From the energy frontier to the rate frontier:

studying bottom and charm decays at Fermilab's Tevatron collider

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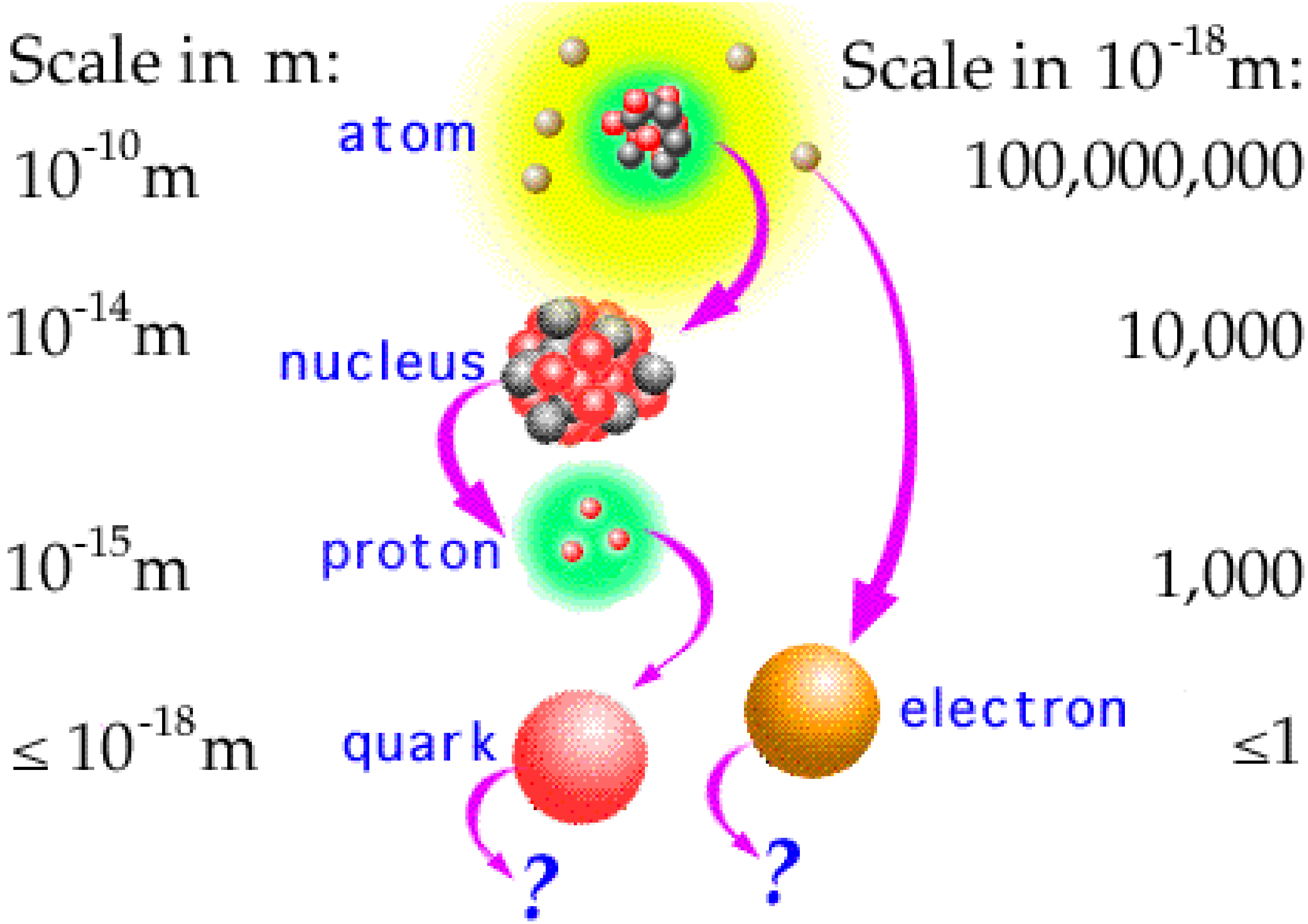
April 14, 2003

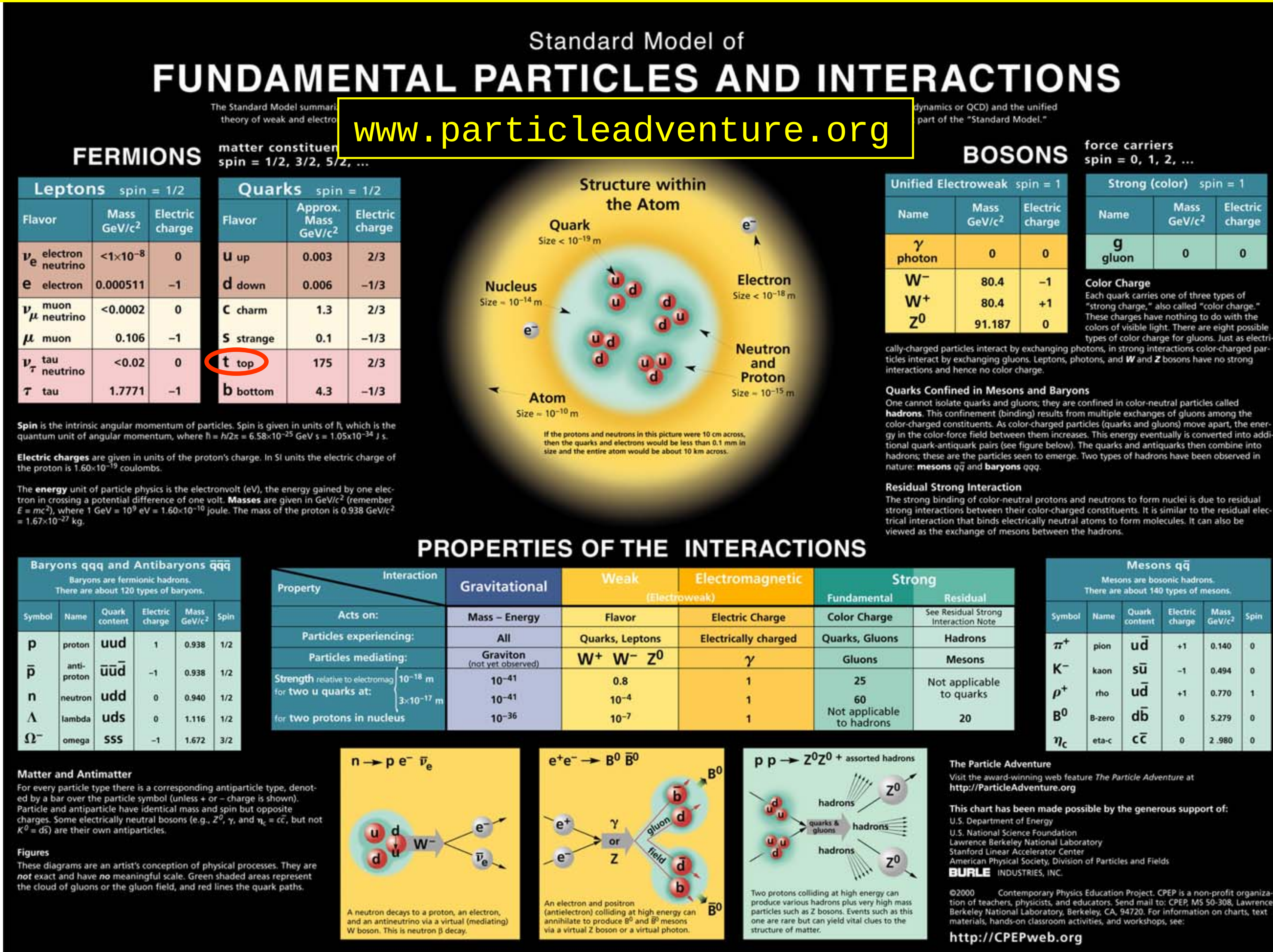
Outline

- 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

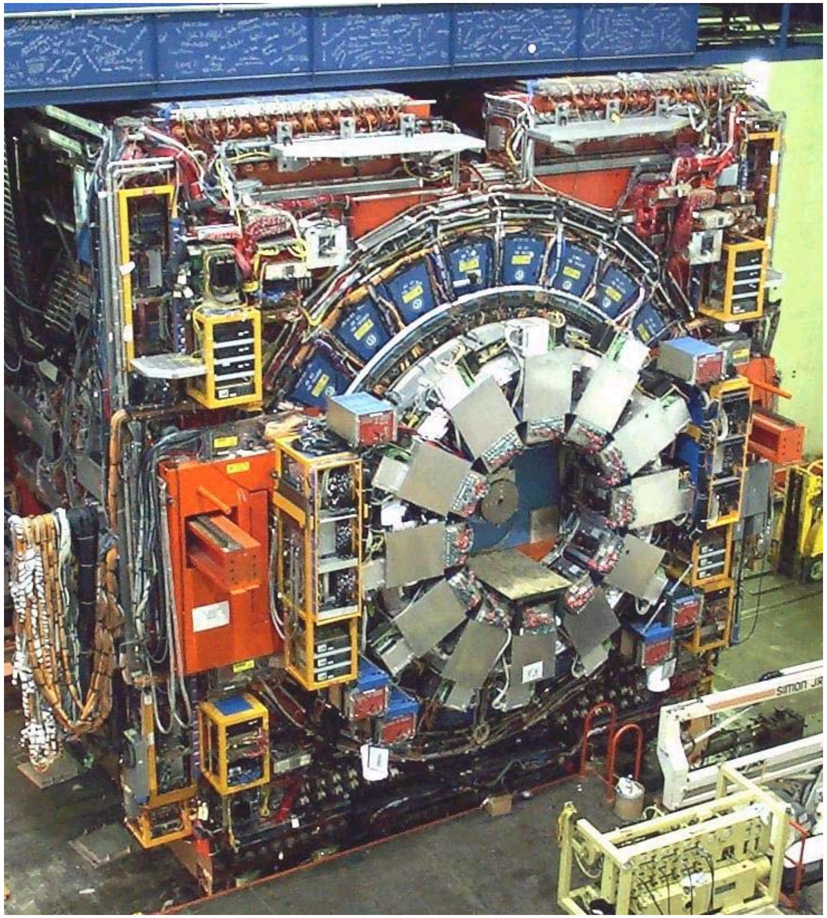
Particle physicists are the ultimate reductionists:
What are Nature's most basic building blocks?
What rules do they obey?



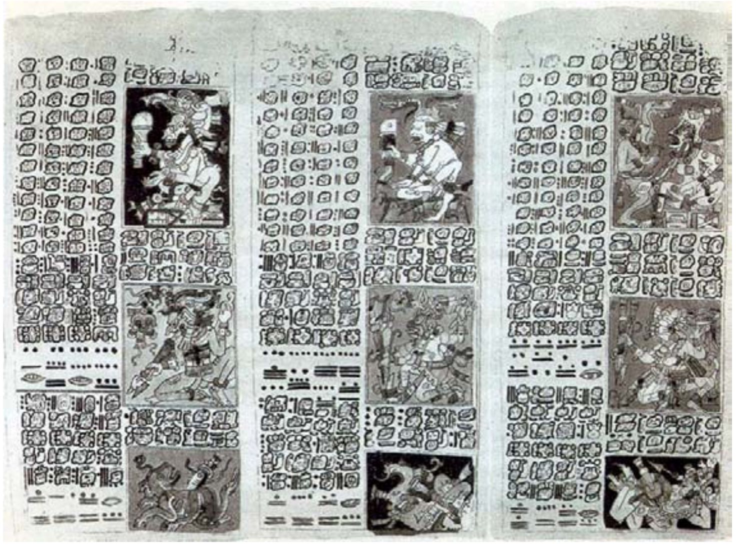
We've come a long way !

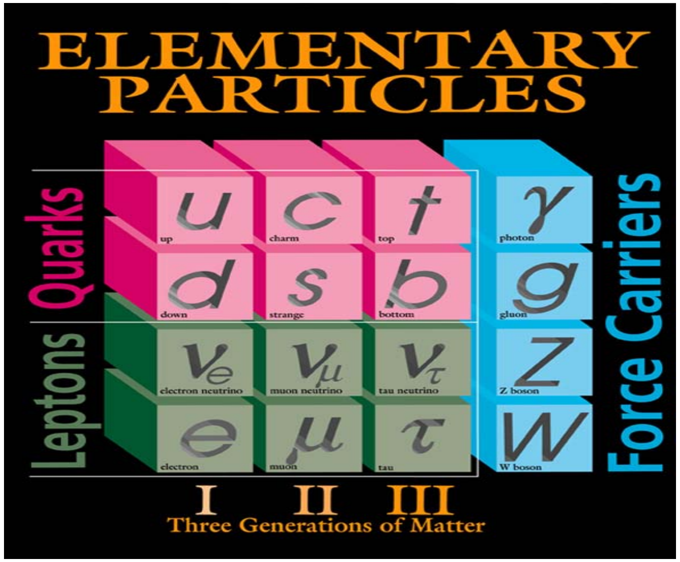


To address these questions, we continue to build the large, specialized tools of the energy frontier



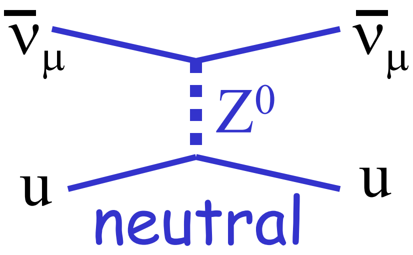
I hope that our knowledge and our creativity will make our culture worth studying, 1000 years from now

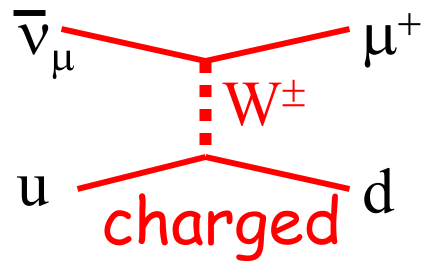




While big discoveries are often made at the energy frontier, even pioneers don't head out to the frontier blindly

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

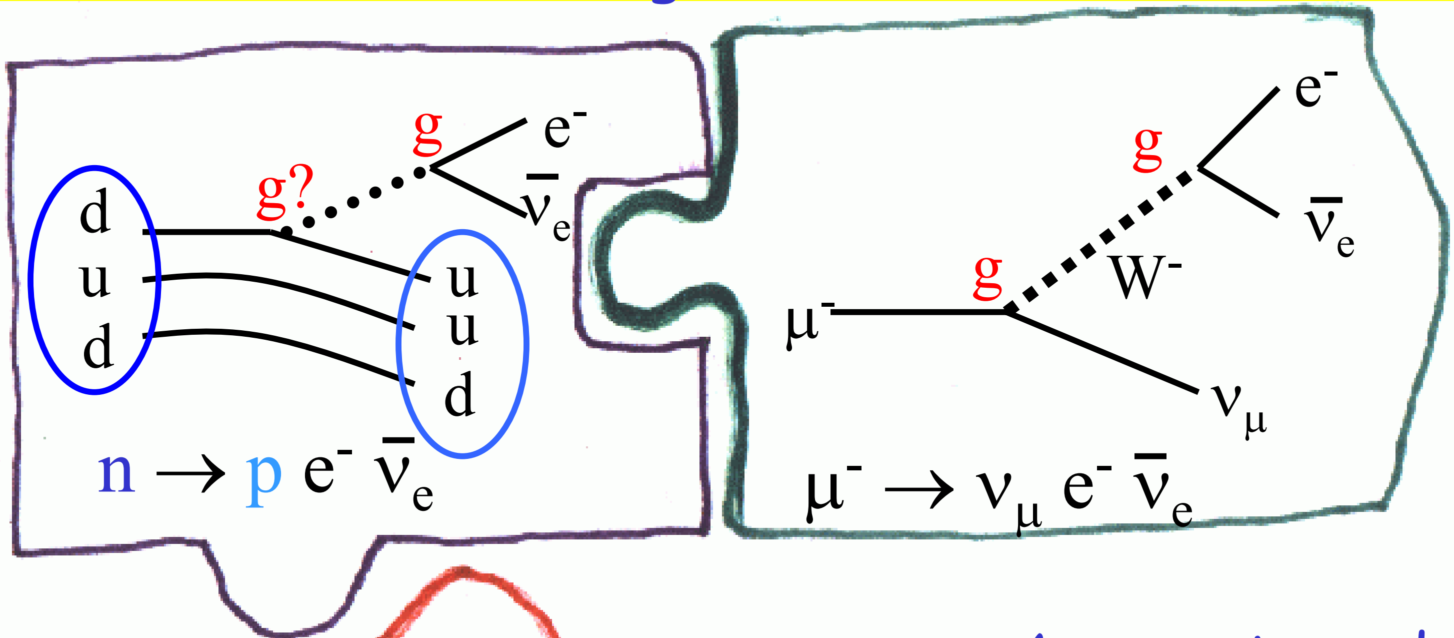
same weak mixing angle, θ_W, relates measured W,Z masses <u>and</u> W,Z couplings

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

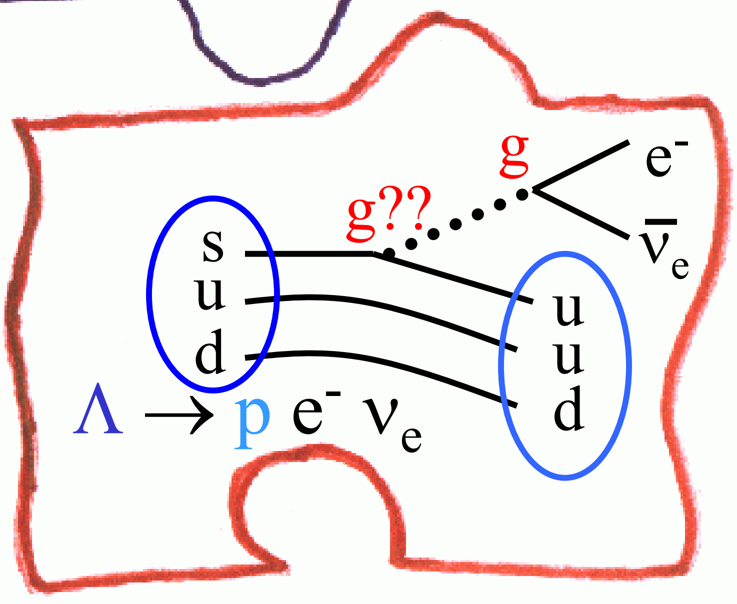
The "indirect" strategy:

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

× 0.95 ?

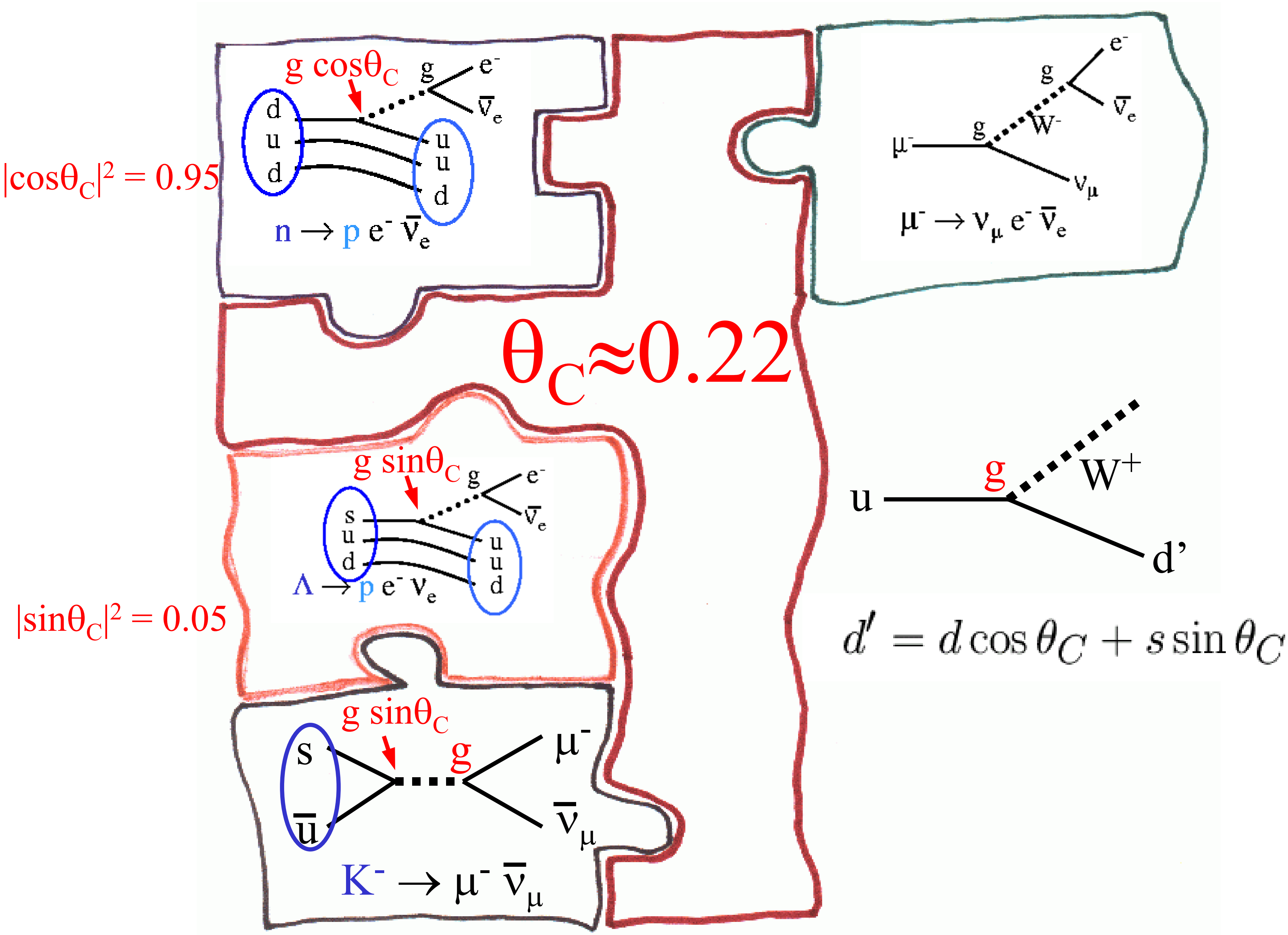


× 0.05 ?



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

Cabibbo mixing angle was the missing piece

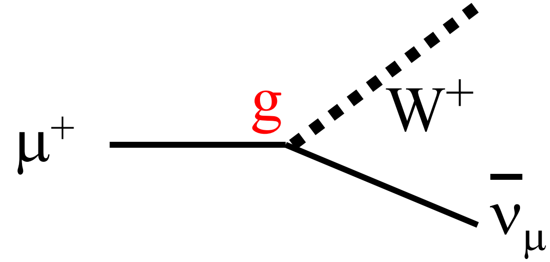


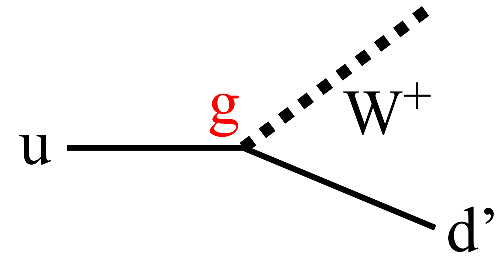
$$d' = d\cos\theta_C + s\sin\theta_C$$

Indirect approach anticipates charm quark discovery

~1970: known quarks & leptons

u		ν_e	ν_μ
d	s	e	μ

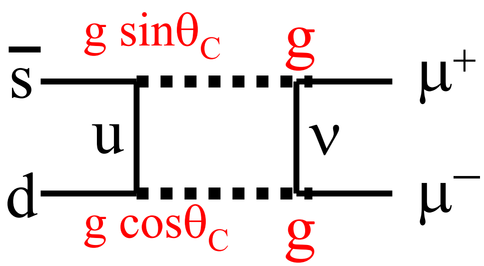




Study K^0 meson $= \bar{s}\, d$

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

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

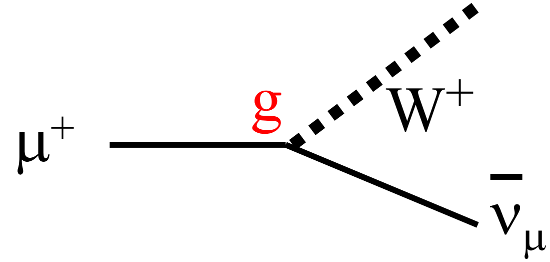


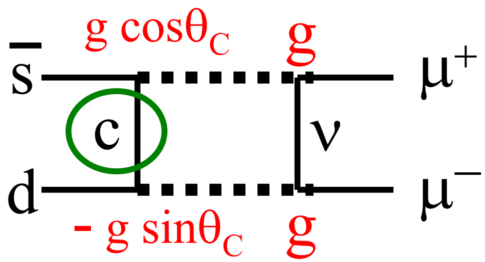
$\propto \sin\theta_C \cos\theta_C\, g^4$

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

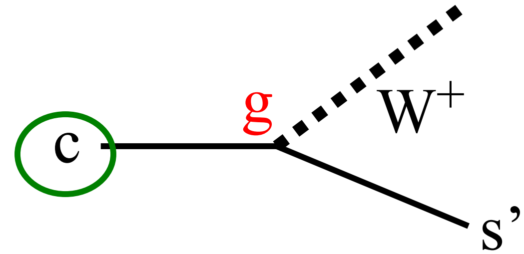
Proposed solution: there must be another quark!

u	c	ν_e	ν_μ
d	s	e	μ

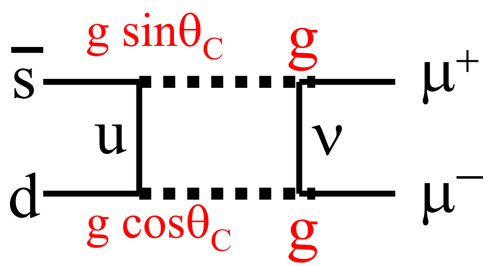




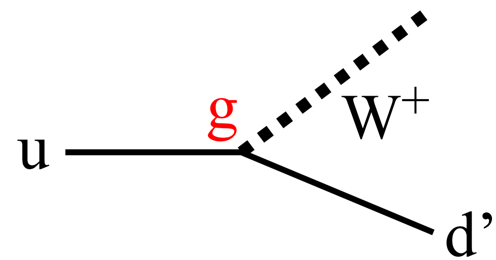
$\propto$ $-\sin\theta_C \cos\theta_C \, g^4$



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



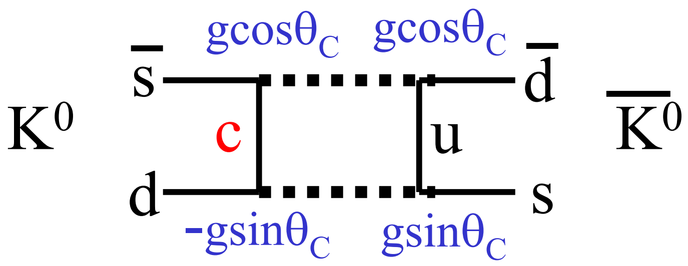
$\propto$ $\sin\theta_C \cos\theta_C \, g^4$

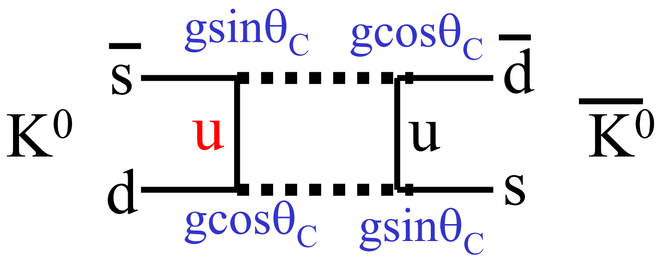


$$d' = d\cos\theta_C + s\sin\theta_C$$

Destructive interference!

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





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

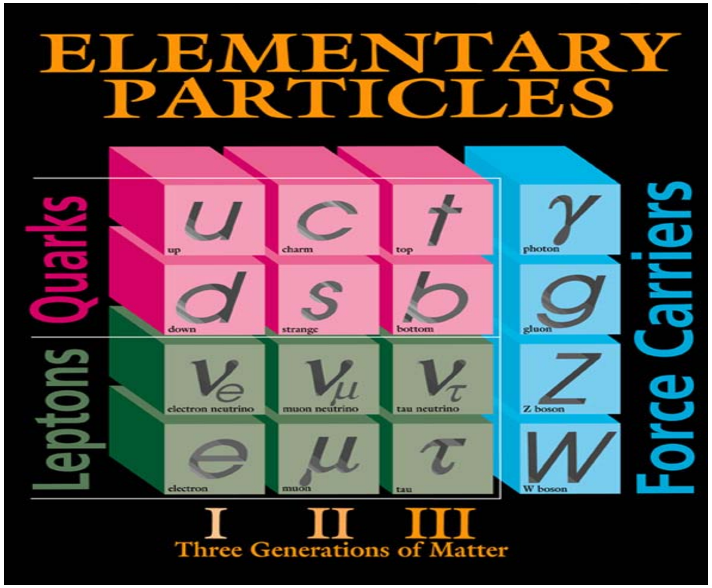
Σ amplitudes $\propto$ $-g^4 \sin^2\theta_C \cos^2\theta_C (m_c^2 - m_u^2)/M_W^2$

predict $m_c \approx 1.5$ GeV (1973)

$c\overline{c}$ meson (mass 3.1 GeV, ≈ 2×1.5 GeV) discovered in 1974, in high-energy collisions at BNL and SLAC

⇒ 1976 Nobel prize

Today, there are many more puzzle pieces to study



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

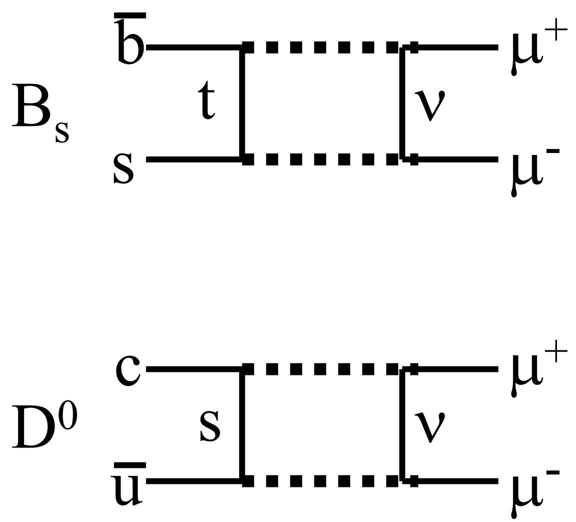
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

6 quarks, 3 euler angles, 1 phase

6 leptons

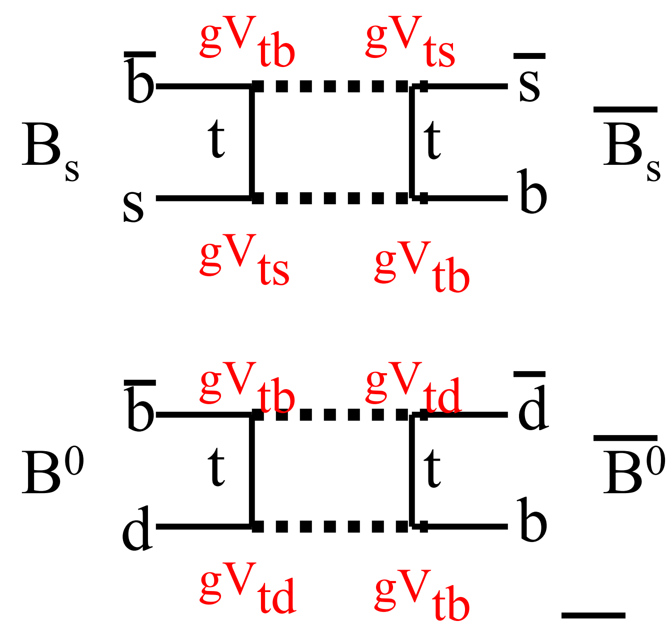
lots and lots of amplitudes to check,
some very small

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 $K^0 \leftrightarrow \overline{K^0}$

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 bb rate:

- about 1 kHz of $b\bar{b}$ pairs, at nominal luminosity
  - $\sigma(b\bar{b}) \sim 100\mu b$ (10 kHz @ $10^{32}\ cm^{-2}s^{-1}$), 10% "usable"
- compare: about 5 Hz of $b\bar{b}$ pairs at $\Upsilon(4S)$, typical BABAR/BELLE luminosity
  - $\sigma(b\bar{b}) \sim 1nb$ (5 Hz @ $5\times10^{33}\ cm^{-2}s^{-1}$)

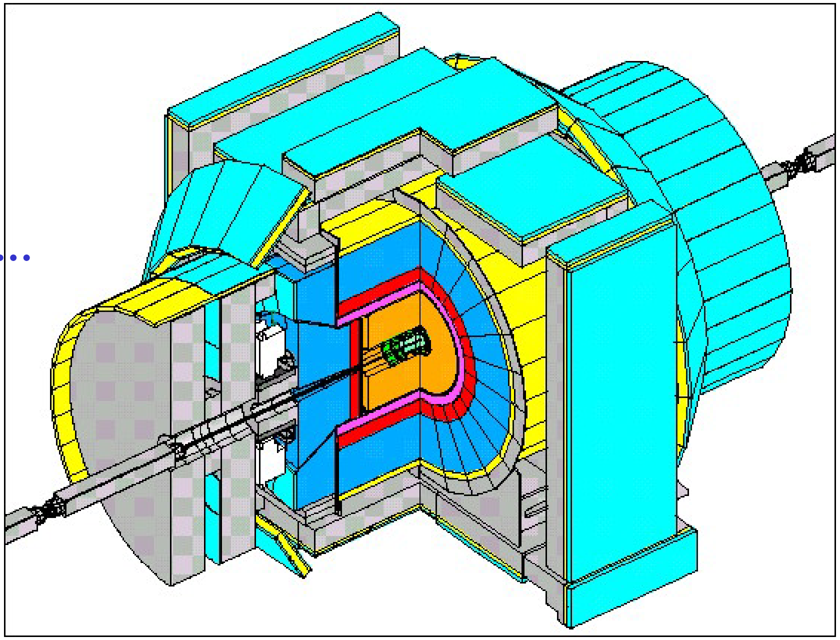
Produce all states: B^0, B^+, Bs, Λ_B, B_C

$c\bar{c}$ rate also large (~ 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

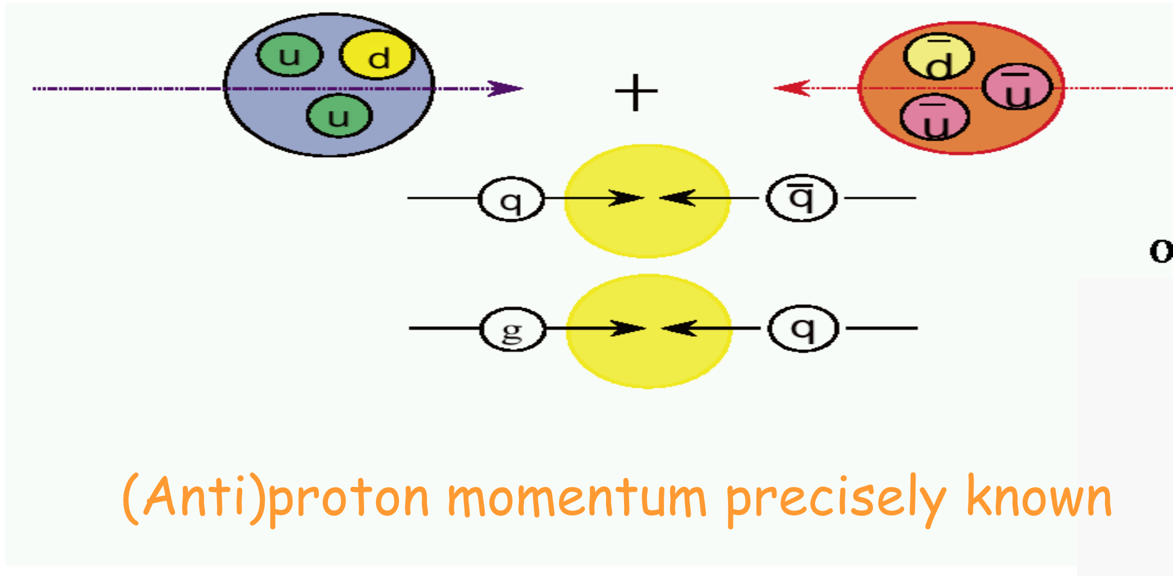
Challenge #1: proton = "broad-band beam of quarks & gluons"

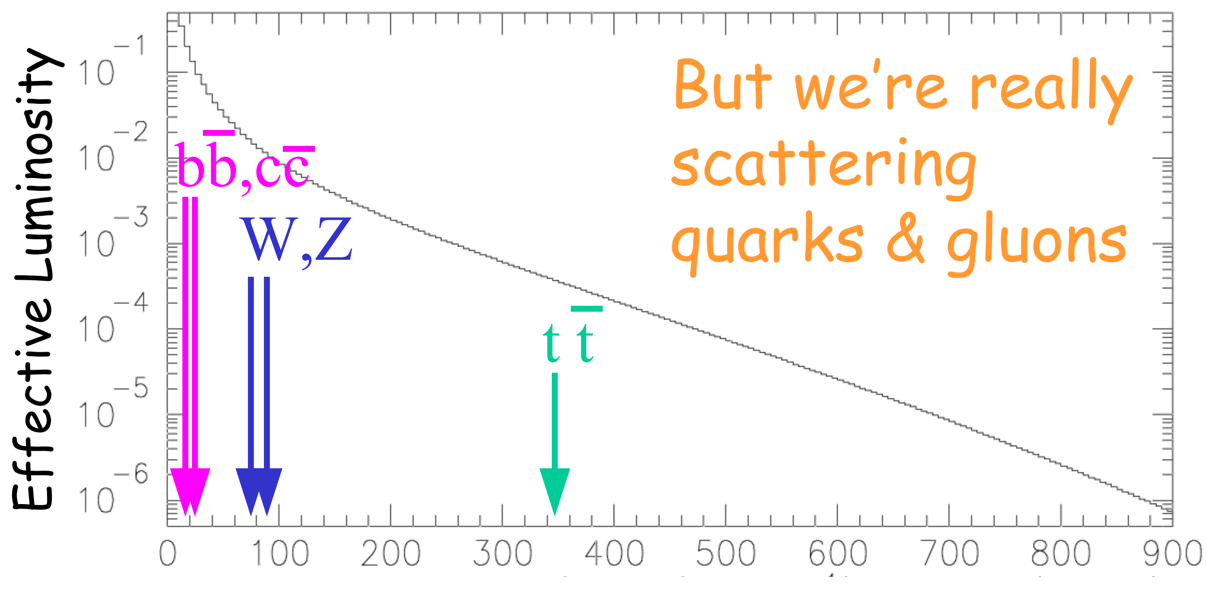
4 numbers describe
bb C.O.M. frame:

Px, Py, Pz, M

2 of them we don't know at all

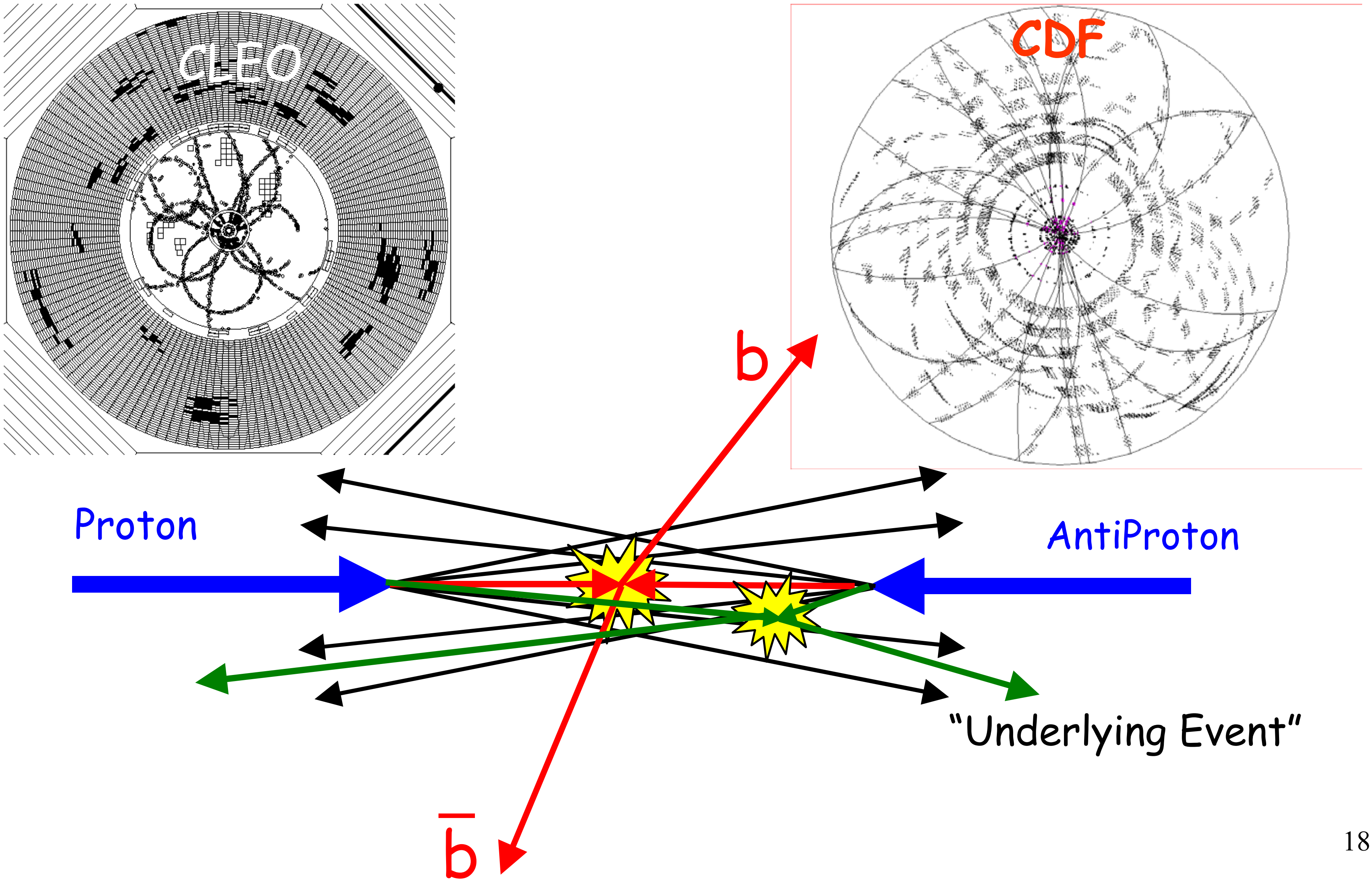
the other 2 we know very poorly



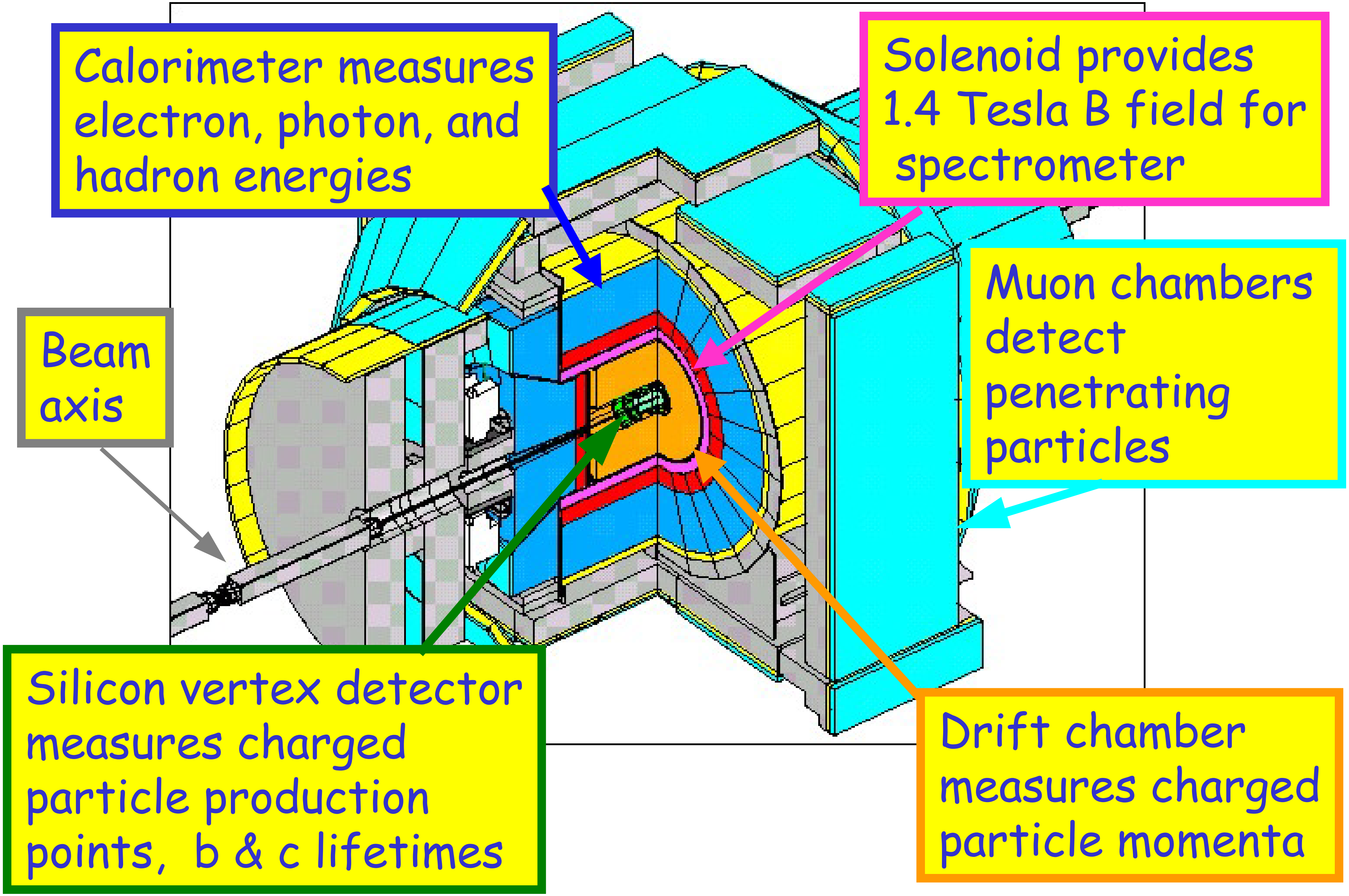


Challenge #2: messy events

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

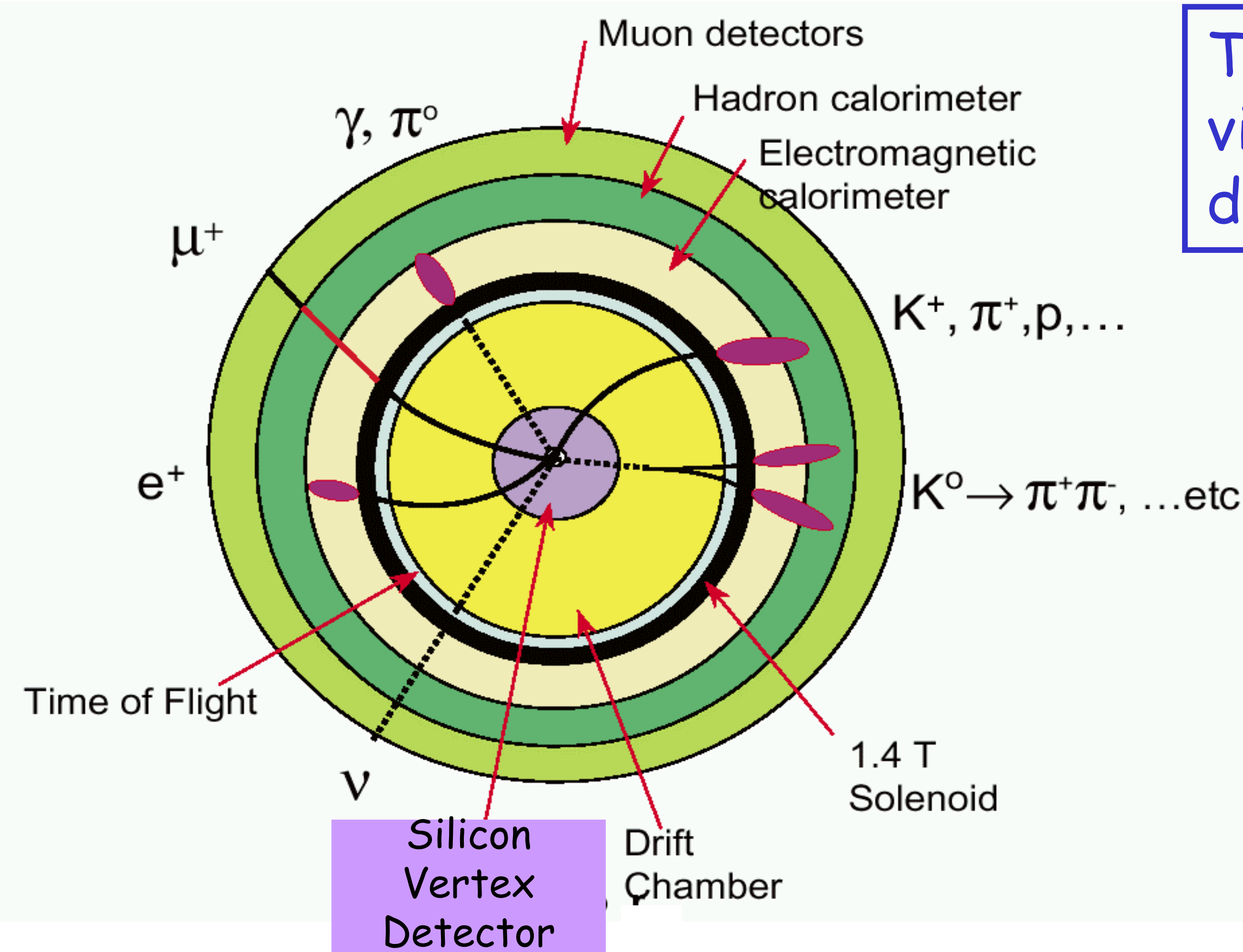


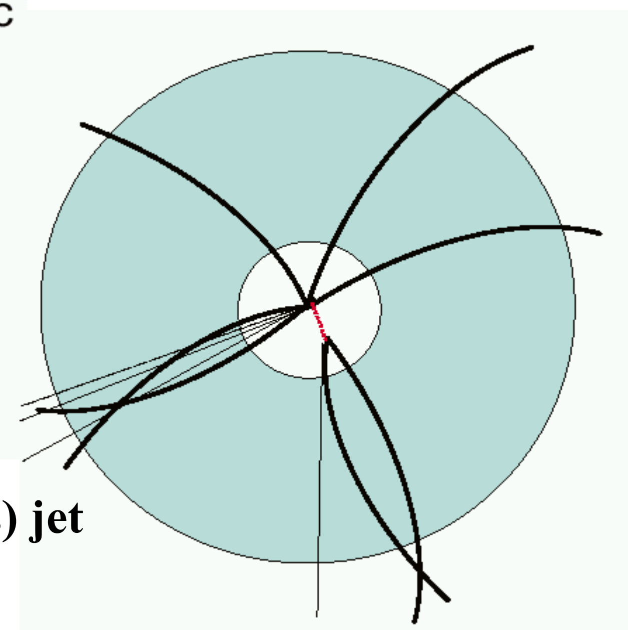
CDF Detector



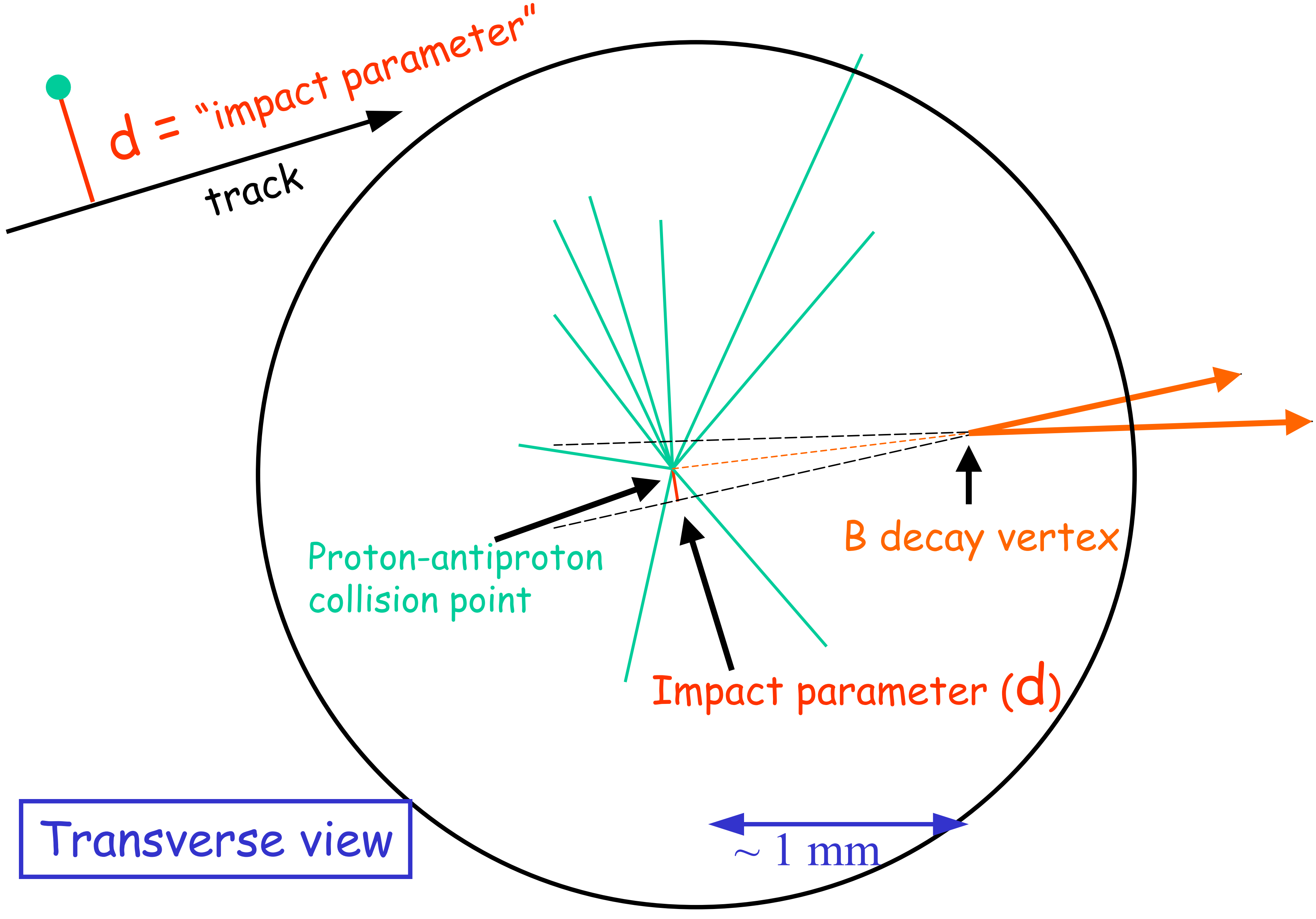
Particle signatures at CDF

Transverse view of detector



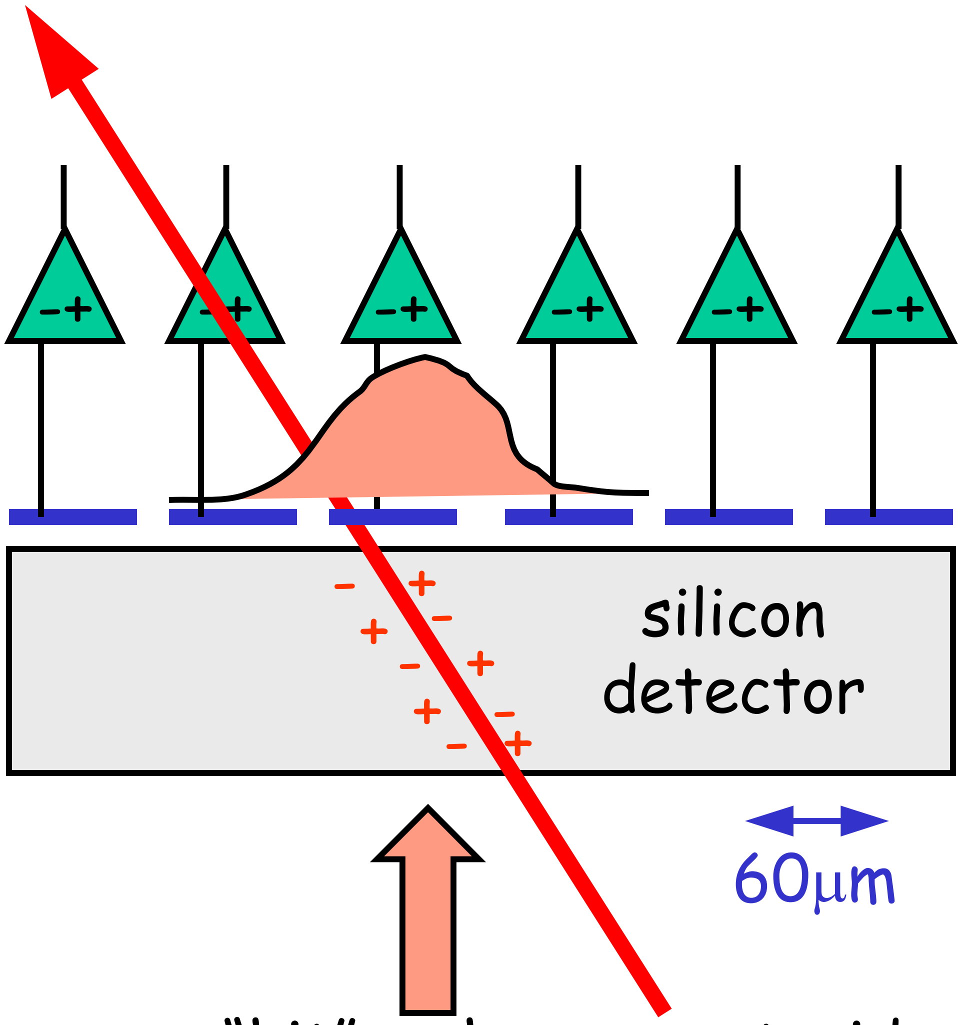


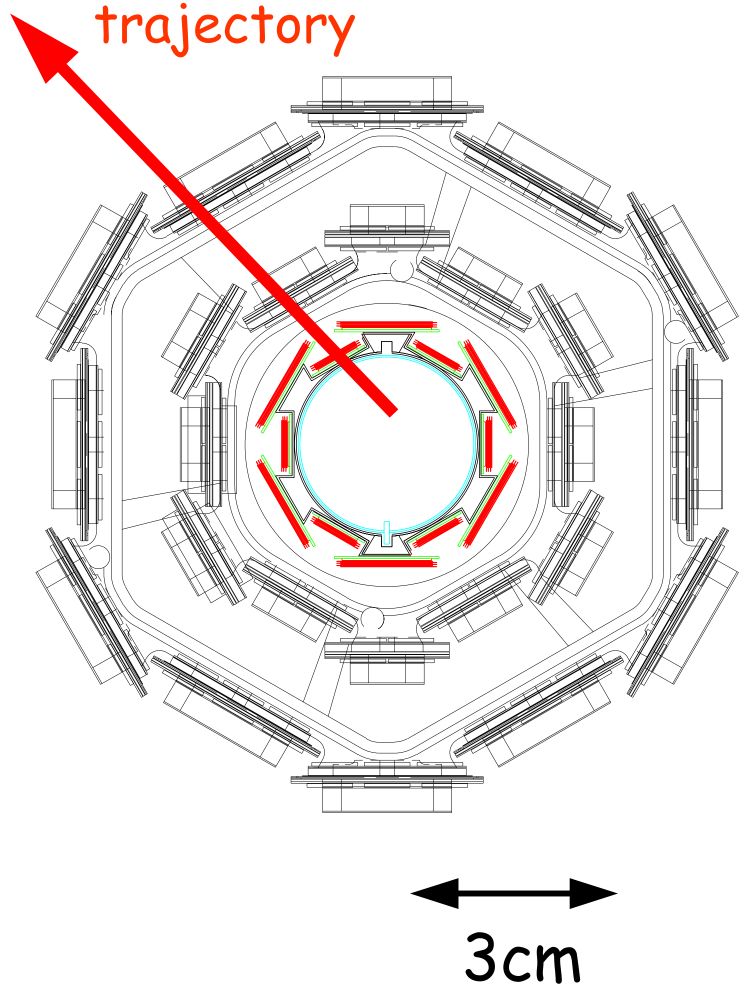
A salient property of b,c decay: lifetime



Transverse view

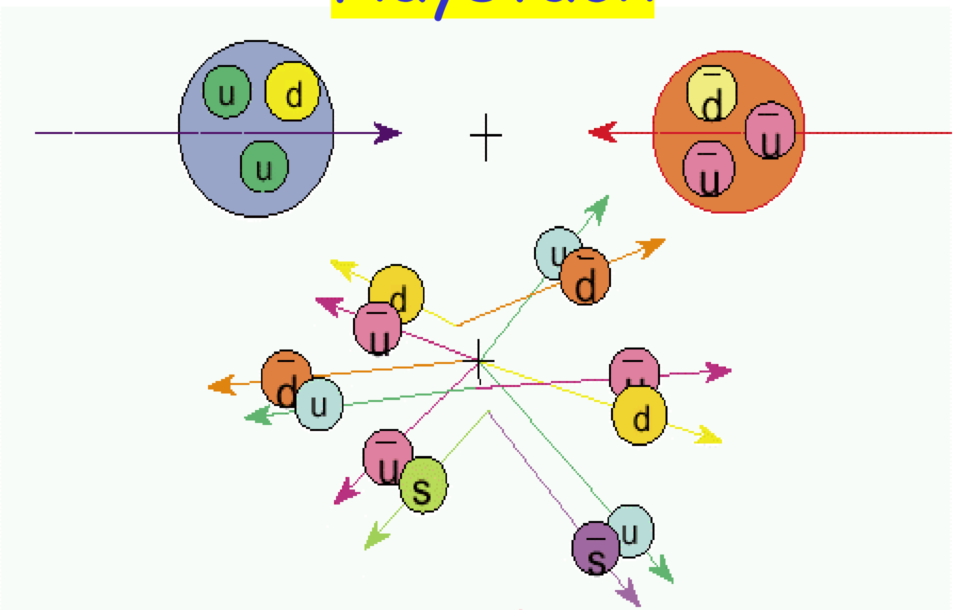
Position measurement ("hit") for charged particle

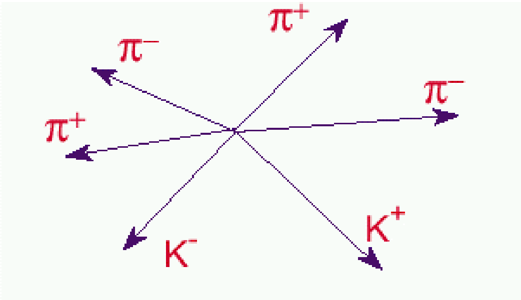




Why do you need a trigger?

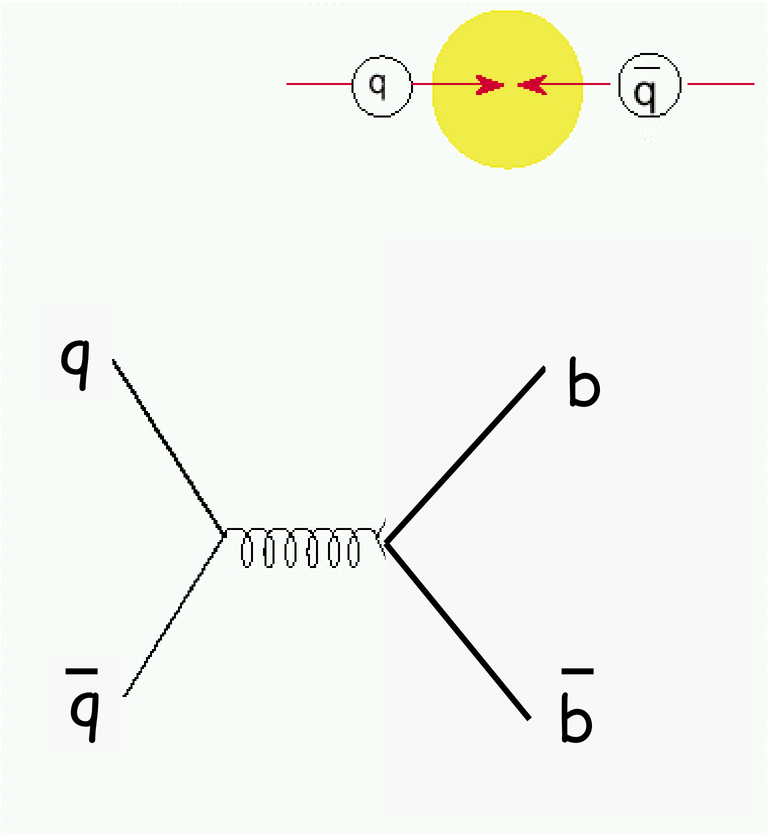
Haystack





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

Needle



×1000 less frequent: bottom quark pair production

Recap

Tevatron produces O(1kHz) 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 | b+c purity

2.5 MHz — ~0.1%

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

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

25 kHz — ~1%

Level 2: ~30 μsec ("Silicon Vertex Trigger")

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

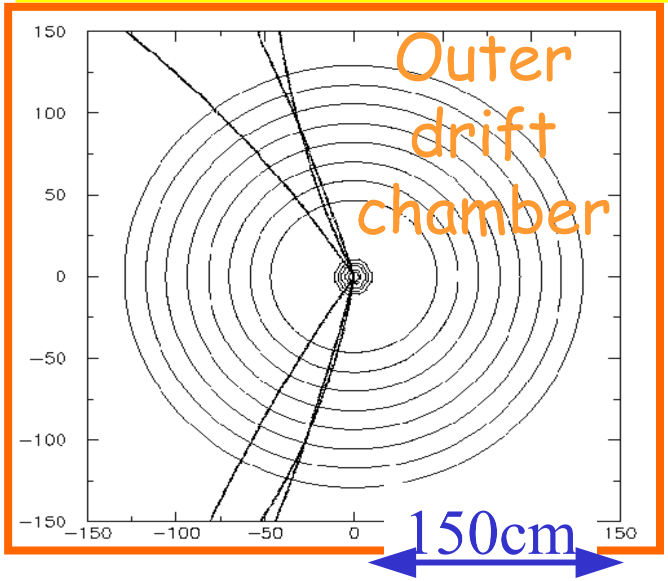
250 Hz — ~50%

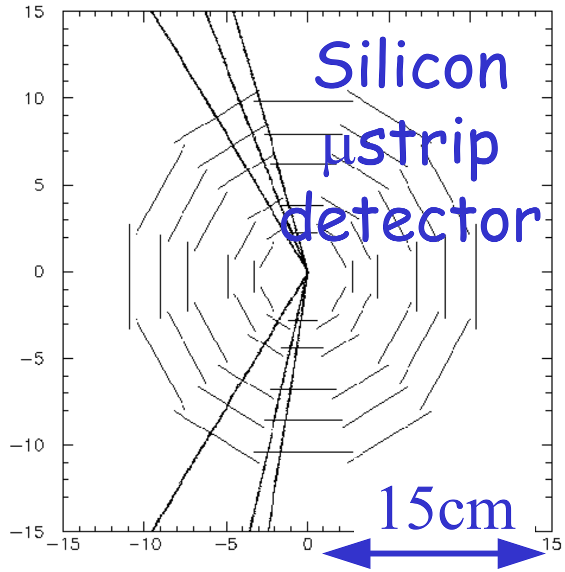
Level 3: ~ 1 second (using ~250 PCs in parallel)

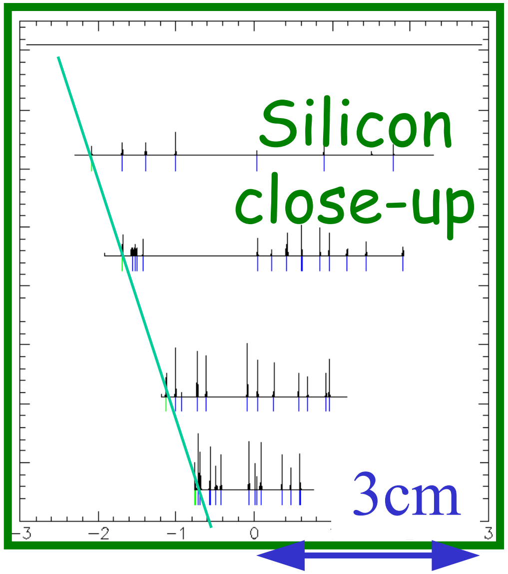
- full-precision tracking
- confirm the fast hardware tracking measurements

50 Hz — ~90%

"Silicon tracking" problem synopsis





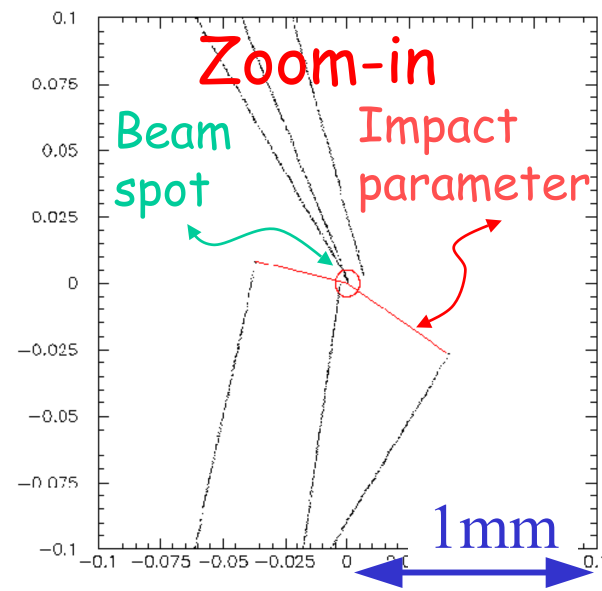


Input (every time Level 1 says "yes"):

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: σ(d)=35um

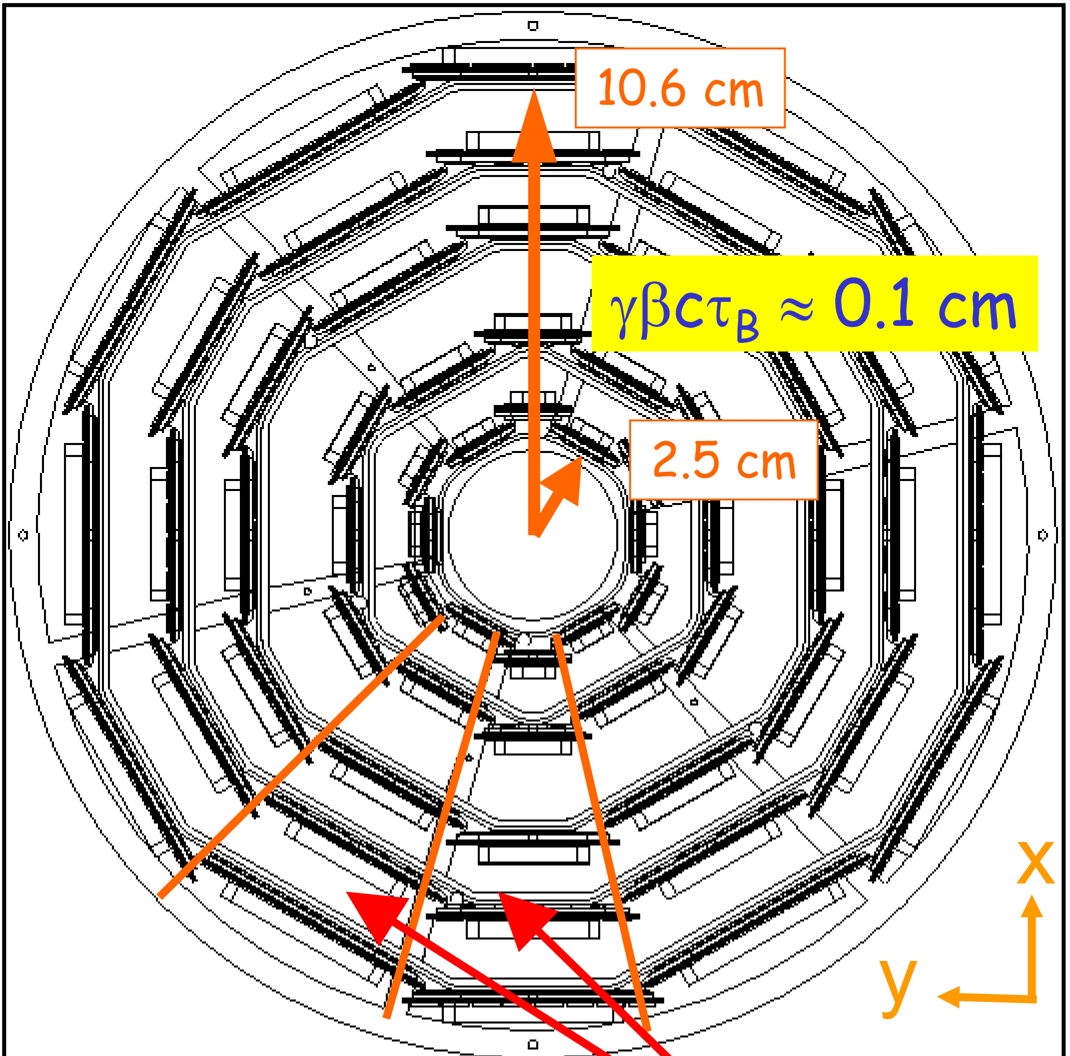
Three of SVT's key techniques …

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

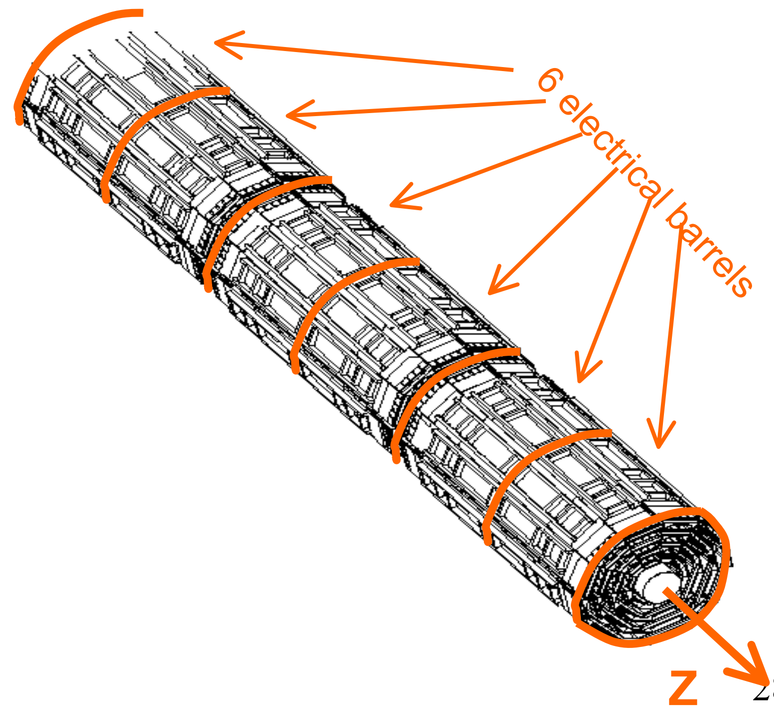
The wisest are the most annoyed by the loss of time. -Dante

Trick #1: symmetry allows parallelism



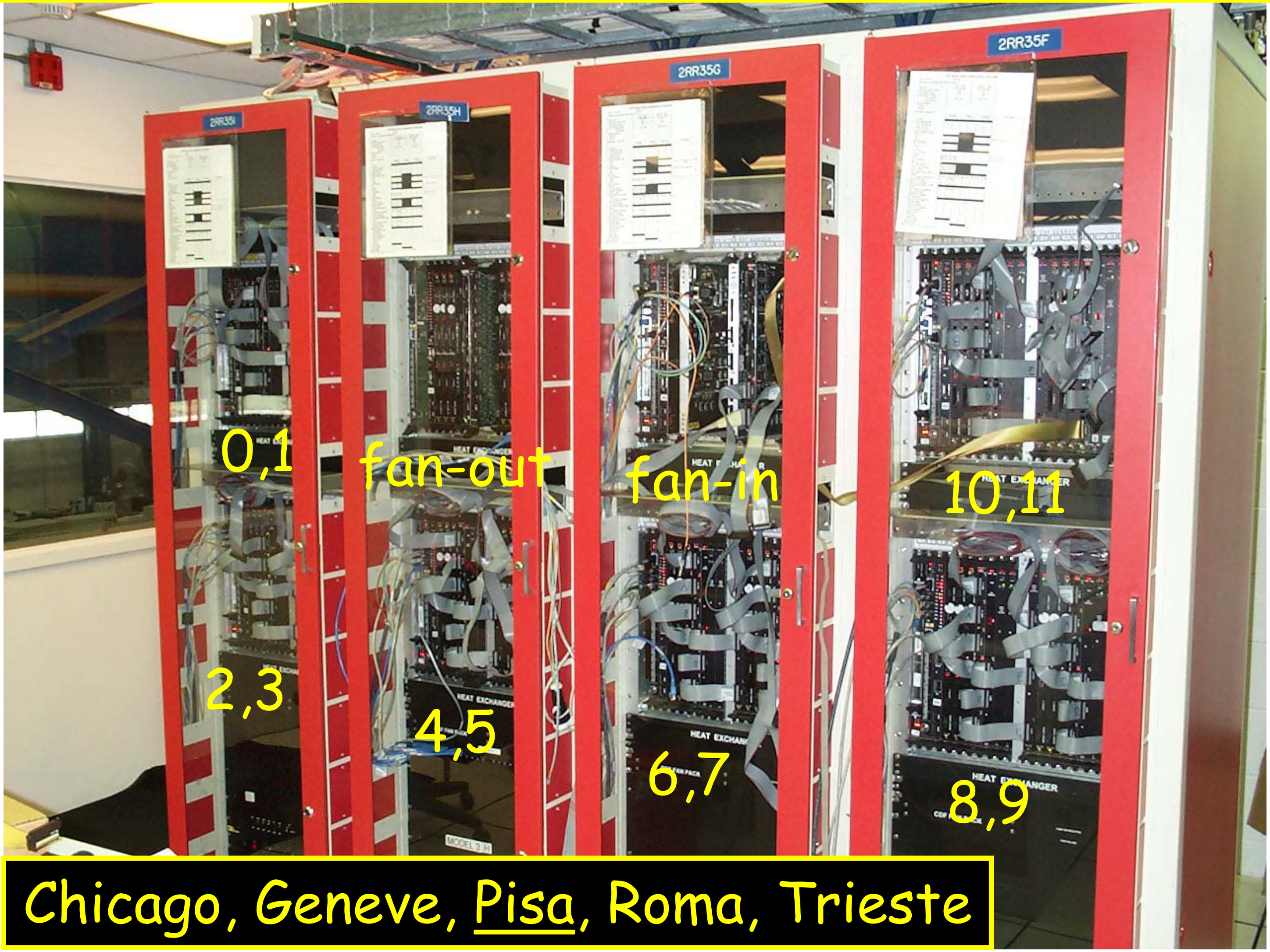
Note "wedge" symmetry

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



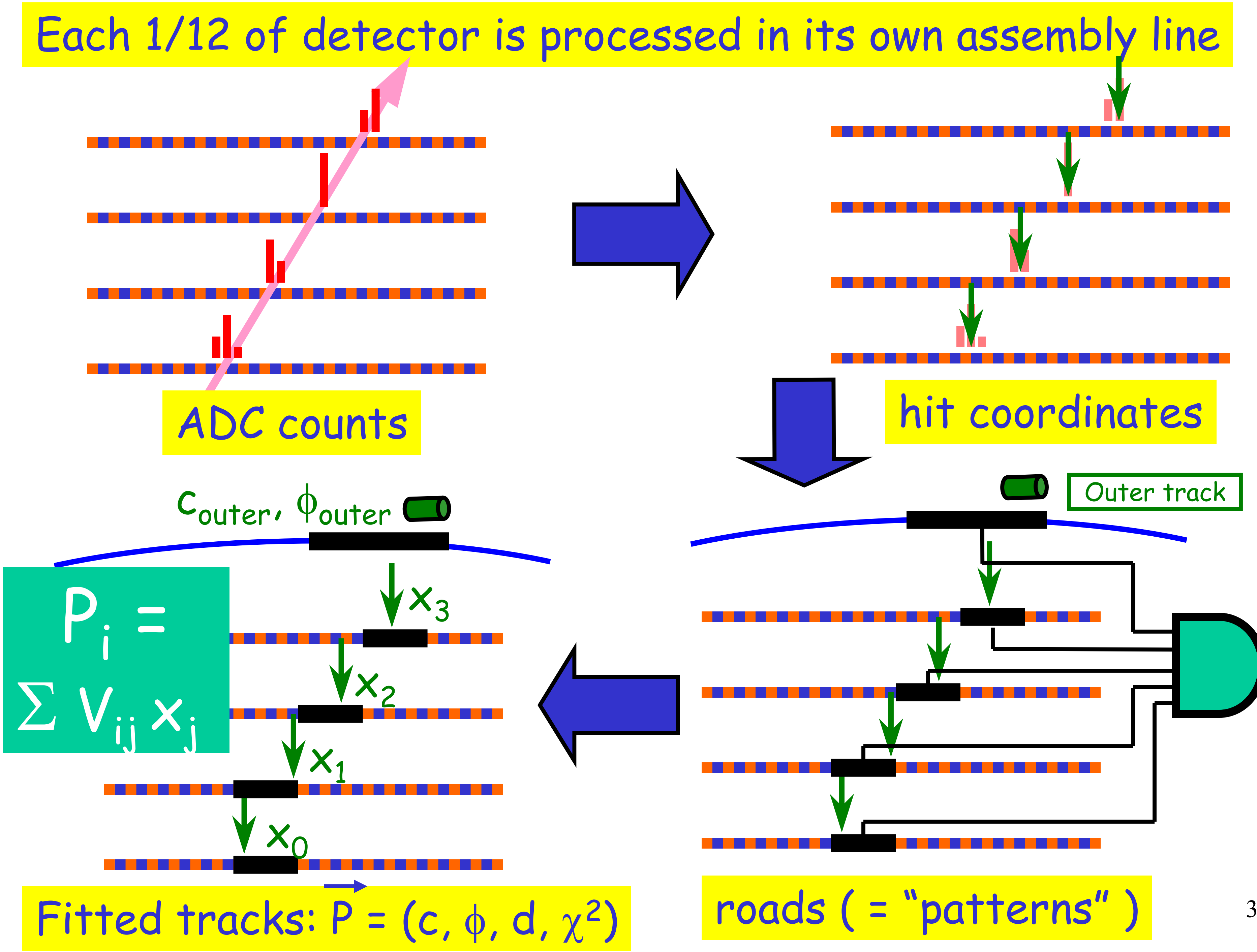
SVT data volume requires parallelism

2 meters



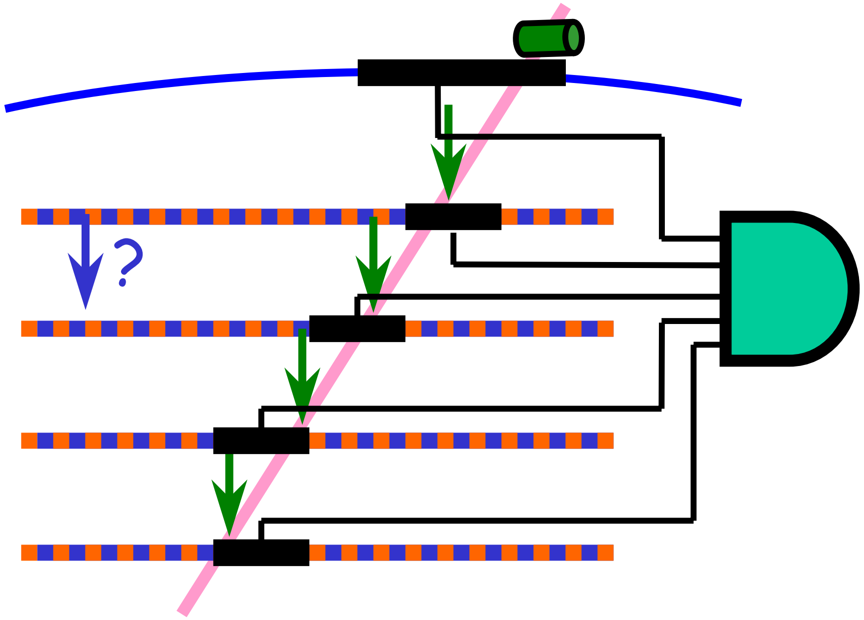
Reduces gigabytes/second to megabytes/second

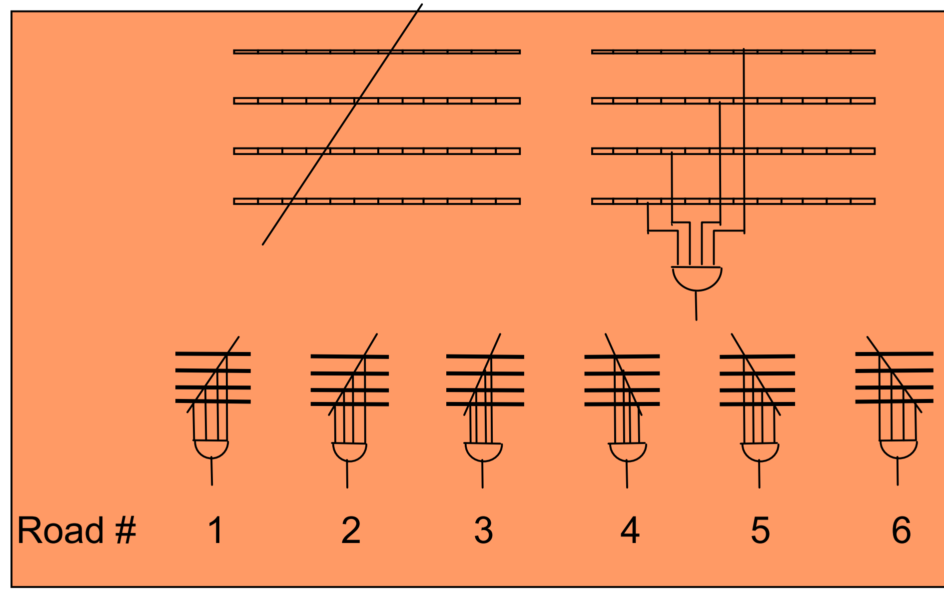
Peak (avg): 20 (0.5) GB/s → 100 (1.5) MB/s



Each 1/12 of detector is processed in its own assembly line
ADC counts
hit coordinates
Outer track
c_{outer}, ϕ_{outer}
$P_i = \sum V_{ij} x_j$
x_3
x_2
x_1
x_0
Fitted tracks: $\vec{P} = (c, \phi, d, \chi^2)$
roads (= "patterns")

2nd trick: streamlined track finding





The way we find tracks is a cross between

- searching predefined roads
- playing BINGO

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

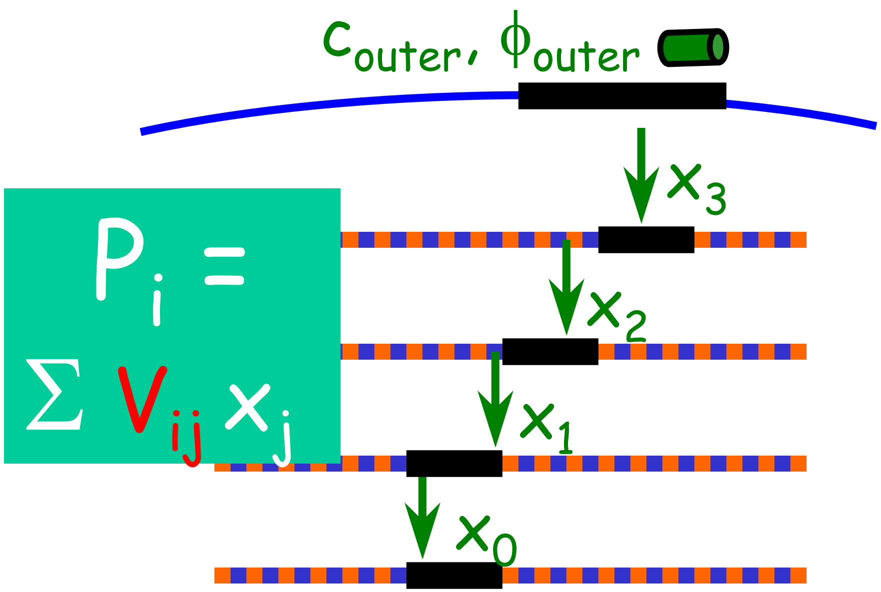
Time ~ $A*N_{hits} + B*N_{matchedroads}$

Trick #3: linear fit

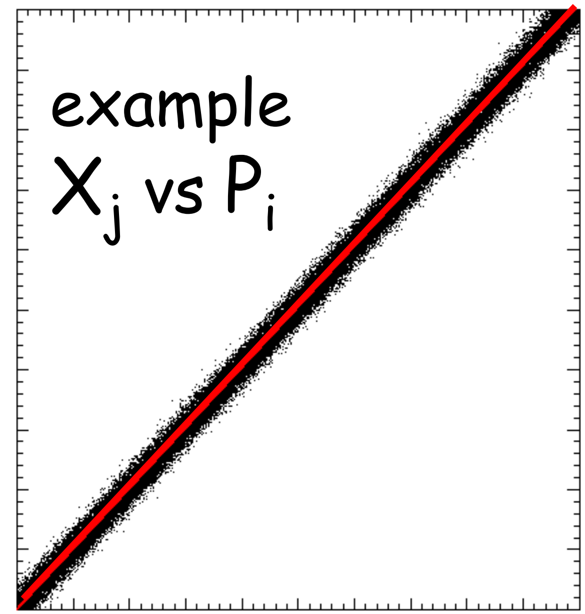
Circle($\vec{P}$) ∩ Planes at points $\vec{x}$

$\vec{x}$ not in general linear in $\vec{P}$

But for P > 2 GeV, d < 1 mm,
linear fit biases d ~ few %
⇒ no problem for trigger



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



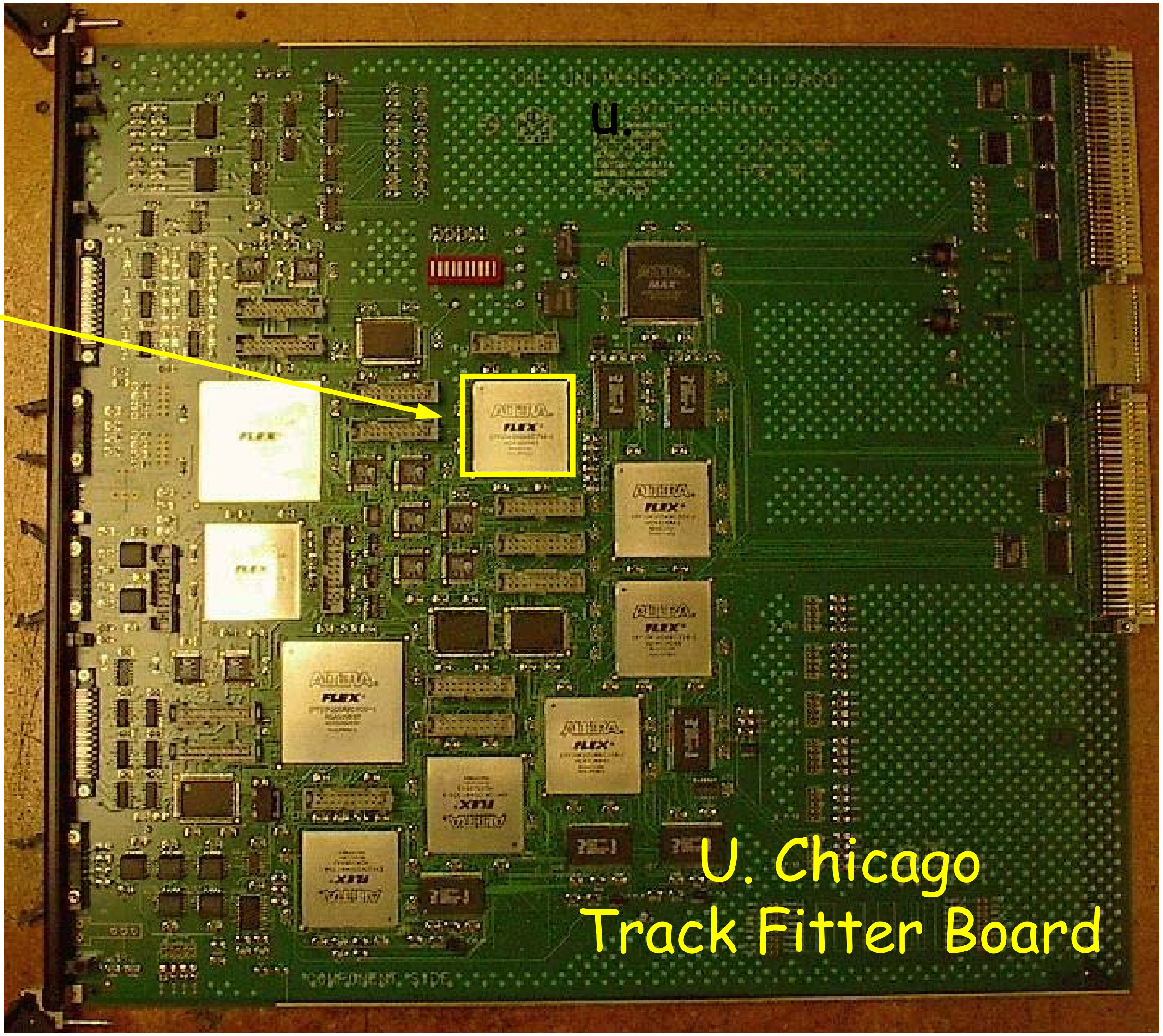
We derive V_{ij} by linear regression to Monte Carlo data

<u>Trick #3a</u>: use road as a hint
precompute $V_{ij} X_j^{road}$
⇒ 250 nsec per fit !

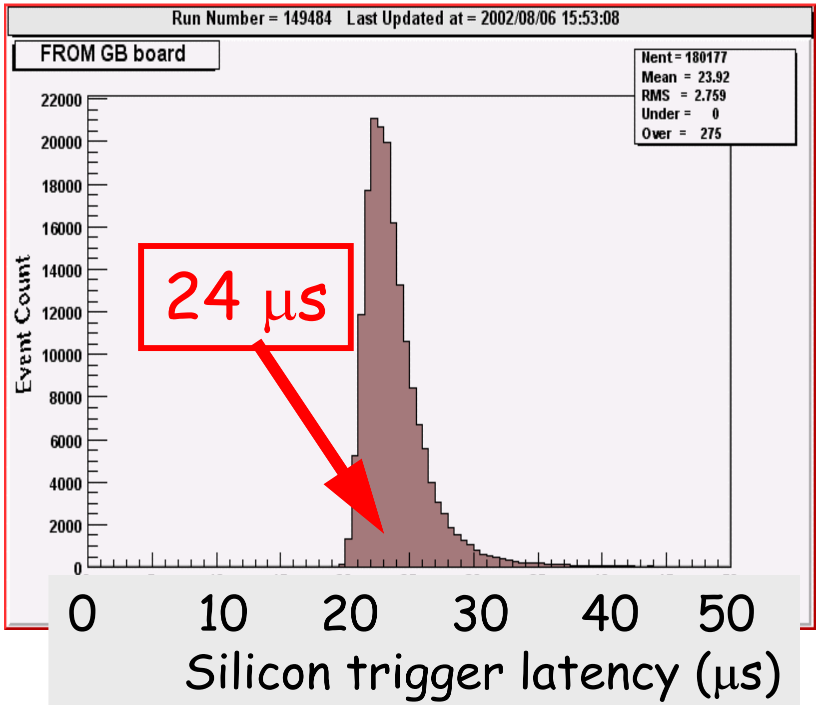
Least squares fit is performed in programmable logic

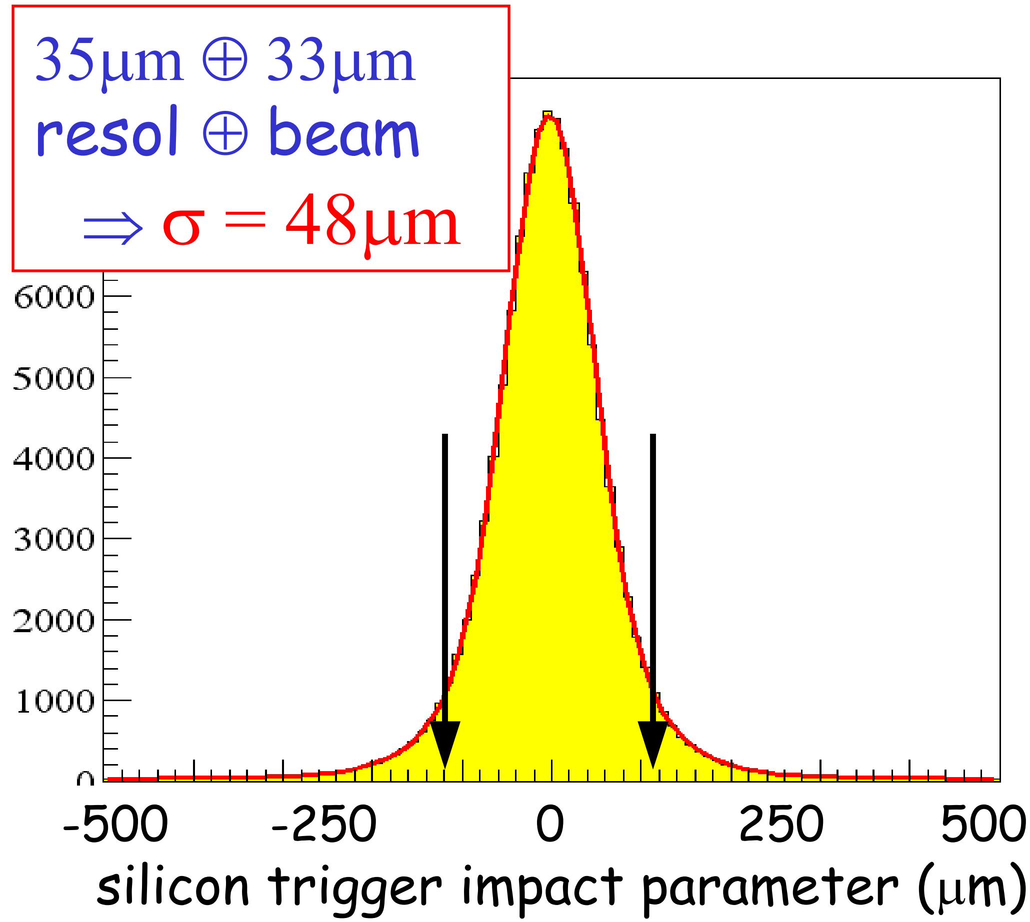
The 6 scalar products are computed in parallel

Each fit done in 250nsec



Success !





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.

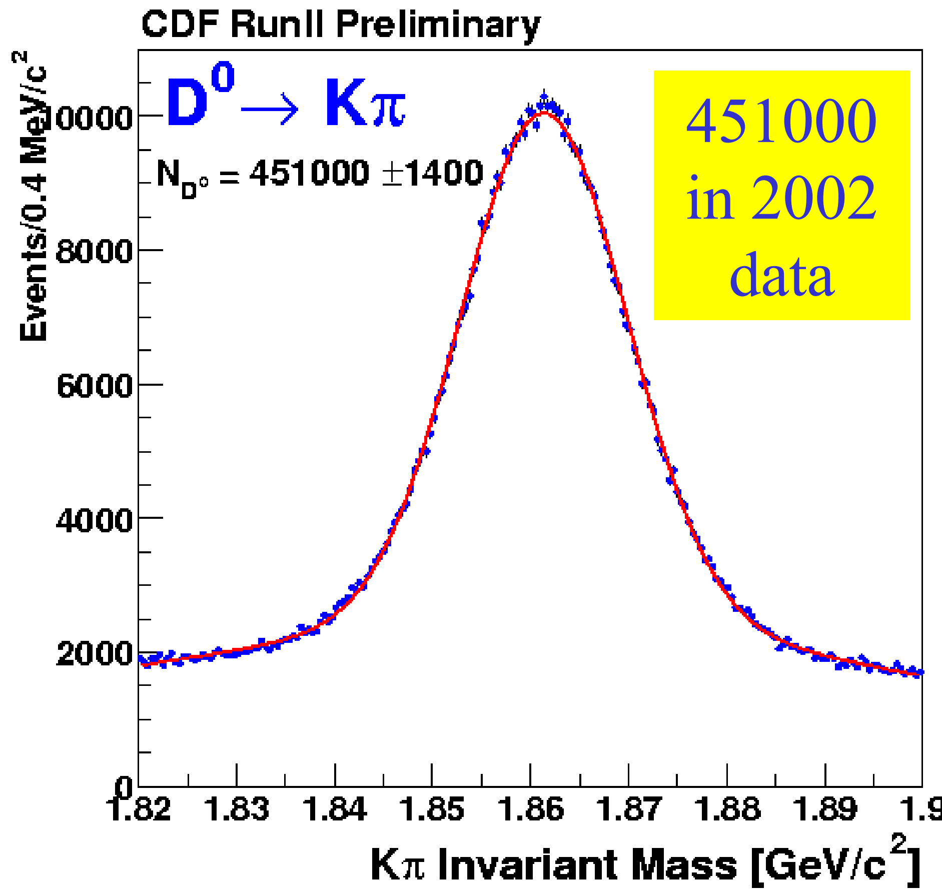
After one year of data taking at CDF, we're still learning, but we're already able to do some new things.

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

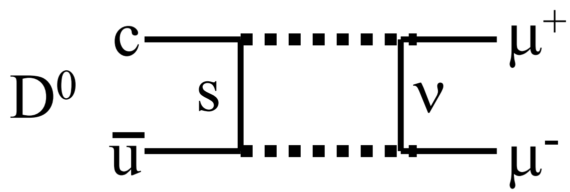


Some are born to discover J/Ψ,
some achieve photoproduction of charm,
and some have charm physics thrust upon 'em

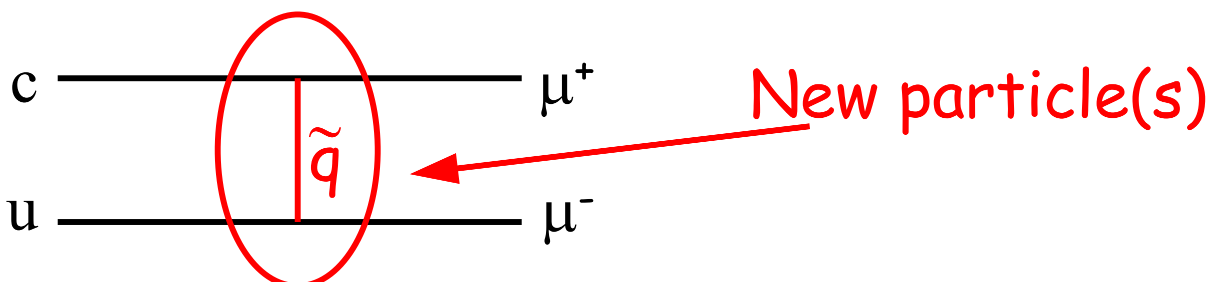
$D^0 \to \mu^+\mu^-$

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

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



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

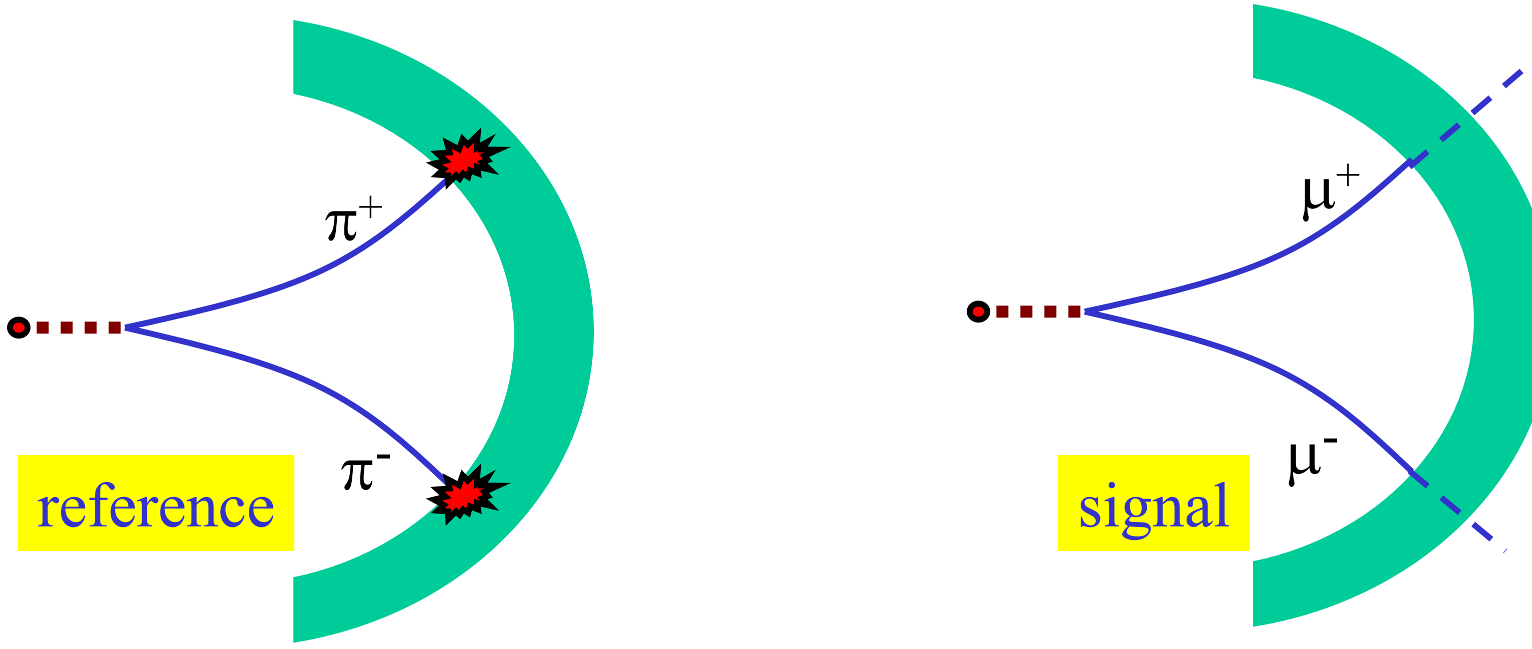


B.R. as large as 3×10^{-6} in some supersymmetry models

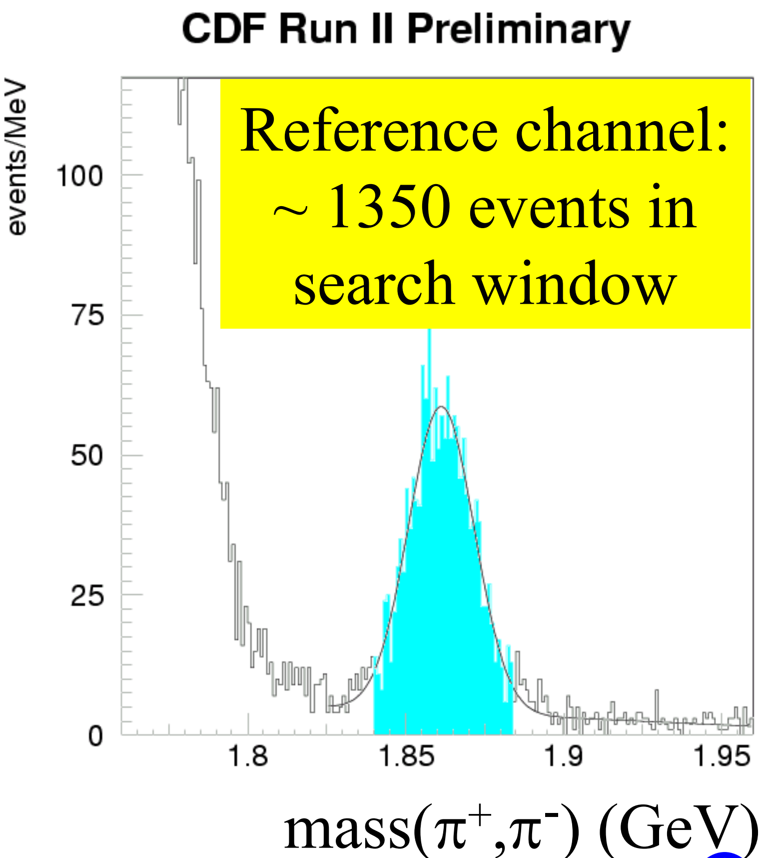
Key: inclusive trigger selection

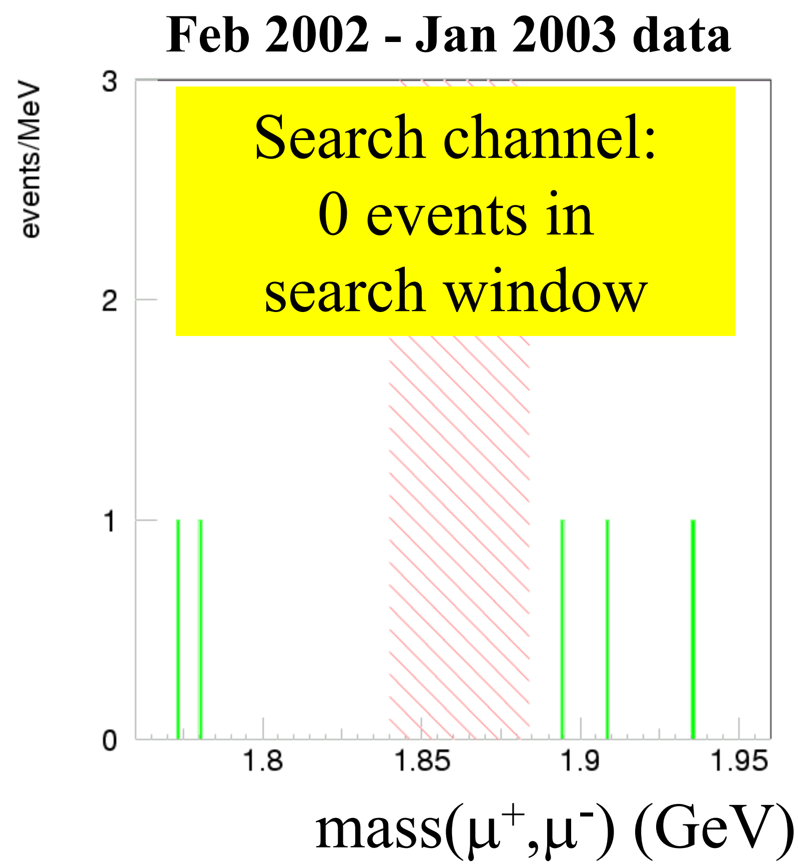
Trigger uses only lifetime information:
treats reference and signal equally

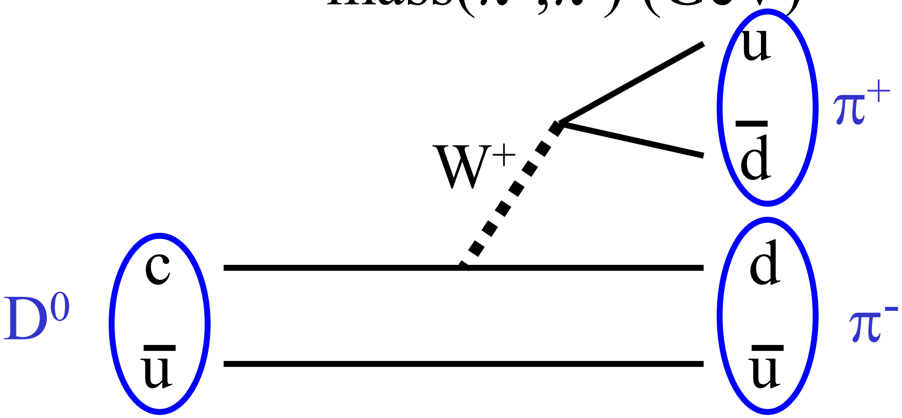
We distinguish them only at the final stage.



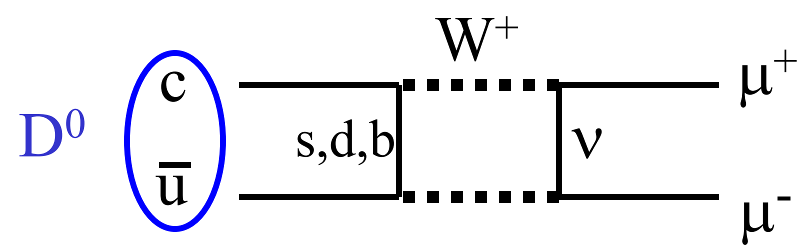
Different decay modes, but identical kinematics







standard model rate ~ 10^{-3}



standard model rate ~ 10^{-13}

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

- Putting the numbers together,

Poisson statistics

Reference branching ratio

$$B.R. < \frac{2.3}{1350} \times 1.4\times10^{-3} = 2.4\times10^{-6}$$

New limit

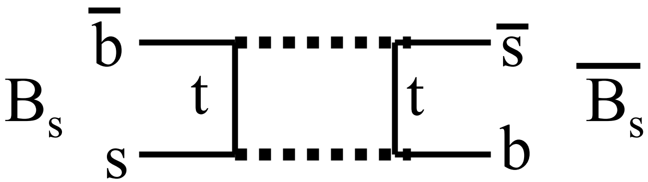
Reference event count

$$\Rightarrow BR(D^0 \to \mu^+\mu^-) < 2.4\times10^{-6} \ @\ 90\% CL$$

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

$B_s \leftrightarrow \overline{B}_s$

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



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

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

Standard Model: $X_s < 31$

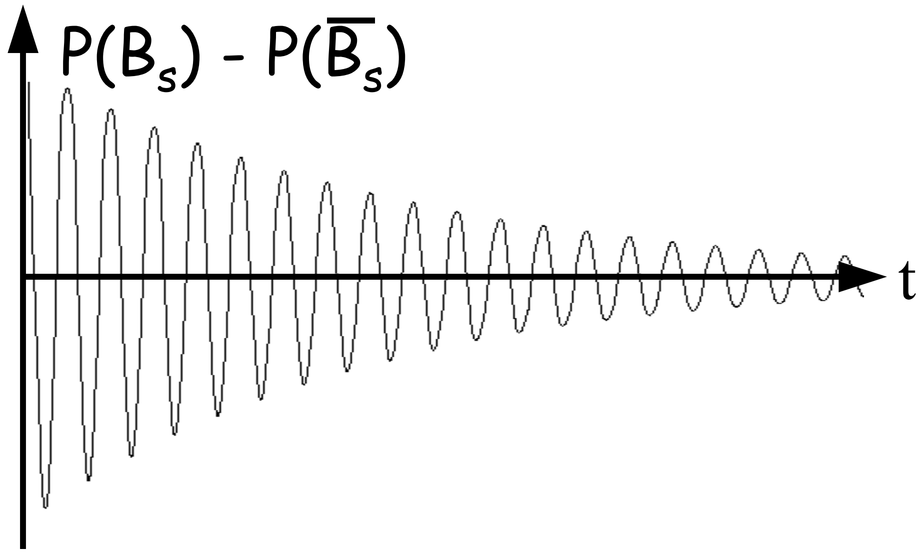
Currently, B_s measurements can be done only at the Tevatron

Mixing 101

Two-state system: $|B_s\rangle$ and $|\overline{B}_s\rangle$

Without mixing, degenerate states:

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



Mixing splits the states:

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

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

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

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

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

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

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

Mixing in the laboratory

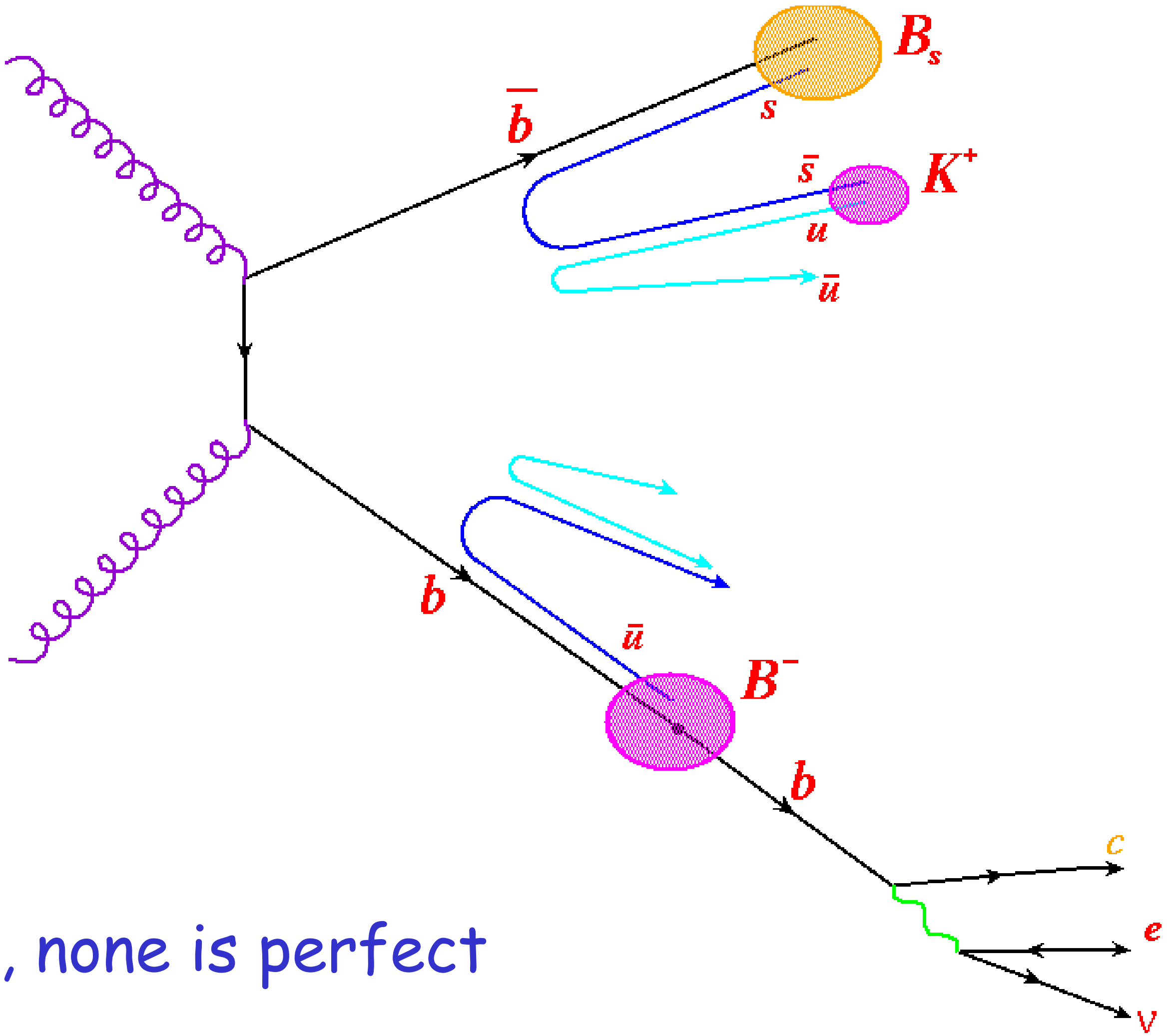
To resolve the oscillations, we need to measure

- B_s vs $\overline{B}_s$ at t=0 (at production)
- B_s vs $\overline{B}_s$ at decay
- proper decay time

for large numbers of events

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

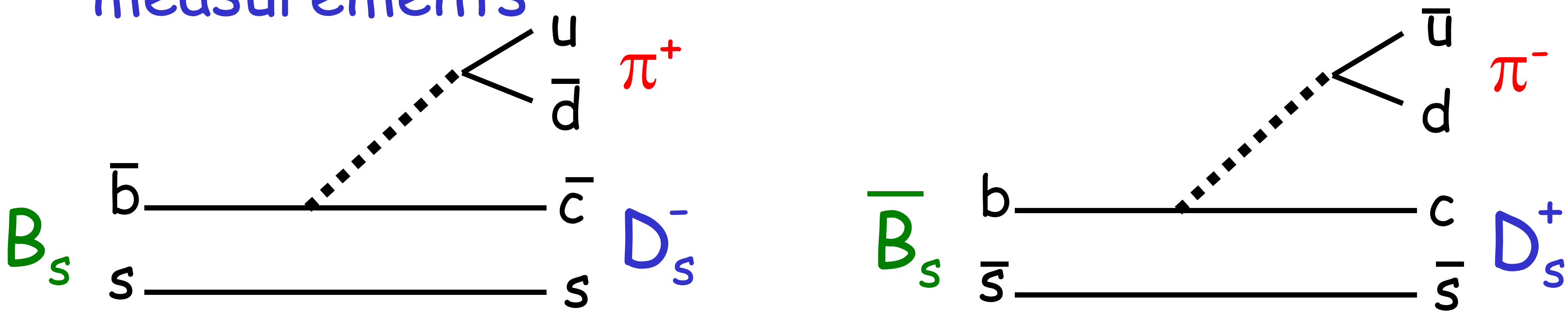
This is an art called "flavor tagging"



Several methods, none is perfect

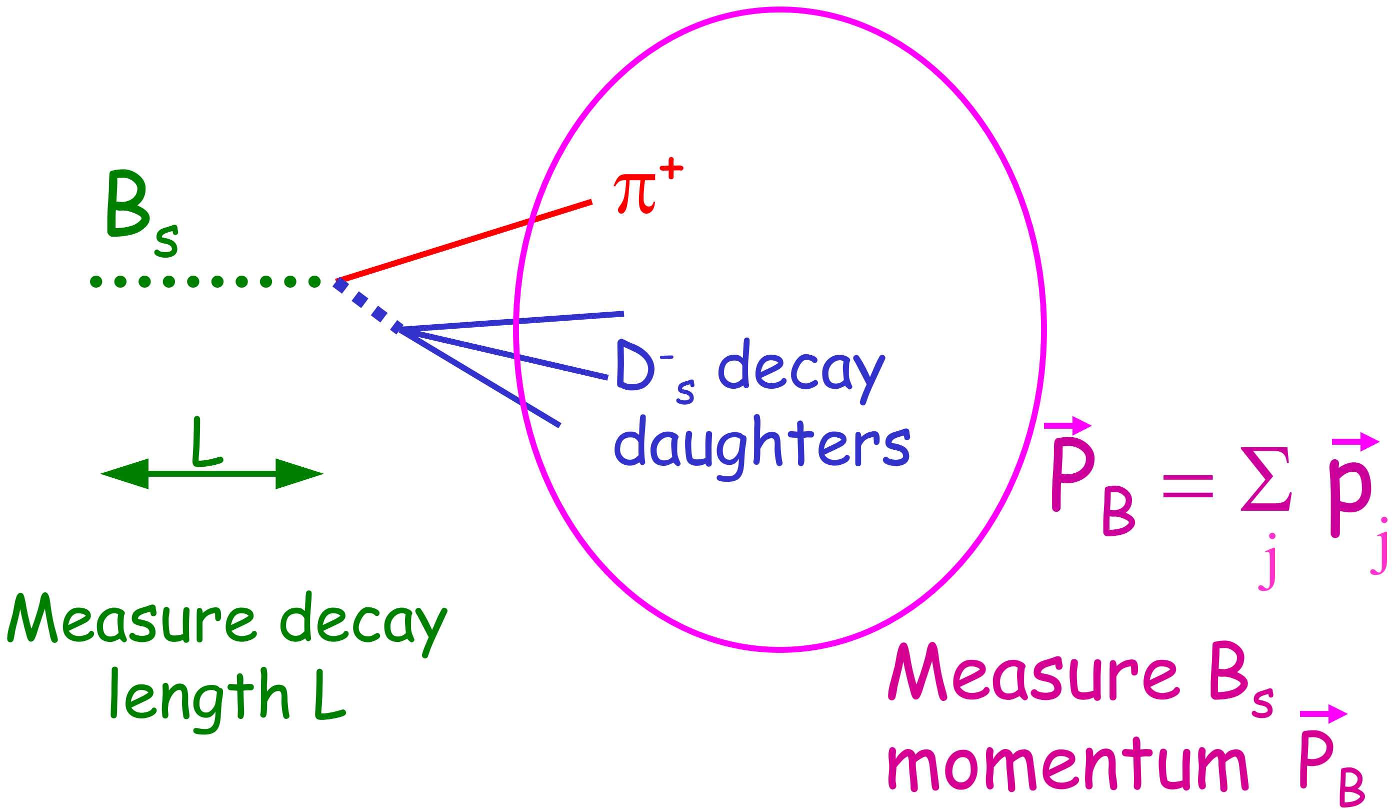
Measuring B_s vs $\overline{B}_s$ at decay

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



Measuring proper decay time

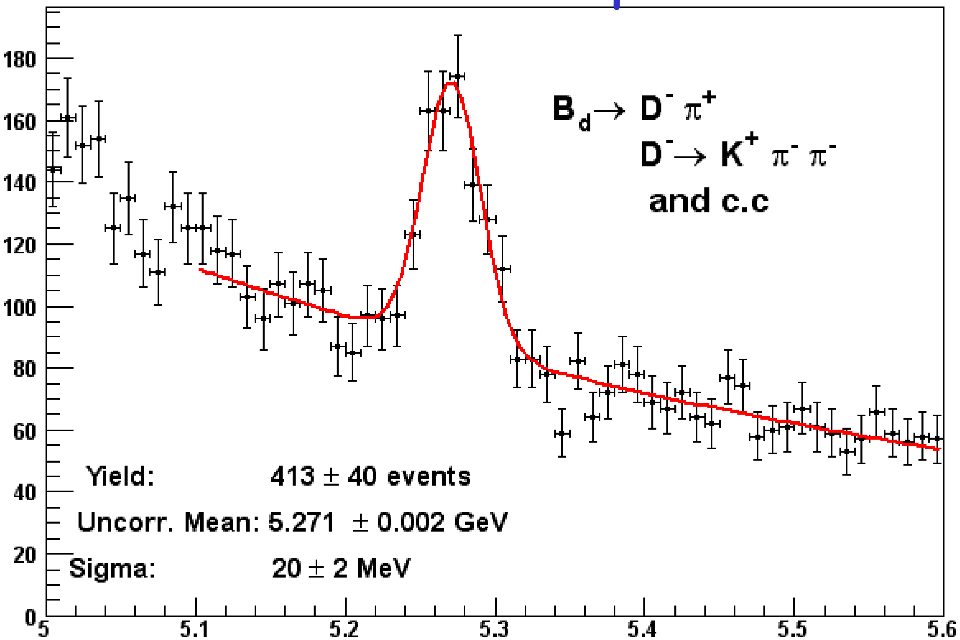
$$t = L / \gamma\beta = L\, m_B / P_B$$



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

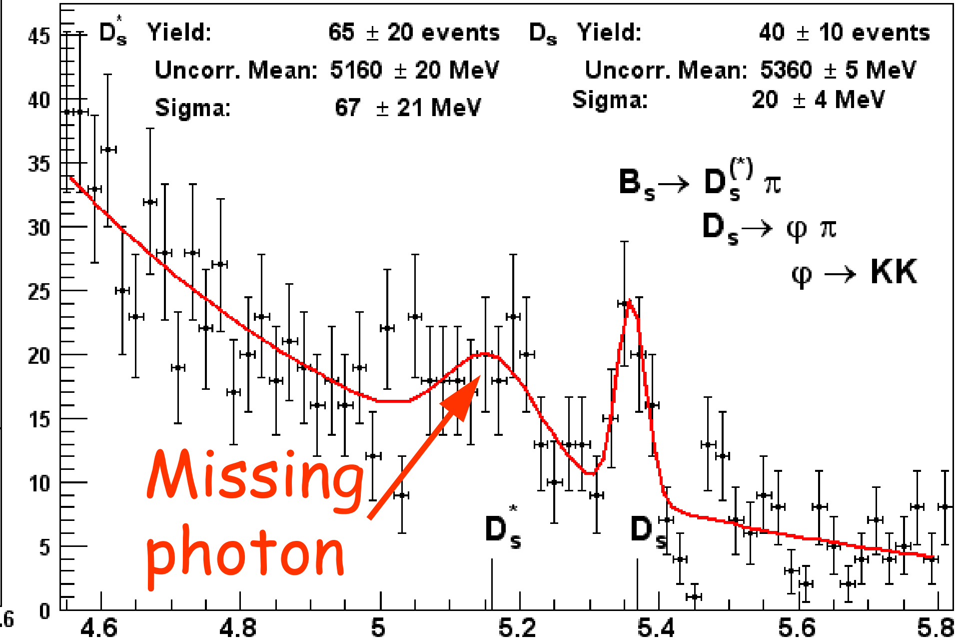
CDF's first $B^0, B_s \rightarrow D\pi$ signals (2002 data)

$B^0 \rightarrow D\pi$ 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.

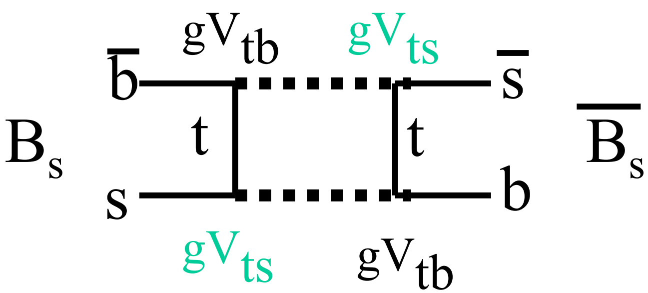
$\Rightarrow$ Use more D_s decay channels

Continue to optimize trigger

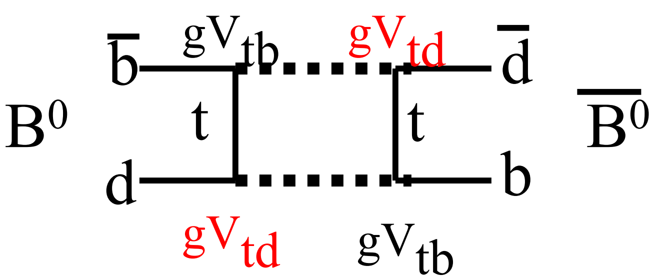
Continue to run experiment

Continue to optimize accelerator

B_s flavor oscillations: recap



$$\frac{\Delta m_s}{\Delta m_d} \propto \frac{|Vts|^2}{|Vtd|^2}$$



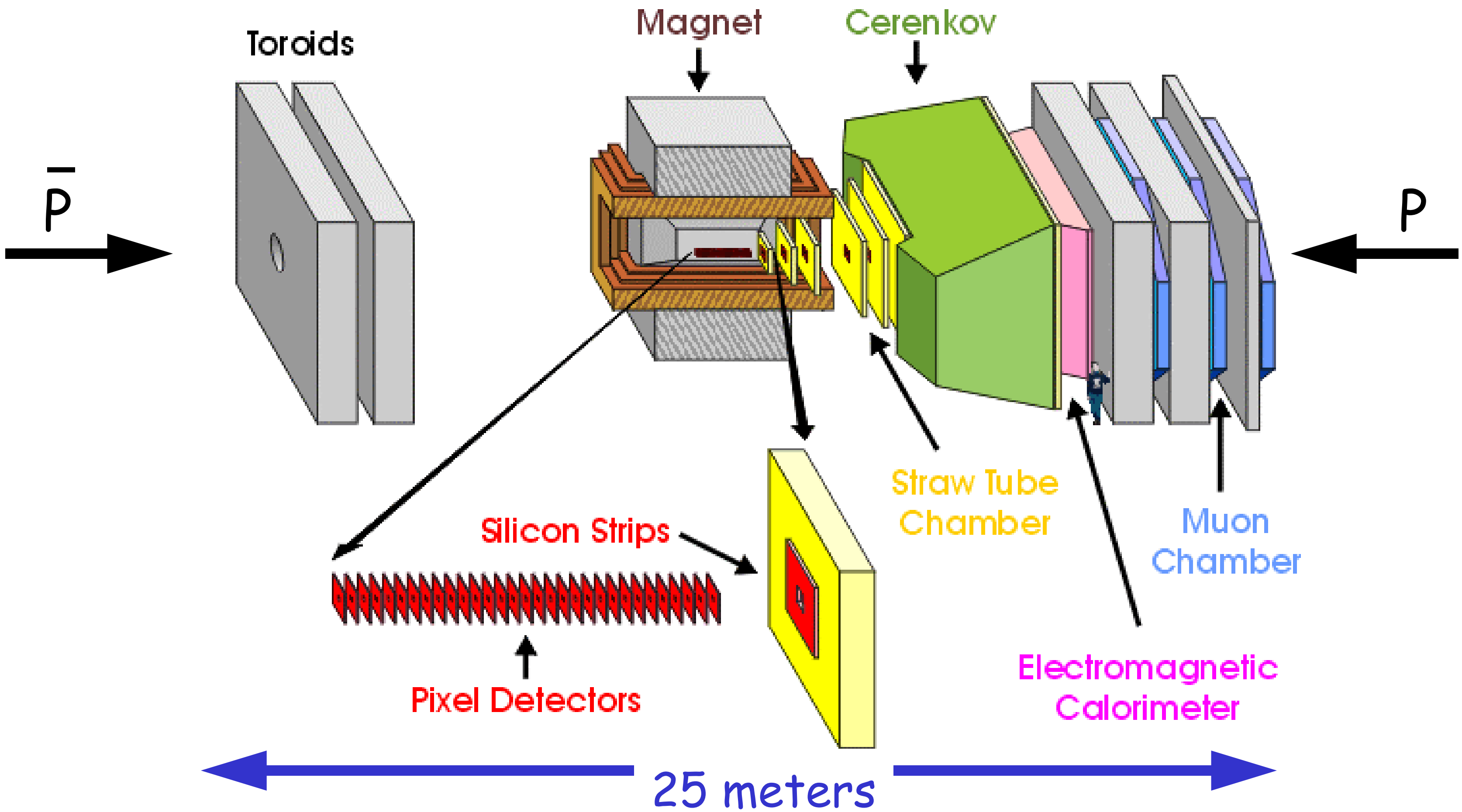
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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.

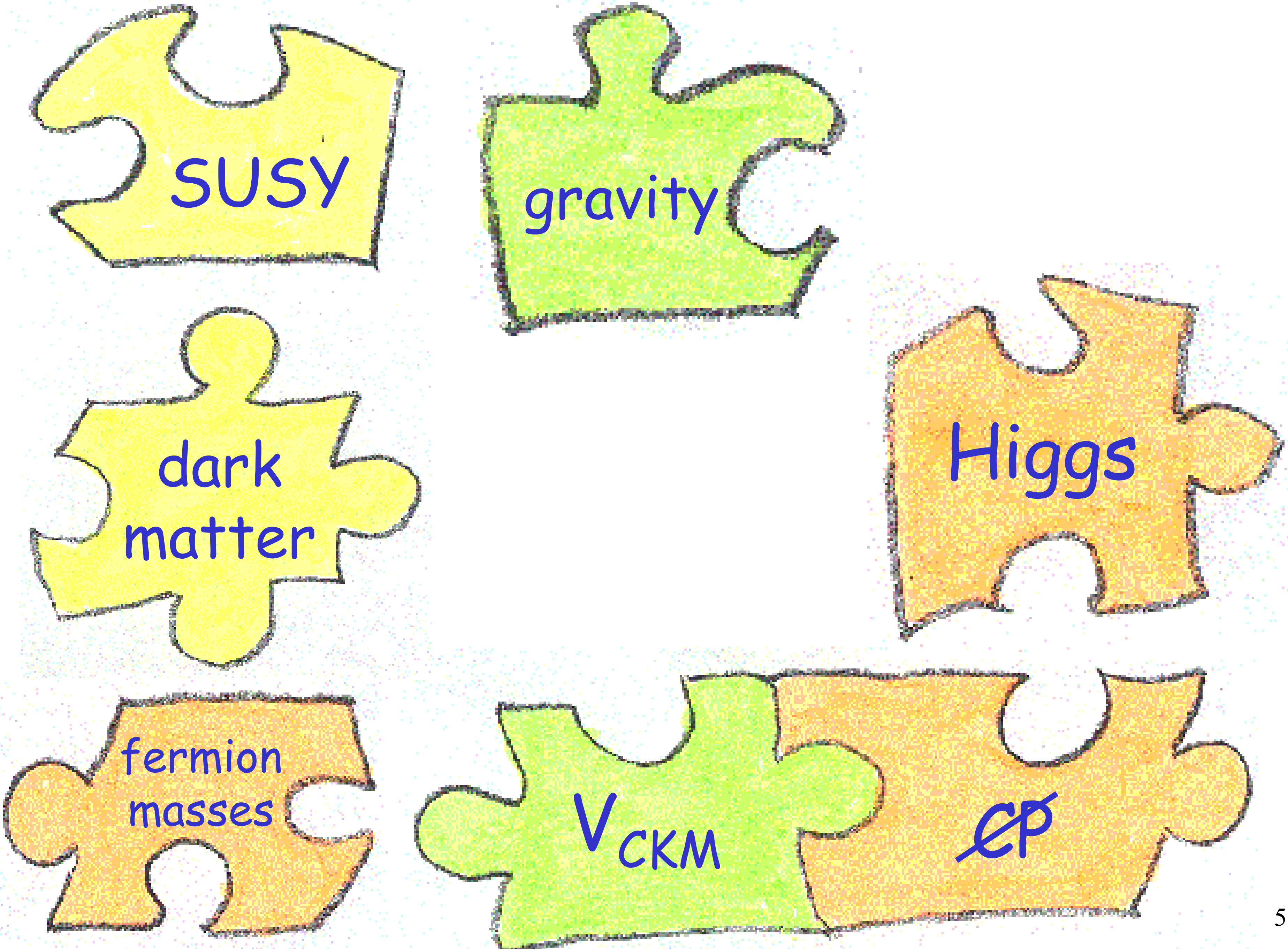
The future??
Dedicated, high-rate b,c experiments at Tevatron, LHC

- 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.

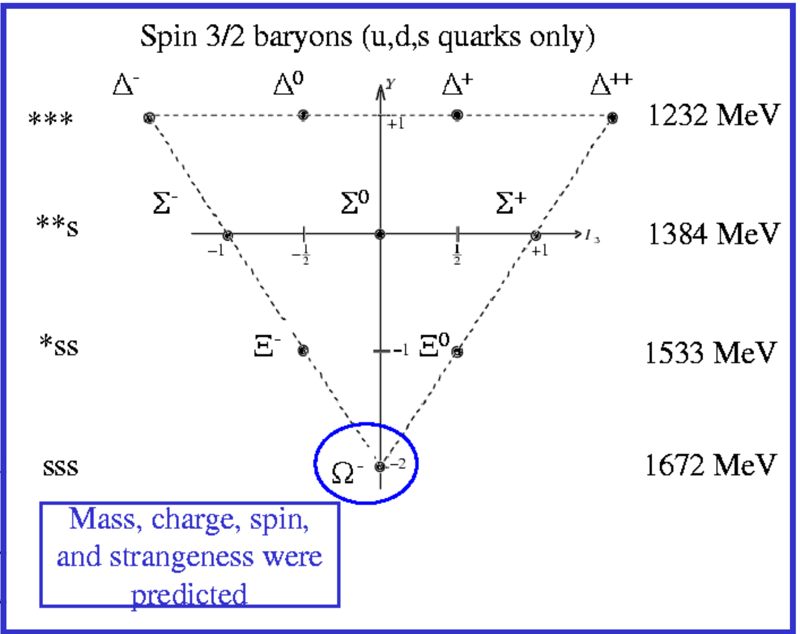

SUSY
gravity
dark matter
Higgs
fermion masses
V_{CKM}
~~CP~~

The End

Everything past this point is backup, notes, etc.

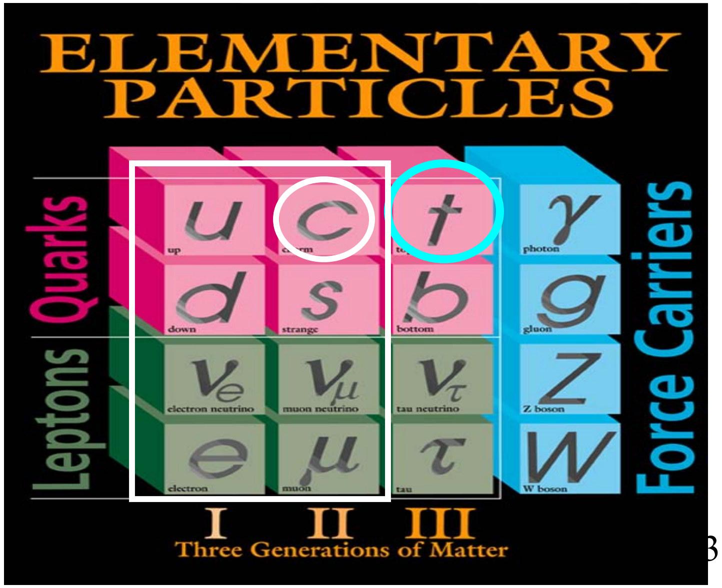
Interplay between direct and indirect discoveries

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	Aluminium 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) 101·7 103·0 106·5
7		Silver Ag	Cadmium Cd	Indium In	Tin Sn	Antimony Sb	Tellurium Te	Iodine I	



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

May 1st, 1991

“trigger”

CDF/DOC/TRIGGER/PUBLIC/1421

SVT
THE SILICON VERTEX TRACKER
Luciano Ristori

May 1, 1991

INTRODUCTION

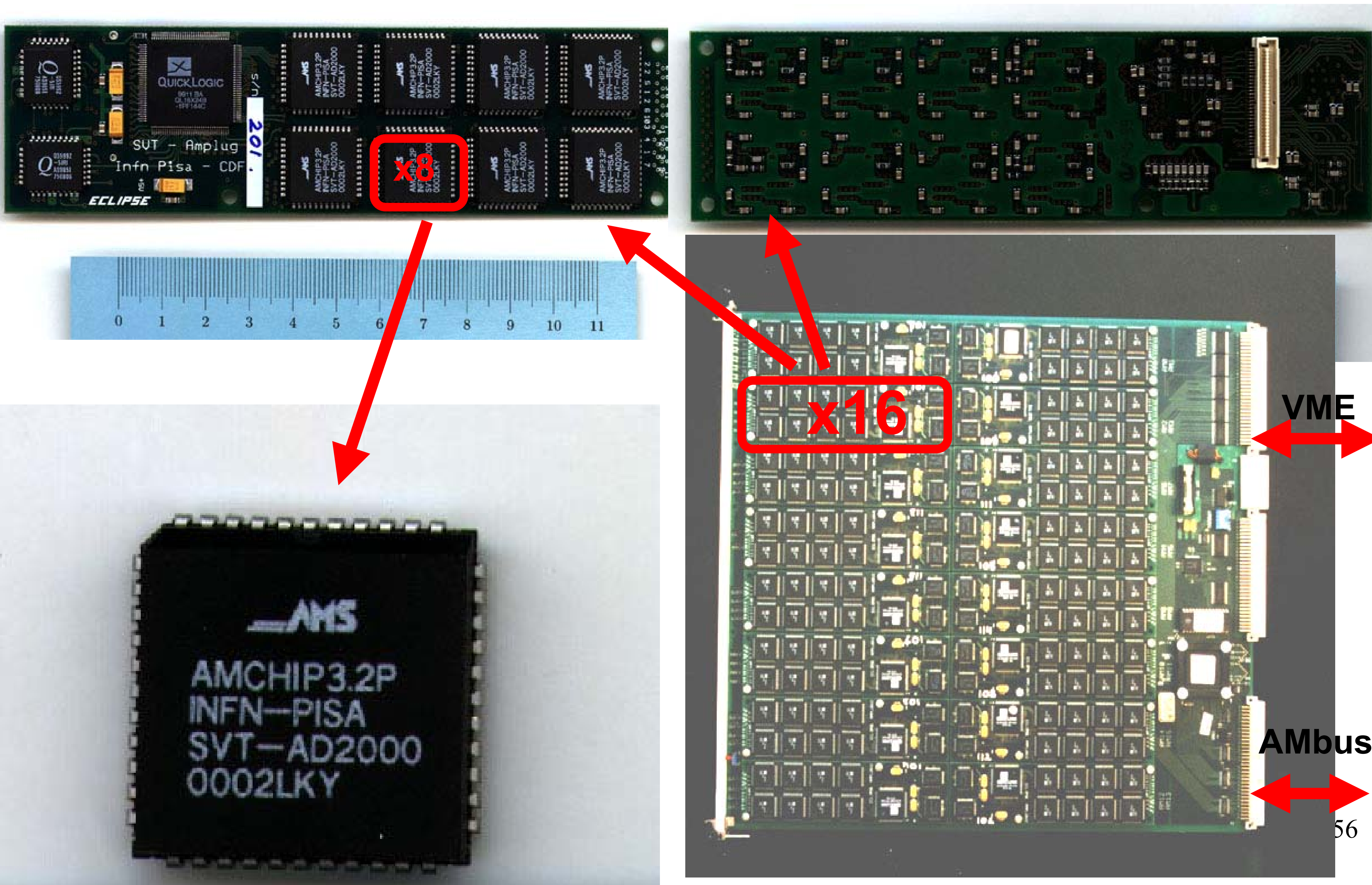
This note describes the architecture of a device we believe we can build to reconstruct tracks in the Silicon Vertex Detector (SVX) with enough speed and accuracy to be used at trigger level 2 to select events containing secondary vertices originated by B decay. We name such a device *Silicon Vertex 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 Pt>20 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

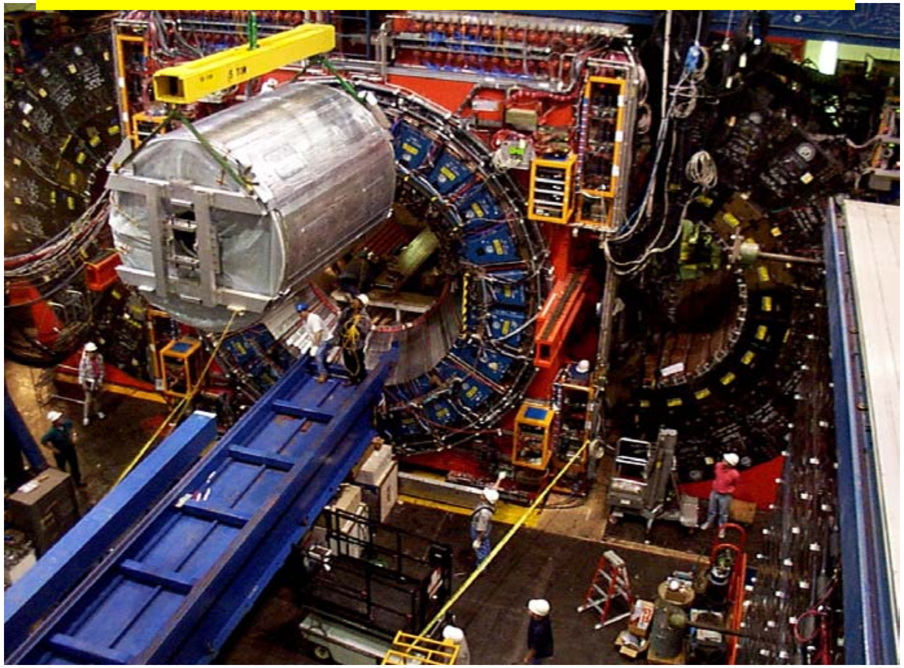
Our friends invested *years* in this Bingo game!



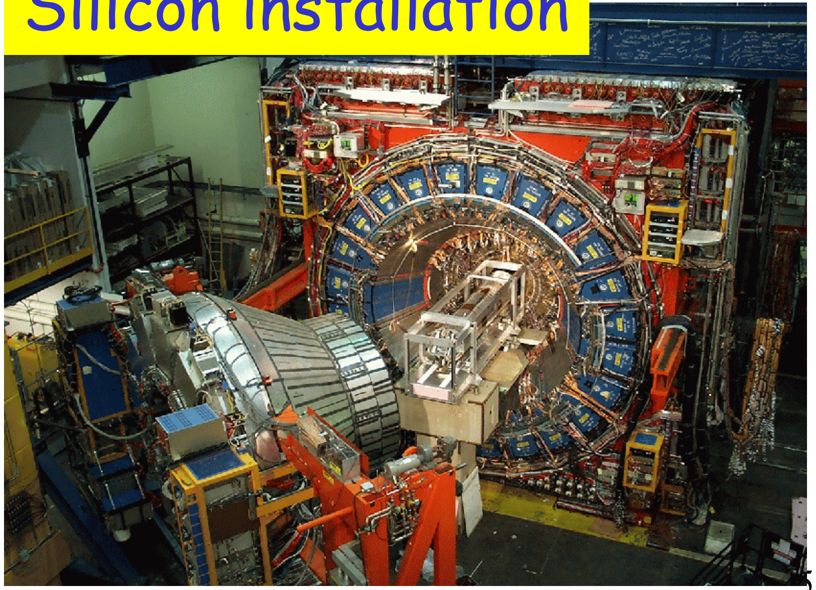
Onward!

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

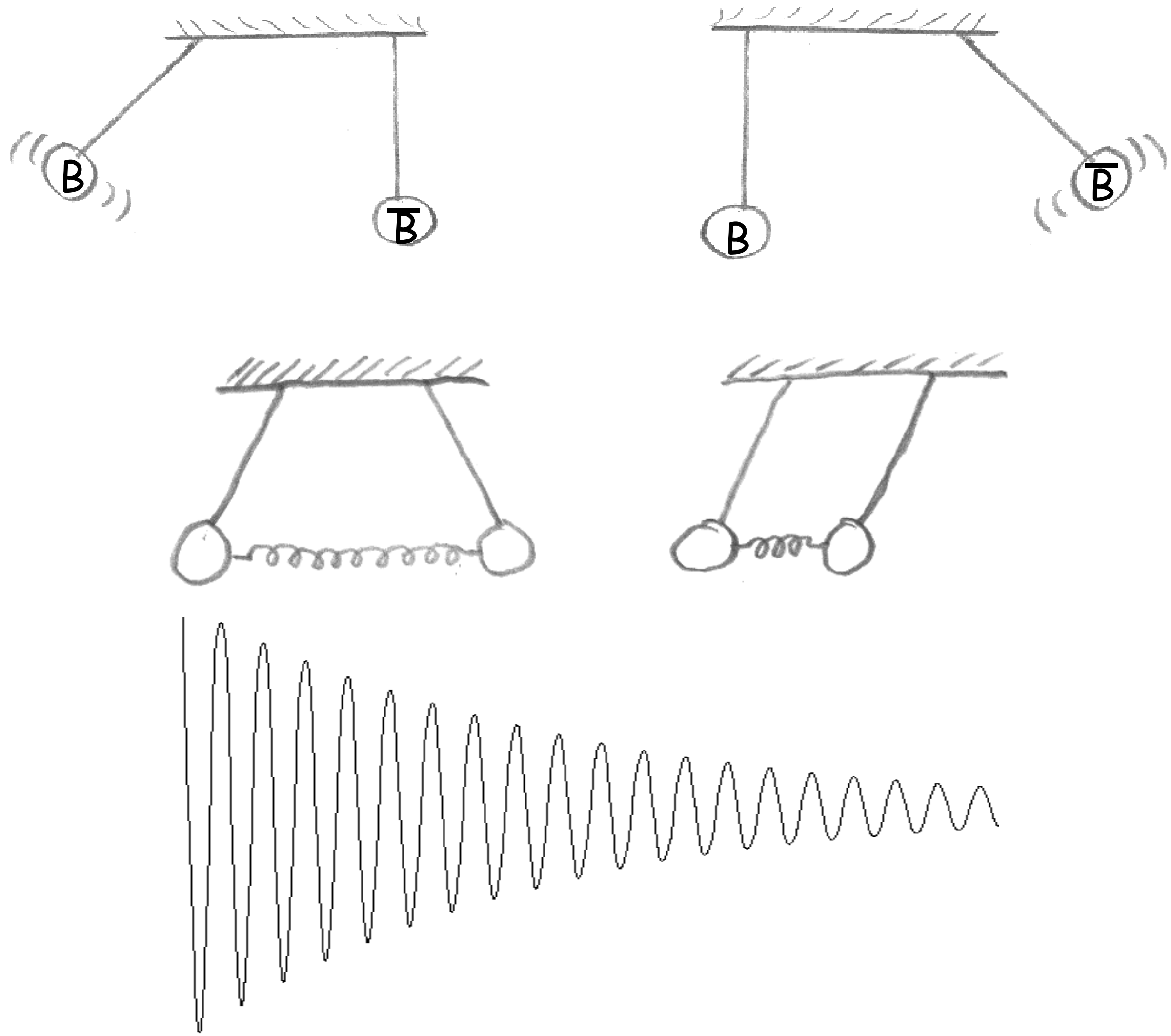
Drift chamber installation



Silicon installation



Mechanical analogue



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

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

Piano tuner uses the same trick

Mixing: simplifications

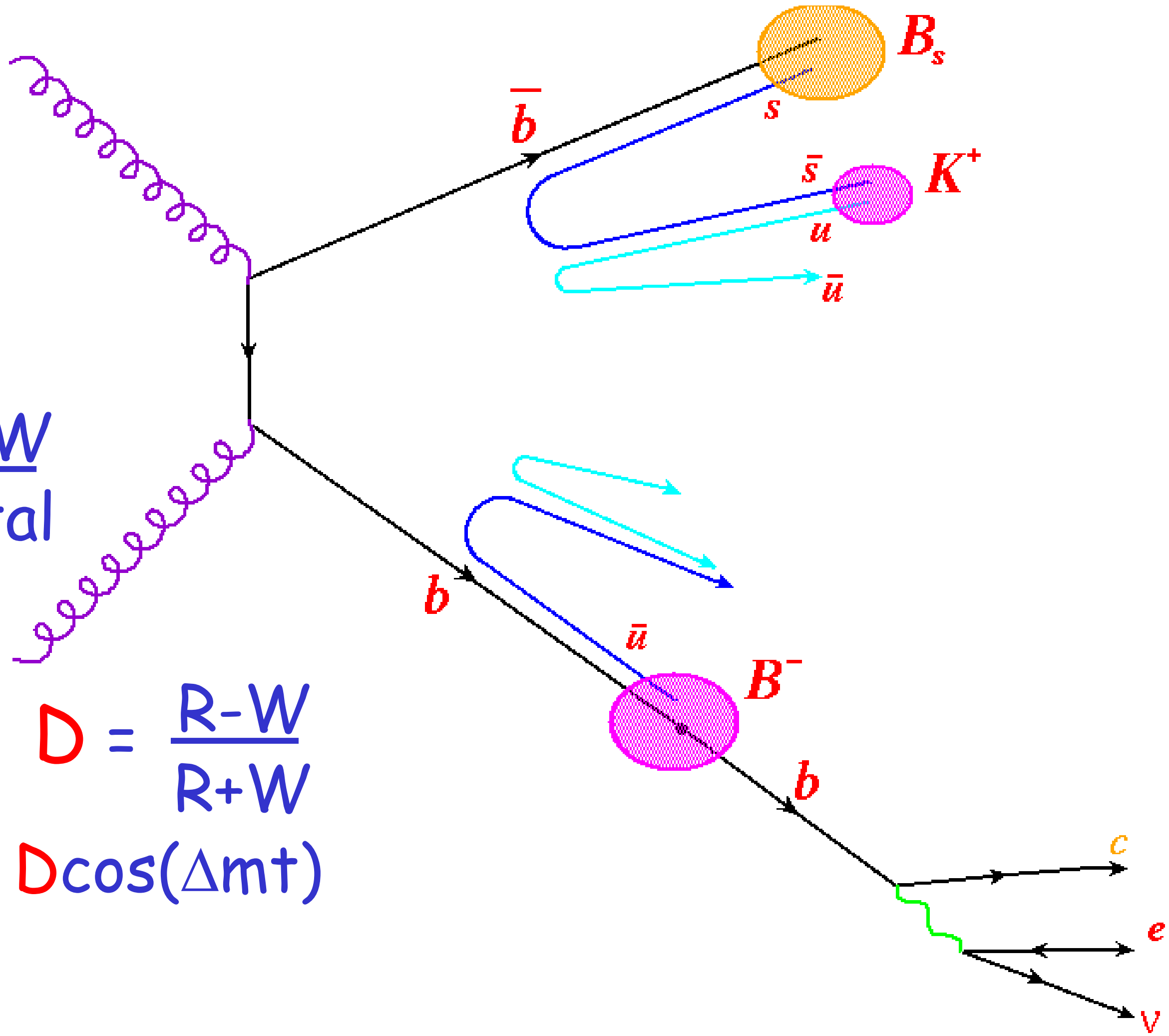
Two important things that I will completely ignore:

(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 $\overline{B}_s$ at t=0

This is an art called "flavor tagging"



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

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

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

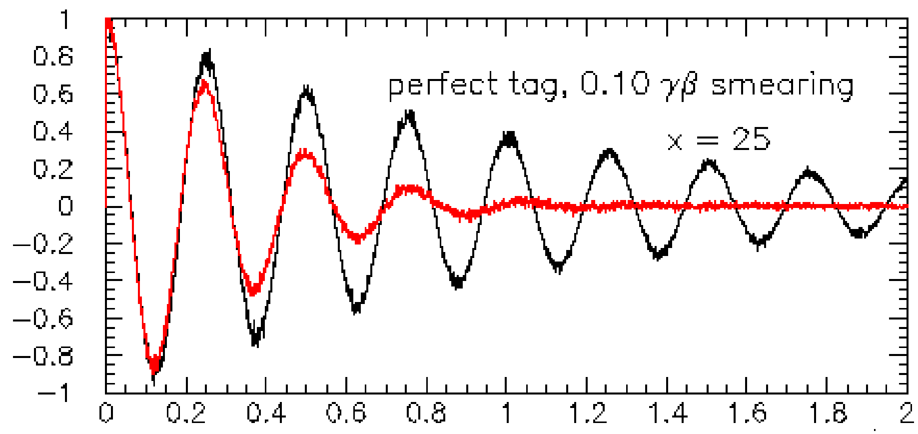
$N \rightarrow \varepsilon D^2 N$

Statistical significance of mixing signal

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

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