Λ_b Lifetime in Fully Reconstructed Decay at CDF

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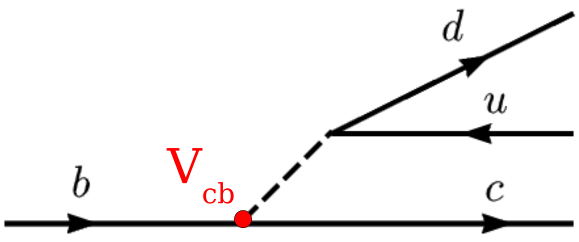
Outline:

- Motivation
- Λ_b Lifetime in fully reconstructed decay

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

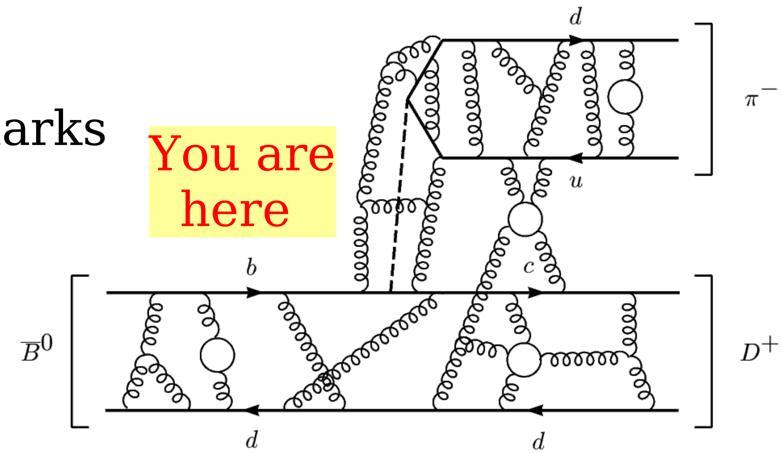


- Weak decay of hadrons depends upon fundamental parameters of the Standard Model we'd like to know

  → 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



hep-ph/9610385

- 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)

b-Hadron Lifetimes: Why Do We Care?

Critical testbed for theoretical framework used in predictions of 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 to reasonably good 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 $m_b \gg \Lambda_{QCD} \rightarrow$ large energy release in decay

  Theoretical uncertainties $\rightarrow$ treat carefully/critically!

  Current experimental precision comparable:

  1% for $\tau(B^+)/\tau(B^0)$, 3% for $\tau(B_s)/\tau(B^0)$, 6% for $\tau(\Lambda_b)/\tau(B^0)$

As a practical matter, for a CDF physicist:

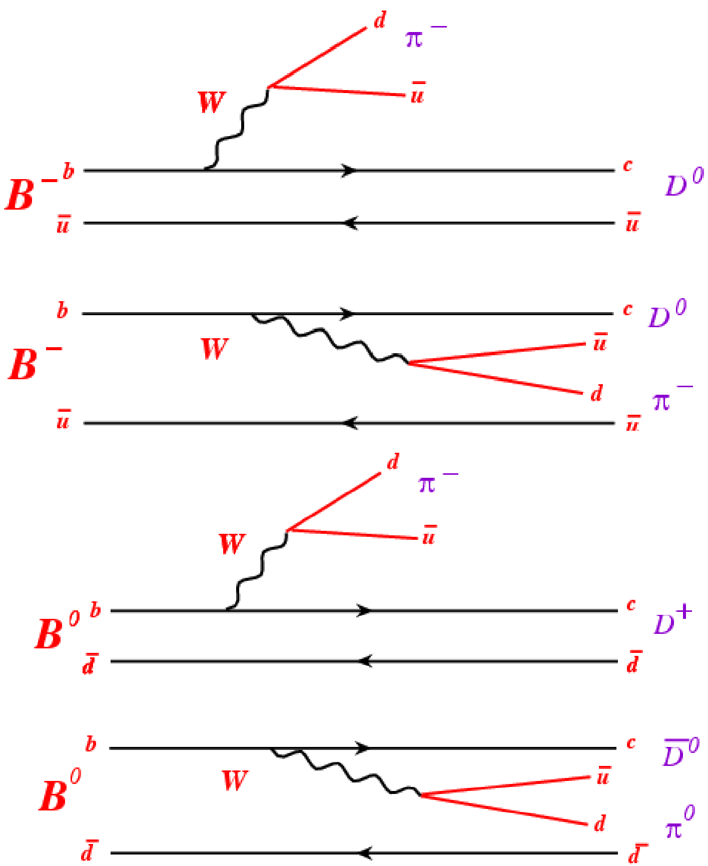
- Important experimental reference
  Overlap with B factories $\rightarrow$ study of potential detector/trigger/analysis biases
- Measure lifetime of species not produced at B factories (e.g. Λ_b)
- Long lifetime of *b*-hadrons a powerful discriminator
  of decay events against backgrounds
- Techniques used in lifetime measurements critical for observing
  time-dependent oscillation of neutral B mesons (e.g. B_s^0-$\overline{B}_s^0$ oscillations)

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 ($m_Q \rightarrow \infty$)

In reality, lifetime differences can arise from spectator quark effects:

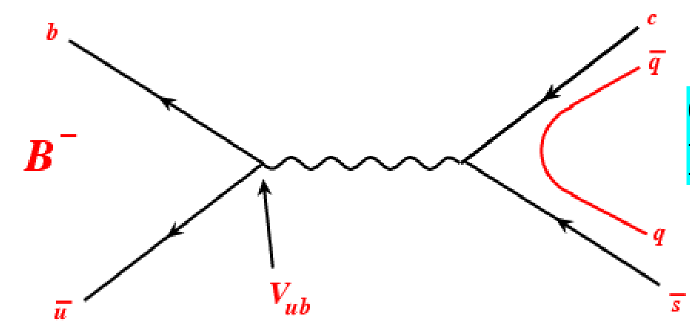
Pauli Interference



Same final state
⇒ interference
(destructive)

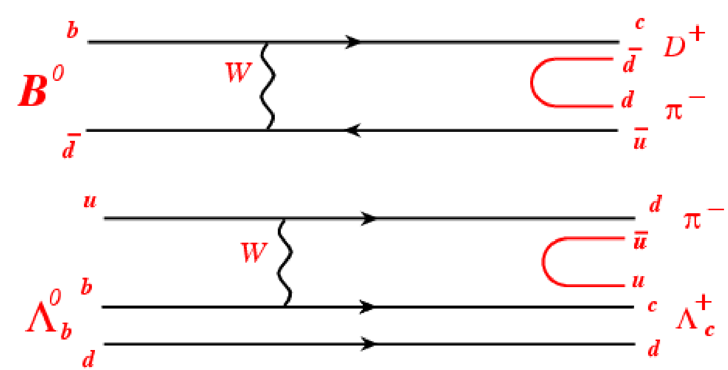
Different final states
⇒ no interference

Weak Annihilation



Only charged B mesons

Weak Exchange

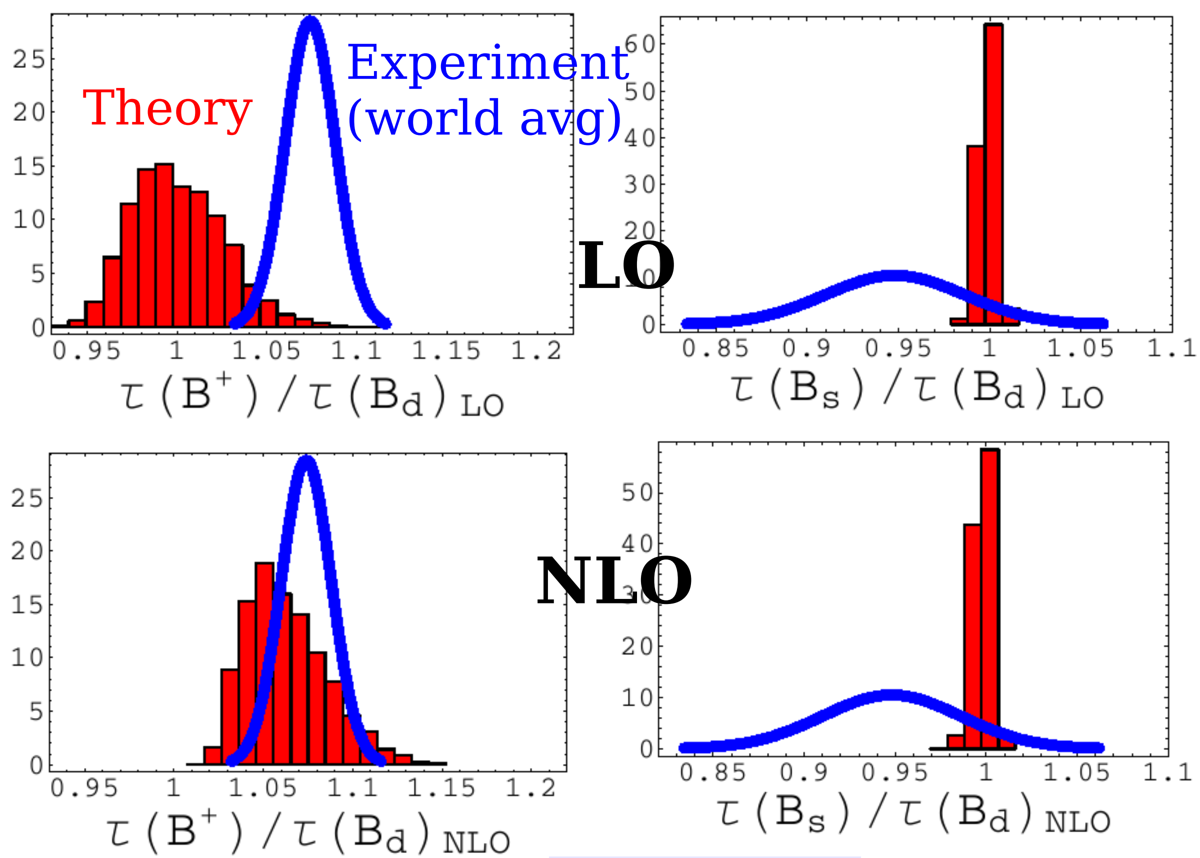


Helicity suppressed in mesons, not baryons

Heavy Quark Expansion

Express inclusive decay width as 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 physics from scales $\geq \mu = O(m_b)$
  → perturbatively calculable
- Matrix elements contain long-distance physics
  → hard! especially for baryons
- Spectator contributions enter at $1/m_b^3$ (~5-10%)

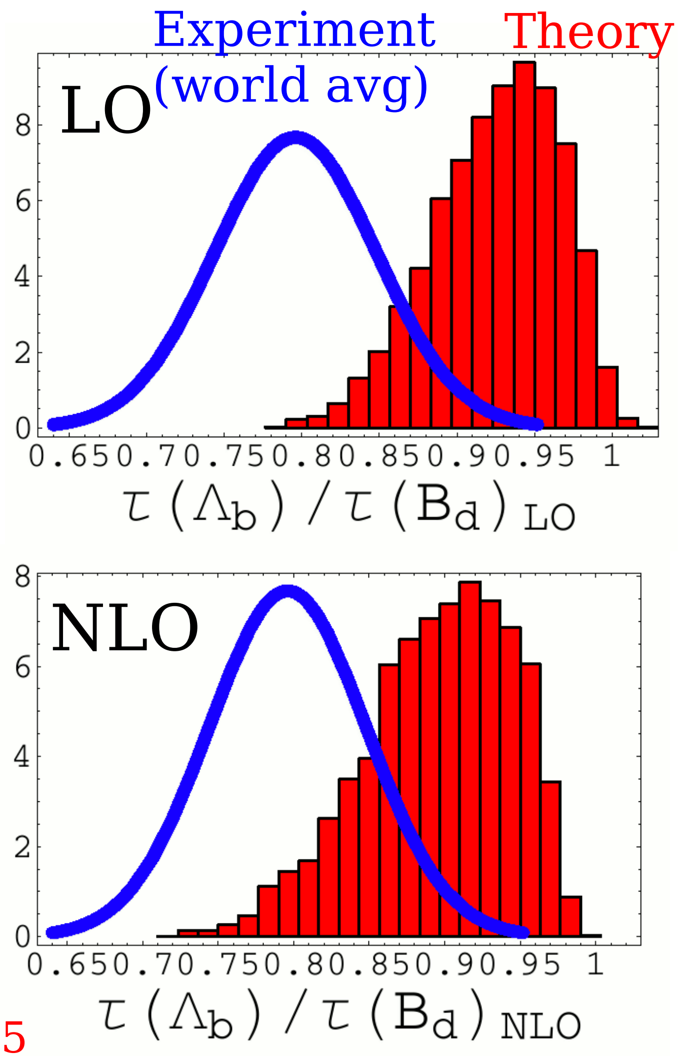
NLO QCD and sub-leading spectator corrections can be important!
For $\tau(\Lambda_b)/\tau(B^0)$:

- NLO QCD: -8%
- Sub-leading spectator: -(2-3)% (hep-ph/0407004)

Λ_b Lifetime - Perfect Storm?

Exp	Method	Data set	$\tau(\Lambda_b)$ (ps)	precision
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%
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%
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%**

HFAG Winter'05 (hep-ex/0505100)



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For $\tau(\Lambda_b)/\tau(B^0)$, early theory predictions (~0.94) and experiment differed by more than 2σ → "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

First Commissioned in 1983

Run I (1992-1995):

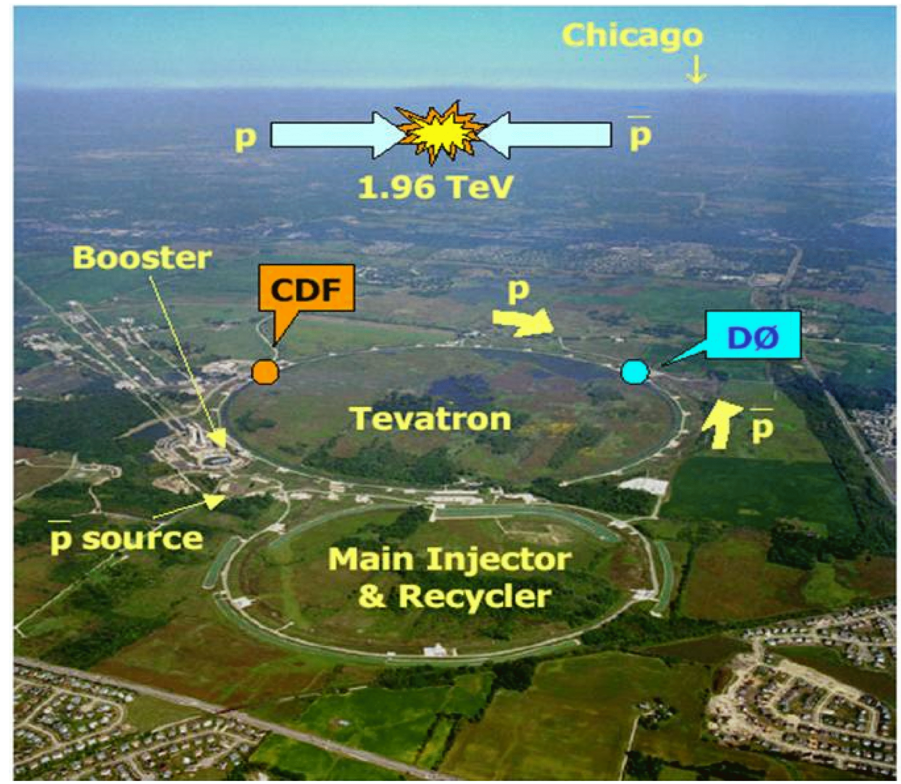
- $\sqrt{s}$=1.8 TeV
- 6×6 bunches, L_{inst}= 16×10^{30} cm^{-2}s^{-1}
- $\int L\,dt$ = 110 pb^{-1}

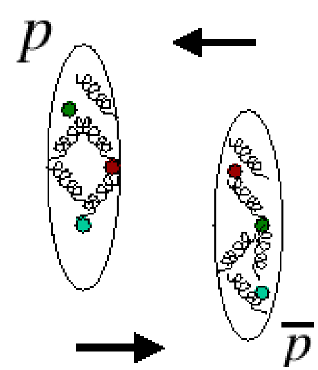
1996-2000 Major Upgrade for Run II:

- Main Injector
- $\bar{p}$ Recycler
- new synchotron
- upgraded $\bar{p}$ source

Run II Started 2001:

- $\sqrt{s}$=1.96 TeV
- 36×36 Colliding $p\bar{p}$ bunches 10^{11}(10^{10}) p($\bar{p}$) per bunch
- L_{inst}= 181.8×10^{30} cm^{-2}s^{-1} (record)
- $\int L\,dt$ = ~1.6 fb^{-1} (~1.3 fb^{-1} to tape) with
  → 4 – 8 fb^{-1} expected by 2009





Collisions:
- gluon-gluon
- quark-anti-quark
- gluon-quark

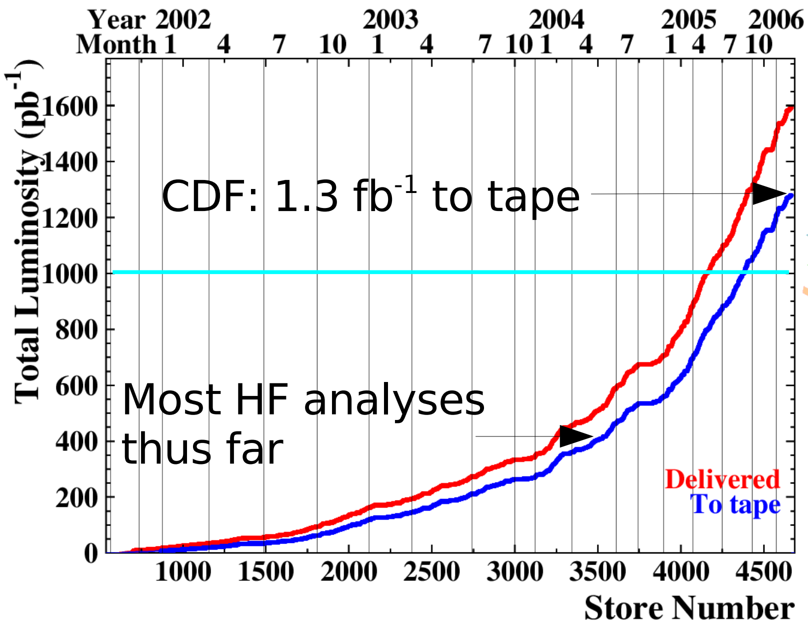
Heavy Flavor Physics at CDF

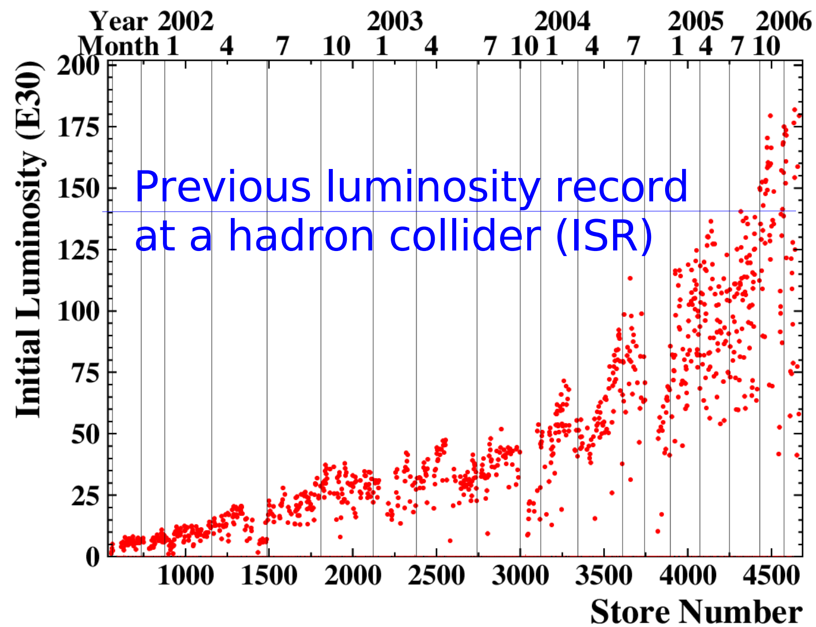
b production at the Tevatron:

- large production cross-section*:* *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...)

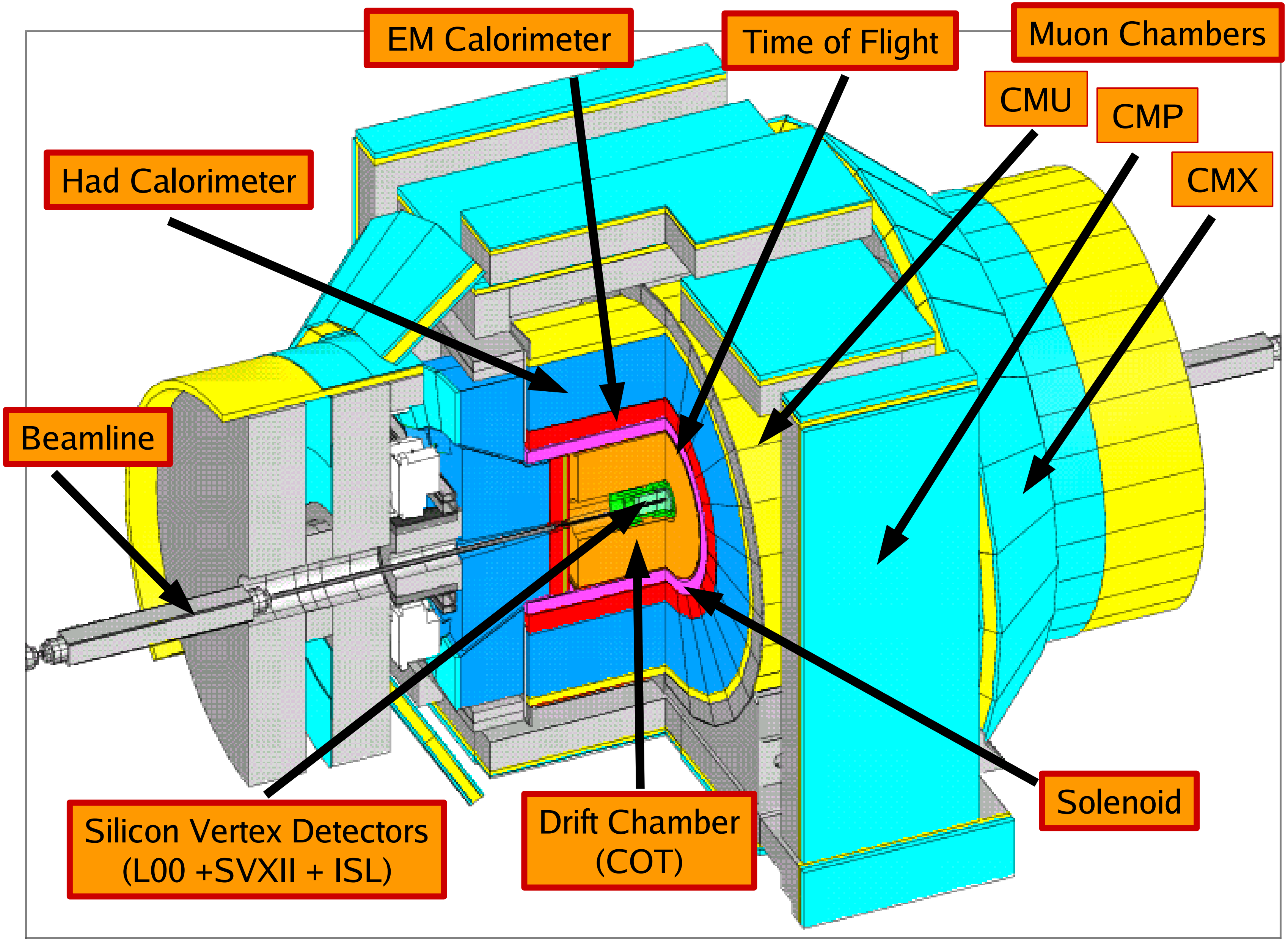
Rich program in heavy flavor:

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





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

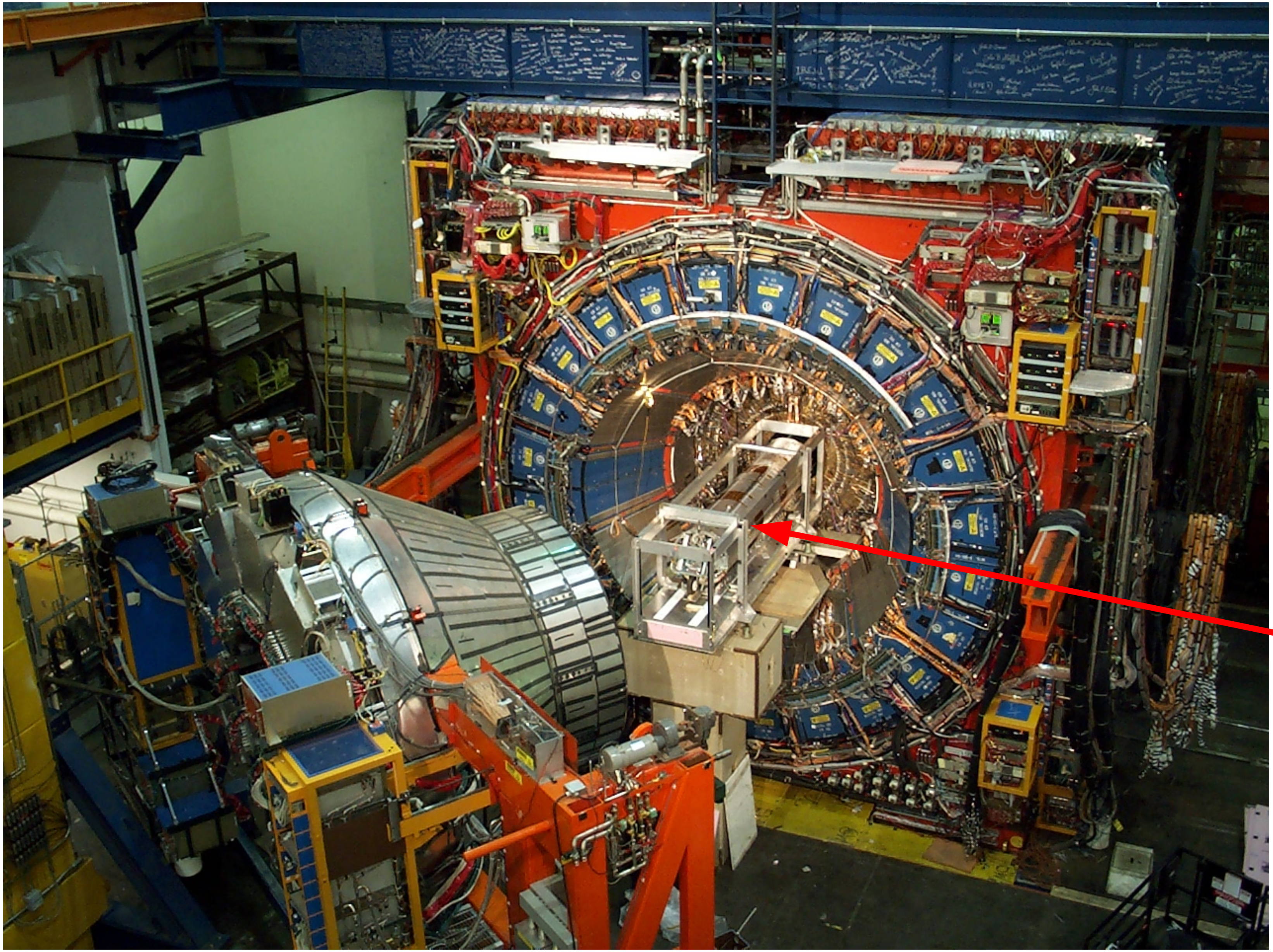
Improved COT
- better stereo
- faster drift

Muons
- improved coverage

Endplug Calorimeter
- larger η coverage for electron ID

SVT Trigger
- triggering on displaced vertices at Level-2

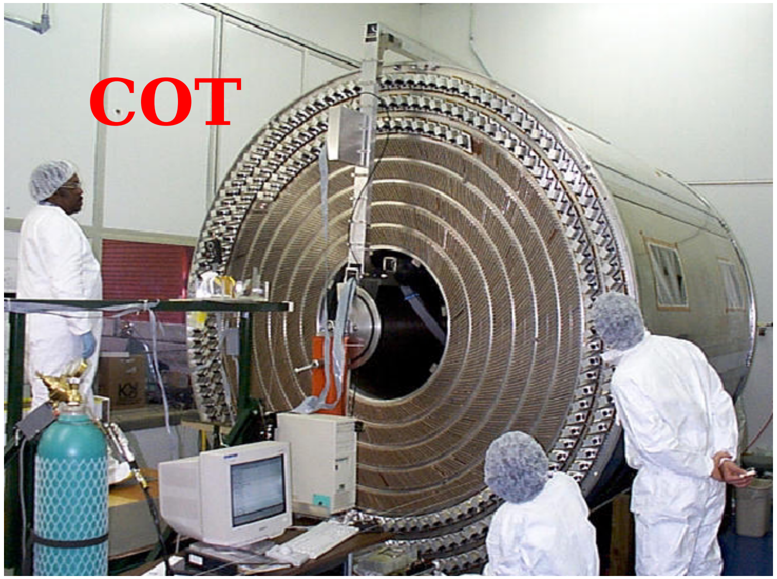
CDF II Detector

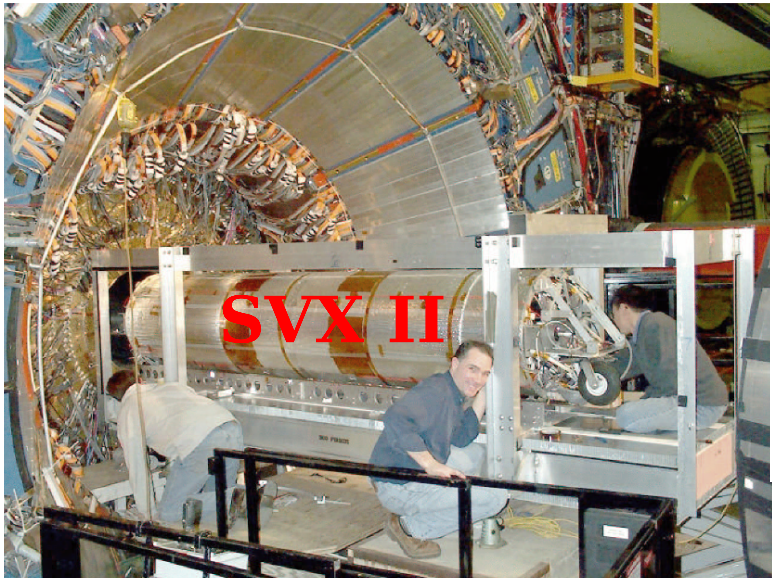


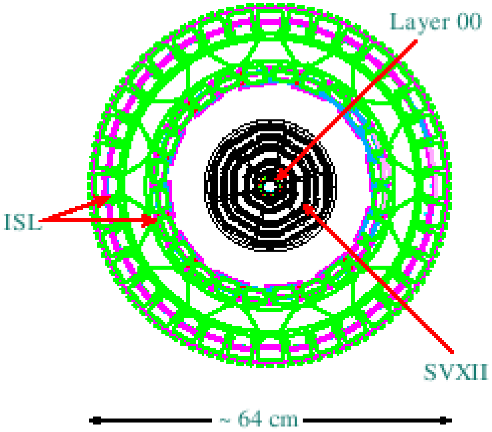
B hadron decay length ~500 μm

Precision vertexing provided by silicon tracking system

Integrated Tracking System







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

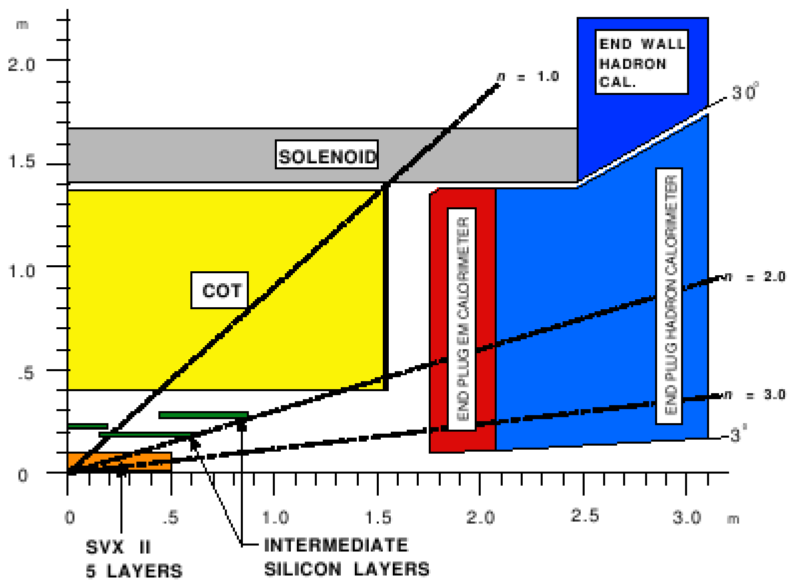
- inner Si layer at beam pipe (R = 1.5 cm)

(L00 not used in our analysis)

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



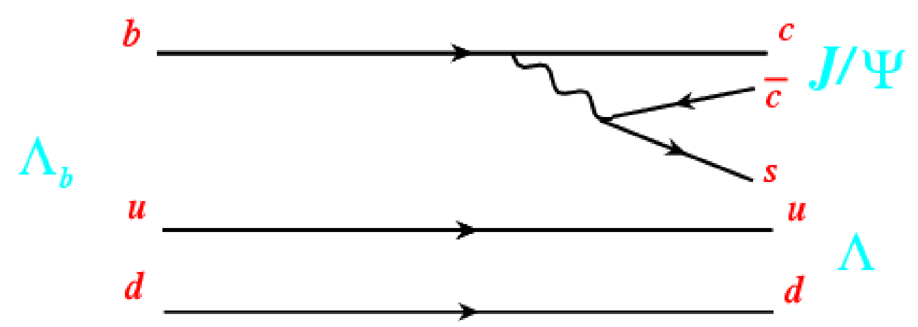
Λ_b Lifetime: Analysis Strategy

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

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)

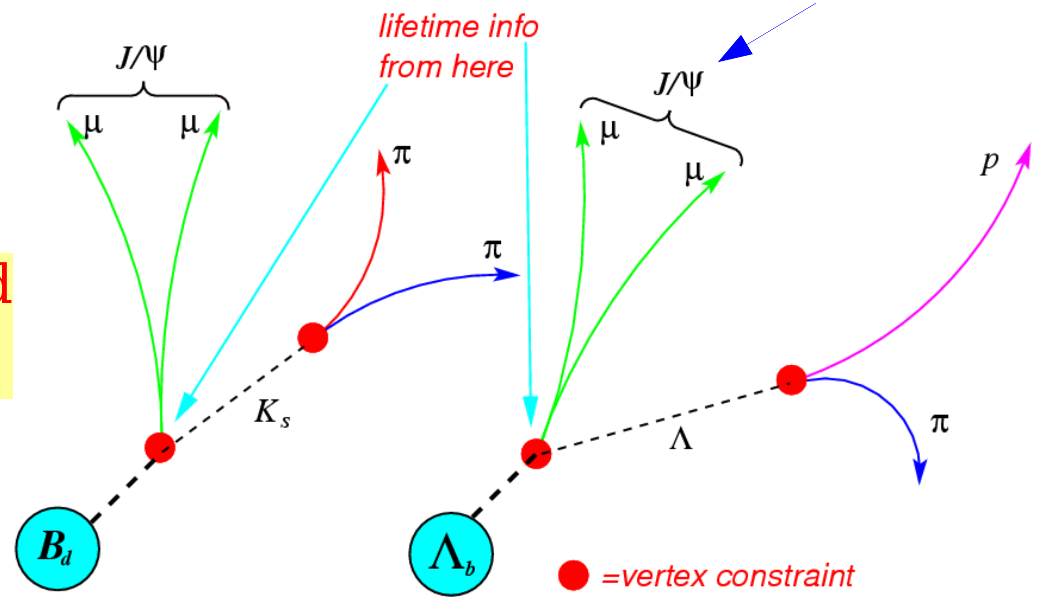
Con:
- Smaller signal $\to$ larger statistical error



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

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

clean trigger for decay



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

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

b-Hadron Lifetimes We Measure

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

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

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

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

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

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

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

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

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

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

← **Statistical errors only (for cross-√)** (applies to the nine modes above)

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

Our primary goal (→ Λ_b)

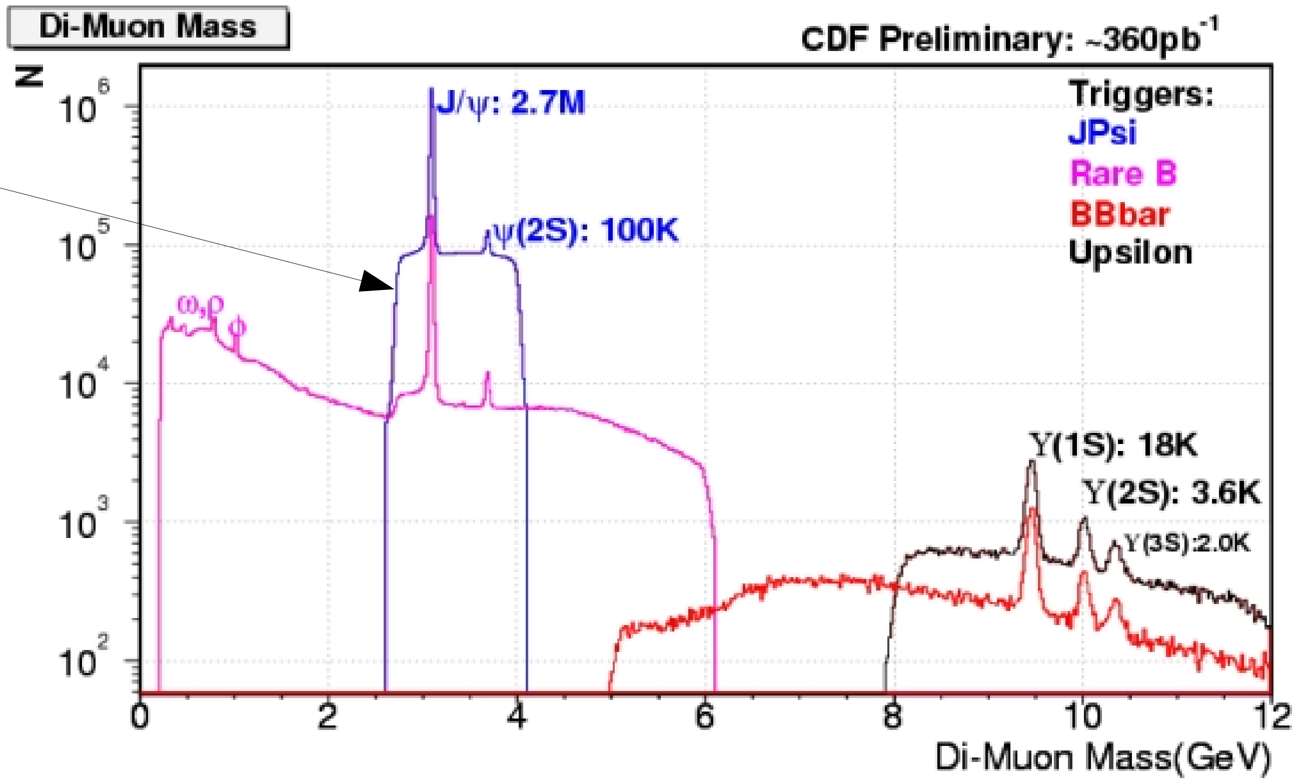
Di-muon Trigger / Dataset

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): $0.6 < |\eta| < 1.0$

$\psi \rightarrow \mu^+\mu^-$ 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 ($\psi \rightarrow \mu^+\mu^-$) trigger

Selection: J/ψ and ψ(2S)

Muons:

- good track-stub match for offline tracks
- ≥3 r-ϕ hits in silicon systems (SVX + ISL)

Vertex quality:

- Prob(χ^2) > 0.1%

want good determination of b-hadron decay vertex

Invariant Mass:

$J/\psi \to \mu\mu$:

$3.014 < M_{\mu\mu} < 3.174$ GeV

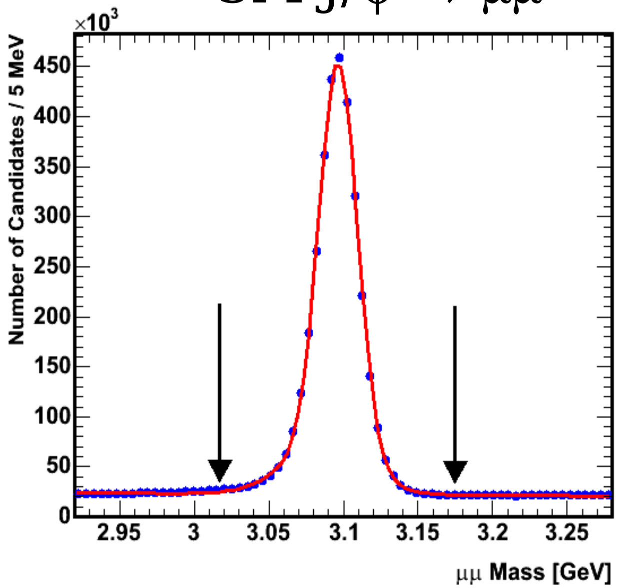
$\psi(2S) \to \mu\mu$:

$3.643 < M_{\mu\mu} < 3.723$ GeV

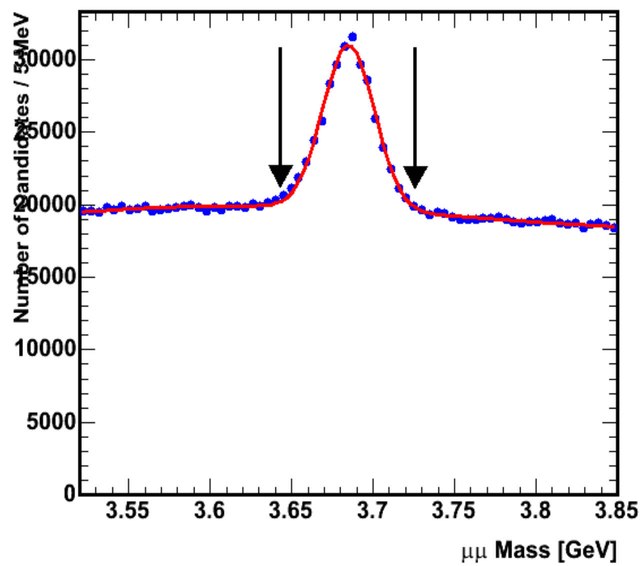
$\psi(2S) \to J/\psi\, \pi^+ \pi^-$:

$3.676 < M_{\mu\mu\pi\pi} < 3.696$ GeV

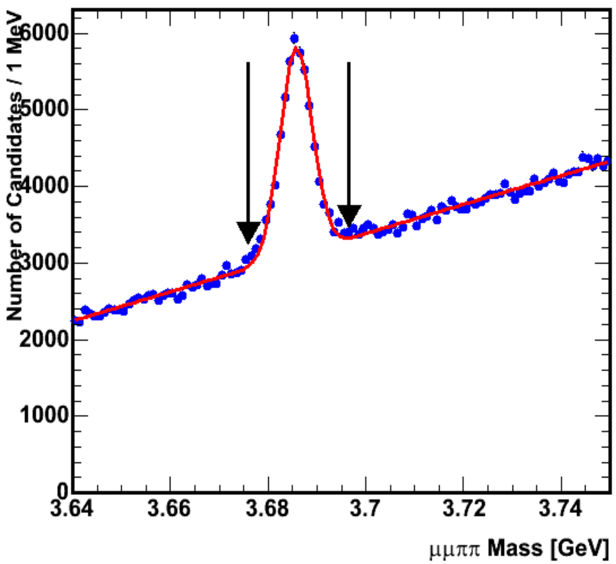
~3M $J/\psi \to \mu\mu$



~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

want high-quality tracks

Vertex quality:

- Prob(χ^2) > 0.1%

common vertex

Decay length:

- L_{xy} > 0.1 cm

not too close to PV (reduce trk comb)

Invariant Mass:

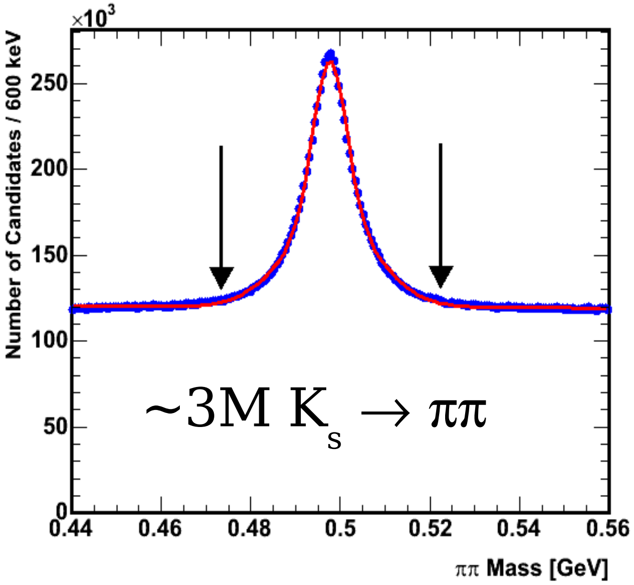
- $K_s \to \pi\pi$: $0.472 < M_{\pi\pi} < 0.523$ GeV
- $\Lambda^0 \to p\pi$: $1.107 < M_{\pi p} < 1.125$ GeV

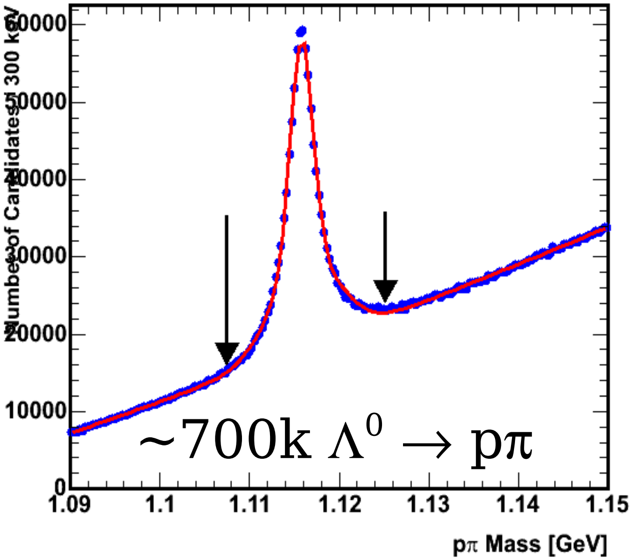
signal region

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

reduce V^0 cross-contamination





Note: $c\tau(K_s)$ = 2.7cm, $c\tau(\Lambda^0)$ = 7.9cm

Selection: *b*-Hadrons

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

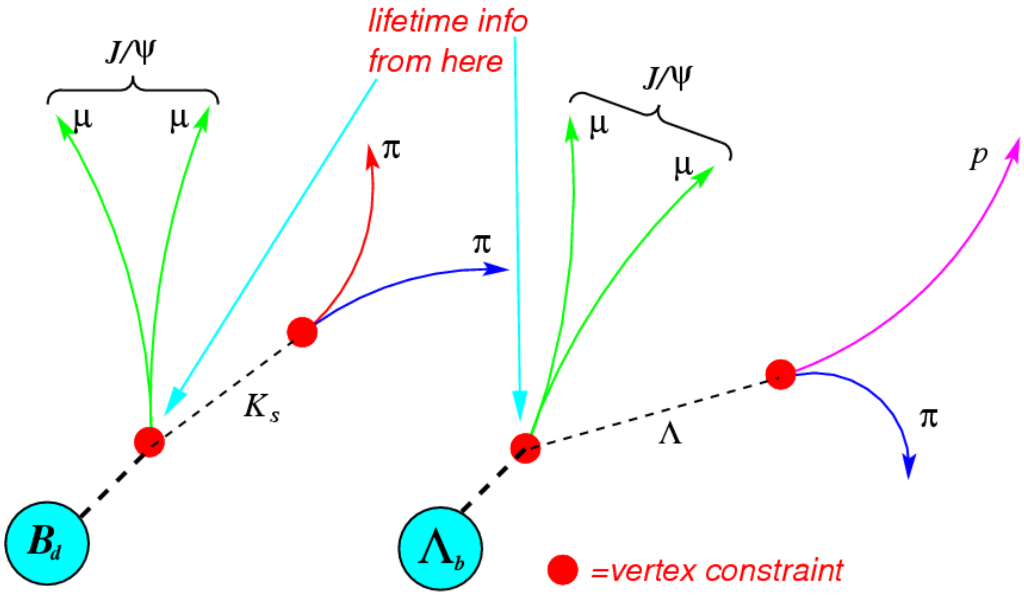
$\to$ Selection/optimization similar for other B modes

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)



Selection Optimization

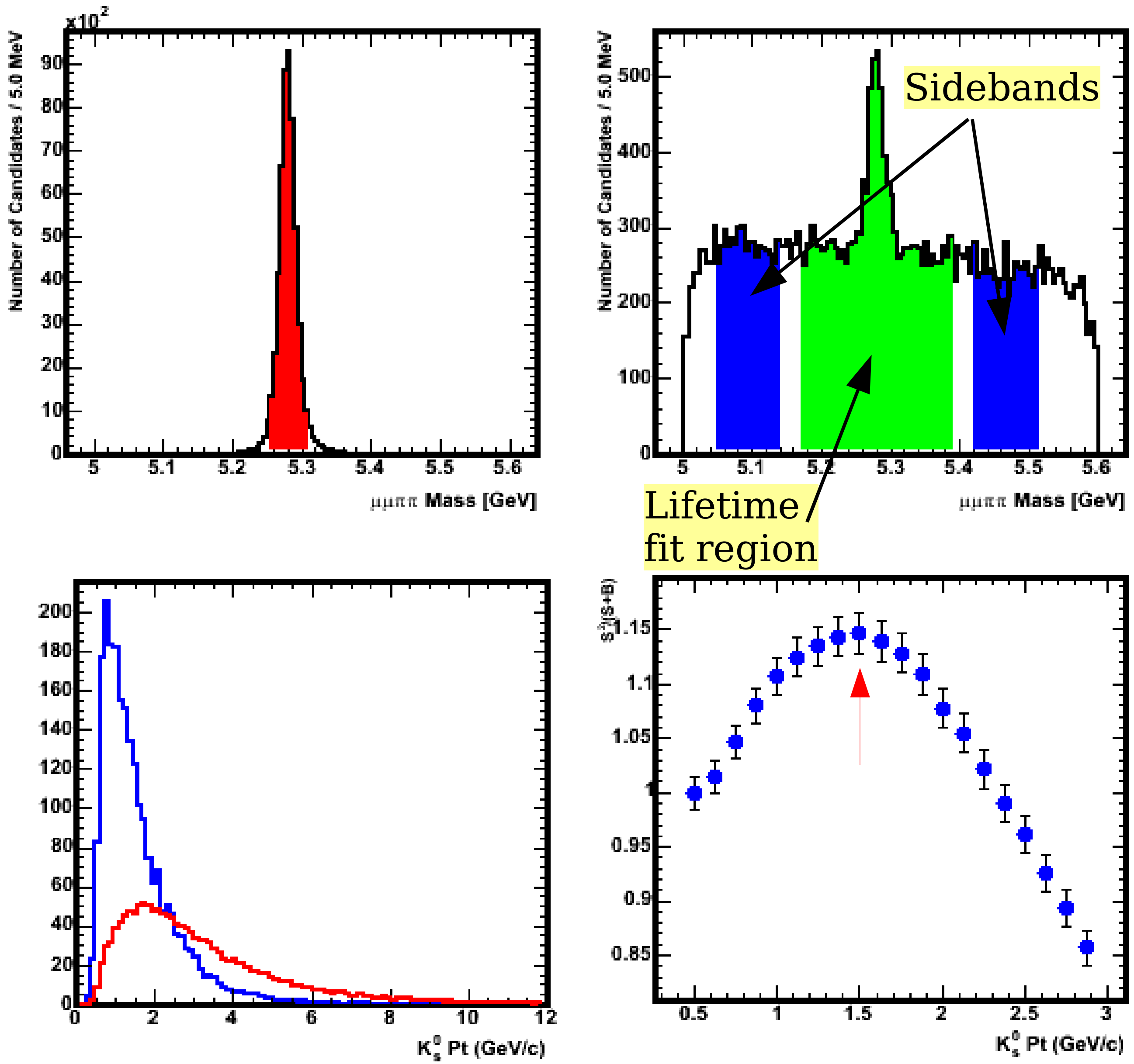
- Single-*b* Monte Carlo for signal
- "Far" sidebands in data for background
- N-1 Optimization of each cut for best for $S^2/(S+B)$

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}

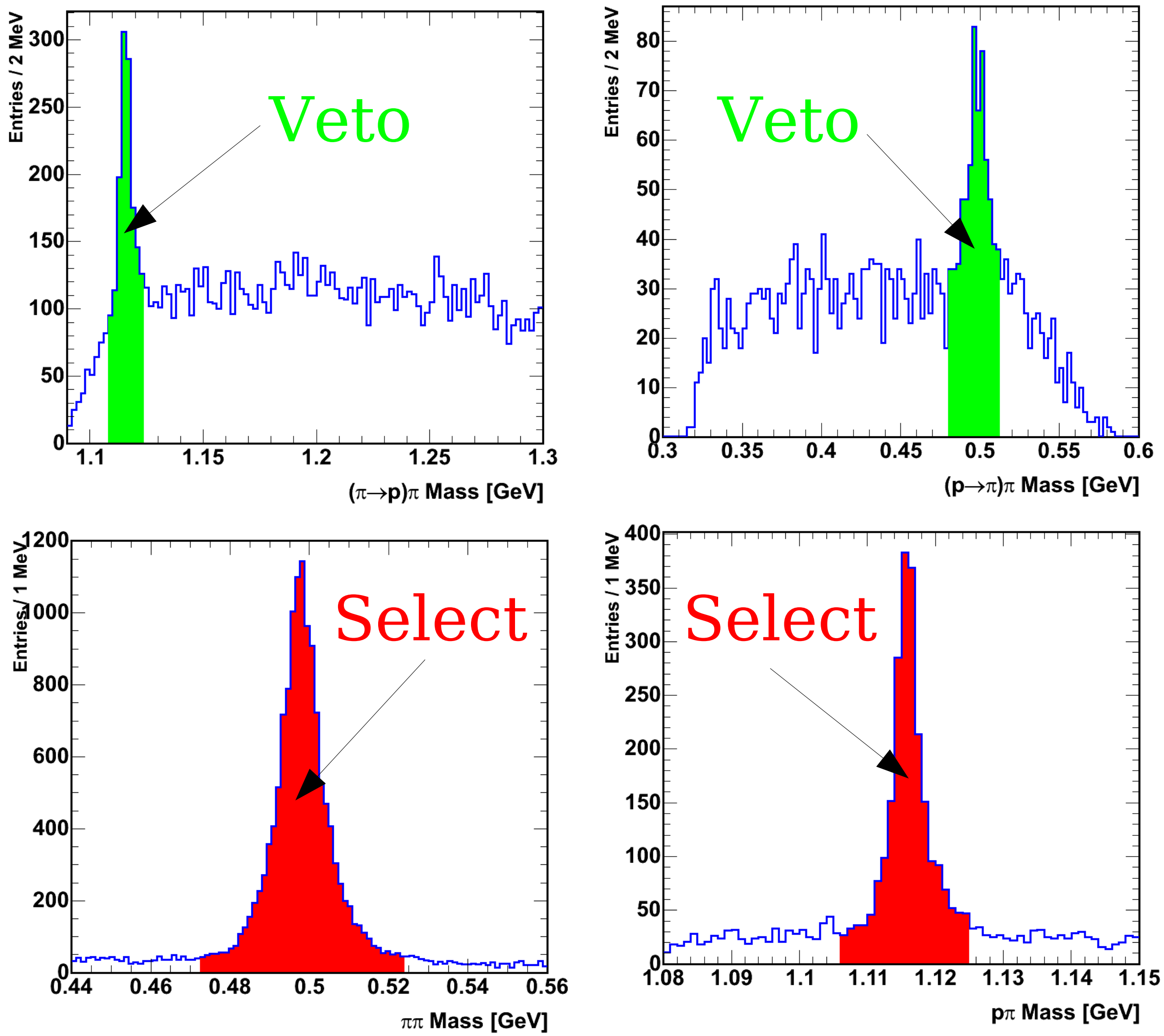


K_s and Λ^0 after *b*-Hadron Selection

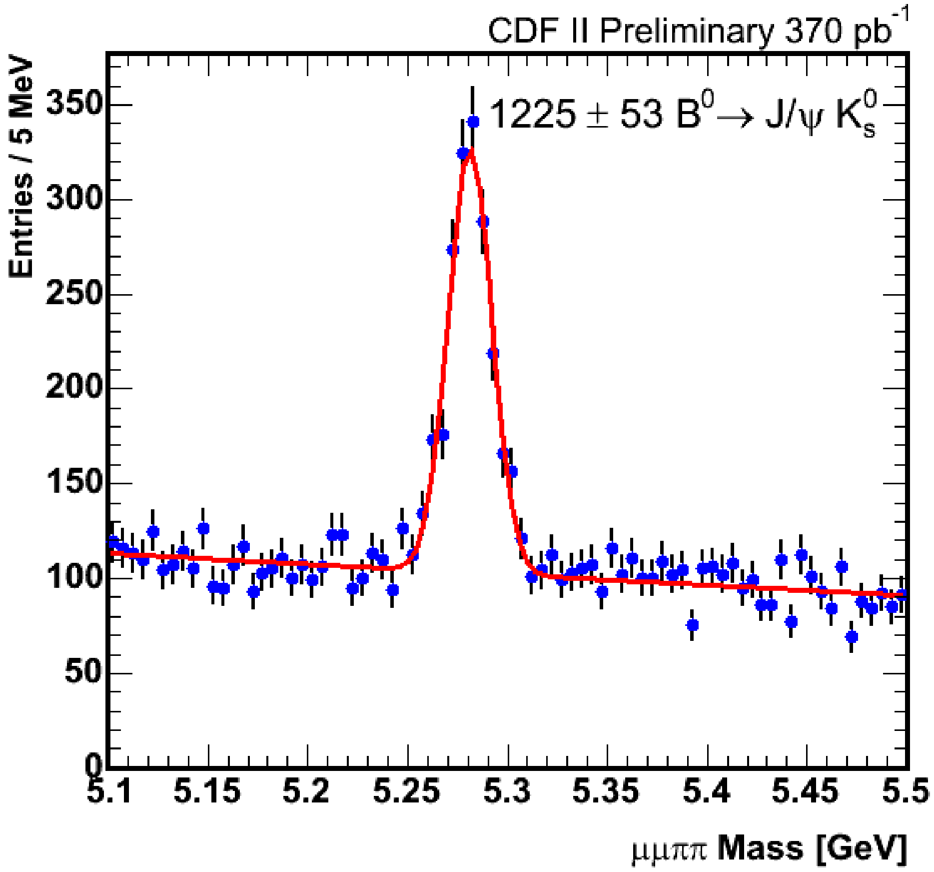
- Veto Λ^0 in K_s and K_s in Λ^0 using $p \leftrightarrow \pi$ swapped-mass hypothesis to suppress V^0 cross-contamination

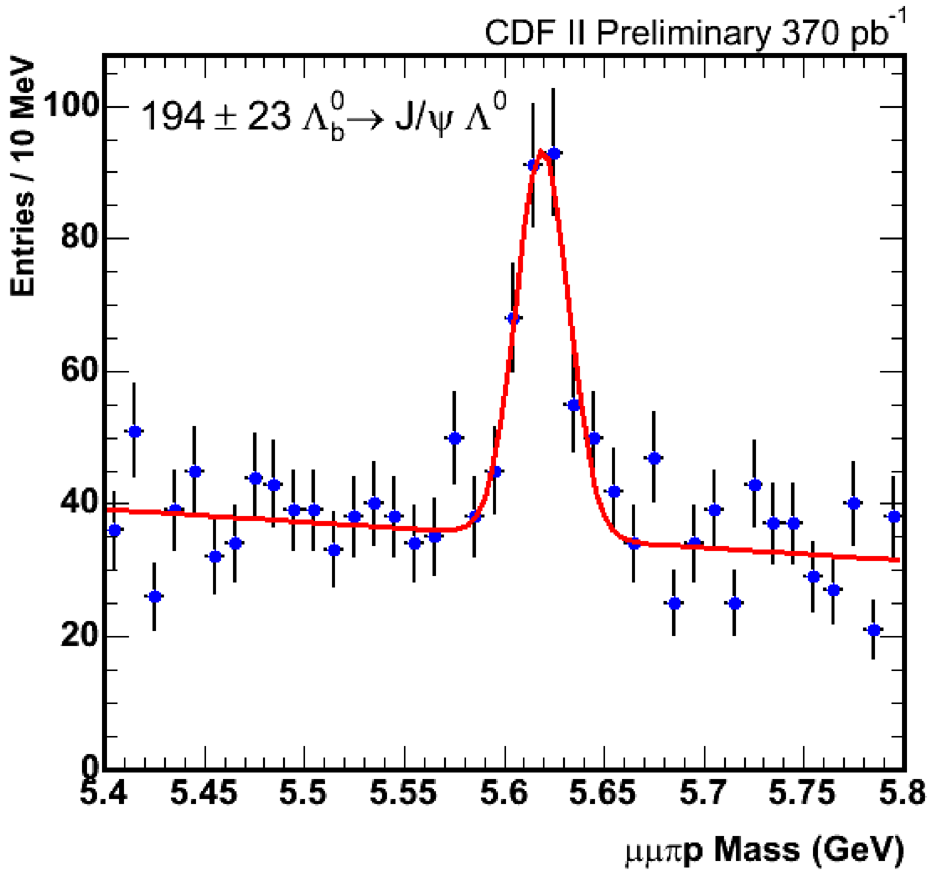
- Very clean $\rightarrow$ Majority of background comes from combinations of real J/ψ and real K_s,Λ^0

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



b-Hadron Yields: B^0 and Λ_b



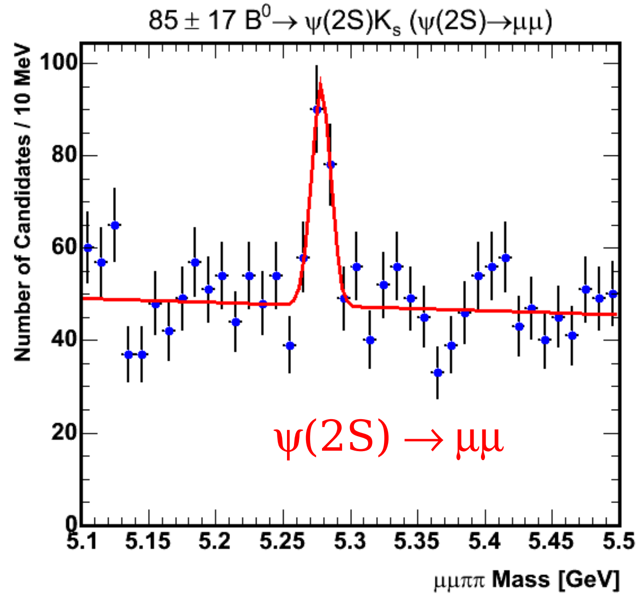


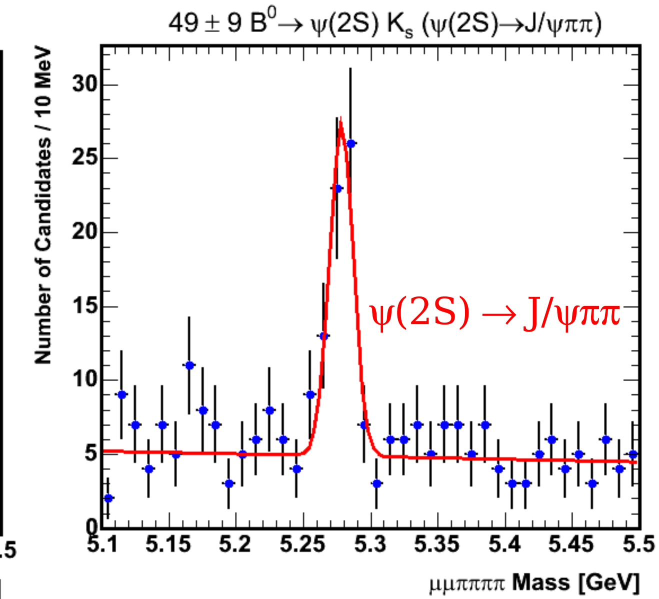
1225 $B^0 \rightarrow J/\psi\, K_s$

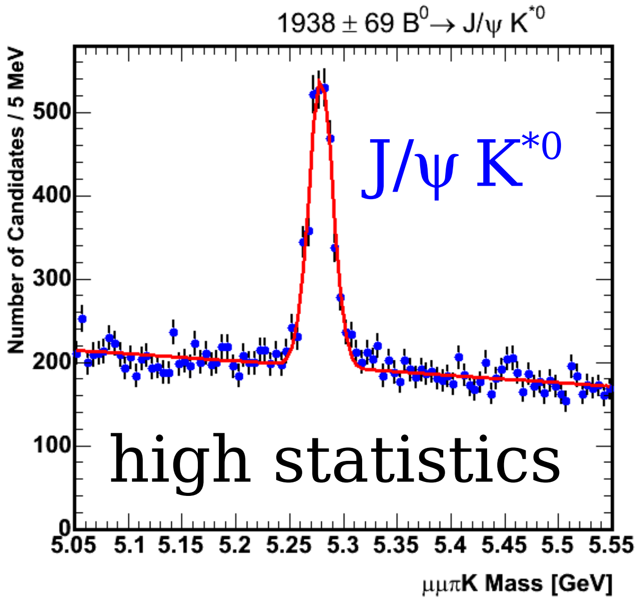
194 $\Lambda_b \rightarrow J/\psi\, \Lambda^0$

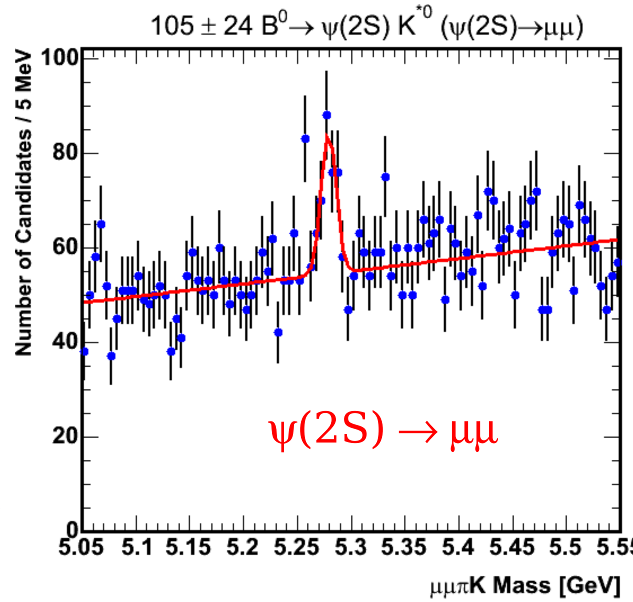
b-Hadron Yields: Other B^0 Modes

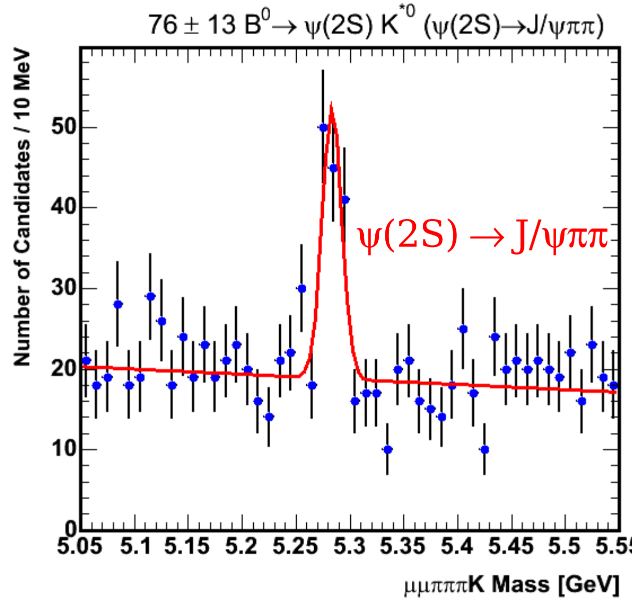
$\psi(2S)\ K_s$







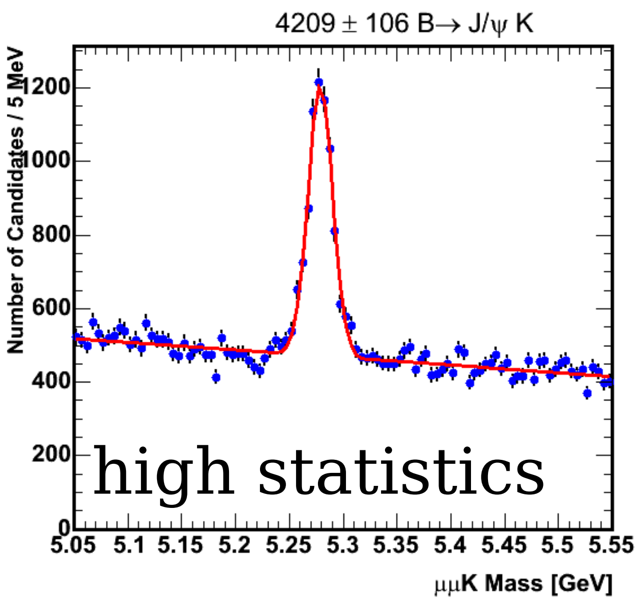


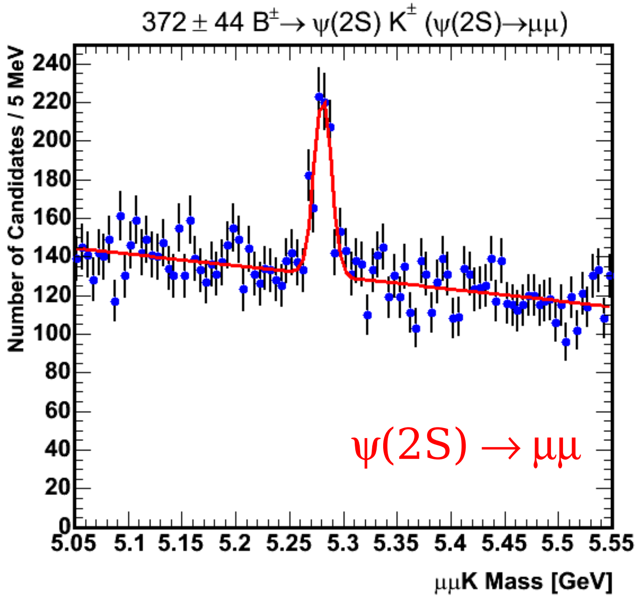


$\psi(2S)\ K^{*0}$

b-Hadron Yields: Other B^+ Modes

$J/\psi\ K^+$

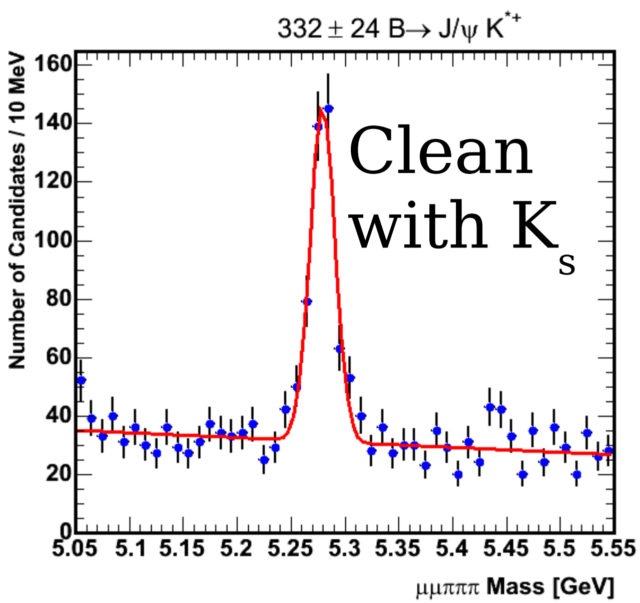


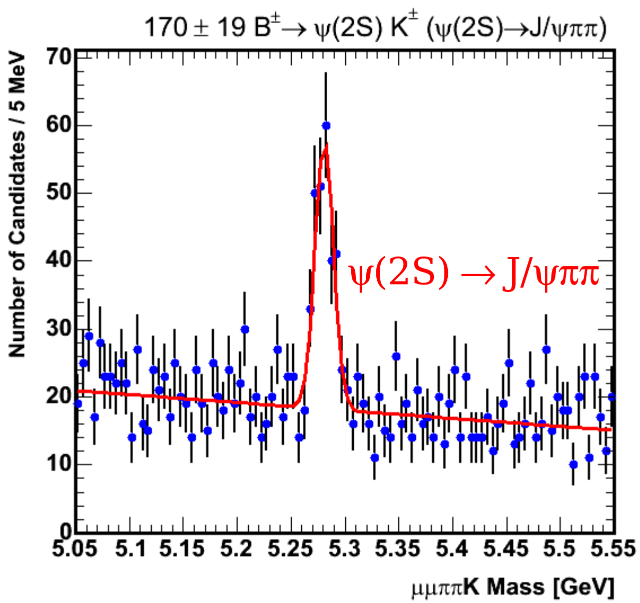


$\psi(2S)\ K^+$

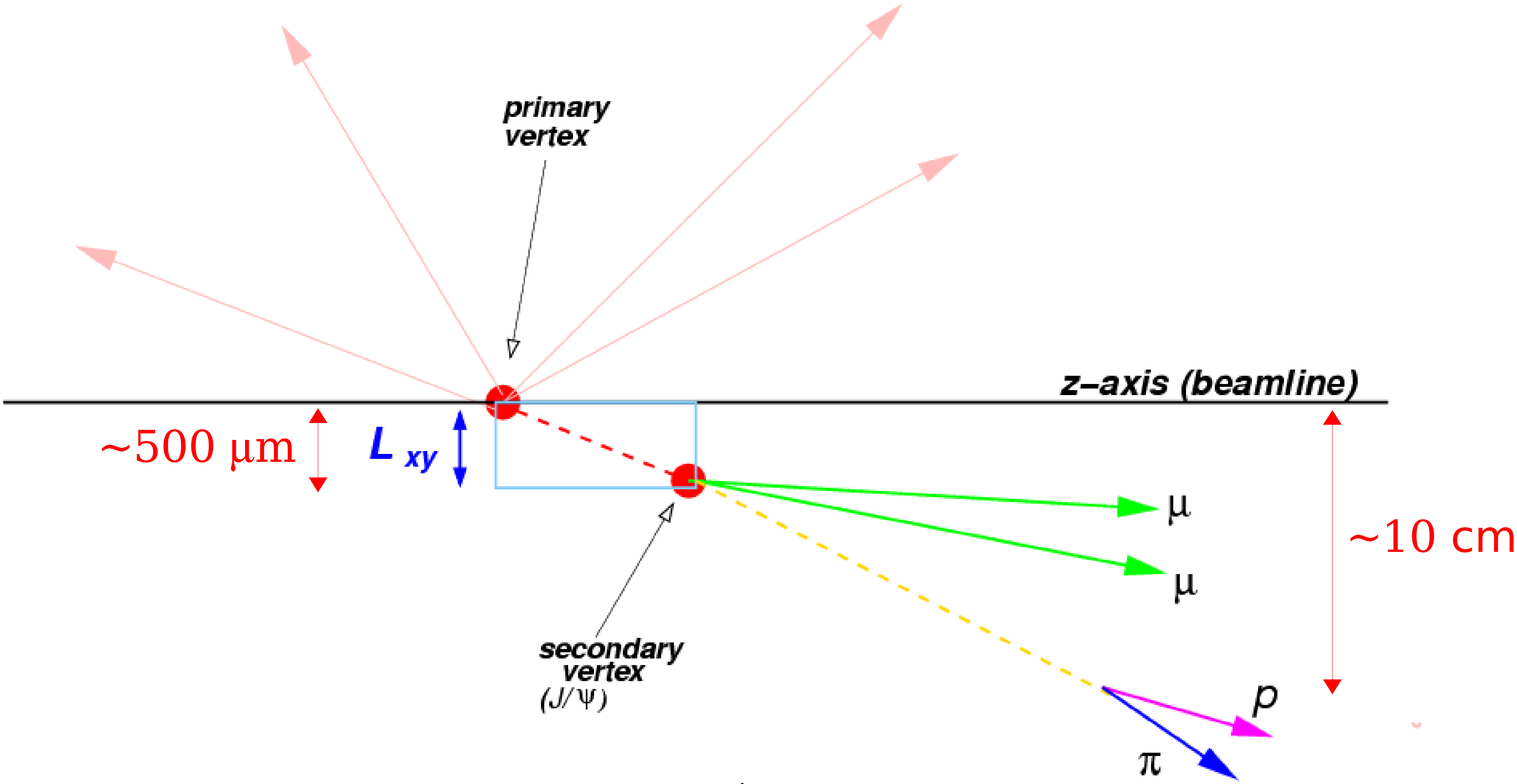
$J/\psi\ K^{*+}$

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





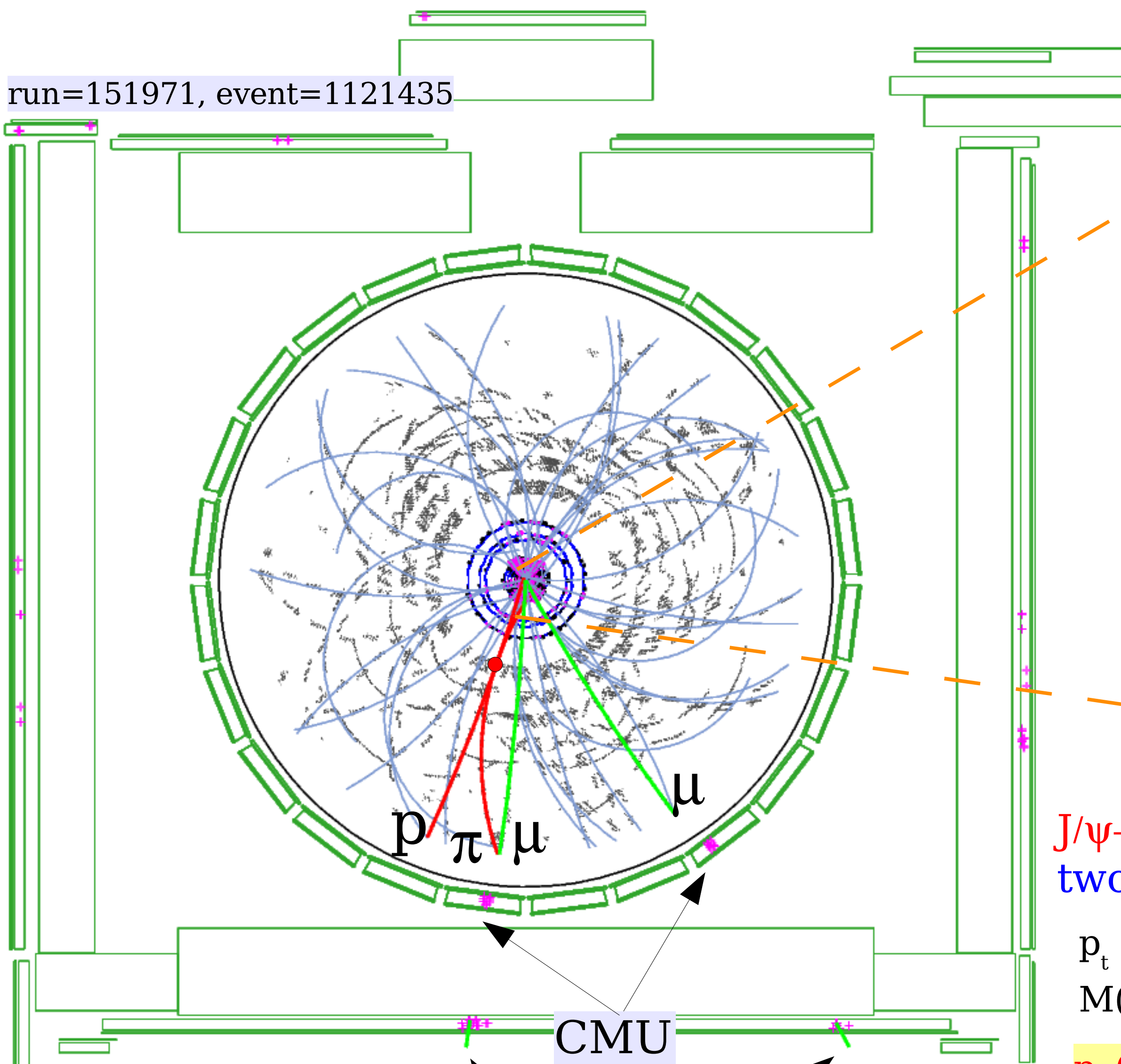
Determining the Lifetime

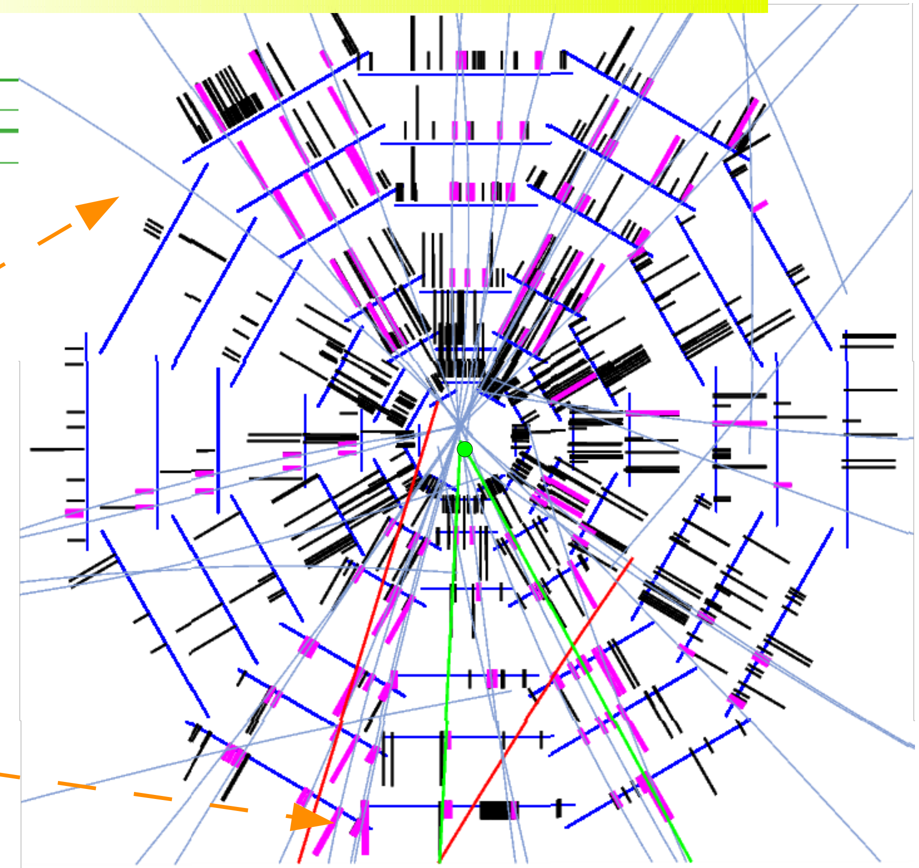


$$\text{Proper Decay Length (PDL)} = \frac{L^b_{xy}}{(\beta\gamma)^b_T} = L^b_{xy}\, c\, \frac{M_b}{p^b_t}$$

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

Λ_b Candidate Event





J/ψ→μμ candidate with two CMUP muons:

$p_t(\mu_1,\mu_2)$ = (5.7,4.0) GeV
$M(\mu\mu)$ = 3.100 GeV/c^2

$p_t(\Lambda_b)$ = 14.0 GeV
$M(\mu\mu p\pi)$ = 5.615 GeV/c^2
ct ~ 2 mm

$\Lambda^0 \rightarrow p\pi$ candidate with good $L_{xy}/\sigma(L_{xy})$:

$L_{xy}(\Lambda^0)$ = 40 cm
$\sigma(L_{xy})(\Lambda^0)$ = 0.4 cm
$p_t(p,\pi)$ = (4.4,0.6) GeV
$M(p\pi)$ = 1.116 GeV/c^2

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 :

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

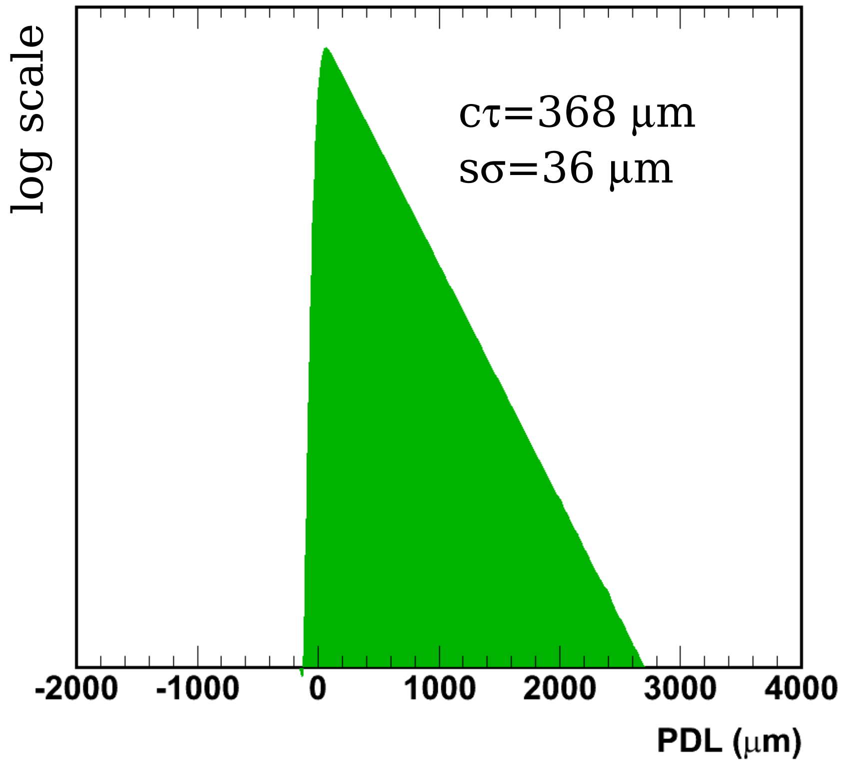
where:

τ = signal lifetime (the goal)

s = overall scale factor on PDL errors

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

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



Fit Model: Background PDL

Background PDL modeled as sum of four components:

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

- zero lifetime (prompt) → $(1-f_- - f_+ - f_{++})\ \delta(0)$
- "negative lifetime" (resolution tails) → $f_-\ E(-\lambda_i|\lambda_-)$
- long-lived background ($b \to J/\psi\ X$ combined with unrelated tracks) → $f_+\ E(\lambda_i|\lambda_+)$, $f_{++} E(\lambda_i|\lambda_{++})$

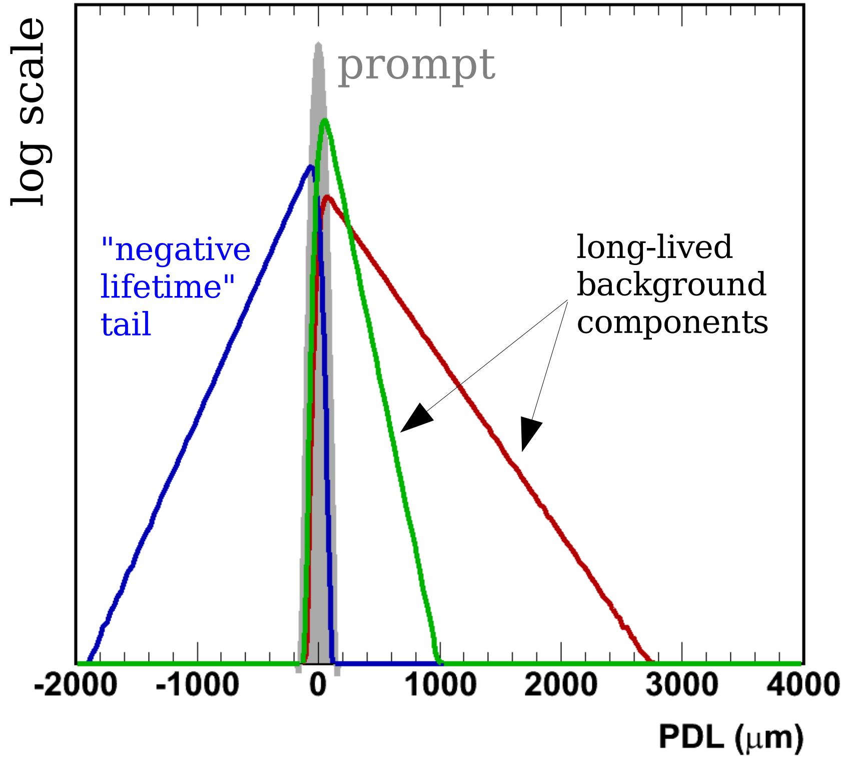
where:

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



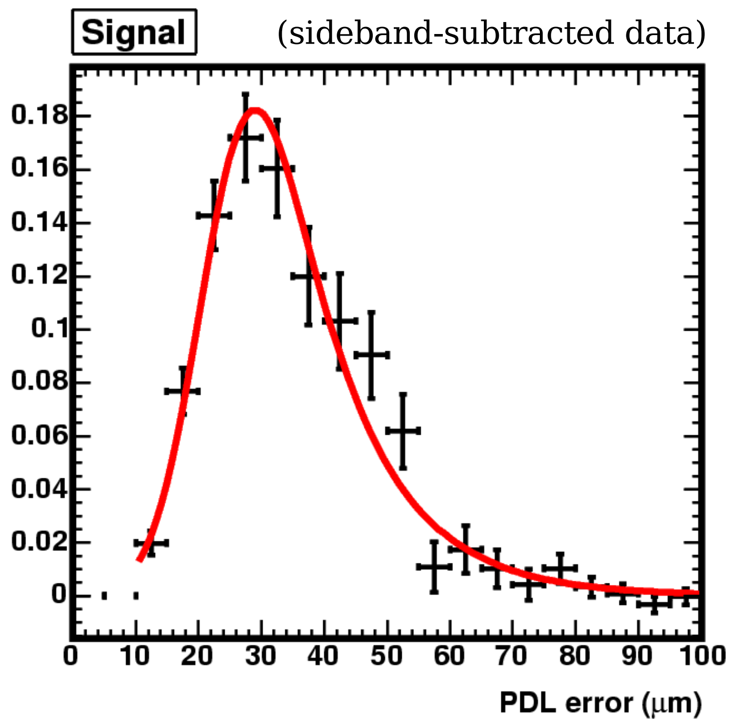
Fits with different shape assumptions used to constrain systematic

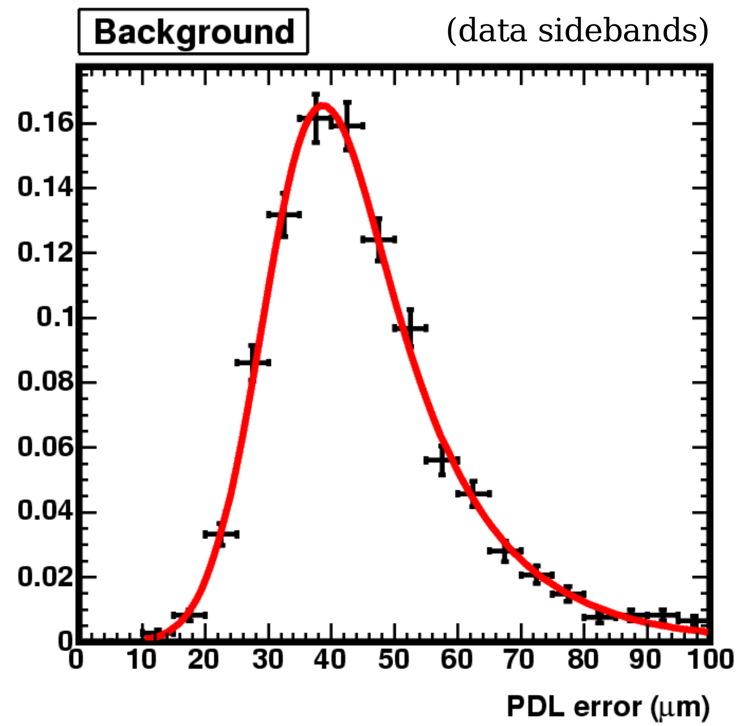
Fit Model: PDL Error

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 $s_M \sigma_i^m$:

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

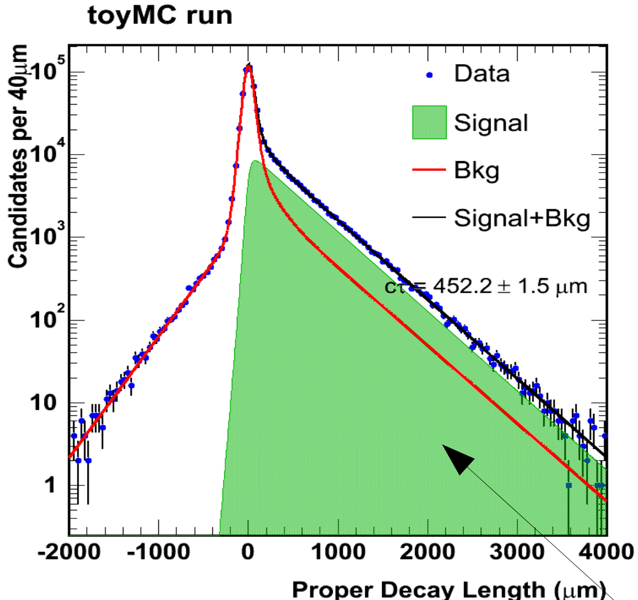
where:

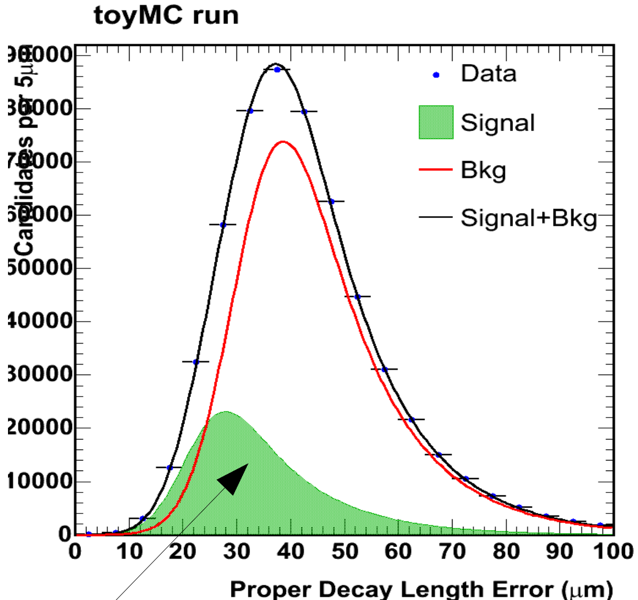
M = mass
s_M = scale factor on mass errors

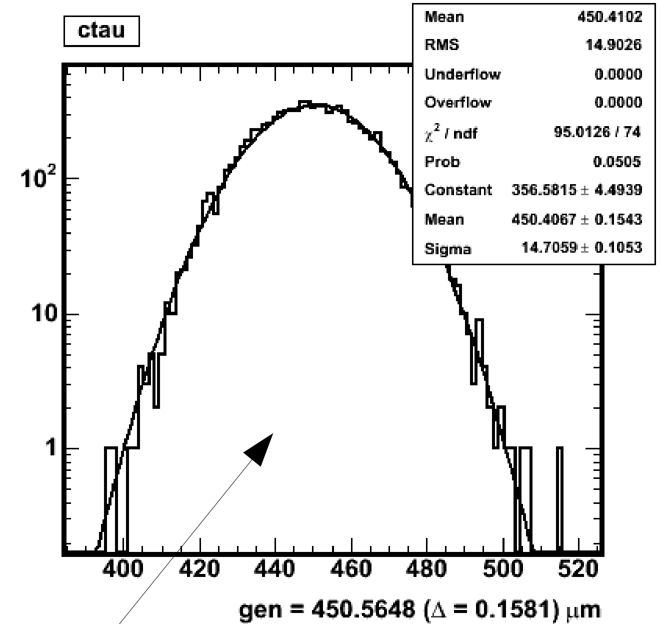
Linear mass shape used as background mass model (single parameter, C_0, after normalization over mass window (M_{low}, M_{high})):

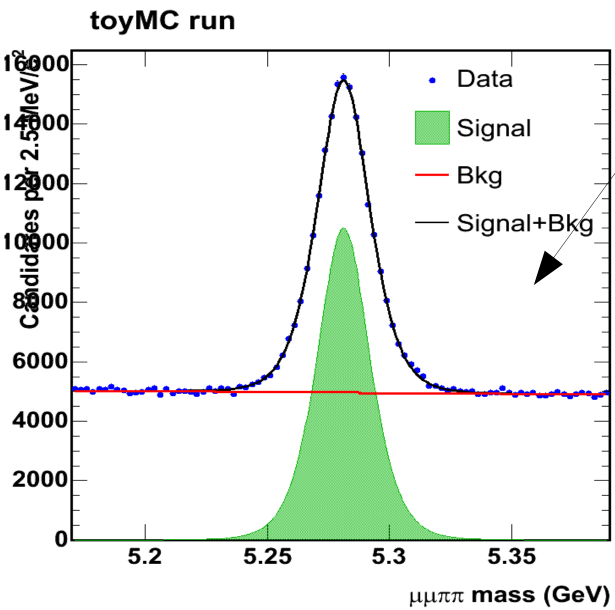
$$P_{bkg}^m(m_i | C_0) = \left(\frac{2}{M_{high}^2 - M_{low}^2} - \frac{2C_0}{M_{high} + M_{low}} \right) m_i + C_0$$

Validation: Toy Monte Carlo



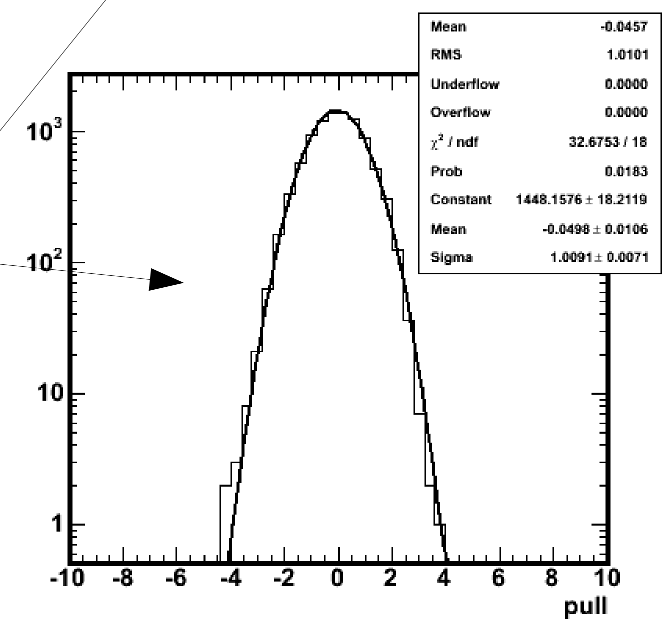






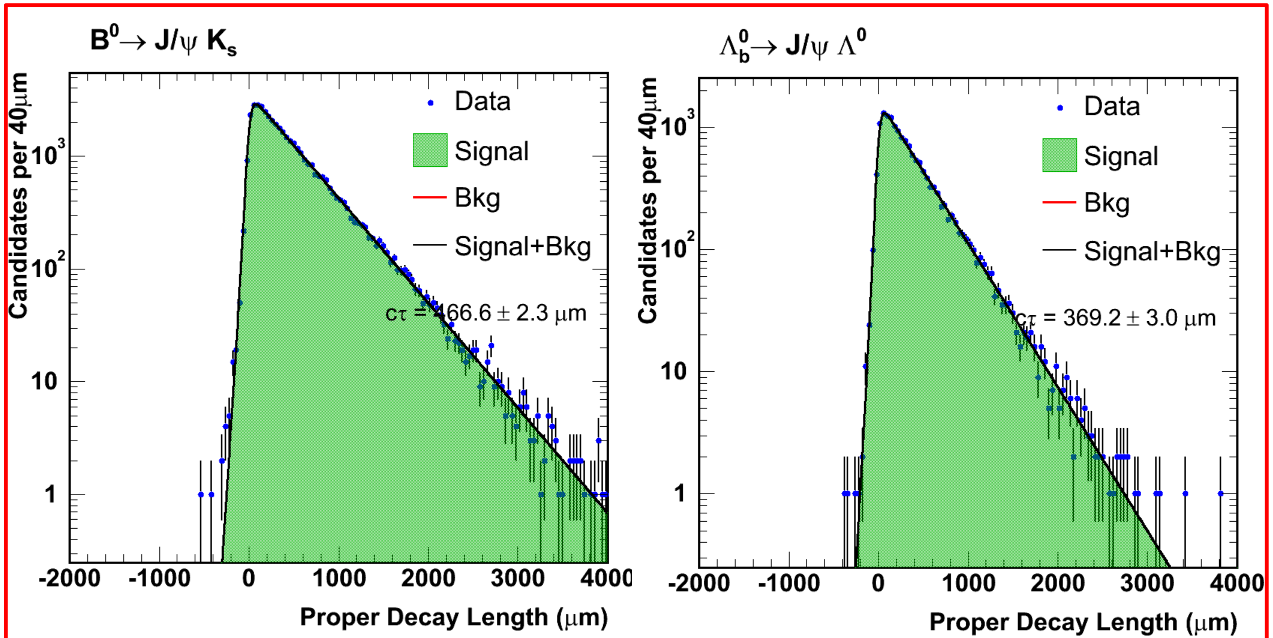
1 toy run with
20× data size

10k toy runs
with same
size as data



Generated parameters
consistent with fitted
⇒ valid fitting procedure

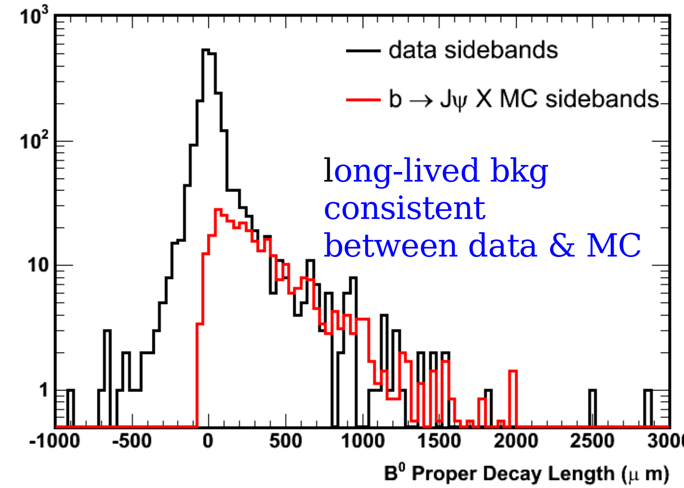
Validation: Realistic MC

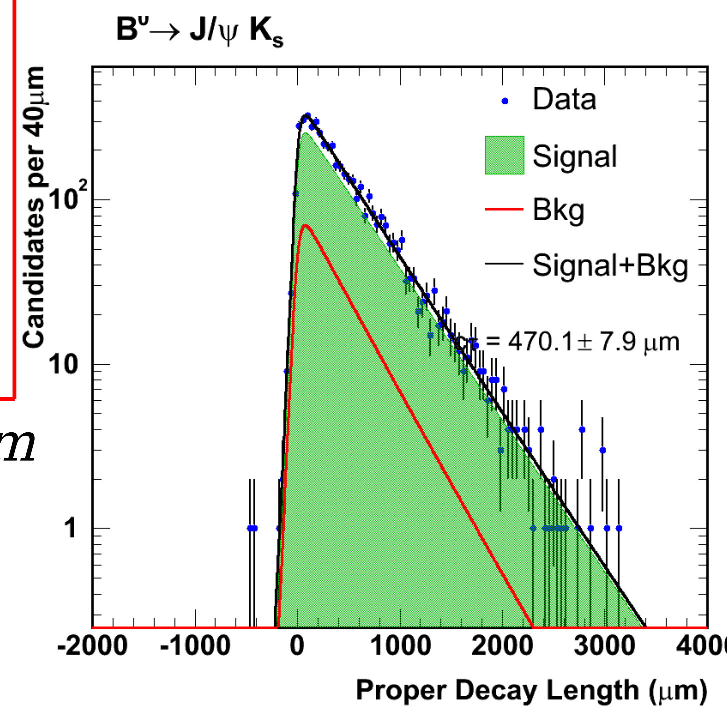


$Fit = 466.6 \pm 2.3\,\mu m$ $Fit = 369.2 \pm 3.0\,\mu m$

$Gen = 464\,\mu m$ $Gen = 368\,\mu m$

Signal MC





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

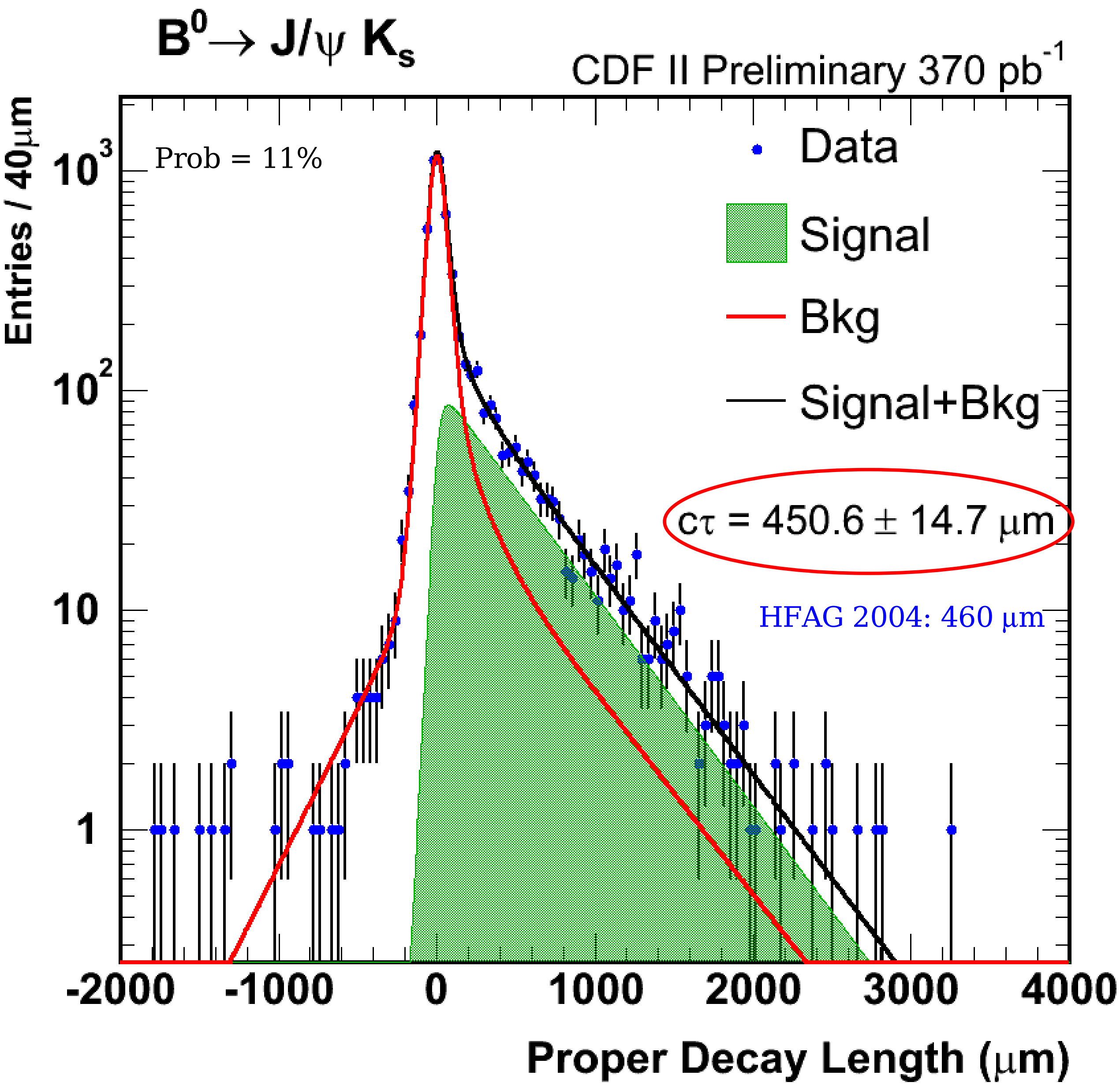
$Gen = 464\,\mu m$

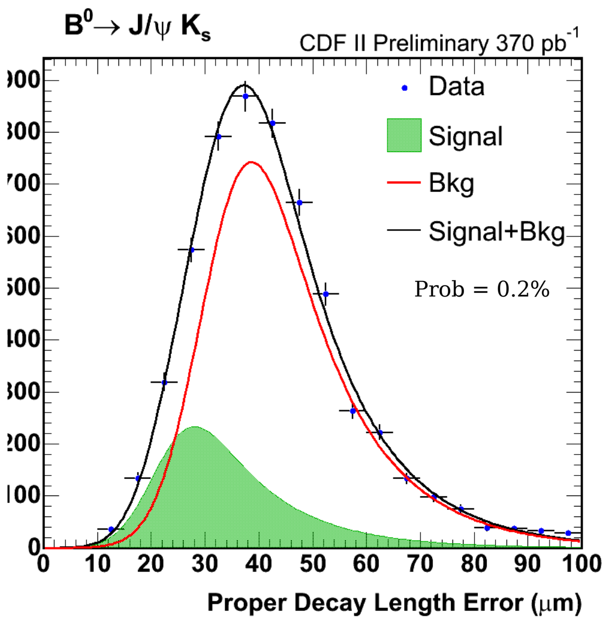
***b* → J/ψ X**

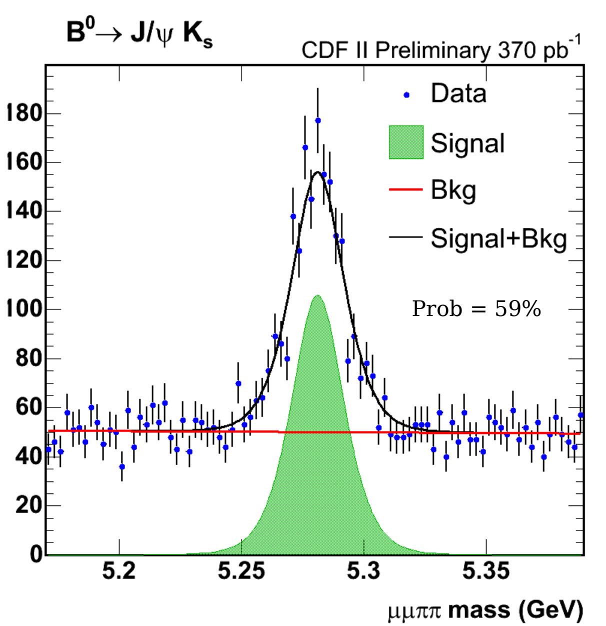
Pythia MC

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

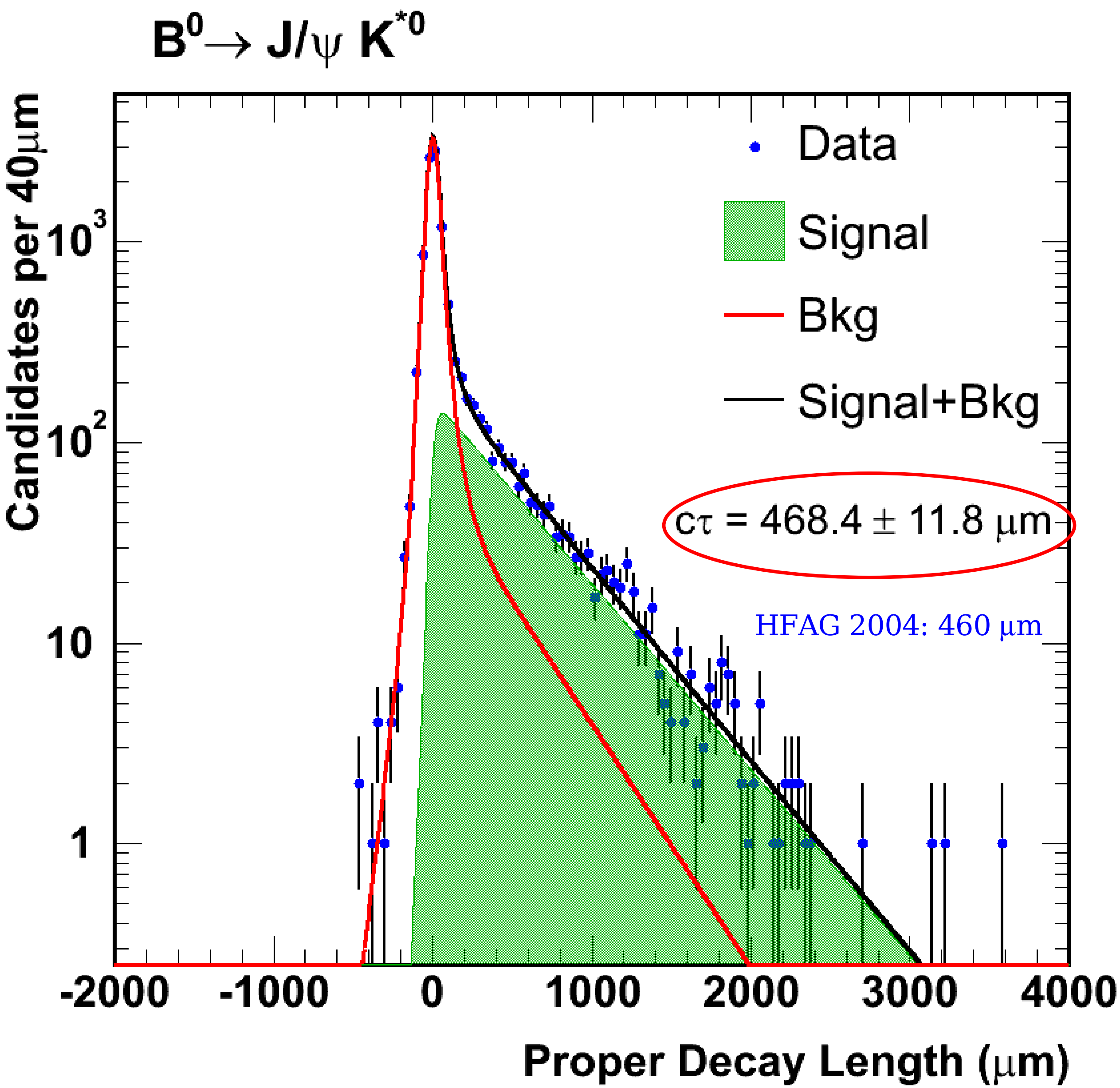
Fit Results: $B^0 \rightarrow J/\psi K_s$

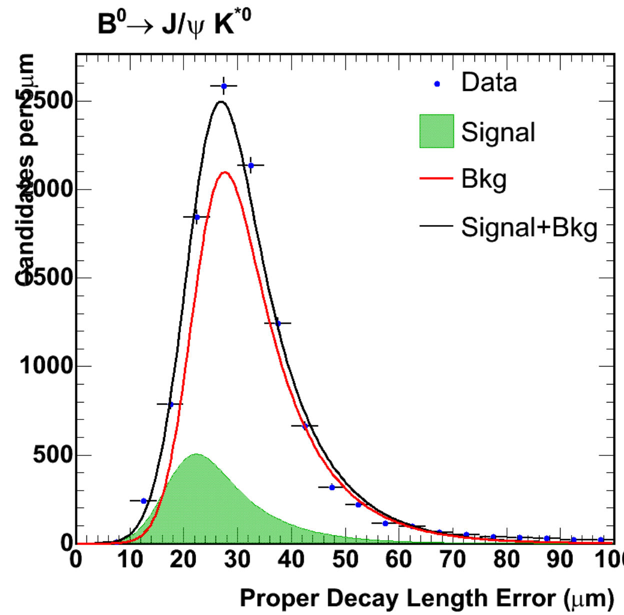


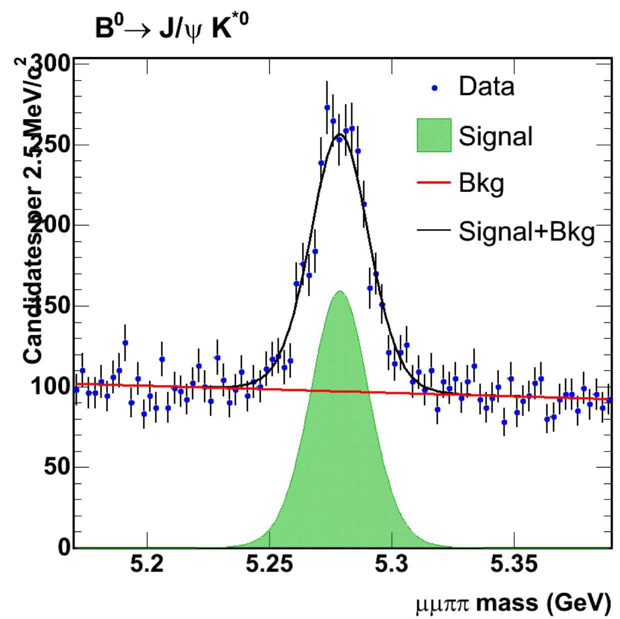




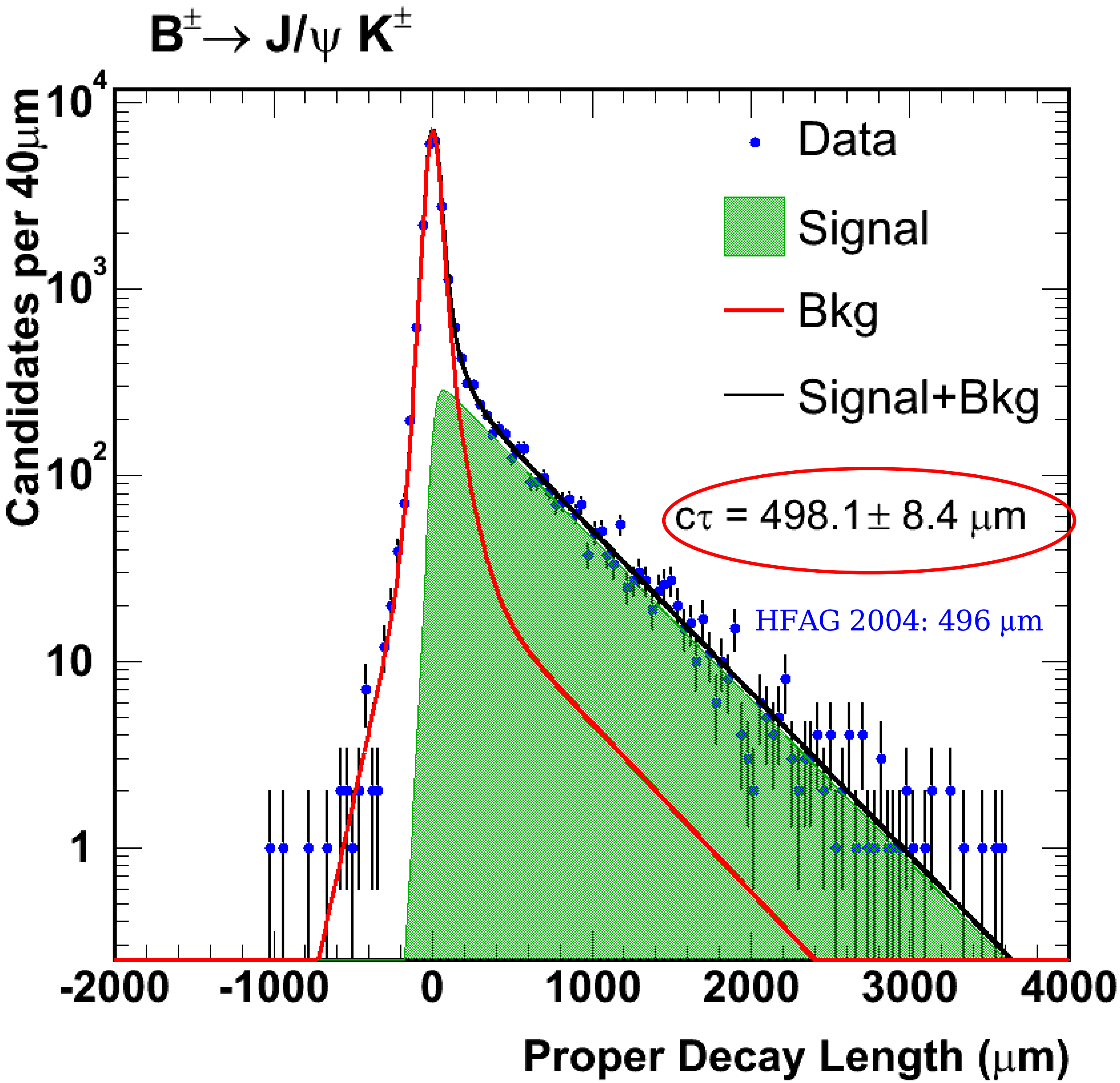
Fit Results: $B^0 \rightarrow J/\psi K^{*0}$

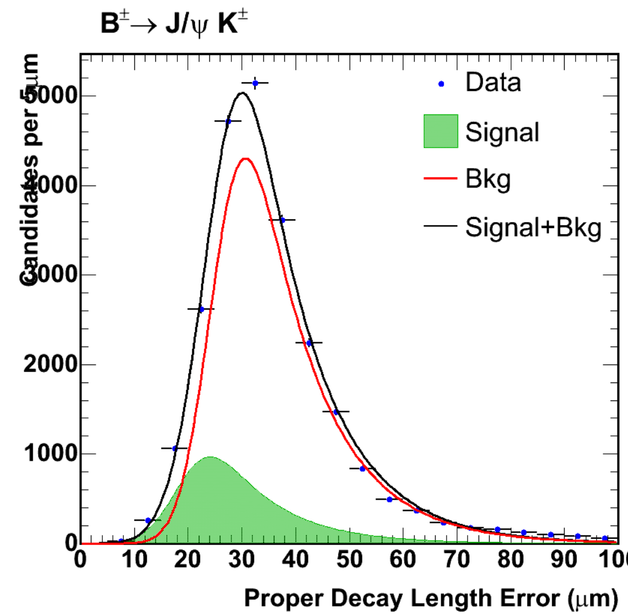


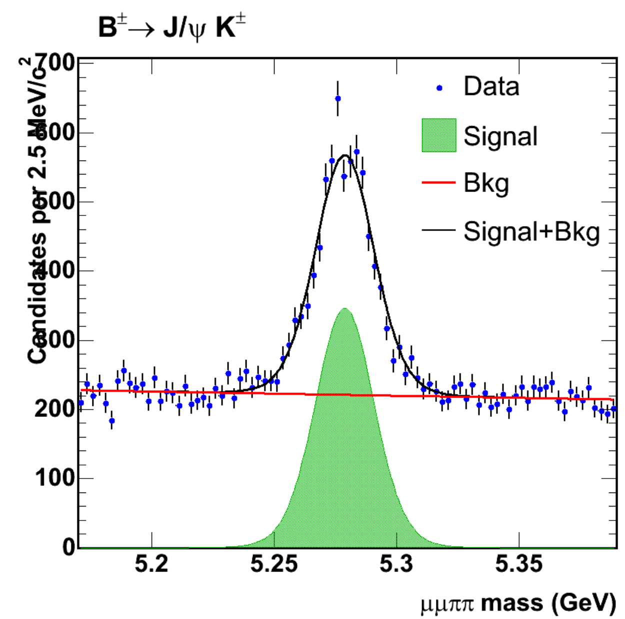




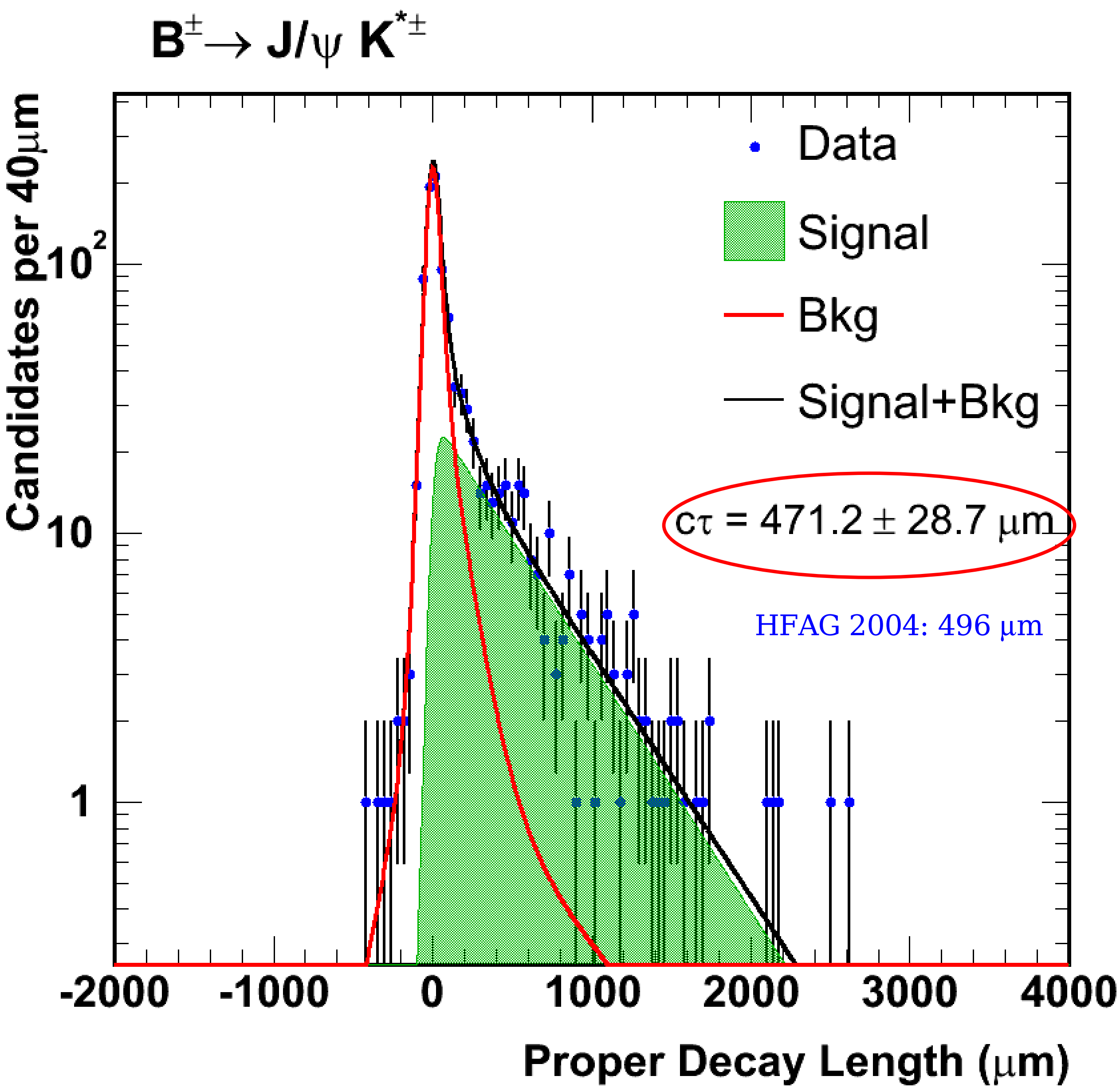
Fit Results: $B^+ \to J/\psi K^+$

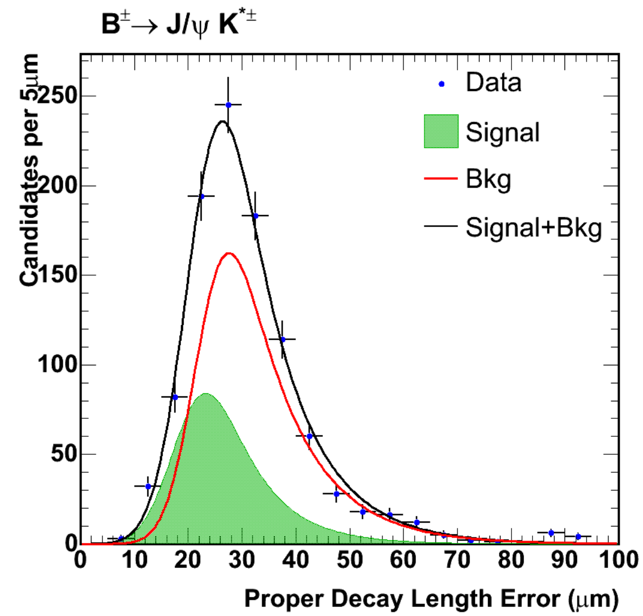


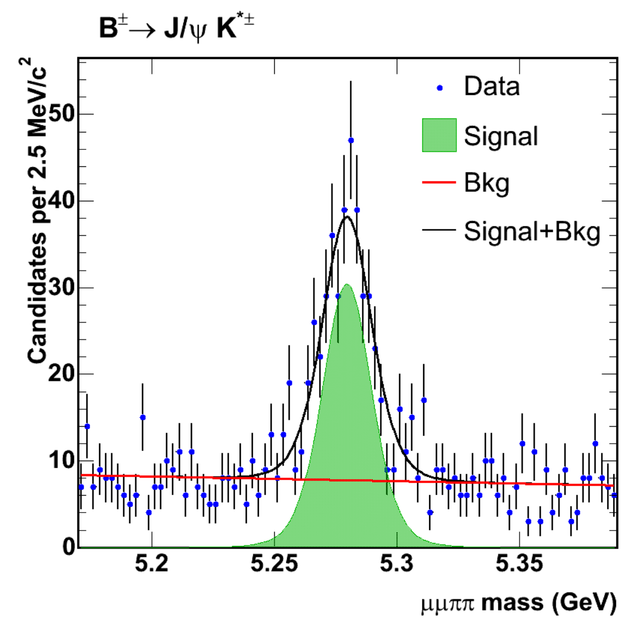




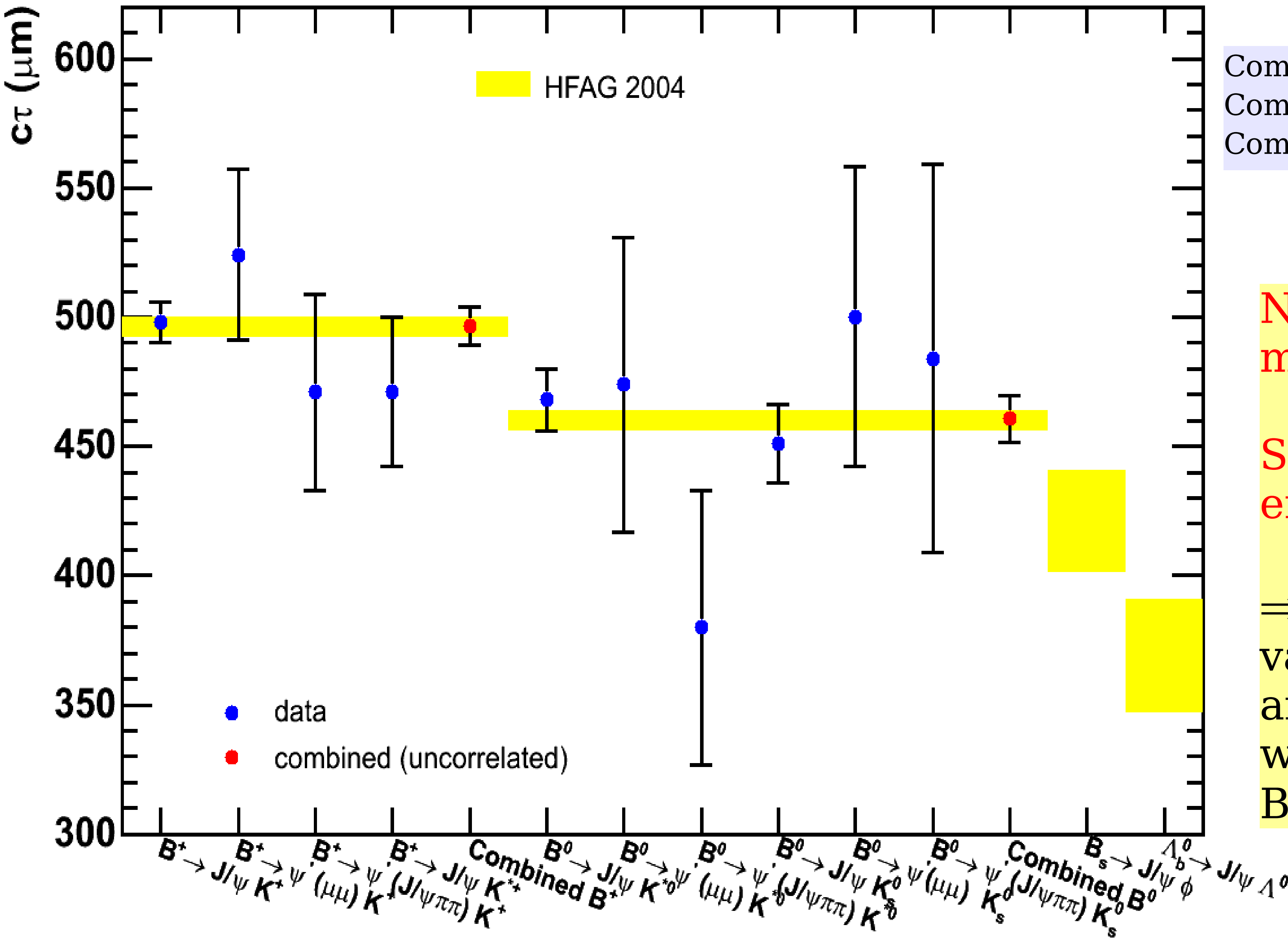
Fit Results: $B^+ \to J/\psi K^{*+}$







b-Hadron Lifetime Summary



Combined B^{+} : 497 ± 7 μm
Combined B^{0} : 461 ± 9 μm
Combined Δ_{PDG}: 0.6 ± 5.6 μm

Not a measurement:

Statistical errors only!

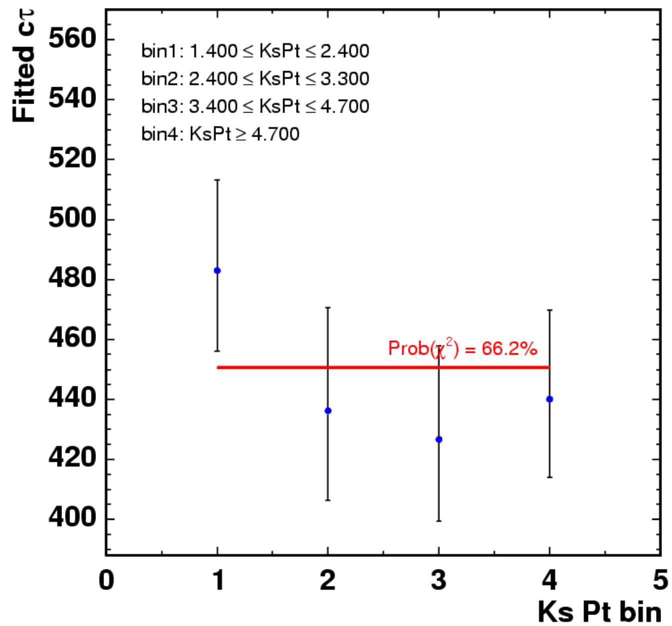
⇒ High-level validation of analysis for well-established B^{0}/B^{+} lifetimes

Lifetime Cross-Checks

Look for unexpected $c\tau$ dependence:

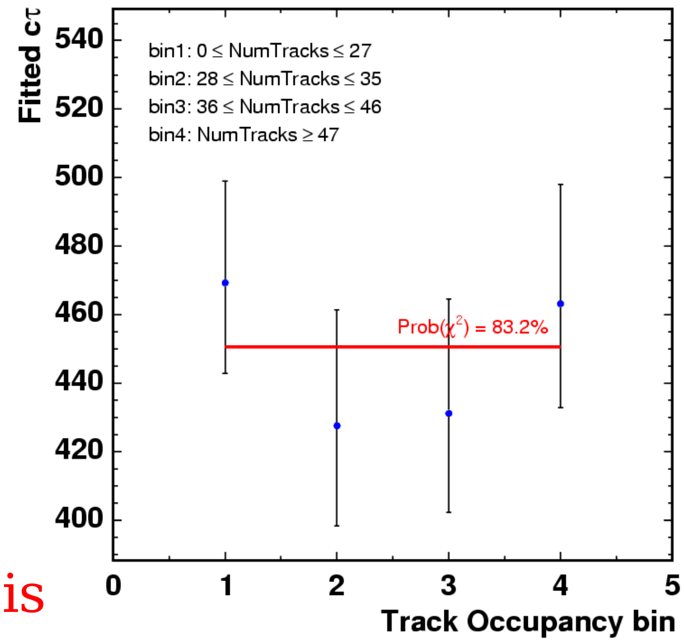
Run range, B^0 vertex prob(χ^2), B^0 p_T, B^0 η, B^0 ϕ_0, B^0 z-position, K_s p_T, track occupancy, K_s L_{xy} and L_{xy} /σ_{Lxy} from J/ψ vertex, K_s and J/ψ r-ϕ silicon hits, fit range, ...

→ No statistically-significant dependence found



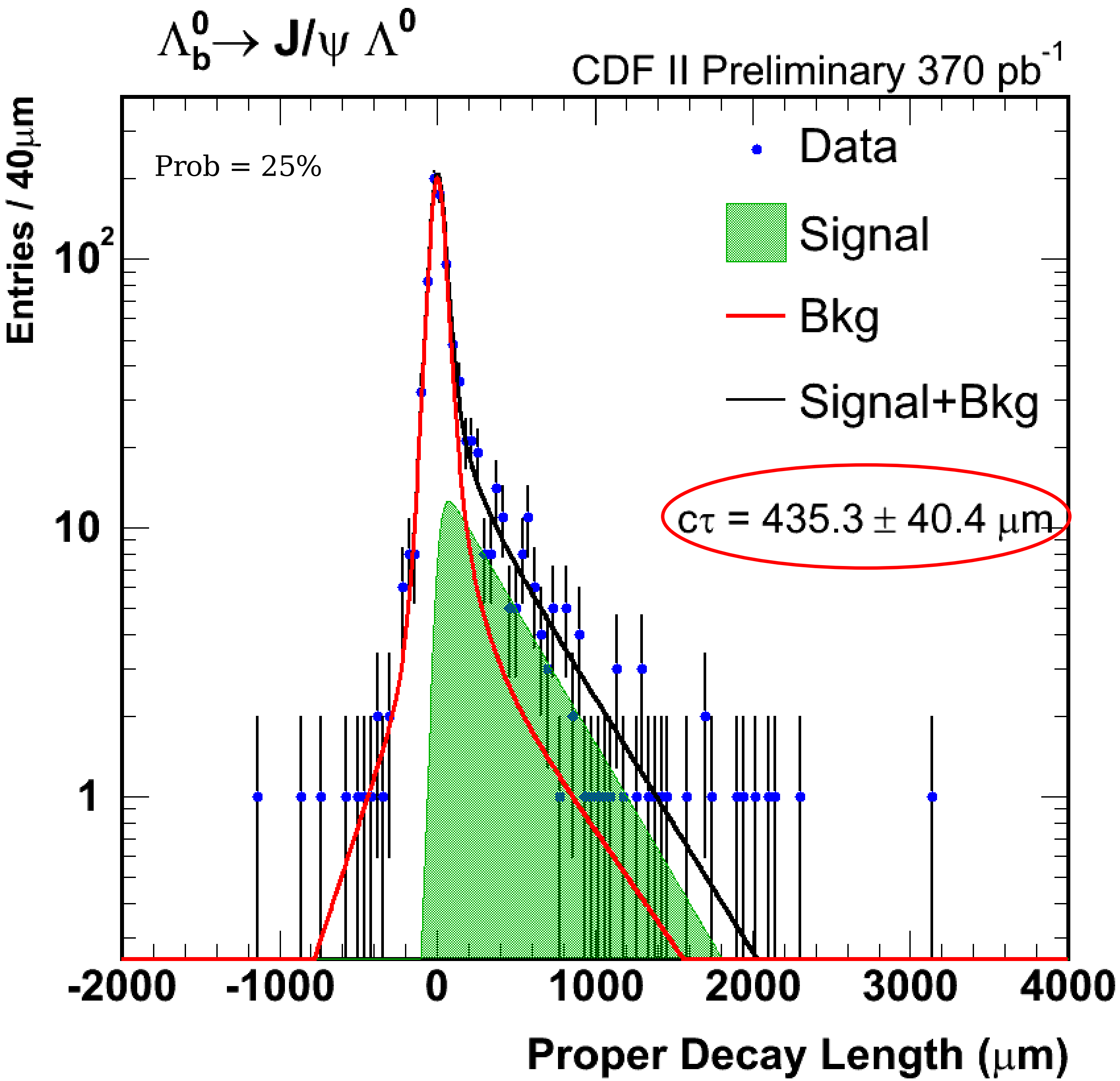
Variations on analysis procedure:

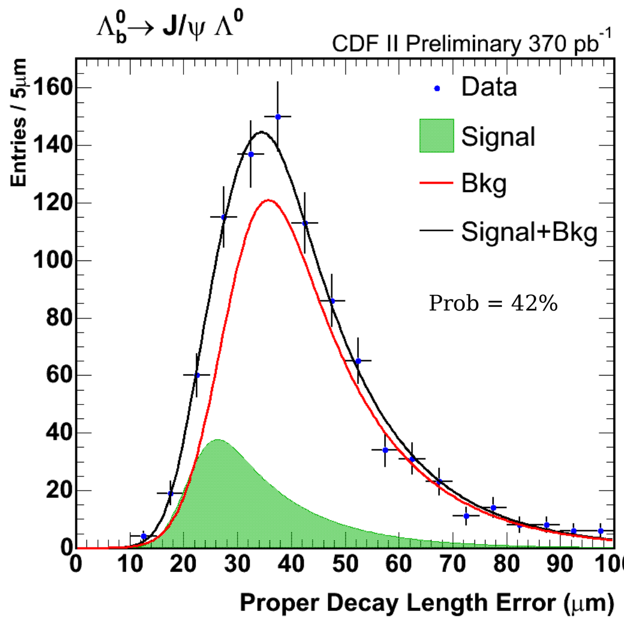
- COT-only tracking for K_s
  - → important check for possible bias from V^0 Si hits
- *b*-hadron kinematic fit constraints
  - → (2-D/3-D pointing constraint, V^0 mass constraint)
- PDL calculation
  - → candidate mass for boost, B^0 vertex for decay vtx

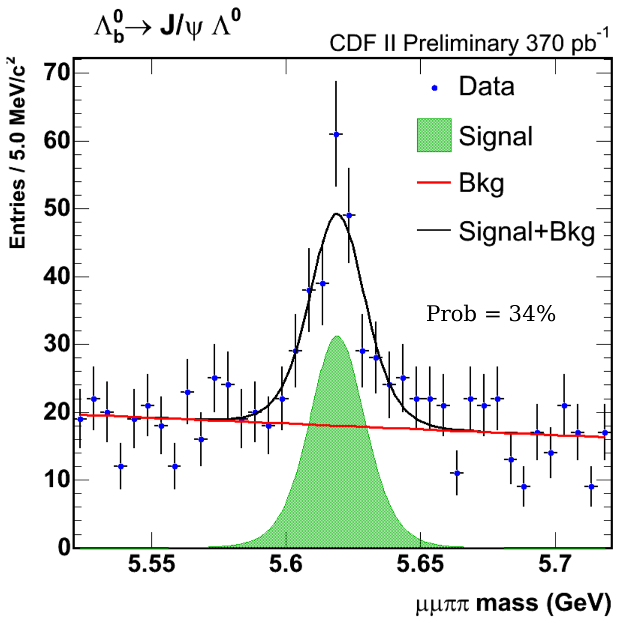


→ Variation results consistent with baseline analysis

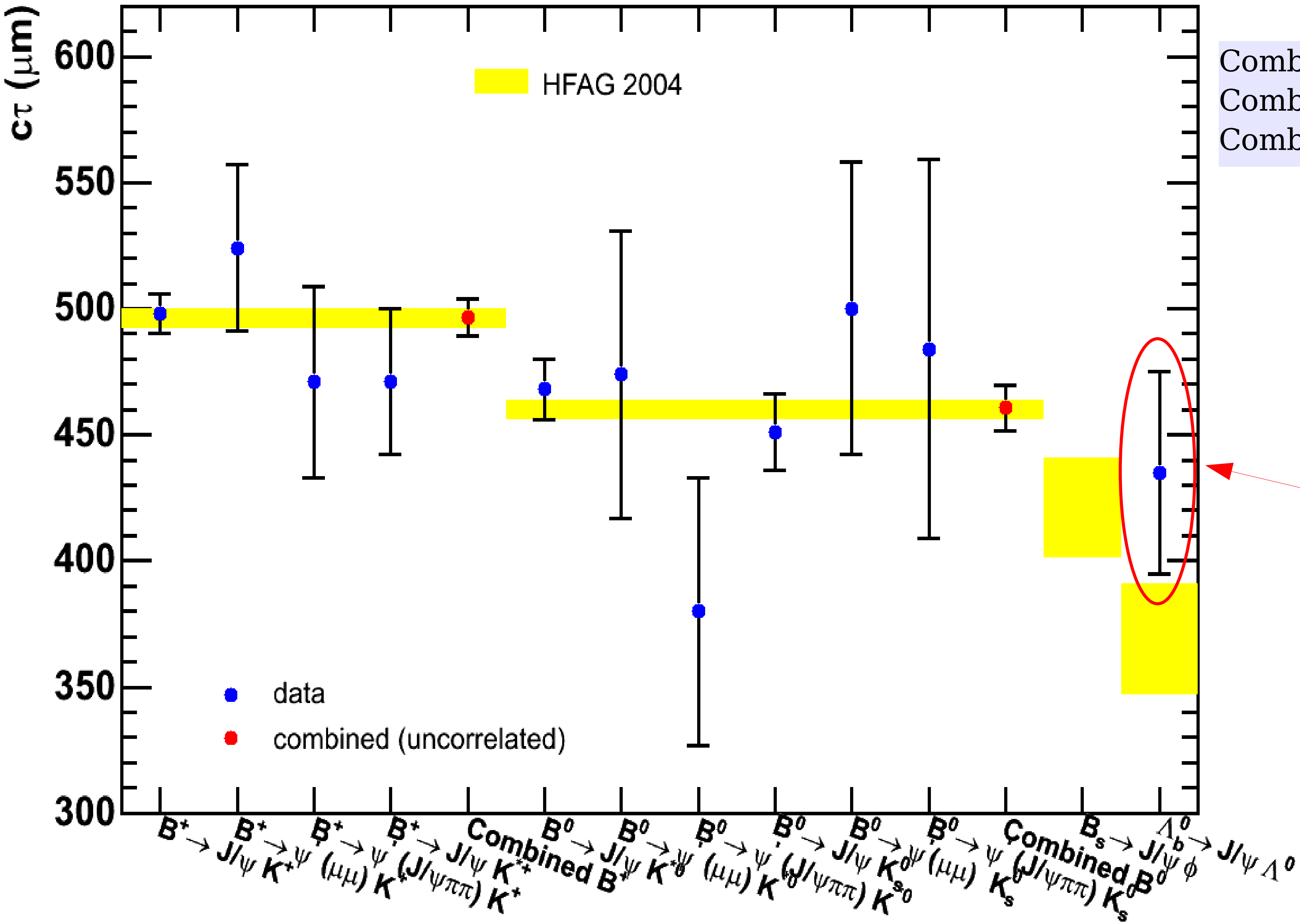
Fit Results: $\Lambda_b \rightarrow J/\psi \Lambda^0$







b-Hadron Lifetime Summary



Combined B^+ : 497 ± 7 μm
Combined B^0 : 461 ± 9 μm
Combined Δ_{HFAG}: 0.6 ± 5.6 μm

Our result

Statistical errors only!

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

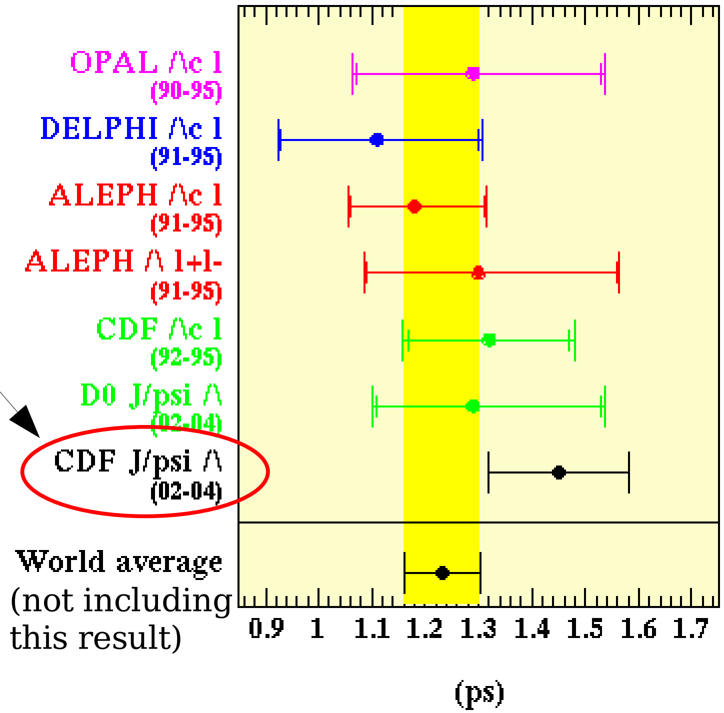
Source	$c\tau(B^0)$ (μm)	$c\tau(\Lambda_b)$ (μm)
Fitter Bias	0.2	0.5
Fit Model:		
PDL Resolution	3.0	1.5
Mass Signal	1.8	1.3
Mass Background	0.1	0.5
PDL Background	0.6	3.7
Mass-dependent PDL Background	0.9	0.9
PDL Error Modeling	0.1	0.1
Mass Error Modeling	0.4	3.0
Primary Vertex Determination	0.2	0.3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

~1/6 times statistical error

Λ_b Lifetime: Summary

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

$$\tau(\Lambda_b) = 1.45\ ^{+0.14}_{-0.13}\ (\text{stat.}) \pm 0.02\ (\text{syst.})\ \text{ps}$$



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

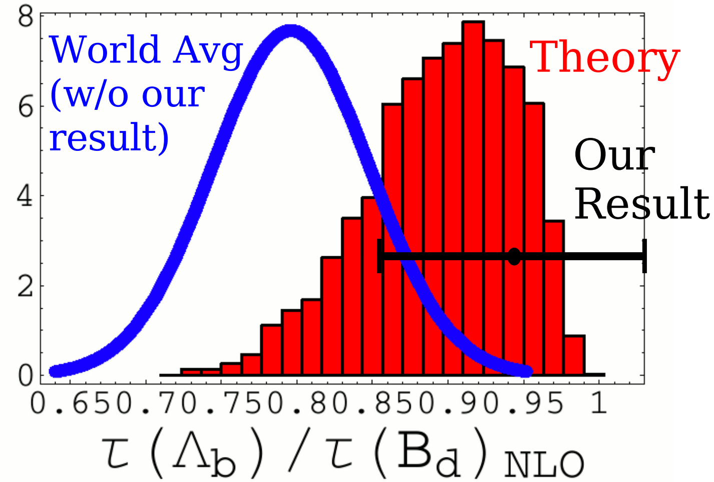
$$\tau(B^0) = 1.503\ ^{+0.050}_{-0.048}\ (\text{stat.}) \pm 0.016\ (\text{syst.})\ \text{ps}$$

consistent w/ PDG 2004 value of 1.536 ± 0.014 ps

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

$$\tau(\Lambda_b)/\tau(B^0) = 0.944 \pm 0.089\ (\text{stat.+syst.})$$

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 as a world's single best measurement

→ best by far in a fully reconstructed decay channel

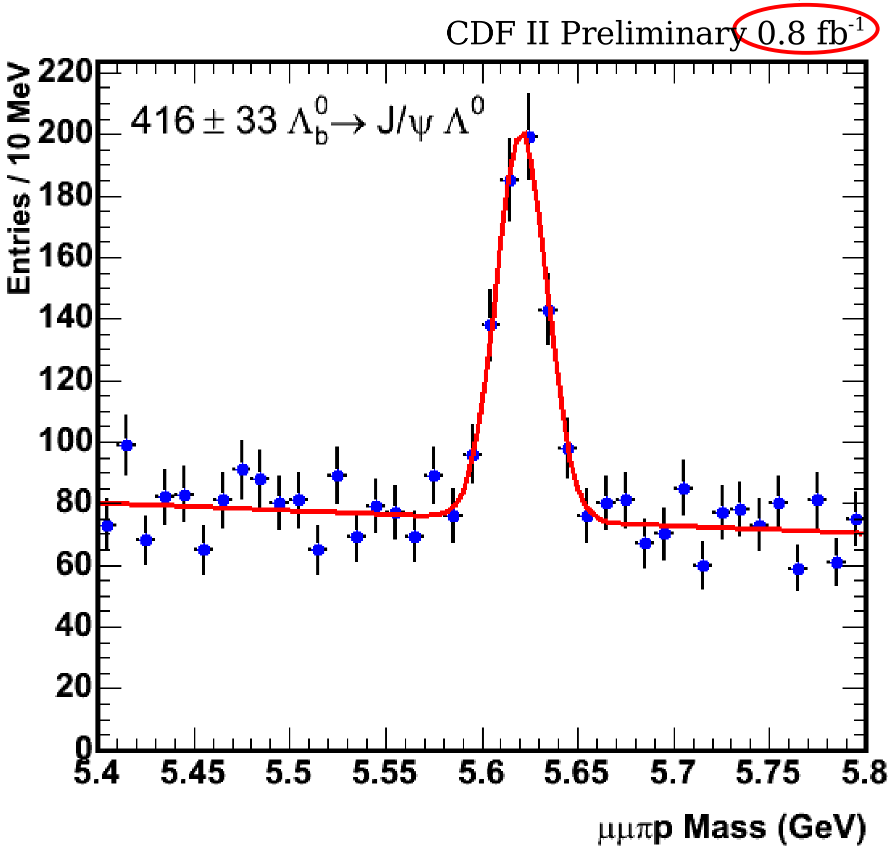
~2 × the data used used in this analysis

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

- Adding new data to this analysis will be very interesting

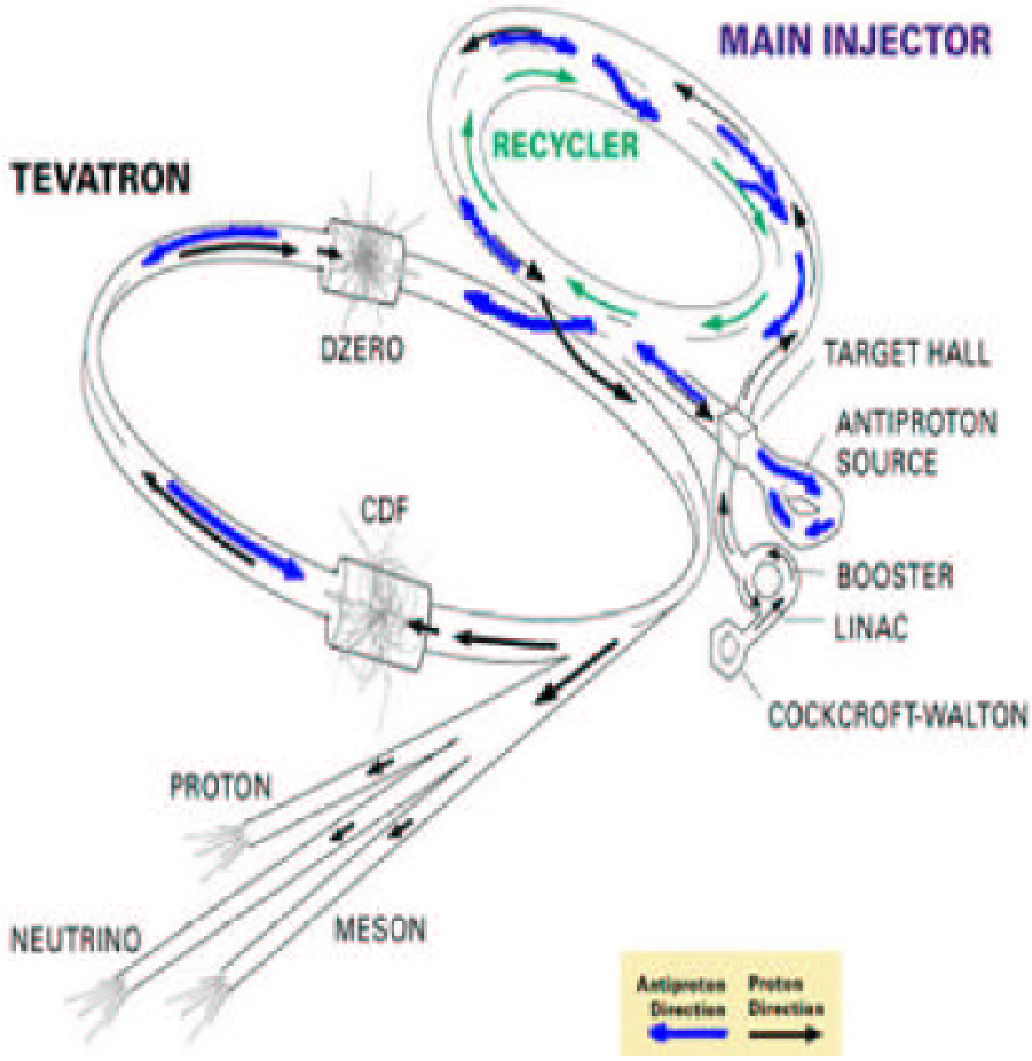
  → precision will approach current world average

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



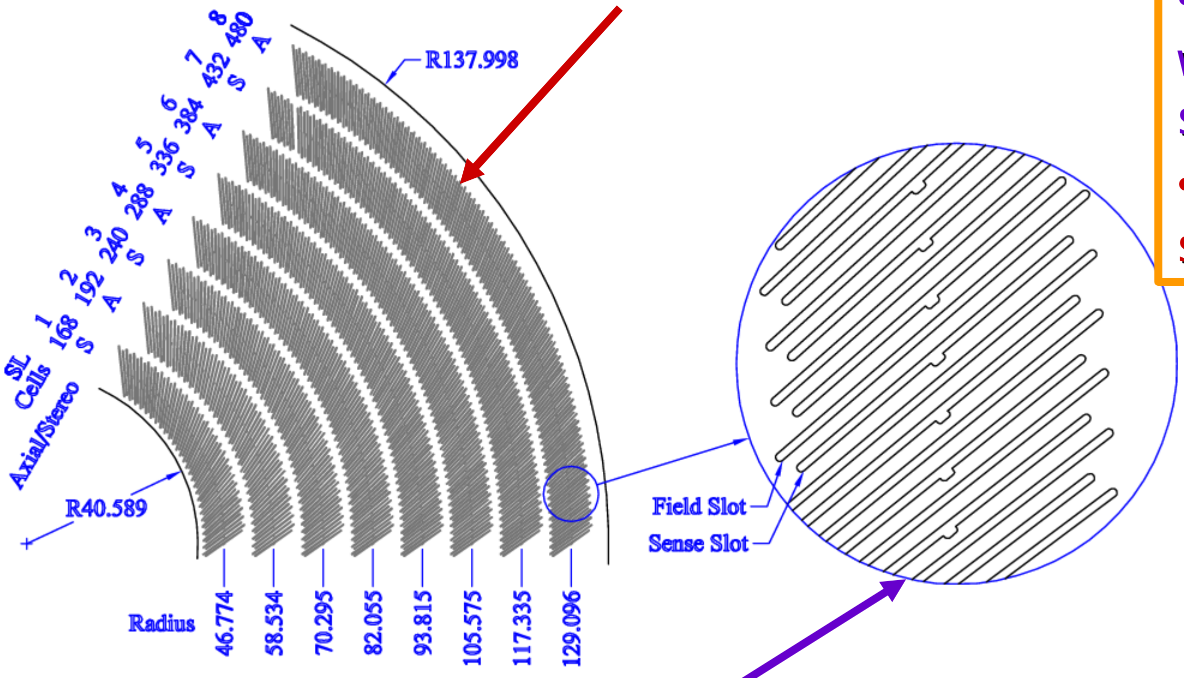
Extras

Fermilab Accelerator



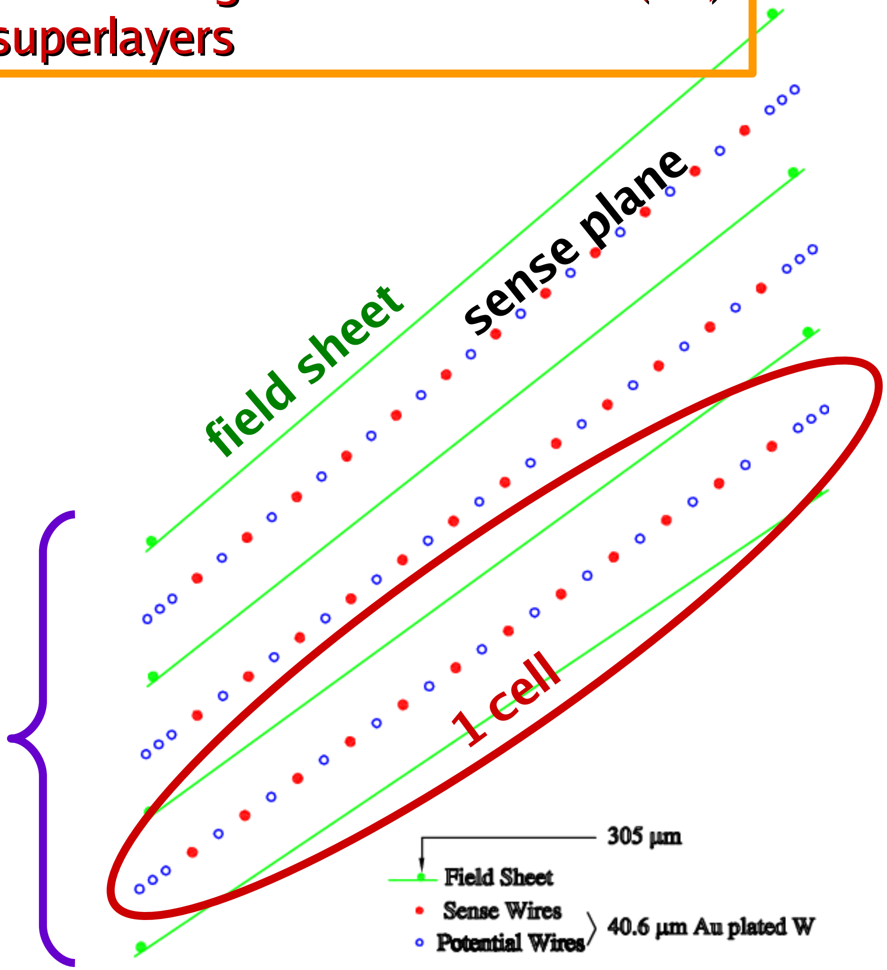
The COT

•End view: Fraction of the endplate



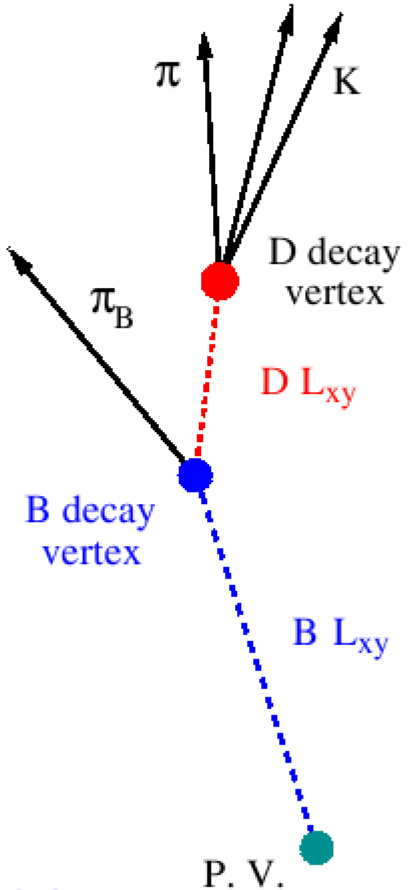
•8 "superlayers"
• alternating planes of sense wires (readout) and field sheets(ground)
• alternating axial and stereo (2 °) superlayers

Closeup of cell layout in 1 superlayer

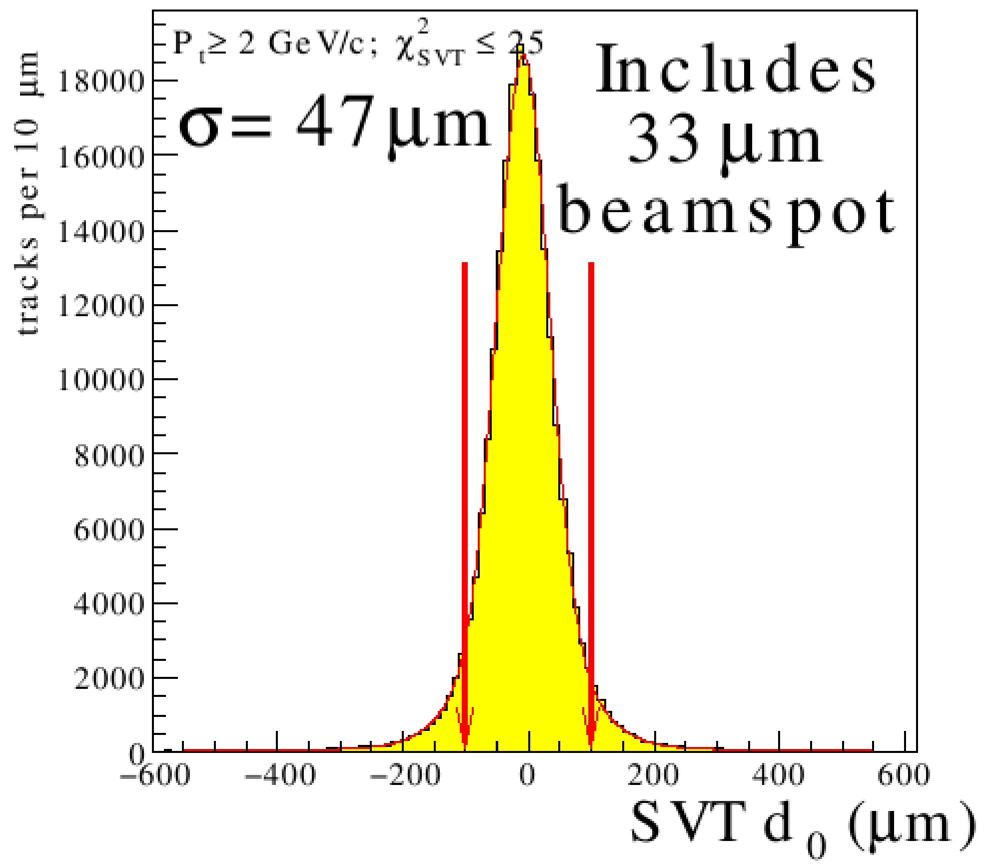


Displaced Track Trigger

Run I: only e, μ trigger



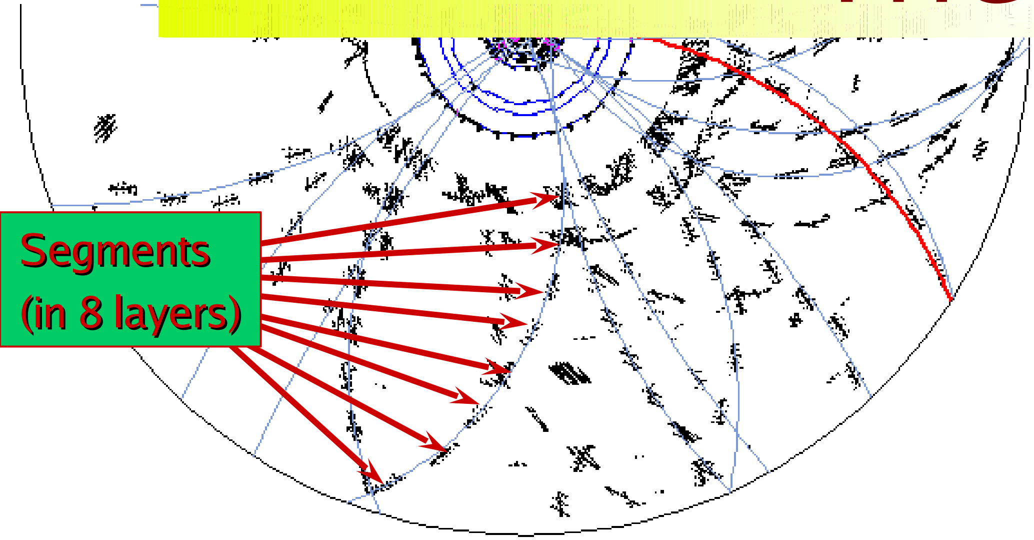
Triggering on tracks with large impact parameter (rich in heavy flavor decays)

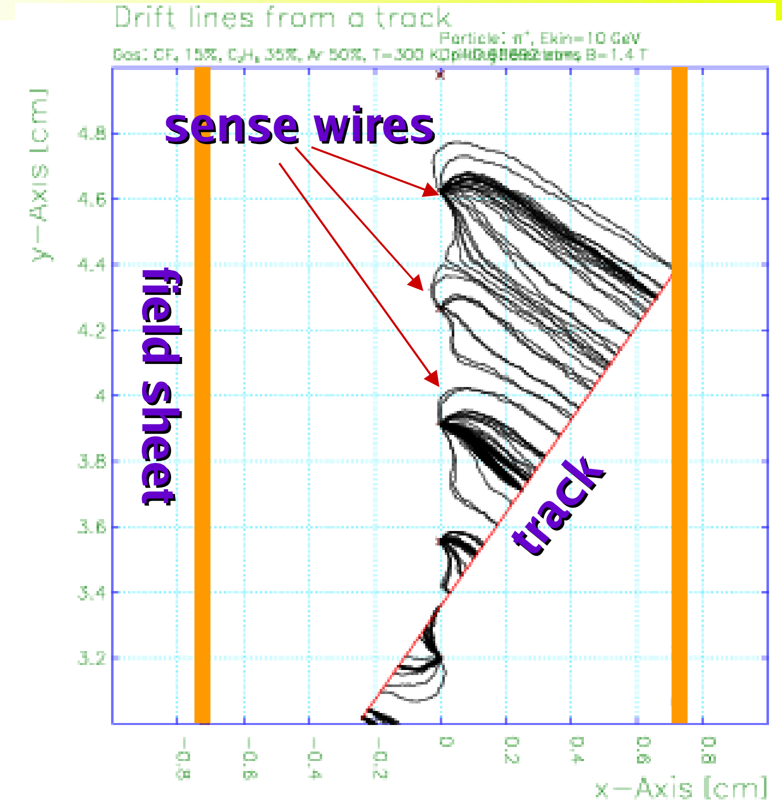


Challenge:

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

The COT





Tracking in a Nutshell:

- Form line segments in 4 axial layers
- Do axial fit, connecting segments
- Form segments in stereo layers
- Add stereo segments to fit
- Final fit

Systematics: Fit Model

PDL, mass shape systematic:

- Fit using different model components
- compare to baseline fit

PDL error, mass error modeling systematic:

- Generate toy data using true error distributions from data, fit with our baseline model
- Compare to baseline toy MC fit

Mass dependent PDL background systematic:

- Fit data separately using low mass and high mass regions

Total fit model systematic:

3.7 μm for B^0

5.3 μm for Λ_b

Variation	$B^0 \to J/\psi K^0_s$ Fitted $c\tau$ (μm)	Shift (μm)
$c\tau$ Res 2 Scales	447.6 ± 14.8	-3.0
Mass Res 2 Scales	451.4 ± 14.6	0.8
Mass Res Fixed Gaus	448.8 ± 14.7	-1.8
Constant Bkg Mass	450.6 ± 14.7	0.0
$(E_- + E_+ + \delta(0)) \otimes G$	450.8 ± 14.6	0.2
$(E_- + E_+ + E_{++} + E_{+++} + \delta(0)) \otimes G$	450.6 ± 14.7	0.0
$E_- + E_+ + (\delta(0)) \otimes G$	450.5 ± 14.6	-0.1
$E_- + E_+ + E_{++} + \delta(0) \otimes G$	450.0 ± 14.7	-0.6
$E_- + E_+ + E_{++} + E_{+++} + \delta(0) \otimes G$	450.0 ± 14.7	-0.6
Low Sideband Only	450.8 ± 15.2	0.2
High Sideband Only	449.0 ± 15.0	-1.6

Variation	$\Lambda^0_b \to J/\psi \Lambda^0$ Fitted $c\tau$ (μm)	Shift (μm)
$c\tau$ Res 2 Scales	433.8 ± 40.3	-1.5
Mass Res 2 Scales	436.3 ± 40.7	1.0
Mass Res Fixed Gaus	434.0 ± 42.0	-1.3
Constant Bkg Mass	434.8 ± 40.4	-0.5
$(E_- + E_+ + \delta(0)) \otimes G$	439.0 ± 39.3	3.7
$(E_- + E_+ + E_{++} + E_{+++} + \delta(0)) \otimes G$	435.3 ± 40.4	0.0
$E_- + E_+ + (\delta(0)) \otimes G$	438.0 ± 39.2	2.7
$E_- + E_+ + E_{++} + \delta(0) \otimes G$	433.8 ± 40.3	-1.5
$E_- + E_+ + E_{++} + E_{+++} + \delta(0) \otimes G$	433.8 ± 40.3	-1.5

Systematics: Alignment

SVX internal: consider 50 μm radial dilation, contraction of silicon sensors

- Realistic Monte Carlo including misalignment ⇒ 2 μm systematic

"Global" translation and rotation of SVX relative to COT

- Magnitudes estimated from data using impact parameter of J/ψ muons:

Translation: COT-SVX beamlines, max offset ~30 μm

Rotation: leads to "false impact parameter": $\phi_i \rightarrow \phi_i + \delta/r_i \Rightarrow d_0 \rightarrow d_0 + \delta$

Fit mean d_0 (COT muons) w/ respect to SVX beam: ~20μm

Based upon MC studies, a 2.4 mrad rotation causes a 20 μm d_0 shift

Systematic uncertainty due translation or rotation of SVX

⇒ 2.2 μm for B^0, 3.2 μm for Λ_b

Total alignment systematic:

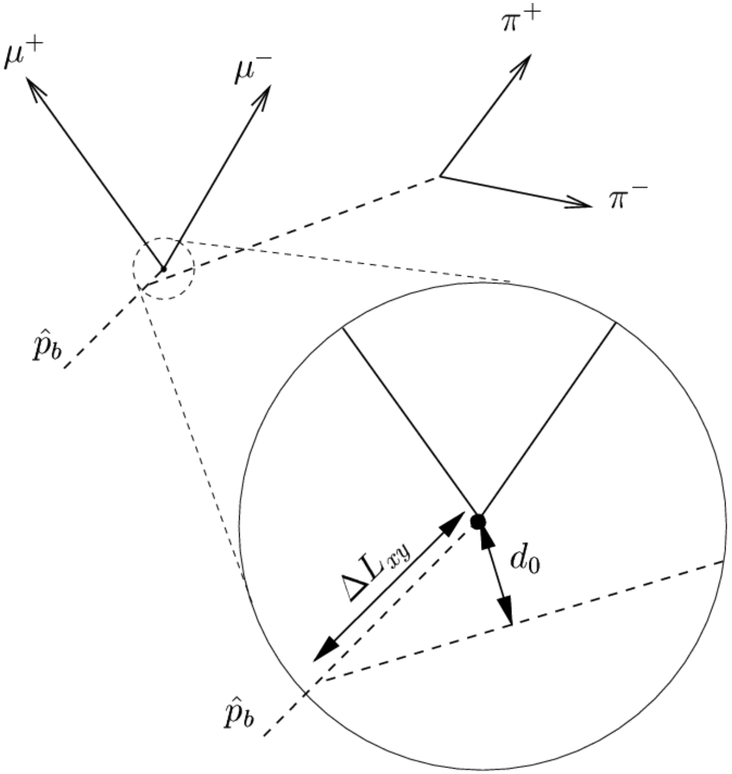
3.0 μm for B^0

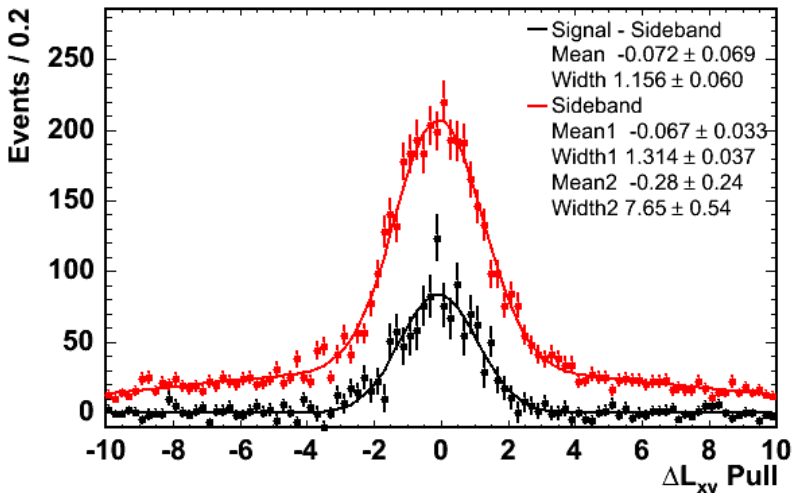
3.8 μm for Λ_b

Alignment	**$c\tau(\Lambda_b)$ (μm)**	**$\Delta(\Lambda_b)$ (μm)**	**$c\tau(B^0)$ (μm)**	**$\Delta(B^0)$ (μm)**
160050 1 GOOD (best)	370.4	-	464.0	-
+ 1 mm z-shift	368.5	-1.9	464.5	+0.5
- 30 μm x-shift	372.1	+1.7	463.3	-0.7
+ 30 μm x-shift	371.1	+0.5	463.6	-0.4
- 30 μm y-shift	373.6	+3.2	466.2	+2.2
+ 30 μm y-shift	368.6	-1.8	462.0	-2.0
+ 2400 μrad z-rot	372.1	+2.1	465.0	+1.0
- 2400 μrad z-rot	371.4	+1.0	464.2	+0.2

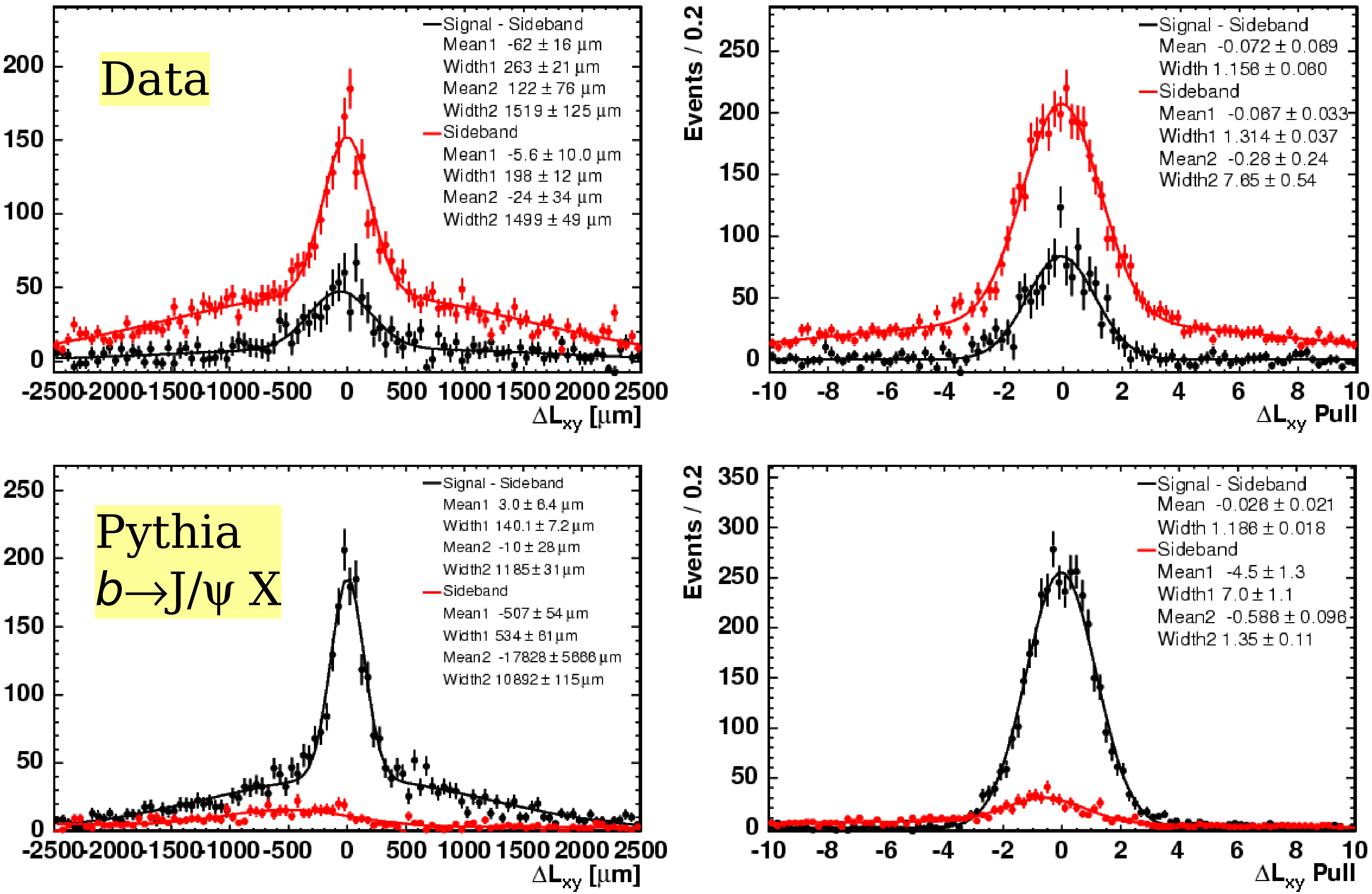
Systematics: V^0 Pointing

- Limit failure of V^0 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 cτ dependent
- Pulls measured in data (K_S)
- Systematic constrained to be small, mostly because probability cut 10^{-4} is loose

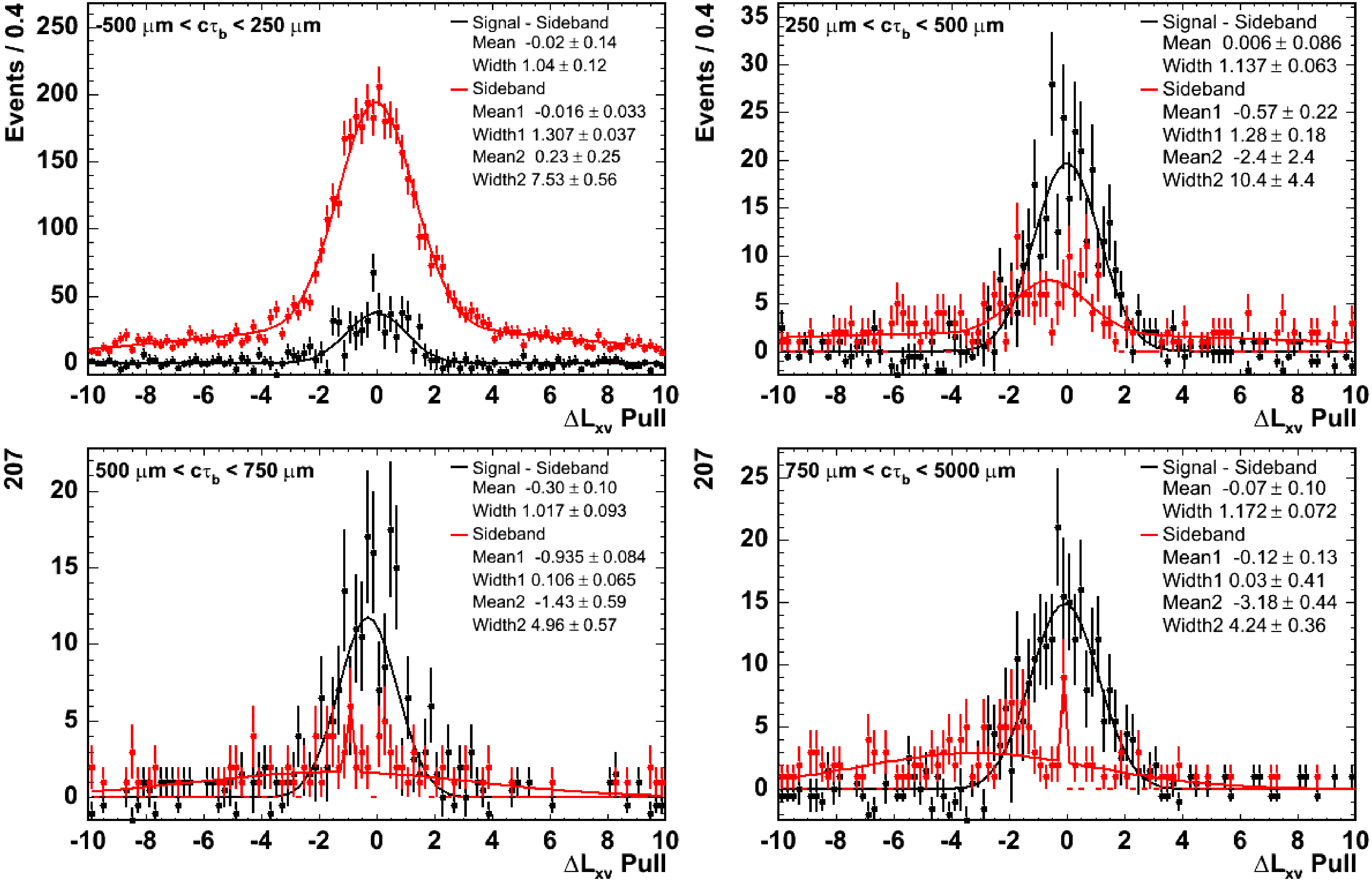




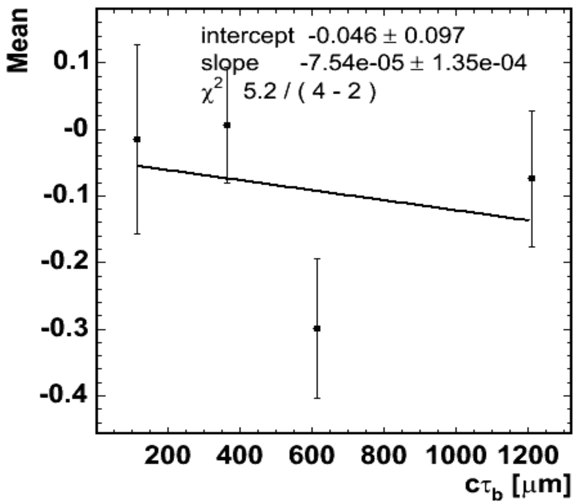
V^0 Pointing: $B^0 \to J/\psi K_s$

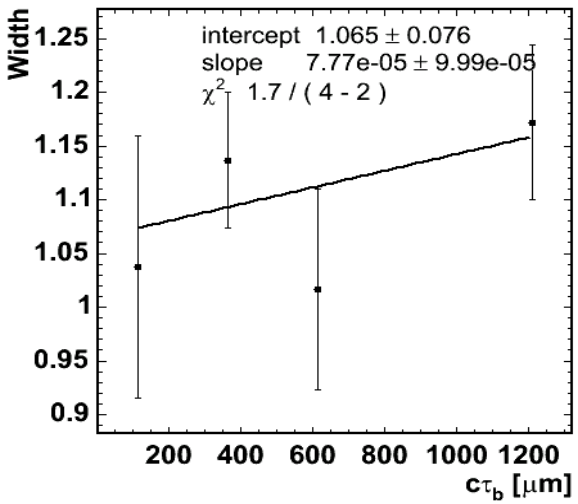


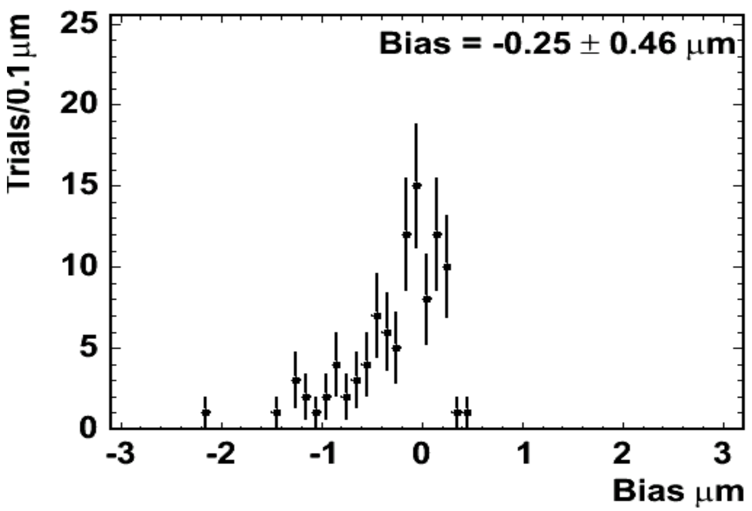
Systematics: V^0 Pointing



Systematics: V^0 Pointing





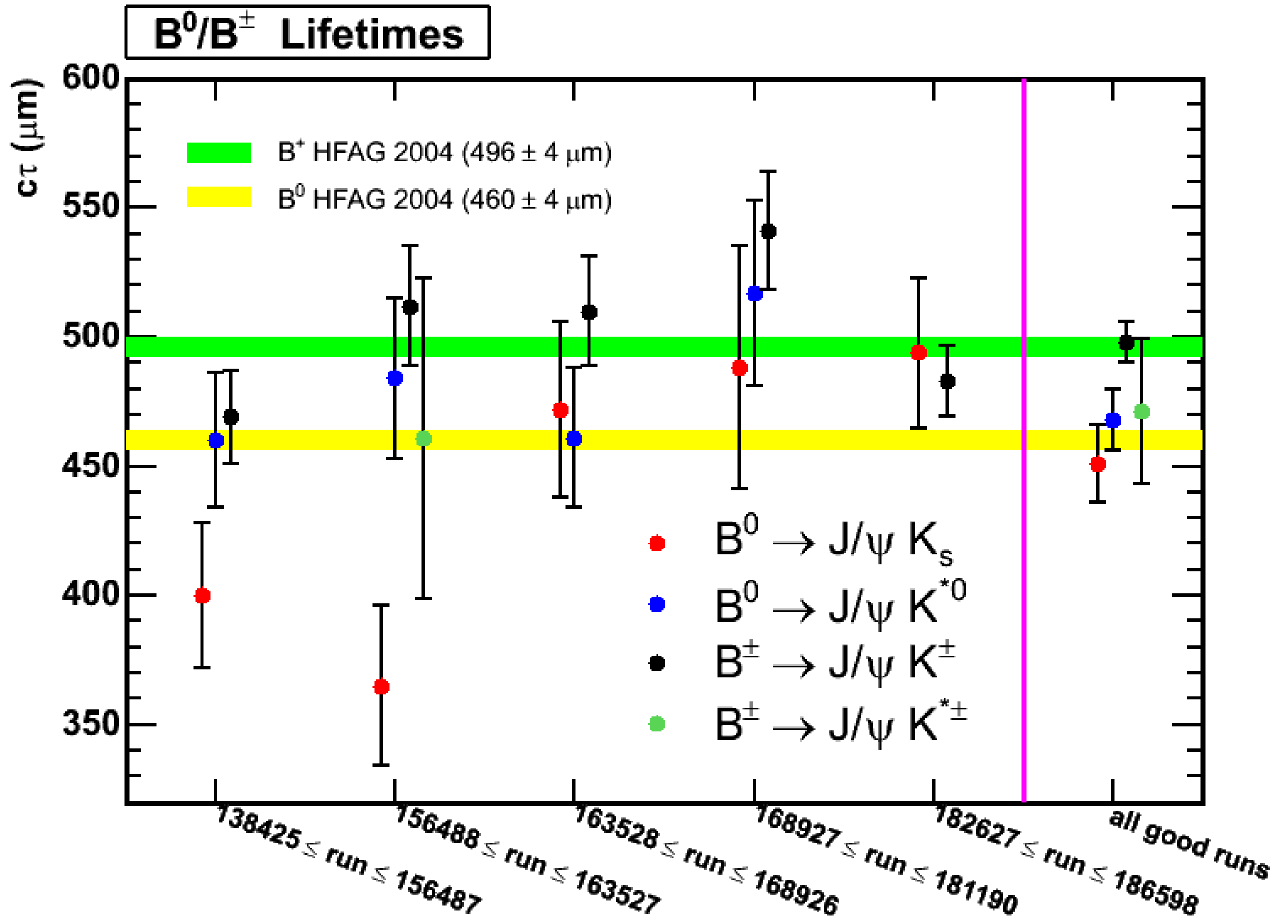


- Fit ΔL_{XY} and z_0 pulls in bins of $c\tau$
- Fit slopes of pull shapes $\sigma(c\tau)$ and $\mu(c\tau)$
- Toy MC integrate over 5-d χ^2 using $\sigma(c\tau)$ and $\mu(c\tau)$
- Calculate $c\tau$ bias of toy MC events
- Find mean+RMS of bias for slopes consistent w/ data

Run Dependence

$B^0 \rightarrow J/\psi\, K_s$ lifetime low in early data:

Trend not seen in other modes



Probability of observed run dependence = 4.3%

Taking in account order (shape), P = 1.9%

⇒ Could not distiguish between systematic problem and fluctuation at this level

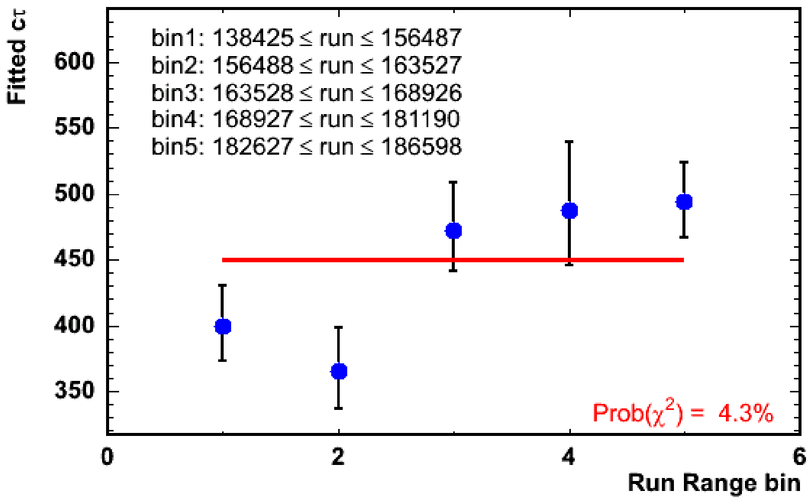
Run Dependence Statistics

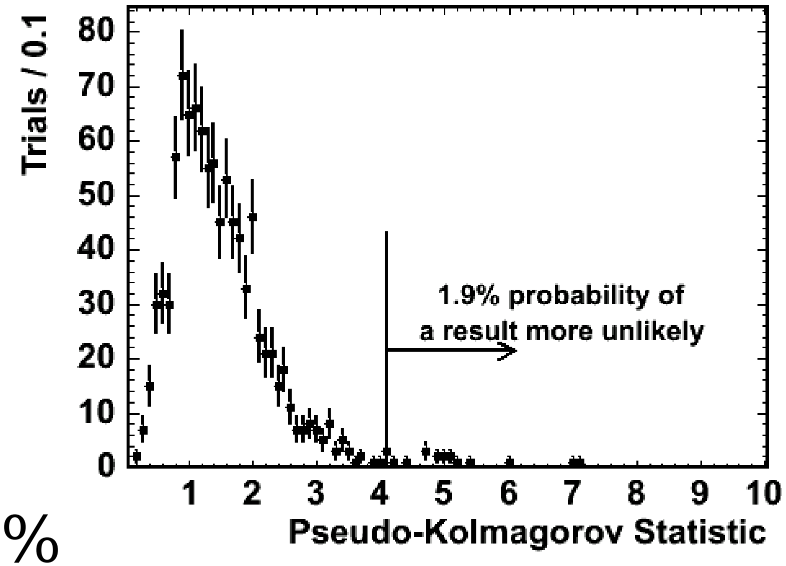
- Early K_S data is low
- How do we assess the significance of the effect?
- Randomly divide data into subsets of the same size as the run bins
- Fit subsets and calculate a pseudo-Kolmagorov statistic:

$$\left| \max_{1 \le i \le n} \sum_{1}^{n} \sigma_n \right|$$

where σ_n is the signifacance of the deviation of bin n from the mean

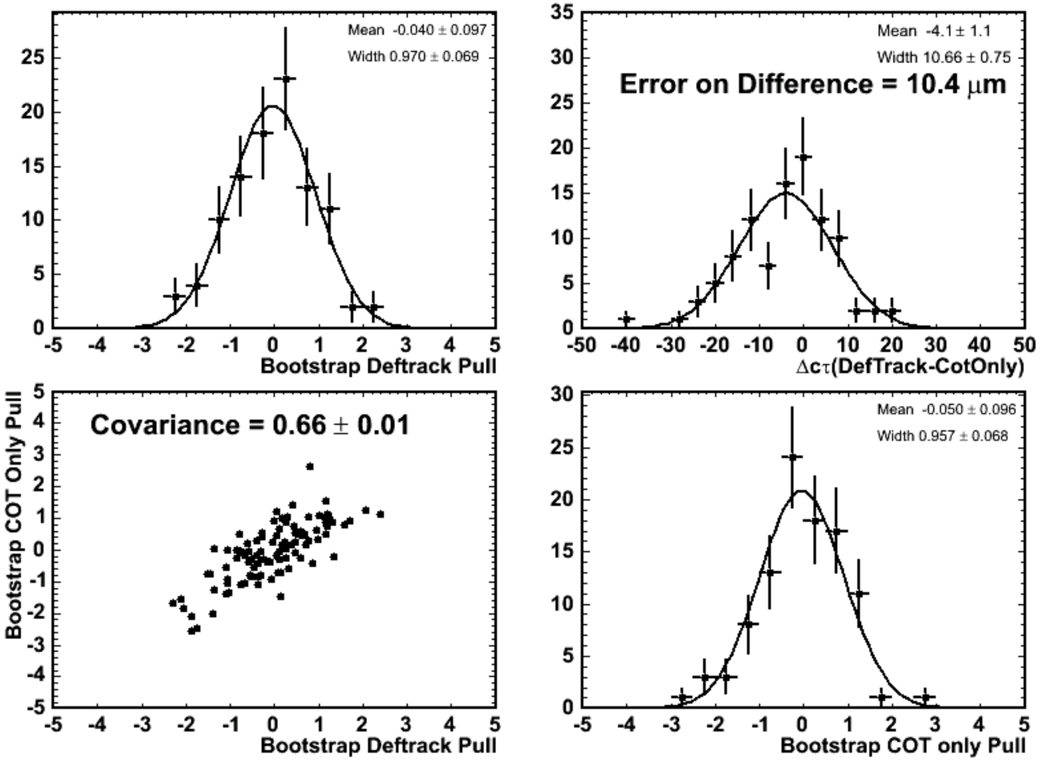
– Distribution is order sensitive
– Probability of observed data 1.9%





Determining the correlation of fits to the same data

- Cross-check: COT-only tracks are used for the K_S
- Bootstrap technique…
- Data is source distribution for toy MC
- Poisson fluctuate events in union of the two subsets
- Generate two outputs A_{boot} with events from A and B_{boot} with events from B
- Study correlation of fit results in A_{boot} and B_{boot}



Deftrack – COT-only result: -4.1 ± 10.4 μm
Stastically consistent

Fit Model: "Punzi Effect"

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

Previous analyses ignore $P^{\sigma^{\lambda}}_{sig,bkg}(\sigma^{\lambda}_i|\vec{\beta})$ and $P^{m}_{sig,bkg}(\sigma^{m}_i|\vec{\delta})$ terms in the PDF

If signal and background differ in σ^{λ}_i or σ^{m}_i (which they do), you just biased in f_b and $c\tau$!

- Pointed out in e-print physics/0401045 and extensively studied within our group

Used toy Monte Carlo generated with true error distributions (but fit w/o) to measure biases

- $c\tau$ biases in the range of 4 - 7 μm depending upon decay mode

Right thing to do is keep $P^{\sigma^{\lambda}}_{sig,bkg}(\sigma^{\lambda}_i|\vec{\beta})$ in the likelihood fit

- $P^{m}_{sig,bkg}(\sigma^{m}_i|\vec{\delta})$ can essentially be ignored for our analysis

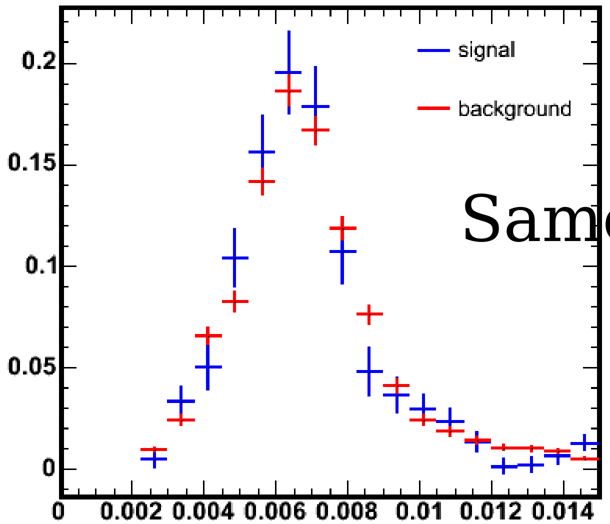
Final form of the overall PDF used in our $c\tau$ fits:

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

Observed shifts using this in LH function compared to wrong PDF consistent with toy MC results

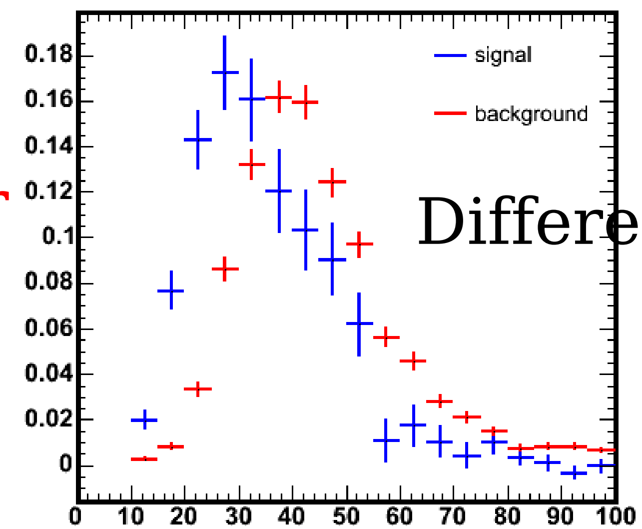
PDL Error and Mass Error

B^0 Mass error



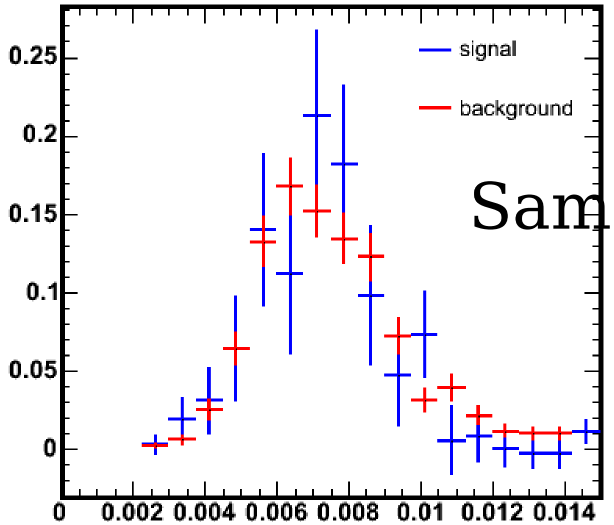
Same

B^0 PDL error



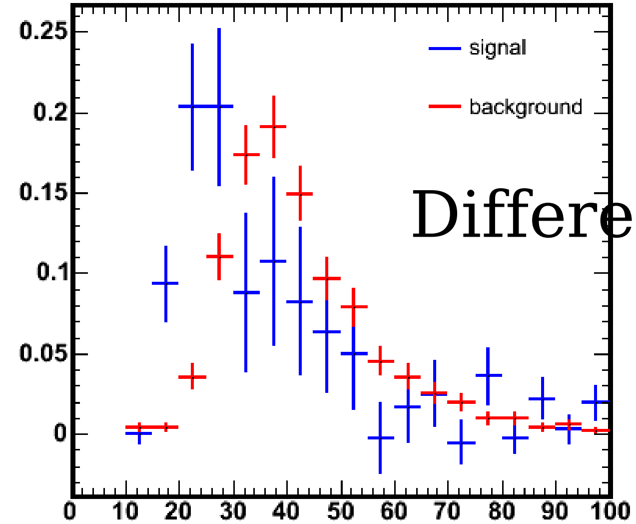
Different!

Λ_b Mass error



Same

Λ_b PDL error



Different!

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

Model parameters:					
Parameter	Fit value	$\pm 1\sigma$ Sym Err	-1σ Minos Err	$+1\sigma$ Minos Err	Units
$c\tau$	450.6	14.7	-14.5	15.0	μm
s	1.252	0.023	-0.023	0.023	
λ_+	141	31	-30	37	μm
f_+	0.077	0.019	-0.020	0.019	
λ_{++}	472	49	-47	58	μm
f_{++}	0.093	0.017	-0.018	0.018	
λ_-	304	36	-34	40	μm
f_-	0.0314	0.0045	-0.0043	0.0048	
f_b	0.7843	0.0070	-0.0070	0.0069	
M	5.2812	0.0004	-0.0004	0.0004	GeV/c^2
s_M	1.761	0.059	-0.058	0.060	
C_0	7.1	5.7	-5.7	5.7	GeV/c^2
λ_{psig}	13.21	0.78	-0.78	0.81	μm
σ_{psig}	5.79	0.40	-0.40	0.42	μm
μ_{psig}	21.81	0.56	-0.56	0.57	μm
λ_{pbkg}	13.77	0.40	-0.40	0.41	μm
σ_{pbkg}	7.33	0.21	-0.21	0.22	μm
μ_{pbkg}	31.40	0.30	-0.30	0.30	μm

Correlation Coefficient

s → μ_{pbkg}

$c\tau$	-0.006	-0.010	0.033	-0.091	-0.007	0.001	-0.010	0.148	-0.020	-0.024	-0.004	0.005	-0.021	-0.042	-0.002

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

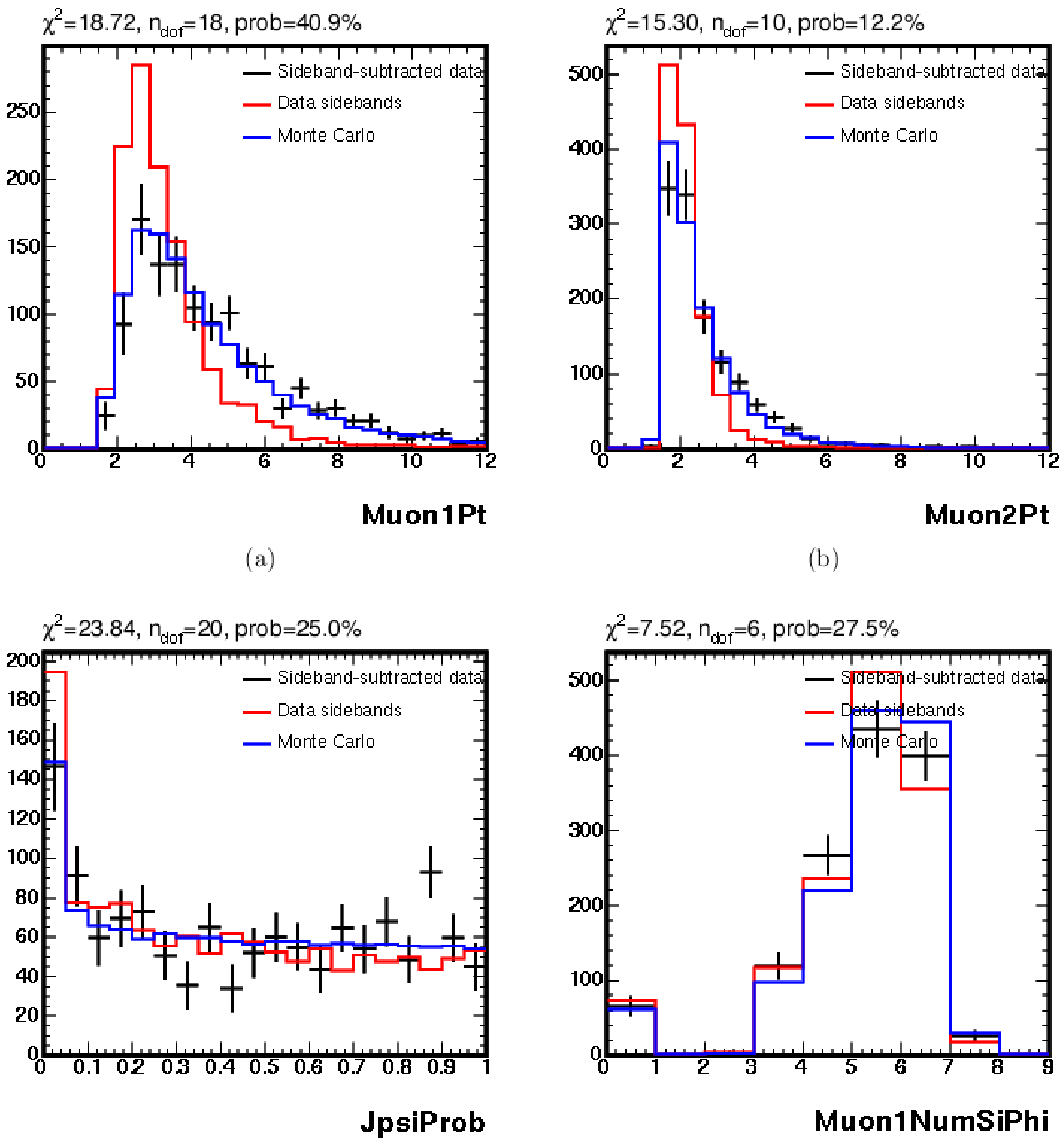
Model parameters:					
Parameter	Fit value	$\pm 1\sigma$ Sym Err	-1σ Minos Err	+1σ Minos Err	Units
$c\tau$	435.3	40.4	-38.9	42.4	μm
s	1.226	0.057	-0.057	0.058	
λ_+	112	61	-45	118	μm
f_+	0.077	0.038	-0.041	0.038	
λ_{++}	507	118	-101	177	μm
f_{++}	0.094	0.030	-0.044	0.031	
λ_-	244	57	-49	69	μm
f_-	0.050	0.014	-0.013	0.016	
f_b	0.808	0.017	-0.017	0.017	
M	5.6190	0.0009	-0.0009	0.0009	GeV/c^2
s_M	1.50	0.12	-0.12	0.13	
C_0	32	19	-19	18	GeV/c^2
λ_{psig}	13.5	2.0	-1.9	2.1	μm
σ_{psig}	4.04	0.78	-0.71	0.88	μm
μ_{psig}	21.2	1.0	-1.0	1.1	μm
λ_{pbkg}	15.8	1.1	-1.0	1.1	μm
σ_{pbkg}	6.43	0.50	-0.49	0.51	μm
μ_{pbkg}	28.54	0.68	-0.68	0.69	μm

Correlation Coefficient

s → μ_{pbkg}

$c\tau$ 0.001 -0.021 0.003 -0.202 0.037 0.004 -0.017 0.165 0.034 -0.057 0.007 -0.112 0.040 0.064 0.036

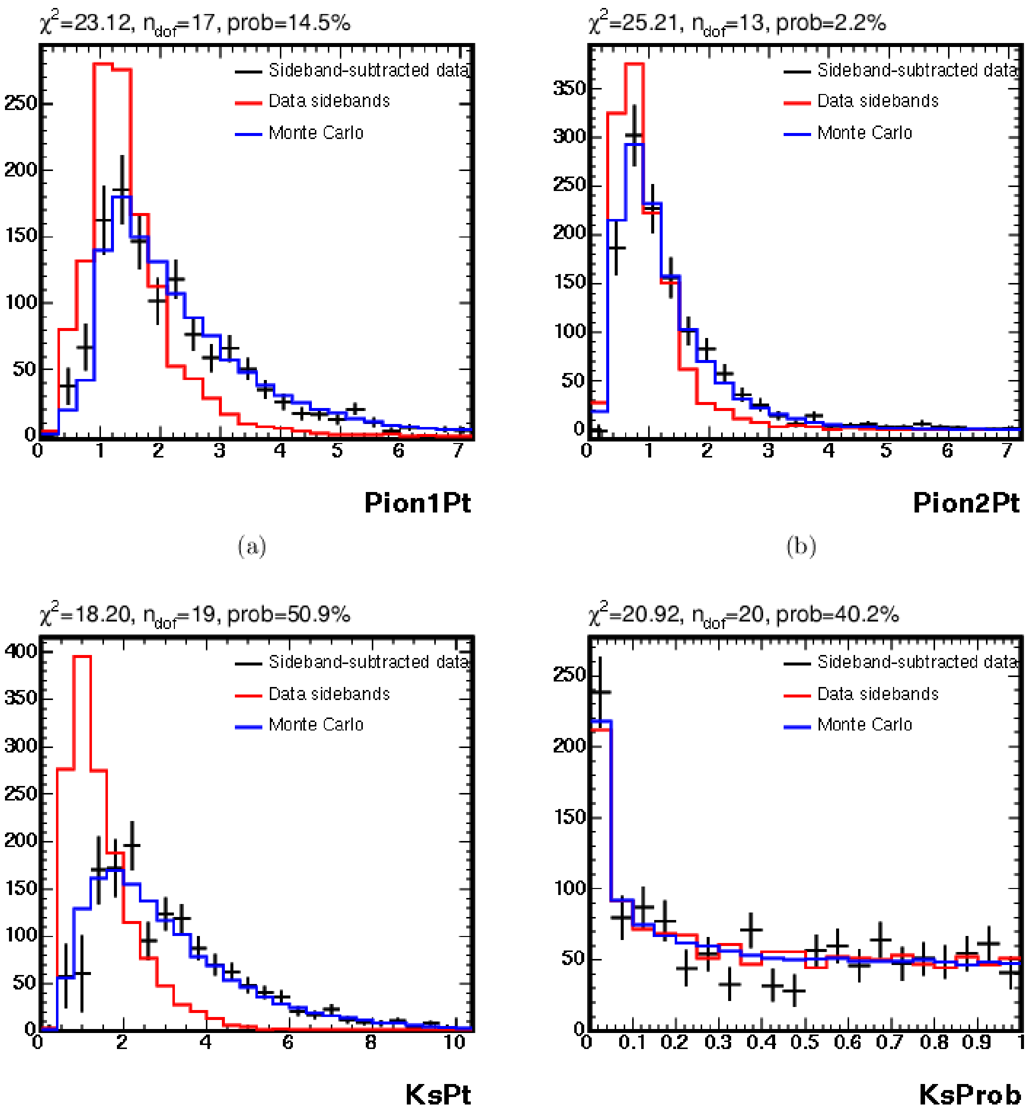
Data/MC Comparisons



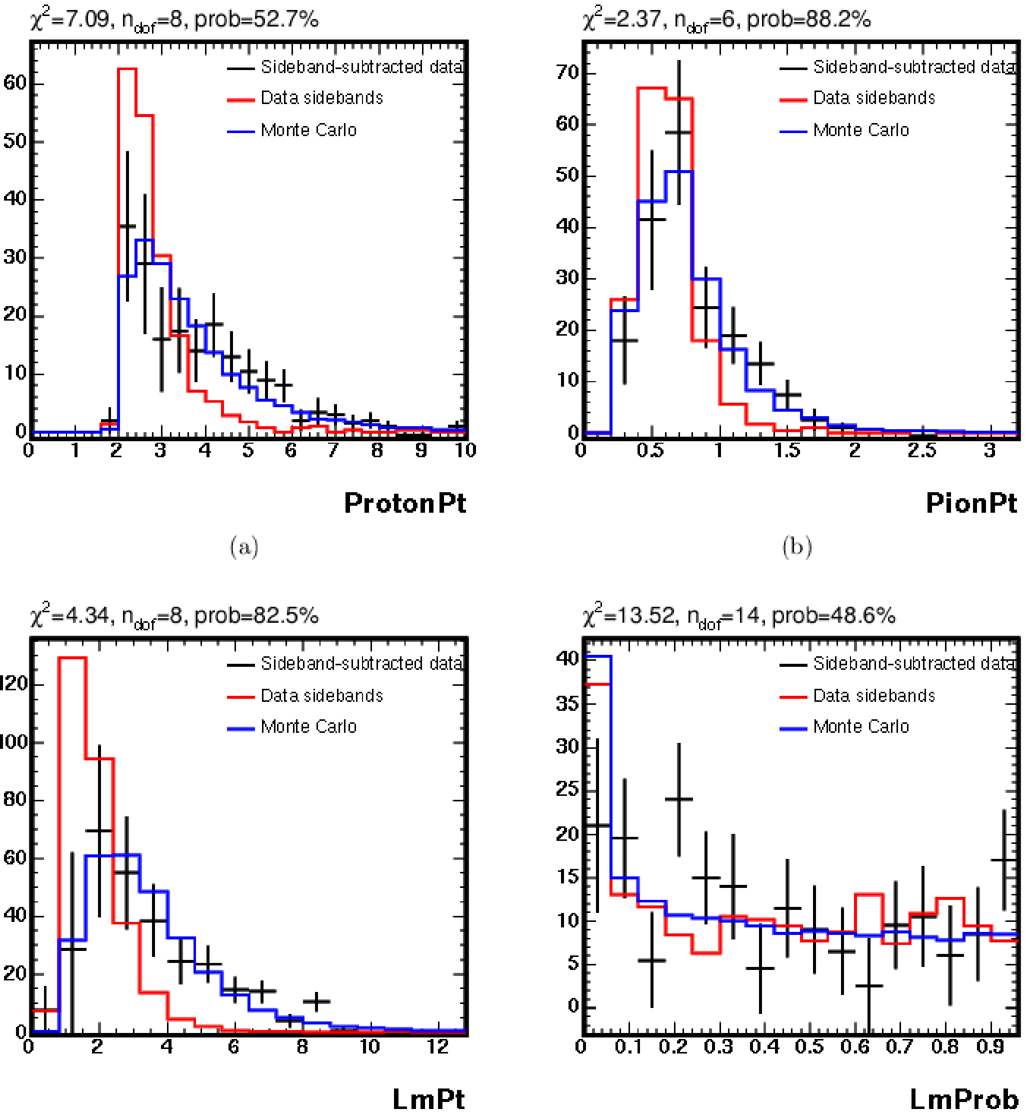
J/ψ from $B^0 \to J/\psi K_s$

Data/MC Comparisons

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



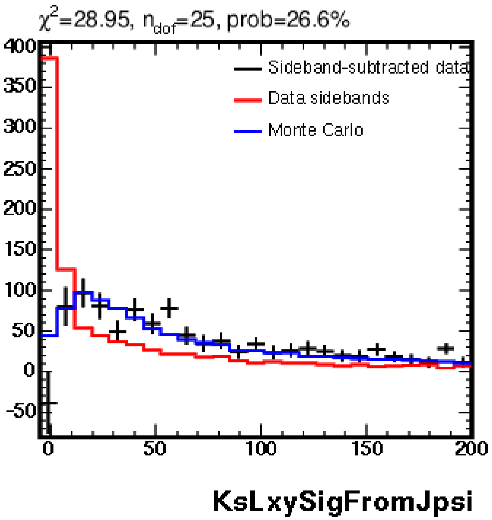
$\Lambda_b \to J/\psi \Lambda^0$



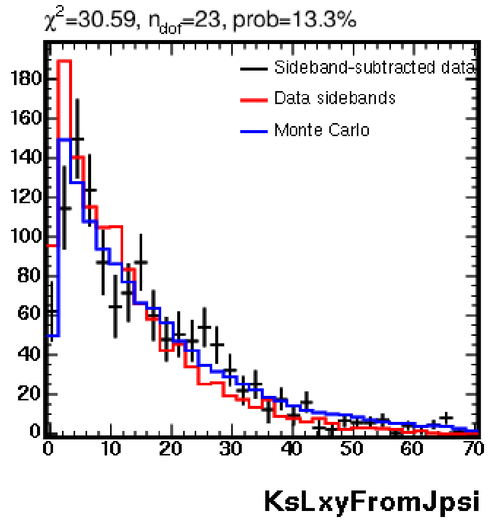
Data/MC: $\Lambda_b \to J/\psi \Lambda^0$

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

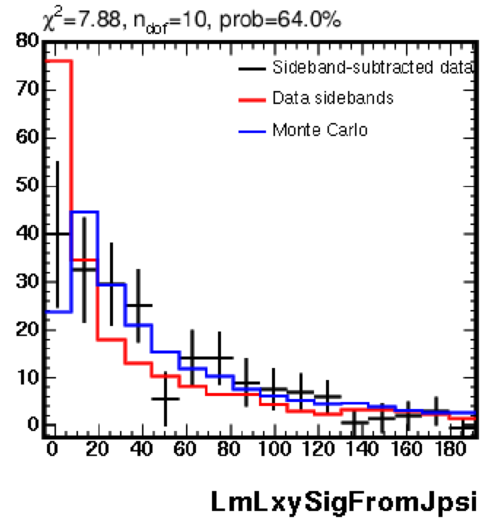
$\Lambda_b \to J/\psi \Lambda^0$



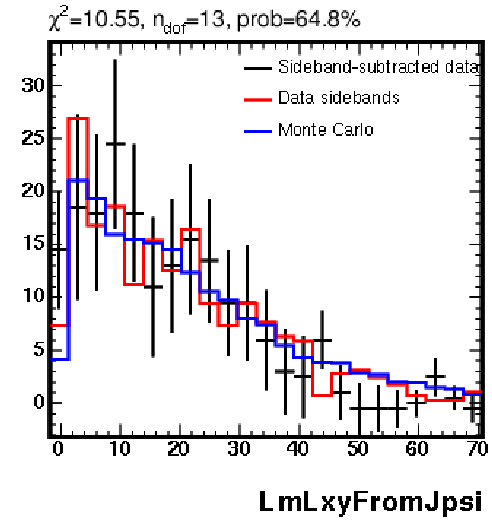
(a)



(b)



(a)



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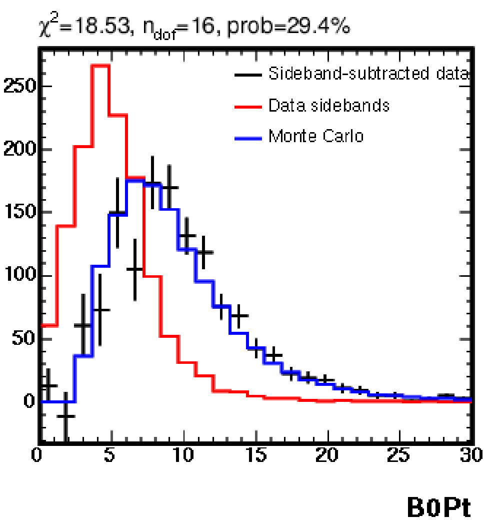
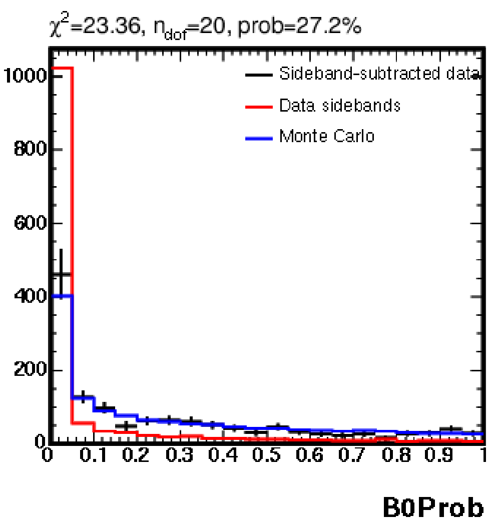
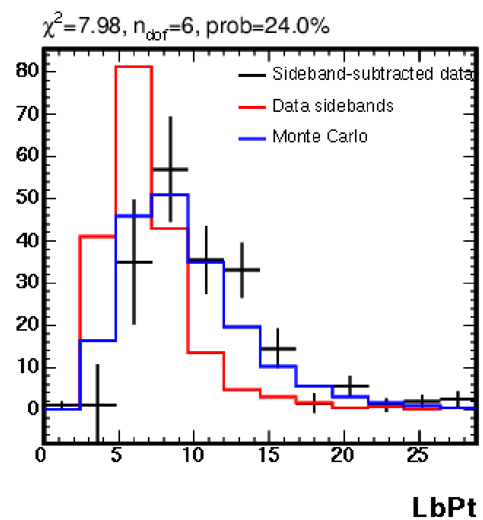
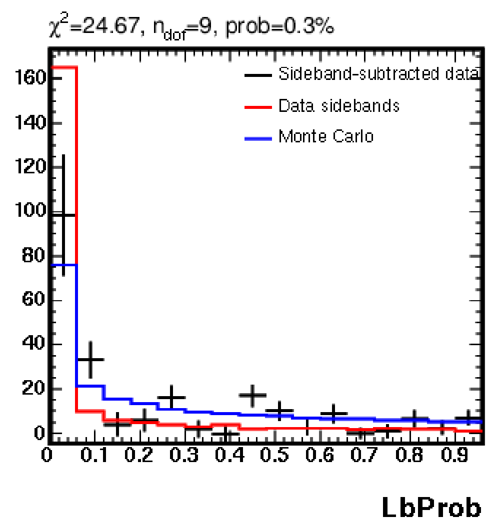
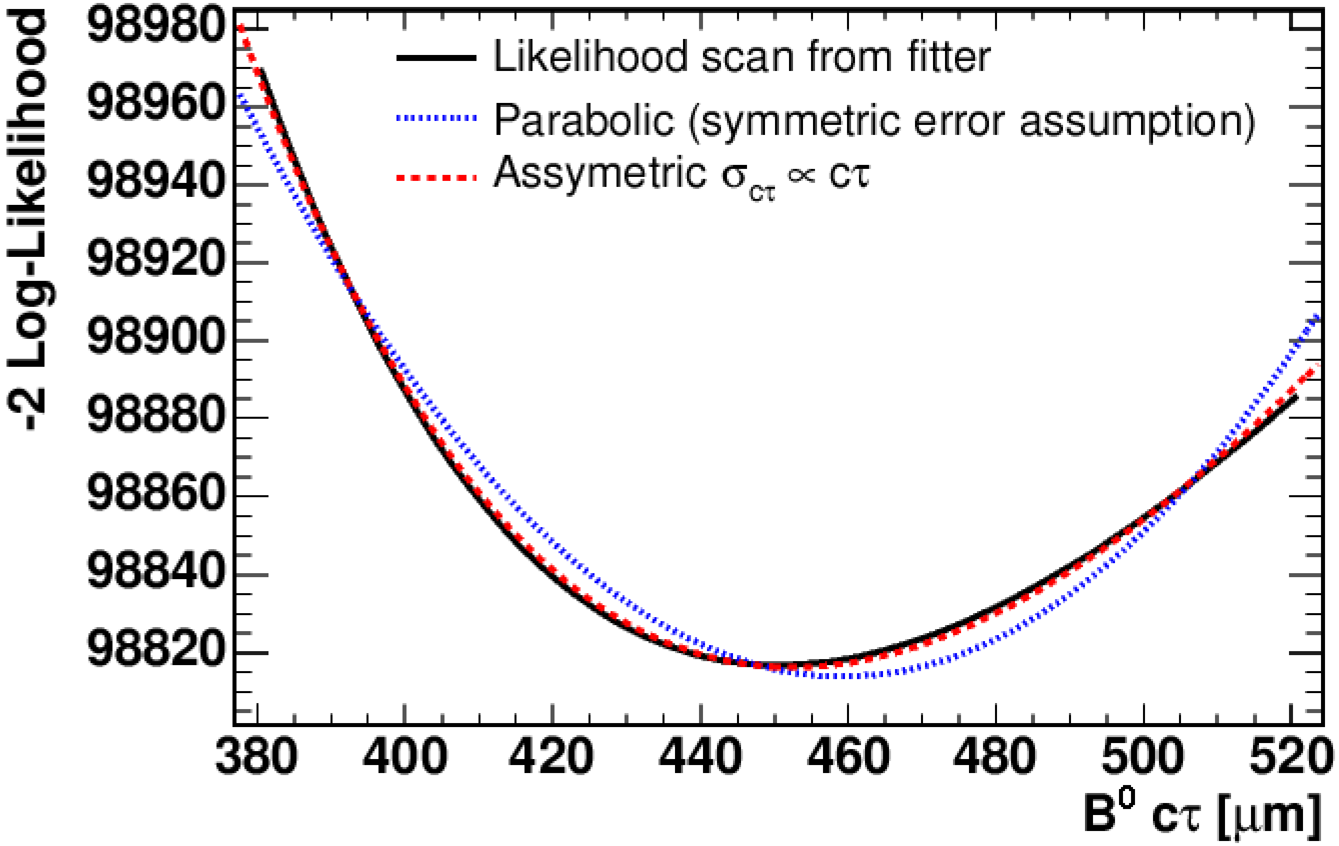




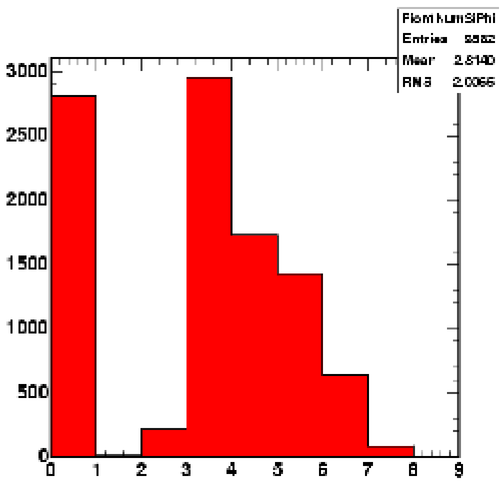


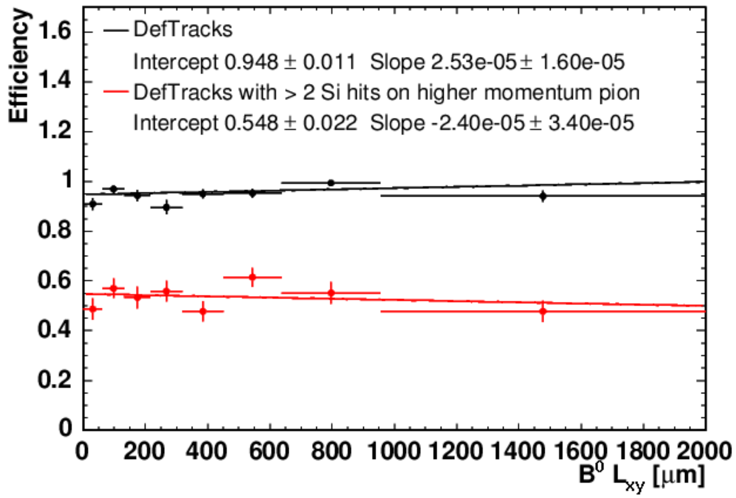


LH Scan for $B^0 \rightarrow J/\psi K_s$



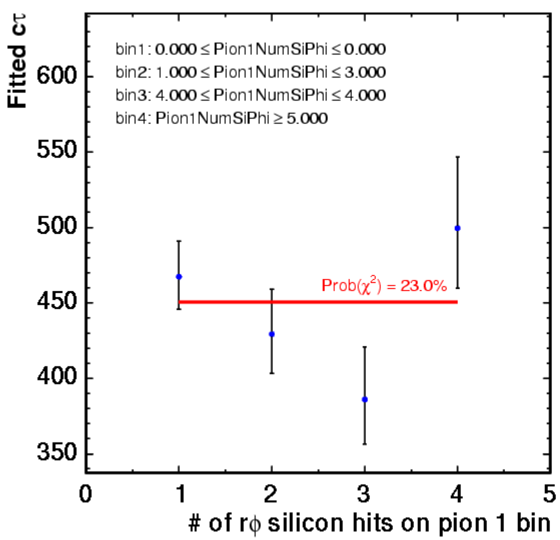
Effect of Silicon Hits on V^0

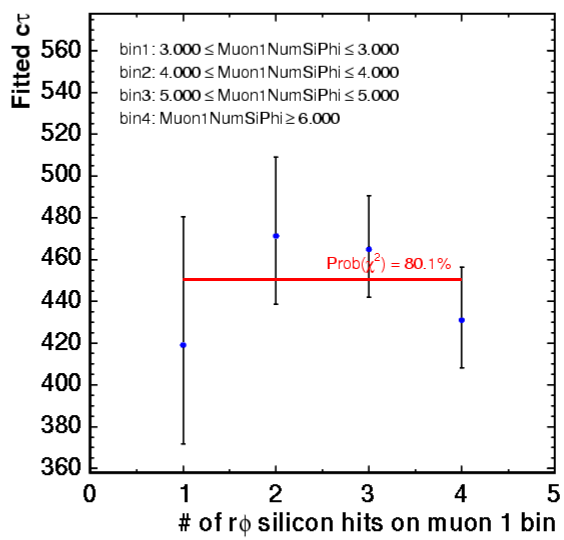




Baseline fit:
450.6 +/- 14.7 μm

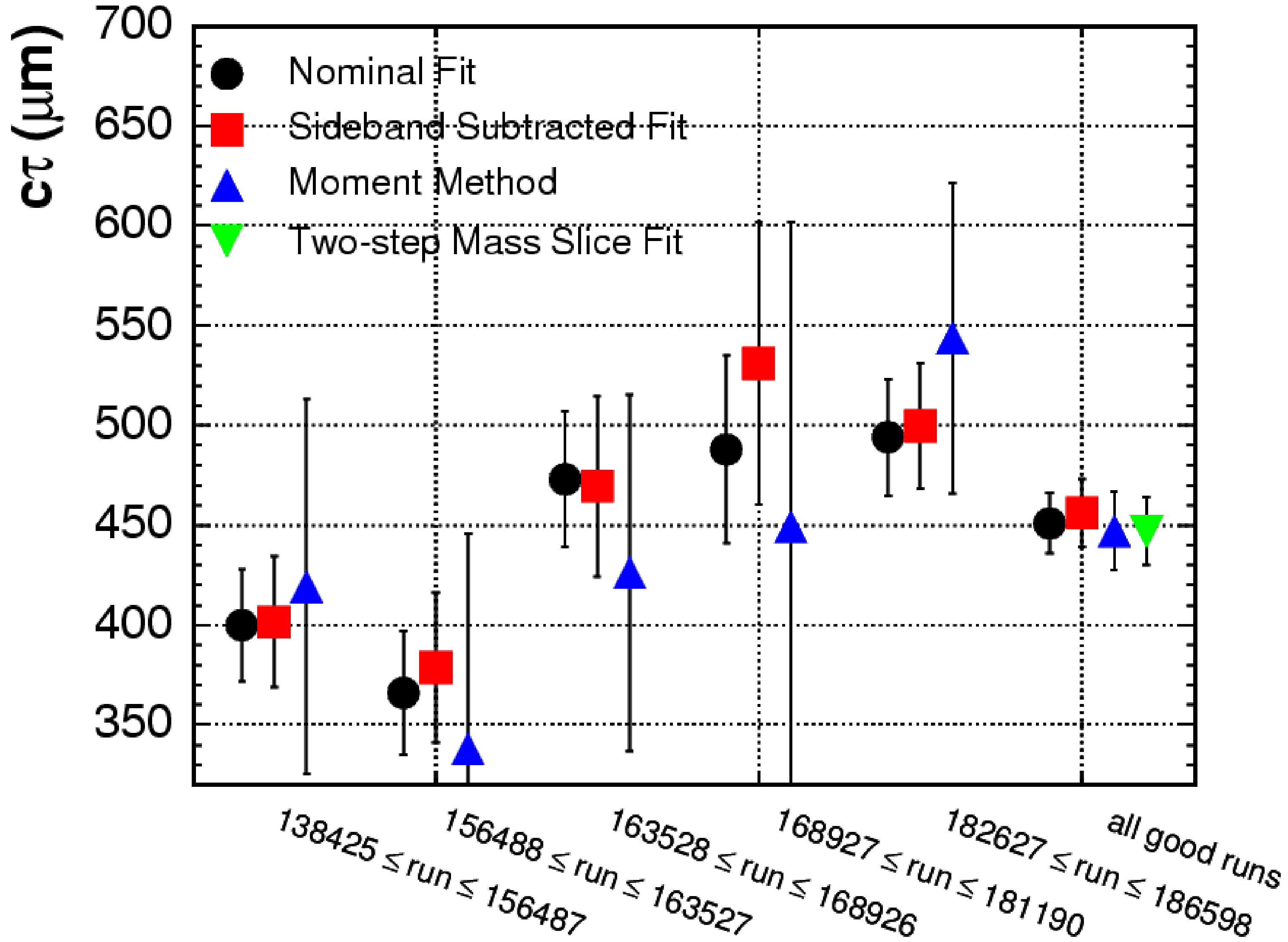
Fit using COT-only tracks for K_s:
455.0 +/- 16.8 μm





Consistent within statistics (taking into account statistical correlation)

Alternative Fitting Methods



Pythia MC for $\Lambda_b \rightarrow J/\psi\Lambda^0$