Recent Theoretical Progresses on Heavy Flavor Physics

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4th China LHC Physics Workshop
第4届中国LHC物理工作会议

Disclaimer: Not Every Interesting Topics covered

Not Every publication mentioned

- Bottom
  - ✓ Anomalies
  - ✓ Corrections
  - ✓ 3-body decays
- Charm
  - ✓ Charmed hadron
  - ✓ Doubly-charmed baryon

Bottom

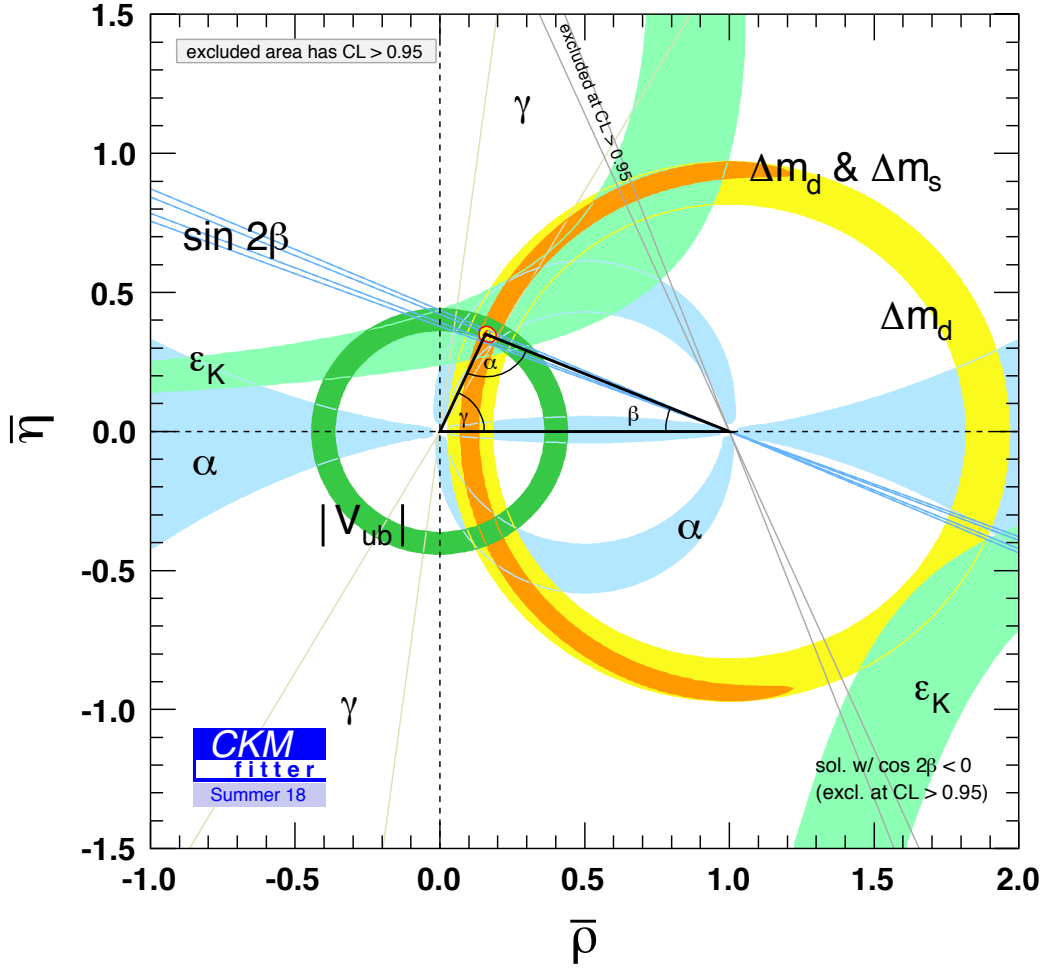
B Physics

- Extract the SM parameters:

  Vub, Vcb, Weak Phases

- Test the SM: unitarity triangle
- Hunt for NP

B Physics

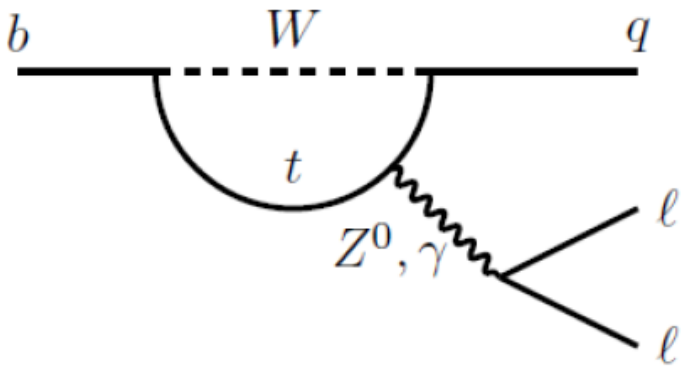


- Looks great, but can be deceived (tension)
- O(10%-15%) NP is still allowed

Anomalies

R_K/R_K^* Anomaly: FCNC

semileptonic



BR ~ 10^{-7}

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$ = 1.000 + $O(m_\mu^2/m_b^2)$ (SM)

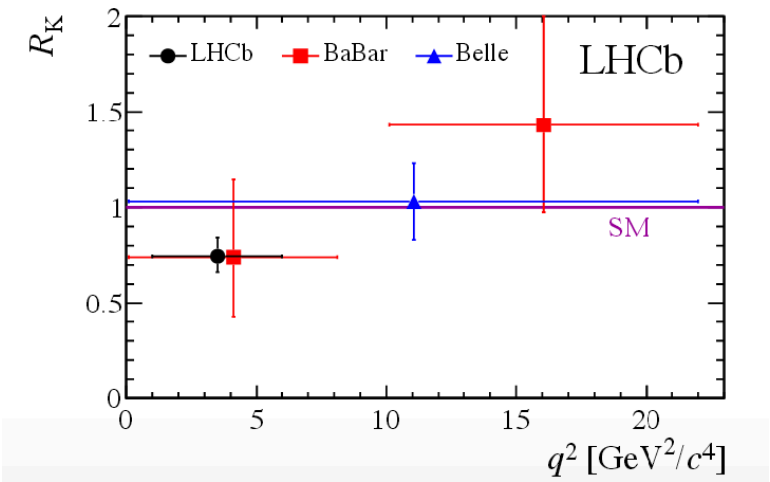
R_K/R_K^* Anomaly:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \quad = 1.000 + O(m_\mu^2/m_b^2) \text{ (SM)}$$

LHCb: PRL, 113, 151601(2014)

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

$1\ \text{GeV} < q^2 < 6\ \text{GeV}$



2.6 Sigma Deviation

R_K/R_K^* Anomaly:

$$R_{K^*}[q^2_{\rm min}, q^2_{\rm max}] \equiv \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 d\Gamma(B \to K^* \mu^+ \mu^-)/dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 d\Gamma(B \to K^* e^+ e^-)/dq^2},$$

Observable	SM results	Experimental data	
$R_K : q^2 = [1,6]\text{GeV}^2$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$	2.6 Sigma Deviation
$R^{\rm low}_{K^*} : q^2 = [0.045, 1.1]\,\text{GeV}^2$	$0.920^{+0.007}_{-0.006}$	$0.66^{+0.11}_{-0.07} \pm 0.03$	2.3 Sigma Deviation
$R^{\rm central}_{K^*} : q^2 = [1.1, 6]\,\text{GeV}^2$	0.996 ± 0.002	$0.69^{+0.11}_{-0.07} \pm 0.05$	2.5 Sigma Deviation

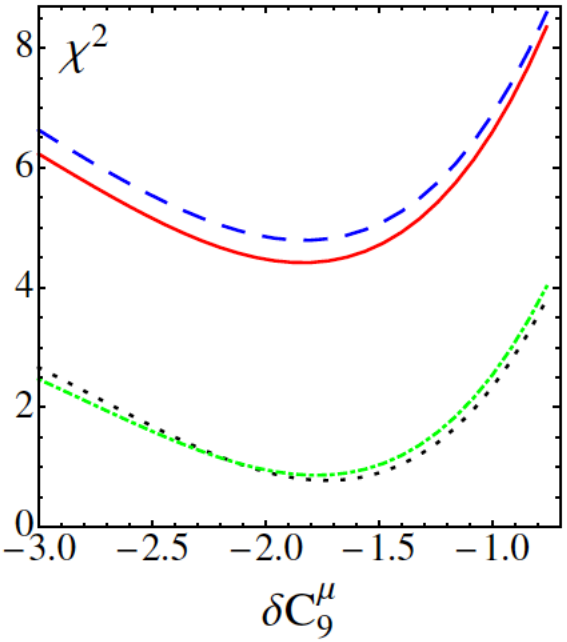
SM: Geng, et.al, 1704.05446

LHCb: PRL, 113, 151601(2014)

LHCb: 1705.05802

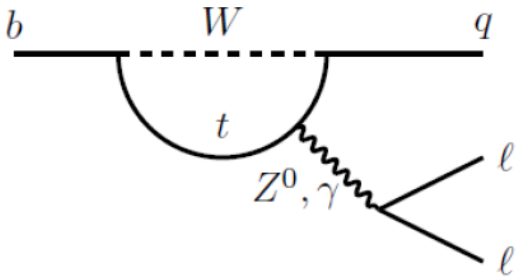
R_K/R_K^* Anomaly

- ✓ At low q2, photon dominates
- ✓ At high q2, SM box+Z dominates



NP with a heavy particle.

semileptonic



BR ~ 10^{-7}

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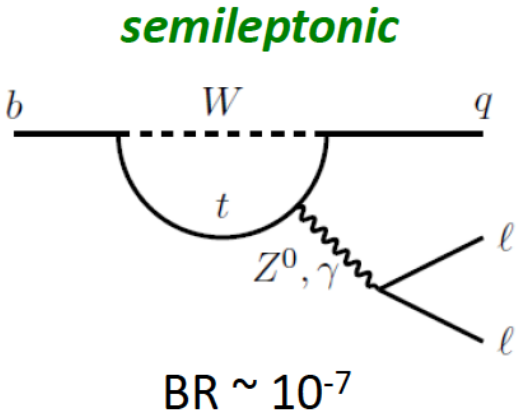
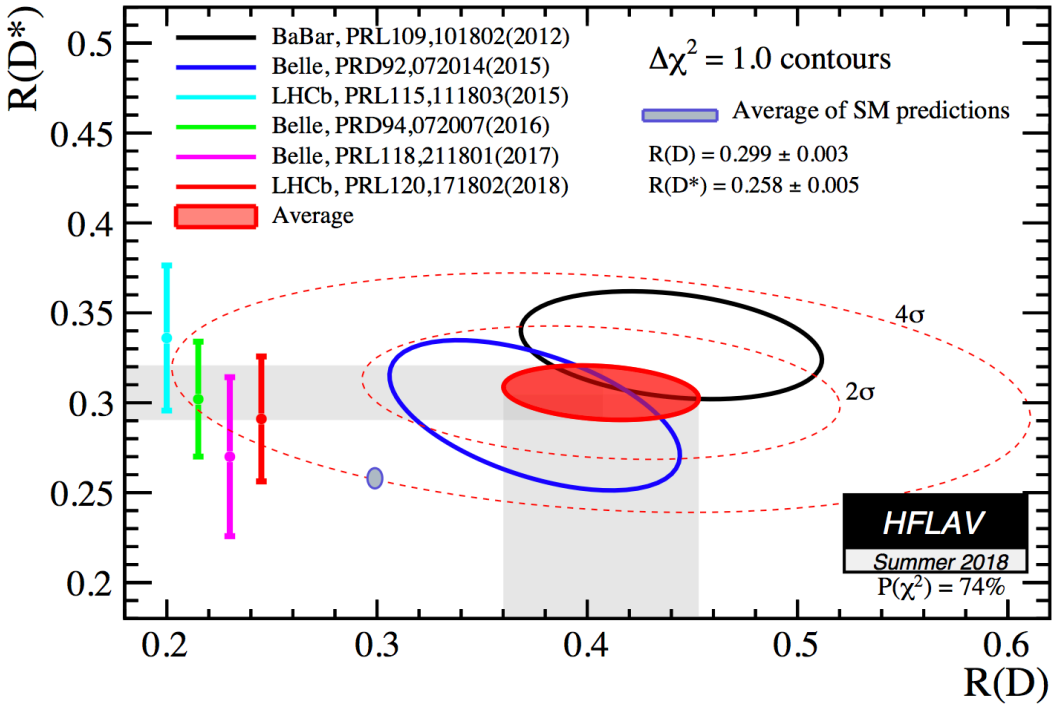


NP with a heavy particle cannot explain R_K^* at low q2.

Effective Field Theory or Many UV models: ….

R(D)/R(D*) Anomaly

$$R(D^{(*)}) = \frac{\mathrm{Br}(B \to D^{(*)} \tau \nu_\tau)}{\mathrm{Br}(B \to D^{(*)} \ell \nu_\ell)}$$



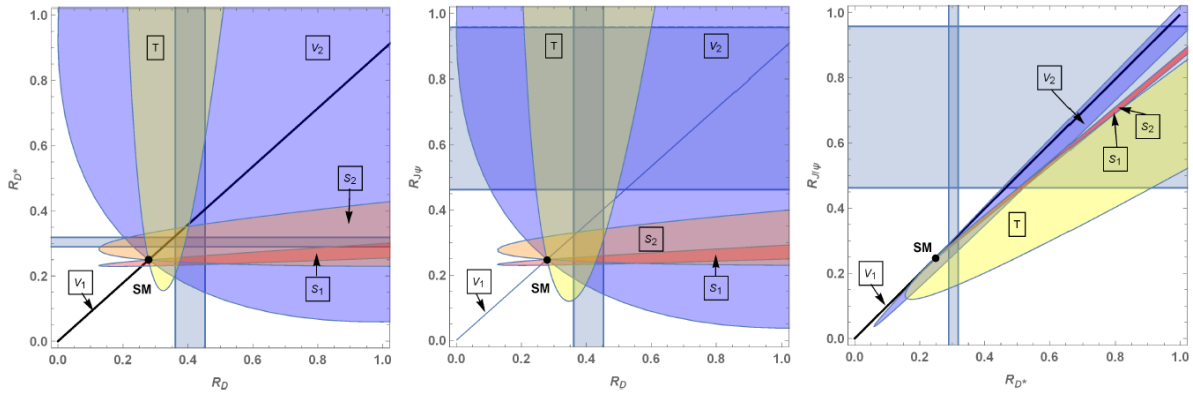
$R(D)_{\mathrm{SM}} = 0.299 \pm 0.003 \quad 2.3\sigma$

$[0.407 \pm 0.039 \pm 0.024]$

$R(D^*)_{\mathrm{SM}} = 0.258 \pm 0.005 \quad 3.0\sigma$

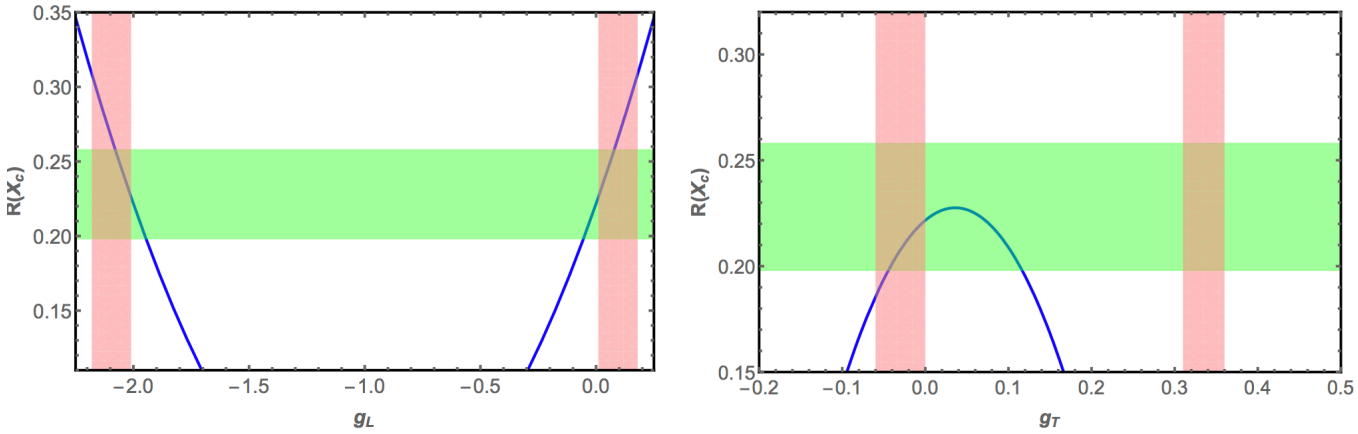
$[0.306 \pm 0.013 \pm 0.007]$

R(D)/R(D*) Anomaly



Huang, et.al., 1808.03565

$R(X_c)$ constraint: [Kamali/Rashed/Datta,1801.08259; Lai/Li/Li/Yang, w.i.p.]



R_H	LHCb data [5]	z-Series approach
$R_{J/\psi}$	$0.71 \pm 0.17(stat) \pm 0.18(syst)$	0.25 ± 0.01

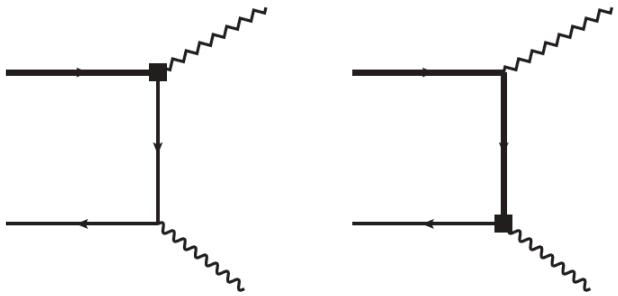
WW, R.L. Zhu,1808.10830

Higher Order/Higher Power

- Higher order radiative corrections:

QCDF at leading power and at NNLO in QCD established and almost complete. Xin-Qiang Li et.al.

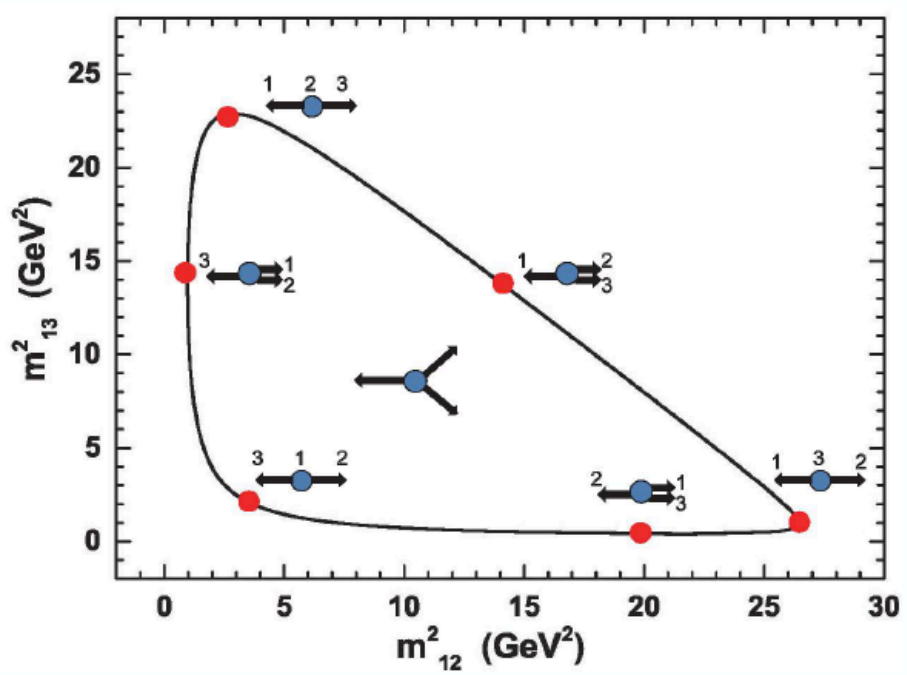
- Higher Power Corrections: (Beneke, Y.M. Wang, C.D.Lu, Y.L.Shen,...)



Subleading power contributions from hadronic photon corrections.

- NLL twist-two hadronic photon effect yields $\mathcal{O}(30\,\%)$ correction at $\lambda_B = 354\,\mathrm{MeV}$.
- Strong cancellation between $F_{V,\mathrm{photon}}^{\mathrm{2PHT,LL}}$ and $F_{V,\mathrm{photon}}^{\mathrm{3P,LL}}$.
- Large-recoil symmetry violation due to $F_{V(A),NLP}^{\mathrm{LC}}$, $F_{V,\mathrm{photon}}^{\mathrm{2PHT,LL}}$ and $F_{V,\mathrm{photon}}^{\mathrm{3P,LL}}$.

Three-body Decays



- ✓ **More sophisticated Phenomena**
- ✓ Resonant vs non-resonant
- ✓ **Lack of reliable theory**

Three-body Decays

(Preliminary) Frameworks:

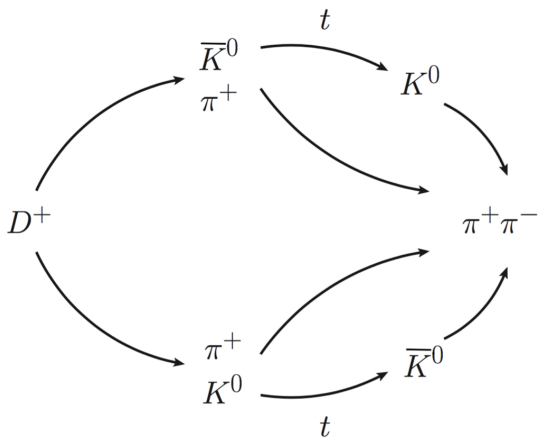
- ✓ Factorization Approach Cheng, Chua, Fajfer, YLi,…
- ✓ PQCD Li, Chen, Wang, Lu, Xiao …
- ✓ QCD Factorization: Krankl, Mannel,Virto,…
- ✓ Diagrammatic Approach combined SU(3):

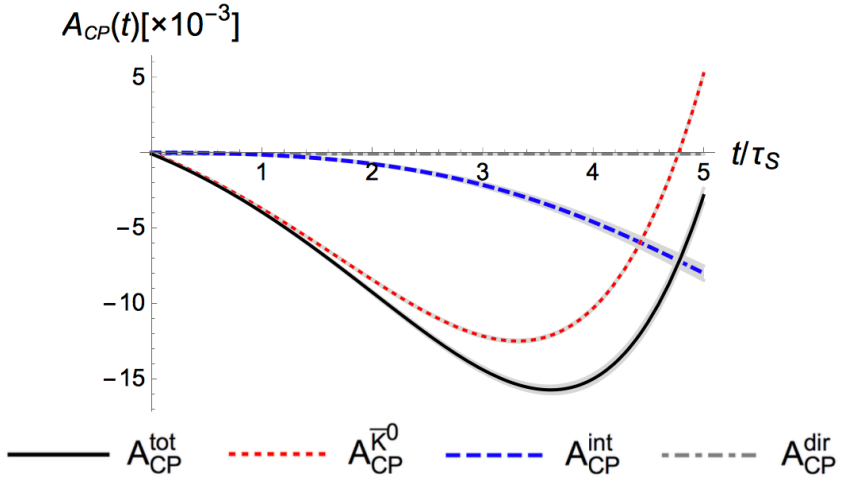
  Gronau,London

Charm

CP violation in Charm

$$D^+ \to \pi^+ K(t)(\to \pi^+\pi^-) \qquad A_{CP}(t) \equiv \frac{\Gamma_{\pi\pi}(t) - \overline{\Gamma}_{\pi\pi}(t)}{\Gamma_{\pi\pi}(t) + \overline{\Gamma}_{\pi\pi}(t)}$$





D.Wang, **FSY**, H.n.Li, Phys.Rev.Lett 119, 181802(2017)

Lifetime of Ω_c

Heavy quark expansion:

$$\Gamma(H_Q \to f) = \frac{G_F^2 m_Q^5}{192\pi^3} V_{CKM} \left(A_0 + \frac{A_2}{m_Q^2} + \frac{A_3}{m_Q^3} + \ldots \right)$$

- to $1/m_c^3$

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}_-$	$\Gamma^{\rm int}_+$	$\Gamma^{\rm semi}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$	$\tau_{\rm expt}(10^{-13}s)$
Λ_c^+	0.886	1.449	−0.397	0.039	0.283	2.26	2.91	2.00 ± 0.06
Ξ_c^+	0.886	0.083	−0.427	0.839	0.771	2.153	3.06	4.42 ± 0.26
Ξ_c^0	0.886	1.559		0.839	0.771	4.055	1.62	$1.12^{+0.13}_{-0.10}$
Ω_c^0	1.019	0.505		2.830	1.881	6.235	1.06	0.69 ± 0.12

Lifetime of Ω_c

Cheng (1807.00916):

$$\Gamma(B_c \to f) = \frac{G_F^2 m_c^5}{192\pi^3} V_{CKM} \left(A_0 + \frac{A_2}{m_c^2} + \frac{A_3}{m_c^3} + \frac{A_4}{m_c^4} \ldots\right)$$

	Γ^{dec}	Γ^{ann}	Γ^{int}_{-}	Γ^{int}_{+}	Γ_{SL}	Γ^{tot}	$\tau(10^{-13}s)$	$\tau_{expt}(10^{-13}s)$
Λ_c^+	1.012	1.883	−0.209	0.021	0.308	3.015	2.18	2.00 ± 0.06
Ξ_c^+	1.012	0.115	−0.189	0.353	0.524	1.854	3.55	4.42 ± 0.26
Ξ_c^0	1.012	2.160		0.351	0.524	4.083	1.61	$1.12^{+0.13}_{-0.10}$
Ω_c^0	1.155	0.126		0.346	0.520	2.855	2.31	0.69 ± 0.12

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

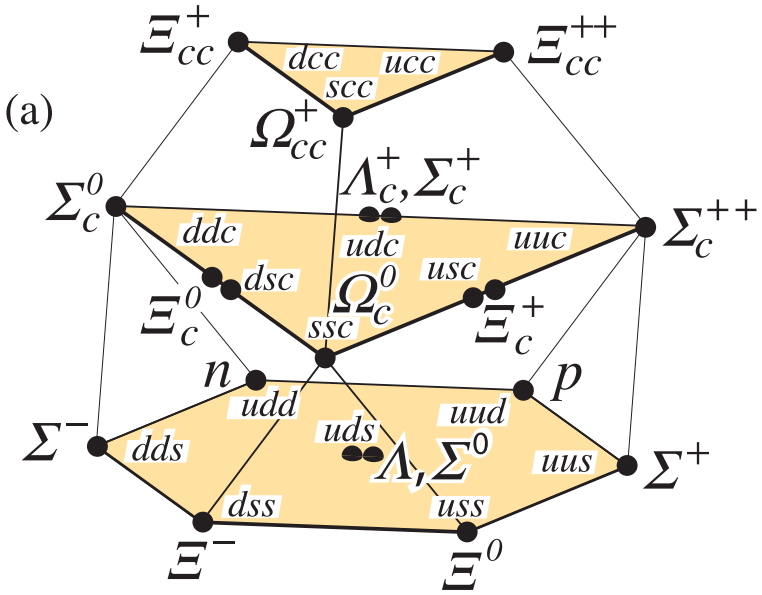
LHCb 1807.02024:

$\tau(\Omega_c^0) = (2.68 \pm 0.24 \pm 0.10 \pm 0.02) \times 10^{-13}$s

Four-times larger than the world average of $(0.69 \pm 0.12) \times 10^{-13}$s from fixed target experiments!

Doubly-Charm Baryons

$J^P = 1/2^+$



LHCb, PRL 119, 112001 (2017)

Ξ_{cc}^{++}

Doubly-Charm Baryons

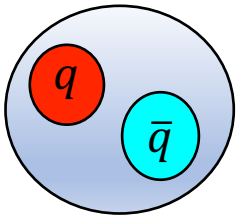
- Study Ξ_{cc}^{++} in more channels?
- Lifetime?
- Ξ_{cc}^{+}?
- $J^P = 1/2^+$?
- Semi-leptonic decay modes?
- CP Violation?
- …

Doubly-Charm Baryons:

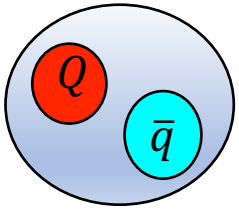
Recent Theoretical Progresses on Weak Decays:

- Form factors in quark model: (Z.X.Zhao)
- Lifetime estimate (H.Y.Cheng)
- Rescattering mechanisms for nonleptonic decays (R.H.Li, F.S.Yu)
- …

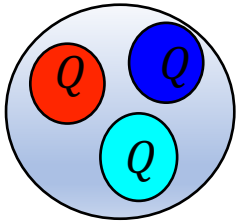
Doubly-Charm Baryons

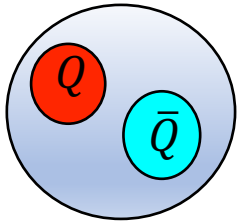


Chiral Perturbation Theory

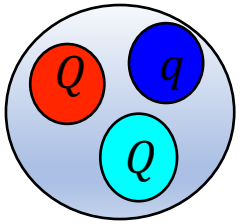


HQET/SCET





NRQCD



? Heavy Diquark EFT?

Summary

- Bottom:

  R_K*, low q2 vs high q2

  Higher Power Corrections

- Charm: New CP; lifetime of Ω_c

- Doubly-charm baryons: model calculations of decays

✓ EFT/LQCD is needed.

Thank you for your attention!