# Properties and decays of the $B_c^+$ meson

Lucio Anderlini
on behalf of the LHCb Collaboration

XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects

Thursday May, 1st – Warsaw, Poland

# $B_c^+$

- $(\bar{b}c)$ bound state
- Heaviest ground-state charged meson in SM;
- "Open-flavour" quarkonium
- Can decay through
  - $c \to s(d)$
  - $\bar{b} \to \bar{c}(\bar{u})$
  - $c\bar{b} \to W^*$

$\Rightarrow$ Many decay modes possible

**Important probe for QCD**

… but few decays observed.

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**2013 Review of Particle Physics.**
Please use this CITATION: J. Beringer *et al.* (Particle Data Group), Phys. Rev. D**86**, 010001 (2012) and 2013 parti
update for the 2014 edition.

$B_c^\pm$

INSPIRE searcl

Quantum numbers shown are quark-model predictions.

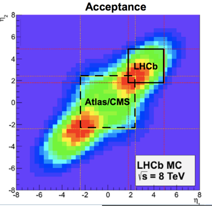
| | |
|---|---|
| $B_c^\pm$ MASS | $6.2745 \pm 0.0018$ GeV |
| $B_c^\pm$ MEAN LIFE | $(0.452 \pm 0.033) \times 10^{-12}$ s |

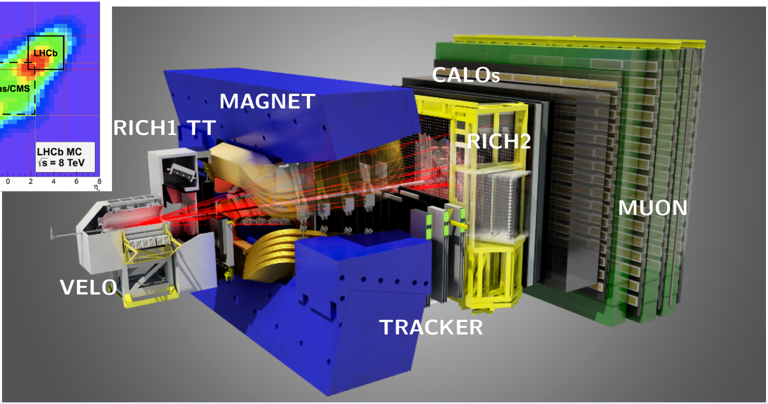
**Decay Modes** show all decays

$B_c^-$ modes are charge conjugates of the modes below.

| $\Gamma_i$ | Mode | Fraction $(\Gamma_i / \Gamma)$ | Scale Factor/ Confidence Level | P (MeV/c) |
|---|---|---|---|---|
| | The following quantities are not pure branching ratios; ratherthe fraction $\Gamma_i/\Gamma$ $\times$ B($\bar{b} \to B_c$ ). | | | |
| $\Gamma_1$ | $B_c^+ \to J/\psi(1S)\ell^+\nu_\ell$ anything | $(5.2\,^{+2.4}_{-2.1}) \times 10^{-5}$ | | |
| $\Gamma_2$ | $B_c^+ \to J/\psi(1S)\pi^+$ | seen | | 2370 |
| $\Gamma_3$ | $B_c^+ \to J/\psi(1S)\pi^+\pi^+\pi^-$ | seen | | 2350 |
| $\Gamma_4$ | $B_c^+ \to J/\psi(1S)a_1(1260)$ | $<1.2 \times 10^{-3}$ | CL=90% | 2169 |
| $\Gamma_5$ | $B_c^+ \to D^*(2010)^+\overline{D}^0$ | $<6.2 \times 10^{-3}$ | CL=90% | 2467 |
| $\Gamma_6$ | $B_c^+ \to D^+K^{*0}$ | $<0.20 \times 10^{-6}$ | CL=90% | 2783 |
| $\Gamma_7$ | $B_c^+ \to D^+\overline{K}^{*0}$ | $<0.16 \times 10^{-6}$ | CL=90% | 2783 |
| $\Gamma_8$ | $B_c^+ \to D_s^+K^{*0}$ | $<0.28 \times 10^{-6}$ | CL=90% | 2751 |
| $\Gamma_9$ | $B_c^+ \to D_s^+\overline{K}^{*0}$ | $<0.4 \times 10^{-6}$ | CL=90% | 2751 |
| $\Gamma_{10}$ | $B_c^+ \to D_s^+\phi$ | $<0.32 \times 10^{-6}$ | CL=90% | 2727 |

# LHCb: A wonderful detector to study $B_c^+$ decays



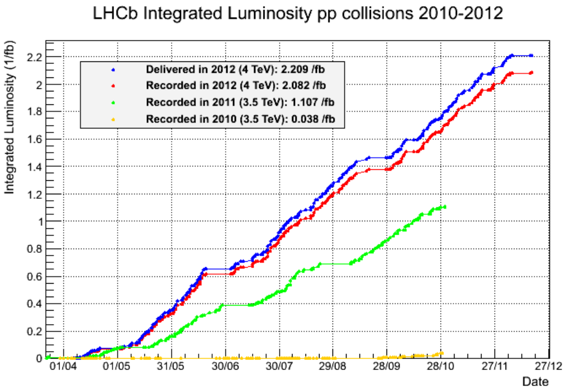




**Discussed in more detail in the LHCb Upgrade talk by Tomasz Szumlak (Tuesday)**

| | |
|---|---|
| Unique geometrical acceptance: | $2 < \eta < 5$ coverage |
| Excellent vertex locator (VELO): | $\sigma_{PV,xy} \sim 10\mu\mathrm{m}$, $\sigma_{PV,z} \sim 60\mu\mathrm{m}$ |
| Tracking system: | $\Delta p/p : 0.35\% \div 0.55\%$ |
| Muon system: | $\epsilon(\mu \to \mu) \sim 97\%$, MisID rate$(h \to \mu) \sim \mathcal{O}(1\%)$ |

## Data taking

$$1\text{fb}^{-1}(2011) + 2\text{fb}^{-1}(2012)$$

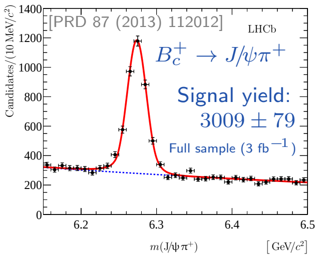



**Trigger**

Multi-level trigger:

- L0 hardware
- HLT 1 software
- HLT 2 software (event reco)

Highly efficient $J/\psi$ lines dedicated at each level!



# A long list of LHCb results on the $B_c^+$

First observation of $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ [PRL 108 (2012) 251802]

Measurement of $B_c^+$ production and mass with the $B_c^+ \to J/\psi\pi^+$ decay [PRL 109 (2012) 232001]

Observation of $B_c^+ \to \psi(2S)\pi^+$ [PRD 87 (2013) 071103]

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First observation of the decay $B_c^+ \to J/\psi K^+$ [JHEP 09 (2013) 075]

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Observation of the decay $B_c^+ \to J/\psi K^+K^-\pi^+$ [JHEP 1311 (2013) 094]

Measurement of the $B_c^+$ meson lifetime using $B_c^+ \to J/\psi\mu^+\nu_\mu X$ decays [arXiv:1401.6932]

Evidence for the decay $B_c^+ \to J/\psi\, 3\pi^+\, 2\pi^-$ [arXiv:1404.0287]

Almost all the studied decays have a $J/\psi \to \mu^+\mu^-$ in the final state

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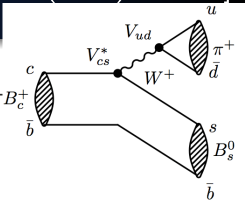
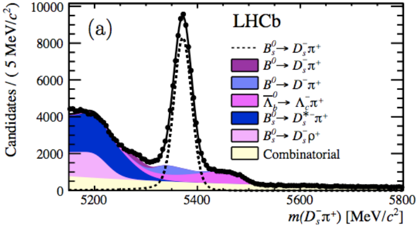
But there is an exception: $B_c^+ \to B_s^0 \pi^+$
First observation of a $B_c^+$ decay due to $c \to s$ transition.

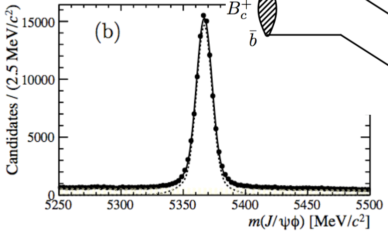
# $B_c^+ \to B_s^0 \pi^+$

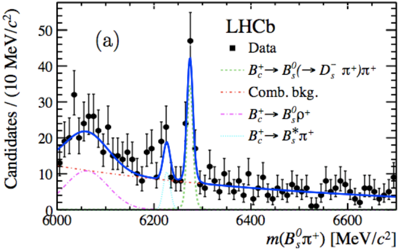
$B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to J/\psi \phi$

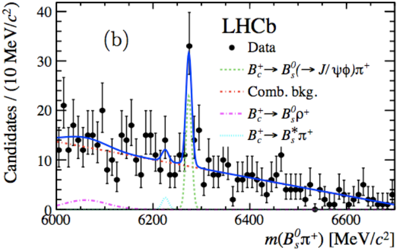



**First observation of $c \to s$ transition in $B_c^+$ mesons**




$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \to B_s^0 \pi^+) = \left(2.37 \pm 0.31(\text{stat}) \pm 0.11(\text{syst})^{+0.17}_{-0.13}(\tau_{B_c^+})\right) \times 10^{-3}$$

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**A Low-$Q$ decay: $B_c^+ \to J/\psi D_s^+$**

Fully reconstructed $J/\psi D_s^+$;

Partially reconstructed $J/\psi D_s^{*+}$ split for helicity:

- $\mathcal{A}_{\pm\pm}$ $J/\psi$: $\pm 1$; $D_s^{*+}$: $\pm 1$;
- $\mathcal{A}_{00}$ $J/\psi$: $0$; $D_s^{*+}$: $0$;

Observed $28.9 \pm 5.6$ $D_s^+$ events in $3\ \mathrm{fb}^{-1}$ (2011+2012);

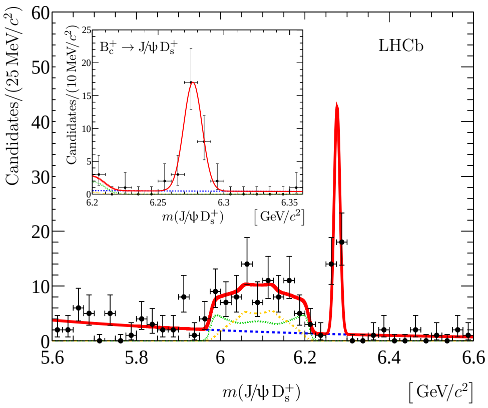
Significance $> 9\sigma$.

$$\frac{N_{B_c^+ \to J/\psi D_s^{*+}}}{N_{B_c^+ \to J/\psi D_s^+}} = 2.37 \pm 0.56;$$

$$\frac{\mathcal{A}_{\pm\pm}}{\mathcal{A}_{\pm\pm} + \mathcal{A}_{00}} = 0.52 \pm 0.20;$$

$$\frac{\mathcal{B}_{B_c^+ \to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+ \to J/\psi D_s^+}} = 2.37 \pm 0.56 \pm 0.10;$$

$$\frac{\mathcal{B}_{B_c^+ \to J/\psi D_s^+}}{\mathcal{B}_{B_c^+ \to J/\psi \pi^+}} = 2.90 \pm 0.57 \pm 0.24$$




The mass of the $B_c^+$ meson has been measured with a very small systematic uncertainty:

$$6276.26 \pm 1.44 \pm 0.28\ \mathrm{MeV}/c^2.$$

Using LHCb measurement of the $D_s^+$ mass. [JHEP06 (2013) 065]

PDG 2013: $6274.5 \pm 1.8\ \mathrm{MeV}/c^2$

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Another LHCb hit: the lifetime measurement

## Input for theory

The precise measurement of $B_c^+$ lifetime provides an essential test of the theoretical models describing its dynamics:

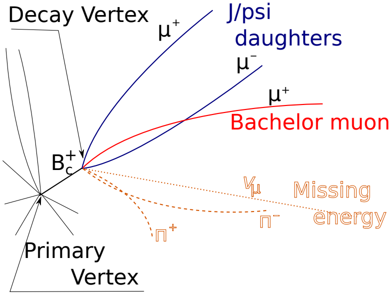
| | |
|---|---|
| Beneke and Buchalla (PRD 53 4991) | $[0.4\,,\ 0.7]$ ps |
| Anisimov *et al.* (PLB 452 129) | $(0.59 \pm 0.06)$ ps |
| Kiselev *et al.* (Nucl. PB 585 353) | $(0.48 \pm 0.05)$ ps |

| Experiment | $\tau_{B_c}$ | | | Mode | |
|---|---|---|---|---|---|
| CDF | 0.46 | $^{+0.18}_{-0.16}$ (stat) | $\pm 0.03$ (syst) | $J/\psi \ell^+ \nu$ | PRL 81 2432 |
| CDF II | 0.463 | $^{+0.073}_{-0.065}$ (stat) | $\pm 0.036$ (syst) | $J/\psi e^+ \nu_e$ | PRL 97 012002 |
| D0 | 0.448 | $^{+0.038}_{-0.036}$ (stat) | $\pm 0.032$ (syst) | $J/\psi \mu^+ \nu_\mu$ | PRL 102 092001 |
| CDF II | 0.452 | $\pm 0.048$ (stat) | $\pm 0.027$ (syst) | $J/\psi \pi^+$ | PRD 87 011101 |
| World Average | 0.453 | $\pm 0.033$ | | | PDG 2013 |
| CDF II | 0.475 | $^{+0.053}_{-0.049}$ (stat) | $\pm 0.018$ (syst) | $J/\psi \mu \nu$ | unpublished |

## Input for experiments

Lifetime uncertainty becomes a dominant systematic uncertainty in several $B_c^+$ analyses.

- Decay $B_c^+ \to J/\psi \mu \nu$ with $J/\psi \to \mu^+ \mu^-$ ;
- Clear $3\mu$ signature allows decay-time unbiased selection;
- High-statistics due to the large BF.
- Semileptonic decay means partial reconstruction;
  - Need simulation to correct for the missing energy
  - The decay time correction is named **$k$-factor**
- Contribution from feed-down decays
  - *e.g.* $B_c^+ \to \psi(2S)\mu^+\nu_\mu$ with $\psi(2S) \to J/\psi X$

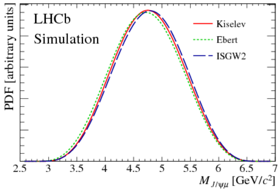



Using a 2D data-model
$M_{J/\psi\mu} \perp$ pseudo-proper decay time $t_{\rm ps}$
to enhance S/B separation.

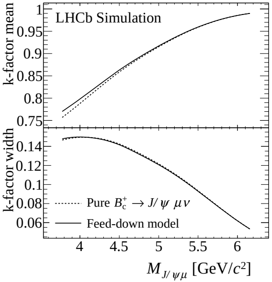
$t_{\rm ps}$ is the decay time in the frame of the $J/\psi\mu$ combination.

**Signal model**

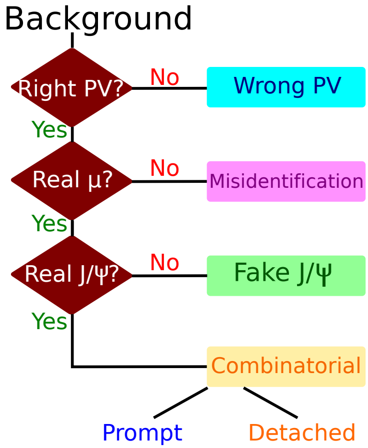
Simulated using a few form-factor models;




Model corrected for feed-down contributions.



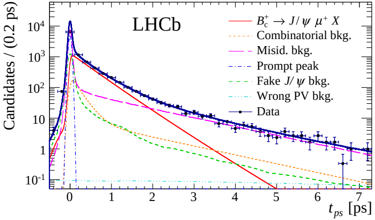

**Background model**

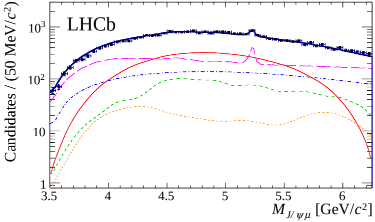



Combinatorial background is simulated.

All other background sources are modeled with data-driven methods.

# Data model

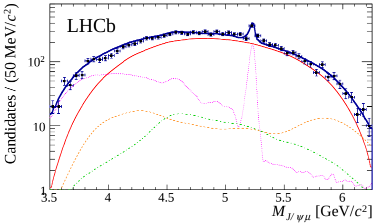



The $B_c^+$ lifetime $\tau$ is determined from a maximum likelihood unbinned fit to the $(M_{J/\psi\mu}, t_{\rm ps})$ distribution of the data sample collected in 2012 (corresponding to $2{\rm fb}^{-1}$).

$$\tau = 509 \pm 8\ ({\rm stat}) \pm 12\ ({\rm syst})\ {\rm fs}$$

$t_{\rm ps} > 150$ fs




Dominant systematic uncertainties:

- Background model ($\pm$ 10 fs)
- Signal model, model dependence ($\pm$ 5 fs)
- Deviation from time-independent eff. ($\pm$ 2 fs)

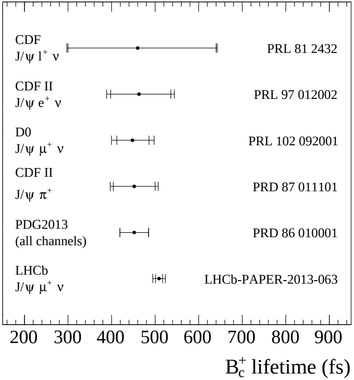
LHCb used $B_c^+ \to J/\psi \mu \nu_\mu$ decays to measure the $B_c^+$ lifetime:

$$\tau = 509 \pm 8 \text{ (stat)} \pm 12 \text{ (syst) fs}$$

This is the most precise measurement of the $B_c^+$ lifetime to date.

It is consistent with current world average and has less than half the uncerteinty.

Further improvements are expected from the LHCb experiment using $B_c^+ \to J/\psi \pi^+$ decays where systematic uncertainties are expected to be largely uncorrelated with those affecting the present measurement.



# Conclusion

The excellent performance of the LHC and of the detector has allowed LHCb to reach several achivements.

- World's best measurement of the $B_c^+$ **lifetime**
- World's best measurement of the $B_c^+$ **mass**
- First observation of a $B$ meson decaying to another $B$ meson ($B_c^+ \to B_s^0 \pi^+$)
- First upper limit on a $B_c^+$ charmless decay ($B_c^+ \to K_S^0 K^+$) [PLB 726 (2013) 646]

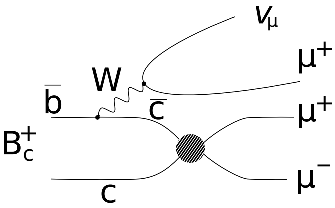
- First observation, and relative BF measurement of
  $B_c^+ \to J/\psi \pi^+ \pi^- \pi^+$
  $B_c^+ \to \psi(2S) \pi^+$
  $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$
  $B_c^+ \to J/\psi K^+$
  $B_c^+ \to J/\psi K^+ K^- \pi^+$
  $B_c^+ \to J/\psi\, 3\pi^+\, 2\pi^-$

This is the dawning of the age of the $B_c^+$

Ren Woods in Hair (1979) – *Aquarius*

# Spare slides

# Hadronic or Semileptonic channels?

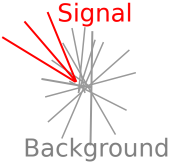


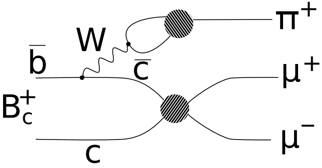

**Semileptonic (SL) decay**

$B_c^+ \to J/\psi \mu^+ \nu_\mu$

- Large statistics, $\sim 20$ times $J/\psi\pi$;
- Rare experimental signature ($3\mu$ vertex)

- Impossible to reconstruct the $B_c^+$ mass
- Includes $c\bar{c} \to J/\psi X$ decays (*feed-down*)



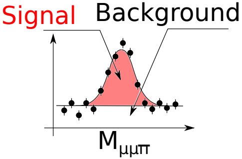




**Non-leptonic (NL) decay**

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

- Simple background model;
- Model independent analysis

- Huge background from PV
- Detachment cuts: time-dependent efficiency




**Competitive and complementary analyses**

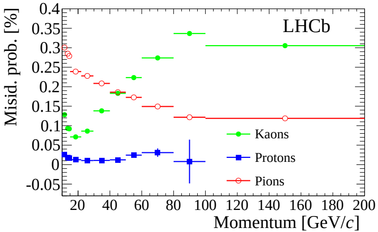
Signal-background separation relies on $3\mu$: $h \to \mu$ misidentification is dangerous.

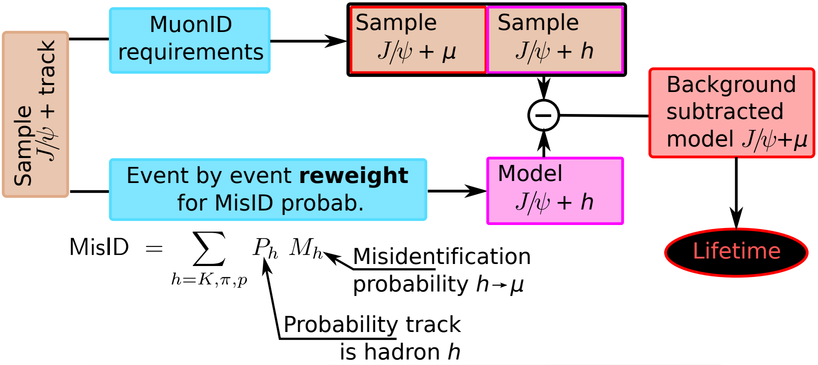
$B \to J/\psi K(\pi)$ is very abundant and detached.

- Require muon hits in $\geq 4$ muon stations;
- Reject $K$ (and $p$) using RICH detectors;
- Reject $K$ decaying to $\mu$ using track kink;
- Reject combinatorial association of muon hits to hadron tracks by
  - Performing a **Kalman filter** track fit using muon hits
  - Rejecting muon candidates with Kalman filter $\chi^2/\mathrm{ndof} > 1.5$;
  - Requiring **each hit is used at most once**.

Average misidentification probability: 0.2%
Single muon identification efficiency: 87%

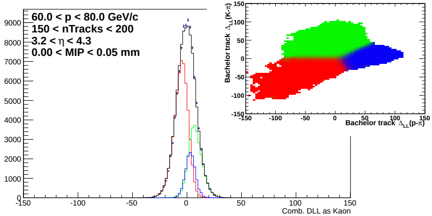
Dominating residual background from decays in flight






$P_h = P_h(p, \eta, \texttt{nTracks})$

$M_h = M_h(p, \eta, \texttt{Impact parameter})$




### Calibration samples

- $D^{*+} \to D^0 \pi_s^+ \to (K^- \pi^+)_D \pi_s^+$
  Flavour tagged with the slow pion $\pi_s$.
- $\Lambda^0 \to p \pi^-$
  Very wrong mass in case of
  $p \to \pi$ & $\pi \to p$.

# Signal spectra

A bad simulation of the $B_c^+$ momentum spectrum can modify the simulated $k$-factor distribution, and thus the lifetime.
**How much?**

Reweighing of the $B_c^+$ spectra ($p_T$ and $\eta$) to assess systematic uncertainty due to data/simulation disagreement

- using $B_c^+ \to J/\psi\pi^+$ distribution to compare data and Simulation
- reweighted signal pdf

(including feed-down decays)

**Small effect**: $0.8\,(p_T)\;\oplus\;0.6\,(\eta) = 1.0$ fs

# Model dependence assessment

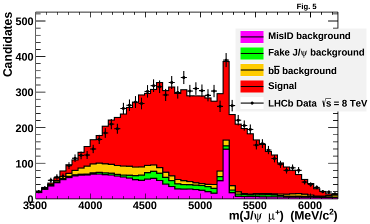
We deform the model (**true variables**):

$$DeformedDalitz(m^2, q^2) = NominalDalitz(m^2, q^2)\ e^{(\alpha_\psi m + \alpha_\nu q)}$$

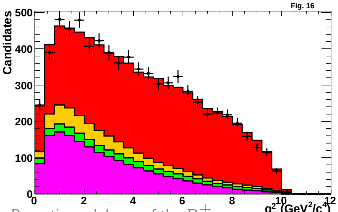
The first step is to reconstruct the $q^2$ using the pointing information.

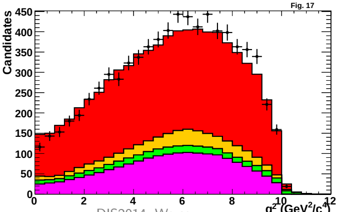
The we check the agreement

With PV and DV perfectly known, one can define the $q^2$ with a twofold ambiguity.

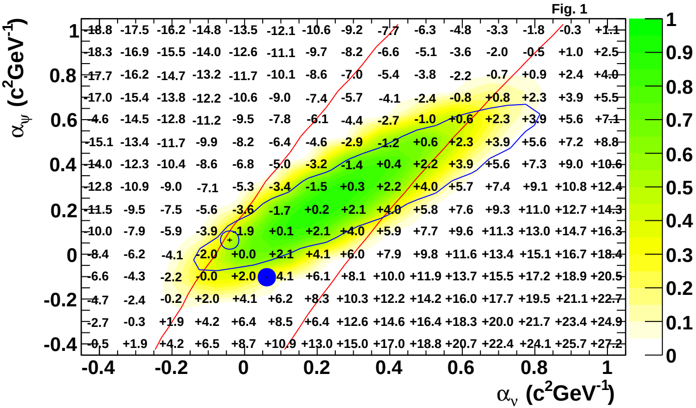



kinematic → different $q^2$ distributions.



Information from the agreement of the 3 distributions ($M_{J/\psi\mu}$, $q^2_H$, and $q^2_L$) is combined.




Red curve: 68% C.L. from $q^2$

Blue curve: 68% C.L. from $m(J/\psi\mu)$

Full marker: Ebert model

Empty marker: ISGW2 model

Model-independent uncertainty on lifetime $\pm$ 5 fs