1^{-+} Hybrid States in Light Meson Sector

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Fu-Yuan Zhang, Qi Huang, and Li-Ming Wang, Phys. Rev. D 113, 014002 (2026).

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第五届强子与重味物理理论与实验联合研讨

Outline：

- 研究背景;
- 1^{-+}混杂态的质量;
- 混杂态的衰变性质研究;
- 总结.

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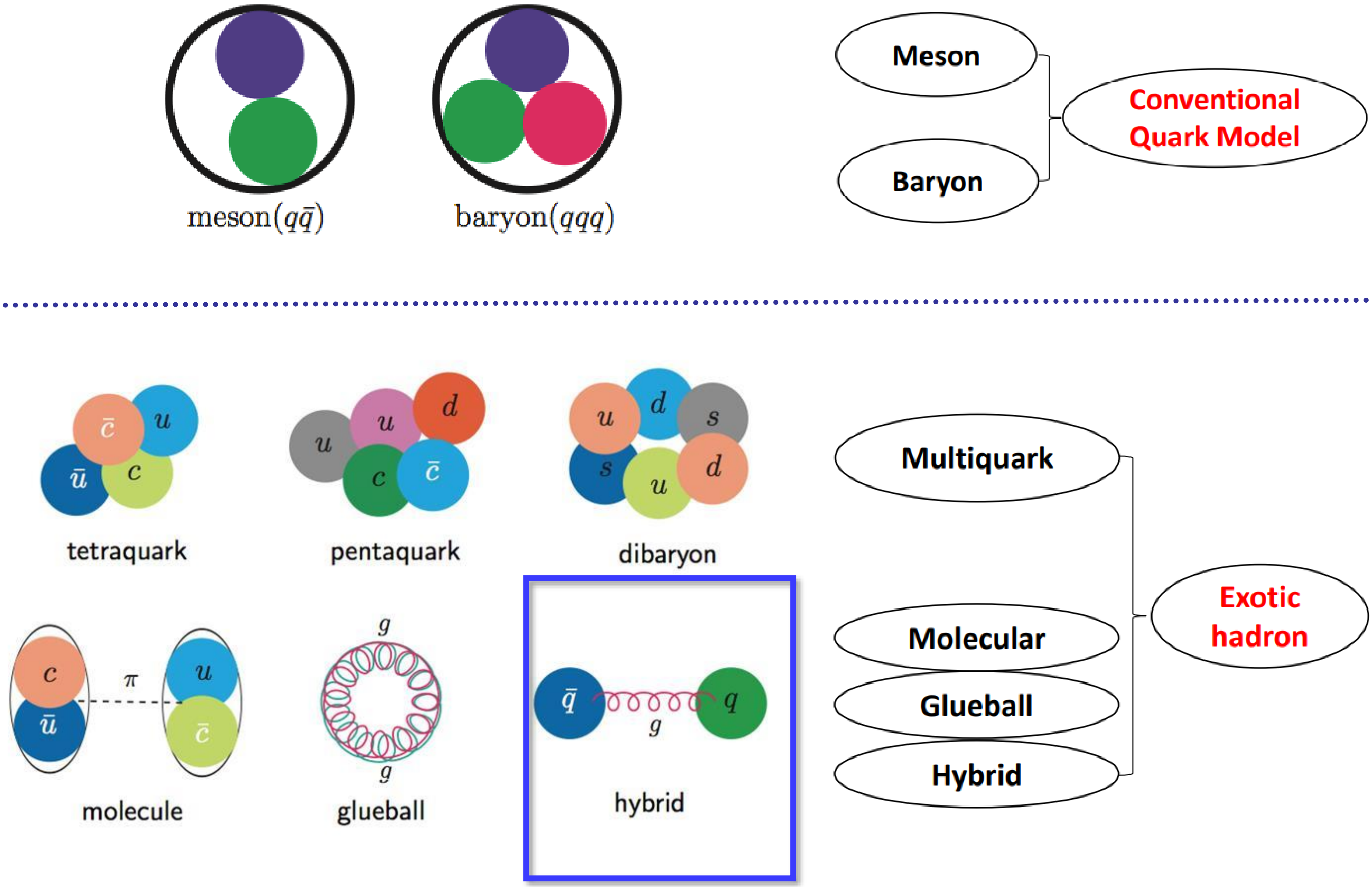
meson($q\bar{q}$)
baryon(qqq)
Meson
Baryon
Conventional Quark Model
tetraquark
pentaquark
dibaryon
molecule
glueball
hybrid
Multiquark
Molecular
Glueball
Hybrid
Exotic hadron

Using a sample of $(10.09 \pm 0.04) \times 10^9$ J/ψ events collected with the BESIII detector operating at the BEPCII storage ring, a partial wave analysis of the decay $J/\psi \to \gamma\eta\eta'$ is performed. The first observation of an isoscalar state with exotic quantum numbers $J^{PC} = 1^{-+}$, denoted as $\eta_1(1855)$, is reported in the process $J/\psi \to \gamma\eta_1(1855)$ with $\eta_1(1855) \to \eta\eta'$. Its mass and width are measured to be $(1855 \pm 9^{+6}_{-1})$ MeV$/c^2$ and $(188 \pm 18^{+3}_{-8})$ MeV, respectively, where the first uncertainties are statistical and the second are systematic, and its statistical significance is estimated to be larger than 19σ.

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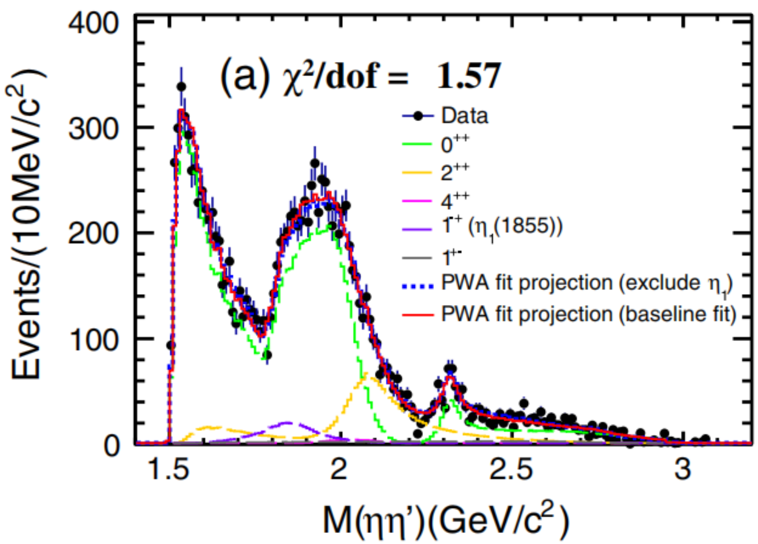
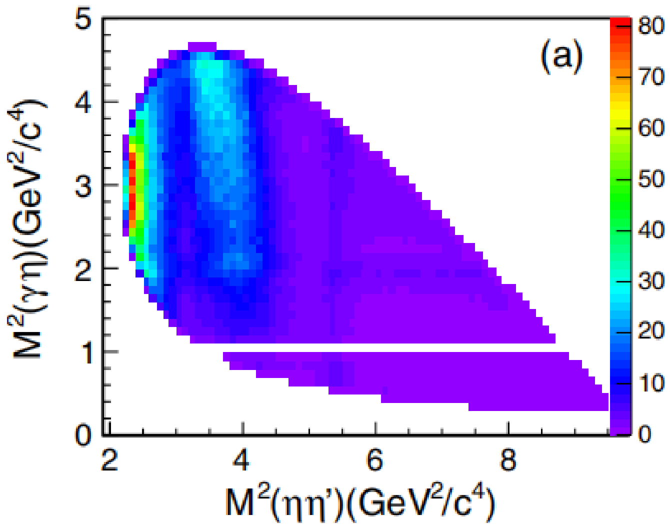




Phys. Rev. Lett.129 (19) (2022) 192002.

Phys. Rev. D 106 (7) (2022) 072012.

$$\eta_1(1855) \; : \; M = 1855 \pm 9^{+6}_{-1} \text{ MeV}/c^2 \,, \quad \Gamma = 188 \pm 18^{+3}_{-8} \text{ MeV} \,.$$

实验上发现的1^{-+}粒子

- $\pi_1(1600)$： $\rho\pi$，$\eta'\pi$，$f_1(1285)\pi$，$b_1(1235)\pi$

Phys. Rev. Lett 81 (1998) 5760-5763.
Phys. Lett. B 563 (2003) 140-149.
Phys. Rev. D 84 (2011) 112009.
Nucl. Phys. A 663 (2000) 596-599.
Phys. Rev. Lett 104 (2010) 241803
Phys. Rev. D 68 (2003) 074505.

$\pi_1(1600)$: $M = 1640^{+40}_{-17}$ MeV
$\Gamma = 340^{+50}_{-60}$ MeV
$I^G J^{PC} = 1^- 1^{-+}$

- $\pi_1(2015)$： $f_1(1285)\pi$，$b_1(1235)\pi$

Phys. Rev. Lett 94 (2005) 032002.
Phys. Lett. B 595 (2004) 109-117.

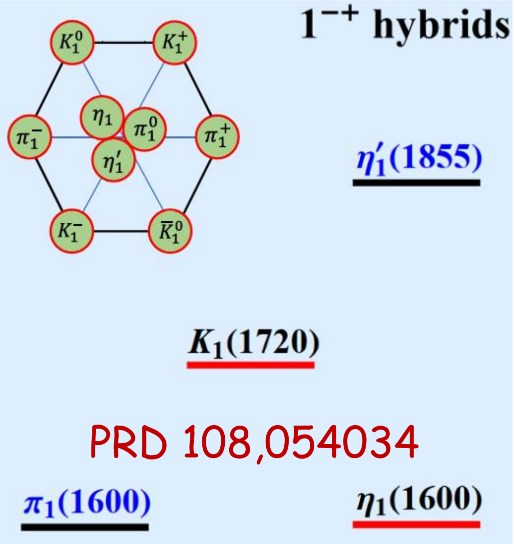
$\pi_1(2015)$: $M = 2014 \pm 20 \pm 16$ MeV
$\Gamma = 230 \pm 32 \pm 73$ MeV
$I^G J^{PC} = 1^- 1^{-+}$

- $\eta_1(1855)$： $J/\psi \to \gamma\eta\eta'$

Phys. Rev. Lett 129 (2022) 192002.
Phys. Rev. D 106 (2022) 072012.

$\eta_1(1855)$: $M = 1855 \pm 9^{+6}_{-1}$ MeV
$\Gamma = 340 \pm 18^{+3}_{-8}$ MeV
$I^G J^{PC} = 0^+ 1^{-+}$

理论研究的分歧



1. $\pi_1(1600)$的争议
   - Hybrid：
     - ➢ lattice QCD PRD 103, 054502
     - ➢ Constituent Gluon Model AHEP 2020, 9105240 PRD 108,054034
     - ➢ Effective Lagrange method PLB 834, 137478
   - Tetraquark/Molecular state PRD 78, 054017 PLB 675 319-325
2. $\pi_1(2015)$的争议
   - 格点 QCD 将其列为第一径向激发混杂态候选。PRD 82,034508
   - 实验数据稀缺，衰变性质几乎未知，无法有效检验其内部结构。
3. $\eta_1(1855)$的多重解释
   - Tetraquark (QCD sum rule) PLB 675 319-325 PRD 106,074003
   - Molecular state ($KK_1(1400)$) NPA 1030, 122571 SCPMA 65, 261011
   - Hybrid (Constituent Gluon Model、flux tube model、QCD sum rule、Effective Lagrange method)
     PRD 108,054034 CPC 46, 051001 CPL39, 051201 PLB 834 137478

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对于混杂态，系统的哈密顿量可以写为：

$$H = \sqrt{p_q^2 + m_q^2} + \sqrt{p_{\bar{q}}^2 + m_{\bar{q}}^2} + V_{q\bar{q}g}(r)$$

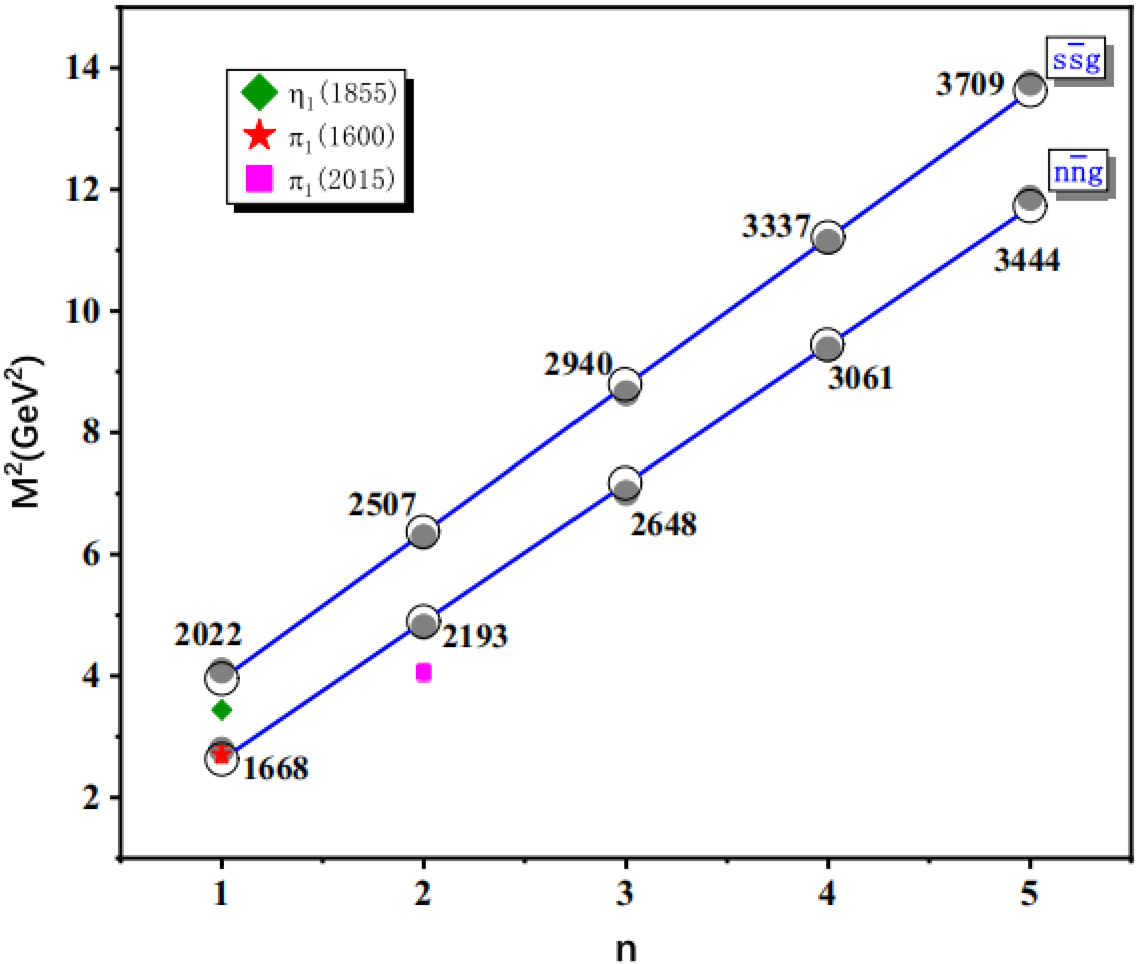
对于最低的$J^{PC} = 1^{-+}$，混杂态(胶子处于TE模式，$J_g^{PC} = 1^{+-}$)有效势：

$$V_{q\bar{q}g}(r) = \frac{A_1}{r} + A_2 r^2 + V_0 + \xi_2 \sqrt{\frac{b}{\xi_1}},$$

类库伦项　禁闭项　常数项　QCD对胶子场的拟合参数

TABLE I. Masses of hybrid states with the radial quantum number n. All masses are in units of GeV.

n	1	2	3	4	5
$q\bar{q}g$	1.668	2.193	2.648	3.061	3.444
$q\bar{s}g$	1.851	2.355	2.799	3.204	3.582
$s\bar{s}g$	2.022	2.507	2.94	3.337	3.709



$$M^2_{s\bar{s}g} = M^2_{s0} + (n-1)\mu_1,$$

$$M^2_{q\bar{q}g} = M^2_{q0} + (n-1)\mu_2,$$

- 对 $s\bar{s}g$： $\mu = 2.41$ GeV²
- 对 $n\bar{n}g$： $\mu = 2.27$ GeV²

这与普通介子的Regge行为一致，混杂态纳入统一的强子谱学框架中。

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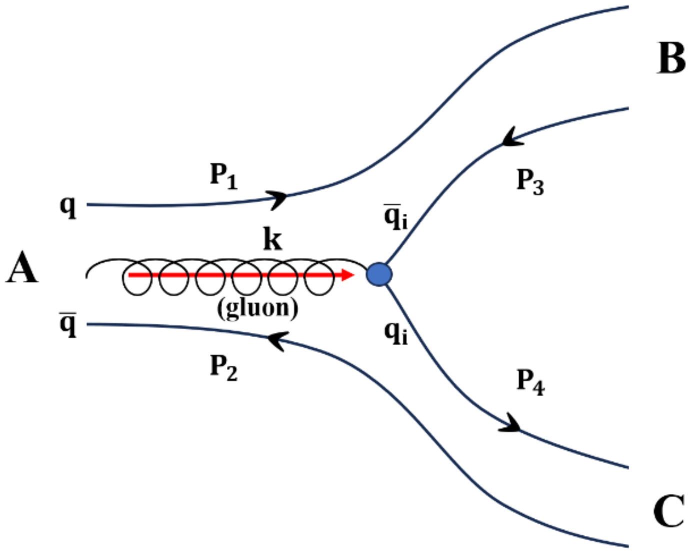
组分胶子模型



(TM) $l_g = 0, \quad l_{q\bar{q}} = 1, \quad S_{q\bar{q}} = 0$

(TE) $l_g = 1, \quad l_{q\bar{q}} = 0, \quad S_{q\bar{q}} = 1$

$J_g^{PC} = 1^{+-}$ **transverse electric (TE)**

TABLE II: Lowest $J^{PC} = 1^{-+}$ $q\bar{q}g$ hybrid mesons and their quantum numbers

P	C	$L_{q\bar{q}}$	L_g	J_g	$S_{q\bar{q}}$	L	J	
−	+	0	1	0	1	0	1	
−	+	0	1	1	1	1	1	胶子激发态
−	+	0	1	2	1	2	1	
−	+	1	0	1	0	1	1	夸克激发态

混杂态波函数

自旋、颜色波函数　　正反夸克空间波函数　　胶子空间波函数

$$
\begin{aligned}
|A(L_g, L_{q\bar{q}}, S_{q\bar{q}}, J_A, M_{J_A})\rangle = {} & \sum \int \frac{d^3\mathbf{p}_1 d^3\mathbf{p}_2 d^3\mathbf{k}}{(2\pi)^9} (2\pi)^3 \chi^{\mu}_{ss'} \frac{\lambda^{c_g}_{c_q, c_{\bar{q}}}}{4} \psi_{L_{q\bar{q}} M_{L_{q\bar{q}}}} \left(\frac{m_{\bar{q}} \mathbf{p}_1 - m_q \mathbf{p}_2}{m_q + m_{\bar{q}}} \right) \psi_{L_g M_{L_g}} \\
& \times \left(\frac{\mathbf{k}(m_{\bar{q}} + m_{\bar{q}}) - (\mathbf{p}_1 + \mathbf{p}_2)\omega_g}{(m_q + m_{\bar{q}})\omega_g} \right) \langle L_g, M_{L_g}; 1, \lambda_g | J_g, M_{J_g} \rangle \langle L_{q\bar{q}}, M_{L_{q\bar{q}}}; J_g, M_{J_g} | L, m' \rangle \\
& \times \langle L, m'; S_{q\bar{q}}, M_{S_{q\bar{q}}} | J_A, M_{J_A} \rangle \delta^3(\mathbf{p}_1 + \mathbf{p}_2 + \mathbf{k} - \mathbf{P}_A) b^{\dagger}_{\mathbf{p}_1 s_1 c_1} d^{\dagger}_{\mathbf{p}_2 s_2 c_2} a^{c_g \dagger}_{\mathbf{k}\lambda_g} |0\rangle .
\end{aligned}
$$

真空中产生正反夸克和胶子

衰变振幅：

flavor overlap

spin overlap

color overlap

spatial overlap

$$
\begin{aligned}
M_{\ell J}(A \to BC) = {} & \sum_{\substack{M_{L_g}, \lambda_g, M_{L_{q\bar{q}}}, M_{S_{q\bar{q}}}, M_{L_B}, M_{S_B}, \\ M_{L_C}, M_{S_C}, M_{J_B}, M_{J_C}, M_J, M_\ell}} \mathcal{CFS}(M_{S_{q\bar{q}}}, \lambda_g, M_{S_B}, M_{S_C}) I(M_{L_{q\bar{q}}}, M_{L_g}, M_{L_B}, M_{L_C}, M_\ell) \langle L_g, M_{L_g}; 1, \lambda_g | J_g, M_{L_g} + \lambda_g \rangle \\
& \times \langle L_{q\bar{q}}, M_{L_{q\bar{q}}}; J_g, M_{L_g} + \lambda_g | L, M_{L_g} + \lambda_g + M_{L_{q\bar{q}}} \rangle \langle L, M_{L_g} + \lambda_g + M_{L_{q\bar{q}}}; S_{q\bar{q}}, M_{S_{q\bar{q}}} | J_A, M_{J_A} \rangle \\
& \times \langle L_B, M_{L_B}; S_B, M_{S_B} | J_B, M_{J_B} \rangle \langle L_C, M_{L_C}; S_C, M_{S_C} | J_C, M_{J_C} \rangle \langle J_B, M_{J_B}; J_C, M_{J_C} | J, M_J \rangle \\
& \times \langle \ell, M_\ell; J, M_J | J_A, M_{J_A} \rangle . \qquad (15)
\end{aligned}
$$

衰变宽度：

$$
\Gamma_{\ell J}(A \to BC) = \frac{\alpha_s}{\pi} \frac{P_B E_B E_C}{M_A} |M_{\ell J}(A \to BC)|^2
$$

$\pi_1(1600)$衰变宽度：

$b_1(1235)\pi$	$f_1(1285)\pi$	Total	Exp. [43]
56.6	8.4	65	370^{+50}_{-60}

$\Gamma(\rho^0\pi^-)/\Gamma_{total}$ **Γ_2/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ALEKSEEV	10	COMP	$190\ \pi^- Pb \to \pi^-\pi^-\pi^+ Pb'$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	NOZAR	09	CLAS	$\gamma p \to 2\pi^+\pi^- n$
not seen	[1] DZIERBA	06	B852	$18\ \pi^- p$

Hybrid→ $S+S$ 抑制

$\Gamma(b_1(1235)\pi)/\Gamma_{total}$ **Γ_4/Γ**

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	35280	[1] BAKER	03	SPEC	$\bar{p}p \to \omega\pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	145k	LU	05	B852	$18\ \pi^- p \to \omega\pi^-\pi^0 p$

[1] $B((b_1\pi)_{D-wave})/B((b_1\pi)_{S\text{-wave}})=0.3 \pm 0.1$.

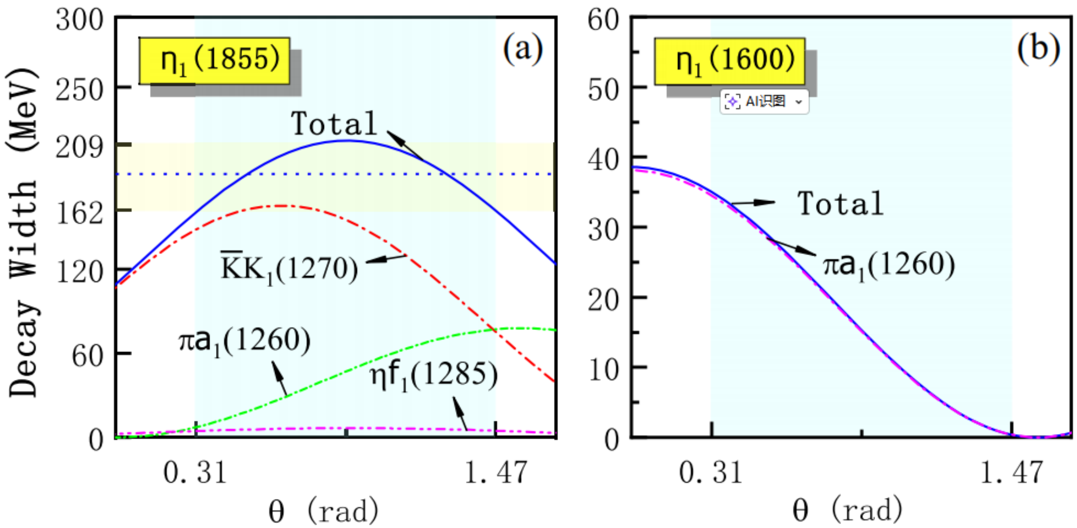
$\pi_1(2015)$衰变宽度：

在$b_1\pi$衰变中，D波贡献几乎为0

$b_1(1235)\pi$	$f_1(1285)\pi$	$h_1(1170)\rho$	$b_1(1235)\omega$	$K_1(1270)\bar{K}$
1.75	0.23	≈0	≈0	≈0
$K_1(1400)\bar{K}$	$a_1(1260)\rho$	$\eta(1295)\pi$	$\eta(1475)\pi$	$\eta_2(1645)\pi$
≈0	≈0	0.4	0.12	0.3
$\rho(1450)\pi$	$\rho(1700)\pi$	$\pi(1300)\eta$		
0.31	≈0	0.1		
			Total	Exp. [43]
			3.21	$230 \pm 32^{+73}_{-73}$

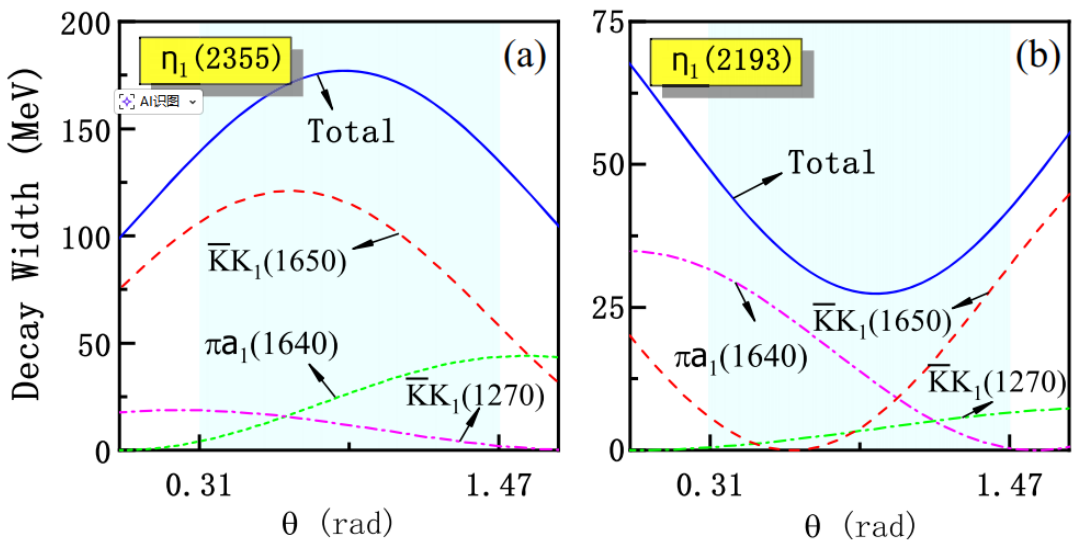
$$M = 2193\ \text{MeV}$$

$$\Gamma = 31.47\ \text{MeV}$$



$$\begin{pmatrix} |\eta_1^H\rangle \\ |\eta_1^L\rangle \end{pmatrix} = \begin{pmatrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{pmatrix} \begin{pmatrix} |n\bar{n}g\rangle \\ |s\bar{s}g\rangle \end{pmatrix}$$

- $\eta_1(1855)$：**得到混合角范围** $17.1° \le \theta \le 84.2°$，需更精确的实验分支比来约束。
- $\eta_1(1855)$：主要衰变道 $KK_1(1270)$和$\pi a_1(1260)$
- $\eta_1(2355)$: 主要衰变道 $KK_1(1650)$、$KK_1(1270)$和 $\pi a_1(1640)$，宽度约150MeV
- $\eta_1(2193)$: 主要衰变道 $\pi a_1(1640)$、$KK_1(1650)$和 $KK_1(1270)$，宽度约40–60 MeV。



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- $\eta_1(1855)$是混**杂态**，混合而成，混合角范围较宽，需更精确的实验分支比来约束;
- $\pi_1(1600)$和$\pi_1(2015)$不支持纯混杂态解释，其衰变宽度与实验严重不符，可能为四夸克态或分子态。
- 预言了$\eta_1(2193)$和$\eta_1(2355)$两个激发态的质量与主要衰变道，为未来实验提供明确目标。;
- 混杂态（至少对同位旋标量）也遵循 Regge 轨迹。

Thank you for your attention