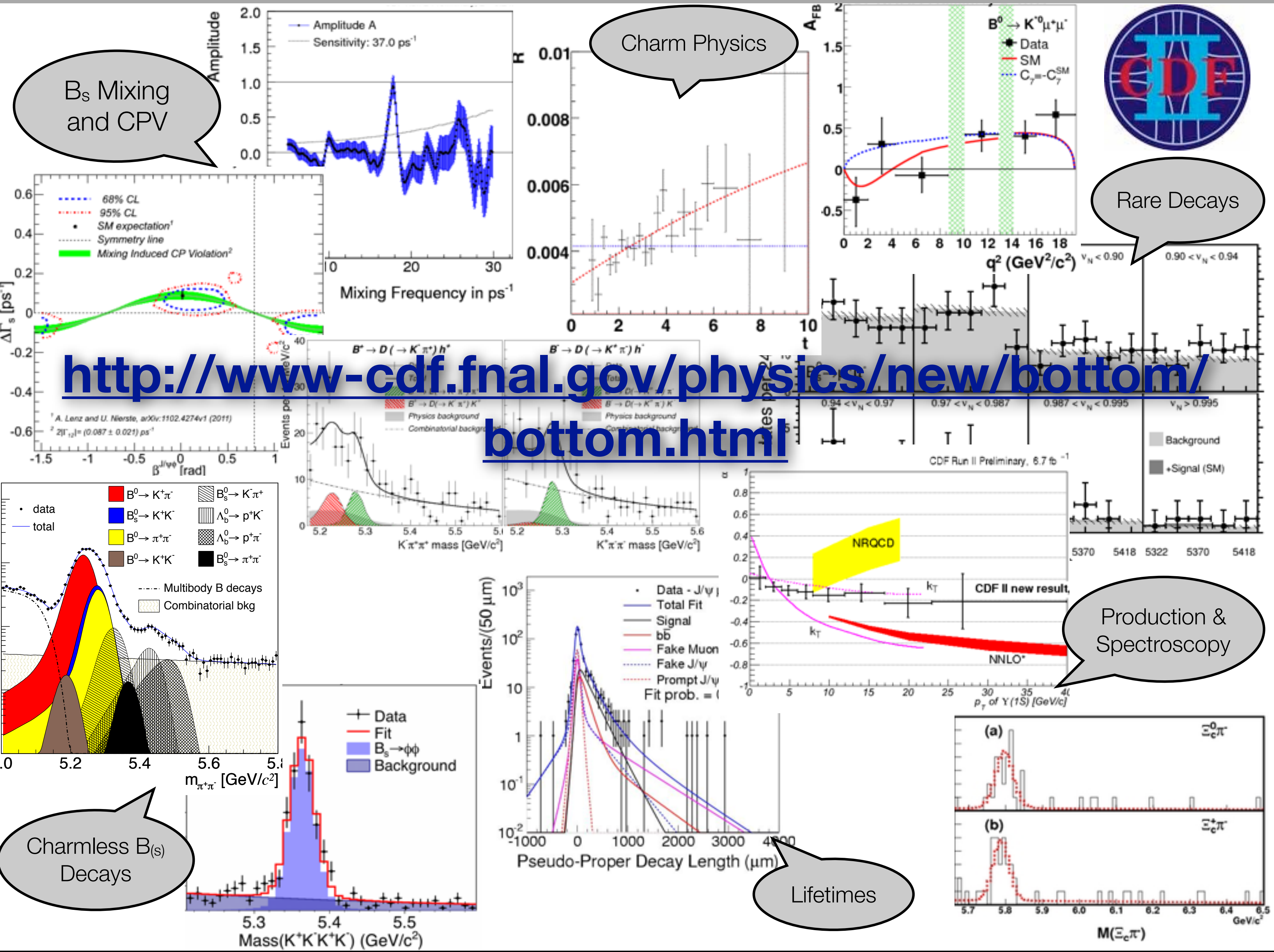
Heavy Flavor at the Tevatron

- In ~10 years of data-taking Tevatron's experiments pioneered and established the study of HF physics in hadron collisions
  - Unique access to B_s physics
  - World-leading rare decays searches
  - World leading masses/lifetimes
  - b-baryons discoveries
  - Precision CPV/mixing in charm

The Tevatron has shown one can do precision b-physics at a hadron collider!


Bs Mixing and CPV
Charm Physics
Rare Decays
Production & Spectroscopy
Charmless B(s) Decays
Lifetimes
http://www-cdf.fnal.gov/physics/new/bottom/bottom.html
Amplitude A
Sensitivity: 37.0 ps^{-1}
Mixing Frequency in ps^{-1}
68% CL
95% CL
SM expectation
Symmetry line
Mixing Induced CP Violation
$\beta_s^{J/\psi\phi}$ [rad]
$\Delta\Gamma_s$ [ps^{-1}]
$B^0 \rightarrow K^{*0}\mu^+\mu^-$
Data
SM
$C_7 = -C_7^{SM}$
q^2 (GeV^2/c^2)
A_{FB}
$B^+ \rightarrow D(\rightarrow K^-\pi^+)h^+$
$B^- \rightarrow D(\rightarrow K^+\pi^-)h^-$
Physics background
CDF Run II Preliminary, 6.7 fb^{-1}
Background
+Signal (SM)
NRQCD
CDF II new result
NNLO*
p_T of $\Upsilon(1S)$ [GeV/c]
data
total
$B^0 \rightarrow K^+\pi^-$
$B_s^0 \rightarrow K^+K^-$
$B^0 \rightarrow \pi^+\pi^-$
$B^0 \rightarrow K^+K^-$
$B_s^0 \rightarrow K^-\pi^+$
$\Lambda_b^0 \rightarrow pK^-$
$\Lambda_b^0 \rightarrow p\pi^-$
$B_s^0 \rightarrow \pi^+\pi^-$
Multibody B decays
Combinatorial bkg
$m_{\pi^+\pi^-}$ [GeV/c^2]
Data
Fit
$B_s \rightarrow \phi\phi$
Background
Mass($K^+K^-K^+K^-$) (GeV/c^2)
Events/(50 µm)
Total Fit
Signal
Fake Muon
Pseudo-Proper Decay Length (µm)
$M(\Xi_c\pi^-)$

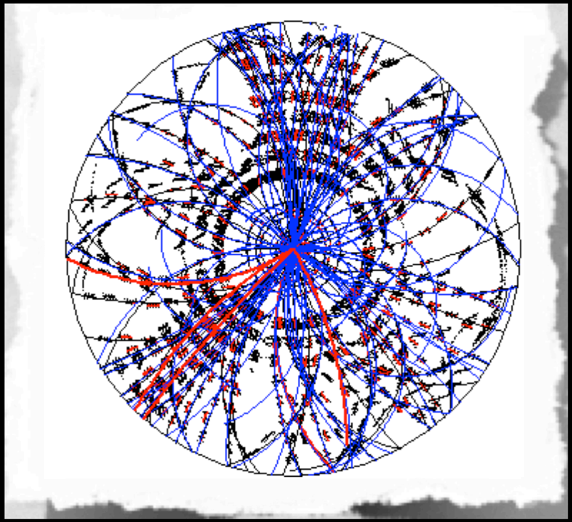
Status

- Over past decade, dedicated experiments, theory and computational advances have achieved formidable success
- Ths SM explains satisfactorily data in leading B transitions to within 10%
- Some of the most promising probes are just now being explored. Many of these probes are only accessible in hadron collisions (B_s physics, high statistics FCNC decays, precision charm….)
- That is what motivates heavy flavor physics at the worlds colliders

Tevatron Heavy Flavor

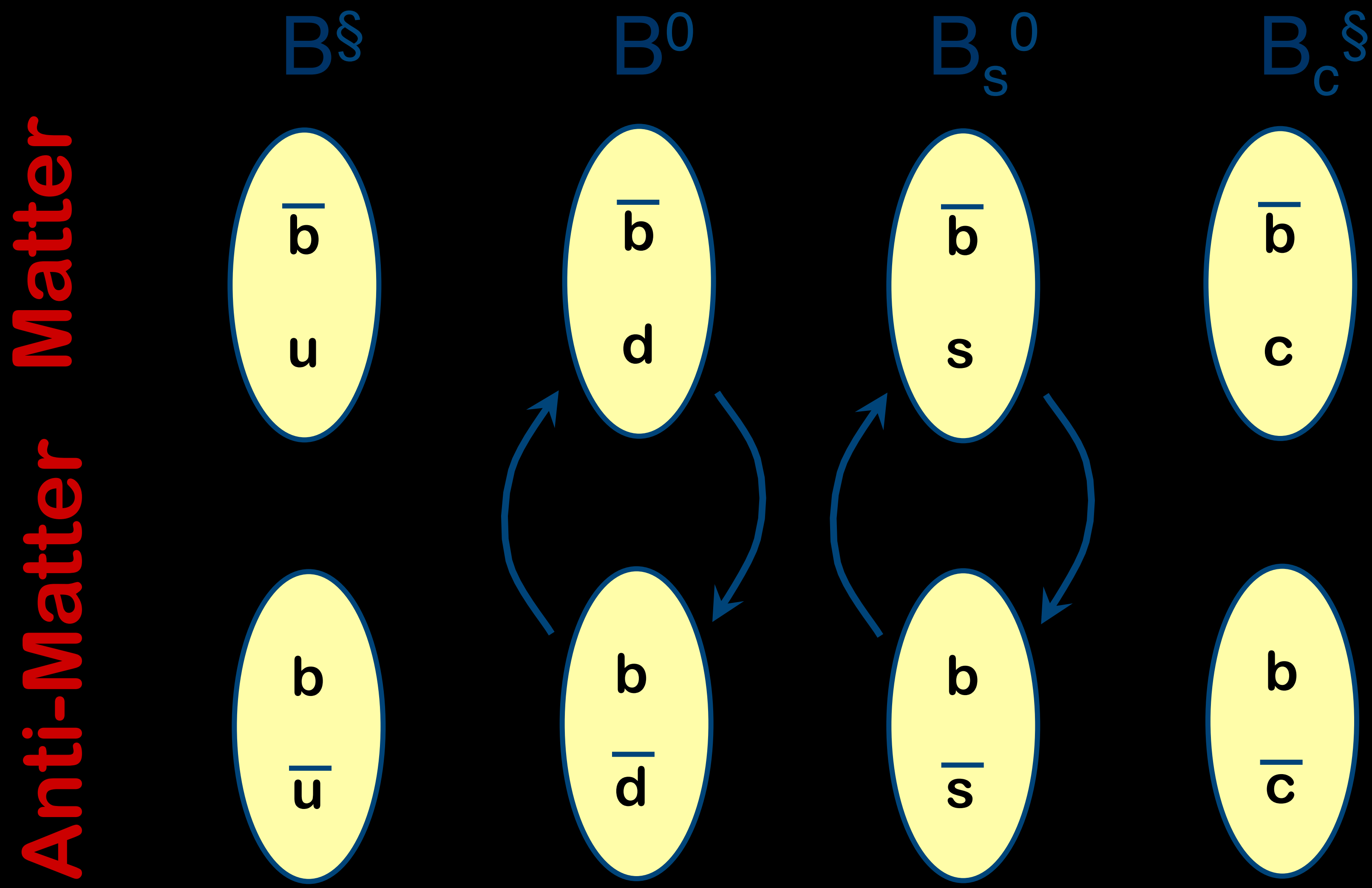
- 2 experiments
- 10^{13} ppbar collisions at 2 TeV in 10 years
- 0.1 - 1% of them yield B/D's
- We are able to get 0.1 – 10% of these on tape
- High rate of all species of heavy flavors. Higher than B factories (though lower than LHCb)
- Symmetric detectors and CP-invariant initial state ensure equal number of particles and antiparticles in acceptance

How do we do it?

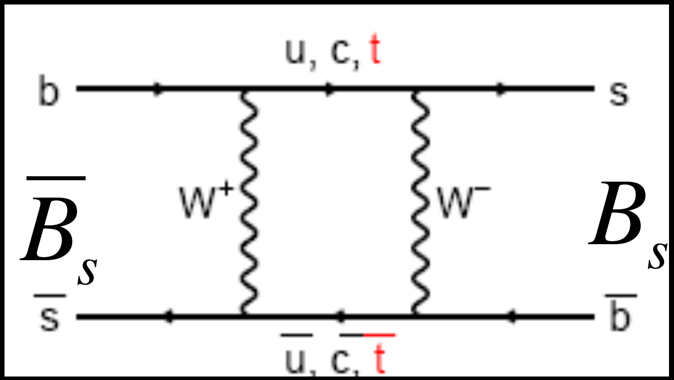


- 1 KHz of reconstructable b-pairs (pt 5-10 GeV)
- Trigger: single lepton and dilepton as well as tracks displaced from primary ppbar vertex
- Degraded efficiency at high luminosity Significant bias on kinematics and decay-time
- Tracking: $\sigma(Pt)/Pt^2 = 0.1\%$. Vertex known within 20 μm. Good muons and some particle ID (1.5σ)
- Usually all charged final states. Absolute efficiencies are normalized with reference decays. Simulation ony used for kinematics
- Analysis challenges: determining quark flavor at production, sample composition of overlapping signals etc

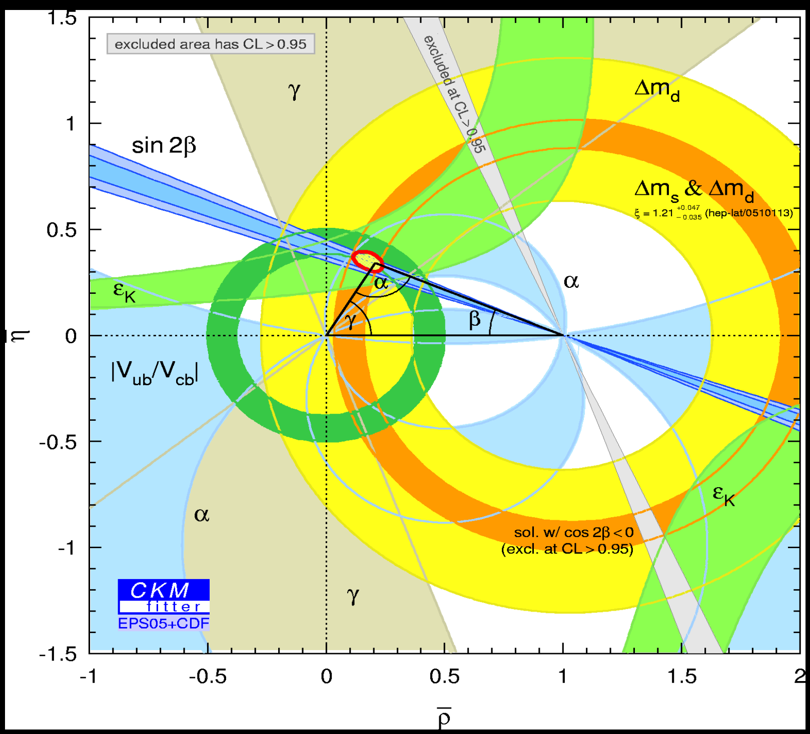
B Mesons


B§
B^0
B_s^0
B_c§
Matter
Anti-Matter
$\bar{b}$ u
$\bar{b}$ d
$\bar{b}$ s
$\bar{b}$ c
b $\bar{u}$
b $\bar{d}$
b $\bar{s}$
b $\bar{c}$

B_s Mixing and Δm_s



$\Delta m_s \sim V_{ts}$



- Measuring the oscillation frequency, Delta M_s, of the Bs system has been a major objective of experimental particle physics.
- Can use Delta(ms) to get the magnitude of the Vts and set limits on the CKM matrix.
- This is a very experimentally challenging measurement.

B Mixing

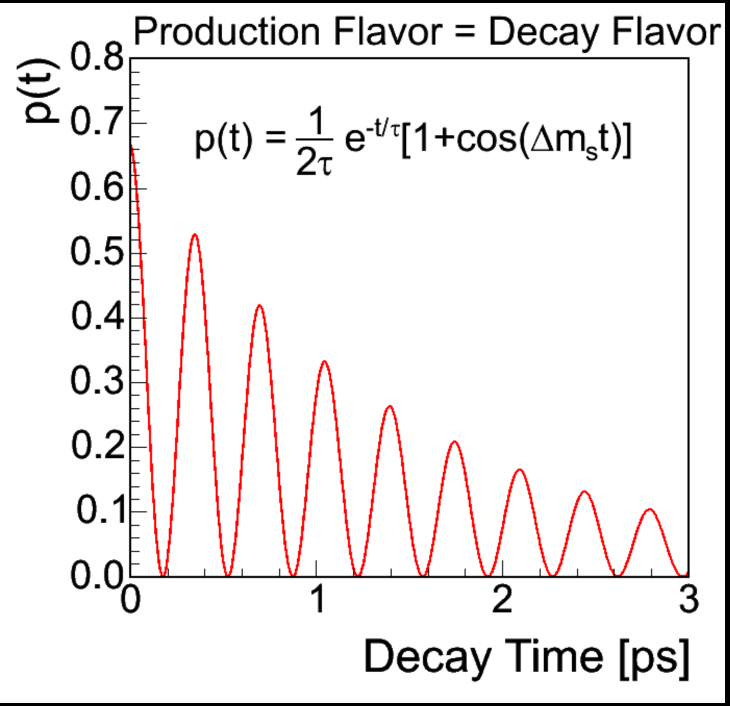
- Neutral B Meson system

$$|B>=(\bar{b}s);\ |\bar{B}>=(b\bar{s})$$

mixture of two mass eigenstates (No CP violation case):

$$|B_H\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle + |\overline{B}\rangle\right)$$
$$|B_L\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle - |\overline{B}\rangle\right)$$

- B_H and B_L may have different mass and decay width
  - $\Delta m = M_H - M_L$ (>0 by definition)
  - $\Delta\Gamma = \Gamma_H - \Gamma_L$



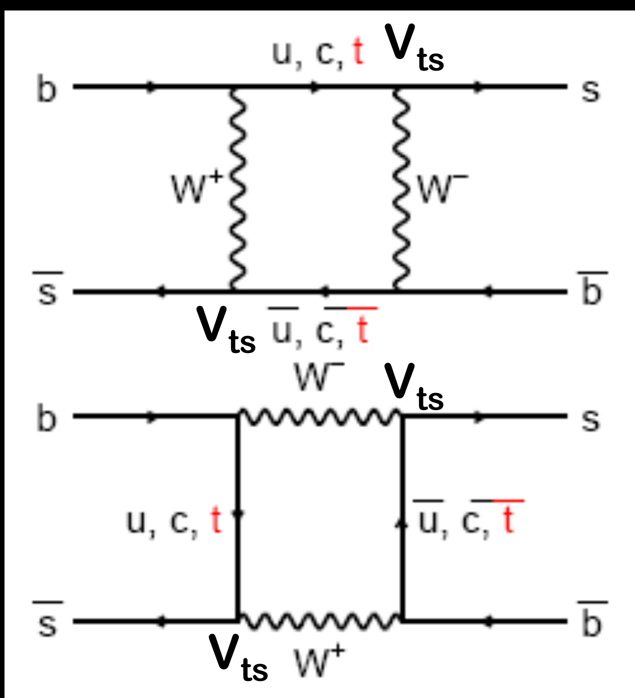
- The case of $\Delta\Gamma = 0$

$$p(B \to B) = \frac{e^{-t/\tau}}{2\tau}(1 + \cos\Delta m t)$$
$$p(B \to \overline{B}) = \frac{e^{-t/\tau}}{2\tau}(1 - \cos\Delta m t)$$

Standard Model Prediction

CKM Matrix   Wolfenstein parameterization

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$



Ratio of frequencies for B^0 and

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \frac{f_{Bs}^2 B_{Bs}}{f_{Bd}^2 B_{Bd}} \frac{|V_{ts}|^2}{|V_{td}|^2} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

$\xi = 1.210^{+0.047}$ from lattice QCD

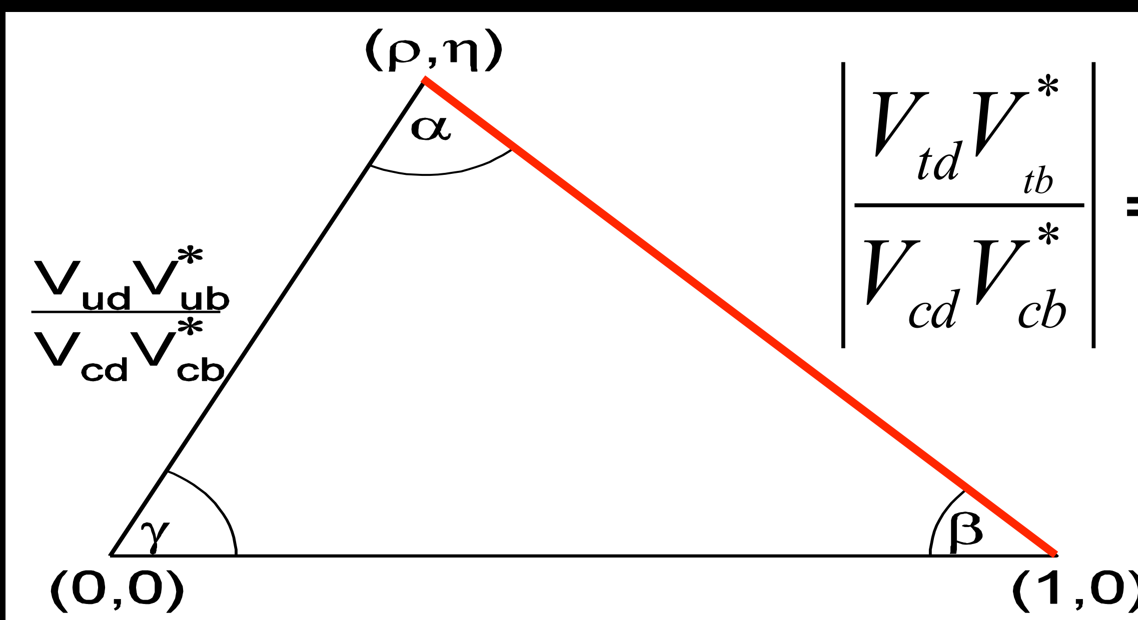
(hep/lat-0510113)

$V_{ts} \sim \lambda^2$, $V_{td} \sim \lambda^3$, $\lambda = 0.224 \pm 0.012$

Unitarity Triangle

CKM Matrix Unitarity Condition

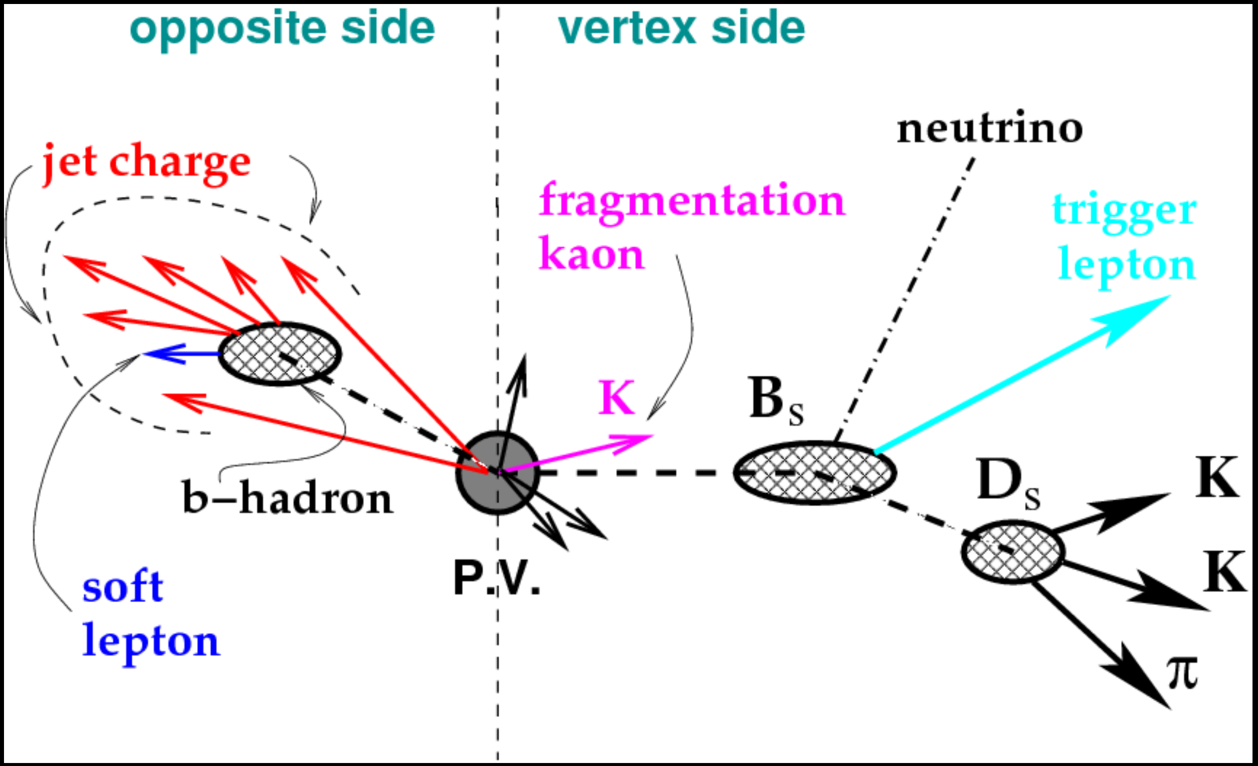
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



$$\left|\frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}}\right| = \frac{|V_{td}|}{|V_{ts}|} \times \frac{1}{|V_{cd}|}$$

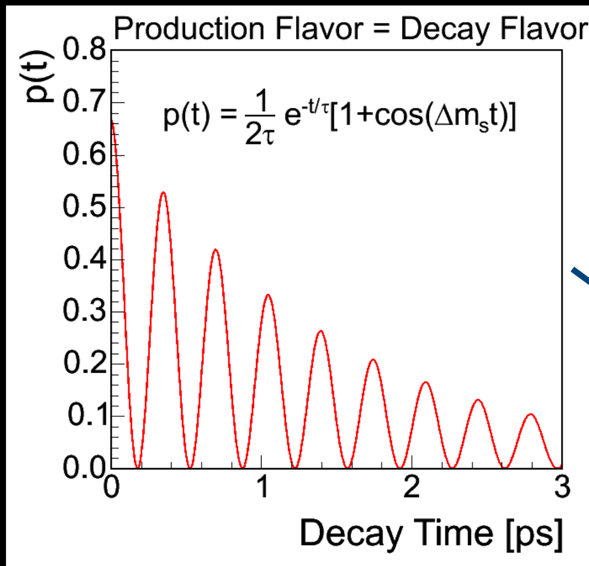
$$\sim \sqrt{\frac{\Delta m_d}{\Delta m_s}}$$

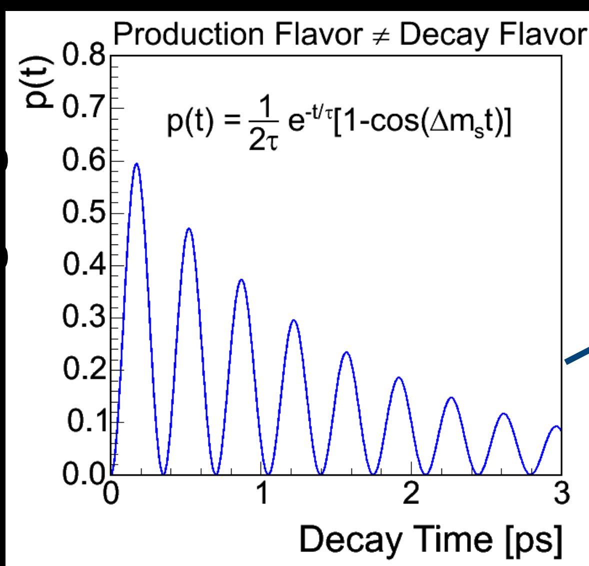
The “Big” Picture



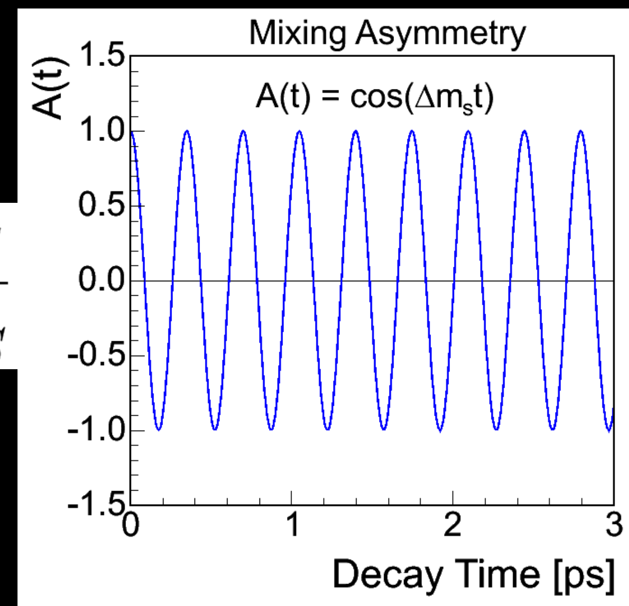
- reconstruct B_s decays ! decay flavor from decay products
- measure proper time of the decay (very precisely)
- infer B_s production flavor (production flavor tagging)

Measurement .. In a Perfect World



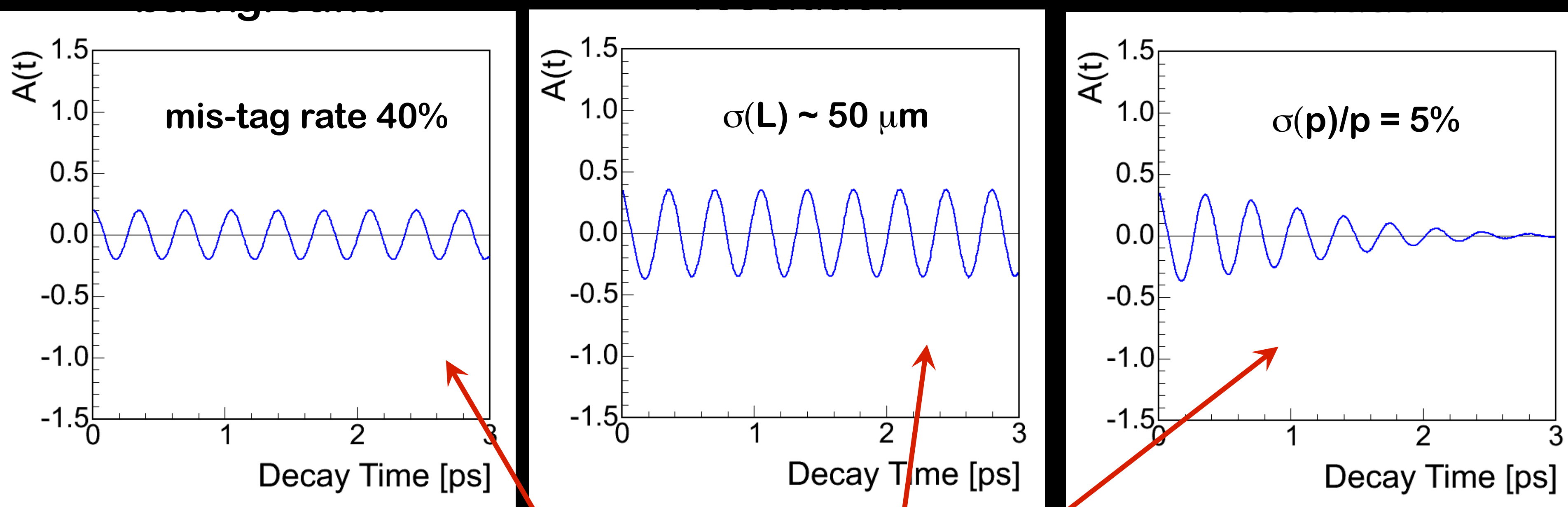


$$A(t) = \frac{N_{RS} - N_{WS}}{N_{RS} + N_{WS}}$$



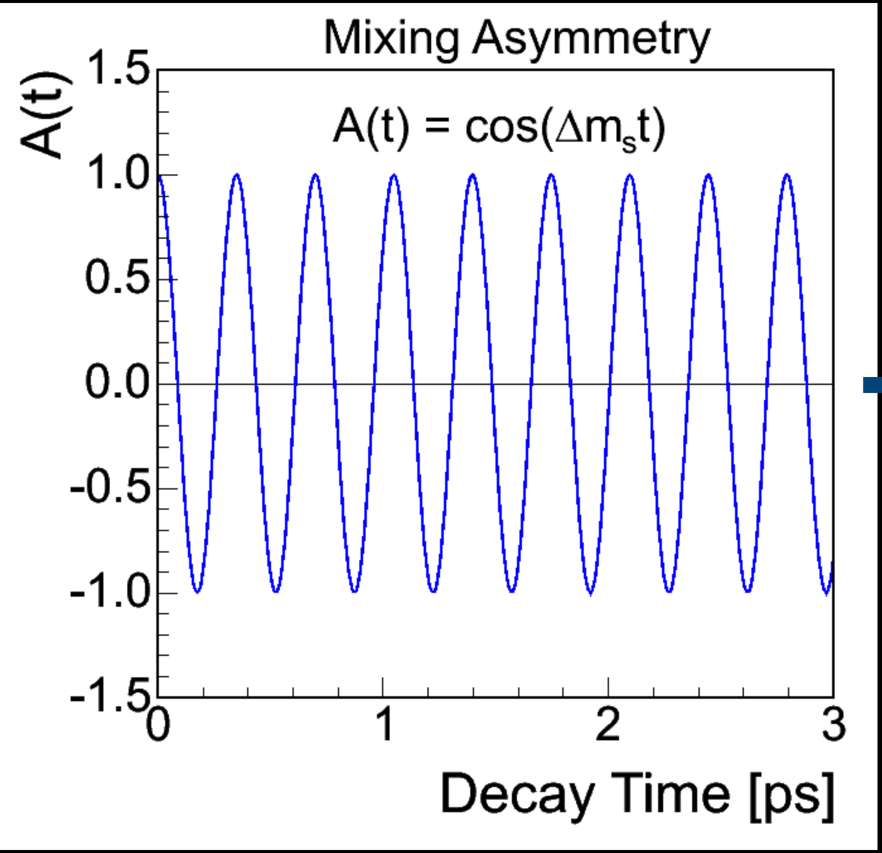
what about detector effects

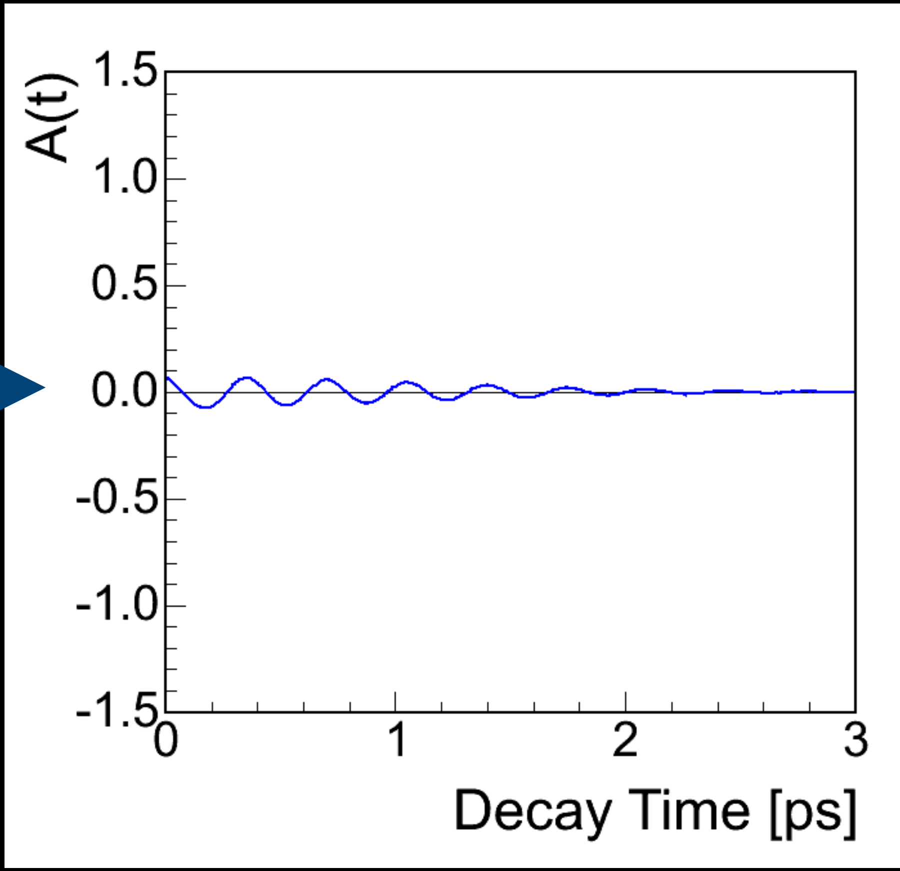
Realistic Effects



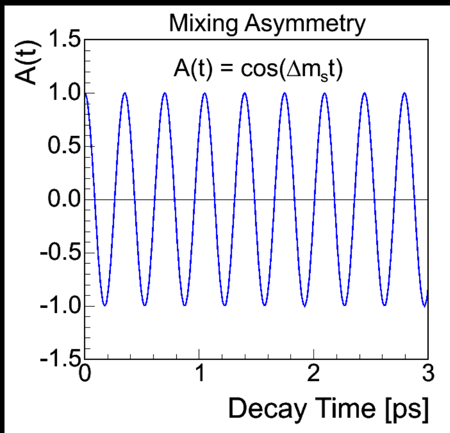
$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}} \sqrt{\frac{S}{S+B}}$$

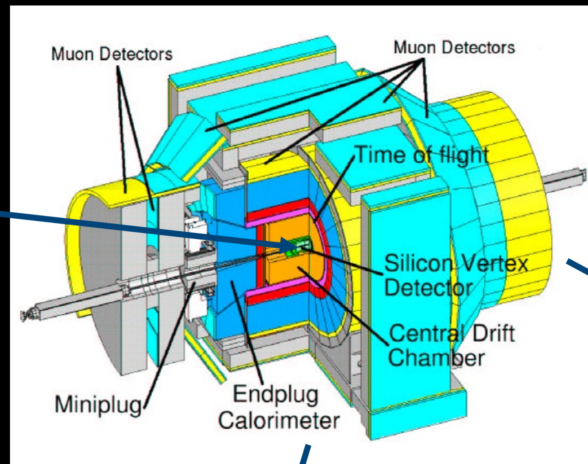
All Effects Together



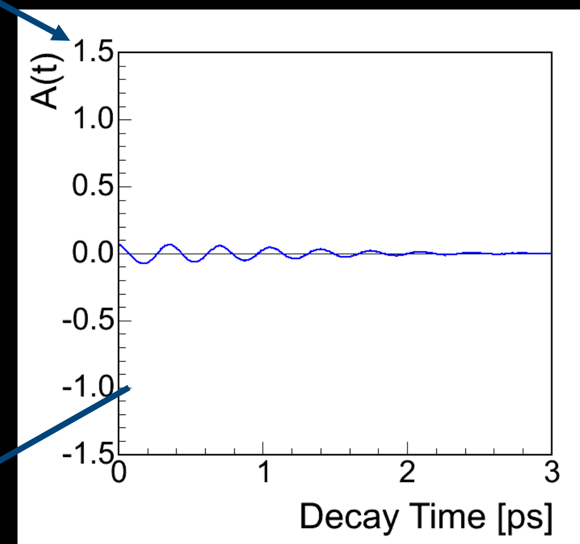


Real Measurement Layout





Data



momentum resolution
displacement resolution

scan for signal

$A(\Delta m_s = 15\ ps^{-1}) = ?$

measure frequency

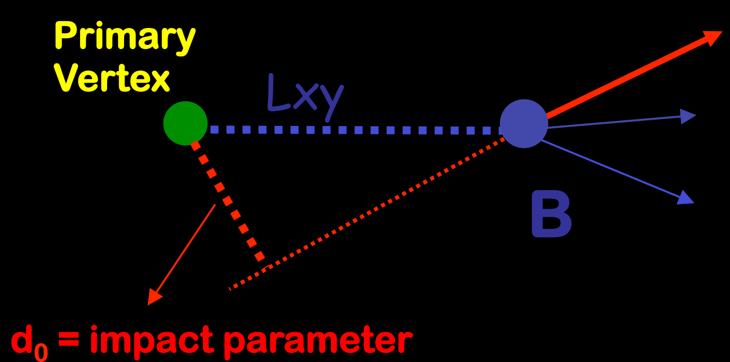
$\Delta\ m_s = ?$

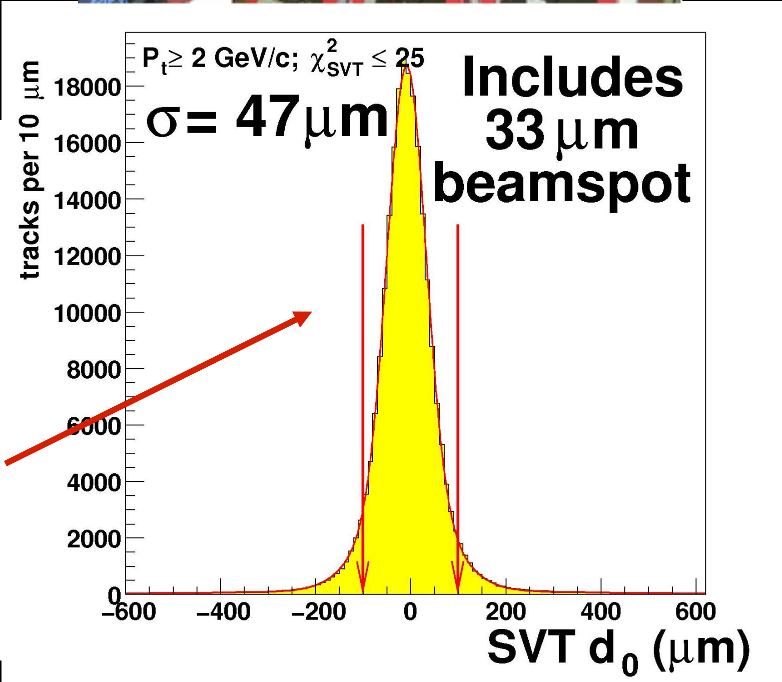
Unbinned Likelihood Fitter

p ~ $e^{-t/\tau}$[1§AD cosΔmt] - R(t)

Triggering On Displaced Tracks

trigger B_s ! $D_s^-\pi$, $\mathbf{B_s}$! $\mathbf{D_s^-\ l^+}$





trigger extracts 20 TB /sec

"unusual" trigger requirement:

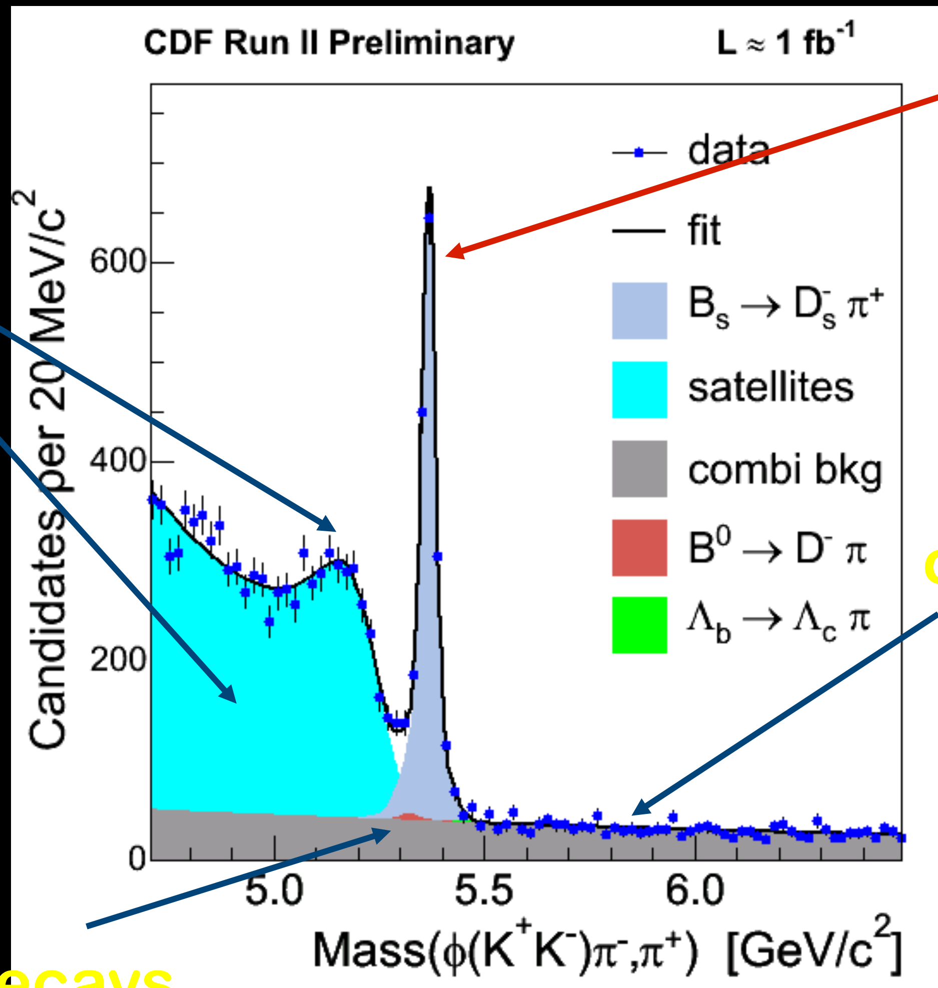
two displaced tracks:

(p_T > 2 GeV/c, 120 μm<$|d_0|$<1mm)

requires precision tracking in SVX

Example Mass Spectrum

partially reconstructed B mesons (satellites)



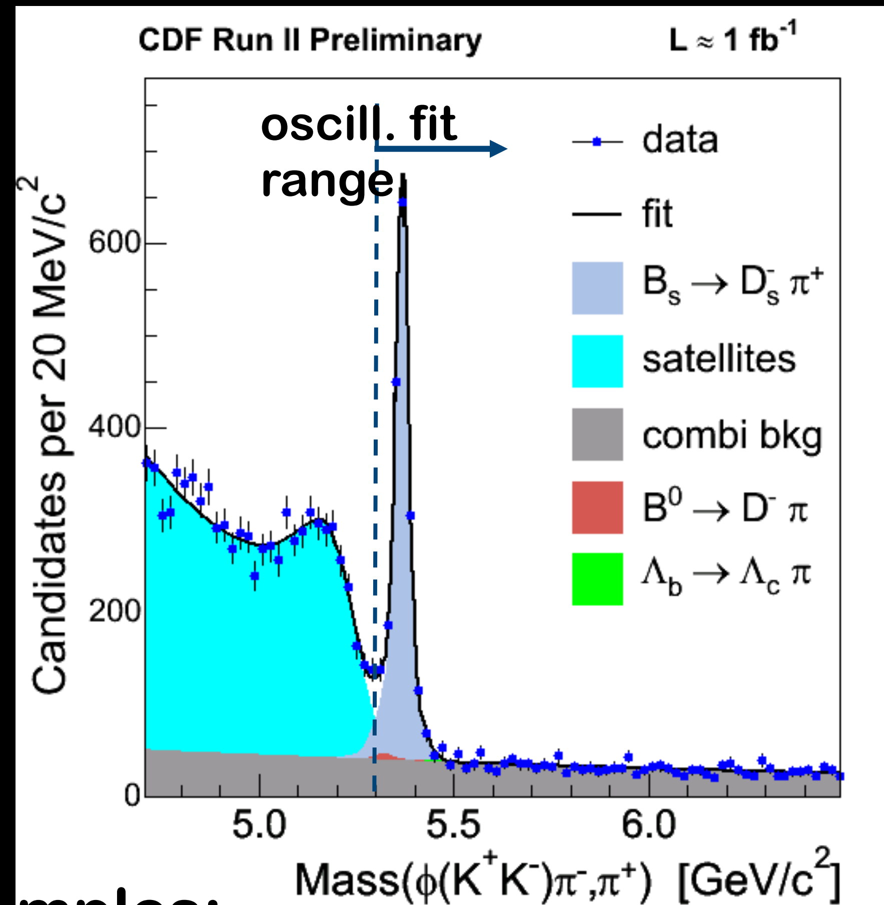
signal
B_s! $D_s\pi$,
D_s ! $\phi\pi$,
ϕ ! K^+K^-

combinatorial background

B^0! $D^-\pi$ decays

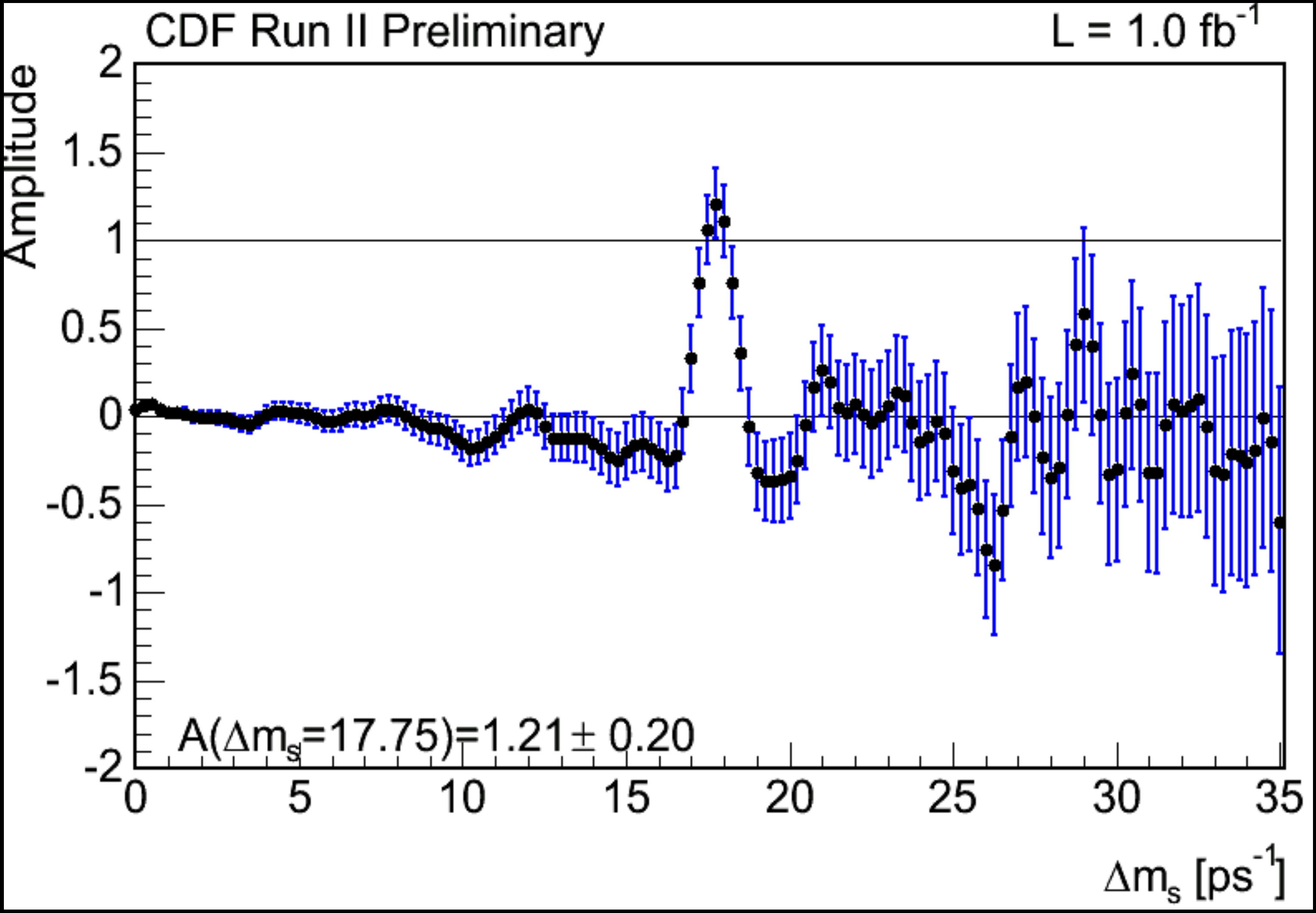
Signal Yield Summary: Hadronic

	Yield
B_s! $D_s\pi$ ($\phi\pi$)	1600
B_s! $D_s\pi$ (K^* K)	800
B_s! D_s π (3π)	600
B_s! $D_s3\pi$ (ϕ π)	500
B_s! $D_s3\pi$ (K^*K)	200
Total	3700



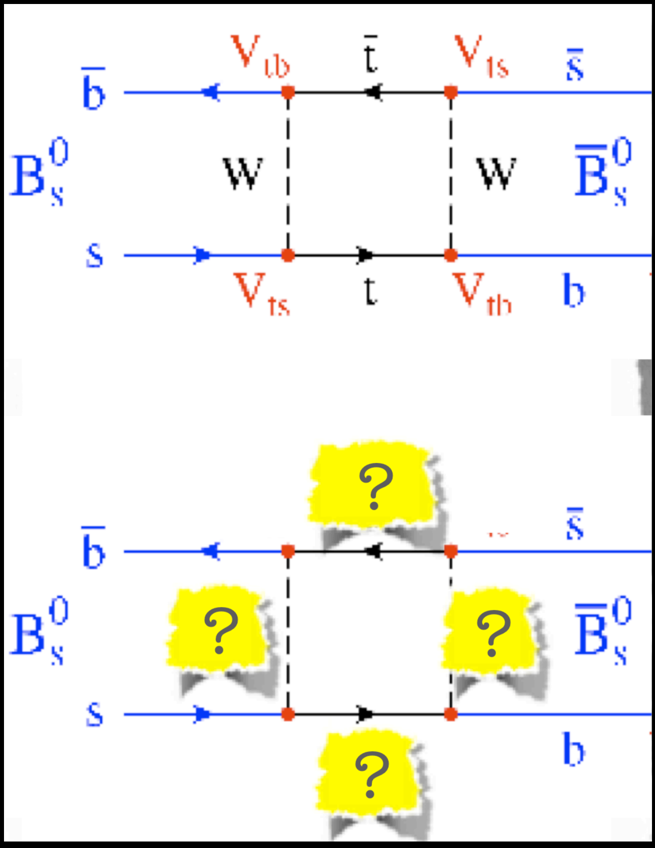
B_s Mixing and Δm_s

$\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ ps^{-1}$



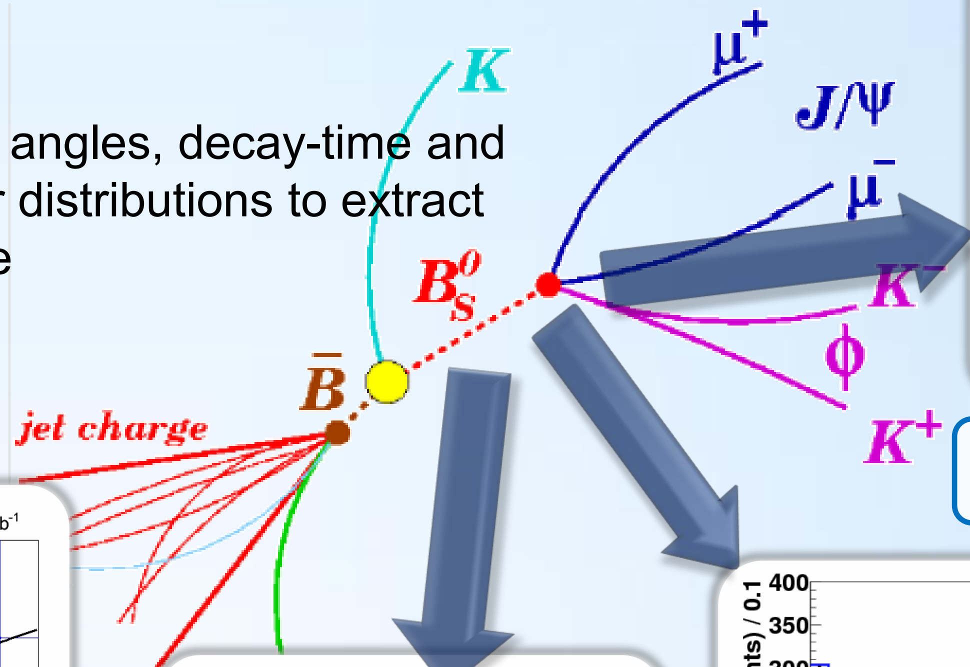
BSM Physics in Mixing

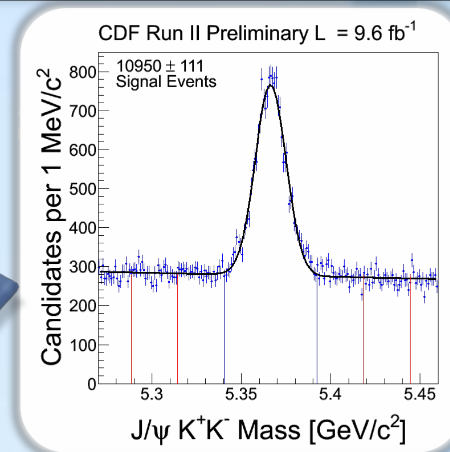
- BSM Physics can alter mixing phenomenology from SM expectation
- Our 2006 mixing measurement (just showed) is consistent with SM expectation (within lattice uncertainties)
- Mixing Phase is unconstrained
  – Large New Physics effects are still possible
- New Physics is accessible through interference between Bs->J/Ψϕ decay with and without flavor oscillations



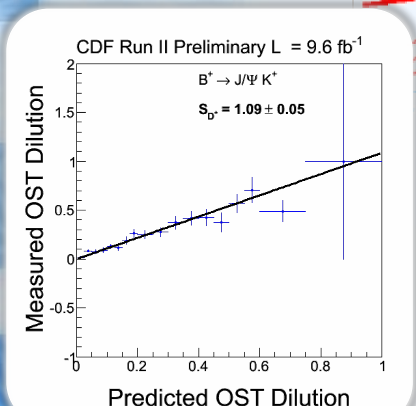
Measurement Outline

Joint fit to mass, angles, decay-time and production flavor distributions to extract the mixing phase

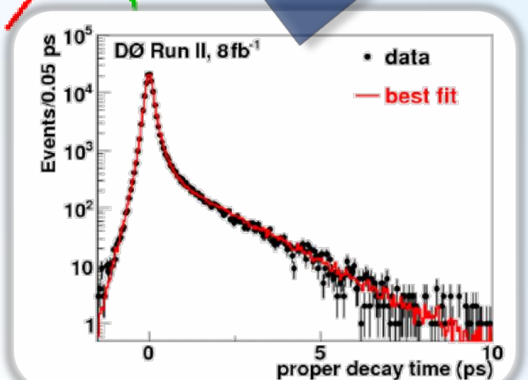




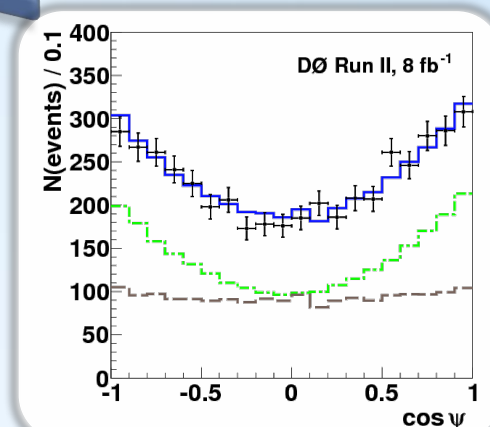
B_s invariant mass fit
to separate signal from BG



Flavor tagging
to determine initial B_s flavor

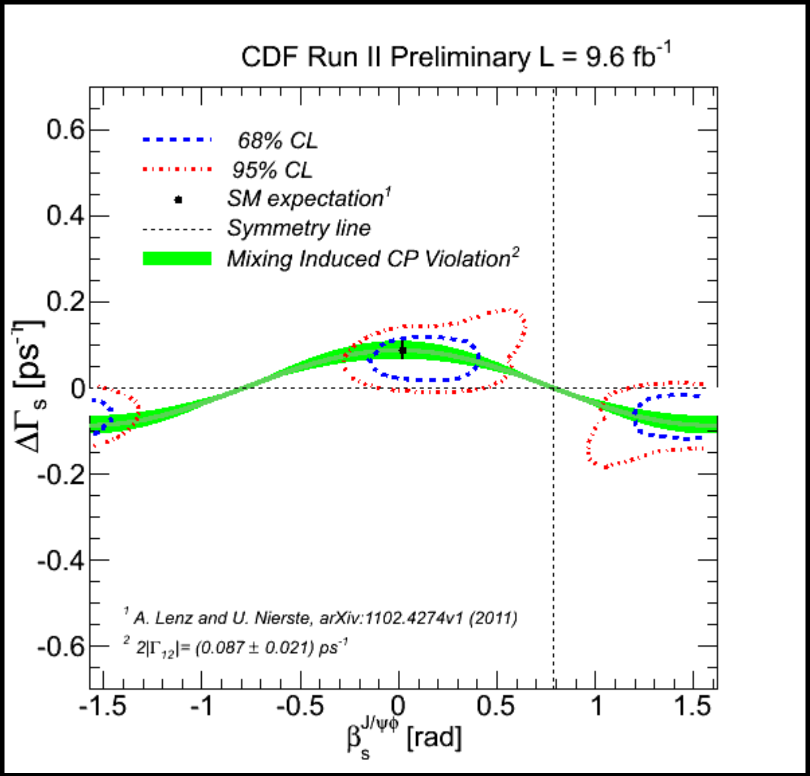


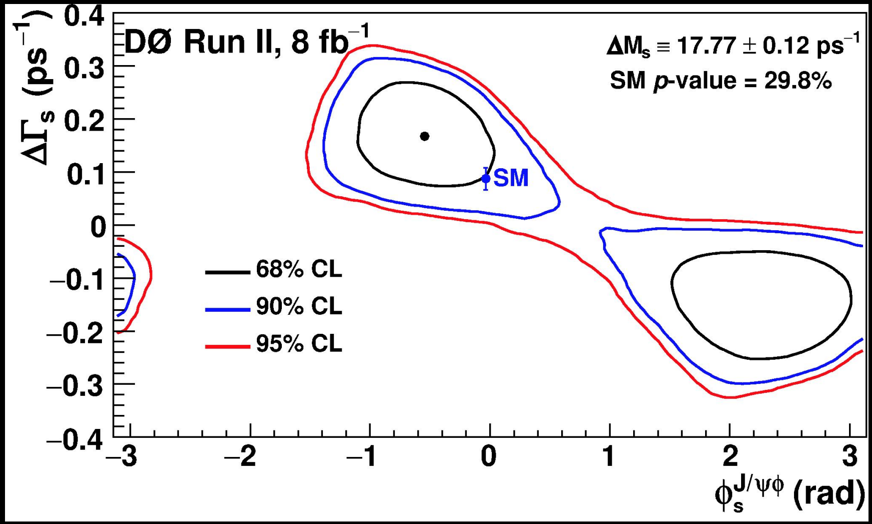
Decay time measurement
to know time evolution



Angular analysis
to separate CP-even/odd

Bs -> J/Ψ φ Result





- **NEW** result using full data!
- Consistent with SM <1σ

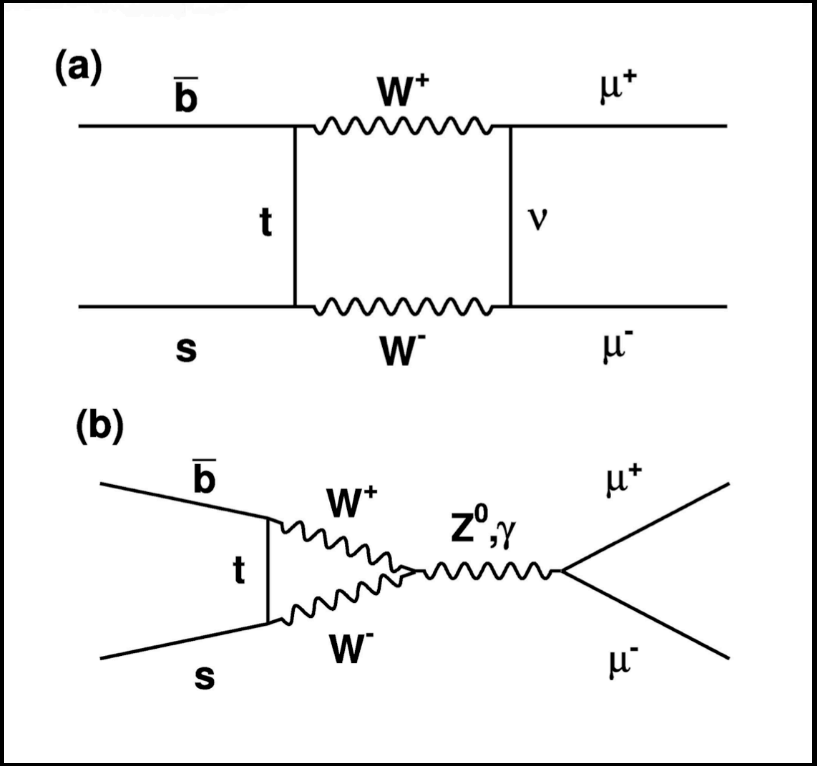
- Consistent with SM ~1σ

arXiv:1109.3166
(accepted by PRD)

First measurements (2008) showed intriguing 2.2σ discrepancy

B -> μ μ

- SM rate is well understood
- SM rate is small 3.2×10^{-9}
- Broad class of NP models w/new scaler operators) enhance it by 10x-1000x
- Experimental signature is very clean



Challenge: reject 10^6 larger bckg. Keep signal efficiency high

The Analysis

Trigger on two muons with $p_T > 1.5 - 2$ GeV/c

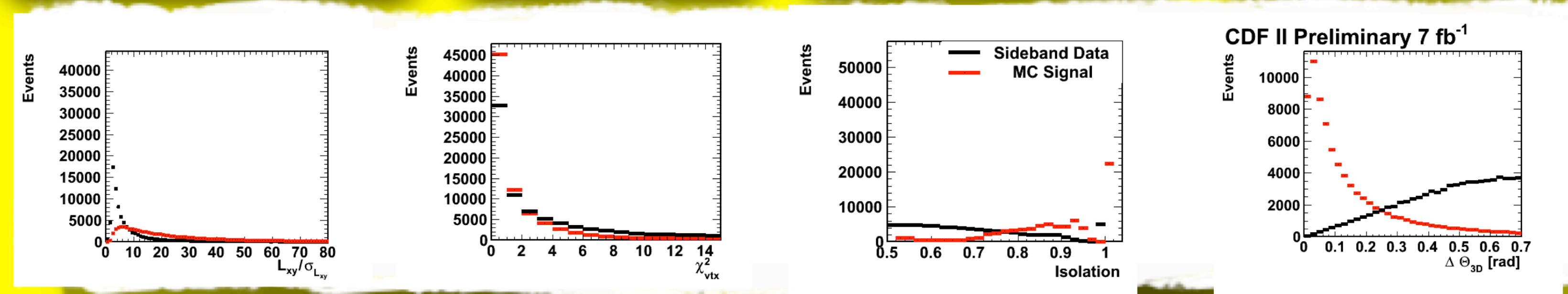
NN classifier separates S from B

lifetime

vertex quality

Isolation

Pointing

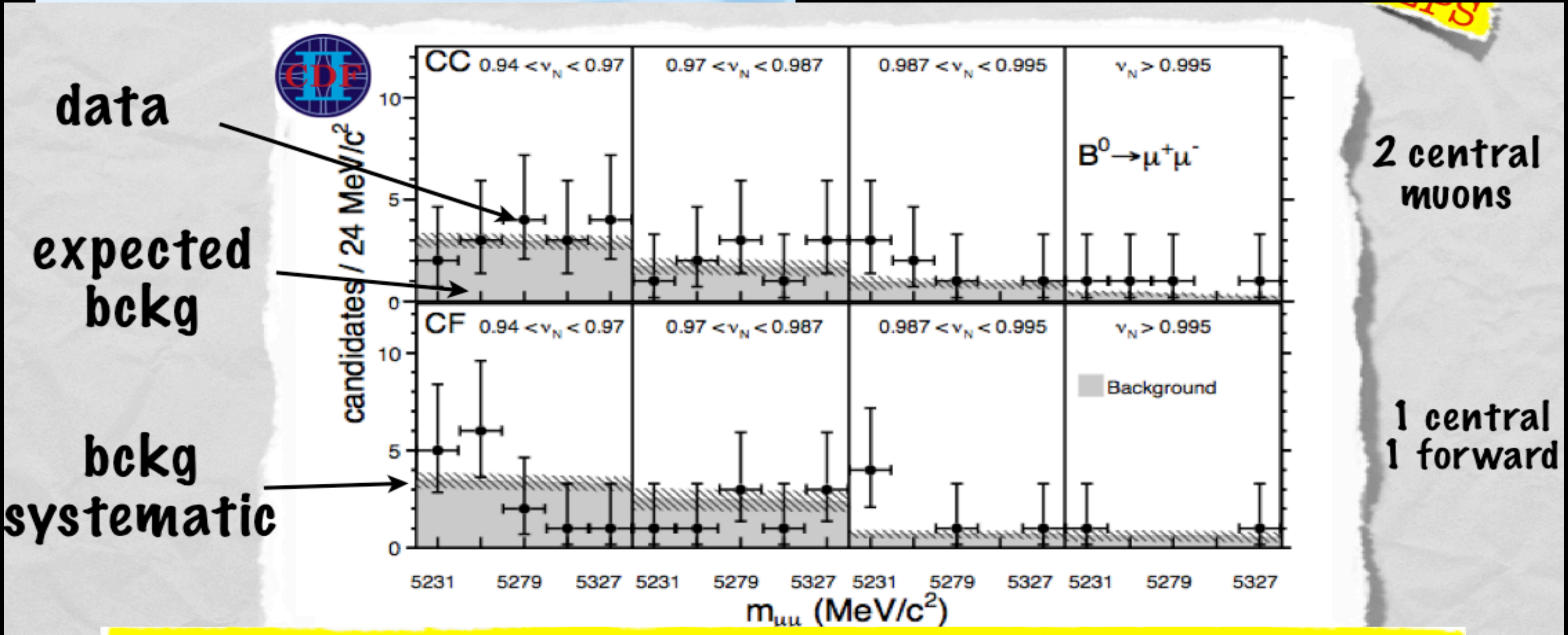


Bckg predicted using mass sidebands (comb.) and fake rates for B→hh. Checked on many control samples

Look at search region in bins of mass and NN.
Rate determined using $B^+ \to J/\psi K^+$ as reference

B^0 Results

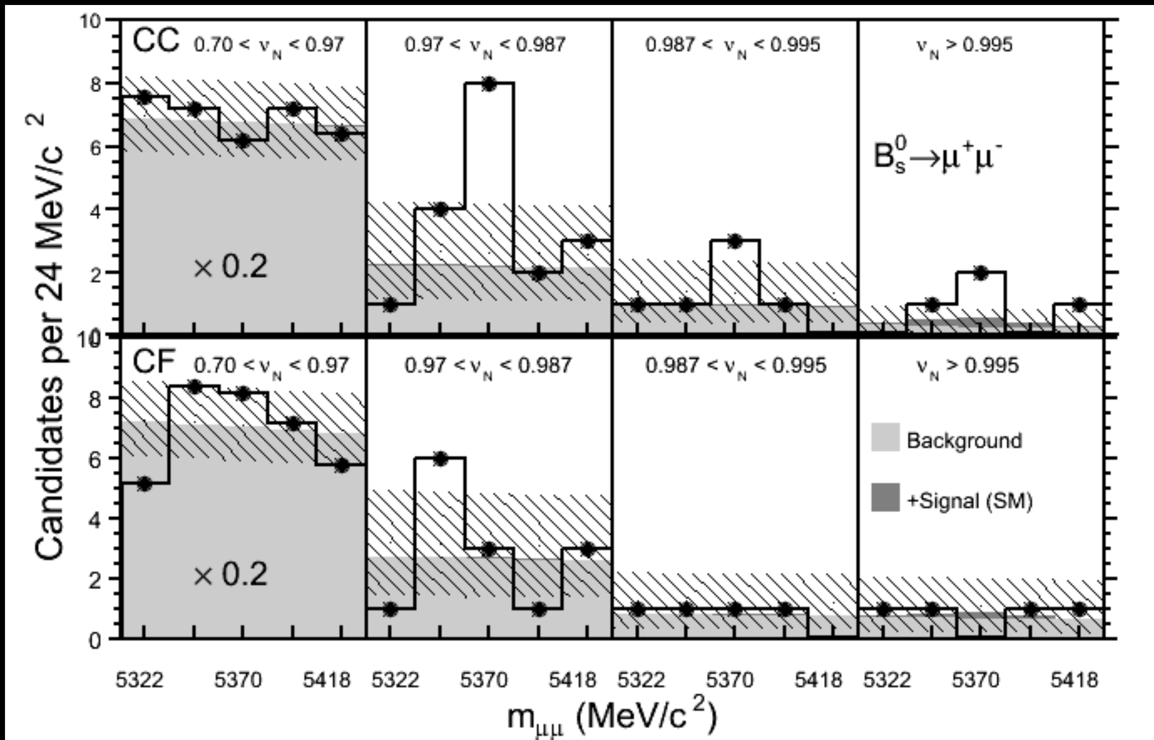
- Divide signal region by NN discriminant
- Estimate BG from each mass sideband

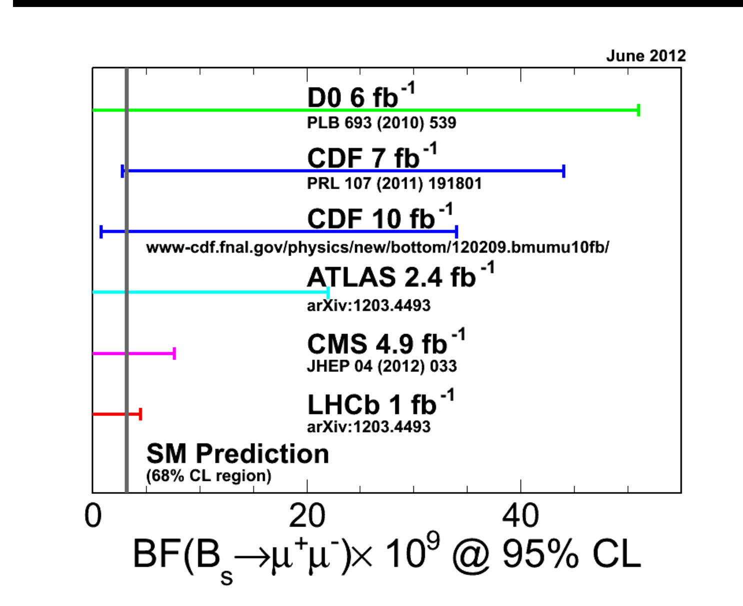


Bckg only fluctuate there or further 23% of times

Br < 6×10^{-9} at the 95% CL (expected < 4.6×10^{-9})

Bs -> μ μ





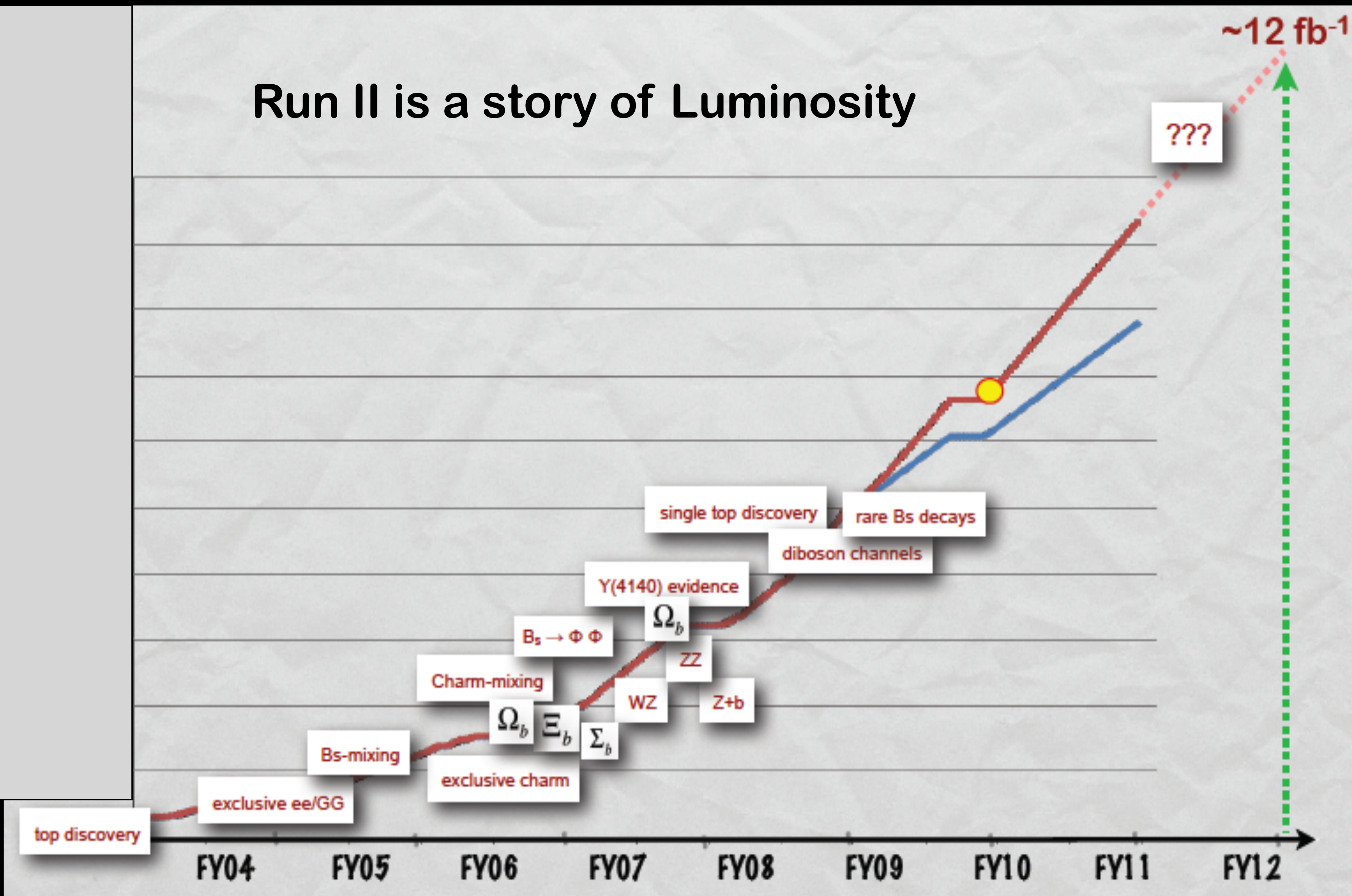
Summer excess not reinforced by new data, but still there

Observe a 2σ fluctuation over BG – so we quote a BR

$BR(B_s \rightarrow \mu^+\mu^-)=(1.3^{+0.9}_{-0.7}) \times 10^{-8}$

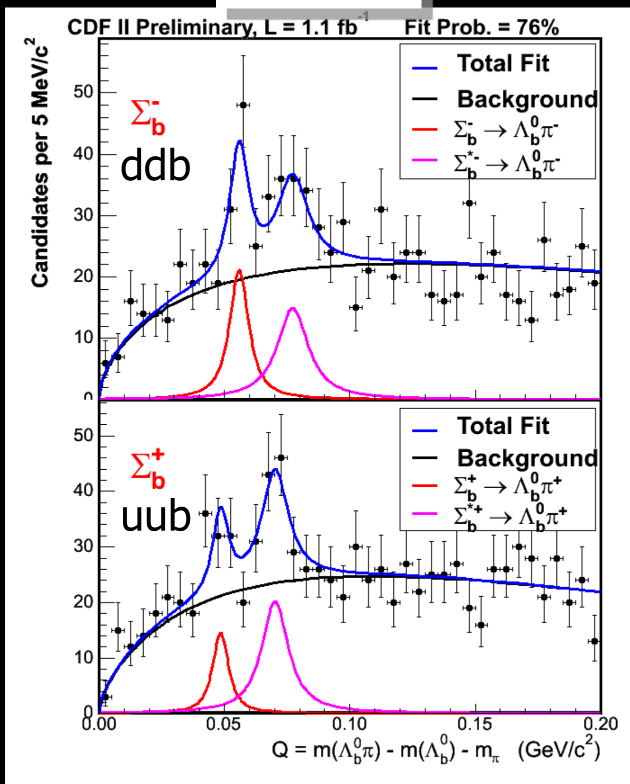
$0.8 \times 10^{-9} < BR(B_s \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-8}$ 95% C.L.

New Physics Shows Up Throughout

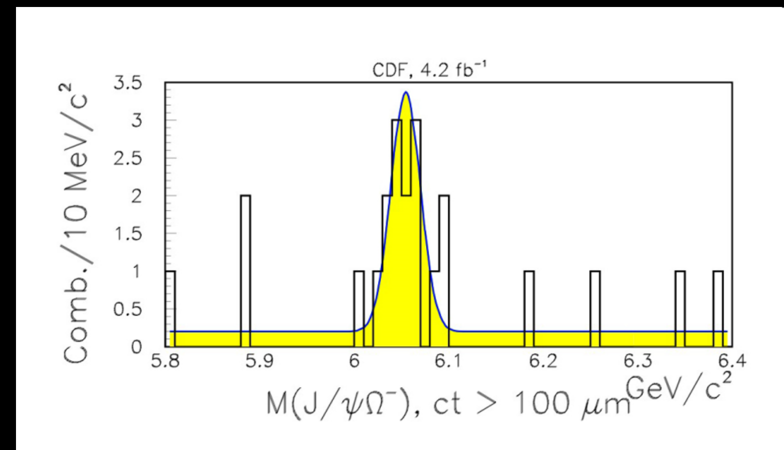


Observation of new heavy baryons

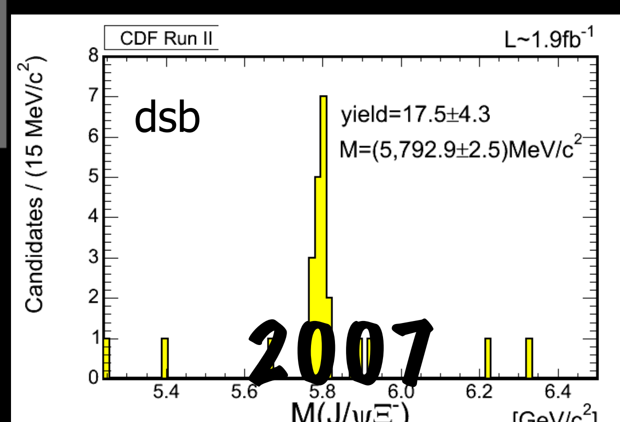
Σ_b



Ω_b

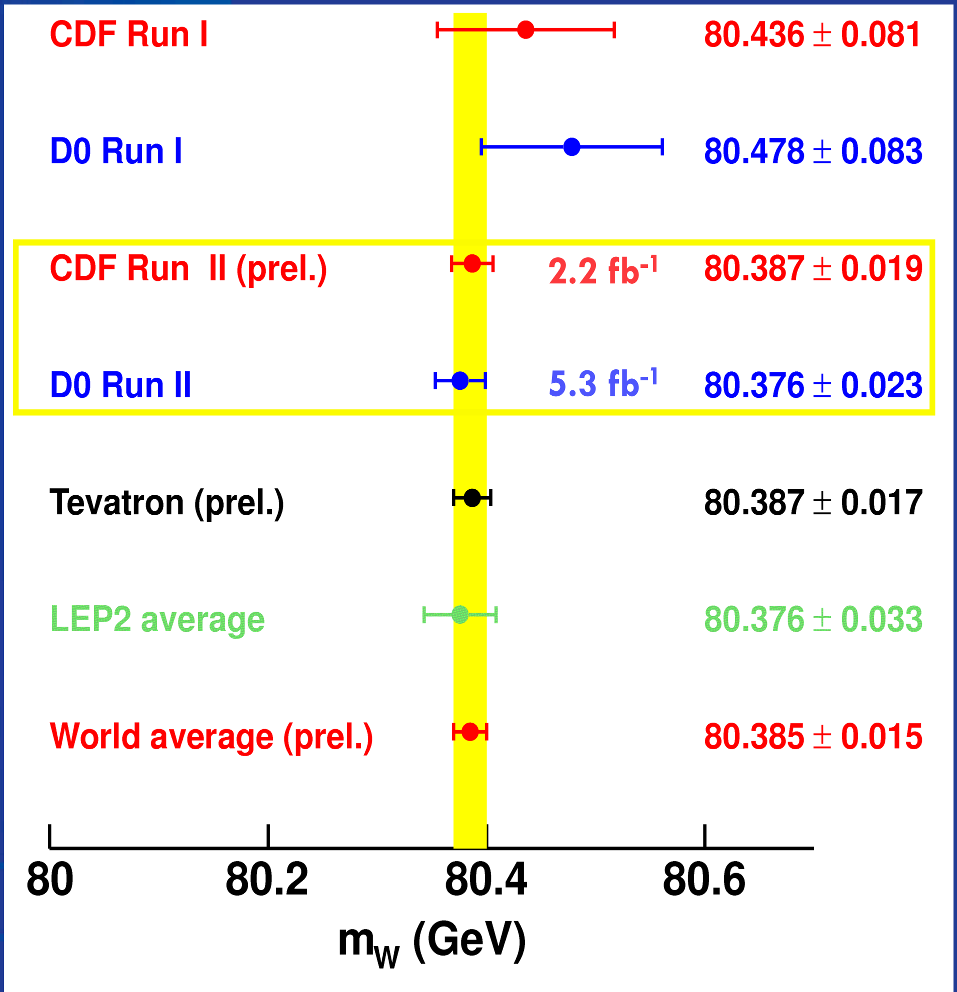


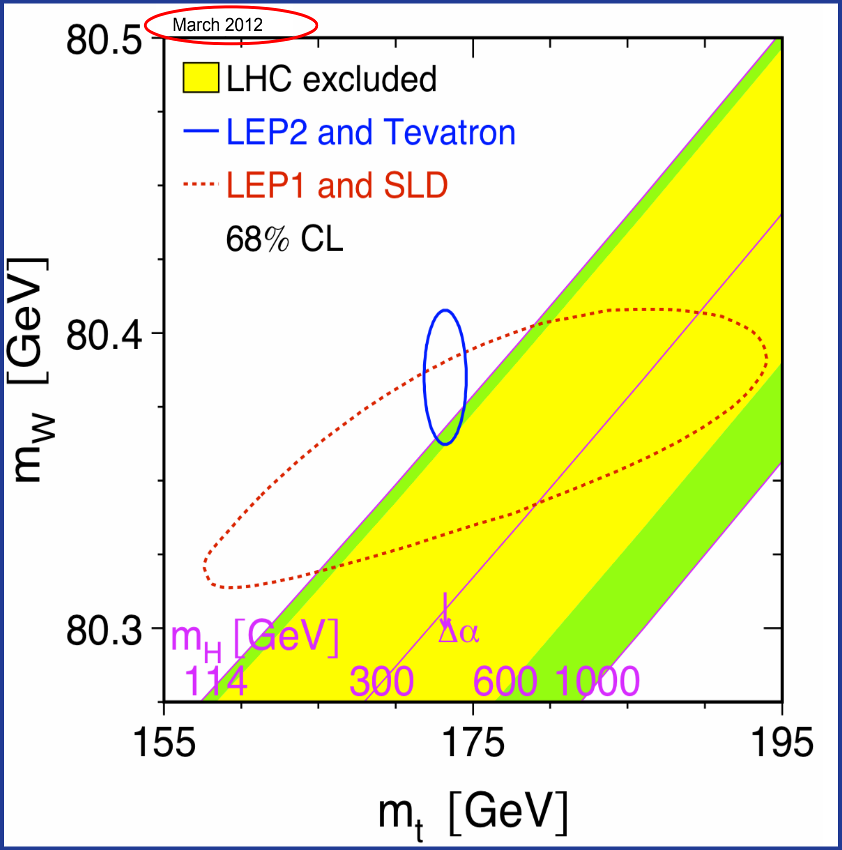
Ξ_b



2007

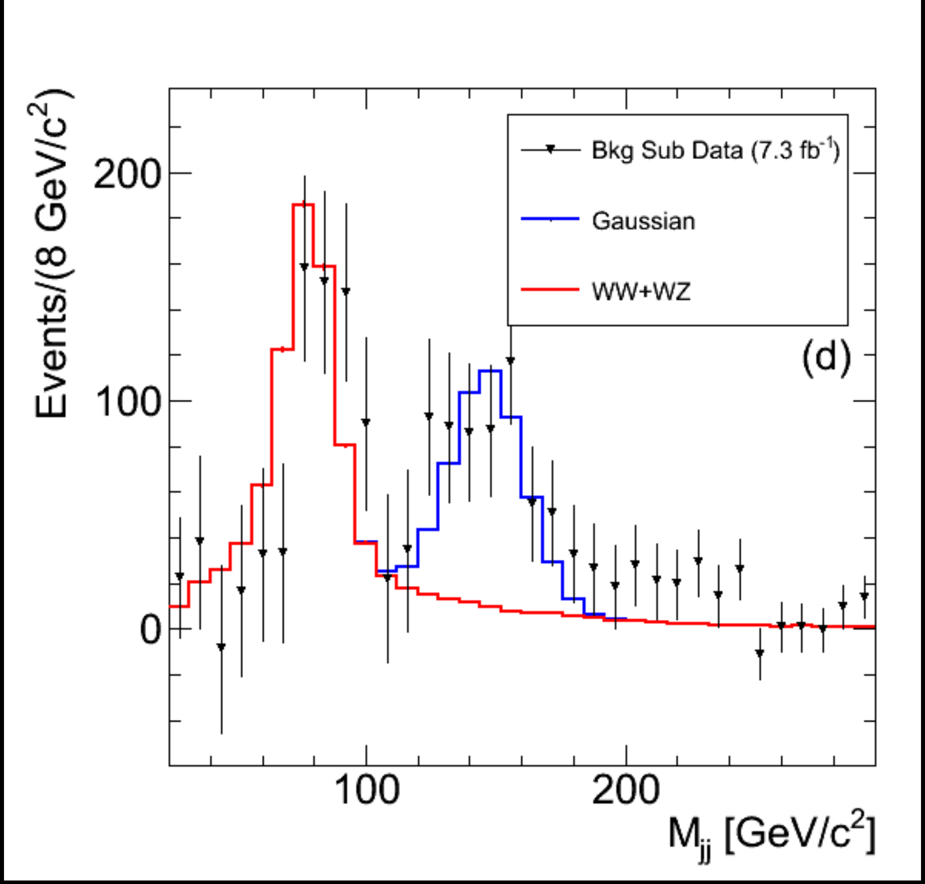
W Boson Mass





Approaching 10 MeV uncertainty

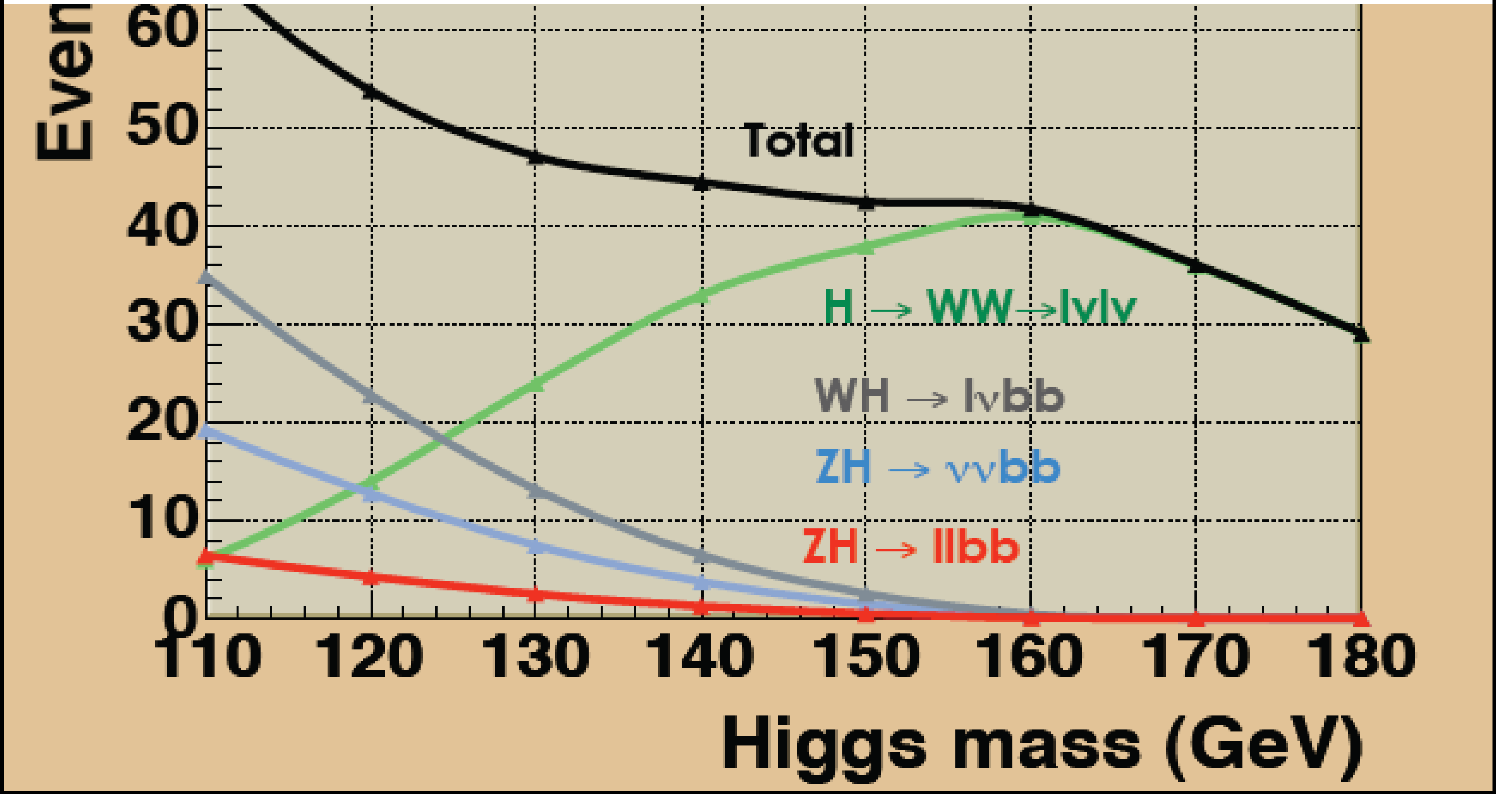
The Bump!!!



Looking for a W boson and 2 quarks (jets)

The challenge

Number of events produced per experiment in 6 months of running



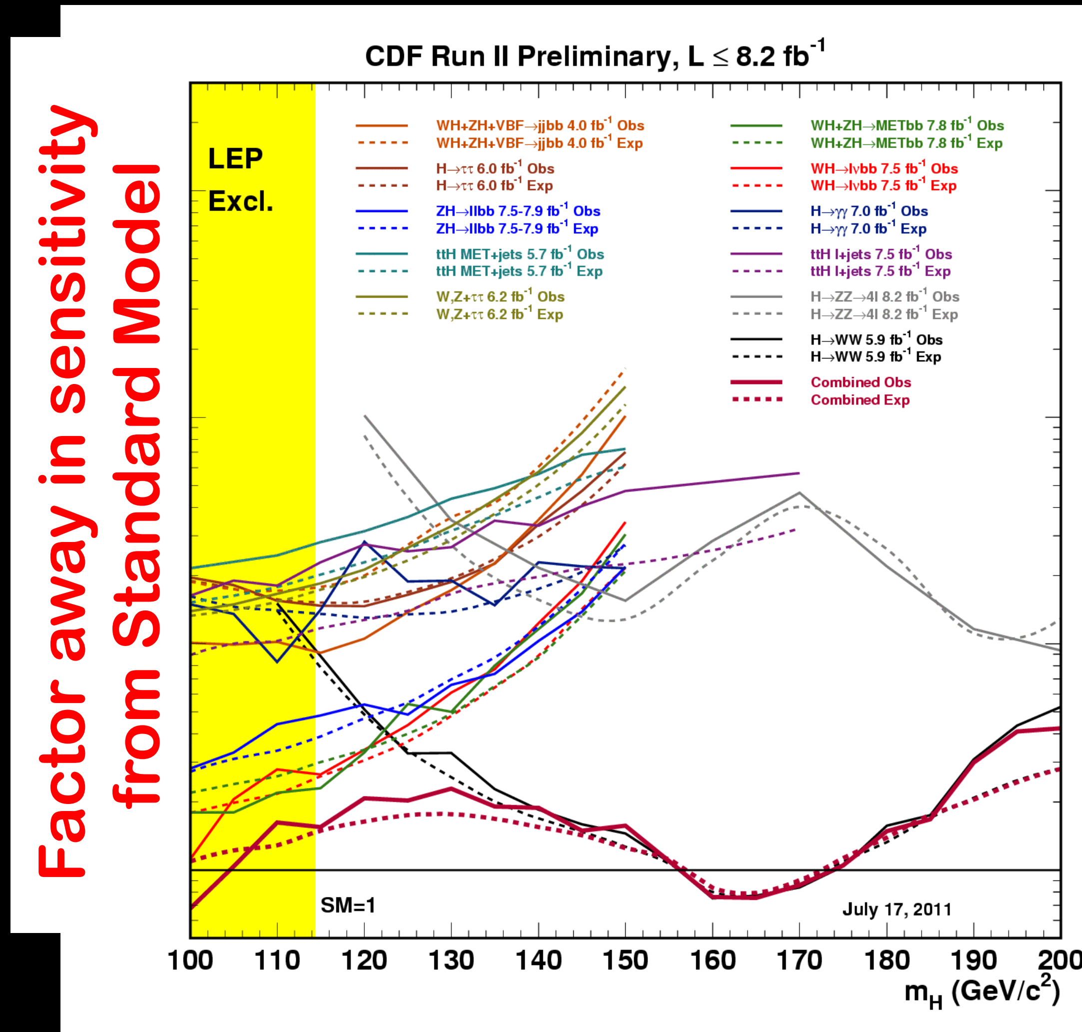
In 10 years, we've made about 500 Higgs in each experiment

This is a hard way to make a living!

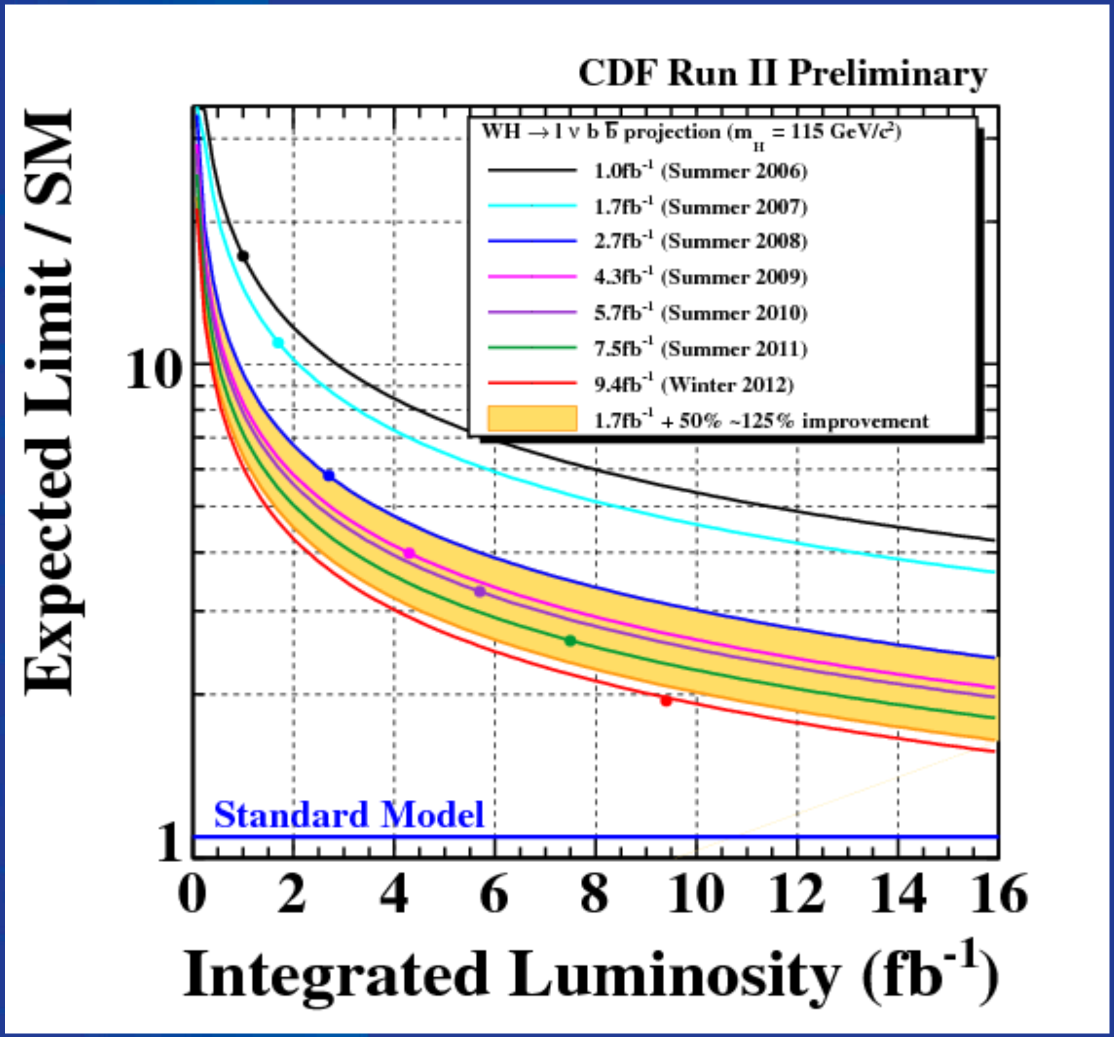
One experiment's channel combination

Four channels contribute almost equally in the interesting region - need to improve all 4!

- ZH→llbb
- WH→lνbb
- ZH→ννbb
- H→WW→lνlν
- Remaining channels have a combined weight of ~10%



Improving the analyses



Improvements beyond simply adding more data

Improved b-tagger (CDF)

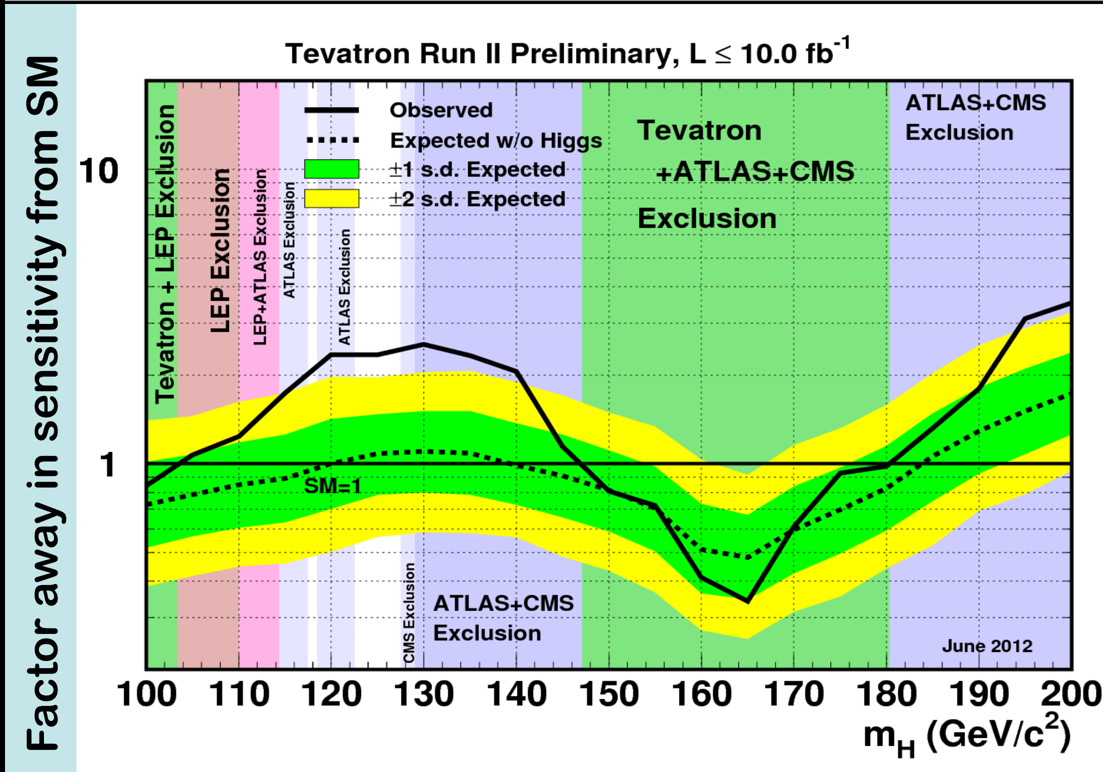
Improved dijet mass resolution (CDF)

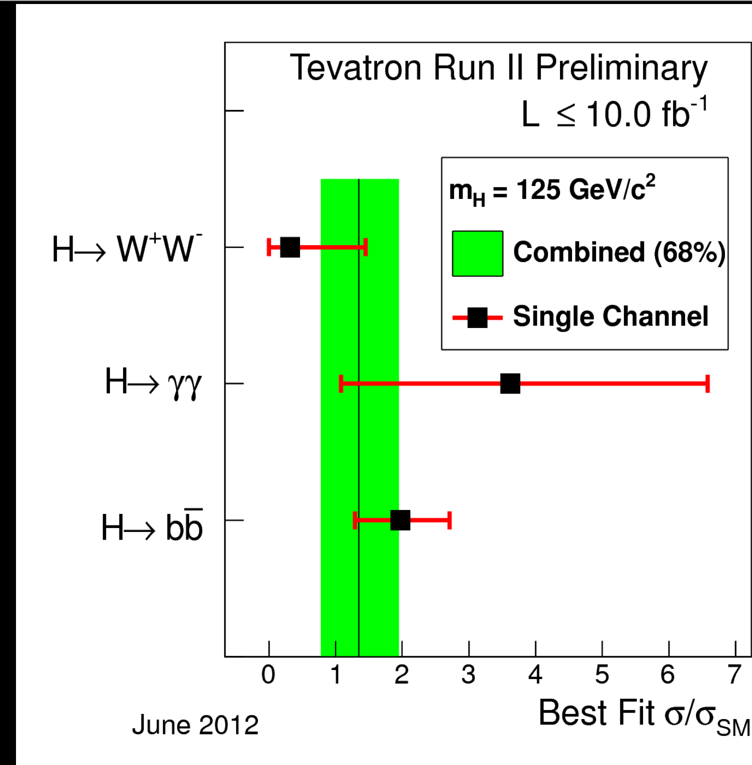
Improved acceptance with track missing momentum (DØ)

Improved multivariate analysis techniques

Improved modeling of backgrounds (with verification using WW/WZ)

CDF and DØ Higgs Searches with Full Data Set



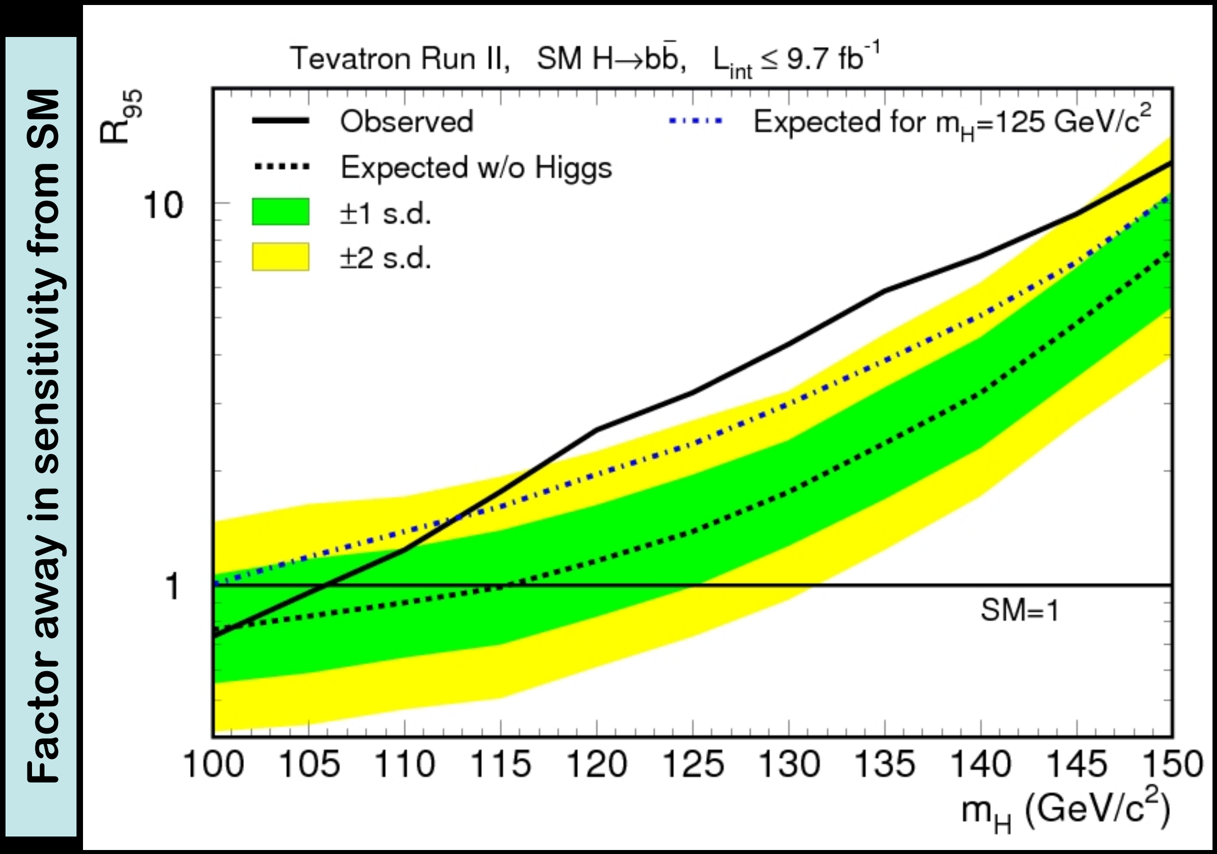


- Tevatron data are incompatible with background only hypothesis
  - For full combination of searches p-values are 3.0σ local or 2.5σ with LEE factor
  - For Higgs to bb channel p-values are 3.3σ local or 3.1σ with LEE factor
- Tevatron data are compatible with Standard Model Higgs boson production in the mass range 115 GeV < M_H < 135 GeV in all studied channels including H → bb, H → WW and H → γγ

CDF and DØ Higgs Searches with Full Data Set

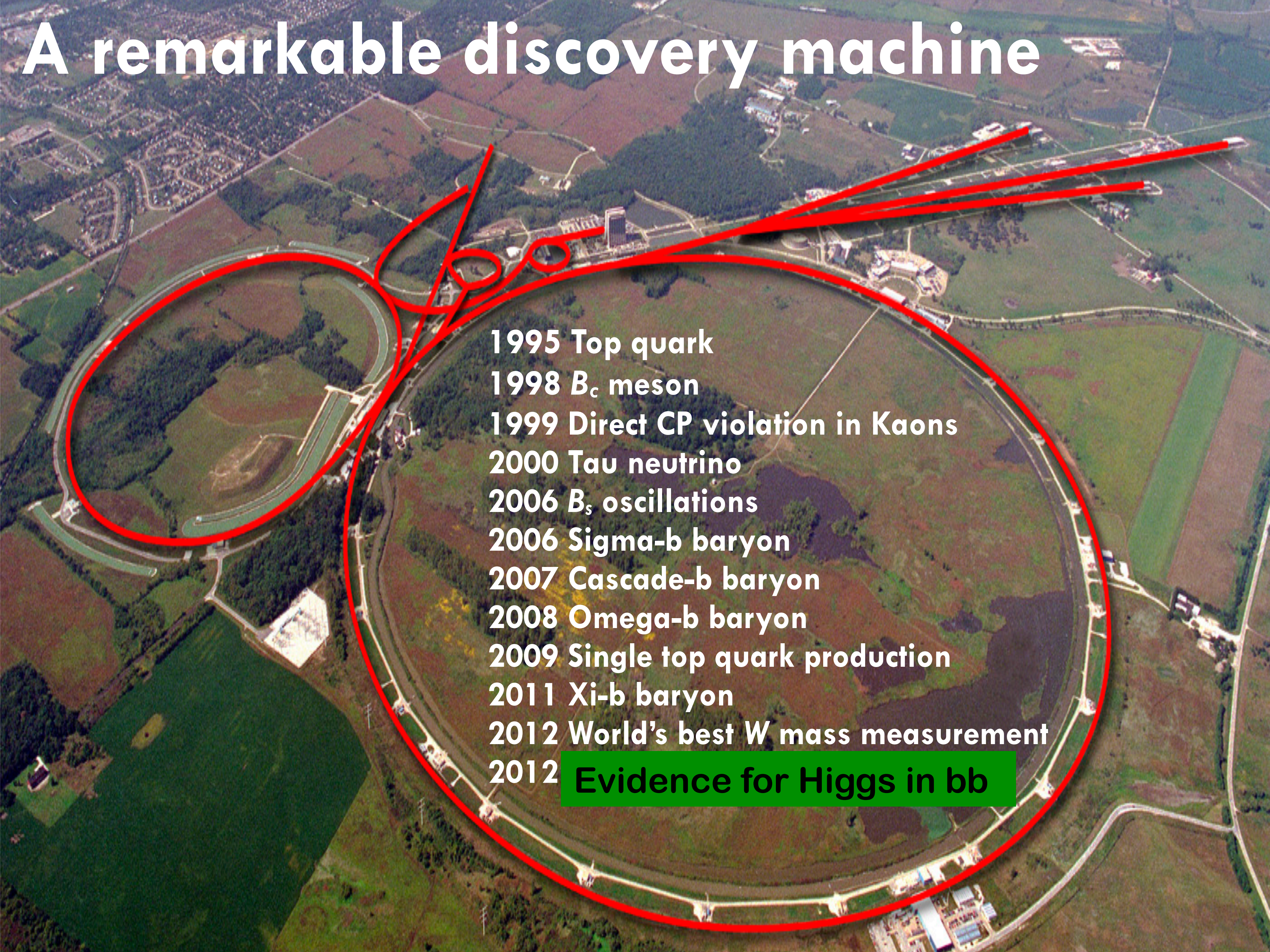
Combine our three primary low mass search channels

- WH→lνbb
- ZH→ννbb
- ZH→llbb



For Higgs to bb channel p-values are

- 3.3σ local
- 3.1σ with LEE factor


A remarkable discovery machine
1995 Top quark
1998 B_c meson
1999 Direct CP violation in Kaons
2000 Tau neutrino
2006 B_s oscillations
2006 Sigma-b baryon
2007 Cascade-b baryon
2008 Omega-b baryon
2009 Single top quark production
2011 Xi-b baryon
2012 World's best W mass measurement
2012 Evidence for Higgs in bb

The Legendary Tevatron

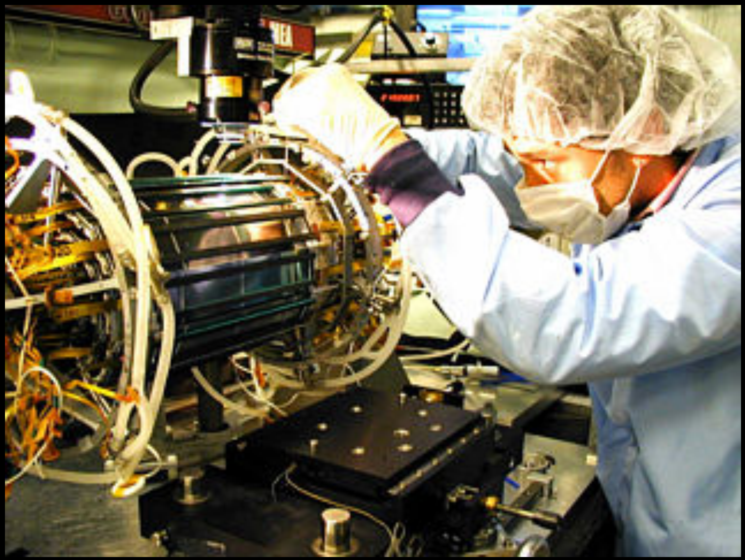
Accelerator Innovations

- First major SC synchrotron
- Industrial production of SC cable (MRI)
- Electron cooling
- New RF manipulation techniques

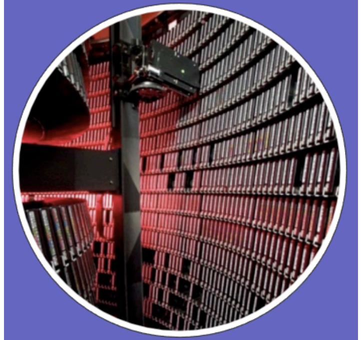
The Legendary Tevatron

Detector innovations

- Silicon vertex detectors in hadron environment
- LAr-U238 hadron calorimetry
- Advanced triggering

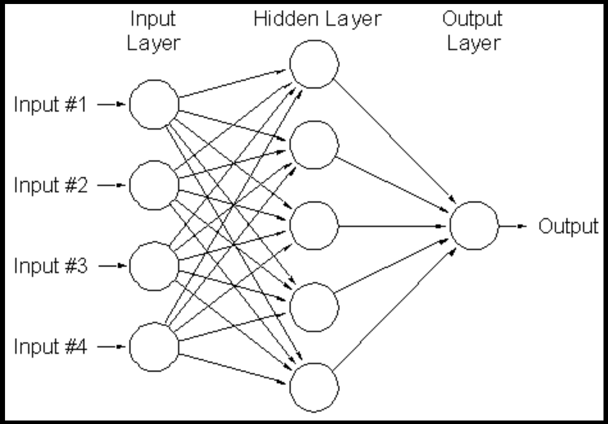


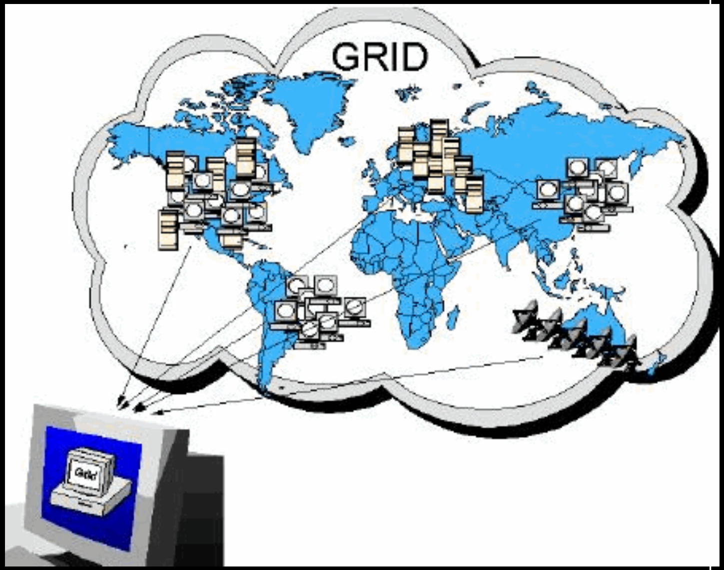
The Legendary Tevatron



Analysis Innovations

- Data mining from Petabytes of data
- Use of neural networks, boosted decision trees
- Major impact on LHC planning and developing
- GRID pioneers





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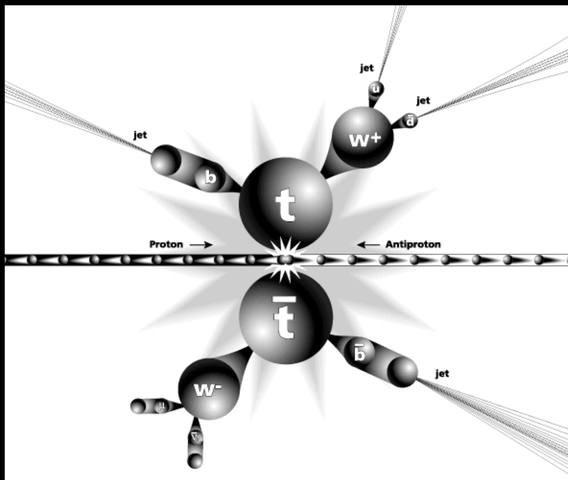
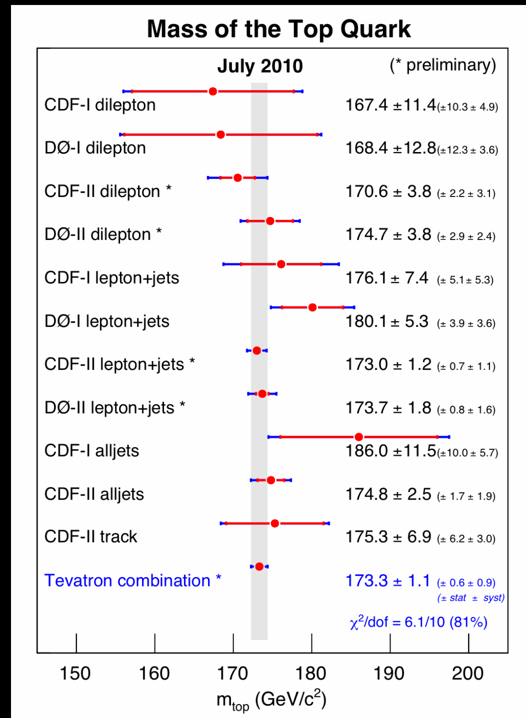
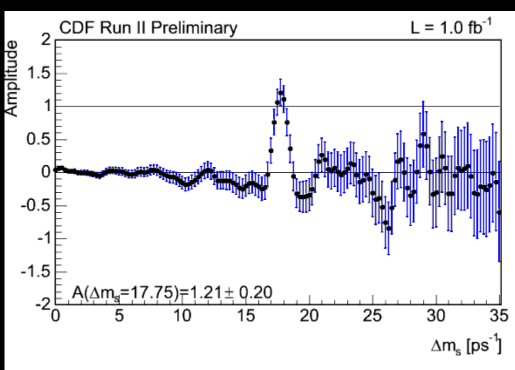
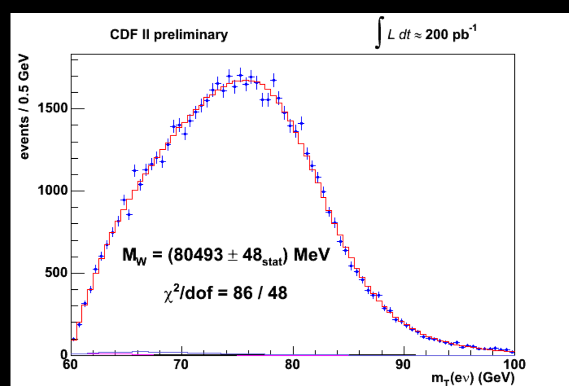








Major discoveries

- Top quark
- B_s mixing
- Precision W and Top mass → Higgs mass prediction
- Direct Higgs searches
- Ruled out many exotica

The Legendary Tevatron

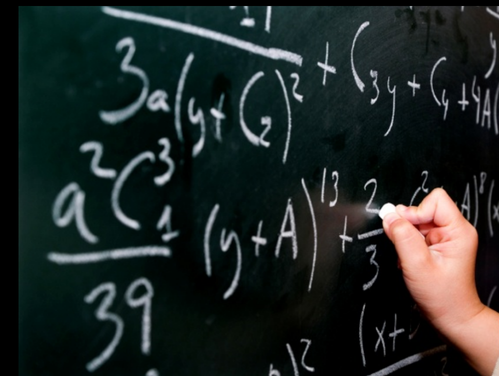
The next generation

- Fantastic training ground for next generation
- More than 500 Ph.D.s
- Produced critical personnel for the next steps, especially LHC

Impacts of Particle Physics on Society

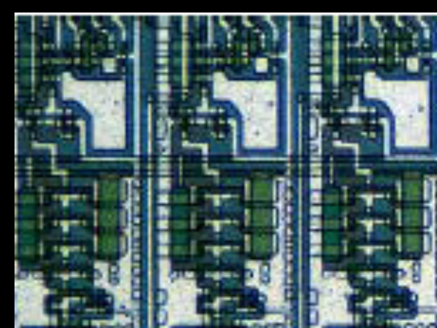
Medical Imaging

Bright x-rays Source
Chemistry, Biology, Materials



Education

Computing and WWW



Silicon Based Technology

Industry

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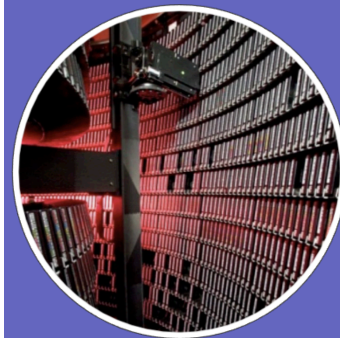

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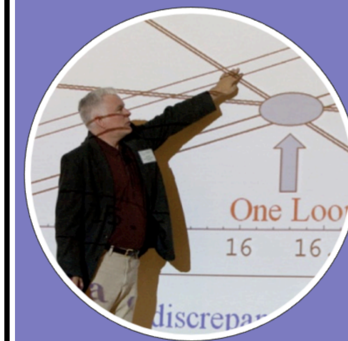

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