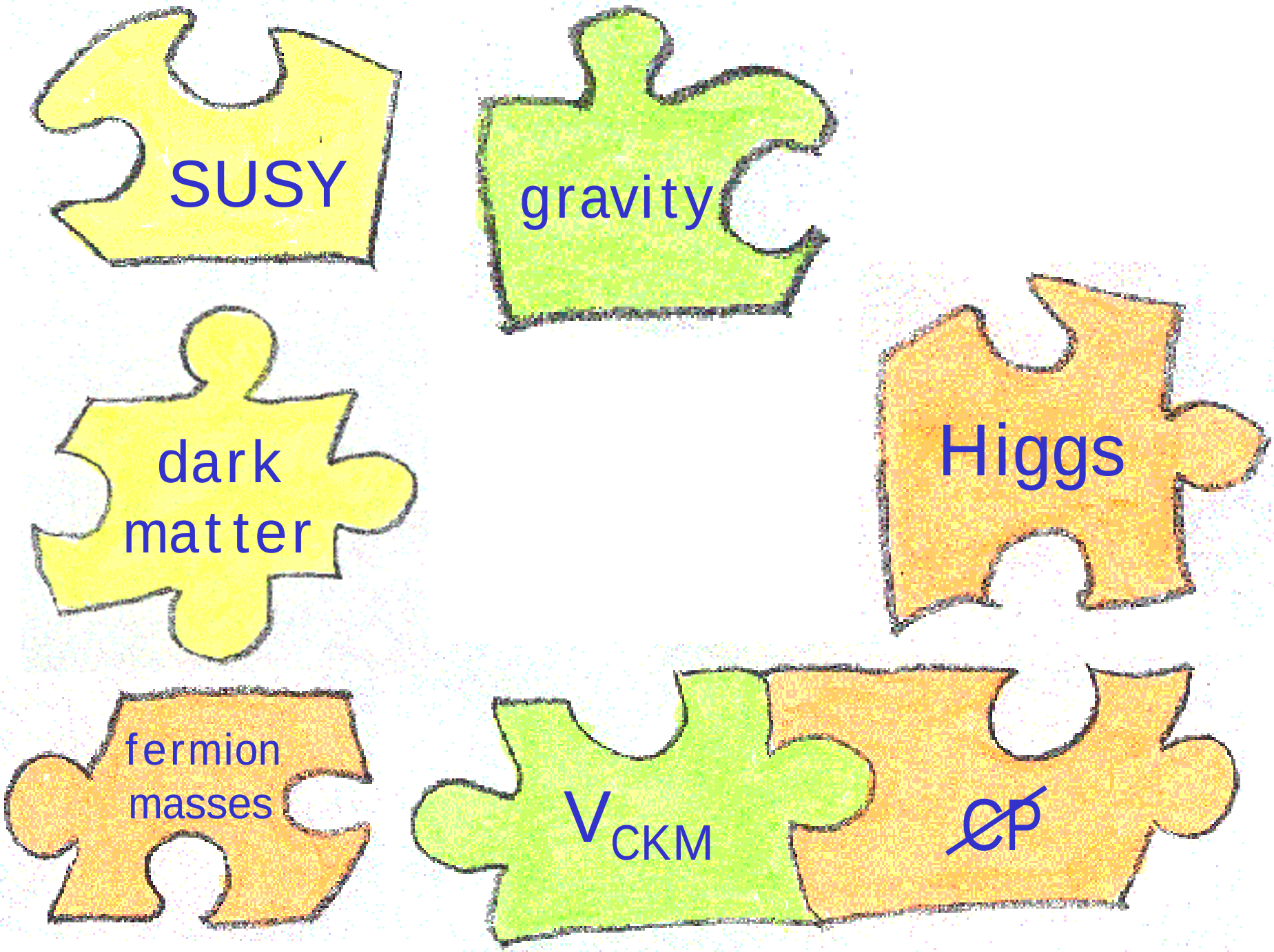
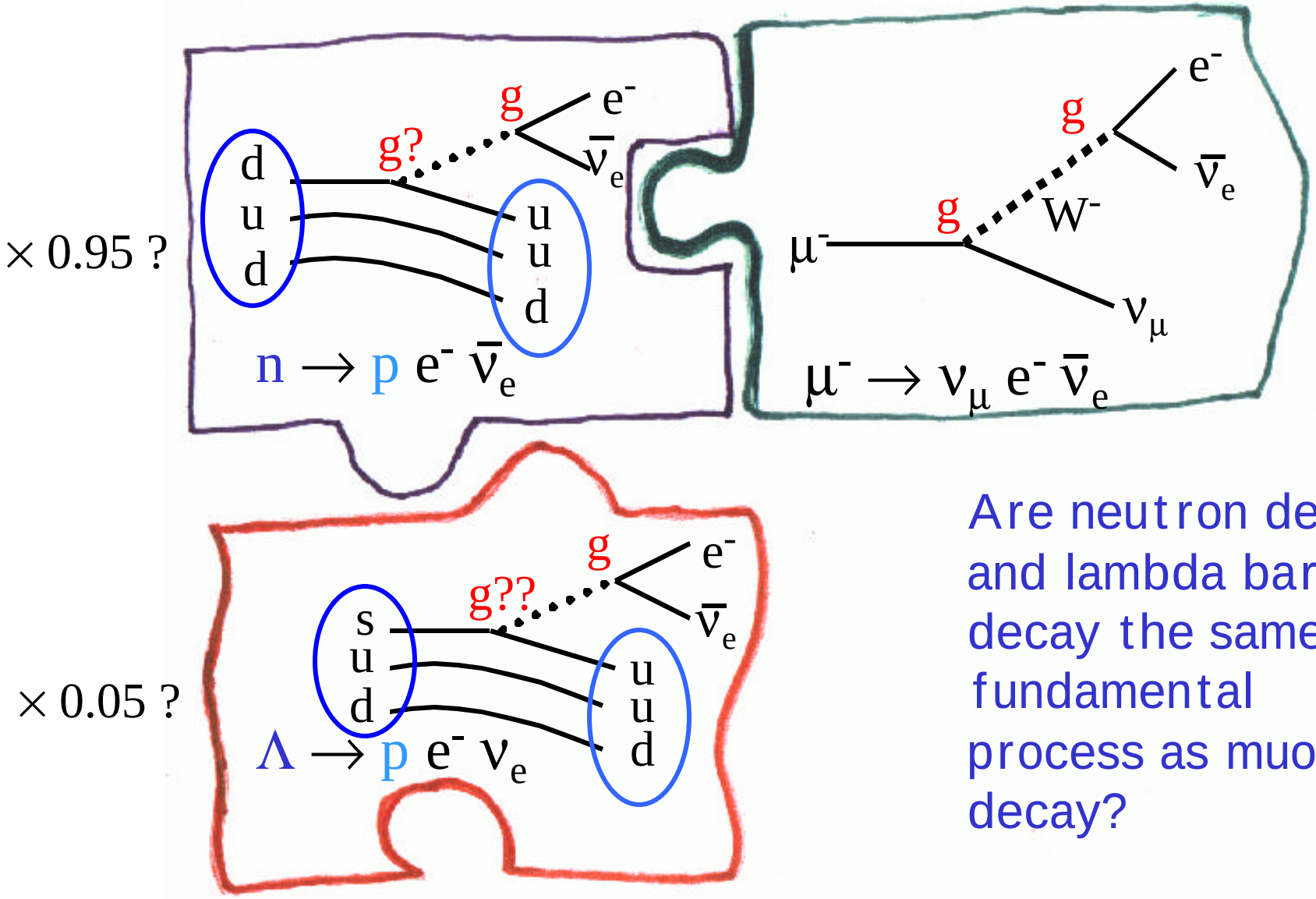
Towards Bs Mixing: the CDF II perspective

Alessandro Cerri, LBNL


SUSY
gravity
dark matter
Higgs
fermion masses
V_{CKM}
$\not{C}\not{P}$

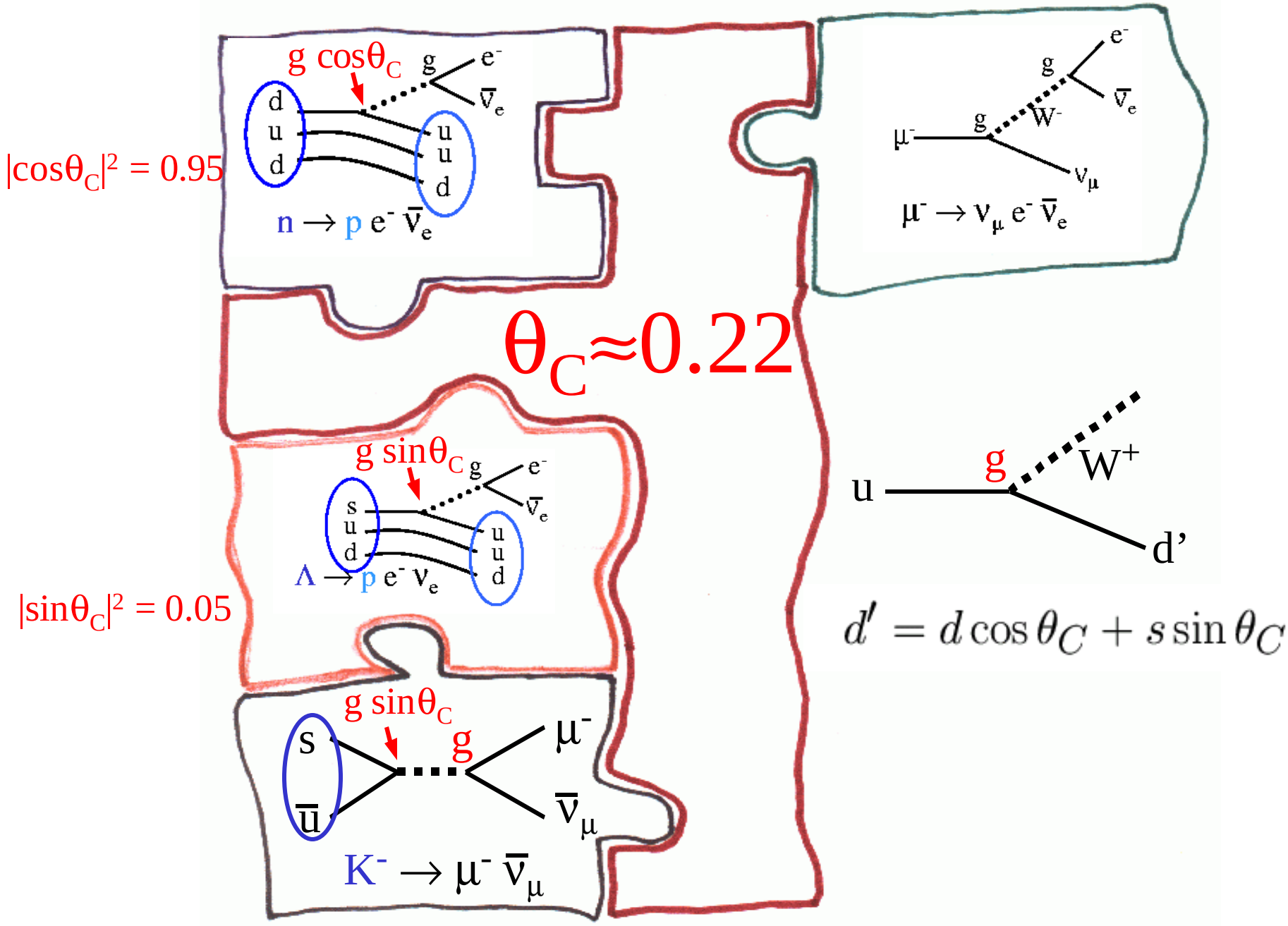
The "indirect" strategy:

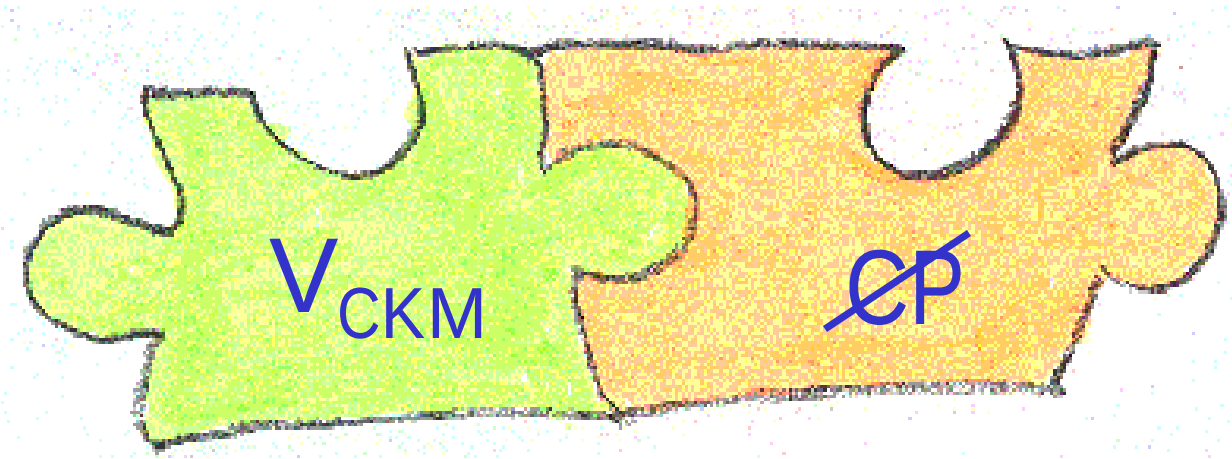
study the known puzzle pieces;
see what's missing or what doesn't fit



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

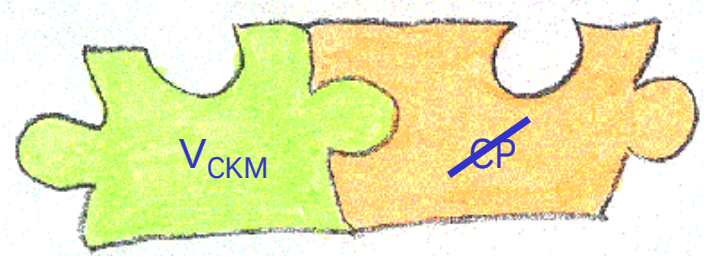
Cabibbo mixing angle was the missing piece




V_{CKM}
$\not{C}\not{P}$

An Arbitrary Choice

- I will not touch several other ways of exploring the edges of our jigsaw puzzle:
  - Charm decays
  - Rare B decays
  - Several other CKM measurements



- Some of those will give results sooner than B_s mixing studies
- In fact some of the results are already public: I will use them in my discussion to clarify some points

Mixing 101

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

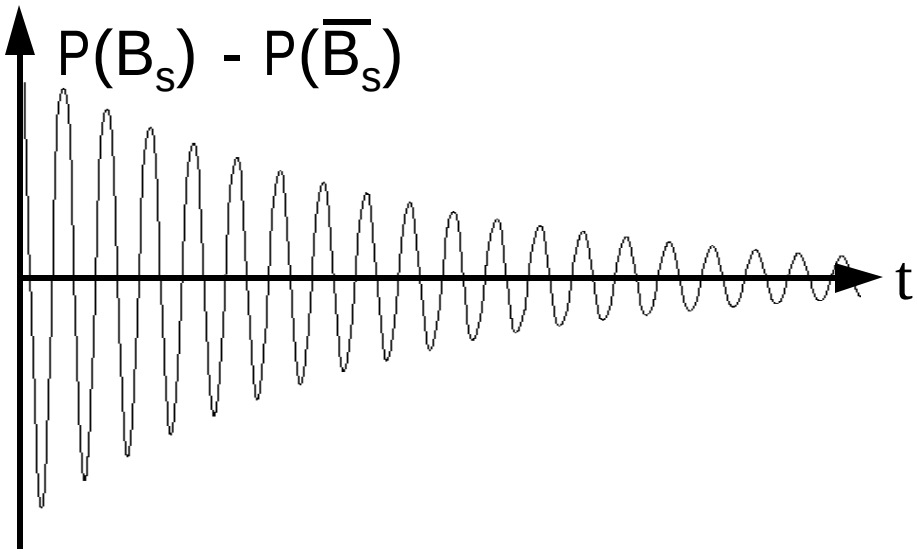
$$|\psi(t)\rangle = |\psi_0\rangle e^{-imt} e^{-\Gamma t/2}$$

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

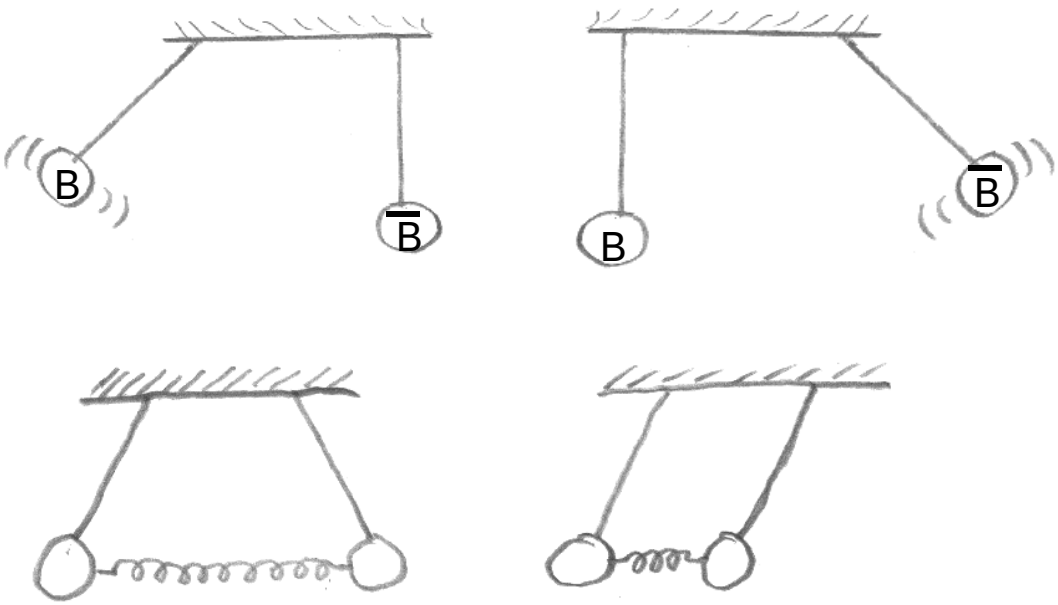
$$|\langle B_s|\psi(t)\rangle|^2 = \frac{1}{2}(1 + \cos(\Delta m t))\, e^{-\Gamma t}$$

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

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

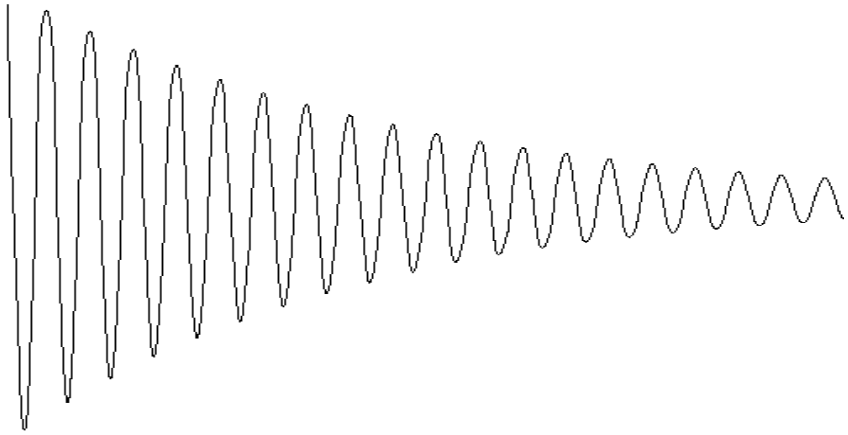
Mechanical analogue

Weak interaction couples states, splits frequencies of normal modes. Weak decay also damps the motion.



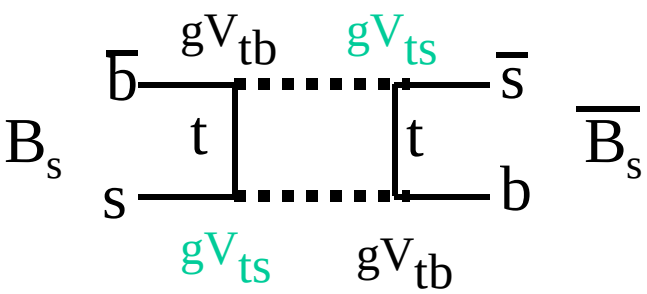
You can measure a frequency difference extremely precisely, by measuring beats.

If x=25, then
$\Delta m/m \sim 2 \cdot 10^{-12}$

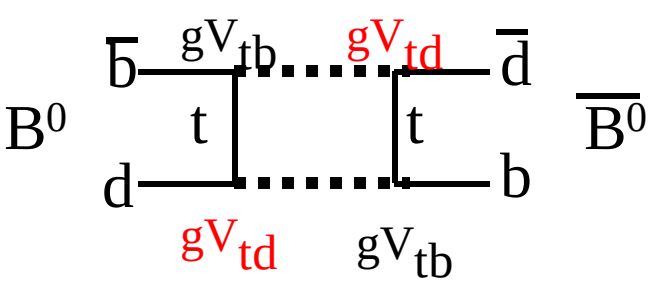


Piano tuner uses the same trick

B_s flavor oscillations



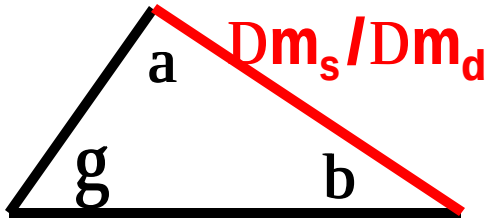
$$\frac{\Delta m_s}{\Delta m_d} \propto \frac{|Vts|^2}{|Vtd|^2}$$



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

Δm_s has never been measured: only lower bounds exist.

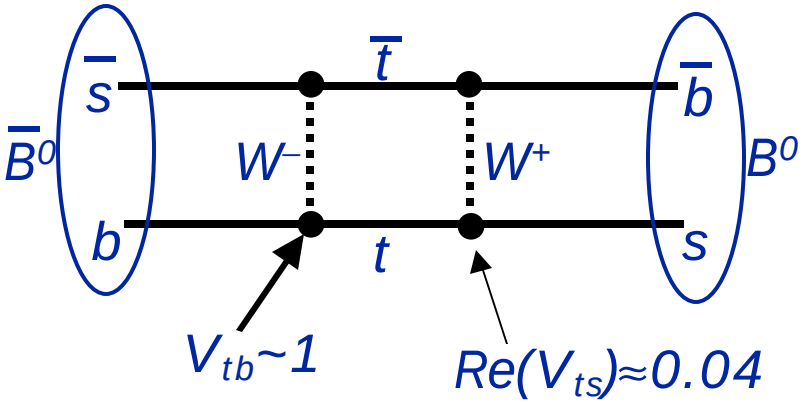
CDF expects to make the first measurement, soon!
To get there, we need lots of ingredients

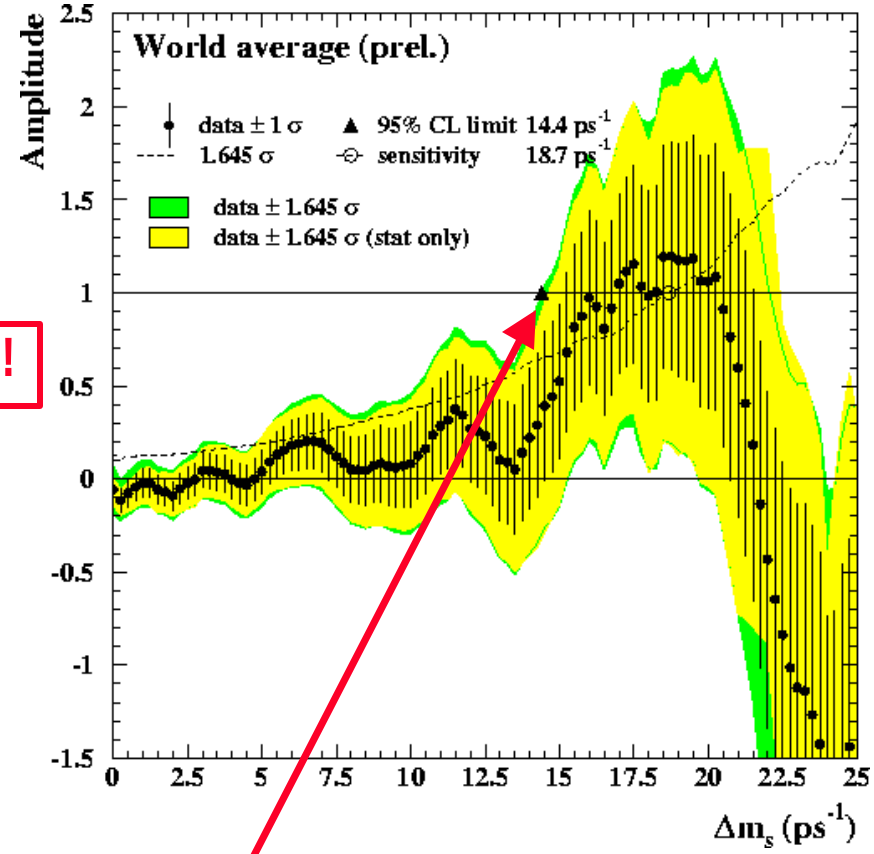


Towards B_s Mixing

- **Measurement of Δm_s helps improve our knowledge of CKM triangle.**
- Combined world limit on B_s mixing
  - $\Delta m_s > 14.4 ps^{-1}$ @95%CL
  - **B_s fully mixes in <0.15 lifetime!!!**
- B_s oscillation much faster than B_d because of coupling to top quark:

$$Re(V_{ts}) \approx 0.040 > Re(V_{td}) \approx 0.007$$





Combined limit comes from 13 measurements from LEP, SLD & CDF Run I

Mixing 101

Proper time resolution

Flavor tagging

Signal-to-noise

Event yield

$$Significance = \sqrt{\frac{S\varepsilon D^2}{2}} e^{-\frac{(\Delta m_s s_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

- Significance (in number of standard deviations) is “average significance”

Event Collection

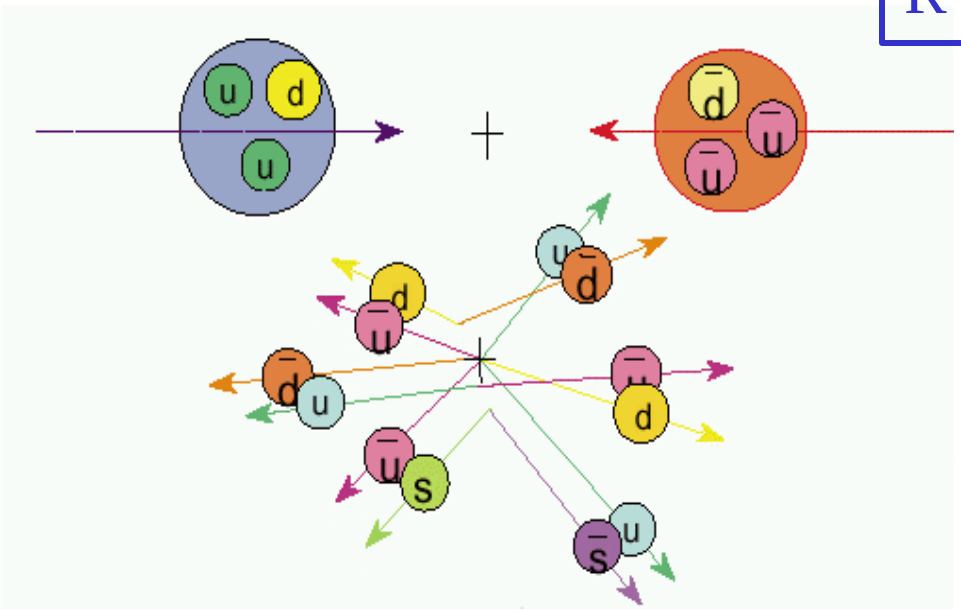
$$Significance = \sqrt{\frac{S e D^2}{2}} e^{-\frac{(\Delta m_s s_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

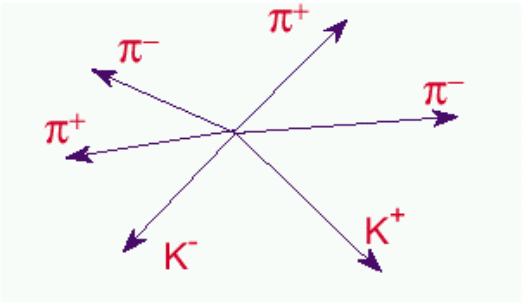
Why do you need a trigger?

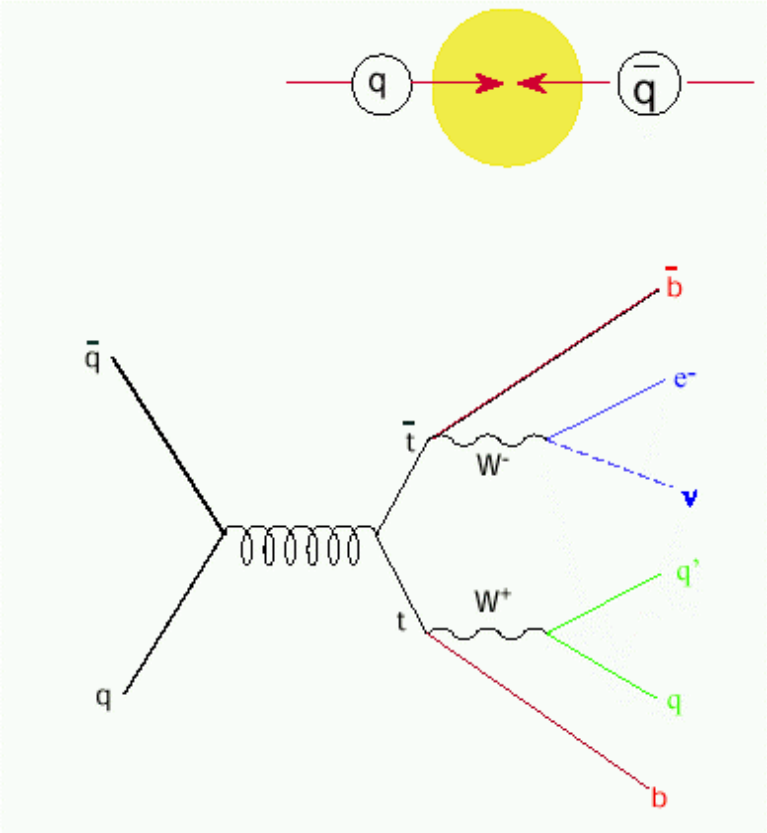
Haystack

R-Z view

Needle





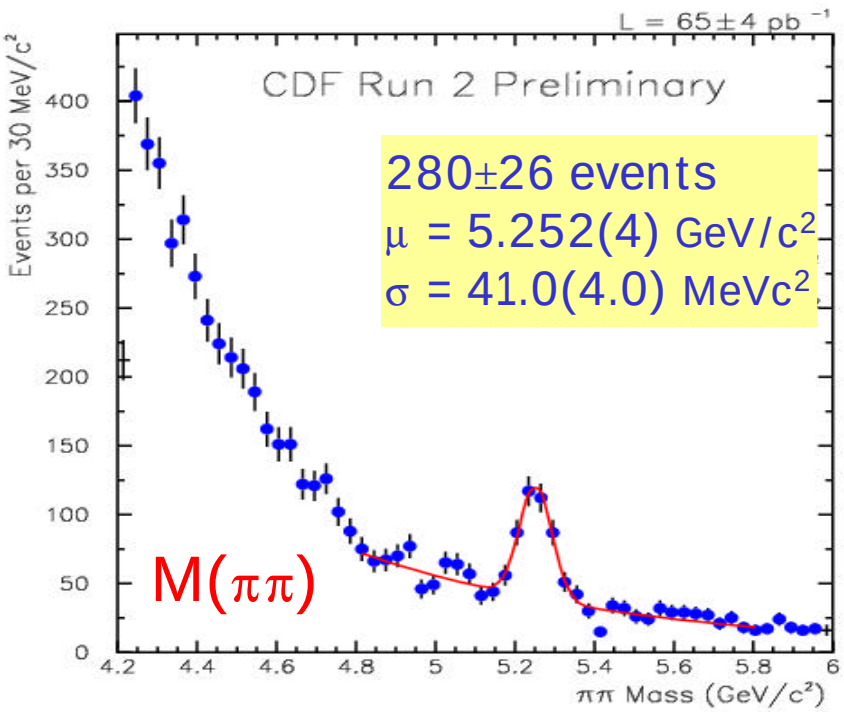


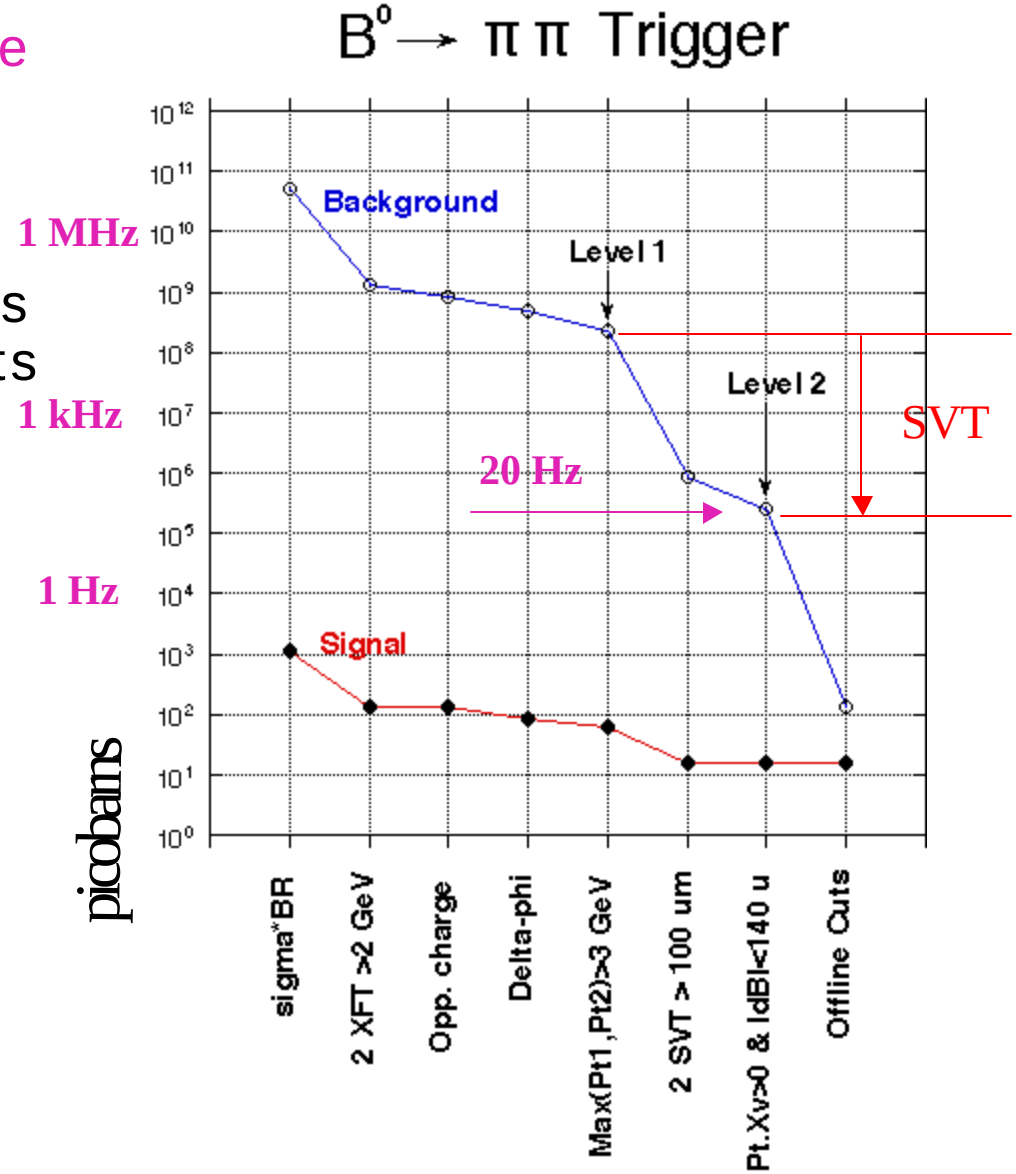
Vast majority of collisions; a democratic trigger would see only this

´1010 less frequent: top quark pair production**

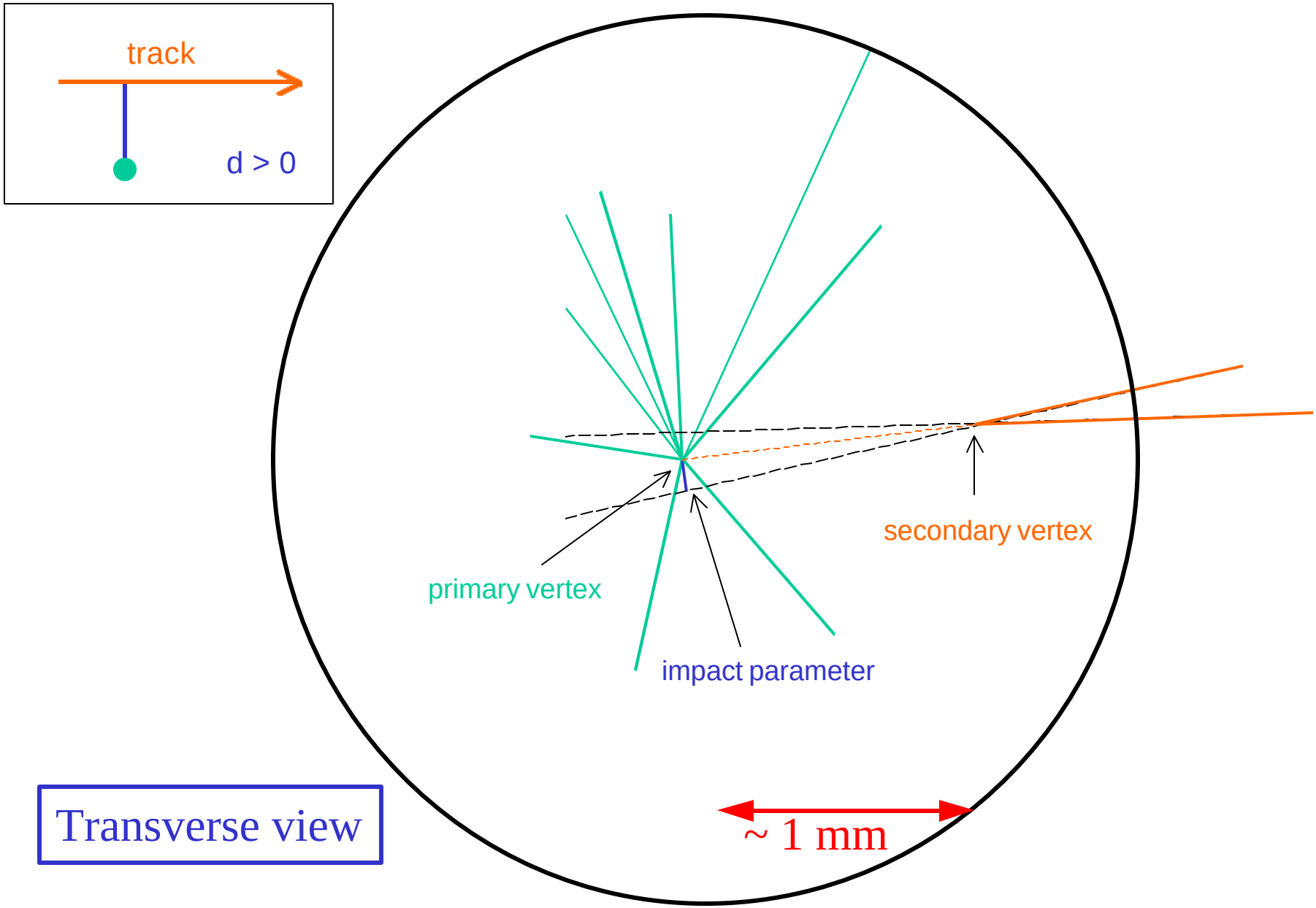
A "0 to 100" example: SVT for $B^0 \rightarrow \pi^+\pi^-$

- SVT reduces the background rate by a factor of 1000
  - data recording possible by DAQ
  - This means going from 0 events in 110pb^{-1} (CDF I) to 300 events in 65pb^{-1} (CDF II)





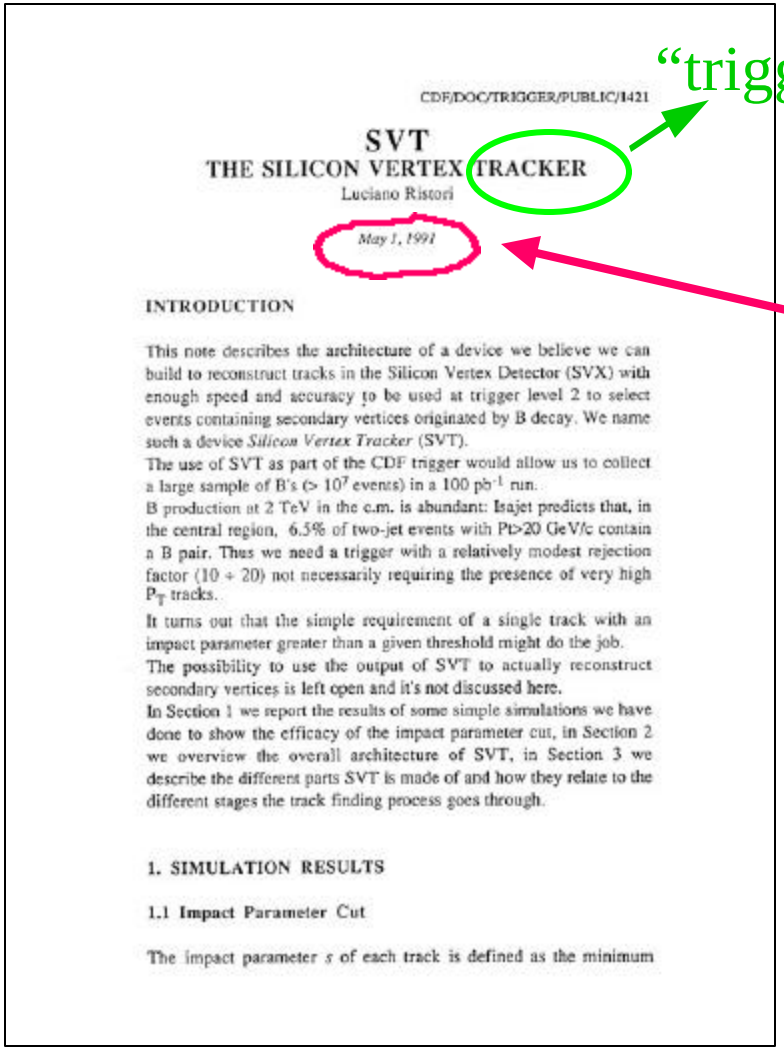
A salient property of b,c decays: lifetime



Transverse view

Introducing … S V T

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



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 ÷ 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

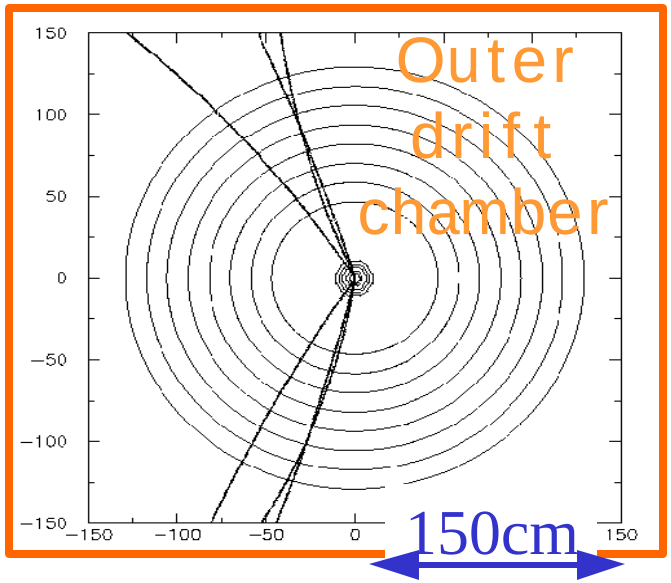
The impact parameter s of each track is defined as the minimum

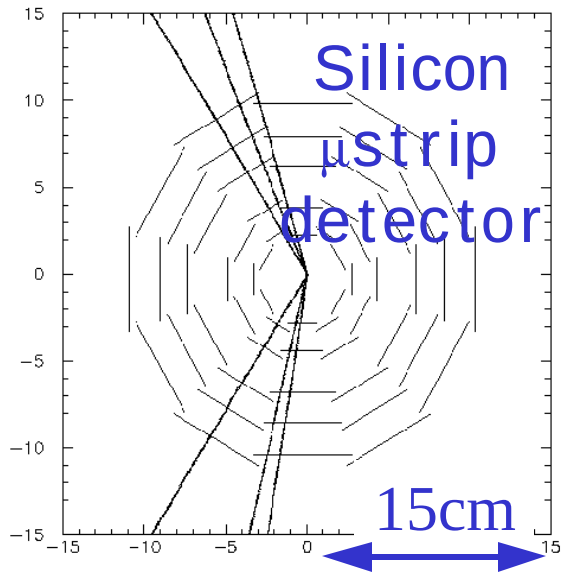
"trigger"

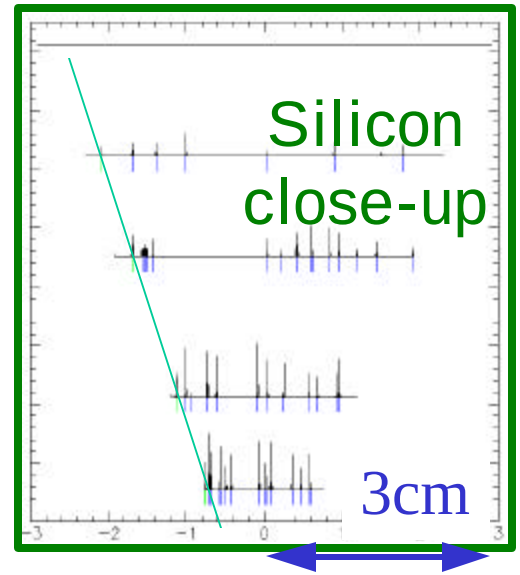
CDF Note 1421
by L. Ristori

May 1st, 1991

Problem synopsis







Input (every incoming event):

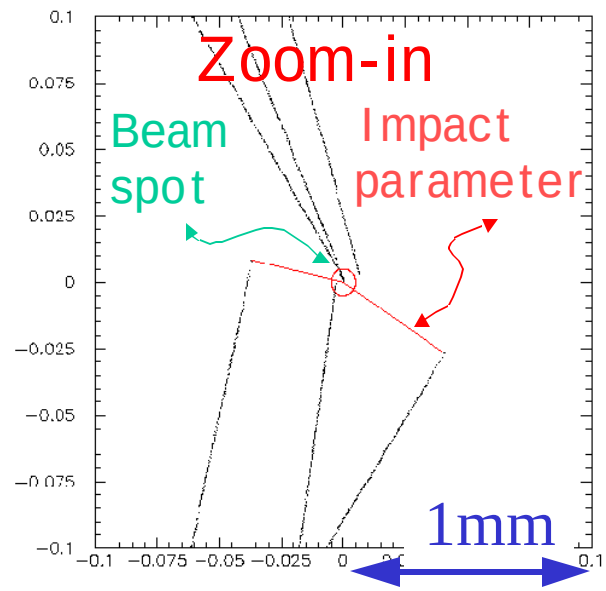
outer drift chamber trajectories

silicon pulse height for each channel

Output (about 20 microseconds later):

trajectories that use silicon points

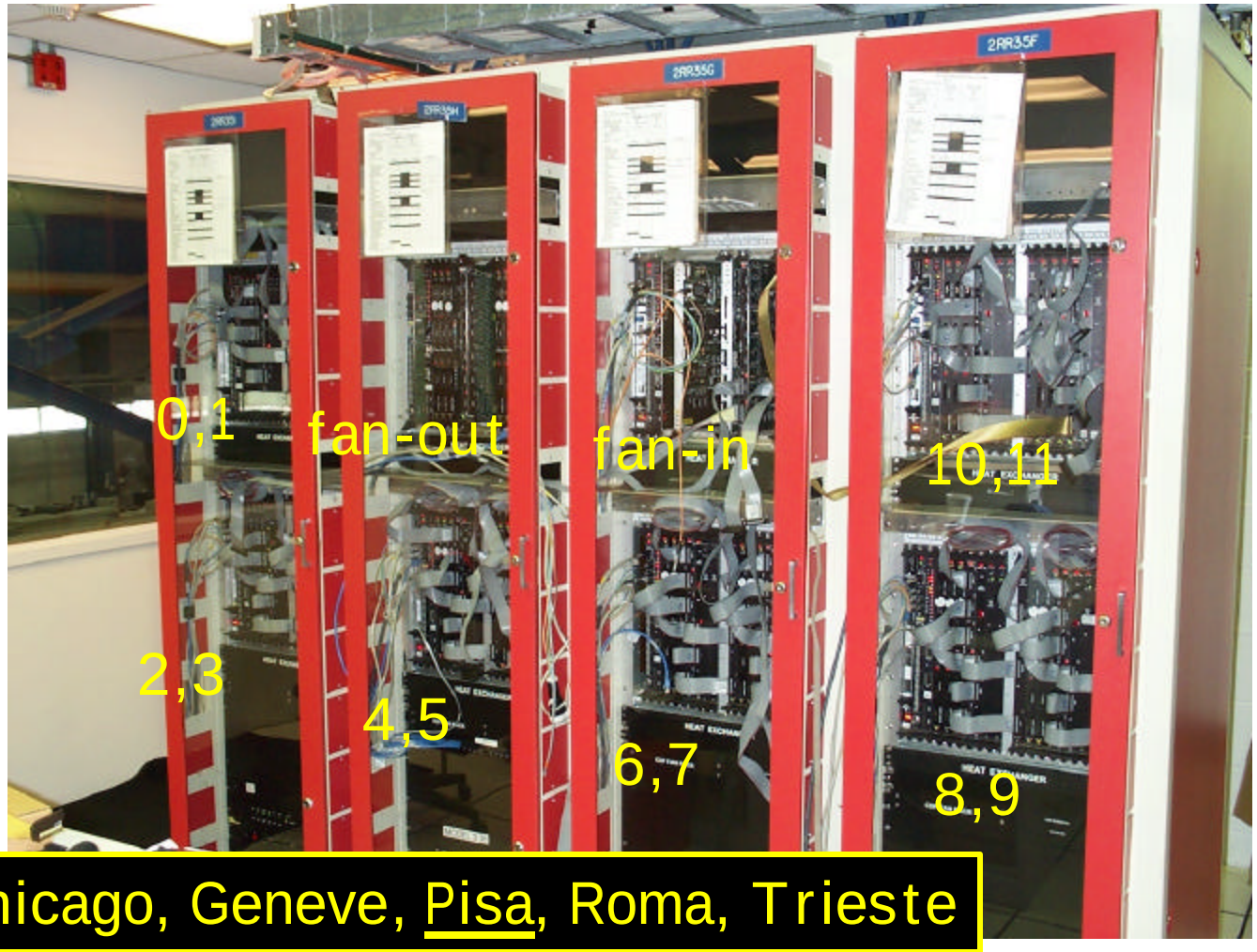
impact parameter: $\sigma(d)=35um$



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

SVT data volume requires parallelism



Chicago, Geneve, Pisa, Roma, Trieste

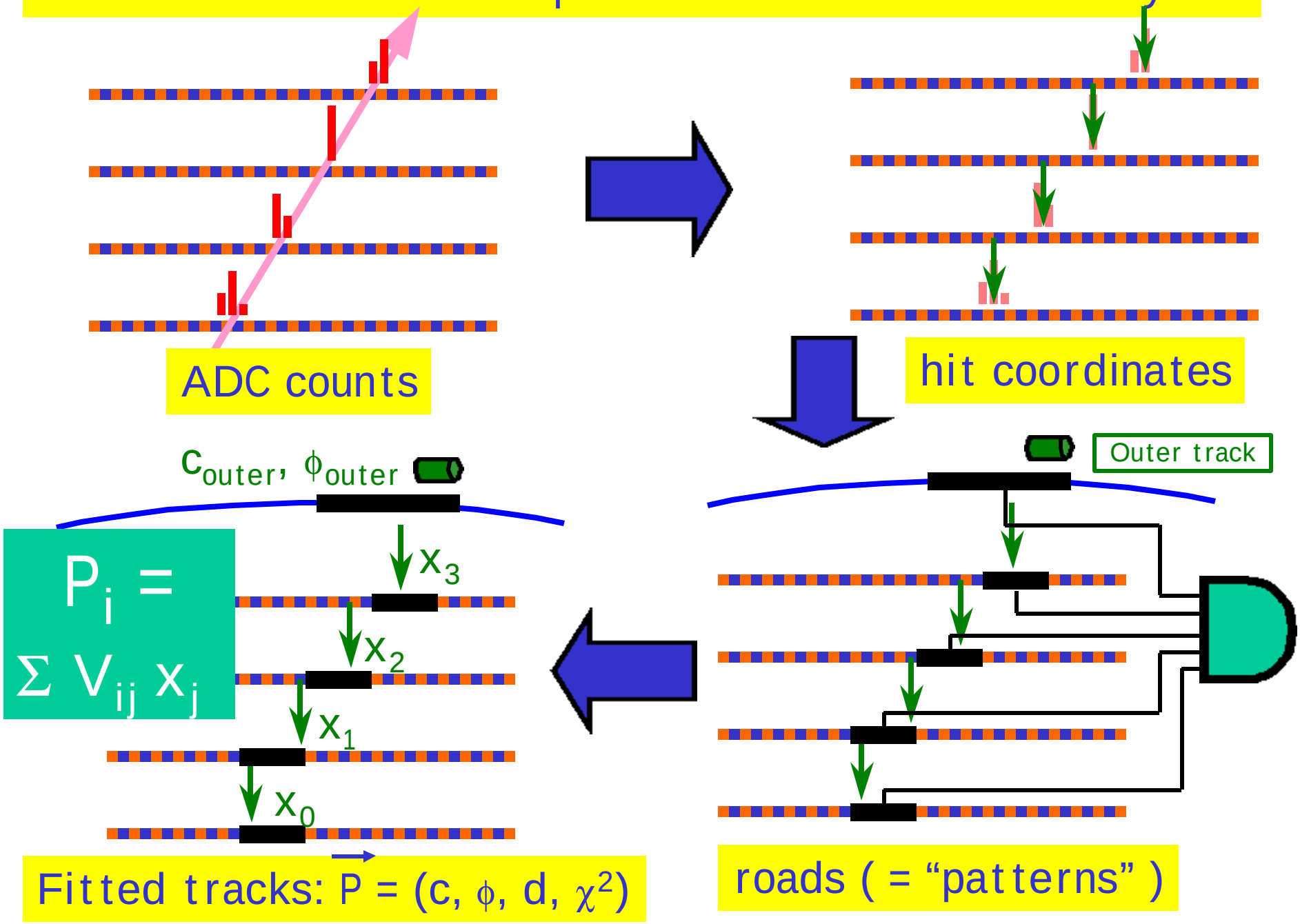
Reduces gigabytes/second to megabytes/second

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

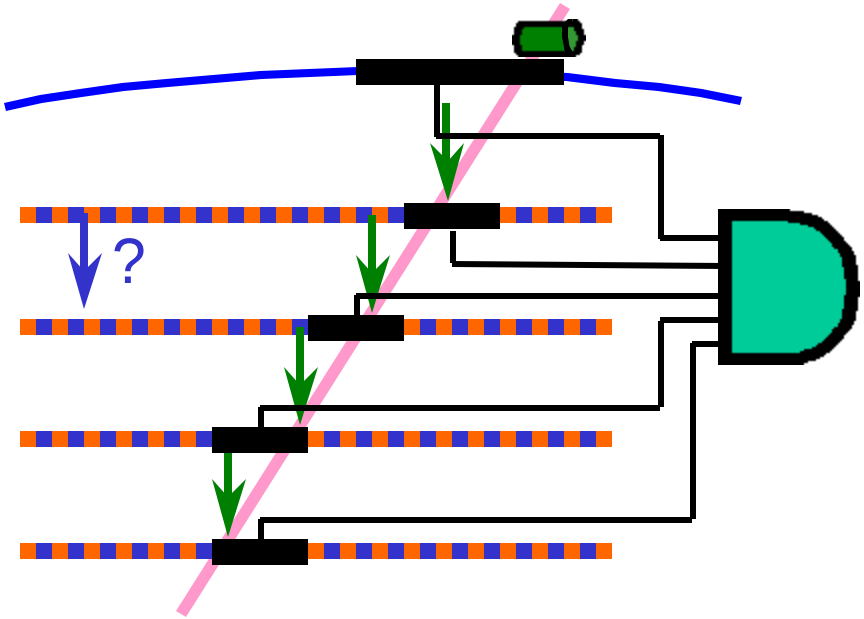
2

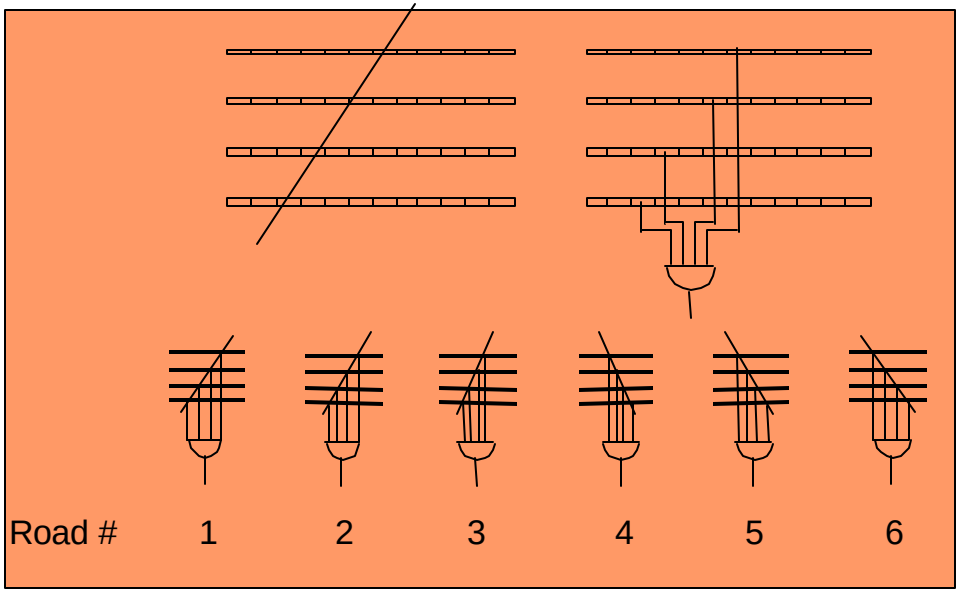
eters

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



2nd trick: streamlined track finding





- The way we find tracks is a cross between
  - searching predefined roads
  - playing BINGO
- Time ~ $A*N_{hits} + B*N_{matchedroads}$

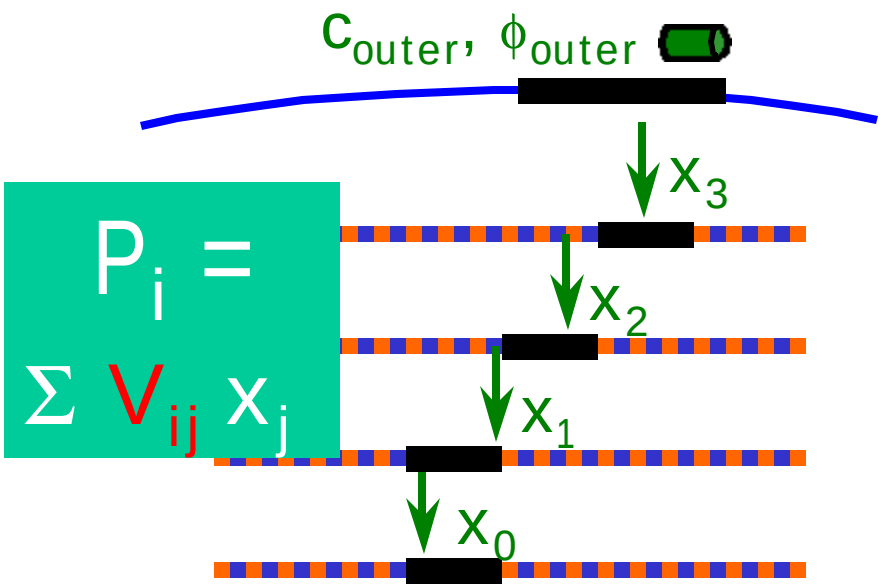
B	I	N	G	O
2	17	35	48	61
10	21	39	53	66
14	20	free	55	65
8	25	41	52	62
6	16	37	46	67

Trick #3: linear fit

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

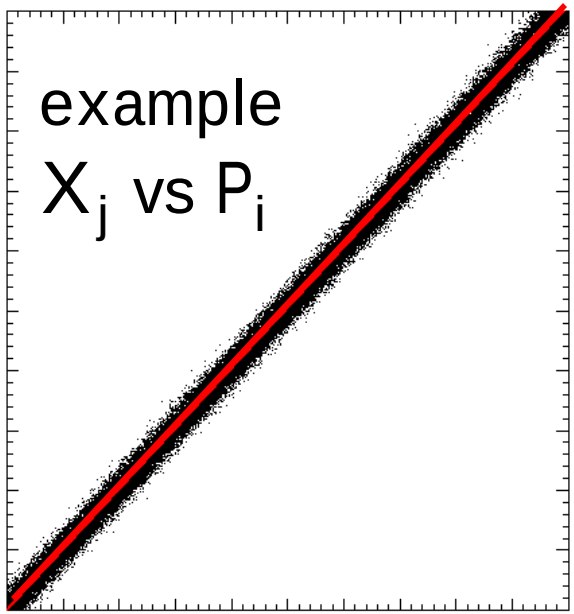
$\vec{x}$ not in general linear in $\vec{P}$

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



$$P_i = \Sigma V_{ij} x_j$$

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



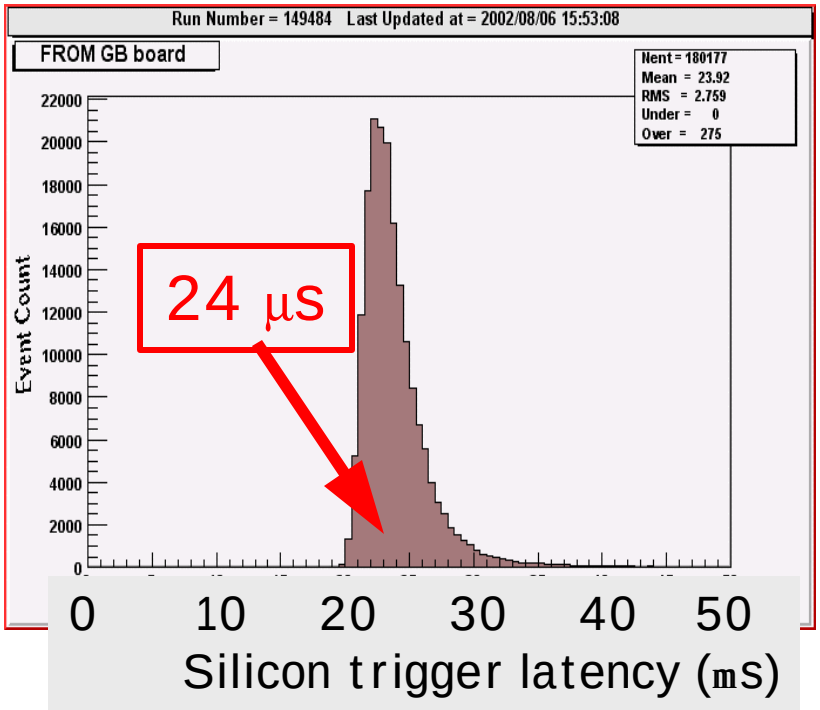
We derive V_{ij} by linear regression to Monte Carlo data

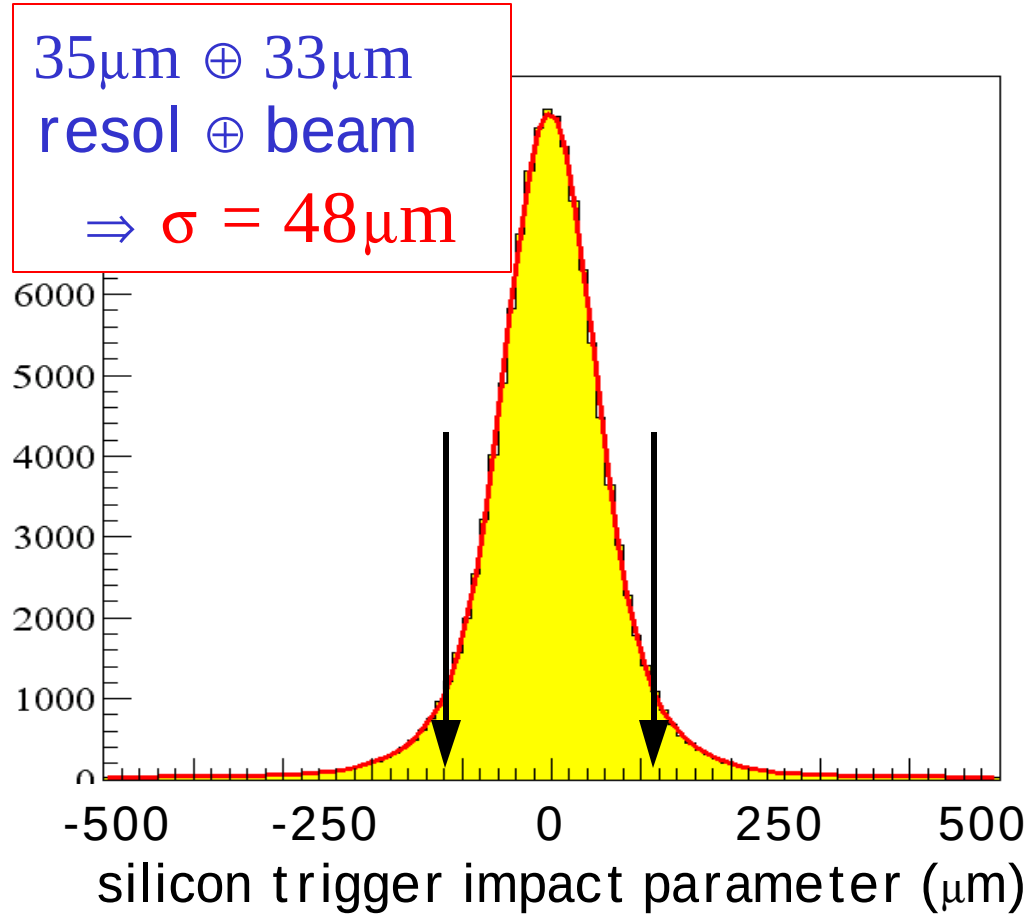
<u>Trick #3a</u>: use road as a hint

precompute $V_{ij} X_j^{road}$

⇒ 250 nsec per fit !

Success !



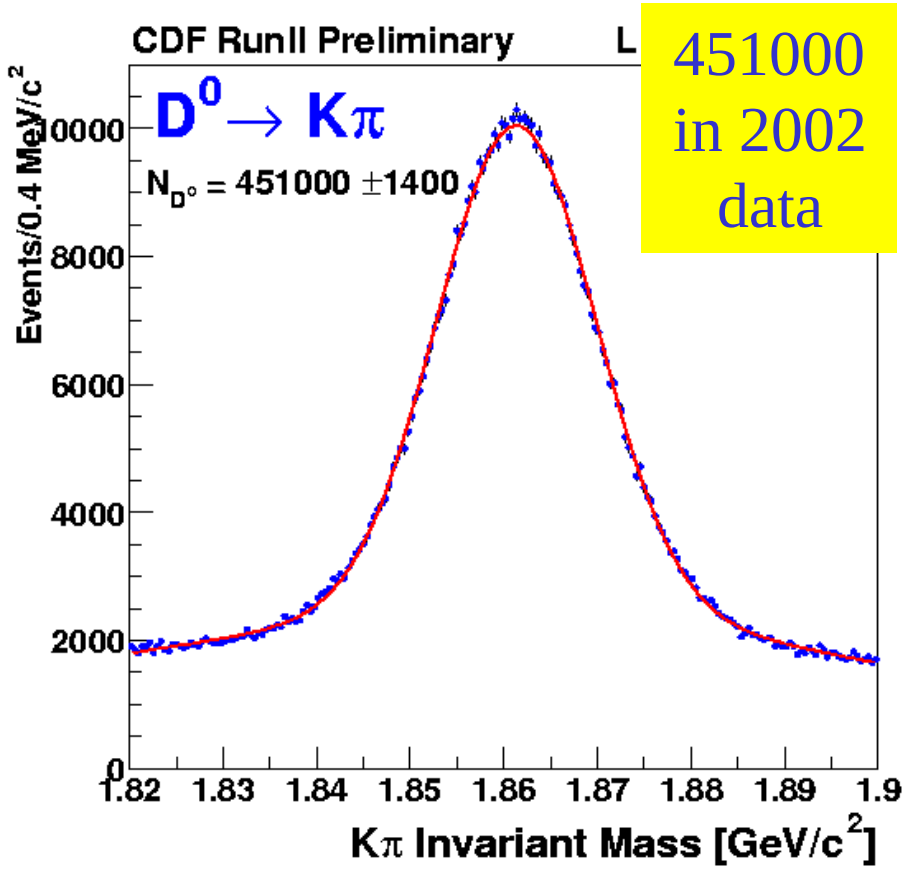


4 orders of magnitude faster than software

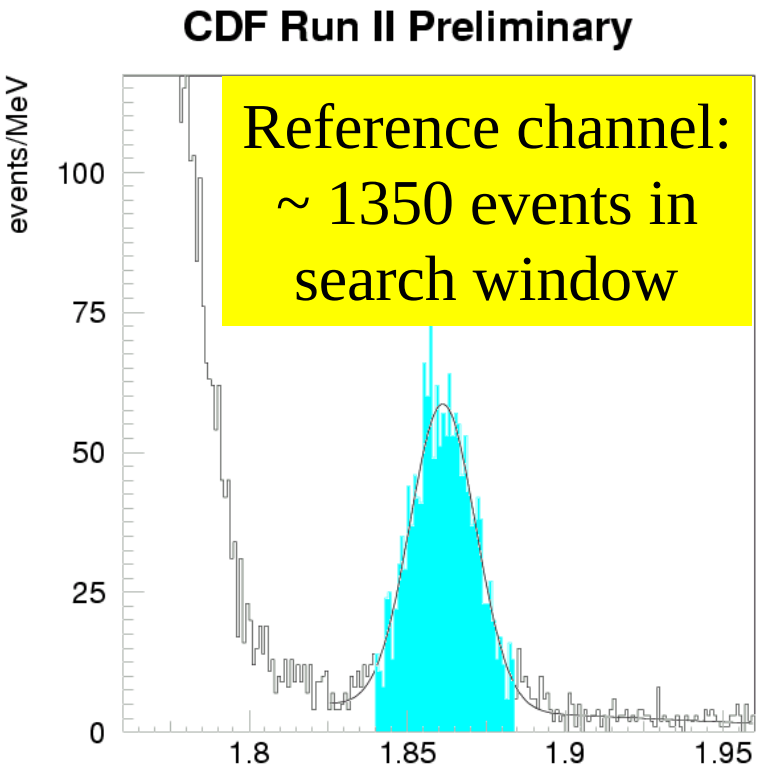
comparable resolution

Large charm signals

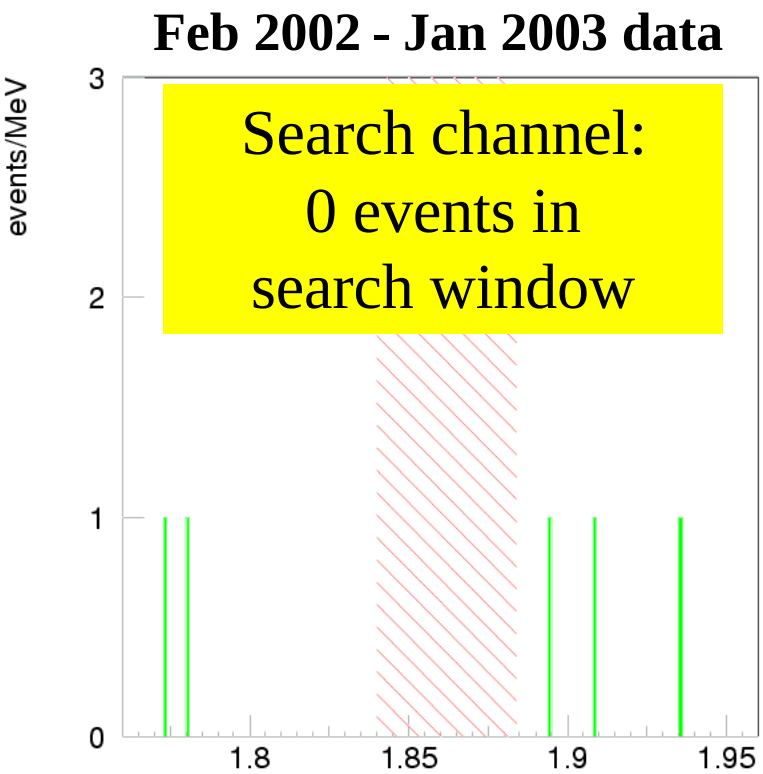
- CDF will reconstruct about 10^7 charm decays in a few years' data (2 fb^{-1})
  - year 2002 (0.07 fb^{-1}) already 3x sample of FOCUS experiment
  - already collecting more per year than B factory experiments



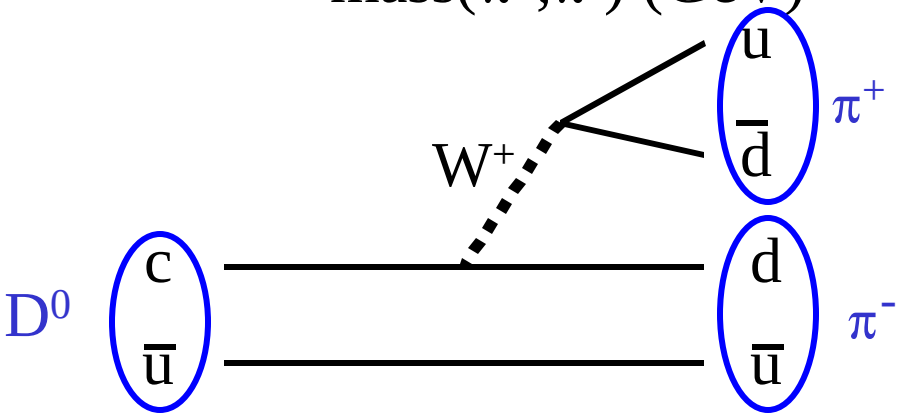
451000 in 2002 data



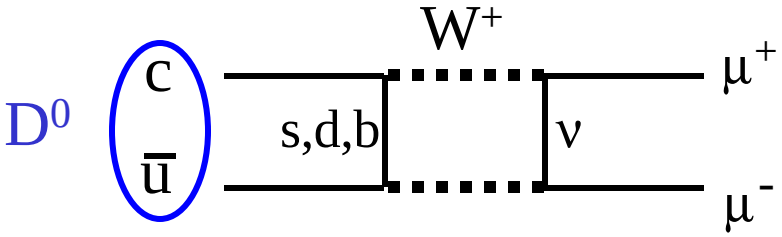
mass(π^+,π^-) (GeV)



mass(μ^+,μ^-) (GeV)



standard model rate ~ 10^{-3}



standard model rate ~ 10^{-13}

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

– Putting the numbers together,

Poisson statistics

Reference branching ratio

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

New limit

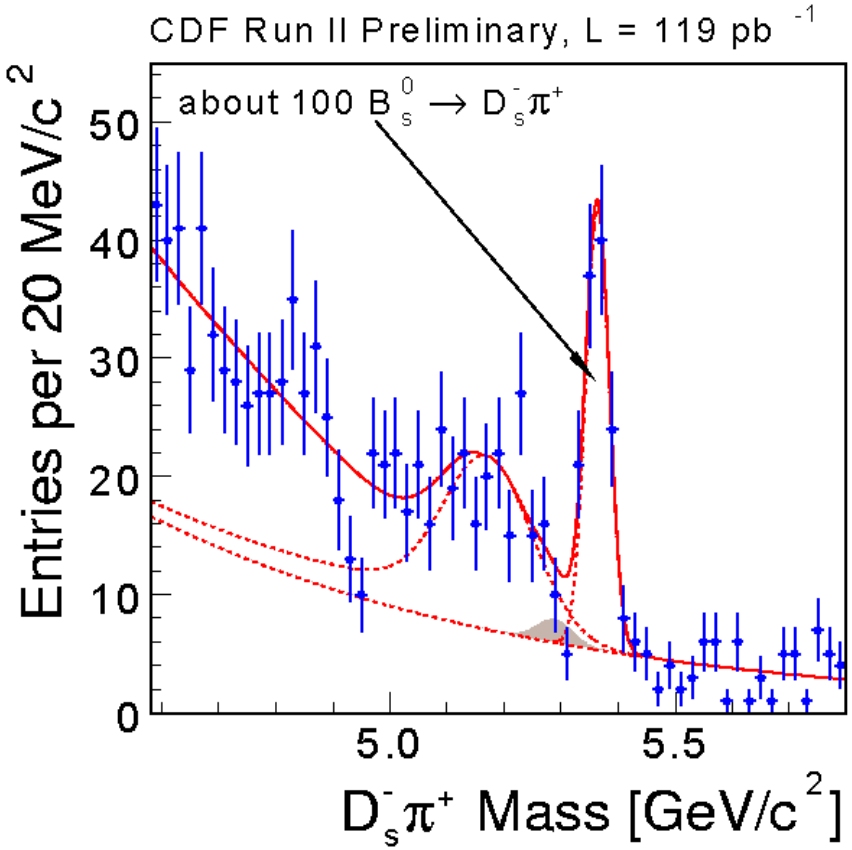
Reference event count

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

– Previous experiment's limit was 4.1×10^{-6} @ 90% CL.

– We should at least ~ triple our data sample this year

We finally see it!



$$BR(B_s \to D_s\, p^{\pm}) = (\,4.8 \pm 1.2 \pm 1.8 \pm 0.8 \pm 0.6)\ \acute{}\ 10^{-3}$$

(Stat) (BR) (sys) (f_s/f_d)

New measurement !

Previous limit set by OPAL: BR ($B_s \to D_s\ \pi^{\pm}$) < 13%

B_s^0 DECAY MODES

These branching fractions all scale with $B(\bar{b} \to B_s^0)$, the LEP B_s^0 production fraction. The first four were evaluated using $B(\bar{b} \to B_s^0) = (10.7 \pm 1.4)\%$ and the rest assume $B(\bar{b} \to B_s^0) = 12\%$.

The branching fraction $B(B_s^0 \to D_s^- \ell^+ \nu_\ell \text{anything})$ is not a pure measurement since the measured product branching fraction $B(\bar{b} \to B_s^0) \times B(B_s^0 \to D_s^- \ell^+ \nu_\ell \text{anything})$ was used to determine $B(\bar{b} \to B_s^0)$, as described in the note on "Production and Decay of b-Flavored Hadrons."

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	D_s^- anything		(94 ± 30) %	
Γ_2	$D_s^- \ell^+ \nu_\ell$ anything	[a]	(7.9 ± 2.4) %	
Γ_3	$D_s^- \pi^+$		< 13 %	
Γ_4	$D_s(*)+ D_s(*)-$		$(23\ ^{+21}_{-13})$ %	
Γ_5	$J/\psi(1S)\phi$		$(9.3 \pm 3.3) \times 10^{-4}$	
Γ_6	$J/\psi(1S)\pi^0$		$< 1.2 \times 10^{-3}$	90%
Γ_7	$J/\psi(1S)\eta$		$< 3.8 \times 10^{-3}$	90%
Γ_8	$\psi(2S)\phi$		seen	
Γ_9	$\pi^+\pi^-$		$< 1.7 \times 10^{-4}$	90%
Γ_{10}	$\pi^0\pi^0$		$< 2.1 \times 10^{-4}$	90%
Γ_{11}	$\eta\pi^0$		$< 1.0 \times 10^{-3}$	90%
Γ_{12}	$\eta\eta$		$< 1.5 \times 10^{-3}$	90%
Γ_{13}	$\rho^0\rho^0$		$< 3.20 \times 10^{-4}$	90%
Γ_{14}	$\phi\rho^0$		$< 6.17 \times 10^{-4}$	90%
Γ_{15}	$\phi\phi$		$< 1.183 \times 10^{-3}$	90%
Γ_{16}	π^+K^-		$< 2.1 \times 10^{-4}$	90%
Γ_{17}	K^+K^-		$< 5.9 \times 10^{-5}$	90%
Γ_{18}	$\overline{K}^*(892)^0\rho^0$		$< 7.67 \times 10^{-4}$	90%
Γ_{19}	$\overline{K}^*(892)^0 K^*(892)^0$		$< 1.681 \times 10^{-3}$	90%
Γ_{20}	$\phi K^*(892)^0$		$< 1.013 \times 10^{-3}$	90%
Γ_{21}	$p\overline{p}$		$< 5.9 \times 10^{-5}$	90%
Γ_{22}	$\gamma\gamma$		$< 1.48 \times 10^{-4}$	90%
Γ_{23}	$\phi\gamma$		$< 1.2 \times 10^{-4}$	90%
	Lepton Family number (LF) violating modes or $\Delta B = 1$ weak neutral current ($B1$) modes			
Γ_{24}	$\mu^+\mu^-$	$B1$	$< 2.0 \times 10^{-6}$	90%
Γ_{25}	e^+e^-	$B1$	$< 5.4 \times 10^{-5}$	90%
Γ_{26}	$e^\pm\mu^\mp$	LF [b]	$< 6.1 \times 10^{-6}$	90%
Γ_{27}	$\phi(1020)\mu^+\mu^-$	$B1$	$< 4.7 \times 10^{-5}$	90%
Γ_{28}	$\phi\nu\overline{\nu}$	$B1$	$< 5.4 \times 10^{-3}$	90%

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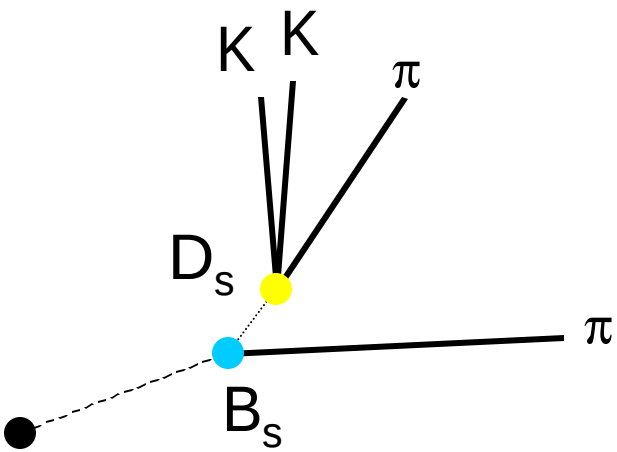
Resolutions

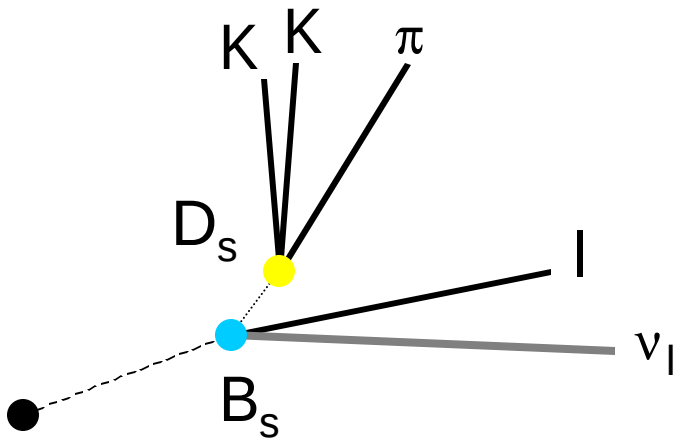
$$Significance = \sqrt{\frac{SeD^2}{2}} e^{-\frac{(\Delta m_s s_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

Strategies

$B_s \to \pi D_s$



$B_s \to l \nu_l D_s$



$$ct = \frac{L_{xy}}{(b\,g)} = \frac{L_{xy} m_B}{p_T}$$

$$s_{ct} = \frac{m_B}{p_T} s_{L_{xy}} \oplus ct\left(\frac{s_{p_T}}{p_T}\right)$$

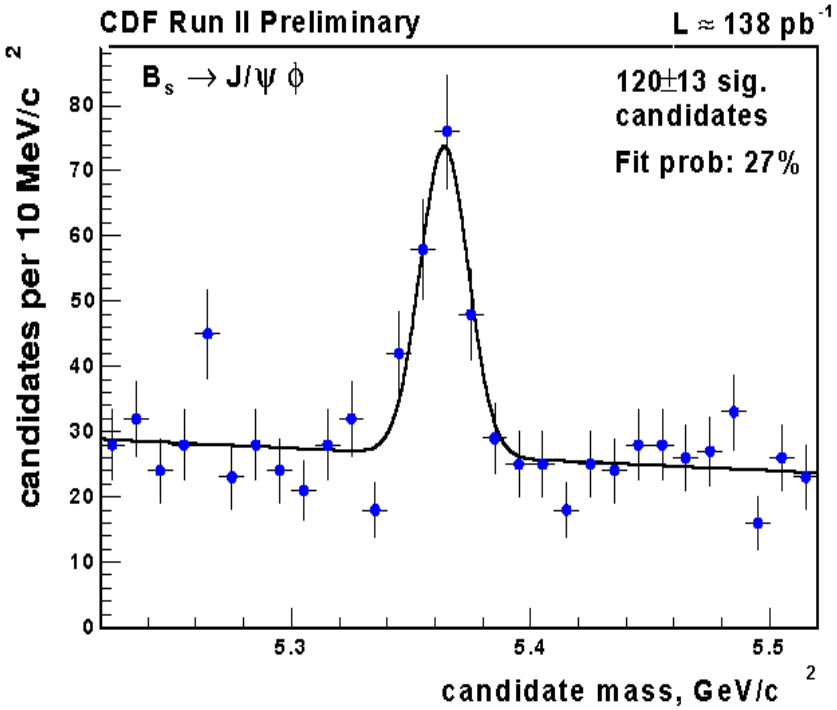
~0.5%

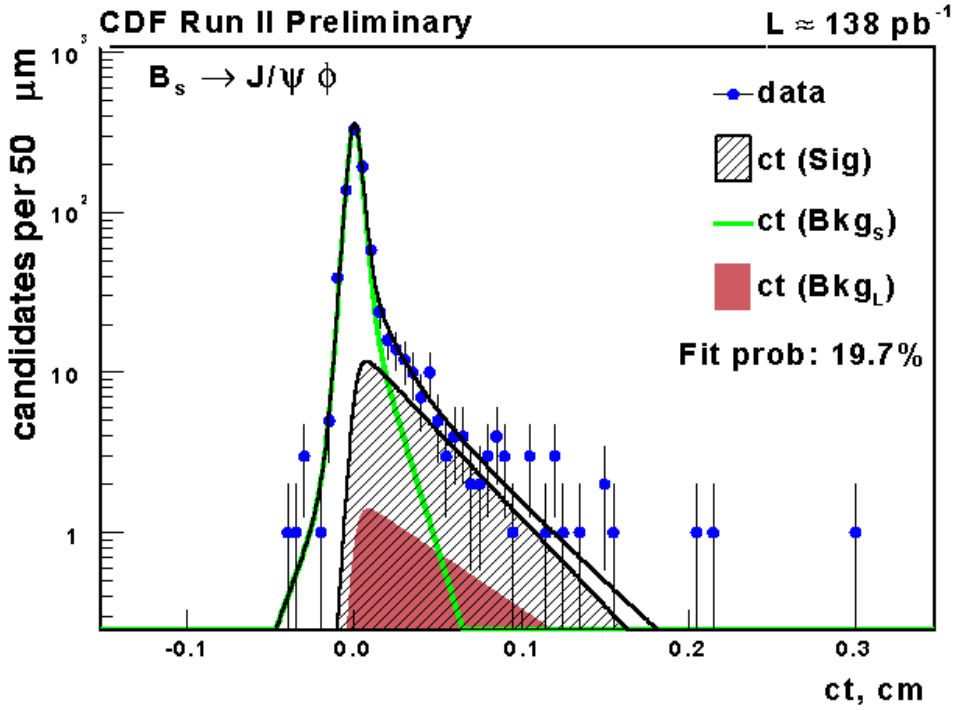
~15%

$$ct = \frac{m_B L_{xy}}{P_t(lD_s)} \cdot \left\langle \frac{P_t(lD_s)}{P_t(B_s)} \right\rangle_{mc}$$

$$s_{ct} = \frac{m_B}{P_t} s_{L_{xy}} \otimes ct\left(\frac{s_{P_t}}{P_t}\right) \otimes s_K$$

Fully reco'd σ

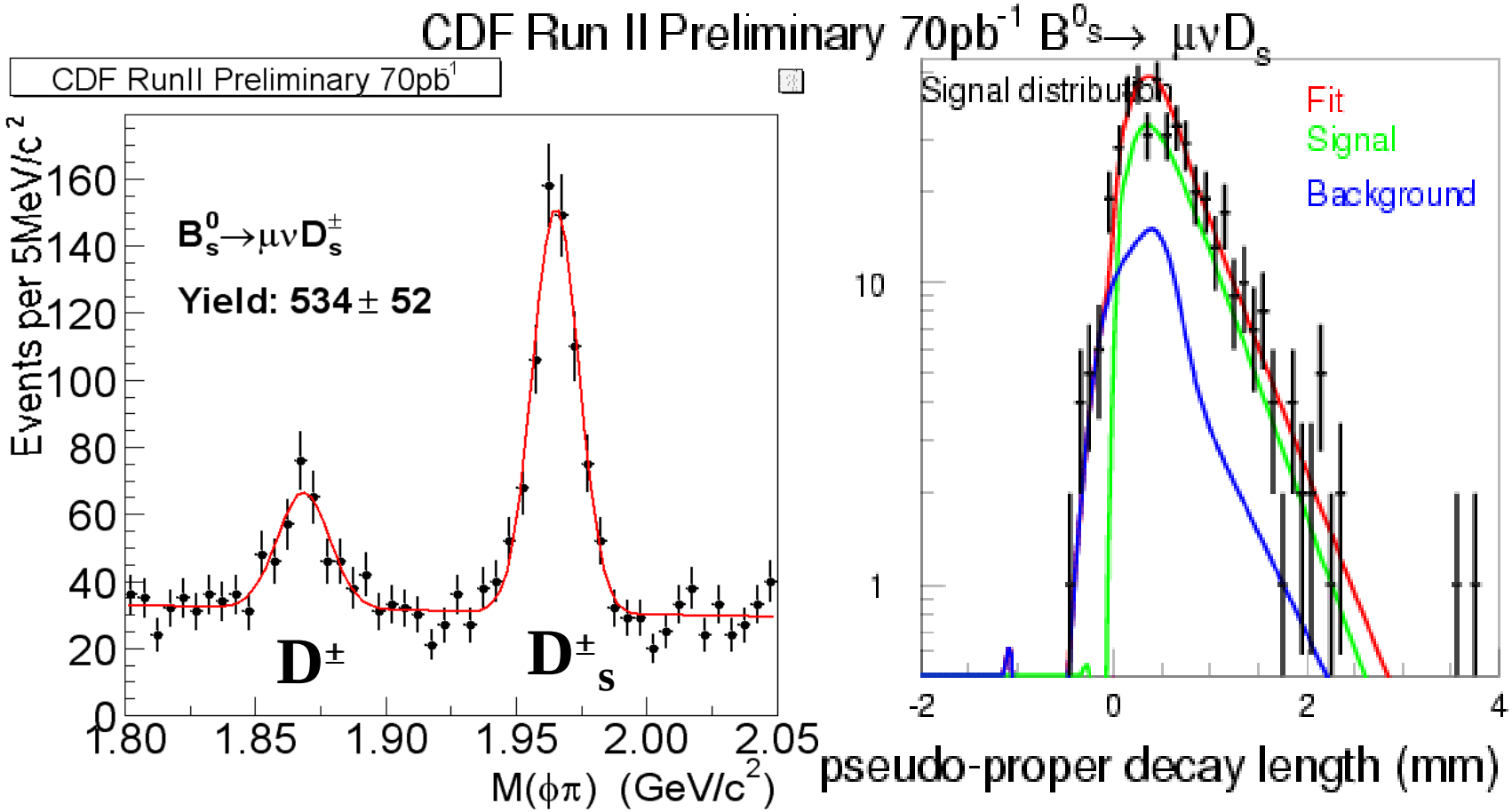




$$\tau(B_s)=1.33\pm0.14(stat.)\ \pm0.02(syst.)\ ps$$

@ ~120 events

Semileptonic σ



$\sigma_{ct} \approx \pm 0.07$ ps @ ~1000 events Sys?!??

Tagging

$$Significance = \sqrt{\frac{SeD^2}{2}} e^{-\frac{(\Delta m_s s_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

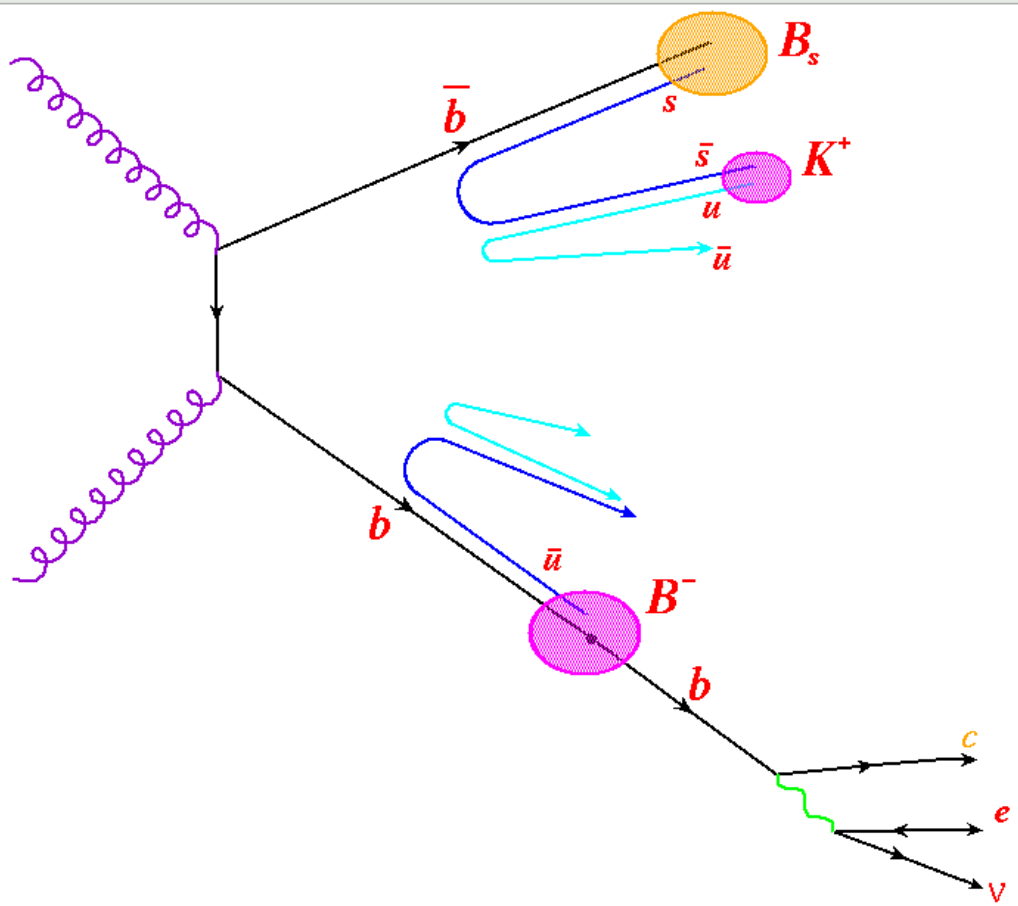
Mixing in the laboratory

- To resolve the oscillations, we need to measure
  - B_s vs $\underline{B_s}$ at t=0 (at production)
  - B_s vs B_s at decay
  - proper decay time
- for large numbers of events

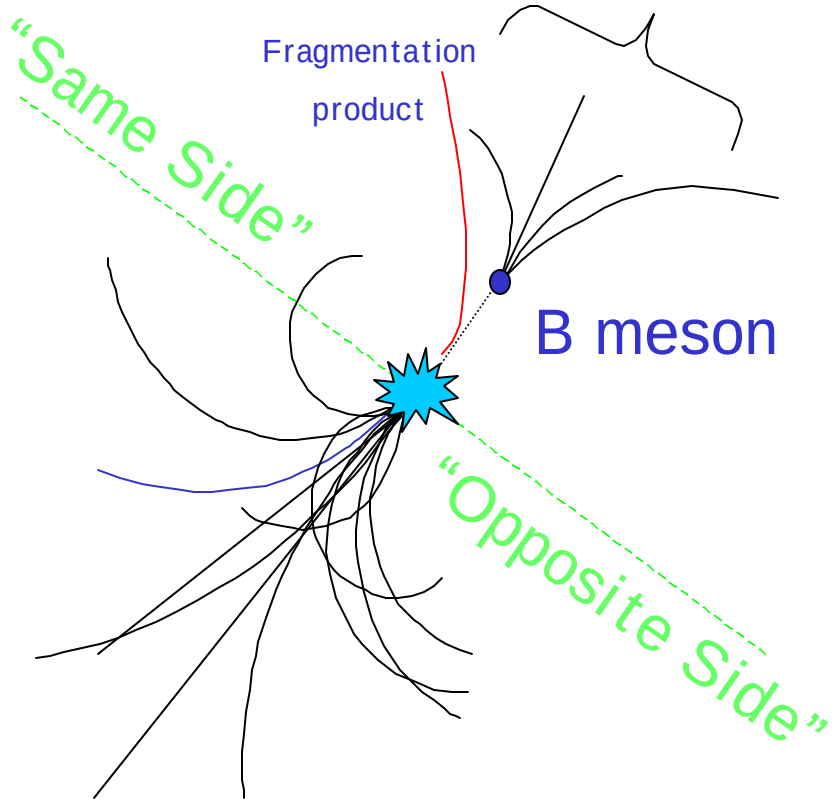
$$A_{meas.}(t) = \frac{N_{same}(t) - N_{different}(t)}{N_{same}(t) + N_{different}(t)}$$

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

- This is an art called "flavor tagging"



Reconstructed decay



Several methods, none is perfect !!!

Building a Tagger

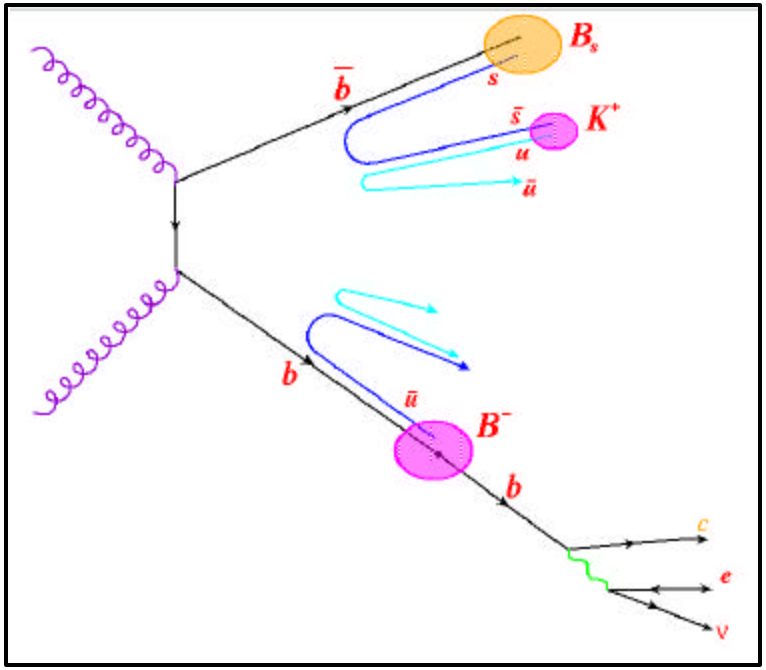
- Pick your favorite algorithm

- Pick a sample where flavor does not change (e.g. $B^+ \rightarrow l^+ \nu_l X$ decays)
- Apply your algorithm
- Measure efficiency

$$e = \frac{N_{taggable}}{N_{tot}}$$

- Count RS and WS tags

$$P_{mistag} = \frac{N_{WS}}{N_{RS} + N_{WS}}$$



Performances

Due to mistagging effects:

$$A_{meas.} = DA_{true}$$

$$D = \frac{N_R - N_W}{N_R + N_W} = 1 - 2P_{mistag}$$

And the algorithm can't be applied to the whole sample:

$$dA_{meas.} \propto \frac{1}{\sqrt{eD^2 N}}$$

eD^2 is mostly a tool for back of the envelope calculations: in reality you use all the events, weighted by their individual D

$B_s \to D_s^- \pi^+ : \epsilon D^2$	
Same-Side Kaon	4.2%
μ tag	1.0%
e tag	0.7%
Jet Charge	3.0%
Opp.-Side Kaon	2.4%
Total (correl. small)	11.3%

(some year ~2000 projections)

Let's stay on the safe side: we assume eD^2 = 4%

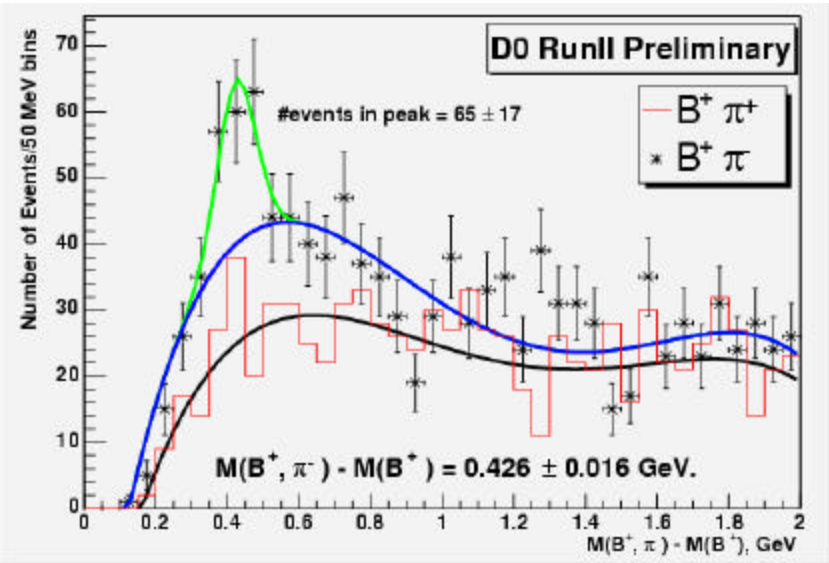
(this is ~ what we have at hand right now)

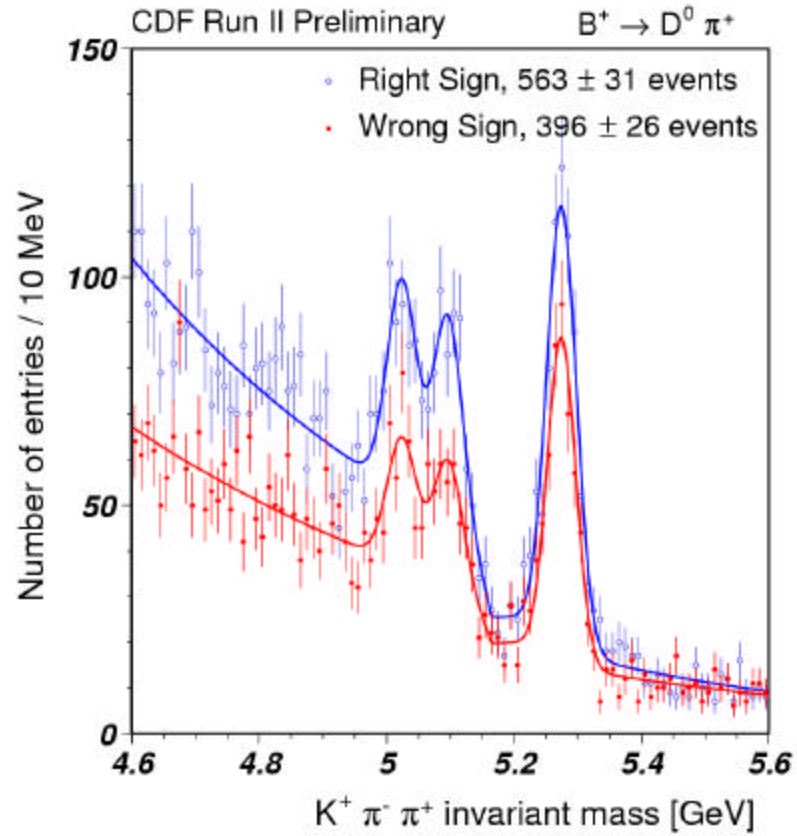
Current Performances

- Strategy: use data for calibration (*e.g.* $B^{\pm} \to J/\psi K^{\pm}$, $B \to$ lepton)
  - "know" the answer, can measure right sign and wrong sign tags.

DØ Results:

- Jet charge $\varepsilon D^2 = (3.3 \pm 1.1)\%$
- Muon tagging $\varepsilon D^2 = (1.6 \pm 0.6)\%$





CDF Results:

- Same-side (B^+) $\varepsilon D^2 = (2.1 \pm 0.7)\%$
  ($B^+/B^0/B_s$ correlations different)
- Muon tagging $\varepsilon D^2 = (0.7 \pm 0.1)\%$

Conclusions

CDF B_s Sensitivity Estimate

- Current performance:

hadronic mode only

  - S=1600 events/fb^{-1} (*i.e.* $s_{effective}$ for produce+trigger+recon)
  - S/B = 2/1
  - $_eD^2$ = 4%
  - s_t = 67fs

2σ sensitivity for Δm_s=15ps^{-1} with ~0.5fb^{-1} of data

    - surpass the current world average

CDF B_s Sensitivity Estimate

- Current performance: **hadronic mode only**
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  - s_t = 67fs

    2σ sensitivity for Δm_s=15ps^{-1} with ~0.5fb^{-1} of data
    - surpass the current world average
- With "modest" improvements
  - S=2000 fb (improve trigger, reconstruct more modes)
  - S/B = 2/1 (unchanged)
  - eD^2 = 5% (kaon tagging)
  - s_t = 50fs (event-by-event vertex + L00)

    5σ sensitivity for Δm_s=18ps^{-1} with ~1.7fb^{-1} of data
    5σ sensitivity for Δm_s=24ps^{-1} with ~3.2fb^{-1} of data
    - ✓ Δm_s=24ps^{-1} "covers" the expected region based upon indirect fits.
- *This is a difficult measurement.*
- *There are ways to further improve this sensitivity…*

Work In Progress

Estimates based current performance plus modest improvements. Further gain is possible on all of these pieces:

- s_t
  - Event-by-event vertex
  - Additional Si layer at ~1cm from the beam pipe (Layer 00)
- Flavor tagging
  - Kaon tagging (same-side and opposite-side)
- Yields
  - Other B_s modes (hadronic and semileptonic)
  - Other D_s modes
  - Triggering
    - Improved use of available bandwidth
    - Improve available bandwidth
    - Improve SVT efficiency

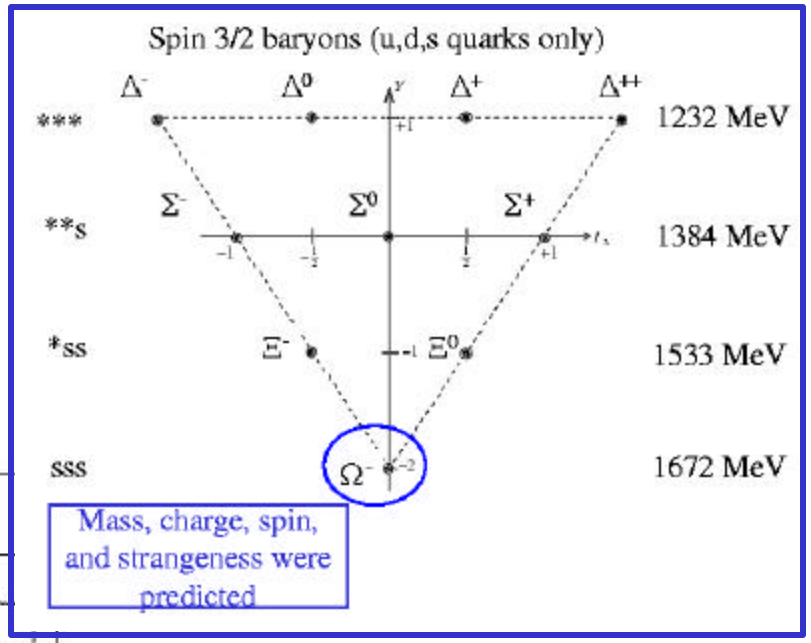
Matters most for going to Δm_s > 20 ps^{-1}

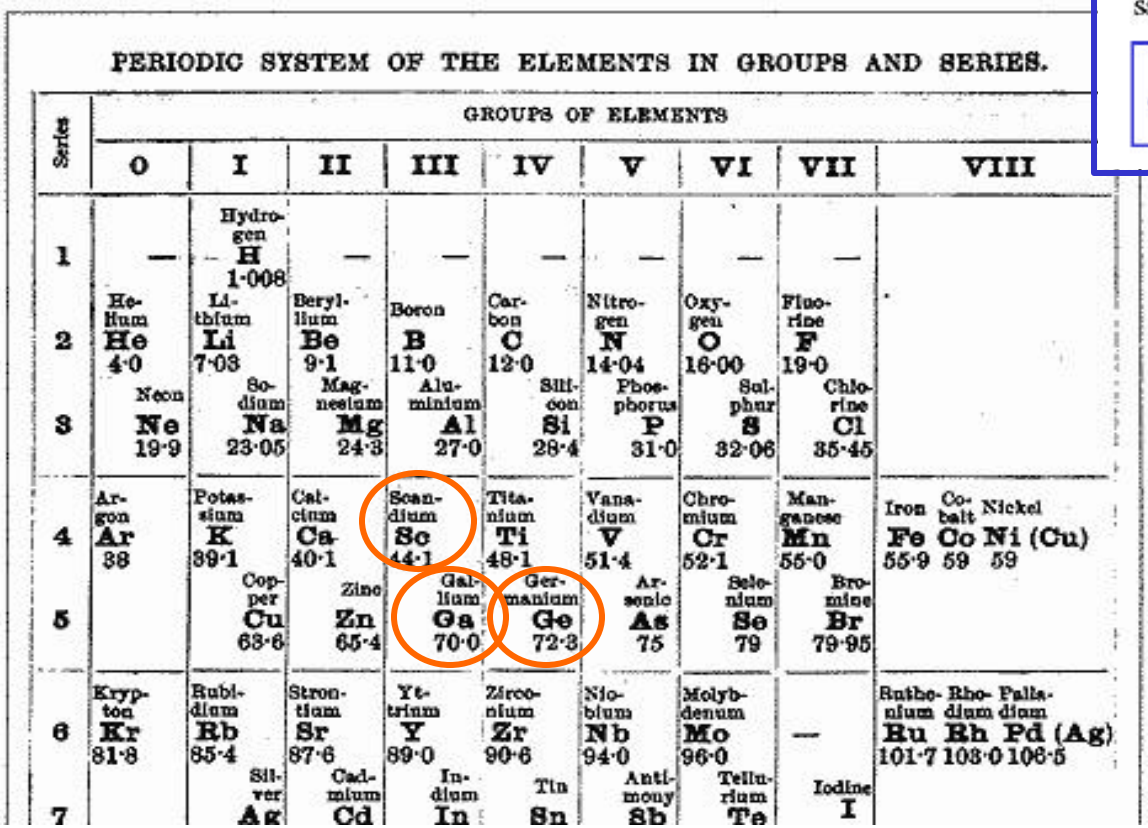
Trigger improvements matter most for yields

It's doable! It will take time, luminosity and more hard work!

Interplay between direct and indirect discoveries

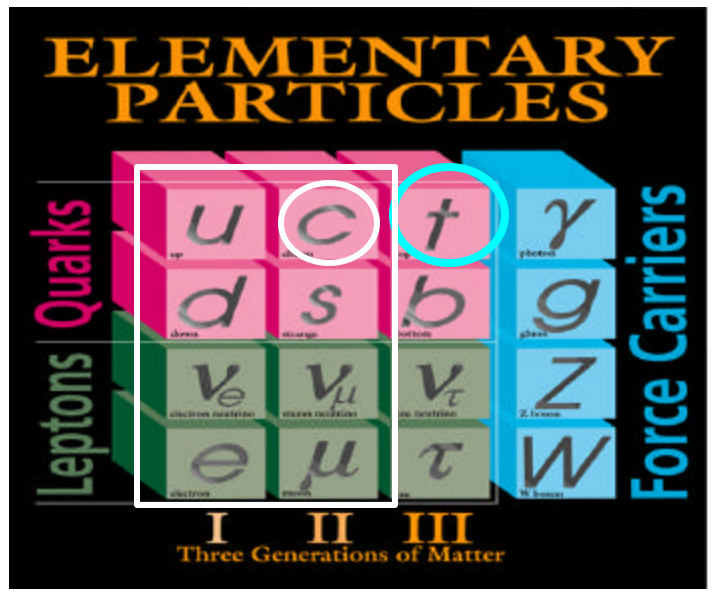
Often, many properties of new particles are known, indirectly, well before direct discovery.



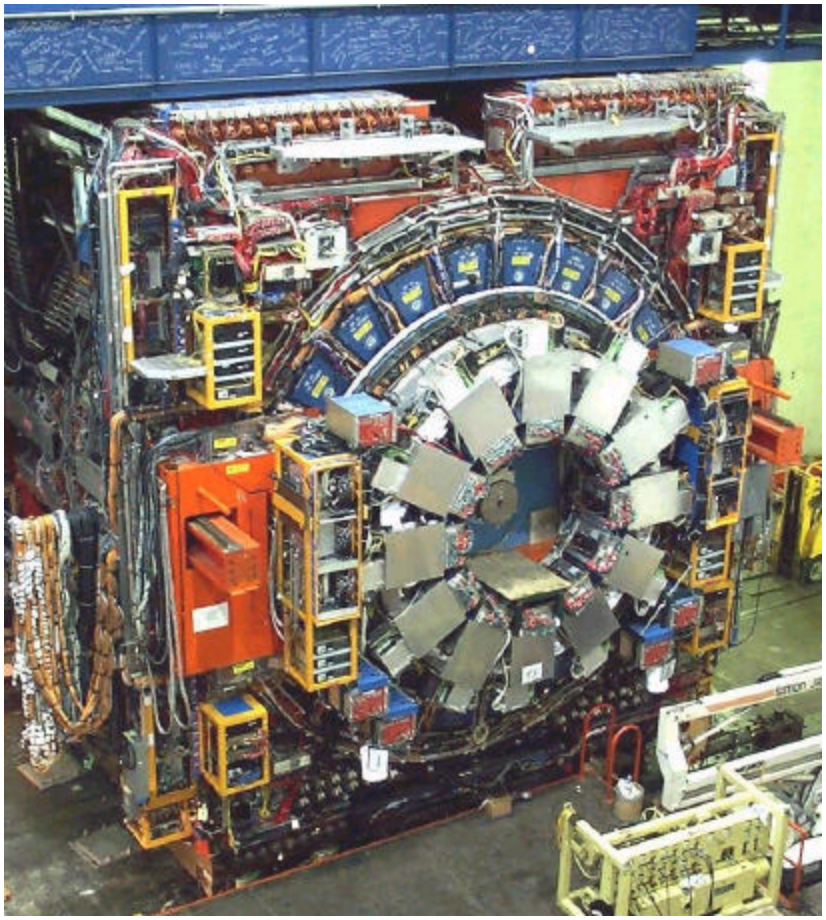
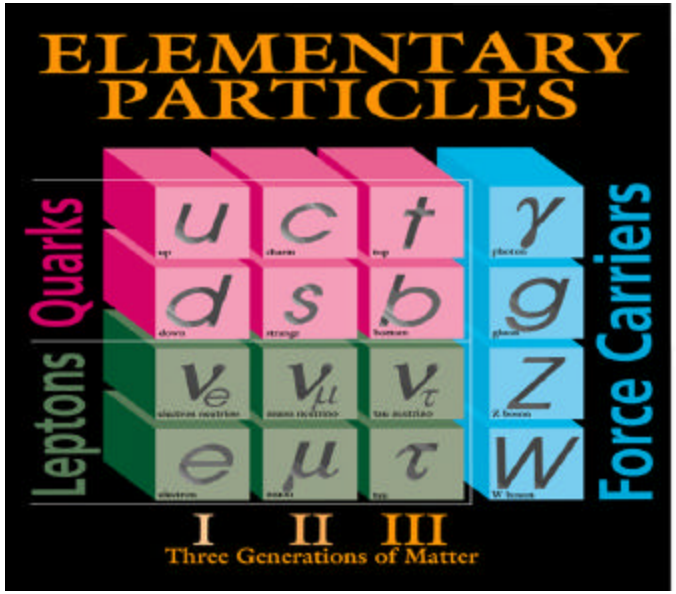


PERIODIC SYSTEM OF THE ELEMENTS IN GROUPS AND SERIES.

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 Fe 55·9, Cobalt Co 59, Nickel Ni 59, (Cu)
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 Ru 101·7, Rhodium Rh 103·0, Palladium Pd 106·5, (Ag)
7		Silver Ag	Cadmium Cd	Indium In	Tin Sn	Antimony Sb	Tellurium Te	Iodine I	



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