# Charm and XYZ Prospects at Belle II

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*for the Belle II Collaboration*

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# Outline

## Introduction: Belle II & Super KEKB

## Charm

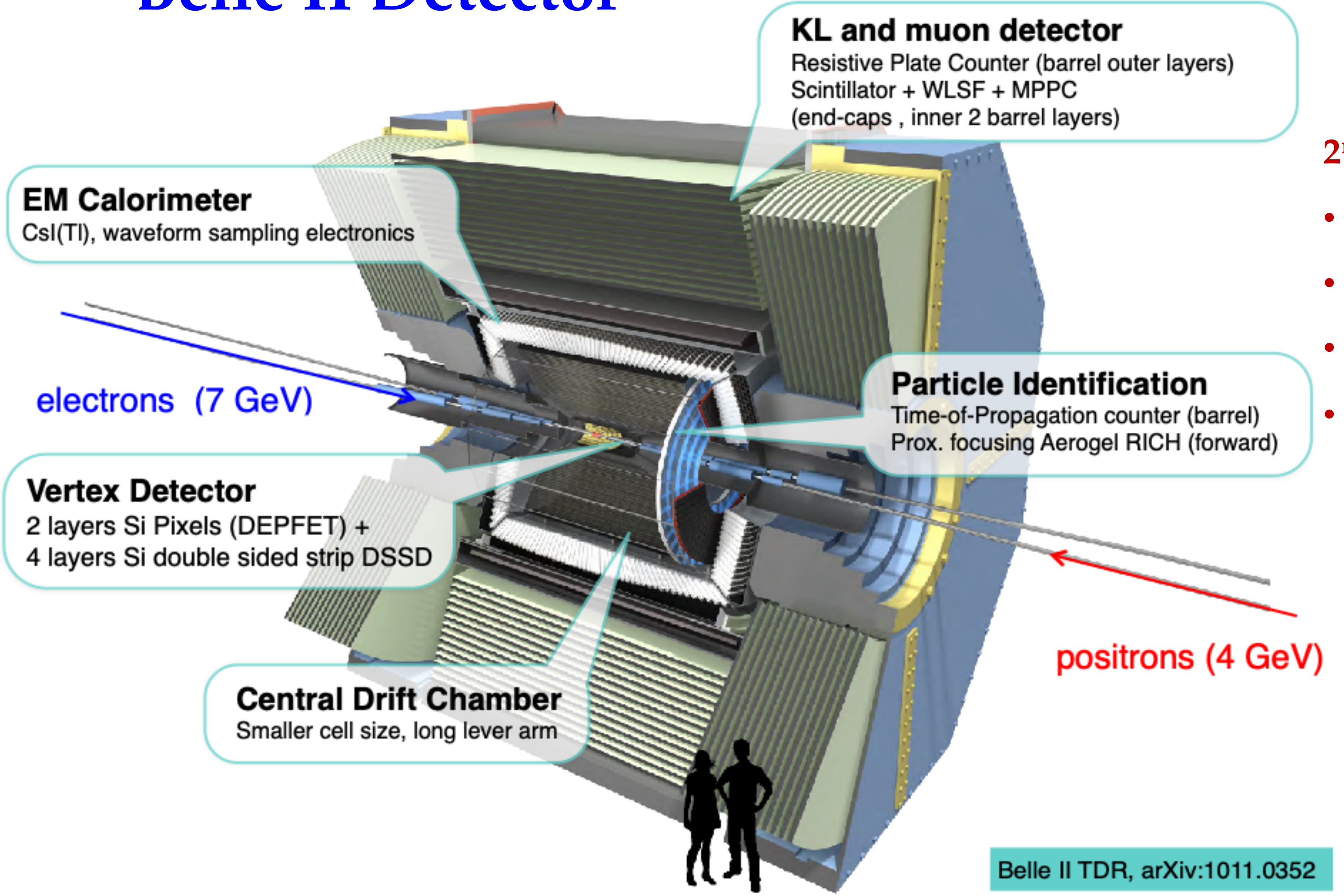
- Overview
- CP Violating Asymmetries
- Lifetimes and Mixing
- (Semi)leptonics
- Spectroscopy & Baryons

## XYZ

- Overview
- Double charmonia, ISR, B decays

## Conclusions

# Belle II Detector



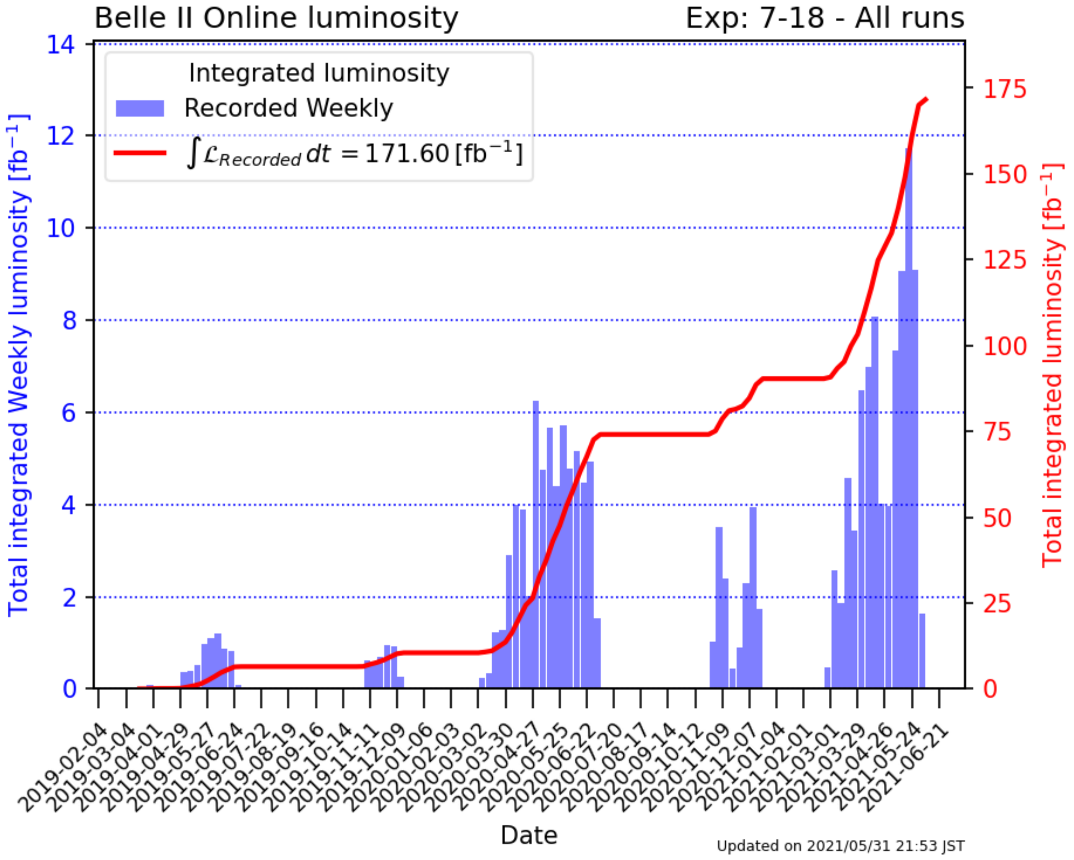

**2nd Generation B-Factory Detector**

- High-luminosity performance
- Much improved vertexing
- Novel Cherenkov PID (TOP)
- Other upgrades…

# Belle II & Super KEK-B Overview

## Our Goal: 50 ab$^{-1}$ dataset [ > 50x Belle ! ]

- The only second-generation $e^+e^-$ B factory
- Current total dataset of >170 fb$^{-1}$
- Running schedule maintained during COVID-19




## Detector

- All components working well
- Shutdown in 2022 to install rest of 2$^{nd}$ inner pixel layer

## Accelerator

- "Nanobeams": aggressive vertical focusing
- Holds ***world luminosity record***: $\mathcal{L}_{peak} \sim 2.9 \times 10^{34}\ /\mathrm{cm}^2/\mathrm{s}$ [ took lead @ $2.4 \times 10^{34}$ in June 2020 ]
  ( and now also has the best integrated day & week for a B factory… )
- Still much more work to get to design goal: $\mathcal{L}_{peak} = 6.5 \times 10^{35}\ /\mathrm{cm}^2/\mathrm{s}$
  → Beam currents now limited: occasional "dust events"; background mitigation work

# Charm

**For Projections:** **Belle II Physics Book**
Prog. Th. Exp. Phys. 2019, 1232C01**; 2020, 029201(E)** [arXiv 1808.10567 ]
Extensive work by Belle II Collaboration & Theorists
*Roadmap for physics with projections, comparisons, …*

# 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 $\pi^0$ & single $\gamma$; recent $B_{(s)}$ semileptonic (!)

**Belle II: can generally cover *all* of the above topics**

LHCb stats are often 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 $\Lambda_c$

nb x $ab^{-1} = 10^9$ → **10-30 billion of each produced in final samples**

**XYZ Exotics** from B decays, ISR, two-photon

# Physics Context

## Precision Studies of tree-level processes :

Over-constrain the CKM matrix

- (Semi-)leptonic - use/test LQCD via decay constants, form factors

Search for anomalous CP Violation

- Direct CP asymmetries : especially SCS decays **[ SCS = Singly Cabibbo Suppressed]**
- T-odd triple products

## Suppressed decays (loops) :

FCNC : Radiative modes, di-leptons **[ FCNC = Flavor-Changing Neutral Currents ]**

## Forbidden decays :

Lepton flavor violation, …

## Exotic States and Spectroscopy

# Belle II & Charm

## Continuum Production

- $e^+e^- \rightarrow c\bar{c}$ : fragmentation…

## Charm from B decays: de-emphasize today

- Good for $J^P$ studies, more constraints…

## Strengths of charm @ $\Upsilon$(4S) :

- $\pi^0$ reconstruction
- $\nu$ reconstruction [ "continuum tagging": find other charm $\oplus$ fragmentation ]
- Kinematics constraints, cleaner events

## Middle ground between LHCb and BESIII

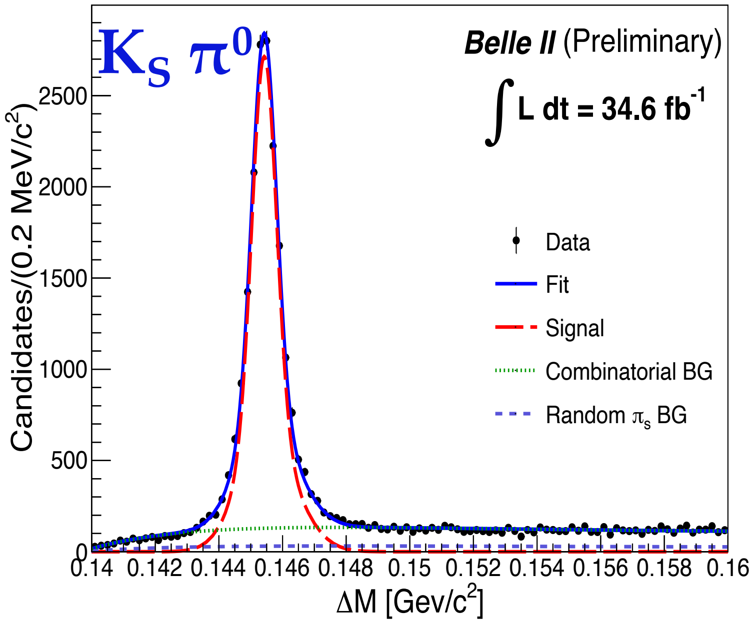
- Lower cross-sections, but simpler events than LHCb
- Not quite as clean as BESIII at threshold, but much higher statistics

## Silicon improved vs. first-generation B factories

## 7 Weakly-decaying ground states: $D^0$ $D^+$ $D_s^+$ $\Lambda_c^+$ $\Xi_c^+$ $\Xi_c^0$ $\Omega_c^0$

- Rich set of decays: Search for CP violation & new physics Map out lifetimes, $D^0$ mixing, …

# Selected Mass Peaks: $D^0$

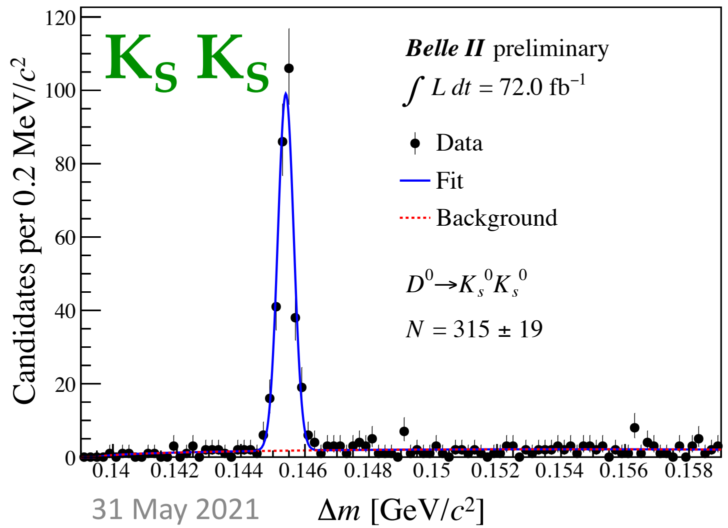


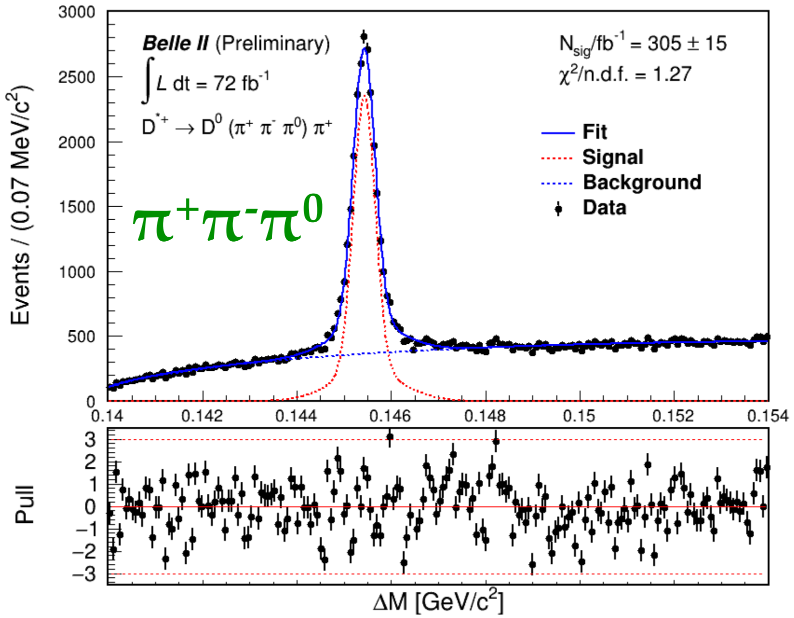

**All analyses here are $D^{*+}$ (flavor) tagged; plots show the $D^*$-D mass differences:**

$$\Delta m = M(D^0\,\pi^+) - M(D^0)$$

where "$D^0$" is the candidate $D^0$ decay

**SCS (Singly-Cabibbo-Suppressed) modes are of interest for CPV studies**



# CP Asymmetries

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

Many modes exploit Belle II's excellent CsI calorimetry :

$D^0 \rightarrow K_S \pi^0 , \pi^0 \pi^0$ $\quad D^+ \rightarrow \pi^+ \pi^0$ $\quad D_s^+ \rightarrow \pi^+ \pi^0$

and others: $\eta$ & $\eta'$ modes, multi-body, …

Neutral D : need $D^*$ tag ; small tag and $\gamma$–Z asymmetries to study

[ easier than larger 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: $D^0 \rightarrow \rho\gamma , \phi\gamma , K^*\gamma$

Single photons = good modes for Belle II !

*Also measure CP asymmetries: reach is ±2% , ±1% , ±0.3%*

FCNC: dileptons → daunting LHCb competition !

# CP Asymmetries

## Belle results and final Belle II precision†

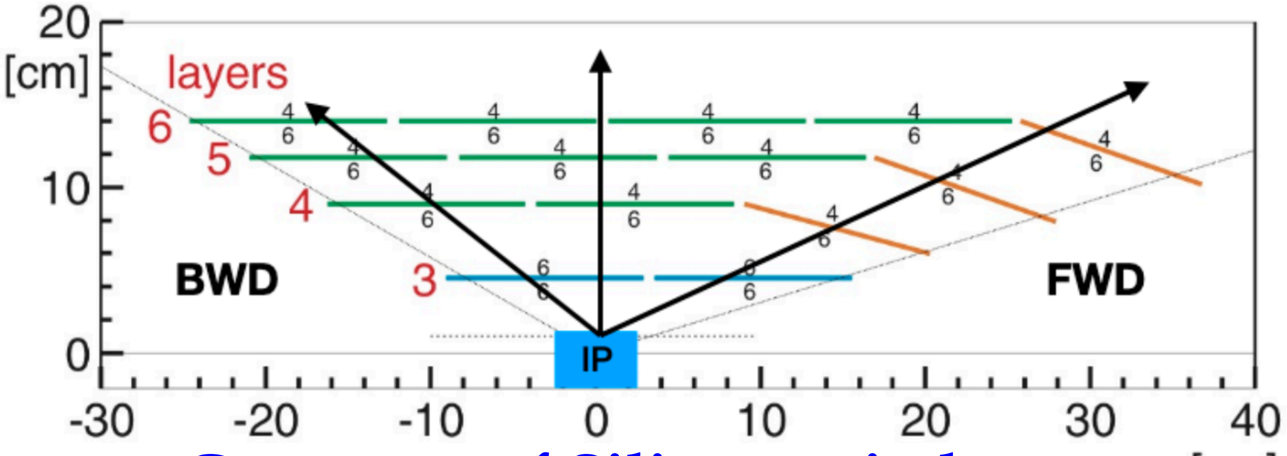
| | Mode | $\mathcal{L}$ (fb$^{-1}$) | $A_{CP}$ (%) | Belle II 50 ab$^{-1}$ |
|---|---|---|---|---|
| | $D^0 \to K^+K^-$ | 976 | $-0.32 \pm 0.21 \pm 0.09$ | $\pm 0.03$ |
| | $D^0 \to \pi^+\pi^-$ | 976 | $+0.55 \pm 0.36 \pm 0.09$ | $\pm 0.05$ |
| * | $D^0 \to \pi^0\pi^0$ | 966 | $-0.03 \pm 0.64 \pm 0.10$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

- * = Best for Belle II (neutrals)

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

# Vertexing

**Current detector:**
4 layers of Si strips
1+ inner pixel layer
[ 1+ = 1 layer + 1 extra ladder ]




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! ]*

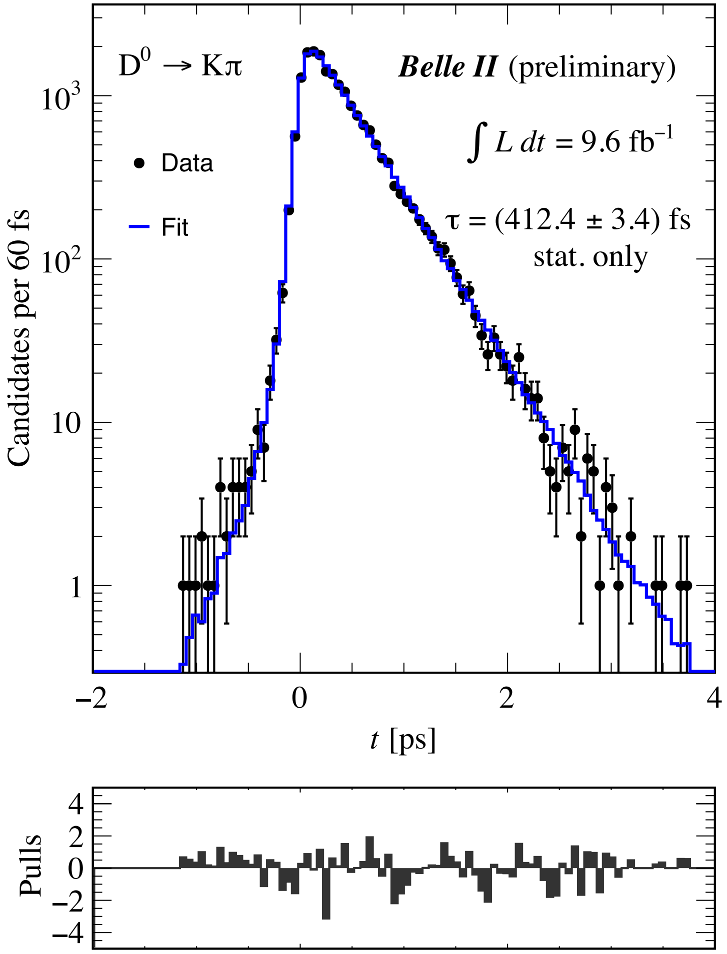
4 Si strip layers readout strip pitch: 50-75 μm & 160-240 μm
2 pixel layers 50 x (50-85) μm pixels

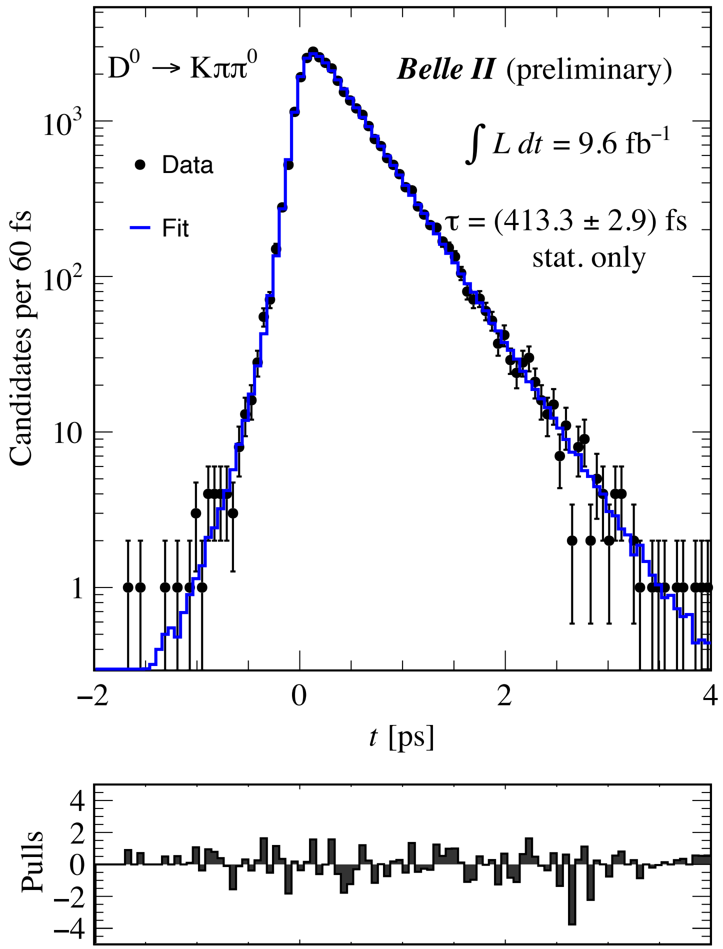
# Charm Lifetimes: $D^0$ as an example

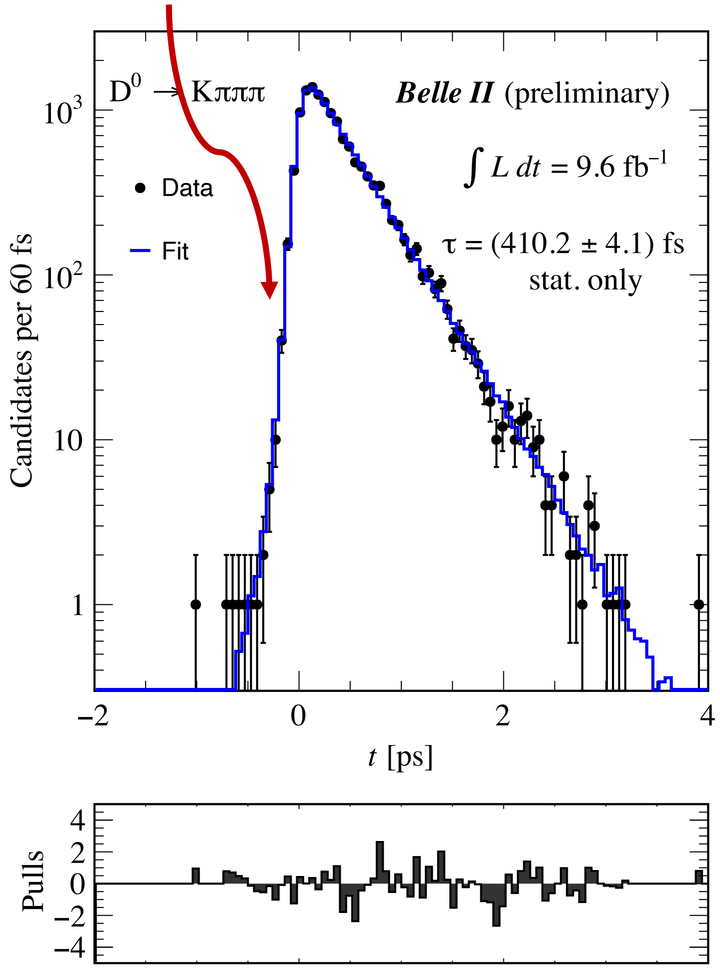
Best single result (by far) FOCUS 2002: $\tau_{D^0} = (409.6 \pm 1.1 \pm 1.5)$ fs

Statistics will not be an issue @ Belle II !

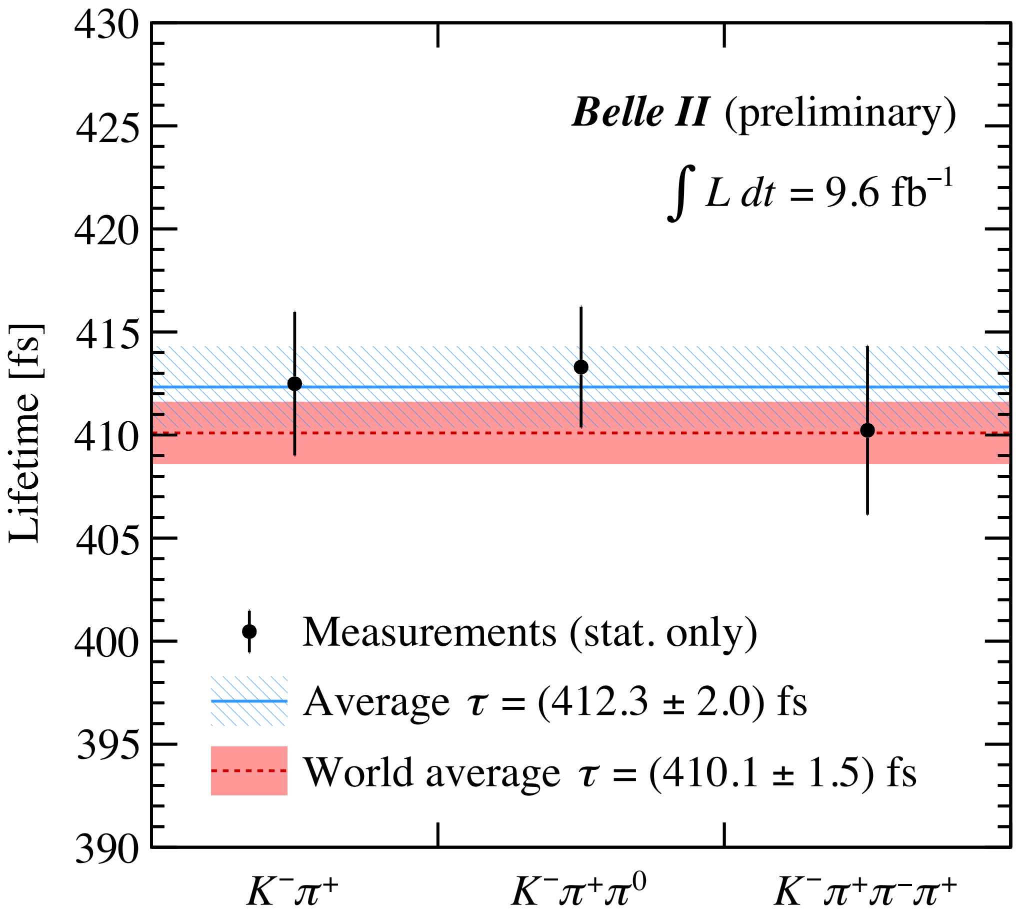
*Beautiful resolution !*



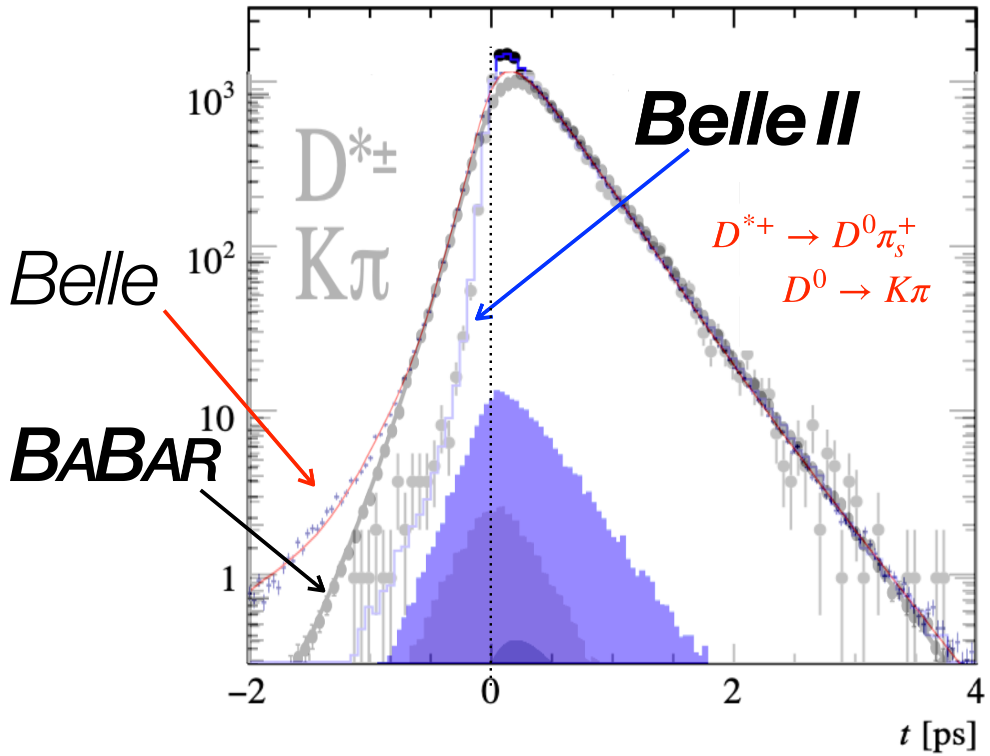



# Charm Lifetimes: $D^0$ as an example



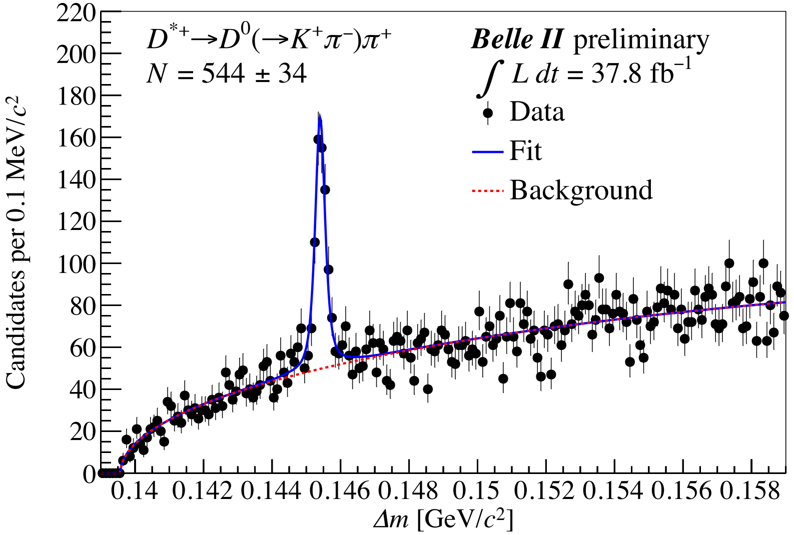

- resolution improvement visible at $t < 0$:

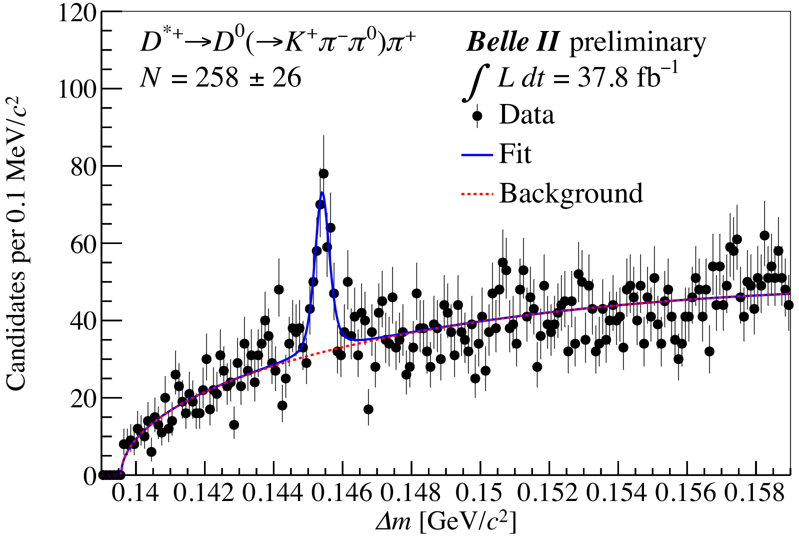


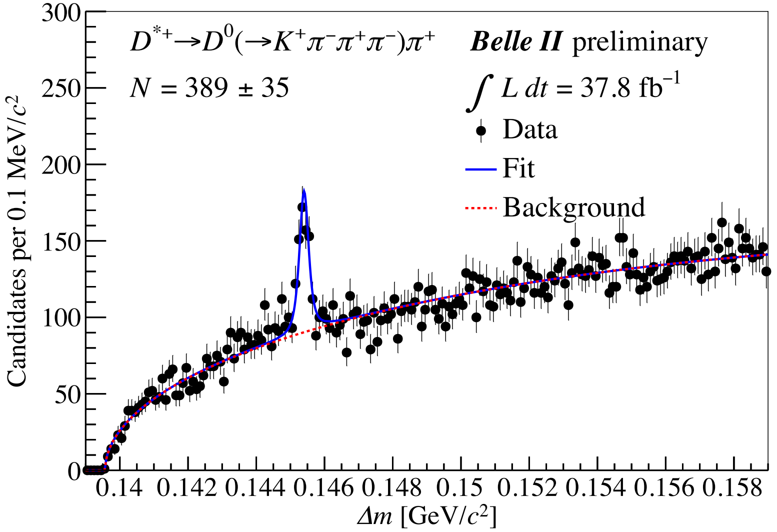

Plot from G. Casarosa, ICHEP2020

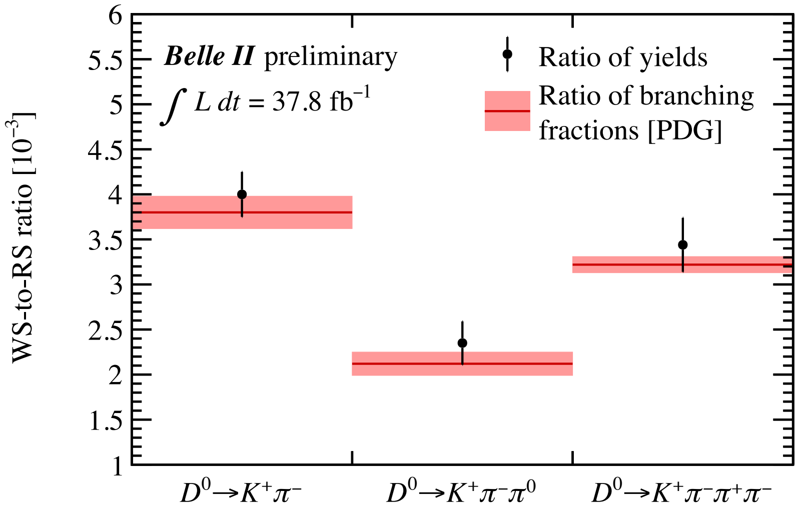
Charm lifetimes were dominated by FOCUS for years; lately LHCb is taking over…

# From Wrong-Sign Decay to Mixing




**Look at three popular $D^0$ modes**

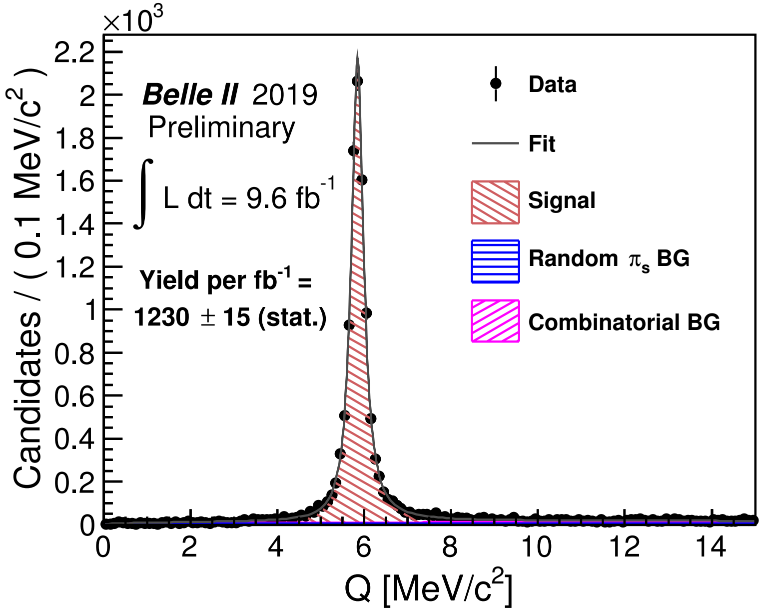
- Good agreement with PDG for integrated wrong-sign rates

(Belle II preliminary: yield ratios w/o efficiency, for now…)

**Time-dependent analyses next:**

- Leverage excellent vertex detector
- Separate DCSD and mixing parts of wrong-sign rates

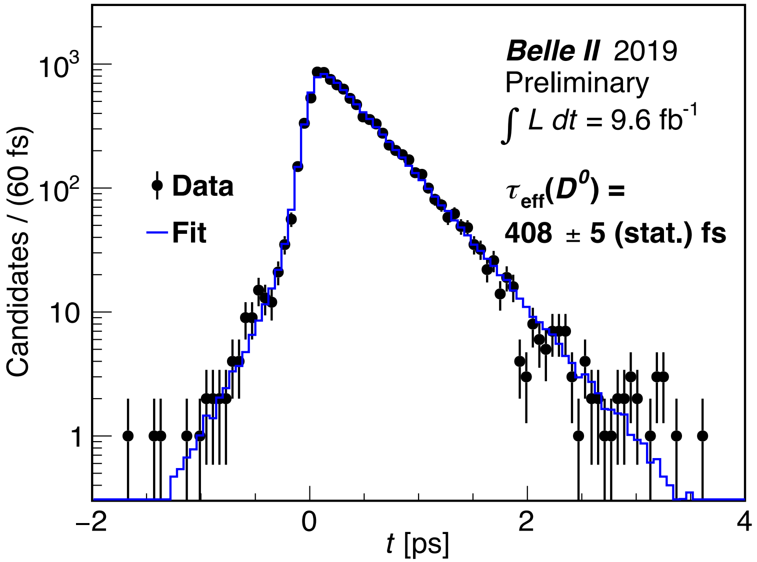
# $D^0 \rightarrow K_S \pi^+ \pi^-$




**2x better resolution than Belle**

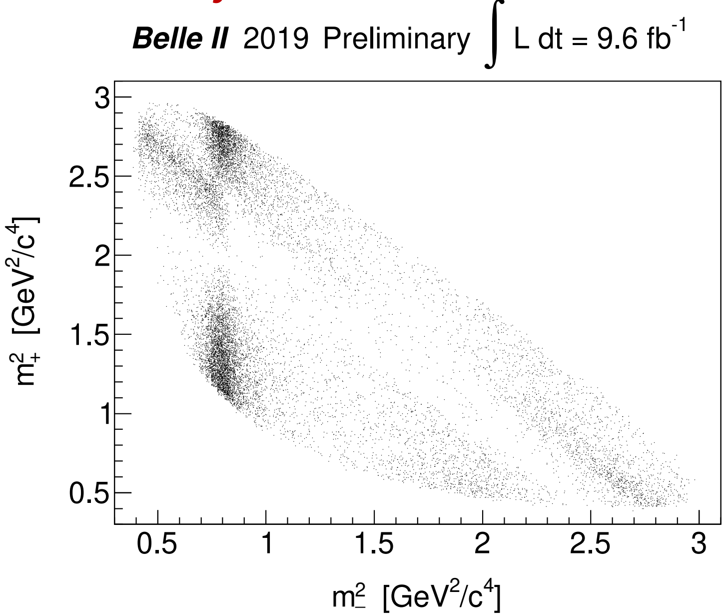
**Direct access to x** ( vs. $x^2$ with K nπ )

**x, y without strong phase rotation*** ( e.g., x′, y′ issue of Kπ )




**Precise time-dependence:**
**→ access to mixing, CPV**

**Eventually: a time-dependent analysis of the Dalitz Plot**




*there are strong phases entering; (c.f. related analysis in B physics for CKM γ angle);
but we have measured inputs from BESIII …

# Charm Mixing

## Belle II Final Reach*

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

**Other modes may be interesting for time-dependent analysis**

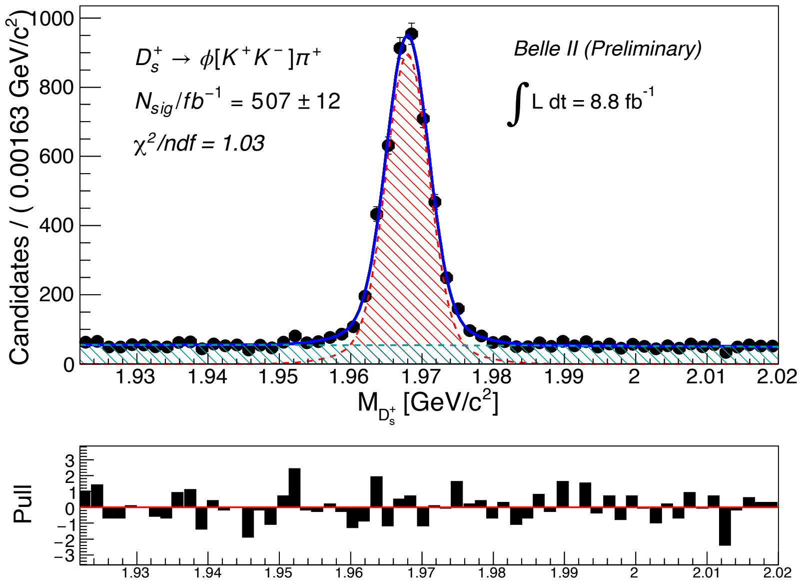
$K_S\,\pi^+\,\pi^-\,\pi^0$ , …

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

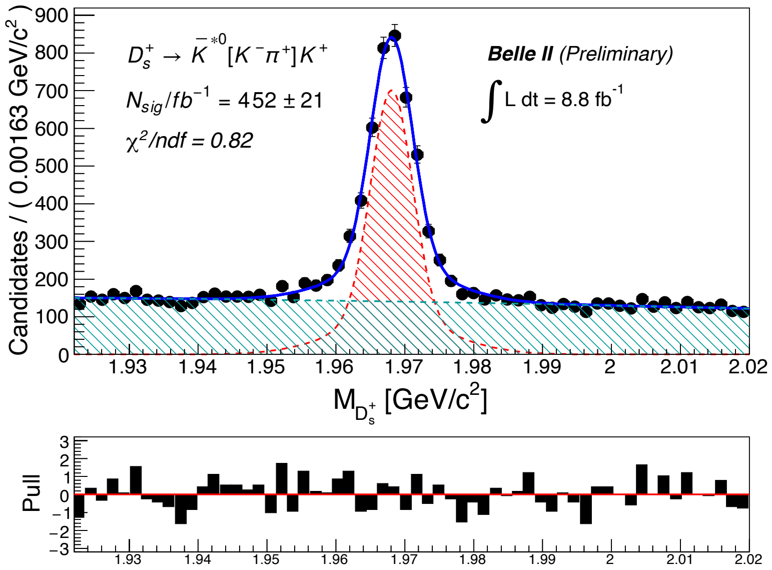
# Selected Mass Peaks: $D_s$ & $\Lambda_c$

## *Golden Modes*

$D_s \rightarrow \phi\,\pi \rightarrow K\,K\,\pi$

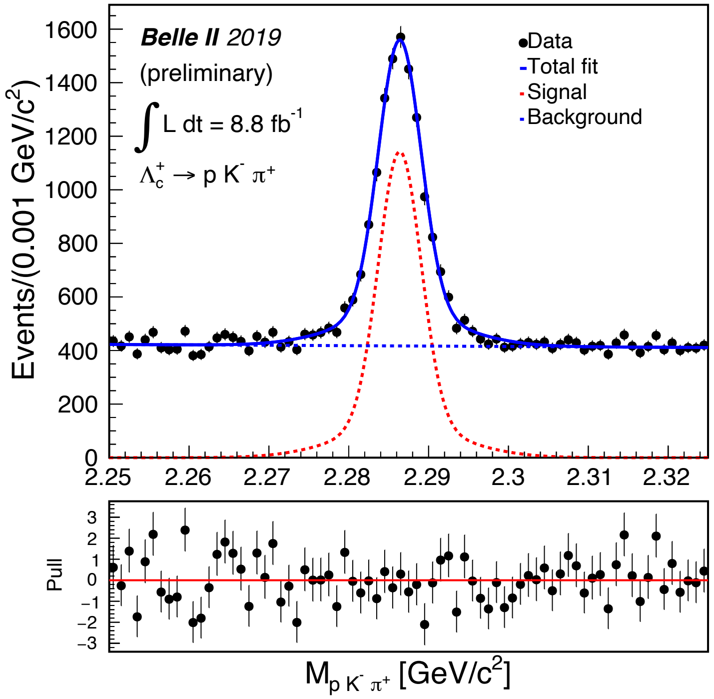



$D_s \rightarrow K^*K \rightarrow K\,K\,\pi$




## *Golden Mode*

$\Lambda_c \rightarrow pK\pi$



# 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 cancellations [ 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 $\Delta M$; but no $\nu$ so broader ]

3) *B factories, **improved**:* "continuum tagging"

charm hadron tag + sets of fragmentation particles

**First done by Belle for $D^0 \rightarrow \pi^- l^+ \nu$ PRL 97, 061804 (2006)**

$D^{(*)}_{tag}\, X\, D^{*-}_{sig}$ where X is a set of fragmentation particles including { $\pi^+, \pi^-, \pi^0$ ($K^+K^-$) }

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

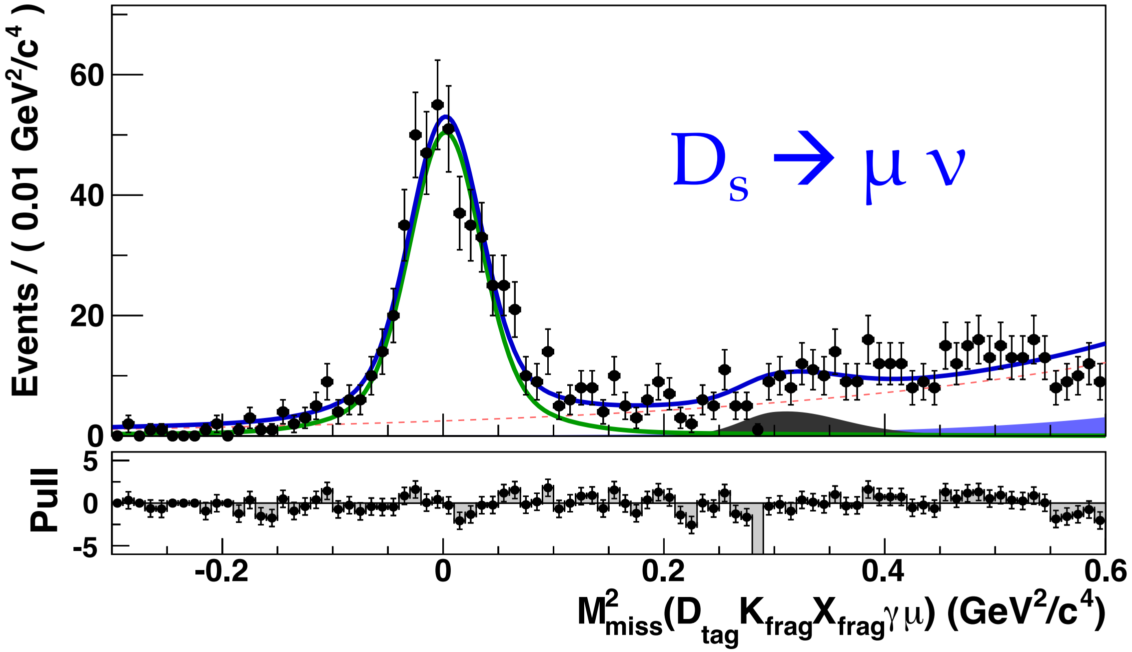
**Continuum tagging at work in Belle for leptonic $D_s$ decay**

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

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

$D_s$ : can try to trade statistics for better systematic control

D : 3% BF (stat. only) is 1.5 % on $f_D$ [ better than current BESIII; only chance to verify? ]




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 $\Lambda_c^+$ $\Xi_c^+$ $\Xi_c^0$ $\Omega_c^0$

- Absolute BFs of golden modes
- Semileptonic BFs to make contact with theory
- Lifetimes

BESIII recently took $\Lambda_c$ pair data at threshold

LHCb also very active

*What will the huge leap to 50 ab$^{-1}$ @Belle II yield ?*

# XYZ States

# User's Guide to X Y Z States

- **Y** (= ψ) $J^{PC} = 1^{--}$ via ISR production @ Belle II [ directly produced via $e^+e^- \rightarrow \psi$ @ BESIII ]
- **Z** $B \rightarrow K Z$ $Y \rightarrow \pi Z$ ; $Z \rightarrow \pi \psi$
- **X** $B \rightarrow K X$ $e^+e^- \rightarrow e^+e^- X$ [ some now classified as $\chi_{cJ}(nP)$ states ]

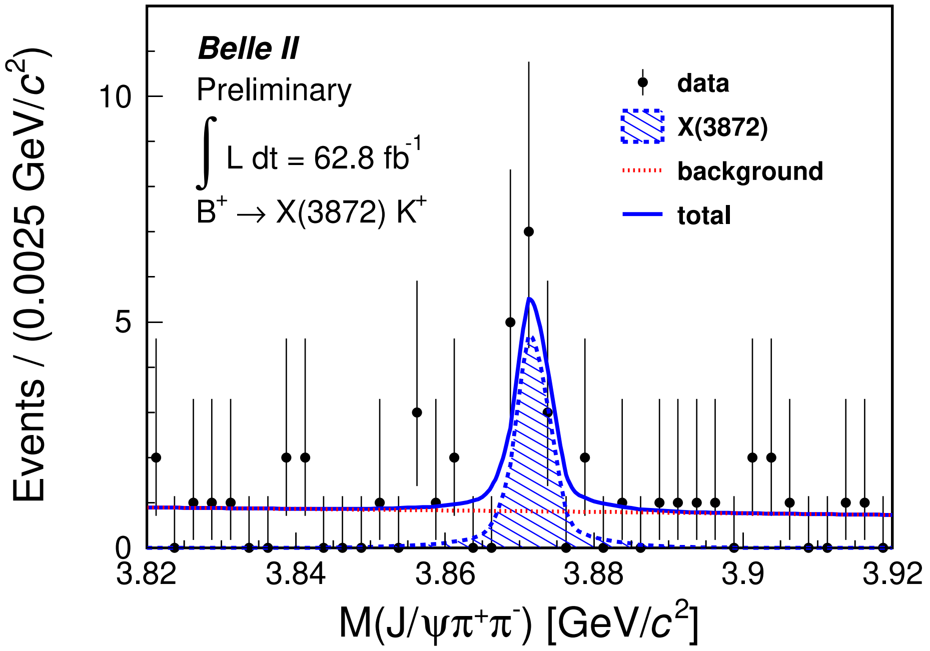
## Issues / Tasks:

- Confirmation of some states
- Spin-parity ($J^P$) determination
- New decays & production modes
- Are some pairs of observations the same state?
- New states !

## Competition

- BESIII: > 0.5 $fb^{-1}$ at 19 $E_{cm}$ points ∈ [4.178, 4.600] GeV
- All-charged final states very doable at hadron machines!

**Belle II**
**X(3872) Re-discovery**

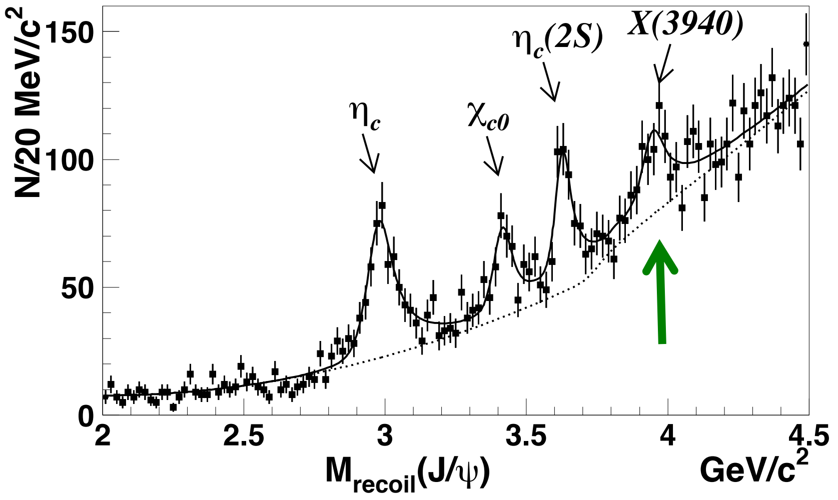


# Double Charmonium

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 → $J/\psi$ X via recoil mass against $J/\psi$**

**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 $\eta_c$ , $\chi_{c0}$ are tougher than $J/\psi$ dileptons ! )

# Exotic States: ISR

**ISR is a “free energy scan”**

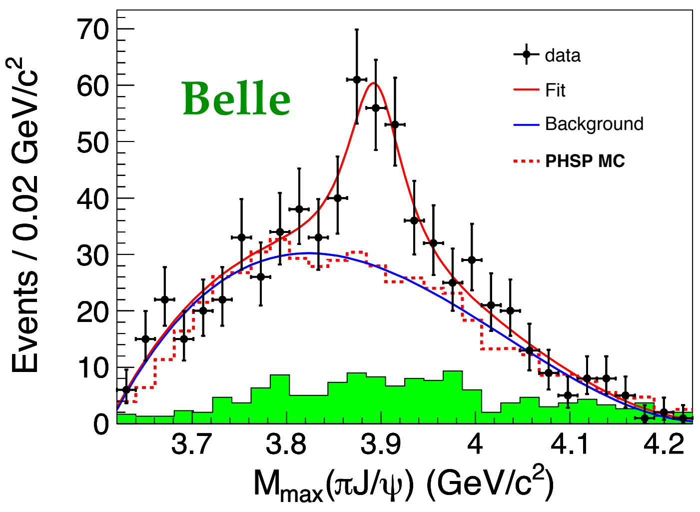
It requires high luminosity → 50 $ab^{-1}$ is huge leap forward !

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

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

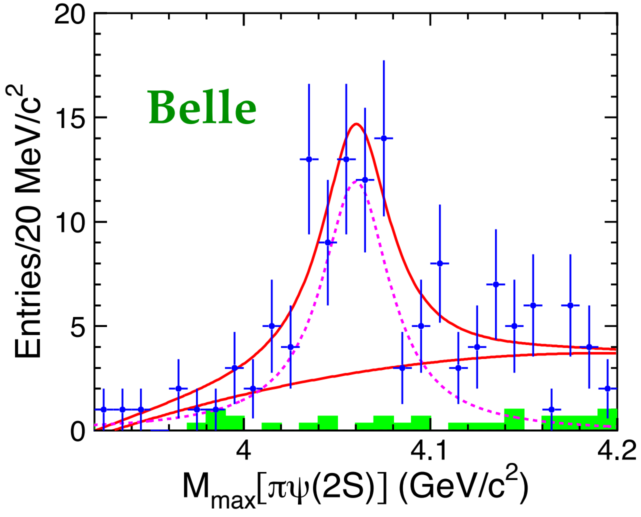
But also: Belle has seen Z states in Y *substructure*

**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 $\chi_{c1}$ , γ $\chi_{c1}$ , …

## Very rich slate of final states

- Good detection of γ and $\pi^0$ 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)

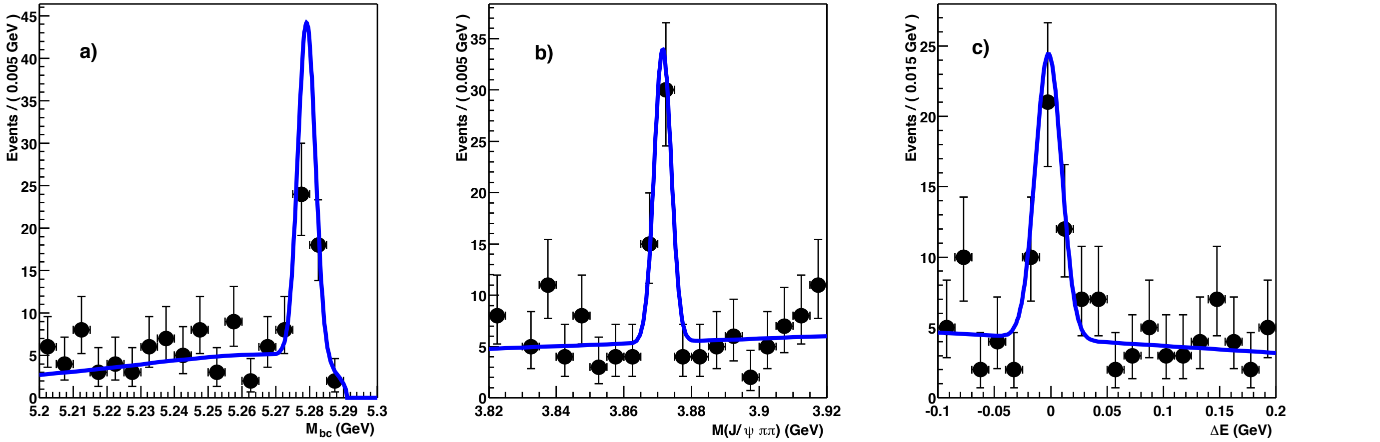



FIG. 2: Signal-band projections of **(a)** $M_{\rm bc}$, **(b)** $M_{\pi^+\pi^- J/\psi}$ and **(c)** $\Delta E$ for the $X(3872) \to \pi^+\pi^- J/\psi$ signal region with the results of the unbinned fit superimposed.

# Conclusions

**We're at the beginning of a long & broad program of Charm & XYZ physics**

*Many opportunities for world-leading analyses*

*Other places to confirm results with independent systematics*

**Charm is an important piece of the flavor physics puzzle…**

**Preliminary results display the foundations we will build upon**

***The legacy of Belle (and BaBar) inspires us;***
***& LHCb and BESIII will push us on as well***

Stay tuned for more on these topics, as well as the rest of our physics program!

# BACKUP

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

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