Λ_b Lifetime in Fully Reconstructed Decay at CDF

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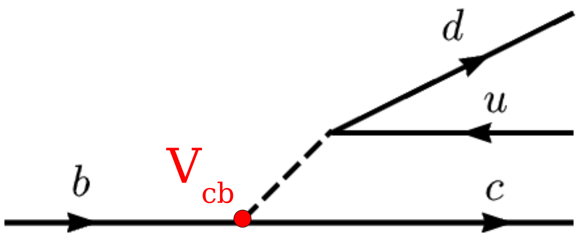
Lifetimes: Why Do We Care?

- The total width (Γ) of a particle, inversely related to the lifetime (τ), characterizes underlying dynamics govering its decay

  → strong, electromagnetic, weak interactions

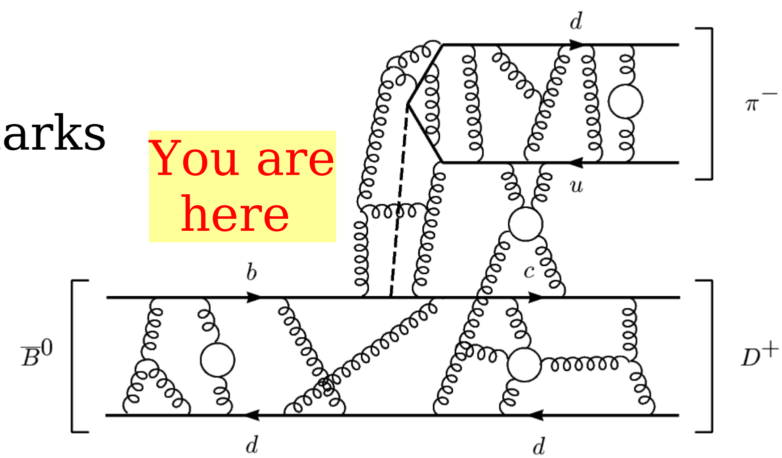


- Weak decay of hadrons depends upon fundamental parameters of the Standard Model we'd like to know

  → CKM matrix elements, quark masses

- Our world is one of quarks (and gluons) confined inside hadrons rather than weakly-decaying free quarks

  → Complicates theory interpretation of observations



- Lifetimes of weakly decaying hadrons of the same heavy flavor provide a quantitative connection between these two worlds

  → study of the interplay between the strong and weak interactions

  → important testbed for understanding of non-perturbative effects in QCD

$\tau(D^+)/\tau(D^0) \approx 2.5 \quad \tau(B^+)/\tau(B^0) \approx 1$

increasing m_Q → ∞ (spectator ansatz)

Lifetimes of *b*-Flavored Hadrons

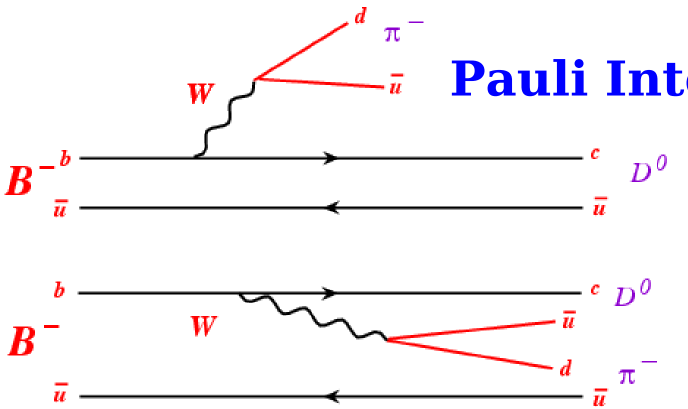
Critical testbed for theoretical framework used to predict heavy quark quantities:

- Qualitatively expect: $\tau(B_c) \ll \tau(\Lambda_b) < \tau(B_s) \approx \tau(B^0) < \tau(B^+)$
  but one can do better than this…!
- *b*-hadron lifetime ratios can be calculated with reasonable precision:

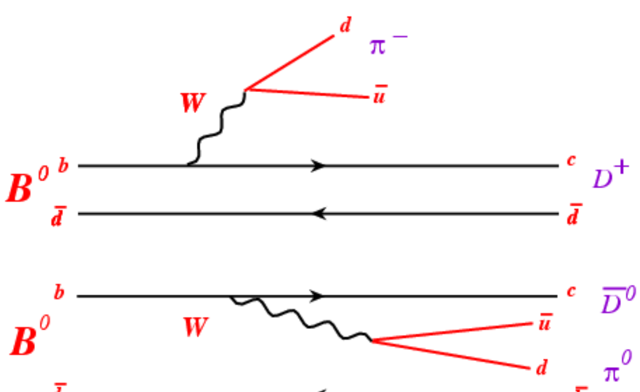
2% for $\tau(B^+)/\tau(B^0)$, 1% for $\tau(B_s)/\tau(B^0)$, 6% for $\tau(\Lambda_b)/\tau(B^0)$

using Heavy Quark Expansion (HQE) since $m_b \gg \Lambda_{QCD}$ → large energy release in decay

Pauli Interference

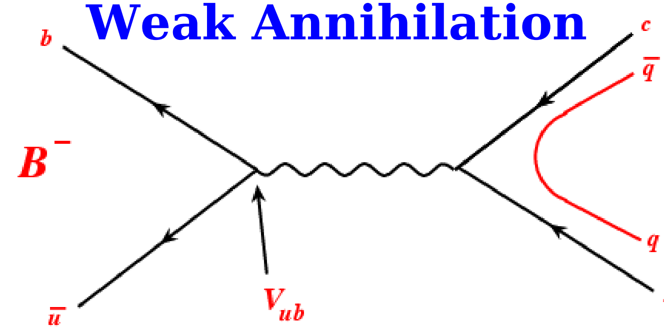


Same final state
⇒ interference
(destructive)



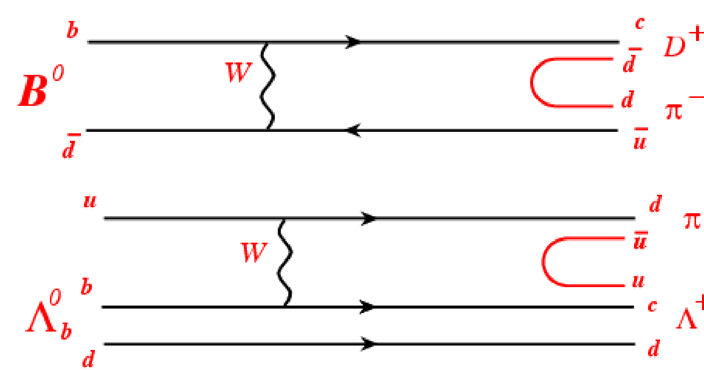
Different final states
⇒ no interference

Weak Annihilation



Only charged B mesons

Weak Scattering/Exchange

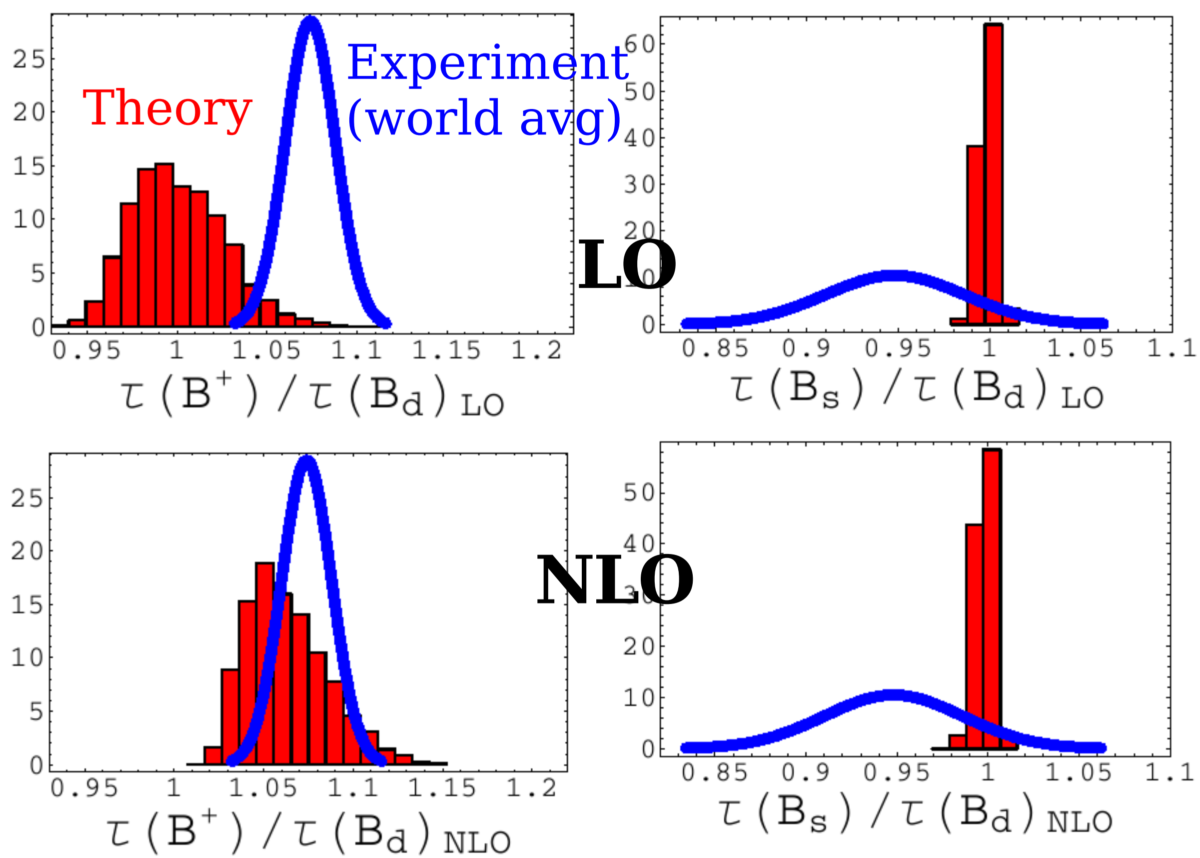


Helicity suppressed in mesons, not baryons

Heavy Quark Expansion

Inclusive decay width expressed as an operator product expansion (OPE) in Λ_{QCD}/m_b and $\alpha_s(m_b)$

$$\Gamma = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3 (2M_B)} \left[c^{(3)} \langle \bar{b} b \rangle + c^{(5)} \frac{g_s}{m_b^2} \langle \bar{b} \sigma_{\mu\nu} G^{\mu\nu} b \rangle + \frac{96\pi^2}{m_b^3} \sum_k c_k^{(6)} \langle O_k^{(6)} \rangle \right] + O(1/m_b^4)$$



Tarantino, et al.
hep-ph/0203089

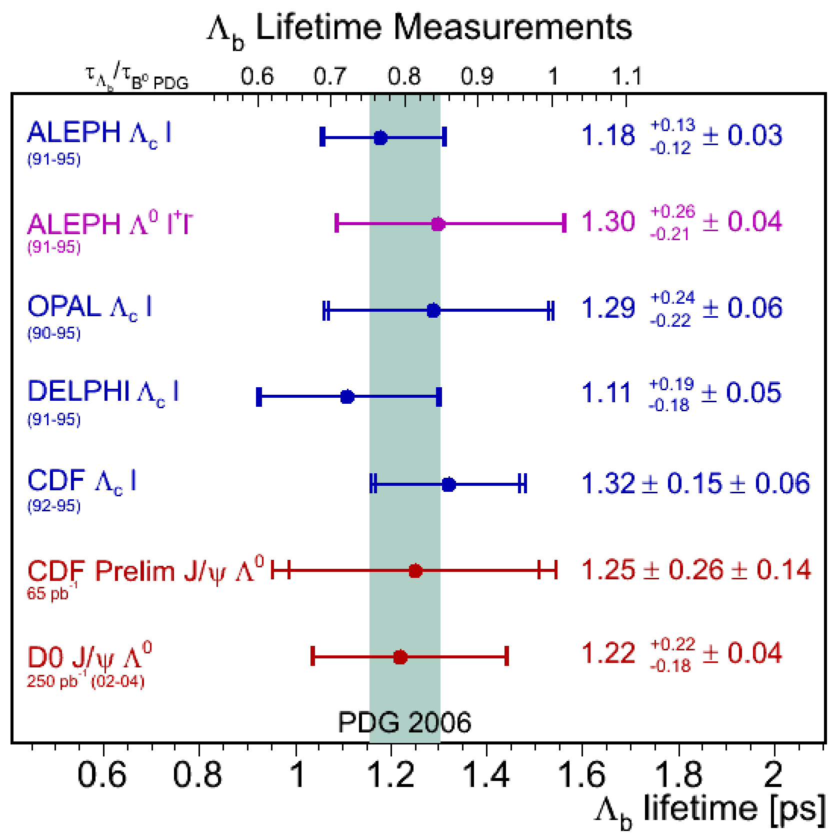
- $c_i^{(n)}$ contain short-distance physics from scales $\geq \mu = O(m_b)$
  $\rightarrow$ perturbatively calculable
- Matrix elements contain long-distance physics
  $\rightarrow$ hard! especially for baryons
- Spectator contributions enter at $1/m_b^3$ (~5-10%)

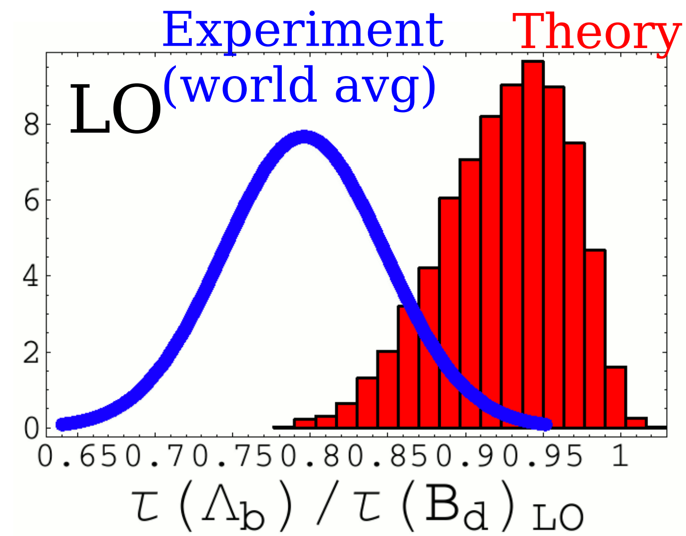
NLO QCD and sub-leading spectator corrections can be important!
For $\tau(\Lambda_b)/\tau(B^0)$:
- NLO QCD: -8%
  (hep-ph/0203089)
- Sub-leading spectator: -(2-3)%
  (hep-ph/0407004)

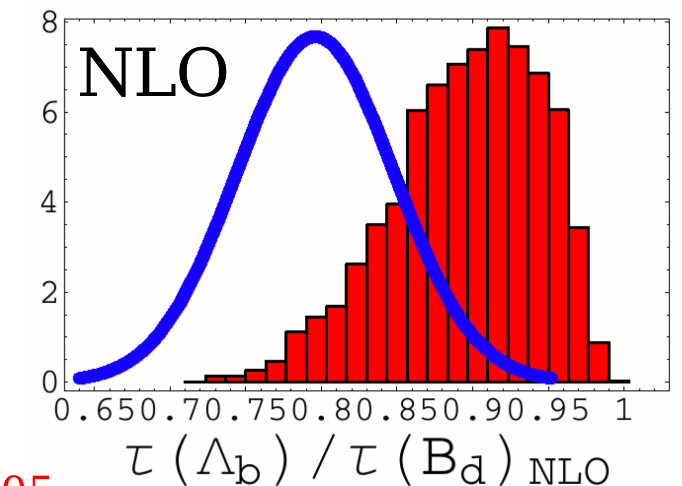
Λ_b Lifetime: Before Us

Semi-leptonic modes (dominant)

Fully -reconstructed modes







Tarantino, et al.
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For $\tau(\Lambda_b)/\tau(B^0)$, early theory predictions (~0.94) and experiment differed by more than $2\sigma \rightarrow$ "Λ_b lifetime puzzle"

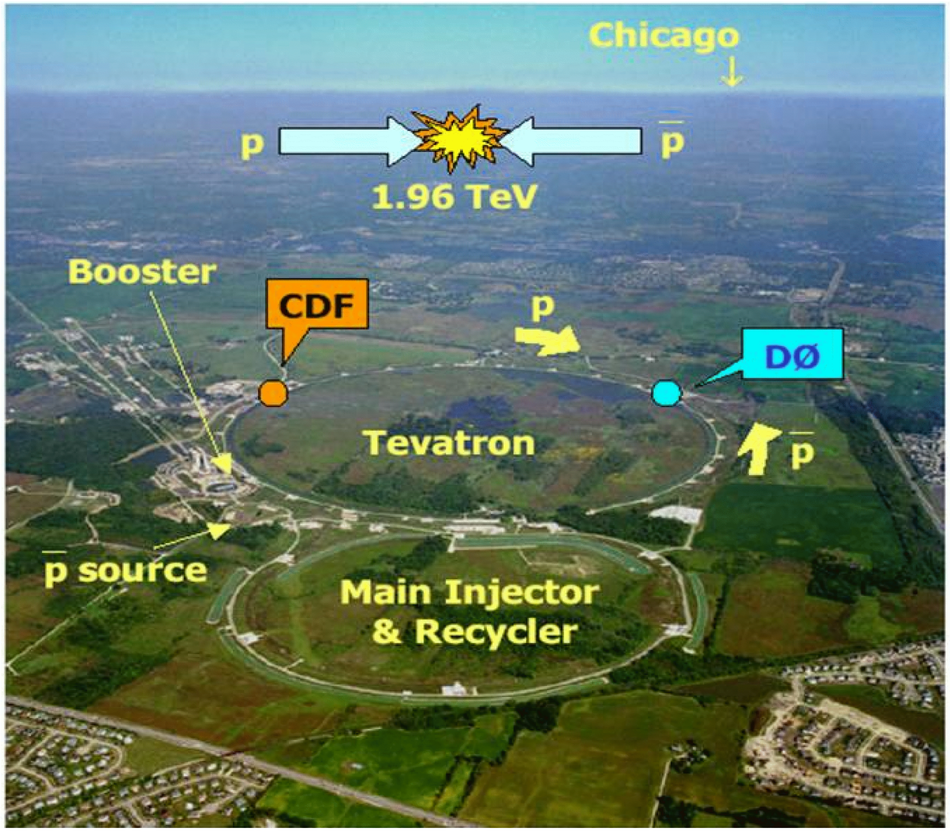
Current NLO QCD + $1/m_b^4$ calculation: $\tau(\Lambda_b) / \tau(B^0) = 0.86 \pm 0.05$

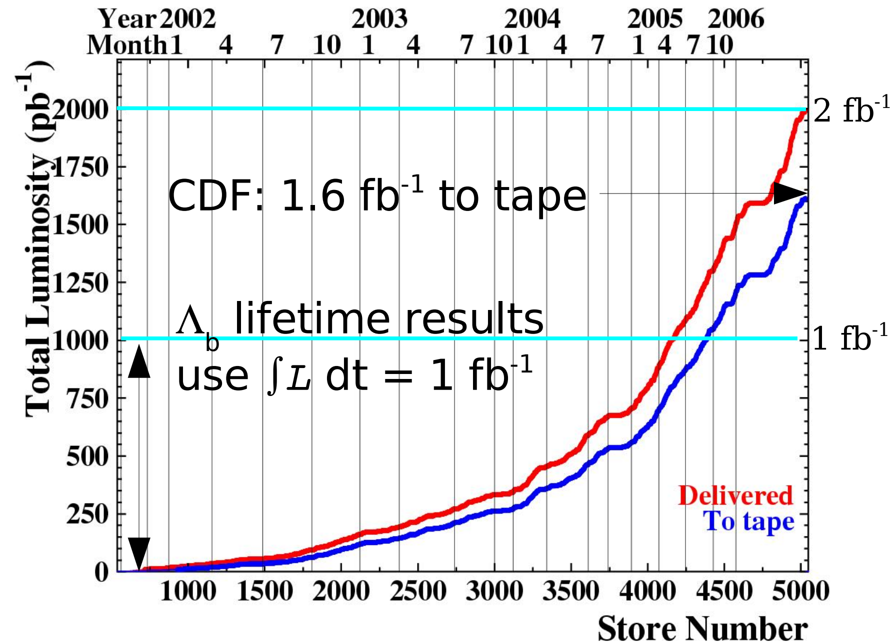
consistent w/ HFAG 2005 world avg: $\tau(\Lambda_b) / \tau(B^0) = 0.803 \pm 0.047$

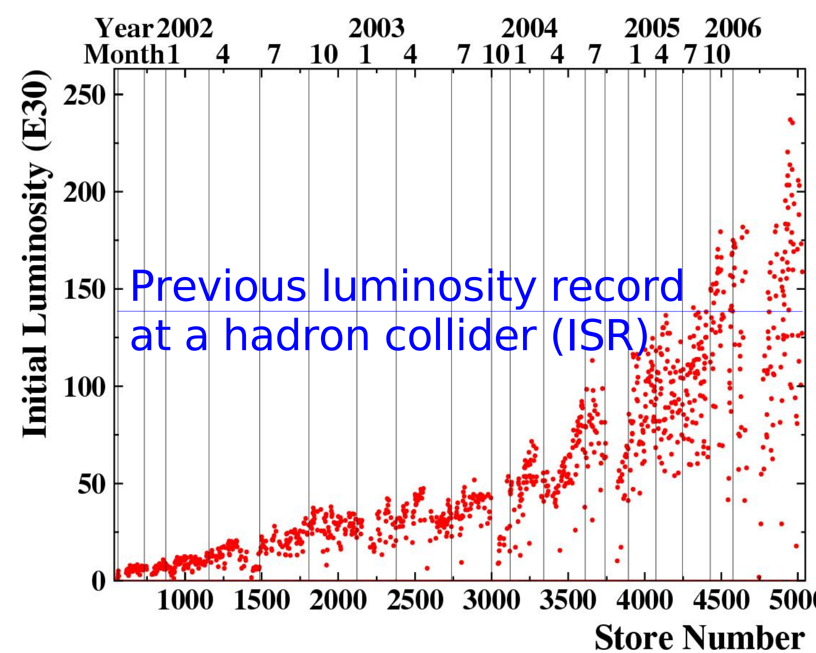
The situation is far from resolved - need more experimental input on $\tau(\Lambda_b)$!

The Fermilab Tevatron

World's highest energy particle collider
until turn-on of LHC @ CERN



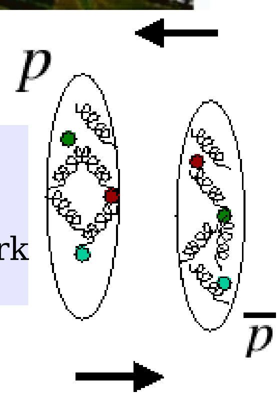




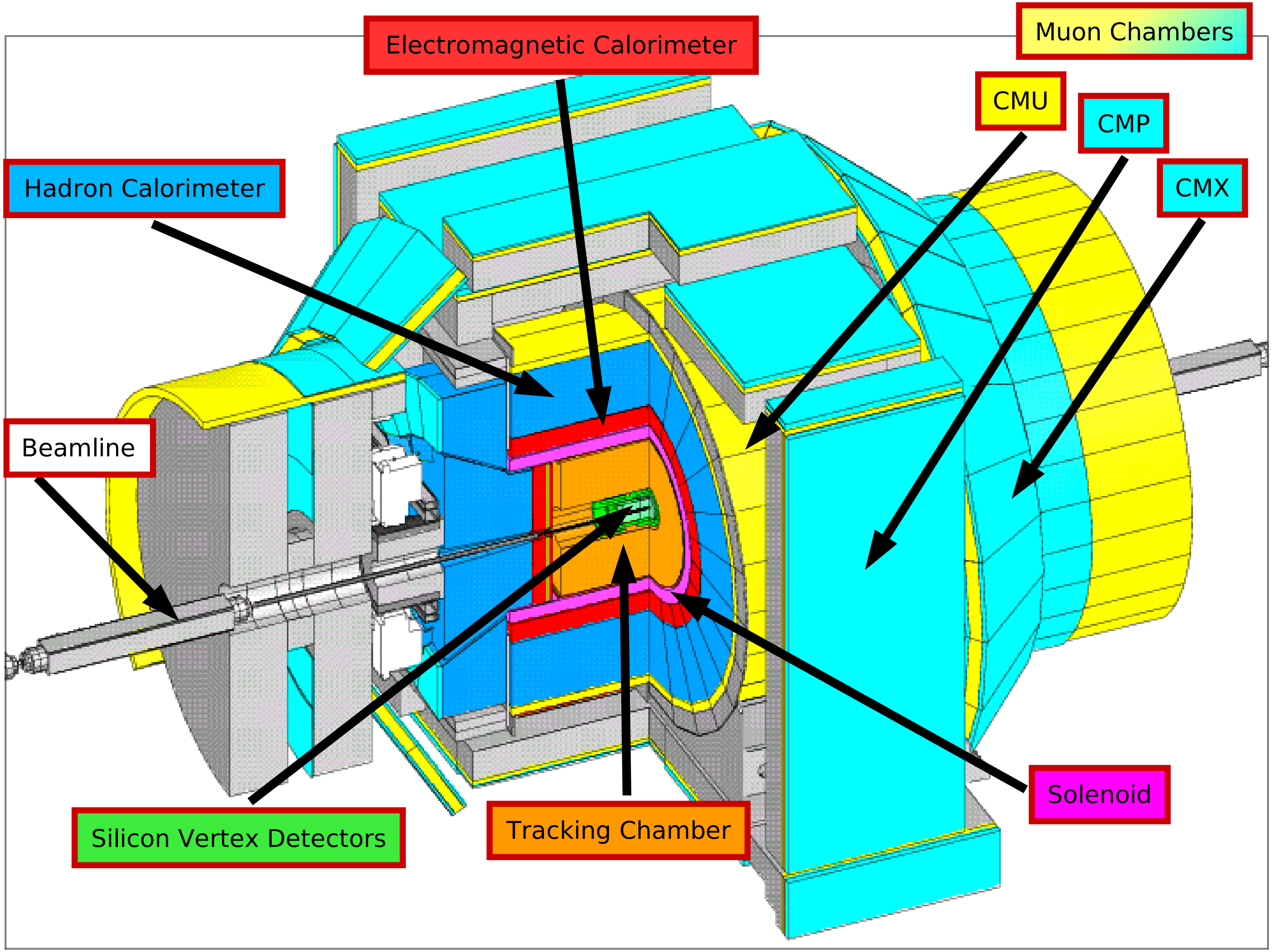
Run II Started 2001:

- $\sqrt{s}$=1.96 TeV
- record luminosity:
  $L_{inst} = 237 \times 10^{30}$ cm^{-2}s^{-1}
- $\int L\, dt$ = ~2 fb^{-1}
  $\rightarrow$ 4 – 8 fb^{-1} expected by 2009

Collisions:
- gluon-gluon
- quark-antiquark
- gluon-quark



The CDF II Detector



Major Upgrades for Run II:

Time-of-Flight
- particle ID

Silicon systems
- larger η coverage for tracking/ b-tagging
- 3D vs. 2D

Improved COT
- better stereo
- faster drift

Muons
- improved coverage

Endplug Calorimeter
- larger η coverage for electron ID

SVT Trigger
- triggering on displaced vertices at Level-2

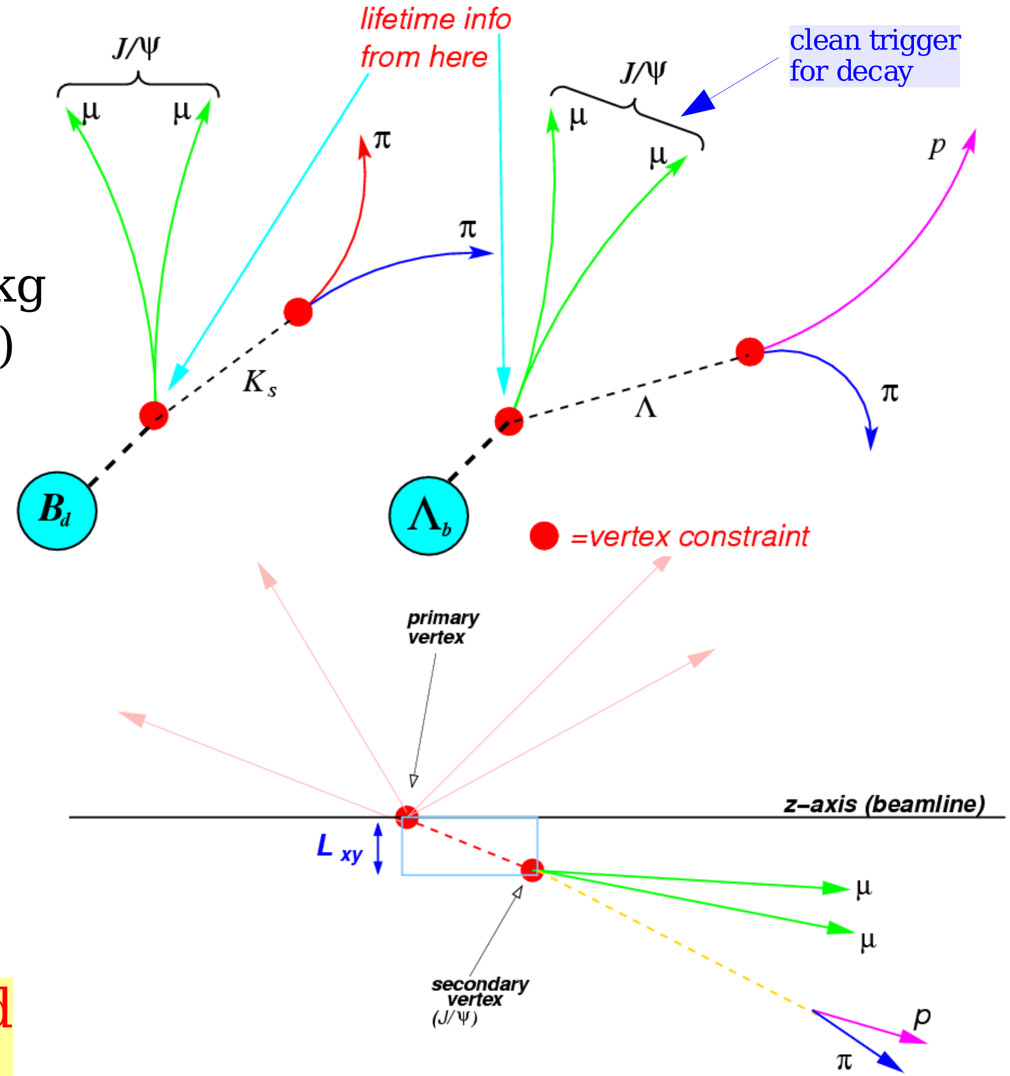
Λ_b Lifetime: Analysis Strategy

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

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 stat. error



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

$\rightarrow$ similar decay: $J/\psi + V^0$ ($V^0 \equiv K_s^0, \Lambda^0$)

$\rightarrow$ larger sample: $\sim 6 \times \Lambda_b$

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

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

$$ct = \frac{L_{xy}^b}{(\beta\gamma)_T^b} = L_{xy}^b \, c \frac{M_b}{p_t^b}, \quad \text{where } L_{xy}^b = \left(\vec{x}(J/\psi) - \vec{x}(PV)\right) \cdot \hat{p}_T^{\,b}$$

b-Hadron Lifetimes We Measure

$B^0 \to J/\psi\, K_s$,	$J/\psi \to \mu\mu,\ K_s \to \pi\pi$	**Full systematics**
$\psi(2S)\, K_s$,	$\psi(2S) \to \mu\mu,\ K_s \to \pi\pi$	
$\psi(2S)\, K_s$,	$\psi(2S) \to J/\psi\pi\pi,\ J/\psi \to \mu\mu,\ K_s \to \pi\pi$	
$B^0 \to J/\psi\, K^{*0}$,	$J/\psi \to \mu\mu,\ K^{*0} \to K\pi$	
$\psi(2S)\, K^{*0}$,	$\psi(2S) \to \mu\mu,\ K^{*0} \to K\pi$	**Statistical errors only (for cross-√)**
$\psi(2S)\, K^{*0}$,	$\psi(2S) \to J/\psi\pi\pi,\ J/\psi \to \mu\mu,\ K^{*0} \to K\pi$	
$B^+ \to J/\psi\, K^+$,	$J/\psi \to \mu\mu$	
$\psi(2S)\, K^+$,	$\psi(2S) \to \mu\mu$	
$\psi(2S)\, K^+$,	$\psi(2S) \to J/\psi\pi\pi,\ J/\psi \to \mu\mu$	
$B^+ \to J/\psi\, K^{*+}$,	$J/\psi \to \mu\mu,\ K^{*+} \to K_s\pi$	
$\Lambda_b \to J/\psi\, \Lambda^0$,	$J/\psi \to \mu\mu,\ \Lambda^0 \to p\pi$	**Full systematics**

Our primary goal

b-Hadron Selection

Select J/ψ:

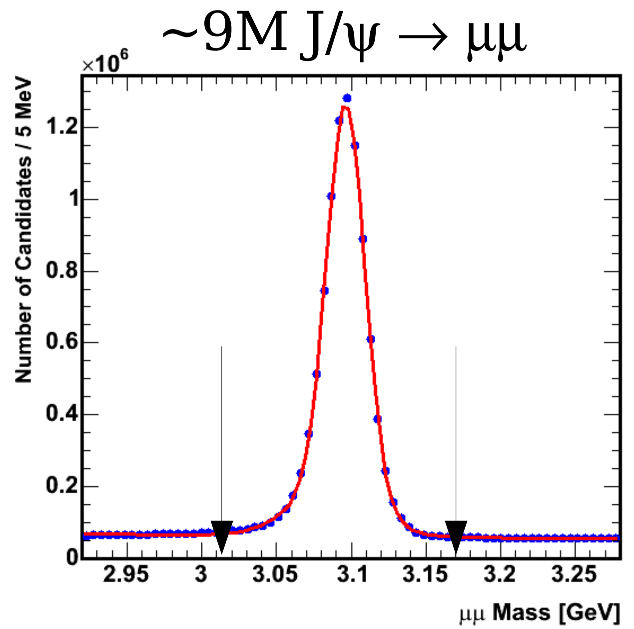
- good track-stub match
- ≥3 r-ϕ hits in silicon systems
- Vertex prob(χ^2) > 0.1%

want good determination of b-hadron decay vertex

Select $V^0 \equiv K_s$, Λ^0:

- ≥2 COT axial,stereo SL with ≥ 5 hits
- no Silicon hits requirement
- Vertex prob(χ^2) > 0.1%

~9M J/ψ → μμ

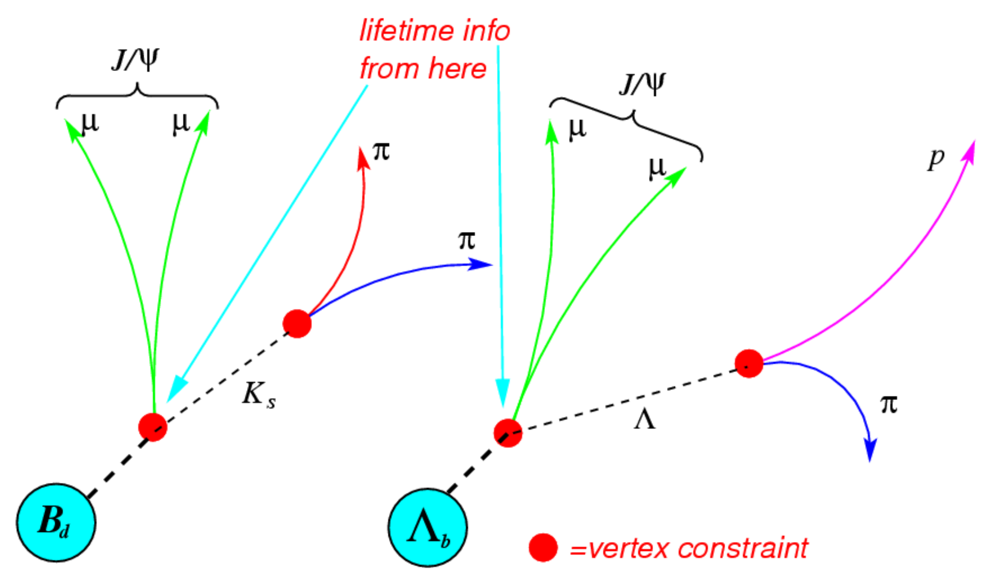


Combine J/ψ and V^0 to construct *b*-hadron Candidates

Vertex Fit with kinematic constraints:

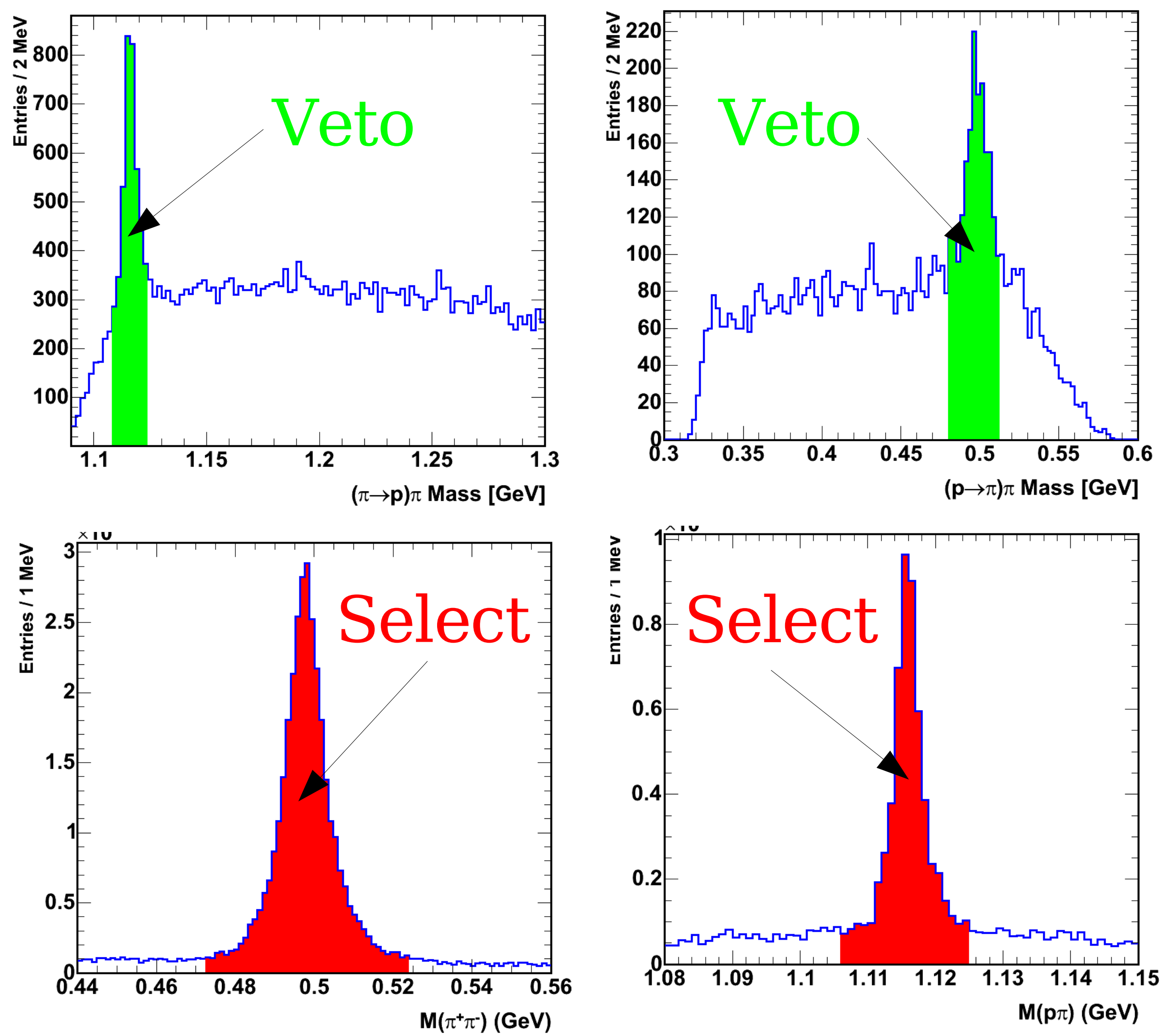
- J/ψ mass constrained to PDG value
- V^0 momentum constrained to point back to J/ψ decay vertex in 3D

Cuts on prob(χ^2) and kinematics variables (e.g. b-hadron Pt), separately optimized for each mode using Monte Carlo for signal and data sidebands for background



K_s and Λ^0 after b-Hadron Selection

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

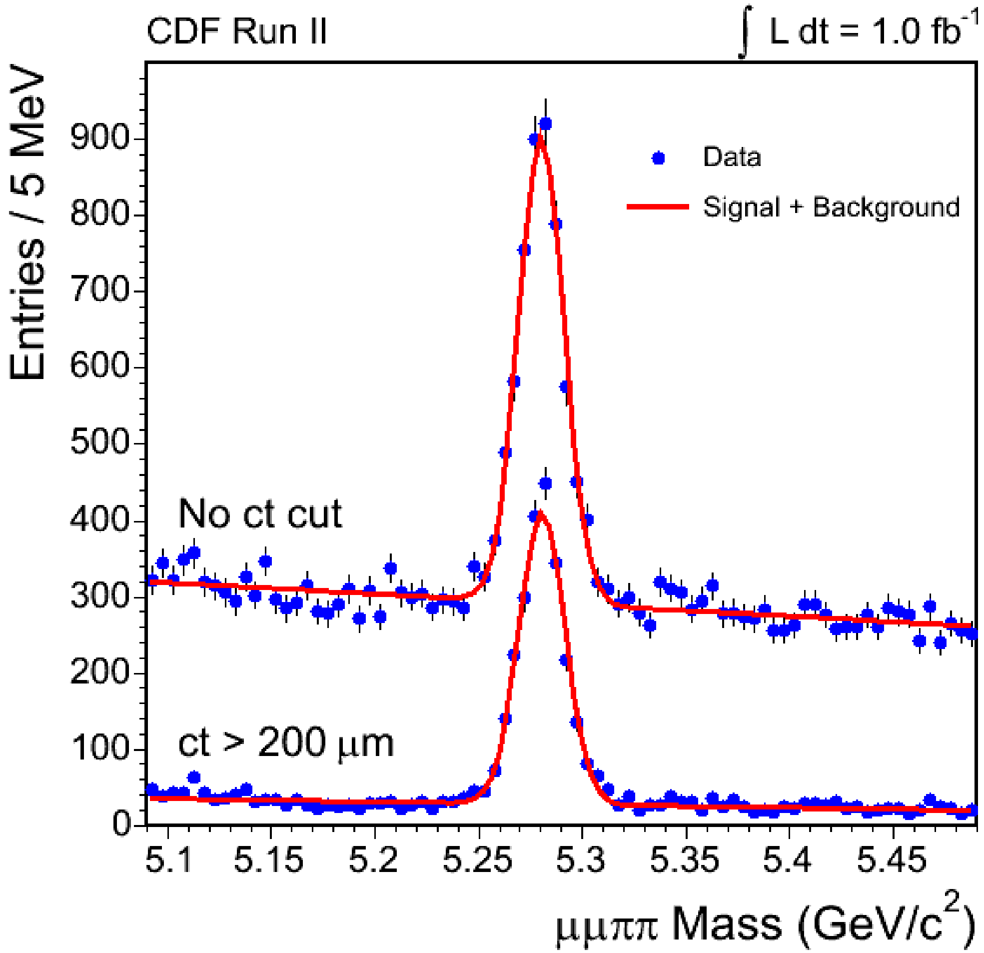


- Veto Λ^0 in K_s and K_s in Λ^0 using $p \leftrightarrow \pi$ swapped-mass hypothesis to suppress V^0 cross-contamination

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

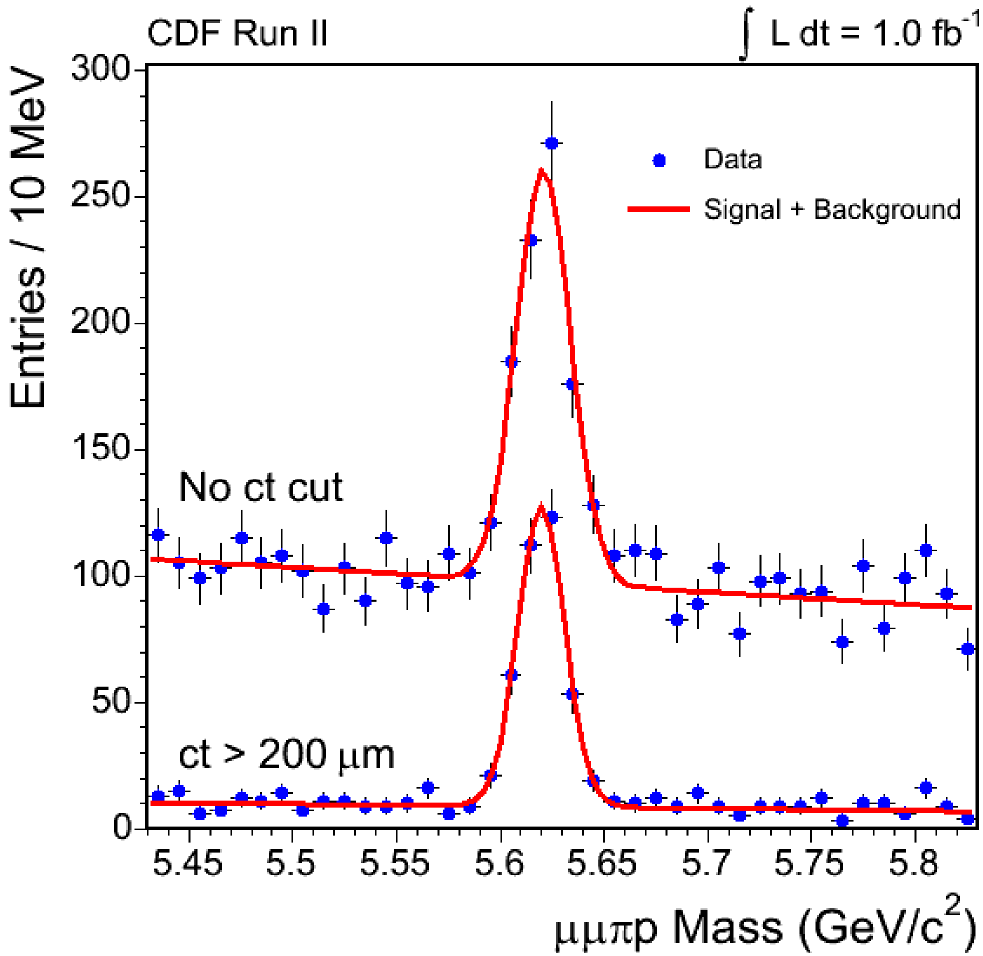
Results: Yield

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



$N(B^0) = 3376 \pm 88$

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



$N(\Lambda_b) = 538 \pm 38$

Fit Model: Overview

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

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

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:

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

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 :

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

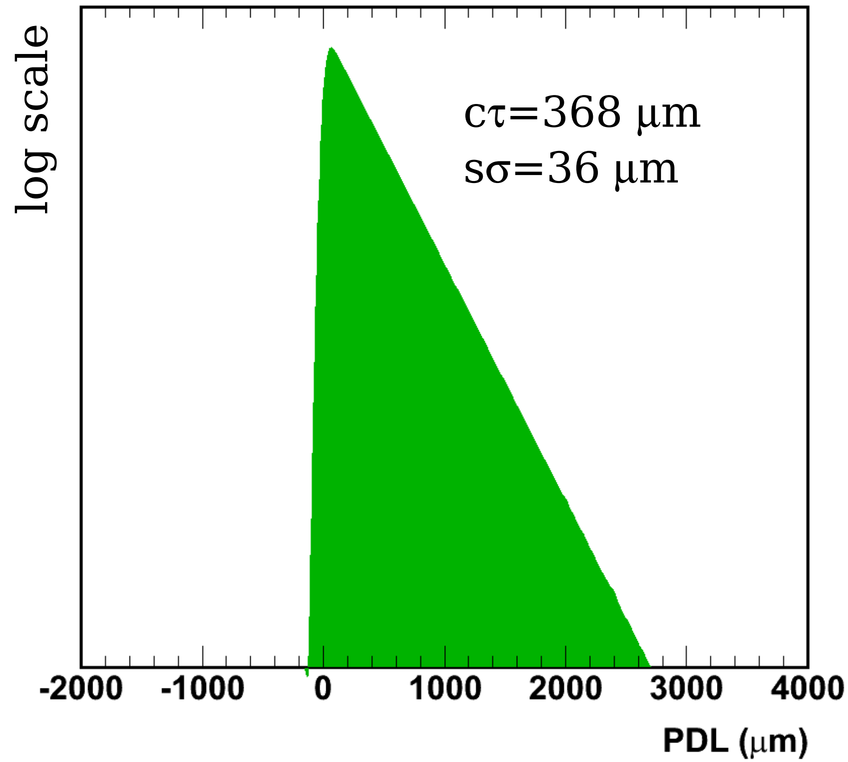
where:

τ = signal lifetime (the goal)

s = overall scale factor on PDL errors

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

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



Fit Model: Background PDL

Background PDL modeled as sum of four components:

$$P^{\lambda}_{bkg}(\lambda_i|\sigma^{\lambda}_i, s, f_-, \lambda_-, f_+, \lambda_+, f_{++}, \lambda_{++}) = G(\lambda_i, \sigma^{\lambda}_i|s) * \left\{ \begin{array}{l} (1 - f_- - f_+ - f_{++})\ \delta(0) \\ +\ f_-\ E(-\lambda_i|\lambda_-) \\ +\ f_+\ E(\lambda_i|\lambda_+) \\ +\ f_{++} E(\lambda_i|\lambda_{++}) \end{array} \right\}$$

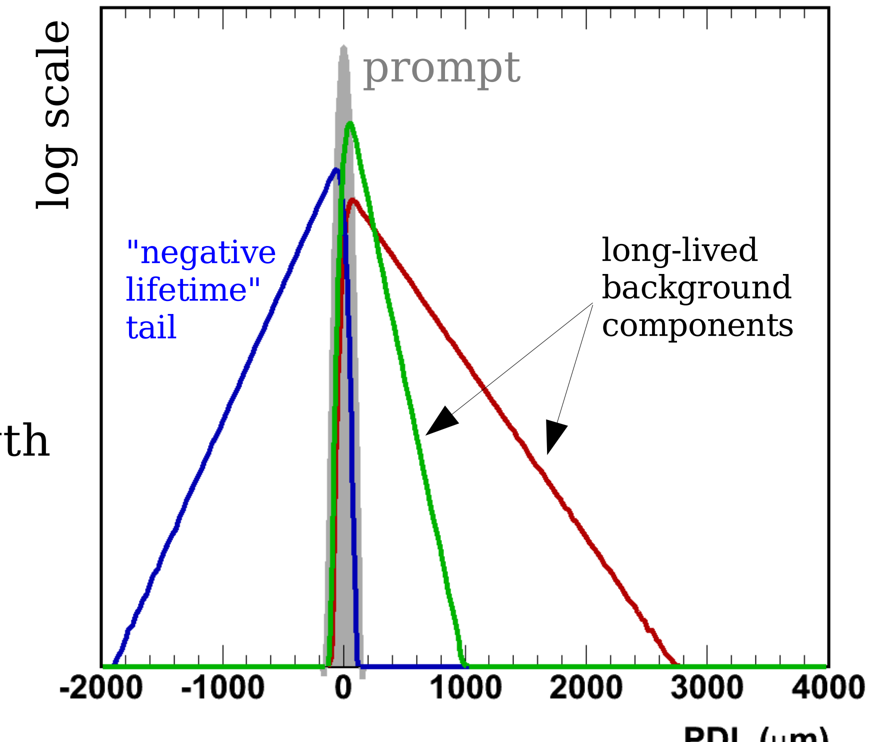
zero lifetime (prompt)

"negative lifetime" (resolution tails)

long-lived background (*b* → J/ψ X combined with unrelated tracks)

where:

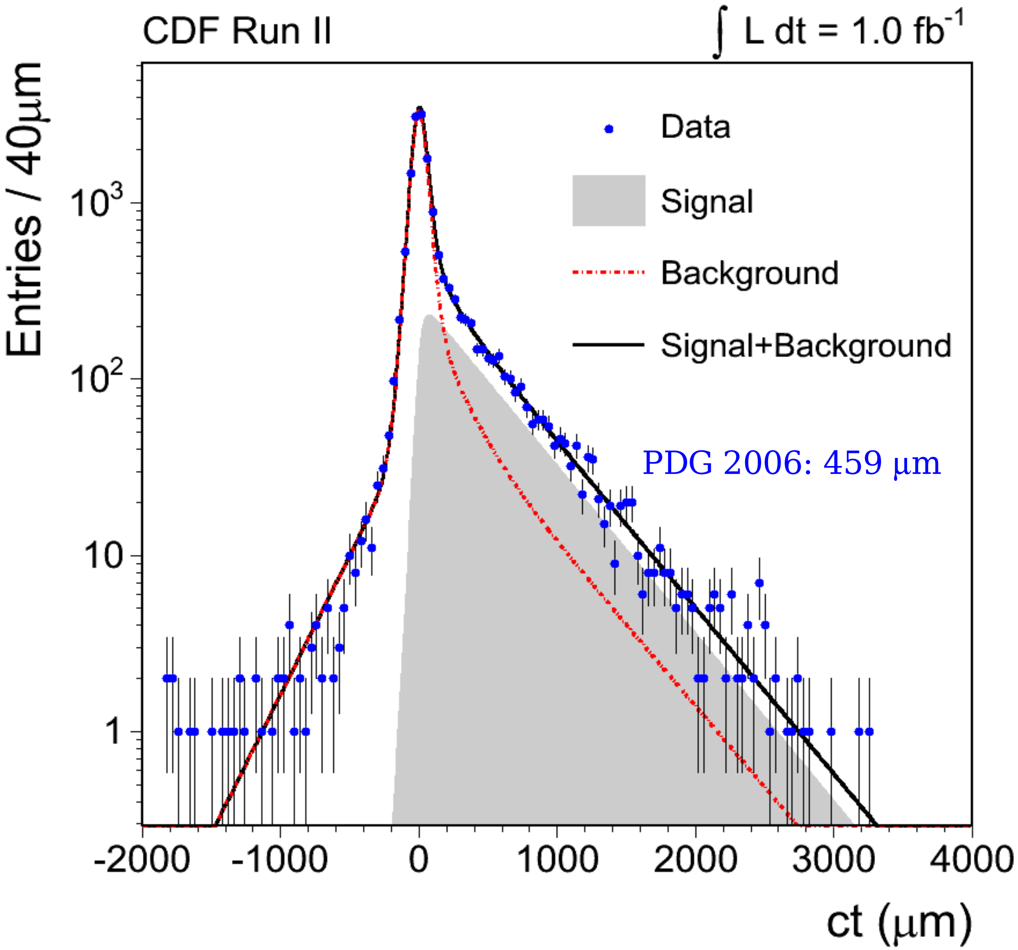
f_-	=	negative exponential fraction
λ_-	=	negative exponential decay length
$f_{+(++)}$	=	$1^{st}(2^{nd})$ positive exponential fraction
$\lambda_{+(++)}$	=	$1^{st}(2^{nd})$ positive exponential decay length



Fits with different shape assumptions used to constrain systematic

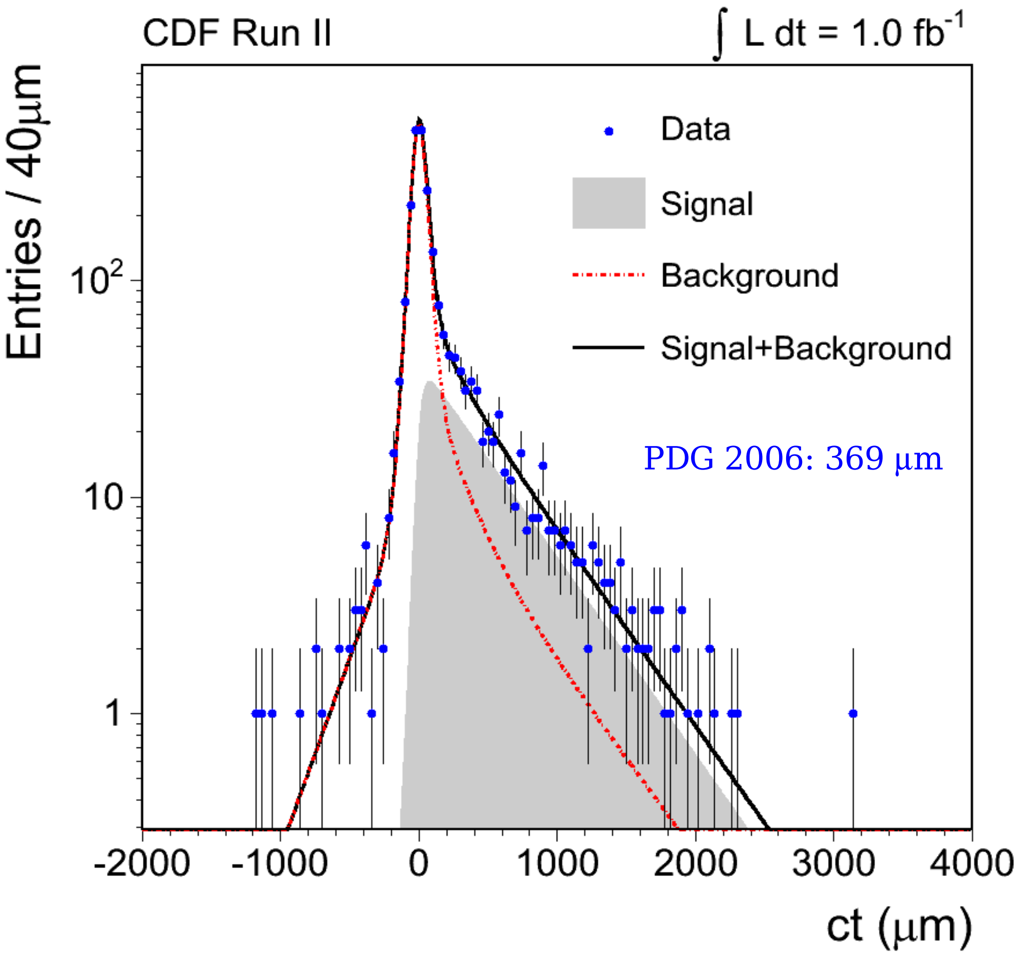
Results: Lifetime

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



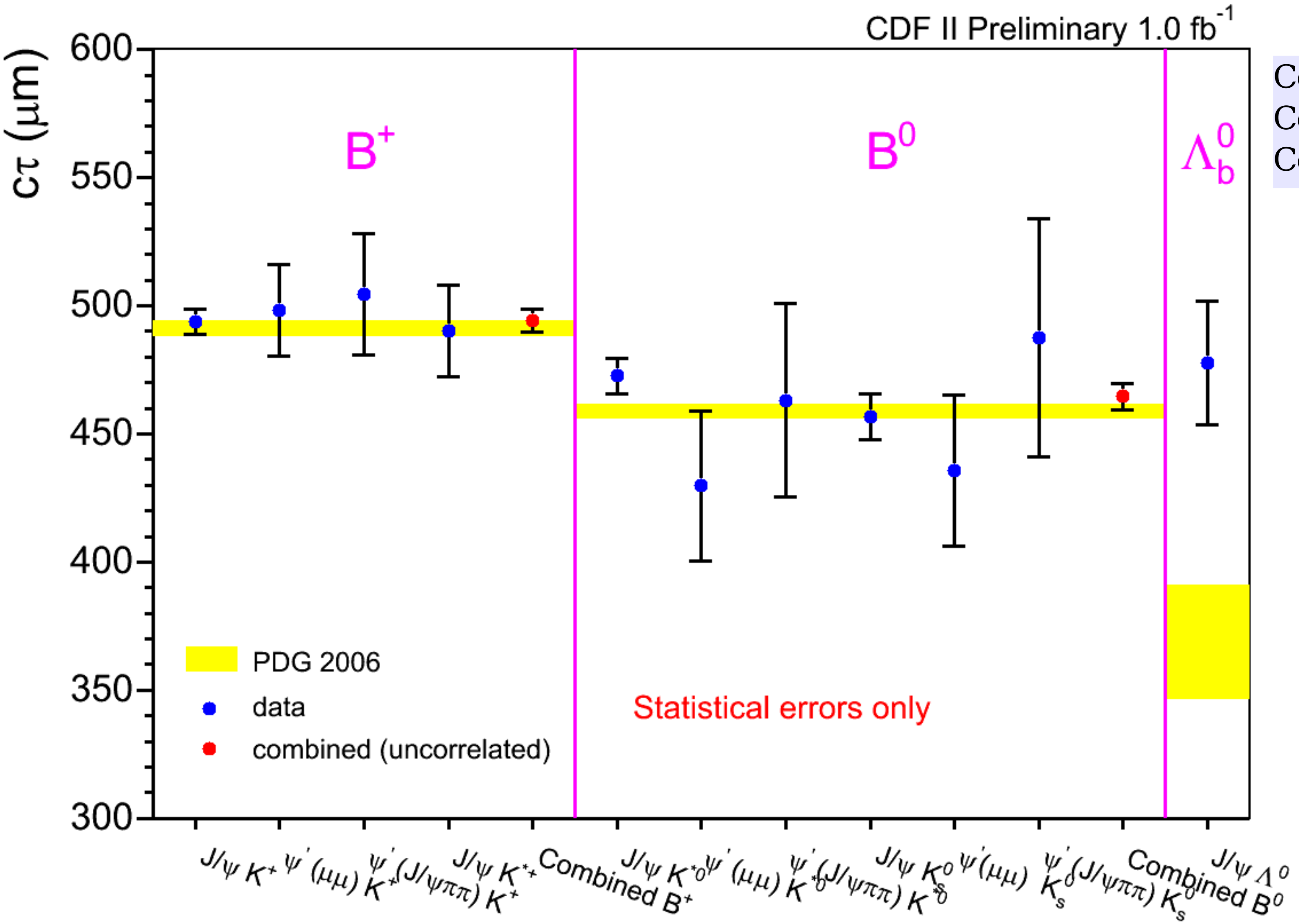
$$c\tau(B^0) = 456.8^{+9.0}_{-8.9}\ \mu m$$

$\Lambda^0 \to J/\psi \Lambda^0$



$$c\tau(\Lambda_b) = 477.6^{+25.0}_{-23.4}\ \mu m$$

b-Hadron Lifetime Summary



Combined B^+ : 494.3 ± 4.5 μm
Combined B^0 : 464.5 ± 5.3 μm
Combined Δ_{PDG}: 4.3 ± 5.5 μm

These are not $\tau(B^0)$, $\tau(B^+)$ measurements:

Statistical errors only!

$\Rightarrow$ High-level validation of analysis for well-established B^0/B^+ lifetimes

We use these results to cross-√ our measurement of lifetimes in fully-reconstructed decay using J/ψ to determine B decay vertex

Systematic Uncertainties

Source	$c\tau$ (B^0) [μm]	$c\tau$ (Λ_b) [μm]
Fitter Bias	0.4	0.5
Fit Model:		
ct Resolution	3.1	5.5
Mass Signal	0.7	2.3
Mass Background	0.1	0.1
ct Background	0.5	0.7
σ^{ct} Distribution Modeling	0.1	0.2
σ^{m} Distribution Modeling	0.6	0.2
Mass-*ct* Background Correlation	1.9	4.1
ct-σ^{ct} Background Correlation	0.3	1.3
Primary Vertex Determination	0.2	0.3
Alignment:		
SVX Internal	2.0	2.0
SVX/COT Global	2.2	3.2
V^0 Pointing	0.6	5.4
Total	**4.9**	**9.9**

Summary of Results

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

$$c\tau\,(B^0) = 456.8\,^{+9.0}_{-8.9}\,(\text{stat.}) \pm 4.9\,(\text{syst.})\ \mu\text{m}$$

$$= 1.524 \pm 0.030\,(\text{stat.}) \pm 0.016\,(\text{syst.})\ \text{ps}$$

consistent w/ PDG 2004 value of 1.530 ± 0.009 ps

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

$$c\tau\,(\Lambda_b) = 477.6\,^{+25.0}_{-23.4}\,(\text{stat.}) \pm 9.9\,(\text{syst.})\ \mu\text{m}$$

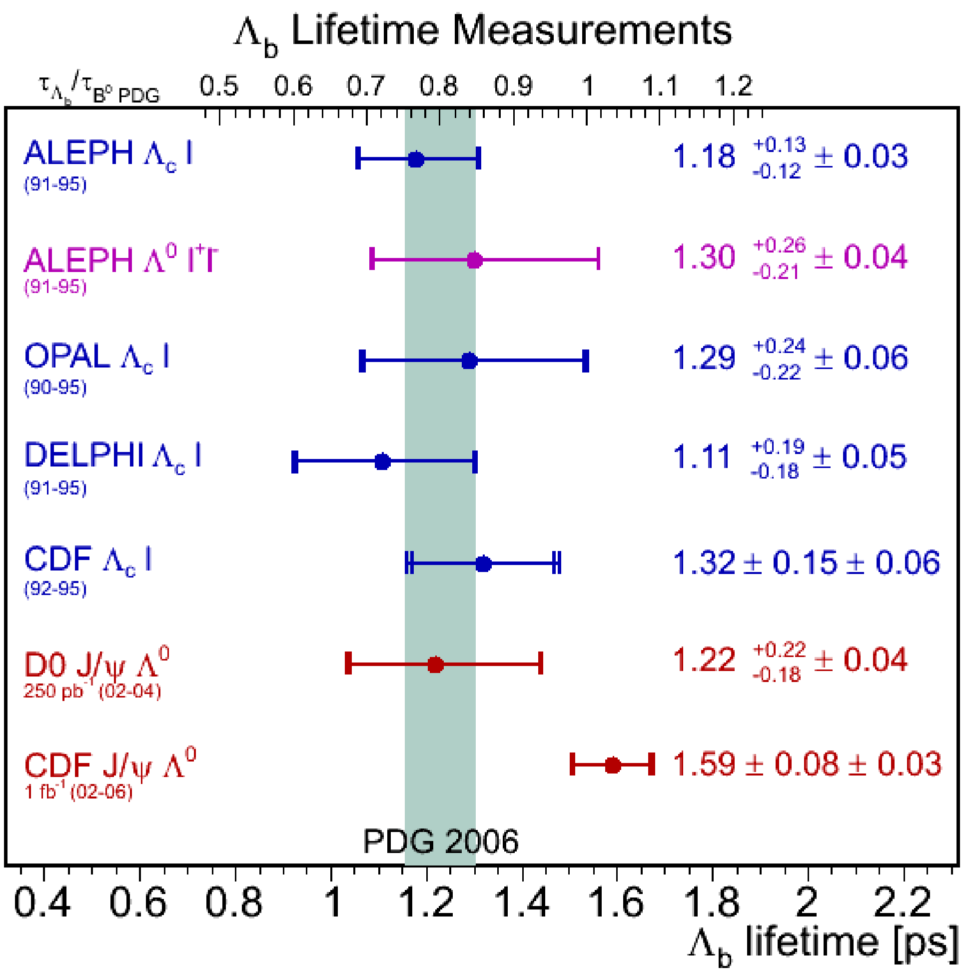
$$= 1.593\,^{+0.083}_{-0.078}\,(\text{stat.}) \pm 0.033\,(\text{syst.})\ \text{ps}$$

Conclusions

Using our Λ_b lifetime and the PDG 2004 B^0 lifetime, we get

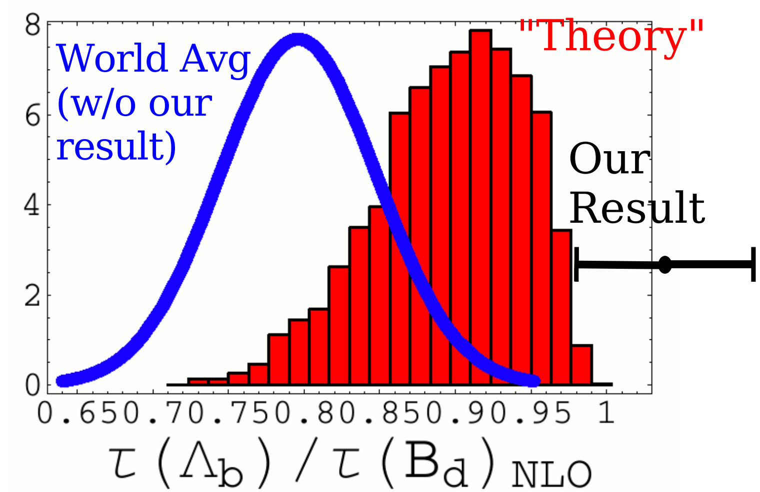
$$\tau(\Lambda_b) / \tau(B^0) = 1.041 \pm 0.057 \text{ (stat.+syst.)}$$

This result is higher than the PDG 2004 world average $\tau(\Lambda_b)$ @ 3.2σ level



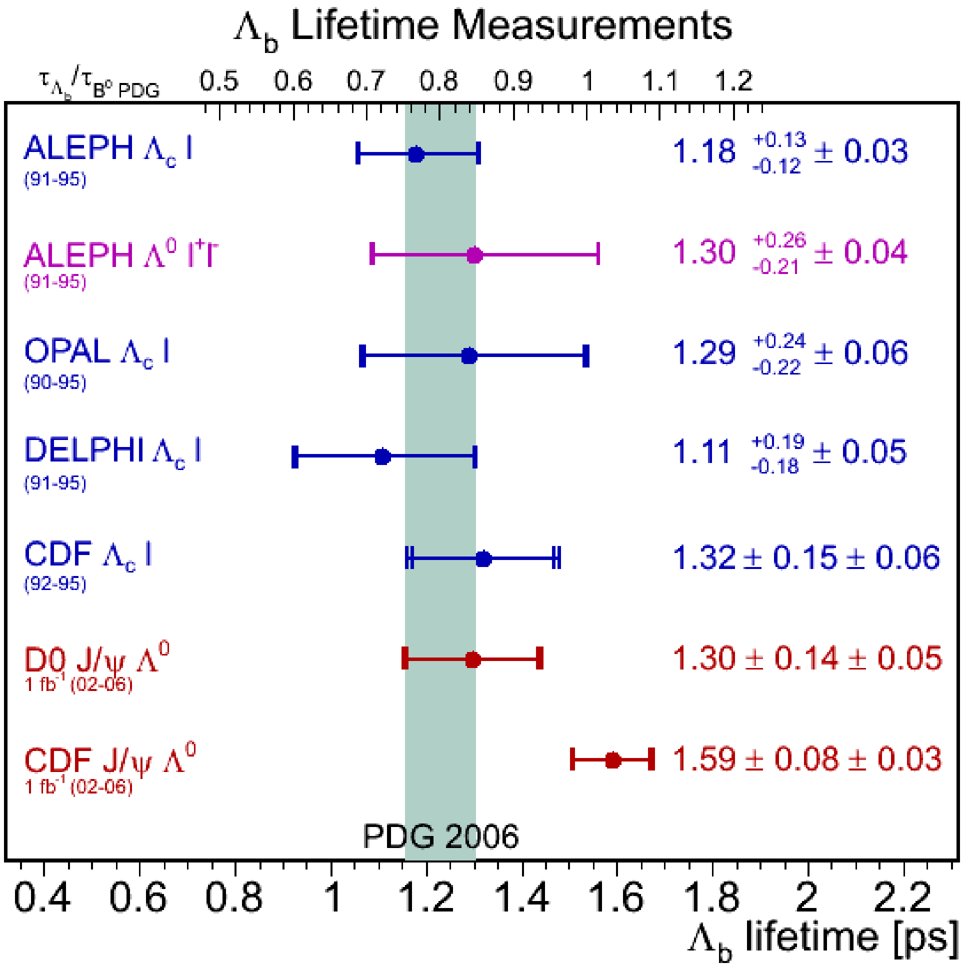
Our $\tau(\Lambda_b)$ measurement is the world's most precise measurement

→ best by far in a fully reconstructed decay channel

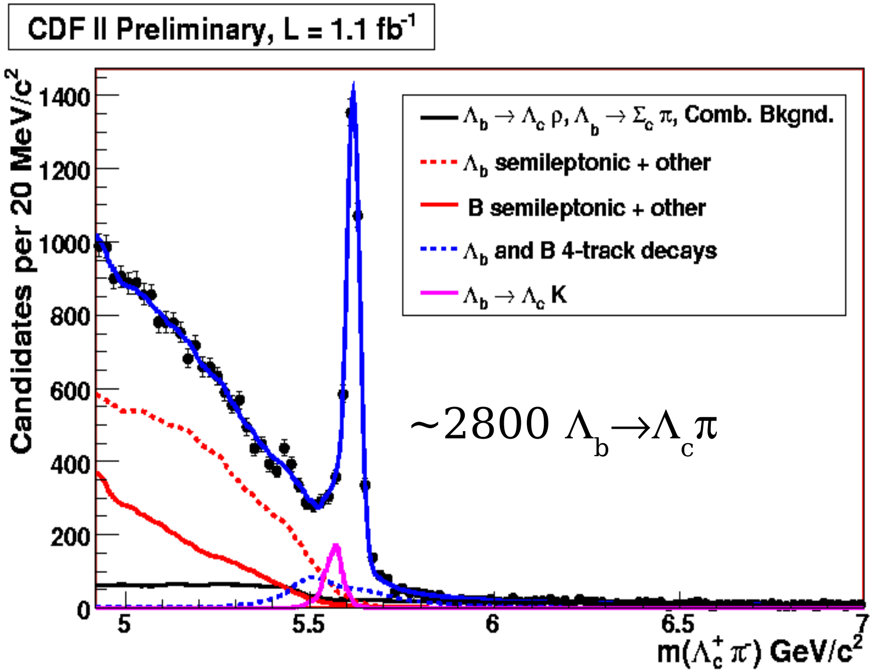


and consistent with theory

Summary / Outlook

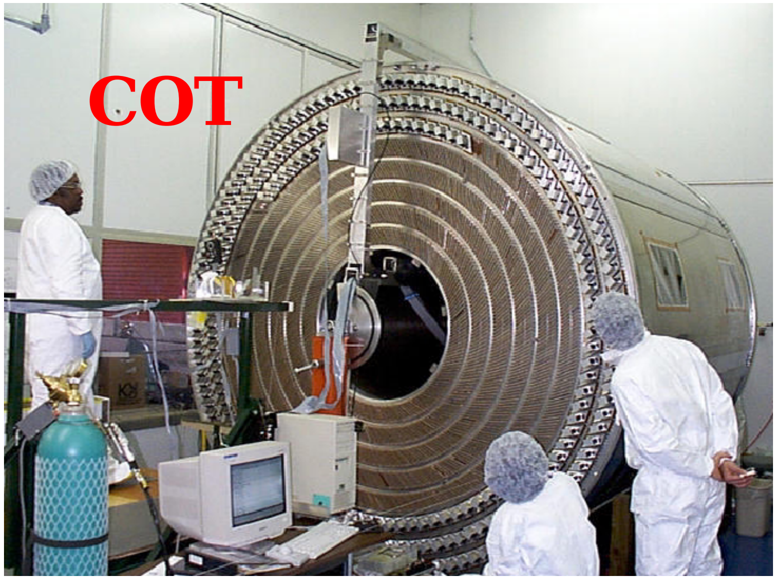


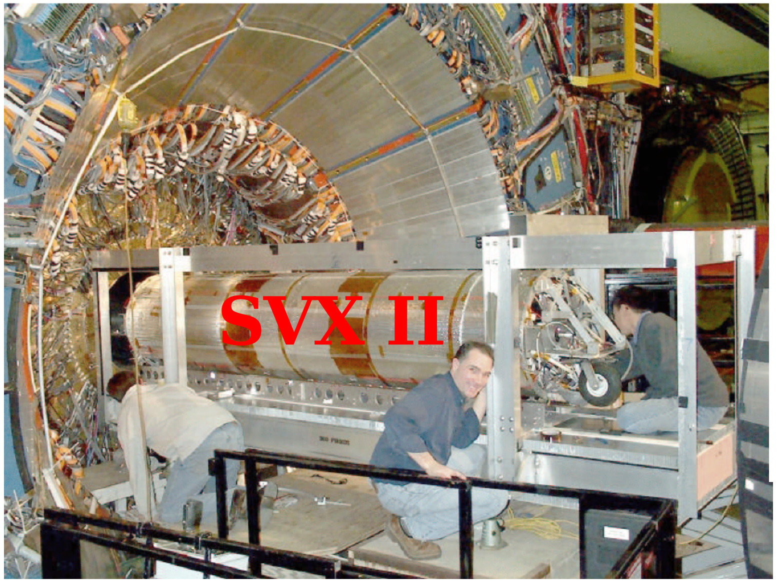
$\tau(\Lambda_b)$ in $\Lambda_b \to \Lambda_c \pi$ from CDF is also coming

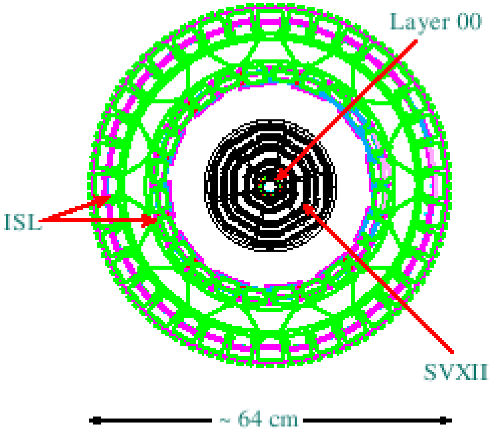


Extras

Integrated Tracking System



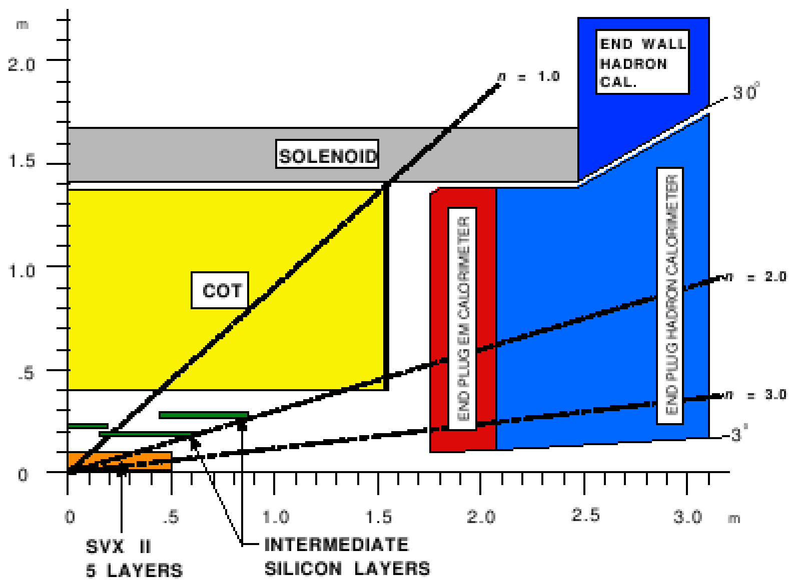




Tracking in a nutshell:

1) Segments formed from hits each COT superlayer (SL)
2) Segments linked together to form 2D track
3) Stereo segments linked into 2D track and helix fit is performed
4) COT track extrapolated into SVXII, outer layers first
5) SVXII hits consistent with COT track are added succession, with track refit after each iteration

CDF Tracking Volume



Silicon system:

SVX II
- 5 layers double-sided silicon → r-ϕ, r-z tracking
- 2.5 < r < 10.6 cm
- 96 cm long
→ ×2 RunI acceptance

ISL
- 2 additional Si layers
- r < 28 cm; cover |η|<2

L00
- inner Si layer at beam pipe (R = 1.5 cm)

(L00 not used in our analysis)

Di-muon Trigger / Dataset

Di-muon triggers use tracks found in the drift chamber (COT) that are matched to stubs in 3 sets of muon chambers:

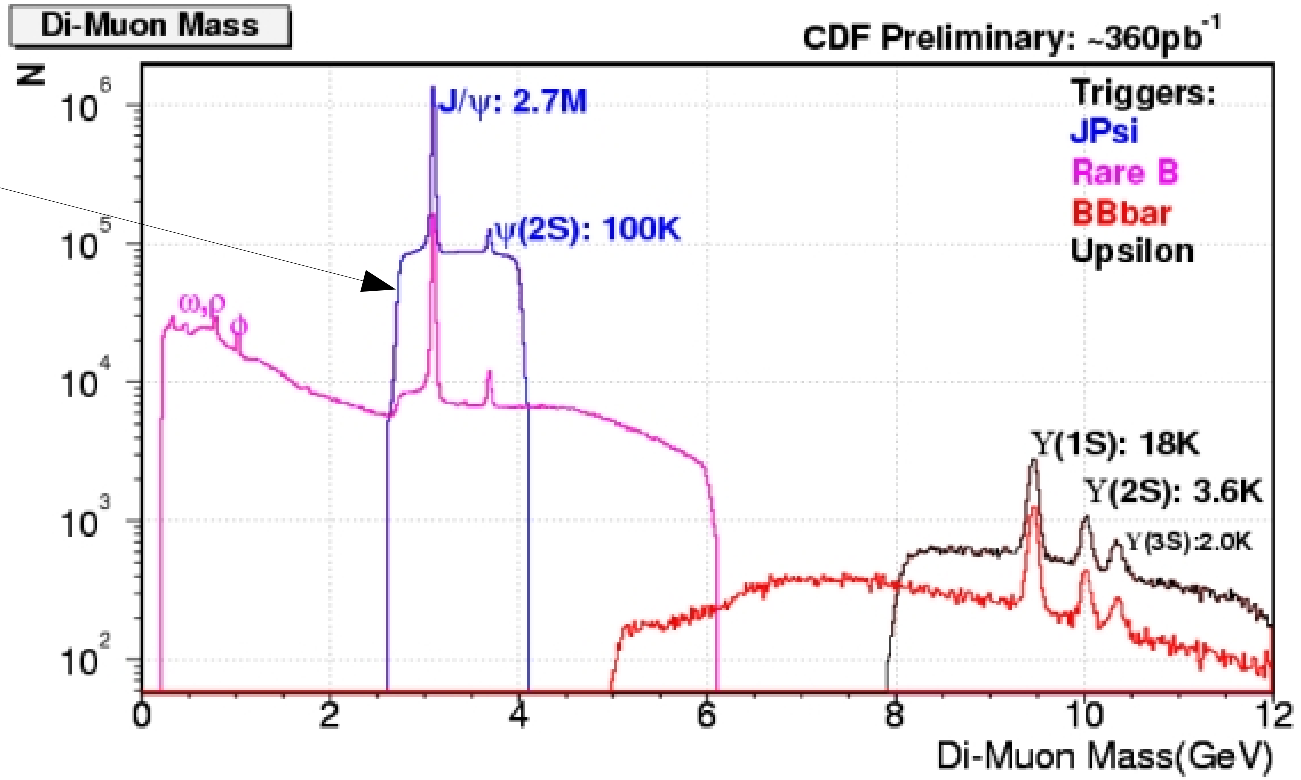
- Central muon chambers (CMU): $|\eta| < 0.6$ (central region)
- Central muon plug (CMP): $|\eta| < 0.6$ (central region beyond CMU radius)
- Central muon extension (CMX): $0.6 < |\eta| < 1.0$

$\psi \to \mu^+\mu^-$ Trigger:

Level 1: 2 muons (CMU-CMU or CMU-CMX)
$p_T(\mu) > 1.5$ GeV/c
Track-stub match

Level 2: Auto

Level 3: Opposite charge
$m(\mu^+\mu^-)$ region for ψ,ψ'
Track-stub match



Our Dataset: ~370 pb^{-1} of integrated luminosity (after good run criteria) collected on JPsi ($\psi \to \mu^+\mu^-$) trigger

Selection Optimization

- Single-*b* Monte Carlo for signal
- "Far" sidebands in data for background
- N-1 Optimization of each cut for best for $S^2/(S+B)$

Λ_b

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}

B^0

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}