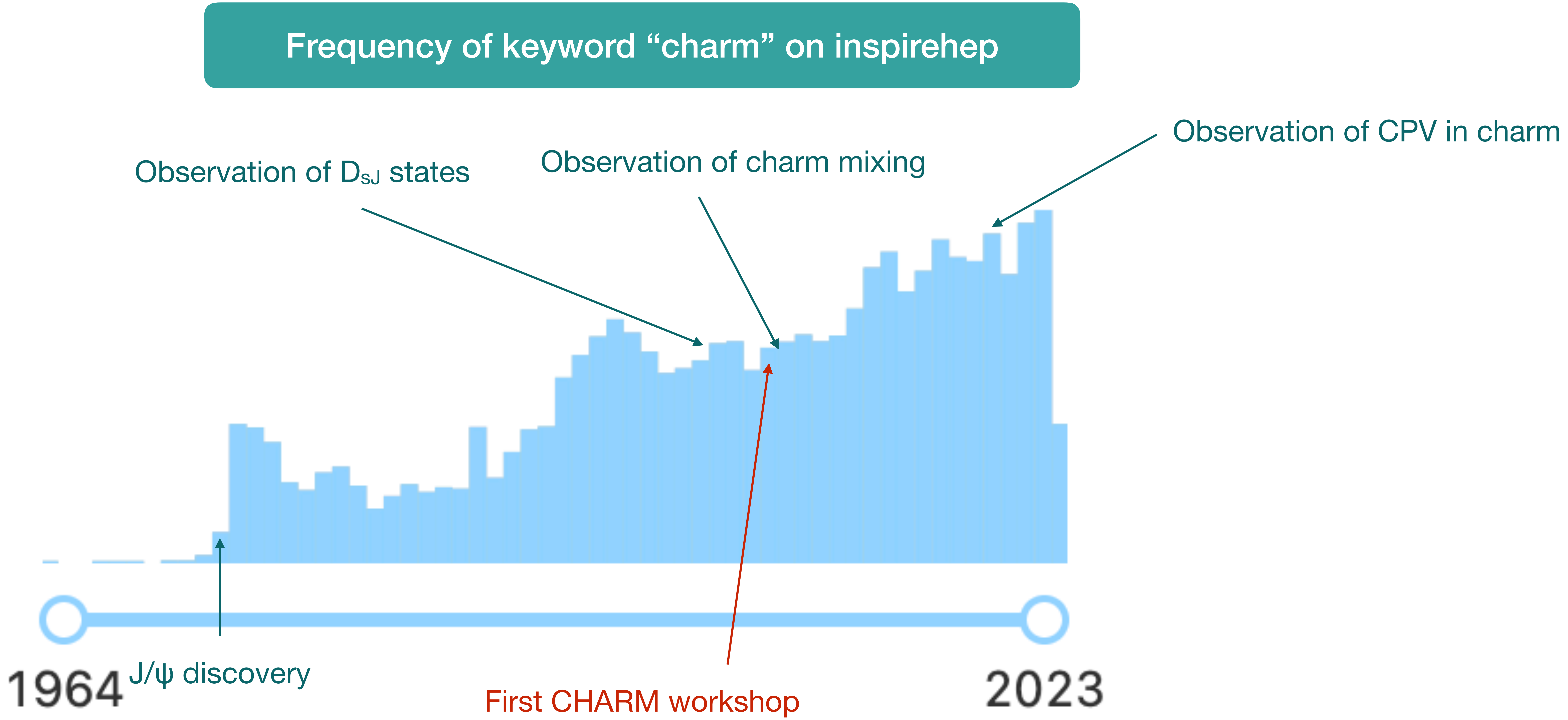
Opening experimental talk

Tara Nanut Petrič

CERN

11th International Workshop on Charm Physics [CHARM 2023]
Siegen, 17th-21st July 2023

Charm in time



→ When is the "era of charm"?

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

This week on the menu

Surely something
to everyone's taste!

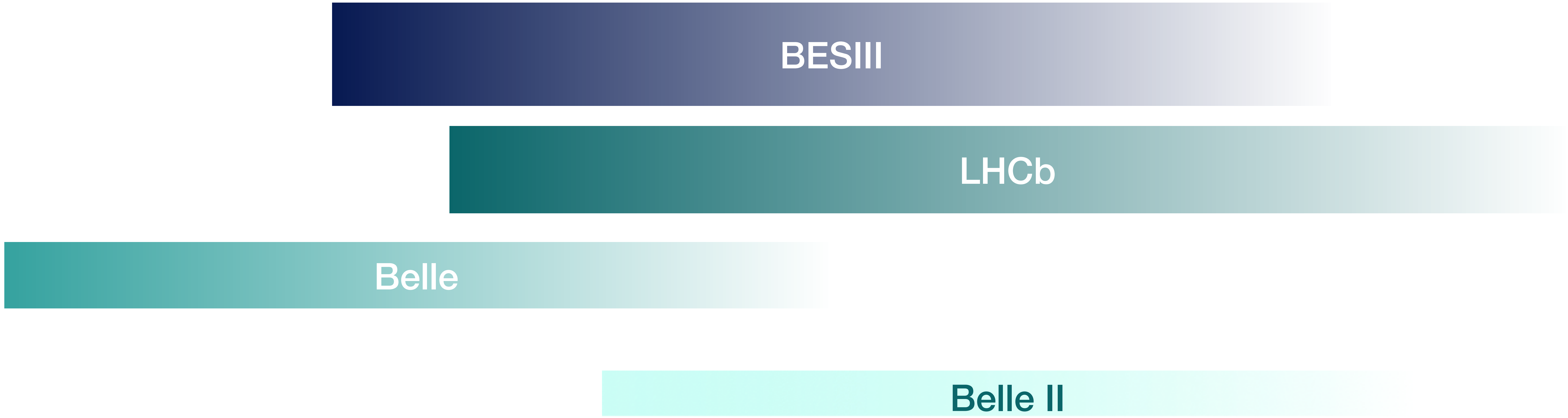
Interplay theory - experiment

Players on the field

Guy's talk Friday morning

Past ——— Present | **Present @ CHARM2023** | **Future**

Experiments @
Tevatron
PEP-II
CESR
BEPC
Fermilab
LEP
SPEAR
…



STCF?

FCC-ee?

Belle 3?

ALICE

CMS

STAR

PHENIX

ATLAS

PANDA

Machines

$\mathscr{L}$, $\sigma_{c\bar{c}}$, acceptance, trigger efficiencies

↓

		$\sqrt{s}$	Yield $D^0 \to KK$	Coverage	Flight distance	σ_t
Charm factory (e^+e^-)	BESIII	3.7 - 4.6 GeV	3fb^{-1}: 0.06M @20 fb^{-1}: 0.5M*	Almost full	/	/
B factory (e^+e^-)	Belle	10.6 GeV	0.25 M	Almost full	~200 μm	~200 fs
	Belle II	10.6 GeV	@50 ab^{-1}: 25M*	Almost full	~200 μm	70-90 fs
Hadron (pp)	LHCb	Run3: 13 TeV Run2: 13 TeV Run1: 7,8 TeV	@23 fb^{-1}: 500M* Run2: 60M Run1: 8M	4% of solid angle; catching ~40% of $\sigma_{Q\bar{Q}}$	0.4 -1 cm	50 fs

*extrapolations

Charm factory

- Background-free
- Lowest statistics
- No boost
- Quantum coherence ★
- Inclusive charm, neutrals and neutrinos
- Absolute branching fractions

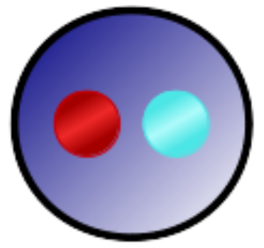
B factory

- Low background
- Low statistics
- Low boost
- Good for neutrals and neutrinos ★
- (Some) absolute branching fractions

Hadron collider

- High background
- High statistics ★
- High boost
- Challenging for neutrals and neutrinos
- Complex and biasing triggers

Conventional spectroscopy



Mesons
D(s) mesons, charmonium

"Conventional" states
Minimal particle content states
Quark model 1964: m, Γ, quant. Numbers

Baryons
Singly, doubly charmed

✓ Ground states

✗ Or maybe… Excited states

Have certainly seen some surprises.

D mesons	✓	WIP	
Charmonium	✓	WIP	
	✓	WIP	SC baryons
	WIP: 1/3	…	DC baryons

Theory corner

Tools: lattice QCD, QCD sum rules, effective field theories, dispersion relation approaches

Relation to experiment:

- Excited states: matching of predicted-observed states, completing the model
- Double-charmed baryons: missing states to observe and compare to predictions

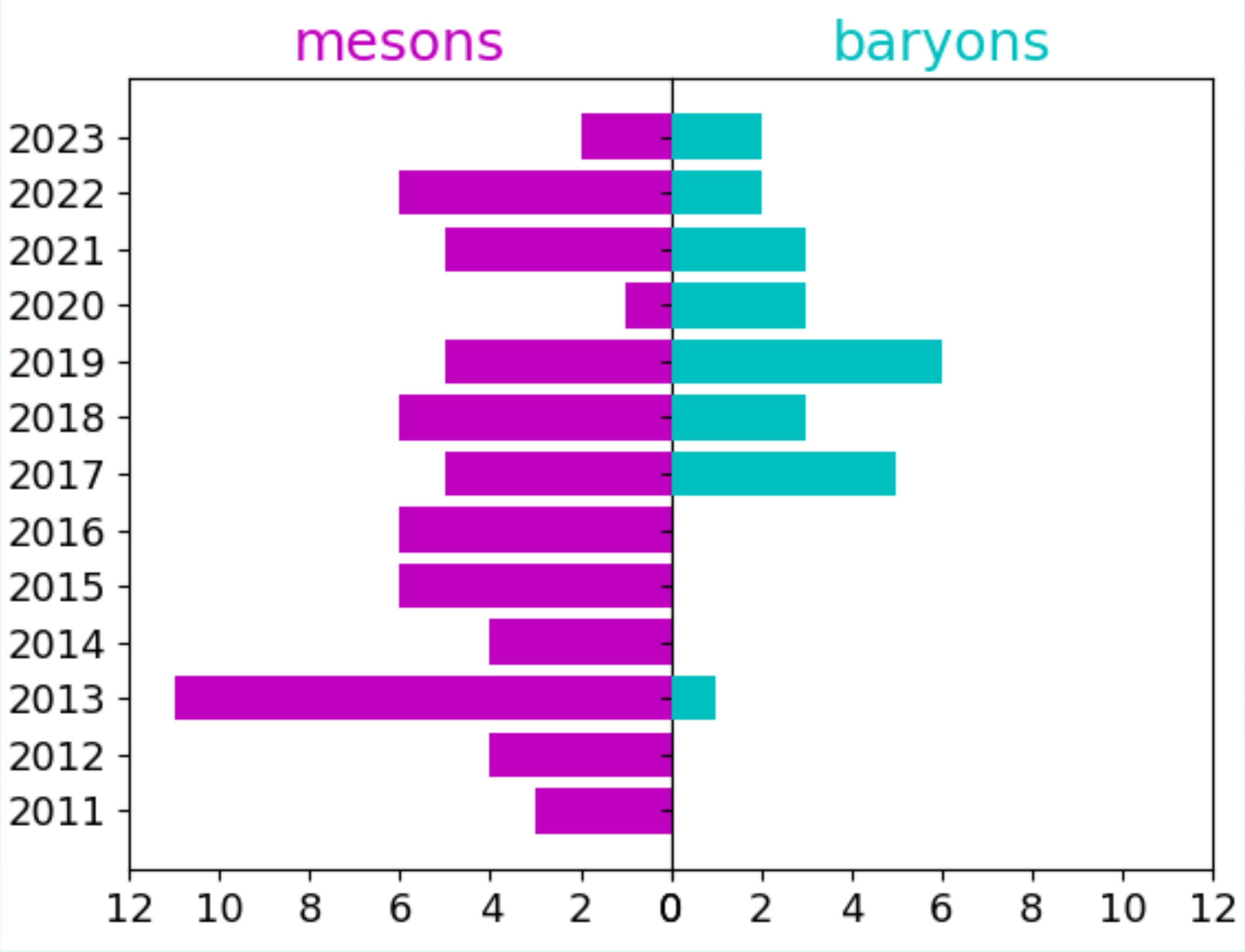
Patrick's overview talk (Tue morning)

⚠ Not all observed peaks are necessarily related to a genuine resonance: kinematic enhancement at thresholds, interference with continuum…?

Baryons

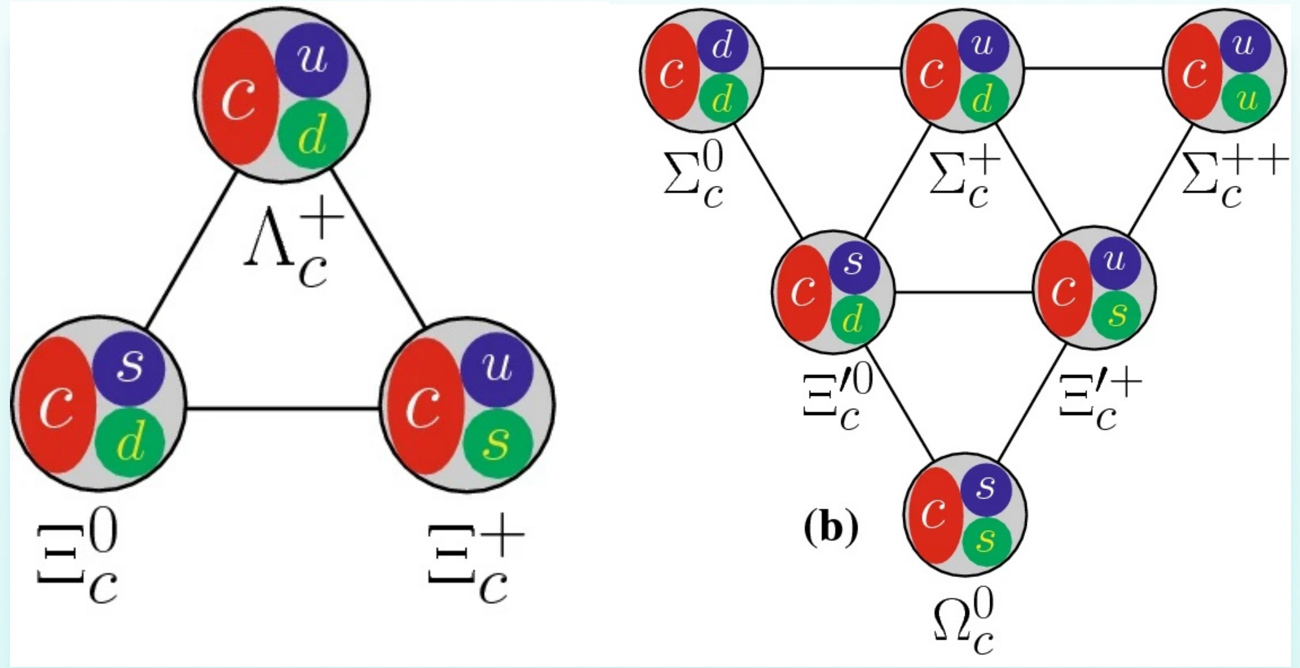
Challenges

- Smaller production
- Shorter liftime
- No clear "golden channels"
- Many more states



LHCb papers on charm meson and baryons.

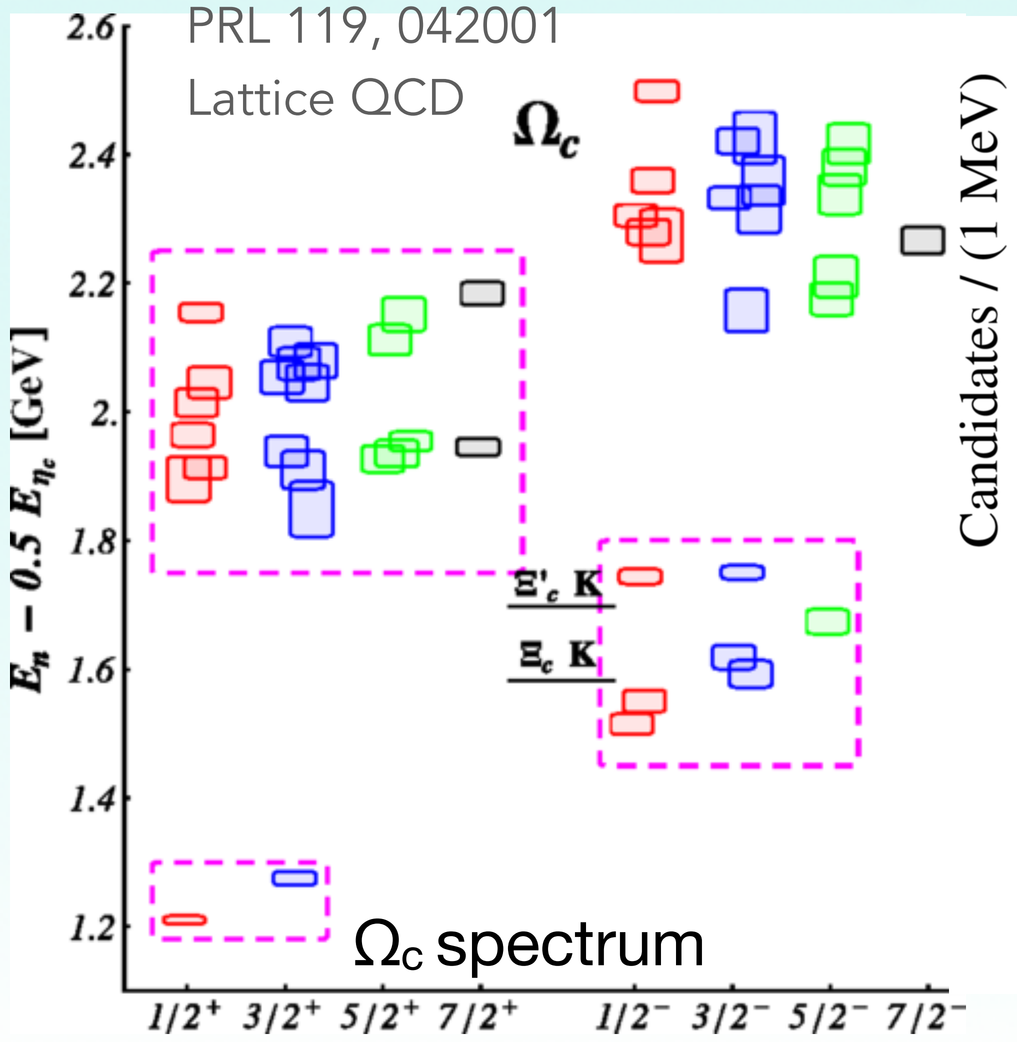
Singly charmed

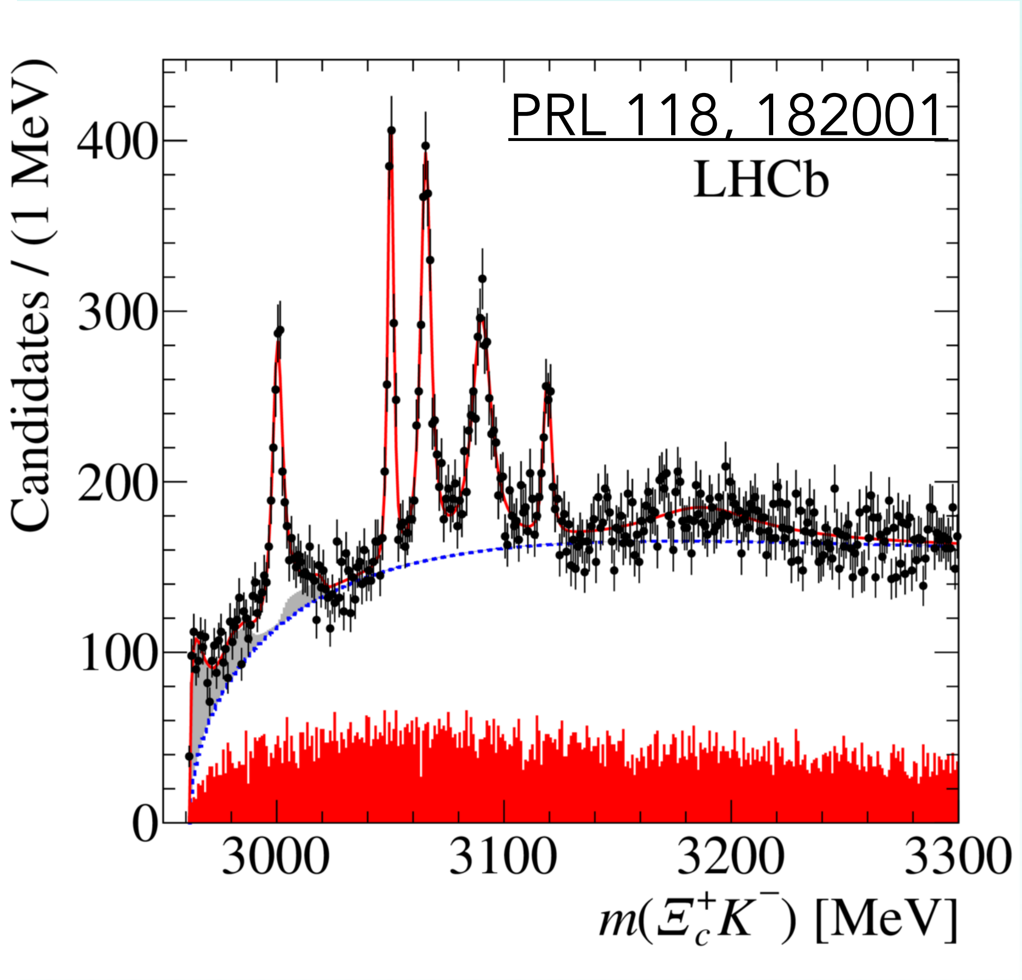


j=0, J = ½ j=1, J = ½

+ another sextet for j=1, J = 3/2

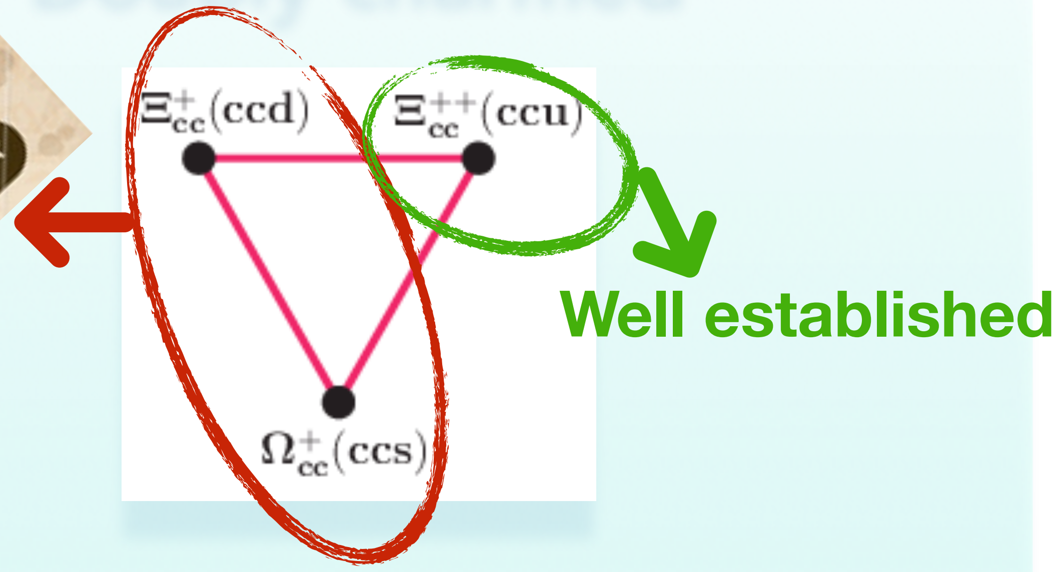
Only few J^P are firmly confirmed by experiment.





Are all splittings experimentally observable as states?

Doubly charmed

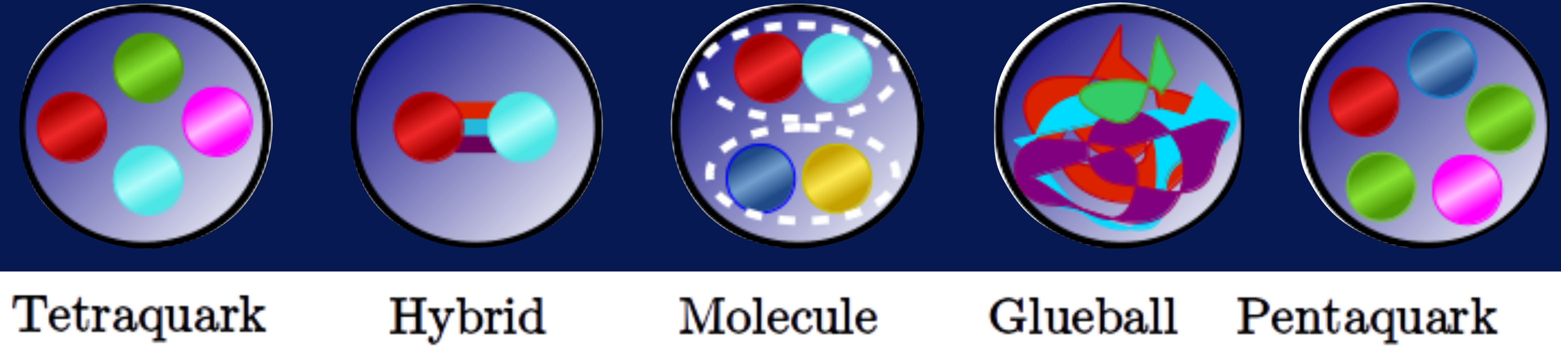


Mass predictions

$m(\Xi_{cc}^{++}) \sim m(\Xi_{cc}^{+})$
$m(\Xi_{cc}^{++}) < m(\Omega_{cc}^{+})$

Experimental data << theoretical predictions

(states, masses, hierarchies)



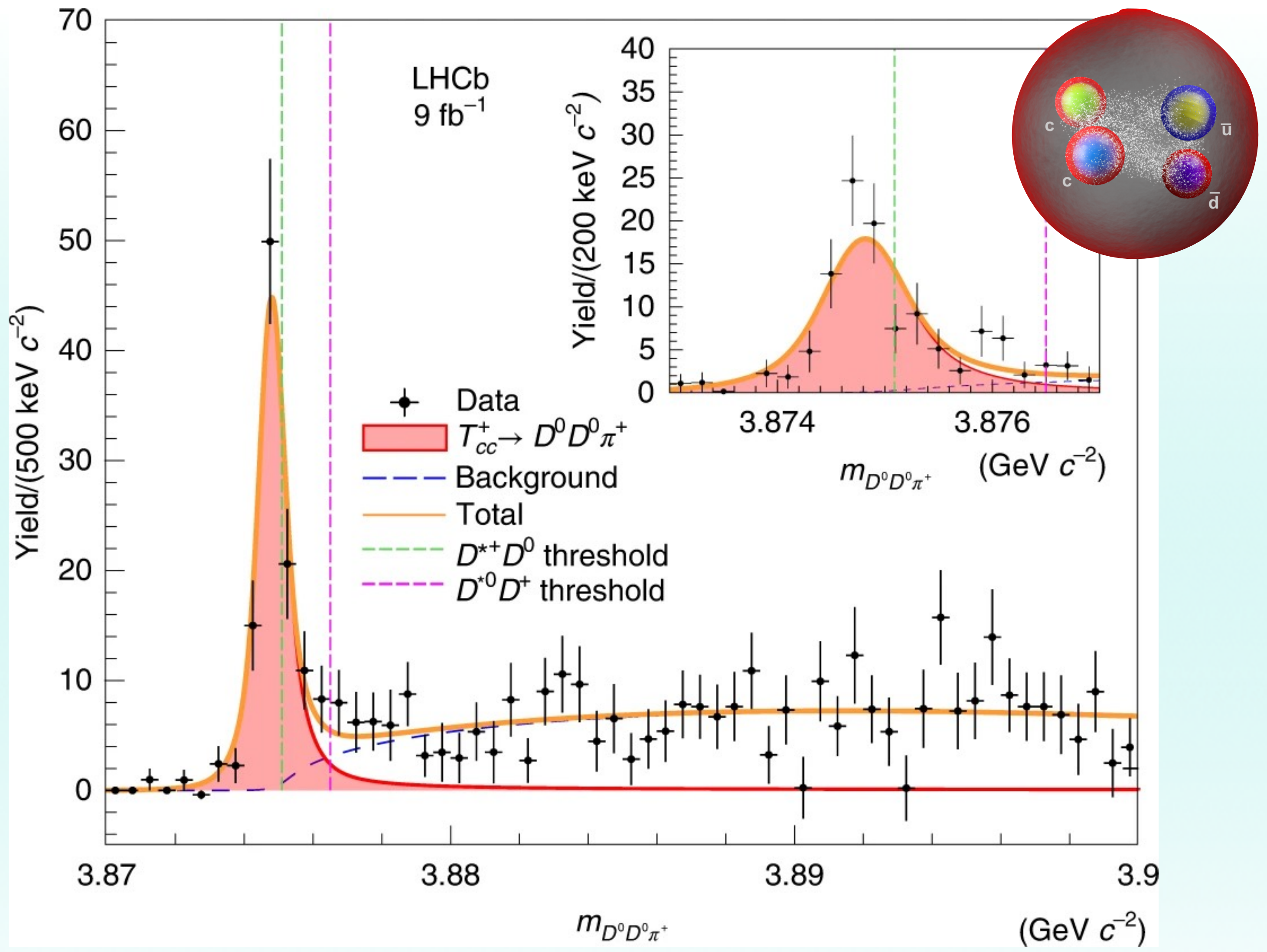
Exotic states

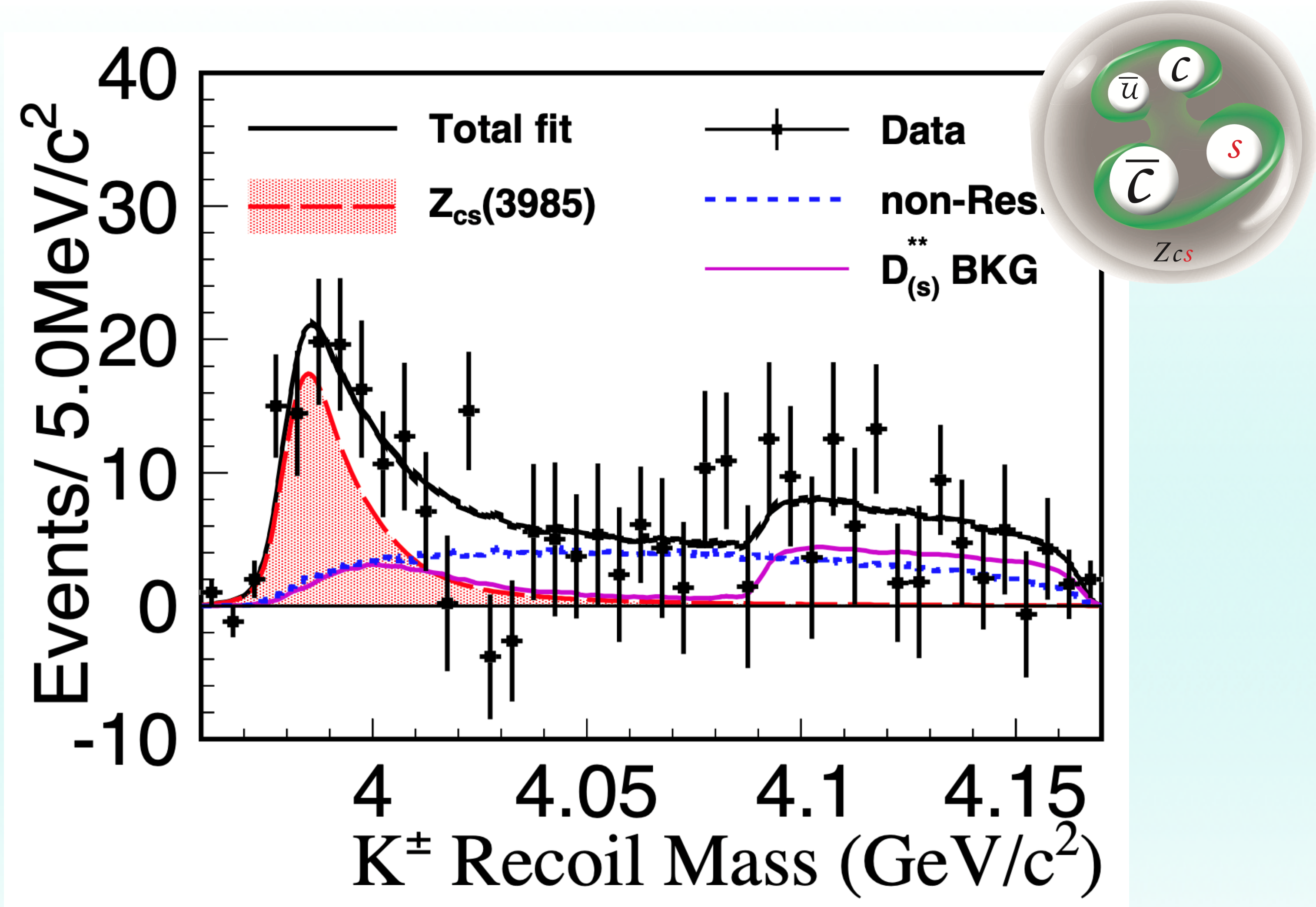
QCD allowed!
(So not all that exotic…)

Quantum numbers

Manifestly exotic

- cannot be reproduced by conventional states





Nature Physics volume 18, (2022)

Phys. Rev. Lett. 126, 102001

Not manifestly exotic

- Harder classification. Need careful analysis of experimental properties and theoretical predictions:
  - masses & widths
  - decay channels & rates,
  - isospin (partners and violation),
  - production…
- Mixing between states sharing the same quantum numbers: intrinsic problem of labelling experimentally observed states

Exotic states - or maybe not?

Example: $\chi_{c1}(3872)$ ~ X(3872)

- First heavy state with properties not fitting a conventional quarkonium state (width, mass).
- Discovered 2003, Belle: *Happy 20th birthday!*

- **Its (non)exotic nature is still ambiguous!**
- Measurements and interpretations are continuing…

Often we speak of "exotic candidates" due to ambiguity of interpretations.

N(exotic (candidates)) ~ N(conventional states)

... the collision vertex in b-hadron decays. This behavior is consistent with a calculation that models the $\chi_{c1}(3872)$ structure as a compact tetraquark. Implications for the binding energy of the $\chi_{c1}(3872)$ state are discussed.

Published in Phys. Rev. Lett. 126 (2021) 092001

An investigation of the analytic structure of the Flatté amplitude reveals a pole structure, which is compatible with a quasi-bound $D^0\overline{D}^{*0}$ state but a quasi-virtual state is still allowed at the level of 2 standard deviations.

Published in Phys. Rev. D102 (2020) 092005

Chunhua's talk on XYZ states [BESIII] (Tue morning)

Theory corner

Relation to experiment:
- Ongoing interpretations of observed states
- Finding missing predicted states

Spectroscopy: field status summary

Most relevant experimental players on the field today

BESIII, LHCb, BELLE, CMS, GlueX, (ATLAS EXPERIMENT)

Talks Tue and Thu afternoon

Some experimental highlights since previous CHARM:

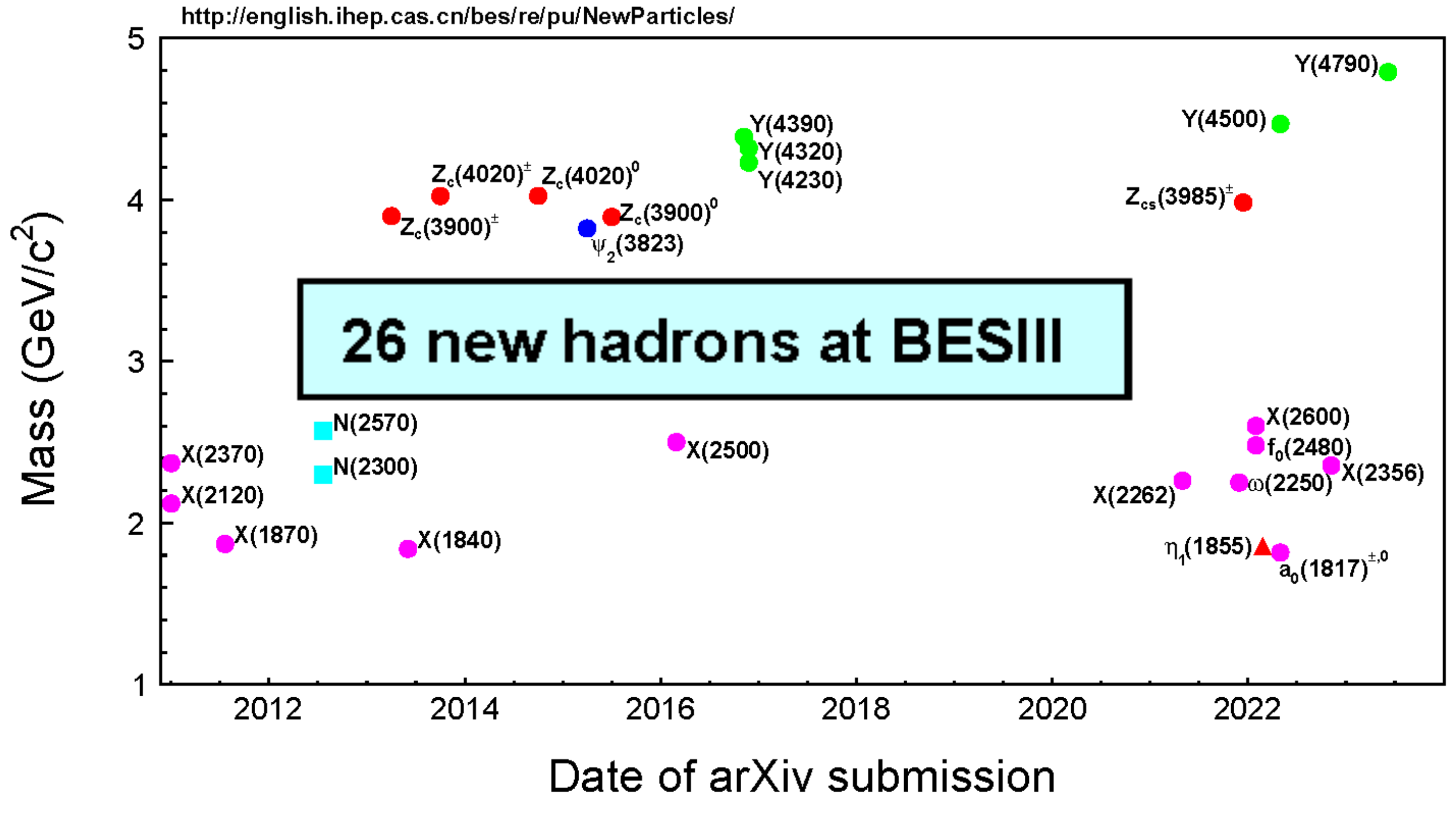
- T_{cc}^{+}: first state with two cc (without $\bar{c}$) Nature Physics volume 18, (2022)
- Z_{cs}: first hidden-charm state with non-zero strangeness PRL 126, 102001
- T_{cs0}: first open charm tetraquark PRL 125 (2020) 242001
- Plenty of new charmonium(-like) signals at BESIII
- Observation of excited Ω_c states PRL 118, 182001

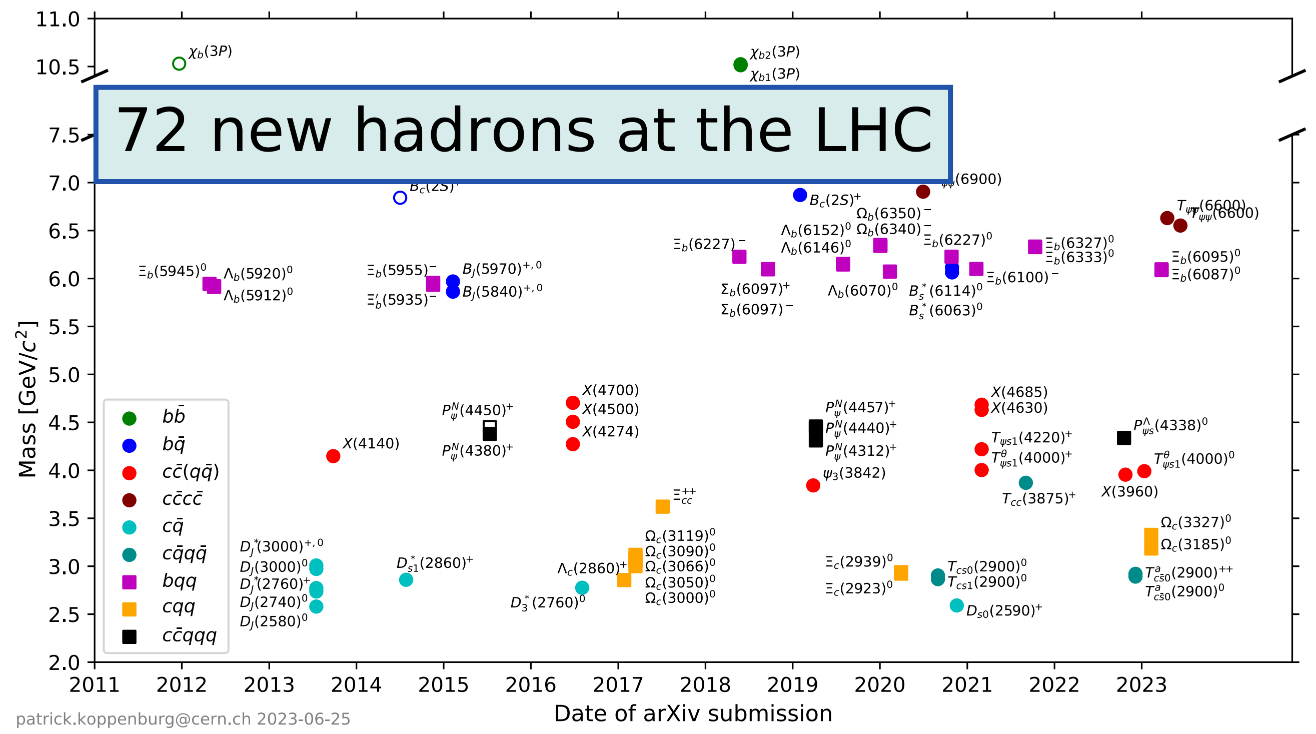
Experimental studies

- TBD: excited, exotic, doubly-charmed baryons
- New states
- New decay channels
  - Observables like Breit-Wigner mass and width of resonances are reaction dependent
- Quantum numbers
- Amplitude analyses
- Potential for improvements: more of advanced models (like K-matrices), studies of coupled channels

Naming sheme(s)

We are constantly adding new particles!





With historical lack of (extendable) conventions, experiments have been deciding on the go (example: XYZ states). A"self-evolving" scheme can easily stop being consistent and cannot consistently accommodate new states.

CERN-LHCb-PUB-2022-013

PDG naming scheme

- Naming is based on measured quantum numbers
- **PROBLEM**: Not covering (future) exotics

→

LHCb-proposed 2023 exotic hadron naming scheme

- Building on PDG scheme. Minimal changes in existing namings (4- or 5-quark states)
- Expands the convention to pentaquarks and future discoveries, missing isospin and quark contents

Future discovered states might need "interim" names until quantum numbers are measured.

Production

Theory corner

Tools:

- Hadronisation: perturbativeQCD with factorisation approach: many sub-models
- QGP properties: lattice QCD

Relation to experiment:

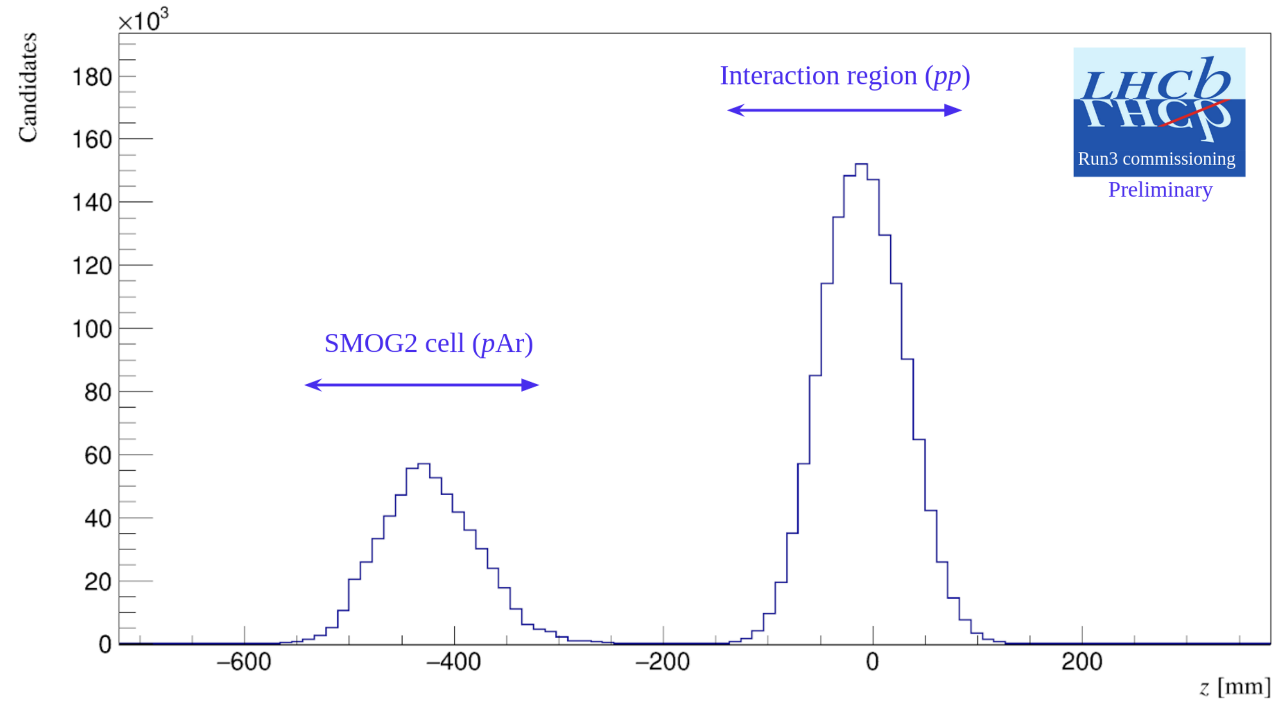
- Experiment constantly challenges theoretical predictions
- Very active iterations!

Open charm

Charmonium

heavy-flavour
hadronisation

p-p, p-Pb, Pb-Pb [LHC, (CDF)]
p-He, p-Ne [LHCb SMOG]
p-heavy gas [LHCb SMOG2]
Au-Au (+others) [RHIC]
(e^+-e^-, pe [B factories, HERA])



SMOG2 can take data simultaneously to LHCb!

In media
Quark-gluon-plasma (QGP)
Nucleus-nucleus collisions

Most relevant experimental players on the field today

ALICE, LHCb, CMS, STAR

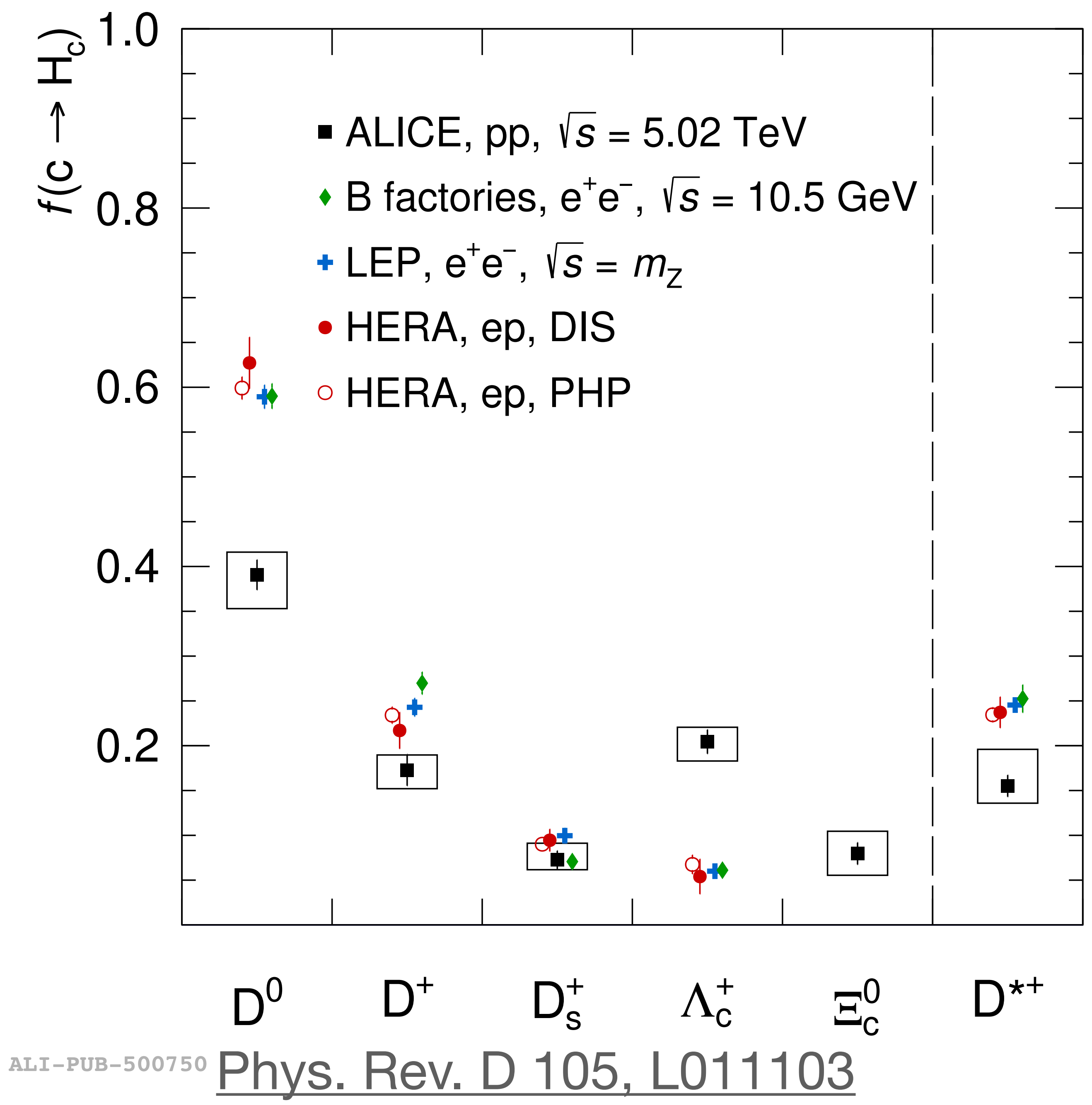
Covering complementary kinematic regions

Production

Open charm

Baryon/meson ratio challenging the assumption of **fragmentation fraction universality** w.r.t. collision system and centre-of-mass energy [ALICE, 2018 and many measurements since]

- WIP with theory: accommodate measurements with heavier charm-strange baryons and at different rapidity



Phys. Rev. D 105, L011103

Charmonium

- History of puzzles: production & polarisaton
- Still testing theoretical models, mostly successfully
- Active field: charmonium in media

In media

- **Affects the hadronisation process**
  - Studied (today) at LHC, RHIC
- **Charmonium suppression**
  - Is it anomalous?
  - Suppression of excited vs. ground states

Krista's overview talk (Wed morning)

Yasemin's talk [BESIII] (Mon afternoon)

Some experimental highlights since previous CHARM:

- Many measurements of baryon/meson production ratios by ALICE, also LHCb, STAR, CMS
- First fragmentation fraction including Ξ_c^0 , Phys. Rev. D 105, L011103

Intrinsic charm

Speculations since long: heavy quarks also exist as a part of the proton wavefunction

$|\text{proton}\rangle = |uud\rangle + |uudc\bar{c}\rangle + \ldots ?$

Ramona's talk
Wednesday morning

Study of Z bosons produced in association with charm in the forward region

LHCb collaboration†

Events containing a Z boson and a charm jet are studied for the first time in the forward region of proton-proton collisions. The data sample used corresponds to an integrated luminosity of 6 fb^{-1} collected at a center-of-mass energy of 13 TeV with the LHCb detector. In events with a Z boson and a jet, the fraction of charm jets is determined in intervals of Z-boson rapidity in the range $2.0 < y(Z) < 4.5$. A sizable enhancement is observed in the forward-most $y(Z)$ interval, which could be indicative of a valence-like intrinsic-charm component in the proton wave function.

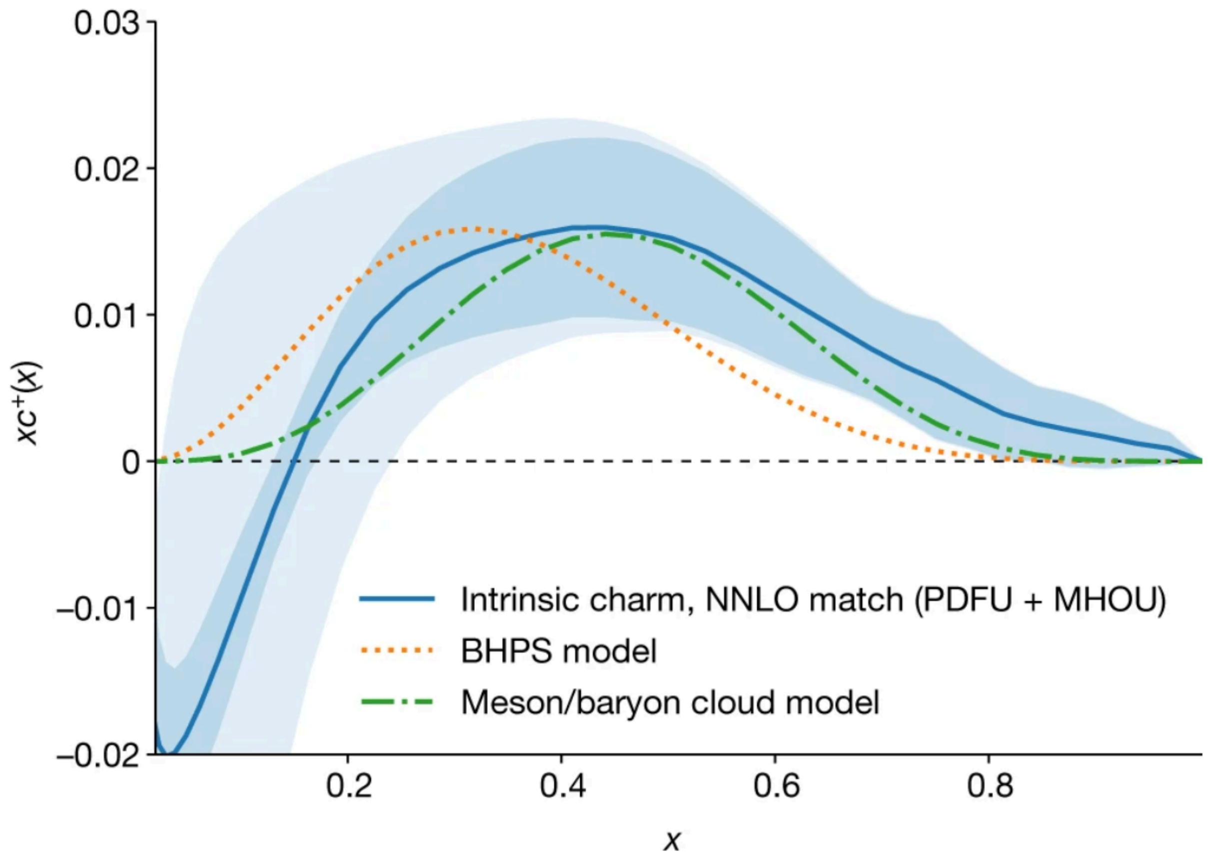
Published as Physical Review Letters **128** (2022) 082001

Article | Open Access | Published: 17 August 2022

Evidence for intrinsic charm quarks in the proton

The NNPDF Collaboration

Nature **608**, 483–487 (2022) | Cite this article



Several experiments will be able to contribute in the coming years to shedding more light on the matter.

Lifetimes

Theory corner

Current tool: HQE

Relation to experiment:

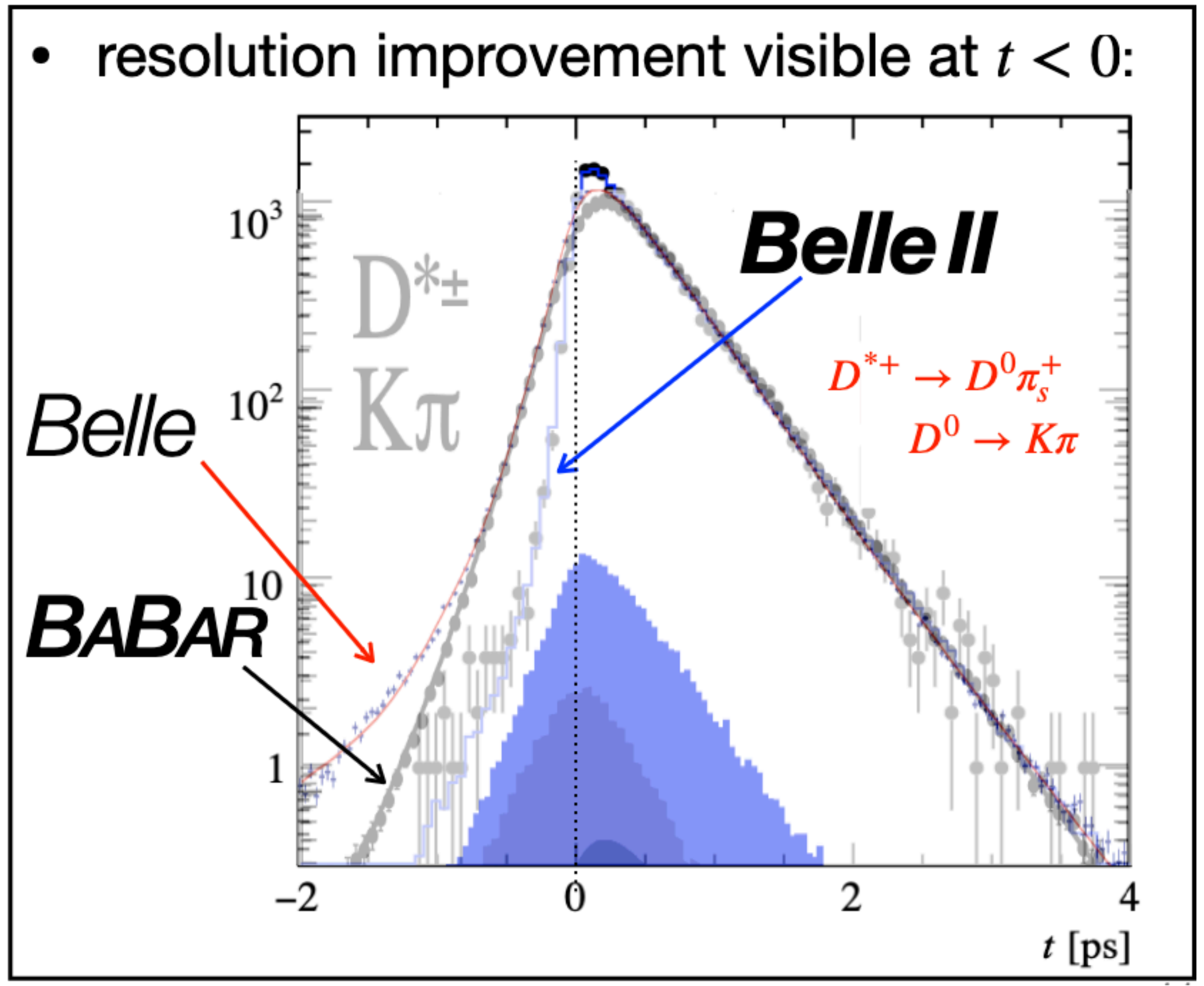
- Test of HQE
- **Historical big bombshell: baryon hierarchy surprise**

Early prediction up to $1/m_c^3$:

$\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$

2018 measurement, later confirmed by others (PRL 121, 092003):

$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$



G. Casarosa, ICHEP2020

Alan and Adam's talks [Belle II, LHCb] (Mon afternoon)

Experimental studies

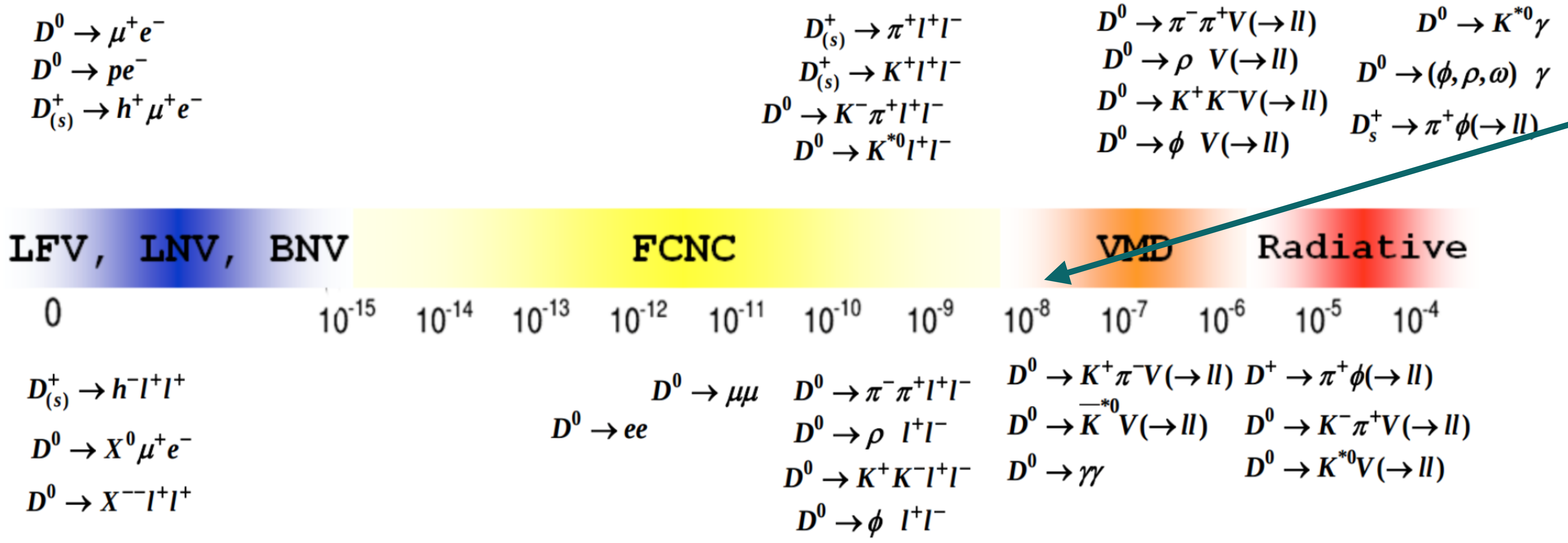
- Very impressive recent results by Belle II: 2x improved performance vs Belle on a much smaller dataset (pixel detector, closer to beam pipe)
- LHCb contributes with ratio-based lifetime measurements, but unlikely to make an absolute measurement
- **Next important milestone: completing doubly-charmed baryons and their hierarchy**

Most relevant experimental players on the field today

Belle II

LHCb

Rare decays



Rarest observed decays
[Phys. Rev. Lett. 119, 181805]

Monday afternoon and Thursday morning talks

Experimental studies

- Branching ratios
- Forbidden decays: LFV, LNV
- LFU ((semi)leptonic, BESIII)
- Angular and CPV asymmetries (LHCb)
- Form factors of (semi)leptonic decay (BESIII)

Theory corner

Tools: lattice QCD, QCD sum rules, HQE, OPE

Relation to experiment:

- New Physics tests:
  - Possible enhancements of branching ratios
  - Clean SM null tests

Some experimental highlights since previous CHARM:

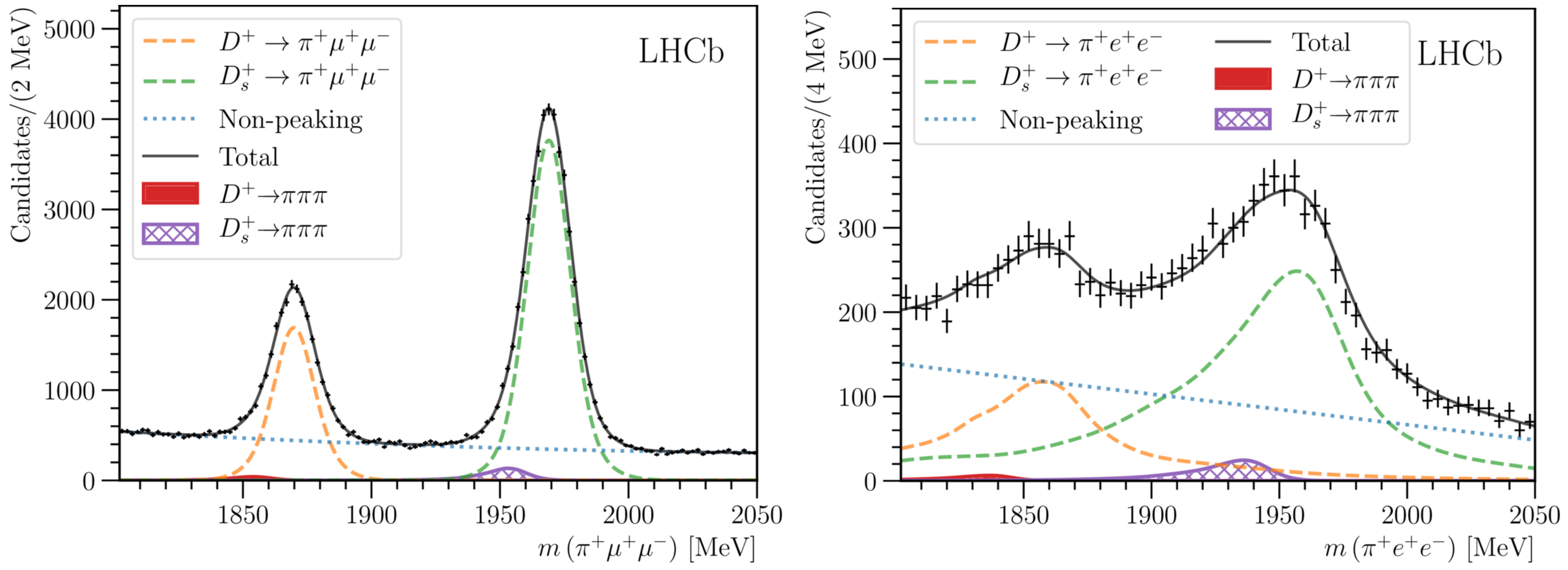
- $D^0 \to hh\mu\mu$: First full angular analysis and CPV search in a rare decay PRL 128, 221801
- [Search] $D^0 \to \pi^0 \nu\bar{\nu}$: First $c \to u\nu\bar{\nu}$ study Phys. Rev. D 105, L071102
- [Search] First radiative baryon study Phys. Rev. D 107, 052002
- [Search] $D_s^* \to e\nu$ @2.9σ - almost evidence! 2304.12159

Most relevant experimental players on the field today

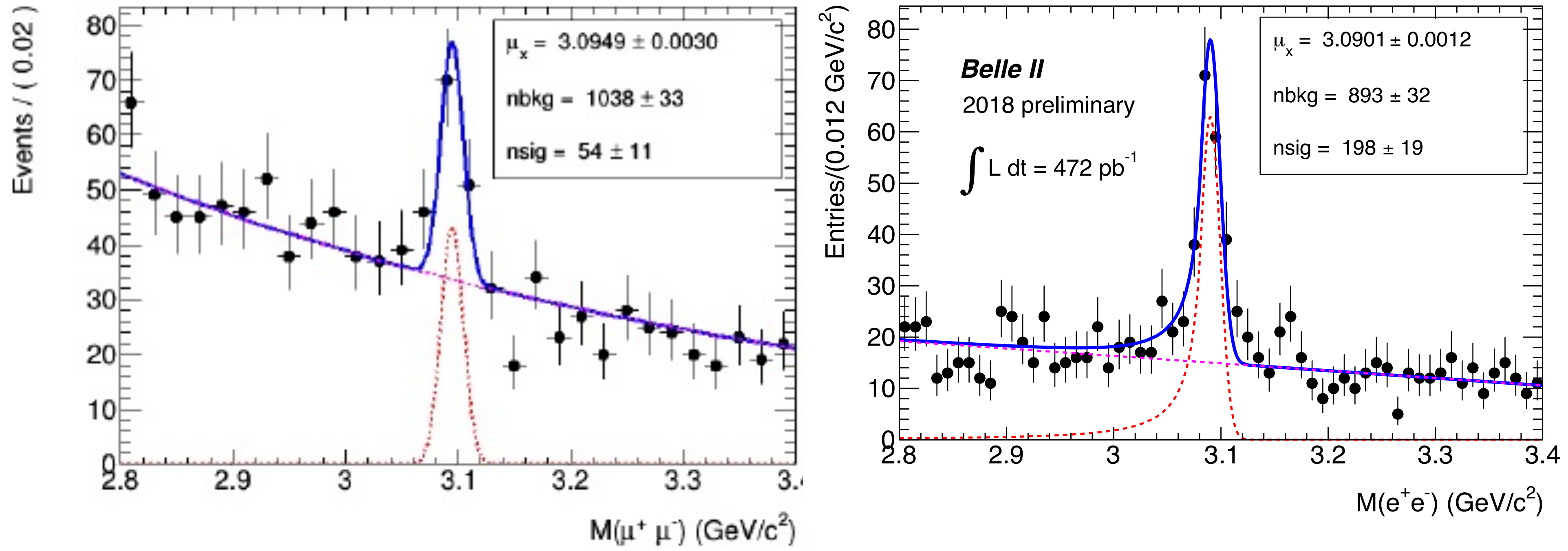
BESIII, LHCb, BELLE (Belle II)

Performance and potential

	BESIII	Belle	LHCb
Charged lepton reconstruction efficiency	e almost as good as μ	e almost as good as μ	e significantly worse than μ
ε(ee)/ ε(μμ) [from B→K*ll]		83%	<45%
Bremsstrahlung	Few e emit Partial recovery	Few e emit Partial recovery	Almost all e emit Partial recovery
Calorimeter resolution	2-4%	<3%	1 + 10√E[GeV]%
Radiative decays	✔	✔	Will do
Decays with neutrinos	✔	✔	Unsure of gain



JHEP 06 (2021) 044



F. Forti, 57. International Winter Meeting on Nuclear Physics

Muon modes: LHCb has the upper hand

Electron modes: LHCb has the highest statistics, but significantly worse electron reconstruction

Radiative modes: Belle is in the lead, LHCb and Belle II can race to overtake

Invisible modes: BESIII is currently most active, Belle II will compete

CPV

A very hot topic, but loooong path toward experimental observations - we have just barely gotten there.
The most exciting time is *now*!

Theory corner

Tools: QCD sum rules, SU(3) symmetry, topologies approach, dispersion relation and other effective field models,…

Relation to experiment:

- Million dollar question: are the experimental observations SM or NP?
  - The newest LHCb measurement of A_{CP} in $D^0 \to KK$ cannot be easily accommodated in all approaches
- Observations in new (SCS) channels are needed to test correlations!
- The ball is in both courts - theory and experiment

Some experimental highlights since previous CHARM:

- A_{CP} in $D^0 \to KK$: First evidence in single channel ($D^0 \to \pi\pi$) LHCb-PAPER-2022-024

Most relevant experimental players on the field today

LHCb, BELLE (Belle II) BESIII

- $a_{CP}(D^0 \to K^+K^-)$ complies with the calculation of Khodjamirian and Petrov.
- For approximate U-spin limit $a_{CP}(D^0 \to K^+K^-) \approx -a_{CP}(D^0 \to \pi^+\pi^-)$ to work, with future data $a_{CP}(D^0 \to K^+K^-)$ must flip sign.
- Will future data decrease $|\Delta a_{CP}|$ and will the 5σ discovery eventually go away?
- Or did LHCb discover new physics in 2019?

U. Nierste, Particle Physics from Early Universe to Future Colliders 2023

CPV

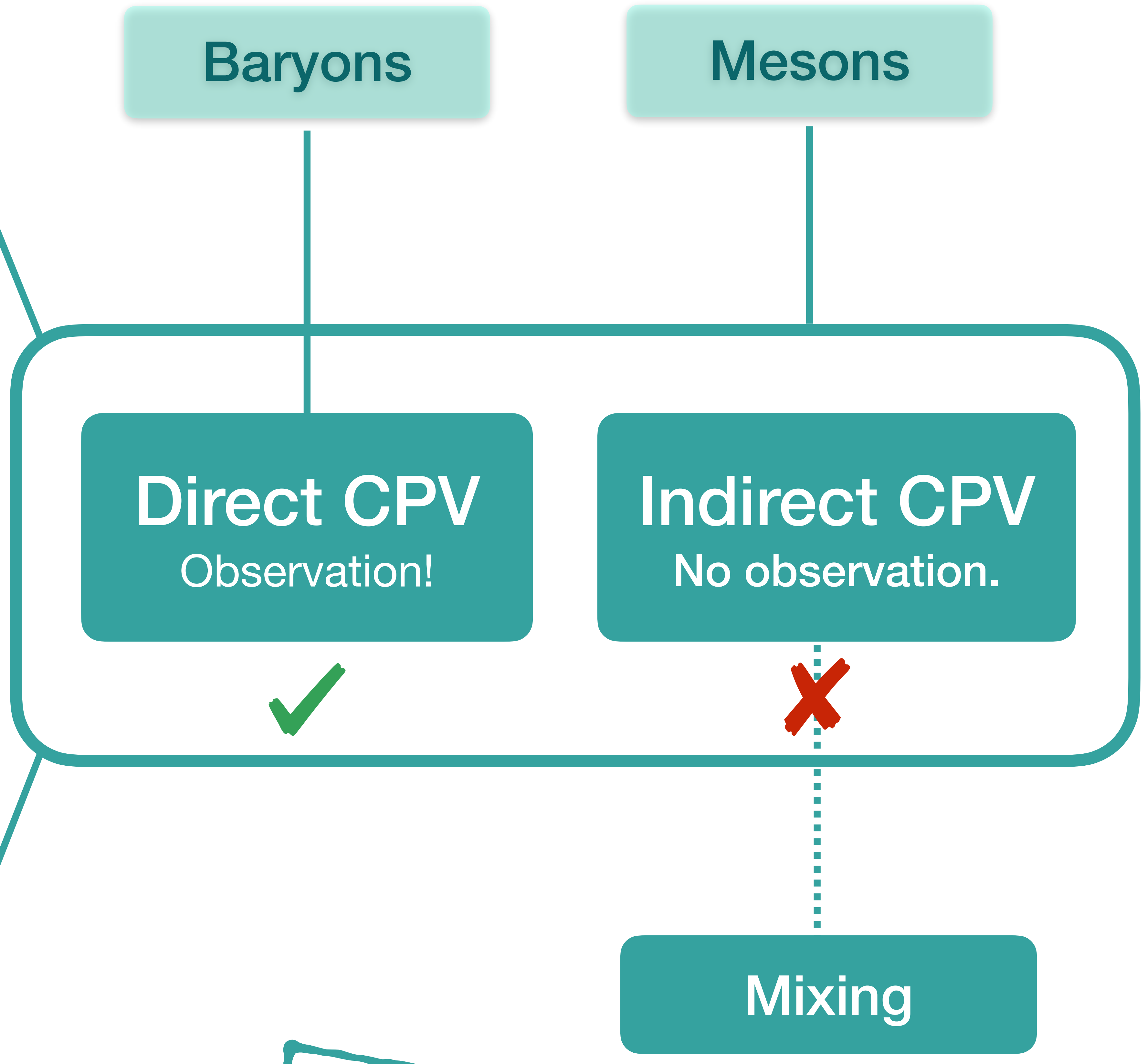
2-body modes
One of the highest statistics

Multi-body modes
Potentially enhanced local effects

Marco's talk on model-independent multi-body methods [LHCb] (Mon afternoon)

Model (in)dependent methods
Uncertainty of models will be key in the future.

(Un)binned methods
Binned methods typically use some averaged quantity. Cross-experiment collaboration may be relevant.



Evelina's talk on direct CPV [LHCb] (Friday morning)

"Discovery methods"

Binary answer, low or no theoretical interpretation

- **Angular asymmetries**
  Null tests
- **T-odd asymmetries**
  ≥4-body modes

$A_{CP} \sim \sin\Delta\phi \sin\Delta\delta$

$a_{CP}^{T\text{-odd}} \sim \sin\Delta\phi \cos\Delta\delta$

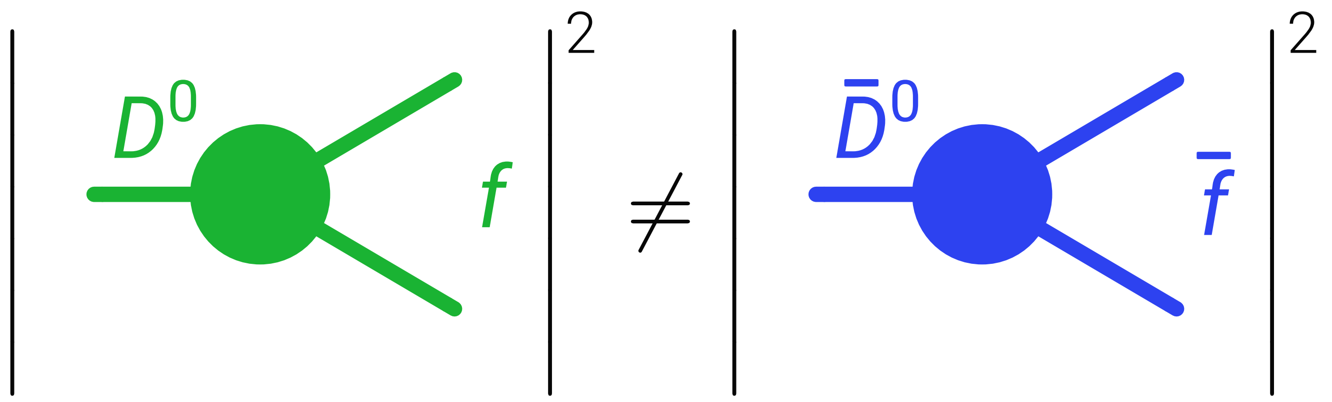
Complementary sensitivity!

- **Miranda method**
  3-body modes
  Bin-by-bin comparison
- **Energy test**
  Two-sample problem

Longke's talk [Belle] (Mon afternoon)

Direct CPV

→ **Mode-dependent**



→ **Recent observation: ΔA_{CP} [Phys. Rev. Lett. 122, 211803]**

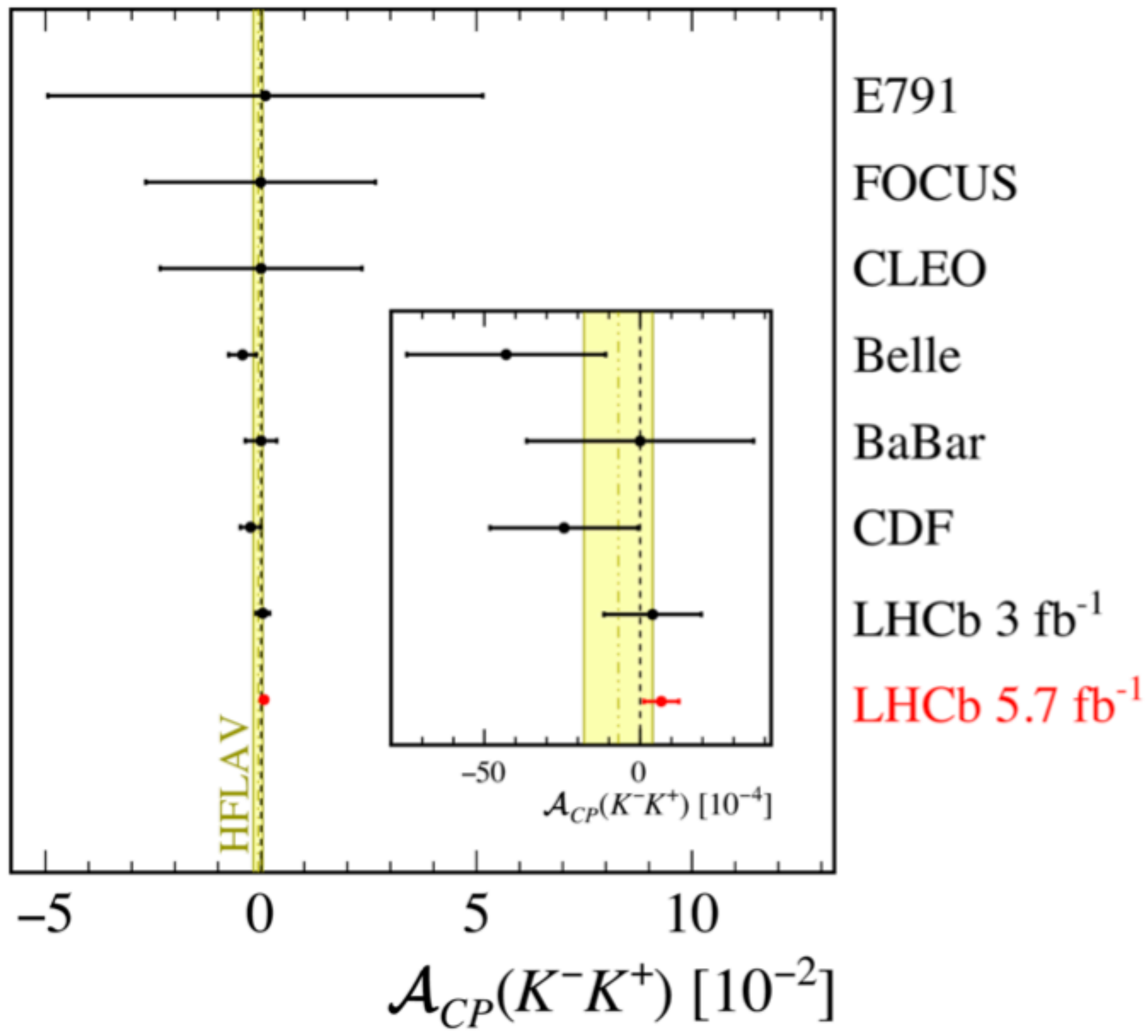
- LHCb has just started to probe the measurable level

→ **Latest: evidence in single channel**

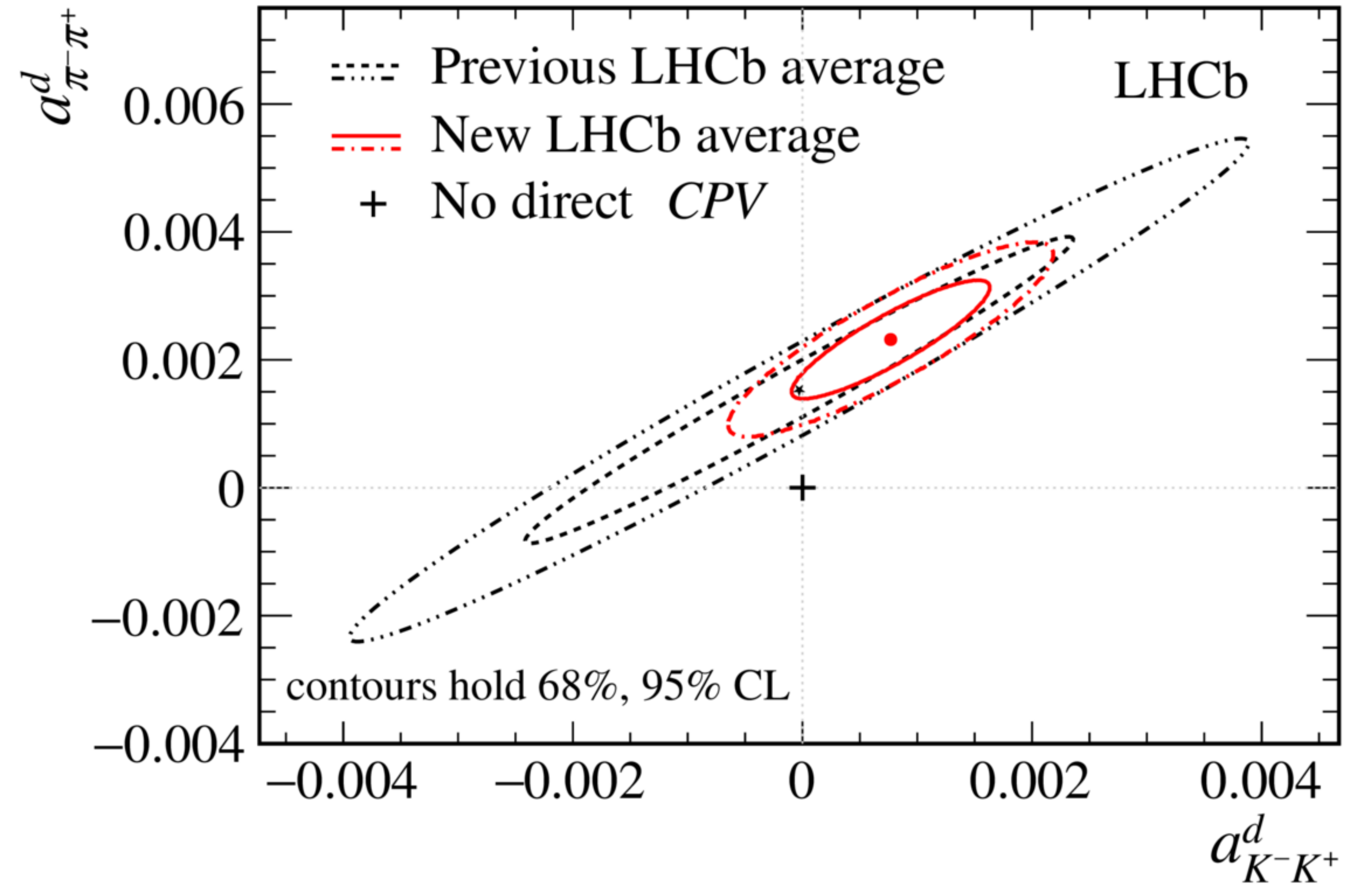
- Evidence in $D^0 \to \pi\pi$ mode when combining with the ΔA_{CP} measurement
- Significant constraint on models: this result isn't necessarily easy to accommodate

→ **Modes with charged and/or neutrals**

- Belle (II) + LHCb complement
- LHCb can explore conversion for neutrals



LHCb-PAPER-2022-024



Direct CPV

→ High statistics

- These types of measurement can have the highest statistics of charm analyses, but we are searching for small effects - controlling the experimental effects is crucial!

→ Nuisance asymmetries

- The measured asymmetry is a combination of the physics asymmetry and experimental nuisance asymmetries

$$A_{raw} = A_{CP} + A_{prod} + A_{det}$$

- We combat this with control channels

C_{D+}:

$$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft}) + A(D^+ \to K^-\pi^+\pi^+) - \left[A(D^+ \to \overline{K}^0\,\pi^+) - A(\overline{K}^0)\right]$$

C_{Ds+}:

$$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft}) + A(D_s^+ \to \phi\pi^+) - \left[A(D_s^+ \to \overline{K}^0\,K^+) - A(\overline{K}^0)\right]$$

- Far from trivial!

→ Beware of correlations!

- We have reached a point where correlations of instrumental uncertainties between different measurements (usage of same control/calibration channels) must be taken into account
  - LHCb is preparing a framework where this data will be available - Announced at Implications Workshop 2022

Mixing

Precision on mixing parameters will eventually be needed to disentangle indirect CPV: $\Delta Y_f \approx -x_{12} \sin\phi_2^M$

Theory corner

Current tools: Inclusive (HQE - quark-level) and exclusive approaches (hadron-level)

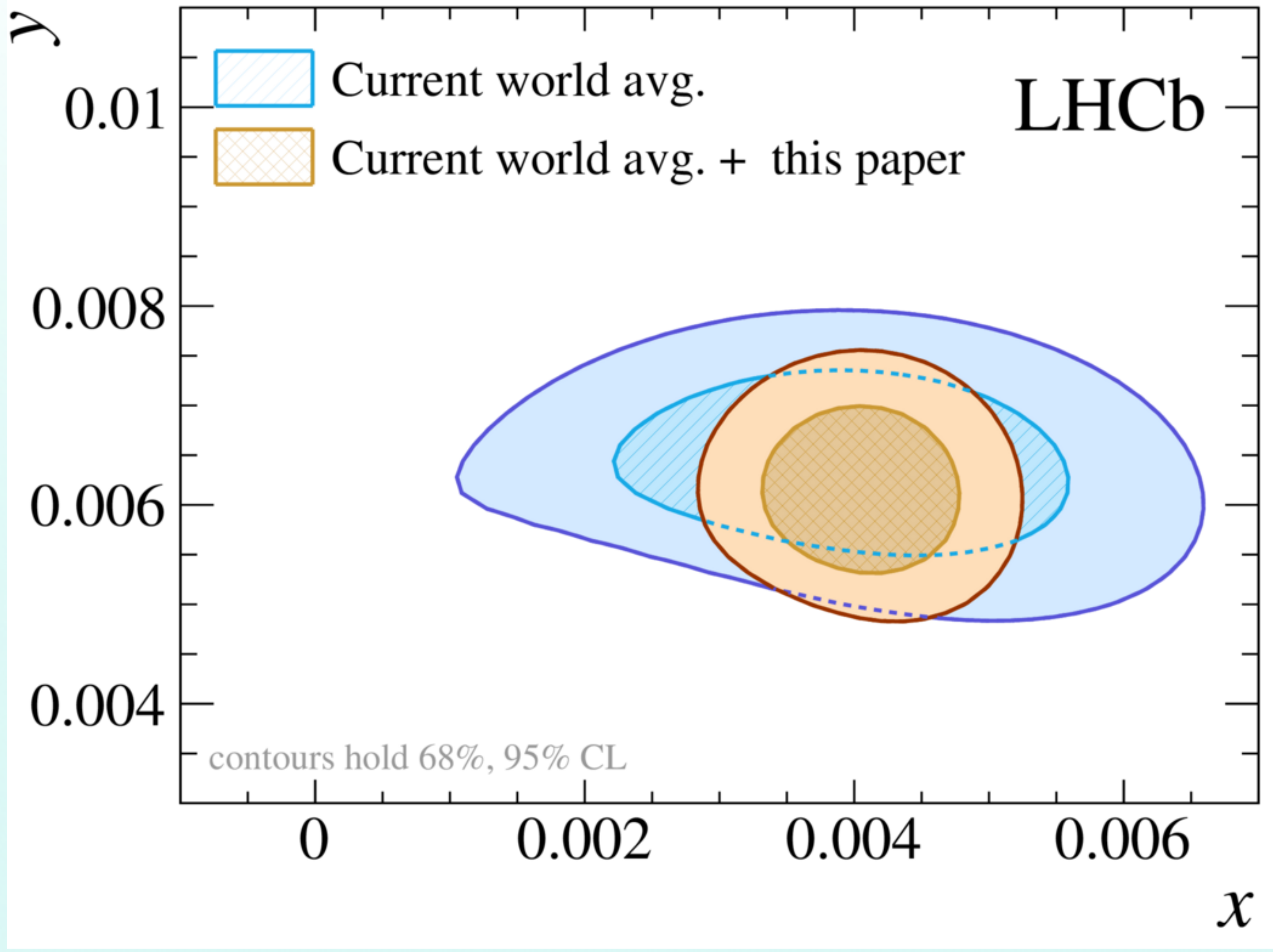
Relation to experiment:

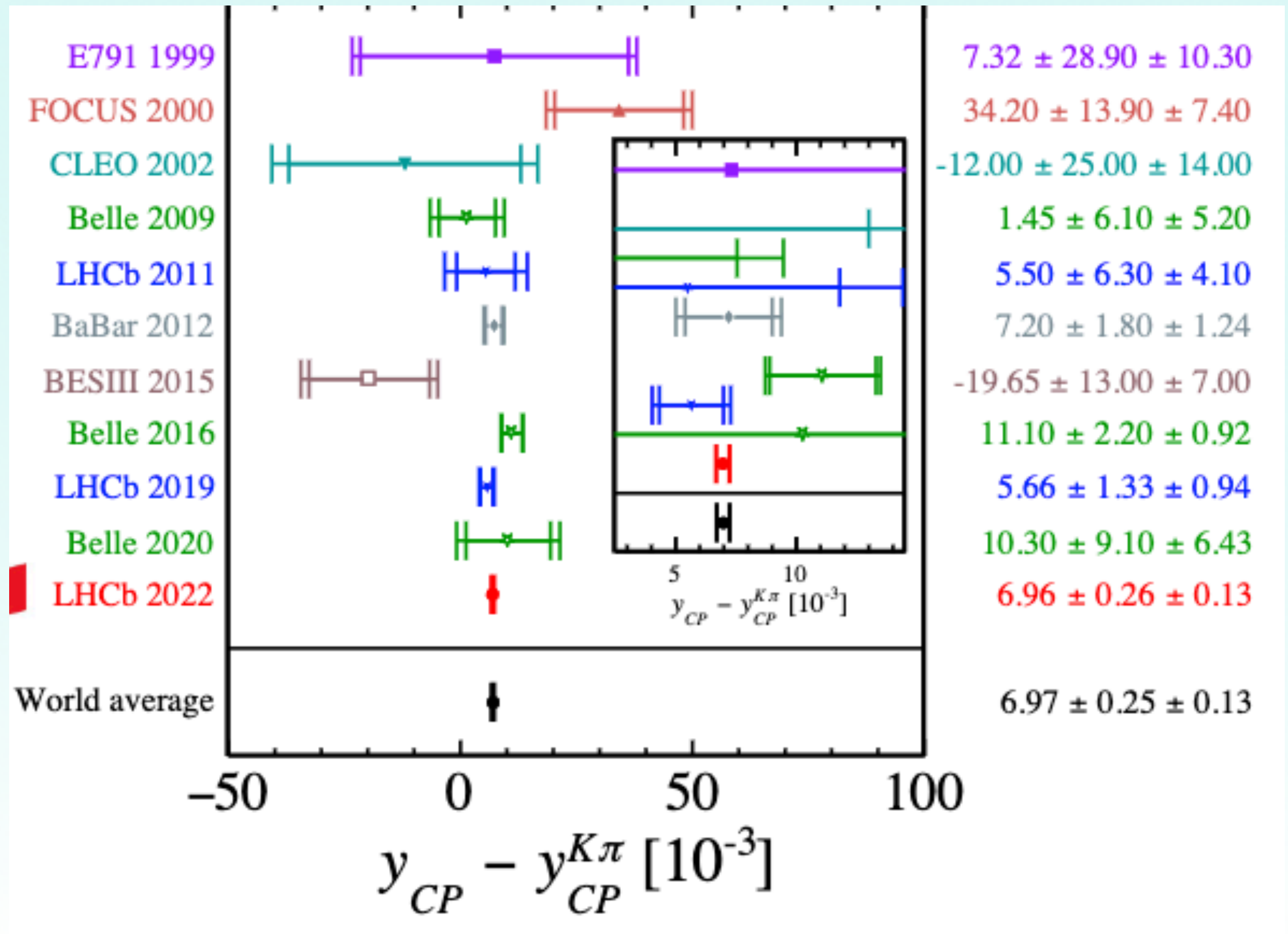
- Theoretical predictions are not expected to close the gap to experimental precision in the near future
- Exclusive approaches would benefit from more measurements of branching ratios and phases

Some experimental highlights since previous CHARM:

- First non-zero observation of x PRL 127, (2021) 111801
- Most precise determination of y Phys. Rev. D 105, 092013
- Simultaneous determination of the CKM angle γ and charm mixing parameters JHEP 2021, 141

Remarkable improvement in precision of both mixing parameters!





Most relevant experimental players on the field today

LHCb (BESIII)

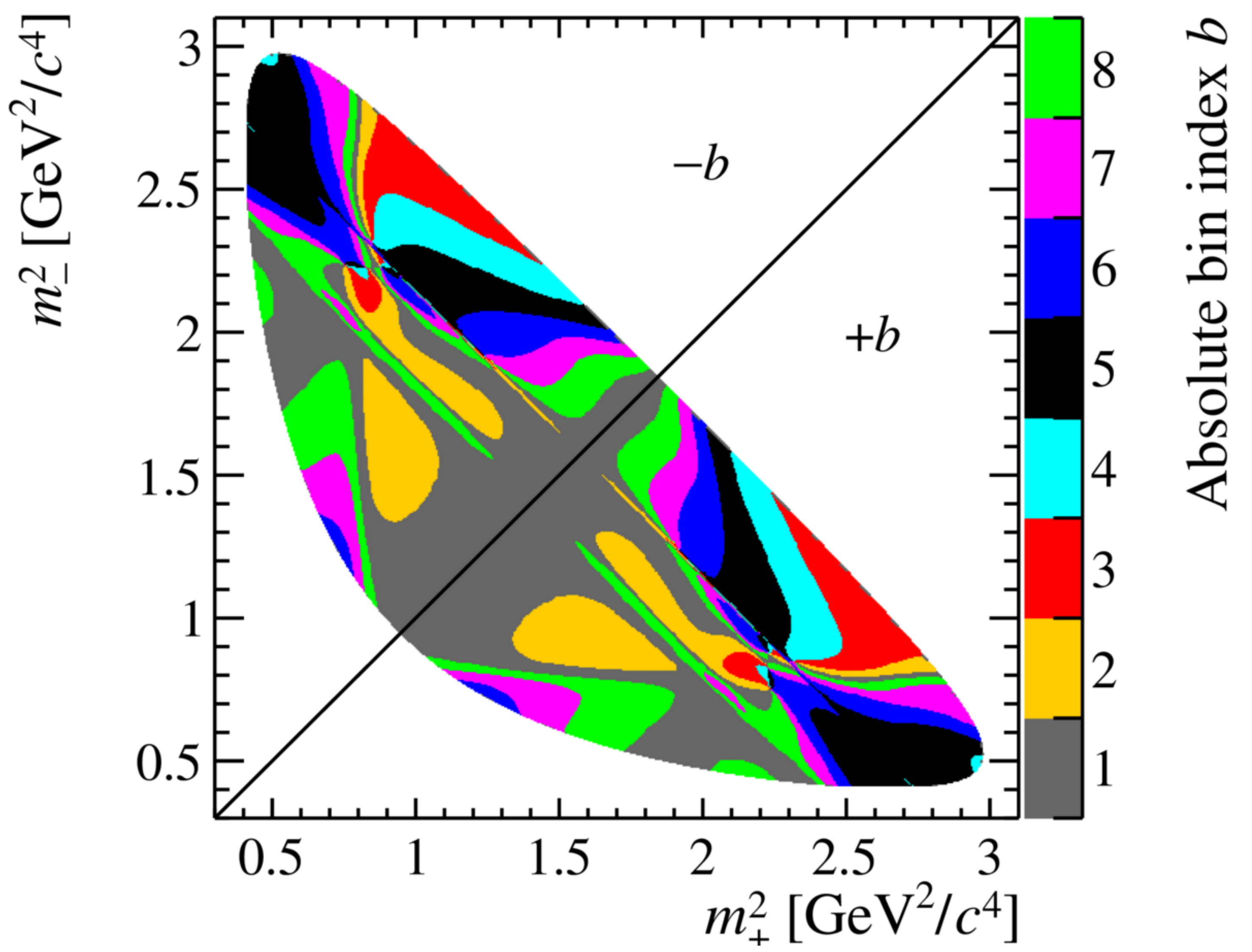
Mixing

Experimental studies

- Most often measured simultaneous with indirect CPV
- Methods:
  - 2 body time-dependent WS/RS
  - Effective lifetimes ratio (particularly y) - current most precise value
  - Multi-body time-dependent analyses:
    - Amplitude analyses
    - Binflip method (particularly x) - current most precise value

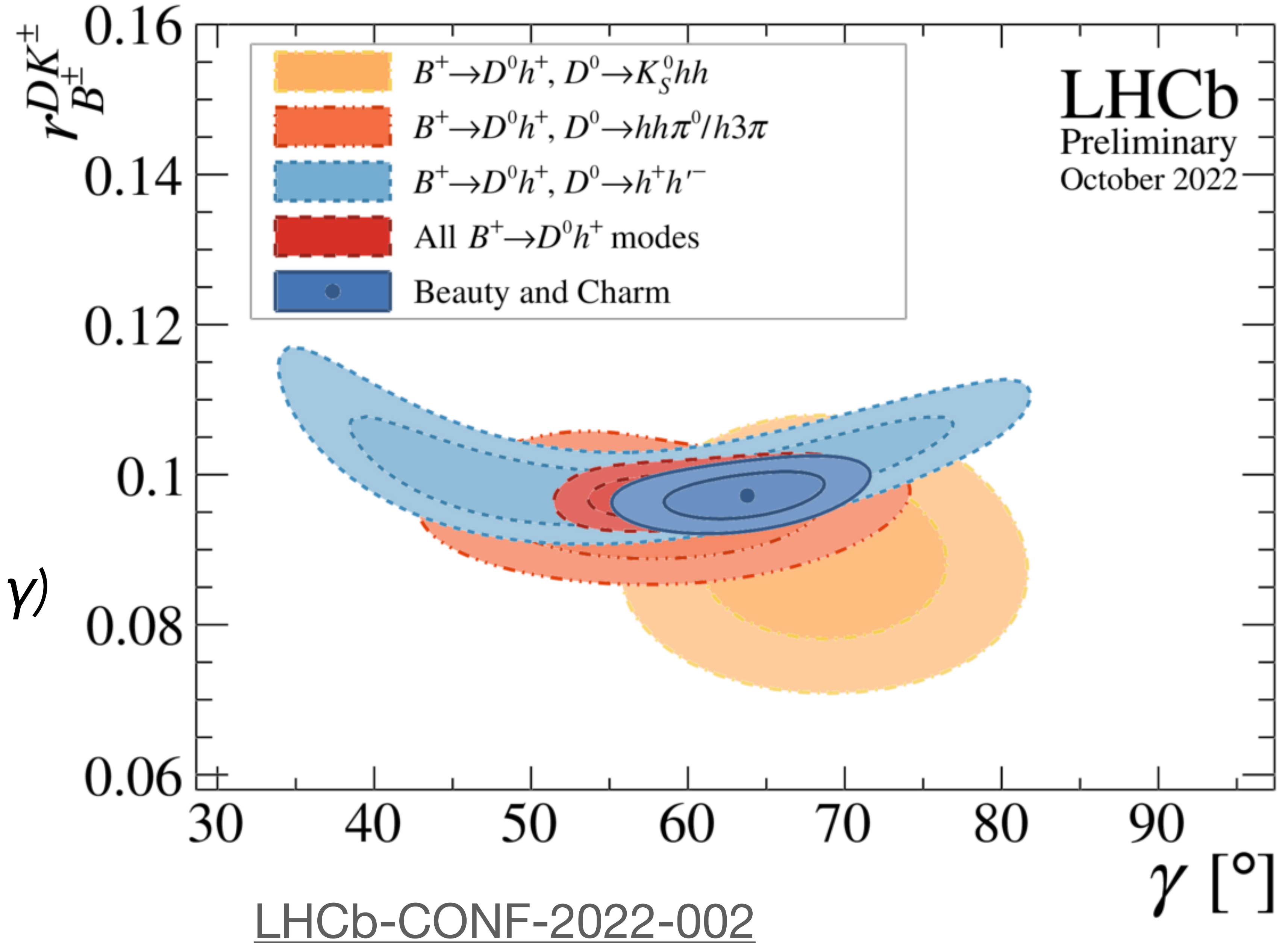
Relatively new

- Strong phases, coherence factors - crucial in some methods: inputs, interpretations (BESIII)
- Gamma combo
  - Framework expanded a for simultaneous measurement of CKM angle γ and D mixing parameters (2021)
  - New measurements are easily and continuously added



Phys. Rev. D82 (2010) 112006

Mutual improvement in precision (charm mixing, γ)

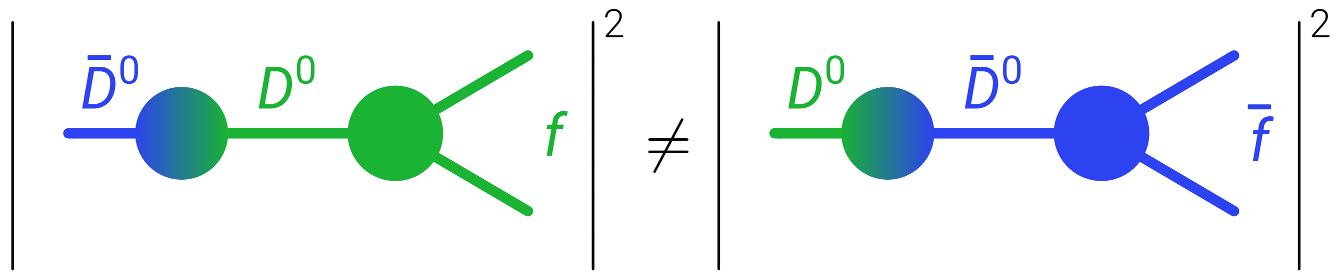


LHCb-CONF-2022-002

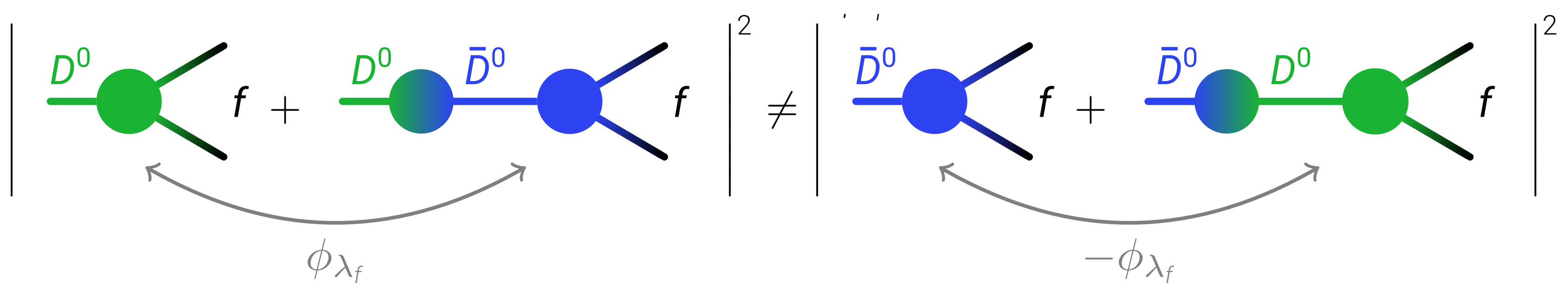
Jonas's talk [LHCb] (Tue afternoon)

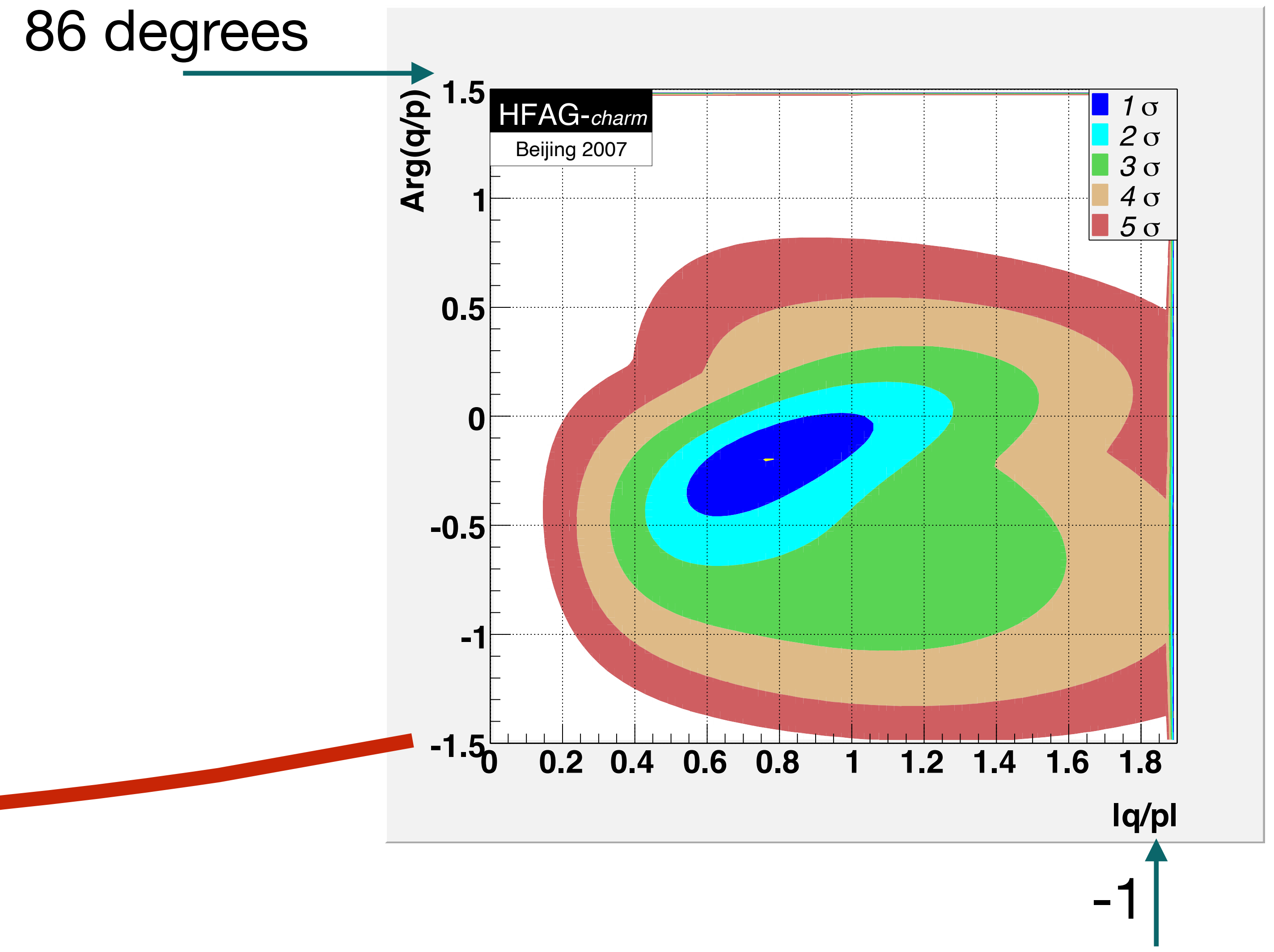
Indirect CPV

In mixing



In interference between mixing and decay

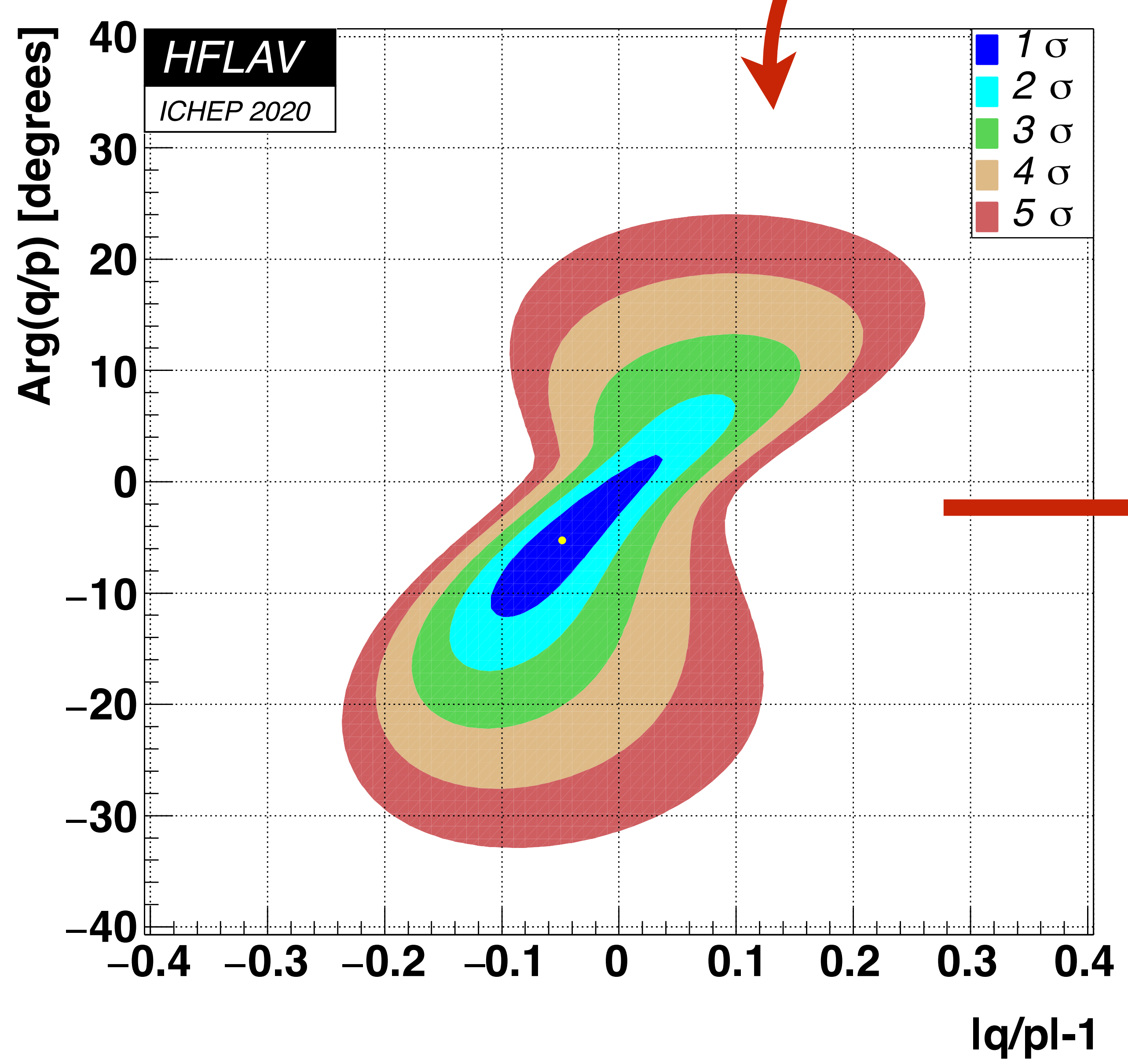


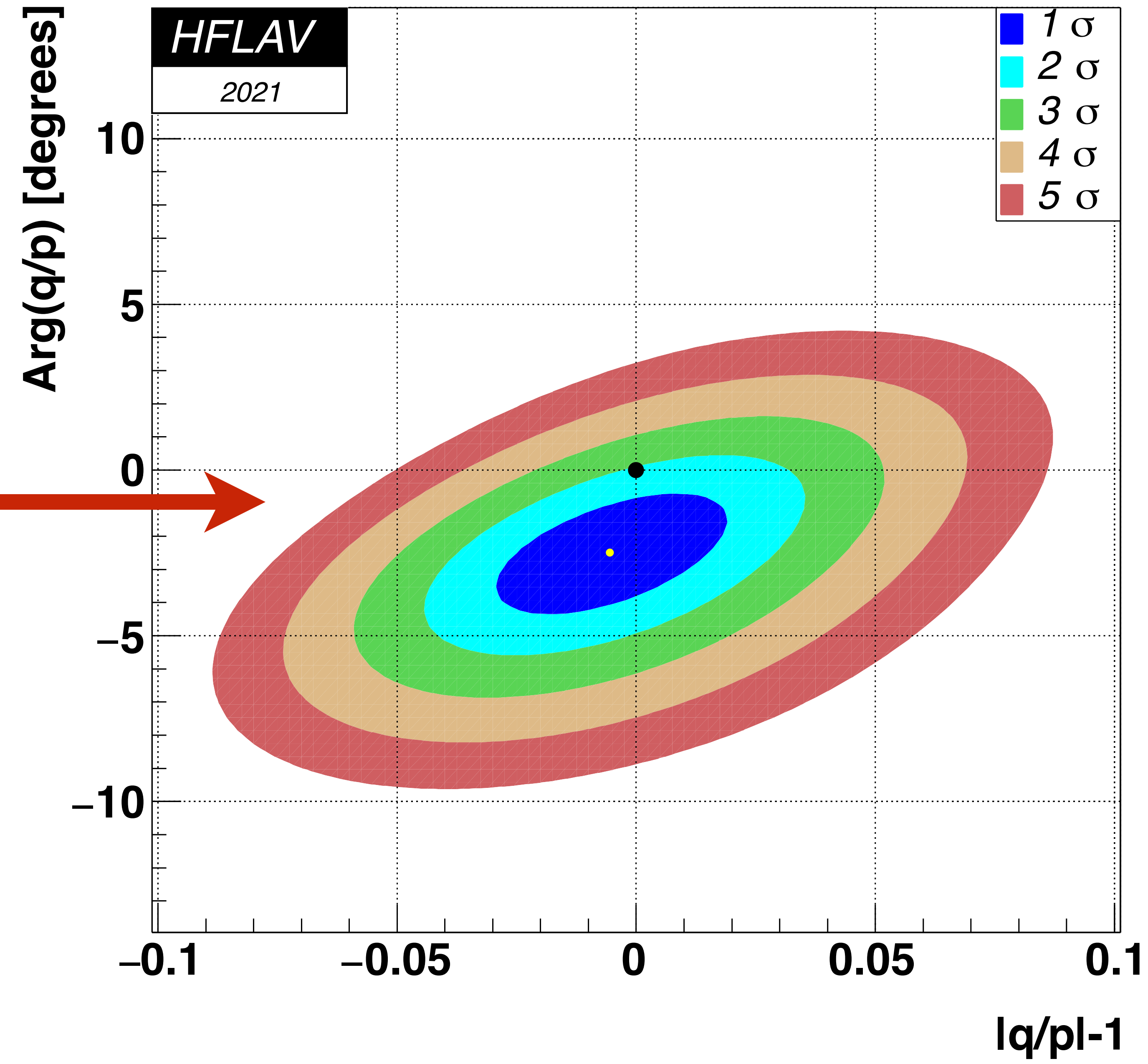


Adam's talk [LHCb]
(Mon afternoon)

Experimental status

Enormous progress has been made since the first CHARM workshop, and also since the previous one. Theory colleagues, please give us more precise SM predictions!





Notations

Many different notations on the market:
q/p, arg(q/p), ϕ, A_Γ, ΔY_f, Δy, Δx, CP-averaged mixing parameters x_{CP} & y_{CP}…

What is the least confusing way forward?

Summary

- The activity in the field of charm physics has been ~constantly **increasing**, and is still.

- Importance of **interplay with theory**! We make each other better.

- **Loads of important results since last CHARM**

  Jonas's summary talk Friday afternoon

  More hadron decays talks (Tue, Thu afternoon [BESIII], Fri morning [overview])

  - New types of exotics, plenty new excited states, evidence of intrinsic charm, several "first measurement of this type" in rare decays, evidence for A_{CP} in single channel, observation of mass difference between neutral charm mesons,

- Lots of important results are still to come. We are in a really good place with the complementary **group of machines** running right now.
  - It's great to see cross-experiment connectivity. And some healthy competition can be fun!

- Both detectors and techniques are improving

  Marko's talk [Belle II] Thu afternoon

  Giulia's talk [LHCb] (Thu afternoon)

  - Examples: Belle II's lifetime precision and tagger, LHCb's Run3 trigger improvements
  - **Beware:** for future predictions, scaling results of old machines with luminosity might not always be reliable

- **High statistics** challenges
  - High requirements on the control of systematic effects
  - Instrumental correlations
  - Will we still be able to do amplitude analyses at high statistics?
  - Storage (reduced data formats) and simulation (fast simulation, data-driven techniques)