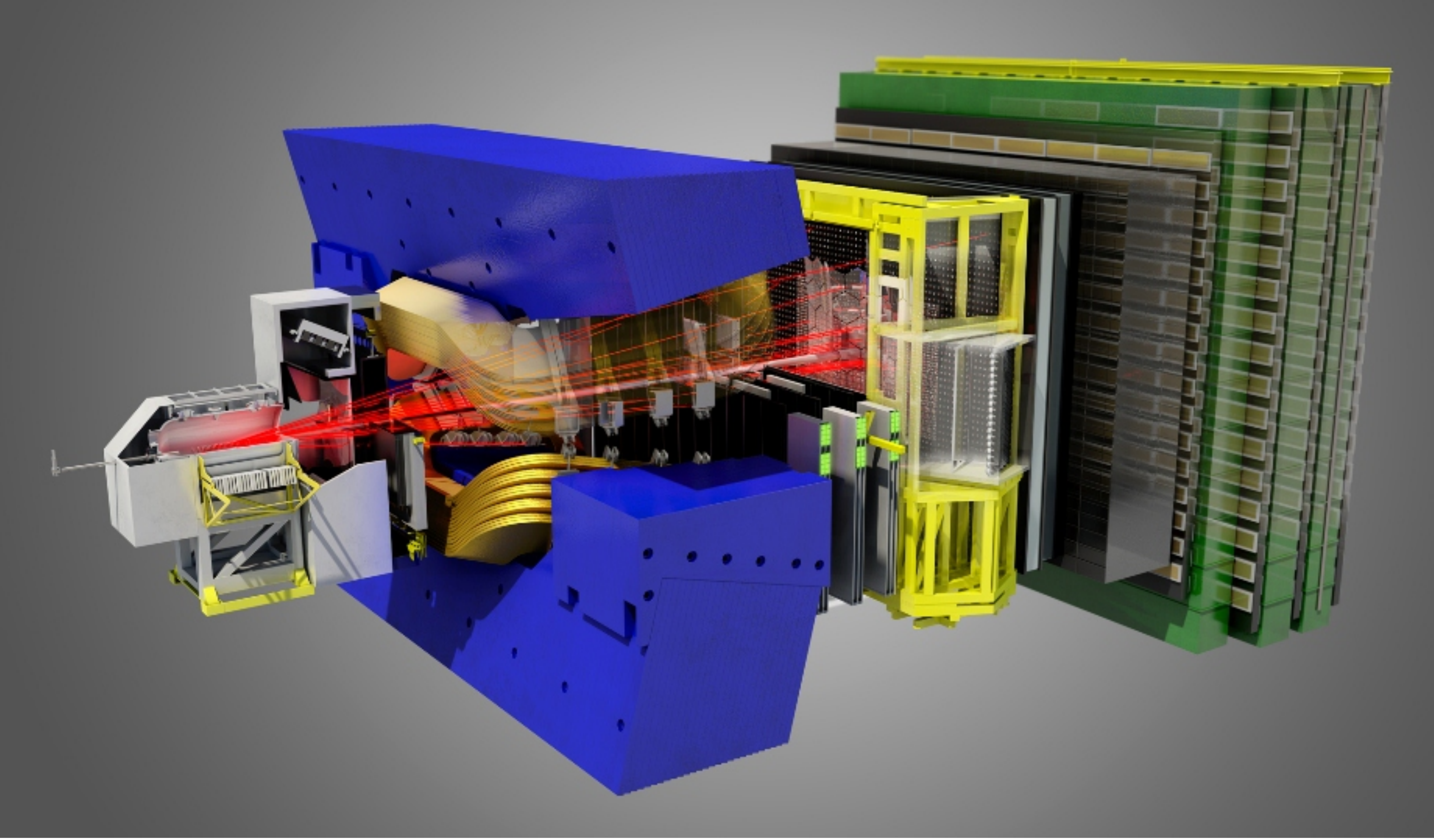
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Recent discoveries at LHCb

Marco Santimaria - LNF seminar 23/05/2019

Outline

1. The LHCb experiment
2. CP violation in charm decays
3. Pentaquarks
4. Lepton Flavour Universality test with R_K



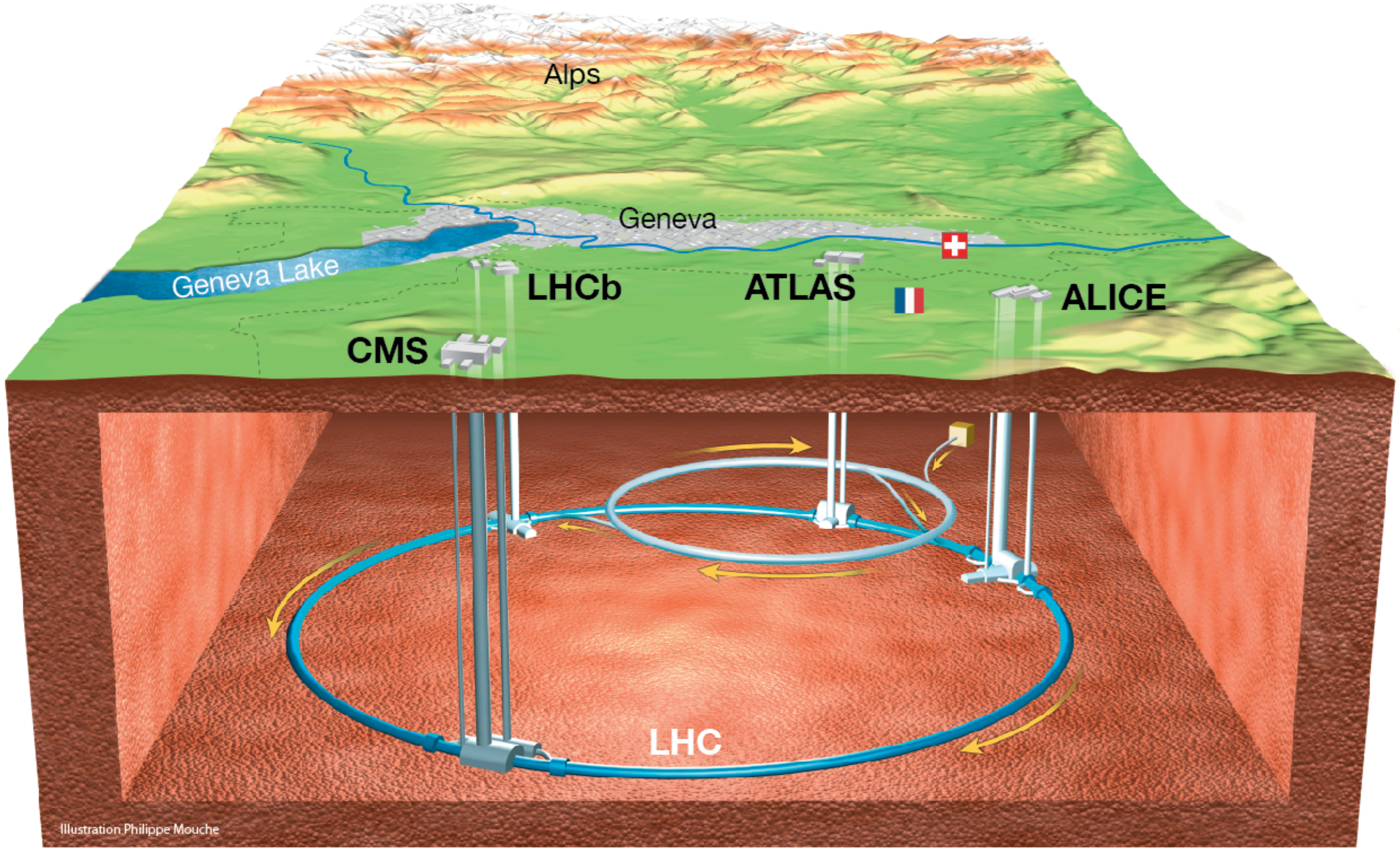
1.

The LHCb experiment

The LHCb experiment

LHCb public page

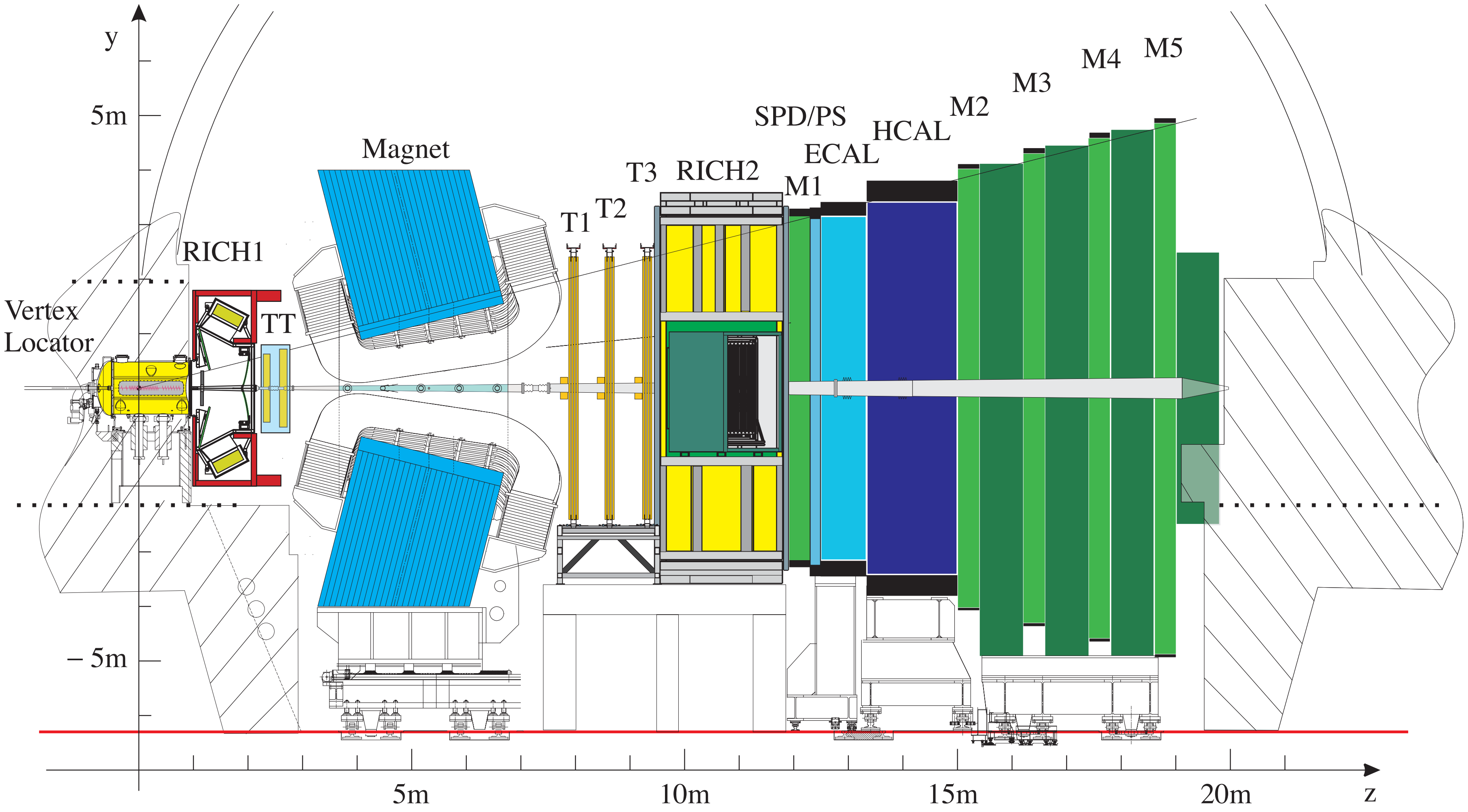
- LHCb is located at IP8 ~100m underground in the Geneva area
- One of the four big LHC experiments (>1200 members), it's primarily devoted to b and c physics
- Main topics concern CKM parameters, CP violation, rare decays: search for New Physics via precision measurements → high discovery potential
- LHC Run 2 at $\sqrt{s}$ =13 TeV ended in 2018, now upgrade phase towards Run 3 (2021)



https://cds.cern.ch/record/1708847

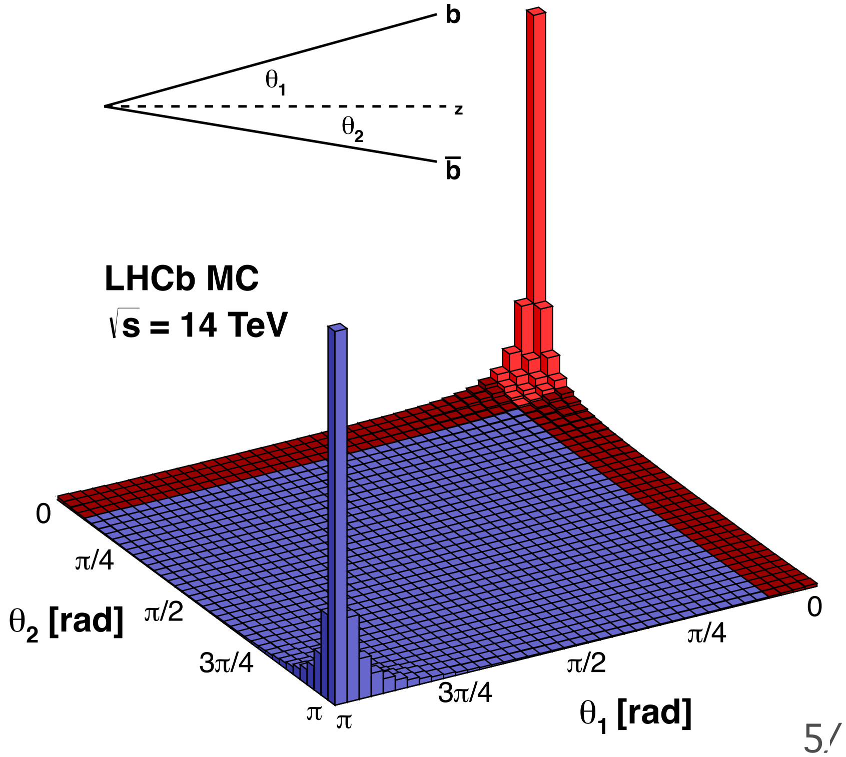
The LHCb detector

JINST 3 (2008) S08005



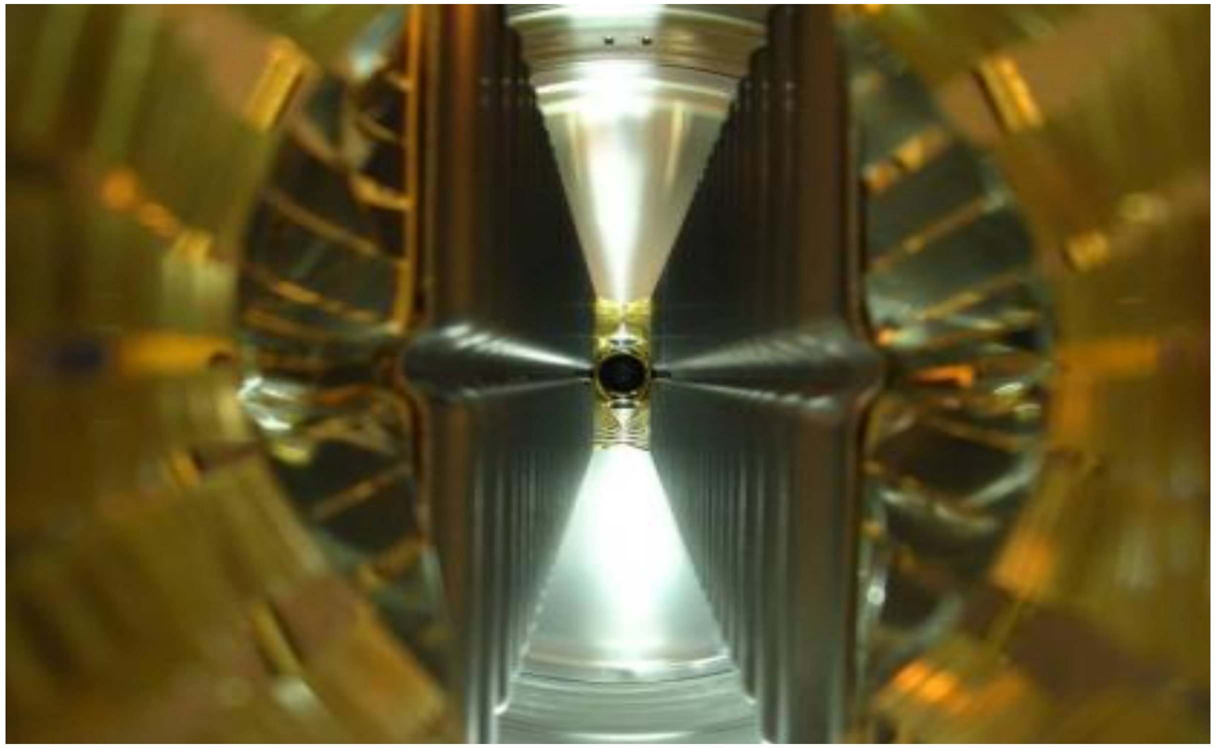
- Large b and c production cross-sections ($2<\eta<5$)
  $\sigma(pp\to b\bar{b})$ ~ 144 μb @ 13 TeV PRL 118 (2017) 052002
  $\sigma(pp\to c\bar{c})$ ~ 2840 μb @ 13 TeV JHEP 03 (2016) 159
  B^0:Λ_b:B_s production ratio is ~ 4:2:1 JHEP 08(2014) 143

- Production of all b hadrons
  B factory energies ~ up to B_s mass



The LHCb strengths

Int. J. Mod. Phys. A30 no. 07, (2015) 1530022



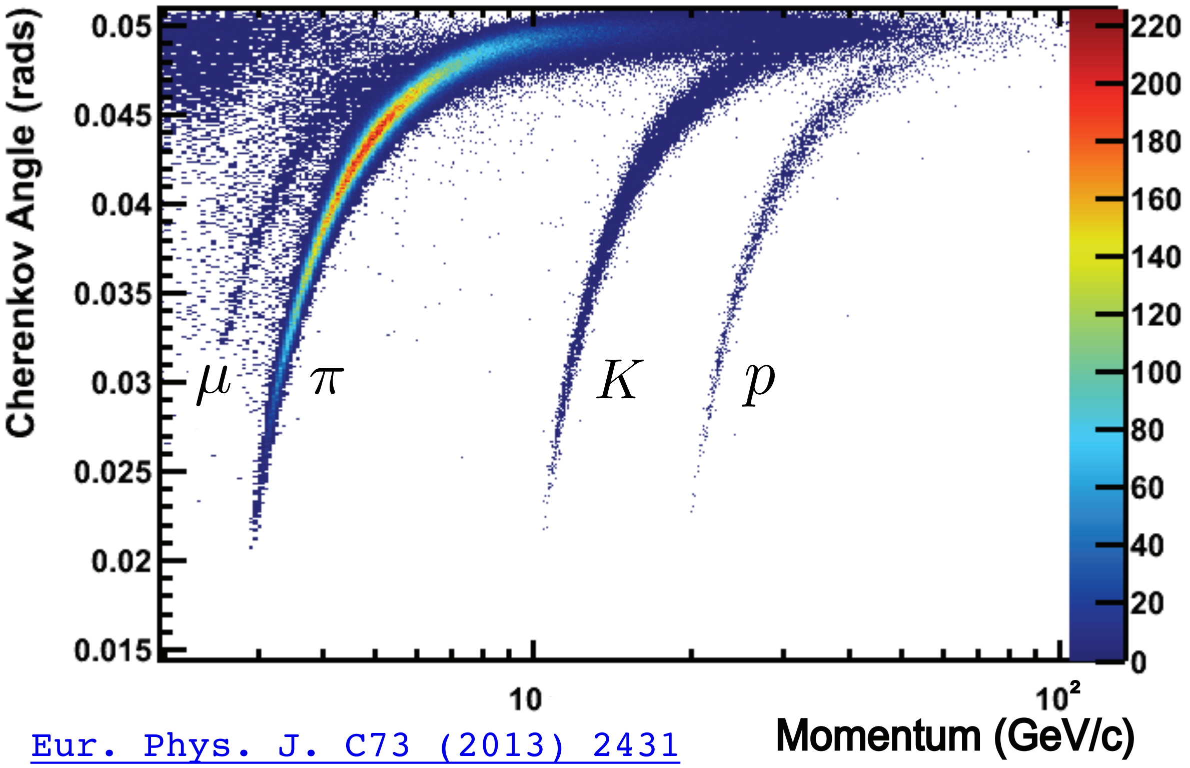
- B meson boost ~ 1 cm

Clear separation of displaced secondary vertex δ(IP) up to 20 μm

- Excellent momentum resolution

δp/p ~ 0.4%-0.6% (p = 5-100 GeV/c)

The VELO active area starts at 8 mm from the beam!



Eur. Phys. J. C73 (2013) 2431

- Particle identification detectors

Typical performances:

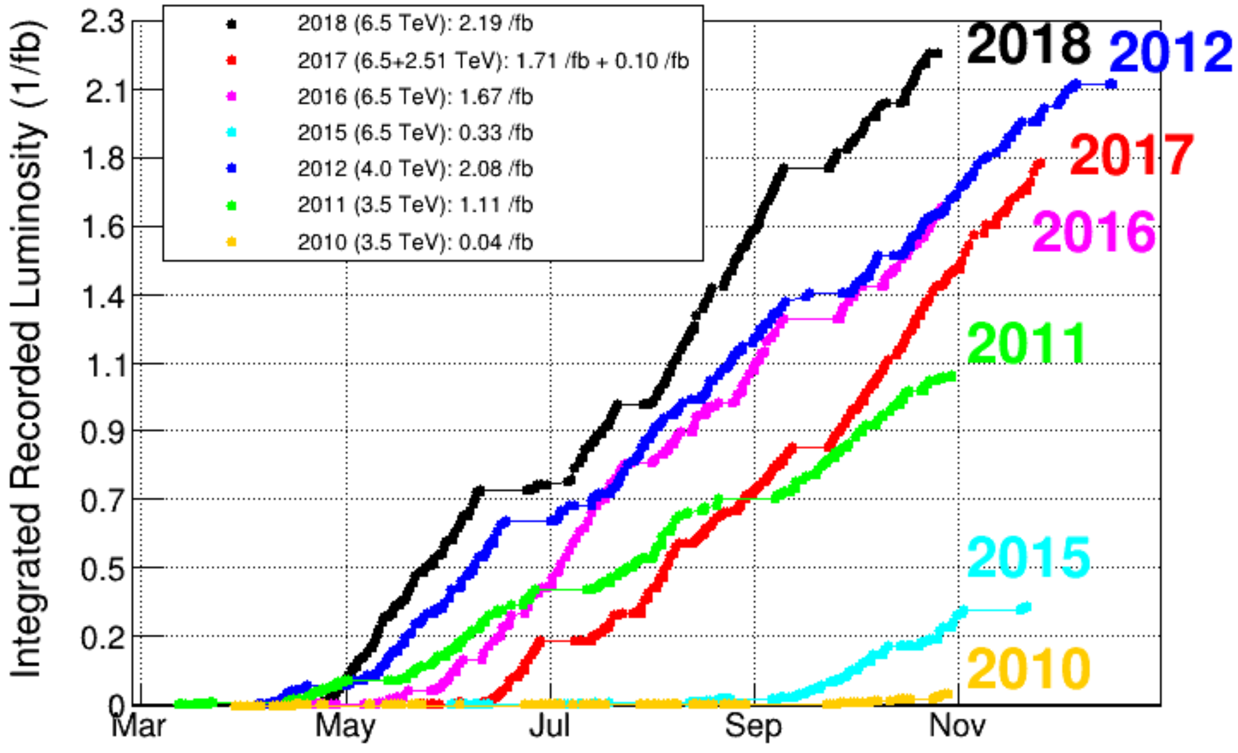
- 5% pion misID rate @ 95% kaon ID efficiency
- <1% hadron misID rate @ 99% muon ID efficiency

The muon detector

- Muons have a primary role in a lot of LHCb analyses
- About half of the 1368 MWPC on the muon detector have been built here in Frascati back in 2004, together with the development of their readout electronics boards

The chambers worked <u>very</u> efficiently for 10 years, and most of them will keep going in 2021!

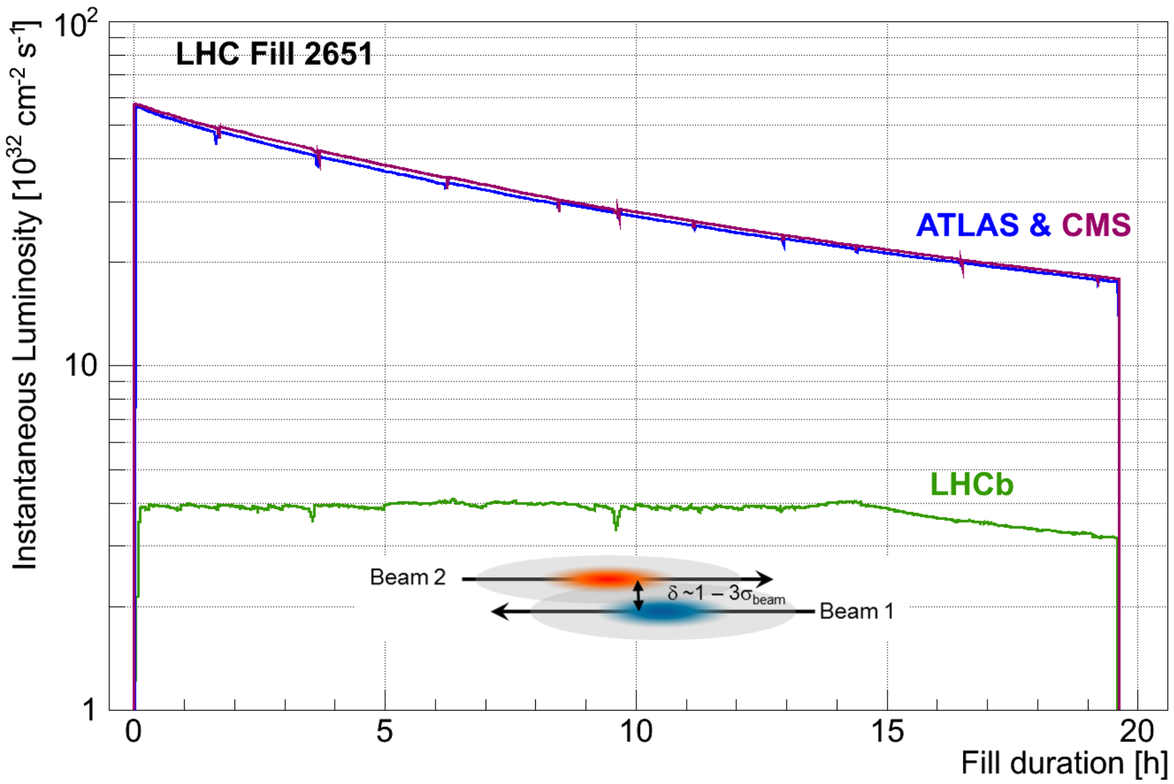
The LHCb data taking



LHCb operations plots webpage

- ~ 60 KHz of $b\bar{b}$ pair in acceptance @ 13 TeV
  ~10^4 more than B factories
- LHCb Run 1 + Run 2 =
  3 + 6 fb^{-1} (2 x b production)

Int. J. Mod. Phys. A30 no. 07, (2015) 1530022



- High LHC availability and efficient data-taking (ε~91%)
- Run 2 instantaneous luminosity levelled to 4.4×10^{32} $cm^{-2}s^{-1}$ (> 2 x design value)
- Average number of interactions per bunch cross is ~ 1.1

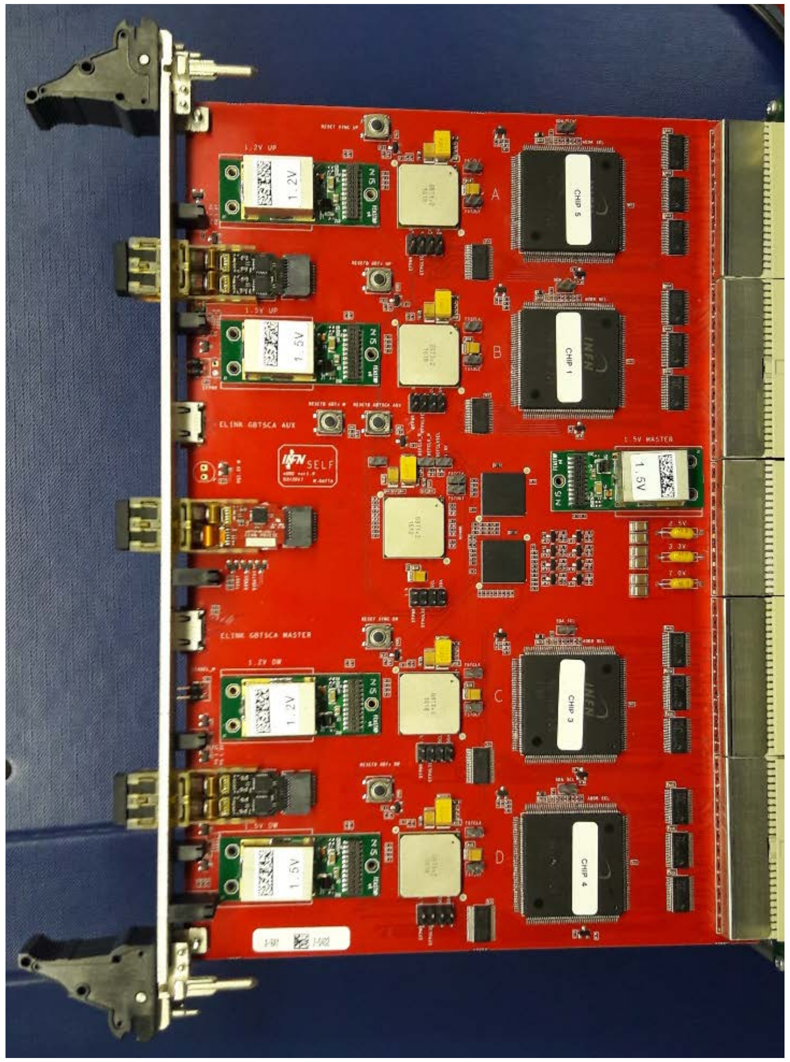
The LHCb Upgrade I (2021)

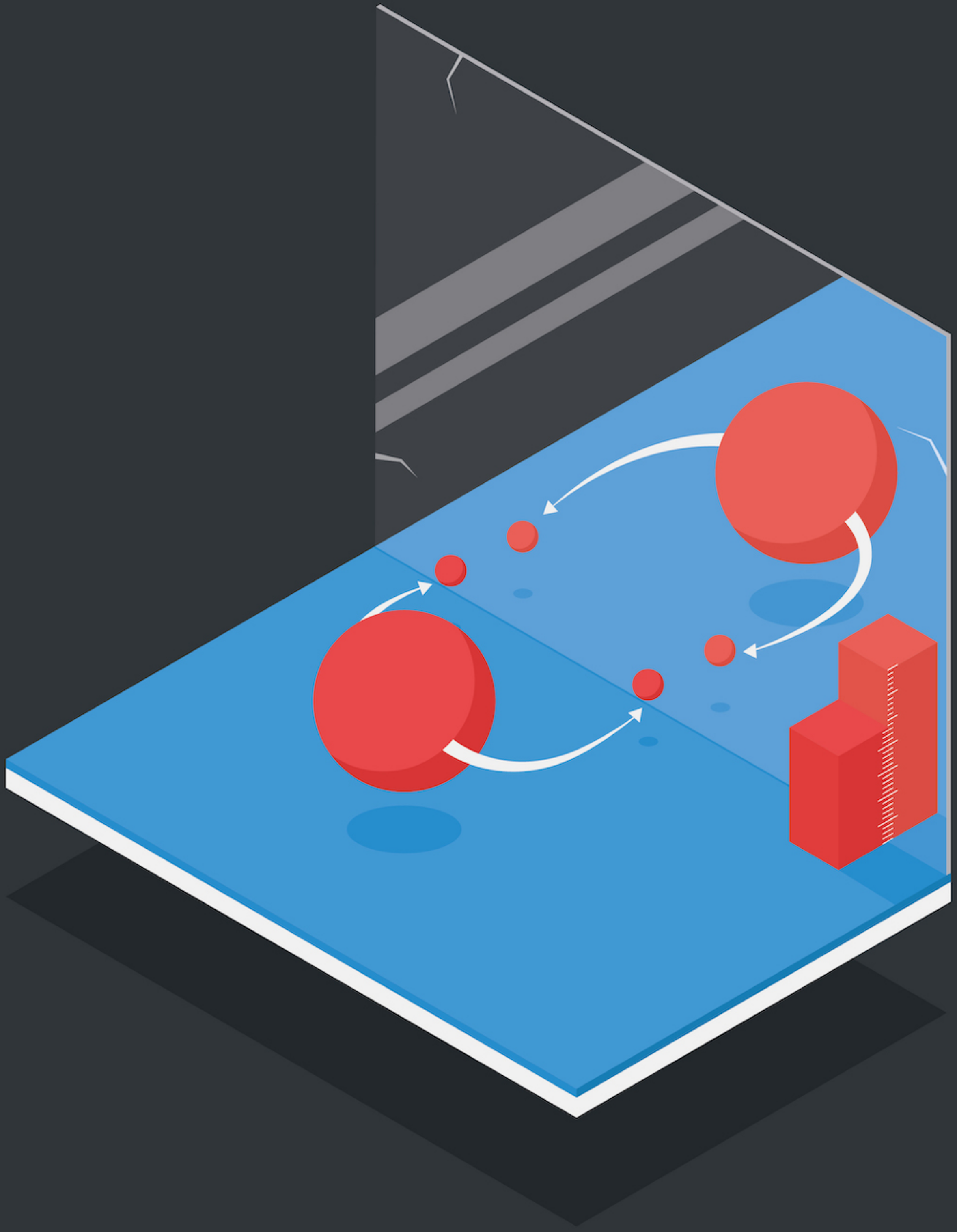
- 5 x more luminosity: $4 \times 10^{32} \rightarrow 2 \times 10^{33}$ $cm^{-2}s^{-1}$
- LHCb will feature a fully software trigger running at 40 MHz (Real Time Analysis)
- Several detector changes

JINST 14 P04006

LNF group is deeply involved in the upgrade:

- Production of 30 spare MWPC chambers
- Design and production of the new muon readout electronics board: from 1 to 40 MHz
- Development of the new muon software trigger





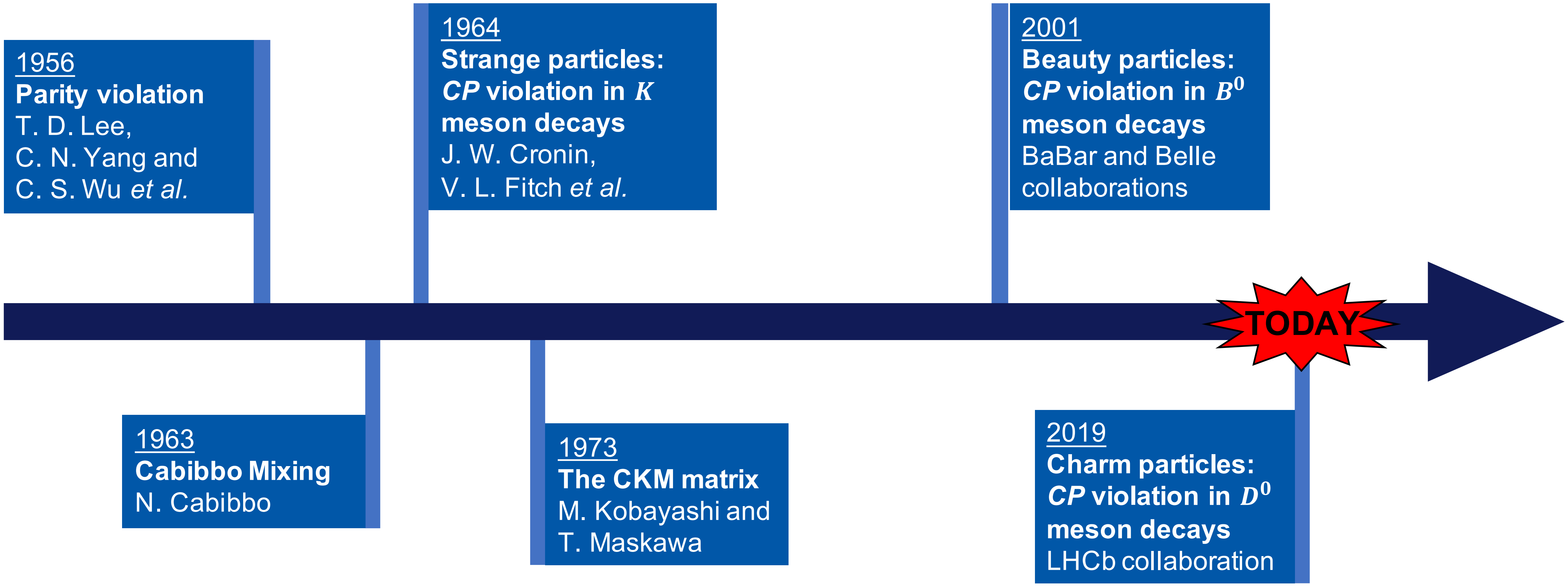
2.

CPV in charm

History of CP violation

Violation of the CP symmetry is an ingredient to explain matter dominance in the universe.

[A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5 (1967) 32.]



1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
***CP* violation in K**
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

1973
The CKM matrix
M. Kobayashi and
T. Maskawa

2001
Beauty particles:
***CP* violation in B^0**
meson decays
BaBar and Belle
collaborations

2019
Charm particles:
***CP* violation in D^0**
meson decays
LHCb collaboration

https://cds.cern.ch/record/2668391

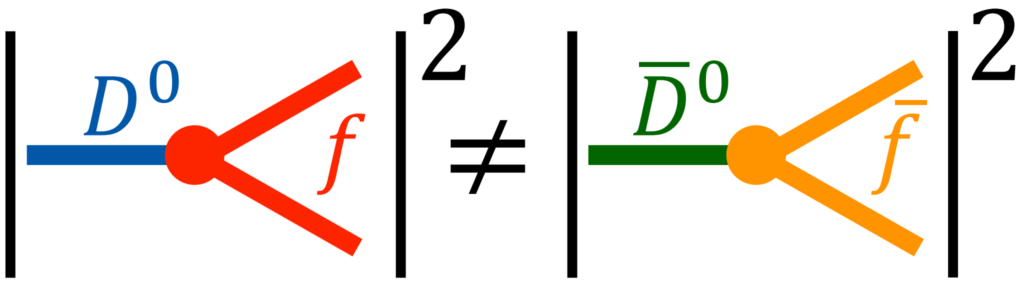
Charming CP violation:

- D meson allow to probe CP violation on up type quarks → complementarity to B and K mesons
- SM prediction burdened by low energy QCD, but tiny asymmetries are foreseen: 10^{-3} - 10^{-4} ArXiv:1111.5000
- Never observed before

Types of CP violation

The time-dependent CP asymmetry is defined as $A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to \overline{f})}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to \overline{f})}$

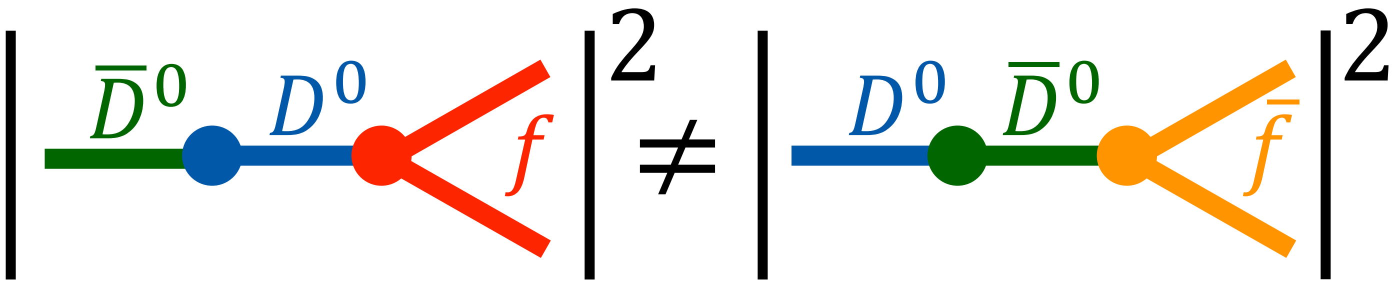
- Direct CP violation: $|A_f|^2 \neq |\overline{A}_{\overline{f}}|^2$



- Indirect CP violation

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

1. In mixing: $|p| \neq |q|$



2. In interference between mixing and decay: $arg\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right) \neq -arg\left(\frac{q}{p}\frac{\overline{A}_{\overline{f}}}{A_{\overline{f}}}\right)$

Definition of ΔA_{CP}

https://arxiv.org/abs/1111.6515v2

The time-integrated asymmetry can be written as $A_{CP}(f) \approx a_{CP}^{\text{dir}}(f) - \frac{\langle t(f) \rangle}{\tau(D^0)} A_\Gamma(f)$

but it's experimentally hard to measure because of production asymmetry (see later).

A cleaner observable can be build as the difference between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ asymmetries:

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \\ &\approx \boxed{\Delta a_{CP}^{\text{dir}}} - \frac{\Delta\langle t \rangle}{\tau(D^0)} A_\Gamma \end{aligned}$$

and it's mostly sensitive to the direct CPV component $\Delta a_{CP}^{\text{dir}} \equiv a_{CP}^{\text{dir}}(K^-K^+) - a_{CP}^{\text{dir}}(\pi^-\pi^+)$

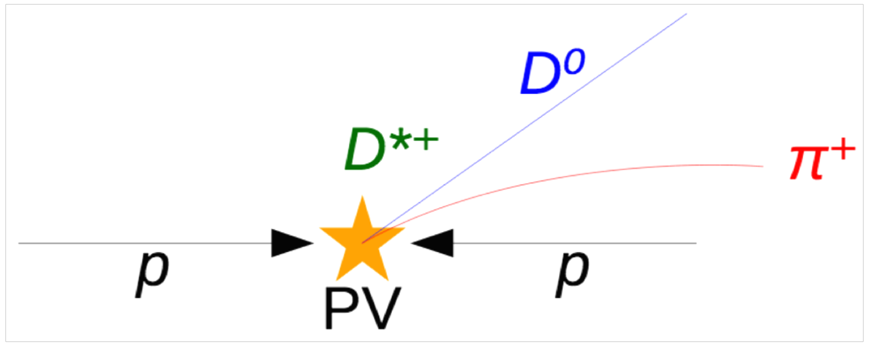
To extract this component from ΔA_{CP} one also needs:

1. The indirect CPV component $A_\Gamma \approx -a_{CP}^{\text{ind}}$ $\quad A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0 \to f} - \hat{\Gamma}_{\bar{D}^0 \to f}}{\hat{\Gamma}_{D^0 \to f} + \hat{\Gamma}_{\bar{D}^0 \to f}}$
2. The mean decay times of the reconstructed samples $\Delta\langle t \rangle = \langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}$

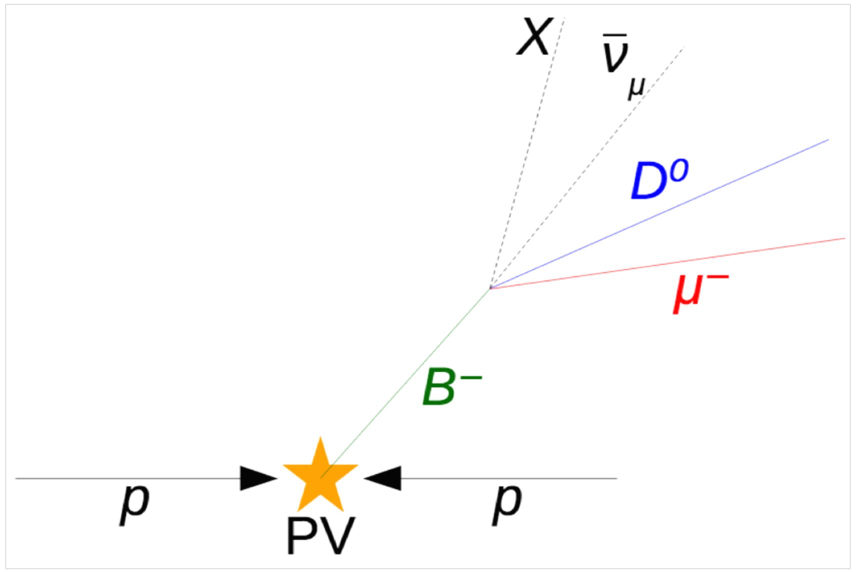
Flavour tagging

To identify the flavour of the D meson we look at the charge of the tagging particle in two samples:

1. Prompt $D^{*+} \to D^0 \pi^+$
   $D^{*-} \to \overline{D}^0 \pi^-$
   - The D^0 points to the Primary Vertex



2. Semileptonic $B^- \to D^0 \mu^- X$
   $B^+ \to \overline{D}^0 \mu^+ X$
   - Displaced vertex



https://cds.cern.ch/record/2668398

Huge charm production at LHCb: > 1 billion of $D^0 \to K^- \pi^+$ decays in the full LHCb sample!

→ complete event reconstruction and selection is performed online (Turbo stream)

Comput. Phys. Commun. 208 (2016) 35

Experimental strategy to measure ΔA$_{CP}$

The raw asymmetry $A_{\mathrm{raw}}(f) \equiv \dfrac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)}$

can be written as

$$A_{\mathrm{raw}}(f) \simeq A_{CP}(f) + A_D(f) + \begin{cases} A_D(\pi_s) + A_P(D^*) & \text{(prompt)} \\ A_D(\mu) + A_P(B) & \text{(semileptonic)} \end{cases}$$

Physical CP asymmetry

Detection asymmetry is 0 for symmetric final states

Detection asymmetry of the tagging particle and production asymmetry of the mother particle

After weighting the KK kinematics to match that of the ππ, ΔACP simply reads:

$$\boxed{\Delta A_{CP} = A_{\mathrm{raw}}(K^- K^+) - A_{\mathrm{raw}}(\pi^- \pi^+)}$$

which is independent of the detection and production asymmetries.

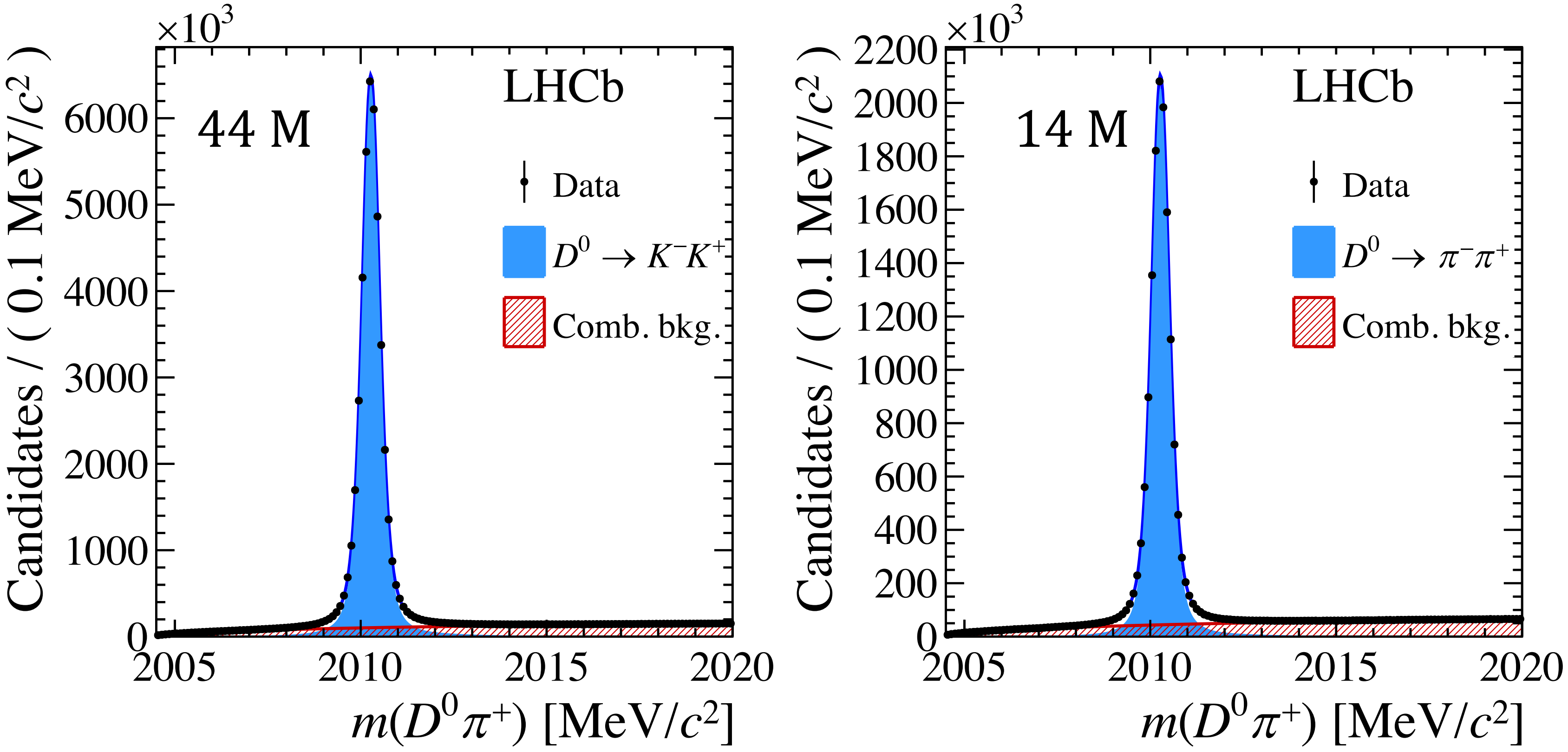
(The detection regions where the raw asymmetries of the tagging particles are large are anyway removed in the event selection)

A_{raw} measurement on Run 2 ($6\ \text{fb}^{-1}$)

ArXiv:1903.08726

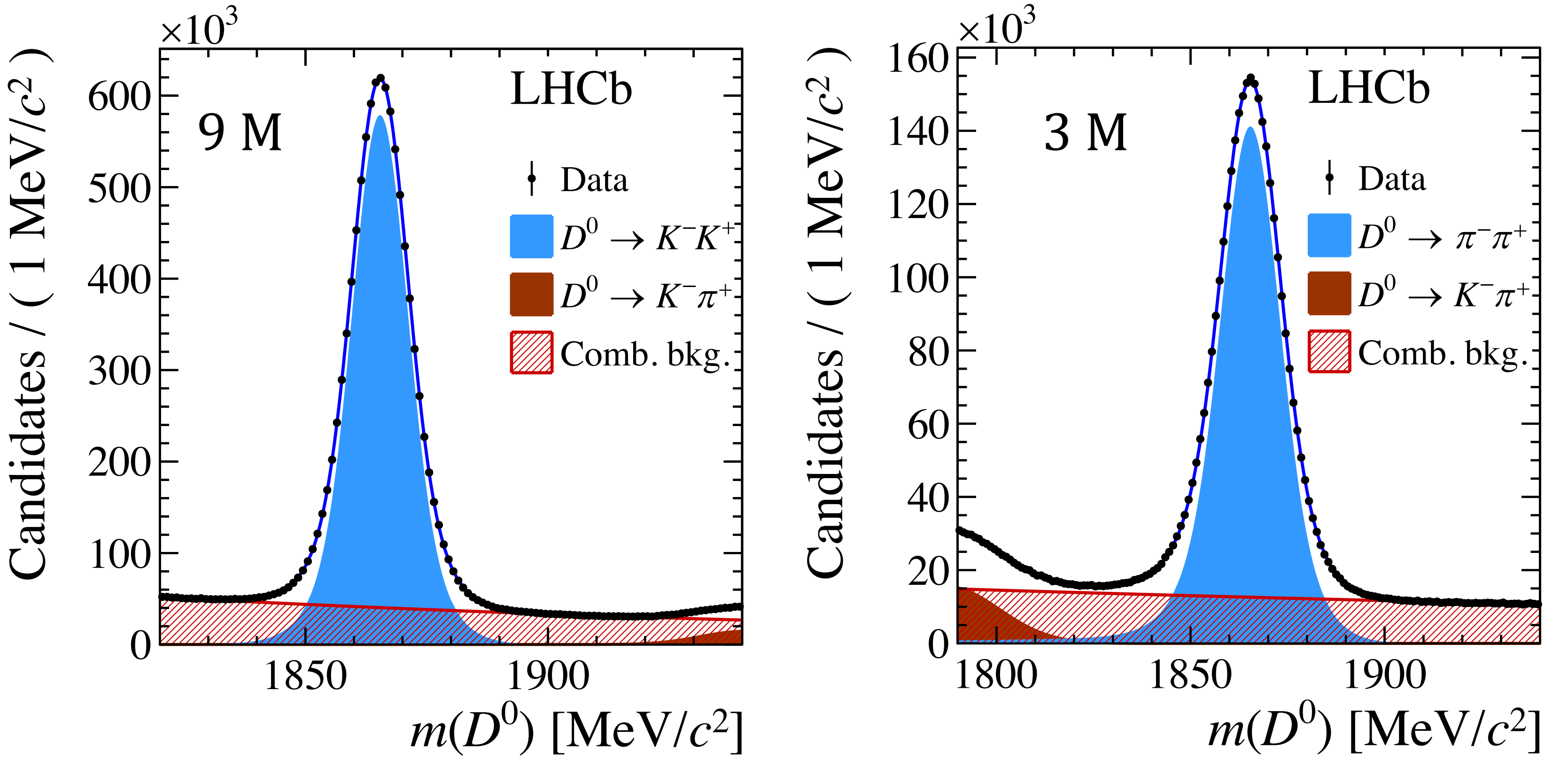
1. Prompt

- Fit to $m(D^0\pi)$
- A_{raw} parameter shared between D^{*+} and D^{*-}
- 44M K^-K^+ and 14M $\pi^-\pi^+$ events



2. Semileptonic

- Fit to $m(D^0)$
- A_{raw} parameter shared between D^0 and $\overline{D}^0$
- 9M K^-K^+ and 3M $\pi^-\pi^+$ events



Results

ArXiv:1903.08726

The fitted raw asymmetry yields

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

which combined with the LHCb Run 1 result gives: PRL 116 (2016) 191601

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

→ CP violation in charm observed at 5.3σ!

From this result, the indirect CP component is measured to be

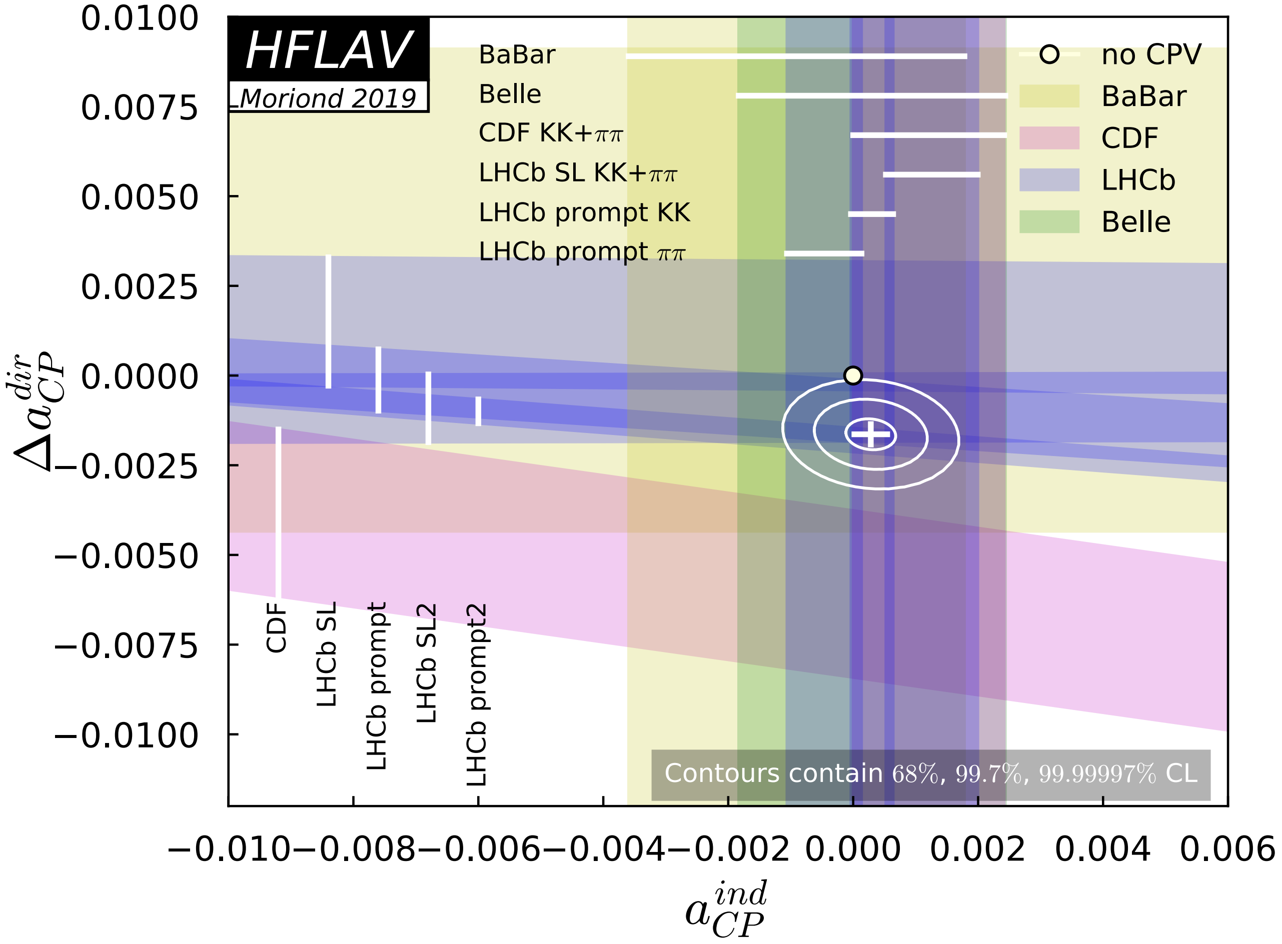
$$\boxed{\Delta a_{CP}^{\text{dir}} = (-15.7 \pm 2.9) \times 10^{-4}}$$

in the upper-end of the SM prediction, but more precision is needed.

Impact and future prospects

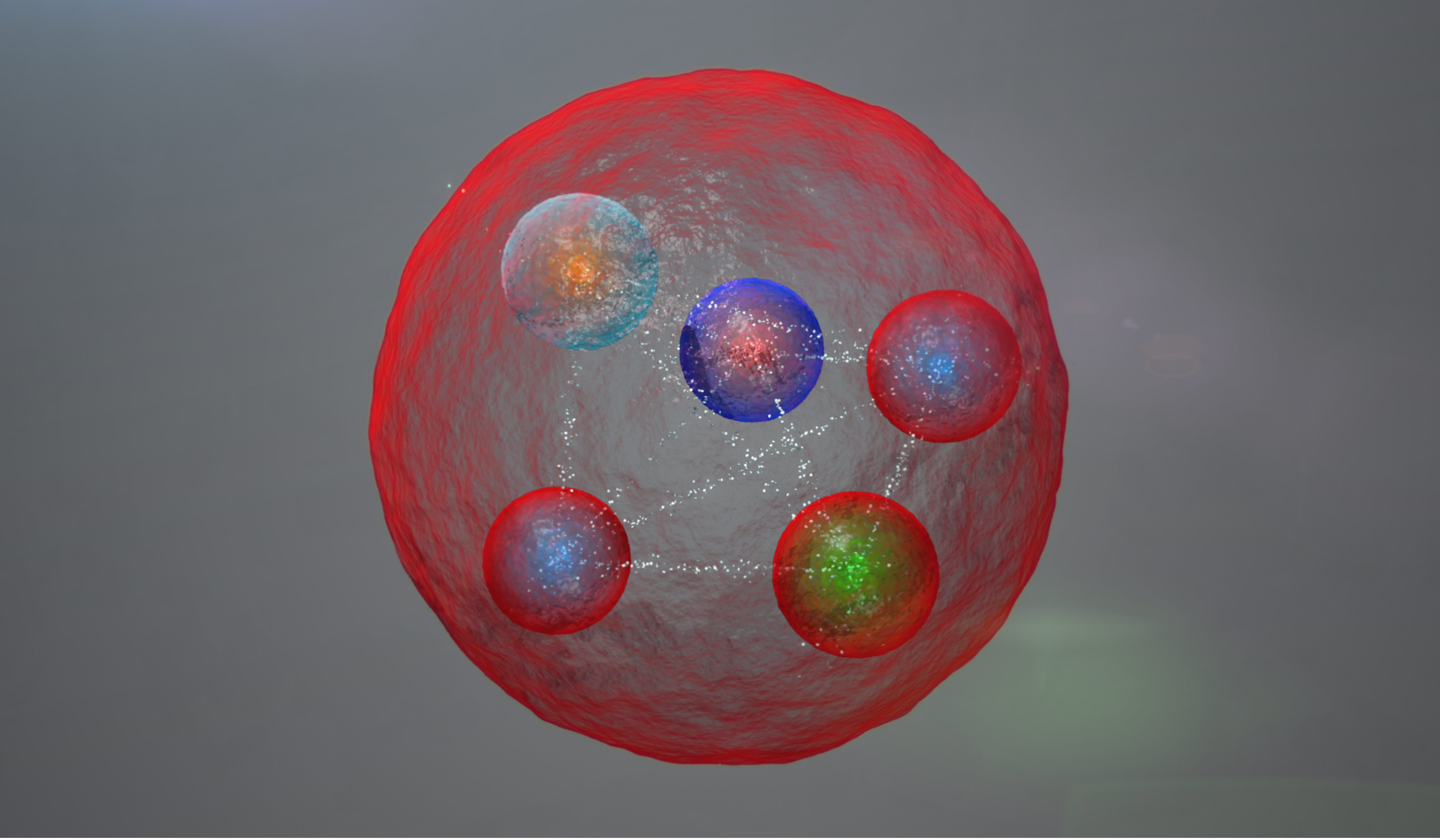
World average: no CPV hypothesis rejected at 5.44σ

The measurement is statistically limited: large improvement is foreseen with more data



Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^-K^+$	Yield $D^0 \to \pi^-\pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

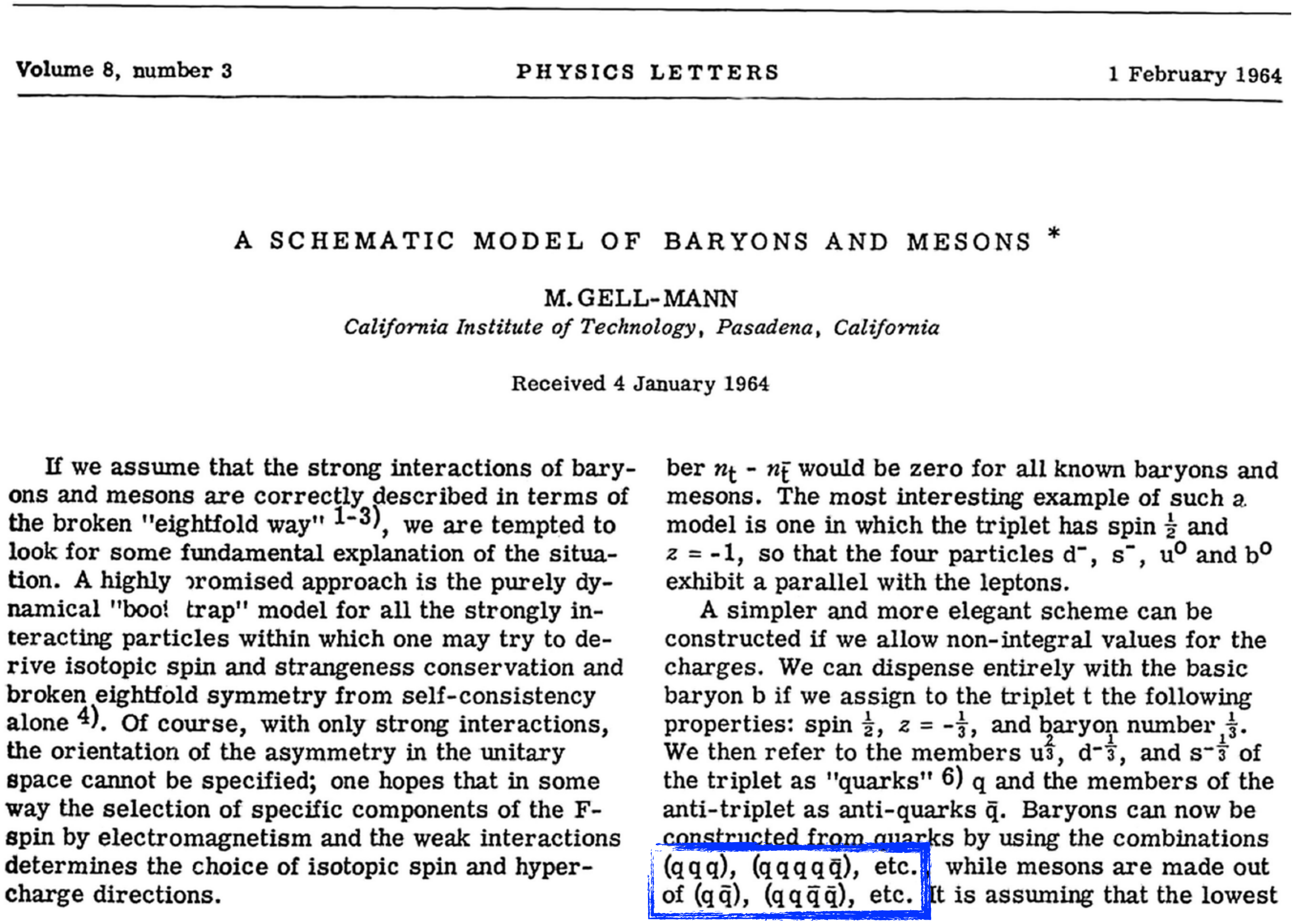
https://cds.cern.ch/record/2320509



3.

Pentaquarks

The quark model



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

Hadrons are built up with minimal quark content in the theory by Gell-Mann and Zweig, but nothing forbids multi-quark states

Semi-relativistic potential quite accurate in describing $c\bar{c}$ and $b\bar{b}$ states in the 70's

$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + \sigma r + \delta(1/r^2)$$

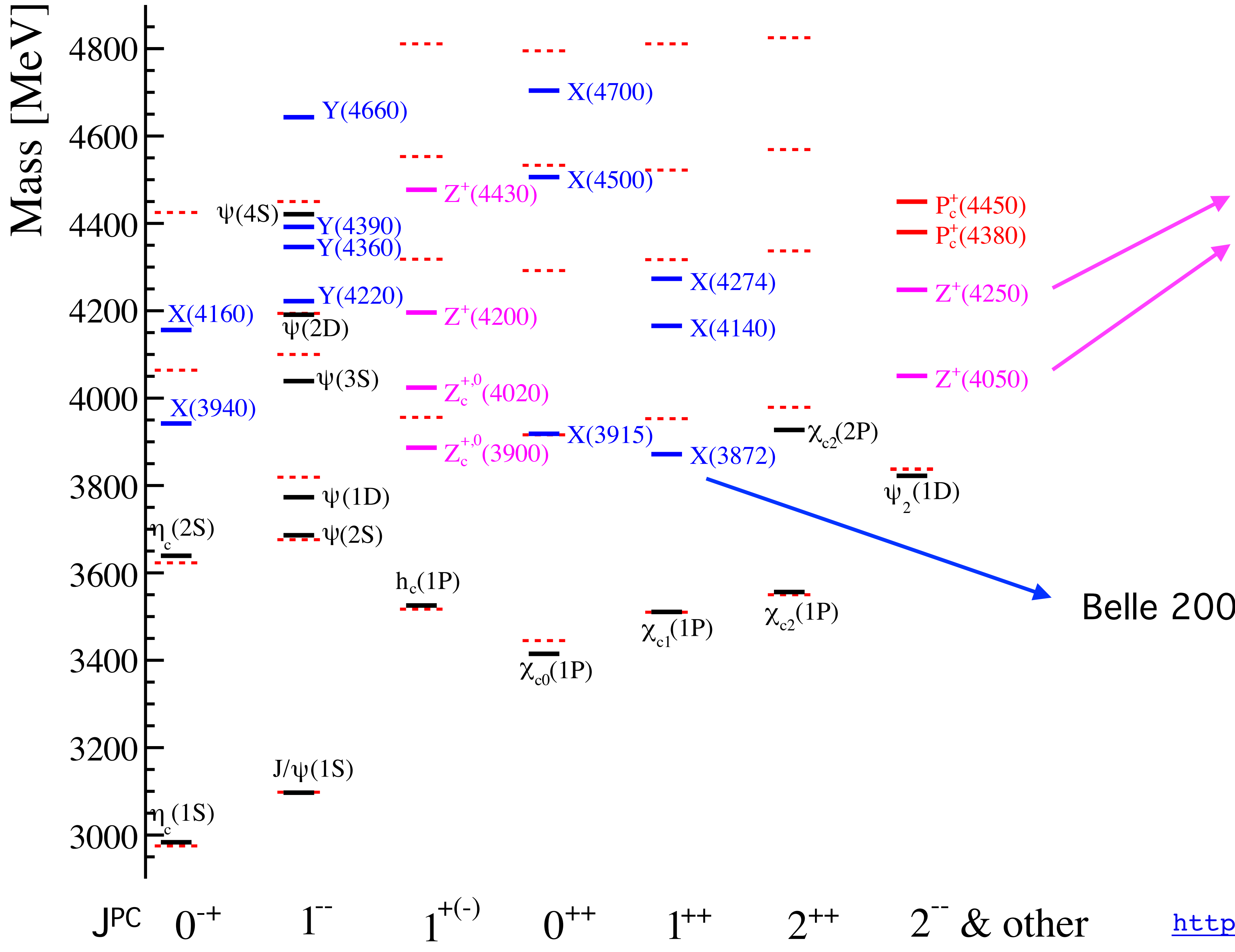
A short-distance **colour potential**

A long-distance **confinement** term

Spin-spin and **spin-orbit** corrections

Charmonium spectrum

Many states (—, —, —) outside the prediction (---) have been discovered in the past 15 years



Charged states decaying to J/ψ: minimal quark content is cc̄dū, a tetraquark!

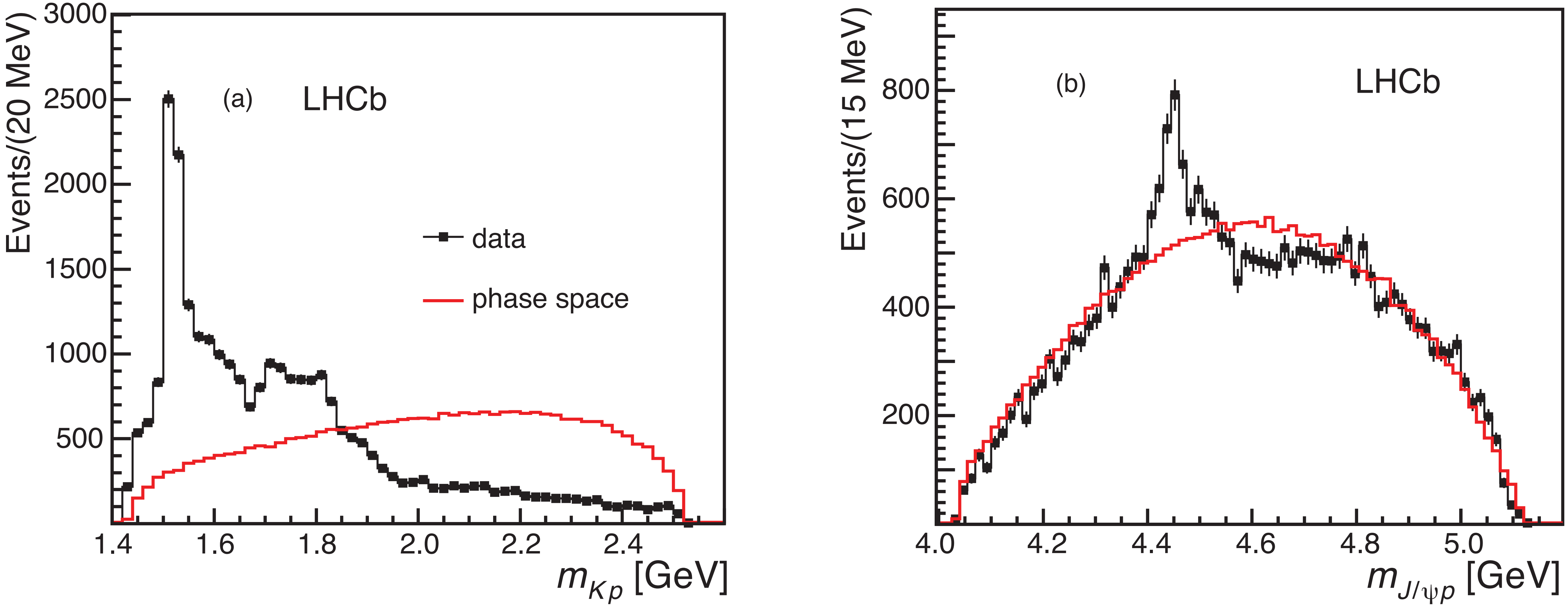
Belle 2003

http://cds.cern.ch/record/2673732

Labelled as “exotic” states: can help us understanding QCD interactions

The pentaquark saga

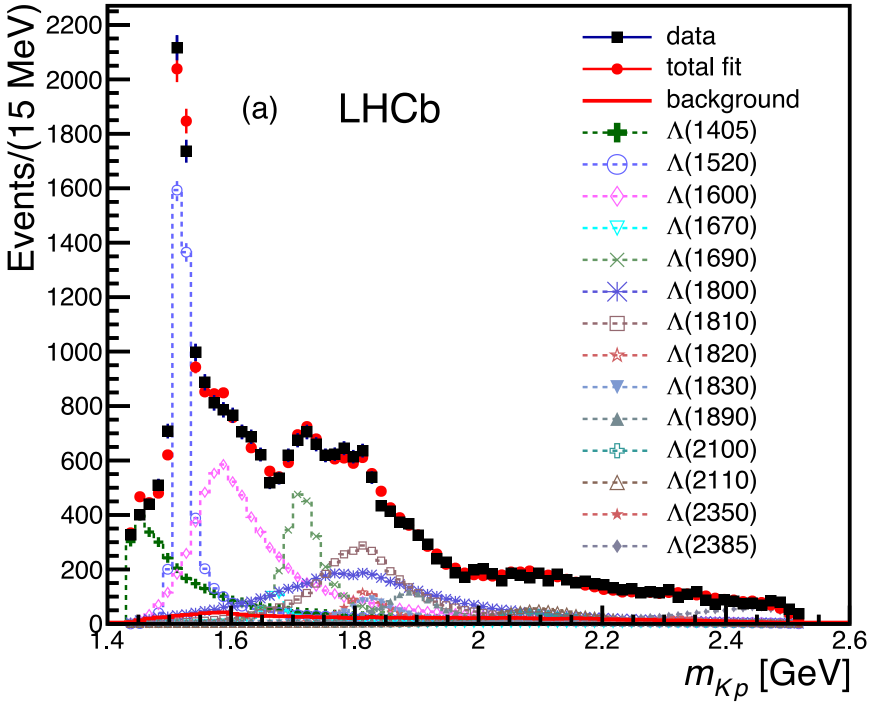
- Pentaquark searches started in the 70’s, no convincing evidence until 2002 with the $\Theta(1540)^+$ (by 3 experiments!) but ruled out by high-statistics runs [EPJH 37 1 (2012)]
- 2013: something strange in $\Lambda_b \to pKJ/\psi$ at LHCb [PRL 111 102003 (2013)] [JHEP 07 103 (2014)]
- 2015: dedicated analysis on Run 1 data reveals a peak in the $J/\psi p$ mass! [PRL 115 (2015) 072001]

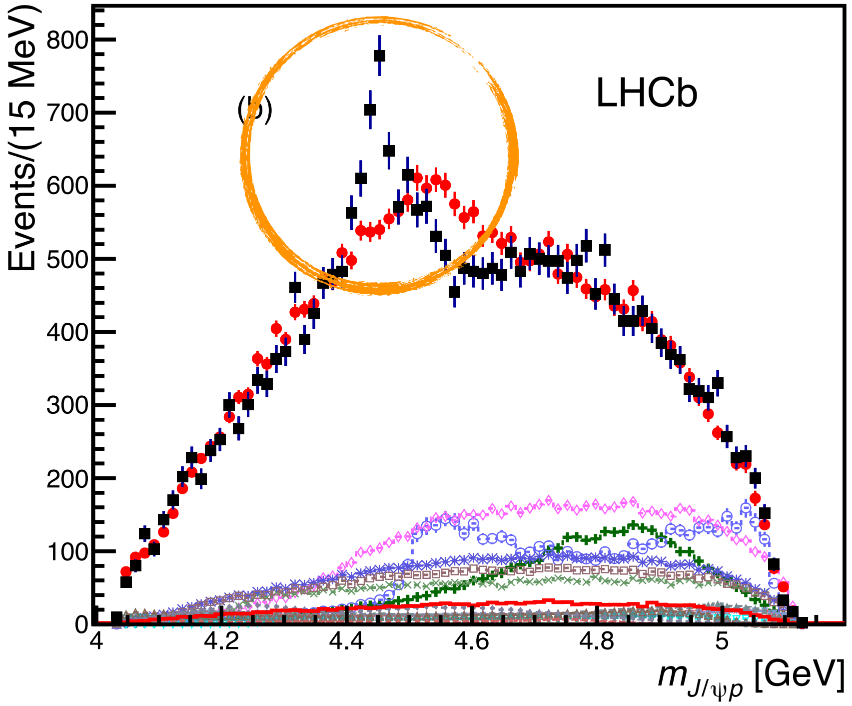


LHCb Run 1 analysis (2015)

[PRL 115 (2015) 072001]

Amplitude analysis with all known Λ* resonances reproduces m(pK) but fails on m(J/ψp).



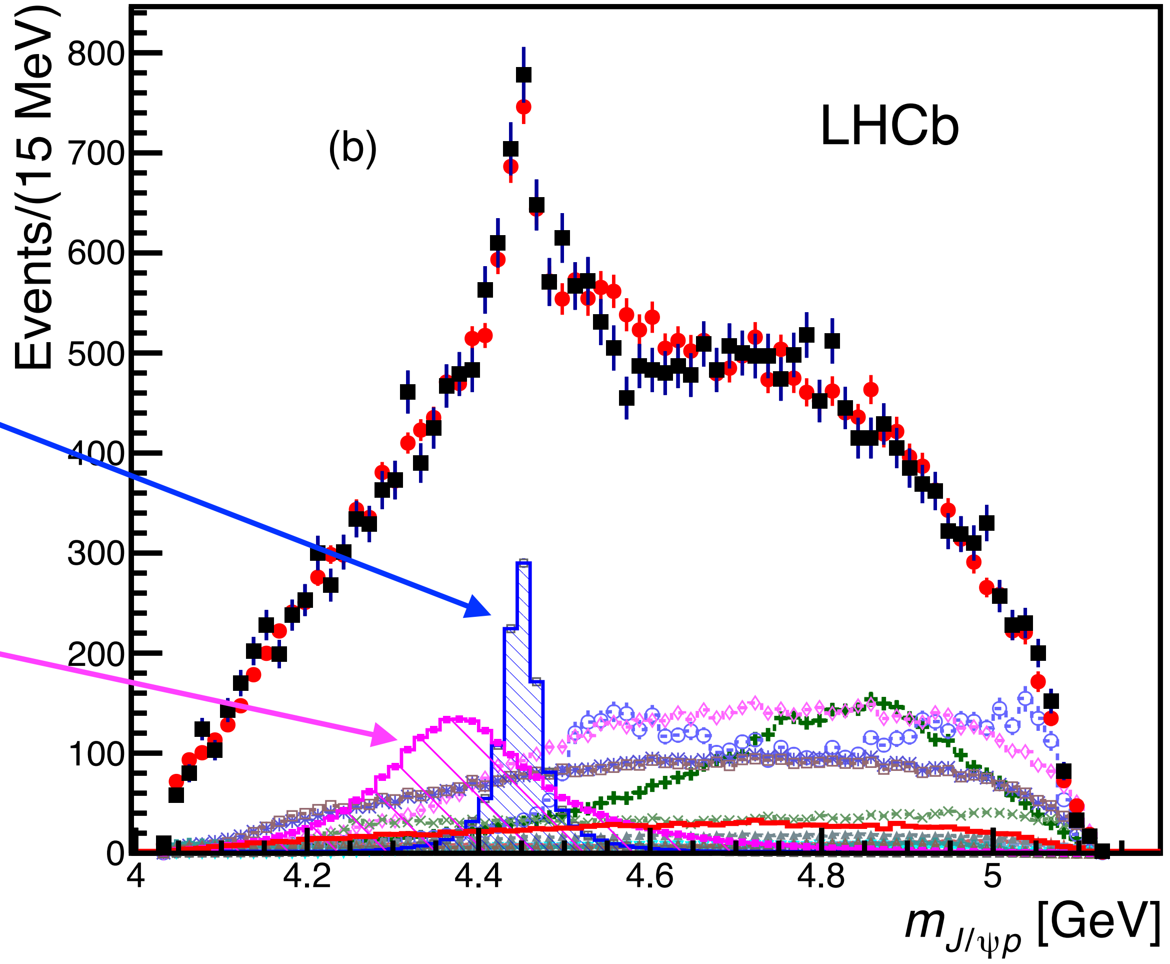


<u>TWO</u> P_c^+ states are needed to describe the data!

$$P_c(4450)^+,\ J^P = 5/2^+,\ \Gamma = 39 \pm 5\ \text{MeV}$$
significance 12σ

$$P_c(4380)^+,\ J^P = 3/2^-,\ \Gamma = 205 \pm 18\ \text{MeV}$$
significance 9σ

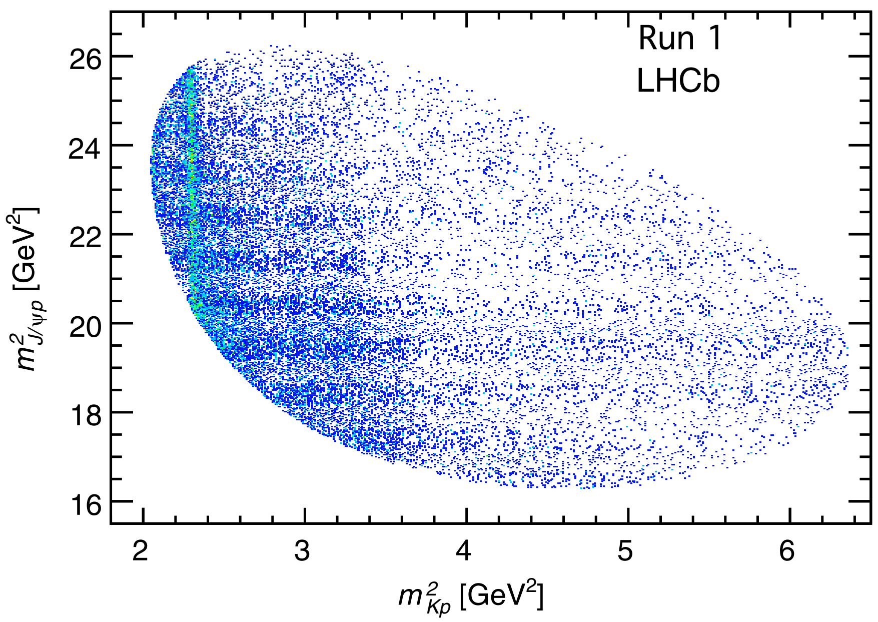
valence quarks: $uudc\bar{c}$

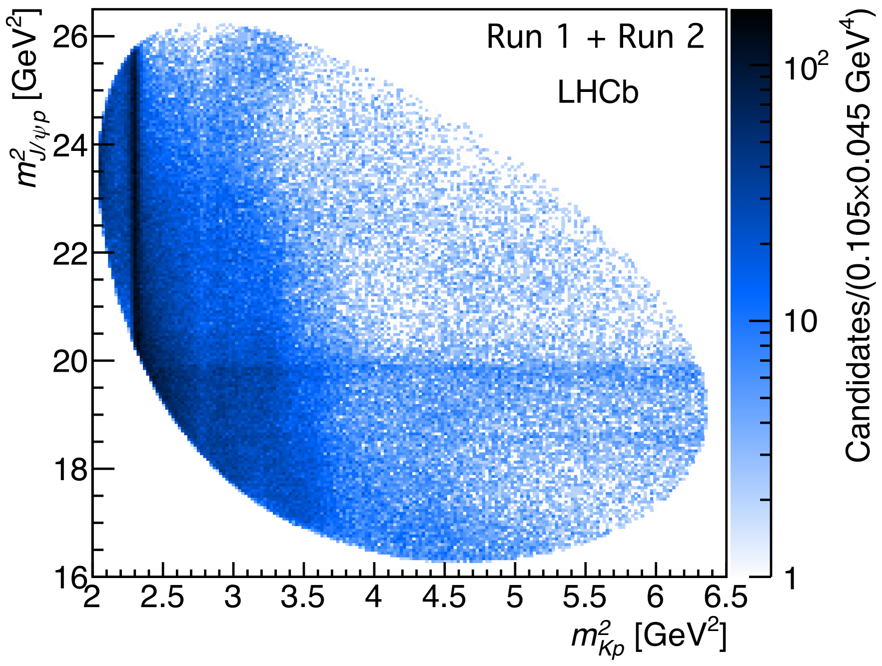


LHCb Run 1 + Run 2 (2019)

ArXiv 1904.03947

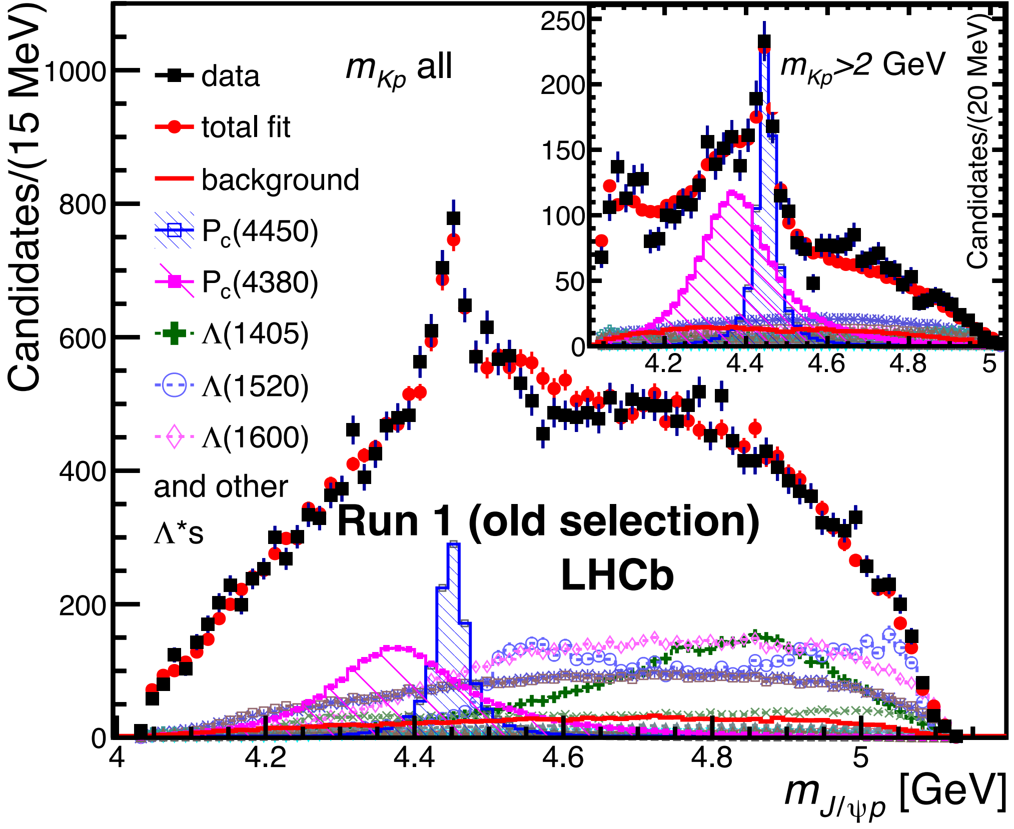
Improved signal selection
+
More data with ~2 x b production rate @ 13 TeV
=
9 x statistics wrt Run 1 only!

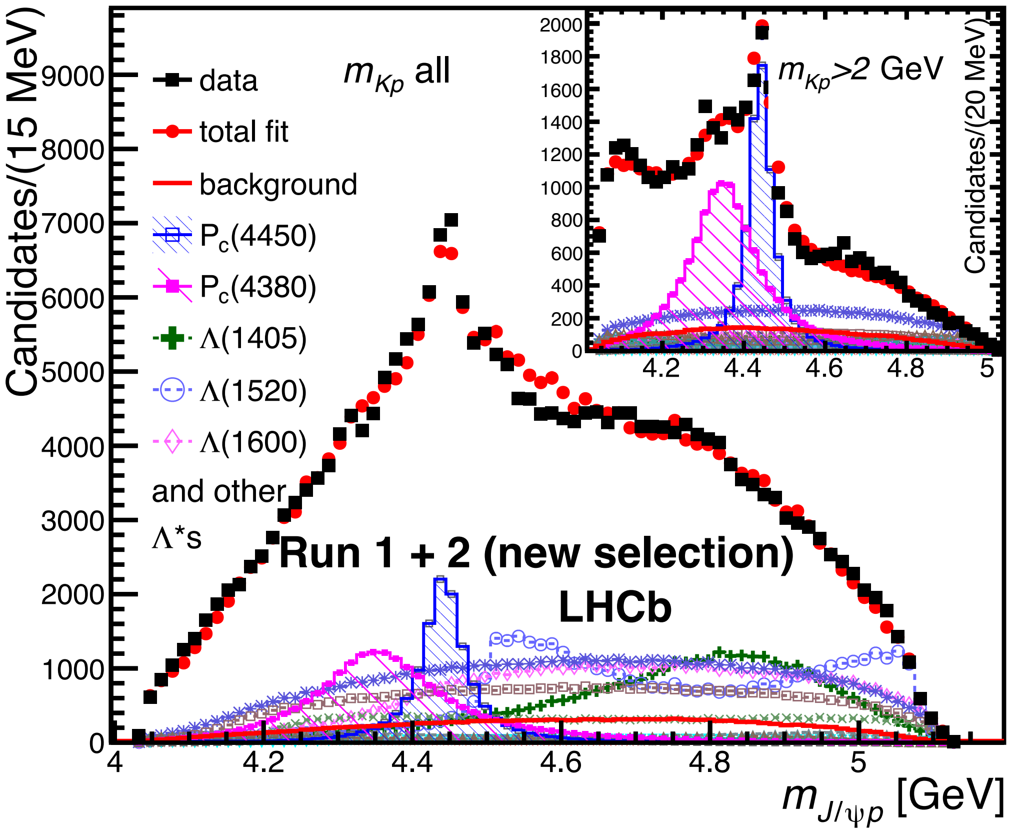




The mass fit with the old model works fine...

PRL 115, 072001 (2015)

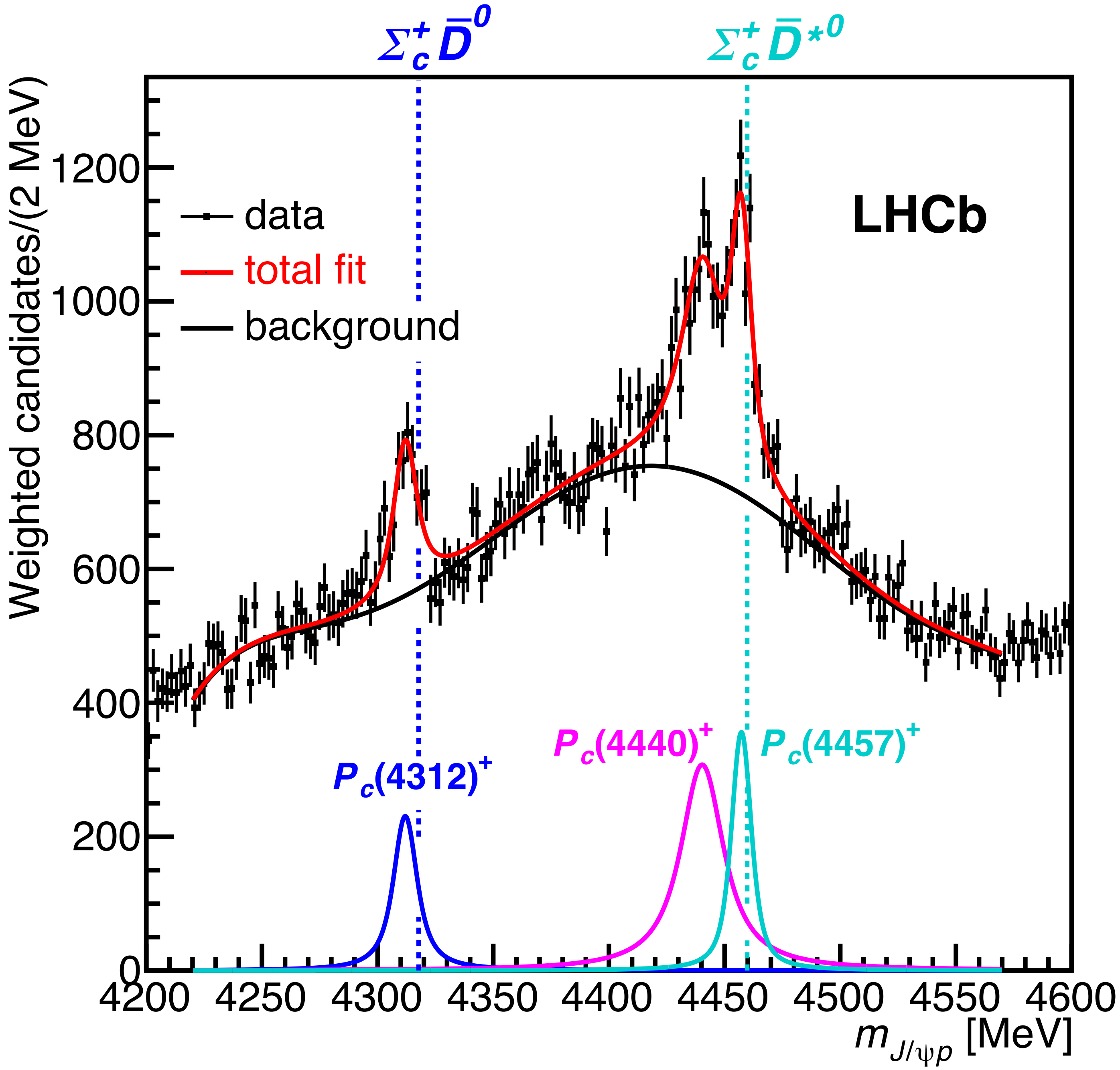




But wait… there's more!

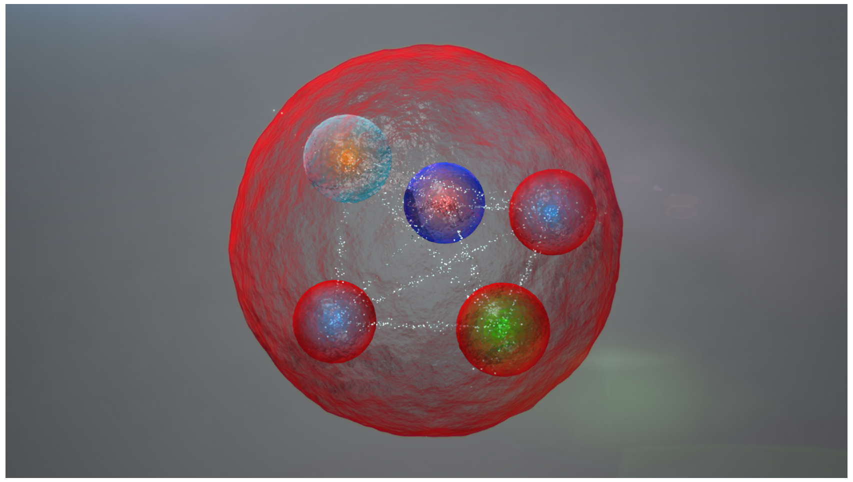
ArXiv 1904.03947

- Previous state at 4450 MeV is now resolved into two adjacent states
- Also a third narrow state is visible at 4312 MeV
- 1D mass fit performed, full amplitude analysis is ongoing to determine J^P
- All states are very close to the $\Sigma_c^+\bar{D}^{(*)0}$ thresholds (---, ---)



State	M [MeV]	Γ [MeV]
● $P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$
● $P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$
● $P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$

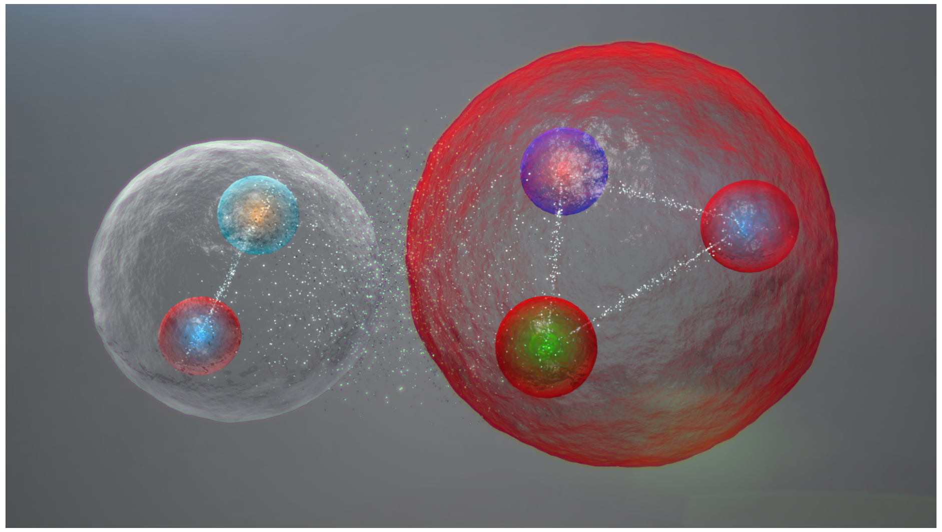
Theoretical interpretations



1. Tightly bound

L. Maiani, A. D. Polosa, V. Riquer, PL B749 (2015) 289

- Decay by fall-apart
- Confining potential: many states expected



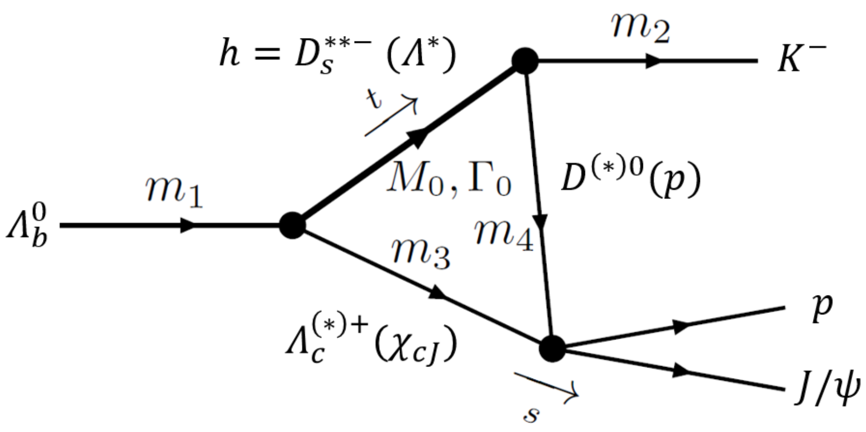
2. Loosely bound

Guo,Meissner,Wang,Yang PRD92 (2015) 071502

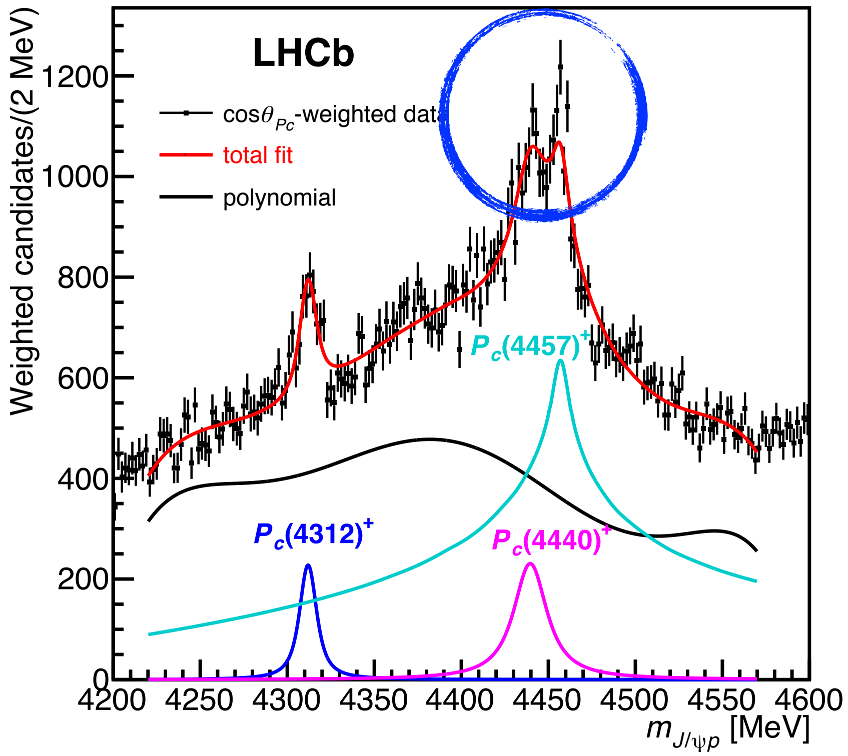
- Confinement partner exchange then fall-apart: narrower states
- Potential well: few states expected

Narrow states just below the $\Sigma_c^+\bar{D}^{*0}$ threshold seem to favour hypothesis #2.

3. Rescattering



Worse fit with two BW + 1 triangle-diagram amplitude: further investigation with amplitude analysis is needed



Understanding QCD

- J^P determination and search for isospin partners will drive the theoretical interpretation of pentaquark states
- Start of a new era in understanding QCD binding mechanisms
- LHCb dominating the scene, Belle II to join on some exotic channels
- Many states to be discovered with enhanced statistics from Run 3!

	LHCb			Belle II
Decay mode	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to X(3872)(\to J/\psi\,\pi^+\pi^-)K^+$	14k	30k	180k	11k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k	4k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M	140k
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100	—
$\Lambda_b^0 \to J/\psi\, pK^-$	340k	700k	4M	—
$\Xi_b^- \to J/\psi\, \Lambda K^-$	4k	10k	55k	—
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k	<6k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600	—
	(Run 1-3)	(Run 1-4)	(Run 1-5)	

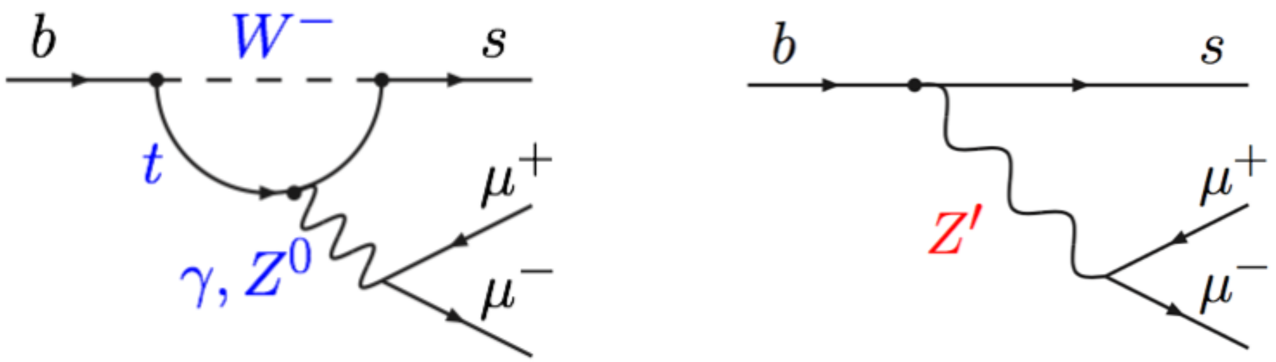
https://cds.cern.ch/record/2320509

4. Lepton Flavour Universality

Probing new physics with rare b decays

Indirect searches have access to New Physics at very high energies wrt direct searches

Precision measurement of a well-predicted observable: b→sl$^+$l$^-$ are FCNC processes that only occur via loop in the SM: BF / angular observables can be altered by new particles



https://cds.cern.ch/record/2668971

Interaction described by an effective hamiltonian $\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\lambda) \mathcal{O}_i(\lambda)$

The Wilson Coefficients C$_i$ are sensitive to NP contributions:

$$\mathcal{A}(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} \boxed{C_i(\lambda)} \boxed{\langle F|\mathcal{O}_i(\lambda)|M\rangle}$$

C$_9$ and C$_{10}$ relevant for b→sl$^+$l$^-$

the hadronic matrix element is parametrised as a form factor and represents the largest source of error in the SM prediction due to non-perturbative QCD.

R$_K$ as a test for Lepton Flavour Universality

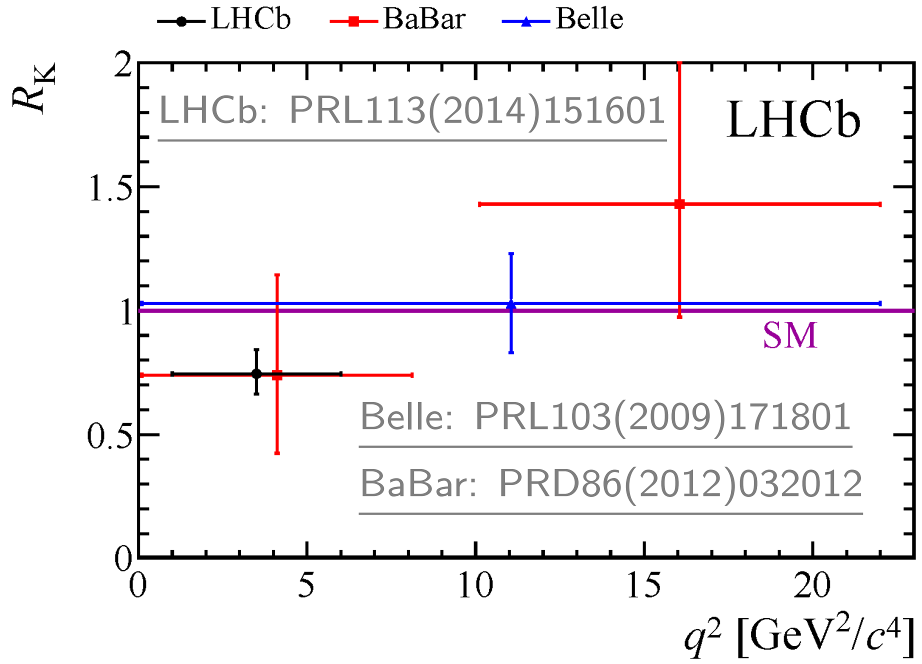
The R$_K$ ratio is free from hadronic uncertainties

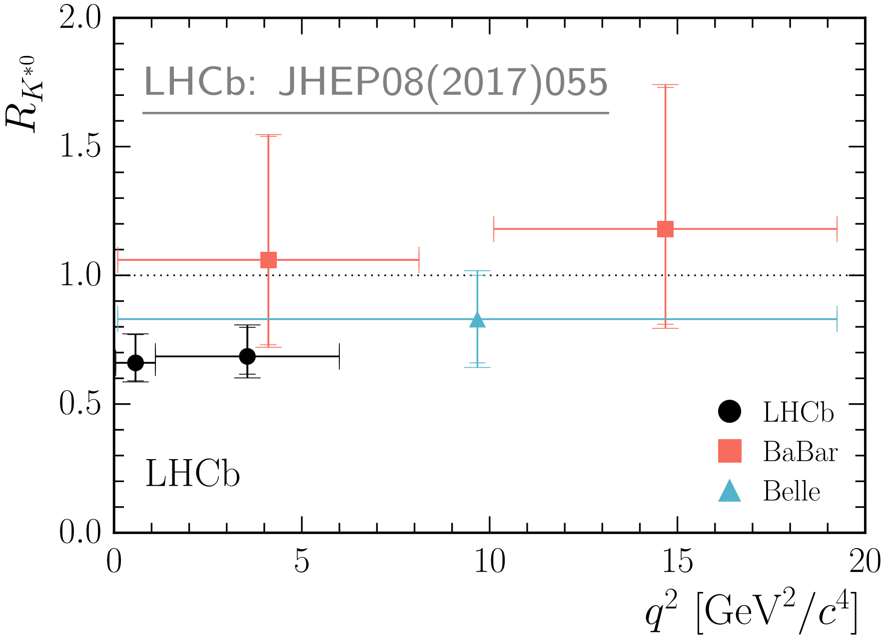
$$R_H = \frac{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{{\rm d}\Gamma[B\to H\mu^+\mu^-]}{{\rm d}q^2}{\rm d}q^2}{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{{\rm d}\Gamma[B\to He^+e^-]}{{\rm d}q^2}{\rm d}q^2}$$

and predicted to be 1 with O(1%) uncertainty (Lepton Flavour Universality) EPJC 76 (2016) 8,440

Tests of LFU in b decays are a hot topic due to many anomalies observed at Belle, BaBar and LHCb:

Run 1 measurements at LHCb are systematically below the SM expectations





$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$ for $1.0 < q^2 < 6.0$ GeV^2, $\sim 2.6\,\sigma$ from SM;

$R_{K^*} = 0.66^{+0.11}_{-0.07} \pm 0.03$ for $0.045 < q^2 < 1.1$ GeV^2, $\sim 2.2\,\sigma$ from SM;

$R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05$ for $1.1 < q^2 < 6.0$ GeV^2, $\sim 2.4\,\sigma$ from SM;

Also R(D)-R(D*) anomalies (tree level) at ~4σ

Many theoretical models with Z’ or LQ can accomodate the “deviations” simultaneously

https://arxiv.org/abs/1903.11517

R_K at LHCb

ArXiv:1903.09252

At LHCb, R_K is measured as a double ratio:*

* LFU holds in J/psi decays up to 0.4% [PDG]

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} \Big/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(ee))}$$

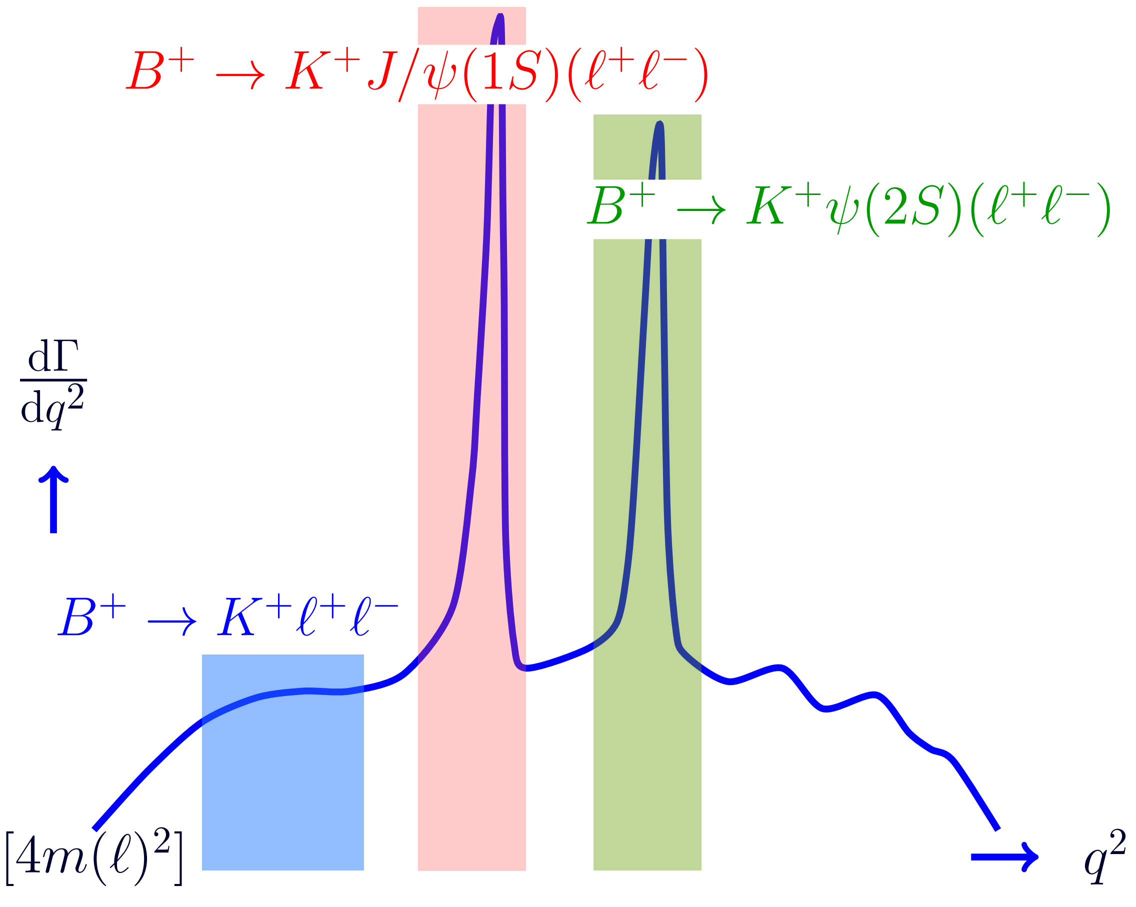
$$= \frac{N(K^+\mu\mu)}{N(K^+J/\psi(\mu\mu))} \cdot \frac{N(K^+J/\psi(ee))}{N(K^+ee)} \cdot \frac{\varepsilon(K^+J/\psi(\mu\mu))}{\varepsilon(K^+\mu\mu)} \cdot \frac{\varepsilon(K^+ee)}{\varepsilon(K^+J/\psi(ee))}$$

to cancel most of the systematic effects.

Rare and resonant modes:

- Same event selection
- Separated by q^2

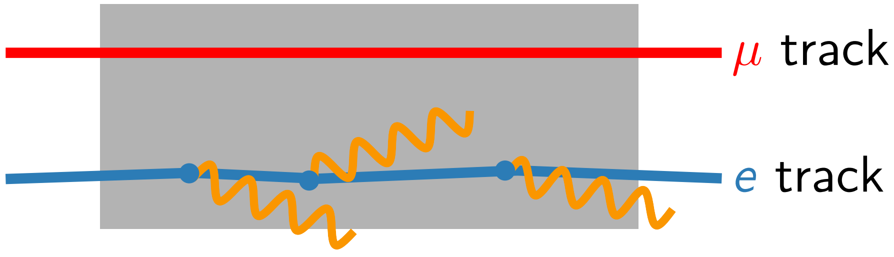
A new measurement is presented here on Run 1 + 2fb^{-1} of Run 2 data



https://cds.cern.ch/record/2668971

Muons vs Electrons

Electrons emit significant bremsstrahlung photons at LHCb: to improve the momentum resolution, a photon cluster in the calorimeter is searched for



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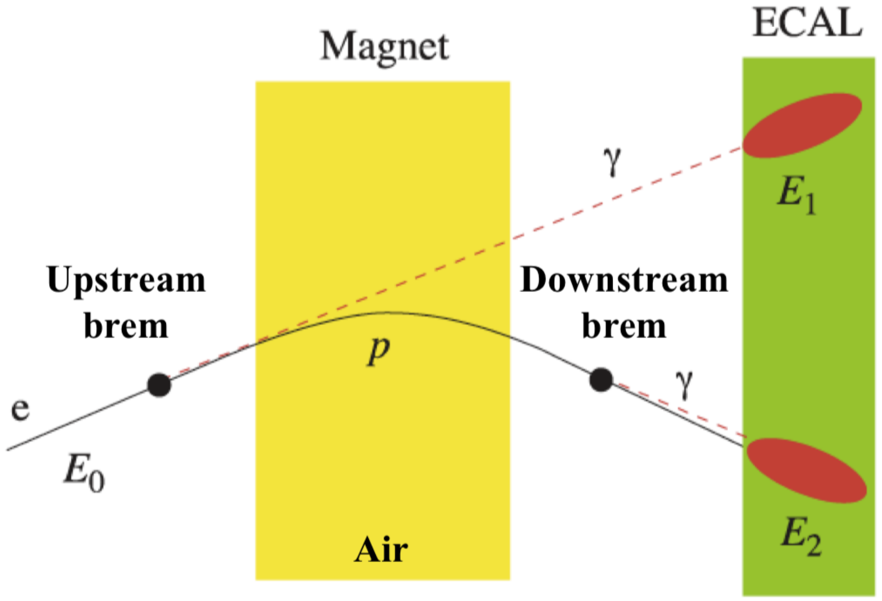
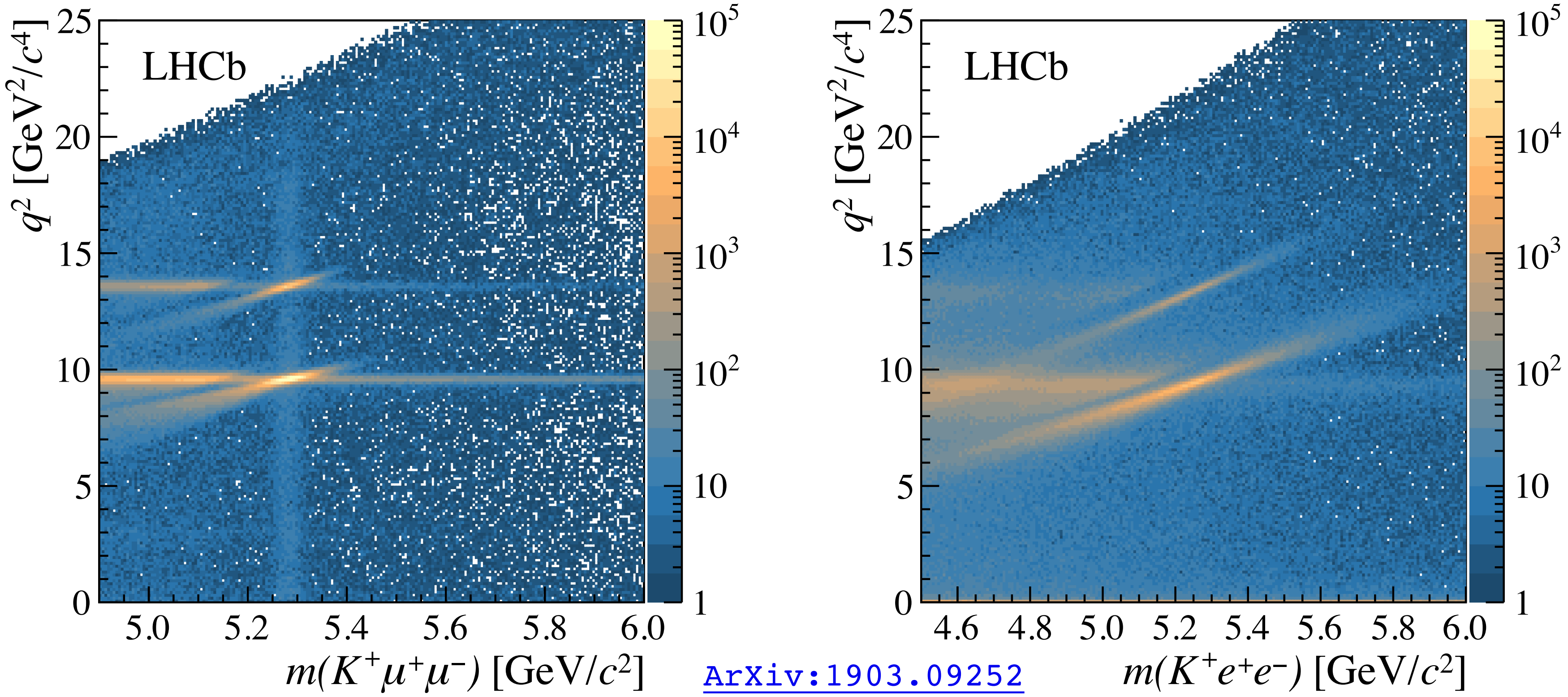


https://cds.cern.ch/record/2668971

However, reconstruction + trigger efficiency and q² resolution are lower for electrons



ArXiv:1903.09252

Controlling efficiencies

ArXiv:1903.09252

Efficiency ratios are computed from simulations and corrected from data concerning:

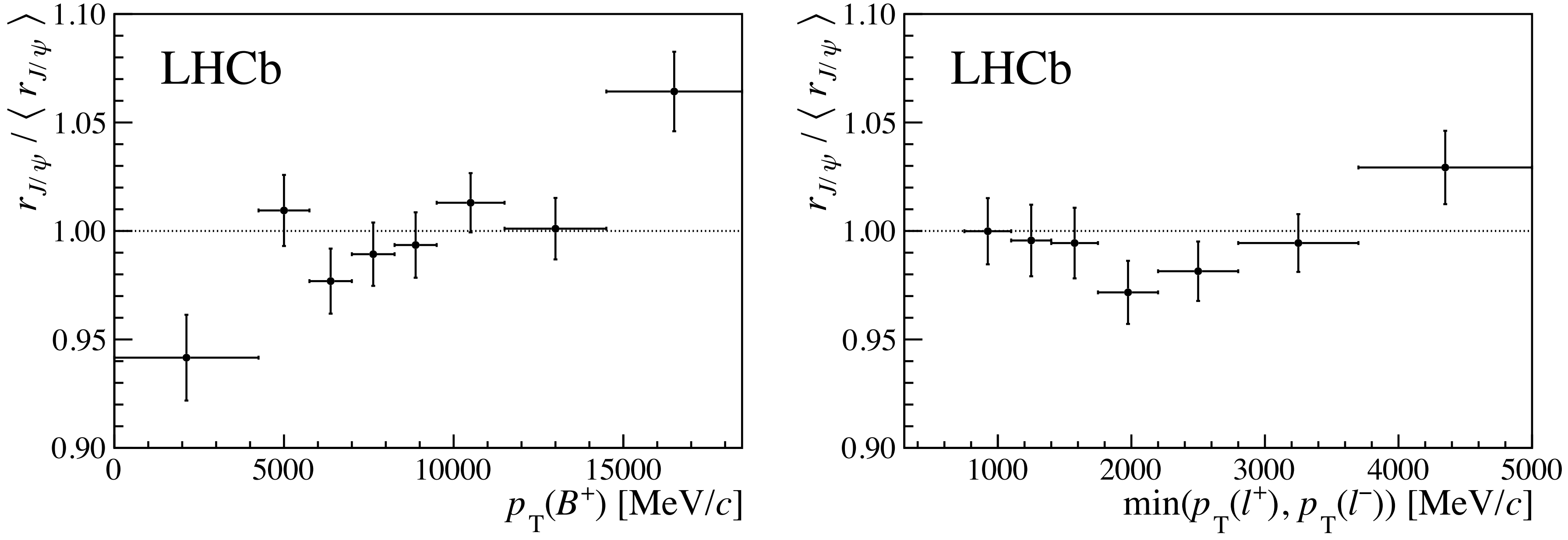
1. PID
2. Mass resolution
3. B^+ kinematics
4. Trigger

The effectiveness of the correction is checked by measuring

$$r_{J/\psi} = \frac{\mathcal{B}(B \to K^+ J/\psi(\mu\mu))}{\mathcal{B}(B \to K^+ J/\psi(ee))} = 1.014 \pm 0.035$$

→ stringent test as it requires muon and electron efficiencies to be controlled individually

Even stronger check vs kinematics:

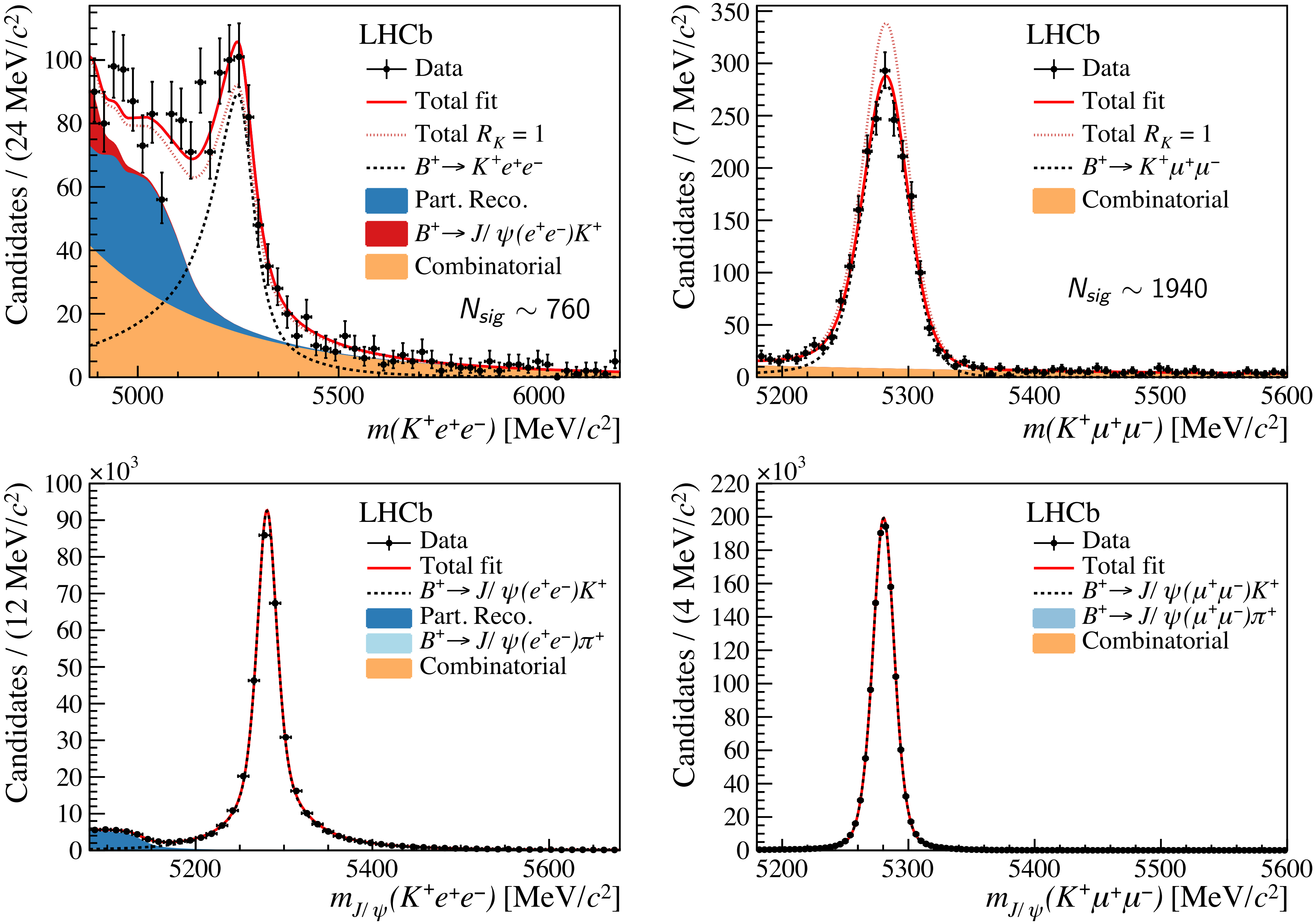


$R_K^{\psi(2S)}$ is also compatible with 1 within 1σ.

Invariant mass fits

ArXiv:1903.09252

A simultaneous fit to rare+resonant electron and muon channels is performed to extract R_K



Rare modes:

Partially reconstructed background and tail from resonant mode are significant in ee

Resonant modes:

Dilepton mass constrained to the J/ψ mass to improve the resolution

Results

ArXiv:1903.09252

Old Run 1 analysis

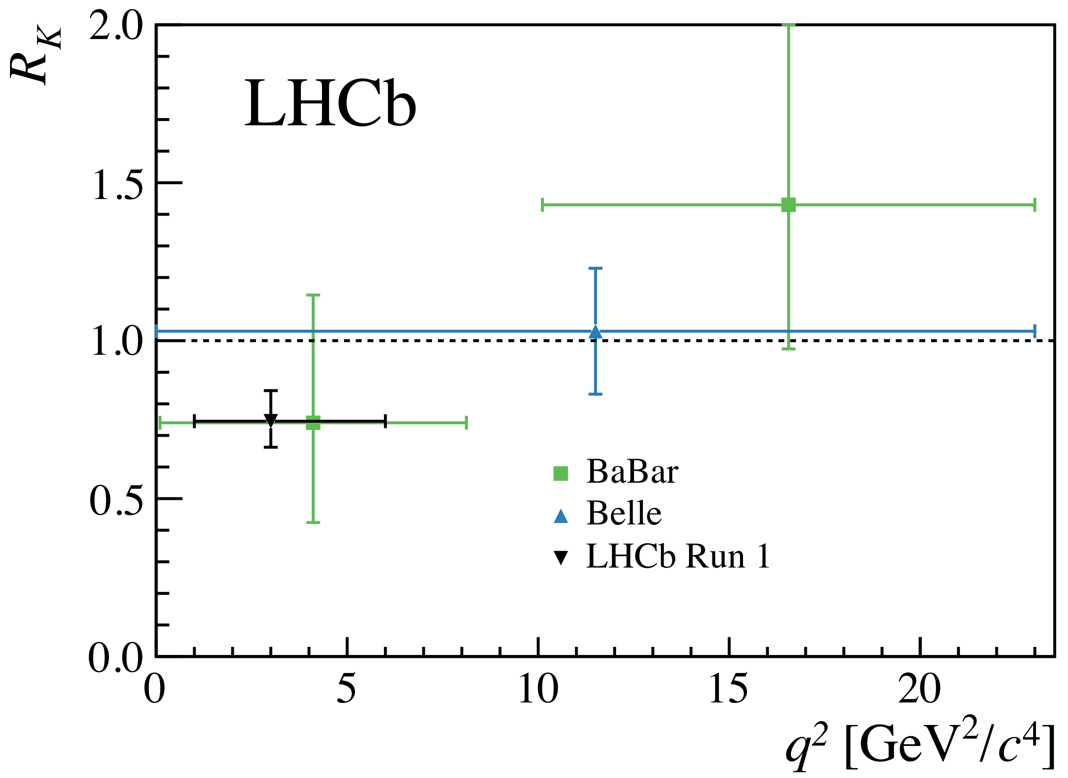
$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat.}) \pm 0.036(\text{syst.})$$

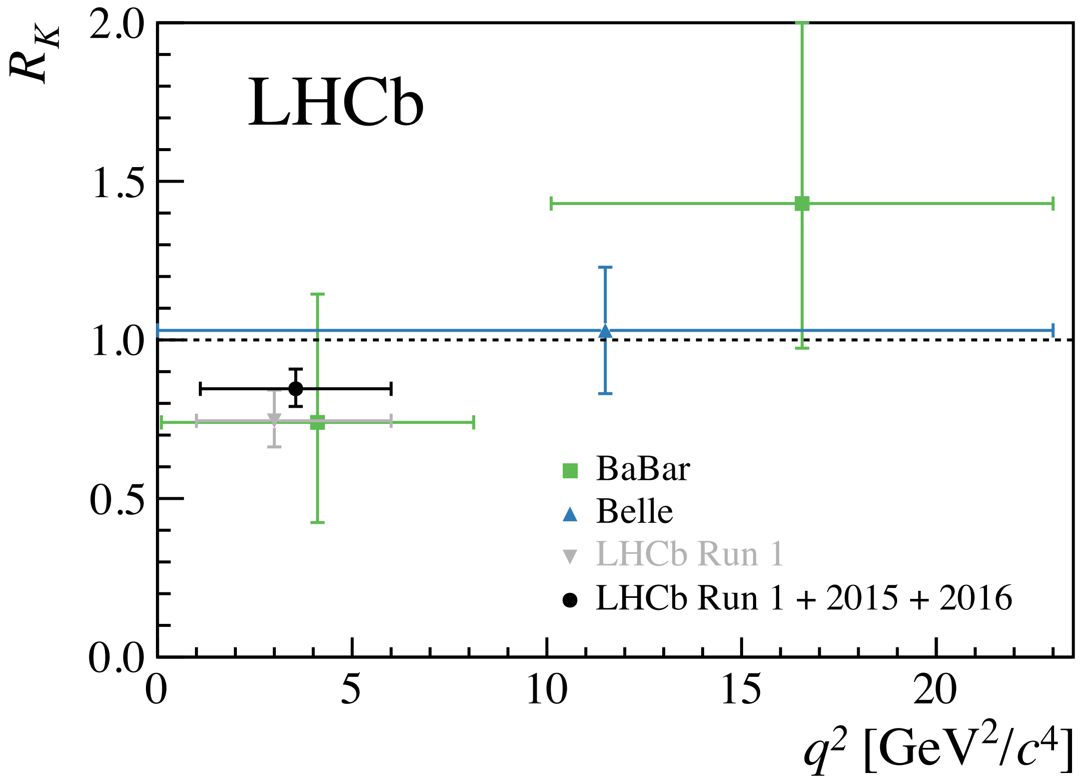
$\sim 2.6\,\sigma$ from SM

New Run 1 + Run 2 (2 fb^{-1}) analysis

$$\boxed{\boldsymbol{R_K = 0.846}\ ^{\boldsymbol{+0.060}}_{\boldsymbol{-0.054}}(\text{stat.})\ ^{\boldsymbol{+0.016}}_{\boldsymbol{-0.014}}(\text{syst.})}$$

$\sim$ **2.5 σ** from SM





By fitting Run 1 and Run 2 data separately:

$$R_{K\ \text{Run 1}}^{\text{new}} = 0.717^{+0.083}_{-0.071}{}^{+0.017}_{-0.016}$$

$$R_{K\ \text{Run 2}} = 0.928^{+0.089}_{-0.076}{}^{+0.020}_{-0.017}$$

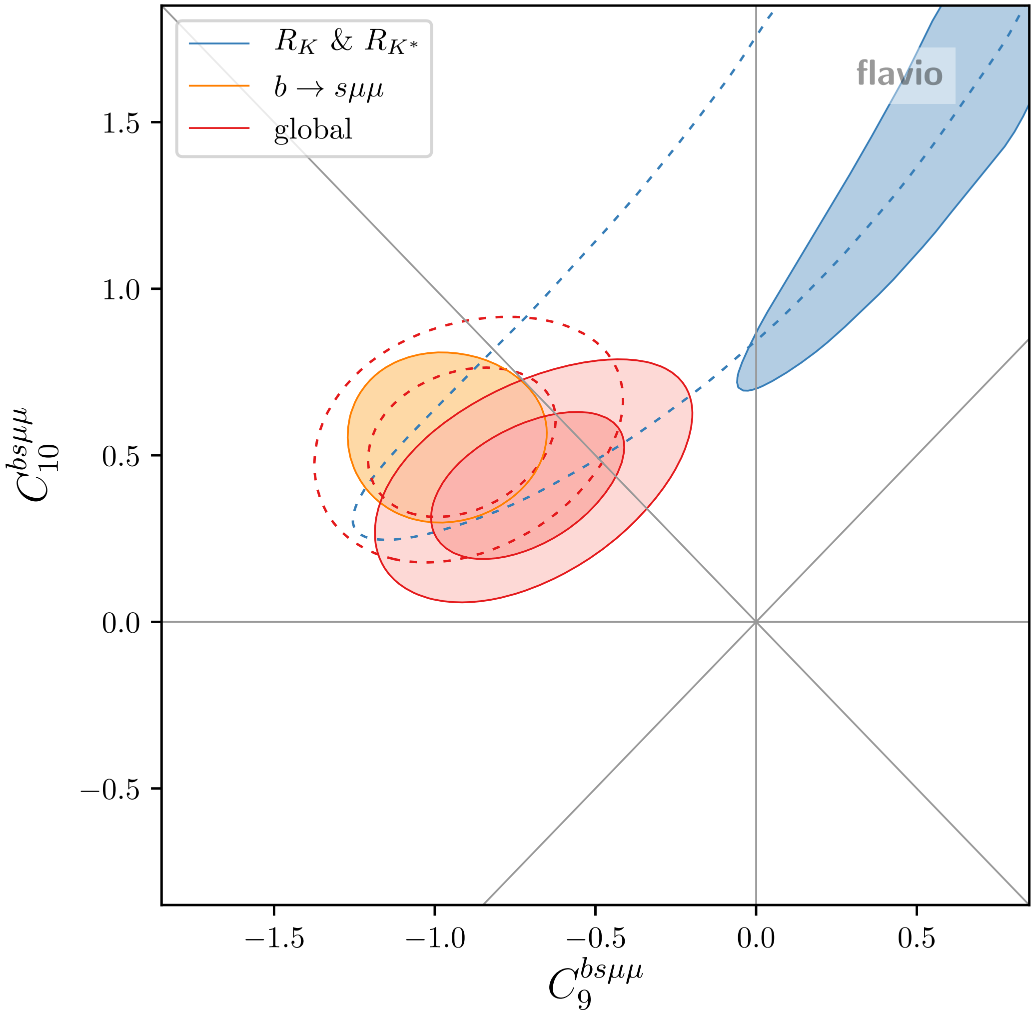
compatible at 1.9σ

The new analysis on Run 1 data (new reconstruction and selection) agrees with the old one within 1σ

Implications of R_K

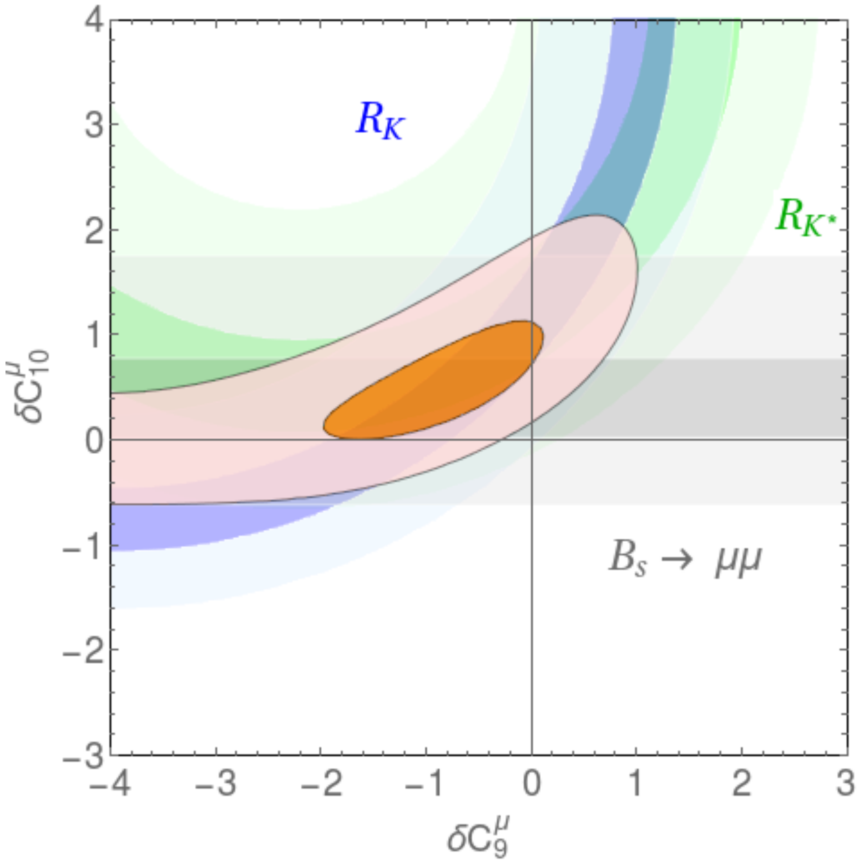
New LHCb measurement has significantly improved precision wrt previous result

- Best fit on Wilson coefficients C_9 and C_{10} a bit closer to SM wrt pre-Moriond 2019 (---)



Straub, Moriond EW 2019

- "Golden channel" $B_s \to \mu^+\mu^-$ is driving C_{10}, leading role of the LNF group in the analysis

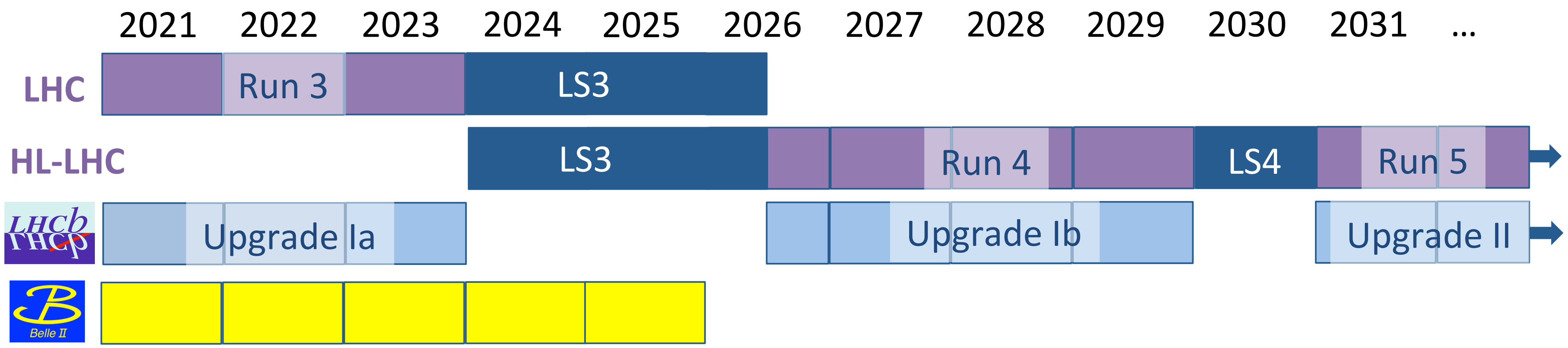


PRD 96, 093006 (2017)

- New R_K, R_{K^*} and $B_s \to \mu^+\mu^-$ measurements with full statistics are ongoing, stay tuned!

Future prospects

- Belle II will take data during LHCb Run 3, aiming at $50ab^{-1}$ at the end of 2025



- Direct competition with LHCb on charged modes, with Belle II having the same efficiency on electrons and muons

R_X precision	Run 1 result	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
R_K	$0.745 \pm 0.090 \pm 0.036$	0.043	0.025	0.017	0.007

LHCb-PUB-2018-009

Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
R_K ($[1.0, 6.0]\,\mathrm{GeV}^2$)	28%	11%	3.6%

BELLE2-PAPER-2018-001

- Belle II also has the advantage on inclusive modes and leptons other than muons (e.g. b→svv)
- Next years will be crucial to understand the LFU picture

Conclusions

Three new exciting results from LHCb Run 2 across different physics sectors:

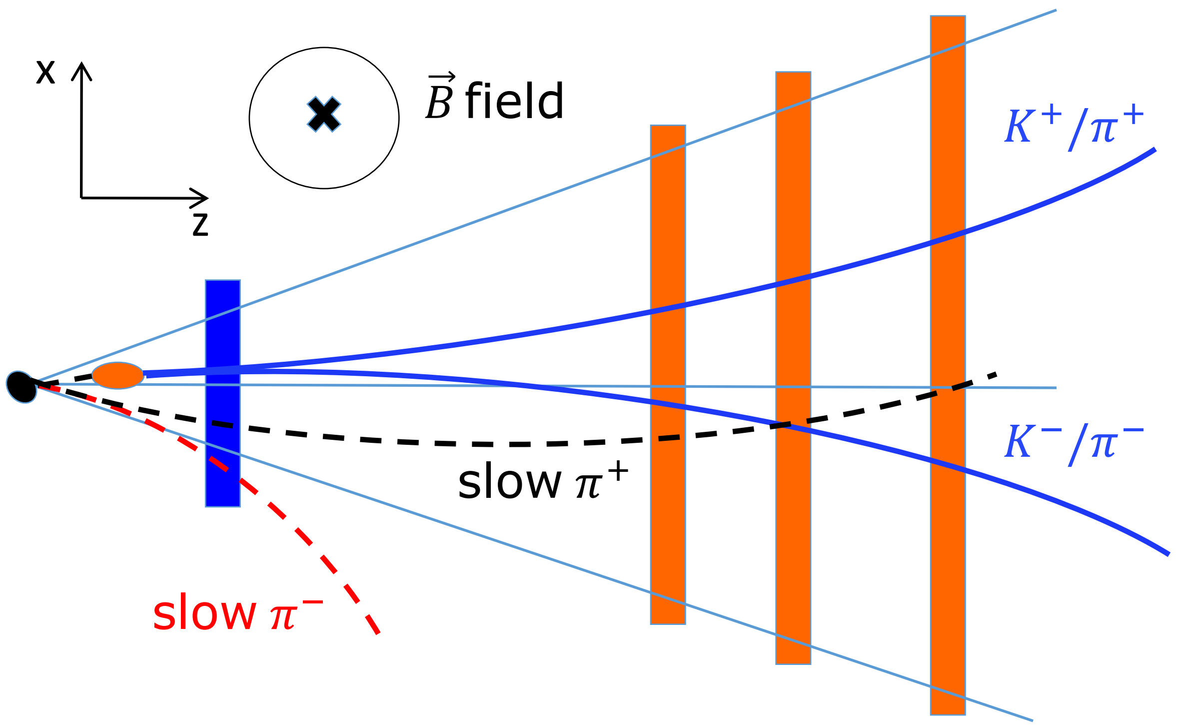
1. First observation of CP violation in charm
    - Another bit in matter asymmetry
2. New pentaquark states
    - 3 new states discovered, many more to come
3. Updated RK
    - Towards the final word on LFU

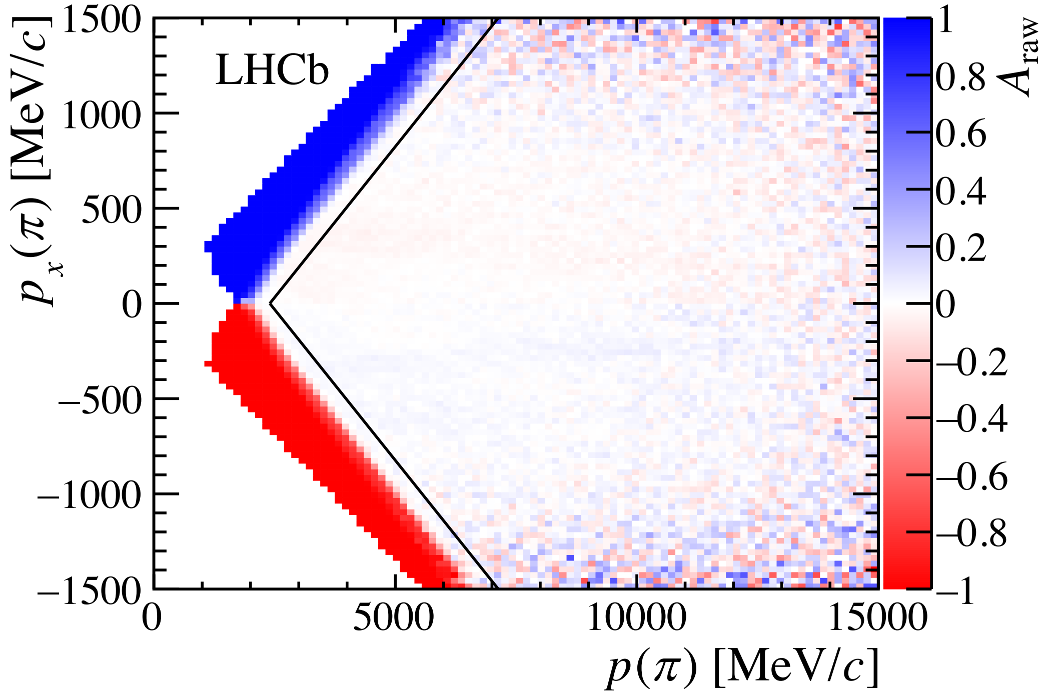
And many more interesting measurements are ongoing!

4.

backup

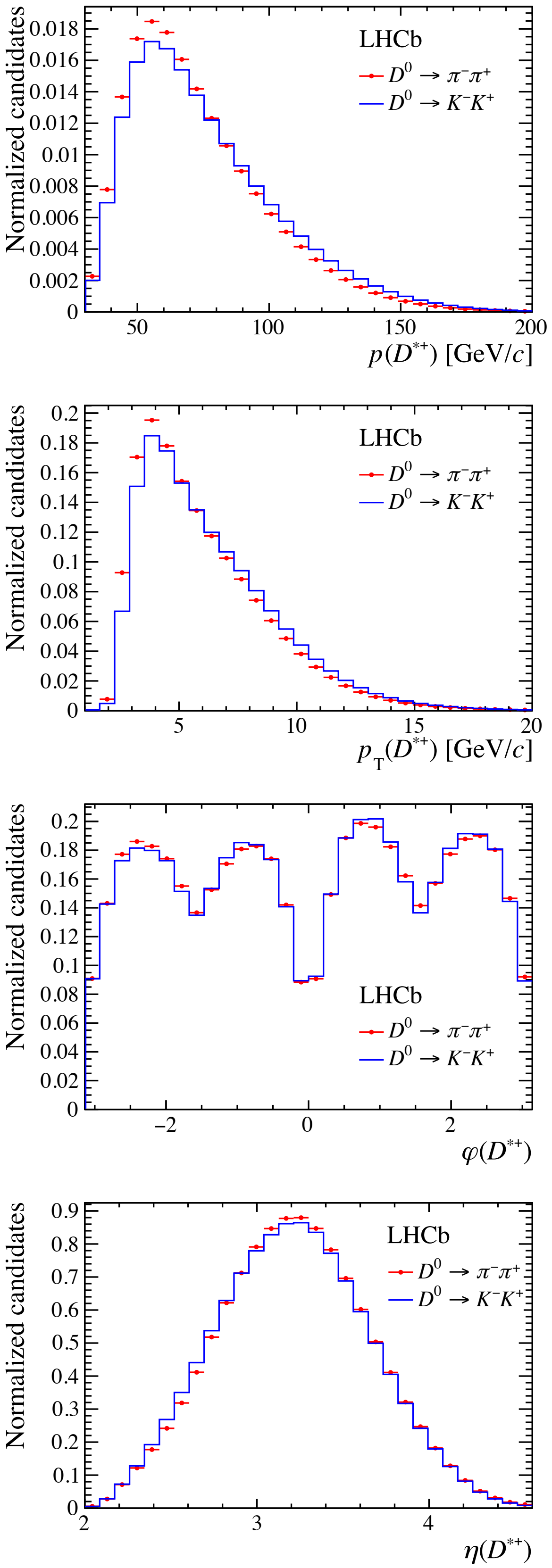
Detection asymmetries



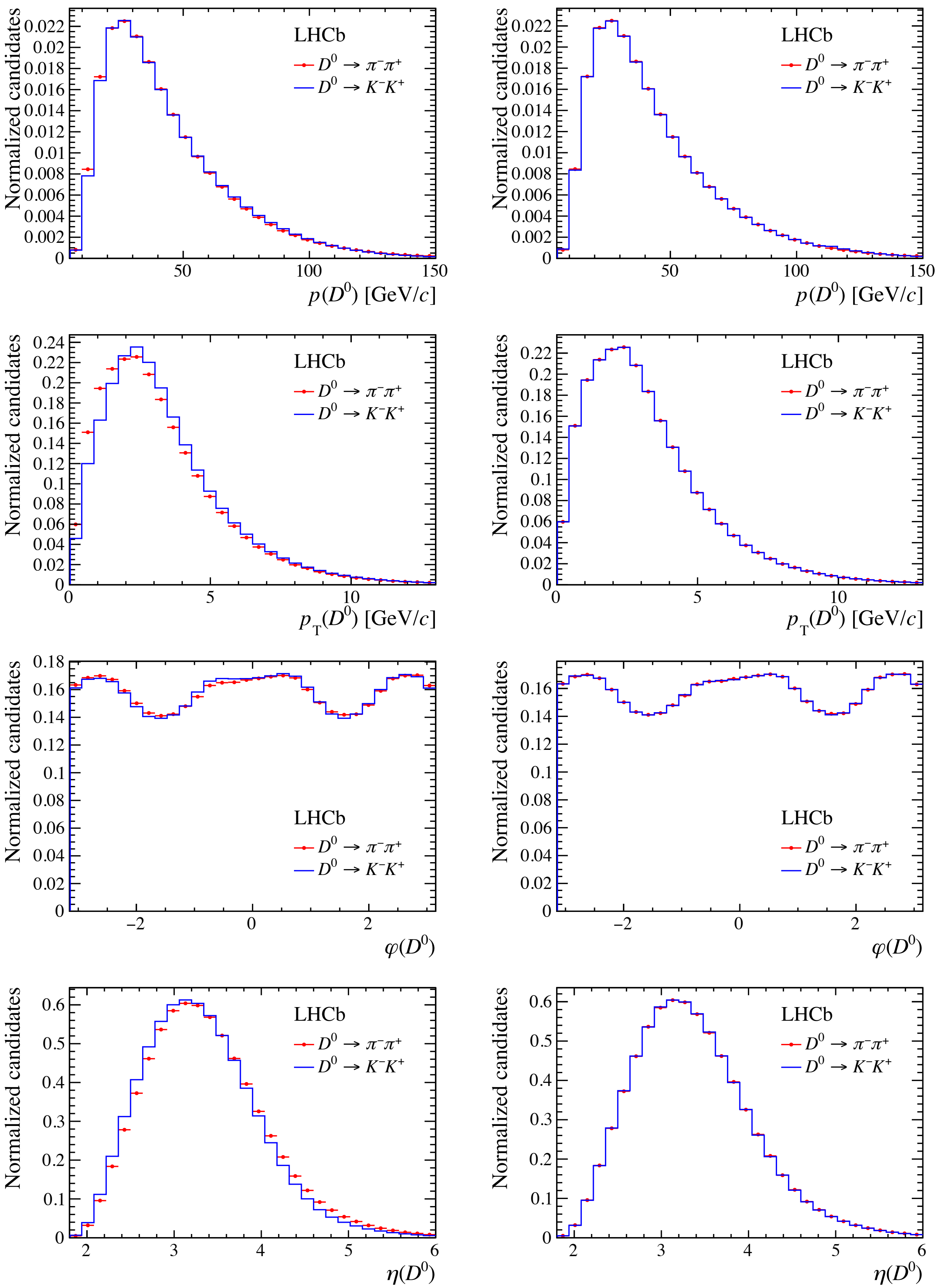


Kinematic reweighting for DACP

(prompt)



(semileptonic)



Systematic uncertainties on DACP

Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B fractions	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

Are the P_c^+ states reflections?

PRL 117 082202 (2016)

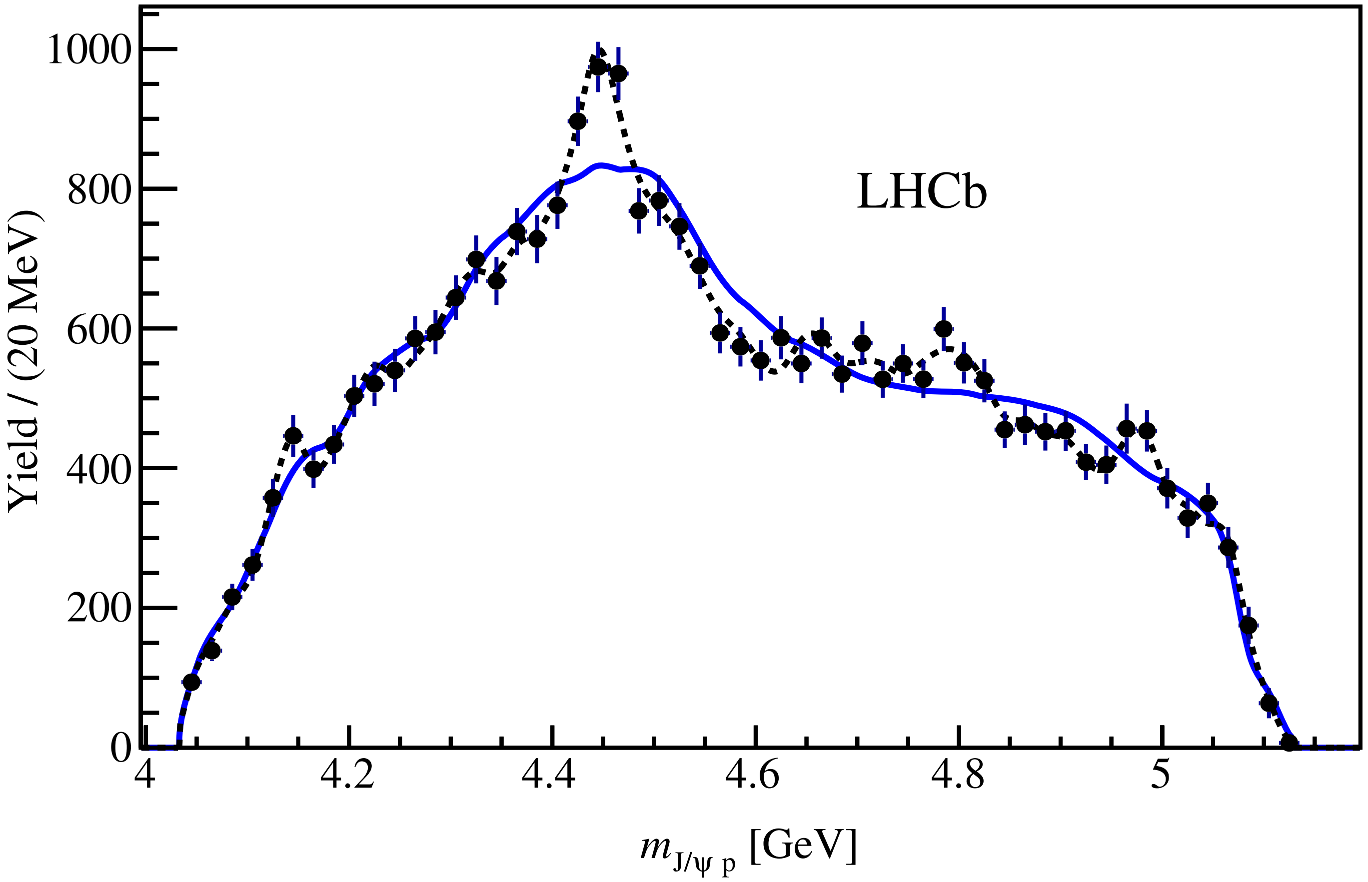
Model independent analysis: check if a sum of pK^- resonances can explain the observed spectrum

- Minimal assumptions on pK^- resonances
- Helicity angle expansion up to J=9/2 with coefficient from m(pK) data

$$dN/d(\cos\theta_{\Lambda^*}) = \sum_{l=0}^{l_{max}} \left\langle P_l^U \right\rangle P_l(\cos\theta_{\Lambda^*}) \qquad \left\langle P_l^U \right\rangle = \int_{-l}^{+l} d\cos\theta_{\Lambda^*} P_l(\cos\theta_{\Lambda^*}) dN/d(\cos\theta_{\Lambda^*})$$

If the structures in m(J/ψp) are reflections, the expansion will be able to describe the spectrum

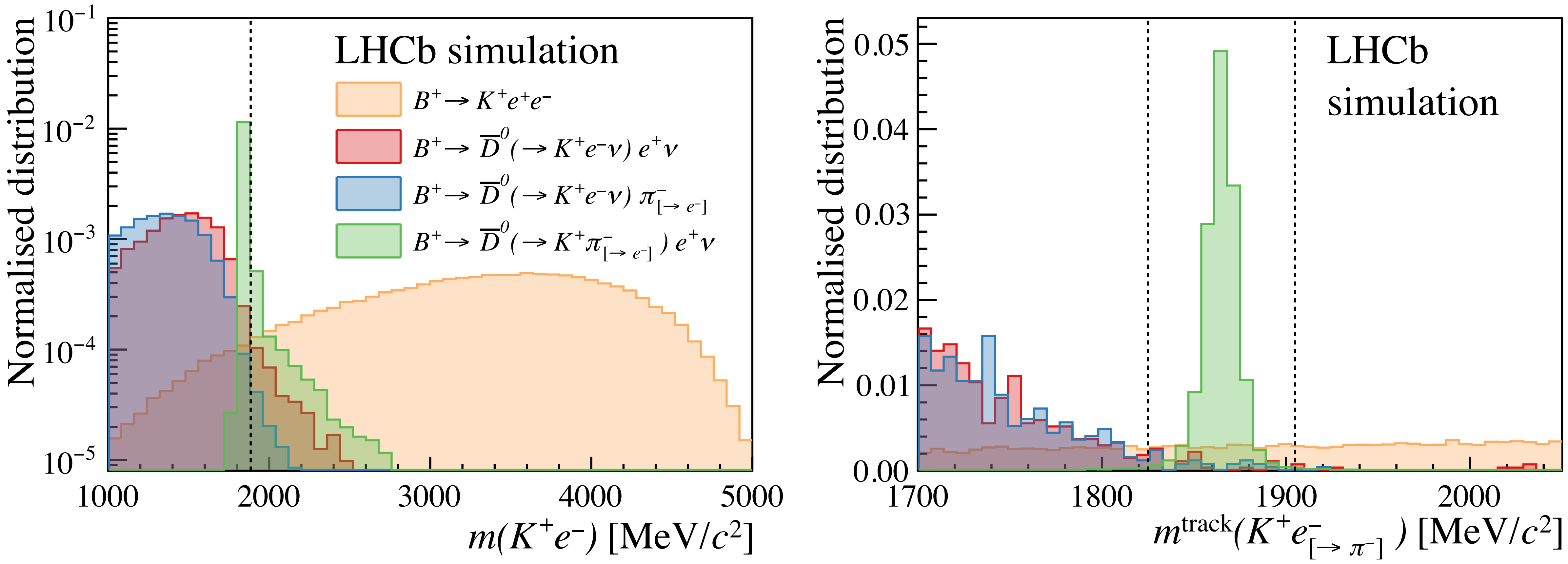
- The model fits the m(pK) spectrum
- ... but still can't describe m(J/ψp)!
- Discrepancy > 9σ



Analysis strategy for R_K

ArXiv:1903.09252

- Using Run 1 + 2 fb^{-1} of Run 2 data (with improved reconstruction)
- Same selection for rare and resonant modes
- Exploit Particle Identification + mass vetoes to wipe out peaking backgrounds (cascade decays and misID backgrounds)

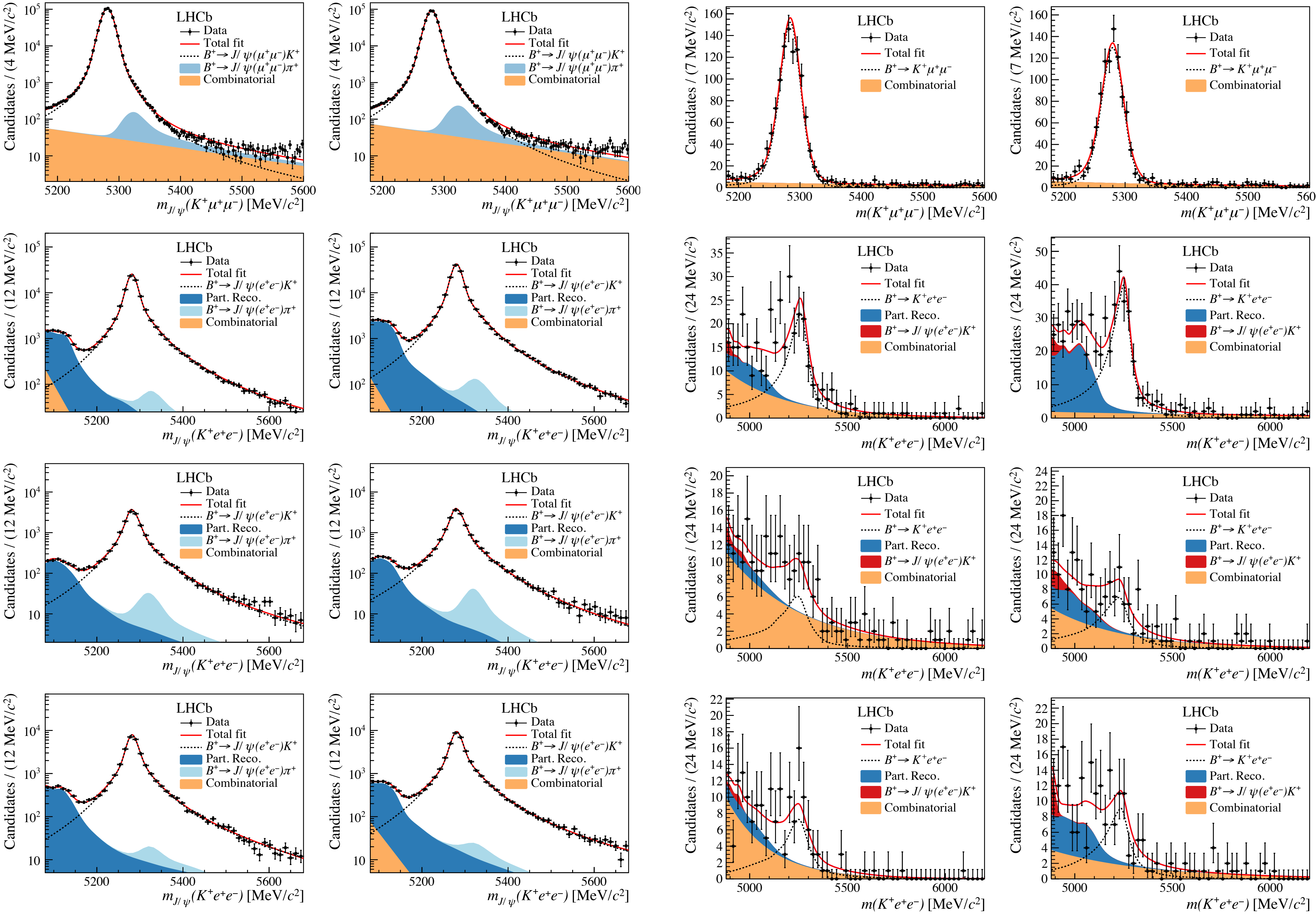


- A Boosted Decision Tree algorithm trained on right data sideband + simulated signal retains 85% of the signal while rejecting 99% of the combinatorial events

Mass fits for each trigger category

Resonant

Rare



L0Muon

L0E

L0H

L0TIS

Run 1

Run 2

Run 1

Run 2