Physics Opportunities with heavy quark system at FAIR

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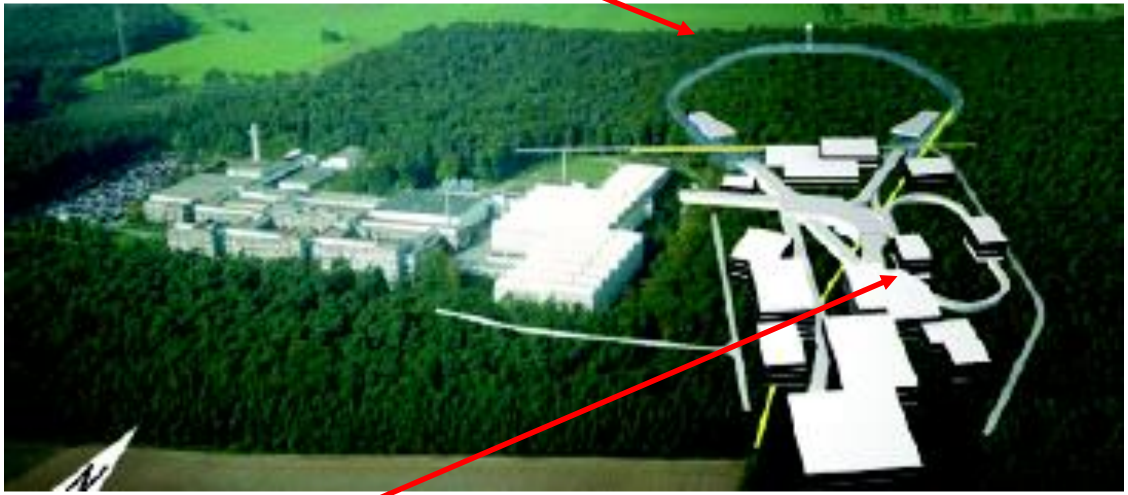
1. Introduction to FAIR
2. Heavy quark system in nuclear medium
3. Heavy exotics from heavy Ion collision
4. Summary

Introduction to FAIR

Facility for Antiproton and Ion Research
at GSI

FAIR

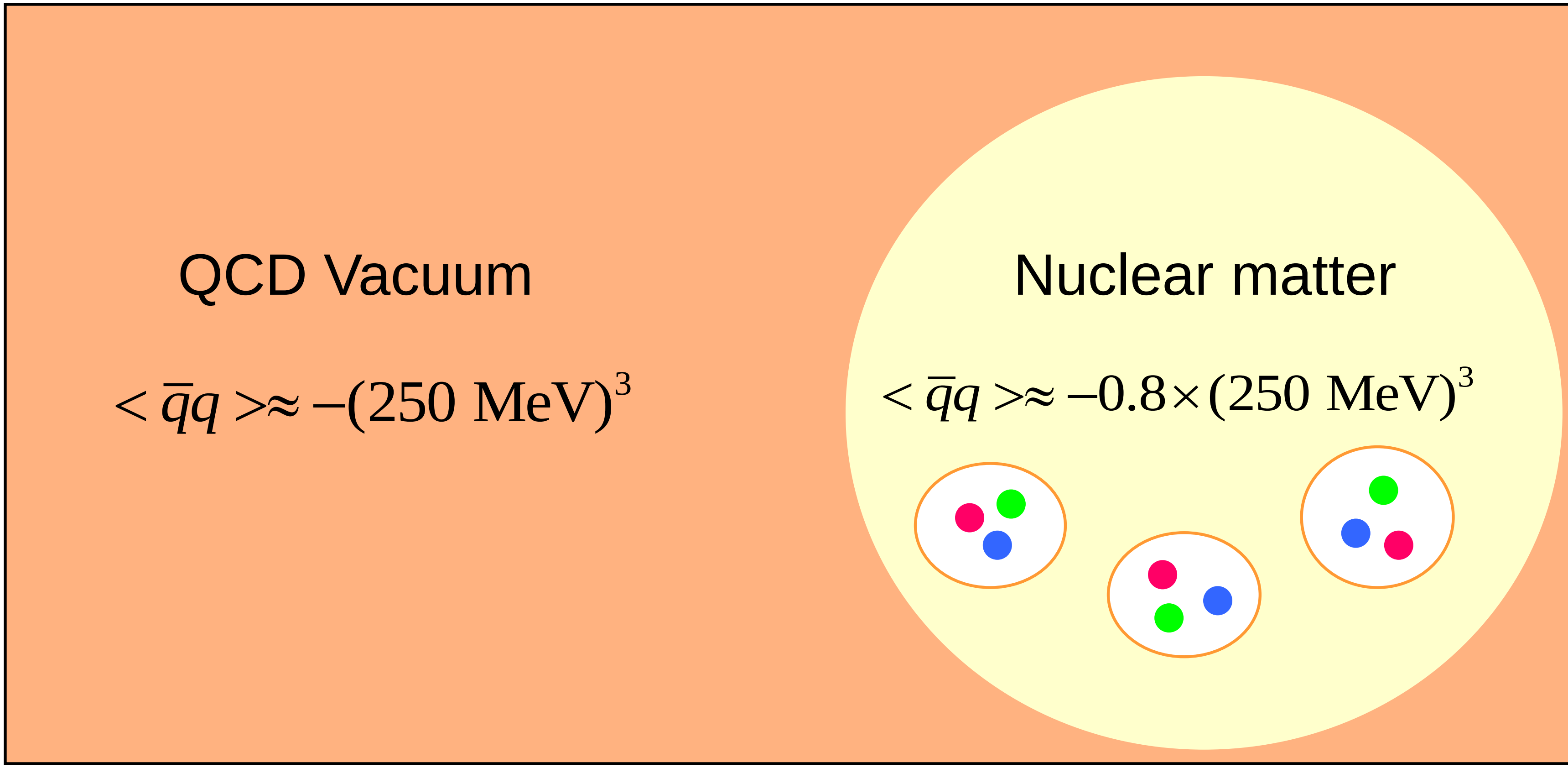
1. CBM 2-35 GeV Heavy Ion (Gold) projectile
   QCD phase diagram at high baryon density



2. PANDA: anti proton project (1-15 GeV)
   charmonium sprectroscopy, origin of hadron mass

Heavy quark system in nuclear medium

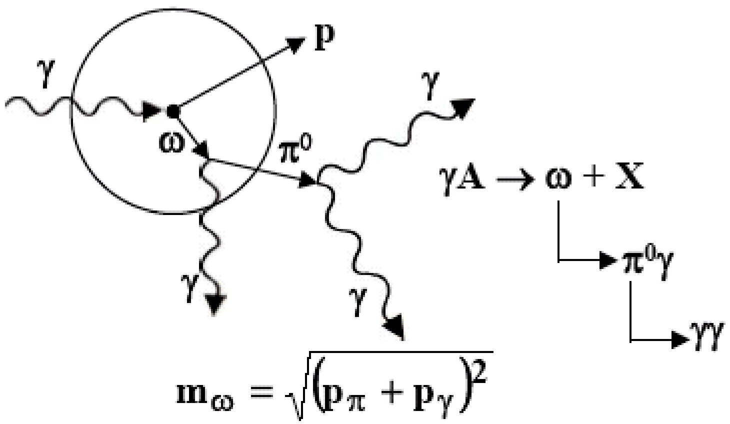
Physics with antiproton beam



Partial Chiral symmetry restoration in nuclear matter

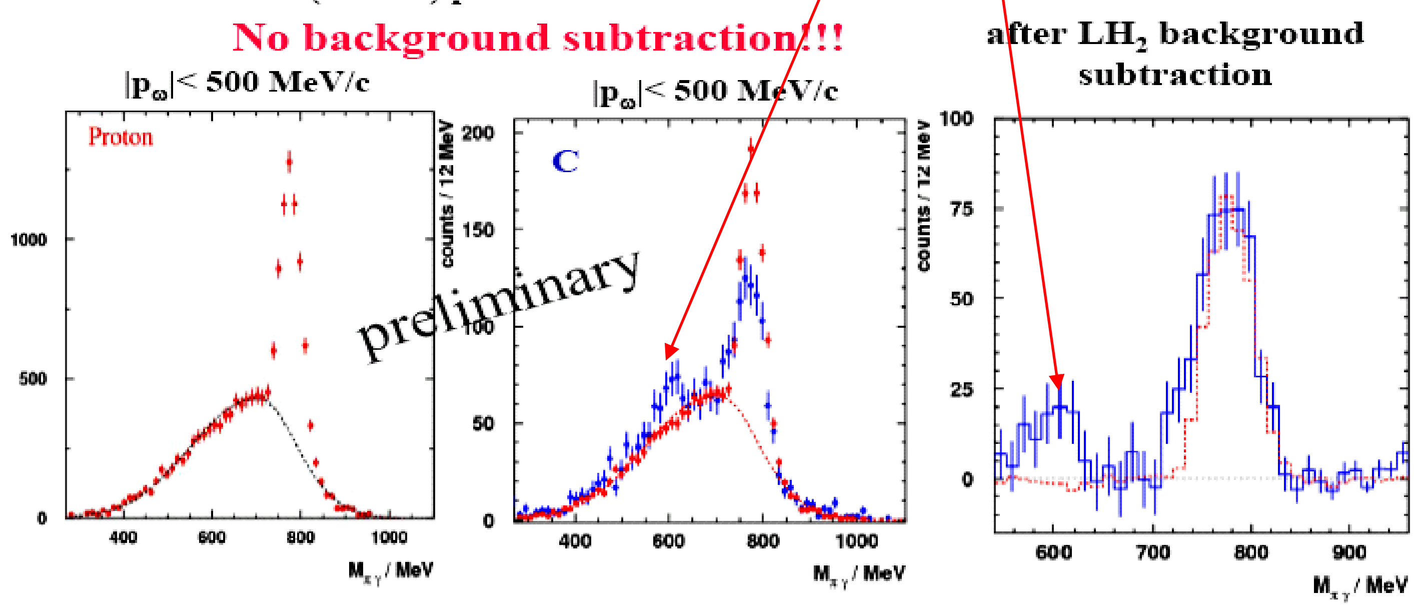
→ Could be probed by light vector mesons

From Volker Metag's recent talk



Shocking result !!

New structure appearing?



QCD Vacuum

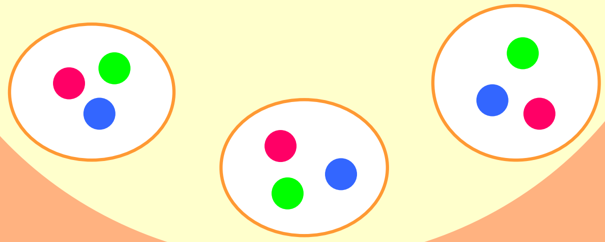
$$< \frac{\alpha_s}{\pi} B^2 > \approx 380 \text{ MeV/fm}^3$$

$$< \frac{\alpha_s}{\pi} E^2 > \approx -380 \text{ MeV/fm}^3$$

Nuclear matter

$$< \frac{\alpha_s}{\pi} B^2 > \approx 365 \text{ MeV/fm}^3$$

$$< \frac{\alpha_s}{\pi} E^2 > \approx -335 \text{ MeV/fm}^3$$

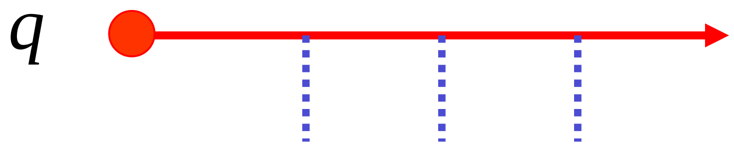


Change of gluonic background in nuclear matter

→ could be probed by heavy quark system

Why Heavy Quark system can probe this gluonic change

1. Heavy quark propagation

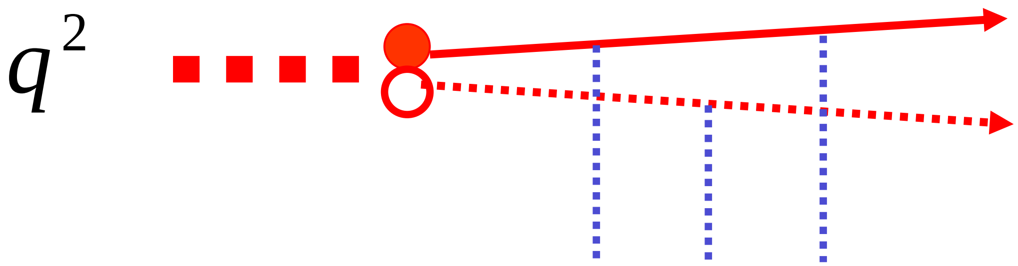


$$S_G(q) = S(q) + S(q)\not{G}S(q) + \ldots\ldots\ldots\ldots \quad \text{where,} \quad S(q) = \frac{1}{\not{q} - m}$$

Perturbative treatment are possible

because $m - \not{q} \; \rangle\rangle \; \Lambda_{QCD}$ even for $q \to 0$

2. System with two heavy quarks

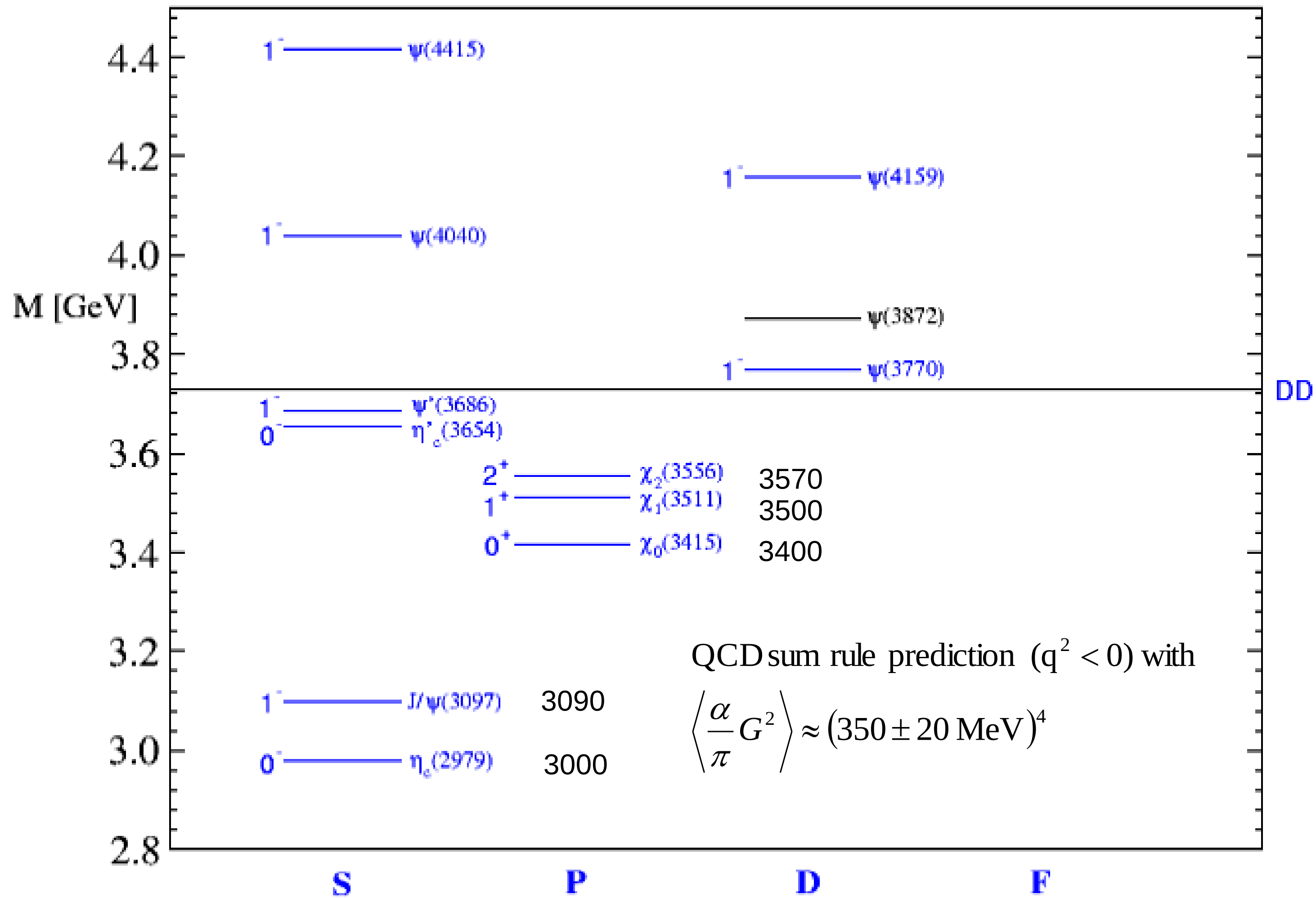


$$\Pi(q) = \ldots + \int_0^1 dx \frac{F(q^2, x)}{\left(4m^2 - q^2 - (x-1/2)^2 q^2\right)^n} \cdot \langle G^n \rangle + ..$$

Perturbative treatment are possible when

$$4m^2 - q^2 \gg \Lambda_{QCD}^2$$

$q^2<0$: QCD sum rules for charmonium ($c\bar{c}$)

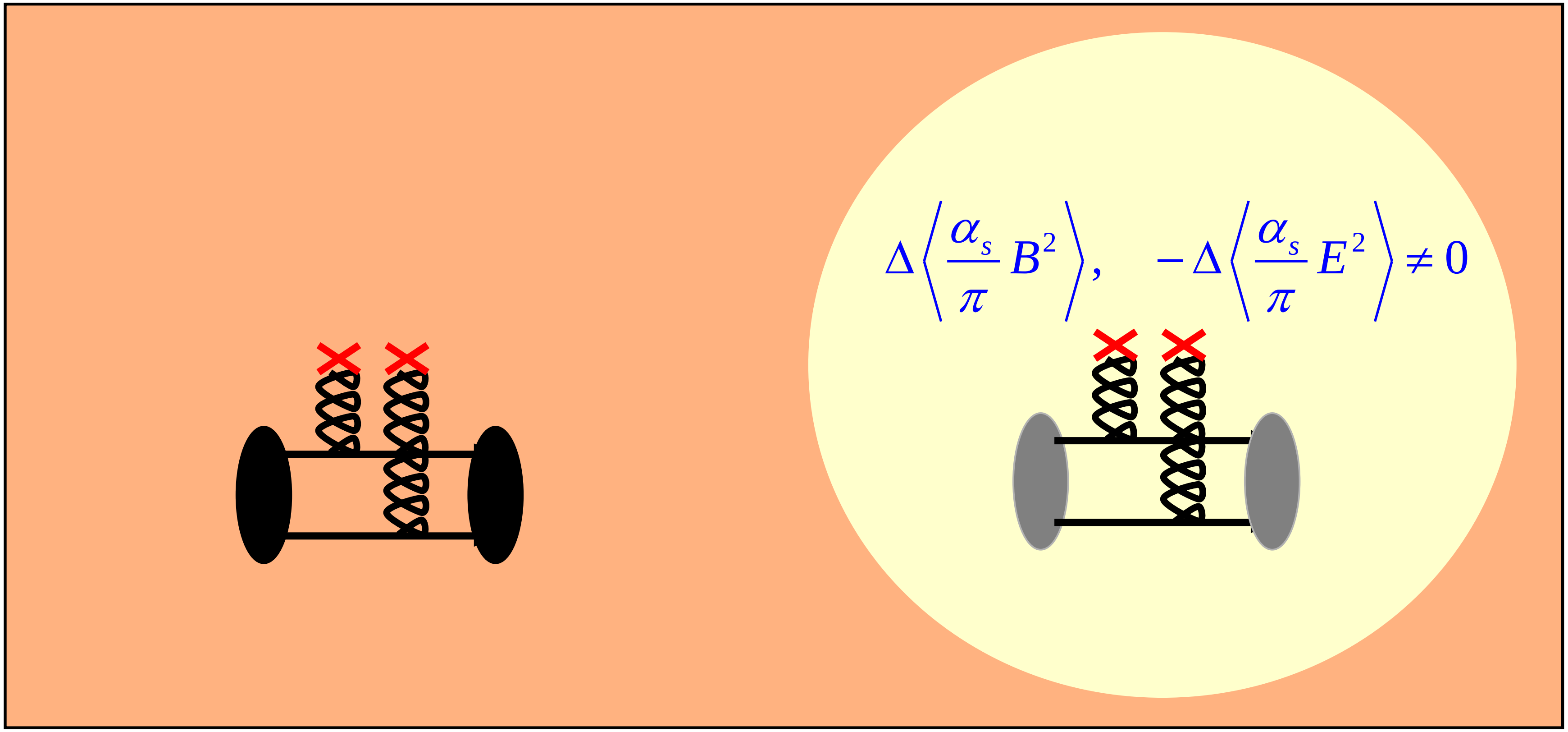


QCD sum rule prediction ($q^2 < 0$) with

$$\left\langle \frac{\alpha}{\pi} G^2 \right\rangle \approx (350 \pm 20\ \text{MeV})^4$$

Heavy quark propagator is sensitive to only gluon fields

and therefore the mass of heavy quark system will change in nuclear medium



$$\Delta\left\langle \frac{\alpha_s}{\pi} B^2 \right\rangle, \quad -\Delta\left\langle \frac{\alpha_s}{\pi} E^2 \right\rangle \neq 0$$

Approaches for charmonium mass shift in nuclear matter

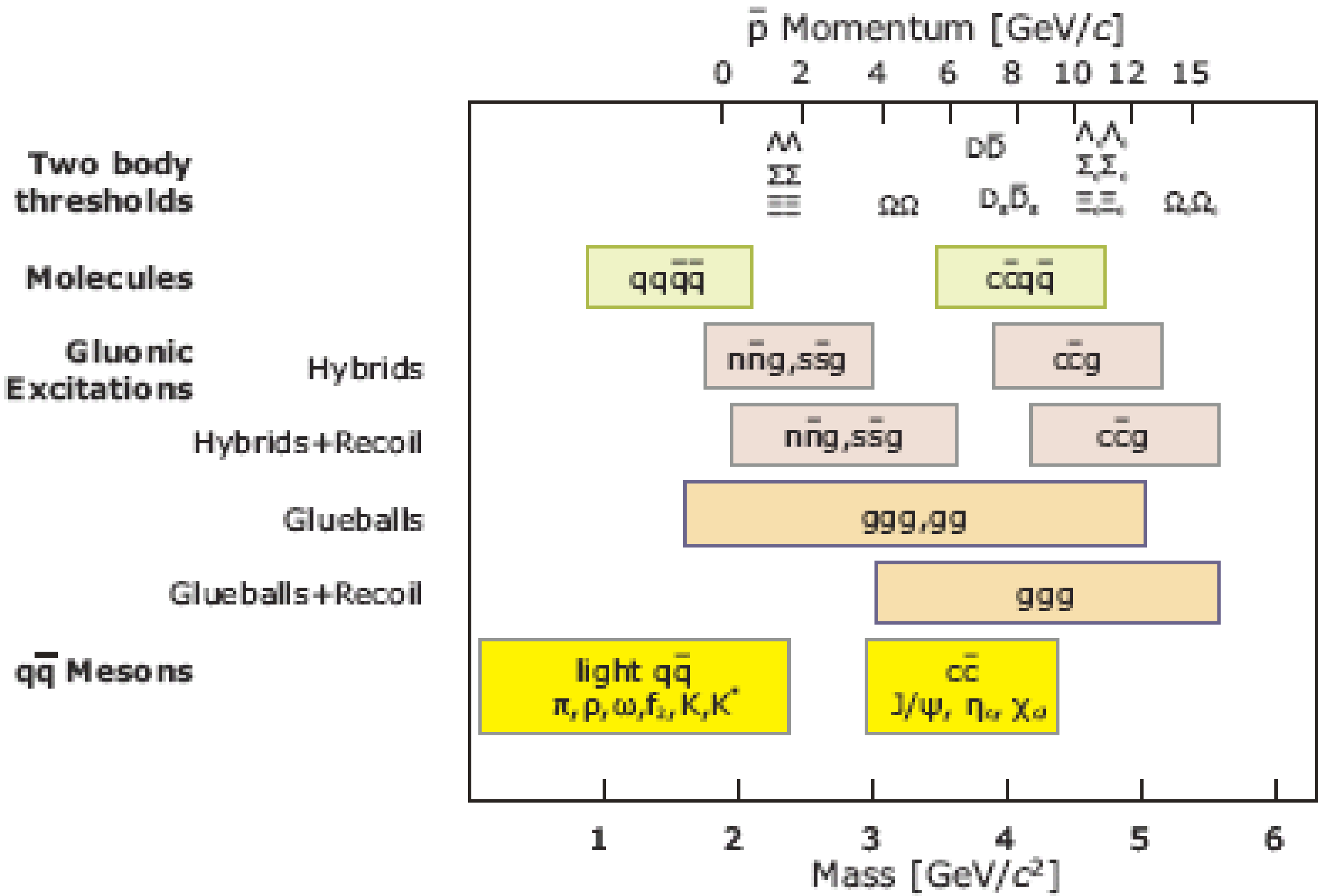
	Quantum numbers	QCD 2nd Stark eff.	Potential model	QCD sum rules	Effects of DD loop
H_c	0^{-+}	–8 MeV		–5 MeV (Klingl, SHL ,Weise)	No effect (SHL, Ko)
J/ψ	1^{--}	–8 MeV (Peskin, Luke)	−10 MeV (Brodsky et al).	–7 MeV (Klingl, SHL ,Weise)	<2 MeV (SHL, Ko)
$\chi_{0,1,2,}$	$0,1,2^{++}$	−40 MeV (SHL)		−60 MeV (SHL)	No effect on χ_1
$\psi(3686)$	1^{--}	−100 MeV (SHL)			< 30 MeV (SHL, Ko)
$\psi(3770)$	1^{--}	−140 MeV (SHL)			< 30 MeV (SHL, Ko)

Such experiment can be done at

1. GSI future accelerator facility

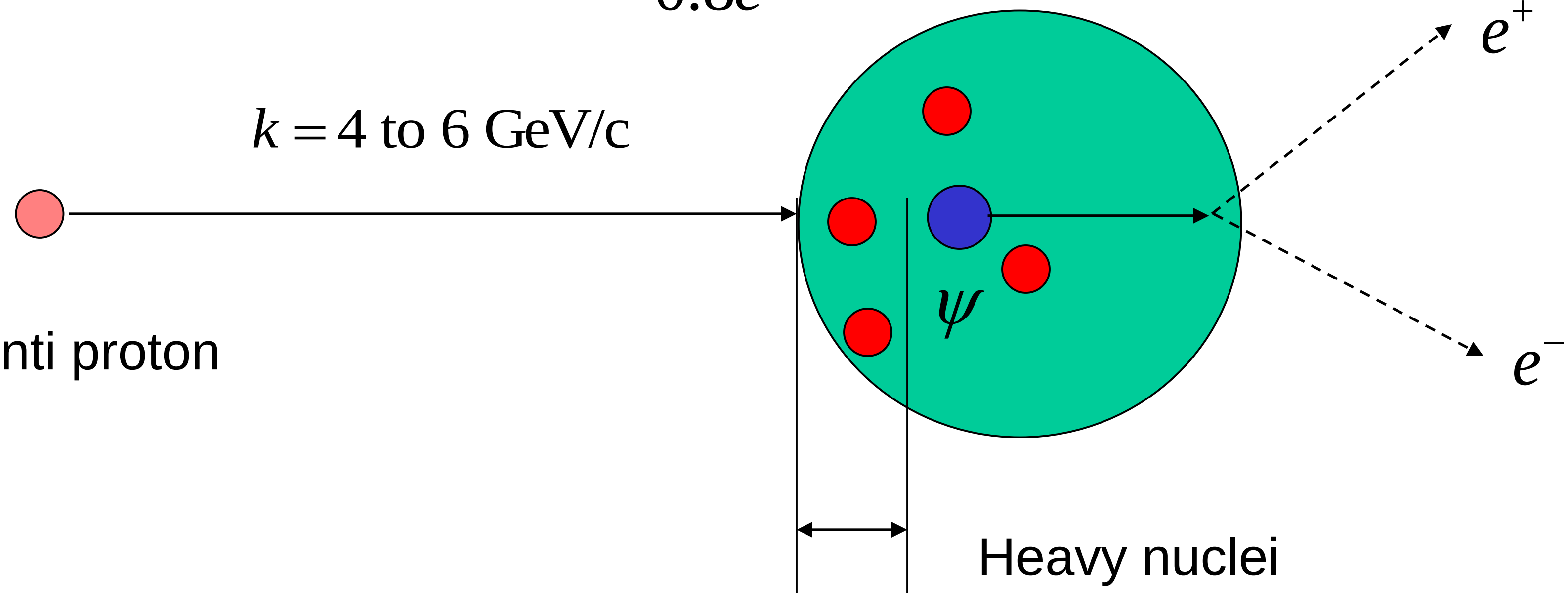
⇒ anti proton project (1-15 GeV)

HESR


p̄ Momentum [GeV/c]
0
2
4
6
8
10
12
15
Two body thresholds
ΛΛ
ΣΣ
ΞΞ
ΩΩ
DD̄
Molecules
qqq̄q̄
cc̄qq̄
Gluonic Excitations
Hybrids
nn̄g,ss̄g
cc̄g
Hybrids+Recoil
nn̄g,ss̄g
cc̄g
Glueballs
ggg,gg
Glueballs+Recoil
ggg
qq̄ Mesons
light qq̄
cc̄
1
2
3
4
5
6
Mass [GeV/c²]

Anti proton project at GSI

$$t = \frac{2\times 1.3 A^{1/3}\gamma^{-1}}{0.8c} = 10\, fm/c \quad \text{for} \;\; \text{A=125}$$



$$\frac{1}{0.17\, fm^{-3}\times 5\, fm^{2}} = 1.2\, fm$$

Anti proton will be absorbed at surface and

Charmonium will decay inside the heavy nuclei

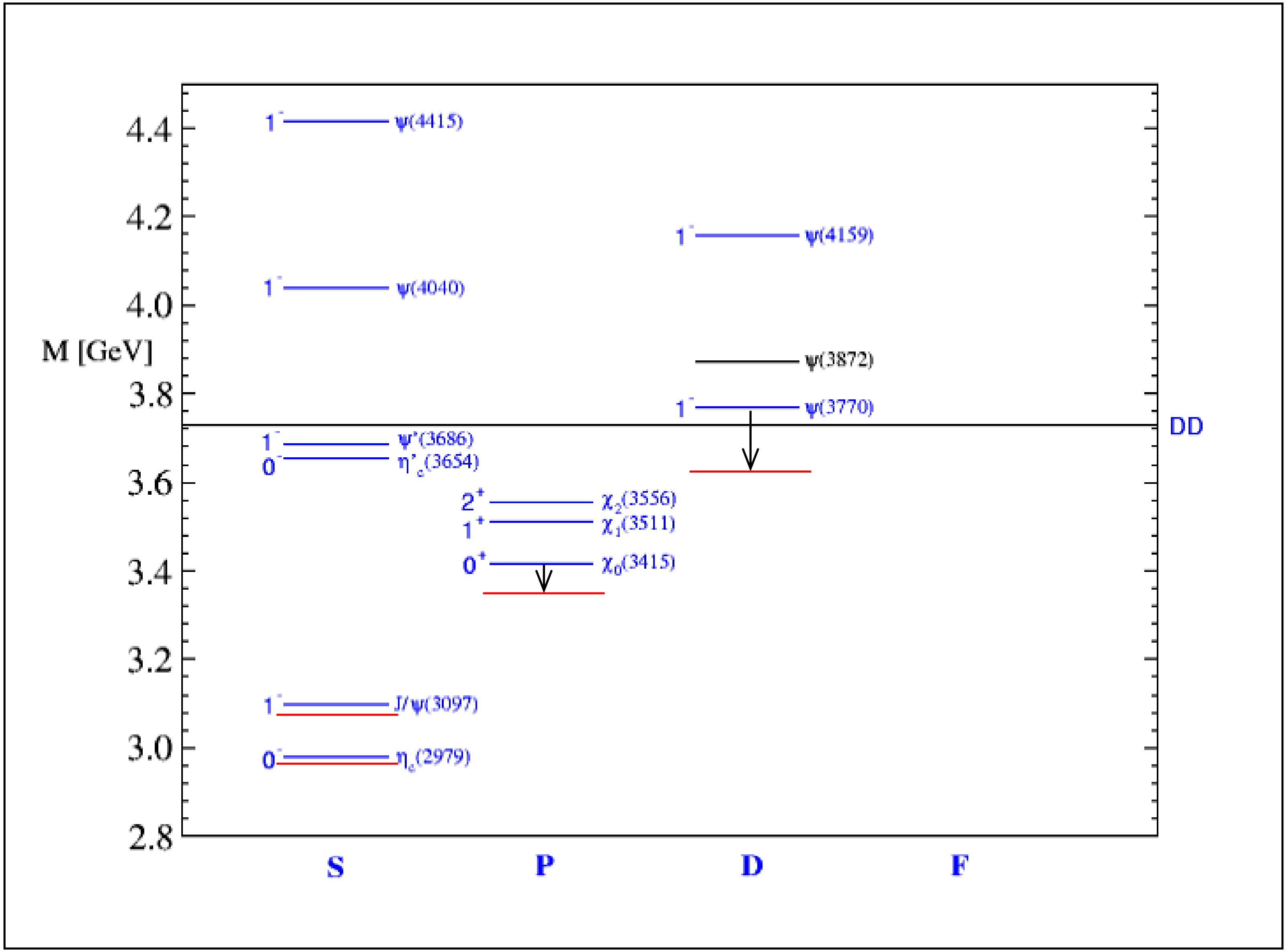
Production rate:

$\text{Luminosity} = 2 \times 10^{32}\, cm^{-2} s^{-1}$

$$\sigma_{BW} = \frac{2J+1}{(2s_1+1)(2s_2+1)} \frac{\pi}{k^2} \frac{B_{in} B_{out} \Gamma_{Total}^2}{(E-E_R)^2 + \Gamma_{Total+medium}^2 / 4}$$

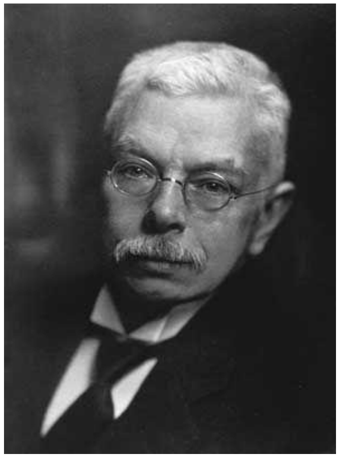
	J^{PC}	Mass shift	Final state	σ to final state	Events per day
J/ψ	1^{--}	−8 MeV	$e^+ + e^-$	6 pb	100
$\psi(3686)$	1^{--}	−100 MeV	$e^+ + e^-$	0.6 pb	10
$\psi(3770)$	1^{--}	−100 MeV	$e^+ + e^-$	1 pb	17
χ_0	0^{++}	−50 MeV	$J/\psi + \gamma$	200 pb	3400
χ_1	1^{++}	−50 MeV	$J/\psi + \gamma$	80 pb	1360
χ_{12}	0^{++}	−50 MeV	$J/\psi + \gamma$	350 pb	5950

Charmonium spectrum

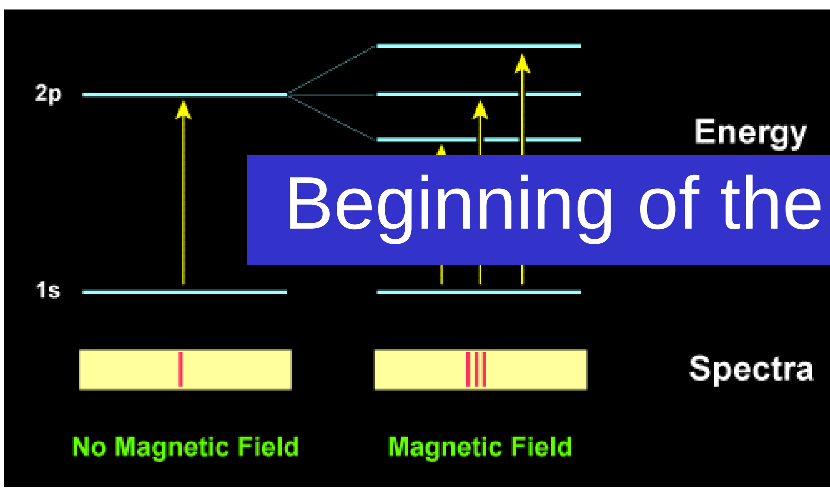


Similar to discoveries in E&M

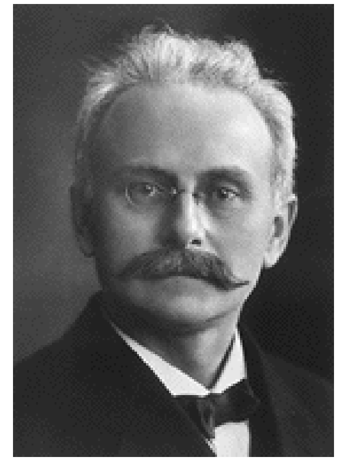
Pieter Zeeman (1865-1943)



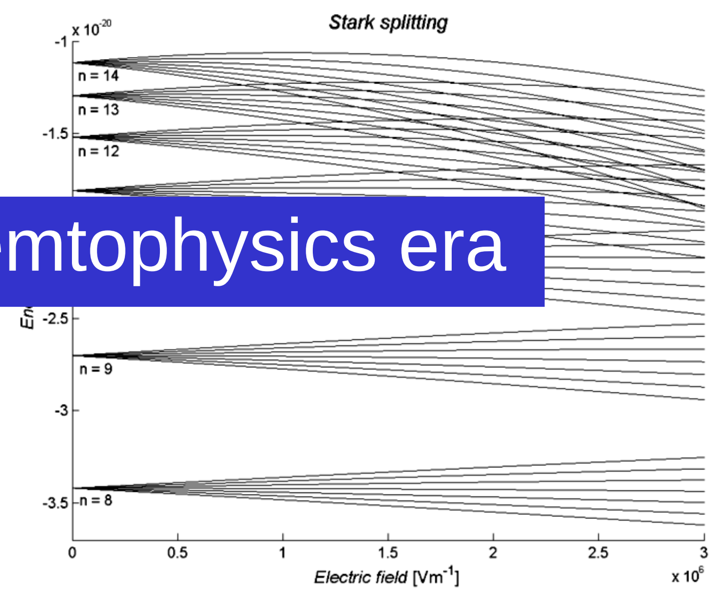
Zeeman effect: Nobel prize 1902



Johannes Stark (1874-1957)



Stark effect: Nobel prize 1919

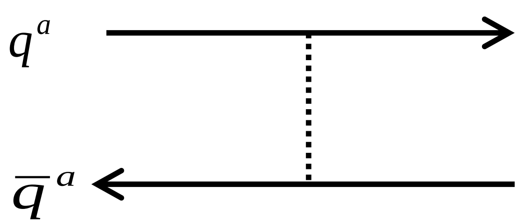


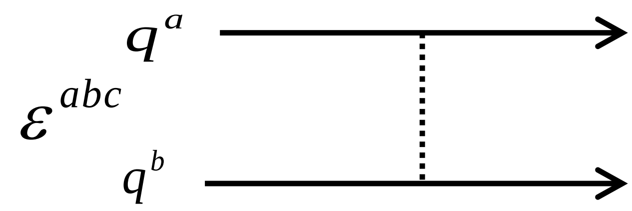
Beginning of the Femtophysics era

Heavy exotics from Heavy Ion collision

Physics with CBM

Attractions in quark-antiquark vs. diquark





$$-\frac{4\alpha}{3}\frac{1}{r} \qquad E \propto -\frac{m_i m_j}{m_i + m_j} \times Z^2 \qquad -\frac{1}{2}\frac{4\alpha}{3}\frac{1}{r}$$

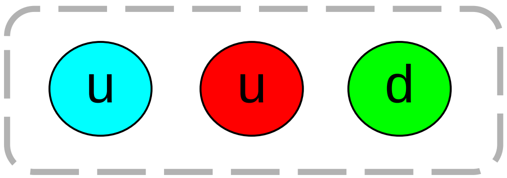
$$\sigma \times r \qquad E \propto -\sqrt{\frac{m_i + m_j}{m_i m_j}} \times Z^{1/2} \qquad \frac{1}{2}\sigma \times r$$

$$\frac{C}{m_i m_k}\sum S_i \cdot S_k \qquad \frac{1}{3}\frac{C}{m_i m_k}\sum S_i \cdot S_k$$

Phenomenological fit to hadron spectrum

color spin interaction

Color spin interaction explains hadron spectrum



Nucleon

$$\frac{C_B}{m_i m_k}\left[s_u \cdot s_u + s_u \cdot s_d + s_u \cdot s_d\right]$$
$$= \frac{C_B}{m_q^2}\frac{1}{2}\left[\left(s_u + s_u + s_d\right)^2 - s_u^2 - s_u^2 - s_d^2\right]$$

Baryon Mass difference

Mass Difference	$M_\Delta - M_N$	$M_\Sigma - M_\Lambda$	$M_{\Sigma_c} - M_{\Lambda_c}$
Formula	$\frac{3C_B}{2m_c^2}$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_s})$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_c})$
Fit	290 MeV	77 MeV	154 MeV
Experiment	290 MeV	75 MeV	170 MeV

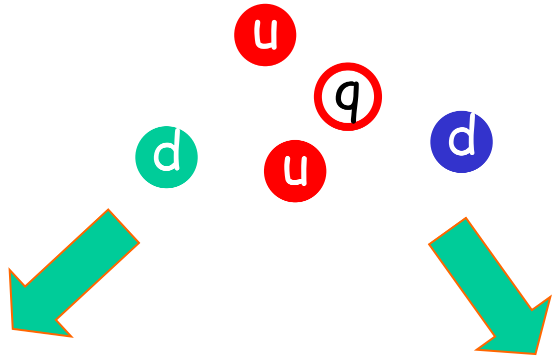
Meson Mass difference

Mass Difference	$M_\rho - M_\pi$	$M_{K^*} - M_K$	$M_{D^*} - M_D$
Formula	$\frac{C_M}{m_u^2}$	$\frac{C_M}{m_u m_s}$	$\frac{C_M}{m_u m_c}$
Fit	635 MeV	381 MeV	127 MeV
Experiment	635 MeV	397 MeV	137 MeV

Works very well with $3C_B = C_M$ = constant

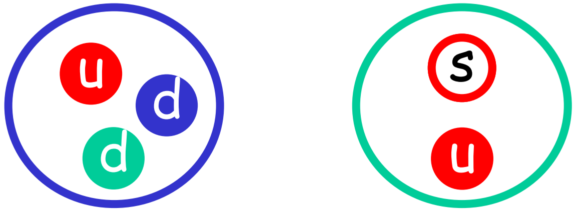
$$m_u = m_d = 300 \text{ MeV}, \quad m_s = 500 \text{ MeV}, \quad m_c = 1500 \text{ MeV}$$

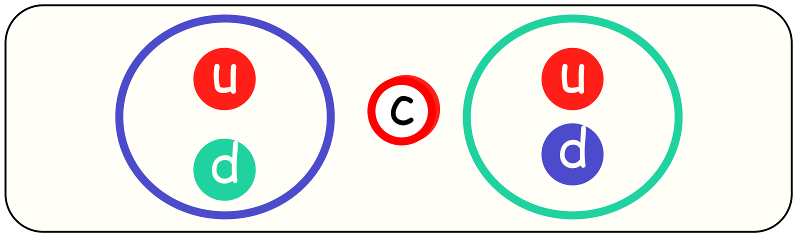
When will a pentaquark form ?



Strong quark-antiquark attraction

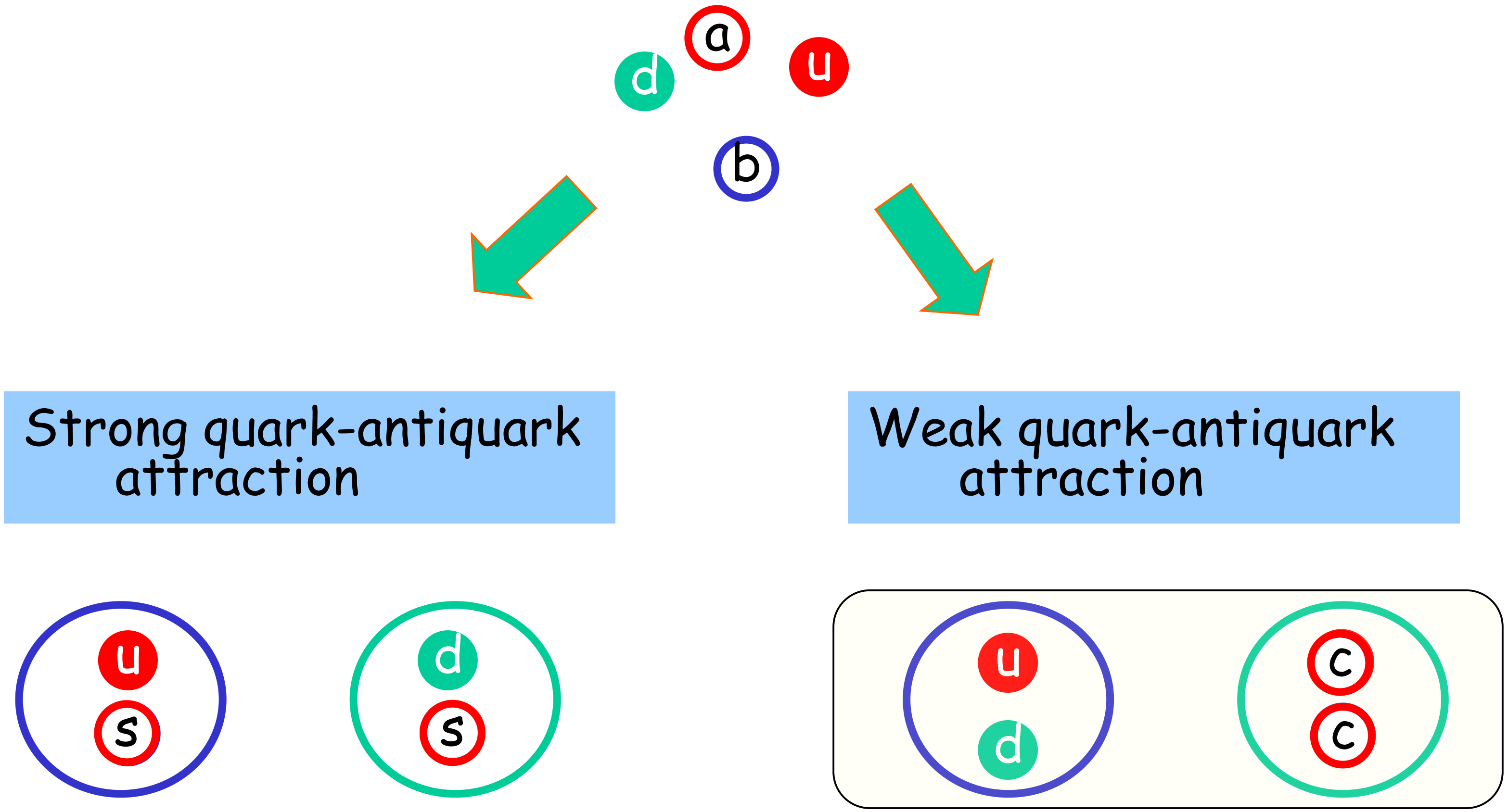
Weak quark-antiquark attraction





$E_{pentaquark}$-$E_{meson\text{-}Baryon}$= -50MeV

When will a tetraquark form ?



$$E_{tetraquark} - E_{2\text{-}meson} = +38 \text{ MeV}$$

Success of statistical model

P. Braun-Munzinger, J. Stachel (95 …)

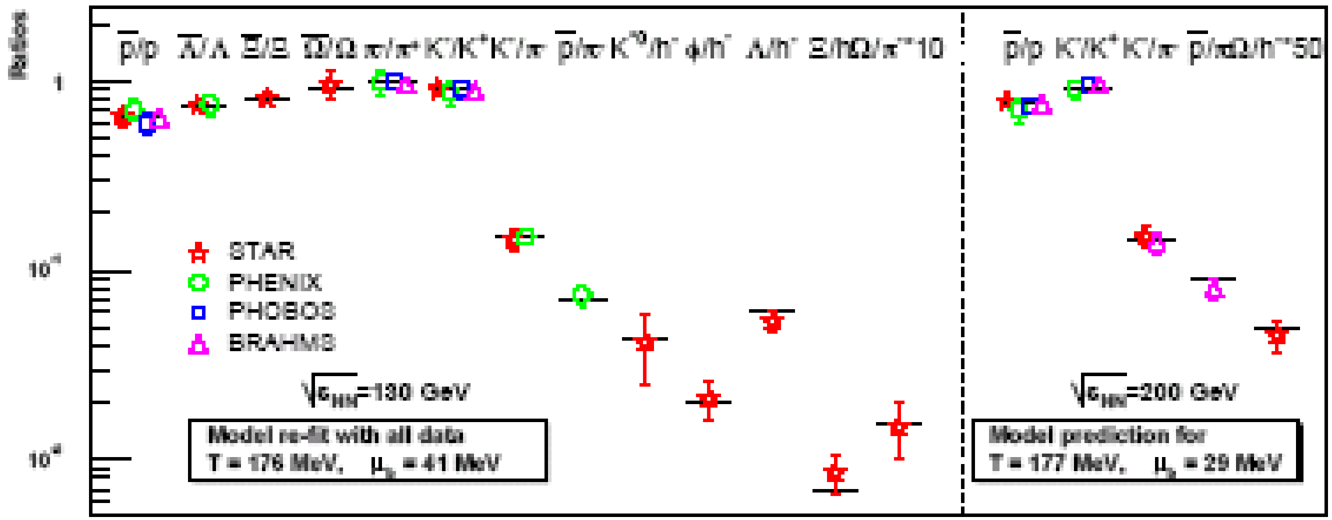
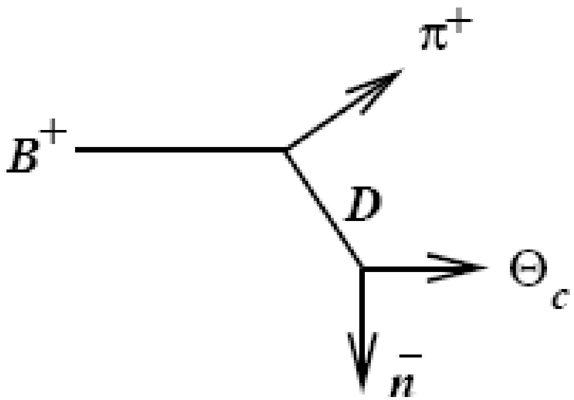
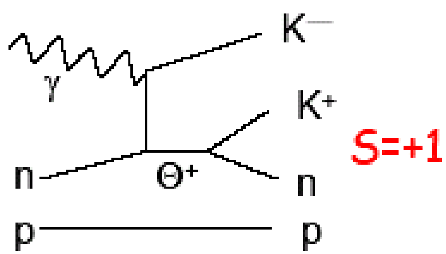


Figure 1. Fit of particle ratios for Au-Au collisions measured at RHIC energies. The measurements are the symbols, the thermal model values are the lines [6, 10]

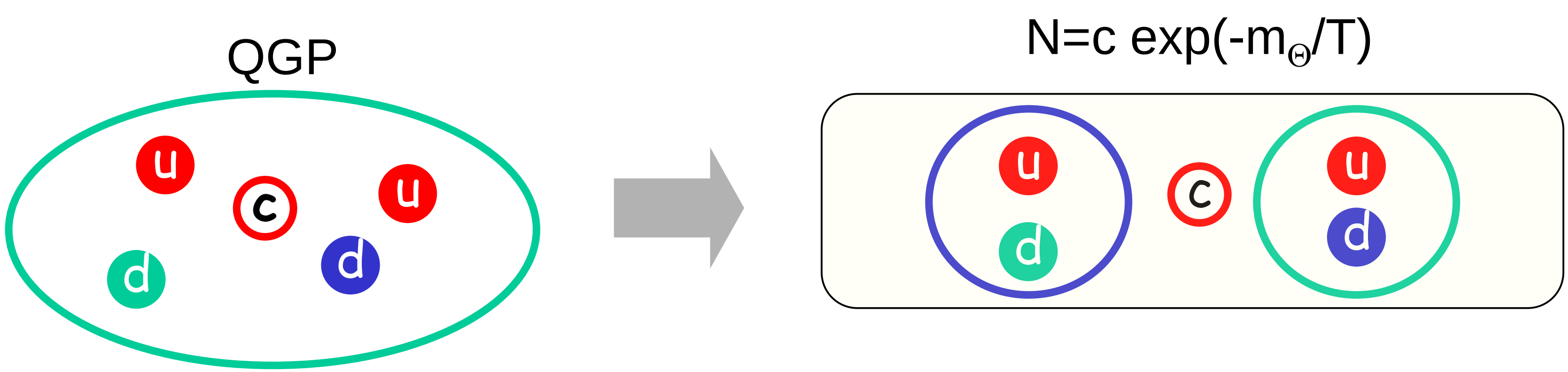
Exotic particle production: elementary vs HIC

Exotic particle production from elementary processes



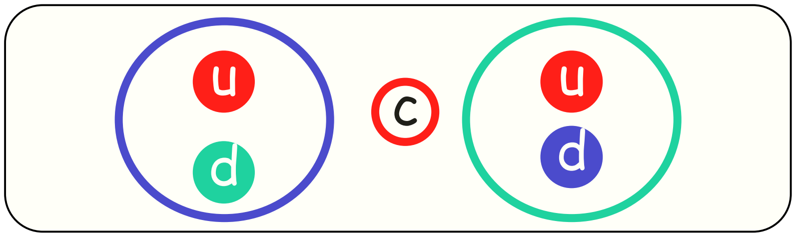


Exotic particle production from Heavy Ion collision



Possible Decay mode of charmed Pentaquark

Θ+

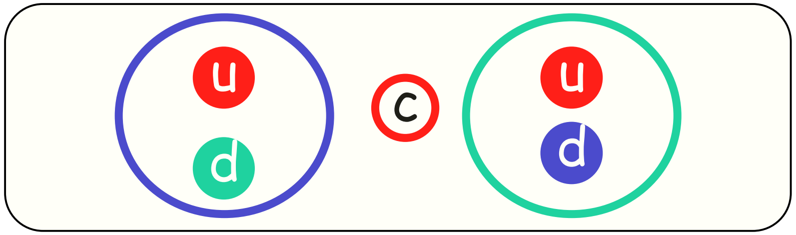


L=1

exotic	Decay mode	Final states	Branching ratio
udus$\underline{c}$	uds(Λ) +u$\underline{c}$($\underline{D}^0$)	Λ + k^0 π^0 (k^+ π^-) Λ + k^0 π^- π^+	2.3 % (3.8 %) 5.97 %
	uud(p) +s$\underline{c}$ (Ds-)	P + k^0 π^- P + k^+ π^- π^-	2.82 % 9.2 %
udud$\underline{c}$	udu (p)+d$\underline{c}$ (D-)	P + k^0 π^- P + k^+ π^- π^-	2.82 % 9.2 %
	udd (n)+u$\underline{c}$ ($\underline{D}^0$)	n + k^0 π^0 (k^+ π^-) n + k^0 π^- π^+	2.3 % (3.8 %) 5.97 %

Rough estimate of events at RHIC

Θ_c



Final state	Decay mode	Final states	Branching ratio
udud$\underline{c}$	udu (p)+d$\underline{c}$ (D-) p + $k^0\,\pi^-$	P + $k^+\,\pi^-\,\pi^-$	2.82 % 9.2 %
	udd (n)+u$\underline{c}$ ($\underline{D}^0$)	n + $k^0\,\pi^0$ ($k^+\,\pi^-$) n + $k^0\,\pi^-\,\pi^+$	2.3 % (3.8 %) 5.97 %

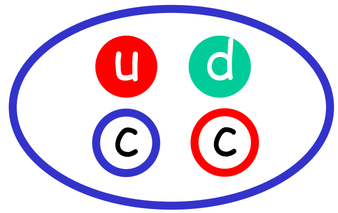
Central collision (0-10%)

$dN_{c\underline{c}}/dy = 2.2$ (phenix)

$$dN_{\Theta c}/dy = dN_D/dy \times \exp[-m_p/T] \times \text{Branching ratio}$$

$$= 2.2 \times \frac{1}{148} \times 0.03 = 0.00045$$

Possible Decay mode of Tetra-quark



exotic	Decay mode	Final states	Branching ratio
us$\underline{cc}$	u$\underline{c}$ ($\underline{D}^0$)+s$\underline{c}$ (Ds-)	$\underline{D}^0$ ($k^0 \pi^0$, $k^+ \pi^-$ $k^0 \pi^- \pi^+$) Ds-($\underline{k^0}k^-$, $k^- k^+ \pi^-$)	3.6 % (4.4 %)
ud$\underline{cc}$	d$\underline{c}$ (D-)+u$\underline{c}$ ($\underline{D}^0$)	D- ($k^0 \pi^{-l} k^+ \pi^- \pi^-$) + $\underline{D}^0$ ($k^0 \pi^0$, $k^+ \pi^-$ $k^0 \pi^- \pi^+$)	

If STAR can do it, CBM can do much better

STAR

$$D^0 \rightarrow k^- \pi^+$$

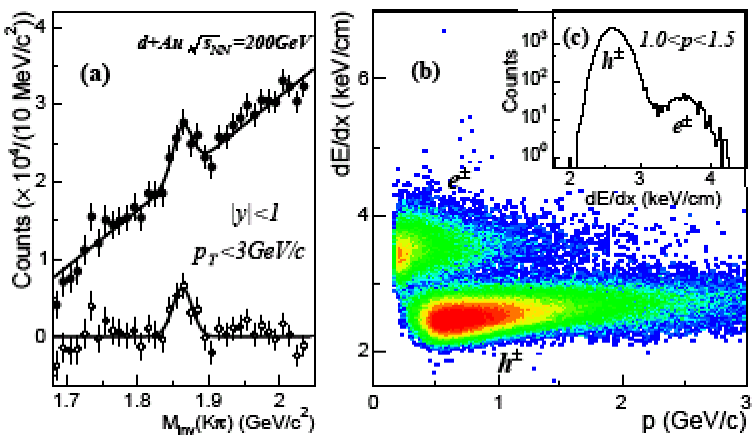


FIG. 1: (a) Invariant mass distributions of kaon-pion pairs from d+Au collisions. The solid circles depict the signal after mixed-event background subtraction, the open circles after subtraction of the residual background using a linear parametrization. (b) dE/dx in the TPC vs. particle momentum (p) with a TOF cut of $|1/\beta - 1| \leq 0.03$. Insert: projection on the dE/dx axis for particle momenta 1< p <1.5 GeV/c.

CBM

4 month Au+Au at 25 AGeV CBM

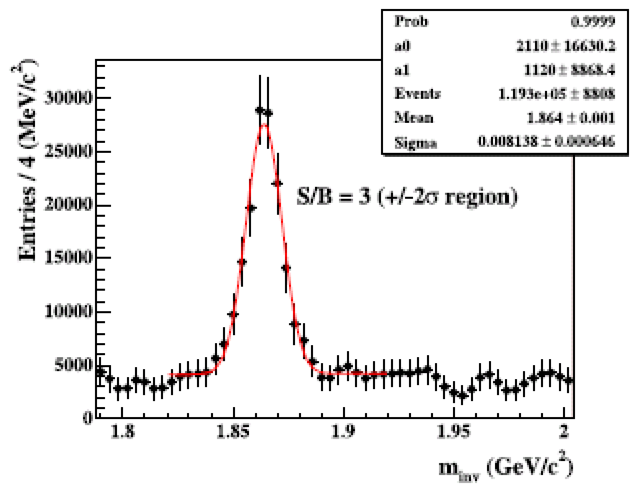
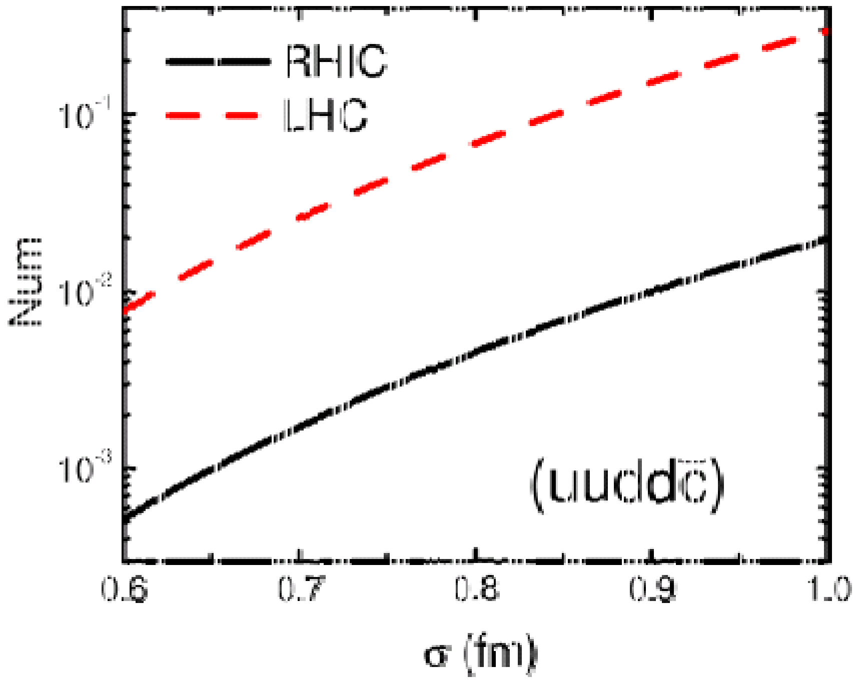


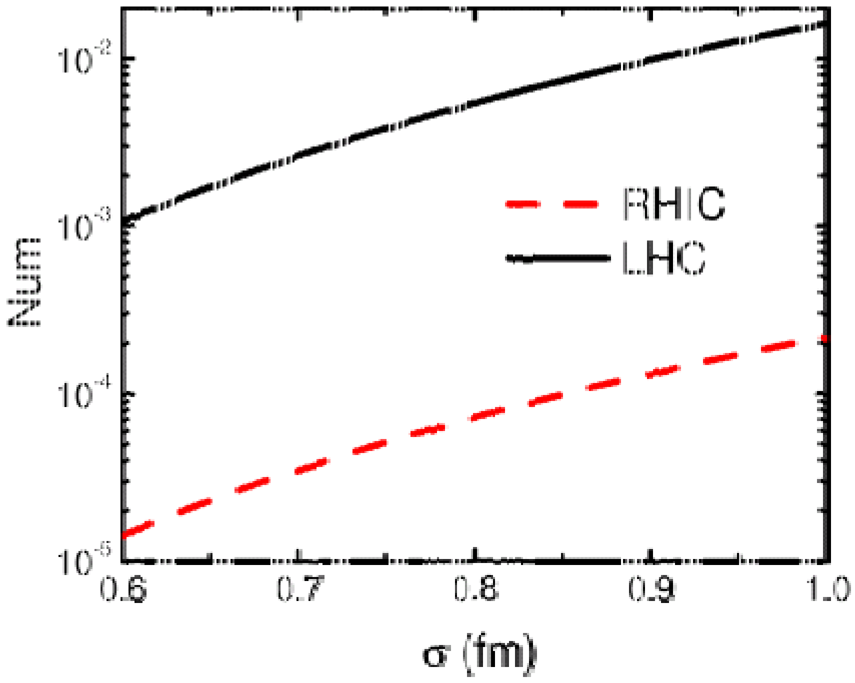
Figure 19.12: Invariant mass spectrum for the simulated signal plus background. The D^0 peak is clearly visible. Estimated data taking time is about 4 months at 0.1 MHz interaction rate.

And also at LHC (W.Liu, C.M.Ko, SHL 07)

udud $\underline{c}$



ud $\underline{cc}$



Summary

1. From PANDA (anti proton beam), can look at the charmonium mass shift in nuclear medium

   → Beginning of Femto Physics

   Hint to confinement and QCD vacuum

3. From CBM (heavy Ion Physics), can look at heavy Exotics

   → New exotic hadron in QCD

   If found the first real exotic ever, will tell us about QCD and dense matter → color superconductivity

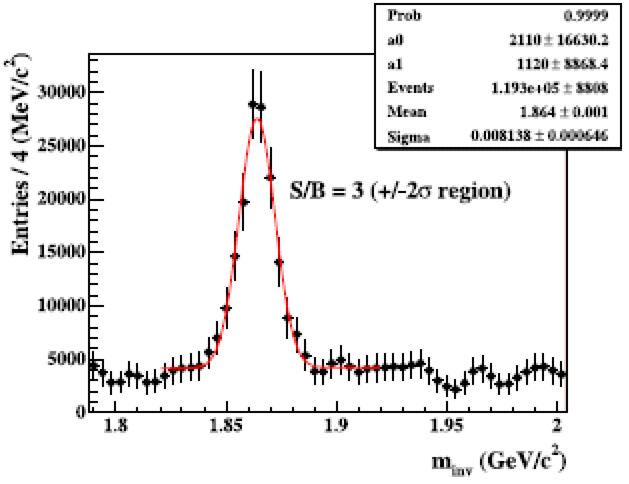
beam energy (AGeV)	J/ψ mult. min. bias	J/ψ yield detected per week	runtime (weeks)
10	$5 \cdot 10^{-8}$	$1.8 \cdot 10^{3}$	10
15	$6 \cdot 10^{-7}$	$2.2 \cdot 10^{4}$	10
20	$2 \cdot 10^{-6}$	$7 \cdot 10^{4}$	10
25	$5 \cdot 10^{-6}$	$1.8 \cdot 10^{5}$	5
30	$1.0 \cdot 10^{-5}$	$3.6 \cdot 10^{5}$	2
35	$1.5 \cdot 10^{-5}$	$5.4 \cdot 10^{5}$	1

Table 12.1: Expected statistics and run time for J/ψ measurements in minimum bias Au+Au collisions

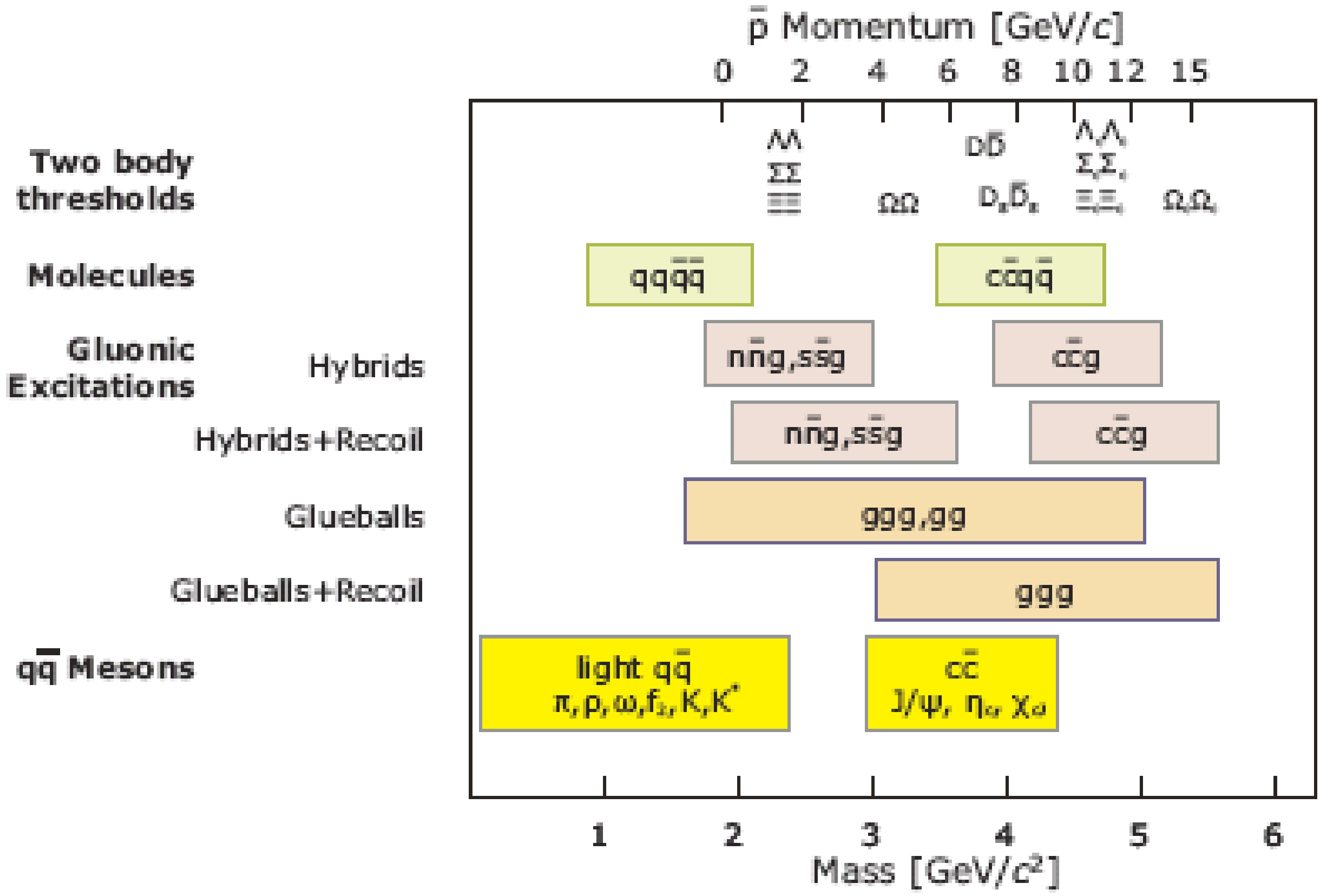
beam energy (AGeV)	D^0 mult. min. bias	D^0 yield detected per week	runtime (weeks)
15	$7 \cdot 10^{-7}$	$8 \cdot 10^{3}$	10
20	$7 \cdot 10^{-6}$	$8 \cdot 10^{4}$	10
25	$3 \cdot 10^{-5}$	$3.3 \cdot 10^{5}$	5
30	$7 \cdot 10^{-5}$	$8 \cdot 10^{5}$	2
35	$1.3 \cdot 10^{-4}$	$1.5 \cdot 10^{6}$	1

Table 12.2: Expected statistics and run time for D^0 meson measurements in minimum bias Au+Au collisions

4 month Au+Au at 25 AGeV CBM



12: Invariant mass spectrum for the simulated signal plus background. The D^0 peak is clearly visible. ata taking time is about 4 months at 0.1 MHz interaction rate.

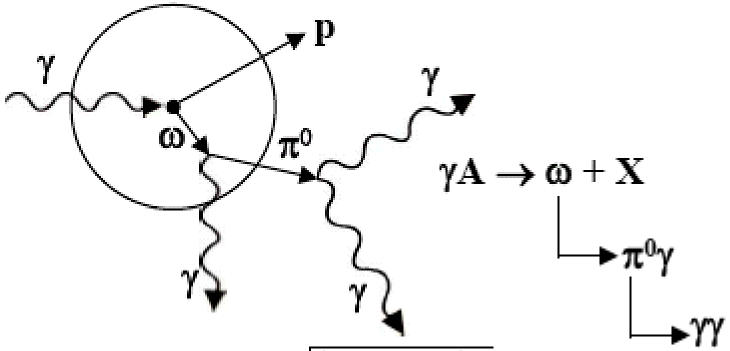


p̄ Momentum [GeV/c]
0 2 4 6 8 10 12 15
Two body thresholds
Molecules
Gluonic Excitations
Hybrids
Hybrids+Recoil
Glueballs
Glueballs+Recoil
qq̄ Mesons
ggg,gg
ggg
light qq̄
π,ρ,ω,f₂,K,K*
cc̄
J/ψ, η_c, χ_cJ
1 2 3 4 5 6
Mass [GeV/c²]

Perturbative treatment are possible when $\mu^2 = 4m^2 - q^2 \;>>\; \Lambda^2_{QCD}$

q^2	process	expansion parameter
negative	QCD sum rules for heavy quarks	$\dfrac{\Lambda^2_{QCD}}{4m^2 + Q^2}$
0	Photo production of open charm	$\dfrac{\Lambda^2_{QCD}}{4m^2}$
$m^2_{J/\psi} > 0$	Dissociation cross section of bound states	$\dfrac{\Lambda^2_{QCD}}{\left(2m + m_{J/\psi}\right)\cdot \varepsilon_0}$

Example: from Volker Metag's recent talk



$$m_\omega = \sqrt{(p_\pi + p_\gamma)^2}$$

Shocking result !!

New structure appearing?