Charm and Charmonium At Belle II

Roy Briere

Carnegie Mellon

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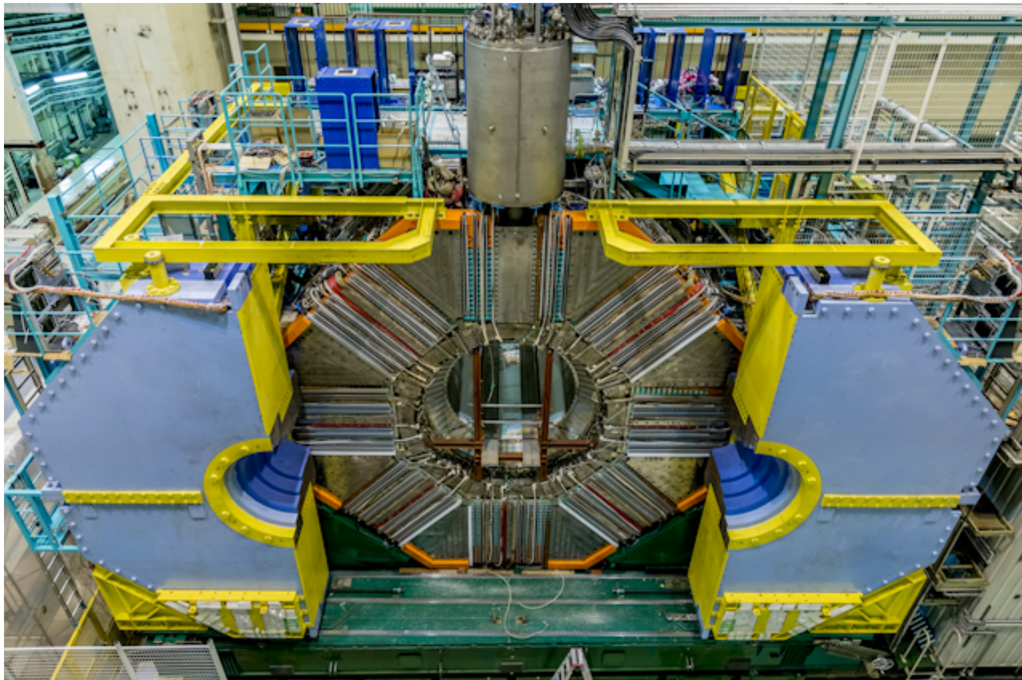

Outline

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Context & Competition
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} **Introduction**

Mixing
CP Violation
Rare Decays
(Semi-)Leptonic
Spectroscopy & Baryons
} **Open Charm**

Charmonium
Exotics
} **Charmonium**

Summary

Overview

PLAN:

We're aiming for **50 ab^{-1}** : more than 50x Belle dataset

→ *Intermediate datasets will already be a big step forward*

High statistics should fuel new ideas for analysis

(topics, techniques, …)

PROJECTIONS:

Prog. Th. Exp. Phys. 2019, 1232C01

Belle II Physics Book [arXiv 1808.10567]

Extensive work by Belle II Collaboration & Theorists

Roadmap for physics with projections, comparisons, …

A rich program awaits !

PROGRESS:

Intensive work on tuning, shielding, background rates, …

May 2020: Operating at levels similar to best Belle numbers

Experimental Context

BESIII: absolute BFs, (semi-)leptonics, charmonia, exotics (XYZ)
Statistics limit CPV, rare decays; no boost for time-dependence
LHCb: excels at CPV, lifetimes, mixing, rare decays, spectroscopy,
Some analyses with π^0 & single γ; recent $B_{(s)}$ semileptonic (!)

Belle II can generally cover all of the above topics
LHCb stats are overwhelming for charged final states (incl. K_S)
BESIII cleanliness very powerful when statistics suffice
But Belle II can perform world's best analyses in many cases,
as well as verify results from others

Open charm mesons, baryons: from continuum (typically)
Cross-sections (in nb) : 0.6 + 0.6 $D^{*+} + D^{*0}$ 0.2 D_s 0.2 Λ_c
nb x $ab^{-1} = 10^9$ → **tens of billions produced in final samples**

Charmonium (incl. Exotics) from B decays, ISR, two-photon

Physics Context

Precision Studies of tree-level processes :

Over-constrain CKM:

→ (Semi-)leptonic - CKM matrix; decay constants, form factors

Search for anomalous CPV

→ T-odd triple products

→ Direct CP asymmetries : especially SCS decays

Suppressed decays (loops) :

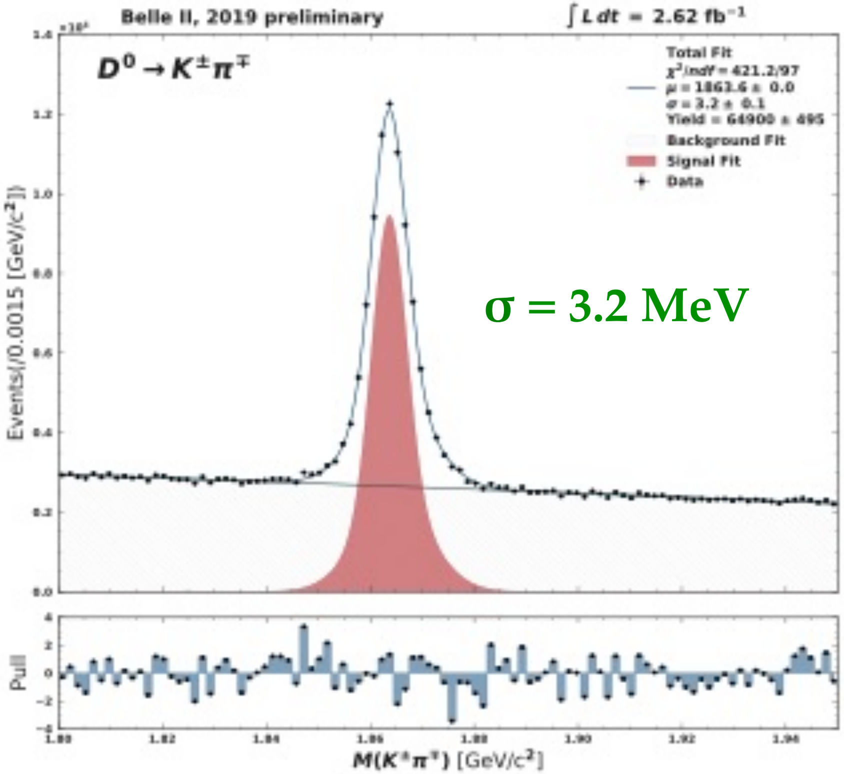
FCNC : Radiative modes, di-leptons

Forbidden decays :

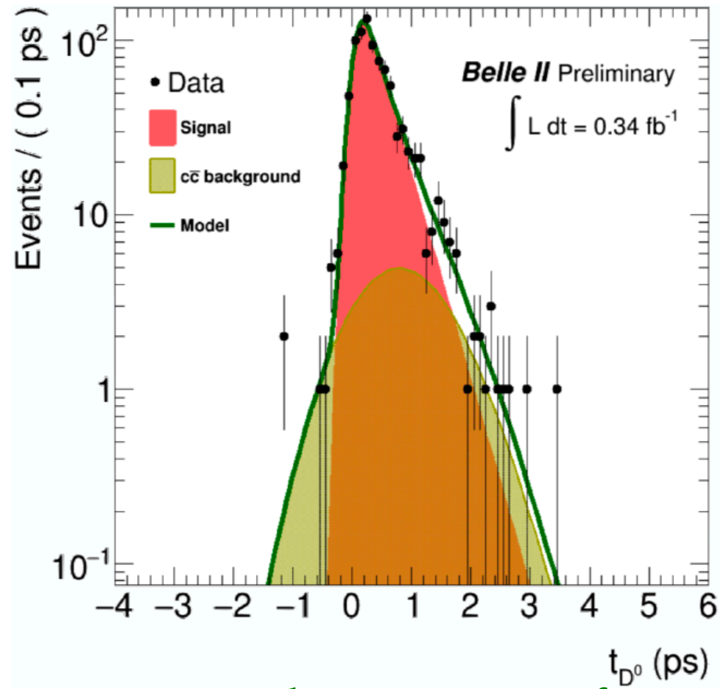
Lepton flavor violation, …

Belle II Data: Open Charm

D^0 mass peak in $K^-\pi^+$



D^0 lifetime in $K^-\pi^+$ (early sample, D^* tag)

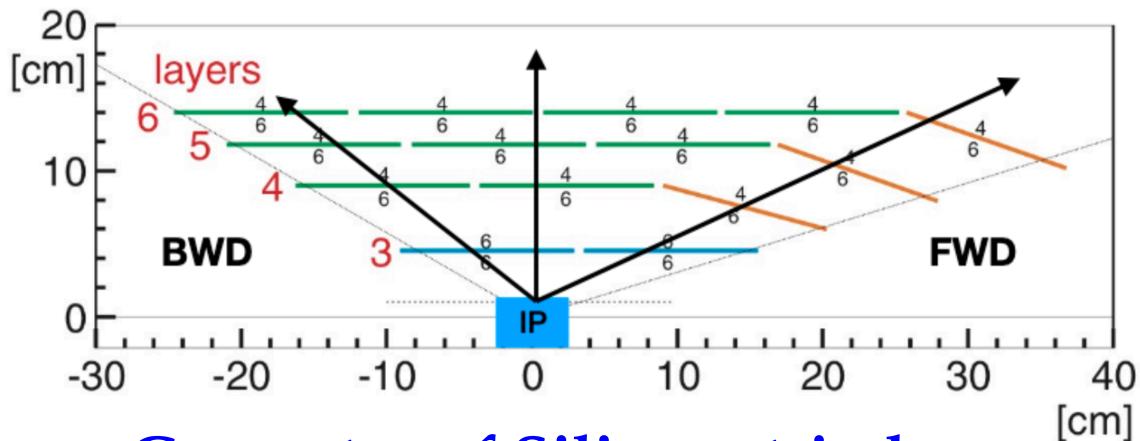


Result: 370± 40 fs
[PDG: 410 fs ✓]

More plots in other FPCP2020 talks form Belle II
→ Look for more updates by ICHEP2020

Vertexing

Current detector:
4 layers of Si strips
+ inner pixel layer



Geometry of Silicon strip layers

Detector performance: ~12 μm impact parameter resolution
~40 μm D^0 flight path resolution

→ *About twice as good as first B factories [pixels at small radius]*

4 Si strip layers	readout strip pitch: 50-75 μm & 160-240 μm
2 pixel layers	50 x (50-85) μm pixels

Charm Mixing

Belle II Final Reach*

Channel	Observable	Belle/BaBar Measurement $\mathcal{L}$ [ab^{-1}]	Value	Scaled 5 ab^{-1}	50 ab^{-1}
Mixing and Indirect (time-dependent) *CP* Violation					
$D^0 \to K^+\pi^-$	x'^2 (%)	0.976	0.009 ± 0.022	± 0.0075	± 0.0023
(no CPV)	y' (%)		0.46 ± 0.34	± 0.11	± 0.035
(CPV allowed)	$\lvert q/p \rvert$	World Avg. [230]	$0.89^{+0.08}_{-0.07}$	± 0.20	± 0.05
	ϕ ($^\circ$)	with LHCb	$-12.9^{+9.9}_{-8.7}$	$\pm 16^\circ$	$\pm 5.7^\circ$
$D^0 \to K^+\pi^-\pi^0$	x'' (%)	0.384	$2.61^{+0.57}_{-0.68} \pm 0.39$	-	± 0.080
	y'' (%)		$-0.06^{+0.55}_{-0.64} \pm 0.34$	-	± 0.070
$D^0 \to K^0_S\pi^+\pi^-$	x (%)	0.921	$0.56 \pm 0.19^{+0.04}_{-0.08}{}^{+0.06}_{-0.08}$	± 0.16	± 0.11
	y (%)		$0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.07}$	± 0.10	± 0.05
	$\lvert q/p \rvert$		$0.90^{+0.16}_{-0.15}{}^{+0.05}_{-0.04}{}^{+0.06}_{-0.05}$	± 0.12	± 0.07
	ϕ ($^\circ$)		$-6 \pm 11 \pm 3^{+3}_{-4}$	± 8	± 4

Other modes may be interesting for time-dependent analysis

$K_S \pi^+ \pi^- \pi^0$, …

* = Belle II Physics Book; PETP 2019, 123C01 (2019)

CP Asymmetries

CPV can be found in mixing, and also in direct asymmetries

Many modes exploit Belle II's excellent CsI calorimetry :

$D^0 \to K_S \pi^0$, $\pi^0 \pi^0$ $D^+ \to \pi^+ \pi^0$ $D_s^+ \to \pi^+ \pi^0$

and others: η & η′ modes, multi-body, …

Neutral D : need D^* tag ; small tag asymmetries to study

[easier than LHCb production asymmetry]

ALSO: T-odd triple products (four-body final states)

Use D Dbar difference to cancel final-state interaction mimicry

CP & Rare Decays

FCNC: Radiative Decays: $D^0 \to \rho\gamma$, $\phi\gamma$, $K^*\gamma$

Single photons = good modes for Belle II !

Measure CP asymmetries: reach is ±2%, ±1%, ±0.3%

FCNC: dileptons → daunting LHCb competition !

CP Asymmetries

Belle results and final Belle II precision*

	Mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II 50 ab^{-1}
	$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
	$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
*	$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
*	$D^0 \to K_S^0\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.02
	$D^0 \to K_S^0 K_S^0$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.23
*	$D^0 \to K_S^0 \eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
*	$D^0 \to K_S^0 \eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
*	$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
*	$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
	$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
	$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
*	$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	± 0.17
*	$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
*	$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
	$D^+ \to K_S^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.02
	$D^+ \to K_S^0 K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.04
	$D_s^+ \to K_S^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
	$D_s^+ \to K_S^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

* = Belle II Physics Book; PETP 2019, 123C01 (2019)

* = Best for Belle II (neutrals)

Leptonic and Semileptonic

PHYSICS: Precise decay constants & form factors

Test Lattice QCD $|V_{cd}|f_D$ $|V_{cs}|f_{Ds}$ $|V_{cd}|f^{\pi}(0)$ $|V_{cs}|f^{K}(0)$

Ratios also useful for various cancellation [CKM, uncertainties]

METHODS: various types of tagging (constrain kinematics)

1) *BESIII at threshold*: tagging; exclusive D D^{bar} production

2) *B factories:* Originally D^* tagging, pseudo-mass-difference
$\delta M = M(\pi_{slow}\, h\, l) - M(h\, l)$ [like usual ΔM; broader]

3) *B factories,* ***improved*** *:* "continuum tagging"
charm hadron tag + sets of fragmentation particles
First done by Belle for $D^0 \to \pi^- l^+ \nu$ PRL 97, 061804 (2006)
$D^{(*)}_{tag}\, X\, D^{*-}_{sig}$ where X is a set of fragmentation particles including { π^+, π^-, π^0 (K^+K^-) }

Leptonic $D^+_{(s)}$ Decays

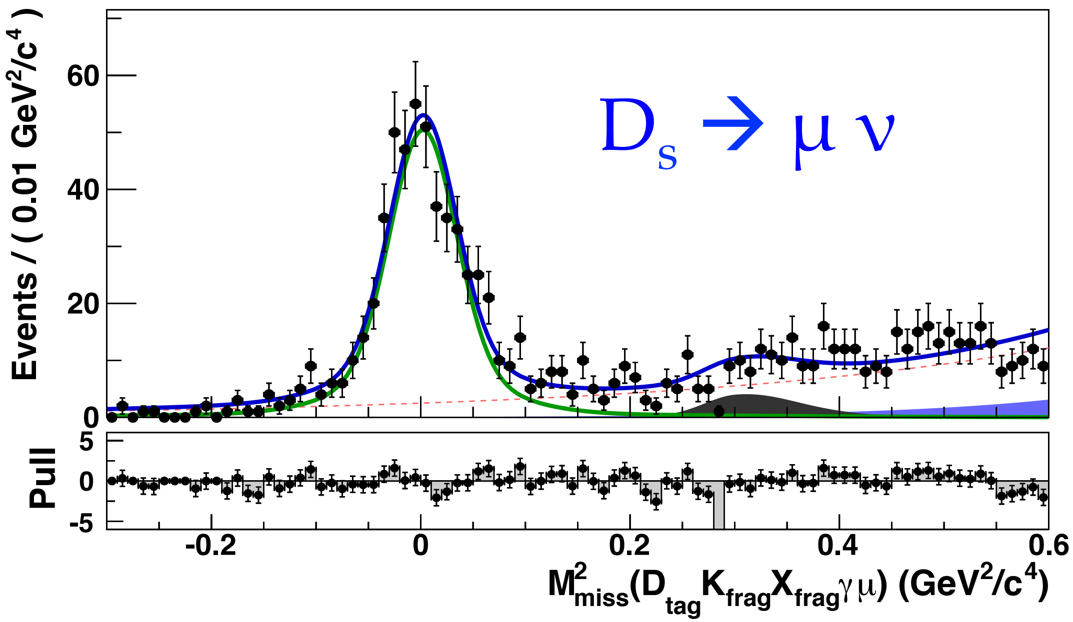
Continnum tagging at work in Belle for leptonic D_s decay

MC studies: also works well for Cabibbo-suppressed mode !

50 ab^{-1} : 27000 $D_s \rightarrow \mu\,\nu$ 1250 $D \rightarrow \mu\,\nu$

D_s : can try to trade statistics for better systematic control

D : 3% BF (stat. only) is 1.5 % on f_D [less than current BESIII]



Belle 0.9 ab^{-1} JHEP 1309, 139 (2013)

Belle result was systematics limited.

Belle II statistics will allow more precise syst. studies & using the best sub-sample of data

Spectroscopy and Baryons

Open Charm Mesons

-- $D^{(*)} n\pi$ systems in B decays [constrain quantum numbers]
-- Continuum

Charm Baryons

-- Searches for new states, new decay modes, …
-- CP Violation studies

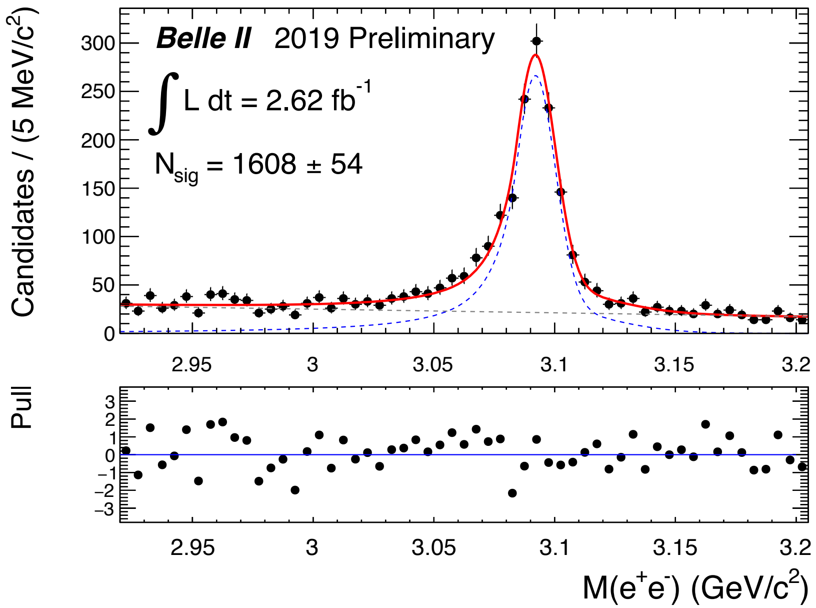
Weakly-decaying baryonic ground-states

Λ_c^+ Ξ_c^+ Ξ_c^0 Ω_c^0

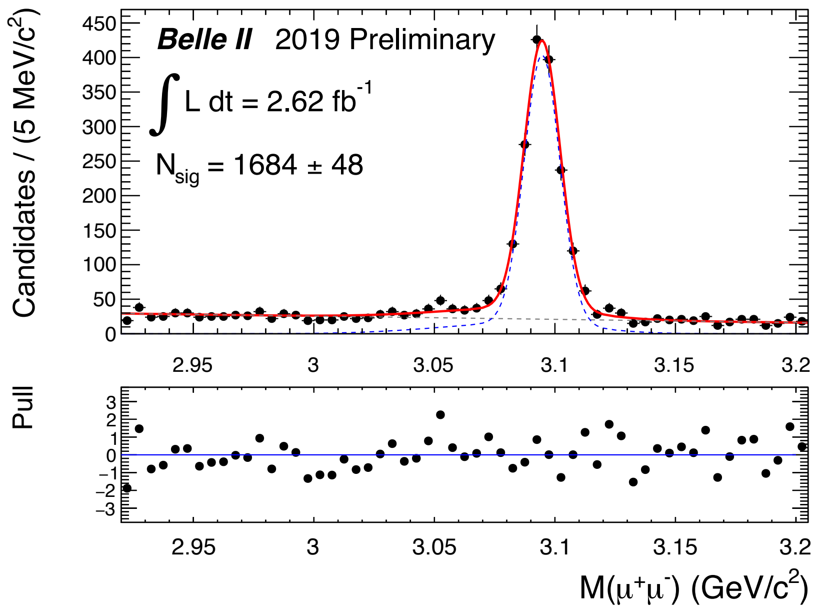
→ Absolute BFs of golden modes
→ Semileptonic BFs to make contact with theory
BESIII is taking Λ_c pair data at threshold data now
Can 50 ab^{-1} confirm, and also extend to the other states ?

Belle II Data: Charmonium

$J/\psi \rightarrow e^+ e^-$ in B-enhanced events



$J/\psi \rightarrow \mu^+ \mu^-$ in B-enhanced events



More plots in other FPCP2020 talks form Belle II

→ Look for more updates by ICHEP2020

Charmonium

Lowest-lying states mostly well-covered at BESIII
In B decays, we have constrained kinematics

Polarized X_{cc} in $B \rightarrow K\, X_{cc}$ can help with spin analysis

Searches for more conventional charmonium

Missing state: $\eta_{2c}(1D)$ $J^{PC} = 2^{-+}$: Search for in $B \rightarrow K\, (h_c\, \gamma)$
Also explore resonances in $B \rightarrow D^{(*)} D^{bar(*)} K^{(*)}$

Two-photon production has some nice features

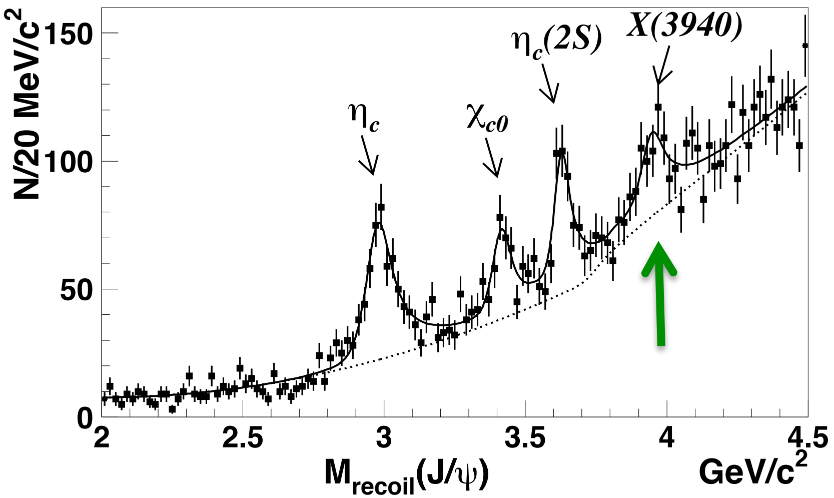
Also invisible J/ψ decays, further studies of known states, …

Double Charmonium

Belle: PRL 98 082001 (2007)

First observed by Belle
Studied via recoil mass spectrum

Interesting re: fragmentation itself
+ exotic state found in spectrum



X(3940) found in ee →J/ψ X via recoil mass against J/ψ

Thus far, all double charmonium is a J=1 vs. a J = 0 state

Is this some general "rule"?
Tests with recoil vs. other states will require high statistics
(hadronic decays of η_c , χ_{c0} are tougher than J/ψ dileptons !)

Exotic States: ISR

ISR is a "free energy scan"

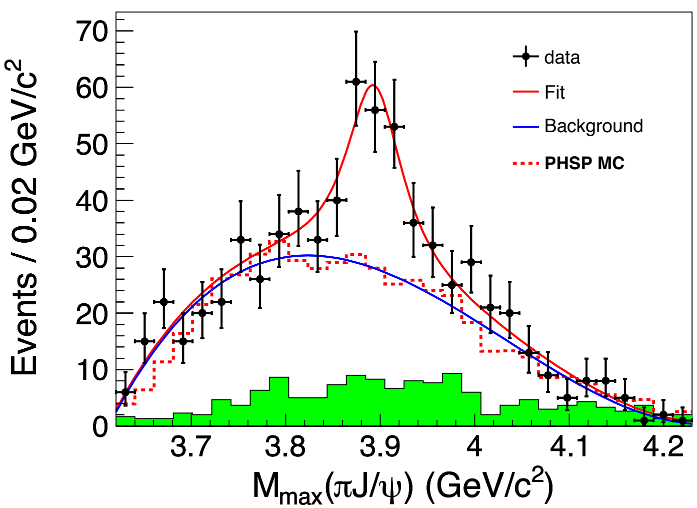
It requires high luminosity → 50 ab^{-1} is huge leap forward !

ISR *directly accesses* Y states with $J^{PC} = 1^{--}$

Y(4260), Y(4360), Y(4630), Y(4660)

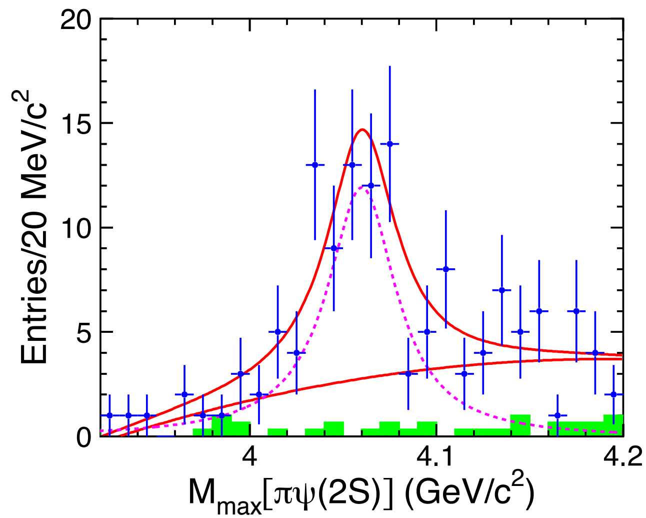
But also: Belle has seen Z states in Y *substructure*

Z(3900) in π J/ψ mass within Y(4260) → π π J/ψ



PRL 110, 252002 (2013)

Z(4020) in π ψ(2S) mass within Y(4360) → π π ψ(2S)



PRD 91, 112007 (2015)

Exotic States: B Decays

B → K X , K Z with X, Z → ππ J/ψ , ω J/ψ , φ J/ψ , γ J/ψ , γ ψ(2S) , D D*bar , π J/ψ , π ψ(2S) , π χ_{c1} , γ χ_{c1} , …

Very rich slate of final states

→ Good detection of γ and π^0 is important for many transitions

→ May also find states with η, η′ , other charmonia, …

Some History:

Belle's 2003 X(3872) discovery

PRL 91, 262001 (2003)

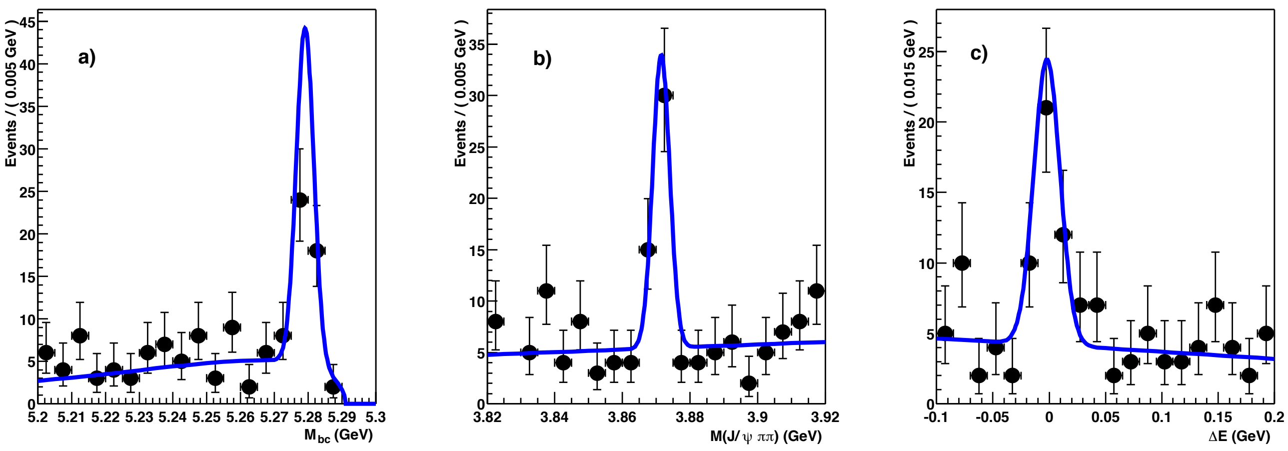


FIG. 2: Signal-band projections of **(a)** $M_{\rm bc}$, **(b)** $M_{\pi^+\pi^- J/\psi}$ and **(c)** ΔE for the $X(3872) \to \pi^+\pi^- J/\psi$ signal region with the results of the unbinned fit superimposed.

SUMMARY

Very good start to data-taking
Smooth operation and rapid improvements

Broad program complements existing experiments
High statistics; good performance for neutrals

Long Program Ahead
Intermediate datasets will be large & very exciting
(some interesting Belle results aren’t full stats)

BACKUP

More tables from the Belle II Physics Book
[PETP 2019, 123C01 (2019)]

Channel	Observable	Belle/BaBar Measurement		Scaled	
		$\mathcal{L}$ [ab^{-1}]	Value	5 ab^{-1}	50 ab^{-1}
Leptonic Decays					
$D_s^+ \to \ell^+\nu$	μ^+ events	0.913	492 ± 26	2.7k	27k
	τ^+ events		2217 ± 83	12.1k	121k
	f_{D_s}		2.5%	1.1%	0.34%
$D^+ \to \ell^+\nu$	μ^+ events	-	-	125	1250
	f_D	-	-	6.4%	2.0%
Rare and Radiative Decays					
$D^0 \to \rho^0\gamma$	A_{CP}	0.943	$+0.056 \pm 0.152 \pm 0.006$	± 0.07	± 0.02
$D^0 \to \phi\gamma$	A_{CP}		$-0.094 \pm 0.066 \pm 0.001$	± 0.03	± 0.01
$D^0 \to \overline{K}^{*0}\gamma$	A_{CP}		$-0.003 \pm 0.020 \pm 0.000$	± 0.01	± 0.003