Lifetime of a Beautiful and Charming Meson:

Semileptonic B_c Decay at Dzero

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March 30, 2010

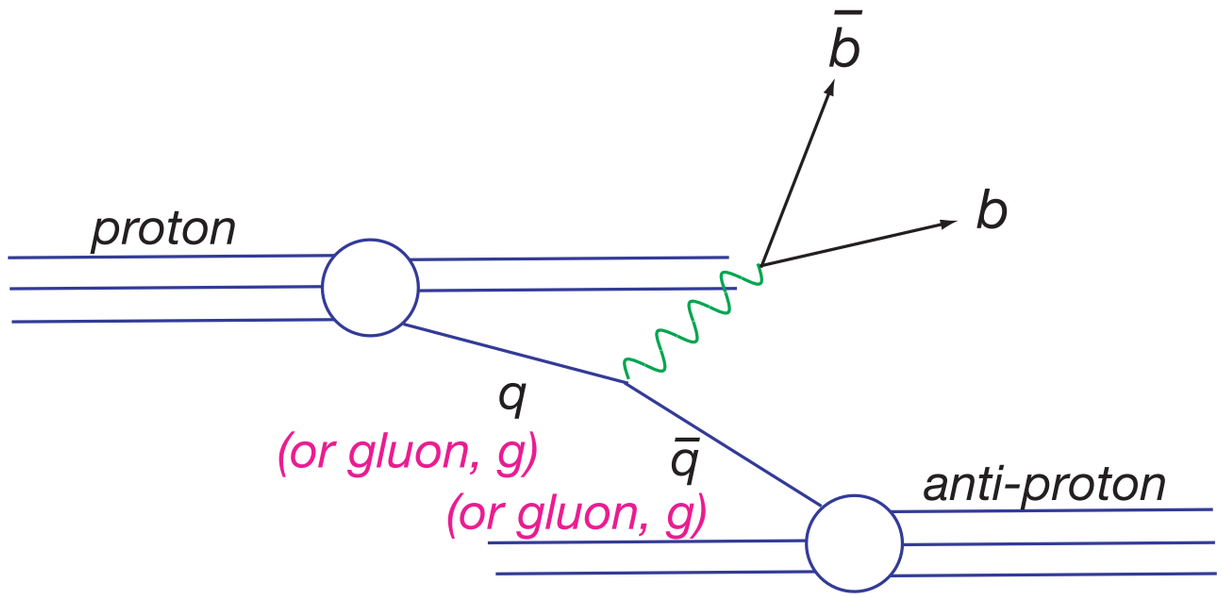
Outline

- What are we looking for here?
  - B_c meson and motivation for measurement
  - Theoretical lifetime predictions for the B_c meson
- Apparatus
  - D-Zero muon detectors
- Data Sample
- Contributions to the Signal
- Demonstration of Signal
- Lifetime Analysis
- Results, Systematics & Conclusions
- Software development

B_c Meson

- B_c meson is the ground state of the *bc* system
- Unique in that it carries two different heavy quarks
  - Each can decay quickly
  - Charmonium or Upsilon also have two heavy quarks but these carry the same heavy quark rather than one of each.
    - These two decay strongly unlike other ground state b-hadrons (including B_c) that decay weakly.

How Do You Get B_c?



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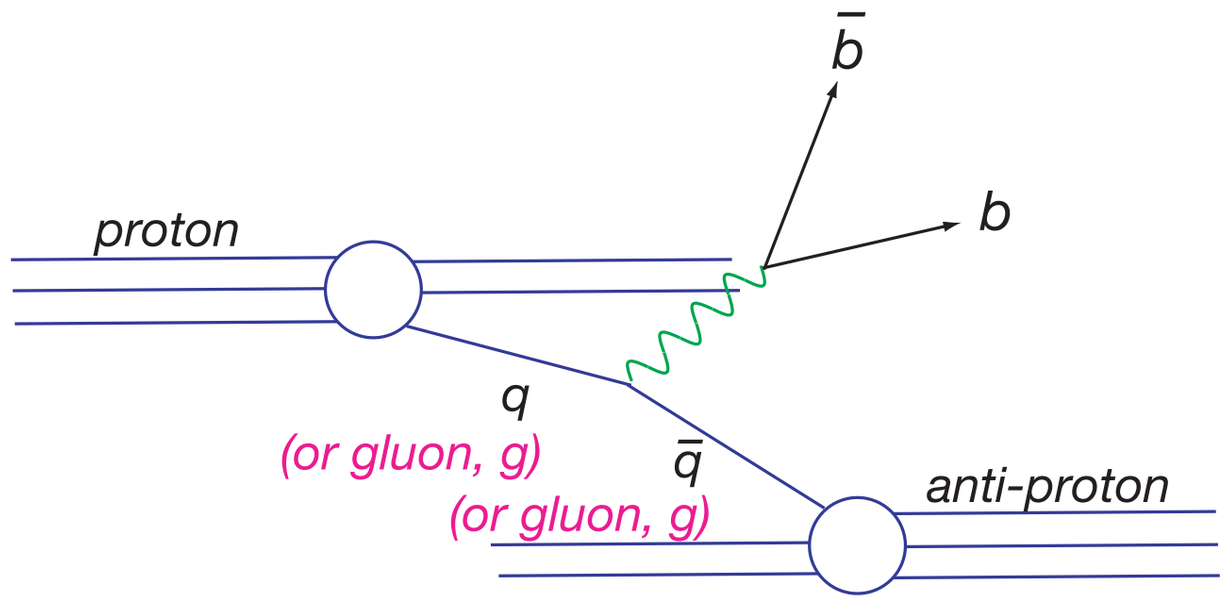

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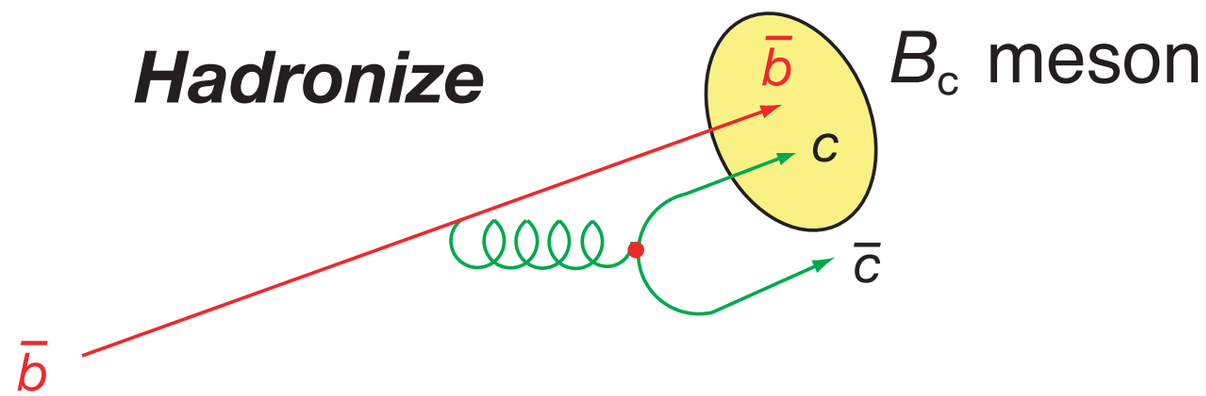

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- However, gluon splitting to heavy quarks is heavily suppressed.
  - 40% to *uu*(bar)
  - 40% to *dd*(bar)
  - 11% to *ss*(bar)
  - 9% to everything else
    - Including to di-quarks, (i.e. *b*-baryons), *cc*(bar)
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- B_c has a smaller cross section than other *B* hadrons by 3 orders of magnitude due to needing both a *bb*(bar) pair and *cc*(bar) pair
  - Due to lower production the B_c meson, properties of this meson can only be studied in detail at high energy hadronic colliders with high luminosity like the Tevatron

How does B_c Decay?

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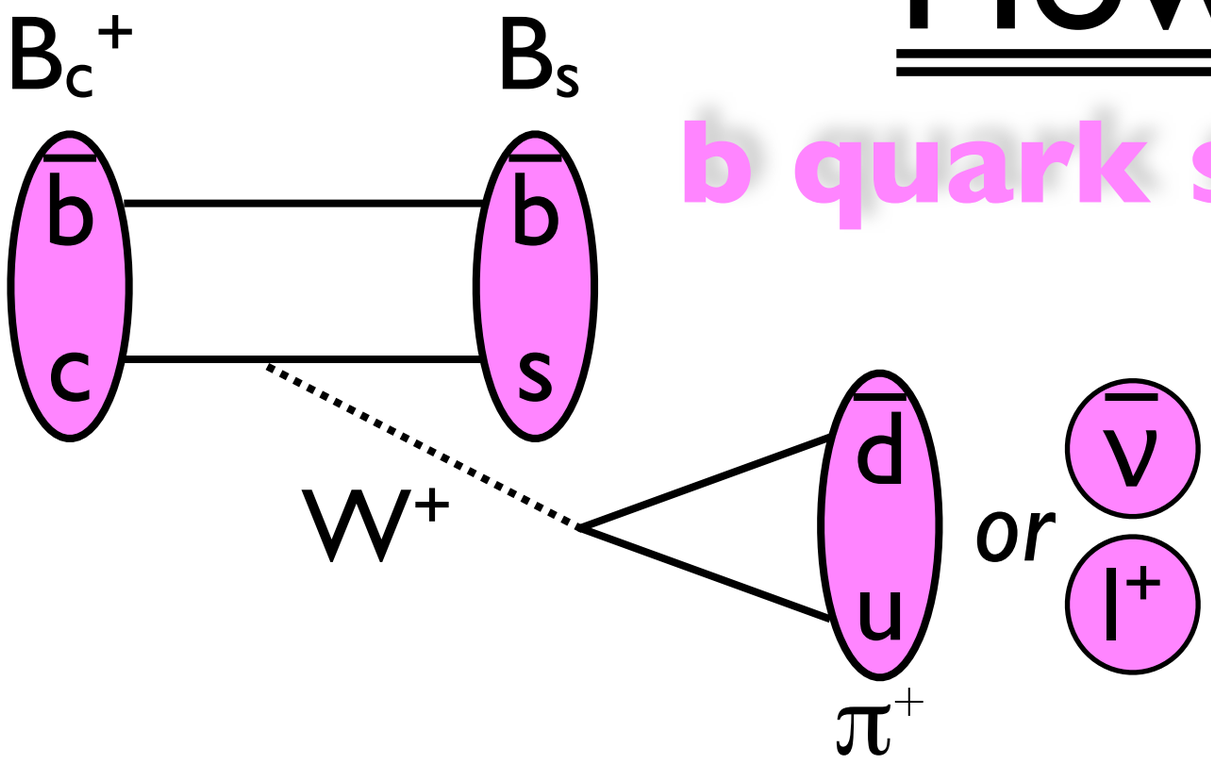

b quark spectates

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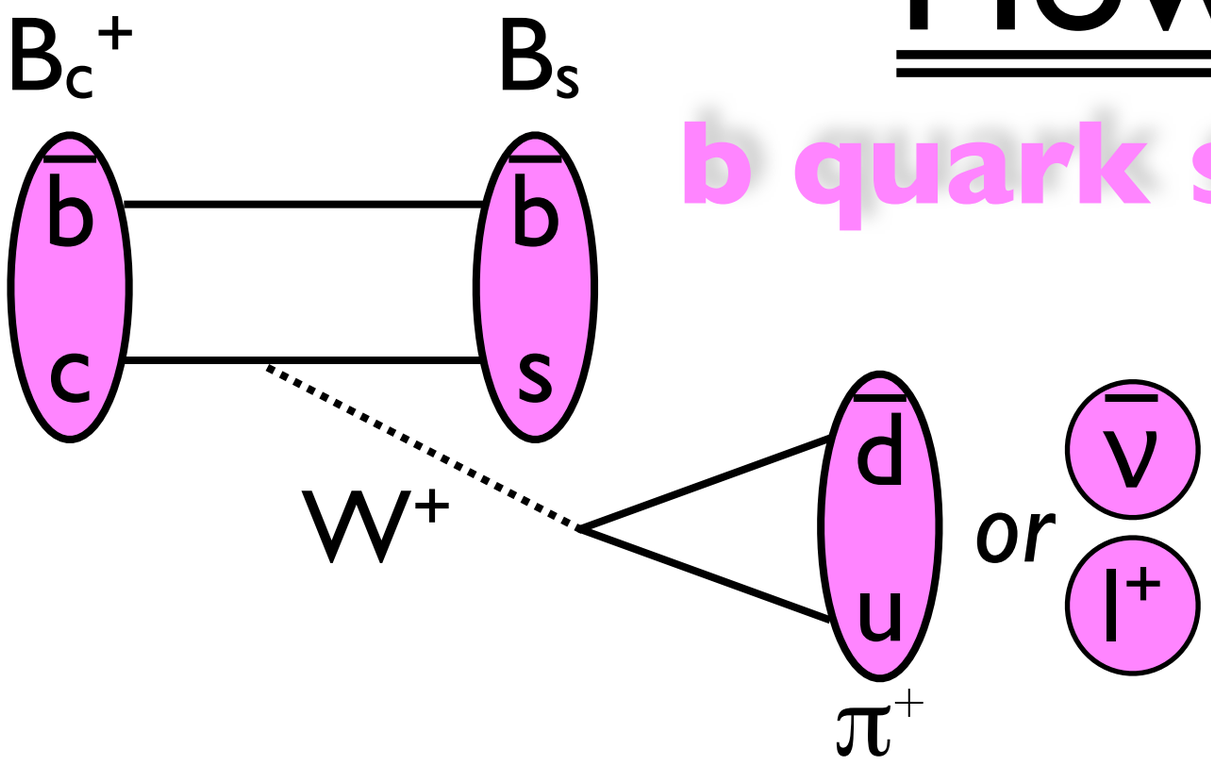

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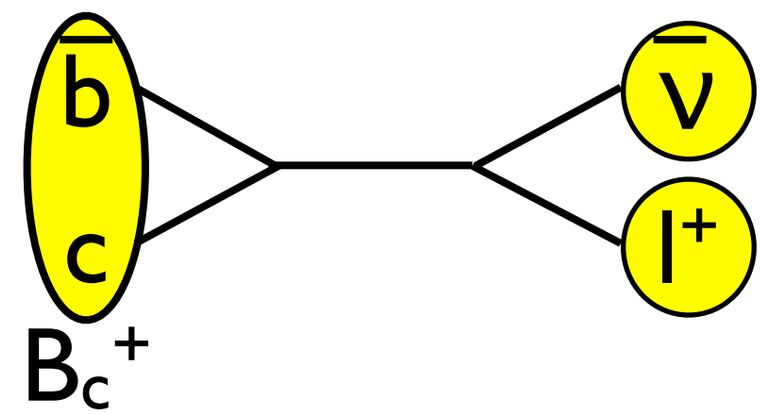
annihilation



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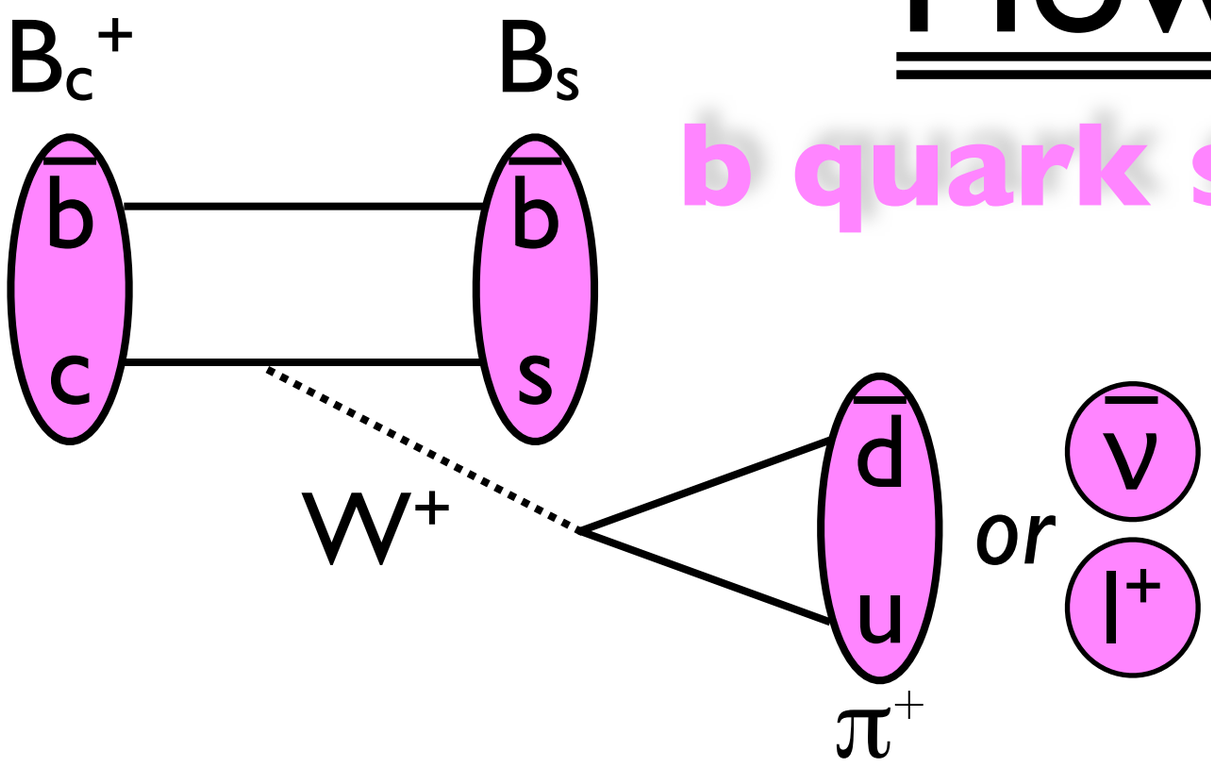

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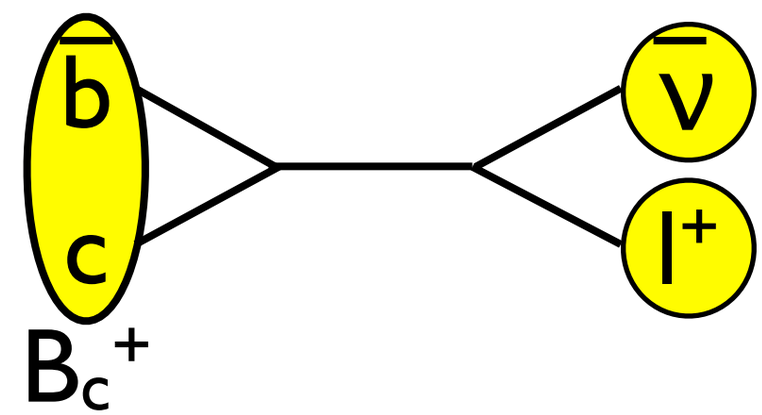
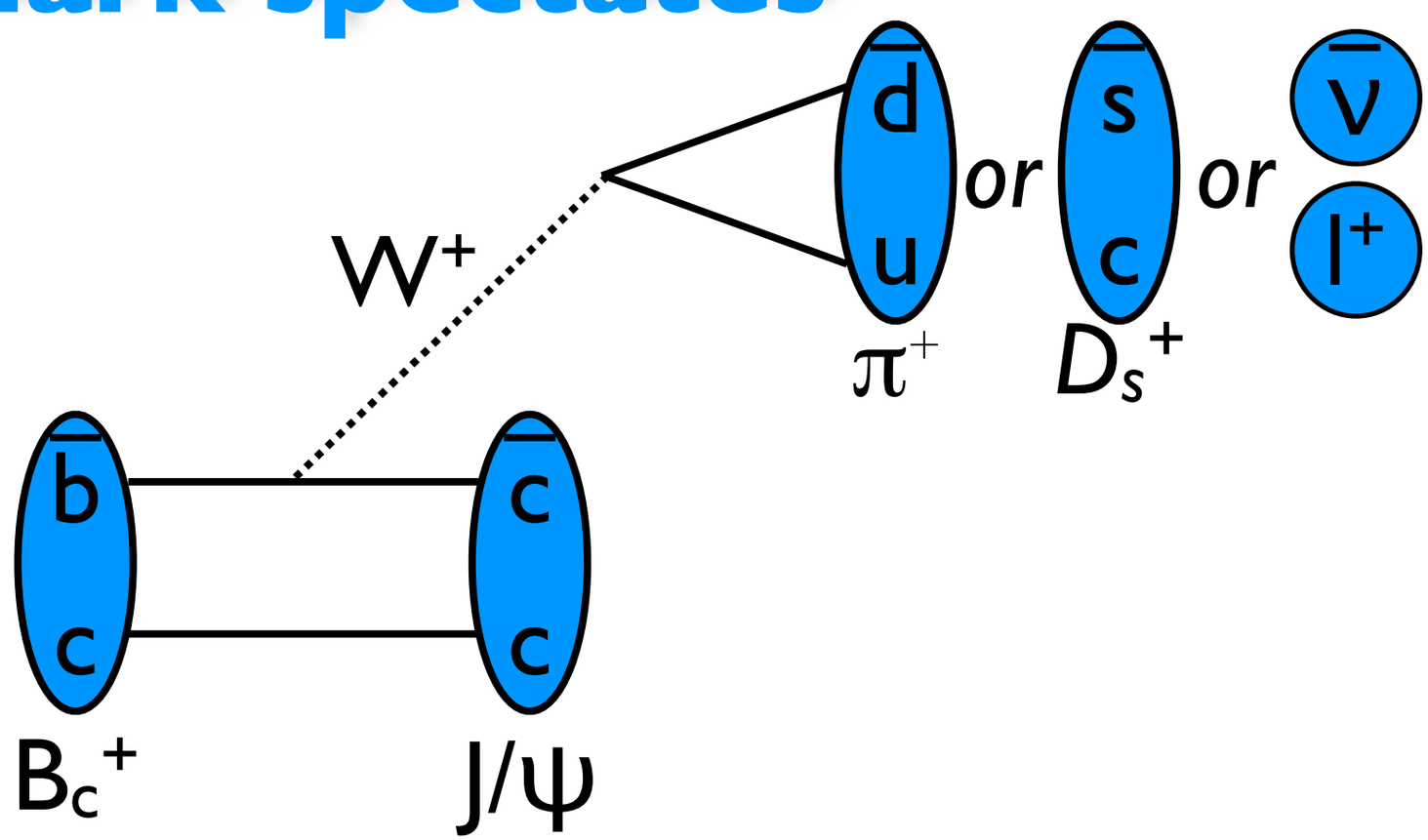


c quark spectates



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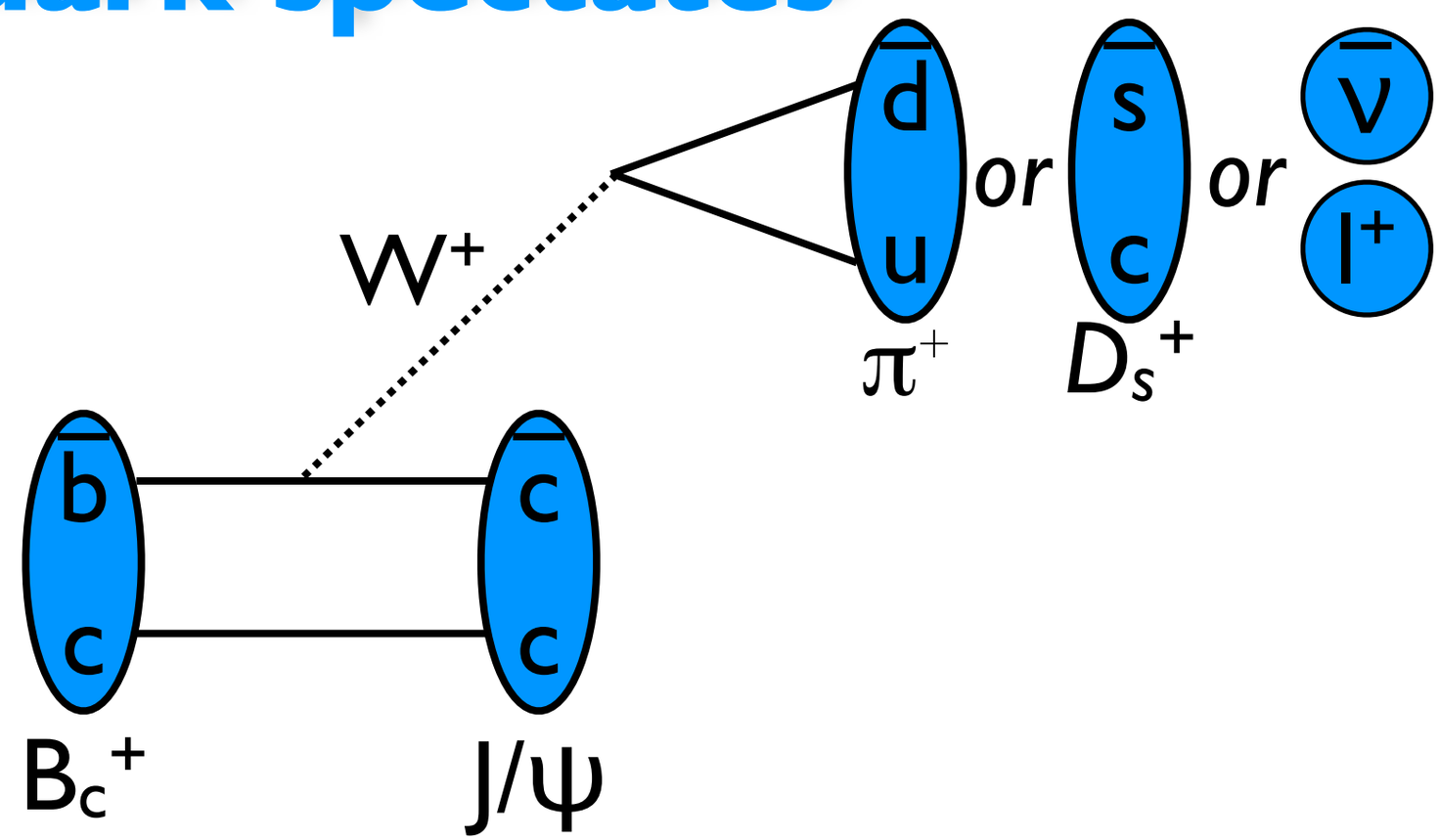

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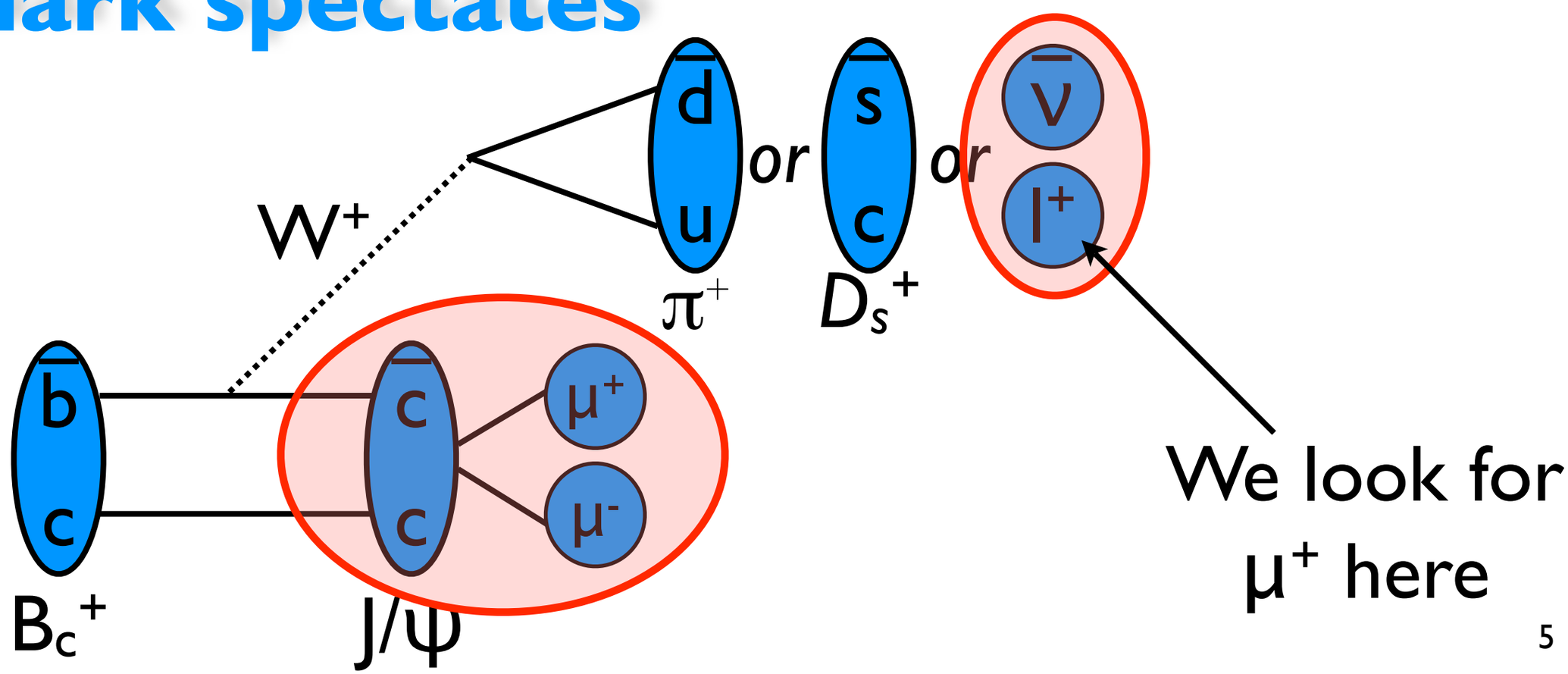

Racing to Decay?

$$\Gamma(B_c)=\Gamma(B_c\rightarrow J/\psi+X)+\Gamma(B_c\rightarrow B_s+X)+\Gamma(B_c \text{ annihilation})$$

[b-quark spectates] **[c-quark spectates]**

- So as you add more more possible decay paths, $\Gamma(B_c)$ increases.
- B_c lifetime is proportional to $1/\Gamma(B_c)$
  - Contribution to the lifetime : *c* quark decay (70%), *b* quark decay (20%), annihilation (10%).
- So when we talk about the quarks racing to decay, we really mean more possible ways to decay.
- All other *B* hadrons are within a few percent of each other, or at most 10-15% different in the case of *b*-baryons.
- However, B_c is predicted to be in the ballpark of a <u>factor of three</u> different in lifetime

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Operator Product Expansion

Operator Product Expansion

- In weak decays of b or c quark, the energy release is large when compared to the scale of bound state dynamics, and thus OPE can be expanded in inverse powers of the heavy-quark mass so $\mathcal{T}$ has the form :

$$\mathcal{T} = \sum_{i=1}^{2} \{ C_1(\mu) \bar{Q}^i Q^i + \frac{1}{m_{Q^i}^2} C_2(\mu) \bar{Q}^i g \sigma_{\mu\nu} G^{\mu\nu} Q^i + \frac{1}{m_{Q^i}^3} O(1) \}$$

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Parameters, GeV	τ_{B_c}
m_b=4.8, m_c=1.35, m_s=0.15	0.75
m_b=5.0, m_c=1.5, m_s=0.15	0.53
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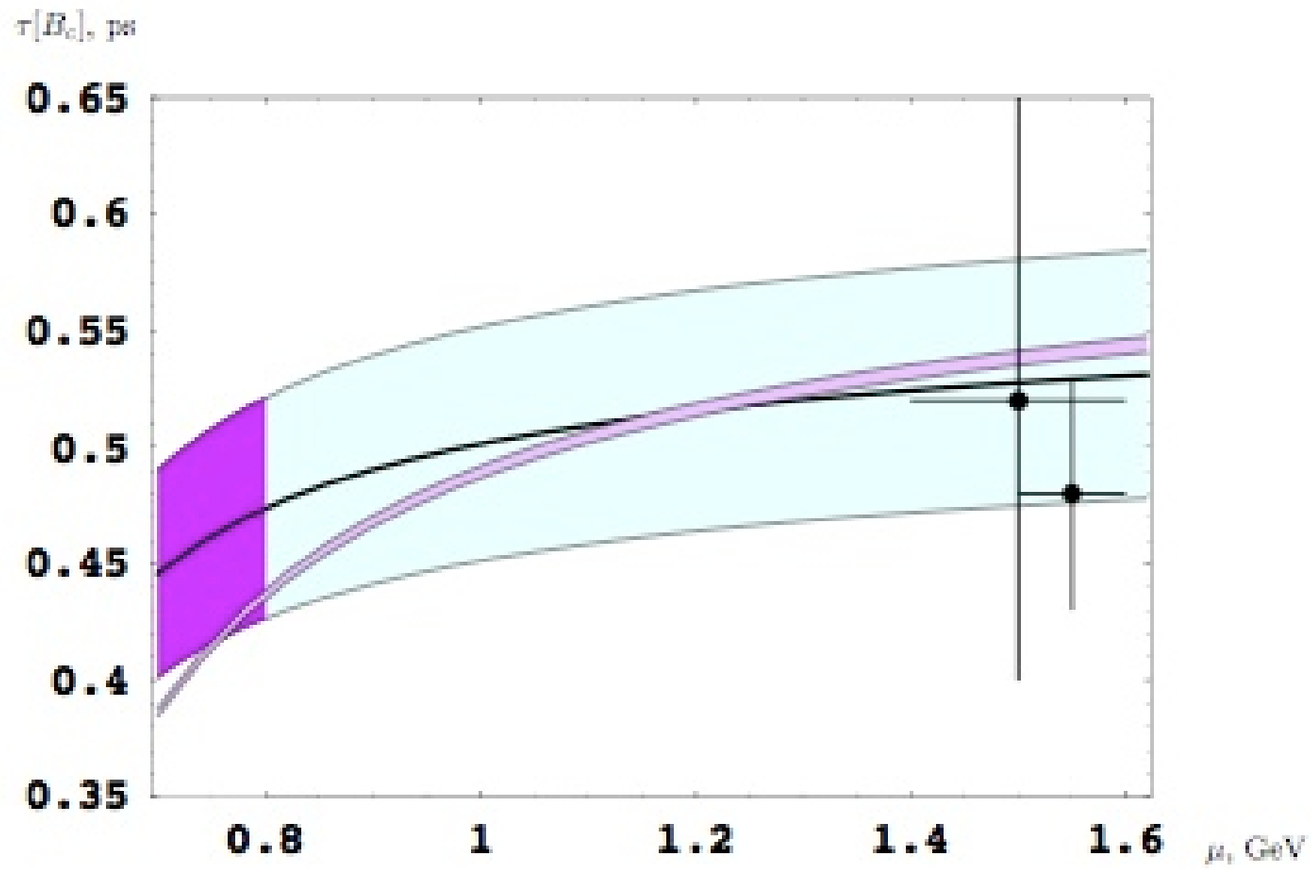
Notice the variation in the resulting lifetime as the mass of the c-quark is varied

QCD Sum Rules

- In contrast to OPE the quark masses are fixed by the two-point sum rules for bottomonia and charmonia
- The accuracy of the prediction in QCD Sum Rules is determined by the choice of the scale μ for the hadronic weak lagrangian.

B_c lifetime predictions as calculated by QCD Sum Rules vs the scale of the hadronic weak lagrangian in decays of the charm quark.



Theoretical Predictions

0.55 ± 0.15 ps

Operator Product Expansion (OPE)

0.48 ± 0.05 ps

QCD Sum Rules

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QCD Sum Rules

The difference in the size of the errors is due to the fact that the quark masses are not involved in the QCD Sum Rules calculation but are a large component of the OPE Calculation

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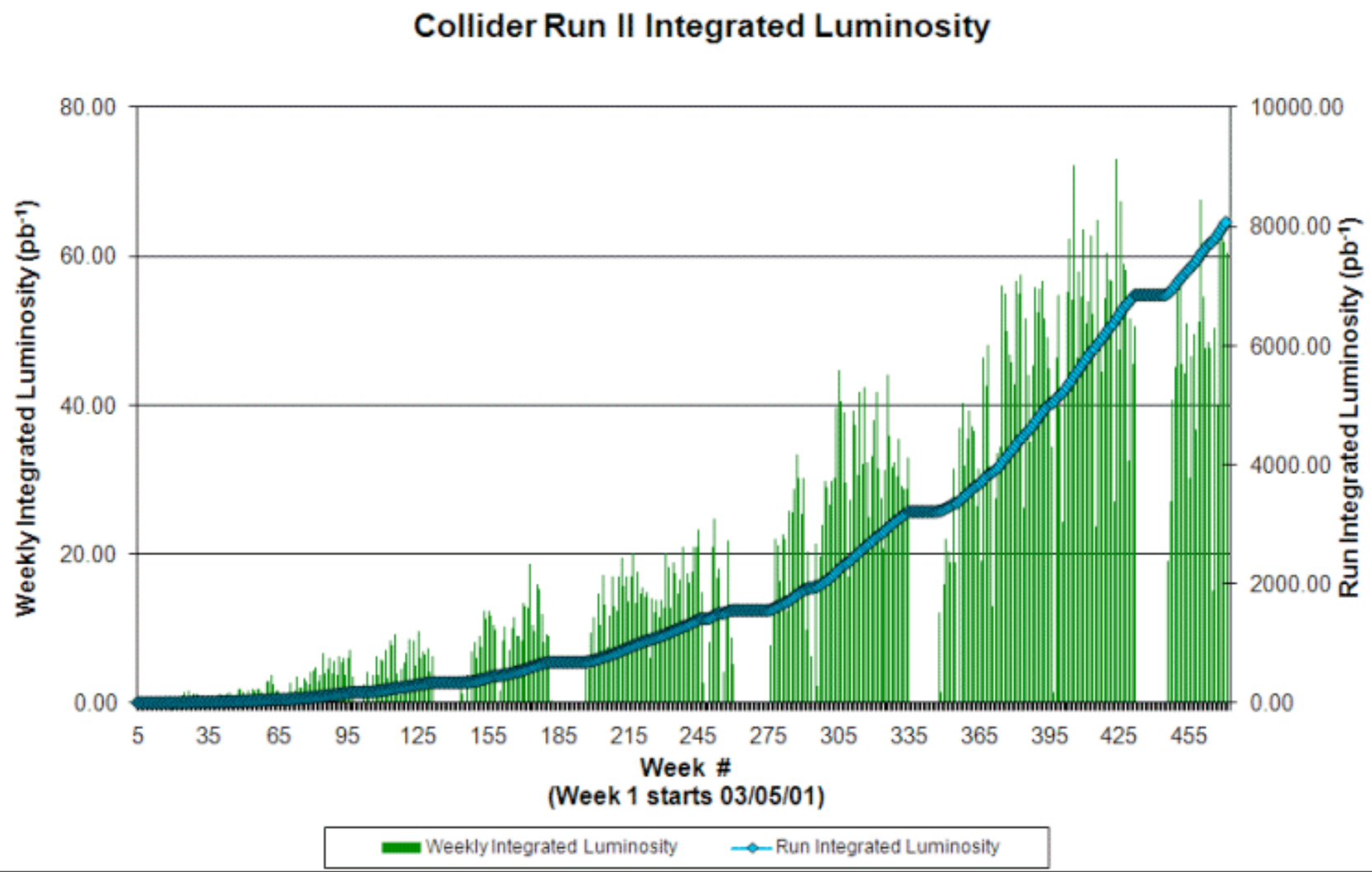
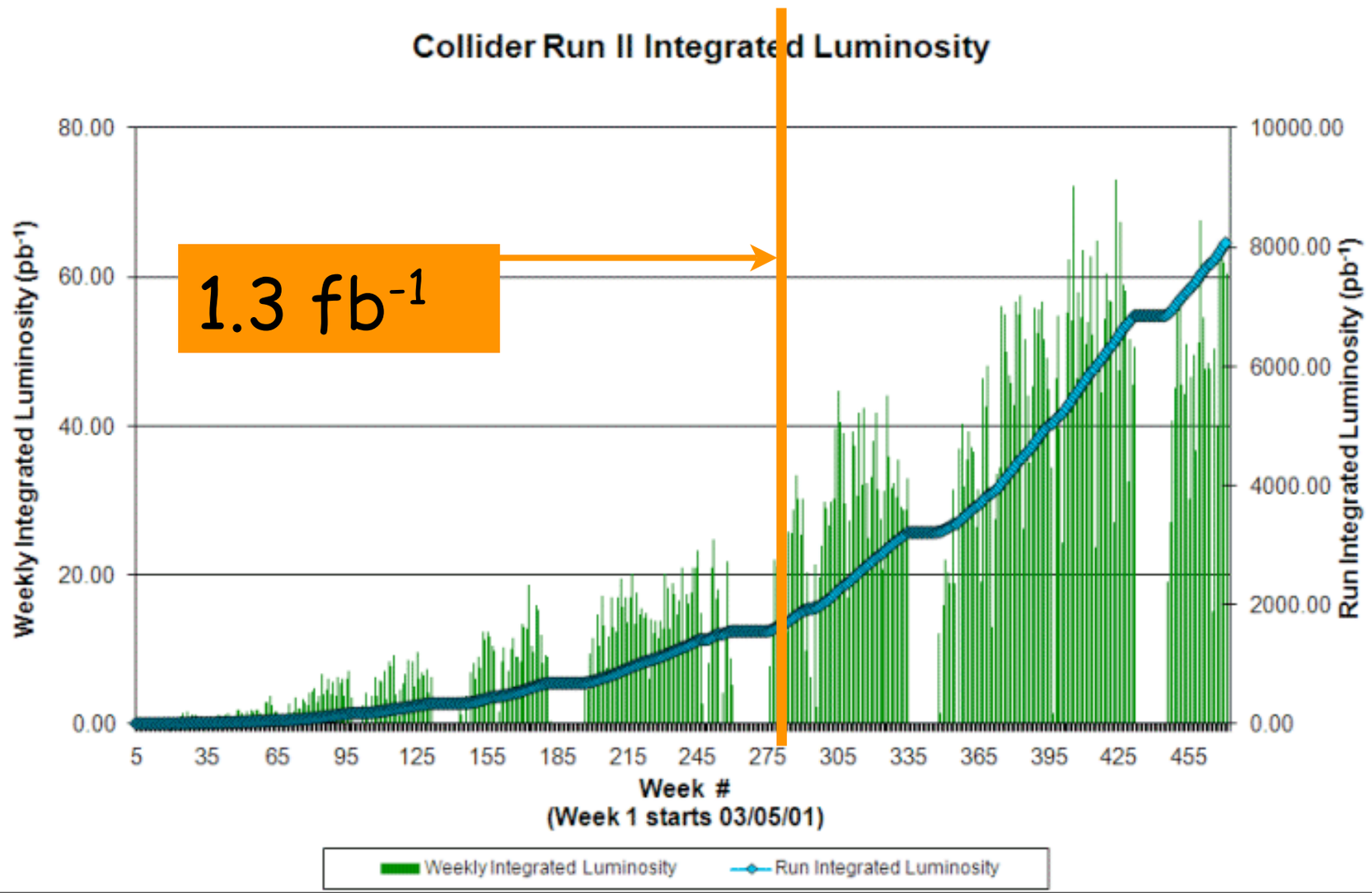
Tevatron Performance



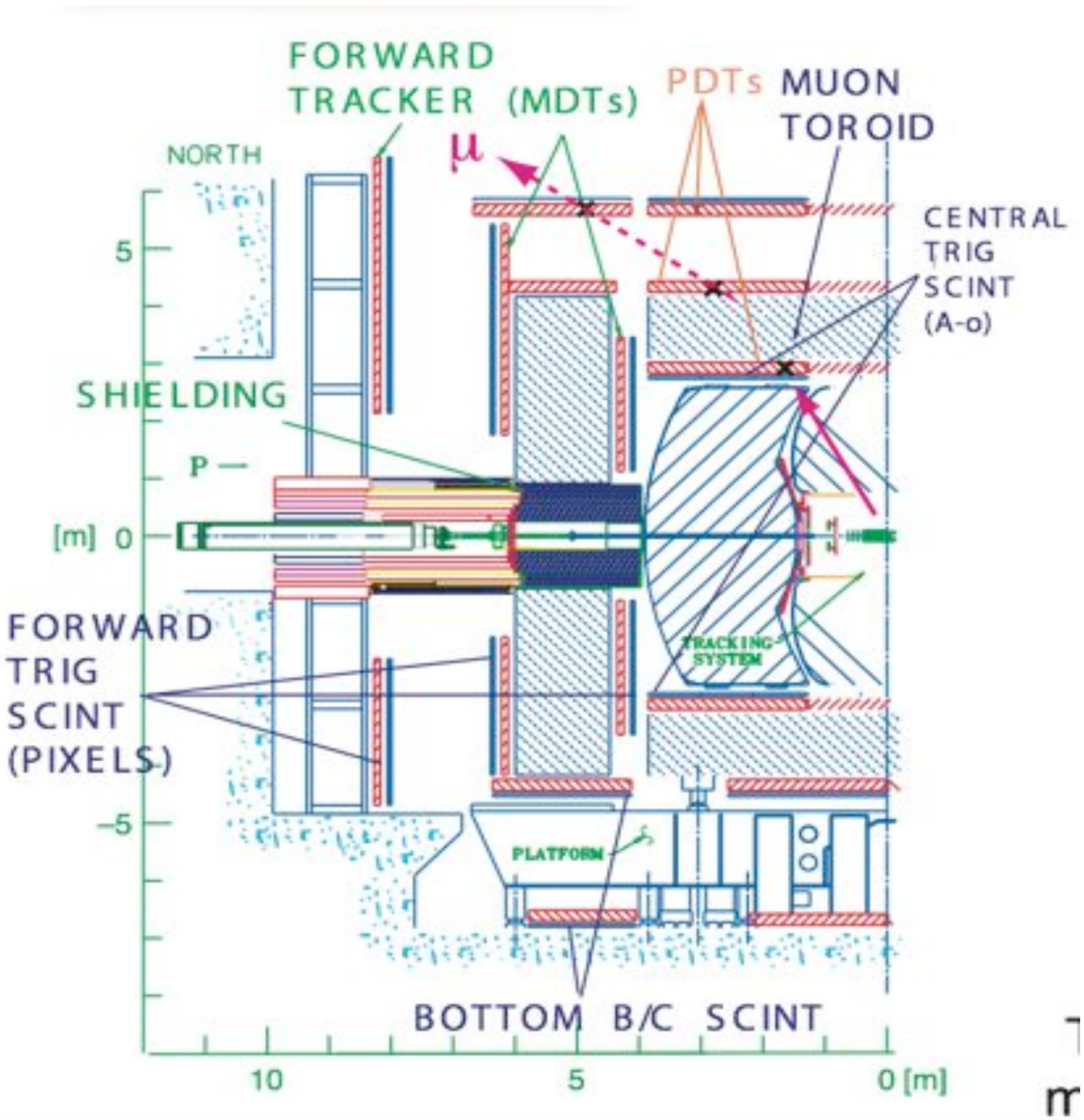
Tevatron Performance

The following analysis
based on Data taken between
2002-2006



D-Zero Experiment

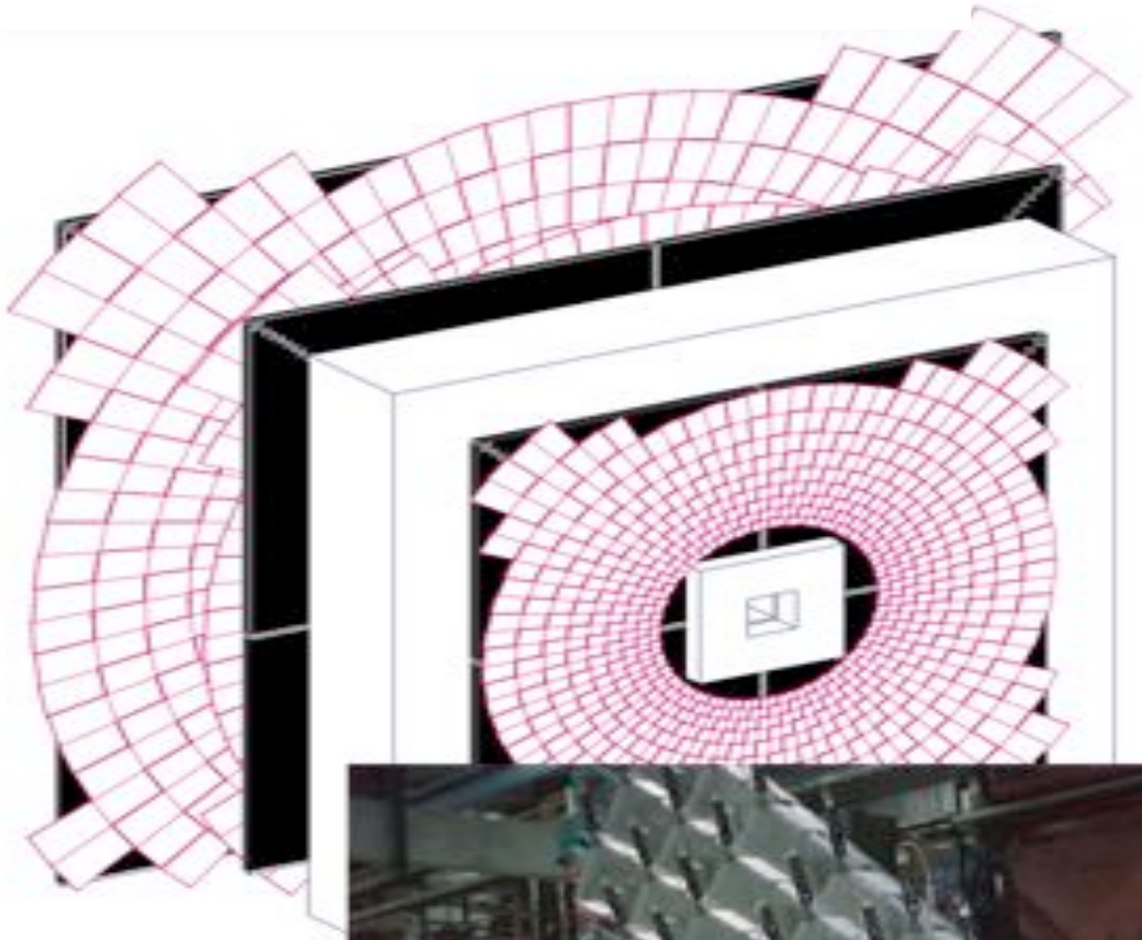
D-Zero : Muon Detectors



- Cosmic ray rejections
  - Scintillator Timing
- Very low punch through
  - Must travel through toroid & calorimeter
  - Minimum p_T to make it through to muon detectors is 2.5 GeV
- Muon Toroid
  - Allows for local momentum measurement
- IU Participation

D-Zero : Muon Detectors

- Tracking Detectors
  - Drift tubes (Mini & Proportional)
  - Fine Granularity (we can measure muon position very precisely)
  - Slow
- Trigger Detectors
  - 3 layers of scintillators
  - Coarse
  - Fast (good for triggering!)



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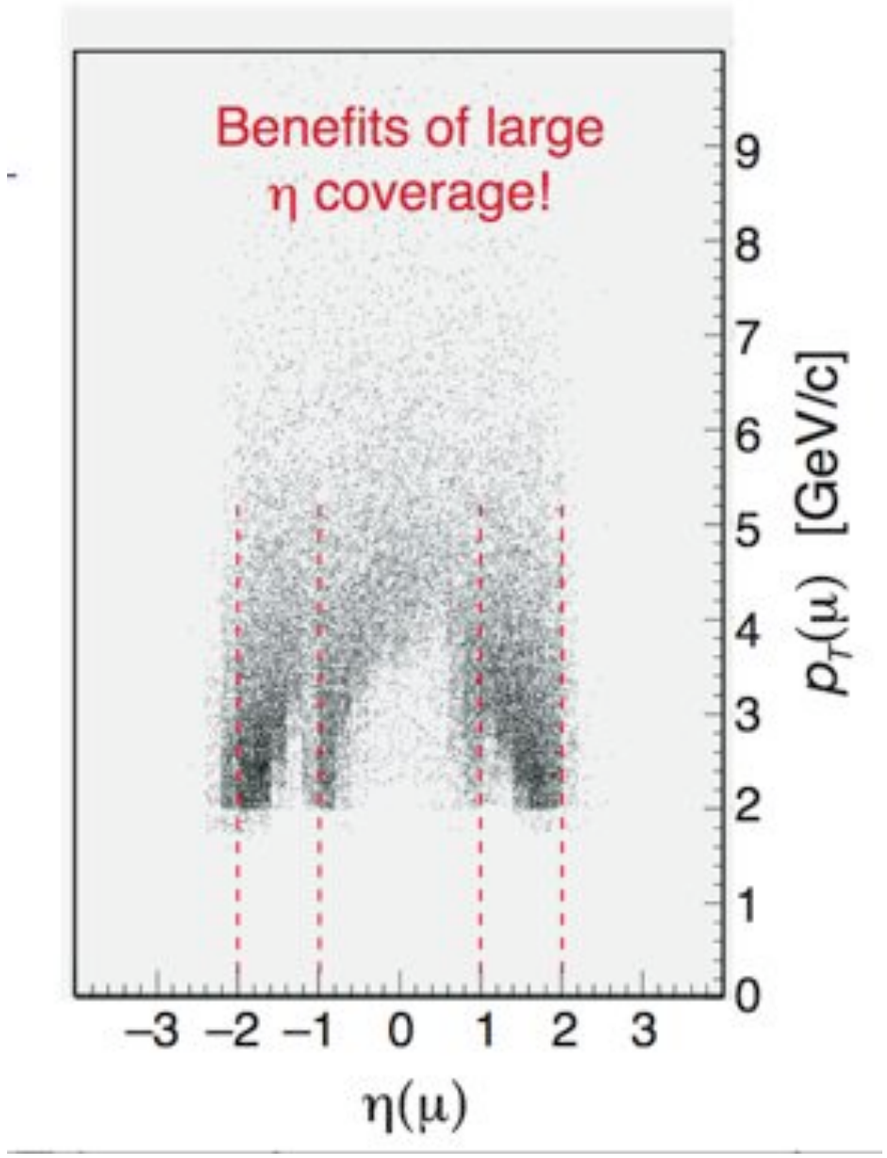
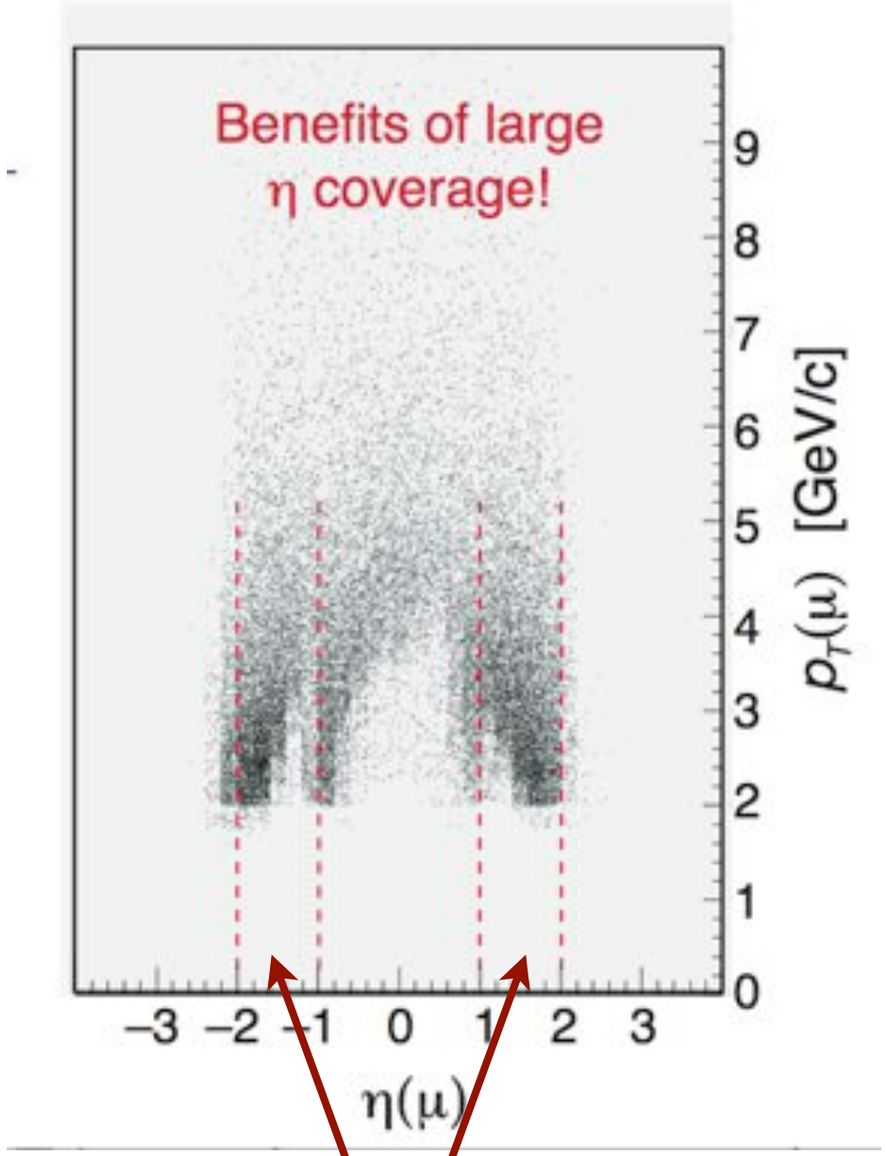


Triggered and reconstructed muons, mostly soft (semileptonic b decays)

D-Zero : Muon Detectors



Large density of muons within $1<|\eta|<2$

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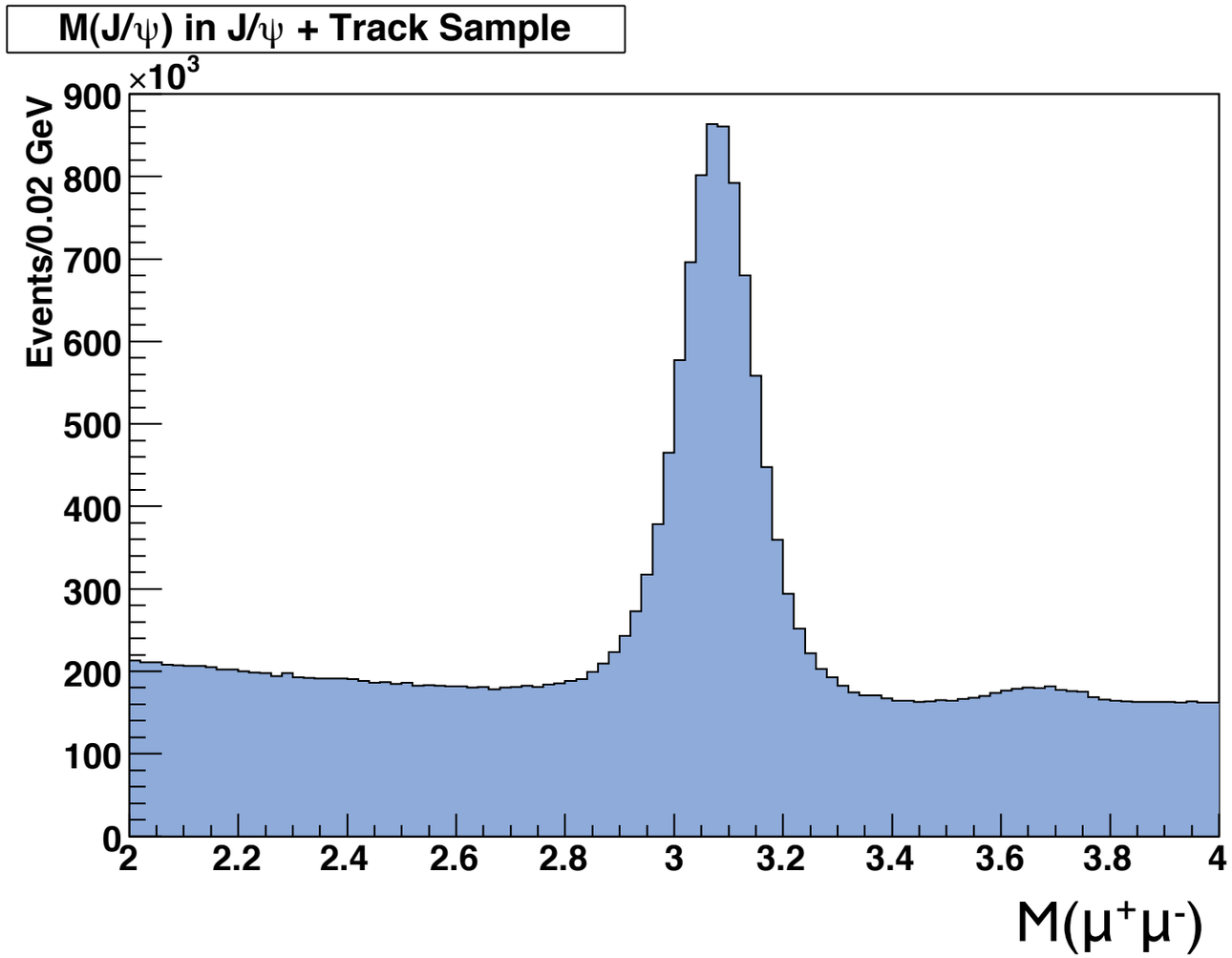
Data Sample

- Entire RunIIa Data set
  - 1.35 fb^{-1} of data
  - Taken btwn 2002-2006
  - Inclusive muon skim
- Run over muon skim and get two sets of data
  - J/ψ + any other track
  - J/ψ + μ (*note that this is a subset of the above)
- Then selection cuts are added to each



Pre-Selection Cuts

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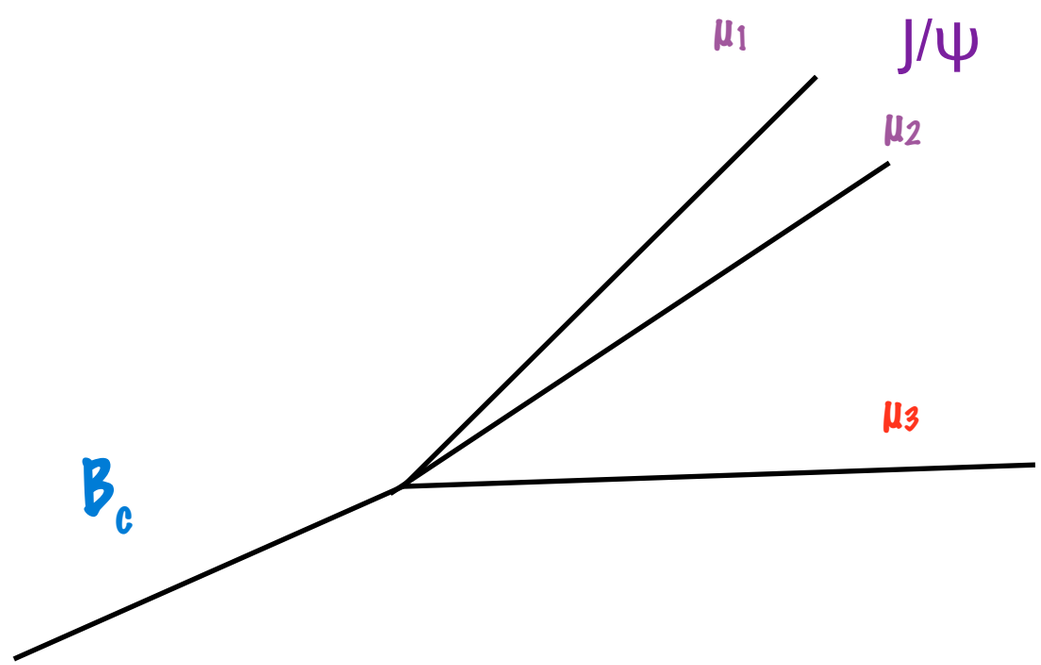

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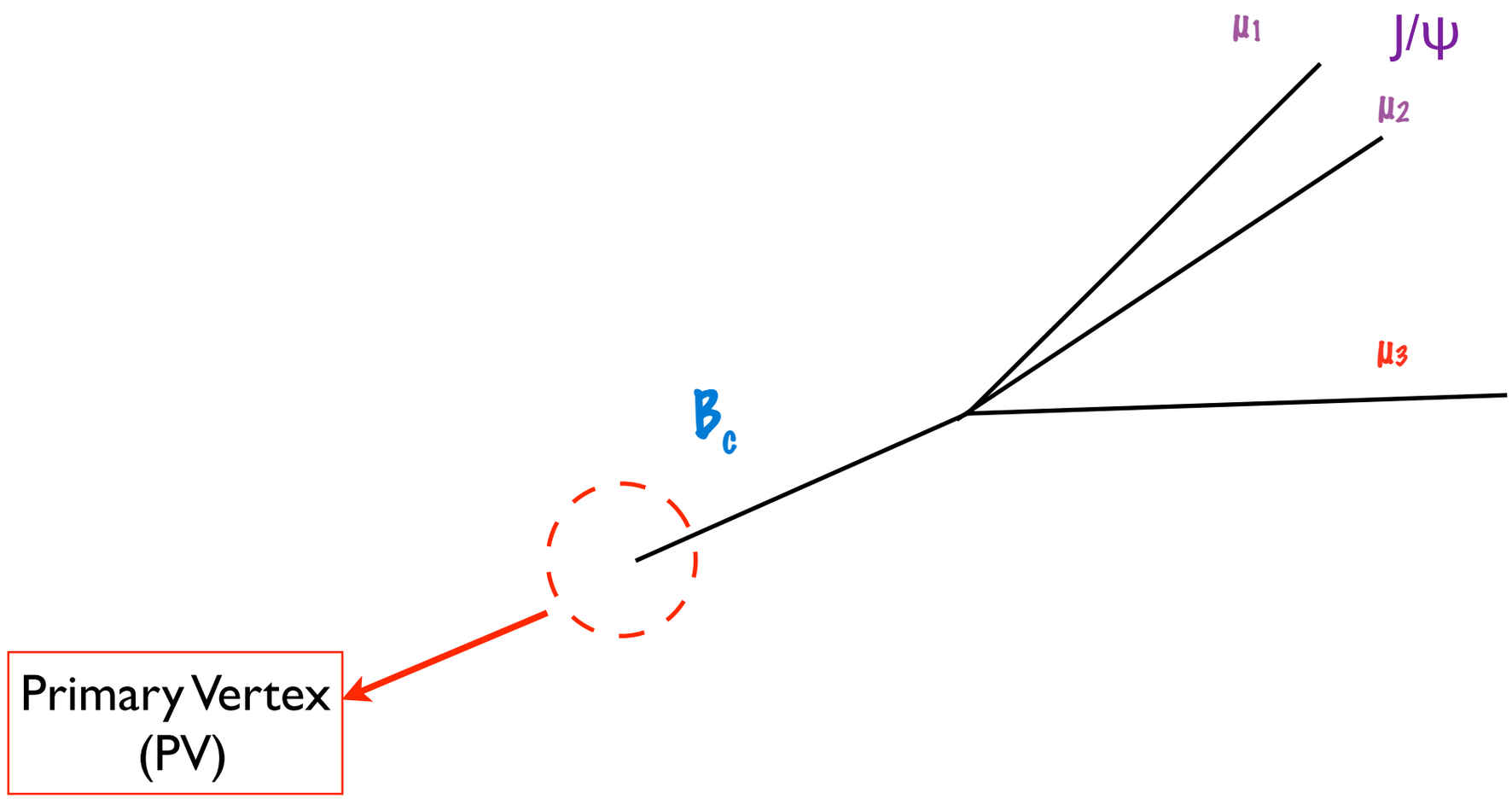

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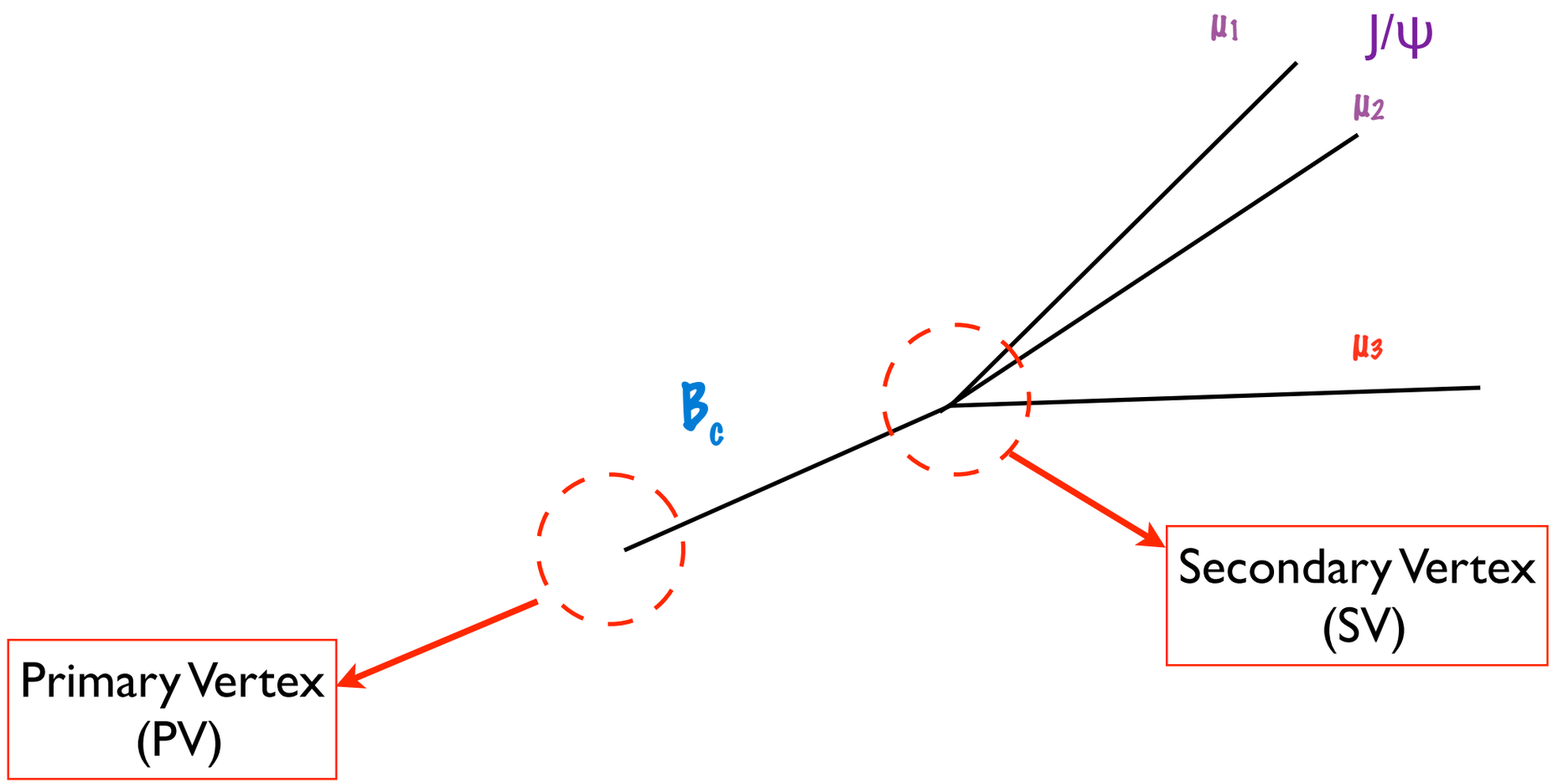
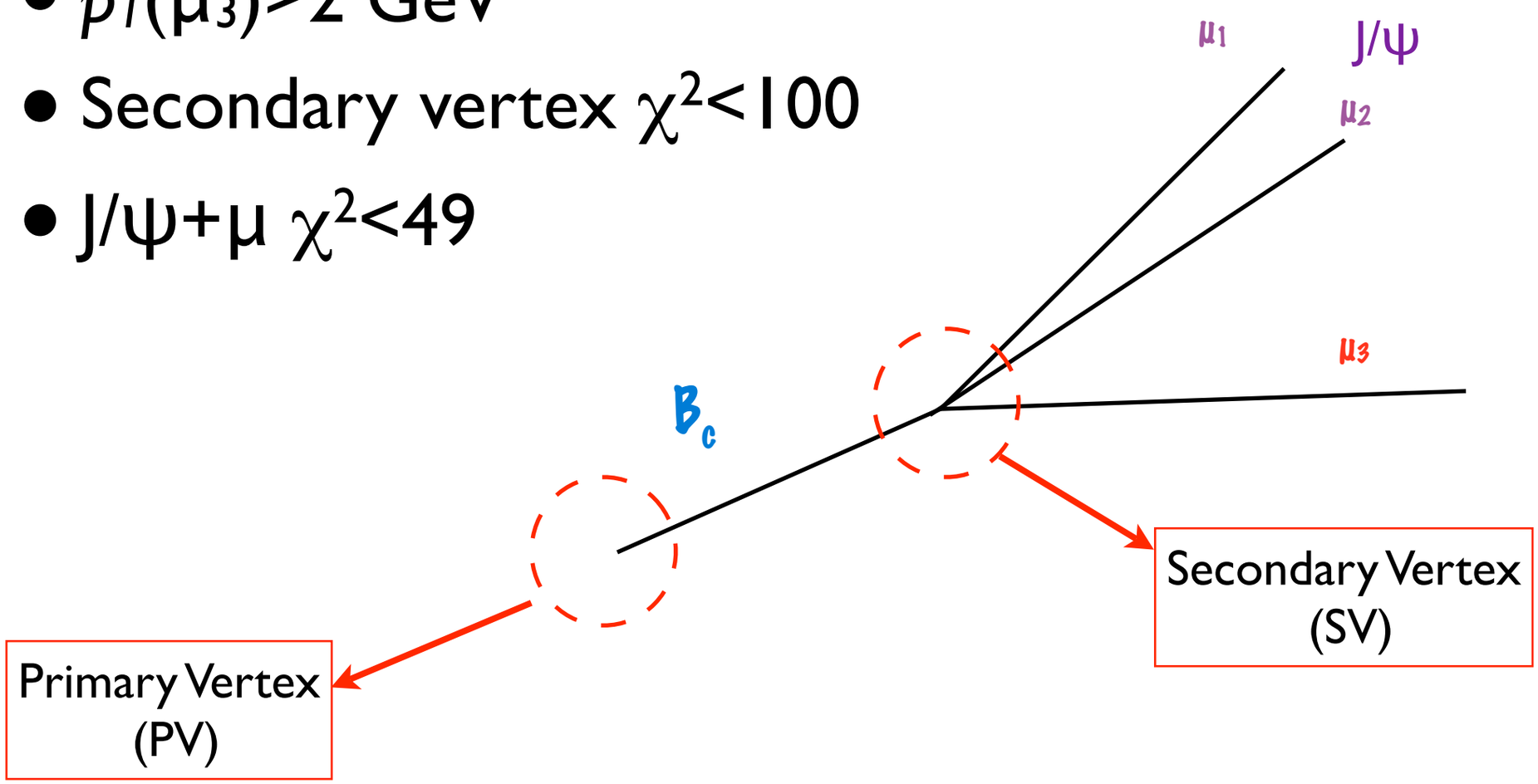


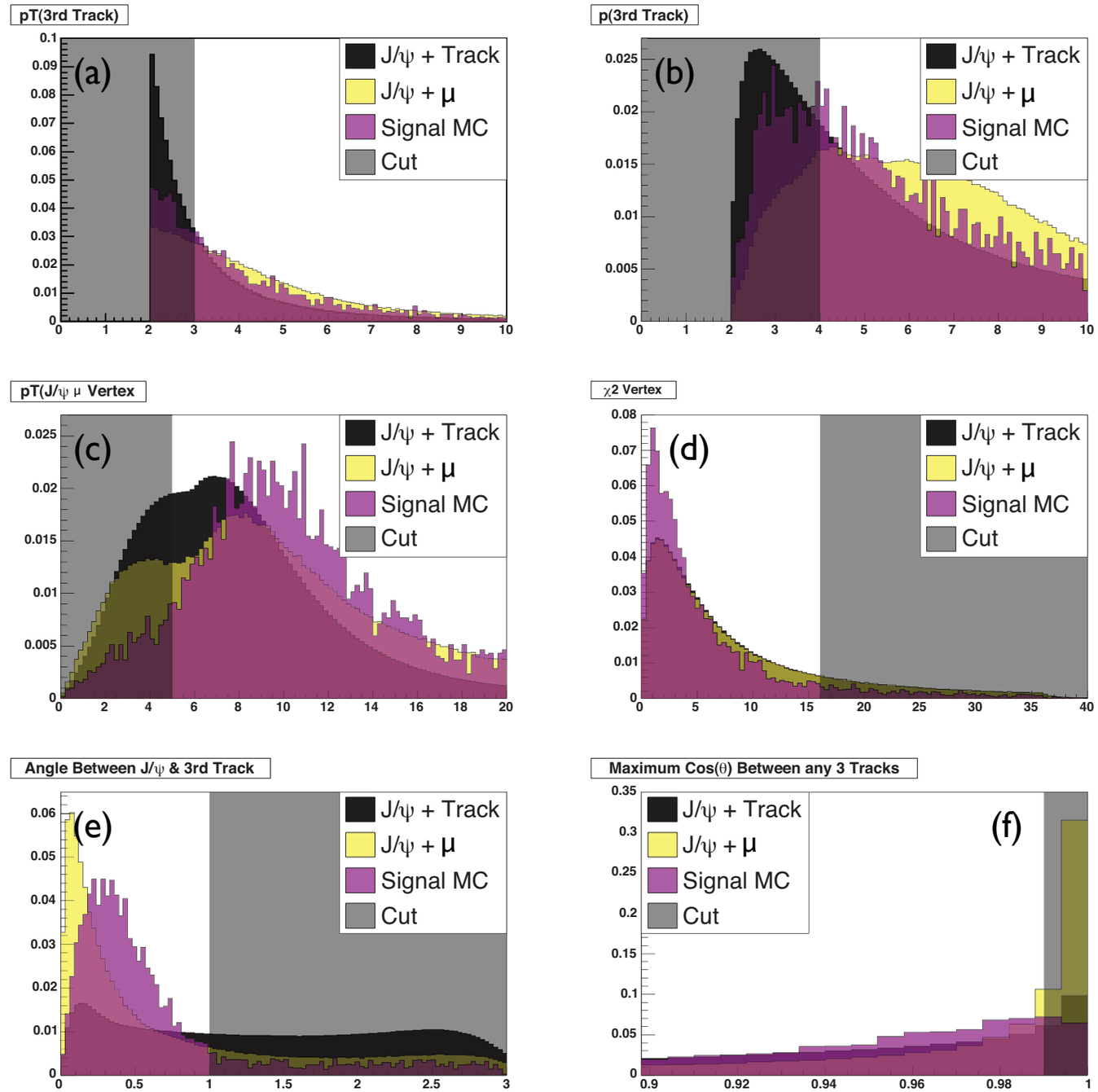
Pre-Selection Cuts

- $p(J/\psi)>4$ GeV
- Each muon must have at least one hit in the silicon detector
  - μ_3 must have two
- $p_T(\mu_3)>2$ GeV
- Secondary vertex $\chi^2<100$
- $J/\psi+\mu$ $\chi^2<49$



Some Cut Variables

(a) : p_T(3rd Track)
(b) : p(3rd Track)
(c) : p_T(J/ψμVertex)
(d) : χ^2 (J/ψμVertex)
(e) : Angle btwn J/ψ & μ
(f) : Cos(θ) btwn any three tracks



*shaded regions are cut away

Final Selection Cuts

- $p_T(\mu_3)>3$GeV
  - Cleanly make it through muon system
- $p(\mu_3)>4$ GeV
- p_T(VERT)>5 GeV
  - B_c candidate not including the neutrino
  - Put higher cut on vertex to reduce background
- $\chi^2<16$
  - High quality vertex to ensure 3 tracks come from same location
- nseg(μ_3)=3
  - High Quality Muons
- Cos(θ) between any two $\mu<0.99$
  - Reduces problems from muon segments in muon detectors associated with tracks which are close in the tracking chamber
- |sctime(A)|<10 ns
  - Scintillator time to rid of cosmics
- IP biased triggers removed
  - Lifetime measurement biased with these
- Angle between J/ψ+μ<1rad
  - Angle reasonably close together so coming from same place

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Contributions

- Signal
  - Signal $B_c \rightarrow J/\psi + \mu + \nu$ Monte Carlo
  - Signal $B_c \rightarrow \psi(2S) + \mu + \nu \rightarrow J/\psi + \mu + \nu$ Monte Carlo
- Real J/ψ + Fake μ
  - Model with J/ψ + Track Sample
- Fake J/ψ + Real μ
  - Model with J/ψ Sideband
- Real J/ψ + Real μ (but each coming from different particle decays)
  - Model with J/ψ + X QCD Monte Carlo
  - Have to include contribution due to gluon splitting $g \rightarrow bb(bar)$
  - $b \rightarrow J/\psi$ other $b \rightarrow \mu$ or $b \rightarrow c \rightarrow \mu$
- B^+
  - $B^+ \Rightarrow J/\psi + K^+$ [$K^+ \Rightarrow \mu^+ \upsilon$]

decay in flight

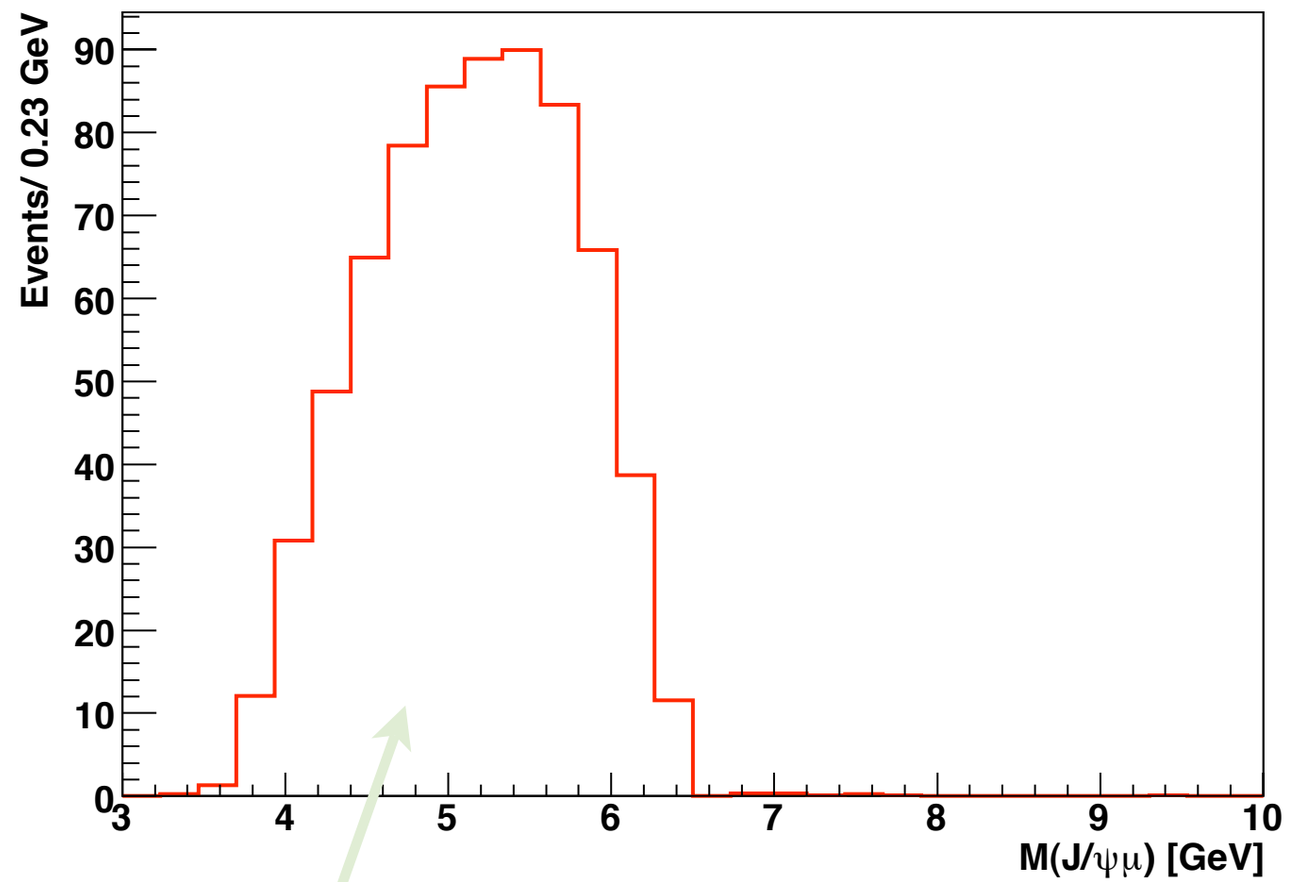
- Prompt (i.e. J/ψ from *cc*(bar))
  - Model with Negative Decay Length J/ψ+μ Data

Analysis Steps

- Invariant mass of trimuon system will be taken as an estimate of the mass of the B_c
- Data and MC simulations are used to form mass templates for each contribution
- Assume well-measured B_c mass (6.300 GeV) for the signal mass template
- Functions, data and MC simulations used to form lifetime models for each contribution
- First use mass-only fits to demonstrate signal, then simultaneous mass and lifetime fits (mass fits help constrain normalization of each lifetime component)

Mass Templates

- Signal
  - Signal $B_c \rightarrow J/\psi + \mu + \nu$ Monte Carlo



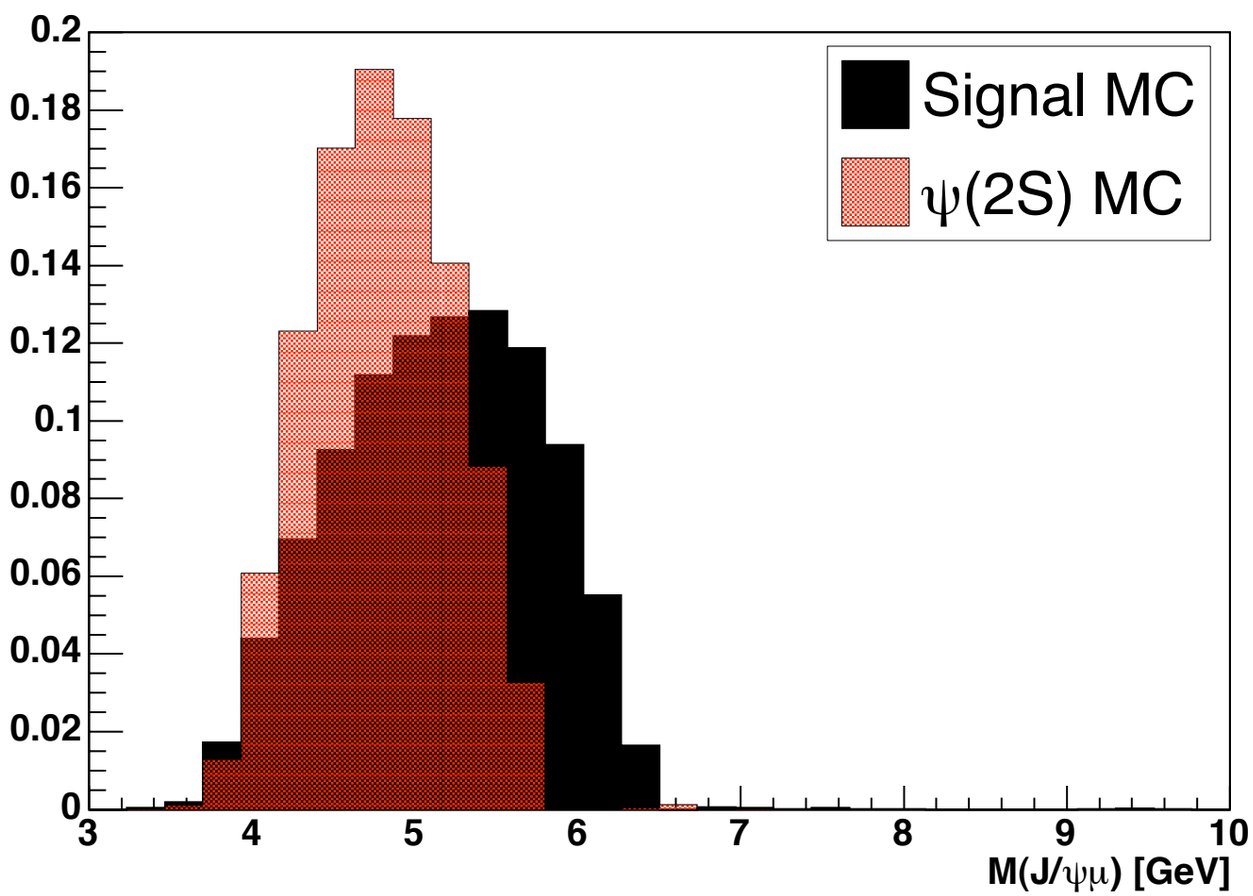
Due to missing neutrino, broad mass distribution

Mass Templates

- Signal

▶ Signal $B_c \to \psi(2S)+\mu+\nu \to J/\psi+\mu+\nu$ Monte Carlo

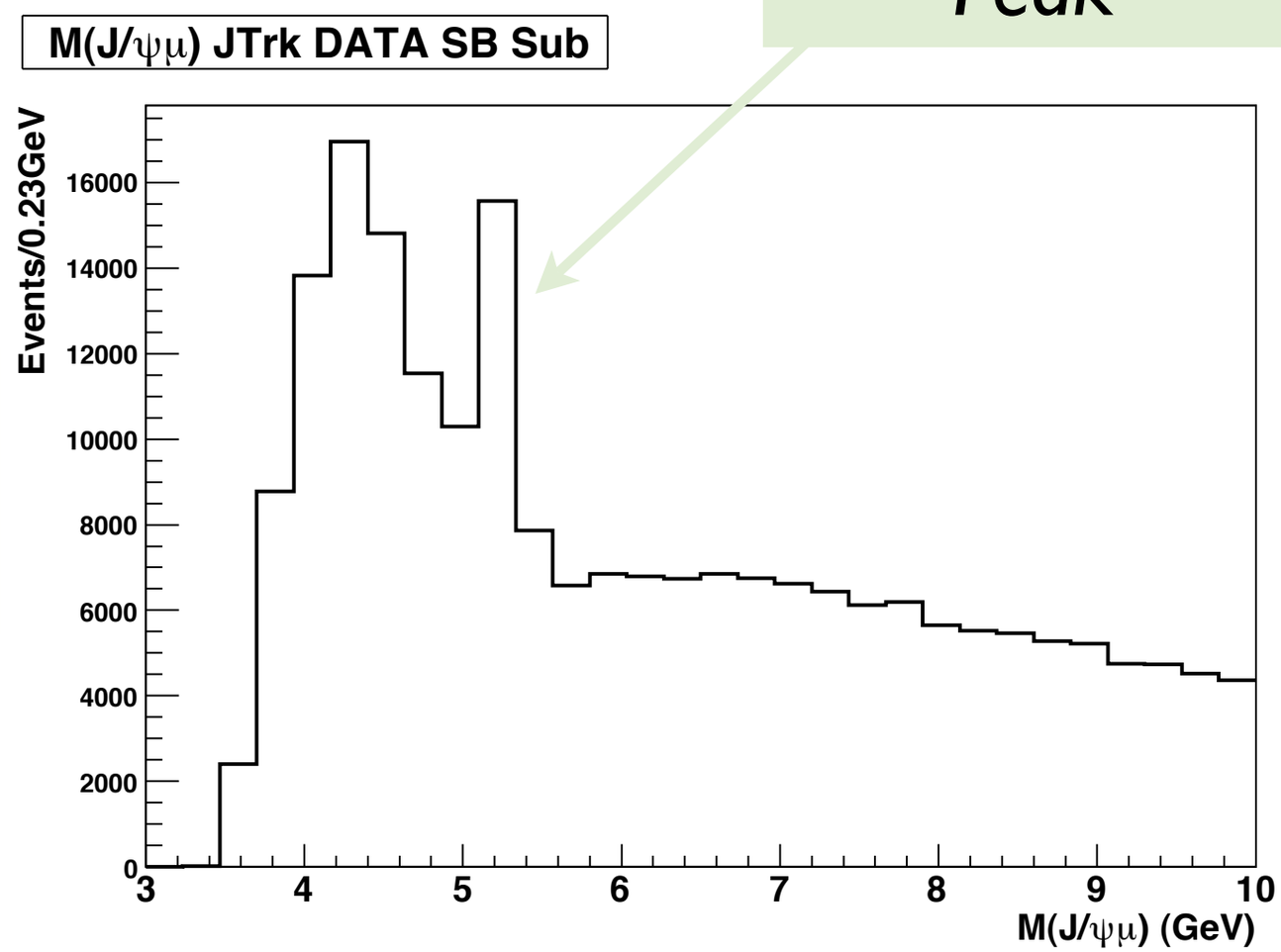
Need to take into account the feed down decay :
$B_c \to \psi(2S)[\to J/\psi\pi^+\pi^-] +\mu+X$



Fraction of this contribution is estimated to be 6.5%. As part of the systematics it is varied to 0% and 13%

Mass Templates

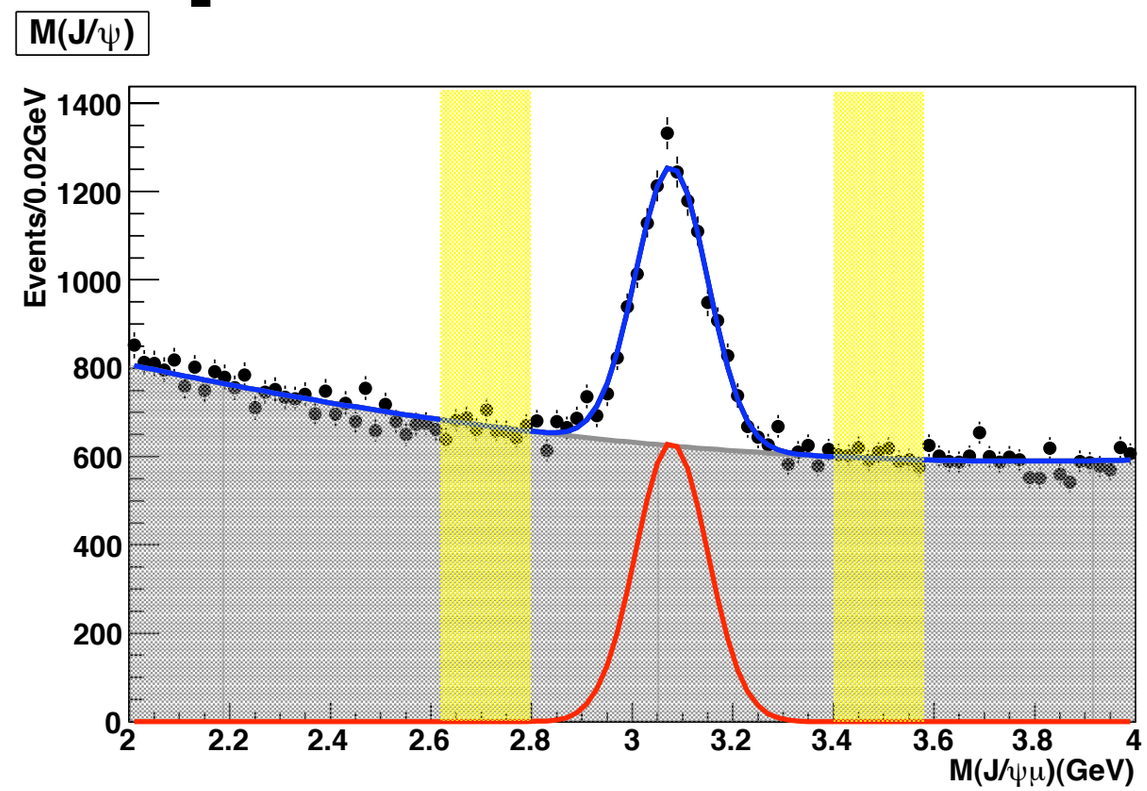
$B^+ \rightarrow J/\psi K^+$
Peak



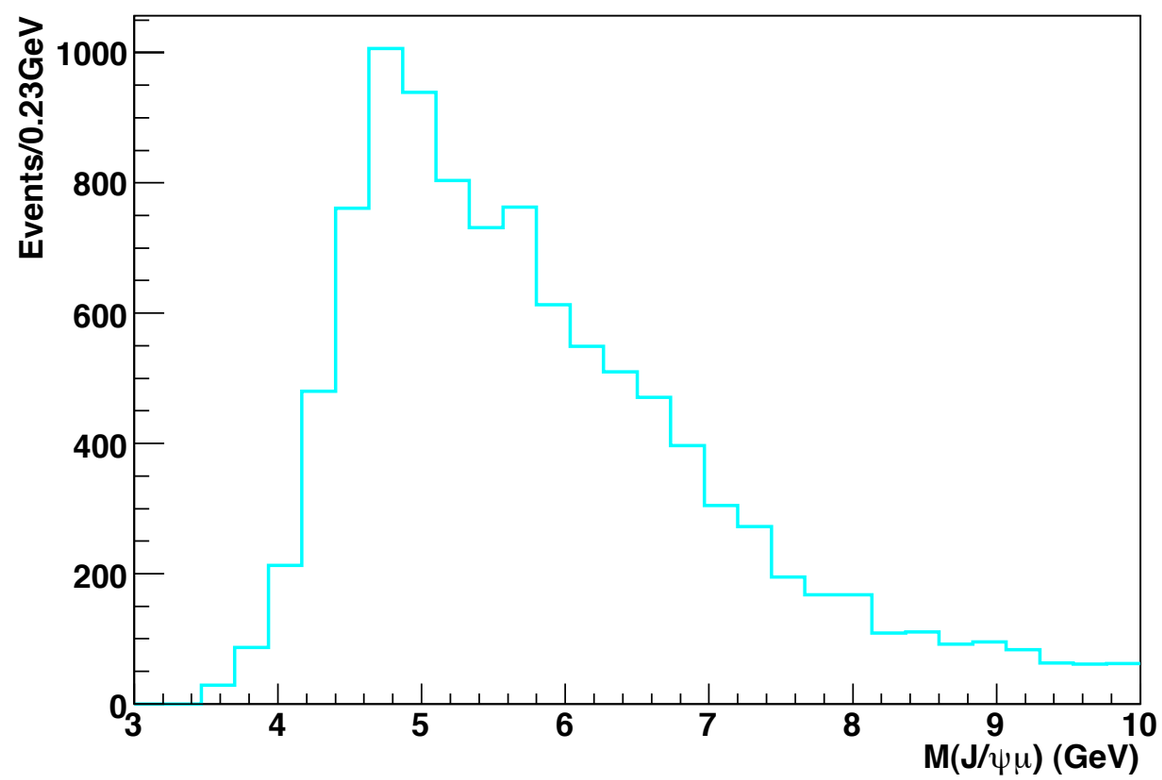
- Real J/ψ + Fake μ
  - Model with J/ψ + Track Sample

Mass Templates

Determine the number of events in the sideband region vs the number in the signal region to get a fraction of times an event is a fake J/ψ

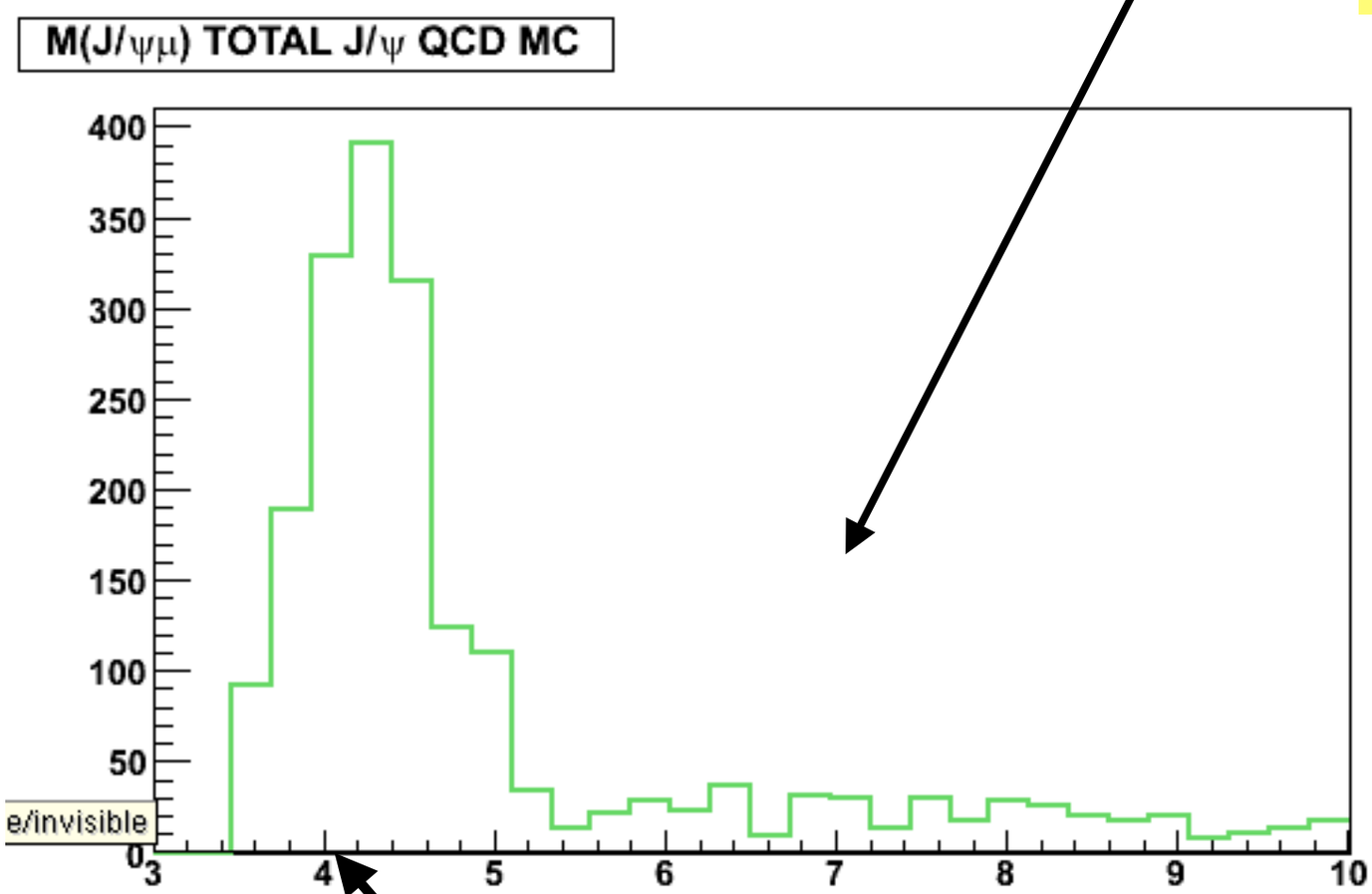


- Fake J/ψ + Real μ
  - Model with J/ψ Sideband



Mass Templates

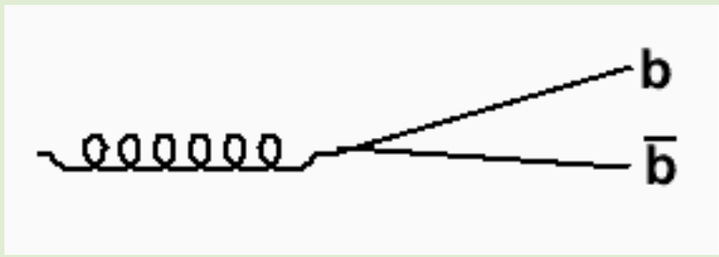
Higher mass stuff mis-reconstructions or *b*'s at large angles to each other



- Real J/ψ + Real μ (but each coming from different particle decays)
  - Model with J/ψ + X QCD Monte Carlo

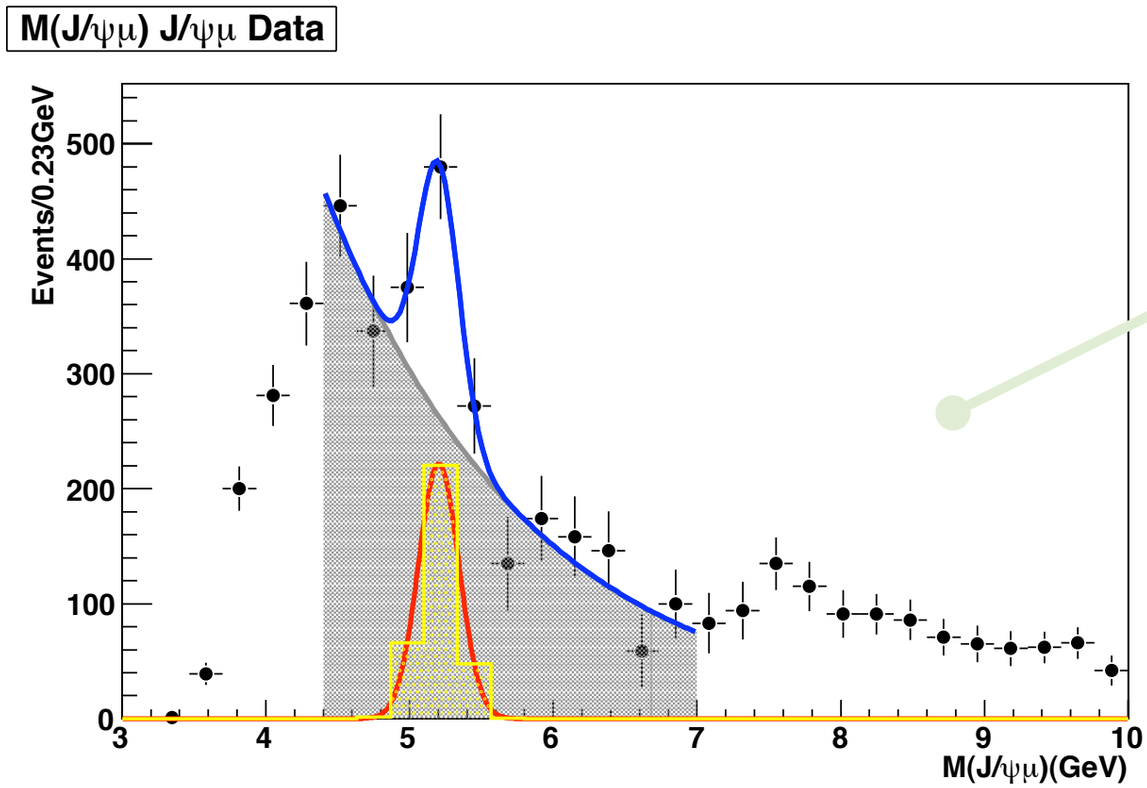
    Have to include contribution due to gluon splitting g->bb(bar)

    $b \rightarrow J/\psi$ other $b \rightarrow \mu$ or $b \rightarrow c \rightarrow \mu$



Accounts for lower mass stuff *if properly reconstructed*

Mass Templates

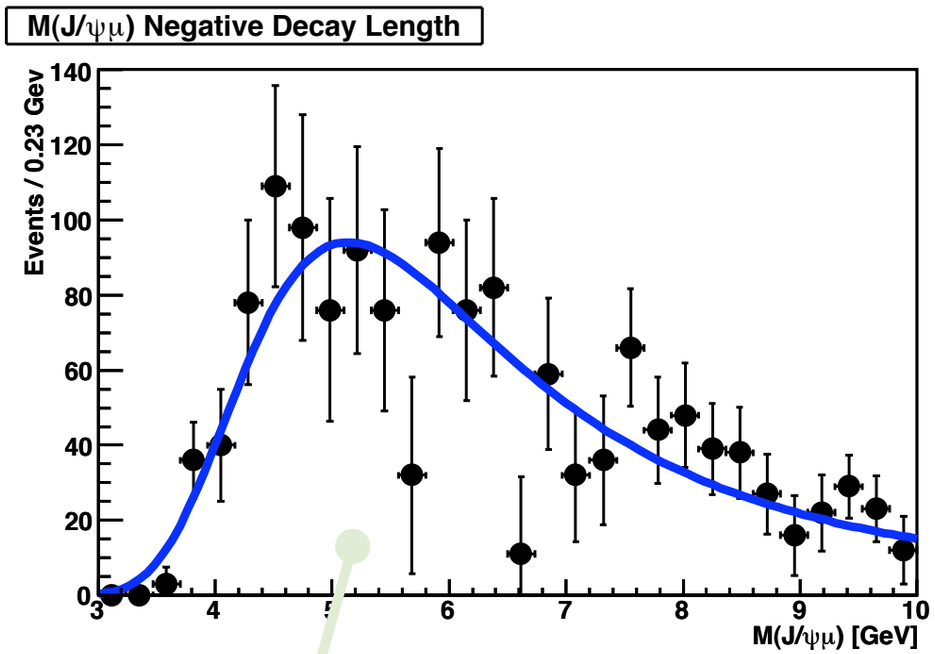


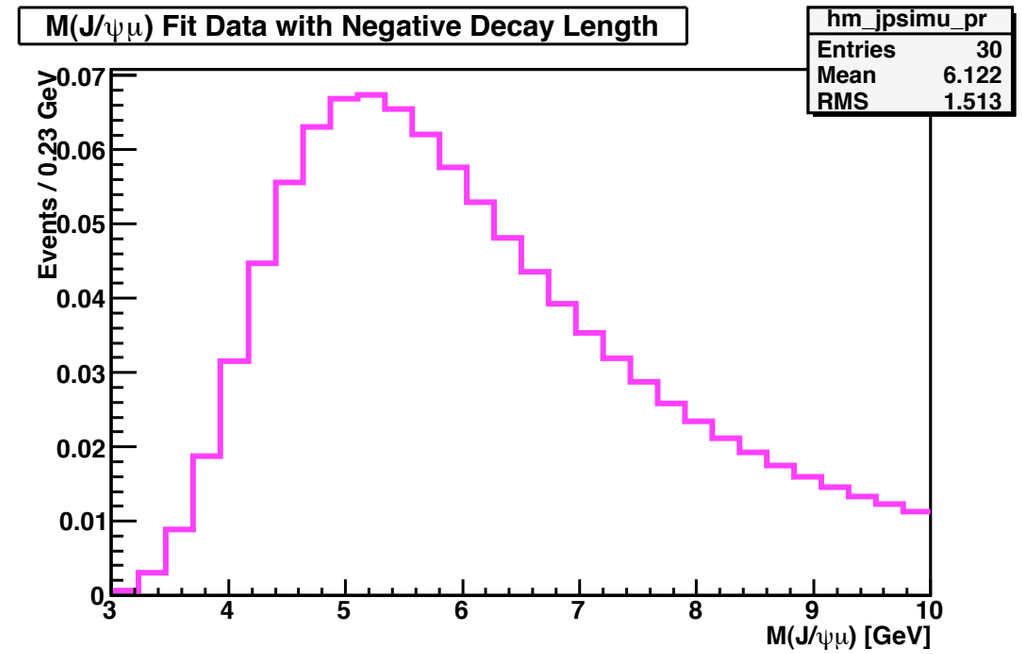
Fit to the B^+ in the data, use to model the B+ component

However, need to subtract this component from the J/ψ MC component so we don't count it twice

- B^+
  - $B^+ \Rightarrow J/\psi + K^+$ [$K^+ \Rightarrow \mu^+ \upsilon$]

Mass Templates





Due to low statistics, fit to the distribution for the template.

- Prompt (i.e. J/ψ from cc(bar))
  - Model with Negative Decay Length J/ψ+μ Data

Outline

- What are we looking for here?
  - B_c meson and motivation for measurement
  - Theoretical lifetime predictions for the B_c meson
- Apparatus
  - D-Zero muon detectors
- Data Sample
- Contributions to the Signal
- Demonstration of Signal
- Lifetime Analysis
- Results, Systematics & Conclusions
- Software development

Time to Fit!

- Using the samples listed on the previous slides, now fit the mass distributions to demonstrate signal component and gain confidence in the background models
- Form Pseudo-Proper Decay length
- Then move on to the simultaneous mass and lifetime fit to measure the B_c lifetime.

Pseudo Proper Decay Length

Lifetime of B_c, tau, is related to the decay length :

$$L = c\tau\beta\gamma = c\tau\frac{p}{m}$$

$c\tau$: proper decay length
p : total momentum
m : B_c mass

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In the transverse plane :

$$L_{xy} = c\tau\frac{p_T}{m}$$

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However when B_c decays in the semileptonic channel, it is not fully reconstructed and thus the p_T of the B_c is not determined.
Need a correction factor, '*K*' :

$$K = \frac{p_{T(J\psi\mu)}}{p_{T(B_c)}}$$

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$$\lambda = L_{xy}\frac{m(B_c)}{p_T(J\psi\mu)} = c\tau\ \frac{1}{K}$$

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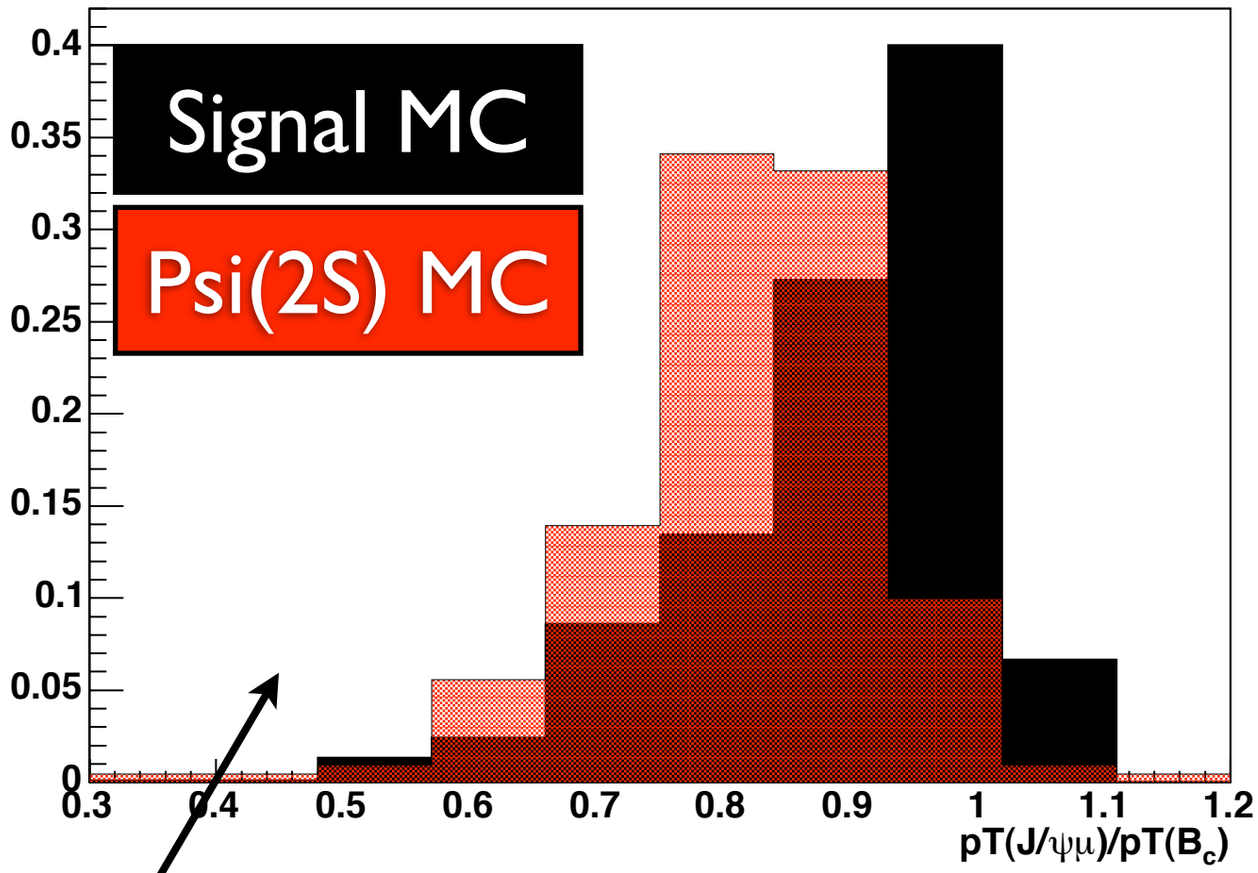
Use well measured mass from CDF experiment :
$m(B_c)$ = 6.274 ± 3.2 ± 2.6 GeV

K Factors

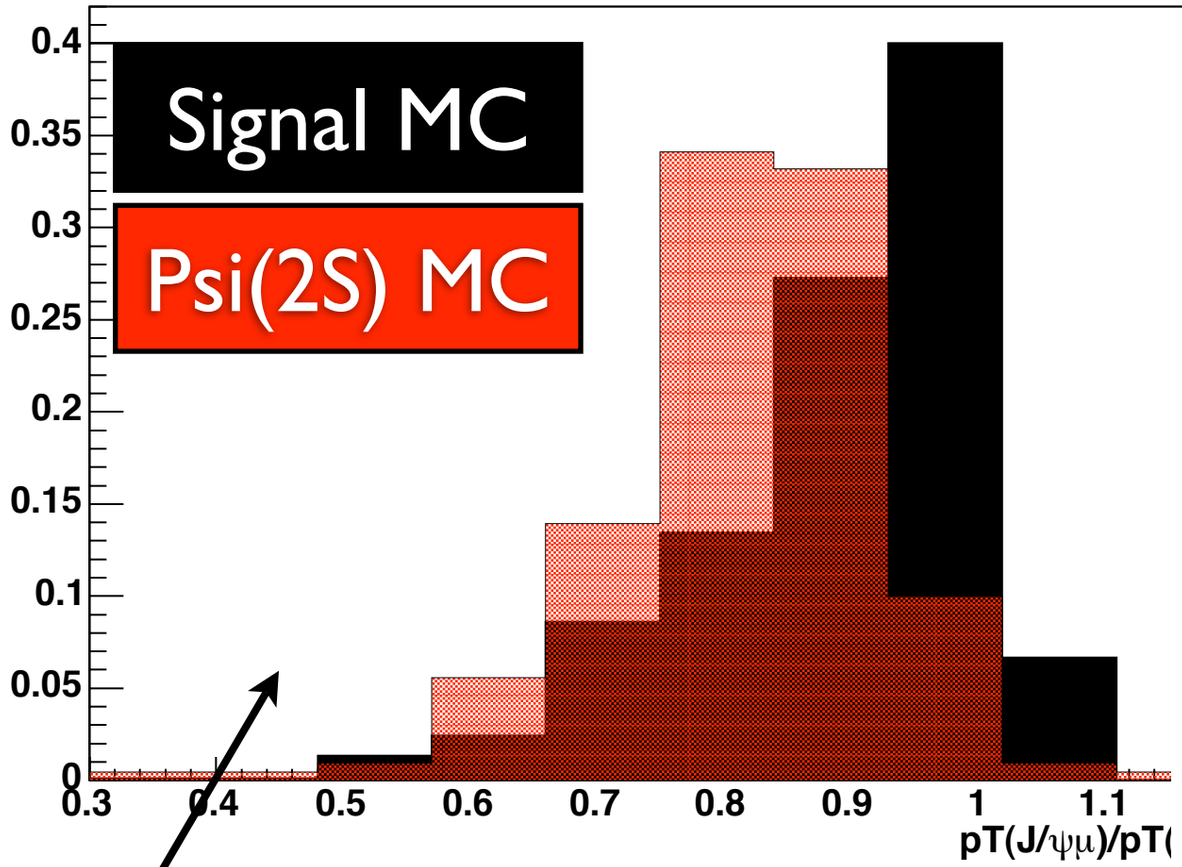
K Factors



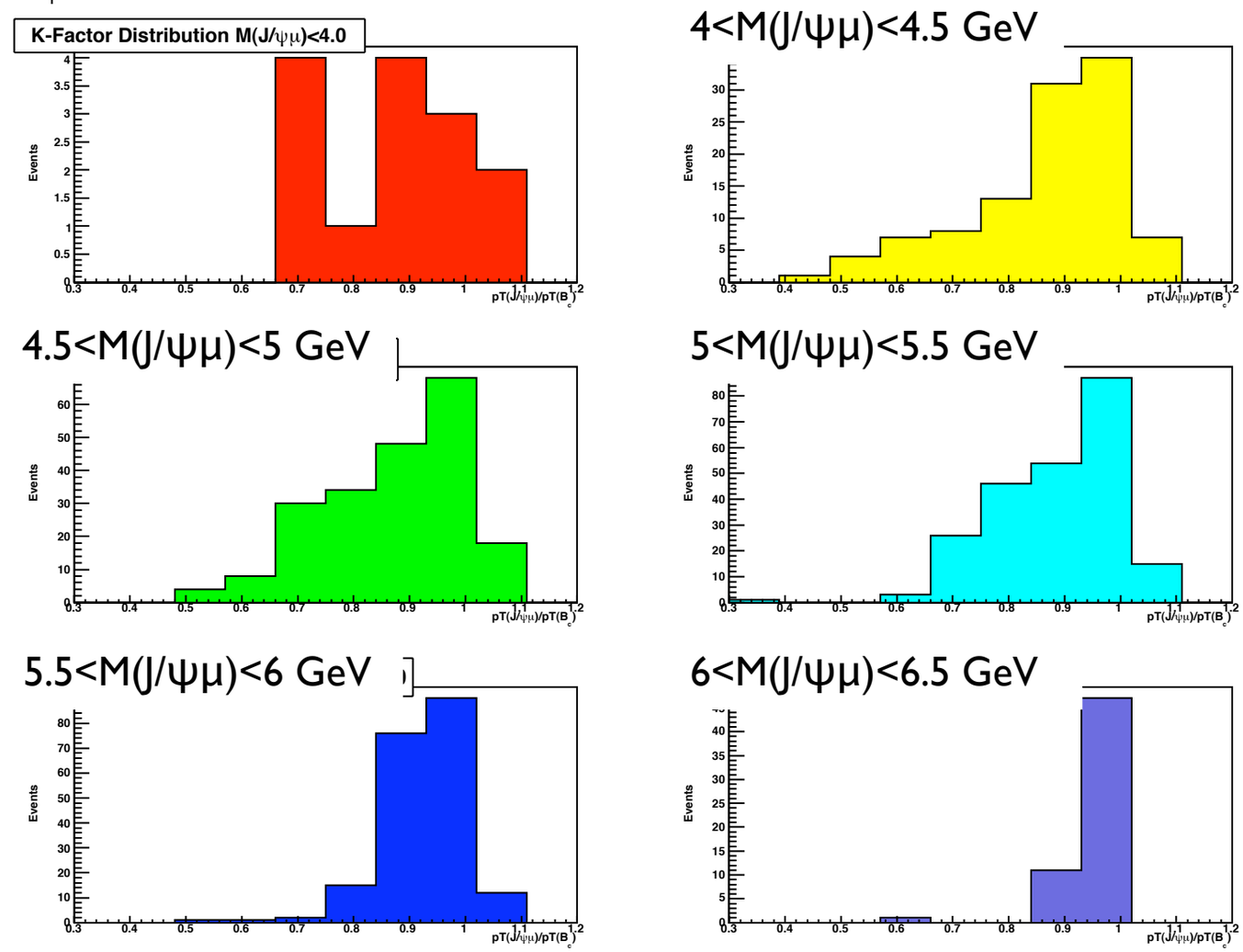
In the ψ(2s) MC you would expect the *K* factors to be shifted lower because the J/ψ that is vertexed with the muon must be softer because it likely comes from ψ(2s) which goes to J/ψ π^+ π^- instead of coming directly from the B_c.

Different *K*-factor distributions are used for the signal vs the feed down components.

K Factors



K-factor is used in bins of M(J/ψμ) to take advantage of events with better resolution (i.e. as M(J/ψμ) approaches B_c mass less energy and momentum carried away by neutrino)



Different *K*-factor distributions are used for the signal vs the feed down components.

Demonstration of Signal :

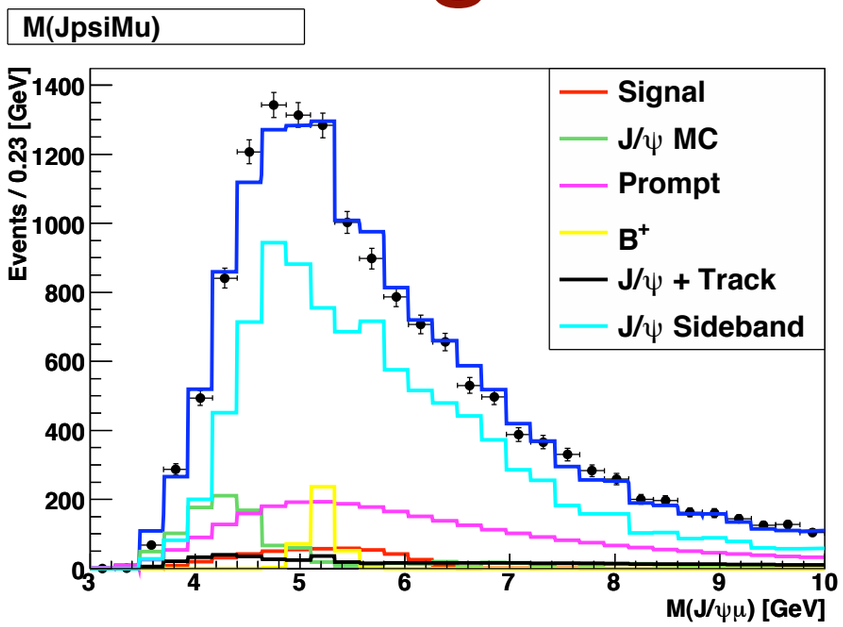
Cutting on Decay Length Significance

Decay Length Significance is defined as:

$$\mathbf{DLS} = \mathbf{d}L/\sigma(\mathbf{d}L)$$

Demonstration of Signal :

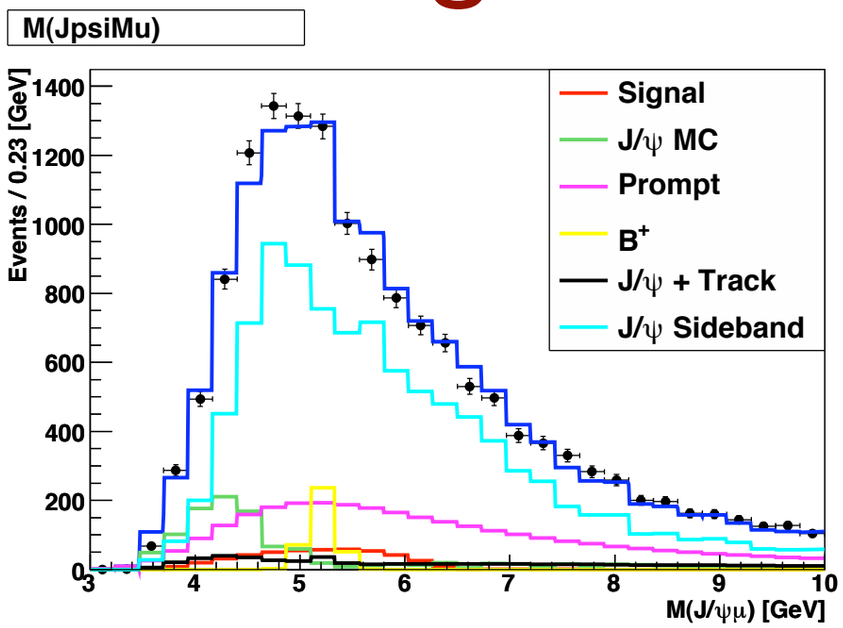
Cutting on Decay Length Significance

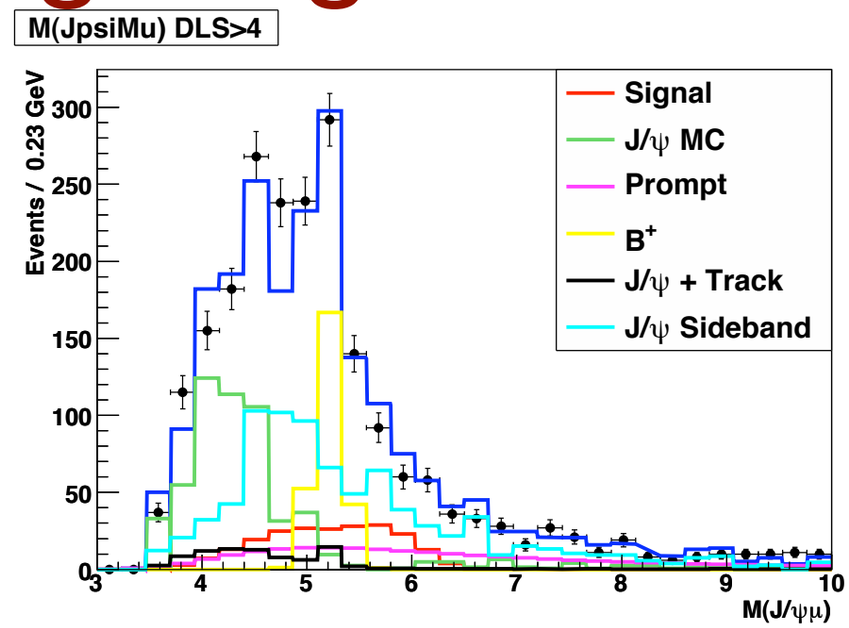


DLS = $dL/\sigma(dL)$

Demonstration of Signal :

Cutting on Decay Length Significance





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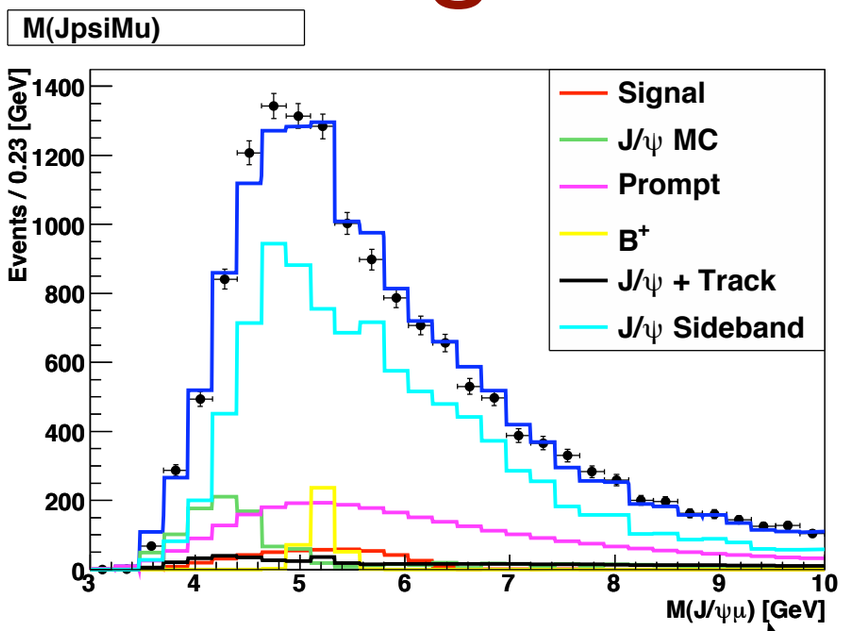

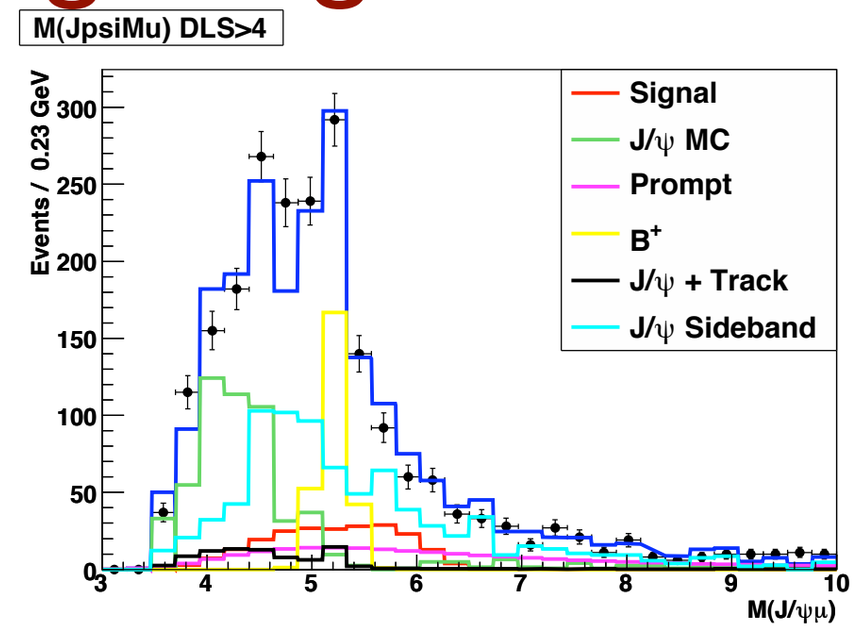

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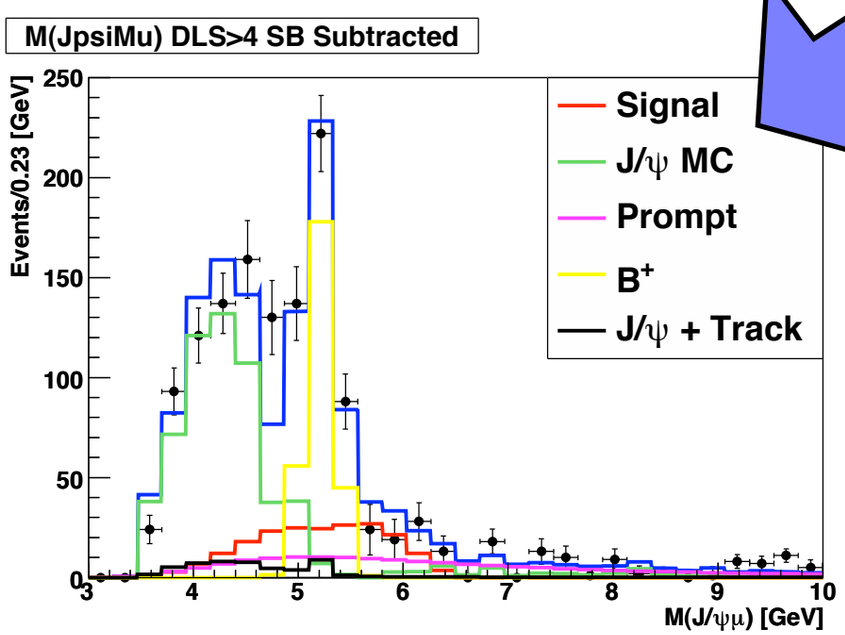

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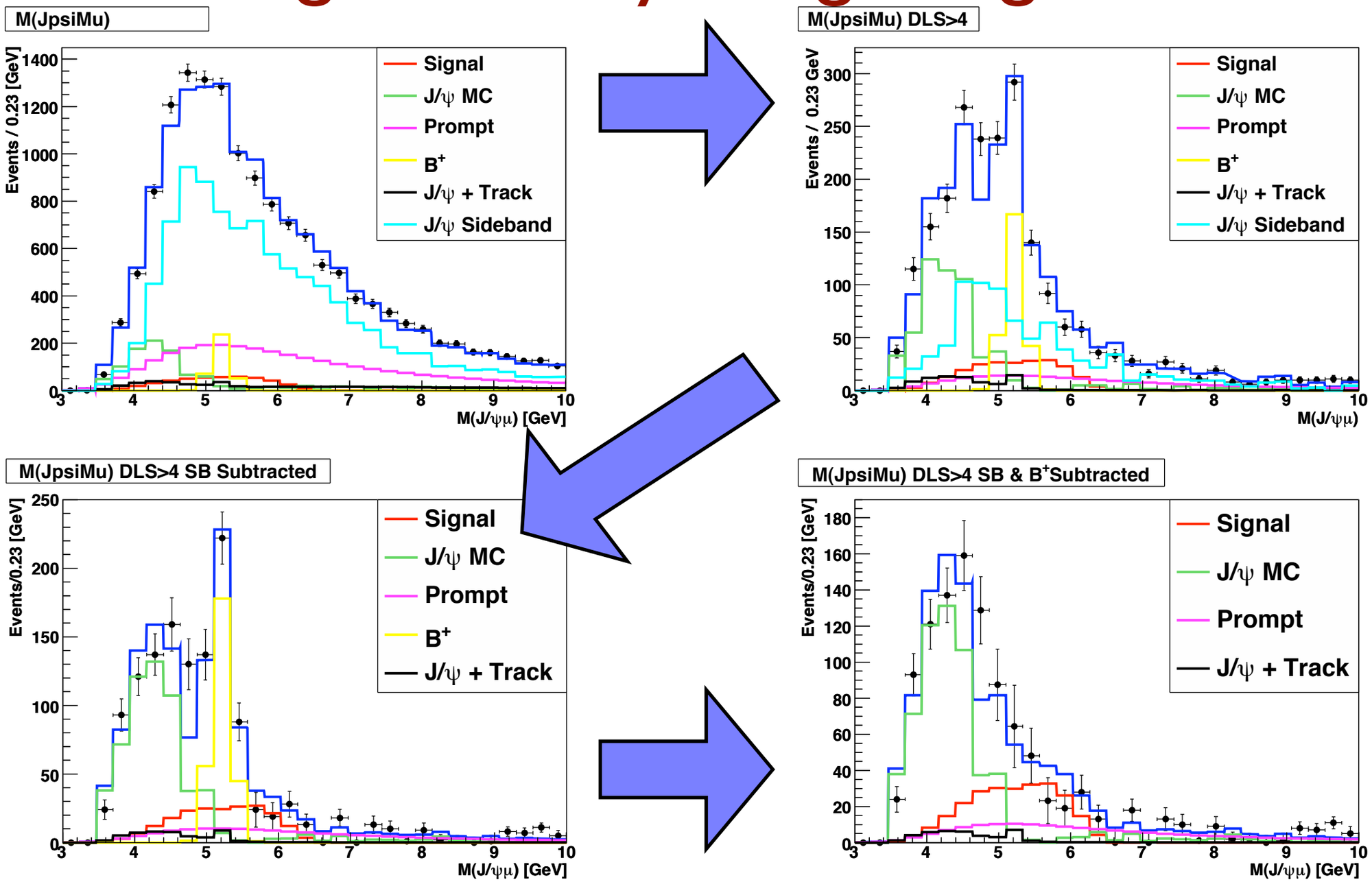

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Demonstration of Signal :

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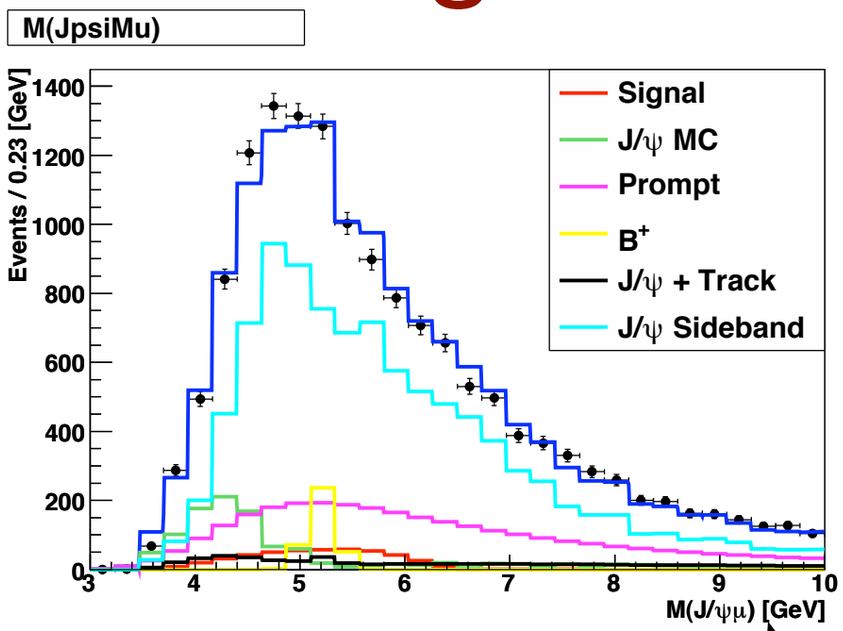

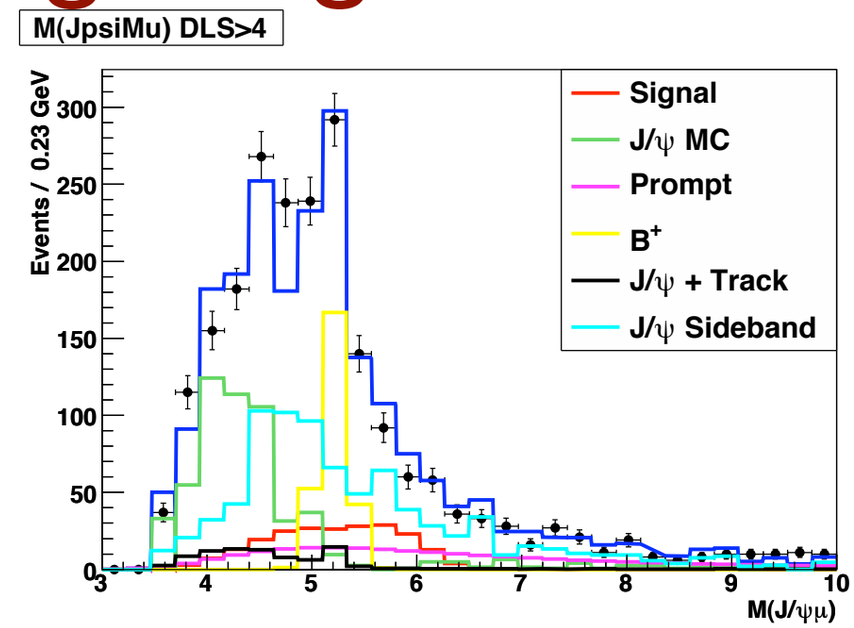

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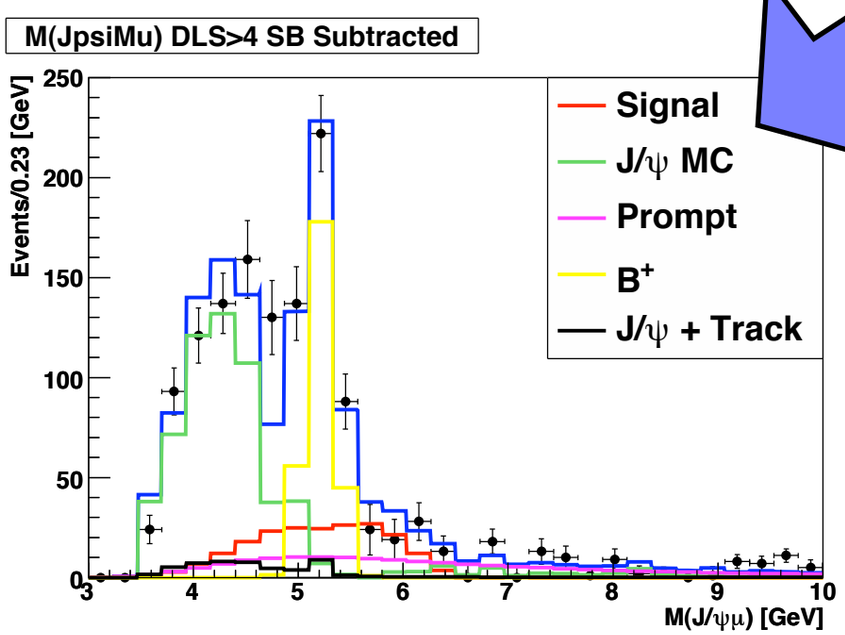
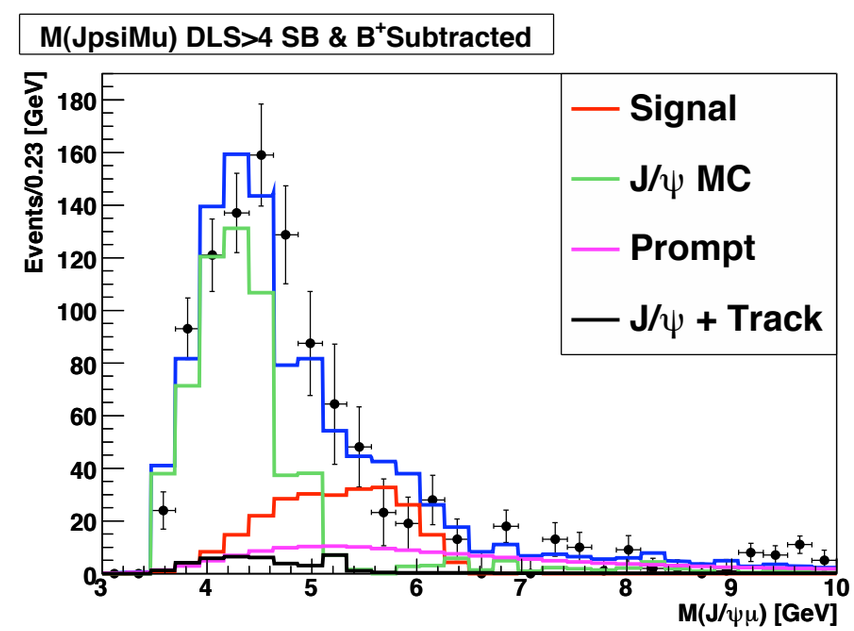




Prob. of bkg to fluctuate up to signal or more > 5σ

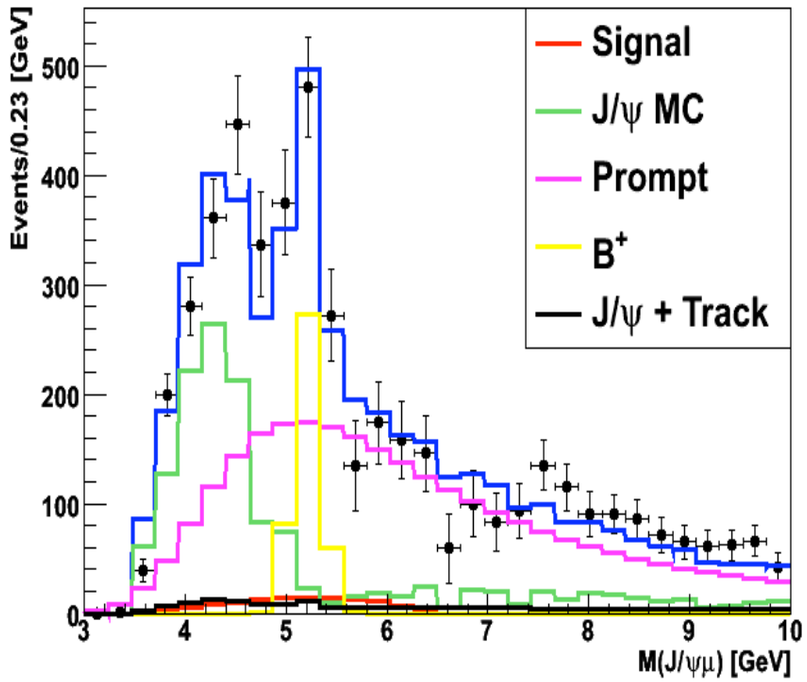
Demonstration of Short Decay Length :

Cutting on Proper Decay Length

Demonstration of Short Decay Length :

Cutting on Proper Decay Length

All PPDL



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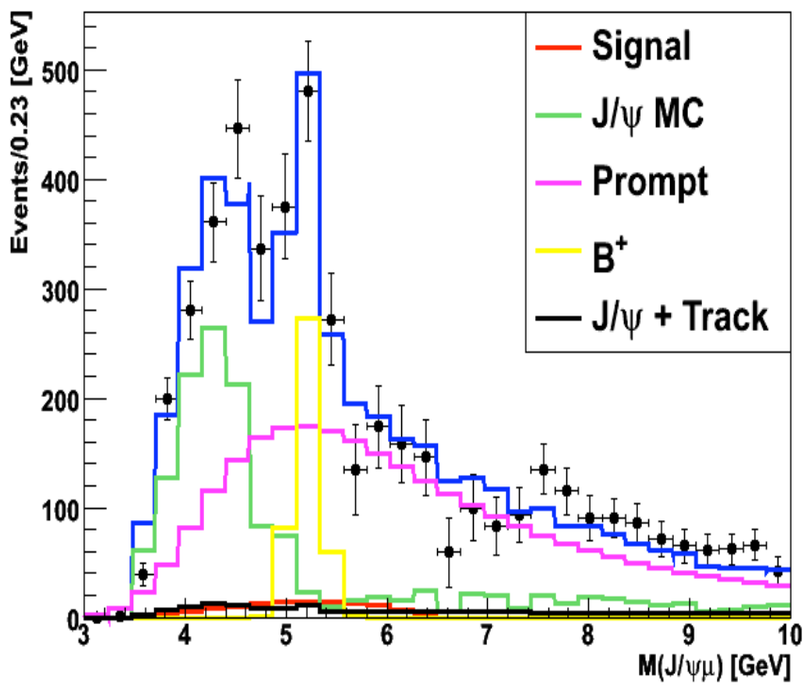
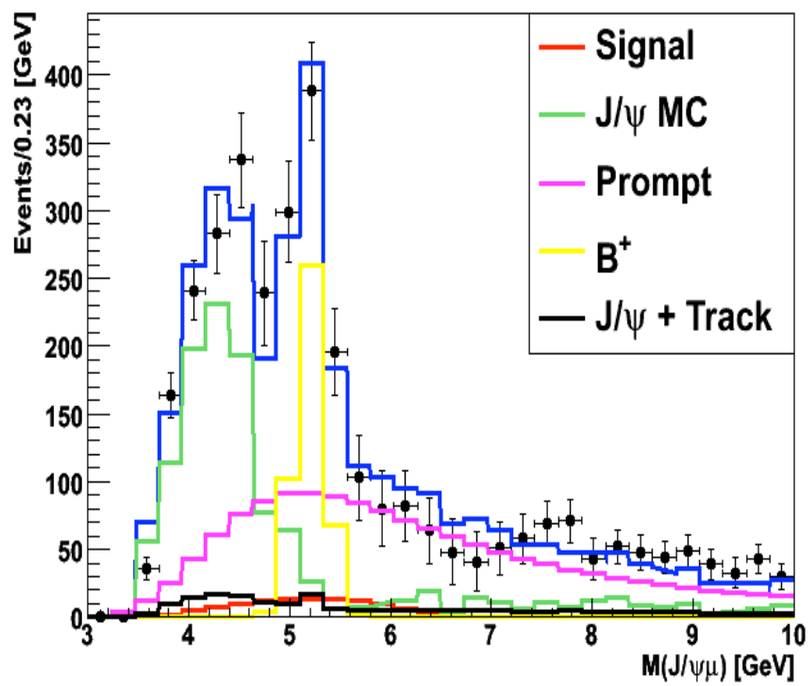


PPDL>0 cm



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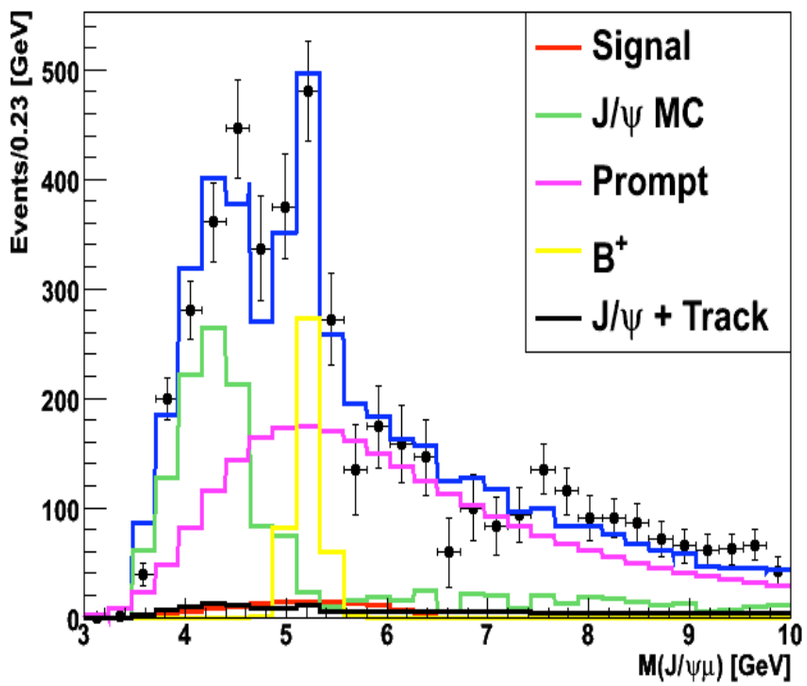

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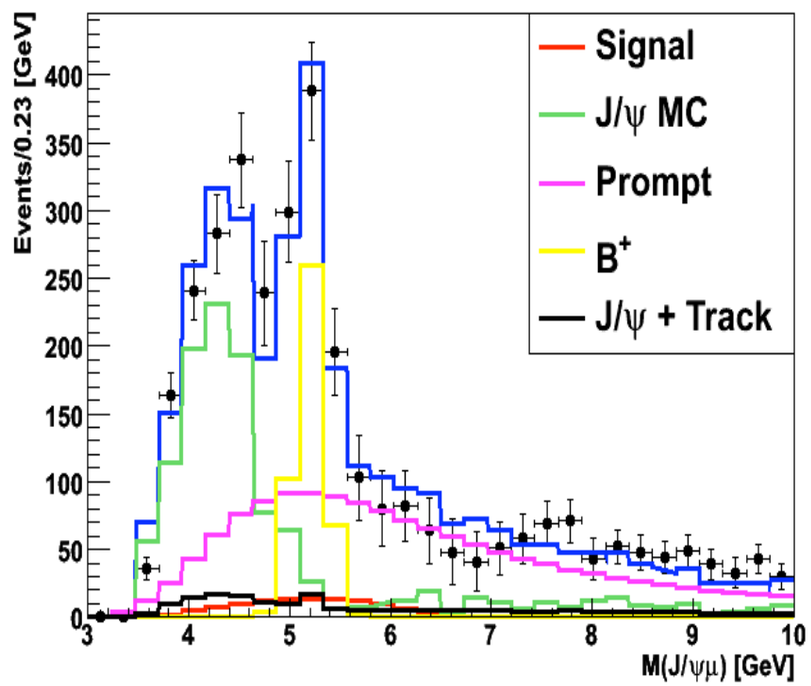
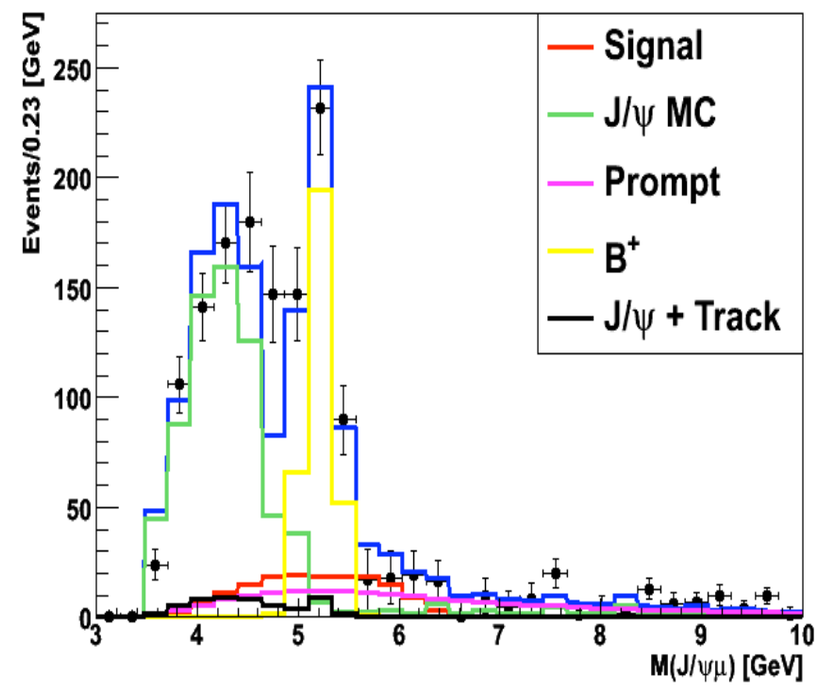


PPDL>0.01 cm



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Cutting on Proper Decay Length

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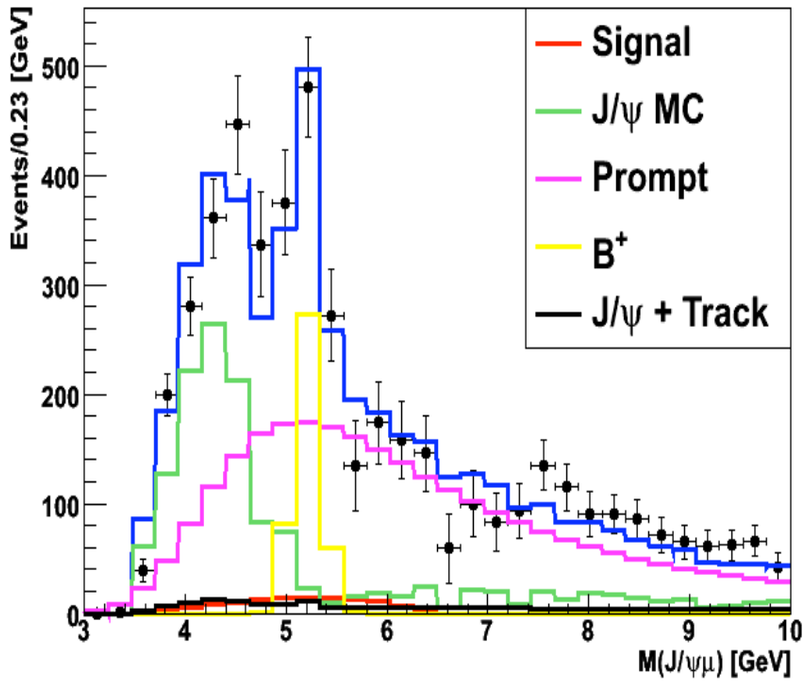
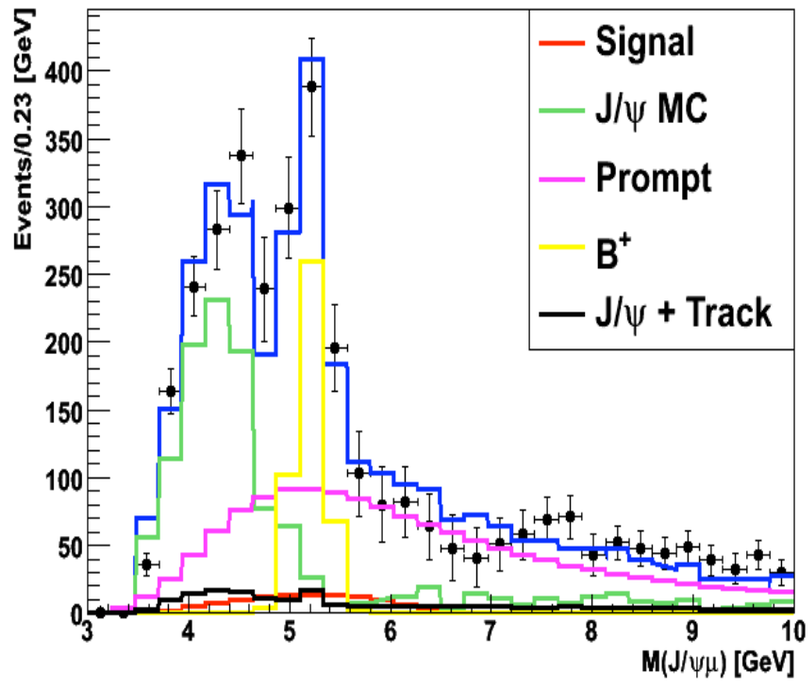
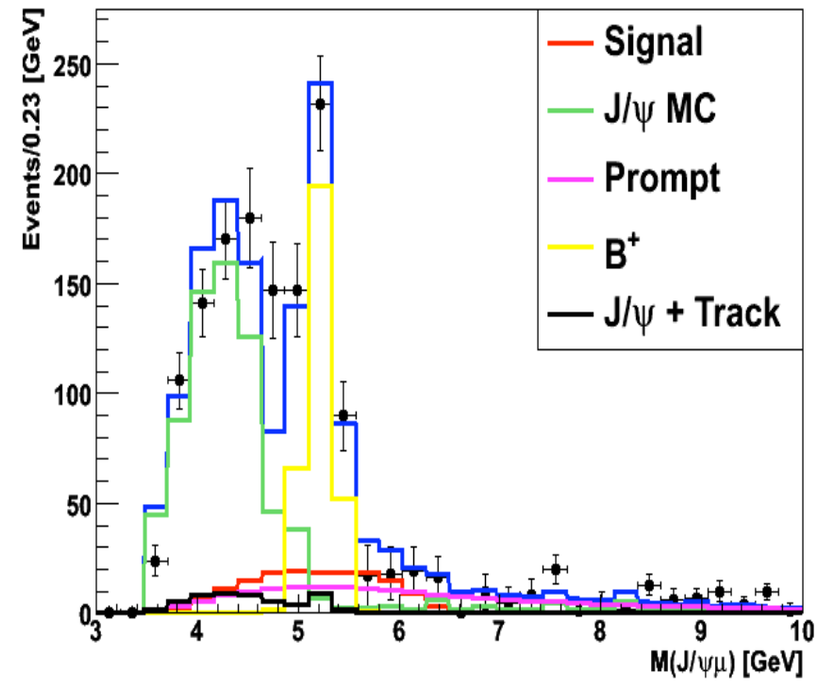


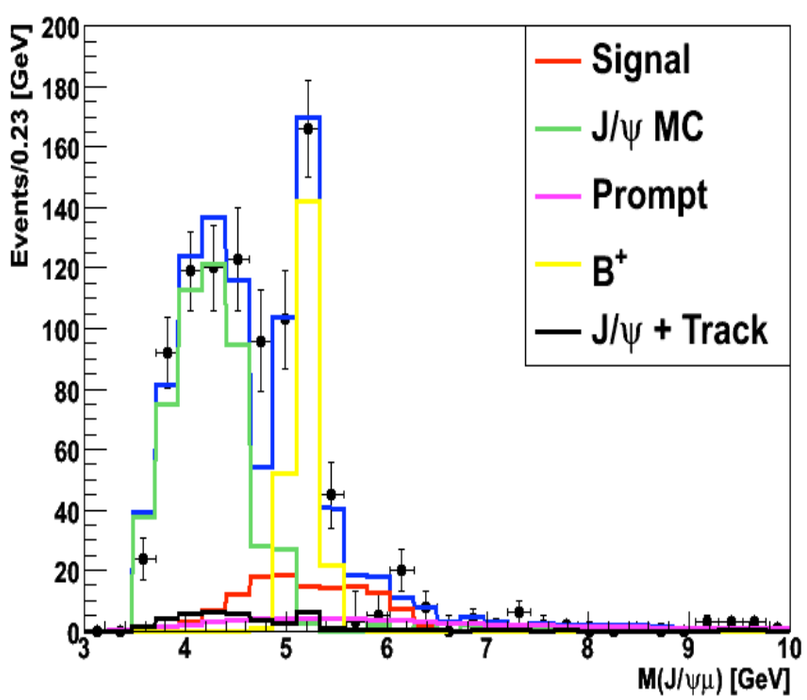
PPDL>0 cm



PPDL>0.01 cm



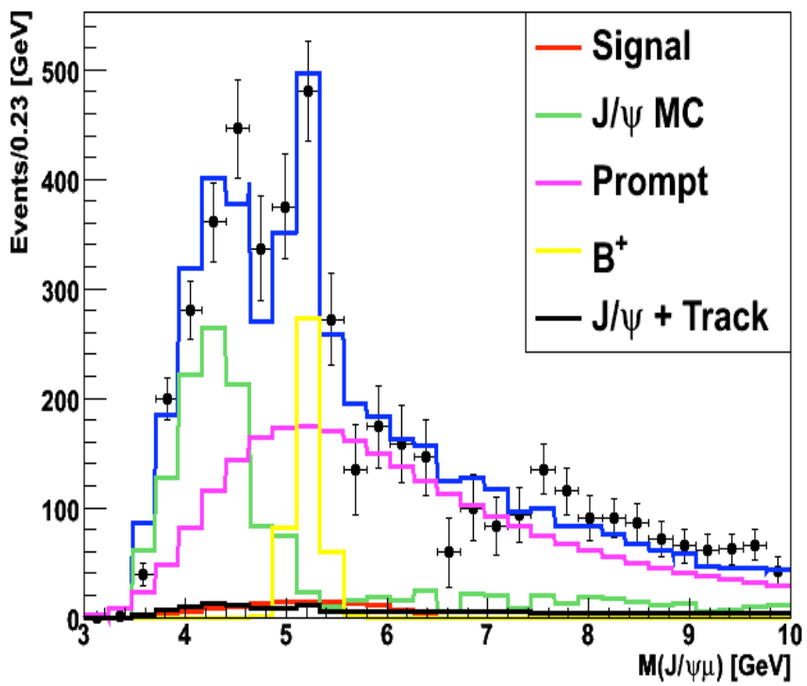
PPDL>0.02 cm



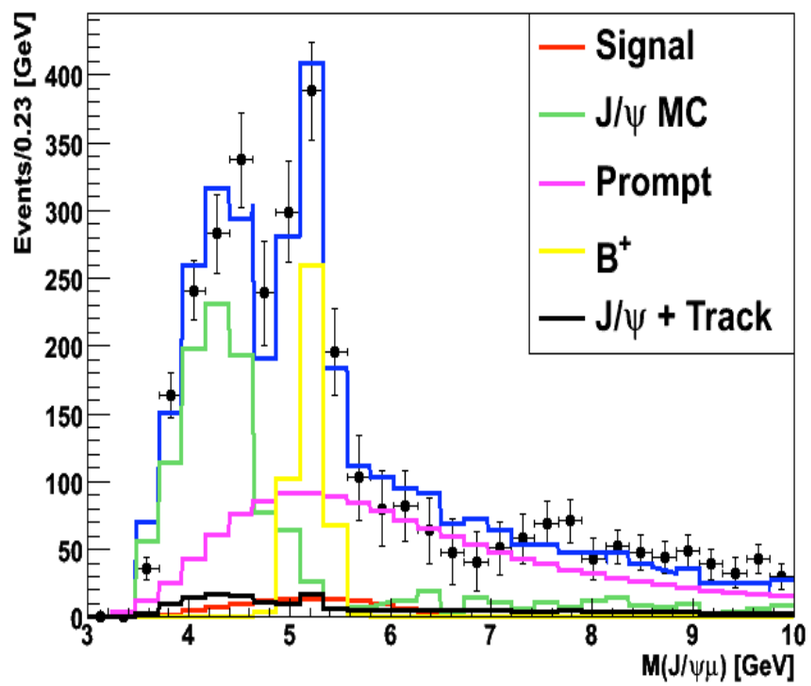
Demonstration of Short Decay Length :

Cutting on Proper Decay Length

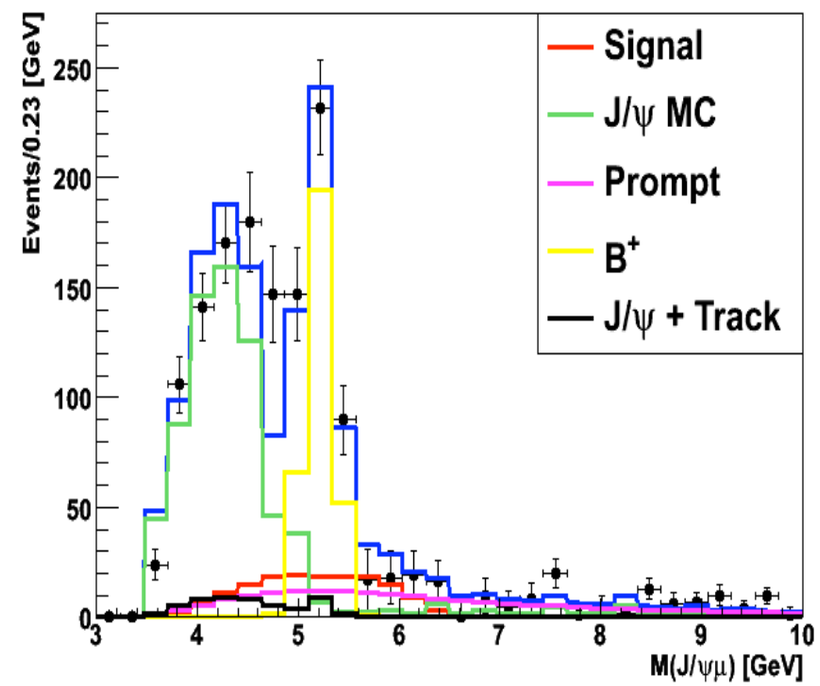
All PPDL



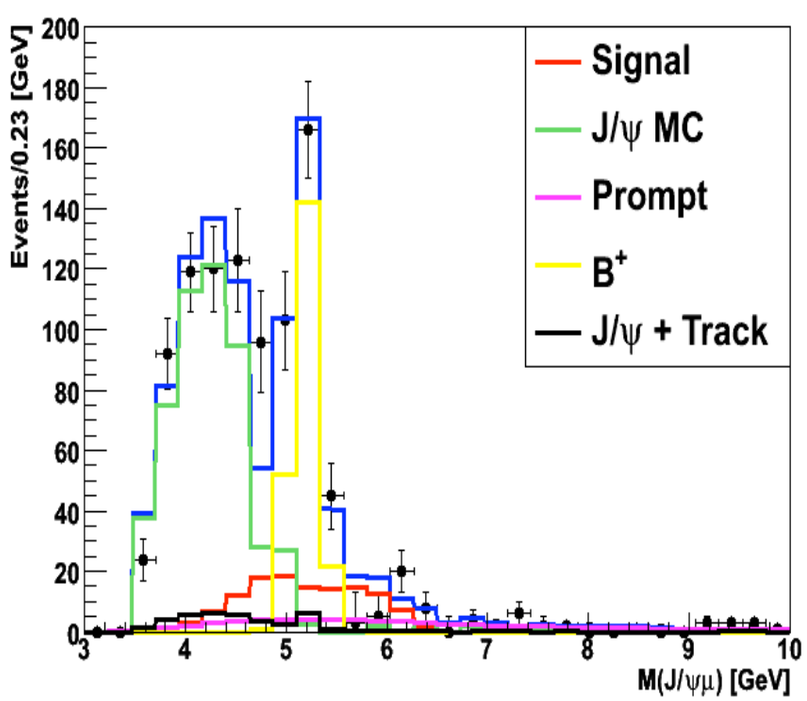
PPDL>0 cm



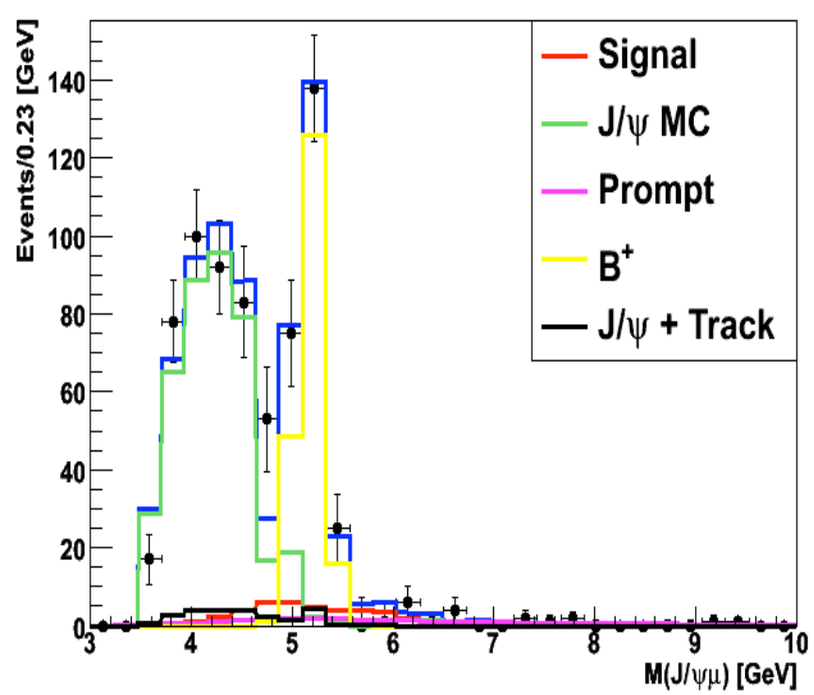
PPDL>0.01 cm



PPDL>0.02 cm



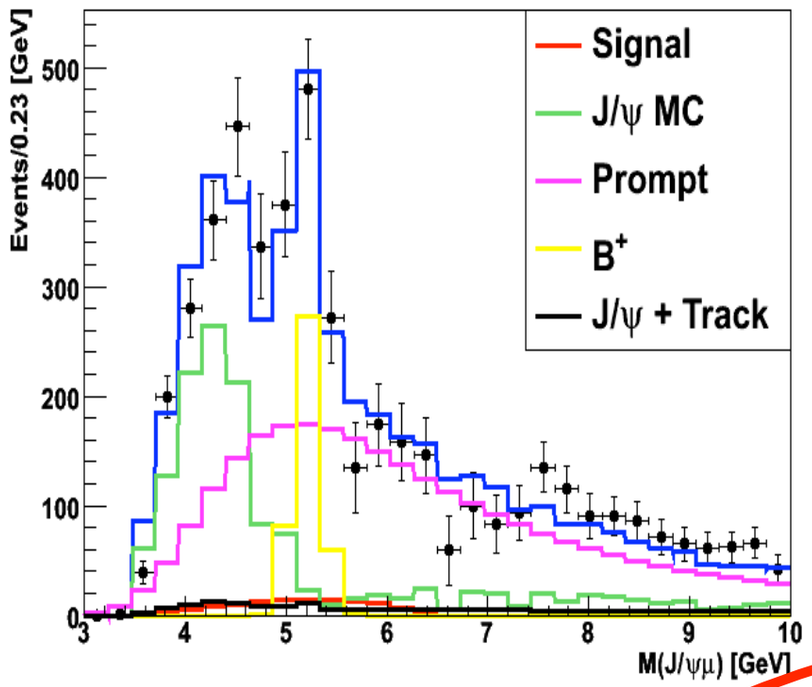
PPDL>0.03 cm



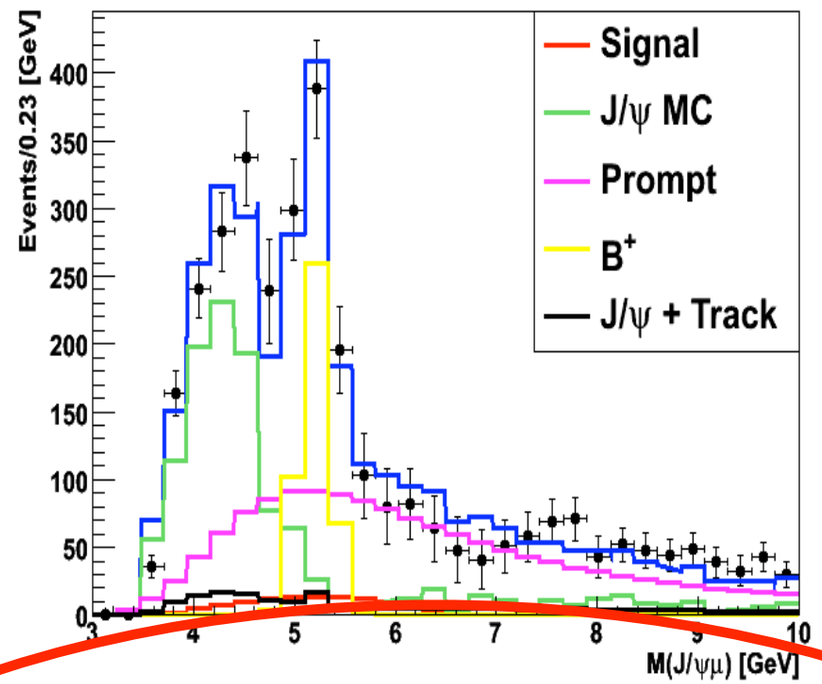
Demonstration of Short Decay Length :

Cutting on Proper Decay Length

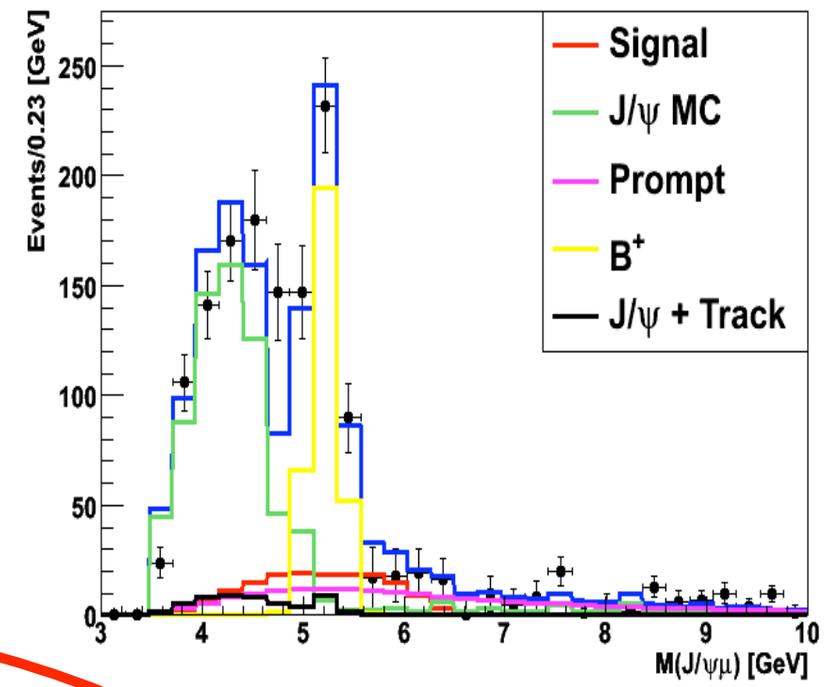
All PPDL



PPDL>0 cm



PPDL>0.01 cm



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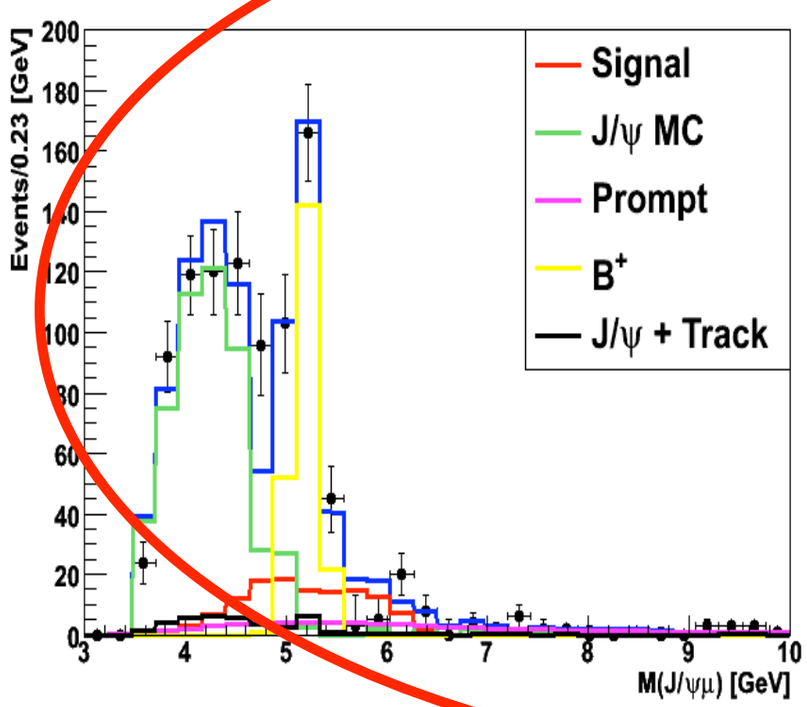

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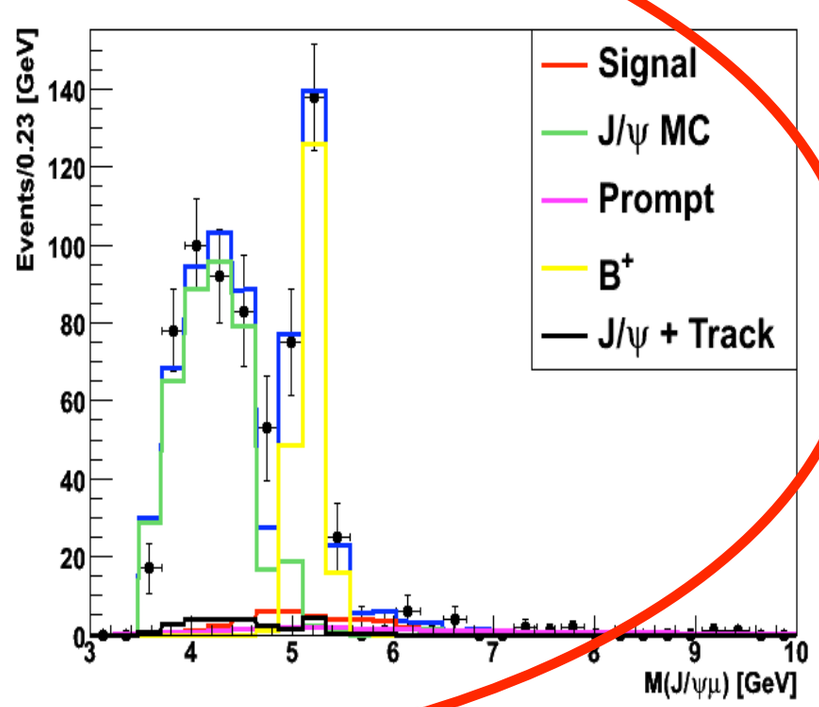

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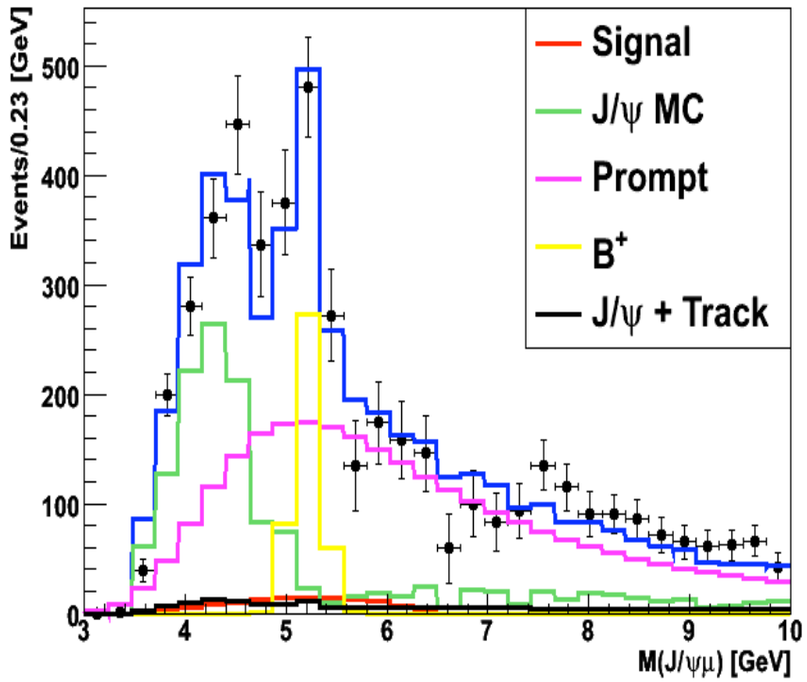
Cutting on Proper Decay Length

All PPDL



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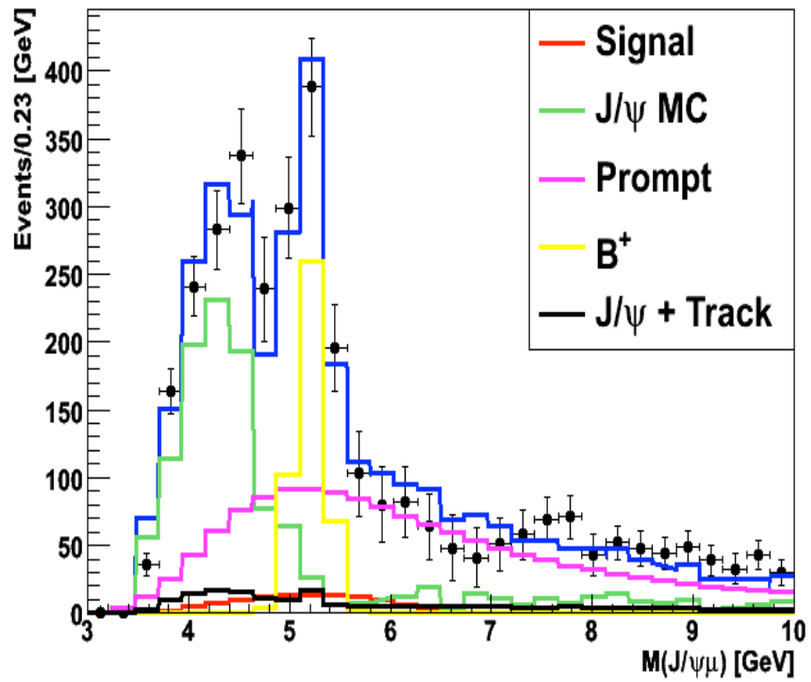

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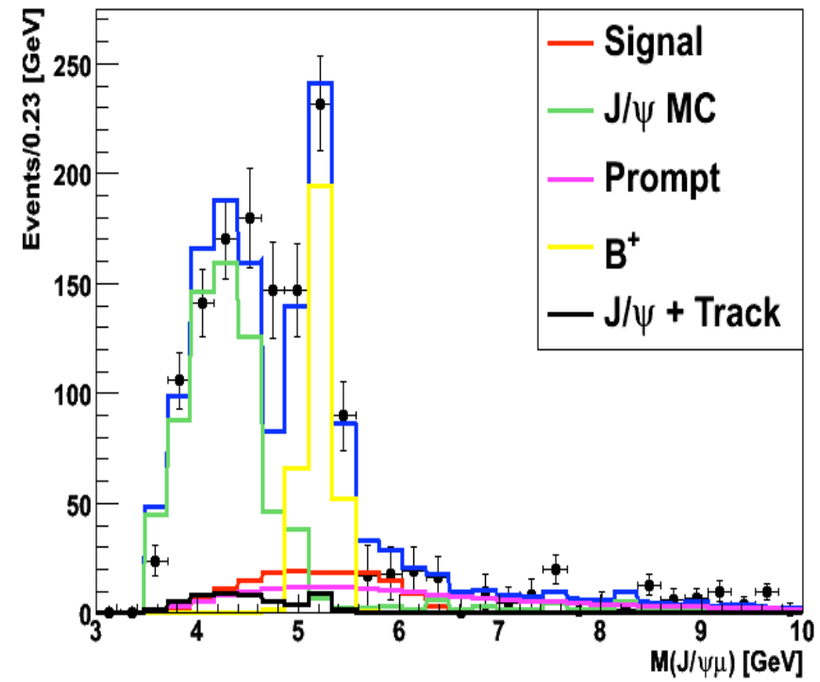

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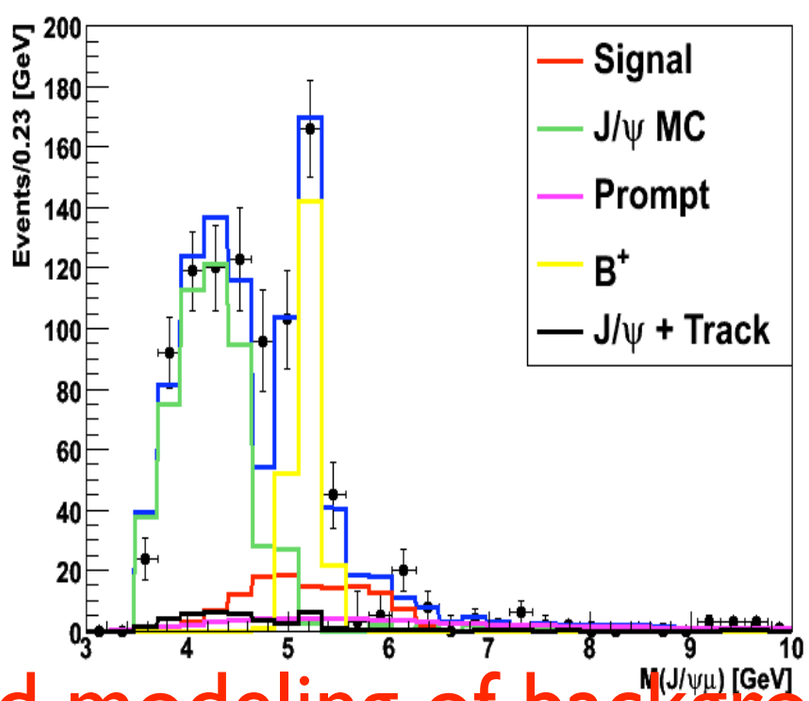

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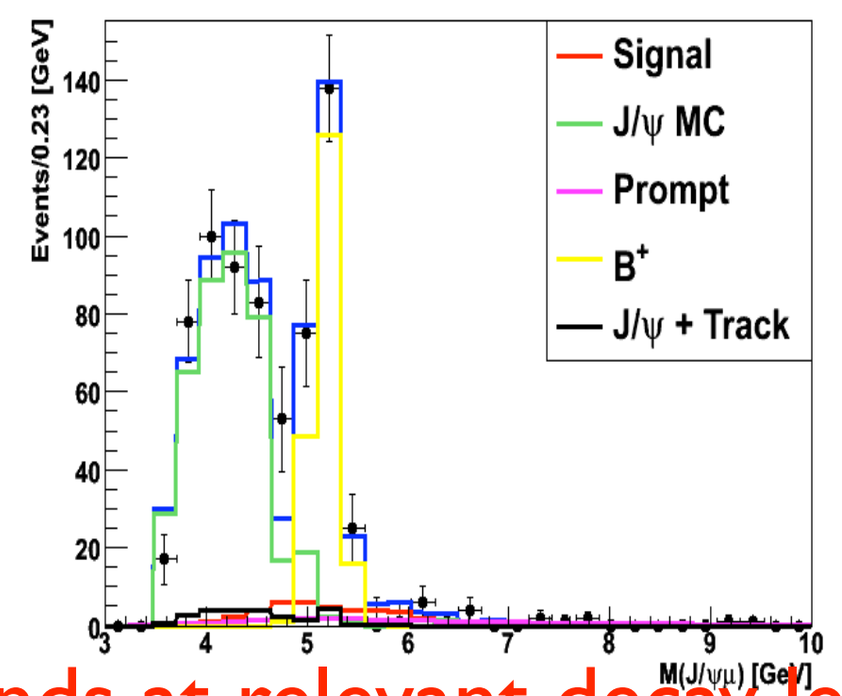


*good modeling of backgrounds at relevant decay lengths

Outline

- What are we looking for here?
  - B_c meson and motivation for measurement
  - Theoretical lifetime predictions for the B_c meson
- Apparatus
  - D-Zero muon detectors
- Data Sample
- Contributions to the Signal
- Demonstration of Signal
- Lifetime Analysis
- Results, Systematics & Conclusions
- Software development

Lifetime Analysis

- With confidence in mass models and B_c signal within the J/ψ+μ sample, move on to the lifetime analysis.
- Method
  - Minimize a log likelihood function
- Each component needs a lifetime functional model, tests were done on each
- Each component also needs a mass model which were tested and shown previously

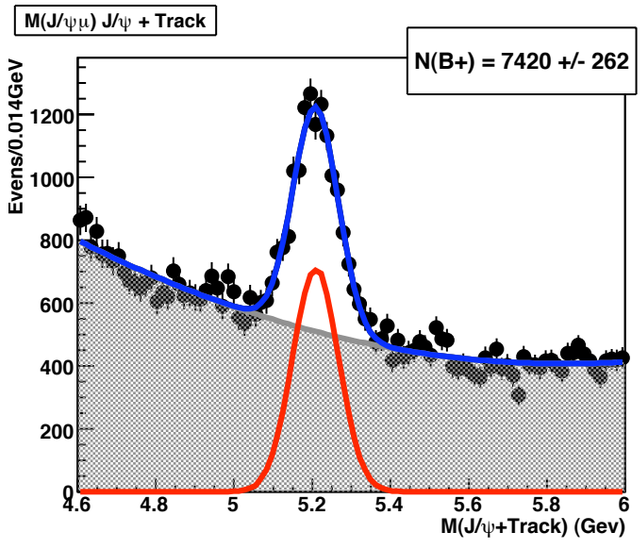
Log Likelihood

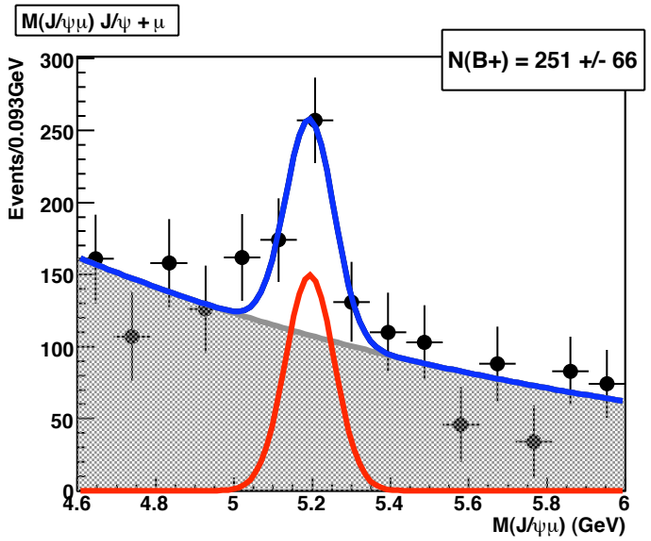
$$\mathcal{L} = \prod_i \left(f_{jtrk} F^i_{Jtrk} + (1 - f_{jtrk}) F^i_{Jmu} \right)$$

Log Likelihood

$$\mathcal{L} = \prod_i \left(f_{jtrk} F^i_{Jtrk} + (1 - f_{jtrk}) F^i_{Jmu} \right)$$

Know the fraction of events that are from real J/ψ and fake μ (i.e. the J/ψ Track Fraction) from studies of the B^+ peak in the J/ψ +Track and J/ψ + μ samples.





$N(B^+Jmu)/N(B^+JTrk) = 0.0338 +/-0.0021$

Log Likelihood

$$\mathcal{L} = \prod_i \left(f_{jtrk} F^i_{Jtrk} + (1 - f_{jtrk}) F^i_{Jmu} \right)$$

$$F^i_{Jmu} = f_{SB} F^i_{SB} + (1 - f_{SB})(f_{sig} F^i_{sig} + f^i_{JMC} F^i_{JMC} + f_{Bp} F^i_{Bp} + (1 - f_{sig} - f_{JMC} - f_{Bp}) F^i_{PR})$$

Each component consists of a mass template and a lifetime model allowing a simultaneous fit to the lifetime and invariant mass distribution.

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Know the sideband fraction from studies of J/ψ mass sideband vs signal regions in + J/ψ μ sample

Each component consists of a mass template and a lifetime model allowing a simultaneous fit to the lifetime and invariant mass distribution.

Log Likelihood

$$F^i_{Jmu} = f_{SB} F^i_{SB} + (1 - f_{SB})(f_{sig} F^i_{sig} + f^i_{JMC} F^i_{JMC} + f_{Bp} F^i_{Bp} + (1 - f_{sig} - f_{JMC} - f_{Bp}) F^i_{PR})$$

$$F^i_{sig}\left(\lambda_i, \sigma(\lambda_i), s\right) = \int dK\, \mathcal{H}(K) \left[\frac{K}{c\tau(B_c)} e^{-K\lambda_i / c\tau(B_c)} \otimes R(\lambda_i, \sigma(\lambda_i), s) \right]$$

Lifetime for the signal is a normalized exponential decay function convoluted with a Gaussian resolution function and smeared with a normalized *K*-factor distribution.

Log Likelihood

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Lifetime for the signal is a normalized exponential decay function convoluted with a Gaussian resolution function and smeared with a normalized *K*-factor distribution.

's' is defined as the scale factor. Each event has an uncertainty on the PPDL from the track parameter error matrix; however, syst. errors and alignment uncertainties not taken into account in this matrix. This factor fits for this underestimate.

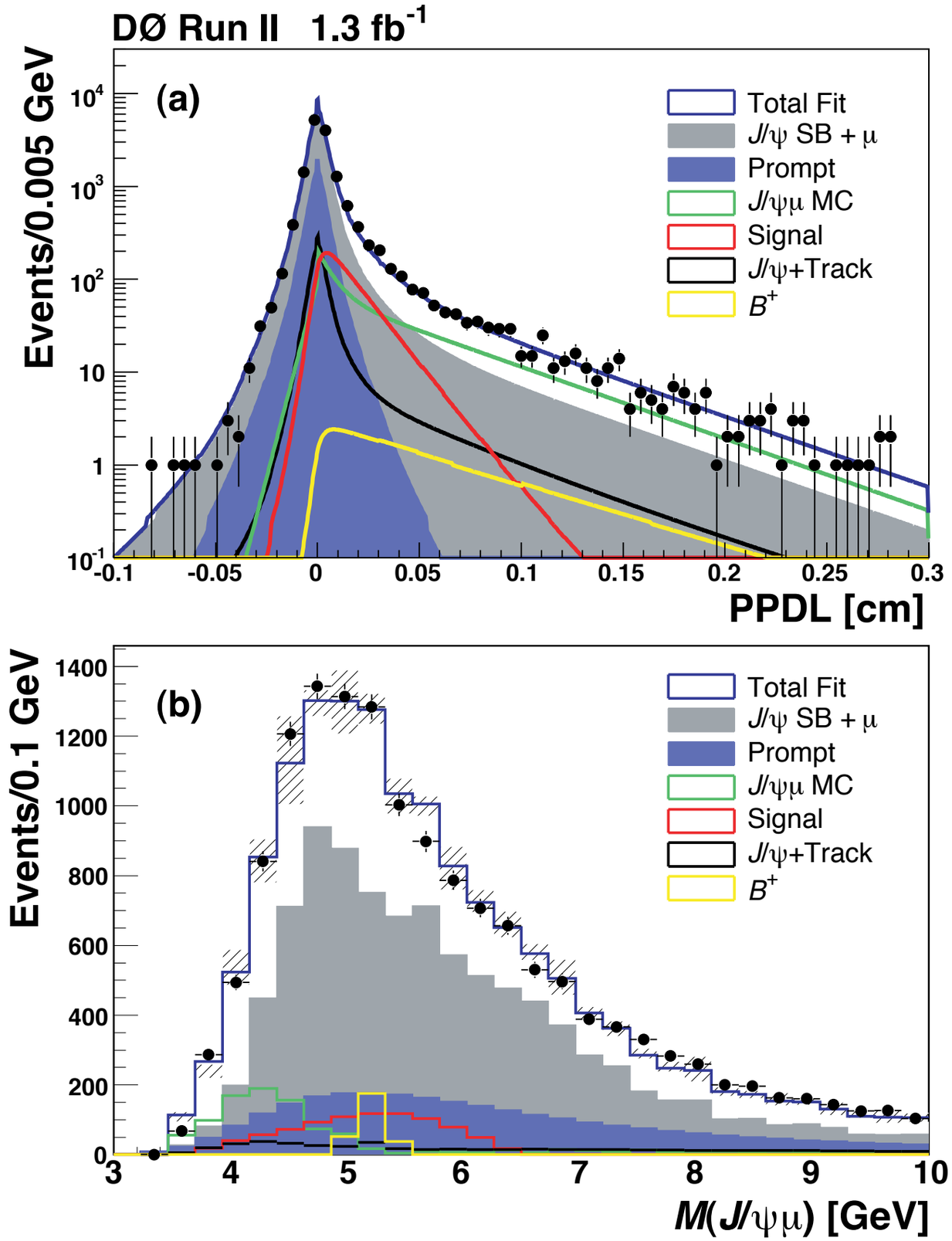
Lifetime Models

- J/ψ Mass Sideband
  - From the data
    - Fixed
- Prompt (cc(bar))
  - 2 Gaussians centered at zero
    - Event-by-event PPDL uncertainty
    - Same scale factor 's' as for signal
- J/ψ MC
  - Form determined from MC distributions
    - Fractions and lifetimes allowed to float within penalty functions
- B^+
  - PDG value
    - Constrained by error in PDG
  - Lifetimes corrected for B^+ mass
- Signal
  - Described already
- J/ψ + Track
  - From the data
    - Shape fixed.

Outline

- What are we looking for here?
  - B_c meson and motivation for measurement
  - Theoretical lifetime predictions for the B_c meson
- Apparatus
  - D-Zero muon detectors
- Data Sample
- Contributions to the Signal
- Demonstration of Signal
- Lifetime Analysis
- Results, Systematics & Conclusions
- Software development

Lifetime of the B_c

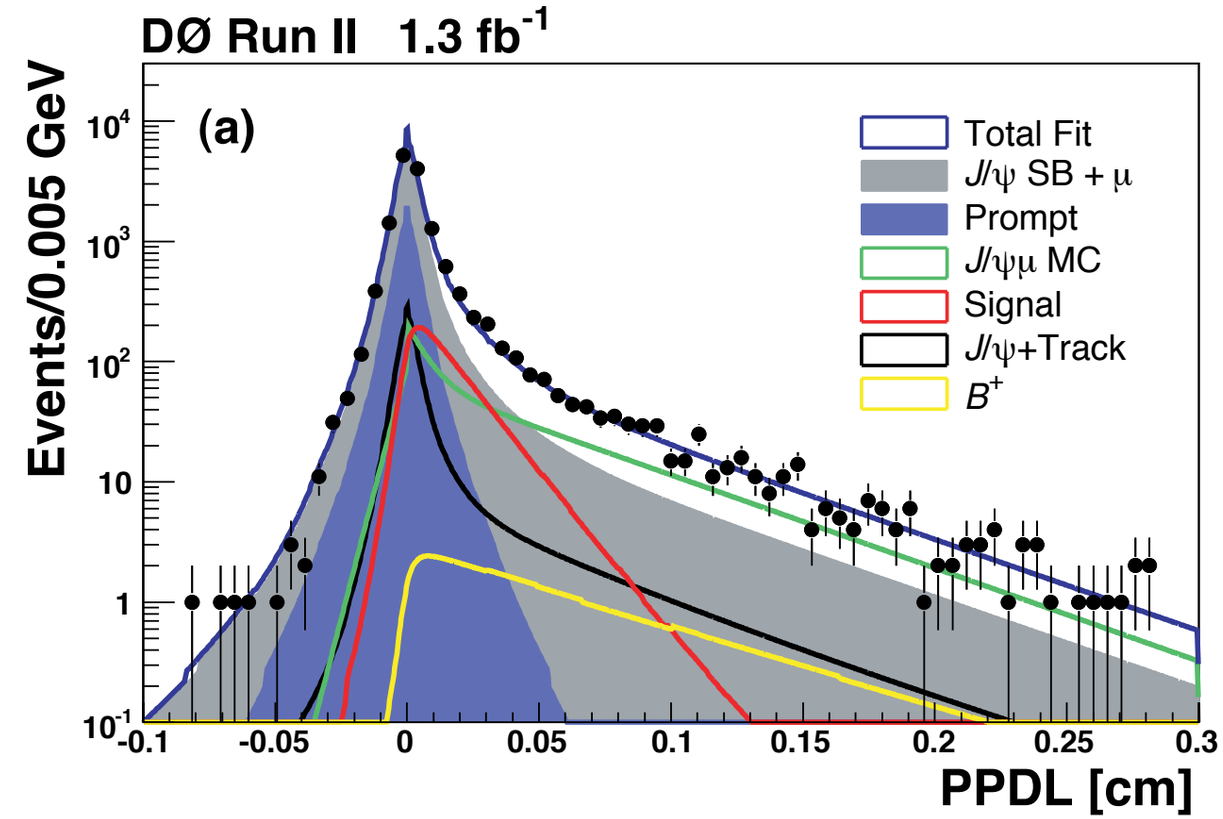


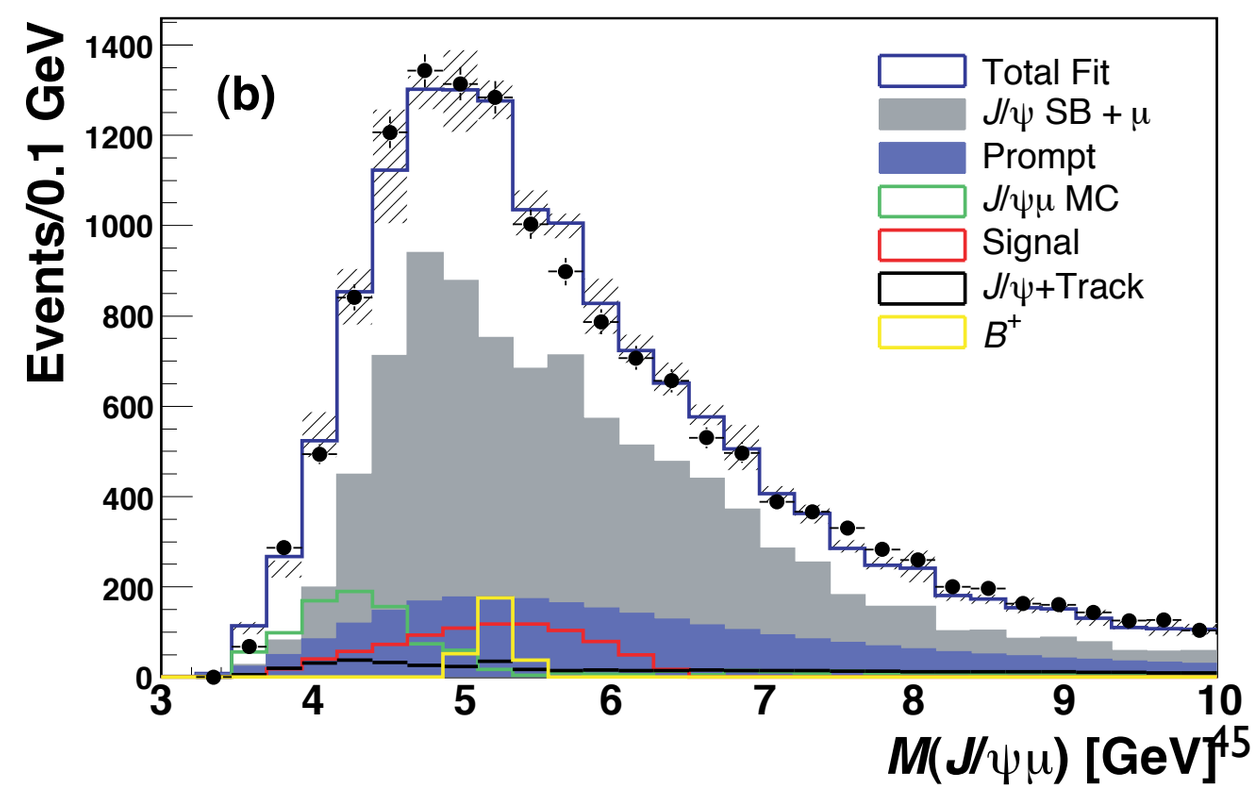
Lifetime of the B_c

Unbinned mass and <u>lifetime fit gives :</u>

$$\tau(B_c) = 0.448^{+0.038}_{-0.036}(stat)^{+0.032}_{-0.031}(sys)\ ps$$

N(Signal Events) = 881 ± 80 (stat)





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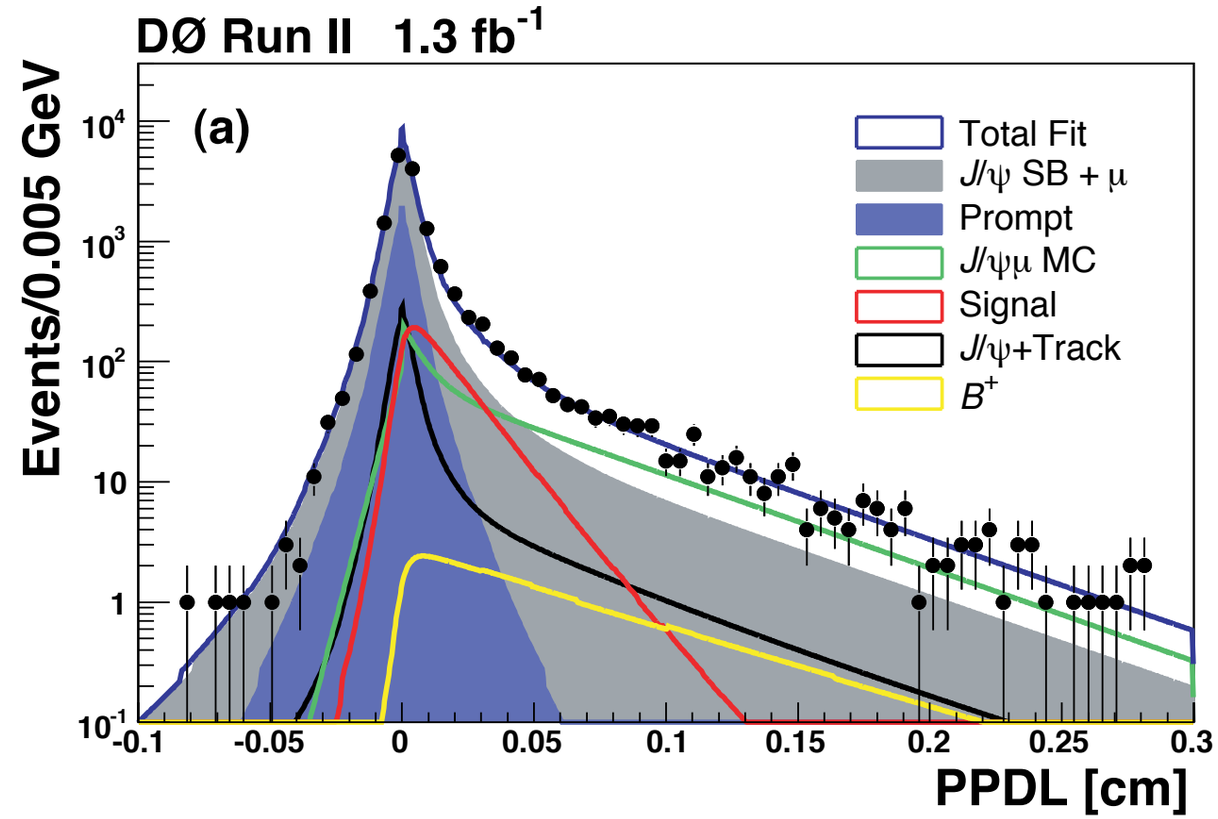
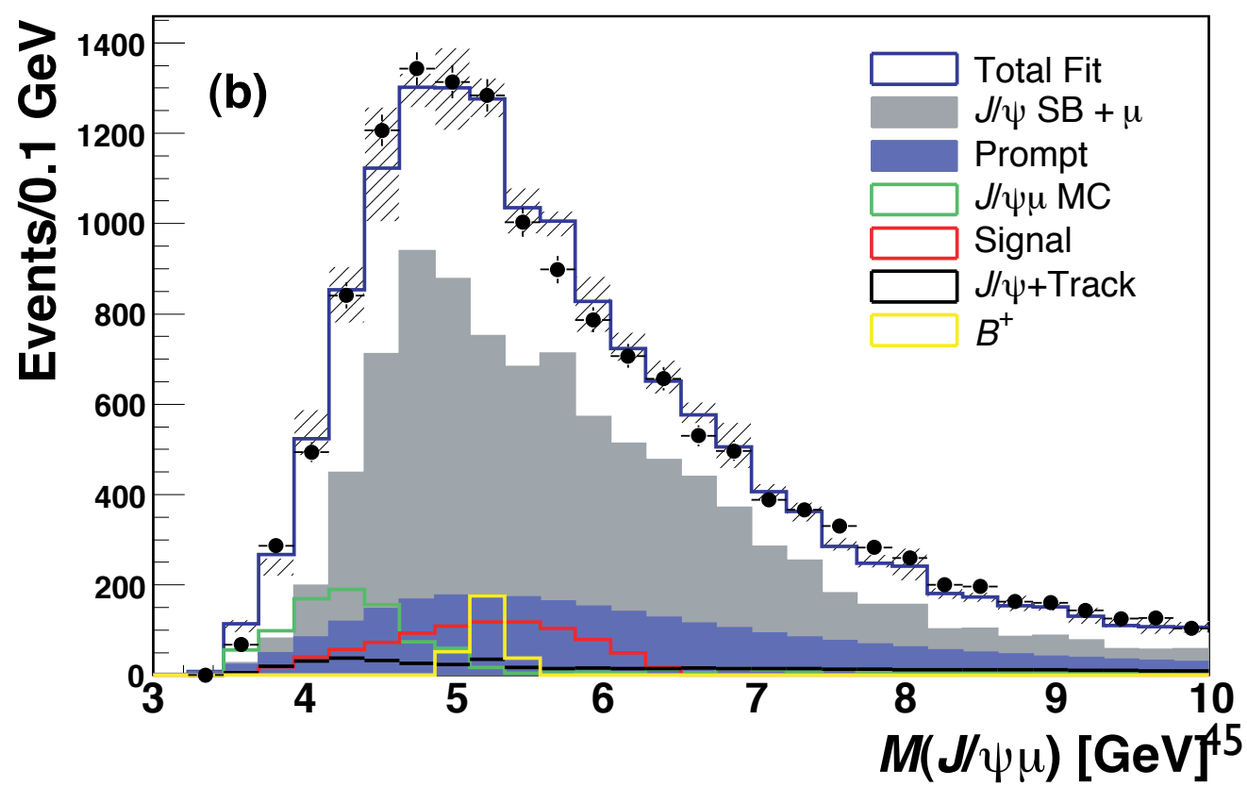


Significance of Signal
(no lifetime cuts) :
11.4σ
(Difference in the likelihood with and without the signal component)



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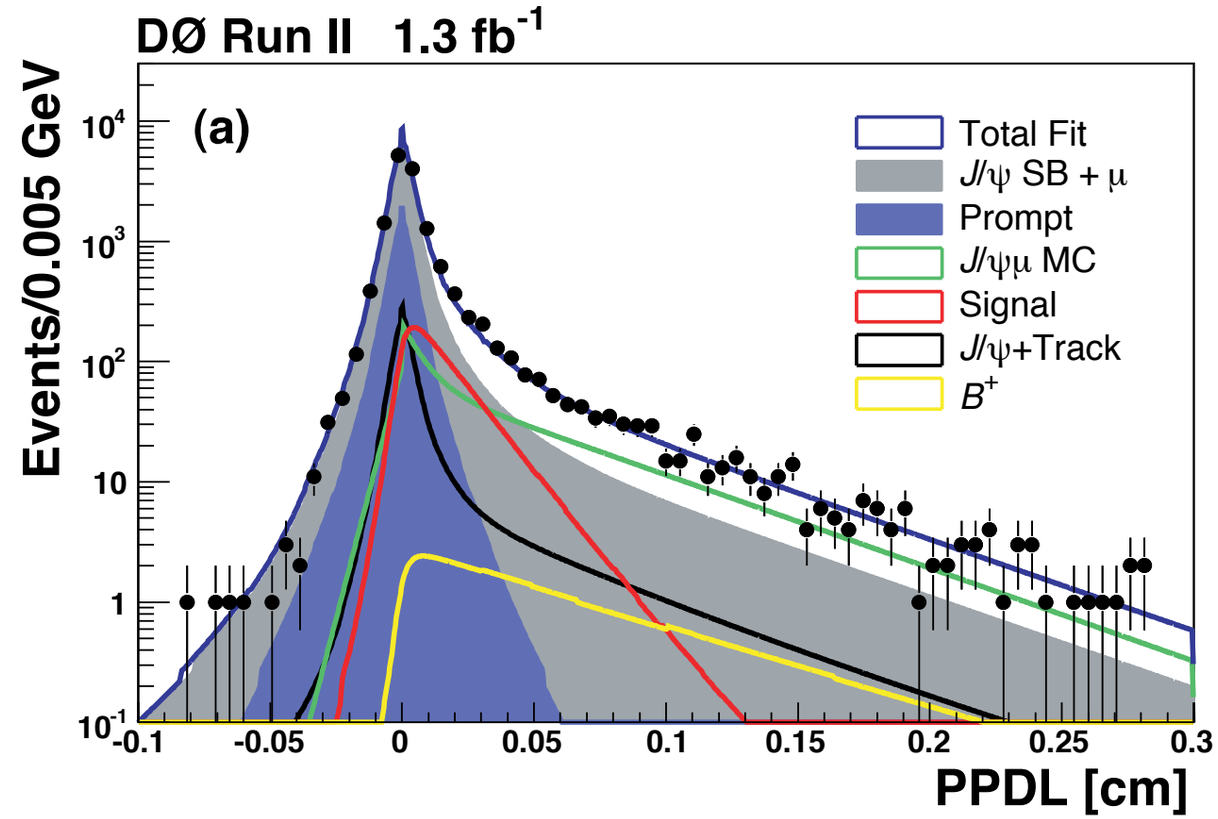

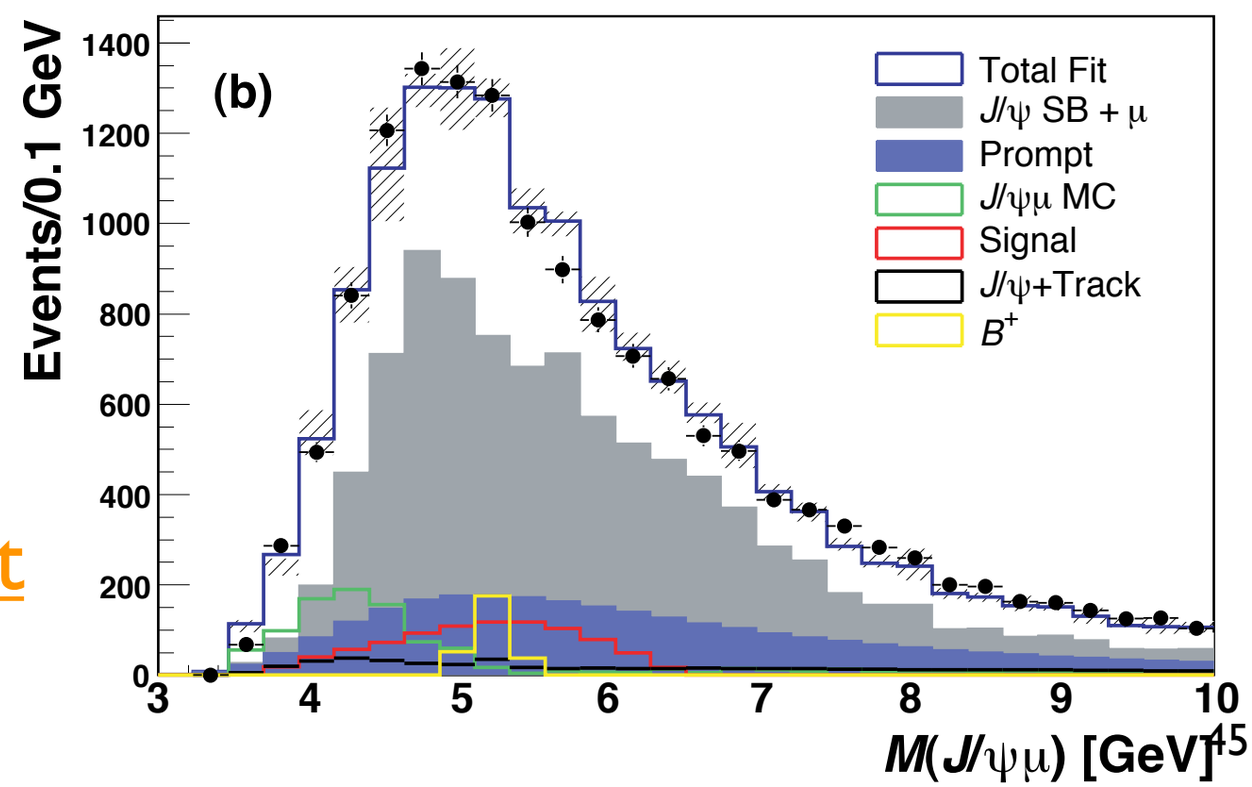

Previous D-Zero Preliminary

$$\tau(B_c) = 0.448^{+0.123}_{-0.095}(stat) \pm 0.121(sys)\ ps$$

Current Published CDF Result

$$\tau(B_c) = 0.463^{+0.073}_{-0.065}(stat) \pm 0.036(sys)\ ps$$

Current Preliminary CDF Result

$$\tau(B_c) = 0.475^{+0.053}_{-0.049}(stat) \pm 0.018(syst)\ ps$$

Split Sample Tests

To check the stability of the measurement, values of important variables were chosen to split the data sample in half.

The B_c lifetime was found for each sample, and the difference calculated.

None of the split sample tests result in a difference of more than 2σ (i.e. within statistical error).

Therefore no systematic was assigned to these checks.

Test	*Delta(τ)*	*N(sigma) Difference*
$\eta(B_c)>0$	0.014	0.204
$\eta(B_c)<0$	0.019	0.273
$5<p_T(B_c)<10$ GeV	0.008	0.114
$p_T(B_c)>10$ GeV	-0.039	0.648
$\eta(\mu_3)>0$	0.035	0.514
$\eta(\mu_3)<0$	0.010	0.137
$\lvert\eta(\mu_3)\rvert<1$ (central)	-0.027	0.401
$\lvert\eta(\mu_3)\rvert>1$ (forward)	0.110	1.438
$\phi(\mu_3)>0$	0.044	0.708
$\phi(\mu_3)<0$	0.015	0.194
$3.0<p_T(\mu_3)<4.5$ GeV	0.033	0.442
$p_T(\mu_3)>4.5$ GeV	0.006	0.091
Run<20490	-0.057	0.852
Run>20490	0.078	1.218

Systematics

- Decay model of Signal
  - Use phase space instead of Isgur-Wise (ISGW2) for the form factor of the decay
    - Changes signal mass model & K factor
- Feed down : $B_c \rightarrow \psi(2S)[\rightarrow J/\psi\pi^+\pi^-]\mu\upsilon$
  - 0% & 13% (worst case)
- Alignment
  - Reconstruct the MC using a new geometry file where silicon sensors are moved around within alignment uncertainty (as in the B_s lifetime)
  - Measure the lifetime in each sample and find the difference between the two.
- J/ψ MC mass distribution
  - Uncertainty due to the modeling of this component, isolated contributions due to bb(bar)production via gluon splitting and flavor excitation.

Systematics

- MC weighting
  - Changes signal, ψ(2S), J/ψ MC mass model & K factor
    - Applies to the p_T of the J/ψ to take into account the dimuon trigger effects
  - Vary $p_T(B_c)$ within theoretical uncertainties (vary scale μ)

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Source of uncertainty on the predicted distribution of $p_T(B_c)$ is due to the choice of the factorization scale μ

Default weighting was $\mu=\mu_R=\sqrt{\left(p_T^2(parton)+m_b^2\right)}$

Weightings were used to vary this distribution to that expected for $\mu=\mu_R/2$ & $\mu=2\mu_R$

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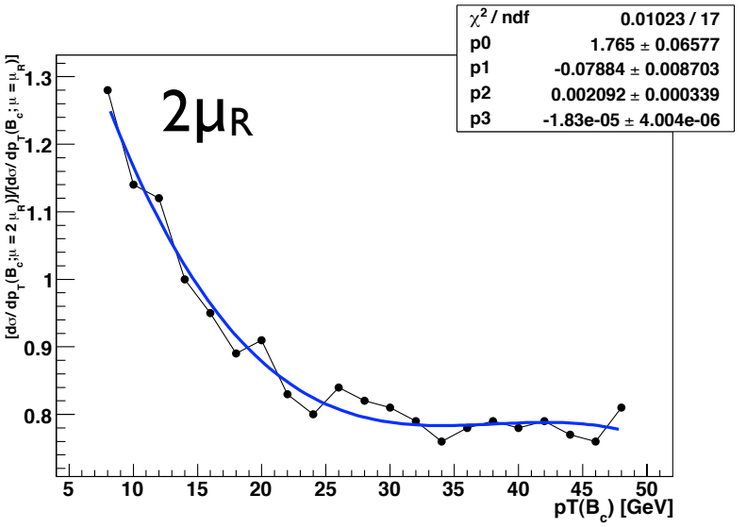

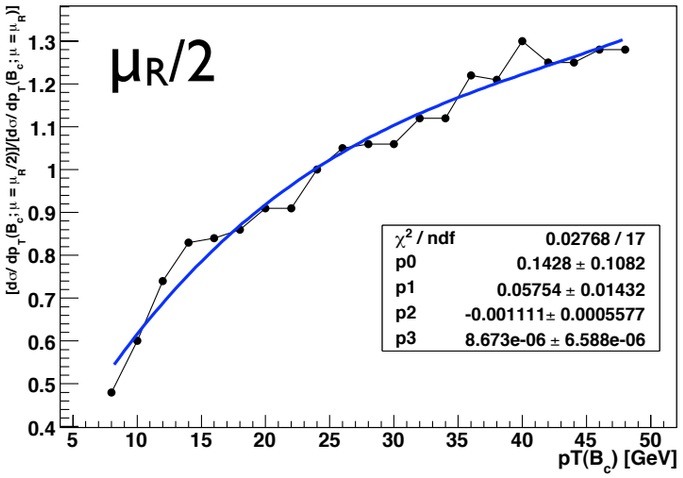

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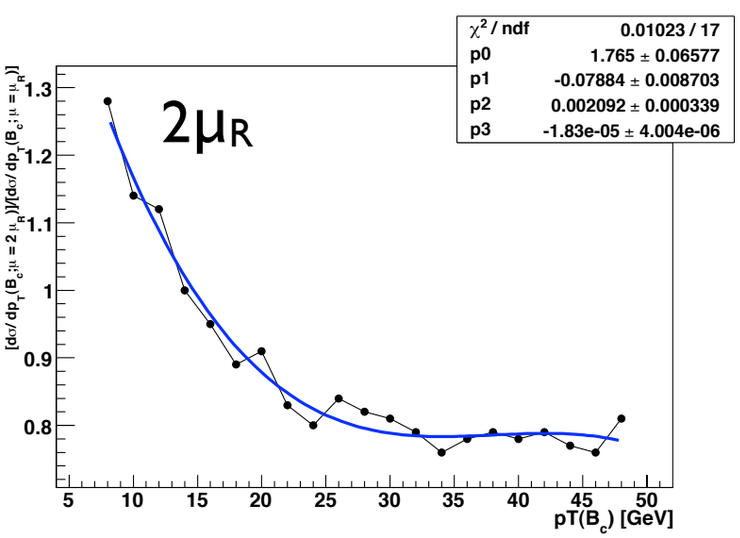
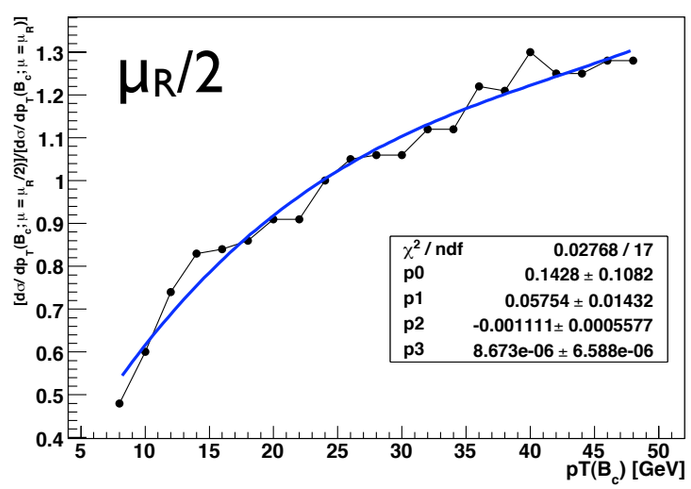
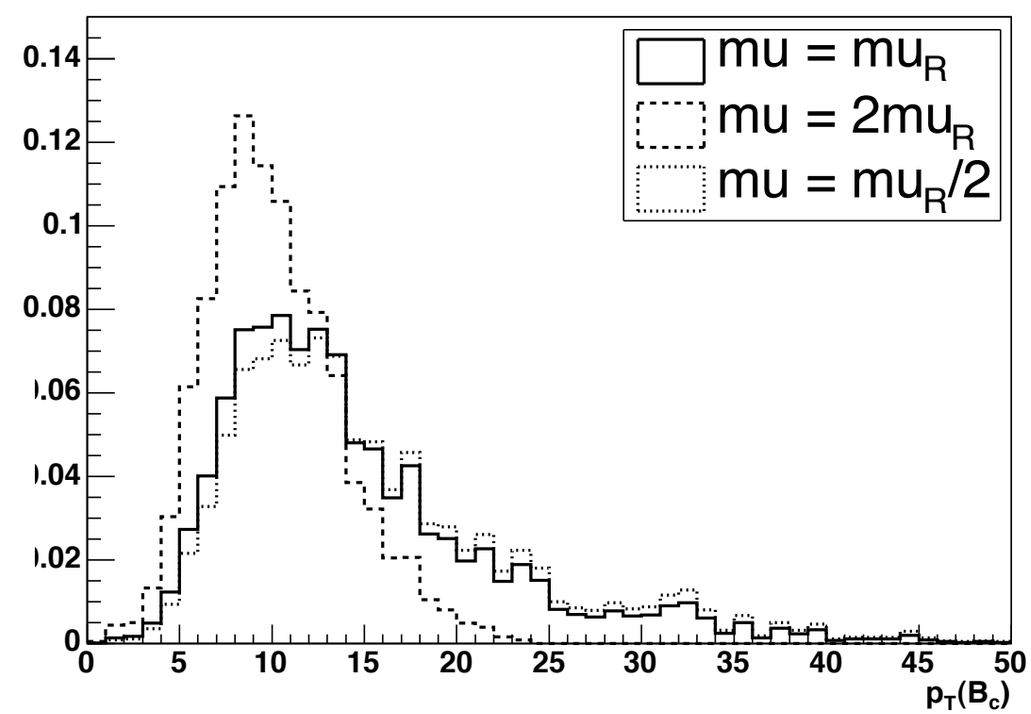
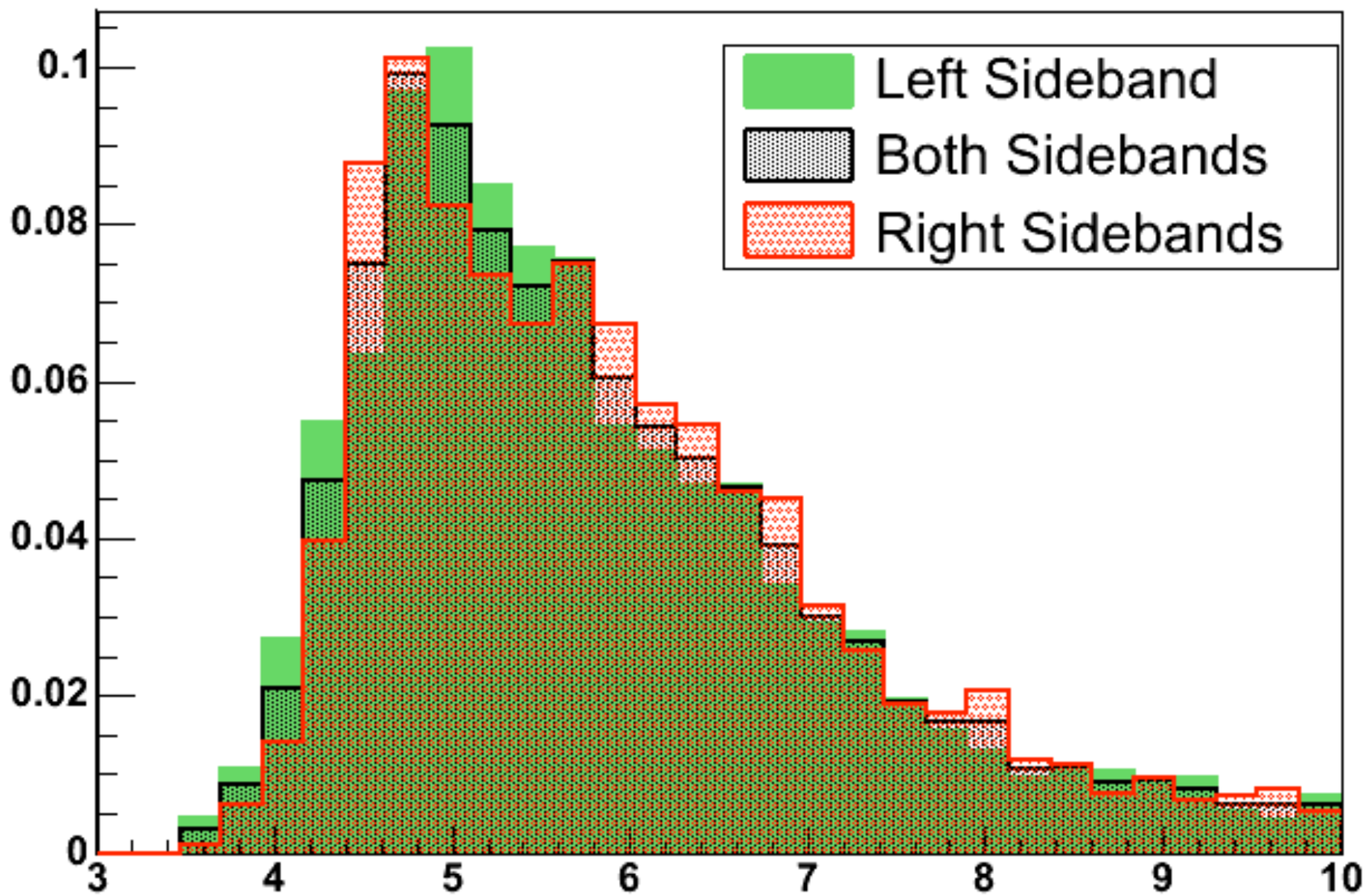






Systematics

- Sideband Mass distribution
  - Only left SB or only right SB



Systematics

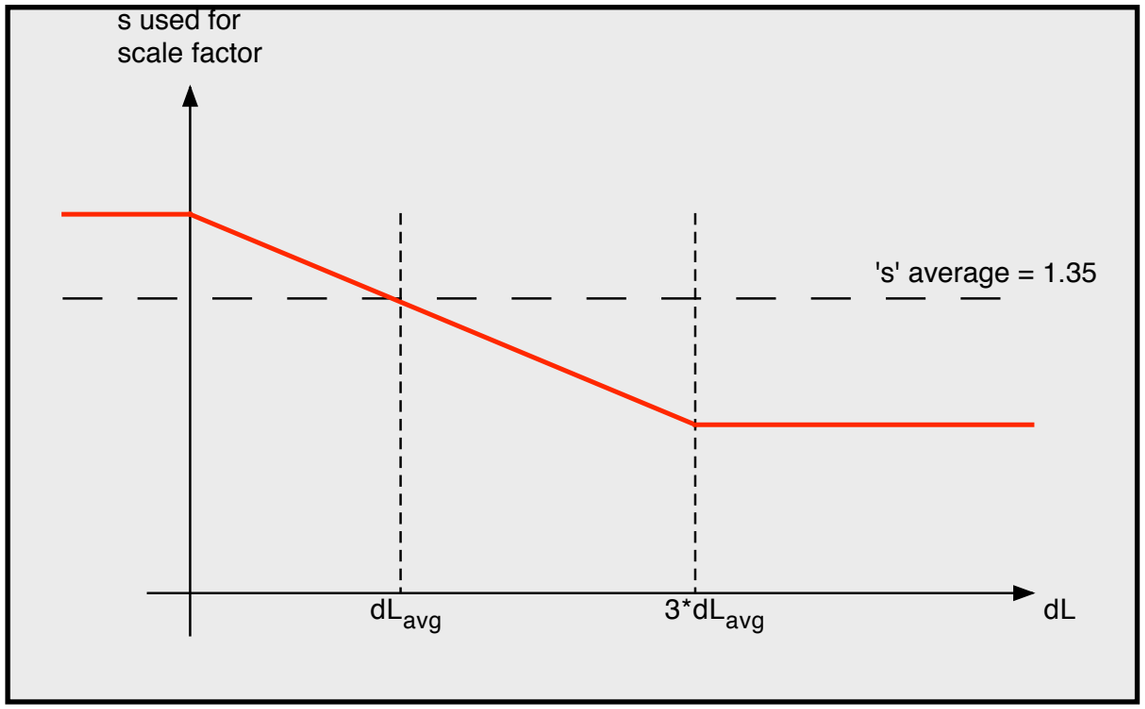
- Lifetime Models
  - Signal
    - Fix 's' = 1.2 & 1.4 (approx. value found in other lifetime analyses)
    - Use a functional form for 's'

There is a possibility that the 's' factor could vary as a function of decay length. A systematic effect such as imperfect alignment would affect the B_c meson more so than longer-lived B hadrons. The following requirements were put in place :

$$dL < 0 : s = s_{avg} + s_{avg} \times F$$

$$dL > 3 \cdot dL_{avg} : s = s_{avg} - 3 \times s_{avg} \times F$$

$$0 < dL < 3 \cdot dL_{avg} : s = s_{avg} - s_{avg} \times F \times \frac{dL - dL_{avg}}{dL_{avg}}$$



Systematics

- Lifetime Models
  - Signal
    - Fix 's' = 1.2 & 1.4 (approx. value found in other lifetime analyses)
    - Use a functional form for 's'
  - Prompt
    - Single Gaussian instead of Double Gaussian
  - Sideband
    - Fix to $\pm 1\sigma$
  - J/ψ MC
    - Values which are fixed within a Gaussian penalty function get new starting point at $\pm 1\sigma$
  - B^+
    - Fixed by Gaussian penalty function same as J/ψ MC
    - Let lifetime fully float
      - Fitted value consistent with PDG B^+ lifetime : 1.877 ±0.19ps (PDG : 1.638±0.011 ps)
      - Giving a further check on the lifetime extraction

Systematics

Systematic Source	$+\Delta\tau$ (ps)	$-\Delta\tau$ (ps)
Signal Decay Model	0.00515	0.00515
0% Feed Down	–	0.00342
13% Feed Down	0.00494	–
Uncertainty on $p_T(B_c)$ $\mu = 2\mu_R$	0.00624	–
Uncertainty on $p_T(B_c)$ $\mu = \mu_R/2$	–	0.00011
Uncertainty on $p_T(b)$	0.00605	0.00605
J/ψ MC Mass Distribution	0.01209	0.01209
Prompt Mass Distribution $+1\sigma$	0.00517	–
Prompt Mass Distribution -1σ	–	0.00444
Signal Lifetime Model $s = 1.2$	0.00649	–
Signal Lifetime Model $s = 1.4$	–	0.00048
Signal Lifetime Model - Function fraction = 0.02	–	0.00721
Signal Lifetime Model - Function fraction = -0.02	0.00850	–
Left Sideband Mass Model	0.01366	–
Right Sideband Mass Model	–	0.01486
Prompt Lifetime	0.00923	0.00923
J/ψ SB Lifetime Model $+1\sigma$	0.01515	–
J/ψ SB Lifetime Model -1σ	–	0.01564
J/ψ MC Lifetime Model $+1\sigma$	0.00306	–
J/ψ MC Lifetime Model -1σ	–	0.00259
B^+ Lifetime Model $+1\sigma$	0.00059	–
B^+ Lifetime Model -1σ	0.00008	–
B^+ Lifetime Model Float	0.00758	0.00758
Alignment	0.00590	0.00590
Total	0.03189	0.03070

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How does B_c compare?

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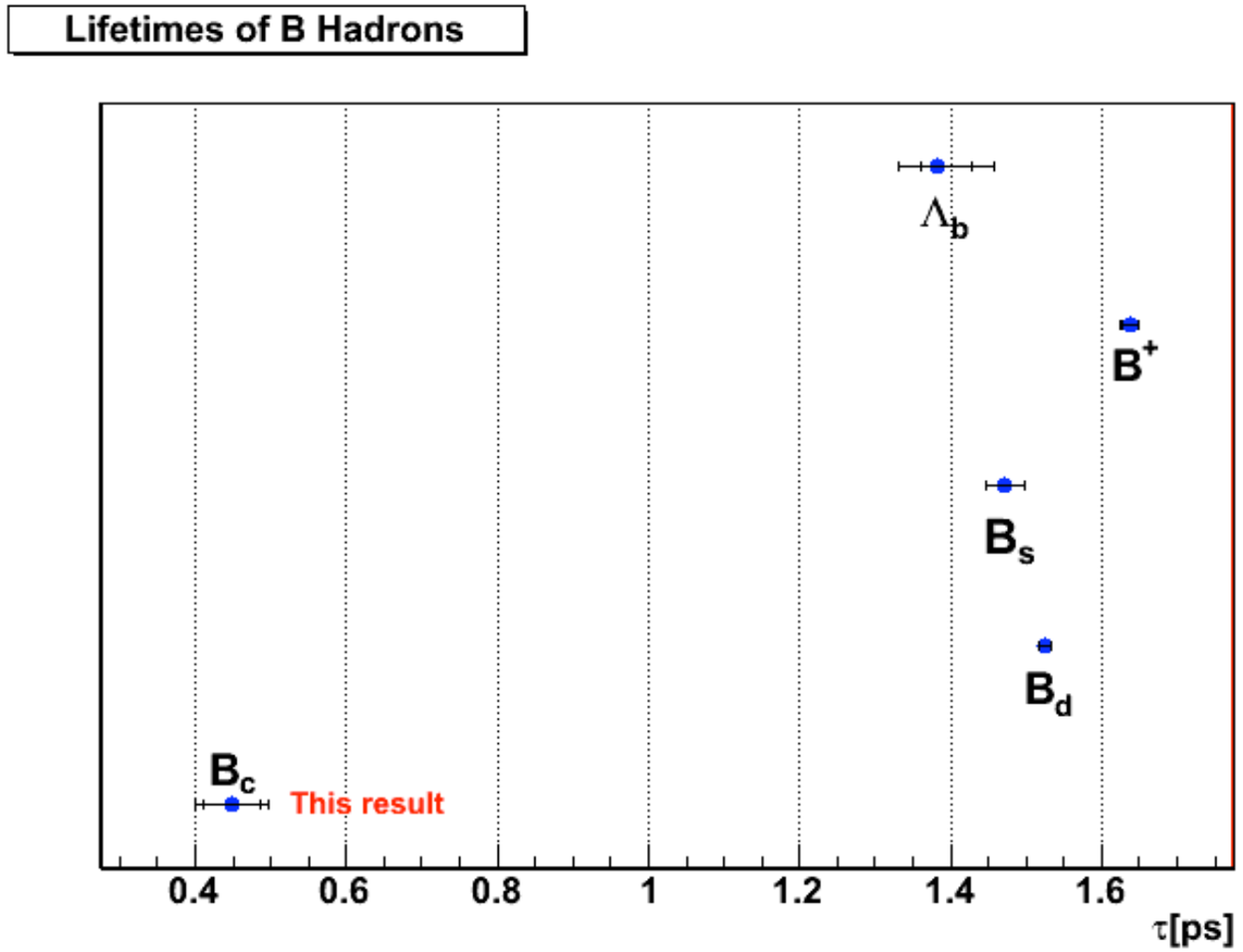

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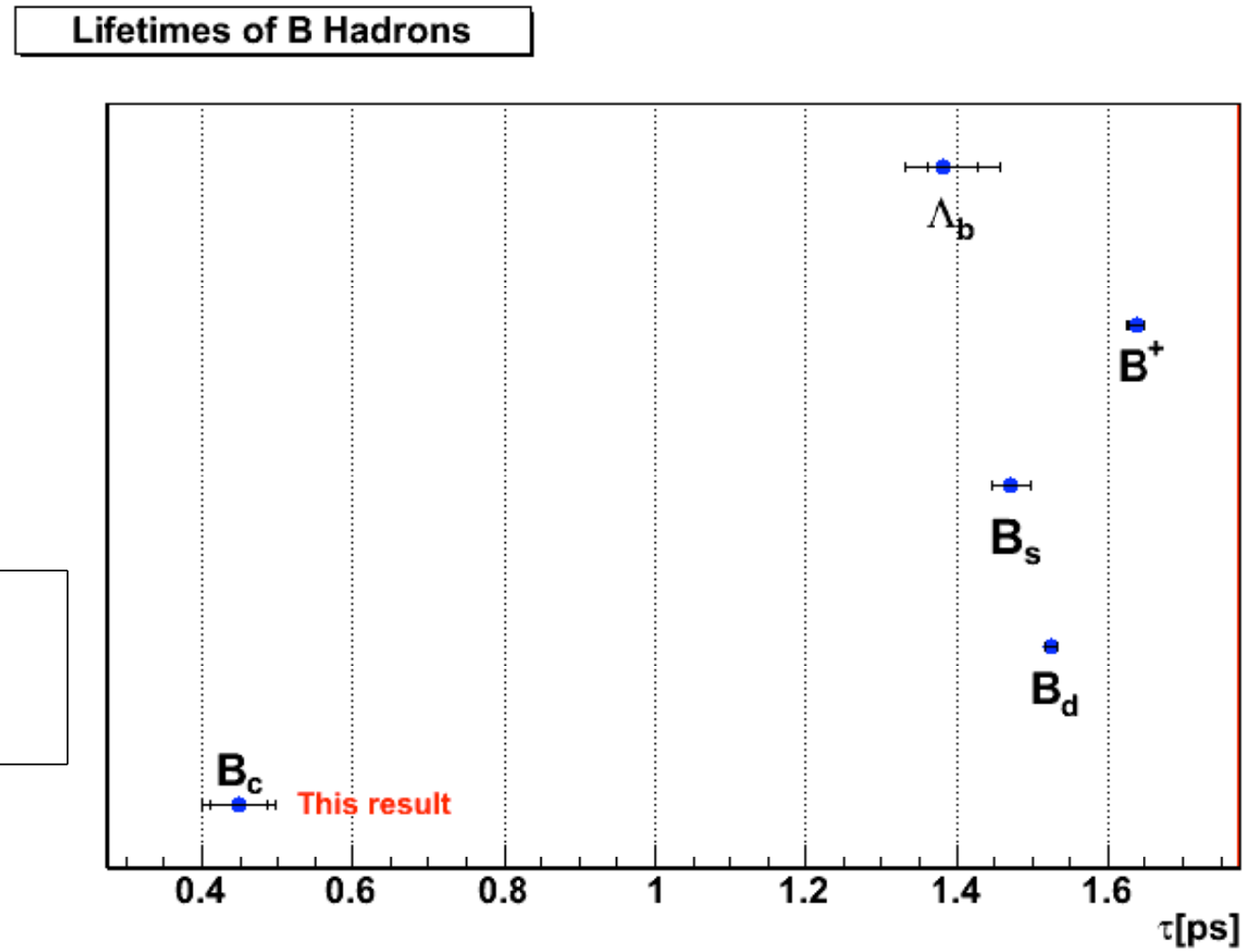

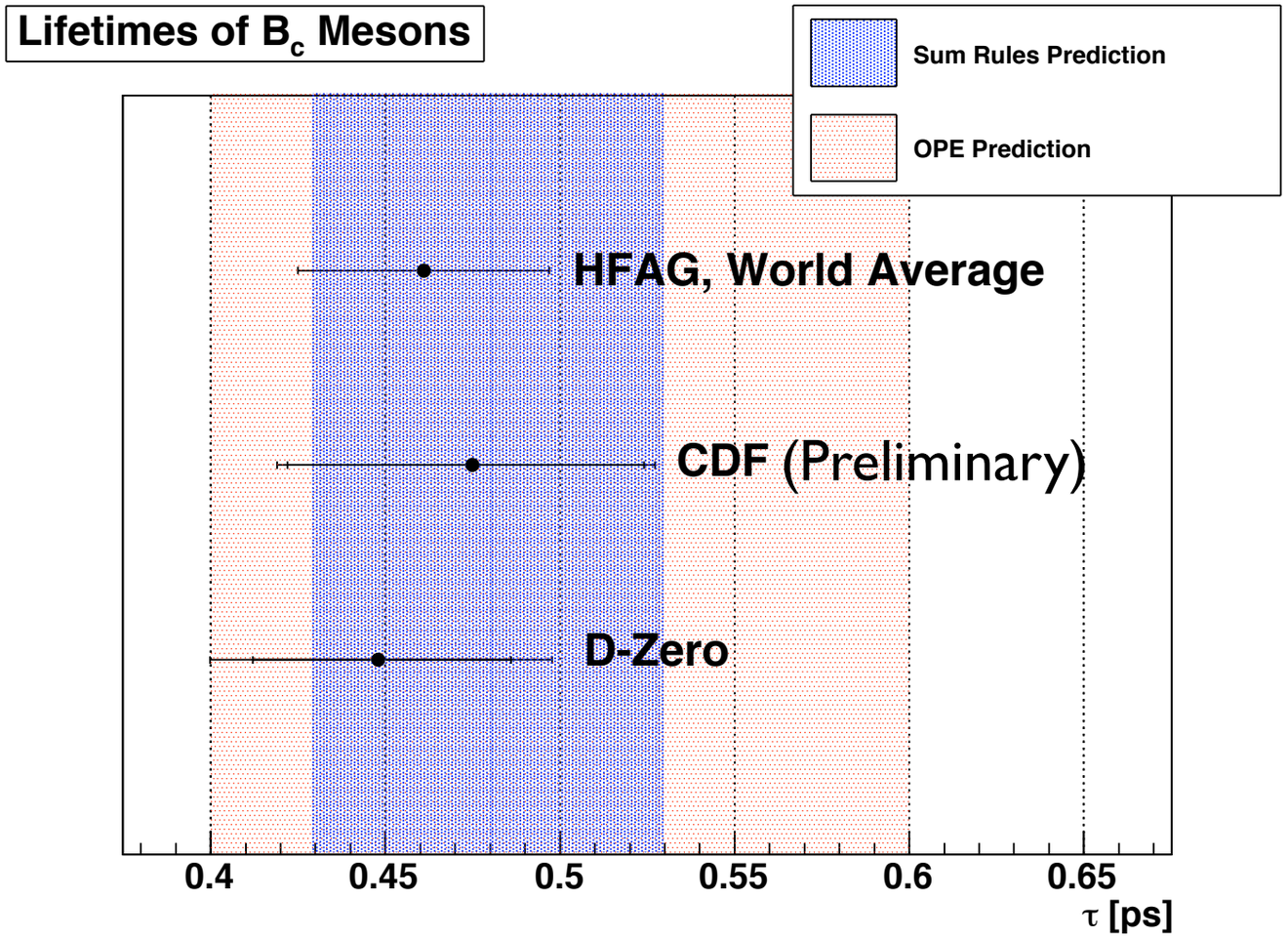

Conclusions

- **World's most precise measurement of B_c lifetime**
- Using 1.3 fb^{-1} of data, a measurement on the B_c meson lifetime has been made in the semileptonic channel : $B_c \rightarrow J/\psi + \mu + X$
- An unbinned likelihood simultaneous fit to the $J/\psi+\mu$ invariant mass and lifetime distributions giving 881 ± 80 signal events and a lifetime of :

$$\tau(B_c) = 0.448^{+0.038}_{-0.036}(stat)^{+0.032}_{-0.031}(sys)\ ps$$

- Published in PRL
  - V.M. Abazov, et al., *Measurement of the Lifetime of the $B_c^{\pm}$ Meson in the Semileptonic Decay Channel*, Phys. Rev. Lett. 102, 092001