New Lifetime & Mixing Results from CDF

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Topics:

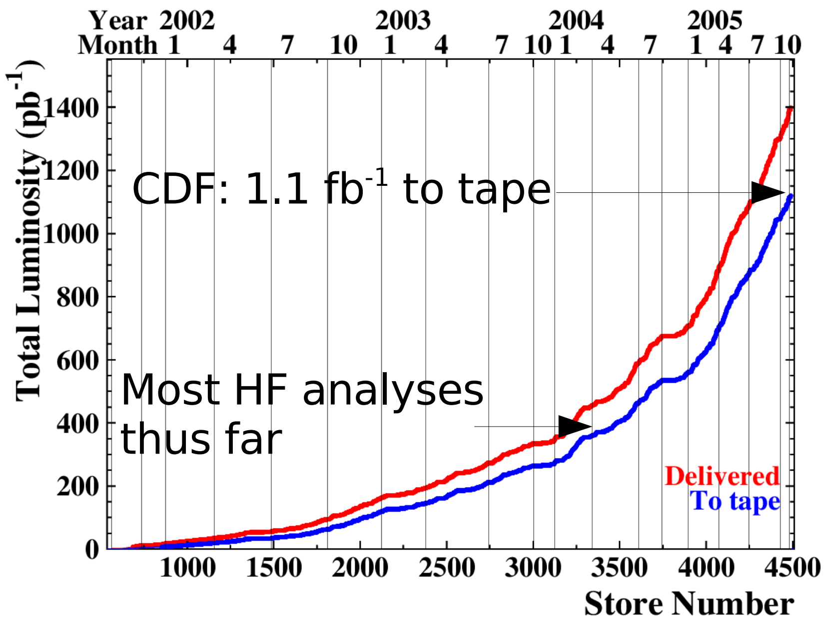
- Lifetimes of *b*-Flavored Hadrons
  - Λ_b lifetime in fully-reconstructed decay
  - B_c, B_s lifetimes
- B_s Mixing

Main focus of this talk

Heavy Flavor Physics at CDF

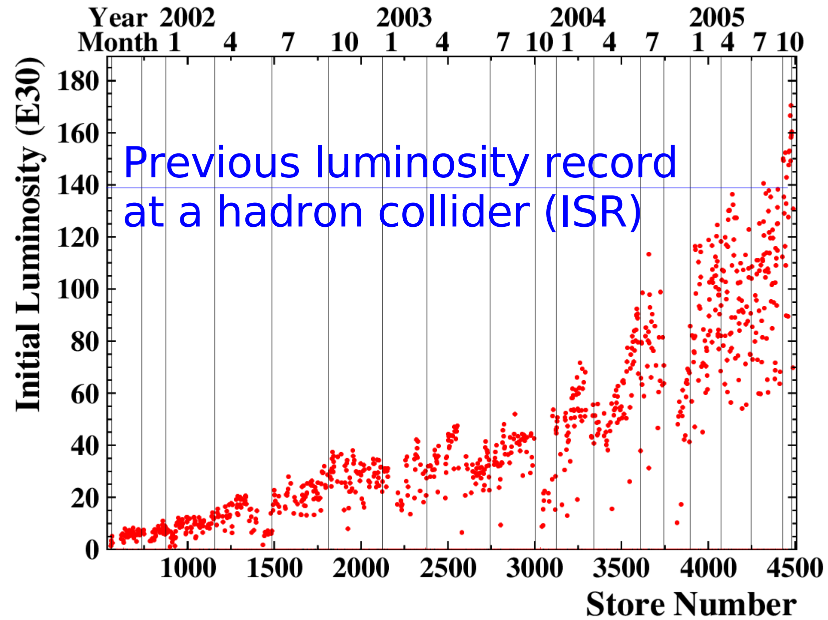
Tevatron competitive in B physics:

- *b* production *O*(1000) x B factories (unfortunately background from other QCD processes *O*(1000) x signal $\rightarrow$ triggering crucial!)
- Produce not only B^0/B^+, but all *b*-species (B^0,B^+,B_s,B_c,B^{**},Λ_b,Ξ_b)

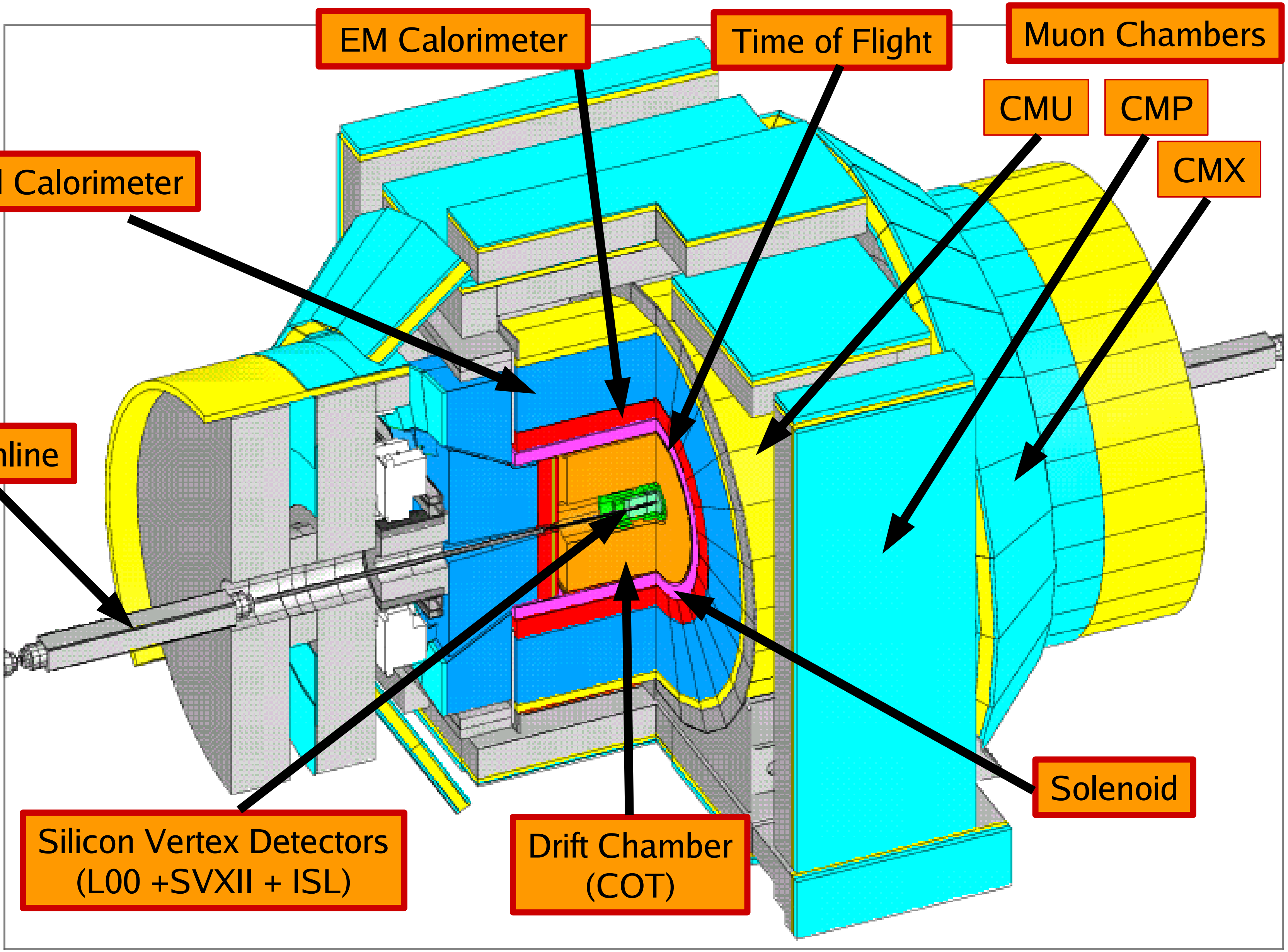


Rich program in heavy flavor:

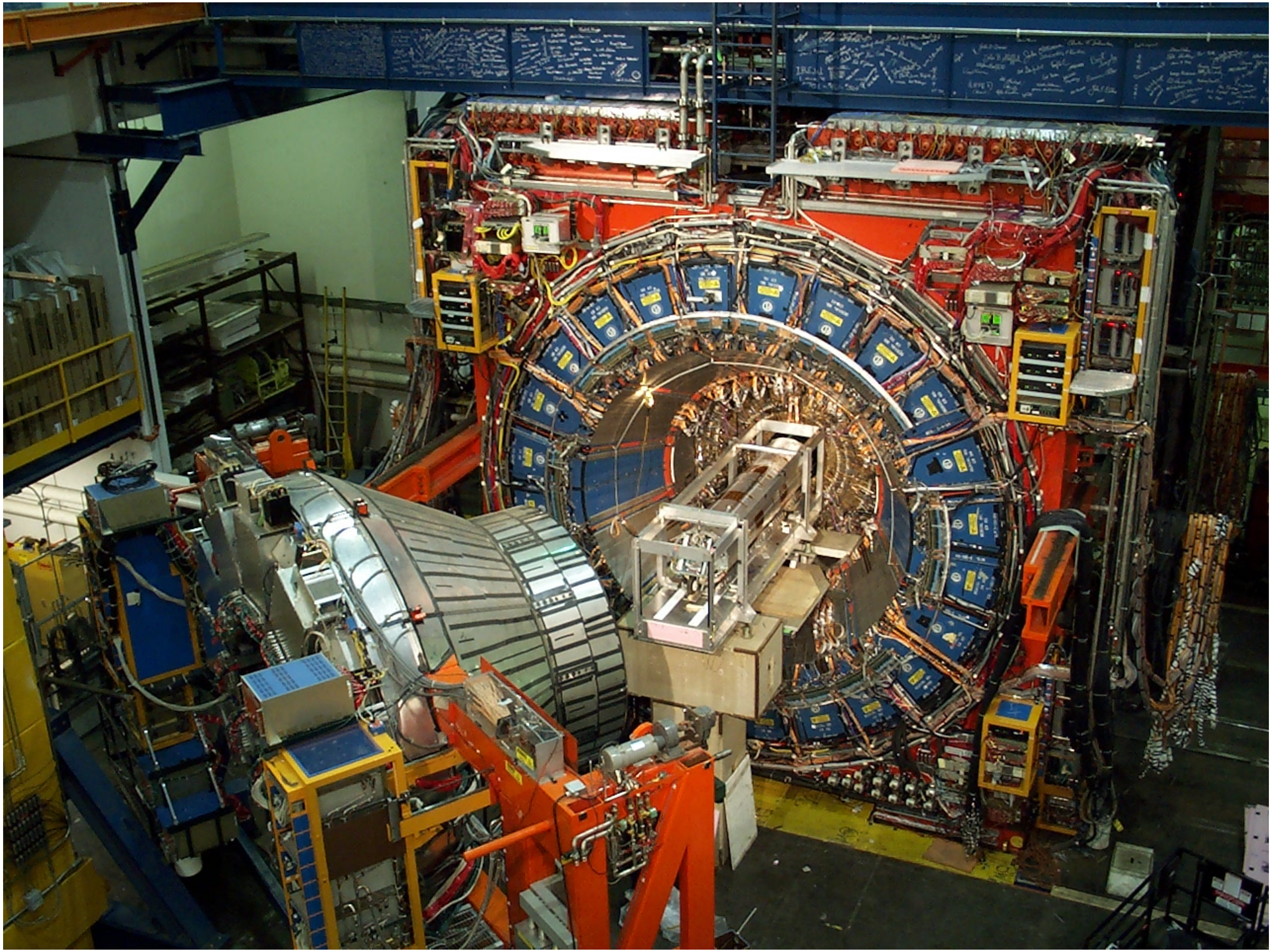
- B, D, and Quarkonium production
- Mixing
- CP violation
- Rare decays
- Spectroscopy
- *b*-Hadron Lifetimes



The CDFII Detector



CDF II Detector



Why Study *b*-Hadron Lifetimes?

Critical testbed for theoretical framework used in predictions of heavy quark quantities:

- not only interesting in themselves, but needed to extract weak interaction quantities from observables
- *b*-hadron lifetime ratios can be accurately predicted (~5% or better)

At Tevatron/CDF:

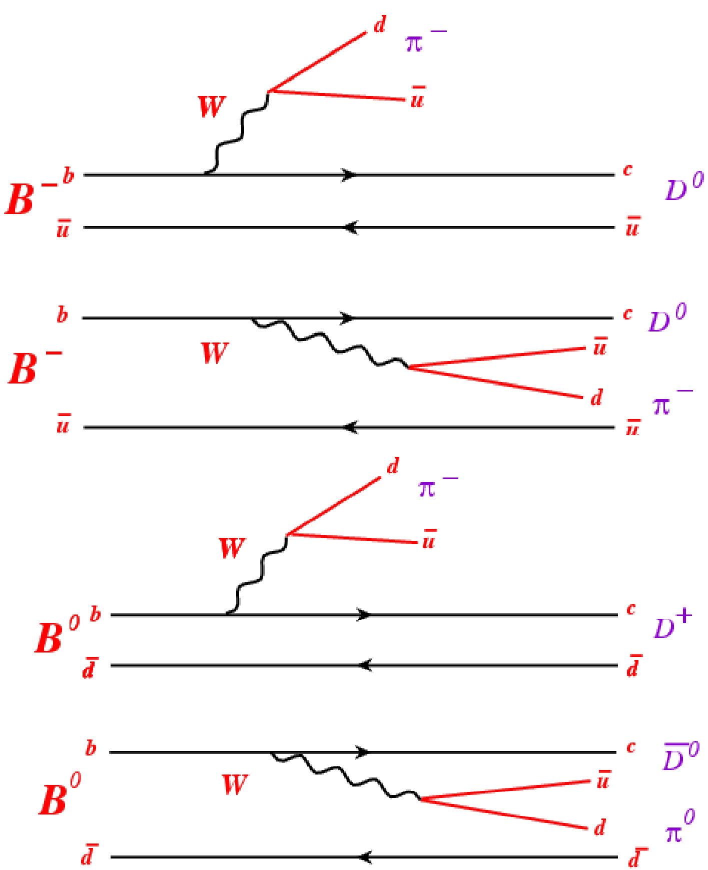
- Important experimental reference
  Overlap with B factories → aid in study of potential detector/trigger/analysis biases
- Measure lifetime of species not produced at B factories
- Experimental techniques used in lifetime measurements are critical for the pursuit of Bs mixing!

Lifetimes of *b*-Flavored Hadrons

All *b*-flavored hadrons have same lifetime via weak transition
$b \rightarrow Wq$ ($q = c, u$) if other quarks considered mere spectators

In reality, lifetime differences arise from non-trivial spectator quark effects:

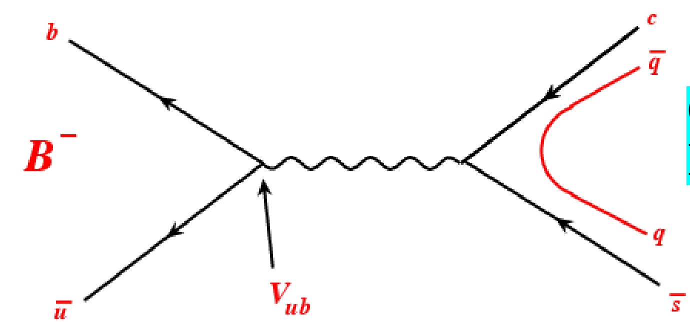
Pauli Interference



Same final state
⇒ interference
(destructive)

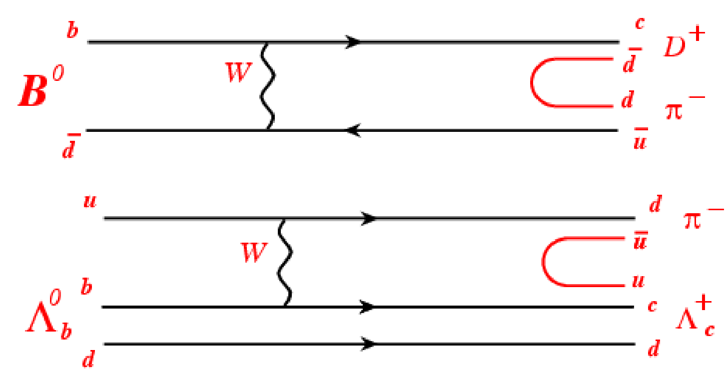
Different final states
⇒ no interference

Weak Annihilation



Only charged B mesons

Weak Exchange



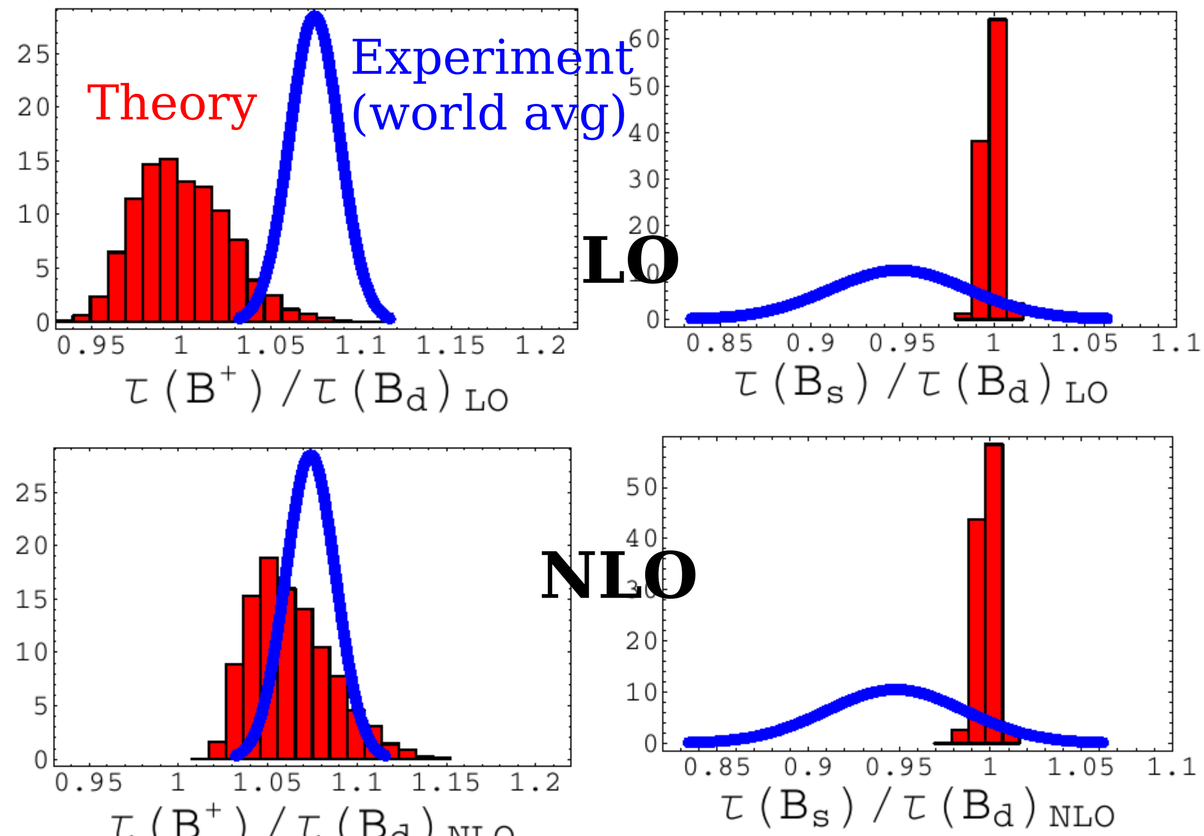
Helicity suppressed in mesons, not baryons

Heavy Quark Expansion

Express decay width (Γ) as operator product expansion (OPE) in $1/m_b$ and α_s

$$\Gamma(H_b) = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3} \left[c^{(3)} \frac{\langle \bar{b} b \rangle_{H_b}}{2M_{H_b}} + c^{(5)} \frac{g_s}{m_b^2} \frac{\langle \bar{b} \sigma_{\mu\nu} G^{\mu\nu} b \rangle_{H_b}}{2M_{H_b}} + \frac{96\pi^2}{m_b^3} \sum_k c_k^{(6)} \frac{\langle O_k^{(6)} \rangle_{H_b}}{2M_{H_b}} \right]$$

$$+O(1/m_b^4)$$



Tarantino, et al.
hep-ph/0203089

- $c_i^{(n)}$ contain physics from scales ≥ μ = $O(m_b)$
  → perturbatively calculable
- Matrix elements contain long-distance physics
  → hard! (lattice, QCD sum rules)
- Spectator contributions enter at $1/m_b^3$ (~5-10%)

NLO $(1/m_b^4)$ can be several %!

Λ_b Lifetime - Current Status

Exp	Method	Data set	$\tau(\Lambda_b)$ (ps)	precision
OPAL	$\Lambda_c^+ l$, $\Lambda l^+ l^-$	'90 - '95	$1.29^{+0.24}_{+0.22} \pm 0.06$	18%
DELPHI	$\Lambda_c^+ l$	'91 - '94	$1.11^{+0.19}_{+0.18} \pm 0.05$	17%
ALEPH	$\Lambda_c^+ l$	'91 - '95	$1.18^{+0.13}_{+0.12} \pm 0.03$	11%
ALEPH	$\Lambda l^+ l^-$	'91 - '95	$1.30^{+0.26}_{+0.21} \pm 0.04$	18%
CDF	$\Lambda_c^+ l$	'91 - '95	$1.32 \pm 0.15 \pm 0.06$	12%
CDF	$J/\psi\ \Lambda$	'02 - '03	$1.25 \pm 0.26 \pm 0.10$	28%
D0	$J/\psi\ \Lambda$	'02 - '04	$1.29^{+0.24}_{+0.18} \pm 0.06$	18%
AVG			**1.232 ± 0.072**	**6%**

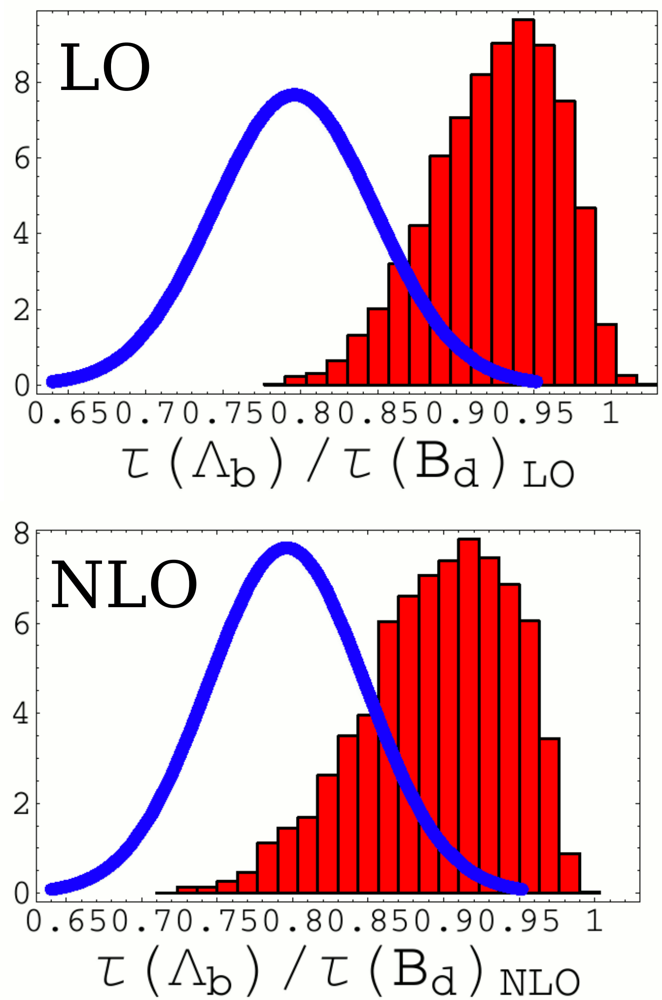
Early theory predictions for $\tau(\Lambda_b)/\tau(B^0)$ ~2σ high

Current NLO QCD calculation gives

$$\tau(\Lambda_b) / \tau(B^0) = 0.86 \pm 0.05$$

consistent at 0.8σ-level w/ HFAG 2005 world avg

$$\tau(\Lambda_b) / \tau(B^0) = 0.803 \pm 0.047$$



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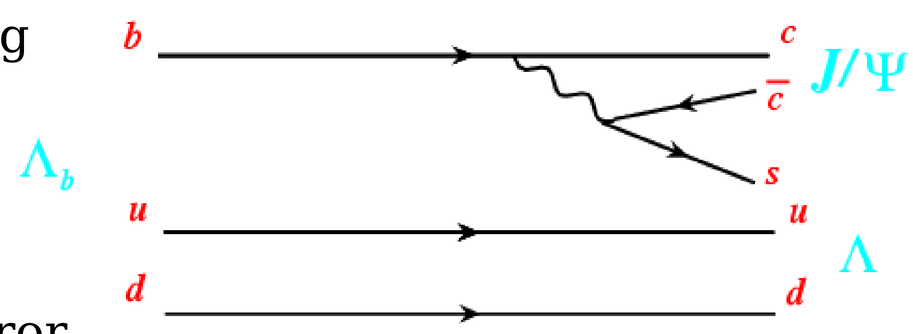
Λ_b Lifetime: Analysis Strategy

- Measure $\tau(\Lambda_b)$ in fully-reconstructed decay mode $\Lambda_b \rightarrow J/\psi \Lambda^0$

relative to semi-leptonics

Pros:
- Mass peak to distinguish signal & bkg
- Event-by-event measure of $\beta\gamma$ (boost)
  (Do not rely on MC to account for unobserved ν as in semi-leptonics)

Con:
- Smaller signal $\rightarrow$ larger statistical error

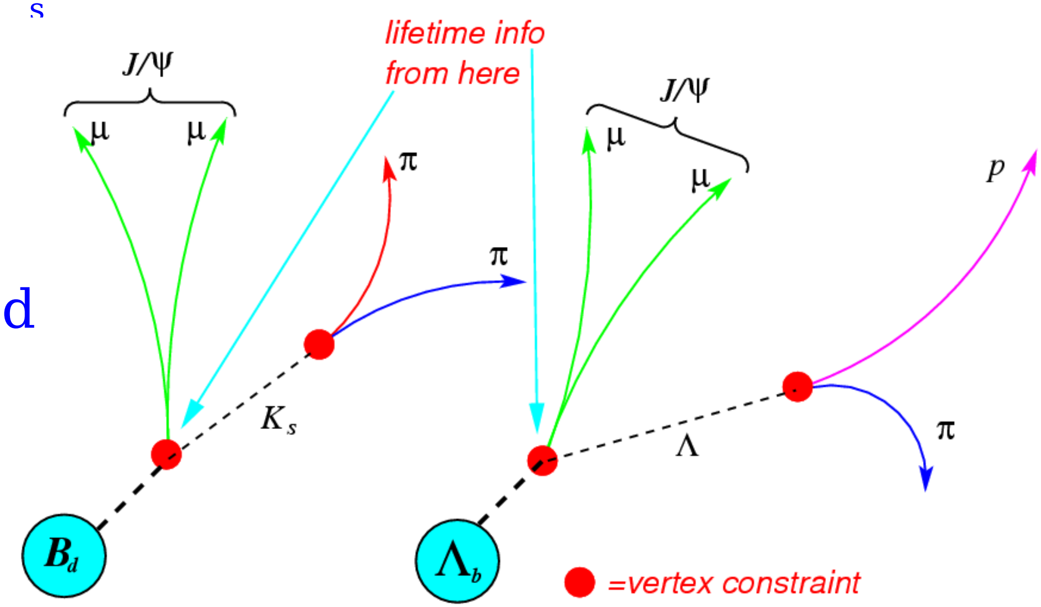


- Use $\tau(B^0)$ measurement in $B^0 \rightarrow J/\psi K_s$ as reference mode

$\rightarrow$ similar decay ($J/\psi + V^0$)
$\rightarrow$ larger sample ($\sim 10\times \Lambda_b$) for systematic studies

- Check lifetime in full-reconstructed $B_{u,d} \rightarrow (J/\psi, \psi') + X$ decay modes

$\rightarrow$ validate lifetime analysis using J/ψ vertex only for all decay modes



b-Hadron Lifetimes We Measure

$B^0 \rightarrow J/\psi\ K_s$, with $J/\psi \rightarrow \mu\mu$, $K_s \rightarrow \pi\pi$ ← **Full systematics**

$B^0 \rightarrow \psi(2S)\ K_s$, with $\psi(2S) \rightarrow \mu\mu$, $K_s \rightarrow \pi\pi$

$B^0 \rightarrow \psi(2S)\ K_s$, with $\psi(2S) \rightarrow J/\psi\pi\pi$, $J/\psi \rightarrow \mu\mu$, $K_s \rightarrow \pi\pi$

$B^0 \rightarrow J/\psi\ K^{*0}$, with $J/\psi \rightarrow \mu\mu$, $K^{*0} \rightarrow K\pi$

$B^0 \rightarrow \psi(2S)\ K^{*0}$, with $\psi(2S) \rightarrow \mu\mu$, $K^{*0} \rightarrow K\pi$

$B^0 \rightarrow \psi(2S)\ K^{*0}$, with $\psi(2S) \rightarrow J/\psi\pi\pi$, $K^{*0} \rightarrow K\pi$

$B^+ \rightarrow J/\psi\ K^+$, with $J/\psi \rightarrow \mu\mu$

$B^+ \rightarrow \psi(2S)\ K^+$, with $\psi(2S) \rightarrow \mu\mu$

$B^+ \rightarrow \psi(2S)\ K^+$, with $\psi(2S) \rightarrow J/\psi\pi\pi$, $J/\psi \rightarrow \mu\mu$

$B^+ \rightarrow J/\psi\ K^{*+}$, with $J/\psi \rightarrow \mu\mu$, $K^{*+} \rightarrow K_s\pi$

(the above, from $B^0 \rightarrow \psi(2S)\ K_s$ to $B^+ \rightarrow J/\psi\ K^{*+}$) ← **Statistical errors only (for cross-√)**

$\Lambda_b \rightarrow J/\psi\ \Lambda^0$, with $J/\psi \rightarrow \mu\mu$, $\Lambda^0 \rightarrow p\pi$ ← **Full systematics**

↑ **Our primary goal**

Selection: J/ψ and ψ(2S)

Di-muon Trigger:

Level 1: 2 opp-Q tracks, p_T > 1.5 GeV/c, track-stub match
Level 2: Auto
Level 3: Full tracking, m(μμ), track-stub match

Muons:

- good track-stub match
- ≥3 r-ϕ Si hits (SVX + ISL)

Vertex quality:

- Prob(χ^2) > 0.1%

Invariant Mass:

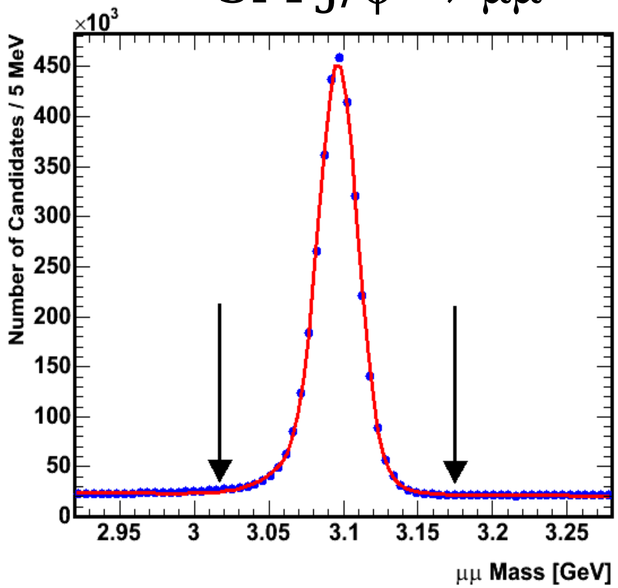
$J/\psi \to \mu\mu$:
$3.014 < M_{\mu\mu} < 3.174$ GeV

$\psi(2S) \to \mu\mu$:
$3.643 < M_{\mu\mu} < 3.723$ GeV

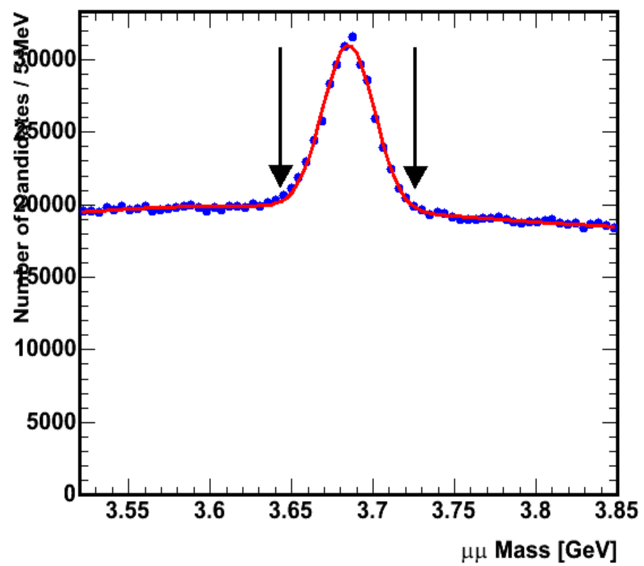
$\psi(2S) \to J/\psi\, \pi^+ \pi^-$:
$3.676 < M_{\mu\mu\pi\pi} < 3.696$ GeV

Dataset: ~370 pb^{-1} of integrated luminosity

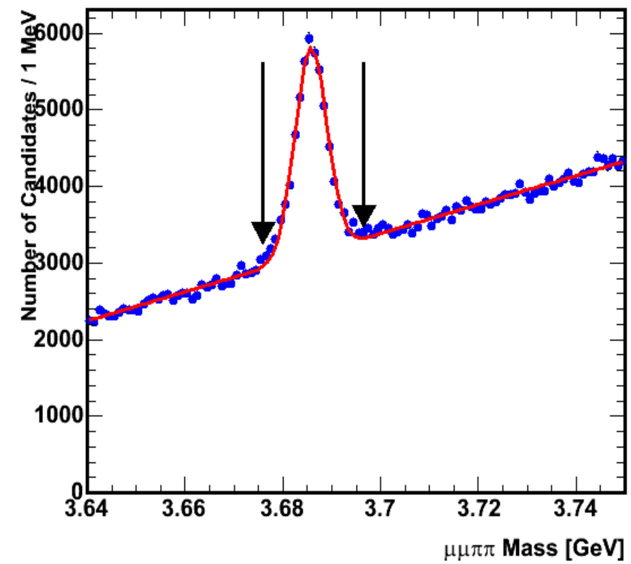
~3M $J/\psi \to \mu\mu$



~300k $\psi(2S) \to \mu\mu$



~70k $\psi(2S) \to J/\psi\, \pi^+ \pi^-$



Selection: K_s and Λ^0

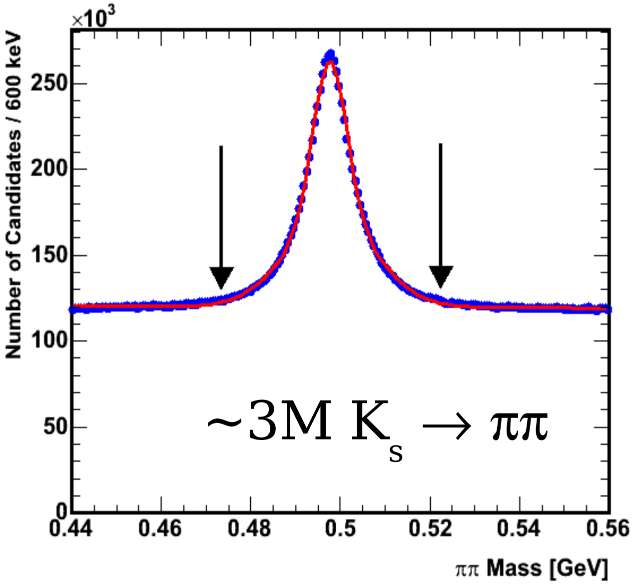
Track quality:
- ≥2 COT axial SL with ≥ 5 hits
- ≥2 COT stereo SL with ≥ 5 hits

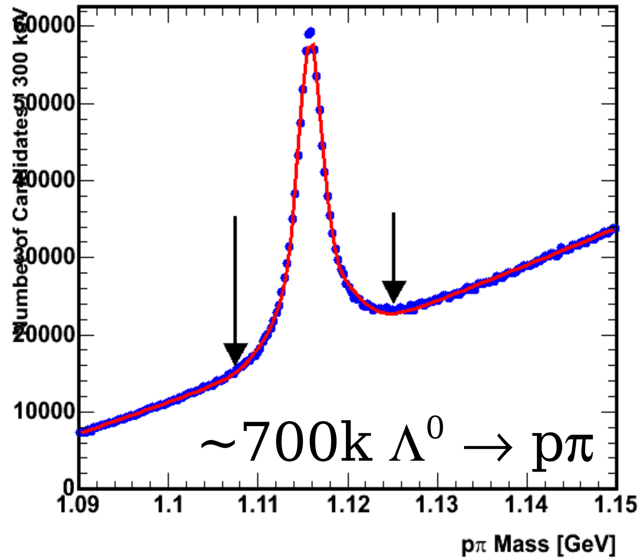
Vertex quality:
- Prob(χ^2) > 0.1%

Decay length:
- L_{xy} > 0.1 cm

Invariant Mass:
- $K_s \to \pi\pi$: $0.472 < M_{\pi\pi} < 0.523$ GeV
- $\Lambda^0 \to p\pi$: $1.107 < M_{\pi p} < 1.125$ GeV

Veto on Swap Mass:
- $K_s \to \pi\pi$: $1.109 < M_{\pi\pi\to p} < 1.124$ GeV
- $\Lambda^0 \to p\pi$: $0.482 < M_{\pi p\to\pi} < 0.511$ GeV





Selection: *b*-Hadrons

Only present here the $B^0 \rightarrow J/\psi\, K_s$ and $\Lambda_b \rightarrow J/\psi\, \Lambda^0$ selection

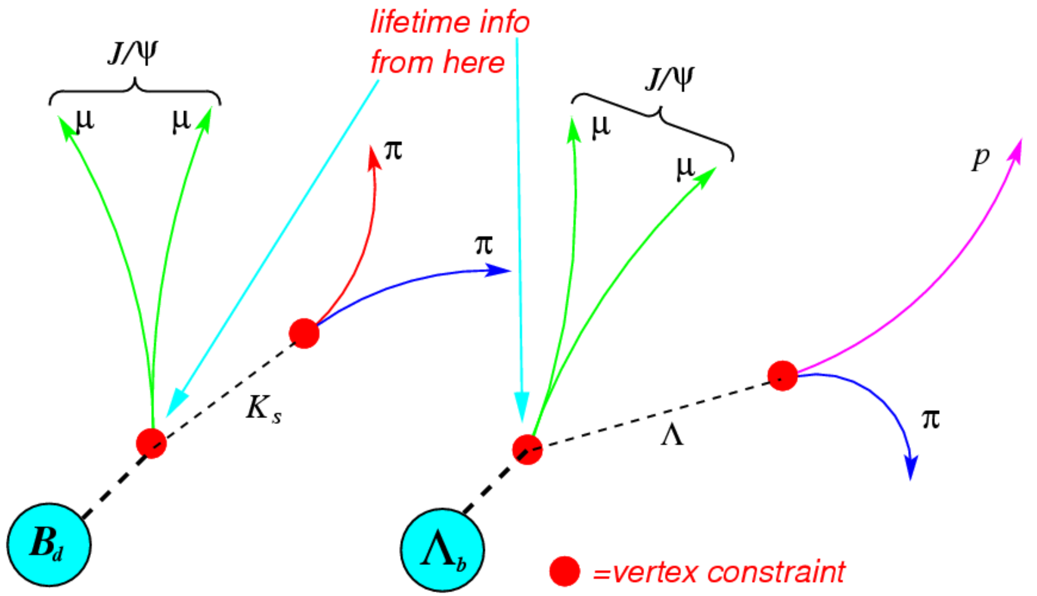
$\rightarrow$ Selection/optimization similar for other B modes

Vertex Fit with kinematic constraints:

- J/ψ mass constrained to PDG 2004 value
- V^0 momentum constrained to point back to J/ψ decay vertex in 3D

Optimize these additional cuts:

- V^0 L_{xy} significance ($L_{xy}/\sigma(L_{xy})$)
- V^0 mass window
- V^0 p_t
- B^0/Λ_b p_t
- B^0/Λ_b Prob(χ^2)

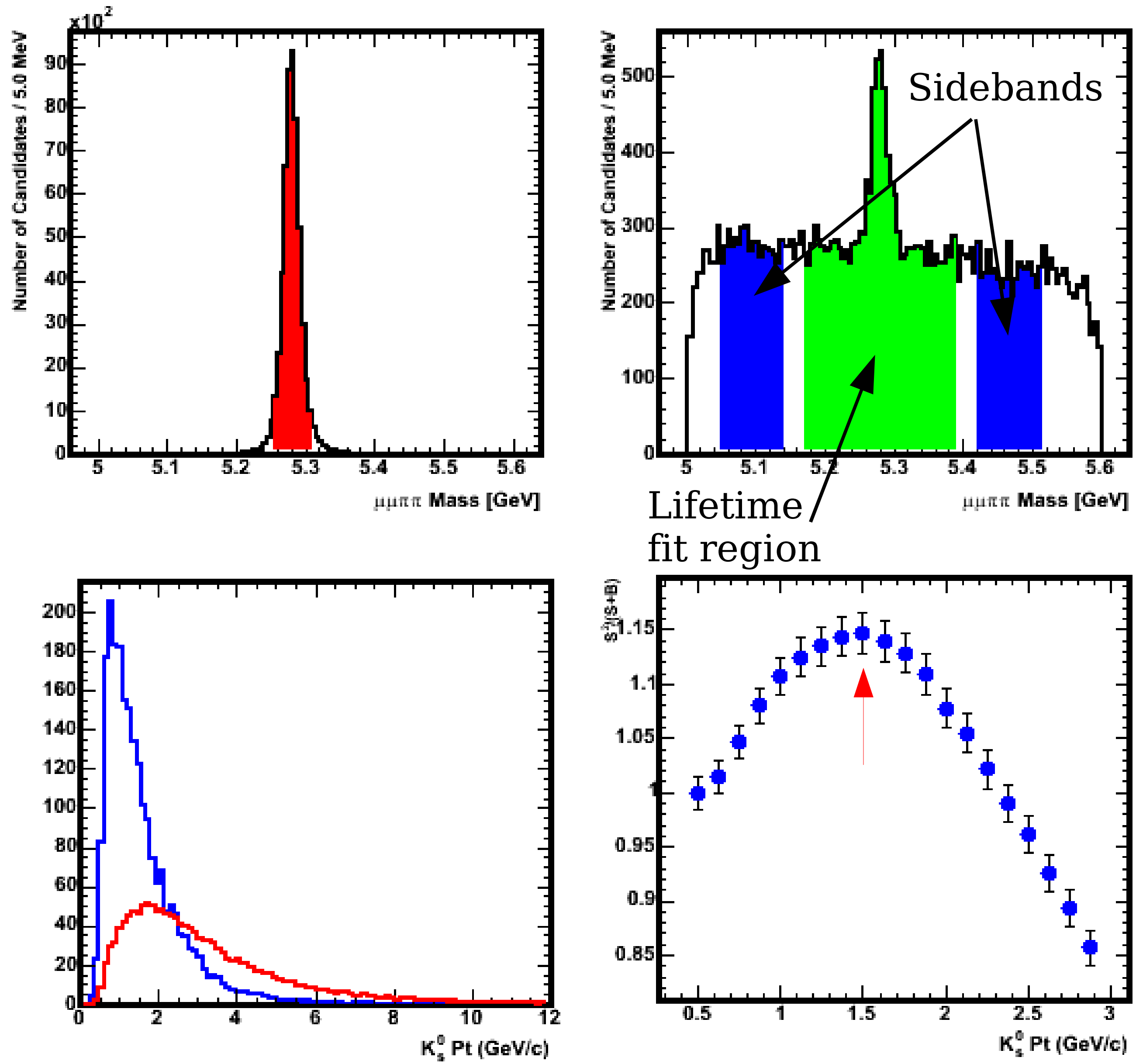


$S^2/(S+B)$ Optimization

- Single-*b* Monte Carlo for signal
- "Far" sidebands in data for background

Λ^0 L_{xy} significance > 4.0
Λ^0 mass window: ± 9 MeV
Λ^0 p_t > 2.6 GeV
Λ_b p_t > 4.0 GeV
Λ_b Prob(χ^2) > 10^{-4}

K_s L_{xy} significance > 6.0
K_s mass window: ±25 MeV
K_s p_t > 1.5 GeV
B^0 p_t > 4.0 GeV
B^0 Prob(χ^2) > 10^{-4}

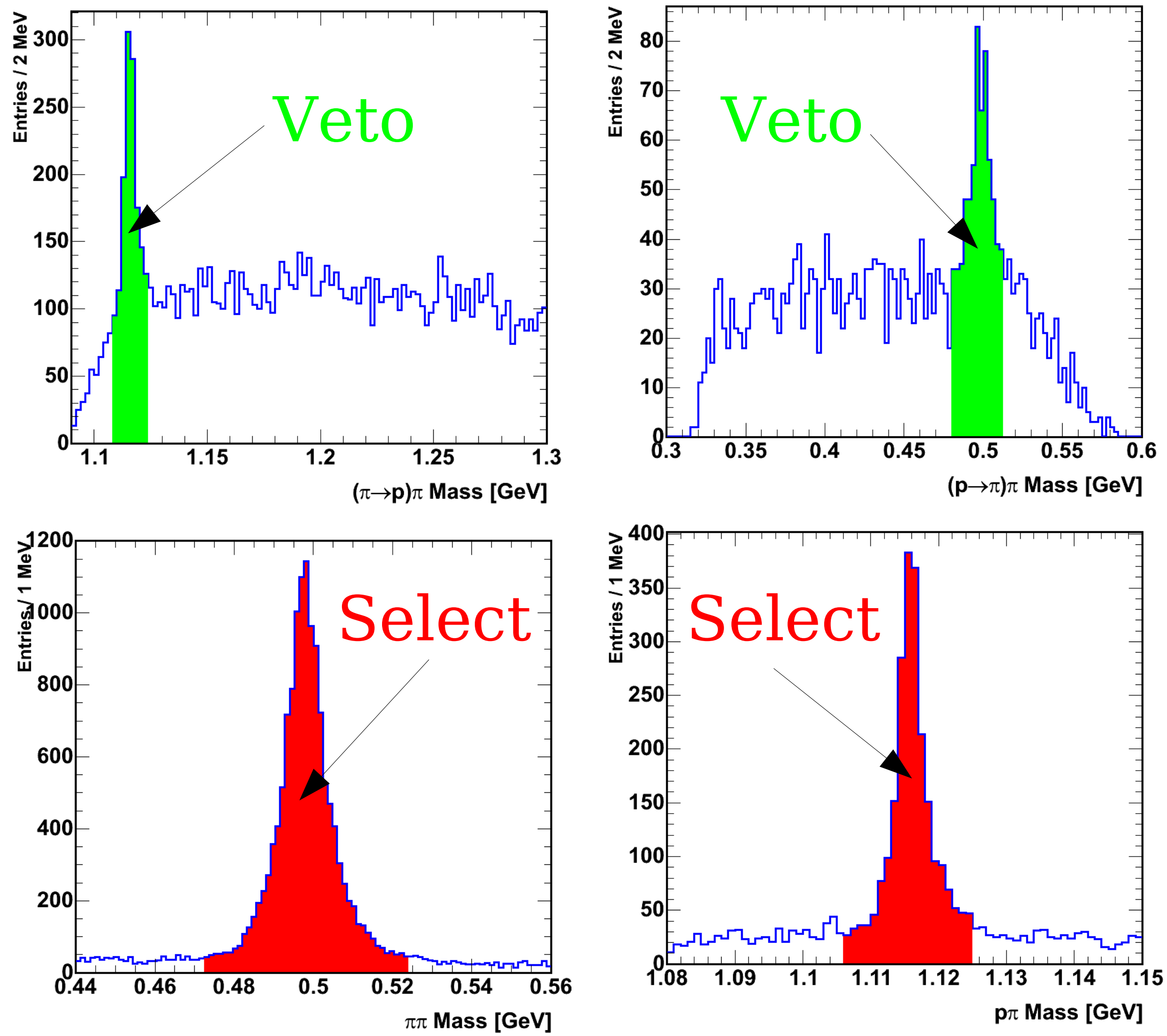


K_s and Λ^0 after *b*-Hadron Selection

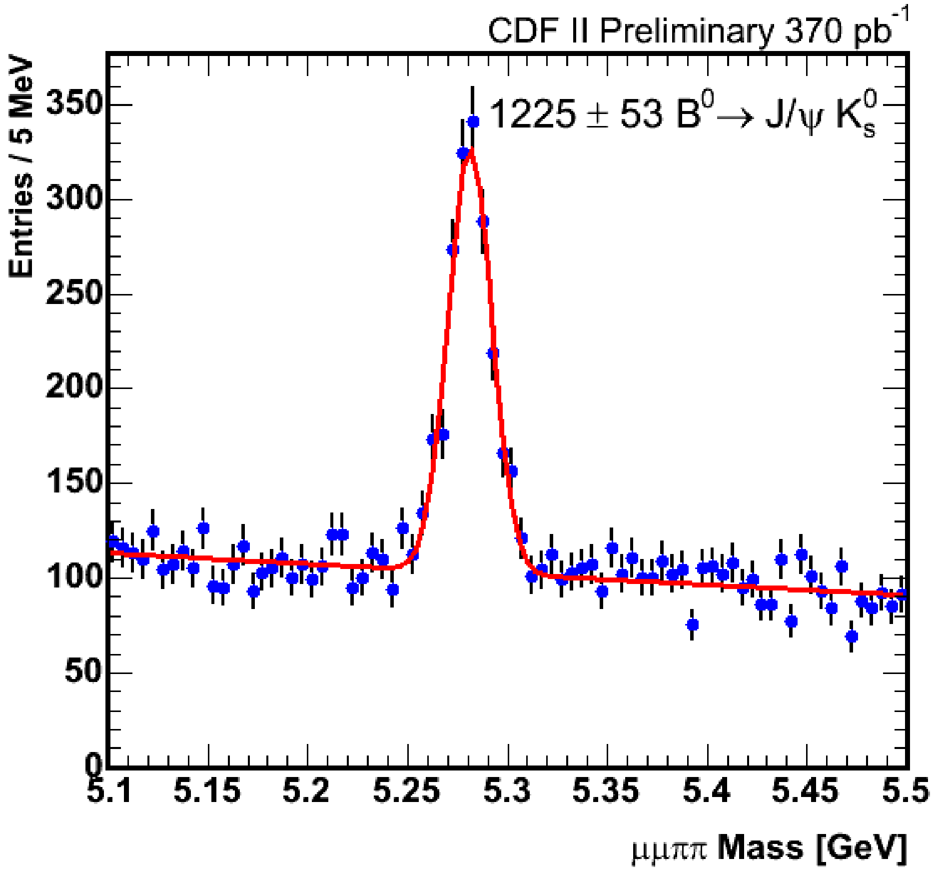
- Veto Λ^0 in K_s and K_s in Λ^0 using $p \leftrightarrow \pi$ swapped-mass hypothesis to suppress V^0 cross-contamination

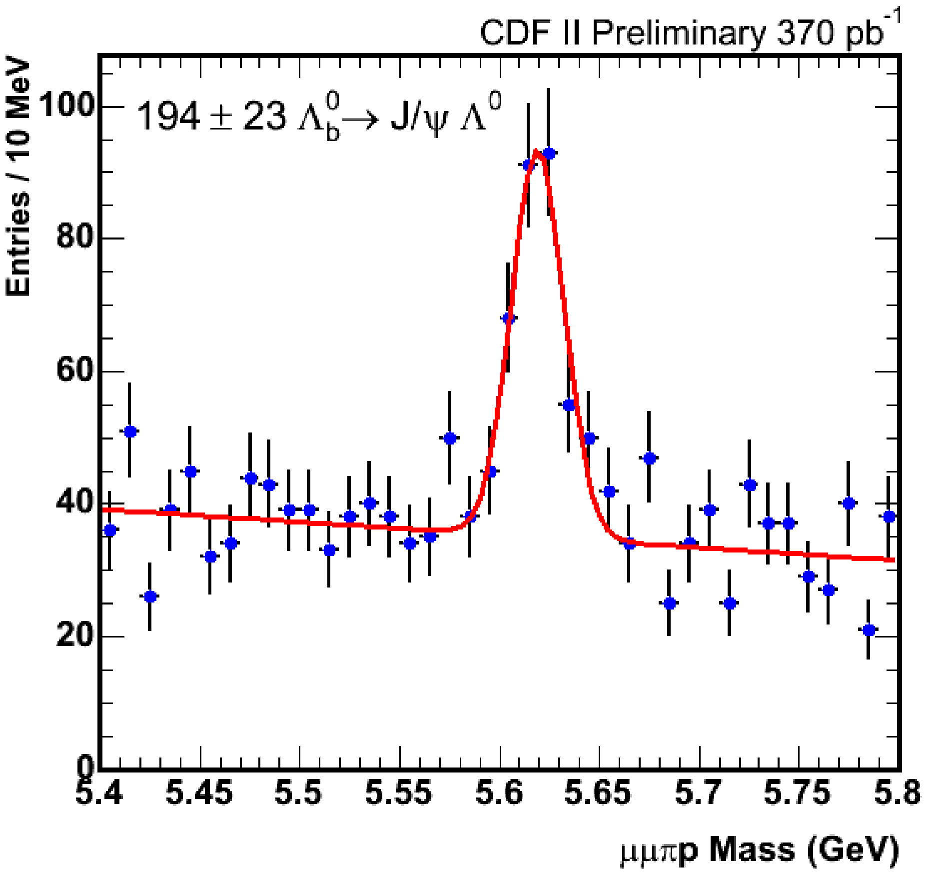
- Very clean → Majority of background comes from combinations of real J/ψ and real K_s, Λ^0

$B^0 \to J/\psi\, K_s$ $\qquad$ $\Lambda_b \to J/\psi\, \Lambda^0$



b-Hadron Yields: B^0 and Λ_b



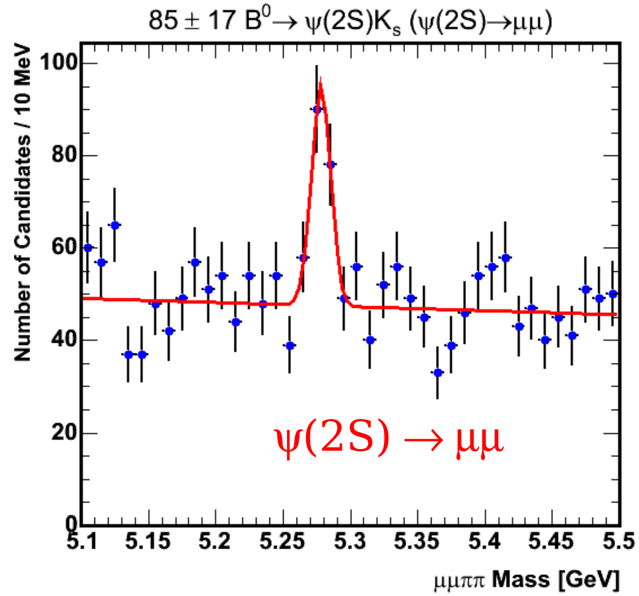


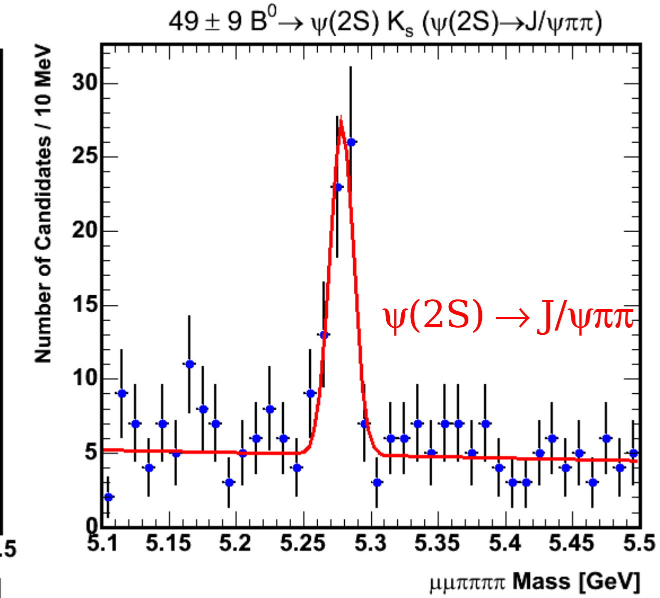
1225 $B^0 \rightarrow J/\psi\, K_s$

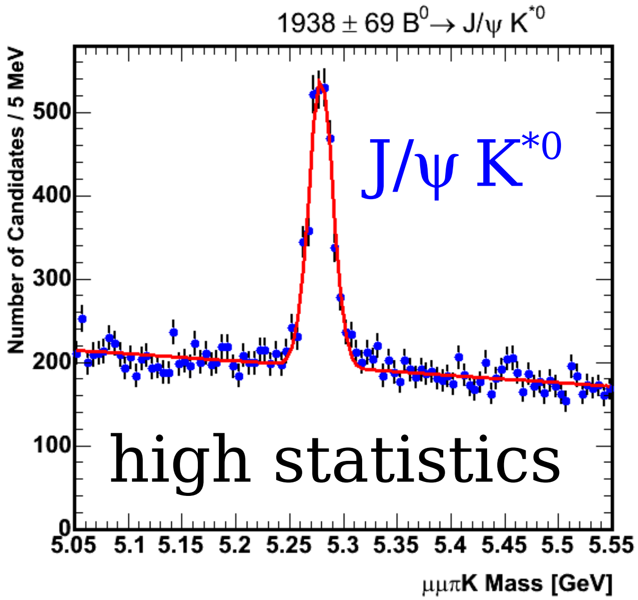
194 $\Lambda_b \rightarrow J/\psi\, \Lambda^0$

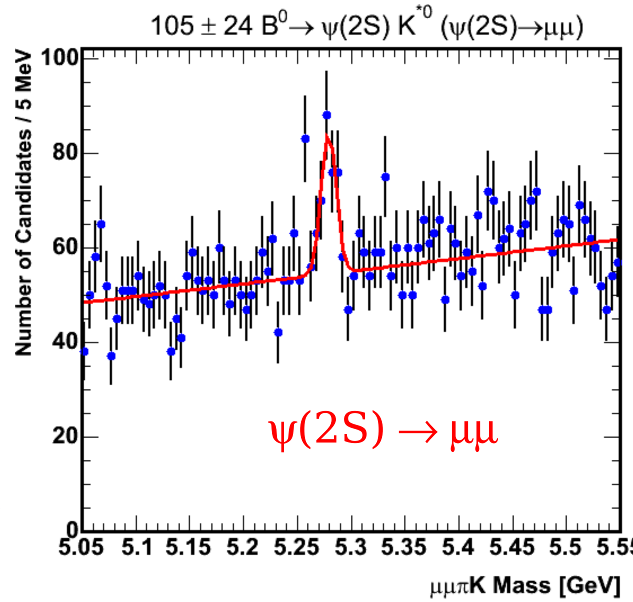
b-Hadron Yields: Other B^0 Modes

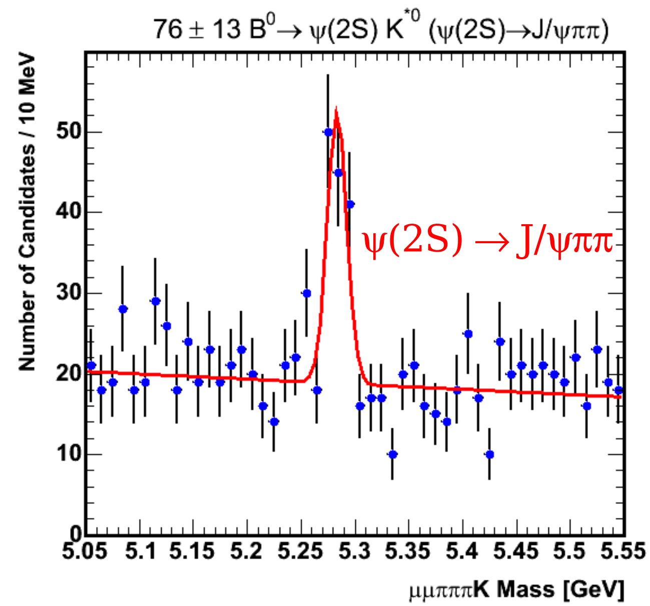
$\psi(2S)\ K_s$







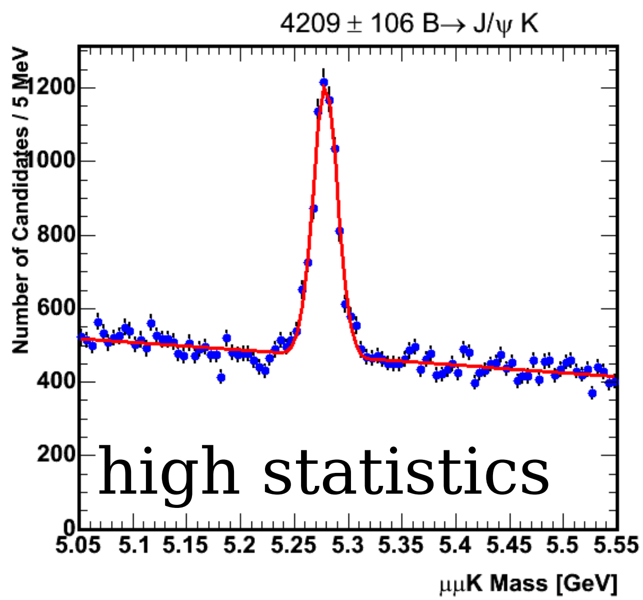


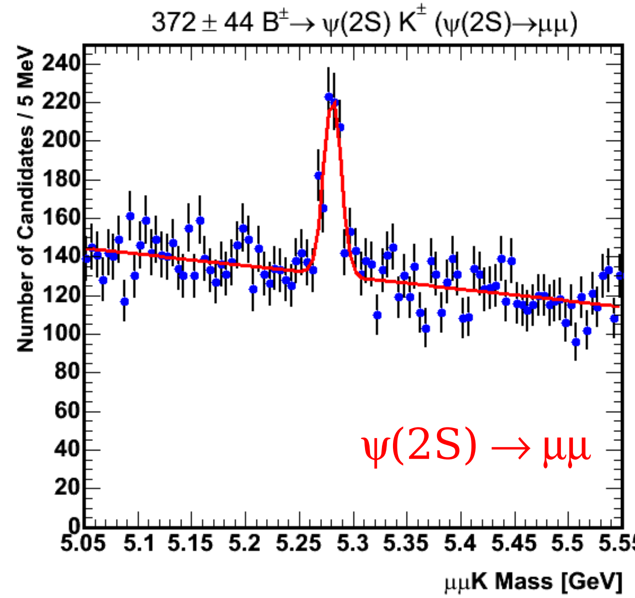


$\psi(2S)\ K^{*0}$

b-Hadron Yields: Other B^+ Modes

$J/\psi\, K^+$

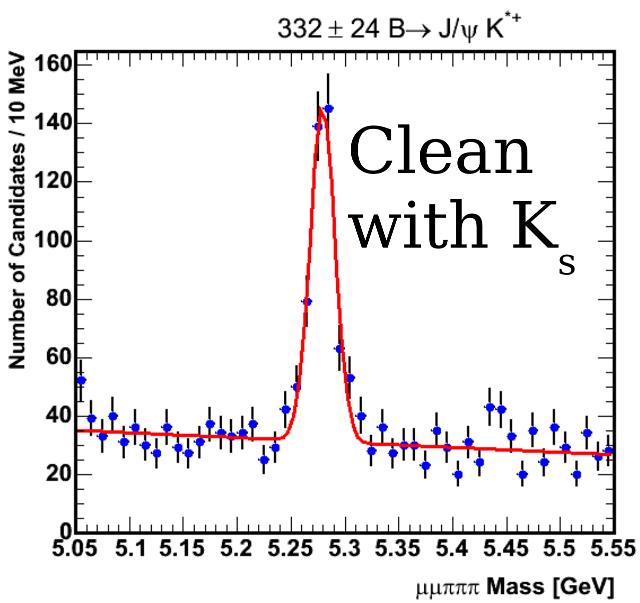


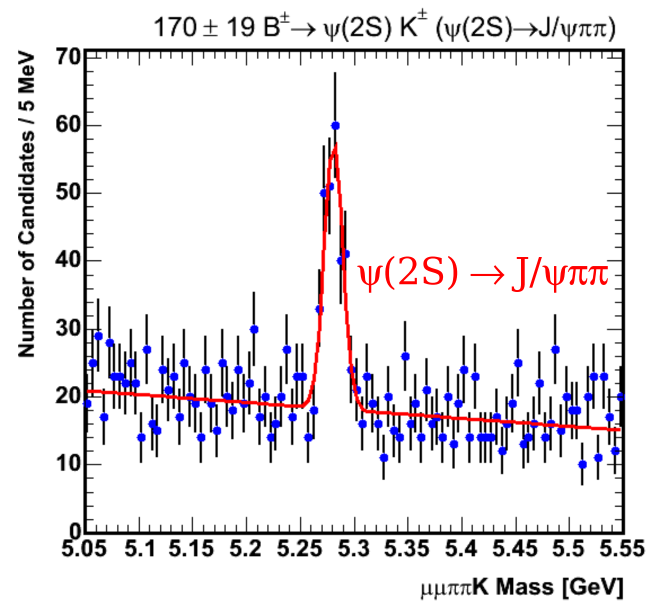


$\psi(2S)\, K^+$

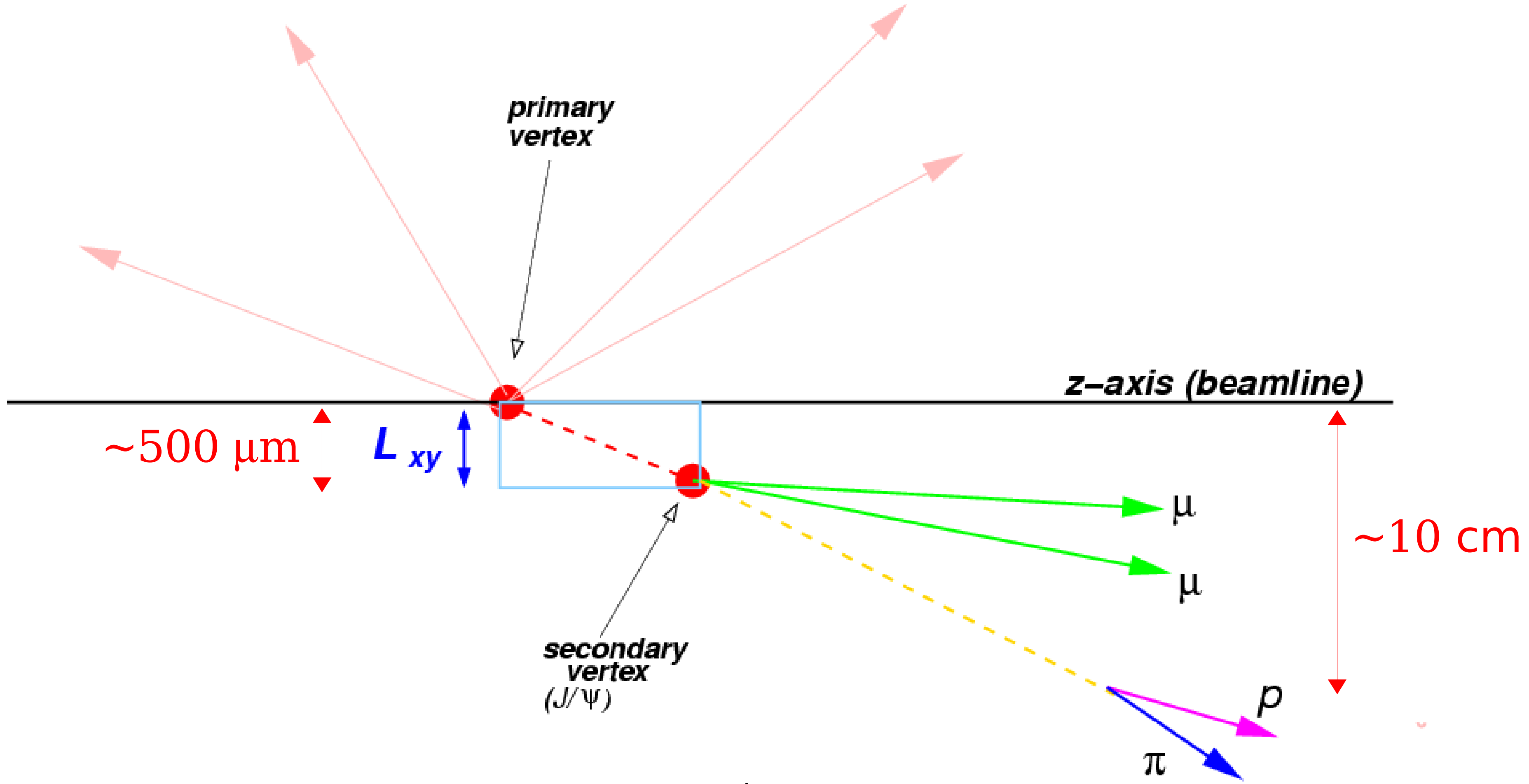
$J/\psi\, K^{*+}$

$(K^{*+} \to K_s \pi)$





Determining the Lifetime



$$\text{Proper Decay Length (PDL)} = \frac{L_{xy}^{b}}{(\beta\gamma)_T^{b}} = L_{xy}^{b}\, c\, \frac{M_b}{p_t^{b}}$$

$$\text{where } L_{xy}^{b} = \left(\vec{x}(J/\psi) - \vec{x}(PV)\right) \cdot \hat{p}_T^{\,b}$$

Fit Model: Overview

Overall probability density function (PDF) is a normalized sum of signal and background contributions:

$$P(\lambda_i, \sigma_i^\lambda, m_i, \sigma_i^m \mid \vec{\xi}) = (1-f_b)\, P_{sig} + f_b\, P_{bkg}$$

where:

λ_i = PDL

σ_i^λ = PDL error

m_i = mass

σ_i^m = mass error

P_{sig}, P_{bkg} = signal, background PDF

f_b = background fraction

$\vec{\xi}$ = fit parameters (including f_b)

P_{sig}, P_{bkg} are products of PDL, PDL error, and mass PDFs:

$$P_{sig,bkg} = P^\lambda_{sig,bkg}(\lambda_i|\sigma_i^\lambda, \vec{\alpha})\; P^{\sigma^\lambda}_{sig,bkg}(\sigma_i^\lambda|\vec{\beta})\; P^m_{sig,bkg}(m_i|\sigma_i^m, \vec{\gamma})$$

Unbinned maximum likelihood fit to extract $\vec{\xi} = \{\vec{\alpha}, \vec{\beta}, \vec{\gamma}, \vec{\delta}\}$

($\vec{\xi}$ contains 18 parameters, including signal $c\tau$)

Fit Model: Signal PDL

Signal PDL modeled as an exponential decay convoluted with a Gaussian resolution function :

$$P^{\lambda}_{sig}(\lambda_i, \sigma^{\lambda}_i | \vec{\alpha}_{sig}) = E(\lambda_i | c\tau) * G(\lambda_i, \sigma^{\lambda}_i | s)$$

where:

τ = signal lifetime (the goal)

s = overall scale factor on PDL errors

$$E(\lambda_i | c\tau) = \begin{pmatrix} \frac{1}{c\tau} e^{-\lambda_i / c\tau} & , c\tau \geq 0 \\ 0 & , c\tau < 0 \end{pmatrix}$$

$$G(\lambda_i, \sigma^{\lambda}_i | s) = \frac{1}{\sqrt{2\pi} s \sigma^{\lambda}_i} e^{\frac{-\lambda_i^2}{2(s\sigma^{\lambda}_i)^2}}$$

Analytic expression after convolution:

$$P^{\lambda}_{sig}(\lambda_i, \sigma^{\lambda}_i | c\tau, s) = \frac{1}{2c\tau} e^{\frac{(s\sigma^{\lambda}_i)^2}{2(c\tau)^2} - \frac{\lambda_i}{c\tau}} \, \mathrm{Erfc}\left(\frac{s\sigma^{\lambda}_i}{\sqrt{2} c\tau} - \frac{\lambda_i}{\sqrt{2} s \sigma^{\lambda}_i} \right)$$

Fit Model: Background PDL

Background PDL modeled as sum of four components:

- zero lifetime background (prompt J/ψ, determines resolution function)
- negative exponential (non-Gaussian tails on resolution function)
- 2 positive exponentials ($b \rightarrow J/\psi X$ long-lived backgrounds)

all convoluted with a Gaussian resolution function

$$P^{\lambda}_{bkg}(\lambda_i|\sigma^{\lambda}_i, s, f_-, \lambda_-, f_+, \lambda_+, f_{++}, \lambda_{++}) = (1-f_- - f_+ - f_{++})\frac{1}{\sqrt{2\pi}\, s\sigma^{\lambda}_i} e^{\frac{-\lambda_i^2}{2(s\sigma^{\lambda}_i)^2}} + \begin{pmatrix} \frac{f_+}{\lambda_+} e^{\frac{-\lambda_i}{\lambda_+}} + \frac{f_+}{\lambda_{++}} e^{\frac{-\lambda_i}{\lambda_{++}}}, & \lambda_i \geq 0 \\ \frac{f_-}{\lambda_-} e^{\frac{\lambda_i}{\lambda_-}}, & \lambda_i < 0 \end{pmatrix} * G(\lambda_i, \sigma^{\lambda}_i | s)$$

where:

f_- = fraction of negative exponential

λ_- = decay constant for negative exponential

$f_{+(++)}$ = fraction of $1^{st}(2^{nd})$ positive exponential

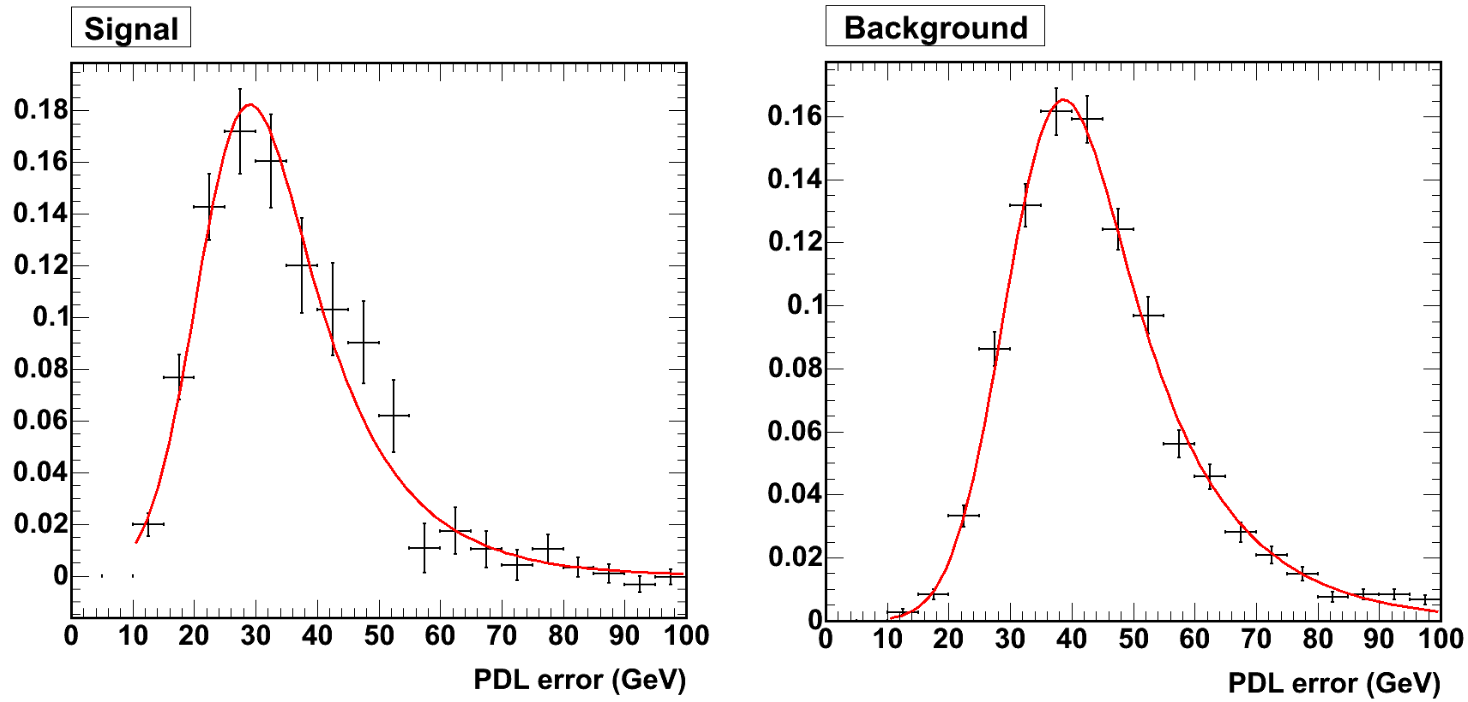
$\lambda_{+(++)}$ = decay constant of $1^{st}(2^{nd})$ positive exponential

Fit Model: PDL Error

Gaussian convoluted with exponential for signal, background PDL error:

$$P^{\sigma^{\lambda}}(\sigma_i^{\lambda} | \lambda_p, \sigma_p, \mu_p) = \frac{1}{2\lambda_p} e^{\frac{\sigma_p^2}{2\lambda_p^2} - \frac{\sigma_i^{\lambda} - \mu_p}{\lambda_p}} \mathrm{Erfc}\left(\frac{\sigma_p}{\sqrt{2}\lambda_p} - \frac{\sigma_i^{\lambda} - \mu_p}{\sqrt{2}\sigma_p} \right)$$

Reasonable (empirical!) model of observed PDL error distributions:



$B^0 \rightarrow J/\psi K_s$

Fit Model: Mass

Signal mass is modeled as a single Gaussian with mean M and width $s_M \sigma_i^m$:

$$P_{sig}^m(m_i \,|\, \sigma_i^m, M, s_M) = \frac{1}{\sqrt{2\pi} s_M \sigma_M} e^{\frac{-(m_i - M)^2}{2(s_M \sigma_i^m)^2}}$$

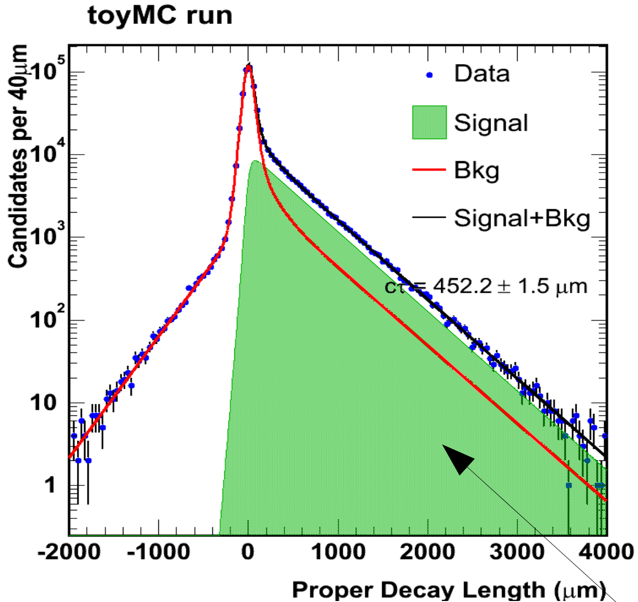
where:

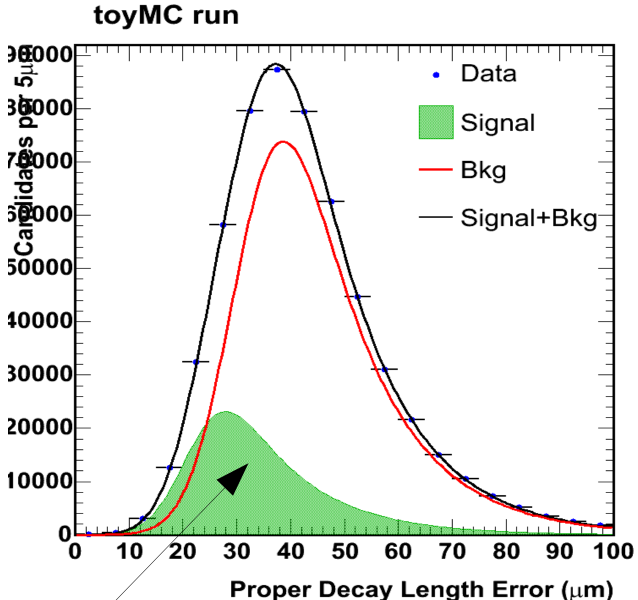
M = mass
s_M = scale factor on mass errors

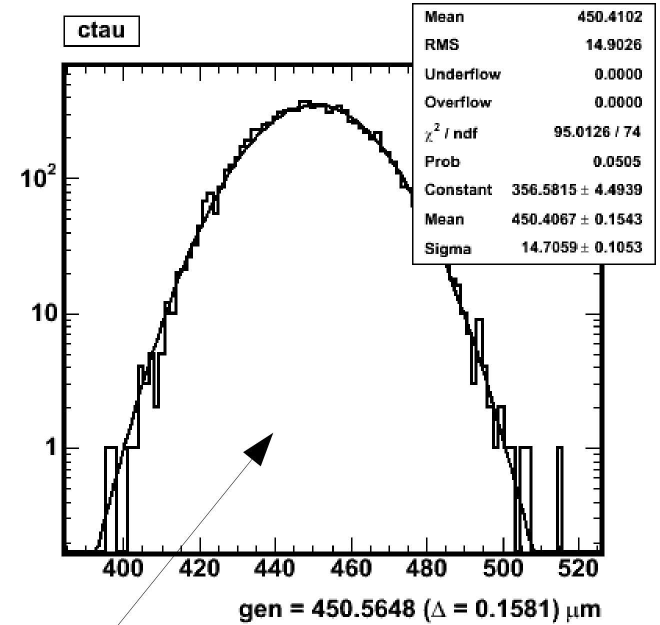
Linear mass shape used as background mass model (single parameter, C_0, after normalization over mass window (M_{low}, M_{high})):

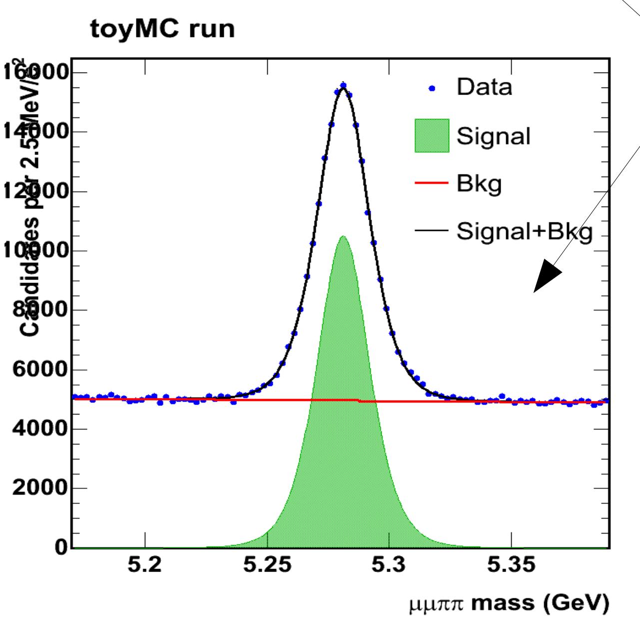
$$P_{bkg}^m(m_i | C_0) = \left(\frac{2}{M_{high}^2 - M_{low}^2} - \frac{2C_0}{M_{high} + M_{low}} \right) m_i + C_0$$

Validation: Toy Monte Carlo



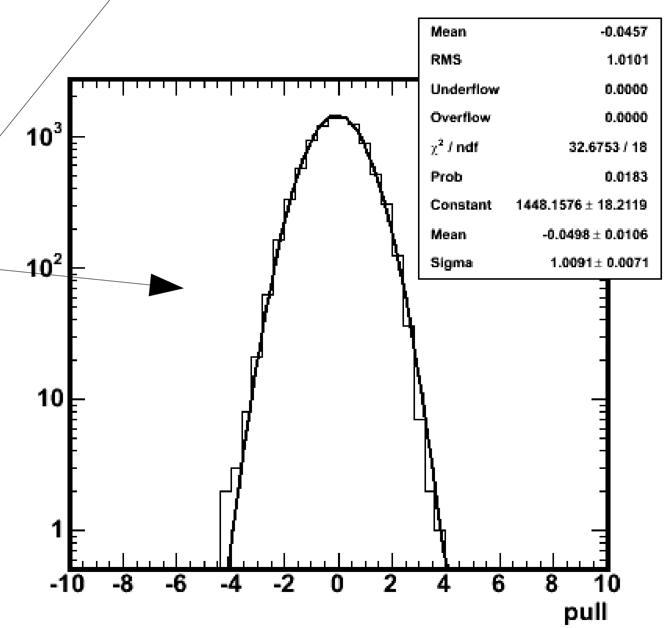






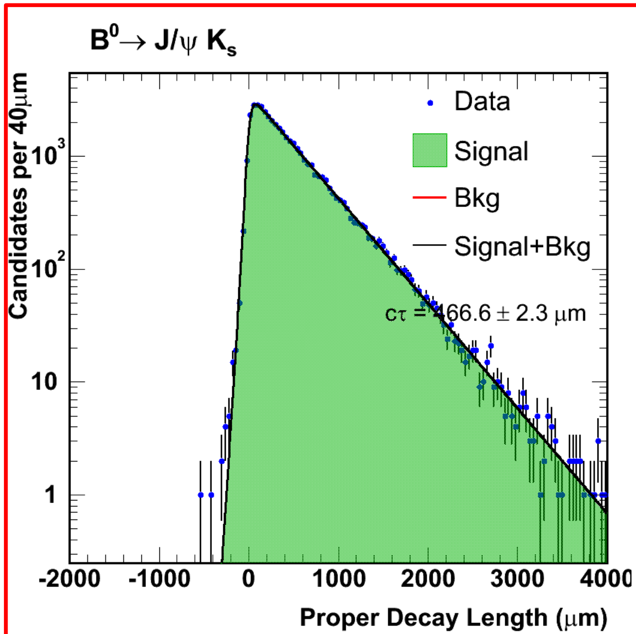
1 toy run with
20× data size

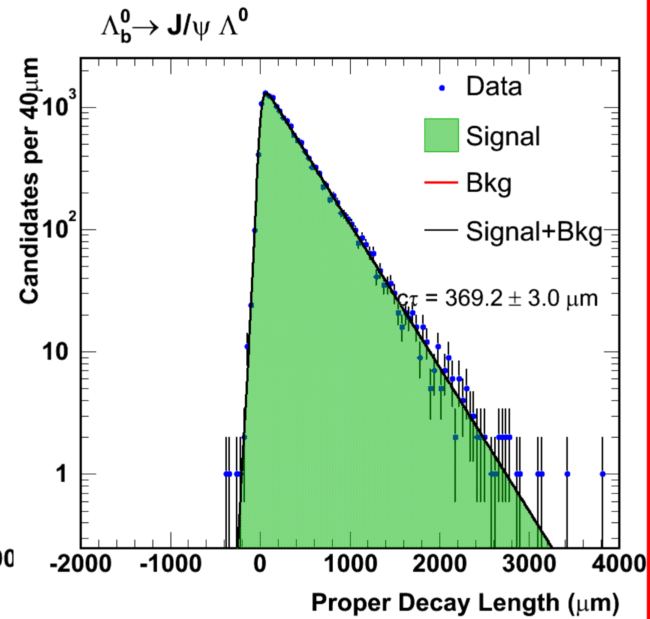
10k toy runs
with same
size as data



Generated parameters
consistent with fitted
⇒ valid fitting procedure

Validation: Realistic MC

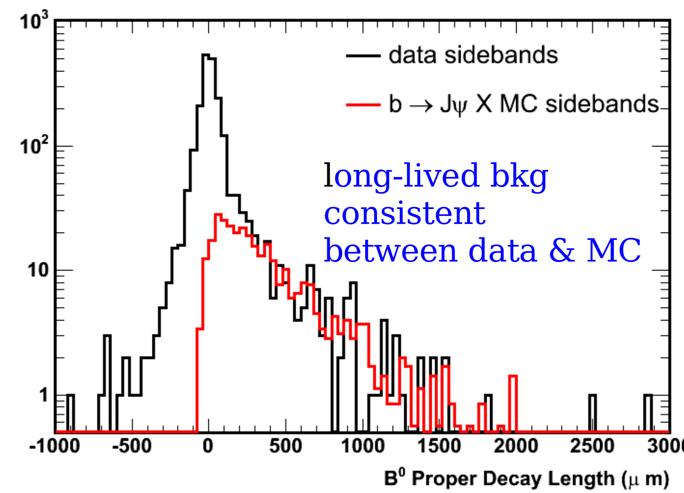


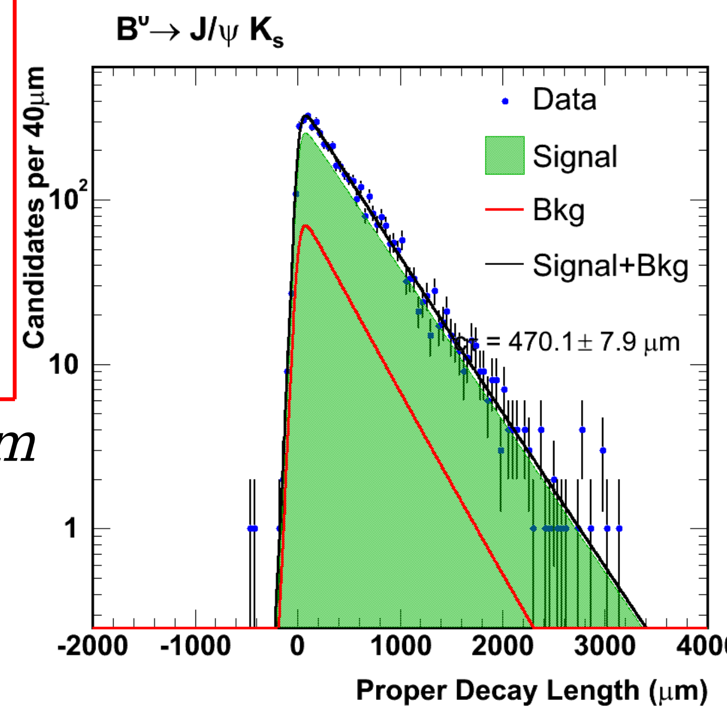


$Fit = 466.6 \pm 2.3\,\mu m$
$Gen = 464\,\mu m$

$Fit = 369.2 \pm 3.0\,\mu m$
$Gen = 368\,\mu m$

Signal MC



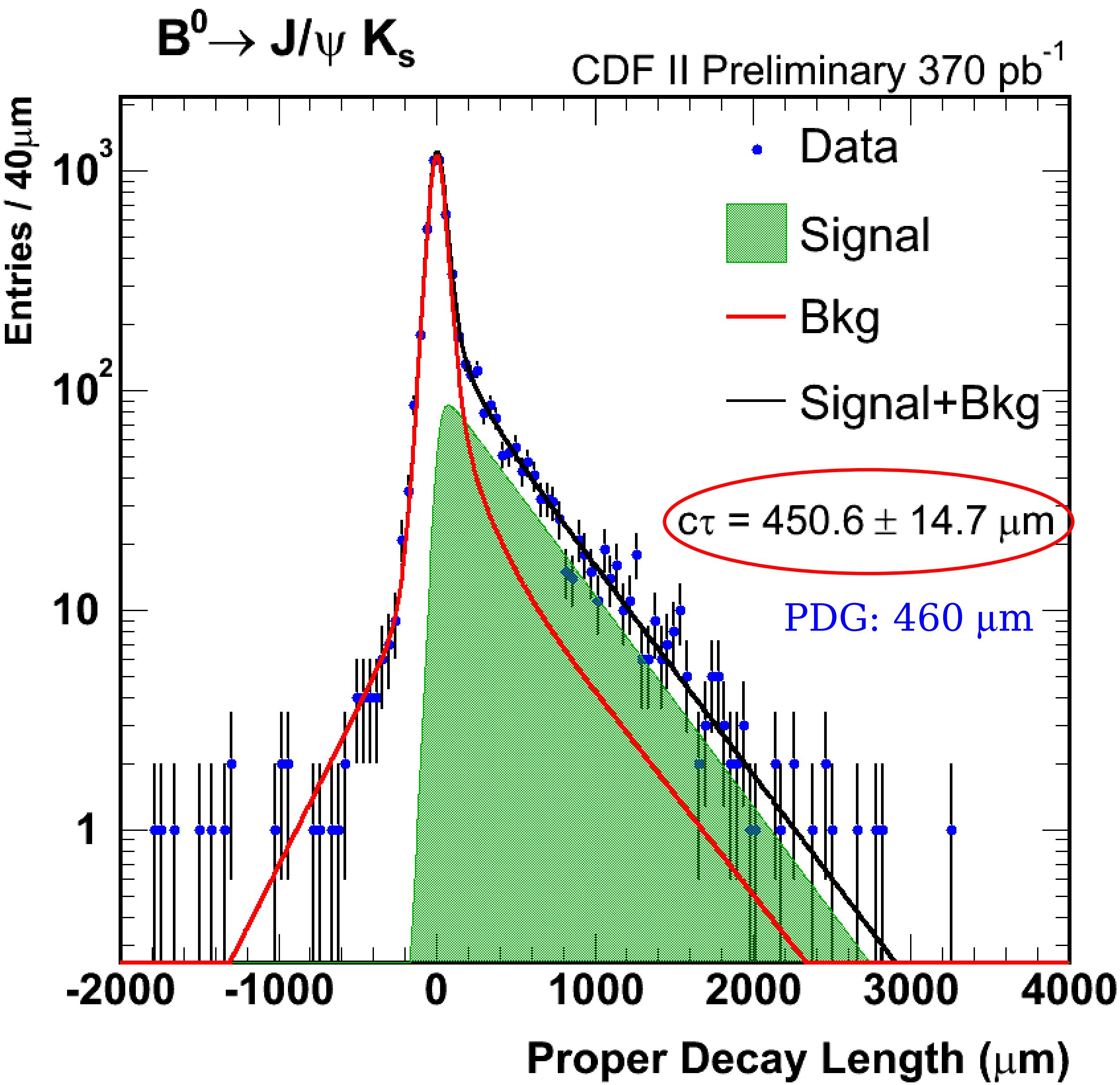


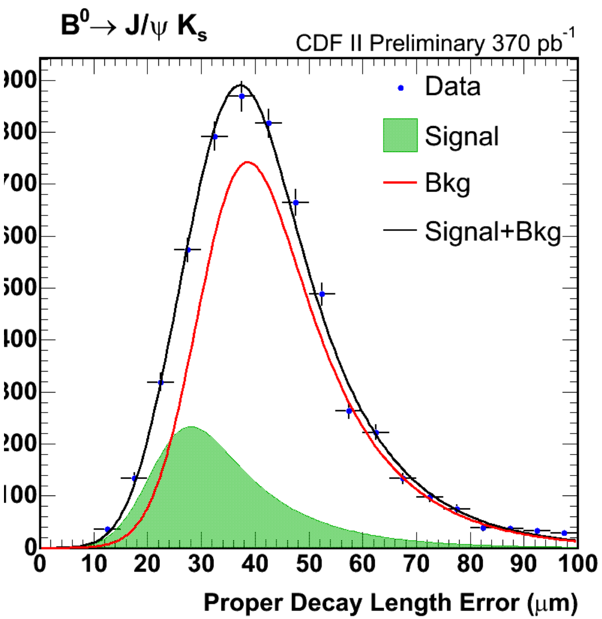
$Fit = 470.1 \pm 7.9\,\mu m$
$Gen = 464\,\mu m$

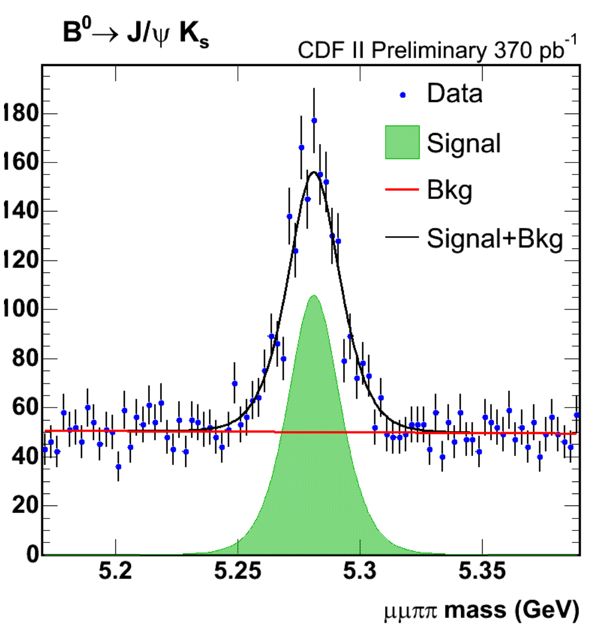
***b* → J/ψ X**
Pythia MC

- Same reconstruction/ selection as for data
- Consistent lifetime fits for:
  - signal
  - signal w/ long-lived bkg

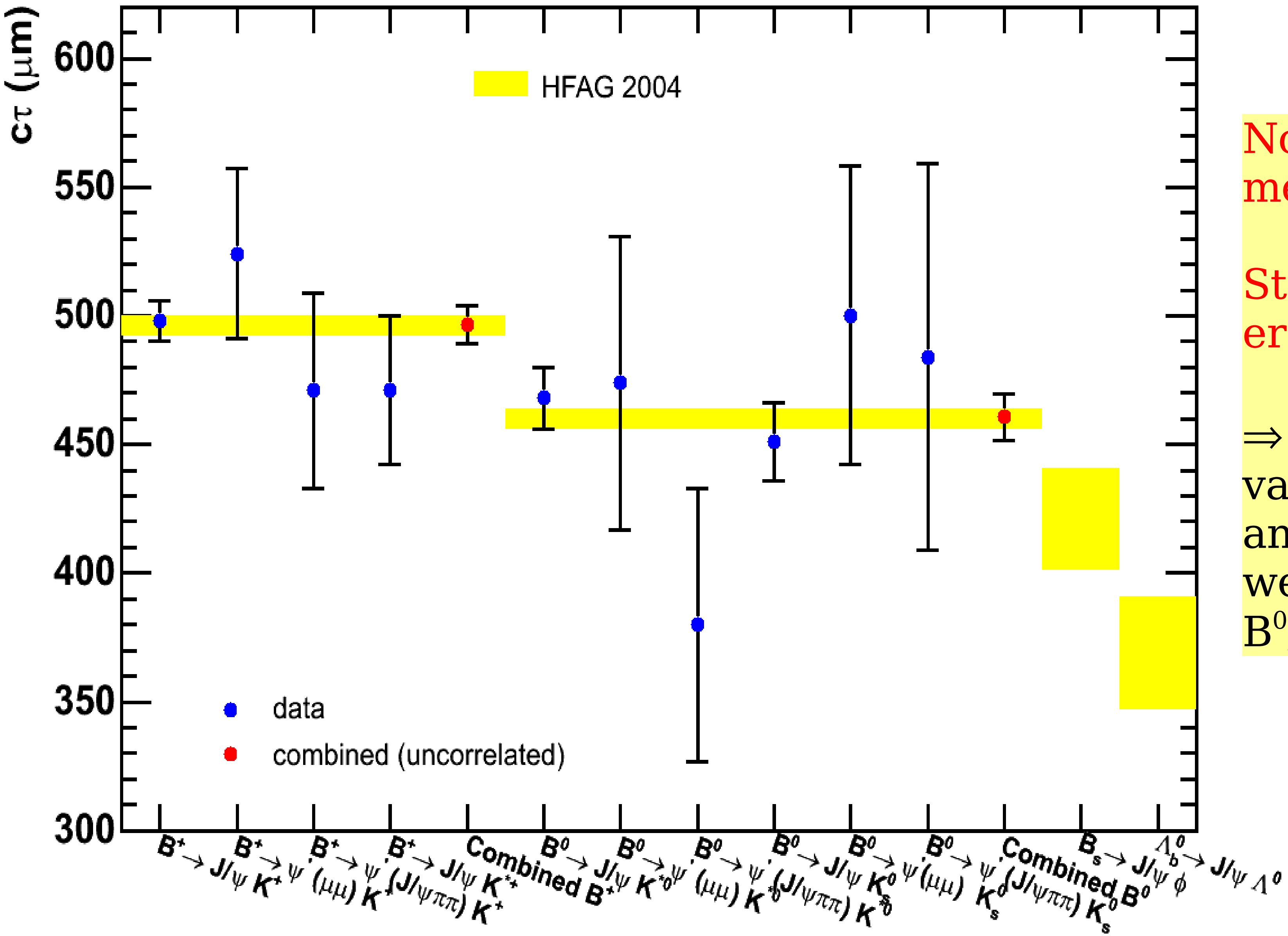
Fit Results: $B^0 \to J/\psi K_s$







b-Hadron Lifetime Summary



Not a measurement:

Statistical errors only!

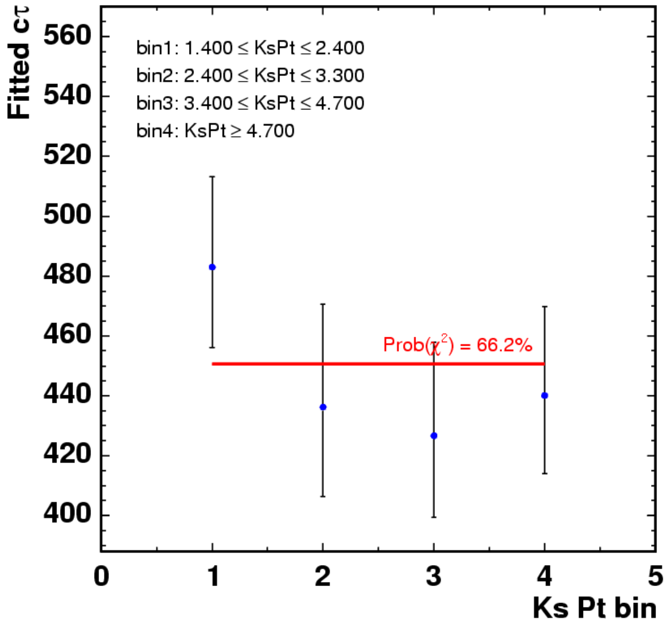
⇒ High-level validation of analysis for well-established B^0/B^+ lifetimes

Lifetime Cross-Checks

Look for unexpected $c\tau$ dependence:

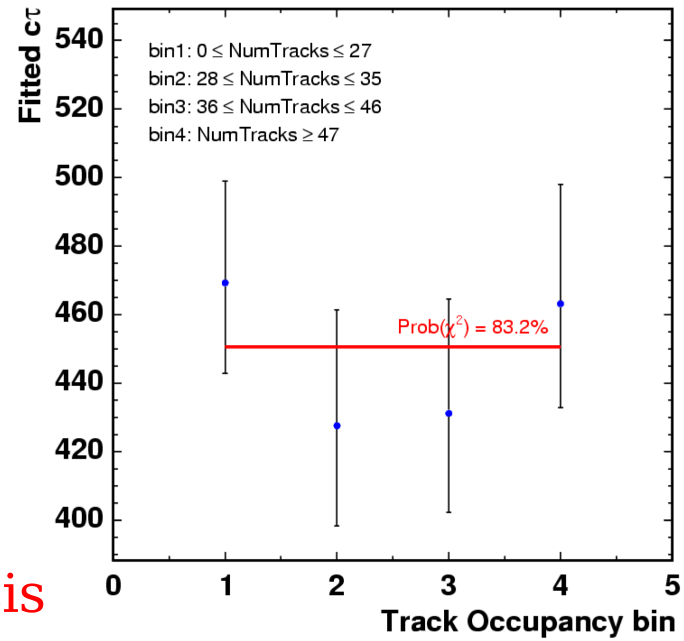
Run range, B^0 vertex prob(χ^2), B^0 p_T, B^0 η, B^0 ϕ_0, B^0 z-position, K_s p_T, track occupancy, K_s L_{xy} and L_{xy}/σ_{Lxy} from J/ψ vertex, K_s and J/ψ r-φ silicon hits, fit range, ...

→ No statistically-significant dependence found



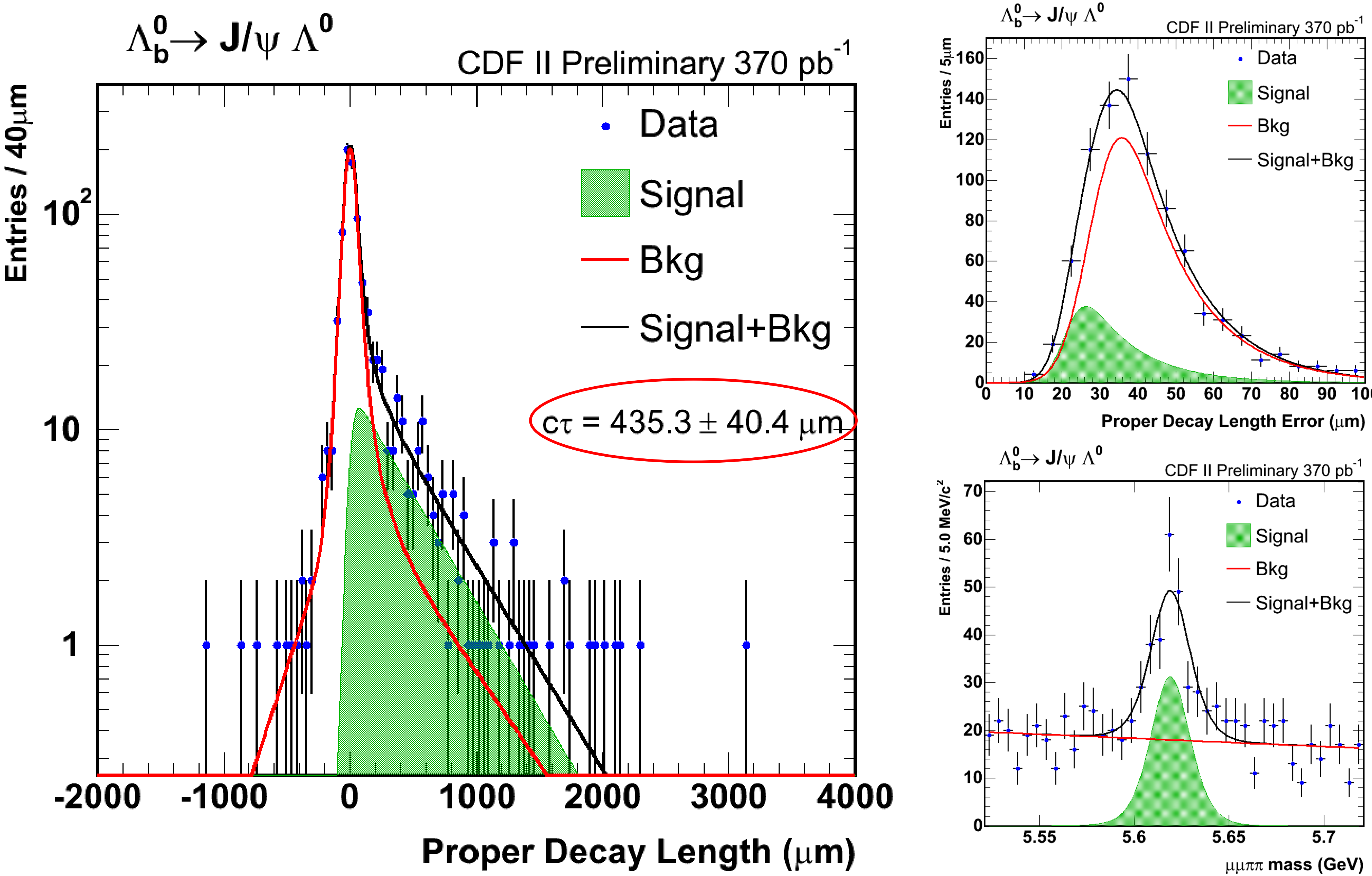
Variations on analysis procedure:

- COT-only tracking for K_s
  - → important check for possible bias from V^0 Si hits
- *b*-hadron kinematic fit constraints
  - → (2-D/3-D pointing constraint, V^0 mass constraint)
- PDL calculation
  - → candidate mass for boost, B^0 vertex for decay vtx



→ Variation results consistent with baseline analysis

Fit Results: $\Lambda_b \to J/\psi \Lambda^0$



Systematic Uncertainties

Fitter bias:
- toyMC studies

Fit Model:
- Variations in choice of resolution function, signal & background models consistent with data,
- probe mass/PDL correlation

PV determination:
- different beamline-z choice

Alignment:
- SVX internal,
- SVX-COT global (translation, rotation)

V^0 Pointing:
- PDL-dependent bias from V^0 to J/ψ pointing constraint

Source	$c\tau(B^0)$ (μm)	$c\tau(\Lambda_b)$ (μm)
Fitter Bias	0.2	0.5
Fit Model:		
PDL Resolution	3.0	1.5
Mass Signal	1.8	1.3
Mass Background	0.1	0.5
PDL Background	0.6	3.7
Mass-dependent PDL Background	0.9	0.9
PDL Error Modeling	0.1	0.1
Mass Error Modeling	0.4	3.0
Primary Vertex Determination	0.2	0.3
Alignment	3.0	3.8
V^0 Pointing	1.0	1.0
TOTAL	**4.9**	**6.6**

Λ_b Lifetime: Summary

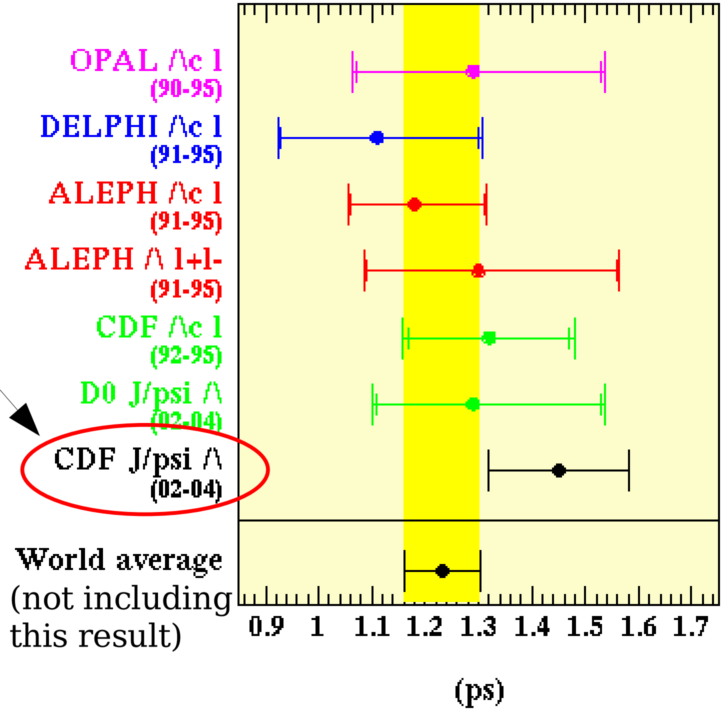
We measure in decay mode $\Lambda_b \to J/\psi \Lambda^0$:

$\tau(\Lambda_b) = 1.45 \pm 0.13$ (stat.) ± 0.02 (syst.) ps

We measure in our control decay mode $B^0 \to J/\psi K_s$:

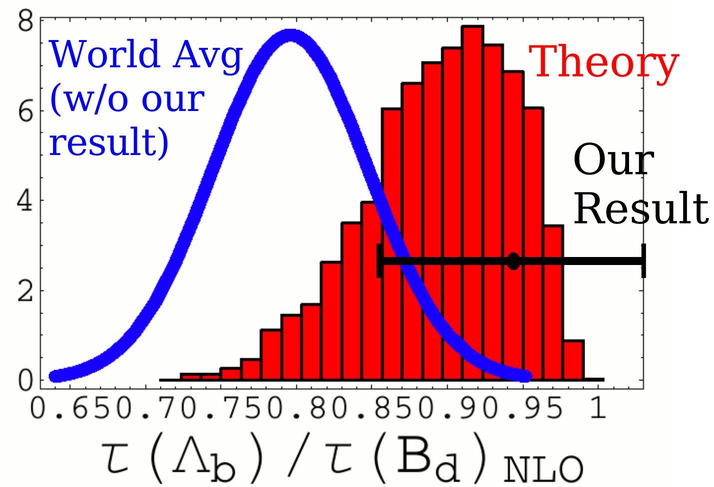
$\tau(B^0) = 1.503 \,^{+0.050}_{-0.048}$ (stat.) ± 0.016 (syst.) ps

consistent w/ PDG 2004 value of 1.536 ± 0.014 ps



Using our $\tau(\Lambda_b)$ measurement and PDG 2004 $\tau(B^0)$:

$\tau(\Lambda_b)/\tau(B^0) = 0.944 \pm 0.086$ (stat.+syst.)



This is consistent w/ world average @ 1.4σ level and current NLO HQE calculations @ 0.8σ level

Λ_b Lifetime: Outlook

- Our measurement of $\tau(\Lambda_b)$ using 370 pb^{-1} is competitive with the world's single best measurement

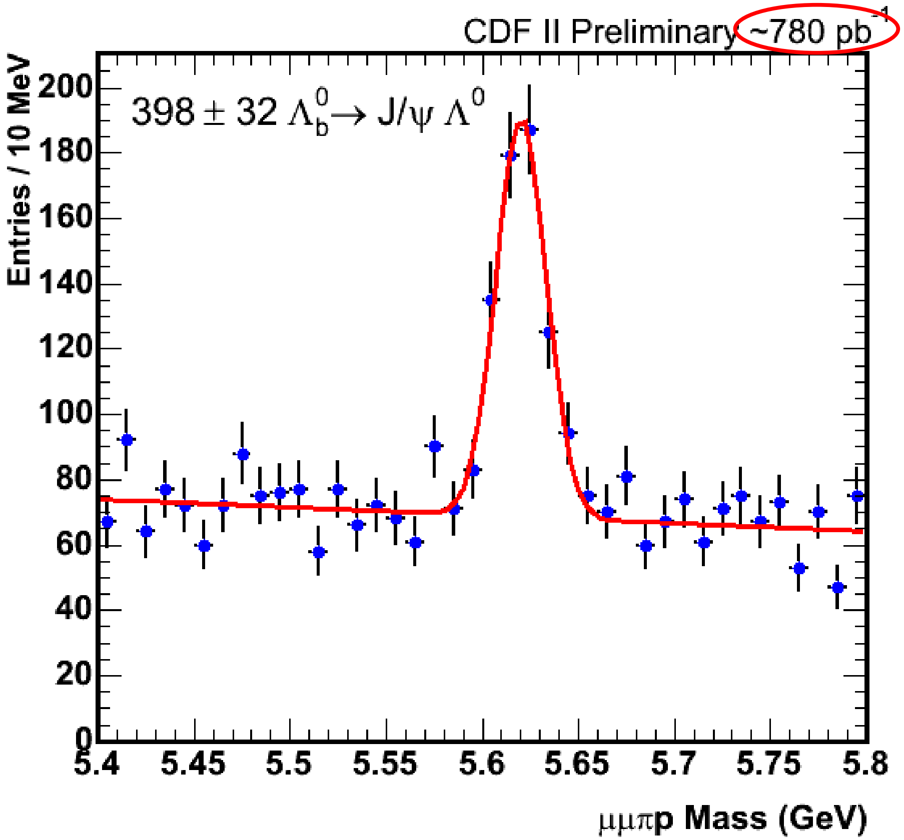
  $\rightarrow$ best by far in a fully reconstructed decay channel

- $\tau(\Lambda_b)$ in $\Lambda_b \rightarrow J/\psi \Lambda^0$ is statistically limited, with small systematics

- Adding new data to this analysis will be very interesting

  $\rightarrow$ precision will approach current world average

  and continue to test the theory of *b*-hadron lifetimes

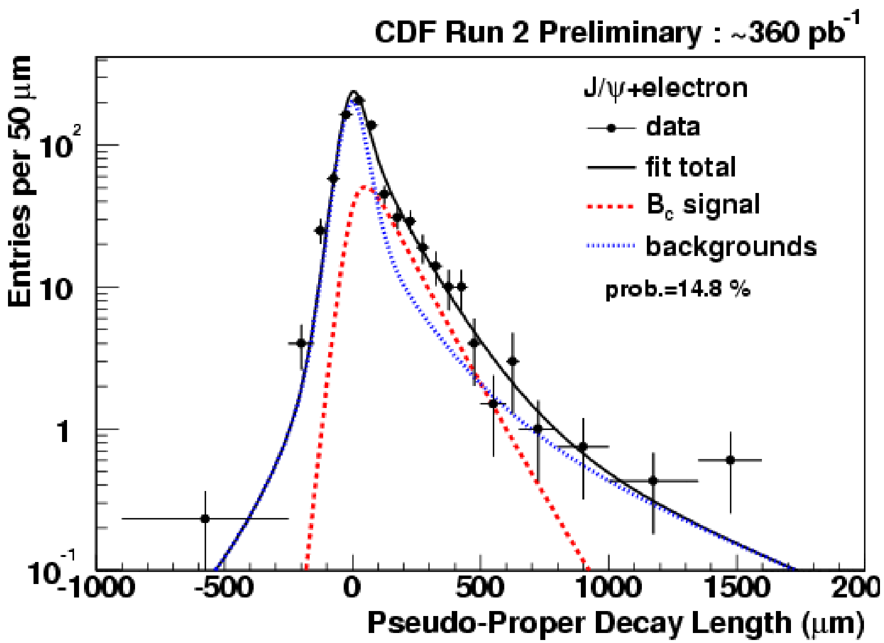


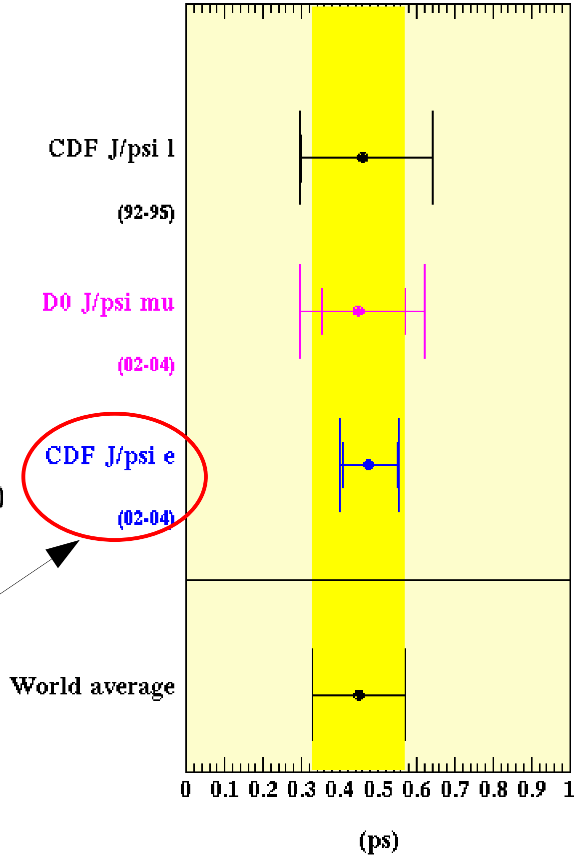
B_c Lifetime

The B_c meson is comprised of a charm and (anti-)bottom quark
→ decay of either contributes to B_c lifetime

Recent calculation using OPE approach predicts:

$\tau(B_c) = 0.55 \pm 0.15$ ps





We measure in $B_c \to J/\psi\, e^+ \nu_e$ decay channel:

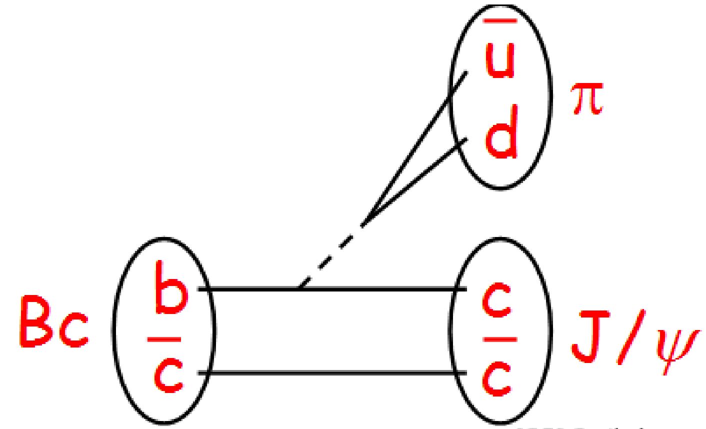
$\tau(B_c) = 0.474^{+0.074}_{-0.066}$ (stat.) $\pm\ 0.033$ (syst.) ps

This is currently the world's best measurement of the B_c lifetime

$B_c \to J/\psi\ \pi$

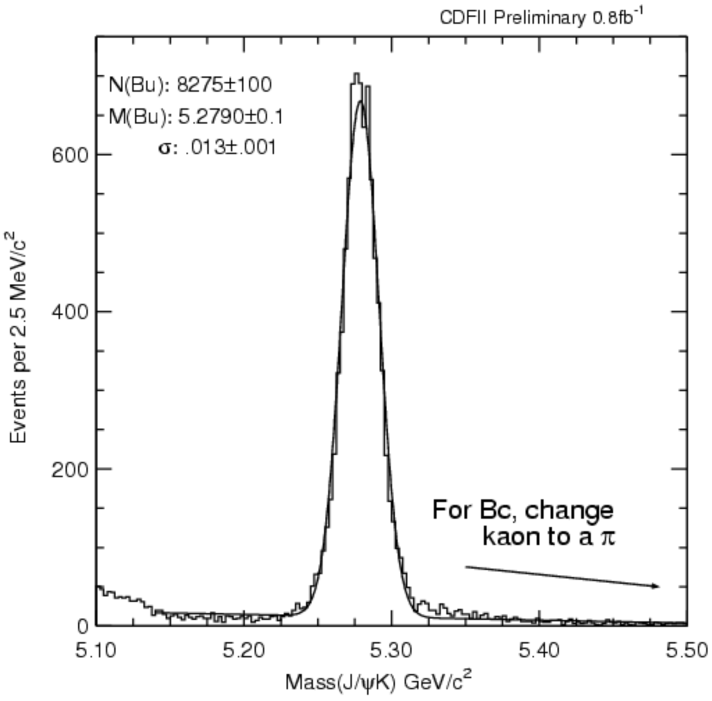
New! (Analysis using 0.8 fb^{-1}
just blessed yesterday)

- B_c not produced at B factories
- Full reconstruction allows for precise mass measurement

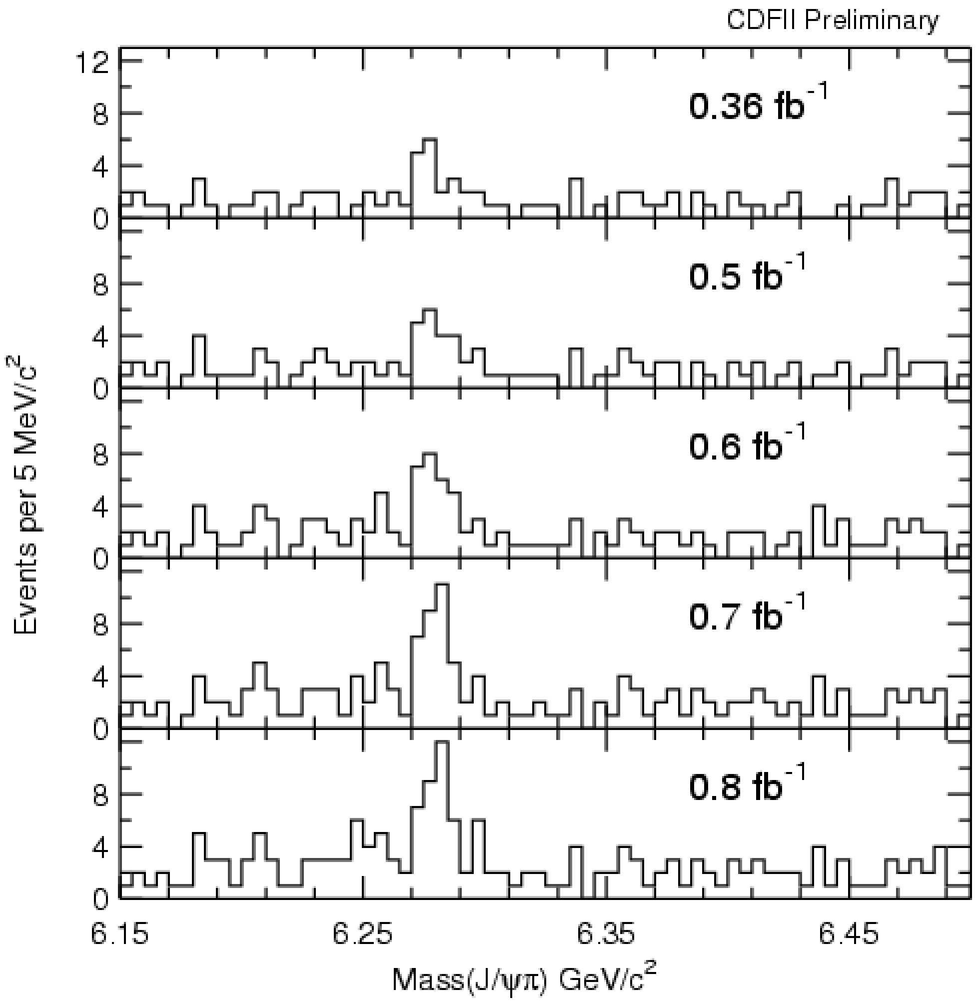


Analysis:

- Tune selection on data:
  $B_u \to J/\psi K$ reference decay
- After approval, open box
- Wait for events to become
  a significant excess
- Measure properties of the B_c

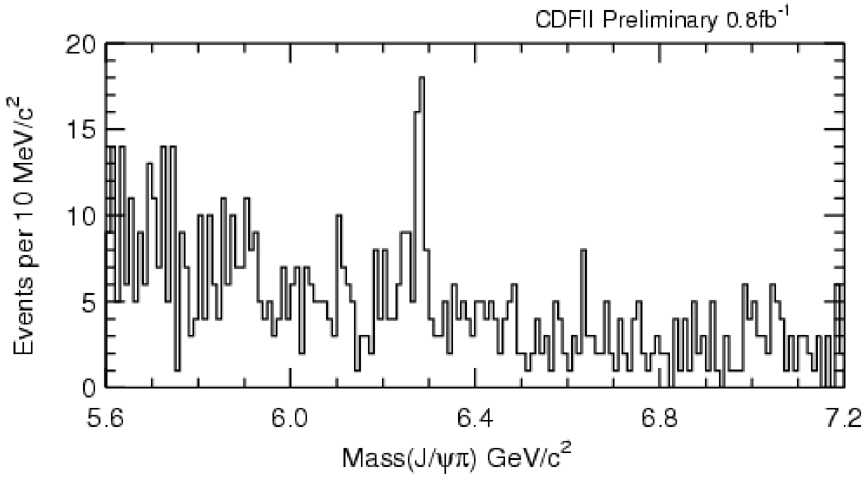


$B_c \to J/\psi\ \pi$



38.9 events over bkg

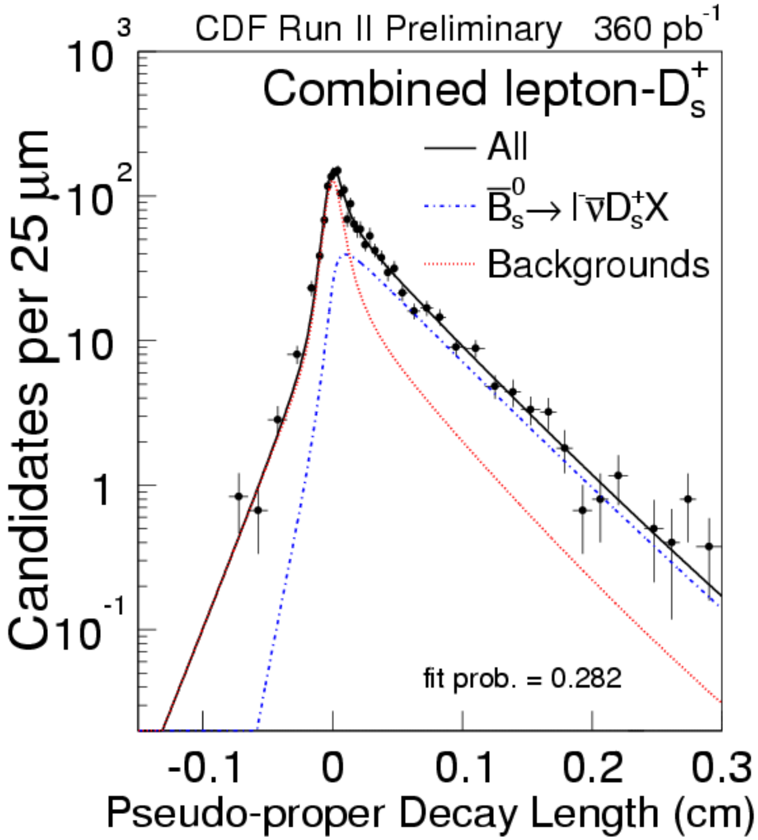
Significance > 6σ over search area

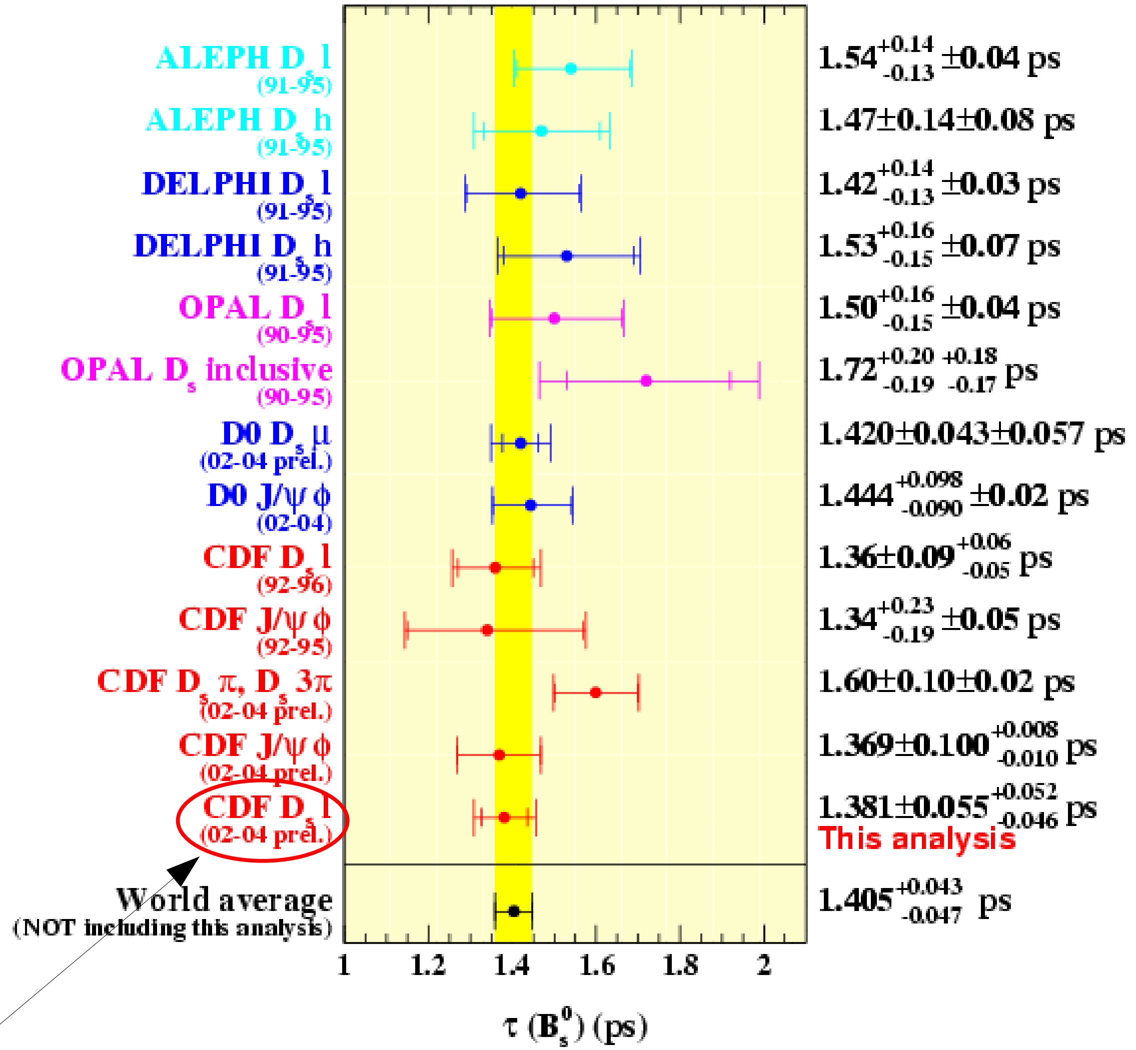


$M(B_c) = 6275.2 \pm 4.3\ (\text{stat.}) \pm 2.3\ (\text{syst.})\ \text{MeV}/c^2$

world best!

B_s Lifetime



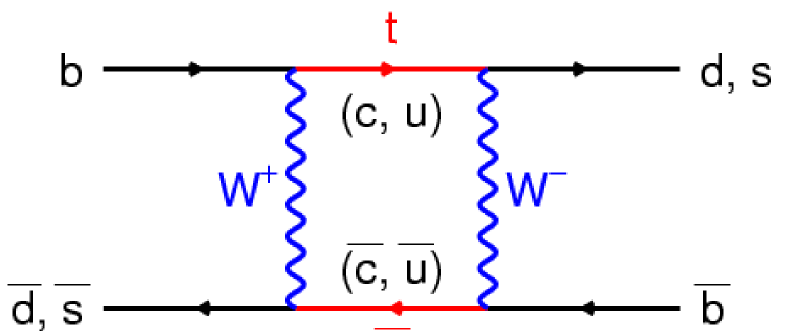


We measure in semileptonic $B_s \rightarrow l\nu D_s X$ decay:

$$\tau(B_s) = 1.381 \pm 0.055\ (\text{stat.})\ ^{+0.052}_{-0.046}\ (\text{syst.})\ \text{ps}$$

B_s Mixing: Motivation

- Neutral B mesons flavor oscillate
- Measure fundamental SM parameters



B_d: $$\Delta m_d = \frac{G_F^2 m_W^2}{6\pi^2} m_{B_d} |V_{td}|^2 \eta_B S_0(x_t) \cdot \hat{B}_{B_d} f_{B_d}^2$$

B_s: (s) (B_s) (ts) (B_s) (B_s)

- Hadronic uncertainties cancel in ratio

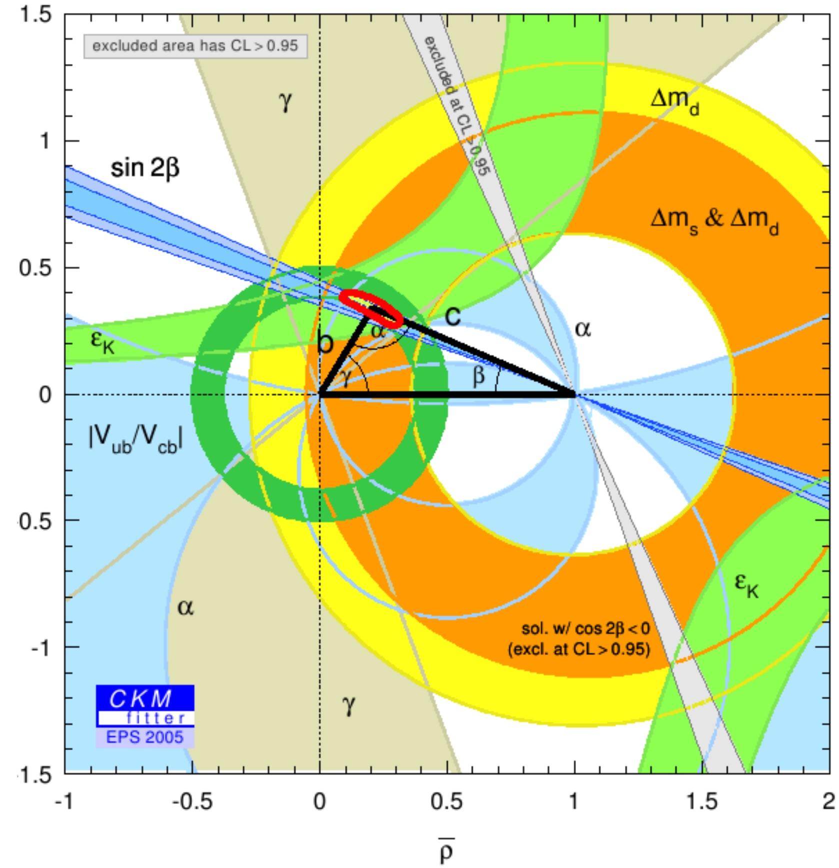
$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \left|\frac{V_{ts}}{V_{td}}\right|^2 \left(\frac{\hat{B}_{B_s} f_{B_s}^2}{\hat{B}_{B_d} f_{B_d}^2}\right) \leftarrow \xi^2$$

- Lattice computation:

$$\xi = 1.21 \pm 0.022^{+0.035}_{-0.014}$$

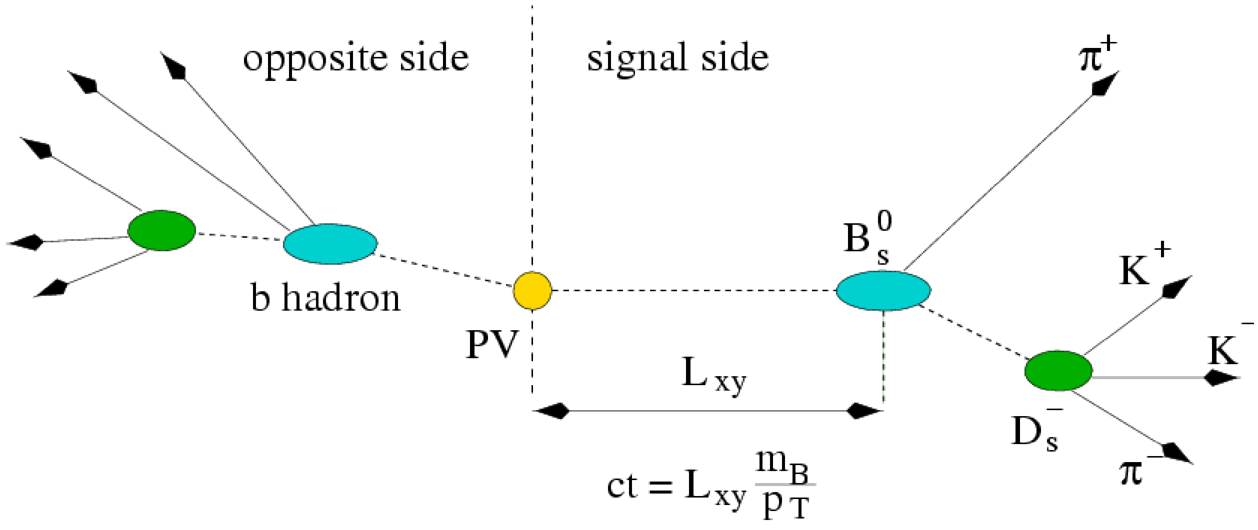
→ Determine $|V_{ts}|/|V_{td}|$ to ~ 2.5%

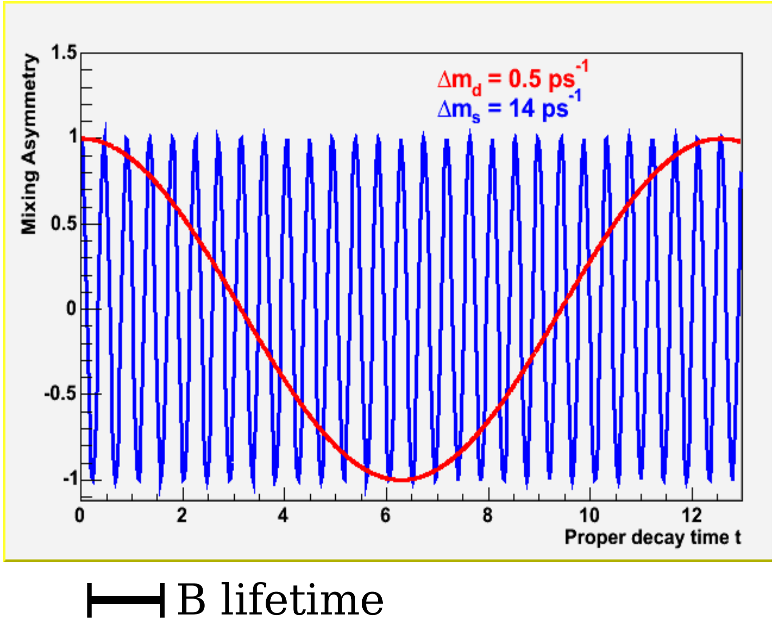
- Δm_s sensitive probe of new physics



CKM Fit Result: $18.3^{+6.5}_{-1.5}$ ps^{-1}

B_s Mixing: Analysis Overview





$\Delta m_s >> \Delta m_d \rightarrow$ challenging!

- Sample: collect $B^+/B^0/B_s$ decay sample using displaced track trigger, reconstructed in semileptonic (lDX) and hadronic ($D\pi(\pi\pi)$) decay mode
- Proper time measurement *ct* $\rightarrow$ understanding of σ_{ct} crucial!
- Flavor tagging $\rightarrow$ calibrate opposite-side taggers on B^0/B^+ sample
- Measure time-dependent asymmetry:

$$\mathcal{A}(t) \equiv \frac{N(t)_{mixed} - N(t)_{unmixed}}{N(t)_{mixed} + N(t)_{unmixed}} = \mathcal{D}\cos(\Delta m_s t), \qquad \mathcal{D} = 1 - 2P_{mistag}$$

B_s Mixing: Improvements

Winter '05 results:

Semileptonic

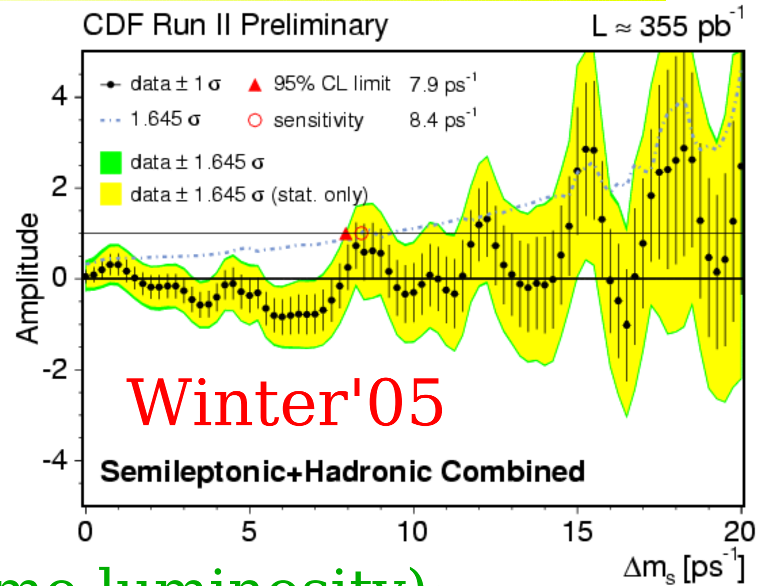
Sensitivity: 7.4 ps^{-1}
95% CL Limit: 7.7 ps^{-1}

Hadronic

Sensitivity: 0.4 ps^{-1}
95% CL Limit: 0.0 ps^{-1}

Semileptonic+Hadronic

Sensitivity: 8.4 ps^{-1}
95% CL Limit: 7.9 ps^{-1}



Improvements compared to Winter '05 (same luminosity):

Flavor Tagging:

- Improved JQT + larger B^0 calibration sample ⇒

mode	ϵD^2 winter 05	ϵD^2 fall 05
hadronic	1.21%	1.55%
semil.	1.45%	1.55%

Improved *ct* resolution:

- Event-by-event PV instead of avg beamline ⇒ +15% (hadronic), +3% semileptonic
- Add L00

Semileptonics in TTT instead of l+SVT:

- Lower lepton momentum ⇒ ~×2 yield, but with worse S/B

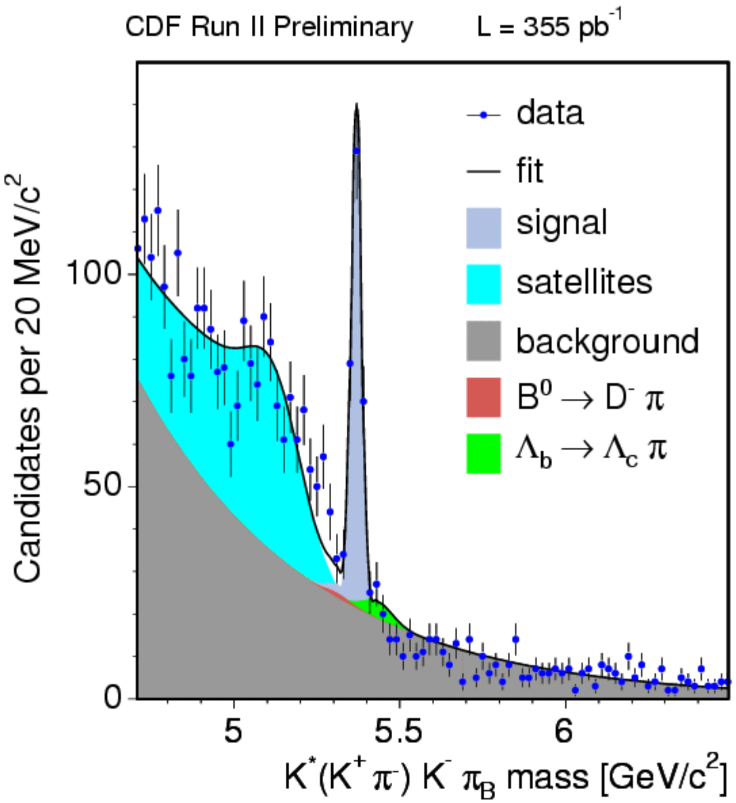
Additional decay modes:

- $B_s \to D_s 3\pi$, $D_s \to \phi\pi$ ⇒ 900 → 1,110 in hadronic yield
- $B_s \to D_s 3\pi$, $D_s \to K^*K$

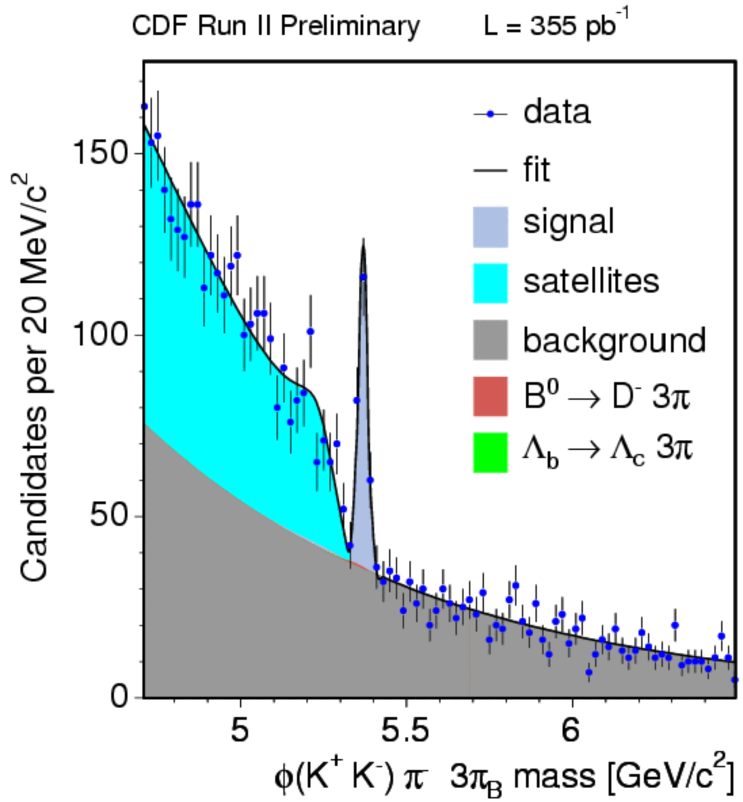
B_s Mixing: Hadronic Signals

$B_s \to D_s\,\pi$, where $D_s \to \phi\pi$, K^*K, 3π

$B_s \to D_s\,3\pi$, where $D_s \to \phi\pi$, K^*K



$B_s \to D_s\,\pi$, $D_s \to K^*K$

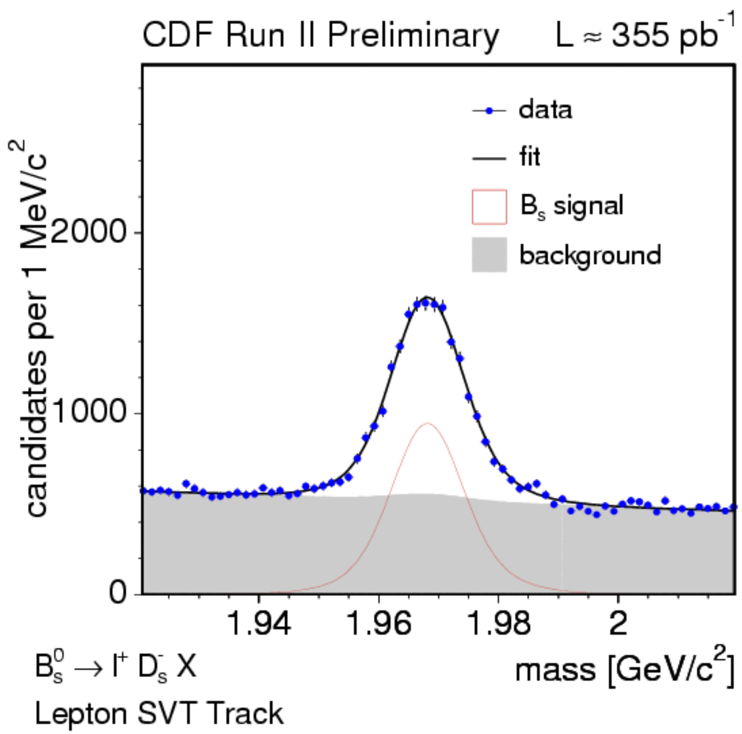


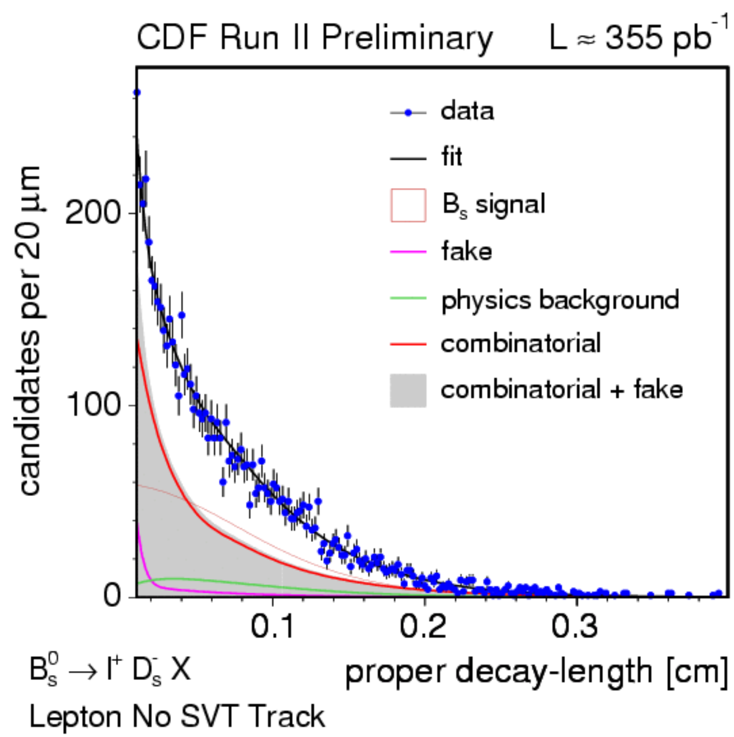
$B_s \to D_s\,3\pi$, $D_s \to \phi\pi$

~1,100 fully-reconstructed B_s candidates available

B_s Mixing: Semileptonic Signals

$B_s \rightarrow lD_s X$, where $D_s \rightarrow \phi\pi, K^*K, 3\pi$





17,084 signal events

Higher statistics but worse *ct* resolution compared to hadronics

$$ct = \frac{L_{xy}}{\gamma\beta};\ \gamma\beta = \frac{p_T(B)}{M(B)} = \frac{p_T(\ell D)}{M(B)} * 1/K\ (K \text{ from MC});$$

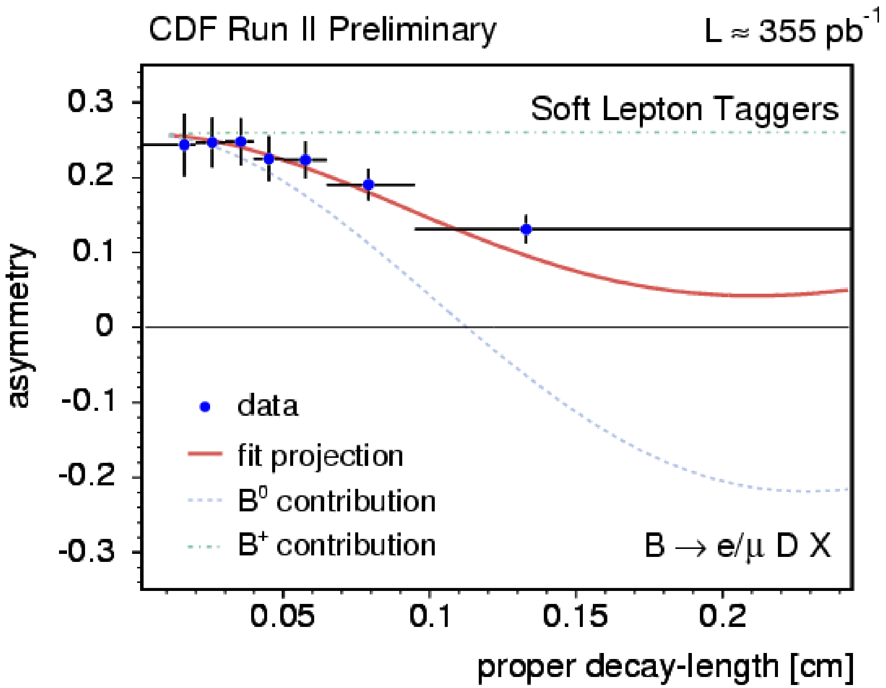
$$\sigma_{ct} = \left(\frac{\sigma_{L_{xy}}}{\gamma\beta}\right) \oplus \left(\frac{\sigma_{\gamma\beta}}{\gamma\beta}\right) * ct$$

Low *ct* candidates have better resolution but worse S/B

B_s Mixing: Δm_d cross-check

B_d mixing: Proof of principle and calibration of tagger performance

- For setting limit, knowledge of tagger performance is critical
  $\rightarrow$ measure tagging dilution in kinematically similar B^0/B^+ samples
- Δm_d and Δm_s fits are complex $\rightarrow$ test fitter framework



Semileptonic modes:

$\Delta m_d = 0.511 \pm 0.020$ (stat) ± 0.020 (syst) ps^{-1}
total εD^2 (OST) $= 1.55 \pm 0.08$ (stat) ± 0.03 (syst) %

Hadronic modes:

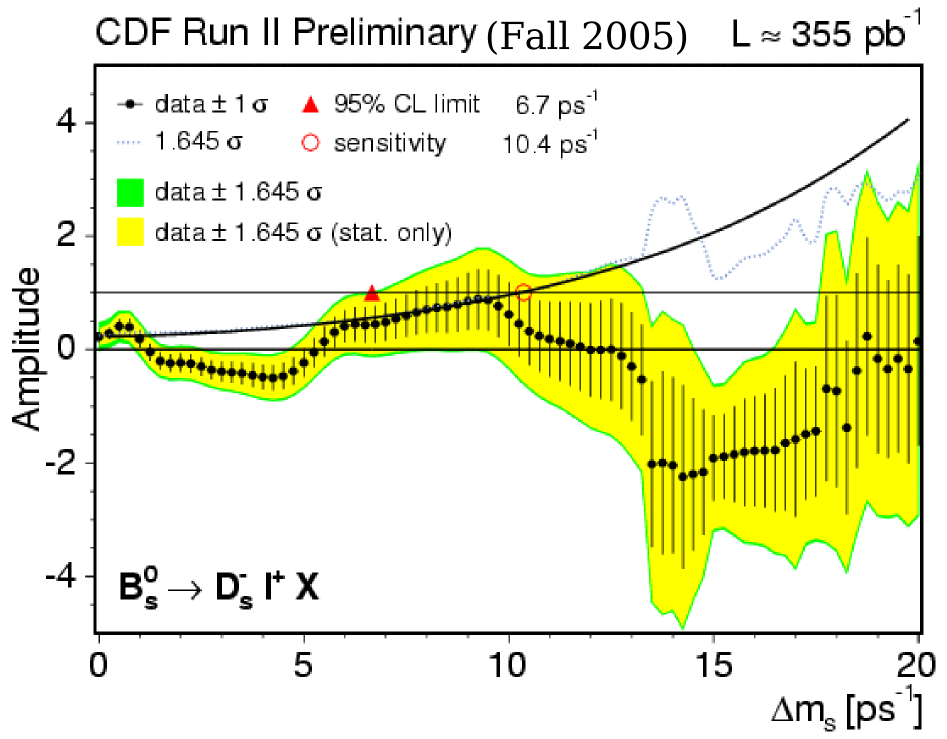
$\Delta m_d = 0.536 \pm 0.028$ (stat) ± 0.006 (syst) ps^{-1}
total εD^2 (OST) $= 1.55 \pm 0.16$ (stat) ± 0.05 (syst) %

PDG 2005: $\Delta m_d = 0.505 \pm 0.005$ ps^{-1}

B_s Mixing: Δm_s Results

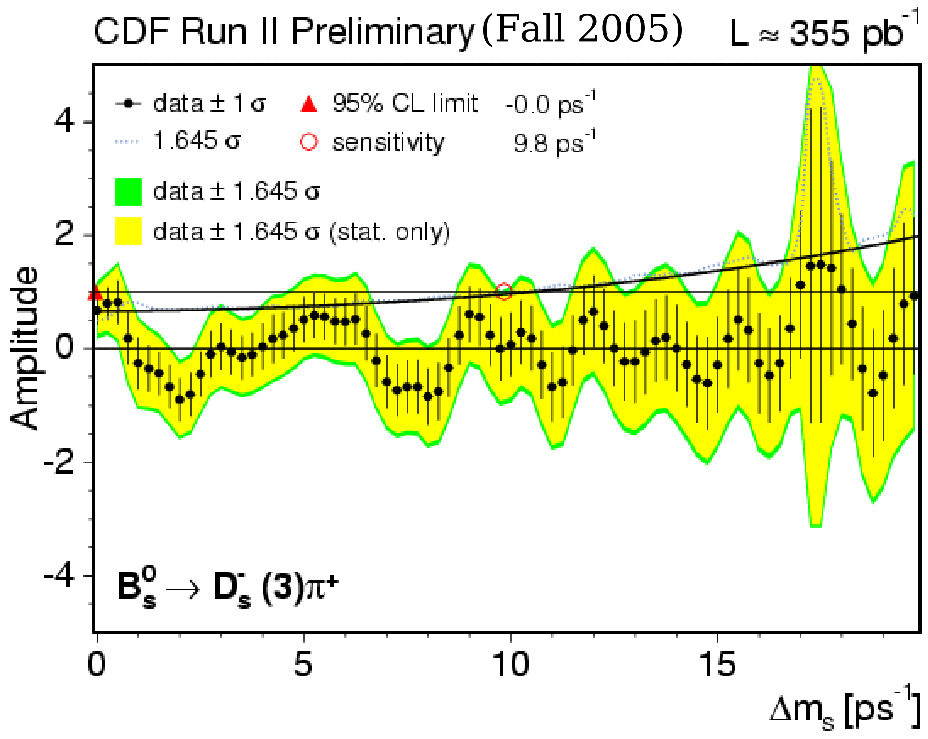
Semileptonic modes

Sensitivity: 10.4 ps^{-1}
95% CL Limit: 6.7 ps^{-1}



Hadronic modes

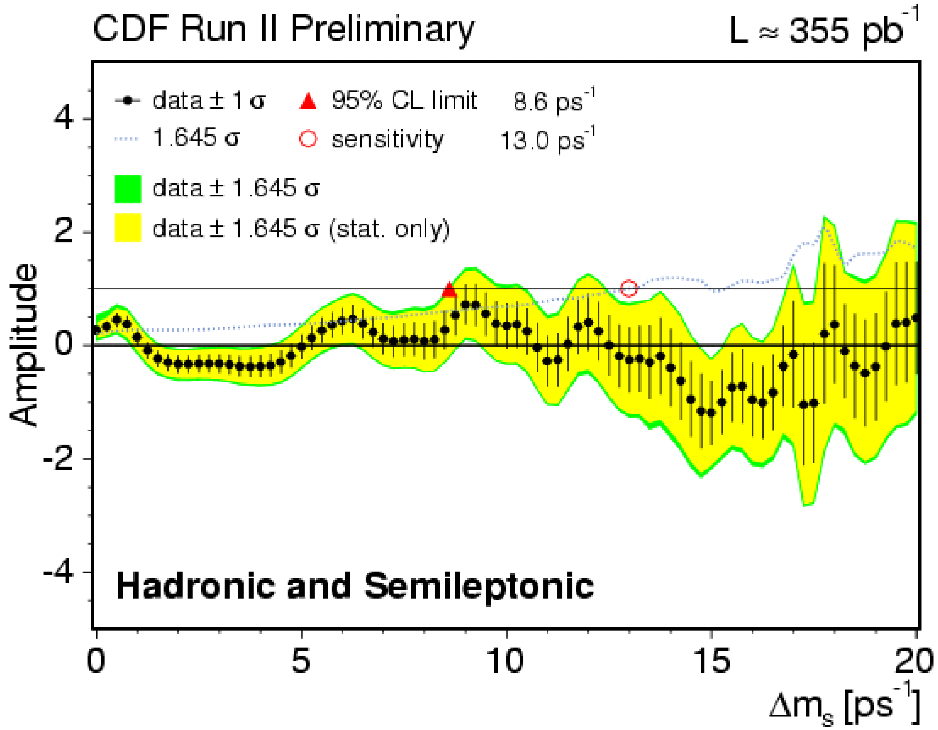
Sensitivity: 9.8 ps^{-1}
95% CL Limit: 0.0 ps^{-1}



B_s Mixing: Combined CDF Result

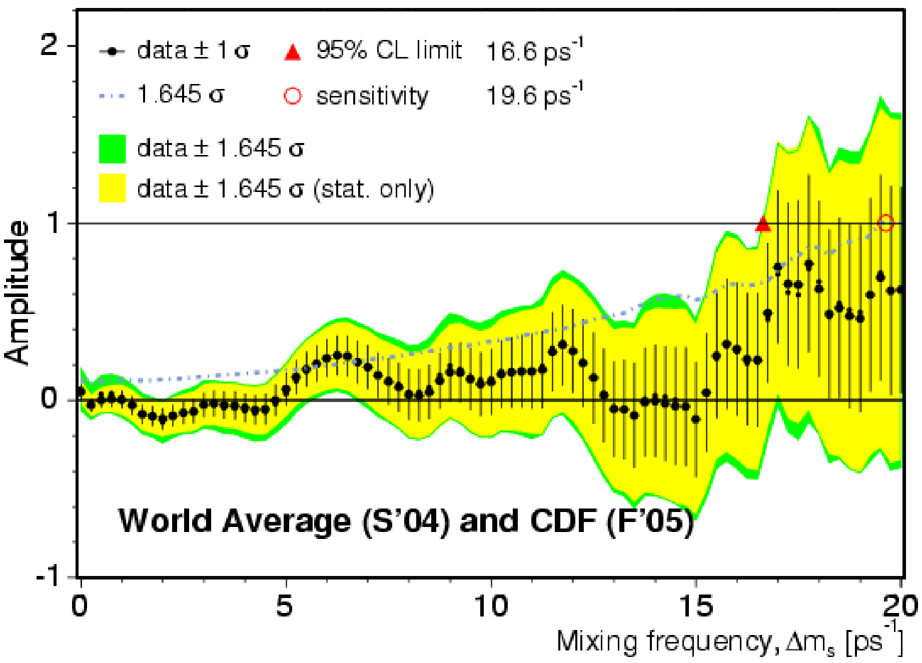
Combined CDF Result

Sensitivity: 13.0 ps^{-1}
95% CL Limit: 8.6 ps^{-1}



Combined CDF+World Avg

Sensitivity: 19.6 ps^{-1}
95% CL Limit: 16.6 ps^{-1}

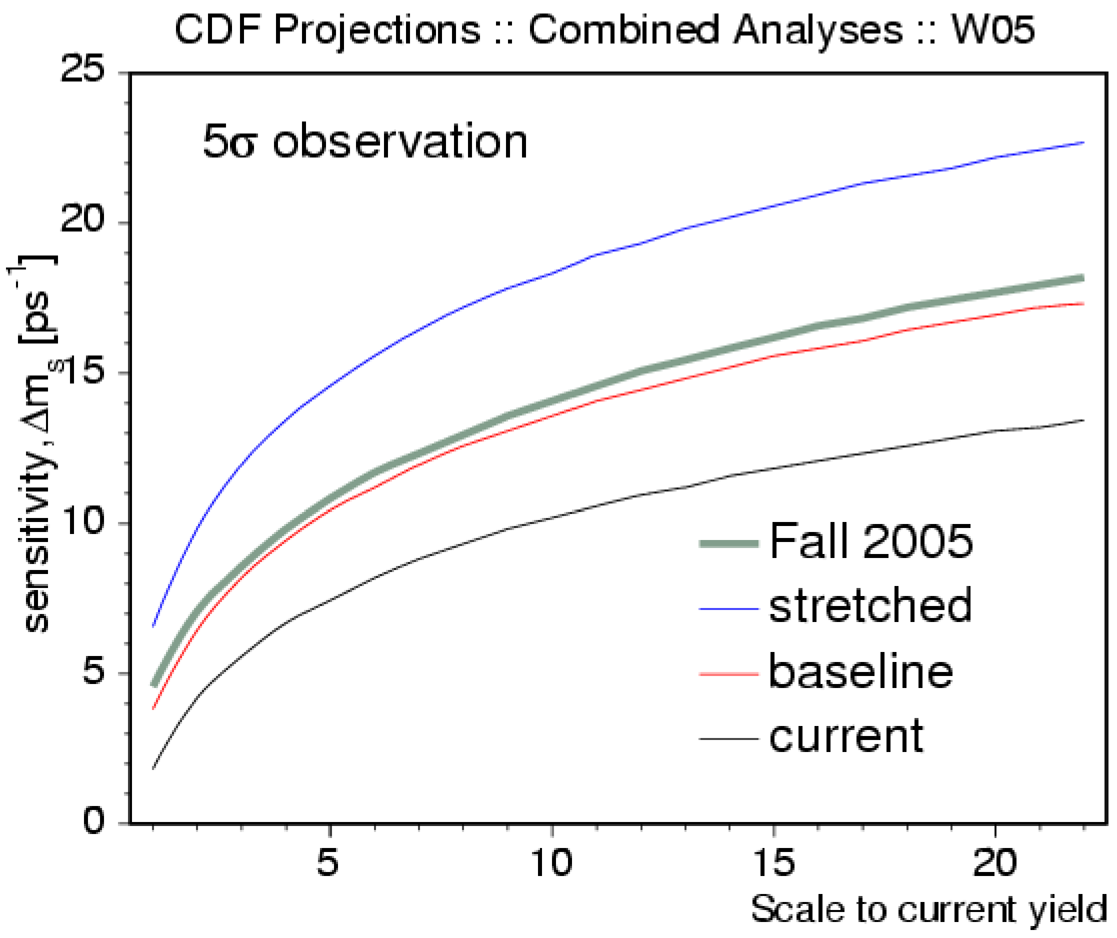


B_s results from CDF → pushing the world avg (previous: $\Delta m_s > 14.4$ ps^{-1})

B_s Mixing: Outlook

Long-term projections for Δm_s measurement

"current" : Winter 2005 results
baseline : +1% εD^2, +10% vertexing
stretched : +3% εD^2, +20% vertexing



Coming improvements in:

- More data (×2 already on tape)
- Same Side Kaon Tagging
- Additional trigger path
- Add satellites in hadronic modes
- Re-optimize event selection (NN)
- m(lD) dependent k-factor binning
- Combined opposite-side taggers
- Better understanding of σ_{ct}

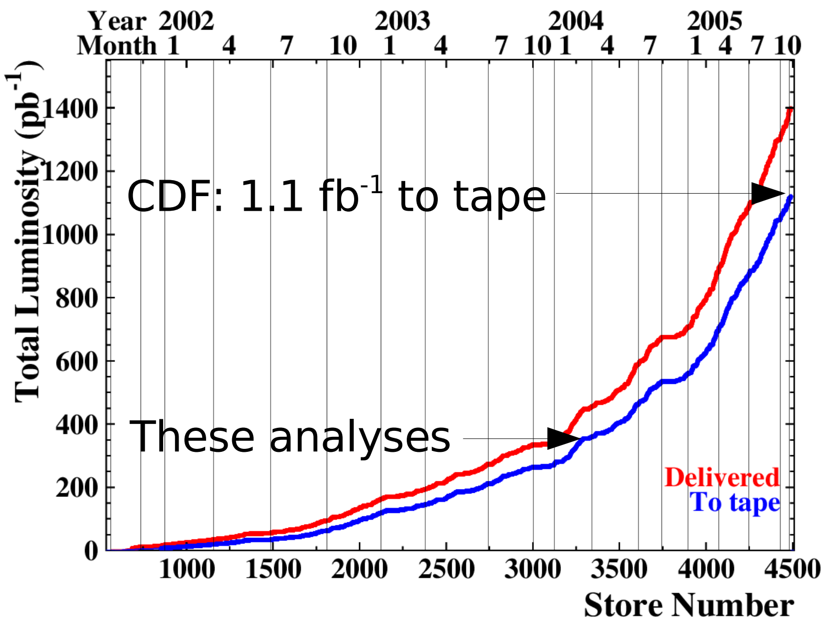
Projections based upon Winter 2005 results,
→ new projections coming

Summary

- New measurements of the Λ_b, B_c, and B_s lifetimes
  - $\rightarrow$ Λ_b and B_s are competitive with world's best measurements
  - $\rightarrow$ B_c is world's best single measurement
    - (also B_c in exclusive decay > 6σ, world's best mass measurement)

- New B_s mixing results push the world average Δm^2 limits
  - $\rightarrow$ more improvements of the analysis on the way!

- These analyses are all limited by statistics
  - $\rightarrow$ substantial improvement with more data

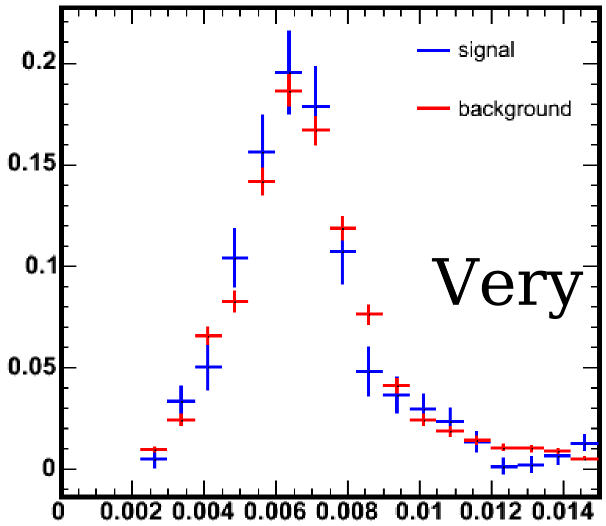


Physics of lifetimes and mixing at CDF is at an exciting stage!

Extras

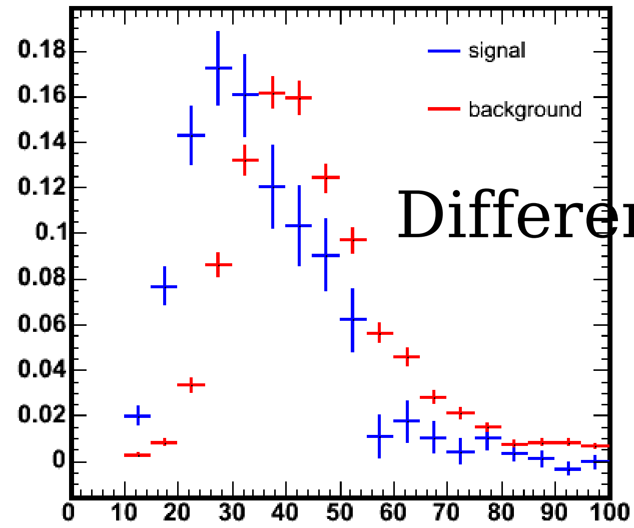
PDL Error and Mass Error

B^0 Mass error



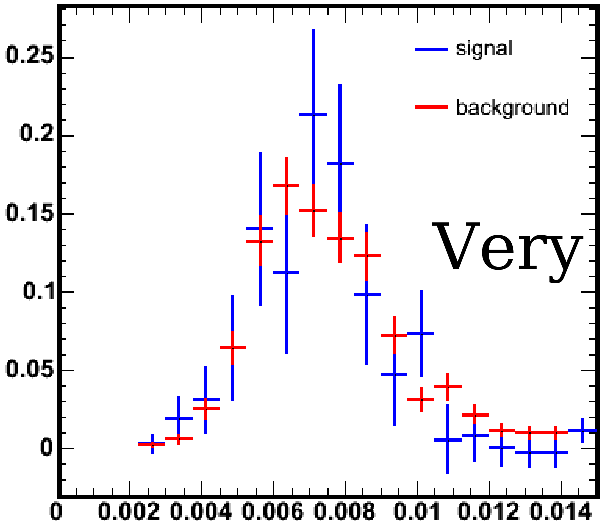
Very Similar

B^0 PDL error



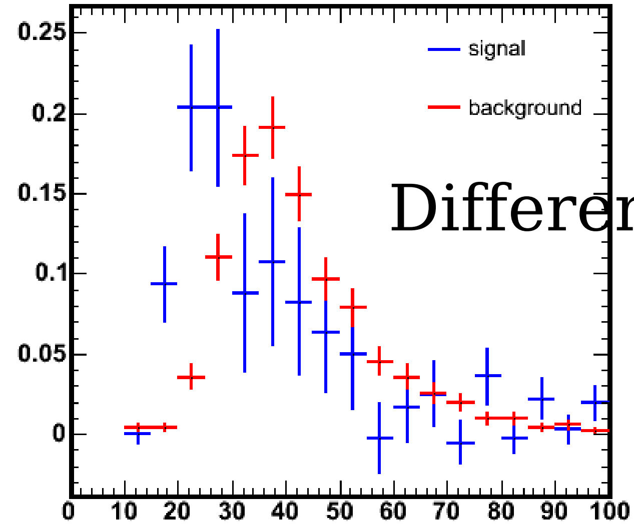
Different!

Λ_b Mass error



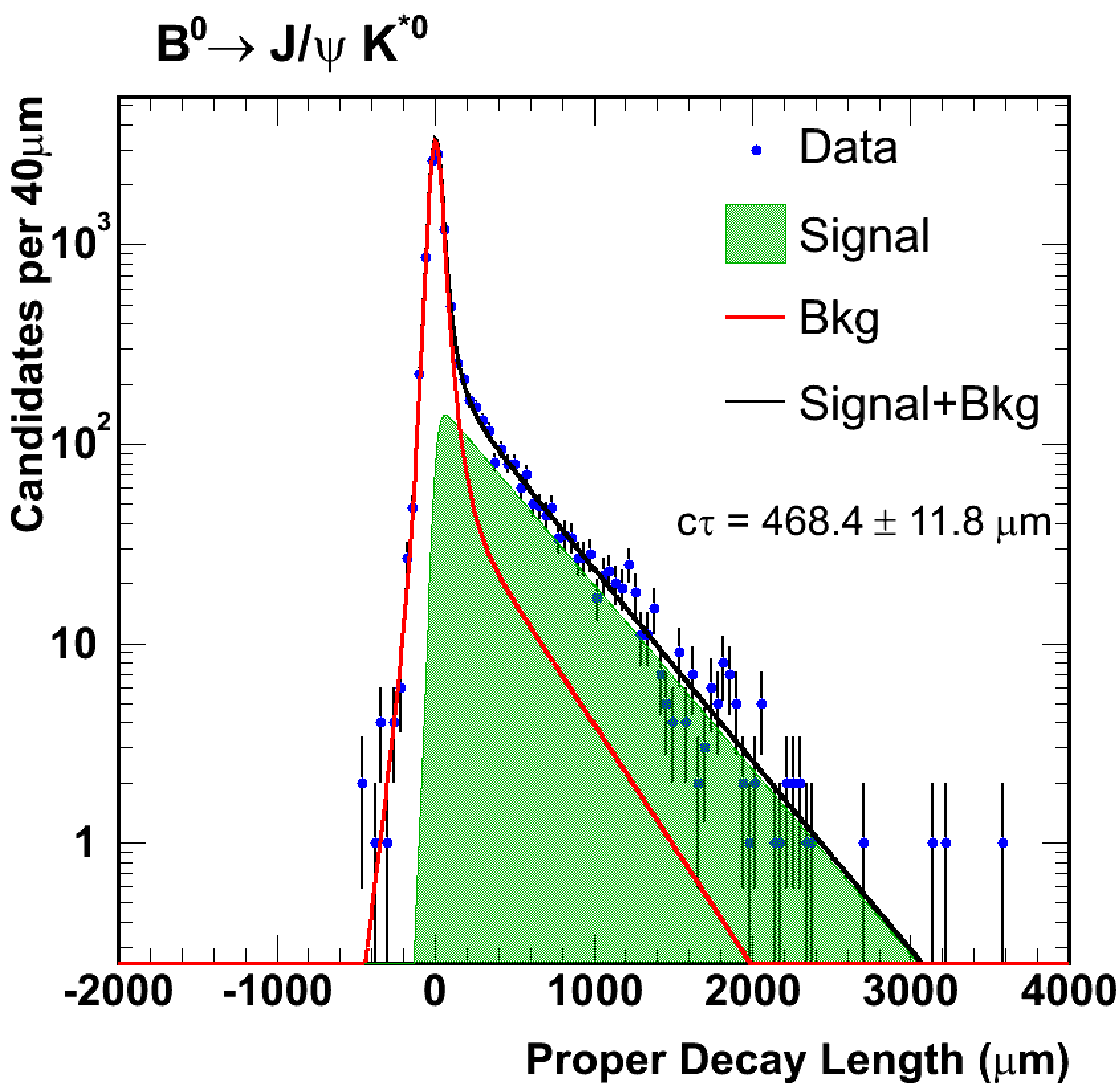
Very Similar

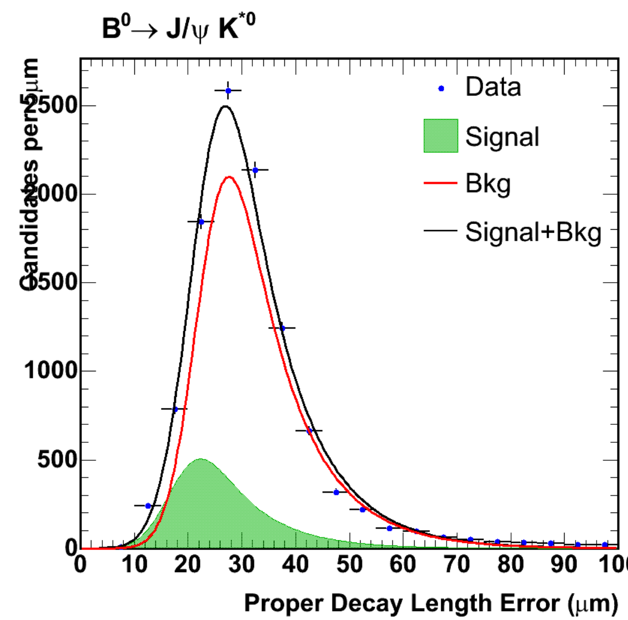
Λ_b PDL error

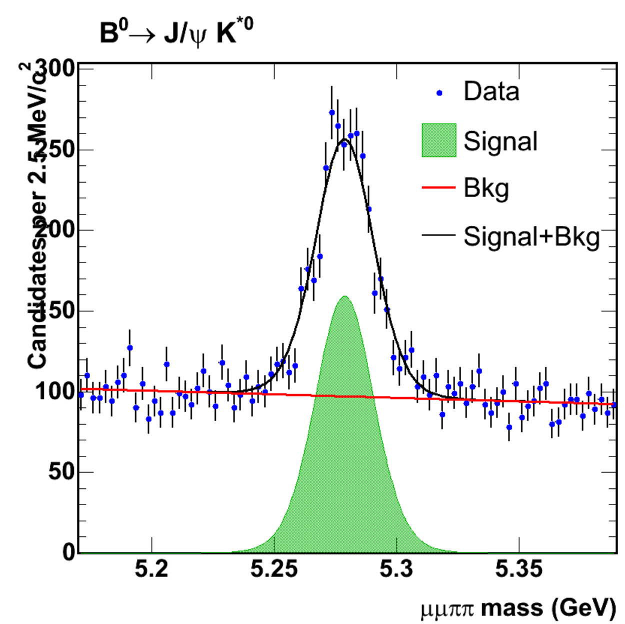


Different!

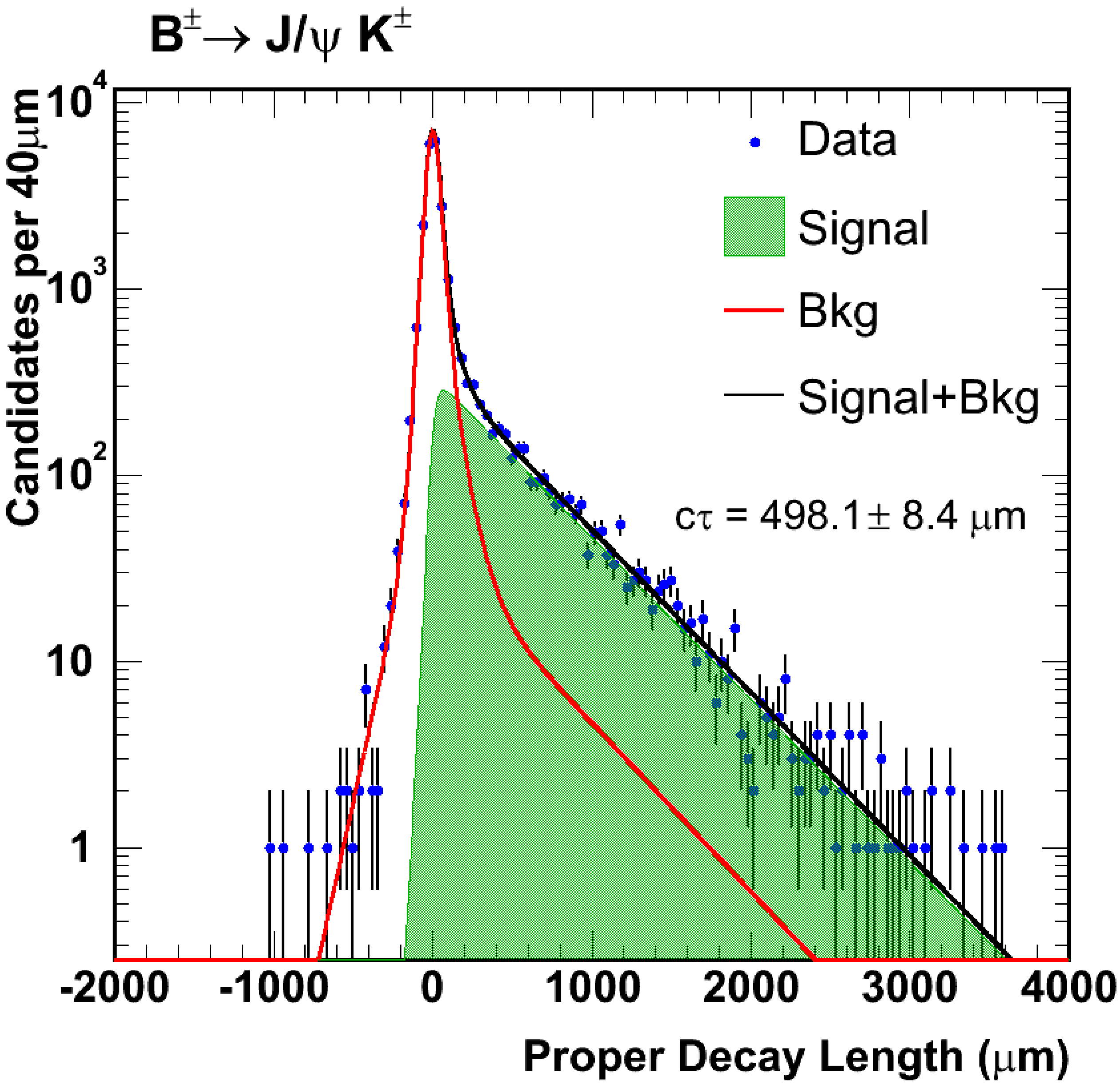
Fit Results: $B^0 \to J/\psi K^{*0}$

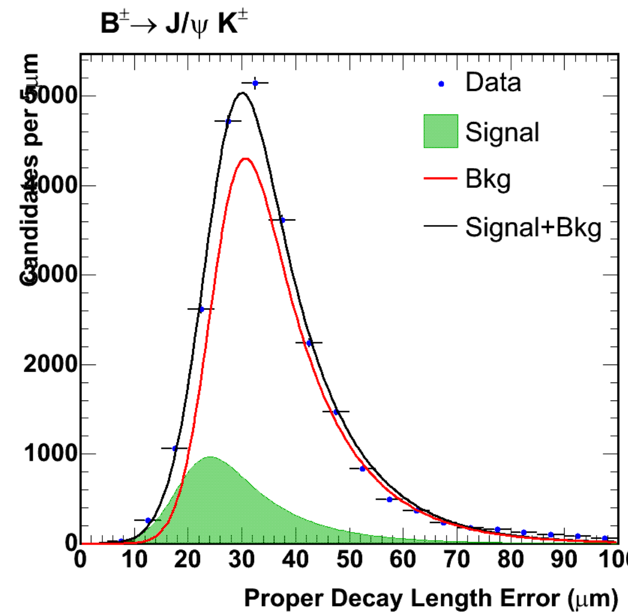


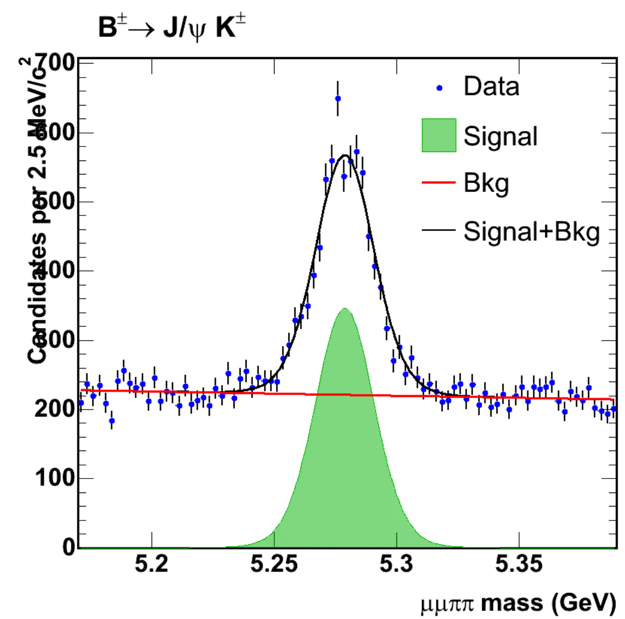




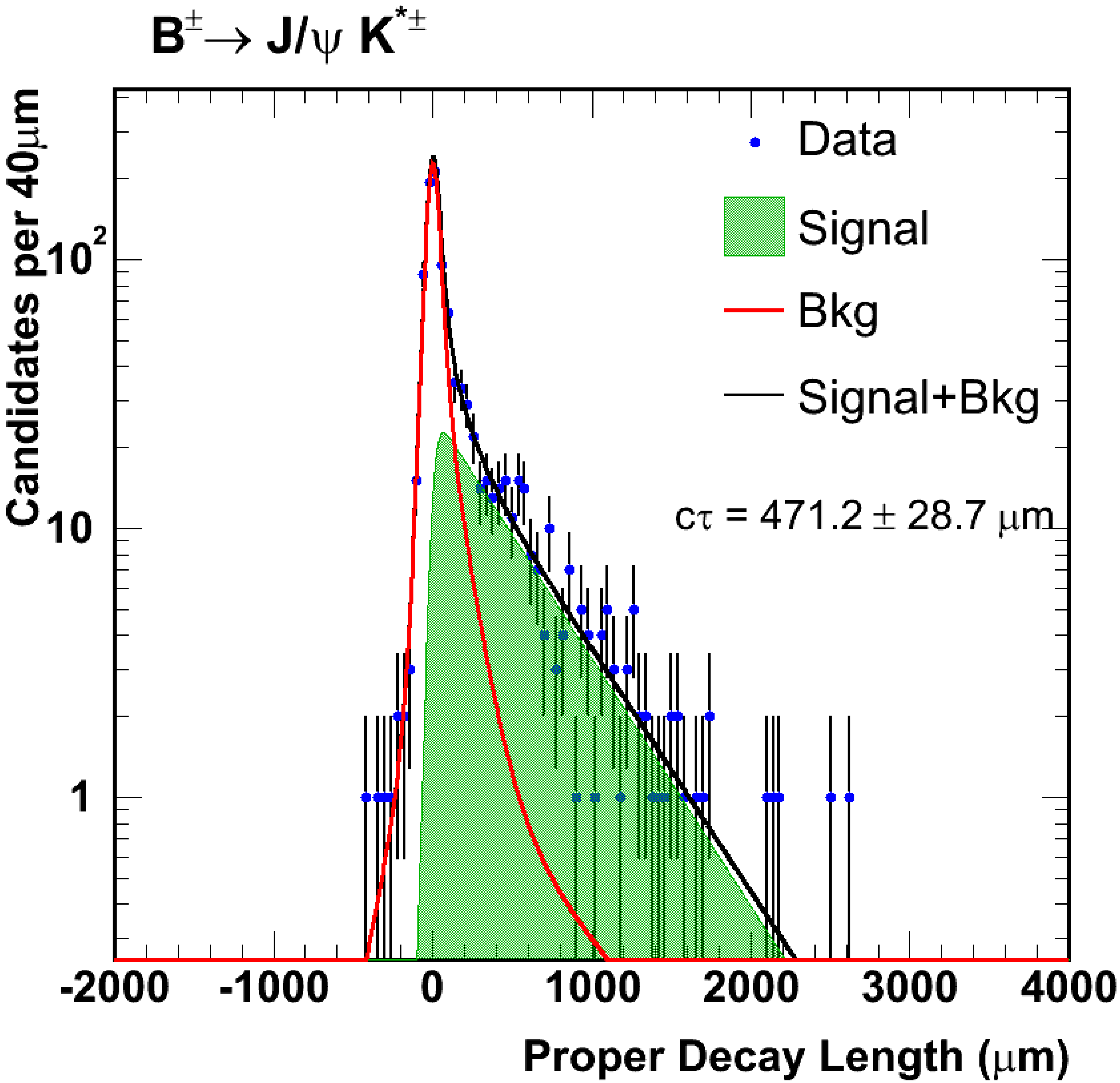
Fit Results: $B^+ \to J/\psi K^+$

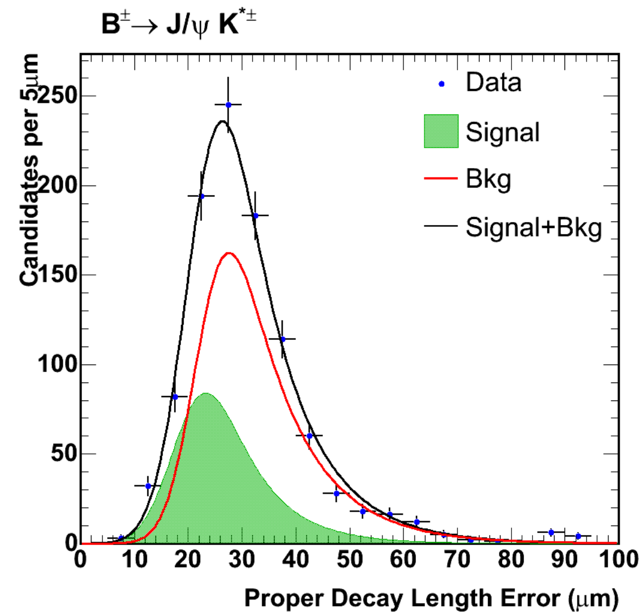


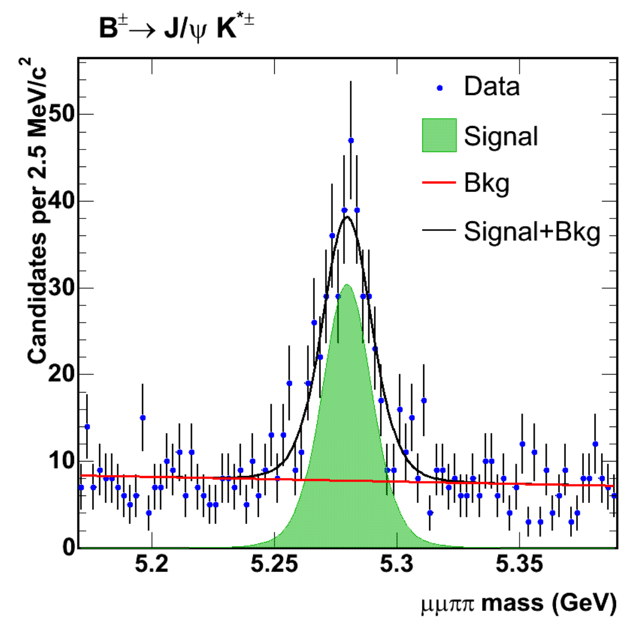




Fit Results: $B^+ \to J/\psi K^{*+}$

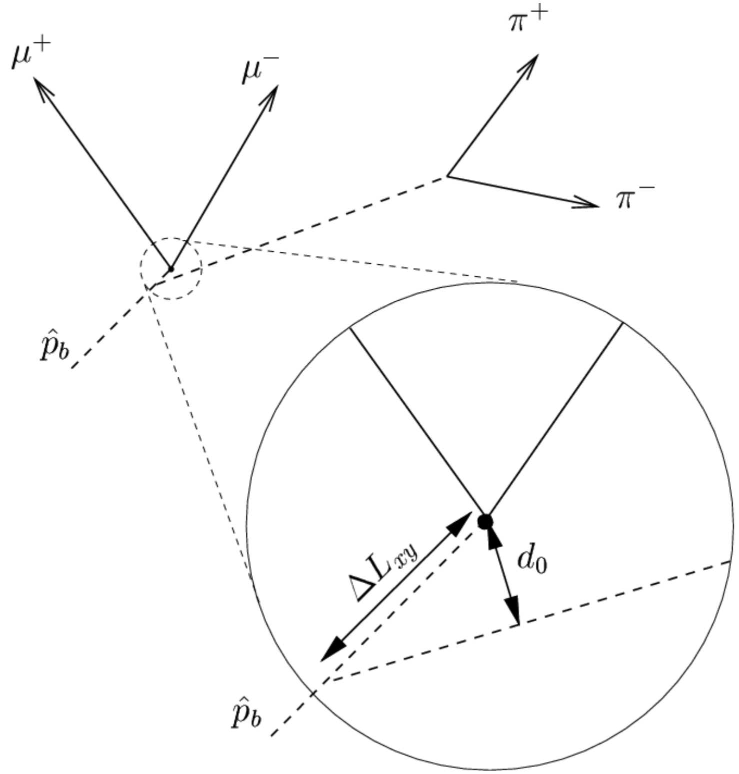


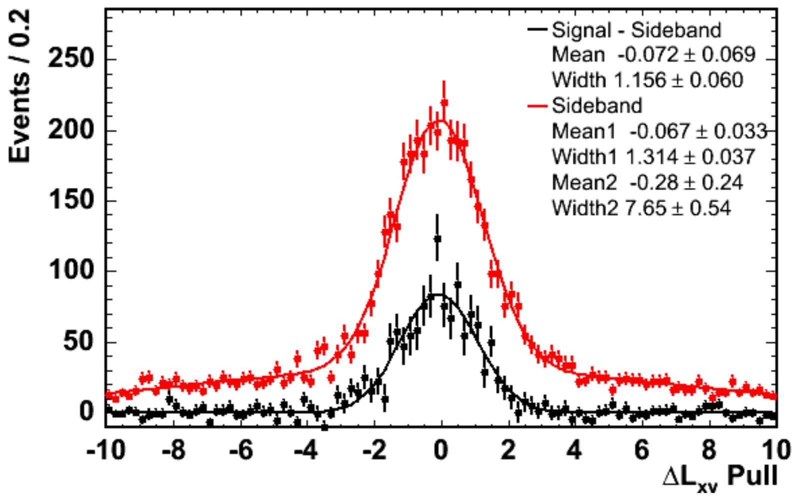




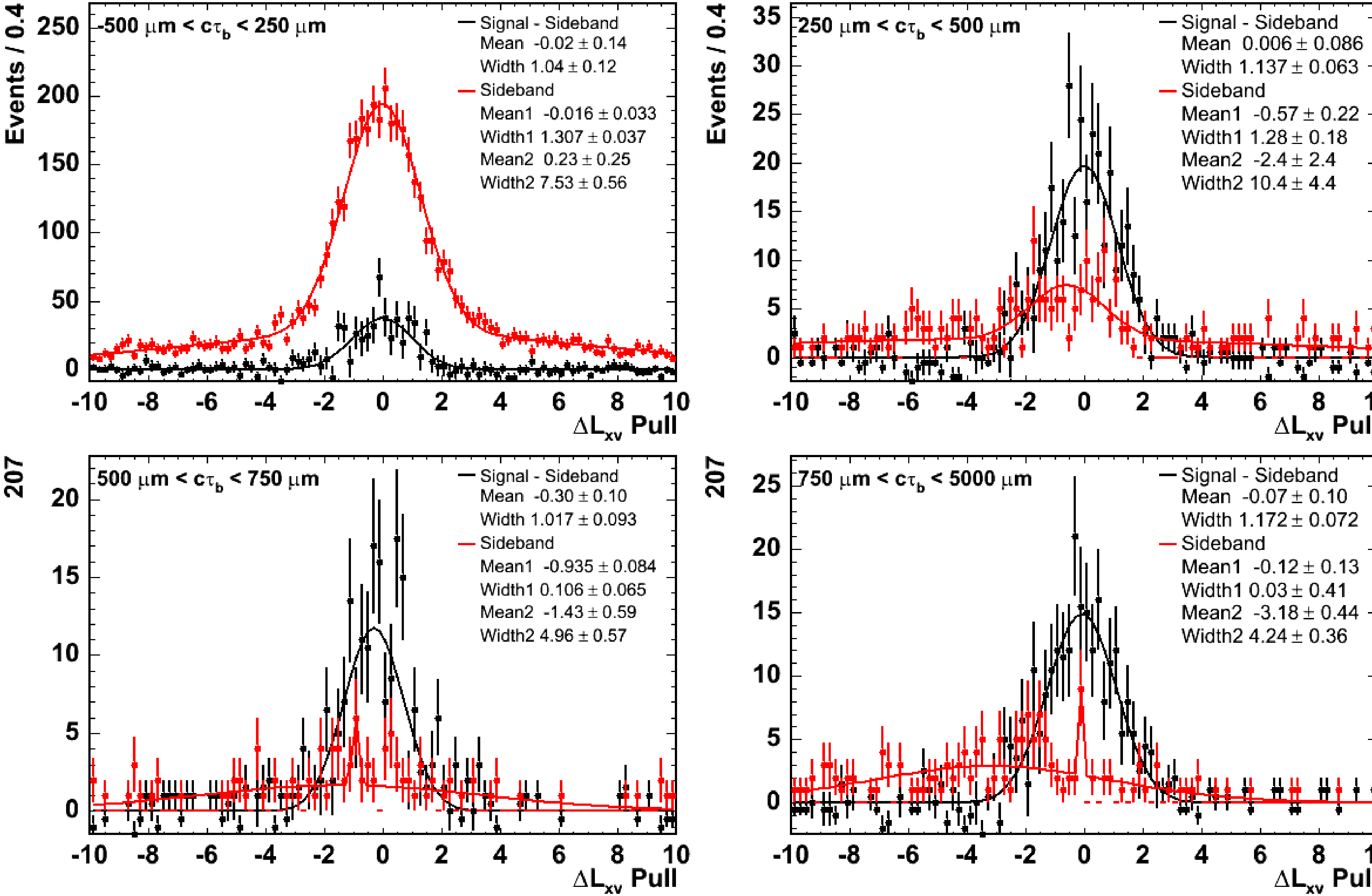
Systematics: V^0 Pointing

- Limit failure of V to point back to J/ψ vertex
- ΔL_{XY} variable (figure)
- Enters selection through the vertex constraint χ^2 cut
- Only causes bias if ΔL_{XY} or z_0 pulls are $c\tau$ dependent
- Pulls measured in data (K_S)
- Systematic constrained to be small, mostly because probability cut 10^{-4} is loose

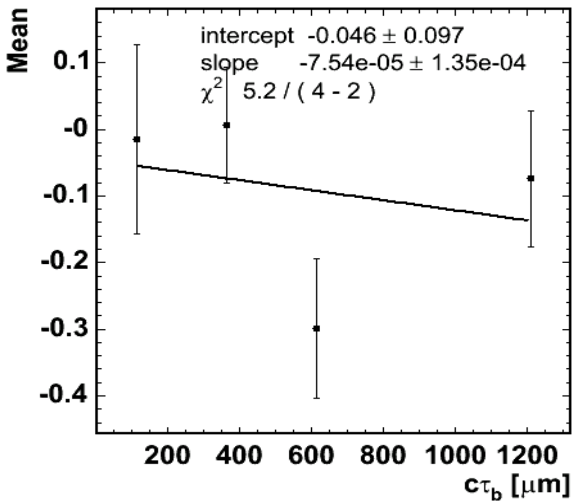


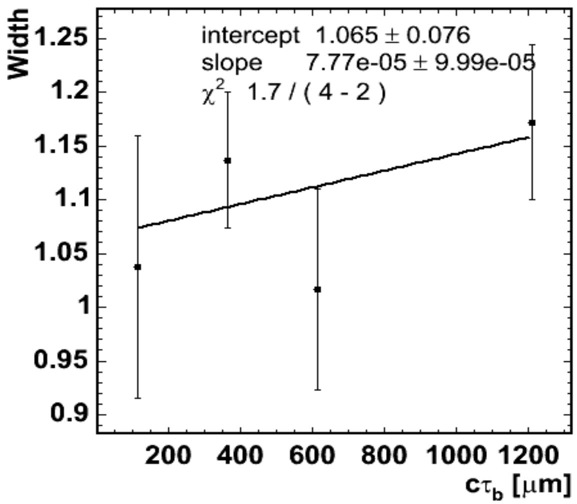


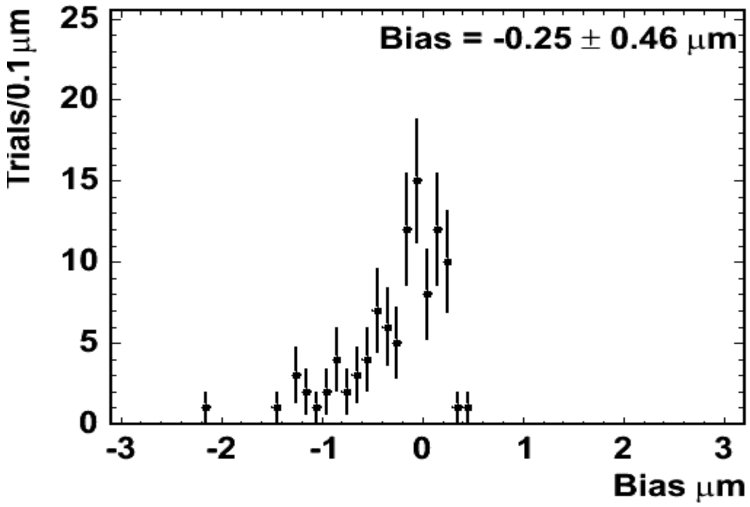
Systematics: V^0 Pointing



Systematics: V^0 Pointing

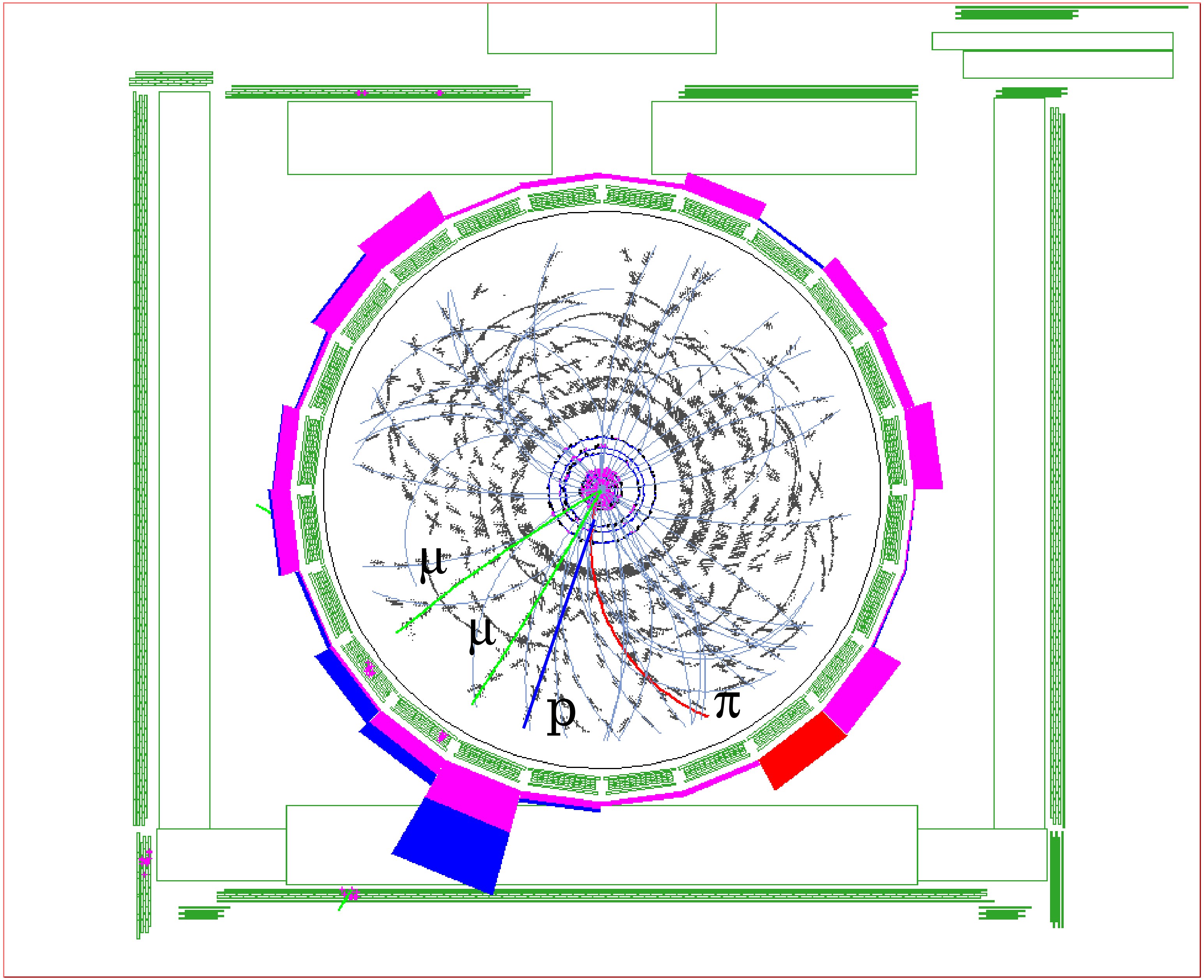




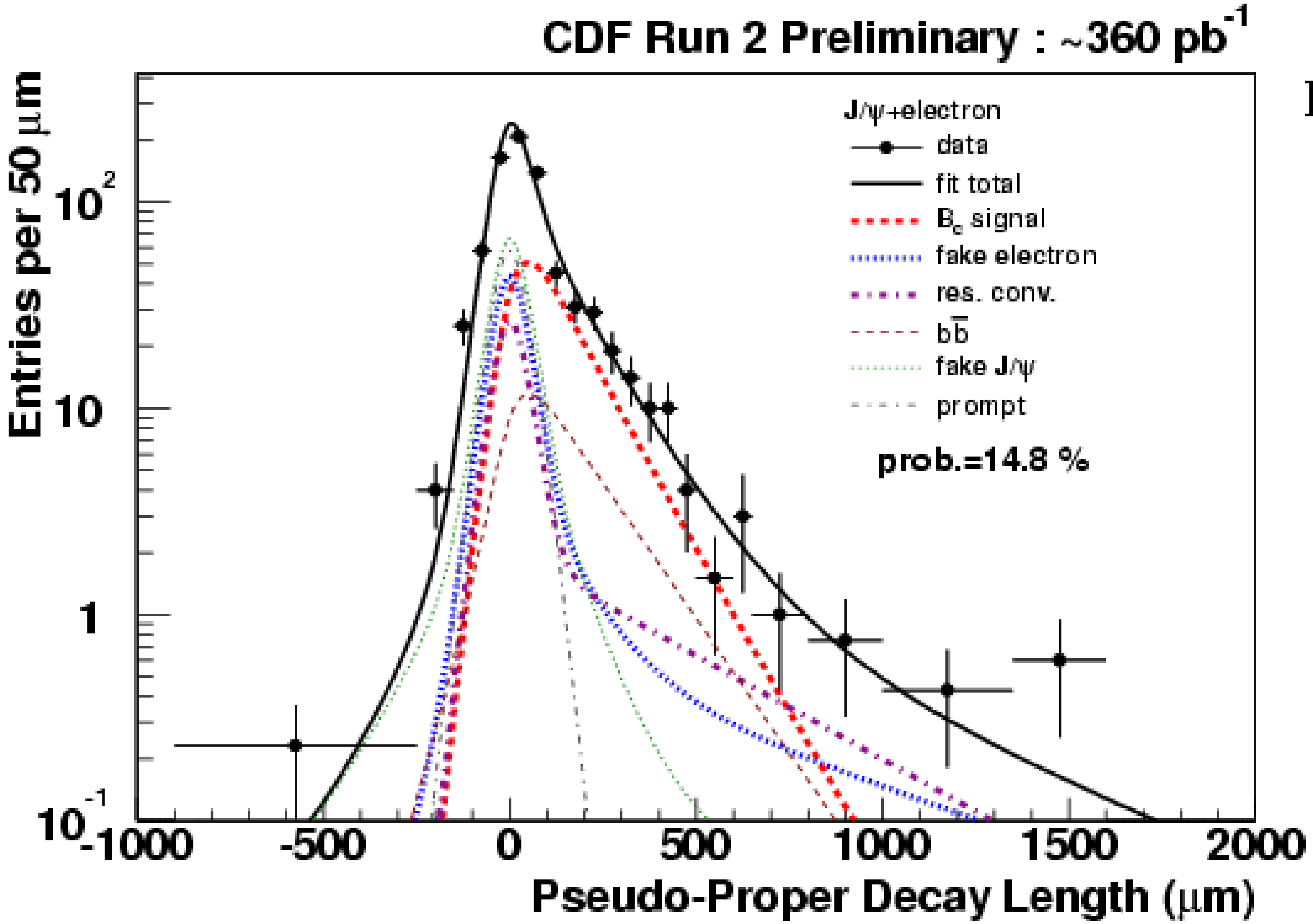


- Fit ΔL_{XY} and z_0 pulls in bins of $c\tau$
- Fit slopes of pull shapes $\sigma(c\tau)$ and $\mu(c\tau)$
- Toy MC integrate over 5-d χ^2 using $\sigma(c\tau)$ and $\mu(c\tau)$
- Calculate $c\tau$ bias of toy MC events
- Find mean+RMS of bias for slopes consistent w/ data

Λ_b Candidate Event Display



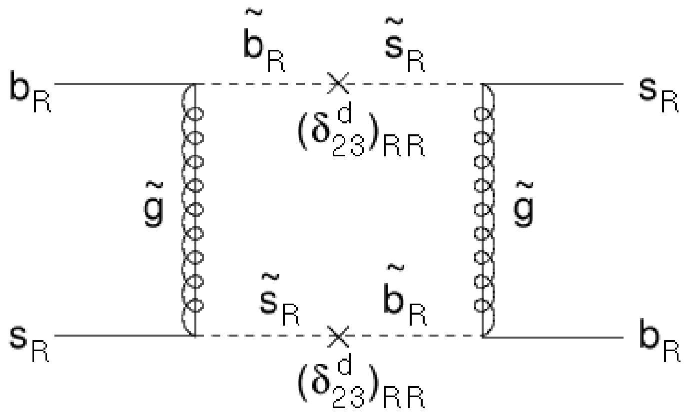
B_c Lifetime: Fit w/Backgrounds



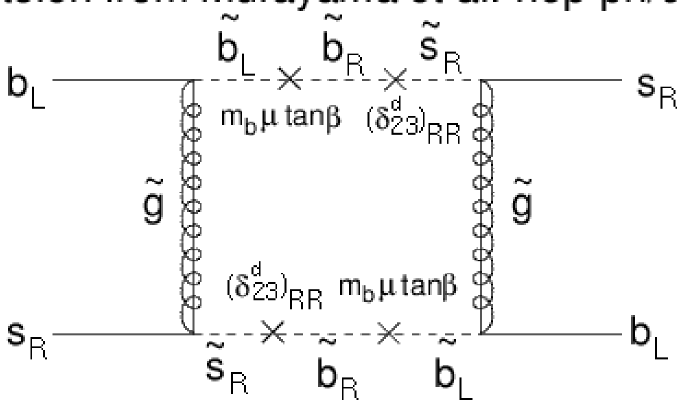
Backgrounds from:

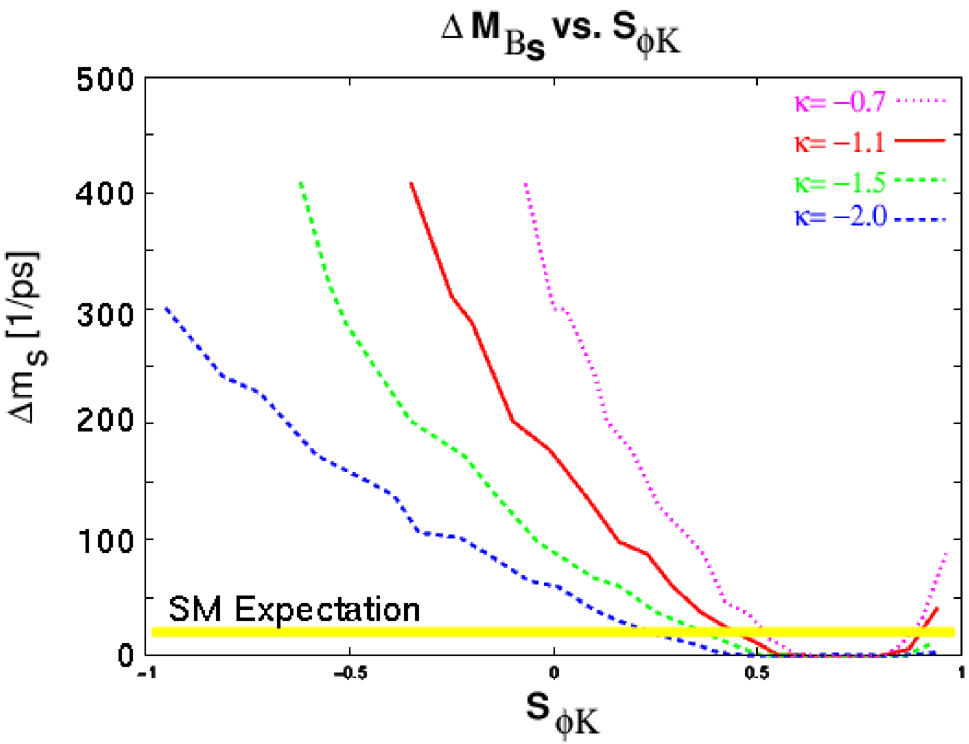
- electron fakes
- residual conversions
- bbar
- fake J/ψ
- prompt J/ψ + e

New Physics in Loops?



stolen from Murayama et al. hep-ph/0212180





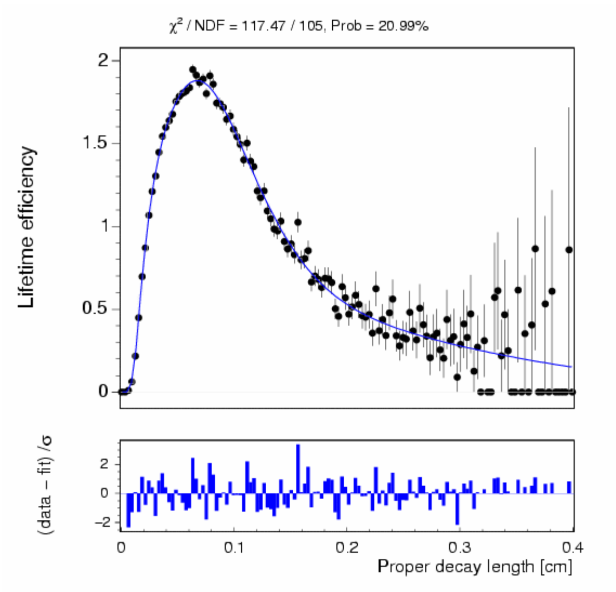
Supersymmetry model

+ gluino in loop
+ squarks in loop
+ describes all data
+ allows very high Δm_s
+ Δm_s excludes models

→ Δm_s sensitive to New Physics

B_s Mixing: Lifetime Measurement

trigger efficiency (ε)



Bias is ct due to trigger cuts
(in hadronic & semileptonic decays:

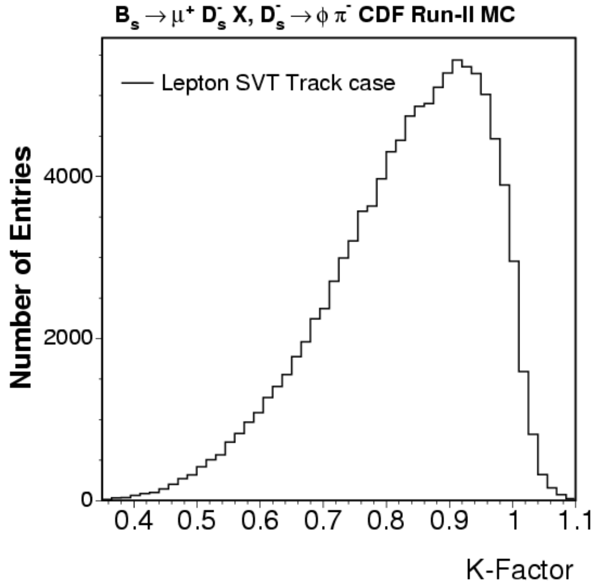
- 2 displaced trigger tracks
- turn-on: $d_0 \geq 120\ \mu m$
- turn-off: $d_0 \leq 1$ mm
- selection increases bias

Adjust probability density:

$$\rho(t) = N(e^{t/\tau} \times G(\sigma_{ct}))\epsilon(t)$$

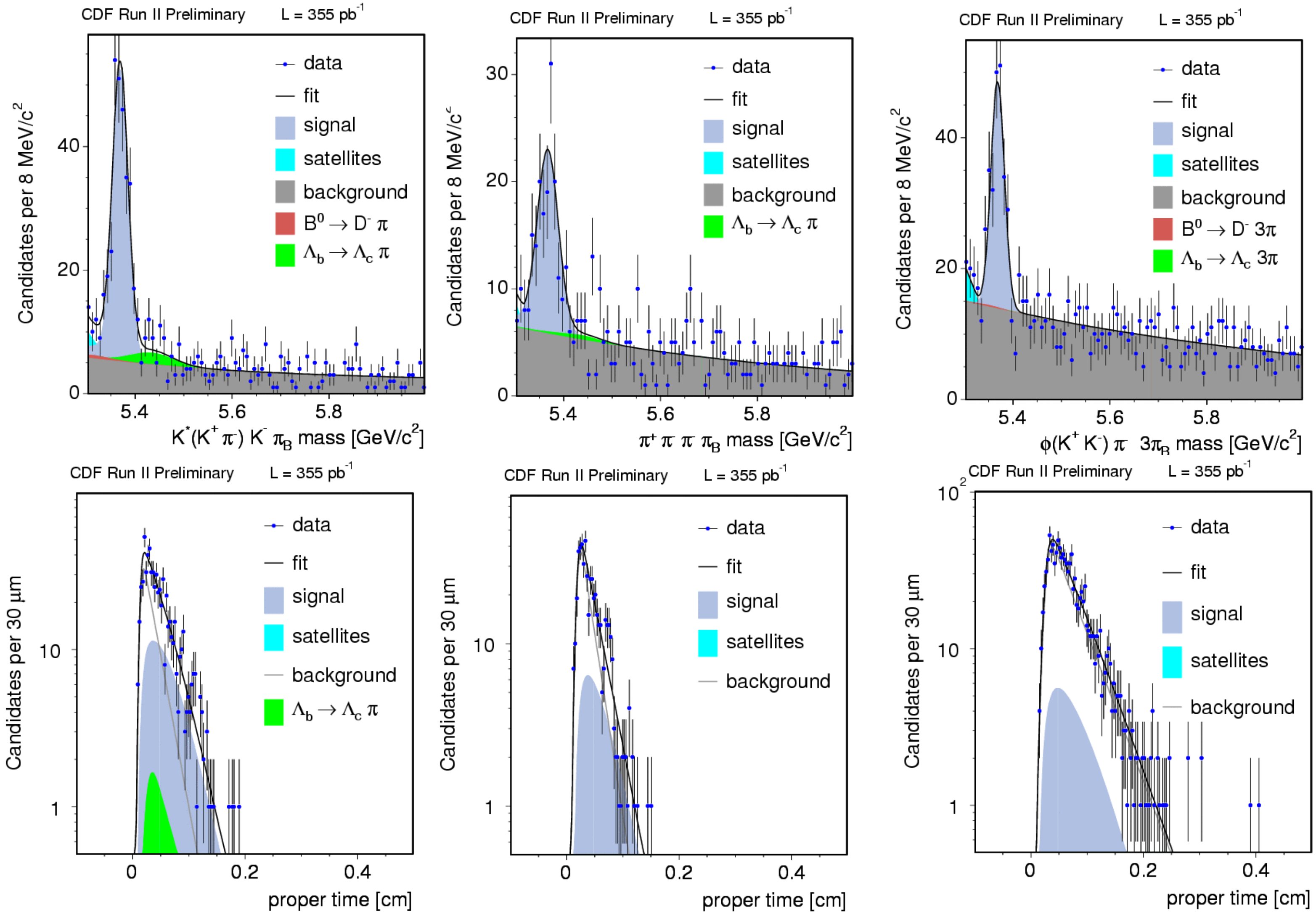
The bias cancels for B_s mixing!

For semileptonic decays, correct for missing momentum



B_s Lifetime: Hadronic

Lifetime fit within narrow mass range (reject background)



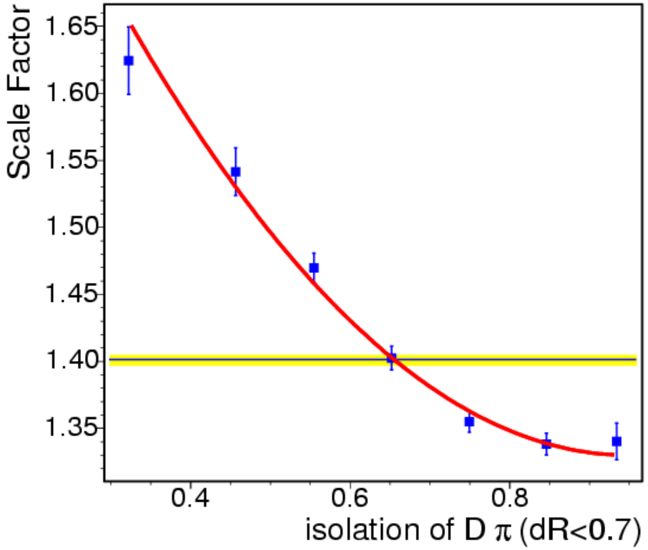
Combined $\tau(B_s)$ consistent w/ PDG (statistical errors only, work in progress)

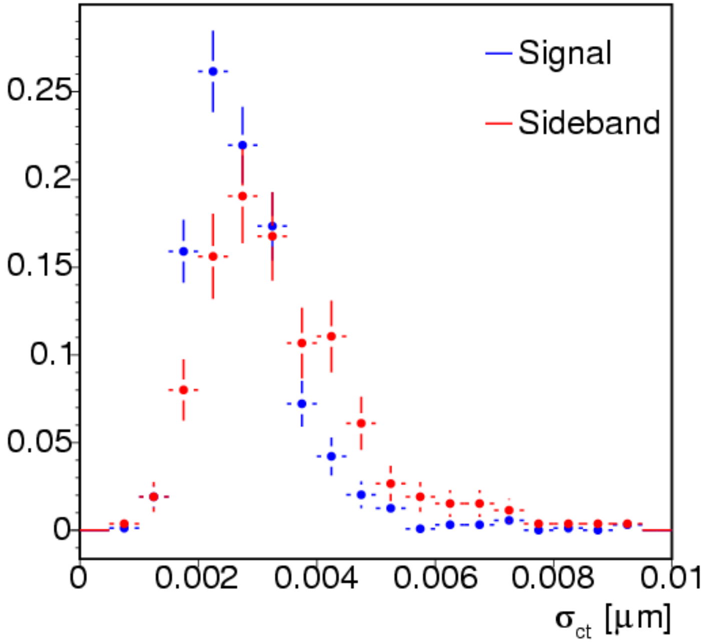
B_s Mixing: PDL Resolution

Mixing sensitivity: $$S = \sqrt{\frac{N_S \epsilon D^2}{2}} \exp\left(-\frac{(\Delta m_s \sigma_{ct})^2}{2}\right) \sqrt{\frac{N_S}{N_S + N_B}}$$

PDL resolution limiting factor at high Δm_s

σ_{ct} determined from high statistics calibration data sample





Mode	$< \sigma(ct) >$ [μm]
$B_s \to D_s(3)\pi$	30
$B_s \to \ell D_s X$	50*

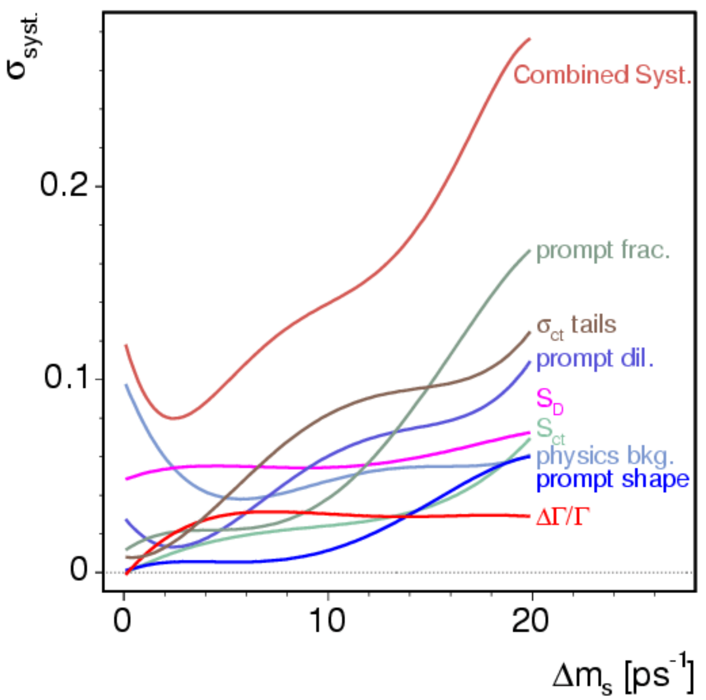
* not include <k-factor> = 0.85

Study dependence on several variables: isolation, vertex fit χ^2, ...

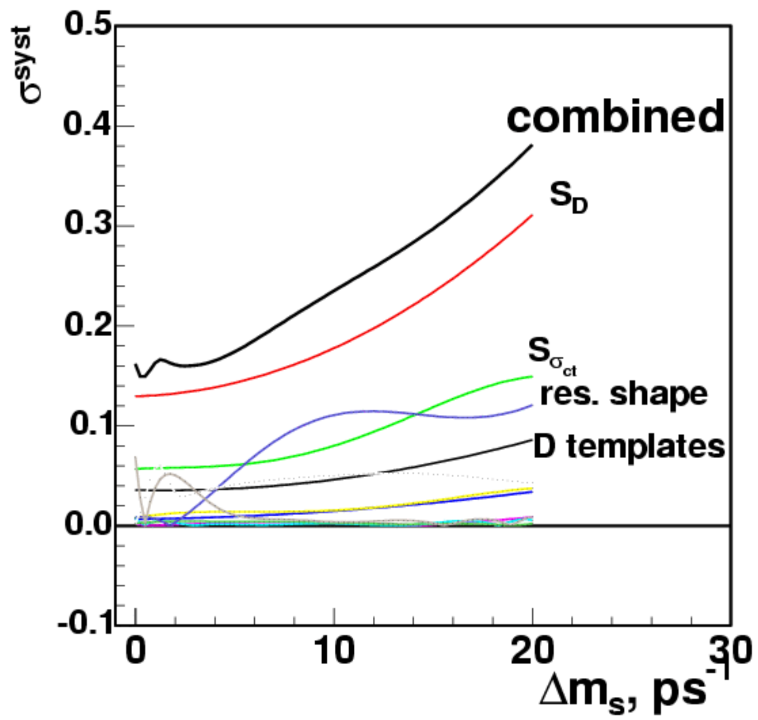
B_s Mixing: Systematics

- A and σ_A are correlated systematics need to be evaluated with many toy MC experiments for each Δm_s value

Semileptonic Modes

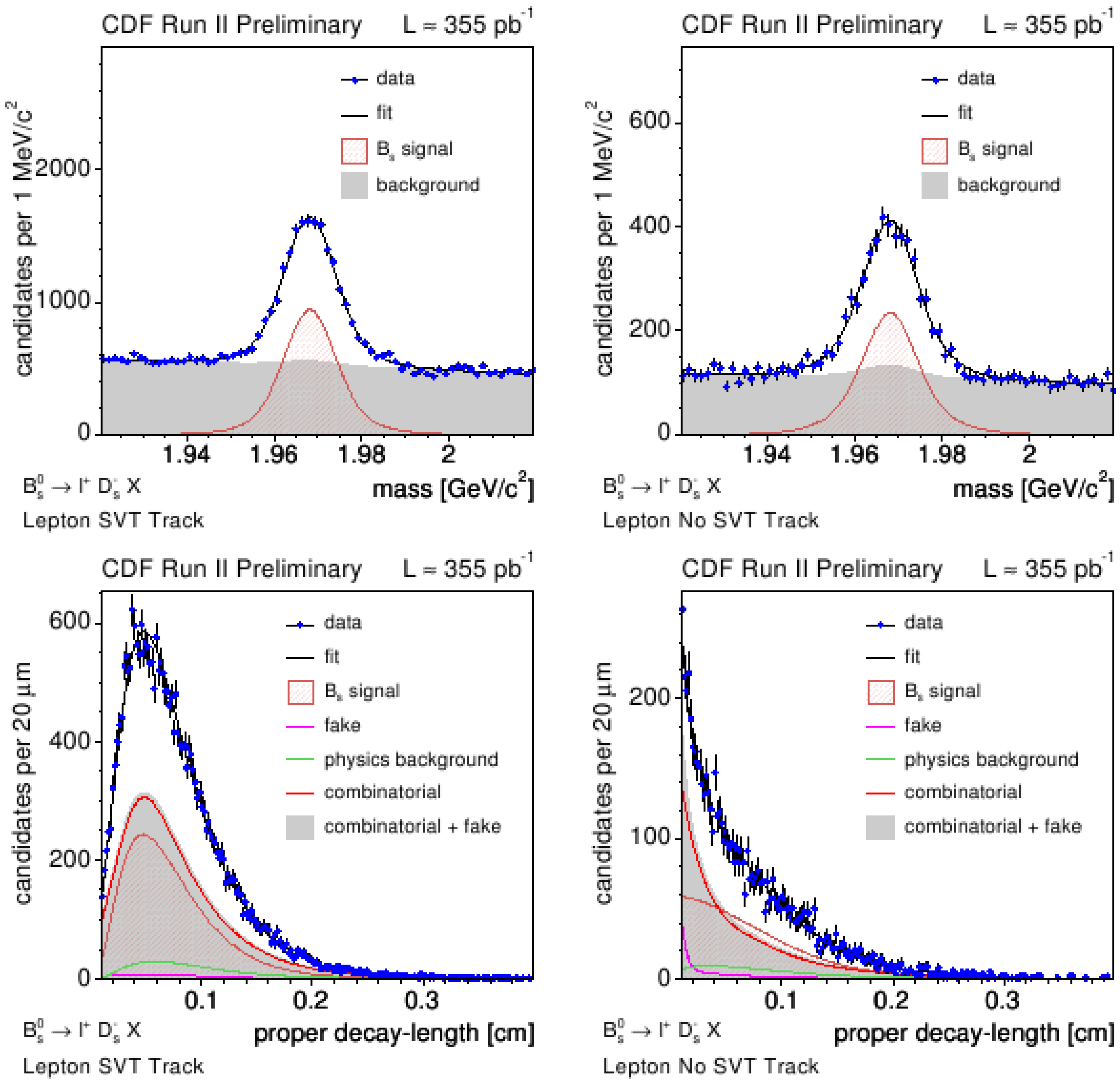


Hadronic Modes



- Measurements dominated by statistics
- With increase in statistics, leading systematics will go down

Semileptonic Decay $\ell D_s X$



17,084 signal events

lepton in trigger

lepton not in trigger

B^0 Mixing: Exclusive Decays

Tagger performance

$\varepsilon D^2 = 1.55 \pm 0.16 \pm 0.05\%$

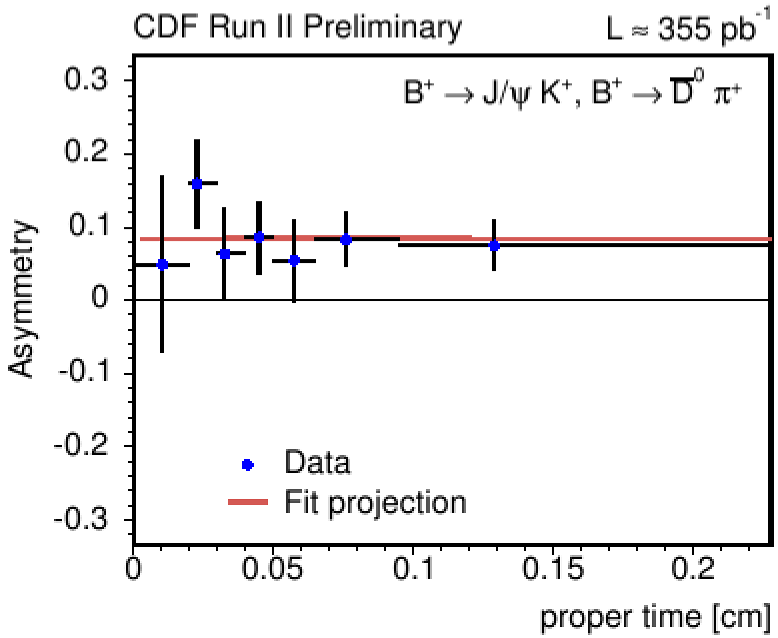
Result Δm_d (blessed)

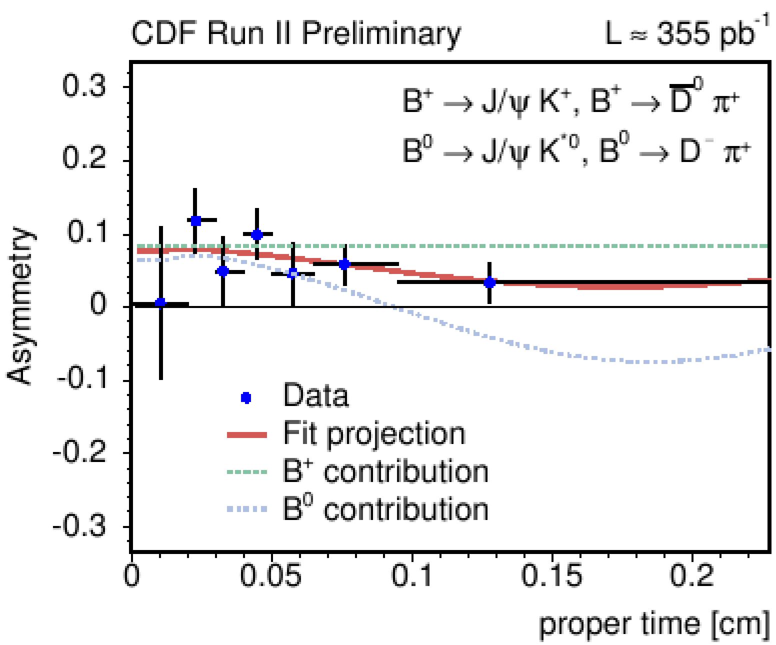
$0.536 \pm 0.028_{\text{(stat)}} \pm 0.006_{\text{(sys)}}\ \text{ps}^{-1}$

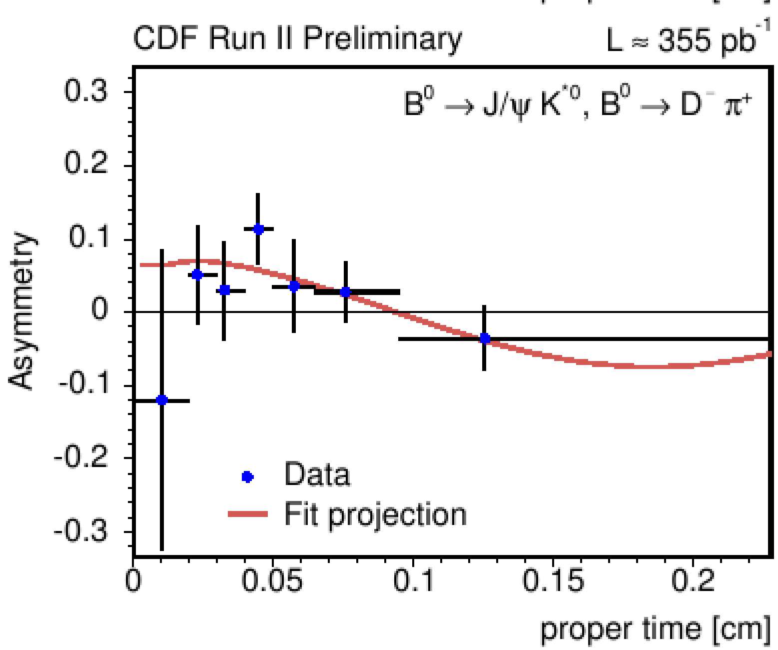
$0.505 \pm 0.005\ \text{ps}^{-1}$ (PDG 2005)

About results

- see clear signal
- only opposite side tags



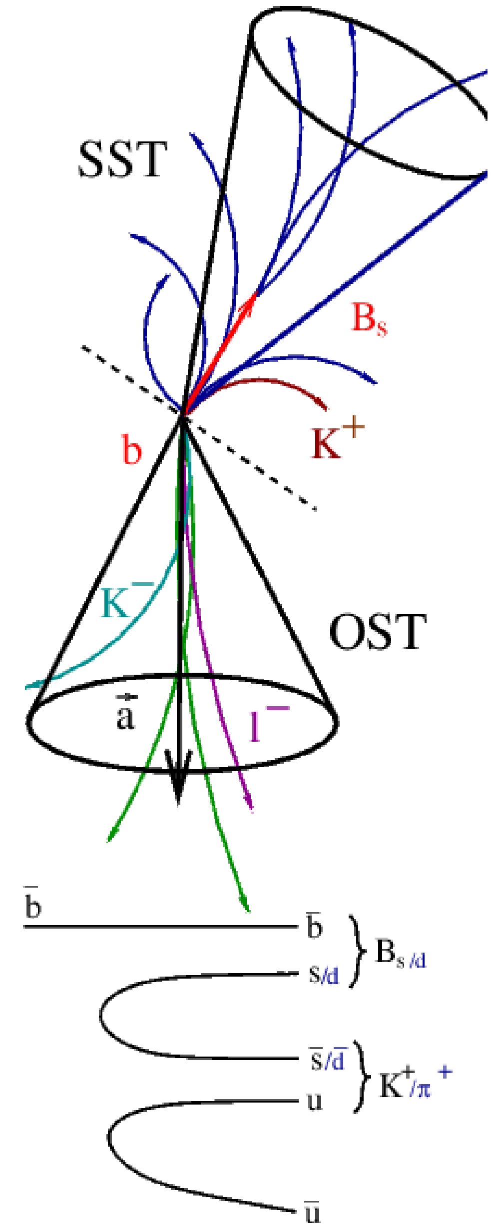




B Flavor Tagging

Opposite Side Tagging:

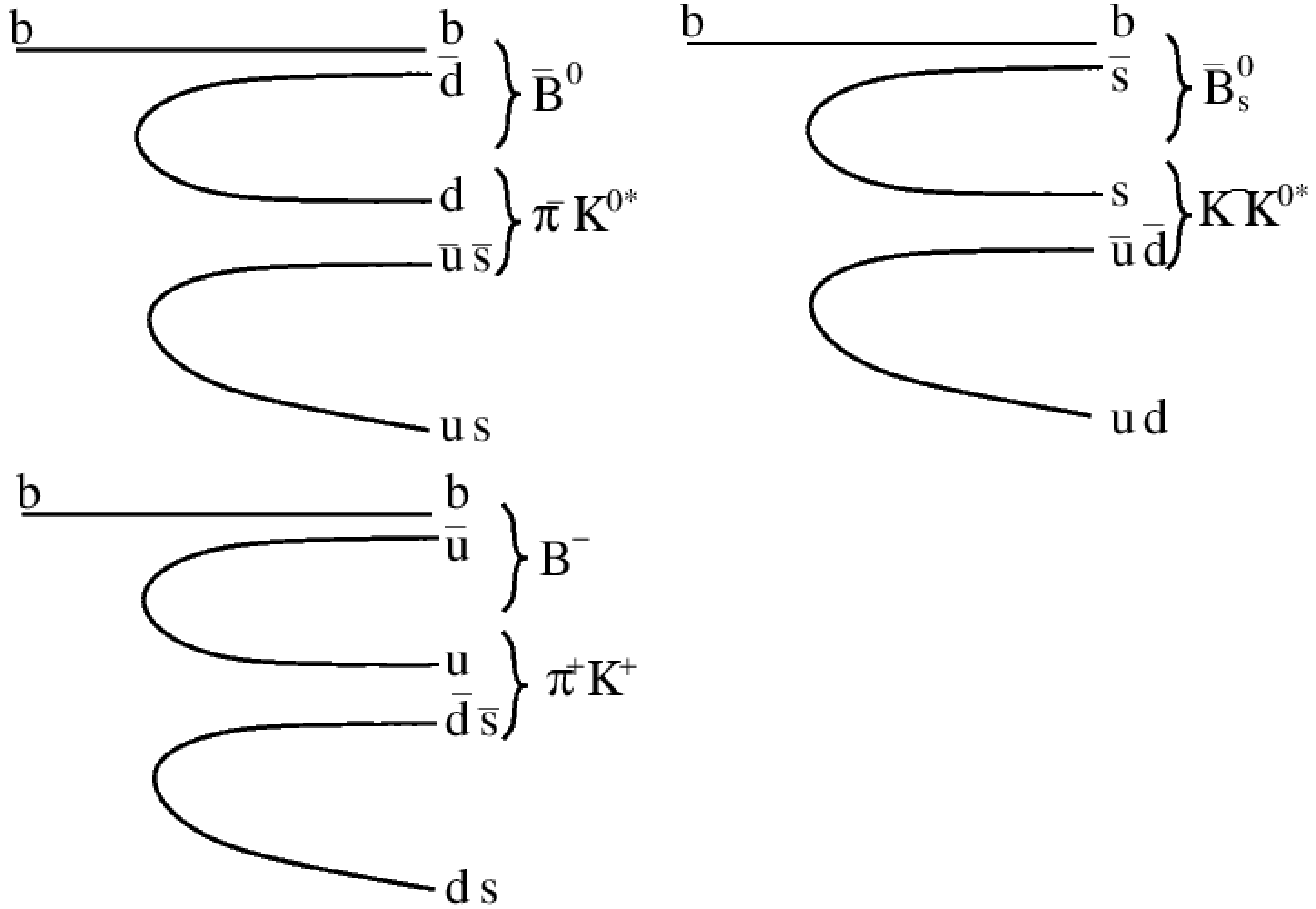
- Jet-Charge-Tagging:
  sign of the weighted average charge of opposite B-Jet
  high efficiency & low dilution
- Soft-Lepton-Tagging:
  identify soft lepton (e, μ) from semileptonic decay of opposite B: $b \rightarrow l^- X$ (BR $\approx 20\%$),
  low efficiency but high dilution
- Kaon-Tagging:
  due to b→c→s it is more likely that a $\bar{B}$ meson contains a K^- than a K^+ in the final state
  (not implemented at CDF)



Same Side Tagging:

- $B_{s/d}$ is likely to be accompanied close by a K^+/π^+
  (ongoing effort but not used in current analysis)

Same Side Tagging



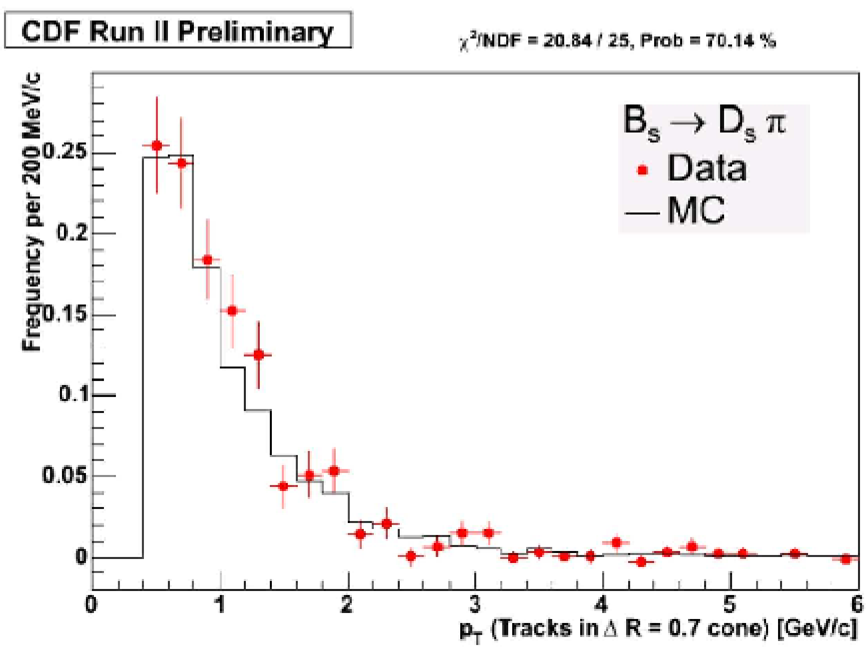
some of the possible species of particles produced in the fragmentation of a b quark to a B meson.

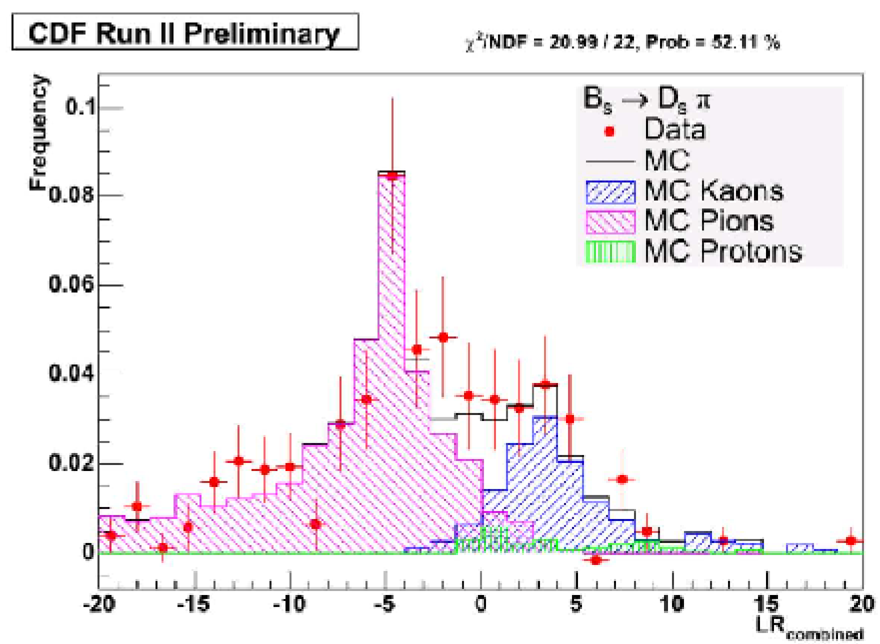
SSKT: Work in Progress

- There is no straight forward way to measure the tagger dilution on data unless we observe mixing
- But we have to know the dilution to set a limit

Have to rely on SSKT Monte Carlo predictions

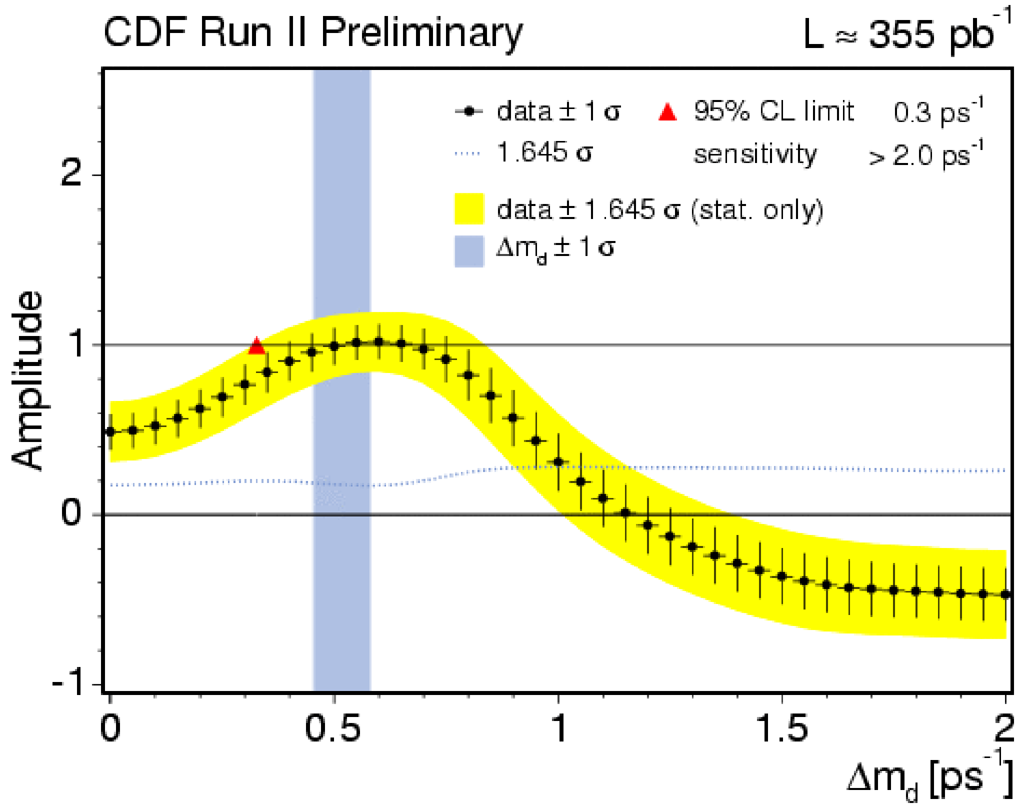
Tuning is in progress!





Amplitude Scan Method

B^0 example scan
Winter 2005 analysis



- Introduce amplitude A into the unbinned ML fit:

$$\mathcal{L} \sim \frac{1 \pm A \cdot D \cdot \cos(\Delta m_s t)}{2}$$

- Fit A for each Δm_s hypothesis
- Record A and σ_A at each Δm_s
- Signal ⇔ unit amplitude, else A consistent with 0

- Sensitivity is smallest Δm_s for which $A + 1.645\ \sigma_A = 1$
- Exclude Δm_s @ 95% C.L. for $A + 1.645\ \sigma_A < 1$