B Physics at the Tevatron and First B_s Mixing Results

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New England Particle Physics Students Retreat
August 14-19, 2005

The Caveats Slide

Who am I?

- + I am a CDF member and working on *B* physics
- + my main interest is measuring B_s mixing at CDF

A word on *B Physics*

- + there are 1001 topics
- + I have picked a very small selection
- + Tevatron does much more ....

My selection of plots

- + CDF and BaBar plots came easy
- + ... does not mean that I do not like DØ and/or Belle

Overview

Motivation and History

+ why do we care about b physics? $\rightarrow$ *CKM* matrix
+ first important B physics measurements

Introduction to the Experimental Setup

+ b production mechanisms as motivation
+ B Factories versus Tevatron
+ BaBar/Belle versus CDF/DØ

Some Details about Mixing Analyses

+ tools for the measurement
+ B^0 mixing
+ first results on B_s mixing

Web Pointers etc.

The experiments

- Tevatron: http://www-cdf.fnal.gov/, http://www-d0.fnal.gov/
- *B* Factories: http://www.slac.stanford.edu/BFROOT, http://belle.kek.jp/

Overview reports

- *B* Physics at the Tevatron: Run II and Beyond
  http://arXiv.org/pdf/hep-ph/0201071
- The BaBar Physics Book
  http://www.slac.stanford.edu/pubs/slacreports/slac-r-504.html

Videos / transparencies on the web

- SLAC summer school 2002:
  http://www-conf.slac.stanford.edu/ssi/2002/
- MIT Course: Heavy Flavor Physics (F. Würthwein)
  http://mit.fnal.gov/˜fkw/teaching/mit8.881.html

Symmetries in Particle Physics

Lewis Carrol's (1872)
Through the Looking Glass

+ Alice climbs through the mirror and .... finds a world very different from the expected reversed world
+ clocks had actual faces, chess pieces walked about, flowers talked *etc*.

+ this seems to be the theme for symmetries in particle physics in the last century
+ broken symmetries had a deep impact on the consciousness of physicists

Symmetries in Particle Physics

Electromagnetism basics understood by 1900

- Maxwell's equations

Quantum Electro Dynamics understood by 1950

- Renormalization of QED

Electromagnetism conserves 3 symmetries

- *P* parity – reversal of the three spatial dimensions
- *C* charge conjugation – particle ⇔ anti–particle
- *T* time reversal

Broken Symmetries in Particle Physics

Weak Interaction violates P, C, T and CP:

P: asymmetric β ray spectrum in polarised Co^{60}

1957 C.S. Wu et al.

C: asymmetry of μ^+ and μ^- polarization from $\pi^\pm$ decay

1957 R.L. Garwin, L.M. Lederman, M. Weinreich

1957 J. Friedman, V. Telegdi

CP: in the neutral kaon system (K_S, K_L decays)

1964 J.H. Christenson, J.W. Cronin, V.L. Fitch, R. Turlay

T: rate difference for $K^0 \to \overline{K}^0$ as a function of proper time

1998 CPLEAR Collaboration

CP: in the neutral B system ($B^0 \to J/\psi K_S$ decays)

2000 BaBar and Belle Collaborations

The CP Puzzle and the CKM Matrix

Matter/antimatter asymmetry

- \+ why so much matter?
- \+ Sakharov says: *CP* must be violated
- \+ *CKM* matrix describes *CP* violation in SM
- \+ amount too small to explain matter/antimatter asymmetry
- \+ good spot for new physics

Sakharov's Conditions (1966)

- \+ proton must decay
- \+ universe had a thermal non-equilibrium phase
- \+ *CP* must be violated

Measure *CKM* matrix elements

- \+ unitarity condition $VV^{\dagger} = 1$
- \+ derive unitarity triangle

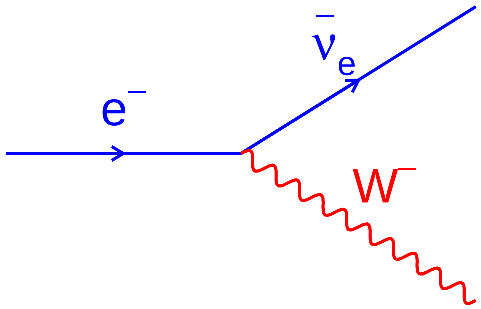
Matter in the Standard Model

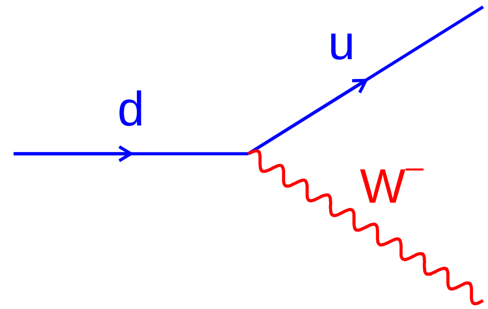
Matter build in families of weak isospin fermion doublets

Leptons $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$

Quarks $\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} b \\ t' \end{pmatrix}_L$

Weak interaction through $W^\pm$ bosons





In general: weak eigenstates ≠ mass eigenstates

+ mixing between families possible
+ lower quark doublet components absorb difference
+ neutrinos also mix

CKM Matrix

General form to describe mixing between quark families:

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

V is the Cabibbo–Kobayashi–Maskawa matrix

Wolfenstein parametrization ($\lambda = 0.224 \pm 0.012$):

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

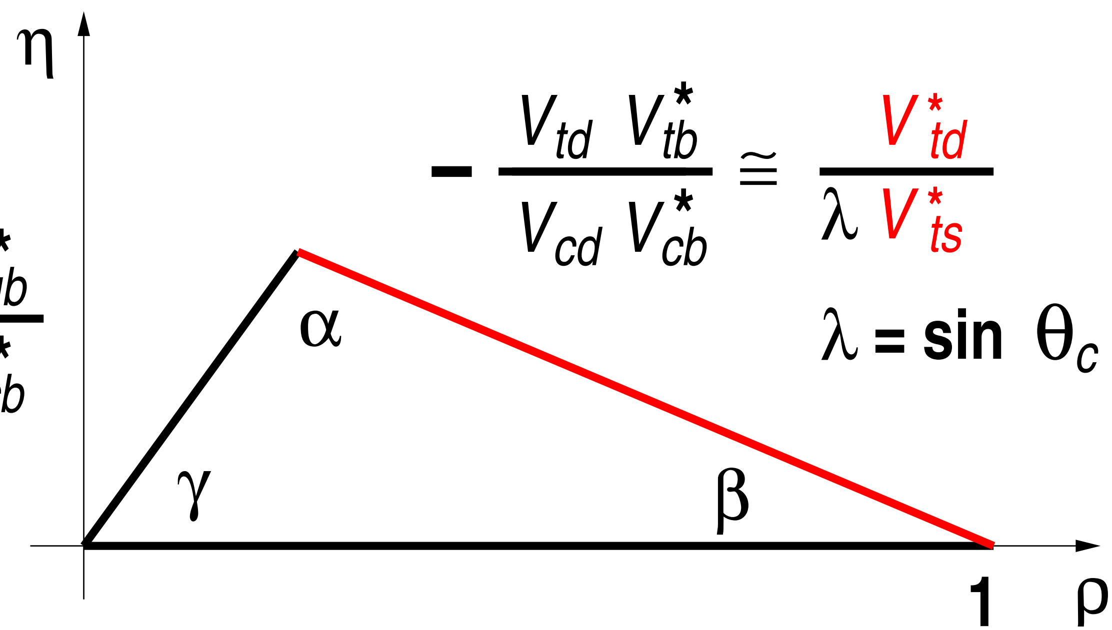
Least known parameters: ρ and η

Unitarity Triangle

Unitarity condition: $V^\dagger V = 1$ $\quad V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

$\rightarrow V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$

$\rightarrow -V_{ud}V^*_{ub}/V_{cd}V^*_{cb} - V_{td}V^*_{tb}/V_{cd}V^*_{cb} = 1$

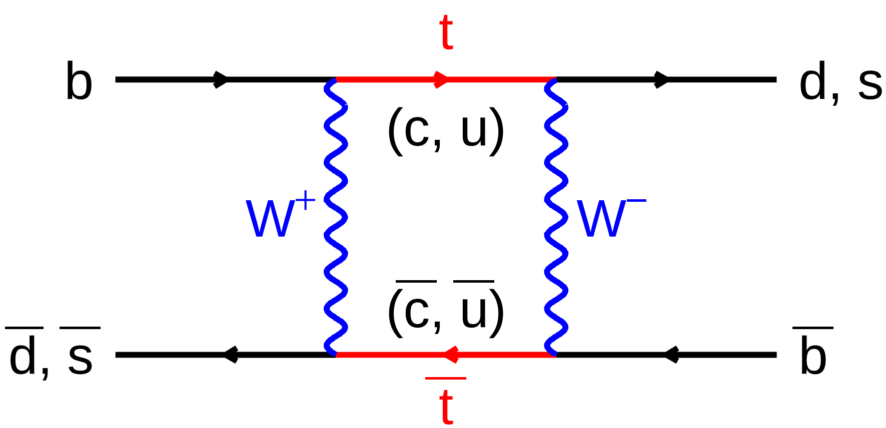


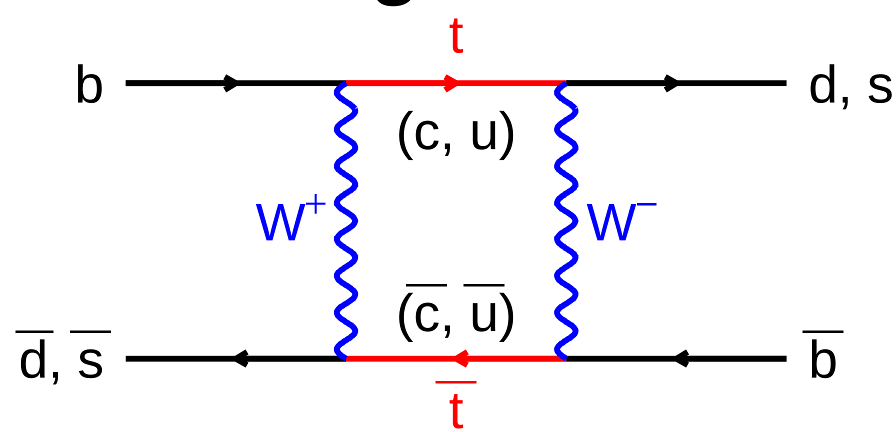
$$-\frac{V_{ud}\,V^*_{ub}}{V_{cd}\,V^*_{cb}}$$

$$-\frac{V_{td}\,V^*_{tb}}{V_{cd}\,V^*_{cb}} \cong \frac{V^*_{td}}{\lambda\, V^*_{ts}}$$

$\lambda = \sin\,\theta_c$

Neutral B Meson Mixing





Theory prediction for B^0/B^0_s mix through box diagram

$$\Delta m_q = \frac{G_F^2}{6\pi}\eta_B m_{B_q} \hat{B}_{B_q} f^2_{B_q} m^2_W S\left(\frac{m_t^2}{m_W^2}\right)\left|V_{tb}V^*_{tq}\right|^2$$

Lattice QCD calculations: $\hat{B}_{B_d} f^2_{B_d} = (246 \pm 11 \pm 25)\,\mathrm{MeV}^2$

old : $(228 \pm 30 \pm 10)\,\mathrm{MeV}^2$

Hadronic uncertainties limit $|V_{td}|$ determination to $\approx 11\%$

In ratio most theory uncertainties cancel

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}}\xi^2 |V_{ts}|^2/|V_{td}|^2 \quad \text{with} \quad \xi^2 = 1.21 \pm 0.02\,^{+0.035}_{-0.014}$$

old $1.21 \pm 0.04 \pm 0.05$

Determine $|V_{ts}|^2/|V_{td}|^2$ to $\approx 2.5\%$

Unitarity Triangle - Who Measures What?

Appex $(\bar{\rho}, \bar{\eta})$

Squeezing along side *b*

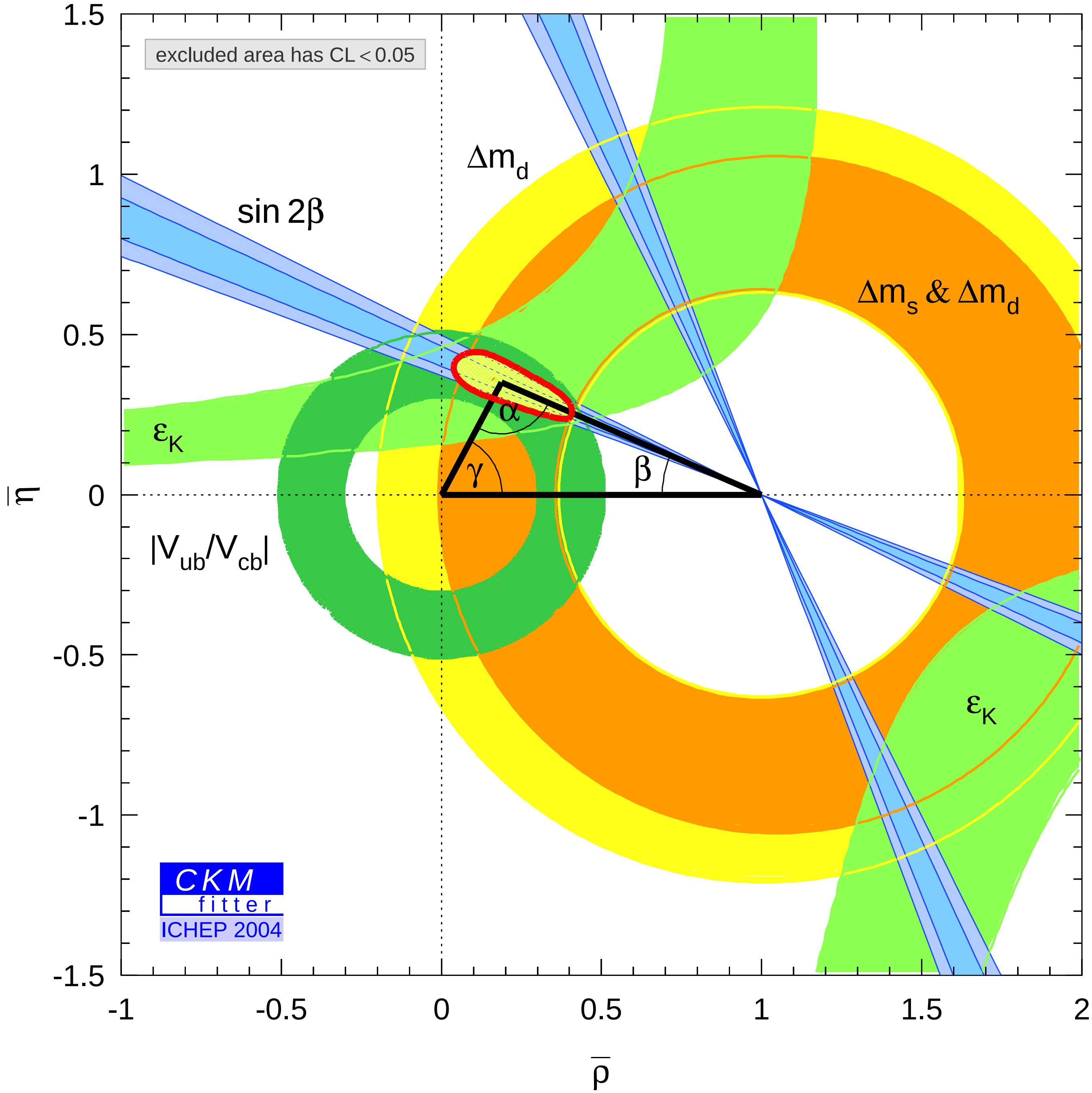
- $+$ $\sin 2\beta$
- $+$ V_{ub}/V_{cb}

Squeezing along side *c*

- $+$ Δm_d
- $+$ Δm_s

CKM fit result:

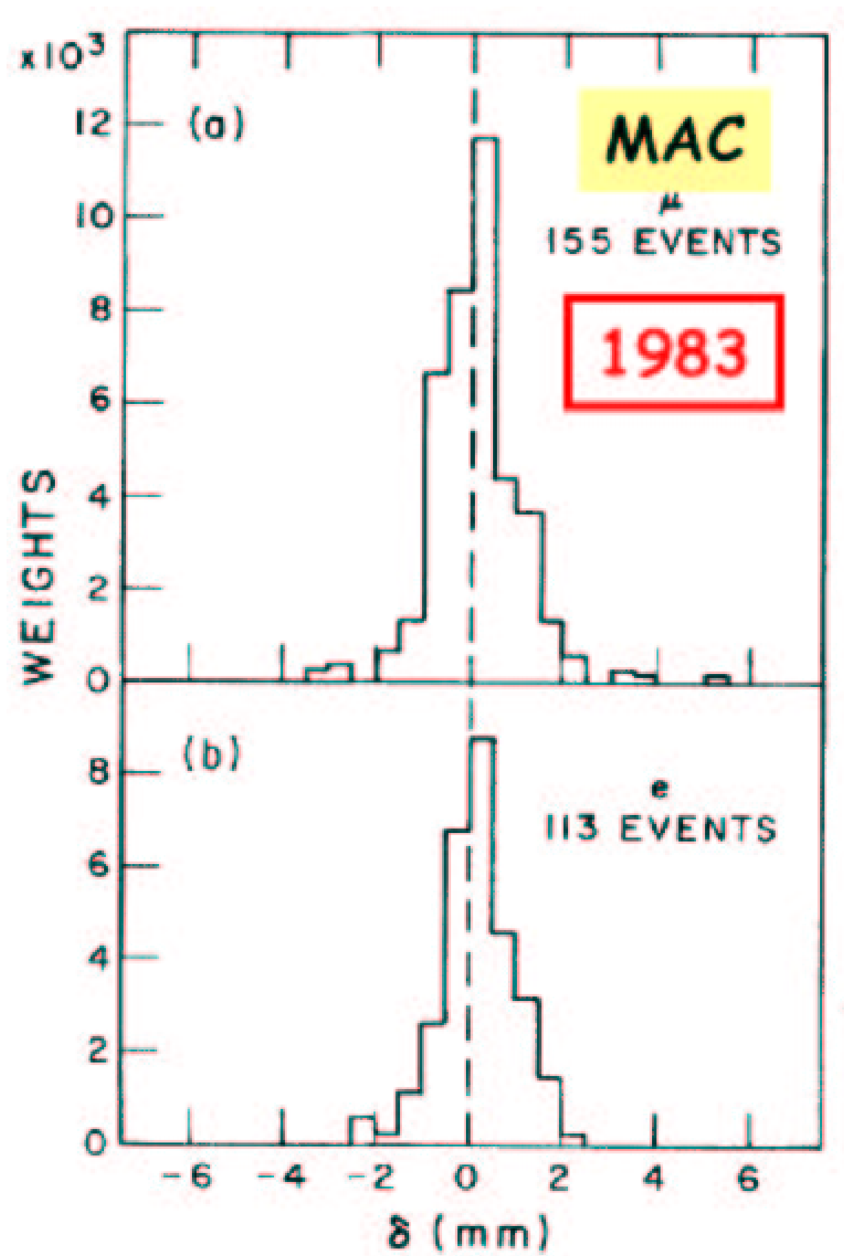
$\Delta m_s = 17.8\,^{+6.7}_{-1.6}\mathrm{ps}^{-1}$



First Measurements: B Lifetime (MAC/Mark II)

Sample of high p_T leptons

- p_T – transverse to thrust axis
- use track impact parameter, δ
- sign determined by jet direction
- 155 – muon events
- 113 – electron events



B lifetime governed by V_{cb}

MAC	$1.8 \pm 0.8 \pm 0.4$ ps	PRL **51** (1983) 1022
Mark II	$1.2 \pm 0.4 \pm 0.3$ ps	PRL **51** (1983) 1316

- larger than expected
- large $c\tau_B$ means small V_{cb}

Experimental details

- e^+e^- at $\sqrt{s} = 29$ GeV
- 109 pb^{-1} integrated luminosity
- about 3,500 $b\bar{b}$ pairs

First Measurements: B^0 Mixing (Argus)

At $\Upsilon(4S)$ resonance

- + $m_{\Upsilon(4S)}(10.580\text{ GeV}) >$
  $> 2 \times m_B(5.279\text{ GeV})$
- + $\Upsilon(4S) \to B^0\overline{B}^0 \to B_1^0 B_2^0$
- + 25 like sign events
- + 270 opposite sign events

Time integrated mixing

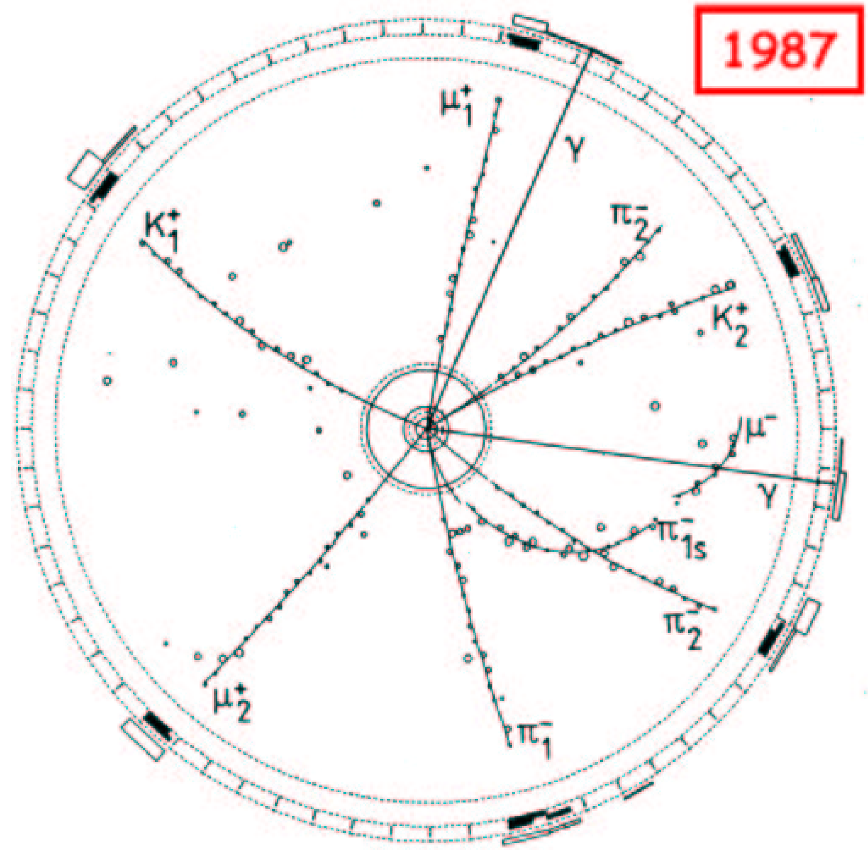
Argus $\chi_b = 0.17 \pm 0.05$ PL B **192** (1987) 245

- + slower than expected
- + indication for heavy top

Experimental details

- + e^+e^- at $\sqrt{s} = 10.58$ GeV
- + 113 pb^{-1} integrated luminosity
- + about 110,000 $b\overline{b}$ pairs

Start of $\Upsilon(4S)$ success story



A like sign event!!

$B_1^0 \to D_1^{*-}\mu_1^+\nu_1; D_1^{*-} \to \overline{D}^0\pi_{1s}^-$

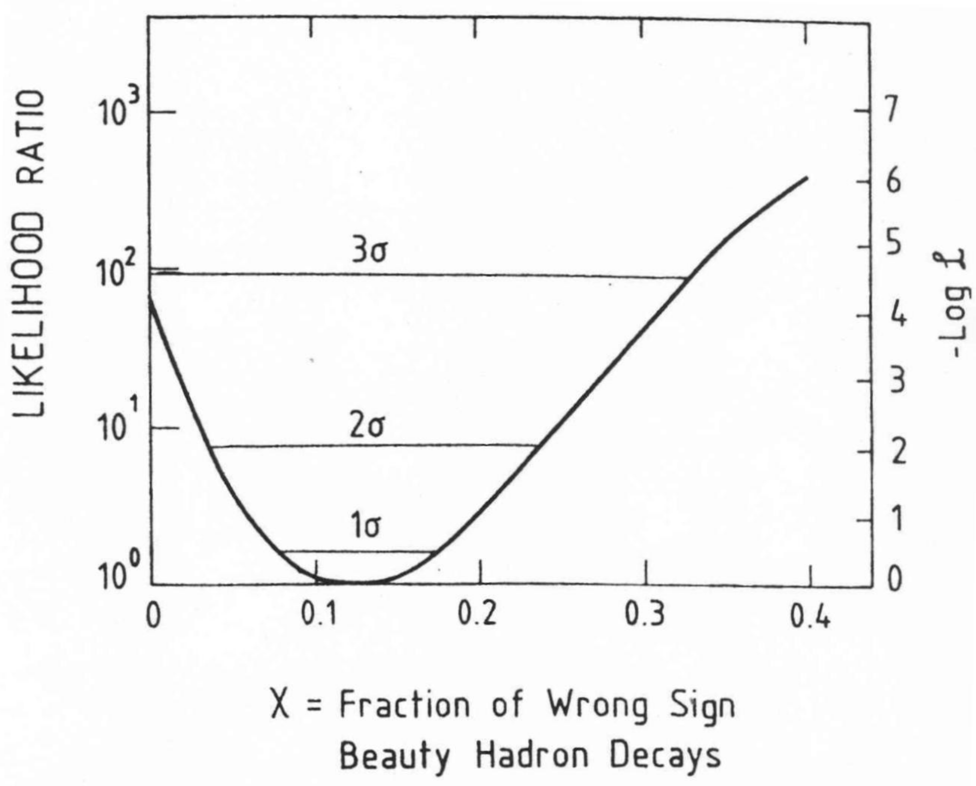
$B_2^0 \to D_2^{*-}\mu_2^+\nu_2; D_2^{*-} \to D^-\pi^0$

First Measurements: B^0 Mixing (UA1)

Inclusive measurement at $p\bar{p}$ collider

PL B **186** (1987) 247

+ signature: like sign high p_T leptons; UA1 got it first: 3 sigma



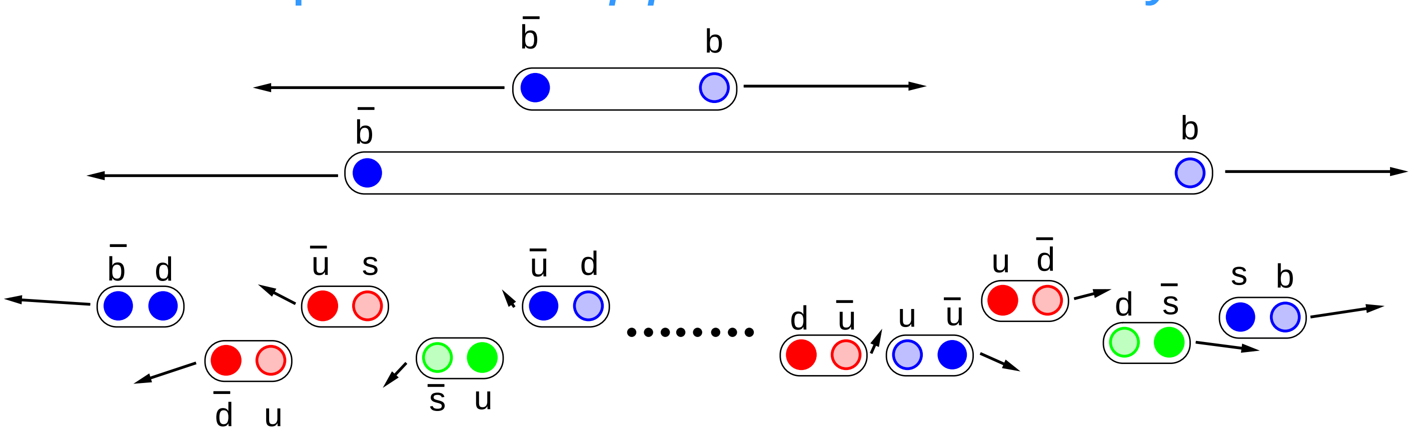
Argus at the time excluded this value at 90% CL

Start of the $p\bar{p}$ B physics success story

Producing b Quarks / b Hadrons

Quark confinement

+ color string between quarks and gluons
+ to the outside: quark ensemble colorless
+ meson: color+anticolor; baryons: blue+green+red, ..
+ energy stored in string increases with distance
+ string breaks up and new quarks are created
+ controlled process (one pair) at $\Upsilon(4S)$ = clean
+ uncontrolled process in $p\bar{p}$ collisions = dirty

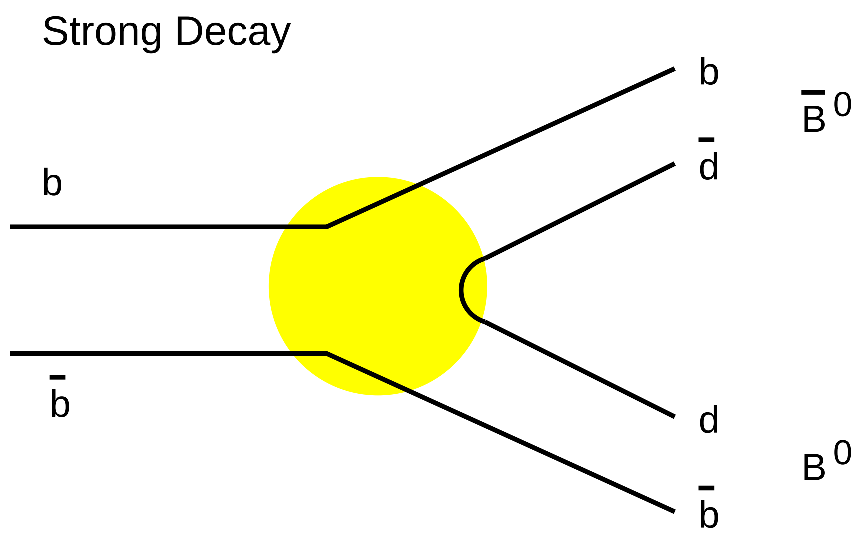


Simplistic but instructive fragmentation model

$\Upsilon(4S)$ *versus* $p\bar{p}$

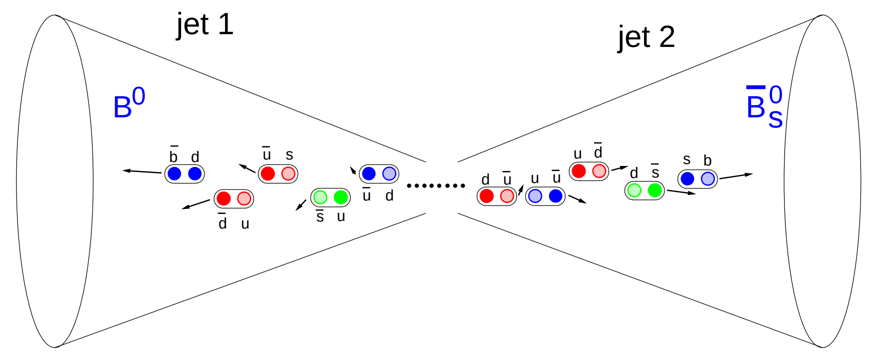
At $\Upsilon(4S)$

- \+ simple e^+e^- as input
- \+ *CM* energy enough for B^0, B^+
- \+ minimal fragmentation
- \+ asymmetric beams cause boost
- \+ coherent $B^0\bar{B}^0$ pair



At $p\bar{p}$ colliders

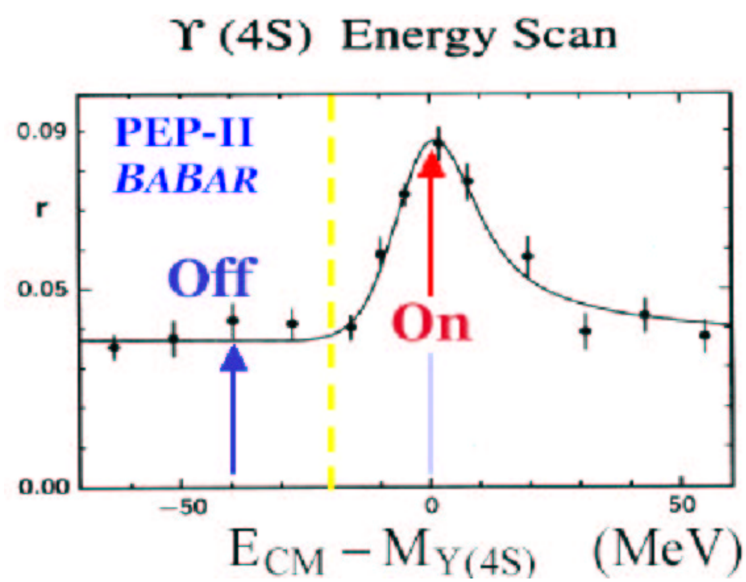
- \+ complicated $p\bar{p}$ as input
- \+ *CM* energy varies tremendously
- \+ always fragmentation
- \+ boost intrinsic:
  $\rightarrow$ hadrons not at rest
- \+ incoherent $b\bar{b}$ pair

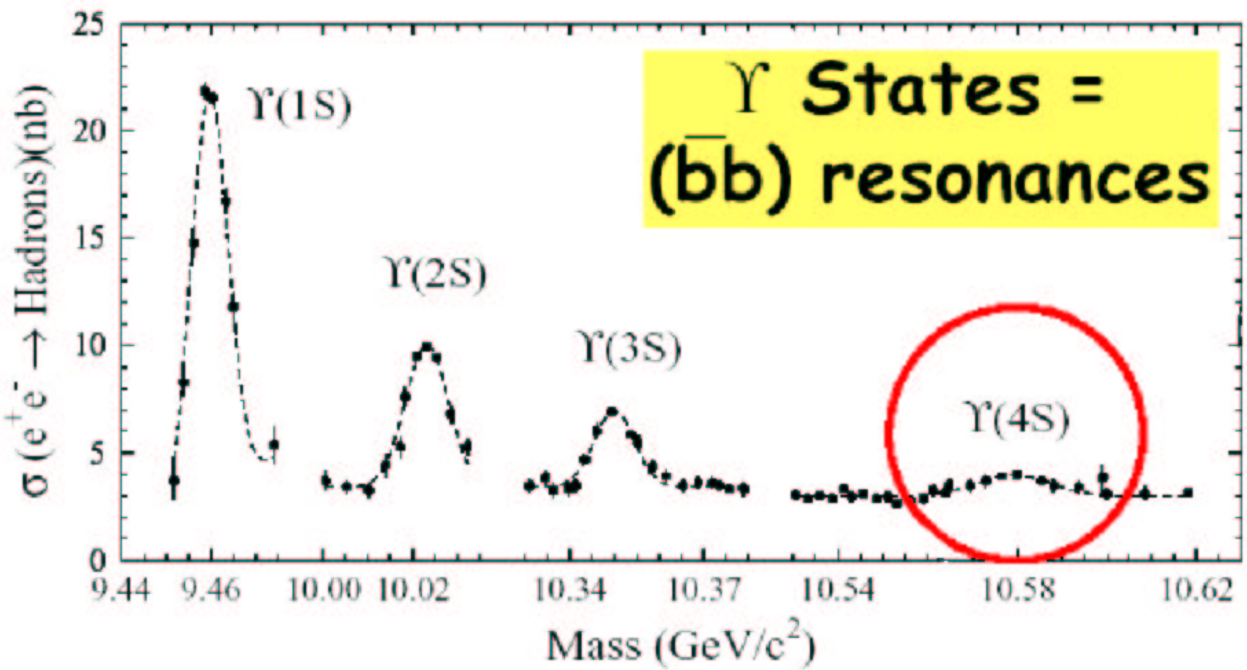


$\Upsilon(4S)$ *Resonance*

Available CM energy $\Upsilon(4S)$

+ $m_{\Upsilon(4S)} = 10.580$ GeV
+ $2 \times m_{B^0,B^+} \approx 10.54$ GeV yes!
+ $m_{B_s} + m_{B^0} \approx 10.64$ GeV no!
+ B_s, B_c^+, Λ_b, Ξ_b .. not accessible





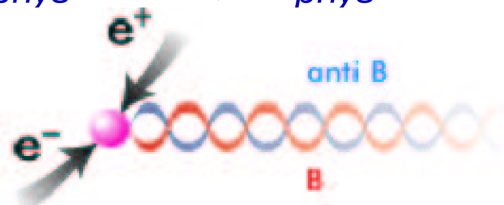
$\Upsilon(4S)$ Cross Sections

+ $\sigma(b\bar{b}) \approx 1.1$ nb
+ $\sigma(c\bar{c}) \approx 1.3$ nb
+ $\sigma(d\bar{d}, s\bar{s}) \approx 0.3$ nb
+ $\sigma(u\bar{u}) \approx 1.4$ nb

Coherent Production of $B^0\bar{B}^0$

Coherent state from $\Upsilon(4S)$ with $L = 1$ with $S(t_f, t_b) =$

$$\frac{\sin\theta}{\sqrt{2}}\left[B^0_{phys}(t_f,\theta,\phi)\bar{B}^0_{phys}(t_b,\pi-\theta,\phi+\pi)-\bar{B}^0_{phys}(t_f,\theta,\phi)B^0_{phys}(t_b,\pi-\theta,\phi+\pi)\right]$$

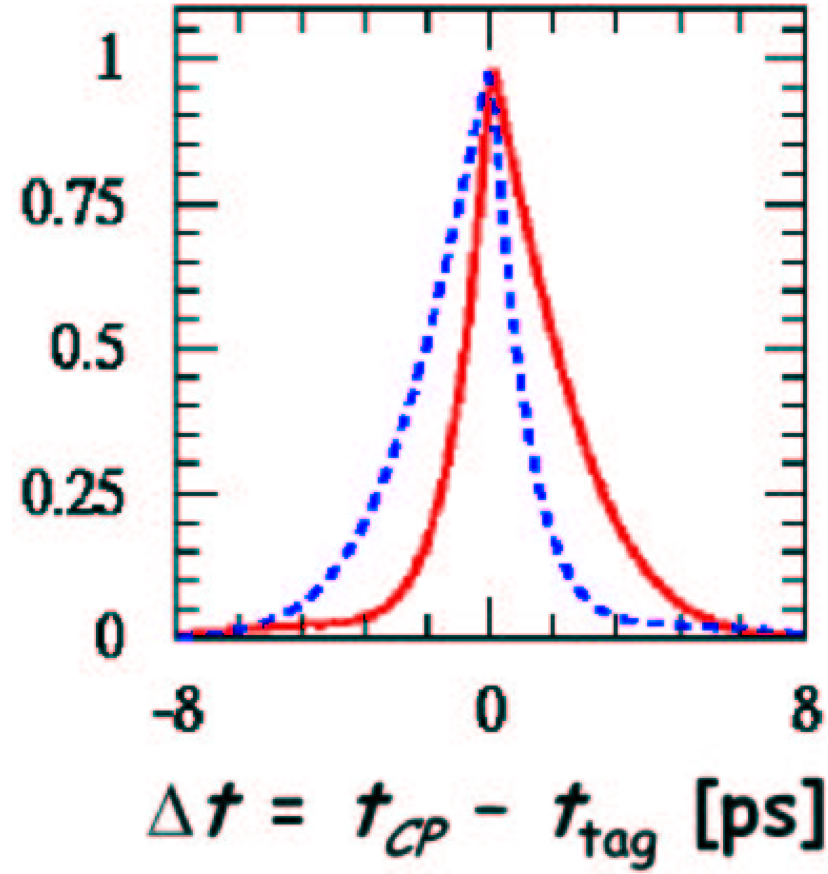


Coherent development means

- exactly one B^0 and one $\bar{B}^0$
- at decay of any, coherence breaks

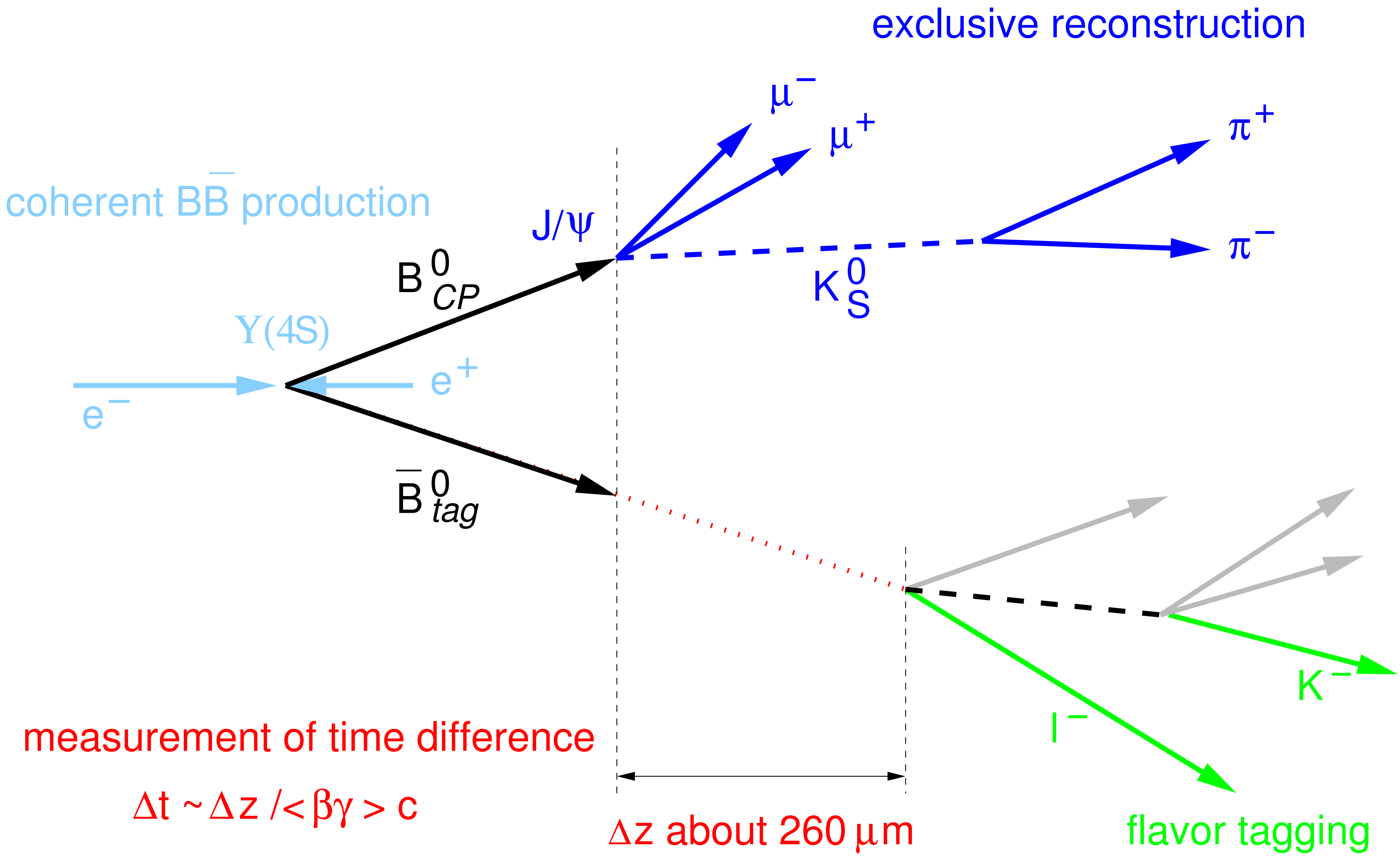
Consequences for measurement

- mixing measurable after first decay
- measure Δt between both decays
- half of the time B_{CP} decays first, t_{CP}
- other meson decay for tag, t_{tag}
- symmetric behavior
- integrated mixing is zero



B^0, $\bar{B}^0$ mesons with $t_{CP} = 0$

Detailed Cartoon of B Decays at $\Upsilon(4S)$



Tevatron Bottom Production - Overview

Cross Section:
$\sigma(b\bar{b}) \approx 100\ \mu$b

Light quark σ(inelast.) 10^3 larger

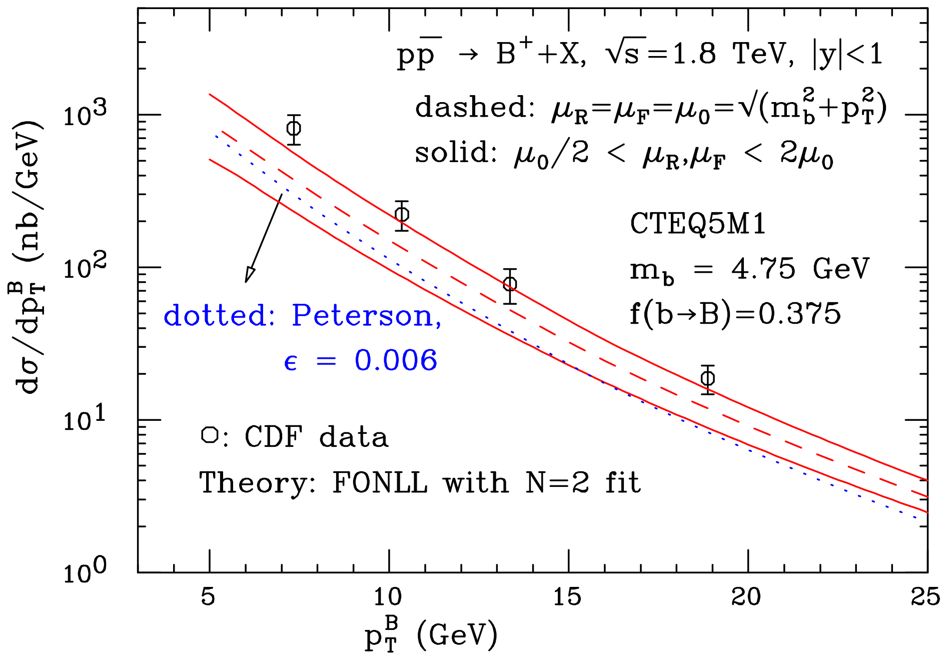
$\rightarrow$ *b*-hadron triggers required

Triggers in Run I

- based on leptons ($\mu^\pm$, $e^\pm$)
- taus are not included
- typically single 8 GeV lepton
- typically two 2-4 GeV lepton
- semilept. decays or $J/\psi \rightarrow \mu\mu$

Triggers in Run II

- all the lepton triggers
- also displaced tracks
- typically two 2 GeV tracks
- hadronic modes available



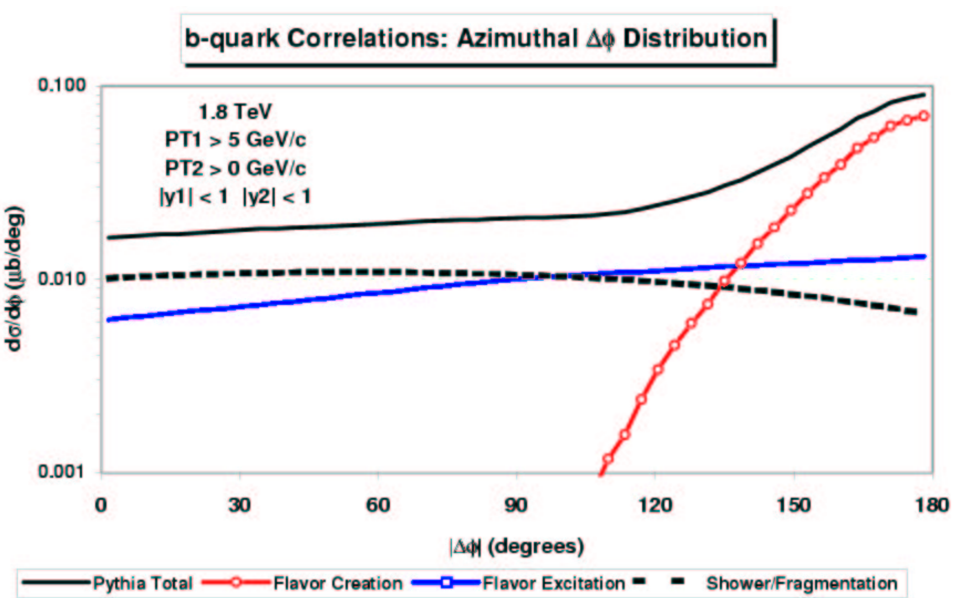
CDF Run I analysis: $B^+ \rightarrow J/\psi K^+$

- single inclusive *B* cross section
- theory update FONLL Cacciari, Nason
- $\sigma_{data}/\sigma_{theory} = 1.7$
- data do not contradict theory

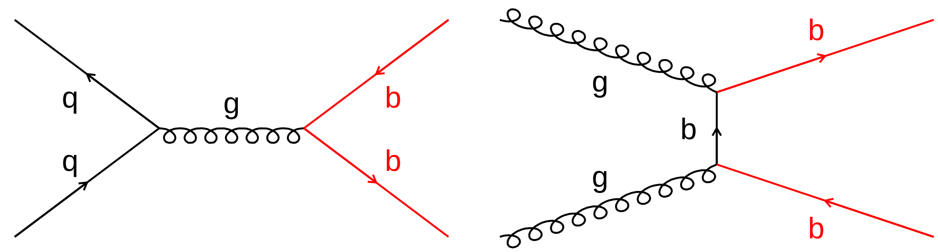
b Quarks / *b* Hadrons at the Tevatron

$p\bar{p}$ collisions

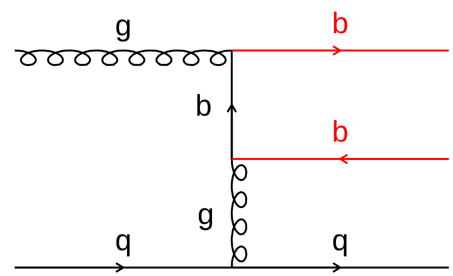
- 1 TeV beam energy
- proton is complicated beast
- collisions quite imbalanced
- large σ(forward,backward)
- often second *b* not in acceptance
- $b\bar{b}$ production not coherent
- always refer to primary vertex



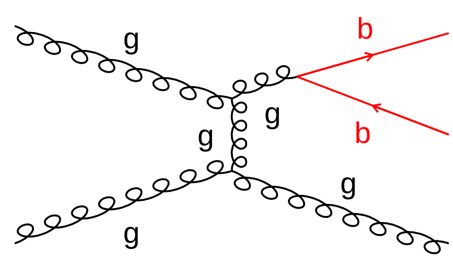
Lowest order



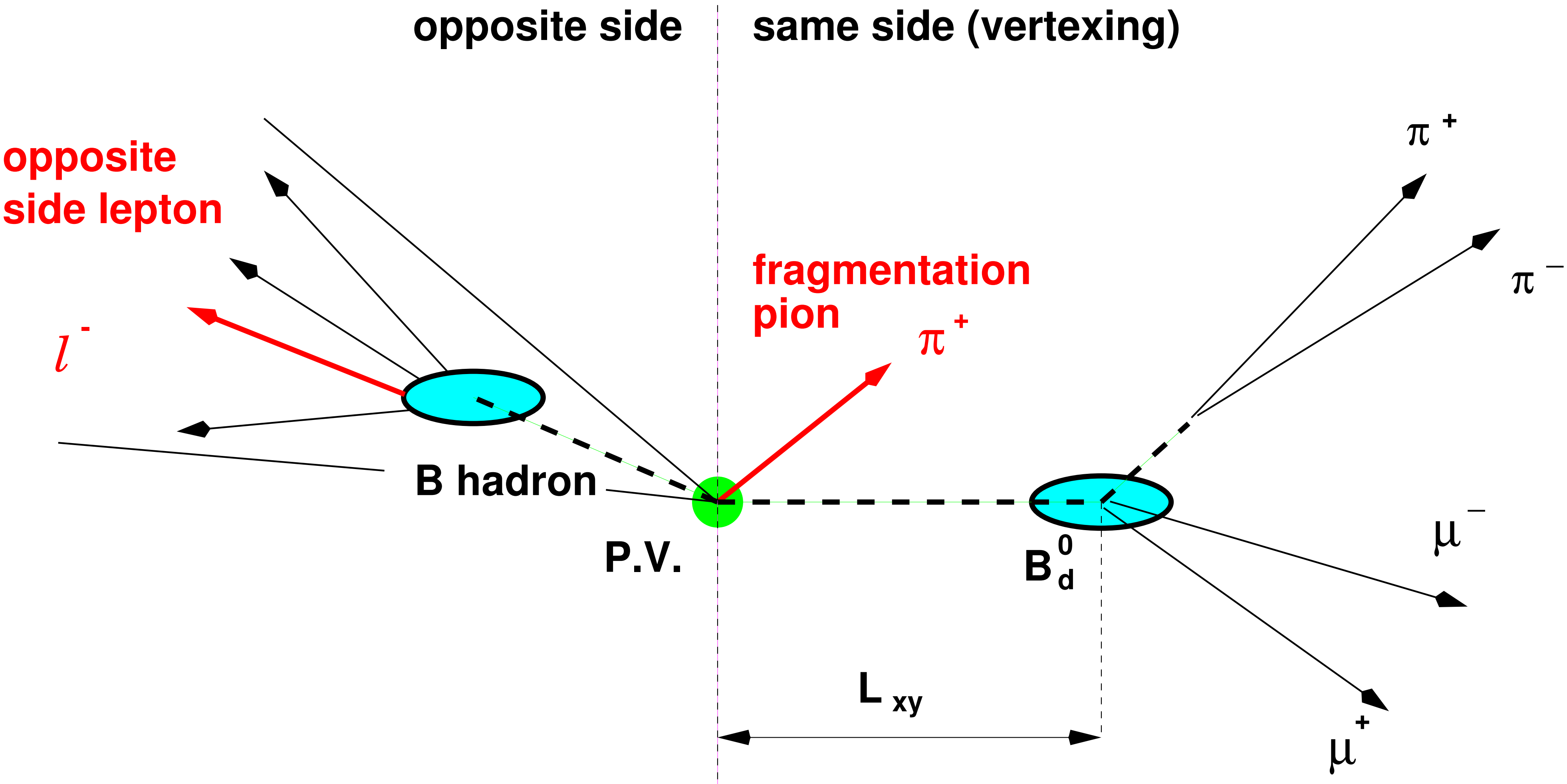
Flavor excitation



Gluon splitting



Detailed Cartoon of B Decays at Tevatron

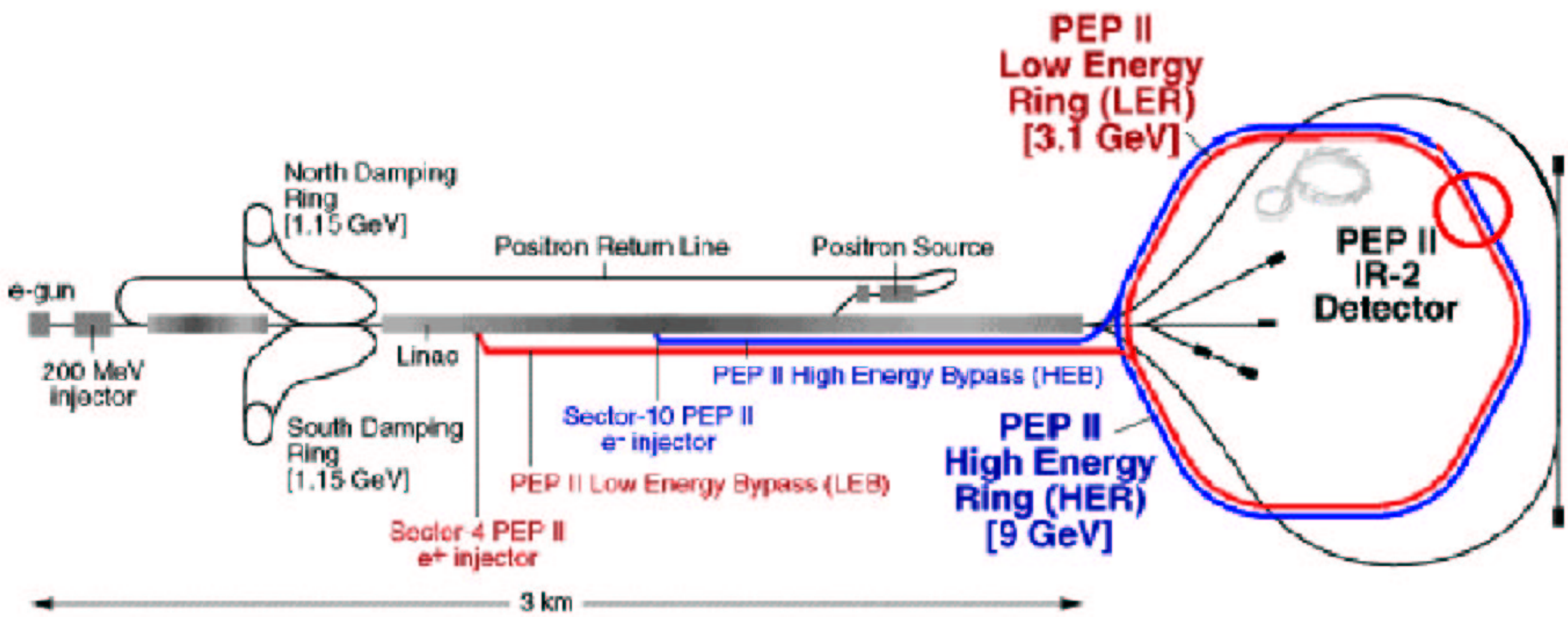


$$ct = L_{xy}\frac{m_B}{p_T}$$

PEP II Machine

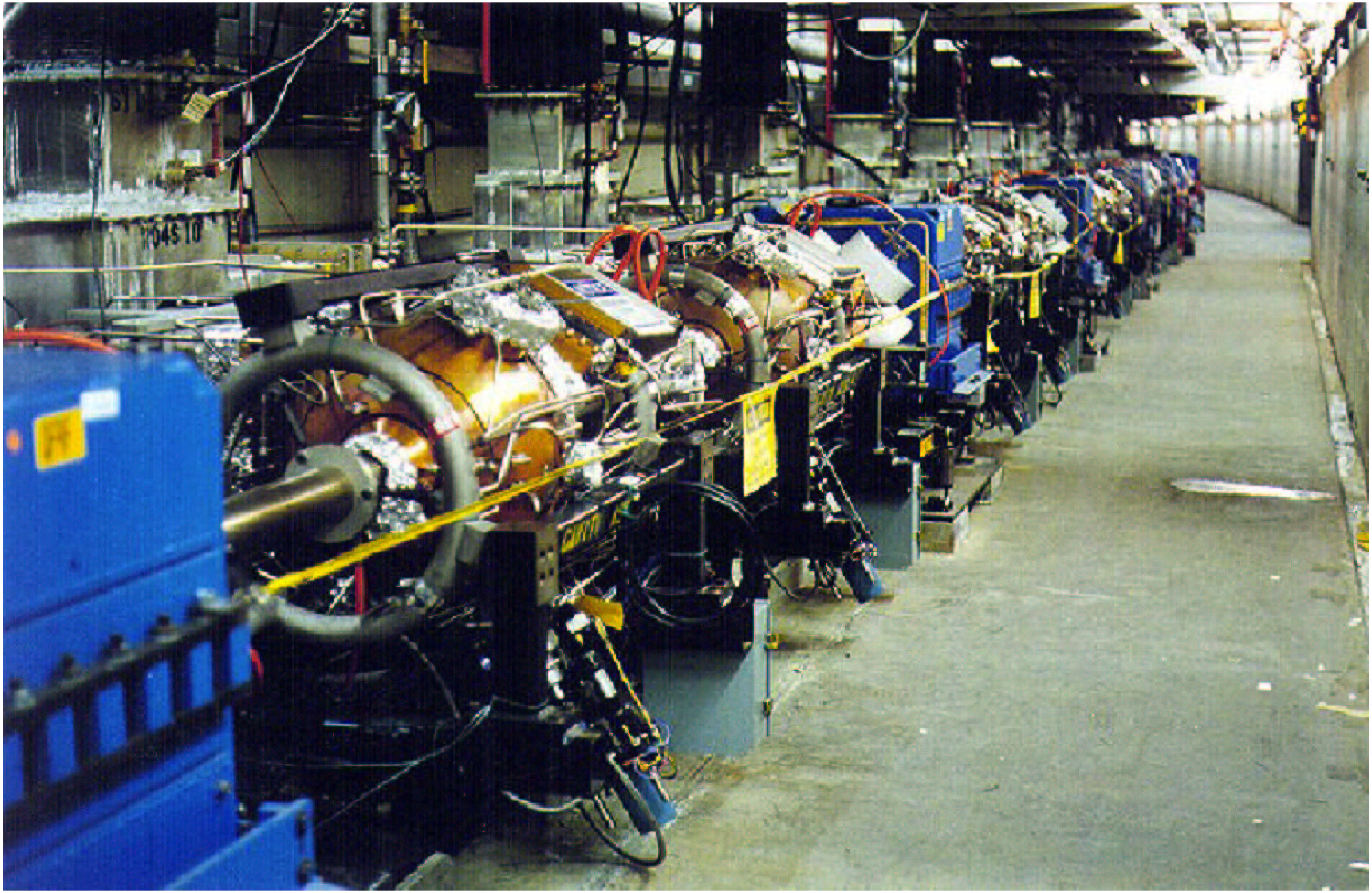
PEP II is located in the 2.2 km PEP tunnel

- 9 GeV electrons on 3.1 GeV positrons
  $\rightarrow \Upsilon(4S)$ boost: $\beta\gamma = 0.55$



PEP II Machine – The Rings

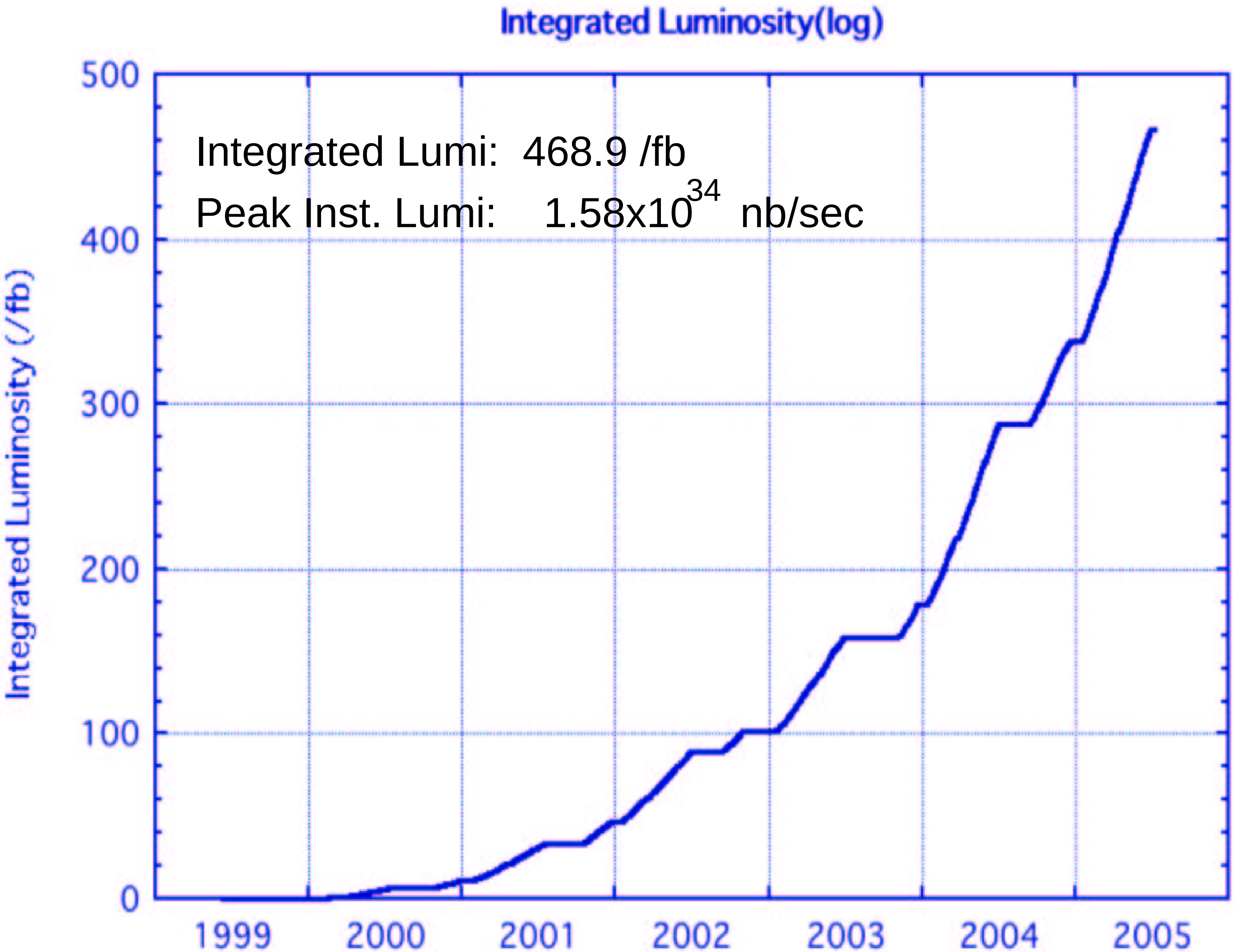
PEP II – The RF Clystrons



PEP II / KEKB Machine Performance

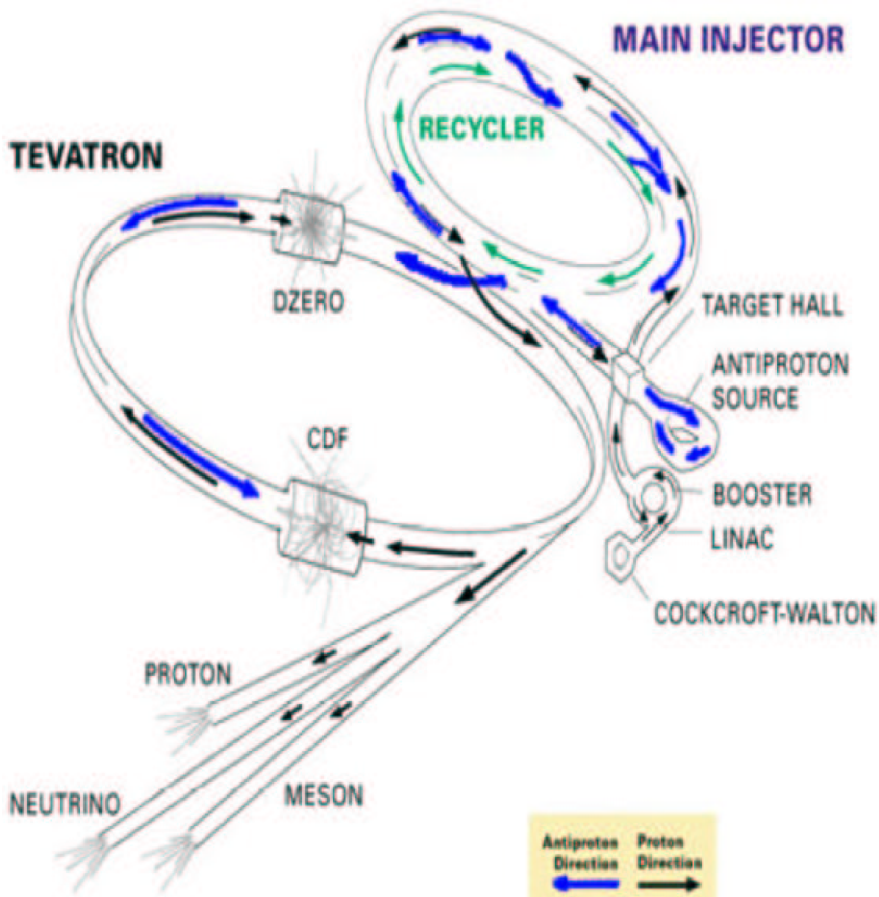
	PEP II		KEKB	
	e^-	e^+	e^-	e^+
Beam energies [GeV]	9	3.1	8	3.5
Currents [A]	1.05	2.14	0.92	1.37
Number of bunches	830		1223	
Luminosity [$\times 10^{33}/cm^2/sec$]	4.6		7.35	
Bunch spacing [m]	2.52		2.4	
Bunch currents [mA]	1.28	2.20	0.71	1.14
Beam stored energy [kJ]	69	41	73	49
Beam power [GW]	9.4	5.6	7	5
Beam RF power [GW]	2.5	1.4	3.2	2.4

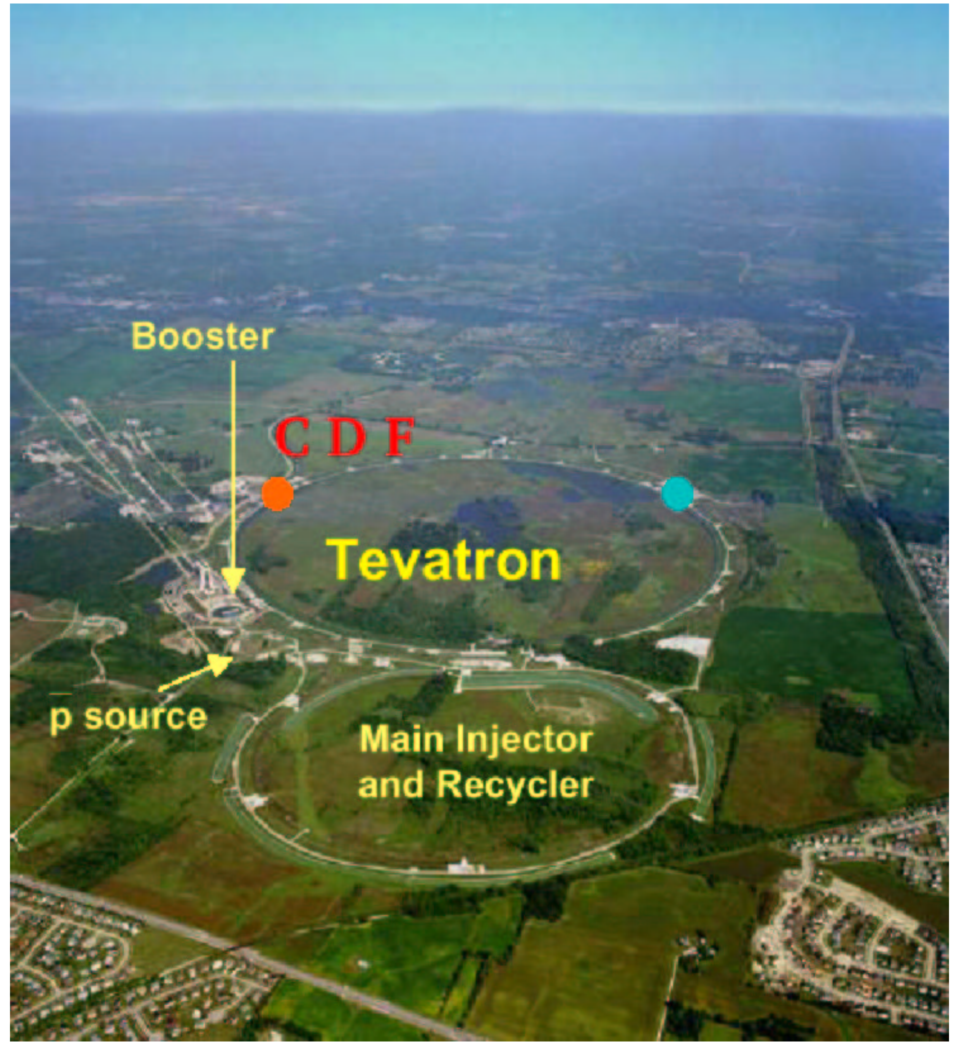
KEKB Machine – Luminosity



Accelerator Setup at Fermilab

Complex accelerator system





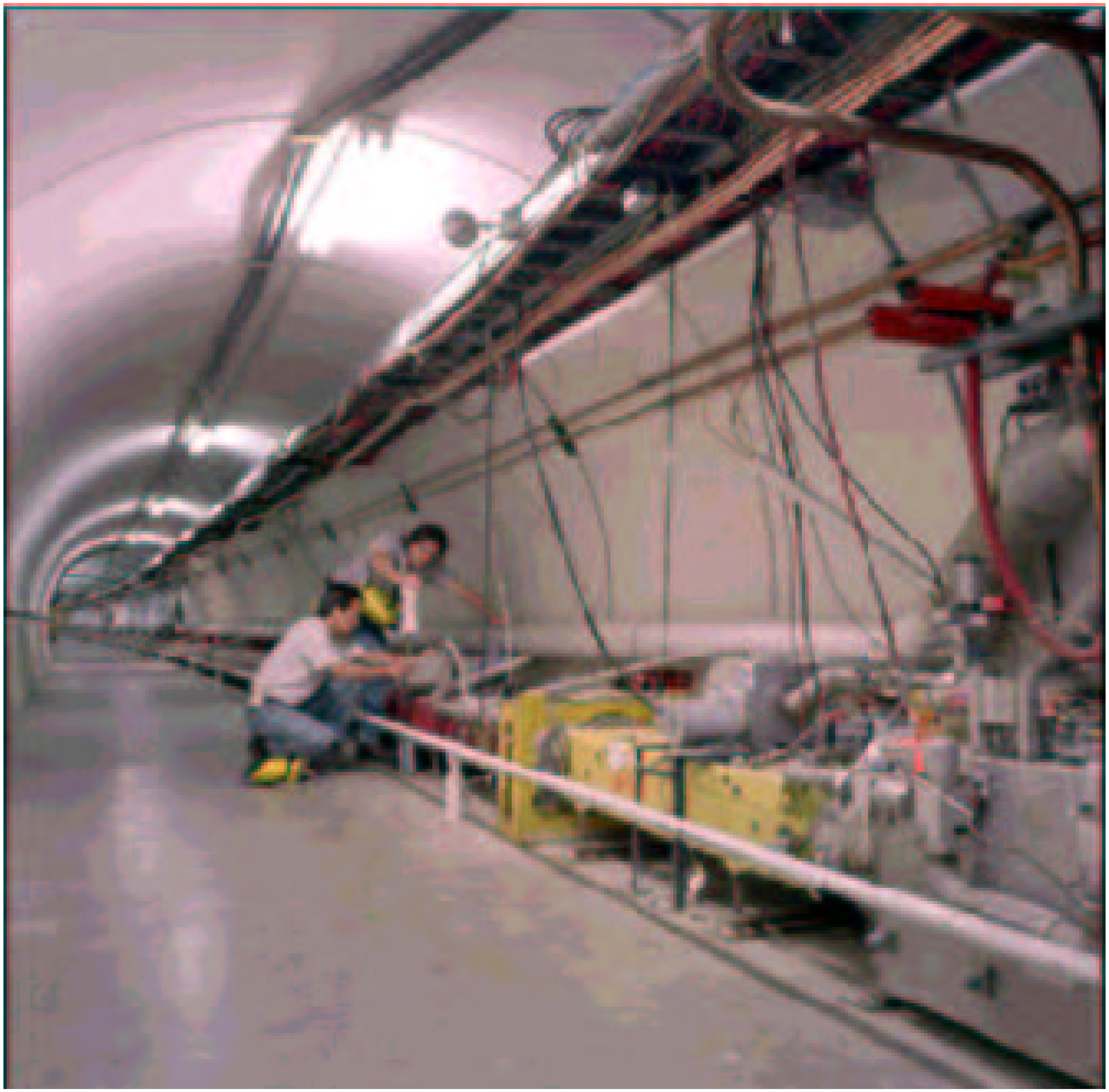
Tevatron Collider

+ Tevatron 1 km ring radius
+ $10^{11}(10^{10})$ $p(\bar{p})$ per bunch
+ 36x36 colliding p, $\bar{p}$ bunches

Goal

+ high beam-beam crossing, few interactions per crossing

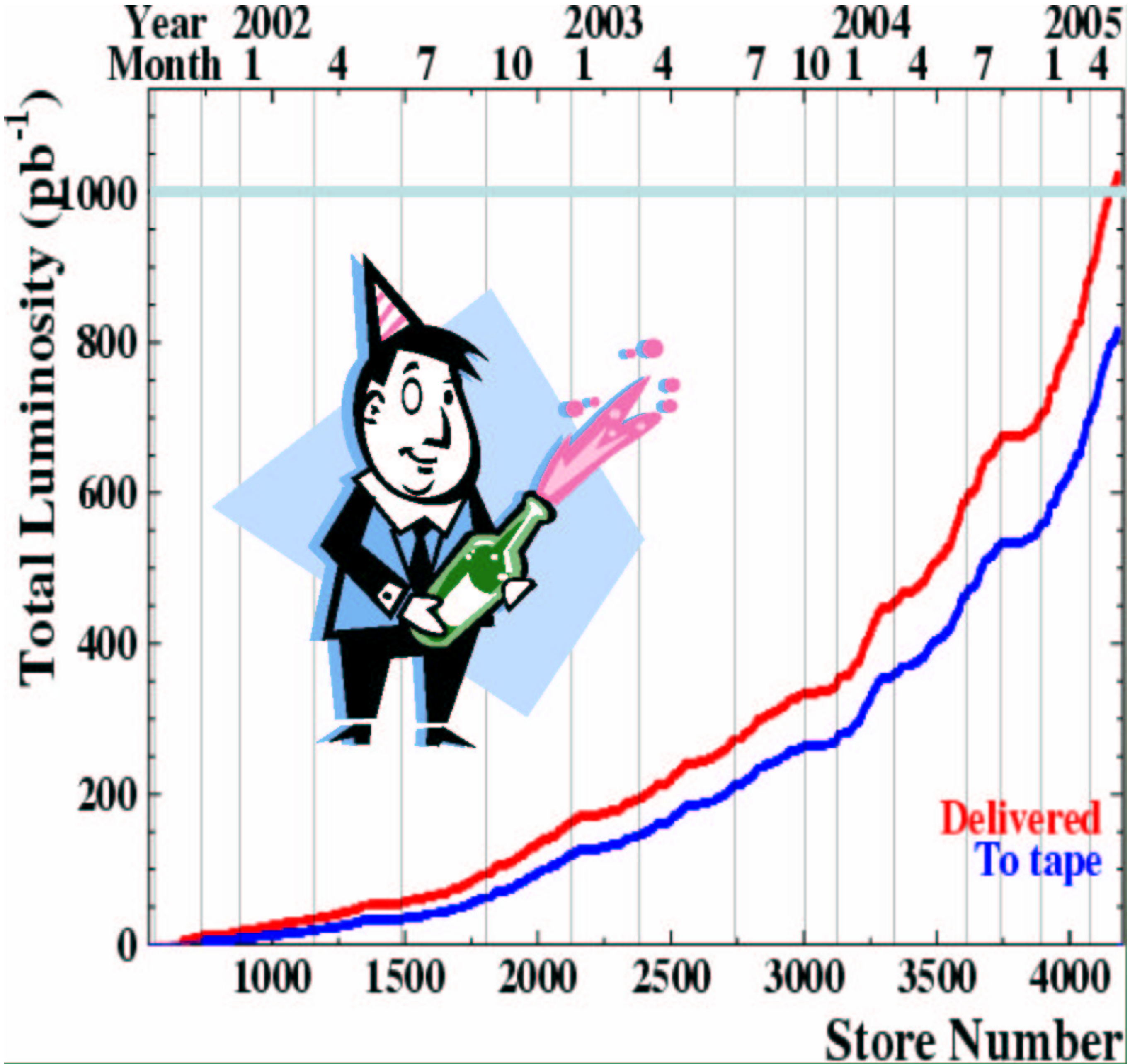
Tevatron – The Ring



Tevatron Machine Performance

	acchieved	Run II goal
Beam energies [TeV]	1	1
Protons/bunch $\times 10^{10}$	≈ 30	27
AntiProtons/bunch $\times 10^{10}$	≈ 4	3.0
Number of bunches	36	36
Luminosity [$\times 10^{31}/cm^2/sec$]	12.9	8.1
Bunch spacing [ns]	396	396
Bunch length proton [cm]	61	37
Bunch length antiproton [cm]	54	37
Integrated Lumi [pb^{-1}/week]	15-25	16

Tevatron Machine Performance – Luminosity



Detector Design – Considerations

Main design elements

- solid angle coverage
- vertex measurement
- momentum measurement
- particle identification: K vs π
- Tevatron: trigger

Drift chambers, Momentum

- resolution $\propto Br^2$
- radius limited by cost of ECAL
- minimize material in front of calorimeters
- solid angle limited by IP setup

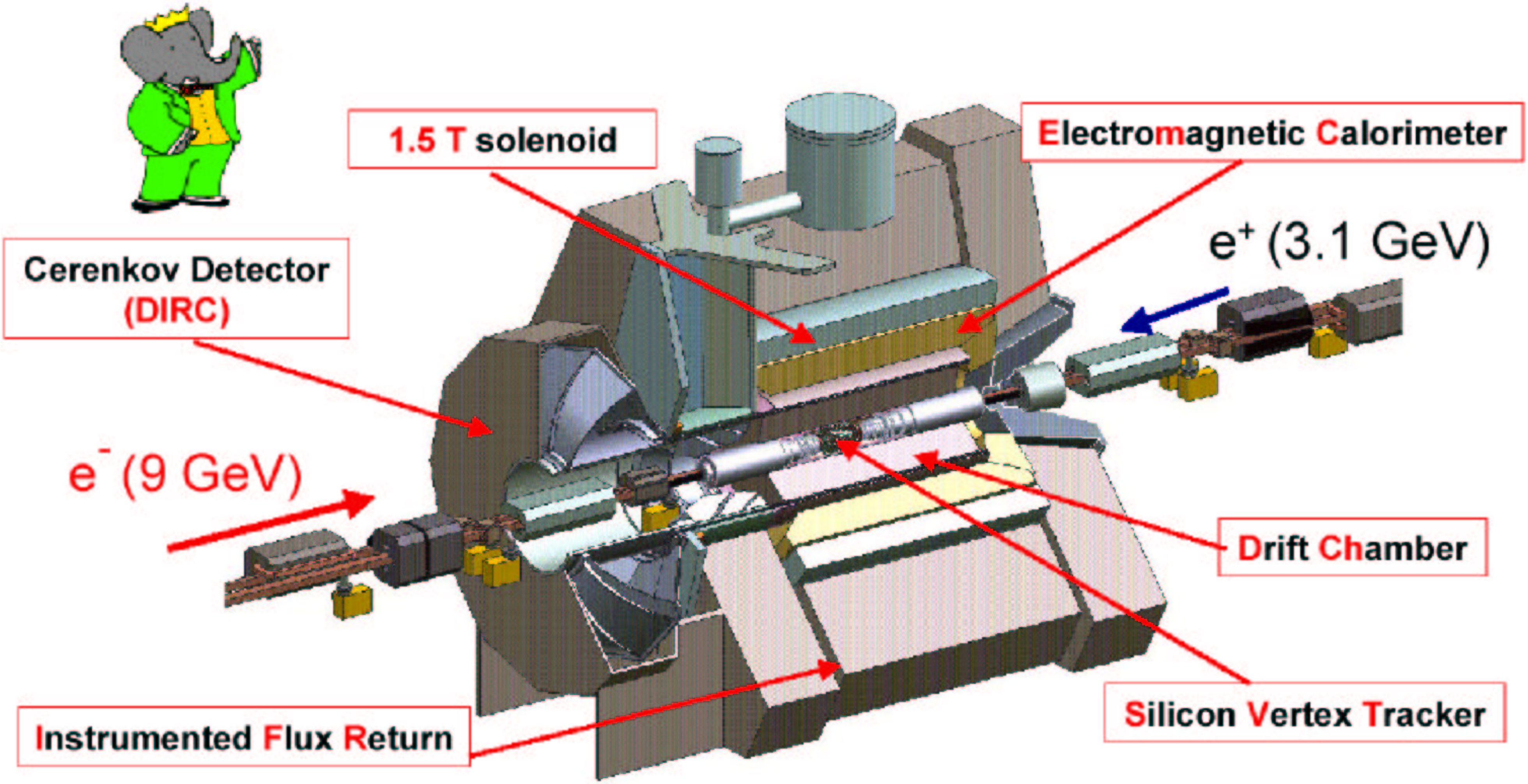
Silicon detectors, Vertex

- close to the interaction point
- little material: avoid MS
- radiation hard
- not to expensive
- $\Upsilon(4S)$: z vertex res. $<$ oscillation
- Tevatron: L_{xy} resolution crucial

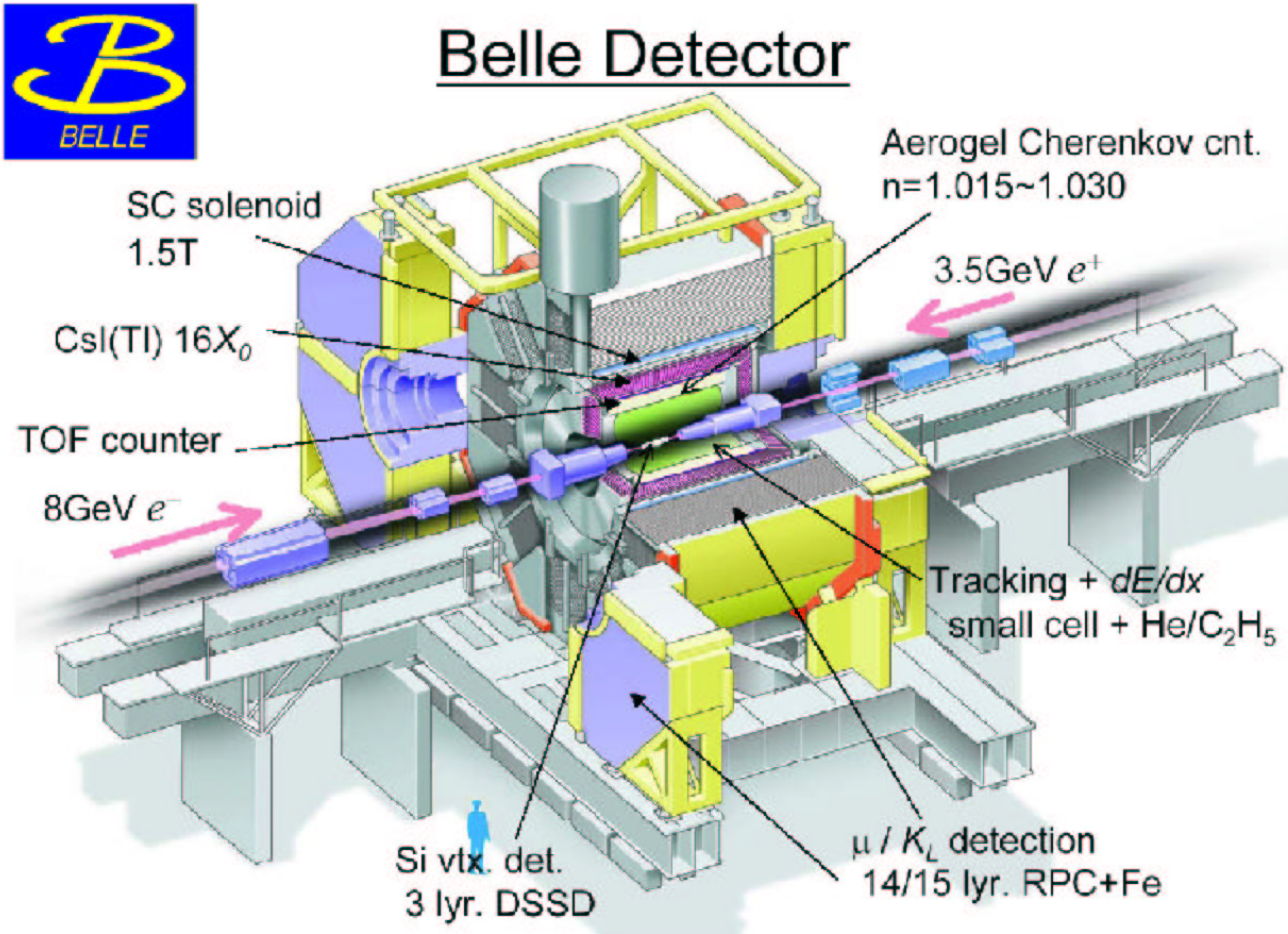
Particle Id detectors

- cover given spectrum
- kaon tagging: 0.6 – 2.0 GeV
- 2 body B decays: up to 4.4 GeV
- various implementations:
  TOF, Transition Rad., DIRC

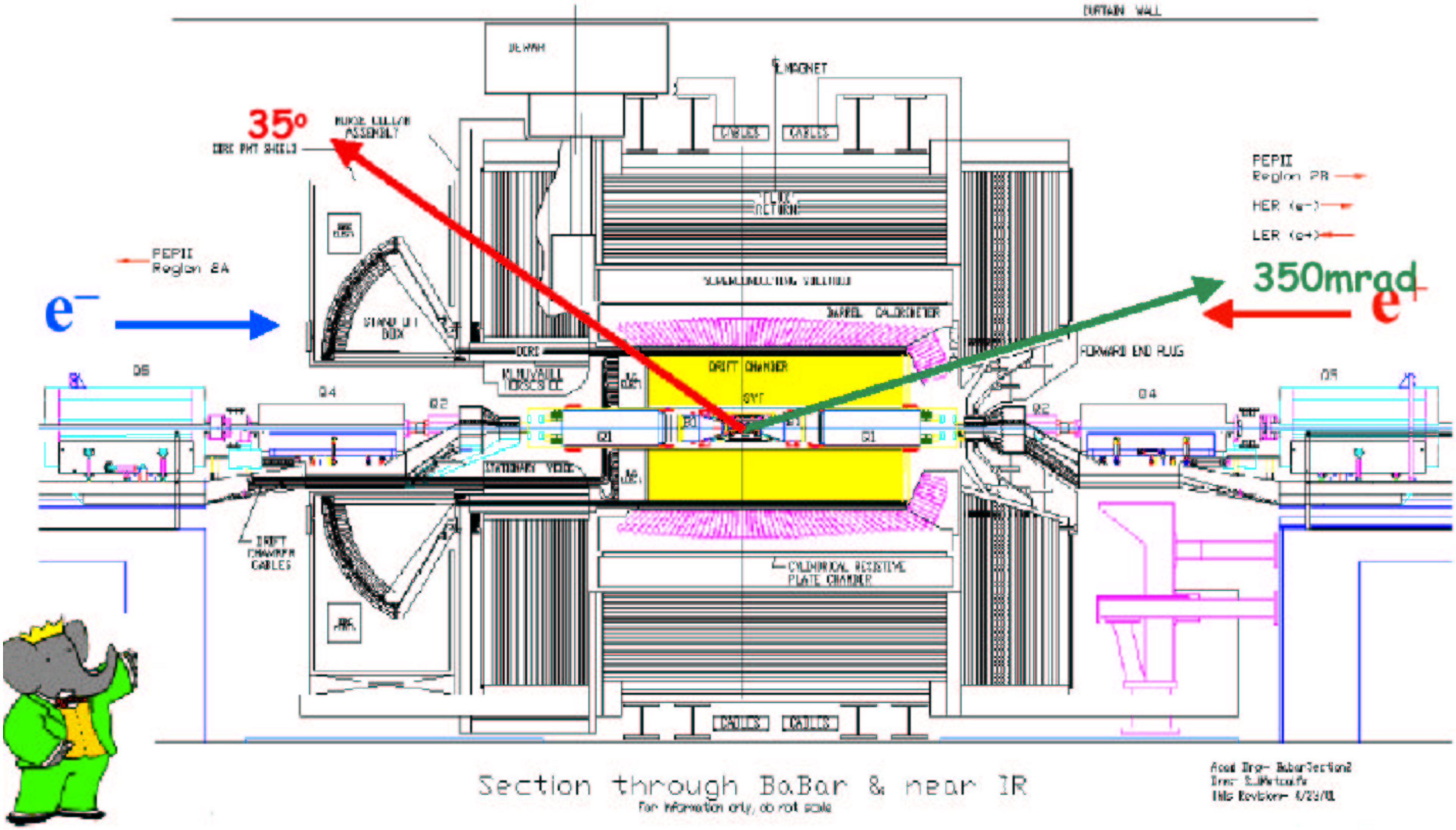
Detector – BaBar



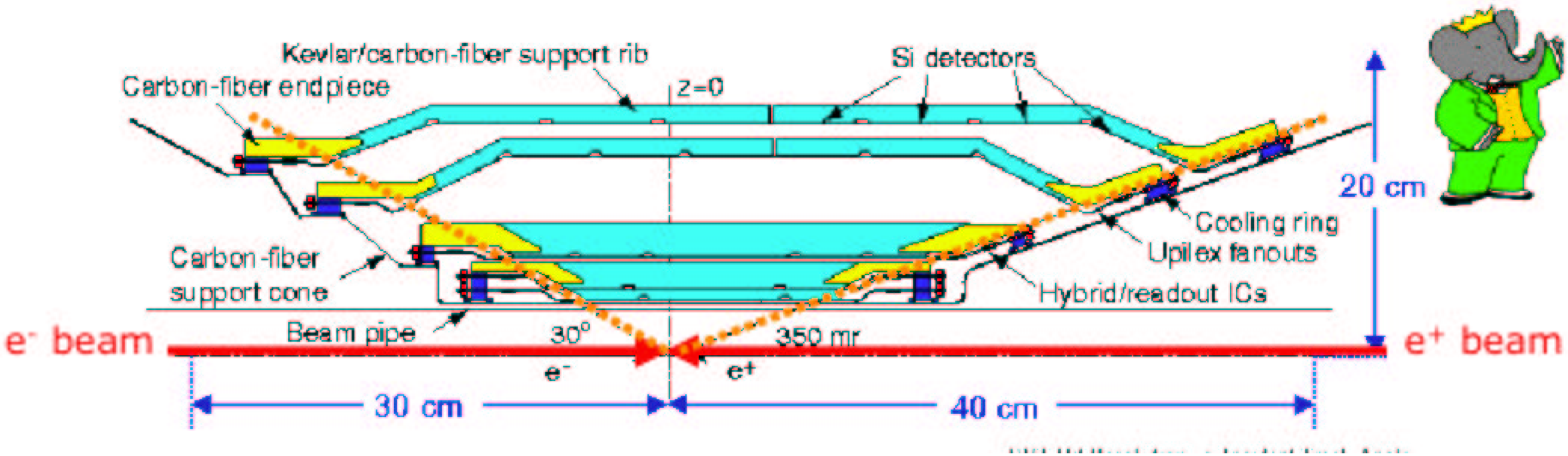
Detector – Belle



BaBar – Asymmetric Design

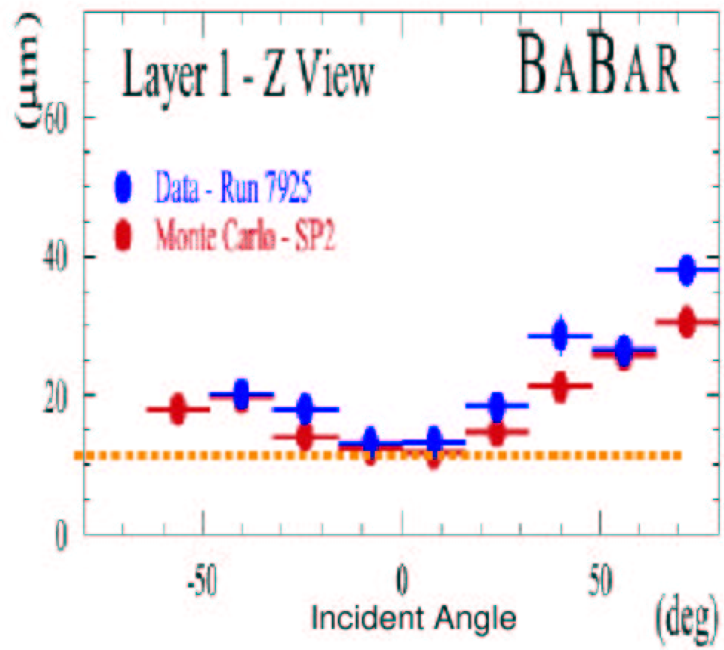


BaBar - Silicon Vertex Detector



Properties

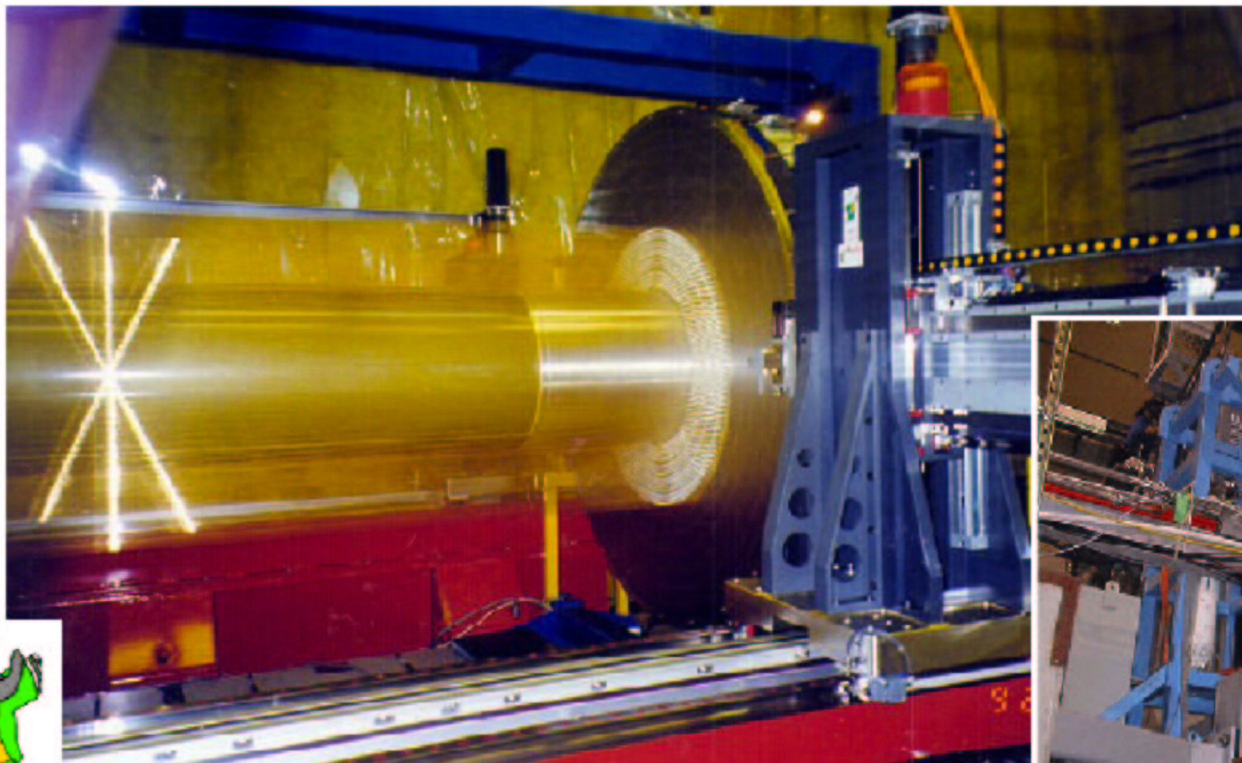
- 5 double sided layers
- AC coupled
- 97% hit reconstr. efficiency
- hit resolution ≈ 15 μm at 90°



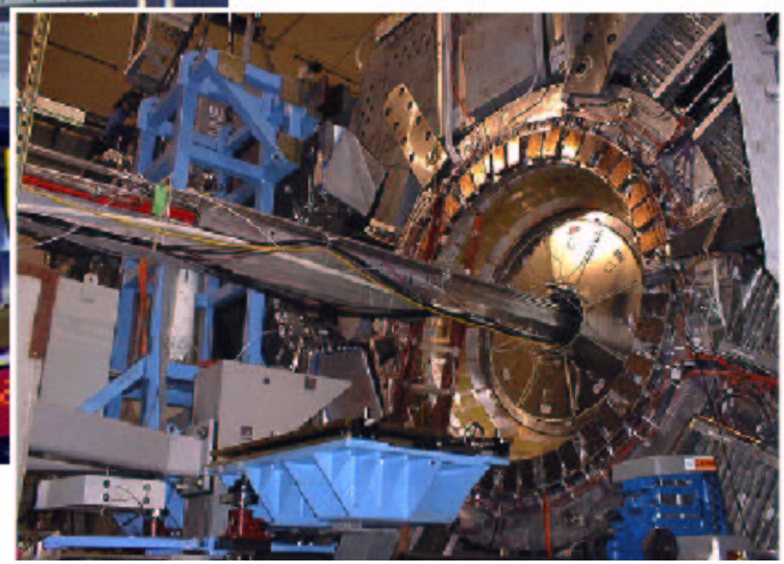
BaBar - Drift Chamber

Properties

- + 40 layers of wires in 1.5 Tesla magnetic field
- + Helium,Isobutane (80:20) gas, Al field wires
- + Beryllium inner wall
- + dE/dx particle id with 7% resolution



$$\frac{\sigma(p_T)}{p_T} = 0.13\% \times p_T + 0.45\%$$

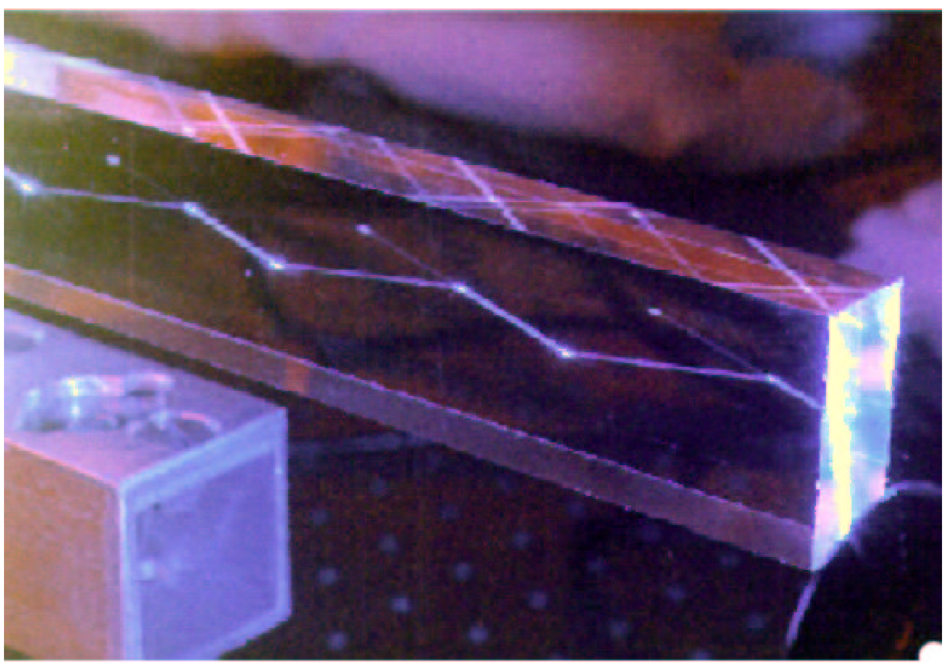


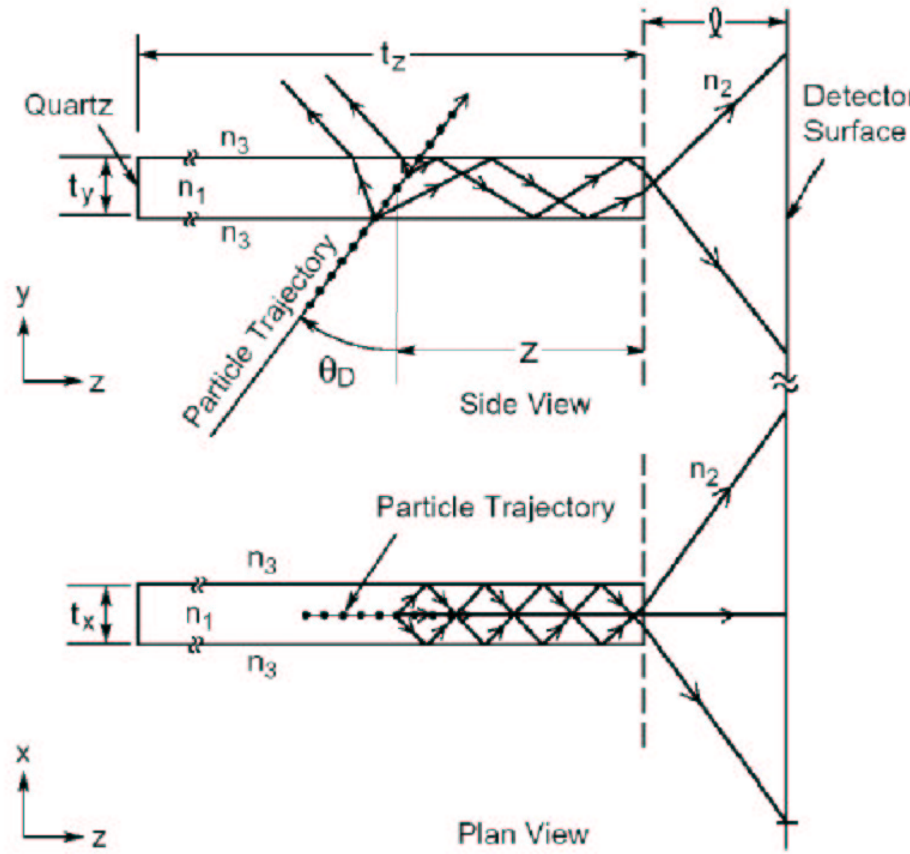
16 axial, 24 stereo layers

Principle of the DIRC

Particle identification

- DIRC consists of quartz bars
- particles emit Cherenkov light
  with $1/\beta$ opening angle
- light transmission via internal reflection
- opening angle is preserved on the precision surfaces
- rings projected in water tanks

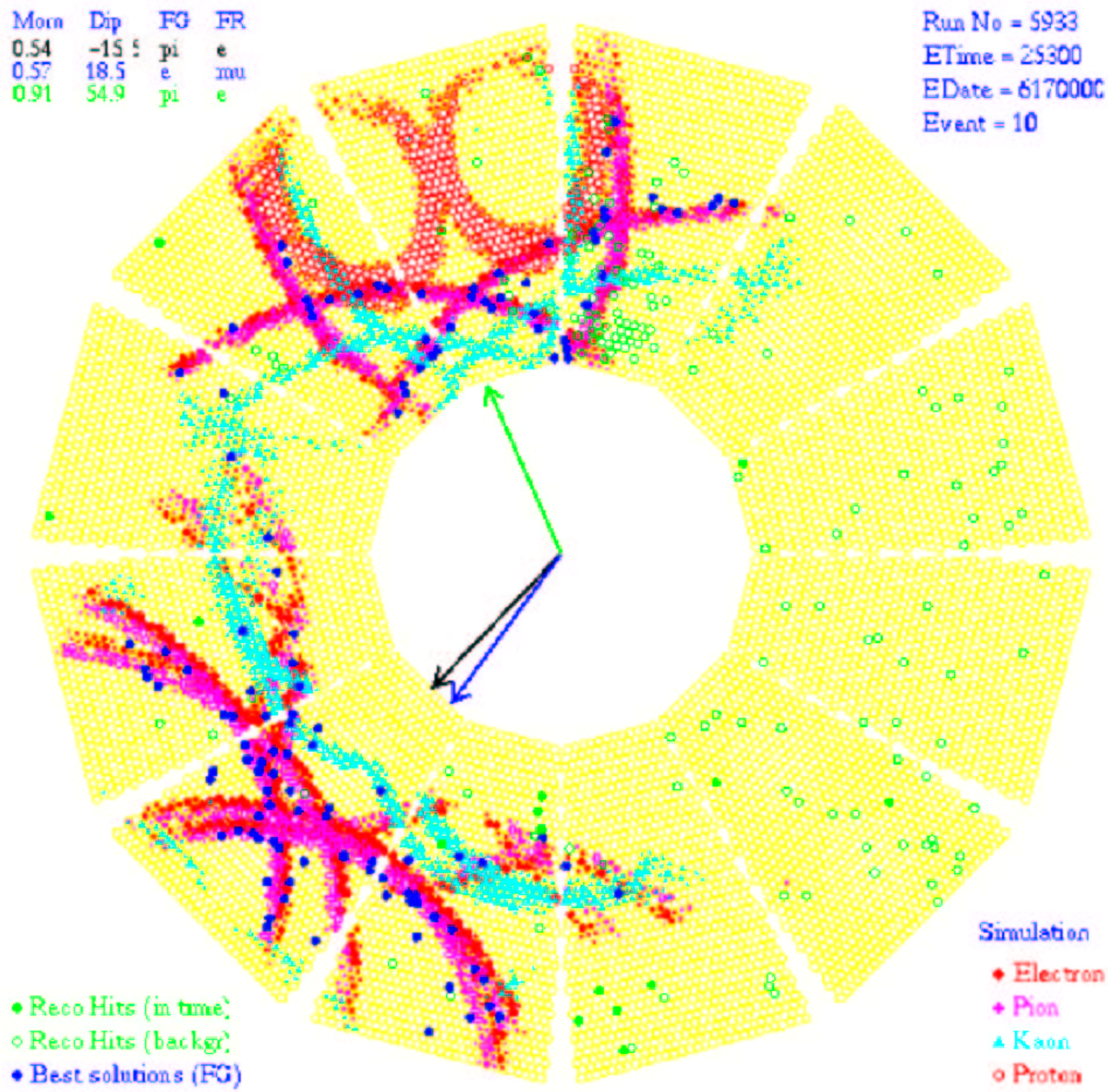




Water tank readout

- about 10k photomultipliers

DIRC Detector Pictures – BaBar



Particle Id Summary – BaBar

Particle identification

- drift chamber dE/dx
- DIRC particle Id system

Drift chamber

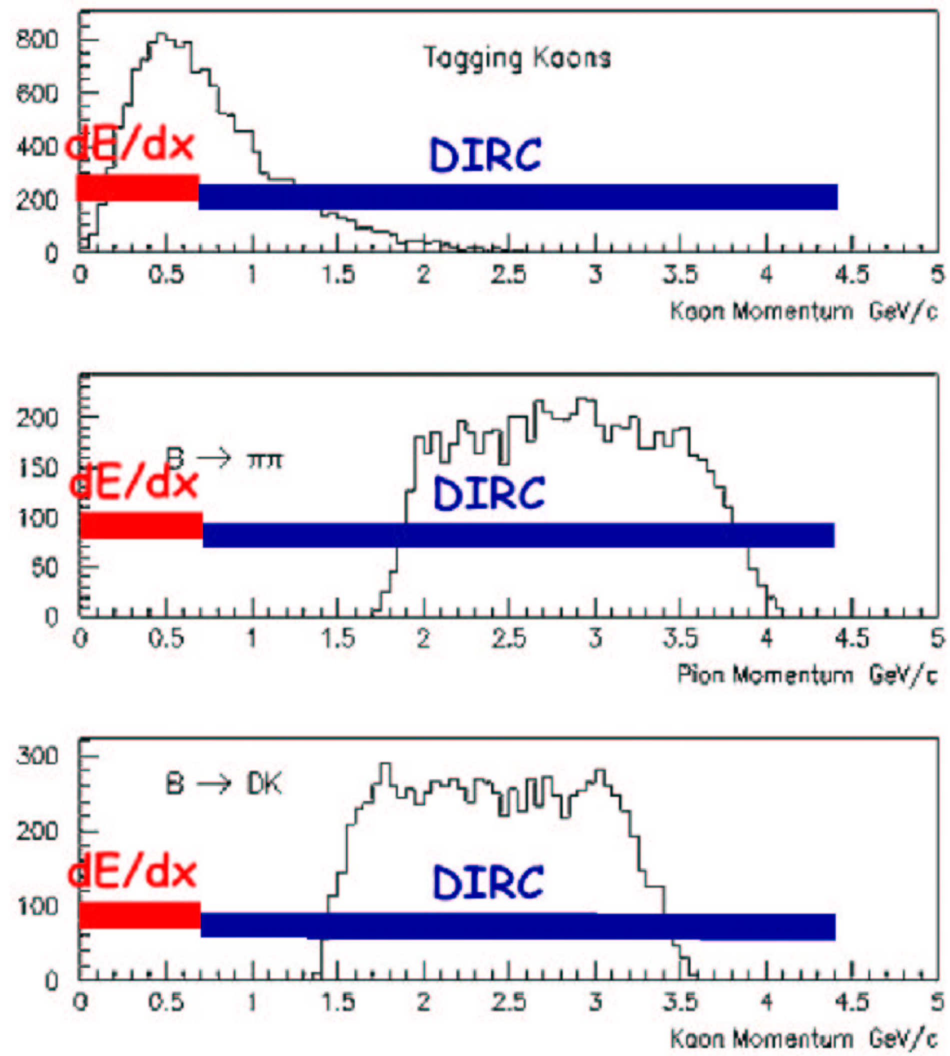
- dE/dx for $p < 1.4$ GeV

DIRC system

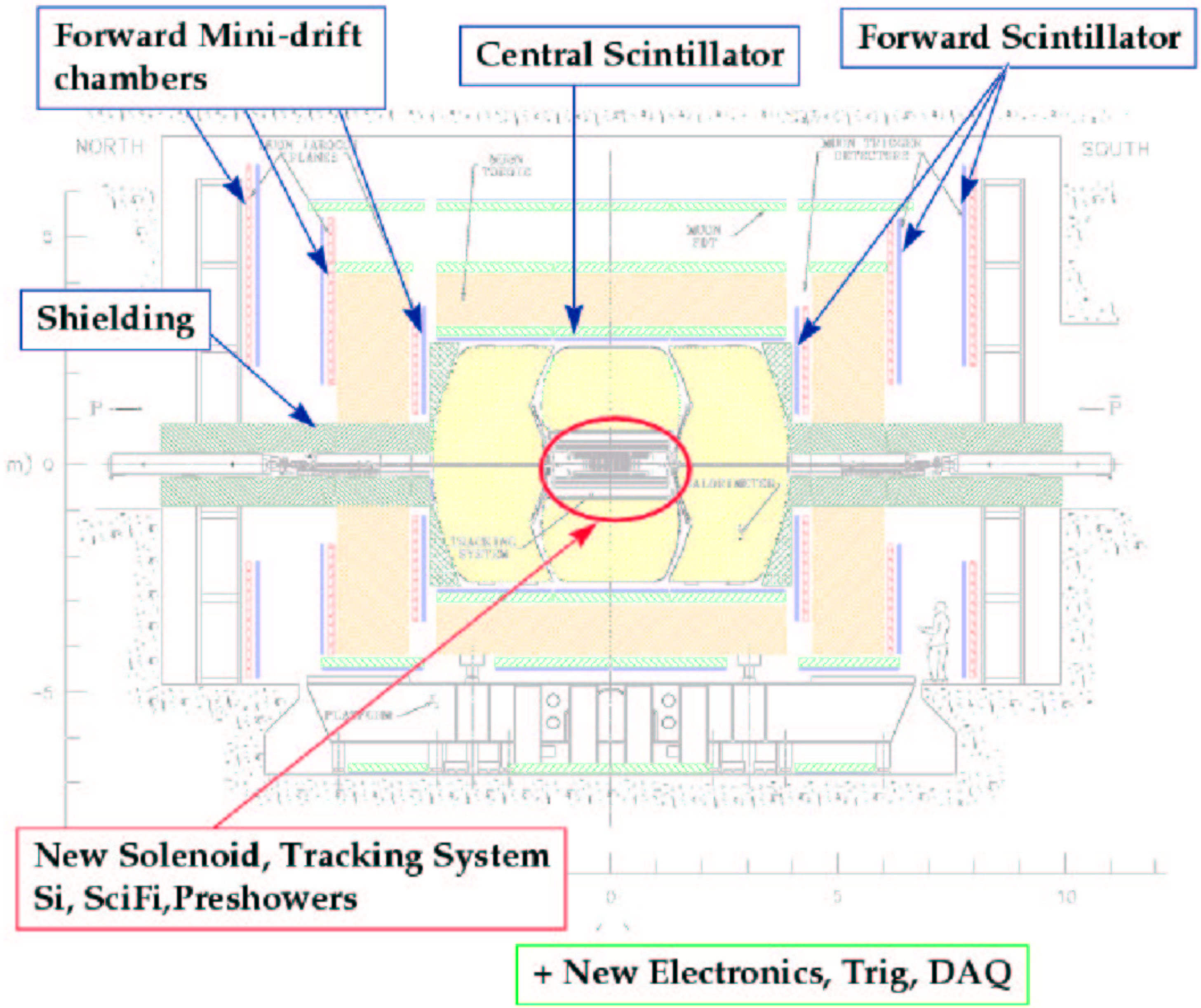
- for 1.4 GeV $< p <$ 4.4 GeV

Combined performance

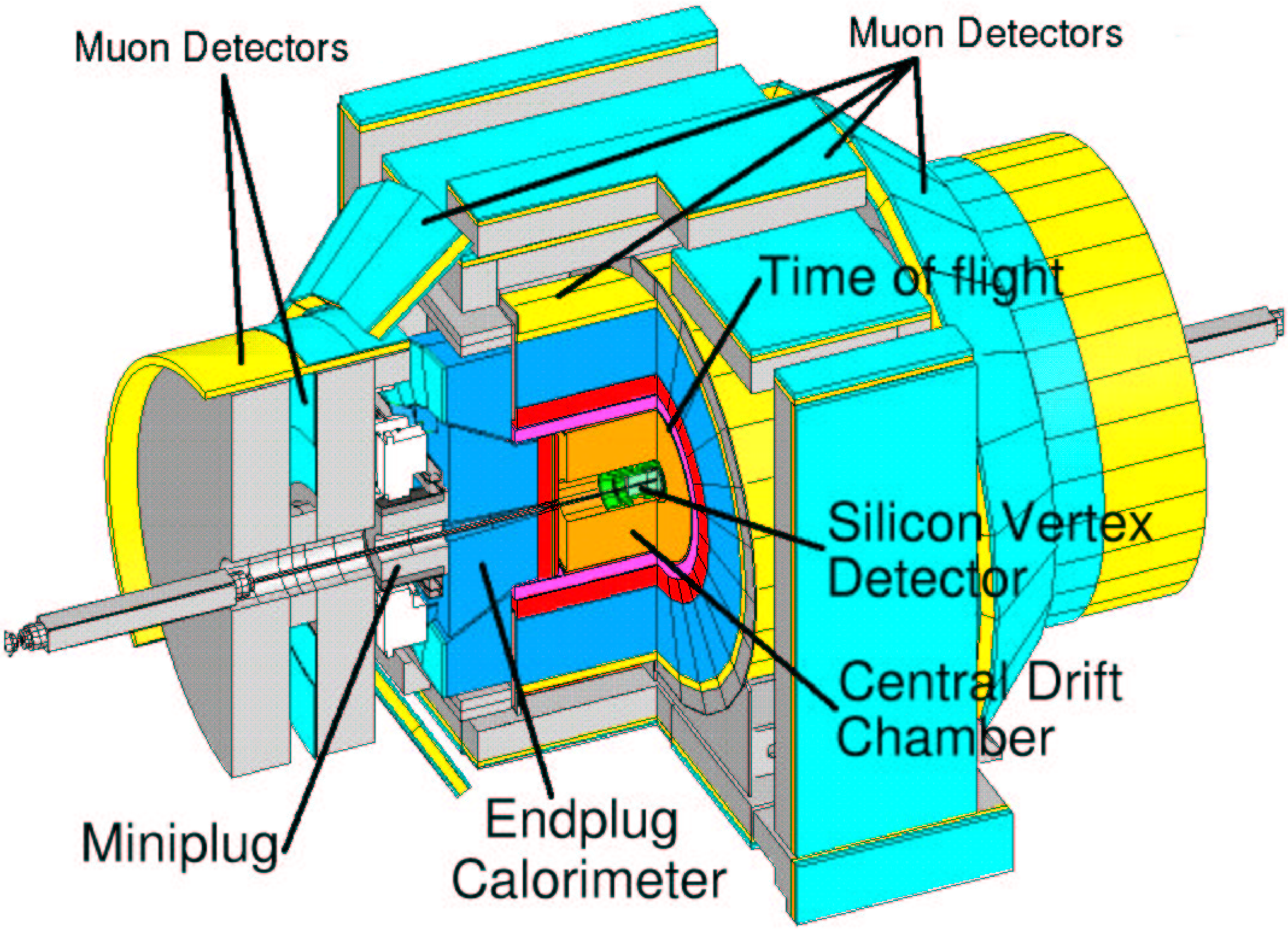
- Kaon identification 85%
- pion misidentified 5%



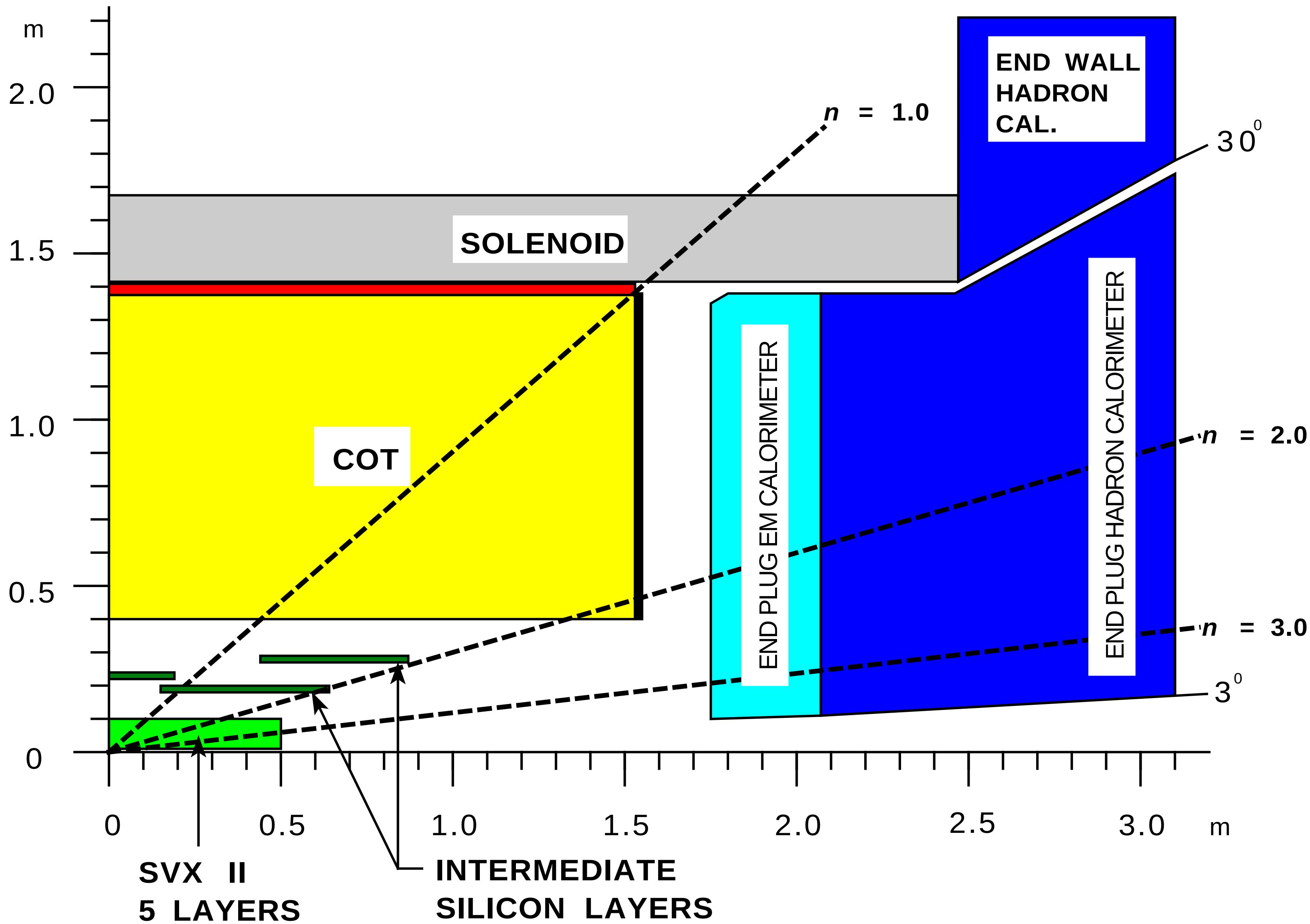
Detector Design – DØ



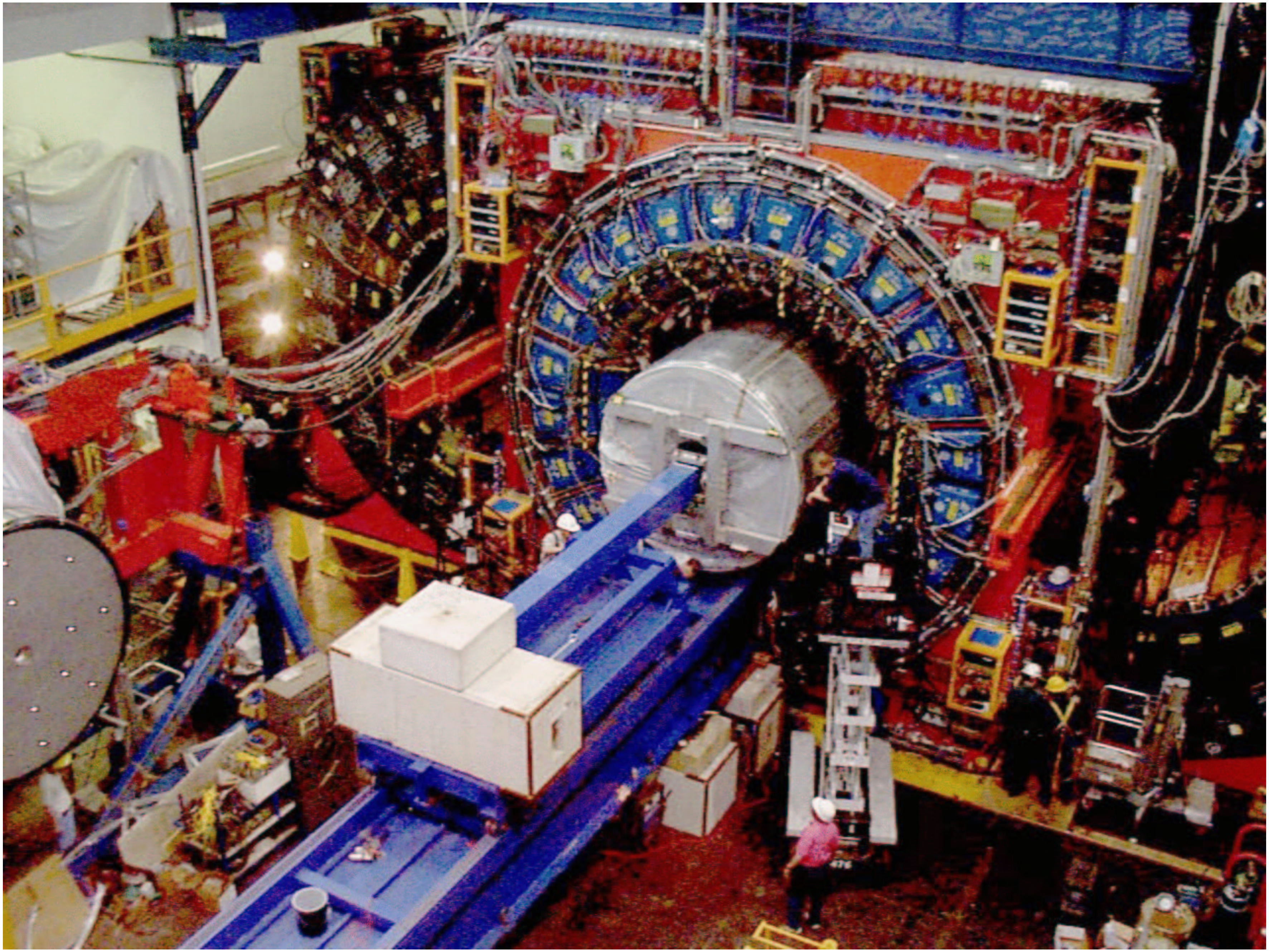
Detector Design – CDF



Detector Design – CDF

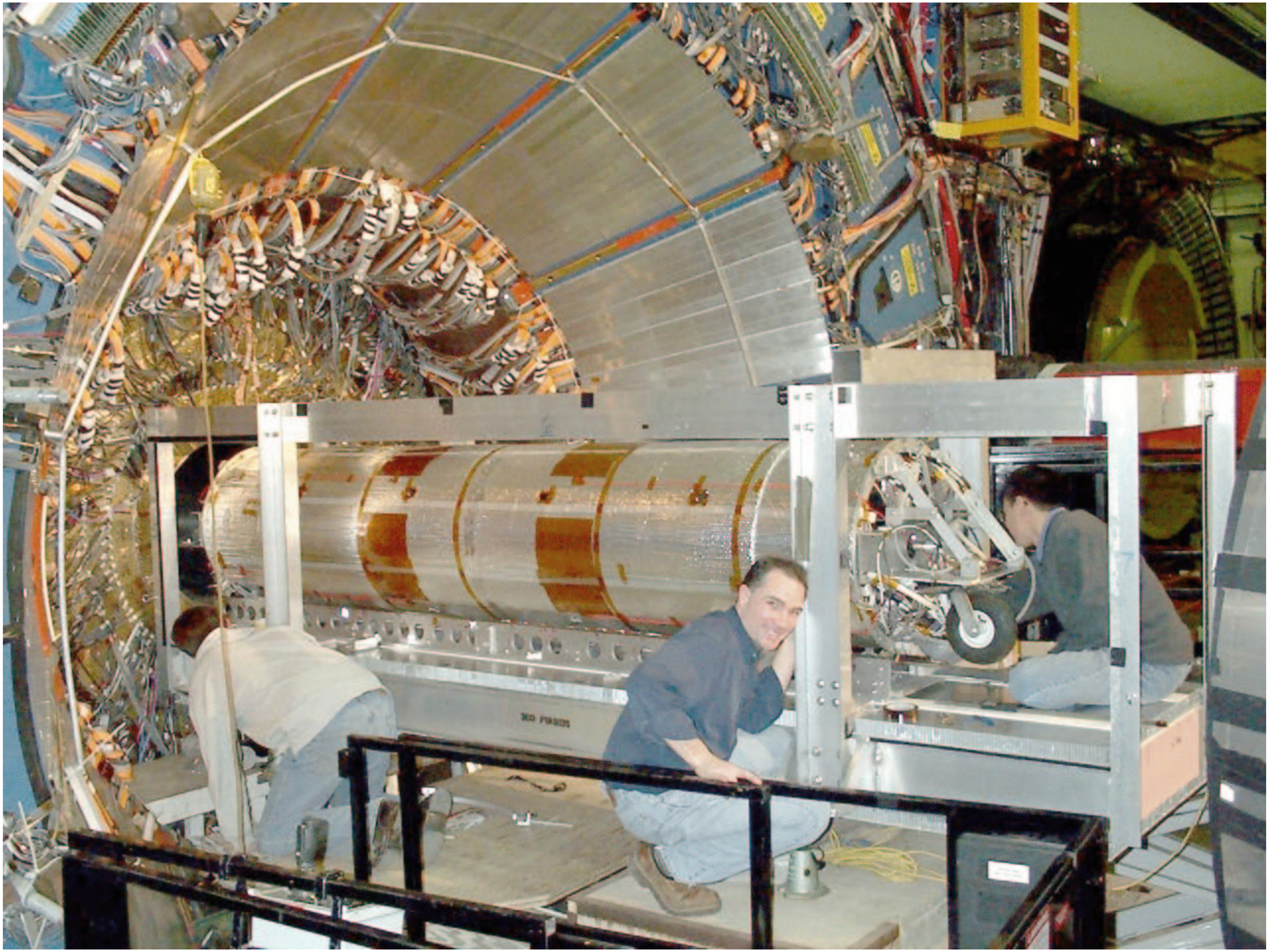


CDF – Drift Chamber – COT

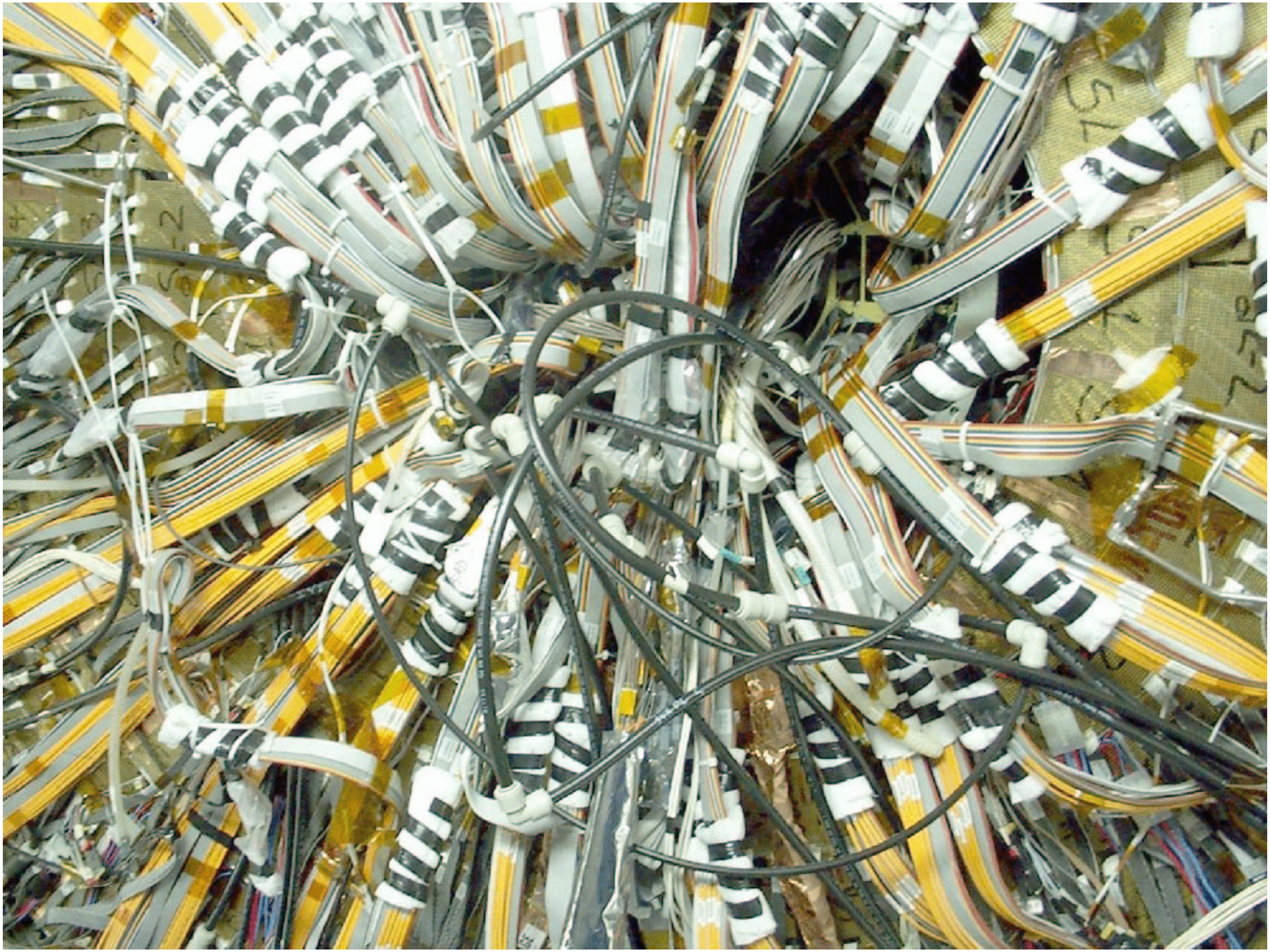


CDF – Silicon Vertex Detector – SVX

CDF – Silicon Vertex Detector – SVX



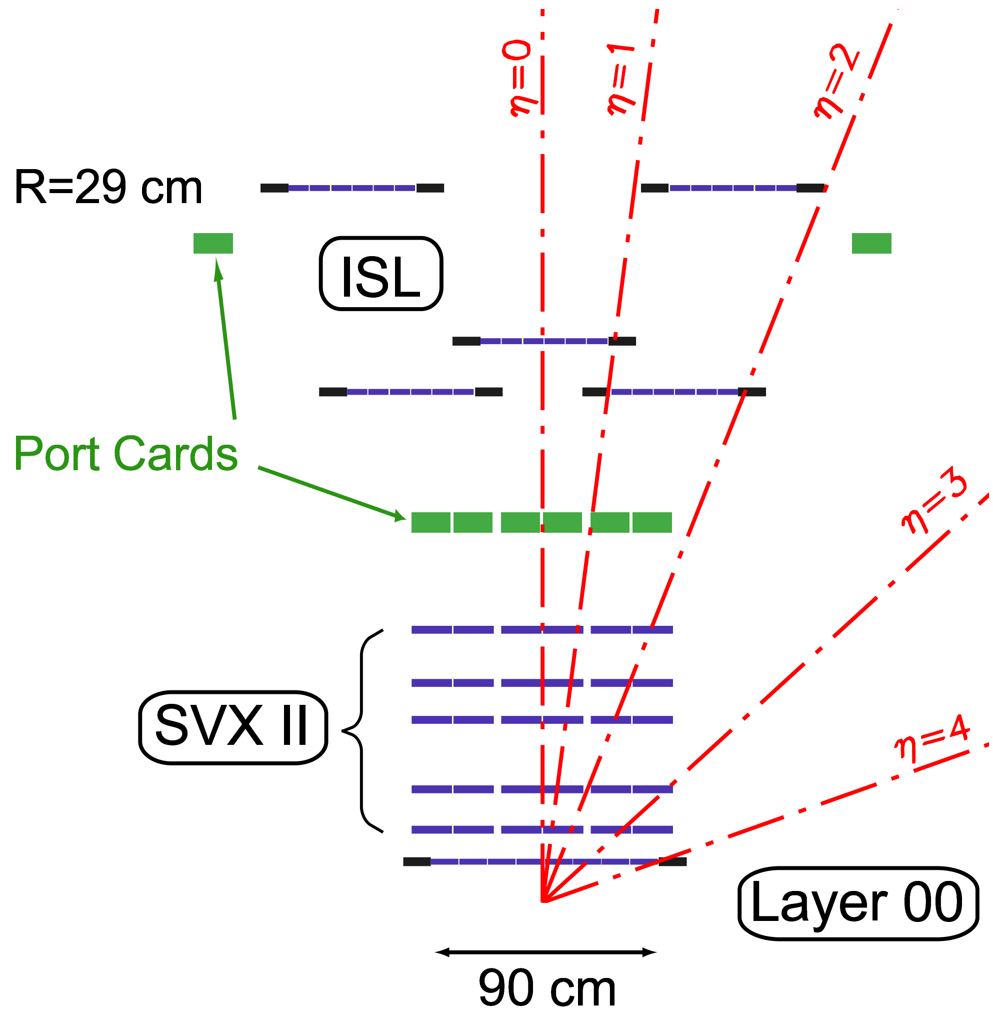
Cabling Up



Run II Upgrades: Silicon Detector

Inner Silicon: L00 and SVX

Number of Layers	6
Number of Barrels	3
Active length	29 cm
Readout	$\phi + z/\phi + \phi'$
Inner Radius	$\approx$ 1 cm
Outer Radius	10.6 cm



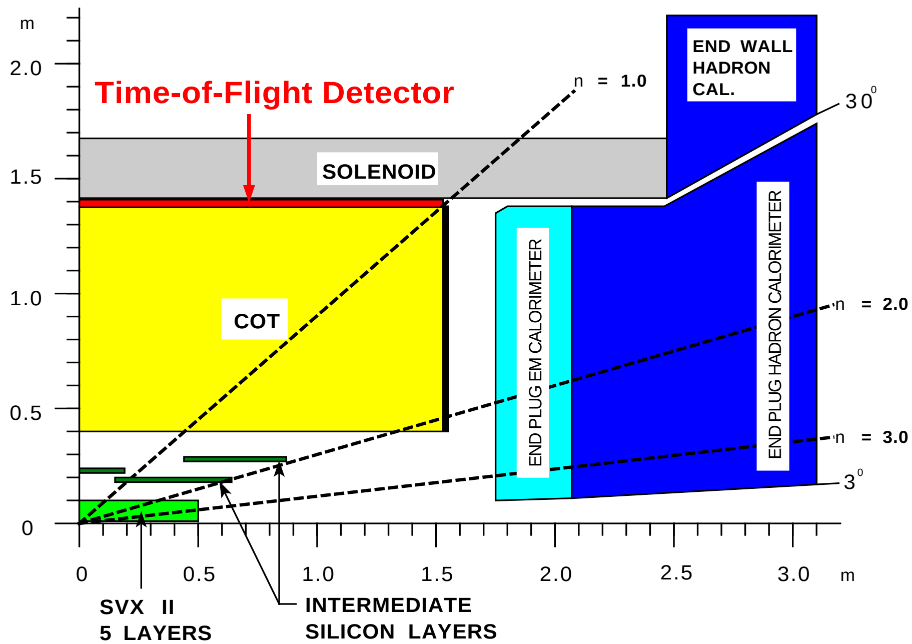
Outer Silicon: ISL

Number of Layers	1 or 2
Number of Barrels	3
Readout	$\phi + z$
Inner Radius	$\approx$ 20 cm
Outer Radius	$\approx$ 30 cm

Run II Upgrades: Time-of-Flight Detector

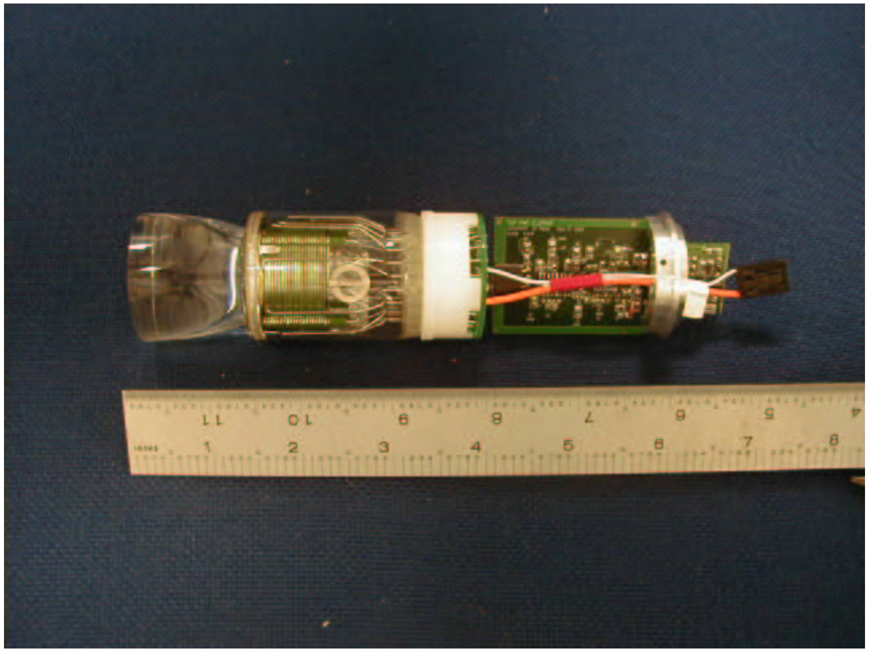
Characteristics of the system

Scintillator Bars	216 (1.7°)
Radius	140 cm
Bar Cross Section	4×4 cm^2
Bar Length Bar	300 cm
Coverage	$\|\eta\| < 1$
Scintillator Material	Bicron–408
Photomultipliers	Hamamatsu
Readout of the Bars	two–sided
Design Resolution	100 ps



Hamamatsu photomultiplier

Type	fine mesh, R7761
Stages	19
Geometry	1.5 inch diam.



PMT operates in 1.4 T B field

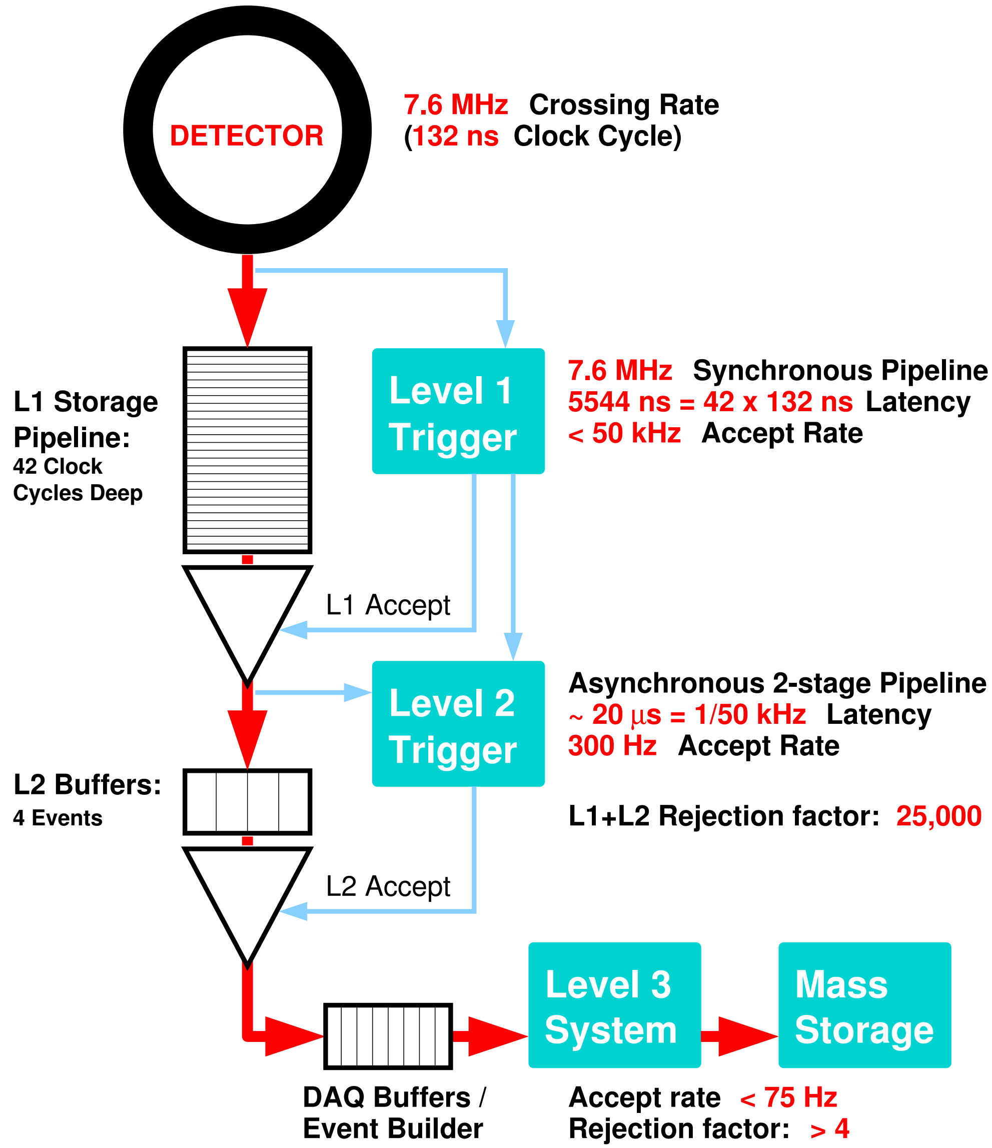
Run II Upgrades: DAQ System

Event Building in Run II

ATM switch	32 ports
input rate [kHz]	0.3 (1)
event size [kB]	150 (250)
total flow [MB/s]	44 (244)

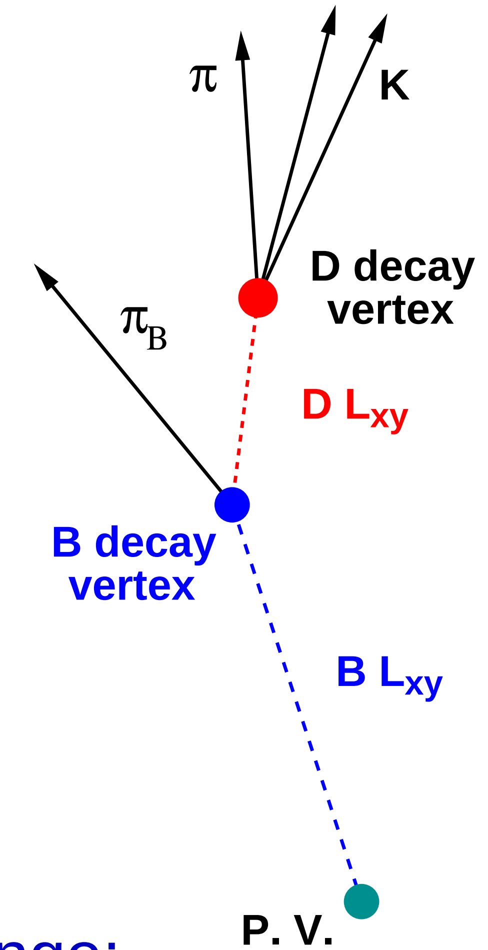
Level-3 Processing for Run II

PC farm (Linux)	250 PCs
input rate [kHz]	0.3 (1)
output rate [Hz]	30 (75)
rejection rate	≈ 10
logging flow [MB/s]	4.4 (18)



Run II Upgrades: Hadronic Trigger

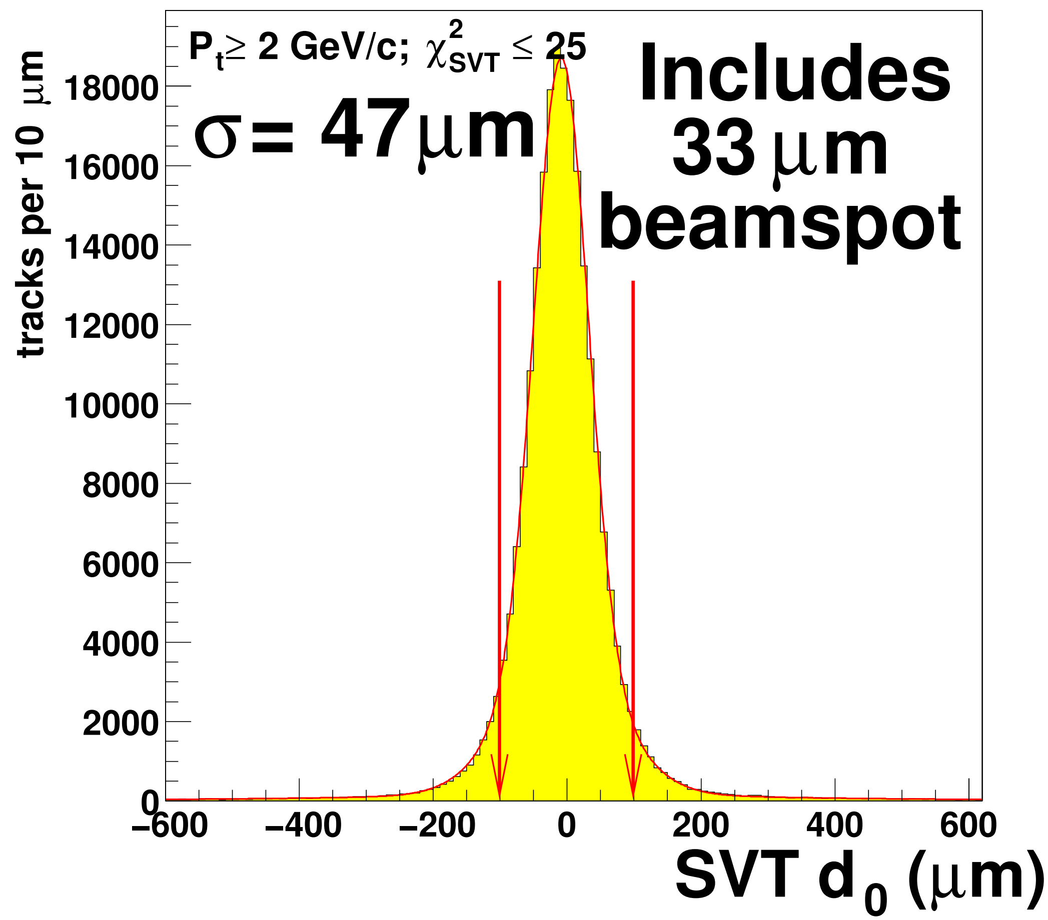
Run I: only e, μ trigger



Level1 track trigger: high p_T

Level2 track trigger: large d_0

Improves Run I sensitivity by 4-5 orders of magnitude



Challenge:

- fast silicon readout (SVX)
- track at 10 kHz (SVT)
- charm dominated

Run II Upgrades: Hadronic Trigger

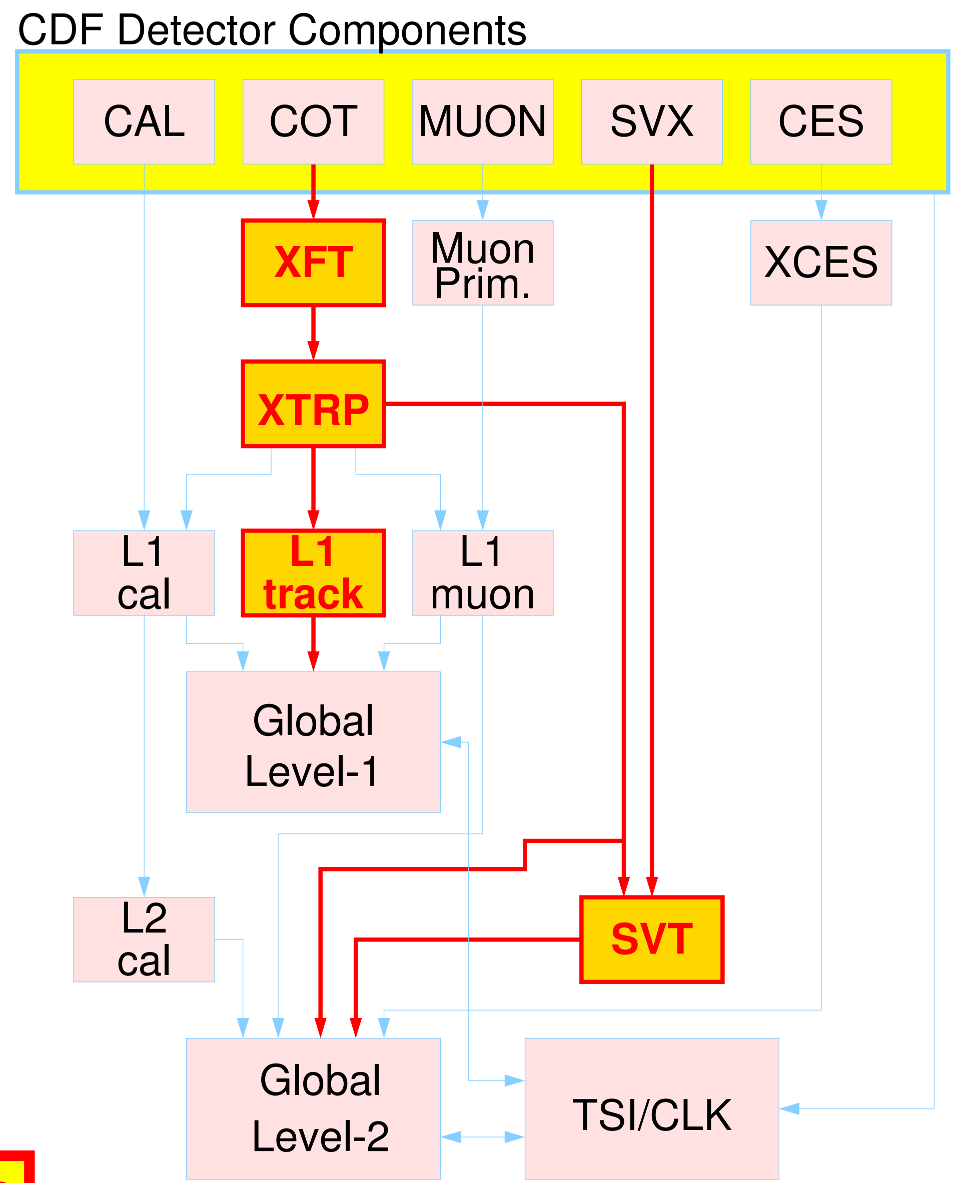
Level 1 track trigger

- based on chamber: $r - \phi$
- opposite charged track pair with $p_T > 2$ GeV each
- sum of $p_T > 5.5$ GeV
- $\Delta\phi < 135^o$

Level 2 track trigger

- based on silicon: $r - \phi$
- repeat level 1
- two large impact par. tracks: $\rightarrow 120\ \mu\text{m} < d_0 < 1$ mm

Improves sensitivity by 4-5 orders of magnitude over Run I



Comparisons of B Experiments

Accelerator	CESR,DORIS	LEP,SLC	PEPII,KEKB	Tevatron
Detector	Argus,CLEO	ADLO,SLD	BaBar,Belle	CDF,DØ
$\sigma(b\bar{b})$	$\approx$ 1 nb	$\approx$ 6 nb	$\approx$ 1 nb	$\approx$ 50 μb
$\sigma(b\bar{b}) : \sigma(had)$	0.26	0.22	0.26	0.001
b hadrons	B^0, B^+	all	B^0, B^+	all
Boost $< \beta\gamma >$	0.06	6	$\approx$ 0.5	2-4
Production	*B*s at rest	$b\bar{b}$ btb	forward boost	$b\bar{b}$ not btb
Event pile-up	no	no	no	yes
Trigger	inclusive	inclusive	inclusive	selective

Comments

+ experimentally LEP/SLC at Z looks ideal – but expensive
+ Babar and Belle produces at moderate cost although not all
+ Tevatron has the highest cross section and can do all but lots of background
+ nice complementary setup

B Mixing Phenomenology

Neutral *B* mesons: mixtures of two mass eigenstates[1]

$$|B_H> = \frac{1}{\sqrt{2}}(|B> + |\overline{B}>) \qquad |B_L> = \frac{1}{\sqrt{2}}(|B> - |\overline{B}>)$$

Heavy and Light states have different mass and width

$$\Delta m = m_H - m_L (> 0 \text{ by def.}) \qquad \Delta\Gamma = \Gamma_H - \Gamma_L$$

Time evolution with $\Delta\Gamma \neq 0$

$$P(t)_{B^0 \to \overline{B^0}} = \frac{1}{2\tau} e^{-t/\tau} (\cosh \frac{\Delta\Gamma t}{2} - \cos \Delta m t) \qquad P(t)_{B^0 \to B^0} = \frac{1}{2\tau} e^{-t/\tau} (\cosh \frac{\Delta\Gamma t}{2} + \cos \Delta m t)$$

With $\Delta\Gamma = 0$ $(\Delta\Gamma_d/\Gamma_d < 0.01, \Delta\Gamma_s/\Gamma_s < 0.20)$

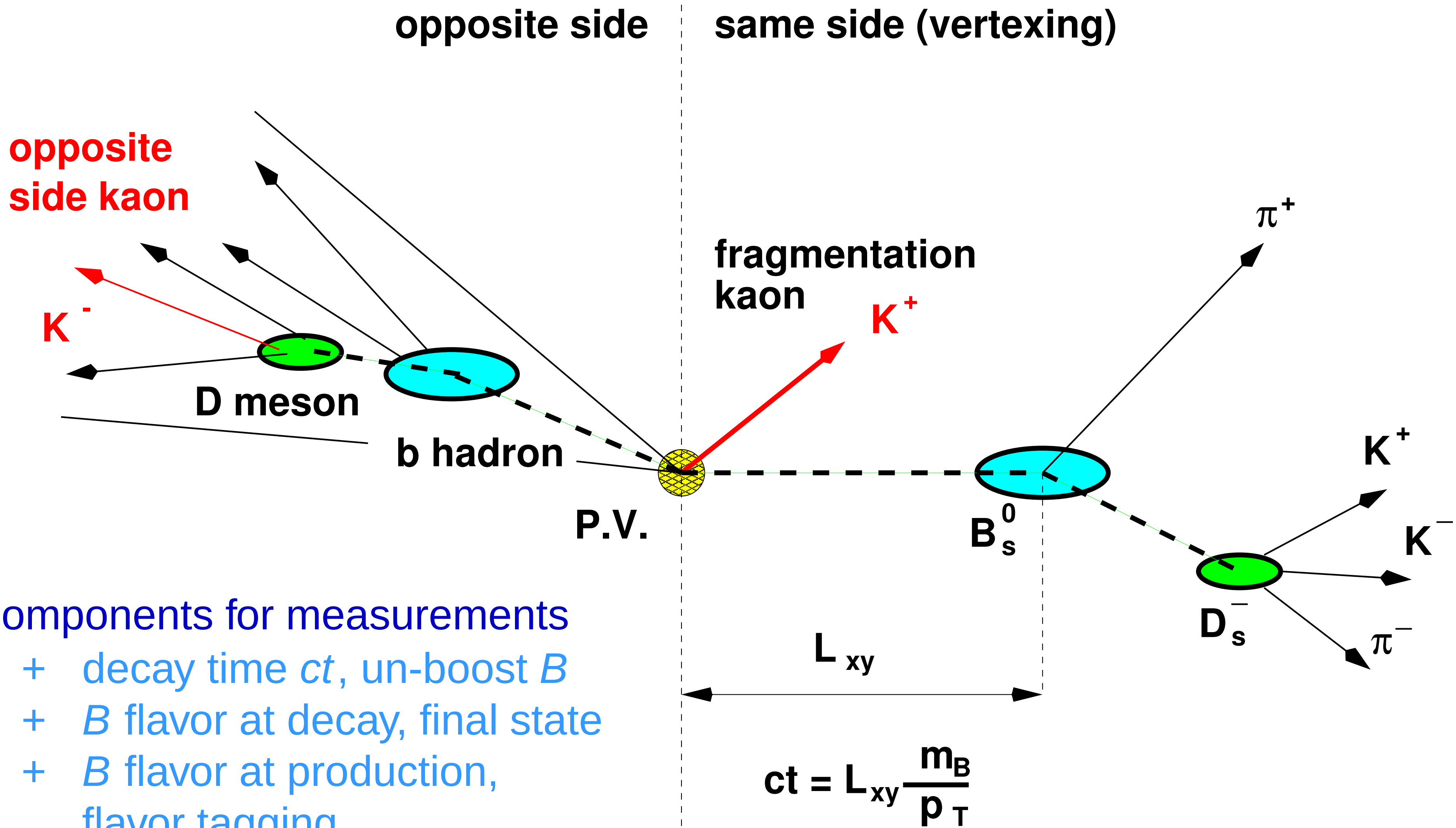
$$P(t)_{B^0 \to \overline{B^0}} = \frac{1}{2\tau} e^{-t/\tau} (1 - \cos \Delta m t) \qquad P(t)_{B^0 \to B^0} = \frac{1}{2\tau} e^{-t/\tau} (1 + \cos \Delta m t)$$

Determine asymmetry

$$A_0(t) = \frac{N(t)_{unmixed} - N(t)_{mixed}}{N(t)_{unmixed} + N(t)_{mixed}} = \cos(\Delta m\, t)$$

[1] Assume no *CP* violation.

B_s Mixing: Experimental Building Blocks



Components for measurements

- decay time *ct*, un-boost *B*
- *B* flavor at decay, final state
- *B* flavor at production, flavor tagging

Measure asymmetry in dependence of time

$$A_0^{meas}(t) \equiv \frac{N(t)_{RS} - N(t)_{WS}}{N(t)_{RS} + N(t)_{WS}} = D\cos(\Delta m_s t) \quad \text{with} \quad D = 2P - 1 = \text{dilution}$$

Why is that so difficult?

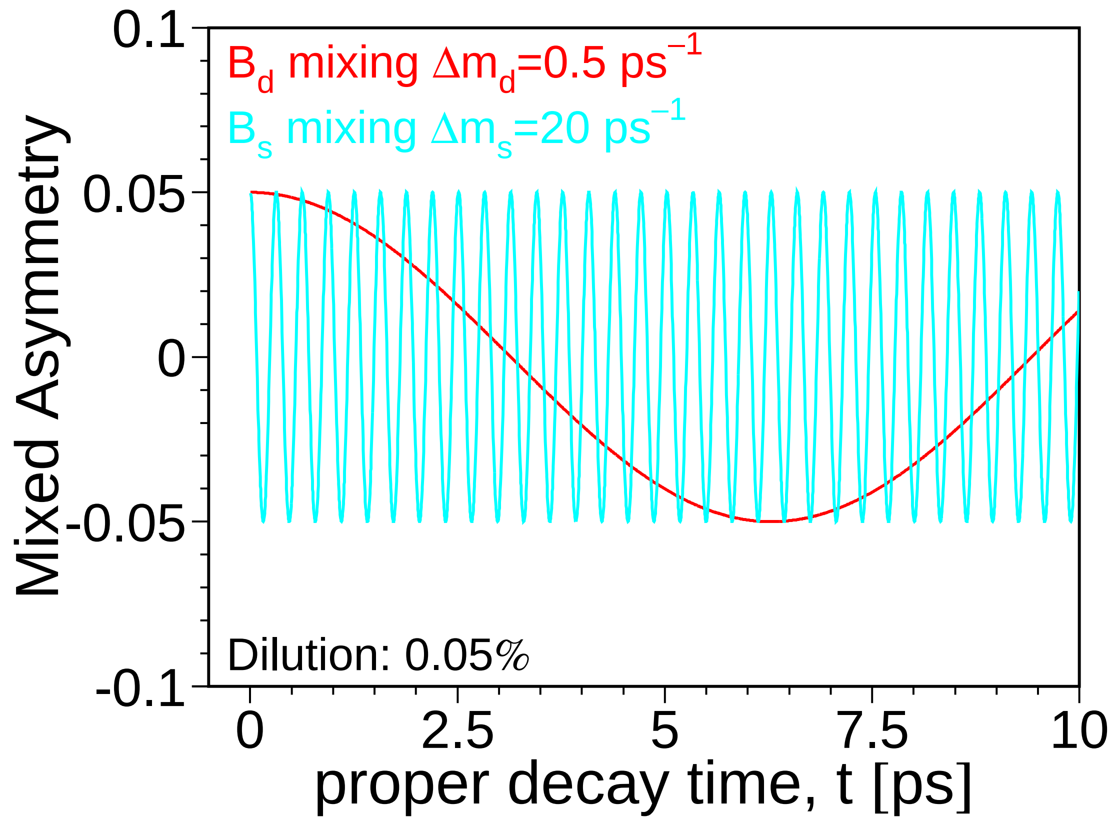
B_s mixing

+ very fast

Challenge

+ precise vertex
+ precise momentum
+ many events
+ tagging essential

Very tricky!



The larger Δm_S the more crucial $\sigma(ct)$

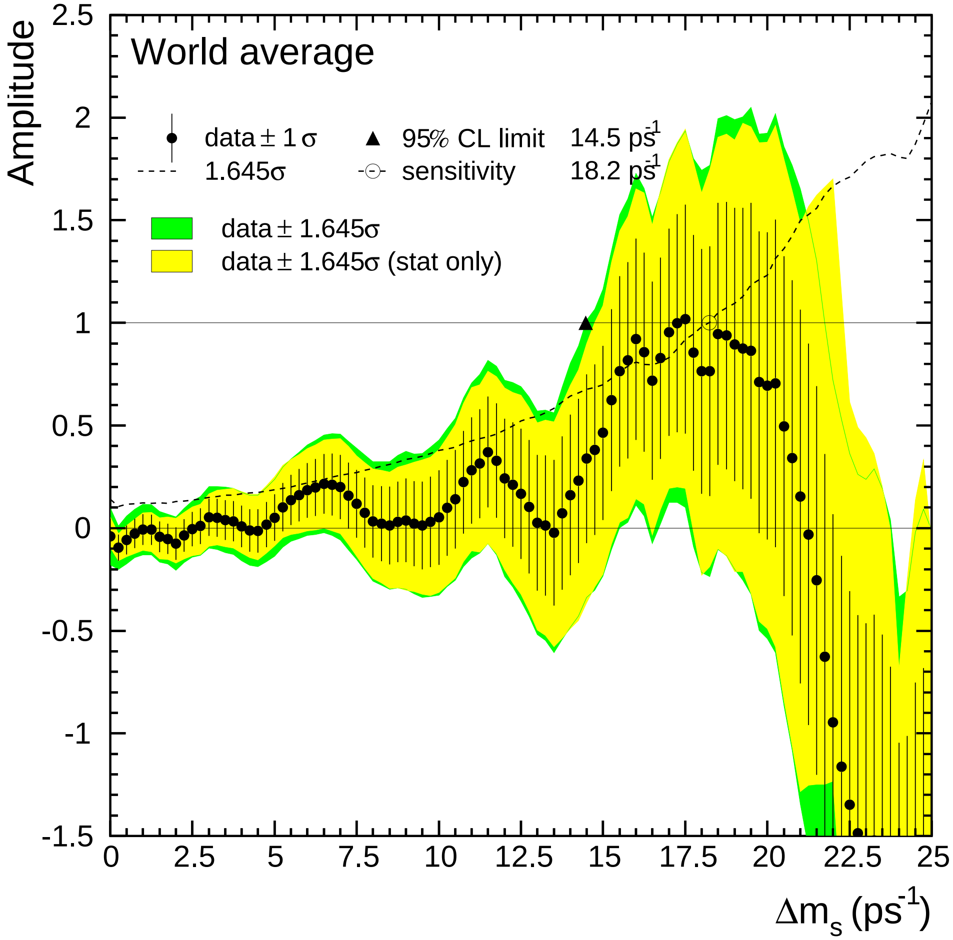
$$\text{significance} = \sqrt{\frac{n_S \varepsilon D^2}{2}} \sqrt{\frac{n_S}{n_S + n_B}} \exp\left(-\frac{(\Delta m_S \sigma_{ct})^2}{2}\right)$$

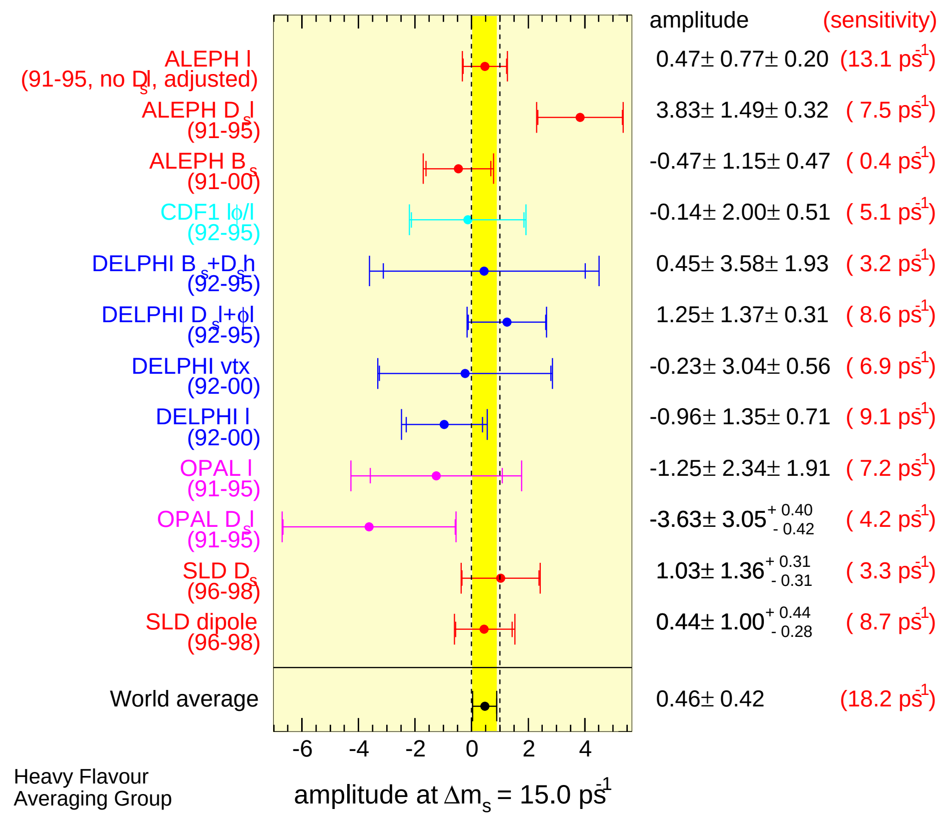
$$\sigma(ct) = \sqrt{(\sigma_{ct}^0)^2 + \left(ct \, \frac{\sigma_p}{p}\right)^2}$$

Present Experimental Results

Summary at 95% CL

- \+ limit: $14.5\ ps^{-1}$
- \+ sensitivity: $18.3\ ps^{-1}$
- \+ data: LEP, SLD, CDF Run I





B_s* mixing frequency more than 30 times faster than for *B^0

→ experimental challenge

B_s *Mixing Analysis - Road Map*

Samples

- + confirm SVT based triggers for the samples
- + reconstruct B signals (B^+, B^0, B_s)
- + optimise $s/\sqrt{S+B}$

Lifetimes

- + SVT and analysis sculpts proper time distribution
- + develop correction for proper time sculpting
- + fit lifetimes for B^+, B^0, B_s

Flavor Taggers

- + calibrate opposite side taggers to parametrize dilution
- + use B^+, B^0 samples
- + use calibrated tagger dilution in fit for mixing

Amplitude scan for B_s mixing with unbinned likelihood

- + test on B^0 sample
- + proper time resolution per candidate
- + tagging power per candidate

Samples

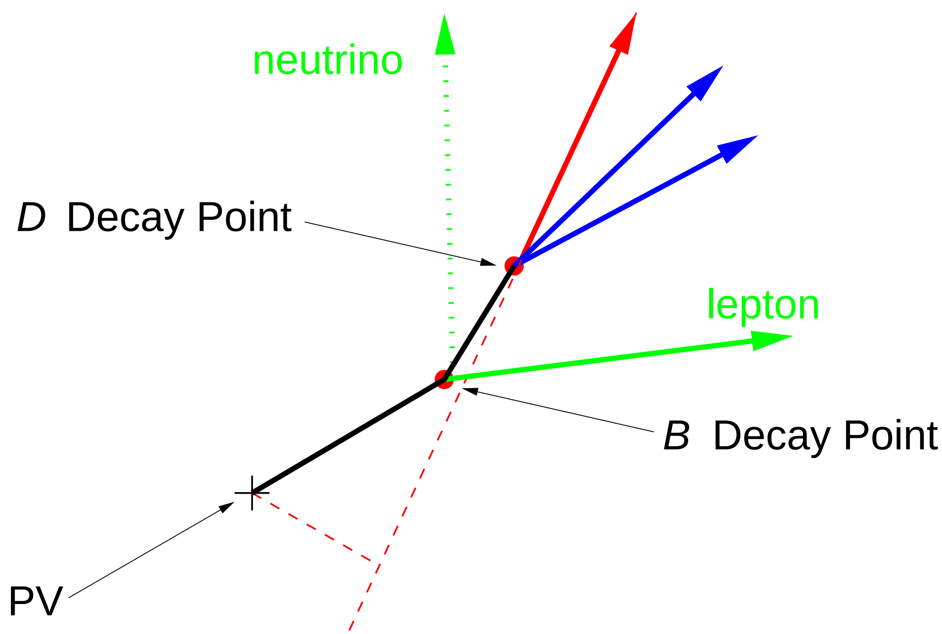
SVT Based Triggers

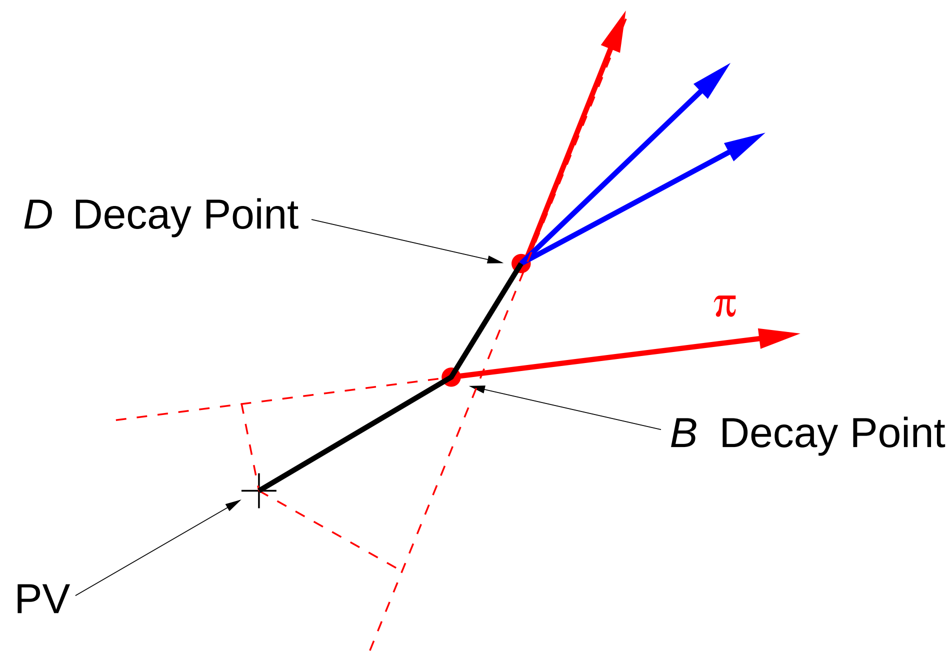
Semileptonic: $B_s \to \ell^+ D_s^- X$

+ one lepton, one SVT track
+ $p_T^\ell > 4$ GeV
+ $p_T^{track} > 2$ GeV
+ $p_{T,1} + p_{T,2} > 5.5$ GeV
+ $120\mu\text{m} < d_0^{track} < 1\text{mm}$

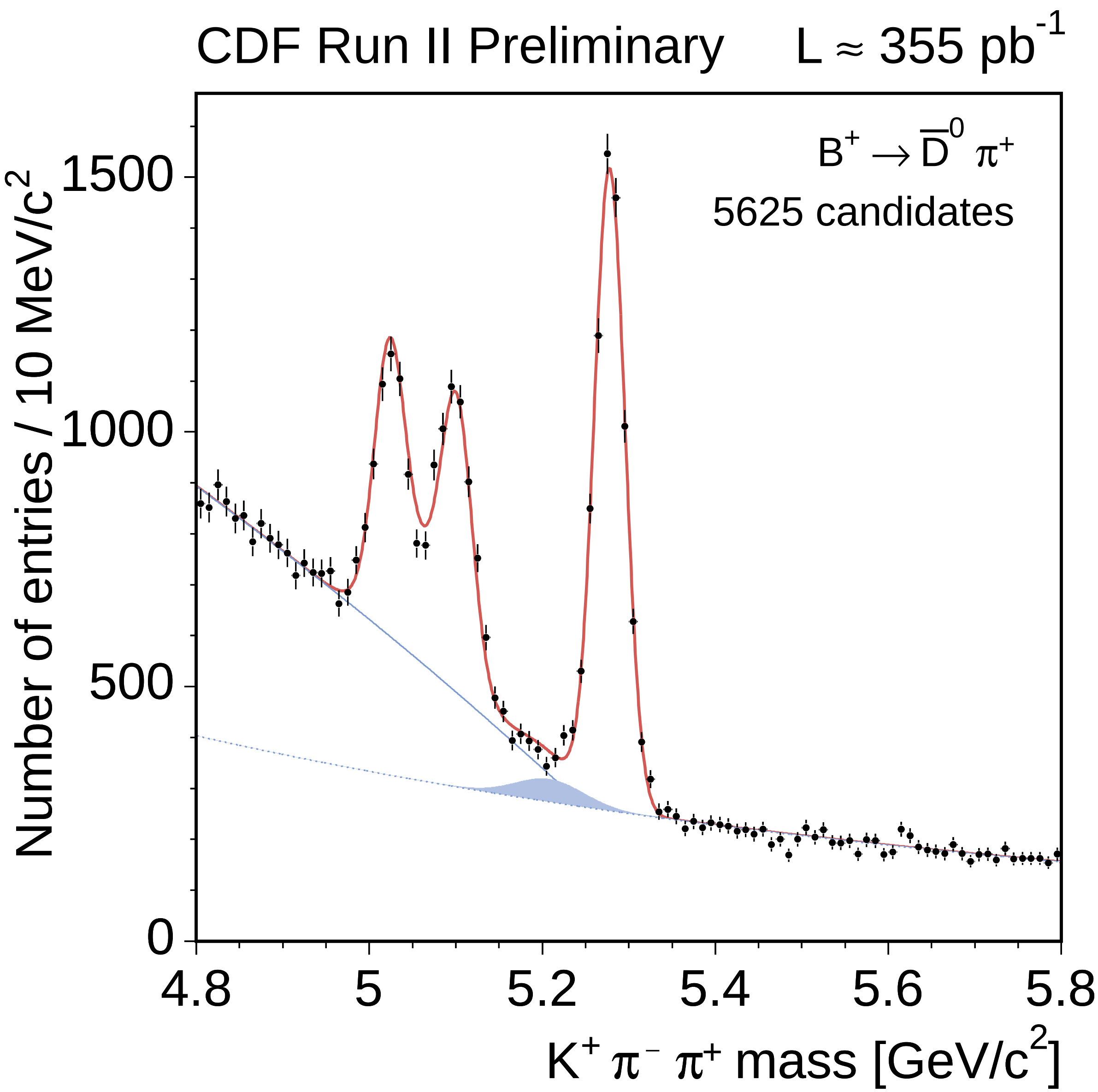
Hadronic: $B_s \to D_s^- \pi^-$

+ two SVT tracks
+ $p_T > 2$ GeV
+ $p_{T,1} + p_{T,2} > 5.5$ GeV
+ opposite charge
+ $120\mu\text{m} < d_0 < 1\text{mm}$
+ $L_{xy} > 200\mu\text{m}$

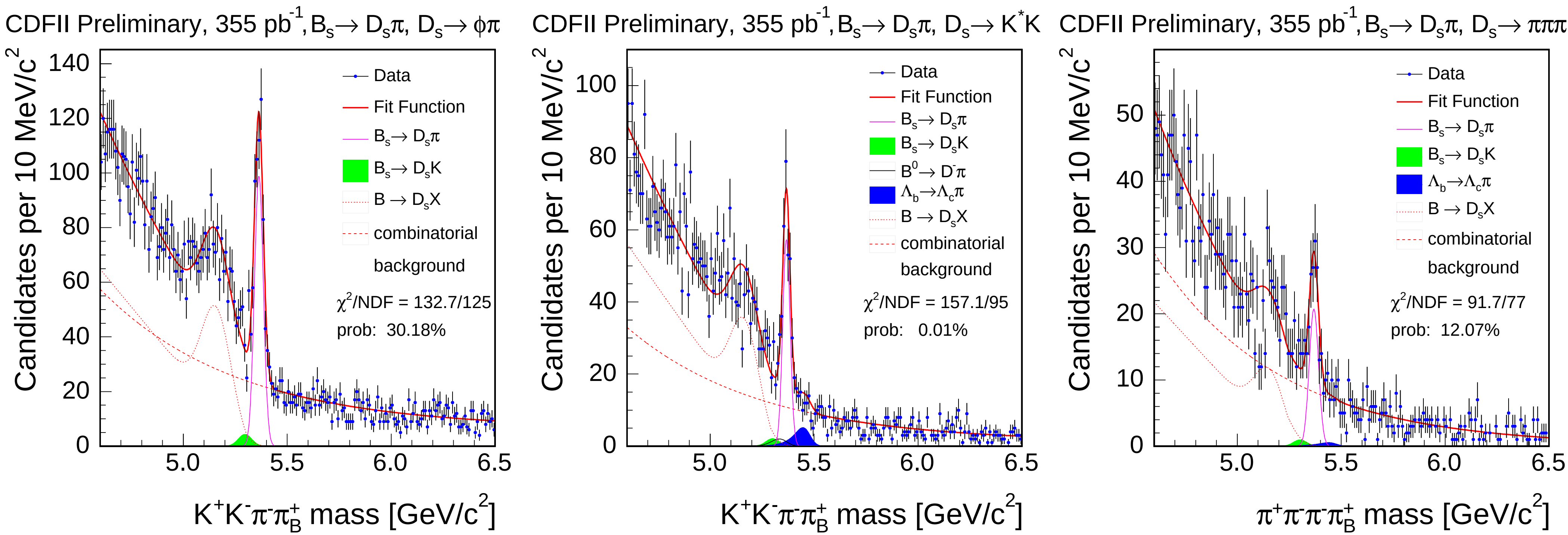




Hadronic Decay Signals $B^+ \to \bar{D}_s^0 \pi^+$



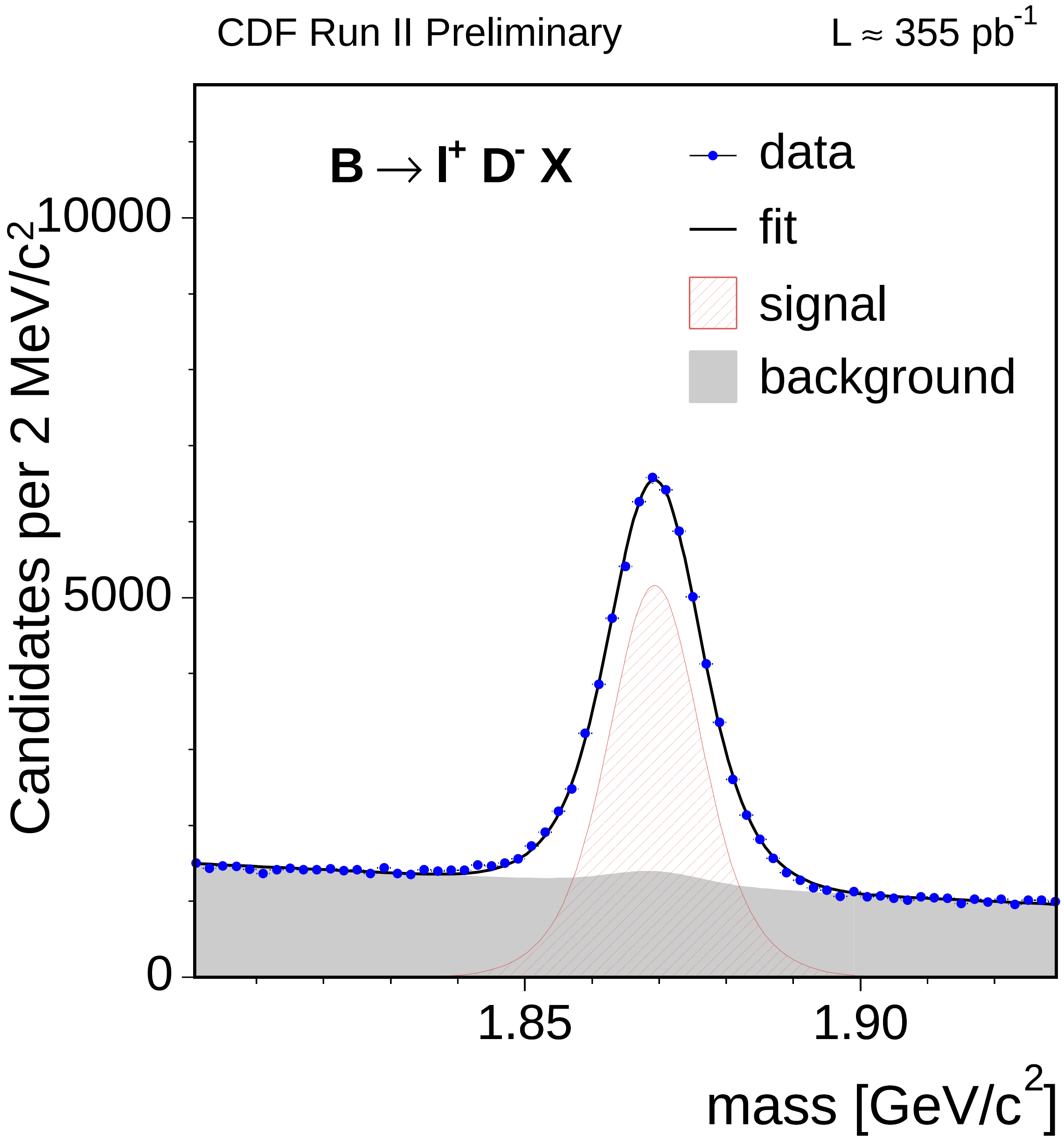
Hadronic Decay Signals $D_s^-\pi^+$



Decent samples of fully reconstructed B_s

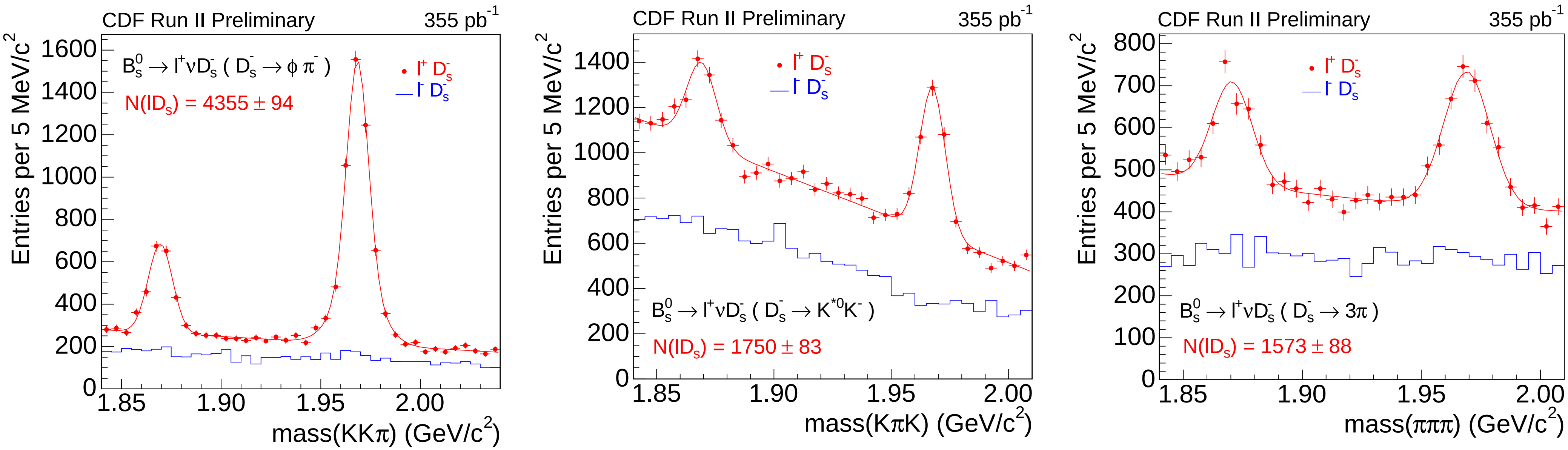
about 900 events

Semileptonic Decay Signals $B^+ \to \ell D^+ X$



Very large sample: about 56k events

Semileptonic Decay Signals $\ell D_s^- X$

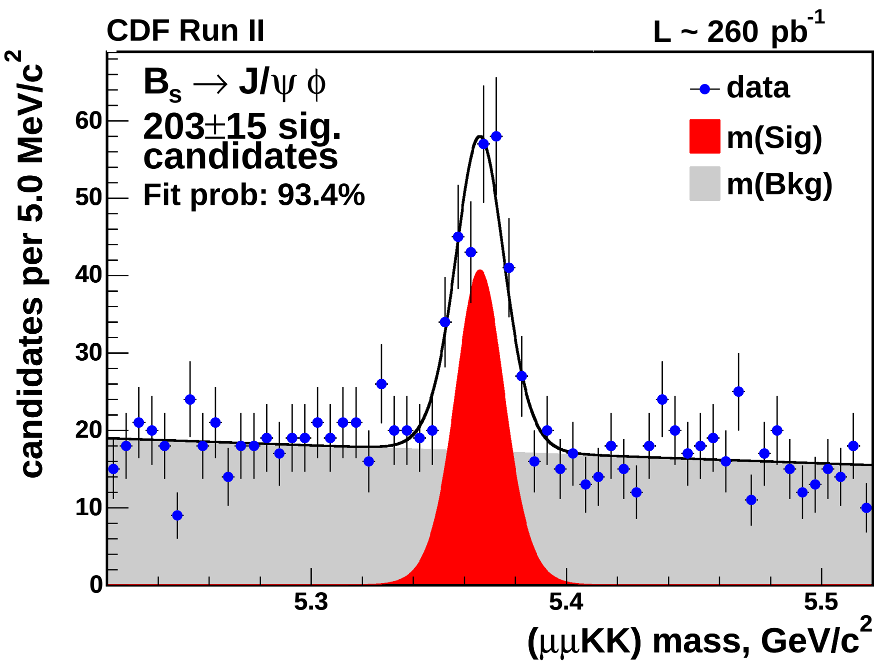


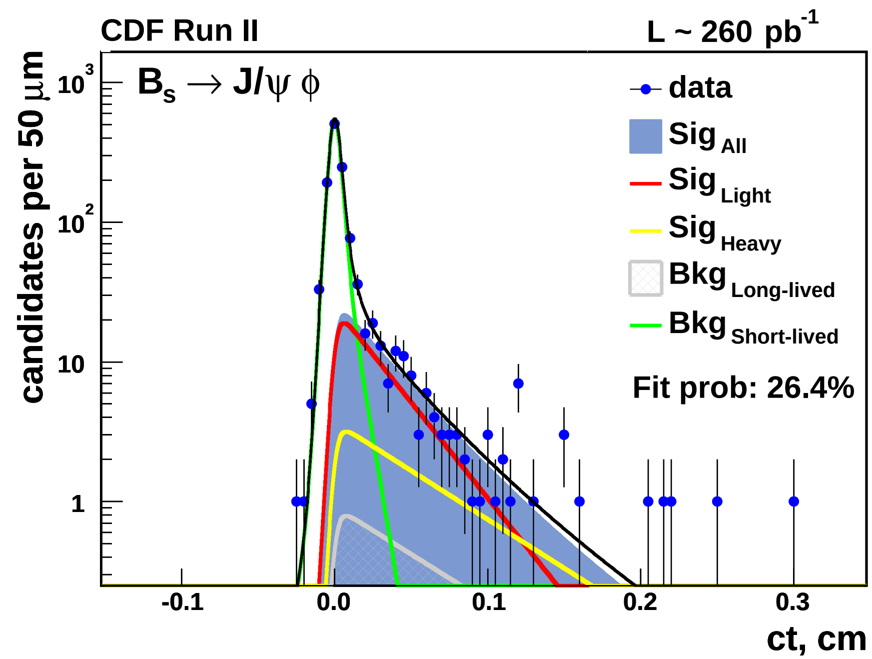
Very decent samples of fully reconstructed B_s

about 7800 events (8.7 times hadronic B_s sample)

Lifetimes

Classic Lifetime Measurement





Analysis sketch ($B_s \to J/\psi\phi$)

- reconstruct p_T, mass, and L_{xy} $\to$ calculate proper time $ct = \frac{L_{xy} m}{p_T}$
- no cuts that bias ct $\to$ signal probability: $p(t) = Ne^{-t/\tau} \times G(\sigma_{ct})$
- background from mass sidebands
- extract $c\tau$ from combined mass and ct fit

Lifetimes in Hadronic Channels

Bias in *ct*

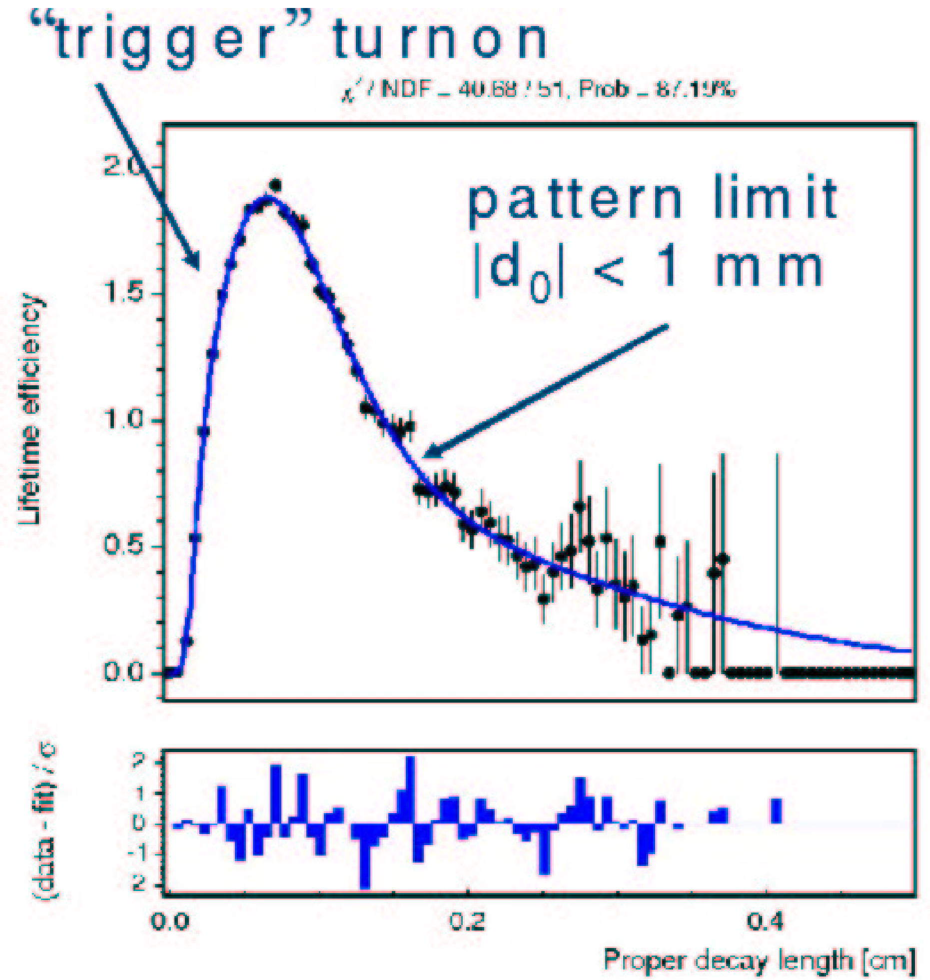
- + two SVT tracks
- + turnon: $d_0 > 120\ \mu$m
- + turnoff: $d_0 < 1$ mm and pattern limit
- + selection increases bias

Adjust probability density

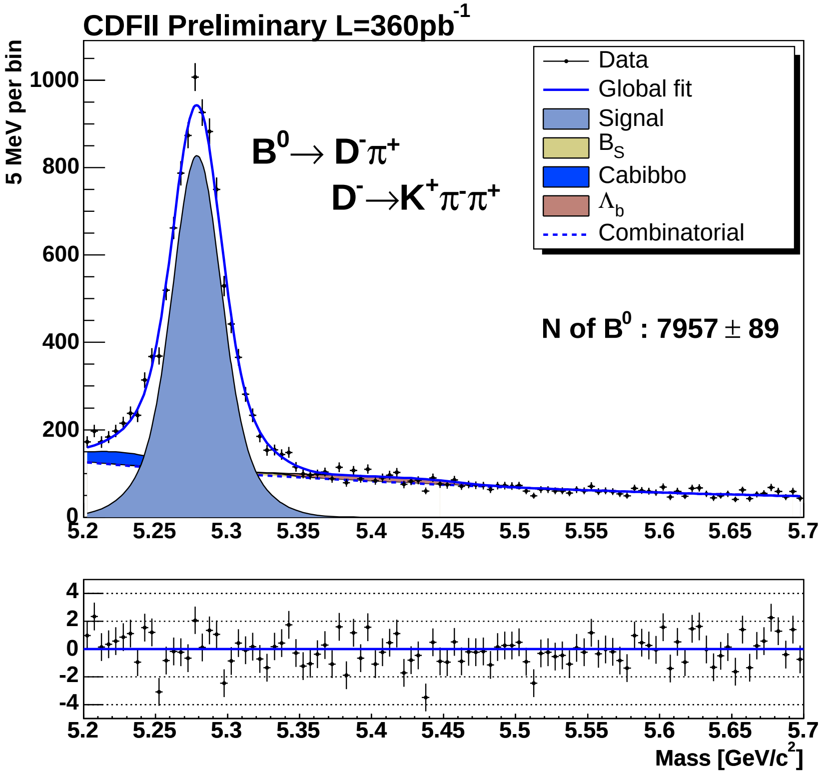
- + $p(t) = N(e^{-t/\tau} \times G(\sigma_{ct}))\ \ \varepsilon(t)$
- + background more complex, still from mass sideband

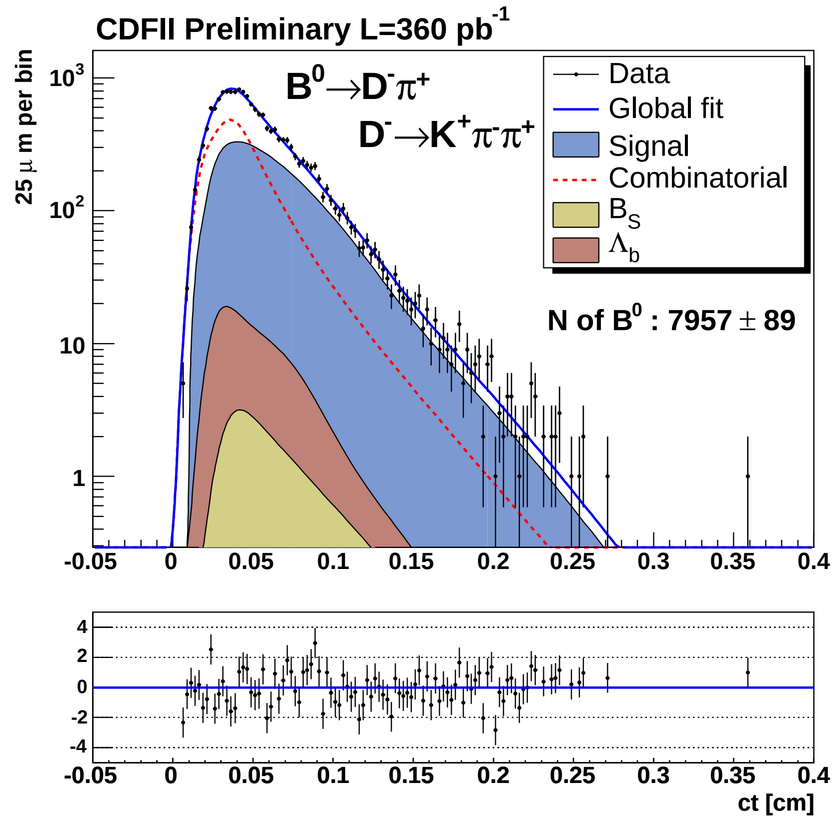
Do we care for mixing?

- + bias cancels!
- + very small effect on mixing



Hadronic Decay $D_s^-\pi^+$ *– Lifetimes*





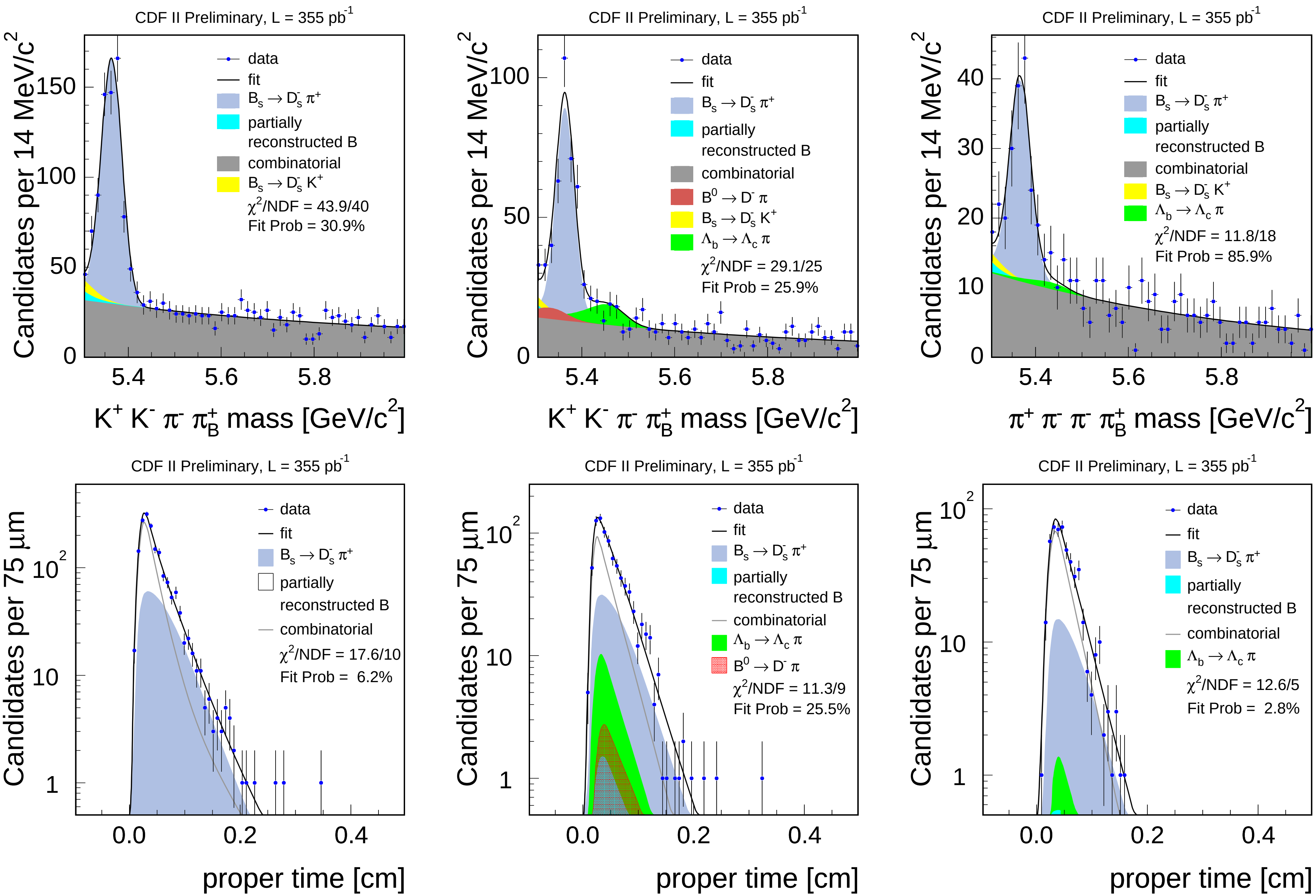
Measure lifetimes of B^+ and B^0 $\rightarrow$ then B_s

$$c\tau(B^+) = 498 \pm 8(stat) \pm 4(syst)\ \mu\text{m}$$

$$c\tau(B^0) = 453 \pm 7(stat) \pm 4(syst)\ \mu\text{m}$$

$$c\tau(B_s) = 479 \pm 29(stat) \pm 5(syst)\ \mu\text{m}$$

Hadronic Decay $D_s^- \pi^+$ – Lifetimes



Lifetimes in Semileptonic Channels

Bias in *ct* (see hadronic)

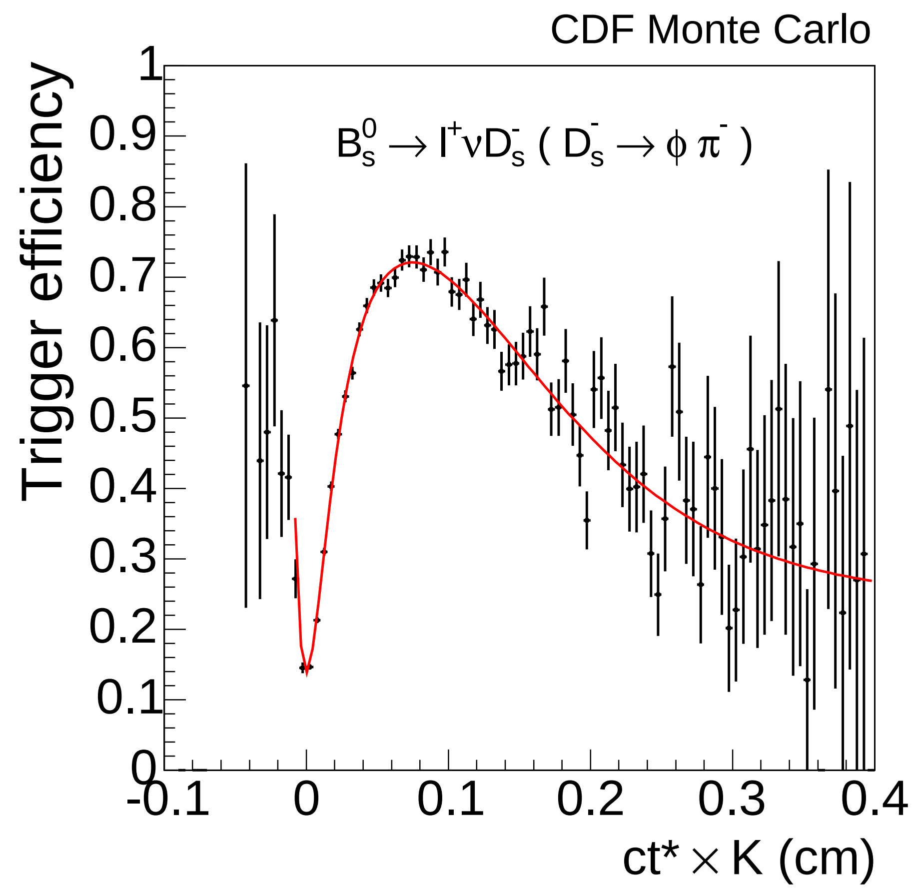
- one SVT track
- turnon: $d_0 > 120\ \mu m$
- turnoff: $d_0 < 1$ mm and pattern limit
- selection increases bias

Corrrect missing momentum

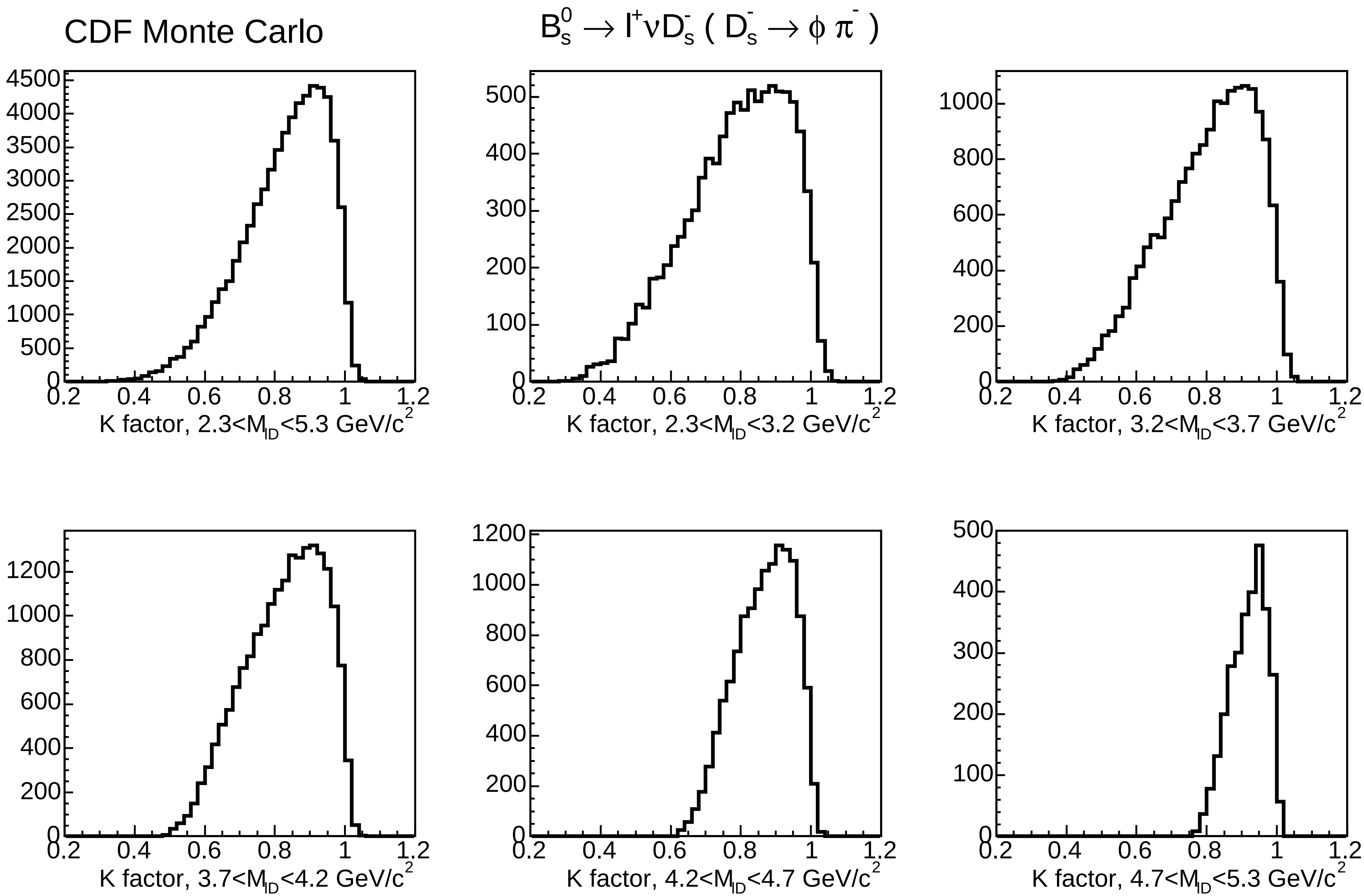
- from Monte Carlo (K factor)
- bin in ℓDX mass

Incomplete reconstruction

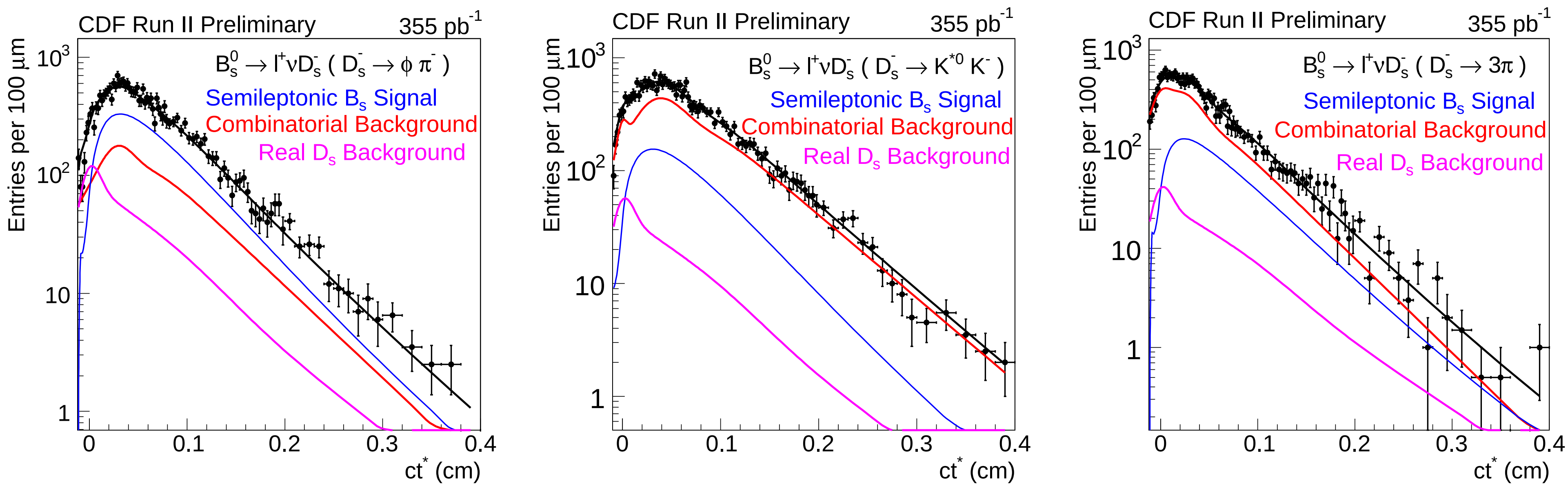
- cross talk B^+, B^0
- prompt D background



Lifetimes in Semileptonic Channels - K Factor



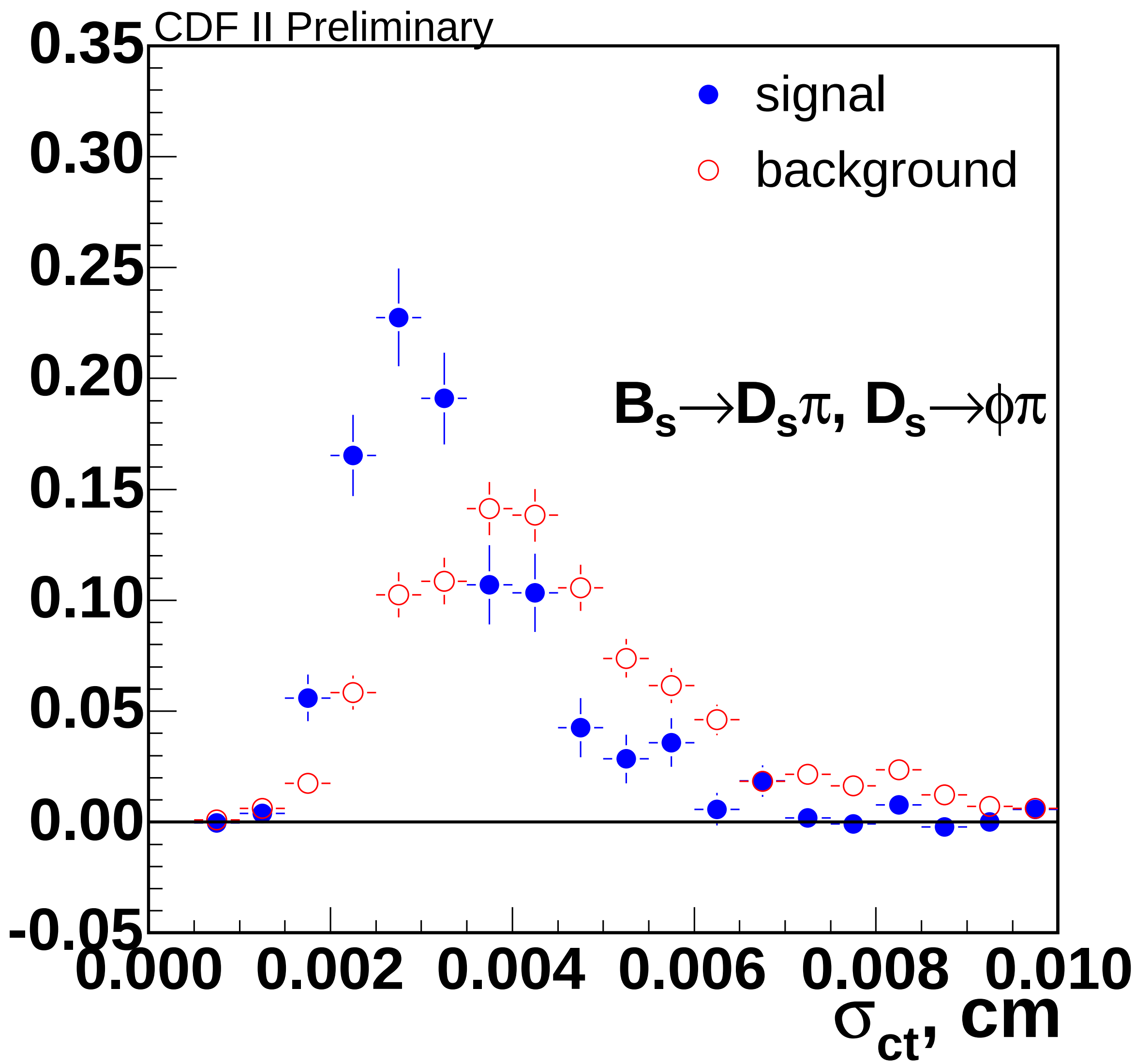
Semileptonic Decay $\ell^+ D_s^- X$ – Lifetimes



Measurement not yet complete only statistical uncertainty

- + B^+, B^0 lifetimes within 20 μm of world average
- + $c\tau(B_s) = 445 \pm 9.5(stat)\ \mu\text{m}$
- + $c\tau(B_s) = 438 \pm 17(tot)\ \mu\text{m}$ – world average

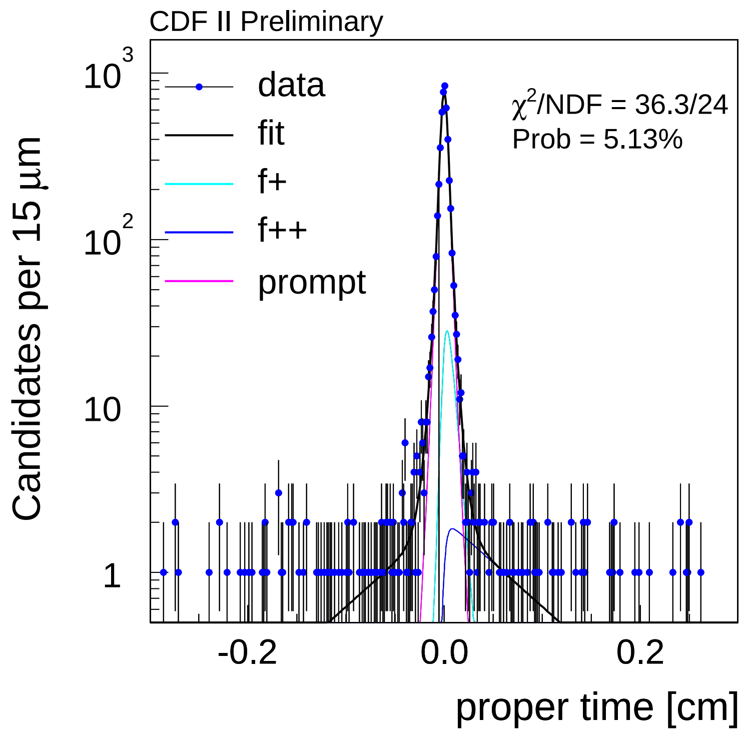
Proper Time Resolution

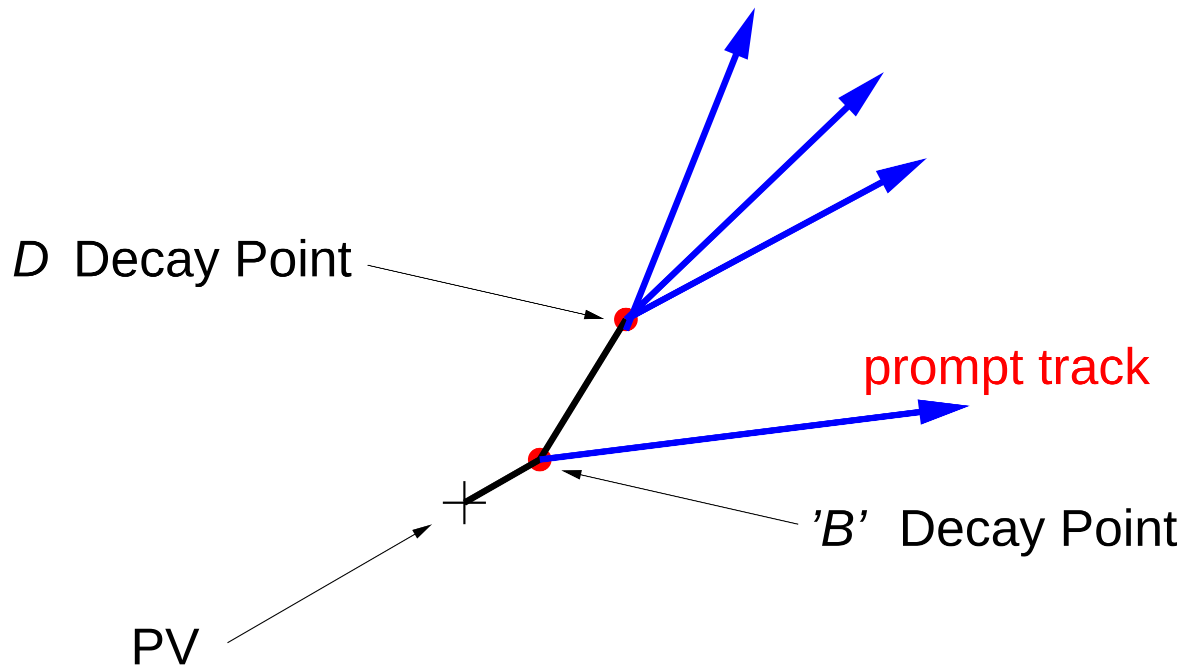


Vertex fitter measures

- + L_{xy}, p_T and corresonding uncertainties
- + but the errors are not reliable → scale factor already applied

Calibration of Proper Scale Uncertainty



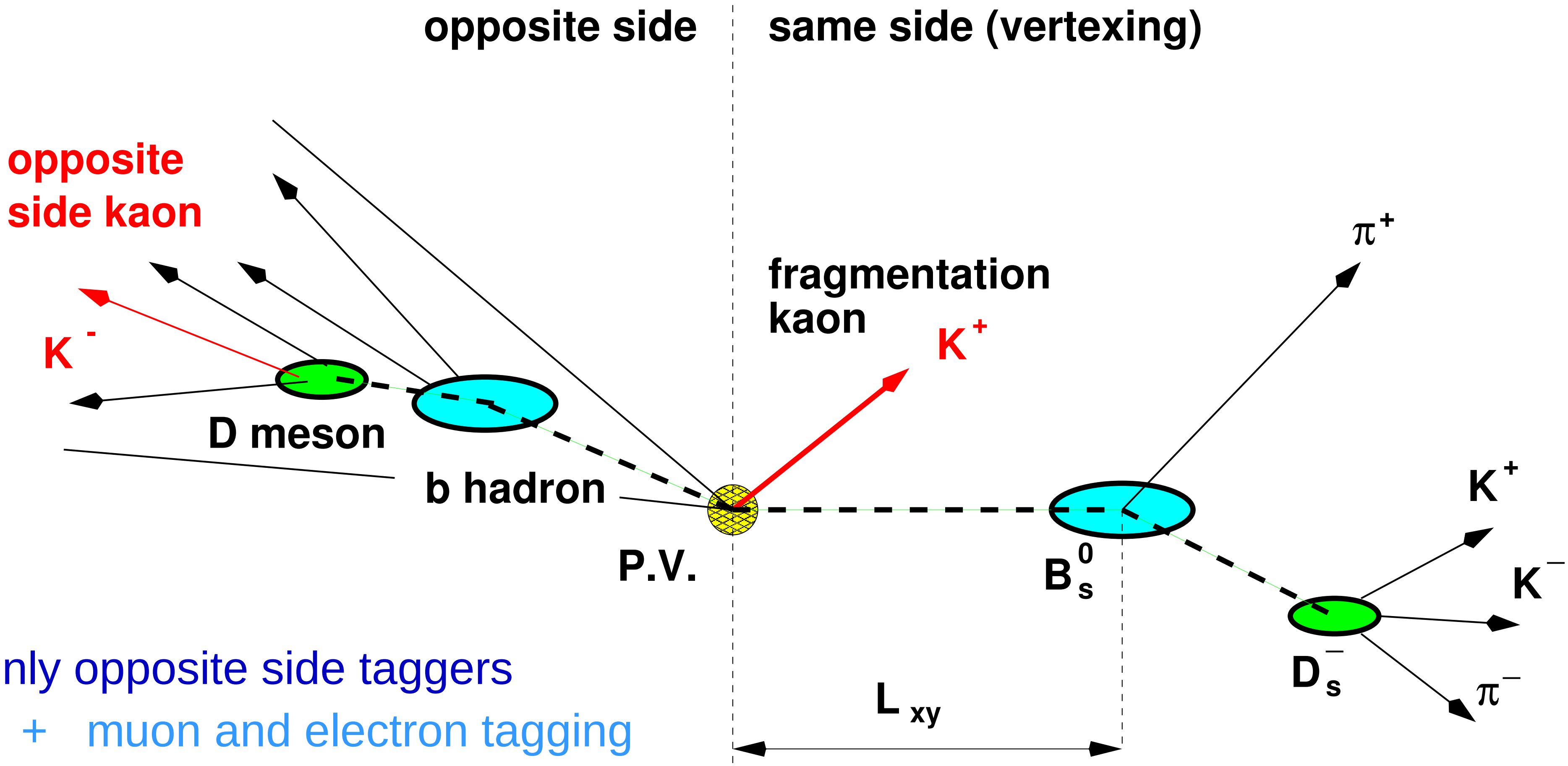


Create unbiased calibration sample

+ hadronic trigger dominated by prompt *D*
+ require *D* to trigger and add unbiased track (not triggered)
+ scale factor applied to uncertainty of each event
+ primary vertex position has to be zero $\rightarrow$ extract scale factor
+ long lived background accounted for in fit

Flavor Taggers

Tagging B Production Flavor



$$ct = L_{xy}\frac{m_B}{p_T}$$

Only opposite side taggers

- + muon and electron tagging
- + jet charge tagging
  vertex, jet probablity, highest p_T

Measure asymmetry in dependence of time

$$A_0^{meas}(t) \equiv \frac{N(t)_{RS} - N(t)_{WS}}{N(t)_{RS} + N(t)_{WS}} = D\cos(\Delta m_s t) \quad \text{with} \quad D = 2P - 1 = \text{dilution}$$

Measuring Δm_d and Tagger Performance

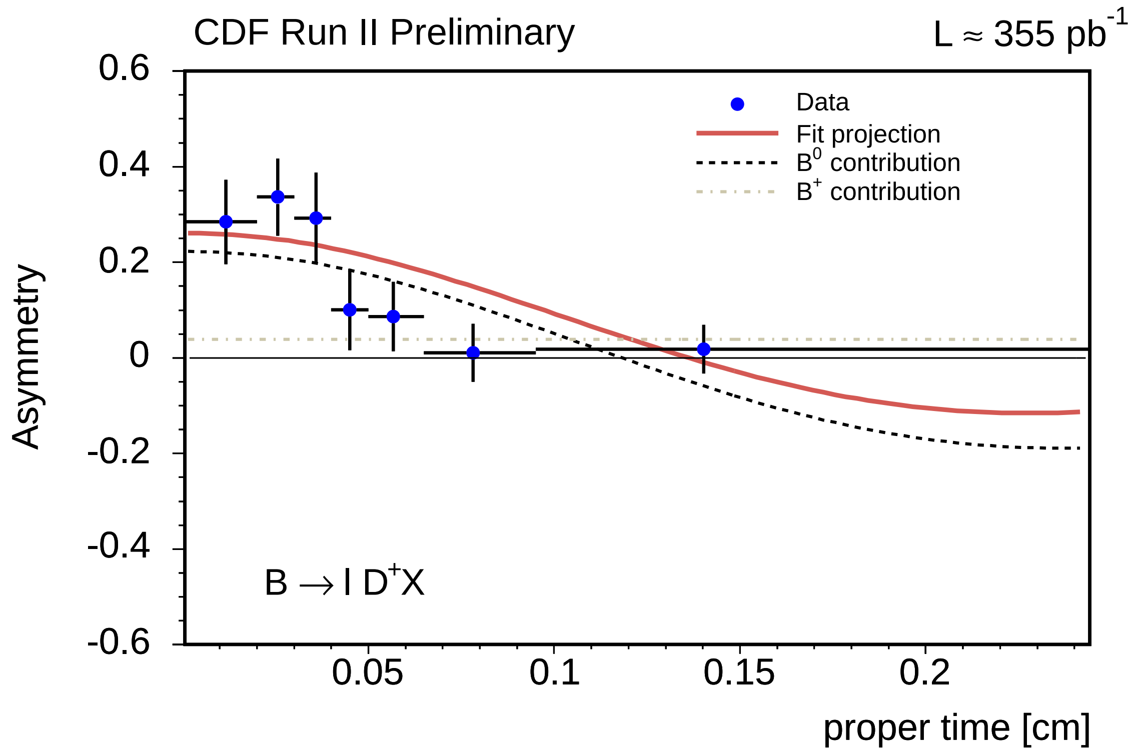
Fitting separately

- hadronic decays
- semileptonic decays

Measure

- Δm_d
- tagger performance

Sample picture: $\ell D^+ X$ SMT



Mixing results

- $\Delta m_d^{had} = 0.503 \pm 0.063 \pm 0.015\ \text{ps}^{-1}$
- $\Delta m_d^{semi} = 0.497 \pm 0.028 \pm 0.015\ \text{ps}^{-1}$
- $\Delta m_d^{HFAG} = 0.502 \pm 0.007\ \text{ps}^{-1}$

Tagger Performance

Measure of tagger performance: εD^2

+ ε if the efficiency
+ D is the dilution: $D = 2P - 1$

Tagger Combination

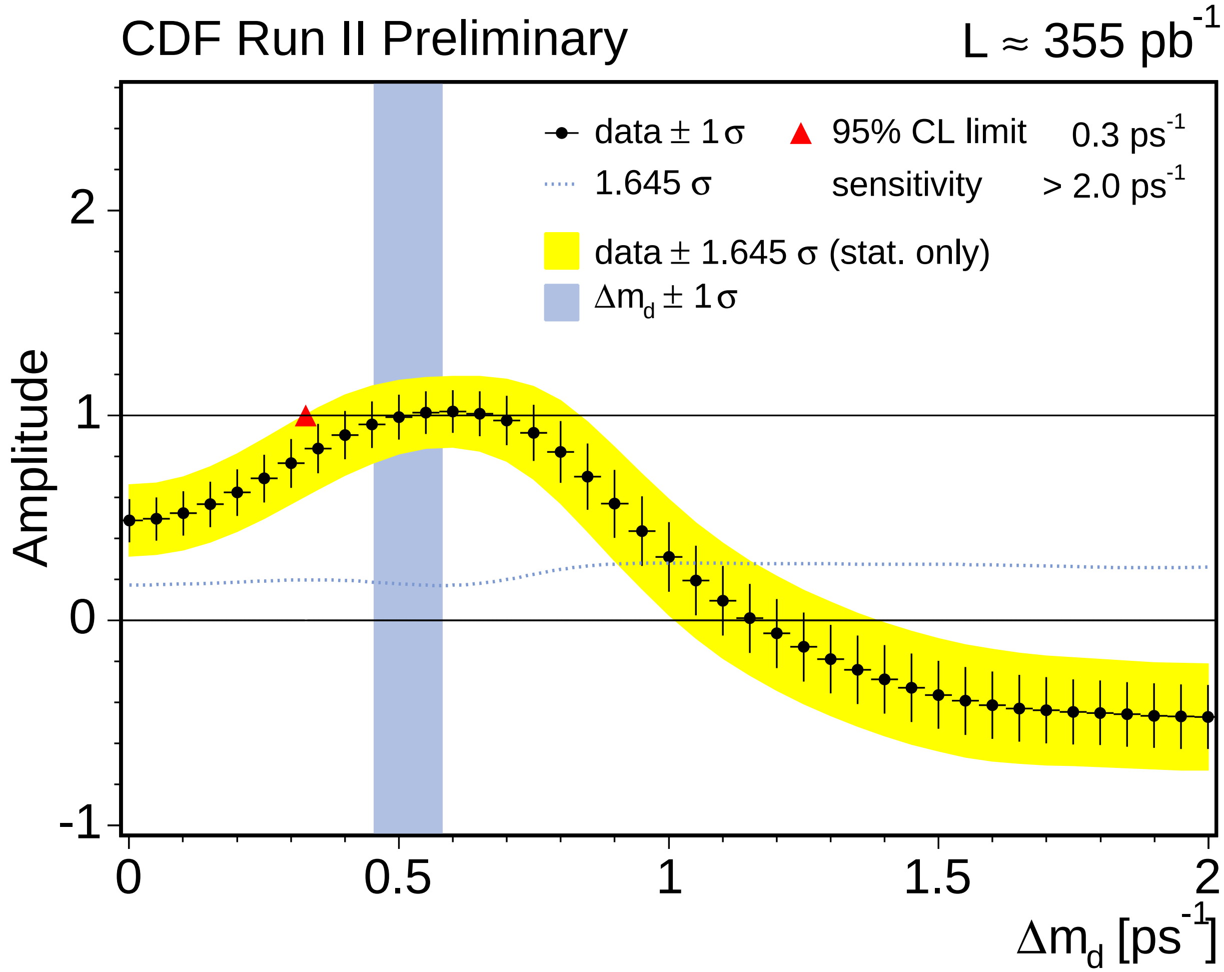
+ taggers are ordered by performance
+ exclusive taging decision, use best available tagger

Corresponding performances

[%]	εD^2 hadronic	εD^2 semileptonic
Muon	$0.46 \pm 0.11 \pm 0.03$	$0.577 \pm 0.047 \pm 0.034$
Electron	$0.18 \pm 0.06 \pm 0.02$	$0.293 \pm 0.033 \pm 0.017$
JQ/Vertex	$0.14 \pm 0.07 \pm 0.01$	$0.263 \pm 0.035 \pm 0.021$
JQ/Prob.	$0.11 \pm 0.06 \pm 0.01$	$0.150 \pm 0.026 \pm 0.015$
JQ/High p_T	$0.24 \pm 0.09 \pm 0.01$	$0.157 \pm 0.027 \pm 0.015$
Total	1.12 ± 0.18	1.429 ± 0.093

Amplitude Scan

Amplitude Scan Method - Using B^0



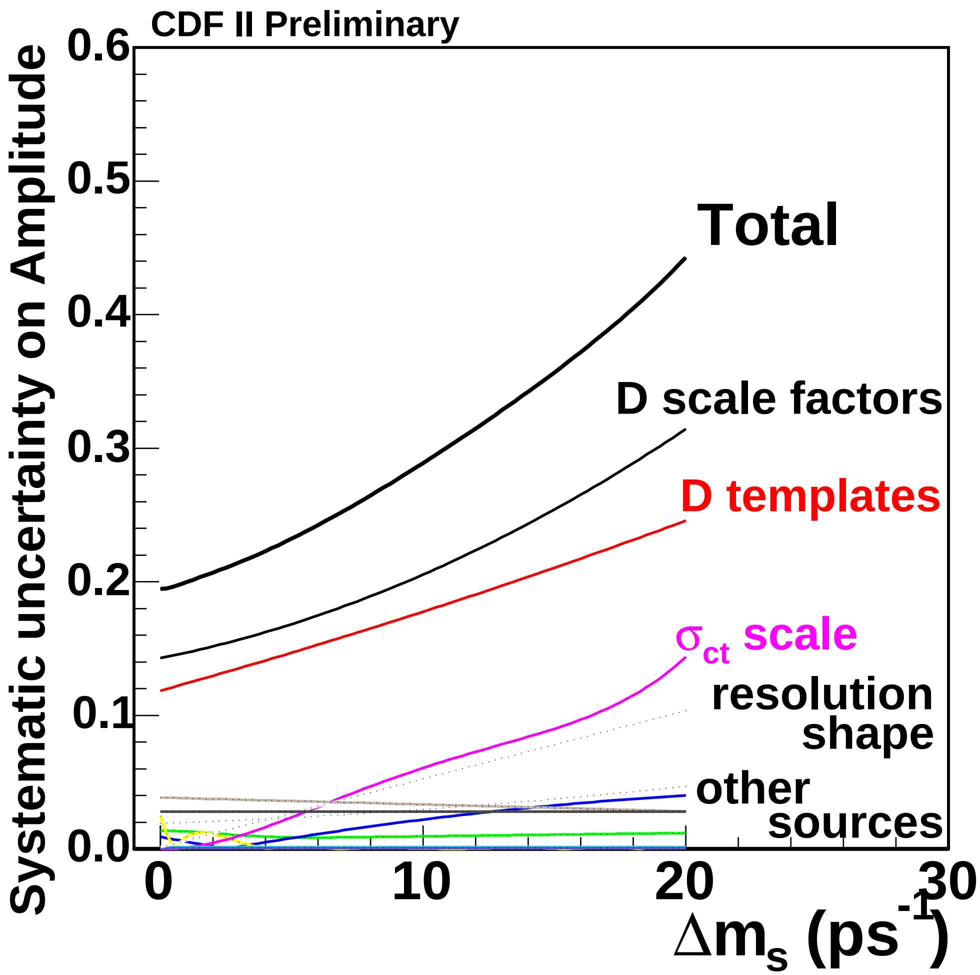
Perform unbinned likelihood fit

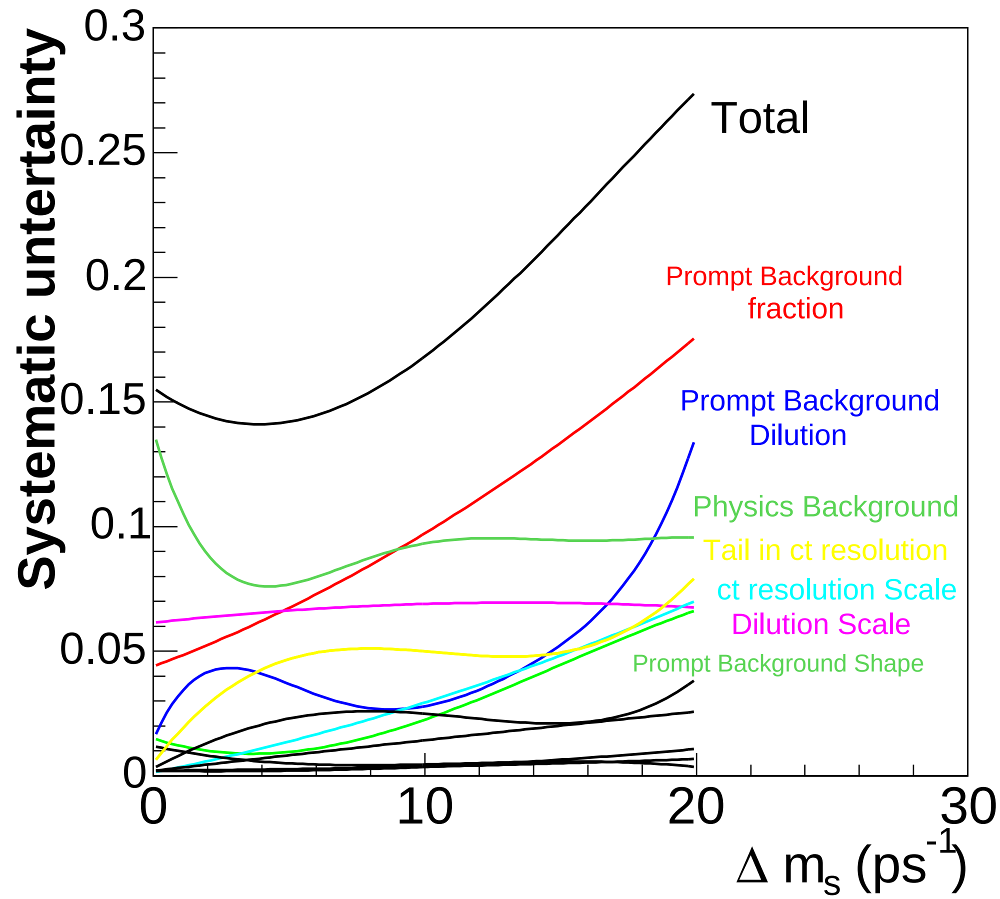
- $p \sim (1 \pm A S_D D_i \cos(\Delta m_s))$
- scan fixed values of Δm_s
- record A and $\sigma(A)$

Signal ≡ unit amplitude

- else A consistent with 0
- exclude Δm_s @95%CL for $(1 - A) > 1.645\sigma(A)$

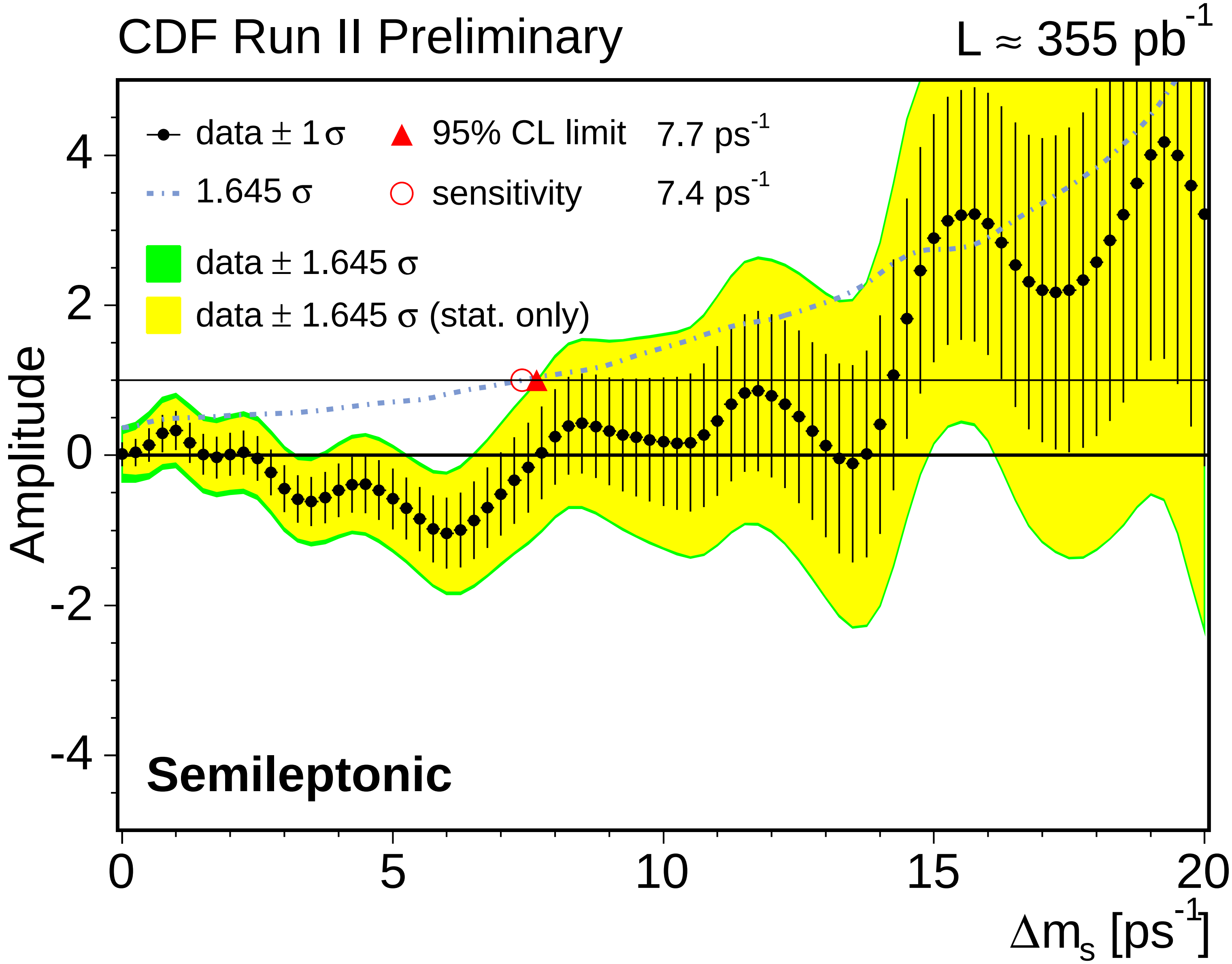
Systematic Uncertainties





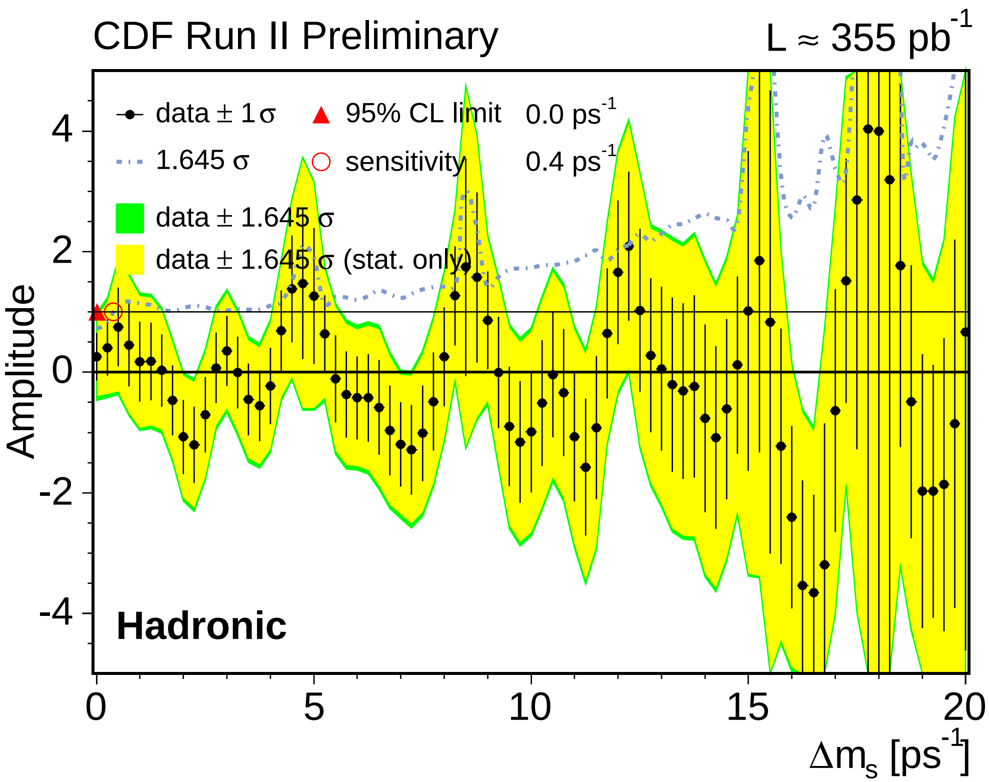
- + absolute errors on amplitude are shown
- + systematic very small compared to statistical uncertainty
- + dominant systematics limited by sample size → will improve

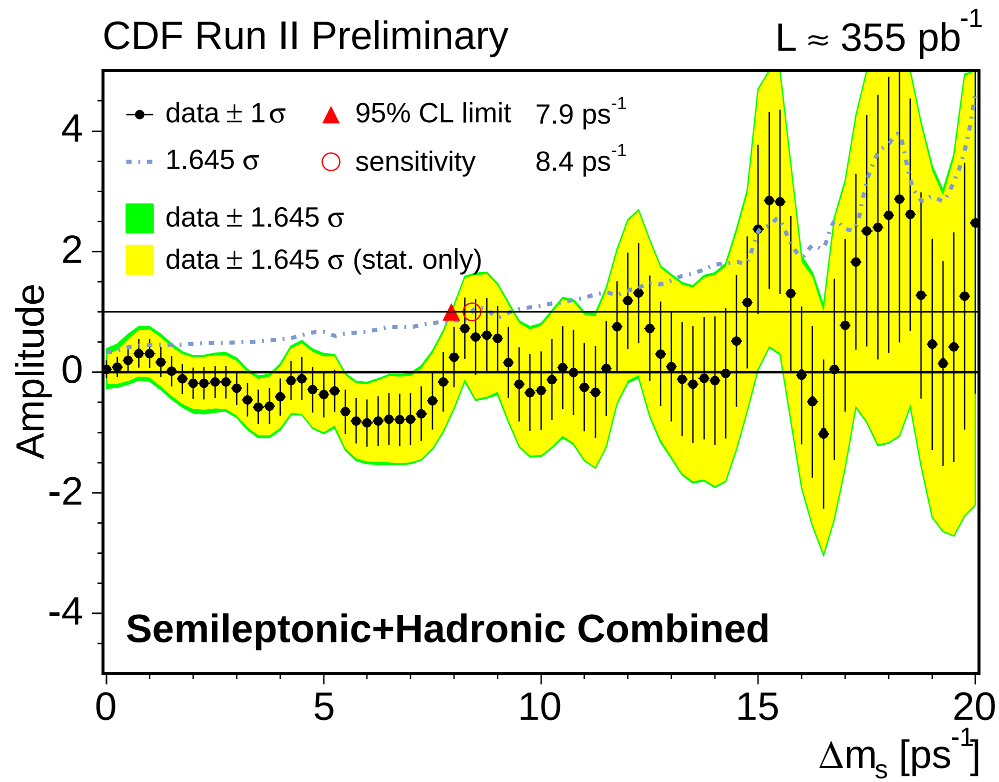
Semileptonic Result



sensitivity: 7.4 ps^{-1} lower limit: 7.7 ps^{-1} at 95% CL

Hadronic and Combined Result

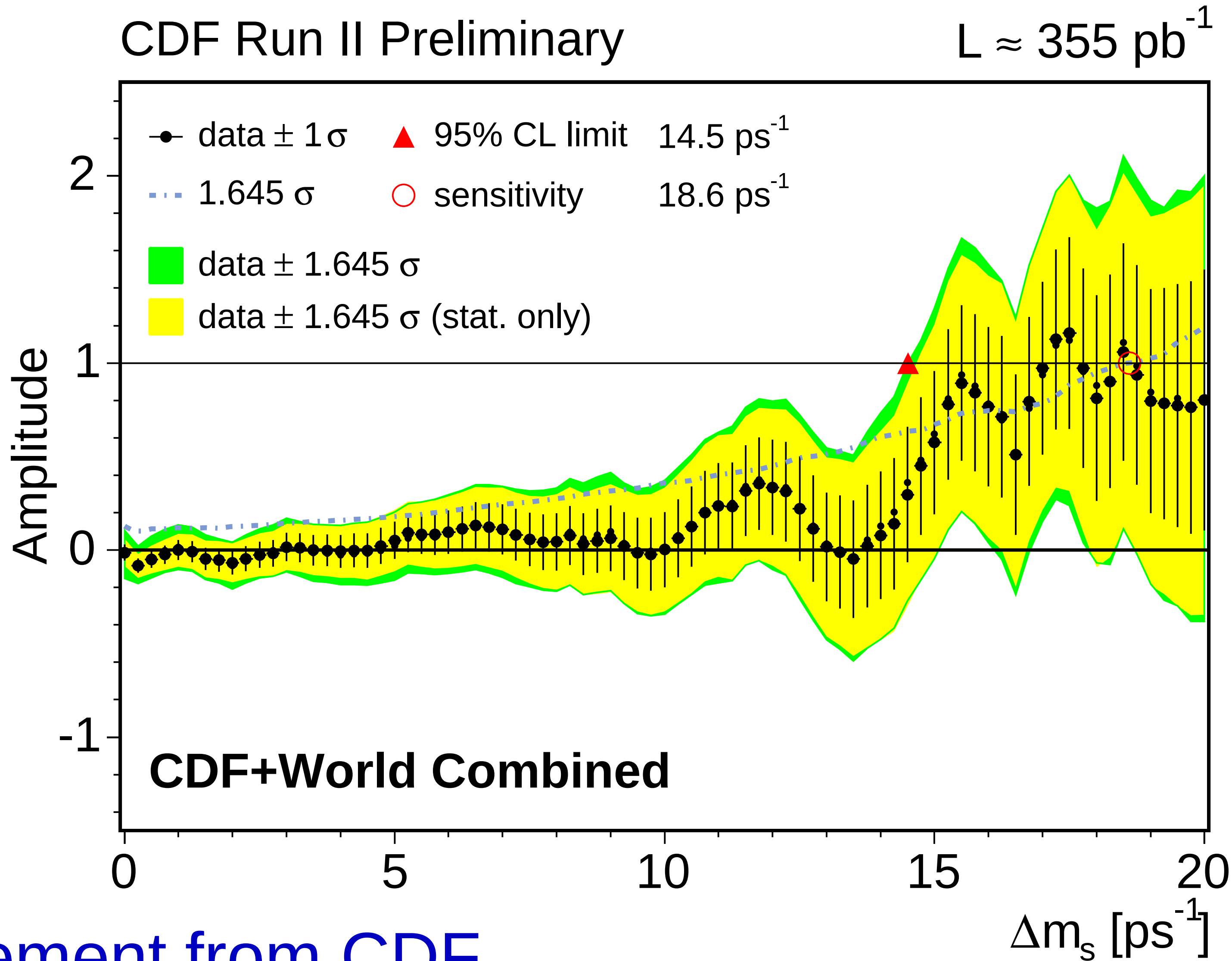




Comments

+ hadronic sample alone has no sensitive (statistics)
+ but helps semileptonic sample in high Δm_s region
+ sensitivity moves from 7.4 ps^{-1} to 8.4 ps^{-1}
+ new limit $\Delta m_s < 7.9$ ps^{-1} at 95% confidence level

CDF II and World Combined Average



Improvement from CDF

- + limit stays the same
- + sensitivity moves from 18.1 ps^{-1} to 18.6 ps^{-1}

Improvements

Statistical power of the sample

+ add same side koan tagger
+ add more B_s decay channels (ex. $B_s \to D_s^- \pi^+ \pi^+ \pi^-$)
+ gather more data

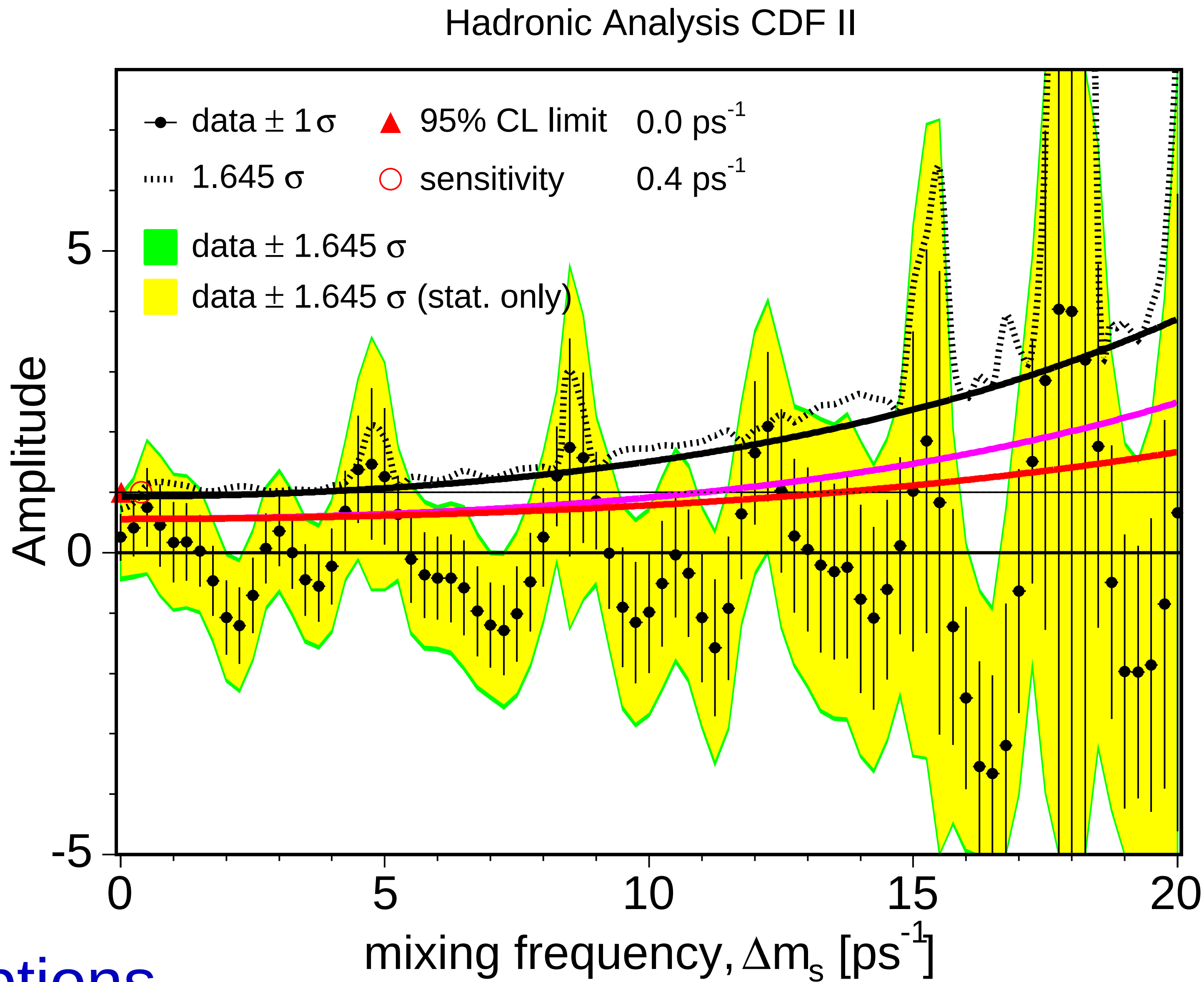
Improve proper time resolution

+ average primary vertex $\rightarrow$ primary vertex per candidate
+ improve reconstruction of innermost layer (Layer 00)
+ treat large silicon clusters more carefully

For illustration of improvements

+ increase statistical power by factor of 4
+ improve *ct* resolution by 20%

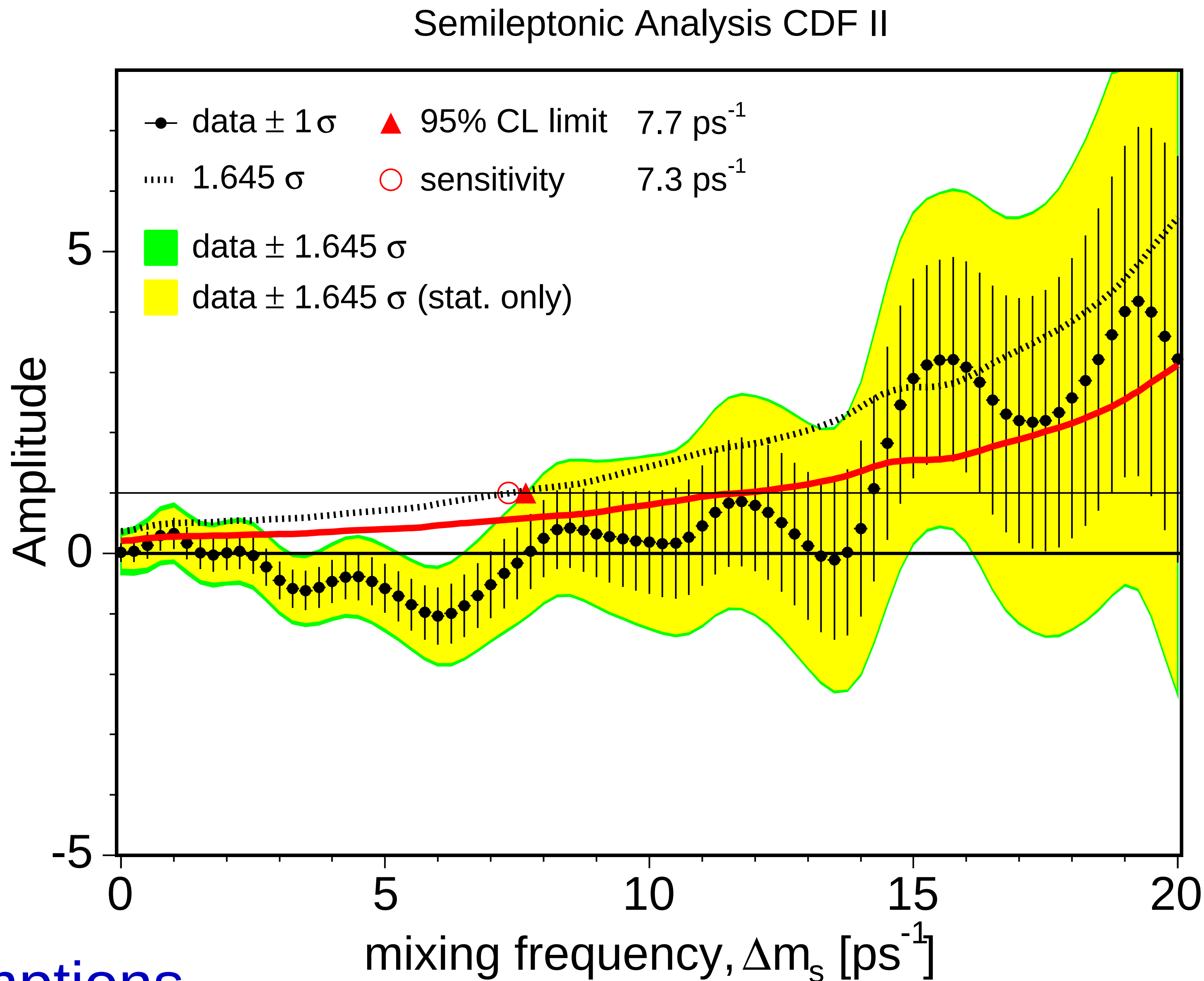
Improvements: Hadronic



Assumptions

- \+ increase statistical power by factor of 4 (new data, taggers)
- \+ improve *ct* resolution by 20% (primary vertex per candidate)

Improvements: Semileptonics



Assumptions

+ increase statistical power by factor of 4 (new data, taggers)

Summary

Worldwide *B* physics program: *CKM* matrix related

- good place to look for new physics, has potential: NP in loops
- complementary, precision program: BaBelle and CDF/DØ
- Tevatron:
  - high cross section
  - all *b* hadrons
  - strong boost
  - low flavor tagging efficiency
  - high background
- *B* factories:
  - clean environment
  - beam energy constraint
  - inclusive trigger
  - excellent flavor tagging
  - only B^+, B^0
  - low boost

Summary

First B_s mixing analyses completed (*DØ* finshed second)

- + sensitivity: $\Delta m_s < 8.4\ \mathrm{ps}^{-1}$(9.5*DØ*) at 95% confidence level
- + exclude: $\Delta m_s < 7.9\ \mathrm{ps}^{-1}$(7.3*DØ*) at 95% confidence level
- + used semileptonic and hadronic samples
- + displaced track trigger (SVT) was crucial
- + byproduct: $c\tau(B_s) = 479 \pm 29(stat) \pm 5(syst)\ \mu\mathrm{m}$

Prospects

- + Tevatron is covering the Standard Model range until Run II end