

HFCPV2025

第二十二届全国重味物理和CP破坏研讨会

THE 22nd NATIONAL SYMPOSIUM ON HEAVY FLAVOR PHYSICS AND CP VIOLATION

北京·西郊宾馆 2025.10.24-10.28

大会总结

李新强



华中师范大学



Institute of Particle Physics
粒子物理研究所

第22届全国重味物理与CP破坏研讨会, 2025/10/27, 北京

成功的大会：参会人数、会议主题、报告人数

2002年第一届重味物理和CP破坏研讨会



实验上，BaBar和Belle运行不久

理论上，QCDF、PQCD、SCET等方法提出不久

第22届全国重味物理和CP破坏研讨会(HFCPV2025)合影留念

2025.10.25 · 北京



230人注册，队伍不断壮大
精确味物理时代

感谢地方组委会和会务组周到、悉心的安排；感谢几位先生的参会，感谢高老师、黄老师、赵老师的致辞；珍惜科研环境、争作更多、更好的原创性成果！

会议主题：涵盖了当前各大实验最新成果和理论进展

实验报告：22

理论报告：51

理论和实验相结合

➤ Heavy Quark Decays

➤ CP Violation

➤ CKM Elements

➤ LFU/LFV

➤ Charm Physics

➤ Tau Physics

➤ Spectroscopy

➤ Physics Beyond the SM

➤ Future facilities

➤ toponium, quantum entanglement

感谢：

顾问委员会：黄涛、高原宁、李湘楠、吕才典、肖振军、杨亚东、郑阳恒

会议组委会：李新强、李营、吕晓睿、沈成平、王伟、于福升、张黎明、朱瑞林

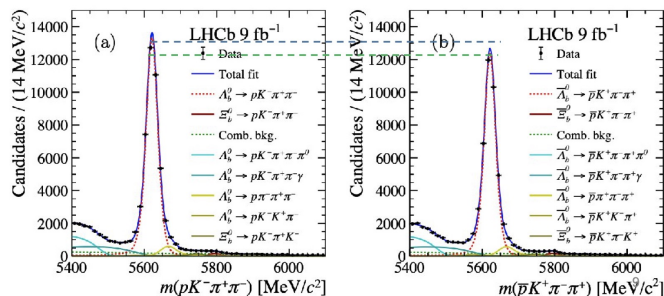
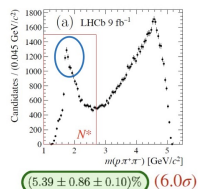
实验： LHCb、BESIII、Belle/BelleII、CMS、ATLAS

Nature 643 (2025) 1223

CPV in $\Lambda_b^0 \rightarrow p K^- \pi^+ \pi^-$ decay

Λ_b 重子CP破坏的首次发现

- Using Runs 1-2 dataset (9 fb^{-1})
- Corrections for production & detection asymmetries as measured in $\Lambda_b^0 \rightarrow \Lambda_c^+ (\rightarrow p K^- \pi^+) \pi^-$ control channel
- Phase-space integrated $A_{CP} = (2.45 \pm 0.46 \pm 0.10) \%$ (5.2σ)
- CP asymmetries also measured in different PHSP regions



CPV in $B^+ \rightarrow J/\psi \pi^+$: first evidence

加深对企业图污染的理解

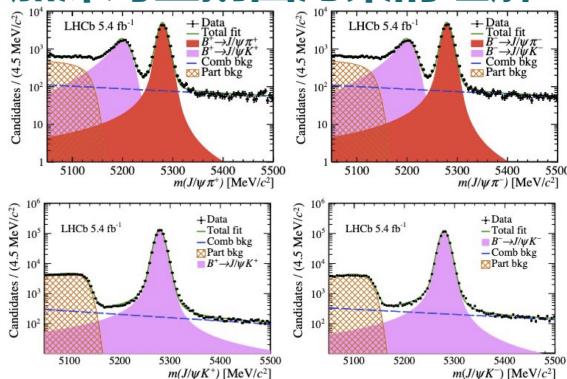
- Using Run 2 dataset
- CP asymmetry measured wrt the control channel $B^+ \rightarrow J/\psi K^+$:

$$\Delta A^{CP} \equiv A^{CP}(B^+ \rightarrow J/\psi \pi^+) - A^{CP}(B^+ \rightarrow J/\psi K^+).$$

- Combined Runs1-2 9 fb^{-1} result:

$$\Delta A^{CP} = (1.42 \pm 0.43 \pm 0.08) \times 10^{-2}$$

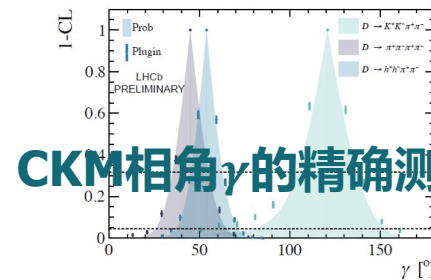
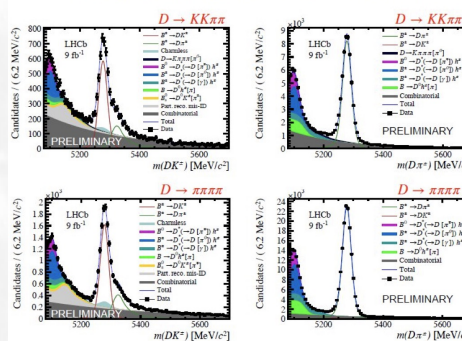
First evidence (3.2σ) of DCPV in beauty decays to charmonia



CKM angle γ with $B^\pm \rightarrow [h^+ h^- \pi^+ \pi^-]_D h^\pm$

- Model-independent measurement of CKM angle γ in $B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D h^\pm$ and $B^\pm \rightarrow [\pi^+ \pi^- \pi^+ \pi^-]_D h^\pm$, with $D = D^0$ or $\bar{D}^0$
- Use BESIII measurement of strong phase in phase-space bins of the $D^0/\bar{D}^0$ decays
- Analysis based on 9 fb^{-1} from Run1+2

BESIII, PRD 112 (2025) 012015



CKM相角 γ 的精确测量

$$\gamma = (53.9^{+9.5}_{-8.9})^\circ$$

13

Legacy Runs1-2 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ measurement

- Two different theory packages are used, which take different approaches, e.g. different non-local form factors

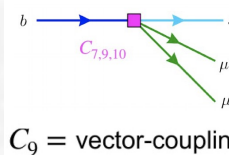
$$H_{eff} \propto \sum_i \mathcal{O}_i C_i$$

$$\Delta Re(C_9) = -0.93^{+0.18}_{-0.16}$$

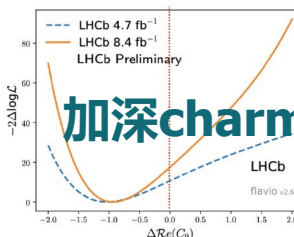
Significance: 4.1σ

$$\Delta Re(C_9) = -0.94^{+0.22}_{-0.22}$$

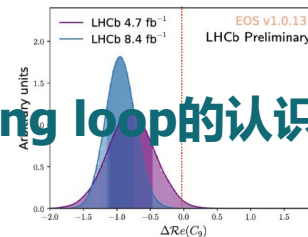
Significance: 4.0σ



$C_9 = \text{vector-coupling}$



加深charming loop的认识



实验：LHCb、BESIII、Belle/BelleII、CMS、ATLAS

BF of D^0, D^+, D_s^+ hadronic decays
粲介子Br和CP破坏的测量

☞ D_s^+ decays:

JHEP05(2024)335, 7.33fb⁻¹@4.178 – 4.226GeV

Mode	$\mathcal{B}$ (%)	$\mathcal{A}_{CP}$ (%)
$D_s^+ \rightarrow K_S^0 K^+$	$1.502 \pm 0.012 \pm 0.009$	$0.29 \pm 0.50 \pm 0.21$
$D_s^+ \rightarrow K^+ K^- \pi^+$	$5.49 \pm 0.04 \pm 0.07$	$0.48 \pm 0.26 \pm 0.24$
$D_s^+ \rightarrow K_S^0 K^+ \pi^0$	$1.47 \pm 0.02 \pm 0.02$	$-0.85 \pm 1.97 \pm 0.46$
$D_s^+ \rightarrow K_S^0 K^+ \pi^+ \pi^-$	$0.73 \pm 0.01 \pm 0.01$	$1.14 \pm 1.58 \pm 0.44$
$D_s^+ \rightarrow K^+ K^- \pi^+ \pi^0$	$5.50 \pm 0.05 \pm 0.11$	$-0.66 \pm 0.91 \pm 0.33$
$D_s^+ \rightarrow K_S^0 K^+ \pi^+ \pi^-$	$0.93 \pm 0.02 \pm 0.01$	$2.00 \pm 2.37 \pm 0.70$
$D_s^+ \rightarrow K_S^0 K^- \pi^+ \pi^+$	$1.56 \pm 0.02 \pm 0.02$	$-0.24 \pm 1.05 \pm 1.07$
$D_s^+ \rightarrow \pi^+ \pi^+ \pi^-$	$1.09 \pm 0.01 \pm 0.01$	$-0.88 \pm 1.17 \pm 0.38$
$D_s^+ \rightarrow \pi^+ \eta$	$1.69 \pm 0.02 \pm 0.02$	$-0.44 \pm 0.89 \pm 0.19$
$D_s^+ \rightarrow \pi^+ \pi^0 \eta$	$9.10 \pm 0.09 \pm 0.15$	$1.05 \pm 1.45 \pm 0.62$
$D_s^+ \rightarrow \pi^+ \pi^+ \pi^- \eta$	$3.08 \pm 0.06 \pm 0.05$	$2.42 \pm 2.85 \pm 0.78$
$D_s^+ \rightarrow \pi^+ \eta'$	$3.95 \pm 0.04 \pm 0.07$	$-0.59 \pm 0.76 \pm 0.20$
$D_s^+ \rightarrow \pi^+ \pi^0 \eta'$	$6.17 \pm 0.12 \pm 0.14$	$-1.60 \pm 2.57 \pm 0.64$
$D_s^+ \rightarrow K_S^0 \pi^+ \pi^0$	$0.51 \pm 0.02 \pm 0.01$	$-2.17 \pm 4.65 \pm 1.10$
$D_s^+ \rightarrow K^+ \pi^+ \pi^-$	$0.620 \pm 0.009 \pm 0.006$	$1.81 \pm 2.01 \pm 0.45$

☞ D^0, D^+ decays:

PRD 111 (2025) 092005, 20.3 fb⁻¹@3.773GeV

Signal decay	$\mathcal{B}_{\text{sig}}(10^{-4})$	$\mathcal{B}_{\text{weight}}(10^{-4})$	$\mathcal{B}_{\text{PDG}}(10^{-4})$
$D^+ \rightarrow K^+ K^- \pi^+ \pi^-$	$0.66 \pm 0.11 \pm 0.03$	...	2.3 ± 1.2
$D^+ \rightarrow \phi \pi^+ \pi^+ \pi^-$	$0.54 \pm 0.19 \pm 0.02$	...	...
$D^+ \rightarrow K_S^0 K^+ \pi^+ \pi^-$	$2.51 \pm 0.34 \pm 0.14$	...	...
$D^+ \rightarrow K_S^0 K^+ \eta$	$2.17 \pm 0.24 \pm 0.08$	$2.27 \pm 0.22 \pm 0.05$	1.8 ± 0.5
$D^+ \rightarrow K_S^0 K^+ \eta \pi^+ \pi^0$	$2.90 \pm 0.59 \pm 0.15$	...	...
$D^+ \rightarrow K_S^0 K^+ \omega$	$2.02 \pm 0.35 \pm 0.10$	...	...

PRD 112 (2025) 012001, 7.9 fb⁻¹@3.773GeV

Signal decay	$\mathcal{B}_{\text{sig}}(\times 10^{-4})$	$\mathcal{B}_{\text{FOCUS}}(\times 10^{-4})$
$D^0 \rightarrow K^- 3\pi^+ 2\pi^-$	$1.35 \pm 0.23 \pm 0.08$	$2.2 \pm 0.5 \pm 0.3$
$D^0 \rightarrow K^- 2\pi^+ \pi^- 2\pi^0$	$19.0 \pm 1.1 \pm 1.5$	...
$D^+ \rightarrow K^- 3\pi^+ \pi^- \pi^0$	$6.57 \pm 0.69 \pm 0.33$	...

☞ CKM matrix elements are fundamental parameters of the Standard Model (SM):

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \cos\phi & \sin\theta_C \sin\phi \\ -\sin\theta_C & \cos\theta_C \cos\phi & \cos\theta_C \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{pmatrix}$$

Charm decays + LQCD
Expected precision < 1% at BESIII

B decays + LQCD

- 3x3 unitary complex matrix
- 4 parameters: 3 mixing angles and 1 phase
- Unitarity: $\sum_i V_{ij} V_{ik}^* = \delta_{jk}$ and $\sum_j V_{ij} V_{kj}^* = \delta_{ik}$

☞ Any deviation of V_{CKM} from unitarity indicates new physics

Revised in PDG2024

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0009 = 1(\text{SM})$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.001 \pm 0.007 = 1(\text{SM})$$

Precision: 0.7%

$$|V_{cd}| = 0.221 \pm 0.004$$

$$|V_{cs}| = 0.975 \pm 0.006$$

$$|V_{cb}| = 0.0410 \pm 0.0012$$

Precision: (0.6-1.8)%

☞ D/D_s (Semi-)leptonic decays provide direct measurements of $|V_{cs}|$ and $|V_{cd}|$

粲重子的全方位测量

(半轻、非轻、稀有衰变)

Recent studies on the Λ_c^+ measurements at BESIII

Semi-leptonic decay

- ✓ Form factors of $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$ and $\Lambda \mu^+ \nu_\mu$
- ✓ $\Lambda_c^+ \rightarrow p K^- e^+ \nu_e$
- ✓ Search for $\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^- e^+ \nu_e$ and $p K_S \pi^- e^+ \nu_e$
- ✓ $\Lambda_c^+ \rightarrow n e^+ \nu_e$

PRL129, 231803 (2022); PRD108, L031105 (2023)

PRD106, 112010 (2022)

PLB843, 137993 (2023)

Nature Commun. 16, 681 (2025)

Neutron-involved decay

- ✓ $\Lambda_c^+ \rightarrow n \pi^+$
- ✓ $\Lambda_c^+ \rightarrow n \pi^+ \pi^0, n \pi^+ \pi^+ \pi^-, n K^- \pi^+ \pi^+$
- ✓ $\Lambda_c^+ \rightarrow n K_S K^+$
- ✓ $\Lambda_c^+ \rightarrow \Sigma^- K^+ \pi^+$
- ✓ $\Lambda_c^+ \rightarrow n K_S \pi^+ \pi^0$

PRL 128, 142001 (2022)

CPC 47, 023001 (2023) (Cover Story)

PRD 109, 072010 (2024)

PRD 109, L071103 (2024)

PRD 109, 053005 (2024)

Hadronic CS decays

- ✓ $\Lambda_c^+ \rightarrow p \pi^0, p \eta, p \omega$
- ✓ $\Lambda_c^+ \rightarrow p \eta'$
- ✓ $\Lambda_c^+ \rightarrow \Lambda K^+, \Lambda K^+ \pi^0, \Lambda K_S \pi^+$
- ✓ $\Lambda_c^+ \rightarrow \Sigma^+ K_S, \Sigma^0 K^+ (\pi^0, \pi^+ \pi^-), \Sigma^+ K^+ \pi^-$

JHEP11, 137 (2023); PRD09, L091101 (2024); PRD111, L051101 (2025)

PRD106, 072002 (2022)

PRD106, L111101 (2022); PRD109, 032003 (2024); PRD111, 012014 (2025)

PRD106, 052003 (2022); JHEP09, 125 (2023); arXiv:2502.11047

Hadronic CF decays

- ✓ PWA of $\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^0$ and $\Lambda \pi^+ \eta$
- ✓ W-exchange-only process $\Xi^0 K^+$
- ✓ $\Lambda_c^+ \rightarrow \Xi^0 K^+ \pi^0$
- ✓ $\Lambda_c^+ \rightarrow p K_L, p K_L \pi^0, p K_L \pi^+ \pi^-$

JHEP 12, 033(2022); PRL134, 021901 (2025)

PRL132, 031801 (2024)

PRD109, 052001 (2024)

JHEP09, 007 (2024)

Inclusive decay

- ✓ Improved BF of $\Lambda_c^+ \rightarrow e^+ X$
- ✓ First BF of $\bar{\Lambda}_c^- \rightarrow \bar{n} X$
- ✓ First BF of $\bar{\Lambda}_c^- \rightarrow K_S^0 X$

PRD107, 052005 (2023)

PRD108, L031101 (2023)

arXiv:2502.20821

Rare decay

- ✓ $\Lambda_c^+ \rightarrow \gamma \Sigma^+$

PRD107, 052002 (2023)

Production and excited Λ_c^+

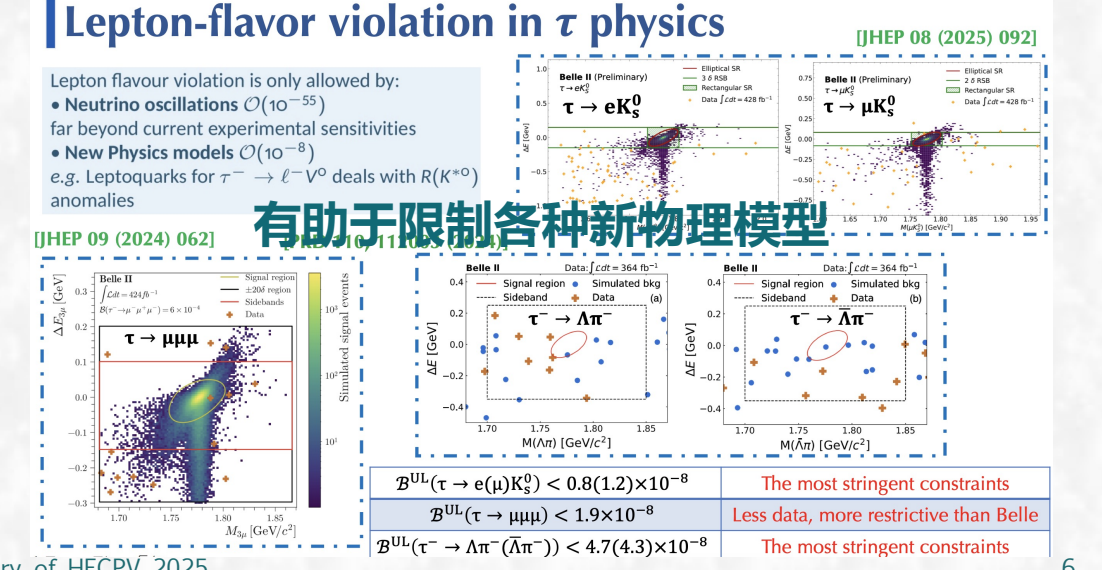
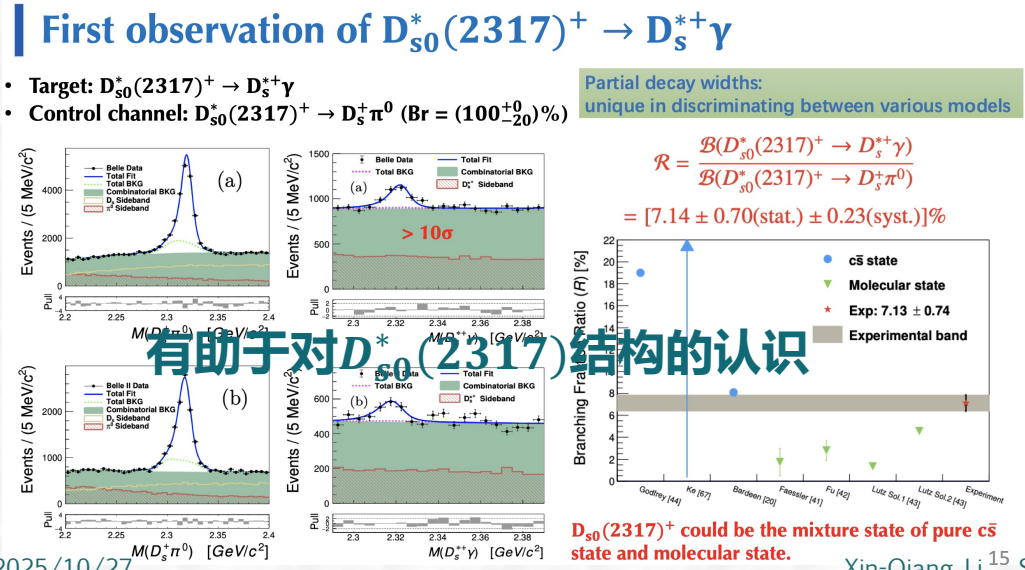
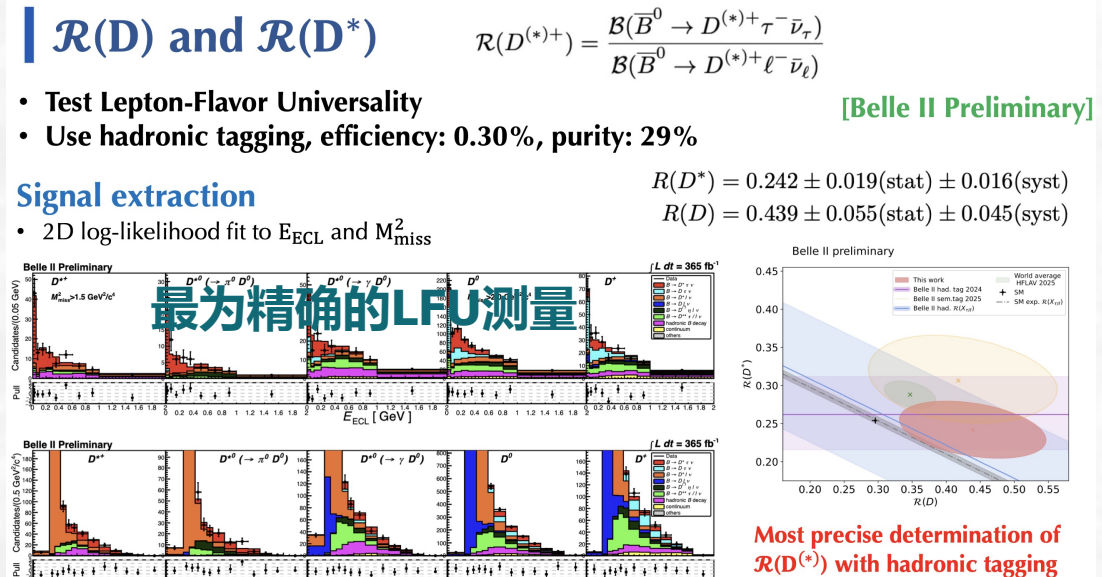
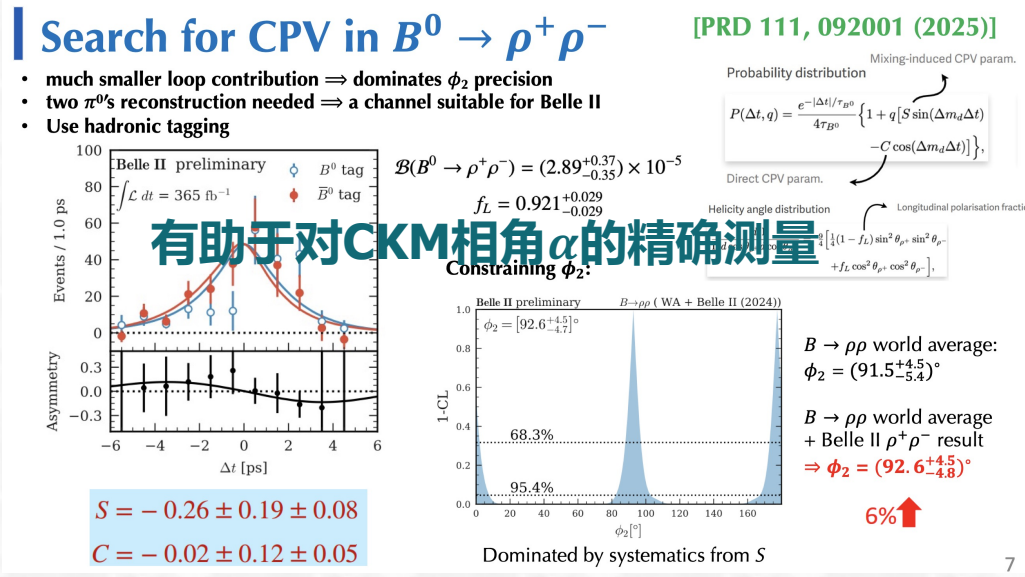
- ✓ $\Lambda_c^+ \bar{\Lambda}_c^-$ lineshape and form factor
- ✓ $\Lambda_c (2595)^+$ and $\Lambda_c (2625)^+$

PRL107, 052002 (2023)

PRD109, L071104 (2024); PRD109, 112007 (2024); arXiv:2503.21413

>33 papers are published

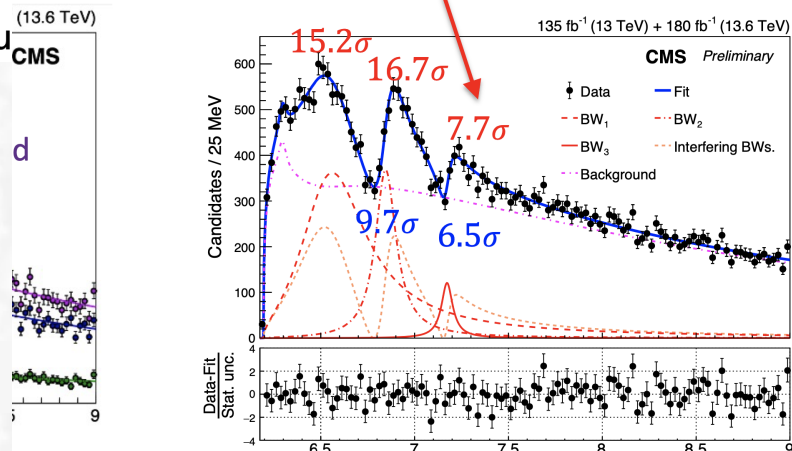
实验：LHCb、BESIII、Belle/BelleII、CMS、ATLAS



实验：LHCb、BESIII、Belle/BelleII、CMS、ATLAS

胡震，大会报告

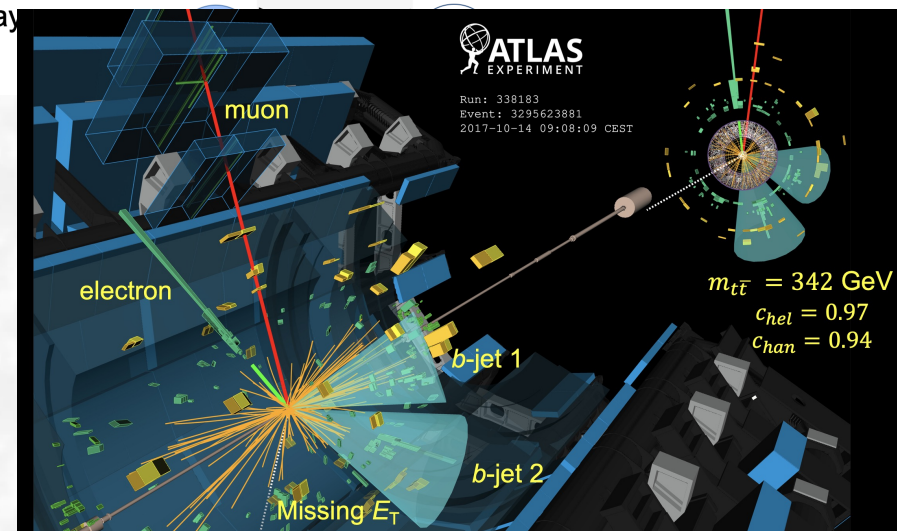
- CMS paint a full picture of fully-charm tetraquarks:
 - Measured masses of 3 resonances with full Run2+3 data
 - Measurement of spin-parity reveal their $J^{PC} = 2^{++}$
- CMS fully exclusively reconstruct, for the first time, B^{*+} , B^{*0} , and B_s^{*0} signals
 - Order of magnitude precision improvement in the Δm values!
 - 18 various measurements, including differences and ratios, are provided for completeness
- The first CMS measurement of CP violation in charm is performed
- Full angular analysis of $B^0 \rightarrow K^{*0} \mu \mu$
- Stay tune First observation of X(7100) CMS-PAS-BPH-24-003



李海峰，大会报告

Conclusions

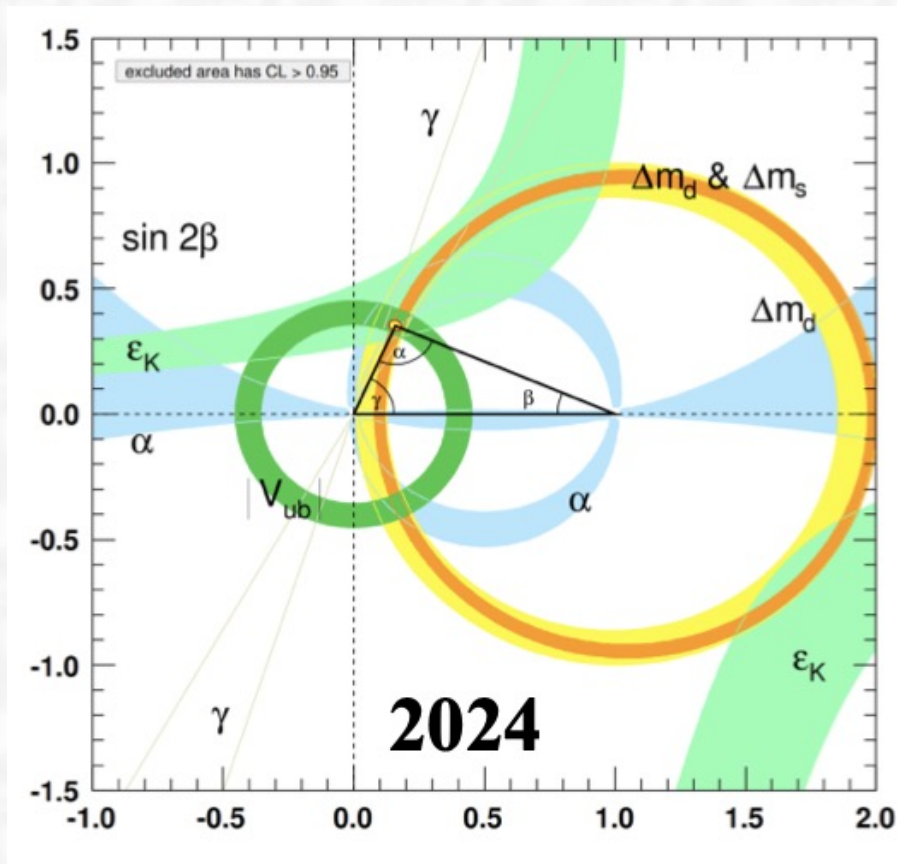
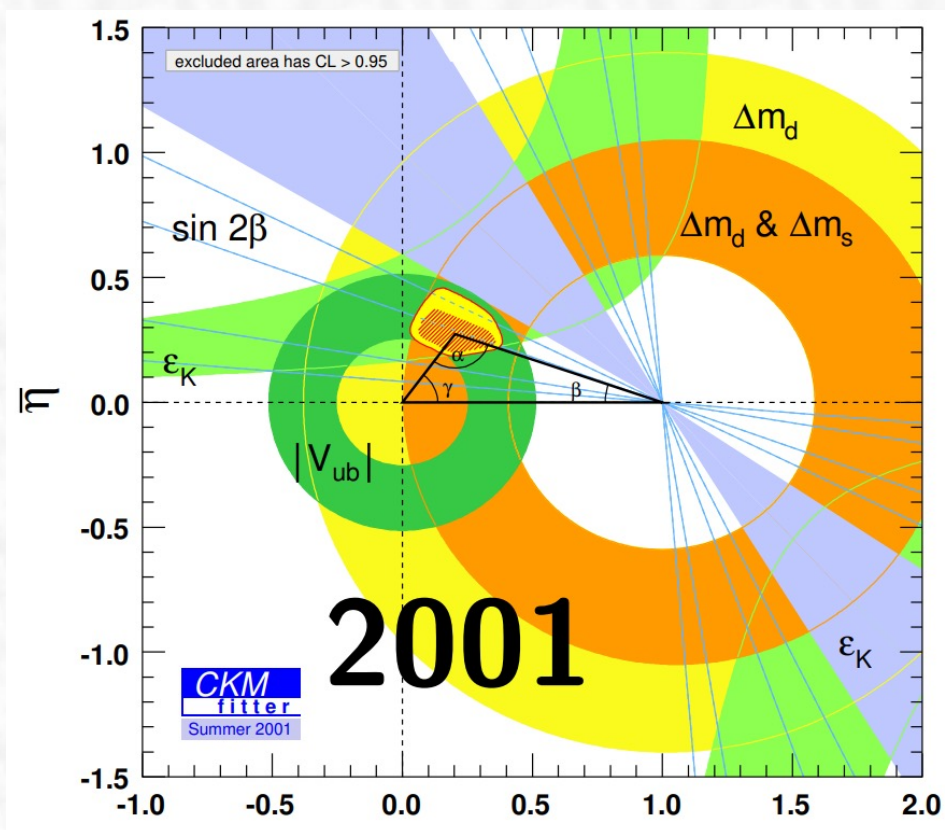
- An excess of events is observed over the NNLO perturbative QCD prediction, with **7.7σ observed (5.7σ expected)** near the $t\bar{t}$ production threshold by ATLAS with LHC Run 2 data. [ATLAS-CONF-2025-008], [ATLAS Physics Briefing]
- This excess is consistent with **color-singlet, S-wave, quasi-bound $t\bar{t}$ states** predicted by NRQCD with **cross-section of 9.0 ± 1.3 pb**
- A more complete model from NRQCD calculation is used in this analysis. Important advantage compared with recent CMS results (Rep. Prog. Phys. 88 (2025) 087801)
- This results show the strength of the LHC as a precision machine
- **Observation of toponium** opens a new field to study NRQCD with top quarks
- More work to characterize this excess and to better quantify the impact of off-shell top-quark decay



精确味物理时代：精确检验SM + 寻找新物理

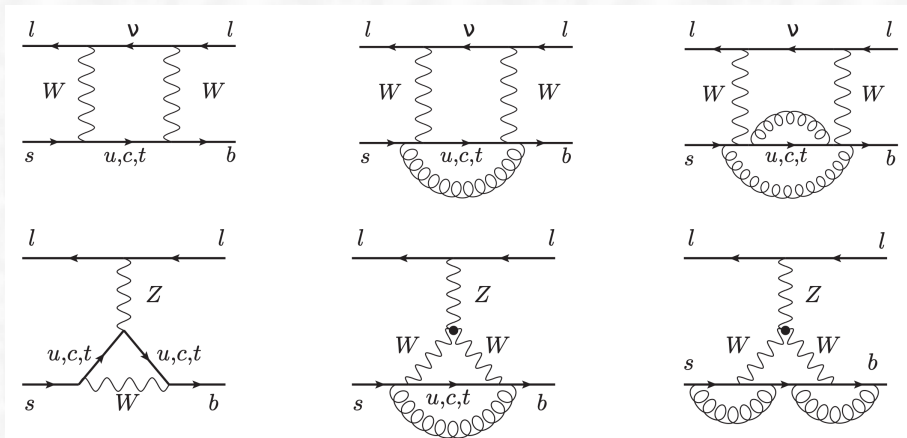


BESIII、LHCb、Belle-II、CMS、ATLAS... + 格点QCD + 理论研究进展

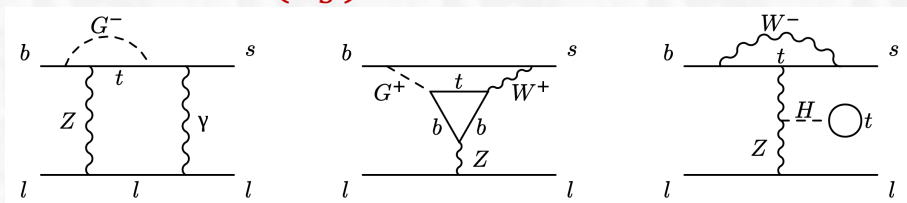


精确味物理时代：精确检验SM + 寻找新物理

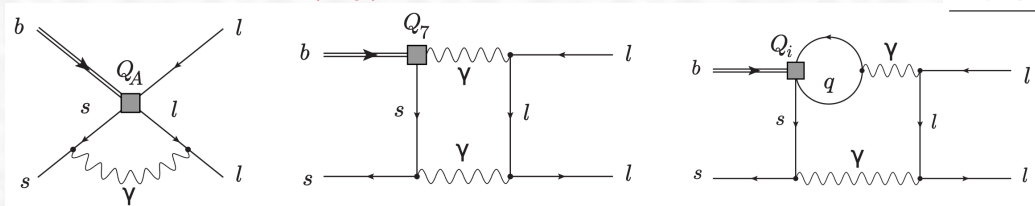
□ 得益于实验+理论+格点进展， $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$ 理论预言和实验符合得很好！



$O(\alpha_s^2)$ QCD correction



$O(\alpha_e)$ EW correction



power-enhanced QED correction

decay constant

Effect of lifetime difference of B_s and B_s -bar

helicity suppression

loop suppression

CKM suppression

power-enhanced QED correction

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = \tau_{B_s} \frac{G_F^2}{\pi} m_{B_s}^2 f_{B_s}^2 m_\mu^2 \frac{\alpha^2}{16\pi^2} |V_{ts}^* V_{tb}|^2 \frac{Y(x_t)^2}{s_W^4} \frac{1}{1-y_s} \eta_{BBS}$$

$$\text{Br}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.64 \pm 0.12)[(3.34 \pm 0.27)] \times 10^{-9}$$

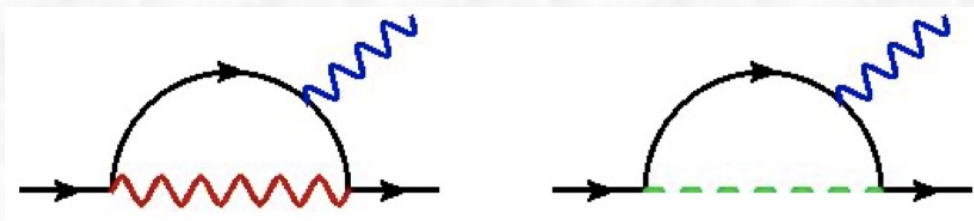
	f_{B_s}	CKM	τ_H^s	M_t	α_s	η_{BBS}	other	non-parametric	Σ
2024 [this paper]	1.1%	2.3%	0.5%	0.5%	0.1%	0.5%	< 0.1%	1.5%	3.2%
2013 [10]	4.0%	4.3%	1.3%	1.6%	0.1%	0.0%	< 0.1%	1.5%	6.4%

✓ parameter uncertainties dominated by $|V_{cb}|$

✓ non-parametric uncertainty from m_t^{pole}

精确味物理时代：精确检验SM + 寻找新物理

□ $\text{Br}(B \rightarrow X_s \gamma)$ 理论预言和实验符合得很好！



$\mathcal{B}_{s\gamma}$ – 2025 prediction



$$\mathcal{B}(\bar{B} \rightarrow X_s \gamma)|_{E_\gamma > 1.6 \text{ GeV}} = \frac{G_F^2 \alpha (m_b^{\text{kin}})^5}{32 \pi^4 \Gamma_{\text{tot}}} |V_{ts}^* V_{tb}|^2 [\tilde{P}(E_0) + \tilde{N}(E_0)]$$

$$\mathcal{B}_{s\gamma}^{\text{SM}} = (3.54 \pm 0.14) \times 10^{-4}$$

[Misiak, Steinhauser et al.'25]

$\pm 2.7\%$ (parametric + non-pert.)

$\pm 3\%$ (higher order)

■ correlated parameters:

$m_b^{\text{kin}}, \bar{m}_c(2 \text{ GeV}), \mu_\pi^2, \rho_D^3, \mu_G^2, \rho_{LS}^3, V_{cb}$

■ uncorrelated parameters:

$\alpha_s(M_Z), M_t, \tau_{B^\pm}, \tau_{B^0}, \dots$

[Carvunis, Finauri, Gambino, Jung, Mächler'25]

■ scale variation: $m_b^{\text{kin}}/4 \leq \mu_c, \mu_b \leq m_b^{\text{kin}}; 80 \text{ GeV} \leq \mu_t \leq 320 \text{ GeV}$

[PDG; HFLAV]

■ CLEO, Babar, Belle $\Rightarrow \mathcal{B}_{s\gamma}^{\text{exp}} = (3.49 \pm 0.19) \times 10^{-4}$ [HFLAV'25]

2001 [Gambino, Misiak]

2006 [Misiak et al. 17 authors]

2015 [Misiak et al. 18 authors]

2020 [Misiak, Rehman, Steinhauser]

2025 [Misiak et al. ?? authors]

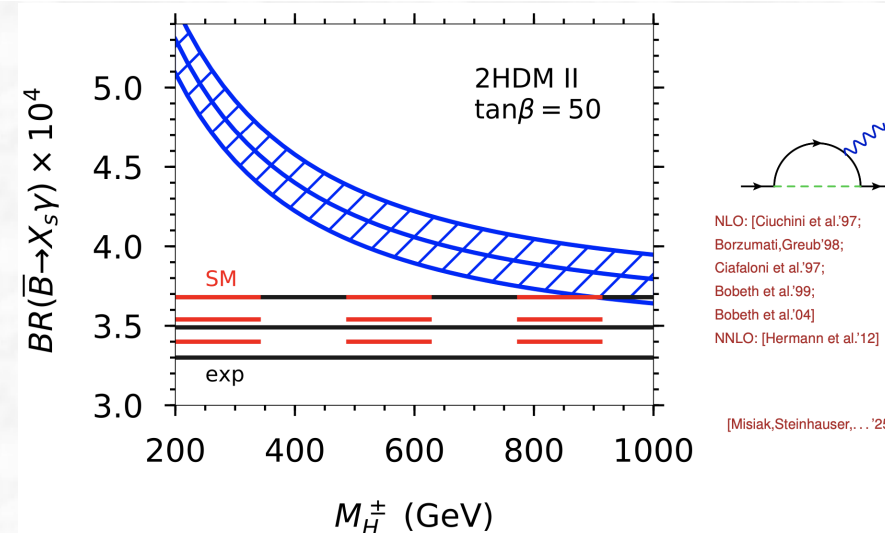
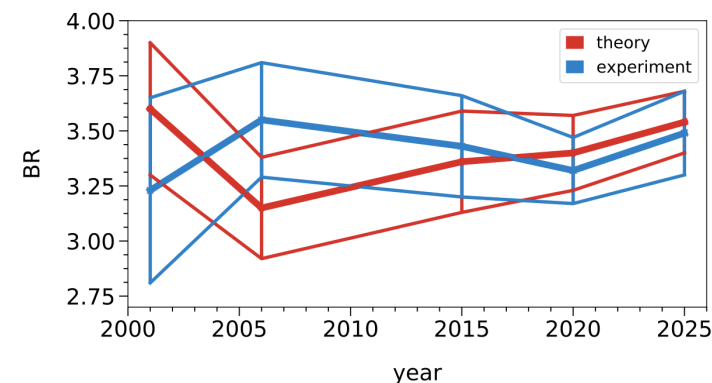
NLO

NNLO, extrapolation of $Q_{1,2} - Q_7$ form large- m_c

NNLO, interpolation of $Q_{1,2} - Q_7$ to $m_c = 0$

update: non-pert., input parameters, exact fermionic $Q_{1,2} - Q_7$

exact $Q_{1,2} - Q_7$

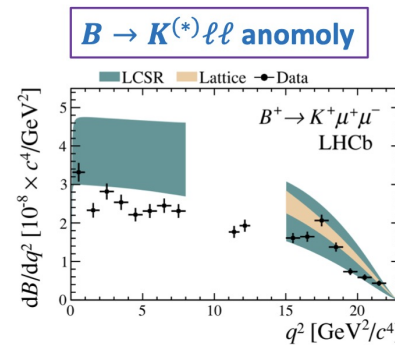
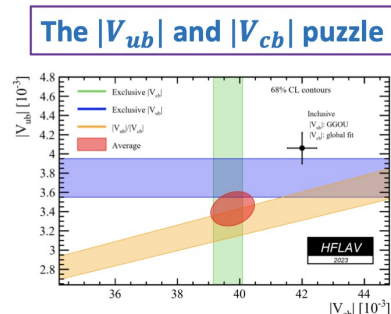
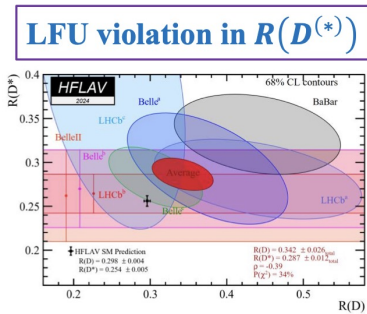


NLO: [Giuchini et al.'97;
Borzumati, Greub'98;
Ciafaloni et al.'97;
Bobeth et al.'99;
Bobeth et al.'04]
NNLO: [Hermann et al.'12]

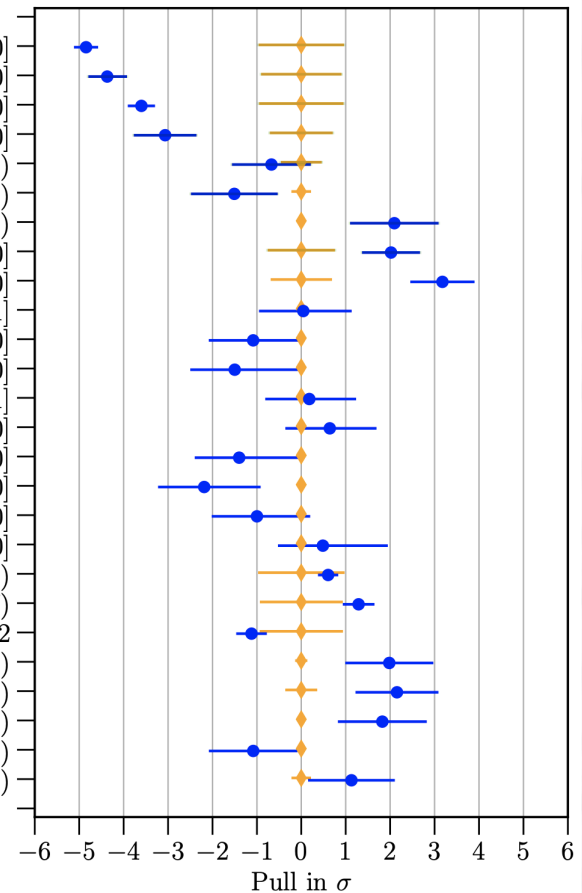
[Misiak, Steinhauser, ... '25]

精确味物理时代：精确检验SM + 寻找新物理

□ Some anomalies or puzzles observed in heavy flavor physics



$B(B^+ \rightarrow K^+ \mu^+ \mu^-)$	[1.1, 6.0]
$B(B^+ \rightarrow K^+ e^+ e^-)$	[1.1, 6.0]
$B(B_s^0 \rightarrow \phi \mu^+ \mu^-)$	[1.0, 6.0]
$B(B_s^0 \rightarrow \phi e^+ e^-)$	[1.1, 6.0]
$B(B_s^0 \rightarrow \mu^+ \mu^-)$	[2.5, 4.0]
$B(B^0 \rightarrow \mu^+ \mu^-)$	[4.0, 6.0]
$B(B^+ \rightarrow K^+ \nu \bar{\nu})$	[0.1, 1.1]
$P_5'(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$	[2.5, 4.0]
$P_5'(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$	[4.0, 6.0]
R_K	[0.1, 1.1]
R_K	[1.1, 6.0]
$R_{K_S^0}$	[1.1, 6.0]
$R_{K^{*0}}$	[0.1, 1.1]
$R_{K^{*0}}$	[1.1, 6.0]
$R_{K^{*+}}$	[0.045, 6.0]
$R_{K\pi\pi}$	[1.1, 7.0]
R_{pK}	[0.1, 6.0]
R_ϕ	[1.1, 6.0]
Muon $g - 2$ (WP)	[1.1, 6.0]
Muon $g - 2$ (BMW)	[1.1, 6.0]
Electron $g - 2$	[1.1, 6.0]
$R(D)$	[1.1, 6.0]
$R(D^*)$	[1.1, 6.0]
$R(J/\psi)$	[1.1, 6.0]
$R(\Lambda_c^+)$	[1.1, 6.0]
$B(B^+ \rightarrow \tau^+ \nu)$	[1.1, 6.0]



$B \rightarrow \pi \pi$ puzzle

$$Br(B^0 \rightarrow \pi^0 \pi^0) = (1.55 \pm 0.16) \times 10^{-6}$$

Much larger than theoretically calculated.

$B \rightarrow \pi K$ puzzle

$$\Delta A_{CP}(\pi K) = A_{CP}(\pi^0 K^-) - A_{CP}(\pi^+ K^-)$$

$$= (11.3 \pm 1.2)\%$$

9σ deviation from isospin limit.

$B \rightarrow K K$ puzzle

$B \rightarrow D_q^{(*)} L$ puzzle

... ..

anom·aly [ə'noməli]

1. something that deviates from what is standard, normal, or expected:

puz·zle ['pʌzl]

1. cause (someone) to feel confused because they cannot understand something:

$\Lambda_b \rightarrow \Lambda_c l \nu$ Decays Mediated by $b \rightarrow cl\nu$

□ $R(\Lambda_c) = \text{Br}(\Lambda_b \rightarrow \Lambda_c \tau \nu_\tau) / \text{Br}(\Lambda_b \rightarrow \Lambda_c \ell \nu_\ell)$:

- At the quark level, also mediated by $b \rightarrow cl\nu$ transitions
- First result reported by LHCb with large error [arXiv:2201.03497]

$$R_{\Lambda_c}^{\text{LHCb}} = 0.242 \pm 0.026 \pm 0.04 \pm 0.059$$



$$R_{\Lambda_c}^{\text{SM}} = 0.324 \pm 0.004$$

exp. central value lower than SM

□ General expressions for the ratios in LEFT:

[see Xing-Bo Yuan's talk]

$$\mathcal{H}_{\text{eff}} = 2\sqrt{2}G_F V_{qb} \left[(1 + C_{V_L}^{ql}) \mathcal{O}_{V_L}^{ql} + C_{V_R}^{ql} \mathcal{O}_{V_R}^{ql} + C_{S_L}^{ql} \mathcal{O}_{S_L}^{ql} + C_{S_R}^{ql} \mathcal{O}_{S_R}^{ql} + C_T^{ql} \mathcal{O}_T^{ql} \right]$$

$$\begin{aligned} \mathcal{O}_{V_L}^{ql} &= (\bar{q}\gamma^\mu P_L b) (\bar{l}\gamma_\mu P_L \nu_l), & \mathcal{O}_{V_R}^{ql} &= (\bar{q}\gamma^\mu P_R b) (\bar{l}\gamma_\mu P_L \nu_l), \\ \mathcal{O}_{S_L}^{ql} &= (\bar{q}P_L b) (\bar{l}P_L \nu_l), & \mathcal{O}_{S_R}^{ql} &= (\bar{q}P_R b) (\bar{l}P_L \nu_l), \\ \mathcal{O}_T^{ql} &= (\bar{q}\sigma^{\mu\nu} P_L b) (\bar{l}\sigma_{\mu\nu} P_L \nu_l) \end{aligned}$$

LEFT

- ✓ assuming only τ modes affected by NP
- ✓ light neutrinos always left-handed
- ✓ a_X^{ij} calculable with FF inputs together with uncertainties inherited from them

$$\begin{aligned} \frac{R_P}{R_P^{\text{SM}}} &= |1 + C_{V_L}^{q\tau} + C_{V_R}^{q\tau}|^2 + a_P^{SS} |C_{S_L}^{q\tau} + C_{S_R}^{q\tau}|^2 + a_P^{TT} |C_T^{q\tau}|^2 \\ &\quad + a_P^{VS} \text{Re} [(1 + C_{V_L}^{q\tau} + C_{V_R}^{q\tau}) (C_{S_L}^{q\tau*} + C_{S_R}^{q\tau*})] + a_P^{VT} \text{Re} [(1 + C_{V_L}^{q\tau} + C_{V_R}^{q\tau}) C_T^{q\tau*}], \\ \frac{R_V}{R_V^{\text{SM}}} &= |1 + C_{V_L}^{q\tau}|^2 + |C_{V_R}^{q\tau}|^2 + a_V^{SS} |C_{S_L}^{q\tau} - C_{S_R}^{q\tau}|^2 + a_V^{TT} |C_T^{q\tau}|^2 \\ &\quad + a_V^{V_L V_R} \text{Re} [(1 + C_{V_L}^{q\tau}) C_{V_R}^{q\tau*}] + a_V^{VS} \text{Re} [(1 + C_{V_L}^{q\tau} - C_{V_R}^{q\tau}) (C_{S_L}^{q\tau*} - C_{S_R}^{q\tau*})] \\ &\quad + a_V^{V_L T} \text{Re} [(1 + C_{V_L}^{q\tau}) C_T^{q\tau*}] + a_V^{V_R T} \text{Re} [C_{V_R}^{q\tau} C_T^{q\tau*}], \\ \frac{R_H}{R_H^{\text{SM}}} &= |1 + C_{V_L}^{q\tau}|^2 + |C_{V_R}^{q\tau}|^2 + a_H^{SS} [|C_{S_L}^{q\tau}|^2 + |C_{S_R}^{q\tau}|^2] + a_H^{TT} |C_T^{q\tau}|^2 \\ &\quad + a_H^{V_L V_R} \text{Re} [(1 + C_{V_L}^{q\tau}) C_{V_R}^{q\tau*}] + a_H^{V_{S1}} \text{Re} [(1 + C_{V_L}^{q\tau}) C_{S_L}^{q\tau*} + C_{V_R}^{q\tau} C_{S_R}^{q\tau*}] \\ &\quad + a_H^{V_{S2}} \text{Re} [(1 + C_{V_L}^{q\tau}) C_{S_R}^{q\tau*} + C_{V_R}^{q\tau} C_{S_L}^{q\tau*}] + a_H^{S_L S_R} \text{Re} [C_{S_L}^{q\tau} C_{S_R}^{q\tau*}] \\ &\quad + a_H^{V_L T} \text{Re} [(1 + C_{V_L}^{q\tau}) C_T^{q\tau*}] + a_H^{V_R T} \text{Re} [C_{V_R}^{q\tau} C_T^{q\tau*}], \end{aligned}$$

Sum Rule for $b \rightarrow c$ Sector

□ **Sum rule among $R(D)$, $R(D^*)$ & $R(\Lambda_c)$:** M. Blanke et al., 1811.09603, 1905.08253 $\text{Re}[(1 + C_{V_L}^{q\tau})C_{S_L}^{q\tau*}]$

$$\boxed{\frac{R_H}{R_H^{\text{SM}}} = b \frac{R_P}{R_P^{\text{SM}}} + c \frac{R_V}{R_V^{\text{SM}}} + \delta_H(C_i)} \quad \Rightarrow \quad b + c = 1 \text{ \& } a_P^{VS} b + a_V^{VS} c = a_H^{VS1}, \text{ so that } \delta_H(C_i) \text{ small}$$

$\Rightarrow$ **model-indep. & holds for any tau-philic NP**

□ **State-of-the-art predictions:** W. F. Duan, S. Iguro, X. Q. Li, R. Watanabe, Y. D. Yang, 2410.21384

$$\boxed{\frac{R_{\Lambda_c}}{R_{\Lambda_c}^{\text{SM}}} = (0.272 \pm 0.015) \frac{R_D}{R_D^{\text{SM}}} + (0.728 \mp 0.015) \frac{R_{D^*}}{R_{D^*}^{\text{SM}}} + \delta_{\Lambda_c}}$$

$$\begin{aligned} \delta_{\Lambda_c} = & (-0.001 \pm 0.005) (|C_{S_L}^{c\tau}|^2 + |C_{S_R}^{c\tau}|^2) + (-0.007 \pm 0.005) \text{Re}(C_{S_L}^{c\tau} C_{S_R}^{c\tau*}) \\ & + (-2.681 \pm 6.907) |C_T^{c\tau}|^2 + (-0.561 \pm 1.439) \text{Re}(C_{V_R}^{c\tau} C_T^{c\tau*}) \\ & + \text{Re}[(1 + C_{V_L}^{c\tau}) \{ (0.041 \pm 0.034) C_{V_R}^{c\tau*} + (0.594 \pm 1.274) C_T^{c\tau*} \}] \\ & + (-0.002 \pm 0.009) \text{Re}[(1 + C_{V_L}^{c\tau}) C_{S_R}^{c\tau*} + C_{S_L}^{c\tau} C_{V_R}^{c\tau*}] . \end{aligned} \quad (3)$$

➤ important to properly consider **correlations** among FF para.s

➤ δ_{Λ_c} mostly sensitive to the **tensor operator** $\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\tau}\sigma_{\mu\nu}P_L \nu_\tau)$

□ **Sum-rule prediction for $R(\Lambda_c)$:**

HFLAG 2024: $R_D^{\text{exp}} = 0.342 \pm 0.026, \quad R_{D^*}^{\text{exp}} = 0.287 \pm 0.012$

$$\Rightarrow \delta_{\text{SR}/\text{exp}} = \frac{R_{\Lambda_c}^{\text{exp}}}{R_{\Lambda_c}^{\text{SM}}} - \left(0.272 \frac{R_D^{\text{exp}}}{R_D^{\text{SM}}} + 0.728 \frac{R_{D^*}^{\text{exp}}}{R_{D^*}^{\text{SM}}} \right)$$

$$R_{\Lambda_c}^{\text{SR}} = 0.372 \pm 0.017 \quad \text{vs} \quad R_{\Lambda_c}^{\text{LHCb}} = 0.242 \pm 0.076 \quad = -0.39 \pm 0.23$$

$B_q^0 \rightarrow D_q^{(*)-} L^+$ class-I decays

□ Mediated by $b \rightarrow c\bar{u}d(s)$ at quark level

all four flavors different from each other, no penguin operators &
no penguin topologies!

- i) only color-allowed tree topology $T = a_1$
- ii) spectator & annihilation power-suppressed
- iii) annihilation absent in $B_{d(s)}^0 \rightarrow D_{d(s)}^- K(\pi)^+$ etc.
- iv) they are theoretically simpler and cleaner

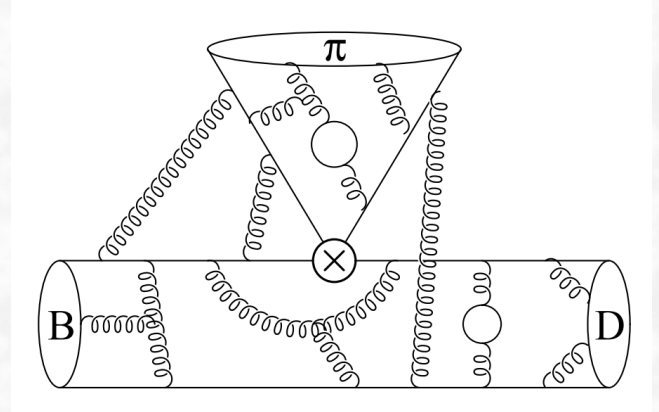
➡ used for factorization test!

□ For class-I decays: QCDF/SCET formula much simpler; only the form-factor term at leading power

[Beneke, Buchalla, Neubert, Sachrajda '99-'03; Bauer, Pirjol, Stewart '01]

□ Hard kernel T : both NLO and NNLO results known;

[Beneke, Buchalla, Neubert, Sachrajda '01; Huber, Kräinkl, Li '16]



$$Q_2 = \bar{d}\gamma_\mu(1-\gamma_5)u \bar{c}\gamma^\mu(1-\gamma_5)b$$

$$Q_1 = \bar{d}\gamma_\mu(1-\gamma_5)T^A u \bar{c}\gamma^\mu(1-\gamma_5)T^A b$$

$$\langle D_q^{(*)+} L^- | Q_i | \bar{B}_q^0 \rangle = \sum_j F_j^{\bar{B}_q \rightarrow D_q^{(*)}}(M_L^2) \times \int_0^1 du T_{ij}(u) \phi_L(u) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right)$$

$$T = T^{(0)} + \alpha_s T^{(1)} + \alpha_s^2 T^{(2)} + \mathcal{O}(\alpha_s^3)$$

Non-leptonic/semi-leptonic ratios

□ **Non-leptonic/semi-leptonic ratios** : [Bjorken '89; Neubert, Stech '97; Beneke, Buchalla, Neubert, Sachrajda '01]

$$R_{(s)L}^{(*)} \equiv \frac{\Gamma(\bar{B}_{(s)}^0 \rightarrow D_{(s)}^{(*)+} L^-)}{d\Gamma(\bar{B}_{(s)}^0 \rightarrow D_{(s)}^{(*)+} \ell^- \bar{\nu}_\ell)/dq^2|_{q^2=m_L^2}} = 6\pi^2 |V_{uq}|^2 f_L^2 |a_1(D_{(s)}^{(*)+} L^-)|^2 X_L^{(*)}$$

free from the uncertainties from V_{cb} & $B_{d,s} \rightarrow D_{d,s}^{(*)}$ form factors

□ **Updated predictions vs data**: [Huber, Kränkl, Li '16; Cai, Deng, Li, Yang '21]

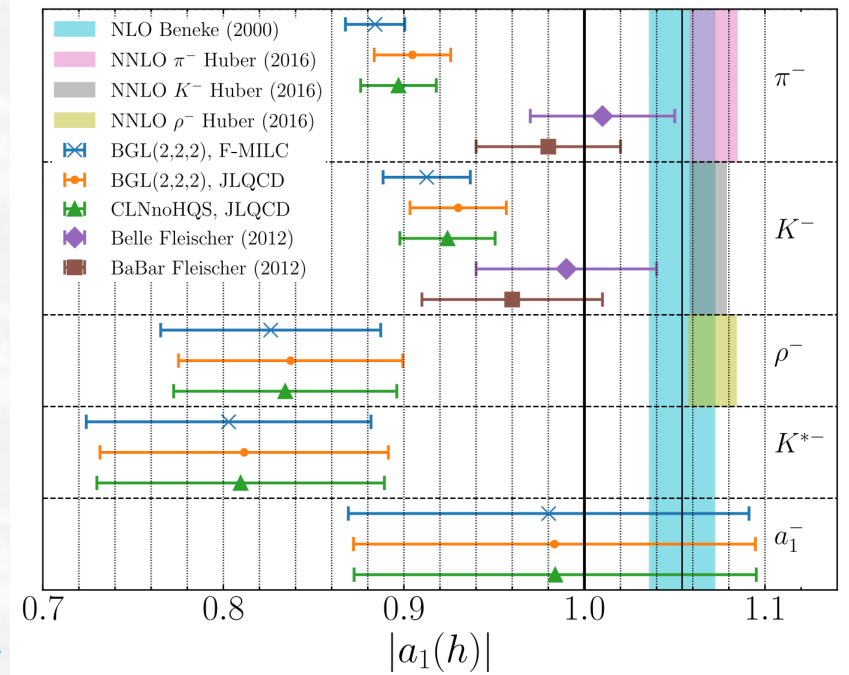
□ **Confirmed by Belle**: 2207.00134

$R_{(s)L}^{(*)}$	LO	NLO	NNLO	Exp.	Deviation (σ)
R_π	1.01	$1.07_{-0.04}^{+0.04}$	$1.10_{-0.03}^{+0.03}$	0.74 ± 0.06	5.4
R_π^*	1.00	$1.06_{-0.04}^{+0.04}$	$1.10_{-0.03}^{+0.03}$	0.80 ± 0.06	4.5
R_ρ	2.77	$2.94_{-0.19}^{+0.19}$	$3.02_{-0.18}^{+0.17}$	2.23 ± 0.37	1.9
$\bar{B} \rightarrow D^+ K^-$ R_K	0.78	$0.83_{-0.03}^{+0.03}$	$0.85_{-0.02}^{+0.01}$	0.62 ± 0.05	4.4
R_K^*	0.72	$0.76_{-0.03}^{+0.03}$	$0.79_{-0.02}^{+0.01}$	0.60 ± 0.14	1.3
R_{K^*}	1.41	$1.50_{-0.11}^{+0.11}$	$1.53_{-0.10}^{+0.10}$	1.38 ± 0.25	0.6
$\bar{B}_s \rightarrow D_s^+ \pi^-$ $R_{s\pi}$	1.01	$1.07_{-0.04}^{+0.04}$	$1.10_{-0.03}^{+0.03}$	0.72 ± 0.08	4.4
R_{sK}	0.78	$0.83_{-0.03}^{+0.03}$	$0.85_{-0.02}^{+0.01}$	0.46 ± 0.06	6.3

$$|a_1(\bar{B} \rightarrow D^{*+} \pi^-)| = 0.884 \pm 0.004 \pm 0.003 \pm 0.016 [1.071_{-0.016}^{+0.020}]$$

15% lower than SM

$$|a_1(\bar{B} \rightarrow D^{*+} K^-)| = 0.913 \pm 0.019 \pm 0.008 \pm 0.013 [1.069_{-0.016}^{+0.020}]$$

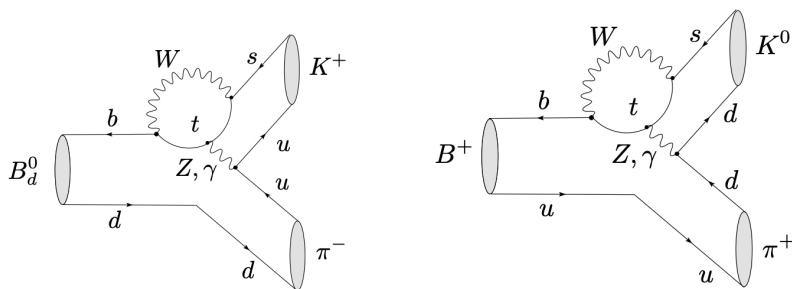


$B \rightarrow \pi K$ puzzle

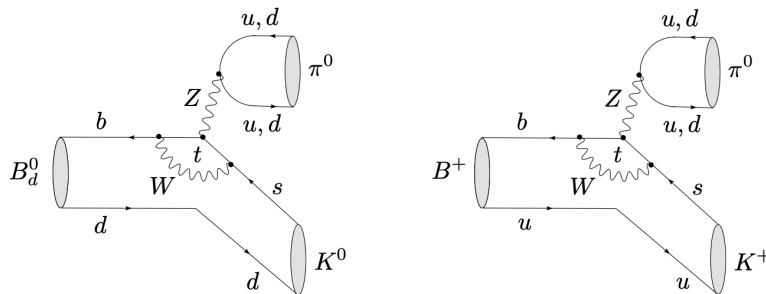
□ $B \rightarrow \pi K$ decays dominated by **QCD penguin**

□ For direct CPV, tree & EW penguin also crucial

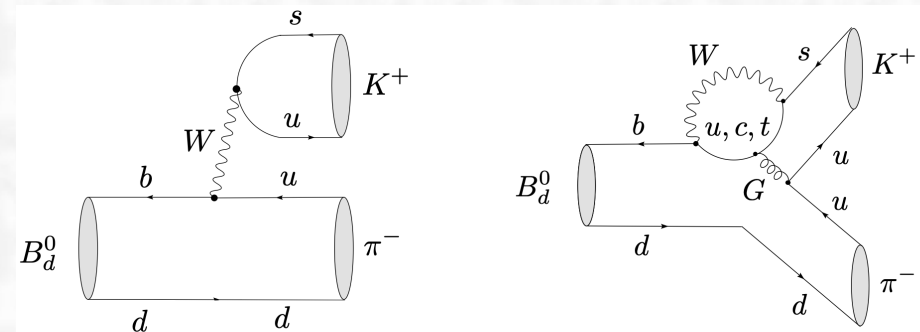
- EW penguins are colour-suppressed: $\rightarrow$ tiny contributions ...



- EW penguins are colour-allowed: $\rightarrow$ sizeable, competing with trees!



Some new mechanism or power corrections or even NP to enhance $C = \alpha_2$ (power-suppressed color-octet four-quark operators) or $P_{EW} = \alpha_{3,EW}^p$?



$$\propto A\lambda^4 R_b e^{i\gamma}$$

$$\propto A\lambda^2$$

$$\lambda^2 R_b = \mathcal{O}(0.02) \Rightarrow$$

QCD penguins *dominate*

$$\begin{aligned} \sqrt{2} \mathcal{A}_{B^- \rightarrow \pi^0 K^-} &= A_{\pi \bar{K}} [\delta_{pu} \alpha_1 + \hat{\alpha}_4^p] + A_{\bar{K} \pi} [\delta_{pu} \alpha_2 + \delta_{pc} \frac{3}{2} \alpha_{3,EW}^c], \\ \mathcal{A}_{\bar{B}^0 \rightarrow \pi^+ K^-} &= A_{\pi \bar{K}} [\delta_{pu} \alpha_1 + \hat{\alpha}_4^p], \end{aligned}$$



$$A_{CP}(\pi^0 K^\pm) - A_{CP}(\pi^\mp K^\pm) = -2 \sin \gamma \left(\text{Im}(r_C) - \text{Im}(r_T r_{EW}) \right) + \dots$$

$$\Delta A_{CP}(\pi K) = A_{CP}(\pi^0 K^-) - A_{CP}(\pi^+ K^-)$$

$$= (11.3 \pm 1.2)\% \text{ differs from 0 by } \sim 9\sigma$$



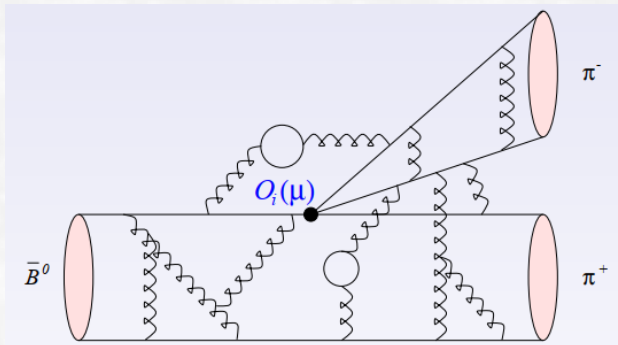
理论困境: Hadronic matrix elements

□ $\langle f | \mathcal{O}_i | \bar{B} \rangle_{\text{QCD, QED}}$: how to reliably and precisely evaluate it? depending on the specific modes

➤ **Exclusive vs. (semi-)inclusive modes?**

➤ **Hadronic decays** $\langle M_1 M_2 | \mathcal{O}_i | \bar{B} \rangle$: depends on spin & parity of $M_{1,2}$ and FSI introduces strong phases, and hence direct CPV

a difficult, multi-scale, QCD & QED problem!



$$\langle M_1 M_2 | \mathcal{O}_i | \bar{B} \rangle = \langle M_1 | \bar{u} \dots b | \bar{B} \rangle \langle M_2 | \bar{d} \dots u | 0 \rangle$$

naïve fact. approach [Bauer, Stech, Wirbel '87]

HQE/OPE, lattice, (QCD sum rules)

QCD factorization, (flavour symmetries)

$$\begin{aligned} \langle 0 | \mathcal{O} | B \rangle \\ \langle B | \mathcal{O} | B \rangle \end{aligned}$$

$$\langle M | \mathcal{O} | B \rangle$$

$$\langle M_1 M_2 | \mathcal{O} | B \rangle$$

Increasingly difficult

$$B \rightarrow X_c \ell \nu, X_s \gamma, X_s \ell \ell$$

$$B \rightarrow \tau \nu_\tau$$

$$B_s \rightarrow \mu^+ \mu^-$$

$$\Delta M_{B_d, B_s}$$

$$\Delta \Gamma_{B_s}$$

$$B \rightarrow D \tau \nu_\tau$$

$$|V_{ub}|$$

$$B \rightarrow K \nu \bar{\nu}$$

$$B \rightarrow \rho \gamma$$

$$B \rightarrow K^{(*)} \ell \ell$$

Direct CP asym

$$B_s \rightarrow \pi K, K K, \dots$$

$$B_s \rightarrow \pi \pi$$

$$B_s \rightarrow \phi \phi, K^{*0} \bar{K}^{*0}$$

- **Dynamical approaches based on factorization theorems:** PQCD, QCDF, SCET, ...

[Keum, Li, Sanda, Lü, Yang '00;

Beneke, Buchalla, Neubert, Sachrajda, '00;

Bauer, Fleming, Pirjol, Stewart, '01; Beneke, Chapovsky, Diehl, Feldmann, '02]

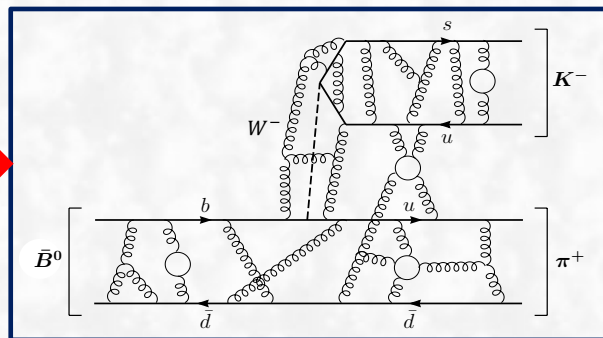
- **Symmetries of QCD:** Isospin, U-Spin, V-Spin, and flavour SU(3) symmetries, ...

[Zeppenfeld, '81;

London, Gronau, Rosner, He, Chiang, Cheng *et al.*]

Example: how to test SM and probe NP?

$\bar{B}^0 \rightarrow \pi^+ K^-$



EW interaction scale $\gg$ ext. mom'a in B rest frame $\gg$ QCD-bound state effects

$$m_W \sim 80 \text{ GeV}$$

$$m_Z \sim 91 \text{ GeV}$$

$$m_b \sim 5 \text{ GeV}$$

$$\Lambda_{\text{QCD}} \sim 1 \text{ GeV}$$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \sum_{p=u,c} V_{pD}^* V_{pb} \left(C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3}^{10} C_i Q_i + C_{7\gamma} Q_{7\gamma} + C_{8g} Q_{8g} \right)$$

electroweak parameters

WCs due to NP

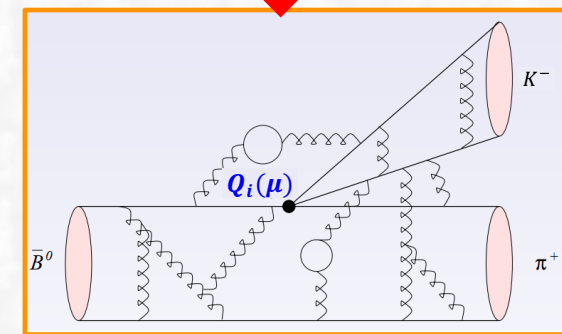
non-perp. parameters

$$\mathcal{A}(\bar{B}^0 \rightarrow \pi^+ K^-) = \frac{G_F}{\sqrt{2}} \sum_{ij} V_{\text{CKM}} (C_i^{\text{SM}} + C_i^{\text{NP}}) \left[F_j^{B \rightarrow \pi}(m_K^2) \int_0^1 du T_{ij}^{\text{I}}(u) \Phi_K(u) + (\pi \leftrightarrow K) \right. \\ \left. + \int_0^1 d\xi du dv T_i^{\text{II}}(\xi, u, v) \Phi_B(\xi) \Phi_\pi(v) \Phi_K(u) \right]$$

related to exp. Br & CPV

WCs from SM, also perp. calculable

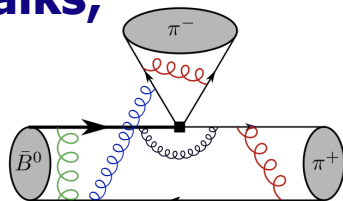
perp. calculable in QCD & QED



Status of QCDF/SCET:

□ For PQCD, see Ya Li, Rui Zhou, Zhi-Tian Zou,

Jia-Jie Han's talks;



$$\langle M_1 M_2 | Q_i | \bar{B} \rangle = F^{B \rightarrow M_1}(q^2 = 0) \int_0^1 du \mathbf{T}_i^{\text{I}}(u) f_{M_2} \phi_{M_2}(u) \\ + \int_0^\infty \frac{d\omega}{\omega} \int_0^1 du dv \mathbf{T}_i^{\text{II}}(u, v, \omega) f_{M_1} \phi_{M_1}(v) f_{M_2} \phi_{M_2}(u) f_B \phi_B(\omega)$$

- perturbative scattering kernels $\mathbf{T}_i^{\text{I,II}}$
- convoluted with universal non-perturbative LCDAs for heavy and light mesons
- holds to all orders in α_s in the heavy-quark limit $m_b \sim E_{\pi, K} \rightarrow \infty$

State of the art:

- NNLO scattering kernels
- 3-loop (2-loop) anomalous dimension for ϕ_M (ϕ_B)
- QED

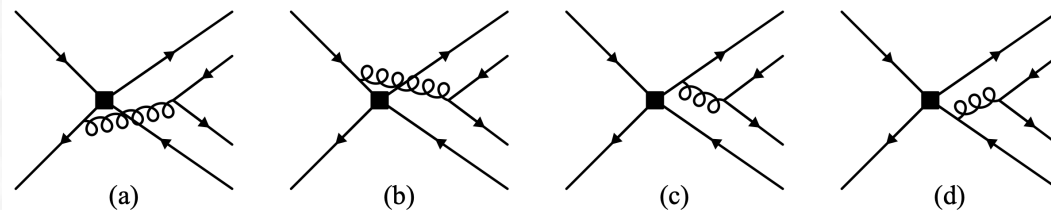
[e.g. Bell, Beneke, Huber, Li]

[Braun et al.]

[Beneke, PB, Finauri, Toelstede, Vos]

factorization of power corrections $\sim \Lambda_{had}/m_b \simeq 0.2$ currently unknown, but much progress achieved!

Michel Stillger, PhD thesis, The power of factorization: resummation of super-leading logarithms & weak annihilation amplitudes



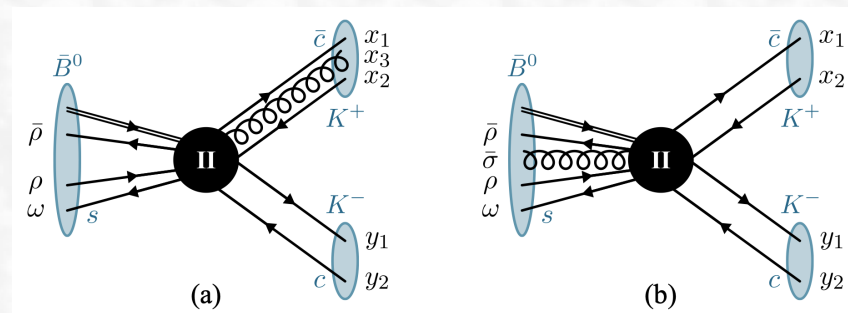
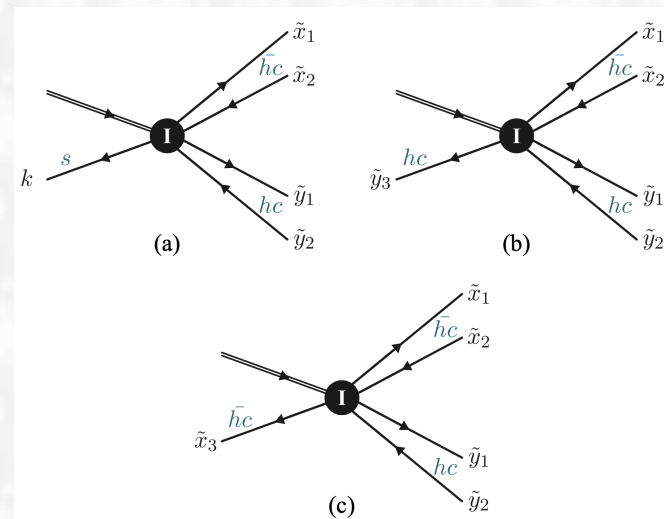
QCD



SCET_I



SCET_{II}



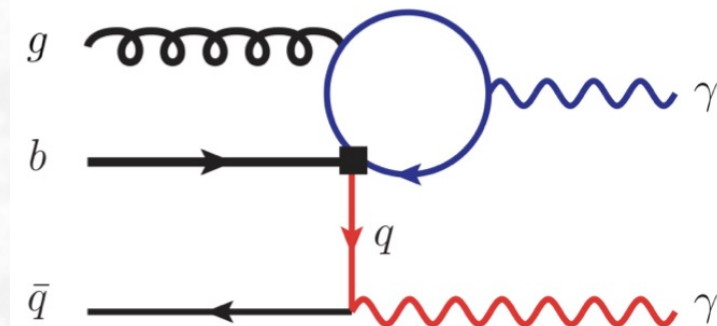
How to improve theoretical precision



- Loop corrections: canonical DE, AMFlow, ...

$$T = T^{(0)} + \alpha_s T^{(1)} + \alpha_s^2 T^{(2)} + O(\alpha_s^3)$$

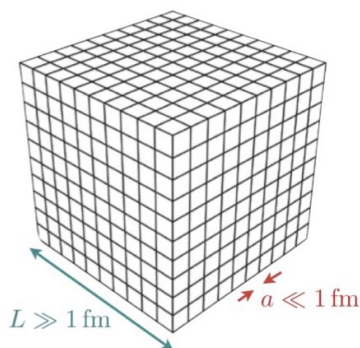
- Power corrections: **SCET-based analysis**, ...



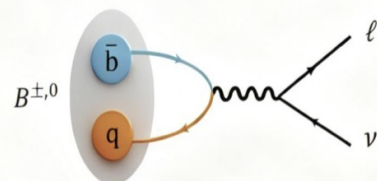
格点QCD：衰变常数、形状因子、bag参数...

Lattice QCD in heavy quark physics

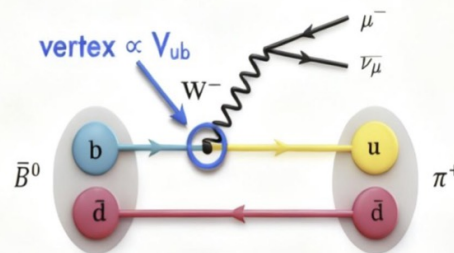
Offering the first-principle results of nonperturbative quantities in heavy quark physics



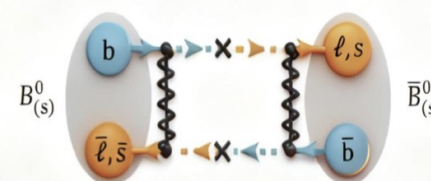
✓ Decay constant: $\langle 0 | J | 1 \rangle$



✓ Form factors: $\langle 1 | J | 1' \rangle$



✓ Mixing parameter: $\langle \bar{1} | J^{\Delta F=2} | 1 \rangle$



LFU violation in $R(D^{(*)})$

- $B \rightarrow D \ell \nu$ form factors at nonzero recoil: MILC collaboration and HPQCD collaboration, PRD 92 (2015)
- Semileptonic form factors for $B \rightarrow D^* \ell \nu$ at nonzero recoil: MILC collaboration, EPJC 82 (2022)
- $B \rightarrow D^*$ and $B_s \rightarrow D_s^*$ form factors for the full q^2 range: HPQCD collaboration, PRD 109 (2024)

The $|V_{ub}|$ and $|V_{cb}|$ puzzle

- $B_s \rightarrow D_s^*$ form factors for the full q^2 range from lattice QCD: HPQCD collaboration, PRD 105 (2022)
- $|V_{ub}|$ from $B \rightarrow \pi \ell \nu$ decays and (2+1)-flavor lattice QCD: Bailey et.al, PRD 92 (2015)
- $B_s \rightarrow D_s$ form factors for the full q^2 range from lattice QCD: HPQCD collaboration, PRD 105 (2020)

$B \rightarrow K^{(*)} \ell \ell$ anomaly

- Rare decay $B \rightarrow K \ell \ell$ form factors from lattice QCD: HPQCD collaboration, PRD 88 (2013)
- SM predictions for $B \rightarrow K \ell \ell$ and $B \rightarrow K \nu \nu$ from Lattice QCD: Parrott, Bouchard, Davies, PRD 107 (2023)

[Lei-Yi Li's talk]

[Yu Meng's talk]

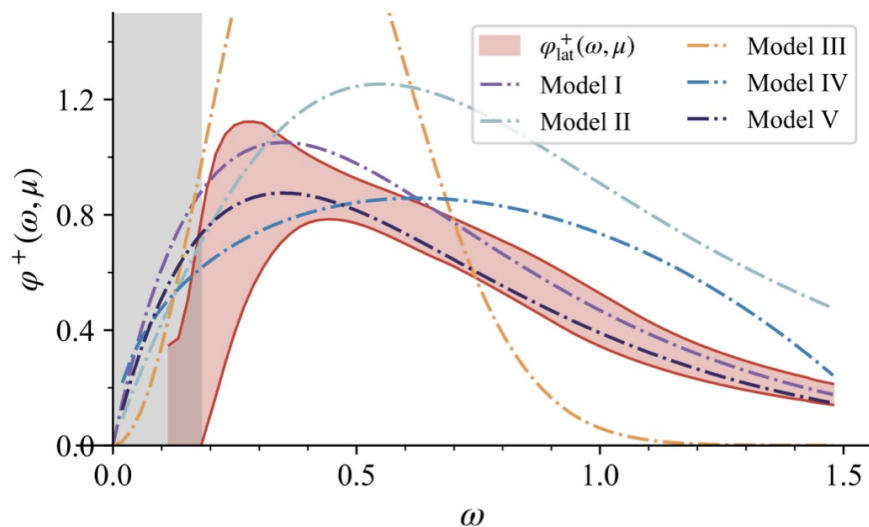
19/30

格点QCD: LCDAs、shape function...

Lattice QCD with LaMET

Light-cone distribution amplitude

- Matching between quasi-DA to LCDA in QCD ✓
- Matching between LCDA in QCD to HQET ✓
- Lattice simulation ✓



[Han, Wang, JX, Zhang, et.al, PRD 111, 3 (2025)]

[Han, Wang, JX, Zhang, et.al, PRD 111, 11 (2025)]

Shape function

- Matching between quasi-SF to SF in QCD ✓
- Matching between SF in QCD to HQET ✓
- Lattice simulation

✓ Systematic uncertainties from non-perturbative renormalization, scale conversion, continuum and infinite-momentum extrapolation etc., are comprehensively addressed.

- Power corrections ($\propto m_H/P^z, \Lambda_{\text{QCD}}/m_Q$) are the most important goal for next stage.

Lattice Parton Collaboration
Ji Xu, Qi-An Zhang, Jun Hua,...

18/30

Inclusive processes: OPE & HQE

□ Lifetime based on HQE in 1/m_b: [J. Albrecht,

F. Bernlochner, A. Lenz, A. Rusov, 2402.04224]

$$\Gamma(\mathcal{B}) = \frac{1}{2m_{\mathcal{B}}} \sum_X \int_{\text{PS}} (2\pi)^4 \delta^{(4)}(p_{\mathcal{B}} - p_X) |\langle X(p_X) | \mathcal{H}_{\text{eff}} | \mathcal{B}(p_{\mathcal{B}}) \rangle|^2$$

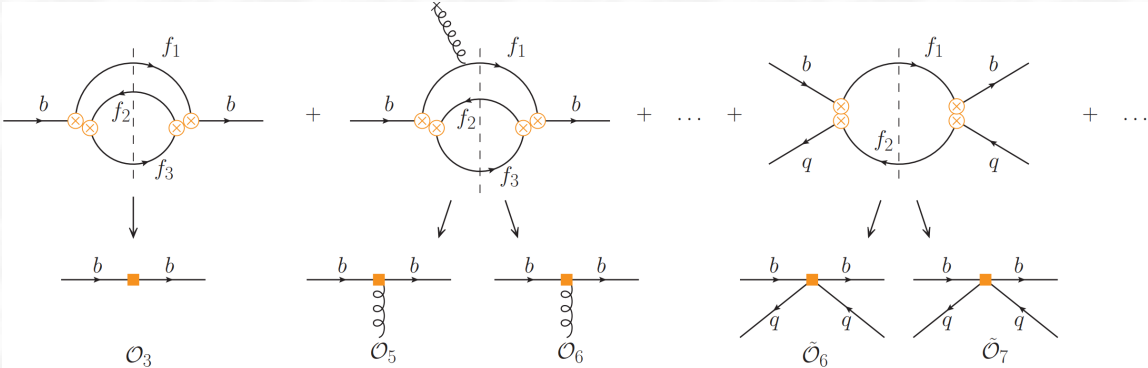
Optical Theorem

$$= \frac{1}{2m_{\mathcal{B}}} \text{Im} \langle \mathcal{B}(p_{\mathcal{B}}) | i \int d^4x \, T \{ \mathcal{H}_{\text{eff}}(x), \mathcal{H}_{\text{eff}}(0) \} | \mathcal{B}(p_{\mathcal{B}}) \rangle$$

□ status of SD coefficients:

	Semi-leptonic				Non-leptonic		
	LO	NLO	N ² LO	N ³ LO	LO	NLO	N ² LO
Γ ₃	✓	✓	✓	✓ [*]	✓	✓	✓
Γ ₅	✓	✓			✓	✓ [•]	
Γ ₆	✓	✓			✓ [◊]	⌚	
Γ ₇	✓				⌚		
Γ ₈	✓						
Γ̃ ₆	✓	✓	⌚		✓	✓	⌚
Γ̃ ₇	✓	⌚			✓	⌚	

◊ [Lenz, Piscopo, AR, 2004.09527], [Mannel, Moreno, Pivovarov, 2004.09485]
^{*} [Fael, Schönwald, Steinhauser, 2011.13654] • [Mannel, Moreno, Pivovarov, 2304.08964 (for m_c = 0)]
 ✓ - known ✓ - partly known ⌚ - in progress or planned [Karlsruhe, Siegen]



$$\Gamma(\mathcal{B}) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \dots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \dots \right]$$

□ status of hadronic matrix elements:

$\langle Q_5 \rangle_{B_d}$	1993/96 2013-2023 2017/18	QCD sum rule [234, 235] Fit of inclusive data [236–241] Lattice QCD [242, 243]
$\langle Q_5 \rangle_{B_s}$	2011	Spectroscopy relations [244]
$\langle Q_5 \rangle_{\mathcal{B}}$	2023	Spectroscopy relations [34]
$\langle \tilde{Q}_6 \rangle_{B_d}$	1994/2022 2013-2023	EOM relation [31, 245] Fit of inclusive data [236–241]
$\langle \tilde{Q}_6 \rangle_{B_s}$	1994/2022 2011	EOM relation [31, 245] Sum rule [244]
$\langle \tilde{Q}_6 \rangle_{\mathcal{B}}$	2023	EOM relation [34]
$\langle \tilde{Q}_6 \rangle_{B_d}$	2017	HQET sum rule [246]
$\langle \tilde{Q}_6 \rangle_{B_s}$	2022	HQET sum rule [247]
$\langle \tilde{Q}_6 \rangle_{\Lambda_b}$	1996	QCD sum rule [248]
$\langle \tilde{Q}_6 \rangle_{\mathcal{B}}$	2023	NRCQM [34]
$\langle \tilde{Q}_7 \rangle$		VIA

Inclusive D decays:

Charged-current bottom decays

❖ **Kolya: An automatic calculation package for $\bar{B} \rightarrow \ell^- \bar{\nu}_\ell X_c$**

[Fael, Milutinb, Vos, '24]

➡ Input favored parameters

➡ Output numerical predictions

$$\Delta\Gamma_{\text{sl}}(E_{\text{cut}}) = \int_{E_l \geq E_{\text{cut}}} \frac{d\Gamma}{dE_l} dE_l, \quad \Delta\Gamma_{\text{sl}}(q_{\text{cut}}^2) = \int_{q^2 \geq q_{\text{cut}}^2} \frac{d\Gamma}{dq^2} dq^2.$$

$$\ell_1(E_{\text{cut}}) = \langle E_l \rangle_{E_l \geq E_{\text{cut}}}, \quad \ell_n(E_{\text{cut}}) = \langle (E_l - \langle E_l \rangle)^n \rangle_{E_l \geq E_{\text{cut}}}$$

$$h_1(E_{\text{cut}}) = \langle M_X^2 \rangle_{E_l \geq E_{\text{cut}}}, \quad h_n(E_{\text{cut}}) = \langle (M_X^2 - \langle M_X^2 \rangle)^n \rangle_{E_l \geq E_{\text{cut}}}$$

$$q_1(q_{\text{cut}}^2) = \langle q^2 \rangle_{q^2 \geq q_{\text{cut}}^2}, \quad q_n(q_{\text{cut}}^2) = \langle (q^2 - \langle q^2 \rangle)^n \rangle_{q^2 \geq q_{\text{cut}}^2}$$

Γ_{sl}	tree	α_s	α_s^2	α_s^3
Partonic		[34]	[35–38]	[39]
μ_π^2, μ_G^2	[1, 2]	[40–43]		
ρ_D^3, ρ_{LS}^3	[44]	[45]		
$1/m_b^4, 1/m_b^5$	[23, 26–28]			
$q_n(q_{\text{cut}}^2)$	tree	α_s	α_s^2	
Partonic		[45, 46]	[47]	
μ_π^2, μ_G^2	[1, 2]	[41, 42]		
ρ_D^3, ρ_{LS}^3	[44]	[45]		
$1/m_b^4, 1/m_b^5$	[23, 28]			
$\ell_n(E_{\text{cut}}), h_n(E_{\text{cut}})$	tree	α_s	α_s^2/β_0	α_s^3
Partonic		[46, 48, 49]	[46]	[33]*
μ_π^2, μ_G^2	[1, 2]	[42, 50]		
ρ_D^3	[44]			
$1/m_b^4, 1/m_b^5$	[26–28]			



Theoretical results

❖ Theoretical results for total decay rate and energy moments (NNLO & $\Lambda_{\text{QCD}}^3/m_c^3$)

NLO analytical integration

NNLO numerical results provided by authors of [Chen,Chen,Guan,Ma,'23]

$$\Gamma_{D_i \rightarrow X_q} = \hat{\Gamma}_0 |V_{cq}|^2 m_c^5 \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \frac{2}{3} \left(\frac{25}{4} - \pi^2 \right) + \frac{\alpha_s^2(\mu)}{\pi^2} \left[\frac{\beta_0}{4} \frac{2}{3} \left(\frac{25}{4} - \pi^2 \right) \log \left(\frac{\mu^2}{m_c^2} \right) + 2.14690 n_l - 29.88311 \right] \right. \\ \left. - 8\rho_{\delta sq} - \frac{1}{2} \frac{\mu_\pi^2(D_i)}{m_c^2} - \frac{3}{2} \frac{\mu_G^2(D_i)}{m_c^2} + \left(6 + 8 \log \left(\frac{\mu^2}{m_c^2} \right) \right) \frac{\rho_D^3(D_i)}{m_c^3} + \frac{\tau_0(D_i \rightarrow X_q)}{m_c^3} + \dots \right\}$$

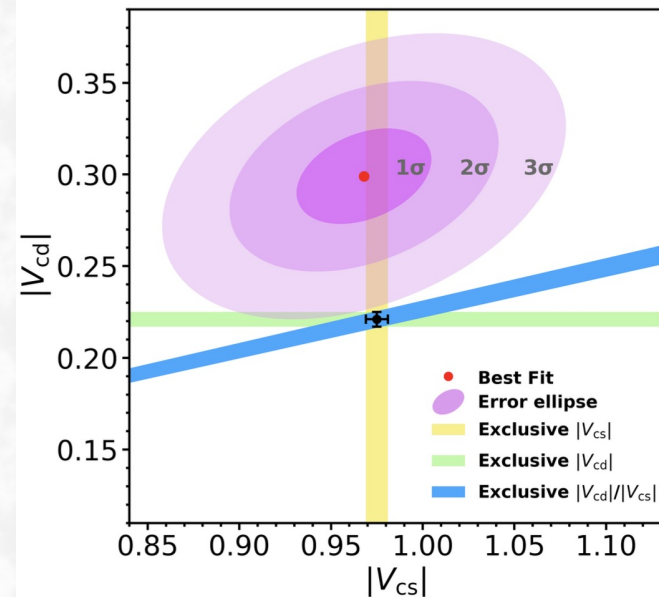
Dim-5, $\Lambda_{\text{QCD}}^2/m_c^2$

Dim-6, $\Lambda_{\text{QCD}}^3/m_c^3$

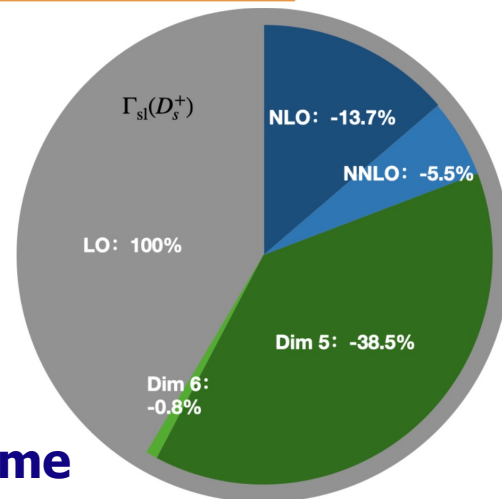
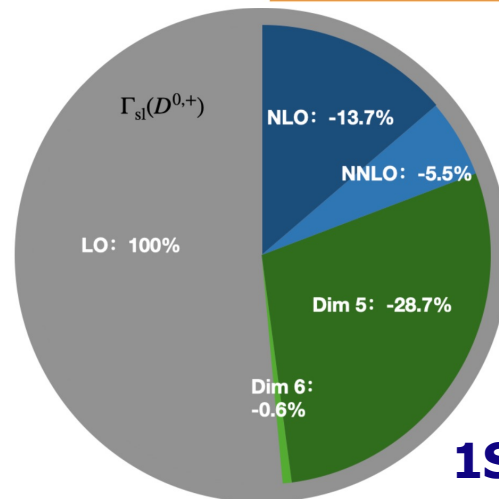
❖ For Dim-6 4-quark operator contributions, practically difficult to extract

➡ Vacuum-Insertion-Approximation (VIA), $\tau_0 = 0$

➡ HQET Sum Rules [King, Lenz, Piscopo, Rauh, '19]



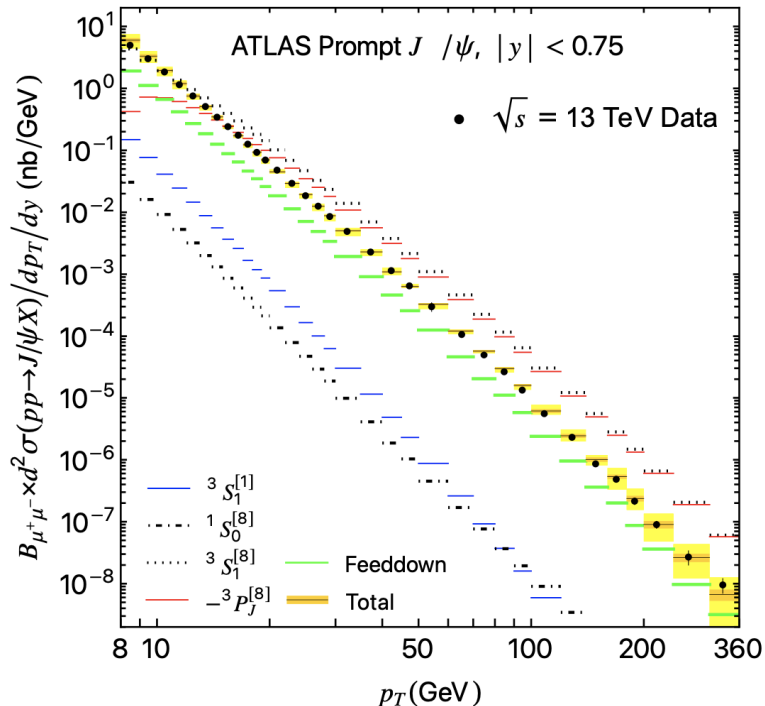
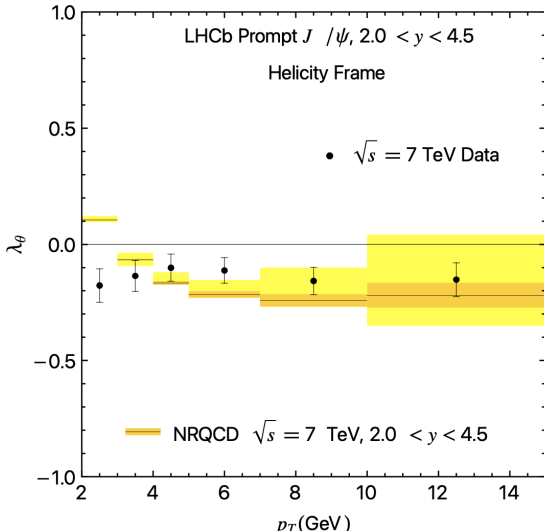
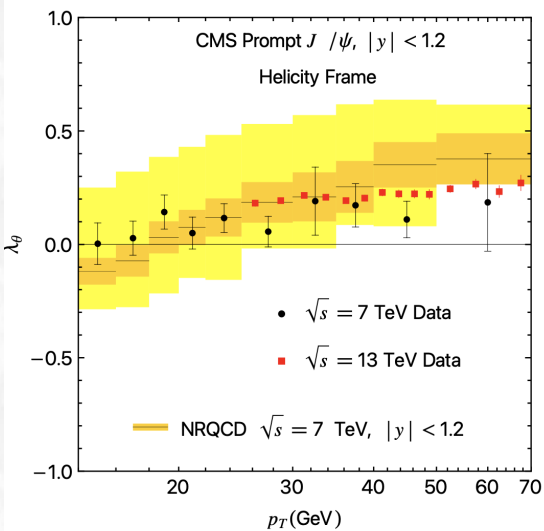
Inclusive vs exclusive: 3σ tension!



1S scheme

Convergent expansions of $\alpha_s(m_c)$ and Λ_{QCD}/m_c !

NRQCD有效理论的应用:



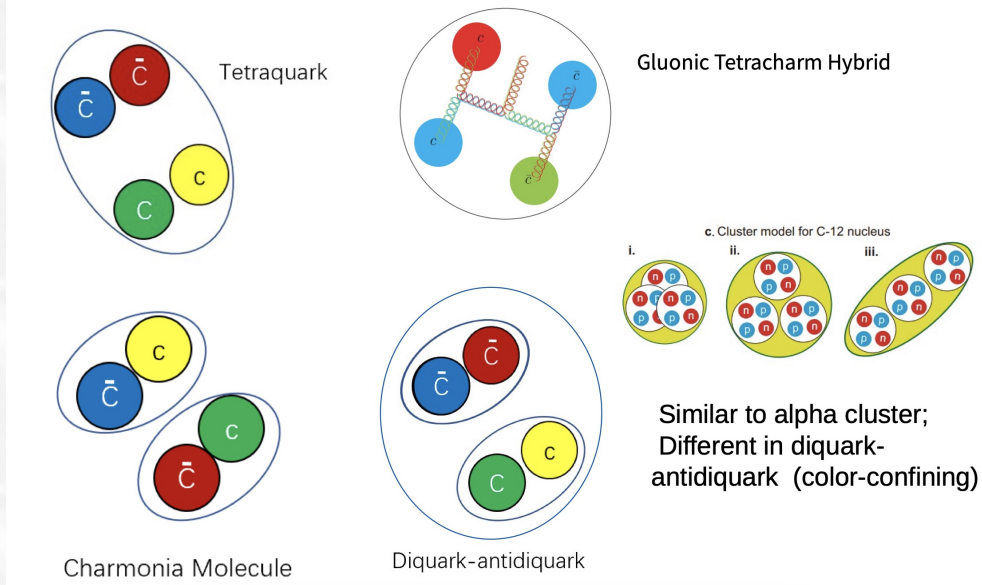
Summary:

- NRQCD factorization works pretty well except for end-point regions, where resummations are needed.
- Good descriptions for $\Upsilon(nS)$ production, highly nontrivial tests of the pNRQCD relations for LDMEs.

pp High p_T : J/ψ	η_c	$\Upsilon(nS)$	pol.	$J/\psi + Z$	e^+e^-	γp	$\gamma\gamma$	pp (Low p_T , J/ψ)
✓	✓	✓	✓	✓(?)	✓(SGF)	✓($z < 0.6$)	✓	✓ (small-x resum)

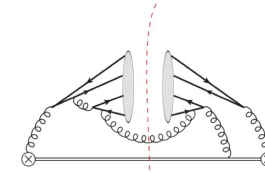
对exotic states的理论解释:

| How to explain these exotic states?



Outlook: measuring the (differential) cross section (or) and the decay angular distribution shall tell us the inner structure of exotics; Color confinement has not been really understood, and its deep investigation is

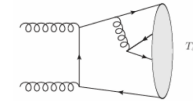
➤ Fragmentation mechanism (based on NRQCD), equally considering the NLO real diagrams (valid for large P_t)



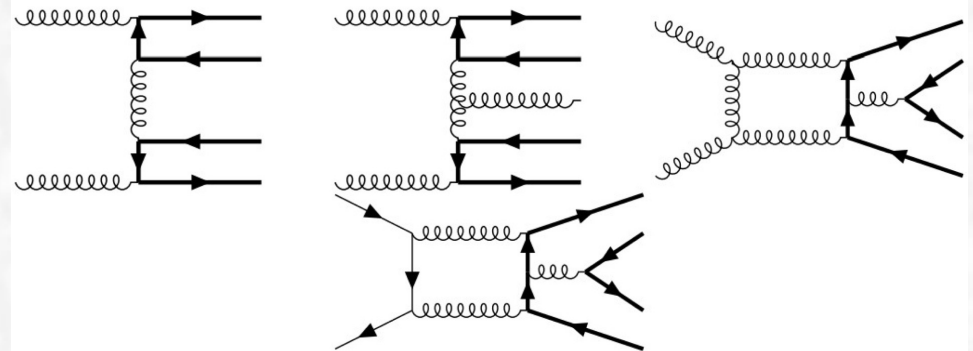
F. Feng, Y. Huang, Y. Jia, W. L. Sang, X. Xiong and J. Y. Zhang, arXiv:2009.08450; F. Feng et al, 2304.11142
Y.Q. Ma, H.F. Zhang, arXiv:2009.08376
I. Belov, A. Giachino, and E. Santopinto, arXiv:2409.12070

➤ NRQCD LO ($P_t=0$)

R.L. Zhu, arXiv: 2010.09082



Wang, Zhu, arXiv:2510.02085



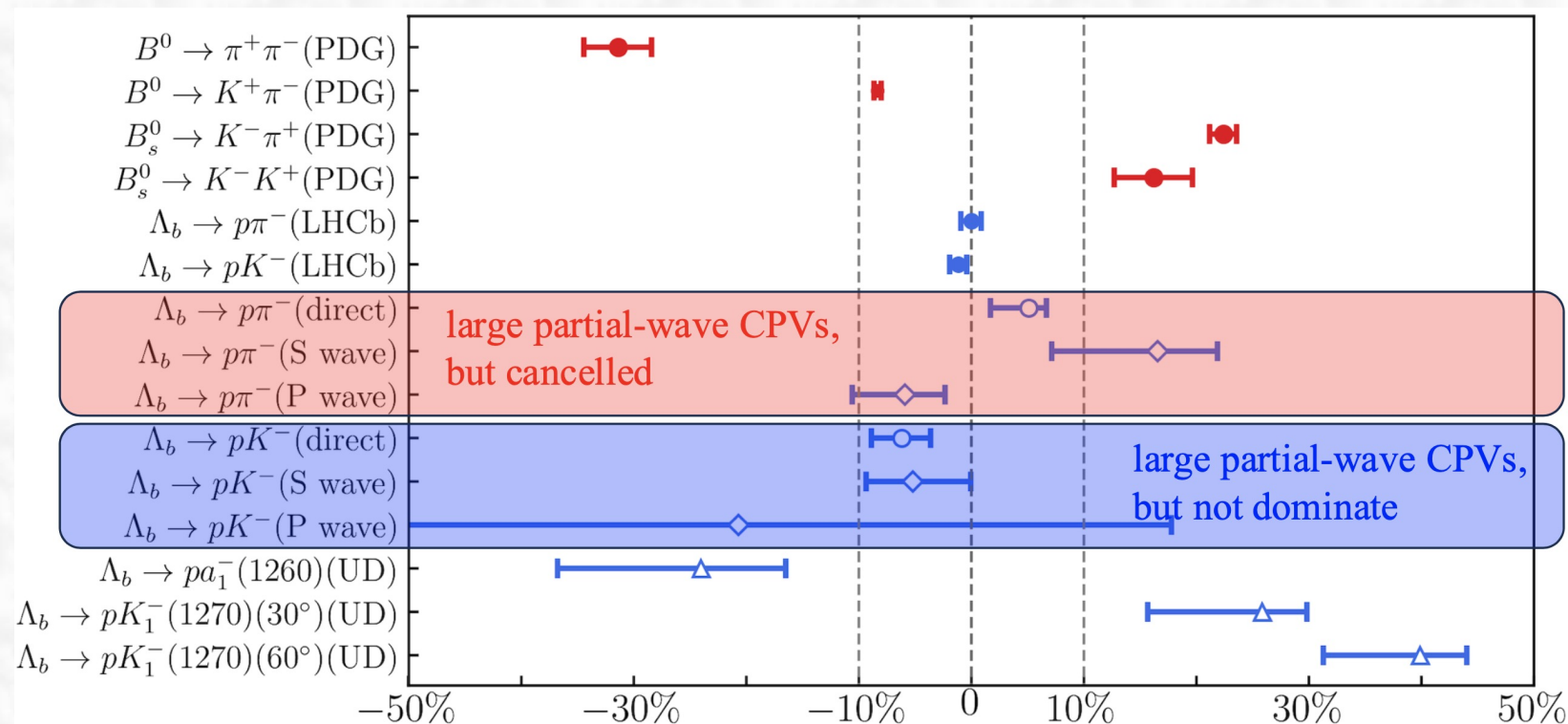
LO: 64(gg) , 4(qqbar)

NLO Virtual: 2008(gg) , 170(qqbar)

NLO Real: 618(gg) , 98(qqbar, qg)

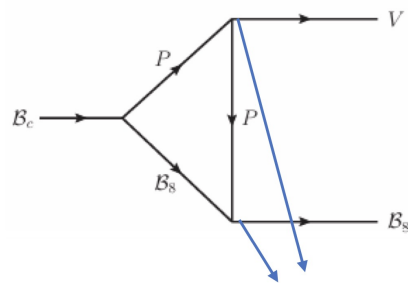
重子CPV in pQCD:

$$A_{CP}^{dir} = \frac{|S|^2}{|S|^2 + \frac{M_-^2}{M_+^2} \frac{1+A_{CP}^{S-wave}}{1+A_{CP}^{P-wave}} |P|^2} A_{CP}^{S-wave} + \frac{\frac{M_-^2}{M_+^2} |P|^2}{\frac{1+A_{CP}^{P-wave}}{1+A_{CP}^{S-wave}} |S|^2 + \frac{M_-^2}{M_+^2} |P|^2} A_{CP}^{P-wave}$$



韩佳杰talk

重子CPV with FSI: 冯天亮talk



$$\mathcal{F} = \left(\frac{\Lambda_1^2 - m_1^2}{\Lambda_1^2 - p_1^2} \right) \left(\frac{\Lambda_2^2 - m_2^2}{\Lambda_2^2 - p_2^2} \right)$$

Model parameter $\Lambda = m + \eta \Lambda_{QCD}$

$$\mathcal{F}(\Lambda, m_k) = \frac{\Lambda^4}{(k^2 - m_k^2)^2 + \Lambda^4}$$

Advantage :no additional phase.

$$\mathcal{M}[P, B_8; P] = -i \int \frac{d^4 k}{(2\pi)^4} g_{BBP} \cdot g_{VPP} \bar{u}(p_4, s_4) \gamma_5 (\not{p}_2 + m_2) (A + B \gamma_5) u(p) \times \varepsilon_\mu^*(p_3, \lambda_3) (p_1 + k)^\mu \frac{\mathcal{F}}{(p_1^2 - m_1^2 + i\epsilon)(p_2^2 - m_2^2 + i\epsilon)(k^2 - m_k^2)}$$

- Hadronic form factors
- divergences in loop integrals
- off-shell effects

- The calculation of 8 channels was performed while keeping the model framework and parameters unchanged, showing the reliability of the FSI.
- Analysis of the results was followed by further kinematic studies, Recommended observables that could reach 100% CPV.
- The FSI framework shows promise for extending to more calculations in future studies.

	BR	Direct CP(10^{-2})
$(\Lambda_b^0 \rightarrow pk^- \pi^0)$		
$\Lambda(1520)\pi^0$	$6.90^{+12.47}_{-4.31} \times 10^{-9}$	$17.4^{+6.9}_{-7.3}$
$(\Lambda_b^0 \rightarrow pk^- \pi^+ \pi^-)$		
$\Lambda(1520)f_0(980)$	$6.01^{+6.98}_{-3.47} \times 10^{-6}$	$2.9^{+3.8}_{-1.6}$
$\Lambda(1520)\rho^0$	$8.51^{+7.58}_{-3.33} \times 10^{-7}$	$25.7^{+16.3}_{-12.8}$
$\Lambda(1520)f_0(500)$	$9.28^{+11.50}_{-5.42} \times 10^{-7}$	$-1.0^{+1.1}_{-0.7}$
$(\Lambda_b^0 \rightarrow pk^- k^+ k^-)$		
$\Lambda(1520)\phi$	$9.16^{+10.73}_{-5.29} \times 10^{-5}$	$-0.5^{+0.4}_{-1.3}$
$\Lambda(1520)f_0(980)$	$6.01^{+6.98}_{-3.47} \times 10^{-6}$	$2.9^{+3.8}_{-1.6}$
$(\Lambda_b^0 \rightarrow pk^- k^+ \pi^-)$		
$\Lambda(1520)k^{*0}$	$1.79^{+1.98}_{-0.92} \times 10^{-5}$	$-6.3^{+5.0}_{-1.7}$
$\Lambda(1520)\kappa(700)$	$1.64^{+1.87}_{-0.93} \times 10^{-7}$	$24.2^{+17.3}_{-17.8}$
$(\Xi_b^- \rightarrow pk^- k^-)$		
$\Lambda(1520)k^-$	$1.79^{+2.03}_{-1.02} \times 10^{-6}$	$-3.4^{+7.9}_{-6.7}$

陶轻子物理:

郭志辉talk

tau的强衰变可以给我们提供什么信息?

- **inclusive**衰变: (某类) 所有的强子末态

$$\tau^- \rightarrow \nu_\tau (\bar{u}d, \bar{u}s)$$

→ 可以用来研究标准模型的基本参数: $\alpha_S, V_{us}, \dots$

- **exclusive**衰变: 衰变至特定的强子末态

$$\tau^- \rightarrow \nu_\tau (P, \mathbf{PP}', P_1 P_2 P_3, \dots)$$

→ 强作用形状因子, 强子共振态, 手征对称性,
→ CPV、轻子味道破坏、...

$$\mathcal{M}(\tau \rightarrow H \nu_\tau) = \frac{G_F}{\sqrt{2}} V_{CKM} [\bar{u}_{\nu_\tau} \gamma^\mu (1 - \gamma_5) u_\tau] H_\mu$$

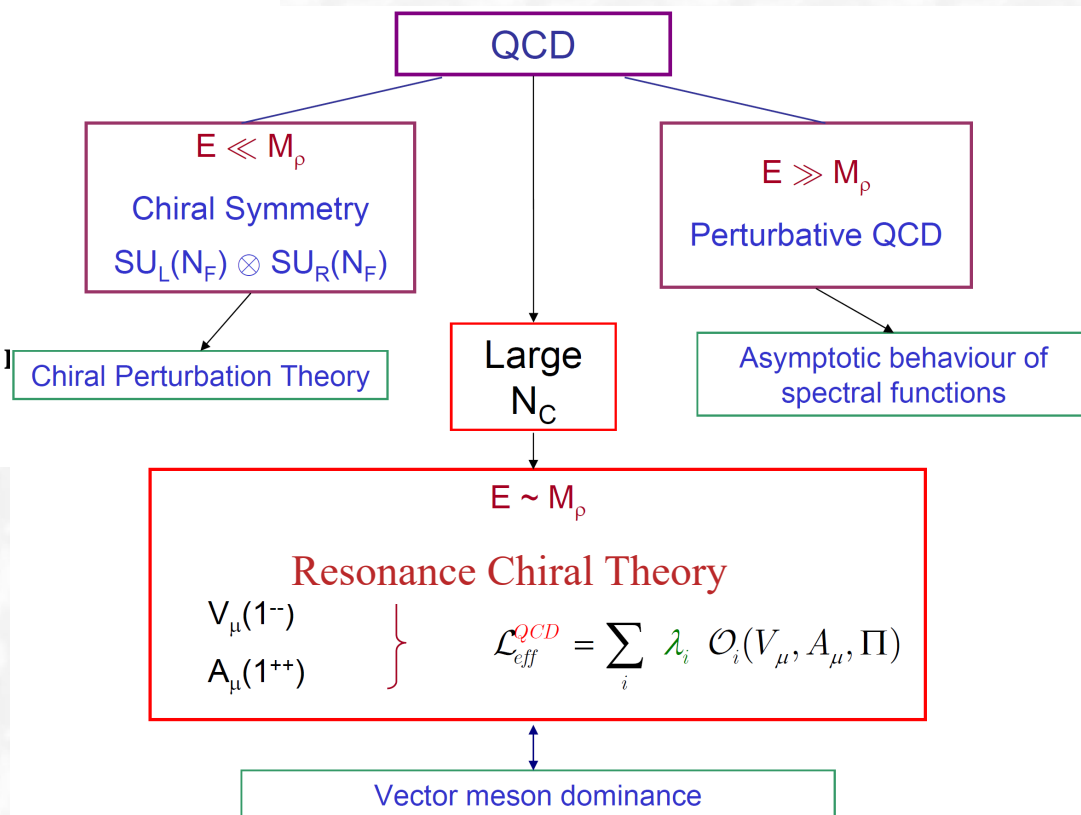
$$H_\mu = \langle H | (\mathbf{v}_\mu - \mathcal{A}_\mu) e^{i\mathcal{L}_{QCD}} | 0 \rangle$$

$$= \sum_i (\dots)^\mu_i \underbrace{F_i(q^2, \dots)}_{\text{Form factor}}$$

Lorentz structure

$$\Gamma_{\tau \rightarrow \nu_\tau + \text{had}} \sim \text{Im} \left\{ \text{Diagram} \right\}$$

IR renormalon problem: FOPT vs CIPT



未来可期:

BES II

ATLAS
EXPERIMENT

Belle II

CMS

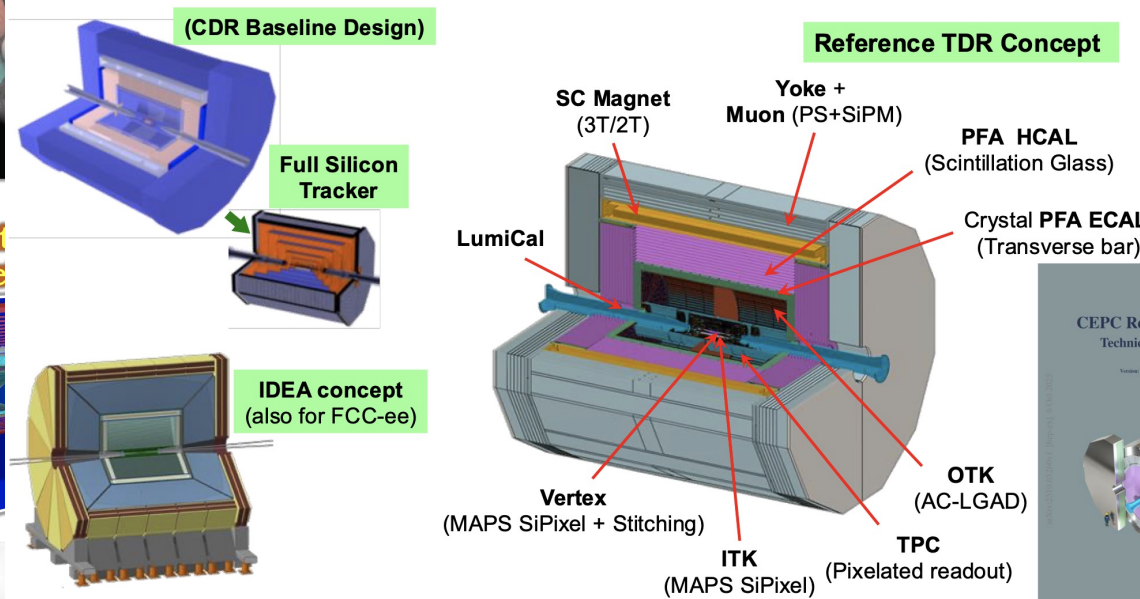
LHCb
HCP

A factory producing massive **tau lepton** and **hadrons**, to unravel the mystery of **how quarks form matter** and the **symmetries** of fundamental interactions.



- $E_{\text{cm}} = 2\text{-}7 \text{ GeV}$, $\mathcal{L} > 0.5 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
- Potential for upgrade to **increase luminosity** and realize **polarized beam**.

CEPC Conceptual Detector Designs

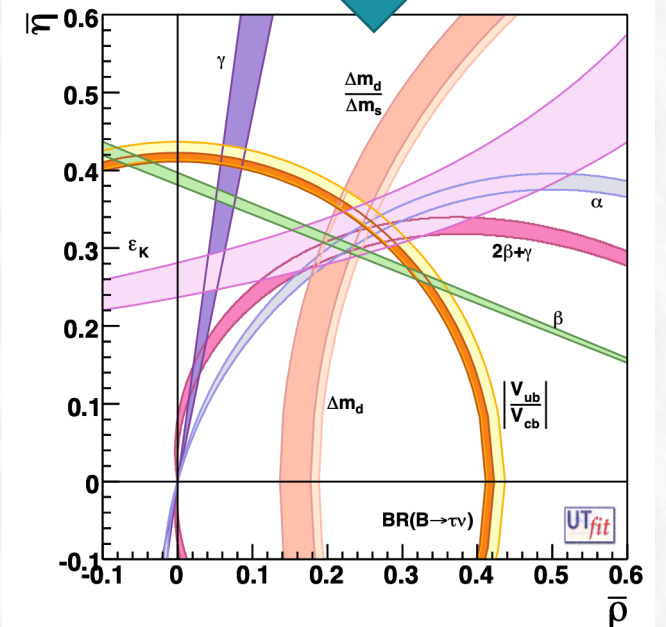
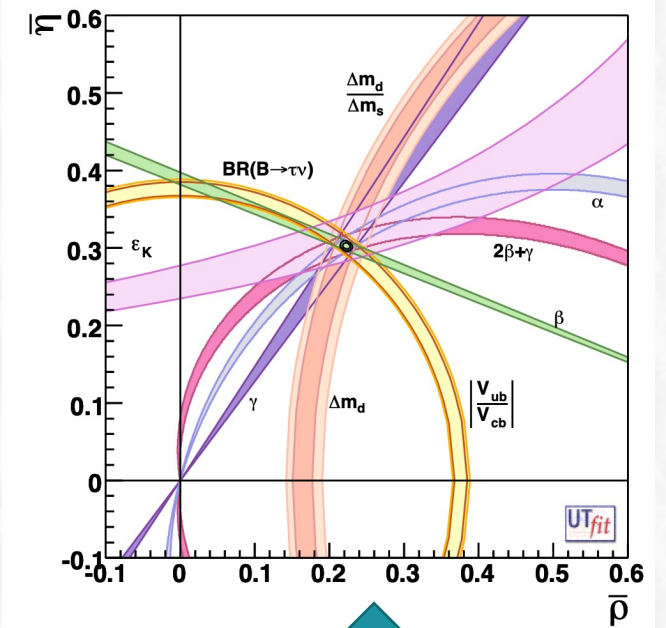


未来可期:

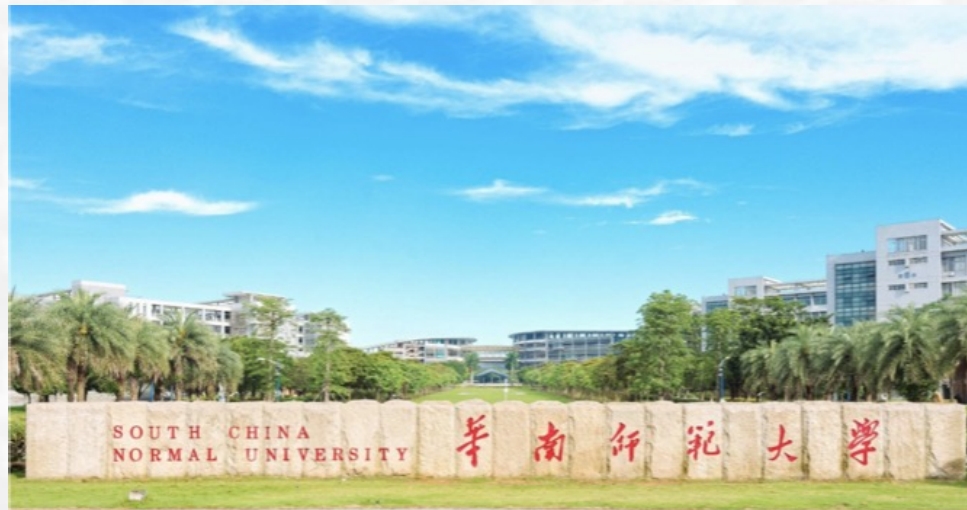
Projections for early 2040s

2503.24346, ESPP

Experiment	ATLAS	CMS	LHCb	Belle II
Assumed data sample	3000 fb^{-1}	3000 fb^{-1}	300 fb^{-1}	50 ab^{-1}
Semileptonic B decays	$\mathcal{O}(5)$ improvement			
$ V_{ub} $	—	—	1%	1.2%
$ V_{cb} $	—	—	—	1.0%
$R(D), R(D^*)$	—	—	3.3%, 3.0%	1.4%, 1.0%
Leptonic B decays				
$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) [10^{-9}]$	(0.33 – 0.40)	0.22	0.16	—
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) [10^{-10}]$	(0.32 – 0.48)	0.12	0.12	—
$\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$	—	—	—	—
$\mathcal{B}(B^+ \rightarrow \mu^+ \nu_\mu)$	—	—	—	—
Flavour-changing neutral current $b \rightarrow s \ell \ell$ decays				
$P_5'(B^0 \rightarrow K^{*0} \mu^+ \mu^-) [10^{-3}]$	(47 – 82)	23	12	—
$\mathcal{B}(B^{+,0} \rightarrow K^{+,*0} \nu \bar{\nu})$	—	—	—	8%, 23%
$\mathcal{B}(B^{+,0} \rightarrow K^{+,*0} \tau^+ \tau^-) [10^{-4}]$	—	—	—	< 0.9, < 1.5
Flavour-changing neutral current $b \rightarrow s \gamma$ decays				
$\mathcal{B}(B \rightarrow X_s \gamma; E_\gamma > 1.6 \text{ GeV})$	—	—	—	(4.7 – 8.8)%
Lepton flavour violation in τ decays				
$\mathcal{B}(\tau^+ \rightarrow \mu^+ \gamma) [10^{-8}]$	—	—	—	< 0.7
$\mathcal{B}(\tau^+ \rightarrow \mu^+ \mu^+ \mu^-) [10^{-8}]$	< (0.13 – 0.64)	< 0.39	< 0.26	< (0.02 – 0.17)



第23届HFCPV将在华南师大 召开，期待更多、更好的成果



再次抱歉没有提到的报告内容，大家
可以参考：

<https://indico.ihep.ac.cn/event/26275/>

再次感谢顾问委员会、会议组委会、地方组委会：

顾问委员会：黄涛、高原宁、李湘楠、吕才典、肖振军、杨亚东、郑阳恒

会议组委会：李新强、李营、吕晓睿、沈成平、王伟、于福升、张黎明、朱瑞林

地方组委会：安刘攀、曹庆宏、冯旭、刘佳、马滢青、王大勇、杨振伟、张艳席、朱华星

谢谢！