Frontiers in Nuclear and Hadronic Physics

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Outline

I. Importance of strong interaction physics

II. Brief history of strong interaction

III. General view on frontiers of nuclear & hadron physics

IV. Frontiers in hadron spectroscopy & hadron structure

V. Prospects

I. Importance of strong interaction physics

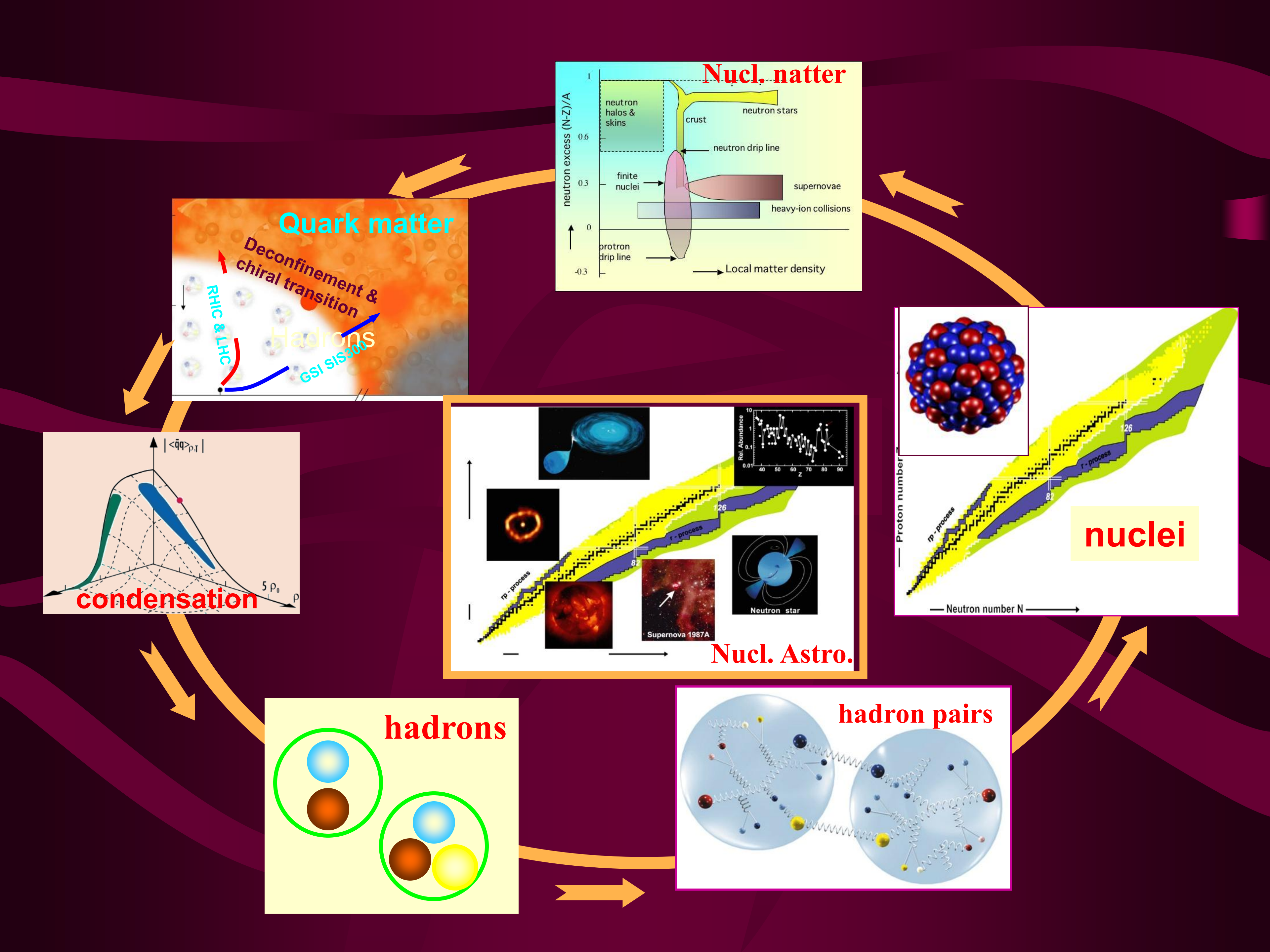
1) Hadron & Nuclei – 2 basic levels of matter structures

- Gravity Universe, heavenly bodies $> 10^{-2}$ m
- EM interaction molecular, atomic structure $> 10^{-10}$ m
- Strong interaction nuclear, hadron structure $10^{-16} \sim 10^{-14}$ m
- Weak interaction quark, lepton transitions $< 10^{-21}$ m

Hadrons - the smallest objects with internal structure observed

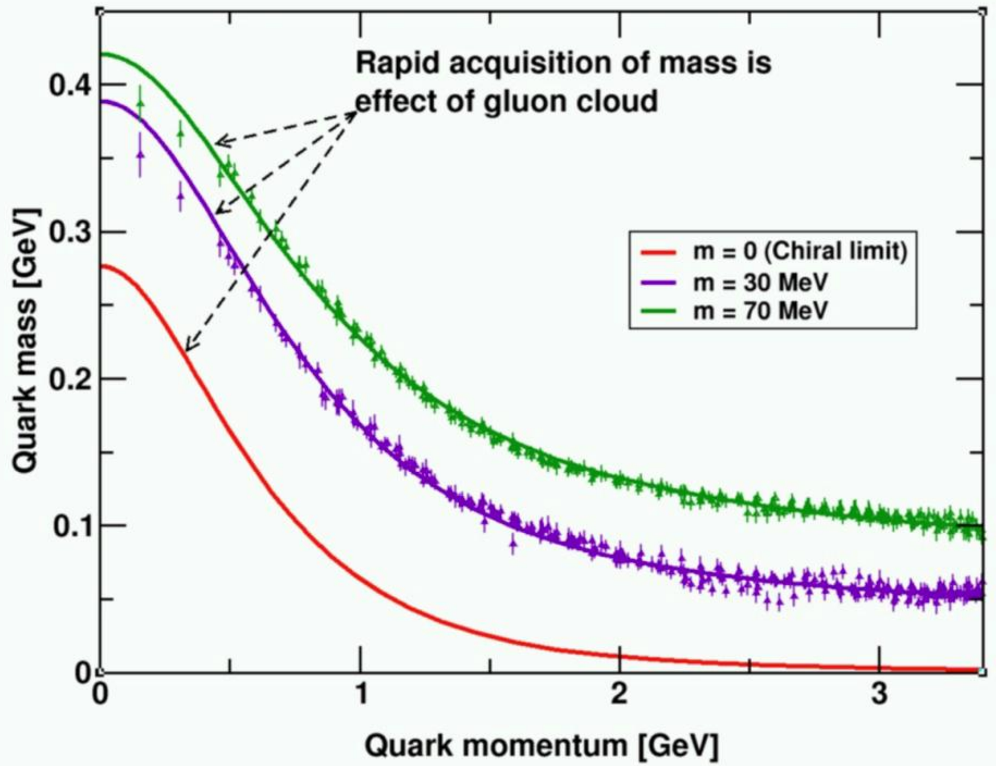
2) strong interaction physics also plays important role for elementary particle physics & universe evolution

hadrons, nuclei ~ 99% visible matter


Nucl. natter
neutron excess (N-Z)/A
1
0.6
0.3
0
-0.3
neutron halos & skins
crust
neutron stars
neutron drip line
finite nuclei
supernovae
heavy-ion collisions
protron drip line
Local matter density
Quark matter
Deconfinement & chiral transition
RHIC & LHC
Hadrons
GSI SIS300
condensation
5 ρ₀
ρ
Rel. Abundance
Neutron star
Supernova 1987A
rp - process
r - process
82
126
Nucl. Astro.
Proton number Z
Neutron number N
nuclei
hadrons
hadron pairs

3）origin of mass: ~1% from Higgs mechanism ~99% from strong interaction

C.D. Roberts, Prog. Part. Nucl. Phys. 61 (2008) 50-65



II. Brief history of strong interaction

1687年 牛顿万有引力定律 $F = \frac{G \cdot m_1 \cdot m_2}{r^2}$ → 天体结构

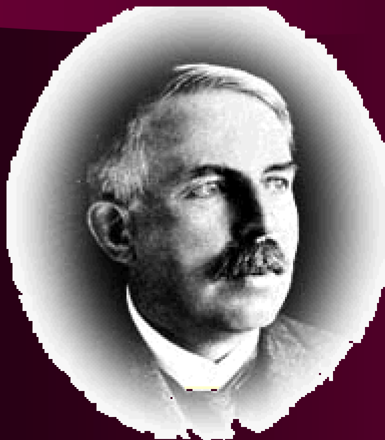
1785年 电力 库仑定律 $\vec{F} = k\frac{q_1 q_2}{r^2}\vec{e_r}$ → 分子、原子结构

1934年 核力 汤川势 $V(r) = -g^2\frac{e^{-\mu r}}{r}$ → 原子核结构

1934年 费米弱力理论 中子→质子+电子+中微子

1901年 首枚诺贝尔物理奖 → 伦琴 W. Röntgen

（1895年发现X射线）



卢瑟福 Ernest Rutherford (1871-1937)

原子核物理、放射化学、原子物理之父

1899年发现天然α射线-带电的氦原子

放射性元素放射α射线变成另一种元素

→ 1908年诺贝尔化学奖

门捷列夫1871年的化学元素周期表

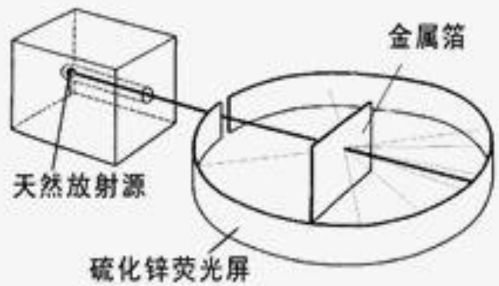
与1906年的诺贝尔化学奖失之交臂，于1907年去世

Reihen	Gruppo I. — R^2O	Gruppo II. — RO	Gruppo III. — R^2O^3	Gruppo IV. RH^4 RO^2	Gruppo V. RH^3 R^2O^5	Gruppo VI. RH^2 RO^3	Gruppo VII. RH R^2O^7	Gruppo VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

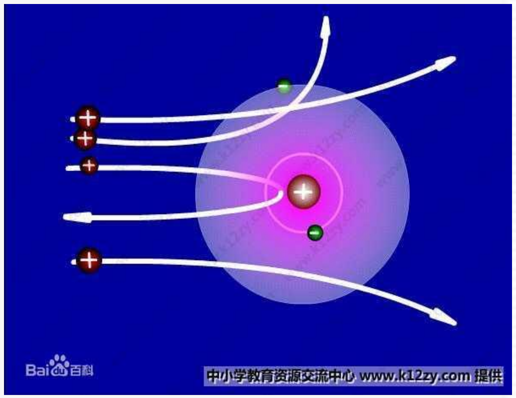
卢瑟福实验：开启了亚原子结构探索及其基本范式

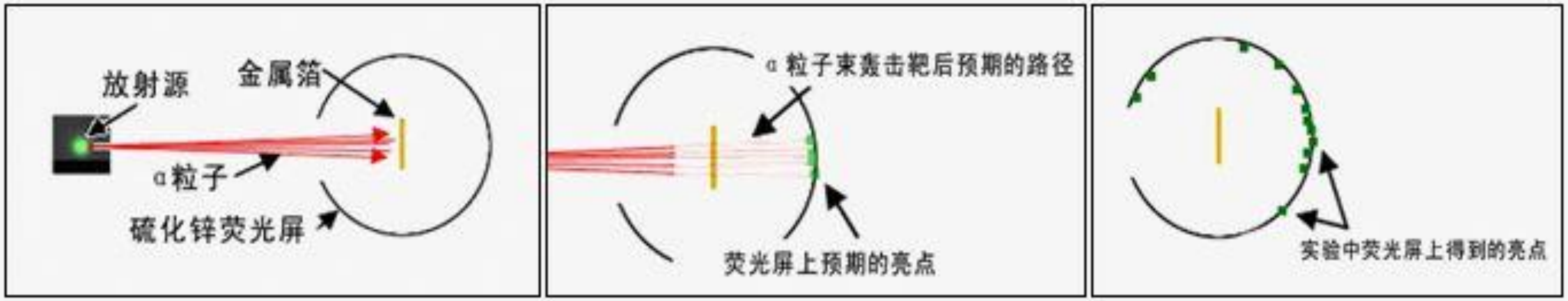
卢瑟福1911年发现原子核 → 原子＝原子核＋外围电子

卢瑟福的实验装置

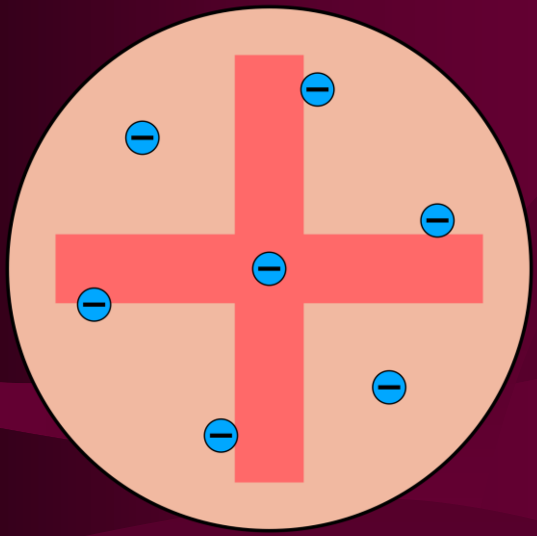


卢瑟福第一次人工核反应实验装置示意图





原子的布丁模型



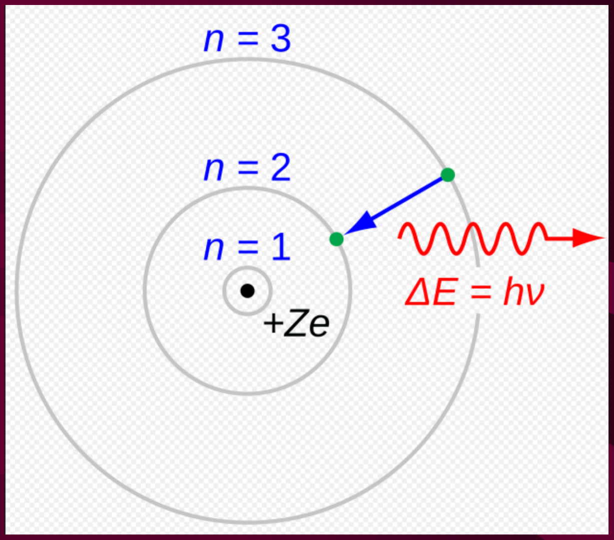
汤姆孙 J.J.Thomson

1897年发现电子

1906年诺贝尔物理奖

卢瑟福的导师

原子的玻尔模型



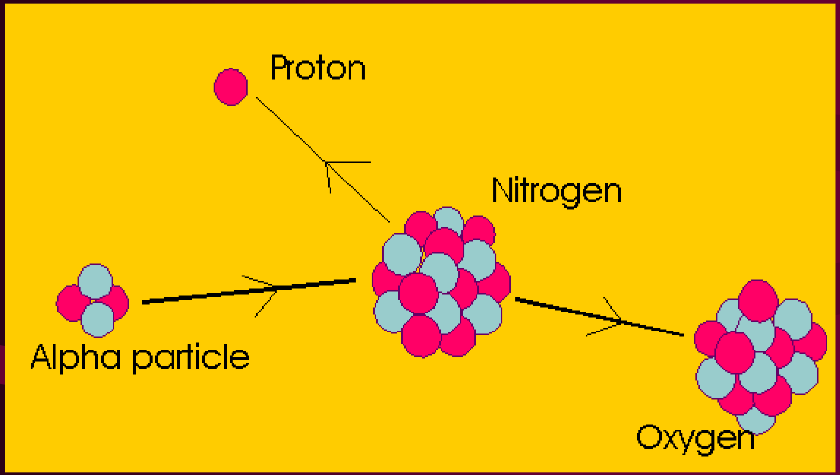
玻尔 Niels Bohr

1913年原子结构模型

1922年诺贝尔物理奖

卢瑟福的博士后

卢瑟福1919 年发现质子 – 最轻的原子核，第一个强子



$\alpha + {}^{14}N \rightarrow p + {}^{17}O$

James Chadwick

1932年发现中子

$\alpha + {}^{9}Be \rightarrow n + {}^{12}C$

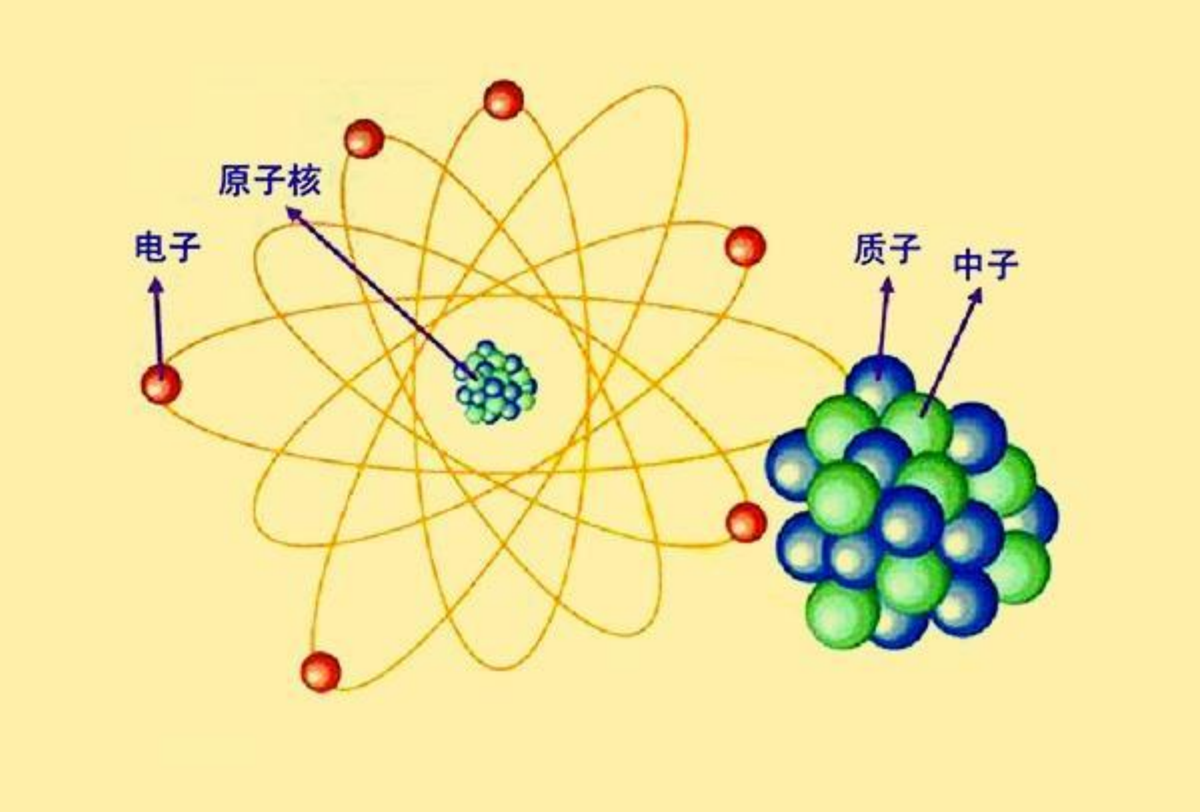
1935年诺贝尔物理奖

卢瑟福的学生

德国物理学家博特&贝克及法国小居里夫妇分别在1930、1931年观测到这种中性辐射，误认为是高能光子；查德威克证明是他导师卢瑟福预言的中子

三代师徒 (J.Thomson, E.Rutherford, J.Chadwick)

分别发现构成原子的三种成分：电子、质子、中子

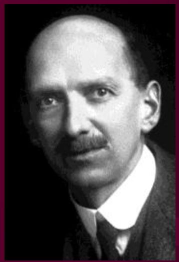


博士后(N.Bohr)给出了轨道量子化的原子结构模型

卢瑟福 – 伟大的科学导师

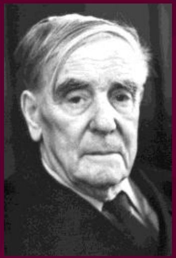
索迪 Fred Soddy
1913年发现同位素
1921年诺贝尔化学奖

阿斯顿 Francis Aston
1919年发明质谱仪，
发现大量新的同位素
1922年诺贝尔化学奖



威尔逊 C. Wilson
1911年发明云雾室
1927年诺贝尔物理奖

布莱克特 P. Blackett
1932年改进云雾室，
观测到丰富的宇宙线
1948年诺贝尔物理奖



卡皮茨 Pyotr Kapitsa
1934年发明液氦批量
制作方法→低温物理
1978年诺贝尔物理奖

哈恩 Otto Hahn
1939年发现重核裂变
1945年诺贝尔化学奖

John Cockcroft & Ernest Walton
1932年发明直流高压加速器：
取代卢瑟福天然放射α束流，
用人工加速粒子实现核反应
1951年诺贝尔物理奖

中子物理

费米 Enrico Fermi (1901-1953)

中子物理学之父、原子能之父

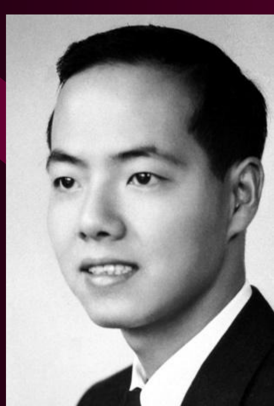
1934年发现慢中子诱发核反应优势，

人造新的放射性“元素”→ 同位素

→ 1938年诺贝尔物理奖

1934年 弱相互作用四费米子VV模型： $n \rightarrow p + e + \bar{\nu}$

V → V–A



李政道 & 杨振宁

1956年发现弱相互作用宇称不守恒

1957年获诺贝尔物理奖

核力的介子交换理论

汤川秀树 **Hideki Yukawa (1907-1981)**

1934年提出核力的介子交换理论，

预言了π介子的存在

1949年诺贝尔物理奖

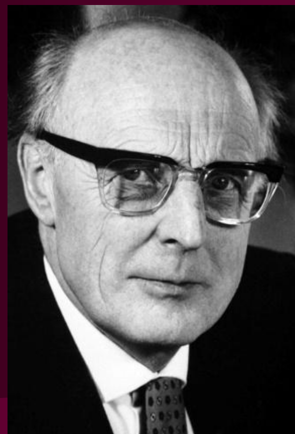
$$V(r) = -g^2\frac{e^{-\mu r}}{r}$$

鲍威尔 **Cecil F. Powell (1903-1969)**

1947年用照相乳胶法发现 π 介子

1950年诺贝尔物理奖

原子核结构



“女性想做科学家，必须嫁一个科学家丈夫”

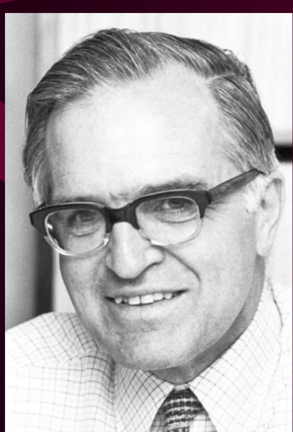
Maria Goeppert Mayer & Hans Jensen

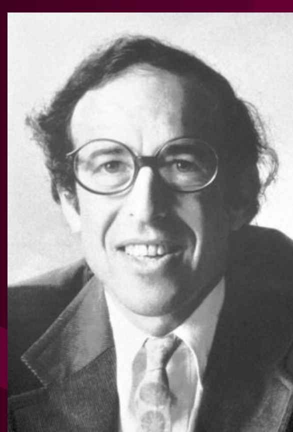
1949年发现原子核的壳层结构

Eugene P. Wigner

1933年对核力性质的研究

1963年诺贝尔物理奖





Aage Bohr & Ben Mottelson

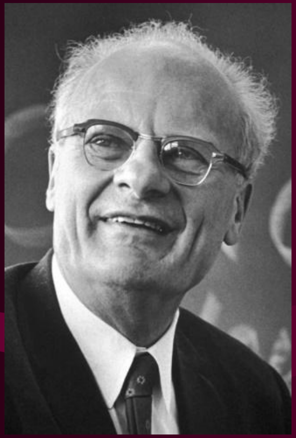
1952年原子核集体运动模型

Leo J. Rainwater

1950年推测原子核形变

1975年诺贝尔物理奖

天体核物理



Hans A. Bethe

1938年发展核反应理论，用核聚变反应解释恒星中能源的产生

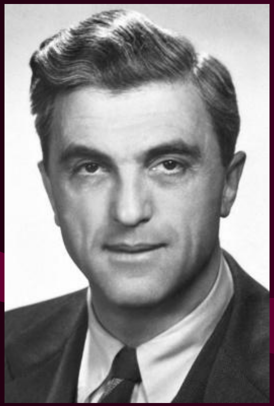
1967年诺贝尔物理奖

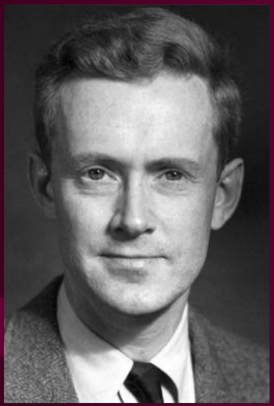
William A. Fowler

1957年对宇宙中形成化学元素的核反应的理论和实验研究

1983年诺贝尔物理奖

核技术应用

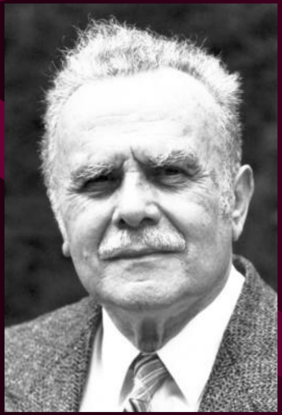




Felix Bloch & Edward Purcell

1946年开发核磁共振精密测量的新方法，有效地研究了各种材料的成分

1952年诺贝尔物理奖



Bertram Brockhouse & Clifford Shull

1951年开发中子频谱学和中子衍射技术，有效地研究了分子和各种材料结构

1994年诺贝尔物理奖

质子有结构

Otto Stern

1933年测出质子磁矩 $\mu_p = 2.5\ \mu_N$ vs prediction

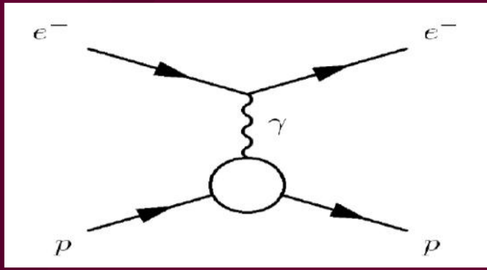
1943年诺贝尔物理奖

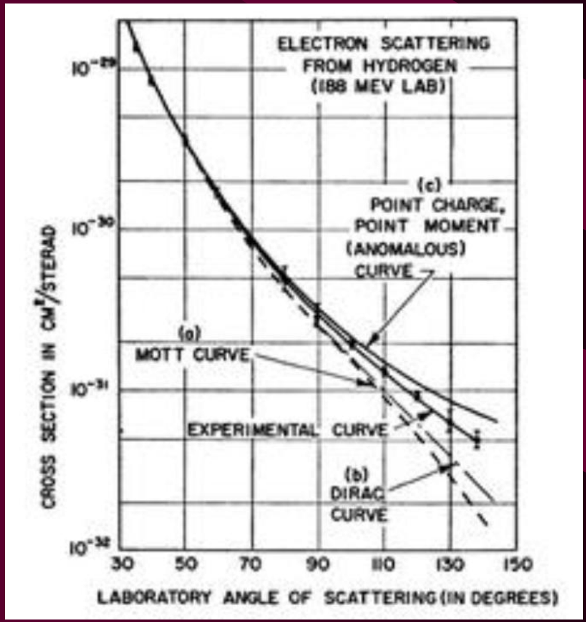
$$\mu_p = \frac{e\hbar}{2m_N c} \equiv \mu_N$$

Robert Hofstadter

1955年ep散射测出质子尺寸

1961年诺贝尔物理奖



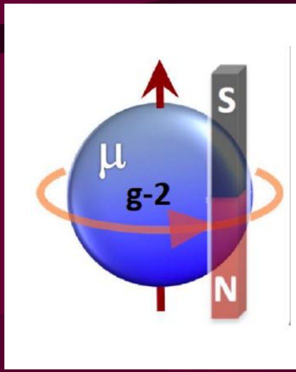


Carl Anderson

1932年发现正电子

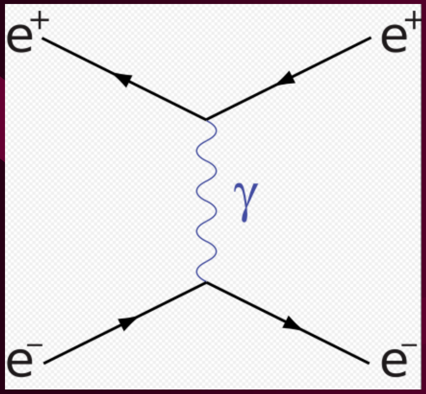
1936年诺贝尔物理奖

同年发现 μ 子



$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

Particle	g-factor	Relative uncertainty
Electron	2.002 319 304 361 18(26)	1.3×10^{-13}
Muon	2.002 331 841 10(47)	2.3×10^{-11}
Proton	5.585 694 689 3(16)	2.9×10^{-10}
Antiproton	5.585 694 690 6(60)	1.5×10^{-9}



LEP@CERN 209GeV → $r_e < 10^{-18}$ m

C. Rubbia& S. van der Meer

1983年 发现 W、Z 粒子

1984年诺贝尔物理奖

奇异介子、超子及强子共振态的发现

云雾室、乳胶室及气泡室发挥重要作用

Donald A. Glaser

1952年发明气泡室, 对强子谱研究做出重要贡献

1960年诺贝尔物理奖

Luis W. Alvarez

1958年发展了氢气泡室技术和数据分析方法，从而发现了一大批共振态

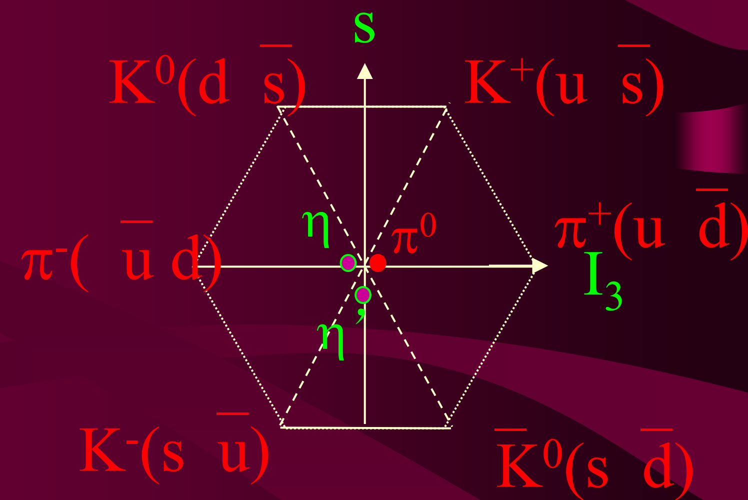
1968年诺贝尔物理奖

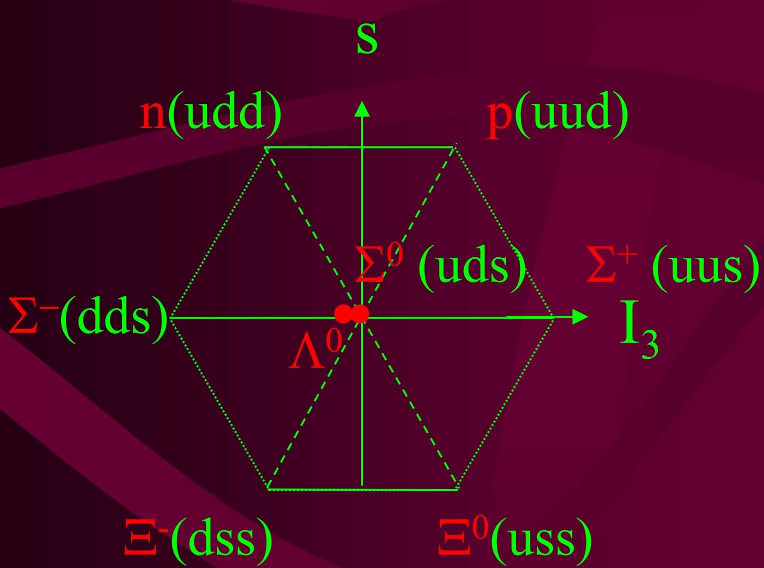
强子的夸克模型

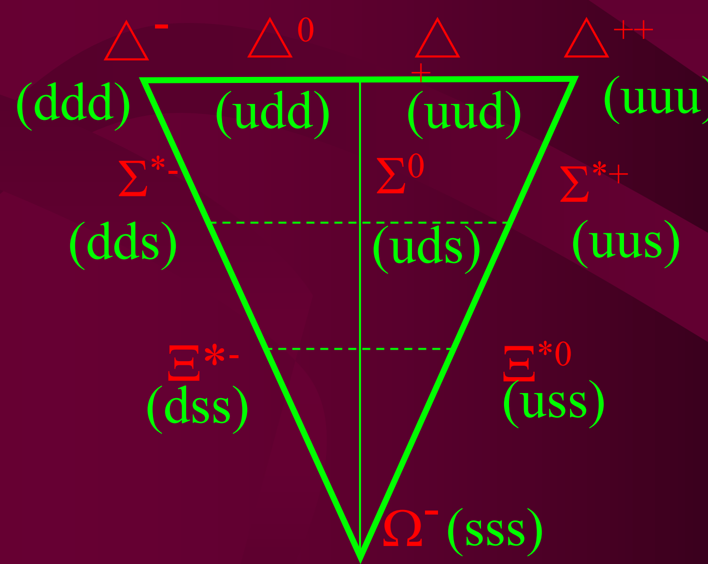
盖尔曼 Murray Gell-Mann

1964年 提出强子夸克模型

1969年诺贝尔物理奖

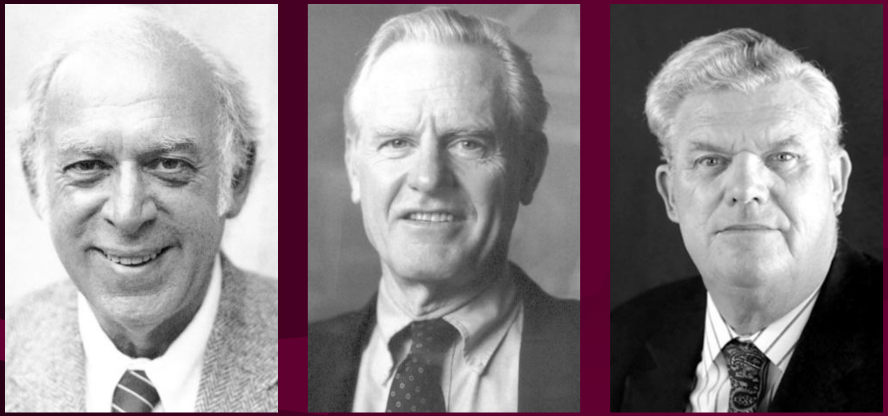


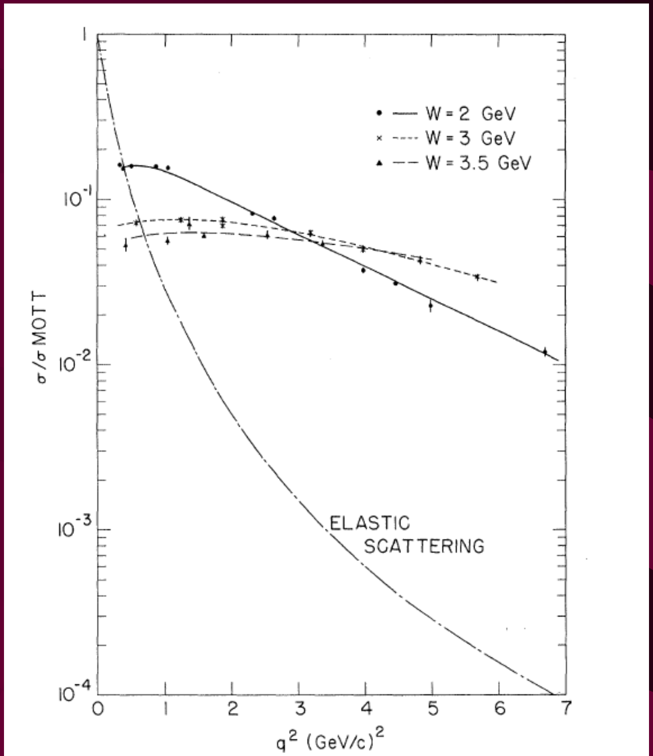




1/2 +　　自旋-宇称　　3/2+

核子由夸克组成的实验验证



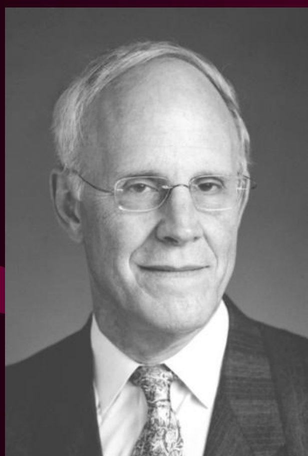


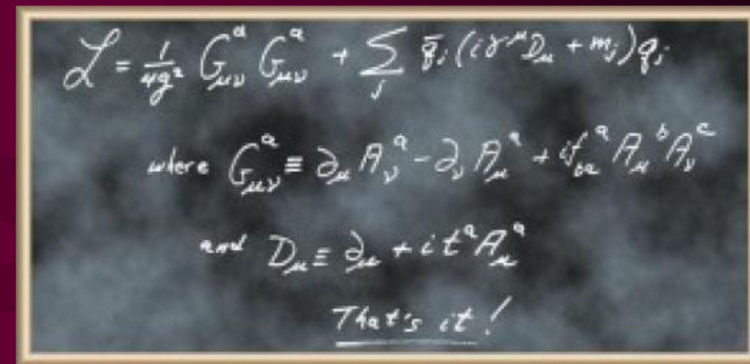
Jerome Friedman，Henry Kendall & Richard Taylor

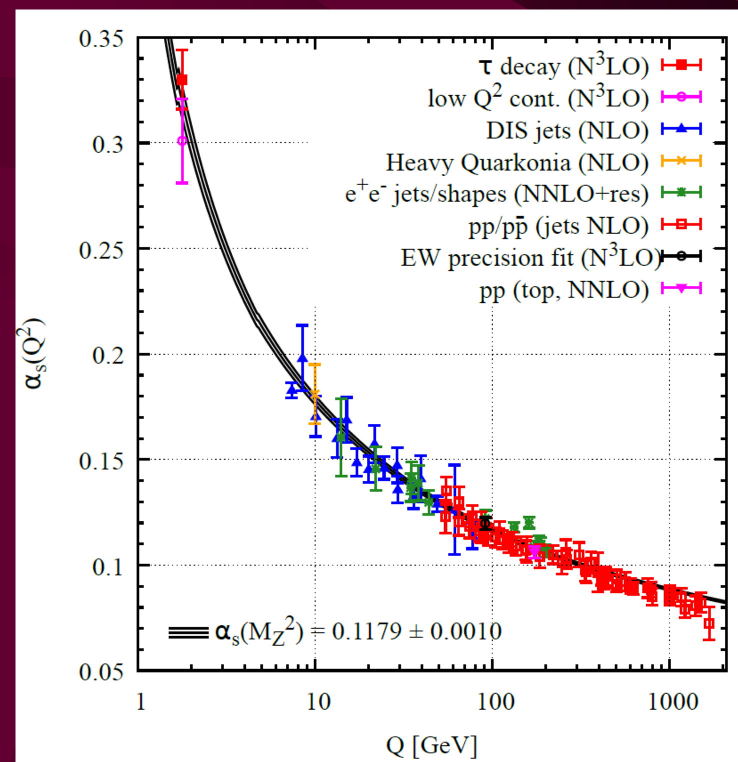
1969年 ep 深度非弹散射证实核子内夸克的存在

1990年诺贝尔物理奖

夸克-胶子的量子色动力学QCD理论







David Gross, Frank Wilczek &

David Politzer

1973年 推出渐近自由的QCD理论

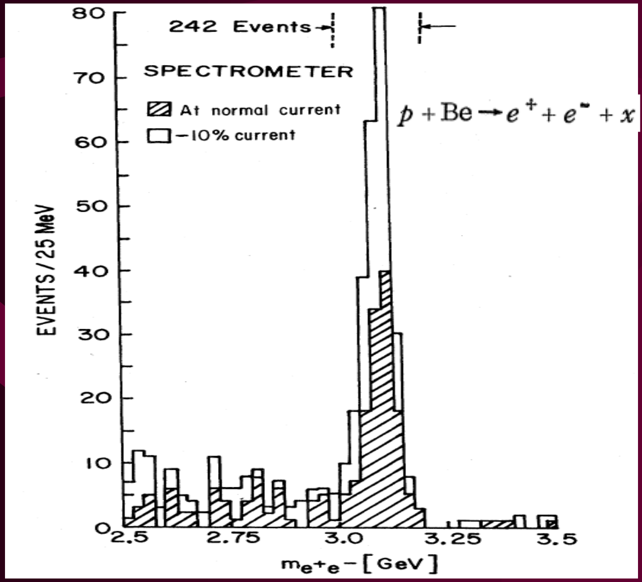
2004年诺贝尔物理奖

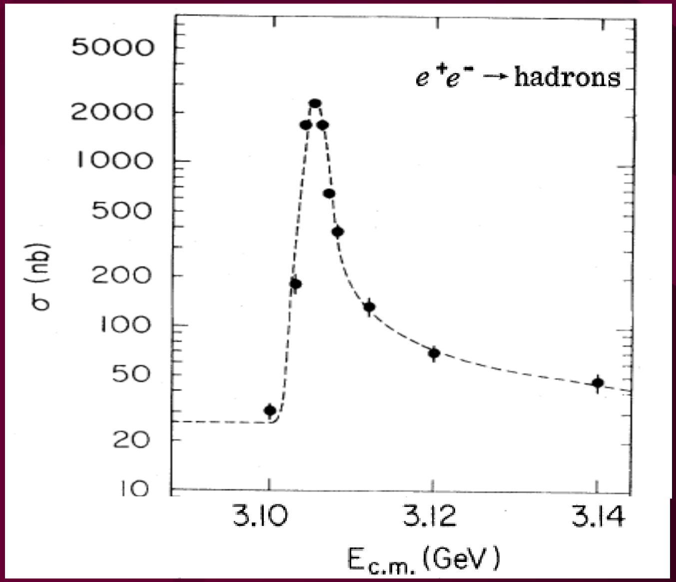
重味夸克组成的强子


丁肇中 & Burton Richter

1974年发现J/ψ粒子，证明存在第4种夸克-粲夸克

1976年诺贝尔物理奖





$\bar{c}c$ + QCD → 具有QCD精神的夸克势模型

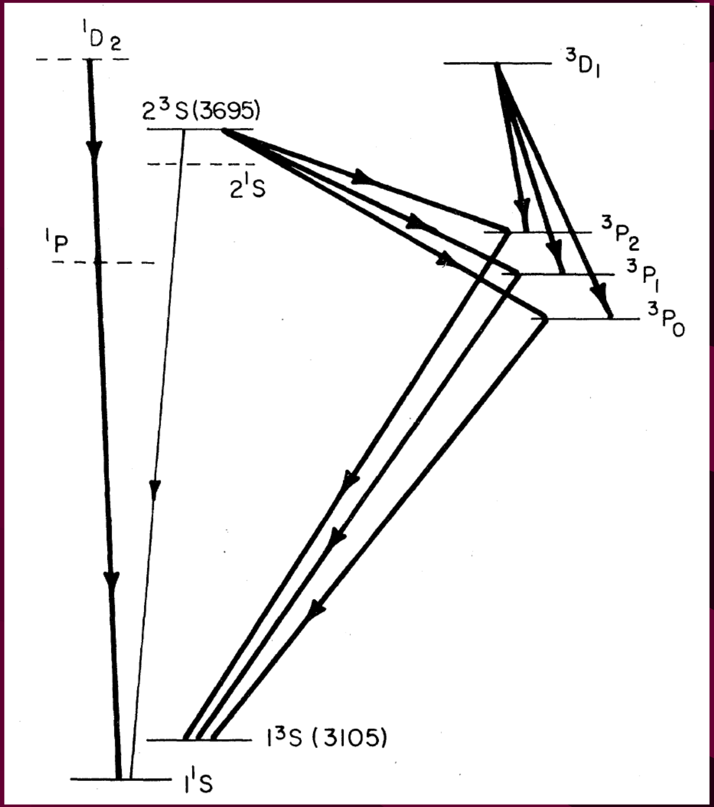
$$\hat{H}_0 = \frac{p^2}{m_Q} + V_0(r) + V_{\rm SD}(r)$$

$$V_0(r) = \sigma r - \frac{\frac{4}{3}\alpha_s}{r} + C_0 \qquad \text{(Cornell potential)}$$

E.Eichten et al., PRL 34 (1975) 369

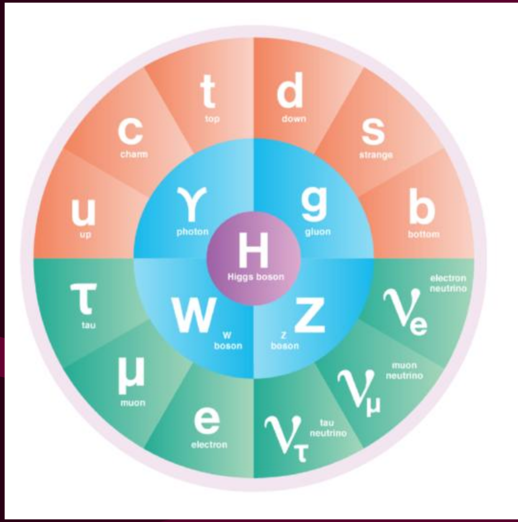
$$V_{SD}(r) = \underbrace{V_{LS}(r)(\boldsymbol{L}\cdot(\boldsymbol{S}_Q+\boldsymbol{S}_{\bar{Q}}))}_{\text{fine structure}} + \underbrace{V_{SS}(r)(\boldsymbol{S}_Q\cdot\boldsymbol{S}_{\bar{Q}})}_{\text{hyperfine structure}}$$

$$+\underbrace{V_{ST}(r)\Big((\boldsymbol{S}_Q\cdot\boldsymbol{S}_{\bar{Q}}) - 3(\boldsymbol{S}_Q\cdot\boldsymbol{n})(\boldsymbol{S}_{\bar{Q}}\cdot\boldsymbol{n})\Big)}_{\text{spin tensor force}} \quad \propto \quad \frac{1}{m_Q^2}$$



预言的这些粲偶素 $\bar{c}c$ 均被实验发现证实，被推广应用于各类强子谱的研究，取得了极大的成功

基本粒子及其标准模型



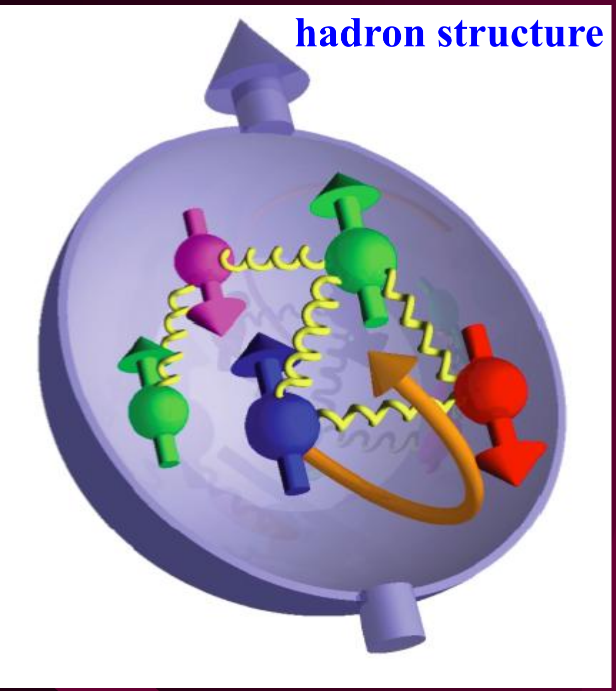
1954年杨-米尔斯理论：将U(1)规范不变的麦克斯韦理论拓展到不可交换群。在接下来的20年里，随着希格斯机制、电弱统一、可重整化、夸克禁闭、渐近自由等一系列物理概念的提出和研究，建立了粒子物理的标准模型。

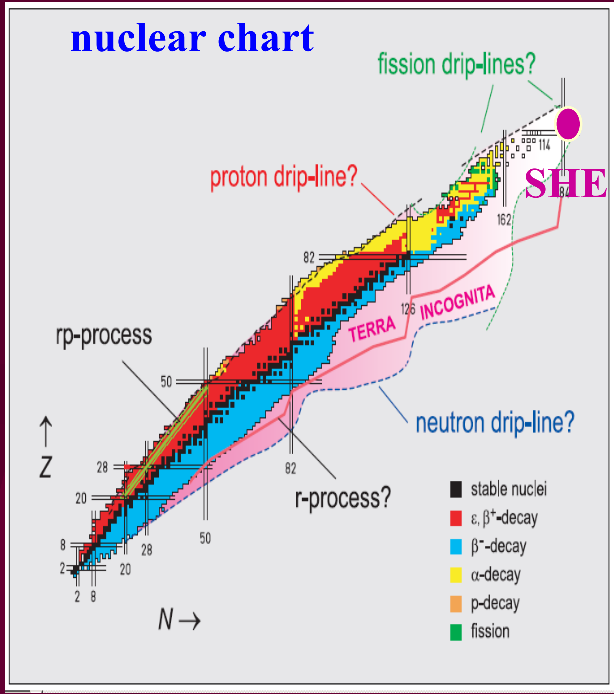
前沿问题：

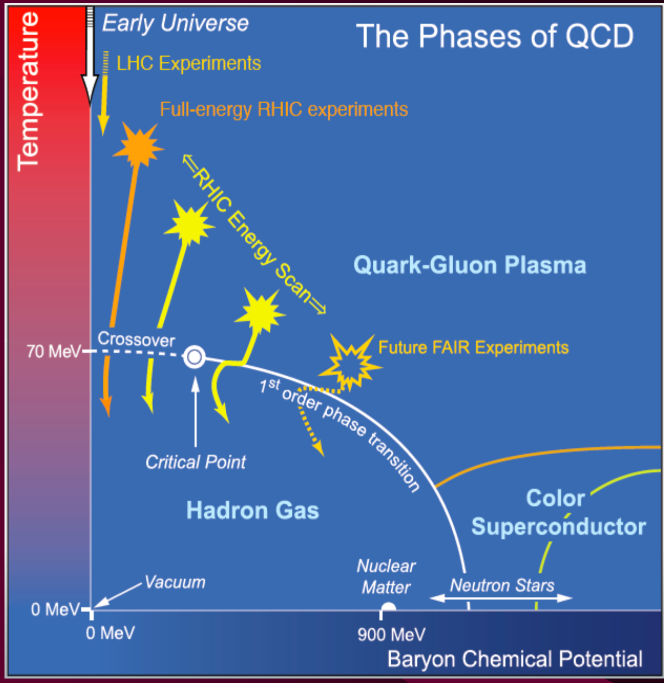
- **Higgs 性质的全面系统研究**
- **中微子质量等性质的研究**
- **强子的夸克胶子结构**
- **…**
- **夸克、轻子内部结构？**
- **新的基本粒子？相互作用？**
- **宇宙中正反物质不对称的根源？**
- **…**

III. General view on frontiers of nuclear & hadron physics

3 major fields:







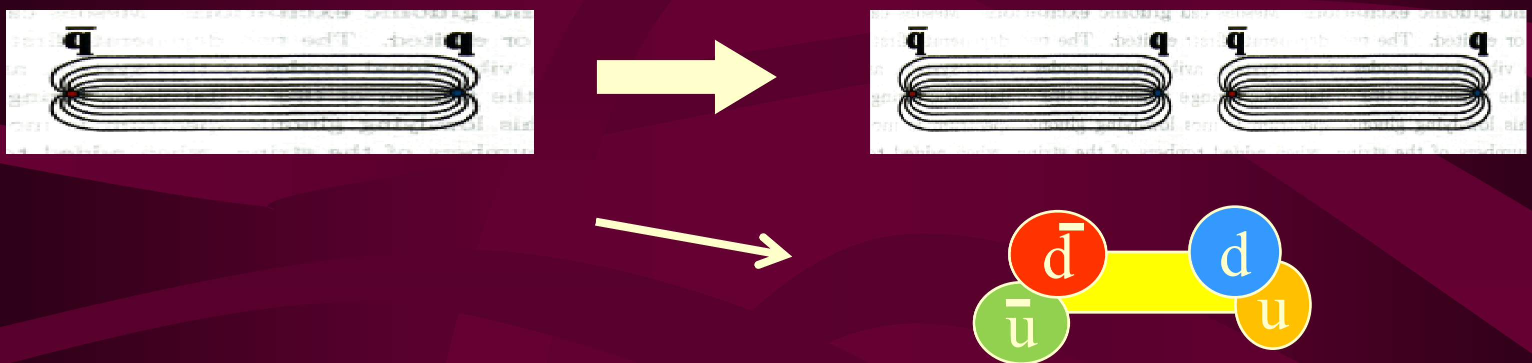
Cross applications :

1） nuclear astro-physics
2） test of SM in nuclear physics
3） nuclear technologies

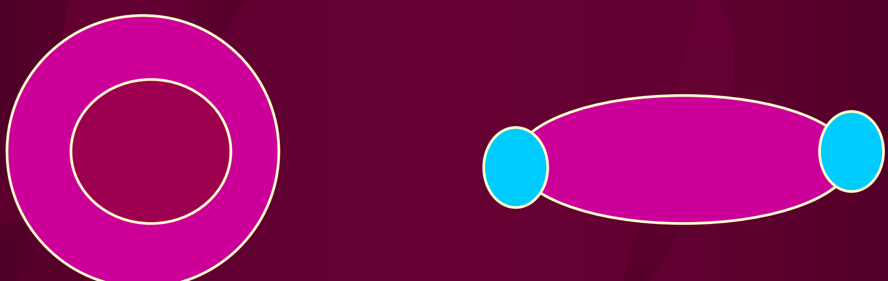
1. Hadron structure:

how quarks & gulons contruct hadrons?

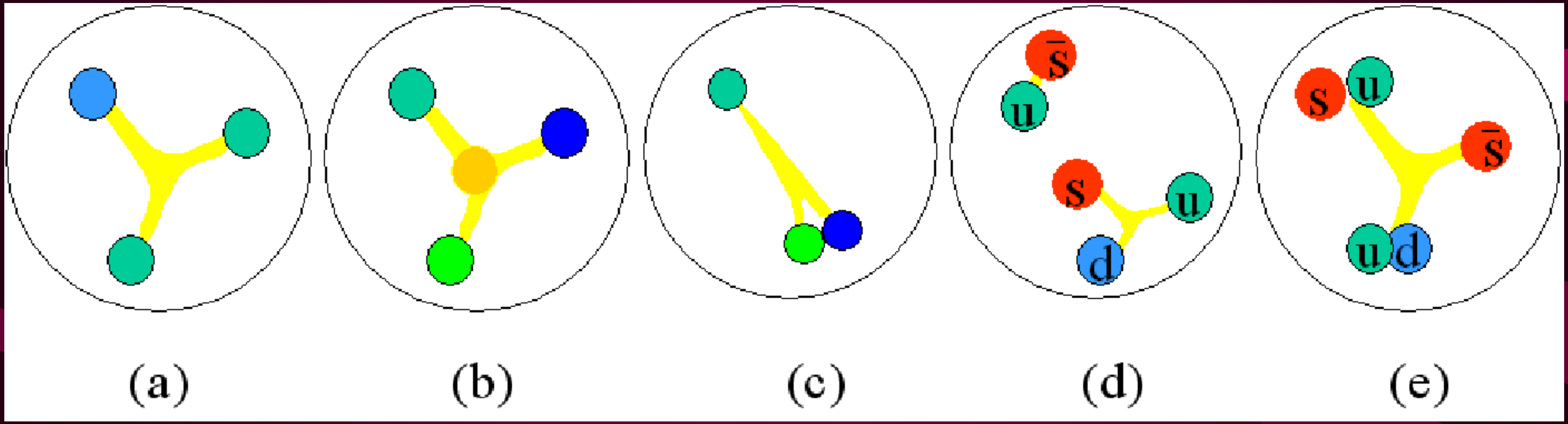
Unquenched dynamics: gluons → $\bar{q}q$
crucial for quark confinement & hadron structure



Mesons: $\bar{q}q$, tetraquarks, glueballs, $\bar{q}qg$-hybrids?



How about baryons?



A. qqq B. qqqg C. q-q^2 D-E. pentaquarks

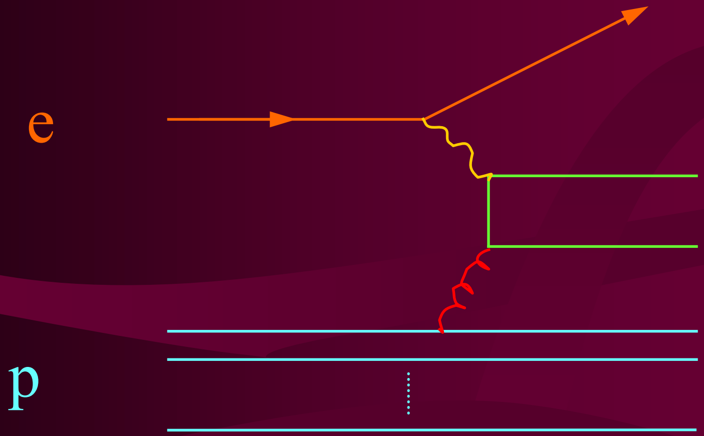
Number of predicted N*: D-E>B>A>C

Number of observed N* <A, "missing"?

Poor knowledge on baryon spectroscopy
Lack effective reliable theoretical predictions

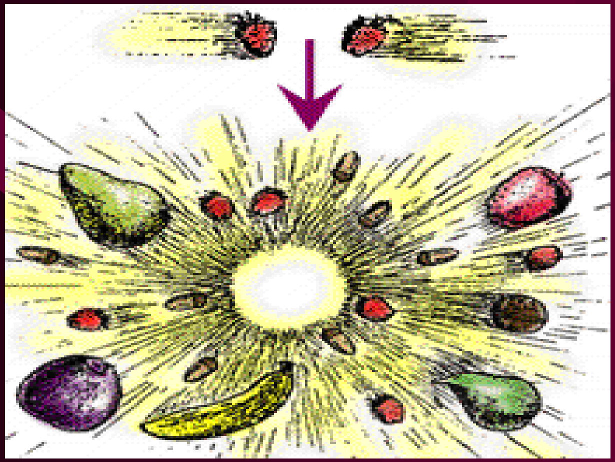
Two major methods for exploring baryon structure

1） lepton-proton scattering → parton distribution of proton



Problem： γ, g, $\bar{q}q$ transition，
intrinsic or extrinsic ?

2） hadrons, leptons, γ collisions → hadron spectroscopy



Atomic spectroscopy → Atomic Quantum Theory

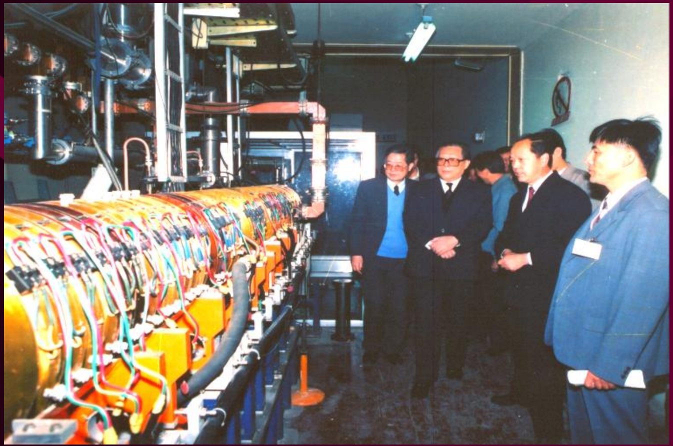
Nuclear spectroscopy → Shell Model &
Collective motion Model

Hadron spectroscopy → ?

北京正负电子对撞机（BEPC）、北京谱仪（BES）

周恩来：

这件事不能再延迟了！



李政道：

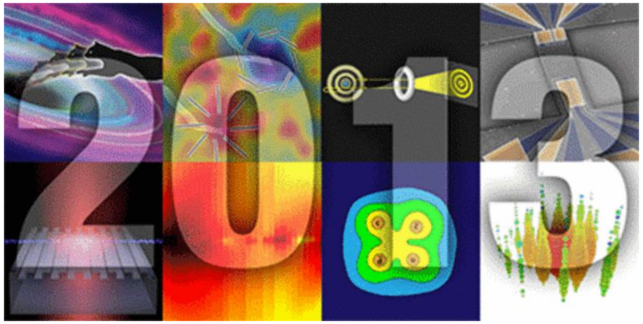
三代领袖尧舜禹，影响文化三千年。

夸克轻子皆三代，BES也需第三代。

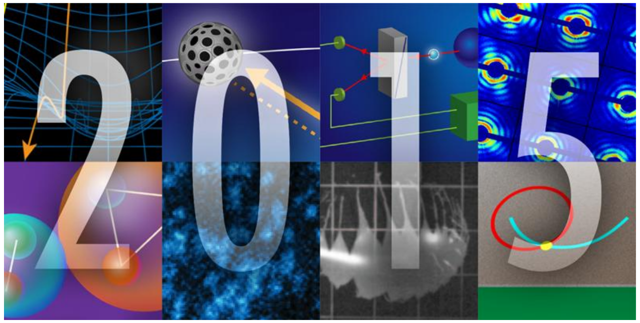
Research highlights

Top highlights in strong QCD in last ten years (APS)

#1. Discovery of Zc(3900) by BESIII & Belle



#2. Discovery of Pc states by LHCb



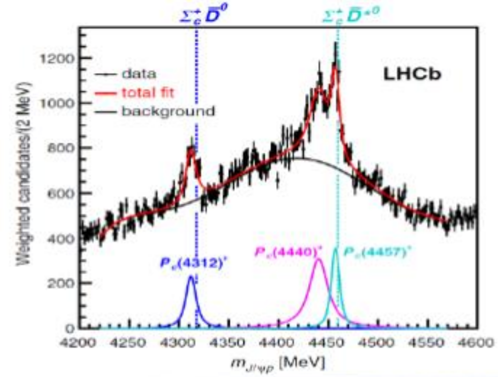
CRC110 PLs played leading role for predictions and explanations

W.Chen, H.X.Chen, X.Liu, S.L.Zhu, Phys. Rept. 639 (2016) 1 — 1250 cites

F.K.Guo, C.Hanhart, U.Meißner, Q.Wang, Q.Zhao, B.S.Zou, Rev. Mod. Phys. 90 (2018) 015004 — 1369 cites

P_c states: observation vs predictions

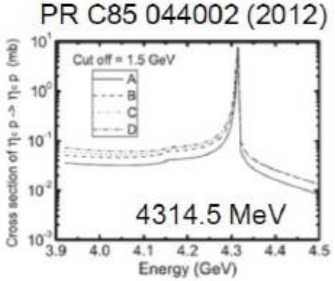
LHCb, PRL122 (2019) 222001



Comparison to numerical predictions

- Many theoretical predictions for $\Sigma_c^+ \bar{D}^{(*)0}$ published before 2015, **some in quantitative agreement with the LHCb data**
  - Wu,Molina,Oset,Zou, PRL105, 232001 (2010),
  - **Wang,Huang,Zhang,Zou, PR C84, 015203 (2011),**
  - **Yang,Sun,He,Liu,Zhu, Chin. Phys. C36, 6 (2012),**
  - **Wu,Lee,Zou, PR C85 044002 (2012),**
  - Karliner,Rosner, PRL 115, 122001 (2015)

PR C85 044002 (2012)



ΔE – binding energy

Example:

Nucleon resonances with hidden charm in coupled-channels models

Jia-Jun Wu, T.-S. H. Lee, and B. S. Zou

Phys. Rev. C **85**, 044002 – Published 17 April 2012

arXiv:1202.1036

TABLE III: The pole position $(M - i\Gamma/2)$ and "binding energy" $(\Delta E = E_{thr} - M)$ for different cut-off parameter Λ and spin-parity J^P. The threshold E_{thr} is 4320.79 MeV of $\bar{D}\Sigma_c$ in PB system and 4462.18 MeV of $\bar{D}^*\Sigma_c$ in VB system. The unit for the listed numbers is MeV.

		PB System		VB System	
$J^P = \frac{1}{2}^-$	Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
	650	-	-	-	-
	800	-	-	$4462.178 - 0.002i$	0.002
	1200	$4318.964 - 0.362i$	1.826	$4459.513 - 0.417i$	2.667
	1500	$4314.531 - 1.448i$	6.259	$4454.088 - 1.662i$	8.092
	2000	$4301.115 - 5.835i$	19.68	$4438.277 - 7.115i$	23.90
$J^P = \frac{3}{2}^-$					
	650	-	-	-	-
	800	-	-	$4462.178 - 0.002i$	0.002
	1200	-	-	$4459.507 - 0.420i$	2.673
	1500	-	-	$4454.057 - 1.681i$	8.123
	2000	-	-	$4438.039 - 7.268i$	23.14

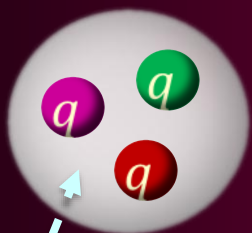
$\Delta E(4312) = 5.8^{+1.0}_{-6.8}$ MeV

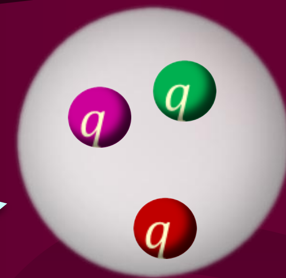
$\Delta E(4457) = 2.5^{+4.3}_{-4.1}$ MeV

$\Delta E(4440) = 19.5^{+4.9}_{-4.3}$ MeV

Λ - cut off on exchanged meson mass.

Physics: **Hadronic molecules**

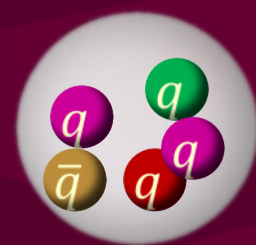




传统夸克模型：
重子激发态 = 3夸克激发态

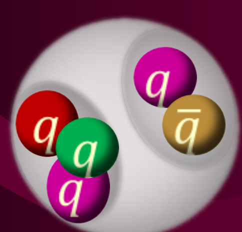
何种激发为主？

注入能量



我们新的观点：
最低的重子激发SU(3)八重态
都已经以5夸克激发为主

要真正了解重子谱，必须研究五夸克态



强子分子态

已观测到的多夸克态均与强子分子态图像相符；

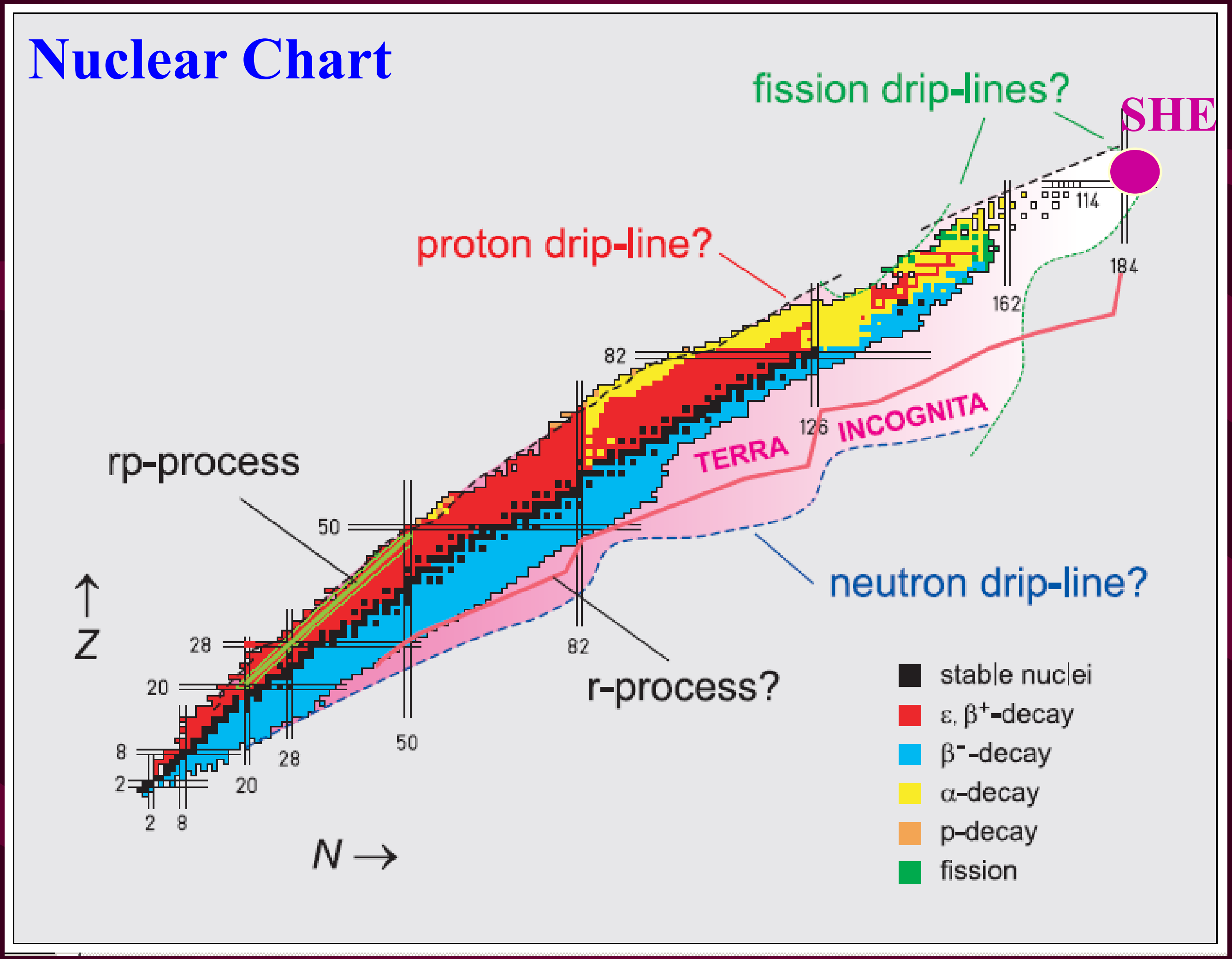
而强子相互作用以矢量介子交换为主（VMD）

2. Nuclear structure of unstable nuclei

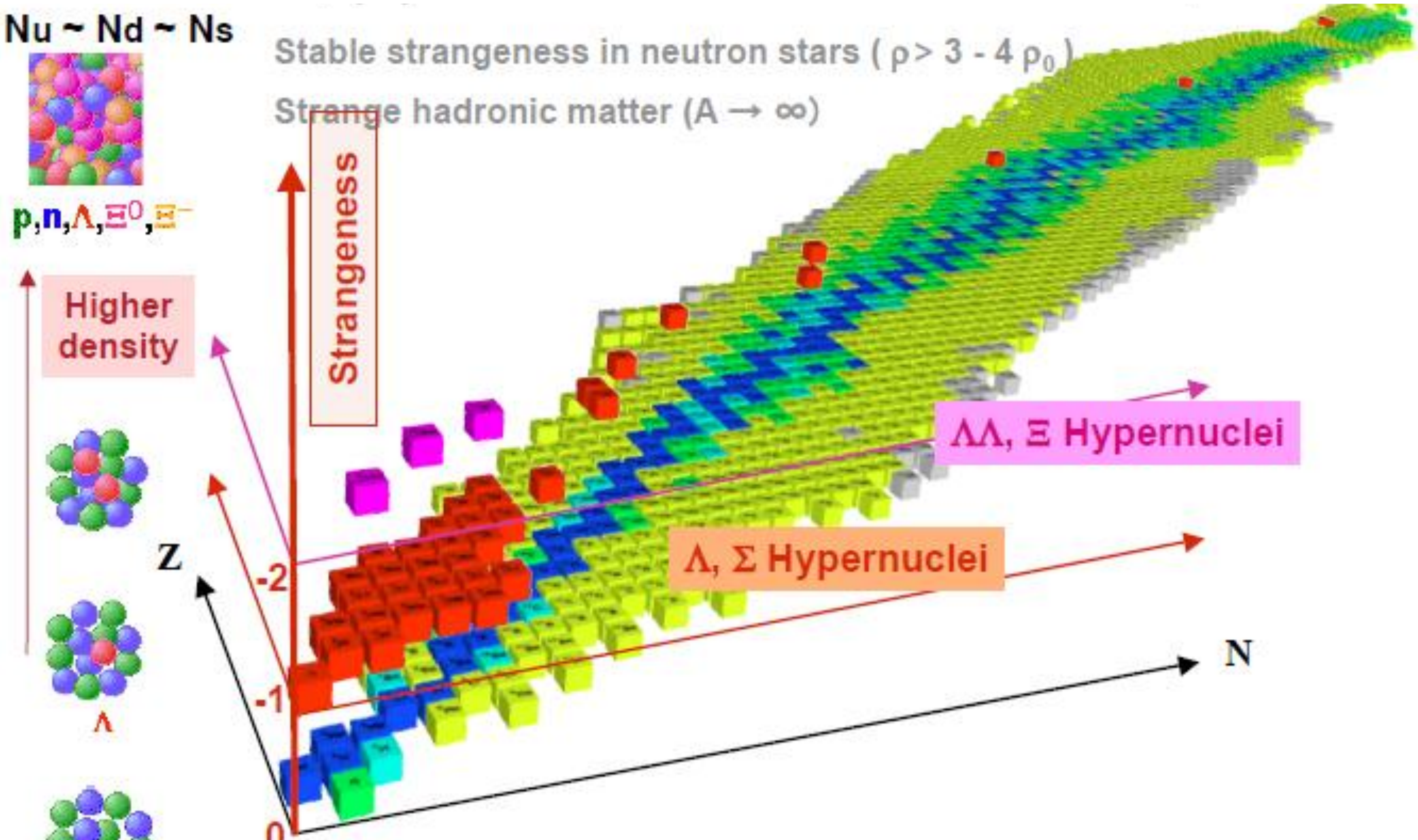
stable nuclei ⇒ shell & collective motion models

unstable nuclei ⇒ more general model?

astro-nuclear reactions



三维核素图



3-dimensional nuclear chart

Tools for exploring structure of nuclei under extreme conditions：

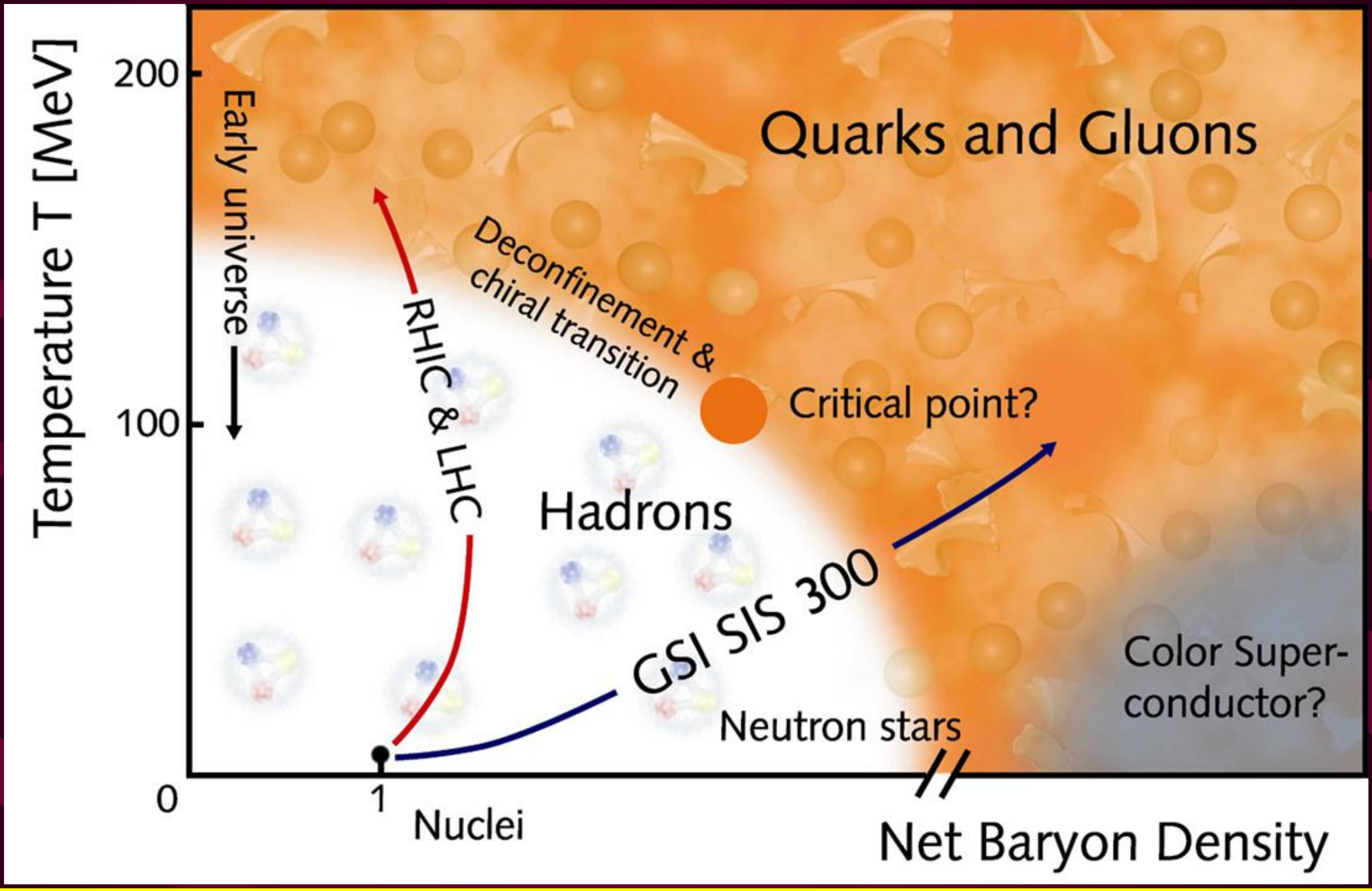
1）various heavy ion and radioactive beams to hit nuclear targets

→ high spin, super-deformed, high n/p ratio, SHE nuclei

2）lepton-nuclear reactions → quark effects in nuclei, non-nucleon degree of freedoms, difference between bound and free nucleons, hypernuclei

3. High temperature & high density nuclear matter: quark gluon plasma?

major tools: high energy heavy ion collisions



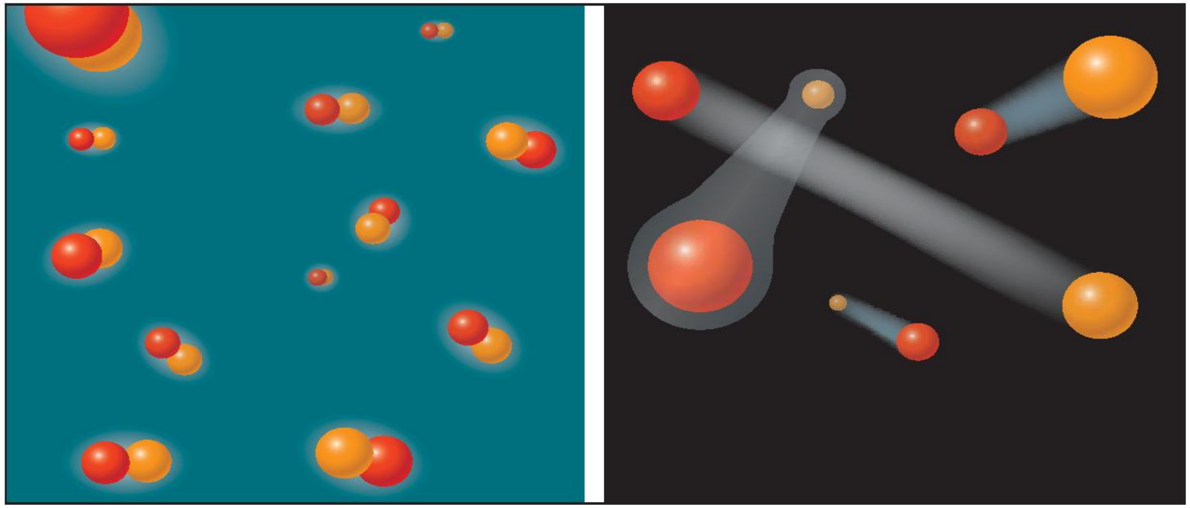
Exploring the phase diagram of strongly interacting matter

A. RHIC/BNL, LHC/CERN: high T / low D

strongly coupled ideal liquid → weak coupled ideal gas ?

B. FAIR/GSI, HIAF/IMP: low T / high D

BEC or BCS diquark correlation? Color superconductor?



Tango or twist? In a magnetic field, atoms in different spin states can form molecules (*left*). Vary the field, and they might also form loose-knit Cooper pairs.

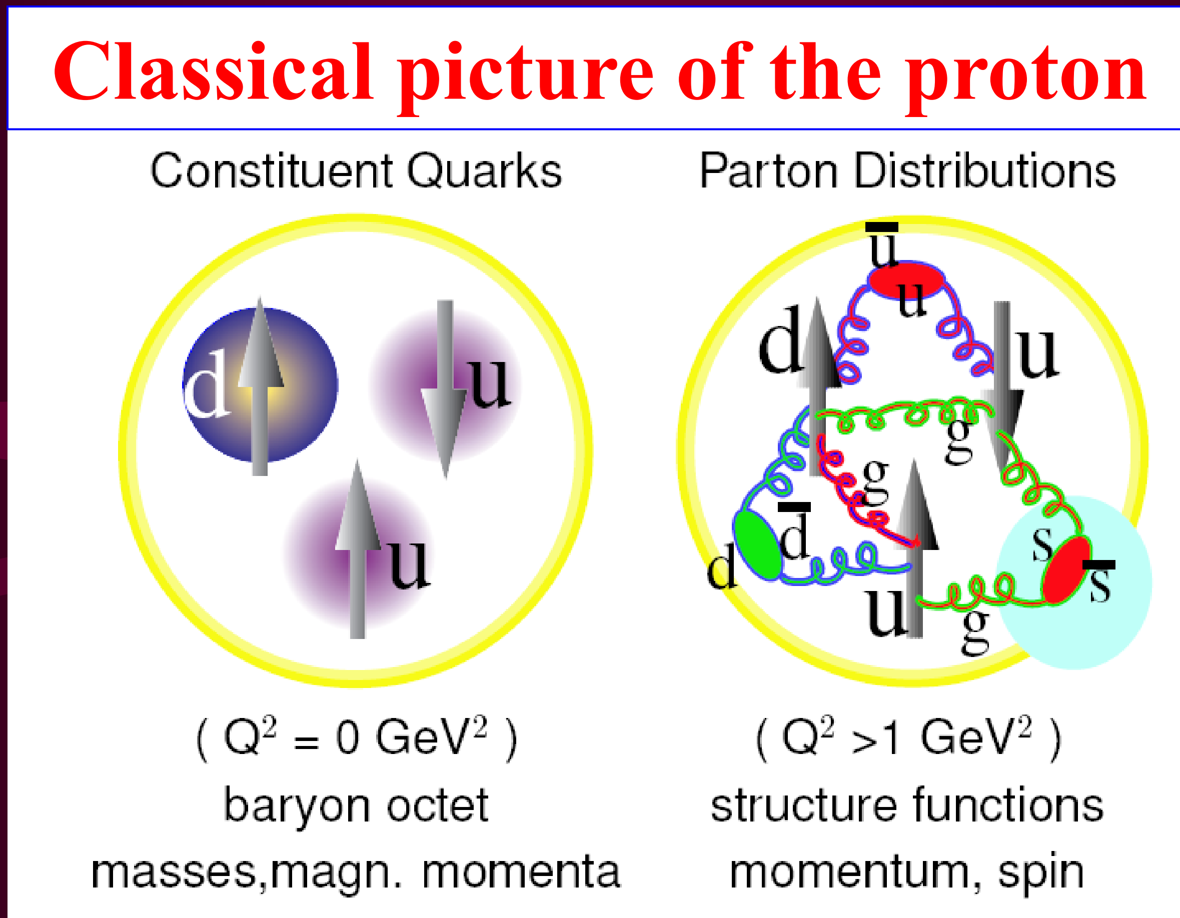
IV. Frontiers in hadron spectroscopy & hadron structure

1. Quark-gluon structure of nucleons

2. Hadron spectroscopy

3. Hadronic molecules and multi-quark states

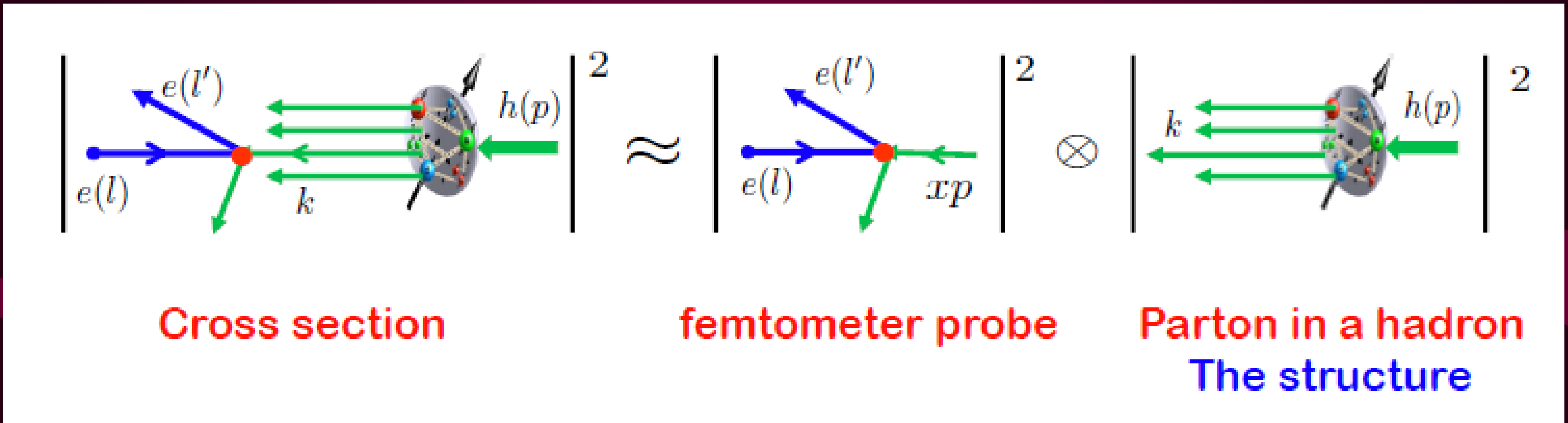
1. Quark-gluon structure of nucleons



$\bar{u}(x) = \bar{d}(x)\ , \quad \bar{s}(x) = s(x)$

1964-1974

1974–1992



QCD factorization → PDF (flavor, spin, momentum) of nucleon

proton spin "crisis" , $\bar{d} - \bar{u} \sim 0.12$, $\bar{s}(x) \neq s(x)$, …

Flavor asymmetry of light quarks in the nucleon sea

Deep Inelastic Scattering (DIS) + Drell-Yan (DY) process

→ $\bar{d} - \bar{u} \sim 0.12$

Garvey&Peng, Prog. Part. Nucl. Phys.47, 203 (2001)

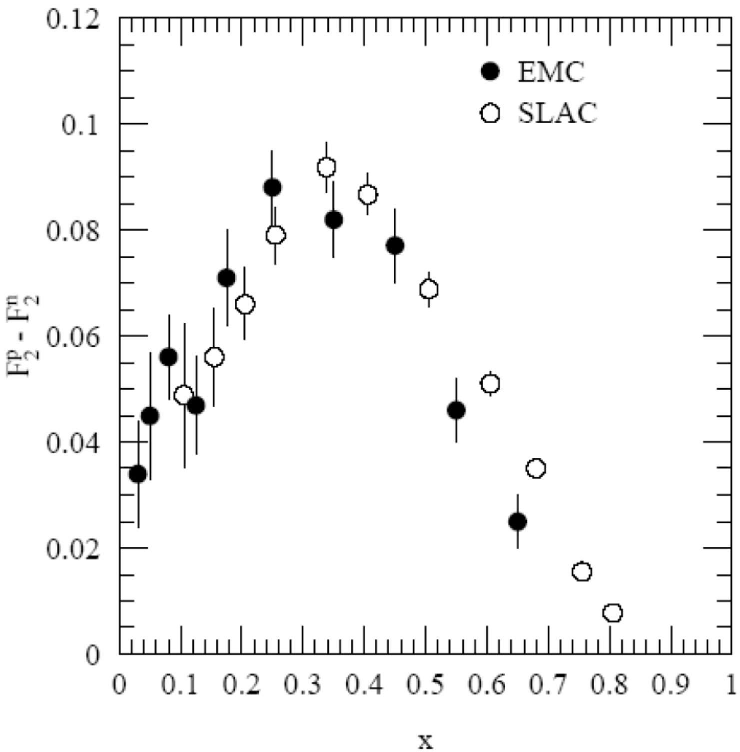
Table 1. Values of the integral $\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$ determined from the DIS, semi-inclusive DIS, and Drell-Yan experiments.

Experiment	$\langle Q^2 \rangle$ (GeV^2/c^2)	$\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$
NMC/DIS	4.0	0.147 ± 0.039
HERMES/SIDIS	2.3	0.16 ± 0.03
FNAL E866/DY	54.0	0.118 ± 0.012

DIS Gottfried Sum Rule : assuming $\bar{d} = \bar{u}$

$$I_2^p - I_2^n = \int_0^1 [F_2^p(x,Q^2) - F_2^n(x,Q^2)]/x \, dx = \sum_i [(Q_i^p)^2 - (Q_i^n)^2] = 1/3.$$

$$\int_0^1 [F_2^p(x,Q^2) - F_2^n(x,Q^2)]/x \, dx = \frac{1}{3} + \frac{2}{3}\int_0^1 [\bar{u}(x,Q^2) - \bar{d}(x,Q^2)] dx.$$



$$\sigma_{DY}(p+d)/2\sigma_{DY}(p+p) \simeq (1+\bar{d}(x_2)/\bar{u}(x_2))/2.$$

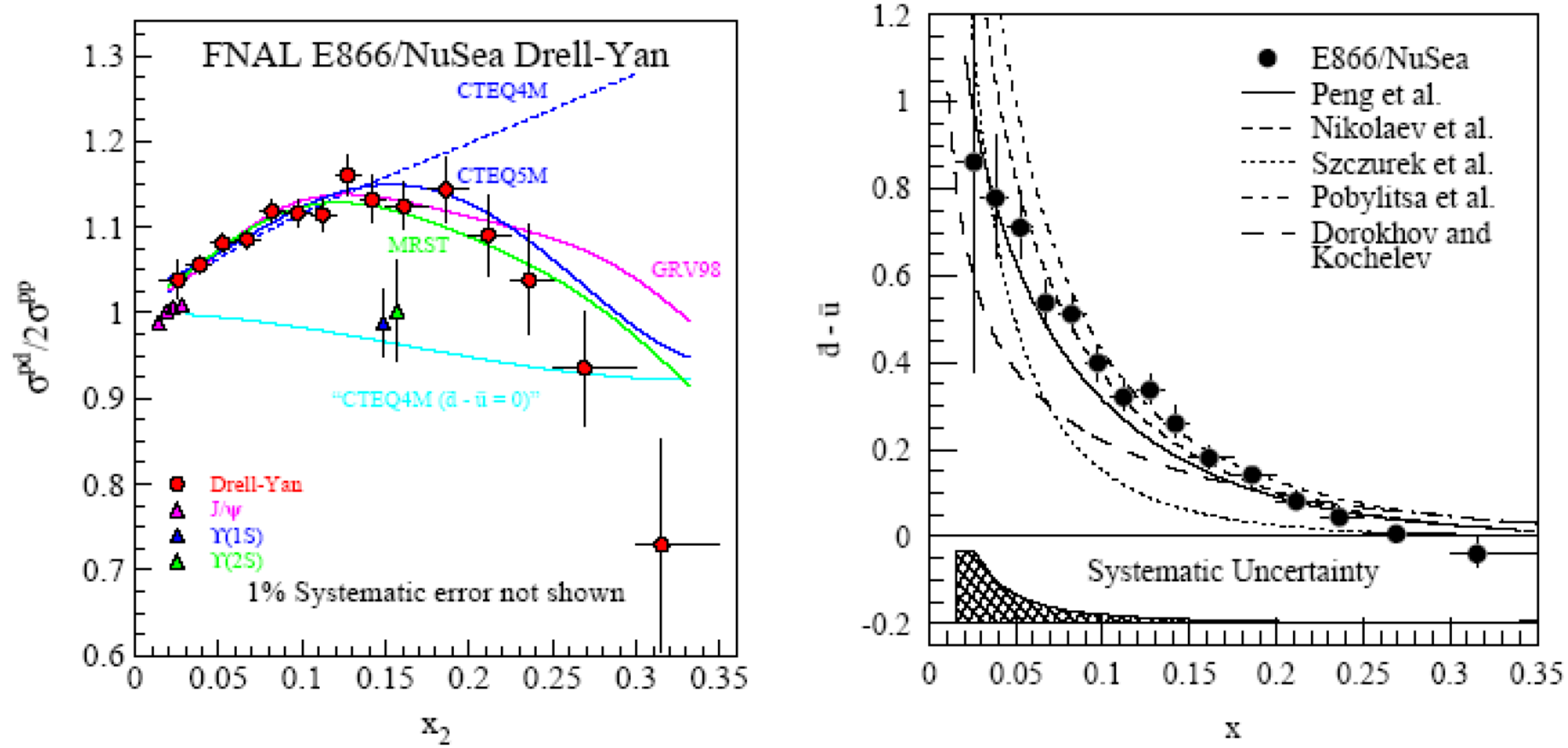
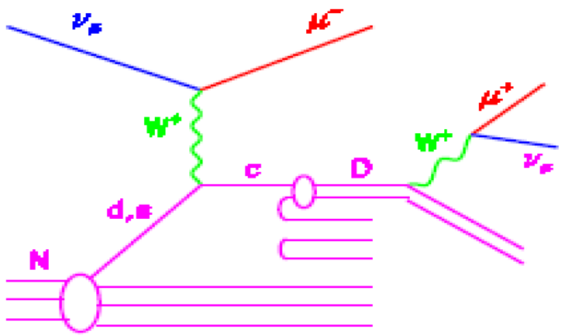


FIGURE 1. Left panel: Cross section ratios of $p+d$ over $2(p+p)$ for Drell-Yan, J/Ψ, and Υ production from FNAL E866. Right panel: Comparison of E866 $\bar{d}-\bar{u}$ data with calculations from various models [2].

neutrino DIS sizable charm production



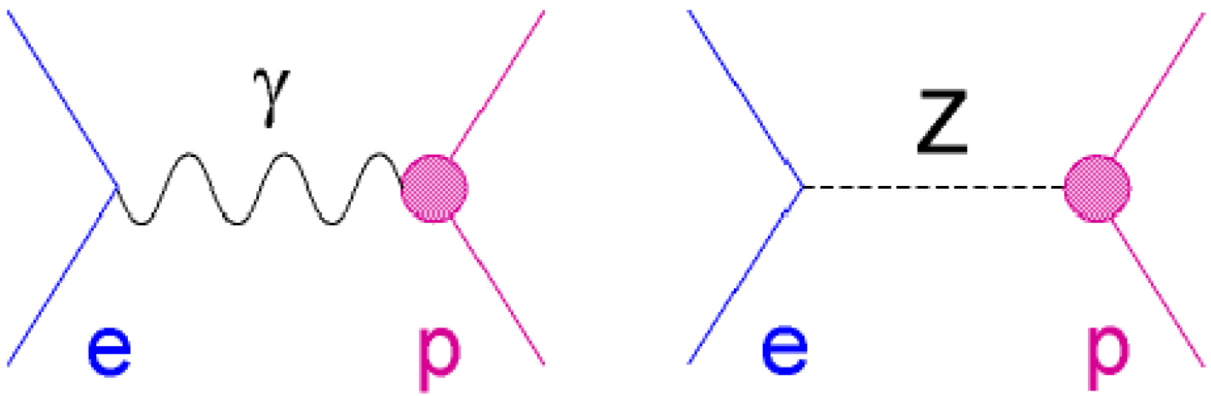
$$\frac{2\int_0^1 dx(s+\bar{s})}{\int_0^1 dx(u+\bar{u}+d+\bar{d})} = 0.42 \pm 0.07 \pm 0.06 \quad , \quad (48 \pm 5)\%$$

πN σ–term, large OZI violating ϕ–production from $\bar{p}p$ annihilations

See reviews by Ellis, Beck, …

Question remained : symmetric $\bar{s}s$ fluctuation from sea ?

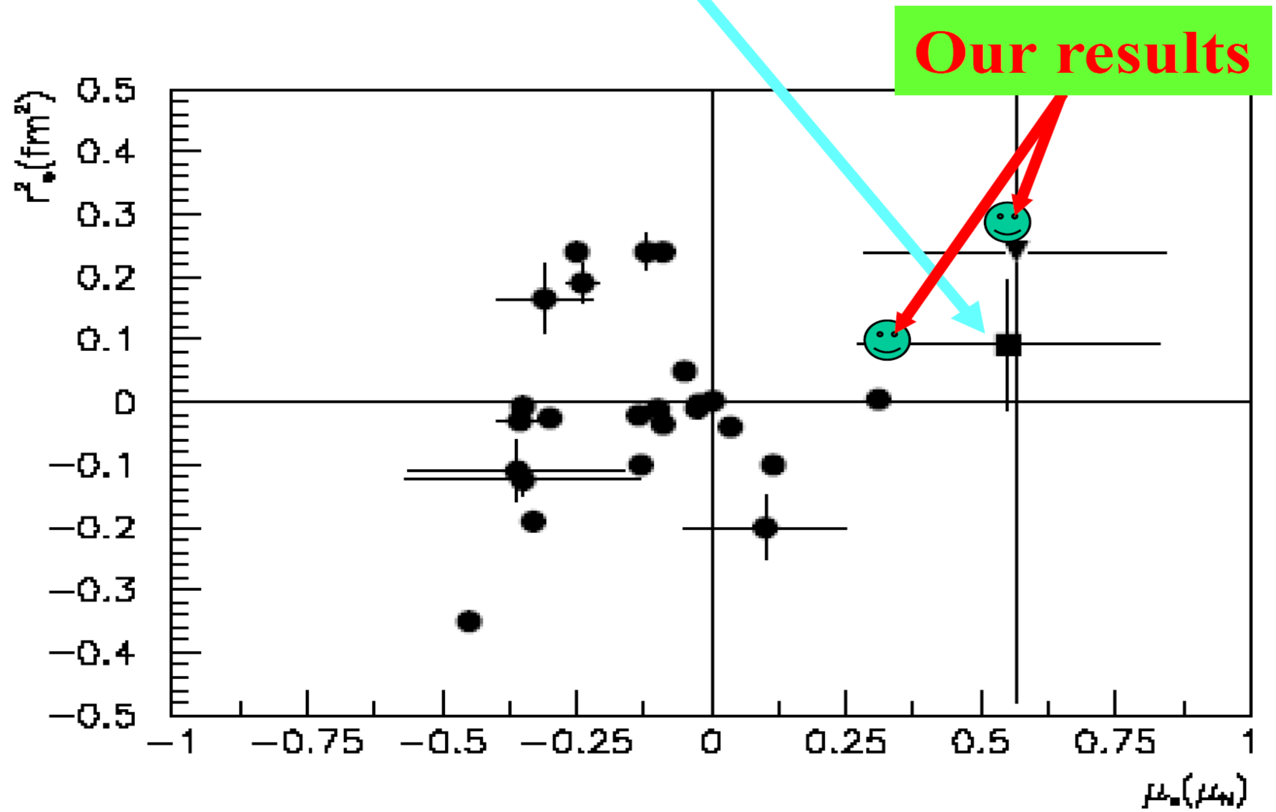
The strange magnetic moment μ_s and radii r_s from parity violating electron scattering



G0,HAPPEX/CEBAF, SAMPLE/MIT-Bates, A4/MAMI

HAPPEX/CEBAF,	Phys.Rev.Lett. 96 (2006) 022003
G0/CEBAF,	Phys.Rev.Lett. 95 (2005) 092001
A4/MAMI,	Phys.Rev.Lett. 94 (2005) 152001
SAMPLE/MIT-Bates:	Phys.Lett.B583 (2004) 79

Theory vs experiment for μ_s and r_s



Zou&Riska, PRL95(2005)072001; Riska&Zou, PLB636 (2006) 265
An-Riska-Zou, PRC73 (2006) 035207

Status in 2006

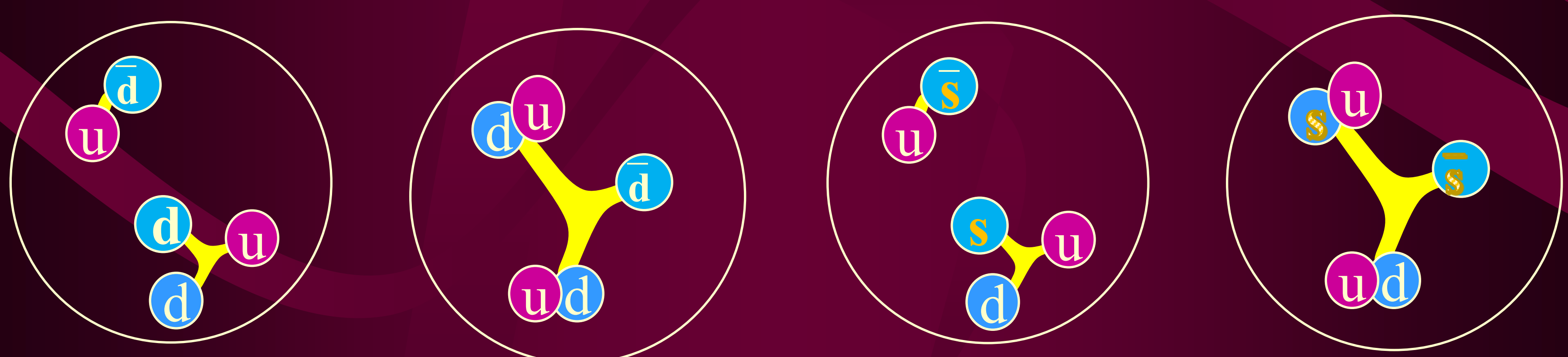
$\bar{d} - \bar{u} \sim 0.12$, $\bar{s}(x) \neq s(x)$ → two possible solutions:

meson cloud: Thomas, Speth, Weise, Oset, Brodsky, Ma, …

$$|p\rangle \sim |uud\rangle + \varepsilon_1 |n(udd)\,\pi^+(\bar{d}u)\rangle$$
$$+ \varepsilon_2 |\Delta^{++}(uuu)\,\pi^-(\bar{u}d)\rangle + \varepsilon' |\Lambda(uds)\,K^+(\bar{s}u)\rangle \ldots$$

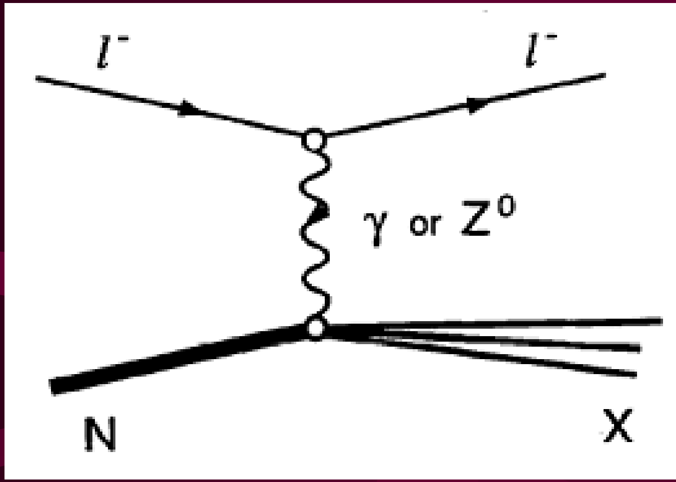
Diquark correlation: Riska, Zou, Zhu, …

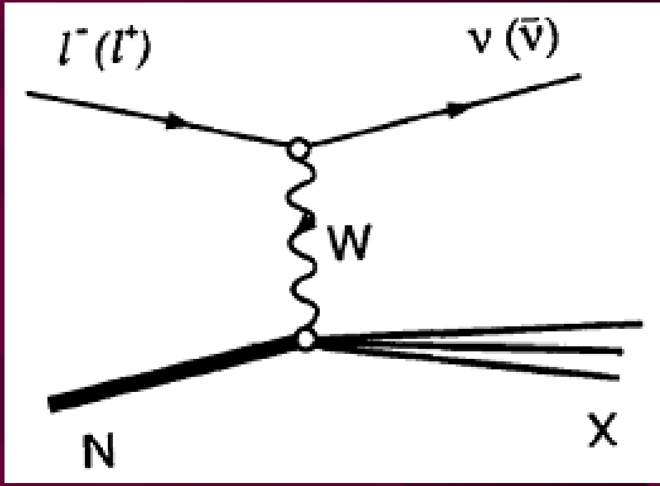
$$|p\rangle \sim |uud\rangle + \varepsilon_1 |[ud][ud]\,\bar{d}\rangle + \varepsilon' |[ud][us]\,\bar{s}\rangle + \ldots$$



Major tool to explore nucleon structure:

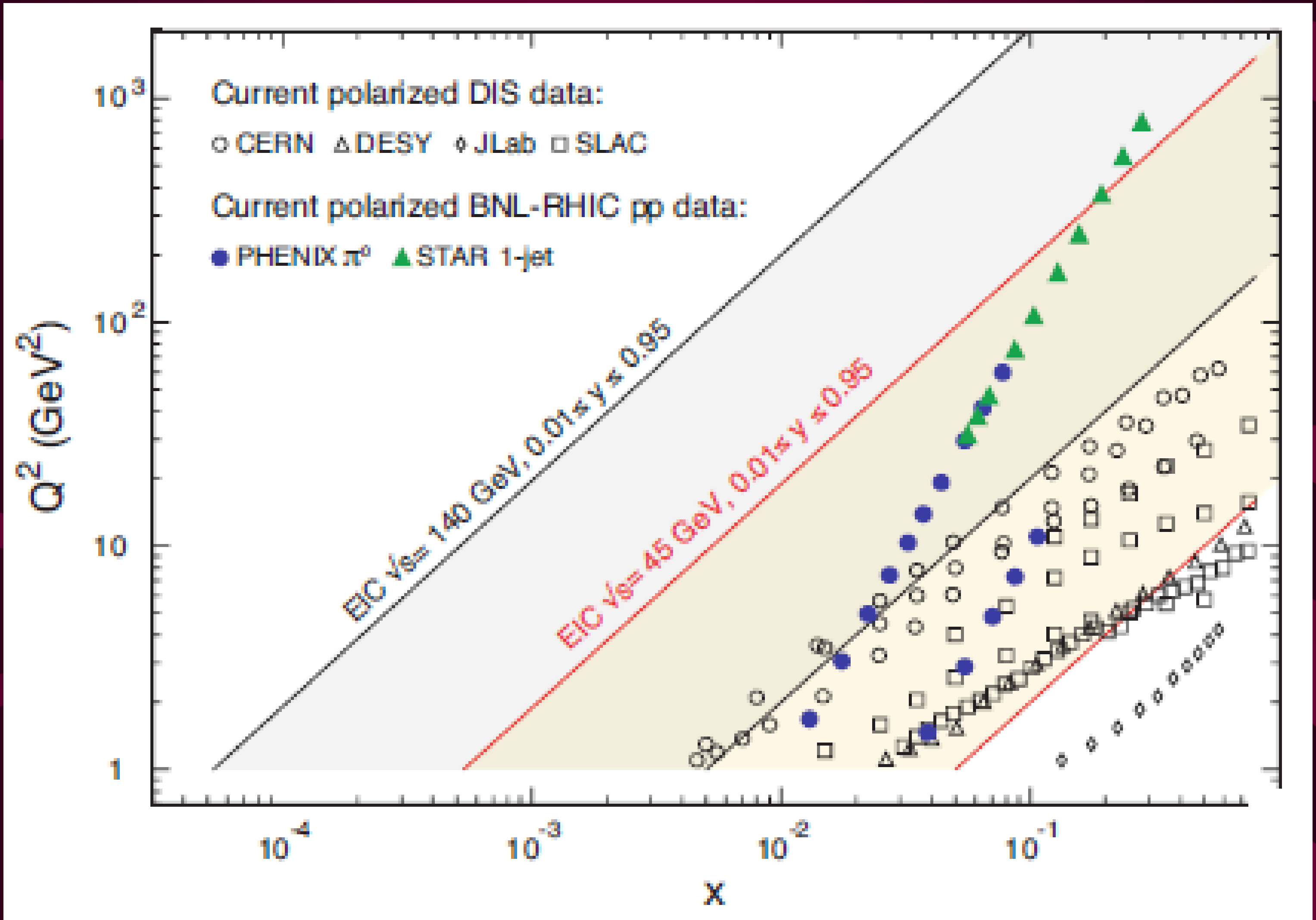
lepton-nucleon deep inelastic scattering





MAMI ~ 1 GeV   ELSA ~ 3 GeV

CEBAF ~ 6-12 GeV   HERA ~ 300 GeV



Various EIC to explore PDF of different momentum range

EIC white paper ArXiv:1212.1701

Orbital angular momentum & nucleon tomography

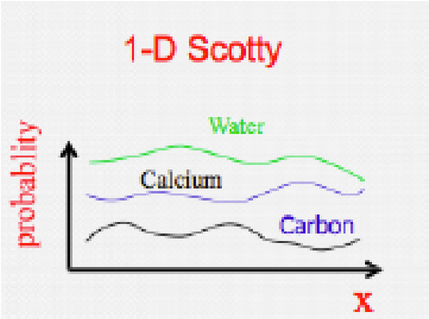
轨道角动量和质子断层摄影术

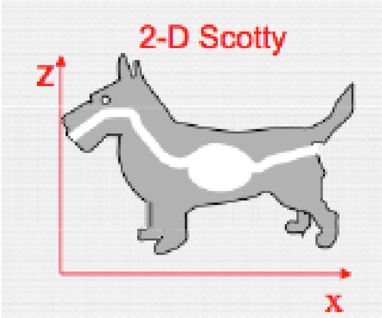
Momentum-space: generalized parton distribution functions (GPDs)

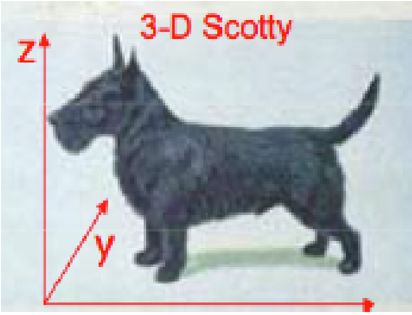
质子动量空间混合断层摄影术

Momentum space: transverse-momentum dependent parton distribution functions (TMDs)

质子三维动量断层摄影术







Deep Inelastic Scattering and Parton Distribution Functions

Deeply Virtual Exclusive Processes and GPDs

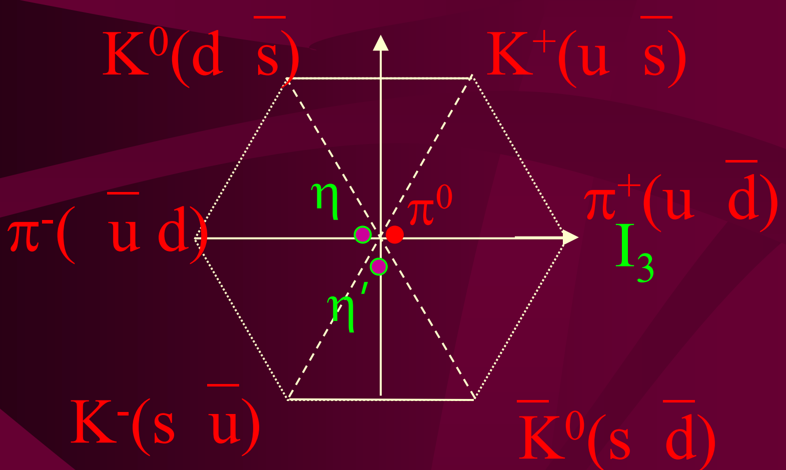
Ji, Yuan, B.Q. Ma, J.P. Ma, Liang, Qiu, etc..

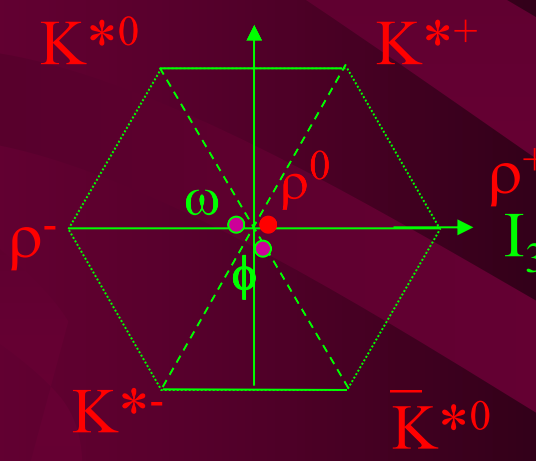
From Gao Hai-yan

2. Hadron spectroscopy

$(q\,\bar{q})$ meson : $^{2S+1}L_J$ J^{pc} $P=(-1)^{L+1}$

$^1S_0$ 0^- $^3S_1$ 1^-



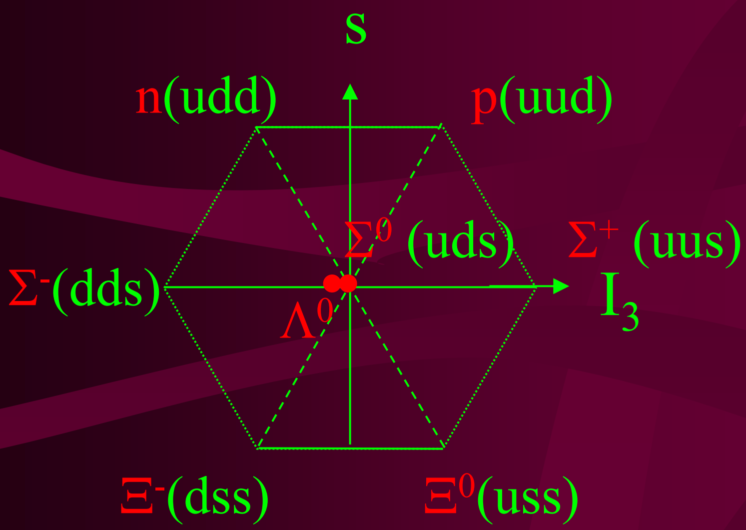


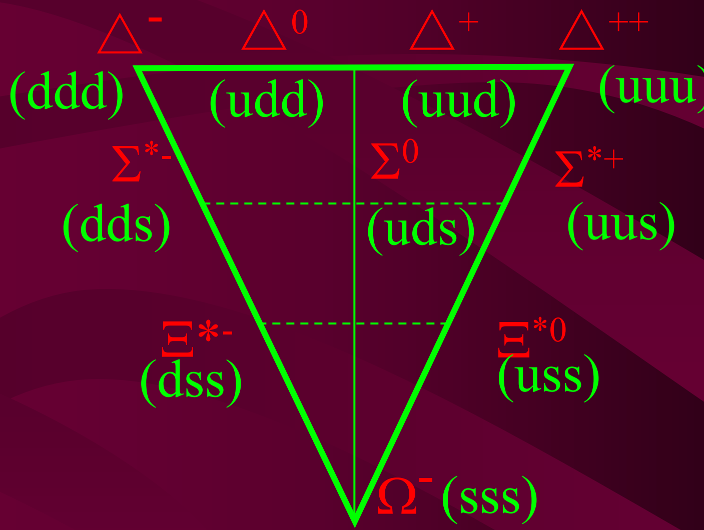
$$\pi^0 = \frac{u\,\bar{u} - d\,\bar{d}}{\sqrt{2}}$$

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $ud,\ \overline{u}d,\ \frac{1}{\sqrt{2}}(d\overline{d}-u\overline{u})$	I = $\frac{1}{2}$ $u\overline{s},\ d\overline{s};\ \overline{d}s,\ -\overline{u}s$	I = 0 f'	I = 0 f
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1380)$	$h_1(1170)$
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$
$1\,^3P_1$	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$
$1\,^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)^\ddagger$		$\omega(1650)$
$1\,^3D_2$	2^{--}		$K_2(1820)^\ddagger$		
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$
$1\,^3F_4$	4^{++}	$a_4(2040)$	$K_4^*(2045)$		$f_4(2050)$
$1\,^3G_5$	5^{--}	$\rho_5(2350)$			
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$
$2\,^3S_1$	1^{--}	$\rho(1450)$	$K^*(1410)^\ddagger$	$\phi(1680)$	$\omega(1420)$

SU(3) quark model: qqq-baryons

$1/2^+$ **J^p** **$3/2^+$**





Very successful for spacial ground states !

mass prediction $m_{\Omega^-} \cong 1670$ MeV

expt → $m_{\Omega^-} \cong 1672.45 \pm 0.29$ MeV

quenched vs un-quenched for mesons

$\bar{q}q$ $^3S_1$ nonet

$\phi(1020)$	$\bar{s}s$
$K(892)$	$\bar{s}d$
$\omega(782)$	$\bar{u}u + \bar{d}d$
$\rho(770)$	$\bar{u}u - \bar{d}d$

$\bar{q}q$ $^3P_0$ or $\bar{q}^2q^2$ nonet ?

$a_0(980)$	$\bar{u}u - \bar{d}d$,	$[\bar{u}\,\bar{s}][us] - [\bar{d}\,\bar{s}][ds]$
$f_0(980)$	$\bar{s}s$,	$[\bar{u}\,\bar{s}][us] + [\bar{d}\,\bar{s}][ds]$
$\kappa(700)$	$\bar{s}d$,	$[\bar{s}\,\bar{u}][ud]$
$f_0(500)$	$\bar{u}u + \bar{d}d$,	$[\bar{u}\,\bar{d}][ud]$

$D^*_{s0}(2317) \sim \bar{s}c\ (L=1) + [\bar{q}\,\bar{s}][qc] + DK + \ldots$

$D^*_{s1}(2460) \sim \bar{s}c\ (L=1) + D^*K + \ldots$

$X(3872) \sim \bar{c}c\ (L=1) + [\bar{q}\,\bar{c}][qc] + D^*D + \ldots$

$1/2^-$ baryon nonet with strangeness

- Mass pattern : quenched or unquenched ?

  uds (L=1) $1/2^-$ ~ $\Lambda^*(1670)$ ~ $[us][ds]\bar{s}$

  uud (L=1) $1/2^-$ ~ $N^*(1535)$ ~ $[ud][us]\bar{s}$

  uds (L=1) $1/2^-$ ~ $\Lambda^*(1405)$ ~ $[ud][su]\bar{u}$

  uus (L=1) $1/2^-$ ~ $\Sigma^*(1390)$ ~ $[us][ud]\bar{d}$

  Zou et al, NPA835 (2010) 199 ; CLAS, PRC87(2013)035206

- Strange decays of N*(1535) and Λ*(1670) :

  N*(1535) large couplings $g_{N^*N\eta}$, $g_{N^*K\Lambda}$, $g_{N^*N\eta'}$, $g_{N^*N\phi}$

  Λ*(1670) large coupling $g_{\Lambda^*\Lambda\eta}$

Important implications:

- $\bar{q}qqqq$ in S-state more favorable than qqq with L=1 !

  & $\bar{q}qqq$ in S-state more favorable than $\bar{q}q$ with L=1 !

$1/2^-$ baryon nonet ~ $\bar{q}q^2q^2$ state + …

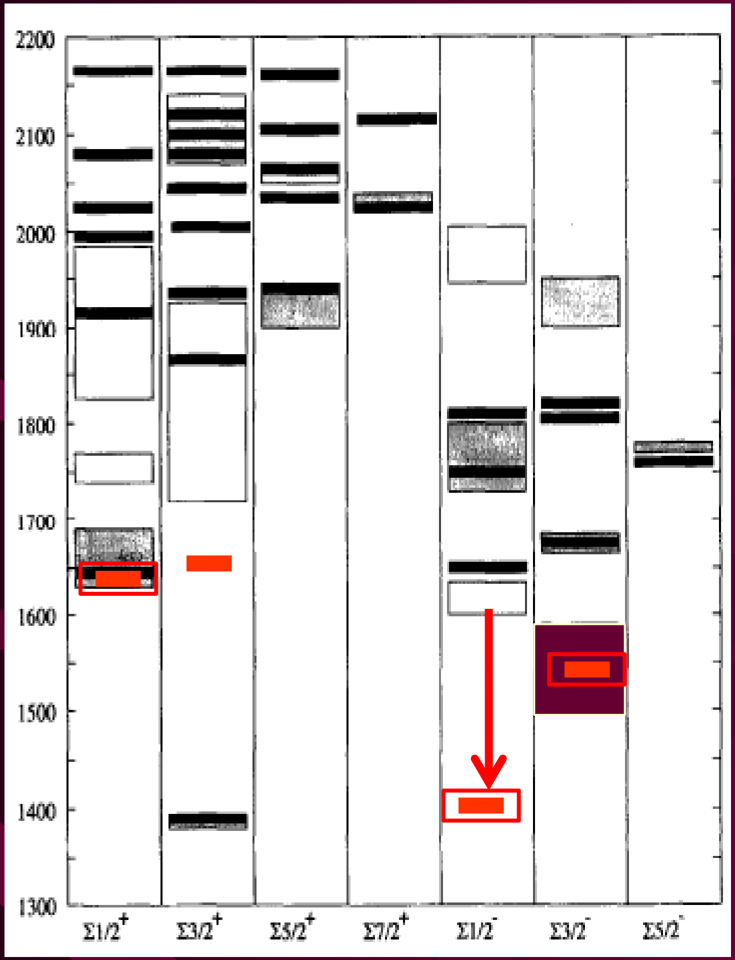
0^+ meson octet ~ $\bar{q}^2q^2$ state + …

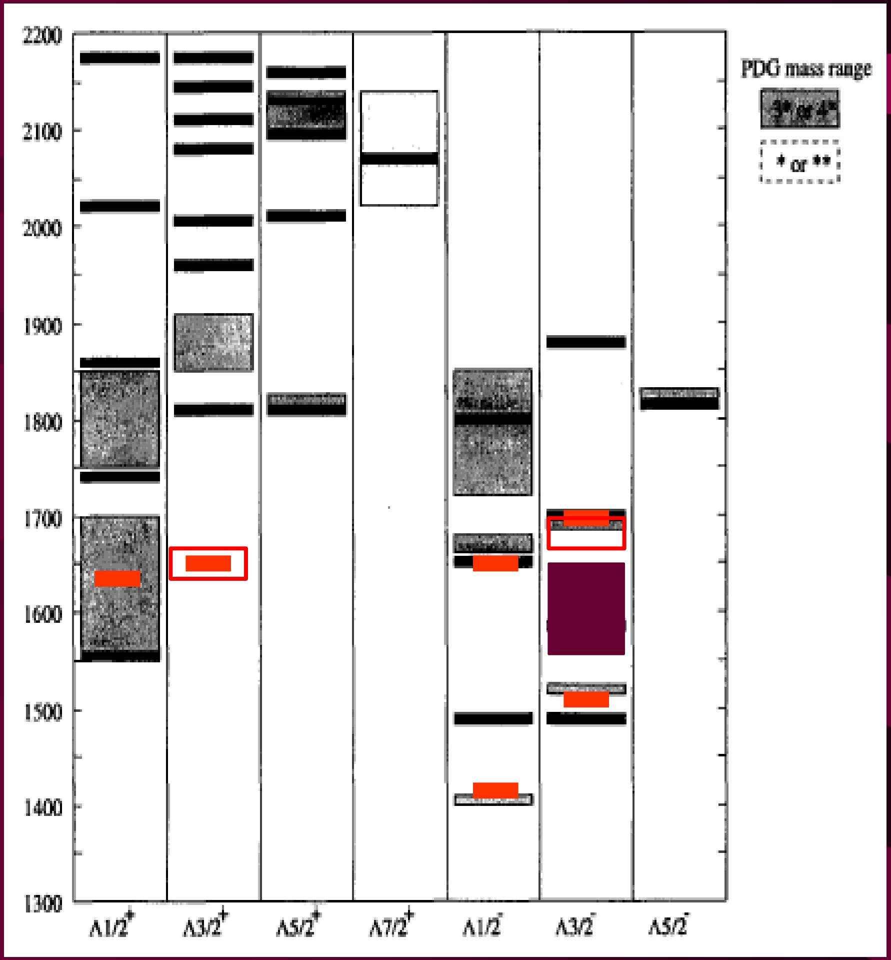
multiquark components are important for hadrons!

Quark model needs to be unquenched !

Distinctive

Predictions by quenched – & unquenched – quark models





Quenched quark model: Capstick-Roberts, Prog.Part.Nucl.Phys. 45 (2000) S241-S331

Unquenched model: Helminen-Riska , Nucl. Phys. A 699 (2002) 624

A.Zhang, S.L.Zhu et al., HEPNP 29 (2005) 250

Predictions for the lowest Ω^* by various models:

$\Omega^*(x/2^-)$ as sss (L=1) : ~ 2020 MeV

Chao, Isgur, Karl, PRD38(1981)155

$\Omega^*(1/2^-)$ as $\bar{K}\Xi$ bound state: ~ 1805 MeV

W.L.Wang, F.Huang, Z.Y.Zhang, F.Liu, JPG35 (2008) 085003

$\Omega^*(x/2^-)$ as $\bar{u}$usss (L=0) : ~ 1820 MeV

Yuan-An-Wei-Zou-Xu, PRC87(2013)025205

$\Omega^*(3/2^-)$ as sss - $\bar{u}$usss mixture : ~ 1780 MeV

by instanton/NJL interaction

An-Metsch-Zou, PRC87(2013) 065207; An-Zou, PRC89 (2014) 055209

K10@JPARC: $K^-p \rightarrow K^+ K^0 \Omega^*$ → $\Omega^*(1780)$?!

BES3@BEPC2: $e^+e^- \rightarrow \bar{\Omega}\,\Omega^*$

Σ^* in PDG: **** $\Sigma(1189)1/2^+$ $\Sigma^*(1385)3/2^+$ $\Sigma^*(1670)3/2^-$
$\Sigma^*(1775)5/2^-$ $\Sigma^*(1915)5/2^+$ $\Sigma^*(2030)7/2^+$

*** $\Sigma^*(1660)1/2^+$ $\Sigma^*(1750)1/2^-$ $\Sigma^*(1940)3/2^-$ $\Sigma^*(2250)$??

** $\Sigma^*(1620)1/2^-$ $\Sigma^*(1690)$?? $\Sigma^*(1880)1/2^+$
$\Sigma^*(2080)3/2^+$ $\Sigma^*(2455)$?? $\Sigma^*(2620)$??

* $\Sigma^*(1480)$?? $\Sigma^*(1560)$?? $\Sigma^*(1580)3/2^-$ $\Sigma^*(1770)1/2^+$
$\Sigma^*(1840)3/2^+$ $\Sigma^*(2000)3/2^-$ $\Sigma^*(2070)5/2^+$ $\Sigma^*(2100)7/2^-$
$\Sigma^*(3000)$?? $\Sigma^*(3170)$??

Ξ^* in PDG: **** $\Xi(1320)\ 1/2^+$, $\Xi(1530)\ 3/2^+$
*** $\Xi(1690)$, $\Xi(1820)\ 3/2^-$, $\Xi(1950)$, $\Xi(2030)$
** $\Xi(2250)$, $\Xi(2370)$
* $\Xi(1620)$, $\Xi(2120)$, $\Xi(2500)$

Ω^* in PDG: $\Omega(1672)\ 3/2^+$ ****, $\Omega(2250)$***, $\Omega(2380)$ **, $\Omega(2470)$ **

Experiment knowledge on hyperon states still very poor !

More expts on hadron spectroscopy are needed !

3. Hadronic molecules & multiquark states

Brief history for the discovery of hadronic molecules

1932: Neutron & Deuteron - the 1-st hadronic molecule

1947: π, K

1959: KN &molecule predicted by Dalitz Tuan, PRL2, 425

1961: $\Lambda(1405) \rightarrow \Sigma\pi$ observed by Alston et al., PRL6, 698

post-1962: $f_0(980)$ & a_0 (980) $\bar{K}K$ molecules? Isgur, …

$f_1(1420)$ $\bar{K}K^*$ molecule ? Tornqvist, …

$f_0(1710)$ $\bar{K}^*K^*$ molecule ? Oset, …

$N^*(1535)$ $\bar{K}\Sigma$ - $\bar{K}\Lambda$ molecule ? Kaiser, …

$D^*_{s0}(2317)$ & $D^*_{s1}(2460)$ $\bar{K}D$ & $\bar{K}D^*$ molecules? Barnes, …

…….

Difficulties to pin down pentaquark states

Fate of the first pentaquark predicted and observed: $1/2^-$

1959: $\bar{K}N$ molecule predicted by Dalitz-Tuan, PRL2, 425

1961: $\Lambda(1405) \rightarrow \Sigma\pi$ observed by Alston et al., PRL6, 698

1964: Quark model (uds) for $\Lambda(1405)$

1995: $\bar{K}N$ dynamically generated -- Kaiser et al., NPA954, 325

2001: 2 pole structure by $\bar{K}N$-$\Sigma\pi$ -- Oller et al., PLB500, 263

PDG2010: "The clean Λ_c spectrum has in fact been taken to settle the decades-long discussion about the nature of the $\Lambda(1405)$ —true 3-quark state or mere $\bar{K}N$ threshold effect?— unambiguously in favor of the first interpretation."

Fate of the last famous fading pentaquark $\theta^+(1540)$: $1/2^+$

1997: $Z^+(1530)$ predicted by Diakonov et al., ZPA359, 305

2003: $\theta^+(1540) \rightarrow K^+n$ claimed by LEPS, PRL91, 012002

2003: $\bar{s}$ (ud)(ud) for $\theta(1540)$ by Jaffe&Wilczek, PRL91, 232003

2003: $\bar{s}$ ud)(ud) for $\theta(1540)$ by Karliner&Lipkin, PLB575, 249

2004: supported by 10 expts → $\theta(1540)$ well-established by PDG

2004: not supported by BESII, PRD70, 012004

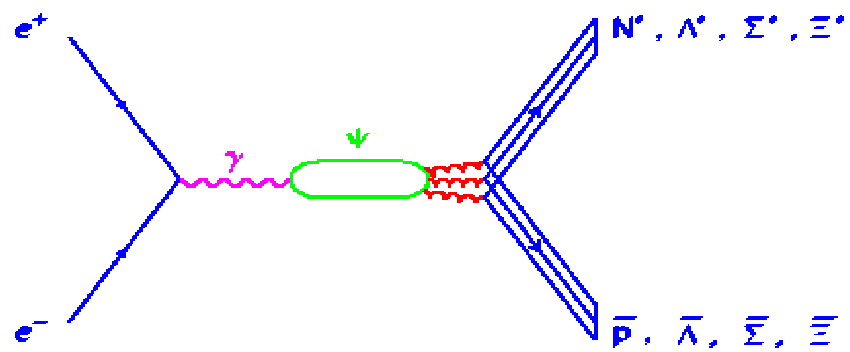
2005: not supported by many high stats experiments

2006: removed from PDG

Note: $\theta^+(1540)$ is not supported by hadronic molecule model & chiral quark model by Huang, Zhang, Yu, Zou, PLB586(2004)69

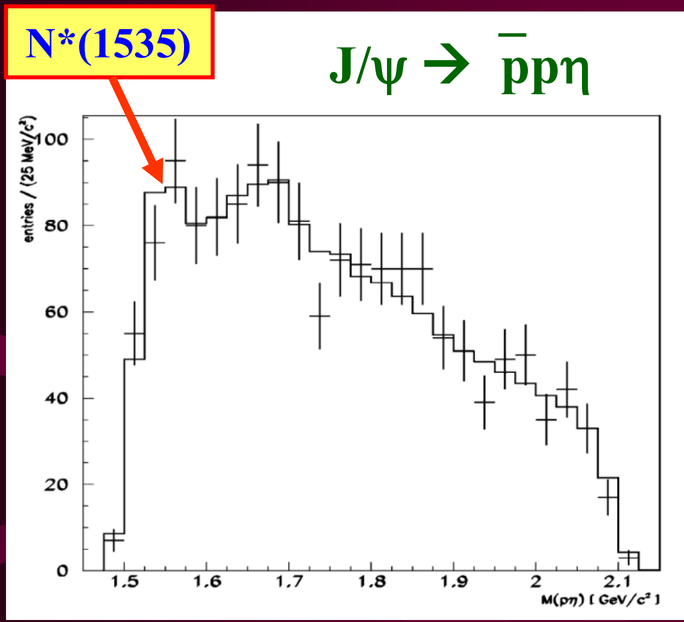
BEPC核子和超子激发态（N*, Λ*, Σ*, Ξ*, Ω*）新项目

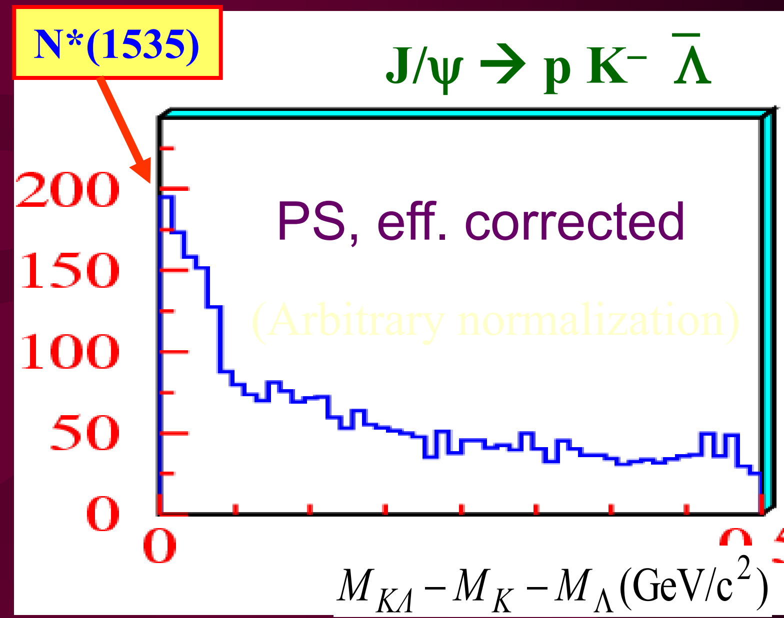
$$\Psi \rightarrow \overline{B}BM \Rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^*, \Omega^*$$



特点和优势： 理想的同位旋、低自旋分离器，独具特色
国际上其它实验 (ep, γp, πp, Kp) 不具备这些优点

KΣ molecule - N*(1535) in J/ψ decays





BES, PLB510 (2001) 75

BESII, IJMPA20 (2005) 1985

B.C.Liu, B.S.Zou, PRL96 (2006) 042002 : N*(1535) ~ $uud\bar{s}s$!

$\bar{s}suud \rightarrow \bar{c}cuud$ 预言了P_c五夸克态 - 被LHCb实验证实

- 我们首次预言了3个可衰变到J/ψ-p的五夸克态 (P_c),
  建议通过J/ψ-p衰变道寻找:

  Wu, Molina, Oset, Zou, PRL 105 (2010) 232001

  Wang, Huang, Zhang, Zou, PRC 84 (2011) 015203

  Wu, Lee, Zou, PRC 85 (2012) 044002

  → 3个 $\bar{c}cuud$- P_c五夸克态: 1个$D\Sigma_c$ + 2个$D^*\Sigma_c$分子态

- 国际系列会议特邀大会报告: HYP2012 (西班牙), NSTAR2015 (日本), MENU2016 (日本), CHARM2018 (俄国)
- 列入美国JLab-12GeV和德国PANDA实验寻找计划
- LHCb实验2015-2019年观测到3个与我们预言相符的P_c态

LHCb观测到与我们预言相符的3个P_c五夸克态

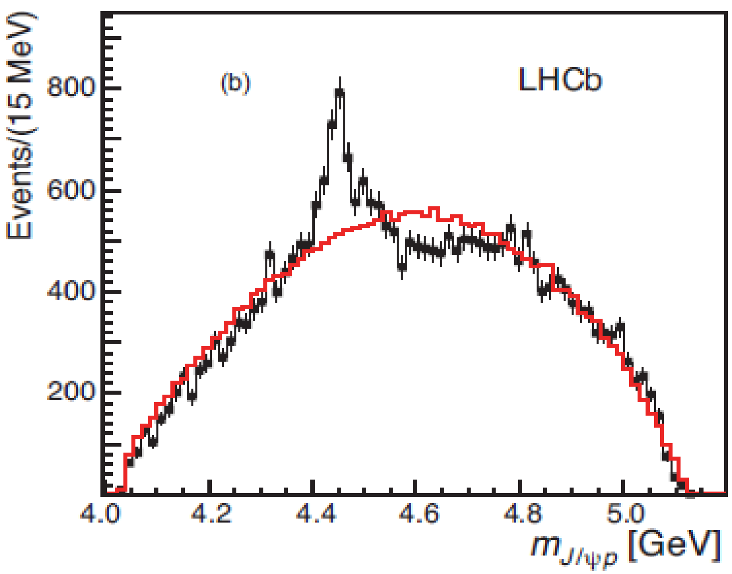
Selected for a Viewpoint in *Physics*

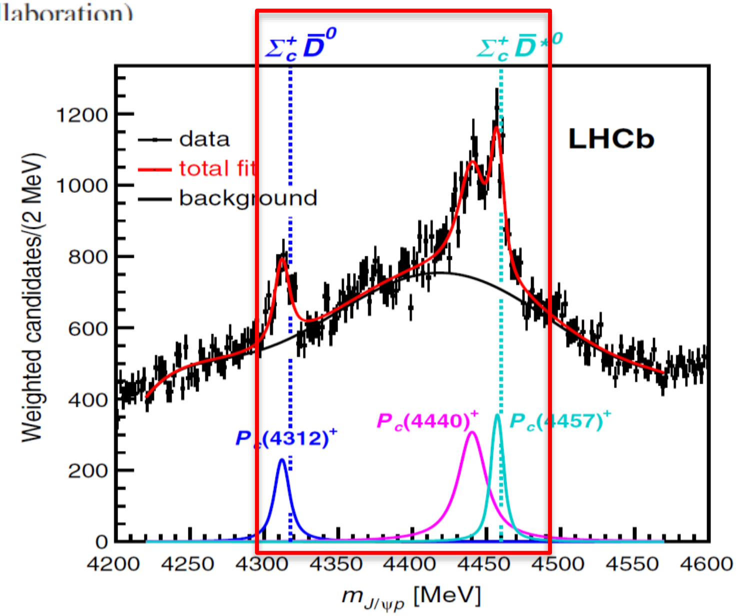
PRL **115**, 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.**
(LHCb Collaboration)

PRL 122 (2019) 222001



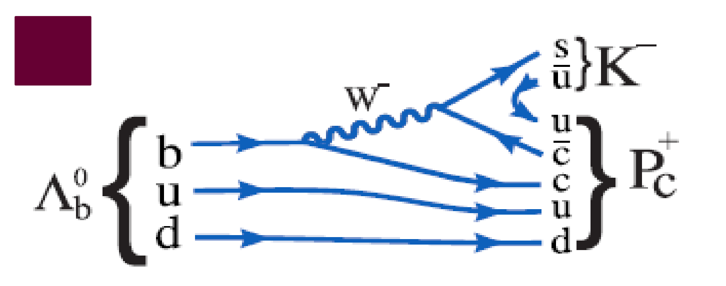


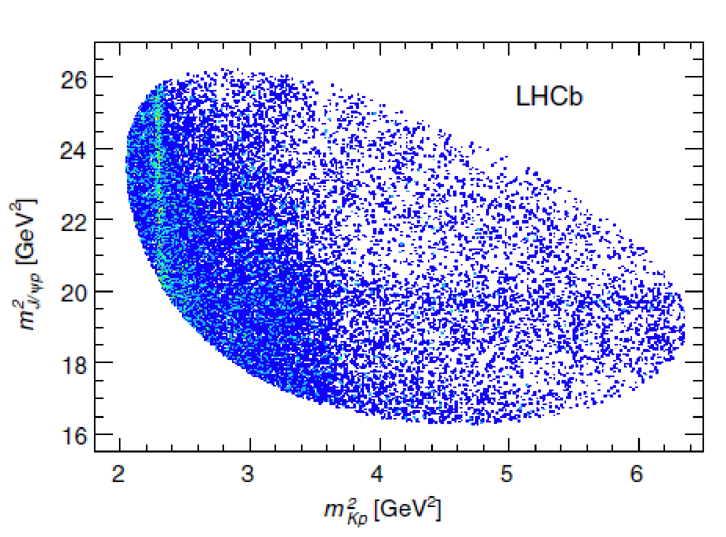
入选美国物理杂志2015年度八大突破之一

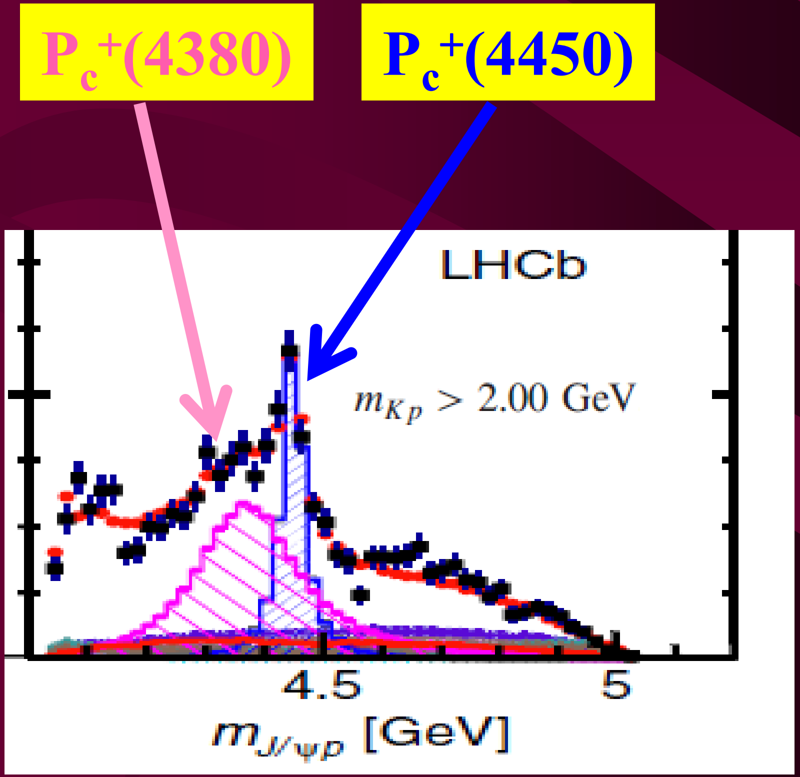
各类五夸克态半个多世纪的寻找，终获确证！

LHCb penta-quark states

LHCb, Phys.Rev.Lett. 115 (2015) 072001 :
Observation of two P_c^+ from $\Lambda_b^0 \to J/\psi K^- p$

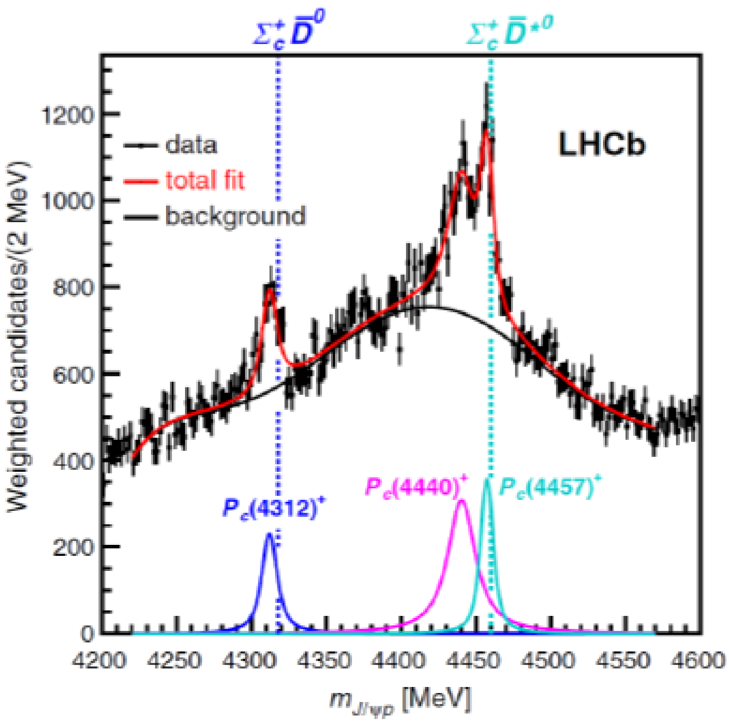


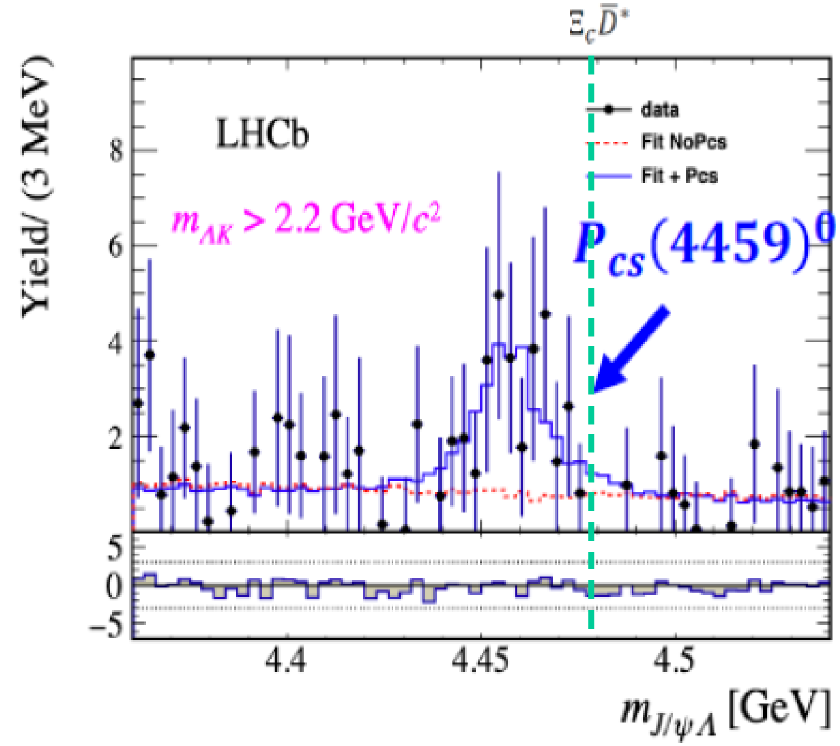




LHCb, PRL122 (2019) 222001

Sci. Bull. (2021) arXiv:2012.10380





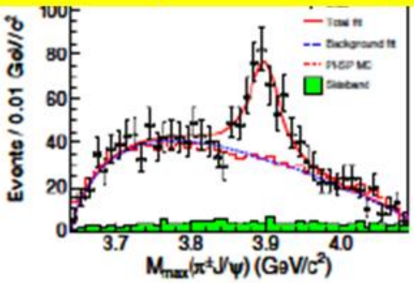
Consistent with expectation for hadronic molecules within theoretical uncertainties

LHCb discoveries – historical achievement for pentaquarks !
very important for understanding whole baryon spectroscopy

BESIII上发现的Zc家族

Zc(3900)$^+$

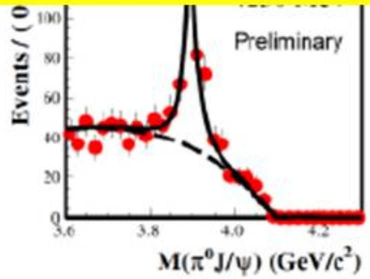
PRL 110, 252001 (2013)



$e^+e^- \to \pi^-\pi^+J/\psi$

Zc(3900)^0

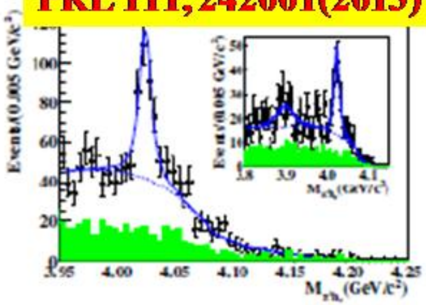
PRL 115, 112003 (2015)



$e^+e^- \to \pi^0\pi^0J/\psi$

Zc(4020)$^+$

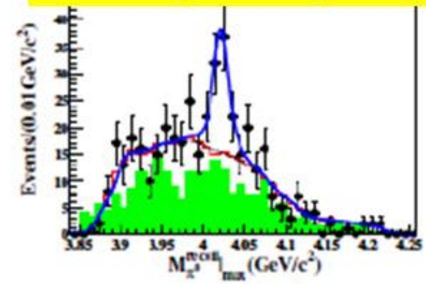
PRL 111, 242001(2013)



$e^+e^- \to \pi^-\pi^+h_c$

Zc(4020)^0

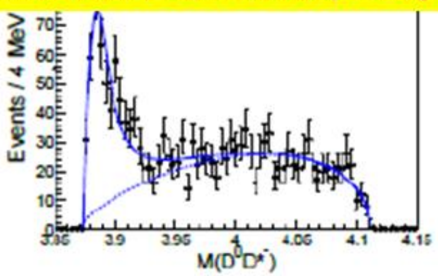
PRL113,212002 (2014)



$e^+e^- \to \pi^0\pi^0h_c$

Zc(3885)$^+$

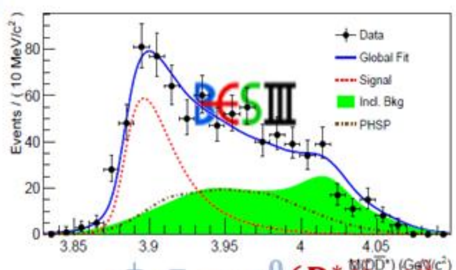
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



$e^+e^- \to \pi^-(D\bar{D}^*)^+$

Zc(3885)^0

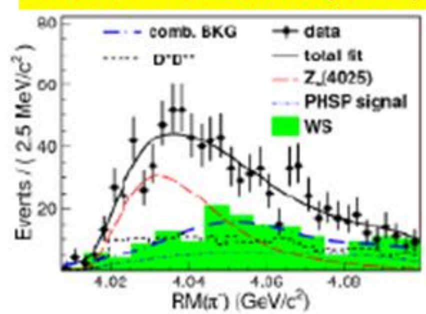
PRL 115, 222002 (2015)



$e^+e^- \to \pi^0(D^*\bar{D})^0$

Zc(4025)$^+$

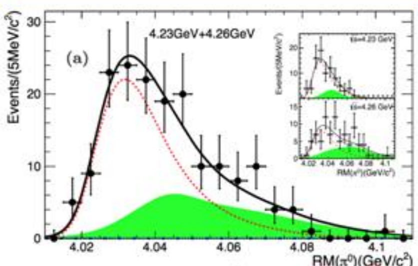
PRL 112, 132001 (2014)



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

Zc(4025)^0

PRL115, 182002 (2015)

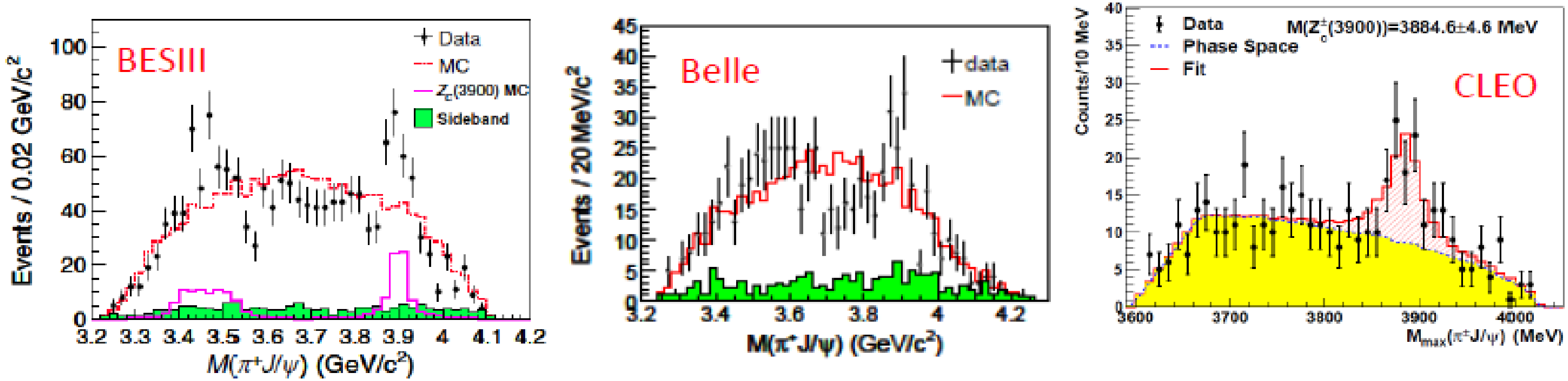


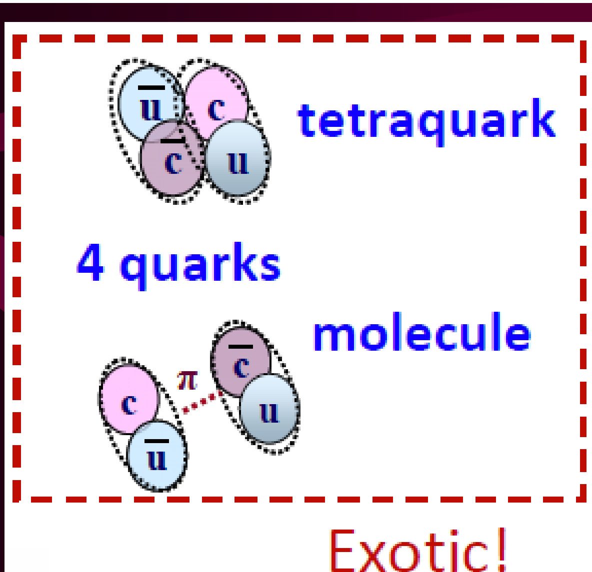
$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

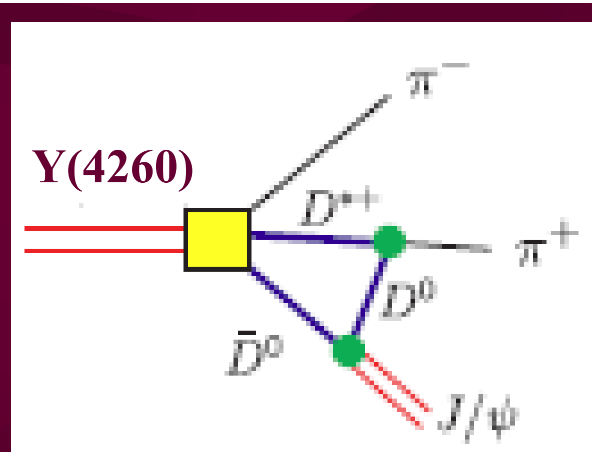
“Y(4260)的结构以及带电Zc(3900)的产生”

PRL 110, 252001 (2013) PHYSICAL REVIEW LETTERS week ending 21 JUNE 2013

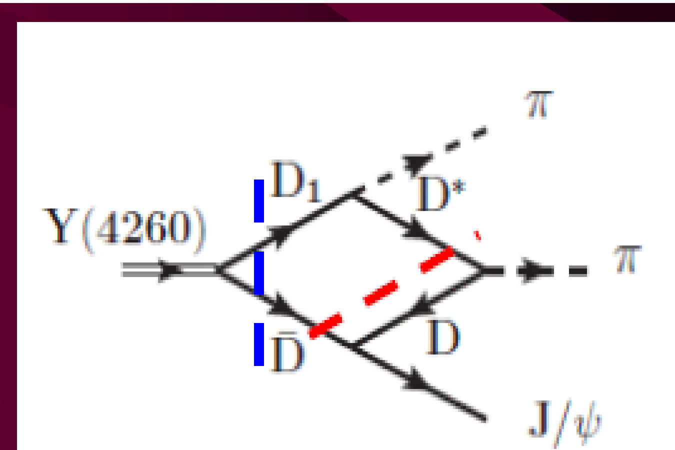
Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV







D.Y.Chen, X.Liu, PRD84(2011)034032



Q.Wang,C.Hanhart,Q.Zhao PRL111(2013)132003

Multiquark states – crucial for hadron structure !

Zc(3900) → top cited paper for BES (2013) 1200 cites

Pc states → top cited paper for LHCb (2015) 1959 cites

H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1:
"The hidden-charm pentaquark and tetraquark states" 1250 cites

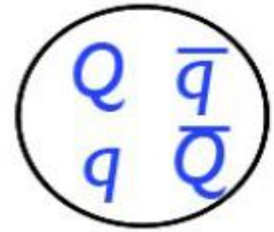
F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou,
Rev.Mod.Phys. 90 (2018) 015004: "Hadronic molecules" 1369 cites

理论和实验的相互配合使我国强子谱研究走在国际最前列

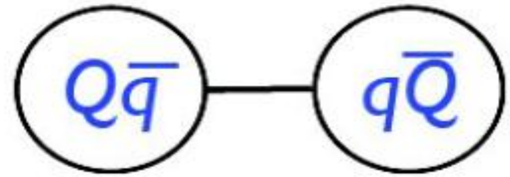
Models for XYZ Mesons

Quarkonium Tetraquarks

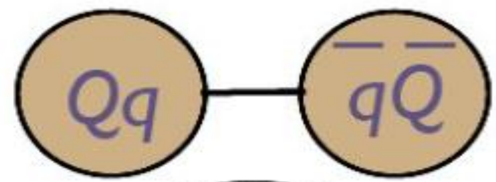
- compact tetraquark



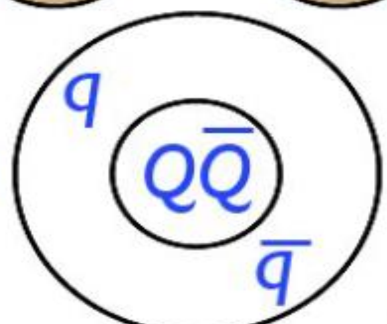
- meson molecule



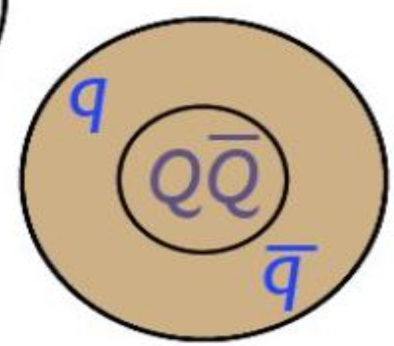
- diquark-onium



- hadro-quarkonium



- quarkonium adjoint meson



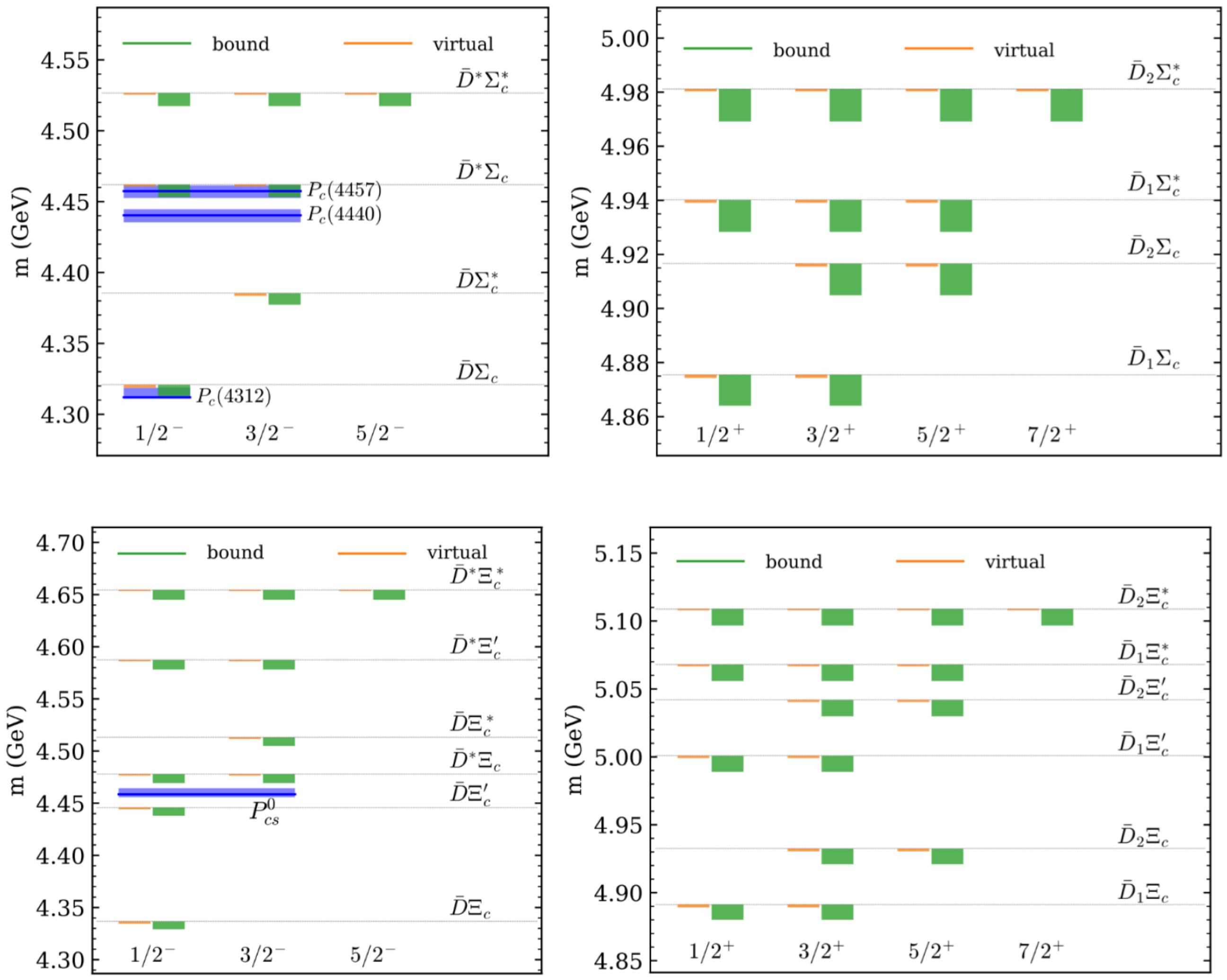
New Particles		relevant thresholds	
Zc(3900)	$\bar{d}u\ \bar{c}c$	D*D	3880 MeV
Zc(4020)		D*D*	4020 MeV
Zb(10610)	$\bar{d}u\ \bar{b}b$	B*B	10605 MeV
Zb(10650)		B*B*	10650 MeV
Pc(4312)	$uud\ \bar{c}c$	$D\Sigma_c$	4317 MeV
Pc(4380)		$D\Sigma_c^*$	4382 MeV
Pc(4440)/ Pc(4457)		$D^*\Sigma_c$	4459 MeV

Hadron-hadron resonances ?

F.K.Guo, Hanhart, Meissner,Q.Wang,Q.Zhao,Zou, **Rev.Mod.Phys.90 (2018)015004**

A survey of hadronic molecules with hidden charm

X.K.Dong, F.K.Guo, B.S.Zou Progr. Phys. 41 (2021) 65

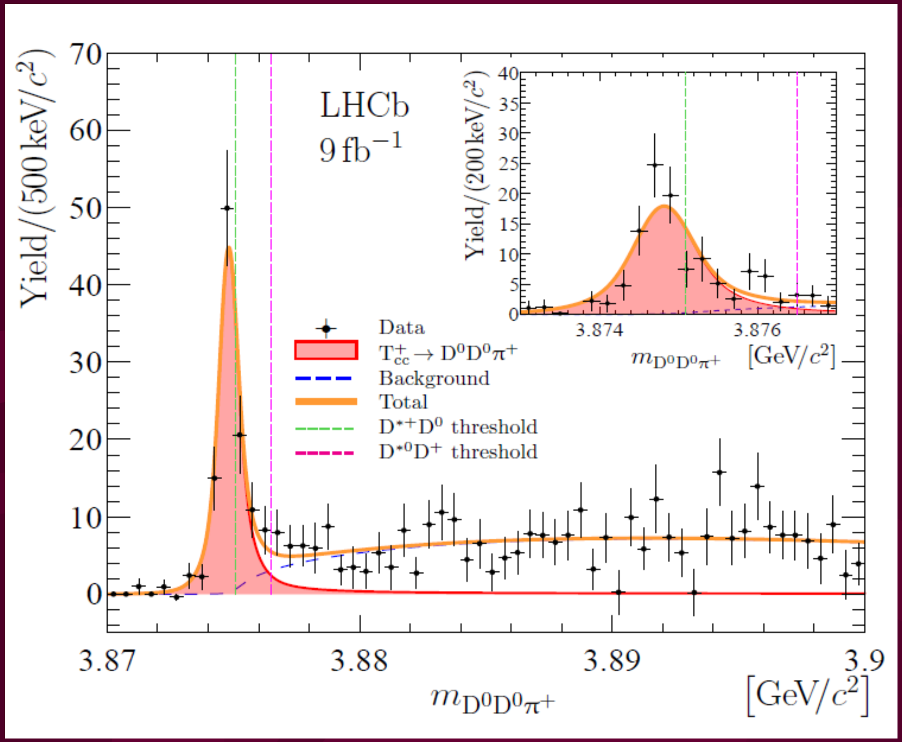


P_c

P_{cs}

Observation of T_{cc}^+ by LHCb

Nature Phys. 18 (2022) 7, 751



Consistent with expectation for D*D molecule

X.K.Dong, F.K.Guo, B.S.Zou, Commun.Theor.Phys.73(2021)125201

T.Barnes, N.Black, D.Dean, E.Swanson, Phys.Rev.C60(1999)045202

D.Janc, M.Rosina, Few Body Syst. 35(2004)175

Y.Yang, C.Deng, J.Ping, T.Goldman, Phys.Rev.D80(2009)114023

T.Caramés, A.Valcarce, J.Vijande, Phys.Lett.B699(2011)291

S.Ohkoda, Y.Yamaguchi, S.Yasui, K.Sudoh, A.Hosaka, Phys.Rev.D86(2012)034019

N.Li, Z.F.Sun, X.Liu, S.L.Zhu, Phys.Rev.D88(2013)114008

M.Z.Liu, T.W.Wu, M.P.Valderrama, J.J.Xie, L.S.Geng, Phys.Rev.D99(2019)094018

H.Xu, B.Wang, Z.W.Liu, X.Liu, Phys.Rev.D99(2019)014027

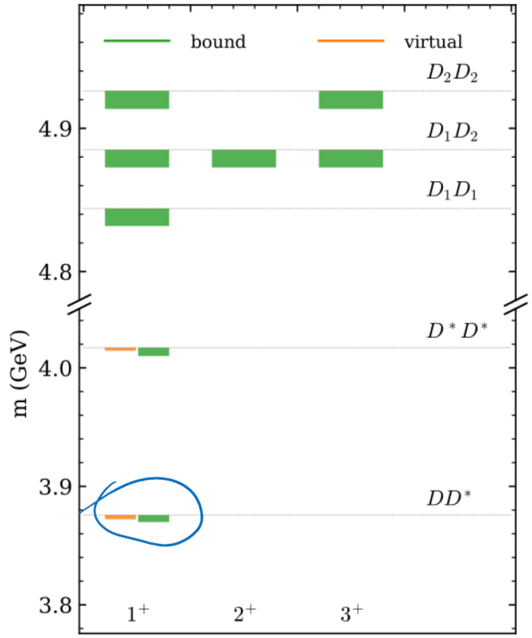
M.Z.Liu, J.J.Xie, L.S.Geng, Phys.Rev.D102(2020)091502

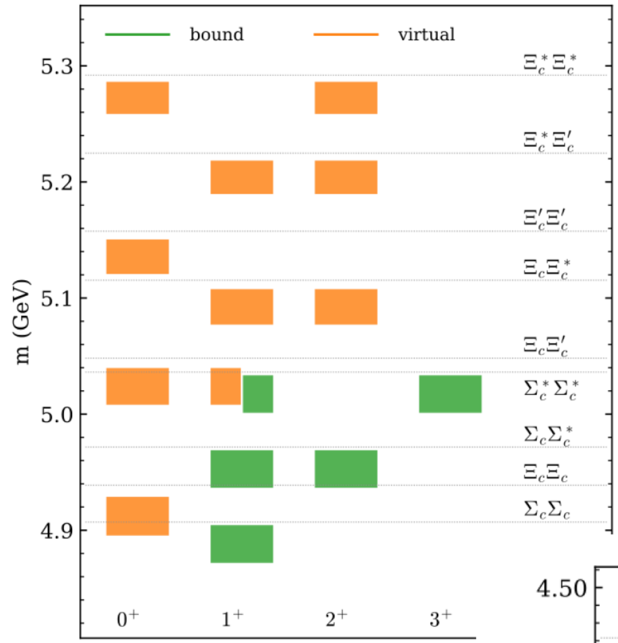
⇓ $V_{\rho,\omega} + V_{\pi} + \dots$

DD*(I=0, $J^P = 1^+$) bound state -- T_{cc}^+

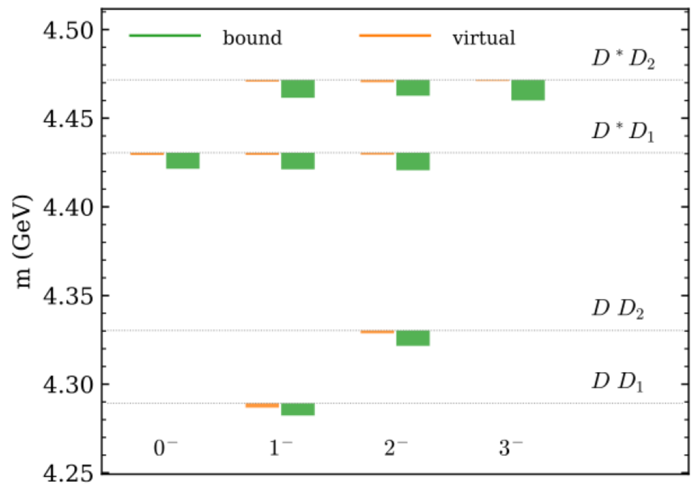
A survey of heavy-heavy hadronic molecules

X.K.Dong, F.K.Guo, B.S.Zou, Commun.Theor.Phys.73(2021)125201





✓ Isoscalar $\Sigma_c^{(*)}\Sigma_c^{(*)}$ dibaryons very likely bound

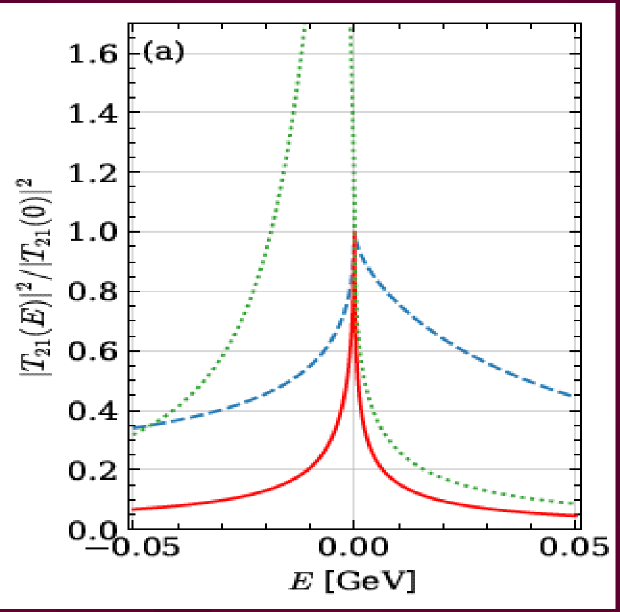


✓ T_{cc} as an isoscalar DD^* bound or virtual state, D^*D^* predicted to be similar, with $P = +$

✓ Similar in $P = -$ sector

Explaining the many threshold structures in hadron spectrum with heavy quarks

X.K.Dong, F.K.Guo, B.S.Zou, PRL126 (2021) 152001



Prediction of a narrow exotic D^*D_1 molecule with $J^{PC} = 0^{--}$

T.Ji, X.K.Dong, F.K.Guo, B.S.Zou, PRL129 (2022) 102002

$e^+e^- \rightarrow \eta\psi_0(4360) \rightarrow \eta\eta\psi$

Hybrid, Glueball or hadronic molecules ?

Observation of $\eta_1(1855)$ with exotic $J^{PC}=1^{-+}$ in $J/\psi \to \gamma\eta\eta'$

BESIII Collaboration, PRL 129 (2022) 192002

Interpretation of the $\eta_1(1855)$ as a $\bar{K}K_1$ (1400)+ c.c. molecule

X.K.Dong, Y.H.Lin, B.S.Zou, SCIENCE CHINA PMA 65 (2022) 261011
M.J.Yan, J.M.Dias, A.Guevara, F.K.Guo, B.S.Zou, Universe 9 (2023) 109

Two dynamical generated a_0 resonances by VV interactions

Z.L.Wang, B.S.Zou, EPJC 82 (2022) 509

$\rho\rho$ / $\rho\omega$ molecules → f_0 (1500) / a_0 (1450)

$\bar{K}^*K^*$(I=0,1) molecules → f_0 (1710) / a_0 (1710)

Observation of a_0(1710-1817) → $K_S^0K^+$ in D_s^+ → $K_S^0K^+\pi^0$ decay

BESIII Collaboration, PRL 129 (2022) 182001

V. Prospects

1. Nucleon structure ep

CEBAF12GeV Ecm : ~ 5 GeV

EIC Ecm : 20 ~ 100 GeV 10y later ?

EicC@HIAF Ecm : ~ 15 GeV 10y later ?

also $c\bar{c}uud$, $b\bar{b}uud$ pentaquarks & cqq， bqq states

νN experiments $\bar{\nu}_{e/\mu} + p \to e^+/\mu^+ + \pi + \Lambda/\Sigma$

2. Hadron spectroscopy

1) $Z_{b/c}$ & P_c states open a new window for studying multiquark states, need systematic study at

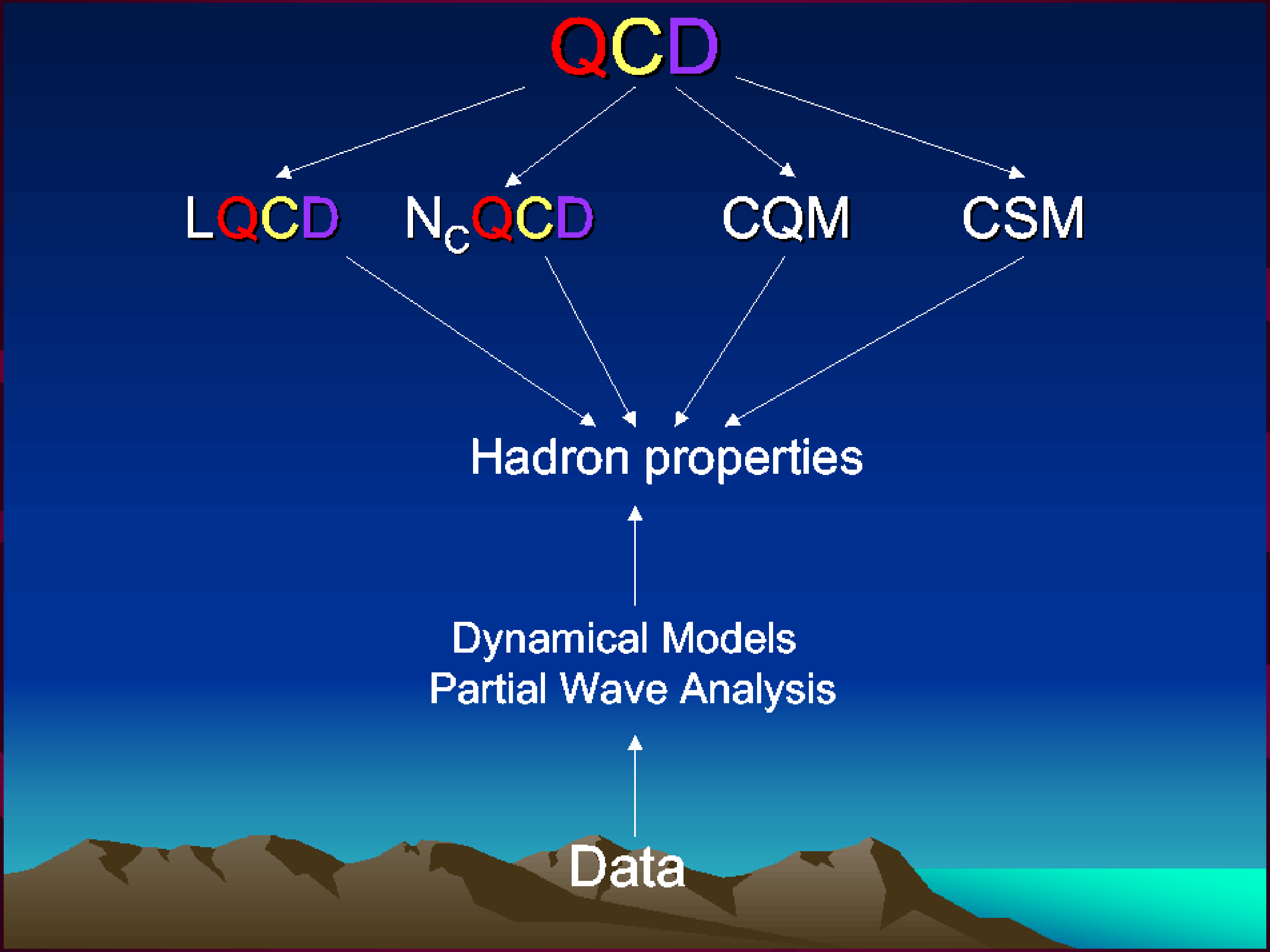
BEPC2-3/super τ-c, BelleII, π10/K10@JPARC, LHCb, ep@JLab, PANDA, EicC, EIC, etc.

2) My favorite strategy:

$\bar{c}cuud$ & $\bar{c}cuds$ → sss - $\bar{q}qsss$ & cqq - $\bar{q}qcqq$
→ hyperons → light baryons

$\bar{c}c$ $\bar{u}d$ & $\bar{c}s$ $\bar{u}d$ → $\bar{c}c$ - $\bar{q}q$ $\bar{c}c$ → $\bar{c}q$ - $\bar{c}q$ $\bar{q}q$
$\bar{c}s$ - $\bar{q}q$ $\bar{c}s$ → light mesons

3) combined efforts from both theory & experiment sides



结束语

强相互作用决定了强子、原子核两个物质微观基本层次的结构，也是基本粒子、宇宙天体演化物理的重要组成部分，还有很多待解之谜。

我国大科学装置的发展（BEPCII,STCF,HIAF,EicC等）、理论和实验的相互配合使我国强相互作用物理的研究走在国际前列，大有可为。

人员短缺，欢迎有志青年加入我们的队伍！

谢谢大家！