Charm(ing) Physics at Belle II

Michel Bertemes - Belle II US Summer Workshop - 07/25/23

HEPHY
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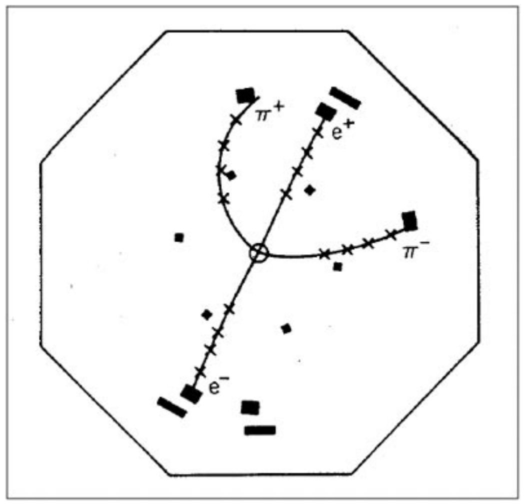
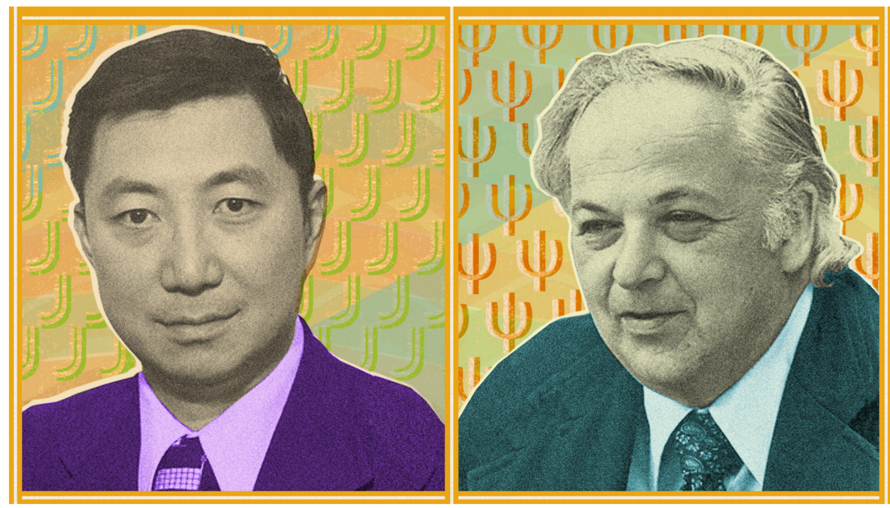
Der Wissenschaftsfonds.

All things charm





$$c\bar{q}$$

$$D^0, D^+, D_s^+, \ldots$$

- Measure property of charmed hadrons
  - Lifetimes
  - D^0-$\bar{D}^0$ mixing
  - CP violation

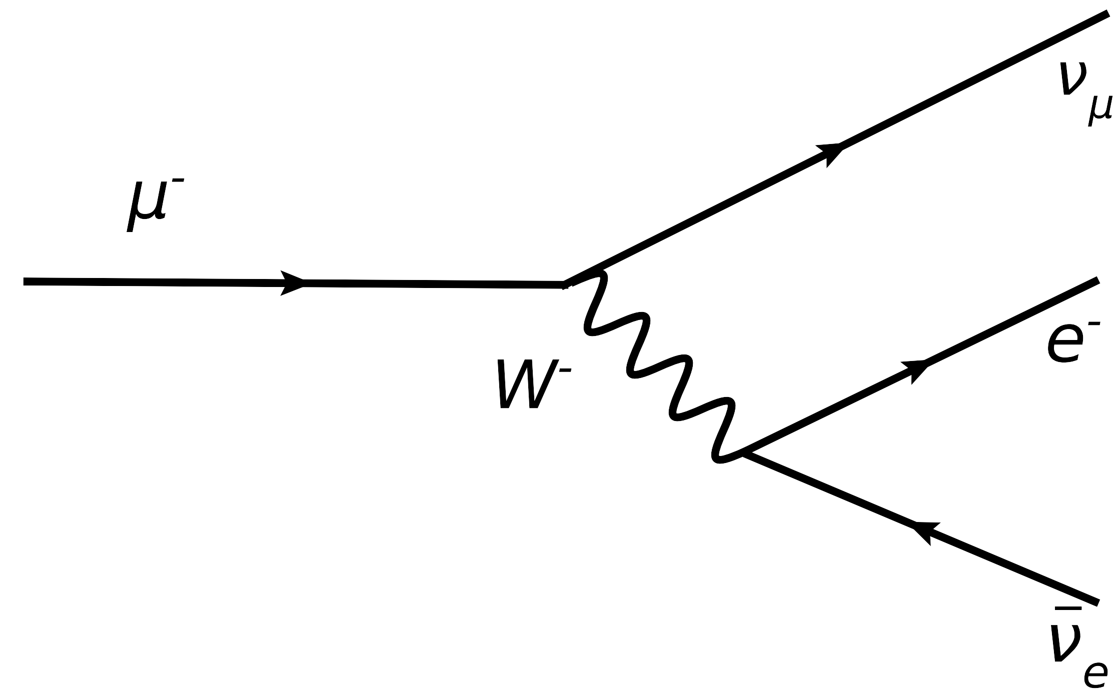
$$cqq$$

$$\Lambda_c^+, \Sigma_c, \Omega_c^0, \Xi_c, \ldots$$

Lifetimes

Lifetime

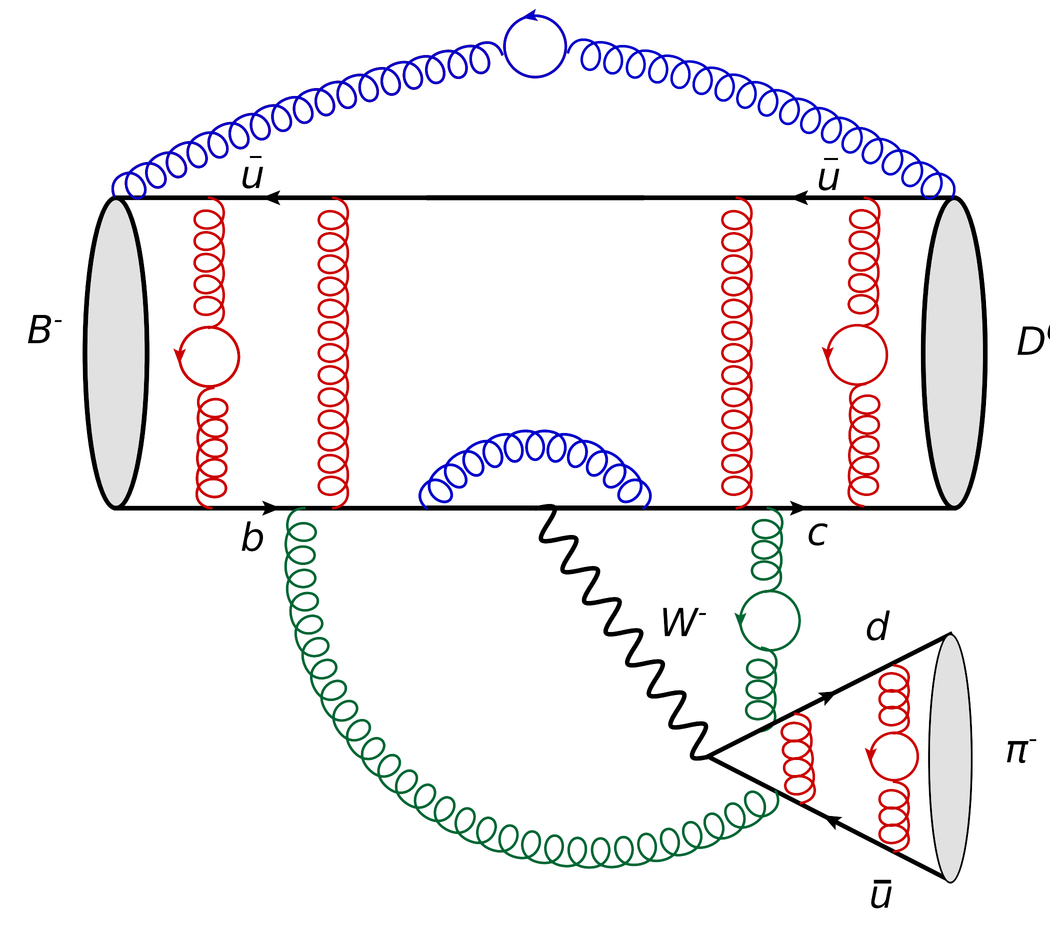
- lifetime is inverse of decay rate, $\tau = 1/\Gamma$
- e.g. decay of muon
- proportional to particle mass m^{-5}
- besides additional electro-weak corrections, this provides good estimate



$$\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3} f\left(\frac{m_e}{m_\mu}\right)$$

Lifetime

- lifetime is inverse of decay rate, $\tau = 1/(\Gamma_{\text{semi-lept}} + \Gamma_{\text{lept}} + \Gamma_{\text{had}})$
- for hadrons:
  - need to consider different types of weak decays
  - QCD effects for initial/final states and everything in between
- use HQE:
  - expansion in mass of heavy quark
  - corrections are significant for charm hadrons



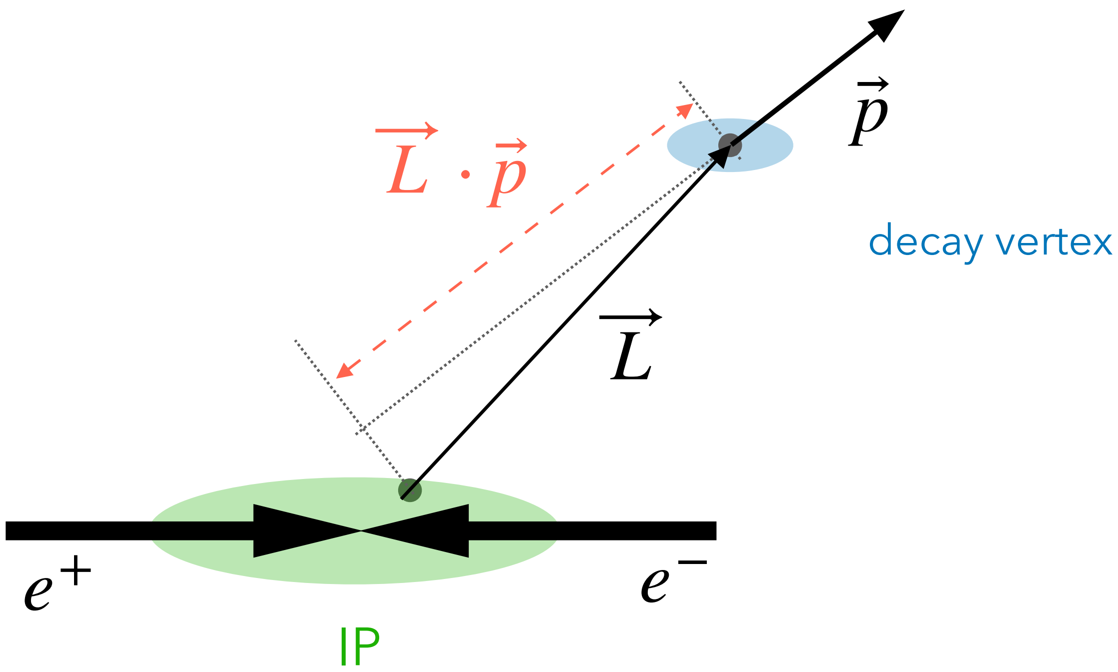
$$\Gamma = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_c^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left(\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_c^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_c^4} + \ldots \right)$$

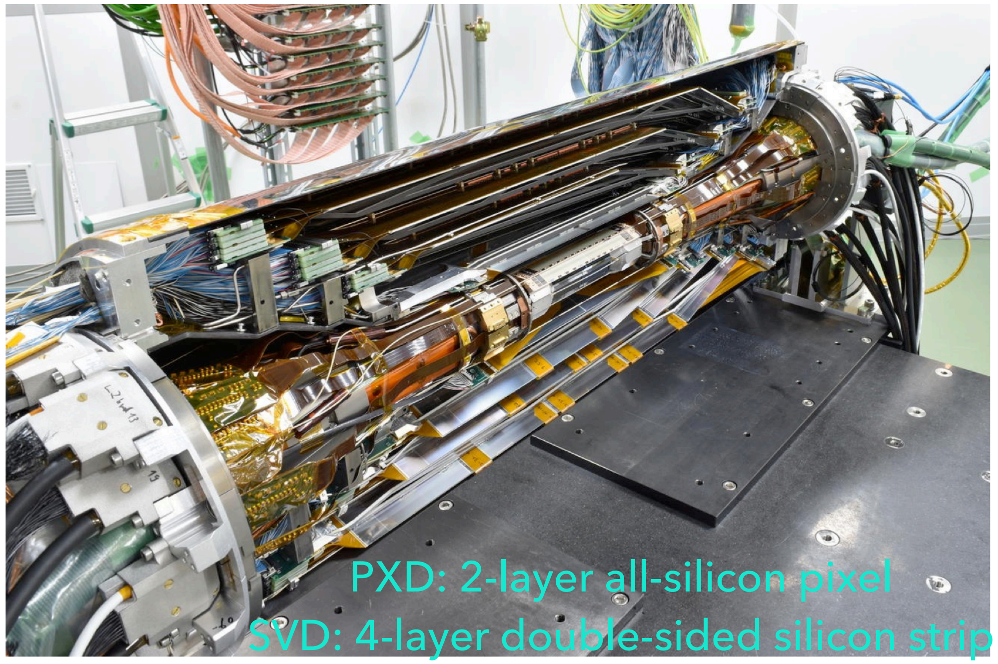
$$\Gamma_i \sim \frac{G_F^2 m_c^5}{192\pi^3} |V_{cs}|^2$$

How to measure a lifetime

- what we want
  - determine decay time t by measuring vertex displacement and momentum
  - decay-time uncertainty σ_t is obtained by propagating uncertainties of $\overrightarrow{L}$ and $\vec{p}$
- what we need
  - accurate VXD alignment,
  - precise calibration of final-state particle momenta
  - powerful background discrimination

$$t = m_C \frac{\overrightarrow{L} \cdot \vec{p}}{|\vec{p}|^2}$$





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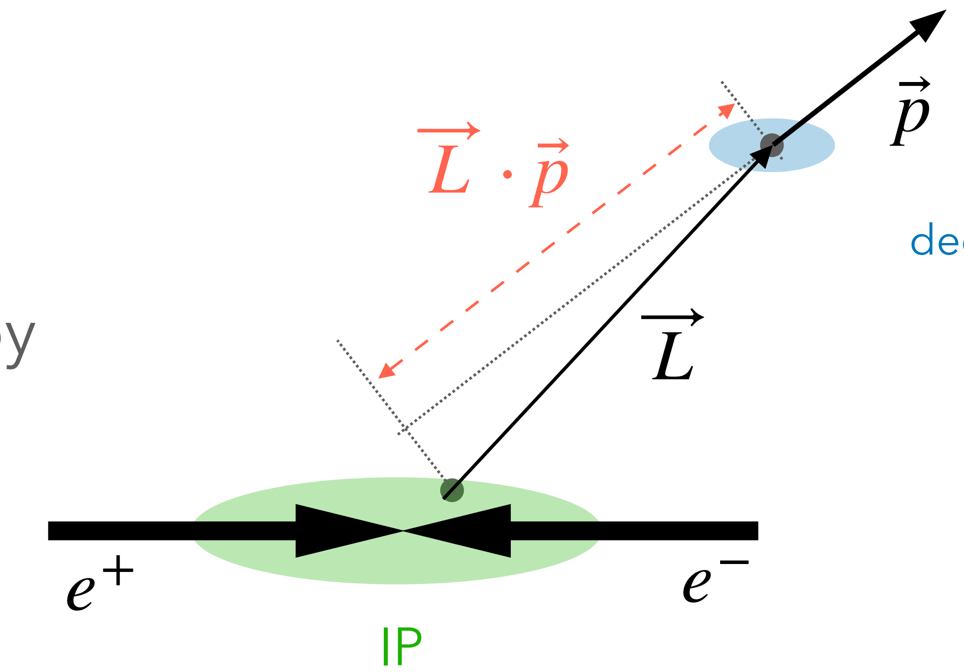
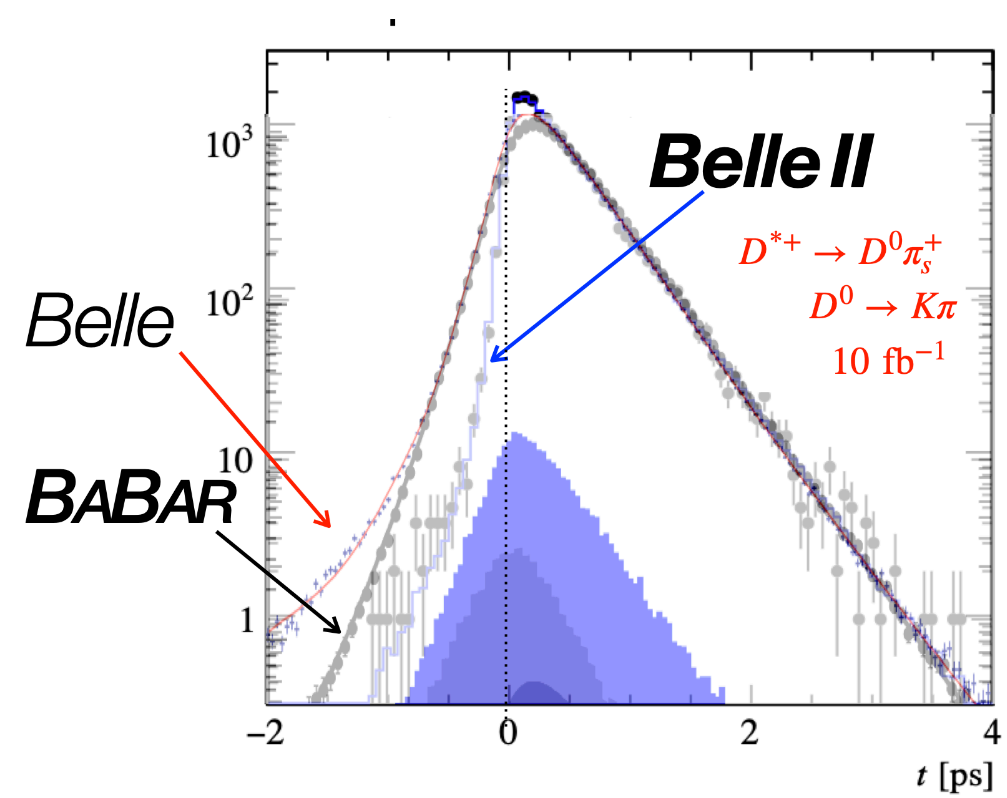
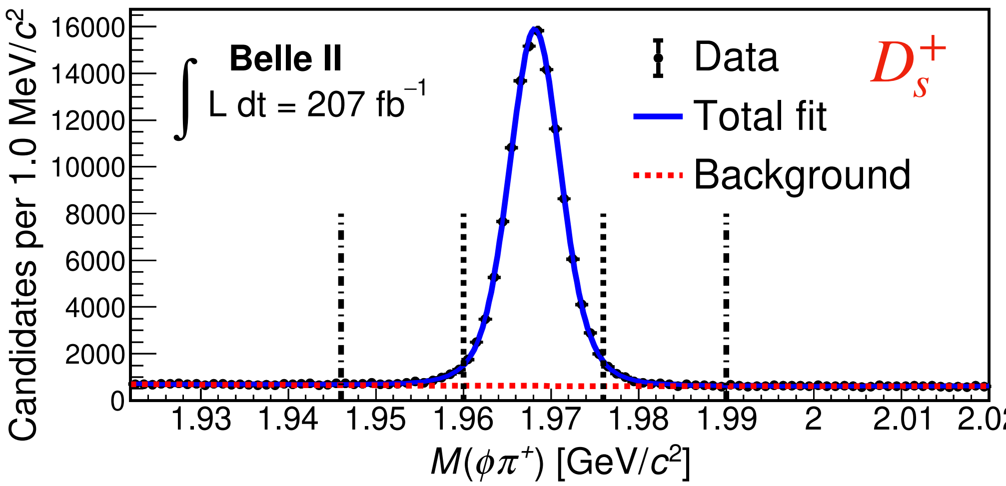
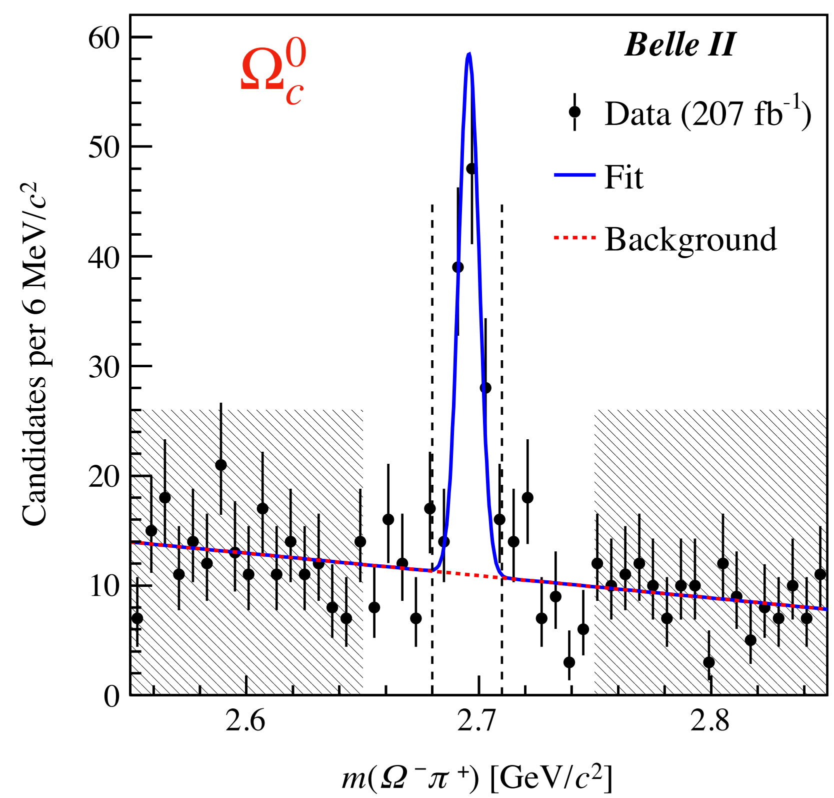




Measurements

- select high-purity samples of:
  - $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$
  - $\Lambda_c^+ \to pK^-\pi^+$
  - $\Omega_c^0 \to \Omega^-\pi^+$
  - $D_s^+ \to \phi\pi^+$
- avoid selection criteria that bias the decay time





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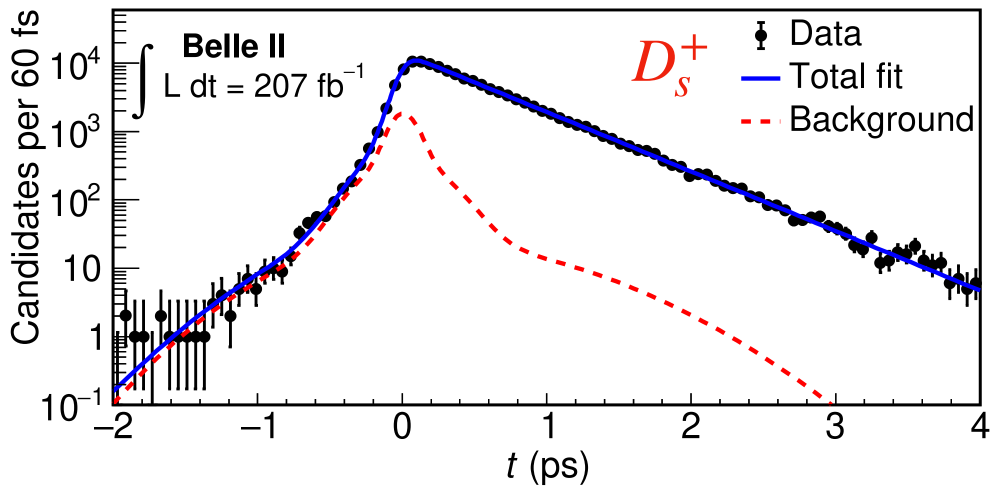
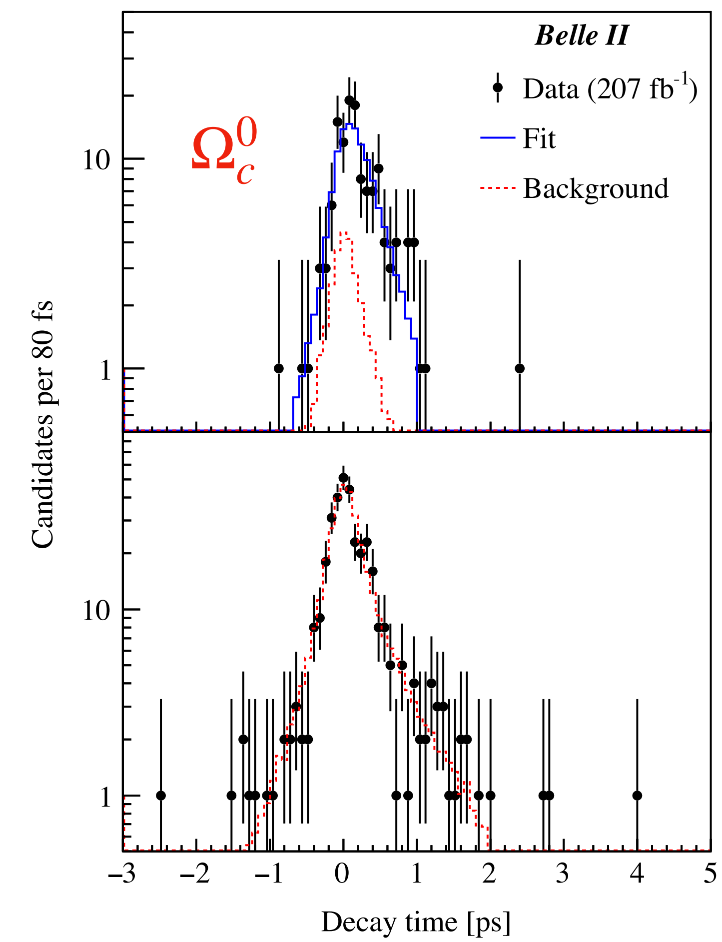
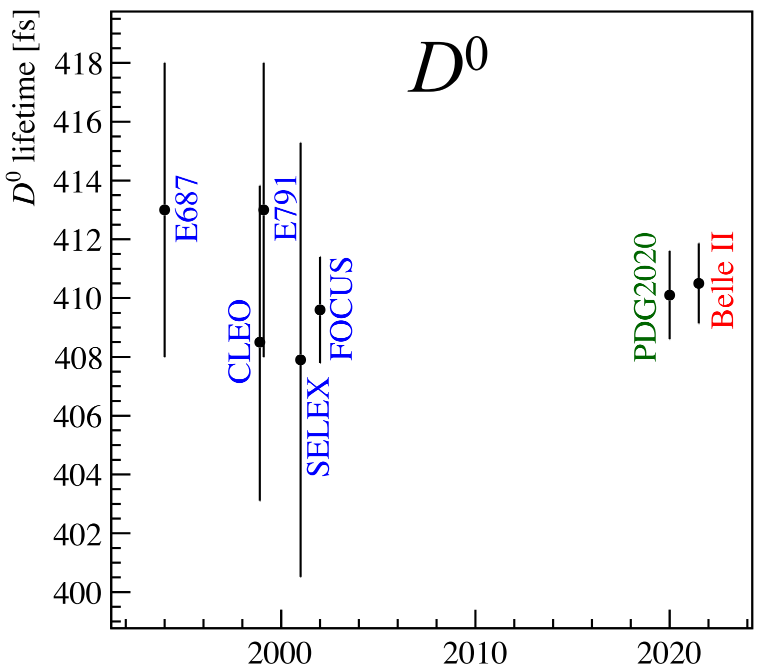
  - $\Omega_c^0 \to \Omega^-\pi^+$
  - $D_s^+ \to \phi\pi^+$
- avoid selection criteria that bias the decay time
- extract lifetime with a fit to the (t, σ_t) distribution
  - σ_t is used as a width of a Gaussian resolution function
- detector misalignment among syst. uncertainties

$$P_{\text{sig}}(t^i \,|\, \tau, \sigma_t^i) \propto \int e^{-t'/\tau} R(t^i - t'; \sigma_t^i) dt'$$

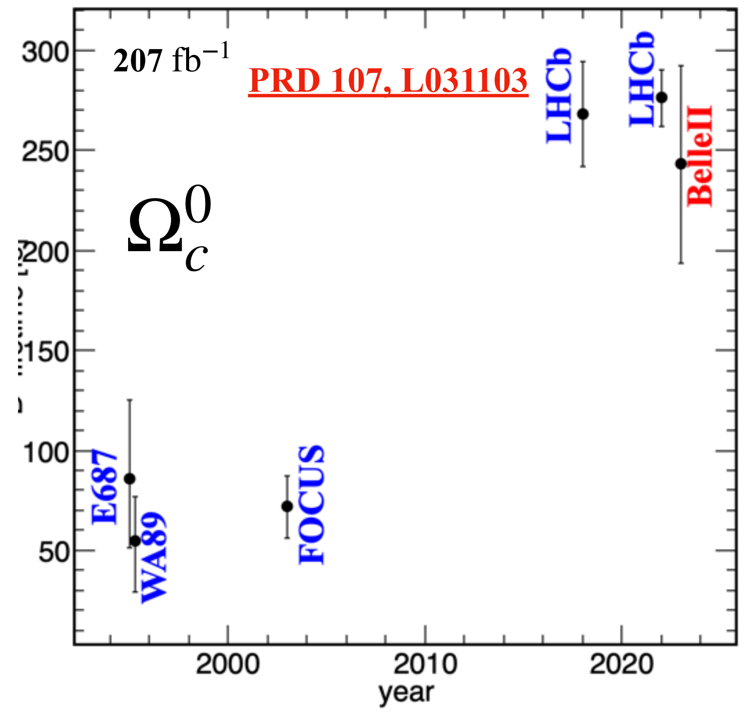




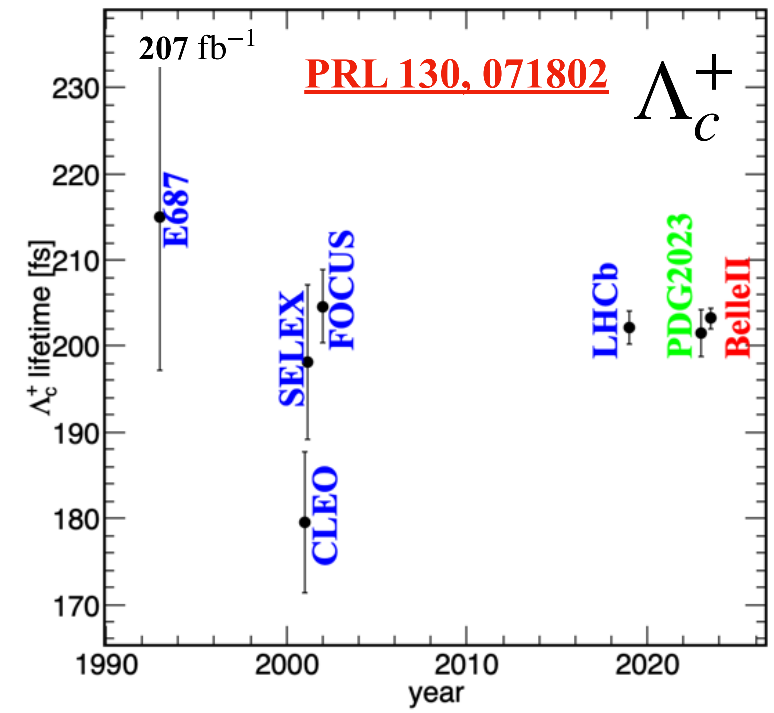
Results



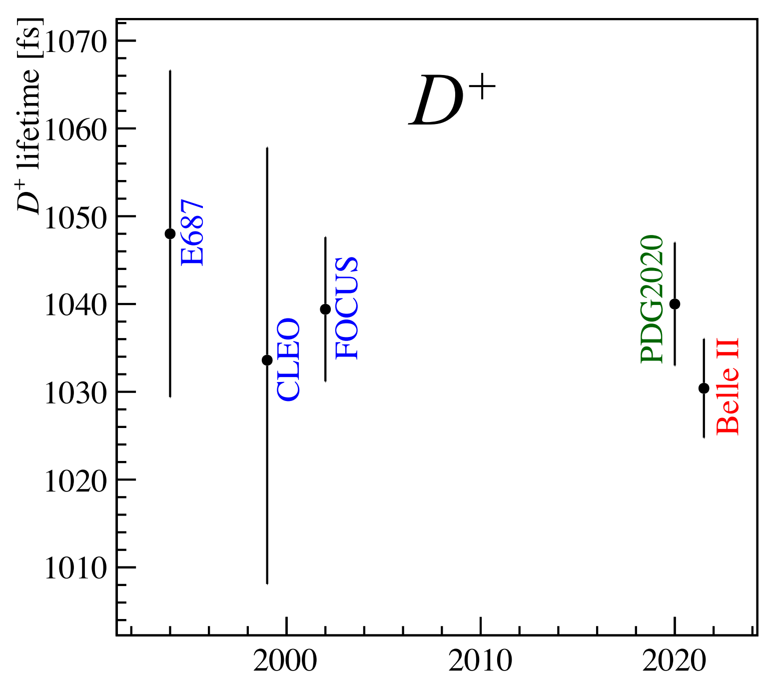
D0
D0 lifetime [fs]
E687
CLEO
E791
SELEX
FOCUS
PDG2020
Belle II



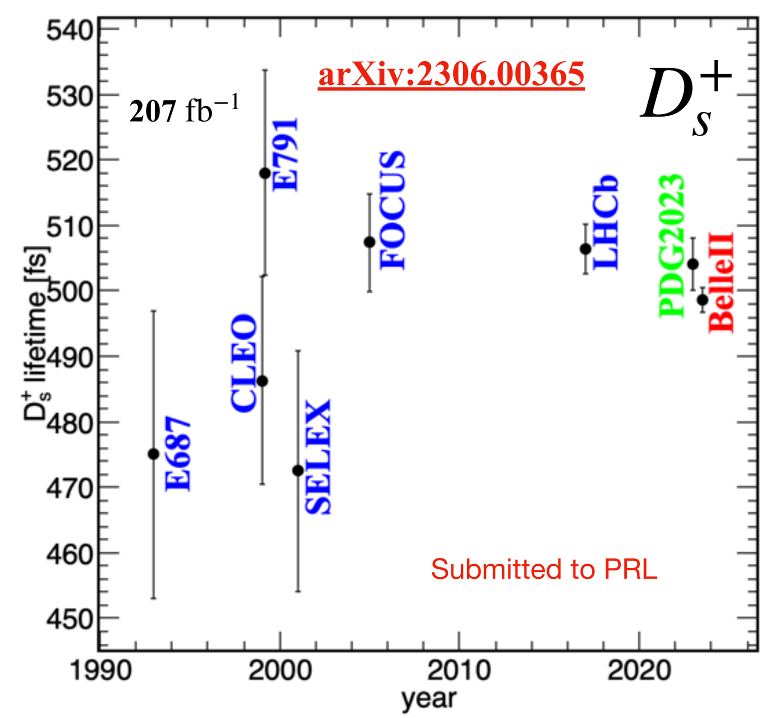
207 fb−1
PRD 107, L031103
Ωc0
E687
WA89
FOCUS
LHCb
LHCb
BelleII
year



207 fb−1
PRL 130, 071802
Λc+
Λc+ lifetime [fs]
E687
SELEX
FOCUS
CLEO
LHCb
PDG2023
BelleII
year



D+
D+ lifetime [fs]
E687
CLEO
FOCUS
PDG2020
Belle II



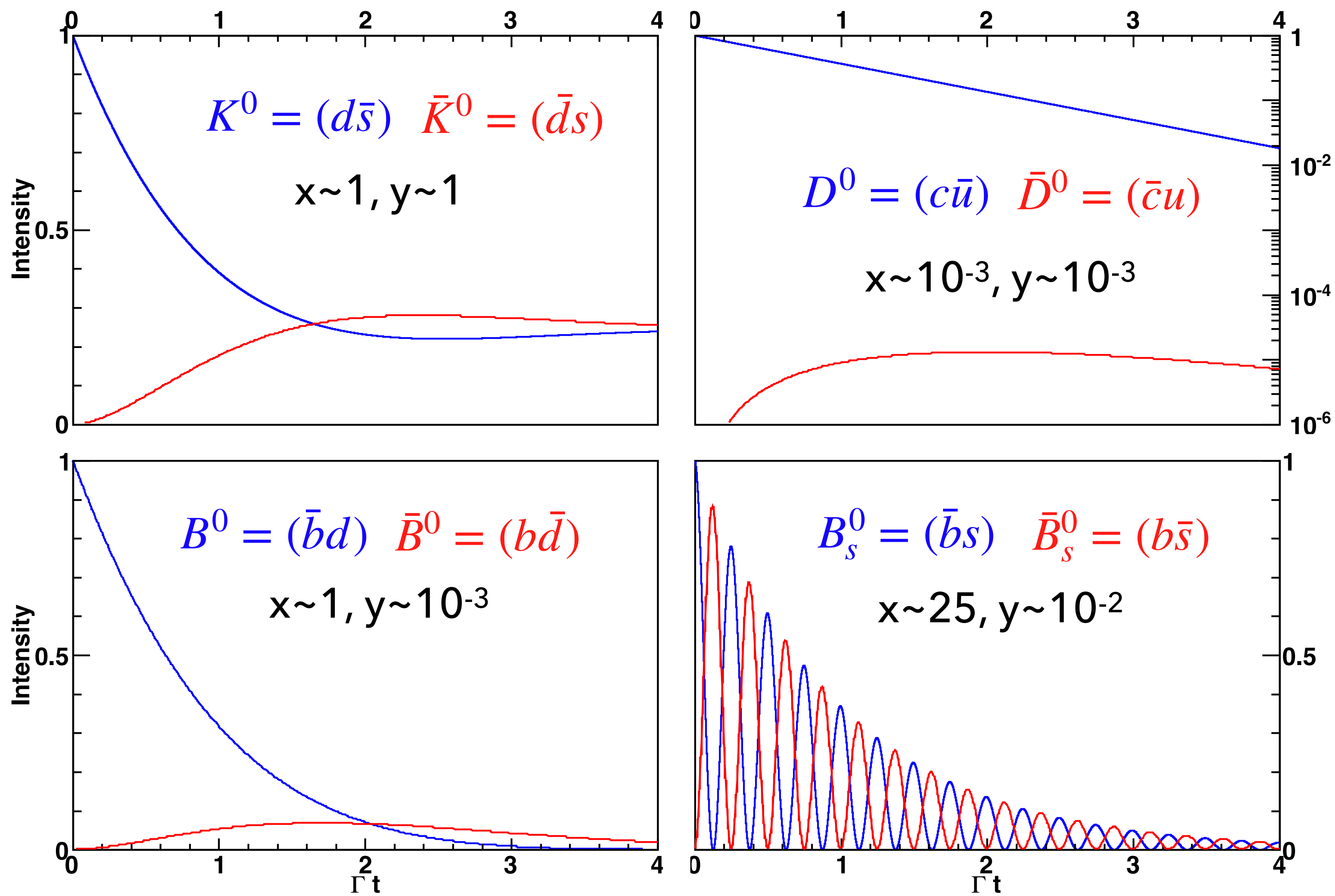
207 fb−1
arXiv:2306.00365
Ds+
Ds+ lifetime [fs]
E687
CLEO
E791
SELEX
FOCUS
LHCb
PDG2023
BelleII
Submitted to PRL
year

Mixing & CP Violation

To mix or not to mix

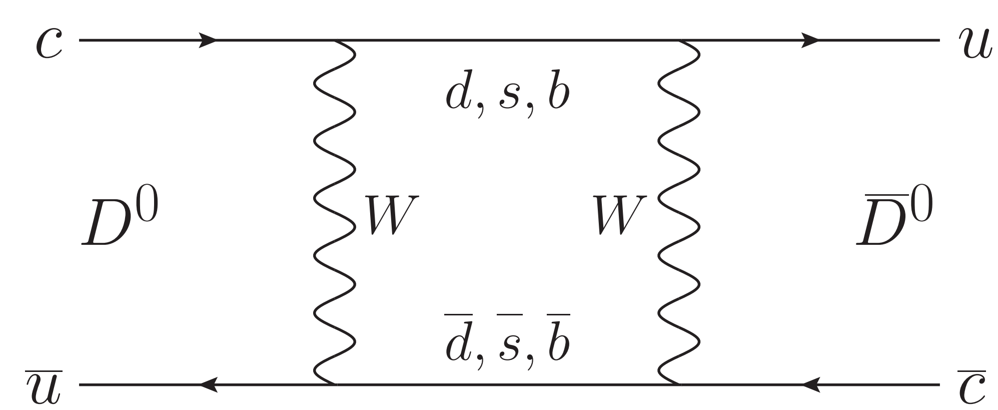
- The eigenstates of the neutral D meson are a mixture of the flavor states:

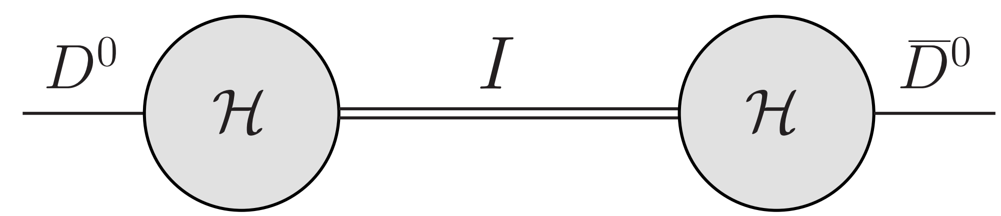
$$|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle \qquad x = \frac{m_2 - m_1}{\Gamma_1 + \Gamma_2} \qquad y = \frac{\Gamma_2 - \Gamma_1}{\Gamma_1 + \Gamma_2}$$



Short & Long

- mixing at short distances
  - box diagram involves loops with (d, s, b) quarks
  - GIM suppression, $(m_s^2 - m_d^2)^2 / m_W^2 m_c^2$
  - CKM suppression, $|V_{ub}V_{cb}^*|^2 / |V_{us}V_{cs}^*|^2 \sim 10^{-6}$
- mixing at long distances
  - non-perturbative, difficult to describe
  - inclusive (HQE) and exclusive (summing over intermediate resonances) approaches give varying estimates
- more to come





CP Violation

Three types of CP violation

- (I) in decay, $|\bar{A}_{\bar{f}}/A_f| \neq 1$
- (II) in mixing, $|q/p| \neq 1$
- (III) in interference between a decay with and without mixing, $\Im(\lambda_f) \neq 0$, $\lambda_f = q/p\,\bar{A}_f/A_f$

Strange	Beauty	Charm
(I), (II) and (III) in $K \to \pi\pi$ (II) also in $K \to \pi\ell\nu$, $K_L \to \pi^+\pi^-e^+e^-$ $\epsilon \sim 10^{-3}$	(I) in various decays of B^0, B^+ and B_s^0 (III) in $b \to c\bar{c}s$, $b \to c\bar{c}d$, $b \to c\bar{u}d$, $b \to q\bar{q}s\ldots$ $\mathscr{A}(K^+\pi^-) \sim 0.08$ $\mathcal{S}(\phi K) \sim 0.7$	

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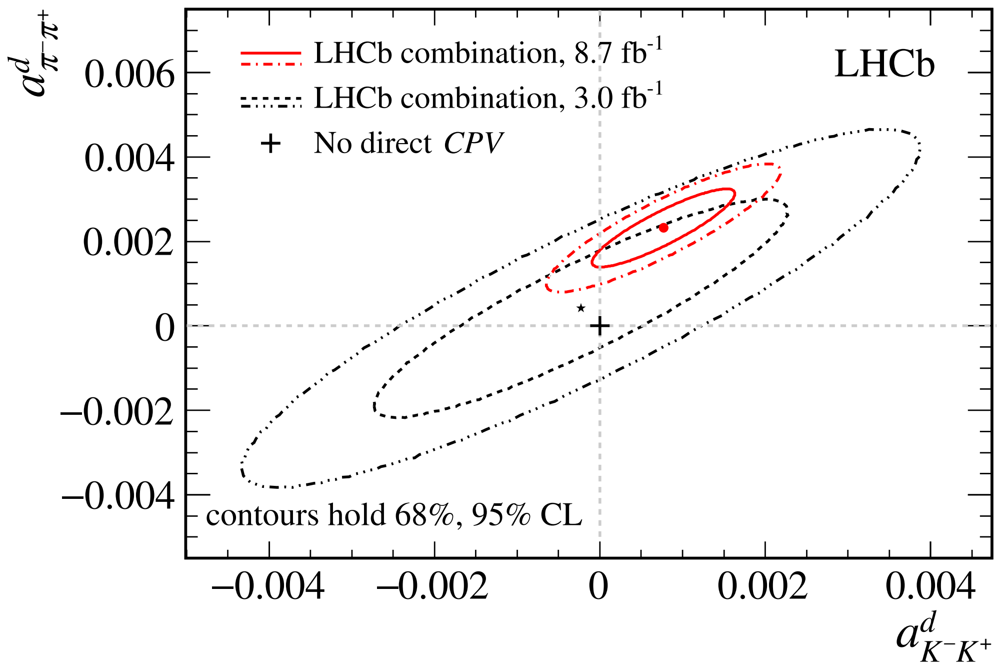
CPV in charm

- direct CPV has been established in 2019 (LHCb, link):
  - $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-0.154 \pm 0.029)\,\%$
- observed value is consistent with SM, challenges calculations and raises the question whether the signal is due to NP
- recent measurement from LHCb indicates direct CP violation in $D^0 \to \pi^+\pi^-$ at 3.8σ (link)
- at Belle II focus on $D^+ \to \pi^+\pi^0$ and $D^0 \to \pi^0\pi^0$ (isospin sum rule)

$$R = \frac{A_{CP}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} + \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} - \frac{A_{CP}(D^+ \to \pi^+\pi^0)}{1 + \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)}$$



CP Asymmetry

$$A_{CP}(D \to f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

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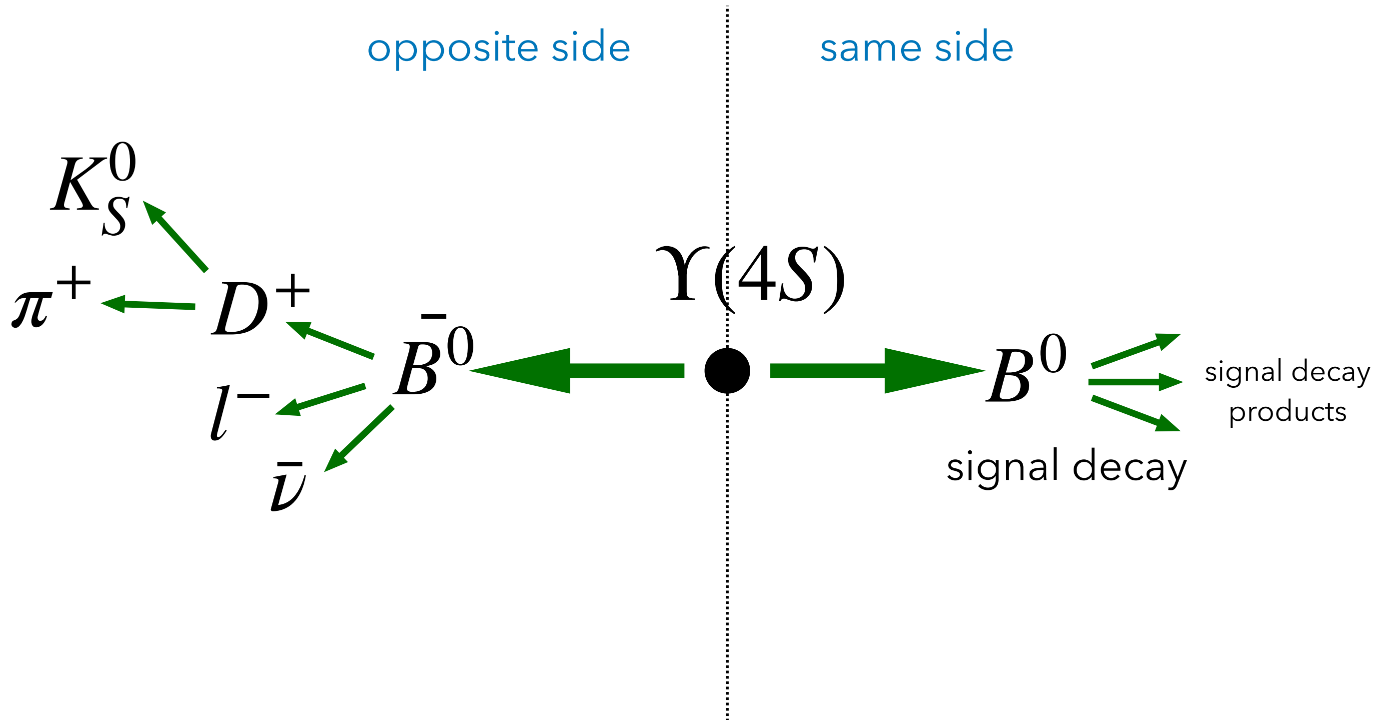
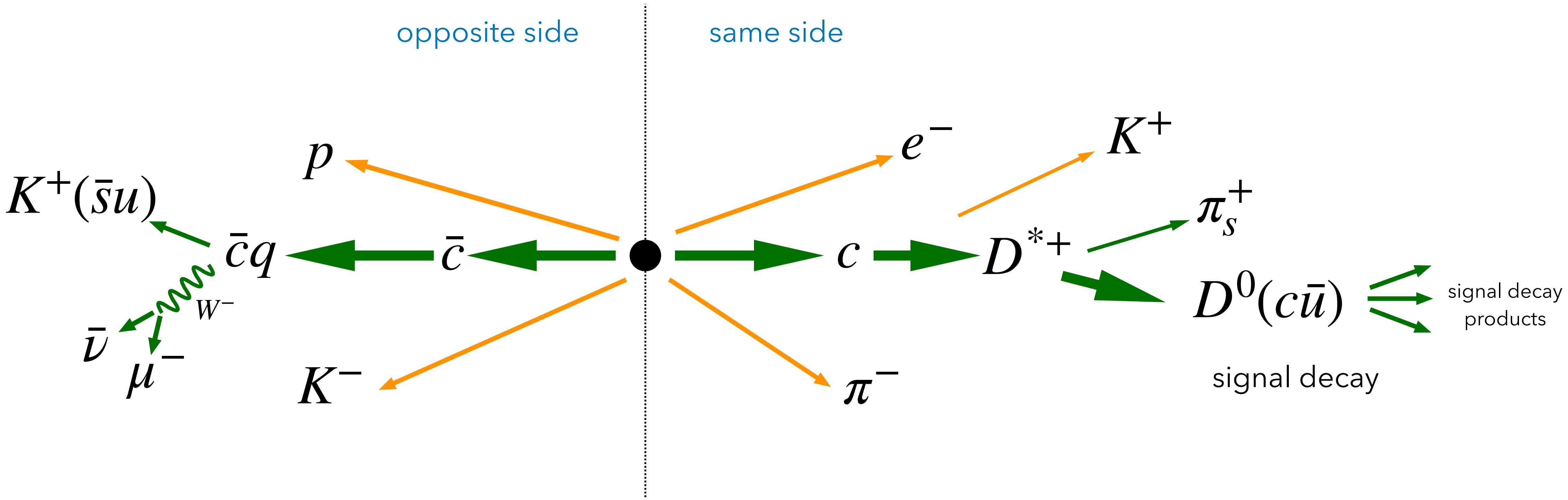
One of the main ingredients of any CPV (mixing) measurements is **flavor tagging**
→determine the signal flavor at the time of production

A typical beauty event



- $e^+e^- \to \Upsilon(4S) \to$ two beauty mesons
  - quantum entanglement
  - flavor of signal B can be determined from flavor of opposite-side B

A charm event is different



- $e^+e^- \rightarrow$ two charm hadrons + fragmentation
  - no entanglement, inaccessible strong phase

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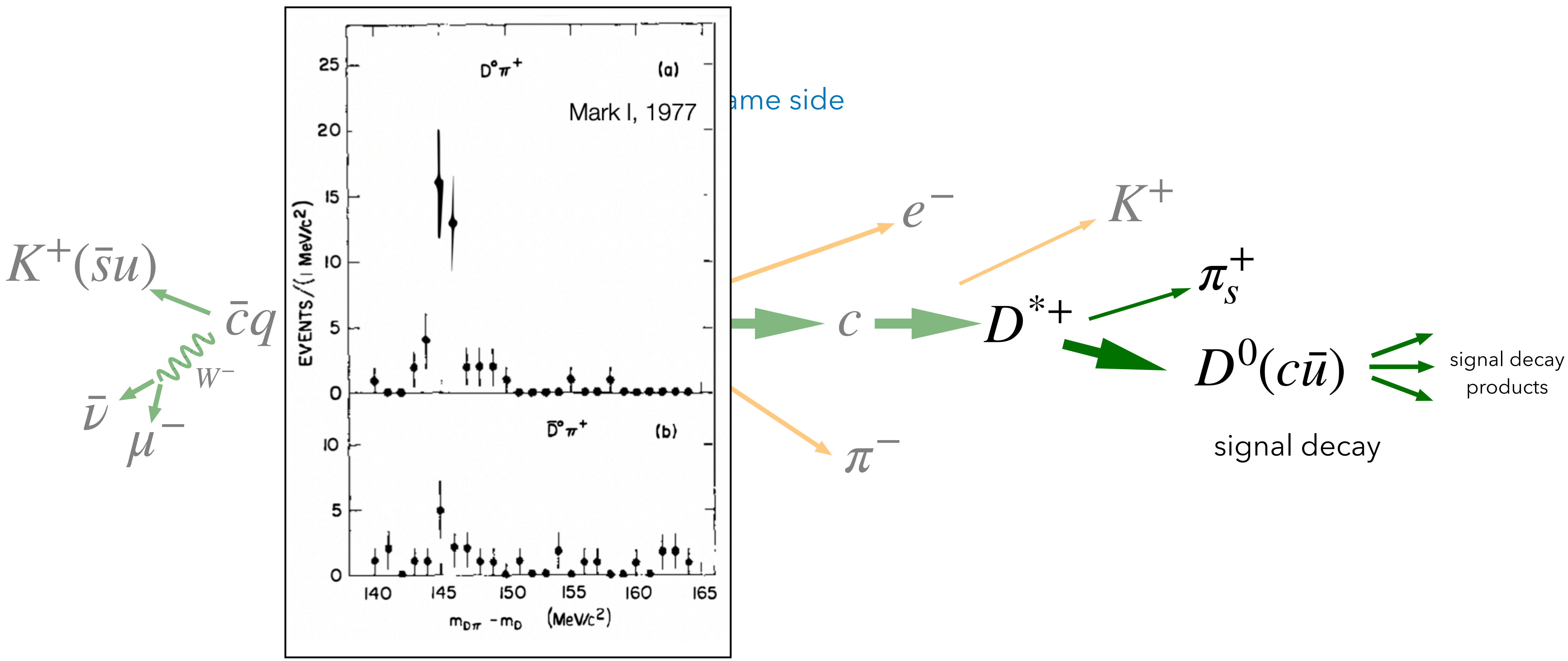

- $e^+e^- \rightarrow$ two charm hadrons + fragmentation
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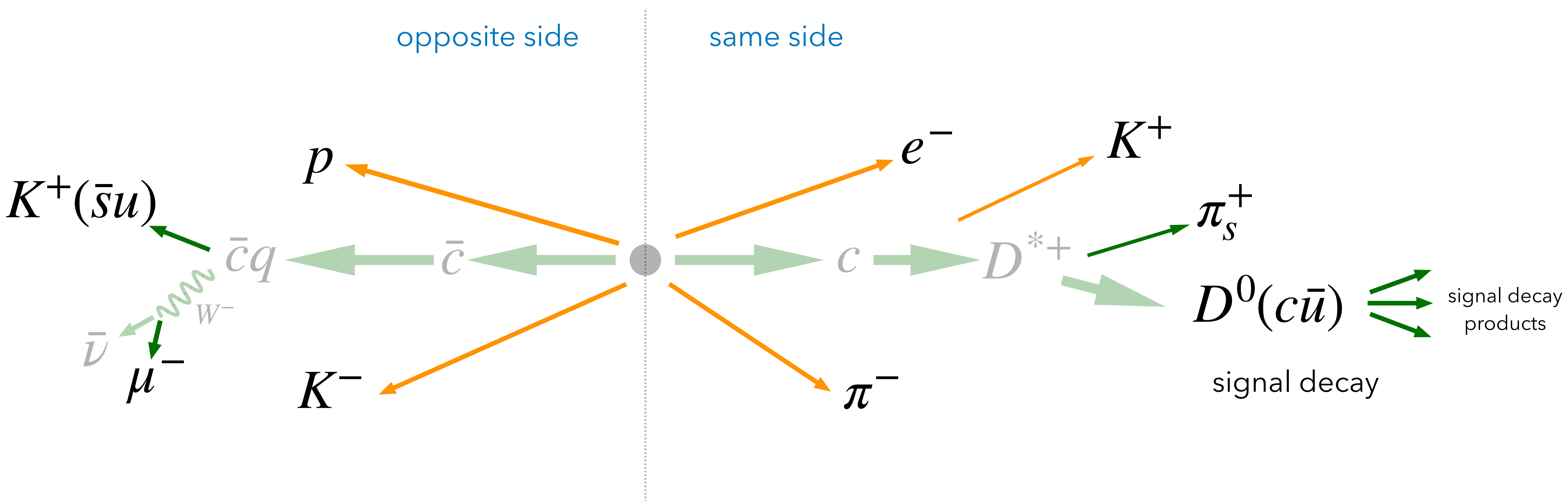
- standard approach (since 1977): **exclusive reconstruction** of strong decay $D^{*+} \rightarrow D^0\pi_s^+$
  - inefficient reconstruction of slow=low momentum pion
  - loss in statistics (only ~25% of all charm quarks hadronize into D^*)

slow pion: $M(D^{*+}) - M(D^0) \approx 145\,\mathrm{MeV}/c^2$

A charm event is different



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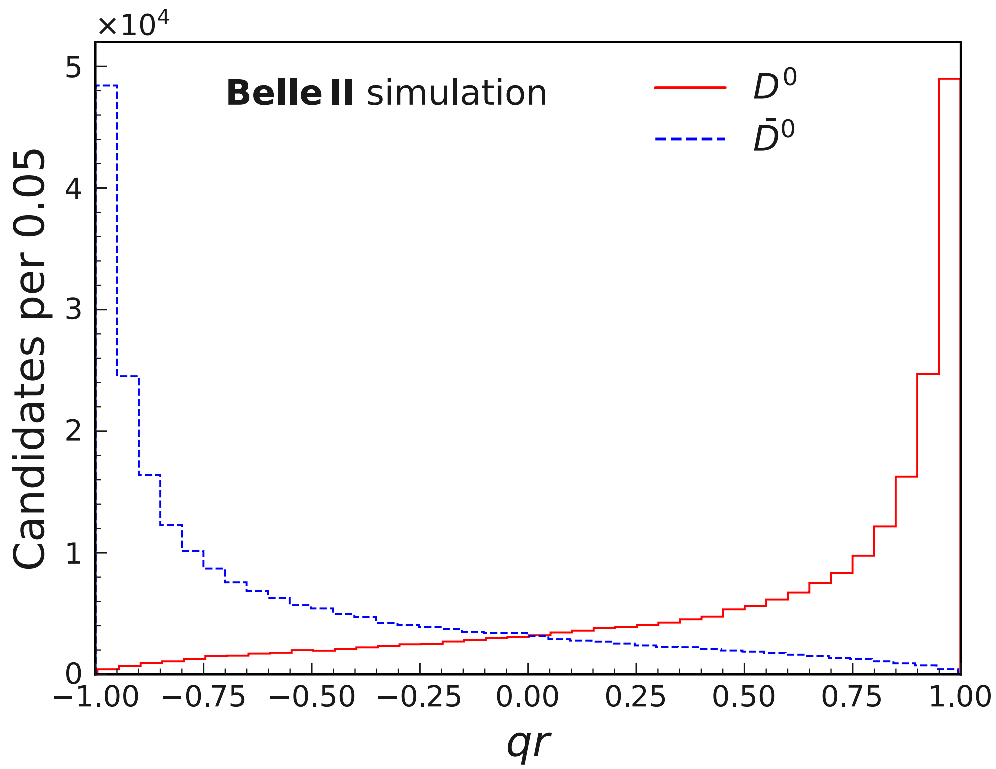
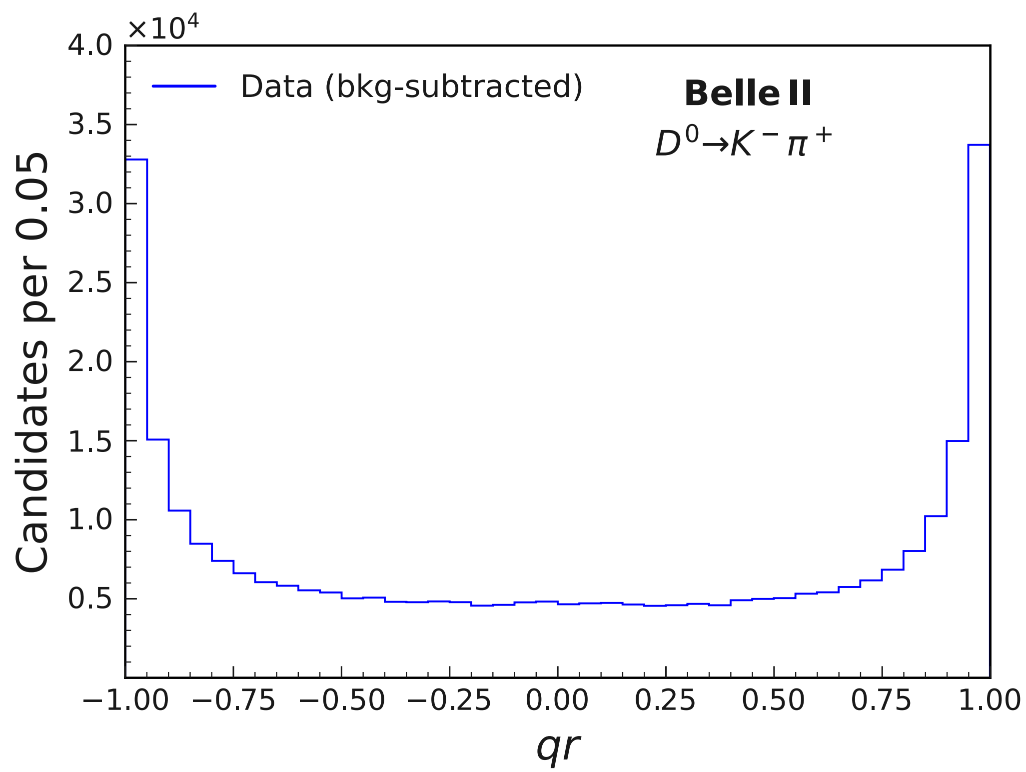
  - loss in statistics (only ~25% of all charm quarks hadronize into D^*)
- a new **more inclusive** method is desirable to exploit correlation between signal flavor and charge of tagging particles

The Charm Flavor Tagger (CFT)

- reconstruct particles most collinear with signal meson
- uses **kinematic features** (ΔR, recoiling mass) and **PID** of tagging particles
- based on BDT, **predicts** qr (tagging decision q and dilution r)
- trained using simulation and calibrated with Belle II data





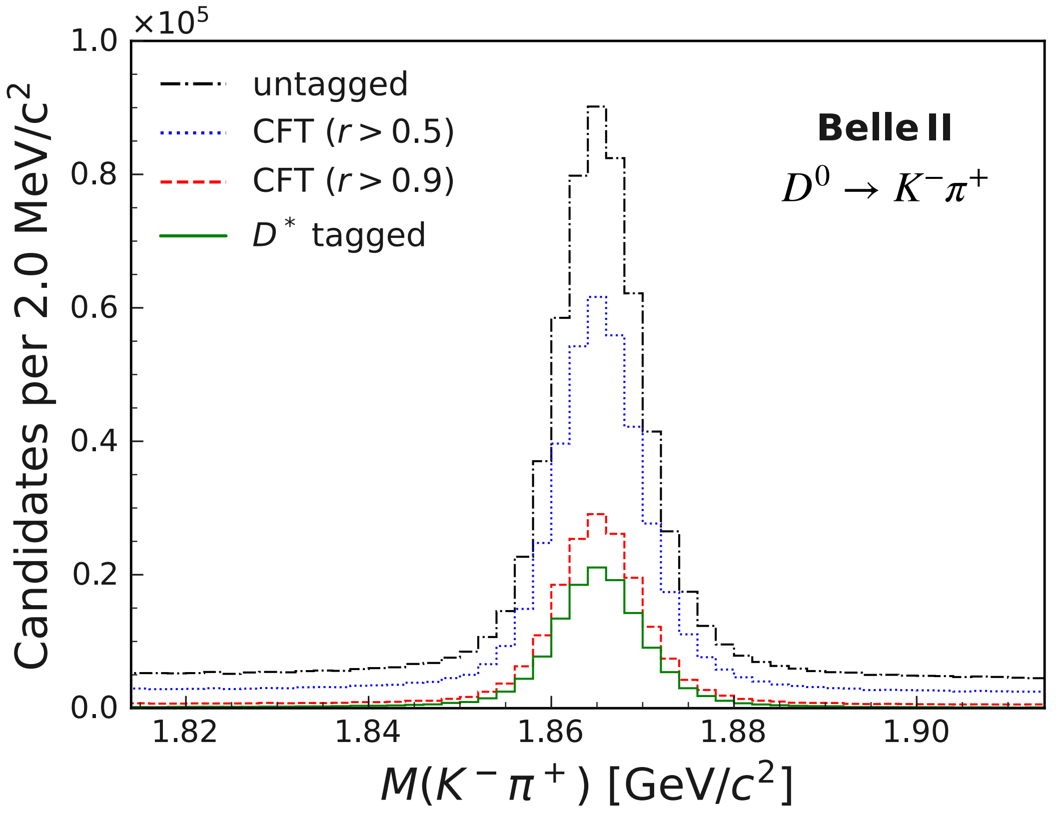
q=+1 for D^0 and -1 for $\bar{D}^0$
r=1 perfect prediction, r=0 random guessing

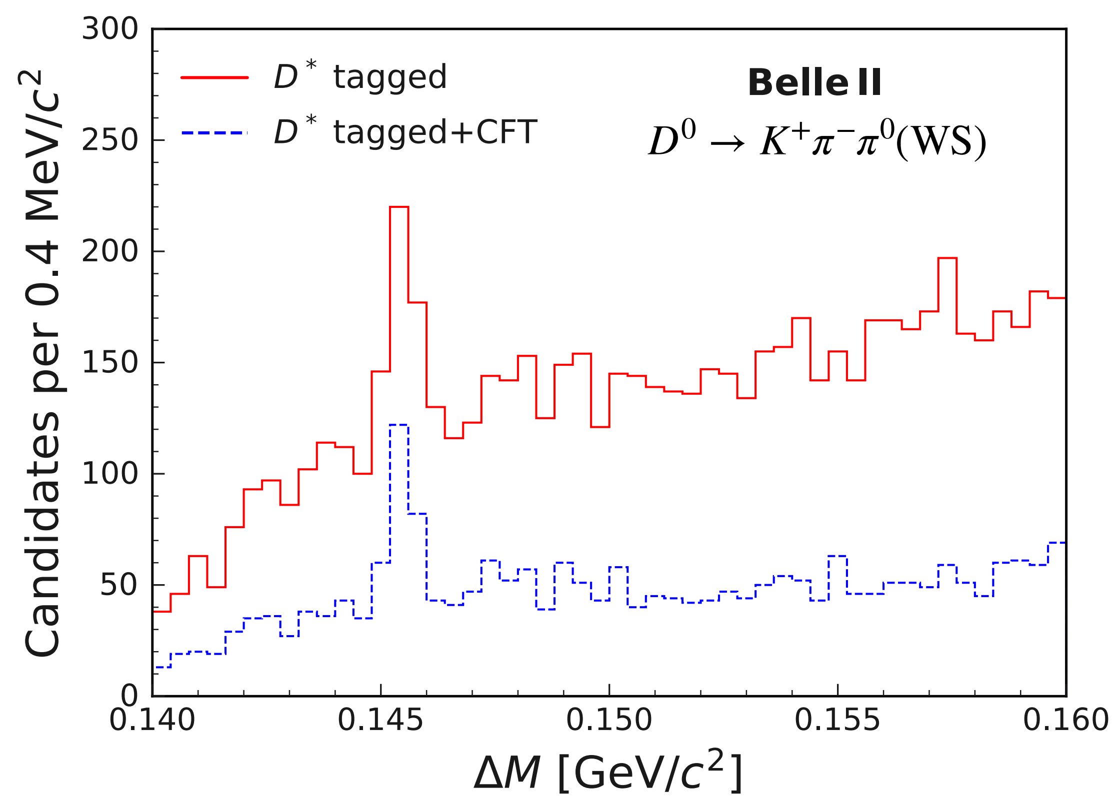
$$\epsilon_{\text{tag}}^{\text{eff}} = (47.91 \pm 0.07(\text{stat.}) \pm 0.51(\text{syst.}))\ \%$$

tagging power: $\epsilon_{\text{tag}}^{\text{eff}} = \epsilon_{\text{tag}} \langle r^2 \rangle$

The Charm Flavor Tagger (CFT)

- **double** the sample **size** w.r.t D^{*+}-tagged events
- provide discrimination between signal and background
- CFT will increase sensitivity for many charm decays:
  - $D^0 \to \pi^0\pi^0, K_S^0 K_S^0, K\pi\pi^0, \pi\pi\pi^0 \ldots$

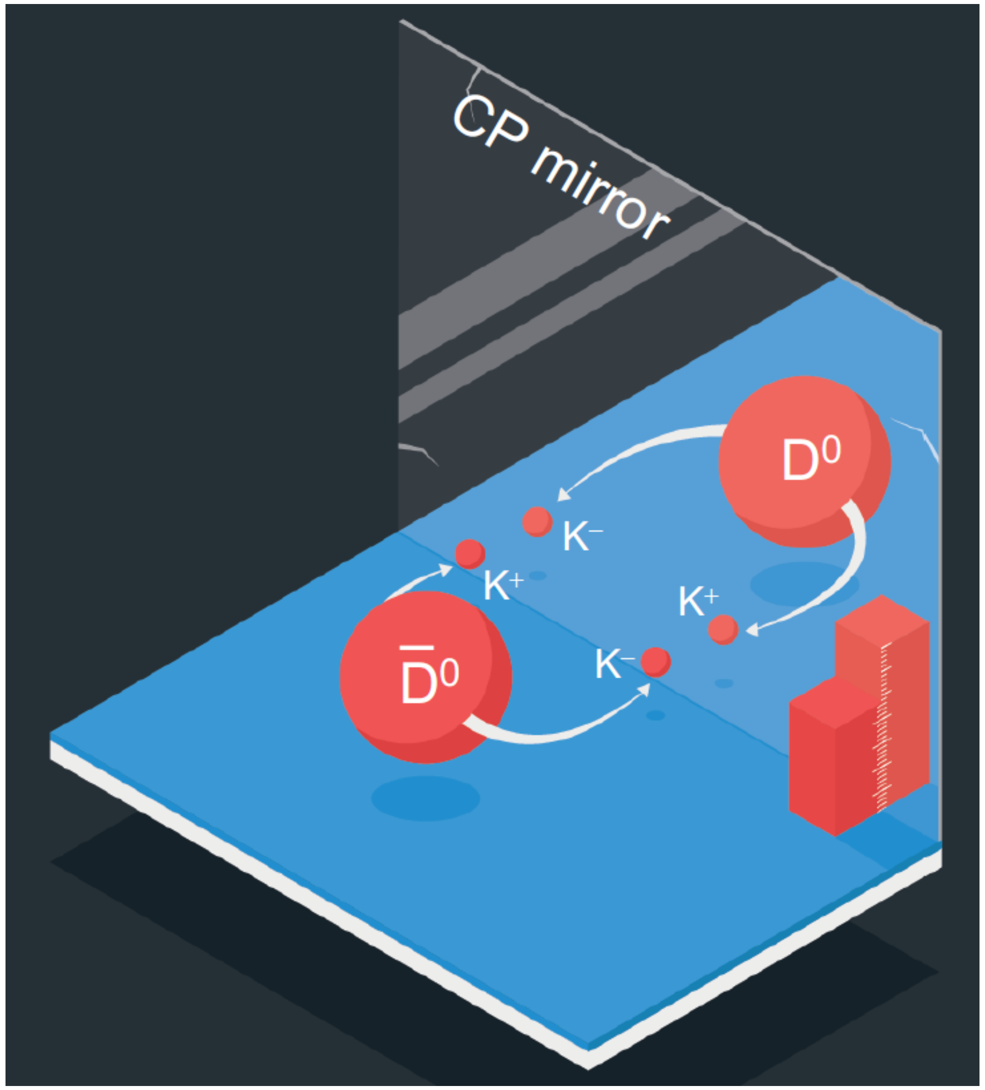




What we are doing

CP Violation

- Direct CPV in:
  - Mesons
    - $D^0 \to \pi^0\pi^0$(link), $D^0 \to K_S^0 K_S^0$(link), $D^+ \to \pi^+\pi^0$
    - neutrals in final state → Belle II territory
  - Baryons
    - $\Xi_c^+ \to \Sigma_+ h^+ h^-$ $(h = K, \pi)$ (link)
    - largely unexplored domain

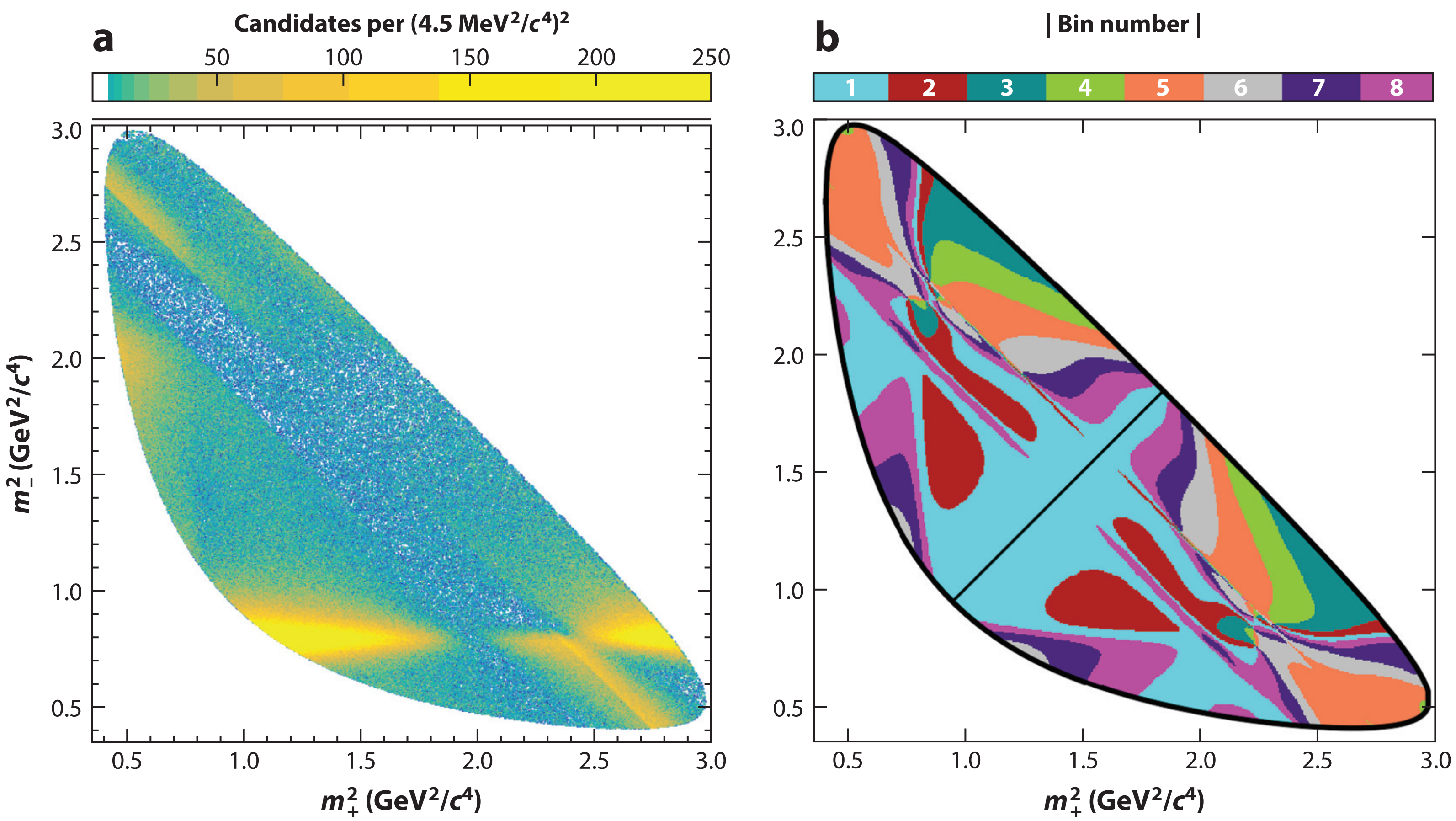


$$A_{\text{raw}} = A_{CP} + A_{\text{det}} + A_{\text{prod}} + A_{\text{tag}}$$

Mixing & CPV

$$R(t/\tau) \approx R_D + \sqrt{R_D}y'(t/\tau) + \frac{x'^2 + y'^2}{4}(t/\tau)^2$$

- flavor eigenstates
  - $D^0 \to K^+\pi^-\pi^0$ (link)
  - ratio of DCS over CF
  - x, y rotated by strong phase
- self-conjugate final states
  - $D^0 \to K_S^0\pi^+\pi^-$(link)
  - direct access to x,y parameters
  - model-independent approach

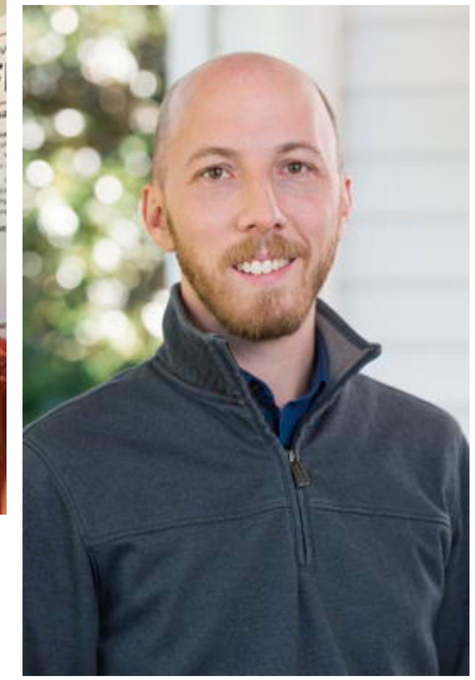


And much more

- $\Gamma(D_s^{*+} \to D_s^+\pi^0)/\Gamma(D_s^{*+} \to D_s^+\gamma)$ (link)
- Absolute BR of $\Xi_c(2790)^0$ (link)
- Inner structure of $D_s(2460)$ (link)
- BR of $D^+ \to \pi^+\ell^+\ell^+$ (link)
- $\Lambda_c^+ \to \Xi^0 K^+$ (link)
- T-odd correlation in $\Lambda_c^+ \to \Lambda K_S^0 h^+$ (link)
- …

Who we are





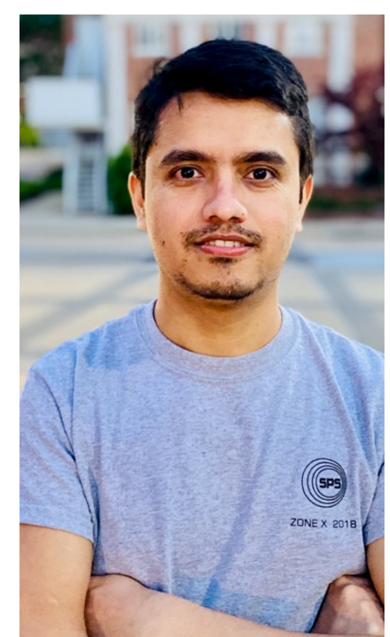














KEEP
CALM
AND
DO
CHARM