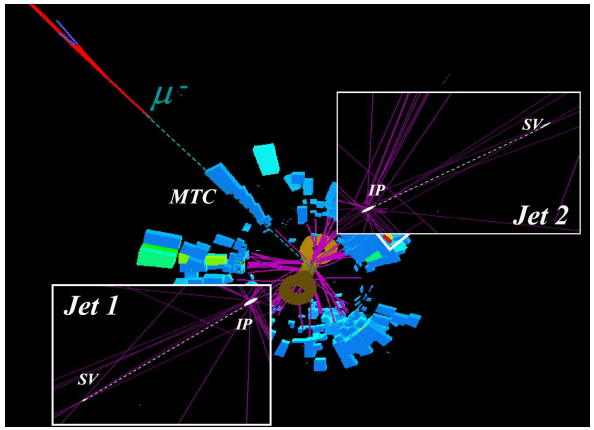
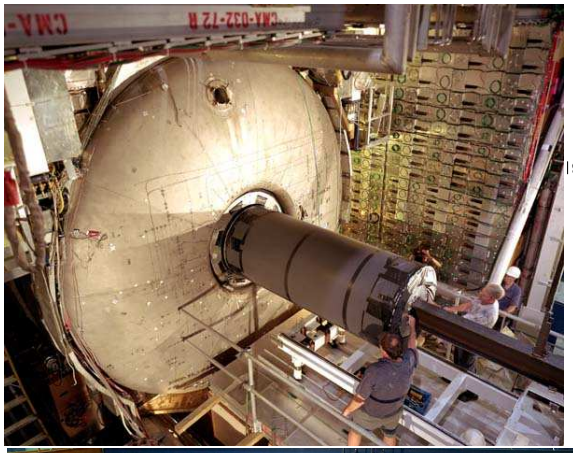
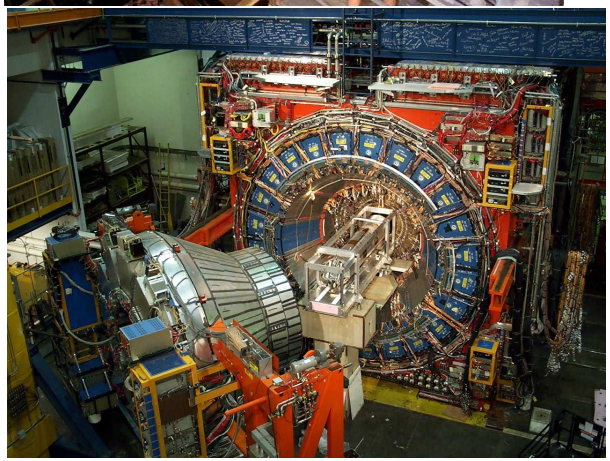
Physics at the Tevatron Experiments

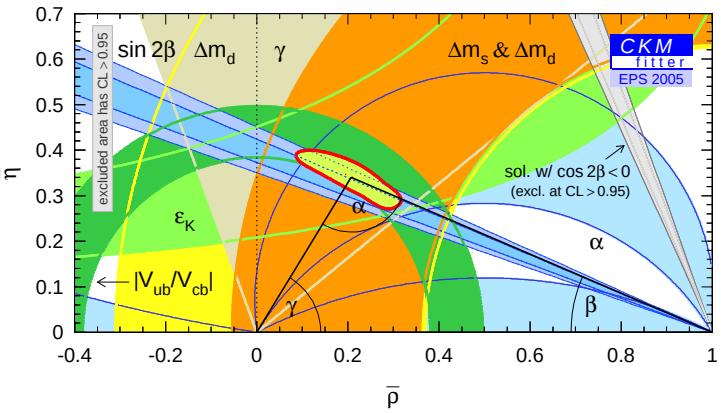
Frank Fiedler, LMU München

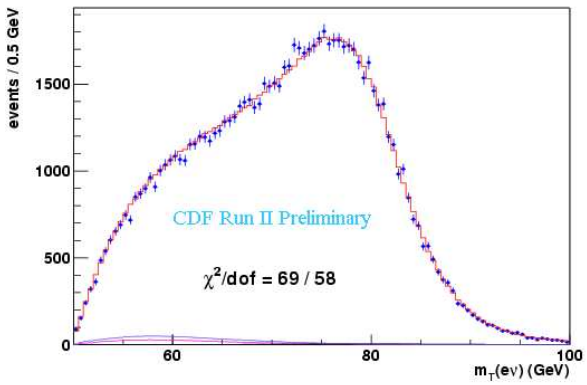
1st Block Course: Physics Topics within the IMPRS
MPI München, October 13, 2005

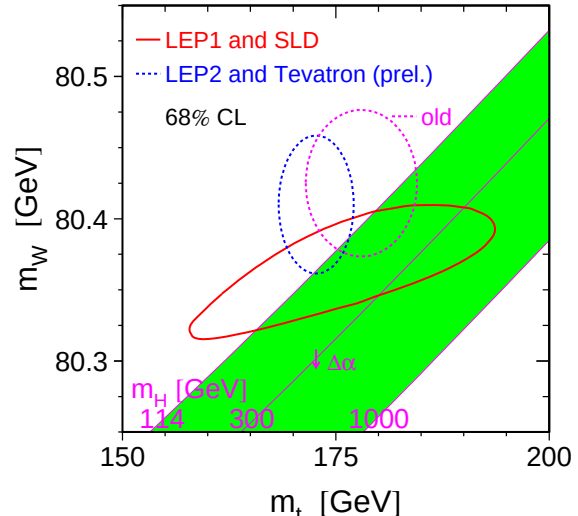






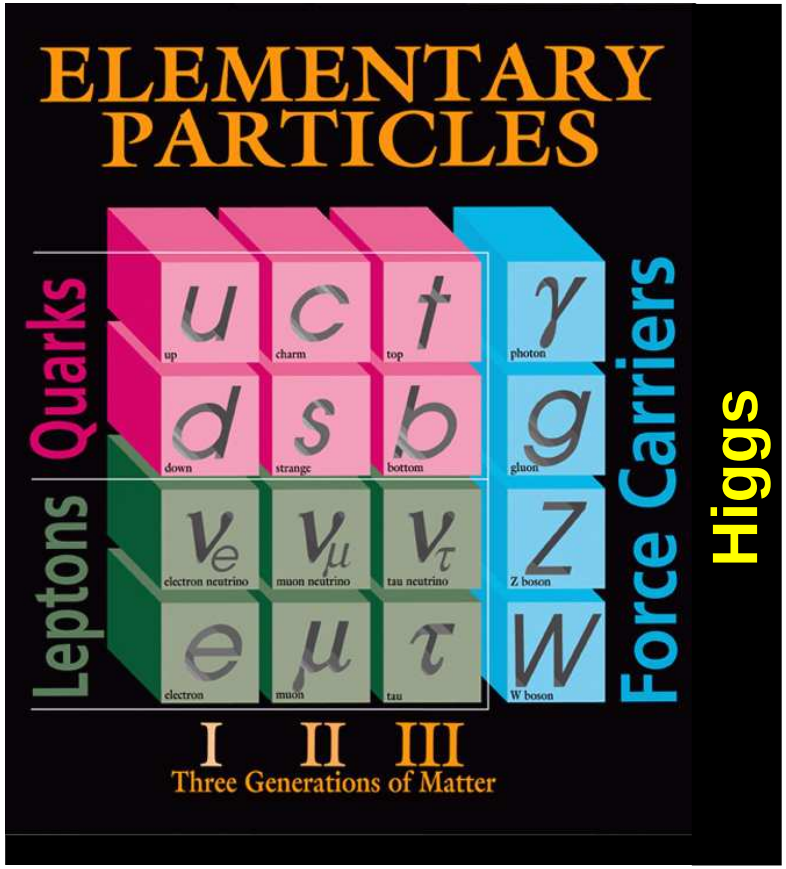






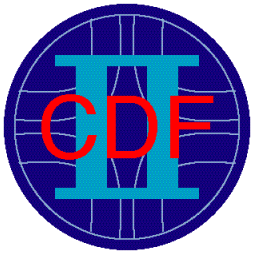
Overview I

Particles in the Standard Model („SM“) of particle physics:

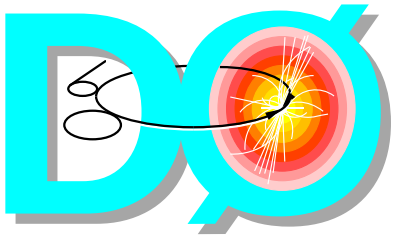


Open questions:

- ? Does the Higgs boson exist?
- ? So many free parameters: masses, couplings, mixing matrix elements, ...
- ? Why 3 generations?
- ? Symmetry between leptons and quarks?
- ? Symmetry between fermions and bosons?
- ? What about the mass hierarchy?
- ? Reason for matter−antimatter asymmetry in the universe?
- ? ...



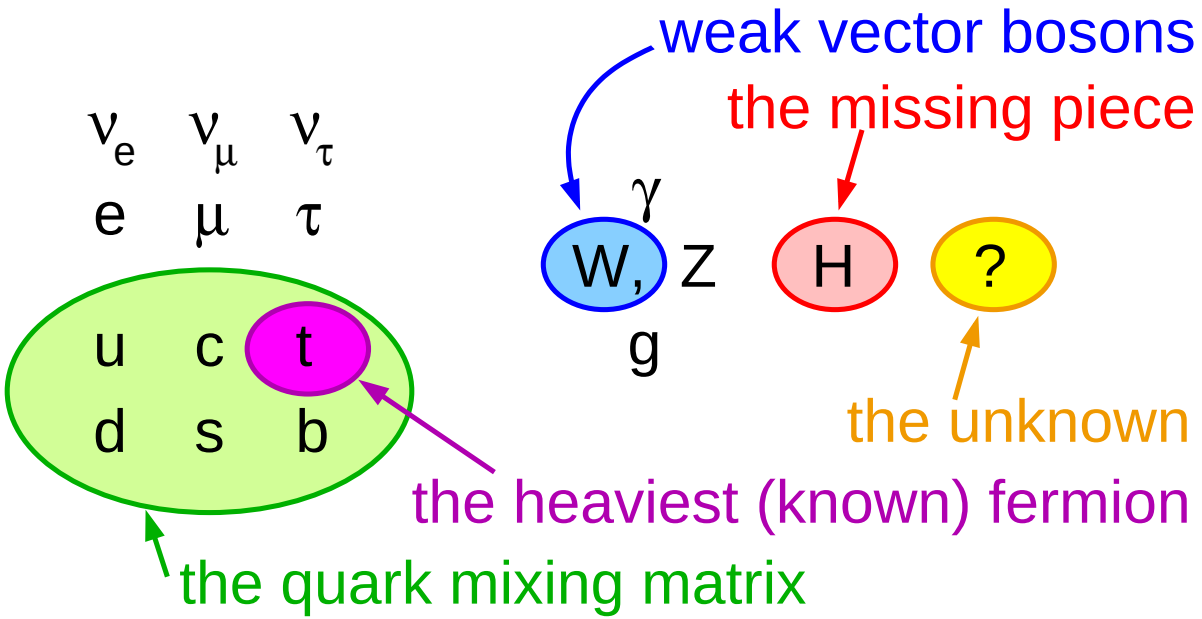
Overview II

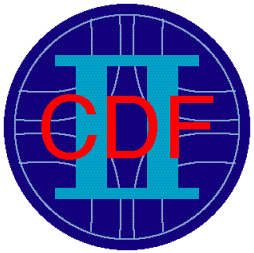


Test the Standard Model:

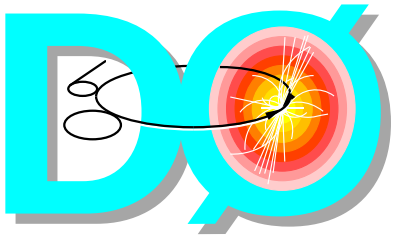
- hunt the Higgs boson,
- confront SM predictions with precision measurements, and
- directly search for effects beyond the SM

Examples of Tevatron measurements:





Overview III



Wide range of physics topics

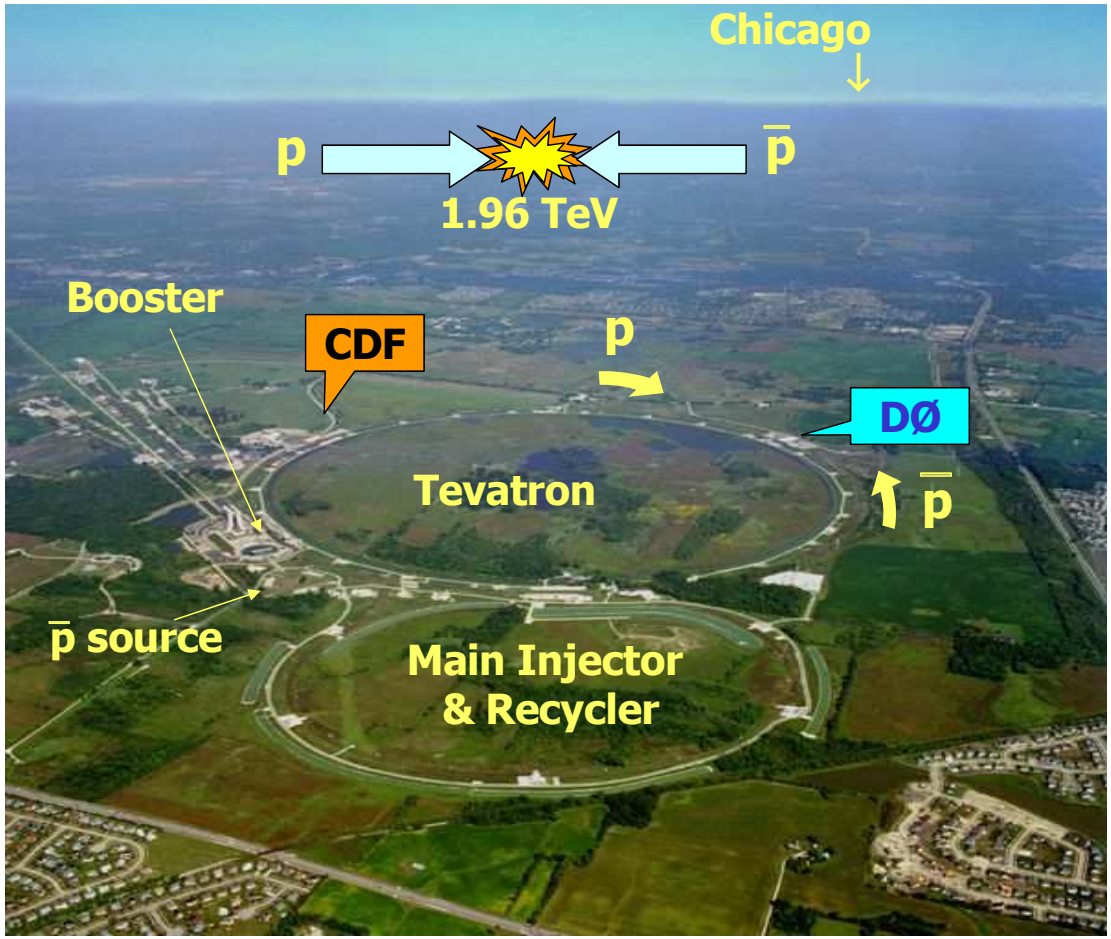
$\rightarrow$ impossible to be complete here!

Instead: examples of key measurements

Overview:

- the Tevatron experiments
- $B_{(s)}$ mixing $\rightarrow$ CKM matrix
- the W boson mass
- the top quark mass
- leptoquarks $\rightarrow$ direct searches for “new physics”

The Tevatron Collider



Proton-antiproton collisions

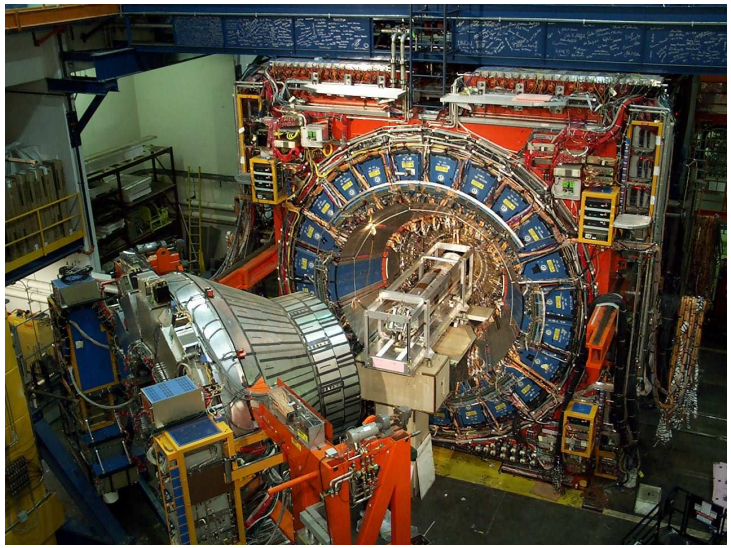
- Run I (1992–1996):
  $E_{\mathrm{CM}} = 1.80\ \mathrm{TeV}$
  $\int \mathcal{L} \mathrm{d}t \simeq 100\ \mathrm{pb}^{-1}$
- Run II (since 2002):
  $E_{\mathrm{CM}} = 1.96\ \mathrm{TeV}$
  $\int \mathcal{L} \mathrm{d}t \simeq 1\ \mathrm{fb}^{-1}$
  (until today)
- Expectation for Run II:
  $\int \mathcal{L} \mathrm{d}t \sim 4 - 9\ \mathrm{fb}^{-1}$

The Tevatron Experiments

Both CDF and DØ: “standard” collider detector configuration

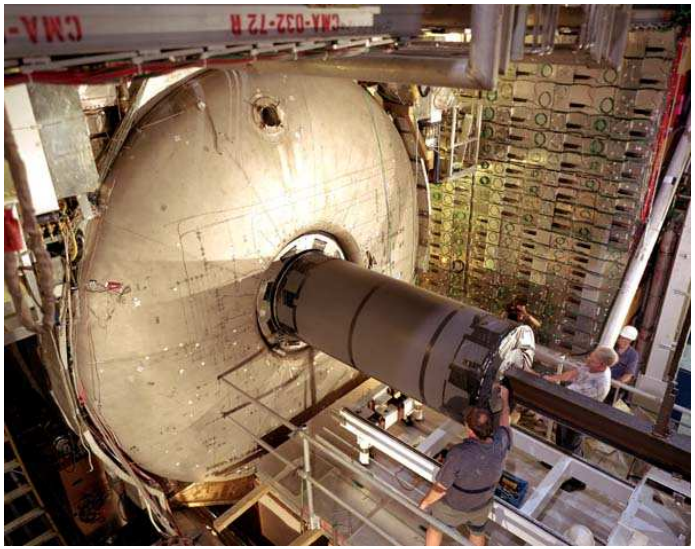
- silicon microvertex and tracking detectors within solenoid
- calorimeter and muon systems
- three trigger levels and DAQ, adapted to Tevatron Run II parameters

CDF:



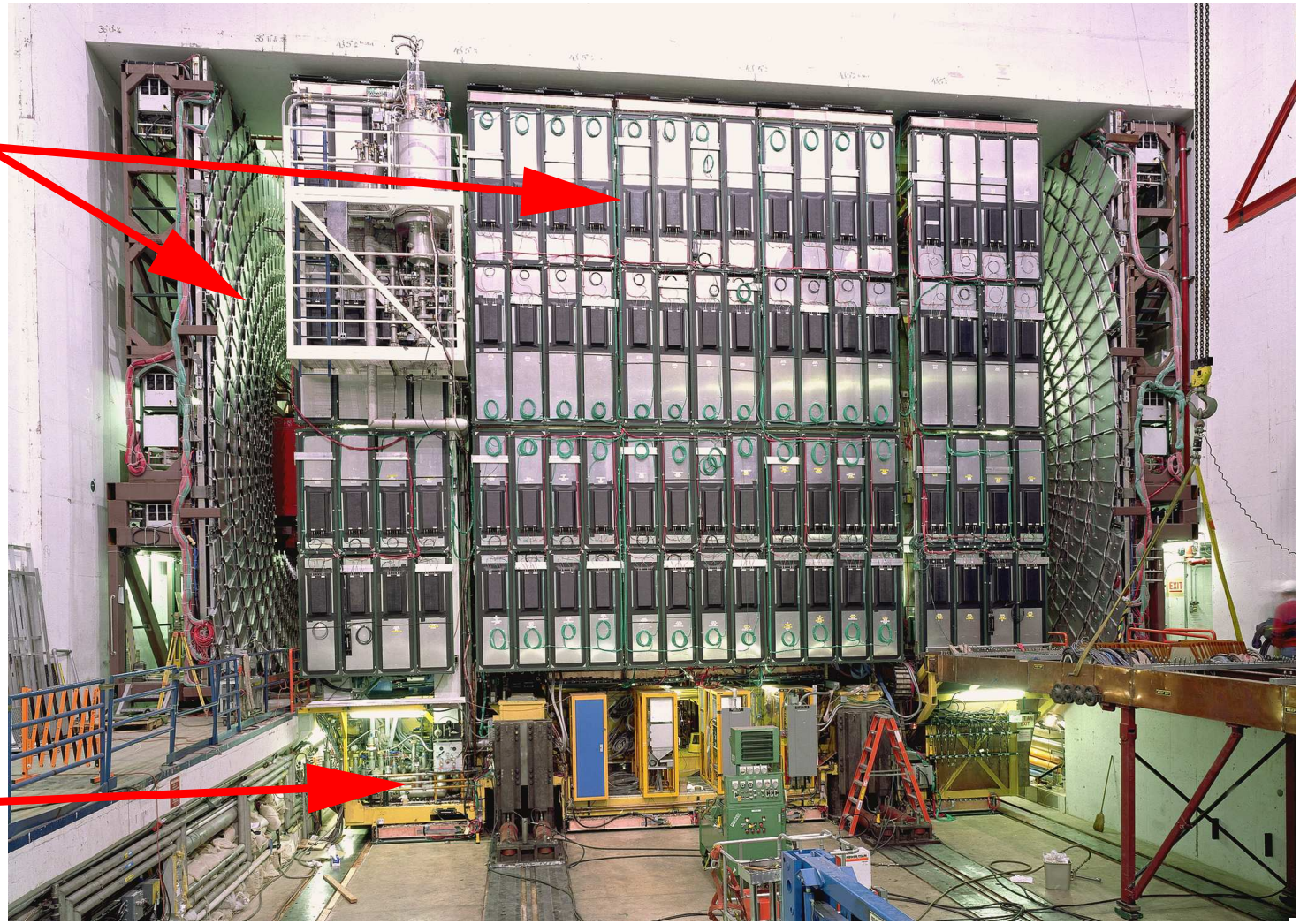
- high rate silicon track trigger
- excellent tracking (i.p., mass resolution)
- particle ID (TOF and dE/dx)

DØ:



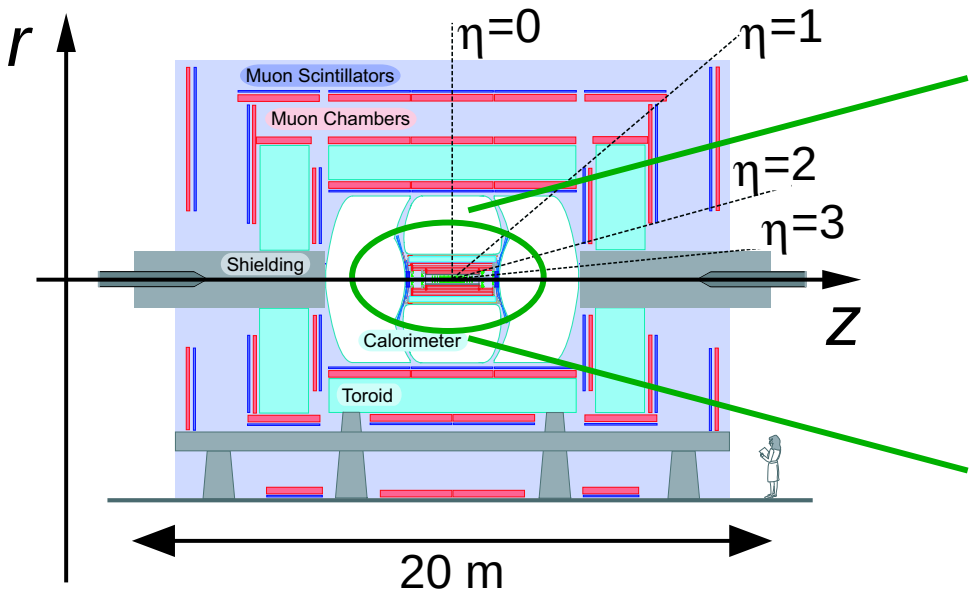
- large muon coverage: $|\eta| < 2.0$
- excellent calorimeter resolution
- central tracking coverage: $|\eta| < 1.6$

The DØ Detector

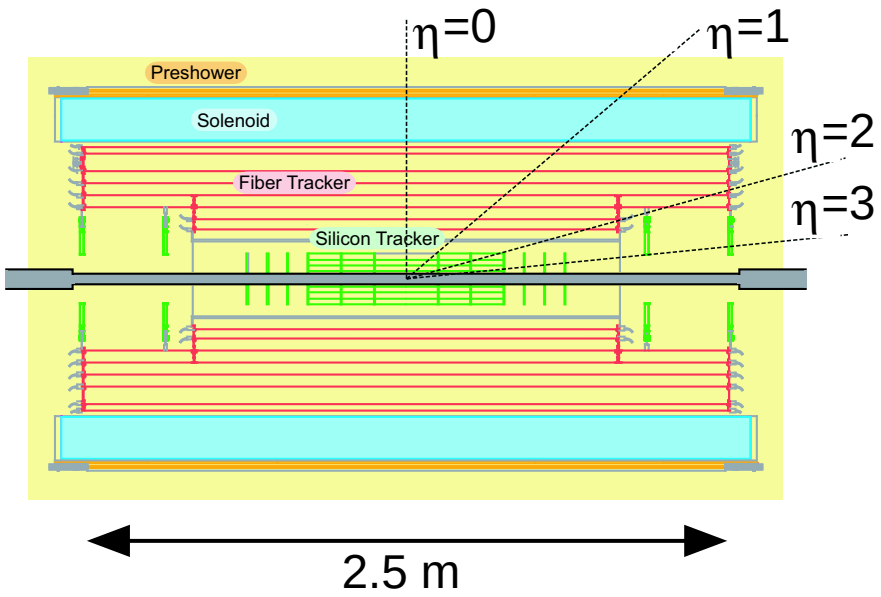


Schematic View of DØ

entire detector:



tracking system:

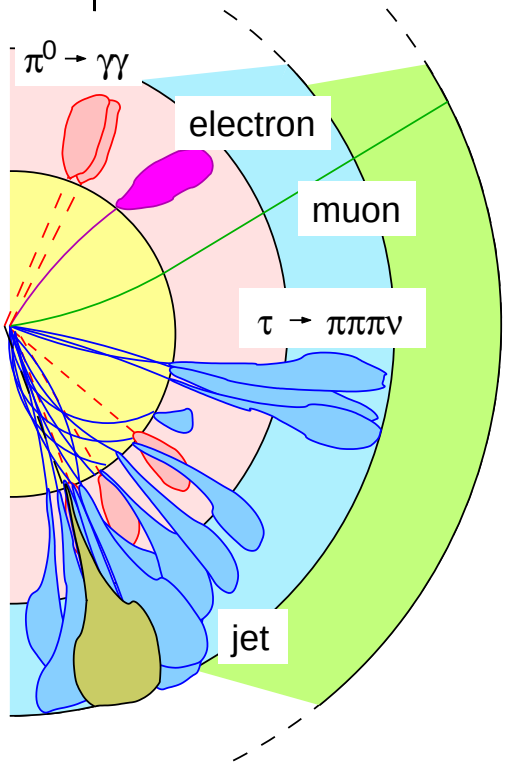


at hadron colliders, use as coordinate system: $(r,\ \eta,\ \phi)$

- pseudorapidity $\eta = -\ln\tan(\theta/2)$ is additive with boosts along the z direction
- helpful because z momentum of colliding partons is unknown

What Do We Want To Measure?

	tracking	calorimeters	muon system
photons		e.m. shower	
electrons	central track	e.m. shower	
muons	central track	little calo energy	muon system track
taus	→ *decay products*		
charged hadrons ($\pi^{\pm}$, $K^{\pm}$, p)	central track	hadronic shower	
neutral hadrons (K^0_L, n)		hadronic shower	
quarks, gluons	→ *particle jet*		
neutrinos	→ *nothing...*		



GeV particles – typically:

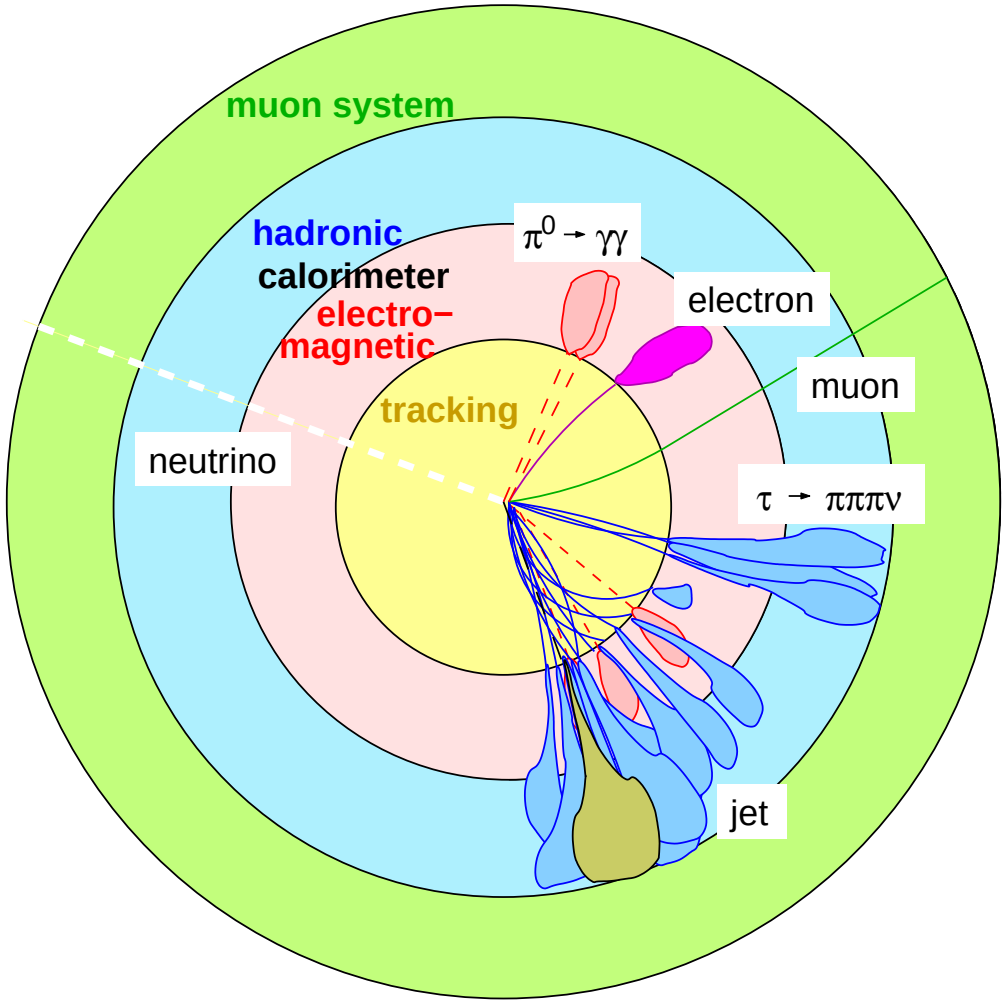
p_t = 1.. 10 GeV: low transverse momentum
p_t = 10..100 GeV: high transverse momentum

What Do We Want To Measure?

neutrinos: leave no trace in detector

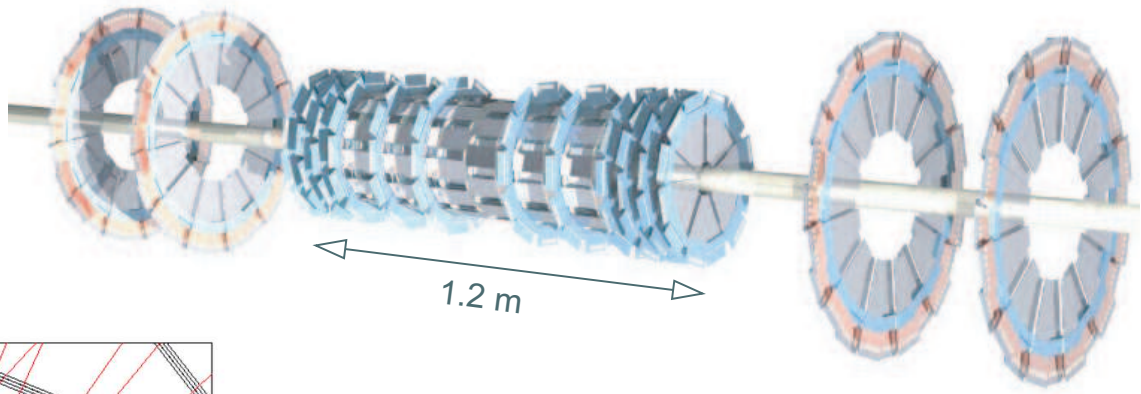
$\rightarrow$ infer transverse momentum from transverse momentum imbalance ($\not\!\!E_{\mathrm{T}}$: "missing transverse energy")

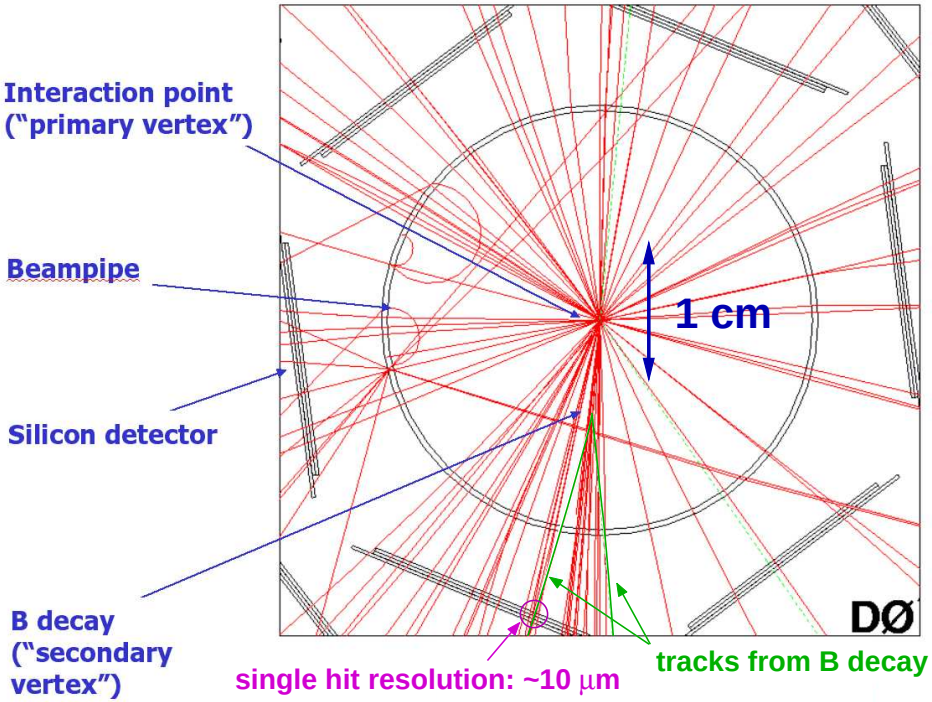
$\rightarrow$ need hermetic detector



Charged Particle Tracking (I)

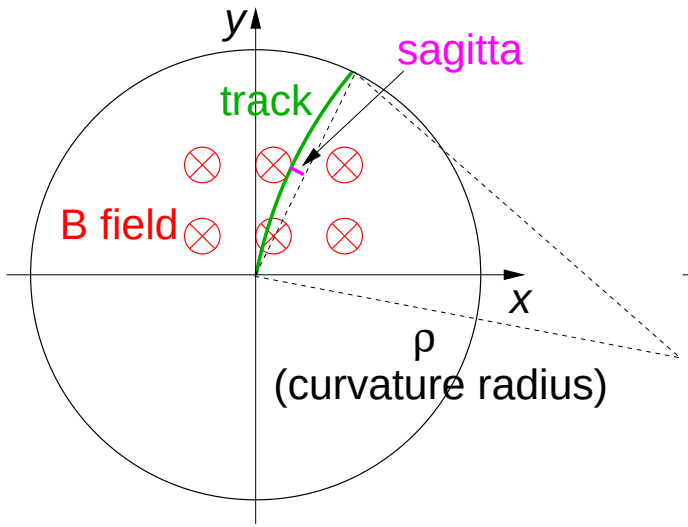
DØ silicon vertex detector:

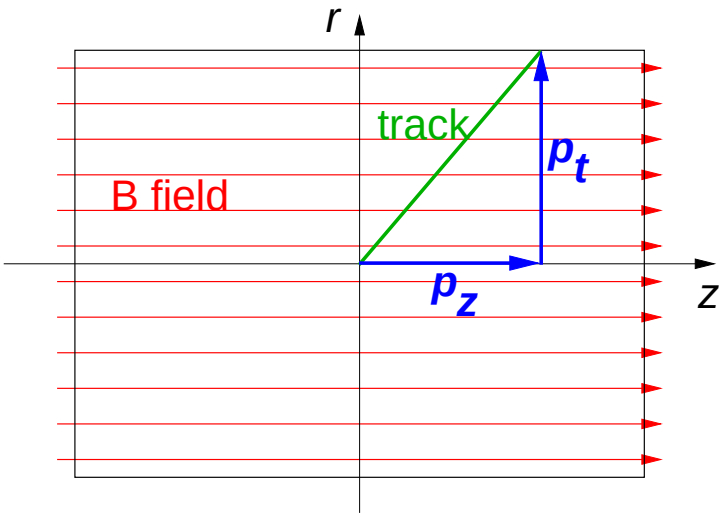




- several layers of silicon strip detectors around beam pipe
- measurement of charged particle origin
  - $\rightarrow$ distinguish several primary vertices (needed at high lumi!)
  - $\rightarrow$ identify b jets, τ decays
  - $\rightarrow$ reject cosmic muon background
- single hit resolution: $\sim 10\mu\mathrm{m}$
  readout channels: $\mathcal{O}(800000)$

Charged Particle Tracking (II)





measurement of charged particle transverse momentum

$\rightarrow$ solenoidal B field

$\rightarrow$ sagitta $s \sim B/p_t$

DØtracking resolution: $\frac{\sigma(p_t)}{p_t} = \underbrace{0.02}_{\text{multiple scattering}} \oplus \underbrace{0.0028 \frac{p_t}{\text{GeV}}}_{\text{geometric resolution}}$

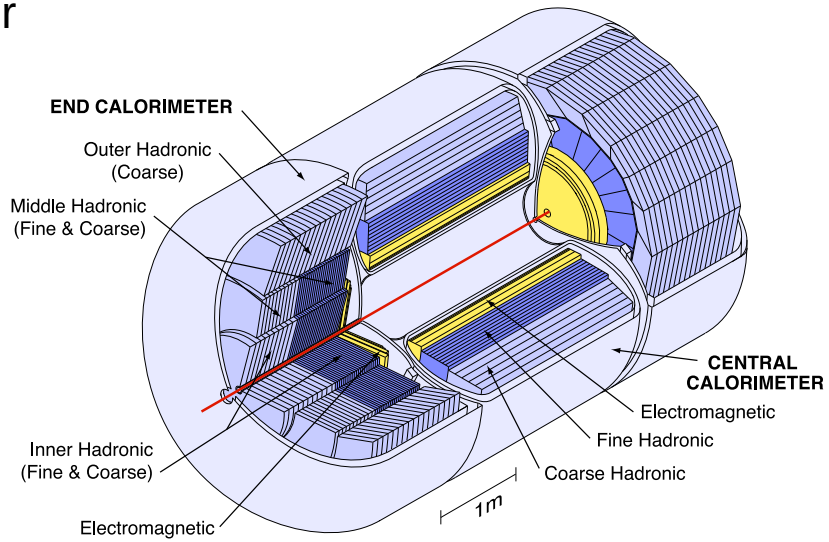
dominates for... small p_t large p_t

Calorimeter System

- **Concept:** destructive measurement of particle energy
- **Electromagnetic showers:** at large energies, ...
  photons lose energy via e^+e^- pair production
  electrons lose energy via bremsstrahlung
- **Hadronic showers:** strong interaction with matter
  production of secondary hadrons
  $\pi^0 \rightarrow \gamma\gamma$ decays: electromagnetic component
- **Energy resolution:**

$$\frac{\sigma(E)}{E} = \underbrace{\frac{a}{\sqrt{E}}}_{\text{statistical shower fluctuations}} \oplus \underbrace{\frac{b}{E}}_{\text{calorimeter noise}} \oplus \underbrace{c}_{\text{signal loss, e.m. vs hadronic energy, mis-calibration}}$$

DØcalorimeter:



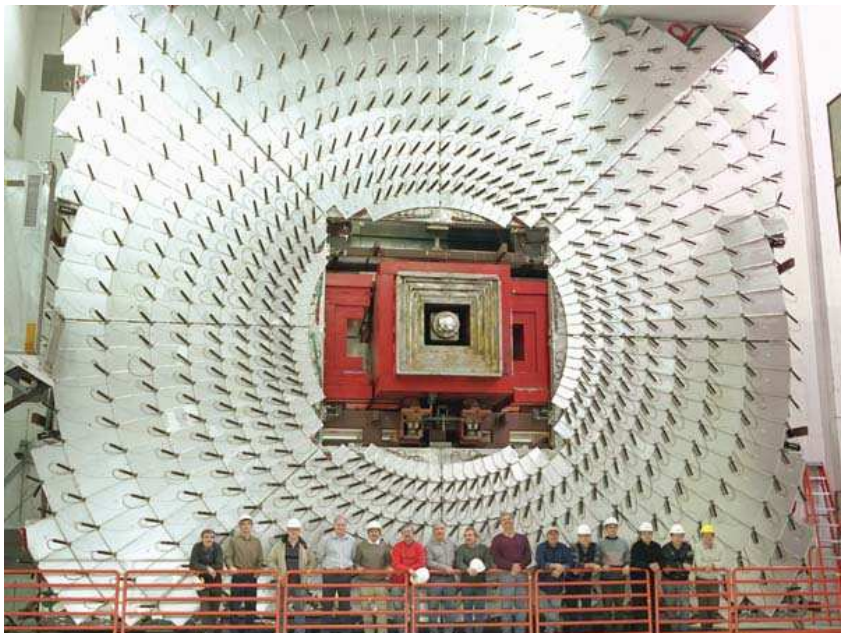
- **Transverse momentum imbalance:** $\rightarrow$ energetic neutrinos
- **(Muon identification)**

Muon System

- Muons: only charged particles that traverse the calorimeter

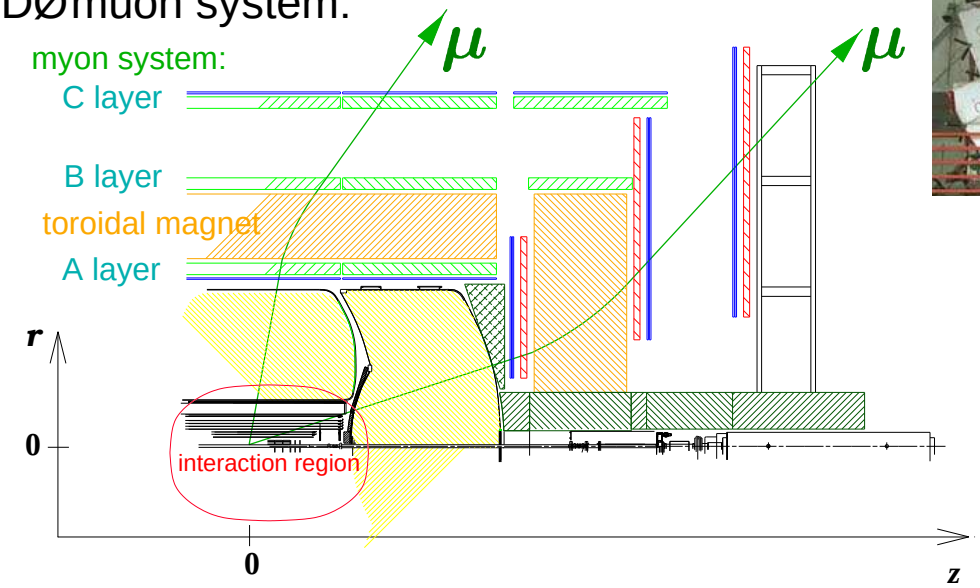
→ reconstruct muon track outside the calorimeter

→ extrapolate to central detector



DØforward scintillators

DØmuon system:



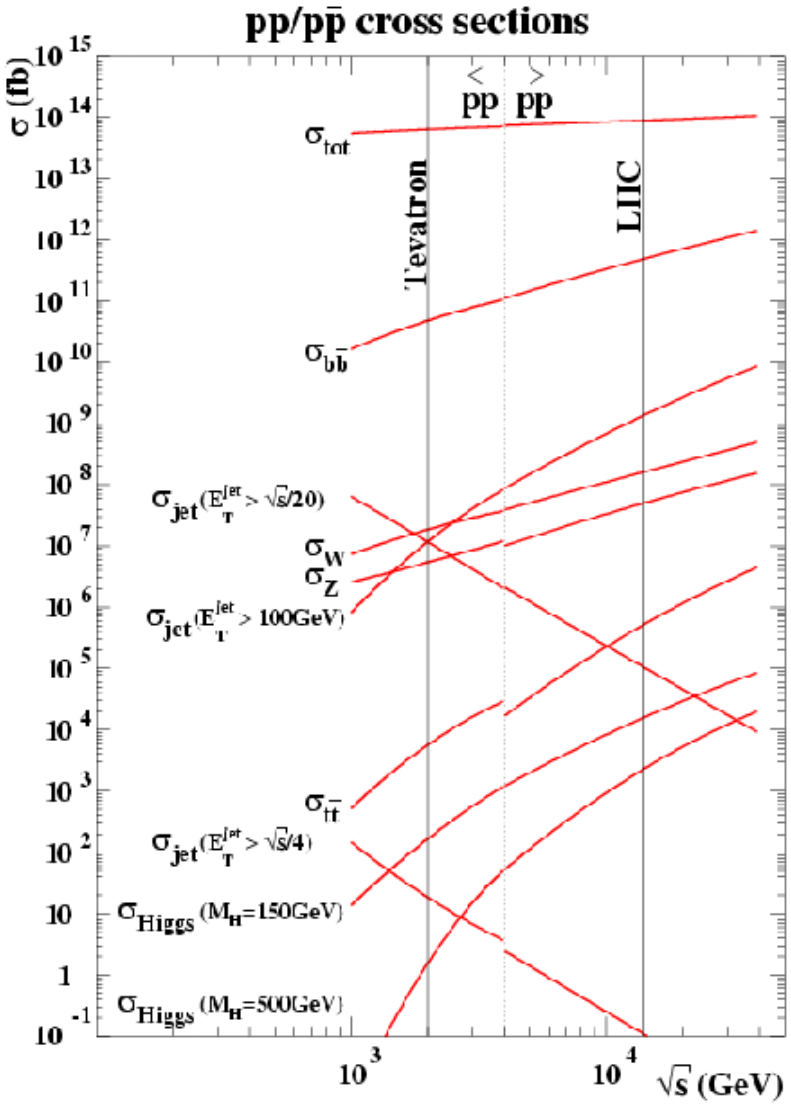
toroidal magnetic field:

→ stand-alone momentum measurement

→ robustness

→ faster than in central detector

What Happens...



total xs

$b\bar{b}$

energetic jet

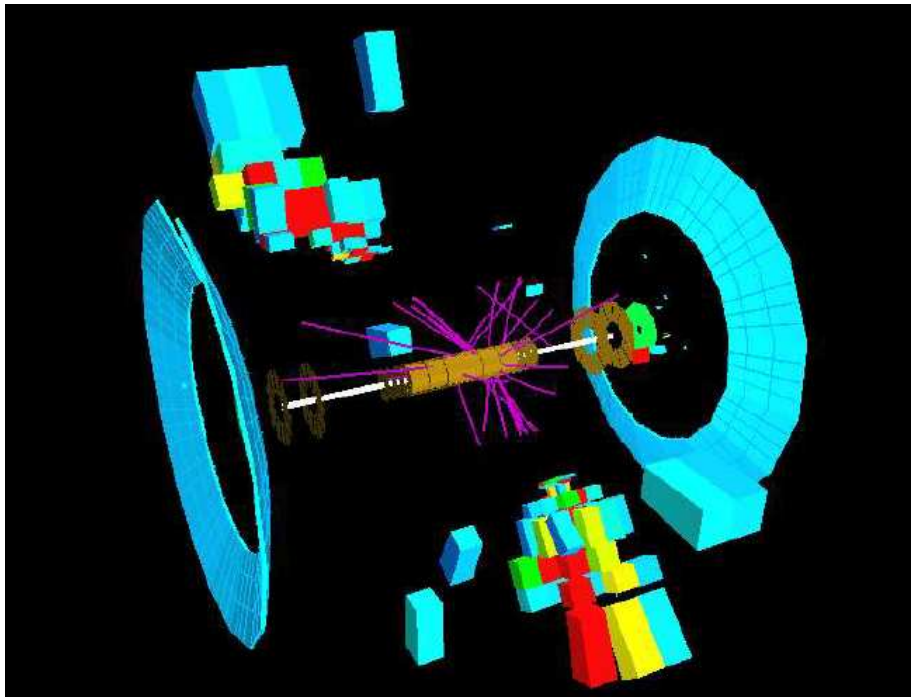
W

Z

$t\bar{t}$

Higgs, m_H
=150 GeV
=500 GeV

...when you switch on accelerator & detector?

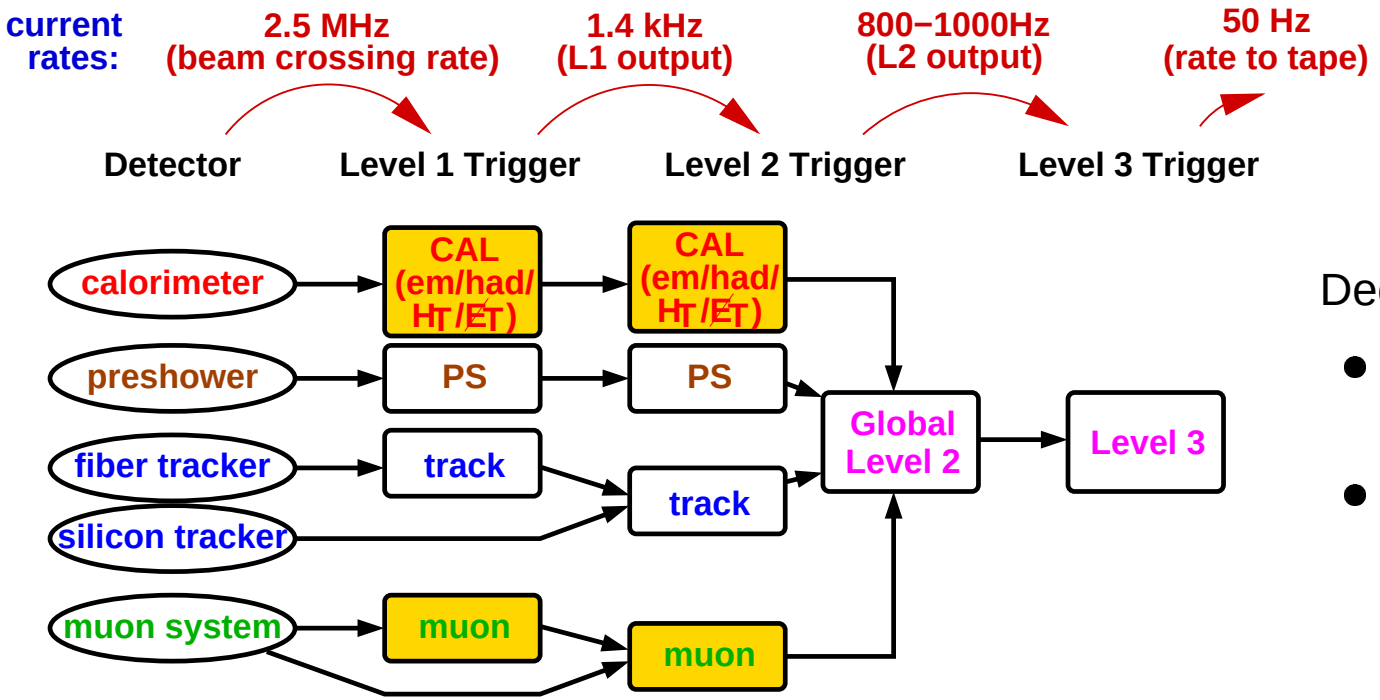


...DAQ overwhelmed with data!

$\rightarrow$ Have to pick the interesting events

Triggering

The DØ trigger system:



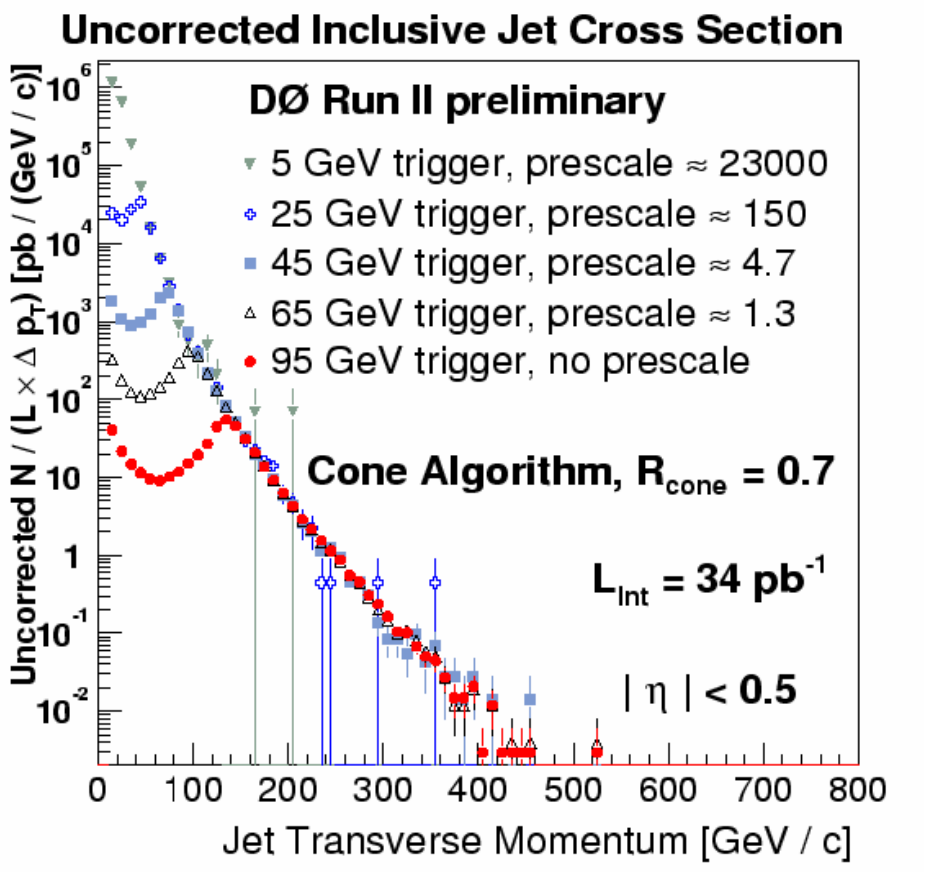
for example:
trigger for top physics based on...

- **energetic jets, electrons**
- **energetic muons**
- **(missing transverse energy)**

Decisions on 3 levels:

- L1: hardware, subdetector-oriented
- L2: preprocessors for every detector element, then event wide correlations
- L3: software, fast event reconstruction

Example: Dijet Events

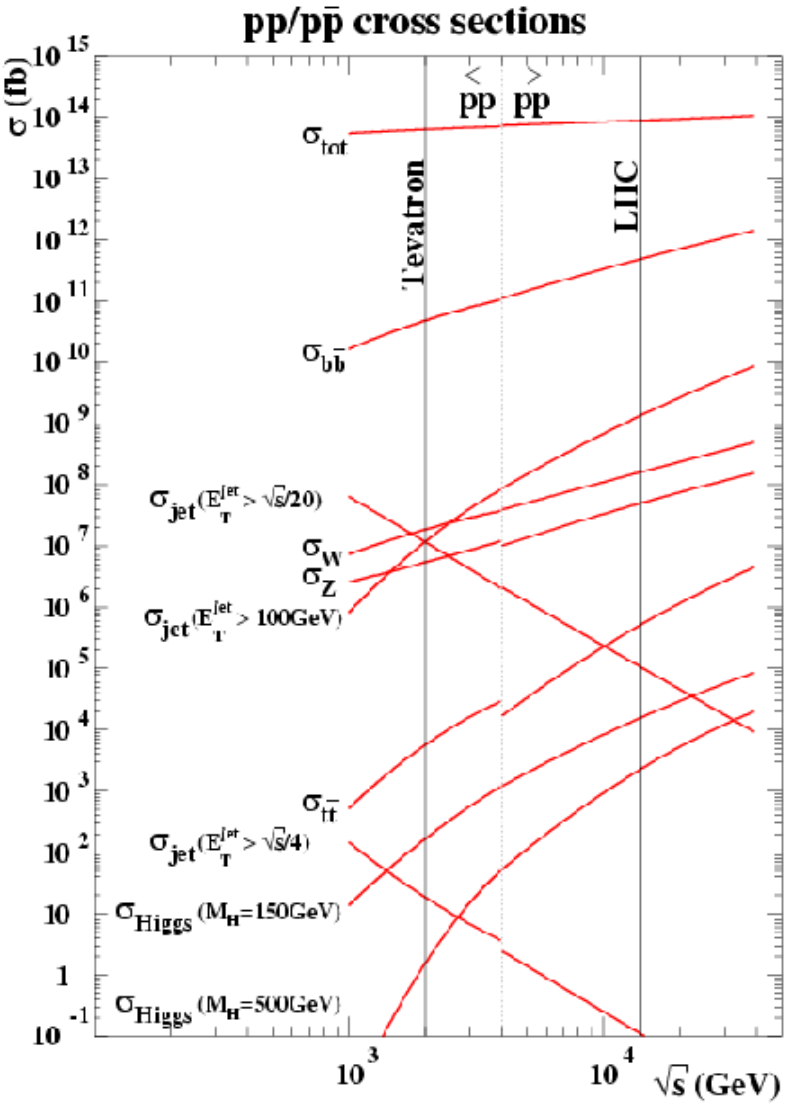


- rate varies over $>$8 orders of magnitude depending on jet p_t

$\rightarrow$ several trigger conditions with different **prescale factors**

$\rightarrow$ similar data rates for each subset of events

The Physics



total xs

$b\bar{b}$

energetic jet

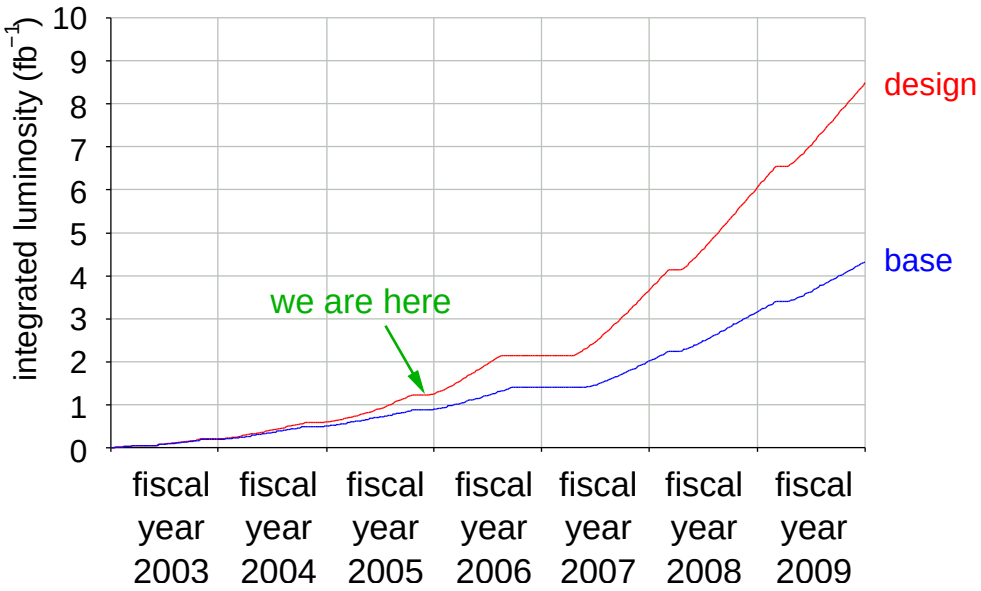
W

Z

$t\bar{t}$

Higgs, m_H
=150 GeV
=500 GeV

projected Tevatron performance:

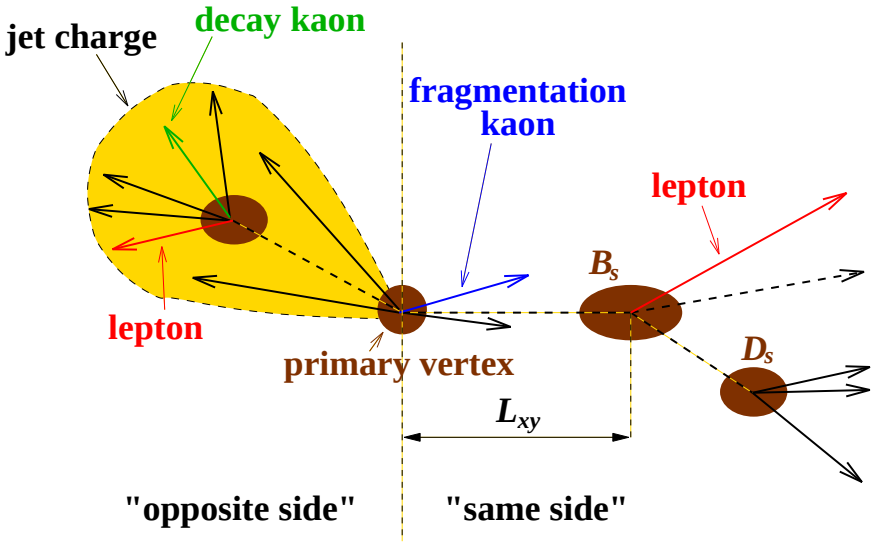


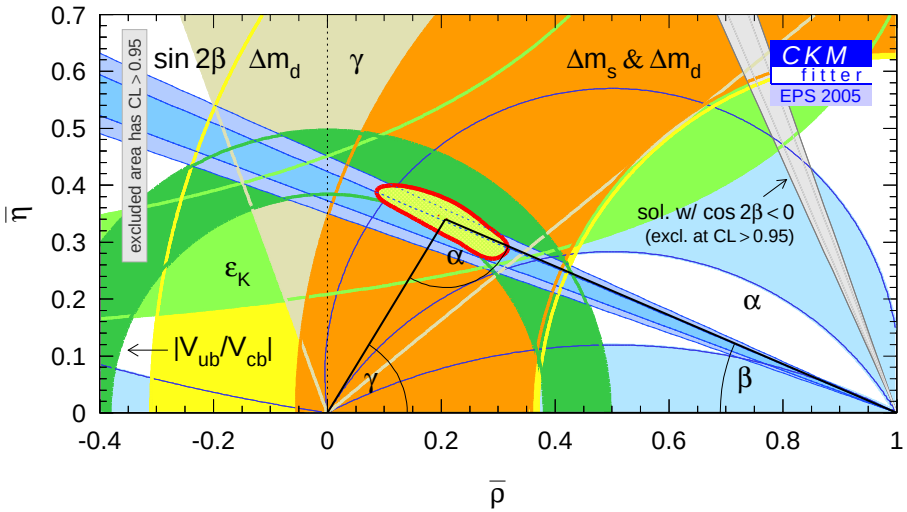
number of events: $n = \sigma \cdot \int \mathcal{L}\,dt$

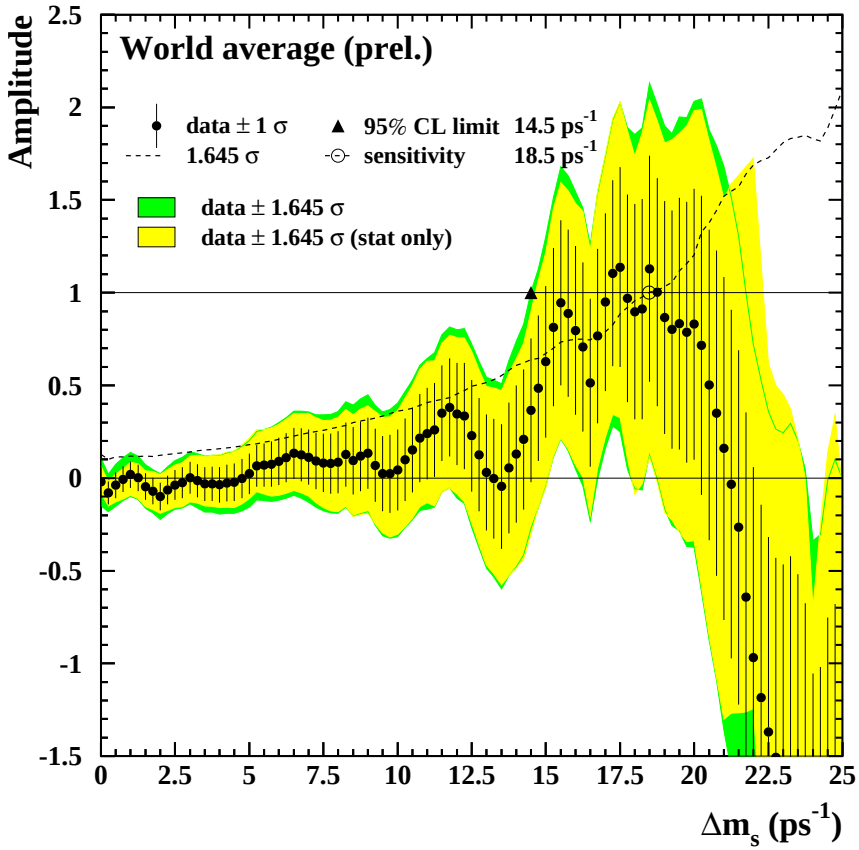
· prescale factor

· efficiency

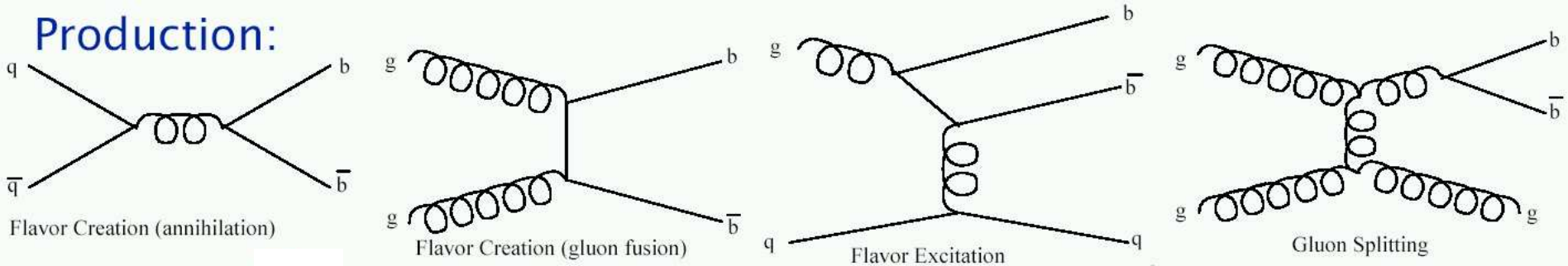
$B_{(s)}$ Mixing


jet charge
decay kaon
fragmentation kaon
lepton
lepton
B_s
D_s
primary vertex
L_{xy}
"opposite side"
"same side"


sin 2β
Δm_d
γ
Δm_s & Δm_d
CKM fitter
EPS 2005
excluded area has CL > 0.95
sol. w/ cos 2β < 0 (excl. at CL > 0.95)
ε_K
|V_ub/V_cb|
α
α
β
γ
ρ̄
η̄


World average (prel.)
data ± 1 σ
1.645 σ
95% CL limit 14.5 ps^-1
sensitivity 18.5 ps^-1
data ± 1.645 σ
data ± 1.645 σ (stat only)
Amplitude
Δm_s (ps^-1)

Why b Physics at the Tevatron?



- large cross-section
- produce all b hadrons

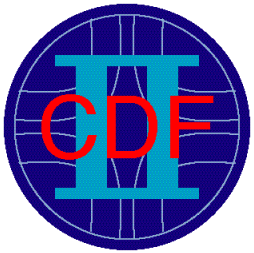
} but {

- background cross-section even larger
- soft p_t spectrum

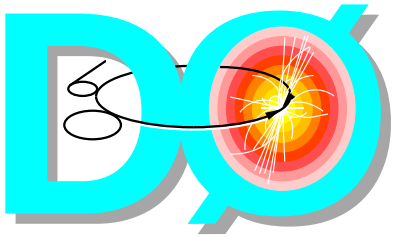
$\rightarrow$ BaBar / Belle $(e^+e^- \rightarrow \Upsilon(4S))$:

$\rightarrow$ Tevatron:

} concentrate on { B_d^0, $B_u^\pm$; B_s^0, $B_c^\pm$, Λ_b



b Physics at the Tevatron



The Tevatron b physics program: complementary to B factories

- $\mathrm{b\bar{b}}$ production cross-section
- spectroscopy
- lifetimes (especially $\mathrm{B_s^0}$, $\mathrm{B_c^+}$, Λ_b)
- searches, for example: $\mathrm{B_s} \to \mu\mu$
- CKM physics:
  - CP violation
  - $\mathrm{B_s}$ oscillations

Concentrate on CKM physics here

The CKM Matrix

weak interaction: couples to “mixture of” quark flavour eigenstates:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

V: relates weak eigenstates and flavour eigenstates

Cabibbo-Kobayashi-Maskawa Matrix (unitary matrix)

$$V = \begin{pmatrix} 0.9739 \text{ to } 0.9751 & 0.221 \text{ to } 0.227 & 0.0029 \text{ to } 0.0045 \\ 0.221 \text{ to } 0.227 & 0.9730 \text{ to } 0.9744 & 0.039 \text{ to } 0.044 \\ 0.0048 \text{ to } 0.014 & 0.037 \text{ to } 0.043 & 0.9990 \text{ to } 0.9992 \end{pmatrix}$$

(PDG 2005)

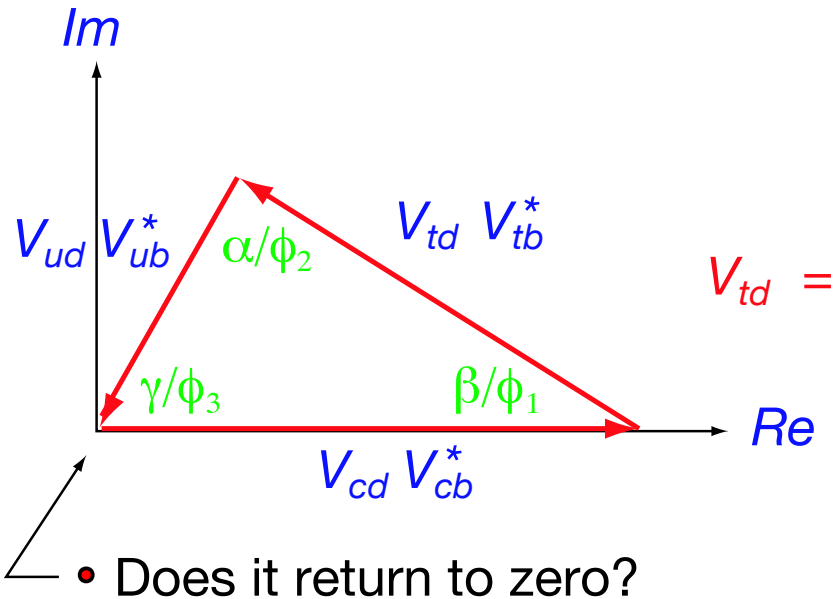
$$\approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

(Wolfenstein parameterisation)

CKM Triangle (I)

- 6 unitarity conditions for the CKM matrix
- most famous one: $V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} + V_{ud}V_{ub}^{*} = 0$

- Vector sum in complex plane:



$V_{td} = |V_{td}|\, e^{-i\beta}$

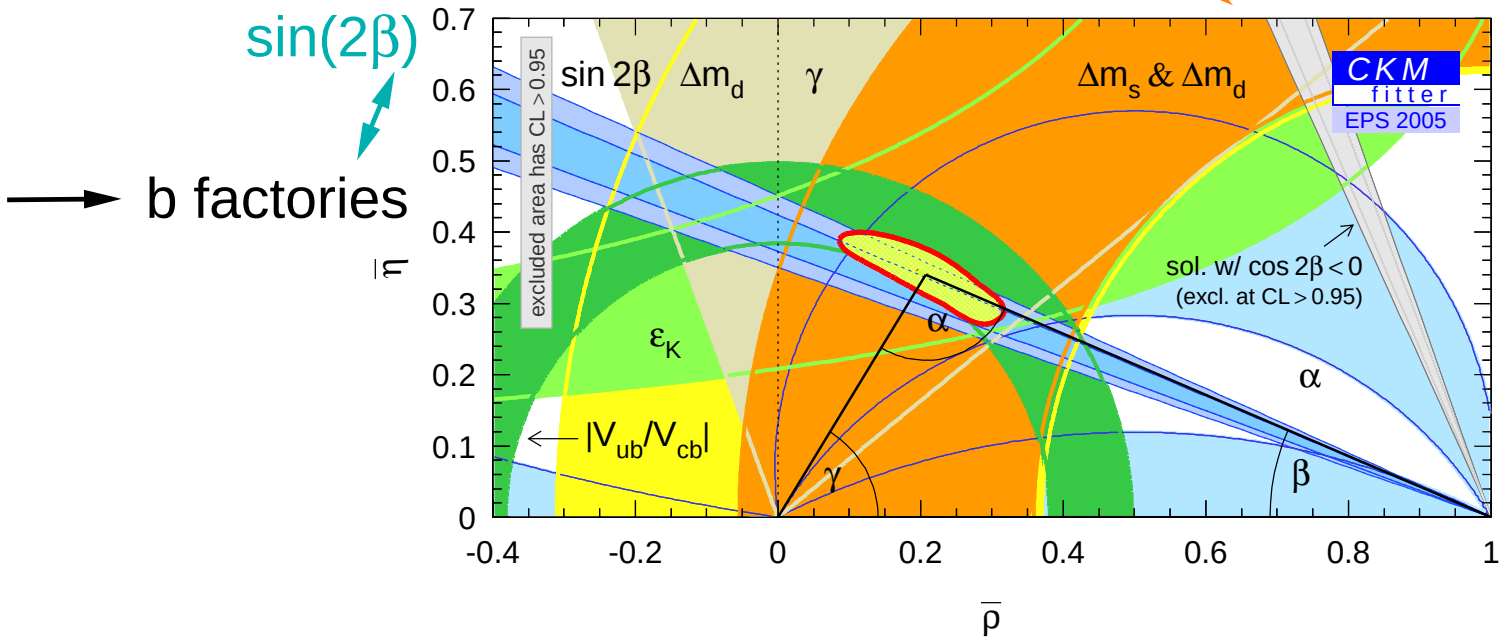
- Does it return to zero?
- Measure lengths of all sides
- Measure all three angles
- Consistent?

CKM Triangle (II)

- 6 unitarity conditions for the CKM matrix
- most famous one: $V_{cd}V_{cb}^* + V_{td}V_{tb}^* + V_{ud}V_{ub}^* = 0$

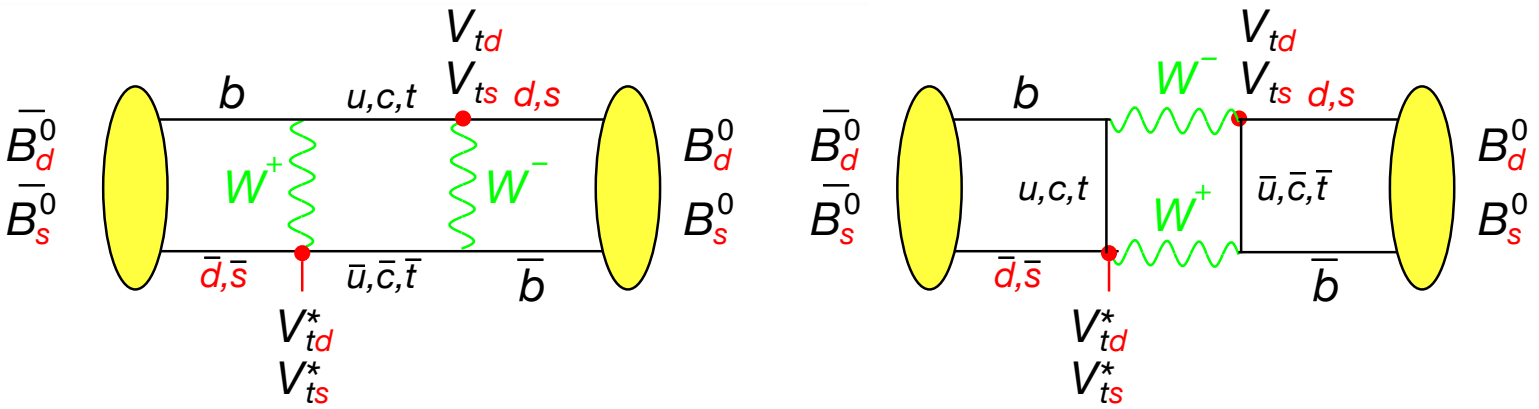
Δm_s → Tevatron

sin(2β) → b factories



B Oscillations

- How B's oscillate:

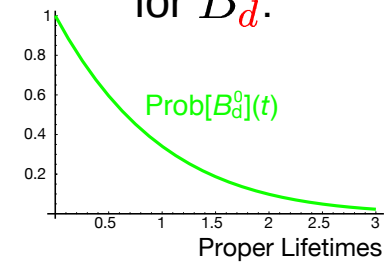


- How a B evolves with time:

$$Prob[B](t) \approx \frac{1}{2}e^{-\Gamma t}\left[1+\cos\left(\Delta m\, t\right)\right]$$

$$Prob[\overline{B}](t) \approx \frac{1}{2}e^{-\Gamma t}\left[1-\cos\left(\Delta m\, t\right)\right]$$

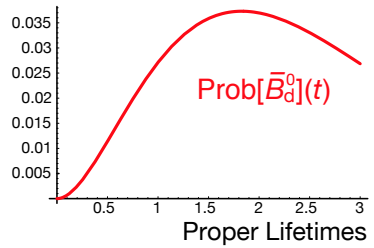
for B_d:



- mass difference $\sim$ oscillation frequency:

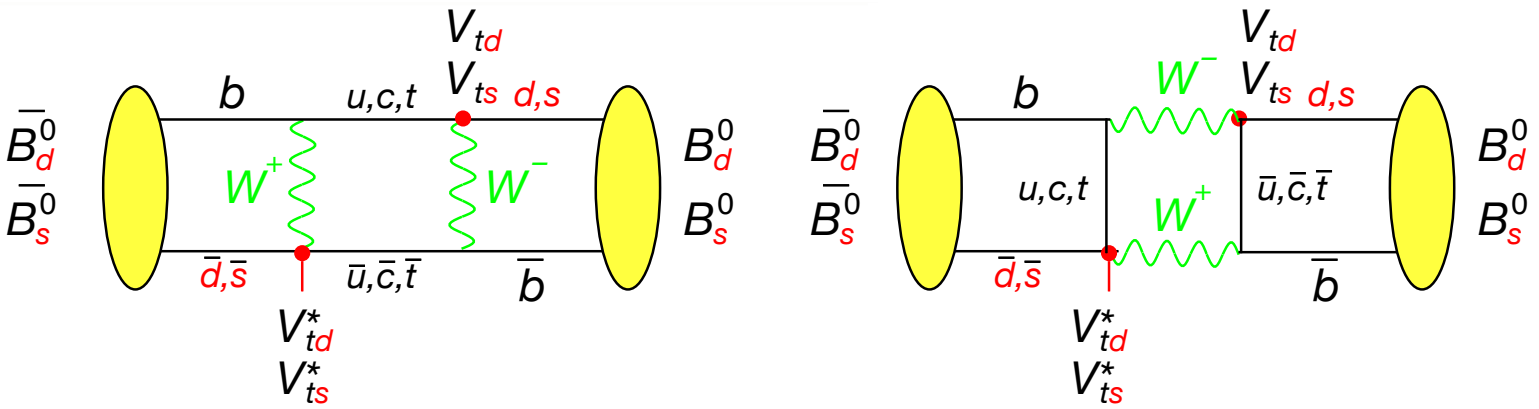
$$\left.\begin{aligned}\Delta m(B_d{}^0) &\sim |V_{tb}^* V_{td}|^2 \\ \Delta m(B_s{}^0) &\sim |V_{tb}^* V_{ts}|^2\end{aligned}\right\}$$

measure both: cancel theoretical uncertainties



B Oscillations

- How B's oscillate:



- How a B evolves with time:

$$Prob[B](t) \approx \frac{1}{2}e^{-\Gamma t}\left[1+\cos\left(\Delta m\, t\right)\right]$$

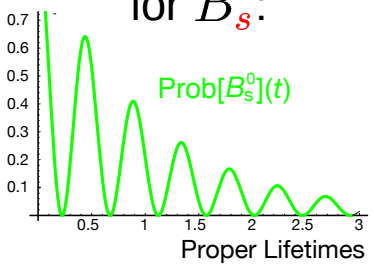
$$Prob[\overline{B}](t) \approx \frac{1}{2}e^{-\Gamma t}\left[1-\cos\left(\Delta m\, t\right)\right]$$

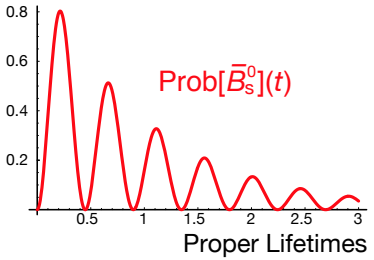
- mass difference $\sim$ oscillation frequency:

$$\left.\begin{aligned}\Delta m(B_d{}^0) &\sim |V_{tb}^* V_{td}|^2 \\ \Delta m(B_s{}^0) &\sim |V_{tb}^* V_{ts}|^2\end{aligned}\right\}$$

measure both: cancel theoretical uncertainties

for B_s:





Mixing Measurements

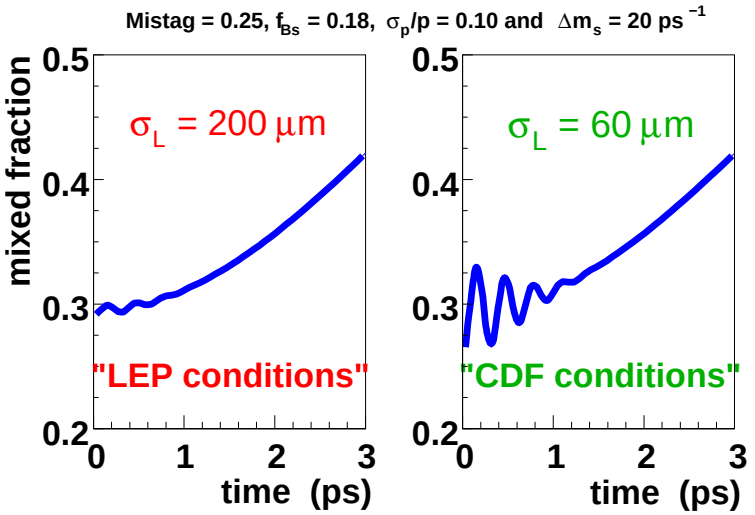
- How to measure B mixing:
  - reconstruct $B_{s/d}$ decays
    typically: B→charged hadrons only
    semimuonic B decays
  - determine proper decay time
    need: decay length
    energy of B
  - determine flavour ($b/\bar{b}$)
    at decay time
    from decay products
  - determine flavour ($b/\bar{b}$)
    at production time
    (...!)

- Significance of a mixing measurement:

$$\sim \sqrt{\frac{S}{S+B}} \cdot e^{-\frac{1}{2}(\Delta m_s \sigma_t)^2} \cdot \sqrt{\epsilon D^2}$$

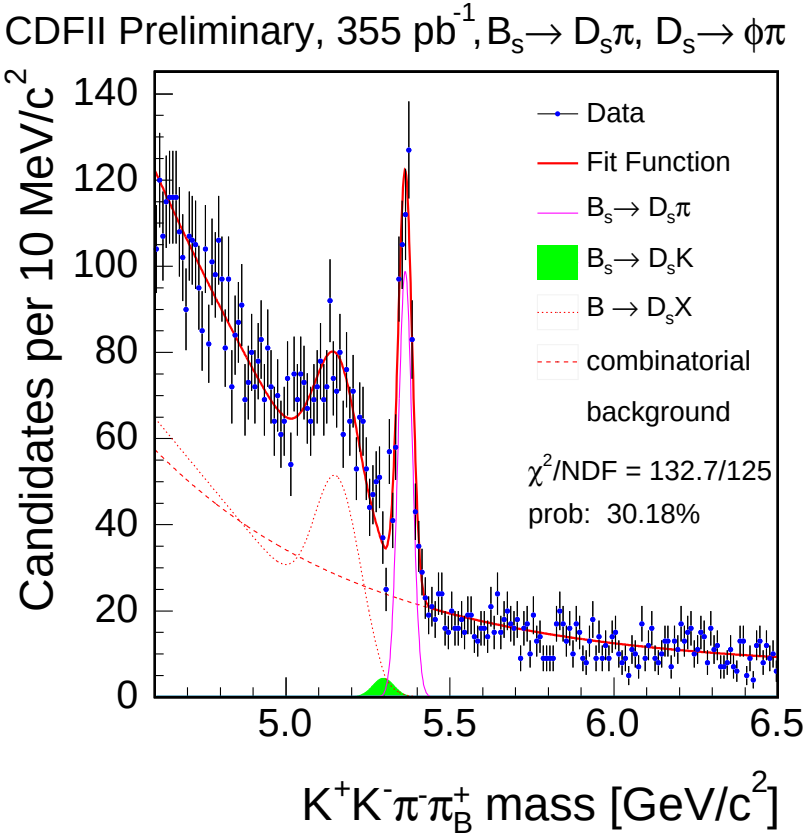
  - signal purity
  - proper time resolution
    → limitation for large Δm_s
  - flavour tag performance

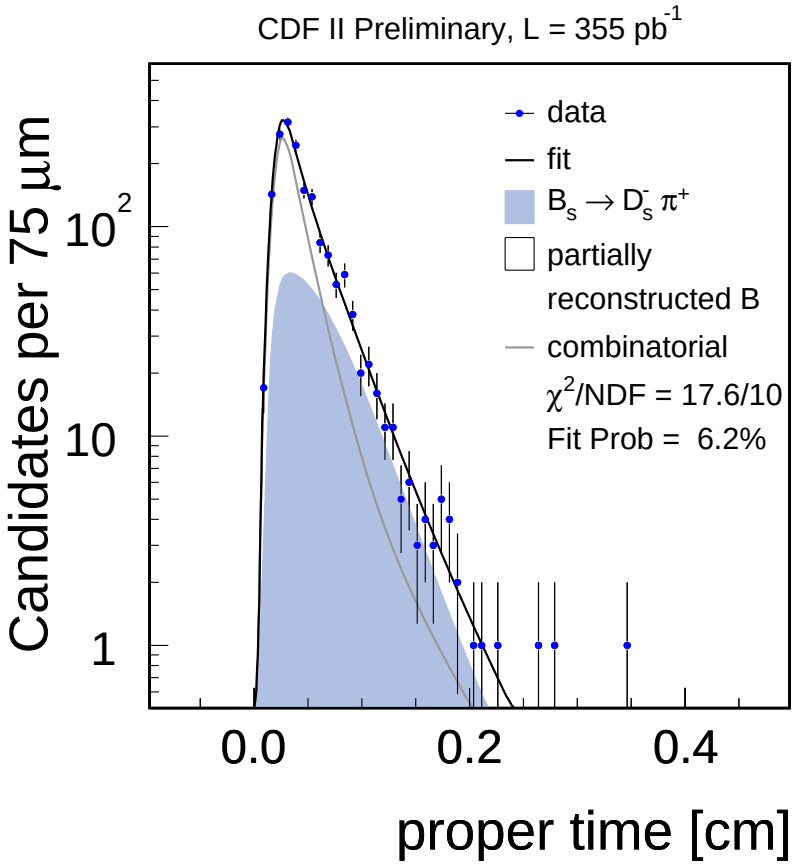
- Measurement conditions:



$B_s \to D_s h$ Decays

- fully reconstructed decay → interesting for B_s mixing





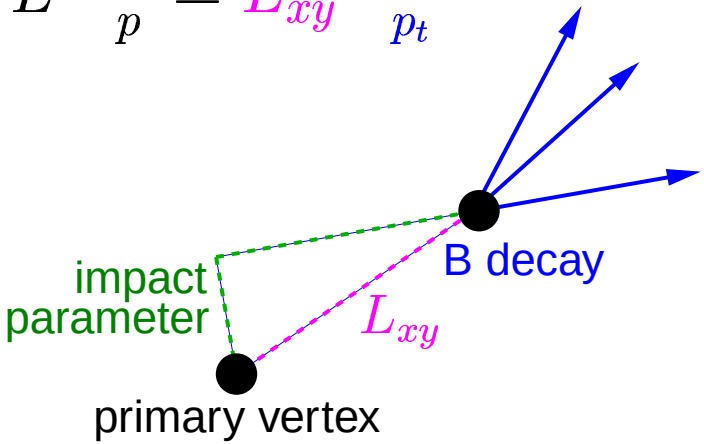
$$B_s^0 \to D_s^+ \pi^-$$
$$D_s^+ \to \phi\,\pi^+$$
$$\phi \to K^+K^-$$

0.1 cm / c = 3.3 ps

$\overline{\tau}(B_s)$ = 1.466±0.059 ps

Decay Time Reconstruction

Proper time reconstruction: $t = L/(\beta\gamma) = L \cdot \frac{m}{p} = L_{xy} \cdot \frac{m}{p_t}$



- hadronic decays: fully reconstructed

  $\Rightarrow \sigma(L_{xy})$ dominates

  $\rightarrow$ CDF: $\sigma(t) = 0.067\,\mathrm{ps}$

  $\rightarrow$ DØ: $\sigma(t) = 0.110\,\mathrm{ps}$

- semileptonic decays: neutrino contribution unknown

  $\sigma(p_t)/p_t \sim 15\%$

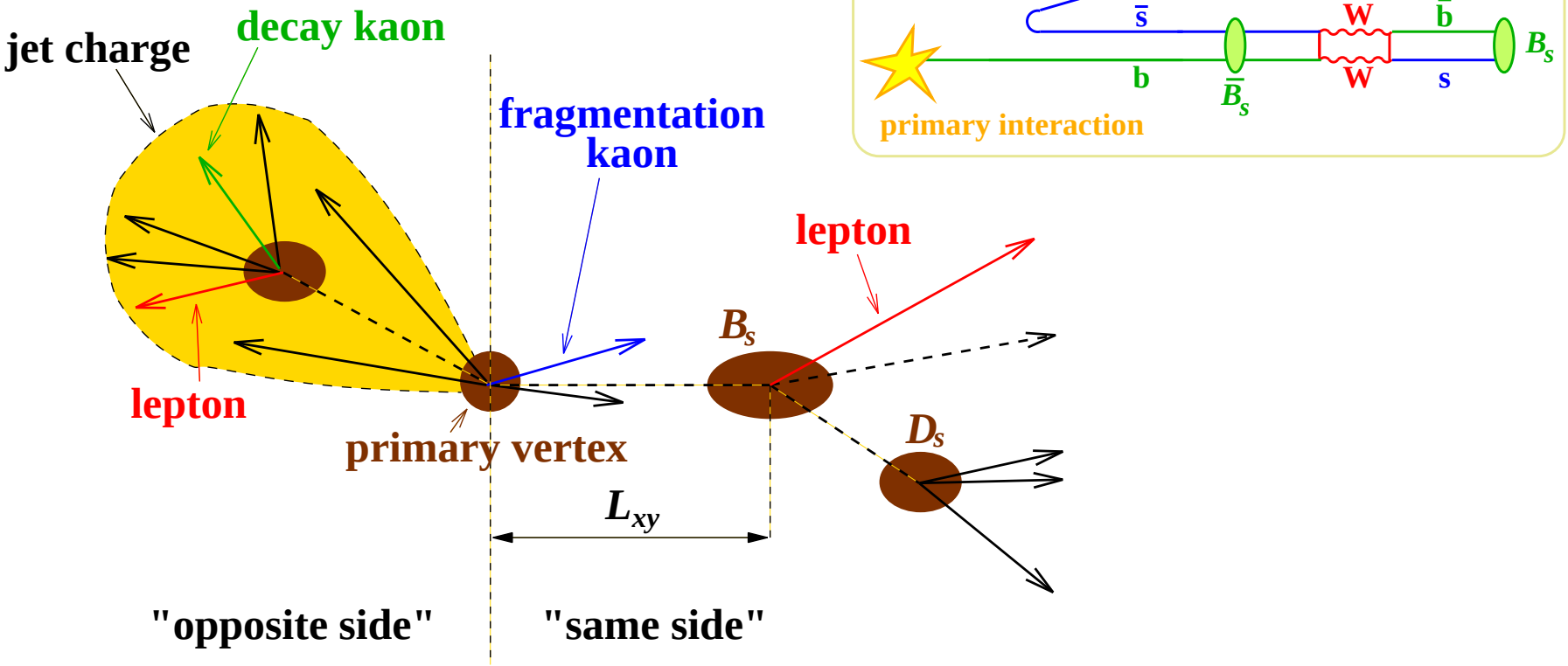
  $\rightarrow \sigma(t) = 0.150\,\mathrm{ps}$

Lifetime: Key for understanding proper time reconstruction

Flavour Identification

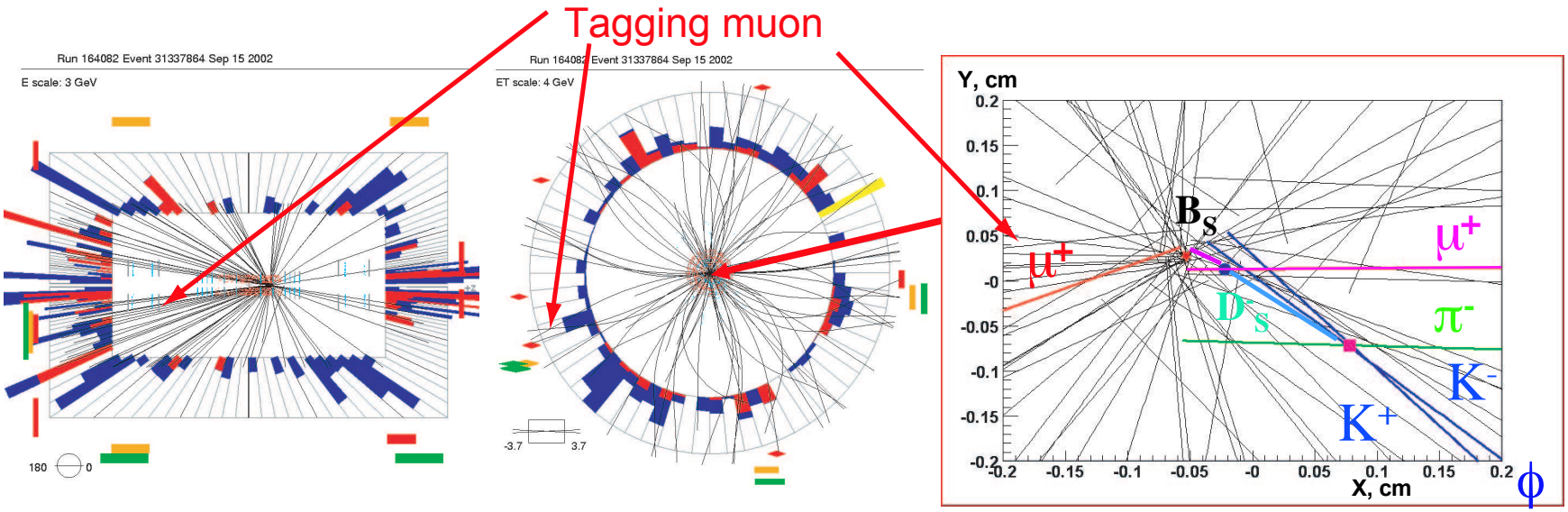
1. identify the B flavour at decay:
   - e.g. pion from $\mathrm{B_s} \rightarrow \mathrm{D_s^- \pi^+}$ decay
   - e.g. lepton from semileptonic $\mathrm{B_s}$ decay

2. identify the B flavour at production:



Event Candidate

- An example of a $B_s \to D_s \mu\nu$ event with $D_s \to \phi\pi$ and a muon in the opposite hemisphere



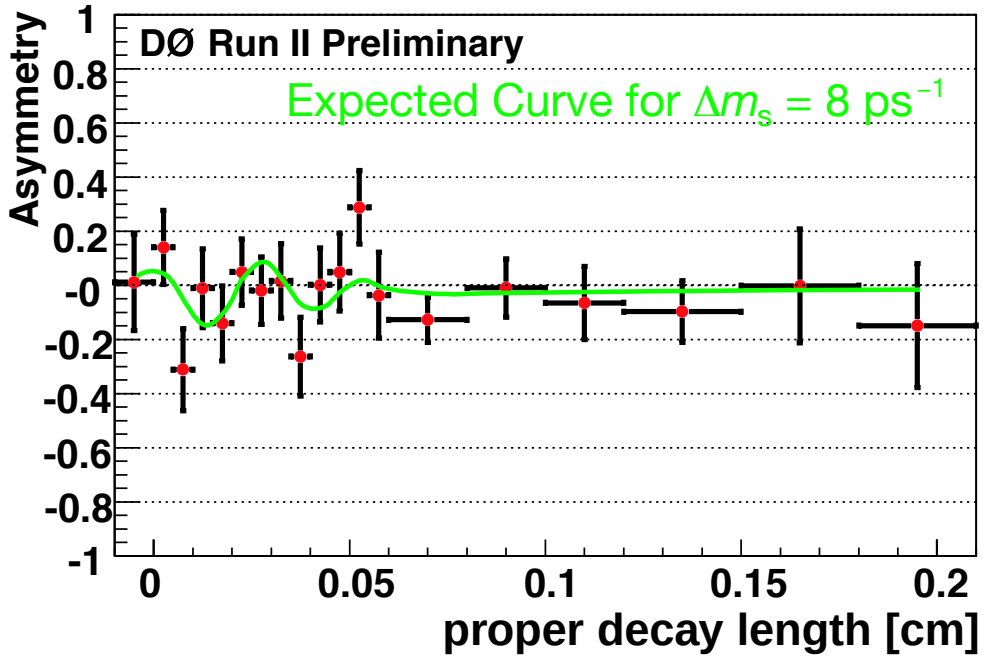
Amplitude Method

- How a B evolves with time: insert ***amplitude A***

$$Prob[B](t) \approx \frac{1}{2}e^{-\Gamma t}\left[1 + A\cos\left(\Delta m\, t\right)\right]$$
$$Prob[\overline{B}](t) \approx \frac{1}{2}e^{-\Gamma t}\left[1 - A\cos\left(\Delta m\, t\right)\right]$$

- expect ***A=1*** for mixing signal, otherwise ***A=0***

$\rightarrow$ scan Δm, measure $A \pm \Delta A$ for each assumed frequency



asymmetry:

$$\frac{unmixed - mixed}{unmixed + mixed}$$

Amplitude Method

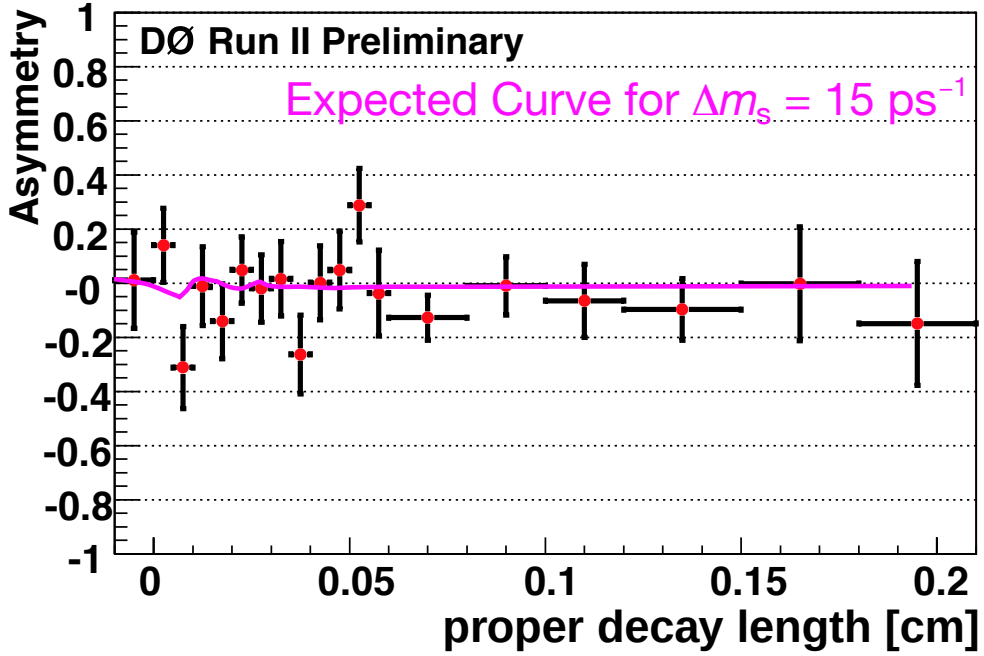
- How a B evolves with time: insert ***amplitude A***

$$Prob[B](t) \approx \frac{1}{2}e^{-\Gamma t}\left[1 + A\cos\left(\Delta m\, t\right)\right]$$

$$Prob[\overline{B}](t) \approx \frac{1}{2}e^{-\Gamma t}\left[1 - A\cos\left(\Delta m\, t\right)\right]$$

- expect ***A=1*** for mixing signal, otherwise ***A=0***

$\rightarrow$ scan Δm, measure $A \pm \Delta A$ for each assumed frequency

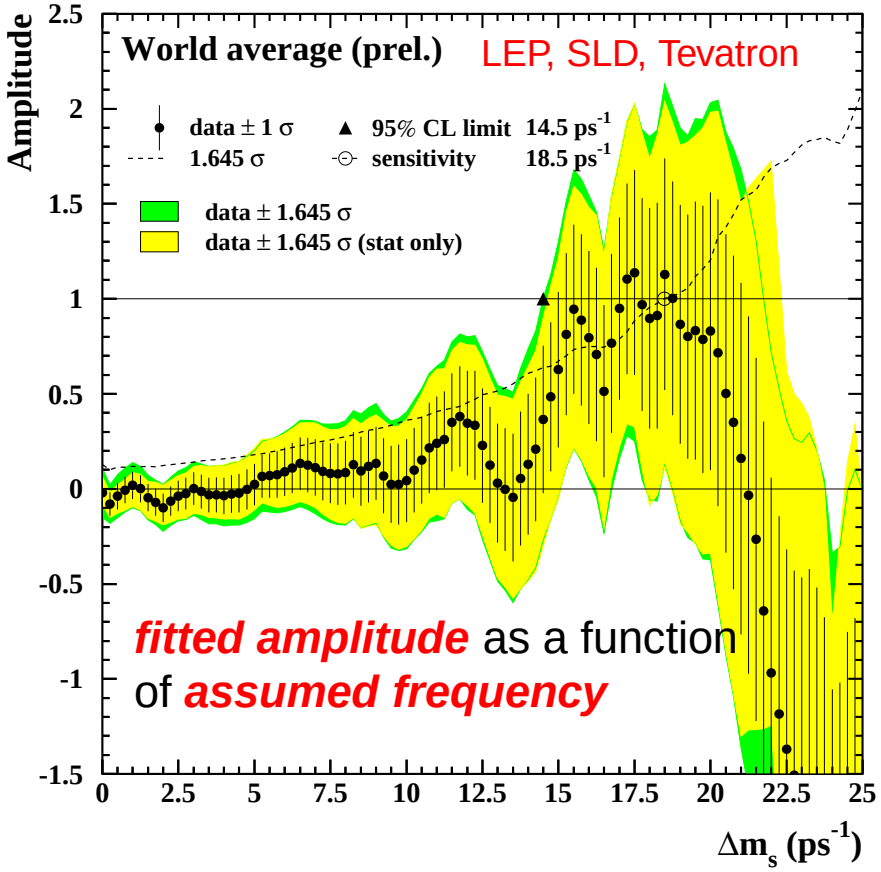


asymmetry:

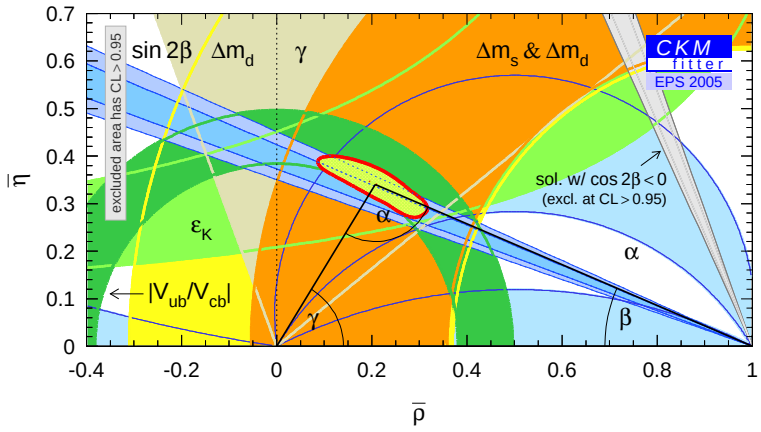
$$\frac{unmixed - mixed}{unmixed + mixed}$$

B_s Oscillations: Status

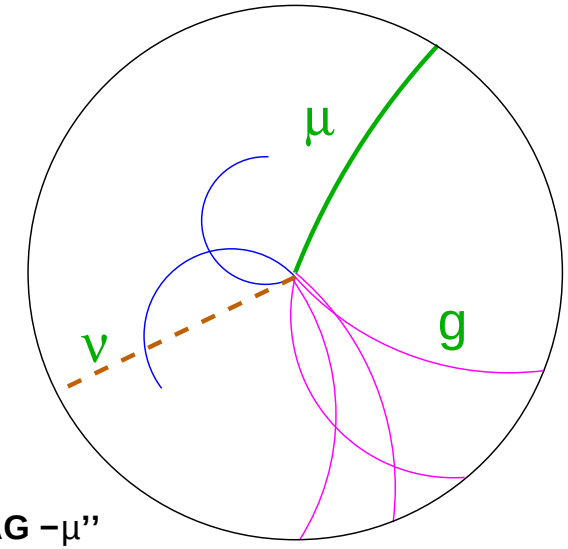
- B_s mixing results so far (HFAG, Winter 2005):



Δm_s → Tevatron

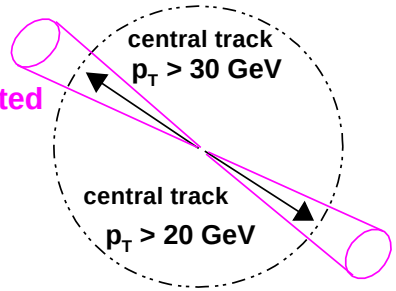


The W Mass

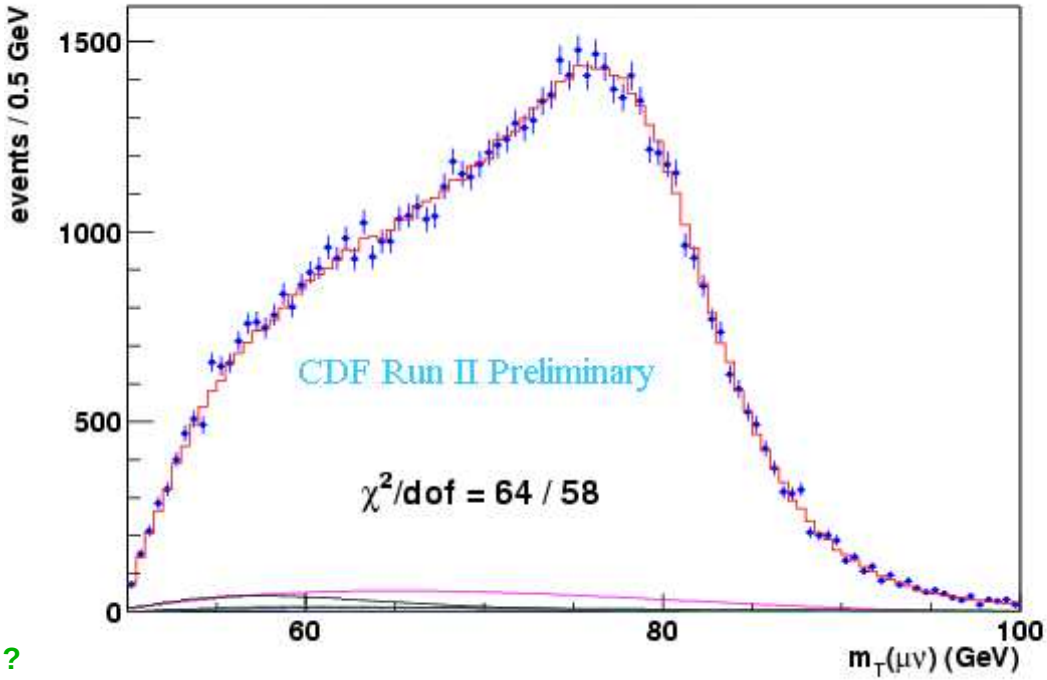


"TAG −μ"

offline μ
fired single μ
trigger

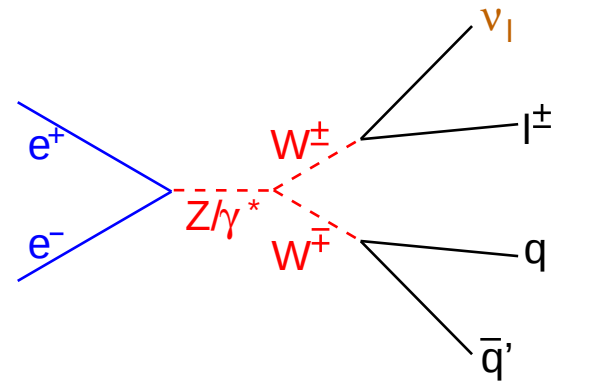


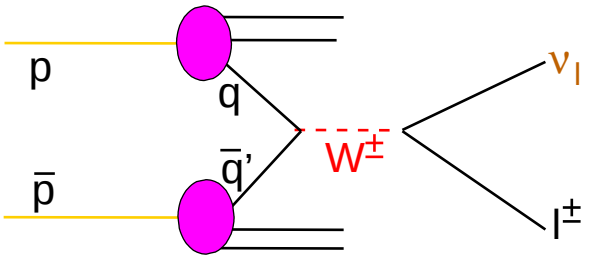
"PROBE −μ"

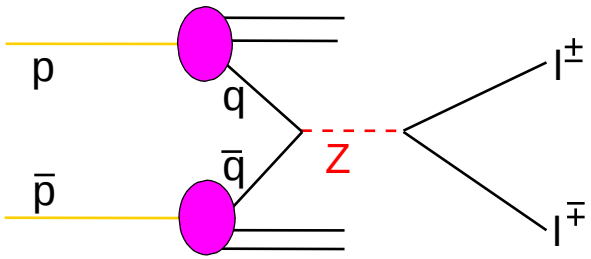


offline μ ?
trigger μ ?

W Production







W production at LEP2:

- pair production
- very clean events
- $\mathcal{O}(10k)$ events per experiment (all channels)

$\mathrm{W} \to \ell\nu$ events at the Tevatron:

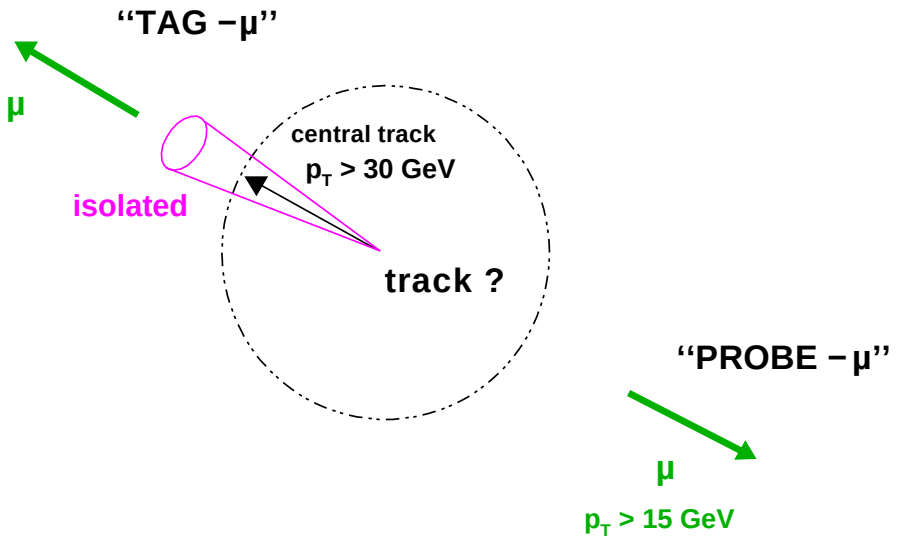
- one energetic isolated charged lepton
- missing transverse energy
- $\mathcal{O}(3M)$ events per experiment
  (assume: 1 fb^{-1}, 50% effi ciency)

$\mathrm{Z} \to \ell\ell$ events at the Tevatron:

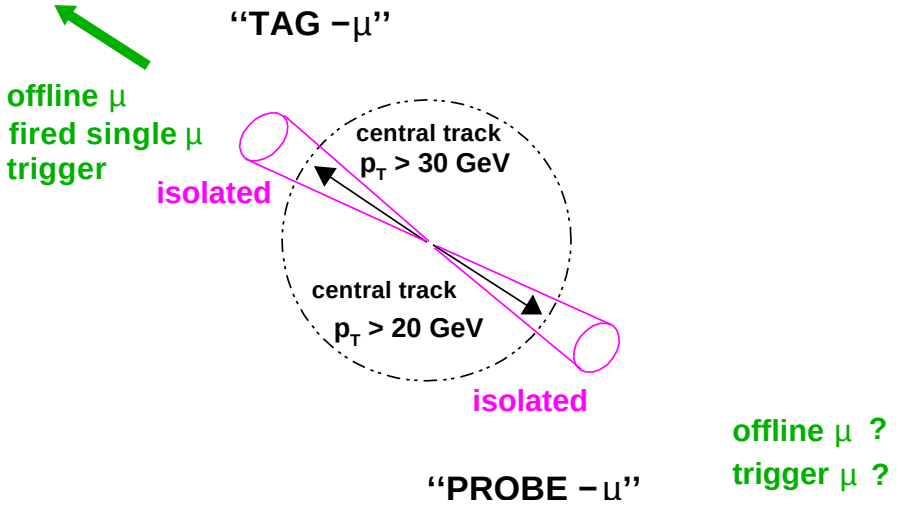
- two energetic isolated charged leptons
- $\mathcal{O}(250k)$ events per experiment
  (assume: 1 fb^{-1}, 50% effi ciency)

Understanding $W \to \ell\nu$ Events (I)

1. central tracking efficiency



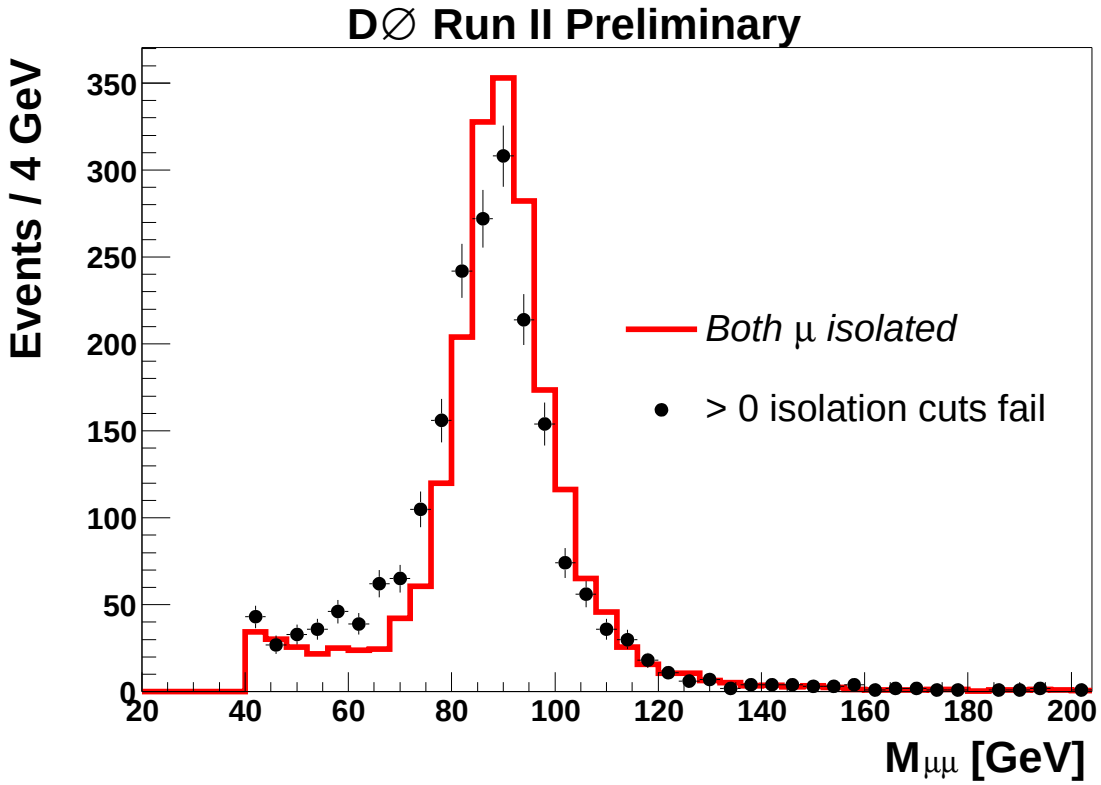
2. muon reconstruction efficiency (trigger and offline)



(corresponding studies for electrons)

Understanding $W \to \ell\nu$ Events (II)

- charged lepton momentum resolution: from $Z \to \ell\ell$ events
- have to understand resolution in detail to measure W mass!
- example: $Z \to \mu\mu$ peak at DØ



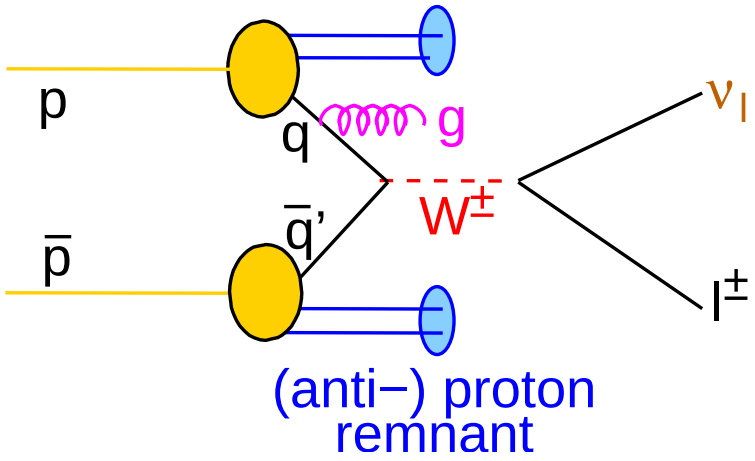
Understanding $W \to \ell\nu$ Events (III)

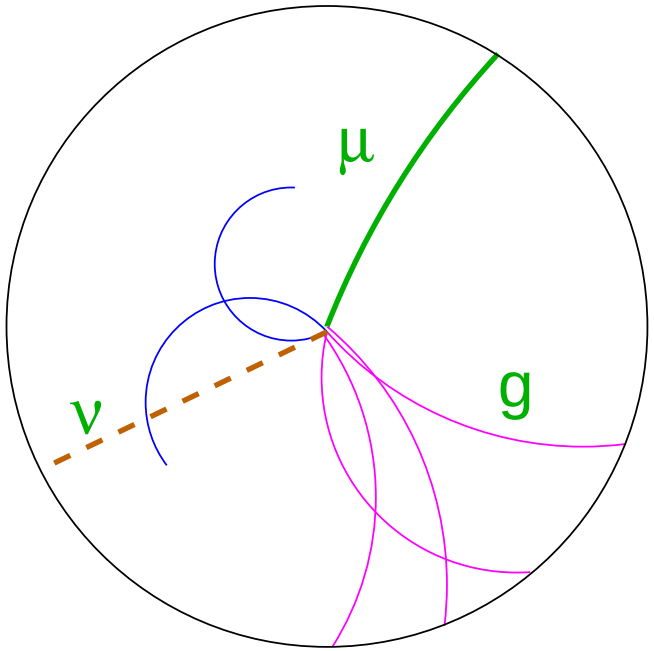
- W not always at rest
  in transverse plane ($p_t^W \neq 0$):

$\to$ recoil against soft jet(s)

- also: (anti-) proton remnant

$\Rightarrow \not{\vec{p}}_{\mathrm{T}} \neq -\vec{p}_t^{\,\ell}$





$\Rightarrow$ test understanding
of $\not{E}_{\mathrm{T}}$ resolution
with $\mathrm{Z} \to \ell\ell$ events

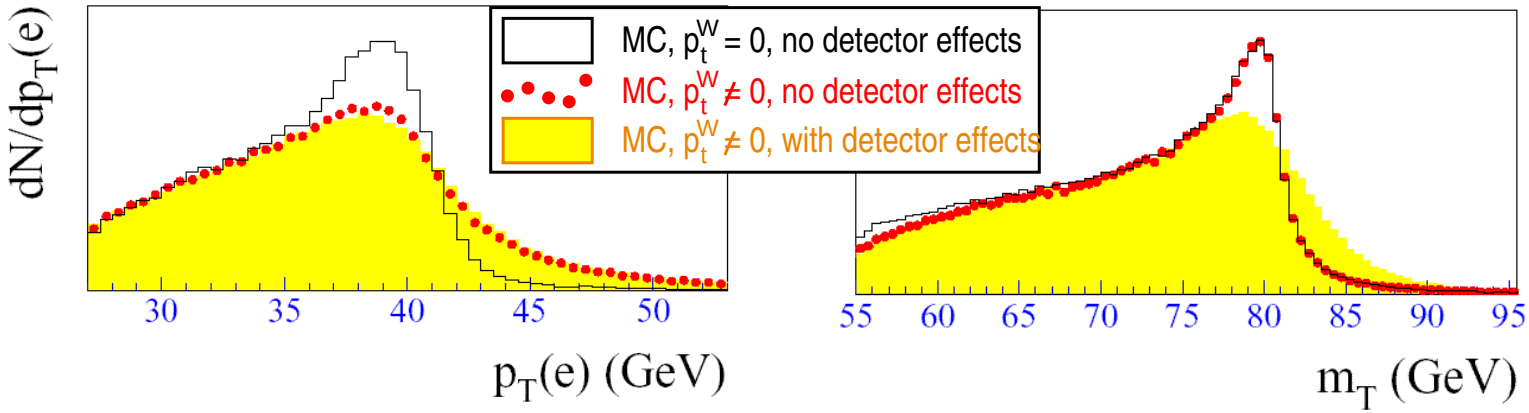
W Mass Measurement: Strategies

- neutrino p_z unknown $\rightarrow$ cannot fully reconstruct W mass!
- two possibilities:

use charged lepton p_t only

reconstruct transverse W mass

$$m_t^W = \sqrt{\left(E_t^\ell + E_t^\nu\right)^2 - \left(\vec{p}_t^{\,\ell} + \vec{p}_t^{\,\nu}\right)^2}$$



- need knowledge of p_t^W distribution
- test with $Z \rightarrow \ell\ell$ events

- broad resolution of $\vec{p}_{\mathrm{T}}$
- test with $Z \rightarrow \ell\ell$ events

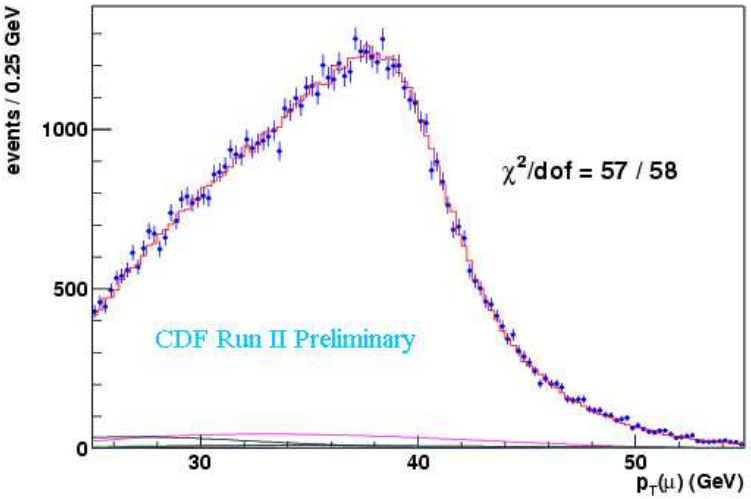
W Mass Measurement: Strategies

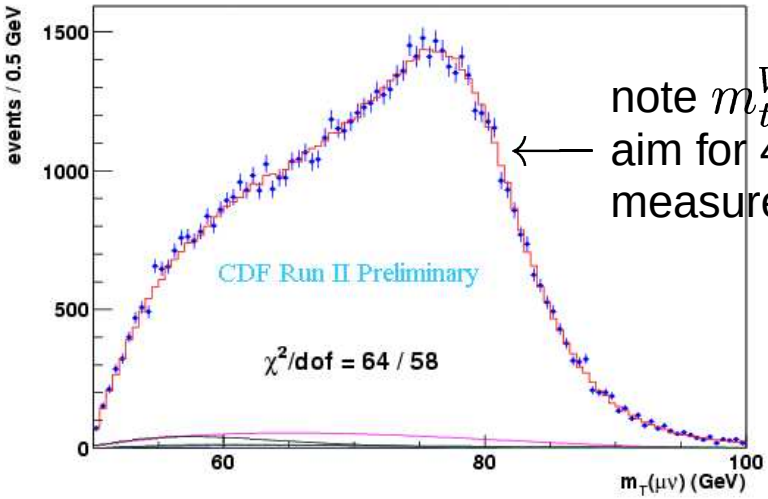
- neutrino p_z unknown $\rightarrow$ cannot fully reconstruct W mass!
- two possibilities:

use charged lepton p_t only

reconstruct transverse W mass

$$m_t^W = \sqrt{\left(E_t^\ell + E_t^\nu\right)^2 - \left(\vec{p}_t^{\,\ell} + \vec{p}_t^{\,\nu}\right)^2}$$



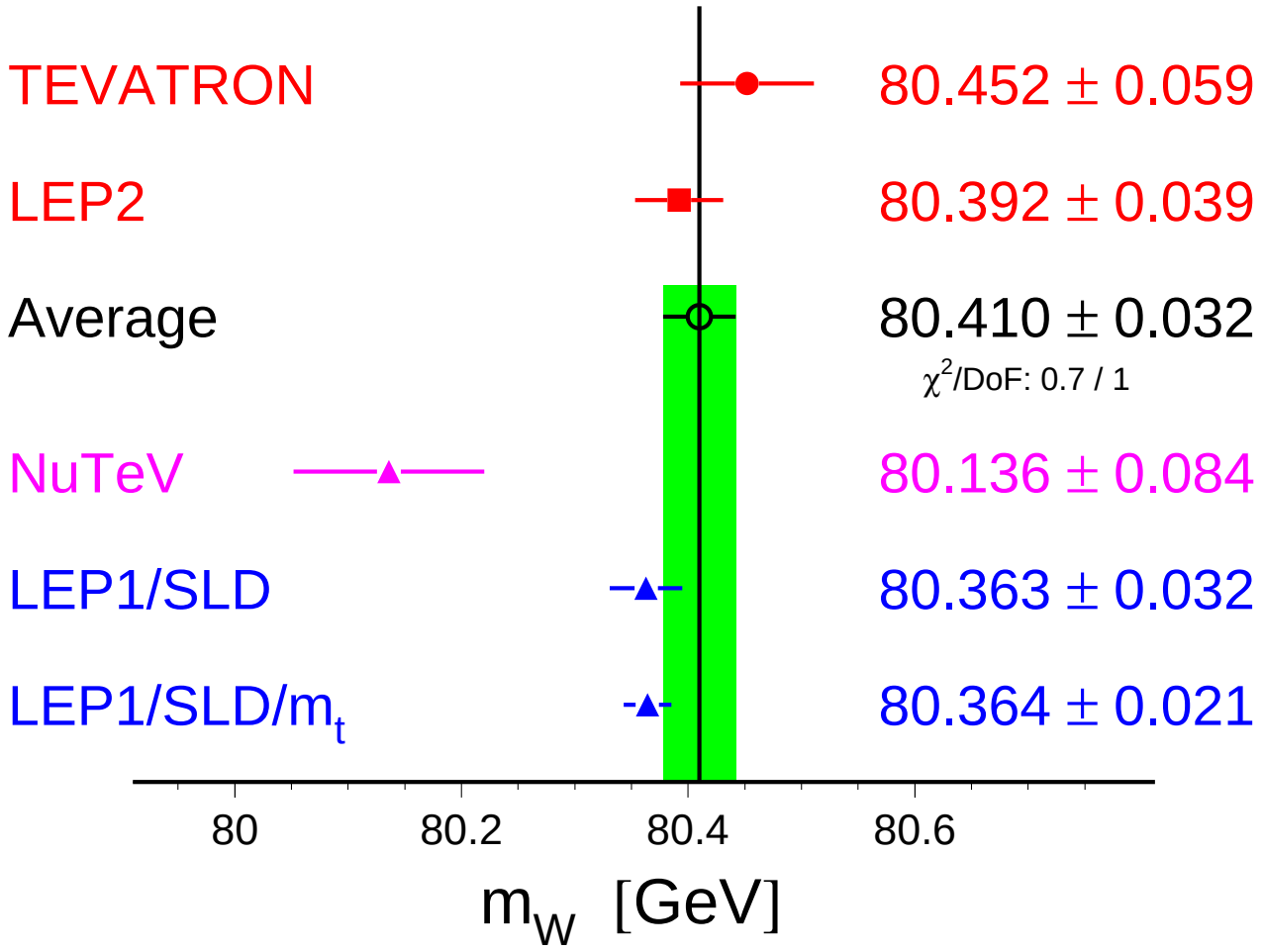


note m_t^W axis scale:
$\longleftarrow$ aim for 40 MeV measurement!

- need knowledge of p_t^W distribution
- test with $Z \rightarrow \ell\ell$ events
- need understanding of backgrounds

- broad resolution of $\not\!\!\vec{p}_T$
- test with $Z \rightarrow \ell\ell$ events
- need understanding of backgrounds

W Mass Measurement: Results

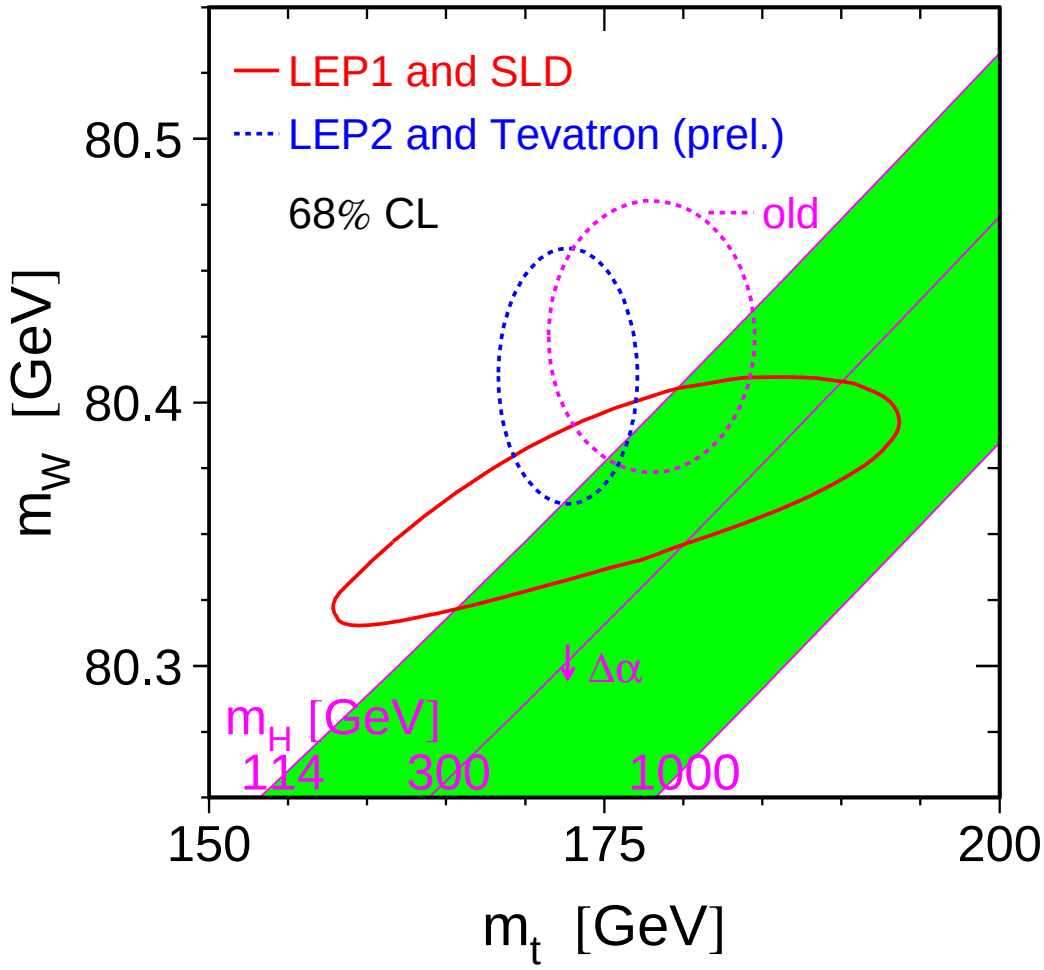


Relevance of the W Mass Measurement

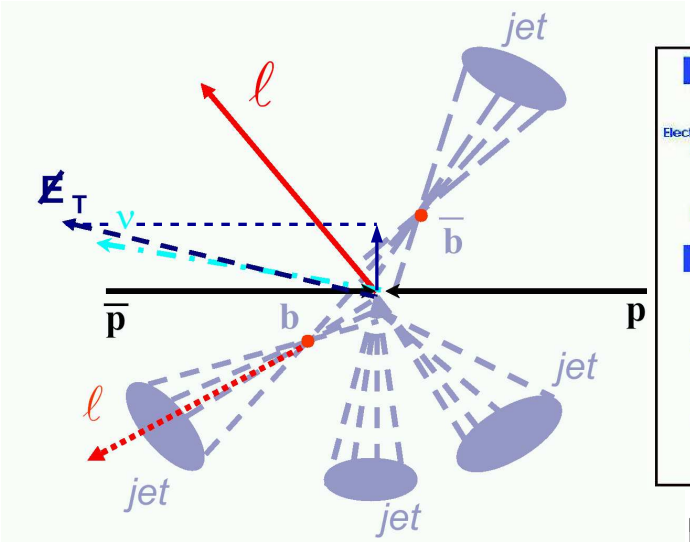
In the Standard Model the W mass depends via loop corrections...

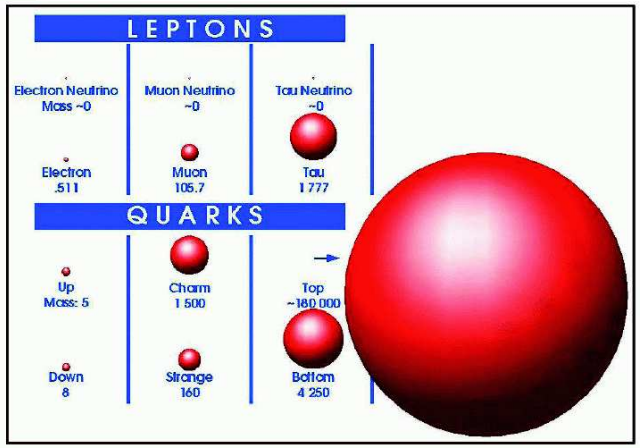
- quadratically on the top quark mass m_{t}
- logarithmically on the Higgs mass m_{H}

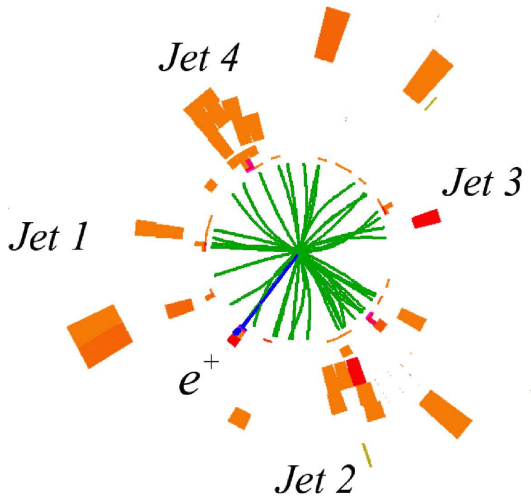
$\Rightarrow$ indirectly infer the Higgs mass
  - from direct measurements of the W and top mass
  - from other electro-weak observables

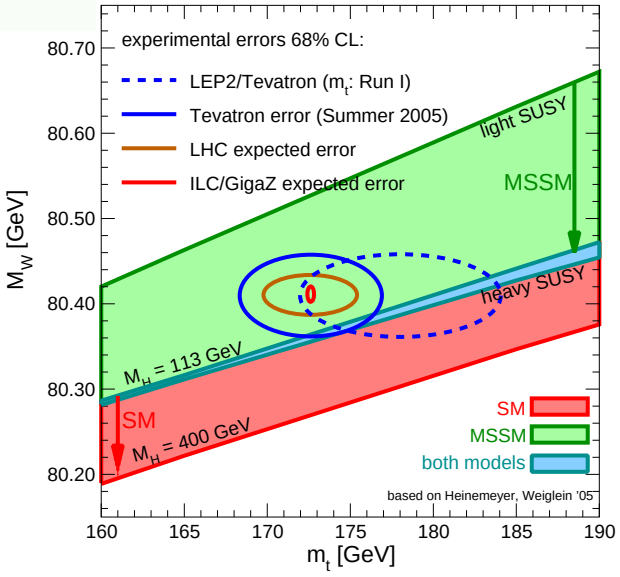


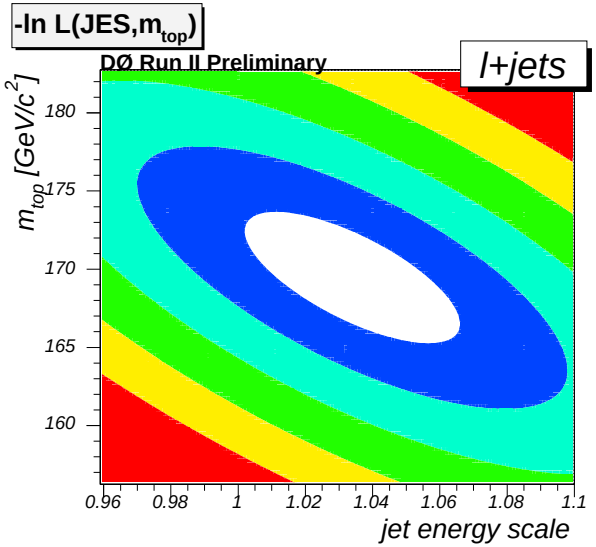
The Top Quark Mass







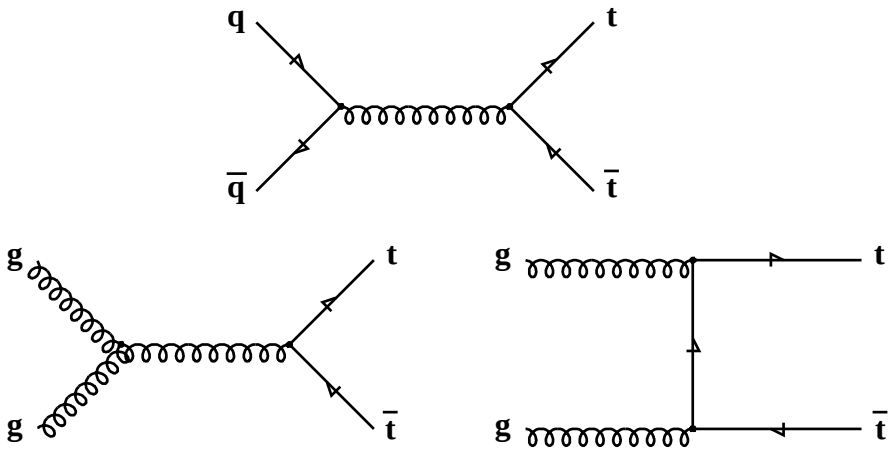




Top Production at Hadron Colliders (I)

top pair production (strong interaction)

Feynman diagrams (LO):



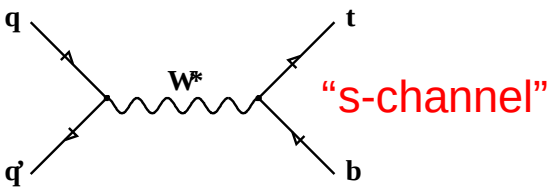
production cross-section:

	Tevatron		LHC
	Run I	Run II	
	$p\bar{p}$ 1.8 TeV	$p\bar{p}$ 1.96 TeV	pp 14 TeV
	90%	85%	5%
	10%	15%	95%
	5 pb	7 pb	800 pb
events:	500 ($100pb^{-1}$)	7000 (per fb^{-1})	8000000 (per $10fb^{-1}$)

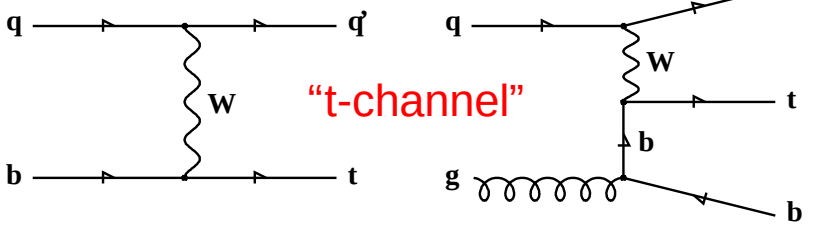
Top Production at Hadron Colliders (II)

single top quark production:
(elektroweak interaction)

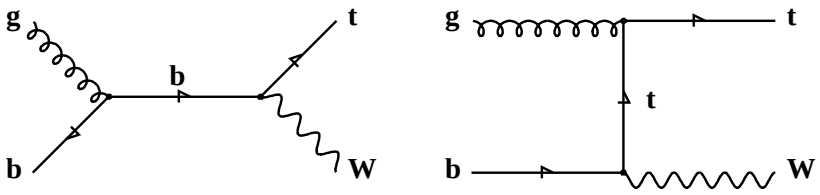
Feynman diagrams (LO):

1.) 

"s-channel"

2.) 

"t-channel"

3.) 

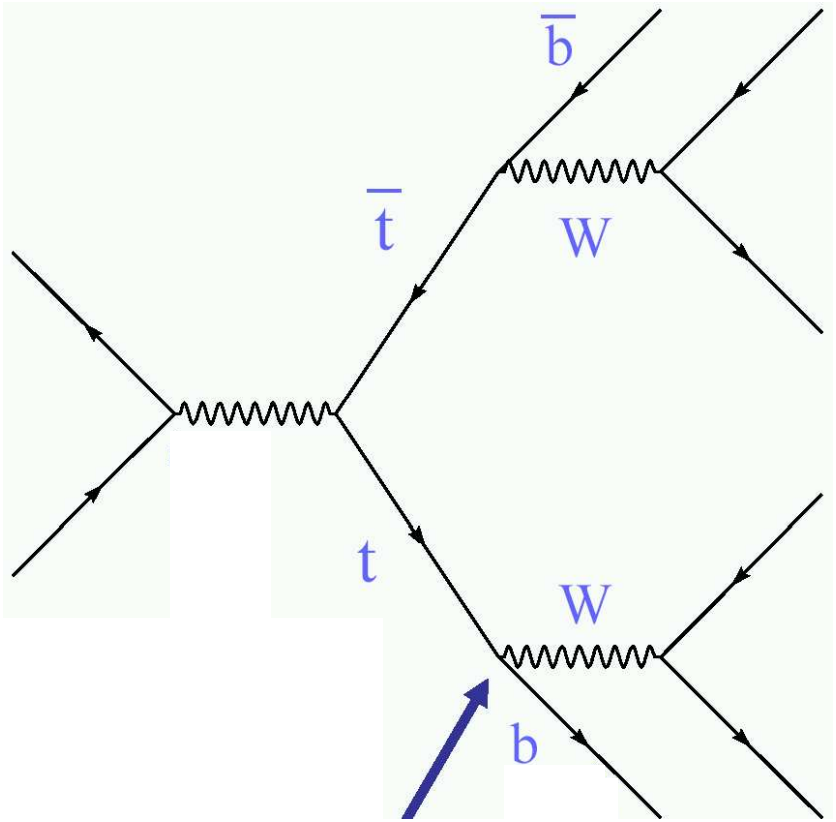
t+W associated production

production cross-sections:

	Tevatron Run I $p\bar{p}$ 1.8 TeV	Tevatron Run II $p\bar{p}$ 1.96 TeV	LHC pp 14 TeV
1.)	0.7 pb	0.9 pb	10 pb
2.)	1.7 pb	2.4 pb	250 pb
3.)	0.07 pb	0.12 pb	60 pb

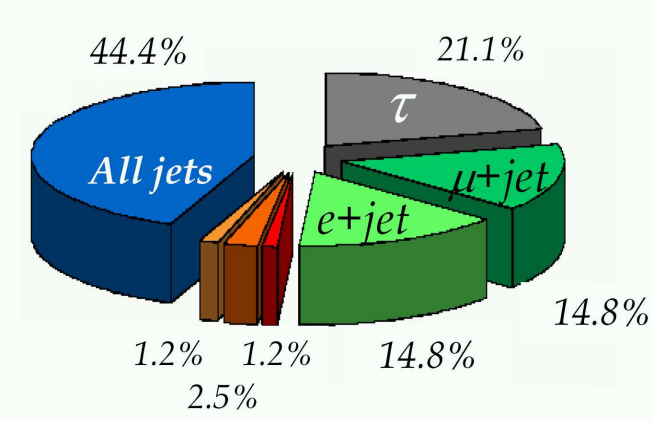
- roughly half the $t\bar{t}$ cross-section
- larger backgrounds
- not yet seen

$t\bar{t}$ Event Topologies (I)



$$|V_{tb}| >> |V_{ts}|, |V_{td}|$$

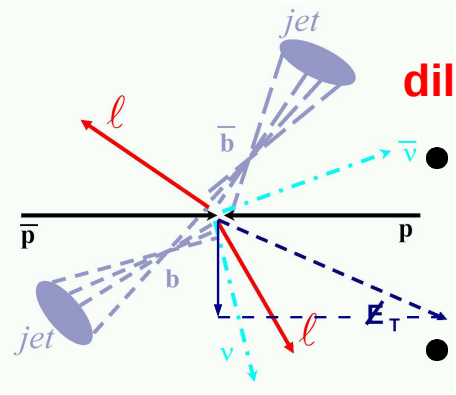
$$\Rightarrow \mathrm{Br}(\mathrm{t} \rightarrow \mathrm{Wb}) \sim 100\%$$



topology determined by W decays:

- 5% dilepton events
- 30% lepton+jets events
- 44% hadronic events
- 21% events with τ leptons

$t\bar{t}$ Event Topologies (II)



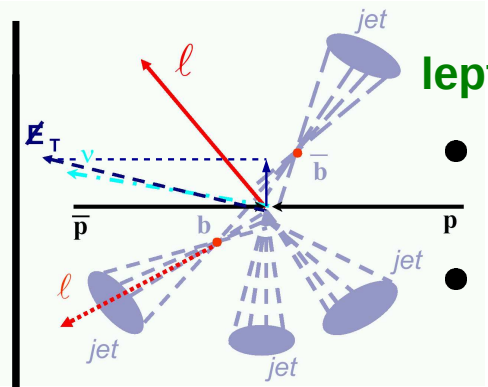
dilepton events:

- 2 energetic, isolated leptons of opposite charge
- 2 energetic b jets
- missing transverse energy

→ event kinematics underconstrained

→ 2 possible jet combinations

→ lepton+jets trigger



lepton+jets events:

- 1 energetic, isolated lepton
- 4 energetic jets (of which 2 b jets)
- missing transverse energy

→ 2 solutions for neutrino momentum component along beam axis

→ event kinematics otherwise fully determined

→ $2 \cdot 12$ possible jet combinations (fewer with b identification)

→ lepton+jets trigger

hadronic events:

- 6 energetic jets (of which 2 b jets)
- event balanced in transverse plane

→ many combinations (⇒b identification!)

→ large background (⇒b identification!)

→ only jet based trigger

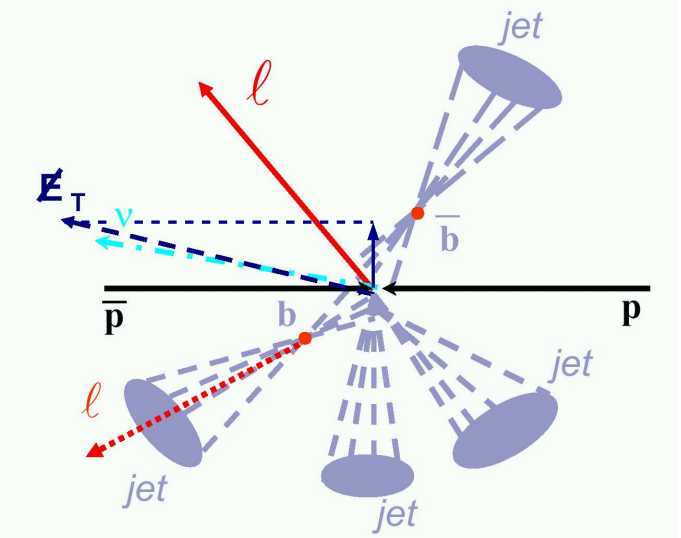
events with τ leptons:

- additional neutrino from τ decay

→ difficult to reconstruct

Selection of Lepton+Jets Events

30% lepton+jets events



Event selection:

- 1 energetic isolated lepton
  (electron or muon)
- 4 energetic jets
- missing transverse momentum

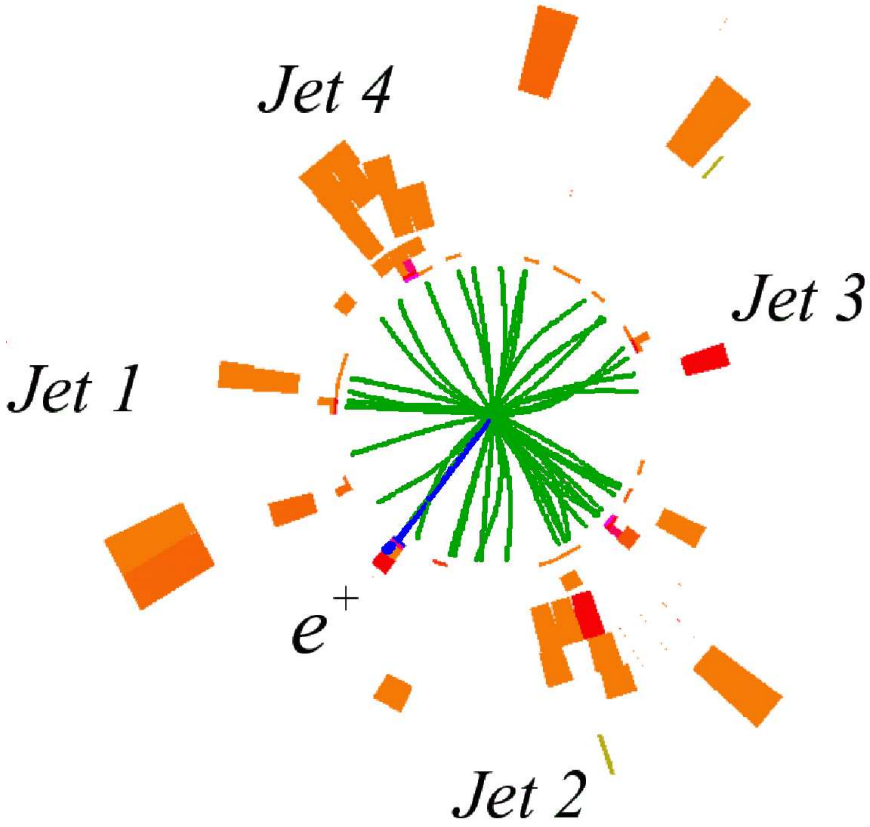
Composition of typical event sample:

signal ~40% top-antitop events

background
- ~50% leptonic W decays + 4 jets
- ~10% multi-jet events with misidentified electron/muon

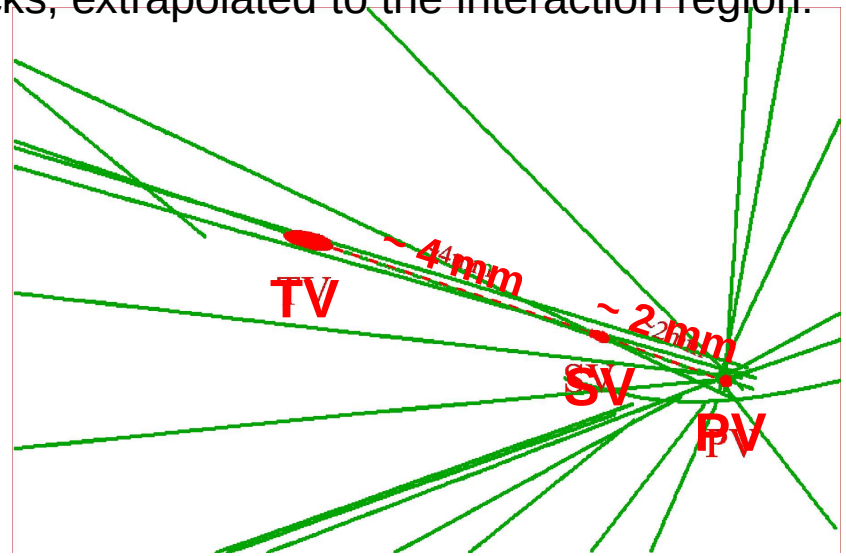
A $t\bar{t}$ Candidate Event

An „electron+jets“-event at DØ:



(projection into the transverse plane)

tracks, extrapolated to the interaction region:

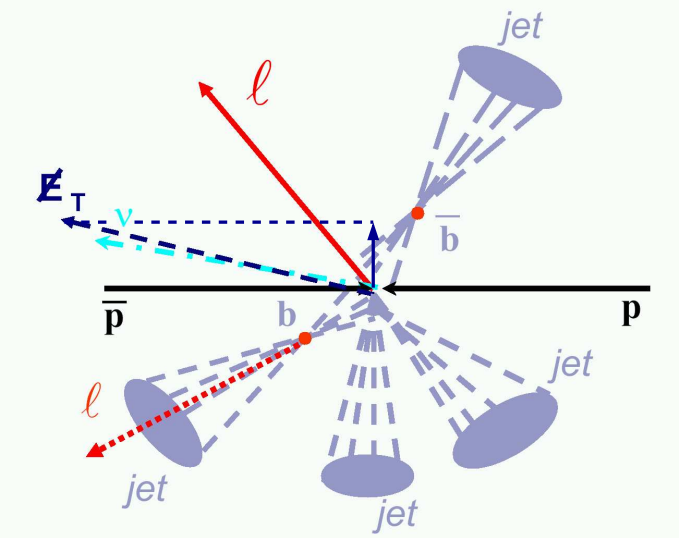


jet 1 with identified b decay:

primary vertex $t \rightarrow Wb$
secondary vertex $B \rightarrow DX$
tertiary vertex $D \rightarrow Y_s Z$

Top Mass in Lepton+Jets Events

30% lepton+jets events



Event selection:

- 1 energetic isolated lepton
  (electron or muon)
- 4 energetic jets
- missing transverse momentum

Reconstruction of the $t\bar{t}$ decay:

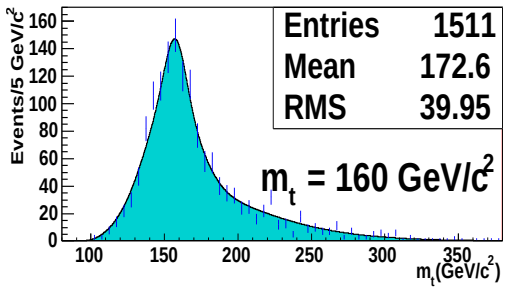
- missing transverse momentum $\longrightarrow$ neutrino transverse momentum
- momenta of colliding partons unknown:
  W mass $\longrightarrow$ neutrino p_z (2 possible solutions)
- 12 possible assignments of jets to quarks in the $t\bar{t}$ decay
  (no need to distinguish jets from hadronic W decay)

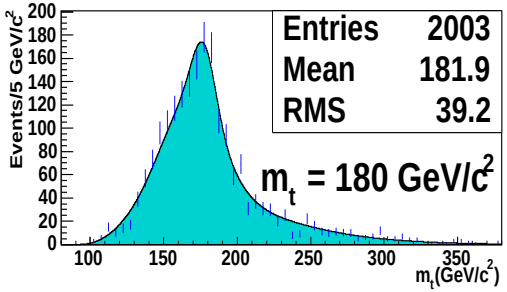
$\longrightarrow$ 24 different possible solutions

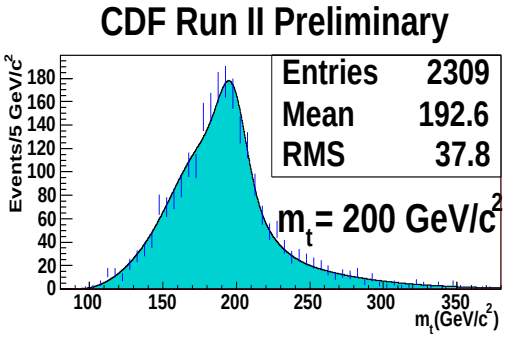
The Template Method

"Traditional" method to measure the top quark mass:

- consider all 24 possible solutions per event,
  select the best solution (smallest χ^2 wrt $t\bar{t}$ hypothesis)
- fill a histogram with reconstructed top mass
  of best solution
- compare with template histograms of simulated events:
  a) $t\bar{t}$ signal (for different top quark masses)
  b) background: mainly W+jets events
  example: signal+background templates at CDF:







- vary the top quark mass (template histogram) in a fit

Room For Improvement (I)

The template method is not optimal:

- consider only the solution with the smallest χ^2

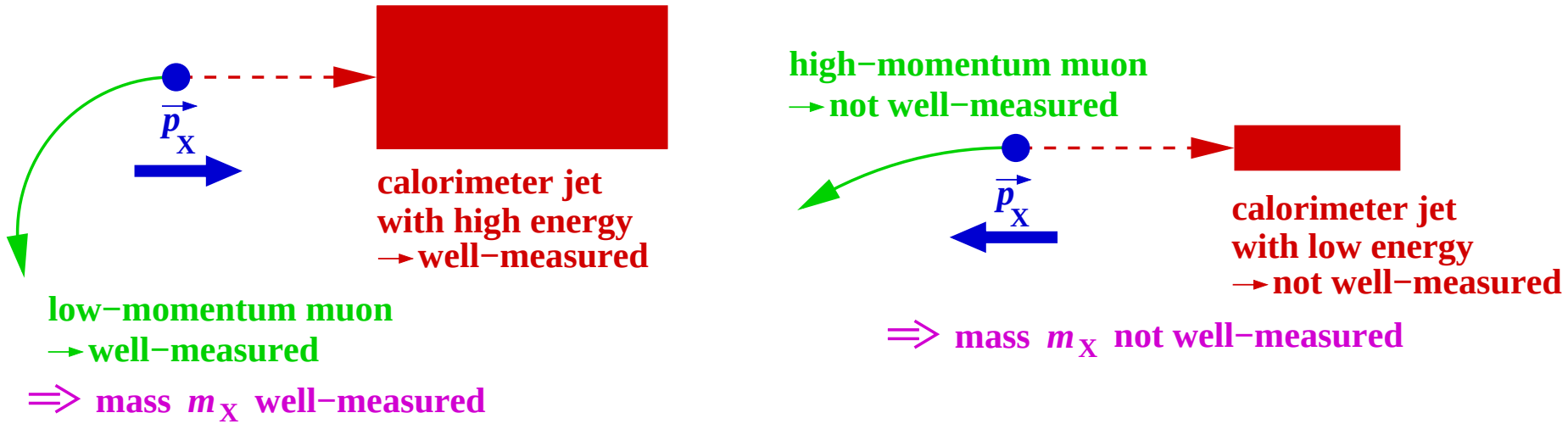
  correct jet-parton assignment in only $\sim$20% of events!

- all events are weighted equally

  $\leftrightarrow$ information content depends on event topology:

  1. relative probability for signal/background
  2. different detector resolution

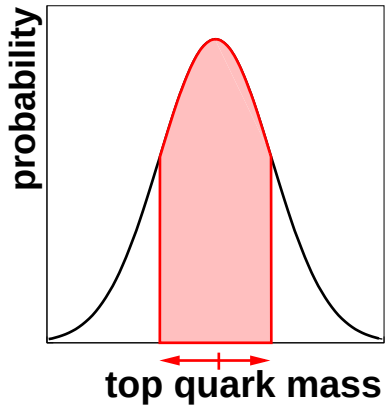
example: reconstruction of $X \rightarrow \mu$ + jet decays



Room For Improvement (II)

Improve the statistical sensitivity:

- use information from all 24 possible solutions per event
- determine a m_{t}-dependent probability $P_i(m_{\mathrm{t}})$ for every single event i
- use the full kinematic information to separate signal and background

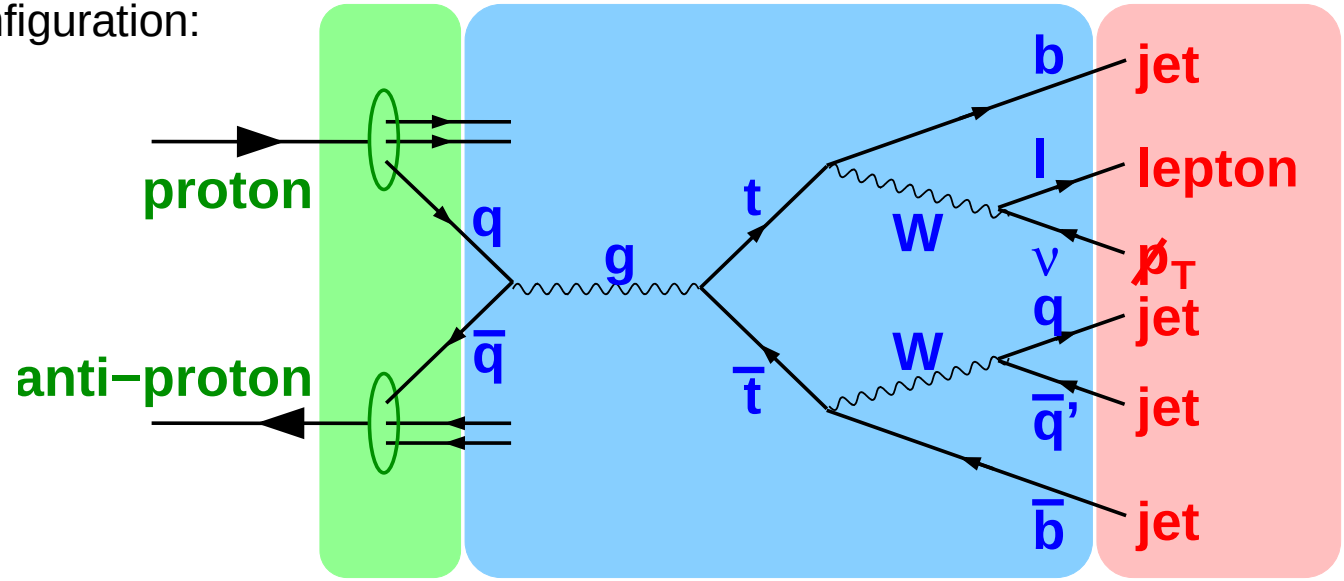


$\Rightarrow$ **"Matrix Element Method" / "Dynamical Likelihood"**

Matrix Element Method: The $t\bar{t}$ Probability

Signal probability $\mathcal{P}_{t\bar{t}}(\vec{x}, m_t)$ for a given solution $\vec{x}_l$ in event i:

- integral over every possible configuration $\vec{y}$ of momenta of decay products
- weight of each configuration:



$$\Rightarrow \mathcal{P}_{t\bar{t}}(\vec{x}_l, m_t) = \underbrace{\frac{1}{\sigma_{t\bar{t}}(m_t)}}_{\text{normalisation}} \int \underbrace{\mathrm{d}p_q \mathrm{d}p_{\bar{q}} f(p_q) f(p_{\bar{q}})}_{\substack{\text{parton} \\ \text{density function}}} \underbrace{\mathrm{d}\sigma_{t\bar{t}}(\vec{y}, m_t)}_{\substack{\text{differential} \\ \text{cross-section}}} \underbrace{W(\vec{x}_l, \vec{y})}_{\substack{\text{transfer} \\ \text{function}}}$$

Understanding the Detector: Jet Energy Scale

Problem I:

- detector calibration: have to determine the absolute jet energy scale to measure the top mass
- but: n-jet events look balanced for any jet energy scale

Problem II:

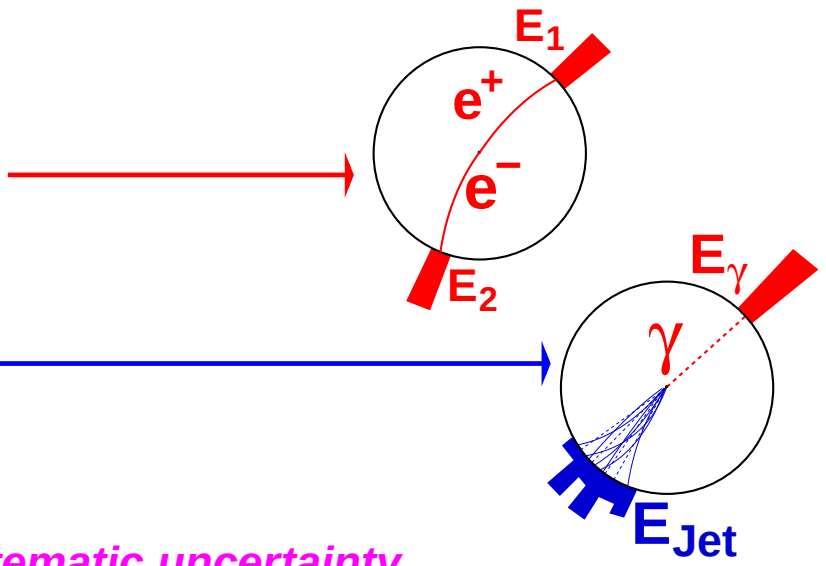
- $\mathrm{W} \to \mathrm{q}\overline{\mathrm{q}'}$ or $\mathrm{Z} \to \mathrm{q}\bar{\mathrm{q}}$ decays: backgrounds too large

Solution: two-step approach

1.) calibrate electromagnetic calorimeter with $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$ decays

1.5) electrons $\approx$ photons

2.) calibrate the jet response with photon+jet events



Limitation:

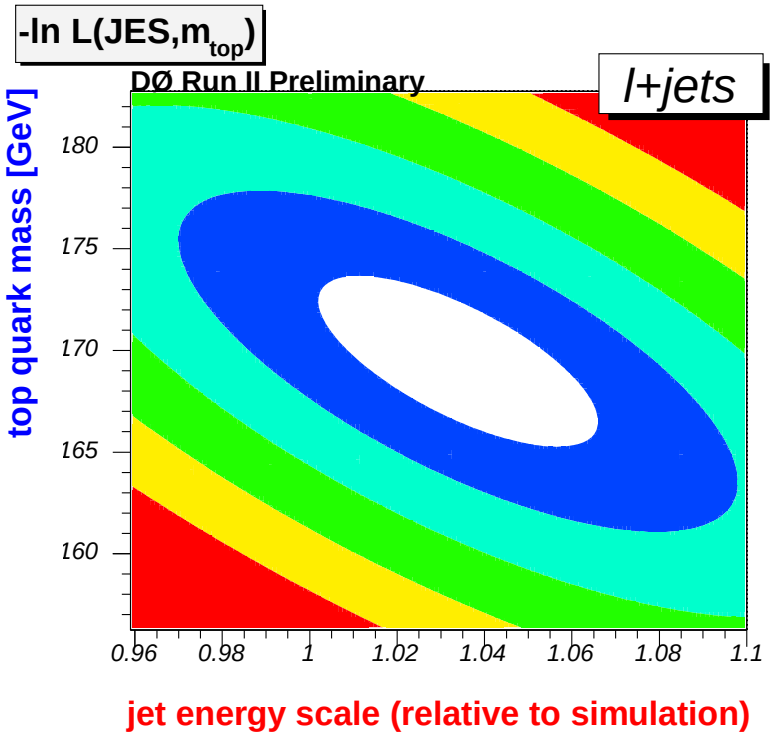
- complicated procedure $\to$ ***limiting systematic uncertainty*** *in "traditional" top mass measurements*

Latest DØ Result

- Look at $W \to q\overline{q'}$ decays in $t\bar{t}$ events:
  measure the **top quark mass** ***and*** the **jet energy scale**!
- DØ result using 320 pb^{-1}:
  top quark mass vs.
  jet energy scale
- Uncertainties on the top mass:

  statistical: ± 4.4 GeV
  systematic: ± 1.3 GeV
  total: ± 4.6 GeV

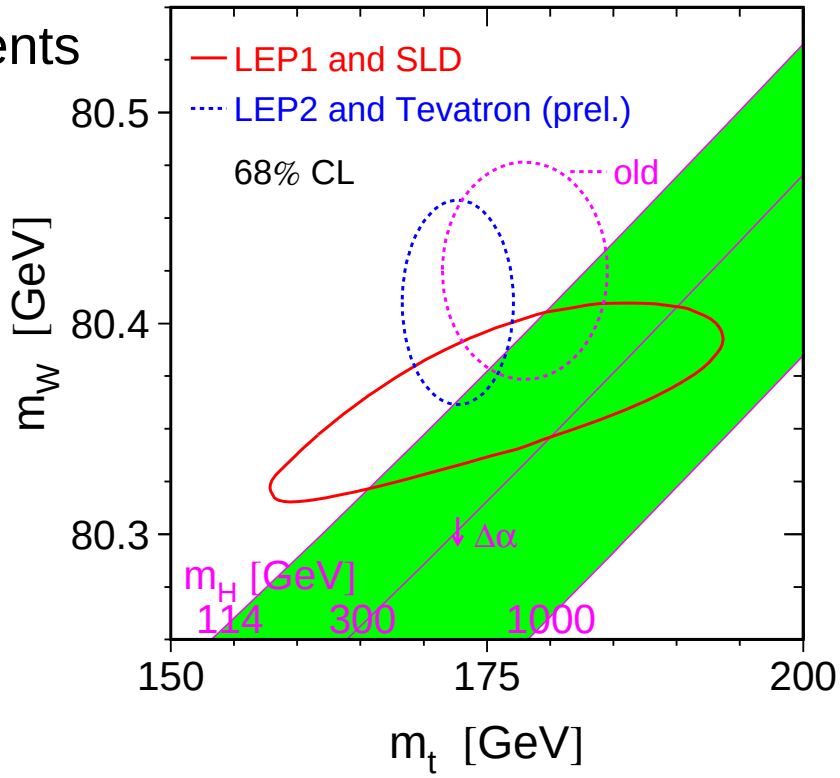
  $\to$ not limited by systematics!
  (expect 10-20 times more data during Tevatron Run II)
- CDF have a measurement with similar precision...



Interpretation (I)

For interpretation within the Standard Model:

- Consistent combination of measurements (taking into account all correlations):
  $m_t = 172.7 \pm 2.9\,\mathrm{GeV}$
- dominant uncertainties:
  statistical error, jet energy scale
  $\rightarrow$ DØ and CDF results / only weakly correlated



Interpretation (II)

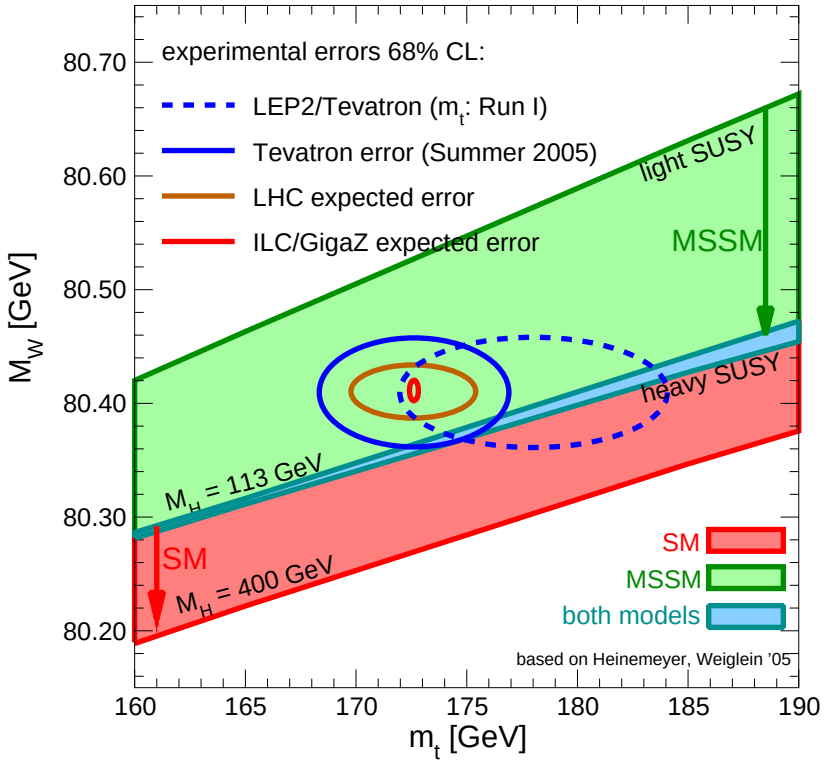
In supersymmetric models:

$\rightarrow$ contributions from additional loop diagrams

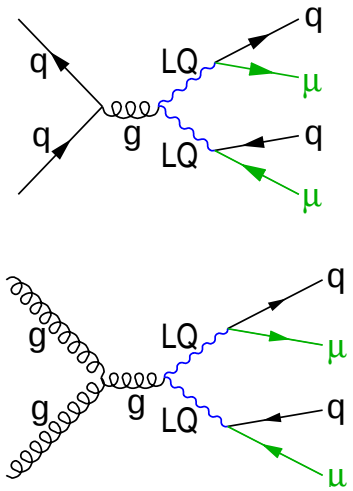
$\rightarrow$ relation between m_{W}, m_{t}, and m_{H} changed

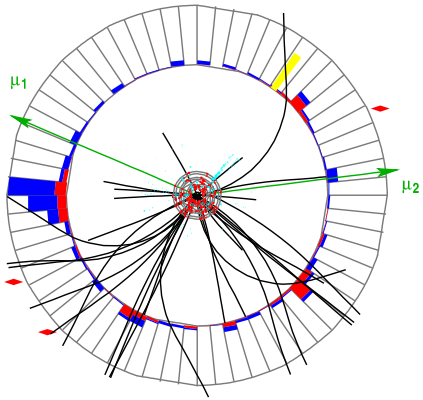
$\Rightarrow$ comparison between predictions of

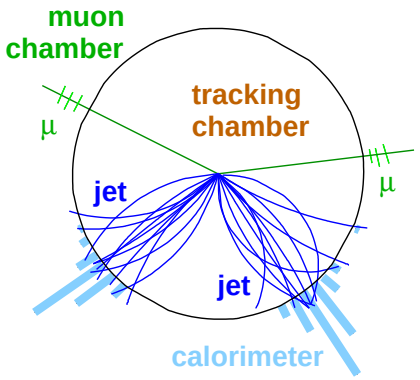
- the Standard Model
- the minimal supersymmetric Standard Model

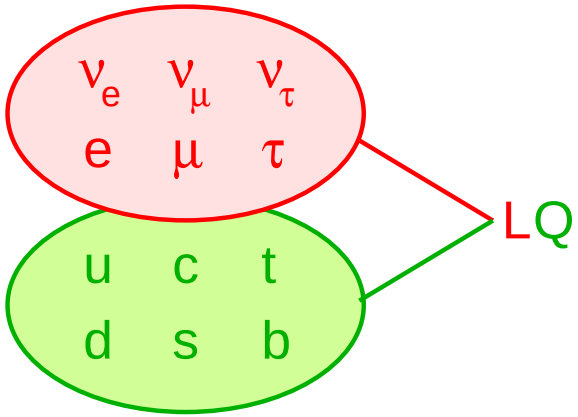


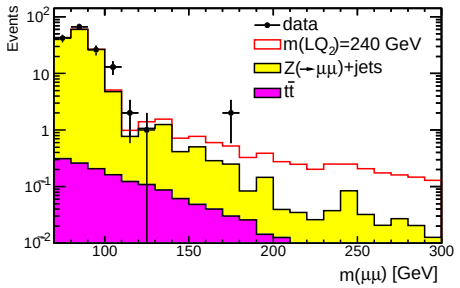
Beyond the Standard Model: Leptoquarks as an Example

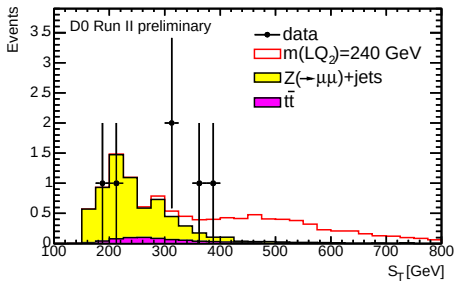








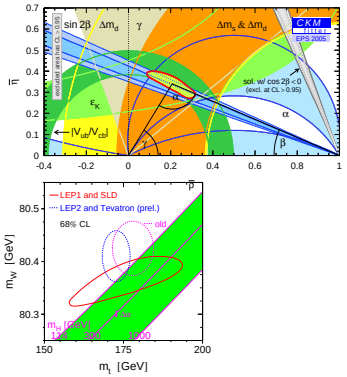




Looking For New Physics

Two approaches:

1. precision measurements of SM parameters:
   - test the unitarity triangle(s)
   - compare W and top masses
   - many more...



2. ***directly search for new particles!***

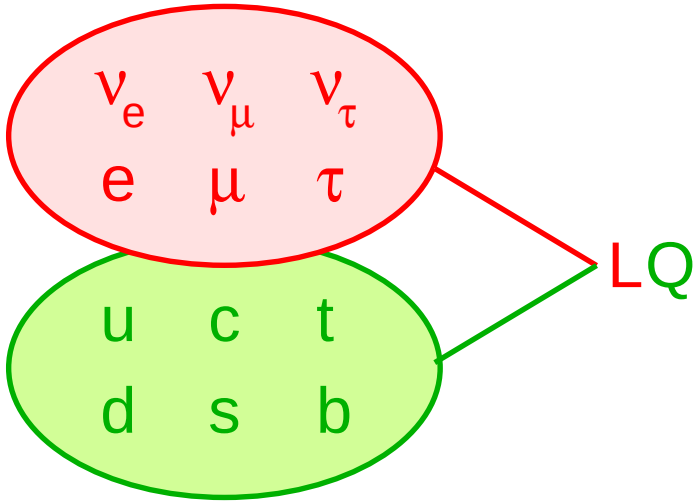
How to recognize events with new particles:

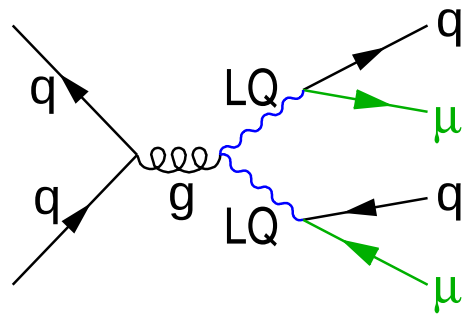
- excess (or deficit) of events with particular topology
- compare measurements with expectation from SM + new theory

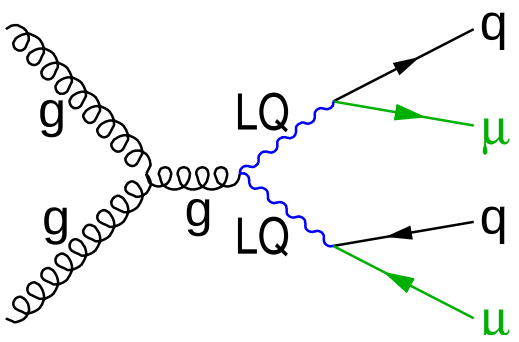
  look at:
  - invariant mass distributions
  - often: missing transverse momentum
  - often: isolated energetic leptons
  - ...

Leptoquarks

- striking symmetry between lepton & quark sectors:
  $\rightarrow$ postulate leptoquarks
  $\rightarrow$ couple to quarks & leptons within one generation







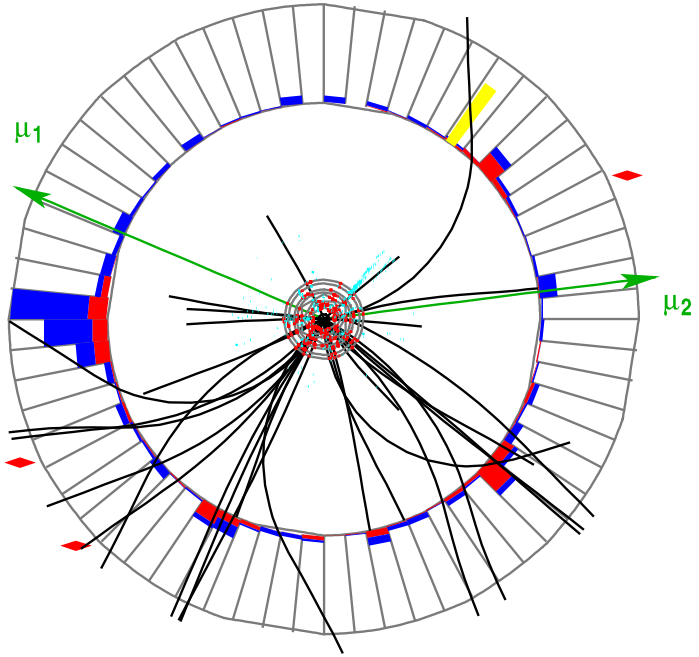
- pair production (strong interaction)
- decay to a lepton and a quark

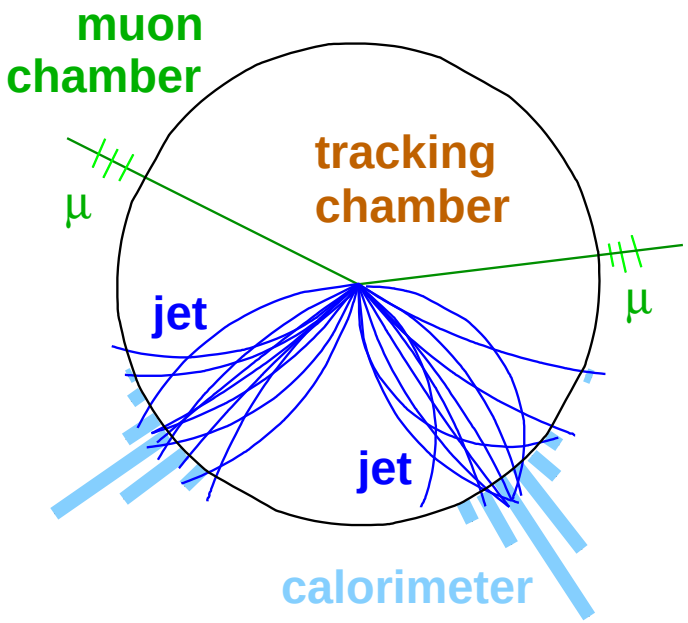
Second Generation Leptoquarks

- Event topology: $LQ\,\overline{LQ} \rightarrow (\mu q)(\mu q)$

$\rightarrow$ two isolated muons (of opposite charge), two jets

- A leptoquark candidate at DØ:



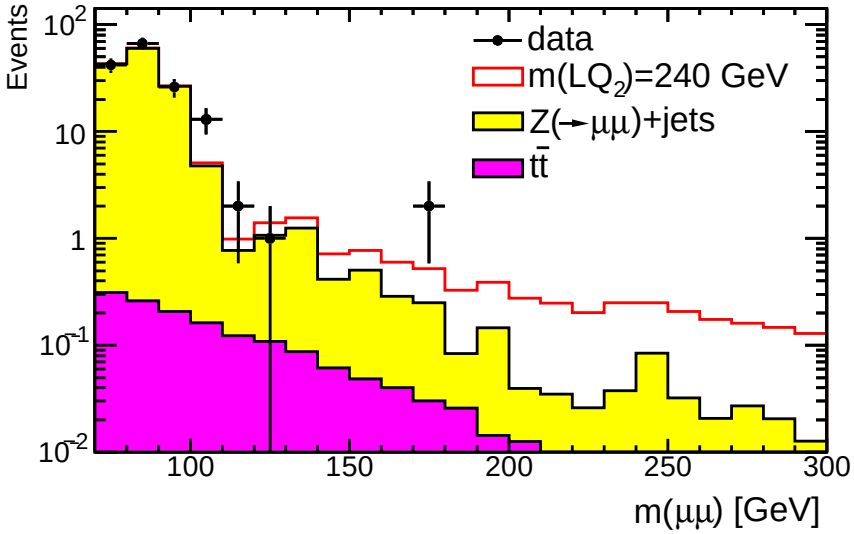


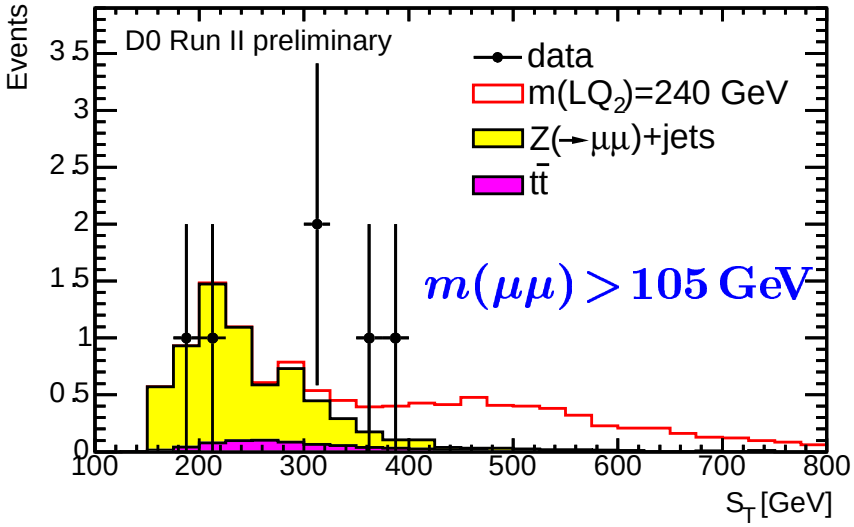
(consistent with $Z/\gamma^* \rightarrow \mu\mu$ + jets)

Leptoquark Search

Selection of candidate events:

- main background: $Z/\gamma^* \to \mu\mu$
  $\to$ cut on $m(\mu\mu)$
- large leptoquark masses:
  $\to$ cut on scalar sum S_T
  of muon and jet
  transverse energies

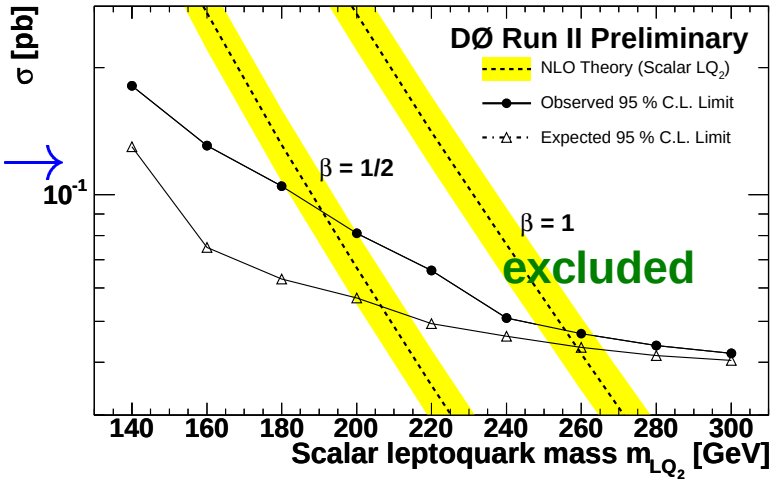


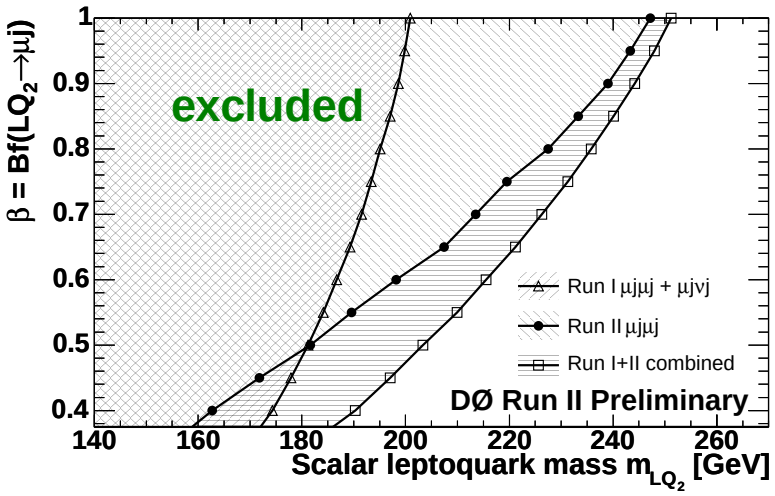


$\int \mathcal{L}\,\mathrm{d}t = 300\,\mathrm{pb}^{-1}$:
data consistent with SM...

Exclusion Limits

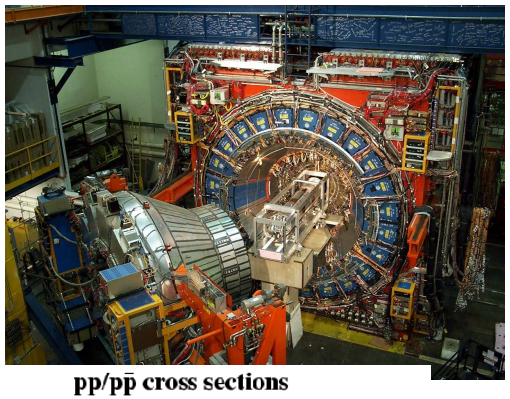
- Analysis result:
  no sign for new physics
  → ***upper limit on cross-section*** →
- Cross-section for pair production of scalar leptoquarks is model independent (given by QCD)
  → ***interpret as limit on leptoquark mass*** →
- Mass limit depends on decay branching ratio β to charged lepton+quark:
  $\beta = 1$: $m(LQ_2) > 251$ GeV
  $\beta = 0.5$: $m(LQ_2) > 204$ GeV



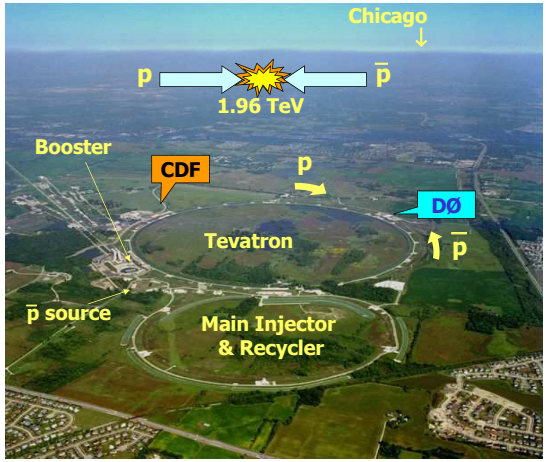


Take Away (I)

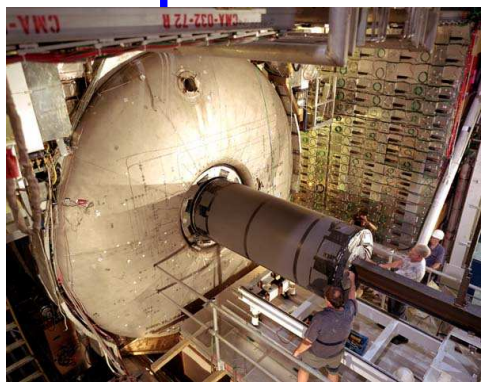
beautiful...

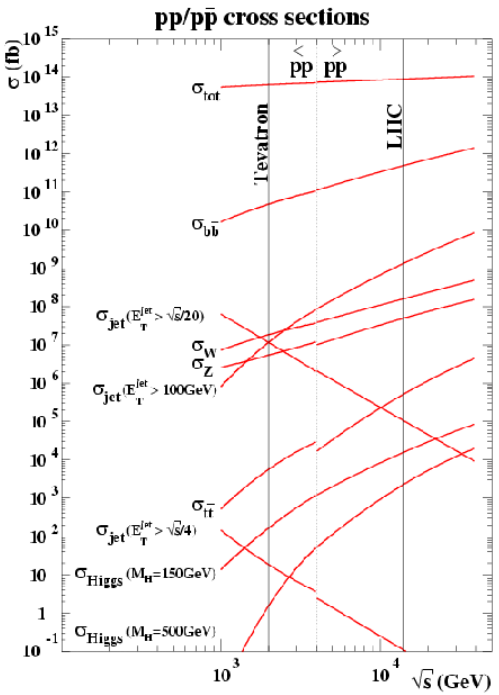


The Tevatron:
1.96 TeV $p\bar{p}$ collisions



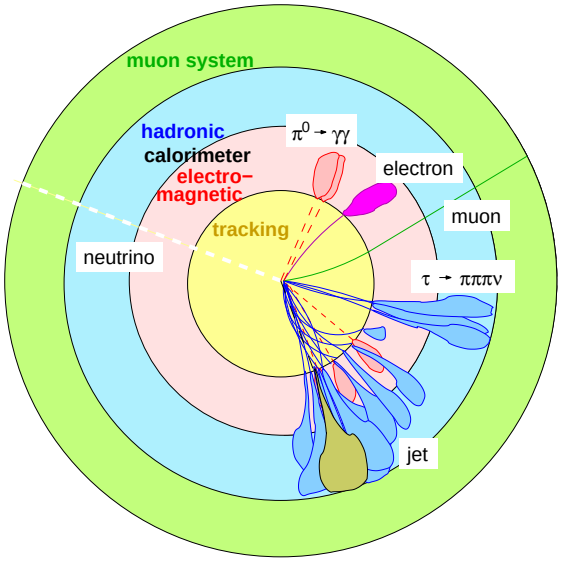
...experiments!





triggering:
needles&
haystacks

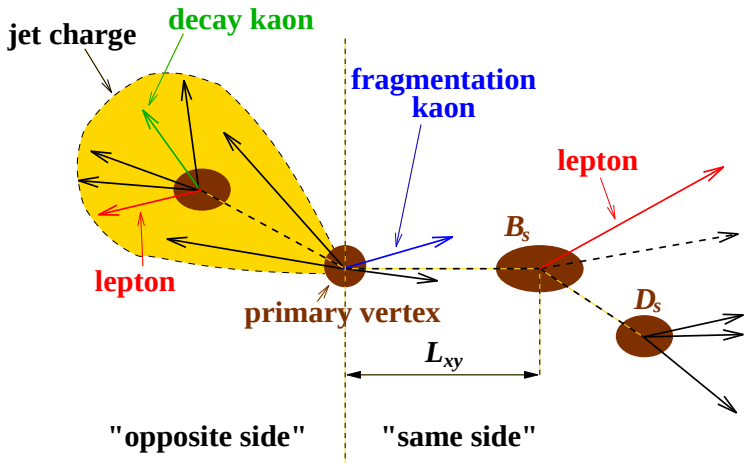
transverse
momentum
balance



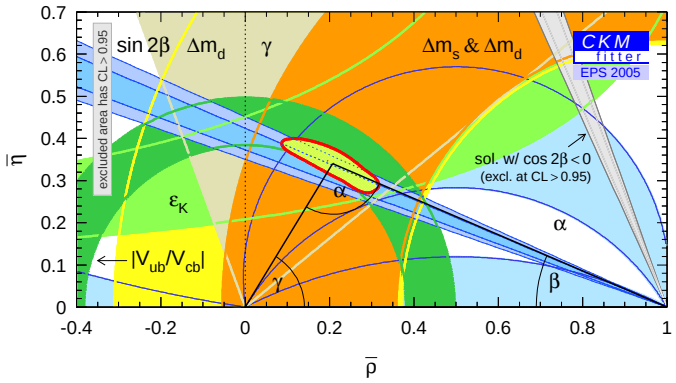
Take Away (II)

B physics $\oplus$ hadron collider

$\Rightarrow$ B_s physics $\Rightarrow$ B_s ***oscillations***

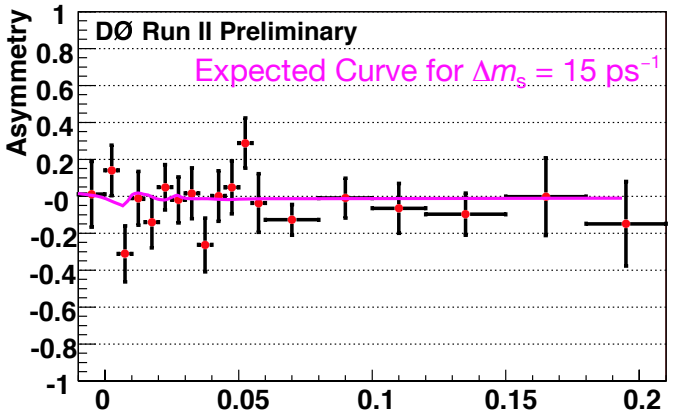


flavour tag

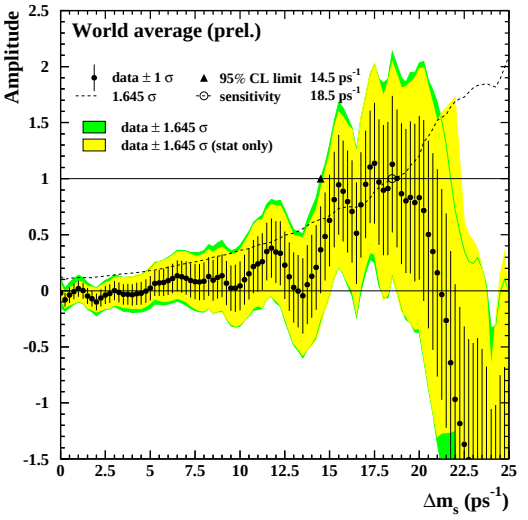


unitarity triangle

beautiful measurements

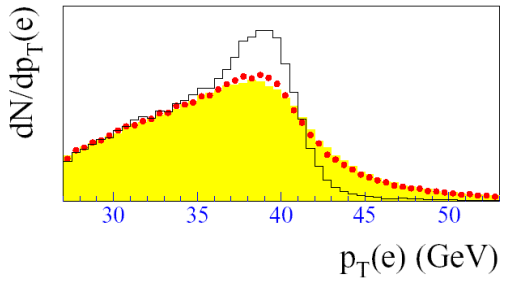


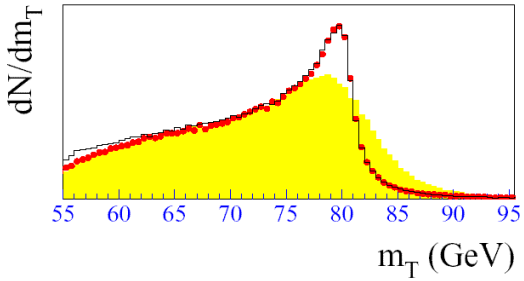
B_s oscillation amplitude

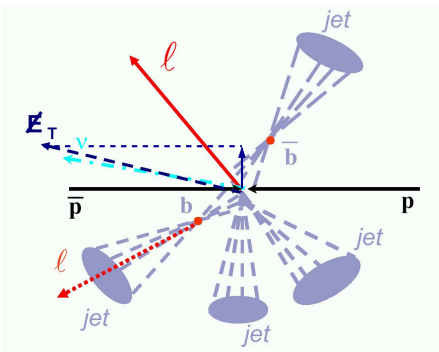


Take Away (III)

- **W mass:** measure in $W \to \ell\nu$ decays
- cannot fully reconstruct events
- use either lepton transverse momentum or W transverse mass

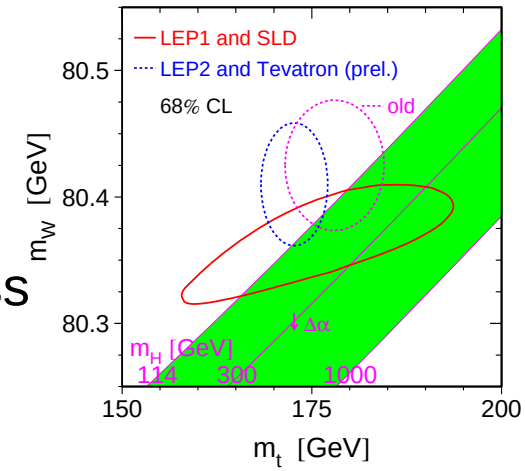






- **top quark mass:** measured best in lepton+jets events
- jet energy scale: largest systematic error

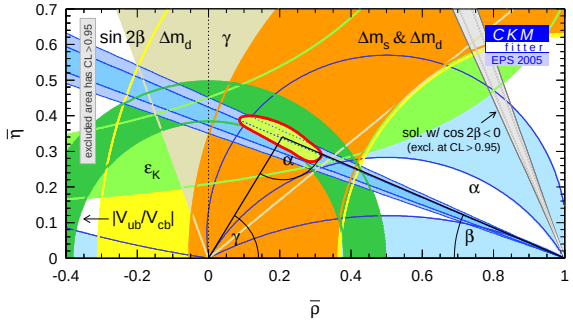
- **interpret** W vs. top mass in the Standard Model



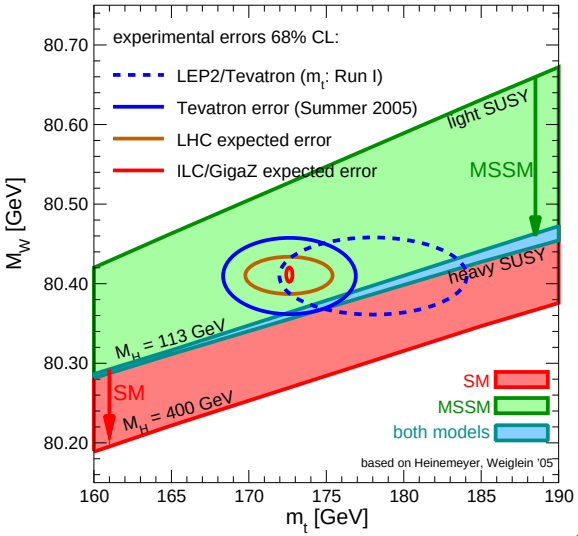
Take Away (IV)

Look for physics beyond the Standard Model

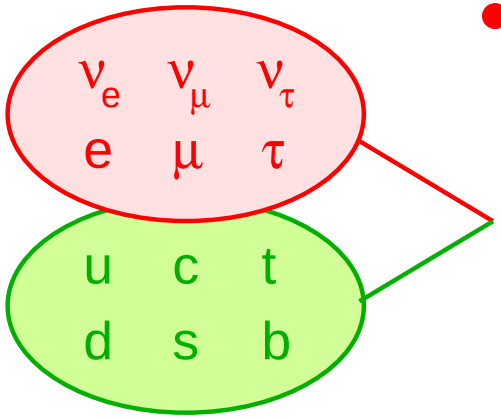
- **with precision measurements**

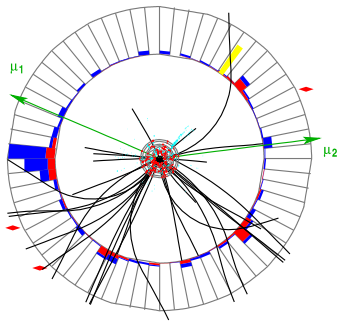


e.g.:
- CKM matrix
- W vs. top mass



- **hunting new particles**, e.g.:
  - leptoquarks





stay tuned for more results!