Invisible Λ_b decay

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Motivation

- The standard model of particle physics (SM) is very successful.
- However, several cosmological observations suggest that the SM should be extended.
  - The existence of the Dark matter.

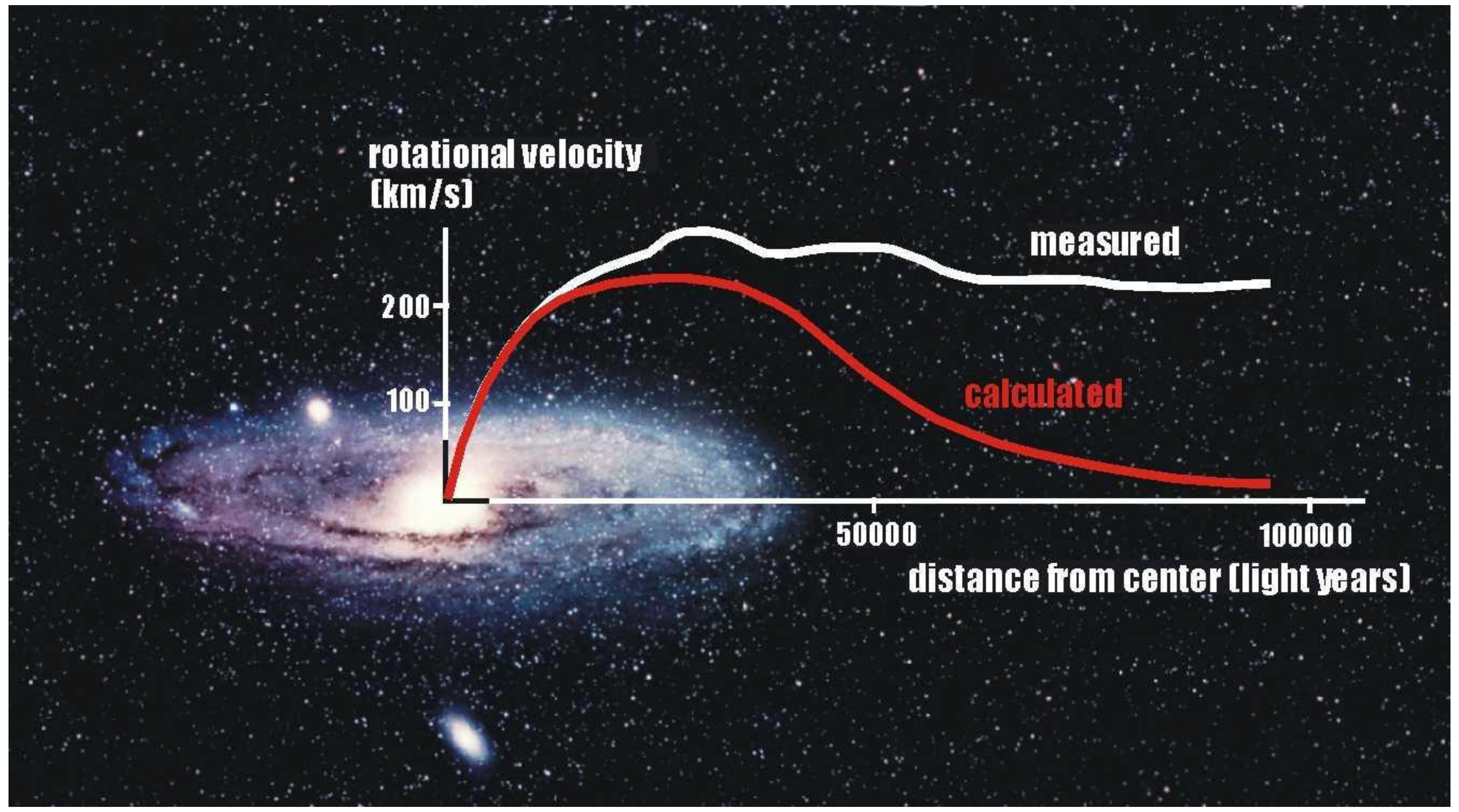
$$\Omega_{\rm DM,0}h^2 = 0.120 \pm 0.001 \ ,$$

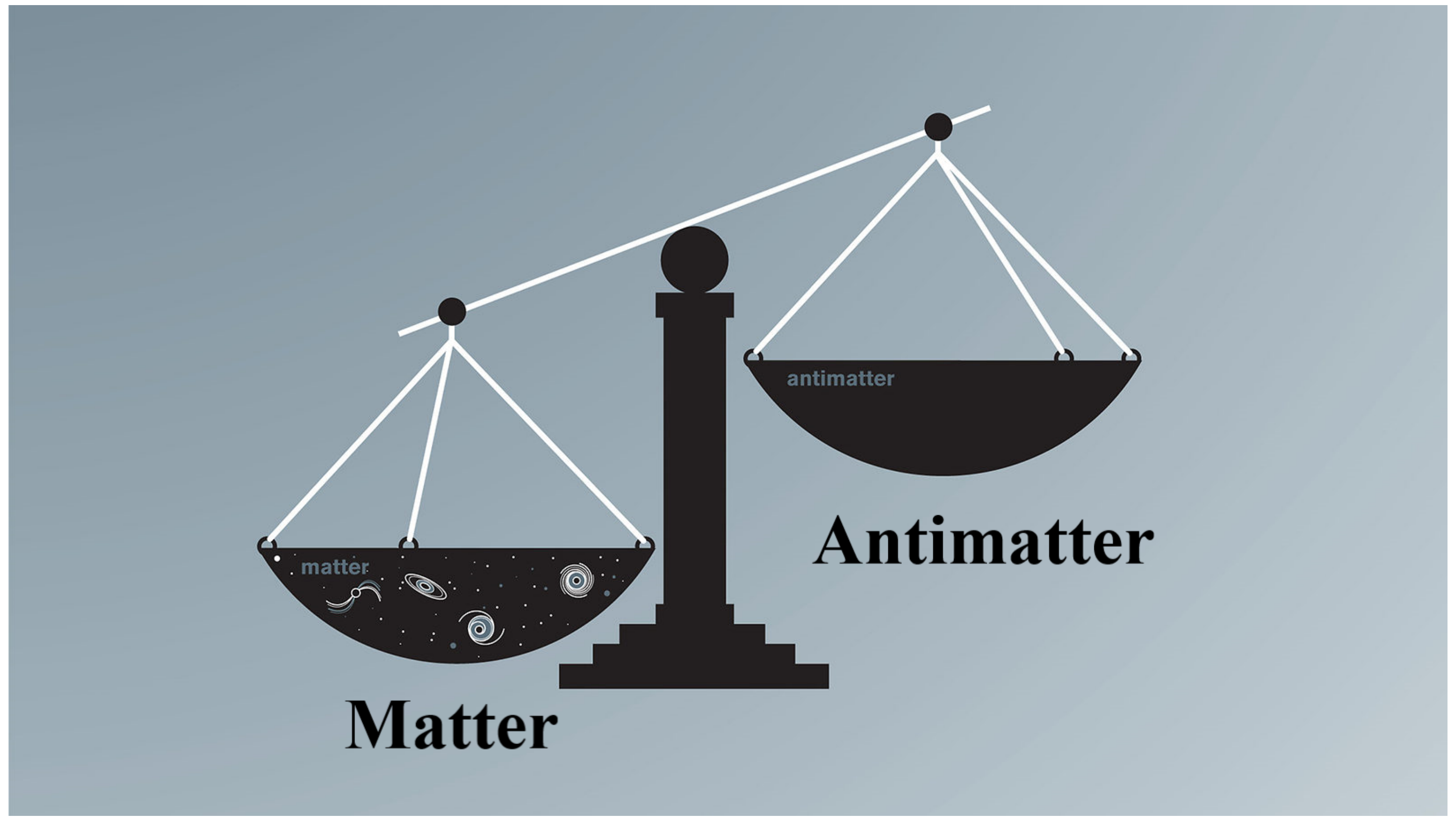
Planck collaboration, Astron. Astrophys. 641 (2020) A6.

  - Asymmetry of matter-antimatter.

$$Y_{B,0} = \frac{n_B - n_{\bar{B}}}{s}\bigg|_0 = (8.75 \pm 0.23) \times 10^{-11}$$

- Matter-antimatter asymmetry and dark matter are long-standing outstanding problems.





Motivation

- The baryon and dark matter energy densities are fairly similar:

$$\Omega_{DM}/\Omega_B = 5.36 \pm 0.06$$ Planck collaboration, Astron. Astrophys. 641 (2020) A6.

- Therefore, **dark matter** and **matter-antimatter asymmetry** have non-trivial relation, perhaps.

- **Invisible baryon decay could explain them simultaneously.**

$$\mathbf{B} \to \xi\phi$$

where **B** is a neutral baryon in SM, ξ is dark baryon, ϕ is also dark matter.

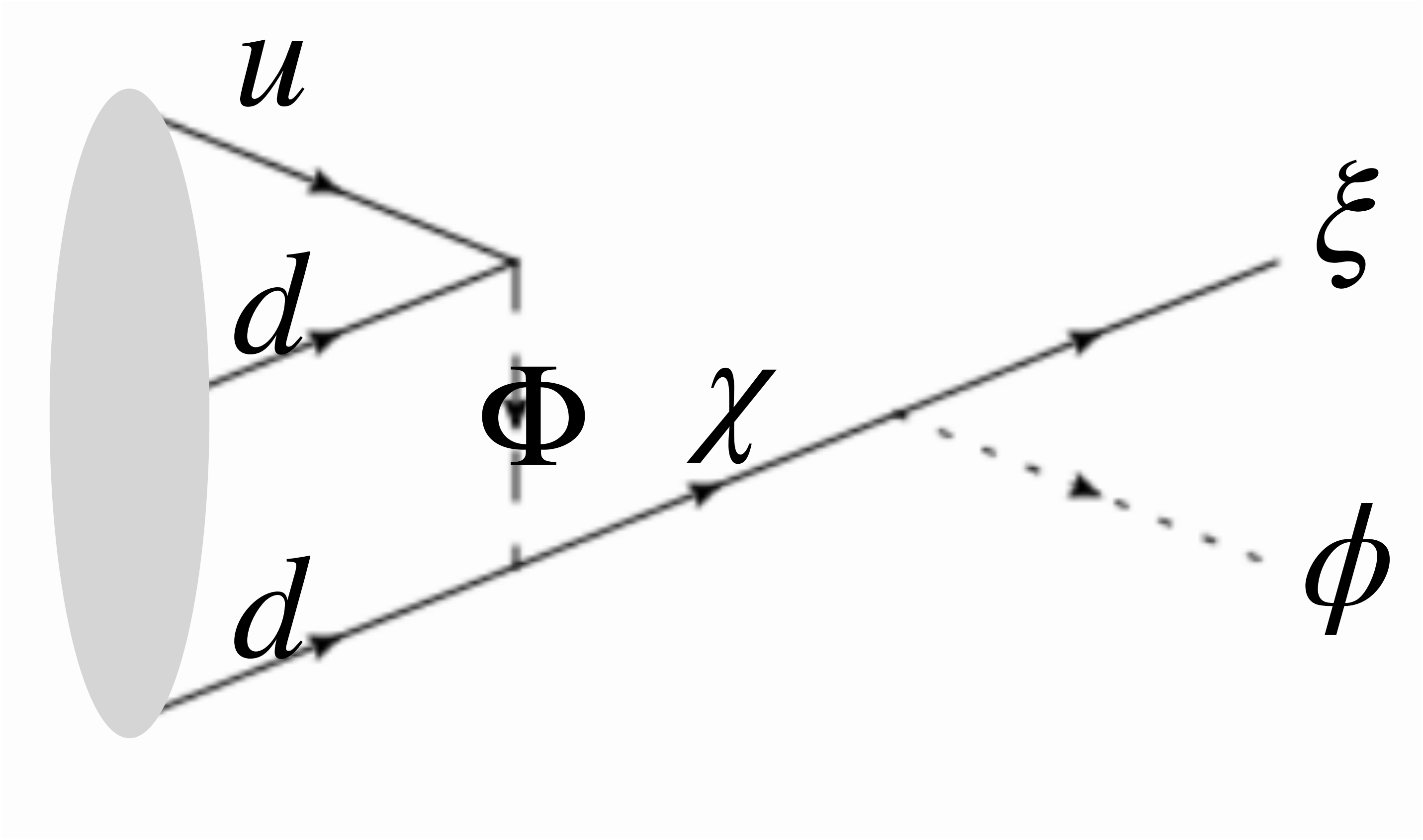
  - **Violate the baryon number in visible universe**
  - **Induce the dark matter**

Motivation

- The invisible baryon decay, whose simplest UV-complete Lagrangian is

Phys. Rev. D 105, 115005 (2022).

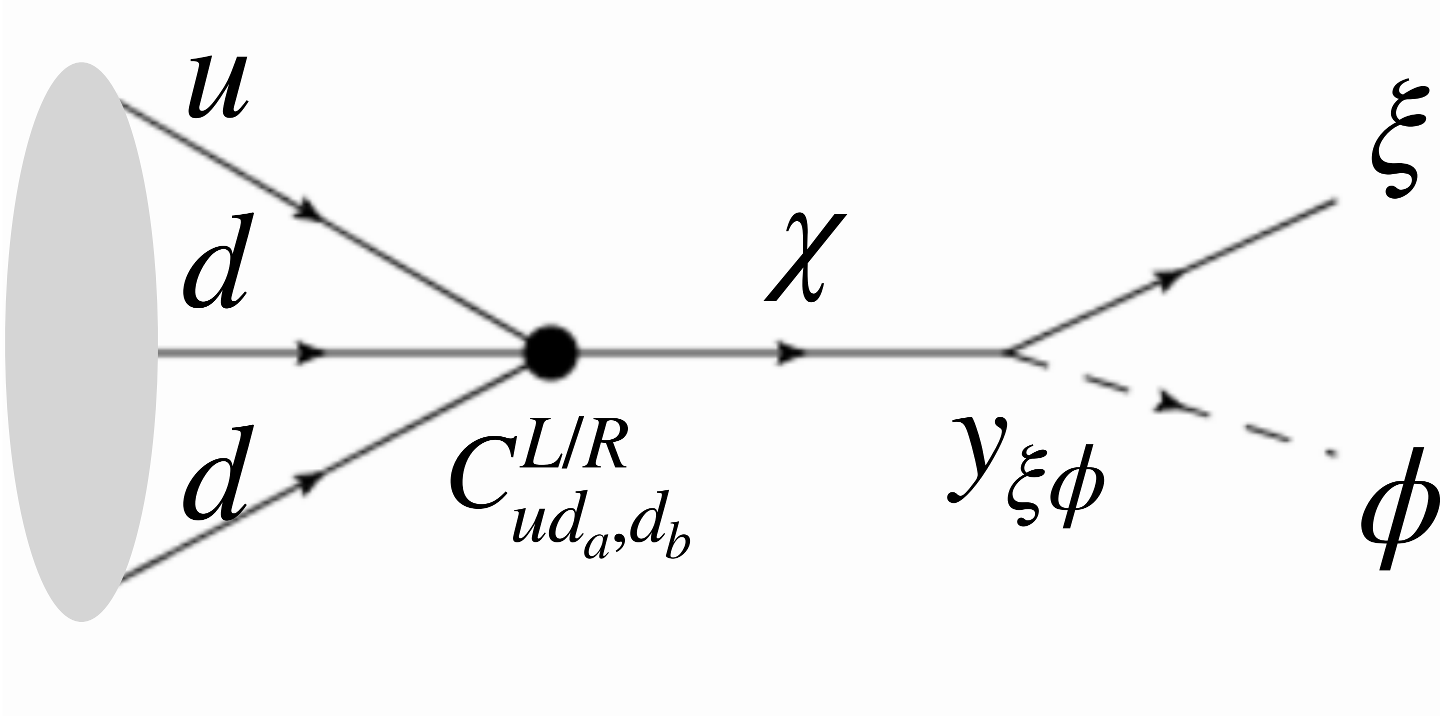
$$\mathscr{L} = -\, y_{u_a d_b} \epsilon_{ijk} \Phi^i u^j_{Ra} d^k_{Rb} - y_{\chi d_c} \Phi^*_i \chi_R d^i_{Rc}$$
$$-y_{\xi\phi} \chi \xi \phi + (L \leftrightarrow R) + h.c.$$



- Integrating out the heavy field Φ obtains the effective operators

u, d: up (down) type quark

$$\mathcal{O}^R_{ud_a,d_b} = \epsilon_{ijk}(u^i_R d^j_{Ra})(\chi_R d^k_{Rb}) \,,$$
$$\mathcal{O}^L_{ud_a,d_b} = \epsilon_{ijk}(u^i_L d^j_{La})(\chi_R d^k_{Rb}) \,,$$



Motivation

- CEPC: ideal platform for invisible Λ_b decay.

Particle	Belle II	LHCb (300 fb^{-1})	CEPC ($4\times$Tera-Z)
B^0, $\bar{B}^0$	5.4×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
$B^\pm$	5.7×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	6.0×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^\pm$	-	1×10^{11}	7.2×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	-	2×10^{13}	1×10^{11}

- From (Lingfeng Li's talk)

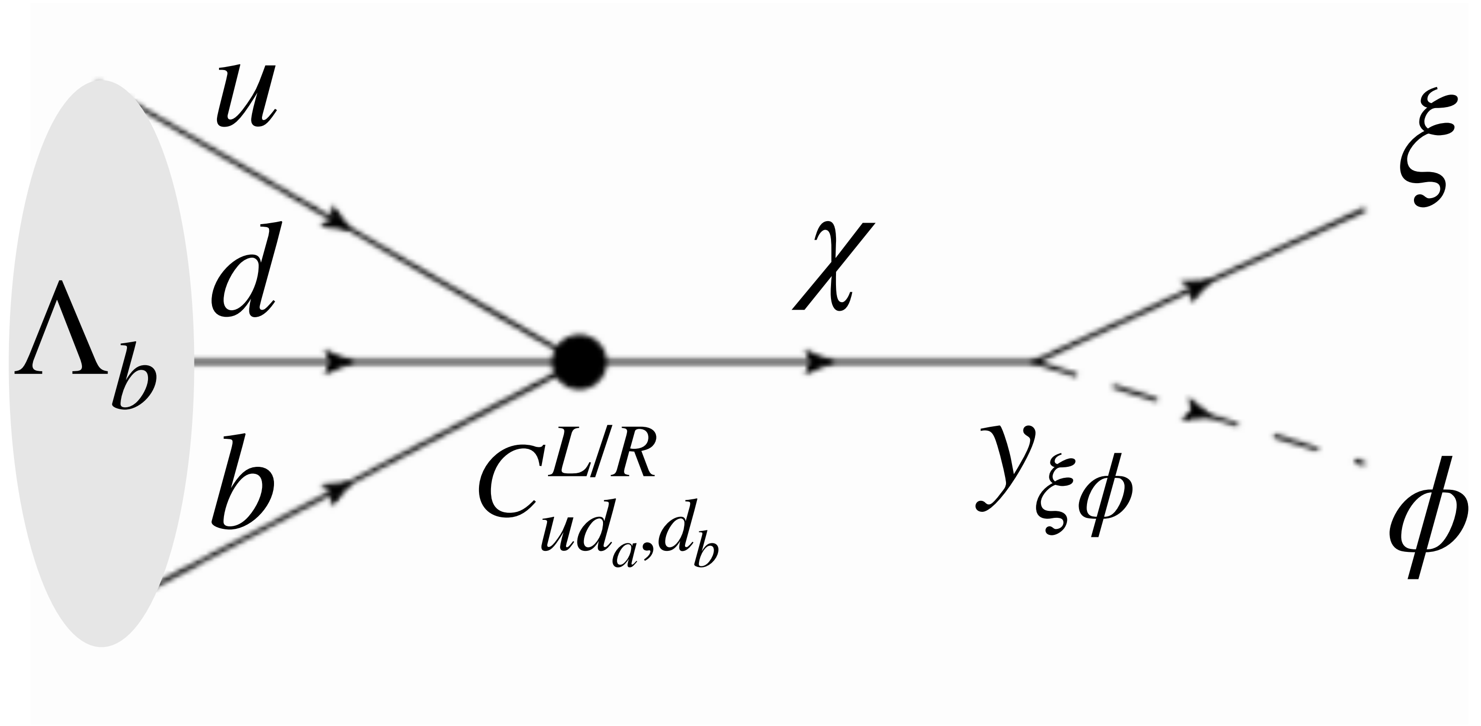
much cleaner environment

Invisible Λ_b decay

- Decay rate for $\Lambda_b \to \xi\phi$,

$$\Gamma_{\Lambda_b \to \xi\phi} = \frac{|\vec{k}|}{8\pi m_{\Lambda_b}} |C^{L/R}_{ud,b}|^2 |y_{\xi\phi}|^2 \, \mathbb{H}^{L/R}_{\Lambda_b}$$

$$\mathbb{H}^{L/R}_{\Lambda_b} = |\lambda^{L/R}_{\Lambda_b}|^2 \frac{E_\xi(m^2_{\Lambda_b} + m^2_\chi) + 2m_{\Lambda_b} m_\chi m_\xi}{(m^2_{\Lambda_b} - m^2_\chi)^2}$$



where $\lambda^{L/R}_{\Lambda_b}$ is the hadronic matrix element.

$$\langle 0 | \varepsilon^{ijk} \left[u_i^T C P_{L/R} d_j \right] P_R b_k | \Lambda_b(p) \rangle = \lambda^{L/R}_{\Lambda_b} P_R u(p)$$

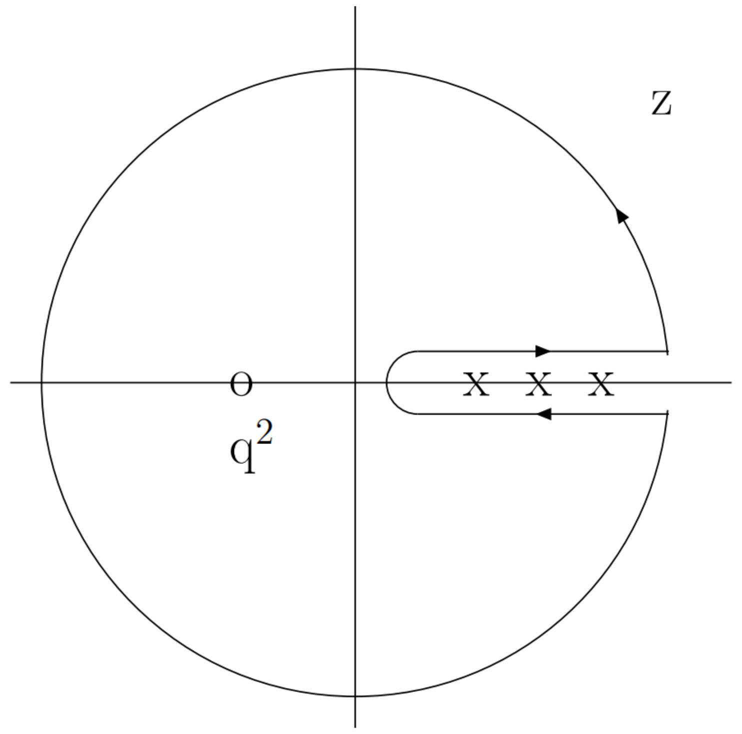
QCD sum rules (QCDSR)

QCDSR for the hadronic matrix elements

$$\langle 0|\, \varepsilon^{ijk} \left[u_i^T C P_{L/R} d_j\right] P_R b_k \,|\Lambda_b(p)\rangle = \lambda_{\Lambda_b}^{L/R} P_R u(p)$$

- QCDSR: a excellent and ripe instrument to calculate the non-perturbative quantities.
- Basic object: correlation functions $\Pi(q) = i \int d^4x e^{iq\cdot x} < 0\,|\,T\{j(x)j(0)\}\,|\,0 >$

$$\Pi(q^2) = \frac{1}{\pi}\int_{t_{min}}^{\infty} ds \frac{\mathbf{Im}\Pi(s)}{s - q^2 - i\epsilon}$$



QCD side

OPE
$\boldsymbol{q^2 \ll 0}$

→ Bridge: **Dispersion relation** ←

Phenomenological side

Hadronic spectrum
Quark-Hadron Duality

QCDSR for the hadronic matrix elements

$$\langle 0|\,\varepsilon^{ijk}\left[u_i^T C P_{L/R} d_j\right] P_R b_k\,|\Lambda_b(p)\rangle = \lambda_{\Lambda_b}^{L/R} P_R u(p)$$

- To obtain this hadronic matrix elements, correlation function is given by

$$\Pi^{L/R}(q) = i\int d^4x e^{iq\cdot x}\langle 0|\,T\left\{\mathscr{J}_{\Lambda_b}^{L/R}(x)\,\bar{\mathscr{J}}_{\Lambda_b}^{L/R}(0)\right\}|0\rangle$$

$$\mathscr{J}_{\Lambda_b}^{L/R} = \varepsilon^{ijk}\left[u_i^T C P_{L/R} d_j\right] P_R b_k,\ \bar{\mathscr{J}}_{\Lambda_b}^{L/R} = \left(\mathscr{J}_{\Lambda_b}^{L/R}\right)^\dagger \gamma^0$$

- Inserting the complete set, gets the phenomenological side,

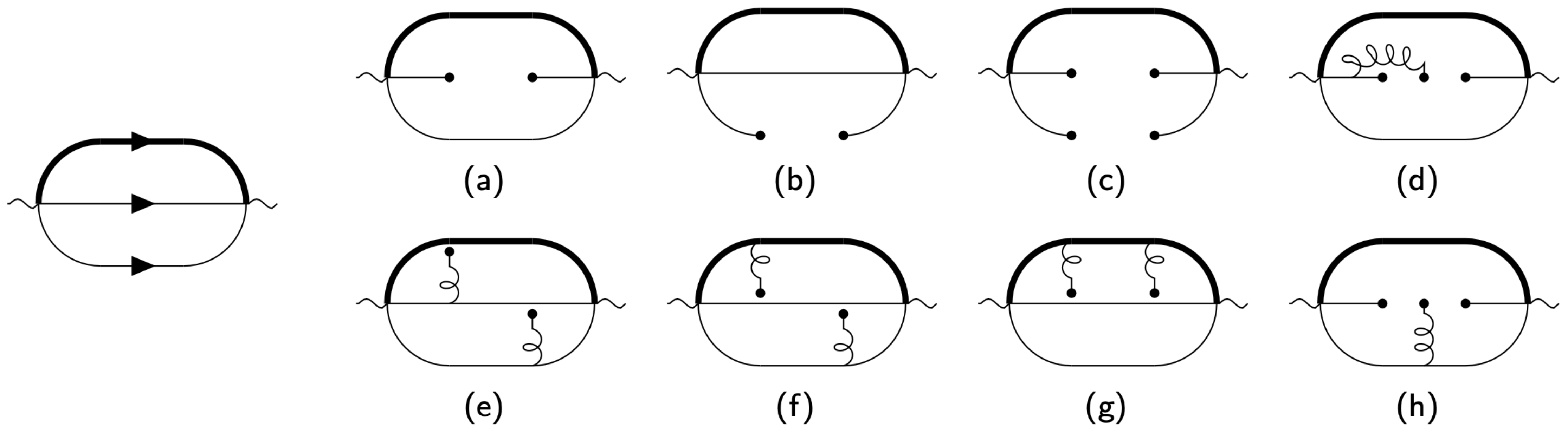
Phenomenological side: $$\frac{1}{\pi}\mathbf{Im}\Pi_1^{L/R}(s) = (\lambda_{\Lambda_b}^{L/R})^2\delta(s-m_{\Lambda_b}^2) + \rho^h(s)\theta(s-s_0^h)$$

Calculated by QCD: $$\Pi_1^{L/R(QCD)}(q^2) = \frac{(\lambda_{\Lambda_b}^{L/R})^2}{m_{\Lambda_b}^2 - q^2} + \frac{1}{\pi}\int_{s_0^h}^{\infty} ds\frac{\rho^h(s)}{s-q^2}$$

QCDSR for the hadronic matrix elements

- QCD side: leading order and the condensates with $d \leq 6$.

$$\Pi^{QCD}(q) = i\int d^4x e^{iq\cdot x} < 0|T\{j(x)j(0)\}|0> = \Pi^{pert}(q) + \Pi^{cond}(q)$$



$$\mathrm{Im}\Pi_1^{L/R(pert)}(s) = \frac{m_Q^4}{2^{10}\pi^3}\left(\frac{1}{x^2} - \frac{8}{x} + 8x - x^2 - 12ln(x)\right)$$

$$\mathrm{Im}\Pi_1^{L/R(\langle\bar{q}q\rangle)}(s) = \frac{m_q\langle\bar{q}q\rangle}{2^5\pi}(1-x^2)$$

$$\mathrm{Im}\Pi_1^{L/R(\langle GG\rangle)}(s) = \frac{\langle g_s^2G^2\rangle}{3\cdot 2^{11}\pi^3}(1+4x-5x^2)$$

$$\Pi_1^{L/R(\langle\bar{q}Gq\rangle)}(s) = -\frac{m_q\langle\bar{q}Gq\rangle}{2^6\pi^2(m_Q^2-s)}$$

$$\Pi_1^{L/R(\langle\bar{q}q\rangle^2)}(s) = \frac{m_q^2\langle\bar{q}q\rangle^2}{3\cdot 2^4}\left[\frac{3}{(m_Q^2-s)^2} + \frac{2s}{(m_Q^2-s)^3}\right]$$

QCDSR for the hadronic matrix elements

$$\Pi_1^{L/R(QCD)}(q^2) = \frac{(\lambda_{\Lambda_b}^{L/R})^2}{m_{\Lambda_b}^2 - q^2} + \frac{1}{\pi}\int_{s_0^h}^{\infty} ds \frac{\rho^h(s)}{s - q^2}$$

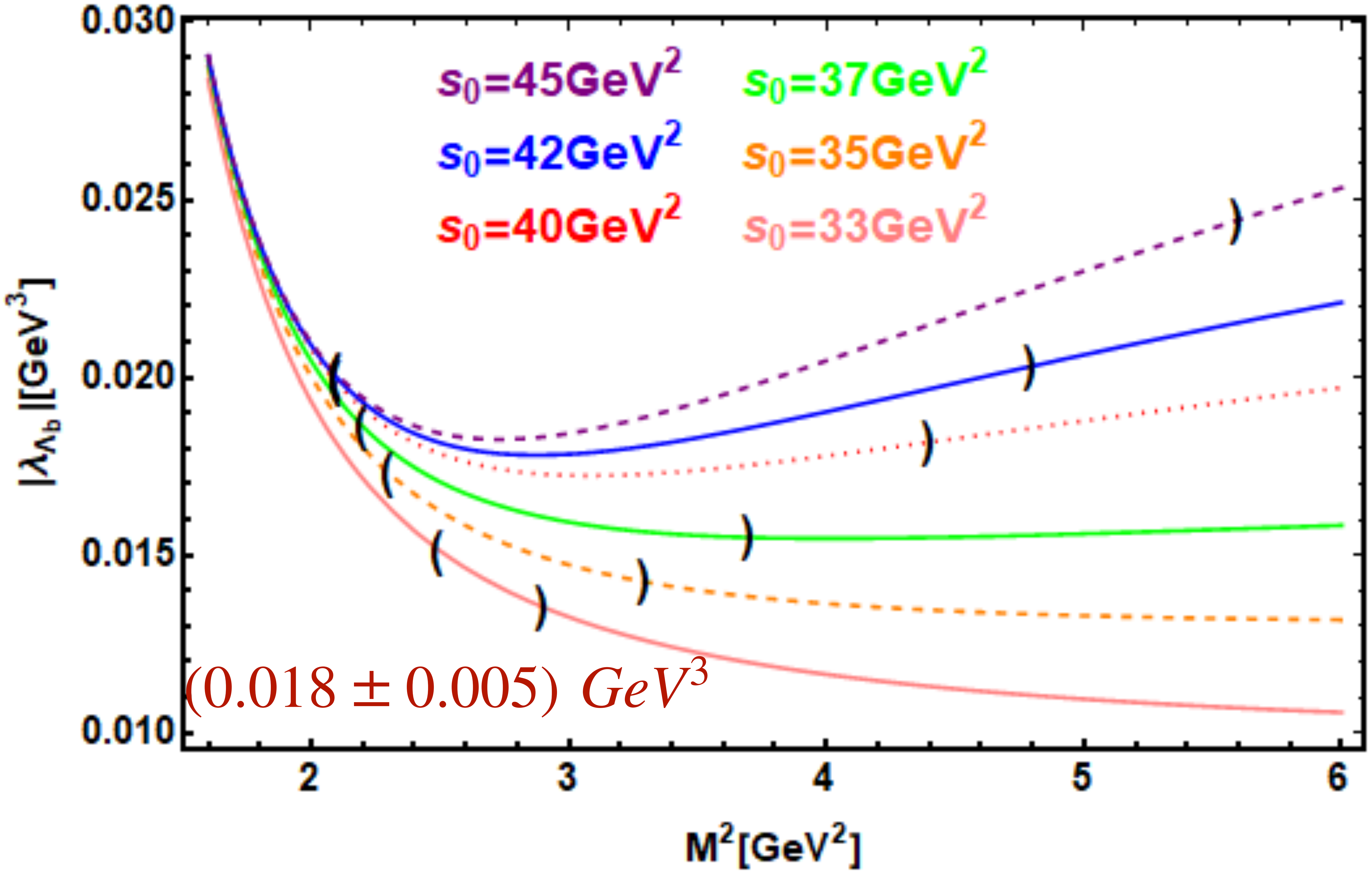
Quark-Hadron duality:

$$\frac{1}{\pi}\int_{s_0^h}^{\infty} ds \frac{\rho^h(s)}{s - q^2} = \frac{1}{\pi}\int_{s_0}^{\infty} ds \frac{\mathbf{Im}\Pi_1^{L/R(pert)}(s)}{s - q^2}$$

Borel transform: M^2

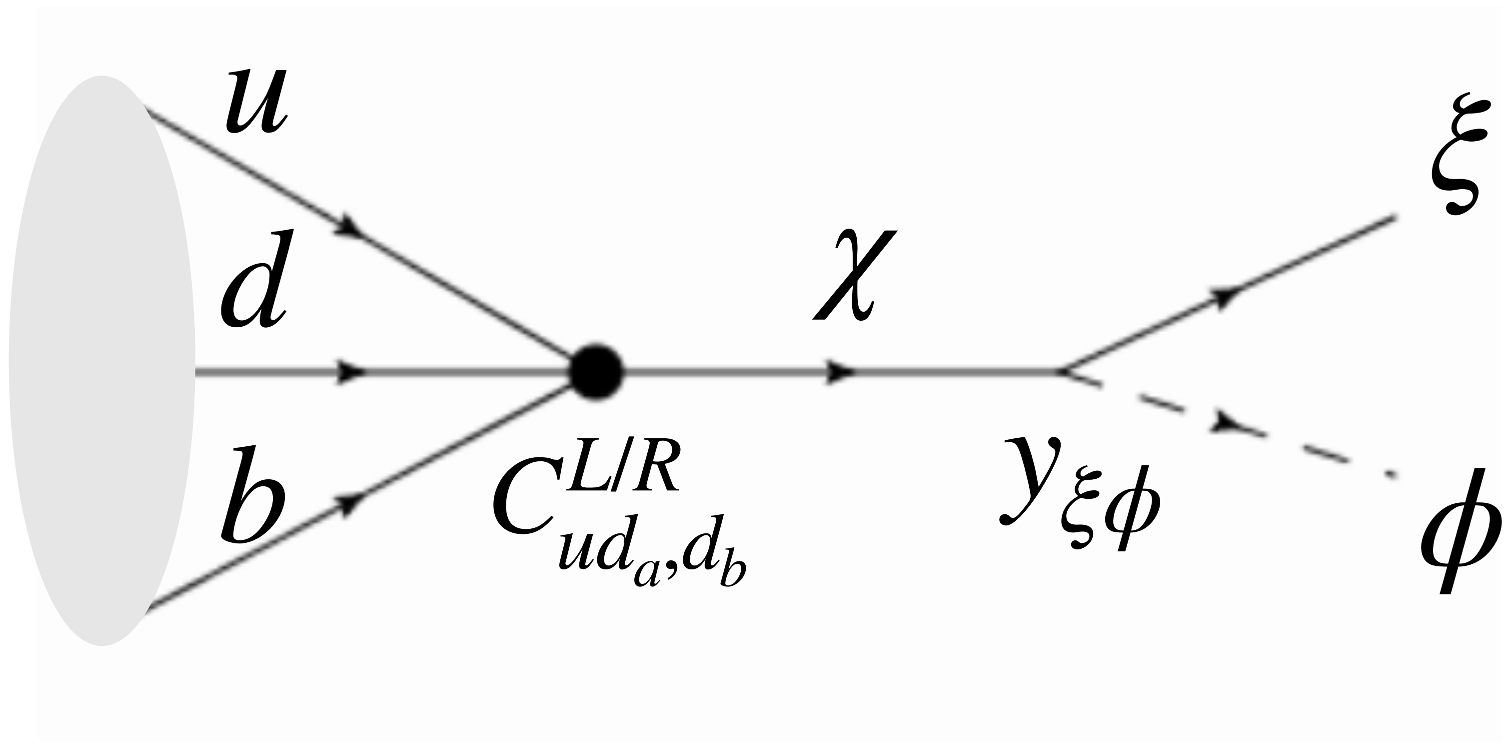
$$B_{M^2}\left[\frac{1}{(m^2 - q^2)^k}\right] = \frac{1}{(k-1)!}\frac{e^{-m^2/M^2}}{M^{2(k-1)}}$$

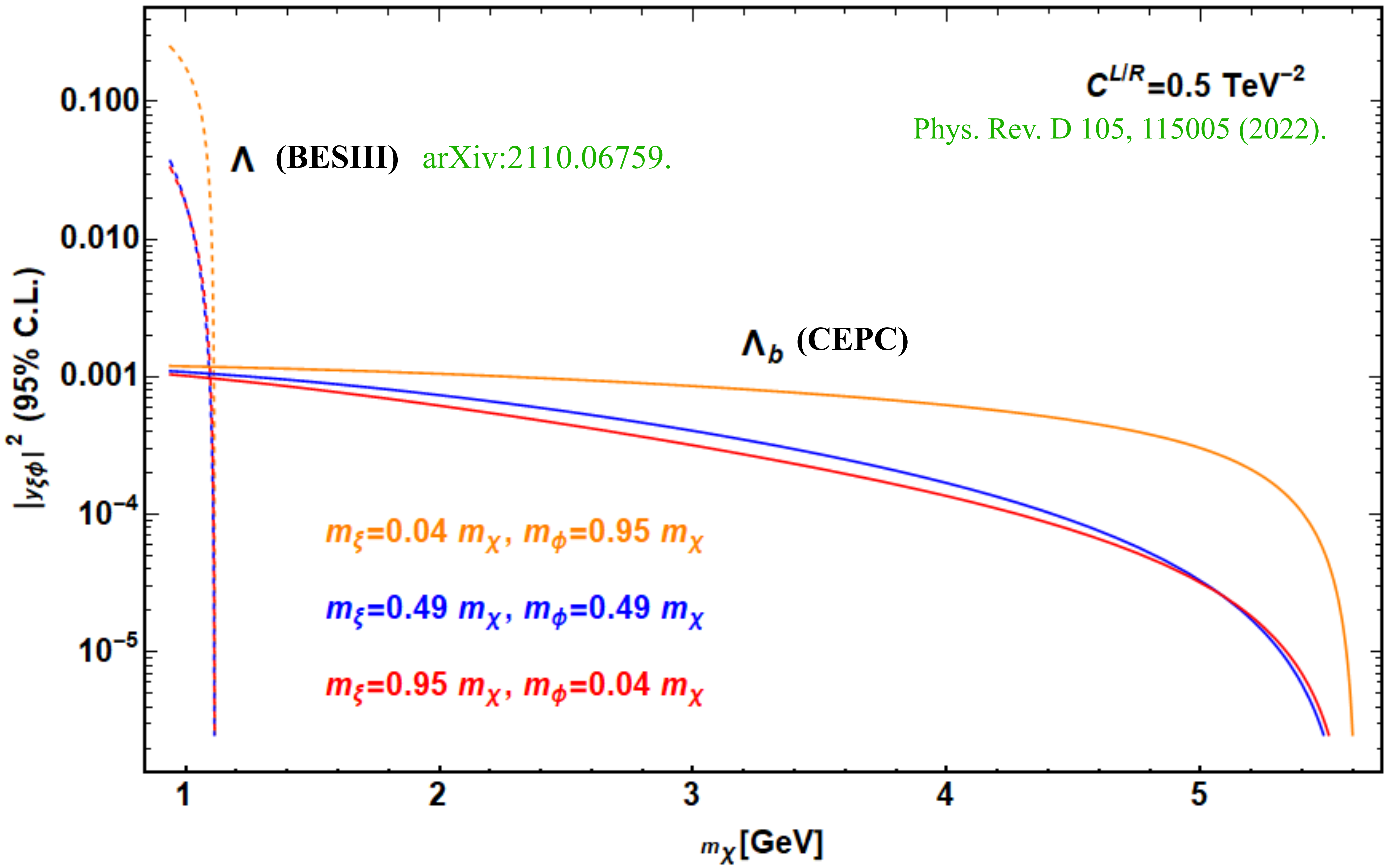
- Our calculation for the $\lambda_{\Lambda_b}^{L/R}$ is shown by



Results

- Finally, when consider the CEPC producing Tera-Z bosons, the constraints are shown as:





- In most mass regions, **at least 10^{-3} orders of magnitude** in invisible Λ_b decay.
- It is better than that in Λ invisible decay (BESIII): **has a larger mass sensitive interval** and **higher accuracy** (almost two orders of magnitude).

Summary

- Invisible baryon decay could understand **dark matter** and **matter-antimatter asymmetry**.
- CEPC is a ideal platform for the invisible baryon decay, especially for Λ_b.
- According to QCDSR, the hadronic decay matrix elements are calculated.
- The constraint what we given:
  - In most mass regions, the coupling parameter is limited to **at least 10^{-3} orders of magnitude** in invisible Λ_b decay.
  - The constraint is better than that in Λ invisible decay: **has a larger mass sensitive interval** and **higher accuracy.**

Thanks for your attention !

Back up

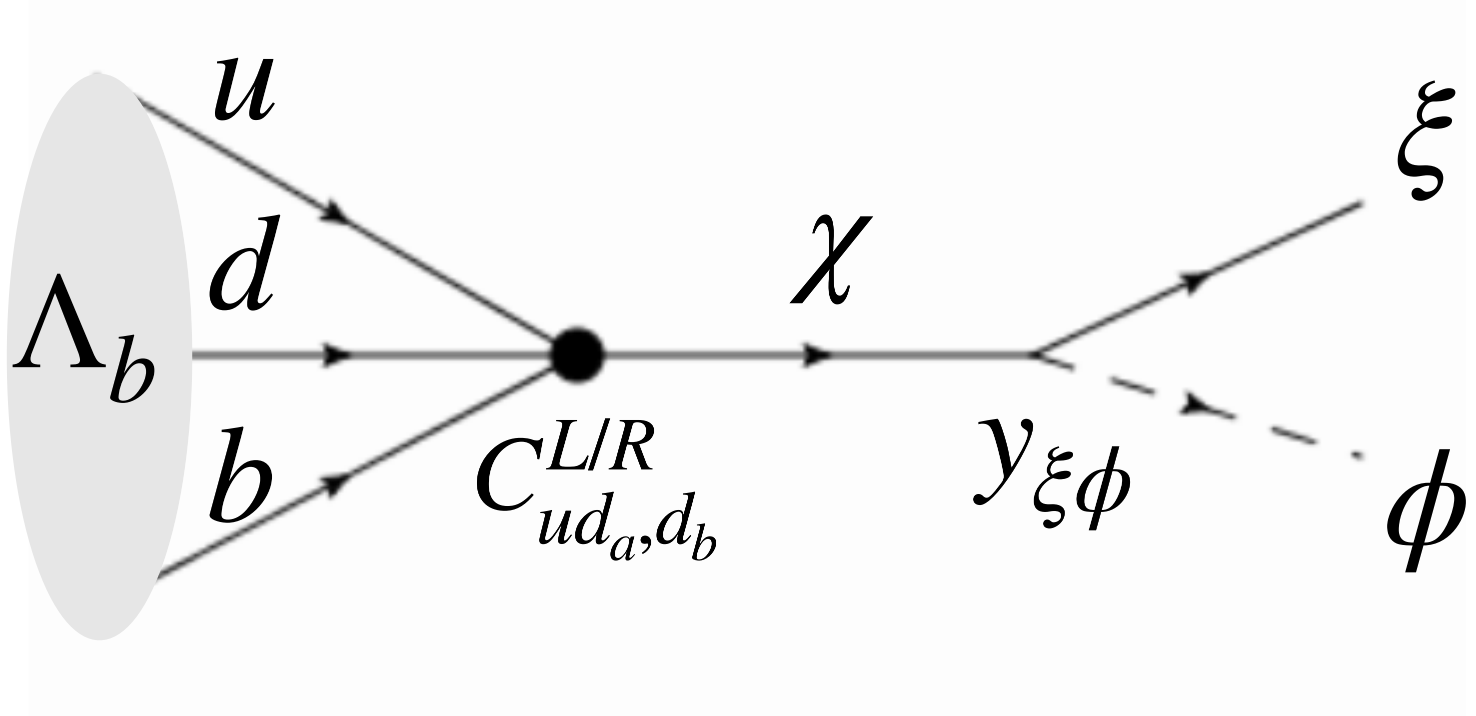
Invisible Λ_b decay

$$\Gamma_{\Lambda_b \to \xi\phi} = \frac{|\vec{k}|}{8\pi m_{\Lambda_b}} |C^{L/R}_{ud,b}|^2 |y_{\xi\phi}|^2 \, \mathbb{H}^{L/R}_{\Lambda_b}$$

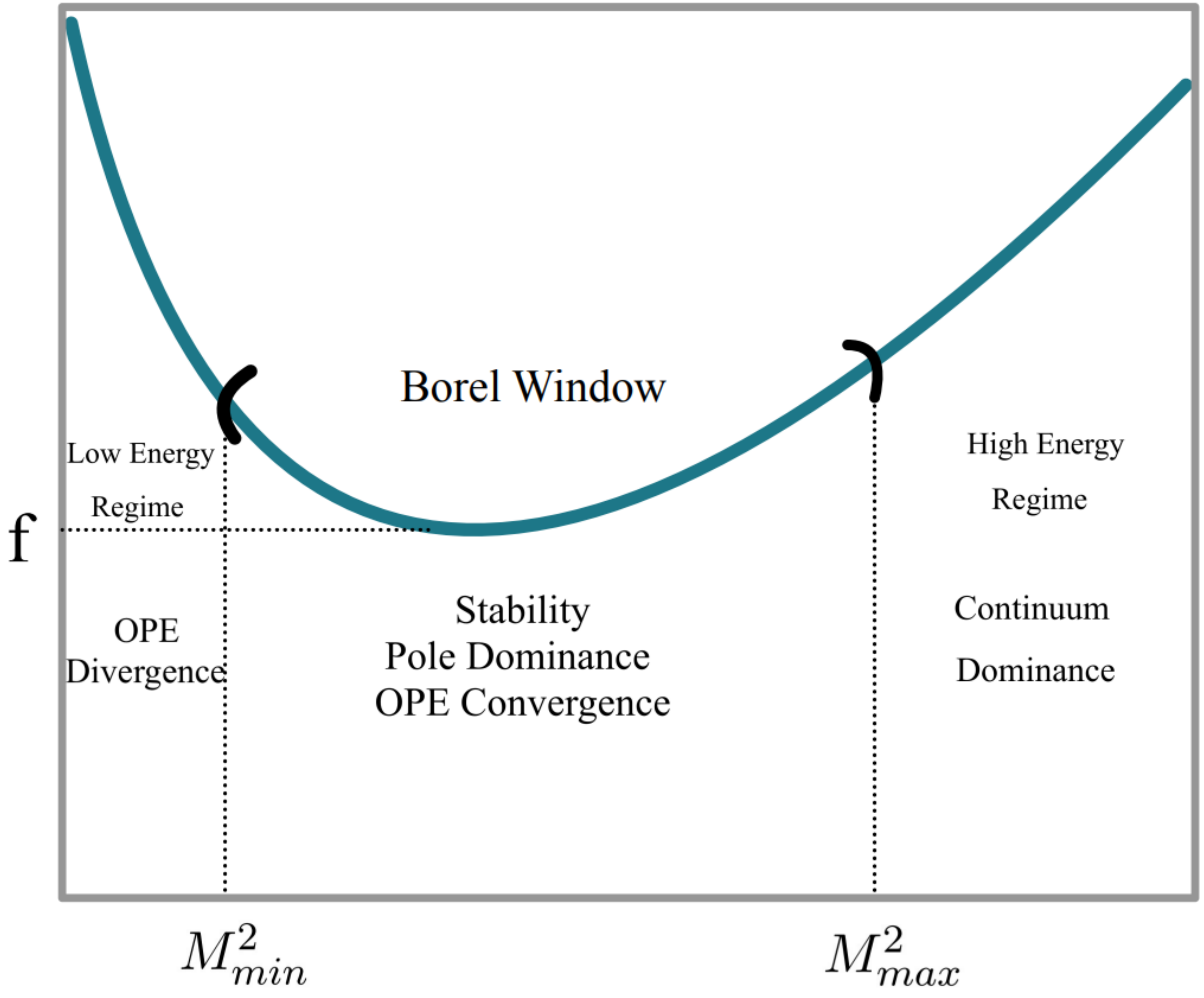
$$\mathbb{H}^{L/R}_{\Lambda_b} = |\lambda^{L/R}_{\Lambda_b}|^2 \frac{E_\xi(m^2_{\Lambda_b} + m^2_\chi) + 2m_{\Lambda_b} m_\chi m_\xi}{(m^2_{\Lambda_b} - m^2_\chi)^2}$$

$$|\vec{k}| = \sqrt{E^2_\xi - m^2_\xi}$$

$$E_\xi = \frac{m^2_{\Lambda_b} + m^2_\xi - m^2_\phi}{2m_{\Lambda_b}}$$



QCD sum rules



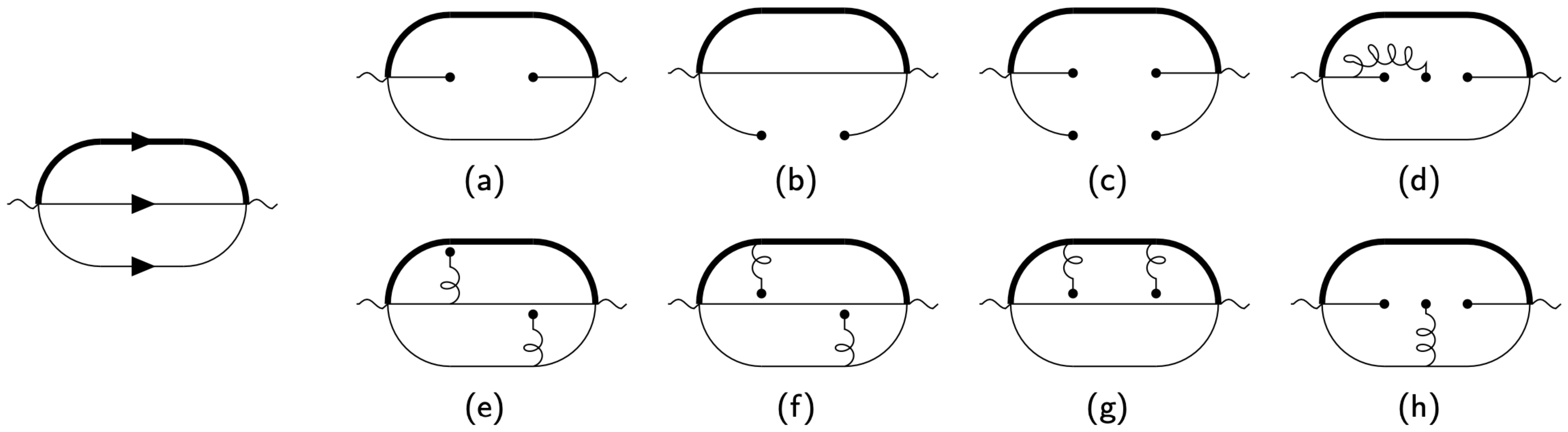
$$B_{M^2}[\frac{1}{(m^2-q^2)^k}] = \frac{1}{(k-1)!}\frac{e^{-m^2/M^2}}{M^{2(k-1)}}$$

$$\Pi^{condensates}(q^2) \sim 1/q^{2k}$$

$$\Pi^{condensates}(M^2) \sim \frac{1}{M^{2(k-1)}}$$

If M is too small,
the higher dimensional contribution
cannot be suppressed effectively,
by contrary,
quark-hardon duality suffers large uncertainty.

QCD sum rules calculation



My calculation

$$\mathrm{Im}\Pi_1^{L/R(pert)}(s) = \frac{m_Q^4}{2^{10}\pi^3}\left(\frac{1}{x^2} - \frac{8}{x} + 8x - x^2 - 12ln(x)\right)$$

$$\mathrm{Im}\Pi_1^{L/R(\langle\bar{q}q\rangle)}(s) = \frac{m_q\langle\bar{q}q\rangle}{2^5\pi}(1-x^2)$$

$$\mathrm{Im}\Pi_1^{L/R(\langle GG\rangle)}(s) = \frac{\langle g_s^2G^2\rangle}{3\cdot 2^{11}\pi^3}(1+4x-5x^2)$$

$$\Pi_1^{L/R(\langle\bar{q}Gq\rangle)}(s) = -\frac{m_q\langle\bar{q}Gq\rangle}{2^6\pi^2(m_Q^2-s)}$$

$$\Pi_1^{L/R(\langle\bar{q}q\rangle^2)}(s) = \frac{m_q^2\langle\bar{q}q\rangle^2}{3\cdot 2^4}\left[\frac{3}{(m_Q^2-s)^2} + \frac{2s}{(m_Q^2-s)^3}\right]$$

$$x = \frac{m_Q^2}{s}$$

Q is b quark for Λ_b

Constraint

- The number of b quark in CEPC (10 ab^{-1} integral luminosity): 0.9152×10^{11}

A high luminosity Z factory that produces 10^{12} Z bosons provides unique opportunities for various flavor measurements. In particular, the decay of 10^{12} Z bosons will result in approximately 10^{11} b hadrons, which is almost two orders of magnitude larger than the

tau leptons (we use the known Z branching fractions $\text{BR}(Z \to b\bar{b}) = (15.12 \pm 0.05)\%$, $\text{BR}(Z \to c\bar{c}) = (12.03 \pm 0.21)\%$, and $\text{BR}(Z \to \tau^+\tau^-) = (3.3696 \pm 0.0083)\%$ [291] and

1811.10545 [hep-ex]

- Fragmentation: $f_{b \to \Lambda_b}$

$$f_{b\to\Lambda_b} = \frac{f_{b\to\Lambda_b} \cdot Br(\Lambda_b \to J/\Psi\Lambda)}{Br(\Lambda_b \to J/\Psi\Lambda)} = \frac{(6.01 \pm 0.60 \pm 0.58 \pm 0.28) \times 10^{-5}}{(3.7 \pm 1.7 \pm 0.7) \times 10^{-4}} = 0.16 \pm 0.09$$

- The number of Λ_b is expected to be about 10 billion.

Constraint

Particle	Tera-Z	Belle II	LHCb
b hadrons			
B^+	6×10^{10}	3×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} ($5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}		1×10^{13}
Λ_b	1×10^{10}		1×10^{13}
c hadrons			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
τ^+	3×10^{10}	5×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	

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CEPC

Conceptual Design Report

Volume II - Physics & Detector

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Constraint

Particle	Belle II	LHCb (300 fb^{-1})	CEPC (4×Tera-Z)
B^0, $\bar{B}^0$	5.4×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
$B^\pm$	5.7×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	6.0×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^\pm$	-	1×10^{11}	7.2×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	-	2×10^{13}	1×10^{11}
D^0, $\bar{D}^0$			5.2×10^{11}
$D^\pm$			2.2×10^{11}
$D_s^\pm$			8.8×10^{10}
$\Lambda_c^\pm$			5.5×10^{10}
$\tau^\pm$	4.5×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)		1.2×10^{11}

2023

See (Lingfeng Li's talk)