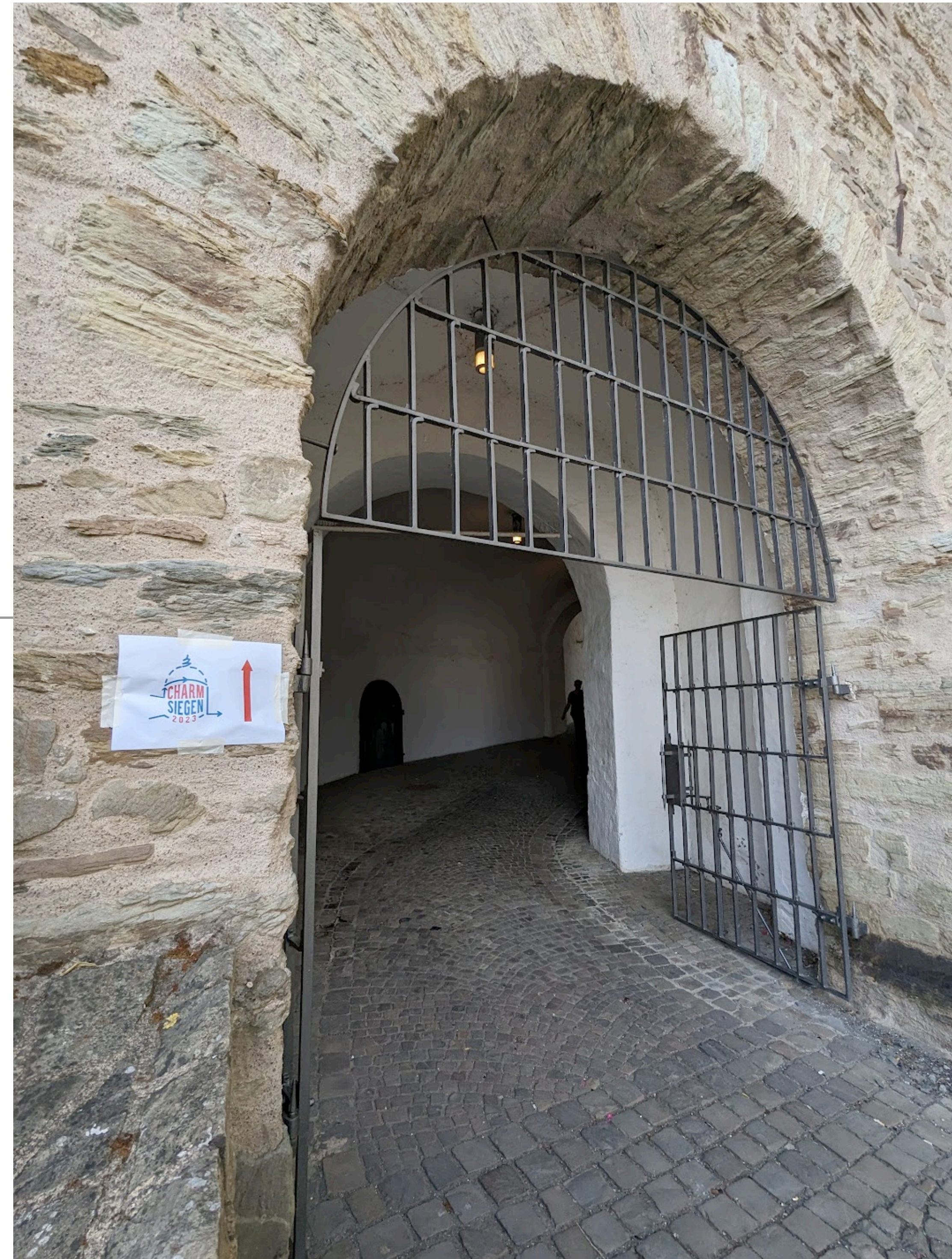
Conference Summary

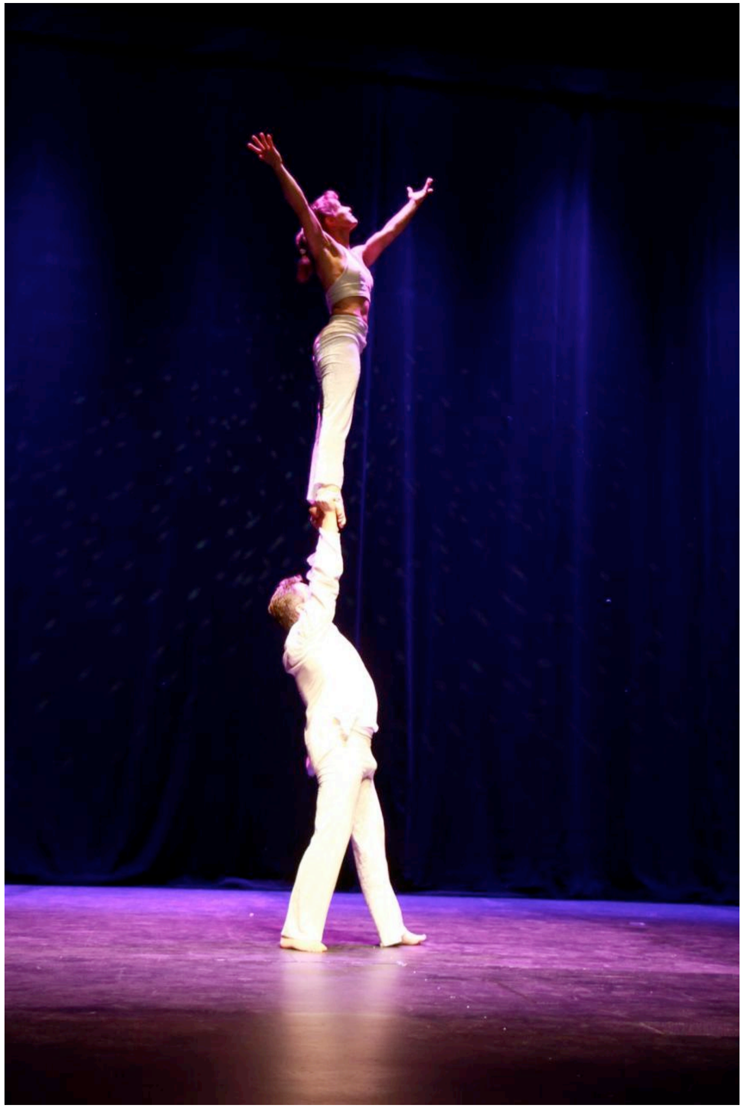
Jonas Rademacker



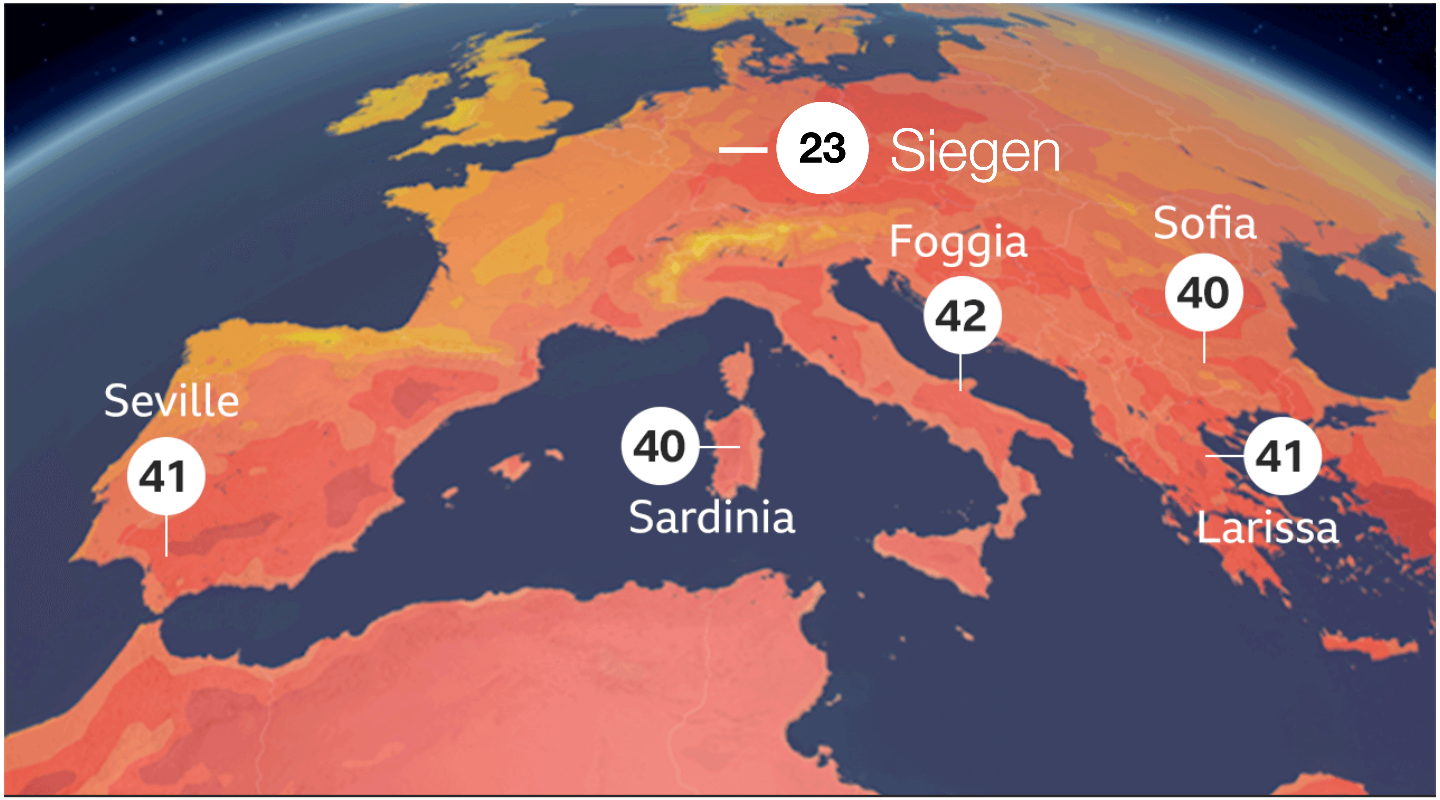
Thank you for a

wild

gravity-defying



perfectly temperature-adjusted



Source: BBC Weather, 13 July 2023

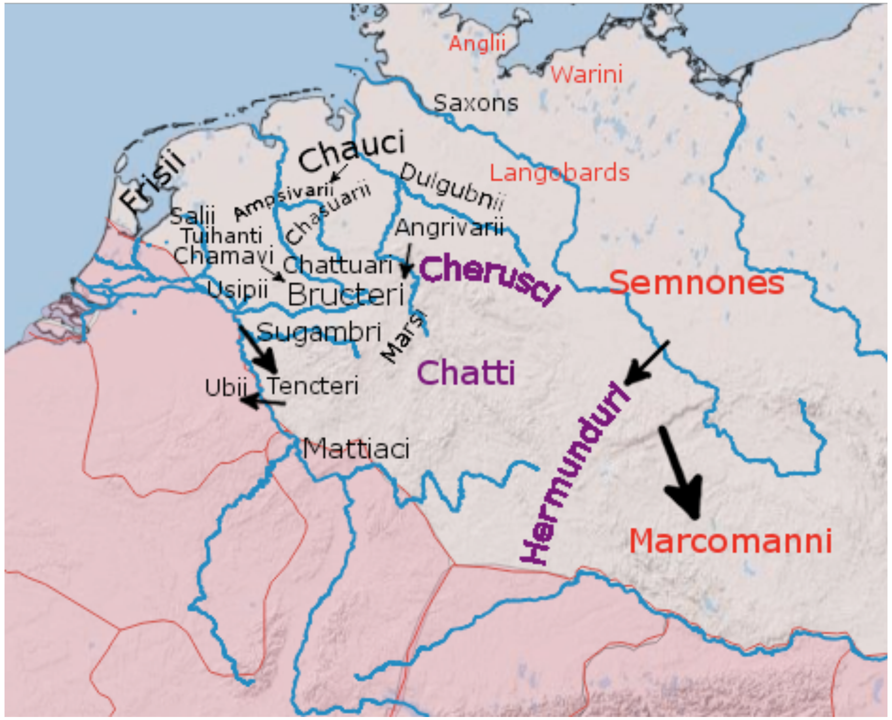
very well organised

Conference

with a beautiful song

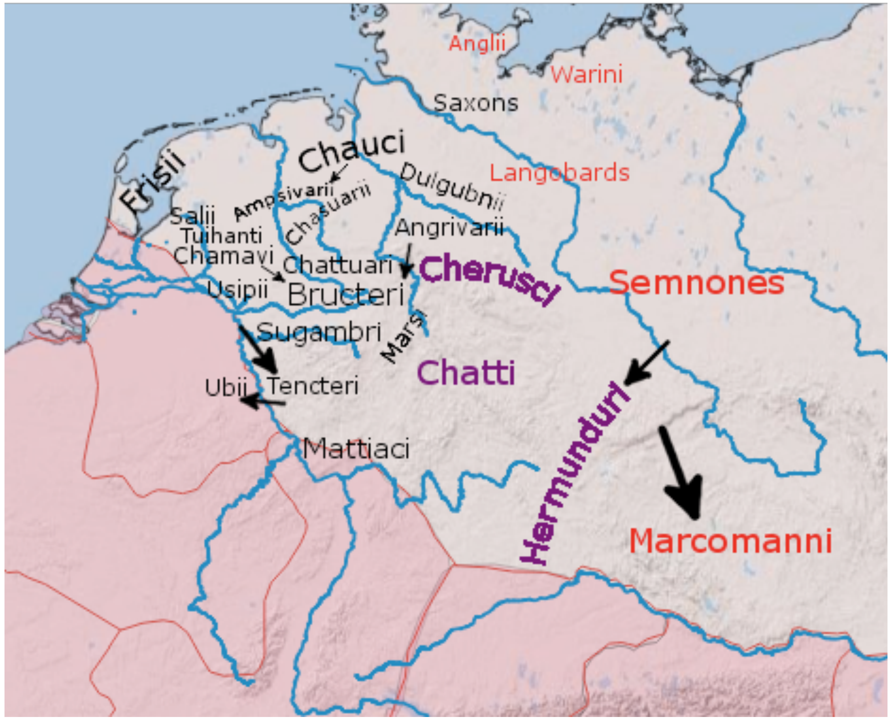
Siegen

- Named after the river Sieg
- …which is **not** named after the German word “Sieg” /ziːk/ = victory
- Instead, it stems from “Sicambri” (also “Sugambri”), a Germanic tribe (with Celtic associations - they had names like Baetorix, Deudorix,…)



Sicambri

- When Caesar defeated the Eburones, he invited all of the peoples that were interested to destroy the remainder. The Sicambri responded to Caesar's call. They took large amounts of cattle, slaves and plunder.
- Caesar commented that "these men are born for war and raids". "No swamp or marsh will stop them".
- After the raid on the Eburones they moved on against the Romans.
- Charming.



Sicambrian spirit in Siegen

Sicambrian spirit in Siegen

Alexey: “Its a sign of an engaging talk if audience members fight with each other”

Sicambrian spirit in Siegen

Alexey: “Its a sign of an engaging talk if audience members fight with each other”

Blaženka: “Do not kill the messenger, kill Alex Lenz”

Sicambrian spirit in Siegen

Alexey: “Its a sign of an engaging talk if audience members fight with each other”

Blaženka: “Do not kill the messenger, kill Alex Lenz”

Every session chair:

Facilites

Tara Nanut Petrič

Charm factory	B factory	Hadron collider
• Lowest statistics • No boost • Quantum coherence ★ • Inclusive charm, neutrals and neutrinos • Absolute branching fractions	• Low statistics • Low boost • Good for neutrals and neutrinos ★ • (Some) absolute branching fractions	• High statistics ★ • High boost • Challenging for neutrals and neutrinos • Complex and biasing triggers
$e^+e^- \rightarrow D^{(*)}\overline{D}^{(*)}$ $e^+e^- \rightarrow \psi(3770) \rightarrow D\overline{D}$	$e^+e^- \rightarrow c\bar{c}$ + some other stuff	$pp \rightarrow c\bar{c}$ + lots of other stuff
BES III STCF in the future	BELLE-II	LHCb

Flavour tagging

$$D^{*+} \to D^0\pi^+$$
$$D^{*-} \to \overline{D}^0\pi^-$$

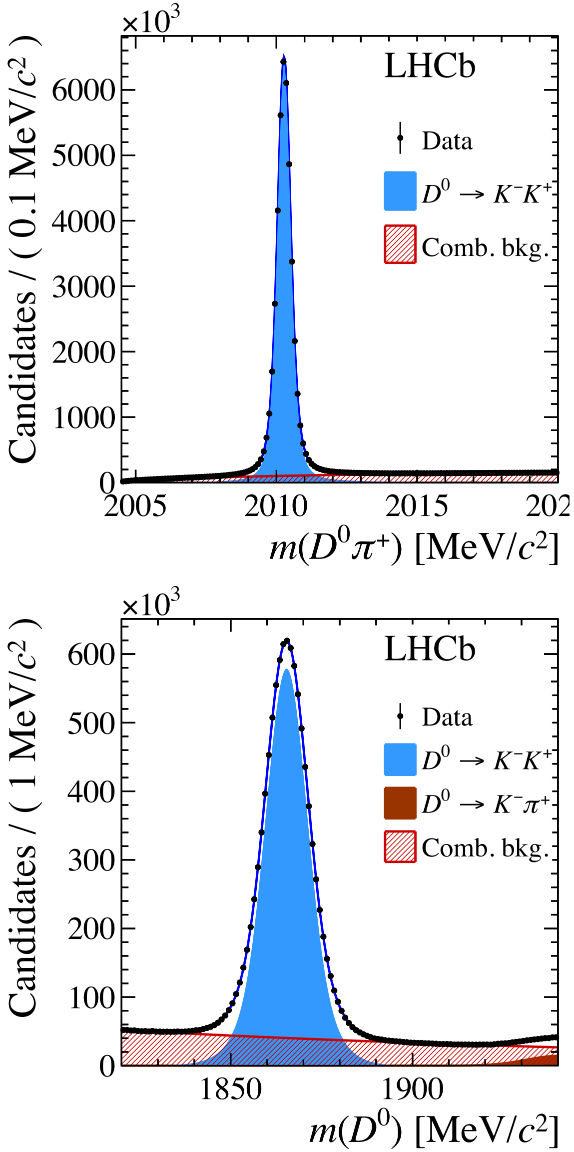
(LHCb, BaBar, BELLE)

$$\overline{B} \to D^0\mu^-\bar{\nu}_\mu X$$
$$B \to \overline{D}^0\mu^+\nu_\mu X$$

(LHCb)

$$e^+e^- \to \psi(3770) \to D_1D_2$$

(BES III)



From LHCb's discovery of CPV in charm,
PRL 122 (2019) 21, 211803

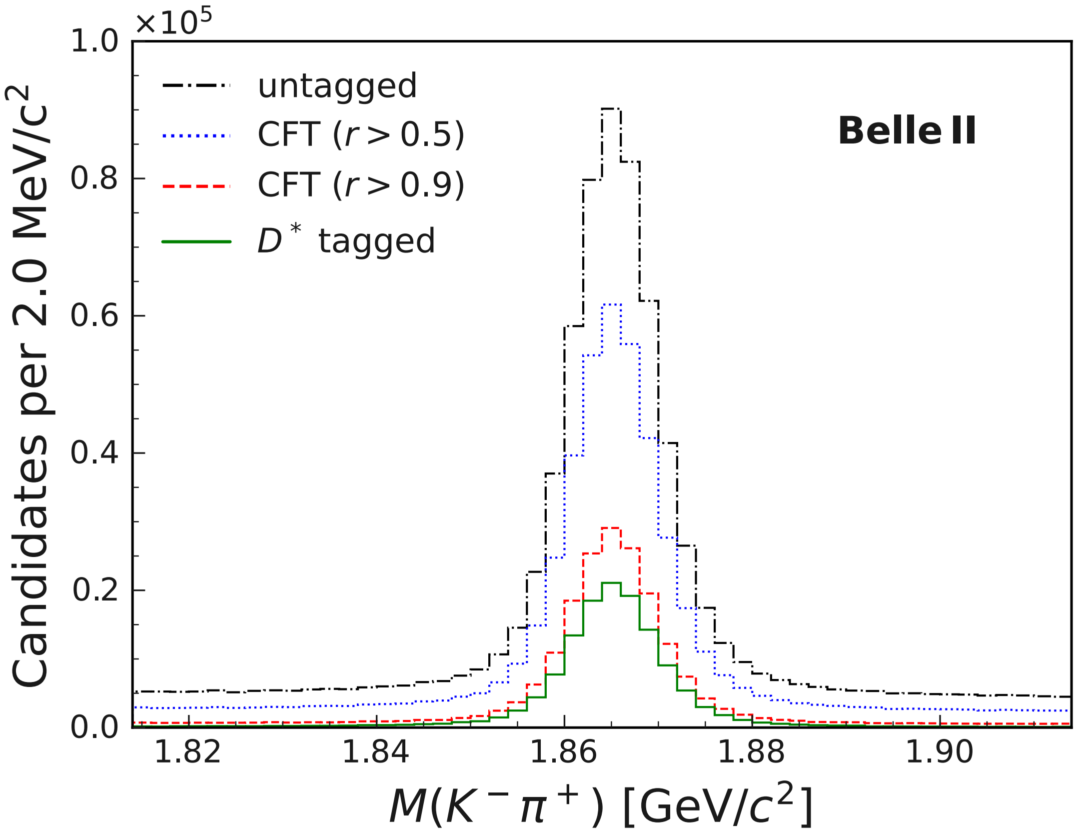
Marco Starič

Flavour tagging: Opposite Side D tagging @ BELLE-II

BELLE II: PRD 107, 112010 (2023)

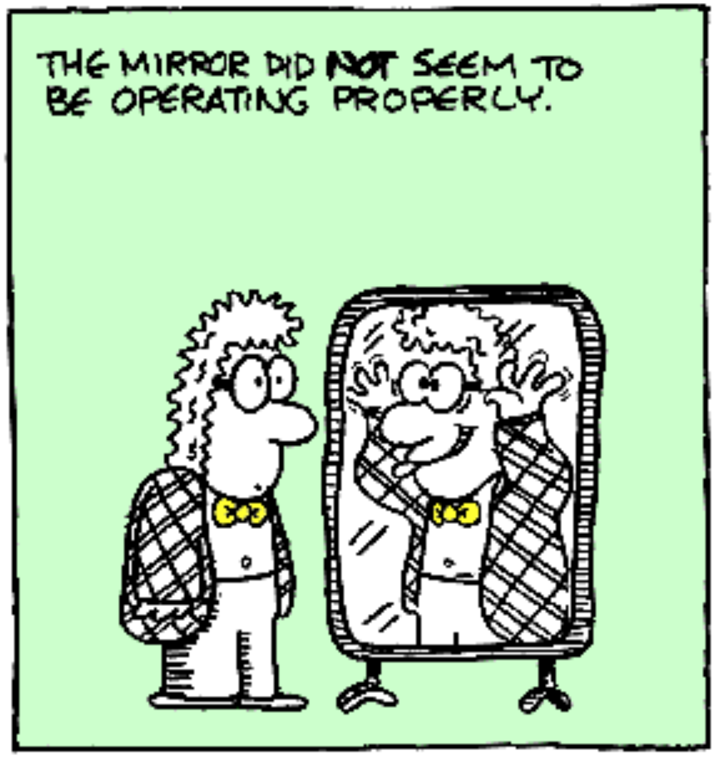
$$e^+e^- \rightarrow c\bar{c} \rightarrow D + \text{rest of event}$$

"rest of event" analysed by neural net which returns tag and estimated dilution



CP Violation

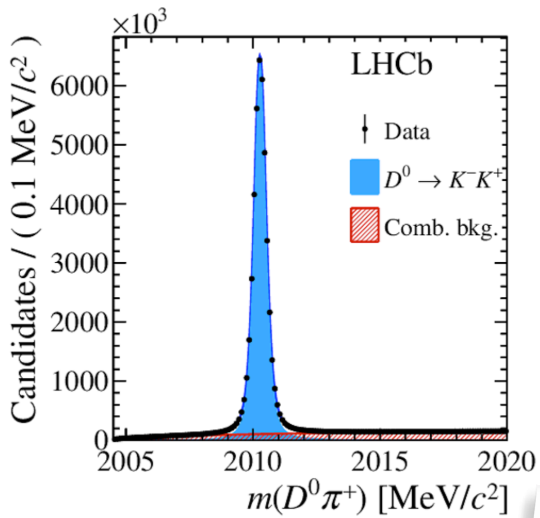
Beauty

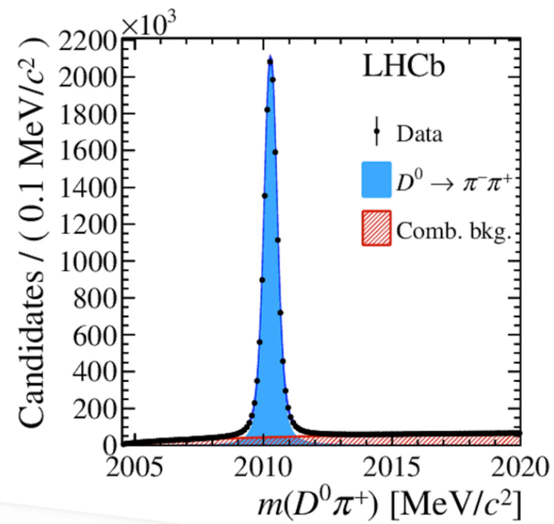


Charm

Discovery of CP violation in Charm in 2019

Eva Gersabeck

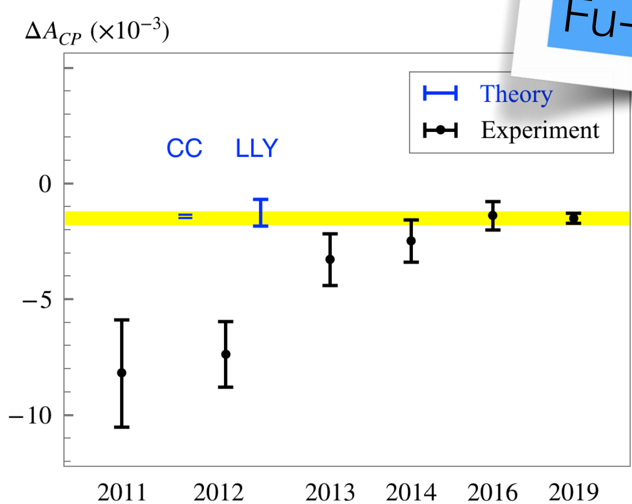




LHCb: PRL 122 (2019) 211803

$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$$
$$= (-15.4 \pm 2.9) \times 10^{-4}$$

Fu-Sheng Yu



Saur, **FSY**, Sci.Bull.2020

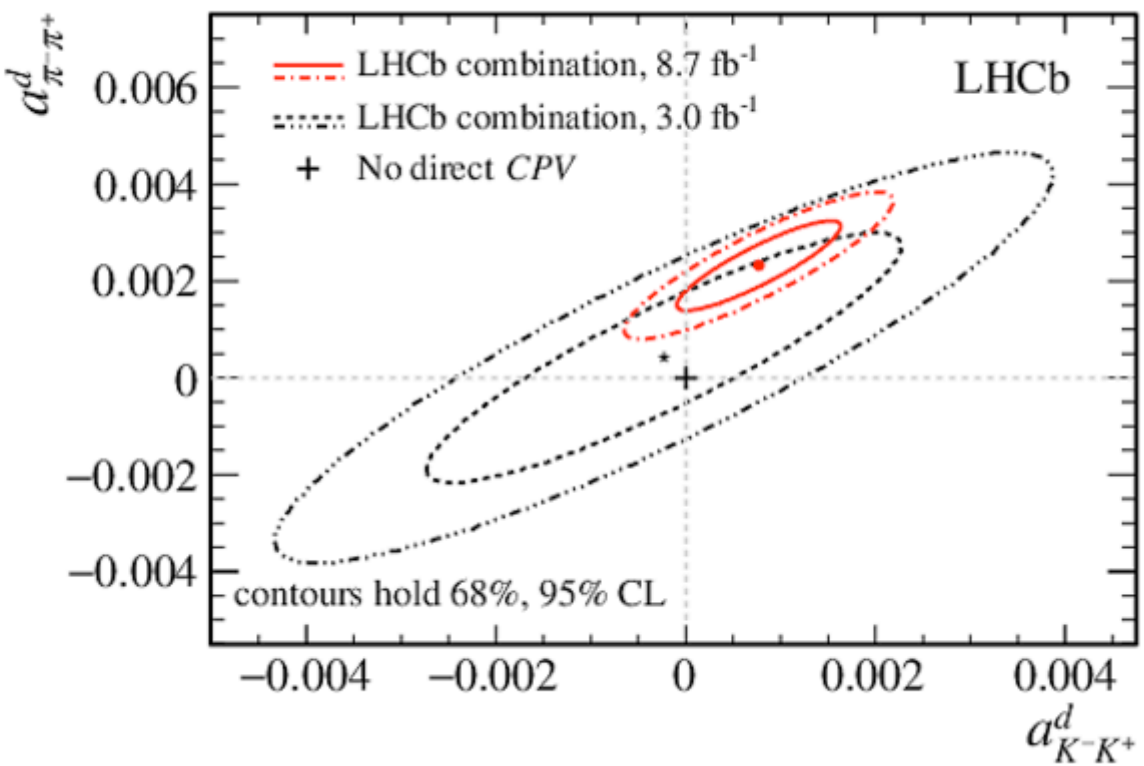
Bigger than generally expected. Still unclear if/how this can be accommodated SM.

Luiz Vale Silva

A_{CP} in $D^0, \overline{D}^0 \to K^+K^-$

Eva Gersabeck

LHCb: arXiv:2209.03179 (2022)



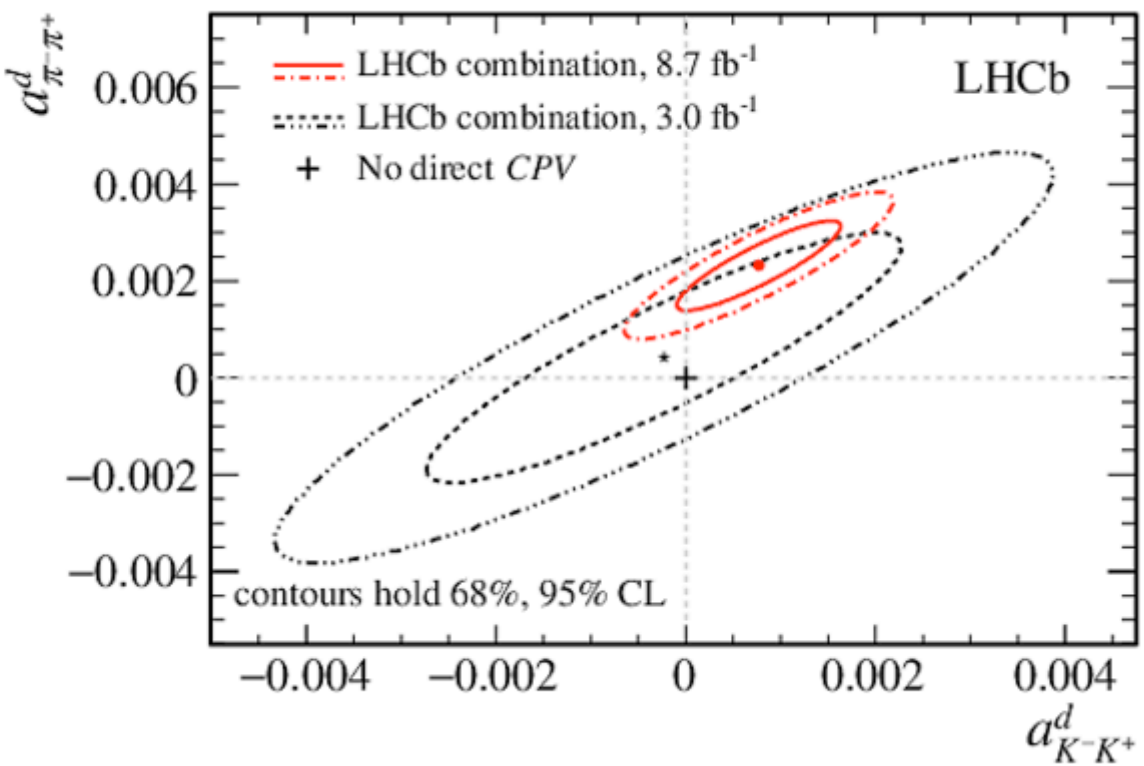
U-spin says:

$$a_{\pi\pi}^{\text{direct}} \approx -a_{KK}^{\text{direct}}$$

A_{CP} in $D^0, \overline{D}^0 \to K^+K^-$

Eva Gersabeck

LHCb: arXiv:2209.03179 (2022)



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experiment says:

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Eva Gersabeck

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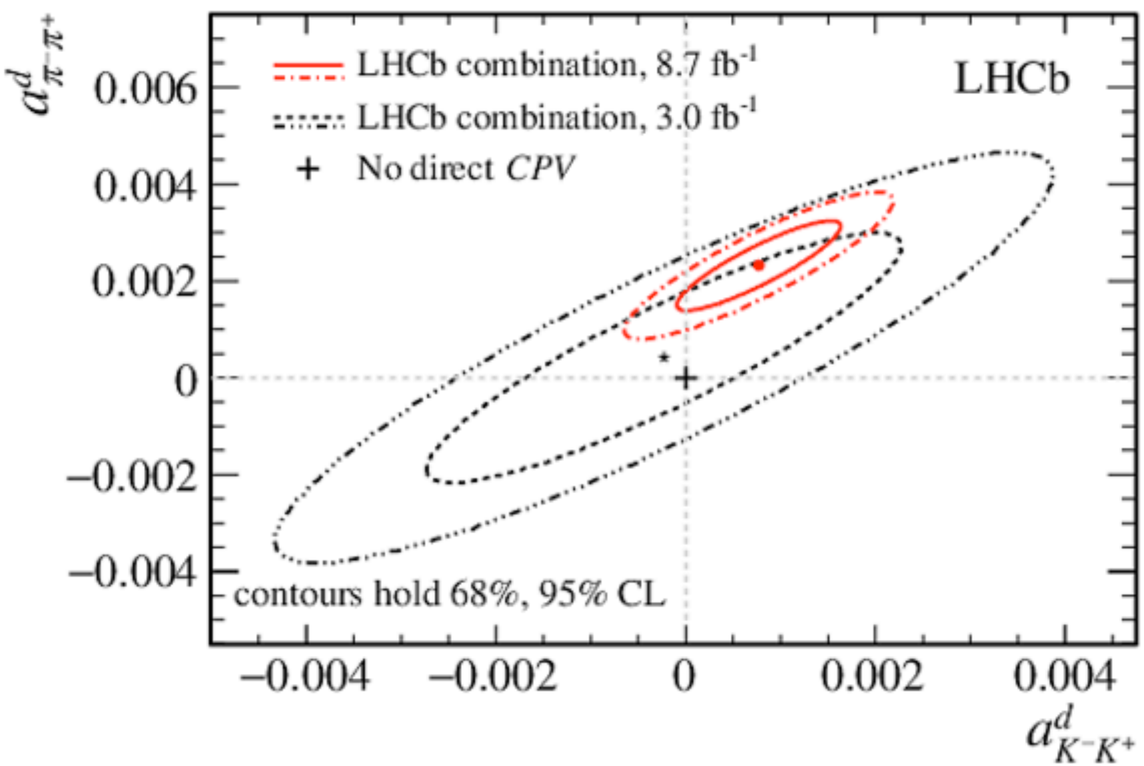

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Eva Gersabeck

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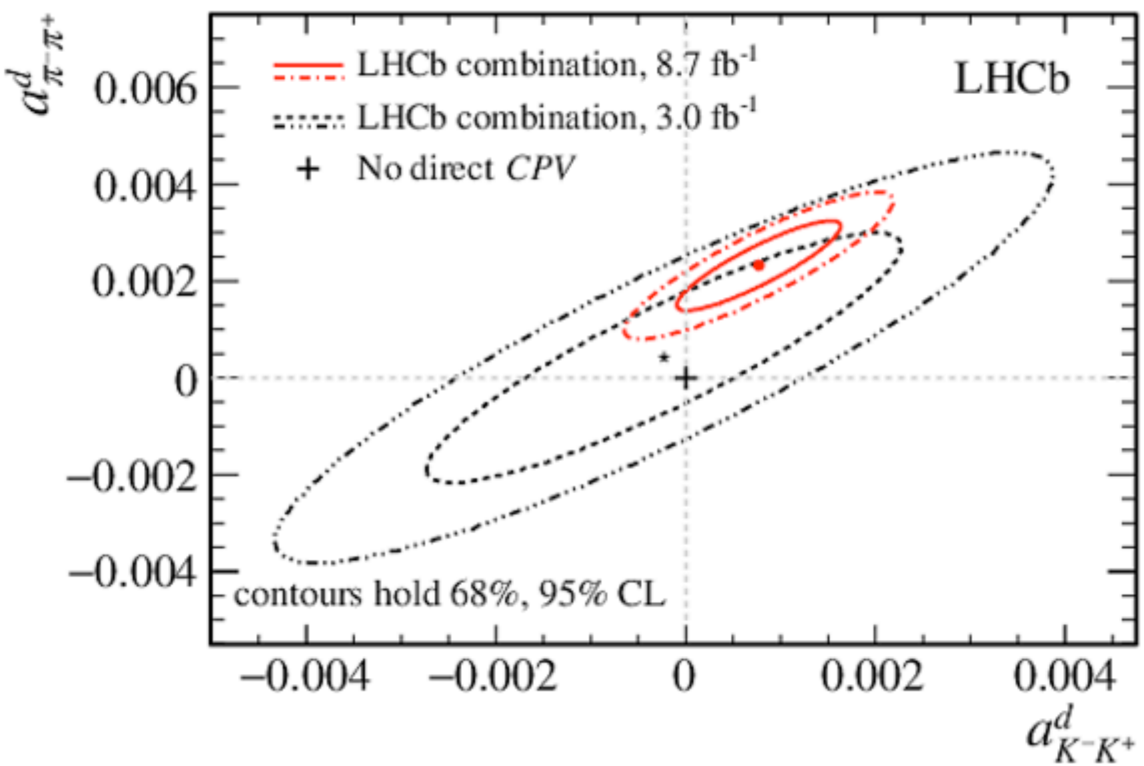
LHCb: arXiv:2209.03179 (2022)



U-spin says:

$$a_{\pi\pi}^{\text{direct}} \approx -a_{KK}^{\text{direct}}$$

experiment says:

$$a_{\pi\pi}^{\text{direct}} = (23.2 \pm 6.1) \times 10^{-4}$$

$$a_{KK}^{\text{direct}} = (7.7 \pm 5.7) \times 10^{-4}$$

No other direct CPV in HFLAV 2021 summary

No other direct CPV in HFLAV 2021 summary

CP Asymmetries in D^0 decays

Year	Experiment	CP Asymmetry in the decay mode D0 to π+π-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2017	LHCb	R. Aaij et al. (LHCb Collab.), Phys. Lett.B 767 177 (2017).	+0.0007 ± 0.0014 ± 0.0011
2012	CDF	T. Aaltonen et al. (CDF Collab.), Phys. Rev. D 85, 012009 (2012).	+0.0022 ± 0.0024 ± 0.0011
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	-0.0024 ± 0.0052 ± 0.0022
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett.B 670, 190 (2008).	+0.0043 ± 0.0052 ± 0.0012
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.019 ± 0.032 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	+0.048 ± 0.039 ± 0.025
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.049 ± 0.078 ± 0.030
		HFLAV average	+0.0012 ± 0.0014
Year	**Experiment**	**CP Asymmetry in the decay mode D0 to π0π0**	**[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]**
2014	BELLE	N.K. Nisar et al. (BELLE Collab.), Phys. Rev. Lett. 112, 211601 (2014).	-0.0003 ± 0.0064 ± 0.0010
2001	CLEO	G. Bonvicini et al. (CLEO Collab.), Phys. Rev. D 63, 071101 (2001).	+0.001 ± 0.048
		HFLAV average	-0.0003 ± 0.0064
Year	**Experiment**	**CP Asymmetry in the decay mode D0 to K0sπ0**	**[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]**
2014	BELLE	N.K. Nisar et al. (BELLE Collab.), Phys. Rev. Lett. 112, 211601 (2014).	-0.0021 ± 0.0016 ± 0.0007
2001	CLEO	G. Bonvicini et al. (CLEO Collab.), Phys. Rev. D 63, 071101 (2001).	+0.001 ± 0.013
		HFLAV average	-0.0020 ± 0.0017
Year	**Experiment**	**CP Asymmetry in the decay mode D0 to K0sη**	**[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]**
2011	BELLE	B.R. Ko et al. (BELLE Collab.), Phys. Rev. Lett. 106, 211801 (2011).	+0.0054 ± 0.0051 ± 0.0016
Year	**Experiment**	**CP Asymmetry in the decay mode D0 to K0sη'**	**[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]**
2011	BELLE	B.R. Ko et al. (BELLE Collab.), Phys. Rev. Lett. 106, 211801 (2011).	+0.0098 ± 0.0067 ± 0.0014

No other direct CPV in HFLAV 2021 summary

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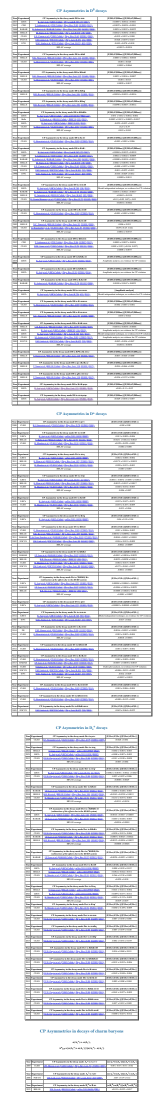


Marco Gersabeck

Search for CPV $D \to \pi^+\pi^-\pi^0$, $D \to K_S K^\pm \pi^\pm$

Probing $D^0 \to \rho\pi, K^*K$, like $\pi\pi, KK$ with added spin

Adding spin

Keeping weak structure

Dear Alex, remember what Blaženka said regarding messengers… for questions related to this slide, please refer to:

@MarcoGersabeck

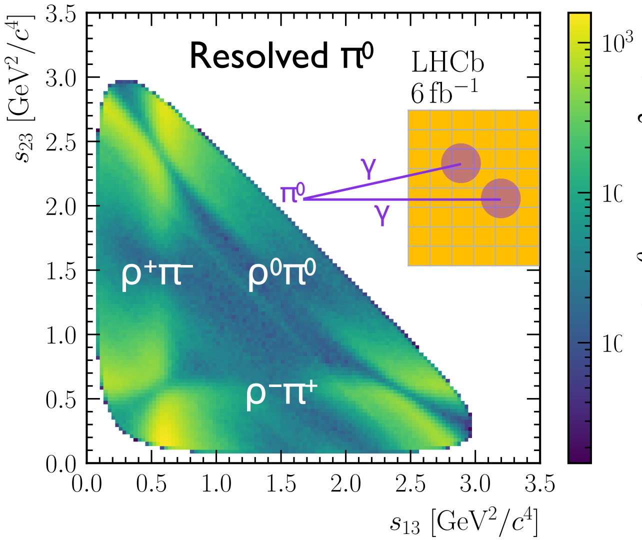
3

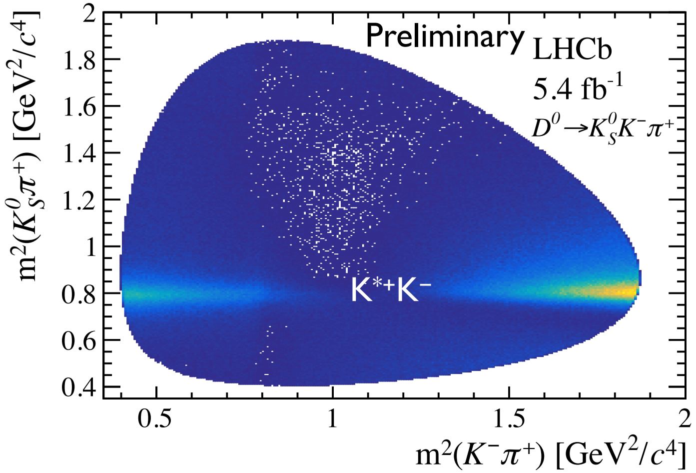
Eva Gersabeck

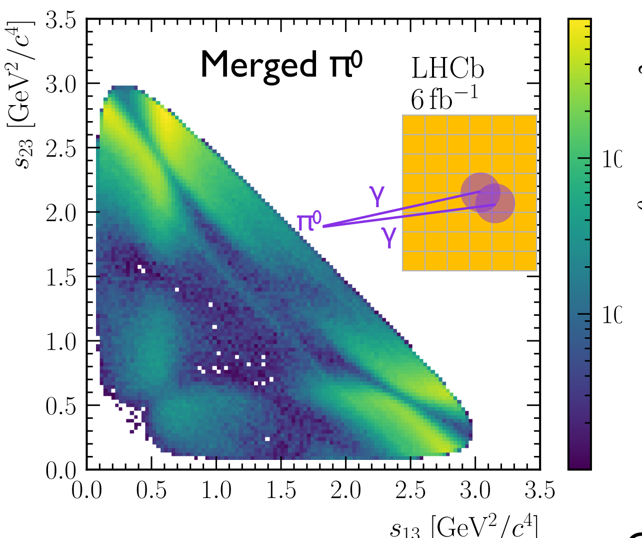
Marco Gersabeck

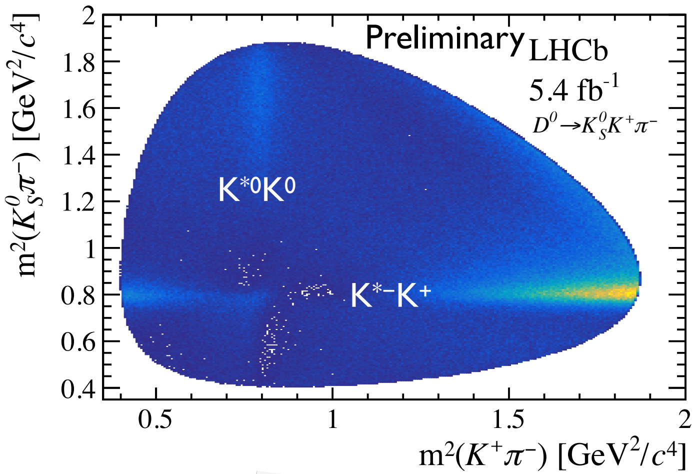
Search for CPV $D \to \pi^+\pi^-\pi^0$, $D \to K_S K^\pm \pi^\pm$

LHCb: arXiv:2306.12746 (2023)
LHCb-PAPER-2023-019









Energy test (~unbinned version of χ^2 test) reveals no significant difference between CP-conjugate Dalitz plots.

Note however, that current sensitivity insufficient to discover CPV at level seen in 2-body decays.

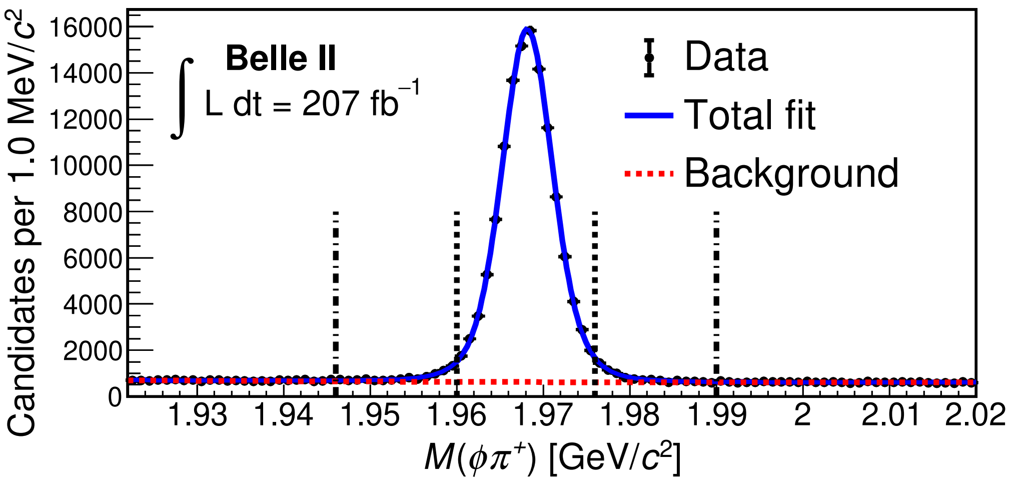
See also: Longke Li Zhi-zhong Xing

Time-dependent measurements

Alan Schwartz

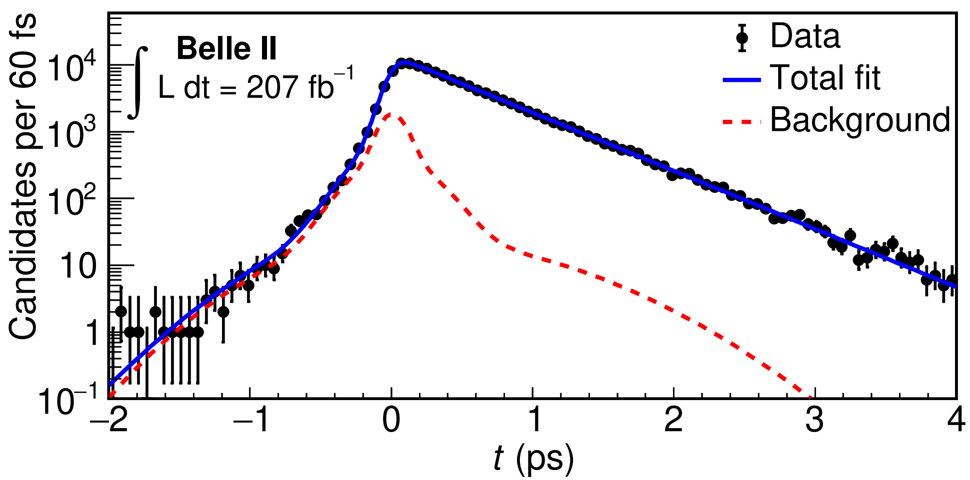
Charm Lifetimes @ BELLE II

BELLE-II: arXiv:2306.00365 (June 2023 (!))



116,000 prompt $D_s^+ \to \phi\pi^+$

Requiring $p(D_s) > 2.5\mathrm{GeV}$ in e^+e^- rest frame eliminates D_s^+ from $B \to D_s\ \ldots$ decays.



$$\tau(D_s) = 498.2 \pm \underbrace{1.7\ {}^{+1.1}_{-0.8}}_{\pm 2\ \mathrm{fs}}\ \mathrm{fs}$$

prev. WA: $\tau(D_s) = 504 \pm 4$ fs

Also most precise D^0, D^+ lifetimes: BELLE-II PRL 127 (2021) 21, 211801

Baryon lifetimes

HQE (up to order $1/m^3$): $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c) < \tau(\Xi_c^+)$

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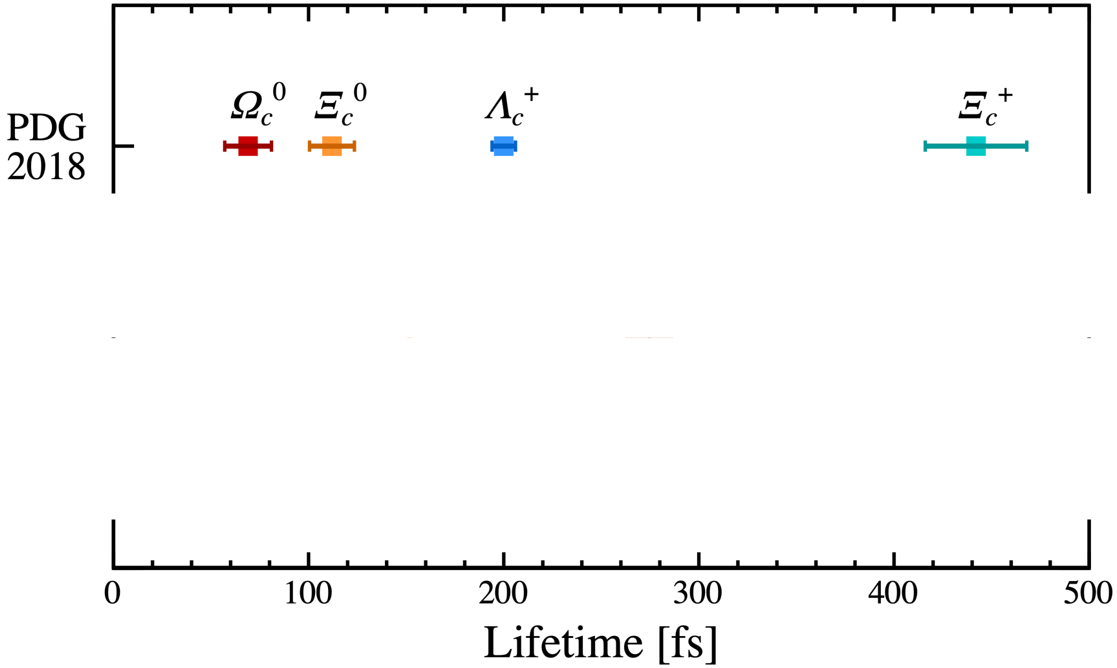

Adapted from Nisar Nellikunnummel @ ICHEP 2022

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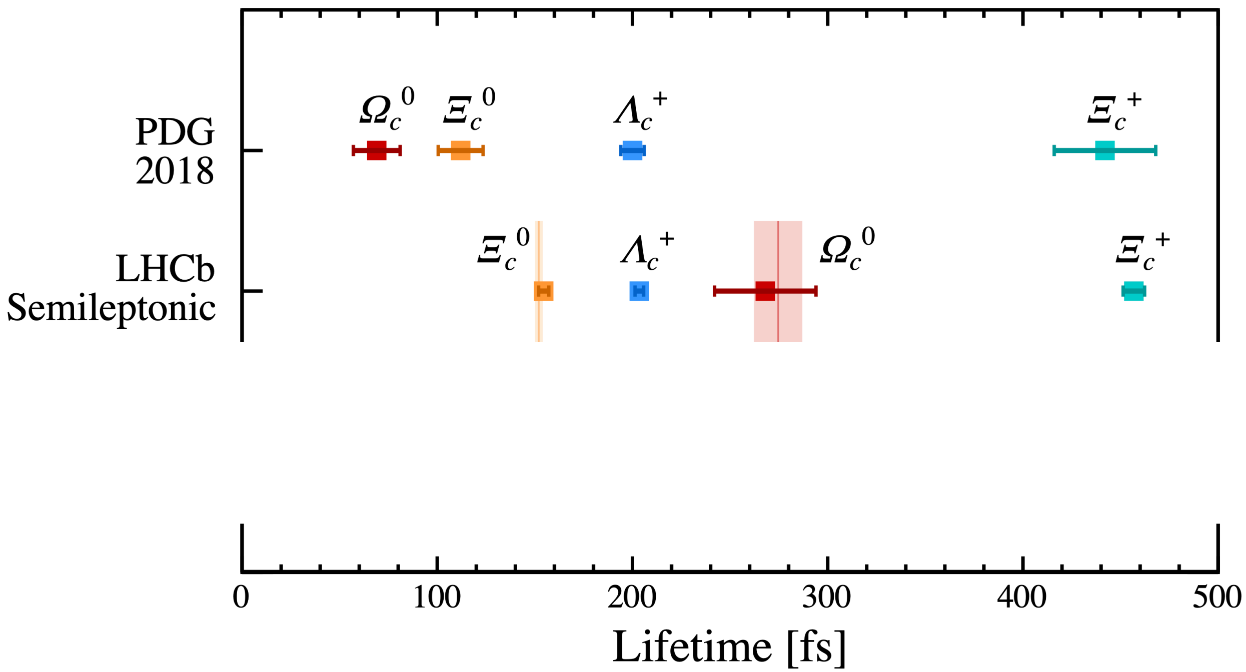

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PRD 100 (2019) 3, 032001

Baryon lifetimes

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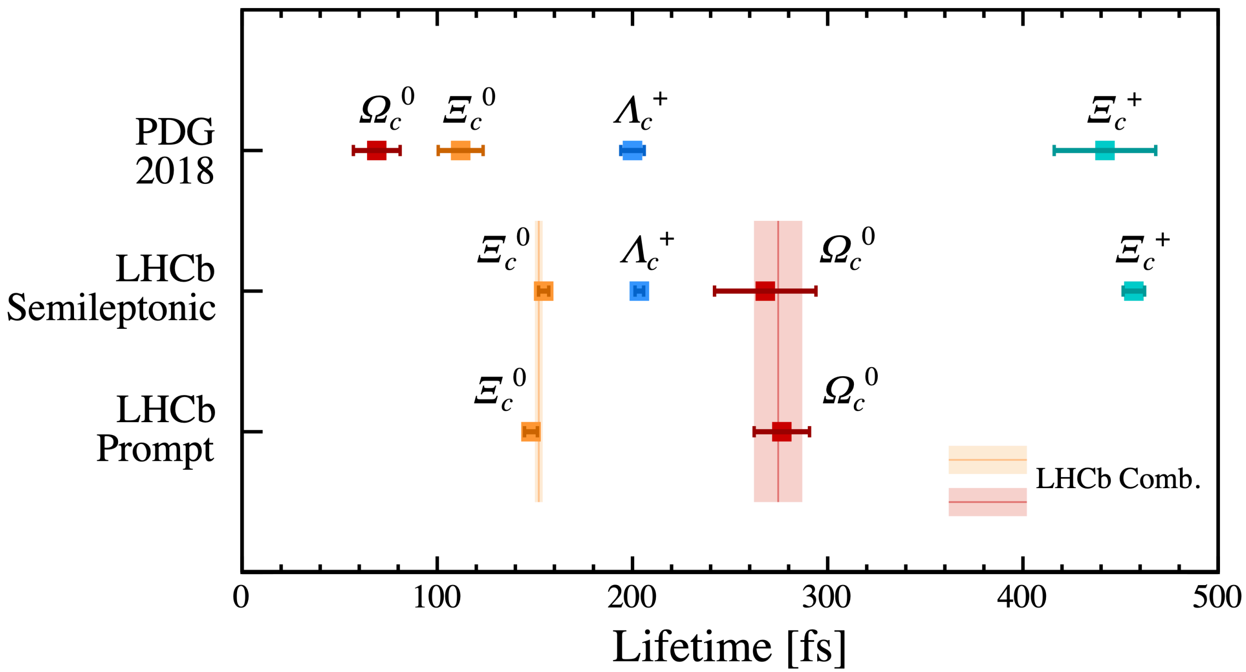

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PRD 100 (2019) 3, 032001

Sci.Bull. 67 (2022) 5, 479-487

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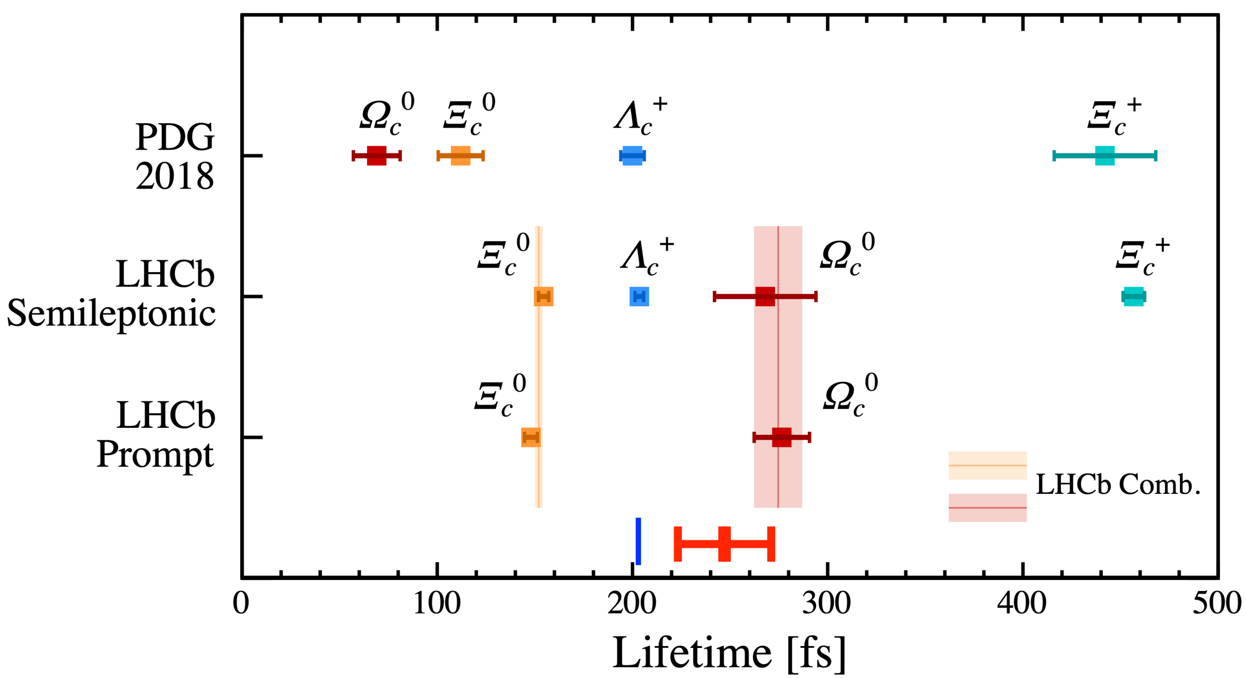

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PRD 100 (2019) 3, 032001

Sci.Bull. 67 (2022) 5, 479-487

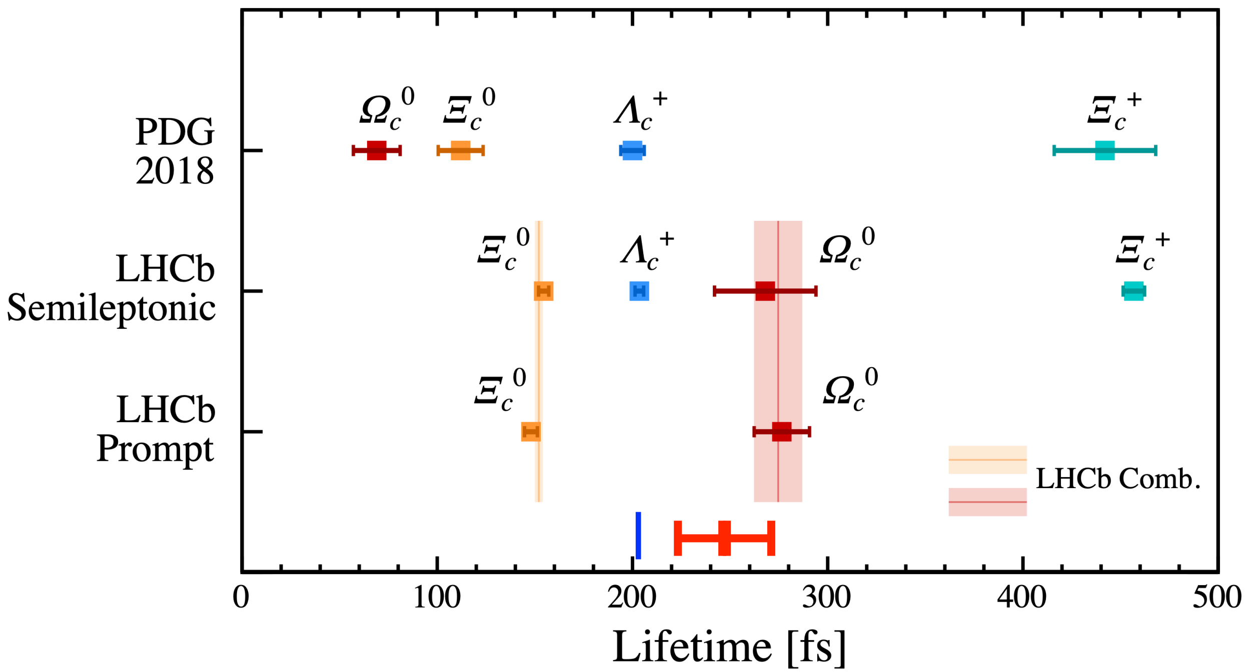
BELLE-II Ω_c^0: PRD 107 (2023) 3, L031103

BELLE-II Λ_c: PRL 130 (2023) 7, 071802

Baryon lifetimes

HQE (up to order $1/m^3$): $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c) < \tau(\Xi_c^+)$

Obervation



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PRD 100 (2019) 3, 032001

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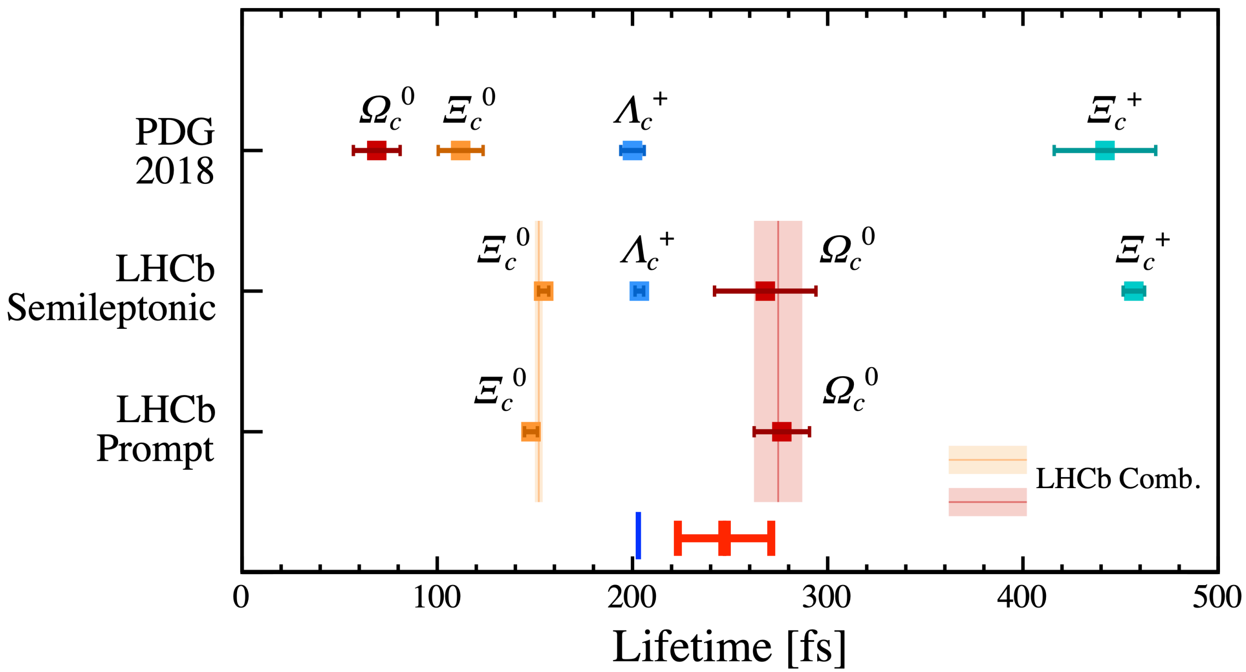
Baryon lifetimes

HQE (up to order $1/m^3$): $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c) < \tau(\Xi_c^+)$

Obervation

HQE, what now?



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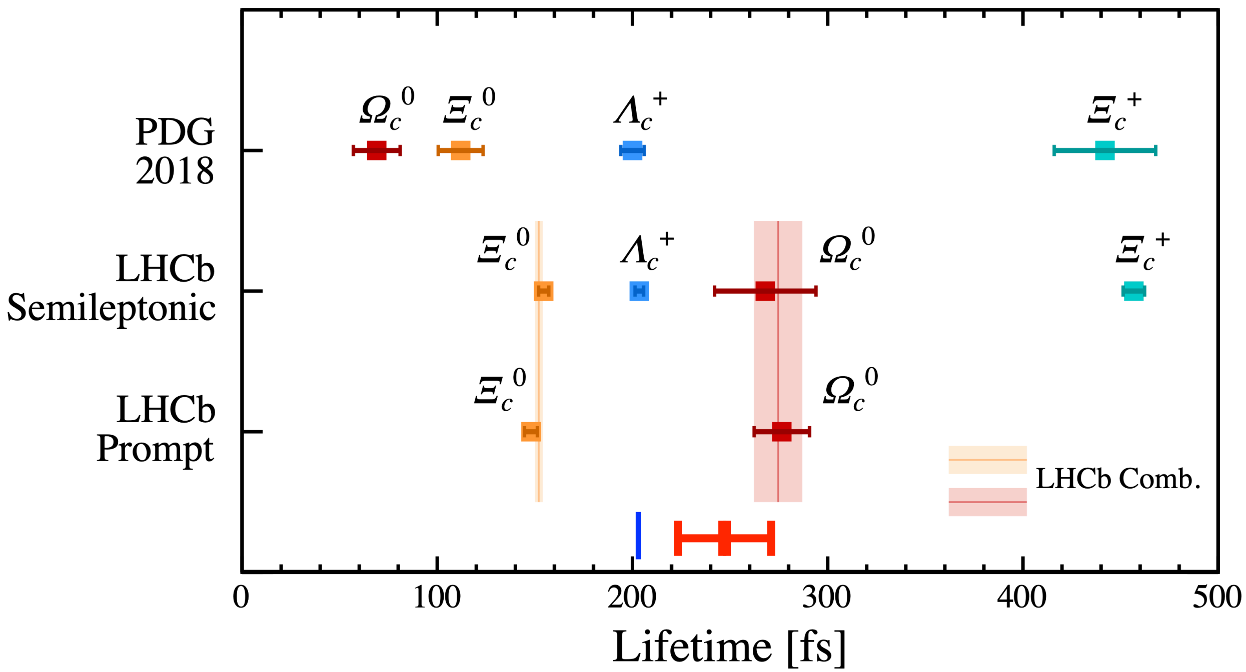
Baryon lifetimes

HQE (up to order $1/m^3$): $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c) < \tau(\Xi_c^+)$

Obervation

HQE, what now?

To higher order!!



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BELLE-II Ω_c^0: PRD 107 (2023) 3, L031103

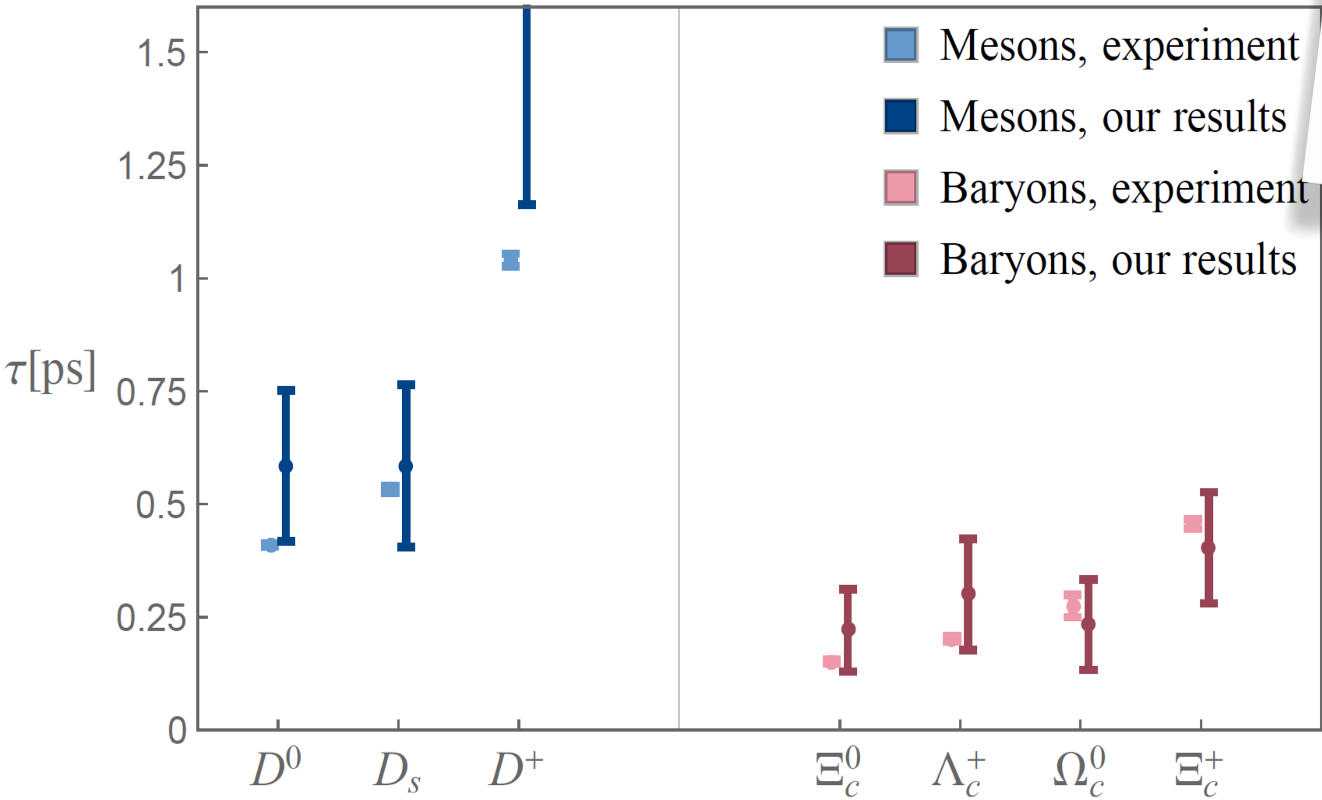
BELLE-II Λ_c: PRL 130 (2023) 7, 071802

Charm lifetimes from HQE

Blaženka Melić

King, Lenz, Piscopo, Rauh, Rusov, 2109.13219
Gratrex, Melic, Nisandzic 2204.11935

See also Hai-Yang Cheng's talk for another HQE-based calculation leading to compatible results.



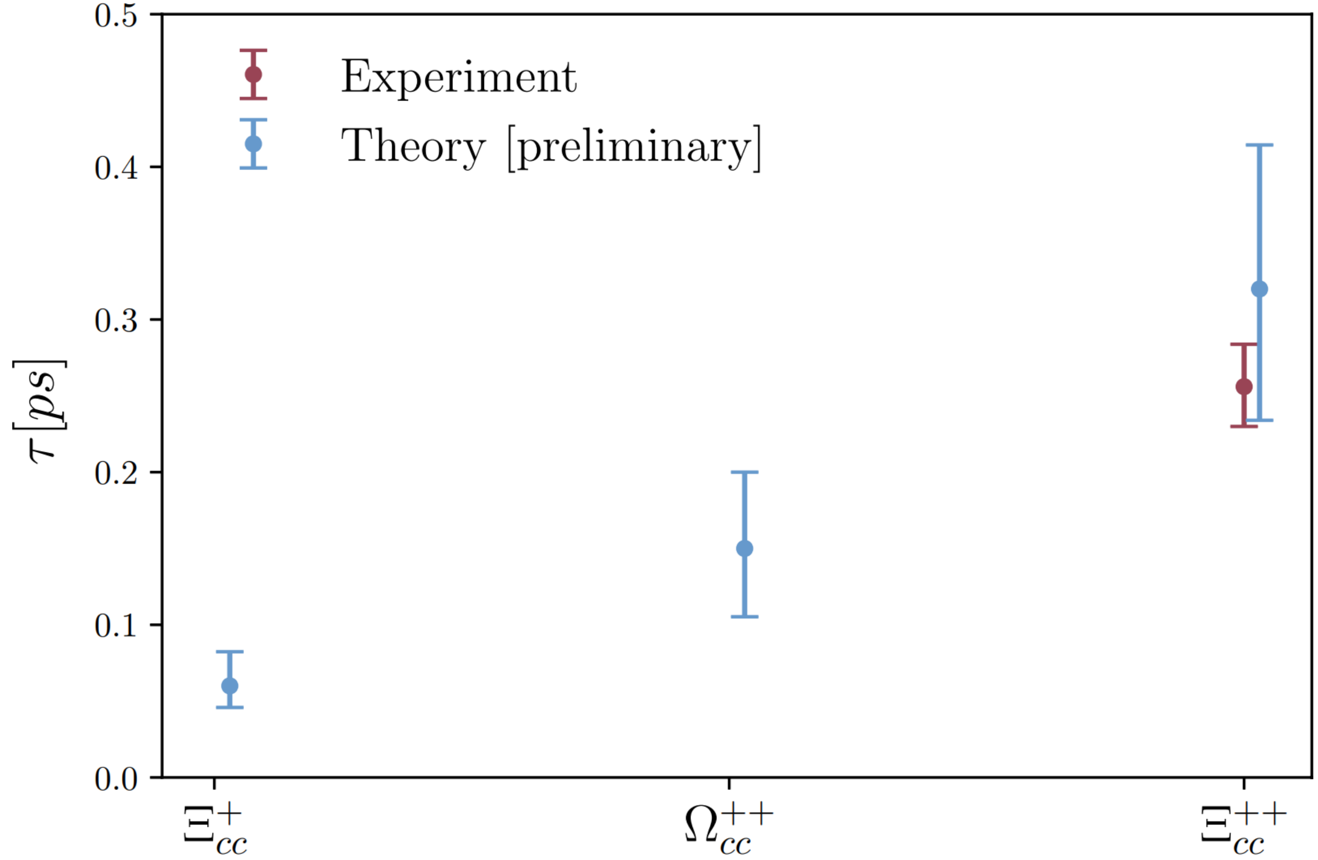
inclusion of newly calculated NLO corrections to μ_G^2 (Mannel, Moreno, Pivovarov 2304.08964) would probably significantly reduce uncertainty

Good agreement with experiment

Charm lifetimes from HQE

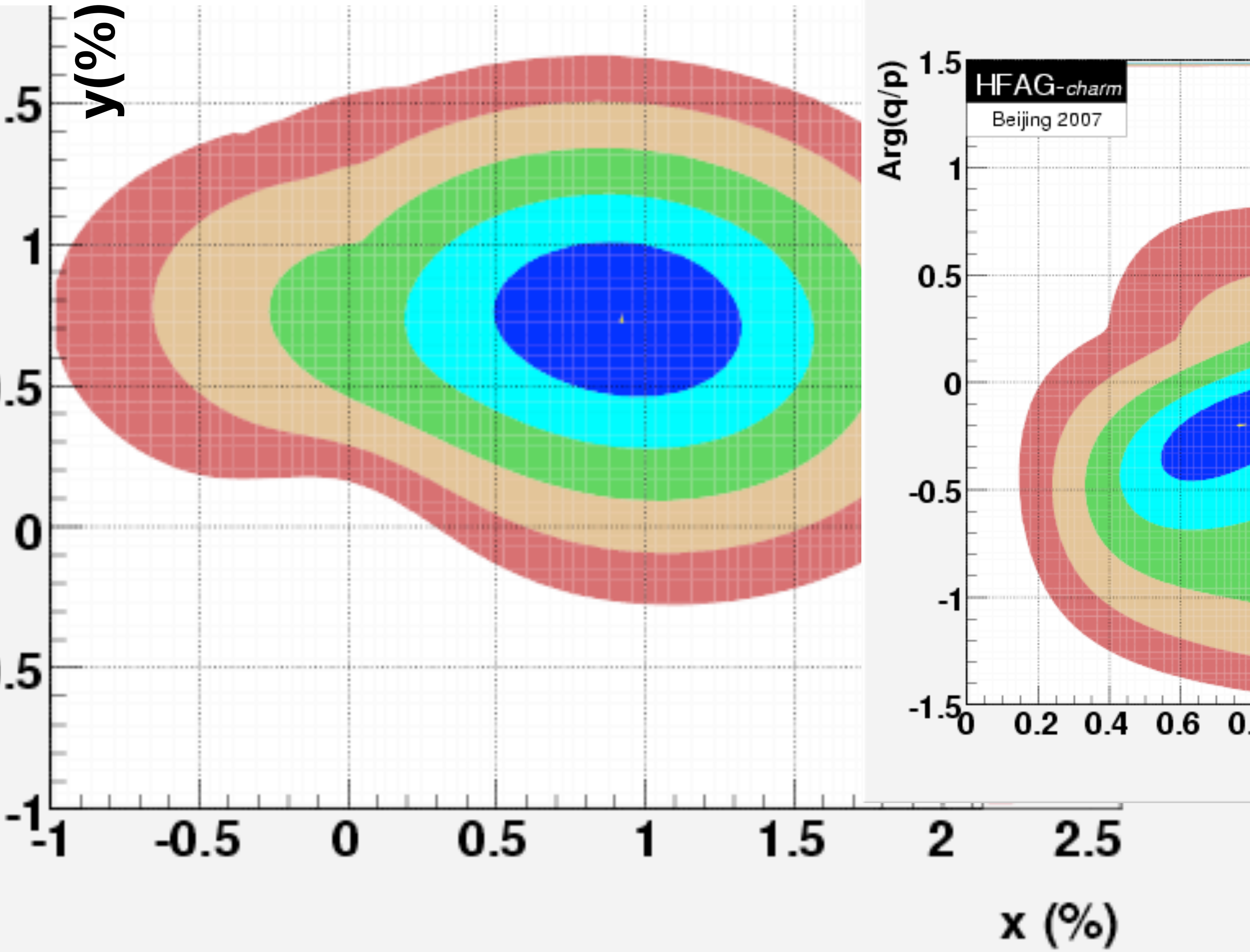
Blaženka Melić

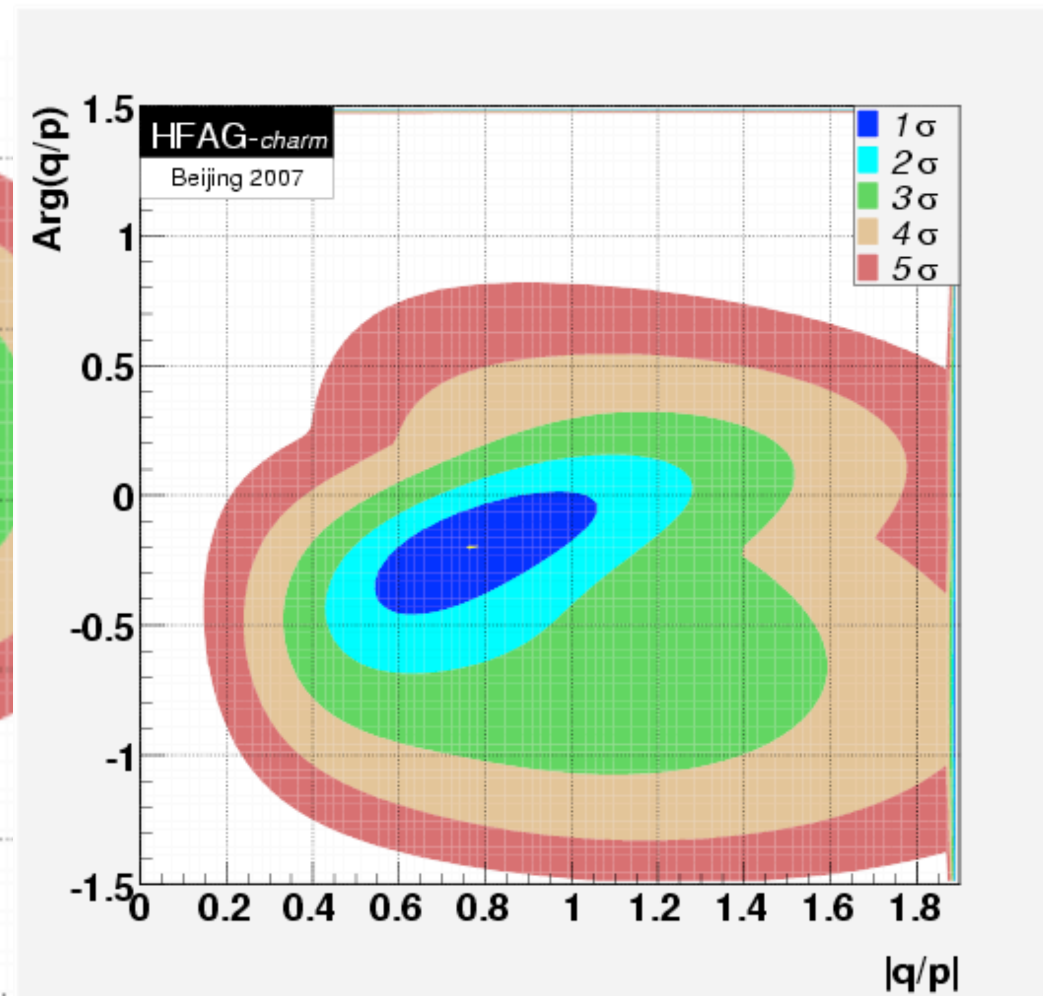
Dulibic, Gratrex, Melic, Nisandzic 2305.02243



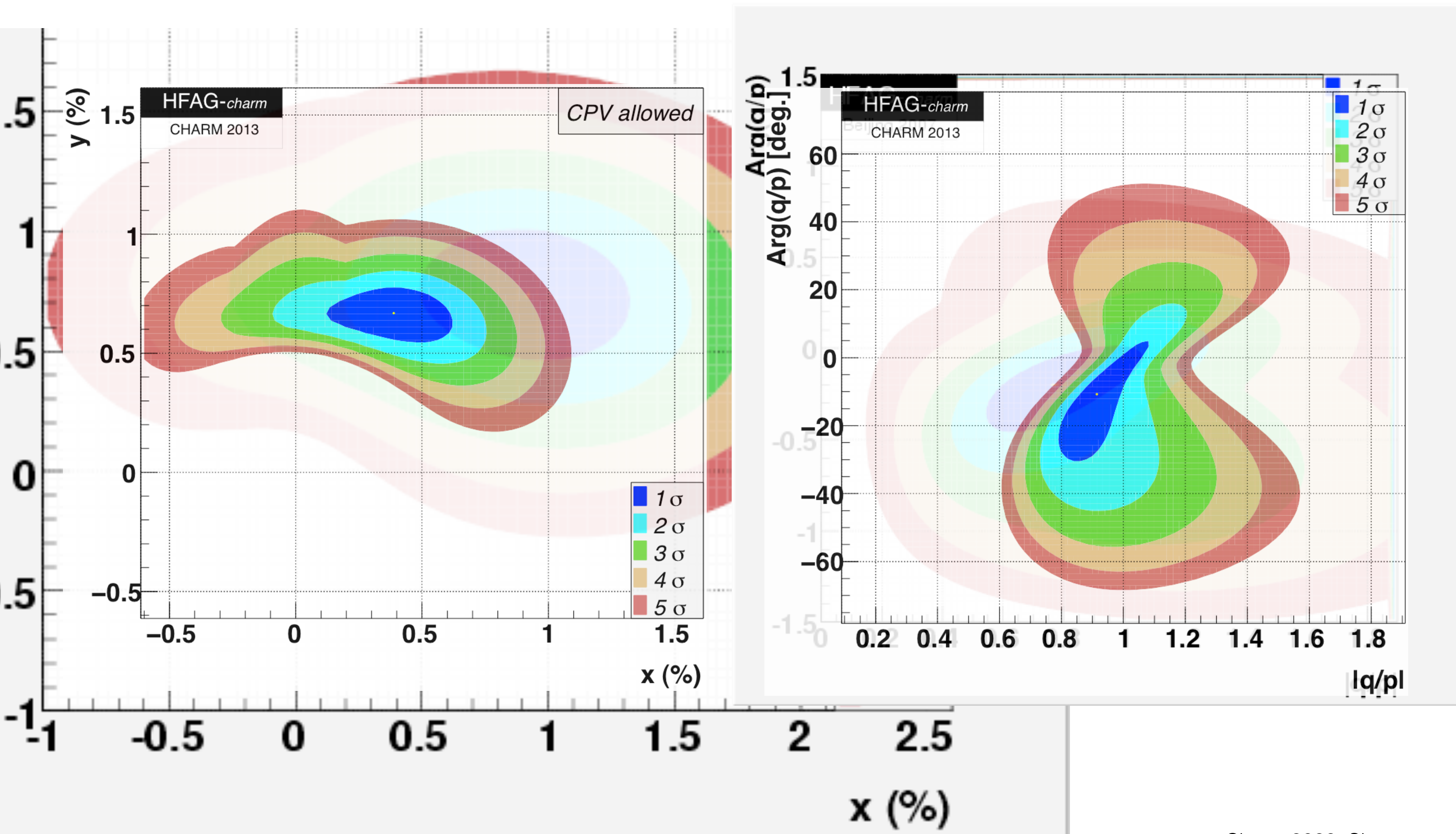
HQE for doubly-charmed baryons

Charm mixing in 2007

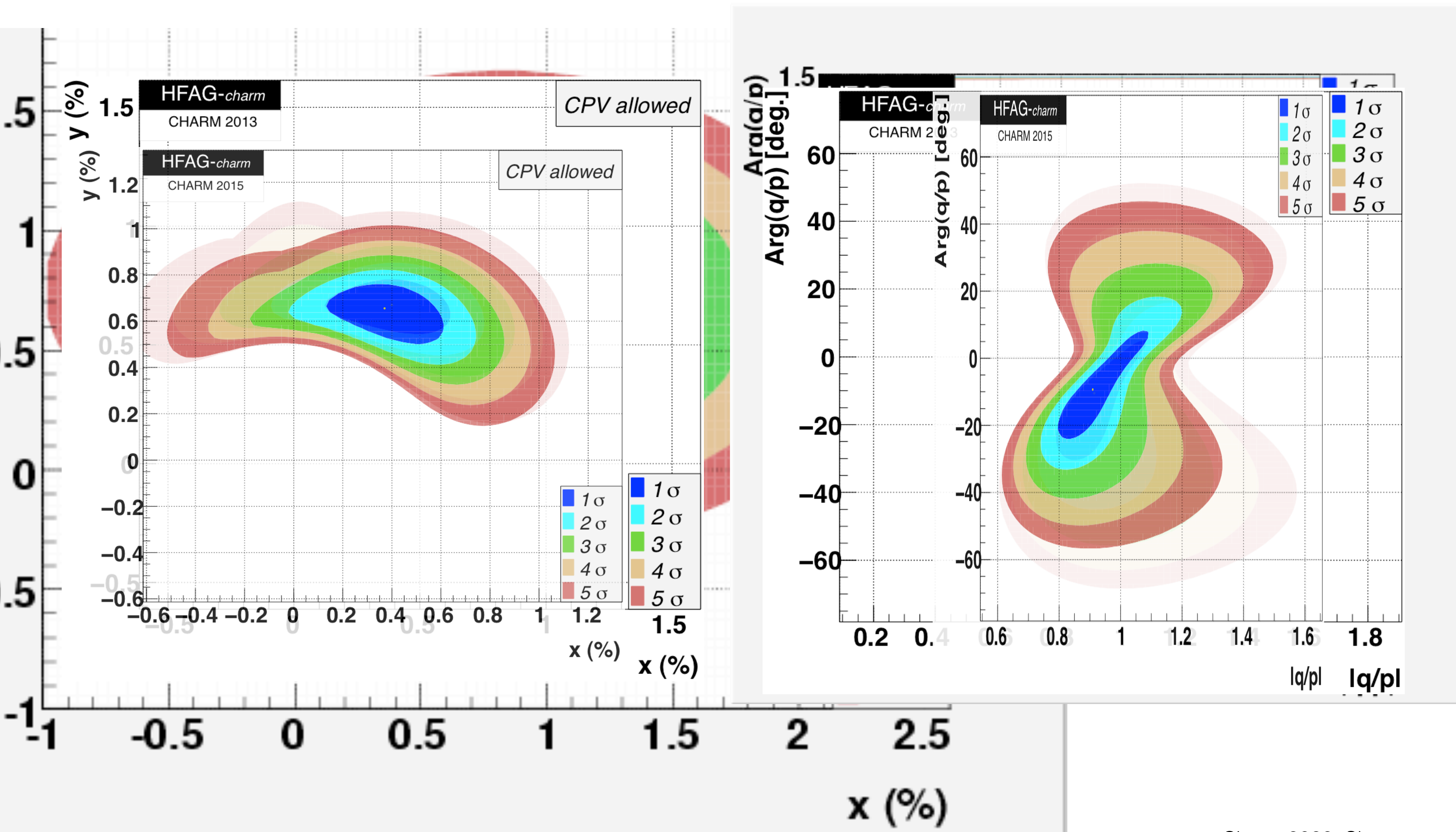




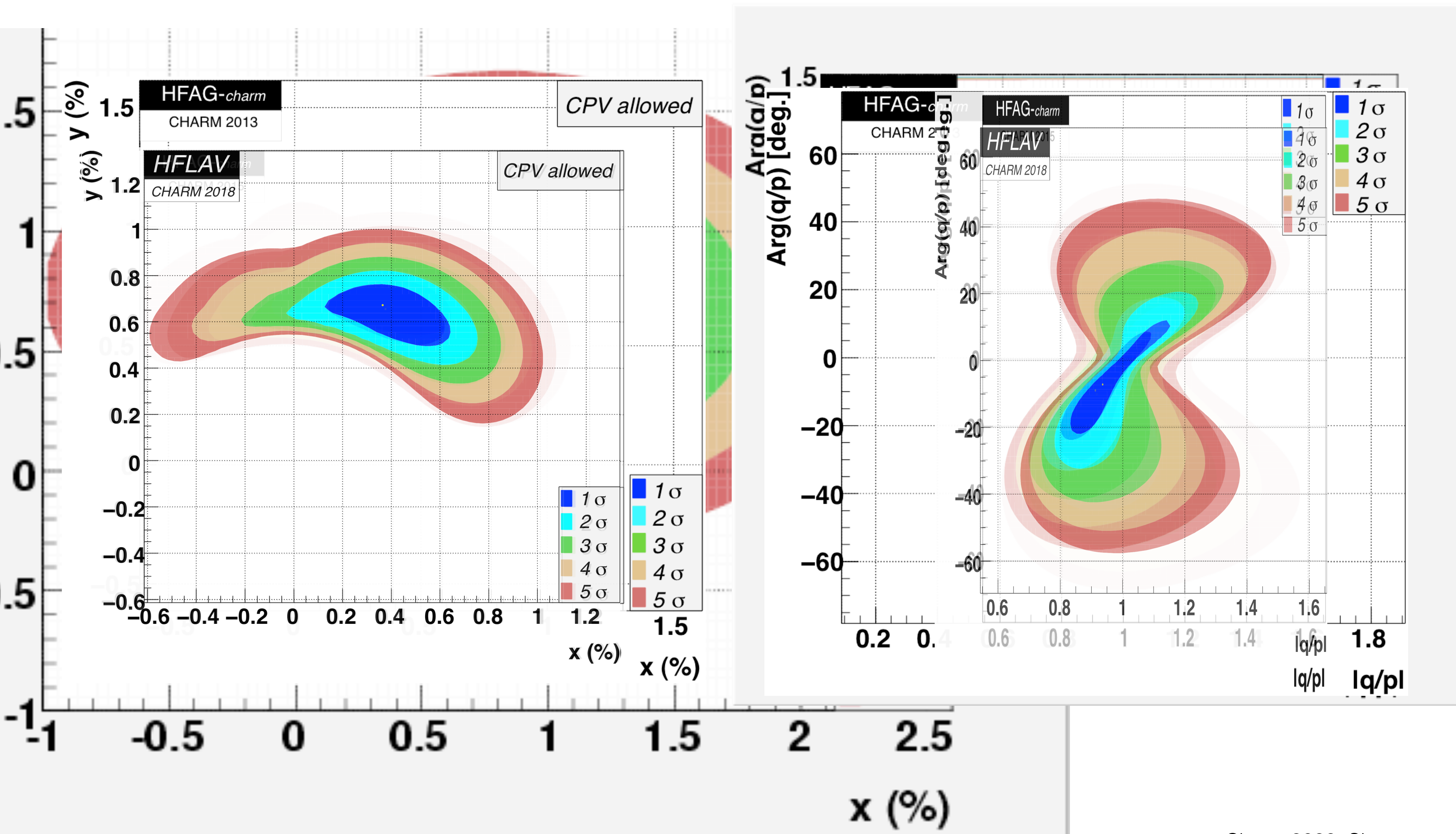
Charm mixing in 2013



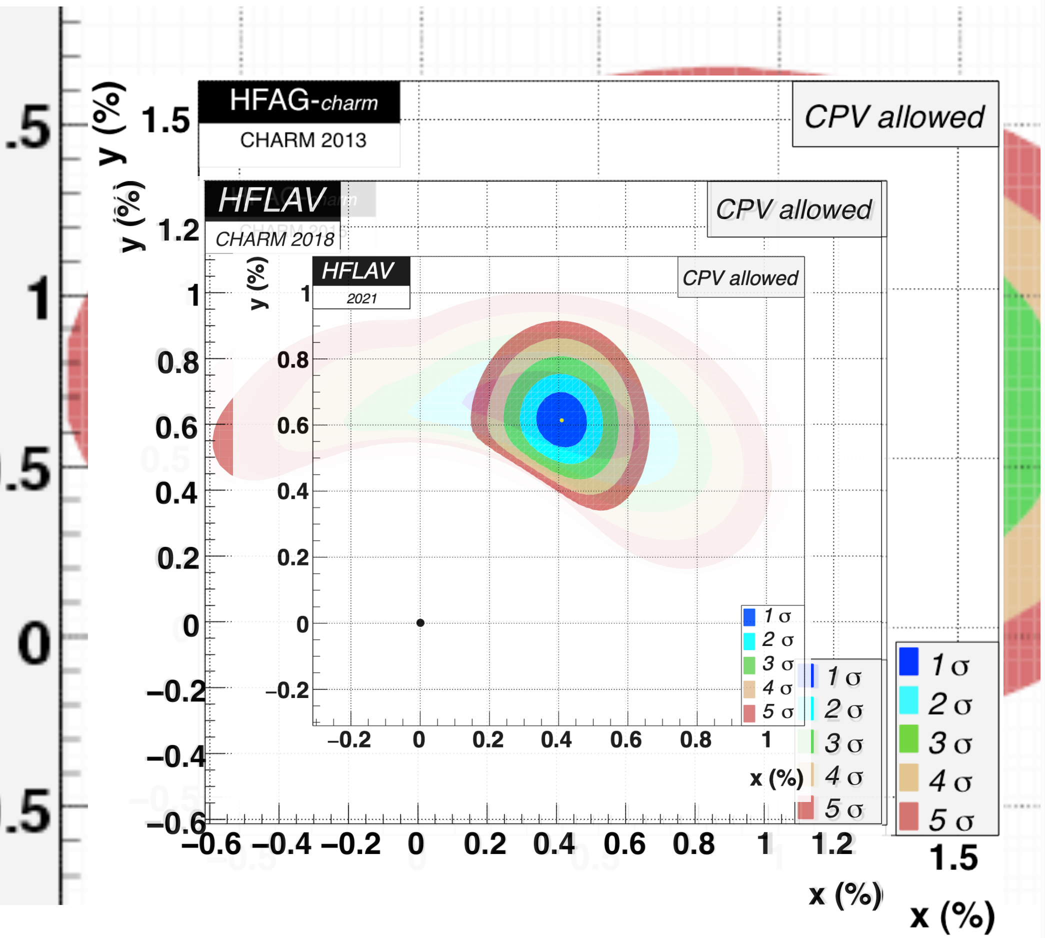
Charm mixing in 2015

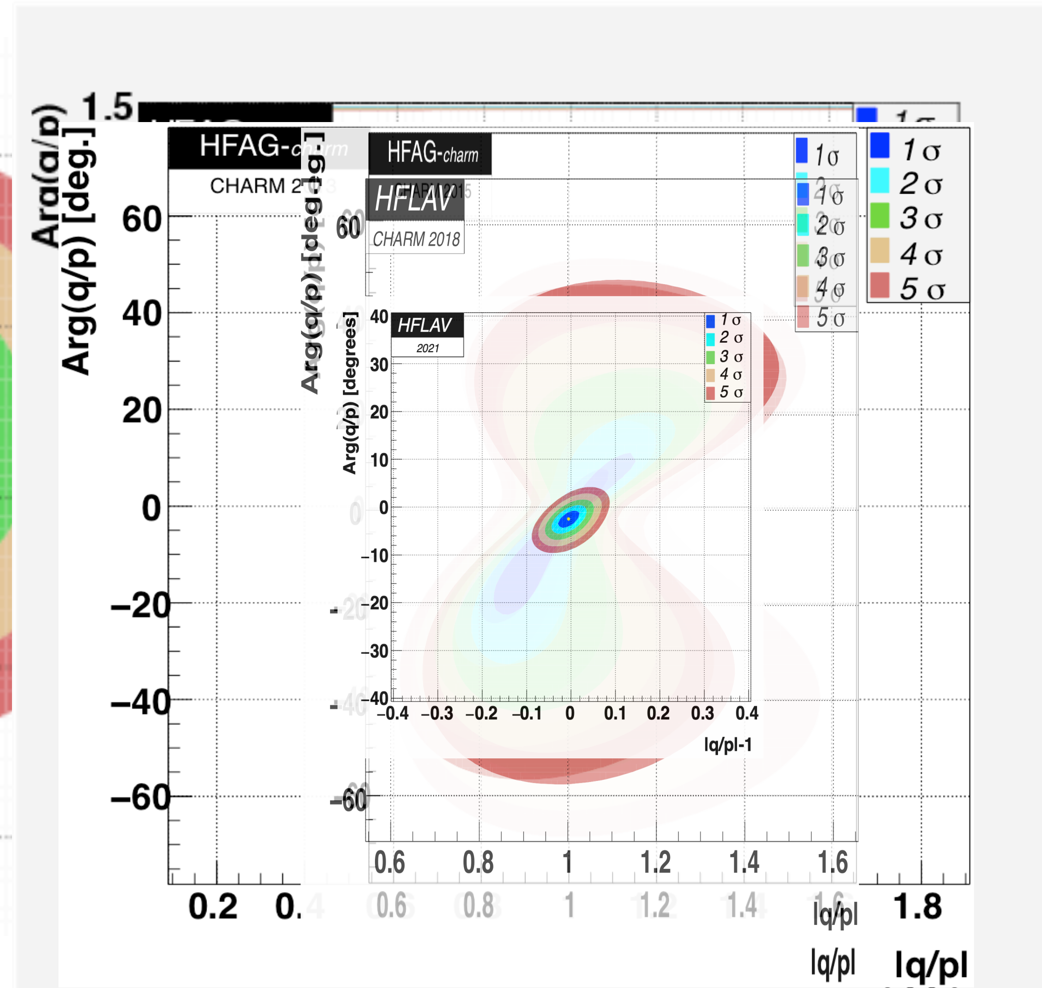


Charm mixing in 2018



Charm mixing in 2021



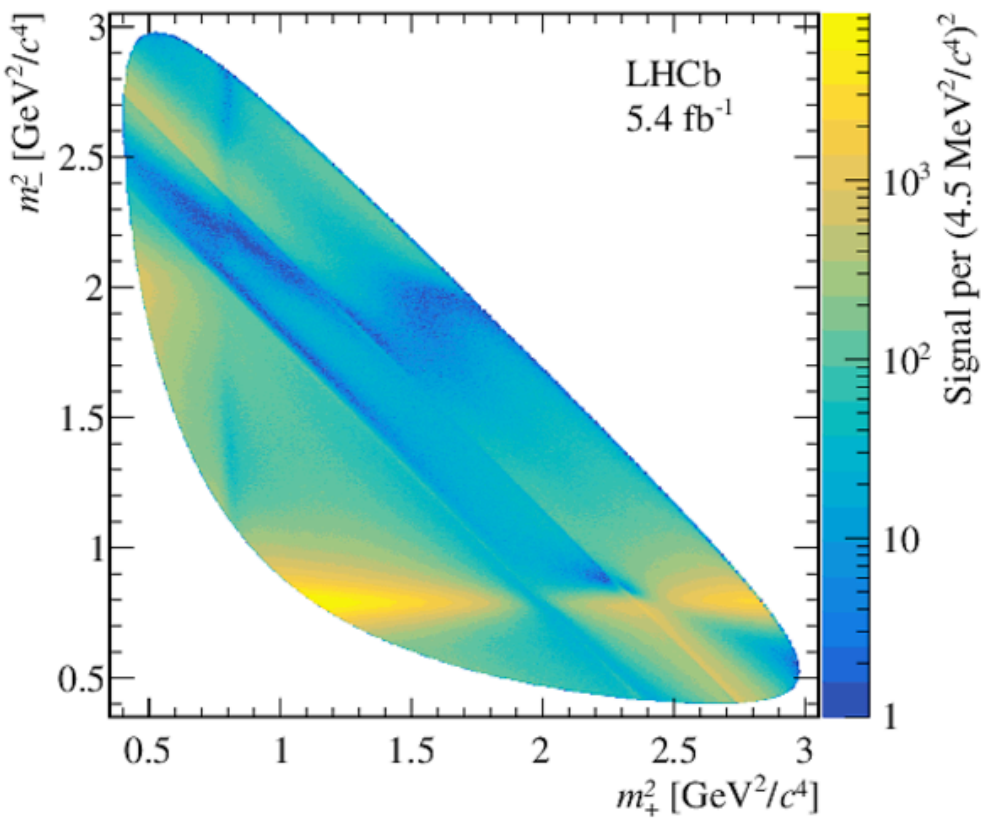


non-zero x at $> 5\sigma$

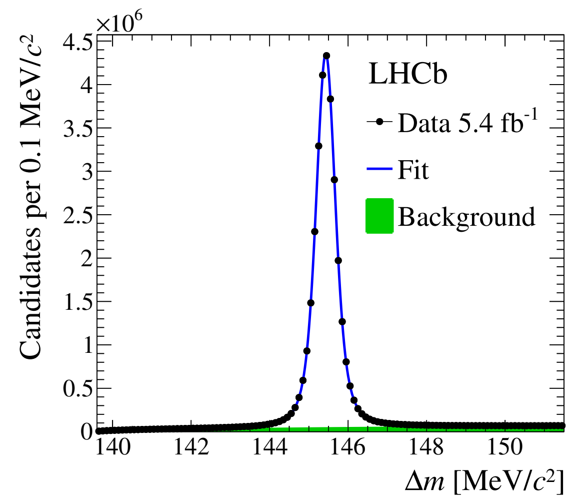
What was that???
LHCb model-independent mixing with $D^0 \to K_S\pi^+\pi^-$

LHCb: PRL 127 (2021) 11, 111801

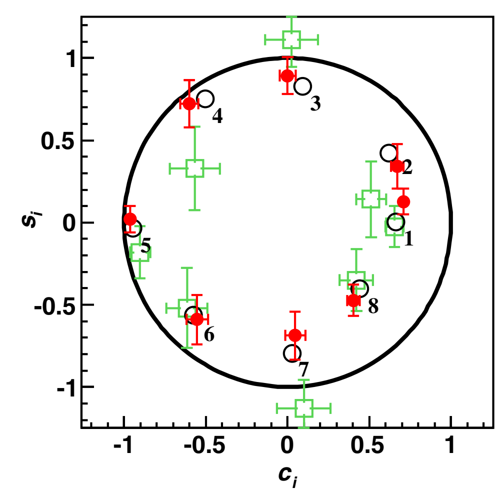
Method: Phys.Rev. D99 (2019) no.1, 012007



$3.1 \times 10^7\ D^0 \to K_S^0\pi^+\pi^-$



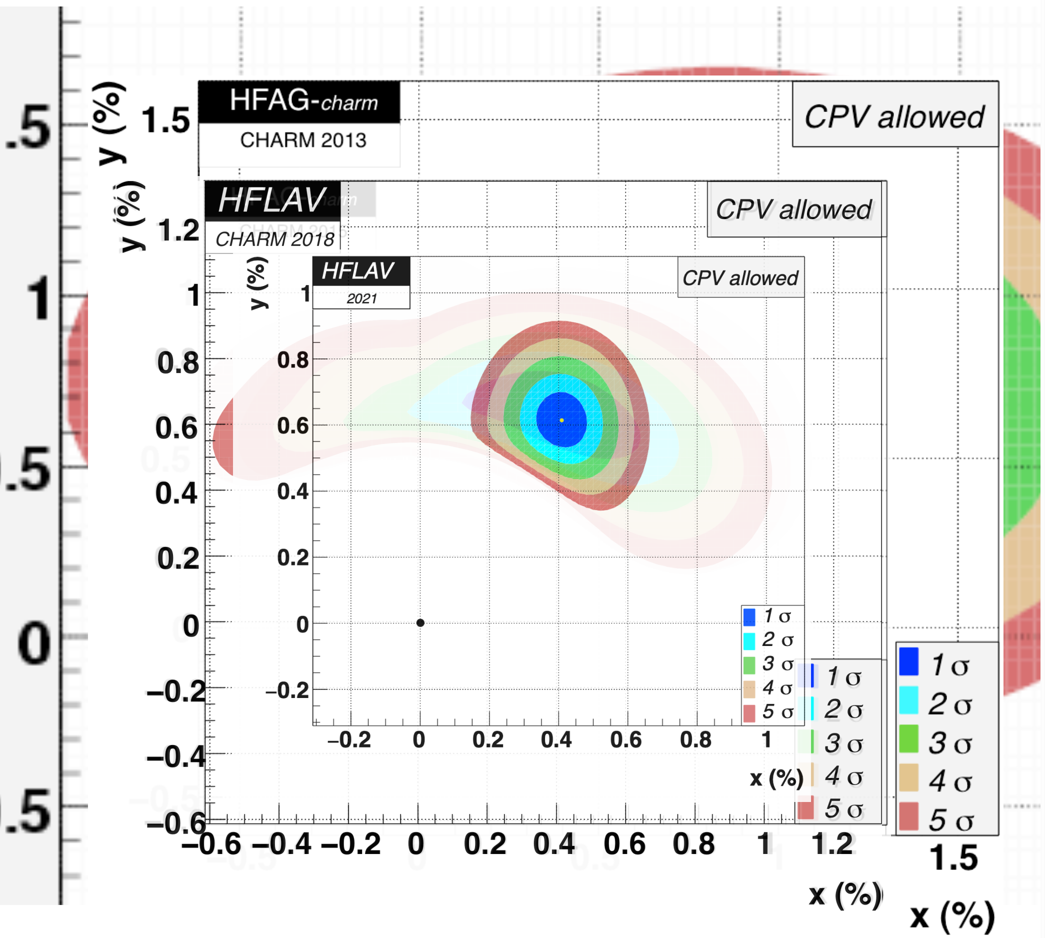
Critical: BES-III input

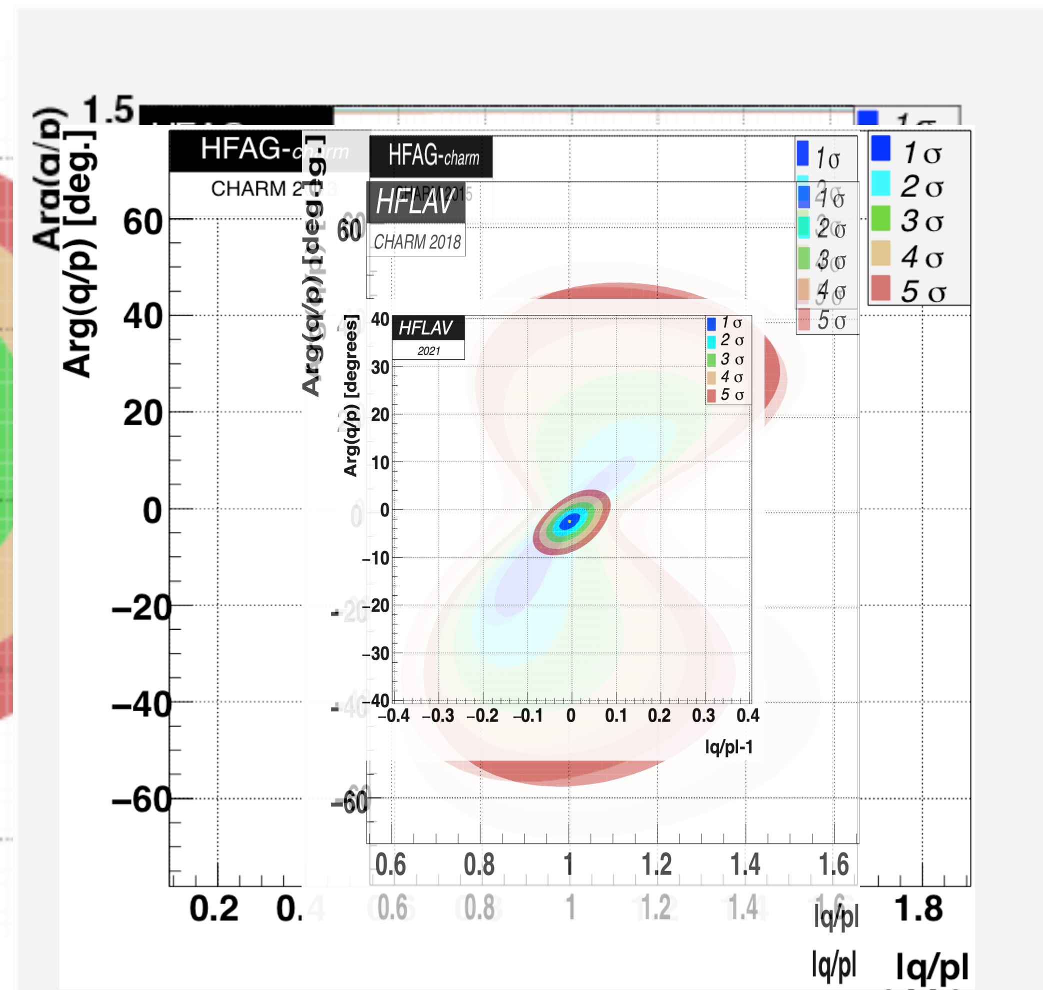


BESIII: PRL 124 (2020) 24, 241802

See also CLEO-c, Phys.Rev. D82 (2010) 112006

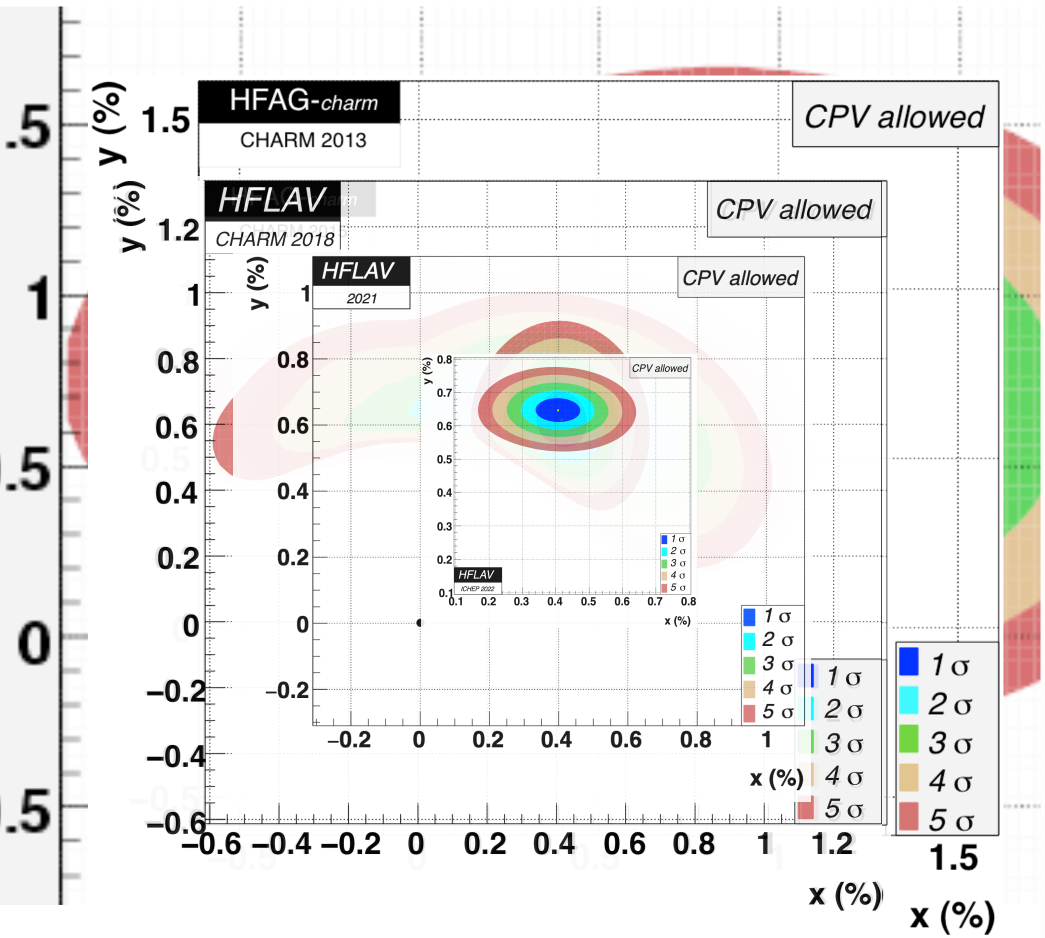
Charm mixing in 2021

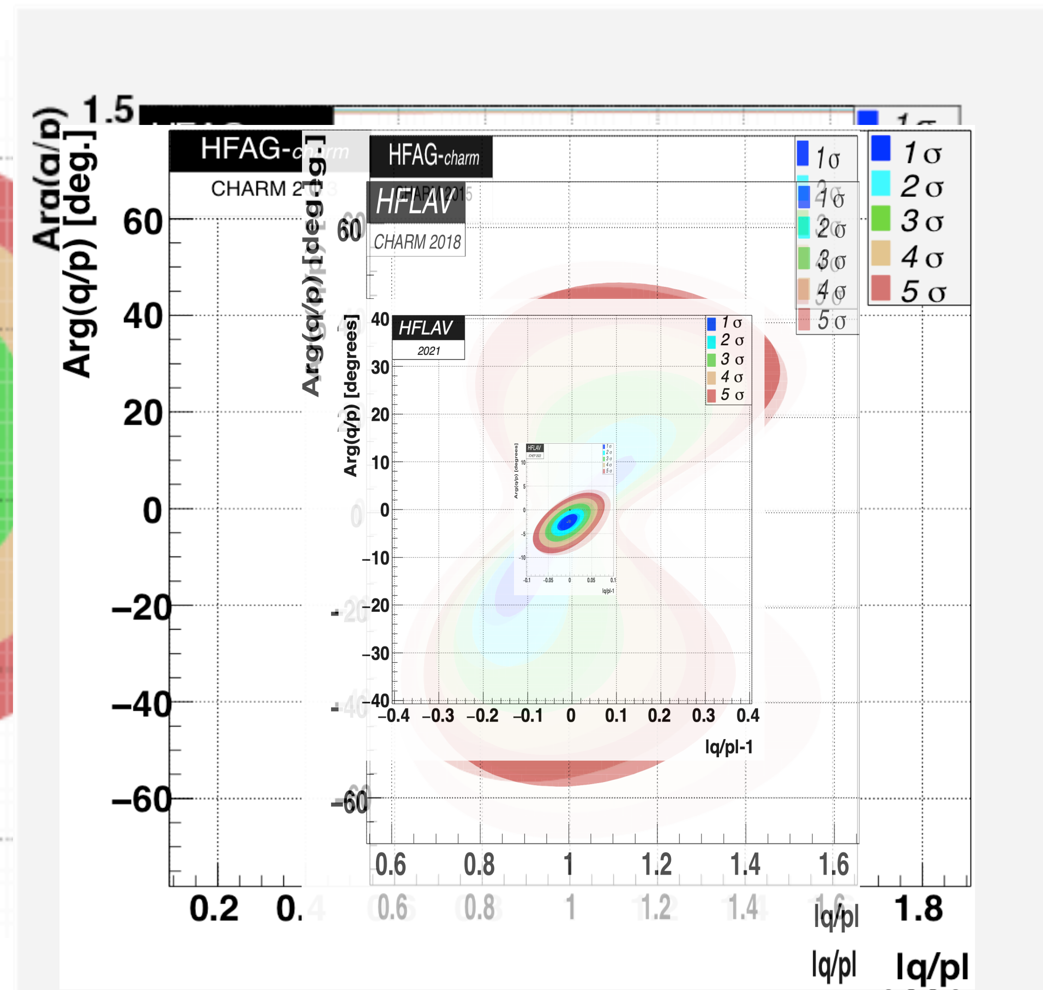




non-zero x at $> 5\sigma$

Charm mixing in 2022

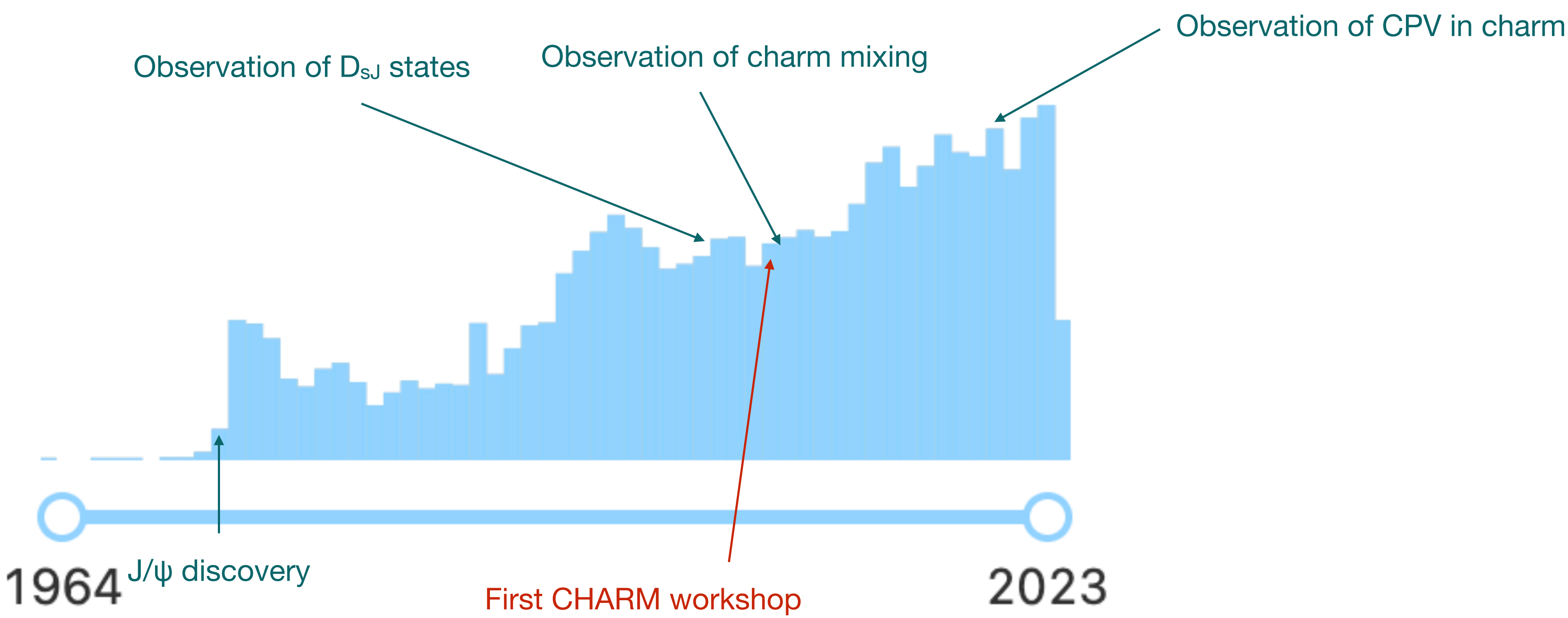




The era of charm

Tara Nanut Petrič

Frequency of keyword "charm" on inspirehep



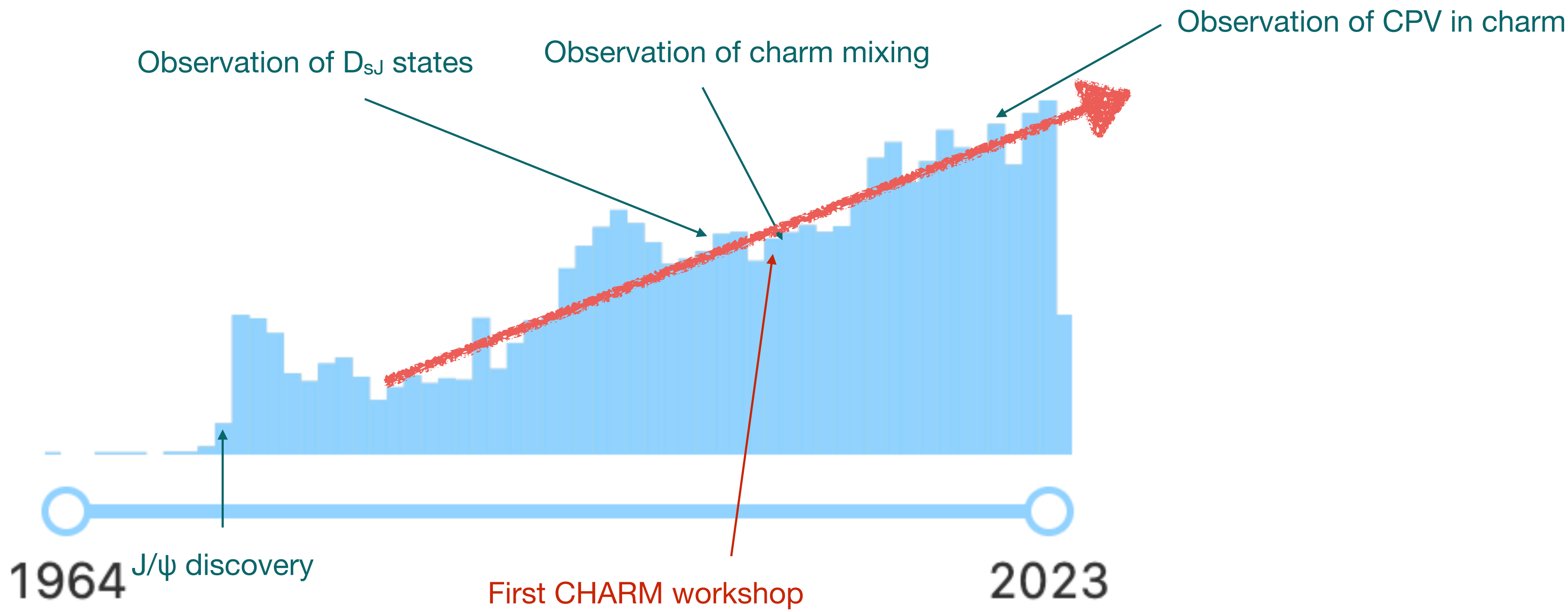
→ **When is the "era of charm"?**

In the last decades, the answer is "NOW"!

The era of charm

Tara Nanut Petrič

Frequency of keyword "charm" on inspirehep



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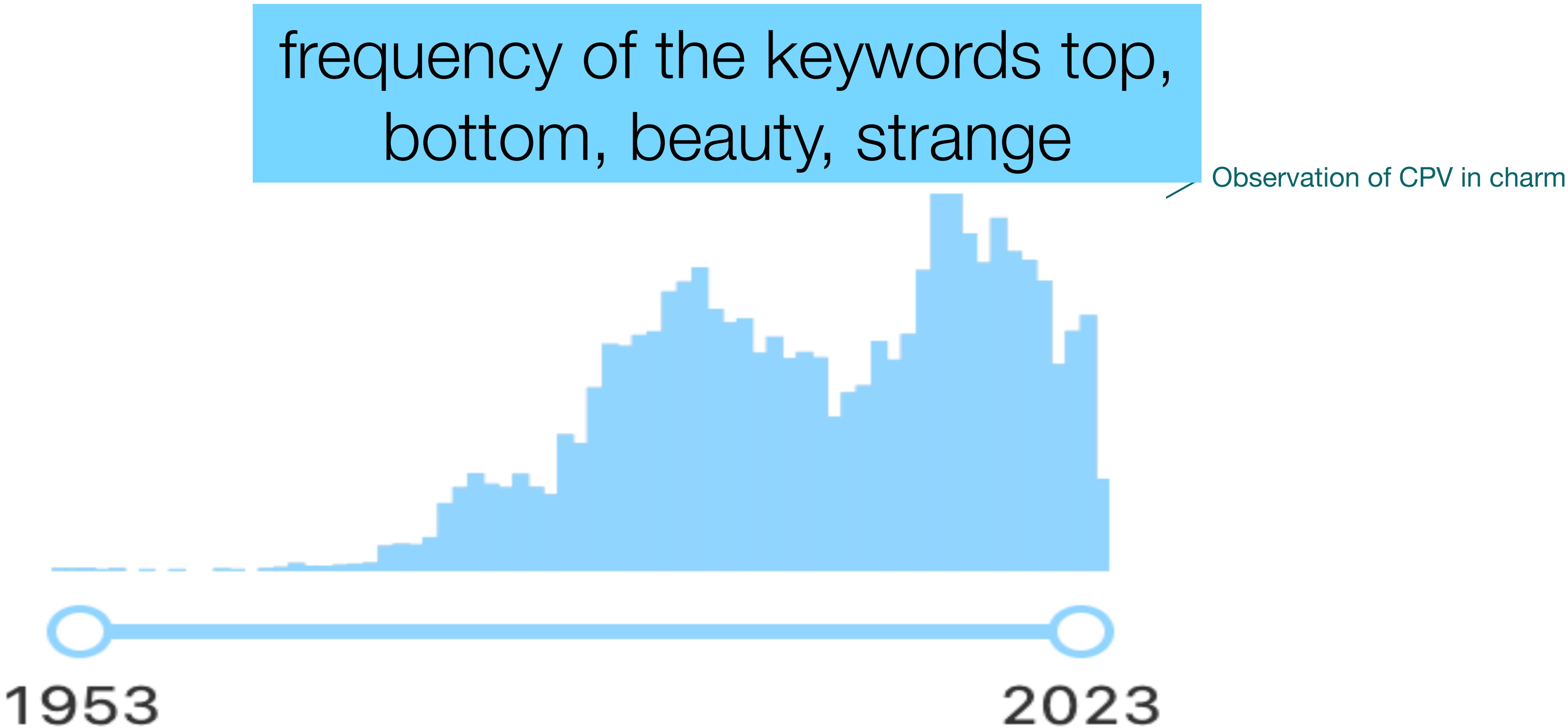

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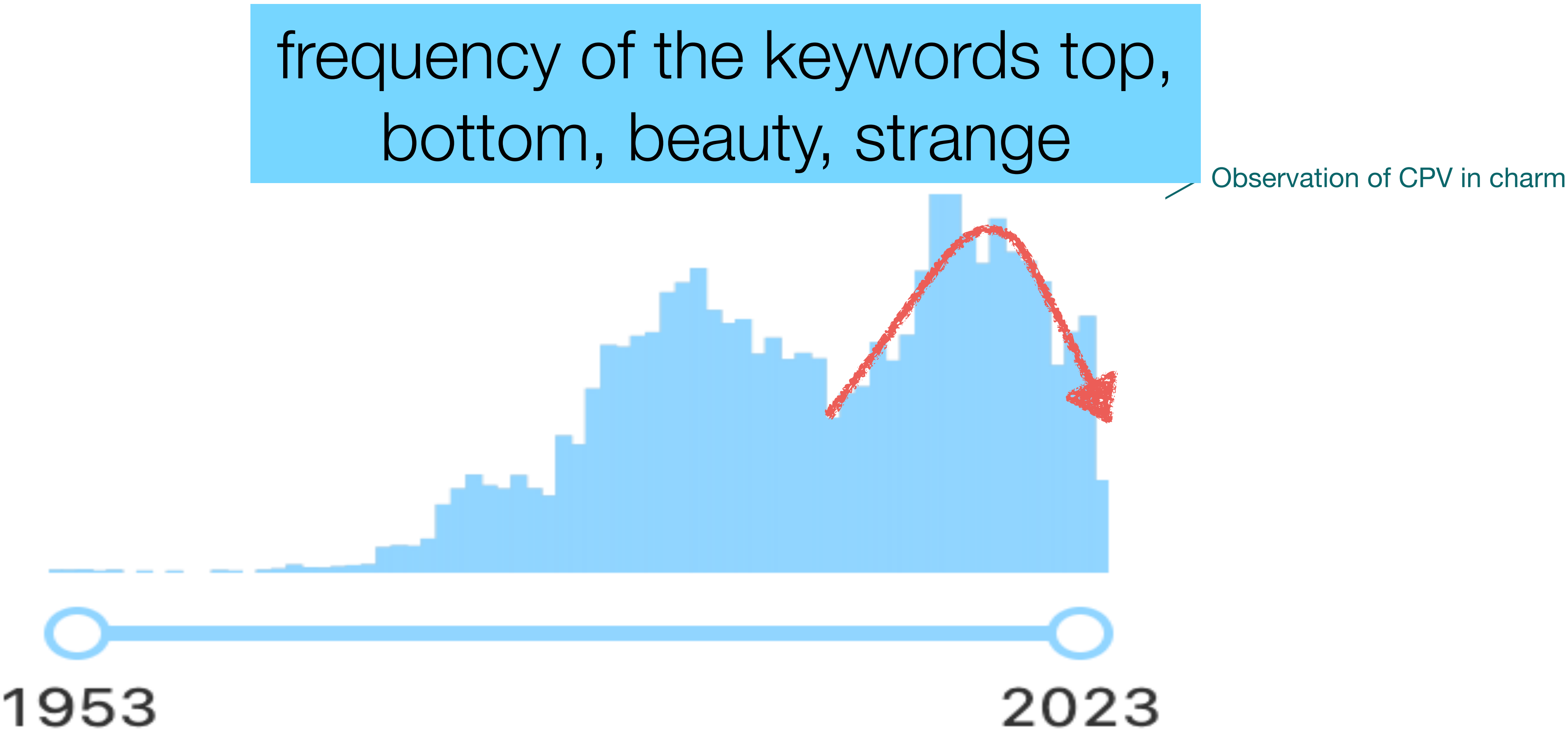
The era of charm

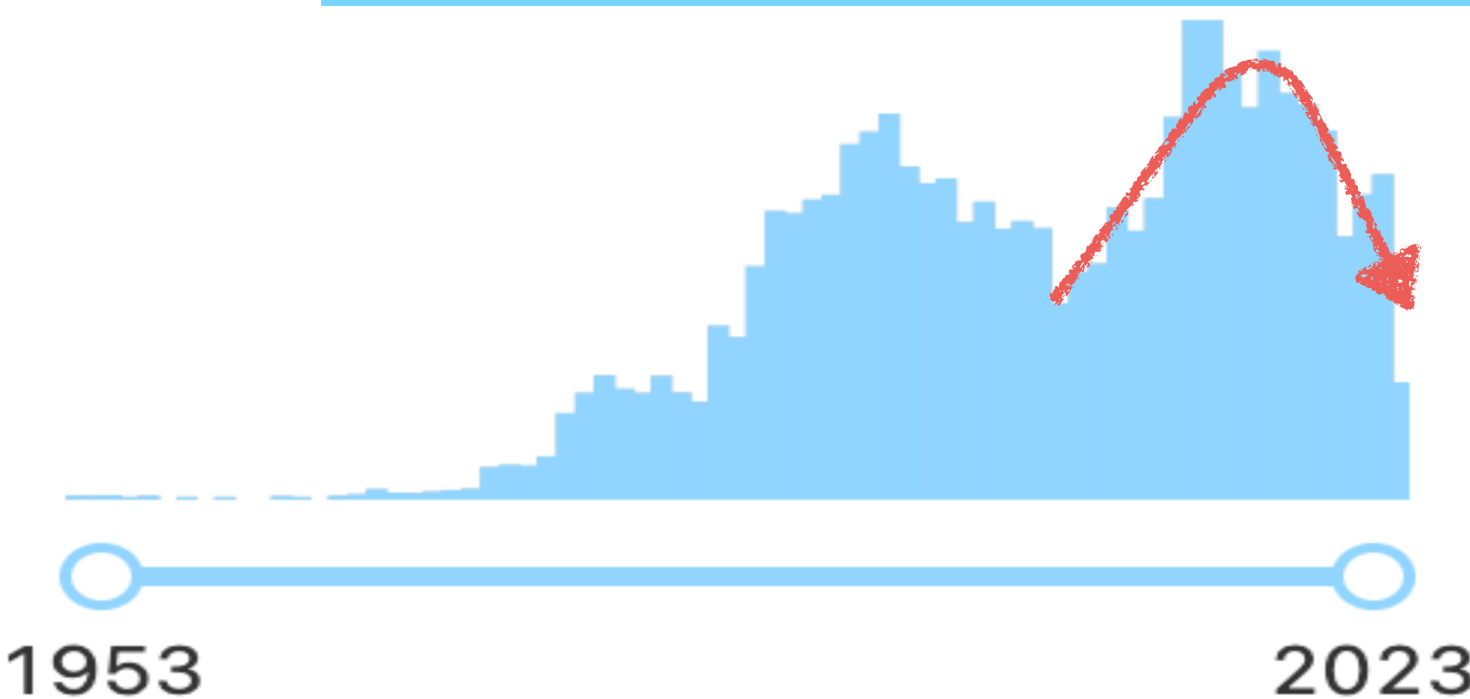


→ When is the "era of charm"?

In the last decades, the answer is "NOW"!

The era of charm

frequency of the keywords top, bottom, beauty, strange

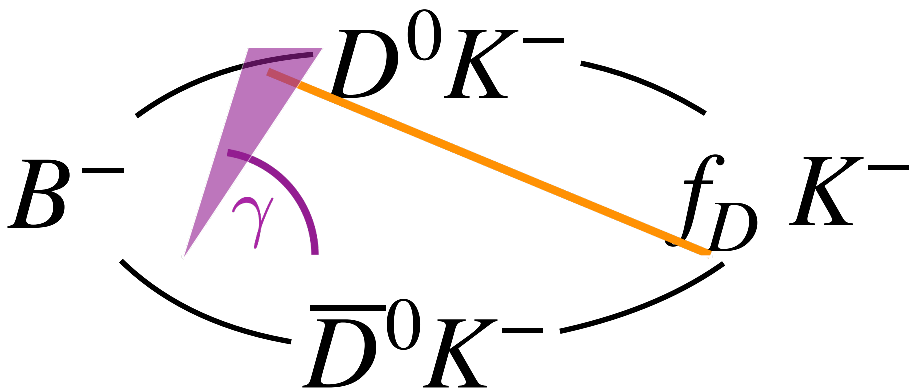


Our colleagues need help!

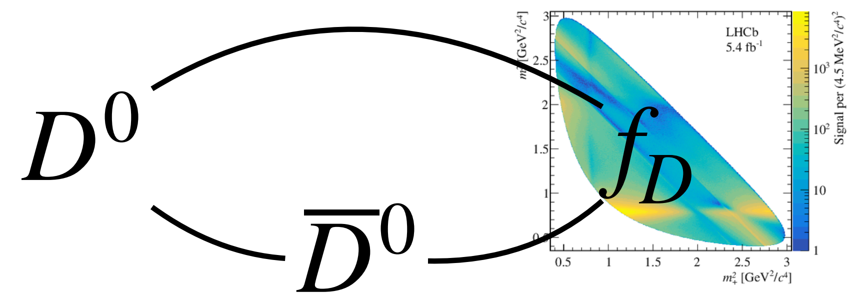
→ When is the "era of charm"?

In the last decades, the answer is "NOW"!

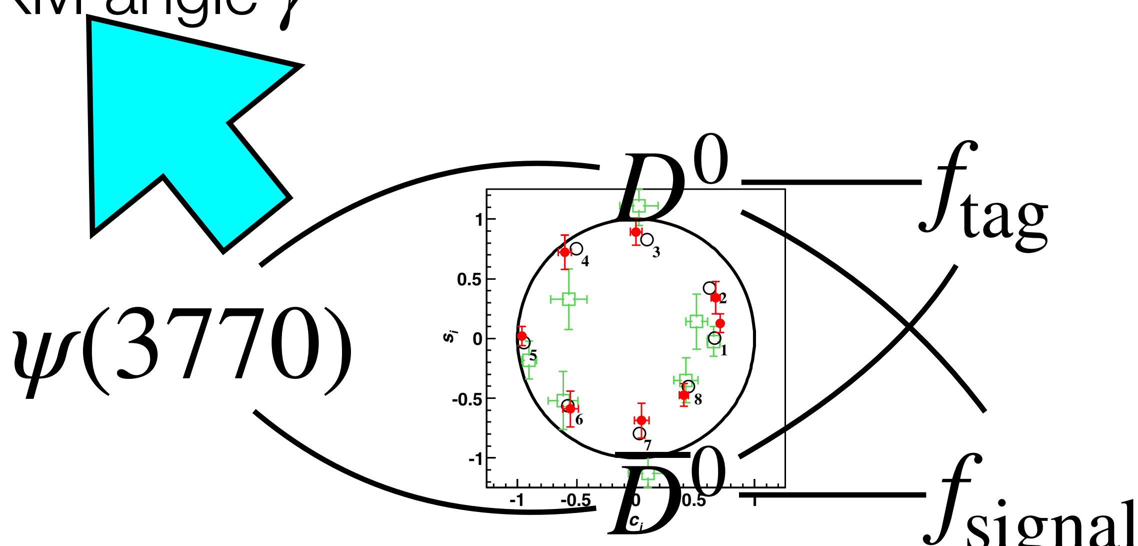
Input from charm threshold and mixing to γ.



measures CKM angle γ



measures charm mixing and CPV



measures charm interference, especially strong phases

$B^- \to DK^-, D \to K^+\pi^-\pi^+\pi^-$

LHCb: arXiv:2209.03692 (2022)

Biggest CPV observed so far

$$\gamma = \left(54.8 \begin{array}{c} +\,6.0 \\ -\,5.8 \end{array} \begin{array}{c} +\,0.6 \\ -\,0.6 \end{array} \begin{array}{c} +\,6.7 \\ -\,4.3 \end{array}\right)^\circ$$

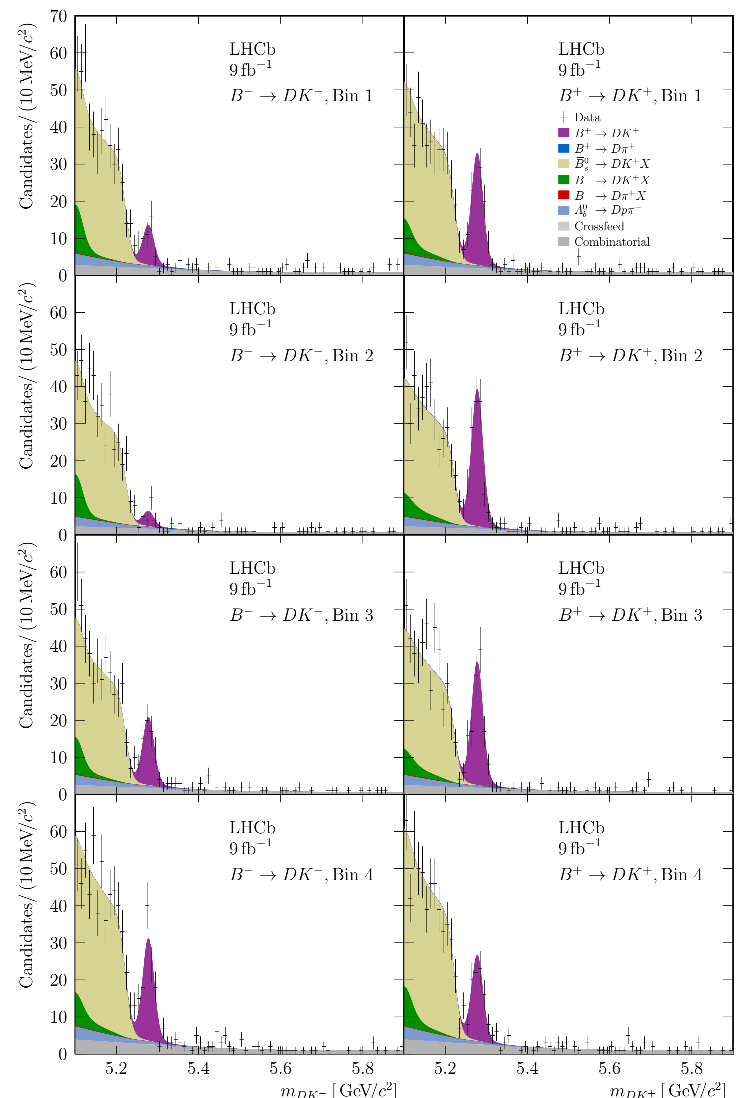
statistical

systematic

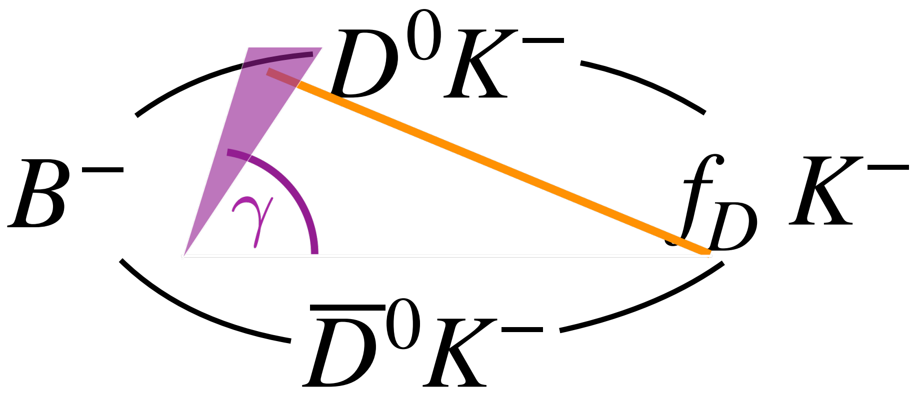
input from charm threshold

hope for more BES III data at

$\psi(3770)$



Input from charm threshold and mixing to γ.



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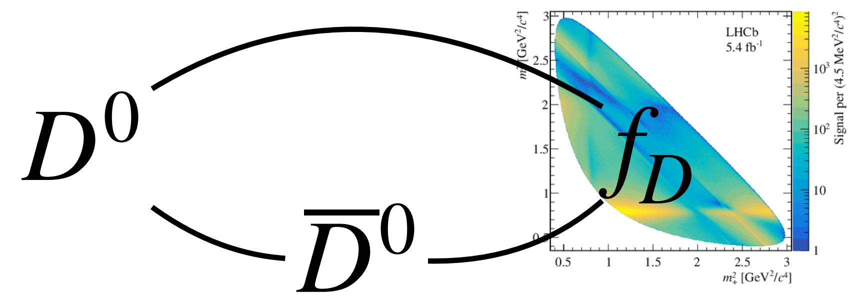

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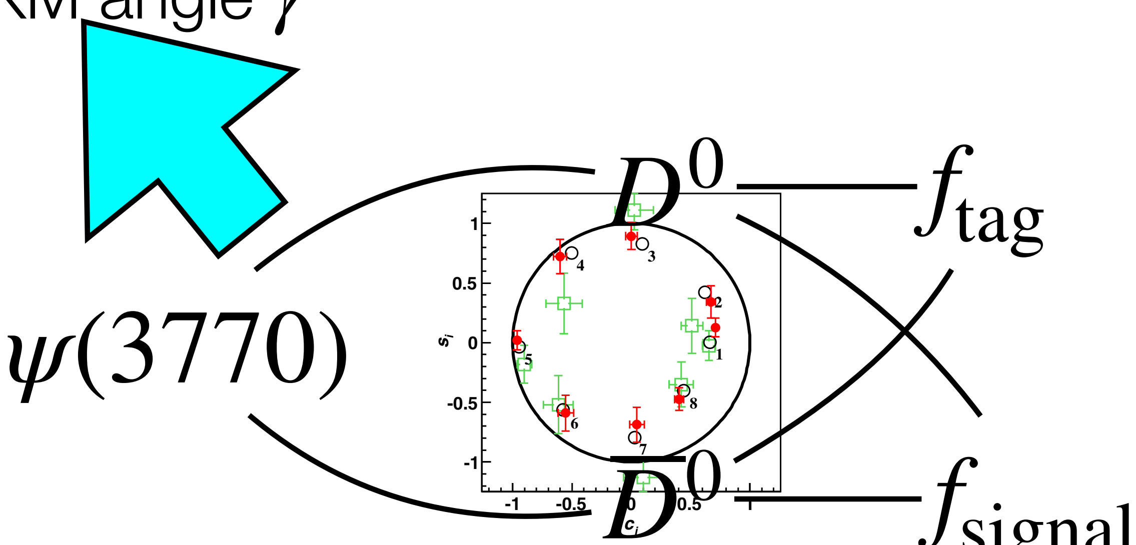
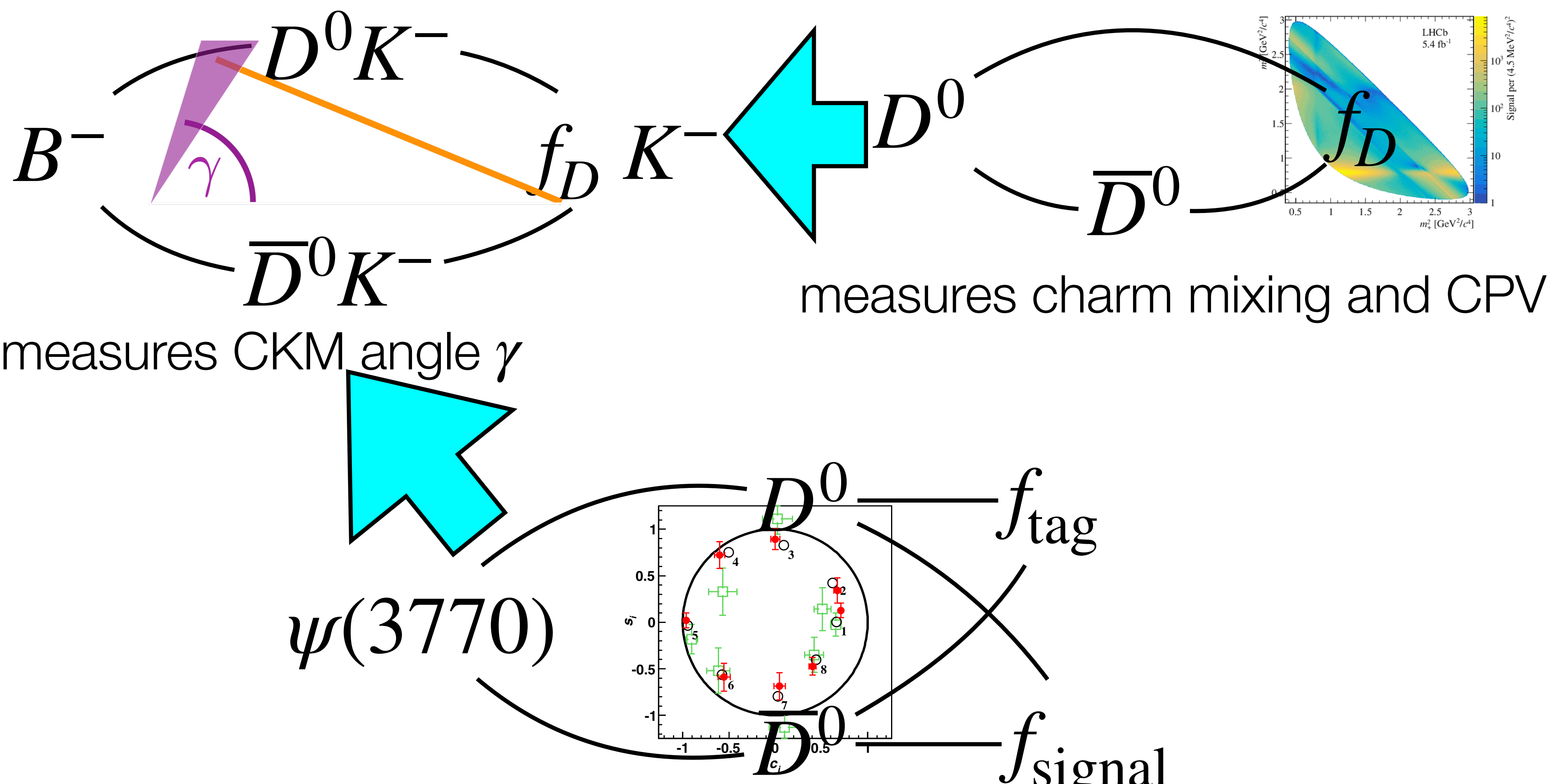


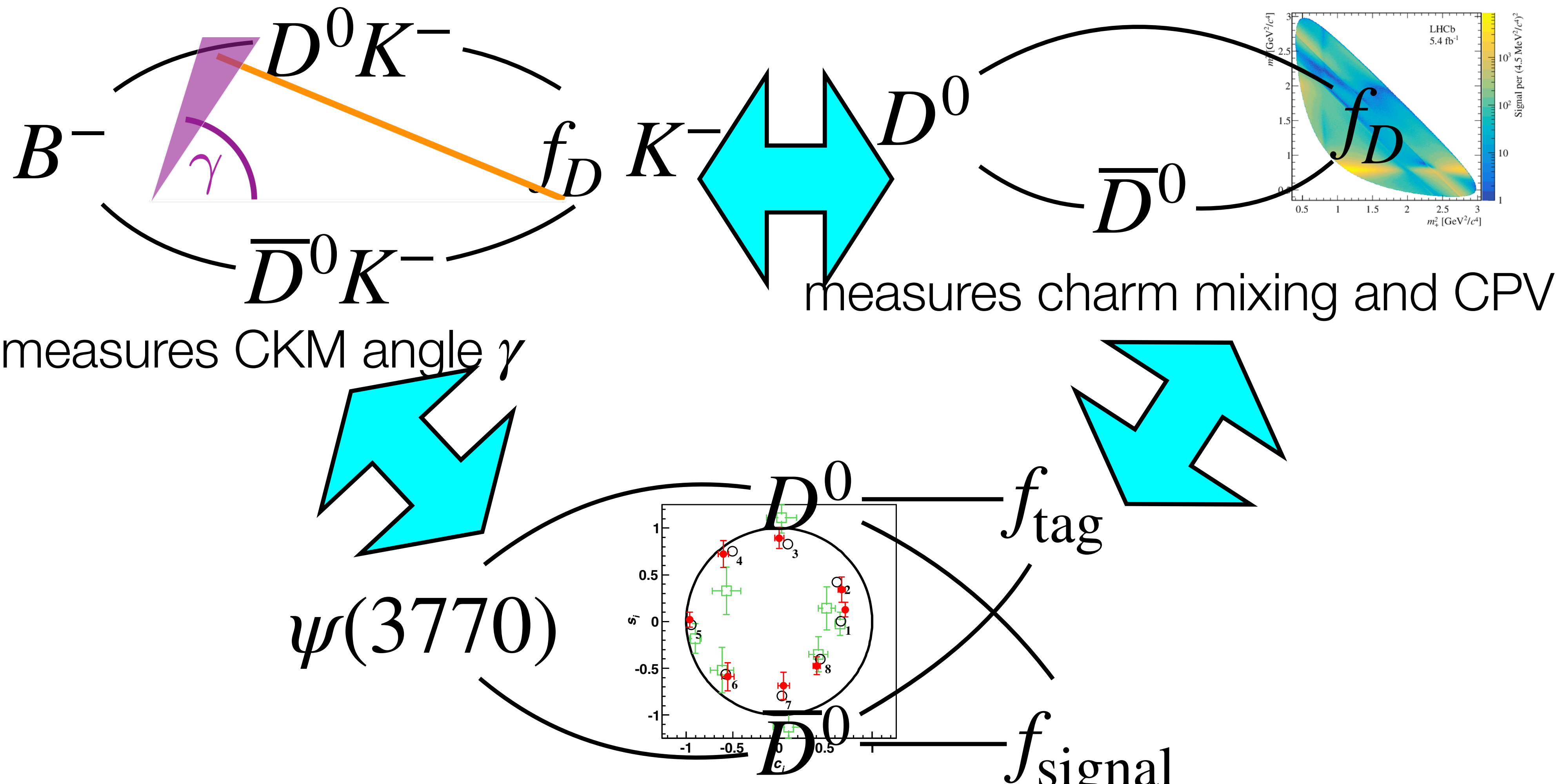
measures charm interference, especially strong phases

Input from charm threshold and mixing to γ.



measures charm interference, especially strong phases

Combined analysis of mixing, threshold data, γ.



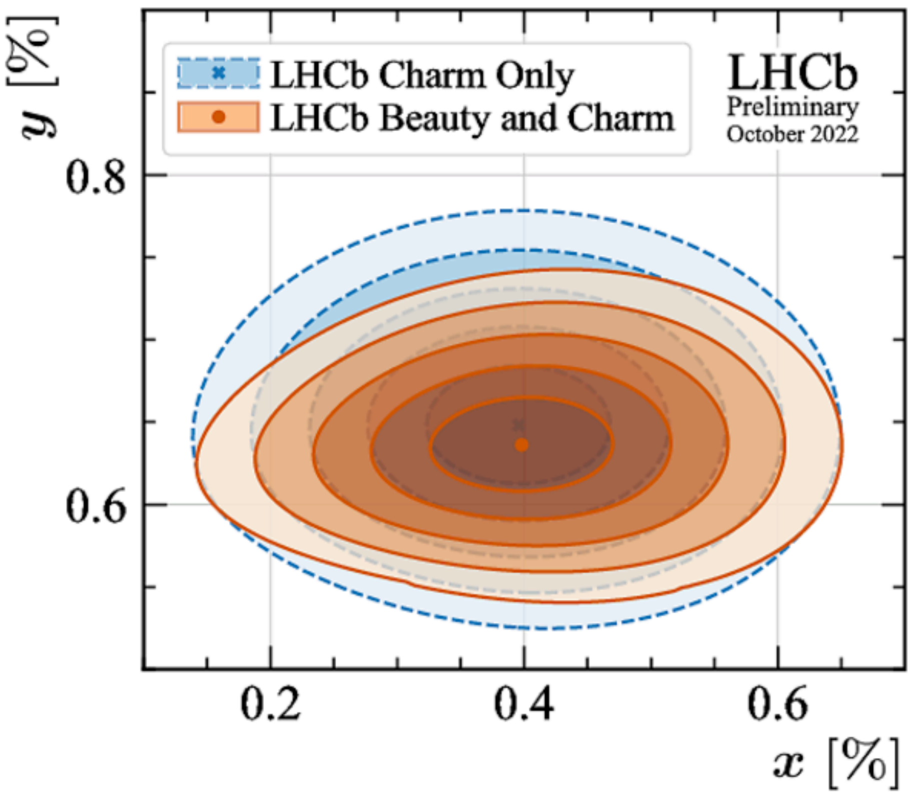
measures CKM angle γ

measures charm mixing and CPV

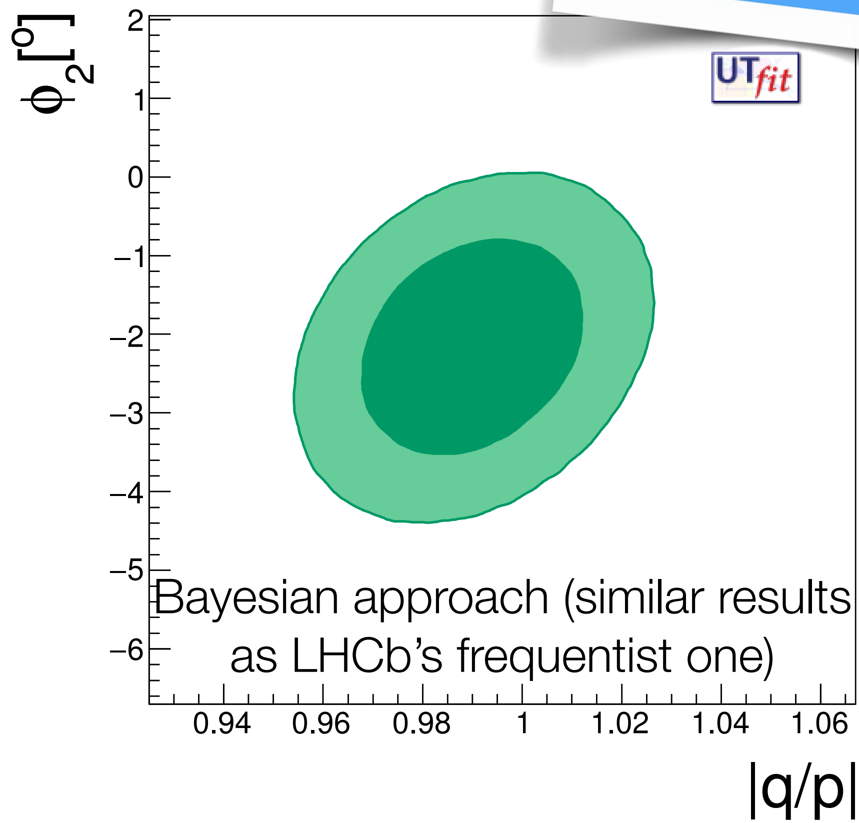
measures charm interference, especially strong phases

Combination of charm and beauty inputs for mixing

LHCb-CONF-2022-003
& JHEP 12 (2021) 141



Roberto di Palma



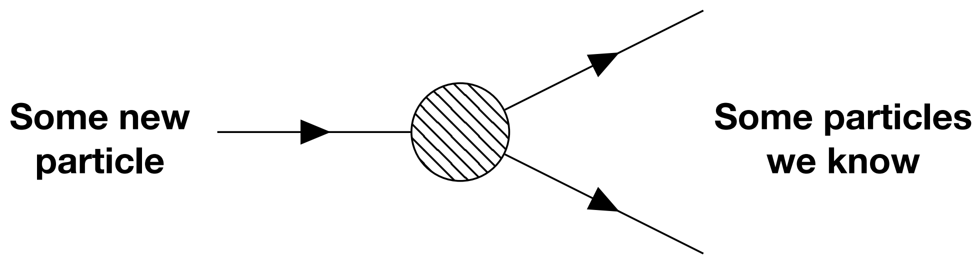
Bayesian approach (similar results as LHCb's frequentist one)

$B \to DK$ input improves charm parameters

Why do I care? The quest for new physics

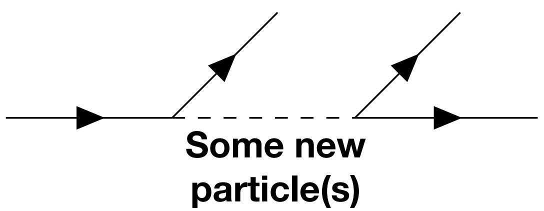
Direct Searches

- Look *directly* for new particles produced



Indirect Searches

- Look for the *indirect* influence of unknown particles on calculable quantities



Each approach is complementary to the other

Adam Davis

Why do I care? The quest for new physics

Direct Searches

s

Indirect Searches

- Look f own particl

Each approach is complementary to the other

adam.davis @ cern.ch D mixing, indirect CPV and charm hadron lifetimes 4 / 22

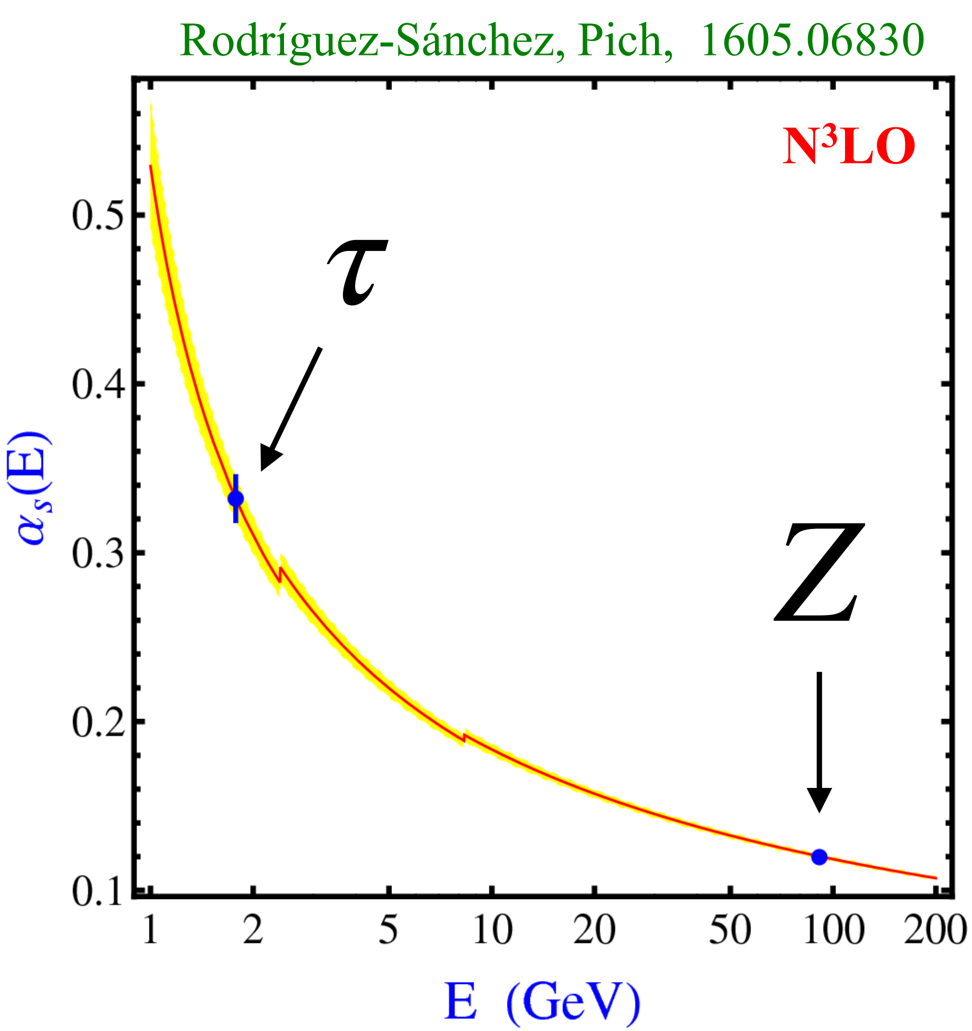
The problem with that:

The problem with that:

Talks by Felix Erben (mixing on the Lattice), Blaženka Malik (mixing with HQE). There is progress, but a lot of heavy lifting remains to be done.

QCD can be beautiful!

Antonio Pich

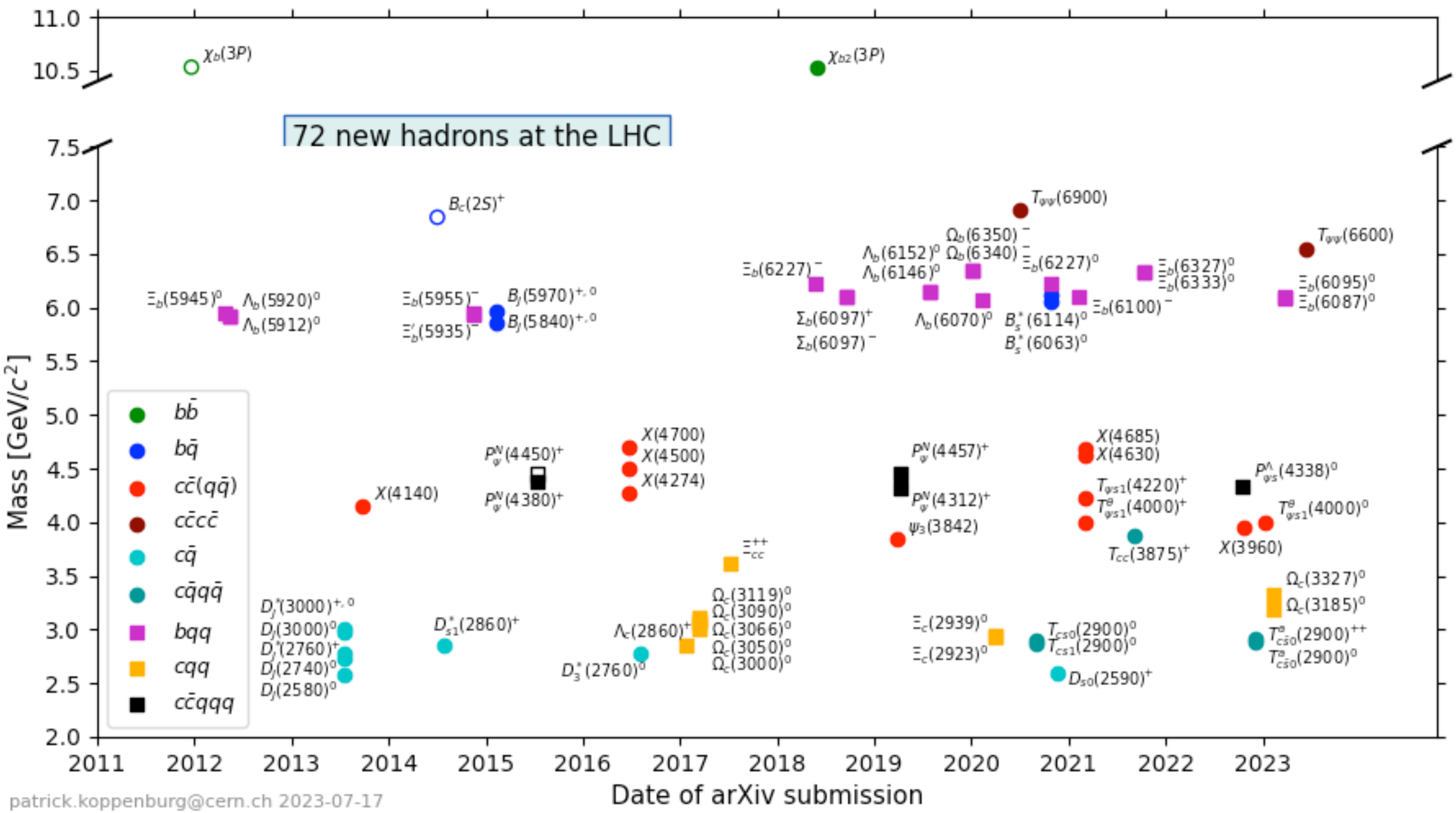


Very precise test of Asymptotic Freedom

$$\alpha_s^\tau(M_Z^2) - \alpha_s^Z(M_Z^2) = 0.0002 \pm 0.0015_\tau \pm 0.0029_Z$$

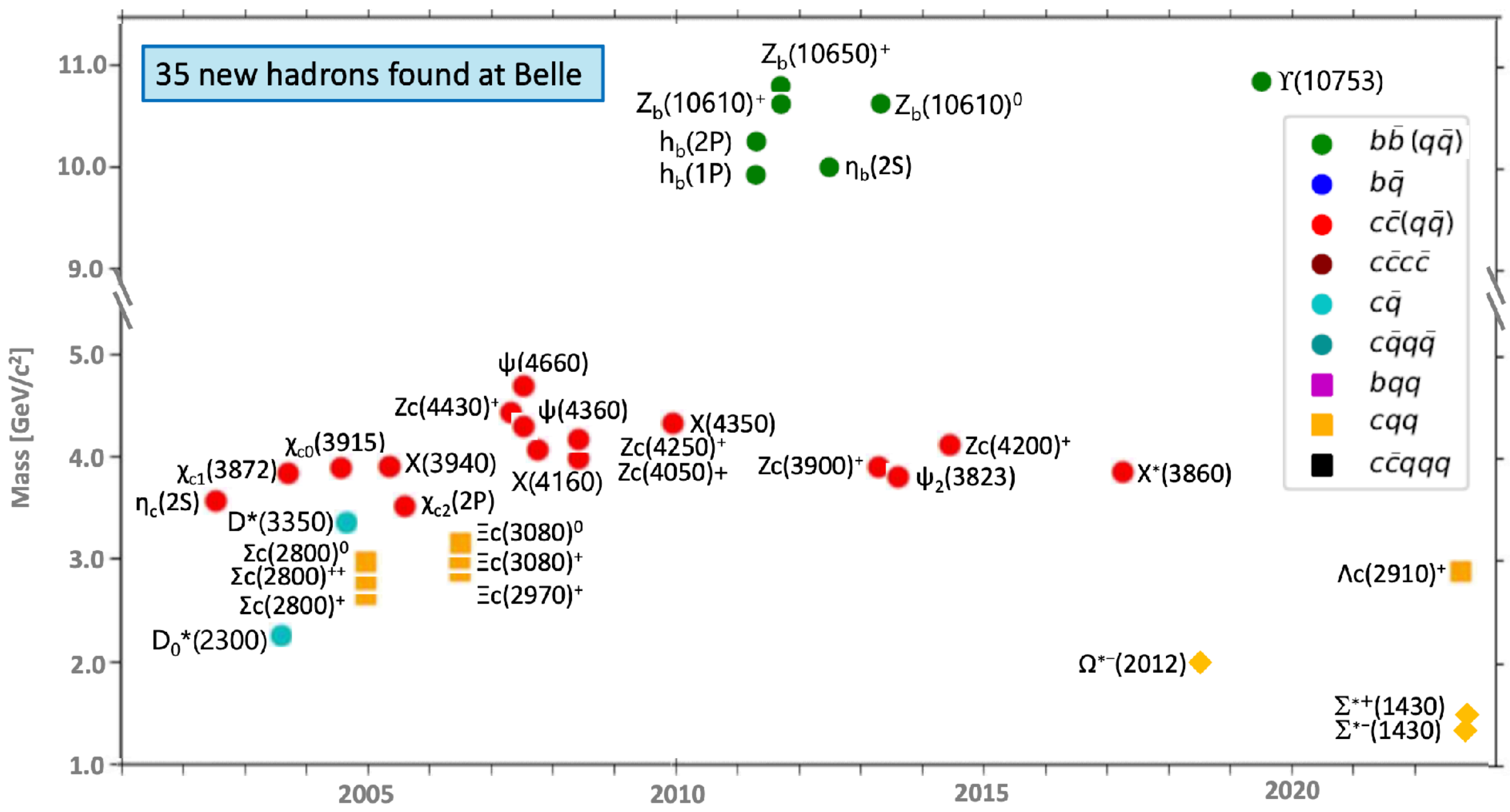
Spectroscopy

72 new hadrons at the LHC



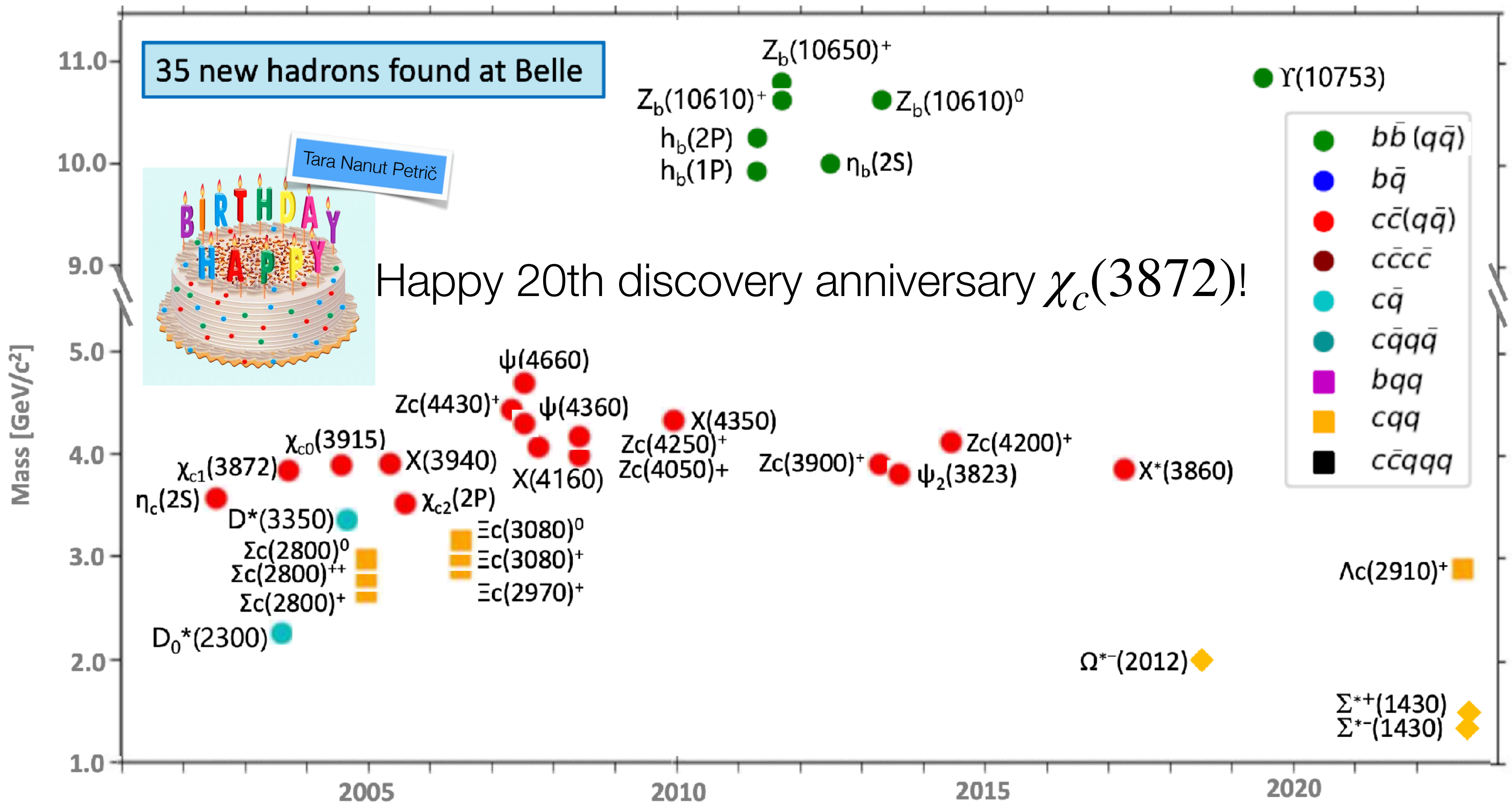
Plot by Patrick Koppenburg: https://www.nikhef.nl/~pkoppenb/particles.html

35 new hadrons at BELLE



Junhao Yin (Korea University) @MIAPbP Heavy Flavour Workshop

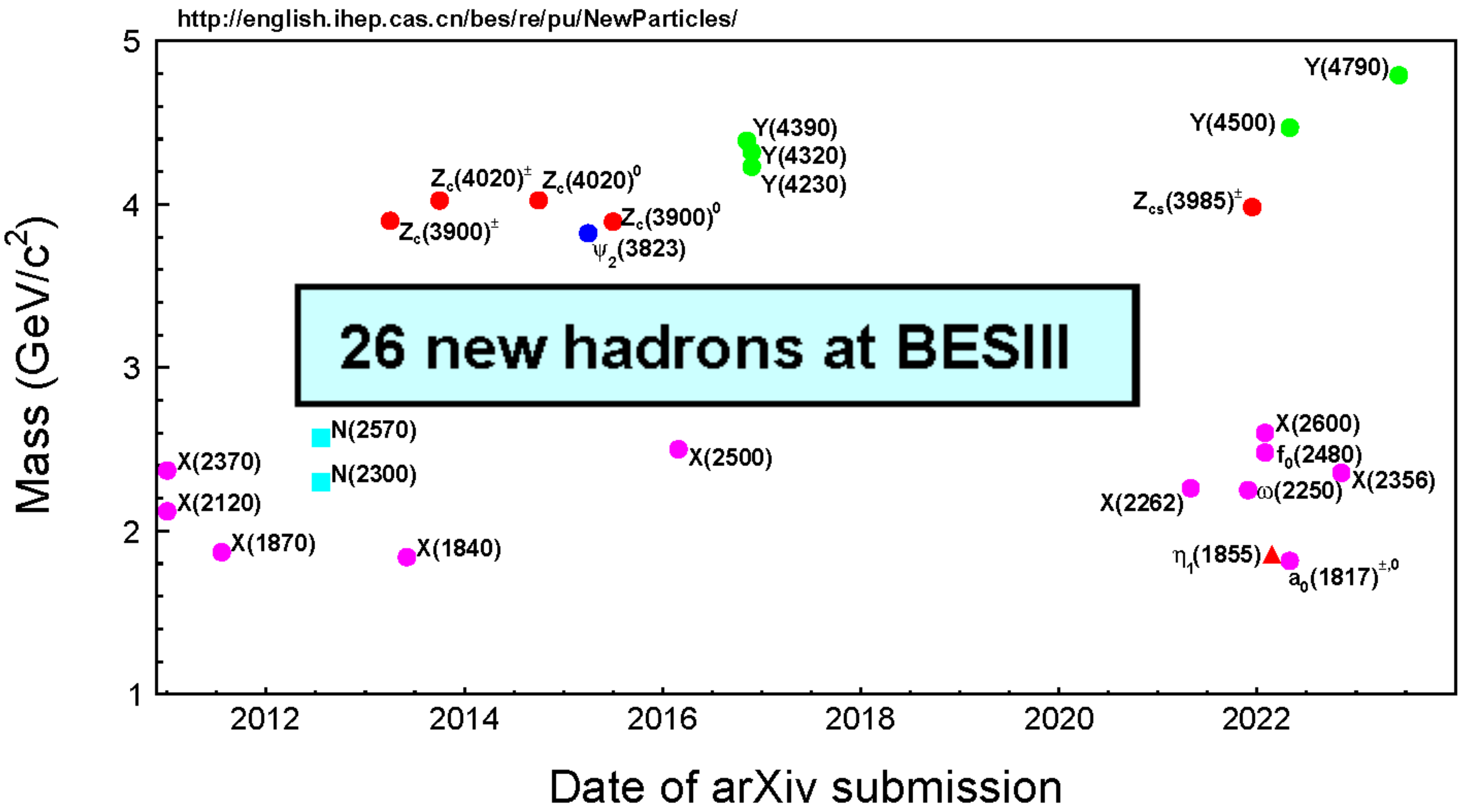
35 new hadrons at BELLE



Junhao Yin (Korea University) @MIAPbP Heavy Flavour Workshop

Chunhua Li

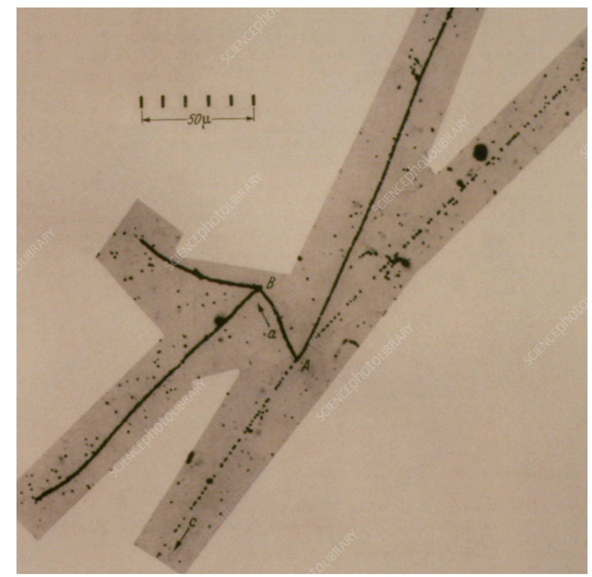
26 new hadrons at BES III



Cecil Powell, 1945

After using a newly developed emulsion technique to measure cosmic radiation high in the Pyrenees (Pic du Midi):

“It was as if, suddenly, we had broken into a walled orchard, where protected trees had flourished and all kinds of exotic fruits had ripened in great profusion.”

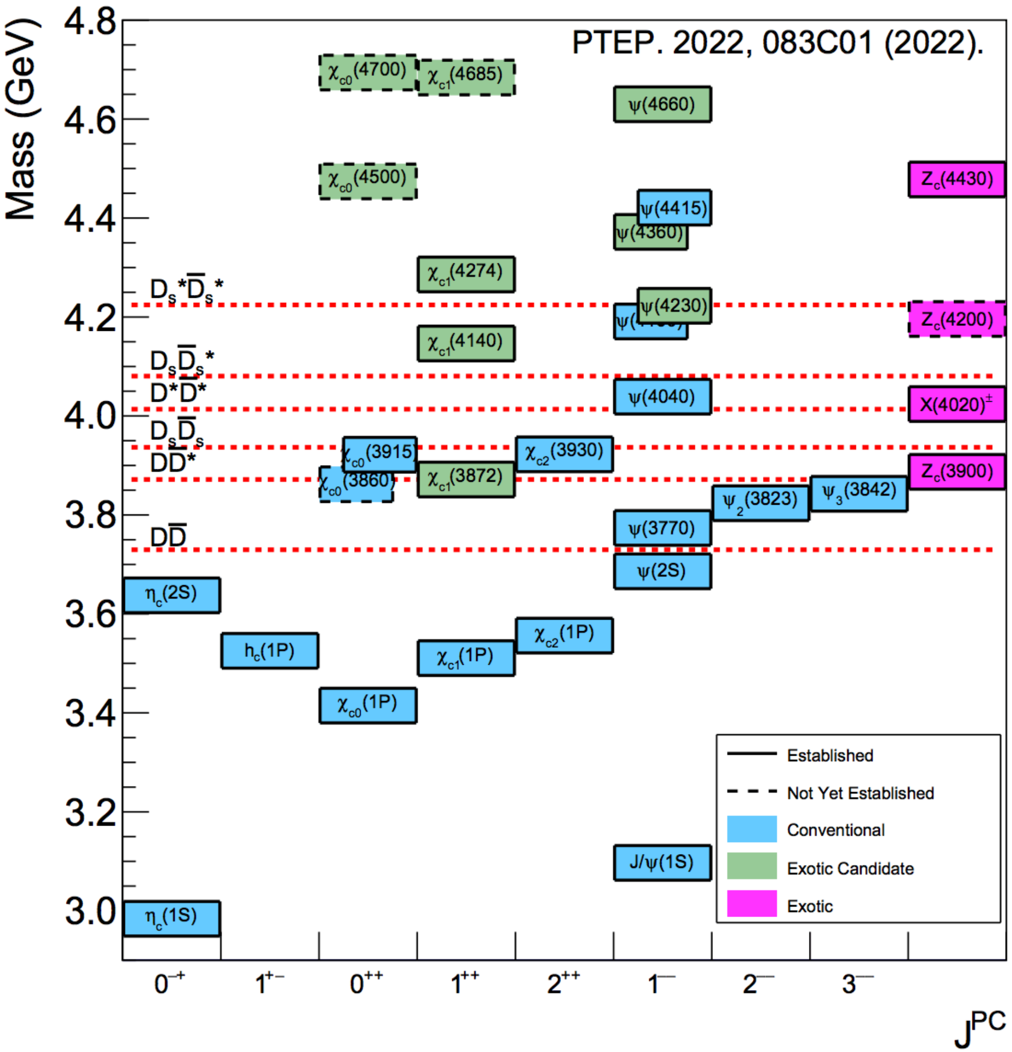


Cecil Powell and Cesar Lattes discovered the pion with their new emulsion technique.

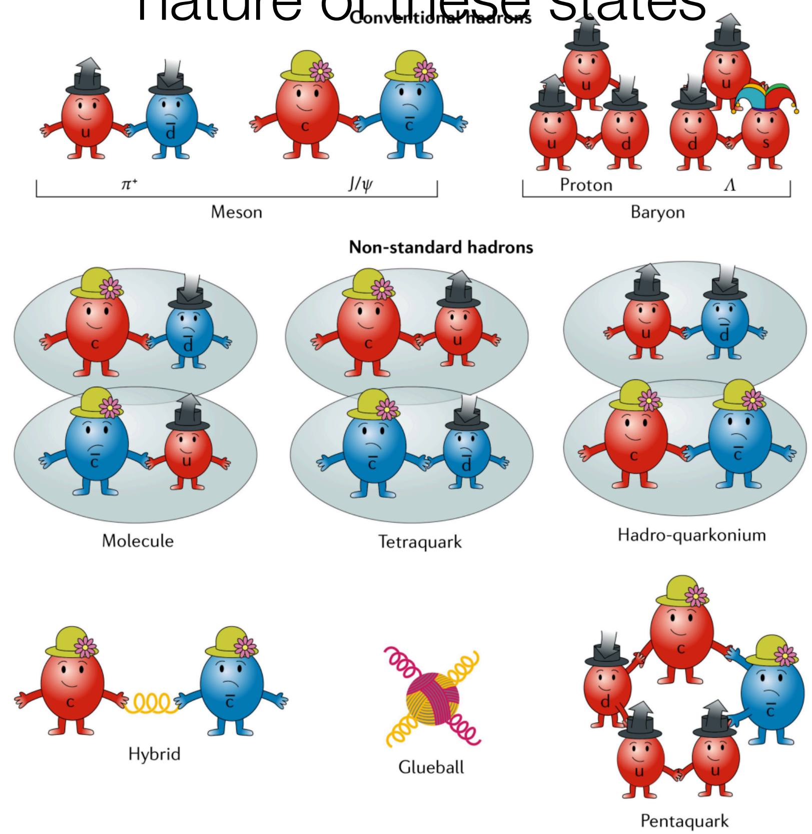
Charmonium Spectrum

Chunhua Li

Antonio Polosa



Much speculation about the nature of these states

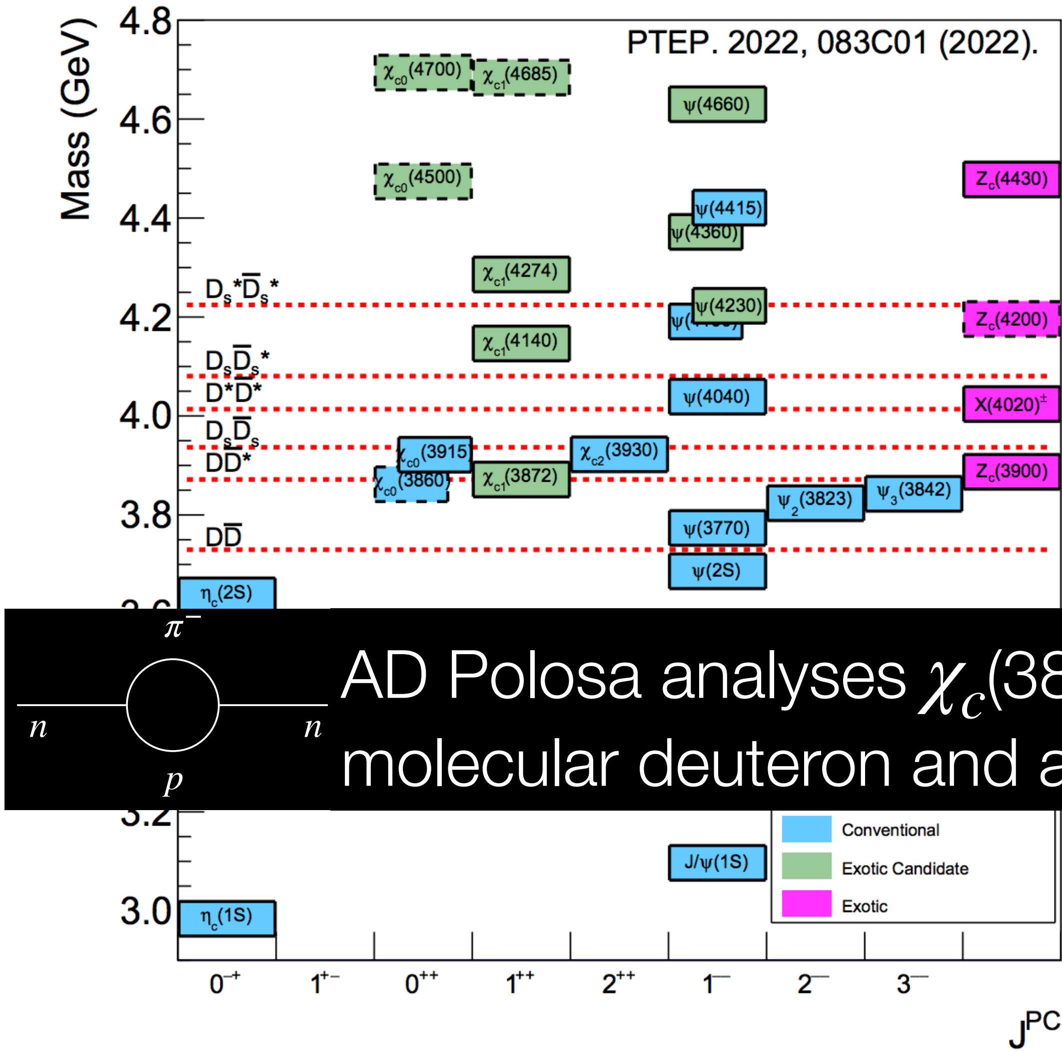


CZY & S.L. Olsen, *Nature Reviews Physics* **1**, 480 (2019)

Chunhua Li

Antonio Polosa

Charmonium Spectrum



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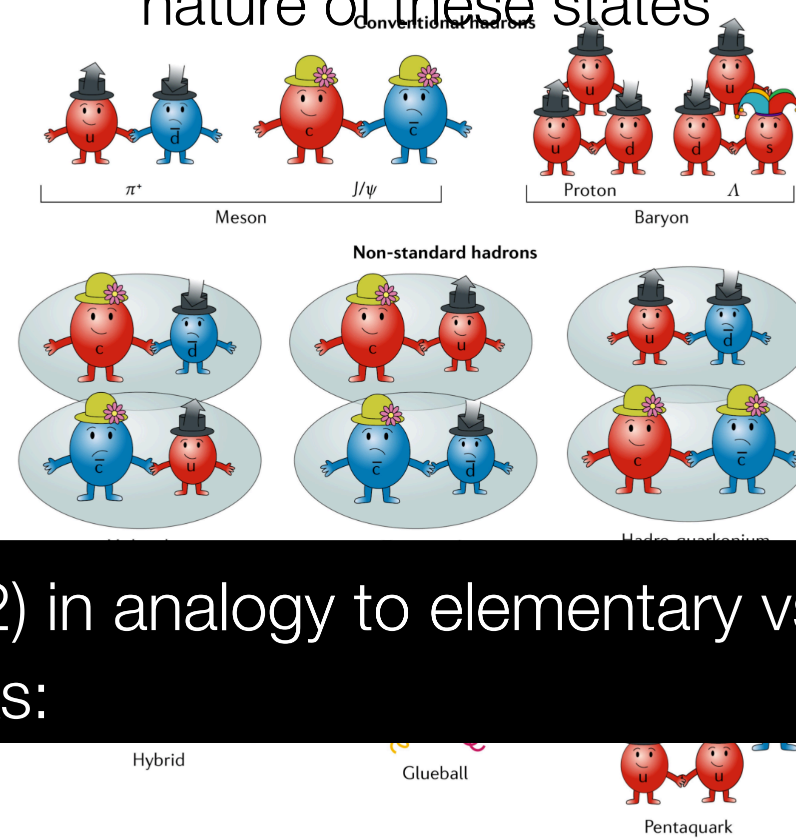


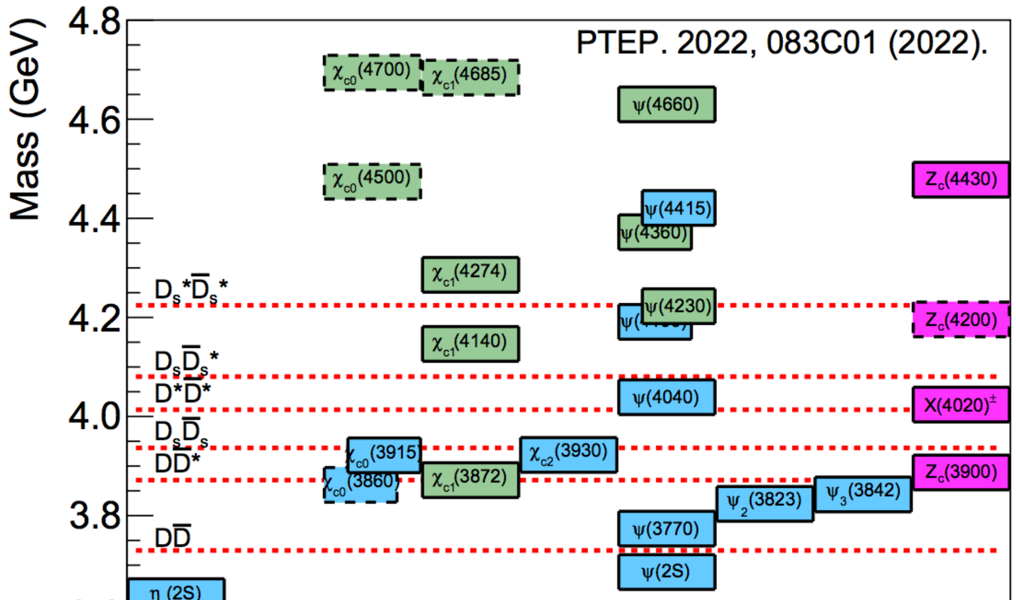
CZY & S.L. Olsen, *Nature Reviews Physics* **1**, 480 (2019)

AD Polosa analyses $\chi_c(3872)$ in analogy to elementary vs molecular deuteron and asks:

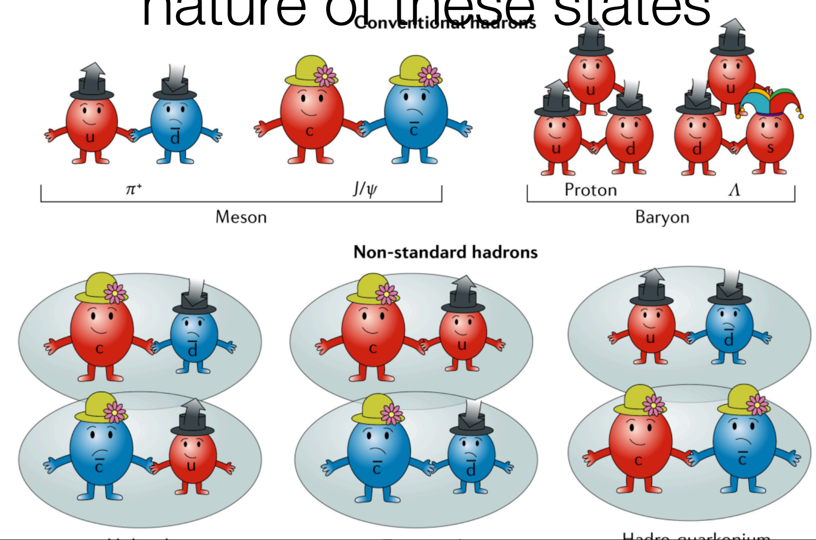
Chunhua Li

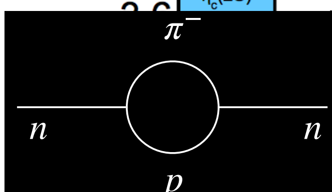
Antonio Polosa

Charmonium Spectrum



Much speculation about the nature of these states





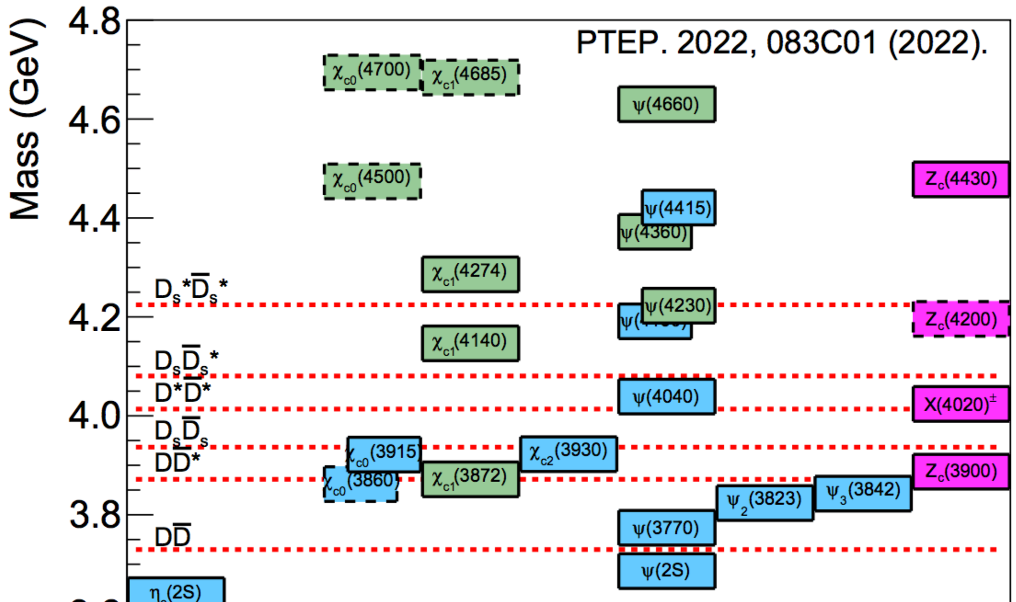
AD Polosa analyses $\chi_c(3872)$ in analogy to elementary vs molecular deuteron and asks:

More basically: are we on the right questions?

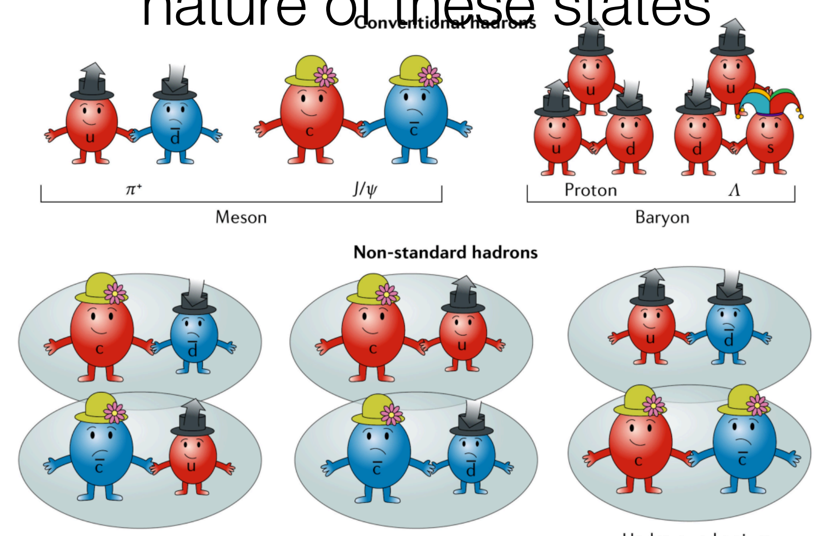
CZY & S.L. Olsen, *Nature Reviews Physics* **1**, 480 (2019)

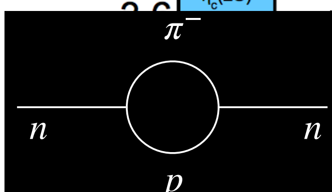
Charmonium Spectrum

Chunhua Li | Antonio Polosa



Much speculation about the nature of these states





AD Polosa analyses $\chi_c(3872)$ in analogy to elementary vs molecular deuteron and asks:

More basically: are we on the right questions?

Thomas Mannel: I'd rather know why it's so narrow.

Charmonium on the Lattice

Sara Collins

Challenges: Dense spectrum of states: a number of states with same/different J^{PC} in a narrow energy region. Multiple two-particle and three-particle decay channels can be open.

[Prelovsek et al.,2011.02542] Coupled channel $D\bar{D}$ and $D_s\bar{D}_s$ S- and D-wave scattering.

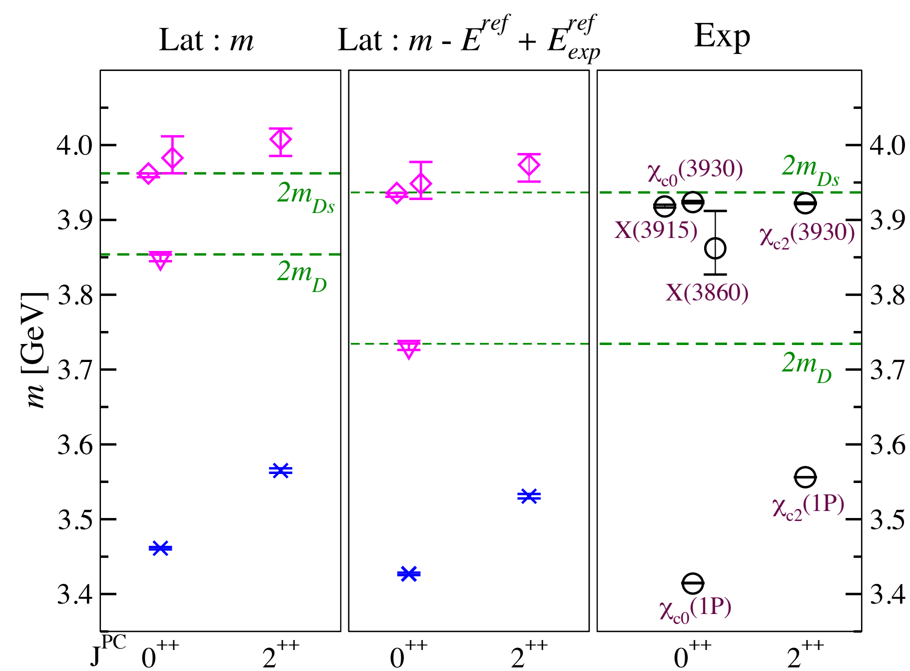
$J/\psi\omega$ and $\eta_c\eta$ channels ignored, $m_c > m_c^{phys}$.

$J^{PC} = 0^{++}$: ★ State just below $D\bar{D}$ threshold ($m_\pi > m_\pi^{phys}$!), not yet observed in expt.

★ Narrow resonance just below $D_s\bar{D}_s$ which may be related to $X(3915)/\chi_{c0}(3930)$.

★ Broad resonance which may be related to $X(3860)$.

★ $J^{PC} = 2^{++}$ similar to $\chi_{c2}(3930)$.



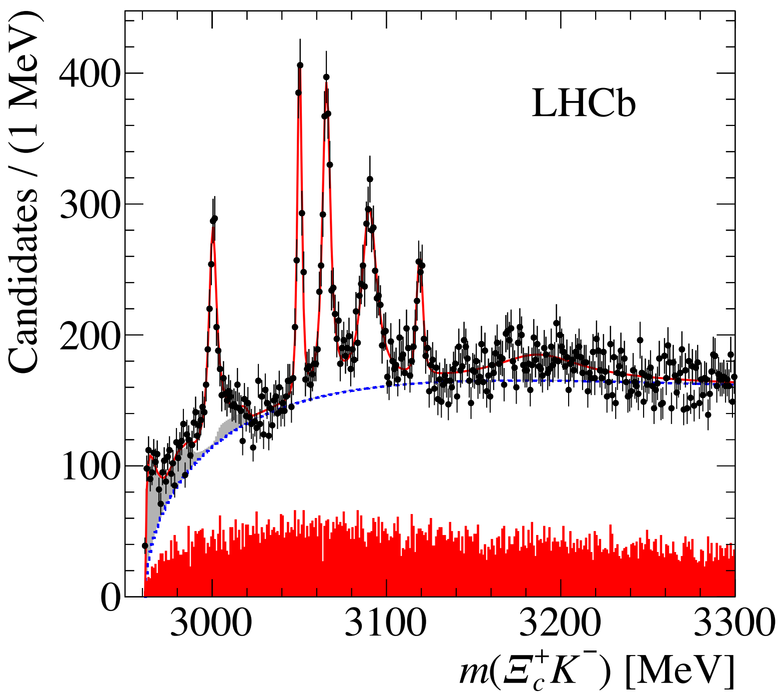
+ much much more on spectroscopy on the lattice in Sara's talk

See also: Juan Andres Urrea Nino

5 excited $\Omega_c \to \Xi_c^+ K^-$

Patrick Spradlin

LHCb: PRL 118 (2017) 18, 182001

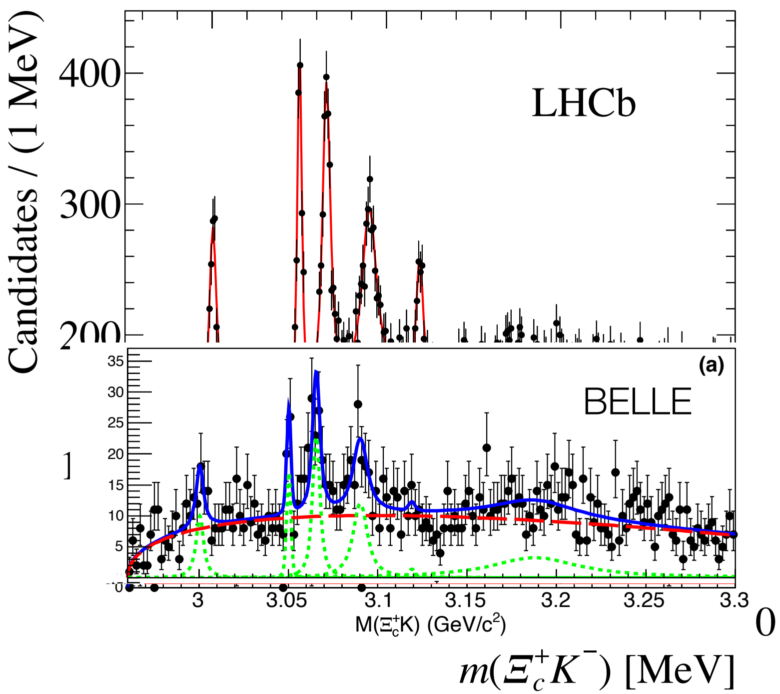


Patrick: “this porcupine just popped up”

5 excited $\Omega_c \to \Xi_c^+ K^-$

Patrick Spradlin

BELLE: PRD 97 (2018) 5, 051102
LHCb: PRL 118 (2017) 18, 182001

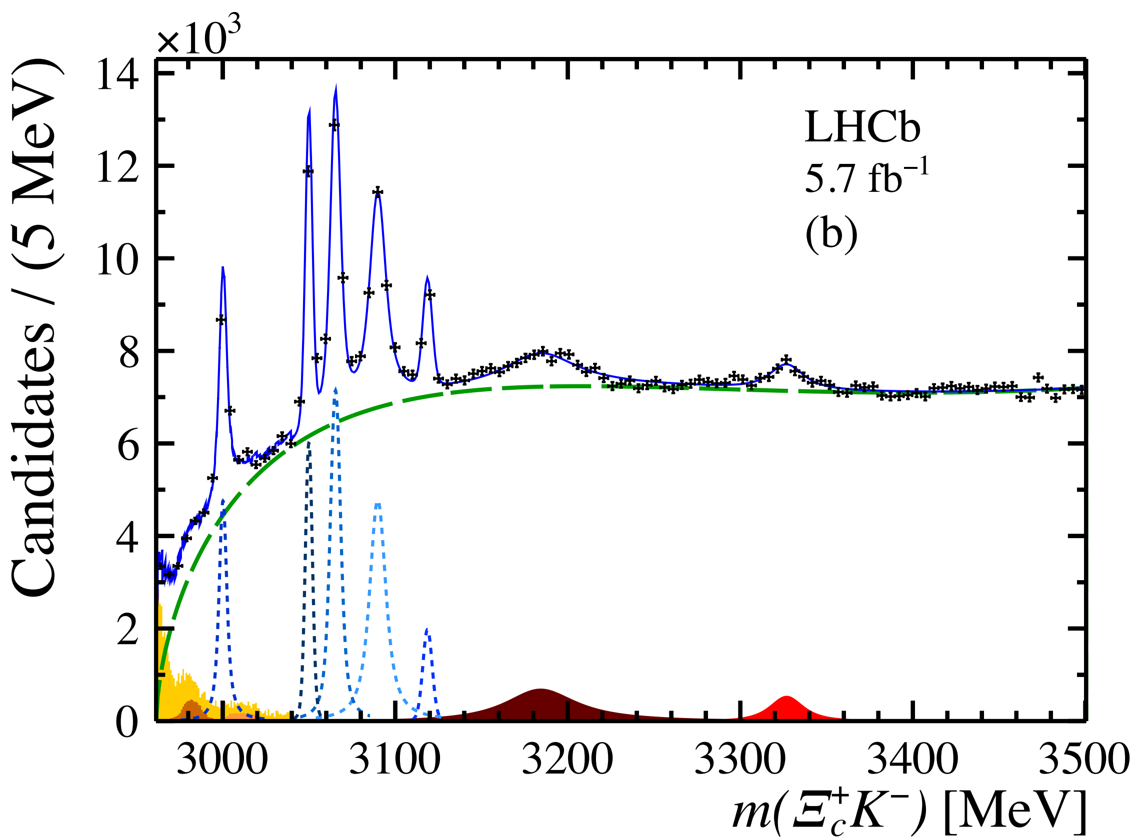


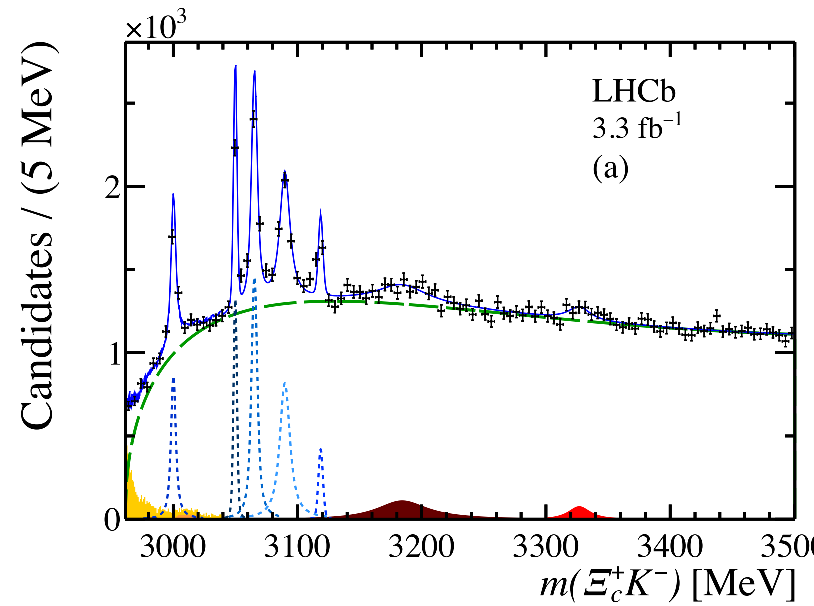
Patrick: “this porcupine just popped up”

~~5~~ 7 excited $\Omega_c \to \Xi_c^+ K^-$

Patrick Spradlin

BELLE: PRD 97 (2018) 5, 051102
LHCb: PRL 118 (2017) 18, 182001
LHCb: 2302.04733 (2023)





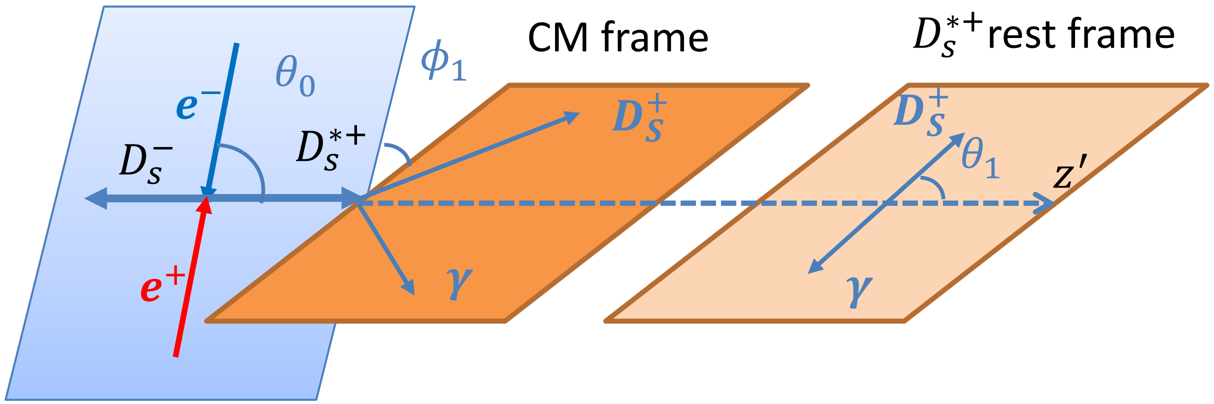
Patrick: “this porcupine just popped up”

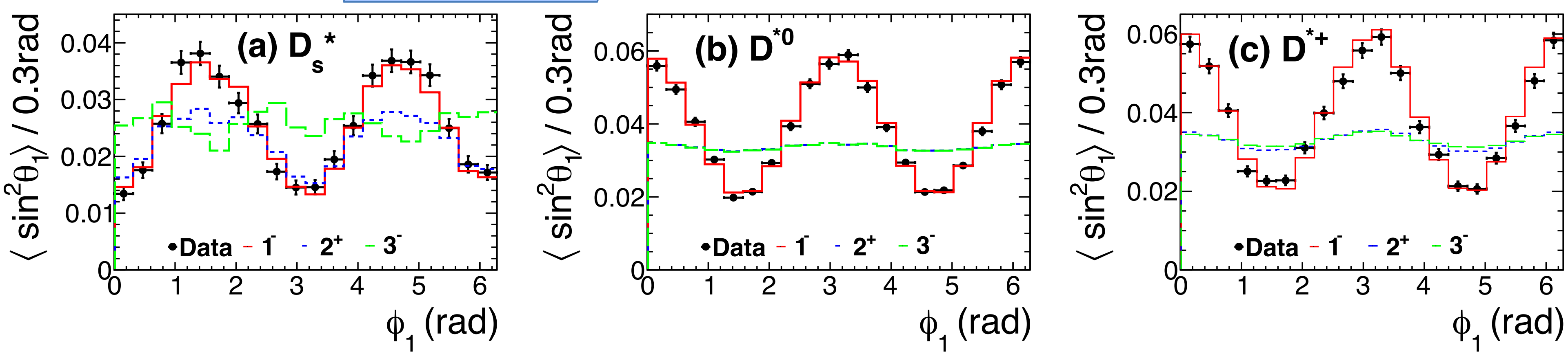
Spin-parity of $D^*_{(s)}$.

Daniel Unverzagt

Patrick Spradlin

BESIII: arXiv:2305.14631 (2023)





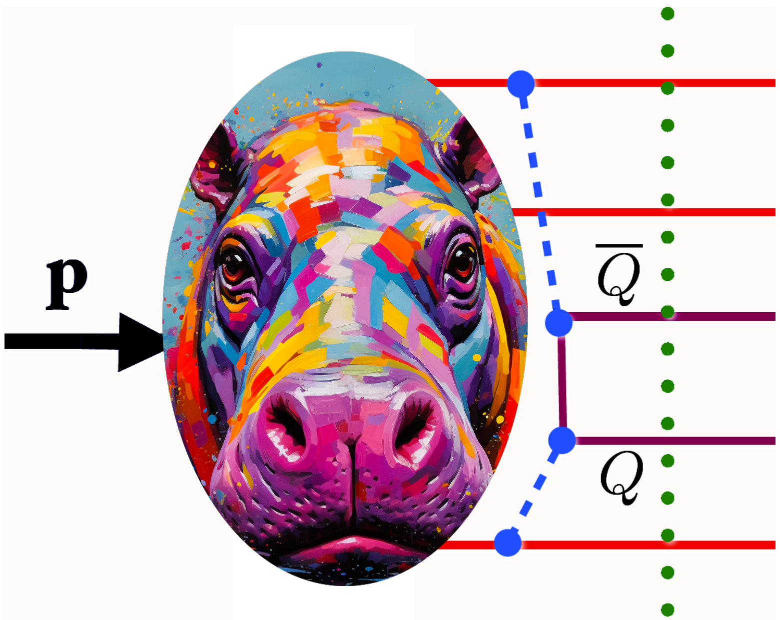
J^P of D_s^*, D^{*0}, and D^{*+} is 1^-

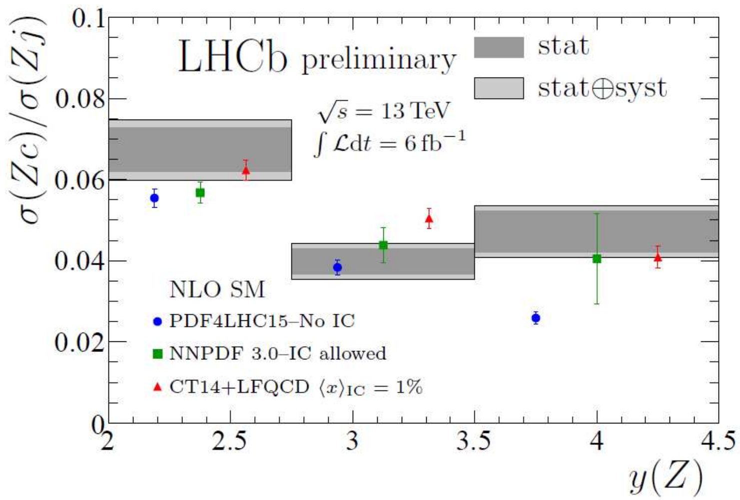
You might think we knew that, but we didn't!

Prior to this measurement, only spin 0 for D^{*0} excluded PRL 39, (1977) 262

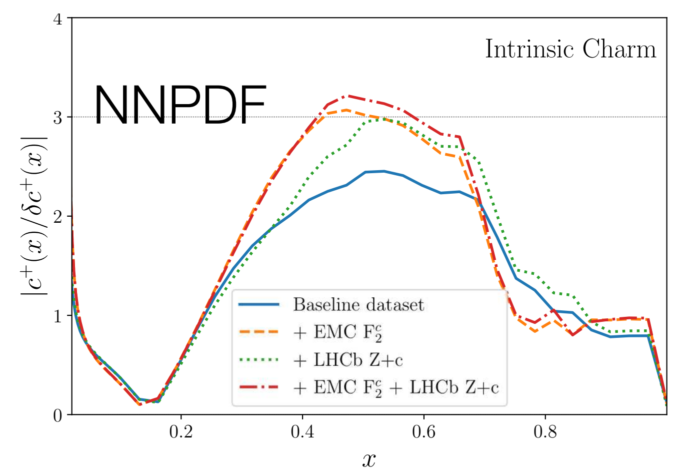
Intrinsic charm

Ramona Vogt





PRL 128, 082001 (2022)

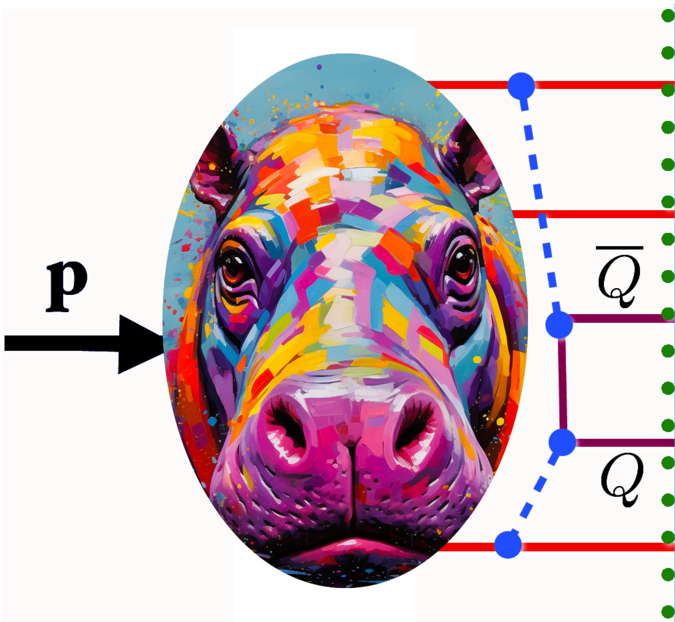


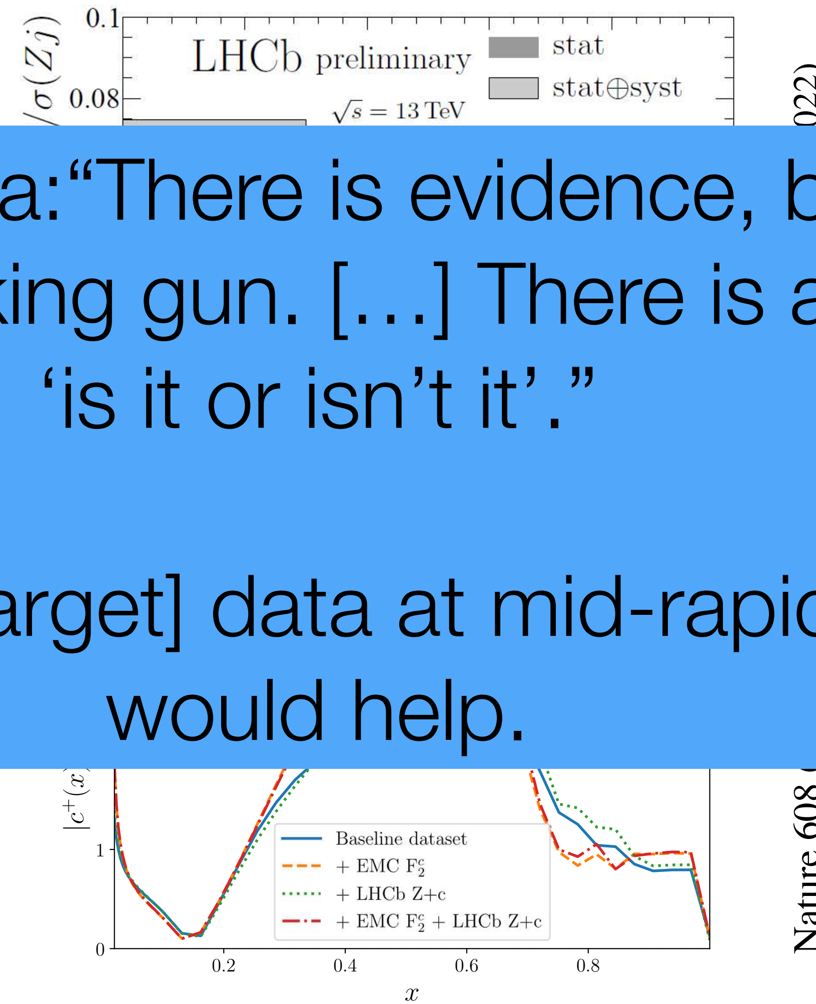
Nature 608 (2022) 483–487

Alternative interpretation e.g. at Guzzi et al., arXiv:2211.01387

Ramona Vogt

Intrinsic charm





Ramona:"There is evidence, but no smoking gun. […] There is a lot 'is it or isn't it'."

[Fixed target] data at mid-rapidity would help.

Alternative interpretation e.g. at Guzzi et al., arXiv:2211.01387

Charm in media

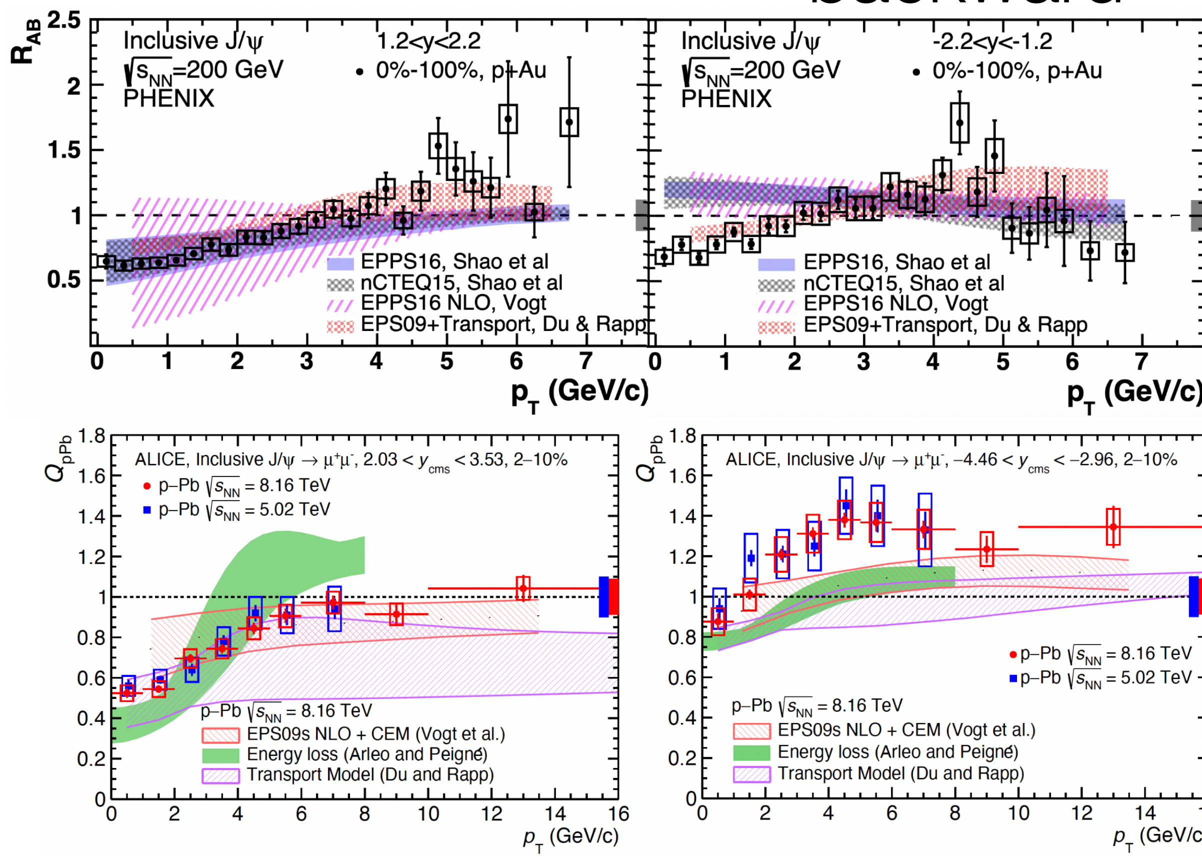
Krista Smith

J/ψ in p-Au, p-Pb collisions

forward backward

RHIC

LHC (ALICE)



PHYS.REV.C 102 (2020) 1, 014902

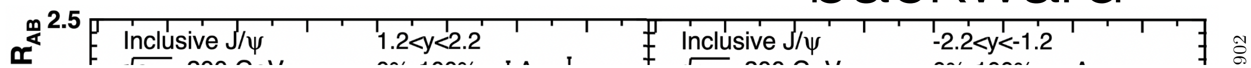
THEORETICAL REFERENCES: [7],[12],[13] JHEP 02 (2021) 002

Charm in media

Krista Smith

J/ψ in p-Au, p-Pb collisions

forward backward

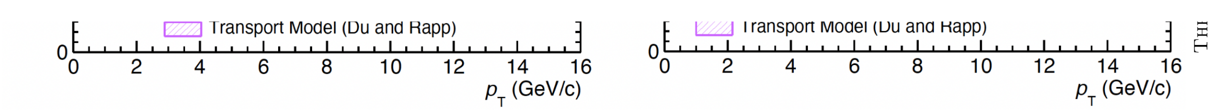


Small System Collisions — pA

- J/ψ modification versus p_T at backward rapidity suggests different nuclear effects contribute at RHIC compared to LHC energies
- Non-zero charm v_2 observed in pPb and high multiplicity pp collisions
- If QGP is formed, it does not appear to be dominant effect on J/ψ

Large System Collisions — AA

- Results indicate regeneration affects charmonia measurements at LHC energies
- Contributions from regeneration in $\Upsilon(1S)$ measurements appear small, if any
- $\Upsilon(1S)$ modification shows similar suppression as J/ψ modification at RHIC

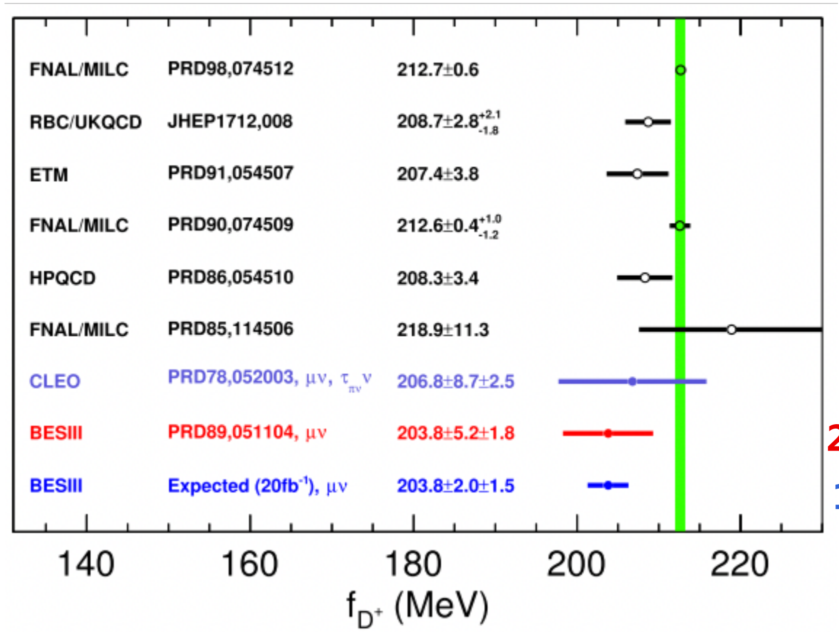


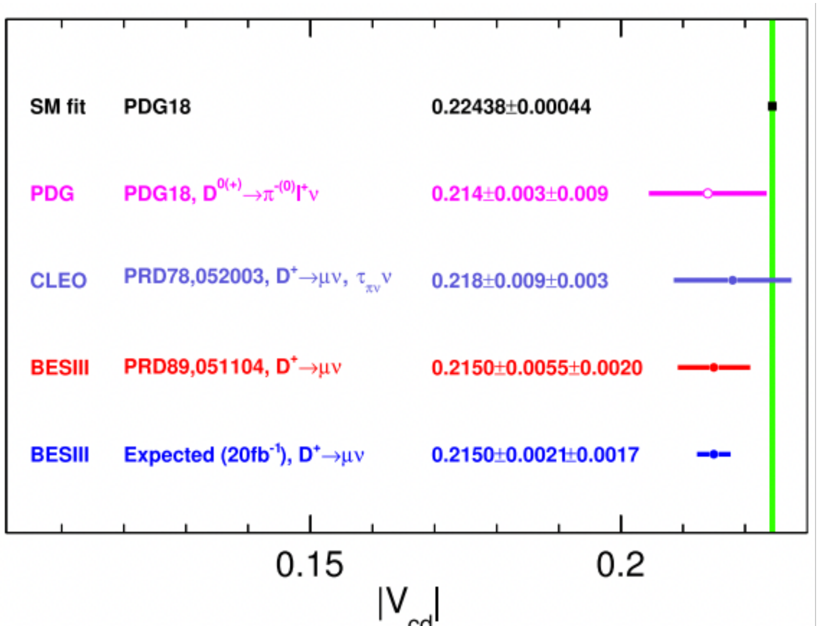
Leptonic decays

Shulei Zhang

Lattice

$$\Gamma(D^+ \to l^+\nu_l) = \frac{G_F^2 f_D^2}{8\pi} |V_{cd}|^2 m_l^2 m_D \left(1 - \frac{m_l^2}{m_D^2}\right)^2$$



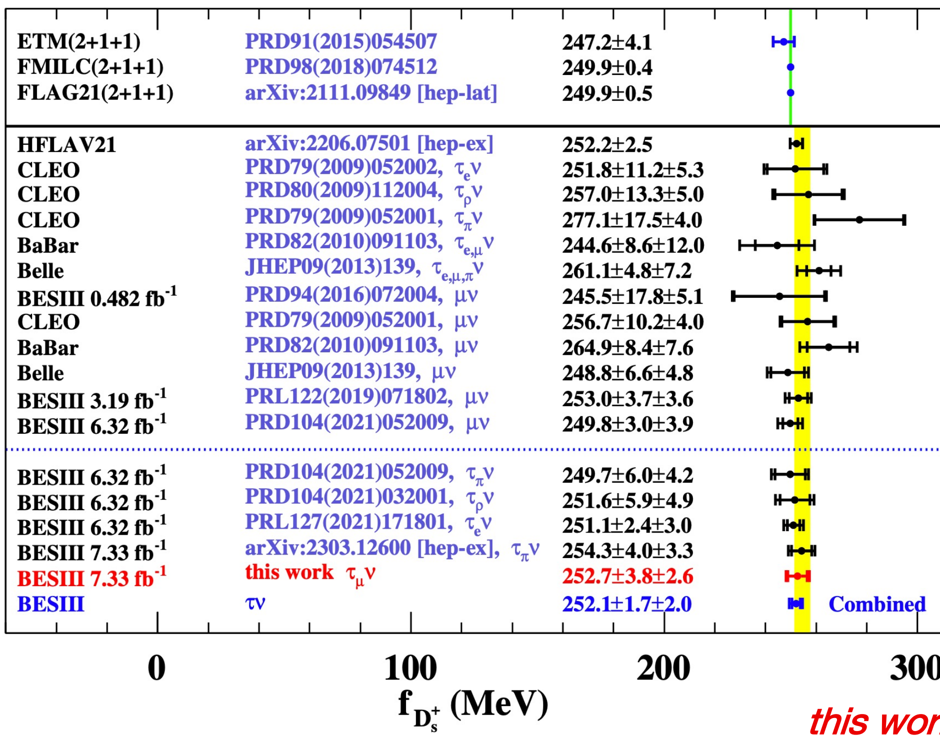


Shulei Zhang

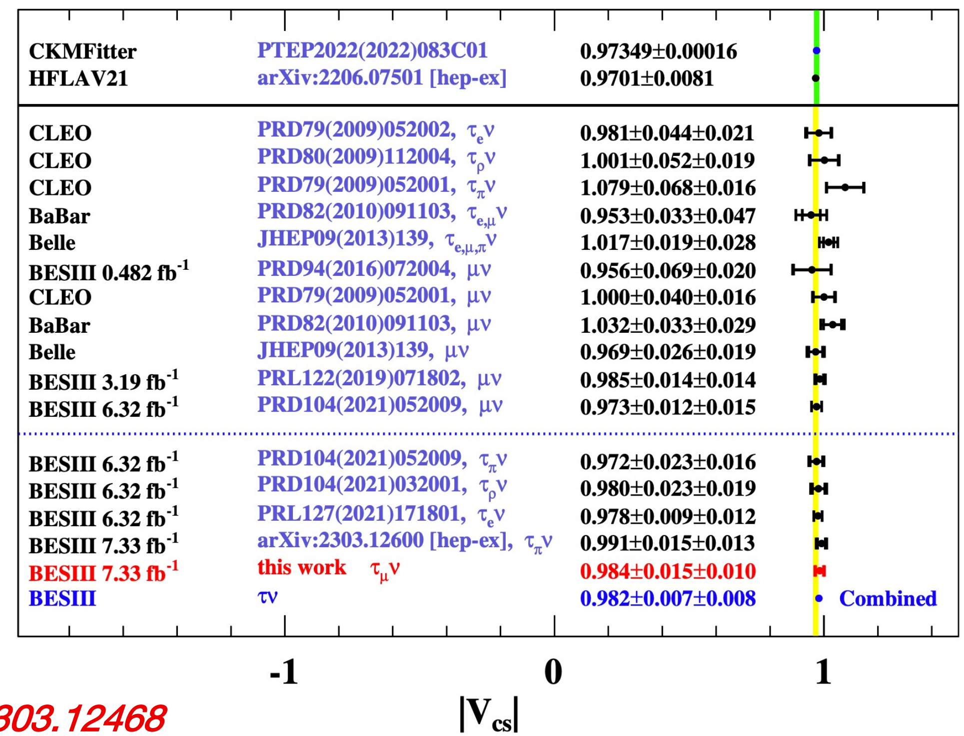
Leptonic decays

Lattice

$$\Gamma(D_s^+ \to l^+\nu_l) = \frac{G_F^2 f_{D_s}^2}{8\pi} |V_{cs}|^2 m_l^2 m_{D_s} \left(1 - \frac{m_l^2}{m_{D_s}^2}\right)^2$$



this work: 2303.12468



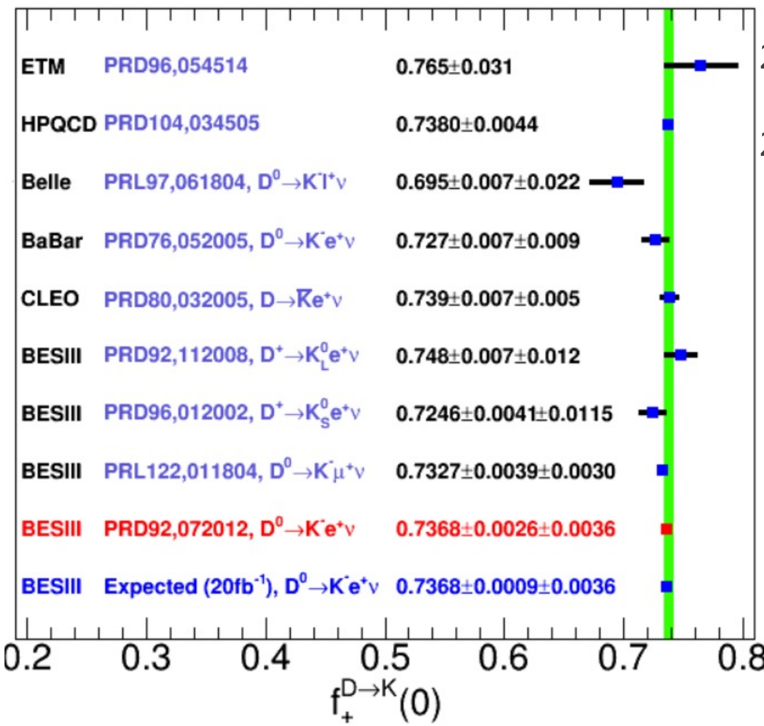
1%

Shulei Zhang

Semileptonic Decays

Lattice

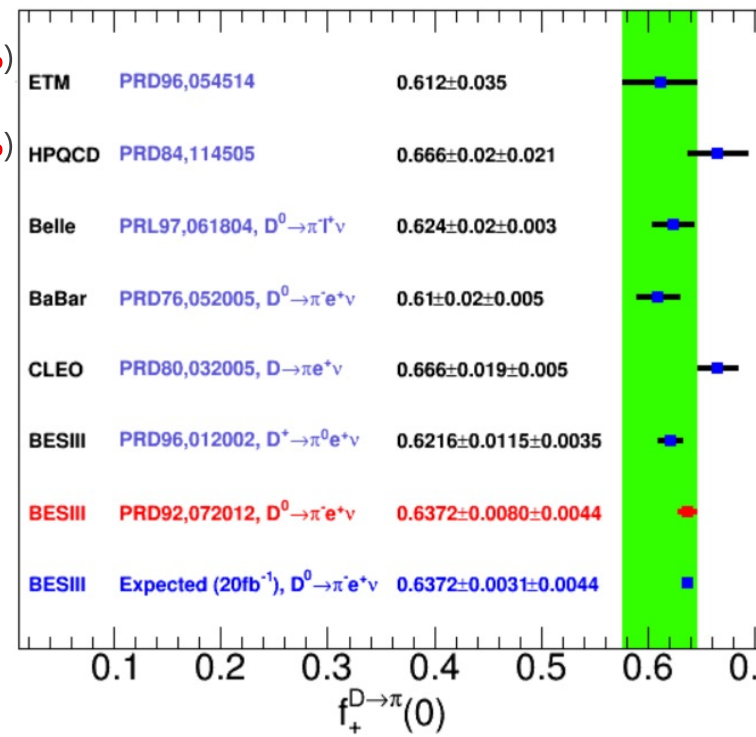
$$\Gamma(D_{(s)} \to P(S)\ell^+\nu_\ell)/dq^2 \;\propto\; |V_{cd(s)}|^2 |f_+(q^2)|^2$$



2010 (2.4%)
⇩
2021 (0.6%)

0.7%

<0.5%



>4%

1.4%

<1%

Experimental precision is comparable to the latest LQCD result

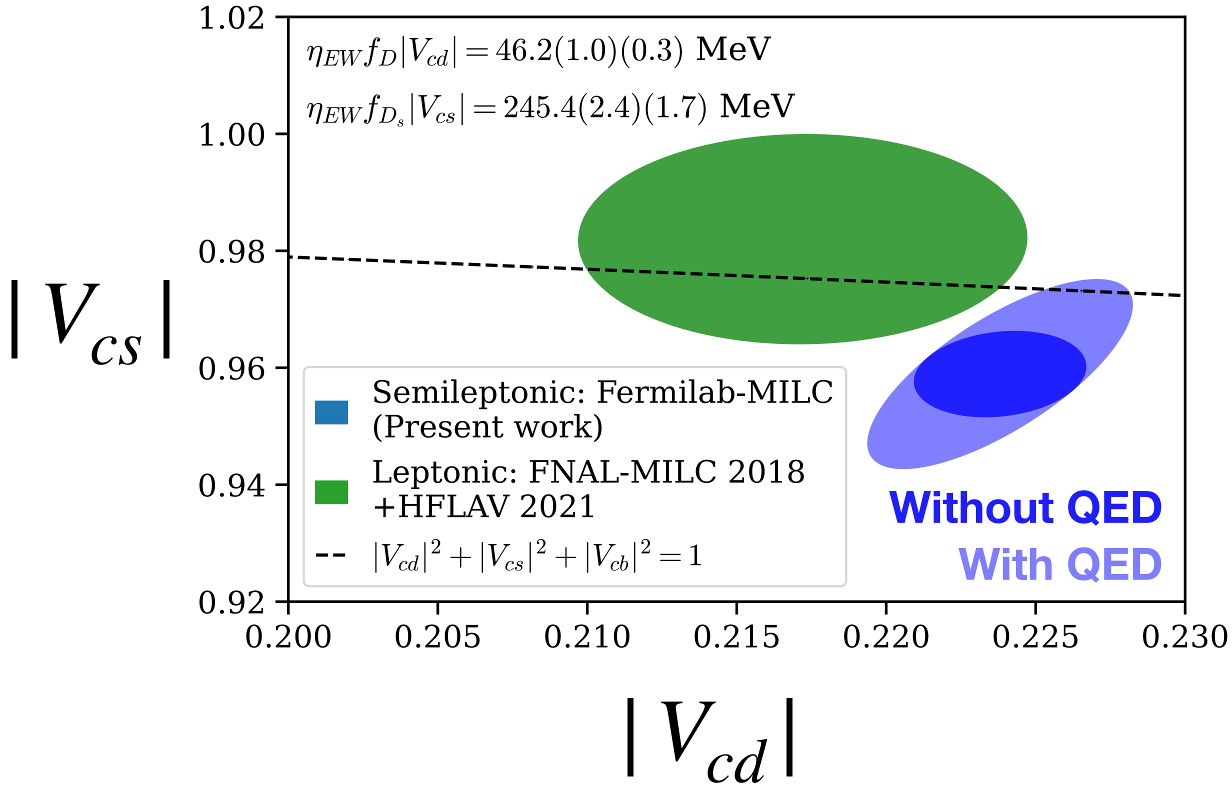
The measurements of the Cabibbo-suppressed decays are still dominated by statistical uncertainties

$|V_{cd}|$, $|V_{cs}|$ from semileptonic decays + lattice

$$|V_{cd}|^{D\to\pi} = 0.2338(11)^{\text{Expt}}(15)^{\text{LQCD}}[22]^{\text{EW/QED/SIB}}$$

$$|V_{cs}|^{D\to K} = 0.9589(23)^{\text{Expt}}(40)^{\text{LQCD}}[96]^{\text{EW/QED/SIB}}$$

Lattice analysis with latest and fanciest HISQ, physical M_π, conducted as blind analysis.



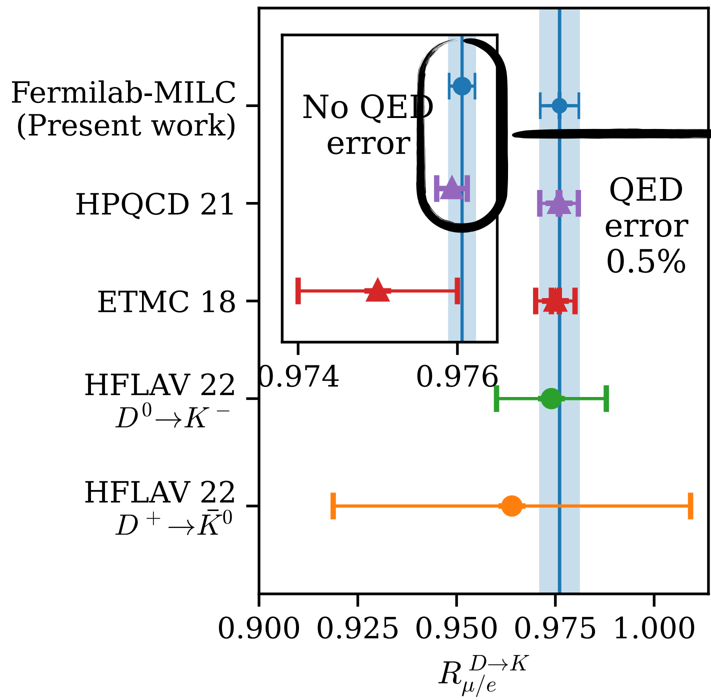
Lepton Flavour Universality

William Jay

$$R^K_{e\mu} := \frac{\mathrm{BF}(D^0 \to K^-\mu^+\nu_\mu)}{\mathrm{BF}(D^0 \to K^-e^+\nu_e)} = \frac{\mathrm{BF}(D^+ \to K^0\mu^+\nu_\mu)}{\mathrm{BF}(D^+ \to K^0e^+\nu_e)}$$

LQCD

Experiment



LQCD agreement at ≈ 0.01%

BES III:

$$R^K_{\mu e} = 0.974 \pm 0.007 \pm 0.012$$

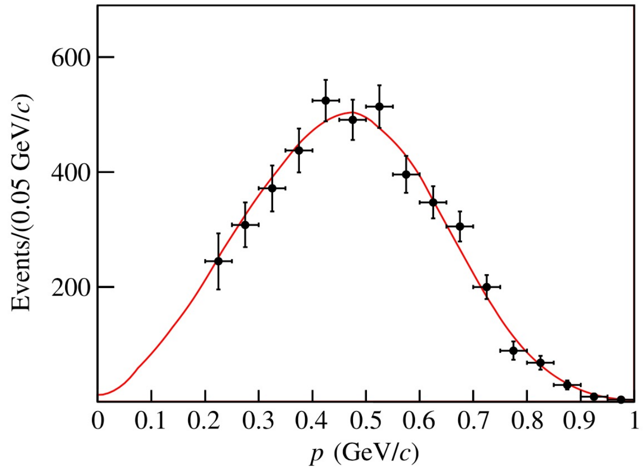
PRL 122, 011804 (2019)

Shulei Zhang

Shulei Zhang

Inclusive semileptonic baryon decays at BES III

Phys. Rev. D. 107, 052005 (2023)

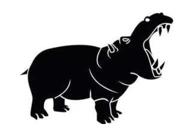


- 4.5 fb^{-1} data @ 4.600-4.699 GeV ➔ $N_{\mathrm{obs}} = 3706 \pm 71$
- $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (4.06 \pm 0.10 \pm 0.09)\%$ (~ 3%)

There is significant theory interest in differential distributions for inclusive decay rates, relevant for HQE treatment of semileptonic decays

Keri Vos

Rare charm decays

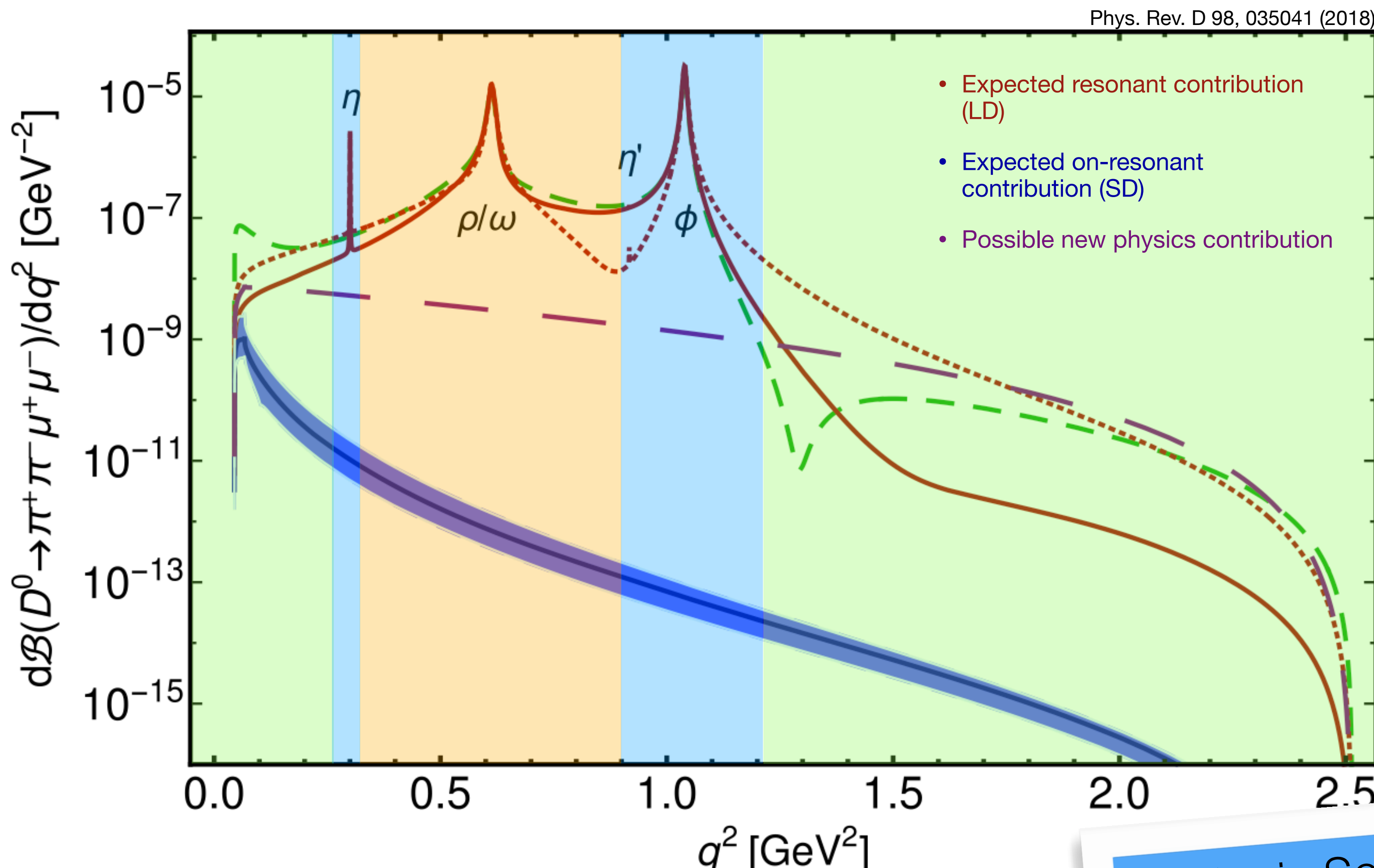
- Good: Gives access to FCNC in up-type quarks (Kaons and B probe down-type FCNC)
- Good: FCNC in charm are even rarer than rare B decays, because GIM works so very well.
- Bad: Long distance effects make interpretation difficult 
- Still, there are powerful “null tests”.

Daniel Unverzagt

$D^0 \to \pi^+\pi^-\mu^+\mu^-, K^+K^-\mu^+\mu^-$

LHCb: PRL 128 (2022) 22, 221801

Full angular analysis and CPV tests.



See also: Eleftheria Solomonidi

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Daniel Unverzagt

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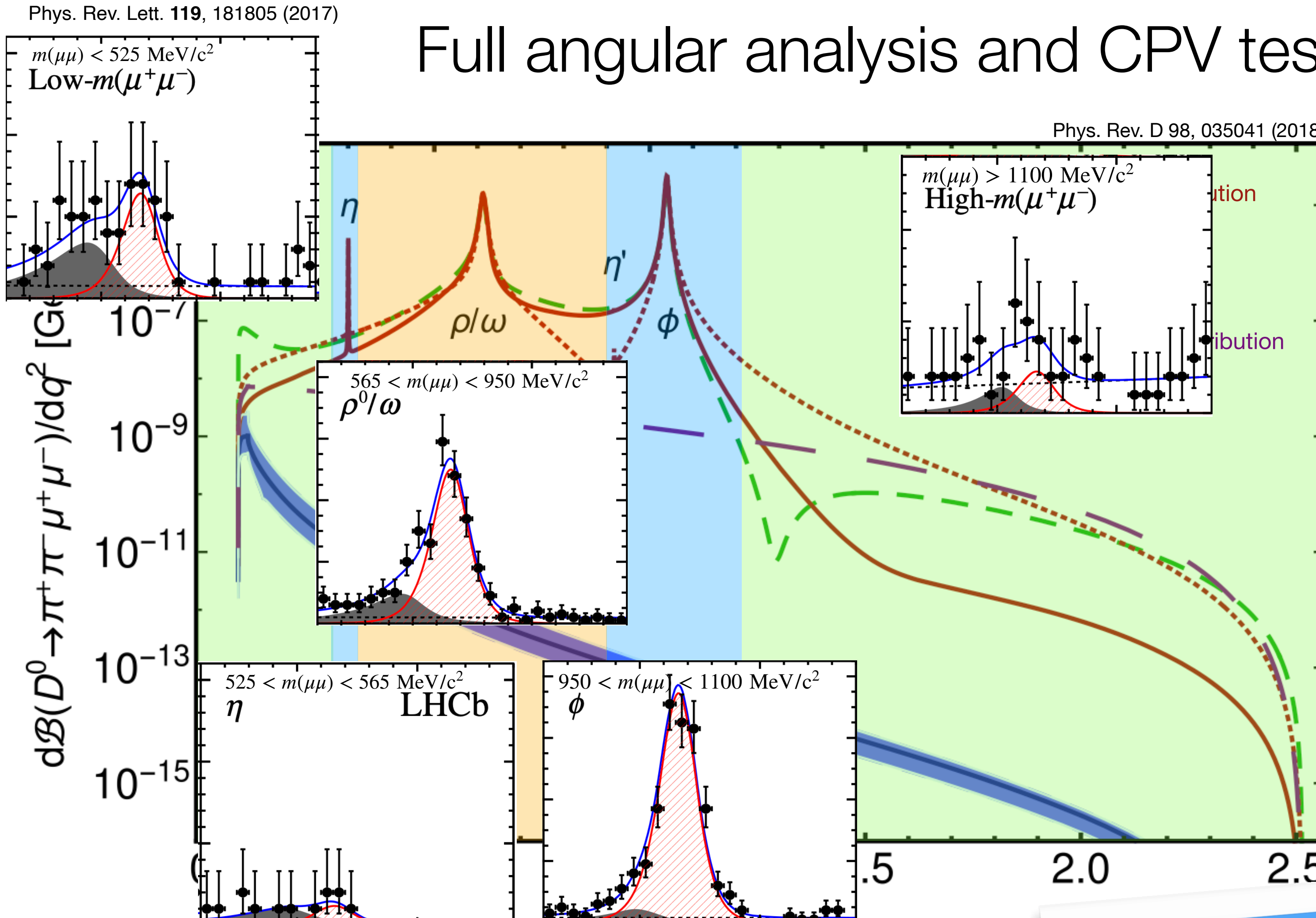


See also: Eleftheria Solomonidi

$D^+_{(s)} \to h^\pm \ell^+ \ell^{(\prime)\mp}$

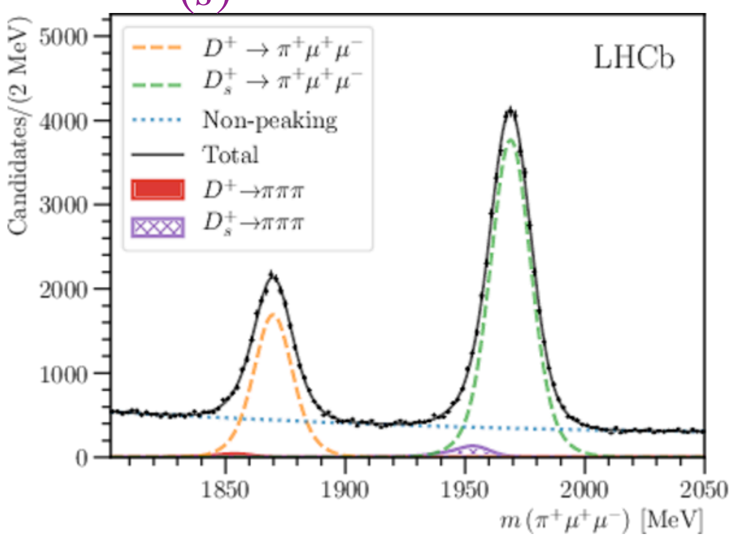
LHCb: JHEP 06 (2021) 044

Search for 25 rare ($h^+\ell^+\ell^-$) or forbidden ($h\mu e$, $h^-\ell^+\ell^+$) charm decays

e.g. $D^+_{(s)} \to \pi^+\mu^+\mu^-$

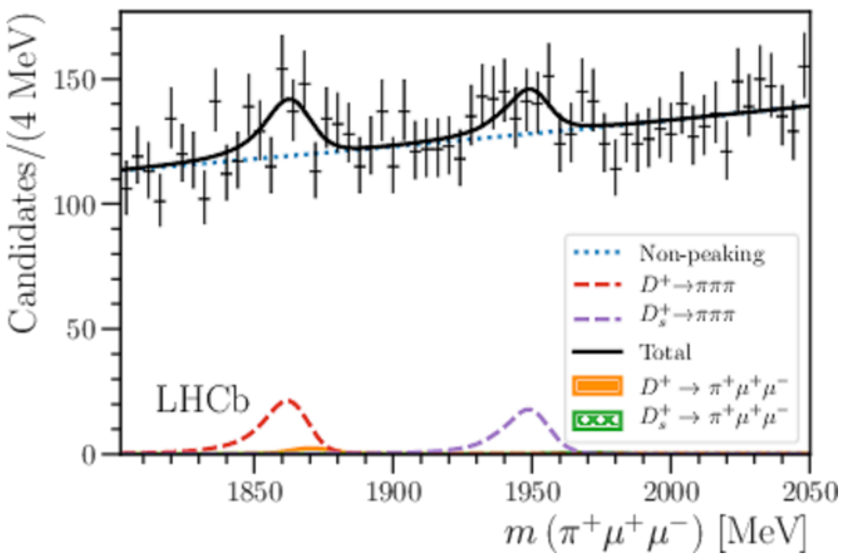
normalisation mode

$D^+_{(s)} \to \pi^+\phi(\mu^+\mu^-)$



signal region away from known di-muon resonance.

$D^+_{(s)} \to \pi^+(\mu^+\mu^-)_{\text{non-res}}$



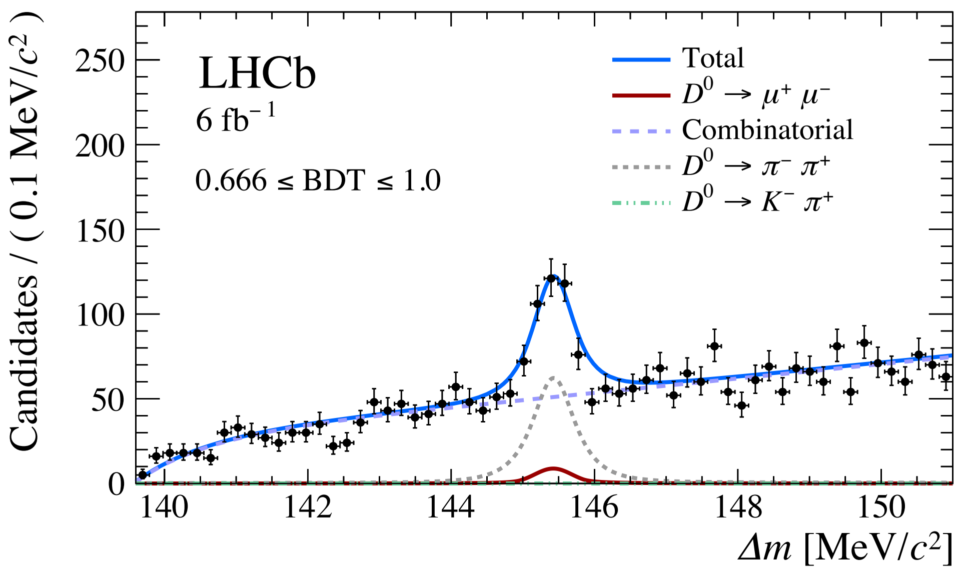
See none, but improve BF limits, typically by one or two orders of magnitude, to $10^{-8} - 6.4 \times 10^{-6}$ at 90% CL

Daniel Unverzagt

$D^0 \to \mu^+\mu^-$

LHCb: arXiv:2212.11203 (2022)

Most sensitive BDT bin, run II, there is also run I and other BDT bins*



SM: short-distance: $\mathcal{O}(10^{-18})$

SM: long-distance via $\gamma\gamma$:

$3 \times 10^{-13} - 2 \times 10^{-11}$

G. Burdman et al PRD 66 (2002) 014009
using BELLE's $D^0 \to \gamma\gamma$ limit PRD 93 (2016) 5, 051102

For comparison: $\mathscr{B}(B_s \to \mu\mu) = 2 \times 10^{-9}$

LHCb run I+II:
$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1 \times 10^{-9}$
Best limit today.

Also: $\mathscr{B}(D^*(2007)^0 \to \mu^+\mu^-) \leq 2.6 \times 10^{-8}$ (90 % CL) LHCb: arXiv:2304.01981 (2023)

*) data are analysed in bins of the boosted decision tree discriminating variable, the results of all bins are then combined. This shows, for illustration, the fit in the most sensitive BDT bin.

Daniel Unverzagt

$D^0 \to \mu^+\mu^-$

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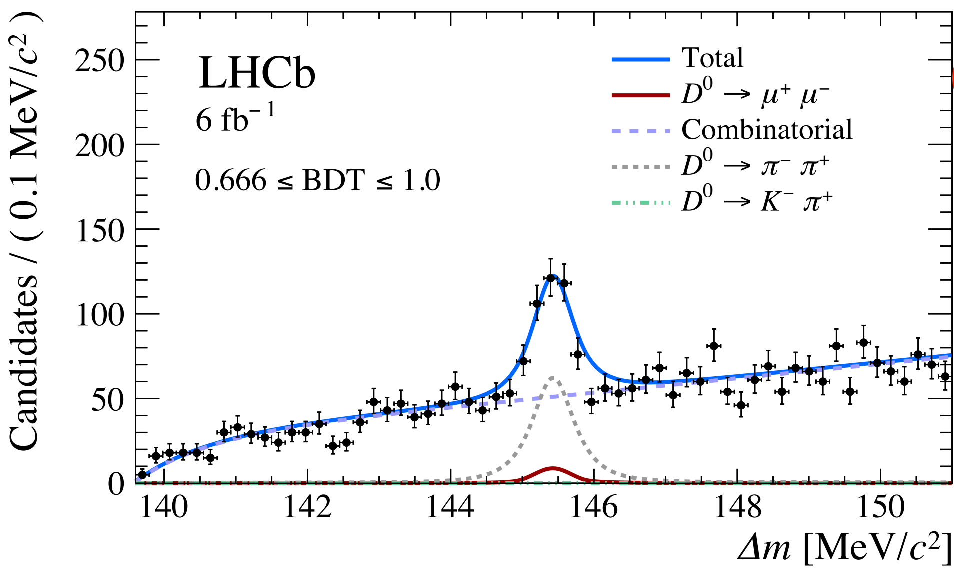

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G. Burdman et al PRD 66 (2002) 014009

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Constrained from data!

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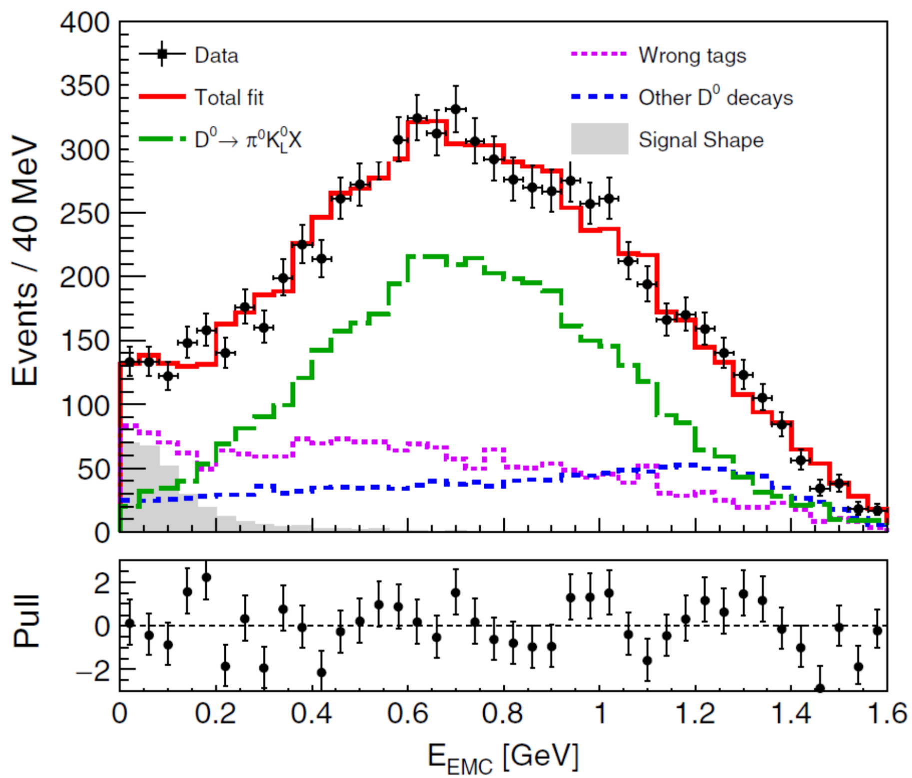
$D^0 \to \pi^0 \nu \bar{\nu}$

Dominik Suelmann

Dr Shulei Zhang

BESIII: PRD 105 (2022) 7, L071102

No long-distance effects in $\nu\bar{\nu}$ system!



$$\mathrm{BR}\left(D^0 \to \pi^0 \nu \bar{\nu}\right) < 2.1 \times 10^{-4}$$

Making connections

Svjetlana Fajfer

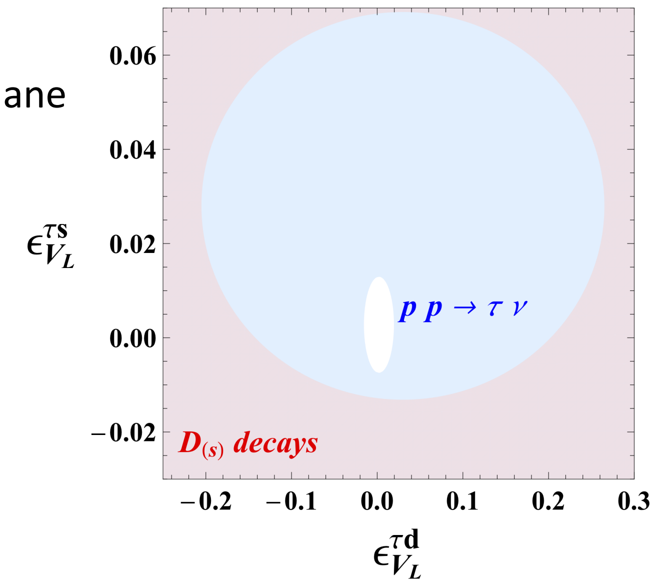
SMEFT to relate NP searches in rare charm and strange decays.

Arman Korajac

Faijer, Korajac et al JHEP 07 (2023) 029

SMEFT also relates flavour and high p_T

Exclusion limits at 95% CL on c → d(s)e⁻ ν transitions in (ε_{VL} , ε_{VL}) plane
pink region → excluded by D(s) meson decays
blue region → excluded by high-pT LHC



Geljo et al arXiv:2002.12421

Future experiments

Guy Wilkinson

Yangheng Zheng

Giulia Tuci

(approved experiments) (proposed experiments)

2020s	2030s	2040s	2070s
LHCb Upgrade I	LHCb Upgrade II		
Belle II	Belle II+ ?	FCC-ee ….	FCC-hh
BESIII	STCF	CEPC ….	SPPC

Summary of the summary

- Spectacular experimental progress - CPV, mixing, rare, decays, a new world of spectroscopy, …

- QCD remains our foe (interpretation of mixing, CPV, rare decays) and friend (it's the reason our field is as rich as it is).

- Hadronic charm calculations are hard. Lots of open questions. But our tools to are getting better!
  Good enough to predict $|q/p|, \phi_D$?

- Lots of high quality data coming our way: LHCb UG I, BELLE II, BES III (+ possible upgrade), LHCb UG II, STCF, CEPC, FCC-ee/hh)

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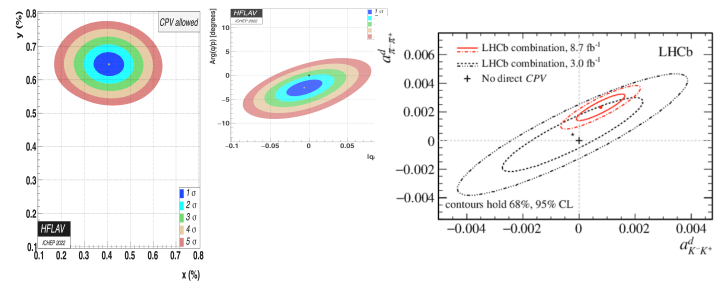

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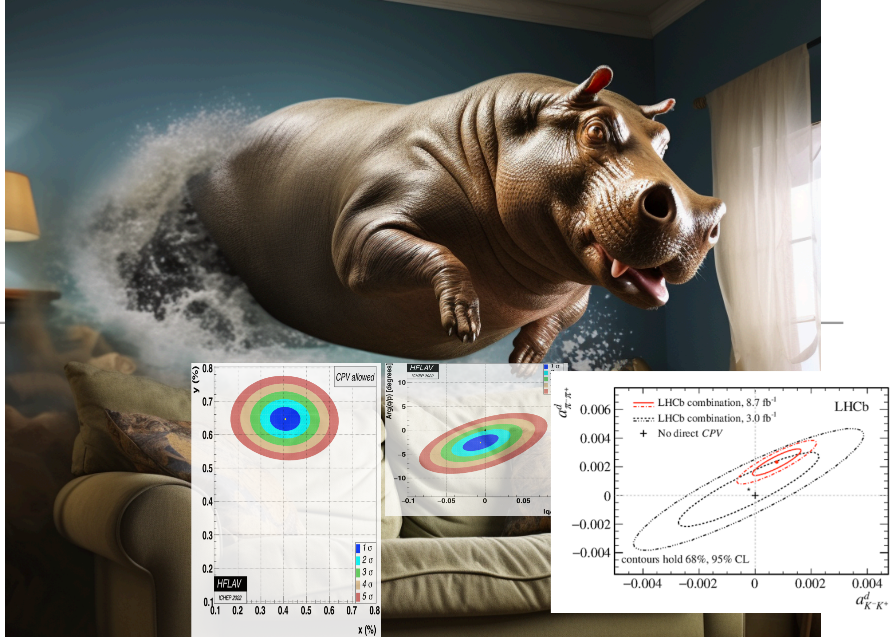

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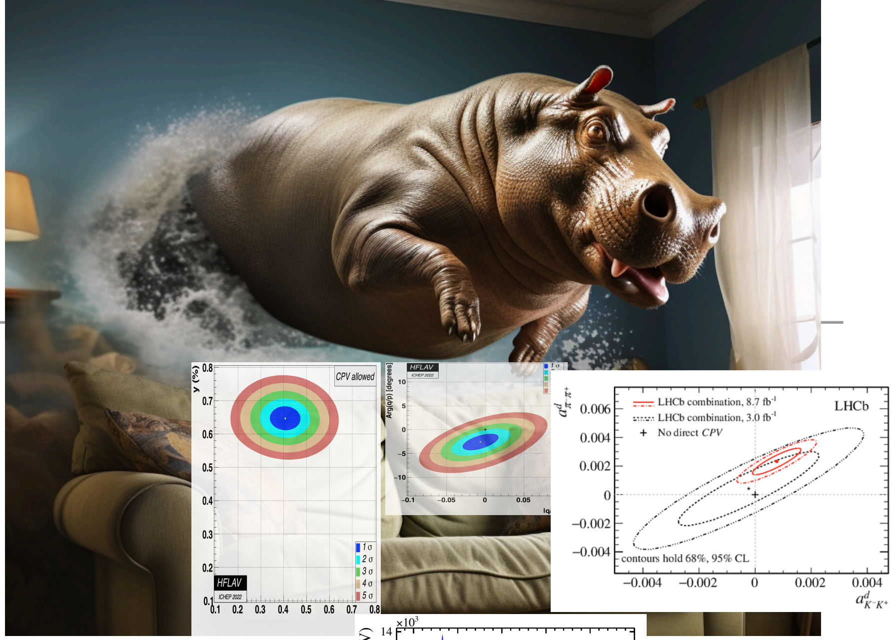

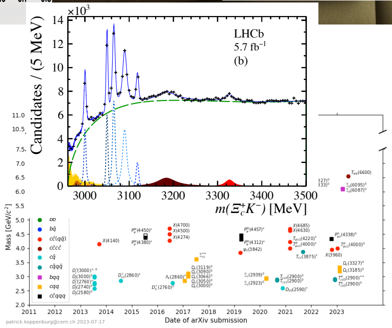

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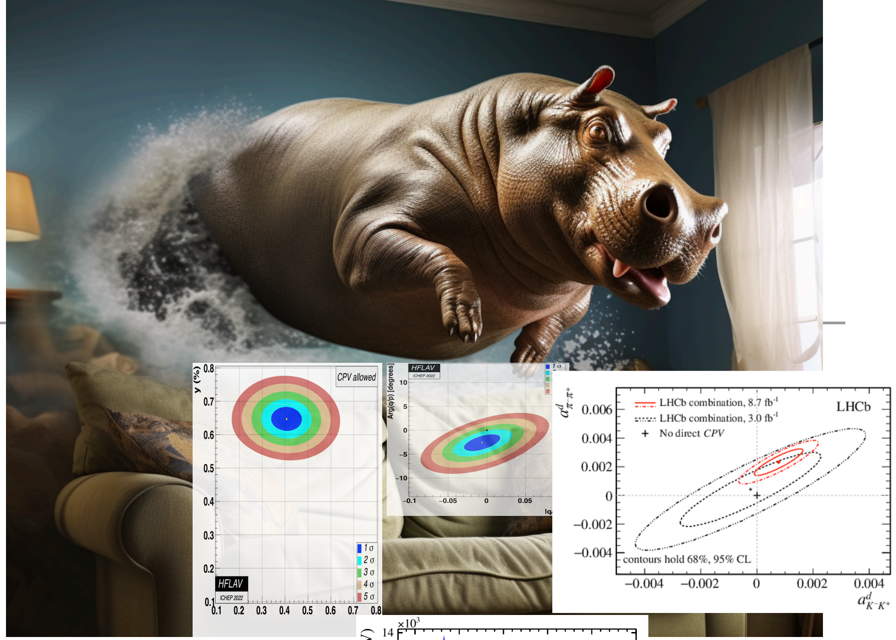
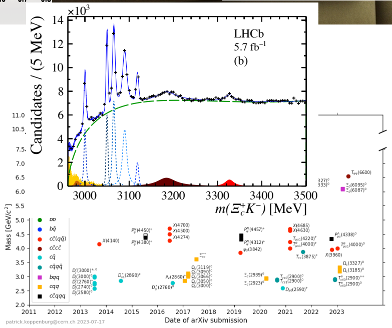
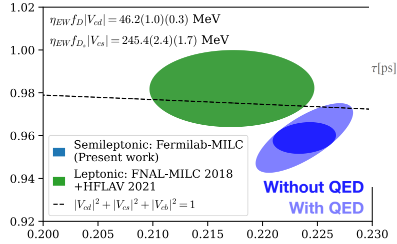
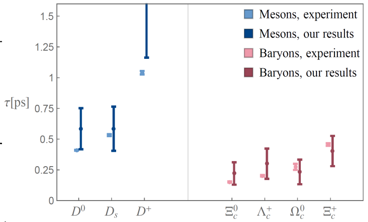








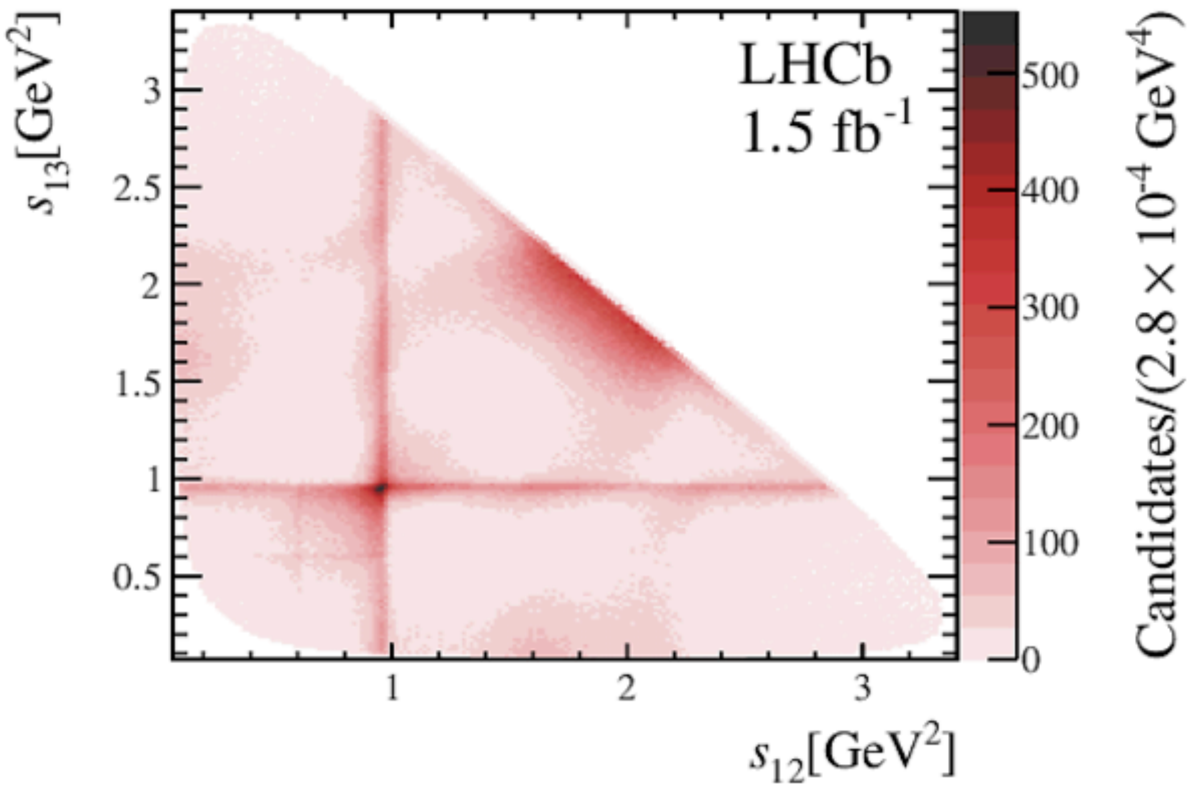
Amplitude Analyses

Bai-Cian Ke

Han Gao

Bachir Moussallam

LHCb: arXiv:2209.09840 (2022)



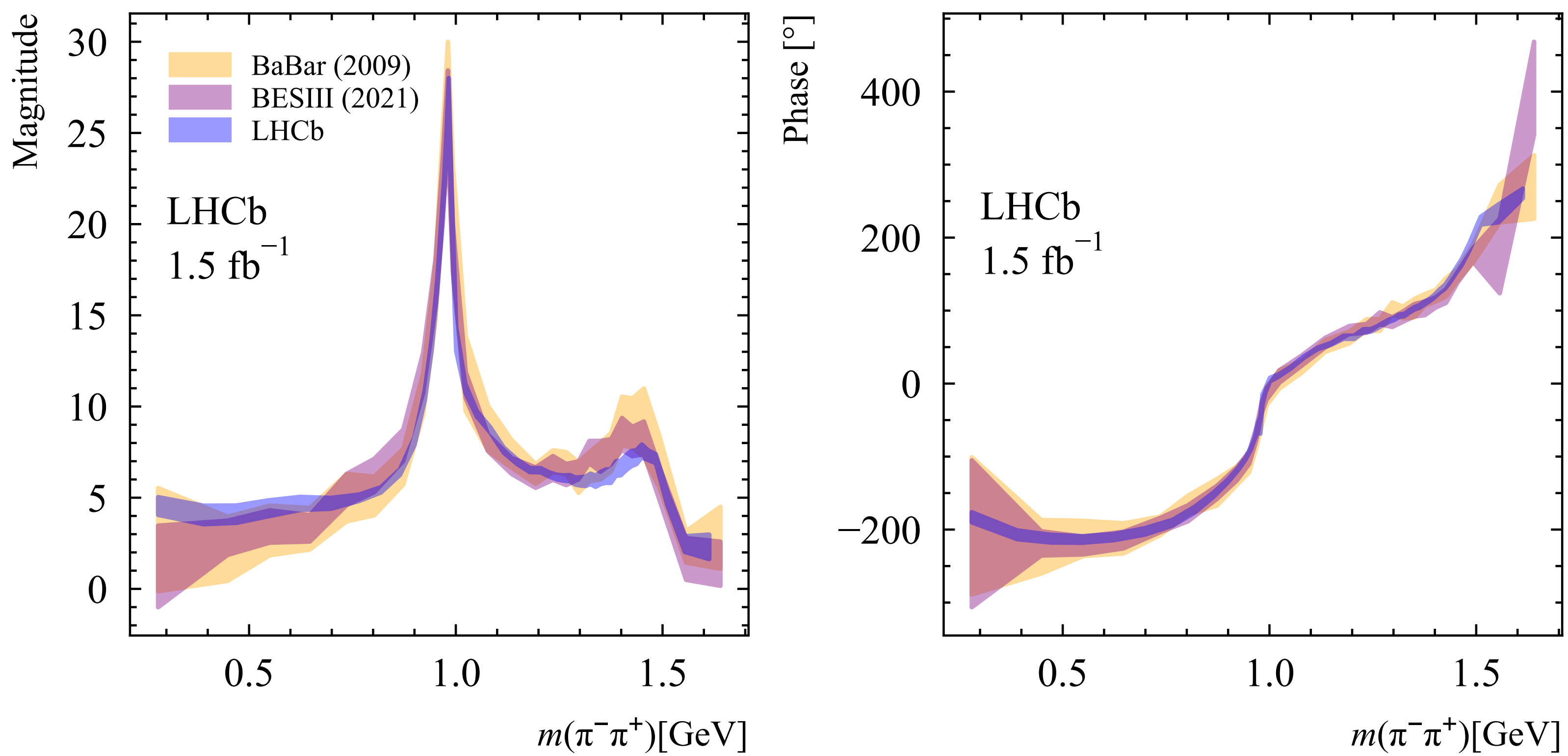
$D_s \to \pi^+\pi^-\pi^+$

LHCb: arXiv:2209.09840 (2022)

BESIII: PRD 106 (2022) 11, 112006.

BaBar: PRD 79 (2009) 032003.

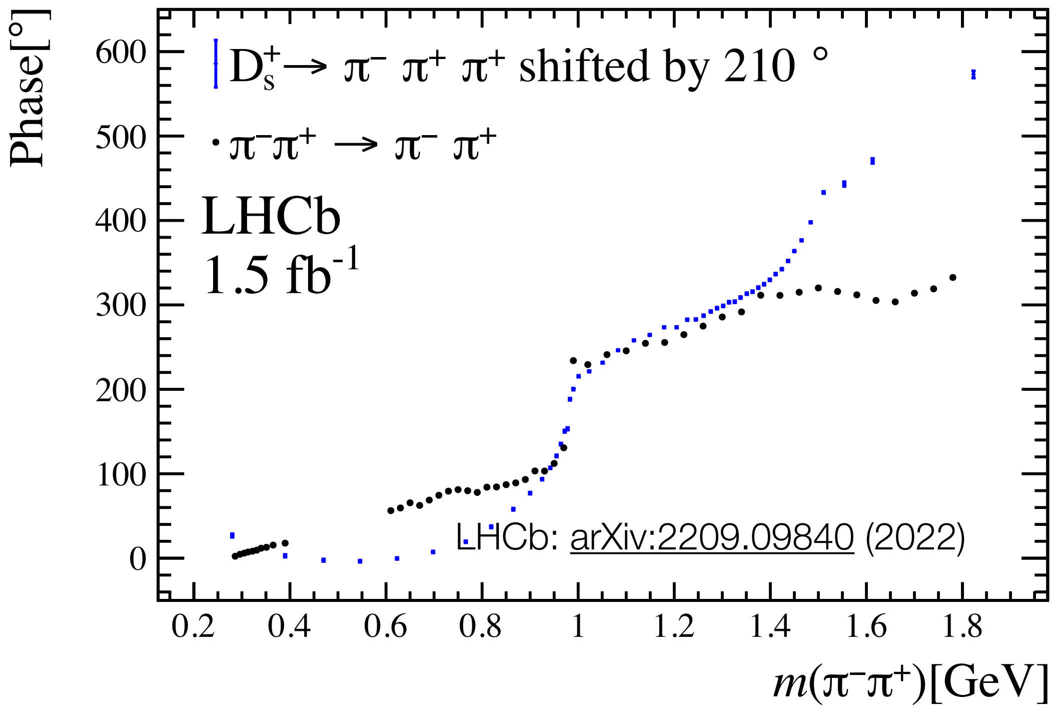
Model-independent* $\pi^+\pi^-$ S-wave in $D_s \to \pi^+\pi^-\pi^+$



*) divide $m(\pi^+\pi^-)$ into bins, fit magnitude and phase independently in each bin.

$D_s, D^+ \to \pi^+\pi^-\pi^+$ and scattering data

Comparing $\pi^+\pi^-$ S-wave in $D_s, D^+ \to \pi^+\pi^-\pi^+$ with that obtained from scattering data.



LHCb: arXiv:2209.09840 (2022)

LHCb: JHEP 06 (2023) 044

Scattering data: CERN-Munich experiment, Nucl. Phys. B64 (1973) 134, and re-analysis of those data by J Ochs, J. Phys. G: Nucl. Part. Phys. 40 043001. Below 0.4GeV from NA48/2: Eur. Phys. J. C70 (2010) 635.

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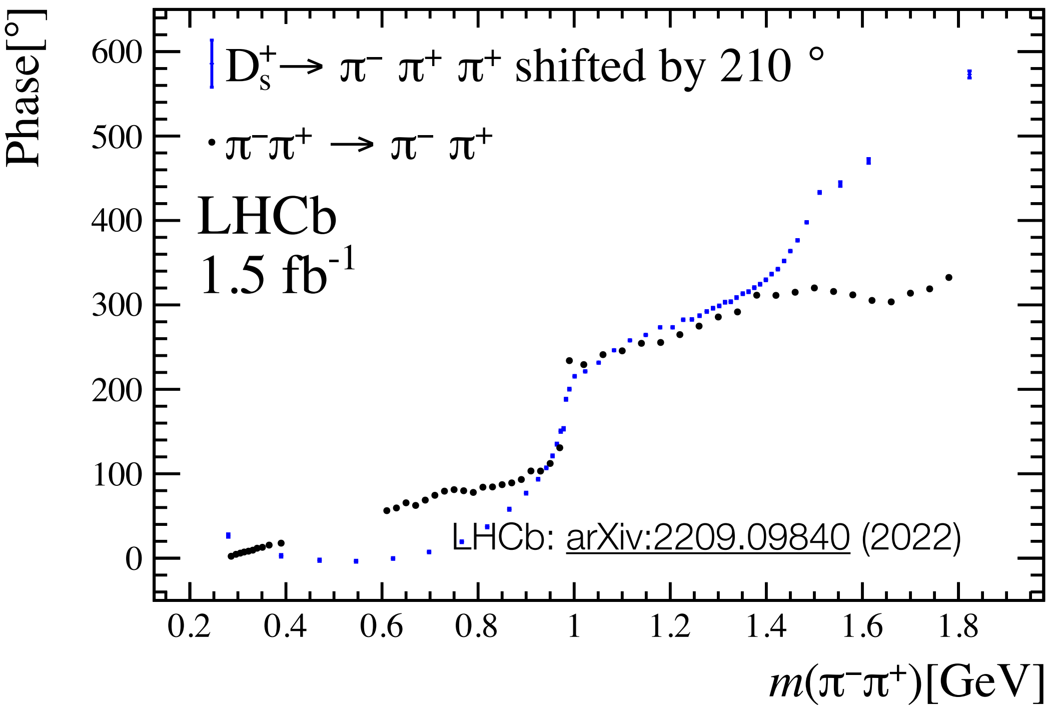

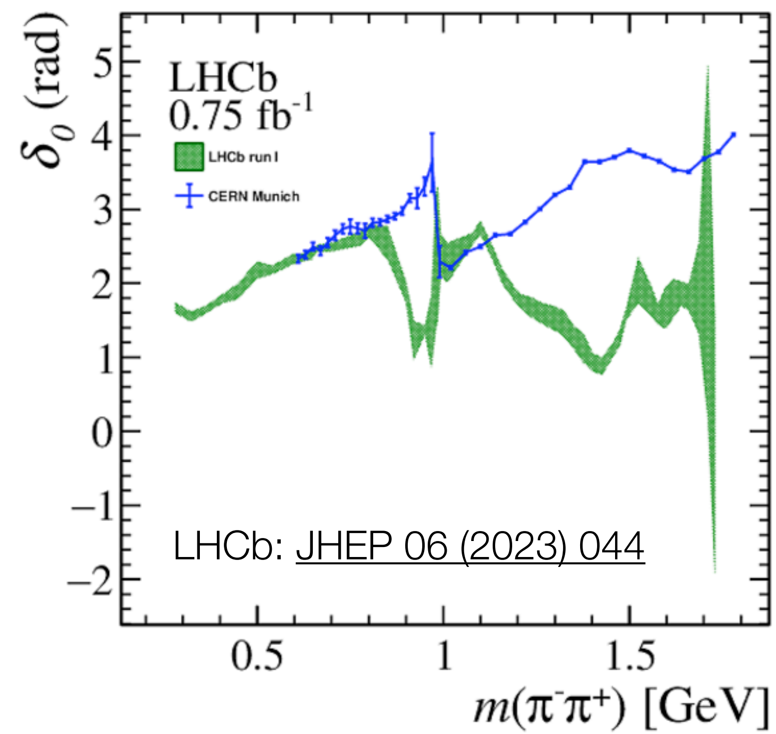

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Recent-ish ≥4-body amplitude analyses

$D^+ \to K_S\pi^+\pi^0\pi^0$ BESIII: arXiv:2305.15879 (2023)

$D_s^+ \to K^+\pi^+\pi^-\pi^0$ BESIII: JHEP 09 (2022) 242

$D_s^+ \to K^+K^-\pi^+\pi^+\pi^-$ BESIII: JHEP 07 (2022) 051

$D_s^+ \to K^+K^-\pi^+\pi^0$ BESIII: PRD 104 (2021) 3, 032011

$D_s^+ \to K_SK^-\pi^+\pi^+$ BESIII: PRD 103 (2021) 9, 092006

$D^+ \to K_S\pi^+\pi^+\pi^-$ BESIII: PRD 100 (2019) 7, 072008

$D^0 \to K^+K^-\pi^+\pi^-$ LHCb: JHEP 02 (2019) 126

$D^0, \overline{D}^0 \to K^+\pi^-\pi^+\pi^-$ LHCb: Eur. Phys. J. C78 (2018) 443

$D^0 \to K^+\pi^-\pi^+\pi^-$ BESIII: PRD 95 (2017) 7, 072010

$D^0 \to K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, CLEO-c data: JHEP 05 (2017)

(4-body analyses are not more important than 3-body ones - we need both. But they are hard, and it's interesting to see this level of activity.)

D^0 modes important for mixing and γ

Recent-ish $\geq$4-body amplitude analyses

$D^+ \to K_S \pi^+ \pi^0 \pi^0$ BESIII: arXiv:2305.15879 (2023)

$D_s^+ \to K^+ \pi^+ \pi^- \pi^0$ BESIII: JHEP 09 (2022) 242

$D_s^+ \to K^+ K^- \pi^+ \pi^+ \pi^-$ BESIII: JHEP 07 (2022) 051

$D_s^+ \to K^+ K^- \pi^+ \pi^0$ BESIII: PRD 104 (2021) 3, 032011

$D_s^+ \to K_S K^- \pi^+ \pi^+$ BESIII: PRD 103 (2021) 9, 092006

$D^+ \to K_S \pi^+ \pi^+ \pi^-$ BESIII: PRD 100 (2019) 7, 072008

$D^0 \to K^+ K^- \pi^+ \pi^-$ LHCb: JHEP 02 (2019) 126

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$D^0 \to K^+ \pi^- \pi^+ \pi^-$ BESIII: PRD 95 (2017) 7, 072010

$D^0 \to K^+ K^- \pi^+ \pi^-$, $\pi^+ \pi^- \pi^+ \pi^-$, CLEO-c data: JHEP 05 (2017)

(4-body analyses are not more important than 3-body ones - we need both. But they are hard, and it's interesting to see this level of activity.)

D^0 modes important for mixing and γ

gripping

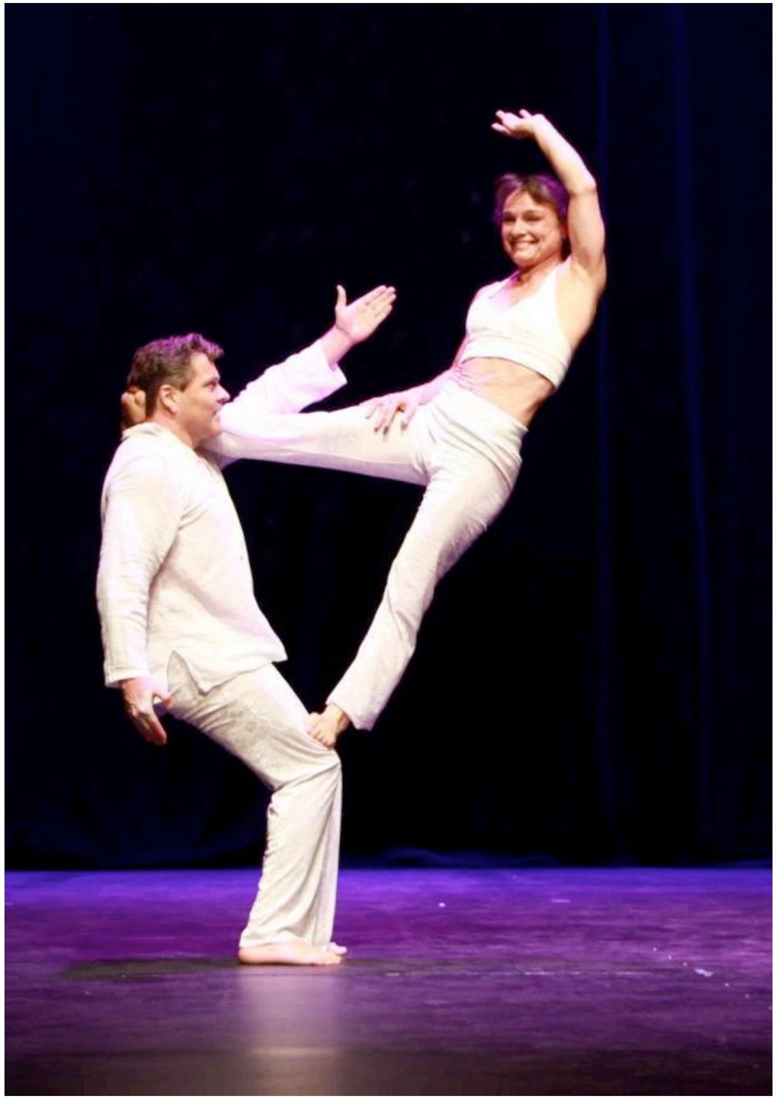
massive

well-catered

well-attended

well-attended

occasionally mind-bending



constructive


CHARM SIEGEN
CHARM SIEGEN

and also for sparing us this

Siegerländer Krüstchen

The end

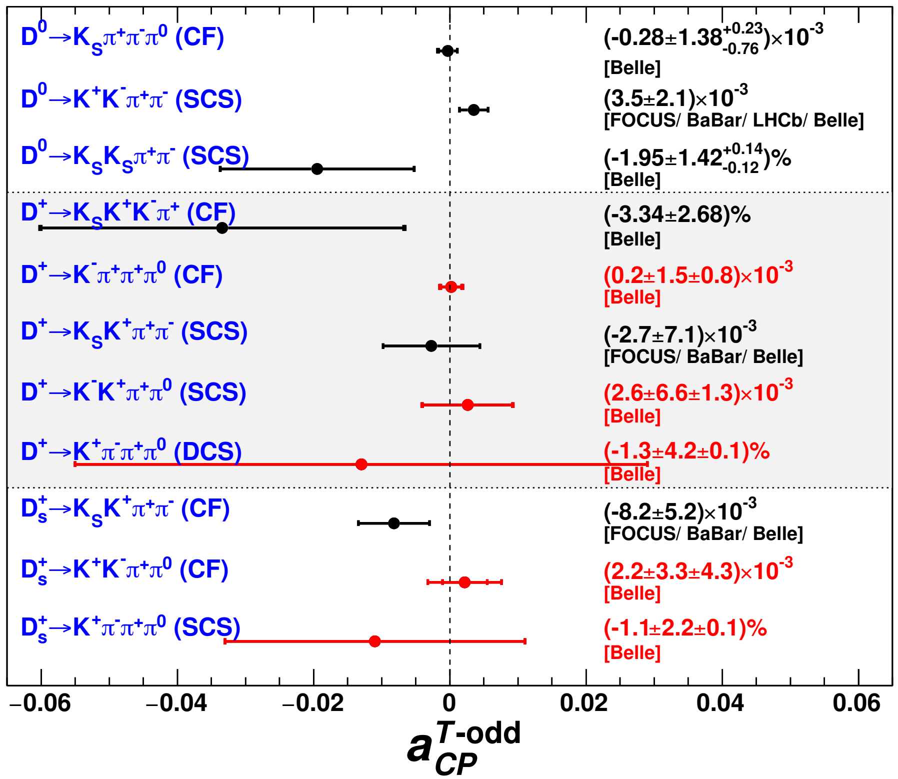
4-body CPV, P-odd moments

$$D^+_{(s)} \to K^+K^-\pi^+\pi^0,$$
$$D^+_{(s)} \to K^+\pi^-\pi^+\pi^0,$$
$$D^+ \to K^-\pi^+\pi^+\pi^0$$

BELLE: arXiv:2305.12806 (2023)

$$D^+_{(s)} \to K^+K_S\pi^+\pi^-,$$
$$D^+_{(s)} \to K^+K_SK^+K^-,$$
$$D^+_{(s)} \to K^+K^-K_S\pi^+$$

BELLE: arXiv:2305.11405 (2023)



Note that recent analyses usually improve sensitivity by applying a phase-spaced-resolved approach - either in bins, unbinned (as in PLB769 (2017) 345-356,), P and CP-odd kinematic variables.

But what does it all mean?

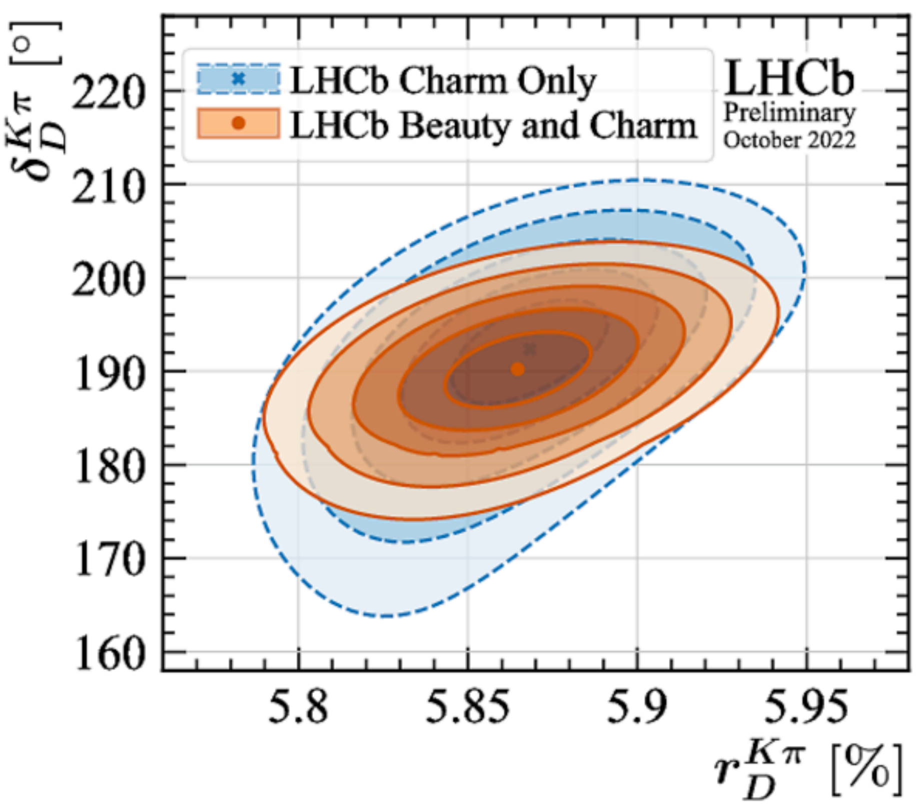
Felix Erben

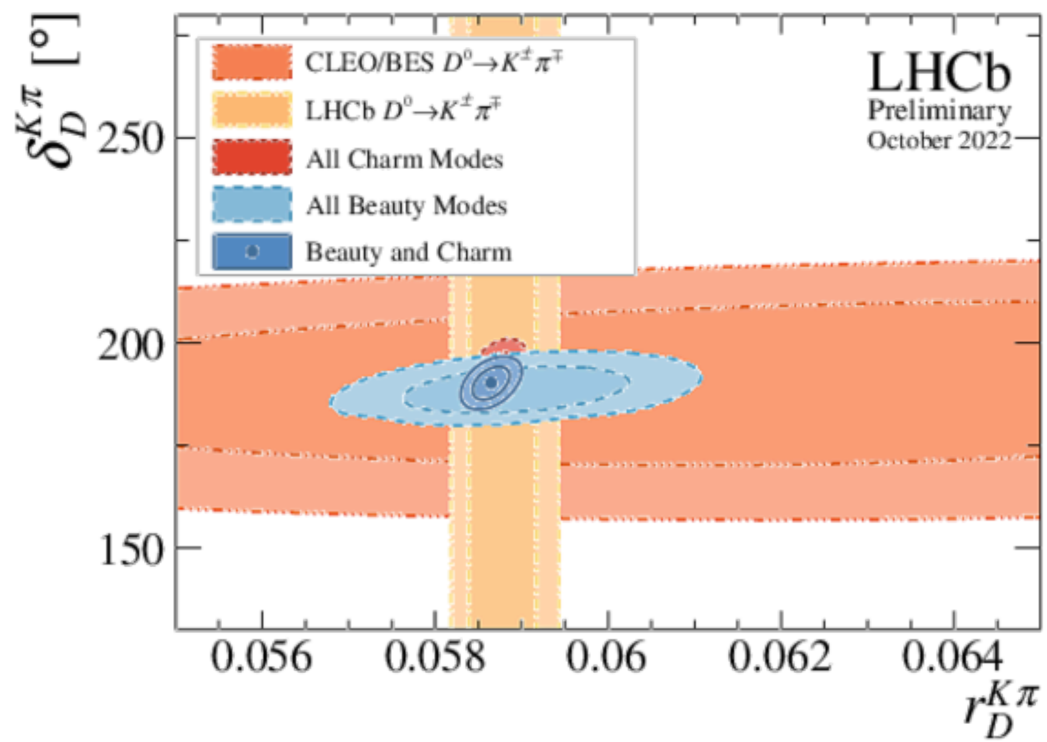
- D-mixing $\Delta C = 2$ bag parameters with fully relativistic c-quark action
- data for full 5-operator basis available
- 15 ensembles, 6 lattice spacings from 2 collaborations, including two ensembles at M_π^{phys}
- programme extends to $B_{(s)}$-mixing and K-mixing:
  - simple renormalisation for chiral Domain-Wall Fermions
  - fully relativistic treatment of heavy-quark
  - very fine lattice spacings
  - large variety of ensembles to control relevant limits
- Long-distance contribution $D - \bar{D}$ mixing very relevant
  - formalism to compute them conceptually clear but very challenging
  - *Max Hansen: Fri 21/7 14:00 Future Theory*

$D \to K\pi$ DCS/CF amplitude ratio in γ combination

$$\frac{A(D^0 \to K^+\pi^-)}{A(\overline{D}^0 \to K^+\pi^-)} = r_D \exp(i\delta_D^{K\pi})$$

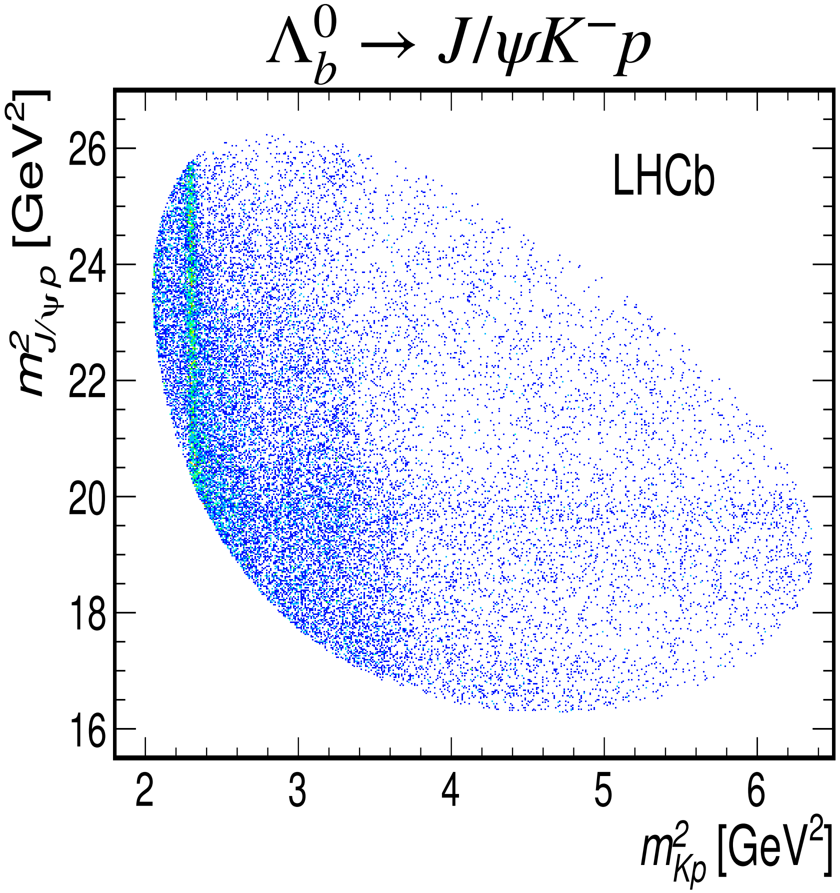
LHCb-CONF-2022-003
& JHEP 12 (2021) 141

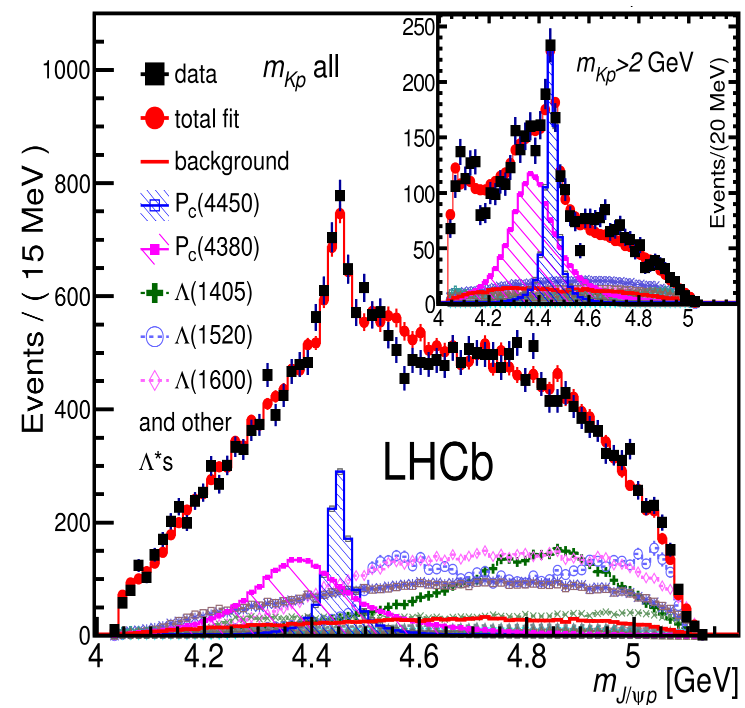




Pentaquarks 2016

LHCb: PRL 115 (2015) 072001

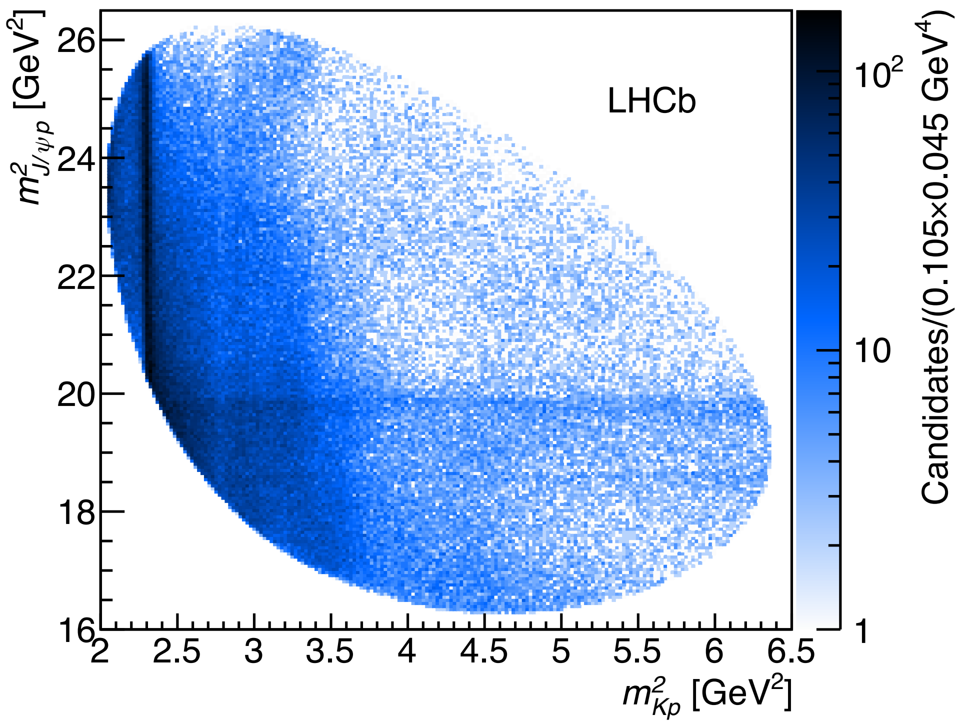


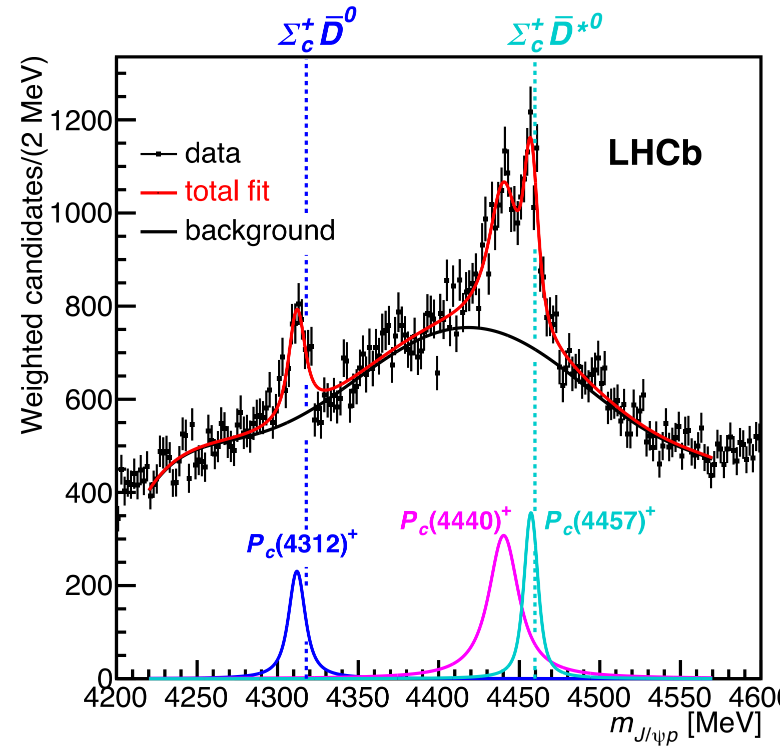


Pentaquarks 2020

$$\Lambda_b^0 \to J/\psi K^- p$$

LHCb: PRL 122 (2019) 22, 222001





9×stats

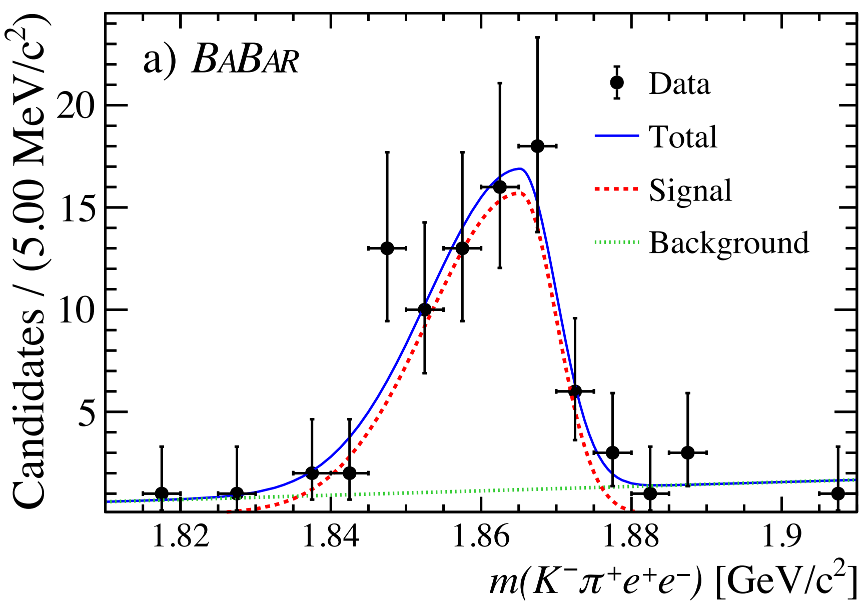
State	M [MeV]	Γ [MeV] (95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$ (< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$ (< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$ (< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

$D^0 \to K^-\pi^+e^+e^-$

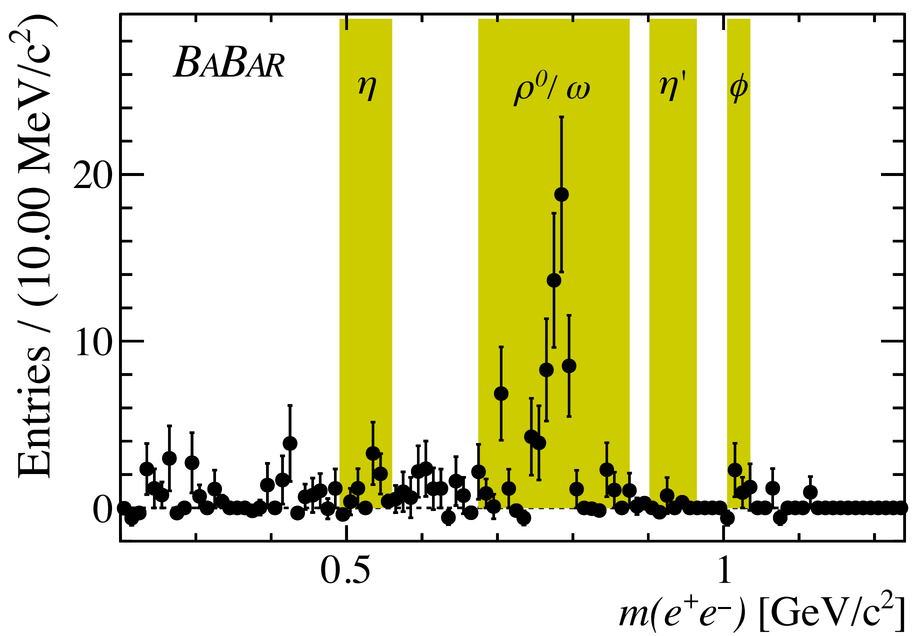
BaBar: PRL 122 (2019) 8, 081802

$c \to u\ell^+\ell^-$ FCNC, analogous to $b \to s\ell^+\ell^-$ but more suppressed (GIM works better in charm). Long distance contribution enhance BF $\mathcal{O}(10^{-9}) \to \mathcal{O}(10^{-6})$

$\mathscr{B}_{\text{total}} = (4.0 \pm 0.55) \times 10^{-6}$



$\mathscr{B}_{\text{non-res}} = < 3.1 \times 10^{-6}$

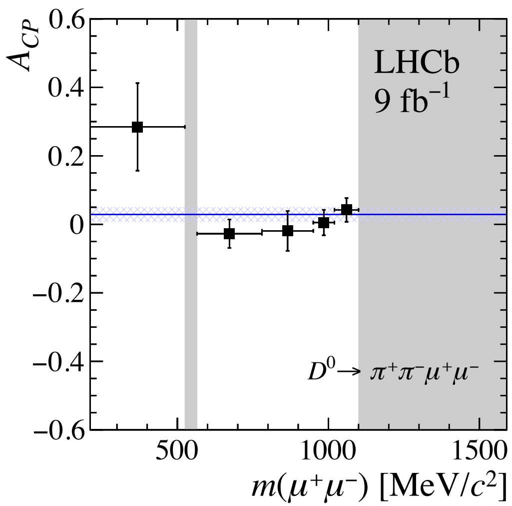


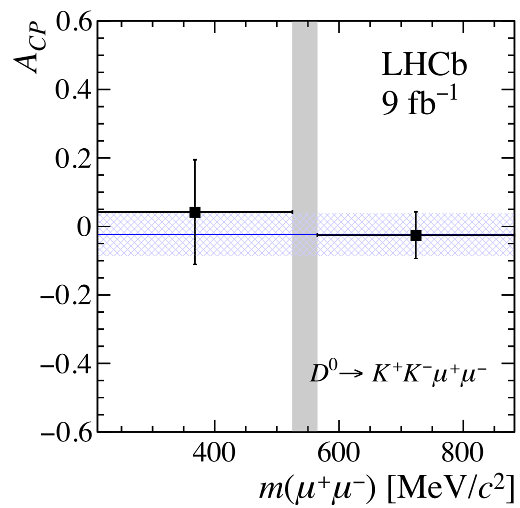
… all from $D \to K^-\pi^+$ hadron, hadron $\to e^+e^-$

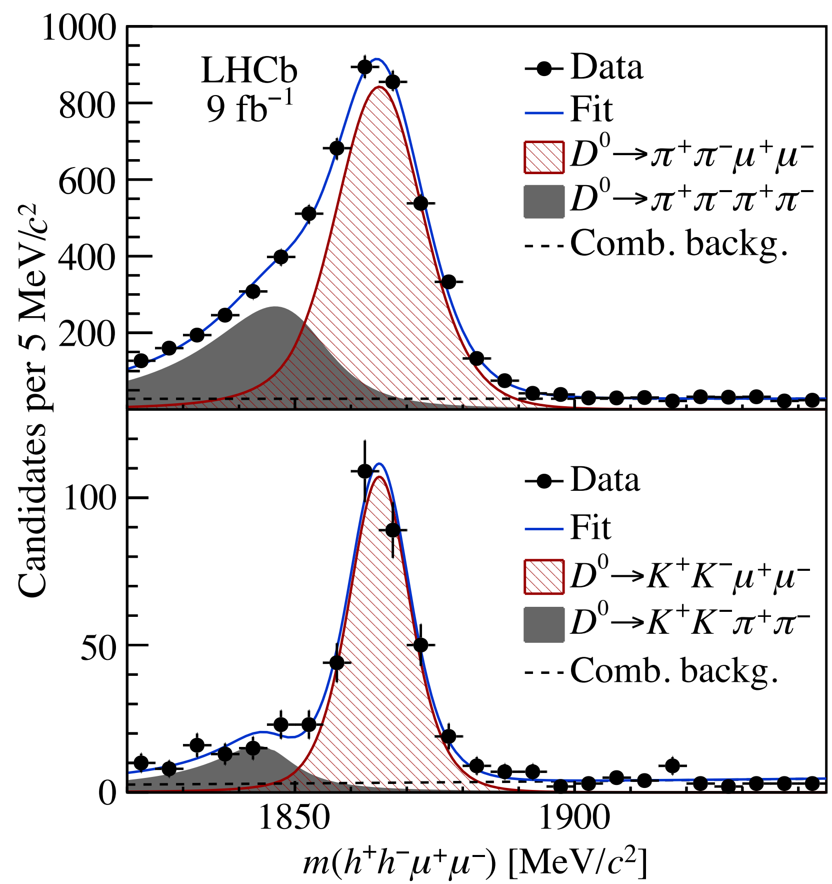
$D^0 \to \pi^+\pi^-\mu^+\mu^-, D^0 \to K^+K^-\mu^+\mu^-$

LHCb: PRL 128 (2022) 22, 221801

Full angular analysis.
Here, for illustration, show only
A_{CP} as fct of $m(\mu\mu)$



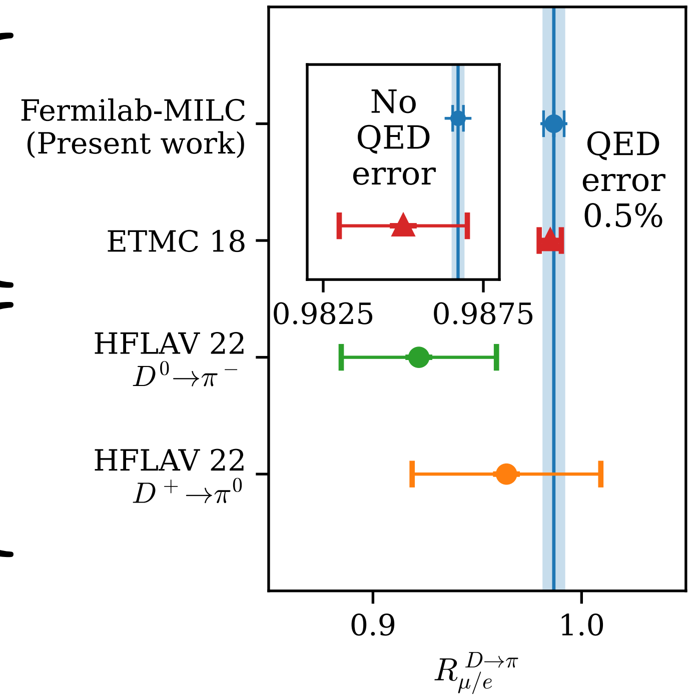




$$R^{\pi}_{e\mu} := \frac{\mathrm{BF}(D^0 \to \pi^-\mu^+\nu_\mu)}{\mathrm{BF}(D^0 \to \pi^-e^+\nu_e)} = \frac{\mathrm{BF}(D^+ \to \pi^0\mu^+\nu_\mu)}{\mathrm{BF}(D^+ \to \pi^0e^+\nu_e)}$$

LQCD

Experiment



Experiment dominated by BES III:

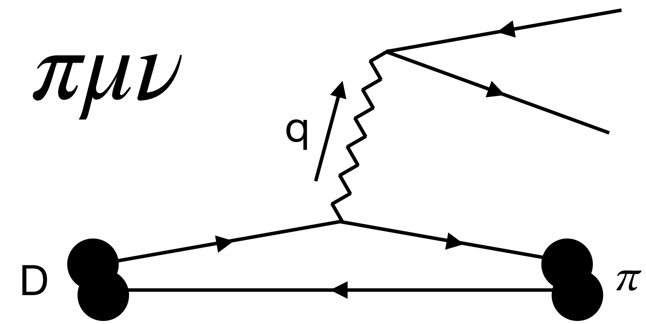
$$R^{\pi}_{\mu e} = 0.964 \pm 0.037 \pm 0.026$$

Lattice (semileptonic)

William Jay

Semileptonic decays: $D \to \pi\mu\nu$

Theoretical preliminaries



$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 \eta_{EW}^2}{24\pi^3} |V_{cd}|^2 (1-\epsilon)^2 (1+\delta_{\mathrm{EM}}) \times$$

$$\left[|\mathbf{p}|^3 \left(1+\frac{\epsilon}{2}\right) |f_+(q^2)|^2 + |\mathbf{p}|\, M_D^2 \left(1-\frac{M_\pi^2}{M_D^2}\right)^2 \frac{3\epsilon}{8} |f_0(q^2)|^2 \right]$$

$$\epsilon = m_\mu^2/q^2 \ll 1$$

: measured decay rate

: (non-perturbative) hadronic form factors

: kinematic factors

: perturbative corrections

At O(1%) precision, all sectors of SM become important: QCD, QED, EW

Blind analysis.

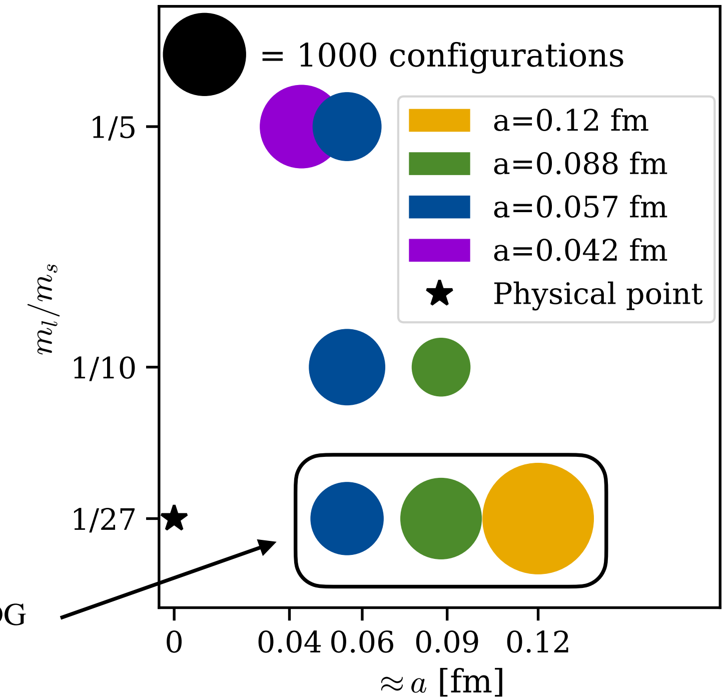
D-meson Semileptonic Decays

Fermilab-MILC [WJ]
PRD 107 (2023) 9, 094516
arXiv:2212.12648

$D_{(s)} \to K/\pi \ell \nu$ and |V$_{cd}$|, |V$_{cs}$|

- (N_f=2+1+1) MILC HISQ ensembles
- Lattice spacings: [0.045 - 0.12] fm
- Valence: heavy HISQ
- Percent-level determinations of |V$_{cd}$|, |V$_{cs}$|
  - Consistent with |V$_{cs}$| from HPQCD 2021
- First-ever |V$_{cd}$| from $D_s \to K \ell \nu$ when combined with recent first measurements from BESIII
- First time that LQCD and experimental errors are commensurate for $D \to \pi \ell \nu$
- All results from a **blinded analysis**

$M_\pi \simeq M_\pi^{\mathrm{PDG}}$

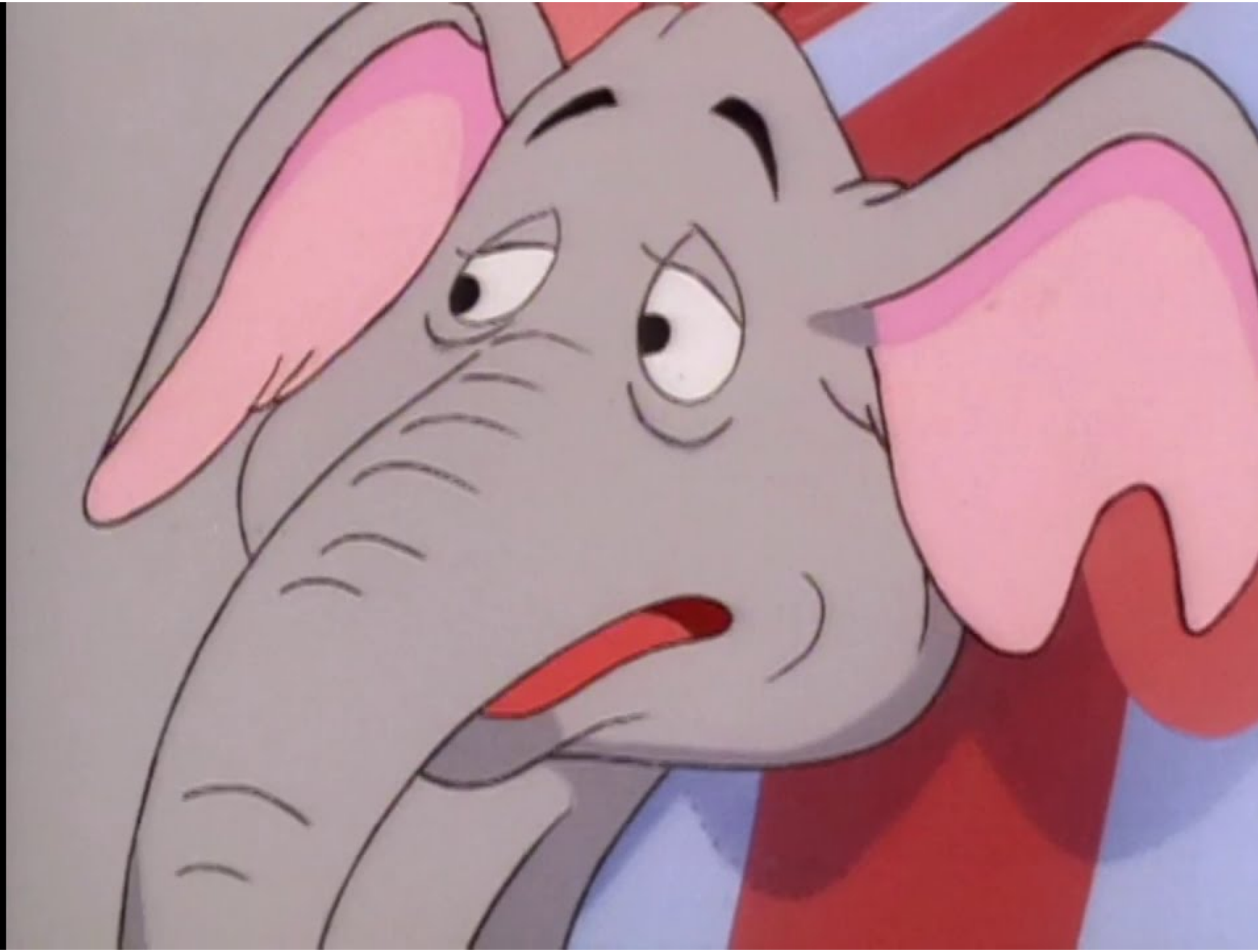


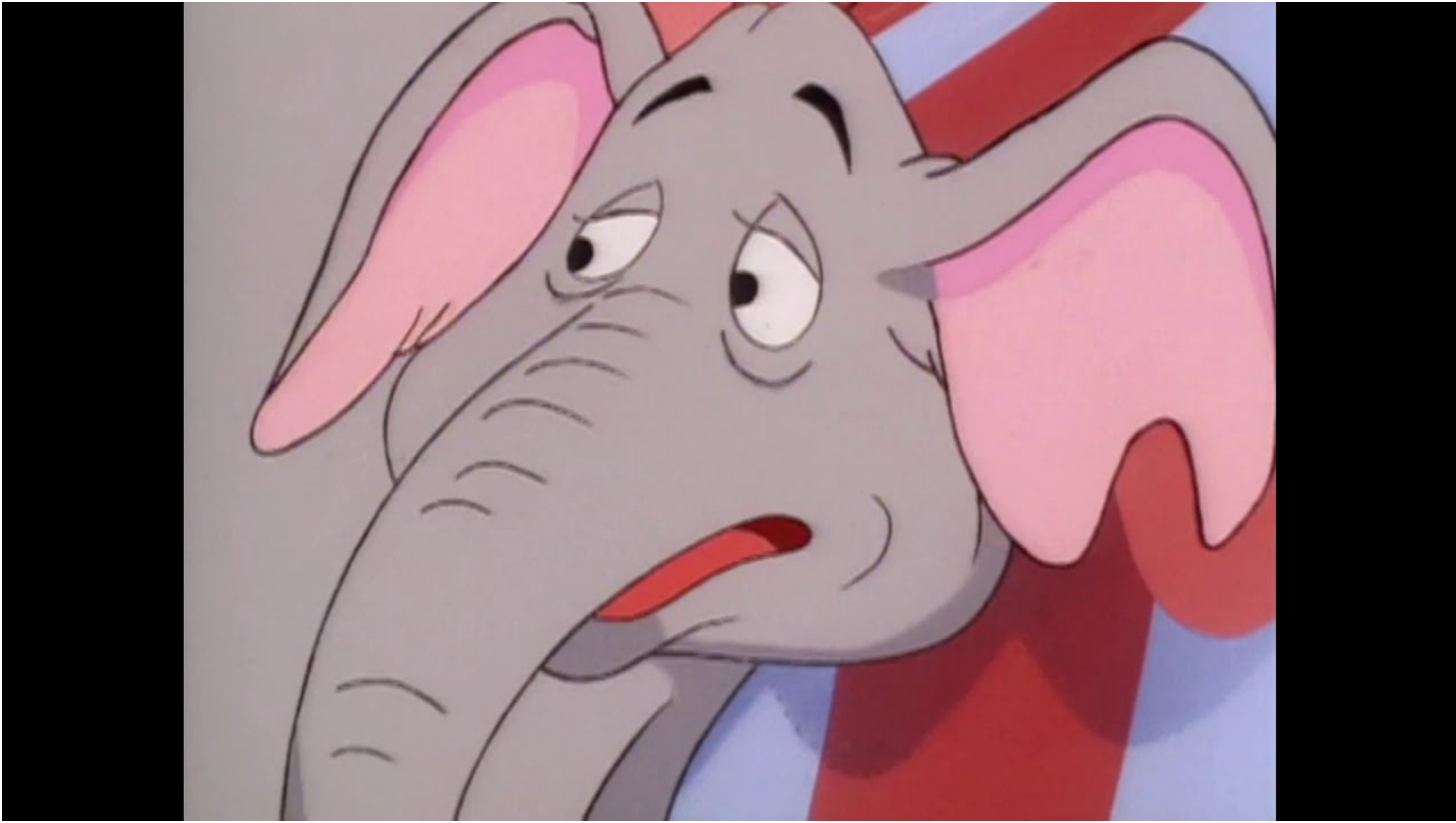
$$|V_{cd}|^{D\to\pi} = 0.2338(11)^{\mathrm{Expt}}(15)^{\mathrm{LQCD}}[22]^{\mathrm{EW/QED/SIB}}$$

$$|V_{cs}|^{D\to K} = 0.9589(23)^{\mathrm{Expt}}(40)^{\mathrm{LQCD}}[96]^{\mathrm{EW/QED/SIB}}$$

Measure: Expt.

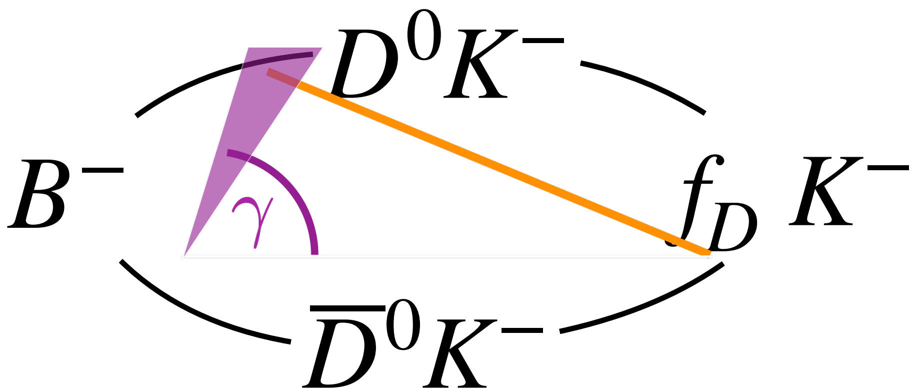
Calculate: LQCD



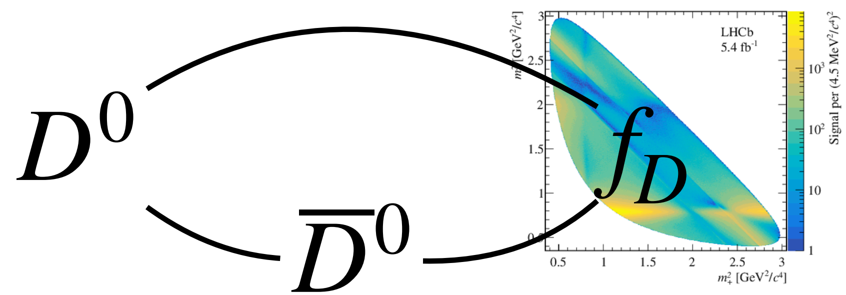


Intrinsic Charm

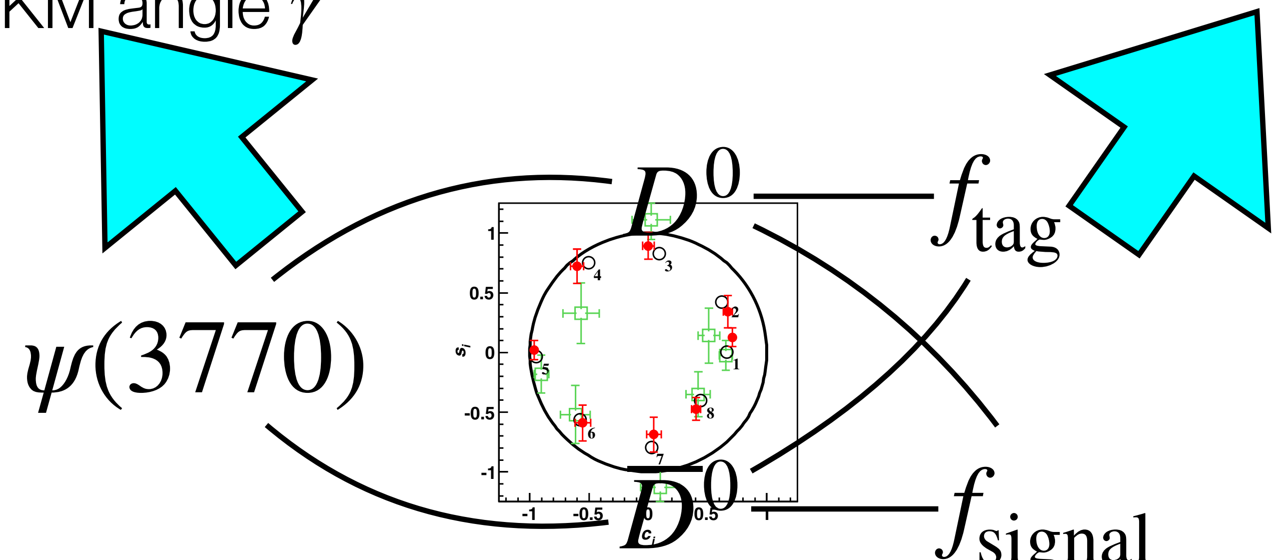
Input from charm threshold to mixing and γ.



measures CKM angle γ

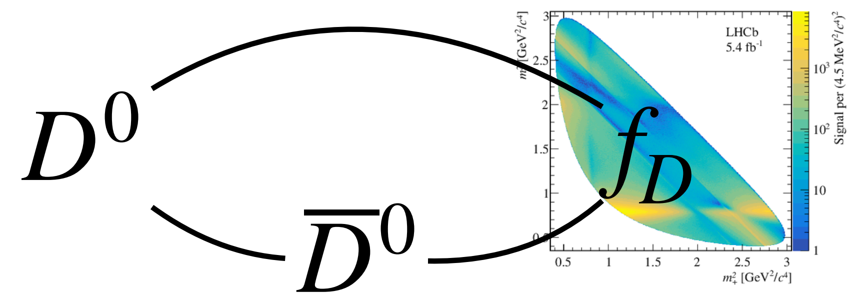


measures charm mixing and CPV

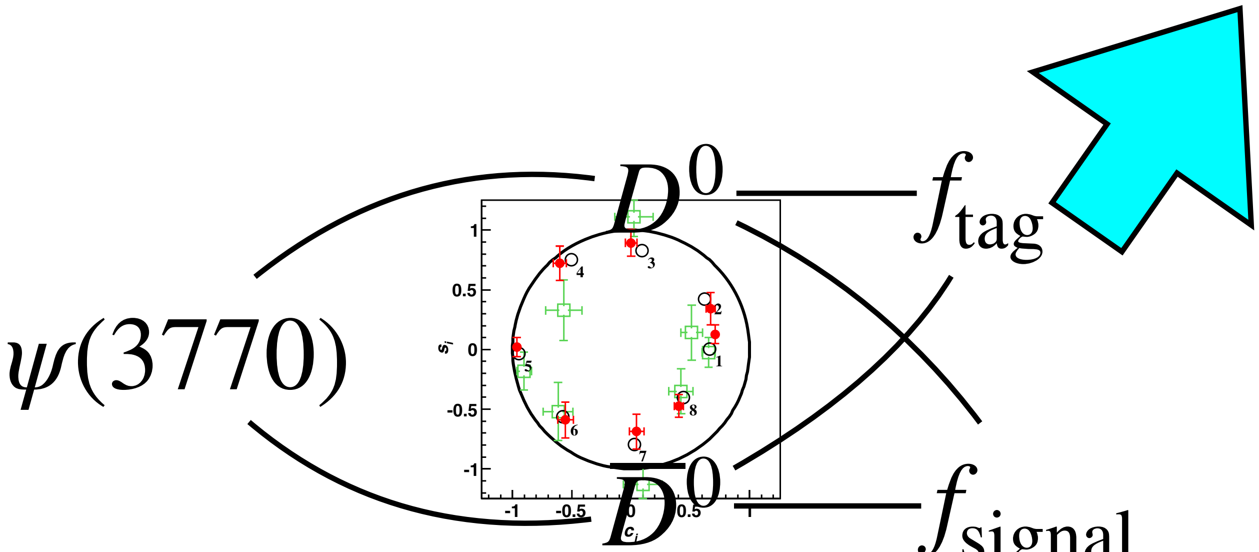


measures charm interference, especially strong phases

Input from charm threshold



measures charm mixing and CPV

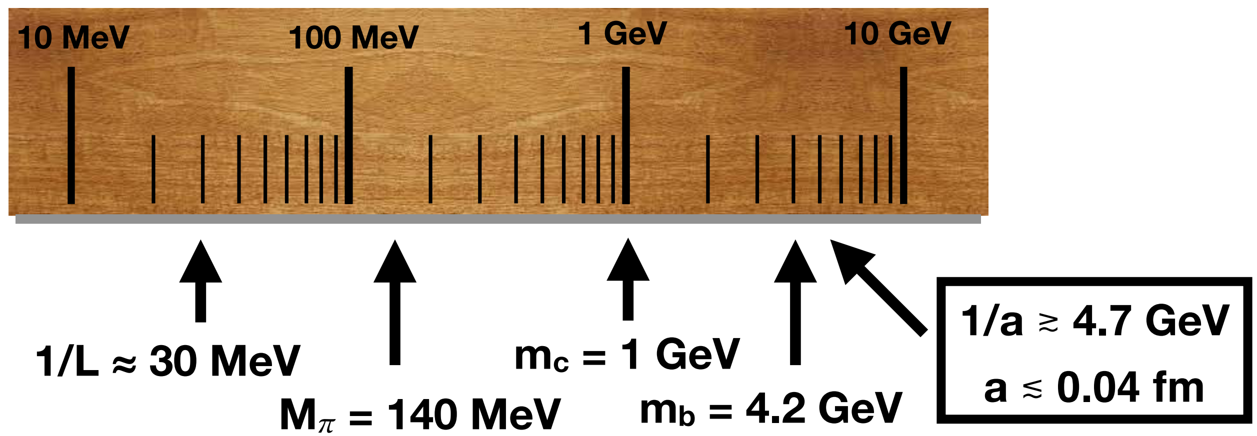


measures charm interference, especially strong phases

William Jay

Lattice QCD with Heavy Quarks

A challenging multi-scale problem



Heavy quarks are hard: lattice artifacts grow like powers $(am_h)^n$ — especially tricky for masses near or above the cutoff

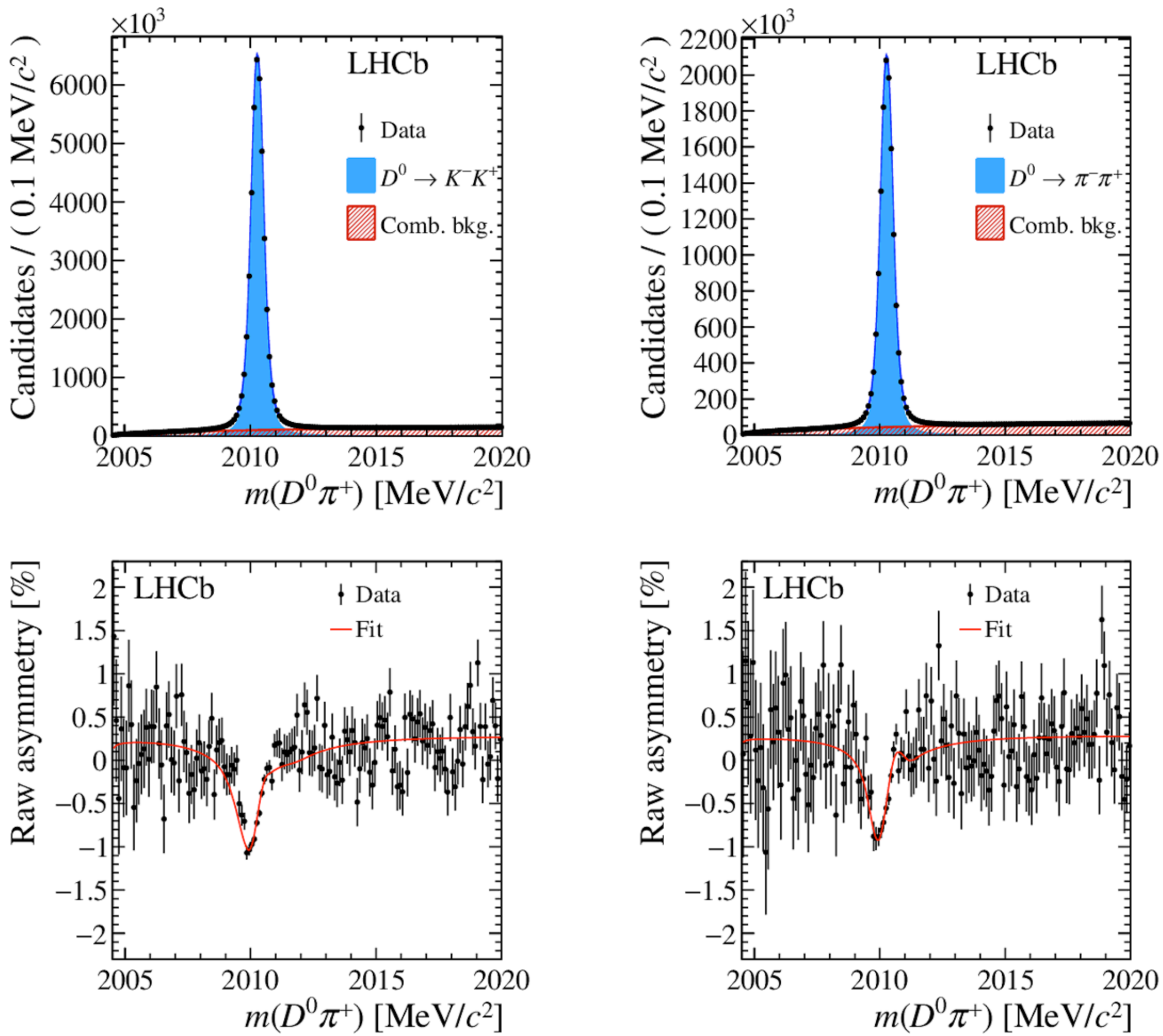
$$\frac{1}{L} \ll M_\pi \ll m_h \ll \frac{1}{a}$$

W.I. Jay — MIT

18

Discovery of CP violation in Charm in 2019

Eva Gersabeck



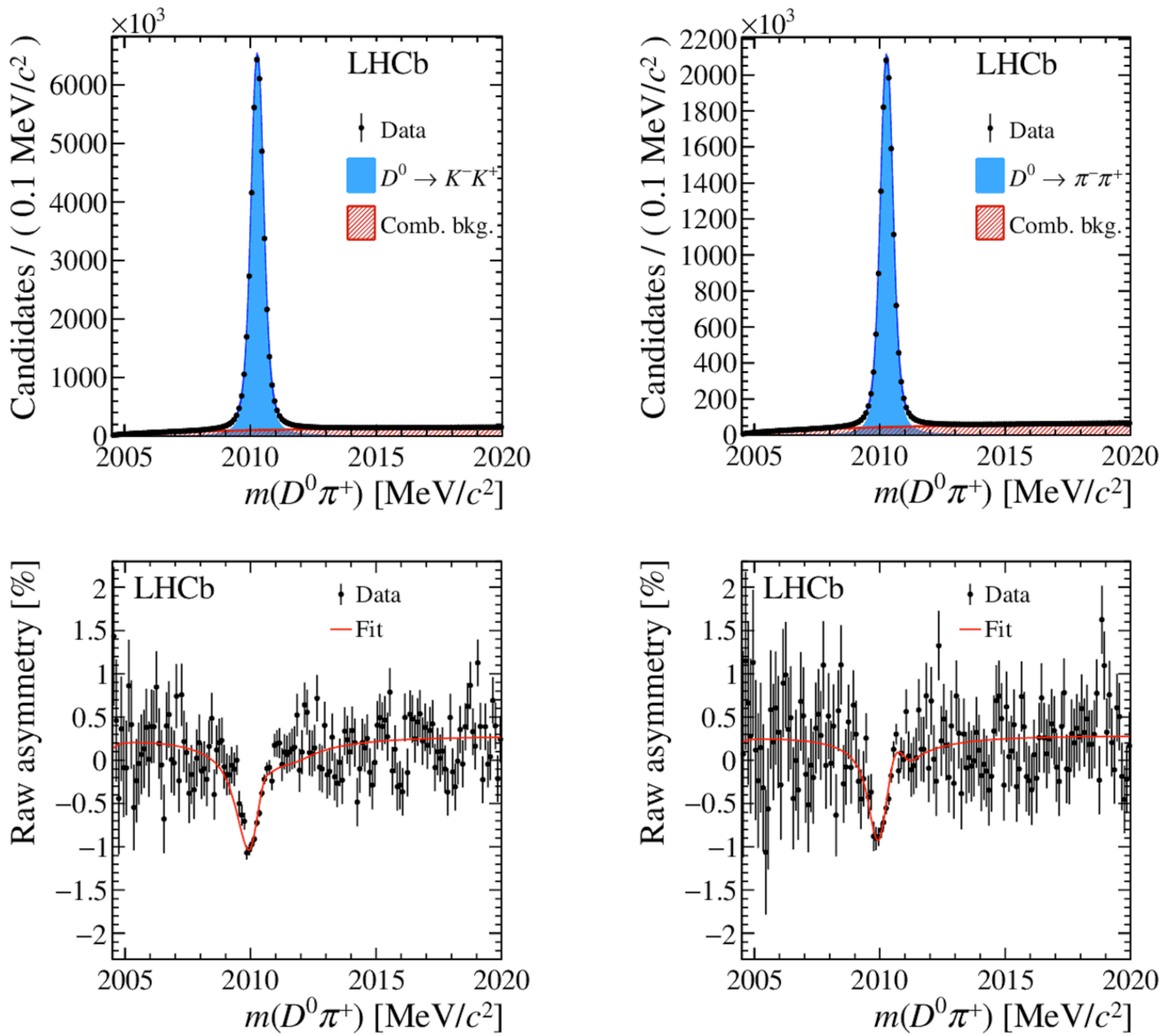
LHCb: PRL 122 (2019) 211803

$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$$
$$= (-15.4 \pm 2.9) \times 10^{-4}$$

Bigger than generally expected. Still unclear if/how this can be accommodated SM.

Luiz Vale Silva

Discovery of CP violation in Charm in 2019



LHCb: PRL 122 (2019) 211803

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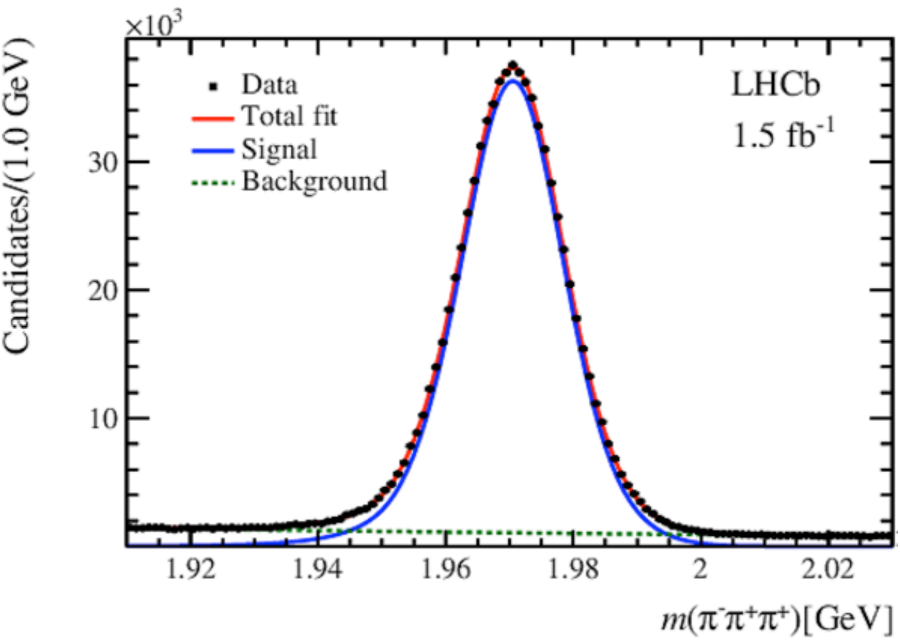
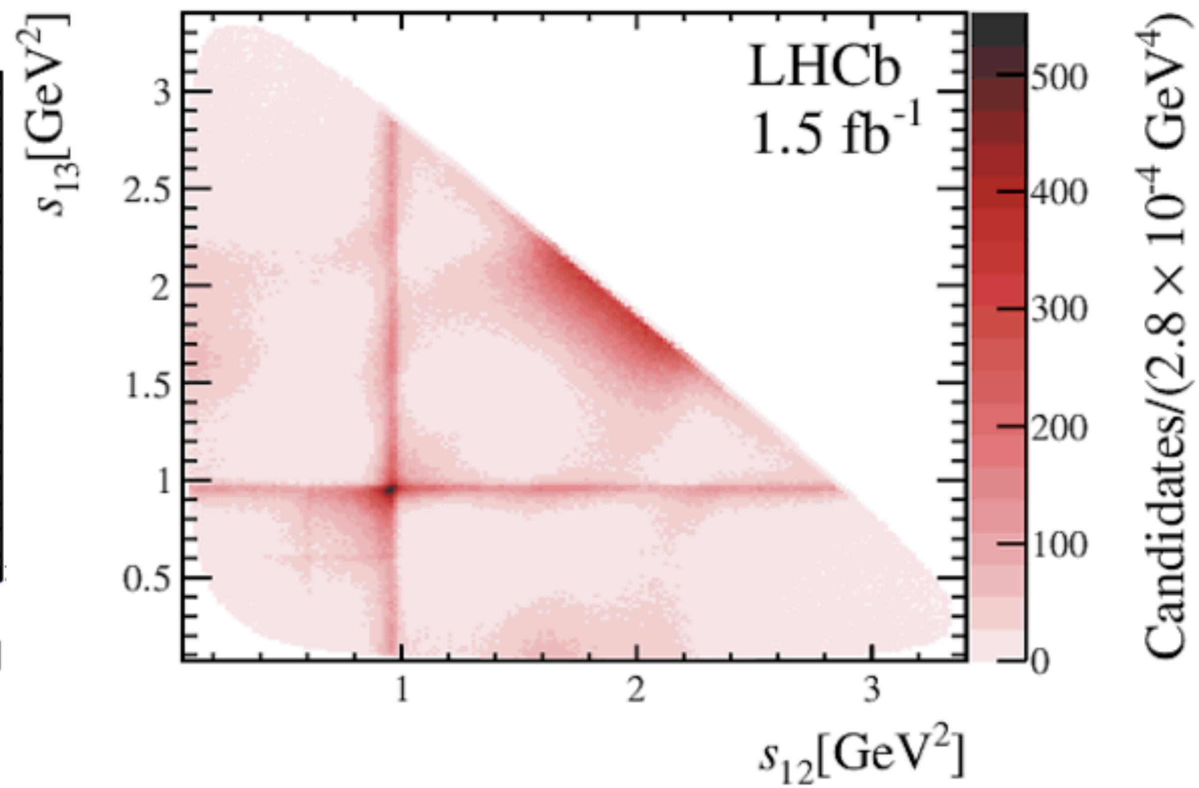
$$= (-15.4 \pm 2.9) \times 10^{-4}$$

Bigger than generally expected. Still unclear if/how this can be accommodated SM.

$D_s \to \pi^+\pi^-\pi^+$

LHCb: arXiv:2209.09840 (2022)





Conference


Welcome to CHARM 2023
The 11th International
Workshop on Charm Physics
July 17-21, 2023
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