APS physics APRIL MEETING 2021

Q2C quarks cosmos

APRIL 17–20 ONLINE

Recent world leading results on charm, and exotic b decays

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(on behalf of the Belle II and LHCb collaborations)

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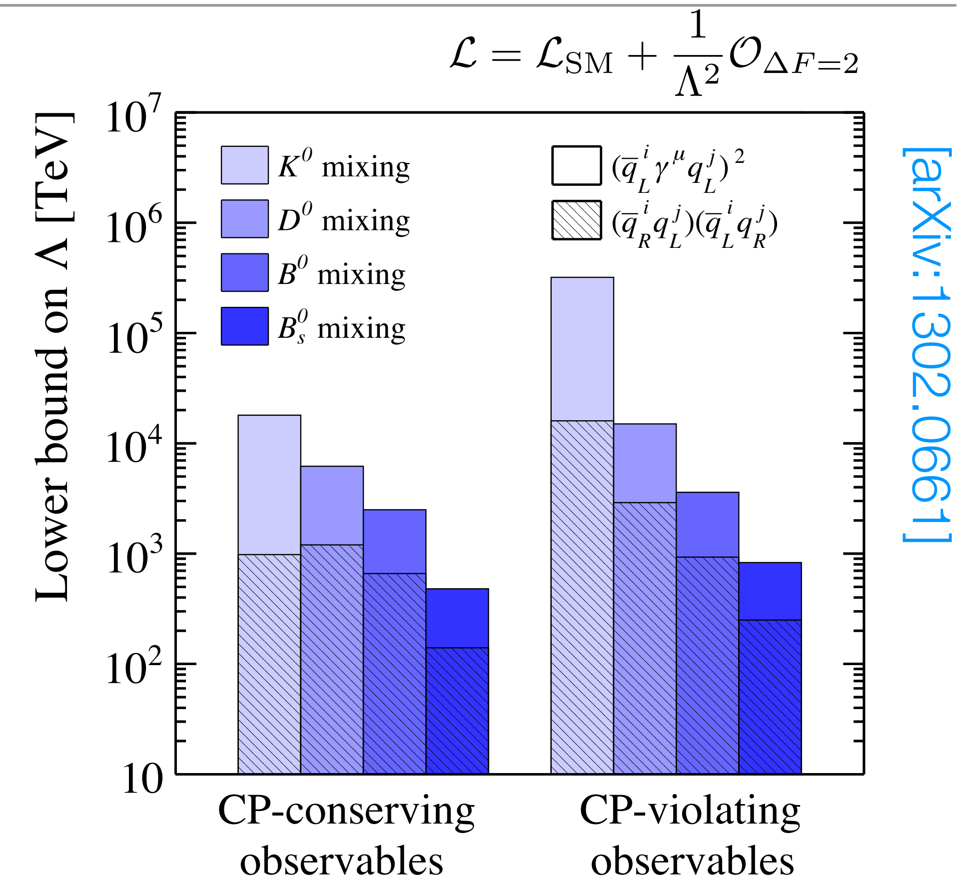
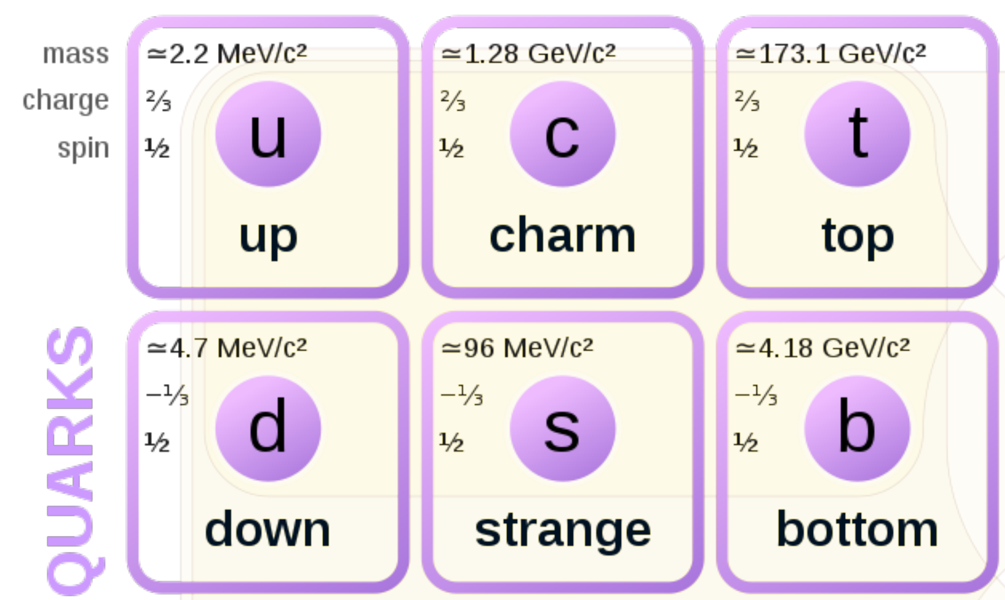
Why shall we bother about charm?

Discovery tool FCNC and *CP* violation are highly suppressed in the standard model. Potential room for new physics to show up

Unique Gives sensitivity to new physics coupling to up-type quarks (complementary to *K* and $B_{(s)}$ decays)

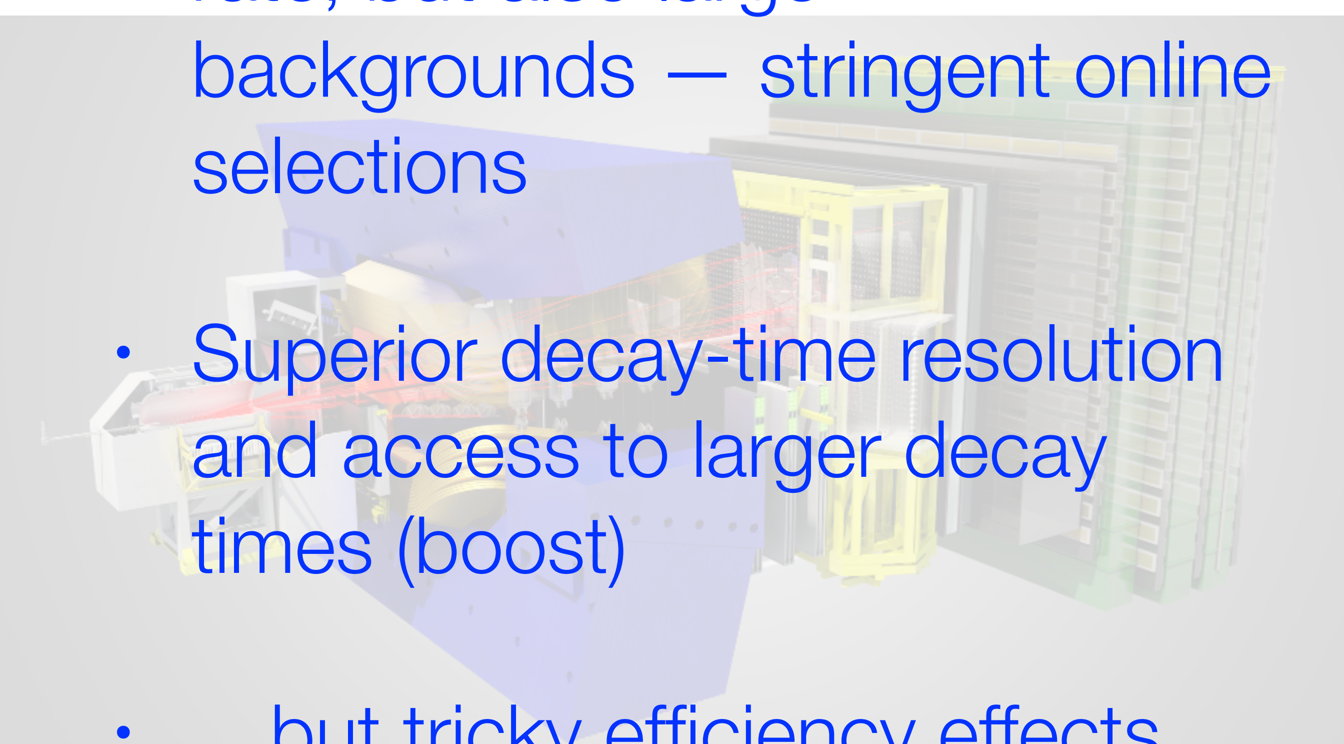
Challenging Predictions are difficult (impossible?), not a precision probe. However, an interesting laboratory for non-perturbative QCD and (exotic) hadron dynamics





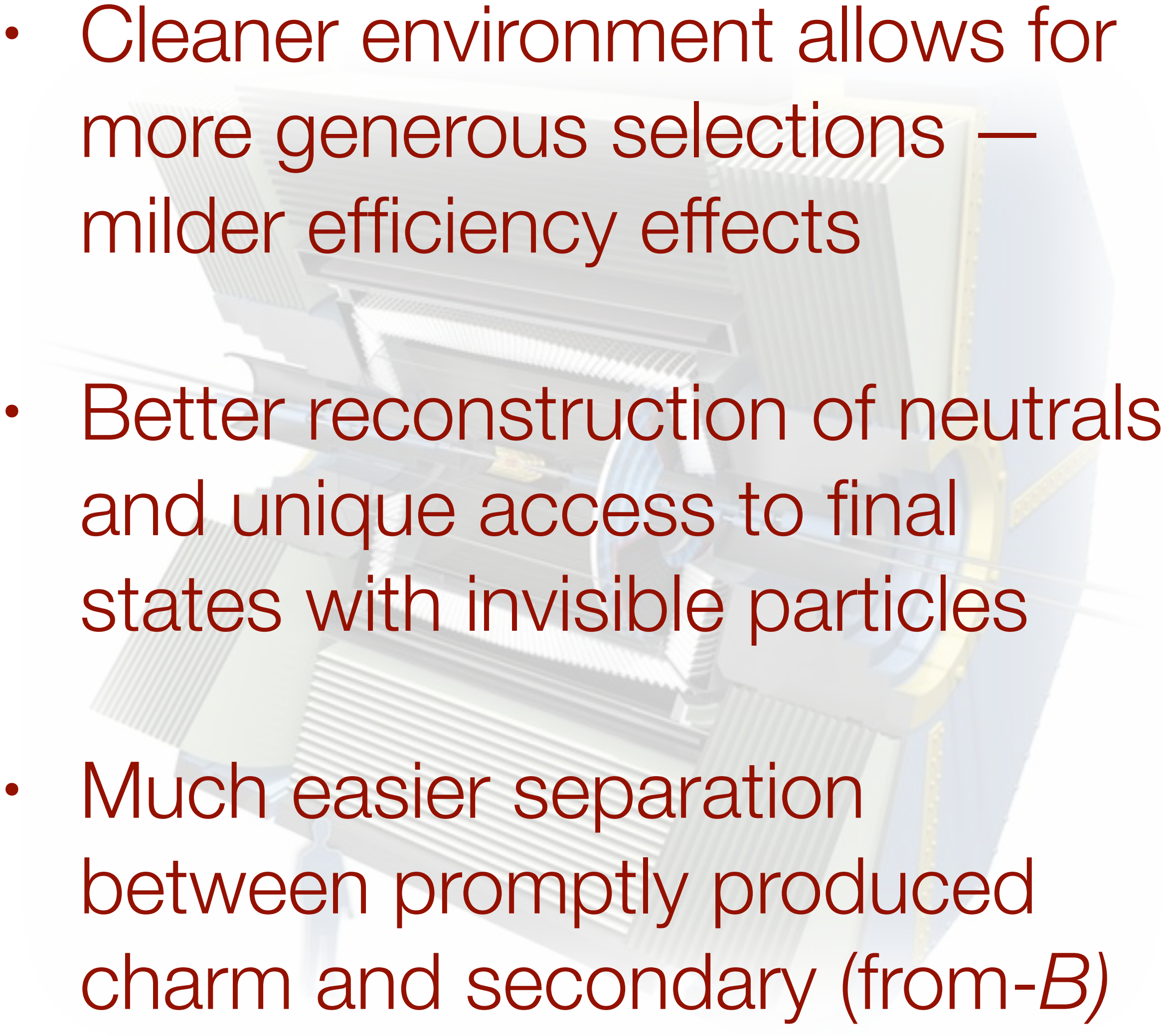
Two concurrent charm factories (not at threshold)

LHCb



- Huge advantage in production rate, but also large backgrounds — stringent online selections
- Superior decay-time resolution and access to larger decay times (boost)
- …but tricky efficiency effects (*e.g.* decay-time acceptance)

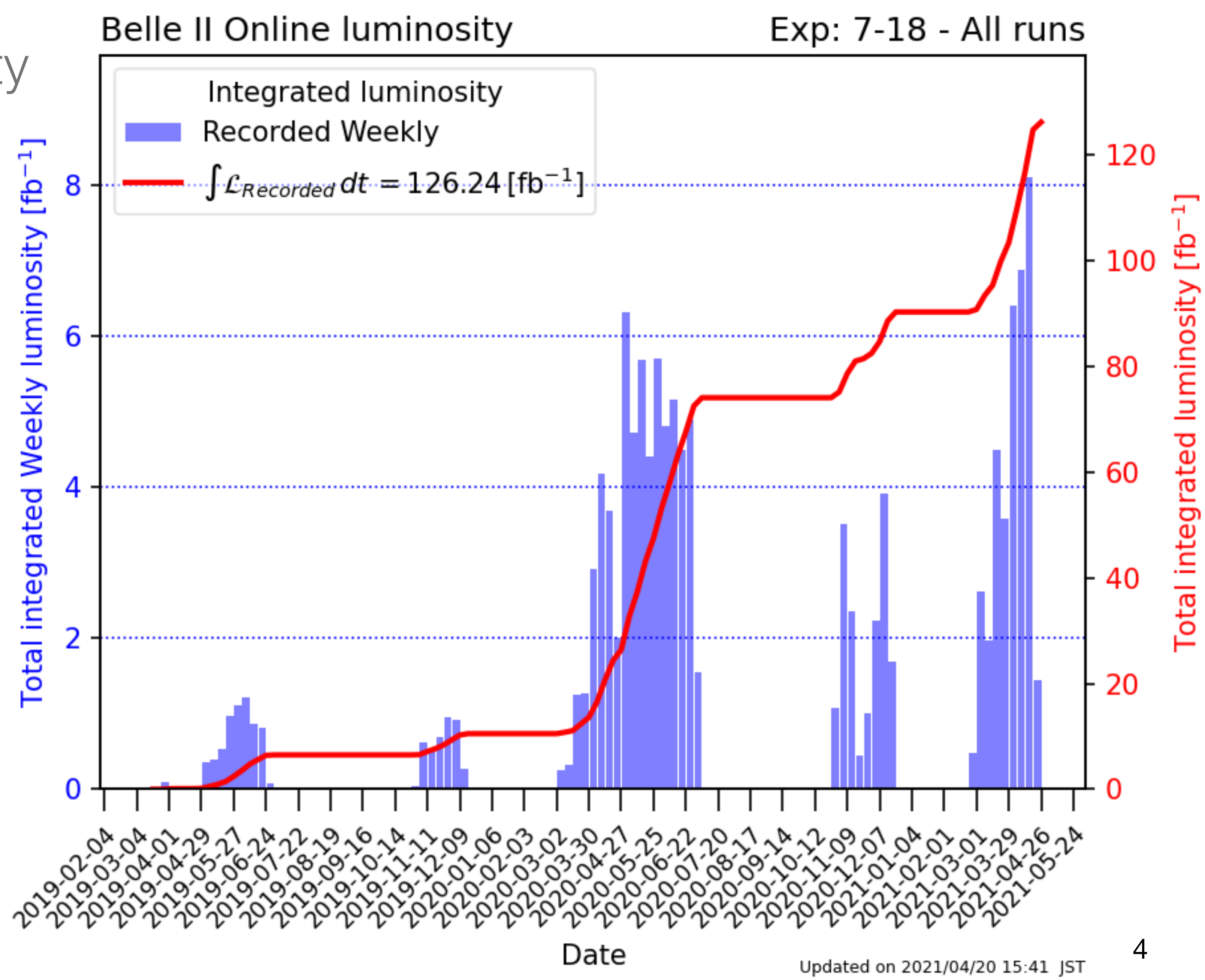
Belle II



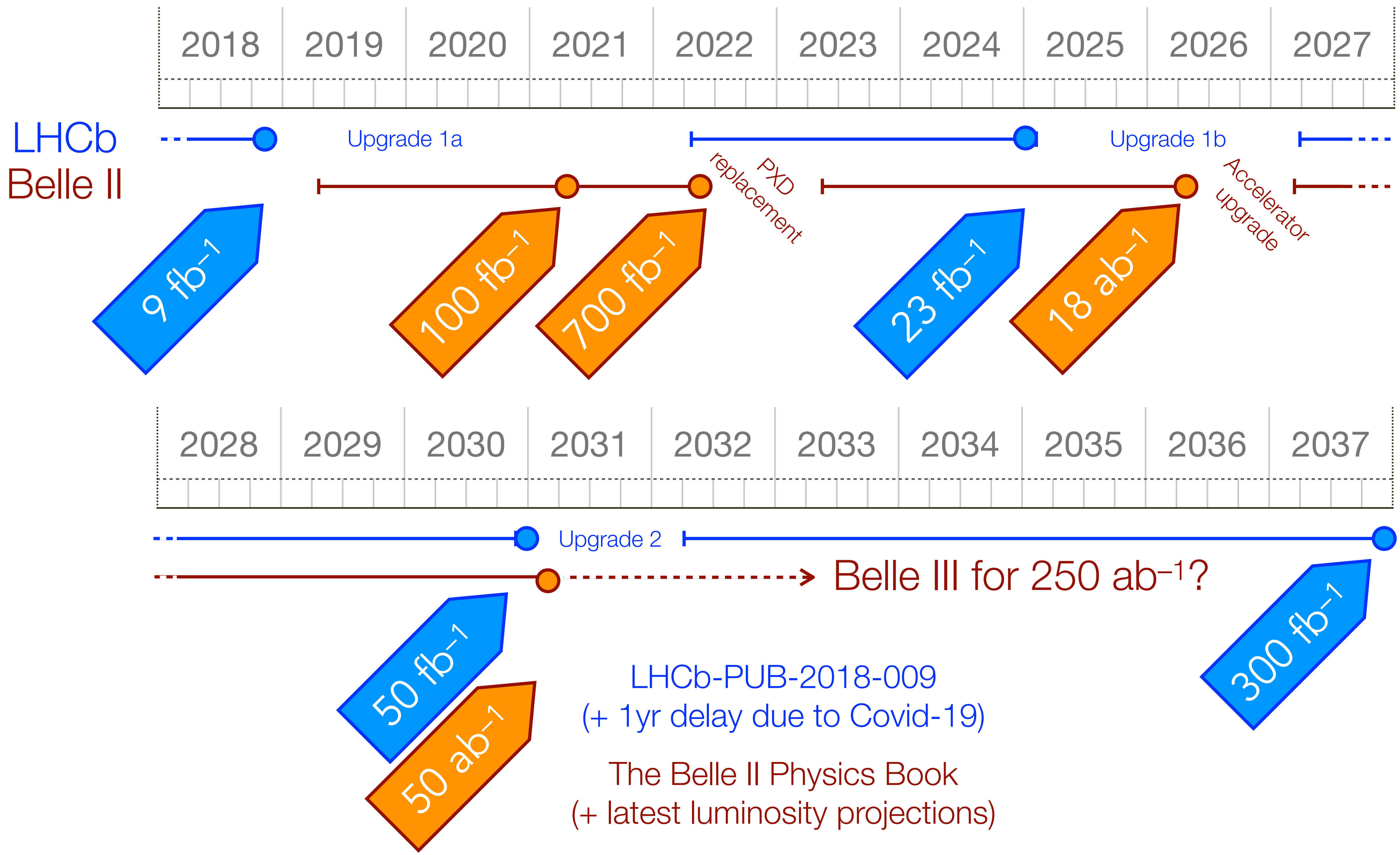
- Cleaner environment allows for more generous selections — milder efficiency effects
- Better reconstruction of neutrals and unique access to final states with invisible particles
- Much easier separation between promptly produced charm and secondary (from-*B*) decays

Belle II status

- Continued data-taking through Covid-19 pandemic
- Peak instantaneous luminosity of ~2.6×10^{32} cm^{-2}s^{-1}
- However, slower luminosity integration rate than initially planned
    - As of today, collected ~126 fb^{-1}



Prospects of data collection



LHCb-PUB-2018-009
(+ 1yr delay due to Covid-19)

The Belle II Physics Book
(+ latest luminosity projections)

The rule of thumb

$$1\ \mathrm{fb}^{-1} \sim 1\ \mathrm{ab}^{-1}$$

@ LHCb @ Belle II

The rule of thumb

~~$1\ fb^{-1} \sim 1\ ab^{-1}$~~

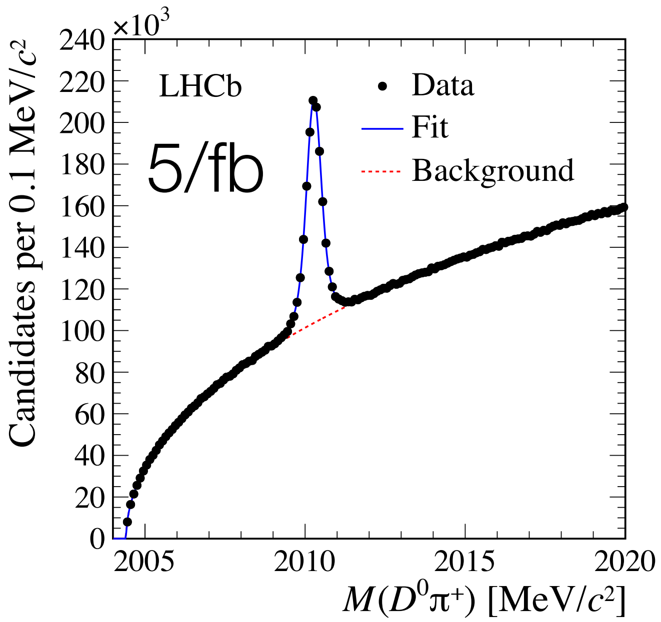
~~@ LHCb~~ ~~@ Belle II~~

does not hold for prompt charm production

The rule of thumb

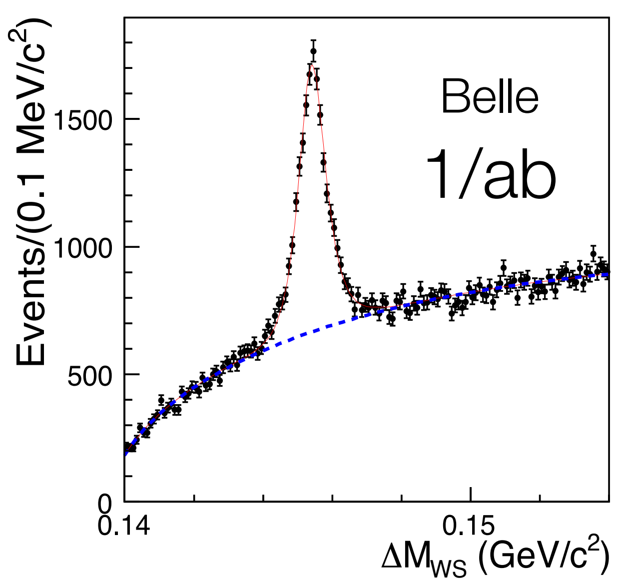
$D^{*+} \to D^0(\to K^+\pi^-)\pi^+$

[PRD 97 (2018) 031101(R)]



$N/\mathcal{L}$~150k

[PRL 112 (2014) 111801]



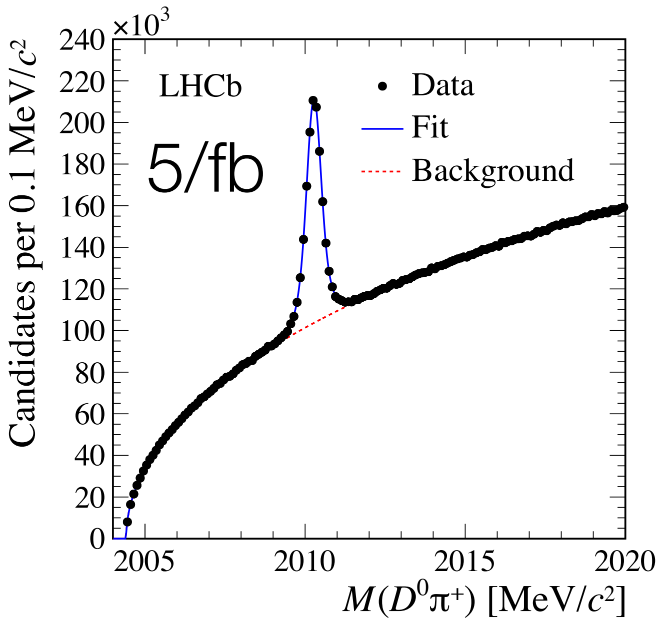
$N/\mathcal{L}$~10k

- Charm production rate in hadron collisions is $O(10^6)$ times larger
- However, at Belle II better reconstruction efficiency for some final state compensates

The rule of thumb

$D^{*+} \to D^0(\to K^+\pi^-)\pi^+$

[PRD 97 (2018) 031101(R)]



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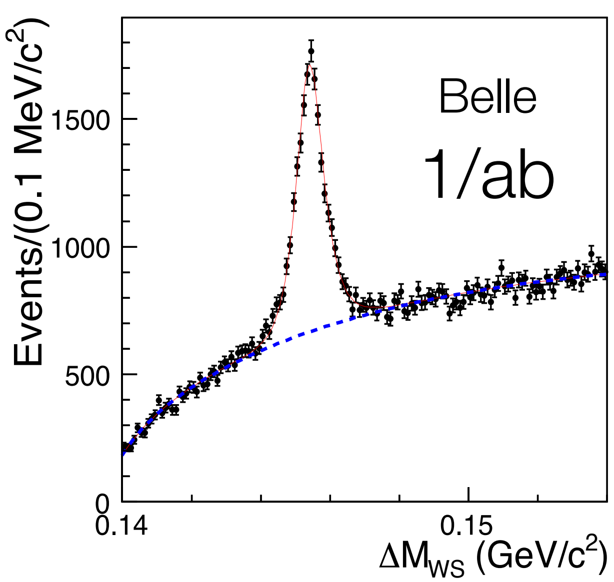
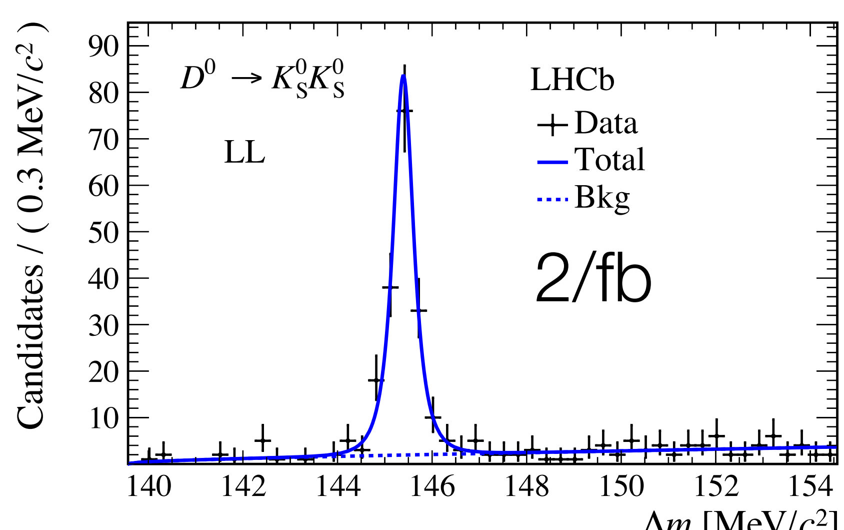


$N/\mathcal{L}$~10k

- Charm production rate in hadron collisions is $O(10^6)$ times larger
- However, at Belle II better reconstruction efficiency for some final state compensates

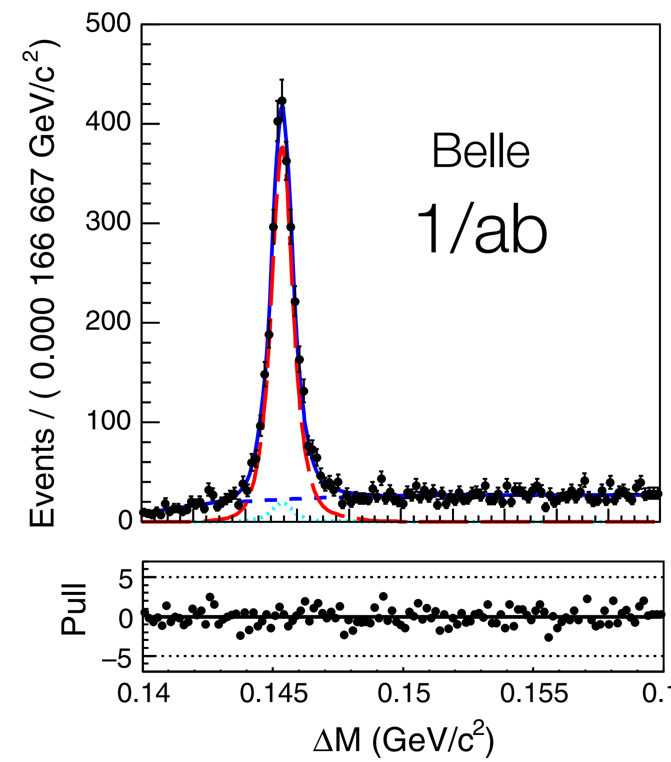
$D^{*+} \to D^0(\to K_S K_S)\pi^+$

$N/\mathcal{L}$~0.5k



[JHEP 11 (2018) 048]

$N/\mathcal{L}$~5.4k

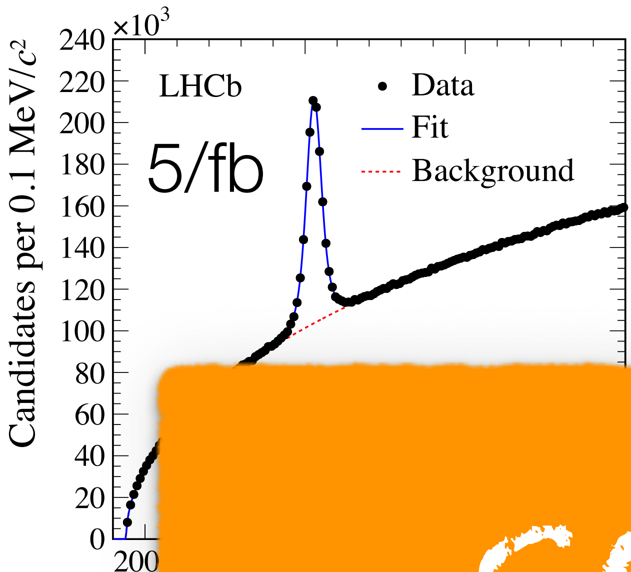


[PRL 119 (2017) 171801]

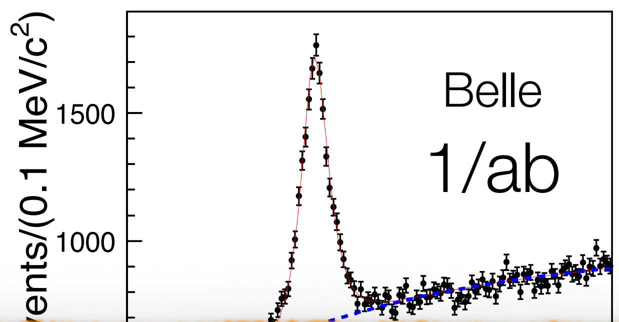
The rule of thumb

$D^{*+} \to D^0(\to K^+\pi^-)\pi^+$

[PRD 97 (2018) 031101(R)]



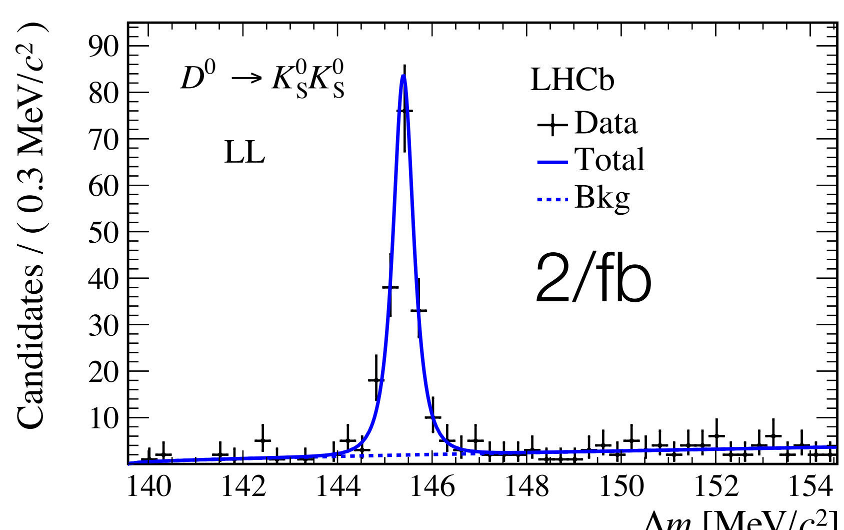
[PRL 112 (2014) 111801]



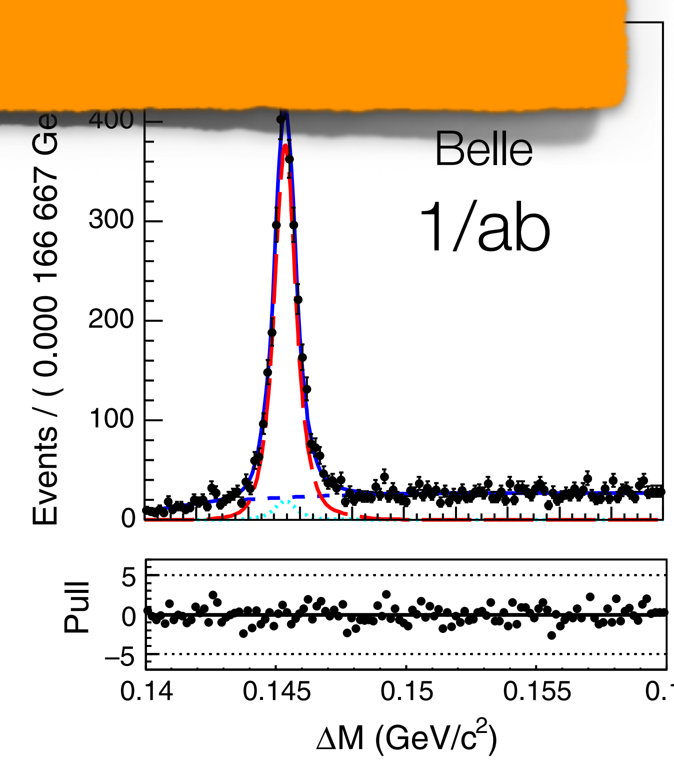
- Charm production rate in hadron collisions is $O(10^6)$ times larger
- However, at Belle II better reconstruction efficiency for some

COMPLEMENTARITY

$D^{*+} \to D^0(\to K_S K_S)\pi^+$



[JHEP 11 (2018) 048]



[PRL 119 (2017) 171801]

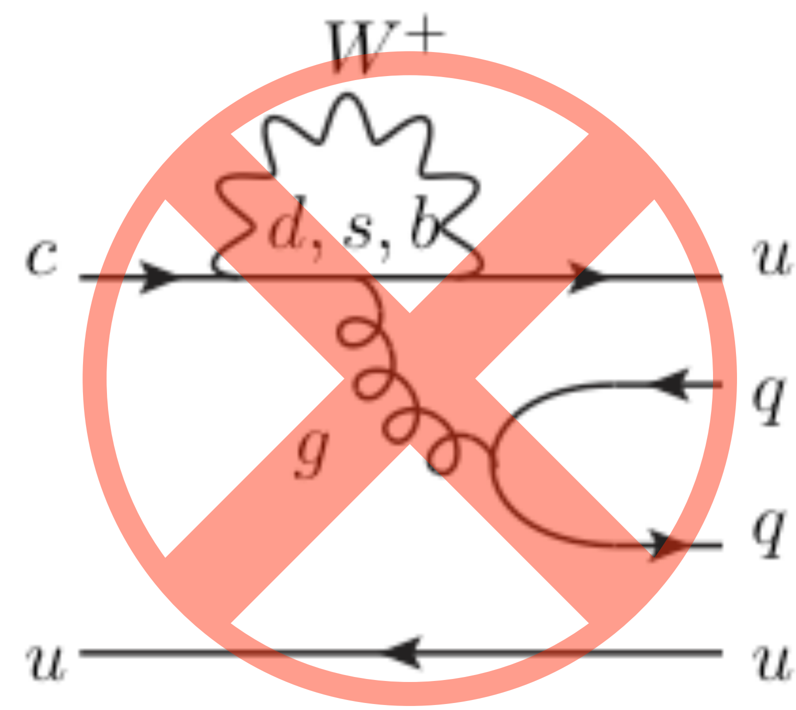
CP violation in charm decays

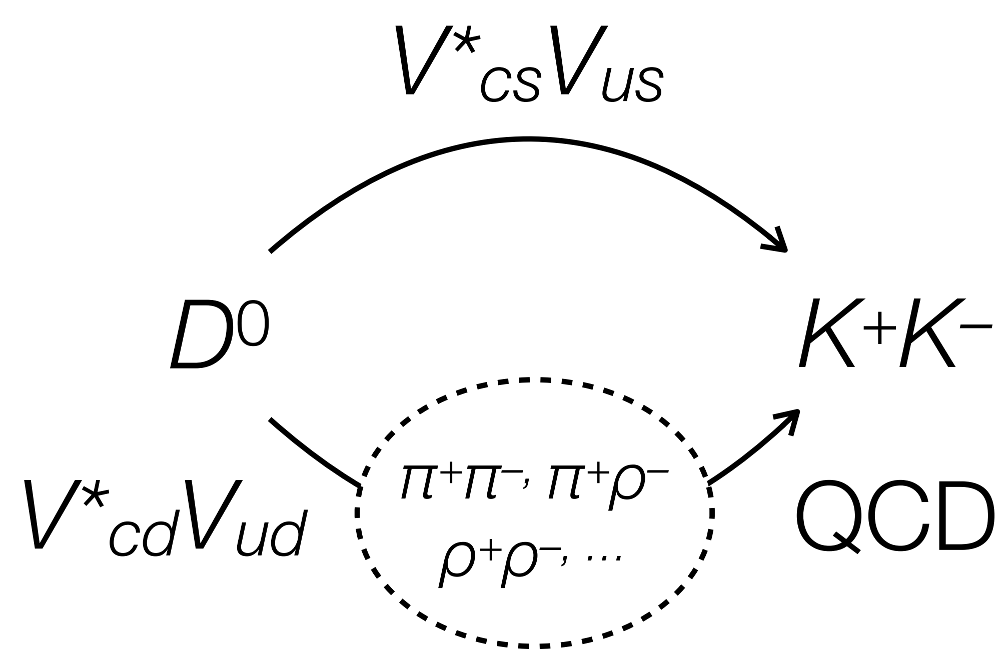
Charm *CP* violation is not about the penguins!

- *CP* violation in *B* decays comes from interference between tree and penguin loop (dominated by top)
- In charm decays, the penguin is irrelevant (CKM and GIM suppressed)
- Interference is between tree and rescattering amplitudes. Assuming *O*(1) rescattering

$$A_{CP} \approx \mathrm{Im}\left(\frac{V_{cs}^* V_{us} + V_{cd}^* V_{ud}}{V_{cs}^* V_{us} - V_{cd}^* V_{ud}}\right)$$
$$= -\mathrm{Im}\left(\frac{V_{cb}^* V_{ub}}{\lambda}\right) \approx -6 \times 10^{-4}$$

[JHEP 1907 (2019) 020]



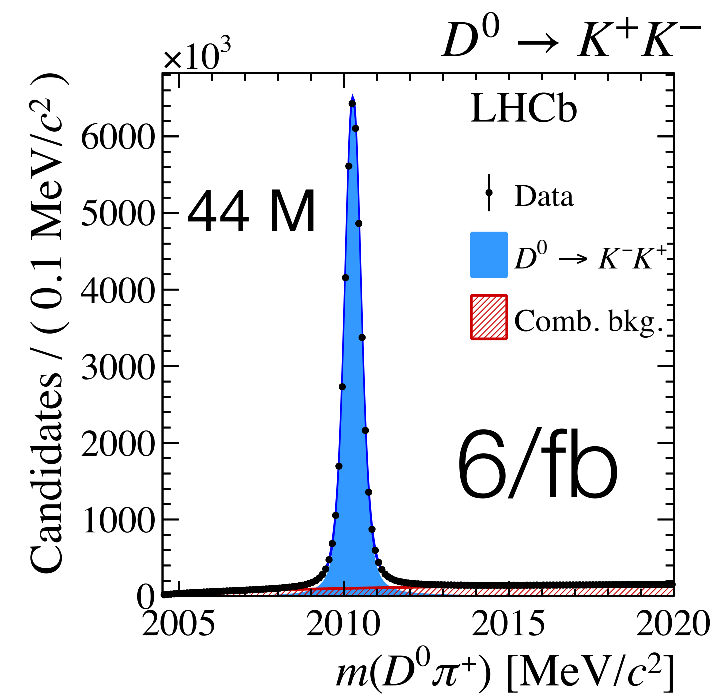


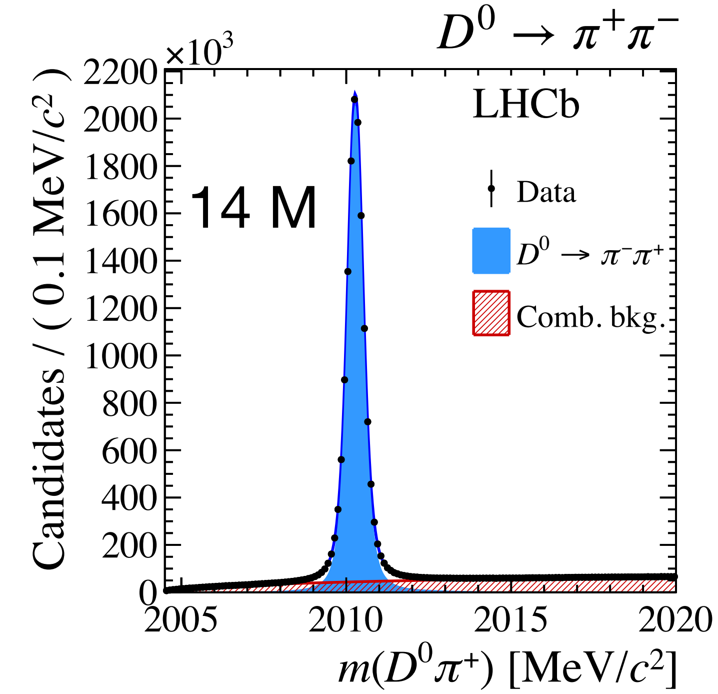
Discovery of *CP* violation in charm decays

- Difference of time-integrated *CP* asymmetries in 2-body Cabibbo-suppressed decays:

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$= (-1.54 \pm 0.29) \times 10^{-3}$$

5.3σ deviation from zero





- In the limit of *SU*(3)/*U*-spin symmetry, $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$ have same magnitude and opposite signs $\Longrightarrow |\Delta A_{CP}| \approx 1.3\times10^{-3}$

- In addition to be robust against experimental biases, ΔA_{CP} provides 2× enhanced sensitivity to *CP* violation

[PRL 122 (2019) 211803]

What is next?

- Measured value is in the ballpark of the standard model value
- Difficult to say whether new physics is at play. Need better control of the QCD effects
- Experimentally look for *CP* violation in radiative/semileptonic decays and test sum rules between *SU*(3) related modes, *e.g.*:

[arXiv:2103.11058]

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

- Huge program of measurements, where complementarity between LHCb and Belle II will be crucial

CP violation in $D^+ \to \pi^+\pi^0$ decays

- In the standard model ΔA_{CP} comes from $\Delta U=0$ transitions: CP violation in $\Delta U=1$, *e.g.* in $D^+ \to \pi^+\pi^0$, would unambiguously be new physics
- If ΔA_{CP} is due to new physics, then expect [PRD 101 (2020) 115006]

$$A_{CP}^{NP}(\pi^+\pi^0) \lesssim 2\,\Delta A_{CP}^{NP} \sim 0.3\%$$

- Current best measurement from Belle

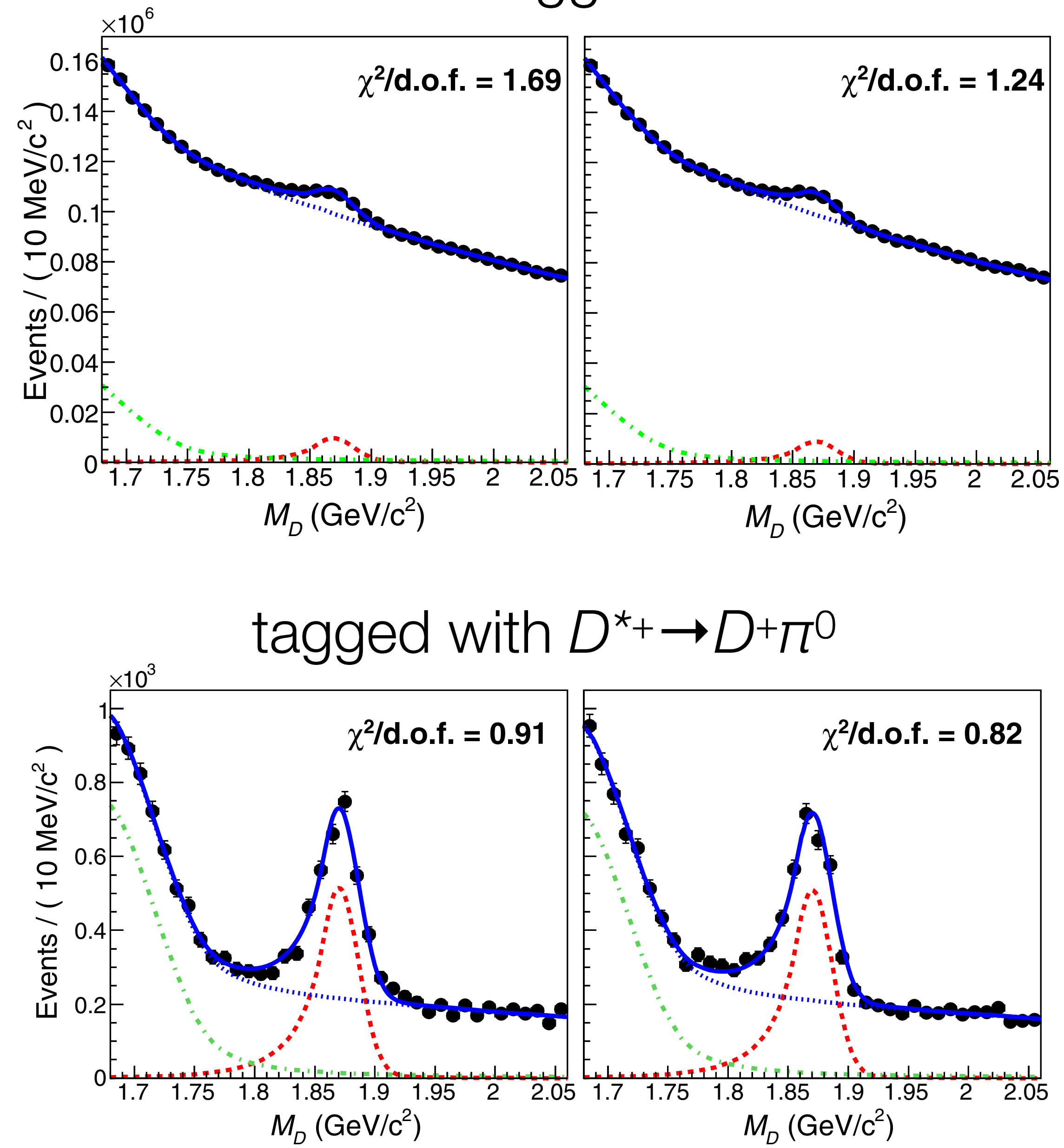
$$A_{CP}(\pi^+\pi^0) = (2.3 \pm 1.2 \pm 0.2)\%$$

- Similar performances expected for Belle II. Sensitivity with 50/ab ~0.17%

Belle (1/ab)

untagged

tagged with $D^{*+} \to D^+\pi^0$



[PRD 97 (2018) 011101(R)]

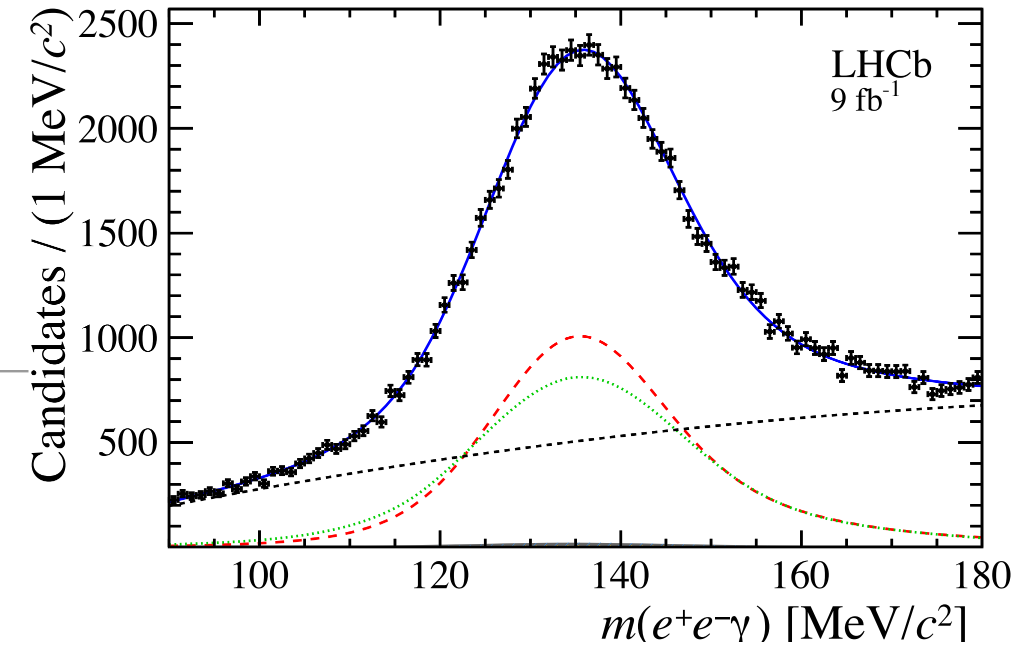
$A_{CP}(D^+ \rightarrow \pi^+\pi^0)$ at LHCb

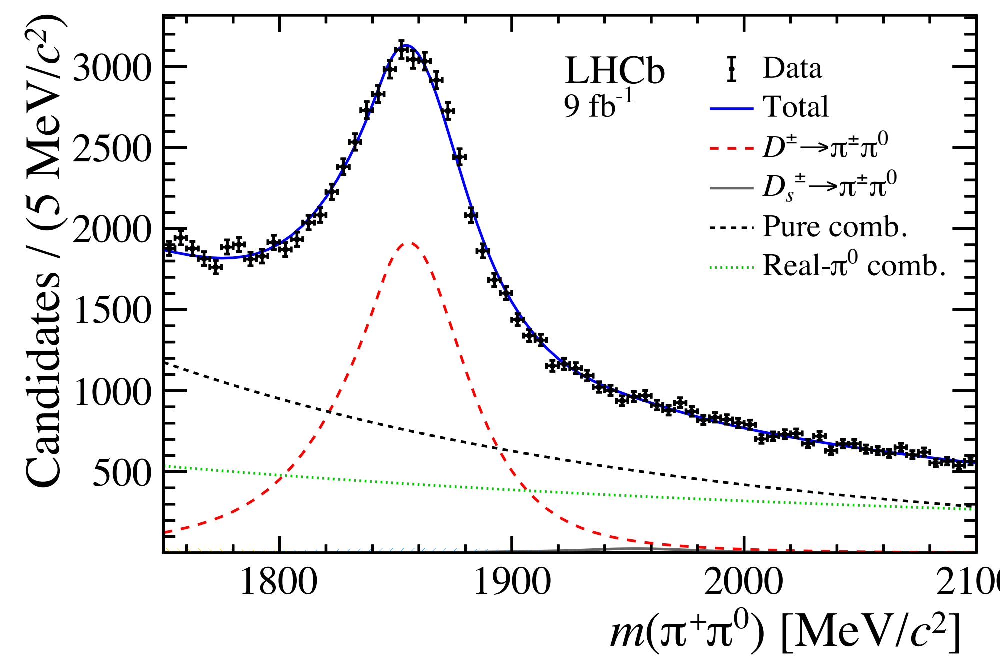
- No displaced vertex with a single track
- Use $\pi^0 \rightarrow e^+e^-\gamma$ and $\pi^0 \rightarrow \gamma\gamma$ with one converted photon
  - Lower BFs compensated by much larger production rate compared to *B* factories
- *CP* asymmetry with 9/fb competitive with Belle (1/ab)

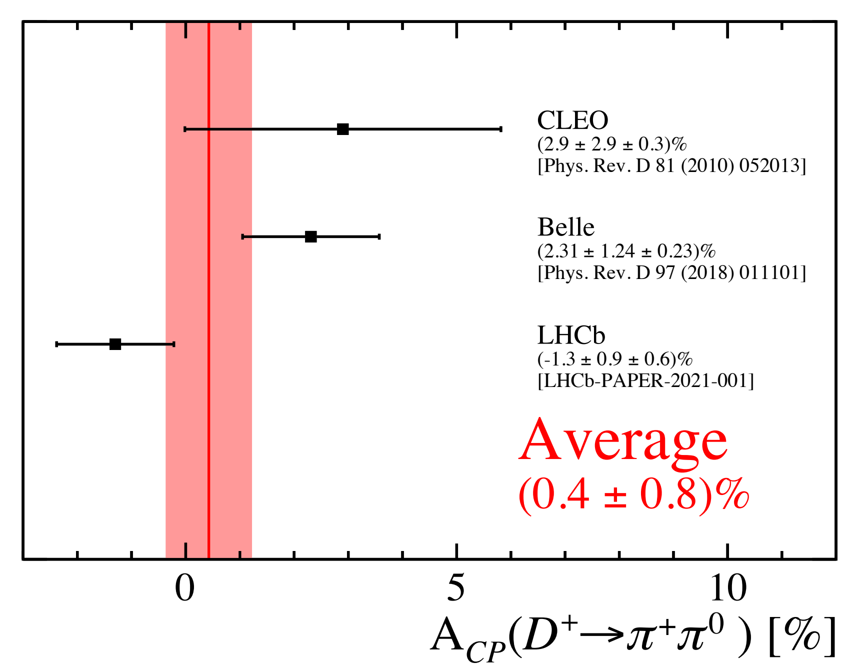
$$A_{CP}(\pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$$

- Updated sum rule consistent with zero:

$$R = (0.1 \pm 2.4) \times 10^{-3}$$





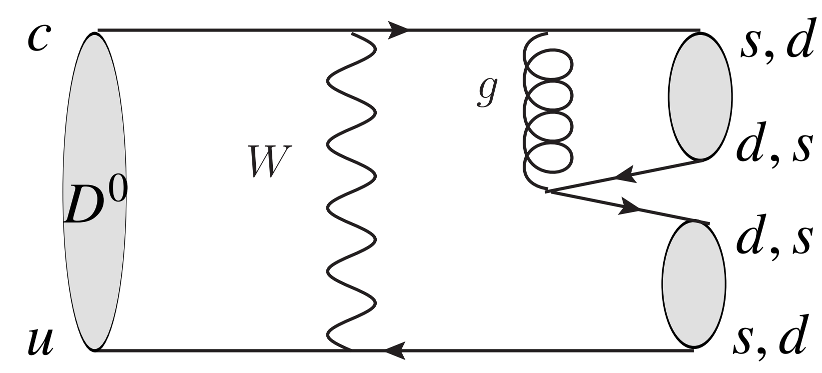


[arXiv:2103.11058]

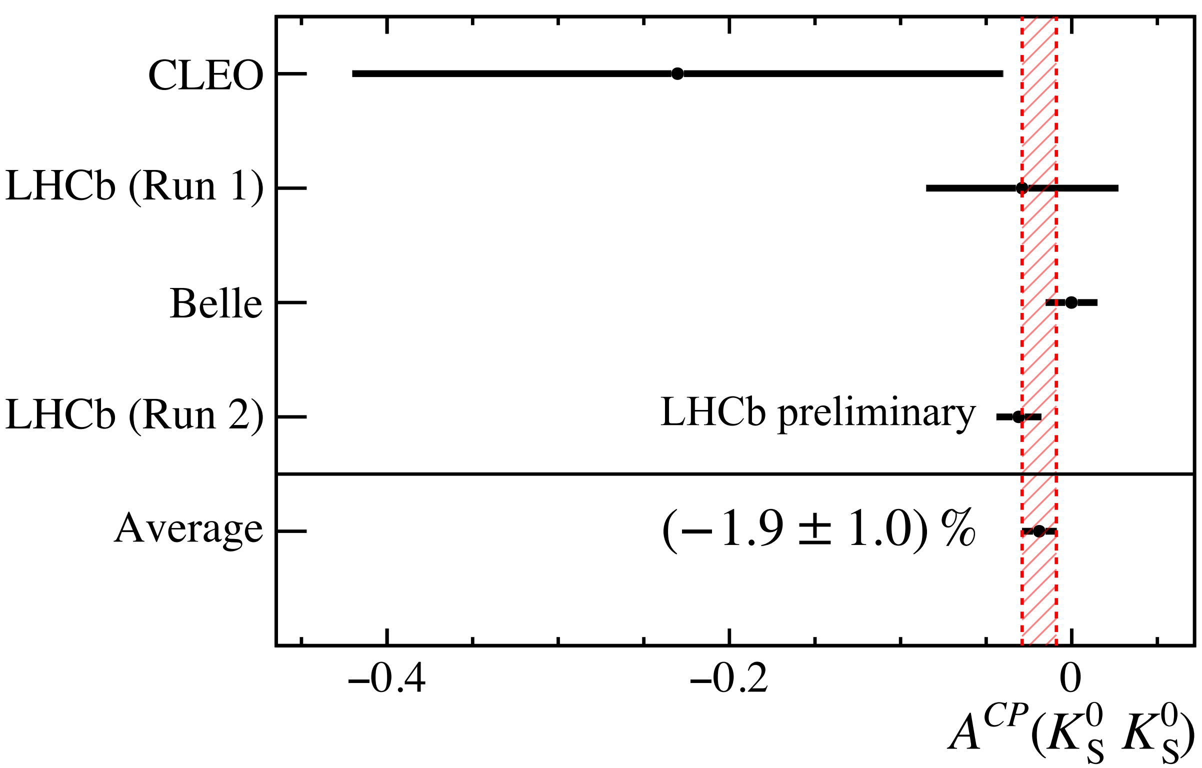
CP violation in $D^0 \to K_S^0 K_S^0$ decays at LHCb

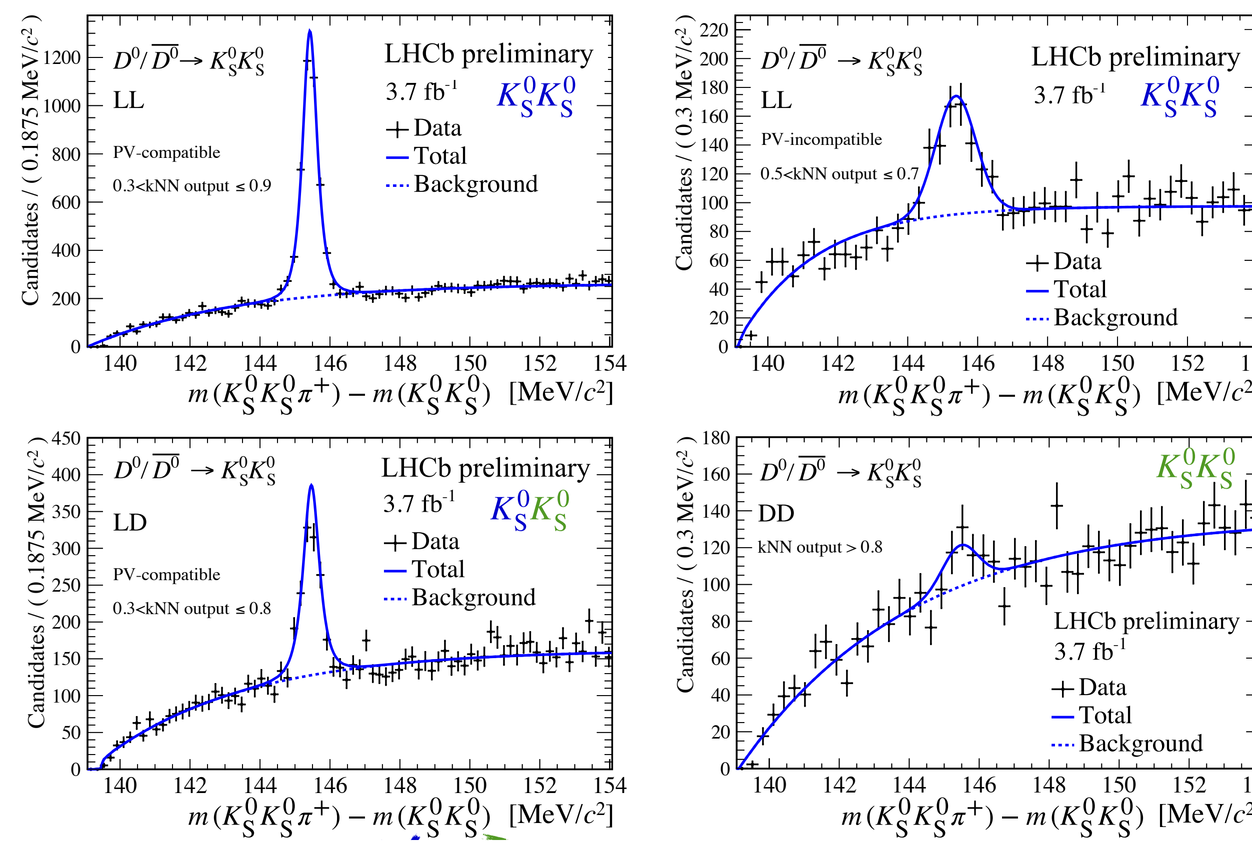
- CP violation enhanced by interference in W-exchange tree-level diagrams
  [PRD 92 (2015) 054036]

$$A_{CP}(K_S^0 K_S^0) \lesssim 1.1\%$$



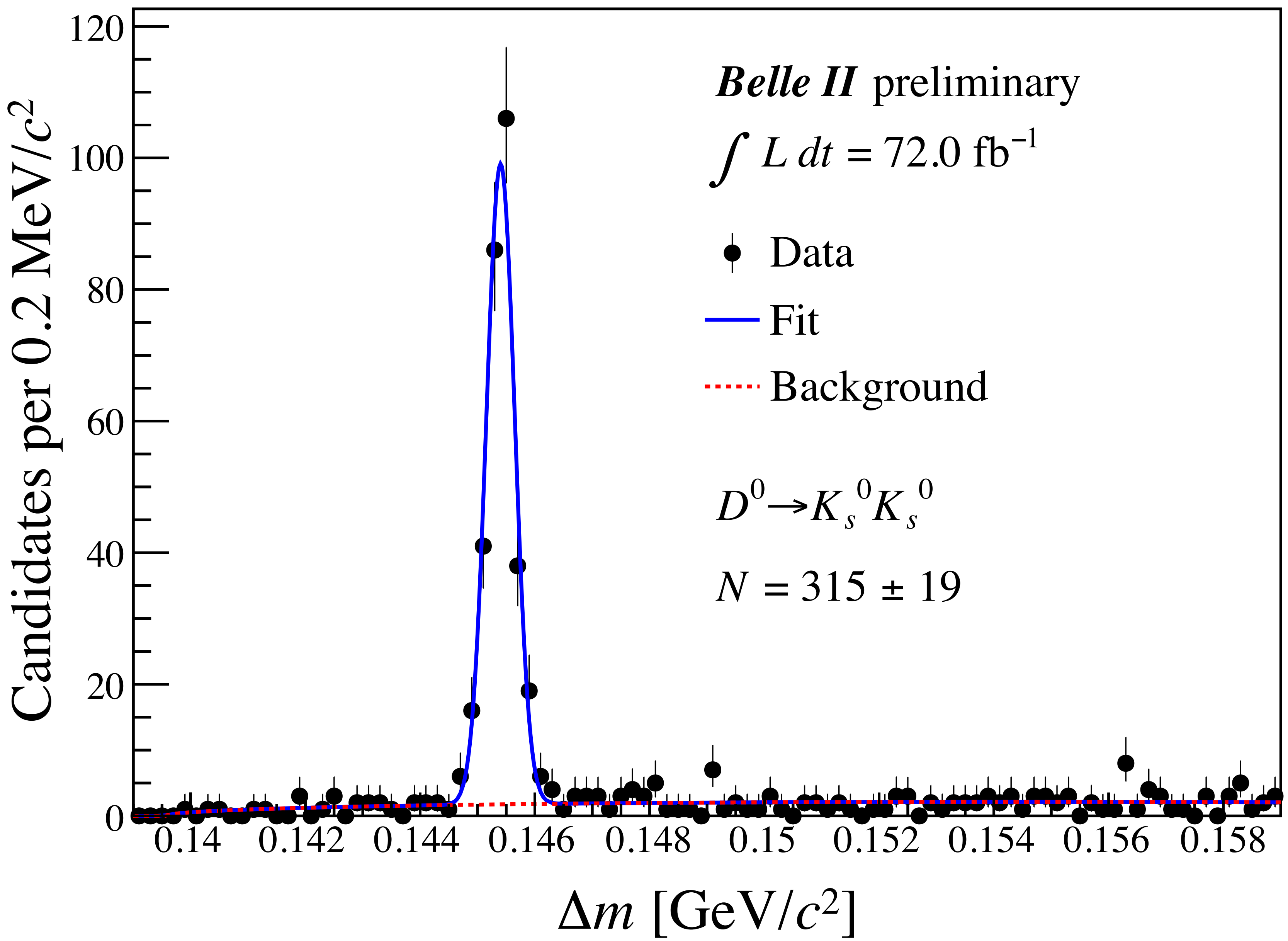
- New result from LHCb with 6/fb competitive with Belle (1/ab)





LHCb-PAPER-2020-047, in preparation

$D^0 \to K_s^0 K_s^0$ decays at Belle II



Similar yield/luminosity to Belle with larger purity

Prospects for direct *CP* violation

LHCb-PUB-2018-009

The Belle II Physics Book

Decay mode	Current best sensitivity (stat + syst) [10^{-3}]		Belle II 50/ab (stat+syst) [10^{-3}]	LHCb 50-300/fb (stat only) [10^{-3}]
ΔA_{CP}	0.29	LHCb (9/fb)	0.6	0.07-0.03
$D^0 \to K^+K^-$	1.8	LHCb (3/fb)	0.3	0.17-0.07
$D^0 \to \pi^+\pi^-$	1.8	LHCb (3/fb)	0.5	0.17-0.07
$D^0 \to \pi^0\pi^0$	6.5	Belle (1/ab)	0.9	(?)
$D^+ \to \pi^0\pi^+$	11/13	LHCb (9/fb)/Belle (1/ab)	1.7	(5.9-2.4)
$D^0 \to K_S K_S$	13/15	LHCb (9/fb)/Belle (1/ab)	2.1	7.0-2.8
$D_s \to K_S \pi^+$	18	LHCb (6.8/fb)	2.9	(0.75)-0.32
$D^+ \to K_S K^+$	0.76	LHCb (6.8/fb)	0.4	(0.28)-0.12
$D^0 \to \phi\gamma$	66	Belle (1/ab)	10	(?)
$D^0 \to \rho^0\gamma$	150	Belle (1/ab)	20	(?)
$D^0 \to K^+\pi^-$	9.1	LHCb (5/fb)	(4.0)	1.4-0.5

(numbers in parentheses are my own, unofficial projections)

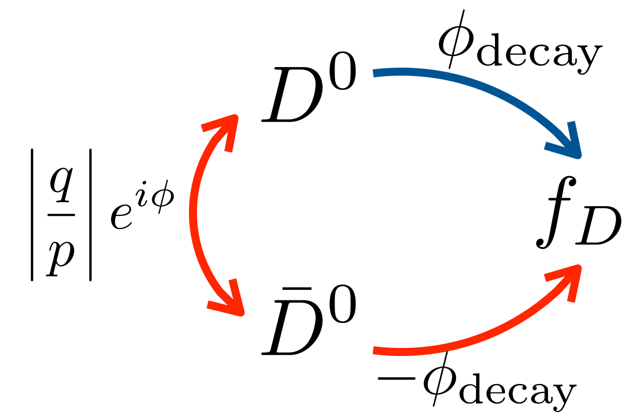
Time-dependent *CP* violation

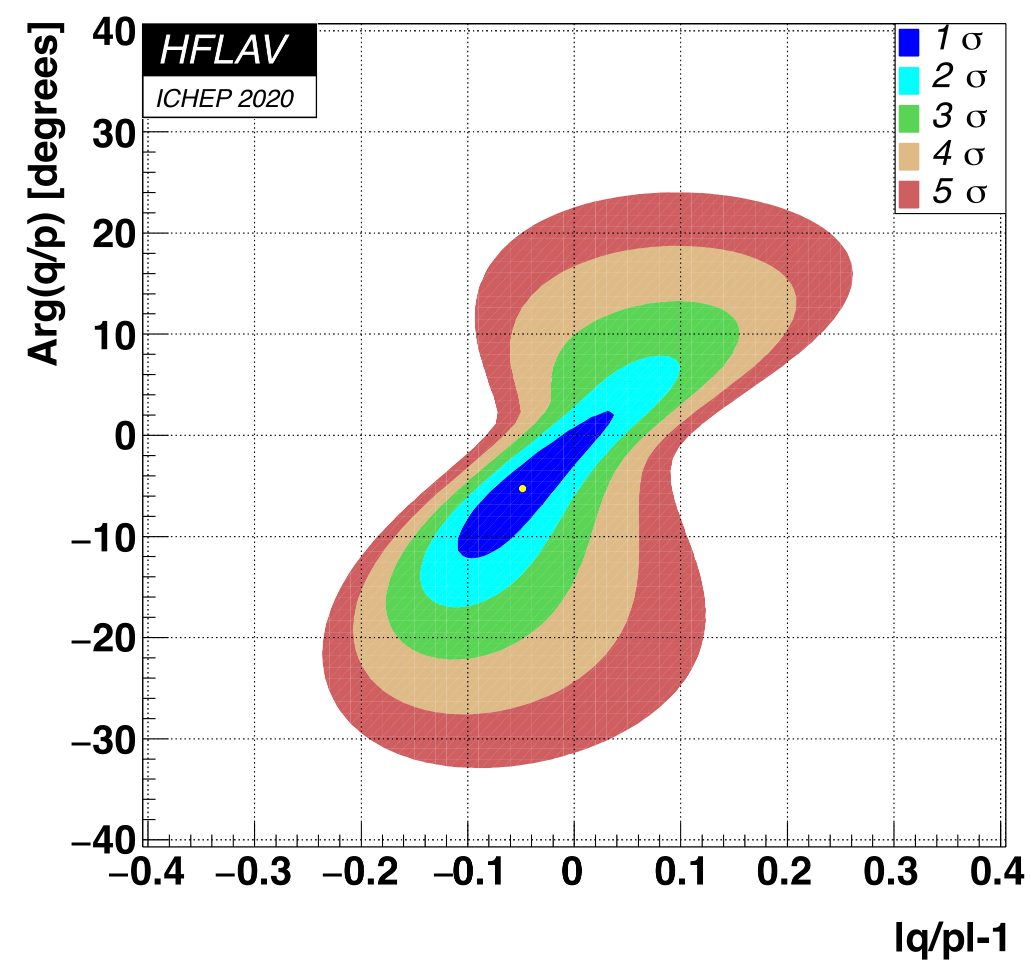
- The eigenstates of the neutral *D* meson are a mixture of the flavor states

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$x = \frac{2(m_1 - m_2)}{\Gamma_1 + \Gamma_2}\,, \qquad y = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

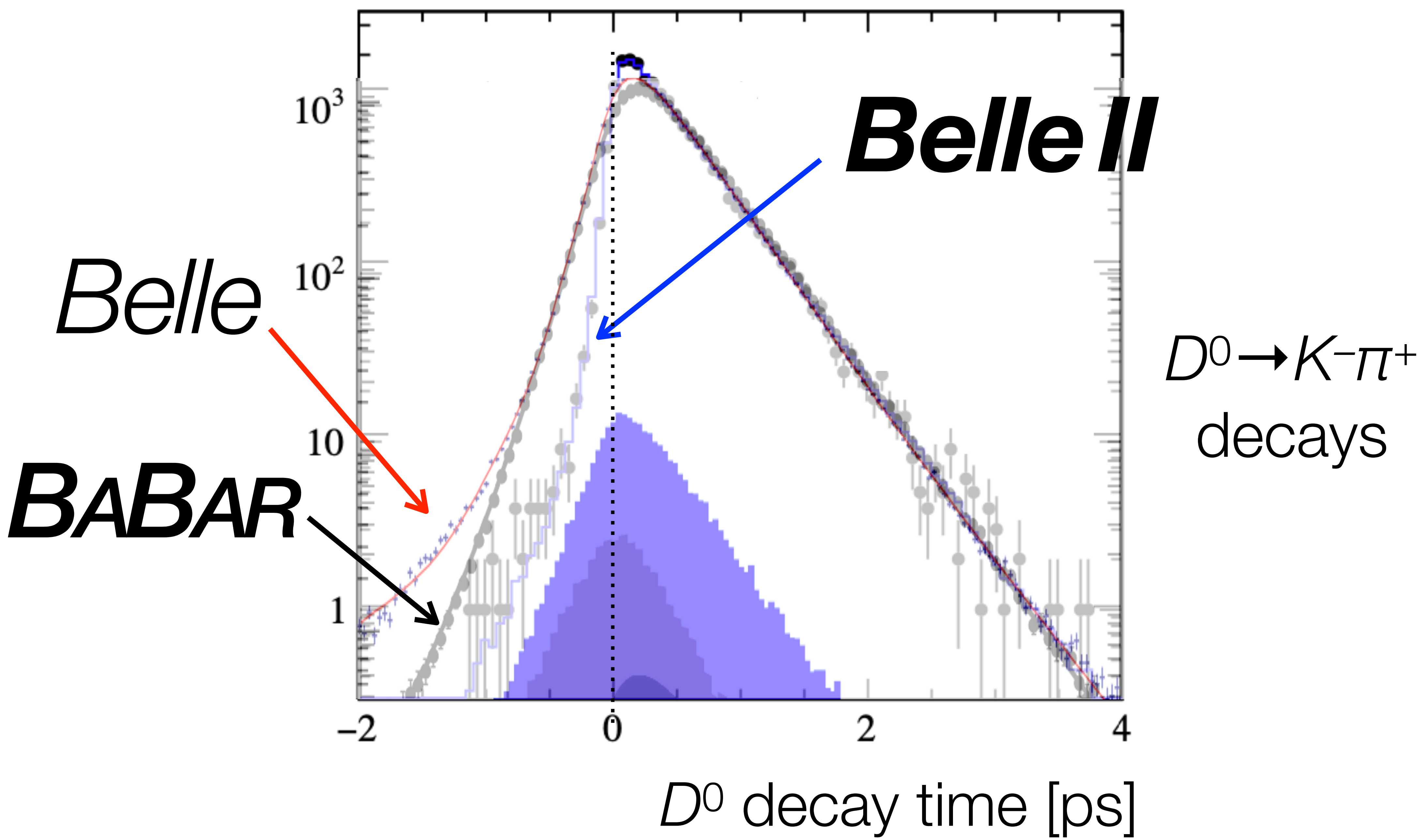
- This results in D^0-$\bar{D}^0$ ($\Delta C = 2$) transitions before decay that provide an additional interfering pattern for *CP*-violation effects
    - Expected to be suppressed by a further order in *U*-spin breaking w.r.t. $\Delta C = 1$ processes $\Longrightarrow$ $\phi \sim O(0.1)$ degrees
    - No experimental evidence to date





Improved decay-time resolution at Belle II

~2× better than Belle/BaBar,
similar to charm from semileptonic *B* decays at LHCb,
and only ~2× worse than prompt charm at LHCb

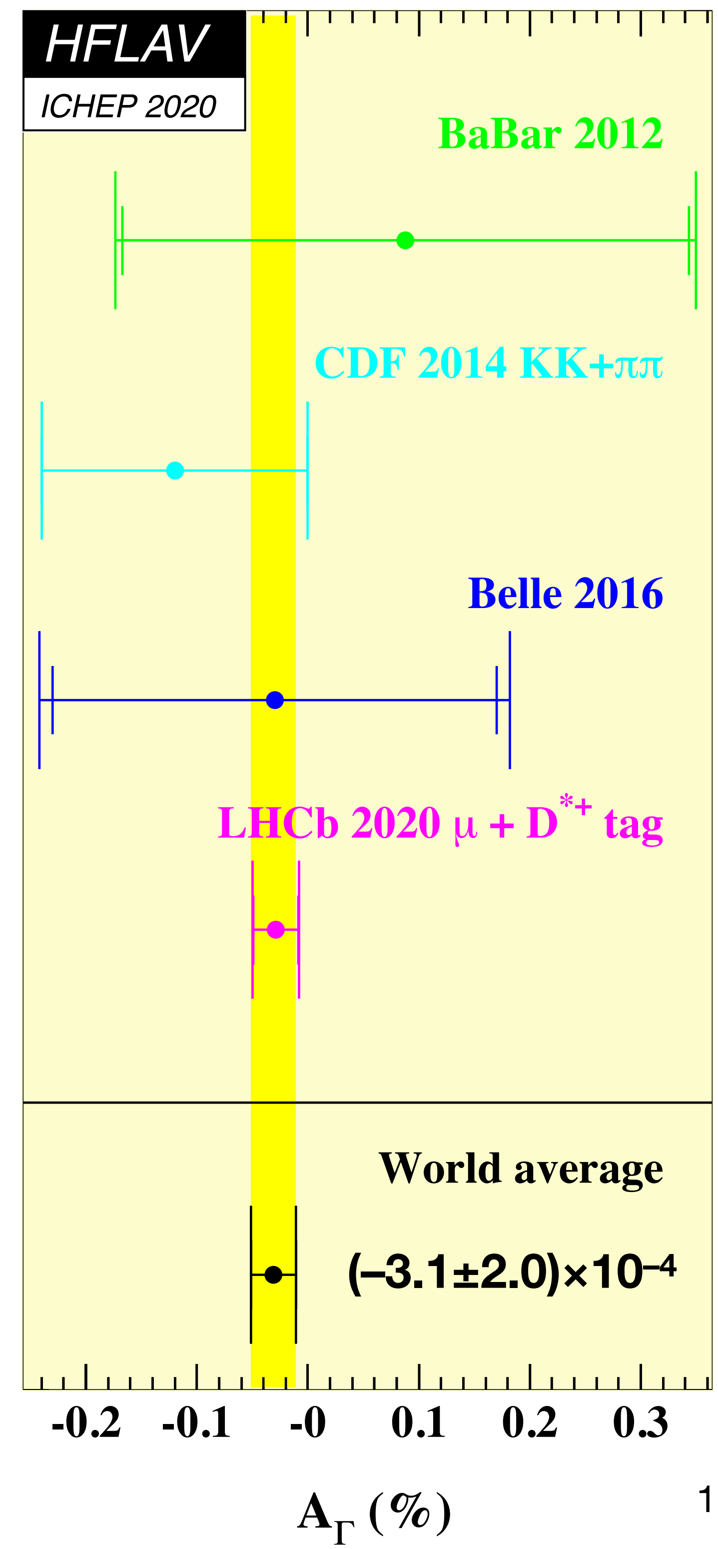


Time-dependent *CP* asymmetry in $D^0 \to h^+h^-$

- Small D^0-$\bar{D}^0$ mixing rate ($x, y \ll 1$) implies that time-dependent *CP* asymmetries can be approximated as

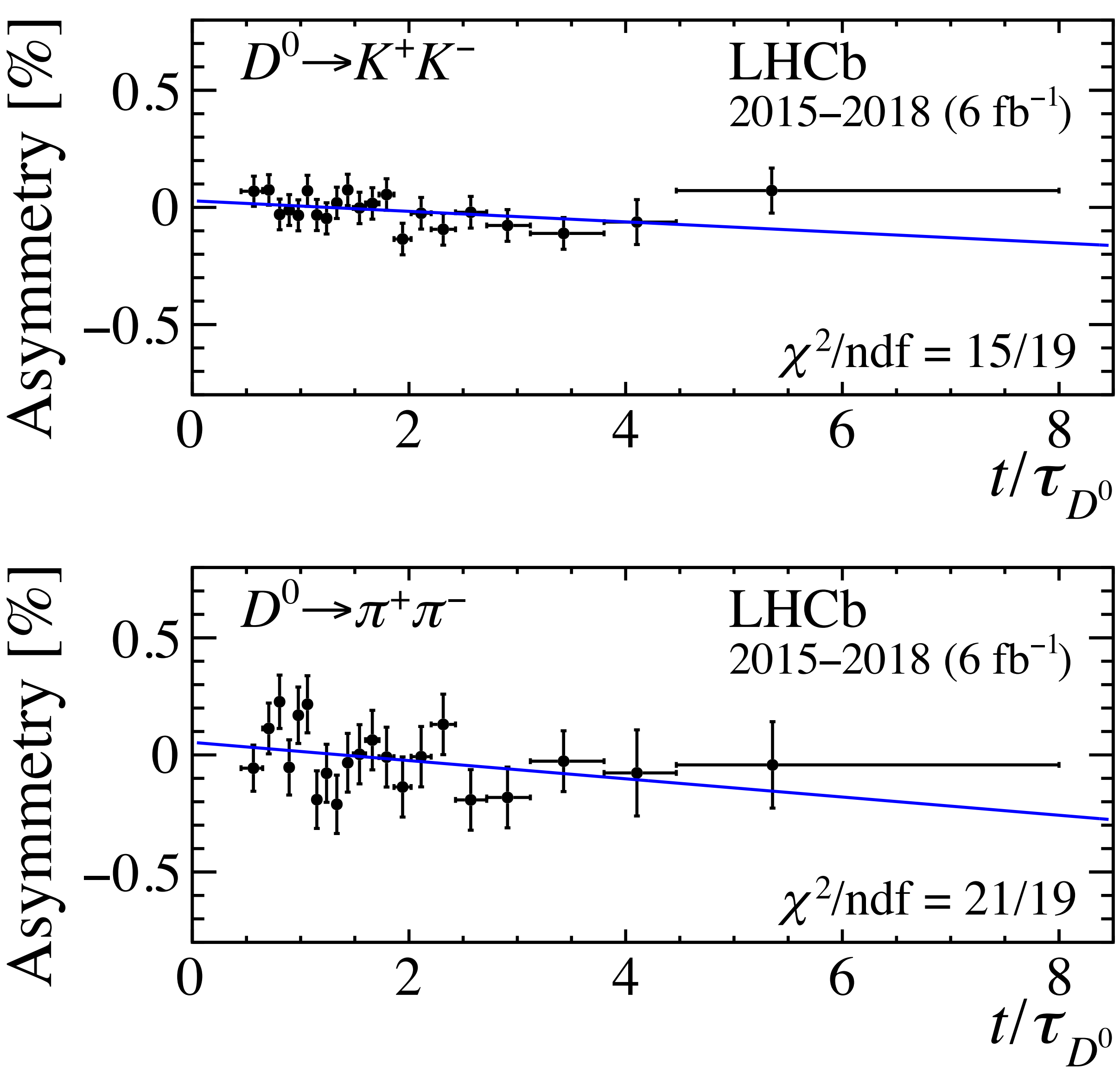
$$A_{CP}(h^+h^-) \approx a_{CP}^{\text{dir}}(h^+h^-) - \frac{t}{\tau} A_\Gamma$$

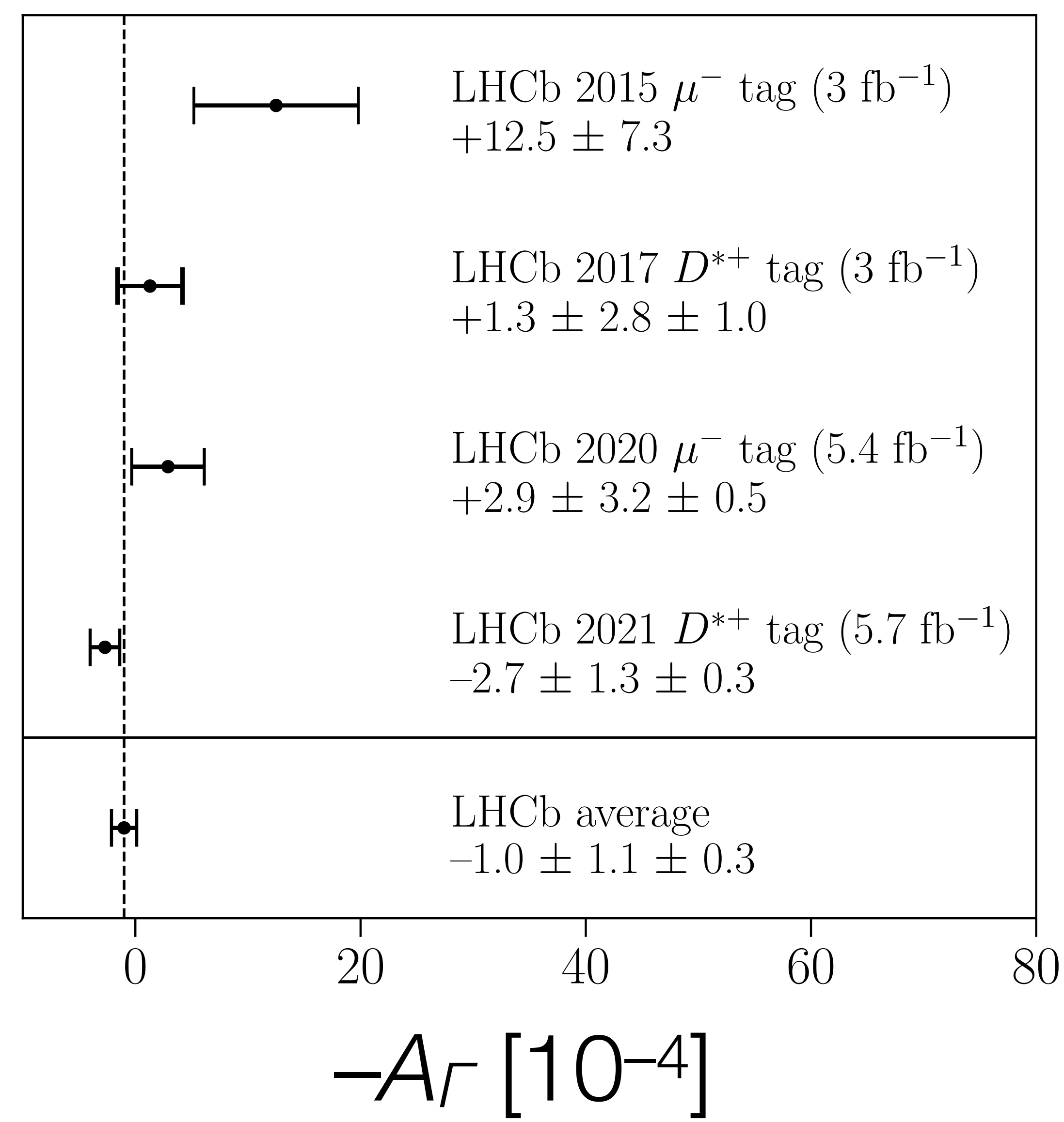
- Mixing-induced *CP* violation results in a nonzero value of the linear term
- Naive expectation is $O(10^{-5}\text{-}10^{-4})$
- Experimental sensitivity is (and will remain) dominated by LHCb



Updated measurement from LHCb Run 2

$$A_{CP}(h^+h^-) \approx a_{CP}^{\rm dir}(h^+h^-) - \frac{t}{\tau} A_\Gamma$$





LHCb-PAPER-2020-045, in preparation

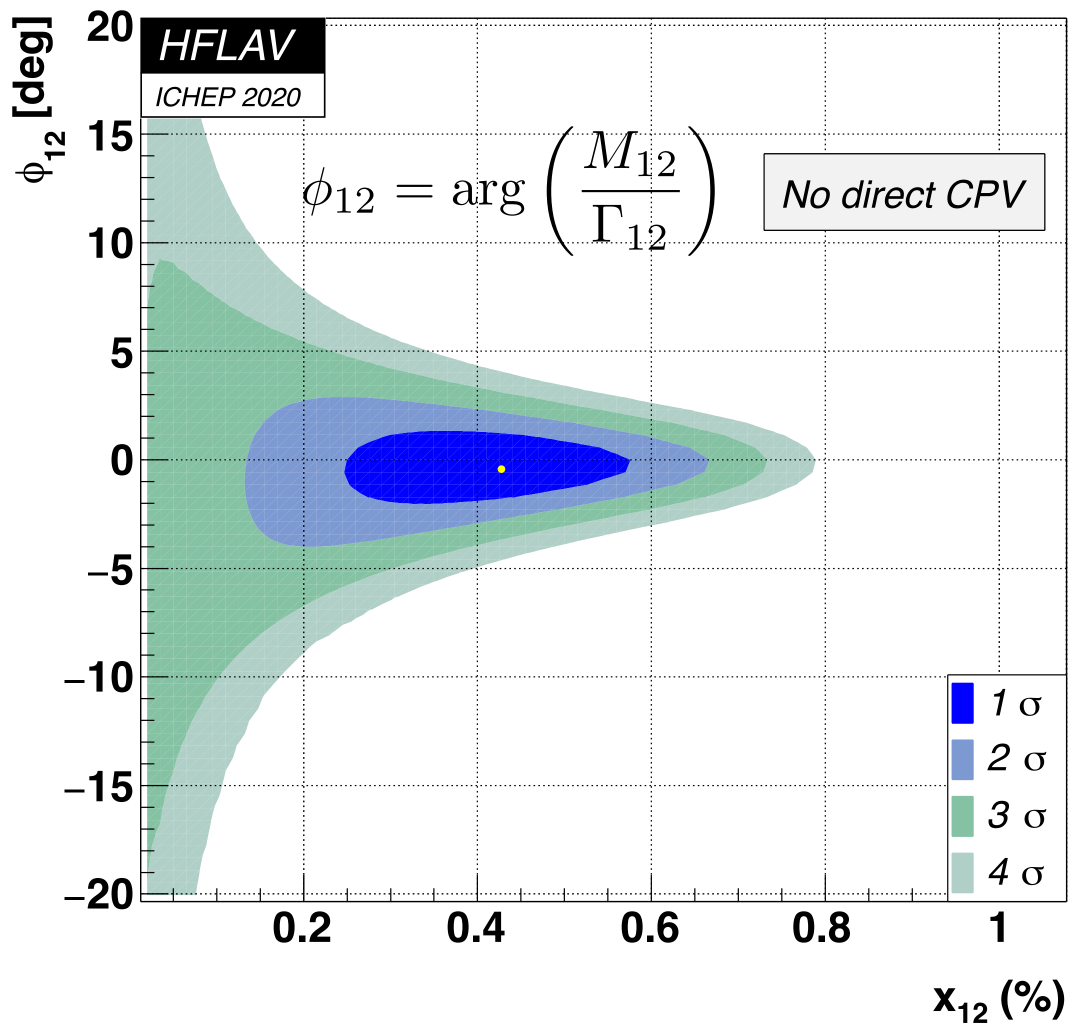
x is the key

- Sensitivity to *CP*-violation phase in mixing limited also by the knowledge of $x_{12} \approx x$ (which is only 3σ away from zero)

- Most sensitive mixing measurements are based on decays to two-body final states (which are primarily sensitive to y)

- Need mixing measurements with decays to multi-body final states that are not *CP*-eigenstates

$$A_{\Gamma} \approx -x_{12} \sin\phi_{12}$$



x from $D^0 \to K_S\pi^+\pi^-$

- Multiple interfering amplitudes enhance the sensitivity to mixing locally on the Dalitz plot

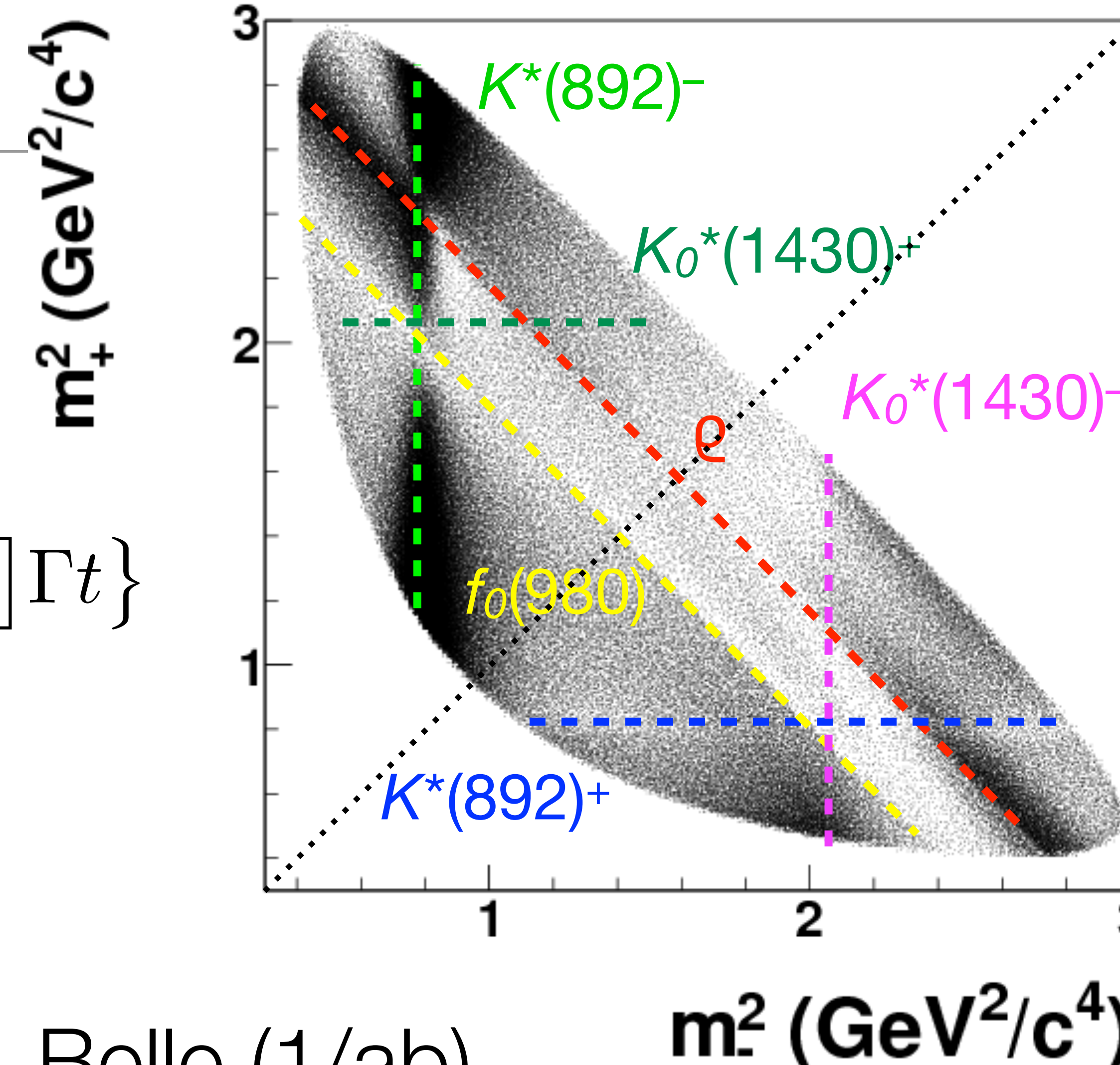
$$\mathcal{P}_{D^0} \propto e^{-\Gamma t}\{|\mathcal{A}_{D^0}|^2 - \mathrm{Re}[\mathcal{A}^*_{D^0}\mathcal{A}_{\overline{D}^0}(y+ix)]\Gamma t\}$$

- LHCb Run 1 and Belle give the best determinations of x with ~1M $D^0 \to K_S\pi^+\pi^-$ decays each

- In Run 2 LHCb has collected ~40× more signal $\Longrightarrow$ expect $\sigma(x)$ ~ 0.5×10^{-3}

- Belle II is expected to collect ~50M decays with 50/ab. Difficult to compete if LHCb keeps reasonable efficiency in Run 3 and 4

[PRD 89 (2014) 091103]



Belle (1/ab)

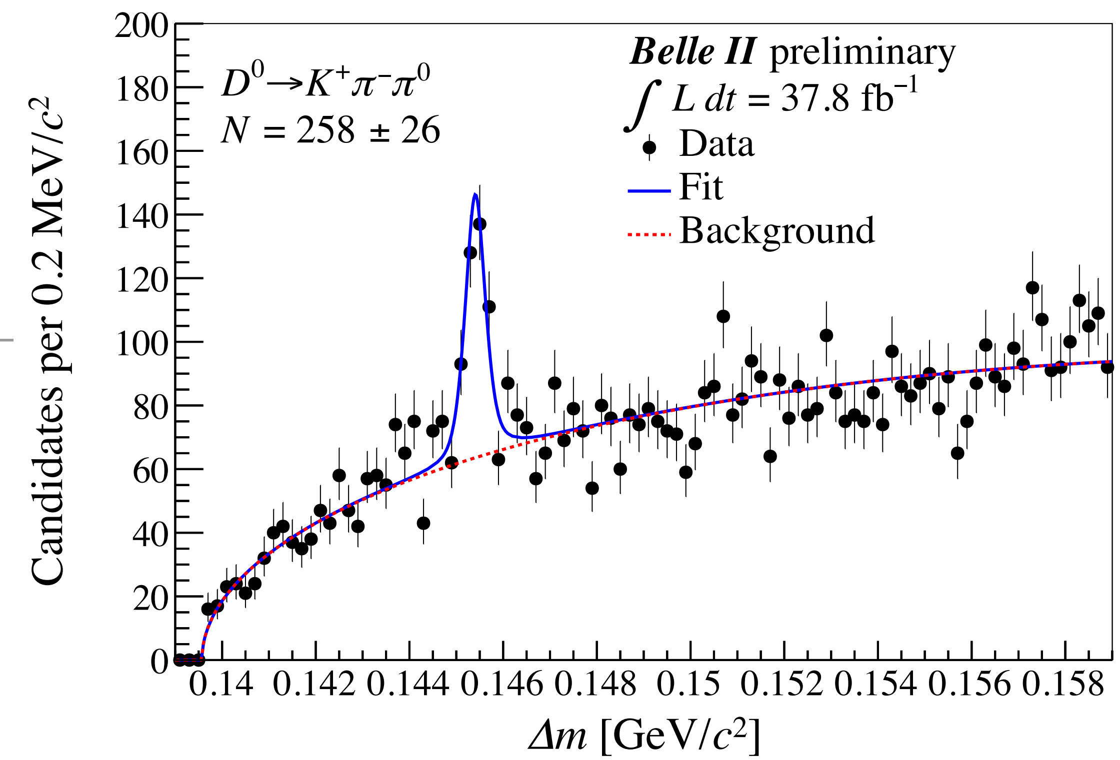
$x = (0.56 \pm 0.19^{+0.04}_{-0.08}{}^{+0.06}_{-0.08})\%$

LHCb (2/fb) [PRL 122 (2019) 231802]

$x = (0.27 \pm 0.16 \pm 0.04)\%$

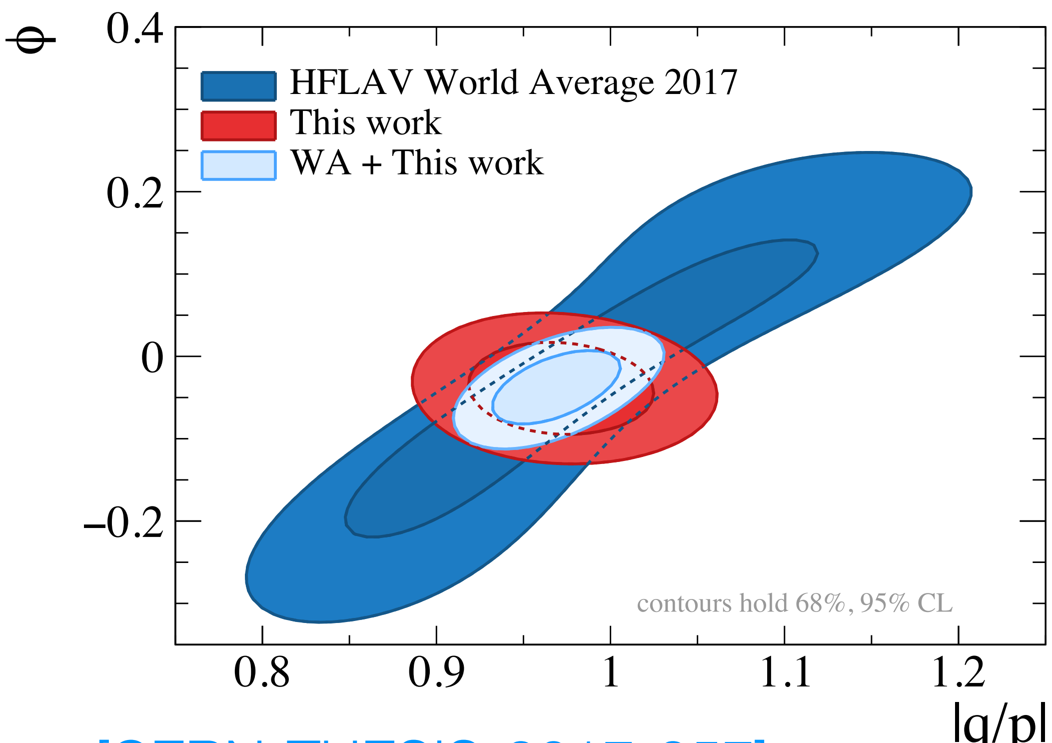
More multi-bodies

- Lots of other promising final states not yet explored/fully exploited experimentally: *e.g.* $D^0 \to K^+\pi^-\pi^0$, $D^0 \to K_S\pi^+\pi^-\pi^0$, $D^0 \to K^+\pi^-\pi^+\pi^-$, …



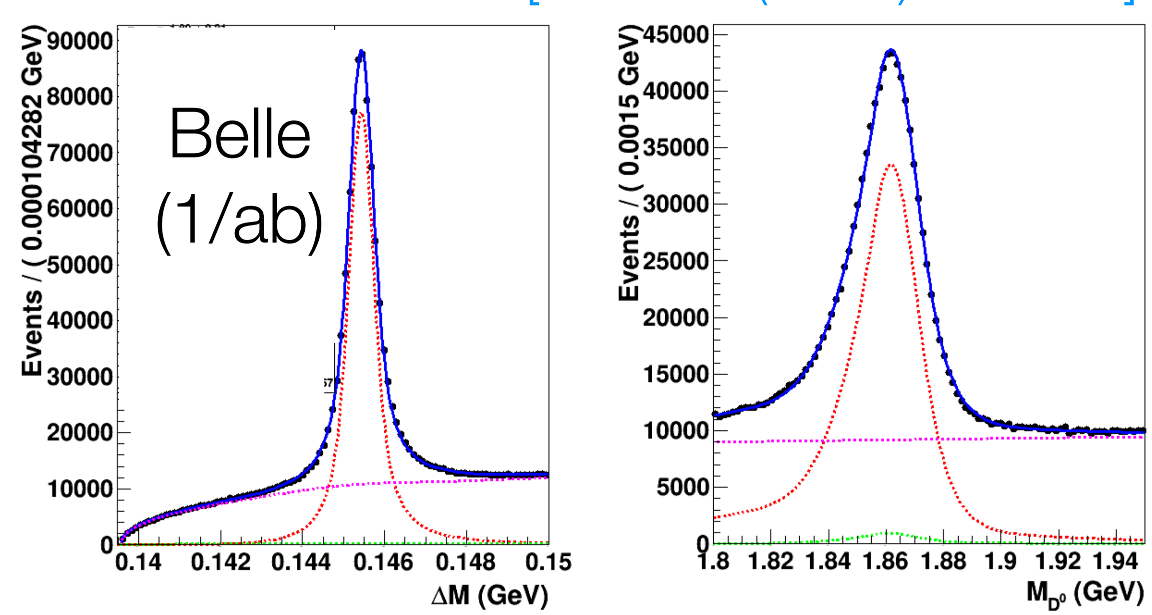
~300k $D^0 \to K^+\pi^-\pi^0$ expected at Belle II (50/ab)

Potential of $D^0 \to K^+\pi^-\pi^+\pi^-$ @ LHCb



[CERN-THESIS-2017-257]

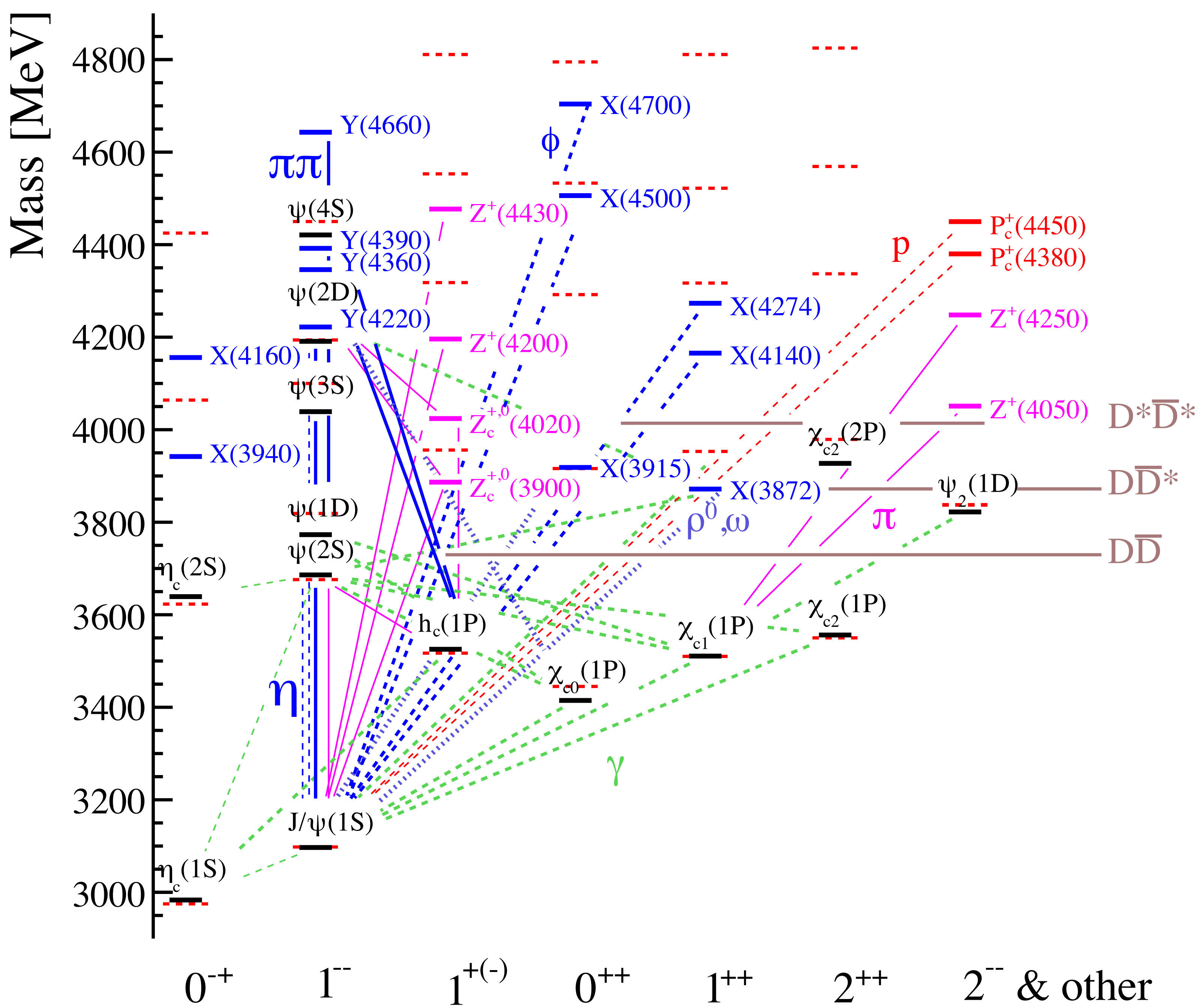
[PRD 95 (2017) 091101]



~750M $D^0 \to K_S\pi^+\pi^-\pi^0$

Exotic charm production in *b* decays

Charmonium-like above threshold



Observed states:

Conventional charmonium

Unconventional neutral states

Unconventional charged states

Pentaquark candidates

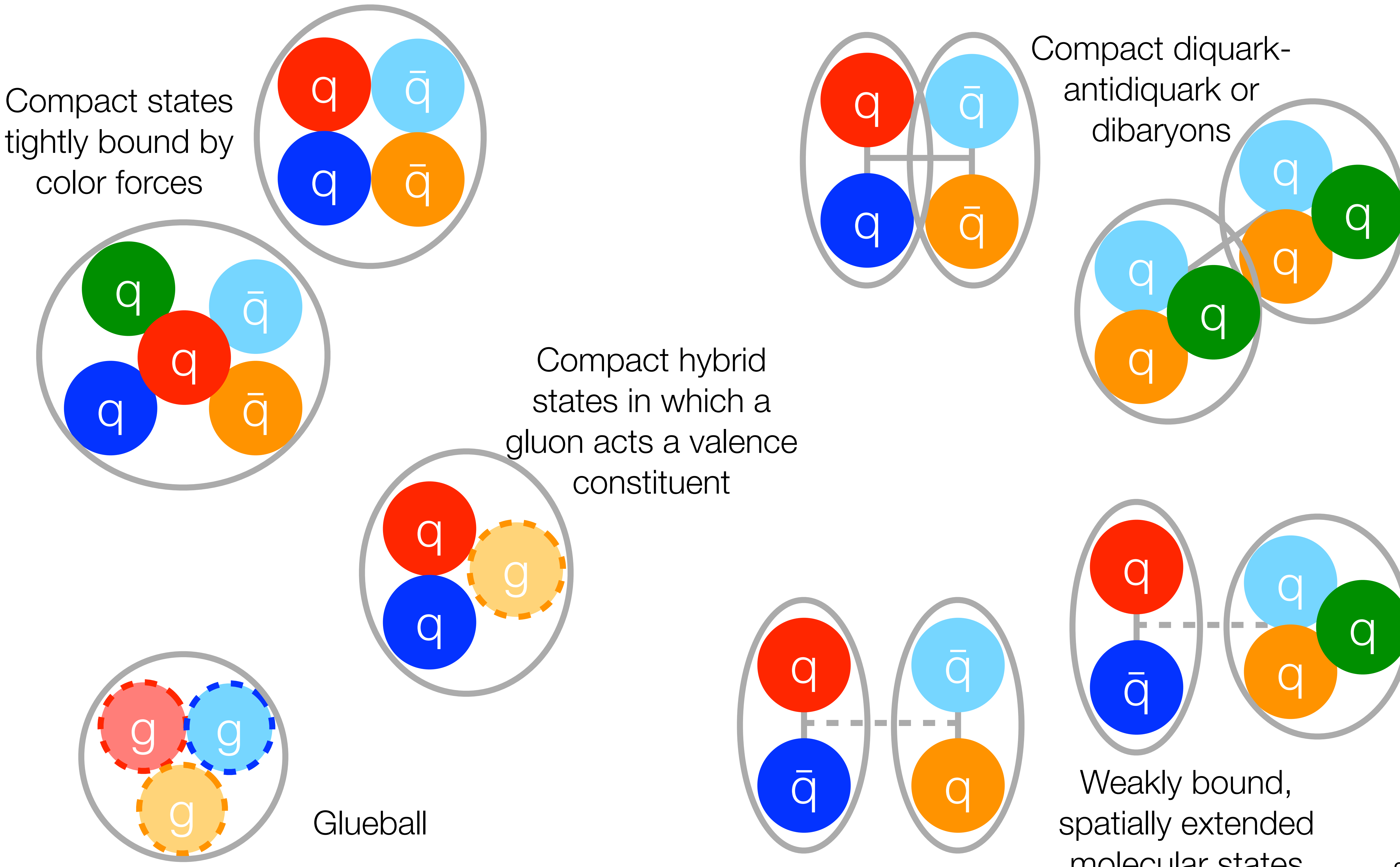
Expected states

Kinematic thresholds

- Mesons/baryons are predominantly ($\bar{q}q/qqq$) bound states below the open flavor threshold
- There is a zoo of more complex states above threshold, which have not yet been understood

[Rev. Mod. Phys. 90 (2018) 15003]

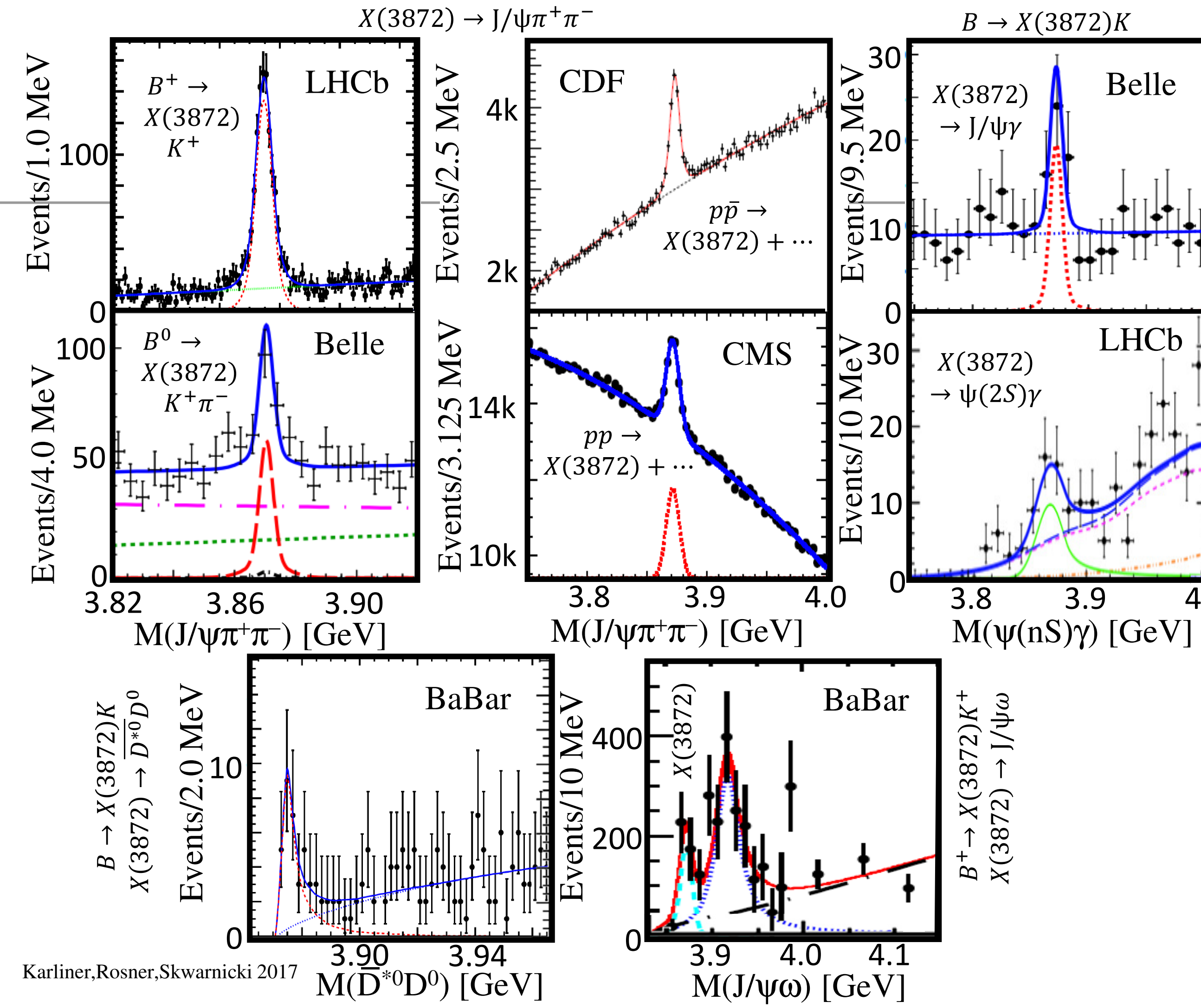
Possible types of exotic states

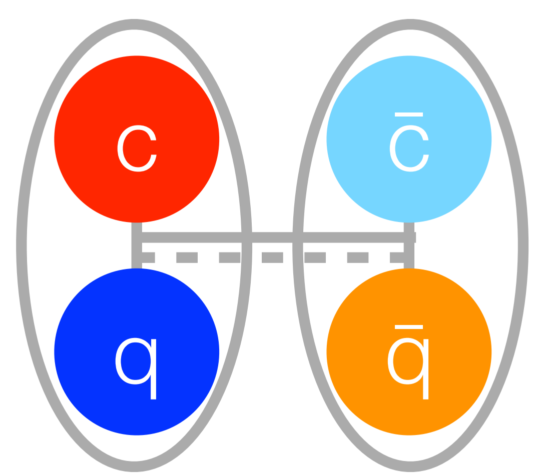


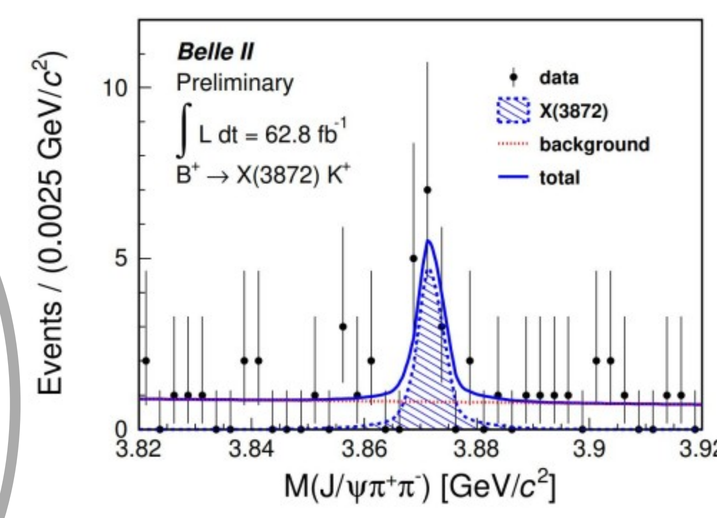
All started with $X(3872)$

- Discovered by Belle ~18 years ago [PRL 91 (2003) 262001]
- The only exotic charmonium-like candidate which shows up consistently in different production mechanisms and in many different decays modes
- Mixture of a compact ($cq\bar{c}\bar{q}$) state and a molecule?
    - Near $D\bar{D}^*$ threshold and narrow width in decays to $c\bar{c}$ states favors molecular interpretation
    - $X(3872)$ production rates in prompt processes more likely for a compact state
- More experimental results needed/expected to clarify the nature of this state

[Ann. Rev. Nucl. Part. Sci. 68 (2018) 17]



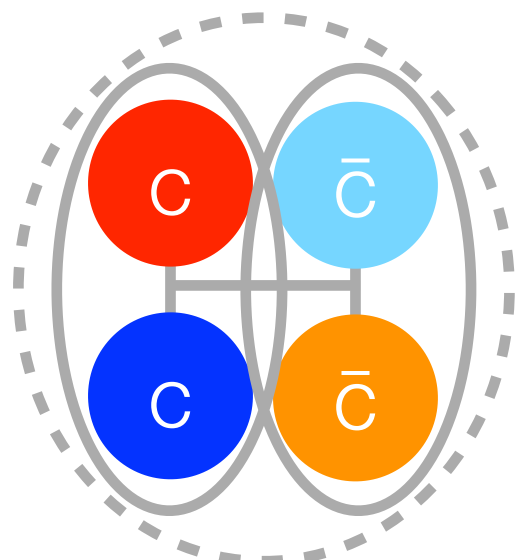




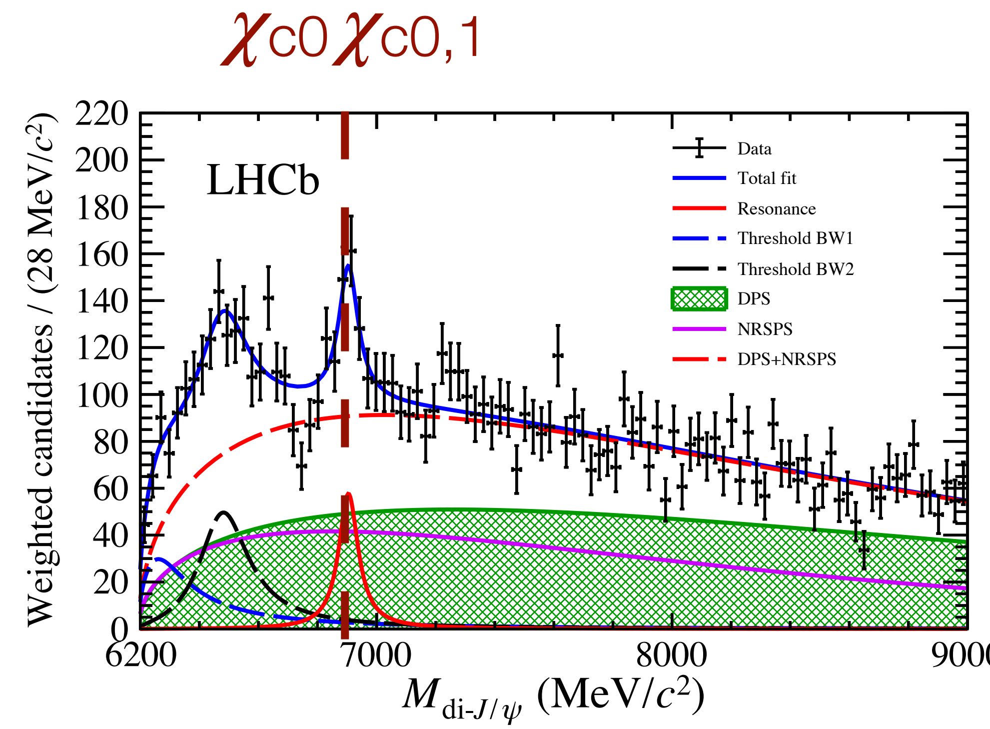
[Science Bulletin 65 (2020) 1983]

Di-charmonium states

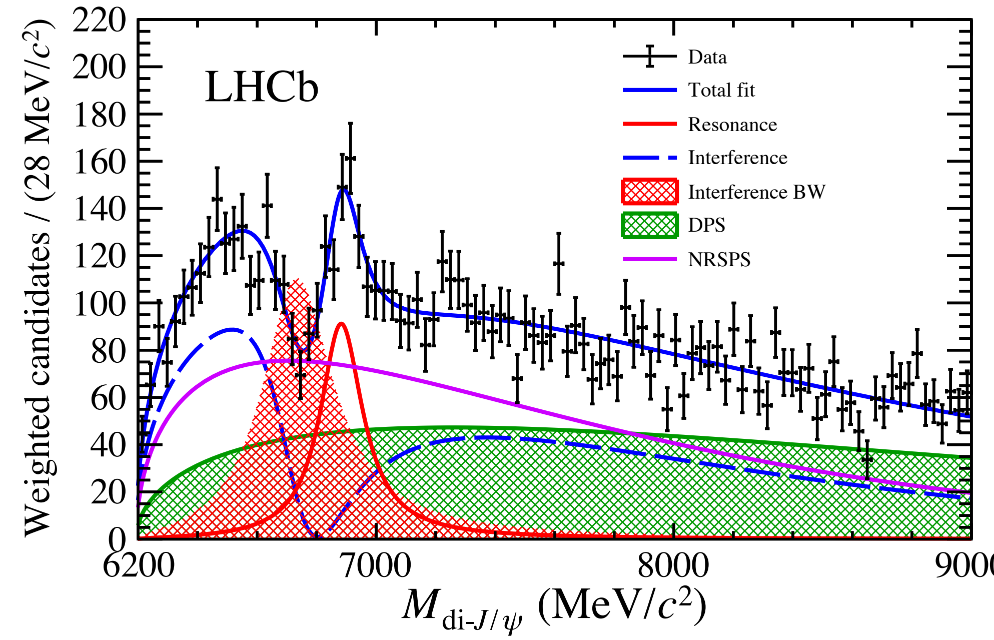
- Very significant structure in *J/ψJ/ψ* mass spectrum
- Interpretation of data is not clear:
  - One, or more (interfering?) resonances
    Possible near-threshold effects?
  - However, no known mechanism for binding forces between two charmonium states, and the *X*(6900) peak seems too wide to be a molecule
  - Likely theoretical interpretation: compact *cc̄cc̄* tetraquark/ diquark-antidiquark state(s)



- More experimental questions remain unanswered: Quantum numbers? Other decay modes?



m = 6905 ± 11 ± 7 MeV/c^2
Γ = 80 ± 19 ± 33 MeV

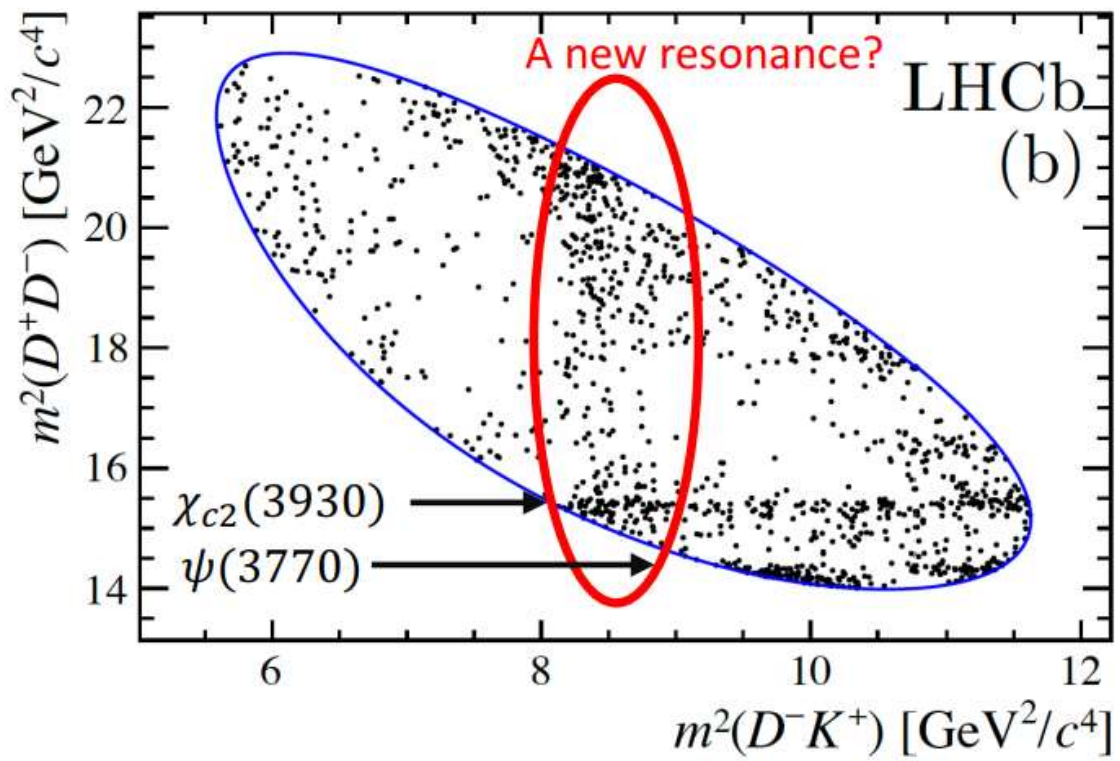


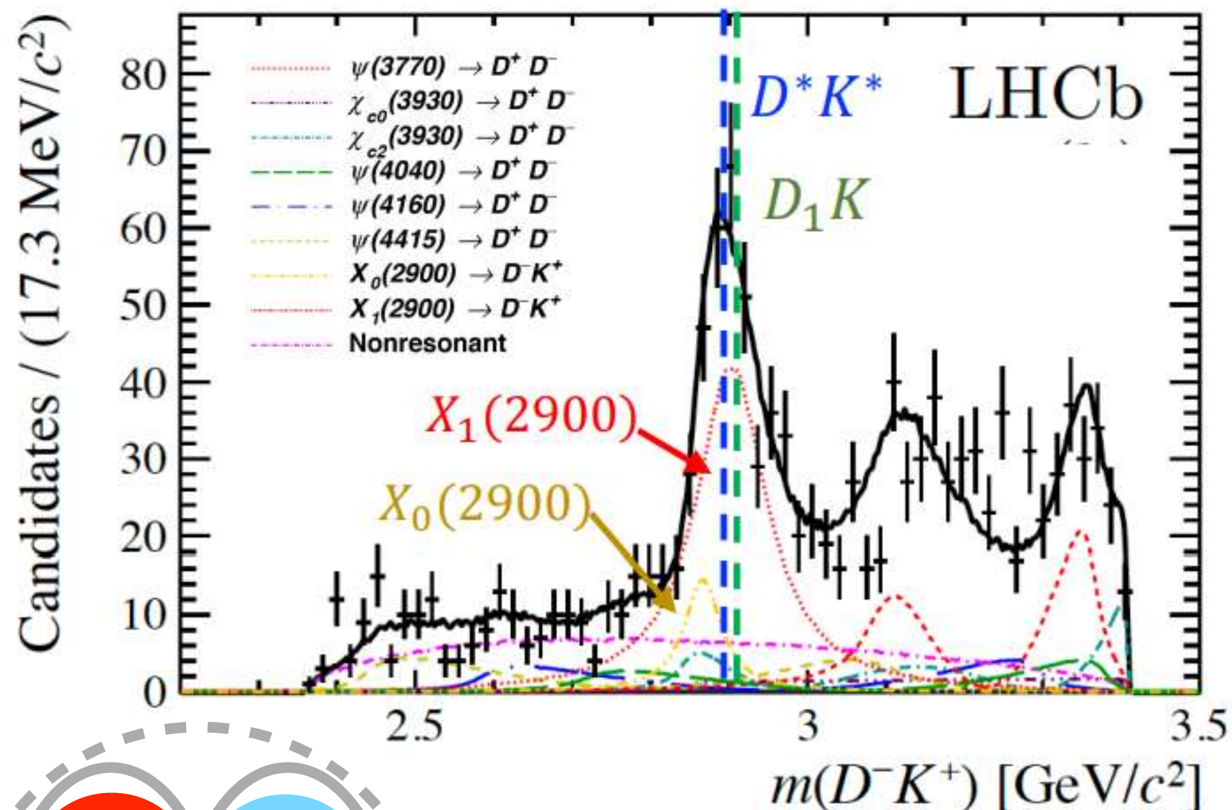
m = 6868 ± 11 ± 11 MeV/c^2
Γ = 168 ± 33 ± 69 MeV

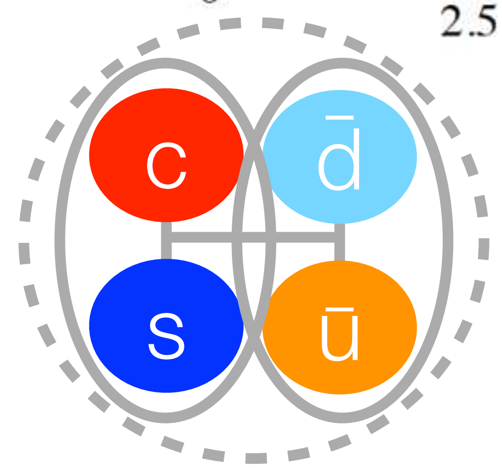
Charming and strange exotic states

$B^+ \to D^+ D^- K^+$

[PRD 102 (2020) 112003]







- The 0^+ is a good candidate for a compact $cs\bar{u}\bar{d}$ state
- However, proximity to the thresholds motivates other explanations: *e.g.*, molecular state or rescattering/triangular amplitudes

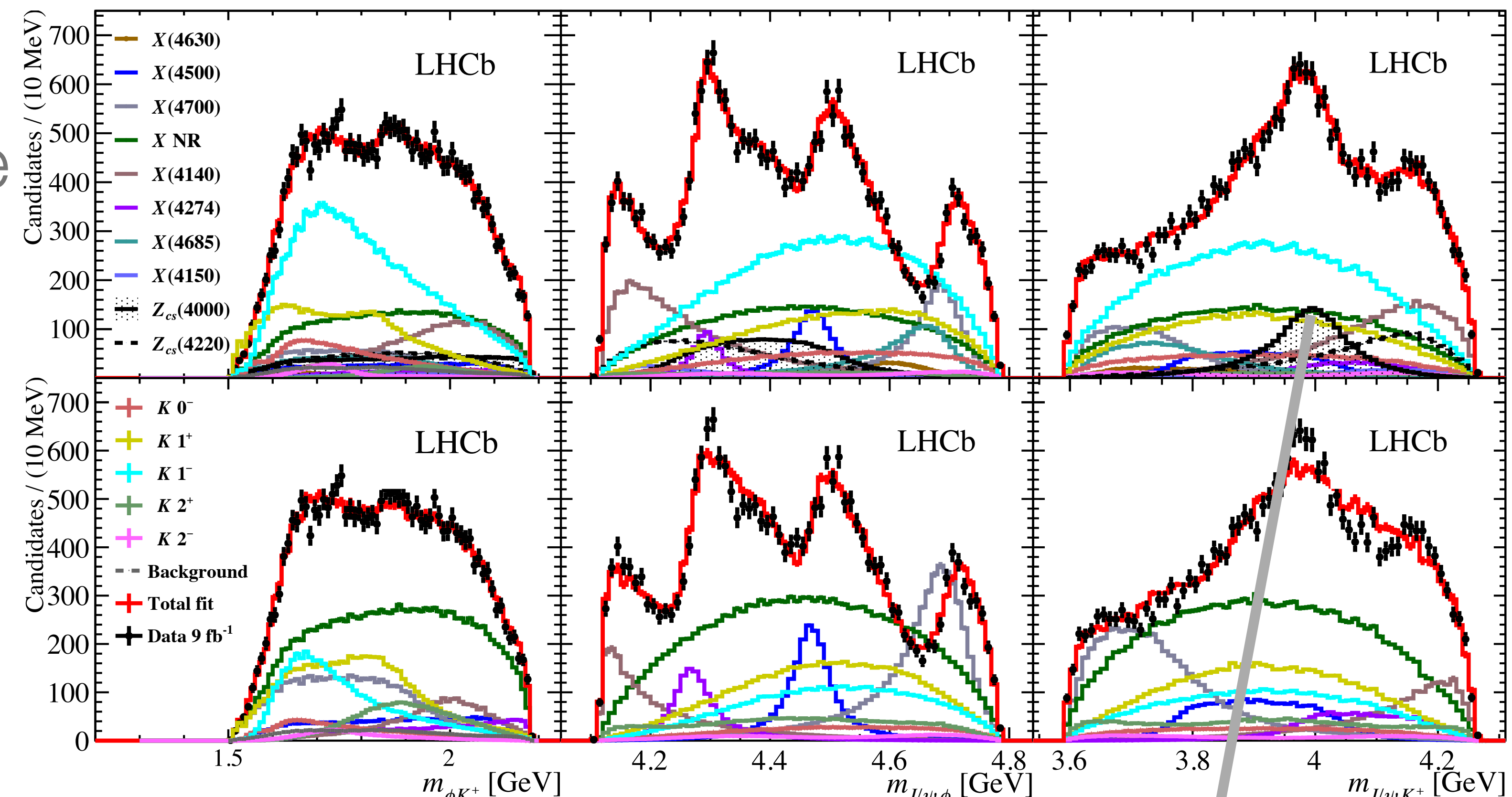
$m_0 = 2866 \pm 7 \pm 2$ MeV/c^2
$\Gamma_0 = 57 \pm 12 \pm 4$ MeV

$m_1 = 2904 \pm 5 \pm 1$ MeV/c^2
$\Gamma_1 = 110 \pm 11 \pm 4$ MeV

Charming and strange exotic states

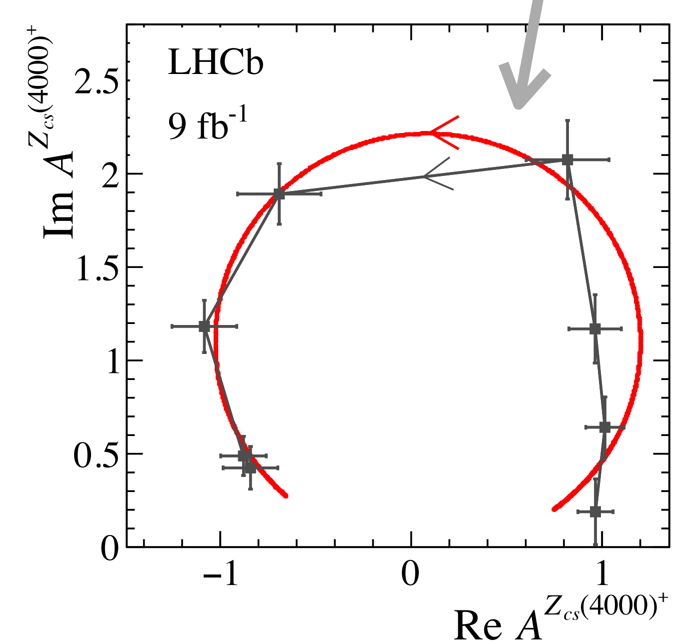
[arXiv:2103.01803]

- Multiple $J/\psi\phi$ structures observed in $B^+ \to J/\psi\phi K^+$ since CDF reported the $X(4140)$ [PRL 102 (2009) 242002]
    - All are broad: unclear if due to exotic hadrons or rescattering effects



- Latest analysis from LHCb shows one 1^+ (or two?) $Z_{CS}^+ \to J/\psi K^+$ candidate(s) with phase variation consistent with a resonance

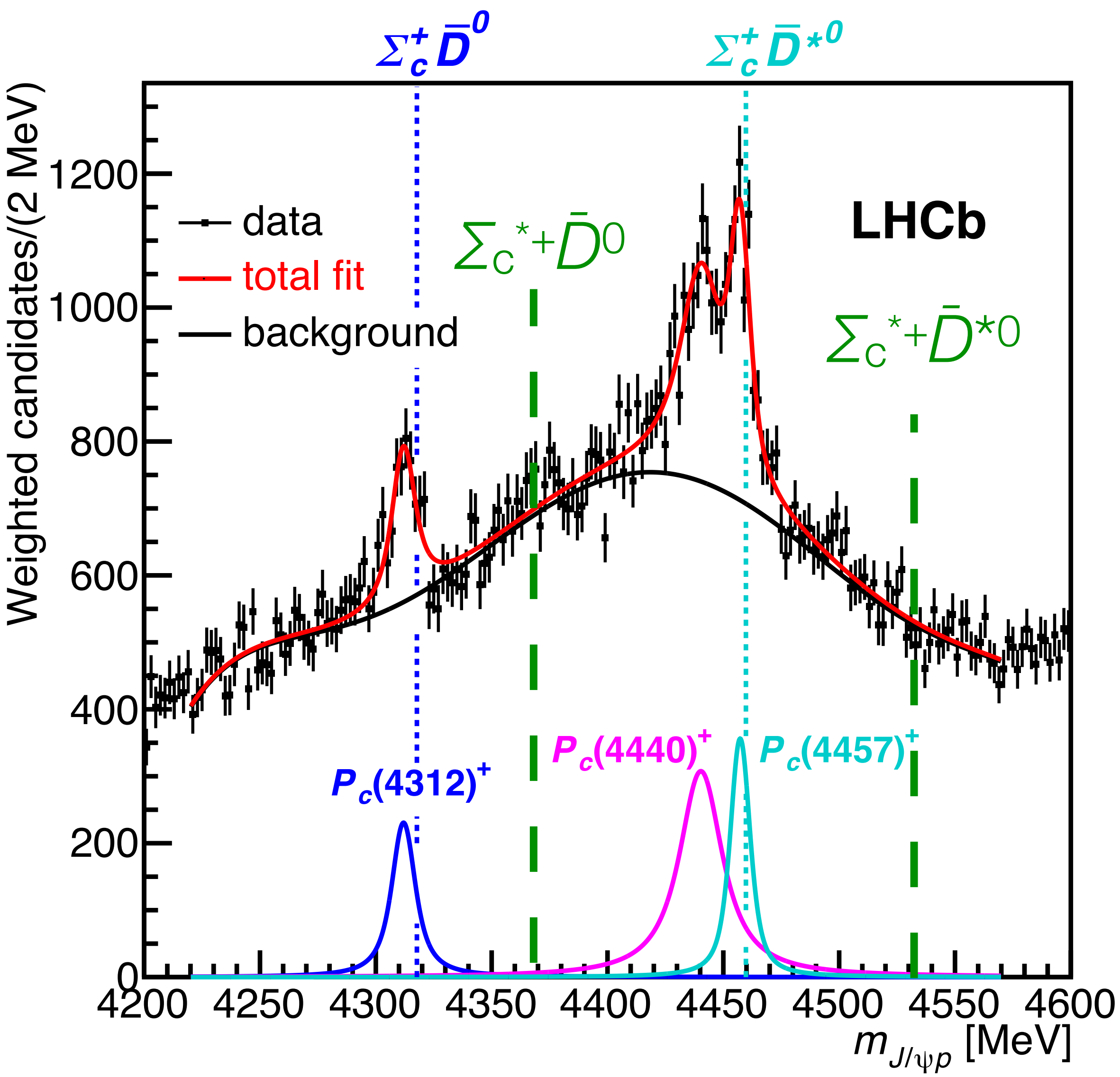
$m = 4003 \pm 6\ ^{+4}_{-14}$ MeV/c^2 $\Gamma = 131 \pm 15 \pm 26$ MeV



- Not consistent with the narrow threshold structure previously reported by BESIII in $D_S^-D^{*0} + D^{*-}D^0$ mass distribution [PRL 126 (2021) 102001]

More pentaquark states?

$\Lambda_b \to J/\psi p K^-$



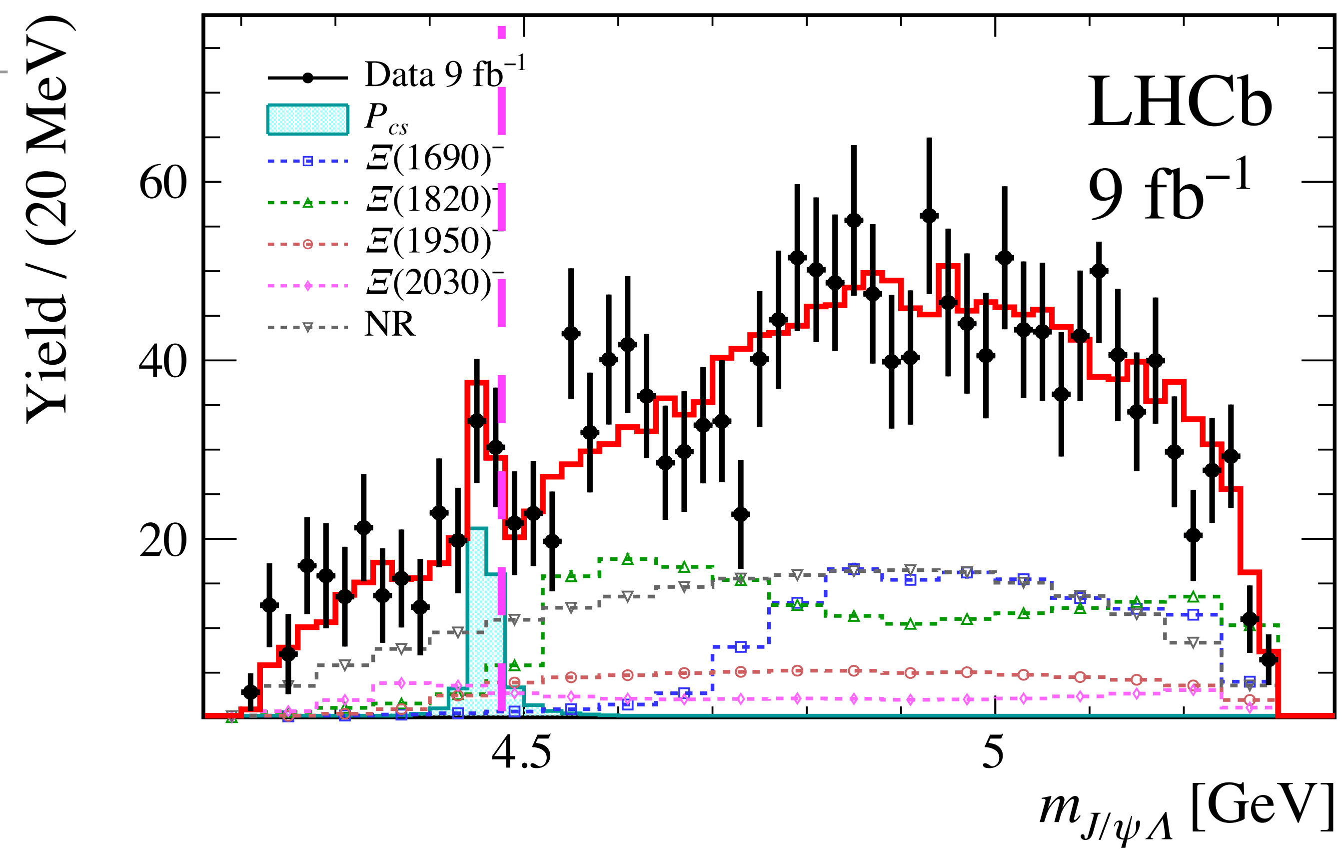
- States in $J/\psi p$ are likely baryon-meson molecular states, more isospin partners are expected

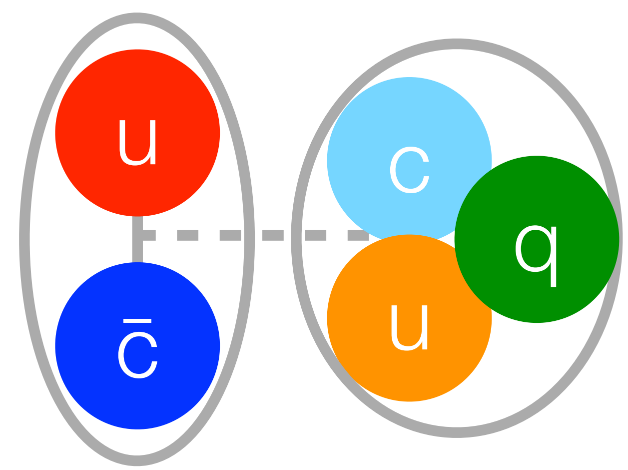
[PRL 122 (2019) 222001]

$\Xi_b \to J/\psi \Lambda K^-$

$\Xi_c^0 \bar{D}^{*0}$

[arXiv:2012.10380]





- Evidence for one (or two?) charming and strange narrow states in $J/\psi \Lambda$ close to threshold

Conclusions

- Precision charm physics has just started. Huge experimental progress expected in the next decade(s) at LHCb, Belle II, BESIII… if we fully exploit the excellent complementarity between the experiments
  - First observation of direct *CP* violation, and in reach of standard-model expectation for *CP* violation in mixing
  - Not shown today: virgin field of new-physics searches, including LF(U)V, in $c \to u\ell\ell'$ and $c \to u\nu\bar{\nu}$ transitions
- Citing Y. Grossman: a win-win situation
  - Hopefully, we will see physics beyond the standard model
  - If not, we are learning about QCD
- More and more exotic hadrons are popping up above open flavor threshold (also with *b*-quark content, not covered here). Nature of all the states is still unclear
  - A lot of work to do for both experimentalists and theorists

Charm is more valuable than beauty. You can resist beauty, but you can't resist charm.

— *Audrey Tautou* —