Double-charm Tetraquark Production at CEPC

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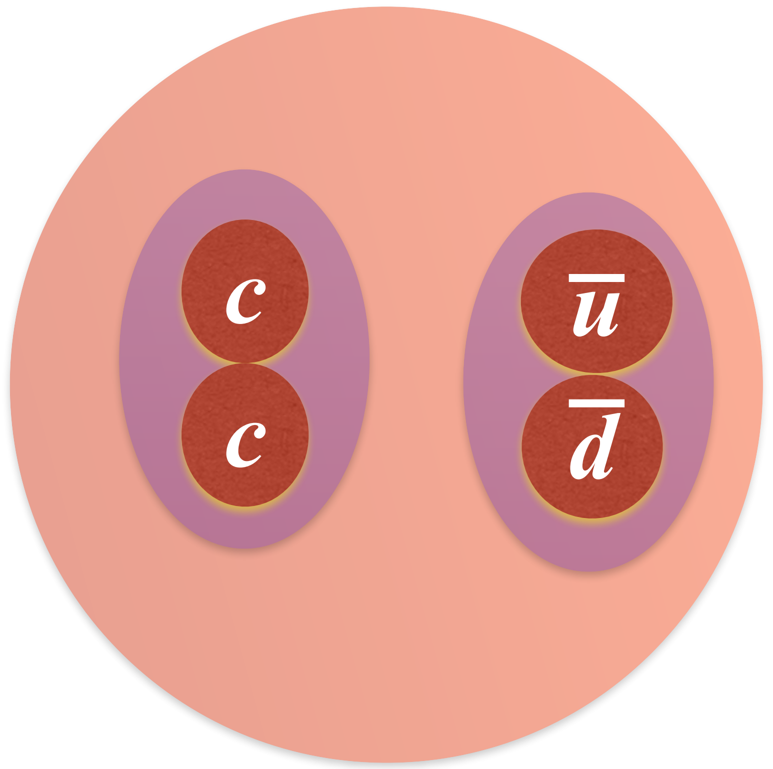


Q.Qin, F.S.Yu, arXiv:2008.08026

The 2020 International Workshop on the High Energy Circular Electron Positron Collider (Oct. 26-28, 2020)

Outline

1. Introduction

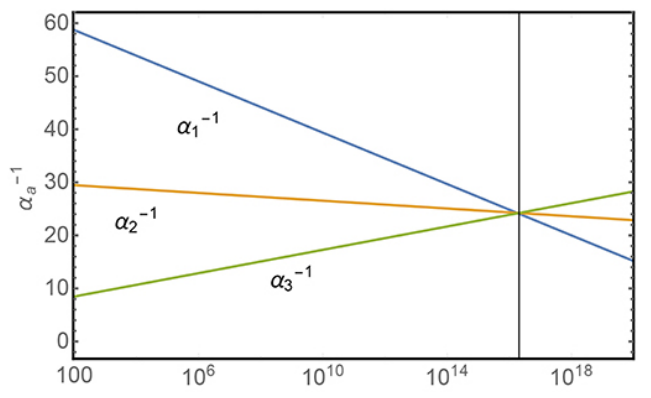
2. Production of cc-tetraquark

3. Decay channels

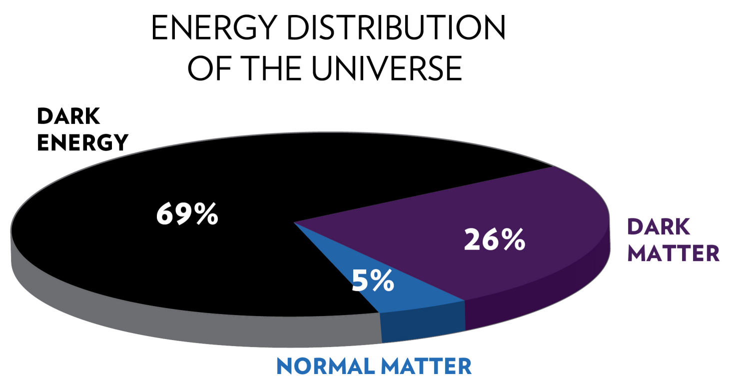
4. Summary

Key problems in particle physics

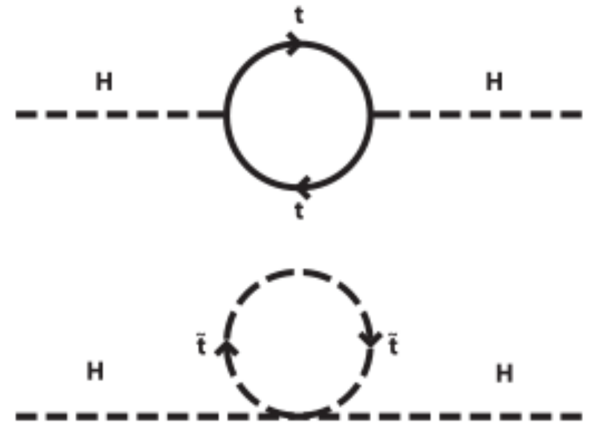
- Beyond the Standard Model: **To search for the new physics**



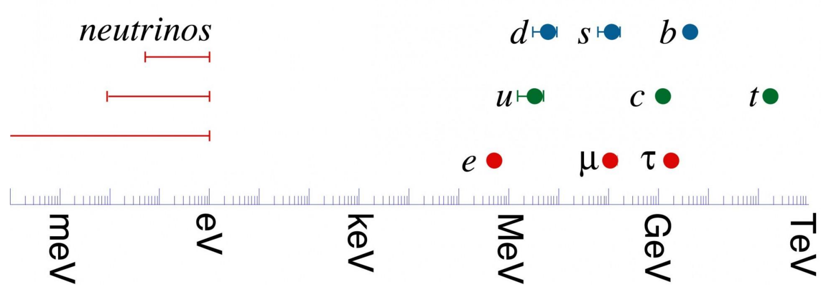
Unification of forces



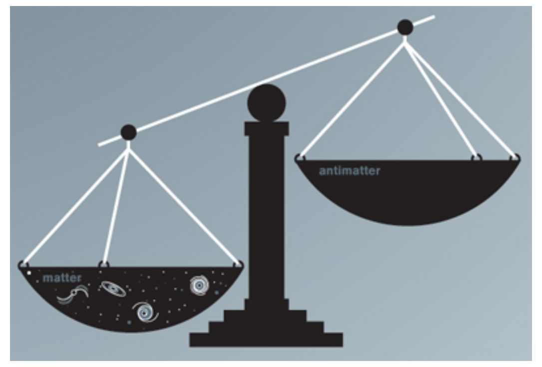
Dark Matter/Energy



Hierarchy problem

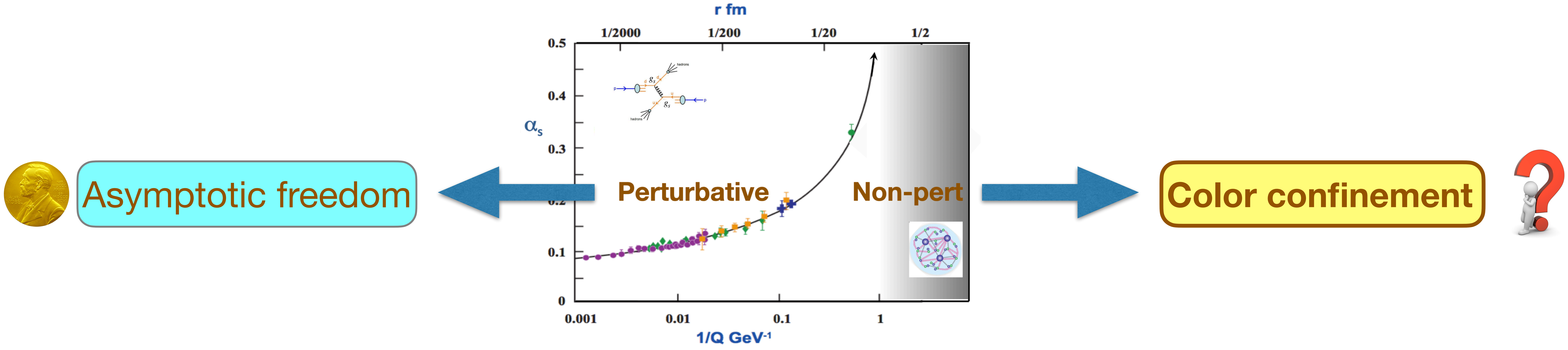


Neutrino mass origin



Baryongenesis

- Within the Standard Model: **To understand the non-perturbative strong interaction**



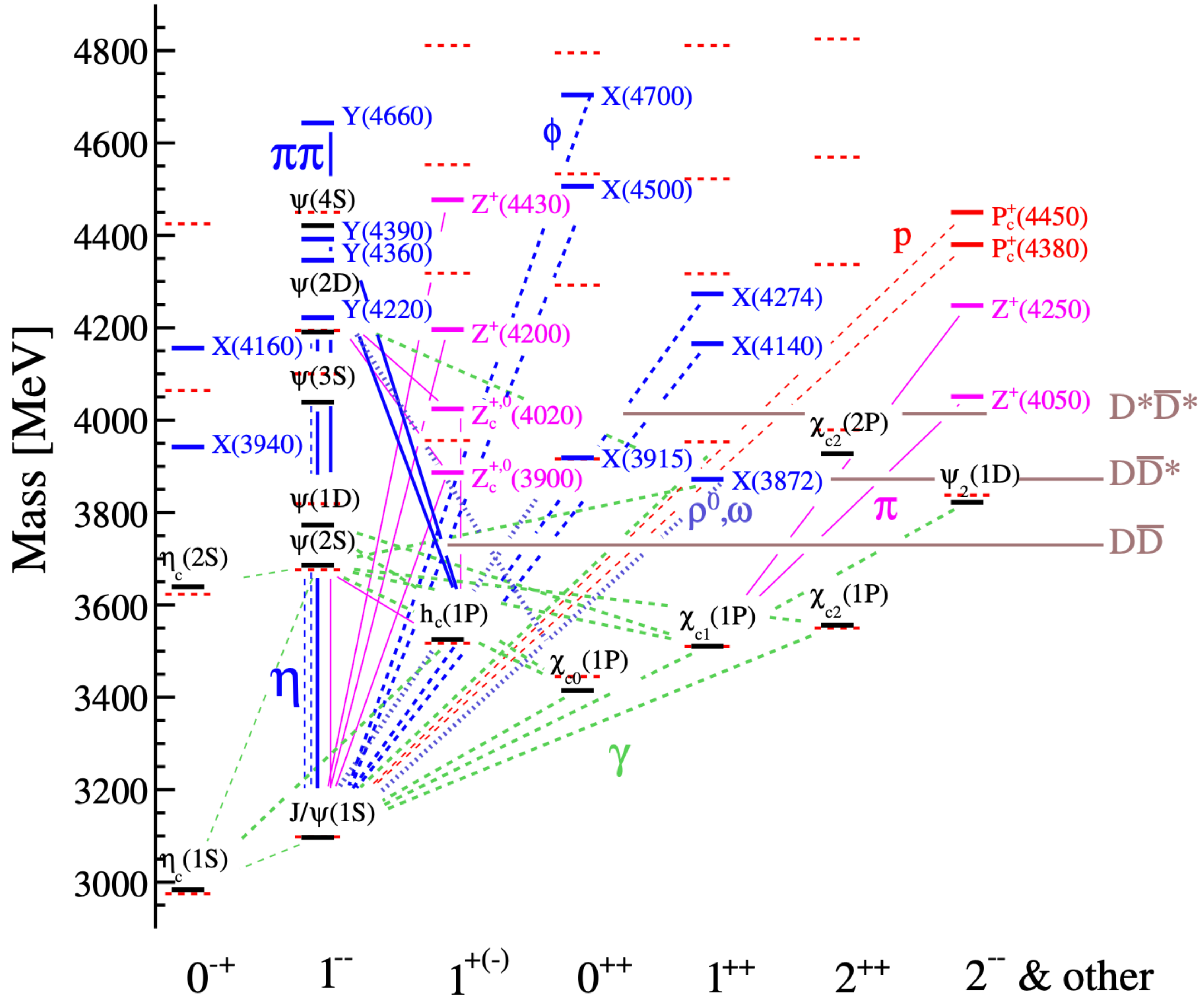
The blind men and the elephant

- The elephant is the new physics or the nature of non-perturbative strong interaction.
- We are the blind men.
- What can we do is investigating from different perspectives.

Non-perturbative strong interaction

- Hadron spectrum: exotic XYZ states…

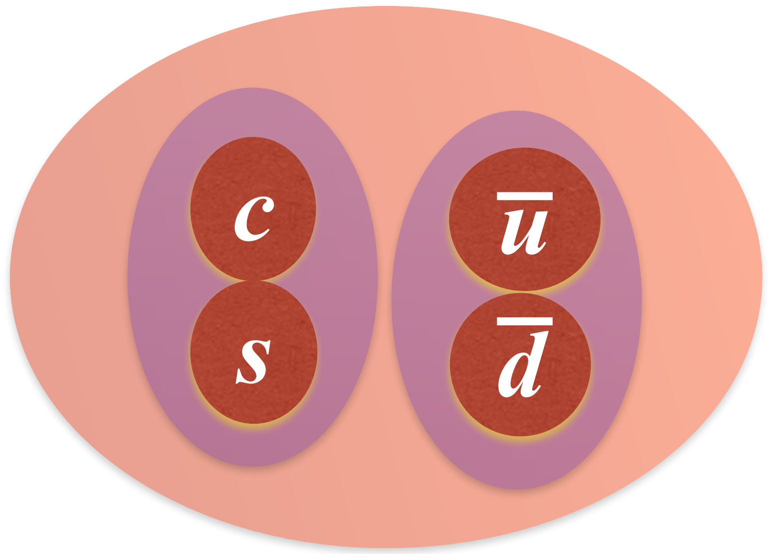
Chen, Chen, Liu, Zhu, '16; Esposito, Pilloni, Polosa, '16; Lebed, Mitchell, Swanson, '16; Guo, Hanhart, Meissner, Wang, Zhao, Zou, '17; Ali, Lange, Stone, '17; Olsen, Skwarnicki, Zieminska, '18 …



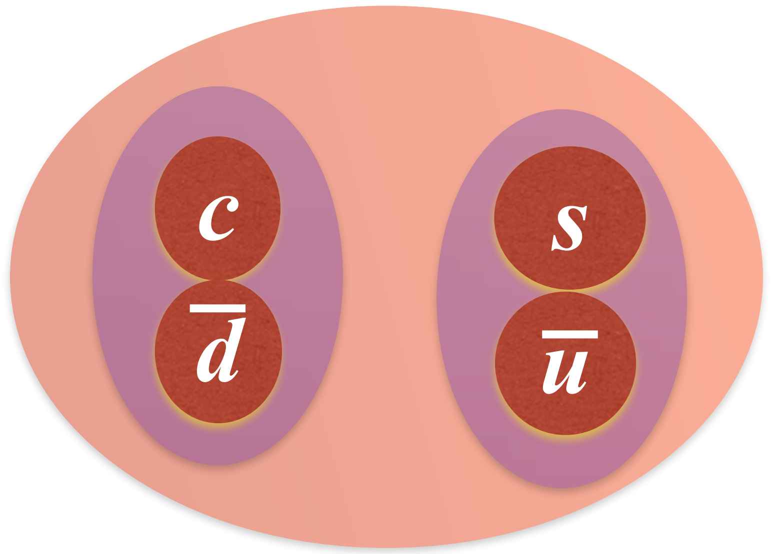
- for example, $X_{0,1}(2900)$

- **Unclear about their nature**

- Bound states & resonances:

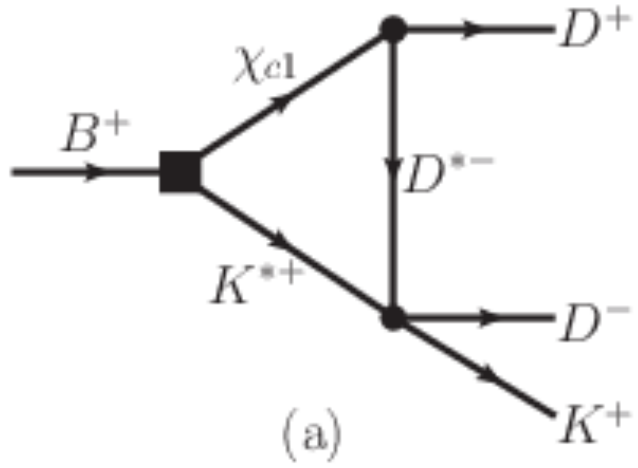


  - compact tetraquarks
  - loosely molecular



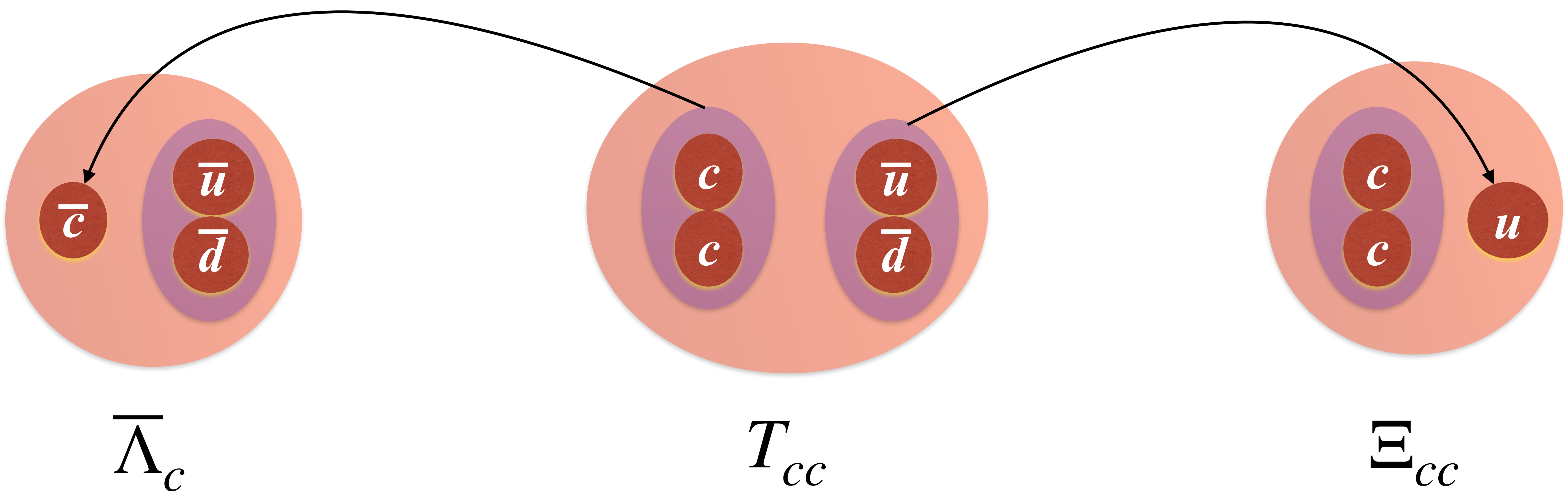
- Kinematic effects:

  - triangle singularity
  - low energy production



Double-heavy tetraquarks

- heavy diquark, light anti-diquark: easily understood, analogous to Λ_c and Ξ_{cc}



- high-energy direct production: not possible kinematic effects

- $bb\bar{u}\bar{d}$ and $bc\bar{u}\bar{d}$ have been extensively studied during the past few years   many references…

  but difficult to be observed due to their hard productions and small decay rates

  Ali, Parkhomenko, Qin, Wang, '18

- $cc\bar{u}\bar{d}$ is the lightest double-heavy tetraquark state, possible to be observed

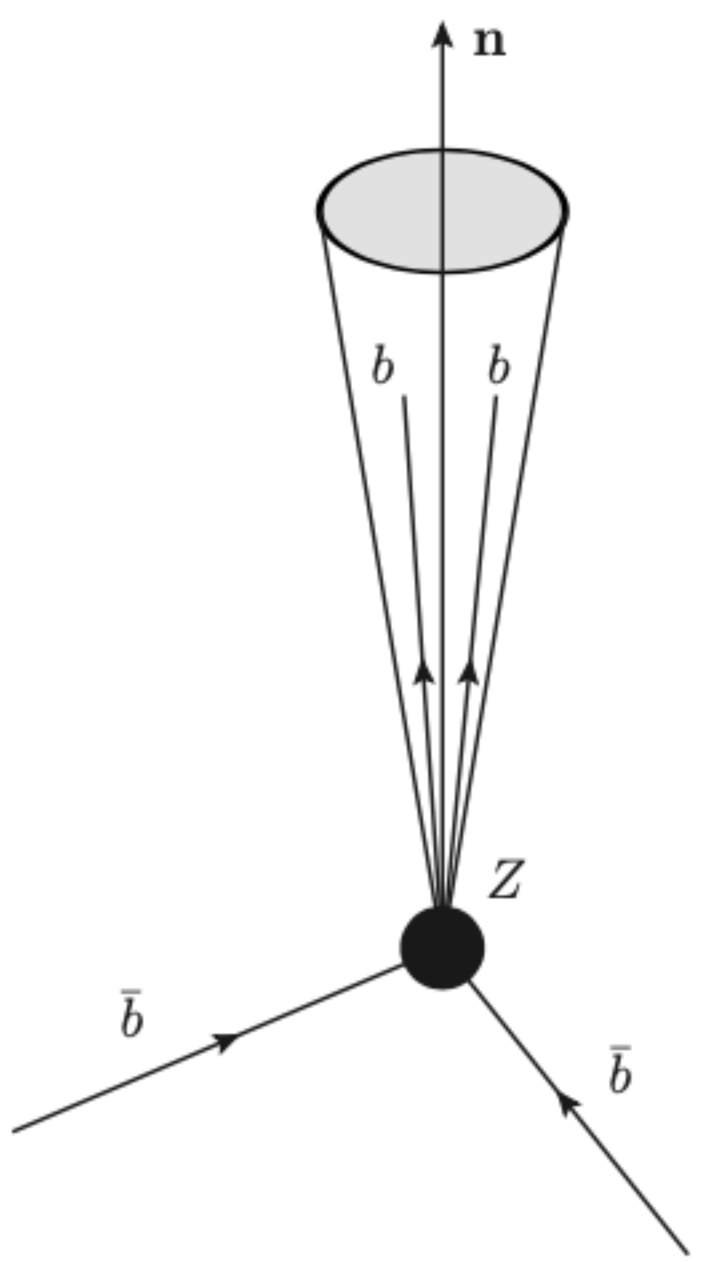
Production of $cc\bar{u}\bar{d}$ at Tera-Z factories

- About 10^{12} Z bosons will be produced at a Tera-Z factory, like CEPC, FCC-ee

- Two steps to produce cc-tetraquarks

1. cc collinear → diquark jet

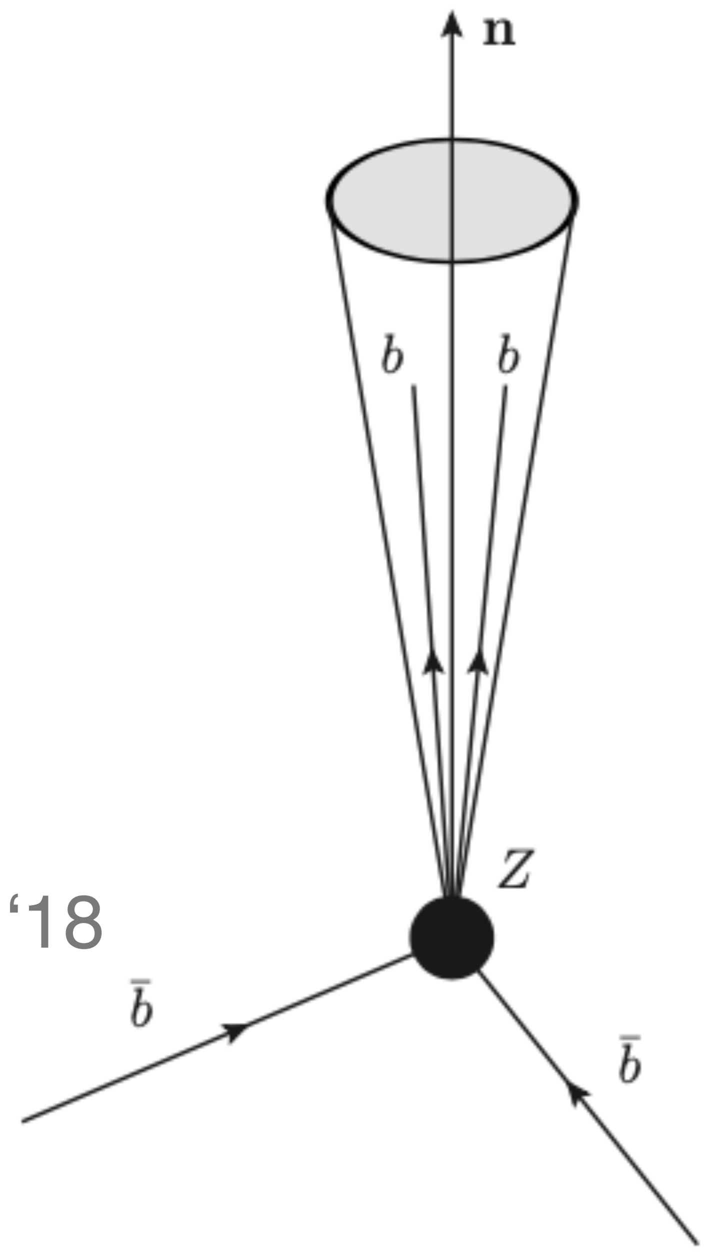
2. cc diquark → fragmentation into hadrons (T_{cc}, Ξ_{cc})



Ali, Parkhomenko, Qin, Wang, ‘18

cc-diquark jet

topology of $Z \to (cc)_{\rm jet} + \bar{c} + \bar{c}$



- cc quarks are produced collinearly
- cc diquark jet requires a jet definition, such as the invariant mass
- $M_{cc-\rm jet} < 2m_c + \Delta M$
- The jet-resolution parameter ΔM is determined by B_c meson production, $b\bar{c} \to B_c$

$$\Delta M = \begin{cases} (2.0^{+0.5}_{-0.4})\ \mathrm{GeV, \ for\ LHCb,} \\ (2.7^{+1.3}_{-0.5})\ \mathrm{GeV, \ for\ Z\ factories.} \end{cases}$$

Ali, Parkhomenko, Qin, Wang, '18

- The results of production rate

$$\sigma(p + p \to H_{cc} + X) = (2.2^{+2.0}_{-0.6}) \times 10^5\ \mathrm{pb}$$ for LHC

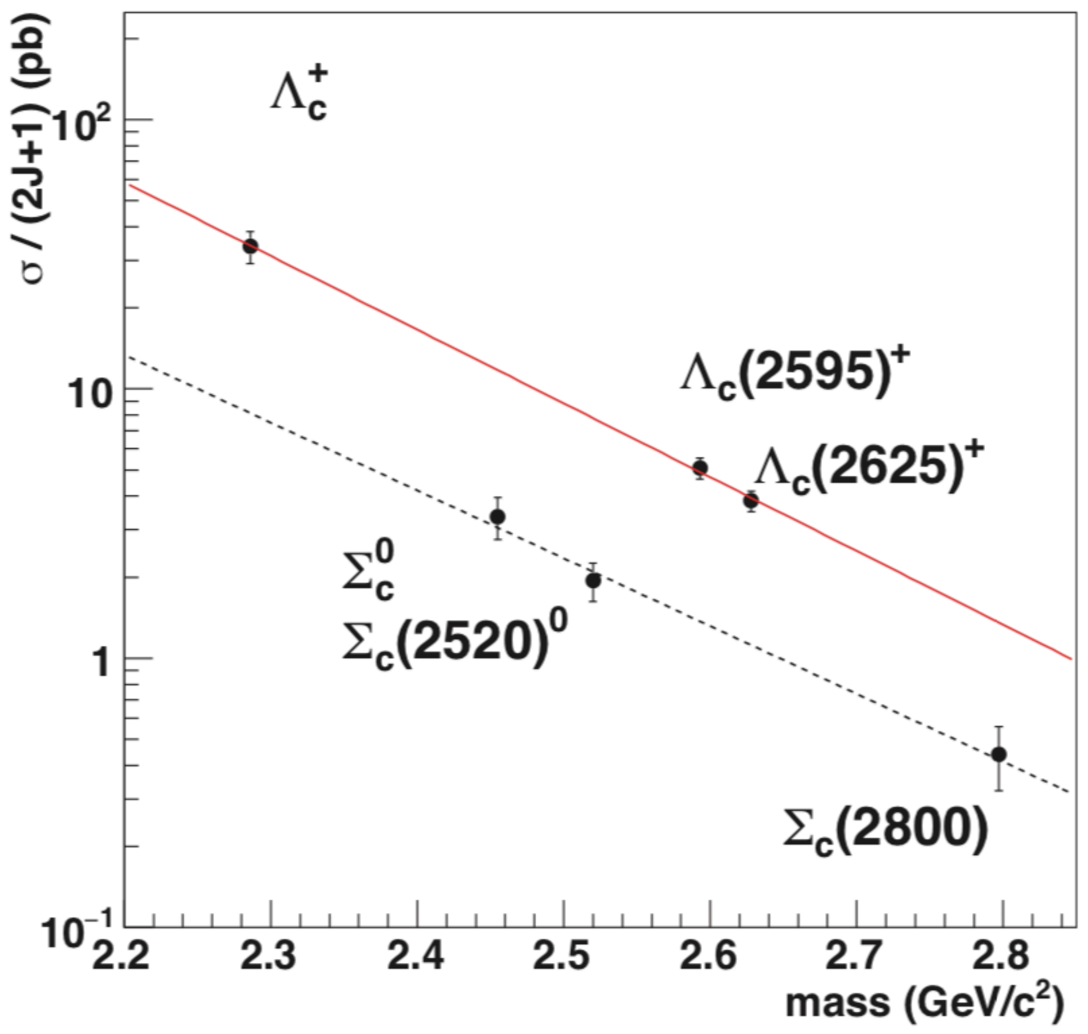
$$\mathcal{B}(Z \to H_{cc} + X) = (3.0^{+2.7}_{-0.9}) \times 10^{-5}$$ for Tera-Z factory

Qin, FSY, '20

Fragmentation

- Different from ordinary heavy mesons and baryons with excited states decaying into the ground states,
- The excited cc-tetraquarks would directly decay into DD mesons, but not the ground states
- Primarily production *v.s.* final production
- The ground-state fragmentation fraction is

$$\frac{f_{T_{cc}}}{f_{\Xi_{cc}}} \approx \boxed{\frac{f_{ud}(\text{primary})}{f_{ud}(\text{final})}} \times \boxed{\frac{f_{ud}(\text{final})}{f_u}}$$



$$\frac{f_{\Lambda_c}}{f_{\Lambda_c+\Sigma_c+\Lambda_c^*}} = 0.48 \pm 0.08$$

Belle, arXiv:1706.06791

$$\frac{f_{\Lambda_b^0}}{f_u+f_d}(p_T) = (1 \pm 0.061)\left[(0.0793 \pm 0.0141) + e^{(-1.022\pm0.047)+(-0.107\pm0.002)\times p_T}\right]$$

LHCb, 1902.06794

Results of production

- Convoluting the cc-diquark jet and the fragmentation

$$\mathcal{B}(Z \to T^{\{cc\}}_{[\bar{u}\bar{d}]} + X) = (1.1^{+1.0}_{-0.4}) \times 10^{-6} \longrightarrow$$ $10^6\ T^{\{cc\}}_{[\bar{u}\bar{d}]}$ for Tera-Z factory

$$\sigma(pp \to T^{\{cc\}}_{[\bar{u}\bar{d}]} + X) = (1.5^{+0.7}_{-0.5}) \times 10^4\ \mathrm{pb} \longrightarrow$$ $10^8\ T^{\{cc\}}_{[\bar{u}\bar{d}]}$ for LHCb $9\ \mathrm{fb}^{-1}$

Possible to be observed !!

- Cross checking the results by double-charm baryon productions at LHC 13TeV

$$\sigma(\Xi^{++}_{cc}) = \sigma(\Xi^{+}_{cc}) \approx 47\ \mathrm{nb} \longleftrightarrow \sigma(\Xi^{++}_{cc}) = \sigma(\Xi^{+}_{cc}) \approx 62\ \mathrm{nb}$$

Qin, FSY, ‘20 | Chang, Qiao, Wang, Wu, ‘06

Decay channels

- Decay channels are important in the experimental searches.
- For example, the prediction of themes favorable decay channels of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ in [FSY, Jiang, Li, Lu, Wang, Zhao, '17] is helpful for the discovery of Ξ_{cc}^{++} by LHCb in 2017.
- The decay processes of cc-tetraquark depend on its mass, which is predicted differently in literature.

Reference	[24]	[25]	[27]	[26]	[28]	[29]	[17]	[19]	[21]	[22]
$T^{\{cc\}}_{\bar{n}\bar{n}'}$	-79	-96	-150	+53	+166	+60	-	AT	+102	+88
$T^{\{cc\}}_{\bar{n}\bar{s}}$	-9	-56	+94	+128	+255	+166	+143	AT	+179	+181
Reference	[30]	[20]	[31]	[32]	[33]	[34]	[18]	[23]		
$T^{\{cc\}}_{\bar{n}\bar{n}'}$	BT	-215	-149	-182	+7	+98	+91	AT		

compared to the DD^* threshold

Decay channels

- The decay processes can be classified into three cases, according to the mass

mass	most favored channel
1. If above DD^* threshold, strong decay:	$T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^0 D^{*+}$
2. If between DD^* and $DD\gamma$ threshold, EM decay:	$T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^0 D^+ \gamma$
3. If below $DD\gamma$ threshold, weak decay:	$T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^+ K^- \pi^+$

Summary

- Double-charm tetraquark states are helpful to understand the non-perturbative strong interaction
- The direct production at high energy collisions would simplify its nature
- It is found 10^6 of cc-tetrquark produced at Tera-Z factory, and 10^8 produced at LHCb
- The most favored decay channels are $T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^0 D^{*+}$ $T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^0 D^{+}\gamma$ $T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^+ K^- \pi^+$

  respectively for different mass cases

Thank you!