Belle II

Fighting ~~Systematics~~ *all-out* in Charm CPV at Belle II

Youngjoon Kwon
Yonsei University

Beauty2019, Sep.30-Oct.4, Ljubljana, Slovenia

Outline

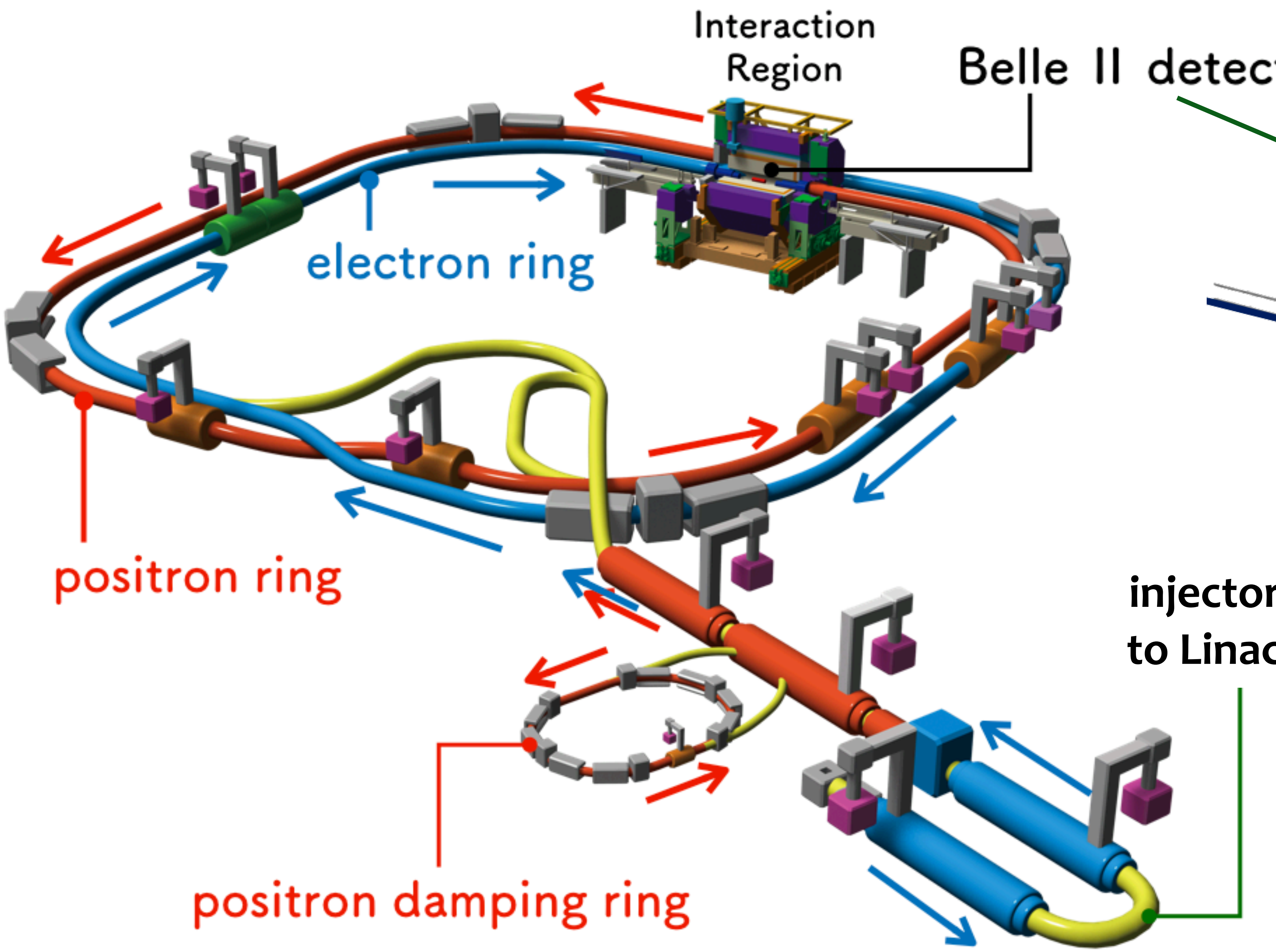
- *I will write something …*
- *BTW, this is a very preliminary version of the slides; no polishing of styles, etc.*

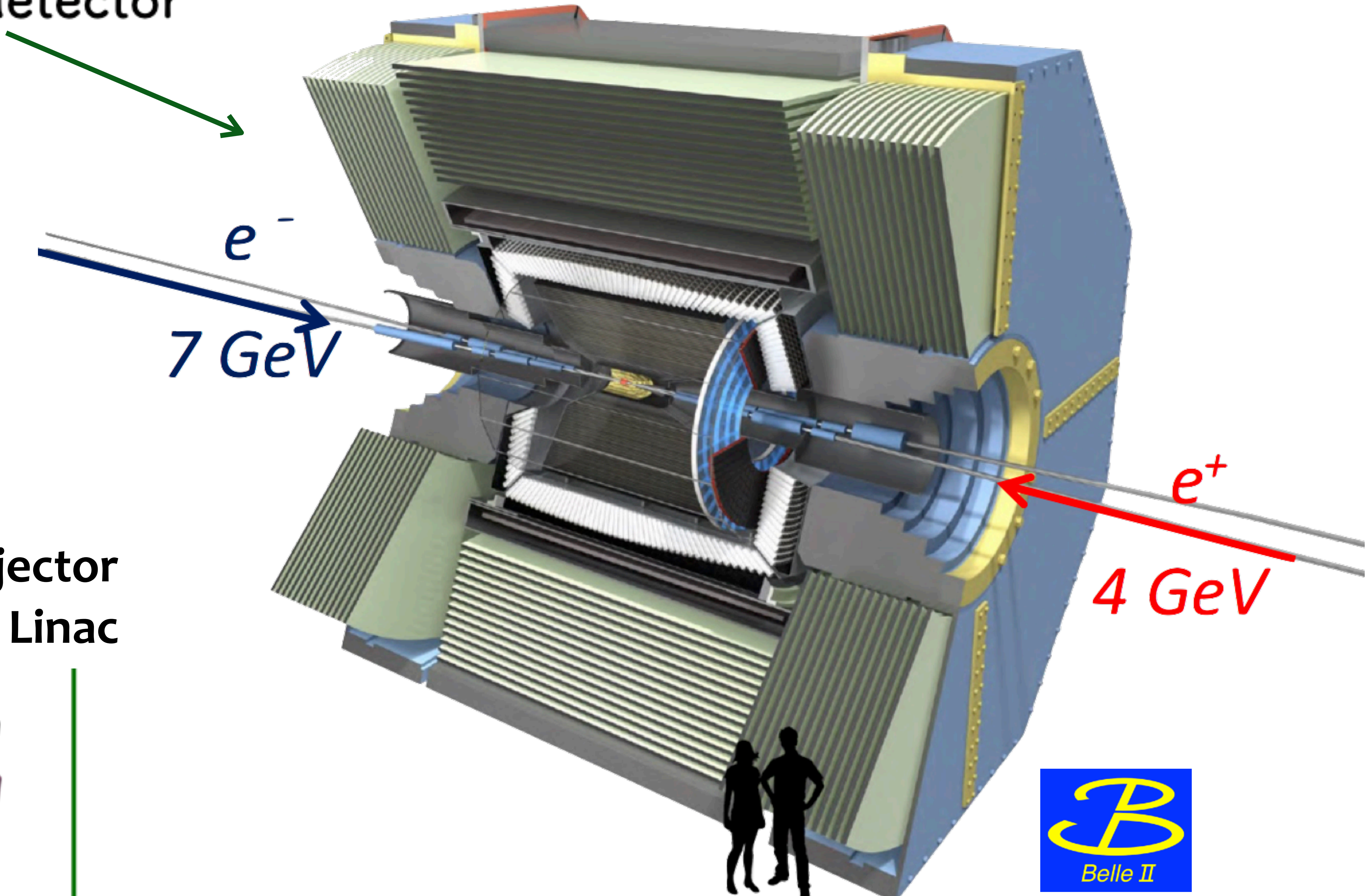
Charm machines, old & new

Experiment	Year	$\sqrt{s}$	$\sigma_{acc}(D^0)$	L	$n(D^0)$
CLEO-c	2003-2008	3.77 GeV	8 nb	$0.5\ \text{fb}^{-1}$	4.0×10^6
BESIII	2010-2011	3.77 GeV	8 nb	$3\ \text{fb}^{-1}$	2.4×10^7
BaBar	1999-2008	10.6 GeV	1.45 nb	$500\ \text{fb}^{-1}$	7.3×10^8
Belle	1999-2010	$10.6 - 10.9$ GeV	1.45 nb	$1000\ \text{fb}^{-1}$	1.5×10^9
CDF	2001-2011	2 TeV	$13\ \mu$b	$10\ \text{fb}^{-1}$	1.3×10^{11}
LHCb	2011	7 TeV	1.4 mb	$1\ \text{fb}^{-1}$	1.4×10^{12}
LHCb	2012	8 TeV	1.6 mb*	$2\ \text{fb}^{-1}$	3.2×10^{12}
Belle II	**2019-202***			**50 ab^{-1}**	

SuperKEKB

Belle II





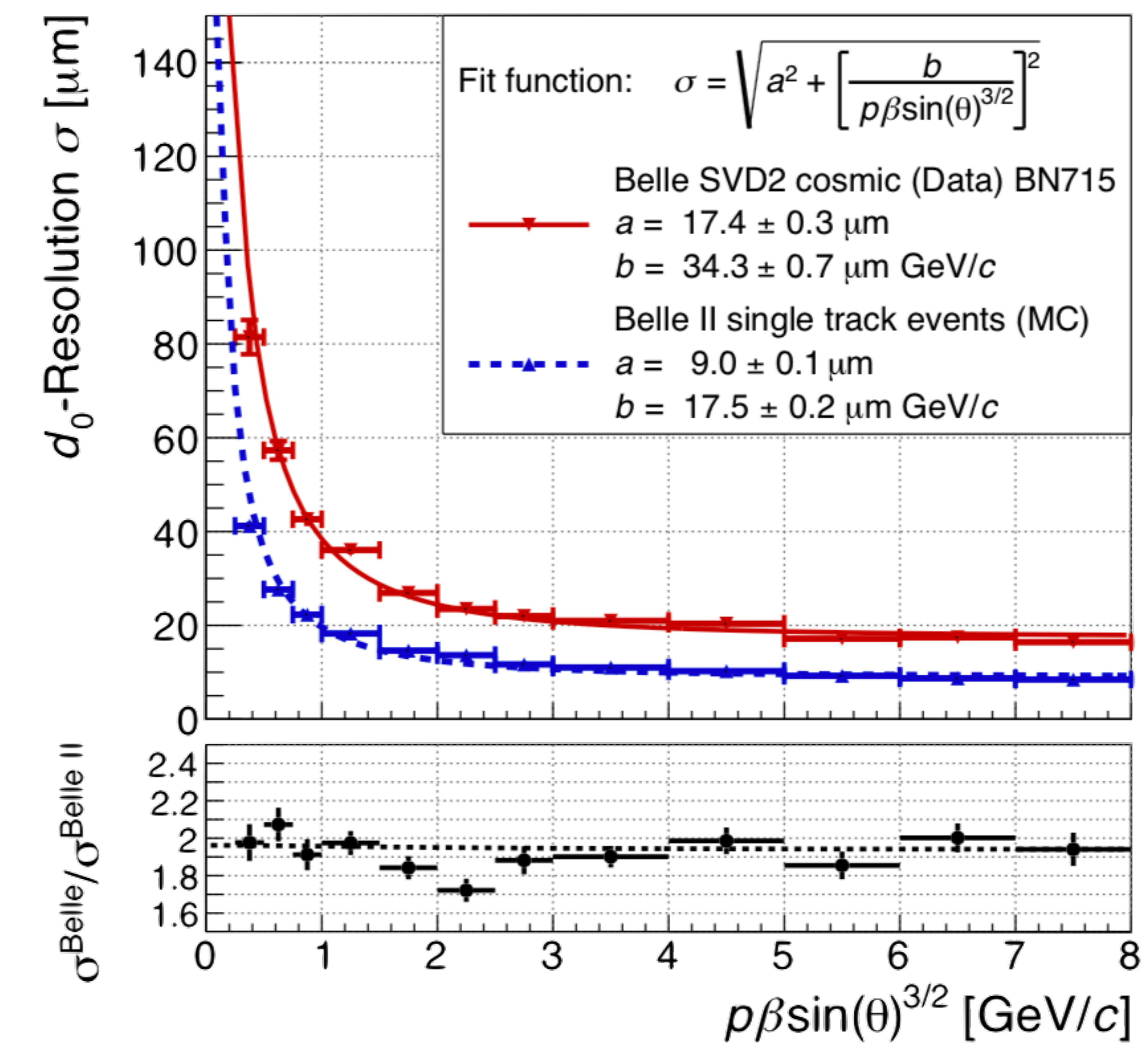
$$e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+$$

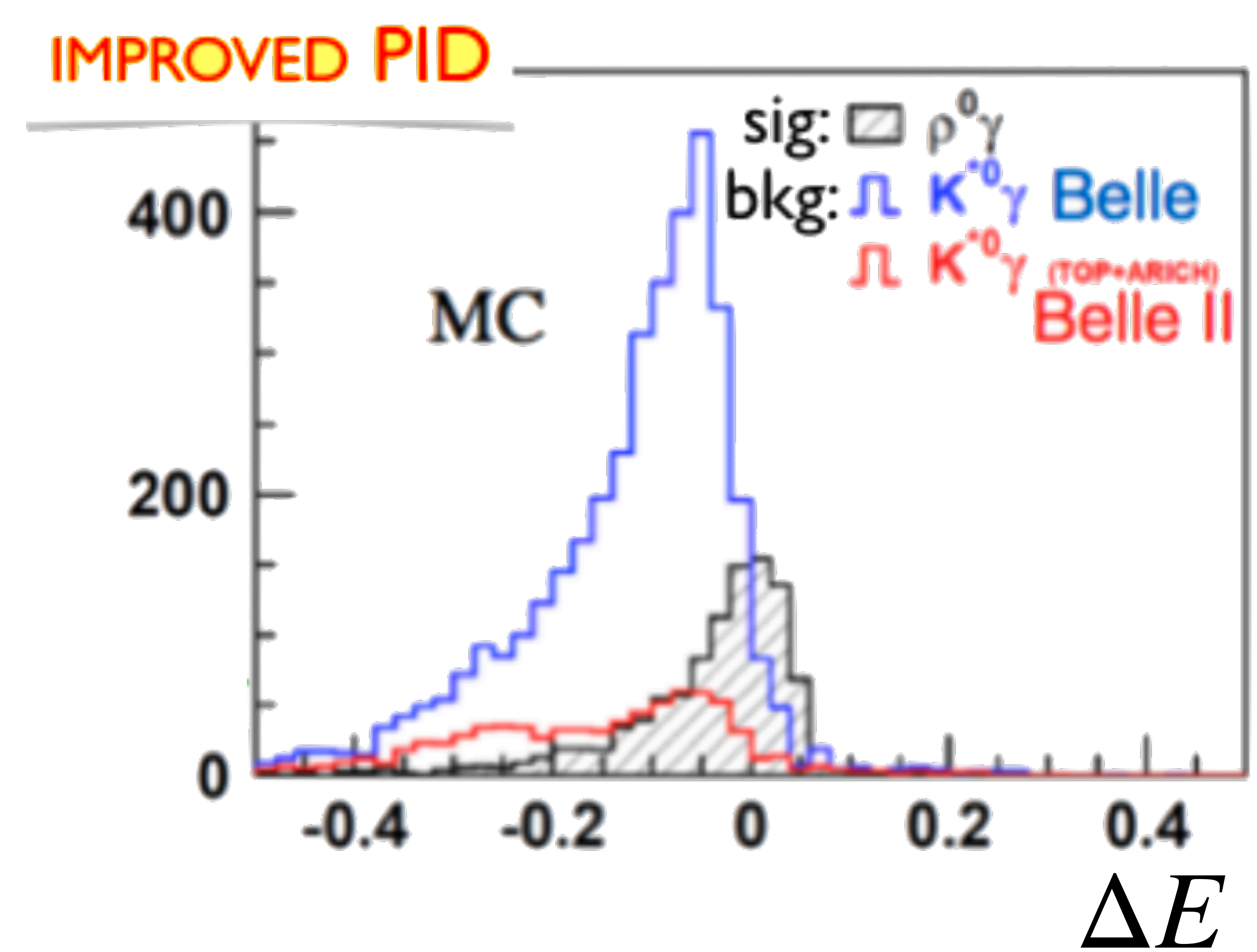
$$\mathcal{L}_{\text{peak}} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

$$\int^{\text{goal}} \mathcal{L}\, dt = 50 \text{ ab}^{-1}$$

Belle II improvements

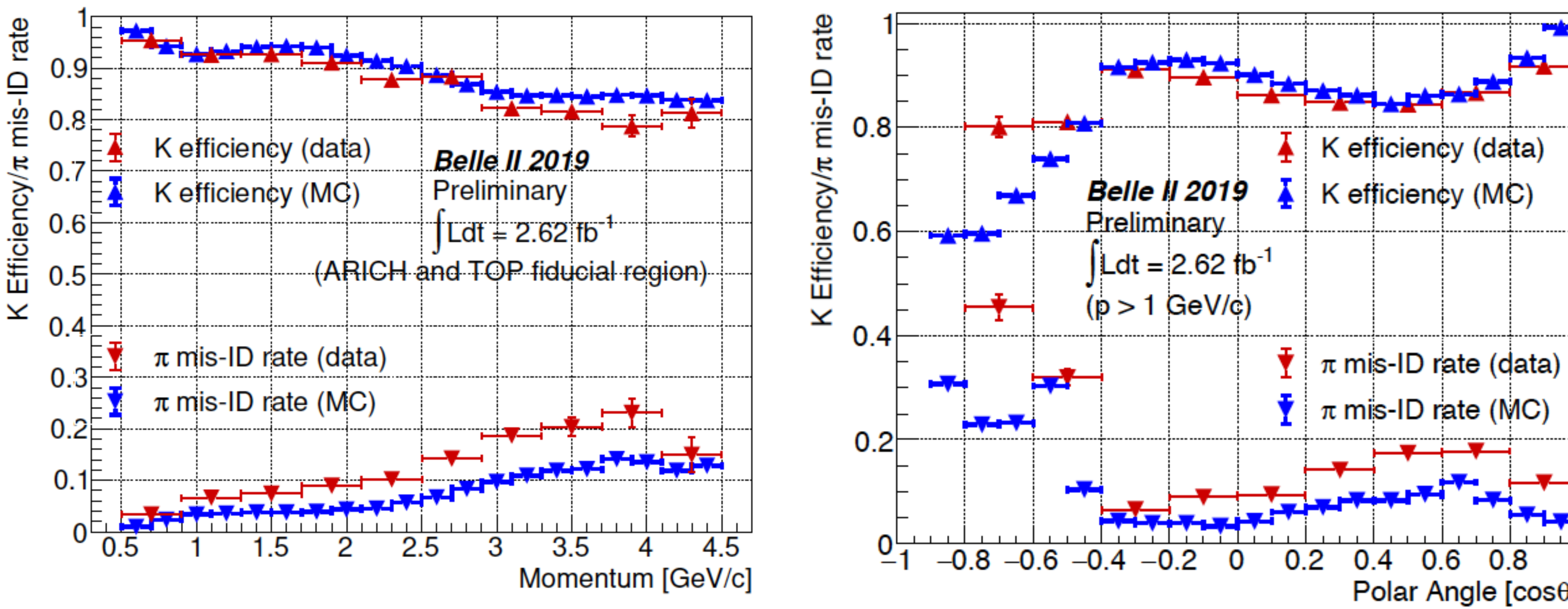
- vertex resolution
- K_S^0 and π^0 reconstruction efficiency
- K/π separation
- hadron & muon ID in the endcaps
- flavor tagging
  - (Belle) D* tagging only
  - (Belle II) D* & ROE tagging



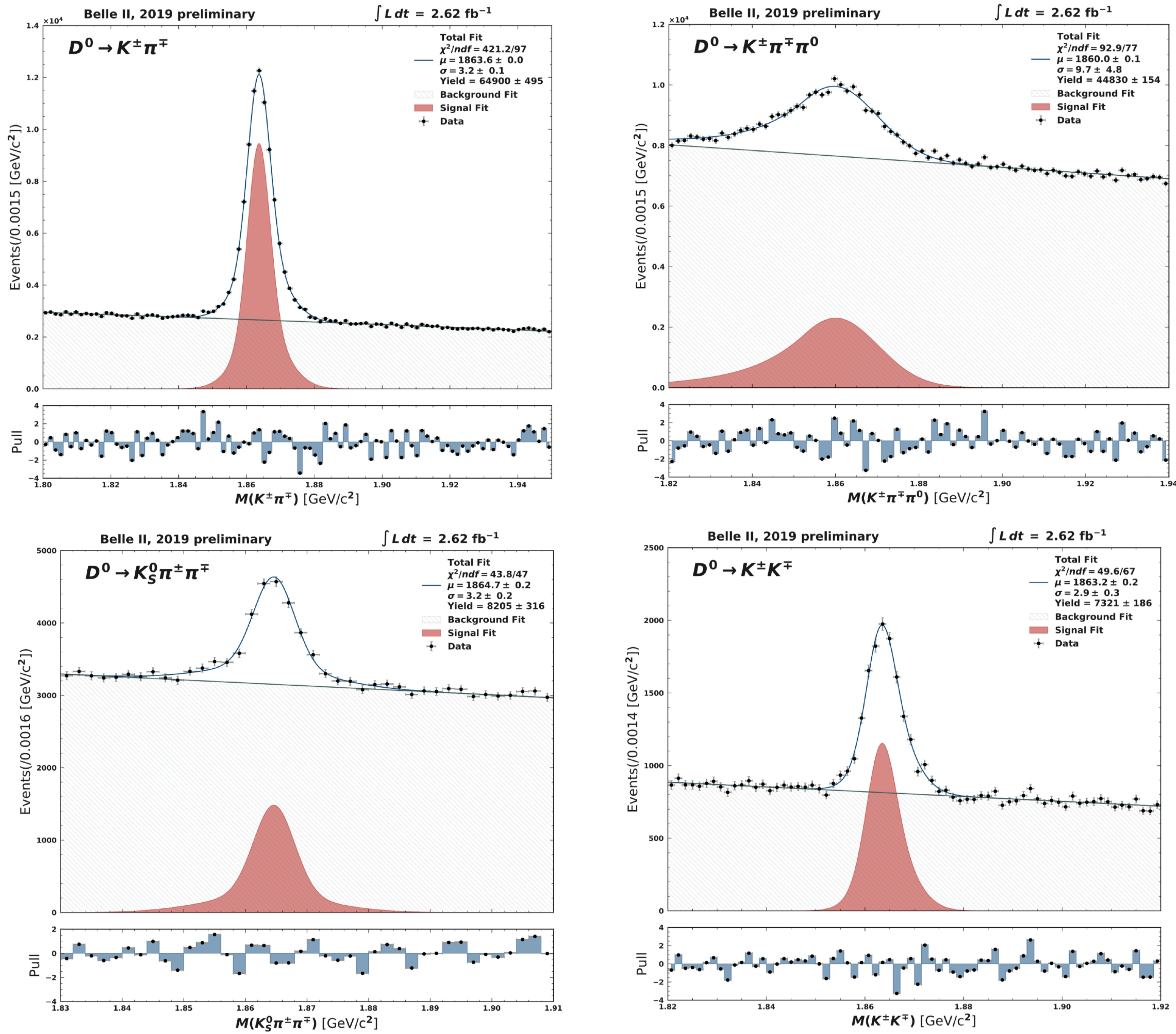


Belle II K/π separation (Phase 3)

$K,\ \pi$ **from** D^{*+}**-tagged** $D^0 \rightarrow K\pi$ **decays**

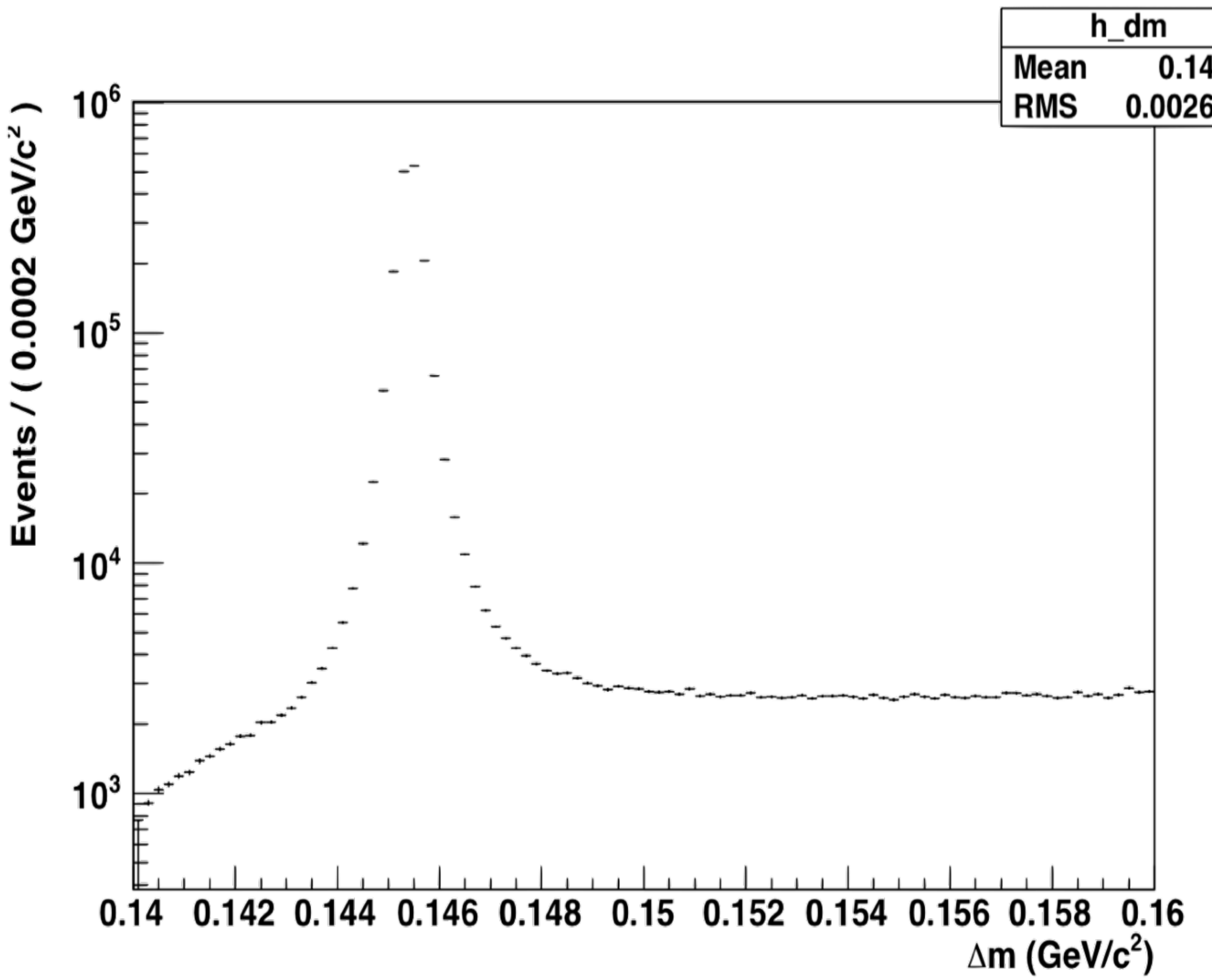


$M(D^0)$ plots (Belle II)



Flavor tagging for charm at Belle II

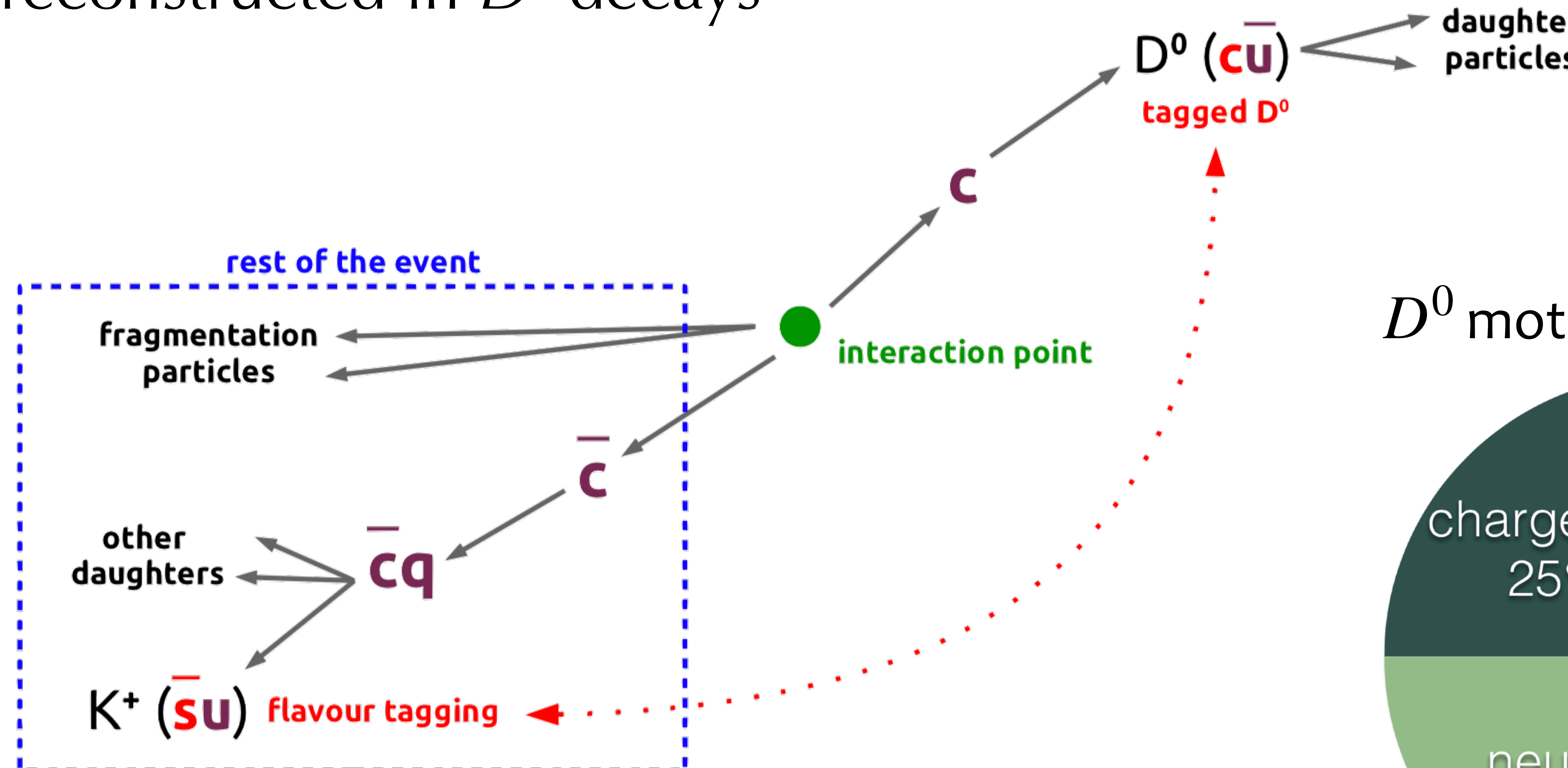
- D* tagging ("golden method")
  - $D^{*+} \to D^0 \pi_s^+$
  - observables: $M(D^0)$, $\Delta M \equiv M(D^*) - M(D)$
  - ΔM resolution at Belle II ~ $180\ \mathrm{keV}/c^2$; factor ~2 better than Belle



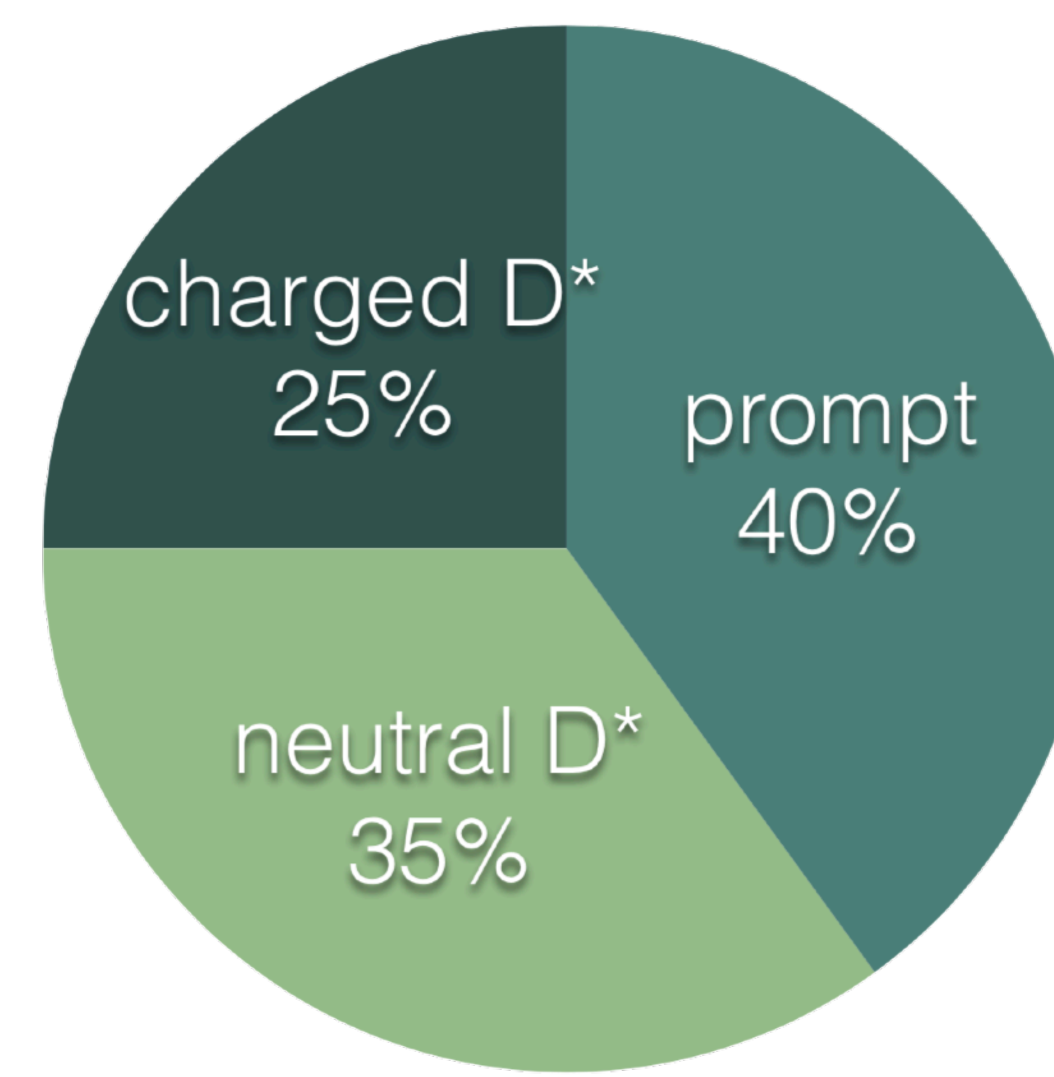
- Rest-of-event (ROE) tagging

Flavor tagging — ROE

- to increase tagged sample size by adding D^0 mesons not reconstructed in D^* decays



D^0 mother in $c\bar{c}$ events



- **reconstruct** a D^0 and look at the rest-of-event (ROE); **select** events with only one $K^{\pm}$ in the ROE; **tag** the flavor of D^0 with the charge of $K^{\pm}$

Flavor tagging — ROE

- lower tagging efficiency (~1/4) is compensated by ~x3 higher production of non-D^* source

comparison of tagging methods

Flavour-tagging Method	Produced D^0 N_{D^0}	Mistagging ω	ϵ	Efficiency $Q = \epsilon\,(1-2\omega)^2$
D^*	1	0.2%	80%	79.7%
ROE - criteria A	3	13.3%	26.7%	20.1%
ROE - criteria B	3	9.8%	16.8%	13.7%
ROE - criteria C	3	4.9%	15.9%	15.7%

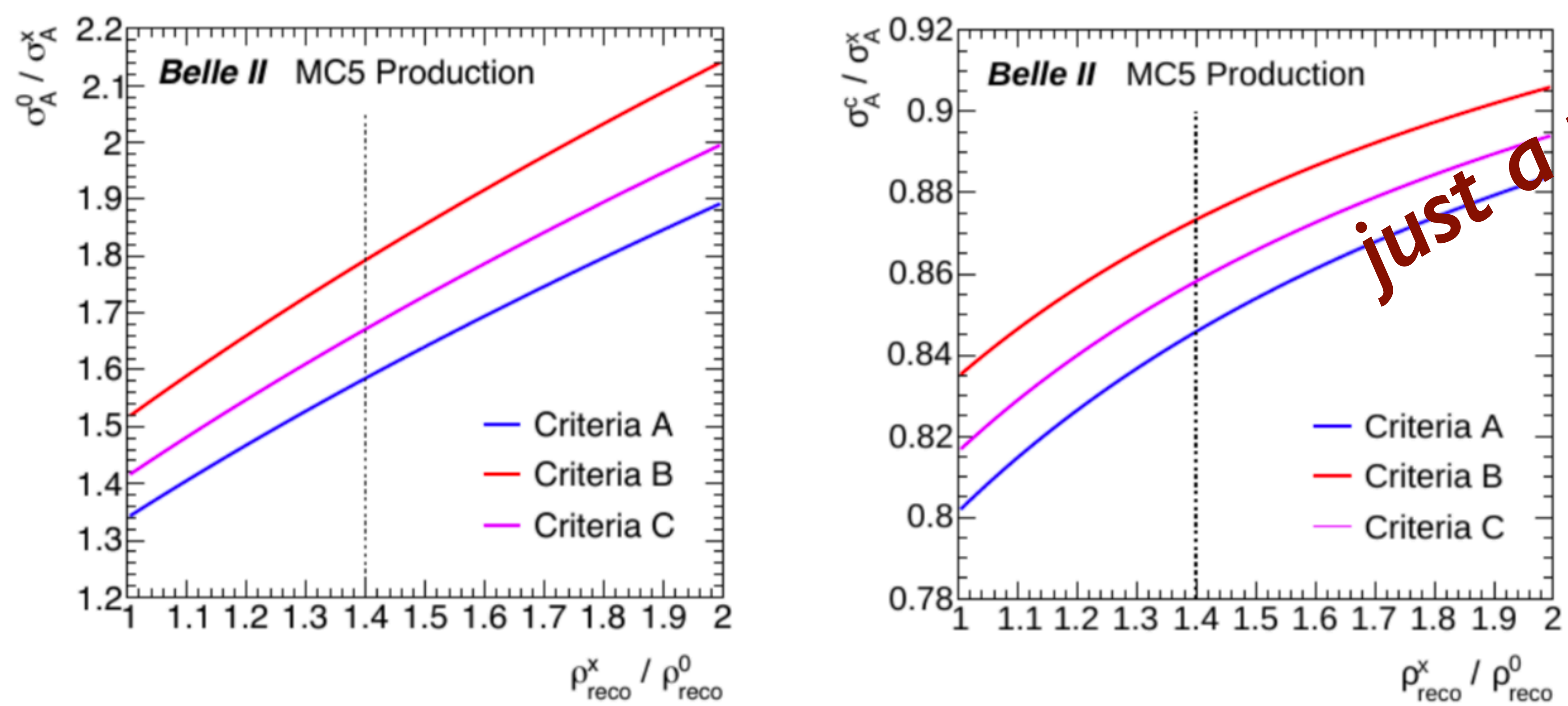
- nearly double the sample; but with higher mistagging and lower purity

A_{CP} improvement with ROE

- The ratio of A_{CP} statistical uncertainties can be written as

$$\frac{\sigma_{A_{CP}}^{ROE}}{\sigma_{A_{CP}}^{D^*}} = \sqrt{\frac{1}{3} \cdot \frac{Q^{D^*}}{Q^{ROE}} \cdot \frac{\rho_{reco}^{D^*}}{\rho_{reco}^{ROE}}} \equiv \alpha$$

- production ratio
- effective tagging efficiency
- sample purity
  - ratio of sample purities ~1.4 BaBar, PRD 87(1), 012004 (2013)
- both methods combined: $\sigma_{A_{CP}} = \frac{\alpha}{\sqrt{1+\alpha^2}} \cdot \sigma_{A_{CP}}^{D^*}$



just a frame-filler; I will write my own after the practice talk

→ expect to increase sensitivity by 15% if combining both methods

Prospects for A_{CP} in Belle II

- Extrapolating Belle results to $50\ \text{ab}^{-1}$
- Systematic uncertainties
  - reducible sys. err. σ_{red} — scale with luminosity
  - irreducible sys. err. σ_{irred} — asym. $K^0/\overline{K}^0$ interactions in matter ($\approx 0.02\,\%$), K^0 CPV, etc.

$$\sigma_{\text{Belle II}} = \sqrt{\left(\sigma_{\text{stat}}^2 + \sigma_{\text{red}}^2\right)^2 \frac{\mathscr{L}_{\text{Belle}}}{50\ \text{ab}^{-1}} + \sigma_{\text{irred}}^2}$$

- In this talk, improvements in detector performance as well as ROE tagging are not included in the extrapolation.

Time-integrated CPV

- $A_{\rm CP}(D^0 \to V\gamma)$
- $A_{\rm CP}(D \to PP')$

Time-integrated A_{CP} (in Belle II)

- **A_{CP} vs. A_{raw}**

$$A_{\rm raw} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\bar{D}^0 \to \bar{f})}$$

$$= A_{\rm D} + A_{\epsilon} + A_{\rm CP}$$

$$\mathcal{A}_{\rm CP} = \frac{\mathcal{B}(D^0 \to f) - \mathcal{B}(\overline{D}^0 \to \overline{f})}{\mathcal{B}(D^0 \to f) + \mathcal{B}(\overline{D}^0 \to \overline{f})}$$

$$\mathcal{A}_{CP}^{\rm sig} = A_{\rm raw}^{\rm sig} - A_{\rm raw}^{\rm norm} + \mathcal{A}_{CP}^{\rm norm}$$

- **tagged (D*, ROE) or self-tagged**

- $A_{\rm D}$ = production asymmetry

  = $A_{\rm FB}(\cos\theta^*)$

  an odd function in $\cos\theta^*$

  can be easily disentangled by

$$A_{\rm CP} = \frac{1}{2}\left[A_{\rm raw}^{\rm cor}(\cos\theta^*) + A_{\rm raw}^{\rm cor}(-\cos\theta^*)\right]$$

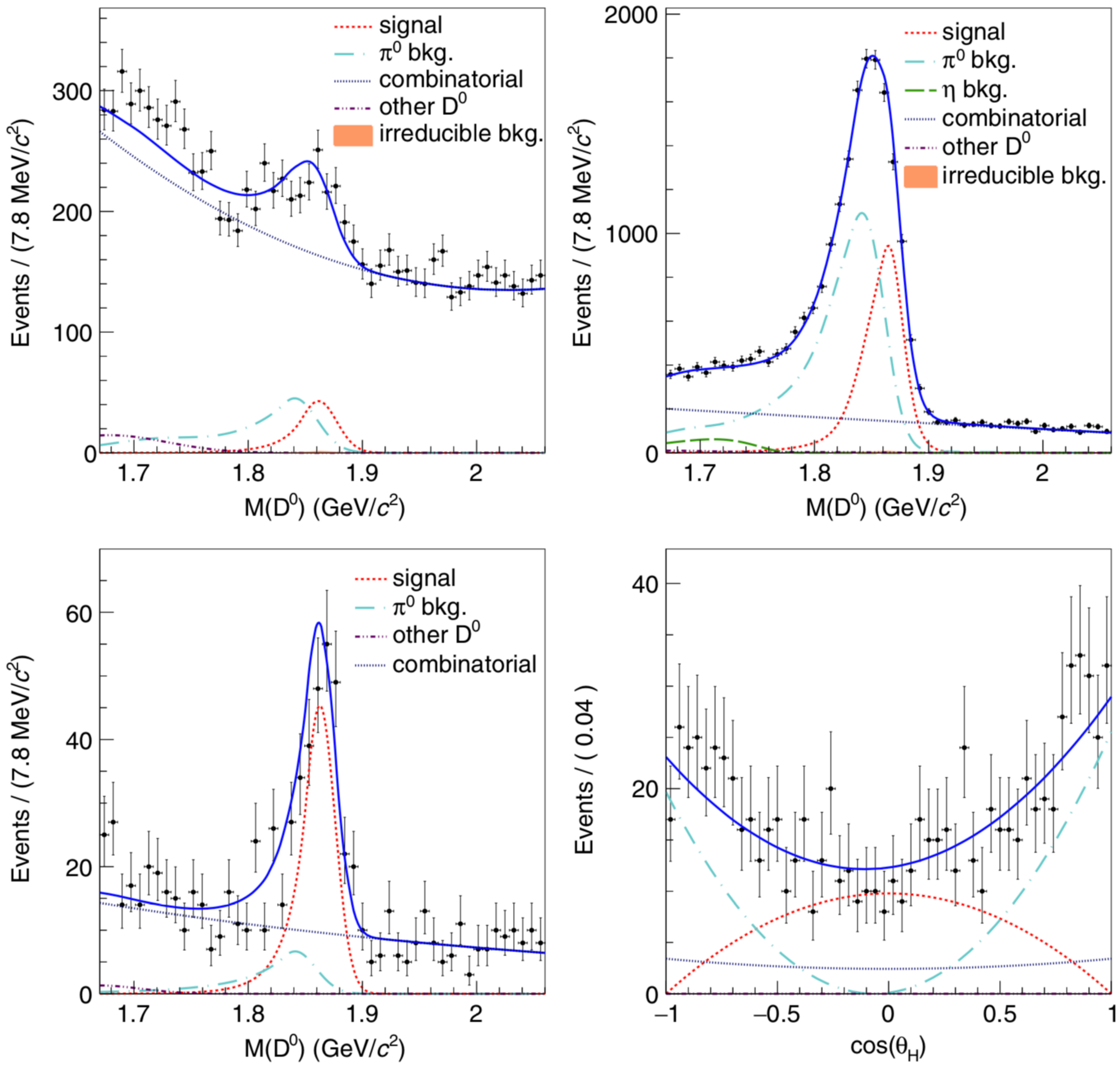
$$A_{\rm FB} = \frac{1}{2}\left[A_{\rm raw}^{\rm cor}(\cos\theta^*) - A_{\rm raw}^{\rm cor}(-\cos\theta^*)\right]$$

- A_{ϵ} = efficiency asymmetry

  measured with enough precision using CF decays

$D^0 \to V\gamma$

PRL **118**, 051801 (2017)



- $A_{\rm CP}^{\rm SM}(D^0 \to V\gamma) \sim O(10^{-3})$

  NP can enhance it to $O(10^{-2})$

- SM: dominated by long-range effect → test of QCD

- use normalization modes to reduce systematic errors

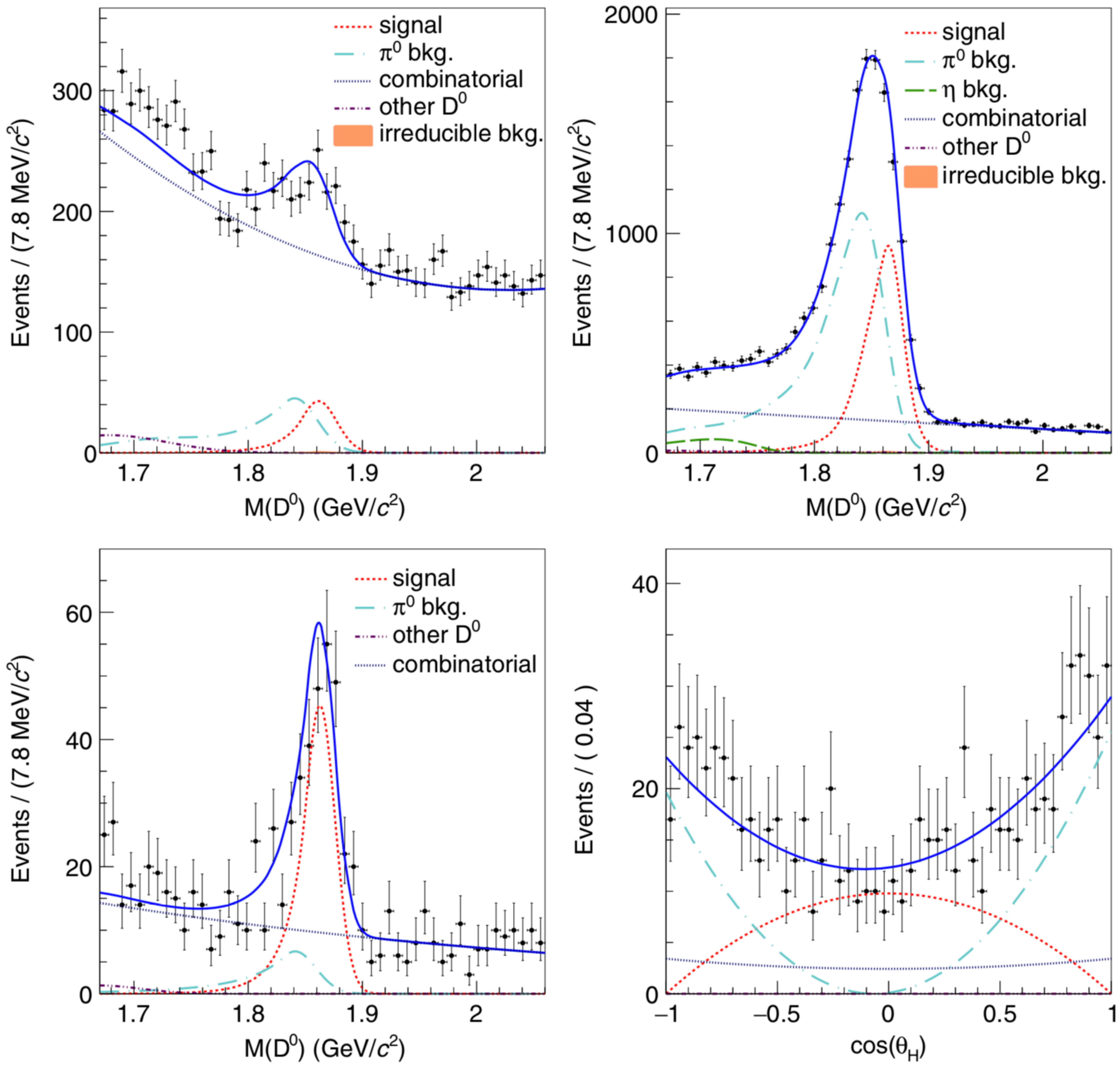
$$A_{\rm raw} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\bar{D}^0 \to \bar{f})}$$

$$\mathcal{A}_{\rm CP} = \frac{\mathcal{B}(D^0 \to f) - \mathcal{B}(\overline{D}^0 \to \overline{f})}{\mathcal{B}(D^0 \to f) + \mathcal{B}(\overline{D}^0 \to \overline{f})}$$

$$\mathcal{A}_{CP}^{\rm sig} = A_{\rm raw}^{\rm sig} - A_{\rm raw}^{\rm norm} + \mathcal{A}_{CP}^{\rm norm}$$

$D^0 \to V\gamma$

PRL **118**, 051801 (2017)



- $A_{CP}^{SM}(D^0 \to V\gamma) \sim O(10^{-3})$

  NP can enhance it to $O(10^{-2})$
- SM: dominated by long-range effect → test of QCD
- Measured by Belle w/ ~1 ab^{-1}

  → dominated by stat. error

$$\mathcal{A}_{CP}(D^0 \to \rho^0\gamma) = +0.056 \pm 0.152 \pm 0.006$$

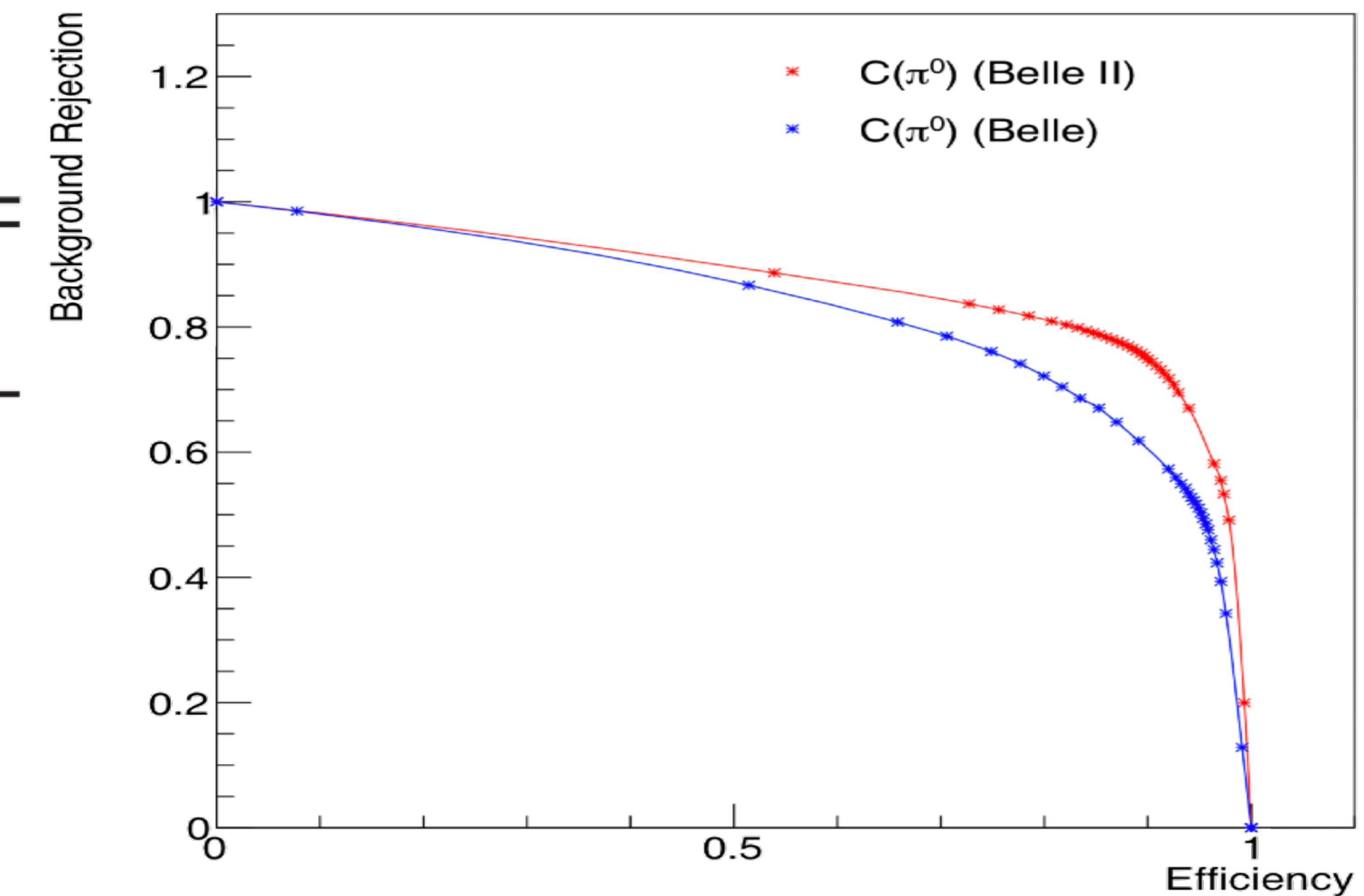
$$\mathcal{A}_{CP}(D^0 \to \phi\gamma) = -0.094 \pm 0.066 \pm 0.001,$$

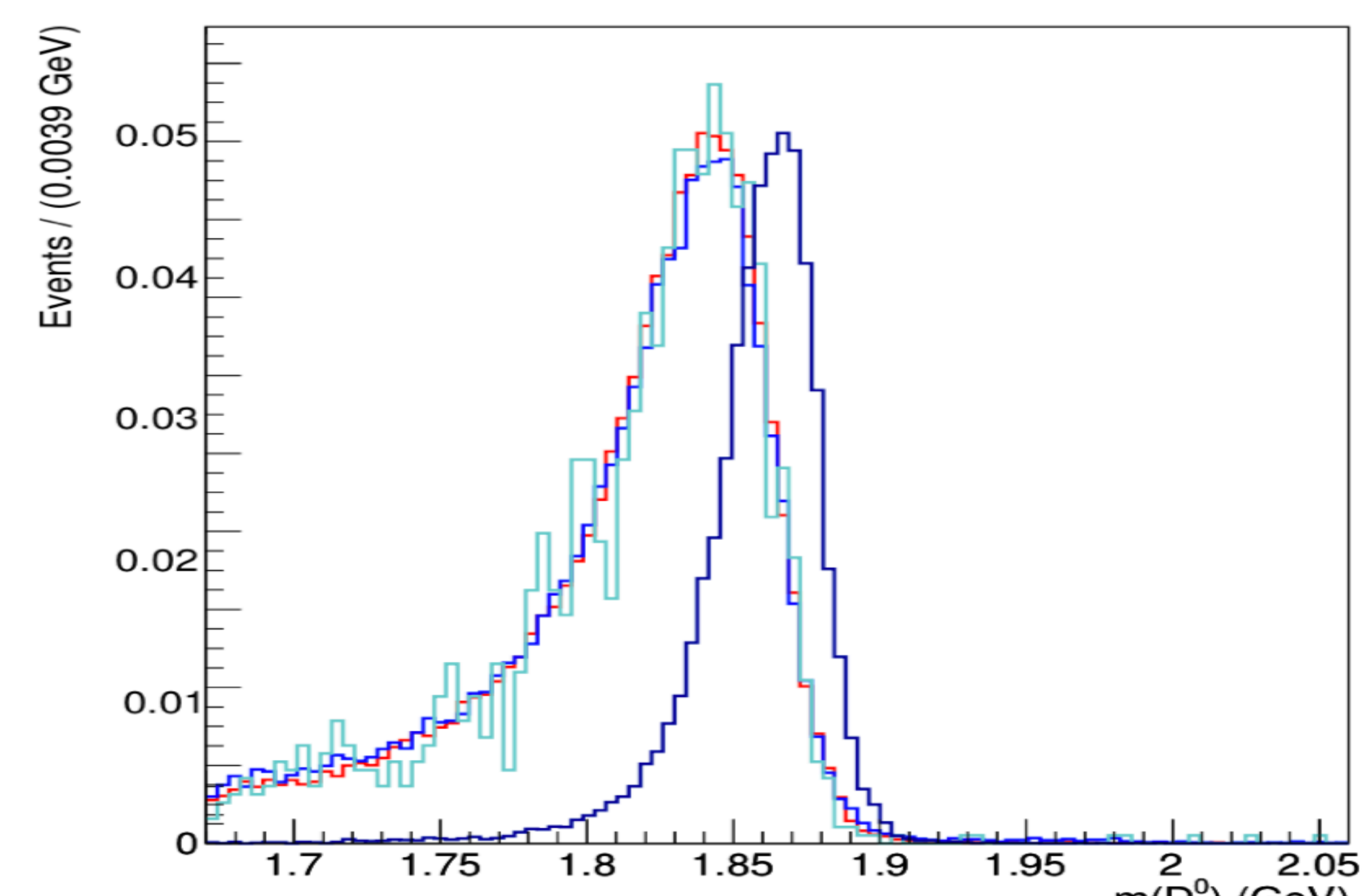
$$\mathcal{A}_{CP}(D^0 \to \bar{K}^{*0}\gamma) = -0.003 \pm 0.020 \pm 0.000,$$

$D^0 \to V\gamma$ systematics (Belle, 2017)

PRL **118**, 051801 (2017)

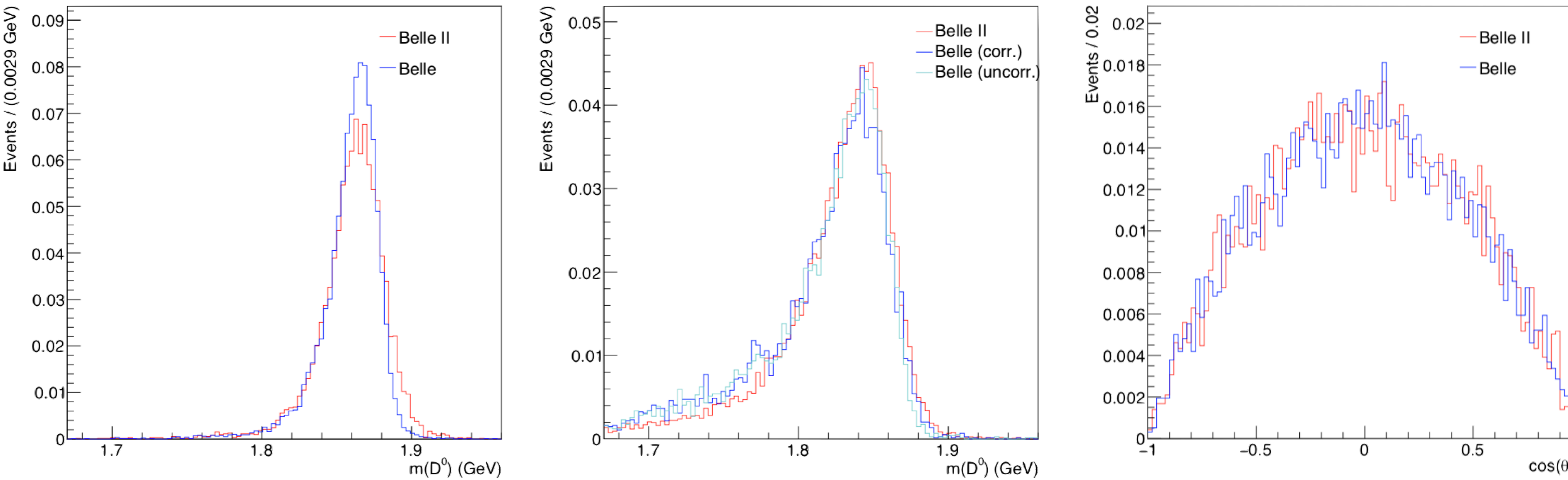
	$\sigma(\mathcal{B})/\mathcal{B}$ (%)			A_{CP} ($\times 10^{-3}$)		
	ϕ	$\bar{K}^{*0}$	ρ^0	ϕ	$\bar{K}^{*0}$	ρ^0
Efficiency	2.8	3.3	2.8	⋯	⋯	⋯
Fit parametrization	1.0	2.8	2.3	0.1	0.4	5.3
Background normalization	⋯	0.3	0.6	⋯	0.2	0.5
Normalization mode	0.0	0.0	0.1	0.5	0.0	0.3
External $\mathcal{B}$ and $\mathcal{A}_{CP}$	2.0	1.0	1.8	1.2	0.0	1.5
Total	3.6	4.5	4.1	1.3	0.4	5.5





- $D^0 \to X\pi^0$ is a dominant background
  - ✓ D^0 mass is shifted ($\because$ a missing γ)
  - ✓ π^0 veto (*slightly better for Belle II*)
- $M(D^0)$ resolution is crucial

$D^0 \to V\gamma$ systematics (Belle, 2017)



- $M(D^0)$ resolution is crucial
- Belle II MC study

  Belle II resolutions for both $M(D^0)$ and $\cos\theta_H$ are comparable to Belle

  $\rightarrow$ we can extrapolate based on luminosity

$D^0 \to V\gamma$ prospects

δA$_{CP}$ on	Belle	Belle II (stat. err.)		
	1 ab^{-1}	5 ab^{-1}	15 ab^{-1}	50 ab^{-1}
$D^0 \to \rho\gamma$	±0.152±0.006	±0.07	±0.04	±0.02
$D^0 \to \phi\gamma$	±0.006±0.001	±0.03	±0.02	±0.01
$D^0 \to \overline{K}^{*0}\gamma$	±0.020±0.000	±0.01	±0.005	±0.003

- $O(\%)$ precision is expected for $A_{\rm CP}(D^0 \to V\gamma)$ at Belle II
- Statistical error will still dominate

$A_{\rm CP}(D \to PP')$

- $A_{\rm CP}^{\rm SM}(D \to PP') \sim O(10^{-3})$

  ✓ not an automatic NP probe, ∵ uncertainties in hadronic matrix elements

  ✓ symmetry (e.g. $SU(3)_F$) can predict patterns among different modes

- existing most precise measurements → **Sum Rule test!**

Mode	A_{CP} [%]	
$D^0 \to K^+K^-$	$0.04 \pm 0.12 \pm 0.10$	**LHCb, 2017**
$D^0 \to \pi^+\pi^-$	$0.07 \pm 0.14 \pm 0.11$	**LHCb, 2017**
$D^0 \to K_S^0 K_S^0$	$-0.02 \pm 1.53 \pm 0.17$	**Belle, 2017**
$D^0 \to \pi^0\pi^0$	$-0.03 \pm 0.64 \pm 0.10$	**Belle, 2014**
$D^+ \to K_S^0 K^+$	$0.03 \pm 0.17 \pm 0.14$	**LHCb, 2014**
$D^+ \to K_S^0 \pi^+$	$-0.36 \pm 0.09 \pm 0.07$	**Belle, 2012**

$A_{\rm CP}(D \to PP')$

- $A_{\rm CP}^{\rm SM}(D \to PP') \sim O(10^{-3})$
  - ✓ not an automatic NP probe, ∵ uncertainties in hadronic matrix elements
  - ✓ symmetry (e.g. $SU(3)_F$) can predict patterns among different modes

→ **Sum Rule test!**

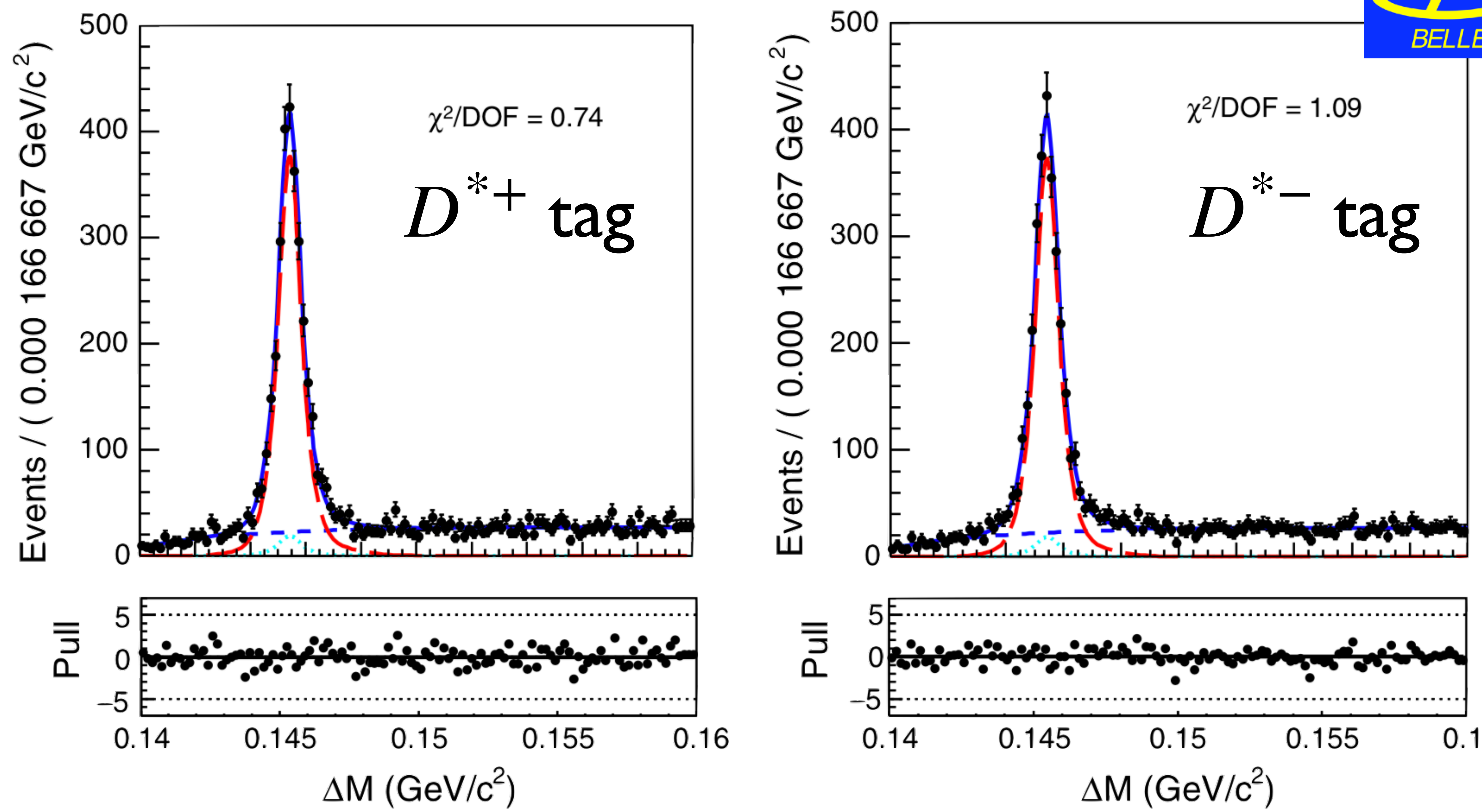
- **key expectations**
  - ✓ $A_{\rm CP}(D^+ \to \pi^+\pi^0) = 0$ in the isospin limit
  - ✓ $A_{\rm CP}(D^0 \to K_S^0 K_S^0)$ — enhanced to O(%) level due to large exchange diagram contribution (*hence a nice place for early discovery*)

    $|A_{\rm CP}| \leq 1.1\,\%$ (95% CL)   Nierste & Schacht (PRD, 2015)
  - ✓ Belle II can do well with neutral particles (π^0, η, η', ρ^+) in the final state

$A_{CP}(D^0 \to K_S^0 K_S^0)$

- $A_{CP}^{SM}(D^0 \to K_S^0 K_S^0) \sim O(1\%)$
  - ✓ promising for discovery
- Belle with 921 fb^{-1}
  - ✓ $A_{CP} = (-0.02 \pm 1.53 \pm 0.17)\ \%$
  - ✓ normalize to $K_S^0 \pi^0$
  - ✓ CPV in K^0 is subtracted
  - ✓ $\sigma_{\text{irred}} \approx 0.02\ \%$
- Belle II expectation
  - ✓ $\sigma_{A_{CP}} = 0.23\ \%$ at 50 ab^{-1}

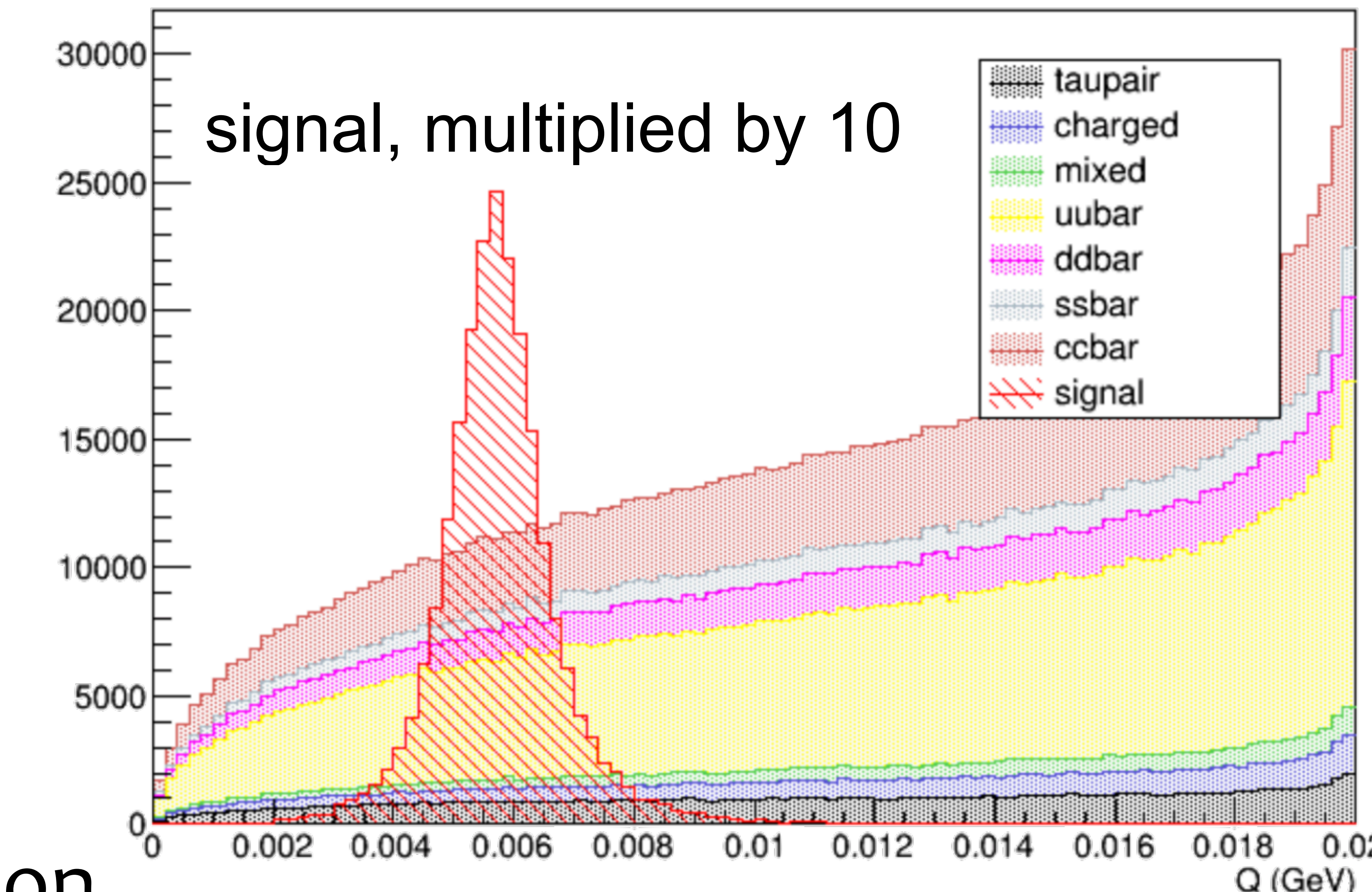
PRL **119**, 171801 (2017)



$A_{CP}(D^+ \to \pi^+\pi^0)$

- $A_{CP}^{SM}(D^+ \to \pi^+\pi^0) = 0$
  - ✓ a smoking gun for NP
- Belle with 921 fb^{-1}
  - ✓ $A_{CP} = (2.31 \pm 1.24 \pm 0.23)\ \%$
  - ✓ normalize to $D^+ \to K_S^0\pi^+$
- Belle II MC study (50 ab^{-1})
  - ✓ using D^{*+} tag for background suppression
  - ✓ efficiency, background rejection, similar to Belle, using earlier recon S/W
  - ✓ can expect further improvement with updated S/W
  - ✓ $\sigma_{A_{CP}} \approx 0.17\ \%$

$Q \equiv M(D^+\pi^0) - M(D^+) - M(\pi^0)$



$A_{\mathrm{CP}}(D \to PP')$ Belle II prospects

Mode	$\mathcal{L}$ (fb^{-1})	$A_{\mathrm{CP}}(\%)$ (Belle)	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

$A_{\mathrm{CP}}^{\mathrm{SM}} \sim 1\,\%$ ($D^0 \to K_S^0 K_S^0$)

$A_{\mathrm{CP}}^{\mathrm{SM}} = 0$ ($D^+ \to \pi^+\pi^0$)

Time-dependent CPV

- CPV in mixing
- CPV in mixing-decay interference

CPV and Mixing — *a quick intro.*

$$|M_{1,2}\rangle = p\,|M^0\rangle \pm q\,|\overline{M}^0\rangle$$

$$|M^0_{\rm phys}(t)\rangle = (g_+(t) + z\,g_-(t))\,|M^0\rangle - \sqrt{1-z^2}\,\frac{q}{p}\;g_-(t)|\overline{M}^0\rangle$$

$$|\overline{M}^0_{\rm phys}(t)\rangle = (g_+(t) - z\,g_-(t))\,|\overline{M}^0\rangle - \sqrt{1-z^2}\,\frac{p}{q}\;g_-(t)|M^0\rangle$$

$z = 0$ if CP or CPT is conserved

$$g_\pm(t) \equiv \frac{1}{2}\left(e^{-im_H t-\frac{1}{2}\Gamma_H t} \pm e^{-im_L t-\frac{1}{2}\Gamma_L t}\right)$$

mixing parameters $x = \dfrac{\Delta m}{\Gamma}$ $\quad y = \dfrac{\Delta \Gamma}{2\Gamma}$

Direct and Indirect CPV

$$\left|\frac{\overline{A}}{A}\right| \neq 1$$

Direct CPV
(decay)

$$\left|\frac{q}{p}\right| \neq 1$$

Indirect CPV
(mixing)

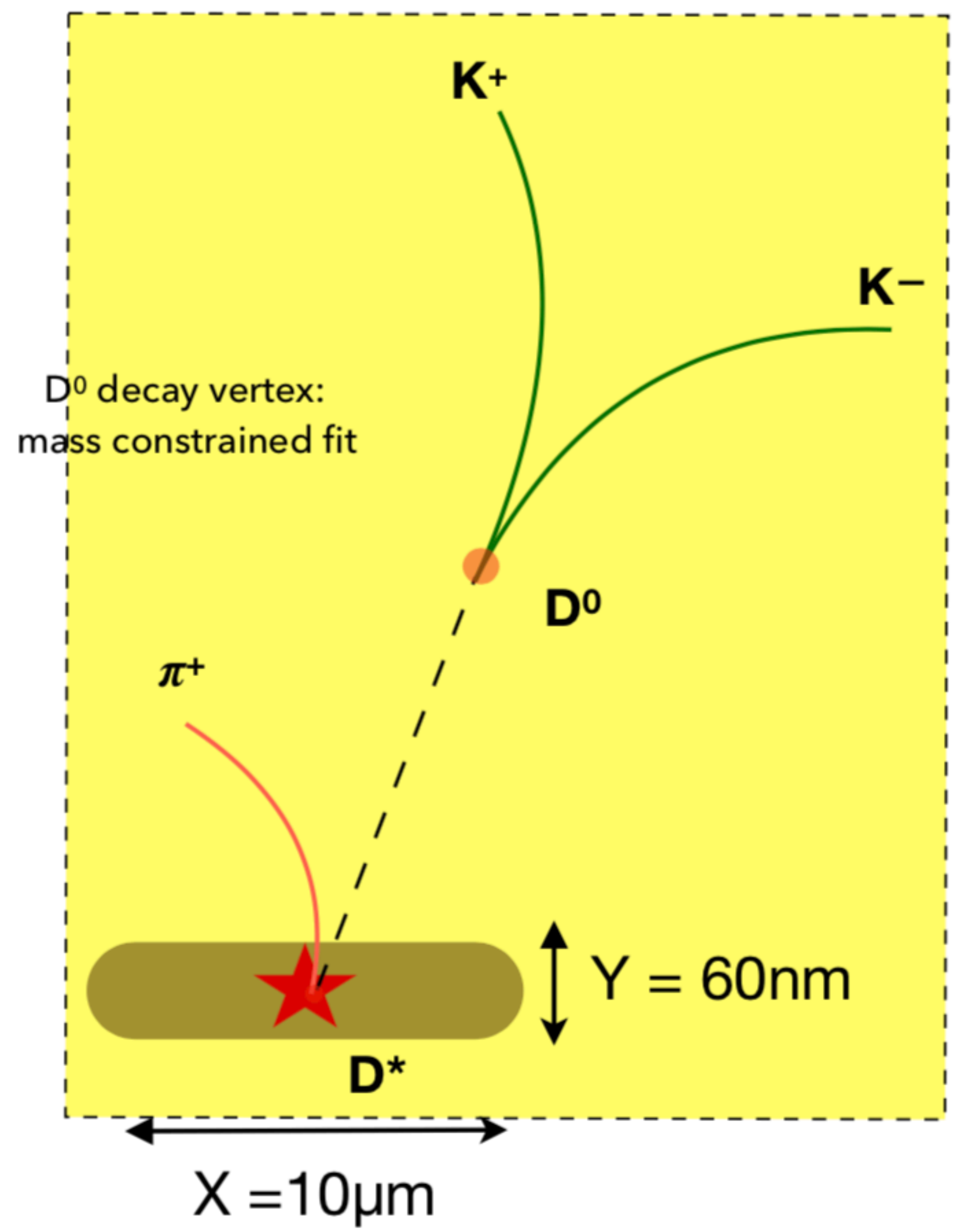
$$Im(\lambda_f) \neq 0$$

$$\lambda_f = -\eta_{\mathrm{CP}} \left|\frac{q}{p}\right| \left|\frac{\overline{A}_f}{A_f}\right| e^{i\phi} \neq 0$$

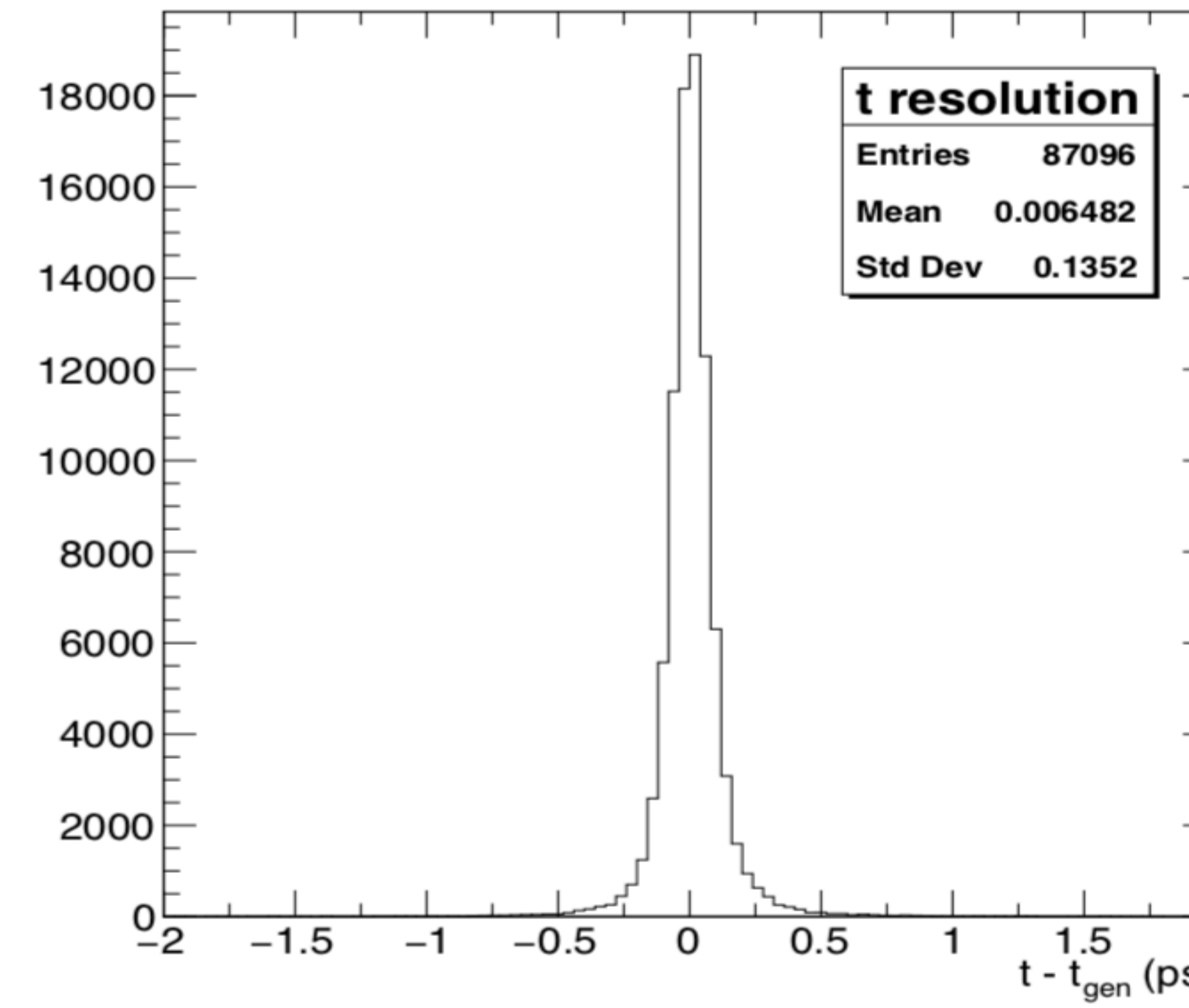
Interference of
mixing and decay

Time & Vertex resolution in Belle II

- factor ~2 better than Belle and BaBar
  - $\delta r_{xy} \sim 40\ \mu m$
  - $\delta t \sim 0.15$ ps



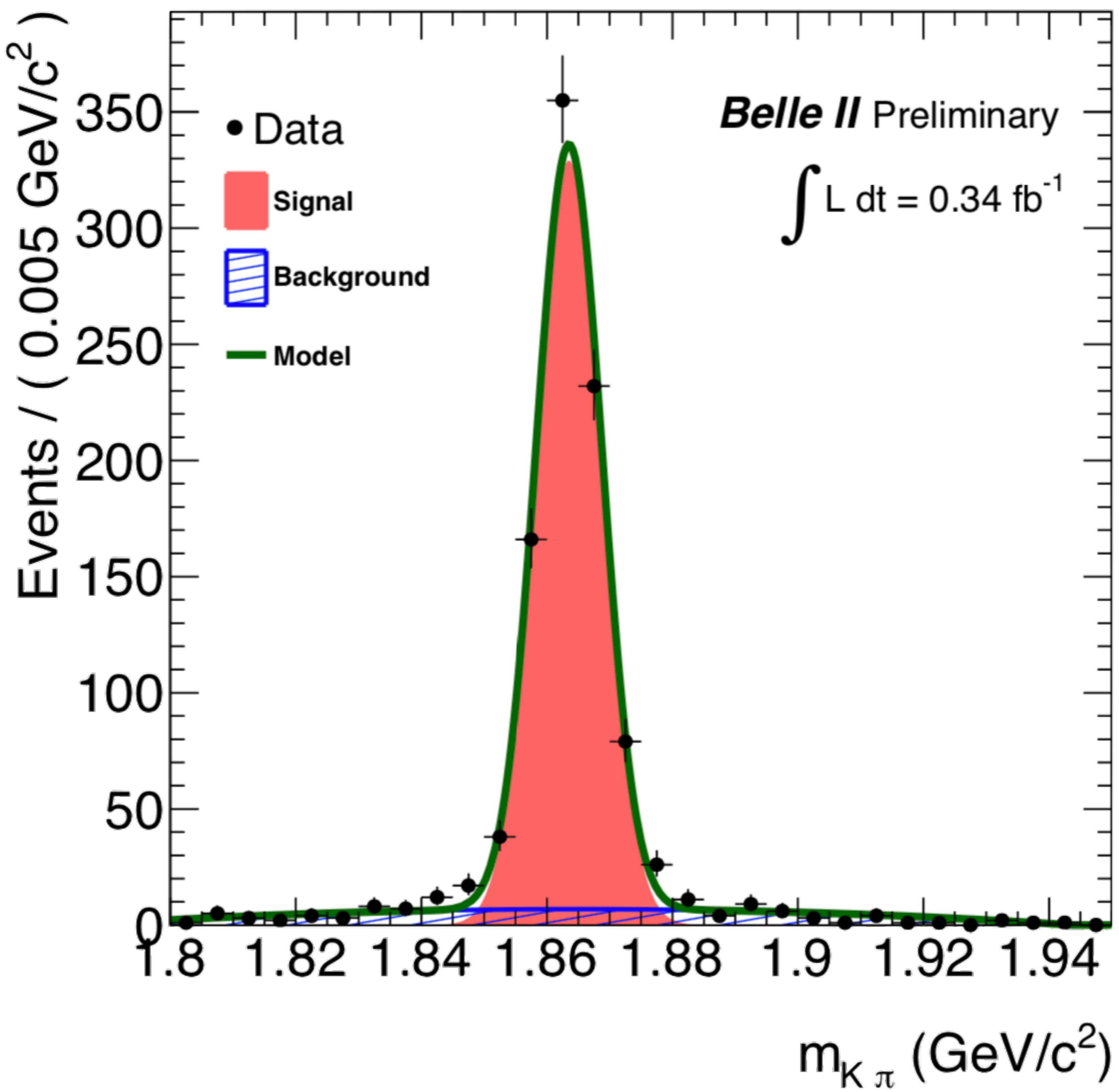
$D^0 \to K^+K^-$ (Belle II MC)

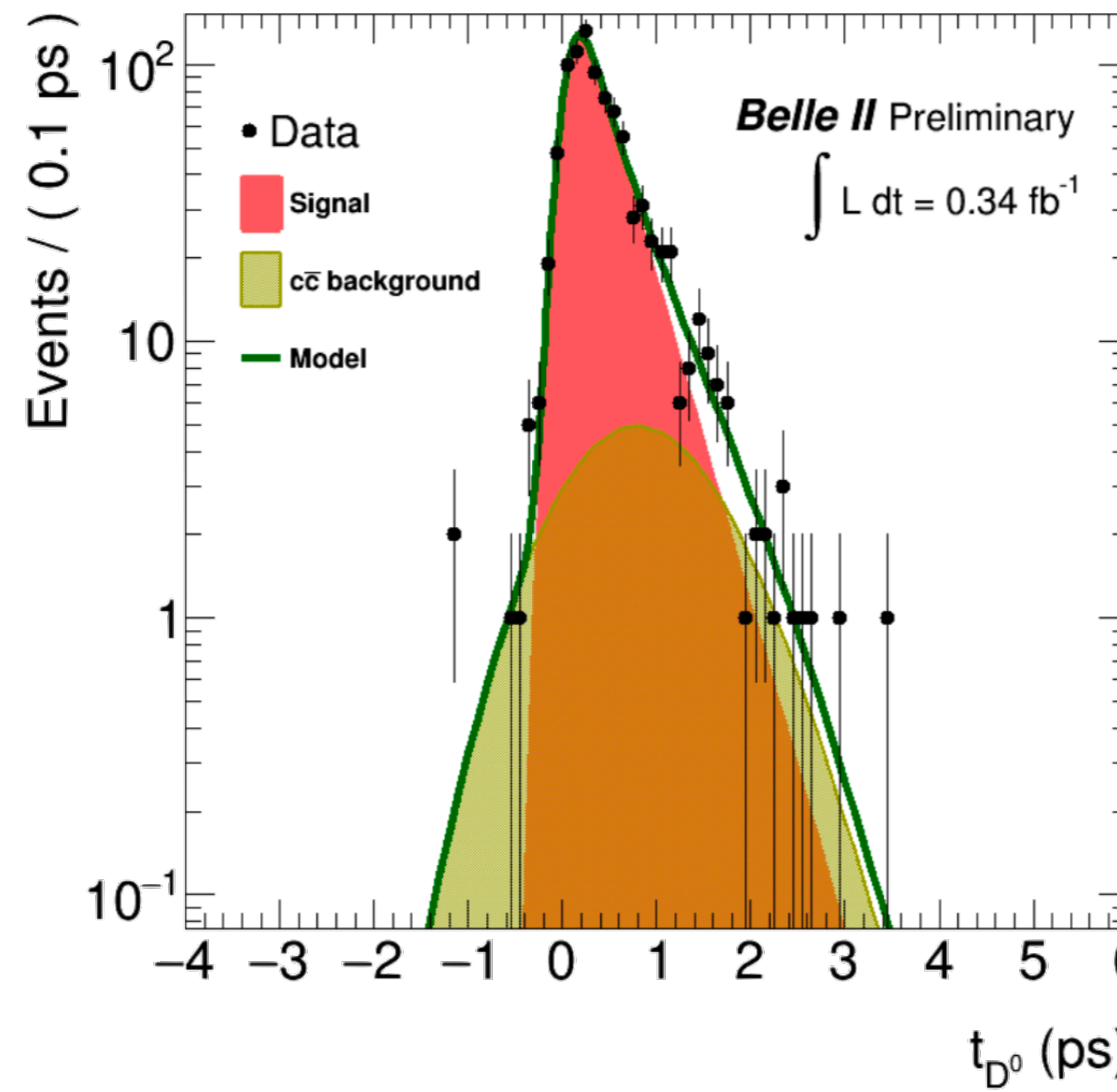


Experiment	t resolution	
	Mean	RMS
Belle II	6.5 fs	135 fs
BaBar	-0.48 fs	271 fs

D^0 lifetime in Belle II (Phase 3)

D^{*+}-tagged $D^0 \to K\pi$ decays (using 1/15 sample of Phase 3)





$$\tau_{D^0} = 370 \pm 40 \text{ fs}$$

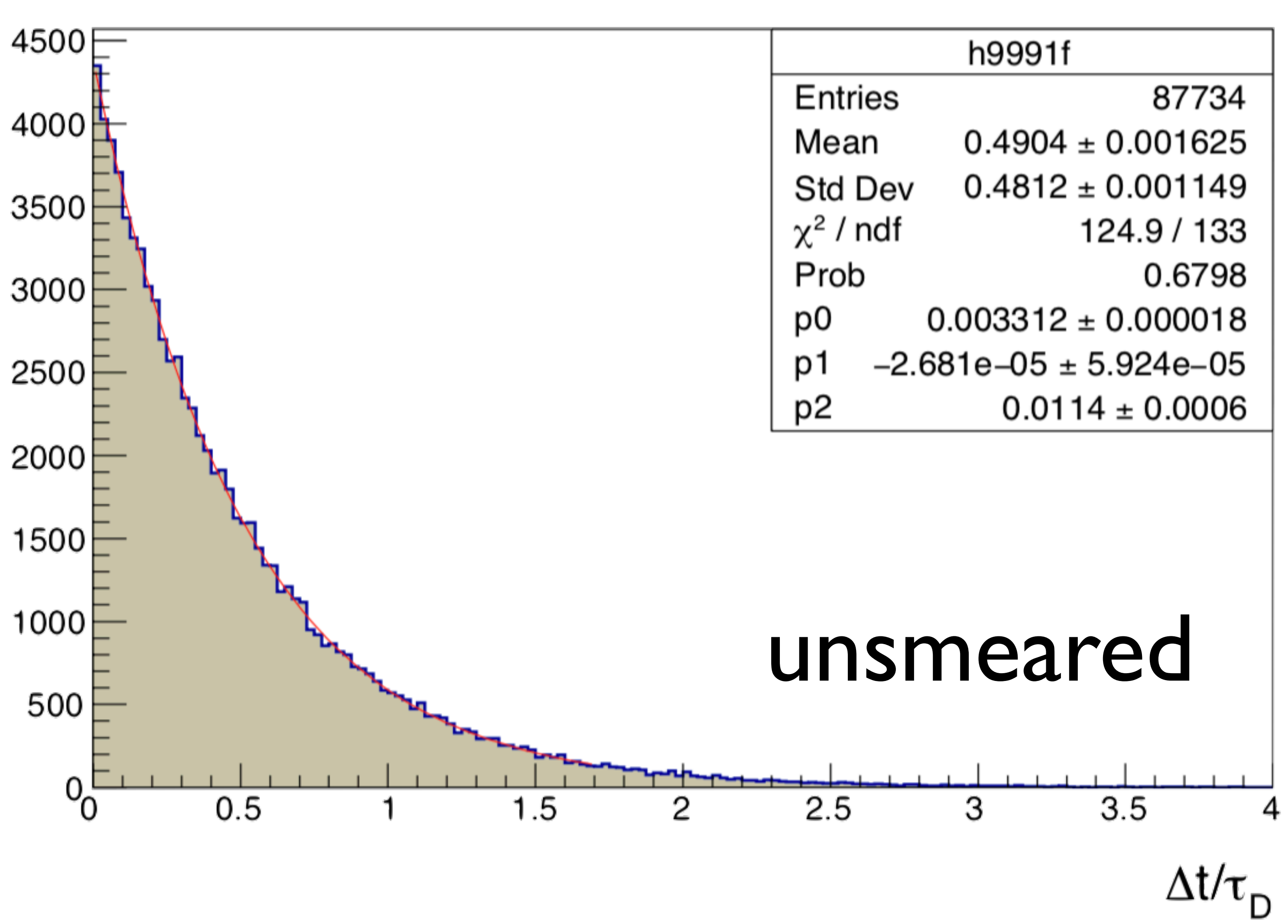
$$\tau_{D^0}^{\text{PDG}} = 410 \text{ fs}$$

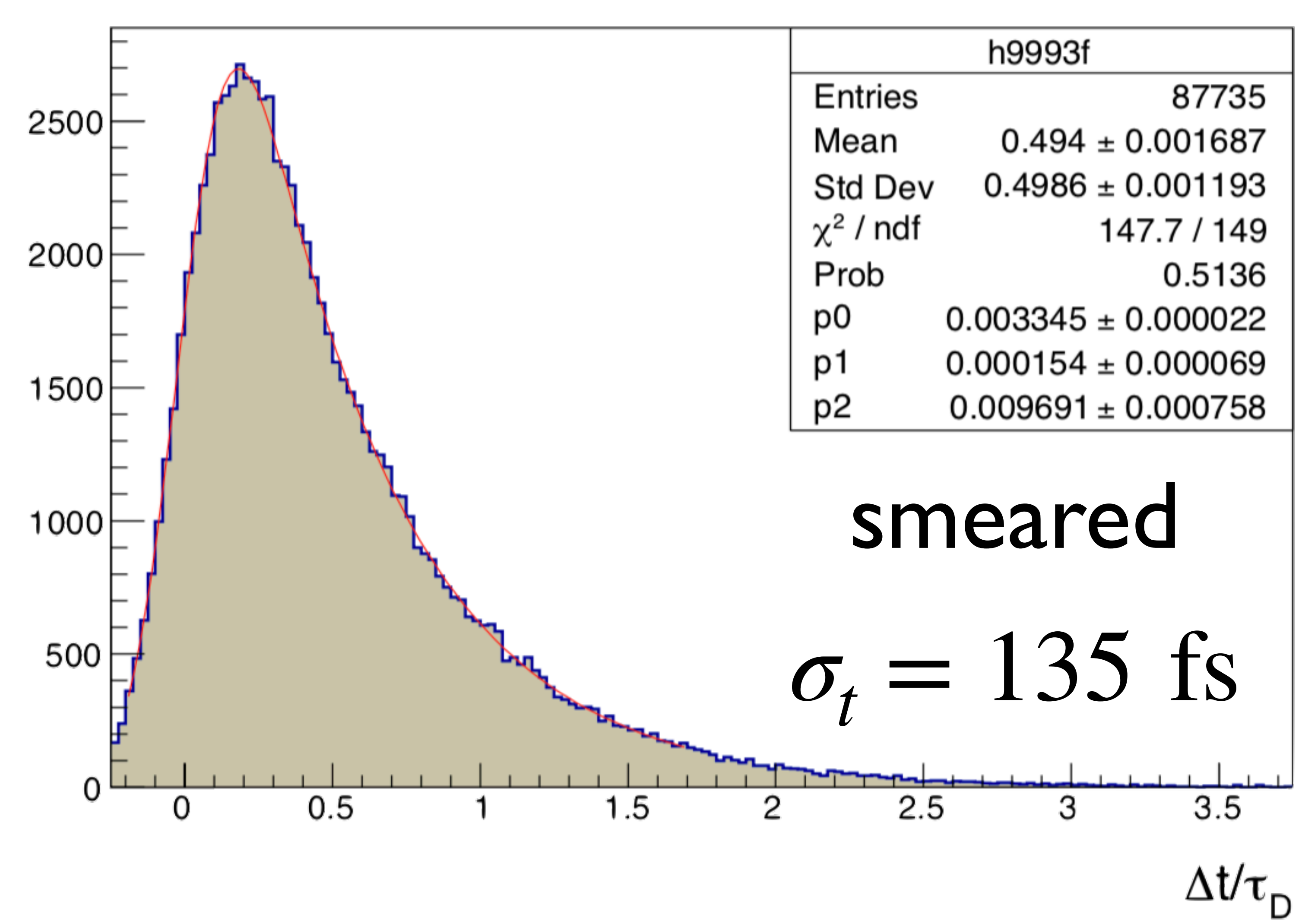
Mixing & CPV in $D^0 \to K^+\pi^-$ (WS)

$$\frac{N(D^0\to f)}{dt} \propto e^{-\overline{\Gamma} t}\left\{R_D + \left|\frac{q}{p}\right|\sqrt{R_D}(y'\cos\phi - x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{q}{p}\right|^2\frac{(x'^2+y'^2)}{4}(\overline{\Gamma}\,t)^2\right\}$$

$$\frac{N(\overline{D}^0\to \bar{f})}{dt} \propto e^{-\overline{\Gamma} t}\left\{\overline{R}_D + \left|\frac{p}{q}\right|\sqrt{\overline{R}_D}(y'\cos\phi + x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{p}{q}\right|^2\frac{(x'^2+y'^2)}{4}(\overline{\Gamma}\,t)^2\right\}$$

$$x' = x\cos\delta + y\sin\delta \qquad y' = y\cos\delta - x\sin\delta$$





Belle II MC (20 ab^{-1})

fit w/o CPV

for R_D, x'^2, y'

Mixing & CPV in $D^0 \to K^+\pi^-$ (WS)

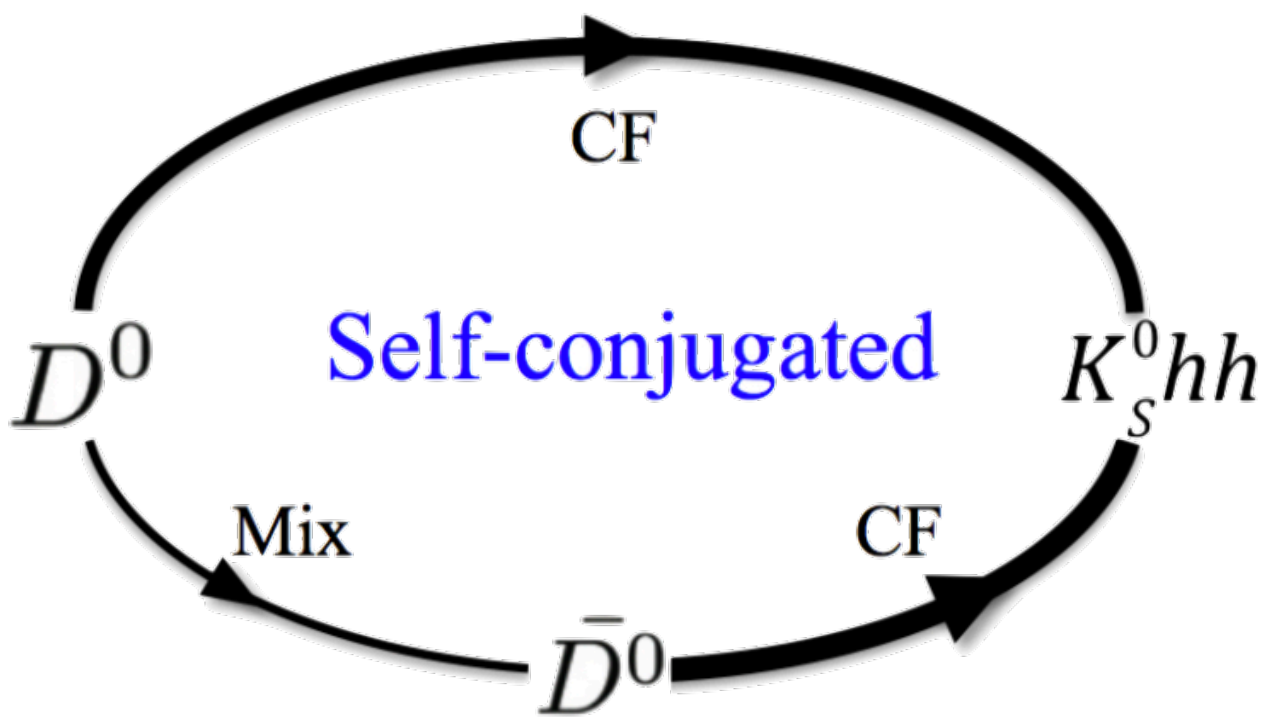
Belle II MC fit

Parameter	$5\ ab^{-1}$	$20\ ab^{-1}$	$50\ ab^{-1}$
$\delta x'^2\ (10^{-5})$	6.2	3.2	2.0
$\delta y'\ (\%)$	0.093	0.047	0.029
$\delta x'\ (\%)$	0.32	0.22	0.13
$\delta y'\ (\%)$	0.23	0.15	0.097
$\delta\lvert q/p\rvert$	0.174	0.073	0.043
$\delta\phi\ (^\circ)$	13.2	8.4	5.4

no CPV

CPV allowed

Mixing & CPV in $D^0 \to K^0_S\pi^+\pi^-$ (Dalitz)



- Systematic error will be dominated by D^0 decay modeling
  - ✓ should improve with strong phase difference to be measured at BESIII

Data	stat.	syst. red.	syst. irred.	Total	stat.	syst. red.	syst. irred.	Total
		σ_x (10^{-2})				σ_y (10^{-2})		
976 fb^{-1}	0.19	0.06	0.11	0.20	0.15	0.06	0.04	0.16
5 ab^{-1}	0.08	0.03	0.11	0.14	0.06	0.03	0.04	0.08
50 ab^{-1}	0.03	0.01	0.11	0.11	0.02	0.01	0.04	0.05
		$\lvert q/p\rvert$ (10^{-2})				ϕ $(^\circ)$		
976 fb^{-1}	15.5	5.2-5.6	7.0-6.7	17.8	10.7	4.4-4.5	3.8-3.7	12.2
5 ab^{-1}	6.9	2.3-2.5	7.0-6.7	9.9-10.1	4.7	1.9-2.0	3.8-3.7	6.3-6.4
50 ab^{-1}	2.2	0.7-0.8	7.0-6.7	7.0-7.4	1.5	0.6	3.8-3.7	4.0-4.2

Summary

- *I will write something here …*

Thank you!