Overview of LHCb status and recent highlights

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Disclaimer

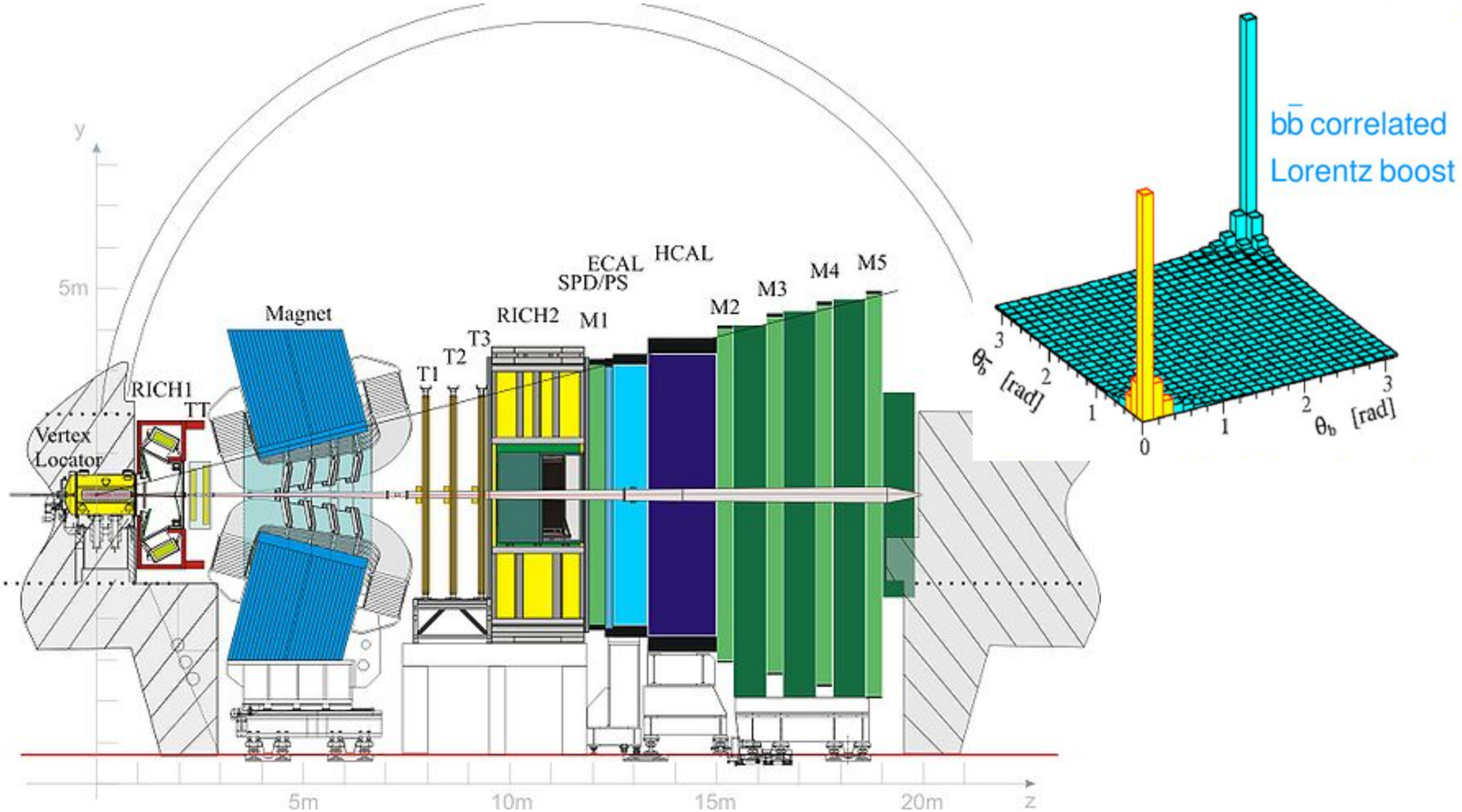
- **Only highlights from LHCb in this talk, details can be found in:**
  - 味物理中的反常 (Jibo He)
  - Hadron spectroscopy and exotics at LHCb (Jinlin Fu)
  - LHCb上b强子非粲重子衰变模式的研究 (Jiesheng Yu)
  - Charm physics at LHCb (Liang Sun)
  - Recent CPV results at LHCb (Yanxi Zhang)
  - LHCb future (Hang Yin)
  - A global picture of all experimental status can be found in Liming Zhang's talk

Fundamental questions (flavor)

- **Structure of particles**
- **New particles or forces**
- **Matter vs anti-matter**
- **Dark matter (not discussed in this talk)**
- **…**

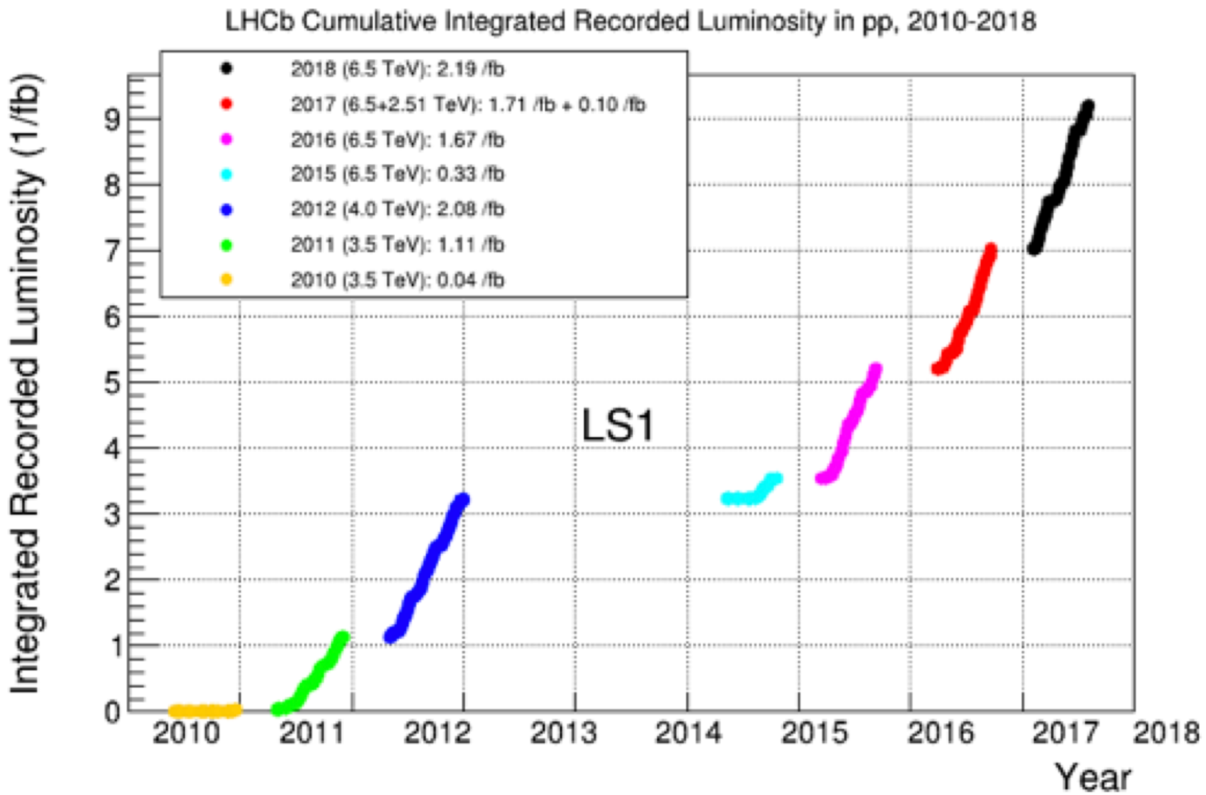
Key players: LHCb, BESIII, BelleII + CMS, ATLAS

A machine emeritus



- **Running from 2010 to 2018**
- **Key for flavor program: excellent vertexing, PID, good momentum resolution, tagging of B flavor**

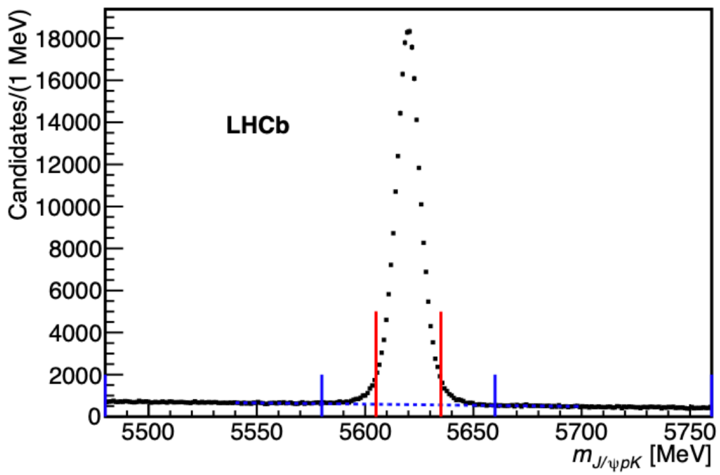
A flavorful machine



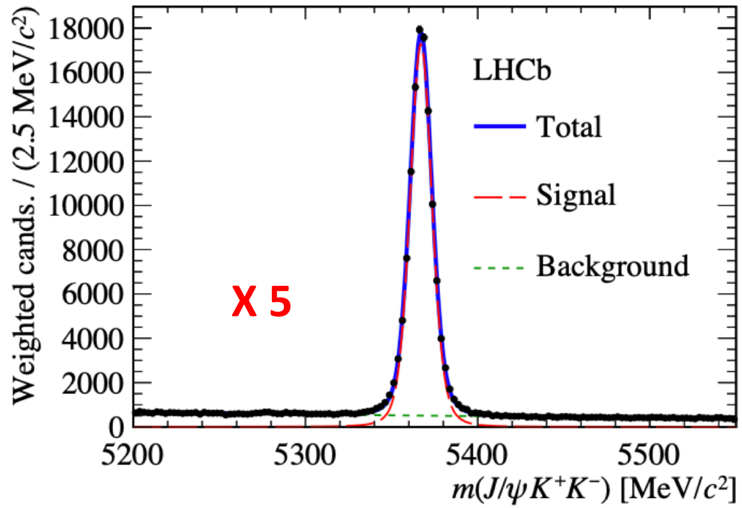
- **Collected around 9 fb^{-1} pp collision data**
- **Around 10^{11} b produced in LHCb and 10^{12} c at the same time**
- **Trigger and selection efficiencies around 1% level ⟹ access to very rare decays and measure precisely CP violation**

Examples

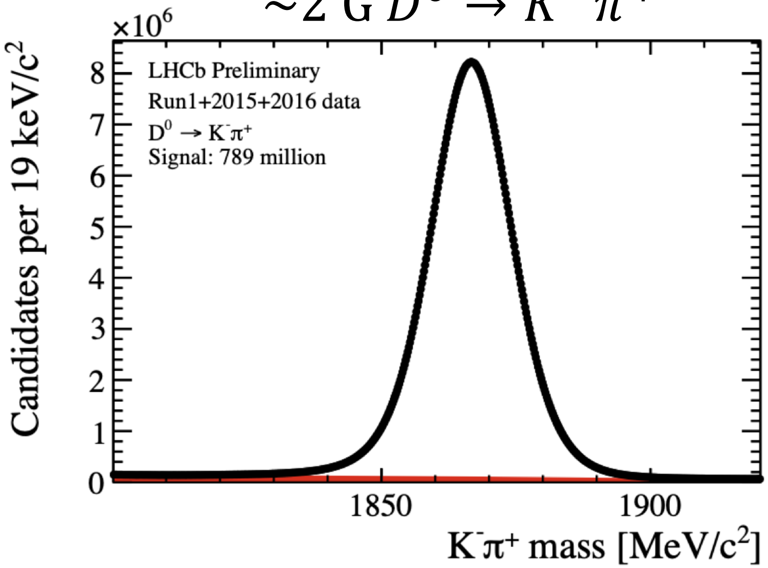
280k $\Lambda_b^0 \to J/\psi p K^-$ (Run1+Run2)



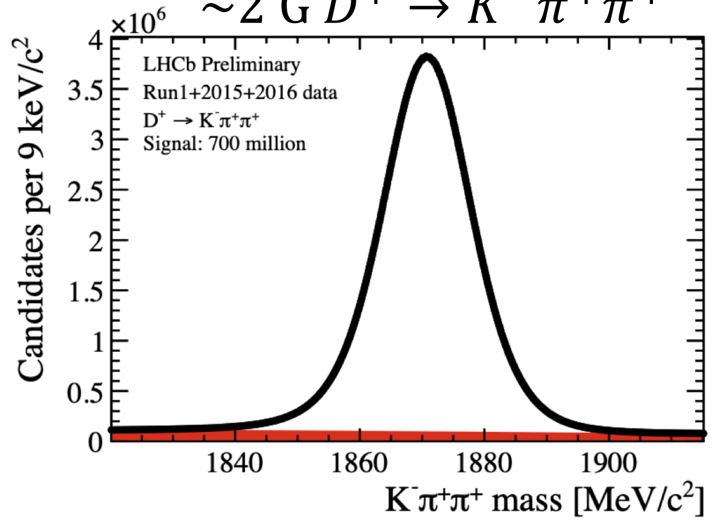
$600K\ B_S \to J/\psi\phi$



$\sim$2 G $D^0 \to K^-\pi^+$



$\sim$2 G $D^+ \to K^-\pi^+\pi^+$



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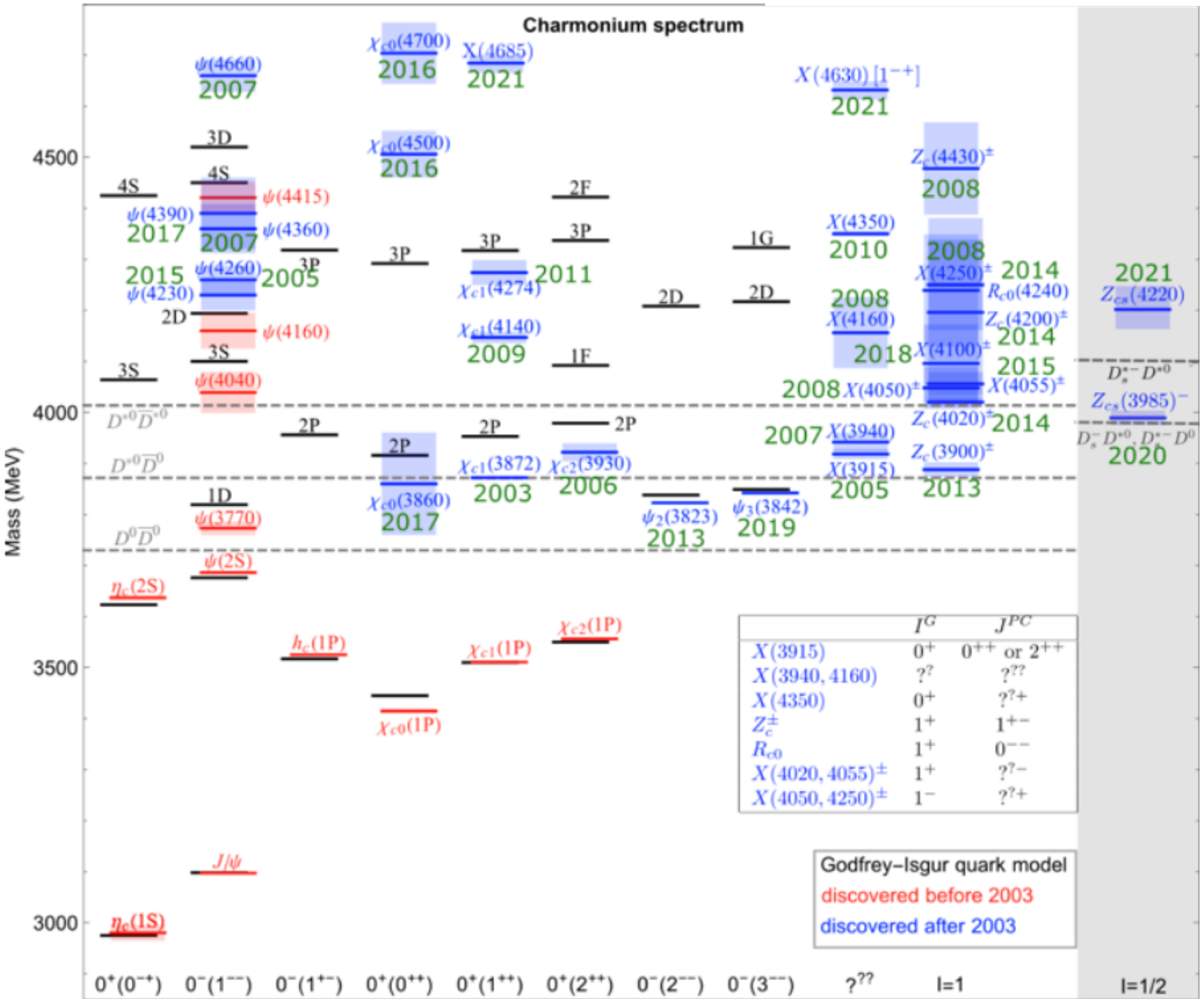
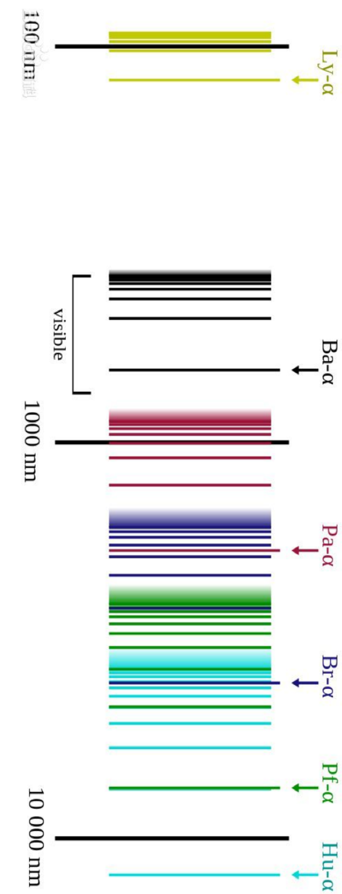
- …

An era similar to 1880s

From F-K. Guo



M. Gell-Mann?



Era of 1880s
Who will be J. Balmer or J. R. Rydberg?

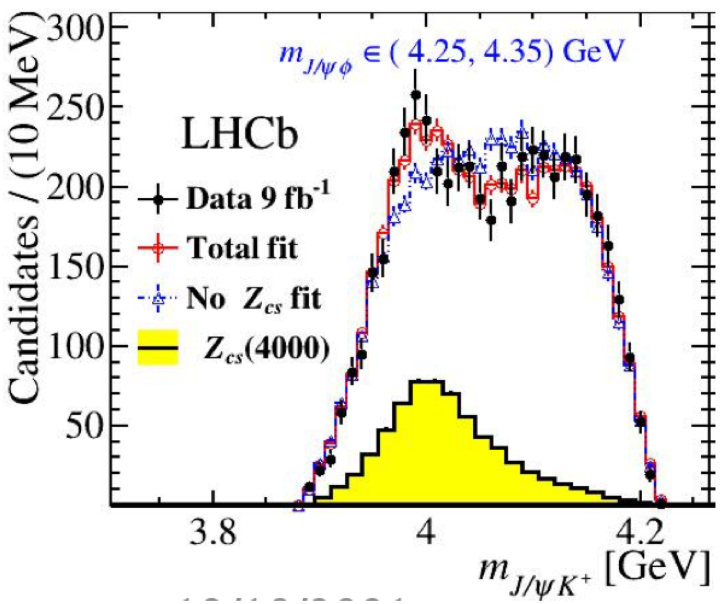
Towards understanding structures

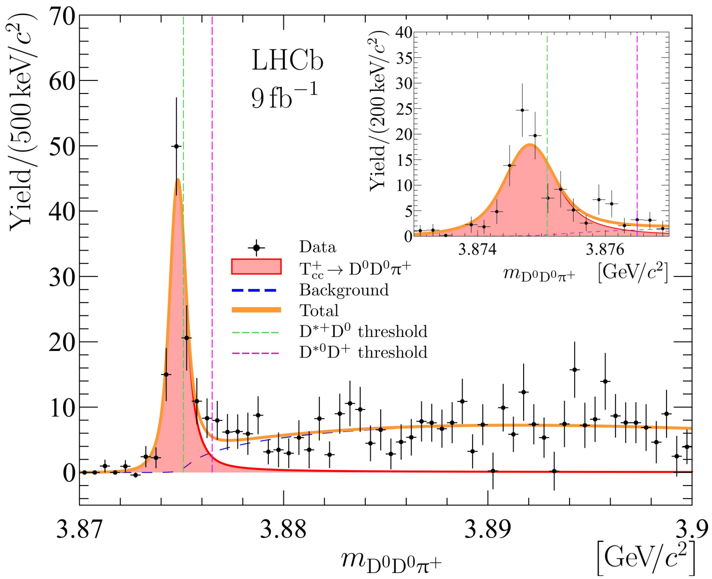
- Searching for new states in new/old channels
- Properties better measured
- Confirm/deny previously observed states
- Better identify observed states: same state or conventional $\bar{c}c$
- Link to other studies in proton etc.
- ……

New Tetraquarks

PRL 127, 082001 (2021)
arXiv:2109.01056
arXiv:2109.01038

- **Families of exotic mesons extend further**
  - SU(3) partners $Z_{cs}(4000)^+$ ($J^P = 1^+$) found in $B^+ \to J/\psi\phi K^+$ decays (similar story in BESIII)
  - An even striking one: very narrow peak at $D^{*+}D^0$ threshold ($cc\bar{d}\bar{u}$)



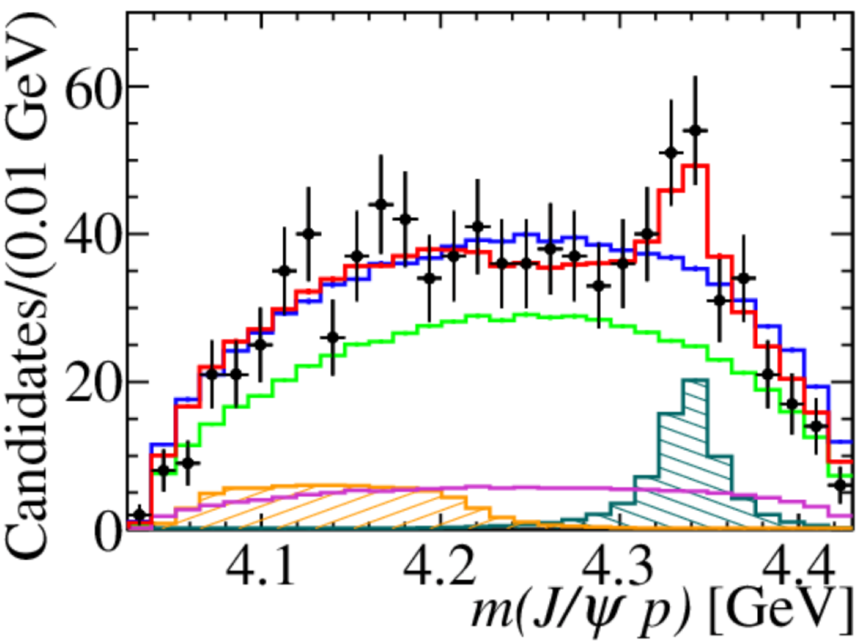


Evidence of new pentaquarks

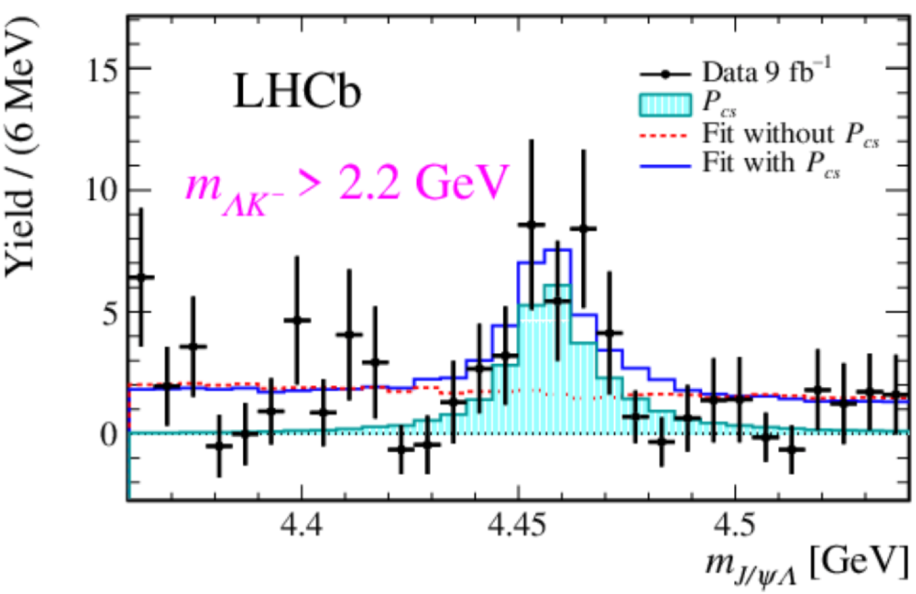
arXiv:2108.04720
Science Bulletin 66 (2021) 1278

- **Families of exotic mesons extend further**
  - Pentaquarks currently only seen in $\Lambda_b \to J/\psi pK$
  - Looking elsewhere, and evidence found

$B_s^0 \to J/\psi p\bar{p}$

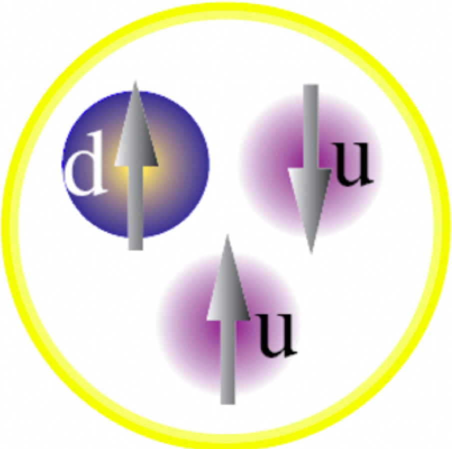


$\Xi_b^+ \to J/\psi \Lambda K^+$

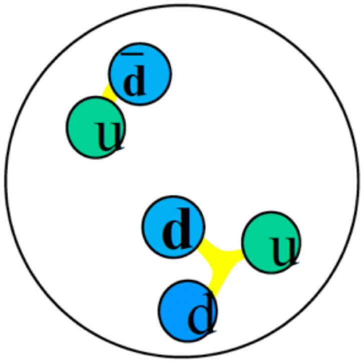


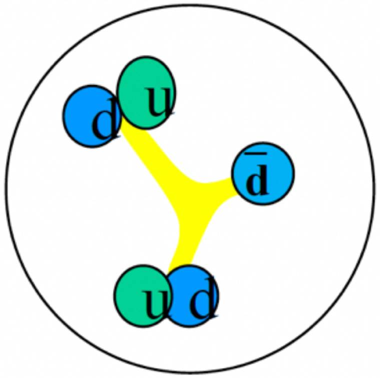
Proton!!!

Constituent quarks



30% of 5-quark component in proton





Garvey & Peng, Prog. Part. Nucl. Phys. 47, 203 (2001)

- **Deep inelastic scattering and Drell-Yan process**
- **Spin crisis of proton**

Meson cloud picture: Thomas, Speth, Henley, Meissner, Miller, Weise, Oset, Brodsky, Ma, …

$$|\, p > \sim |\, uud > + \varepsilon_1 \,|\, n\,(\,udd\,)\,\pi^+(\,\bar{d}u\,) > + \varepsilon_2 \,|\, \Delta^{++}(\,uuu\,)\,\pi^-(\,\bar{u}d\,) > + \varepsilon' \,|\, \Lambda\,(uds)\,K^+(\,\bar{s}u\,) > \ldots$$

Penta-quark picture : Riska, Zou, Zhu, …

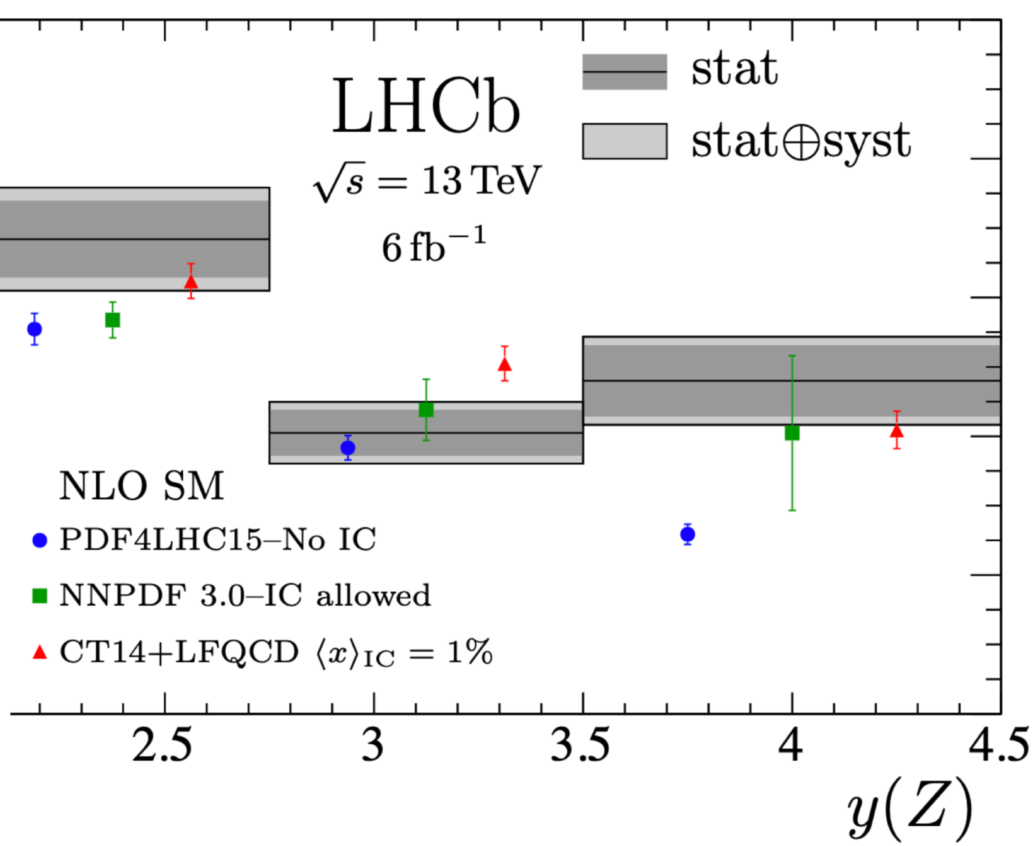
$$|\, p > \sim |\, uud > + \varepsilon_1 \,|\, [ud][ud]\,\bar{d} > + \varepsilon' \,|\, [ud][us]\,\bar{s} > + \ldots$$

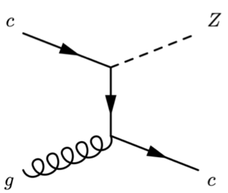
From B. Zou

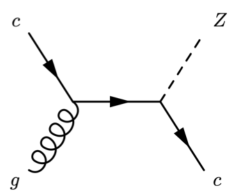
New insights on particle structures

arXiv:2109.08084

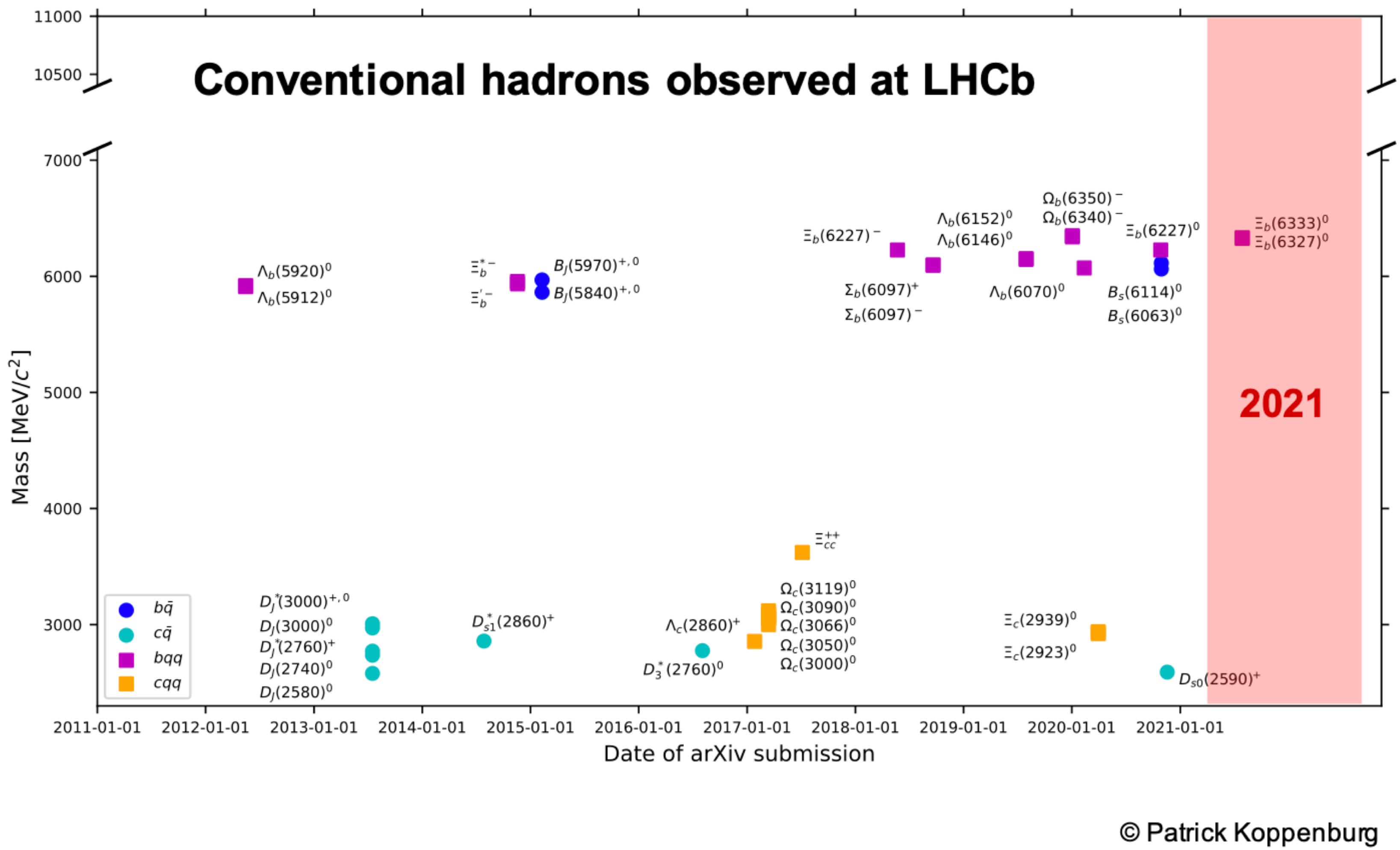
- (Valence-like) Intrinsic charm: $|uudc\bar{c}>$
- Study via Z boson + c jet in forward region: $R_j^c = \sigma(Zc)/\sigma(Zj)$







Harvest of LHCb



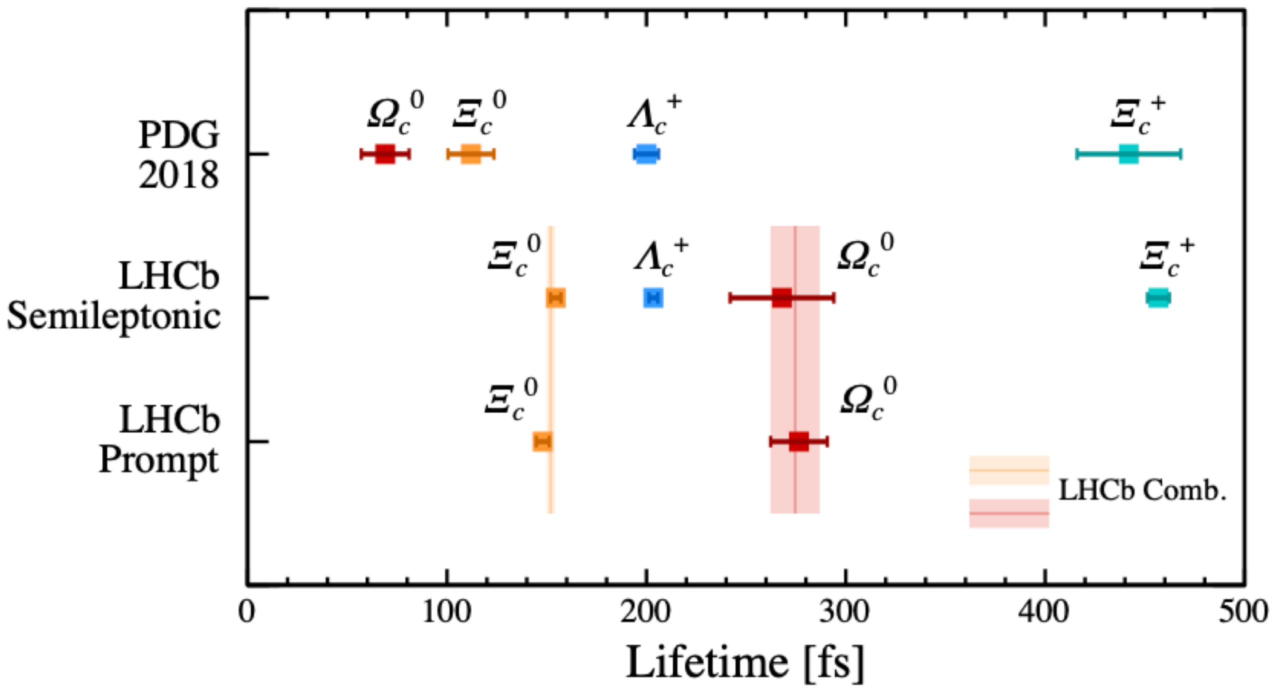
- **Many searches on other doubly heavy flavor baryons, though null yet, but high possibilities with Run3 data**

New picture of lifetime hierarchy

arXiv:2109.01334

- **LHCb results from semileptonic b decays quite different from known values and lifetime hierarchy changed dramatically**
- **Our new measurements with prompt production confirm semileptonic results and new lifetime hierarchy cast in stone**

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



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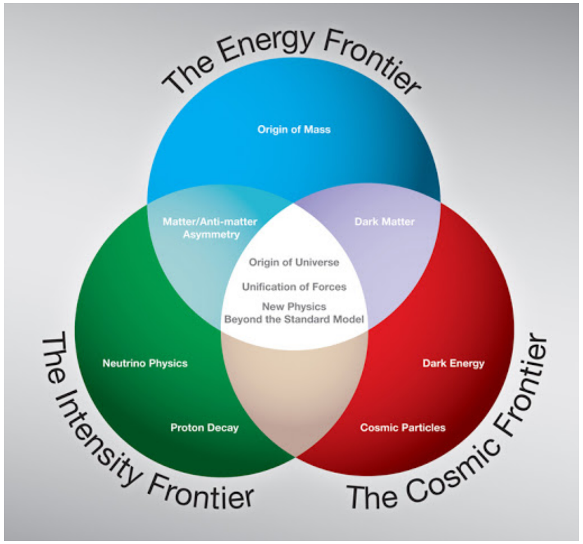
New Physics search

- All SM particles, including Higgs, have been found;
- However new mechanism needed for DM, matter-antimatter asymmetry, hierarchy problems etc.;
- Two ways to search for New Physics: direct search and indirect search through precision measurements;
- Examples in history: many beyond "current" model New Physics first found through indirect search

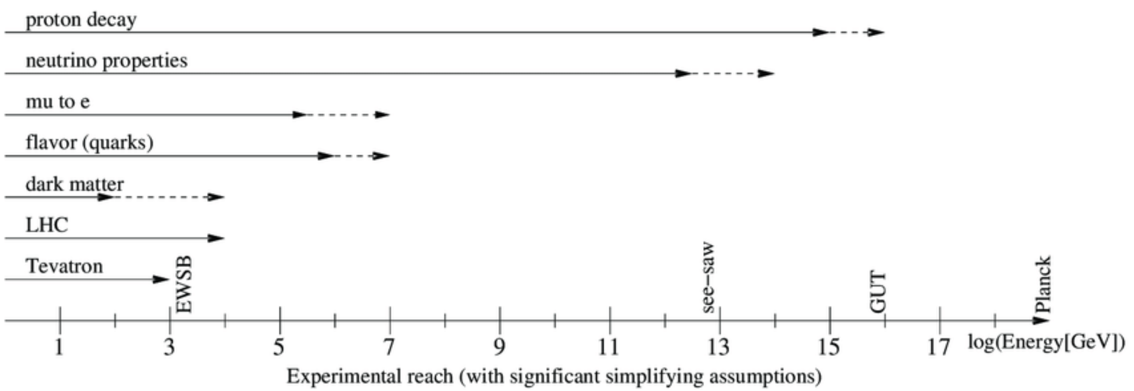


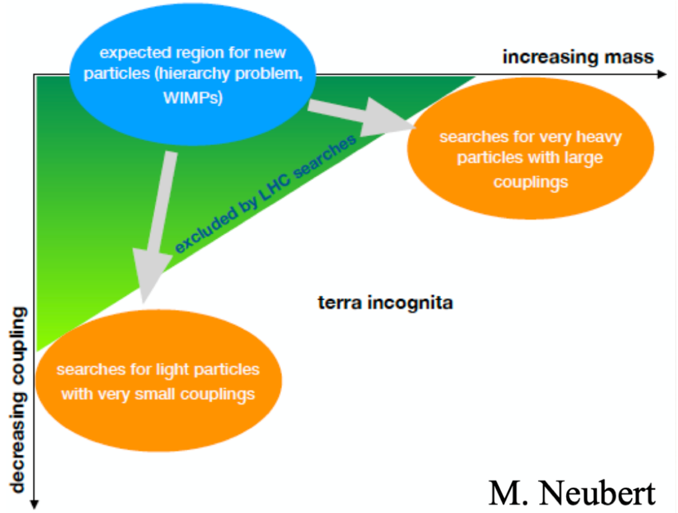
New Physics search at flavor sector

- Sensitive to New Physics scale much higher than direct search: 1-10^4 TeV

Couplings $\mathcal{O}(1)$ to avoid fine tuning

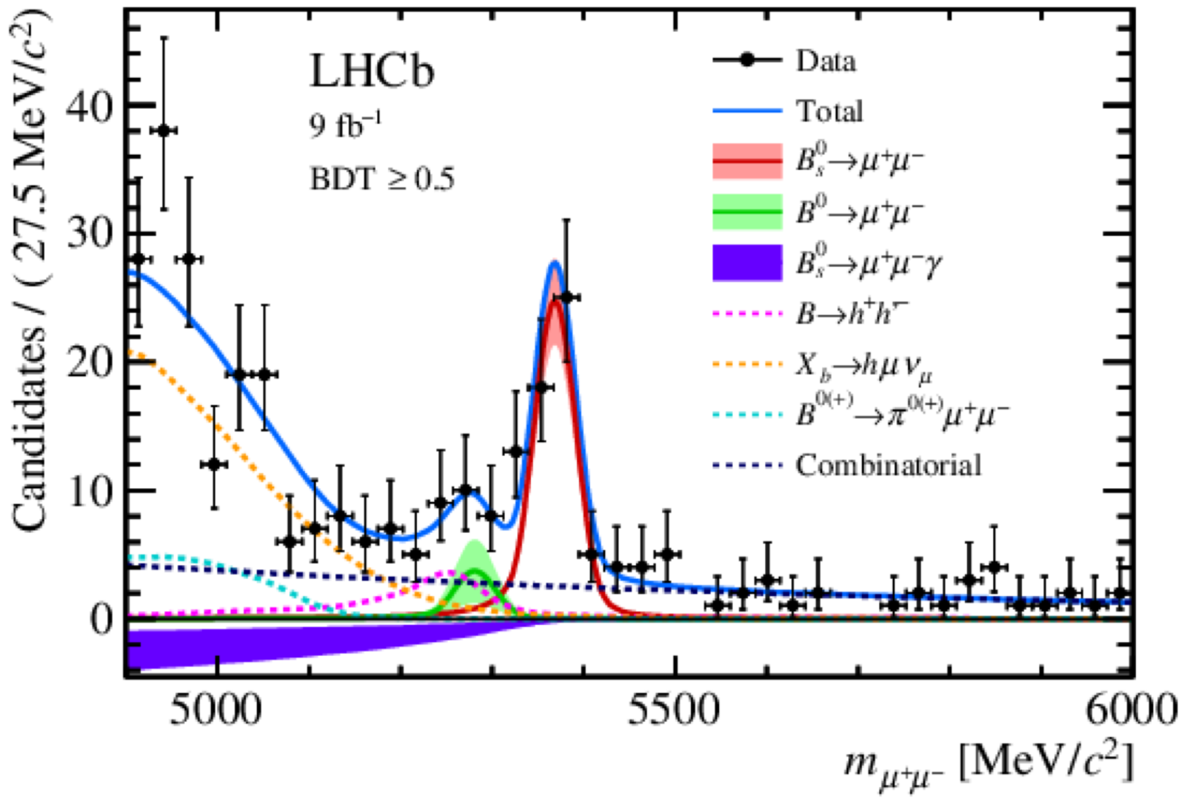
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields}).$$





- Also "tasteful", not only can tell there is New Physics, but also tell properties of New Physics based on flavor it couples to
- Statistics or precision is key for flavor program: New Physics scale, i.e. Dim = 6, proportional to $\sqrt[4]{\text{statistics}}$ or $1/\sqrt{\text{Uncertainty}}$,

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



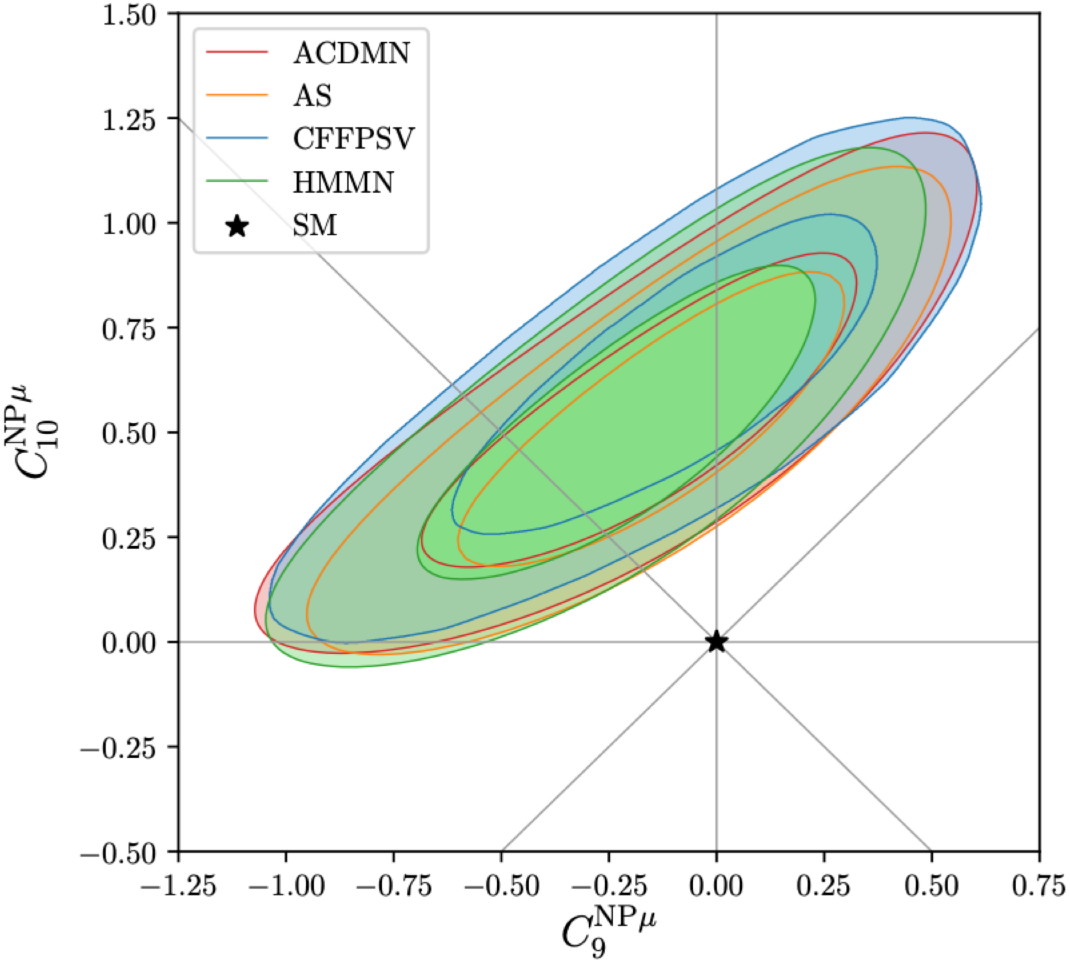
- **Legacy LHCb measurements with full Run1+2 data: branching fractions of $B_s^0 \to \mu^+\mu^-(\gamma)$, $B^0 \to \mu^+\mu^-$, + lifetime of $B_s^0 \to \mu^+\mu^-$**

New violation of symmetry?

- **Symmetries at low energy could be violated at higher energy**
- **Three identical replica of leptons at gauge (however already broken when interact with Higgs)**
- **Current anomalies from $b \to sl^+l^-$ and $b \to cl\nu$**
- **$b \to cl\nu$: anomalies found between τ and μ**
- **$b \to sl^+l^-$: anomalies found between μ and e (driven by μ) + μ channel alone on angular variables, Br. etc.**
- **Possible new physics explanations: leptoquark, Z' etc.**

SMEFT fits

B. Capdevila, M. Fedele, S. Neshatpour, P. Stangl @LHCb implication workshop

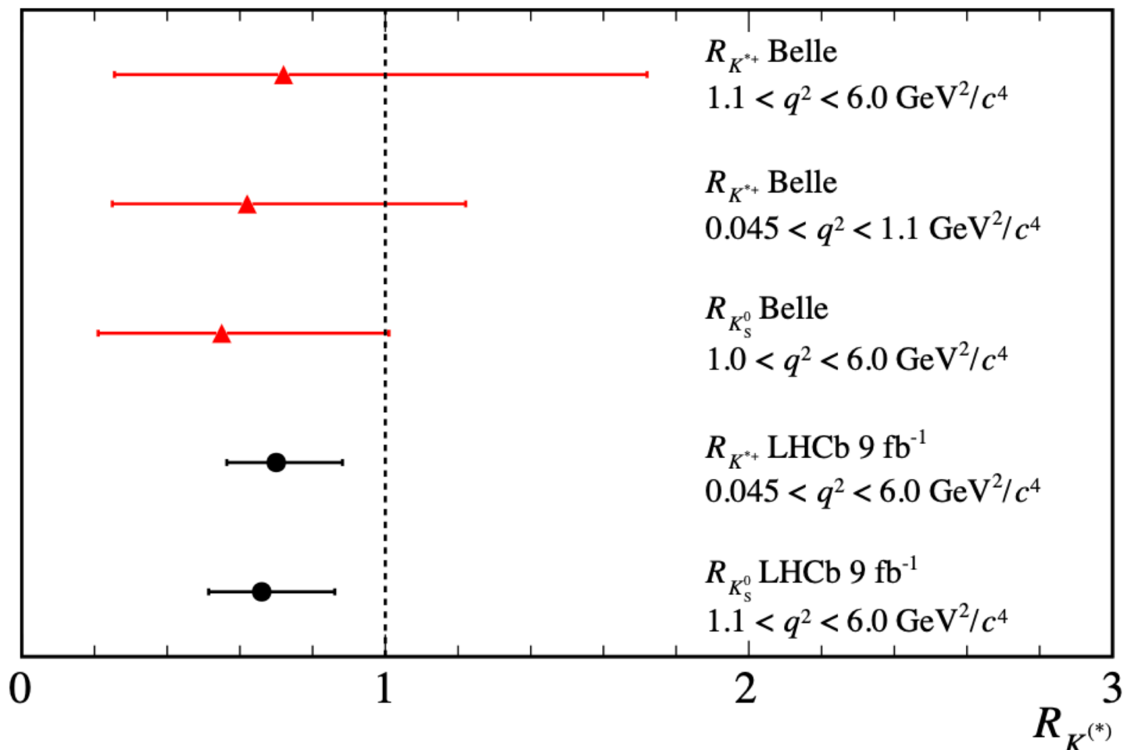


fit to LFU observables + $B_s \to \mu\mu$

Highlights on new LU test results

arXiv:2110.09501

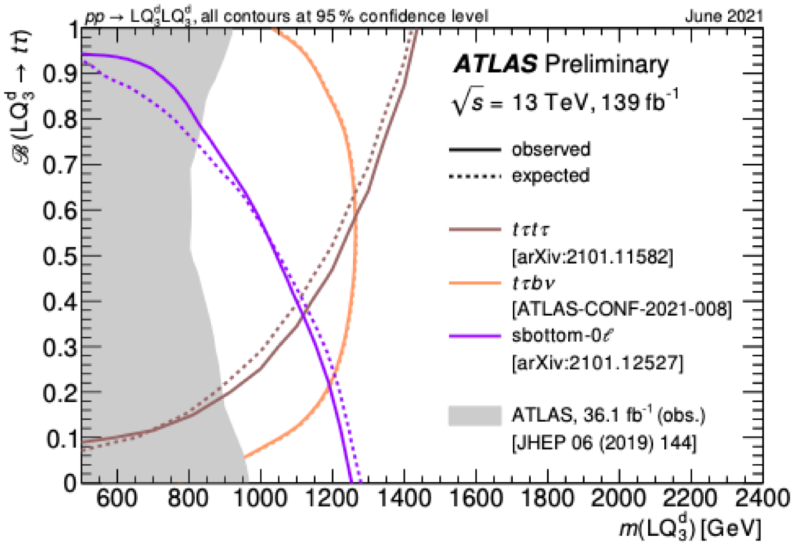
$$R^{-1}_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)} e^+ e^-)}{\mathcal{B}(B \to J/\psi\,(e^+ e^-)\,K^{(*)})} \Big/ \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to J/\psi\,(\mu^+ \mu^-)\,K^{(*)})}$$

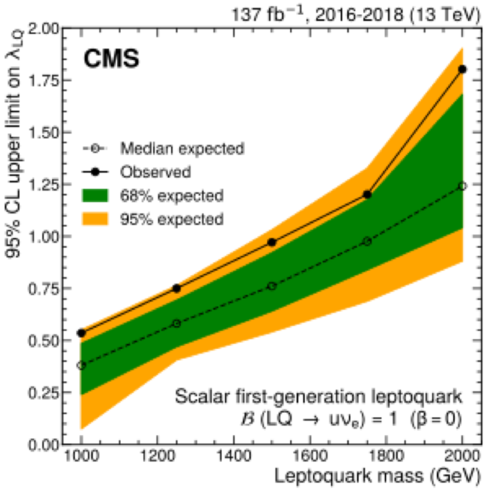


- **Results on $R_{K^0_s}, R_{K^{*-}}$ recently released**
- **Same pattern as $R_{K^+}, R_{K^{*0}}$**

Interplay with other measurements

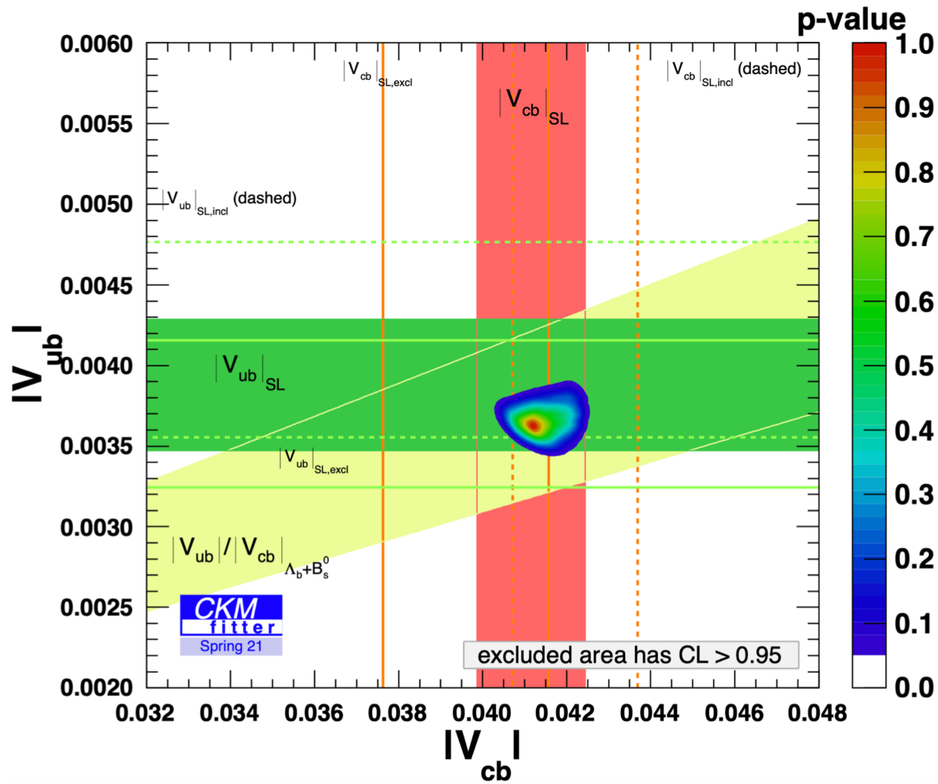
- **If leptoquark or Z'， would be interesting to search directly in ATLAS or CMS**





- **Currently null results from direct search**
- **May be interesting to look for symmetry breaking at flavor sector, i.e. B-L processes**

Precision measurements of CKM



- Long saga of V_{ub} and V_{cb} puzzles from inclusive and exclusive measurements
- Disaster for new physics searches if we don't understand CKM elements precisely

Changing $|V_{cb}|$: $\boxed{39\cdot 10^{-3} \Rightarrow 42\cdot 10^{-3}}$

changes $|V_{cb}|^2$: by 16% $\left(B_{s,d} \to \mu^+\mu^-,\ \Delta M_{s,d}\right)$

$|V_{cb}|^3$: by 25% $\left(K^+ \to \pi^+ \nu\bar{\nu}, \varepsilon_K\right)$

$|V_{cb}|^4$: by 35% $\left(K_L \to \pi^0 \nu\bar{\nu}, K_S \to \mu^+\mu^-\right)$

From A. Buras

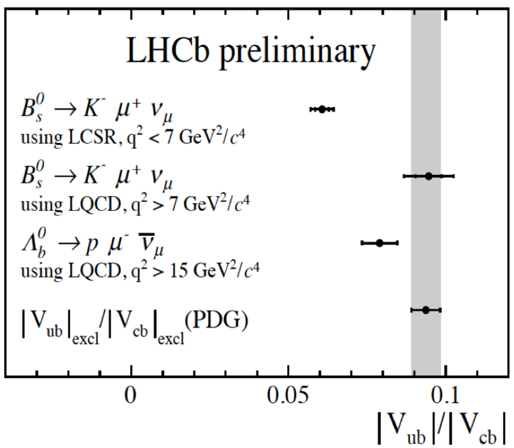
Highlights on V_{ub}, V_{cb}

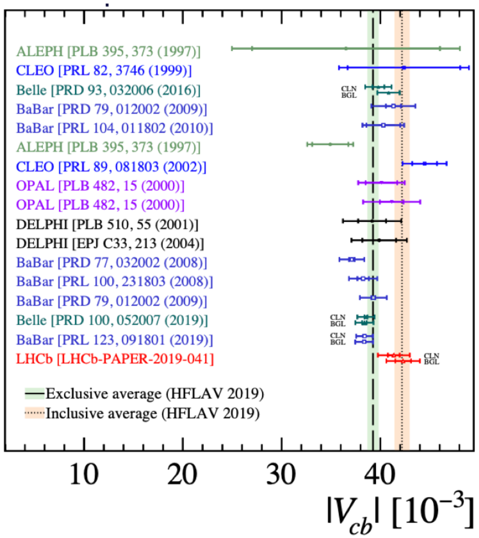
PRL 126, 081804 (2021)

- **Two new measurements, one $|V_{ub}|/|V_{cb}|$ from $B_s \to K\mu\nu_\mu$ vs $B_s \to D_s^- \mu^+ \nu_\mu$**

$$|V_{ub}|/|V_{cb}|(\text{low}) = 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008(D_s) \pm 0.0030(FF) \quad \textbf{LQCD}$$

$$|V_{ub}|/|V_{cb}|(\text{high}) = 0.0946 \pm 0.0030(\text{stat})^{+0.0024}_{-0.0025}(\text{syst}) \pm 0.0013(D_s) \pm 0.0068(FF) \quad \textbf{LCSR}$$





- **Discrepancy found in high and low q^2 region with different form factors, further investigation from both experimental and theoretical parts needed**

- **The other one, $|V_{cb}|$ from $B_s \to D_s^{(*)-} \mu\nu_\mu$ using branching fraction information from $B^0 \to D^{(*)-} \mu^+ \nu_\mu$ (set scale)**

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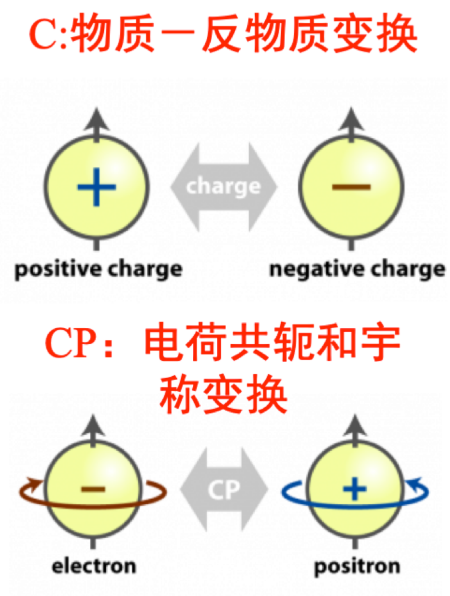
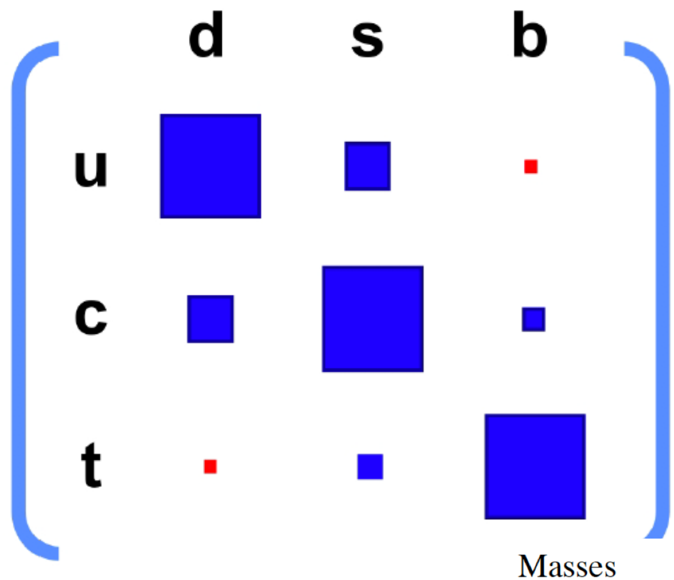
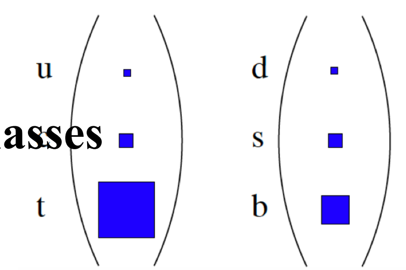
CP violation and CKM matrix

- **Predicted matter antimatter difference much smaller than observed in Universe**
- **Need new CPV mechanism needed to explain**
- **CPV in SM from CKM matrix (closely linked to Yukawa couplings)**

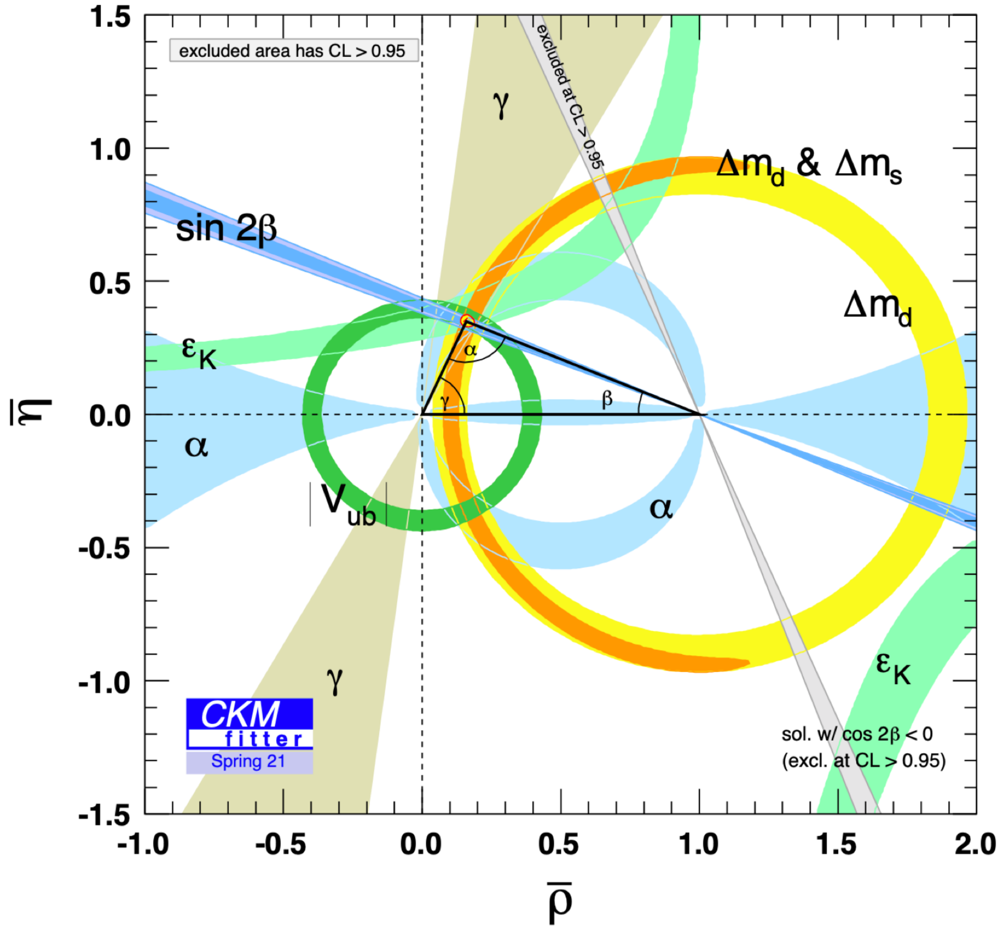




- **Though successful, still many puzzles with CKM matrix**
- **Large hierarchy between elements, similar to hierarchy of masses**
- **Very different from neutrino sector**



Ways towards discovery



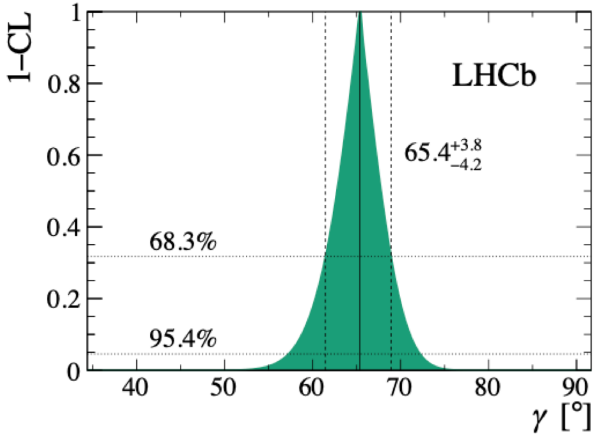
- **Probe new physics by over constraining CKM triangles**
- **Key elements, $|V_{cb}|$, $|V_{ub}|$, angles etc.**

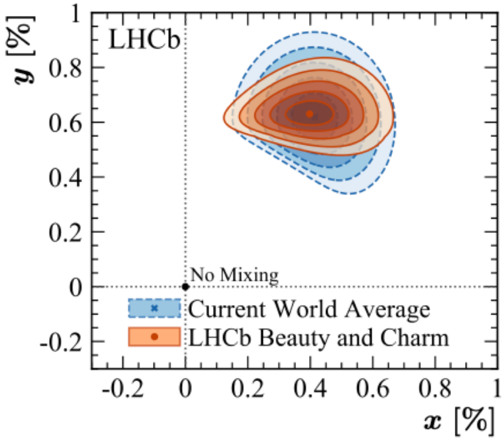
New γ combination

arXiv:2110.02350

- Using all LHCb measurements on γ
- Charm contributions important, also including results from charm factories and LHCb (CP violation in charm, W. Wang, PRL 110 (2013) 061802)
- Not only constraining γ, but also on charm mixing parameters

$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$





$$x_D = (4.00^{+0.52}_{-0.53}) \times 10^{-3}$$

$$y_D = (6.30^{+0.33}_{-0.30}) \times 10^{-3}$$

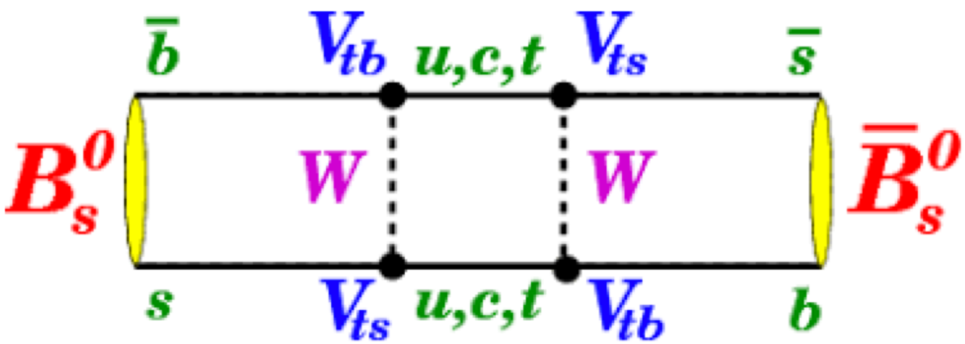
$$\delta_D^{K\pi} = (190.0^{+4.2}_{-4.1})^\circ$$

$$r_D^{K\pi} = (58.67 \pm 0.15) \times 10^{-3}$$

- Uncertainties still twice larger than obtained from indirect measurements
- Need more channels to further constraining it

Mixing parameter

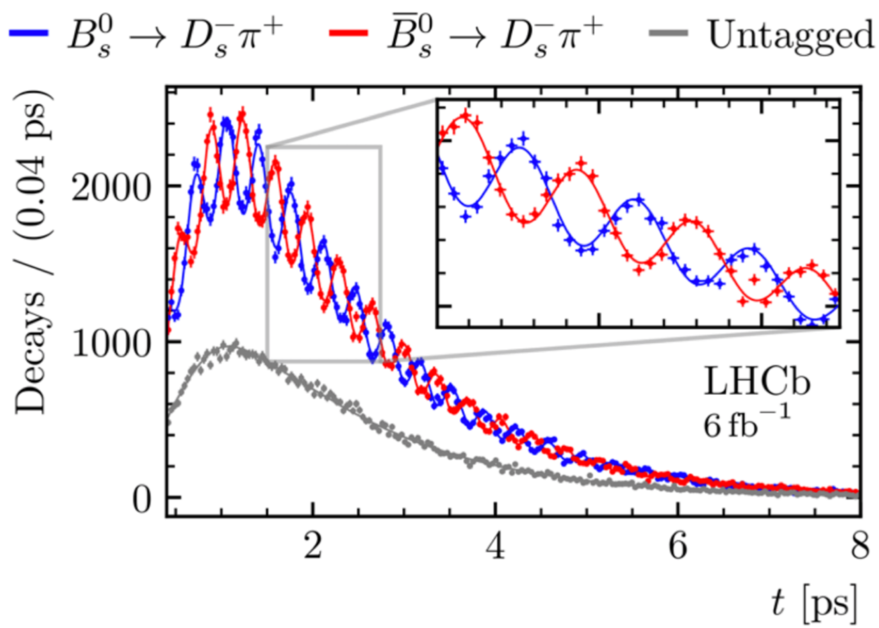
JHEP 03 (2021) 137
arXiv:2104.04421

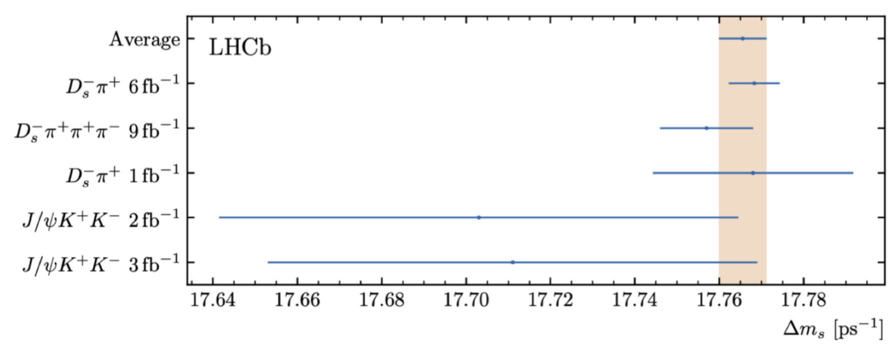


Together with $B_s^0 \to D_s^- \pi^+$, yields the most precise determination of oscillation frequency!!!

Better precision from lattice needed

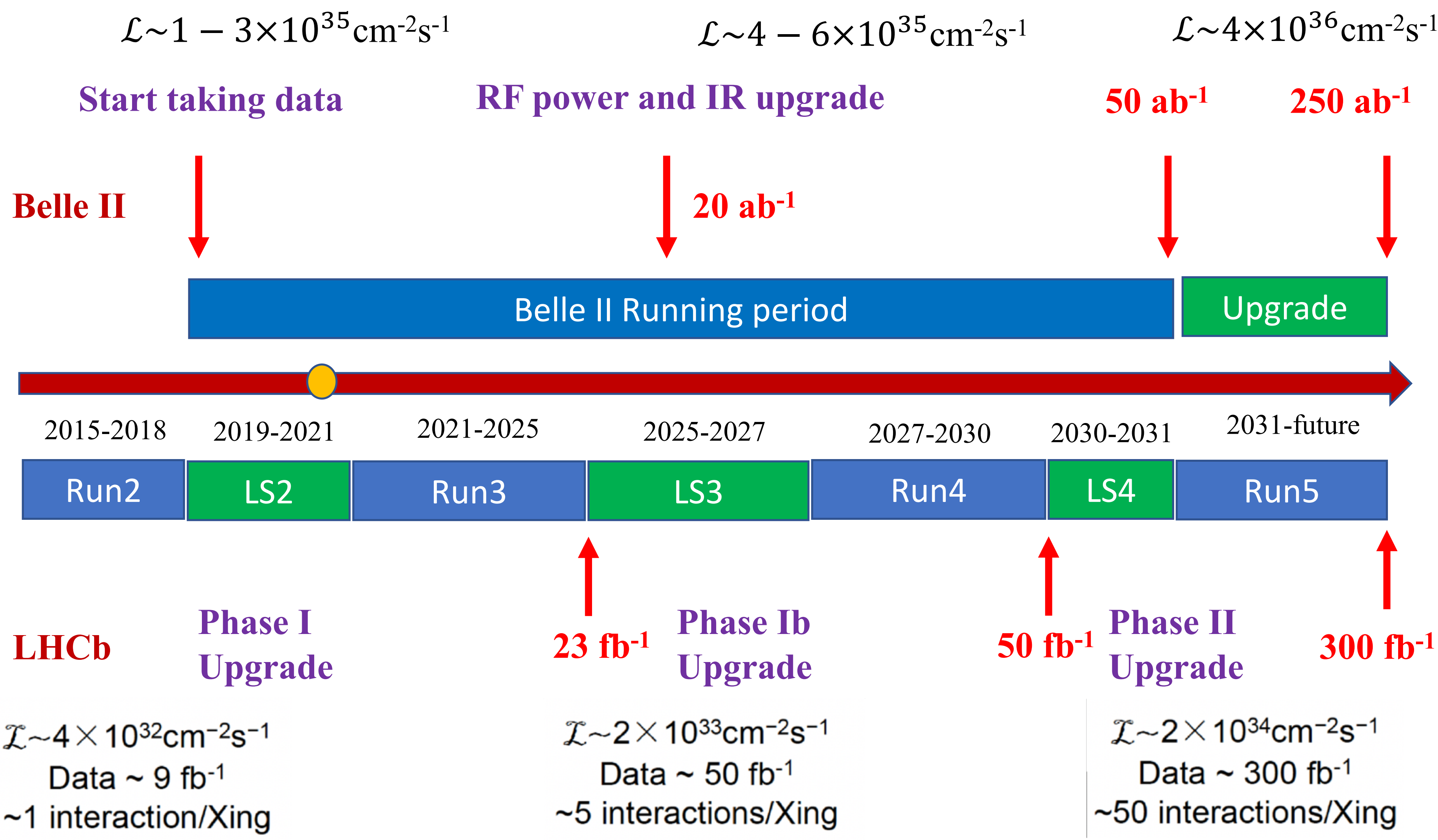
- Mass eigenstates different from flavor eigenstates: Δm_s





$$17.7656 \pm 0.0057\,\mathrm{ps}^{-1}$$

Future data taking plans



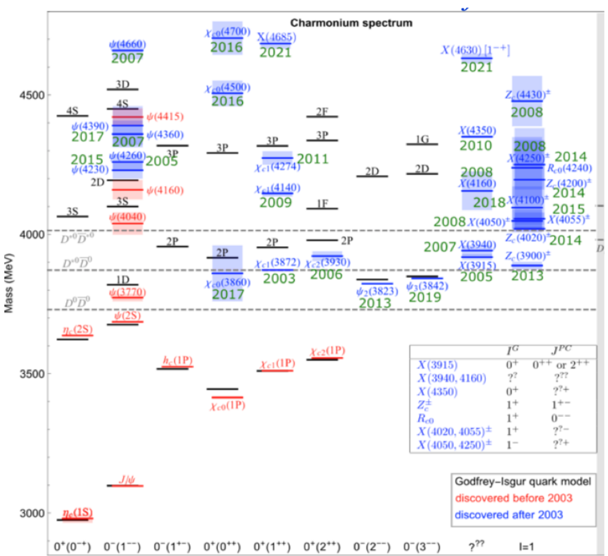
LHCb potential in near future

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})
CKM tests				
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°
ϕ_s ($B_s^0 \to J/\psi\phi$)	49 mrad	[8]	14 mrad	10 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	—
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}
Charm				
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	17×10^{-5}	—
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	13×10^{-5}	[38]	4.3×10^{-5}	—
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}
Rare Decays				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	71%	[40, 41]	34%	—
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}$($B_s^0 \to \phi\gamma$)	$^{+0.41}_{-0.44}$	[51]	0.124	0.083
$S_{\phi\gamma}$($B_s^0 \to \phi\gamma$)	0.32	[51]	0.093	0.062
α_γ($\Lambda_b^0 \to \Lambda\gamma$)	$^{+0.17}_{-0.29}$	[53]	0.148	0.097
Lepton Universality Tests				
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.10	[61]	0.031	0.021
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	—

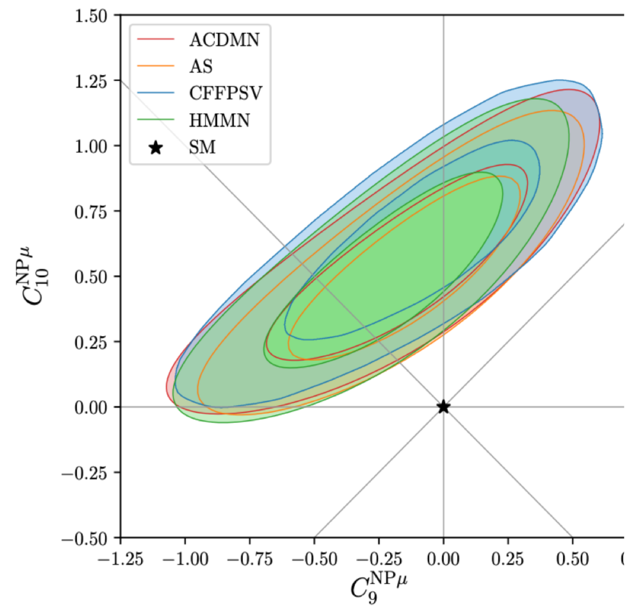
Conclusion

- **A flavorful era of particle physics**

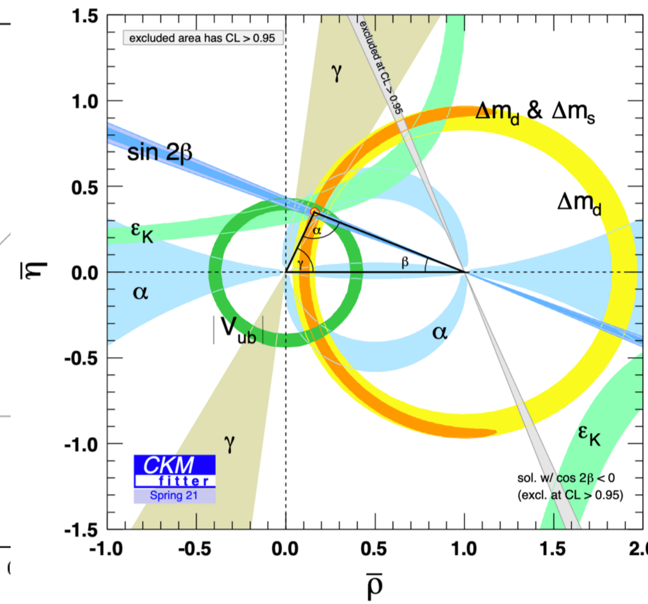
Particle zoo



Flavor anomalies



CP violation



Thank you for your attention