

From the energy frontier to the rate frontier:

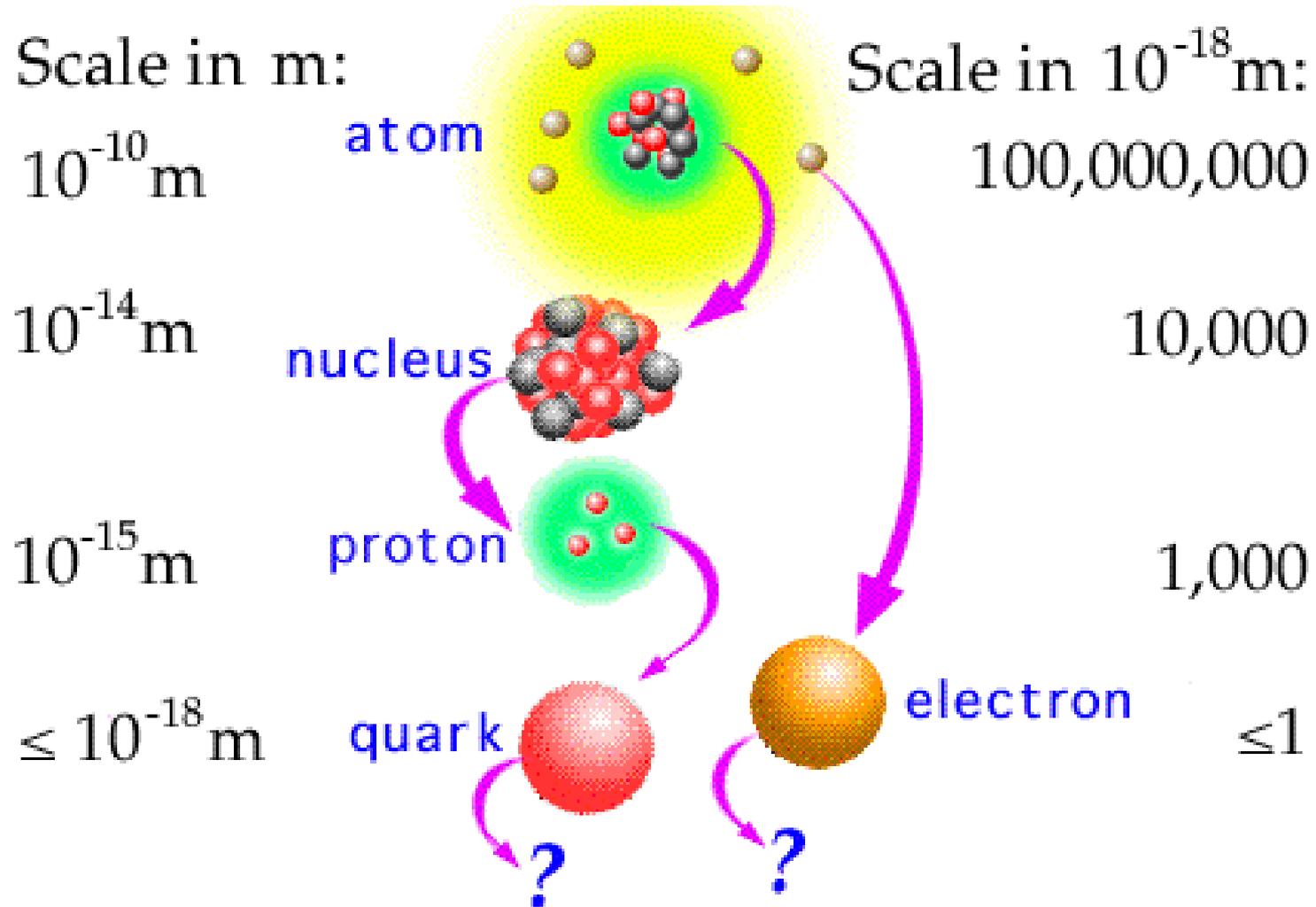
studying bottom and charm decays at
Fermilab's Tevatron collider

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University of Chicago
April 14, 2003

Outline

- Precision bottom and charm studies as an indirect path to discovering new physics
- A new, high-speed tool that allows the CDF experiment (at the energy-frontier Fermilab Tevatron collider) to collect large, inclusive bottom and charm samples
- What CDF can measure with these samples
- A brief look at a future high-rate experiment that may allow the Tevatron collider to become a super-B-factory, once its energy-frontier days are over

Particle physicists are the ultimate reductionists:
What are Nature's most basic building blocks?
What rules do they obey?



We've come a long way!

Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

www.particleadventure.org

FERMIONS

The Standard Model summarizes the theory of weak and electromagnetic interactions and quantum chromodynamics or QCD) and the unified part of the "Standard Model."

matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c ²	Electric charge
ν_e electron neutrino	$<1 \times 10^{-8}$	0
e^- electron	0.000511	-1
ν_μ muon neutrino	<0.0002	0
μ^- muon	0.106	-1
ν_τ tau neutrino	<0.02	0
τ^- tau	1.7771	-1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c ²	Electric charge
u up	0.003	2/3
d down	0.006	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	175	2/3
b bottom	4.3	-1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of \hbar , which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58 \times 10^{-25} \text{ GeV s} = 1.05 \times 10^{-34} \text{ J s}$.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (remember $E = mc^2$), where $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10} \text{ joule}$. The mass of the proton is $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27} \text{ kg}$.

BOSONS

force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c ²	Electric charge
γ photon	0	0
W^-	80.4	-1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge
g gluon	0	0

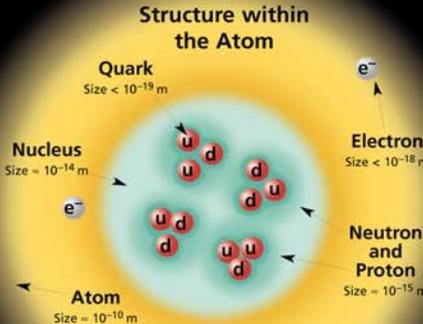
Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq .

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

PROPERTIES OF THE INTERACTIONS

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$					
Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
p	proton	uud	1	0.938	1/2
\bar{p}	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	-1	1.672	3/2

Property	Interaction	Weak		Electromagnetic		Strong	
		Gravitational	(Electroweak)	Fundamental	Residual		
Acts on:		Mass - Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note	
Particles experiencing:		All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons	
Particles mediating:		Graviton (not yet observed)	$W^+ W^- Z^0$	γ	Gluons	Mesons	
Strength relative to electromagnetic for two u quarks at:						Not applicable to quarks	
	10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks	
	$3 \times 10^{-17} \text{ m}$	10^{-41}	10^{-4}	1	60	Not applicable to quarks	
		10^{-36}	10^{-7}	1	Not applicable to hadrons	20	

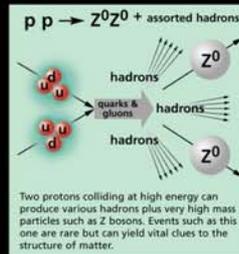
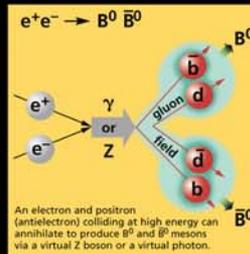
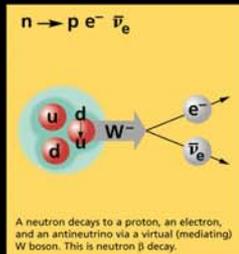
Mesons $q\bar{q}$					
Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0 , γ , and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

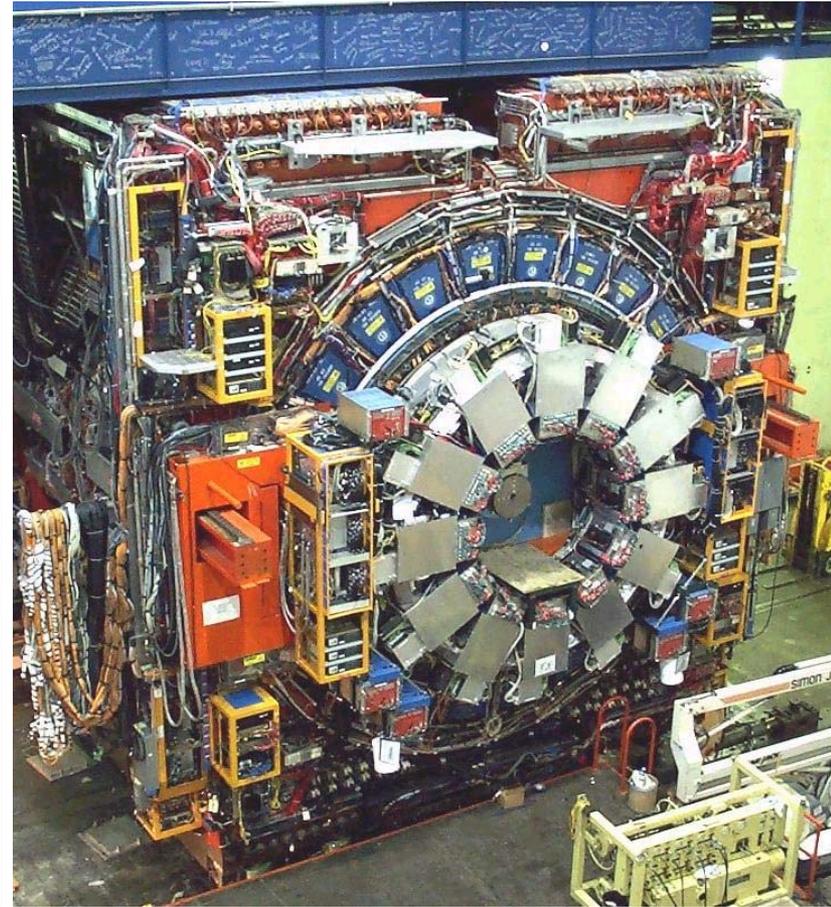
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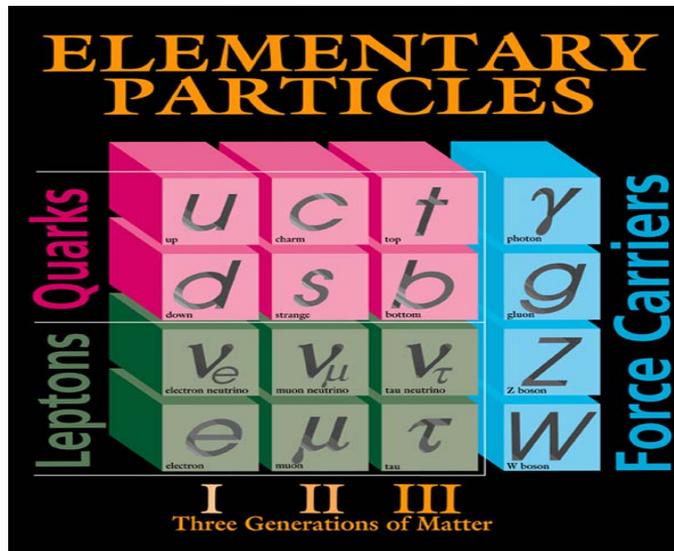
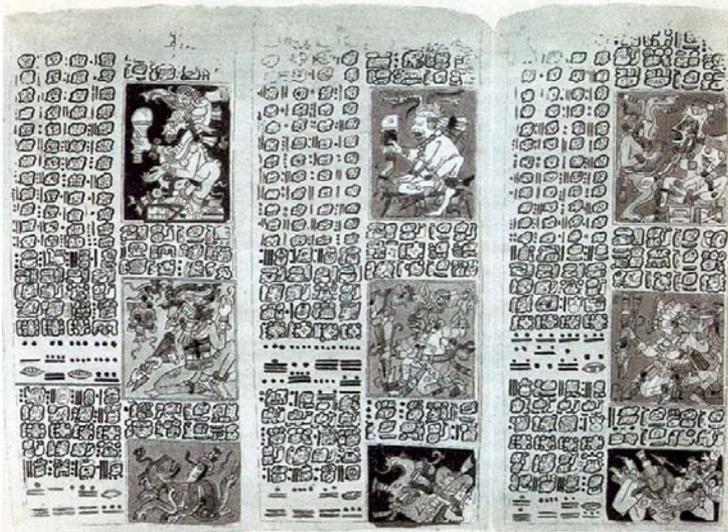
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To address these questions, we continue to build the large, specialized tools of the energy frontier

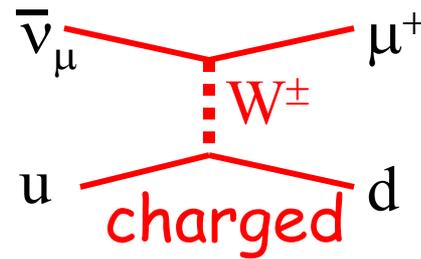
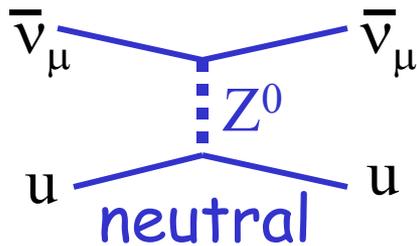


I hope that our knowledge and our creativity will make our culture worth studying, 1000 years from now



While big discoveries are often made at the energy frontier, even pioneers don't head out to the frontier blindly

neutral currents in νN scattering pointed the way to Z (and W) boson discovery



b discovery told us that top should exist

- we knew what its charge and spin should be, and how it should decay, before we found it

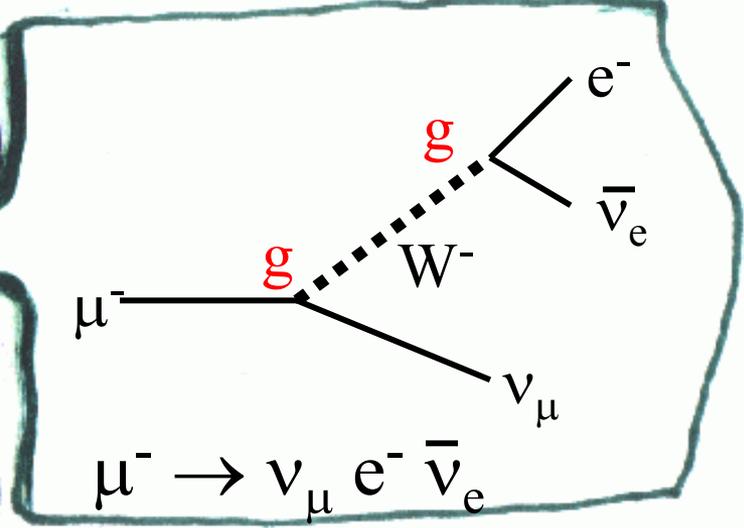
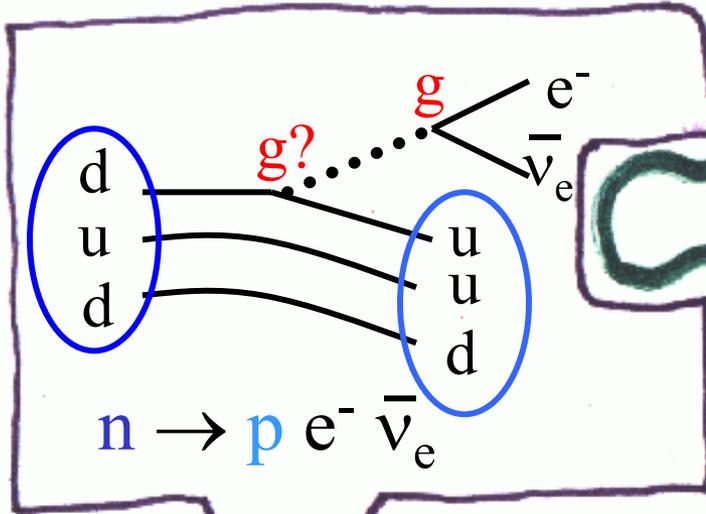
same weak mixing angle, θ_W , relates measured W, Z masses and W, Z couplings

- we expect to find the Higgs particle responsible for this mechanism

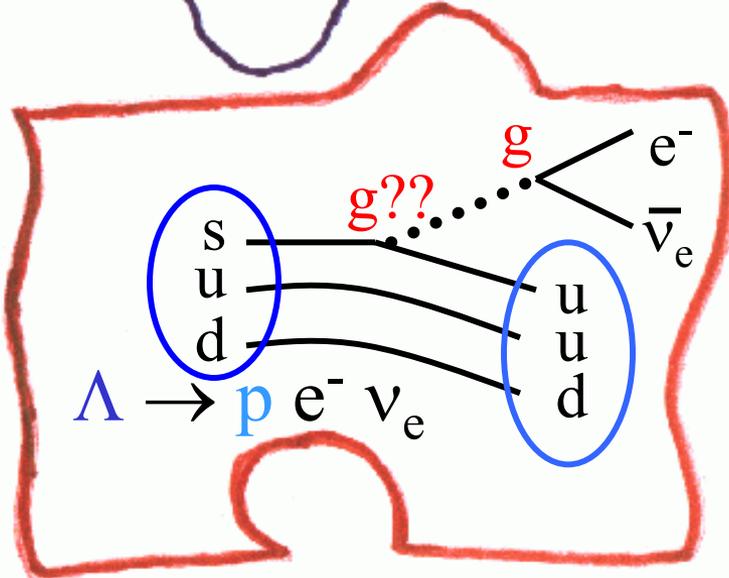
The "indirect" strategy:

study the known puzzle pieces;
see what's missing or what doesn't fit

$\times 0.95 ?$

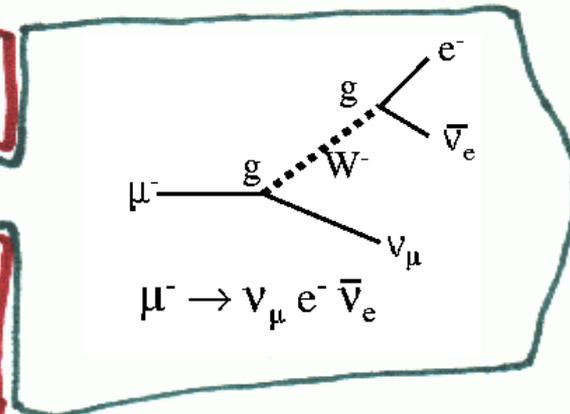
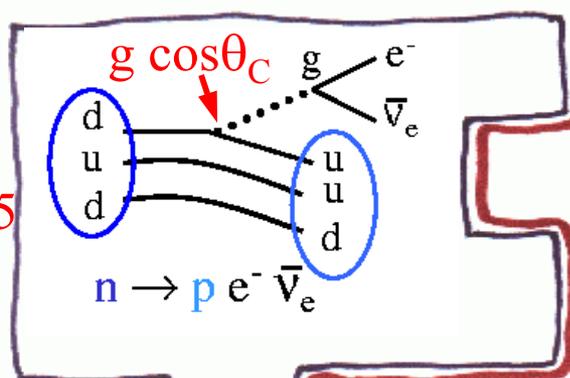


$\times 0.05 ?$



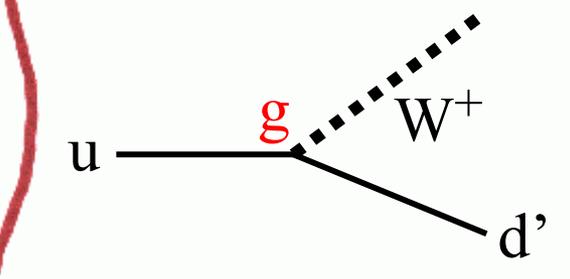
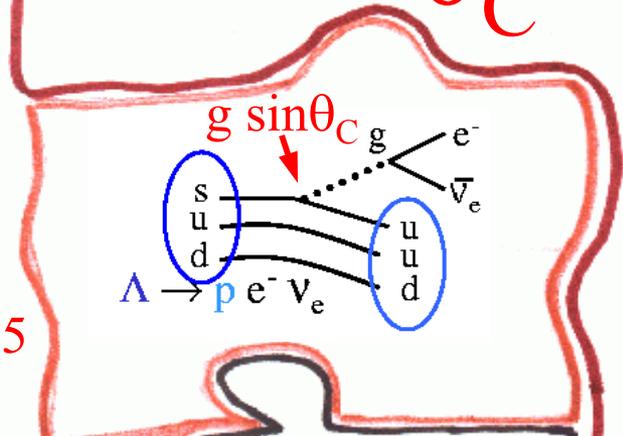
Are neutron decay and lambda baryon decay the same fundamental process as muon decay?

Cabibbo mixing angle was the missing piece



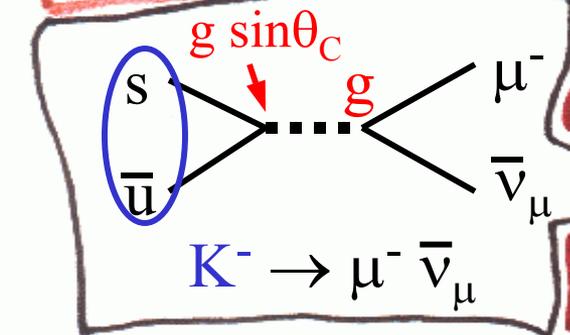
$|\cos \theta_C|^2 = 0.95$

$\theta_C \approx 0.22$



$|\sin \theta_C|^2 = 0.05$

$d' = d \cos \theta_C + s \sin \theta_C$



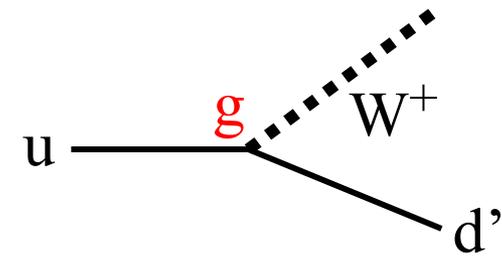
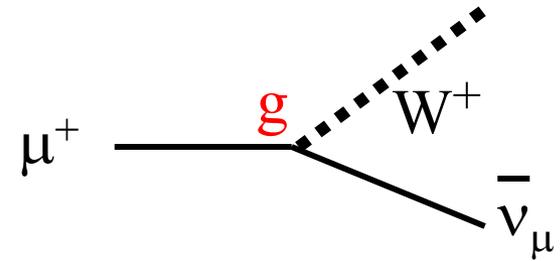
Indirect approach anticipates charm quark discovery

~1970: known quarks & leptons

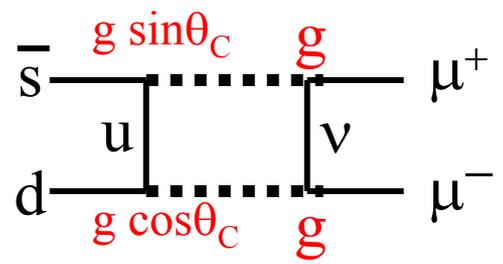
u	ν_e	ν_μ
d	s	e
		μ

Study K^0 meson = $\bar{s}d$

rare decay mode $K^0 \rightarrow \mu^+\mu^-$



$$d' = d \cos \theta_C + s \sin \theta_C$$

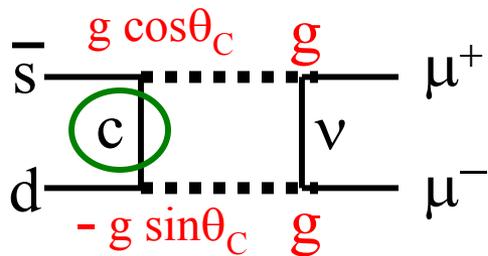


$$\propto \sin \theta_C \cos \theta_C g^4$$

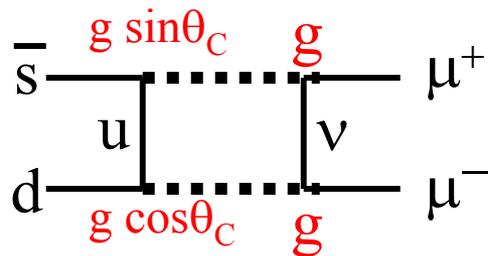
But measured $K^0 \rightarrow \mu^+\mu^-$ decay rate much smaller than calculation

Proposed solution: there must be another quark!

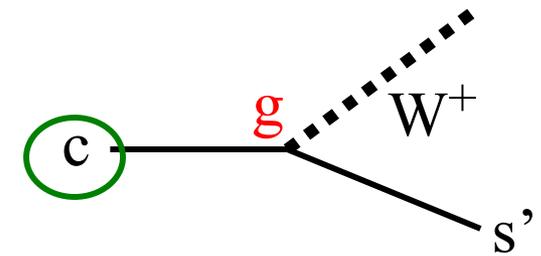
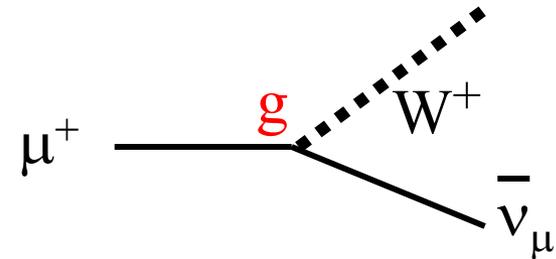
u	c	ν_e	ν_μ
d	s	e	μ



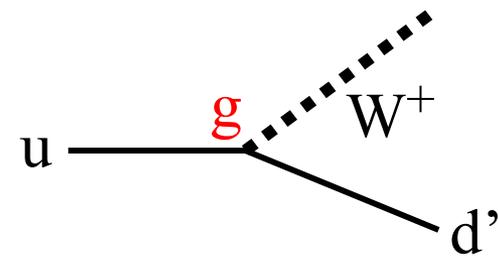
$$\propto -\sin \theta_C \cos \theta_C g^4$$



$$\propto \sin \theta_C \cos \theta_C g^4$$



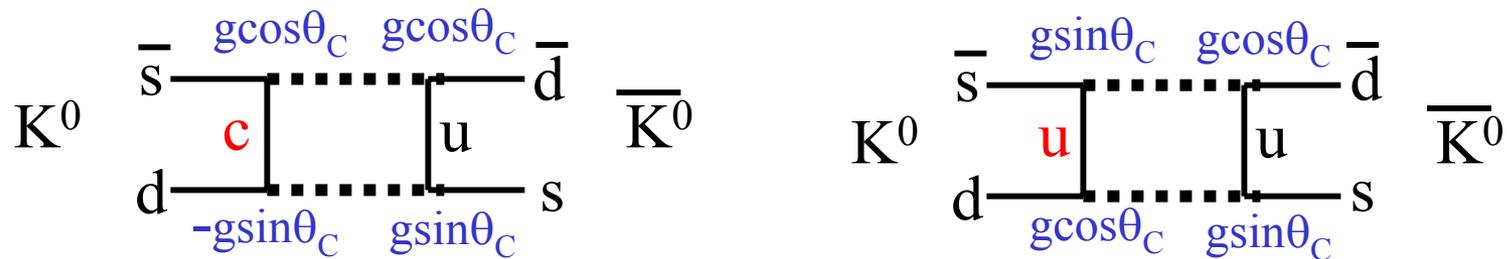
$$s' = s \cos \theta_C - d \sin \theta_C$$



$$d' = d \cos \theta_C + s \sin \theta_C$$

Destructive interference!

$K^0 \leftrightarrow \bar{K}^0$ oscillation rate \Rightarrow predict charm quark's mass



Destructive interference not perfect, because $m_c \neq m_u$

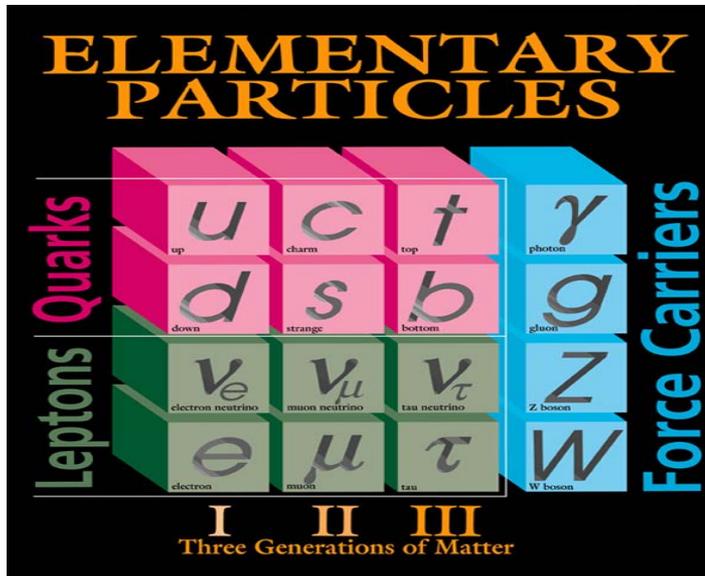
$$\Sigma \text{ amplitudes} \propto -g^4 \sin^2 \theta_C \cos^2 \theta_C (m_c^2 - m_u^2) / M_W^2$$

predict $m_c \approx 1.5 \text{ GeV}$ (1973)

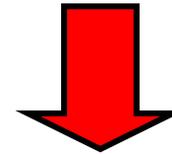
$c \bar{c}$ meson (mass 3.1 GeV , $\approx 2 \times 1.5 \text{ GeV}$) discovered in 1974,
in high-energy collisions at BNL and SLAC

\Rightarrow 1976 Nobel prize

Today, there are many more puzzle pieces to study



$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos \theta_C & \sin \theta_C \\ -\sin \theta_C & \cos \theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$



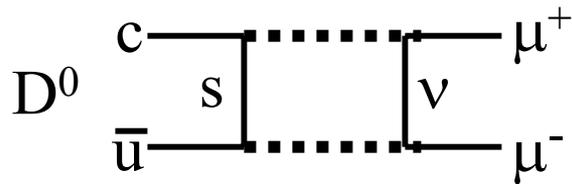
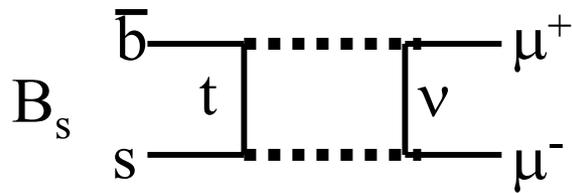
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

6 quarks, 3 euler angles, 1 phase

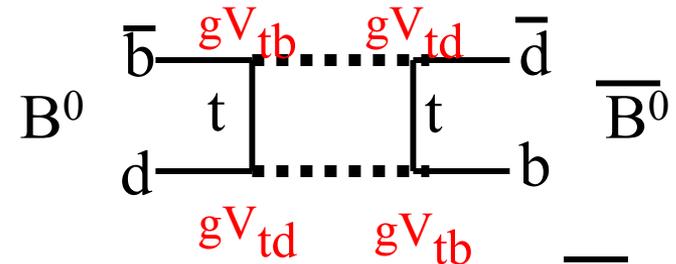
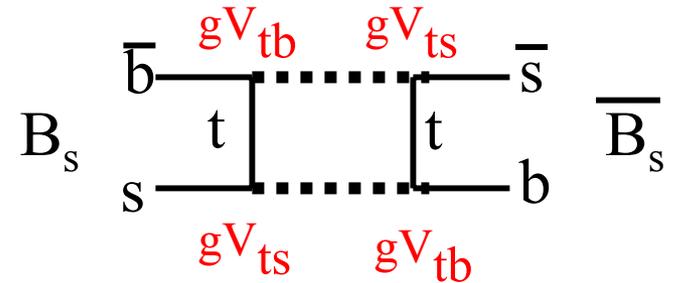
6 leptons

lots and lots of amplitudes to check,
some very small

To make progress, you pick an unfinished region of the puzzle, and study the shapes carefully. Bottom and charm decays are a promising region to study.



Analogues of $K^0 \rightarrow \mu^+ \mu^-$
Small amplitudes



Analogues of $K^0 \leftrightarrow \bar{K}^0$
Precision measurements

Let's put the indirect approach to work, by collecting lots of b and c decays. Maybe we'll find new clues.

Fermilab's Tevatron collider produces lots of b's, c's

Very large Tevatron $b\bar{b}$ rate:

- about 1 kHz of $b\bar{b}$ pairs, at nominal luminosity
 - $\sigma(b\bar{b}) \sim 100\mu\text{b}$ (10 kHz @ $10^{32} \text{ cm}^{-2}\text{s}^{-1}$), 10% "usable"
- compare: about 5 Hz of $b\bar{b}$ pairs at $Y(4S)$, typical BABAR/BELLE luminosity
 - $\sigma(b\bar{b}) \sim 1\text{nb}$ (5 Hz @ $5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$)

Produce all states: B^0 , B^+ , B_s , Λ_B , B_C

$c\bar{c}$ rate also large (\sim a few \times $b\bar{b}$ rate)

CDF, an existing Tevatron collider experiment, can already exploit this potential

“general-purpose” experiment at the energy frontier

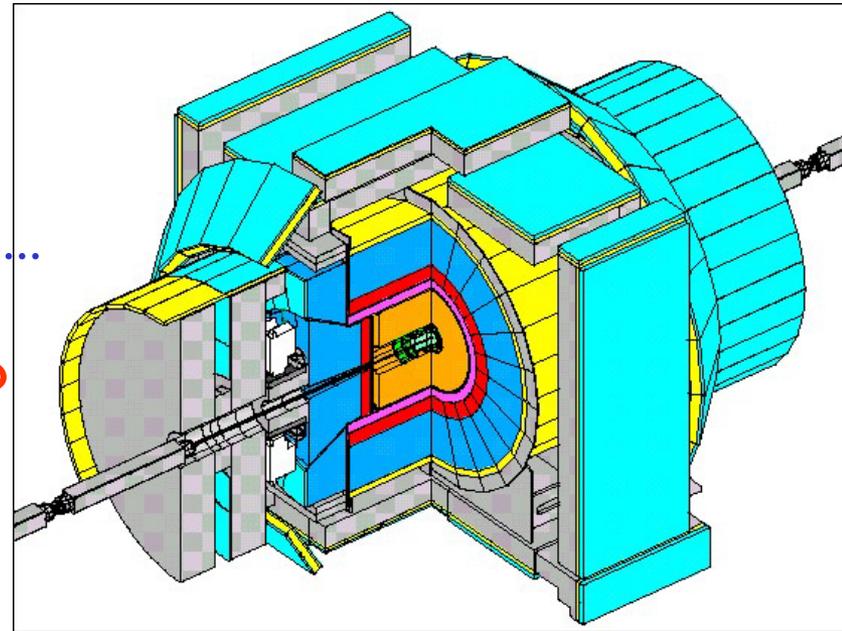
- facility, like large telescope: many researchers divide bandwidth
- traditional mission: top, W, Z, SUSY, ...

Can we adapt CDF for b,c physics?

- Yes, we did -- had to build the tools

Caveats:

- “general-purpose” - not fully optimized for b physics
- CDF can only record about 50 Hz to tape
- proton collider is a challenging place to work



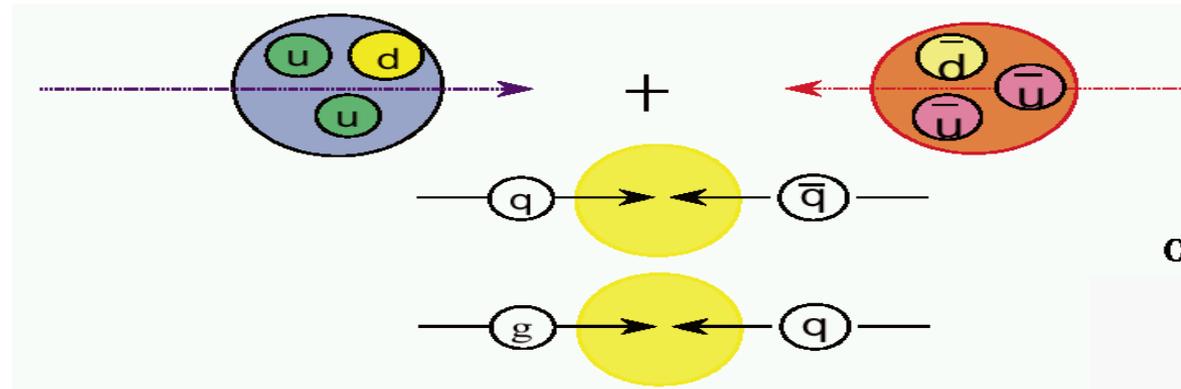
Challenge #1: proton = "broad-band beam of quarks & gluons"

4 numbers describe
bb C.O.M. frame:

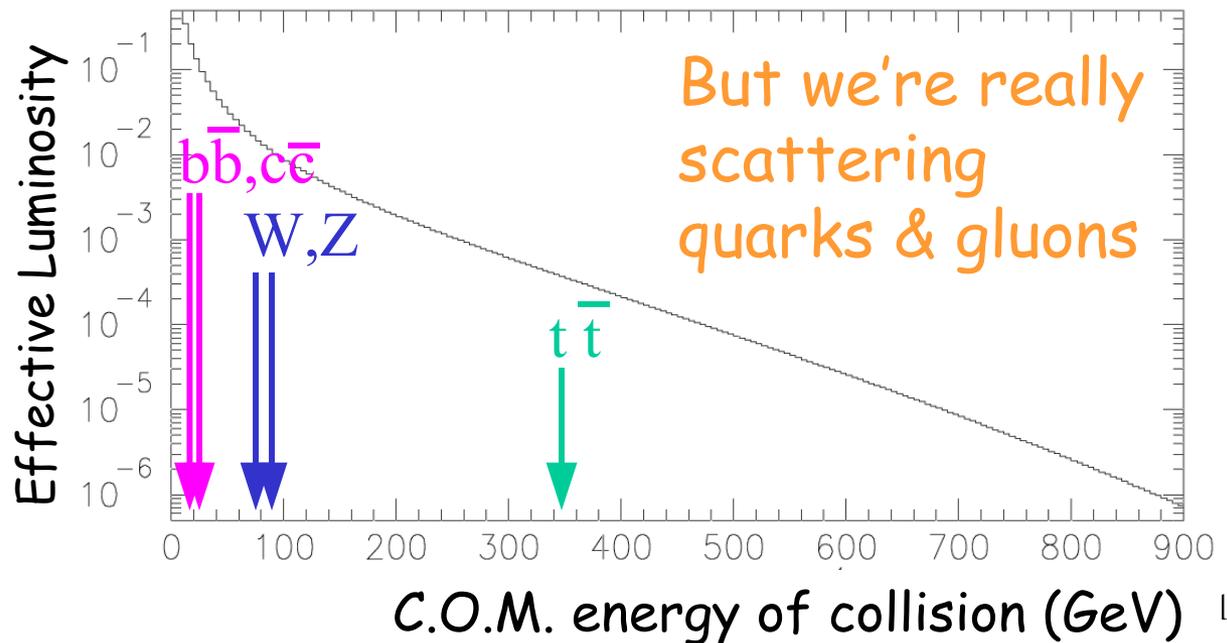
P_x, P_y, P_z, M

2 of them we don't
know at all

the other 2 we
know very poorly

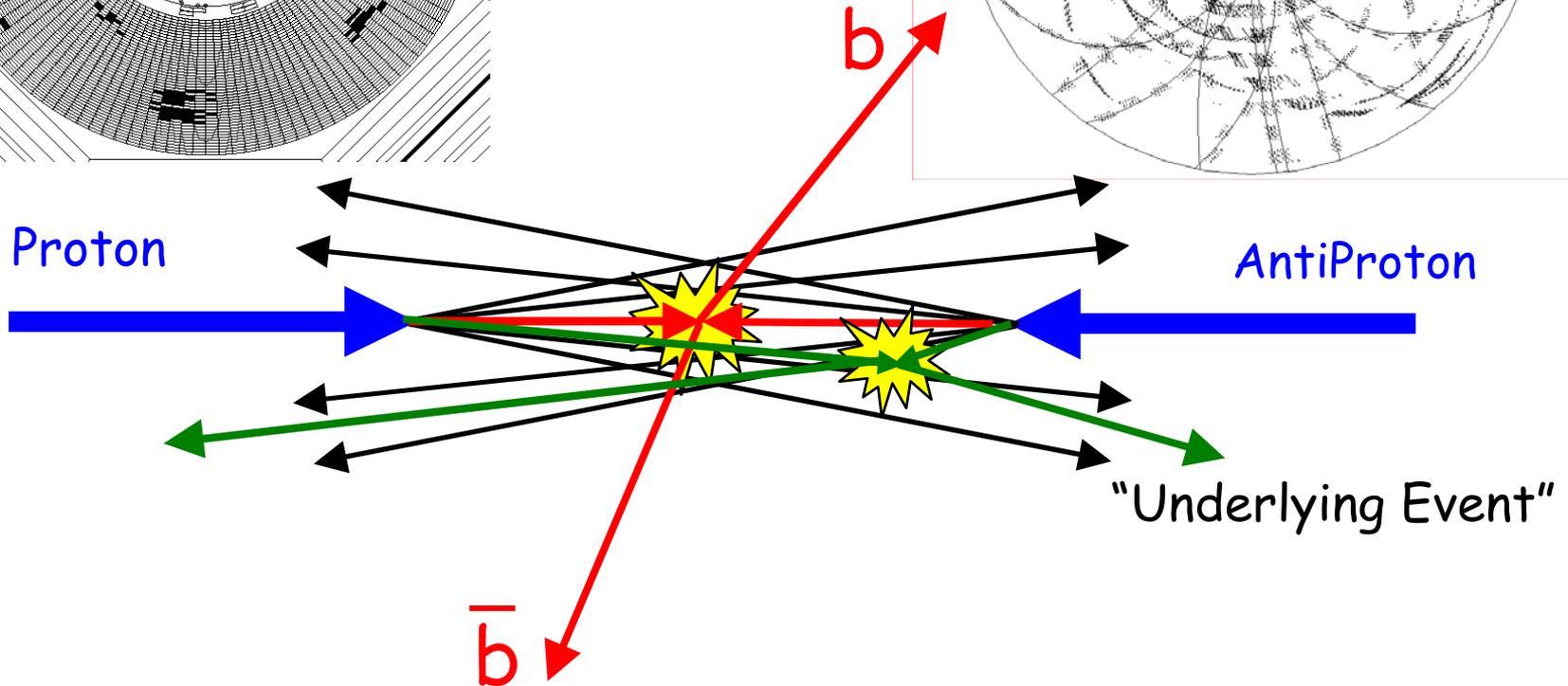
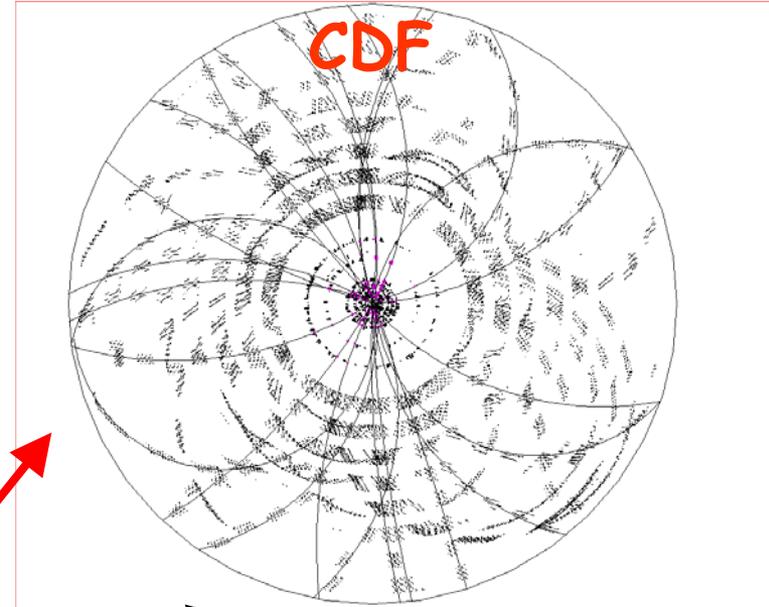
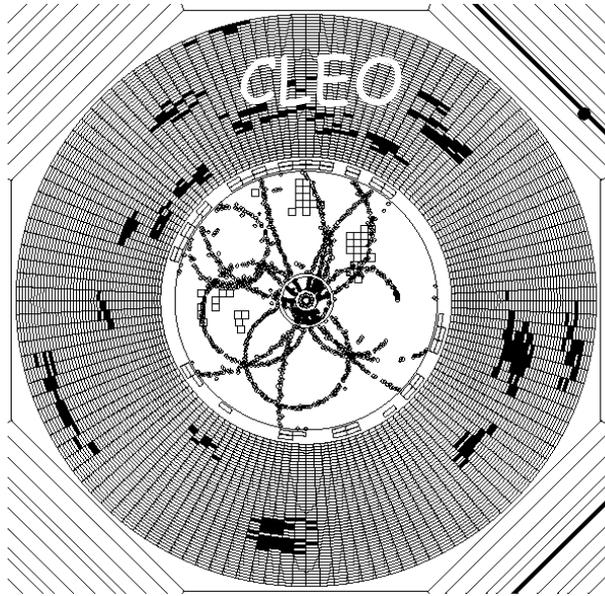


(Anti)proton momentum precisely known



Challenge #2: messy events

The $B\bar{B}$ pair at CDF is accompanied by $O(10)$ charged particles.



CDF Detector

Calorimeter measures electron, photon, and hadron energies

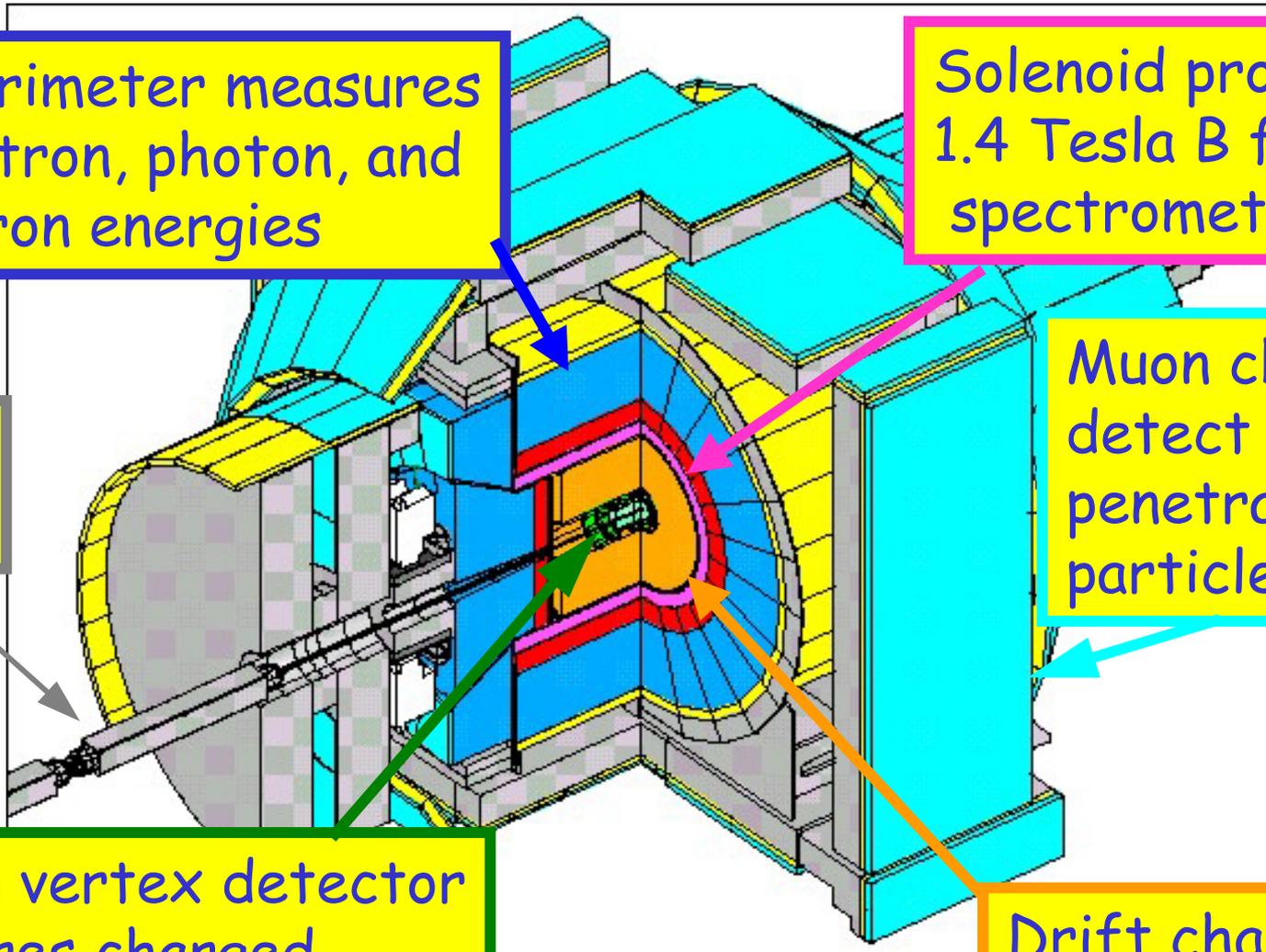
Solenoid provides 1.4 Tesla B field for spectrometer

Beam axis

Muon chambers detect penetrating particles

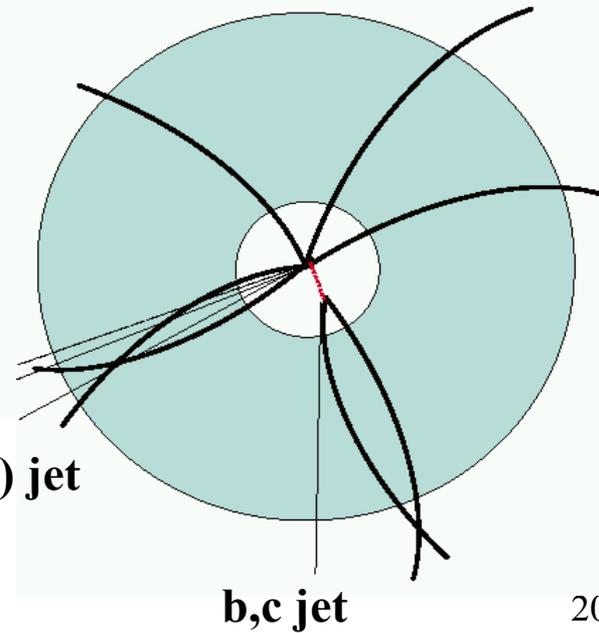
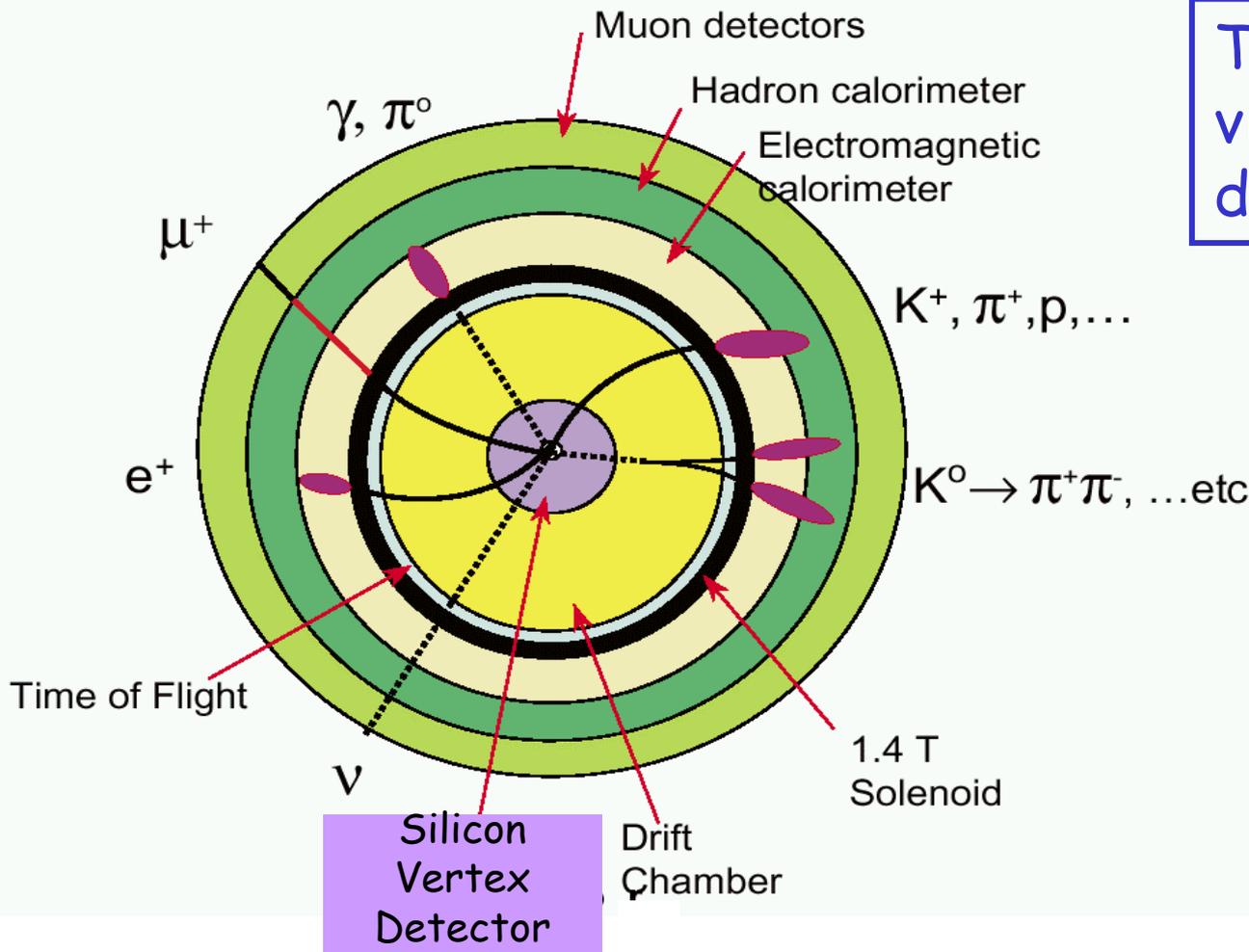
Silicon vertex detector measures charged particle production points, b & c lifetimes

Drift chamber measures charged particle momenta

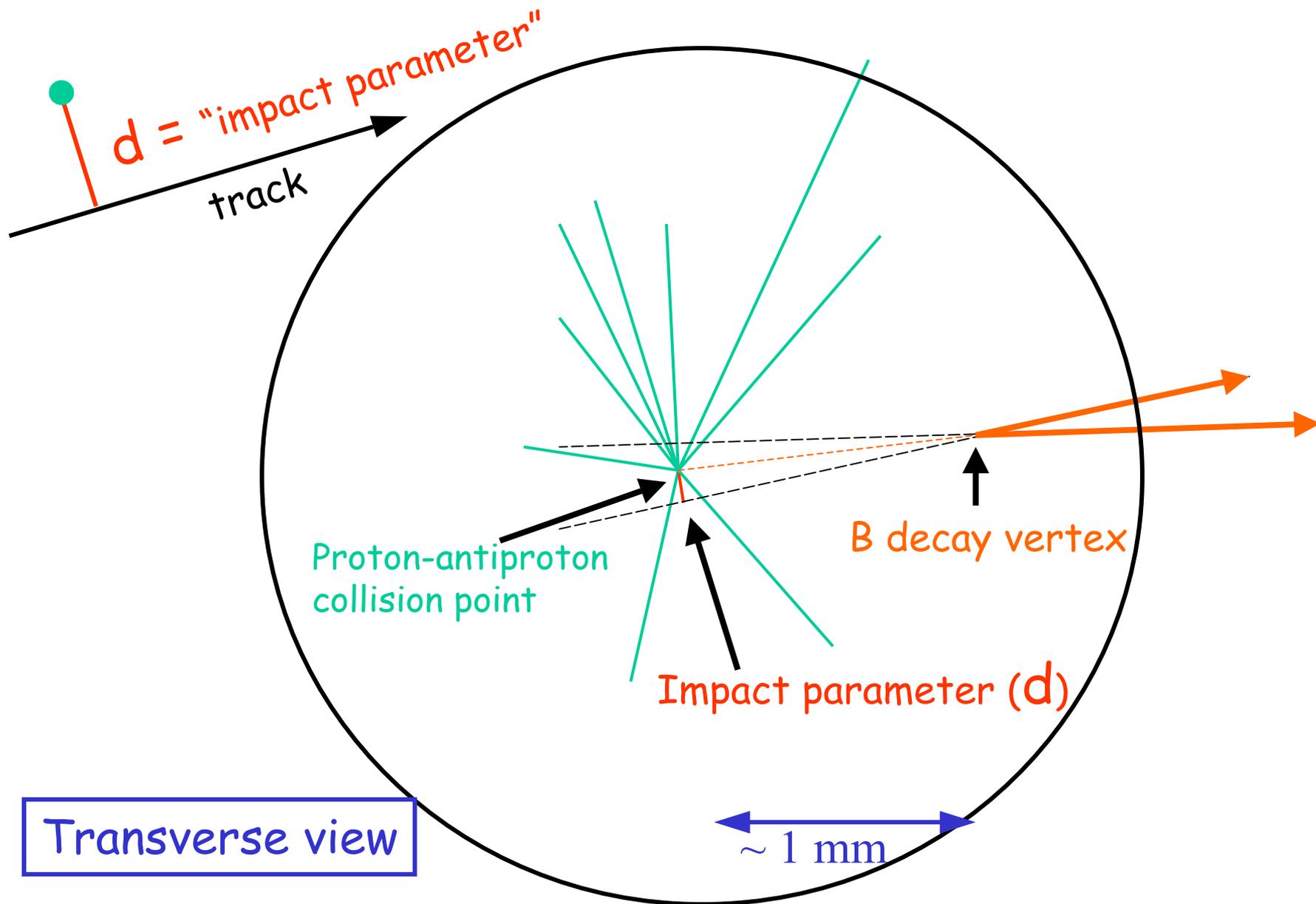


Particle signatures at CDF

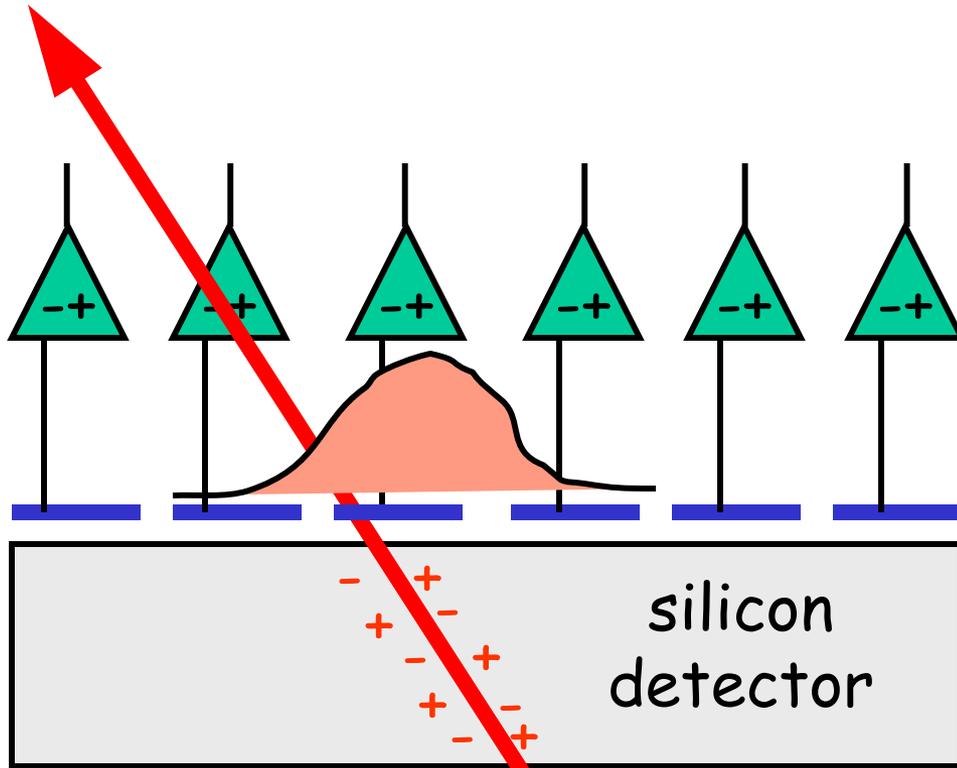
Transverse view of detector



A salient property of b,c decay: lifetime



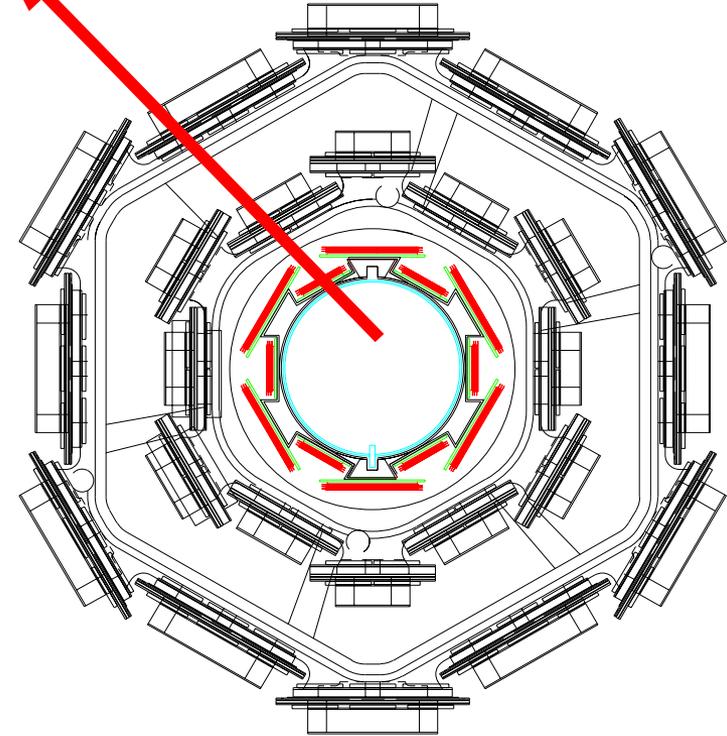
Position measurement ("hit") for charged particle



60 μm

"hit" = charge centroid

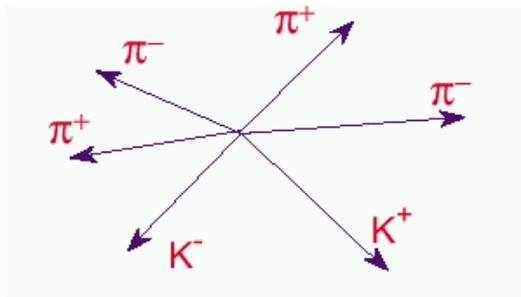
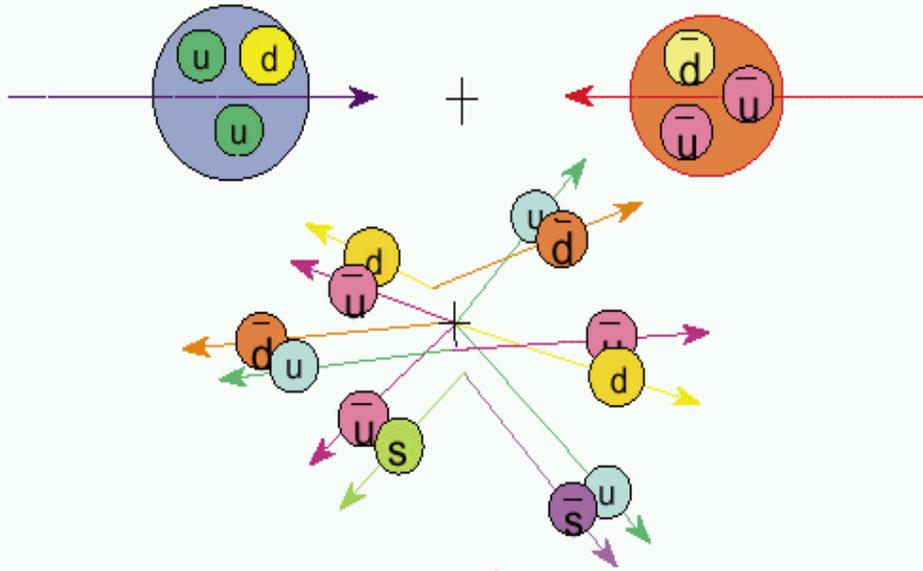
Charged particle trajectory



3cm

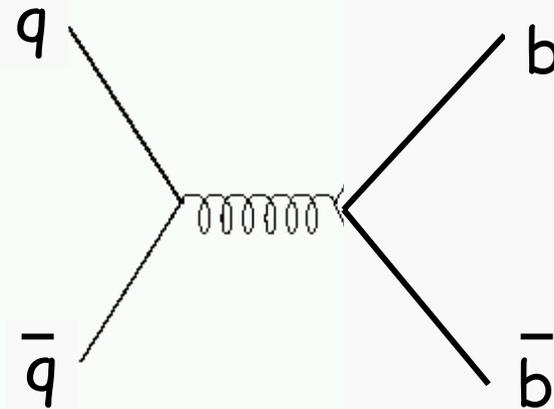
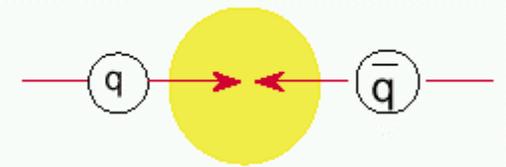
Why do you need a trigger?

Haystack



Vast majority of collisions; without a trigger, we would see only this

Needle



$\times 1000$ less frequent: bottom quark pair production

Recap

Tevatron produces $O(1\text{kHz})$ of B's "usable" by CDF

Tevatron produces 2.5 MHz of uninteresting events

CDF can write out 50 Hz total

To maximize the fraction of that 50 Hz that contains B's, we **select very quickly**, based on **lifetime information**.

Use silicon microstrip detector to measure each particle's impact parameter.

In the trigger (tens of microseconds).

Nobody has solved this problem at this rate before.

Division of labor: 3-step selection

Maximum rates

2.5 MHz



25 kHz



250 Hz



50 Hz

Level 1: ~ 5.5 μ sec (pipeline ~14 beam crossings deep)

- drift chamber tracks (charged particle trajectories)
- look for 2 tracks with momenta > 2 GeV

Level 2: ~30 μ sec ("Silicon Vertex Trigger")

- fast silicon tracking (measure lifetime info)
- look for 2 tracks with impact parameters > 120 μ m

Level 3: ~ 1 second (using ~250 PCs in parallel)

- full-precision tracking
- confirm the fast hardware tracking measurements

b+c purity

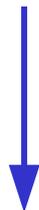
~0.1%



~1%

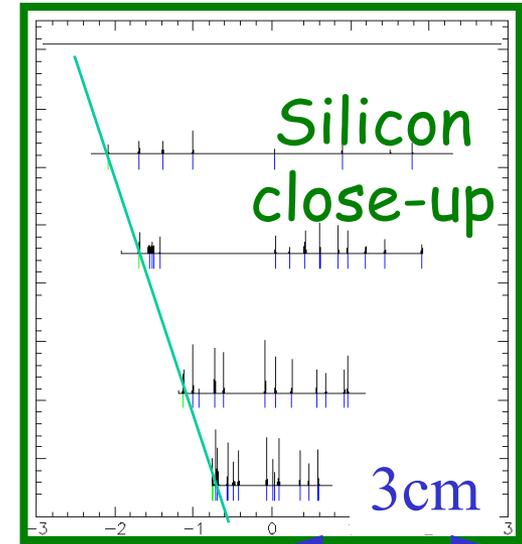
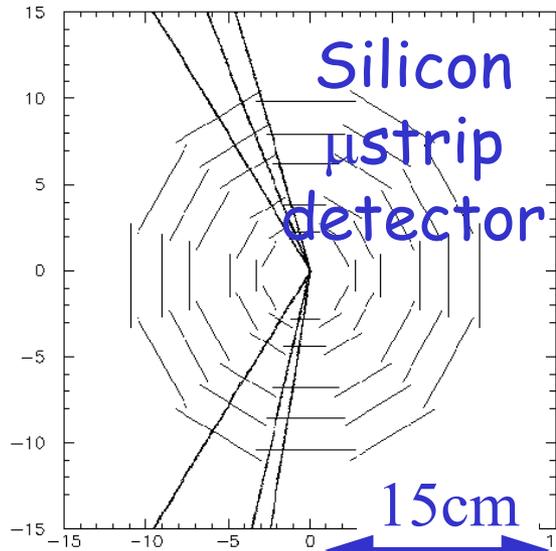
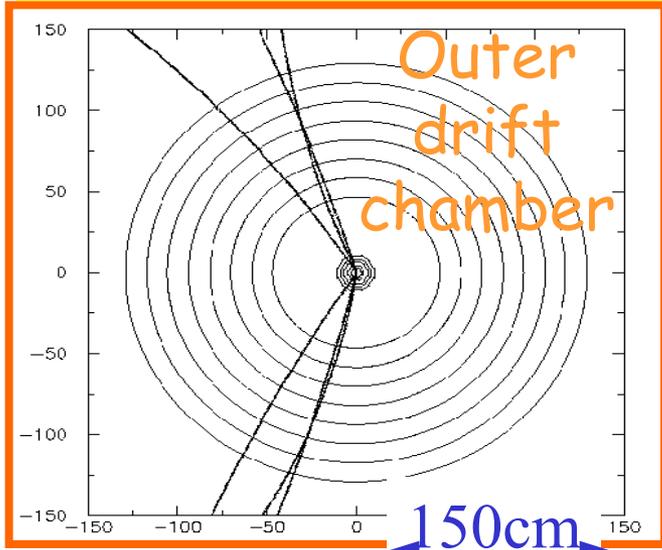


~50%



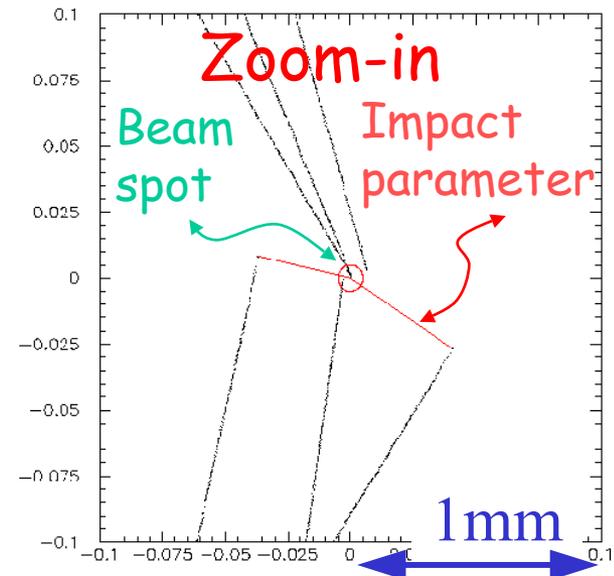
~90%

"Silicon tracking" problem synopsis



Input (every time Level 1 says "yes"):
outer drift chamber trajectories
azimuth and curvature only
silicon pulse height for each channel

Output (about 20 microseconds later):
trajectories that use silicon points
improved azimuth and curvature
impact parameter: $\sigma(d)=35\mu\text{m}$



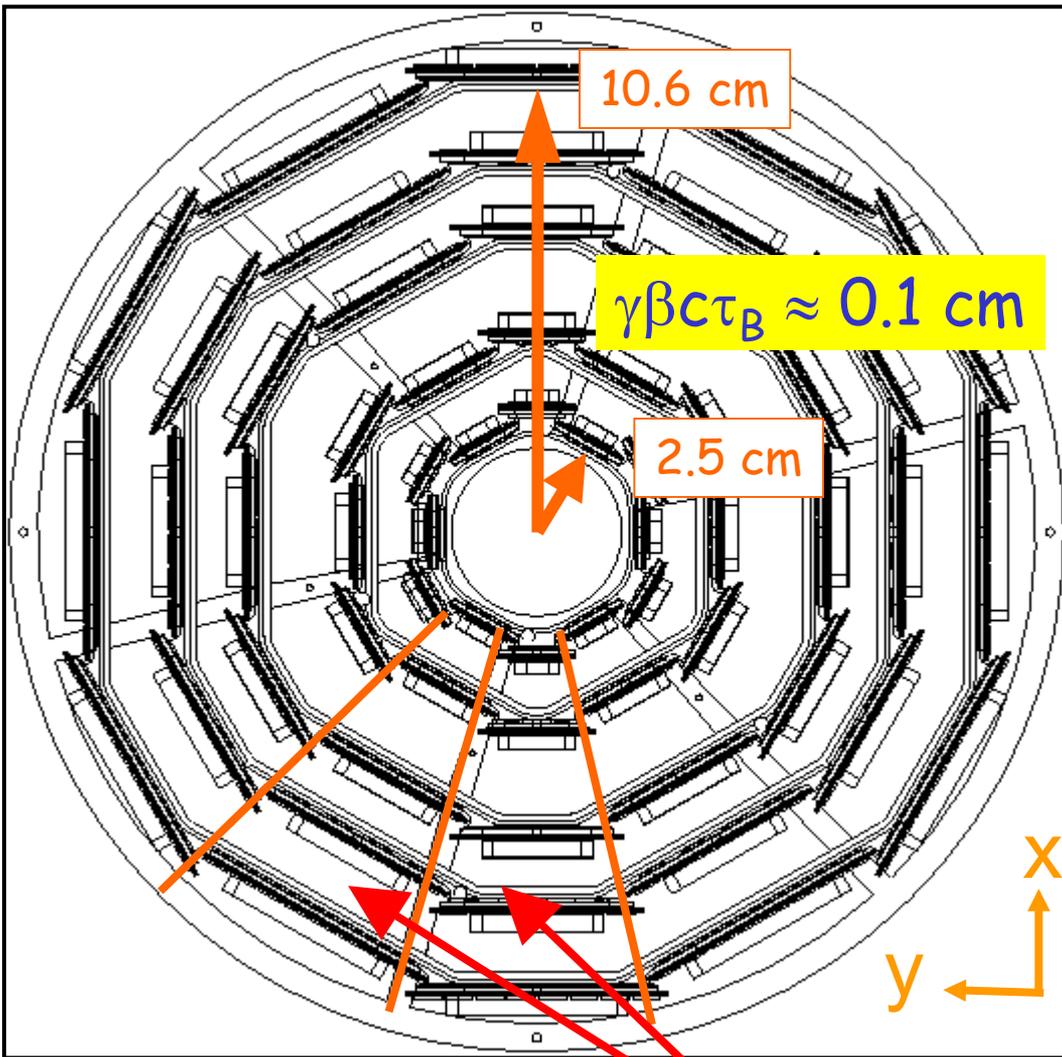
Three of SVT's key techniques ...

How do we measure particle trajectories in about 20 microseconds per event, when software takes typically ~ one second?

- (1) Do everything you can in parallel and in a pipeline.
- (2) Streamlined pattern recognition
 - Bin coordinate information coarsely into roads.
 - Examine all possible patterns in parallel (of course).
 - This is done in a custom VLSI chip.
- (3) Linearize the fitting problem.
 - i.e. solvable with matrix arithmetic

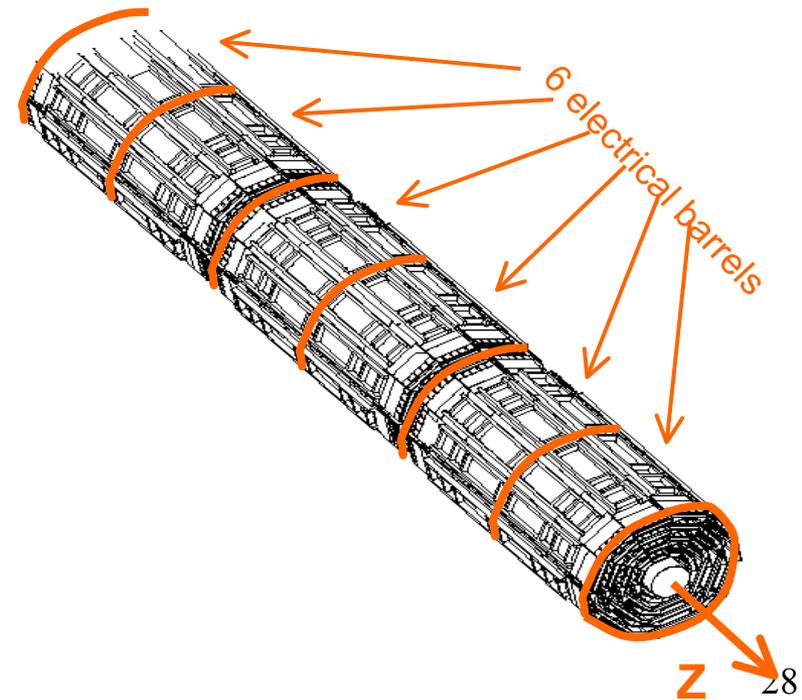
The wisest are the most annoyed by the loss of time. -Dante

Trick #1: symmetry allows parallelism



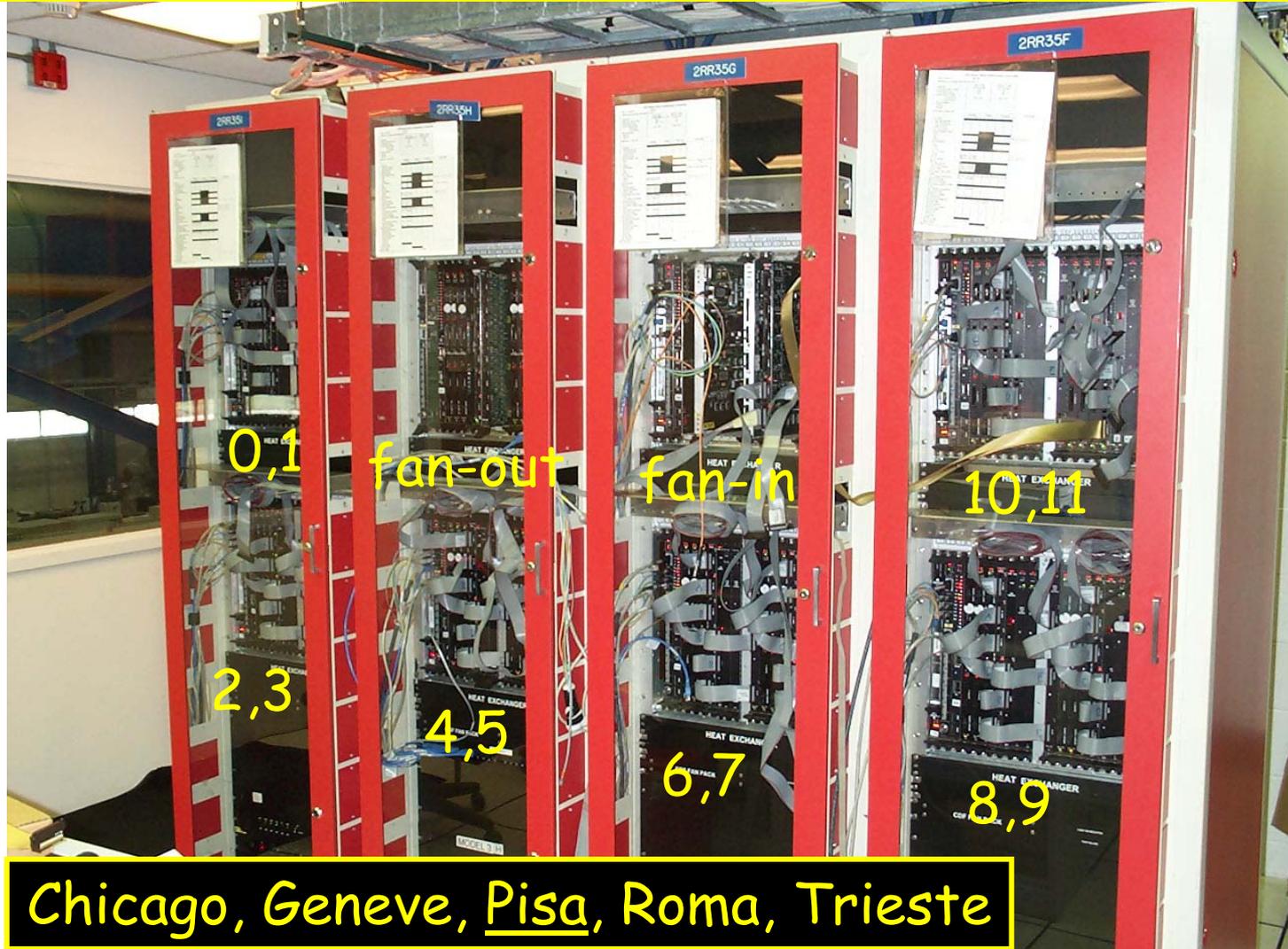
Note "wedge" symmetry

Symmetric, modular geometry of silicon vertex detector lends itself to parallel processing



SVT data volume requires parallelism

2 meters

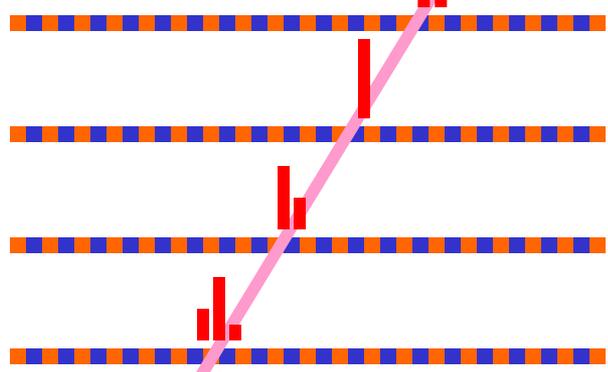


Chicago, Geneve, Pisa, Roma, Trieste

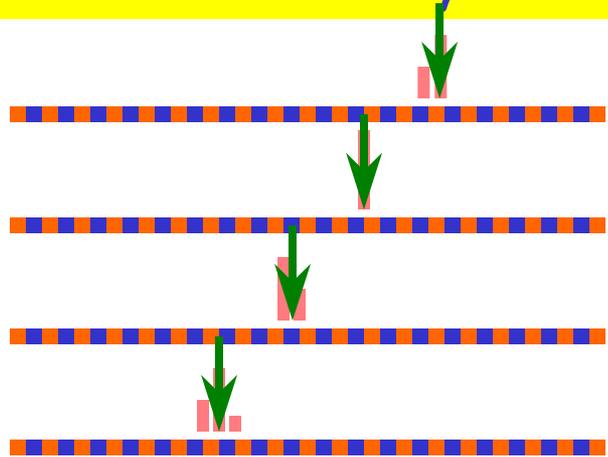
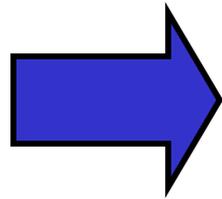
Reduces gigabytes/second to megabytes/second

Peak (avg): 20 (0.5) GB/s → 100 (1.5) MB/s

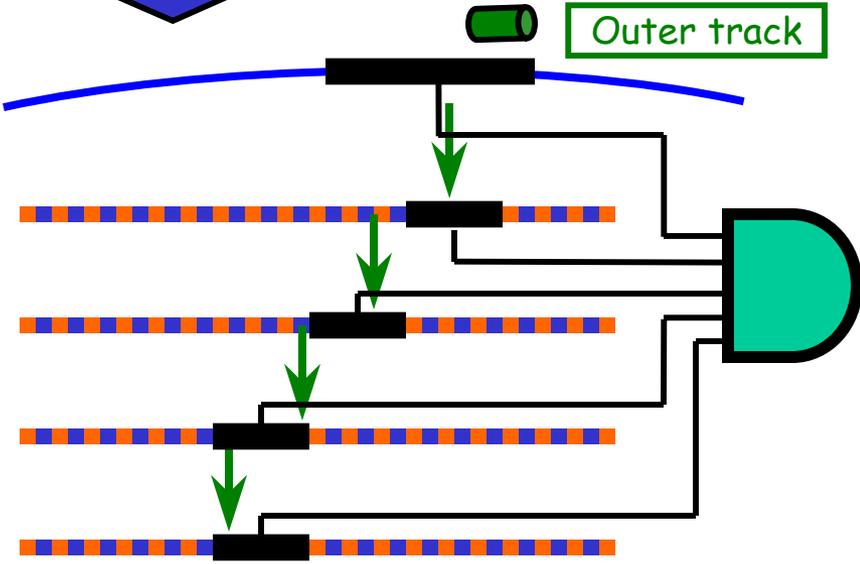
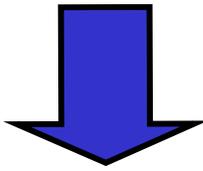
Each 1/12 of detector is processed in its own assembly line



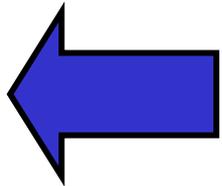
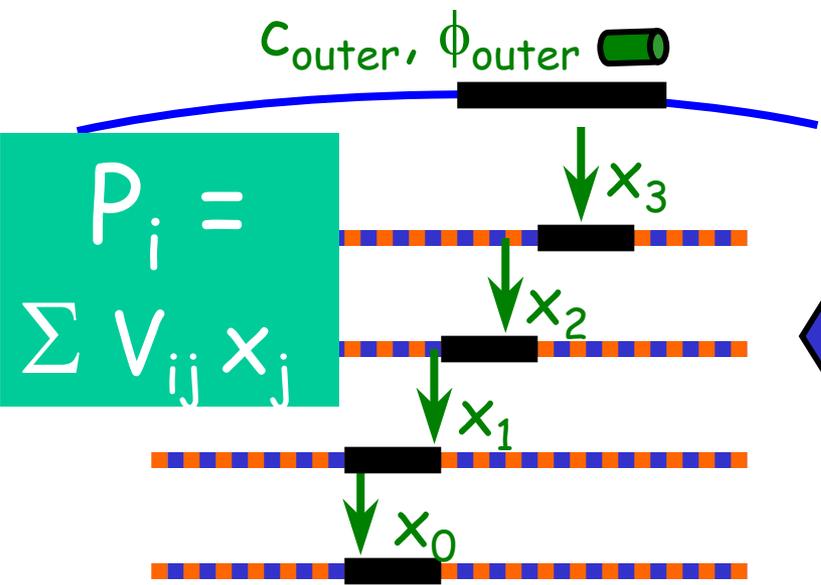
ADC counts



hit coordinates

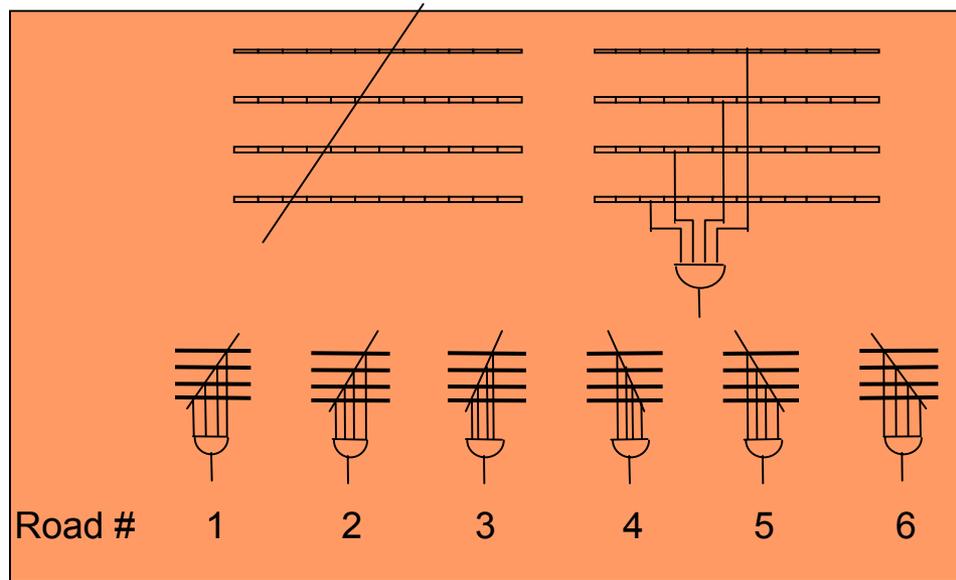
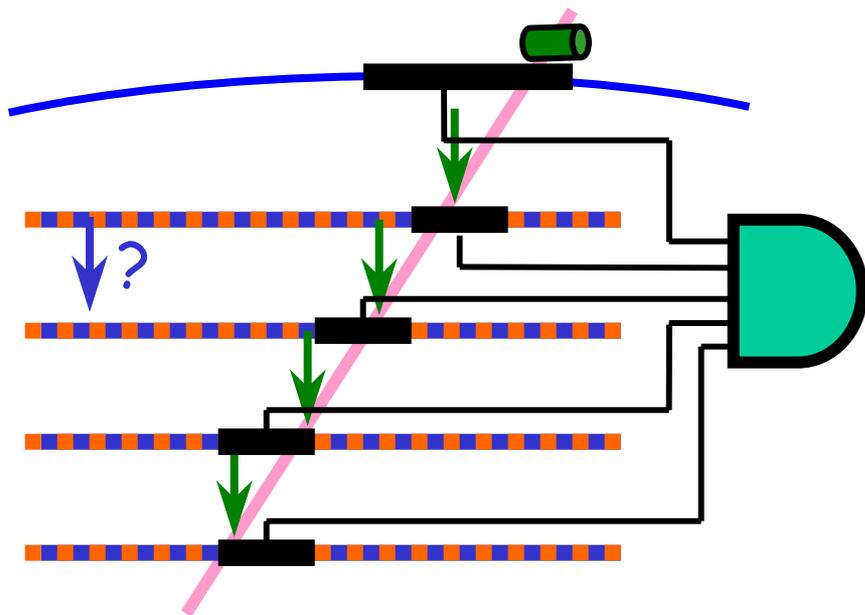


roads (= "patterns")



Fitted tracks: $P = (c, \phi, d, \chi^2)$

2nd trick: streamlined track finding



The way we find tracks is a cross between

- searching predefined roads
- playing BINGO

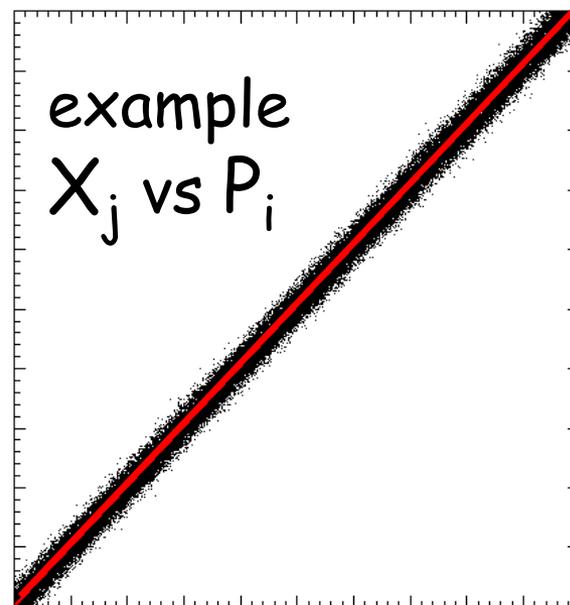
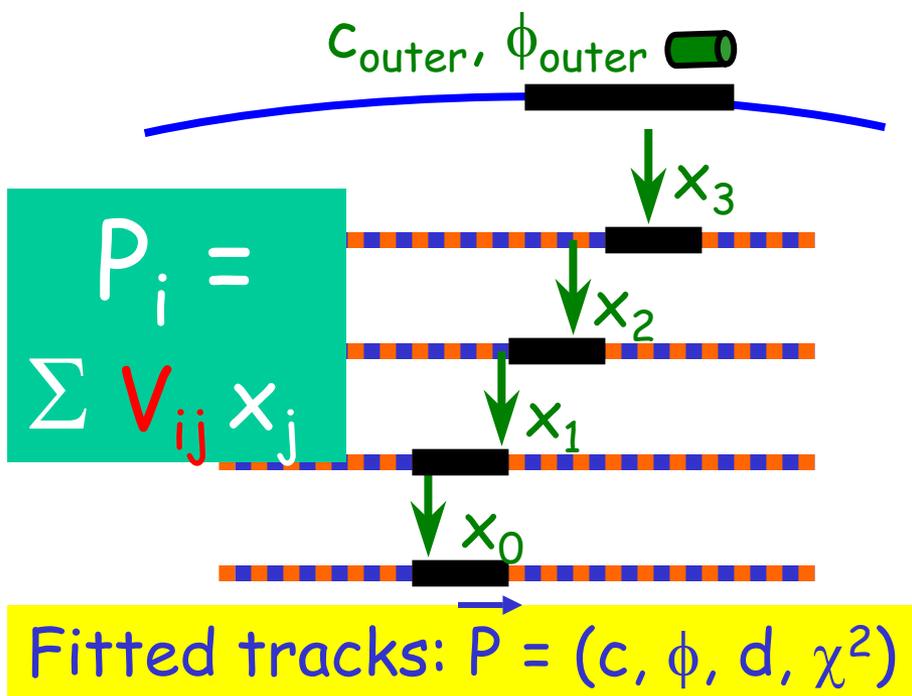
$$\text{Time} \sim A \cdot N_{\text{hits}} + B \cdot N_{\text{matchedroads}}$$

	B	I	N	G	O
2	2	17	35	48	61
10	10	21	39	53	66
14	14	20	free	55	65
8	8	25	41	52	62
6	6	16	37	46	67

Trick #3: linear fit

Circle(\vec{P}) \cap Planes at points \vec{x}
 \vec{x} not in general linear in \vec{P}

But for $P > 2 \text{ GeV}$, $d < 1 \text{ mm}$,
 linear fit biases $d \sim \text{few } \%$
 \Rightarrow no problem for trigger



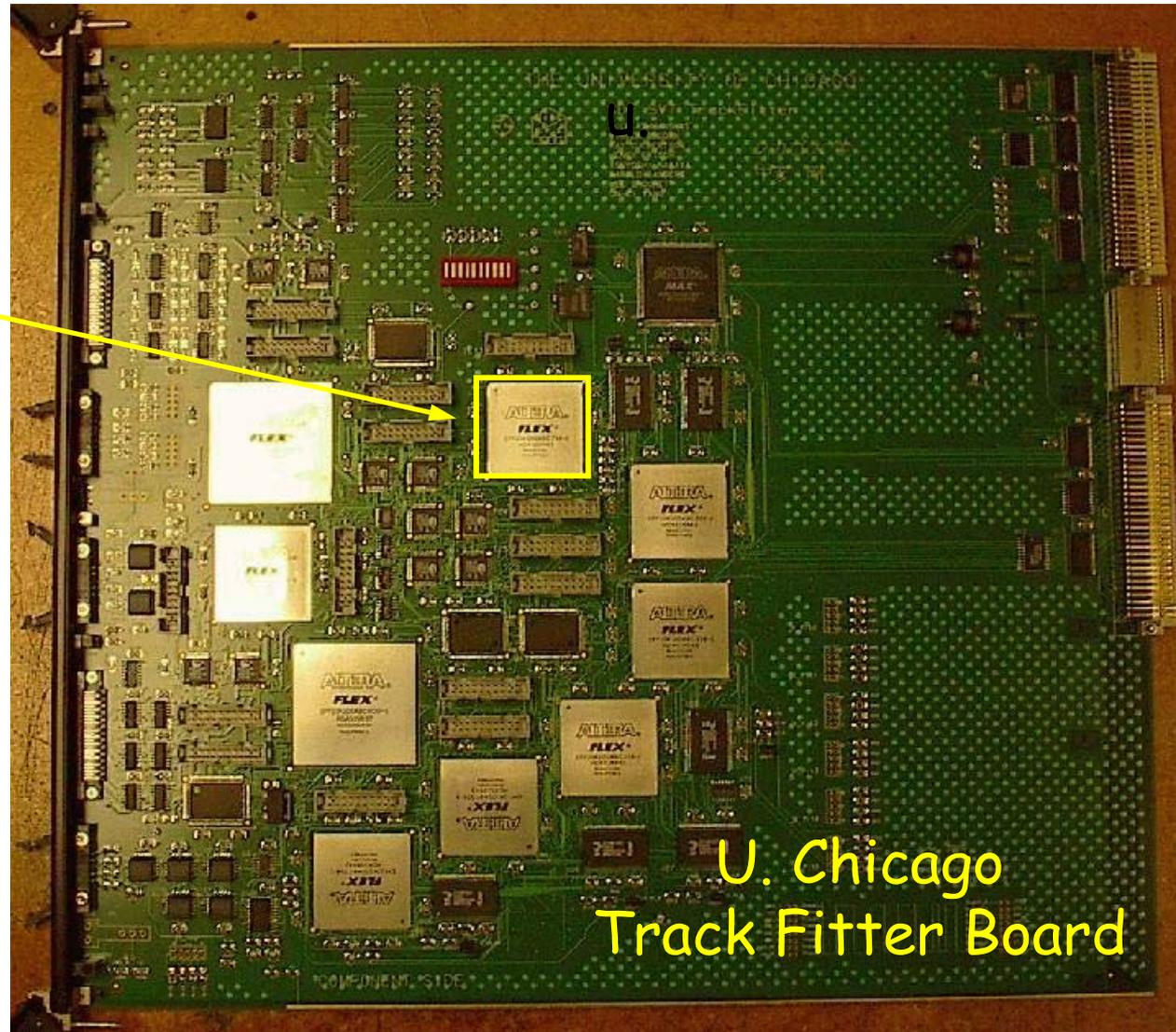
We derive V_{ij} by linear regression to Monte Carlo data

Trick #3a: use road as a hint
 precompute $V_{ij} X_j^{\text{road}}$
 $\Rightarrow 250 \text{ nsec per fit!}$

Least squares fit is performed in programmable logic

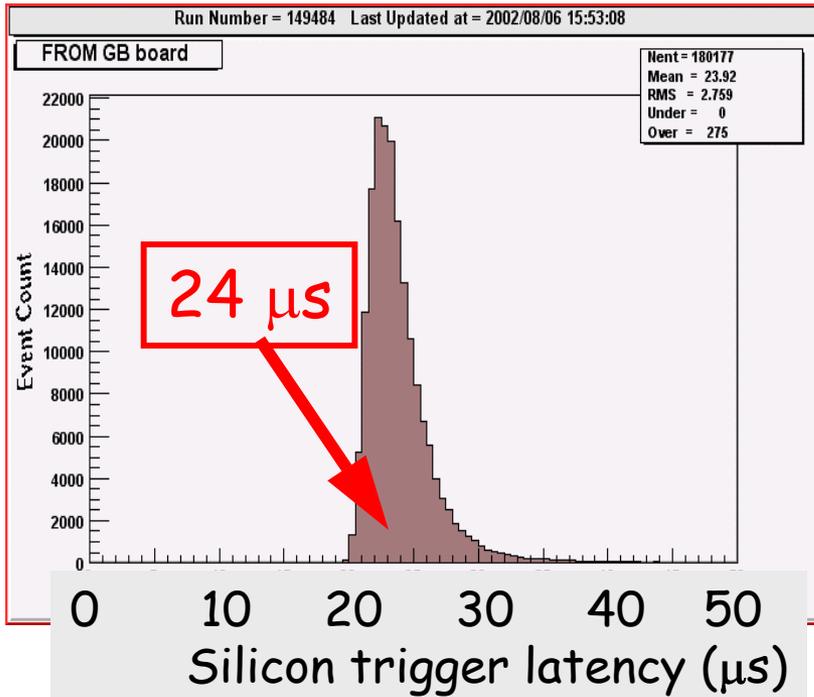
The 6 scalar products are computed in parallel

Each fit done in 250nsec

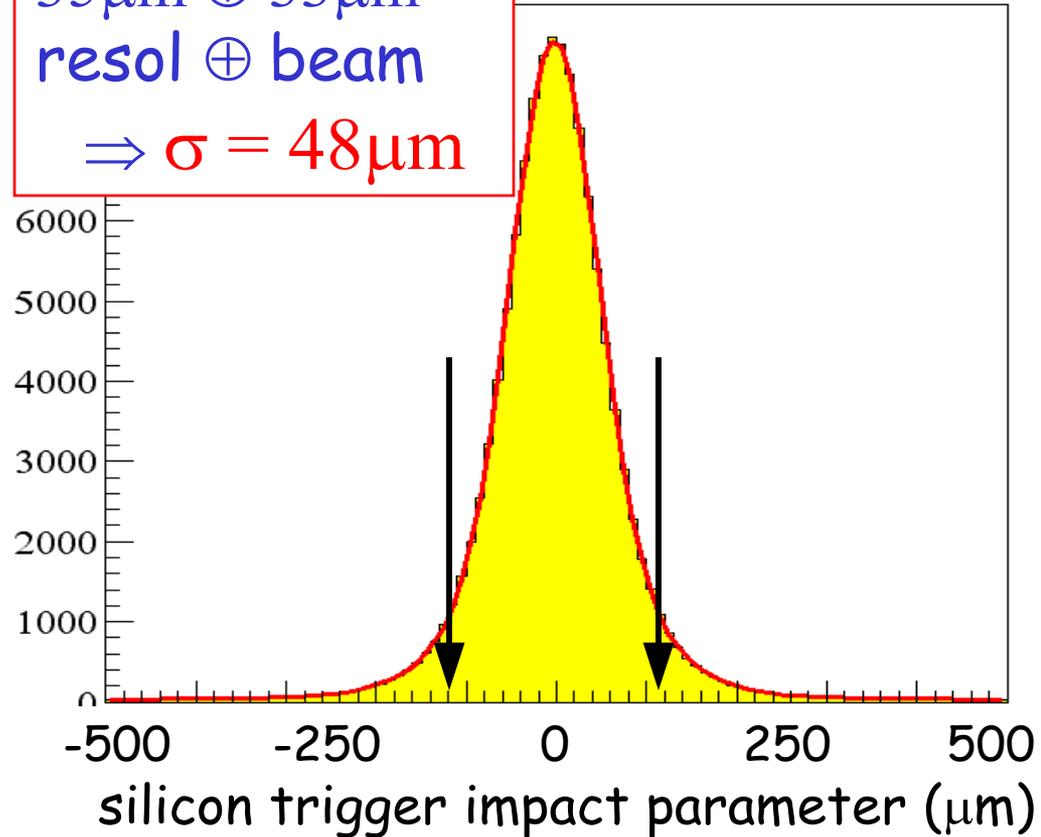


U. Chicago
Track Fitter Board

Success !



$35\mu\text{m} \oplus 33\mu\text{m}$
resol \oplus beam
 $\Rightarrow \sigma = 48\mu\text{m}$



4 orders of magnitude
faster than software

comparable resolution

First year's results

Building a lifetime trigger for a proton collider experiment is a new approach.

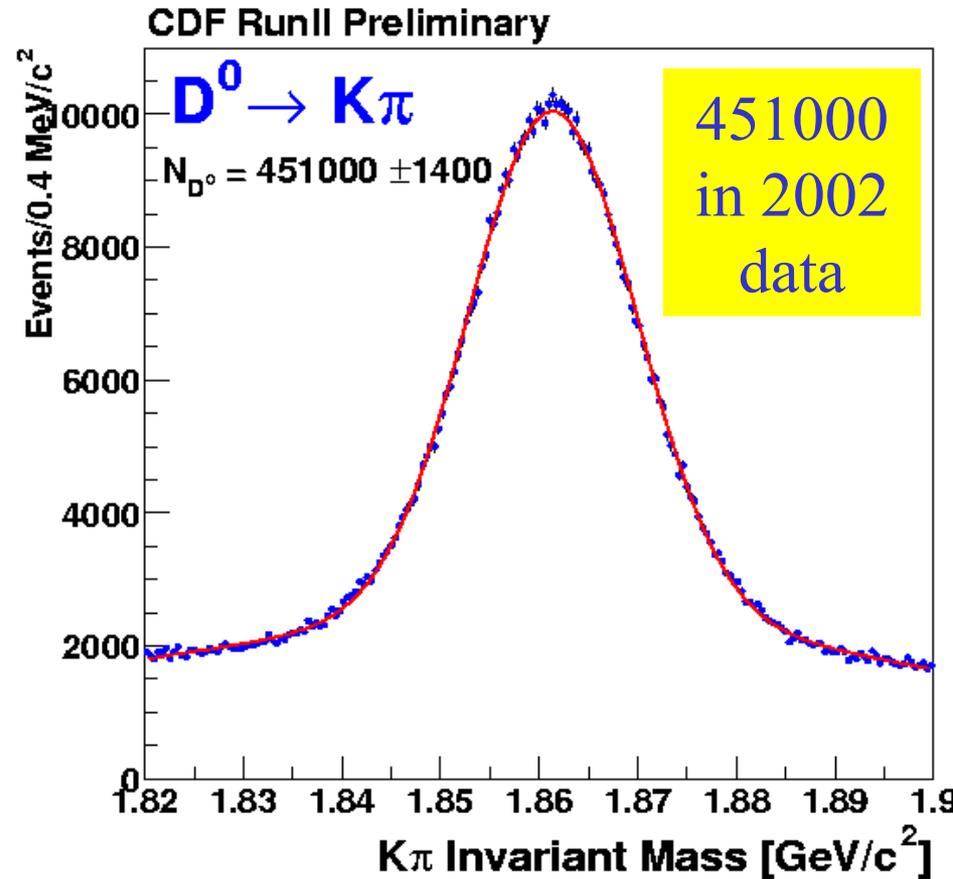
After one year of data taking at CDF, we're still learning, but we're already able to do some new things.

I'll illustrate one charm measurement we've already done and one bottom measurement we're working on.

Large charm signals

CDF will reconstruct about 10^7 charm decays in a few years' data (2 fb^{-1})

- year 2002 (0.07 fb^{-1}) already 3x sample of FOCUS experiment
- already collecting more per year than B factory experiments

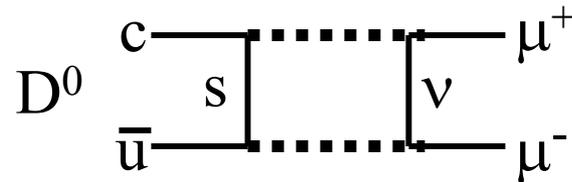


Some are born to discover J/Ψ ,
some achieve photoproduction of charm,
and some have charm physics thrust upon 'em³⁶

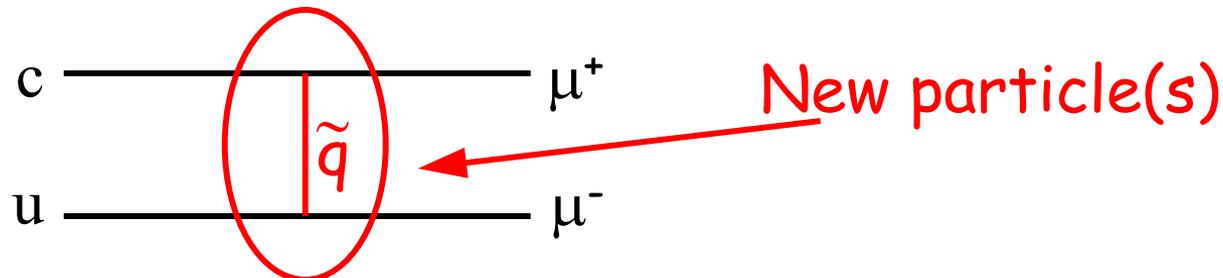
$$D^0 \rightarrow \mu^+ \mu^-$$

Analogous to $K^0 \rightarrow \mu^+ \mu^-$ search that led us to charm

Previous searches: Branching Ratio $< 4.1 \times 10^{-6}$ @ 90% CL



Suppressed in Standard Model: B.R. $\approx 3 \times 10^{-13}$

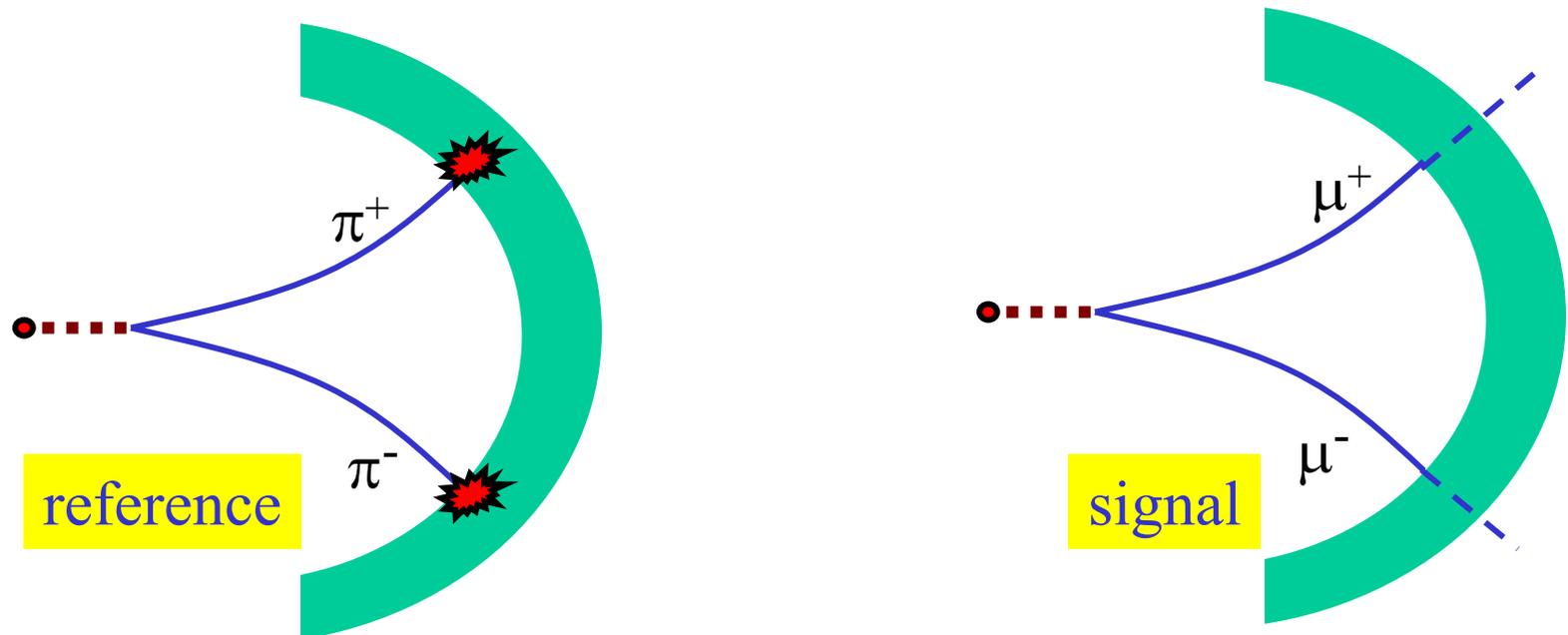


B.R. as large as 3×10^{-6} in some **supersymmetry** models

Key: inclusive trigger selection

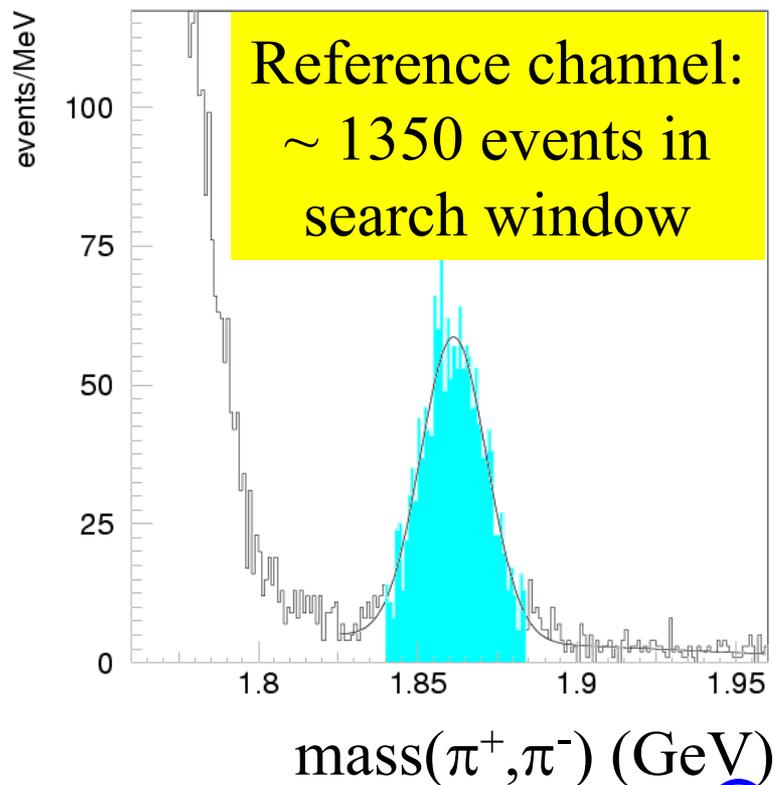
Trigger uses only lifetime information:
treats reference and signal equally

We distinguish them only at the final stage.

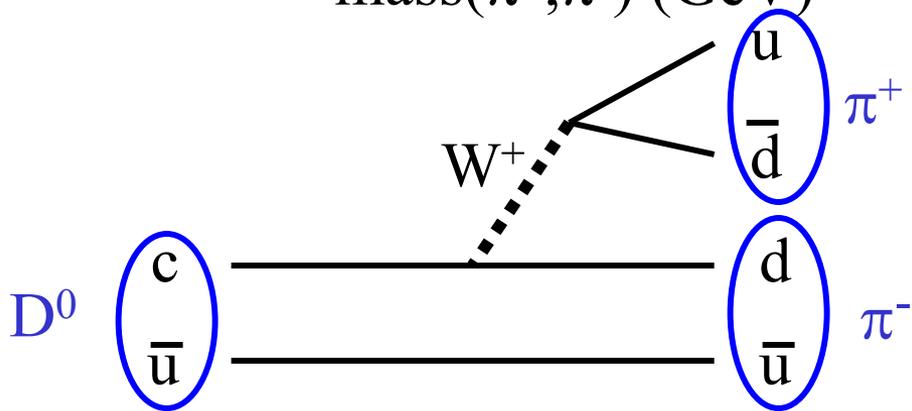
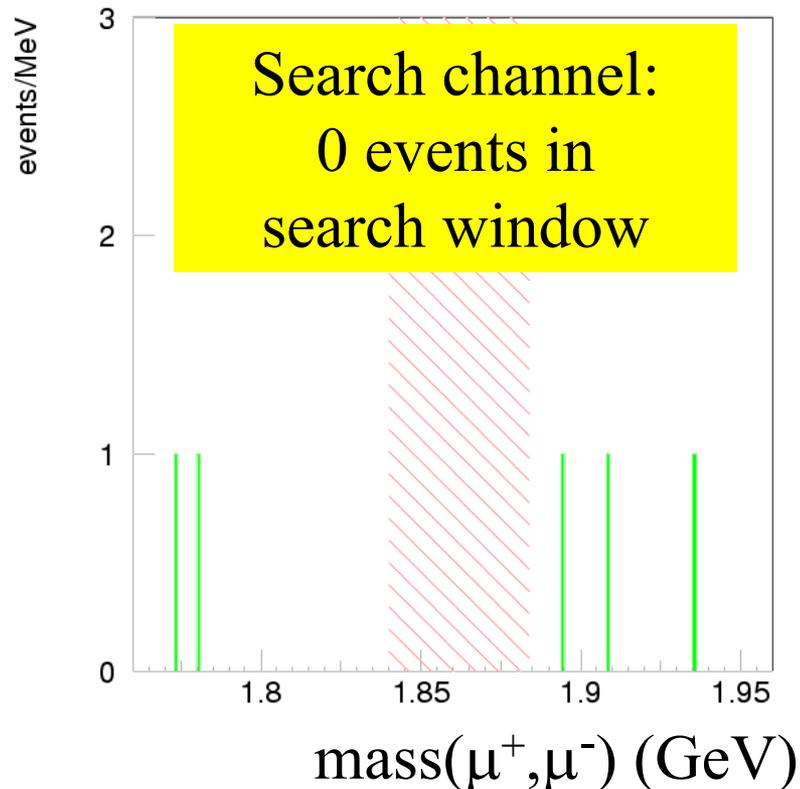


Different decay modes, but identical kinematics

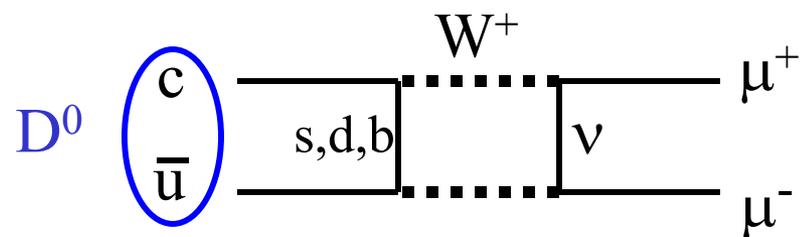
CDF Run II Preliminary



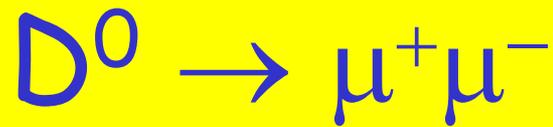
Feb 2002 - Jan 2003 data



standard model rate $\sim 10^{-3}$



standard model rate $\sim 10^{-13}$ ₃₉



➤ Putting the numbers together,

$$\text{B.R.} < \frac{2.3}{1350} \times 1.4 \times 10^{-3} = 2.4 \times 10^{-6}$$

Poisson statistics

Reference branching ratio

New limit

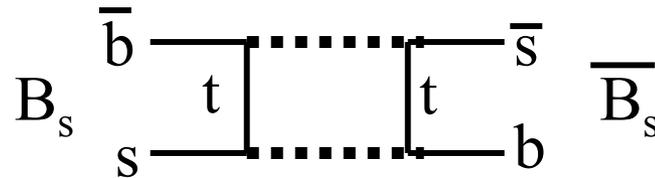
Reference event count

$$\Rightarrow BR(D^0 \rightarrow \mu^+ \mu^-) < 2.4 \times 10^{-6} @ 90\% CL$$

- Previous experiment's limit was 4.1×10^{-6} @ 90% CL.
- We should at least ~ triple our data sample this year

$$B_s \leftrightarrow \bar{B}_s$$

Analogous to $K^0 \leftrightarrow \bar{K}^0$ measurement, with which charm quark mass was predicted



$$X_s \equiv \frac{B_s \leftrightarrow \bar{B}_s \text{ transformation rate}}{B_s \text{ decay rate}}$$

Experimental bound: $X_s > 19$ @ 95% CL

Standard Model: $X_s < 31$

Currently, B_s measurements can be done only at the Tevatron

Mixing 101

Two-state system: $|B_s\rangle$ and $|\bar{B}_s\rangle$
Without mixing, degenerate states:

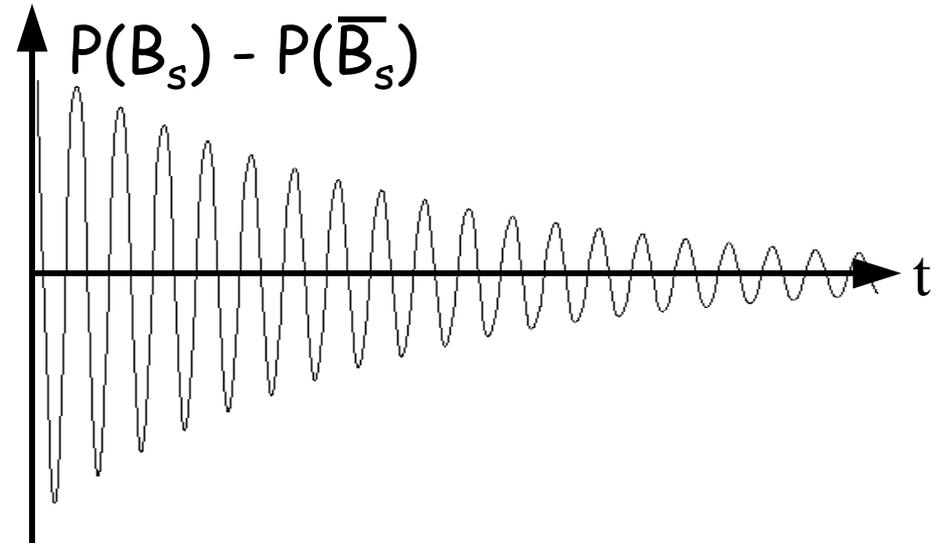
$$|\psi(t)\rangle = |\psi_0\rangle e^{-imt} e^{-\Gamma t/2}$$

Mixing splits the states:

$$\mathcal{H} = \begin{pmatrix} m - i\frac{\Gamma}{2} & \frac{\Delta m}{2} \\ \frac{\Delta m}{2} & m - i\frac{\Gamma}{2} \end{pmatrix}$$

$$|B_{H,L}\rangle = \frac{|B_s\rangle \pm |\bar{B}_s\rangle}{\sqrt{2}}$$

$$E_{H,L} = m \pm \Delta m$$



If we measure $|\psi_0\rangle = |B_s\rangle$, then

$$|\langle B_s | \psi(t) \rangle|^2 = \frac{1}{2} (1 + \cos(\Delta m t)) e^{-\Gamma t}$$

$$|\langle \bar{B}_s | \psi(t) \rangle|^2 = \frac{1}{2} (1 - \cos(\Delta m t)) e^{-\Gamma t}$$

$$\Delta m = \Gamma x = x/\tau$$

Mixing in the laboratory

To resolve the oscillations, we need to measure

➤ B_s vs \bar{B}_s at $t=0$ (at production)

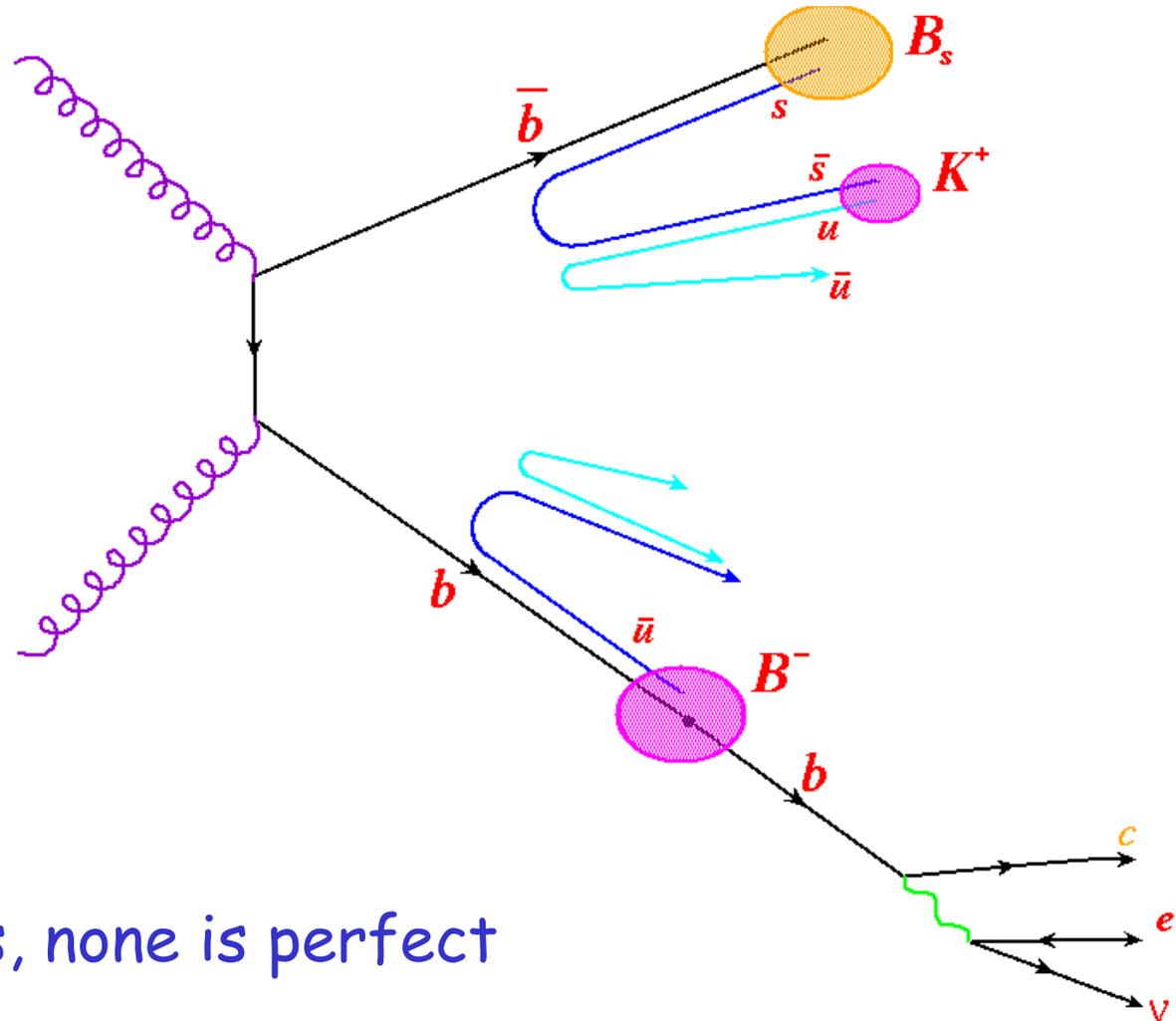
➤ B_s vs \bar{B}_s at decay

➤ proper decay time

for large numbers of events

Measuring B_s vs \bar{B}_s at $t=0$

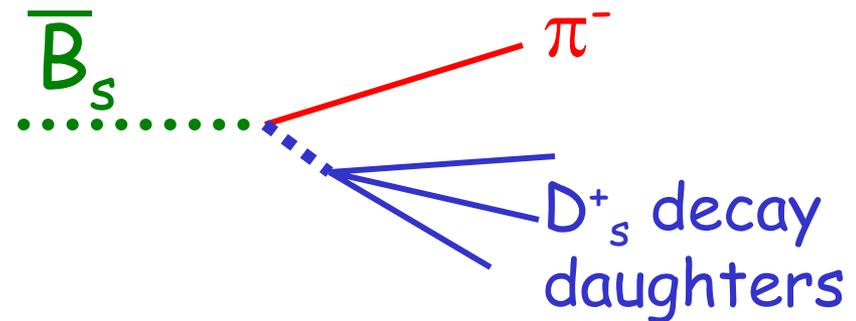
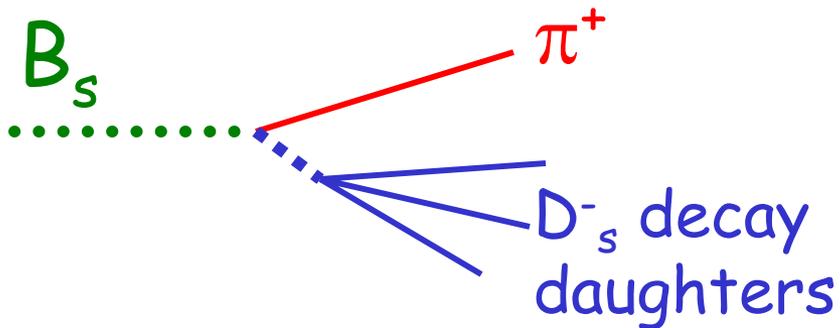
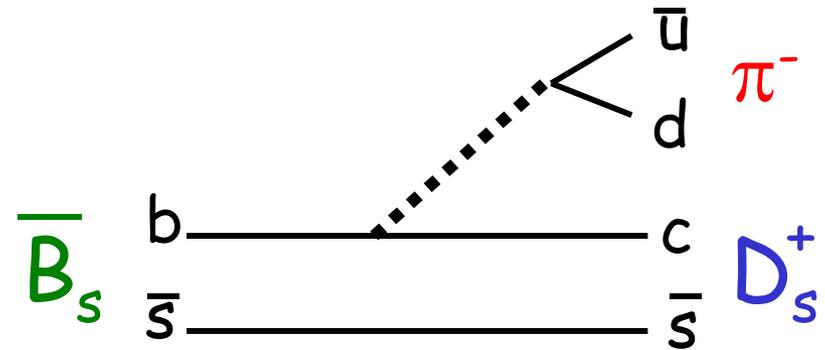
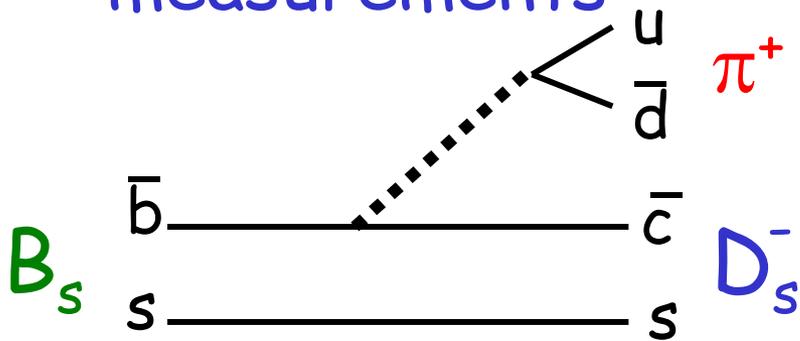
This is an art called "flavor tagging"



Several methods, none is perfect

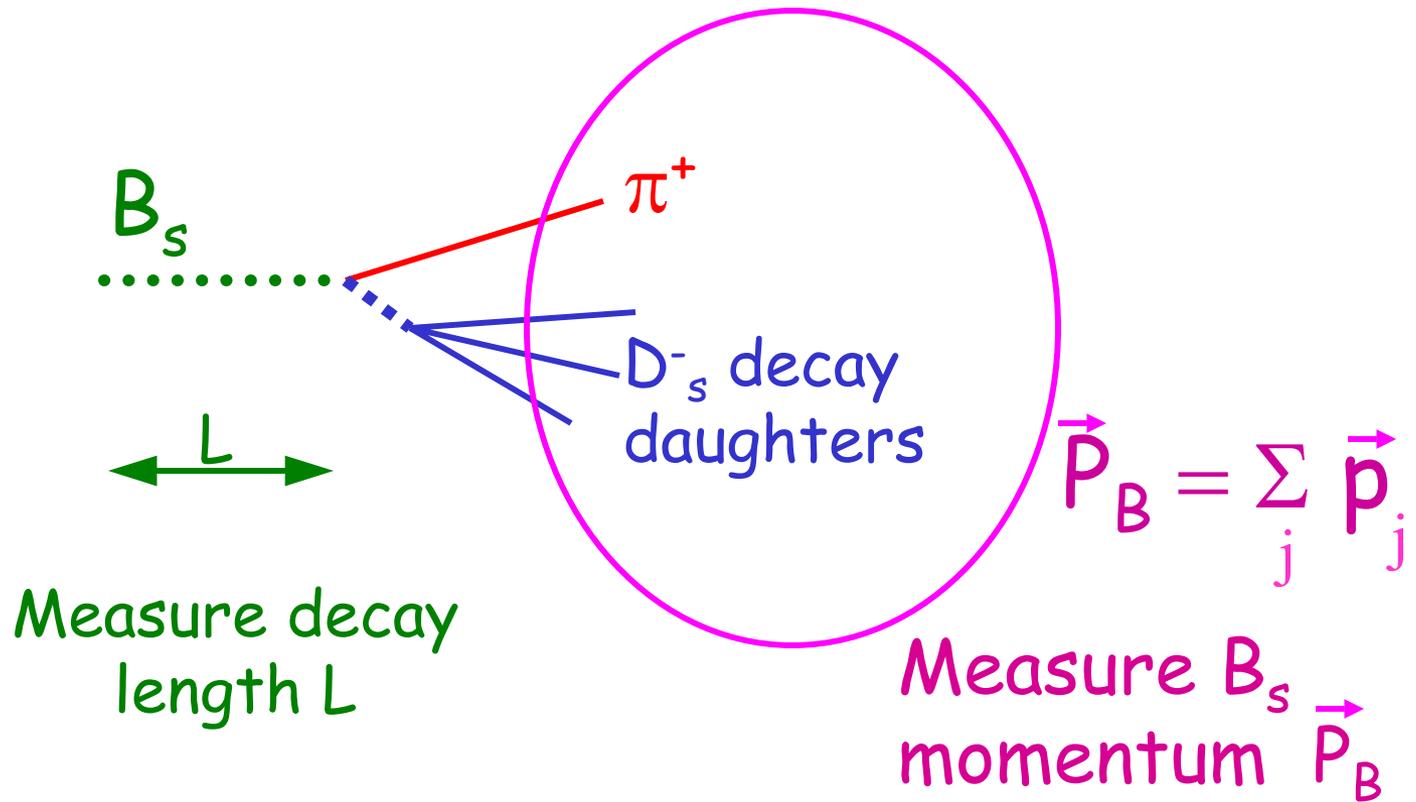
Measuring B_s vs \bar{B}_s at decay

For most decay modes, this comes for free, from spectrometer charge measurements



Measuring proper decay time

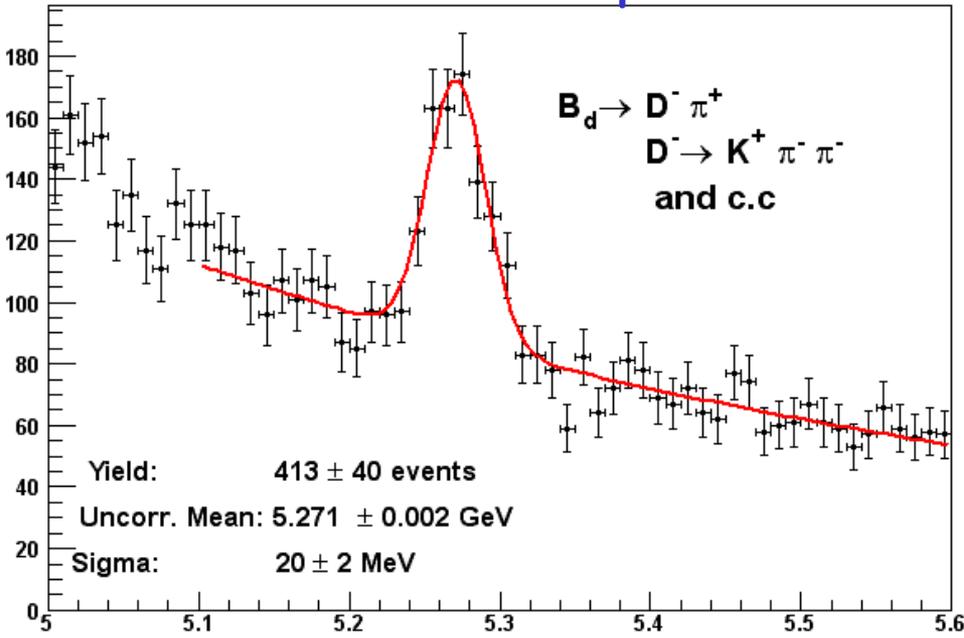
$$t = L / \gamma\beta = L m_B / P_B$$



NB: If B_s daughters include neutrinos, $\gamma\beta$ is poorly measured

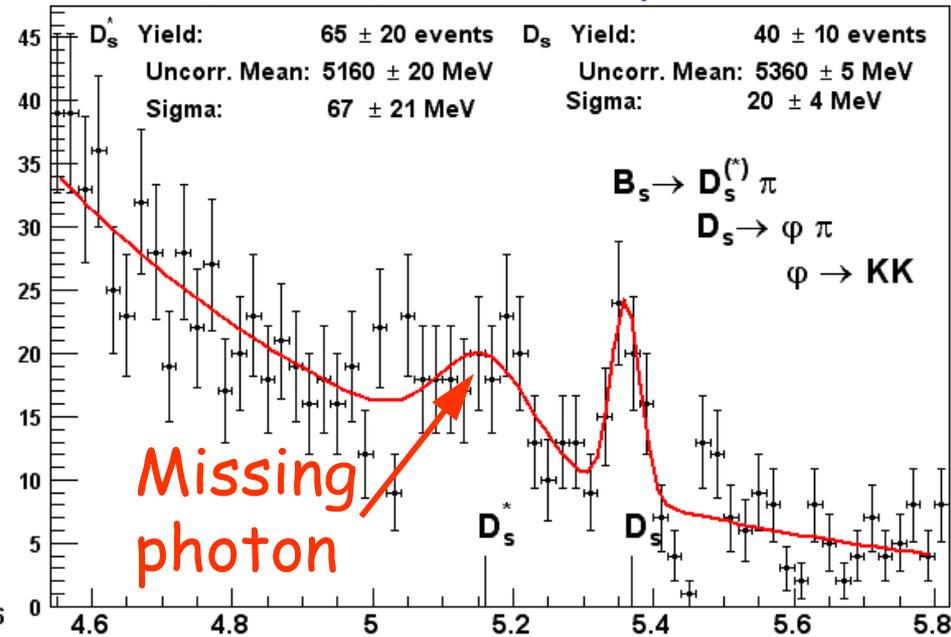
CDF's first $B^0, B_s \rightarrow D\pi$ signals (2002 data)

$B^0 \rightarrow D\pi$ mass spectrum



B^0 Candidate mass (GeV)

$B_s \rightarrow D_s \pi$ mass spectrum



B_s Candidate mass (GeV)

A good start. But 1000s of events are needed.

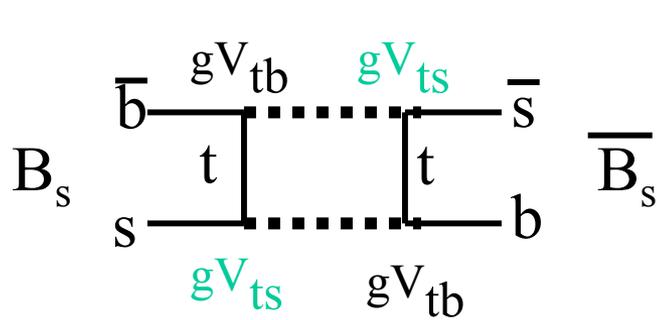
⇒ Use more D_s decay channels

Continue to optimize trigger

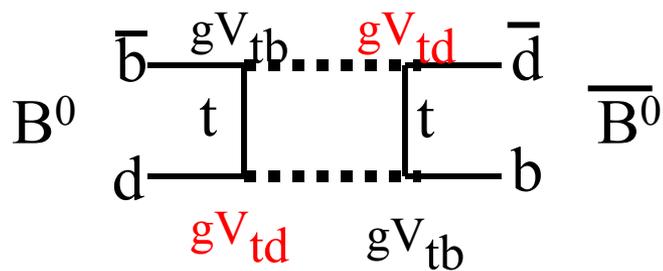
Continue to run experiment

Continue to optimize accelerator

B_s flavor oscillations: recap



$$\frac{\Delta m_s}{\Delta m_d} \propto \frac{|V_{ts}|^2}{|V_{td}|^2}$$



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

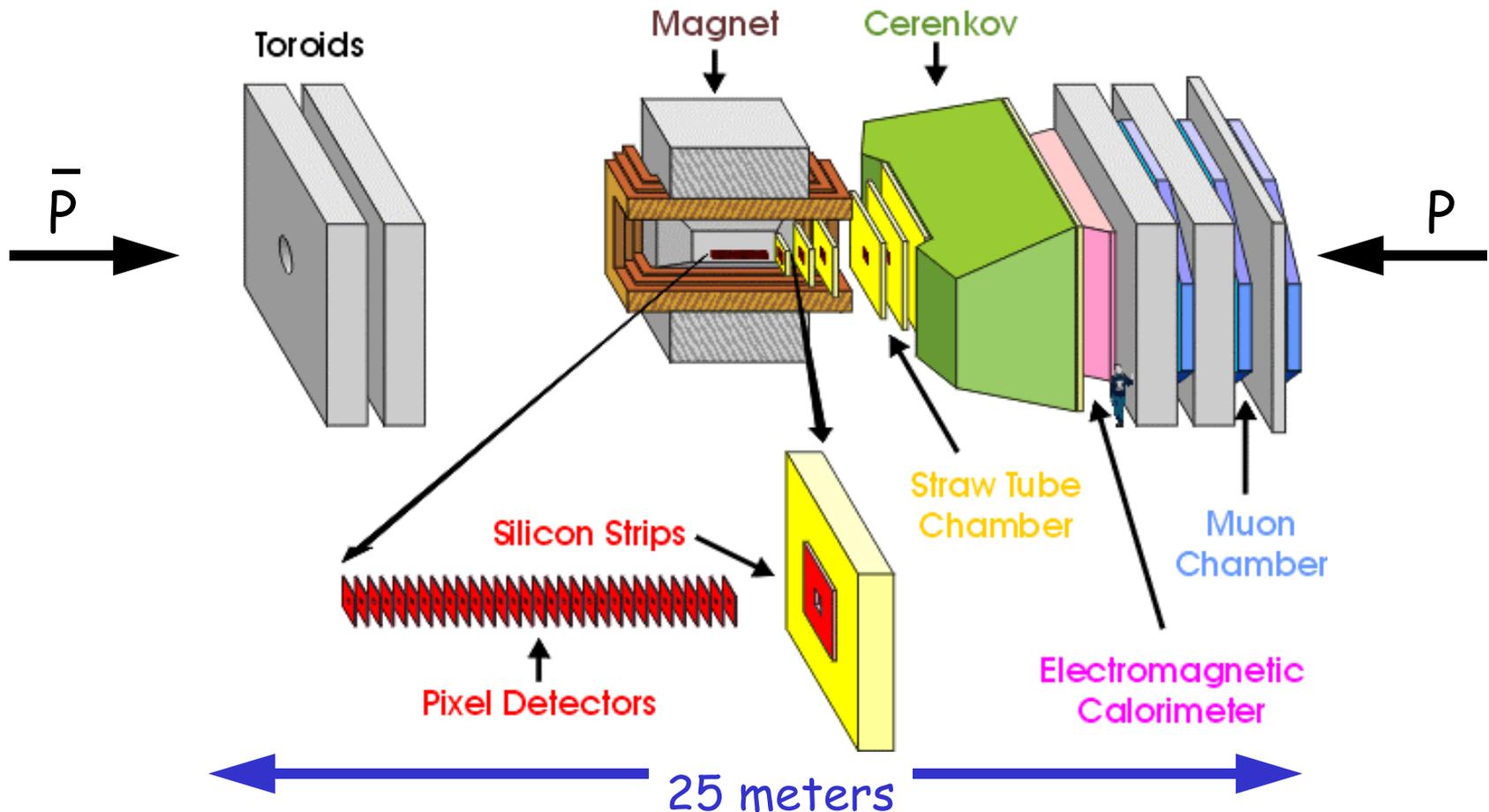
Δm_s has never been measured: only lower bounds exist.

CDF expects to make the first measurement, next year.
To get there, we need lots of B's.

The future??

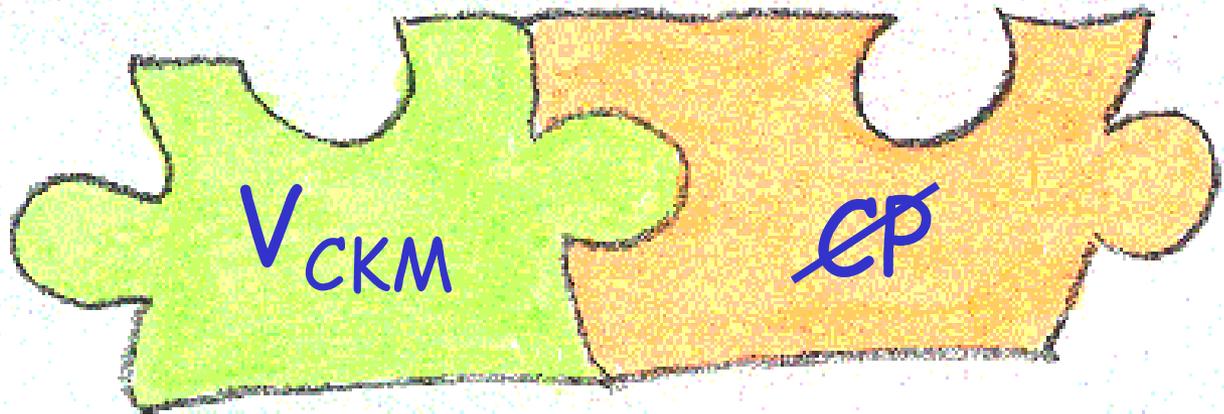
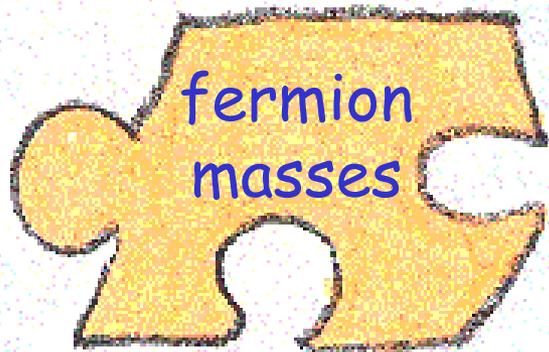
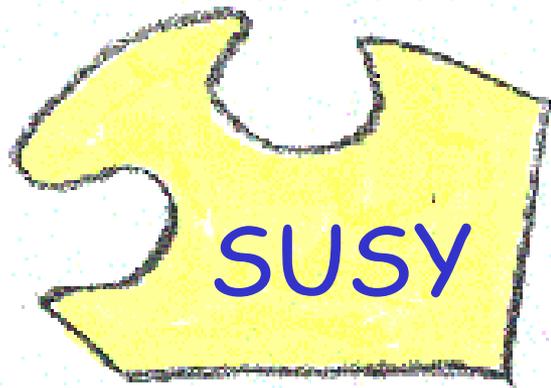
Dedicated, high-rate b,c experiments at Tevatron, LHC

- ◆ Lifetime-based trigger a key feature -- as in CDF
- ◆ Huge (1 kHz) output rate -- keep more of the B's
- ◆ Calorimeter & particle ID optimized for B physics
- ◆ "Forward" detector -- B's get large Lorentz boost



Summary

- In the indirect approach to discovery, we aim to study the known puzzle pieces closely.
- To do this, we build tools, often making use of existing facilities, existing technology, and our instincts as experimenters.
- CDF's new lifetime trigger is already producing competitive measurements, with more to follow
- The lifetime trigger concept may be extended by future proton collider experiments.

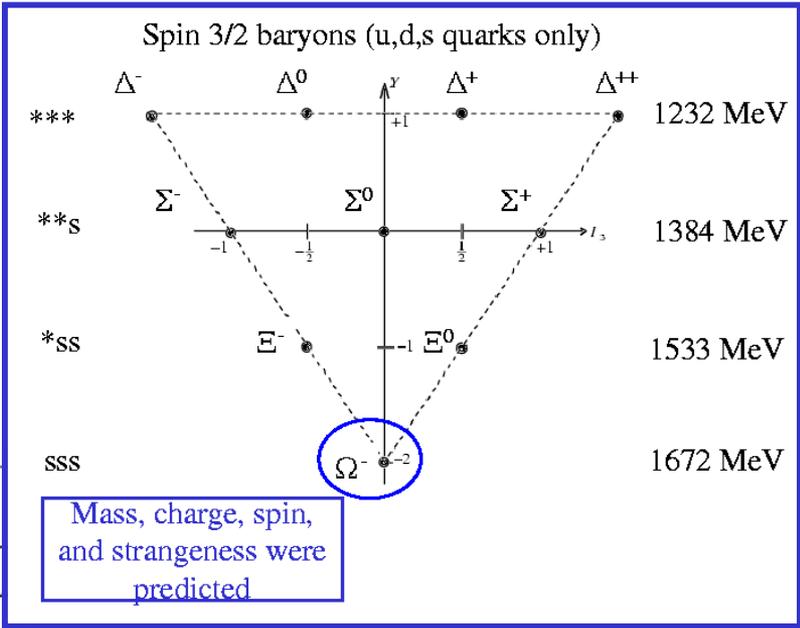


The End

Everything past this point is backup, notes, etc.

Interplay between direct and indirect discoveries

Often, many properties of new particles are known, indirectly, well before direct discovery.



PERIODIC SYSTEM OF THE ELEMENTS IN GROUPS AND SERIES.

Series	GROUPS OF ELEMENTS								
	0	I	II	III	IV	V	VI	VII	VIII
1	—	Hydrogen H 1.008	—	—	—	—	—	—	—
2	Helium He 4.0	Lithium Li 7.03	Beryllium Be 9.1	Boron B 11.0	Carbon C 12.0	Nitrogen N 14.04	Oxygen O 16.00	Fluorine F 19.0	—
3	Neon Ne 19.9	Sodium Na 23.05	Magnesium Mg 24.3	Aluminum Al 27.0	Silicon Si 28.4	Phosphorus P 31.0	Sulphur S 32.06	Chlorine Cl 35.45	—
4	Argon Ar 38	Potassium K 39.1	Calcium Ca 40.1	Scandium Sc 44.1	Titanium Ti 48.1	Vanadium V 51.4	Chromium Cr 52.1	Manganese Mn 55.0	Iron Cobalt Nickel Fe Co Ni (Cu) 55.9 59 59
5	—	Copper Cu 63.6	Zinc Zn 65.4	Gallium Ga 70.0	Germanium Ge 72.3	Arsenic As 75	Selenium Se 79	Bromine Br 79.95	—
6	Krypton Kr 81.8	Rubidium Rb 85.4	Strontium Sr 87.6	Yttrium Y 89.0	Zirconium Zr 90.6	Niobium Nb 94.0	Molybdenum Mo 96.0	—	Ruthenium Rhodium Palladium Ru Rh Pd (Ag) 101.7 108.0 108.5
7	—	Silver Ag	Cadmium Cd	Indium In	Tin Sn	Antimony Sb	Tellurium Te	Iodine I	—

ELEMENTARY PARTICLES

Quarks: u (up), d (down), c (charm), s (strange), t (top), b (bottom)

Leptons: e (electron), μ (muon), τ (tau), ν_e (electron neutrino), ν_μ (muon neutrino), ν_τ (tau neutrino)

Force Carriers: γ (photon), g (gluon), Z (Z boson), W (W boson)

I II III
Three Generations of Matter

Three different ways 10 people finish a job every Δt that 1 person would do in $10\Delta t$

Dividing the tasks among specialized components

10-step assembly line ("pipelining")

Dividing up the detector

10 people paint 1 house

Dividing up the events

1 line, 10 bank tellers

Level 1 uses mostly the 1st (some 2nd),
Level 2 uses mostly the 2nd (some 1st), and
Level 3 uses exclusively the 3rd.

Introducing ... S V T

Both the name and the details of the physics goals have evolved over time ...



CDF Note 1421
by L. Ristori

INTRODUCTION

This note describes the architecture of a device we believe we can build to reconstruct tracks in the Silicon Vertex Detector (SVX) with enough speed and accuracy to be used at trigger level 2 to select events containing secondary vertices originated by B decay. We name such a device *Silicon Vertex Tracker* (SVT).

The use of SVT as part of the CDF trigger would allow us to collect a large sample of B's ($> 10^7$ events) in a 100 pb^{-1} run.

B production at 2 TeV in the c.m. is abundant: Isajet predicts that, in the central region, 6.5% of two-jet events with $P_T > 20 \text{ GeV}/c$ contain a B pair. Thus we need a trigger with a relatively modest rejection factor ($10 \div 20$) not necessarily requiring the presence of very high P_T tracks.

It turns out that the simple requirement of a single track with an impact parameter greater than a given threshold might do the job.

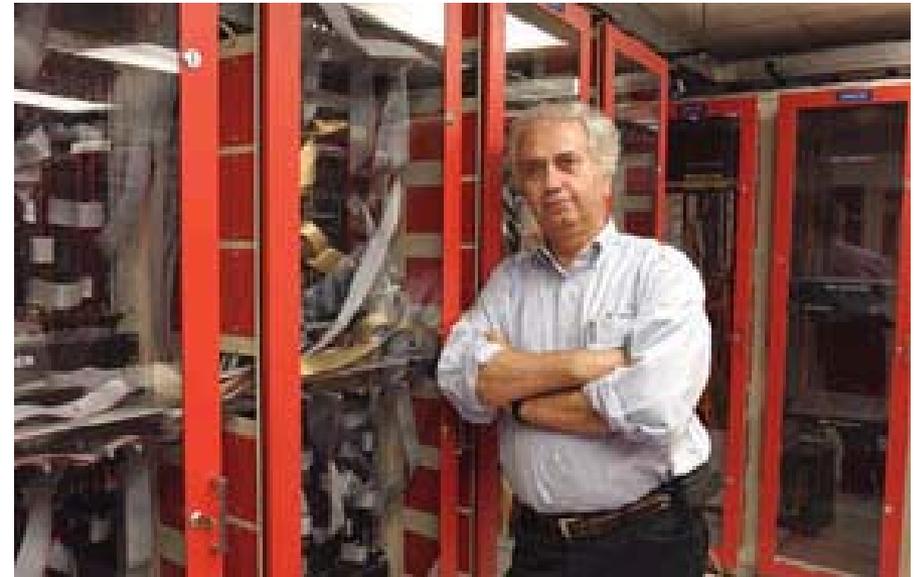
The possibility to use the output of SVT to actually reconstruct secondary vertices is left open and it's not discussed here.

In Section 1 we report the results of some simple simulations we have done to show the efficacy of the impact parameter cut, in Section 2 we overview the overall architecture of SVT, in Section 3 we describe the different parts SVT is made of and how they relate to the different stages the track finding process goes through.

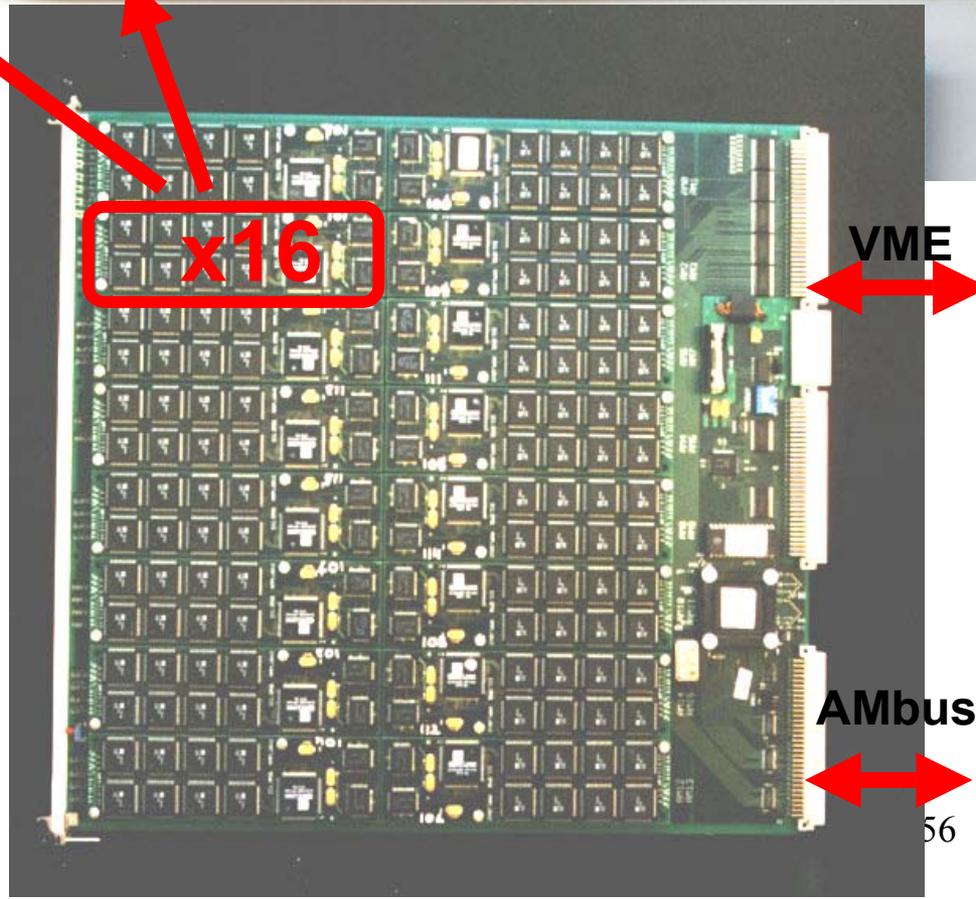
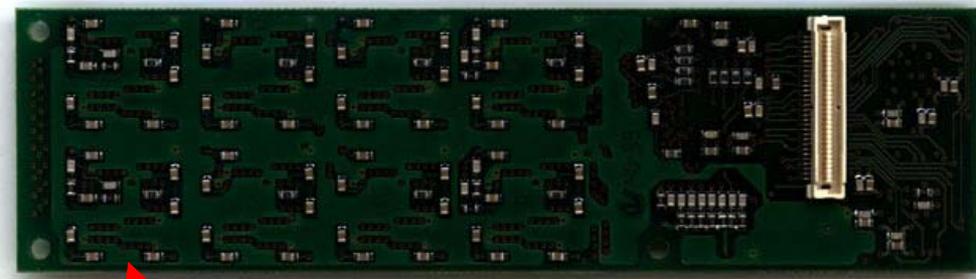
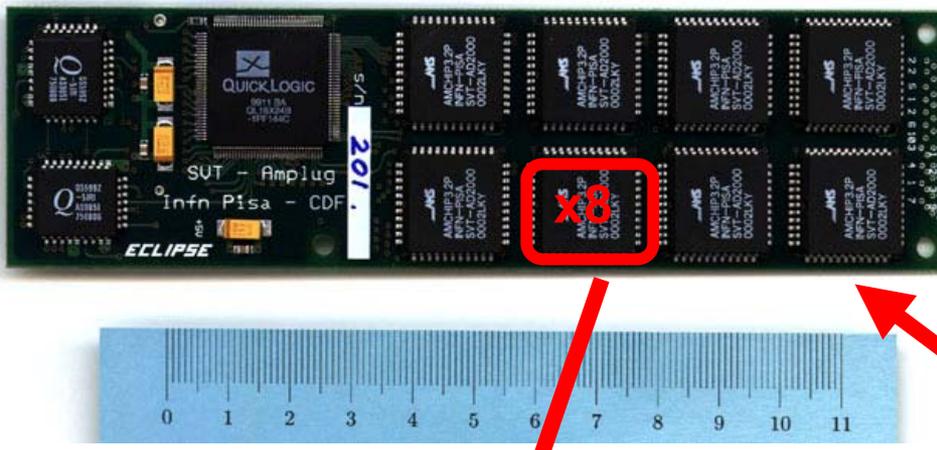
1. SIMULATION RESULTS

1.1 Impact Parameter Cut

The impact parameter s of each track is defined as the minimum



Our friends invested *years* in this Bingo game!

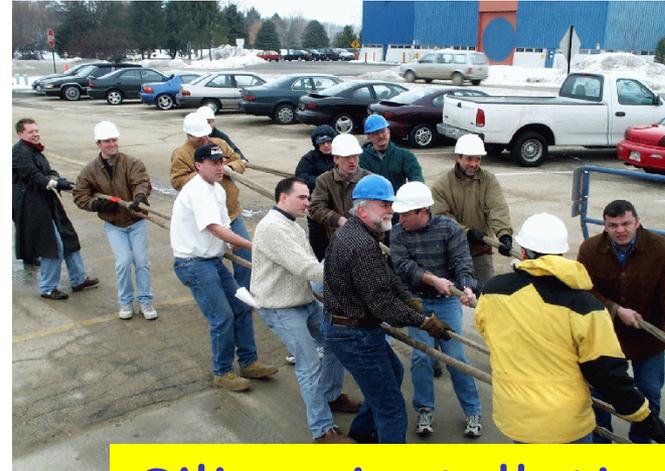


Onward!

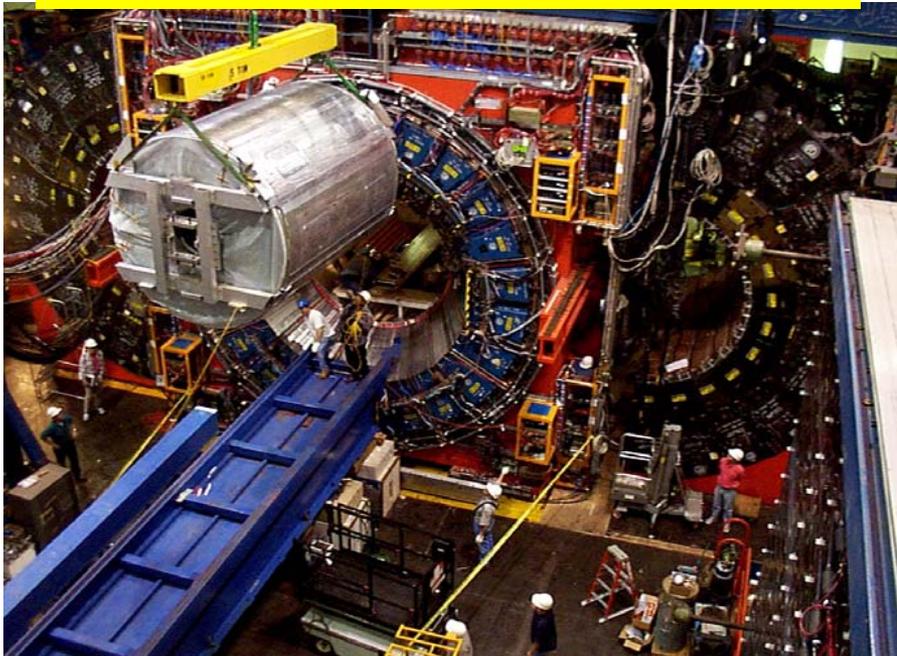
- Now that the heavy lifting is done, let's see what we can do with this device ...



Drift chamber installation



Silicon installation

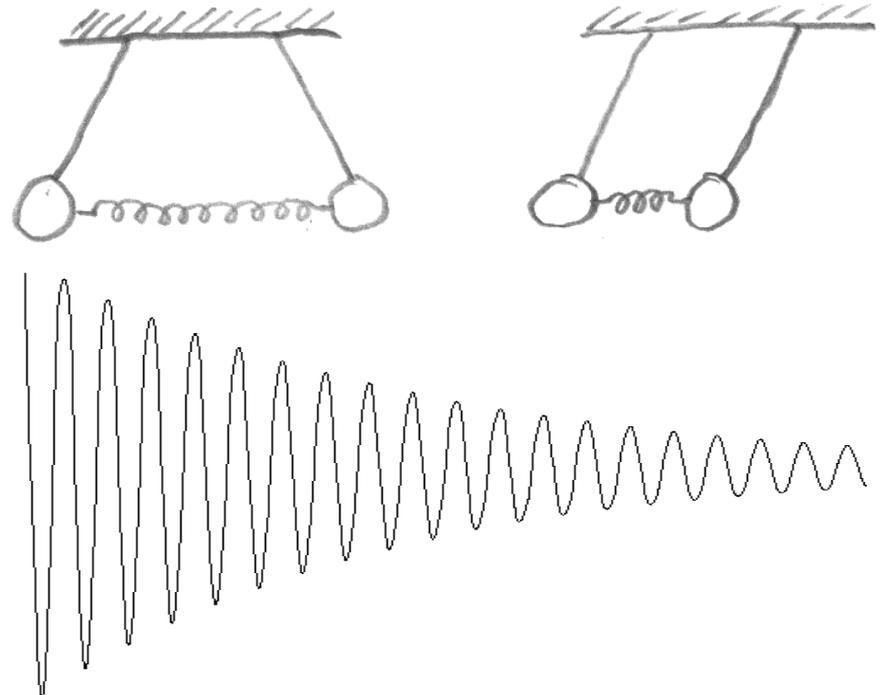


Mechanical analogue



You can measure a frequency difference extremely precisely, by measuring beats.

$$\text{If } x=25, \text{ then} \\ \Delta m/m \sim 2E-12$$



Piano tuner uses the same trick

Mixing: simplifications

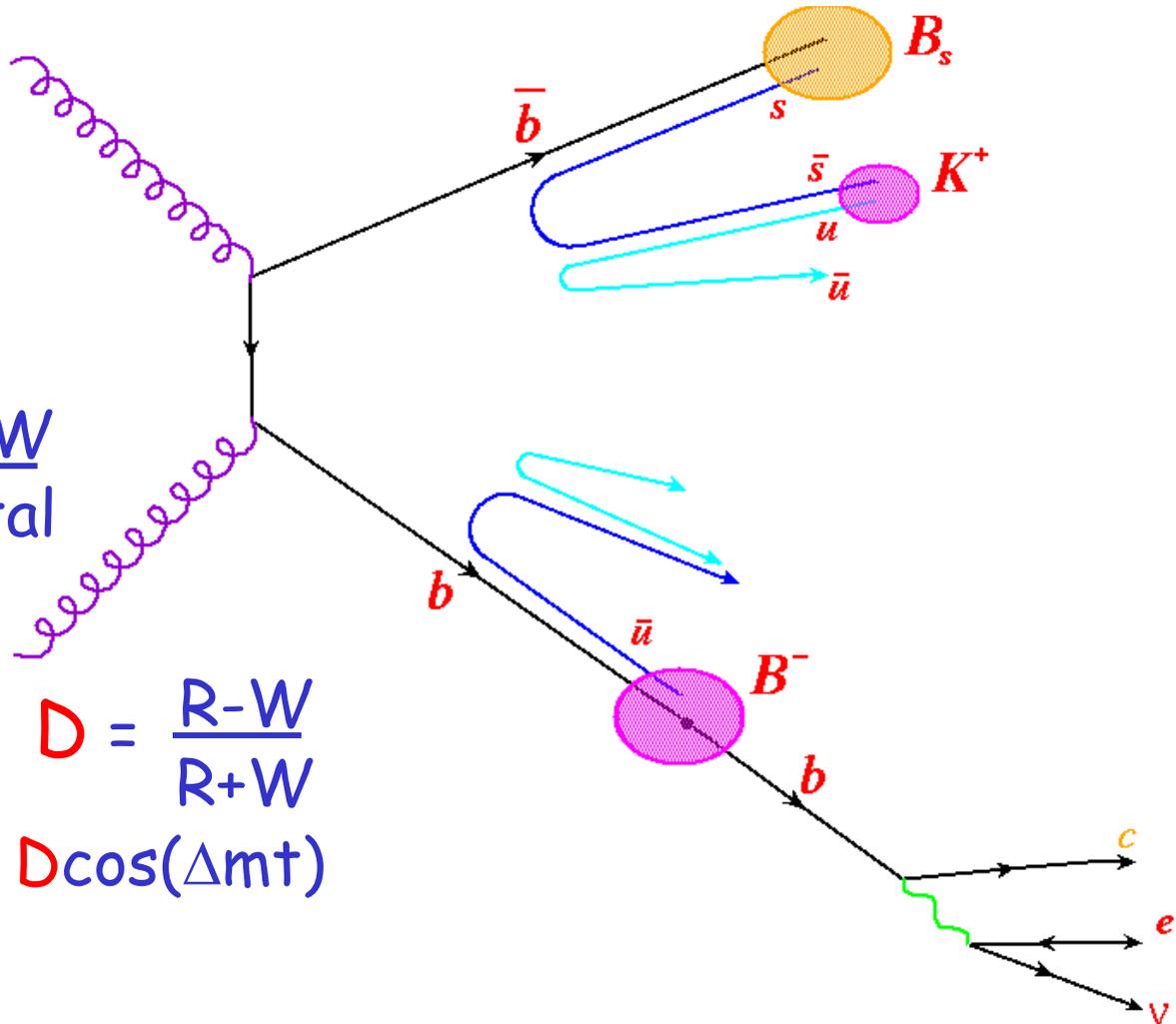
Two important things that I will completely ignore:

(1) CP violation, i.e. that the two pendula may not be precisely interchangeable

(2) that the two normal modes may decay at different rates (e.g. energy is dissipated when the spring stretches and compresses)

Measuring B_s vs \bar{B}_s at $t=0$

This is an art called "flavor tagging"



Efficiency $\varepsilon = \frac{R+W}{\text{total}}$

Purity ("dilution") $D = \frac{R-W}{R+W}$

$1 + \cos(\Delta mt) \rightarrow 1 + D \cos(\Delta mt)$

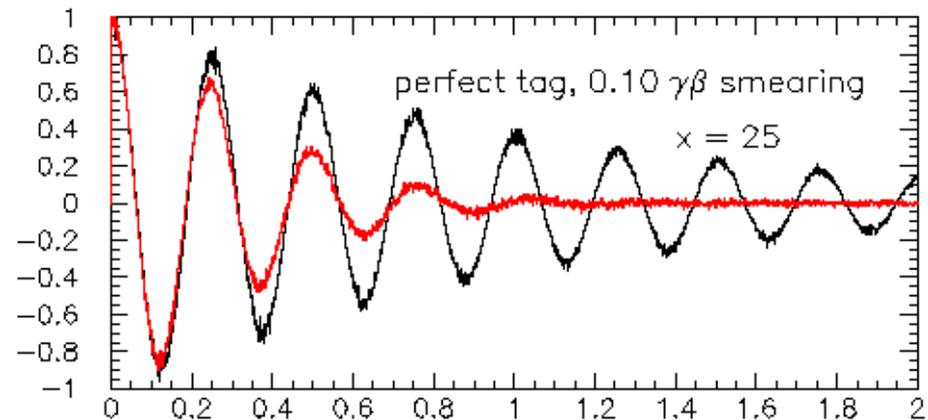
$N \rightarrow \varepsilon D^2 N$

Statistical significance of mixing signal

$$\text{Sig}(x) = e^{-\frac{1}{2}(x\sigma_t/\tau)^2} \sqrt{\frac{N\epsilon D^2}{2}} \sqrt{\frac{S}{S+B}}$$

So important ingredients are:

- Event yield N
- Clean signals (S/B)
- Vertexing resolution σ_t
- Flavor tagging: ϵD^2



unmixed - mixed vs t/τ

⇒ We want as many “fully reconstructed”
(no **neutrinos**) events as we can get