Tools for Spectroscopy

Michael Pennington
Durham, September 2017

Window on confinement

Resonances in QCD

$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b,t} \bar{q} (i \gamma_\mu D^\mu - m_q) q - \frac{1}{4} \mathcal{G}^{\mu\nu} \mathcal{G}_{\mu\nu}$$

Resonances in QCD

Hadrons: effective degrees of freedom

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Resonances in QCD

Hadrons: effective degrees of freedom

how do these depend on flavour, *b*,*c*,*s*,*d*,*u*

$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b,t} \bar{q}\,(i \gamma_\mu D^\mu - m_q)\, q \; - \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$$

Resonances in QCD

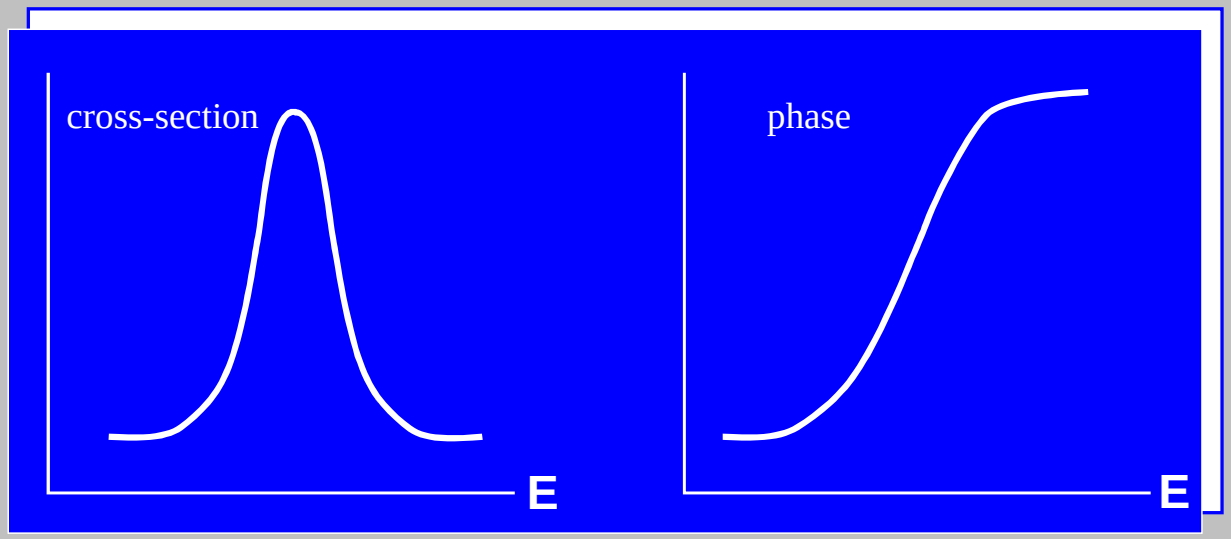
Hadrons: effective degrees of freedom

how do these depend on flavour, *b,c,s,d,u*

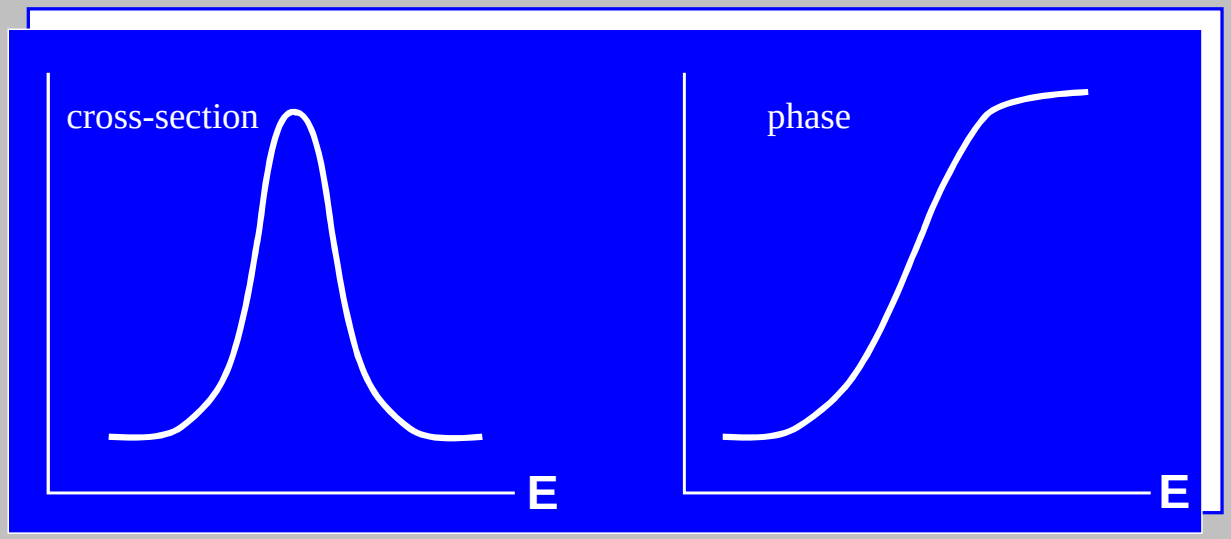
Hadron interactions: universality

$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b,t} \bar{q} \left(i \gamma_\mu D^\mu - m_q \right) q - \frac{1}{4} \mathcal{G}^{\mu\nu} \mathcal{G}_{\mu\nu}$$

Hadron States



Hadron States

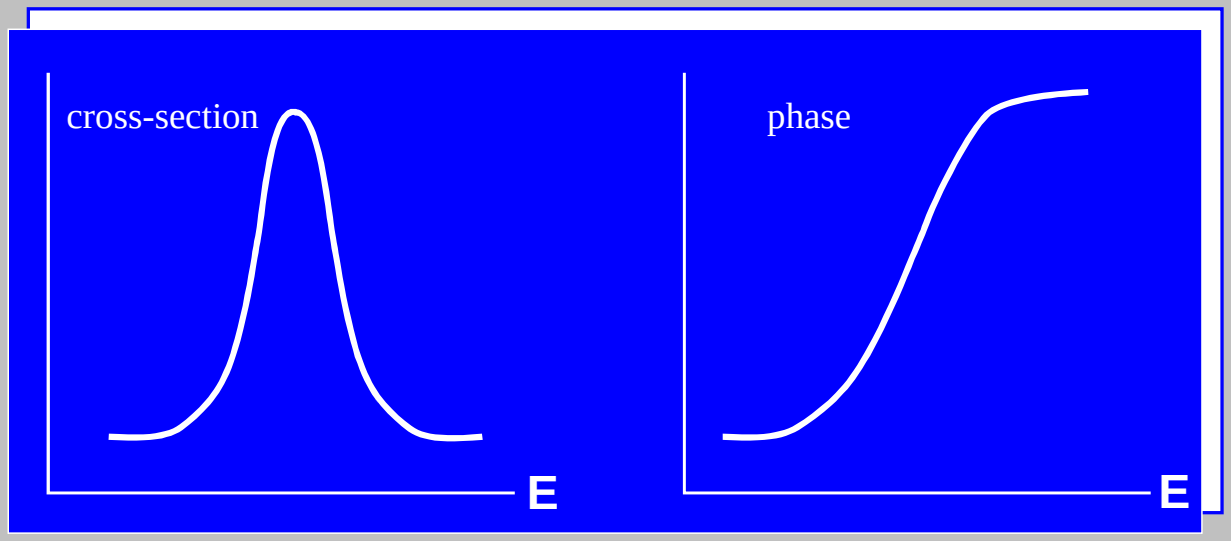


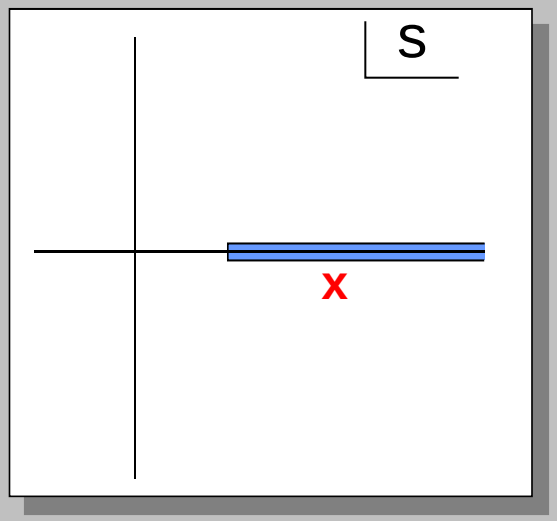
$s = E^2$

Breit-Wigner

$$\frac{1}{M^2 - s - iM\Gamma}$$

Hadron States





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Breit-Wigner

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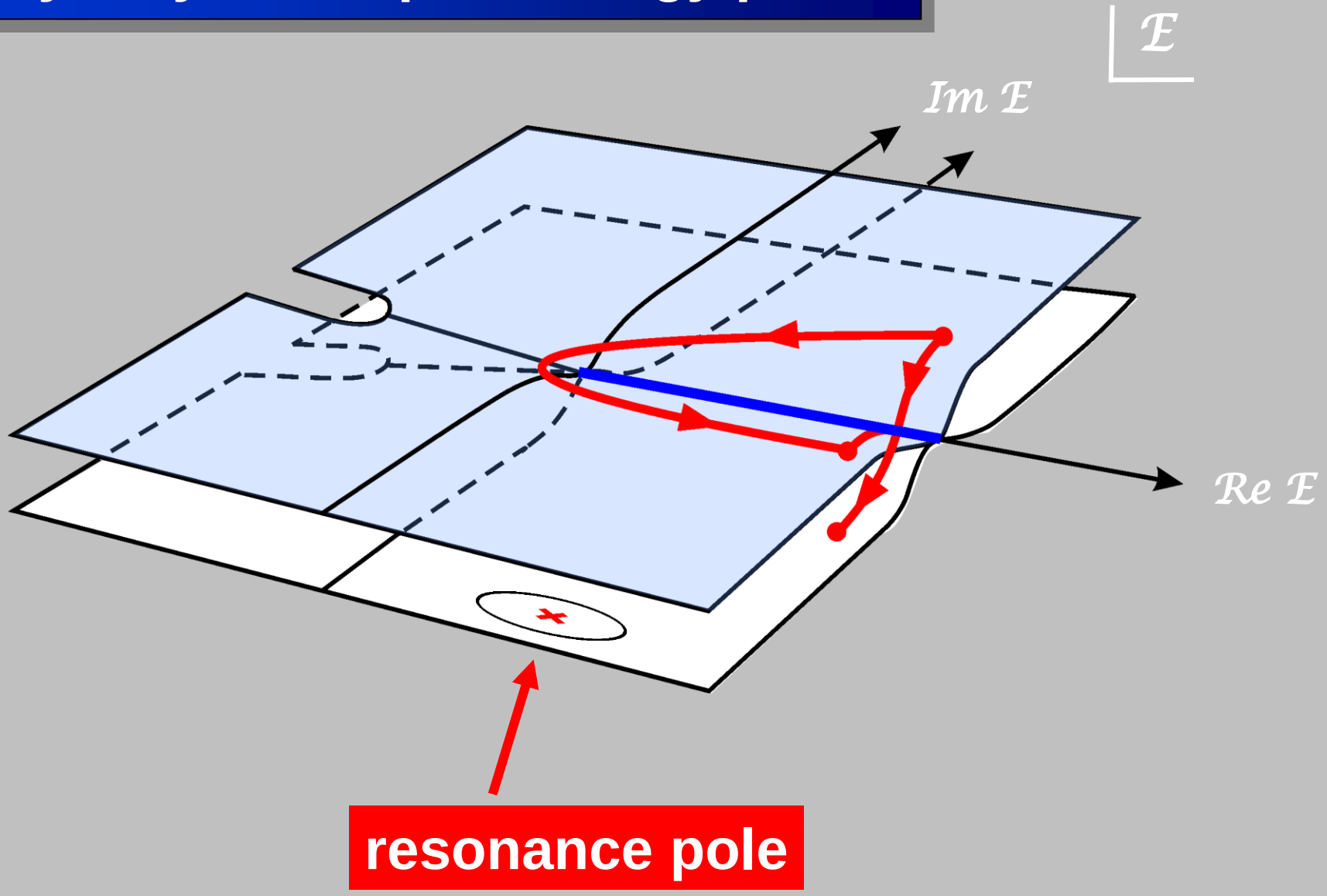
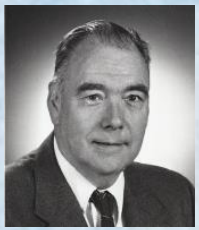
analyticity & complex energy plane



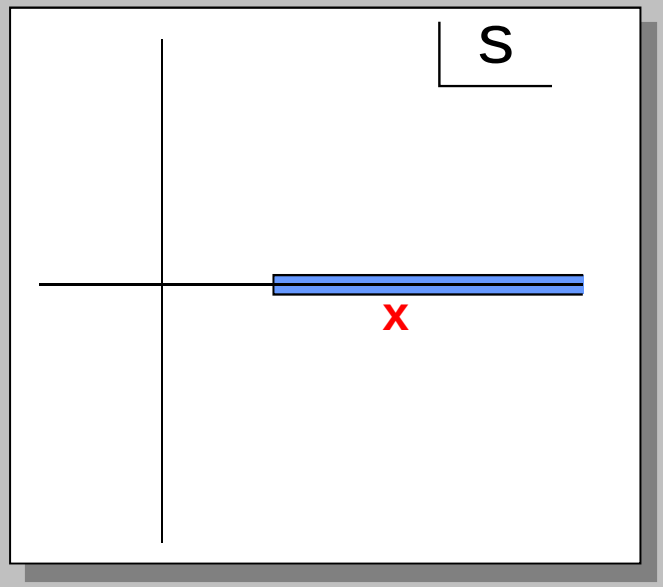
Landscape to be explored



Res Jost

A world with cuts

and overlapping peaks



$$s = E^2$$

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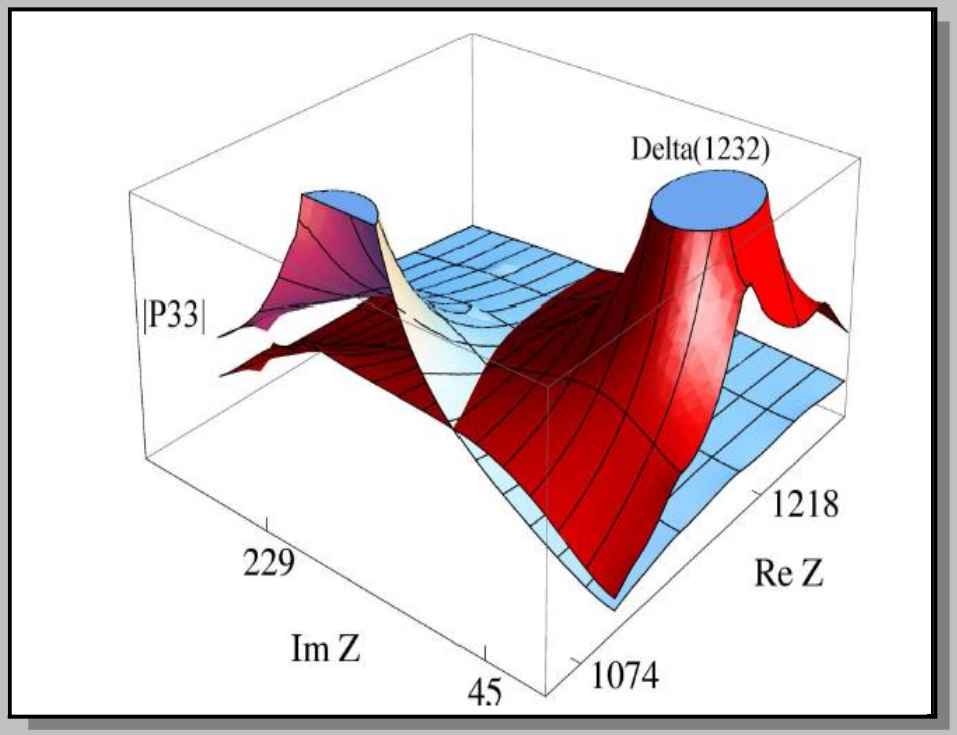
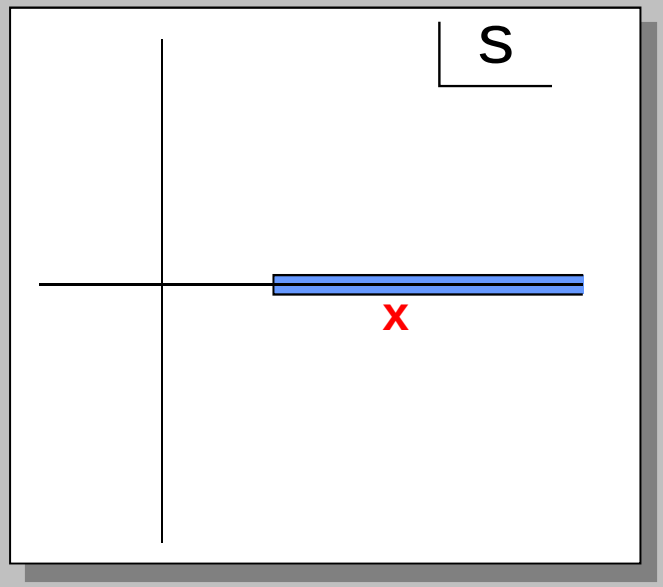
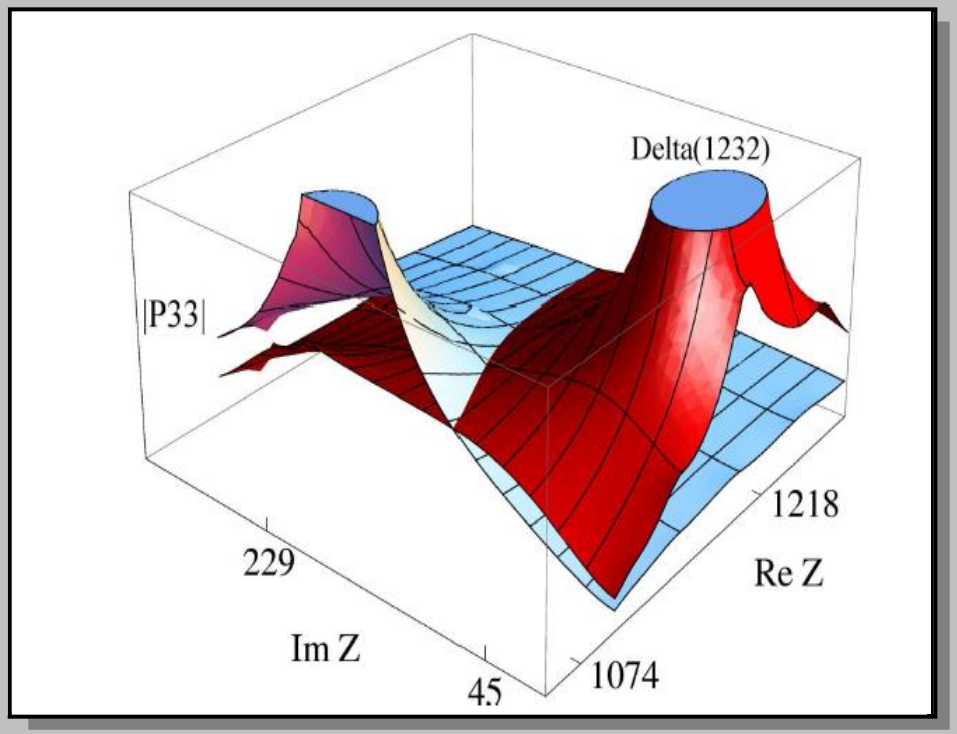




$s = E^2$



Breit-Wigner

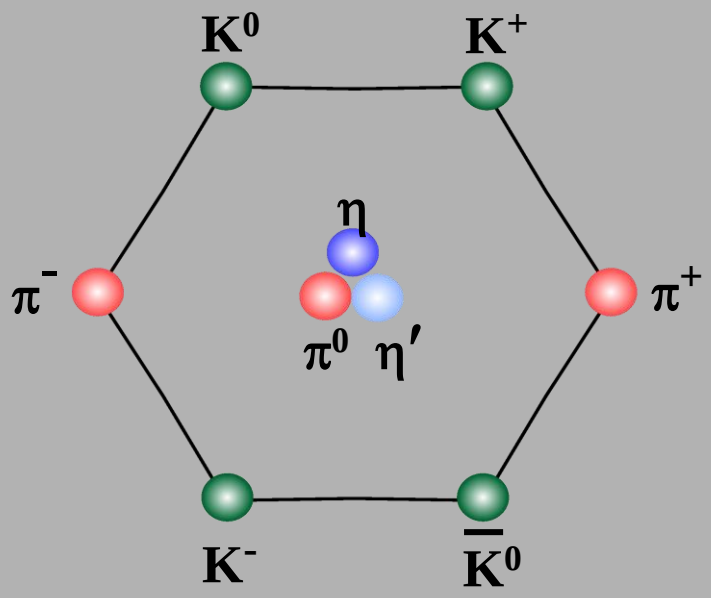
$$\frac{1}{M^2 - s - iM\Gamma}$$

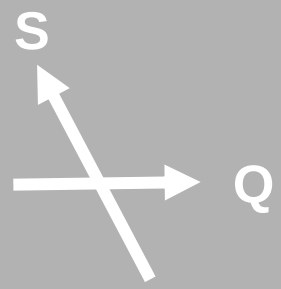
merely an approximation valid in the region of the pole

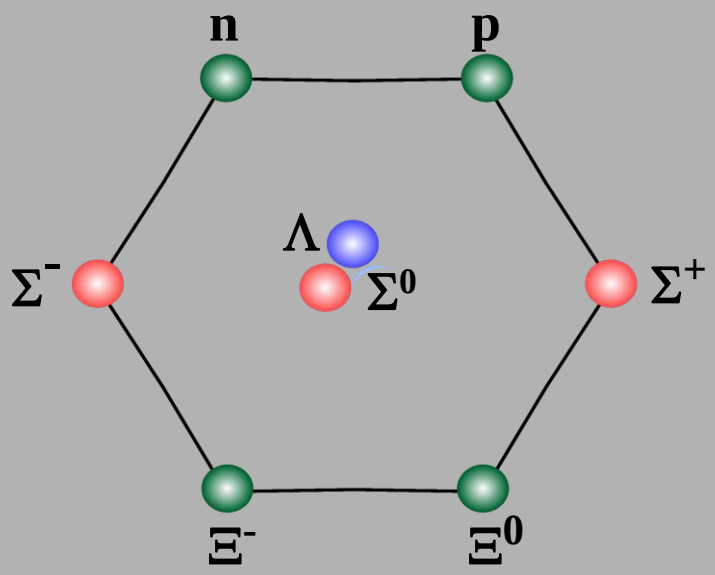
$$\frac{1}{M^2(s) - s}$$

Quark model spectrum

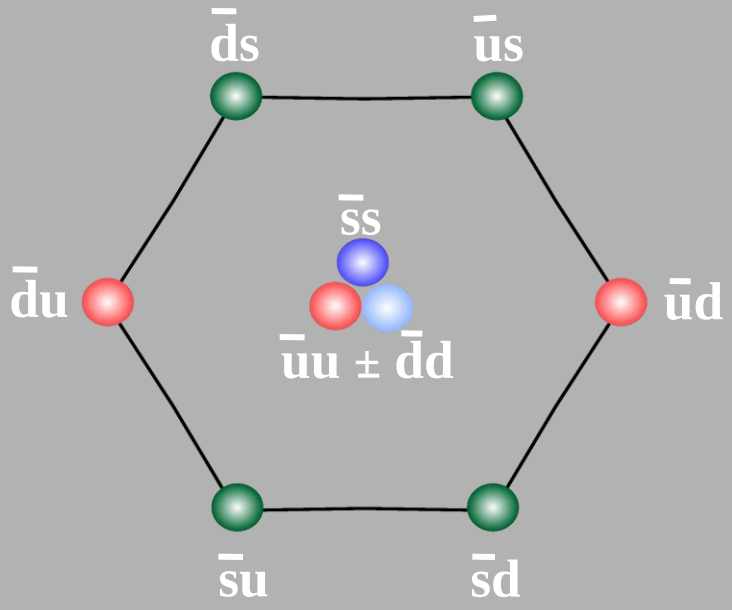
ground states

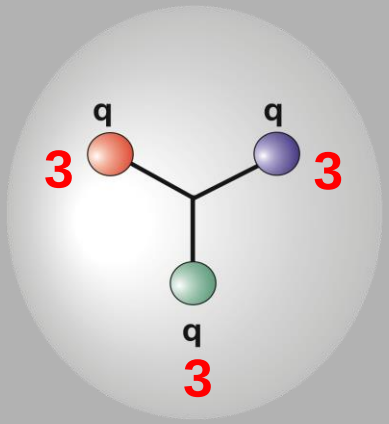


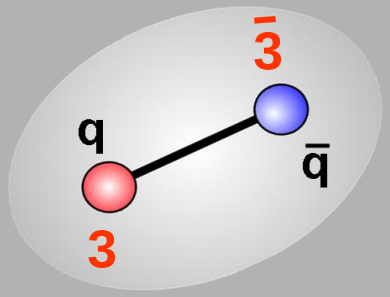


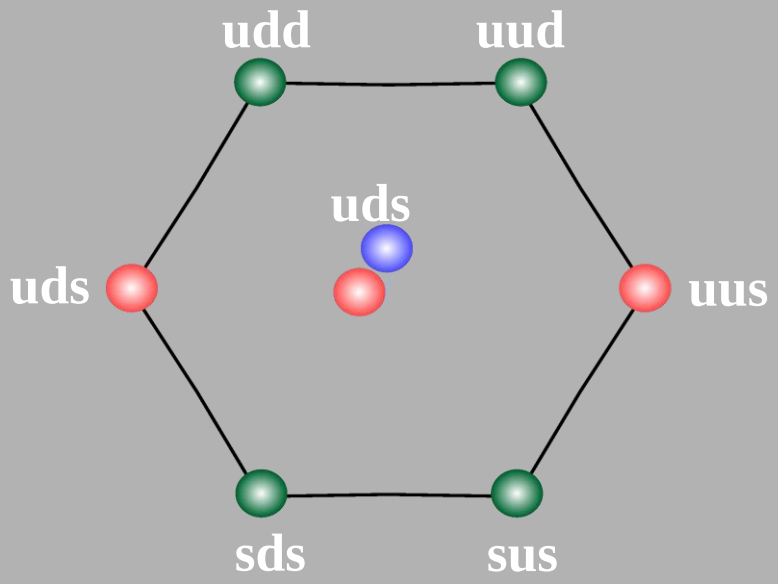


Quark model spectrum

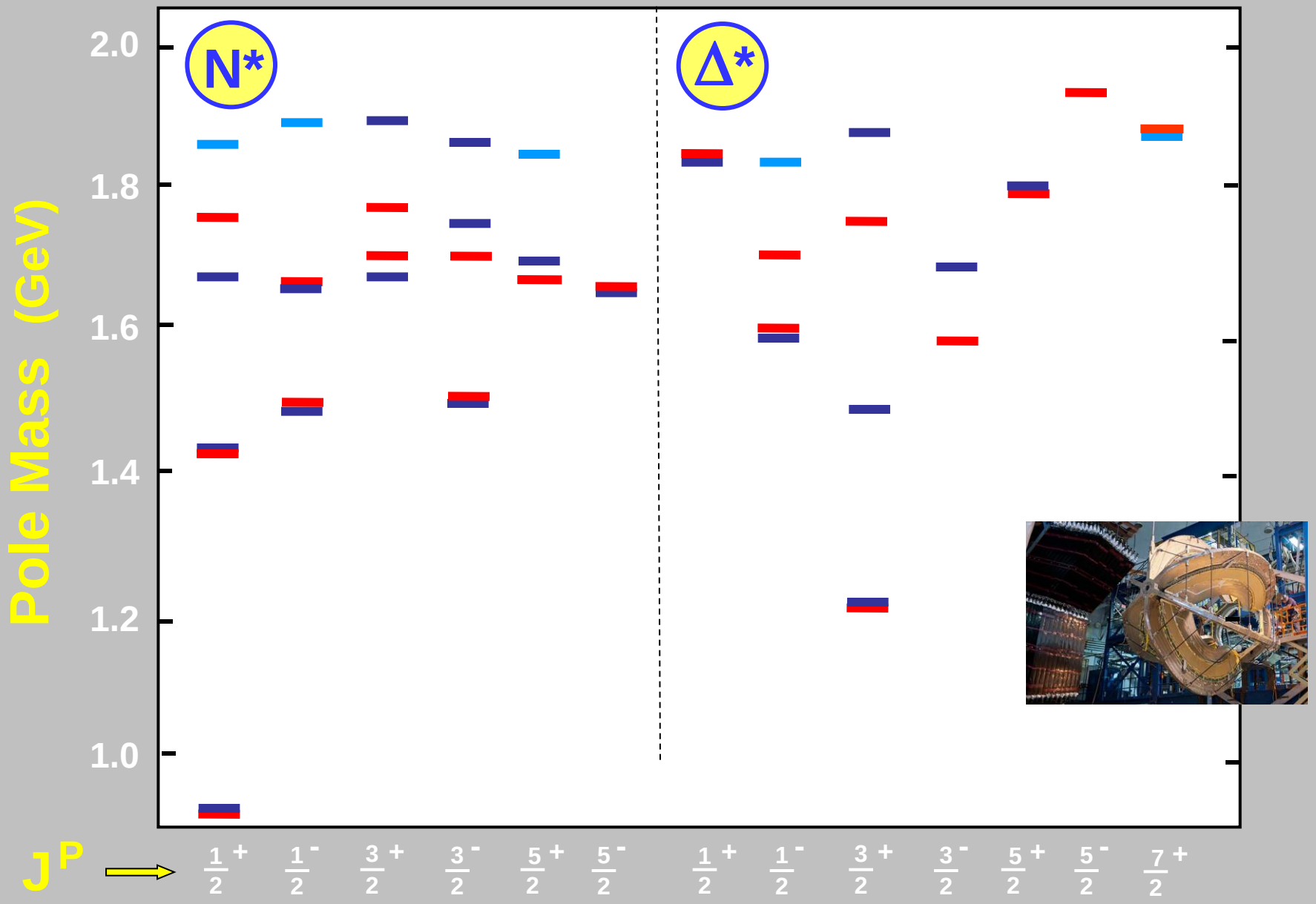




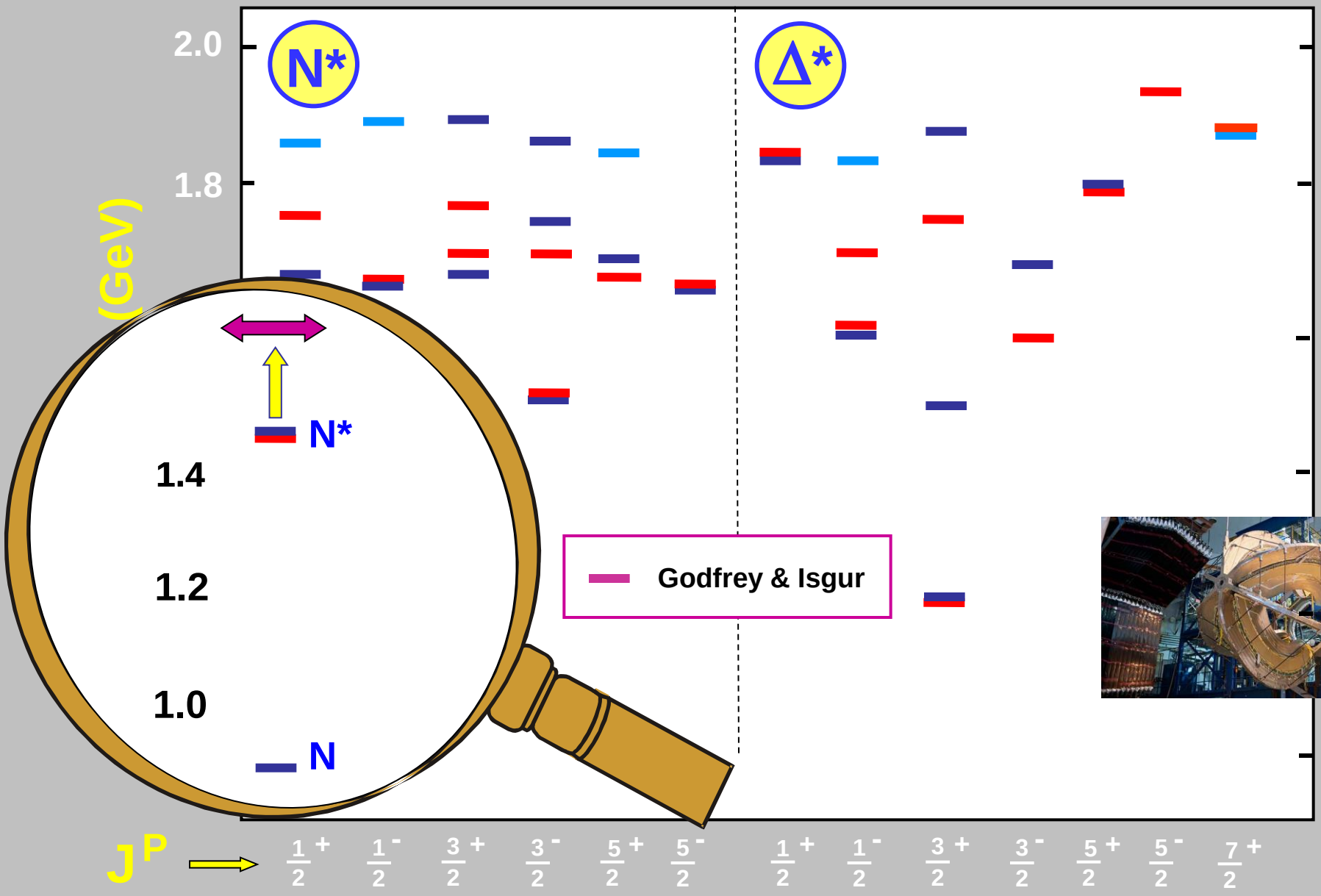




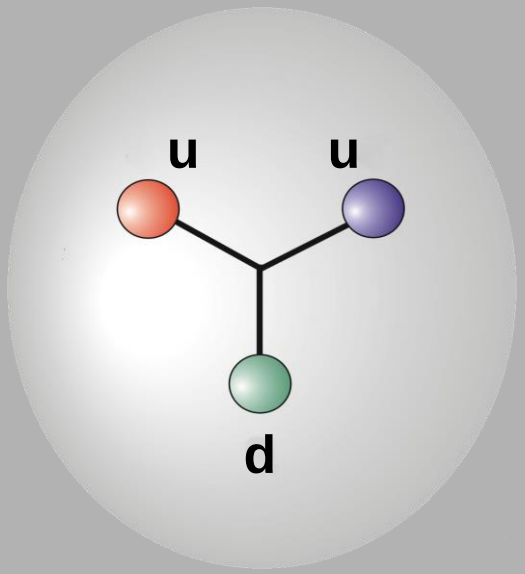
Baryon spectrum from ANL-Osaka & Bonn-Ga

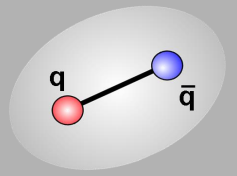


Baryon spectrum from ANL-Osaka & Bonn-Ga

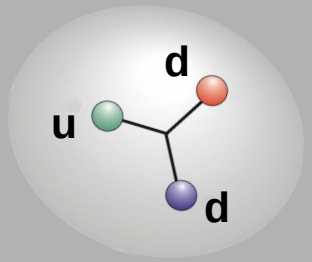


N*(1440) colour wave-function





π



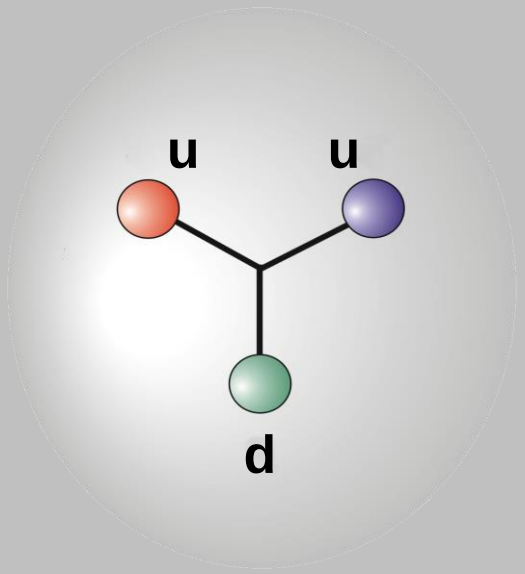
N

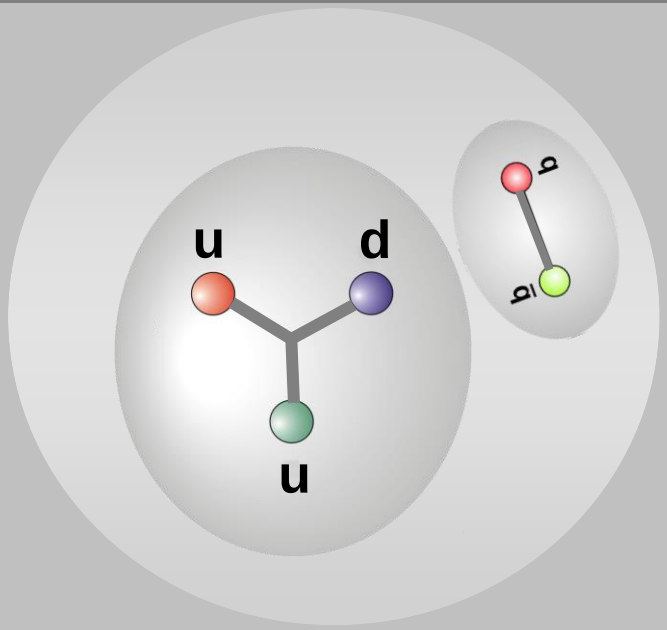
Roper

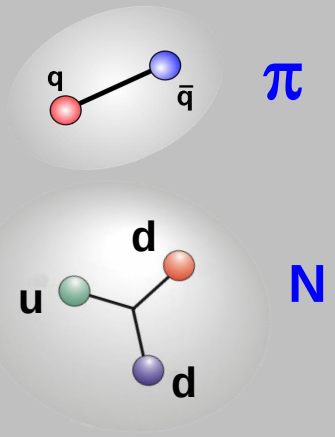
$$N^{*+} = \frac{1}{\sqrt{6}} [\ uud + uud + uud - uud - uud - uud\ ]$$

$N_c = 3$

N*(1440) colour wave-function







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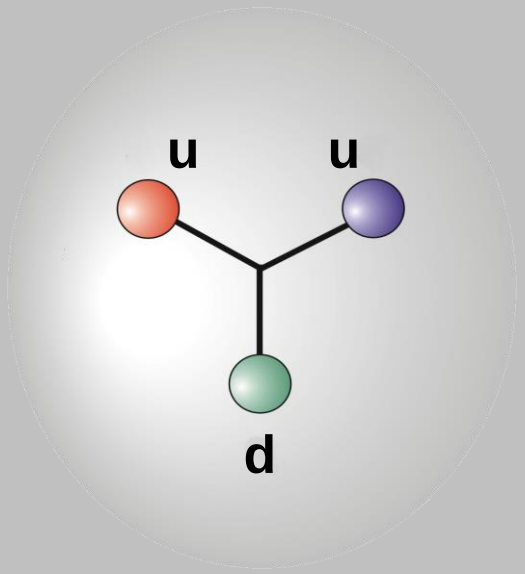
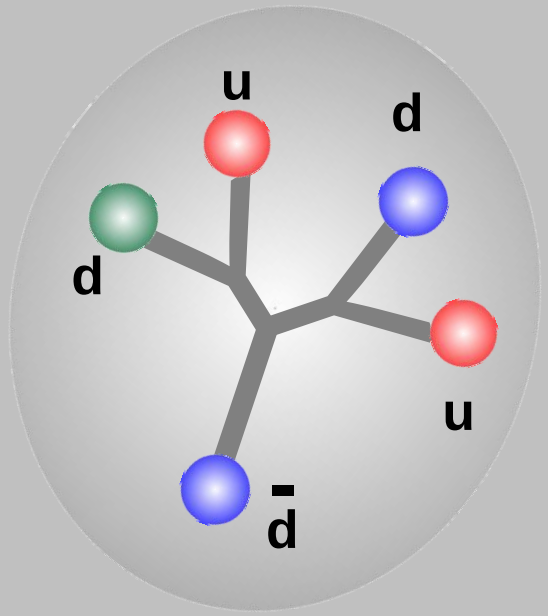
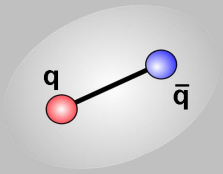
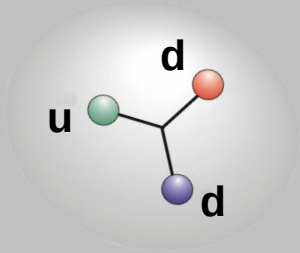






π



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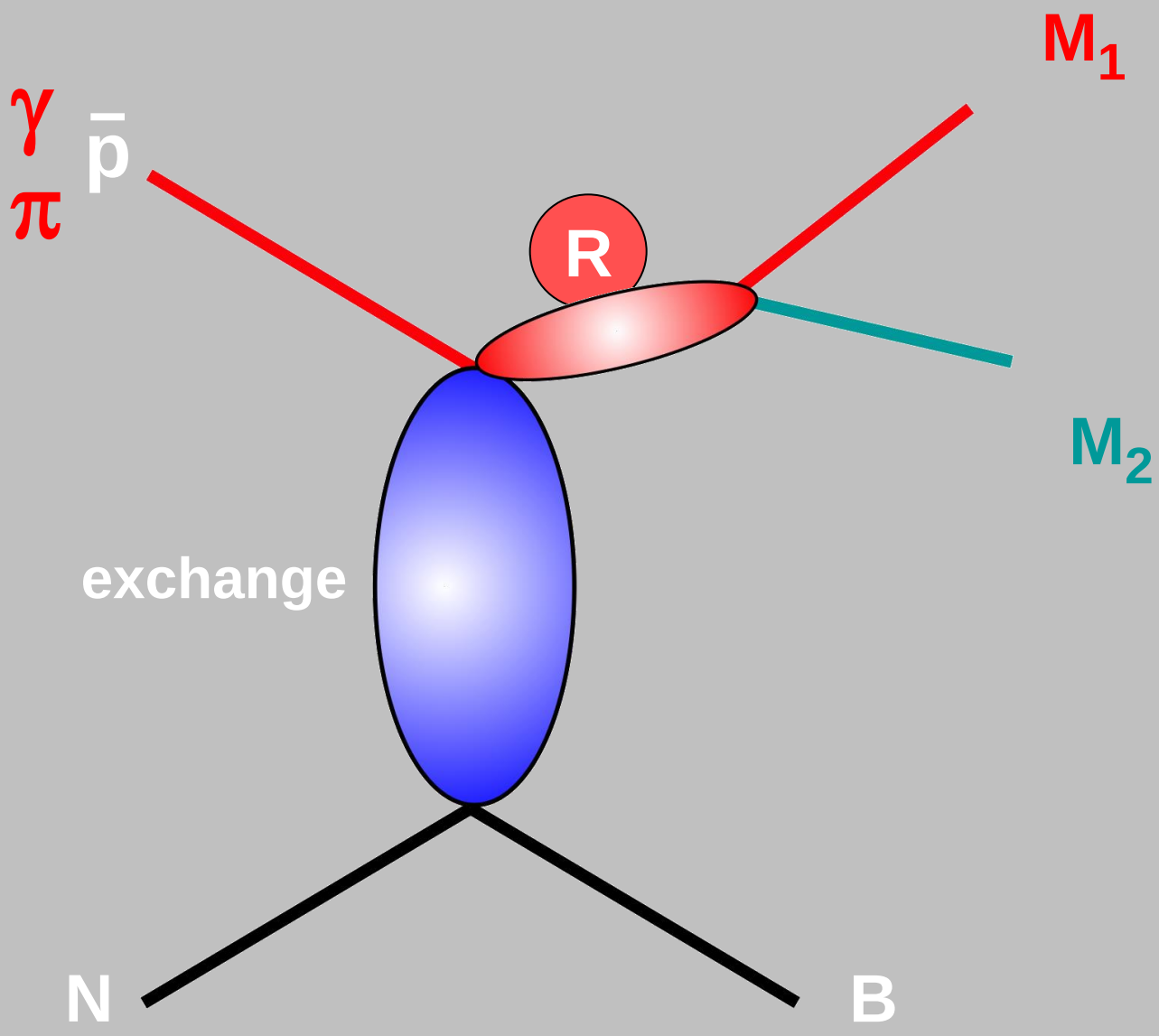
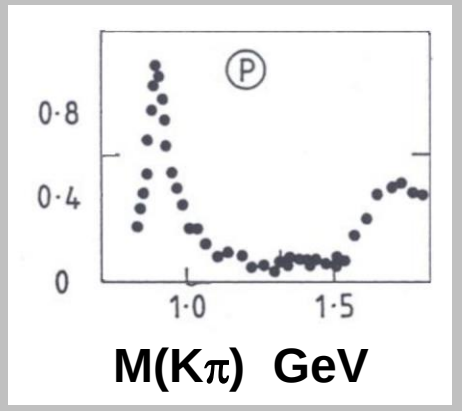
Hadroproduction





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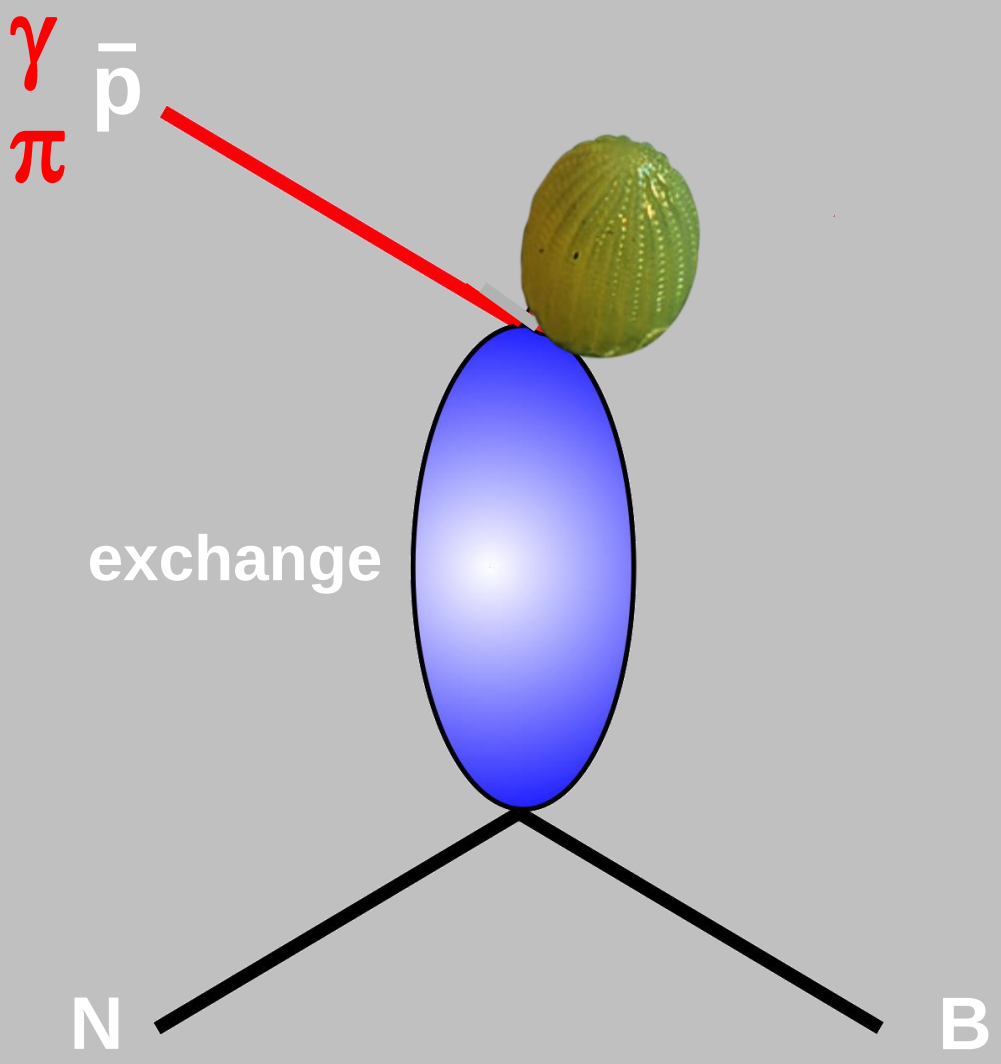

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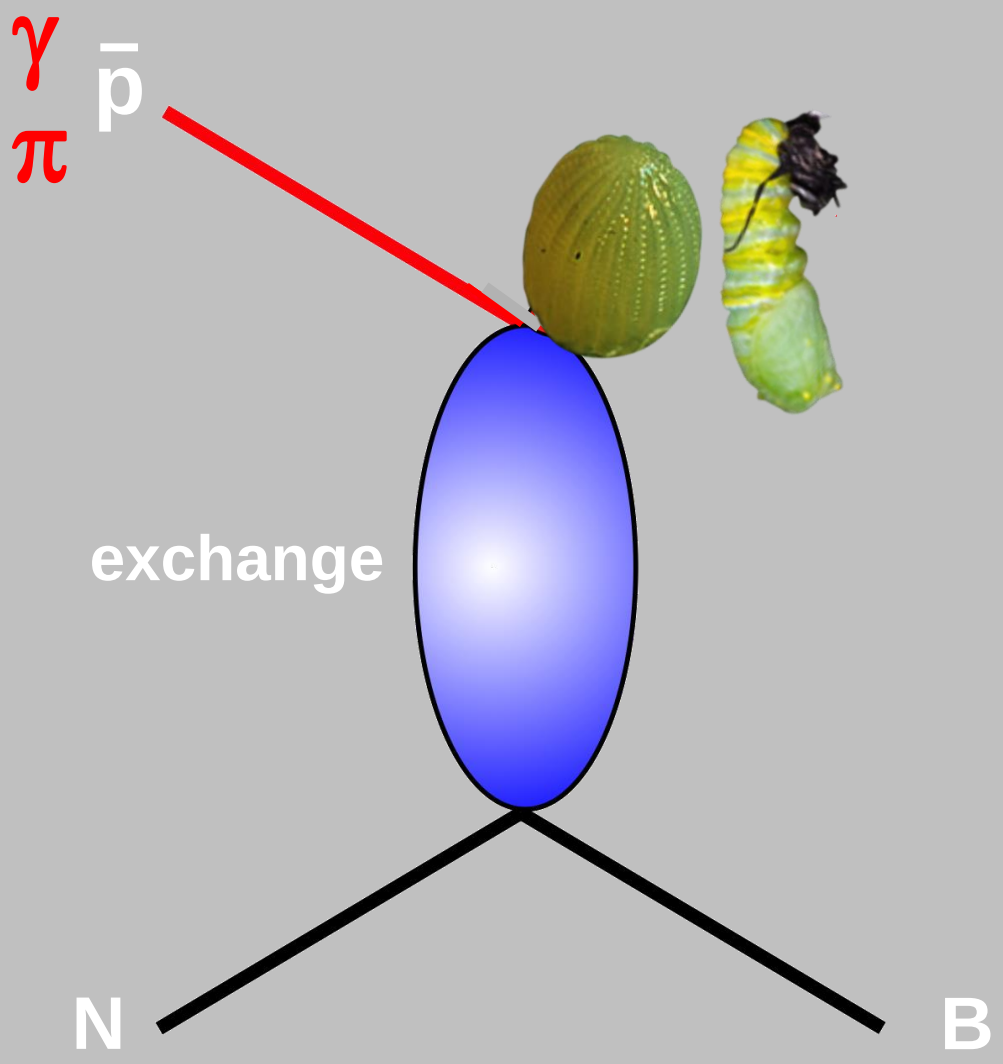

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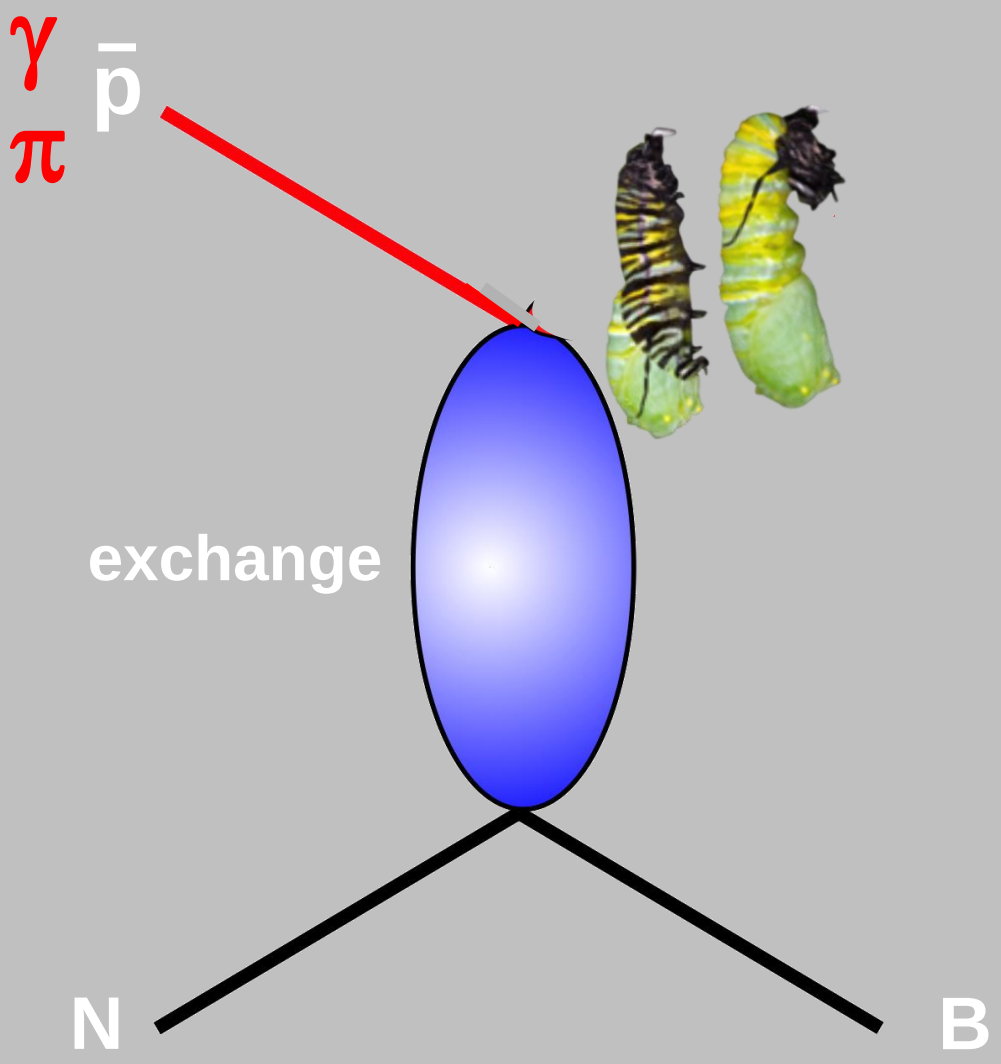

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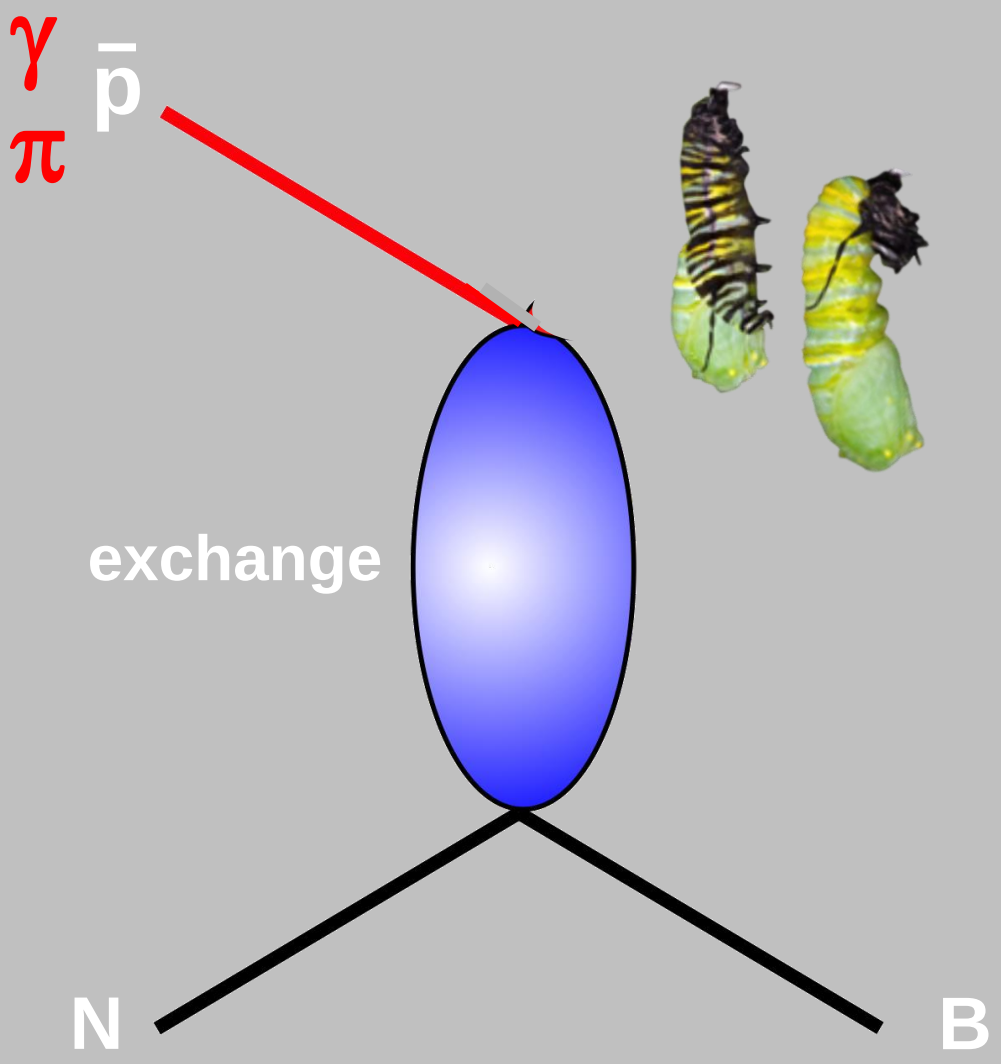

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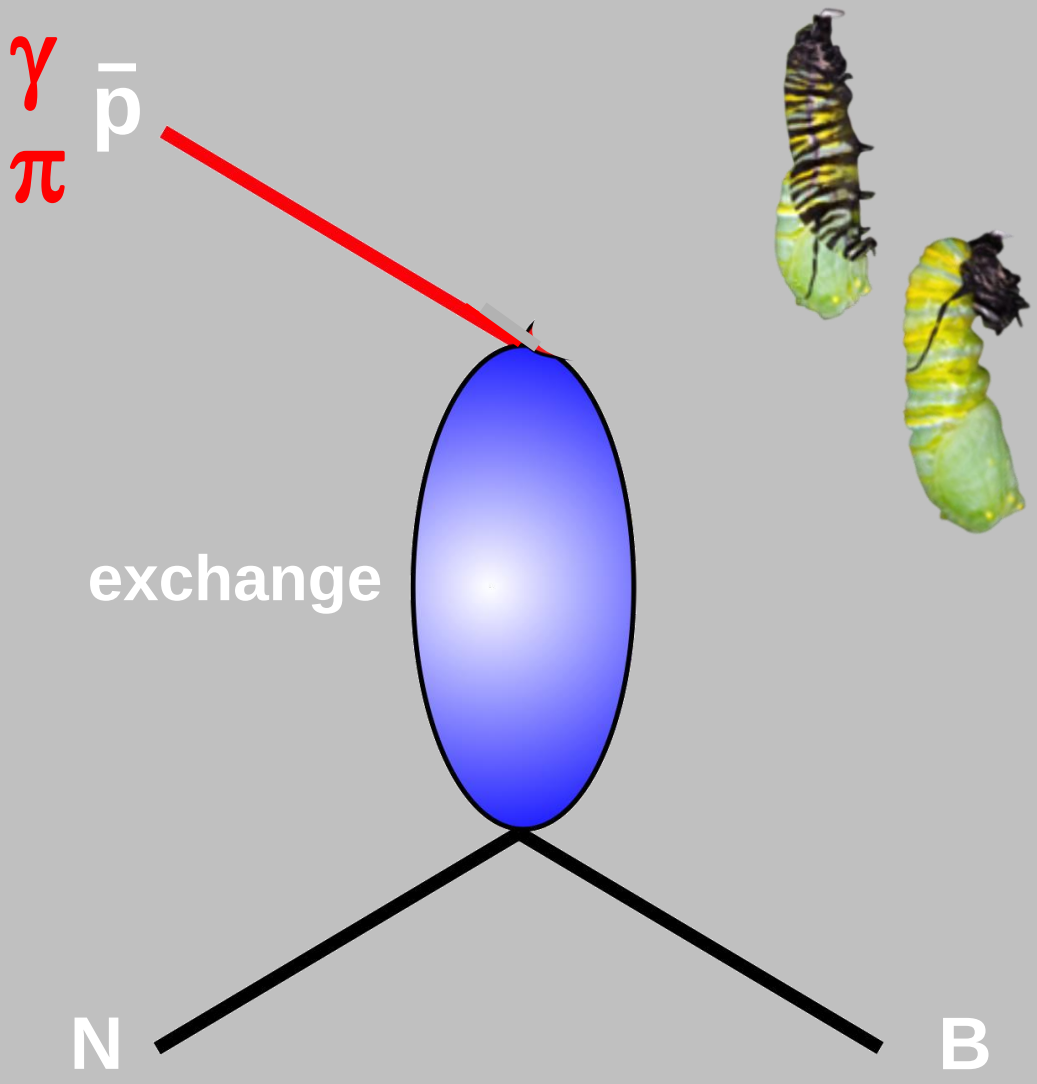

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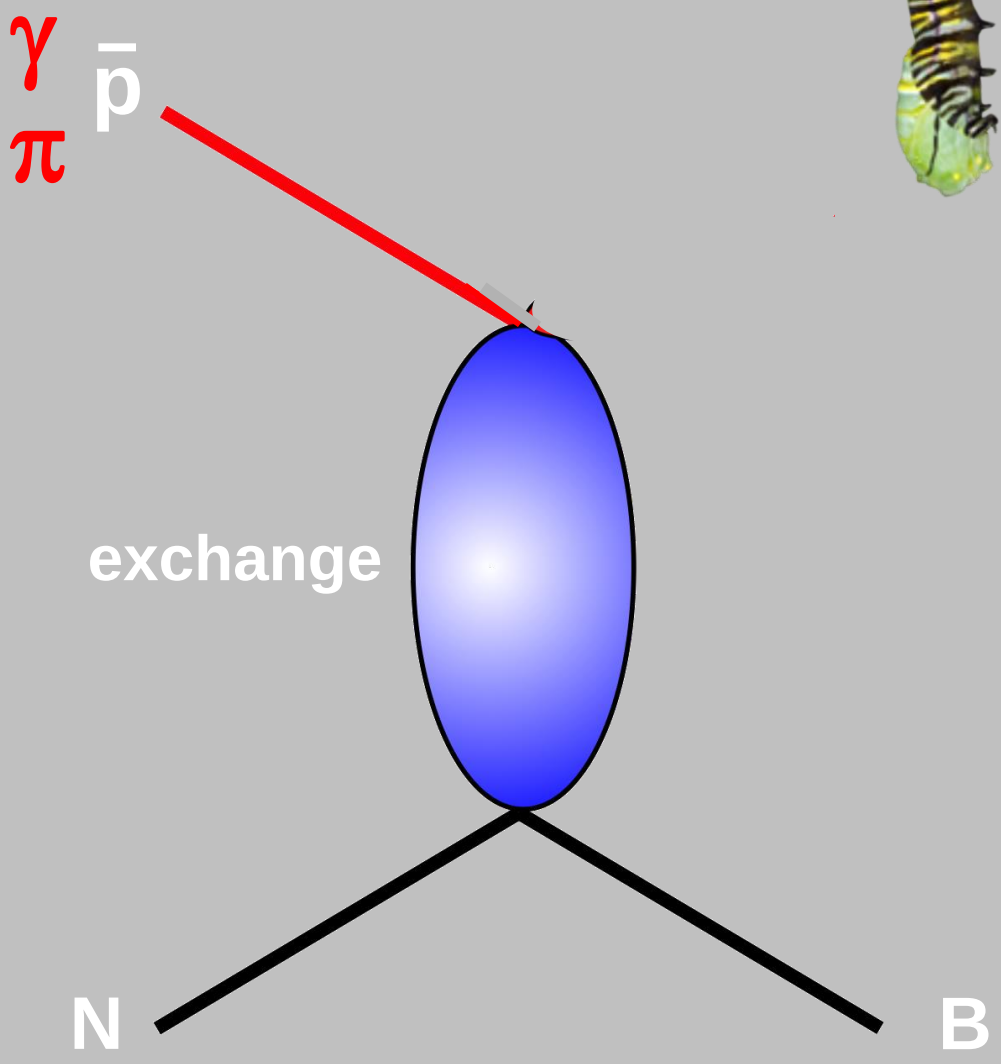

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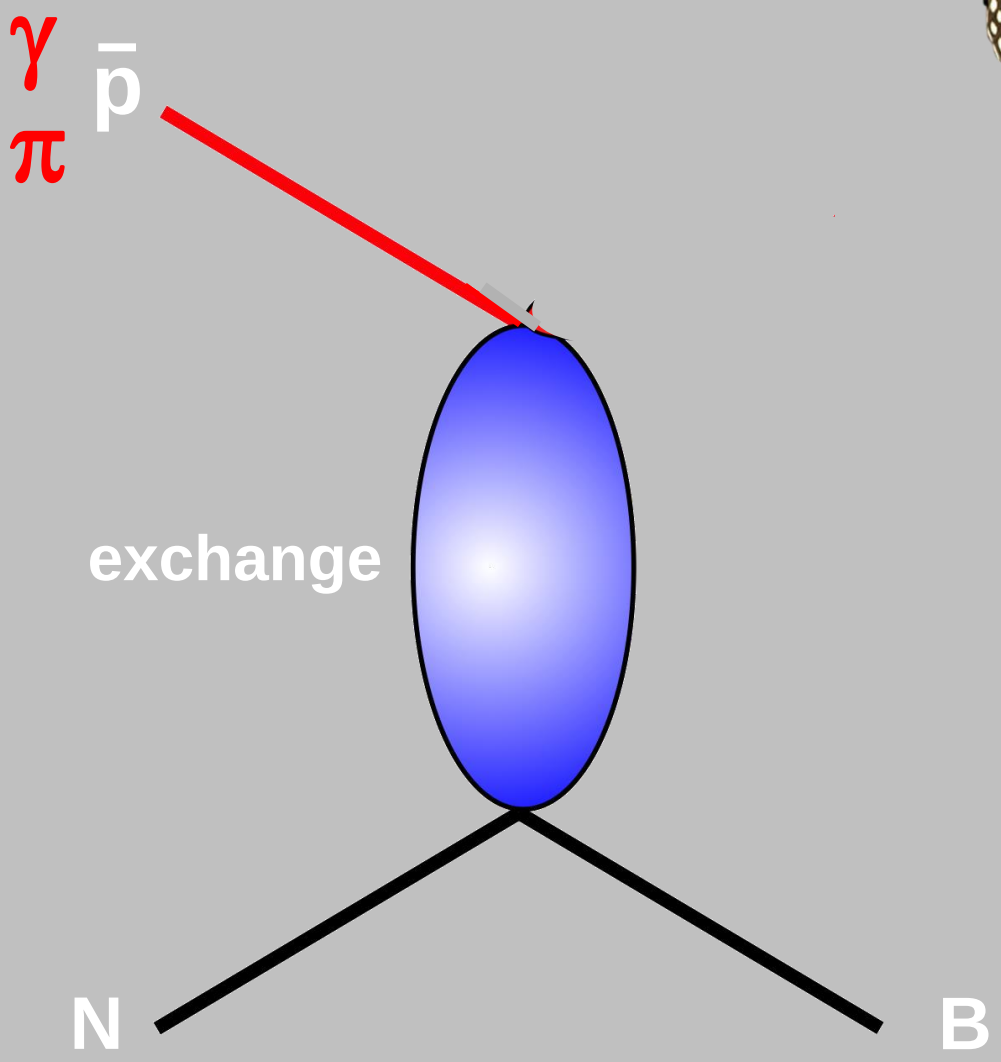

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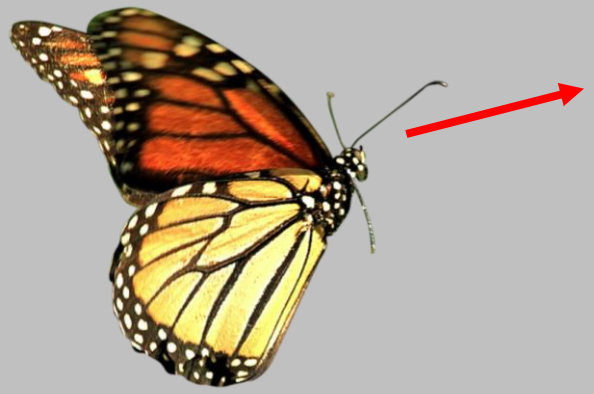
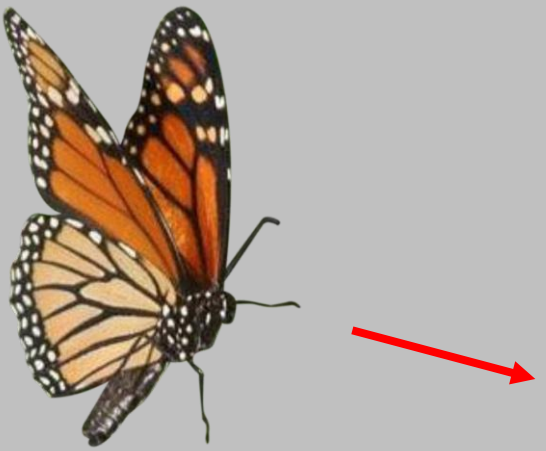
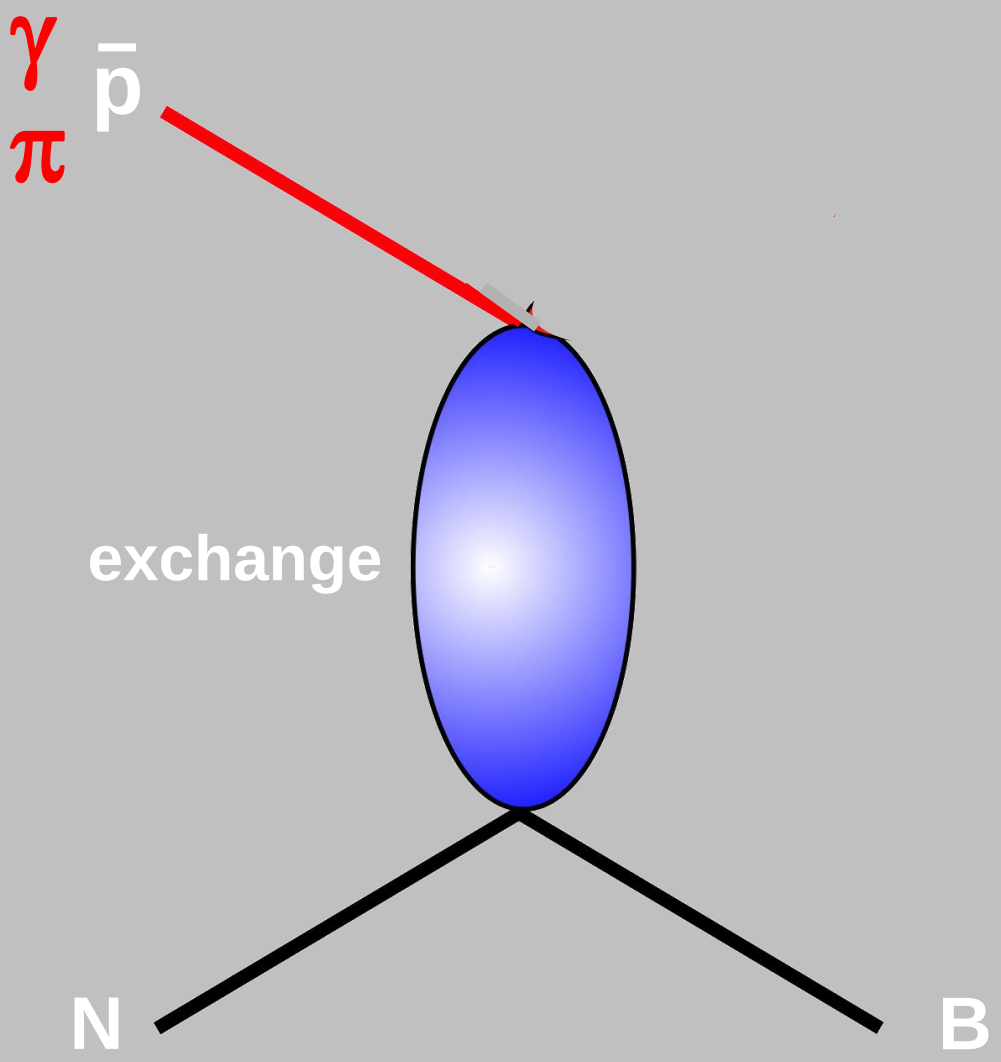
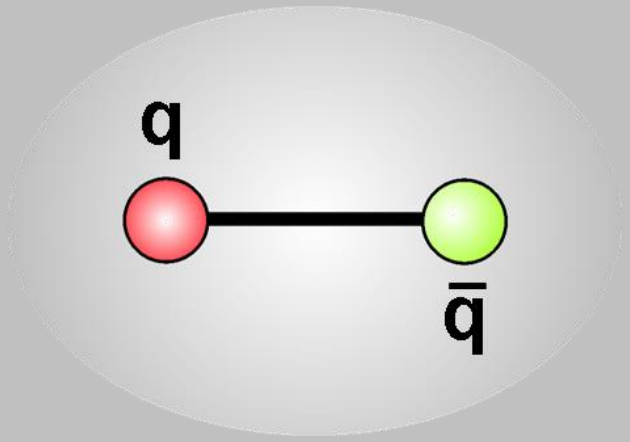






ρ(770)



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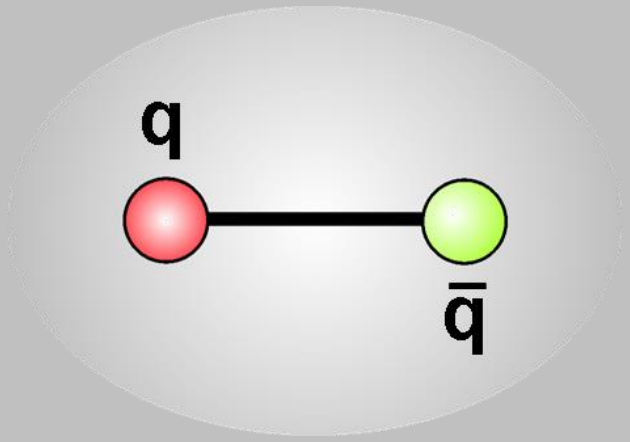
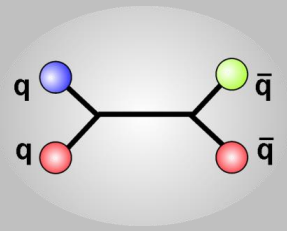
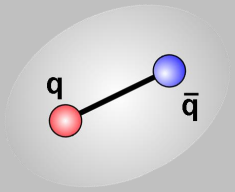
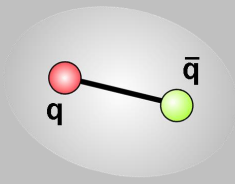


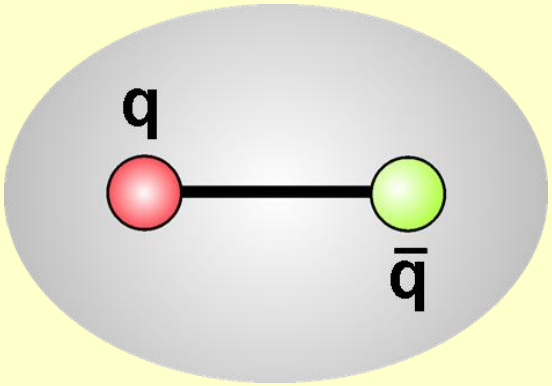


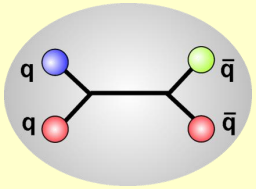


π^+



π^-


q
q̄


q
q
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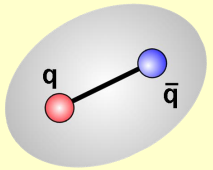
q̄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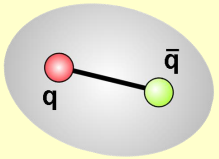
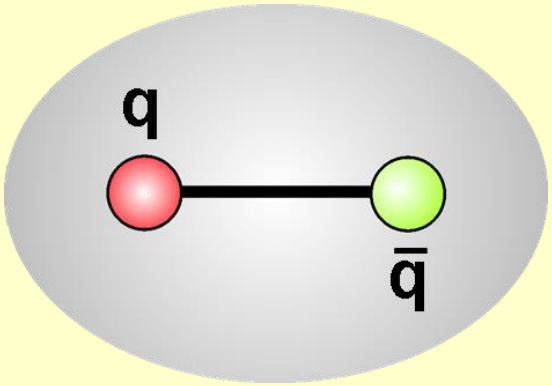
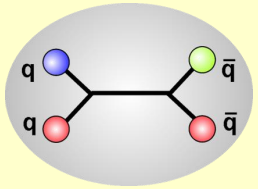
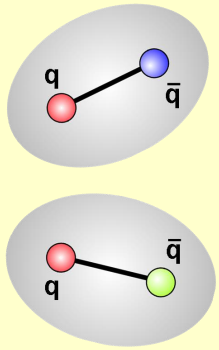
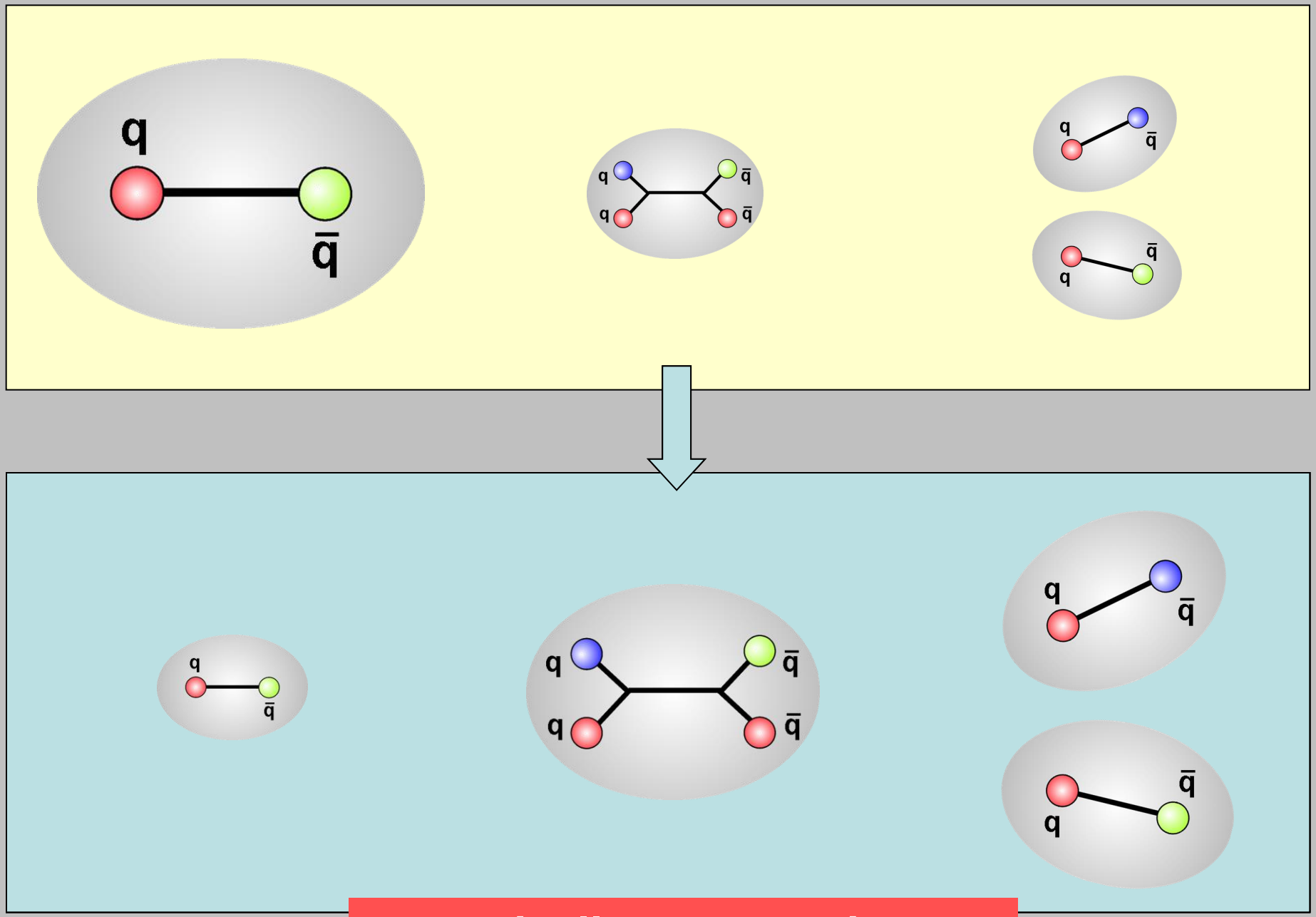

q̄
q







Degrees of freedom


q
q̄
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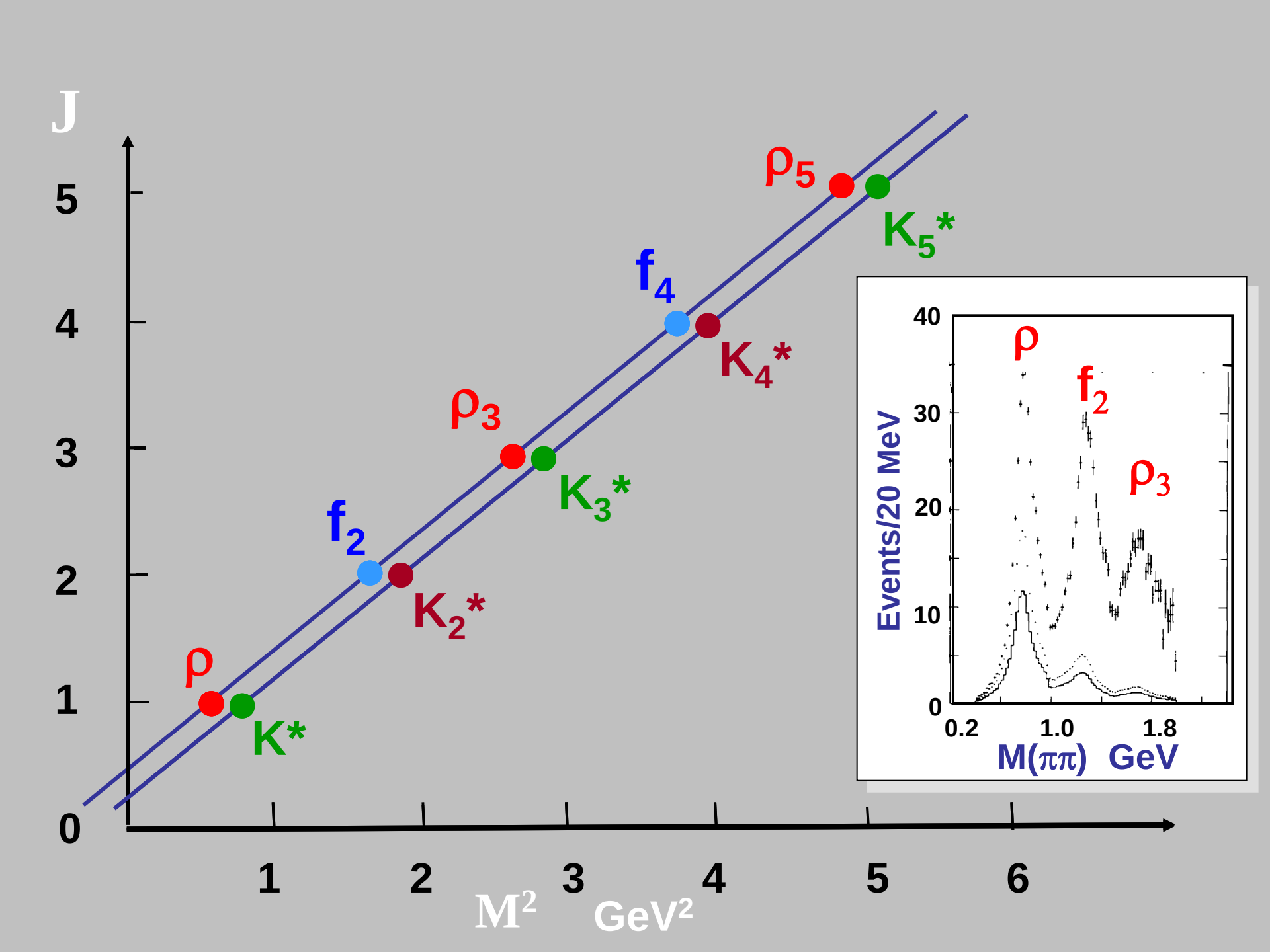
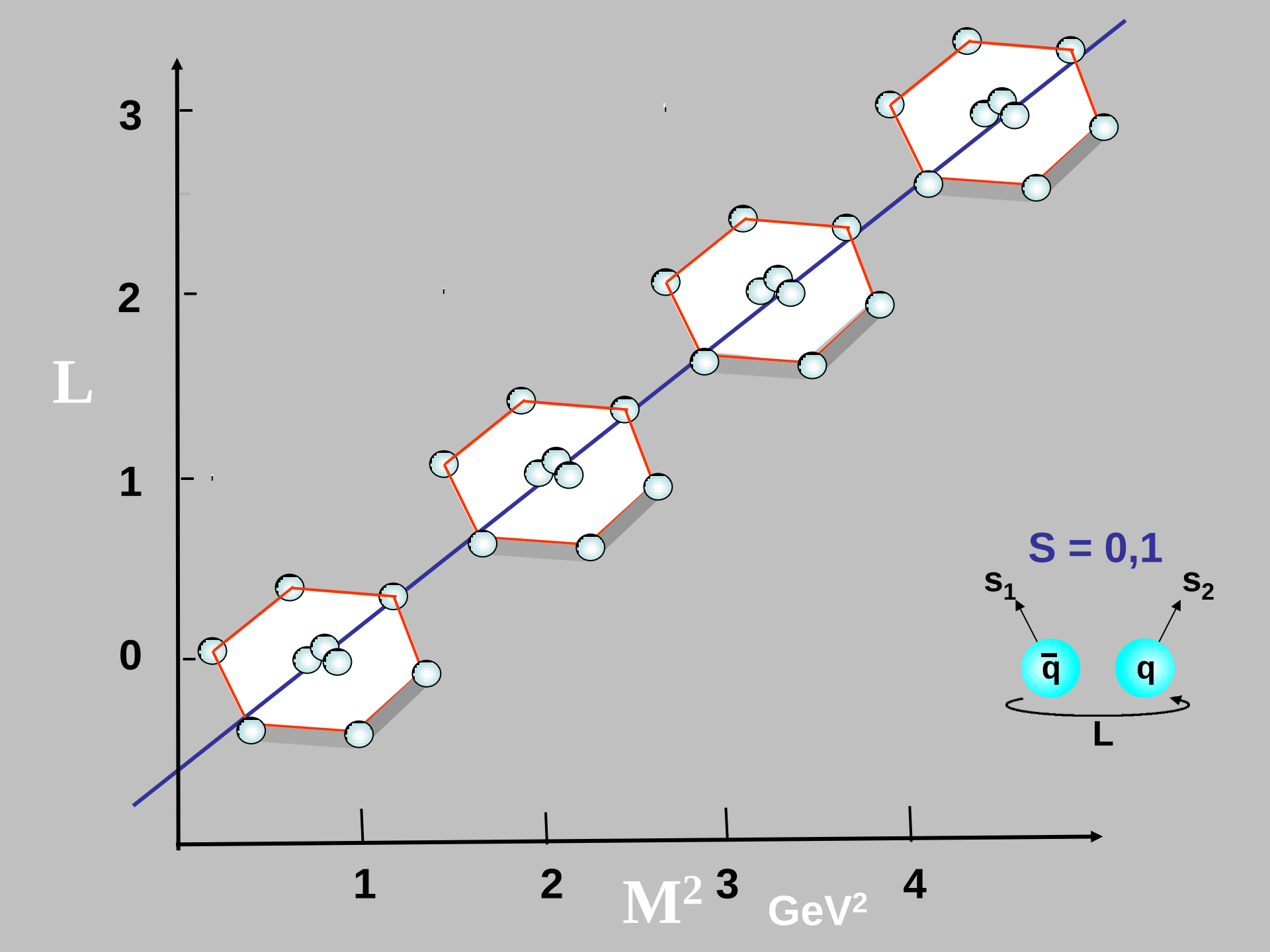
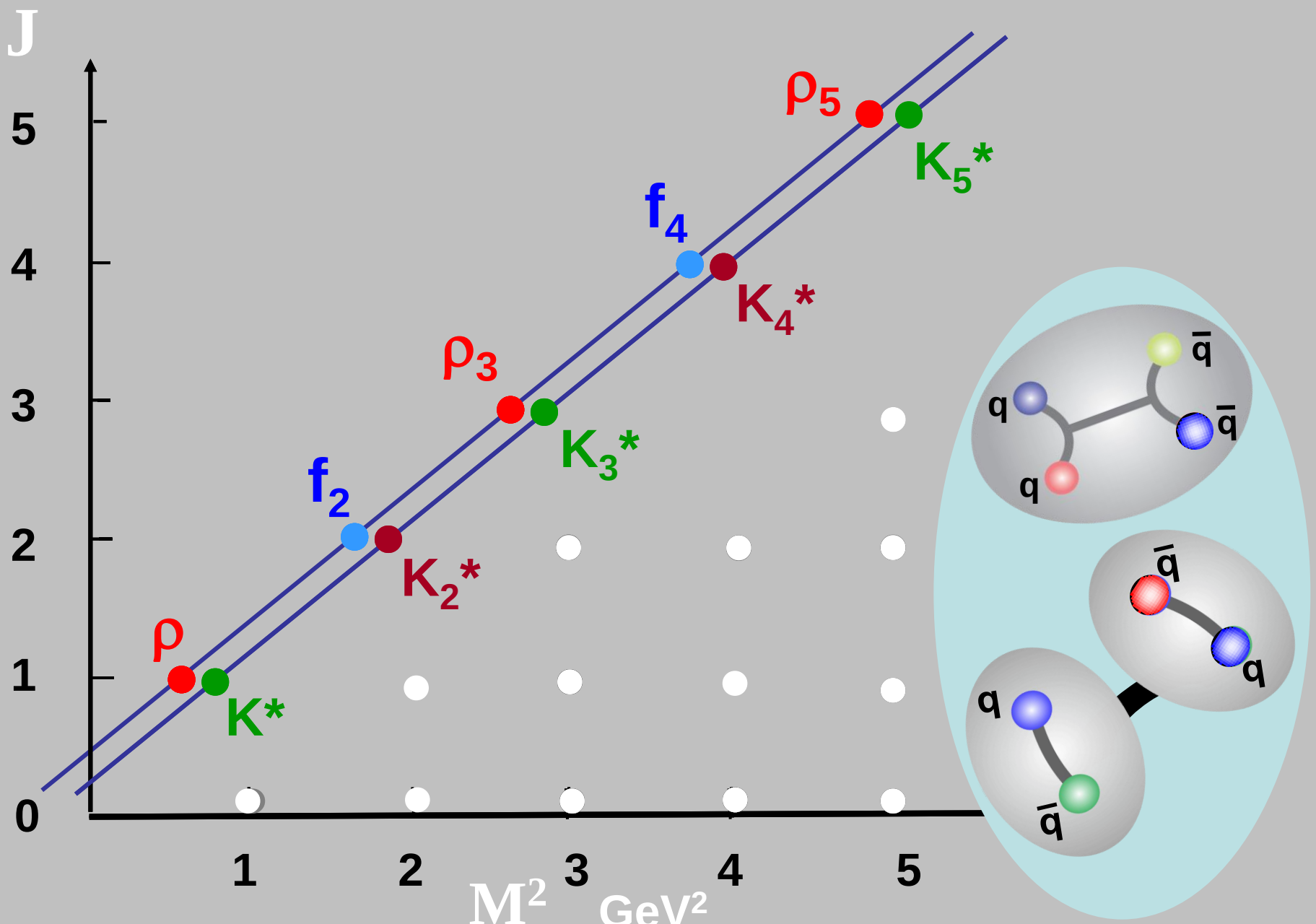
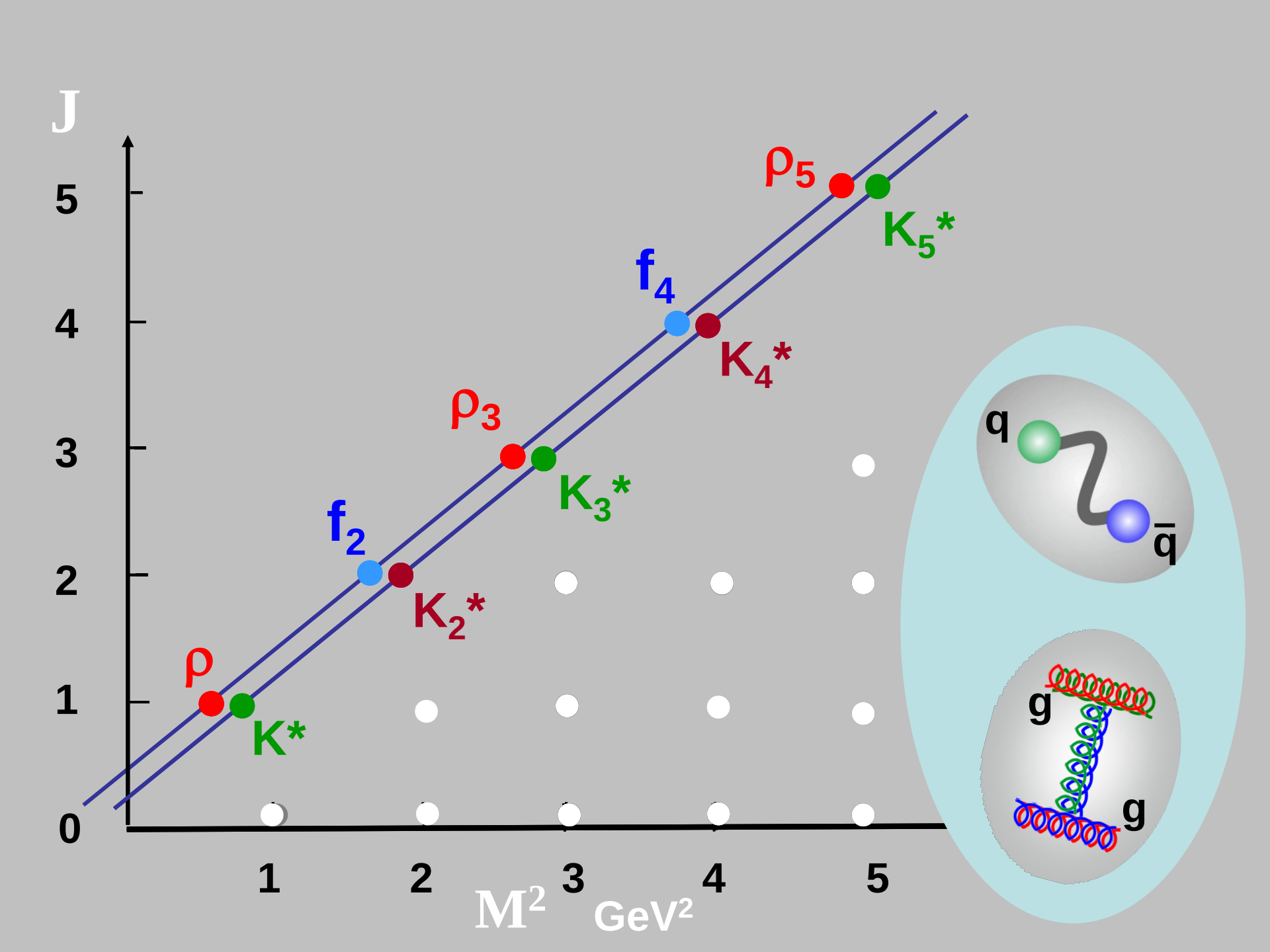
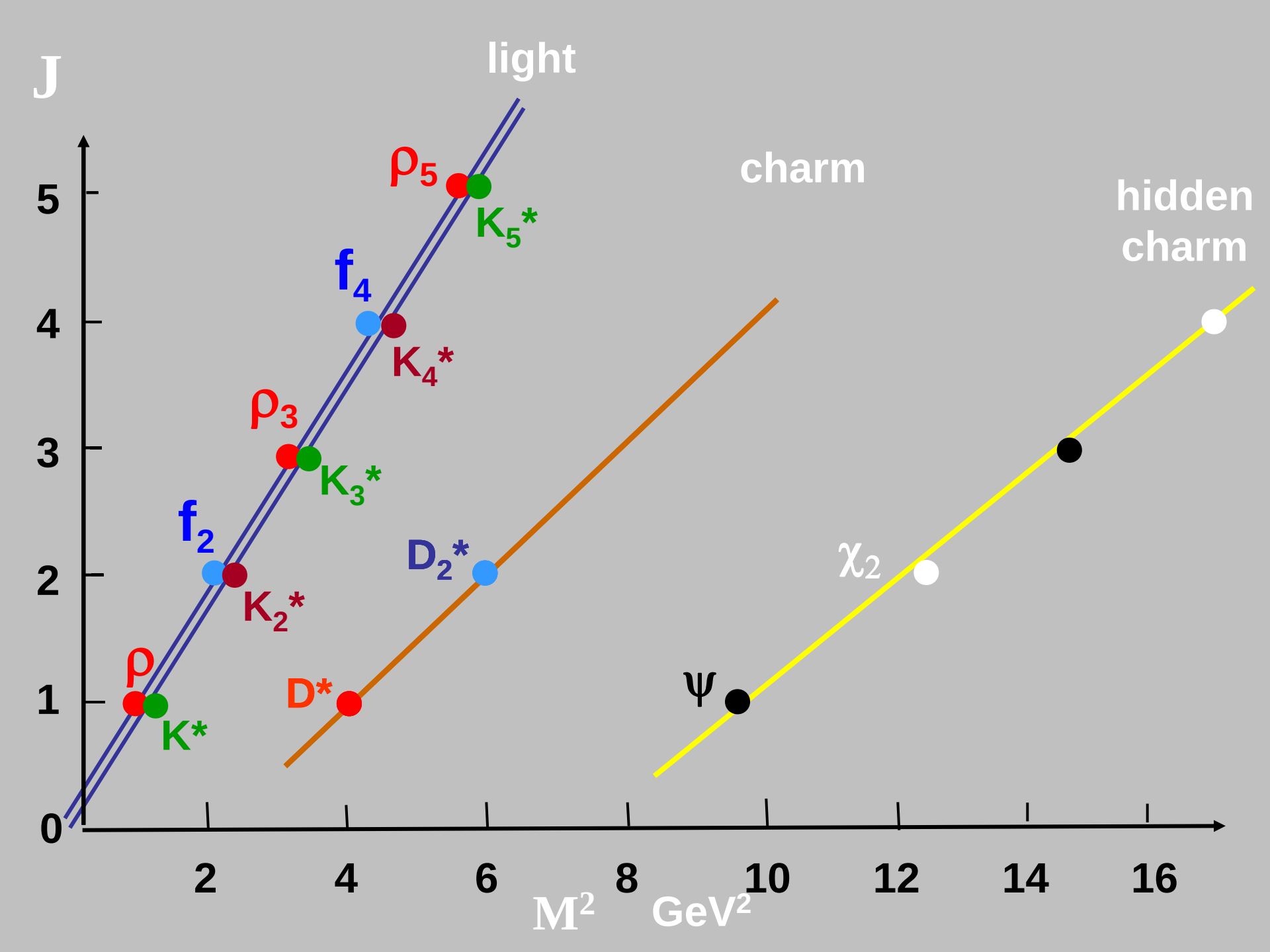
Dynamically generated states


J
5
4
3
2
1
0
1
2
3
4
5
6
M² GeV²
ρ
K*
f2
K2*
ρ3
K3*
f4
K4*
ρ5
K5*
Events/20 MeV
40
30
20
10
0
0.2
1.0
1.8
M(ππ) GeV
ρ
f2
ρ3

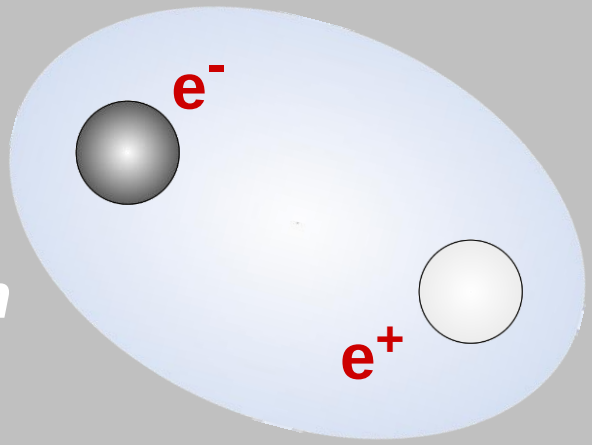

L
3
2
1
0
1
2
3
4
M² GeV²
S = 0,1
S1
S2
q̄
q
L


J
5
4
3
2
1
0
1
2
3
4
5
M² GeV²
ρ
K*
f₂
K₂*
ρ₃
K₃*
f₄
K₄*
ρ₅
K₅*
q
q̄
q
q̄
q̄
q
q
q̄

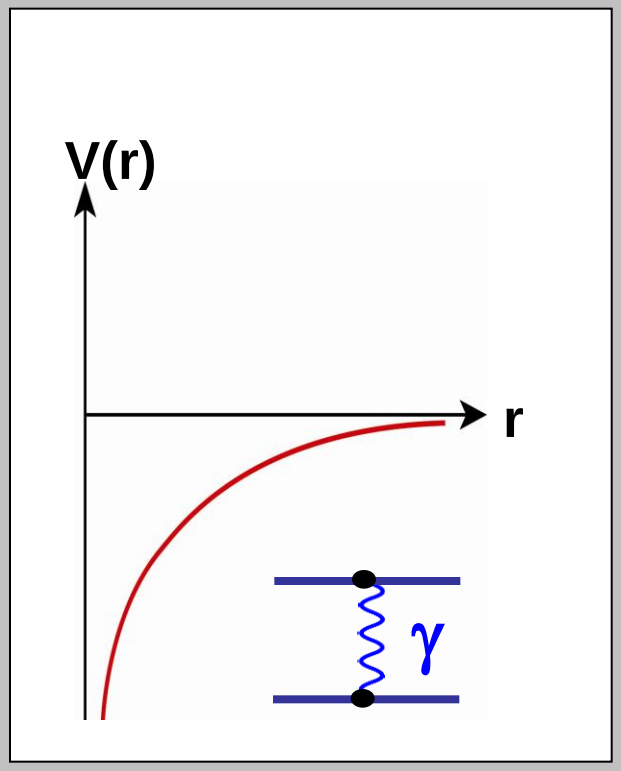

J
5
4
3
2
1
0
1
2
3
4
5
M² GeV²
ρ
K*
f2
K2*
ρ3
K3*
f4
K4*
ρ5
K5*
q
q̄
g
g


J
light
charm
hidden
charm
ρ5
K5*
f4
K4*
ρ3
K3*
f2
K2*
ρ
K*
D2*
D*
χ2
ψ
0
1
2
3
4
5
2
4
6
8
10
12
14
16
M2 GeV2

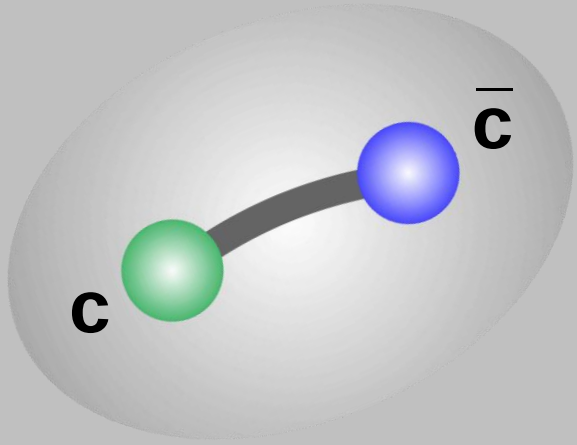
positronium



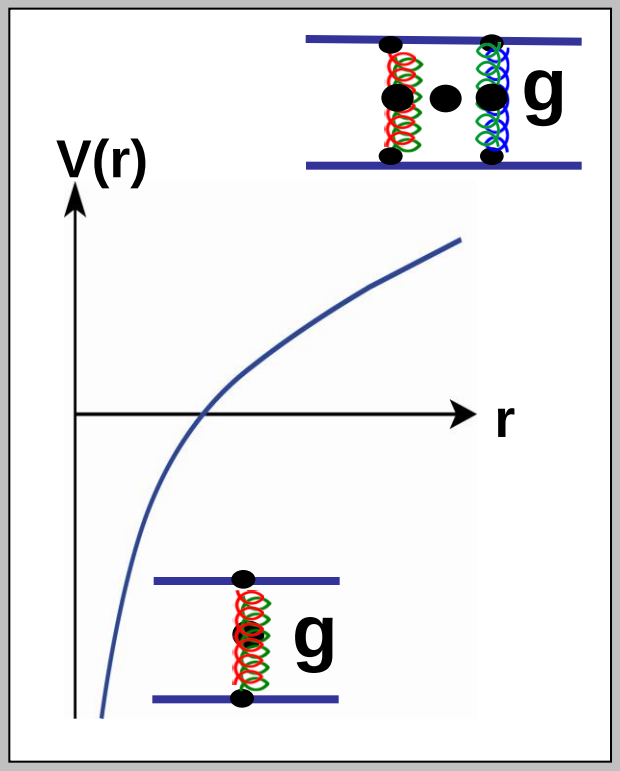
0.1 *nm*



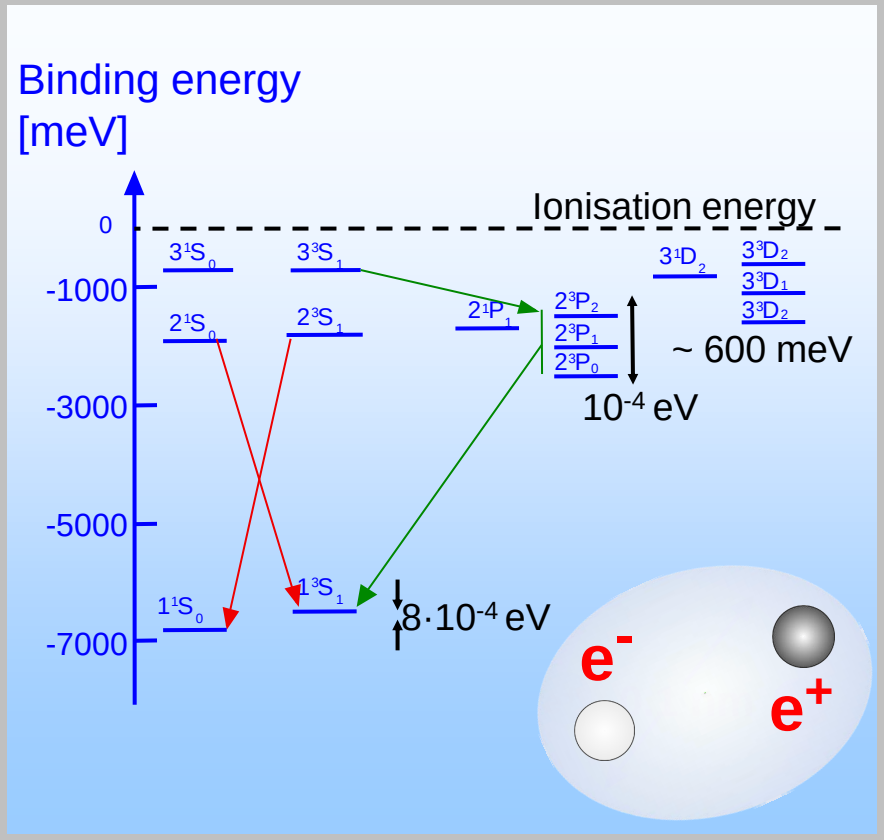
charmonium



1 *fm*

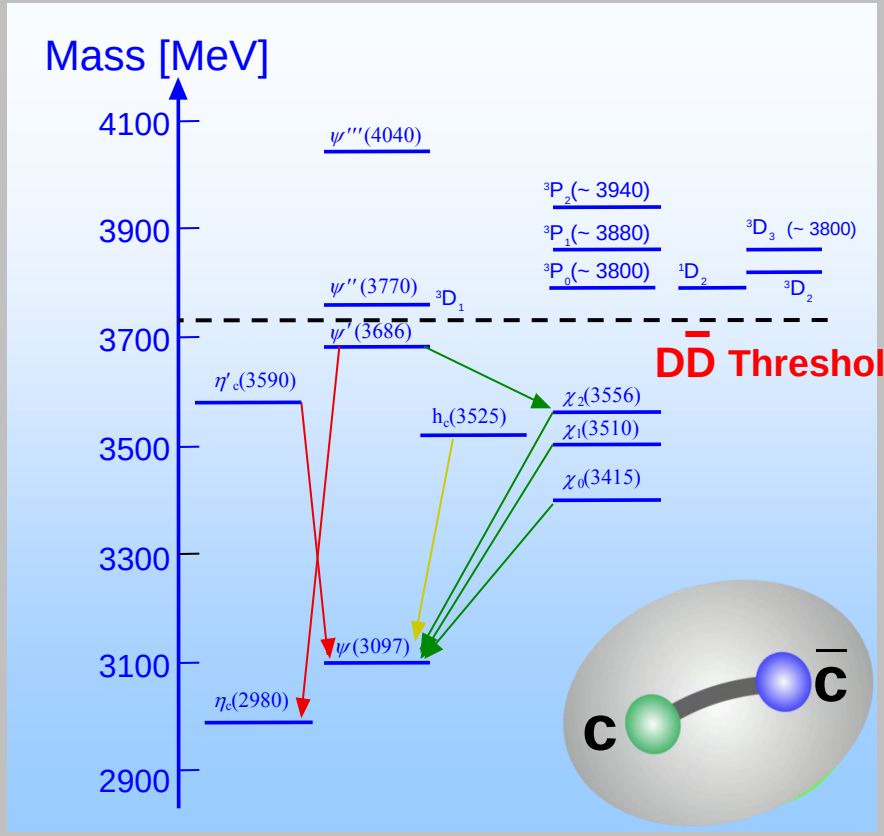


positronium



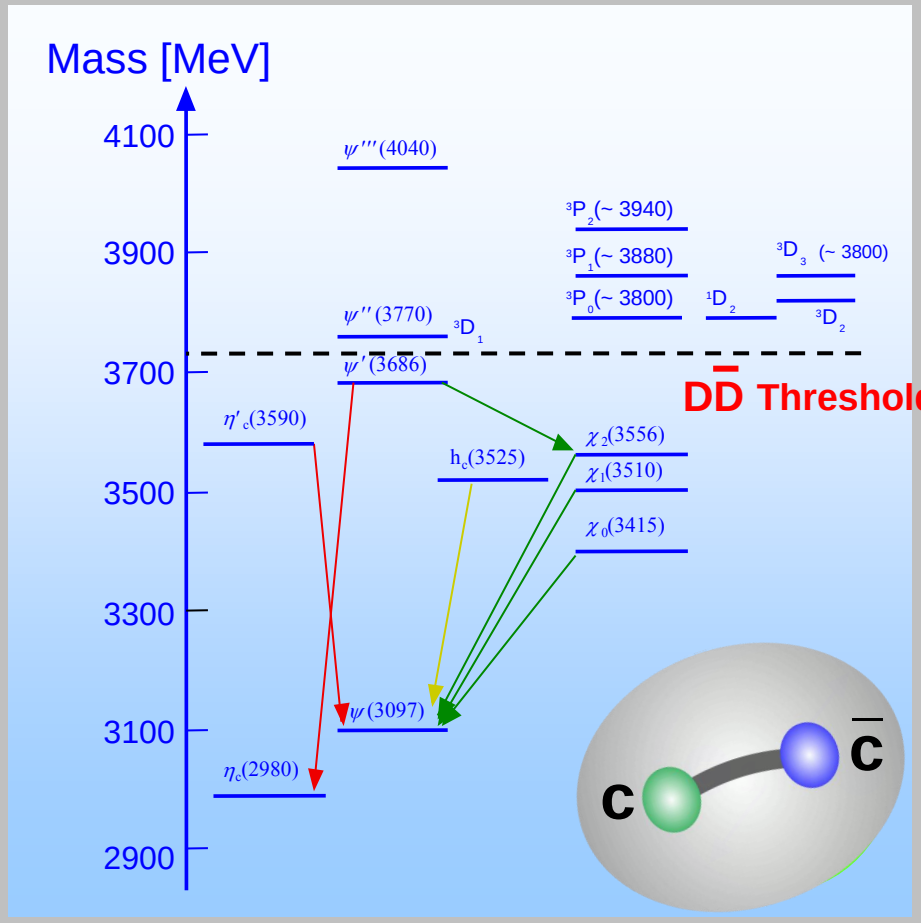
0.1 *nm*

charmonium

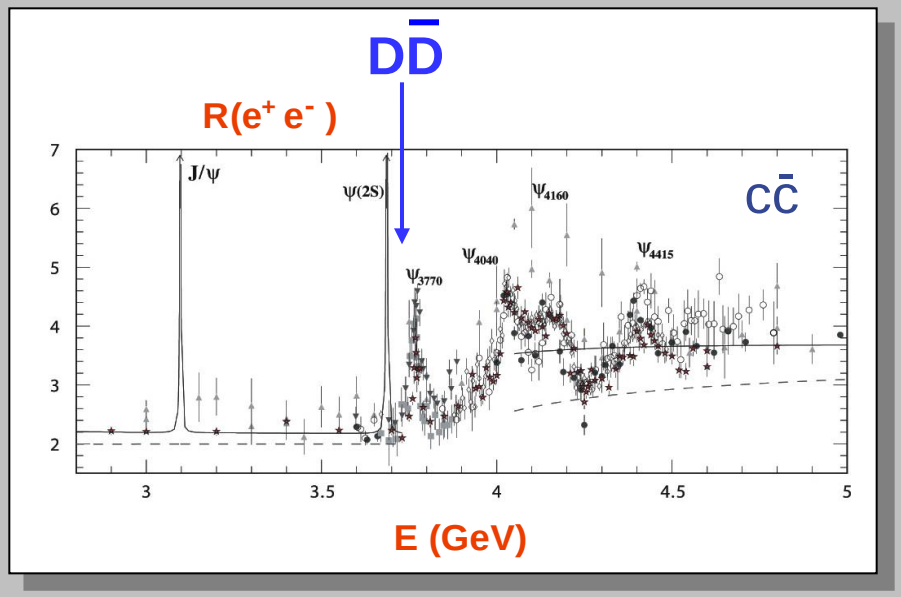


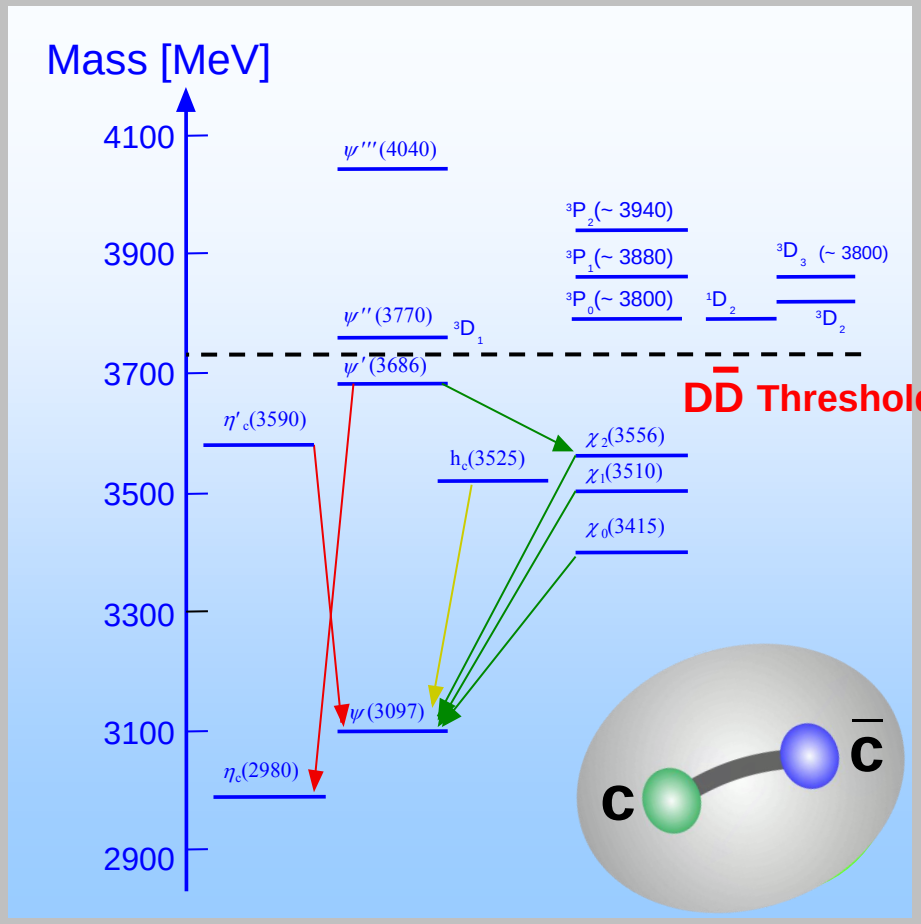
1 *fm*

charmonium

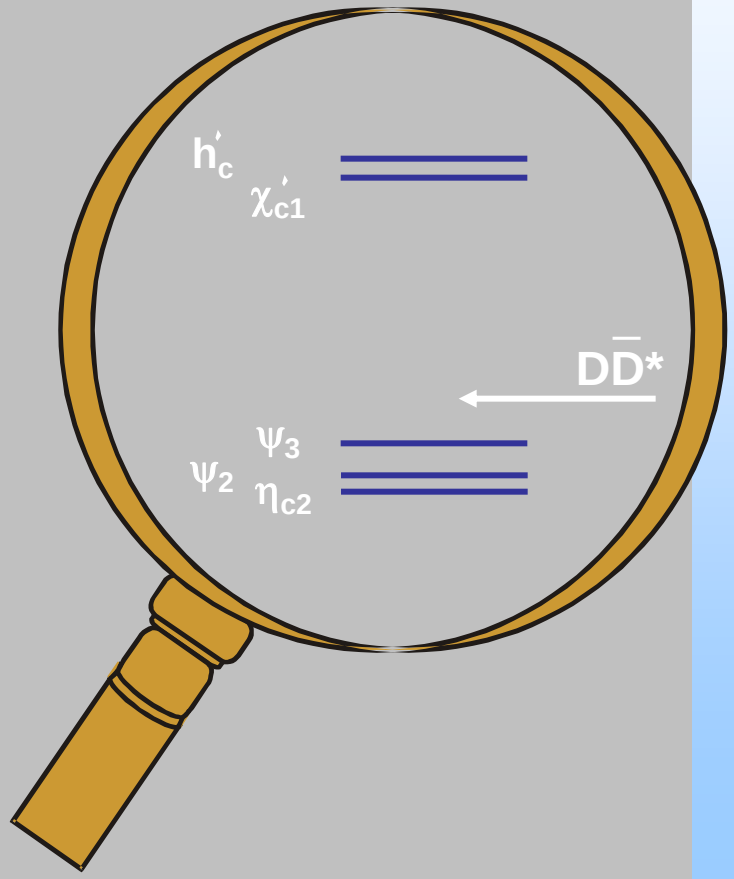

Mass [MeV]
4100
3900
3700
3500
3300
3100
2900
ψ‴(4040)
³P₂(~ 3940)
³P₁(~ 3880)
³P₀(~ 3800)
¹D₂
³D₃ (~ 3800)
³D₂
ψ″(3770)
³D₁
ψ′(3686)
DD̄ Threshold
η′c(3590)
hc(3525)
χ₂(3556)
χ₁(3510)
χ₀(3415)
ψ(3097)
ηc(2980)
c
c̄

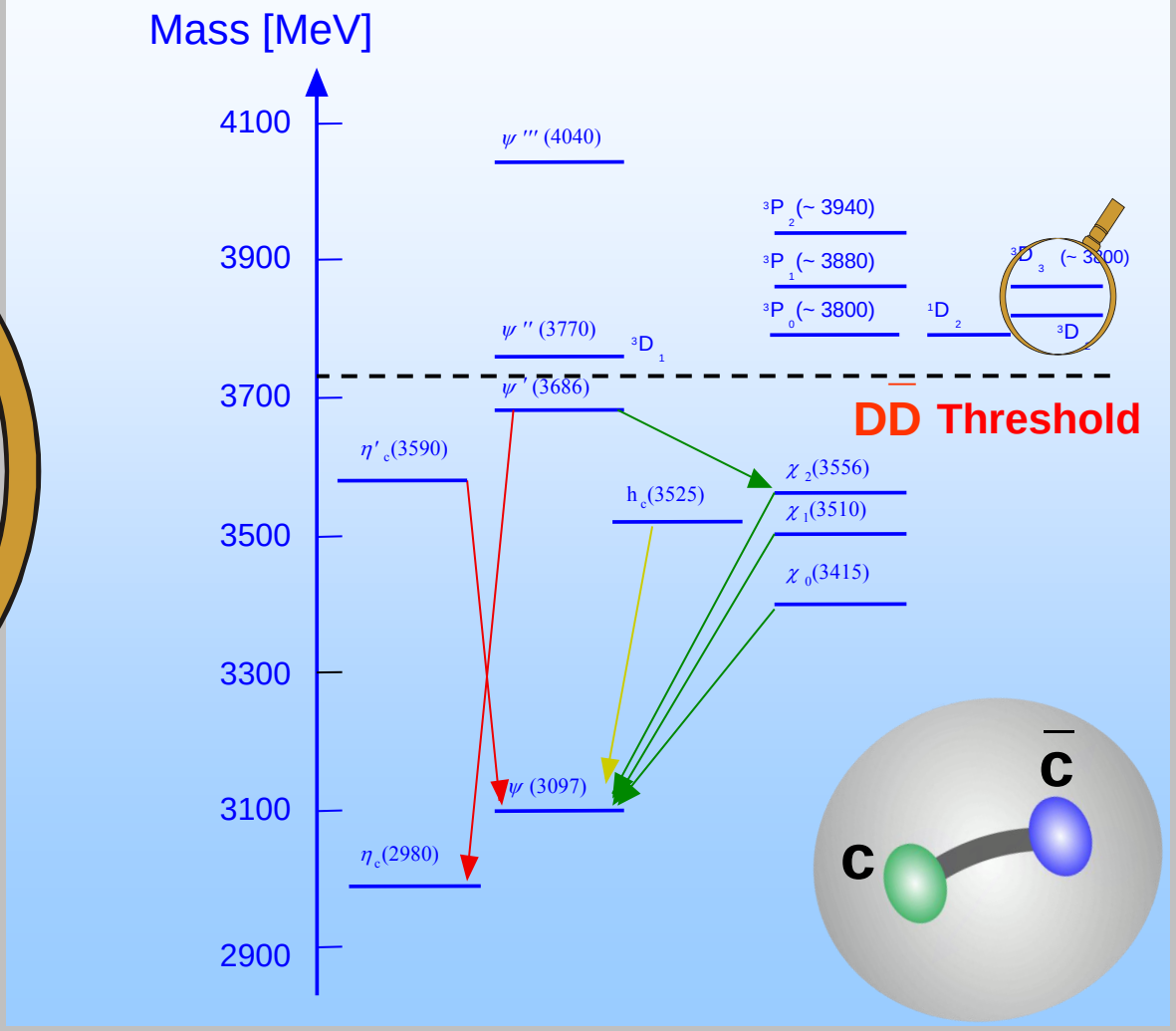
charmonium

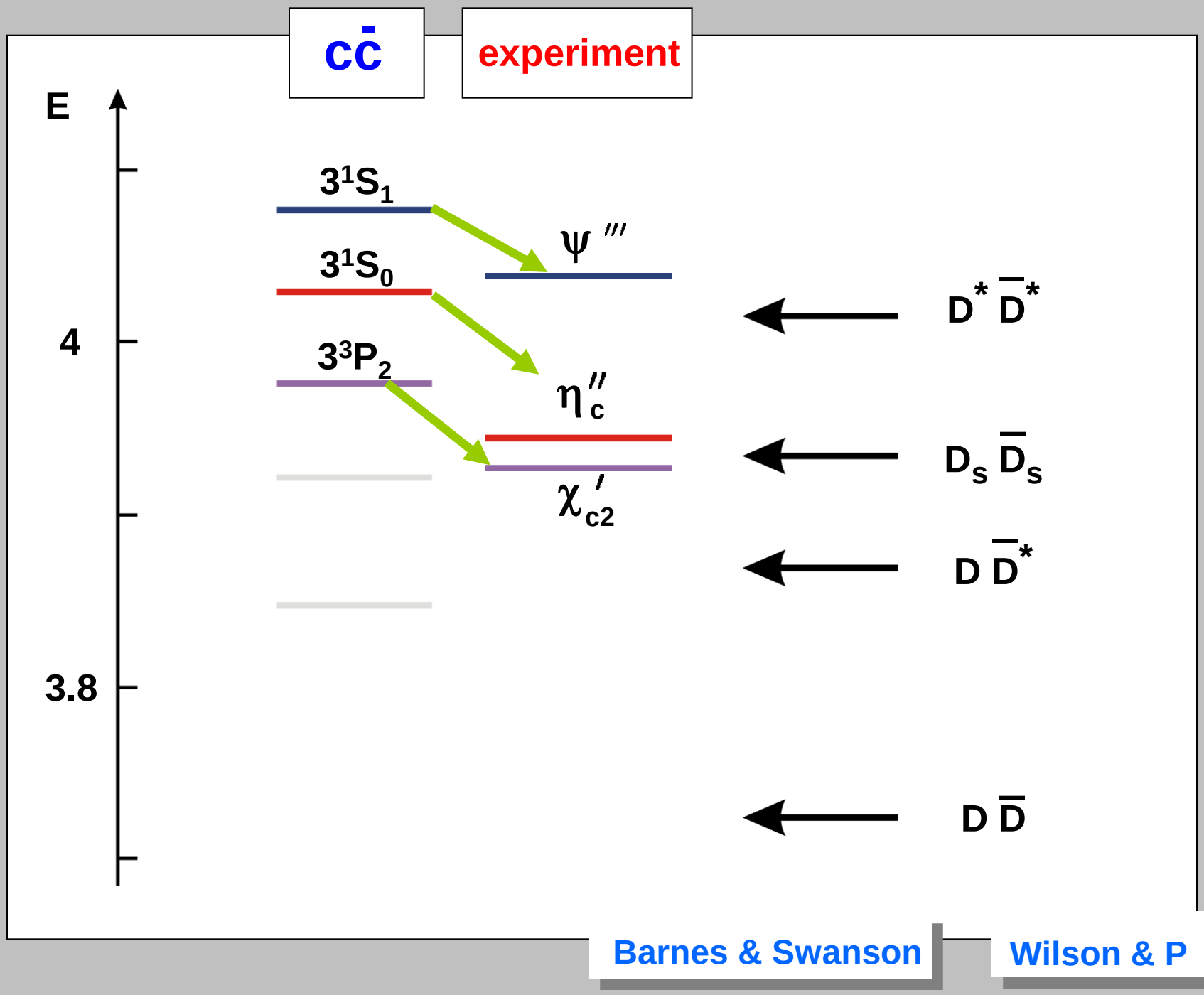

DD̄
R(e+ e-)
J/ψ
ψ(2S)
ψ3770
ψ4040
ψ4160
ψ4415
cc̄
E (GeV)

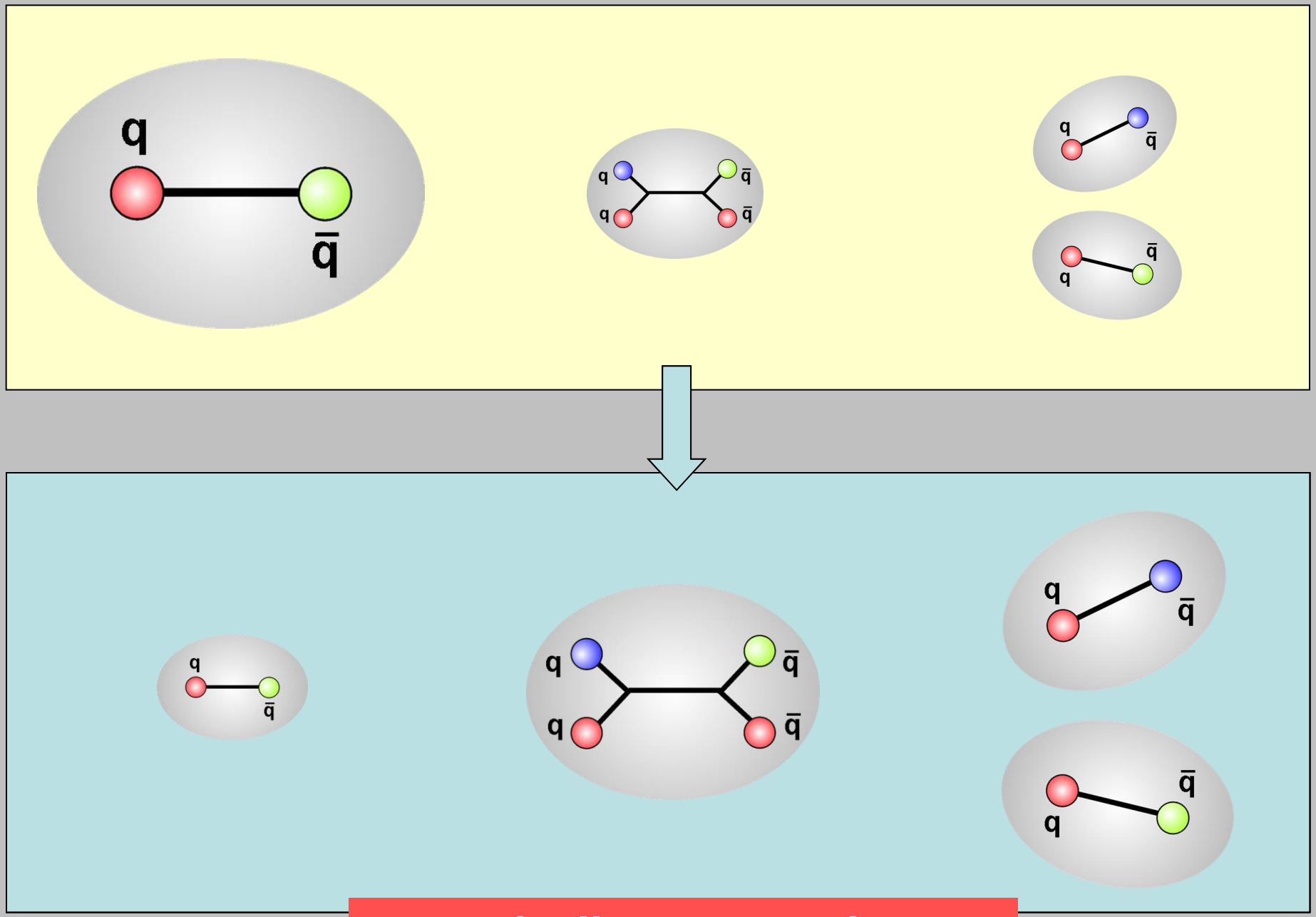

Mass [MeV]
4100
3900
3700
3500
3300
3100
2900
ψ'''(4040)
3P2(~ 3940)
3P1(~ 3880)
3P0(~ 3800)
1D2
3D3 (~ 3800)
3D2
ψ''(3770)
3D1
ψ'(3686)
DD̄ Threshold
η'c(3590)
hc(3525)
χ2(3556)
χ1(3510)
χ0(3415)
ψ(3097)
ηc(2980)
c
c̄

charmonium


h'c
χ'c1
DD̄*
ψ3
ψ2
ηc2


Mass [MeV]
4100
3900
3700
3500
3300
3100
2900
ψ ''' (4040)
3P2 (~ 3940)
3P1 (~ 3880)
3P0 (~ 3800)
1D2
3D3 (~ 3800)
3D1
ψ '' (3770)
ψ ' (3686)
DD Threshold
η'c(3590)
hc(3525)
χ2(3556)
χ1(3510)
χ0(3415)
ψ (3097)
ηc(2980)
c̄
c


cc̄
experiment
E
4
3.8
3¹S₁
3¹S₀
3³P₂
ψ‴
η″c
χ′c2
D* D̄*
Ds D̄s
D D̄*
D D̄
Barnes & Swanson
Wilson & P

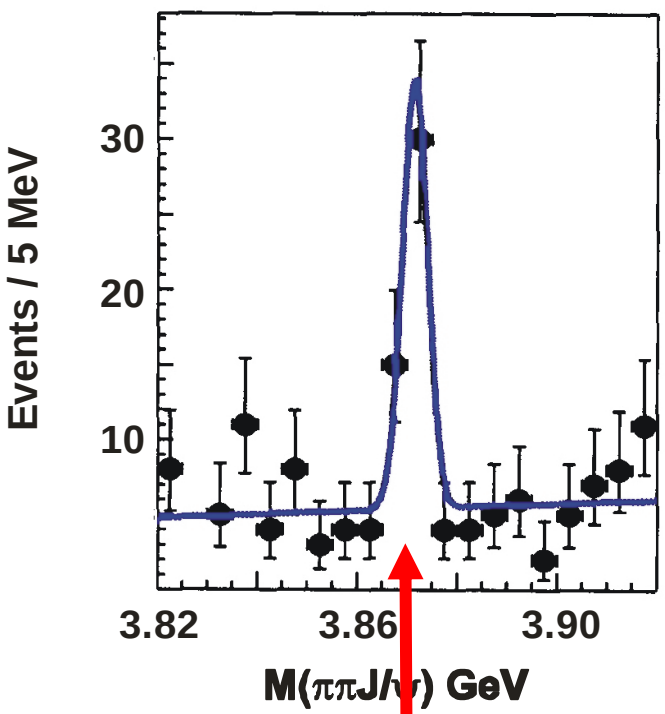

q
q̄
q
q
q̄
q̄
q
q̄
q
q̄
q
q̄
q
q̄
q
q̄
Dynamically generated states

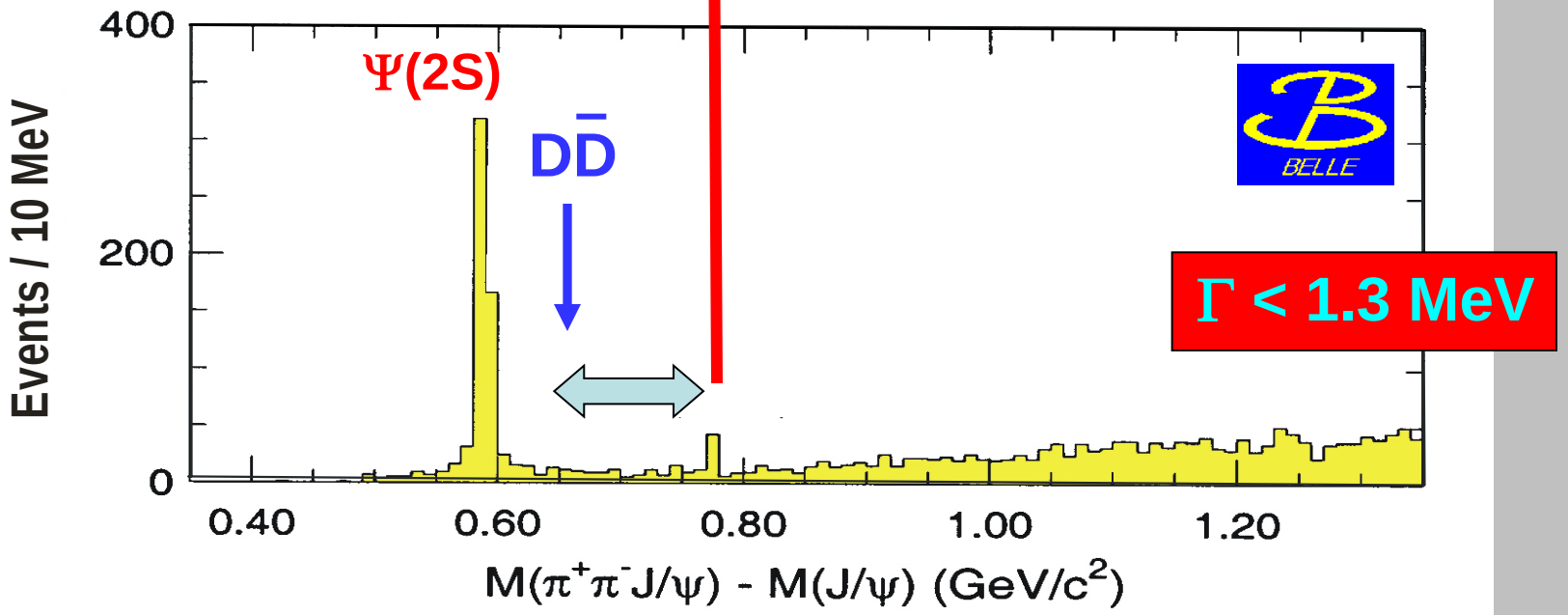
X(3872)

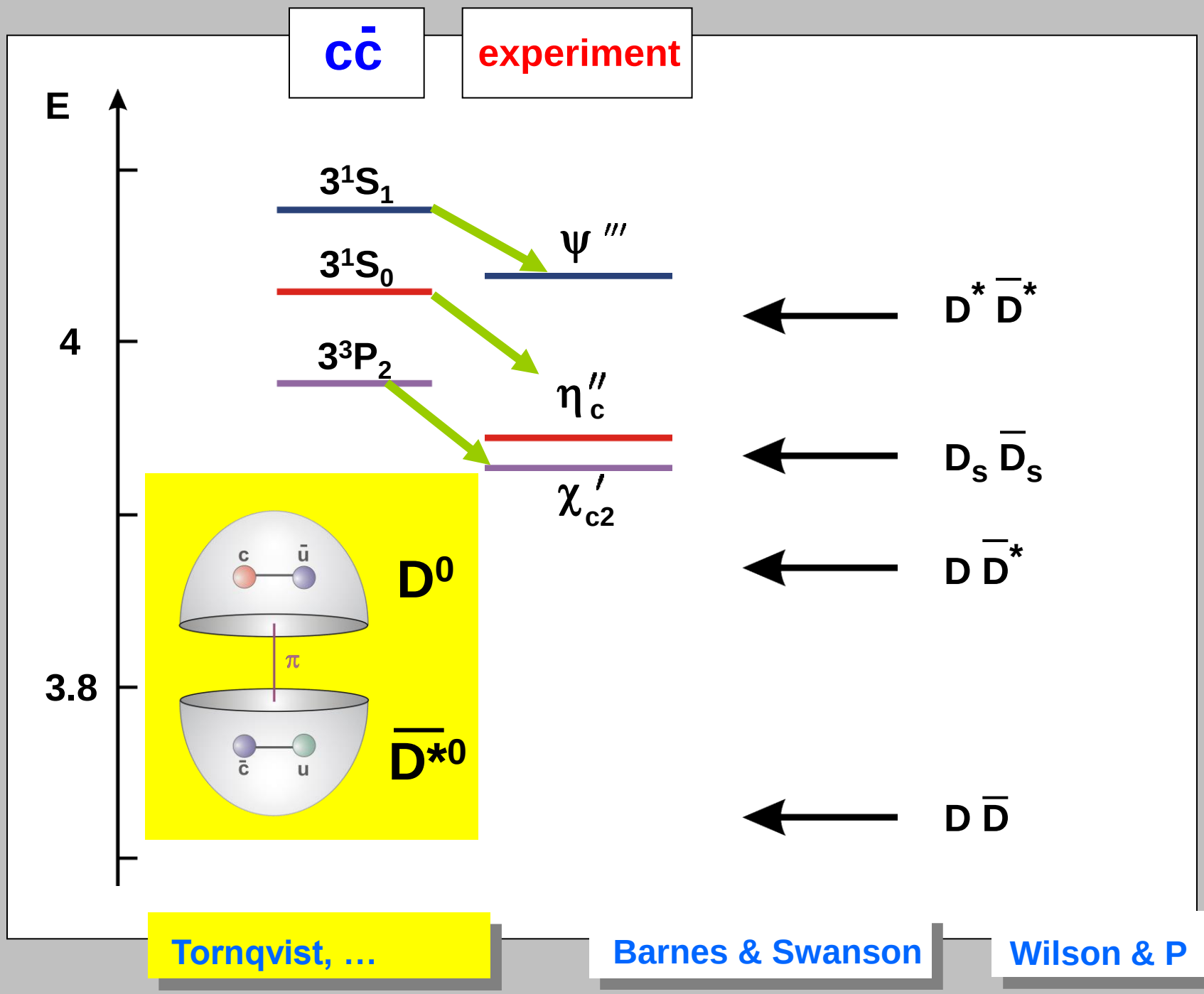
304M B's

$B \rightarrow KX$

$X \rightarrow \pi^+\pi^- J/\psi$

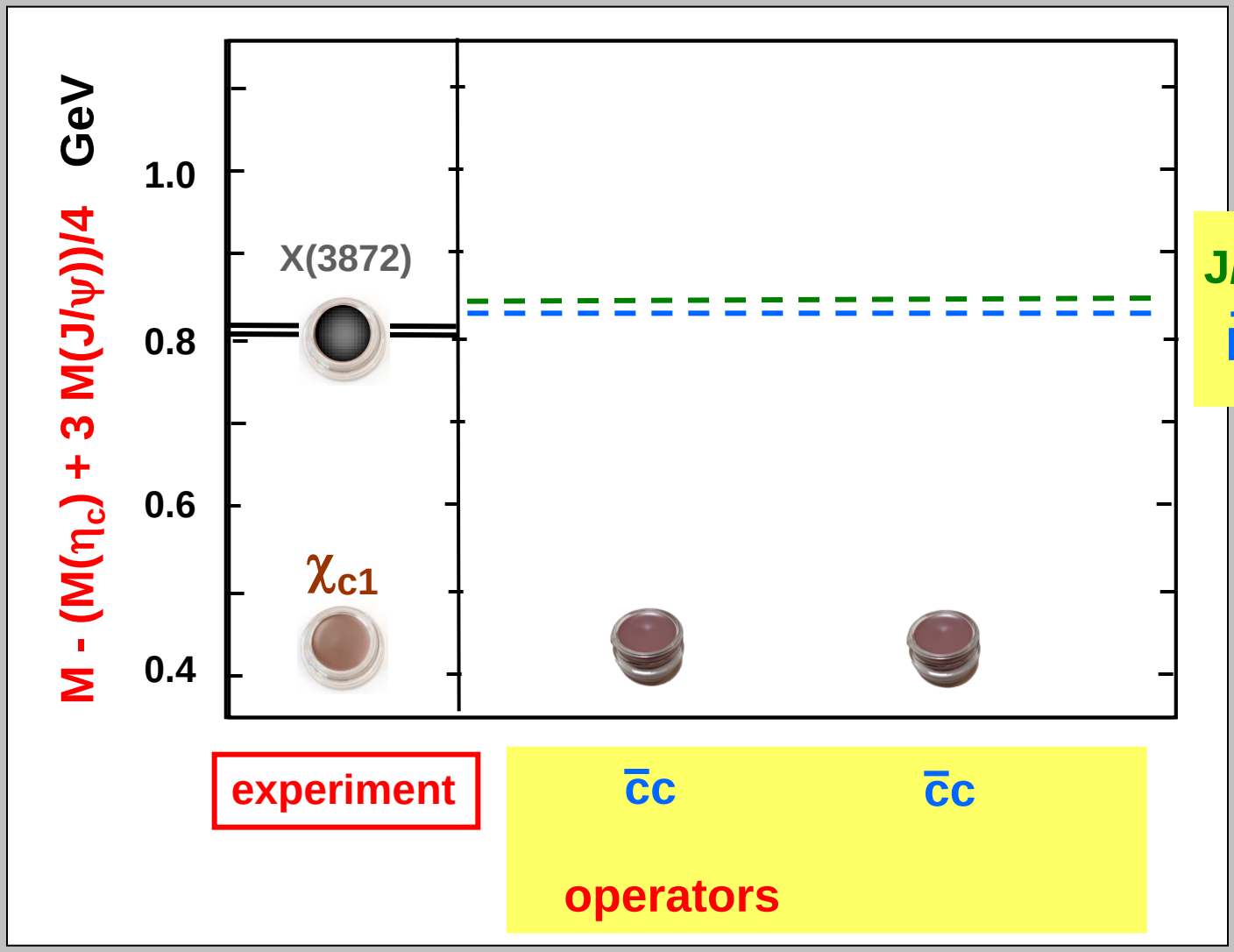





cc̄
experiment
E
4
3.8
3¹S₁
3¹S₀
3³P₂
ψ‴
η″c
χ′c2
D* D̄*
Ds D̄s
D D̄*
D D̄
D⁰
D̄*⁰
π
c
ū
c̄
u
Tornqvist, …
Barnes & Swanson
Wilson & P

X(3872) & 1^{++} charmonium

m_π 296 MeV

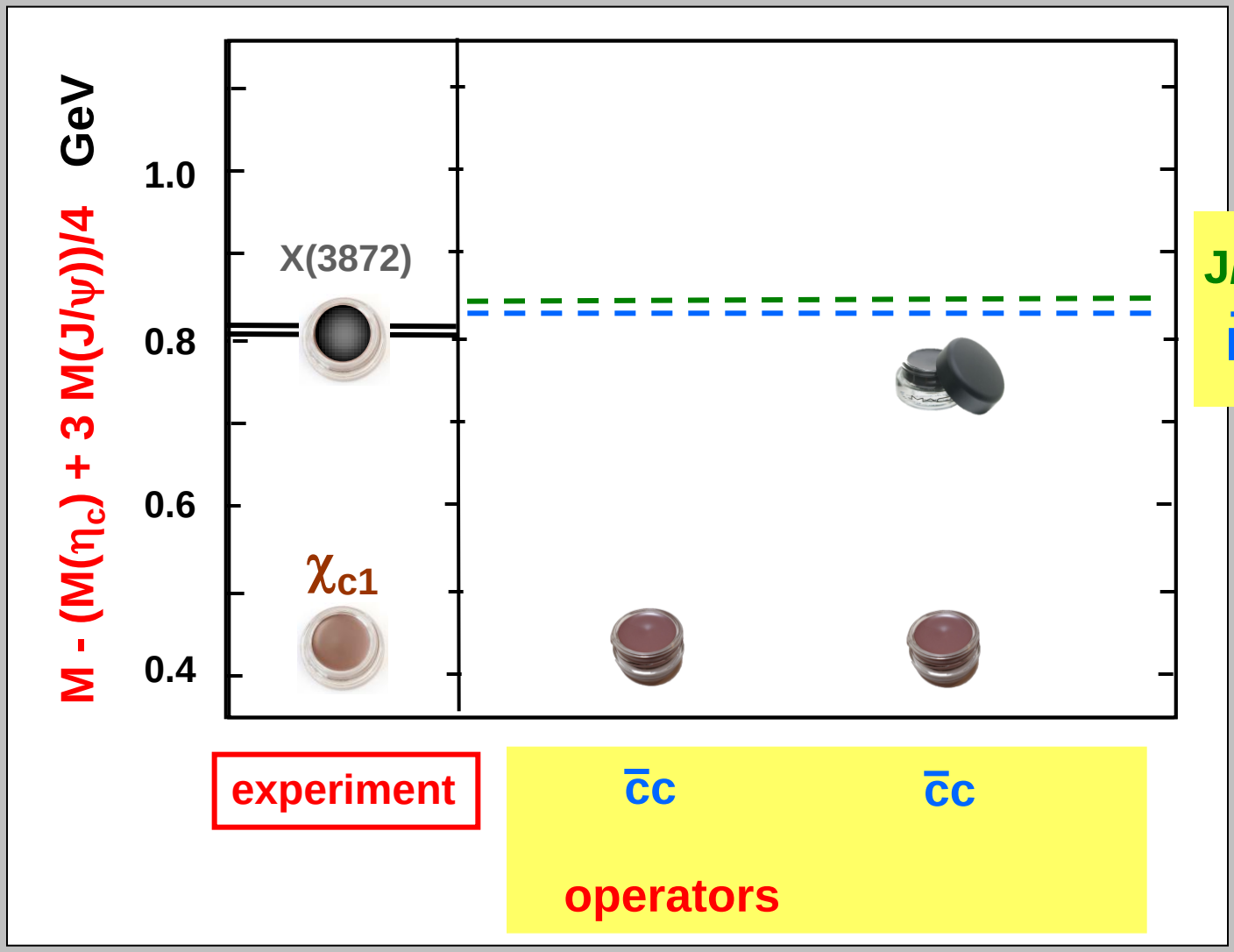


Prelovsek & Leskovec

Lee, De Tar, Na, Mohler

X(3872) & 1^{++} charmonium

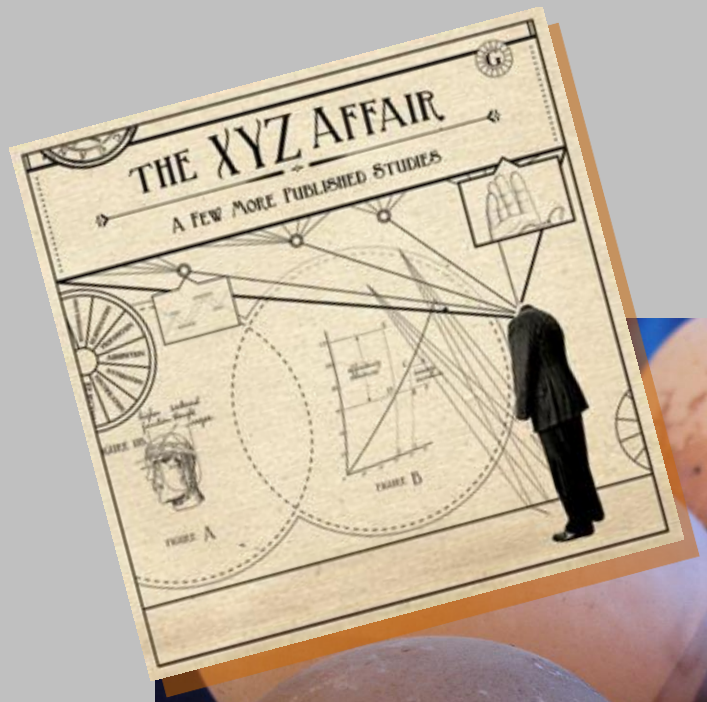
m_π 296 MeV

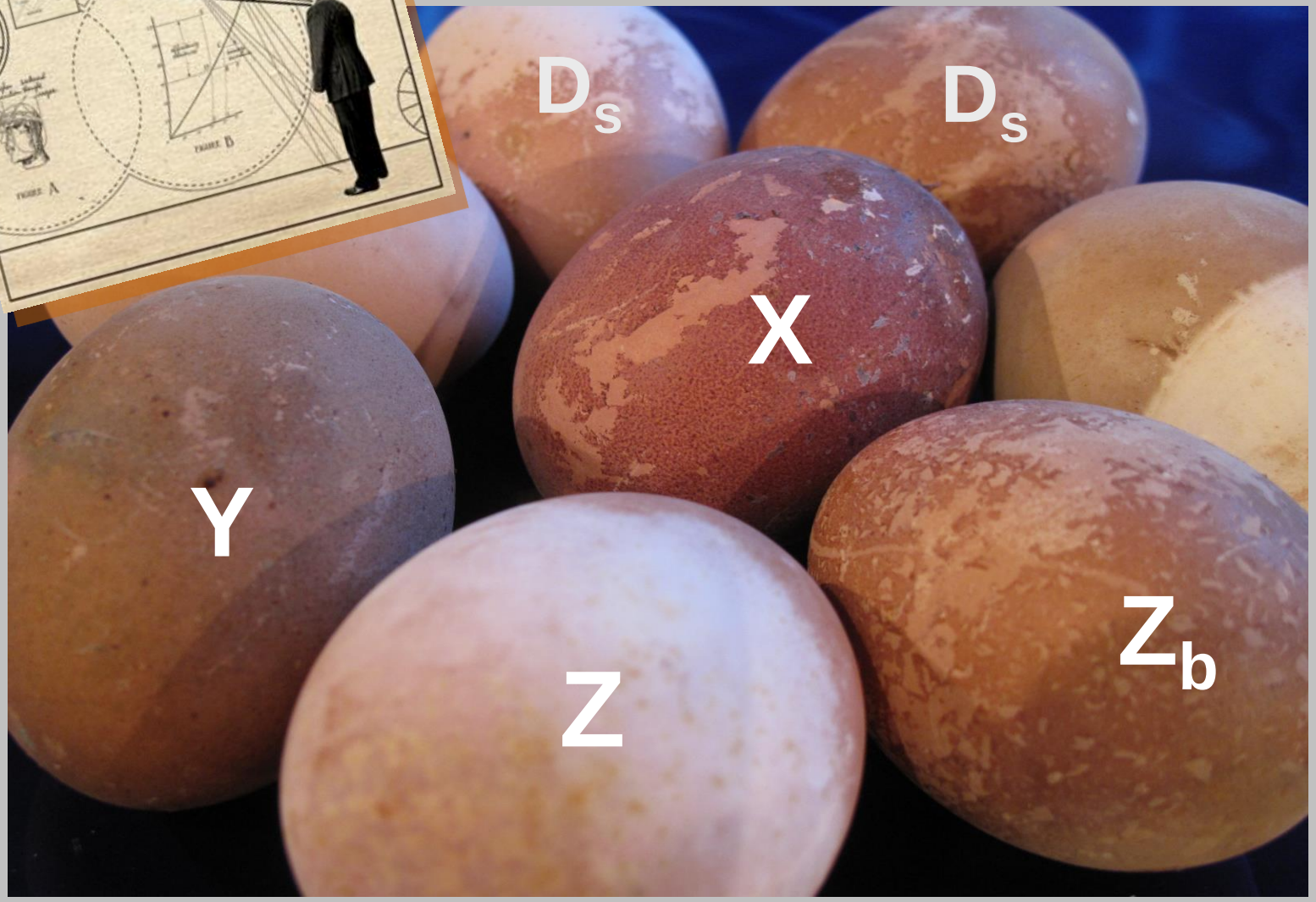


Prelovsek & Leskovec

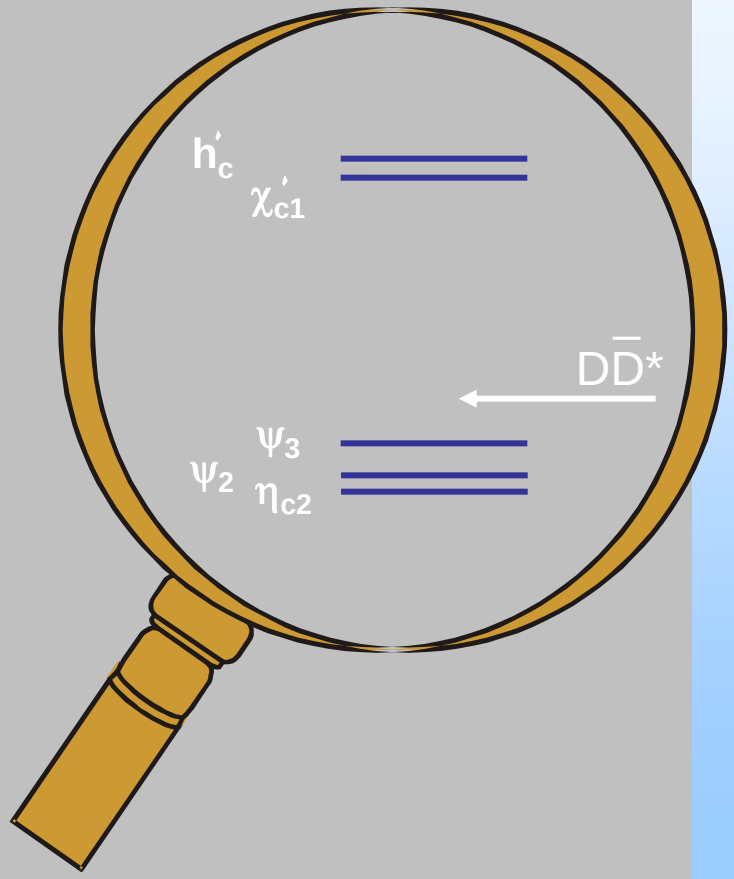
Lee, De Tar, Na, Mohler

THE XYZ AFFAIR





charmonium



$Z_c^{\pm}$

Z(4430)

Y(4360)

Y(4260)

Z(4250)

Mass [MeV]

Z(4060)

Y(3915)

X(3940)

Z(3900)

X(3872)

4100

3900

3700

3500

3300

3100

2900

ψ ''' (4040)

ψ '' (3770)

$^3D_1$

ψ ' (3686)

$^1D_2$

$^3D_3$ (~ 3800)

$^3D_2$

$^3P_0$ (~ 3800)

DD̄ Threshold

η'c(3590)

hc(3525)

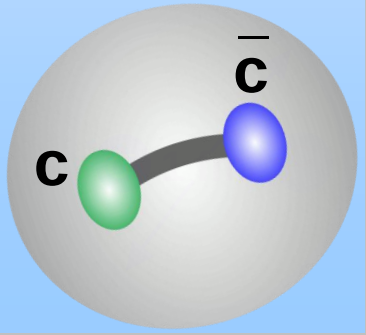
χ2(3556)

χ1(3510)

χ0(3415)

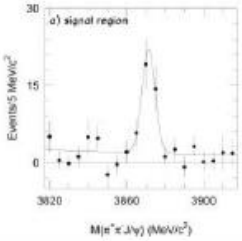
ψ (3097)

ηc(2980)

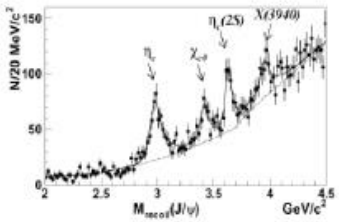


XYZ states

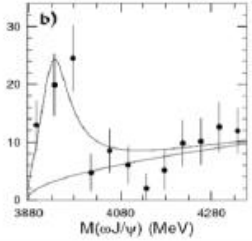
X(3872)
PRL 91,262001 (2003)



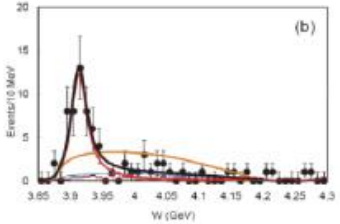
X(3940)
PRL 98,082001 (2007)



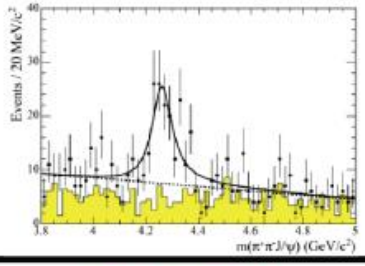
Y(3940)
PRL 94,182002 (2005)



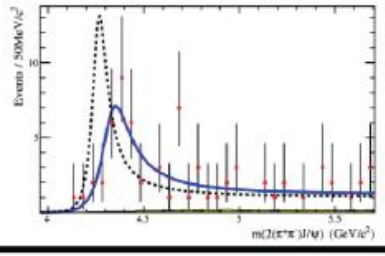
X(3915)
PRL 104,092001 (2010)



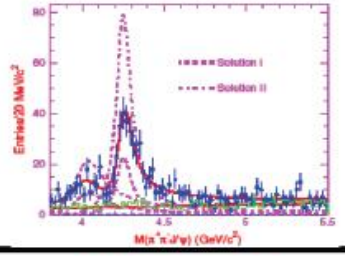
Y(4260)
PRL 95,142001 (2005)



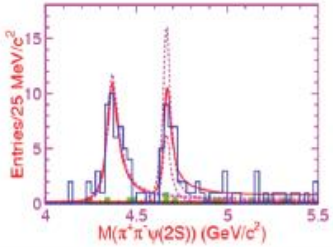
Y(4350)
PRL 98,212001 (2007)



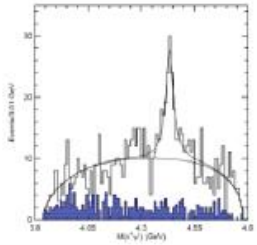
Y(4008)
PRL 99,182004 (2007)



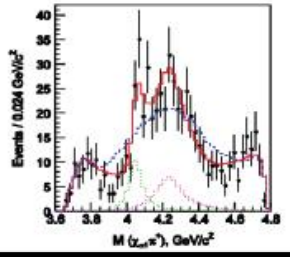
Y(4660)
PRL 99,142002 (2007)



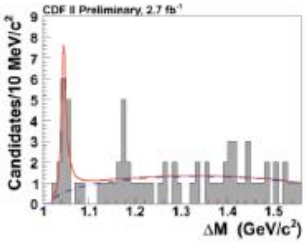
$Z^-(4430)$
PRL 100,142001 (2008)



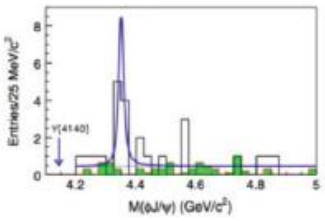
Z_1^-/Z_2^-
PRD 78,072004 (2008)



Y(4140)
PRL 102,242002 (2009)

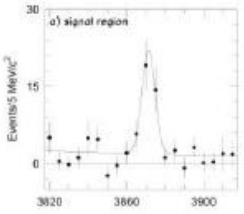


X(4350)
PRL 104,112004 (2010)

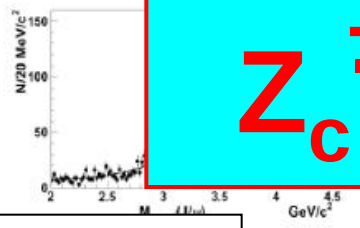


XYZ states

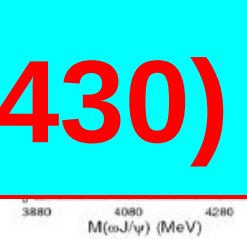
X(3872)
PRL 91,262001 (2003)



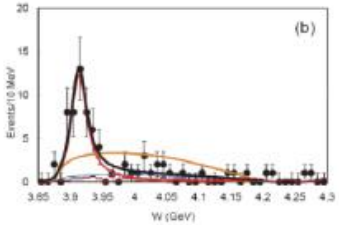
X(3940)
PRL 98,082001 (2007)



Y(3940)
PRL 94,182002 (2005)

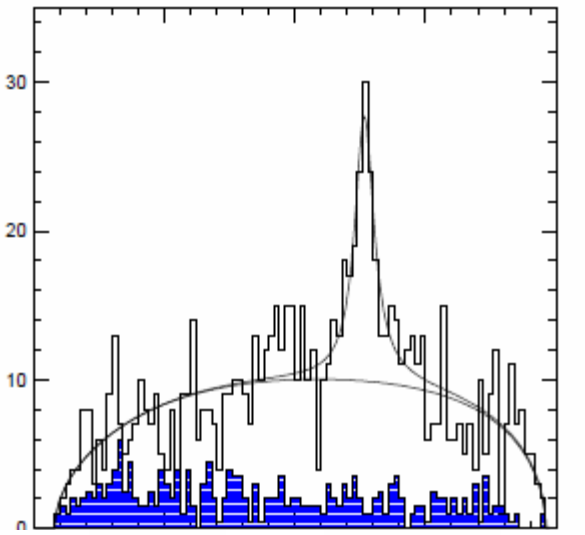


X(3915)
PRL 104,092001 (2010)

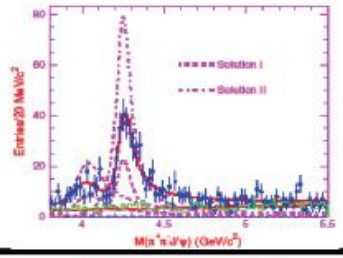


$Z_c^{\pm}(4430)$

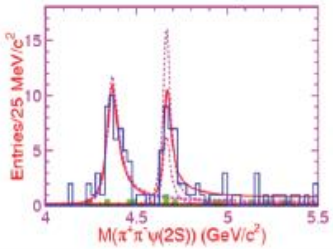
$B \rightarrow K\pi^{\pm}\psi'$



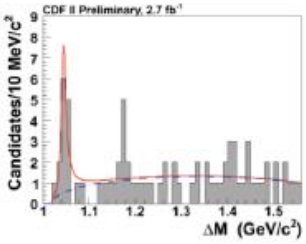
Y(4008)
PRL 99,182004 (2007)



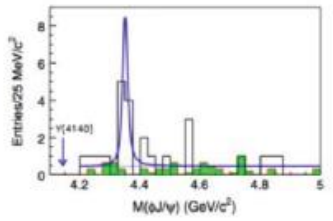
Y(4660)
PRL 99,142002 (2007)



Y(4140)
PRL 102,242002 (2009)



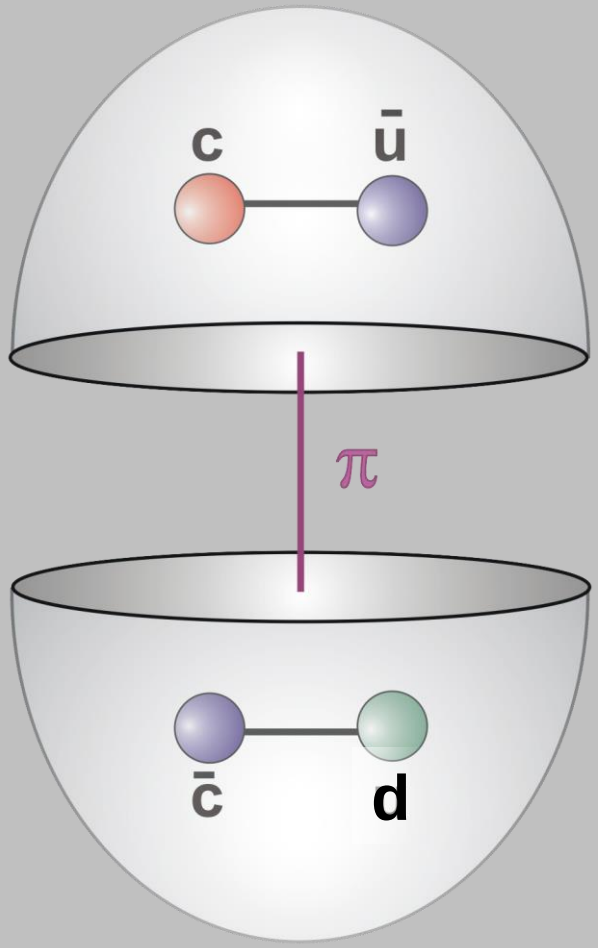
X(4350)
PRL 104,112004 (2010)



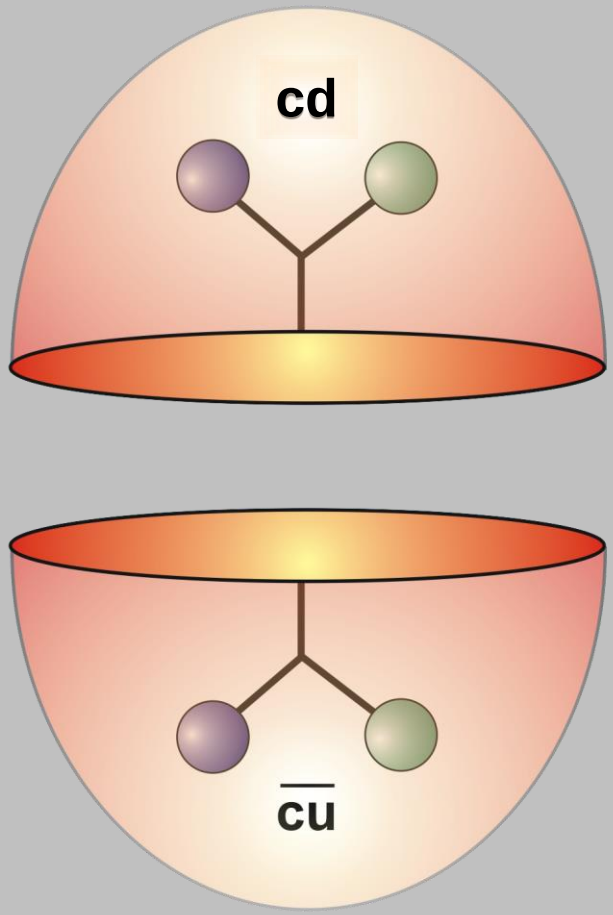
BELLE

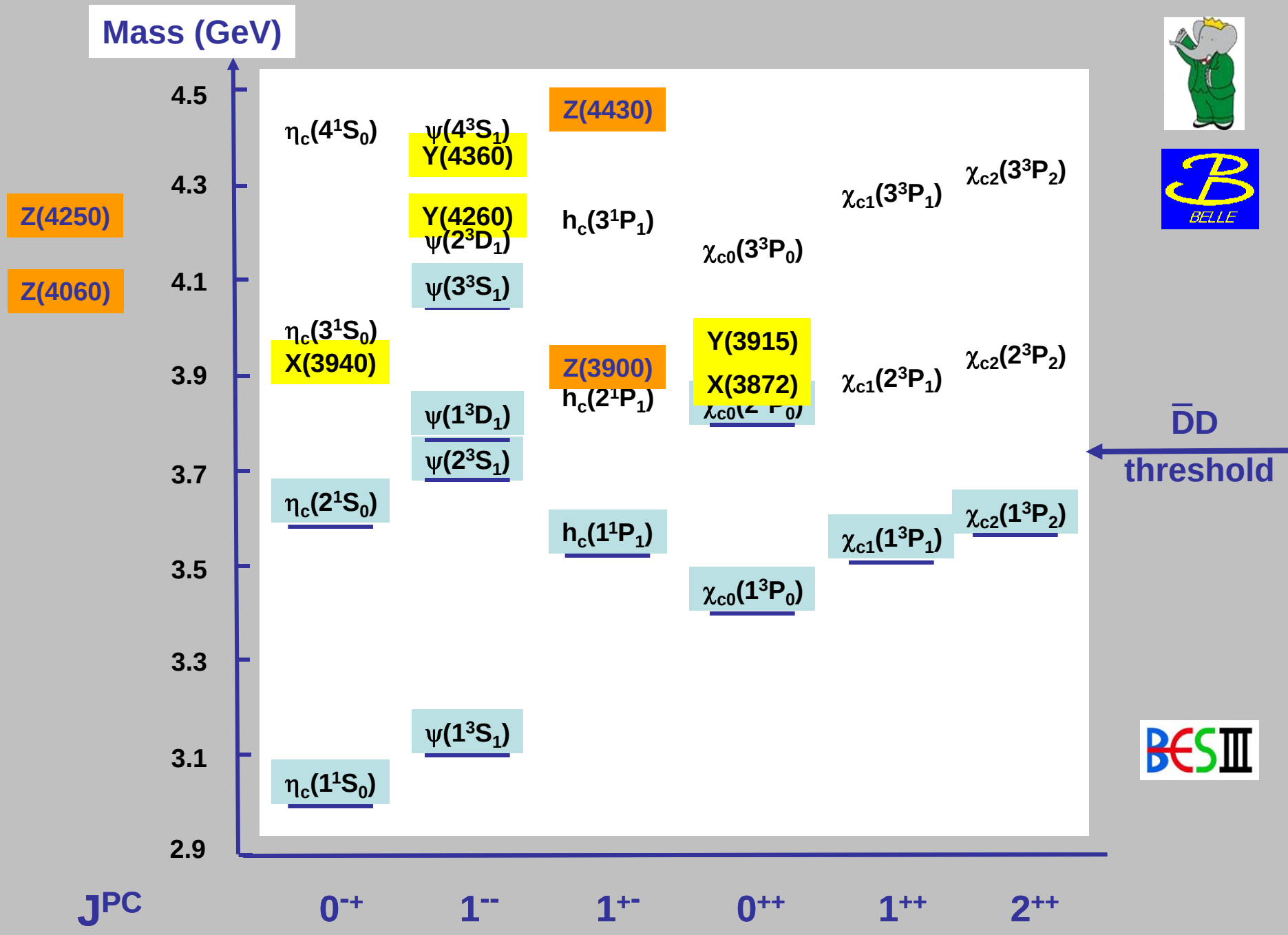
Z_c^-

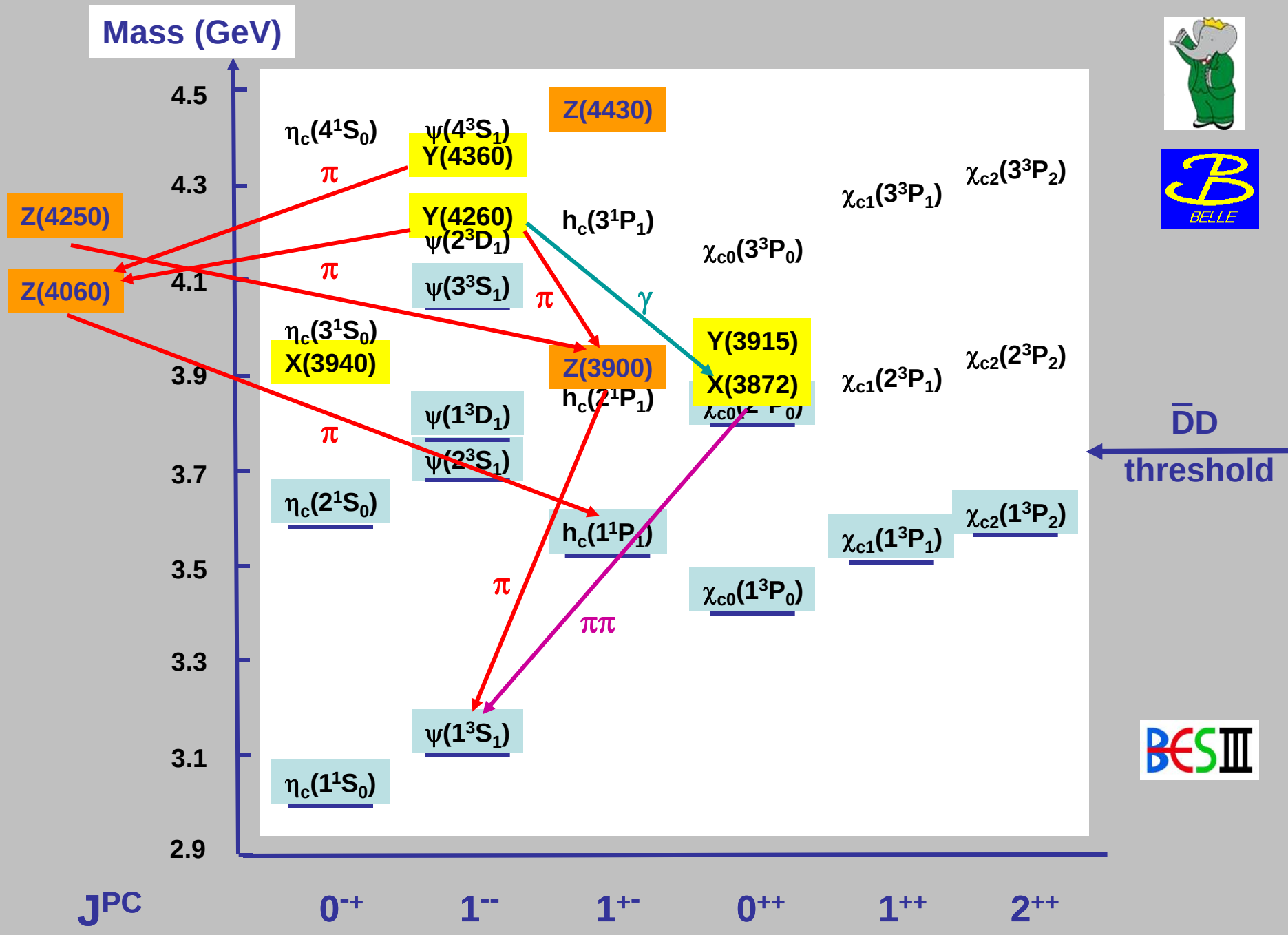
molecule

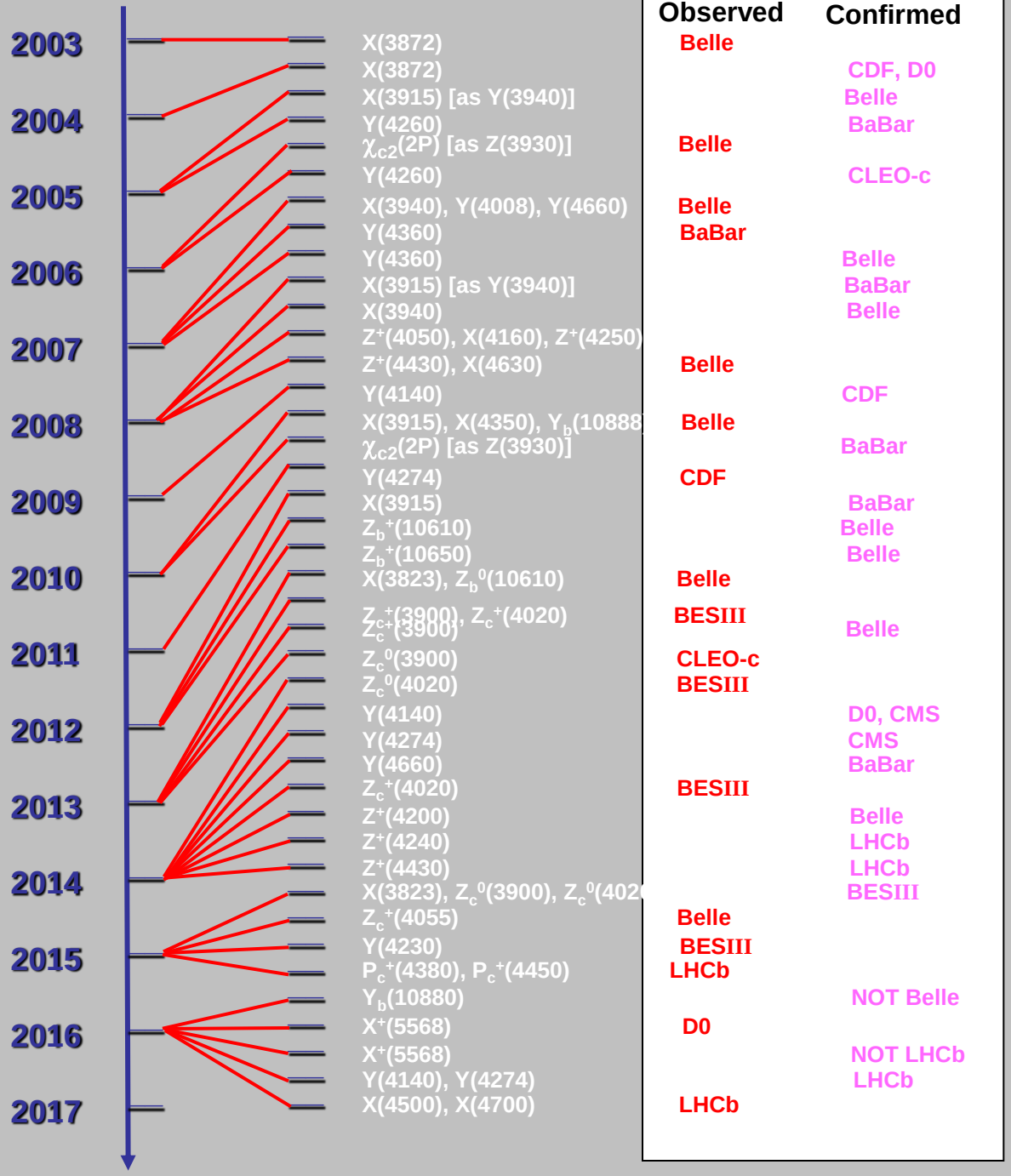


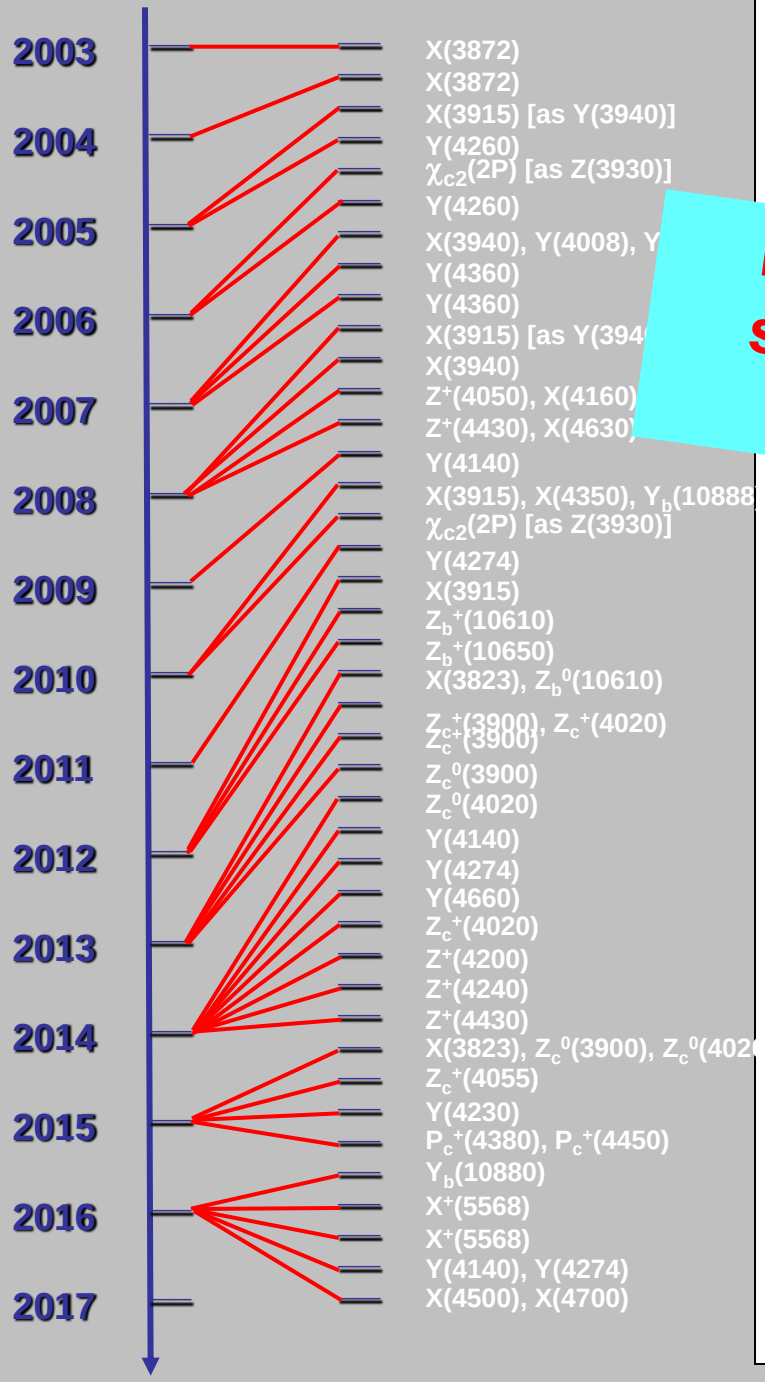
tetraquark




Mass (GeV)
4.5
4.3
4.1
3.9
3.7
3.5
3.3
3.1
2.9
Z(4250)
Z(4060)
$\eta_c(4^1S_0)$
$\psi(4^3S_1)$
Y(4360)
Z(4430)
Y(4260)
$\psi(2^3D_1)$
$h_c(3^1P_1)$
$\chi_{c0}(3^3P_0)$
$\chi_{c1}(3^3P_1)$
$\chi_{c2}(3^3P_2)$
$\psi(3^3S_1)$
$\eta_c(3^1S_0)$
X(3940)
Y(3915)
X(3872)
Z(3900)
$h_c(2^1P_1)$
$\chi_{c1}(2^3P_1)$
$\chi_{c2}(2^3P_2)$
$\psi(1^3D_1)$
$\psi(2^3S_1)$
$\bar{D}D$ threshold
$\eta_c(2^1S_0)$
$h_c(1^1P_1)$
$\chi_{c1}(1^3P_1)$
$\chi_{c2}(1^3P_2)$
$\chi_{c0}(1^3P_0)$
$\psi(1^3S_1)$
$\eta_c(1^1S_0)$
J^{PC}
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
BELLE
BESIII


Mass (GeV)
4.5
4.3
4.1
3.9
3.7
3.5
3.3
3.1
2.9
Z(4250)
Z(4060)
ηc(4¹S0)
ψ(4³S1)
Y(4360)
Z(4430)
Y(4260)
ψ(2³D1)
ψ(3³S1)
ηc(3¹S0)
X(3940)
Z(3900)
hc(2¹P1)
ψ(1³D1)
ψ(2³S1)
ηc(2¹S0)
hc(1¹P1)
ψ(1³S1)
ηc(1¹S0)
hc(3¹P1)
χc0(3³P0)
χc1(3³P1)
χc2(3³P2)
Y(3915)
X(3872)
χc0(2³P0)
χc1(2³P1)
χc2(2³P2)
χc2(1³P2)
χc1(1³P1)
χc0(1³P0)
π
π
π
π
γ
π
ππ
D̄D
threshold
JPC
0-+
1--
1+-
0++
1++
2++
BELLE
BESIII


2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
X(3872)
X(3872)
X(3915) [as Y(3940)]
Y(4260)
χc2(2P) [as Z(3930)]
Y(4260)
X(3940), Y(4008), Y(4660)
Y(4360)
Y(4360)
X(3915) [as Y(3940)]
X(3940)
Z+(4050), X(4160), Z+(4250)
Z+(4430), X(4630)
Y(4140)
X(3915), X(4350), Yb(10888
χc2(2P) [as Z(3930)]
Y(4274)
X(3915)
Zb+(10610)
Zb+(10650)
X(3823), Zb0(10610)
Zc+(3900), Zc+(4020)
Zc+(3900)
Zc0(3900)
Zc0(4020)
Y(4140)
Y(4274)
Y(4660)
Zc+(4020)
Z+(4200)
Z+(4240)
Z+(4430)
X(3823), Zc0(3900), Zc0(402
Zc+(4055)
Y(4230)
Pc+(4380), Pc+(4450)
Yb(10880)
X+(5568)
X+(5568)
Y(4140), Y(4274)
X(4500), X(4700)
Observed
Confirmed
Belle
CDF, D0
Belle
BaBar
Belle
CLEO-c
Belle
BaBar
Belle
BaBar
Belle
Belle
CDF
Belle
BaBar
CDF
BaBar
Belle
Belle
Belle
Belle
BESIII
CLEO-c
BESIII
D0, CMS
CMS
BaBar
BESIII
Belle
LHCb
LHCb
BESIII
Belle
BESIII
LHCb
NOT Belle
D0
NOT LHCb
LHCb
LHCb

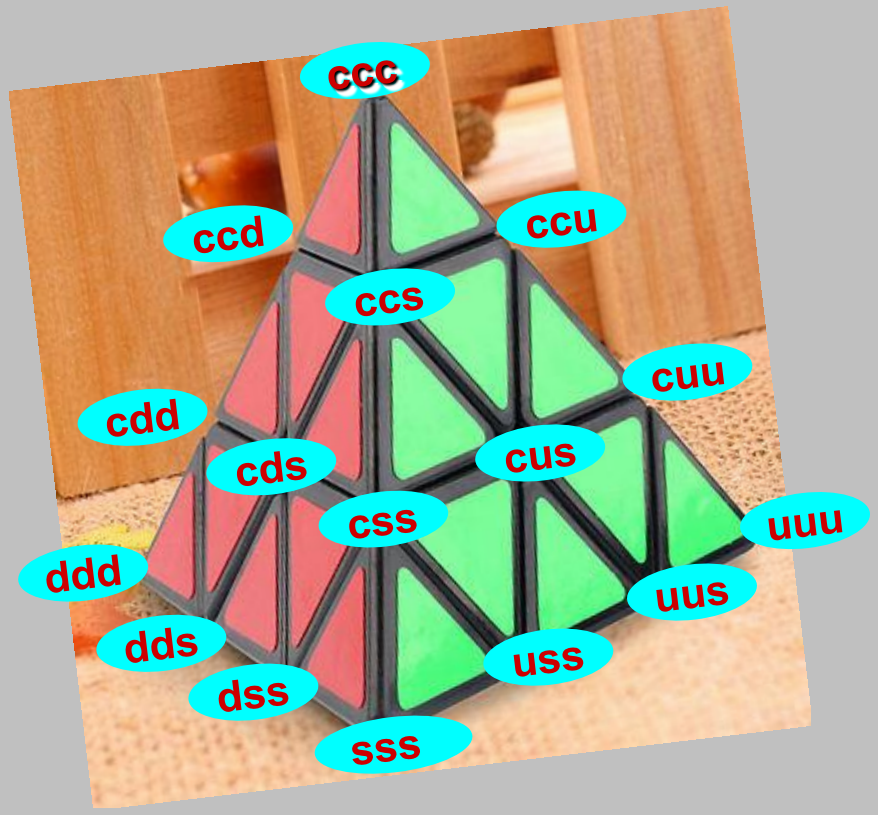


Observed	Confirmed
Belle	
	CDF, D0
	Belle
	BaBar
Belle	
	CLEO-c
Belle	
	BaBar
CDF	
	BaBar
	Belle
	Belle
Belle	
BESIII	
	Belle
CLEO-c	
BESIII	
	D0, CMS
	CMS
	BaBar
BESIII	
	Belle
	LHCb
	LHCb
	BESIII
Belle	
BESIII	
LHCb	
	NOT Belle
D0	
	NOT LHCb
	LHCb
LHCb	

Essential to confirm all such states and their connections with robust analyses

Discovering New Worlds

LHCb discoveries 2017



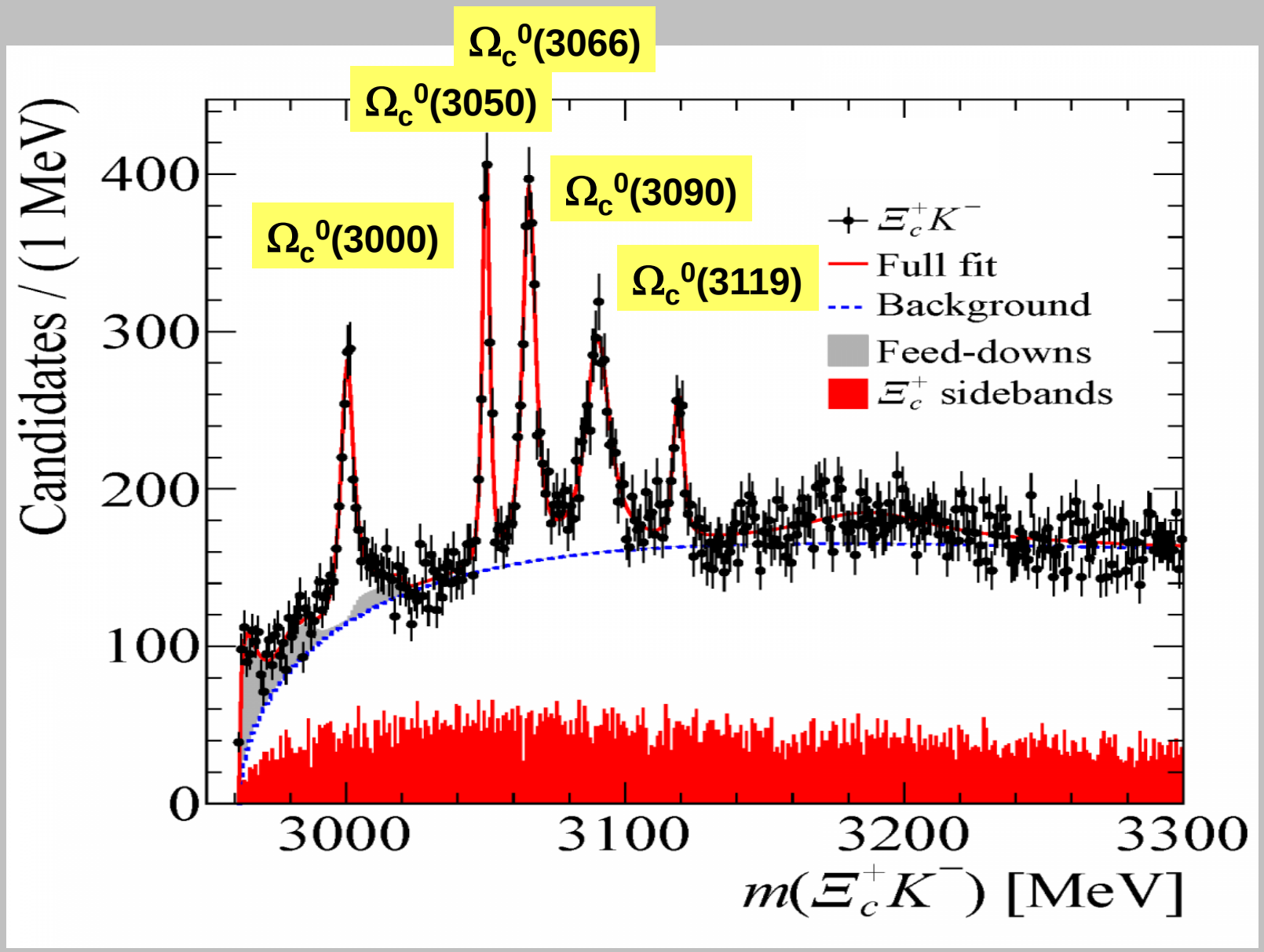
$\Omega_c^0 \rightarrow \Xi_c^+ K^-$

$\Xi_c^+ \rightarrow p K^- \pi^+$

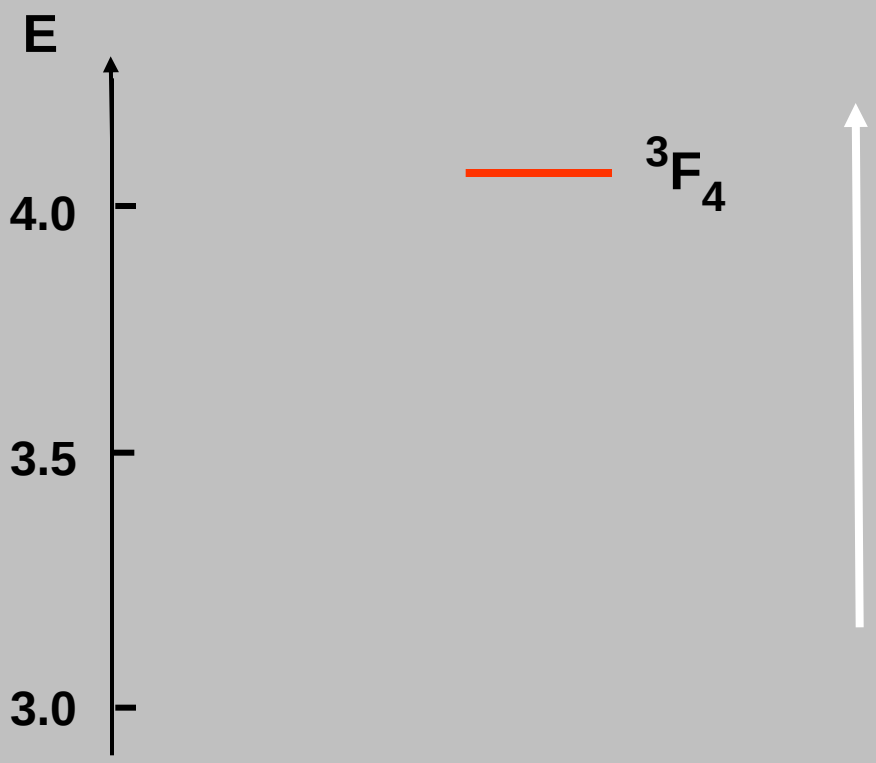
$css \rightarrow csu\ \bar{u}s$

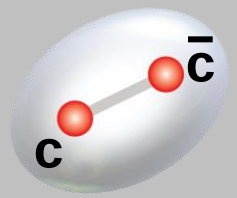
$csu \rightarrow dus\ W^+ \rightarrow duu\ \bar{u}s\ u\bar{d}$

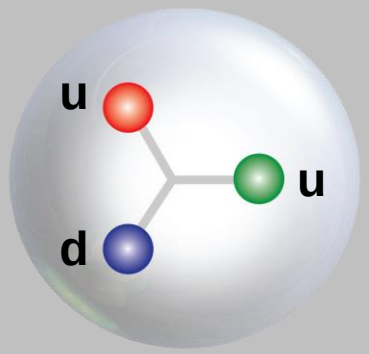
LHCb discoveries 2017

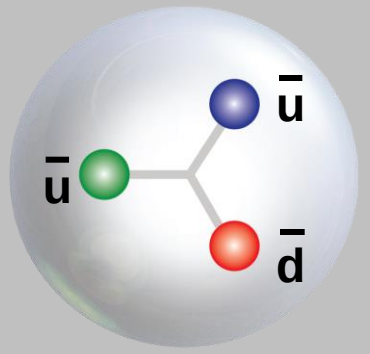


$1\,^3F_4$	$1\,^3D_3$	χ_{c2}	J/ψ
$J^{PC}=4^{++}$	$J^{PC}=3^{--}$	$J^{PC}=2^{++}$	$J^{PC}=1^{--}$
4095 MeV	3849 MeV	3556 MeV	3097 MeV
Γ=8.3 MeV	Γ=0.5 MeV	Γ=2.0 MeV	Γ=0.3 MeV
E_γ=246 MeV	E_γ=338 MeV	E_γ=413 MeV	-







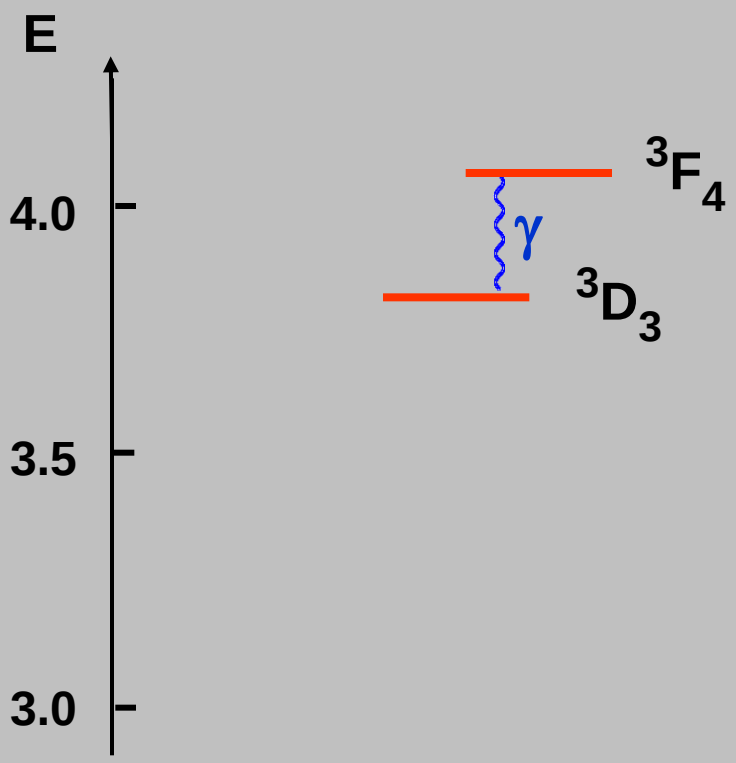


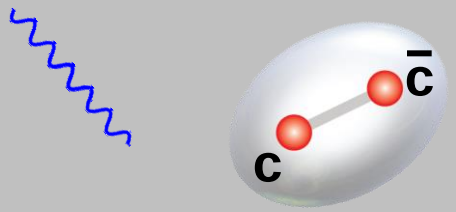
p

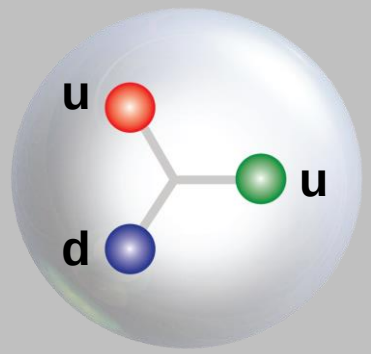
$\bar{p}$

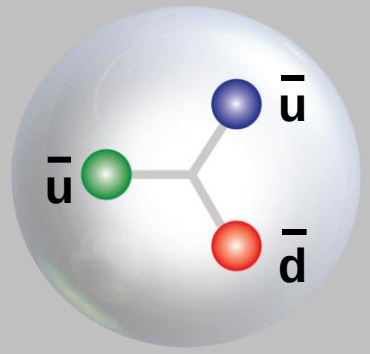
Lange, Prencipe *et al.*

$1\,^3F_4$	$1\,^3D_3$	χ_{c2}	J/ψ
$J^{PC}=4^{++}$	$J^{PC}=3^{--}$	$J^{PC}=2^{++}$	$J^{PC}=1^{--}$
4095 MeV	3849 MeV	3556 MeV	3097 MeV
Γ=8.3 MeV	Γ=0.5 MeV	Γ=2.0 MeV	Γ=0.3 MeV
E_γ=246 MeV	E_γ=338 MeV	E_γ=413 MeV	-









p

p̄

Lange, Prencipe *et al.*

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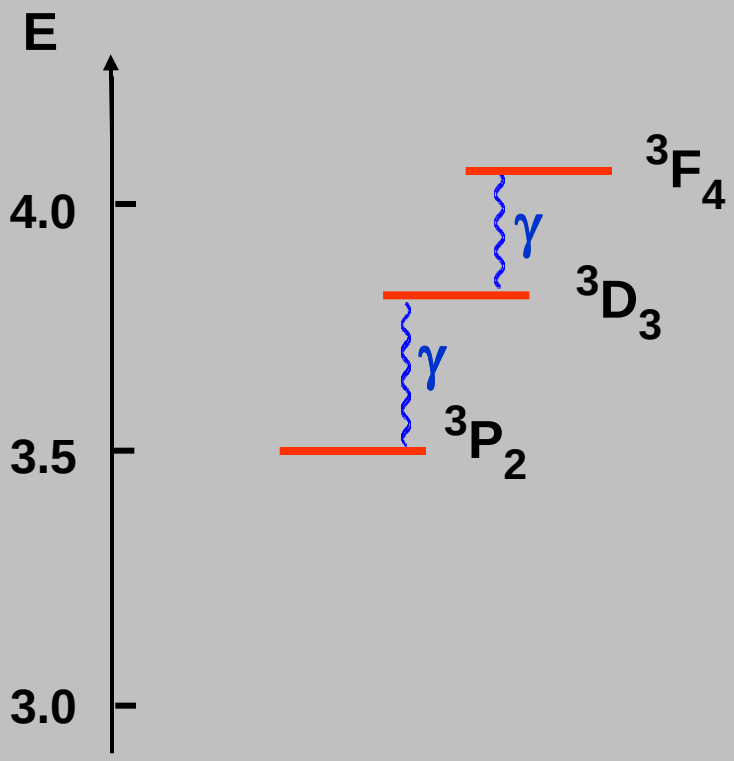
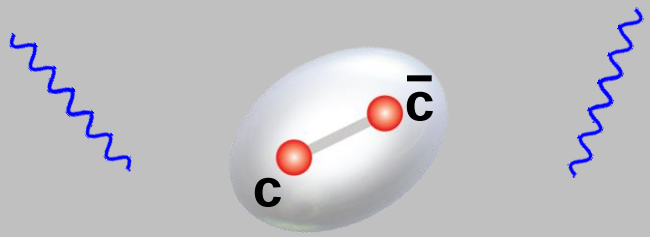
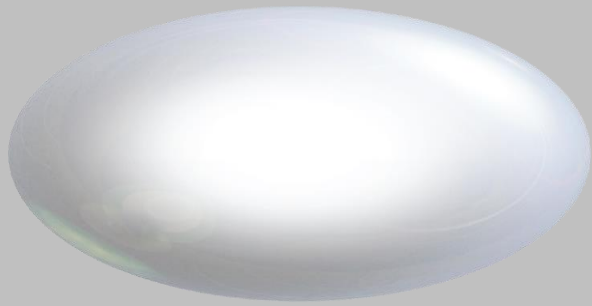
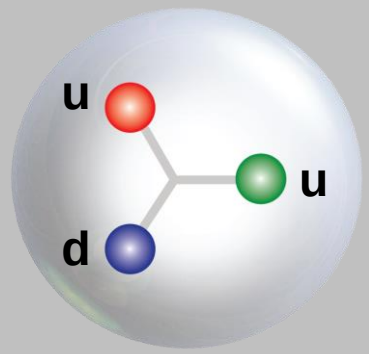
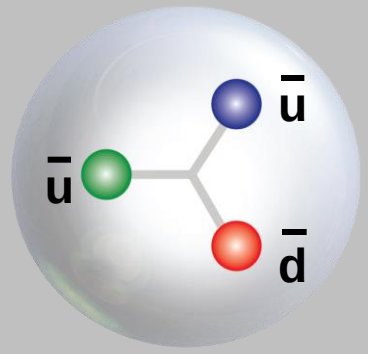
4095 MeV	3849 MeV	3556 MeV	3097 MeV
Γ=8.3 MeV	Γ=0.5 MeV	Γ=2.0 MeV	Γ=0.3 MeV
E_γ=246 MeV	E_γ=338 MeV	E_γ=413 MeV	-









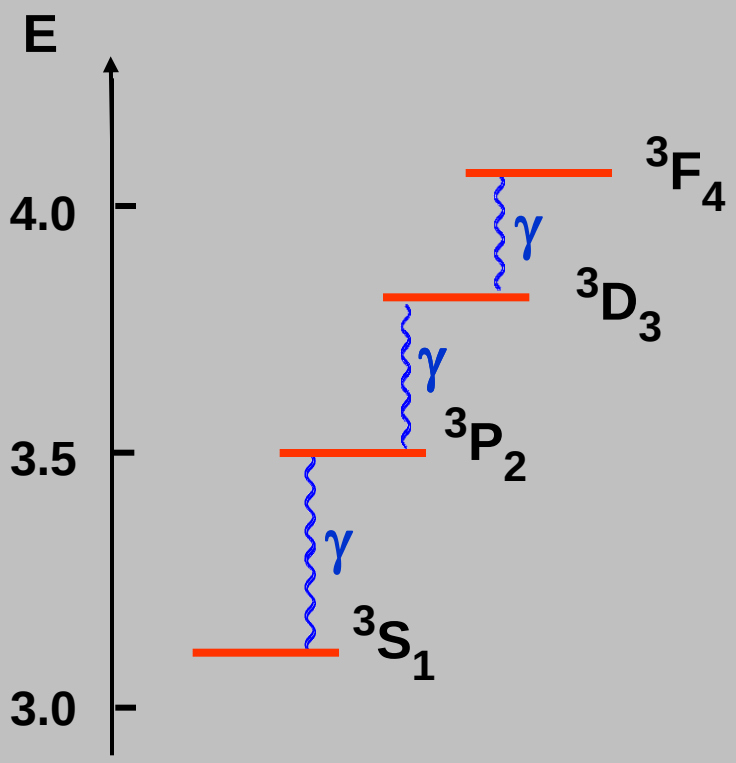


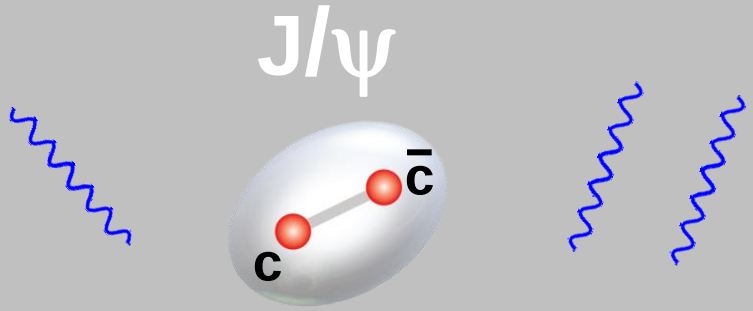
p

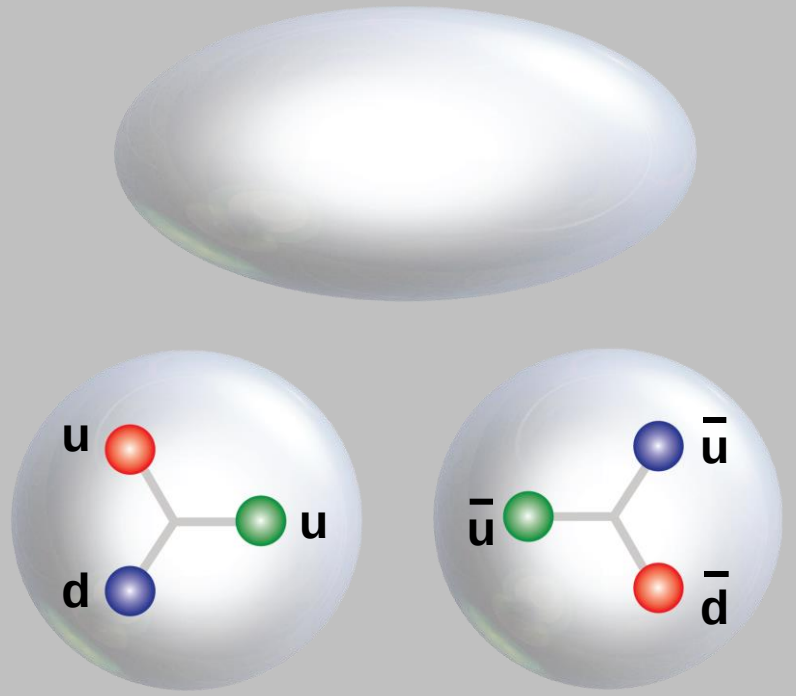
$\bar{p}$

Lange, Prencipe *et al.*

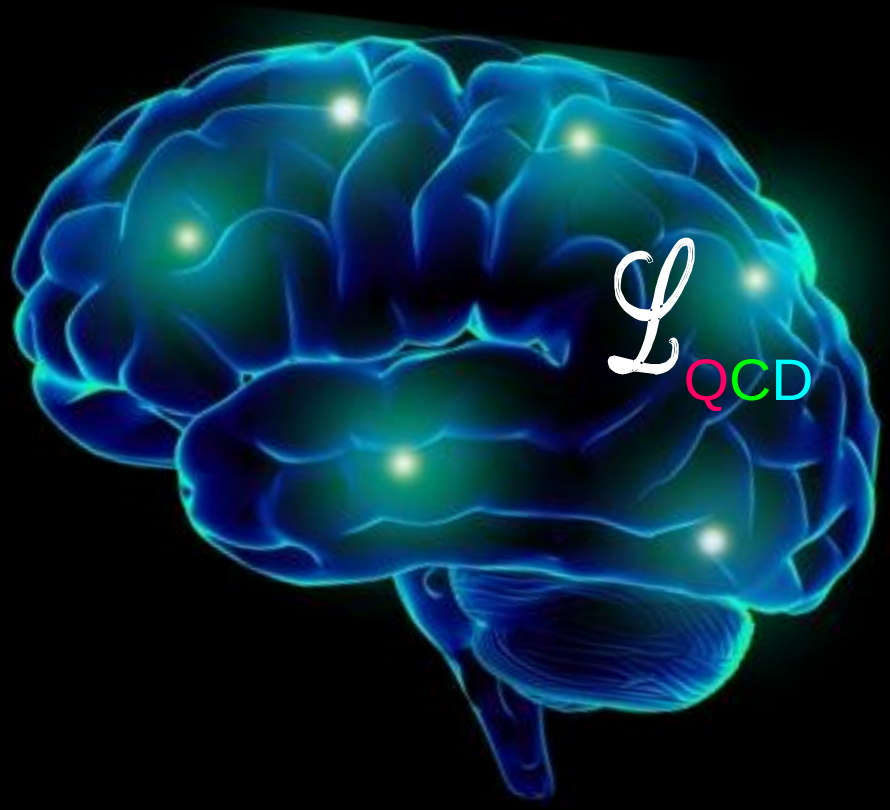
$1\,^3F_4$	$1\,^3D_3$	χ_{c2}	J/ψ
$J^{PC}=4^{++}$	$J^{PC}=3^{--}$	$J^{PC}=2^{++}$	$J^{PC}=1^{--}$
4095 MeV	3849 MeV	3556 MeV	3097 MeV
Γ=8.3 MeV	Γ=0.5 MeV	Γ=2.0 MeV	Γ=0.3 MeV
E_γ=246 MeV	E_γ=338 MeV	E_γ=413 MeV	-



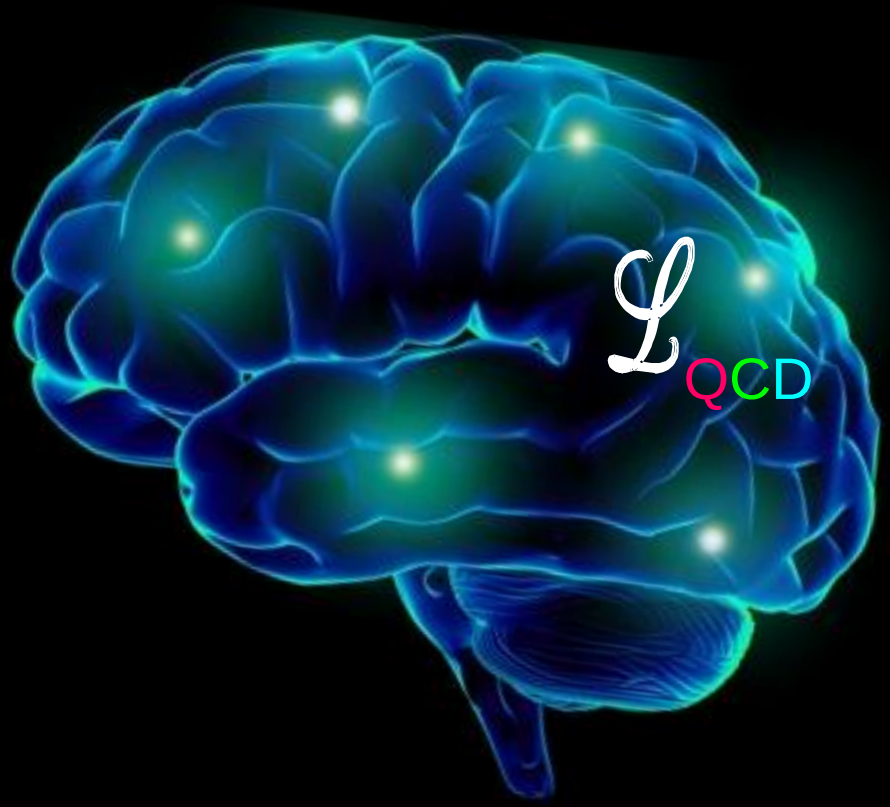




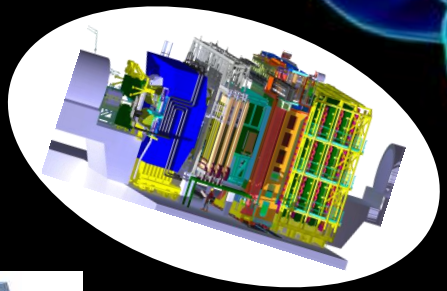
Lange, Prencipe *et al.*

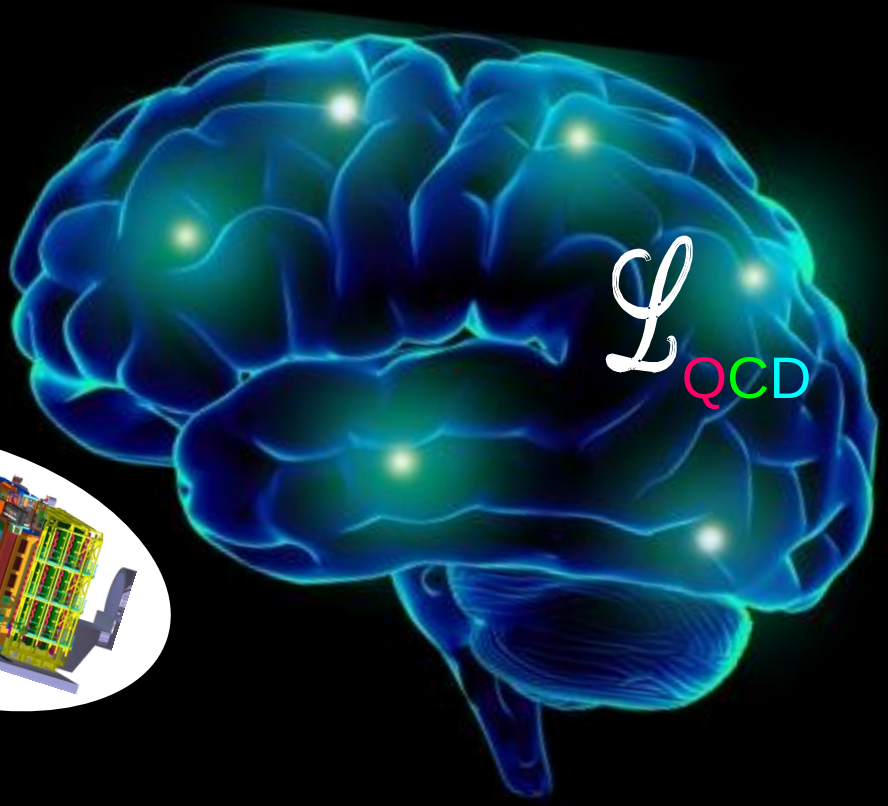

$\mathcal{L}_{QCD}$

precision research

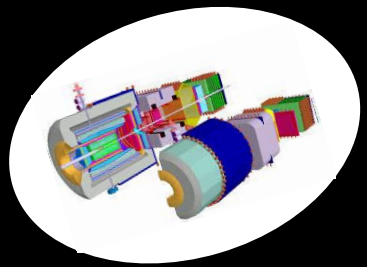


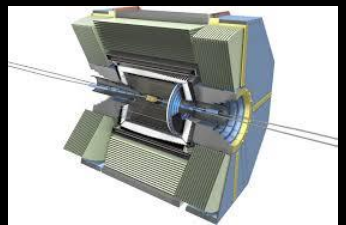
precision research





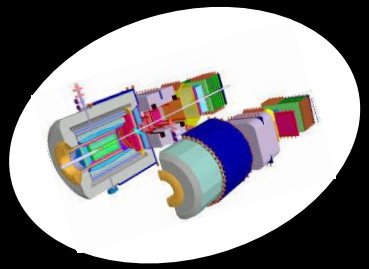
precision tools

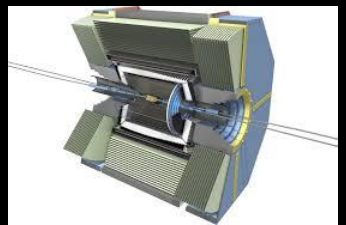


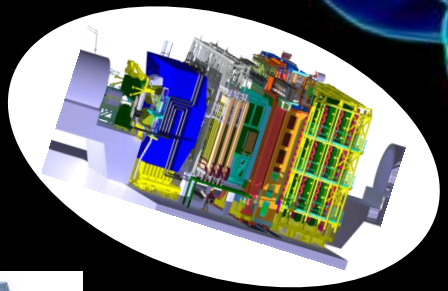


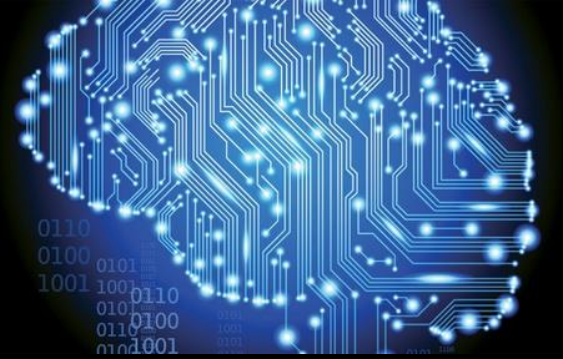
precision research

precision tools

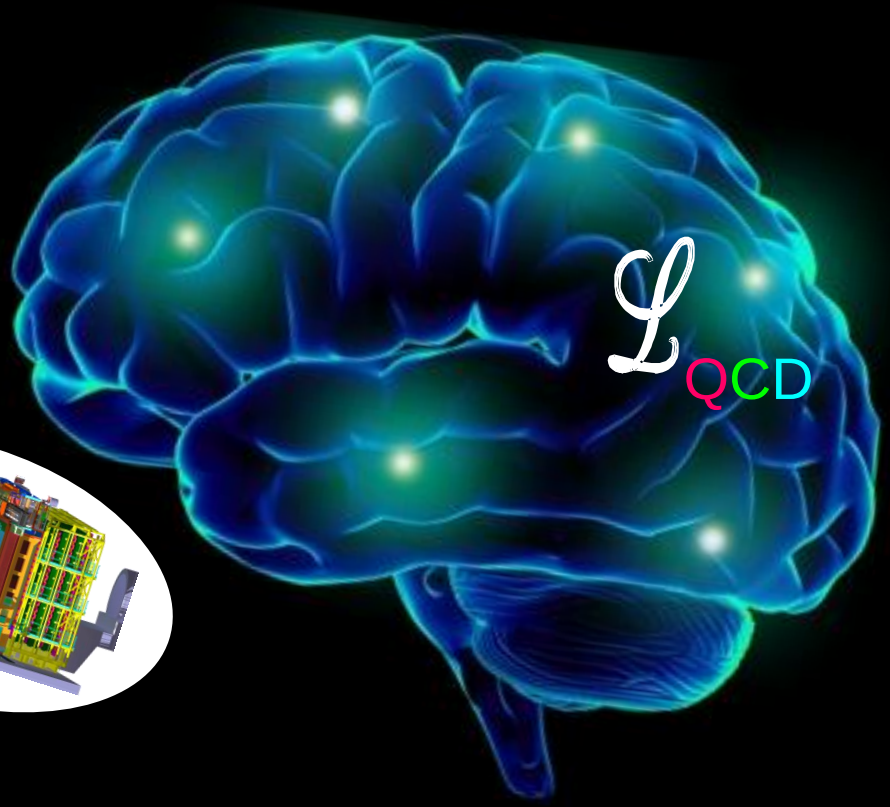








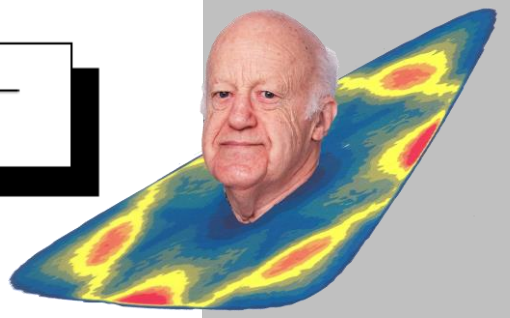
accurate modelling

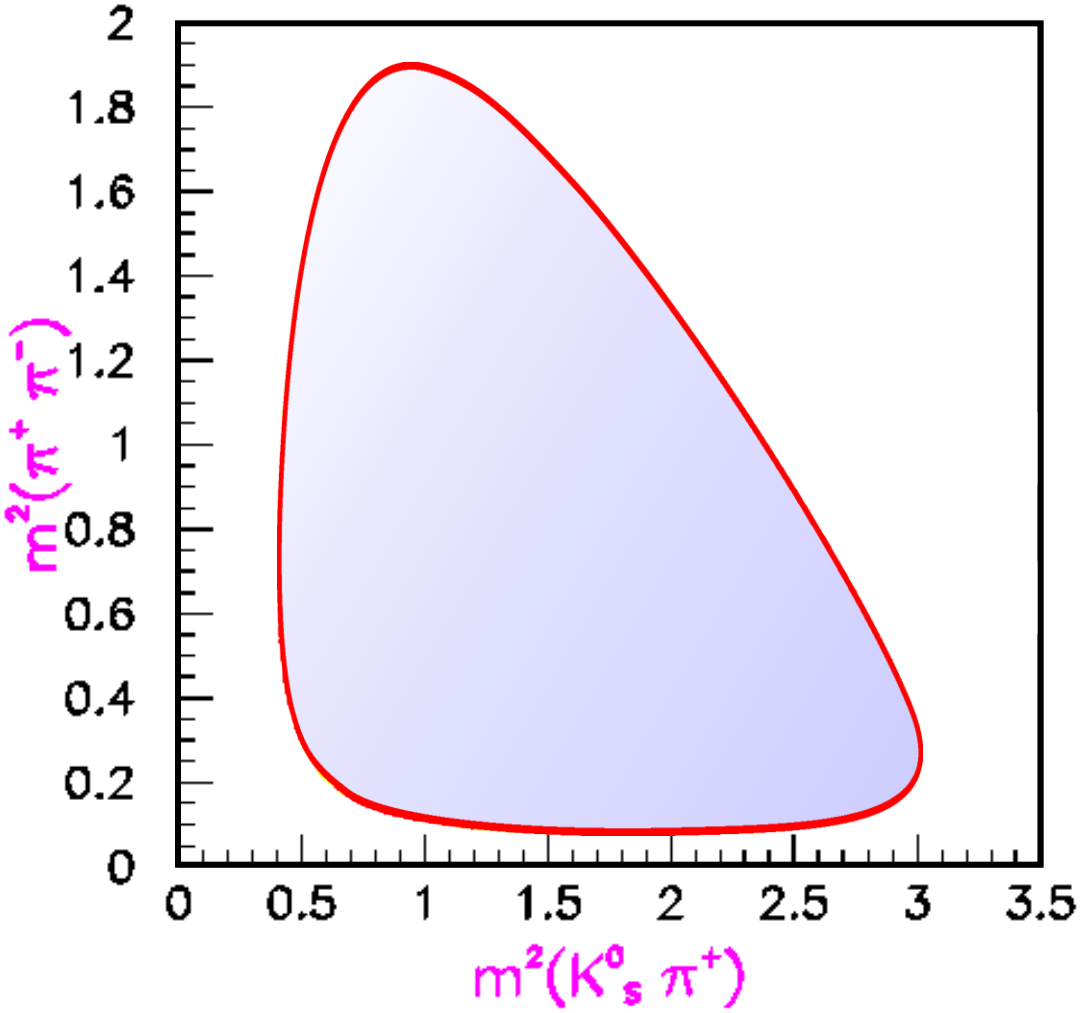


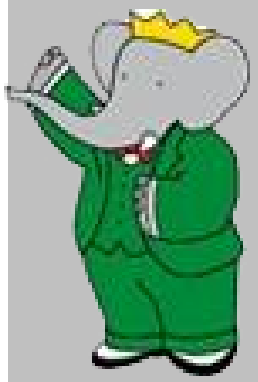
เอส-แมททริกซ์
S-Matrix

SNATUR
Center

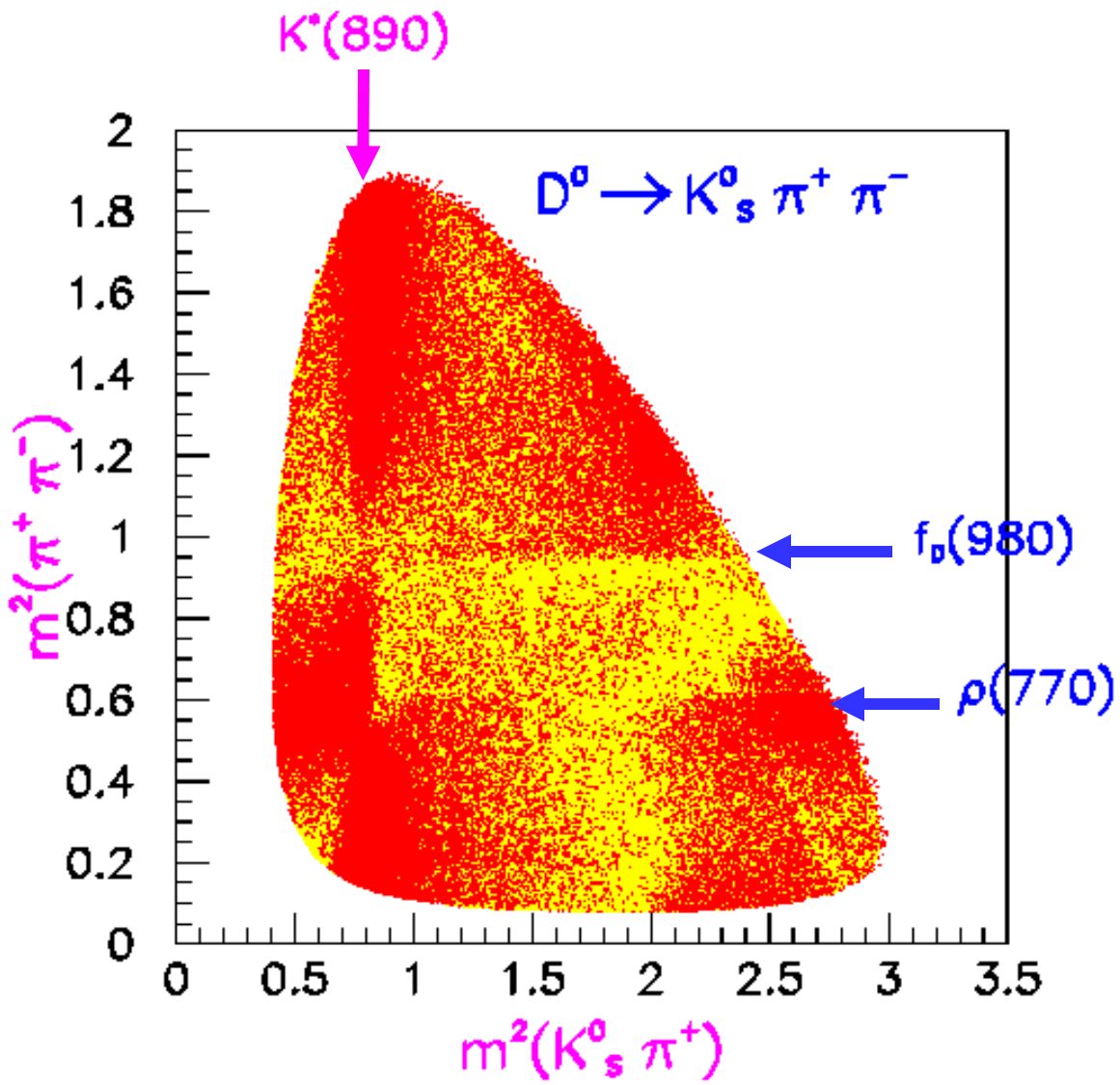
Dalitz plot of $D^0 \to \bar{K}^0\pi^+\pi^-$

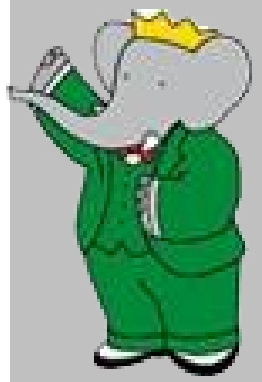




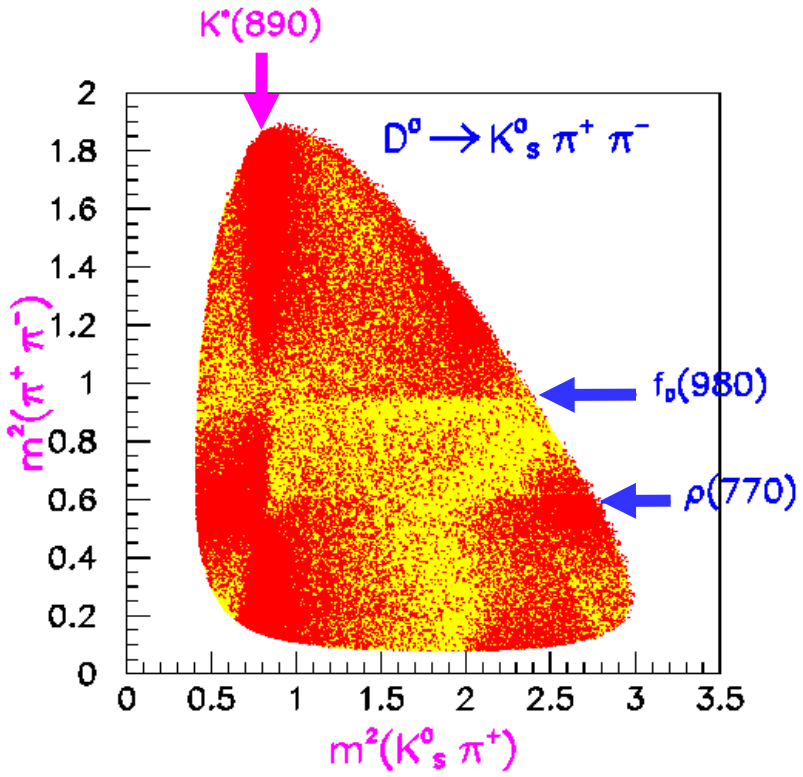


Dalitz plot of $D^0 \to \bar{K}^0\pi^+\pi^-$

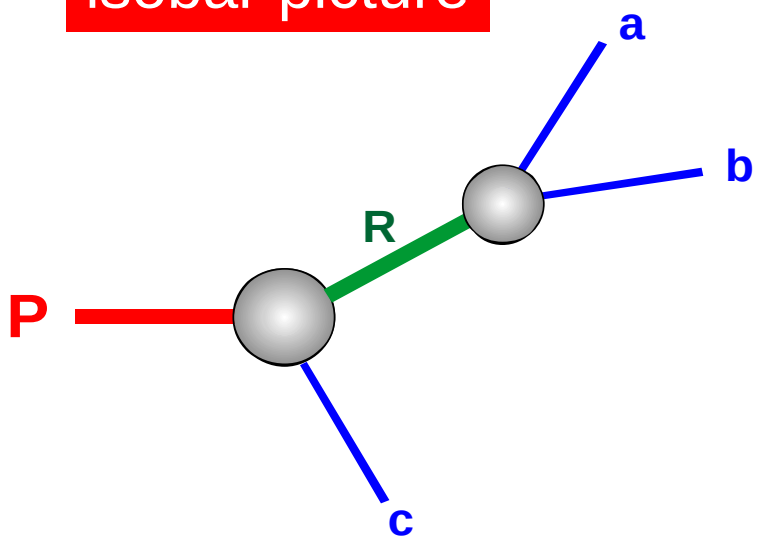




Dalitz plot of $D^0 \to \bar{K}^0\pi^+\pi^-$



isobar picture



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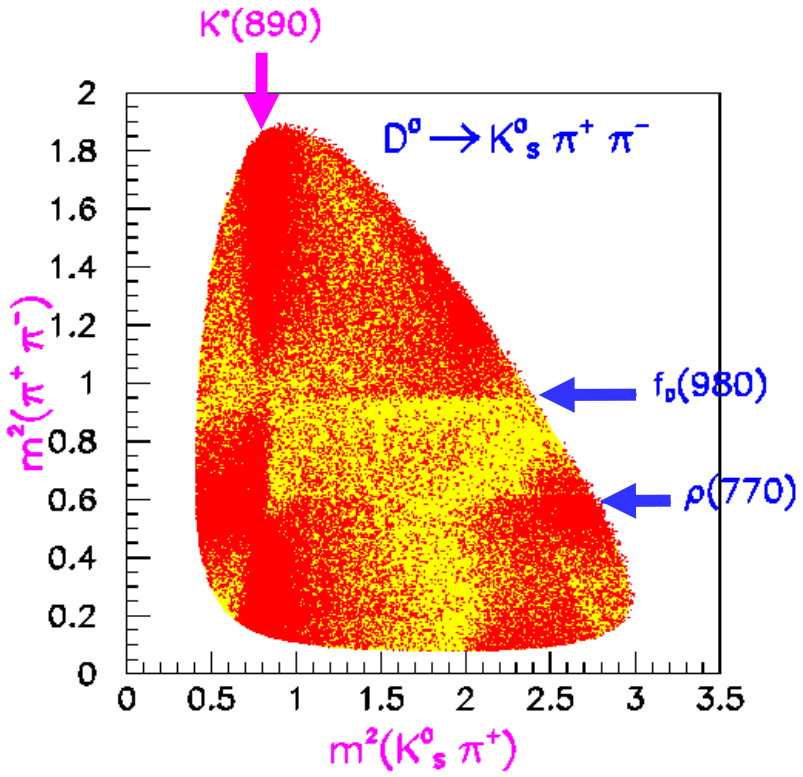

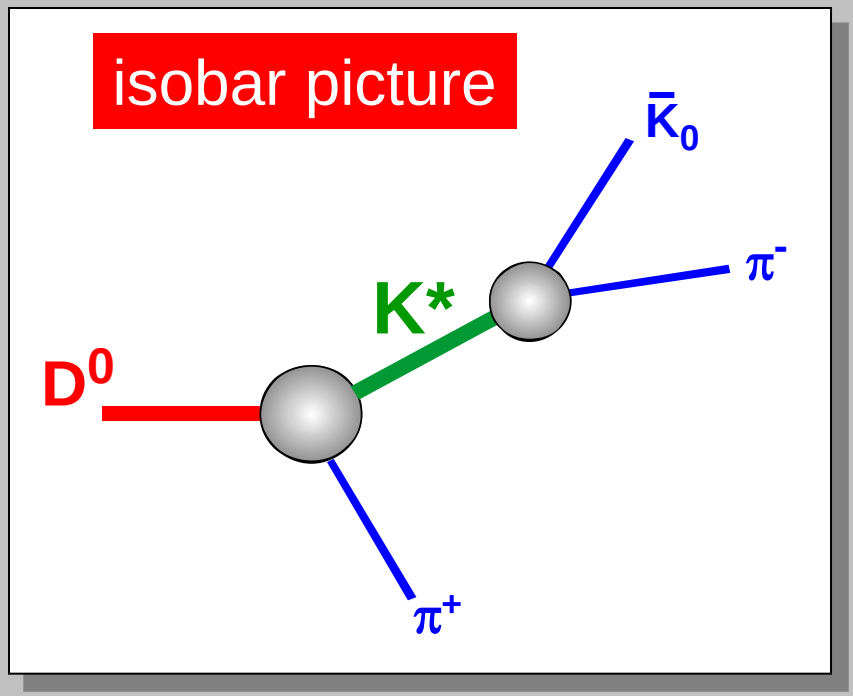

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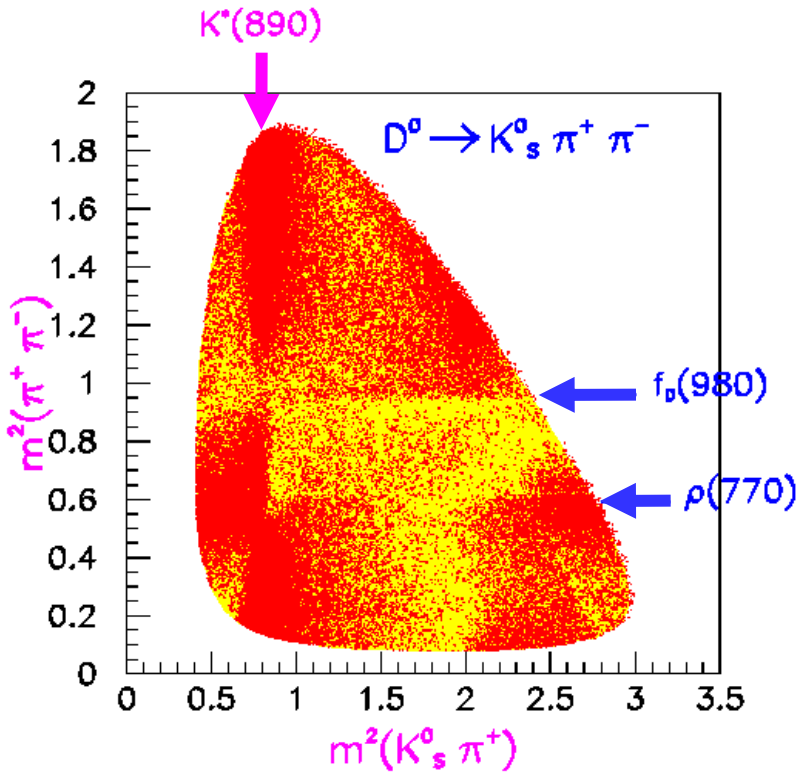

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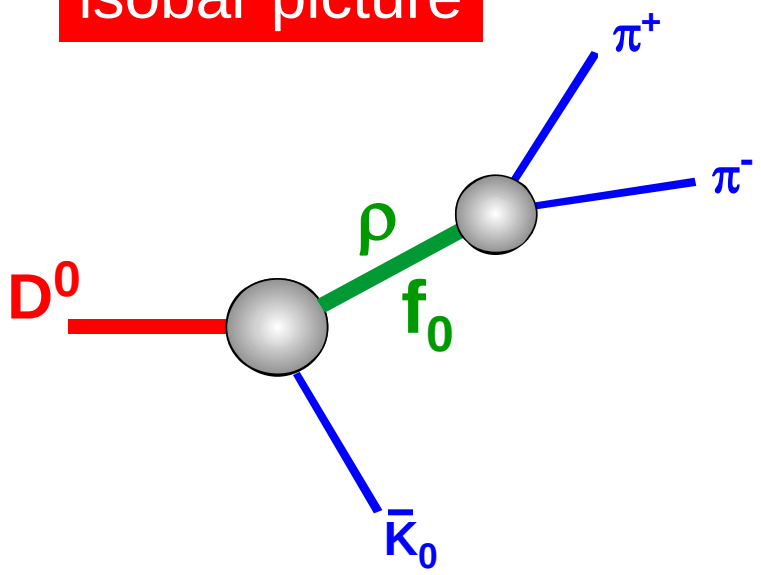

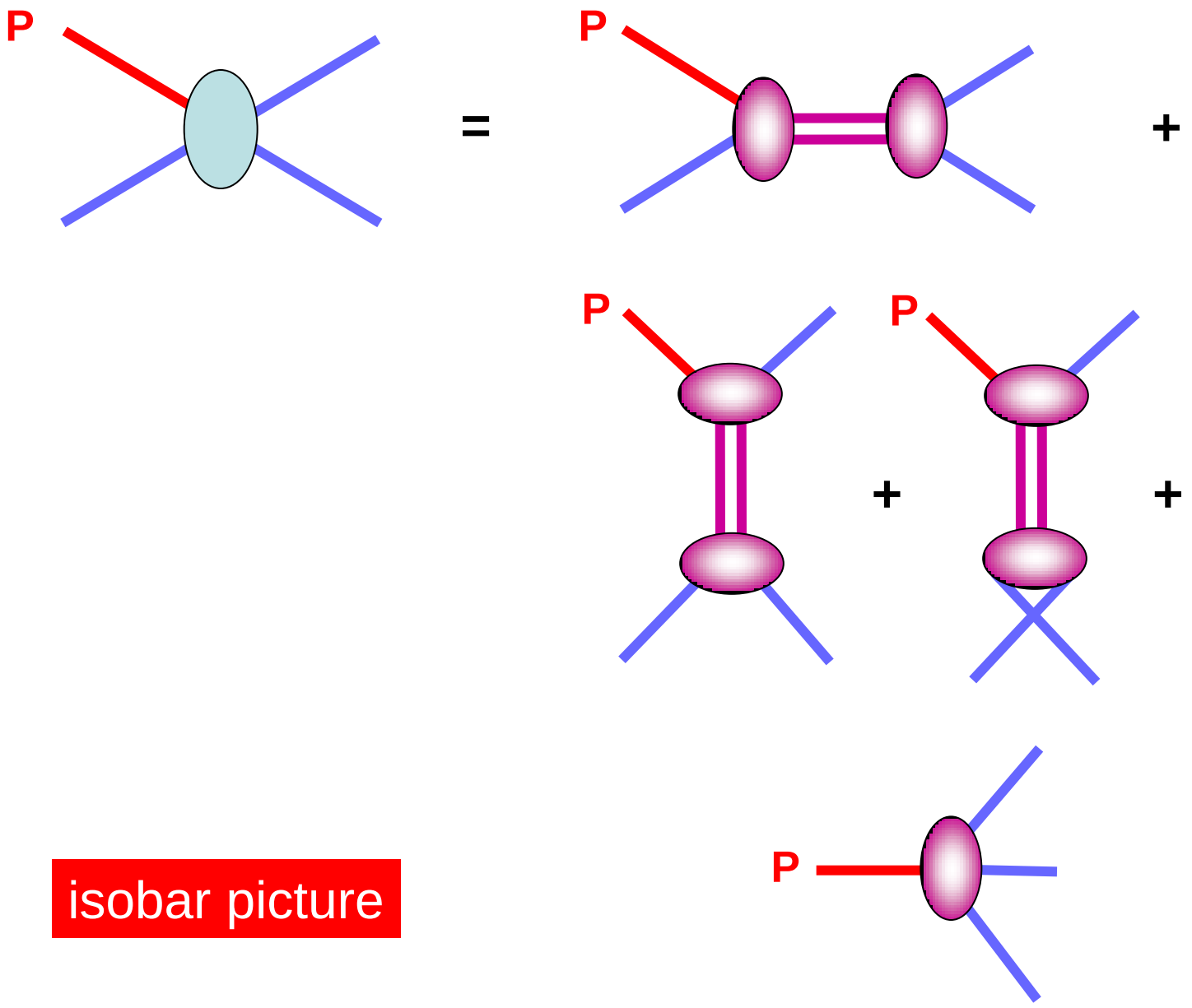

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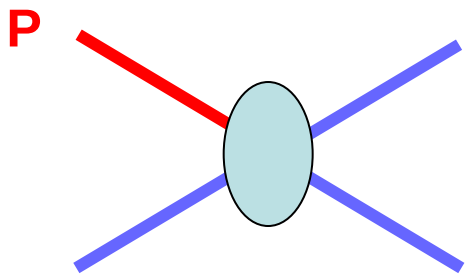

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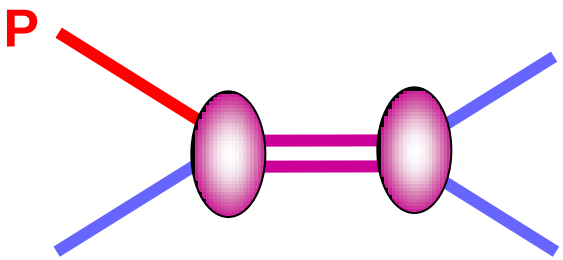

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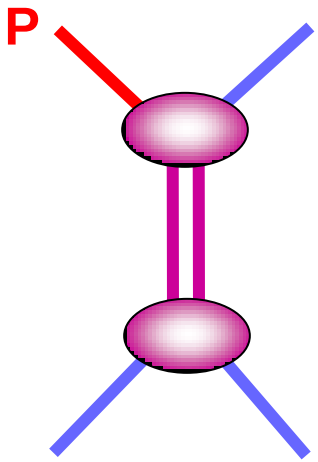

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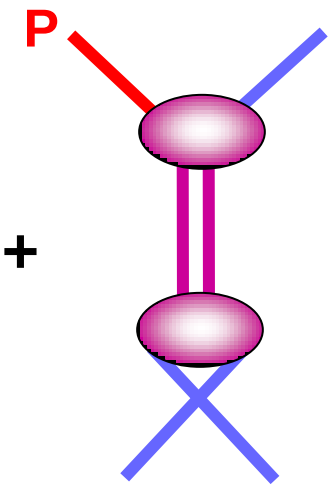

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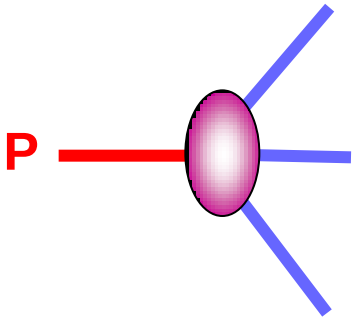

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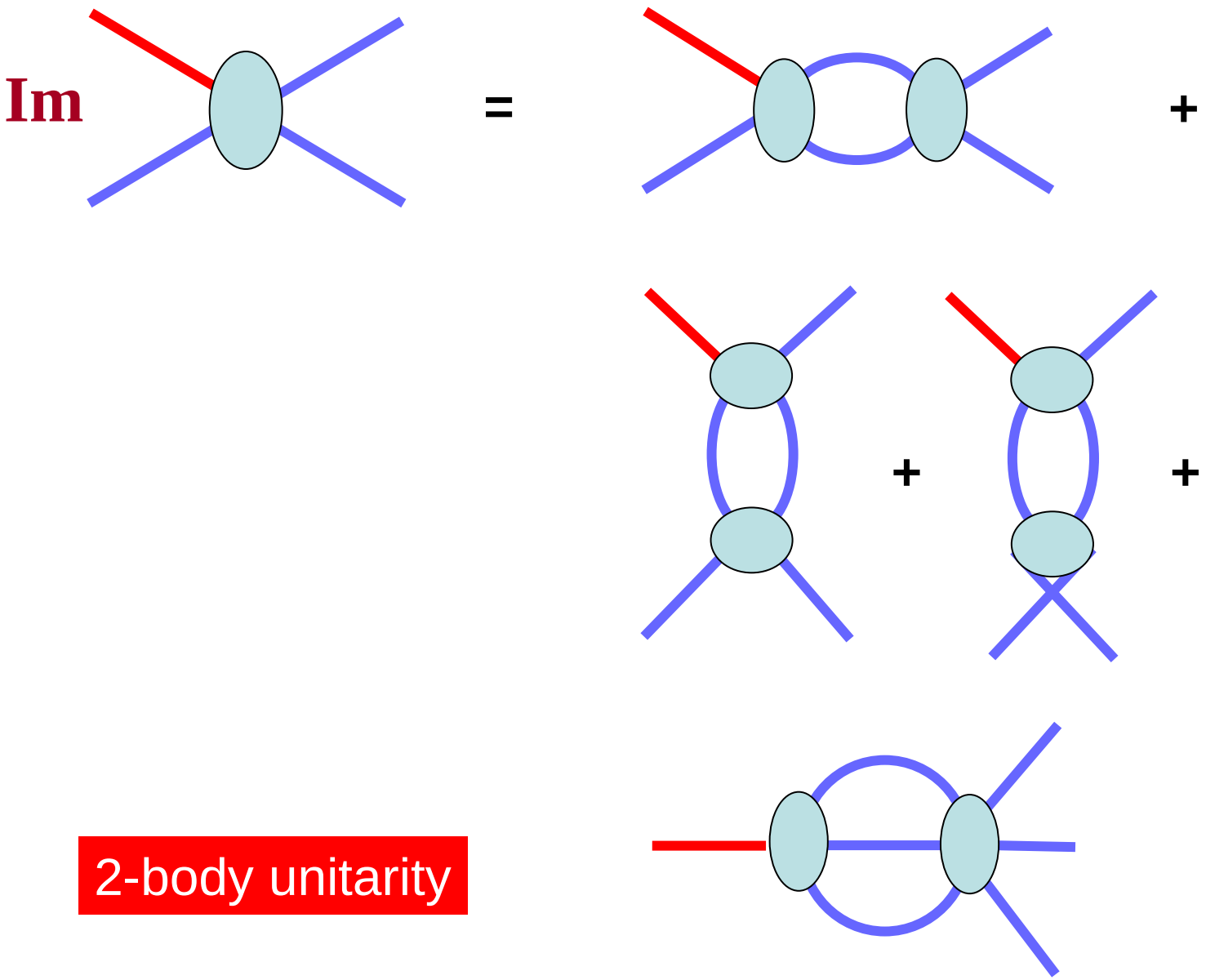
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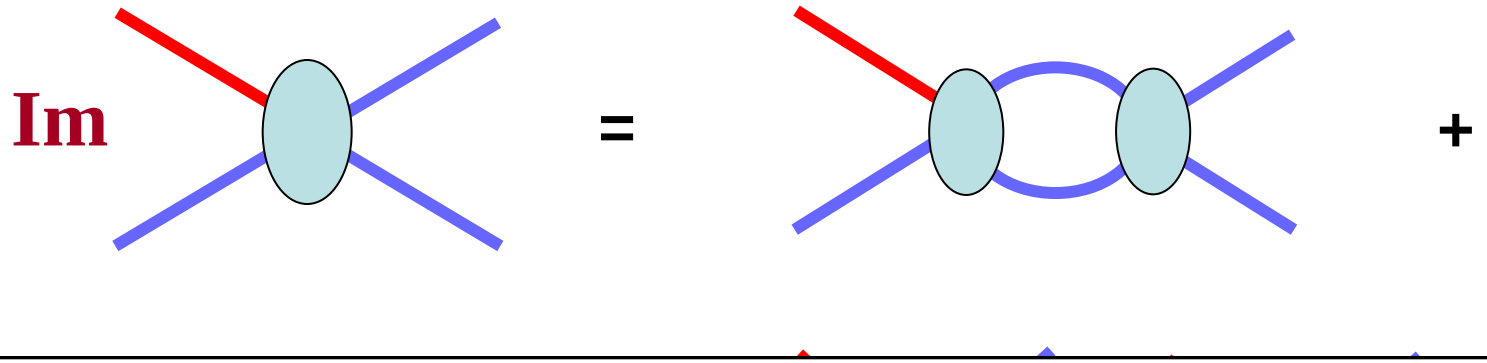
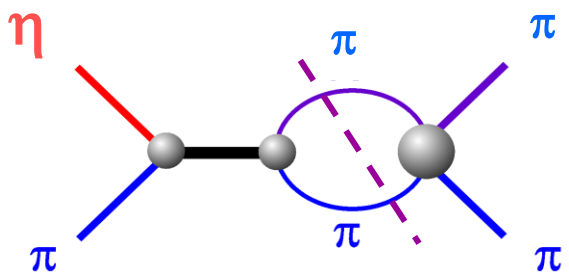
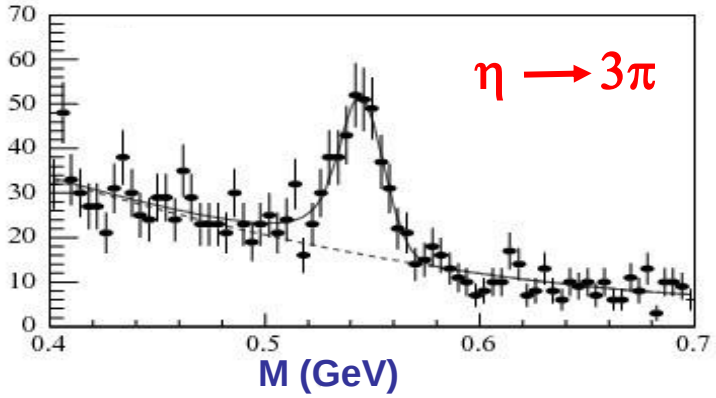
2-body unitarity

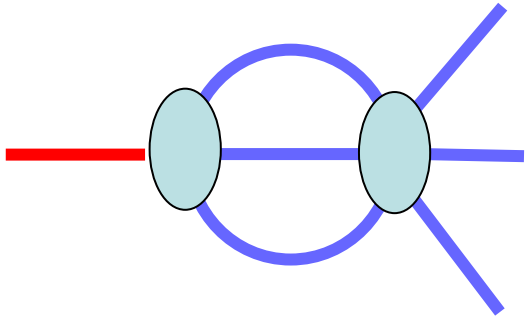


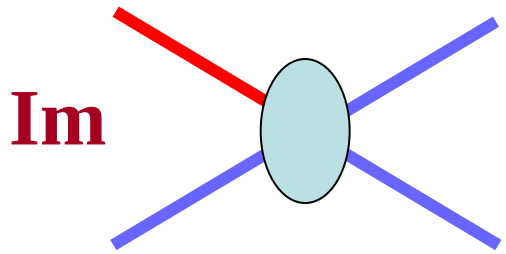


Khuri-Treiman relations



2-body unitarity





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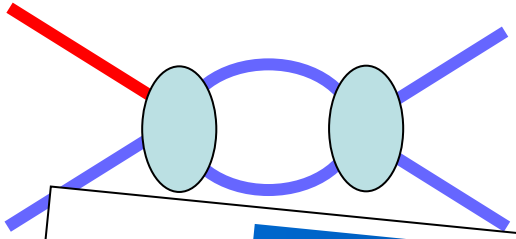

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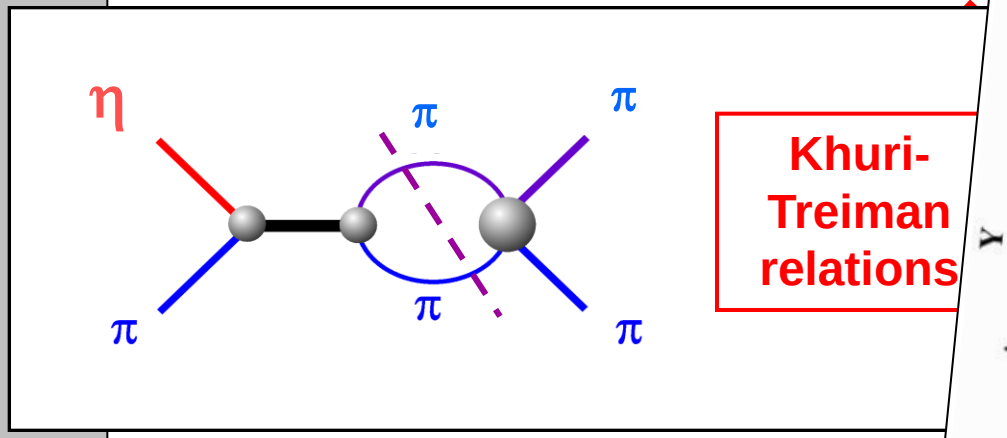

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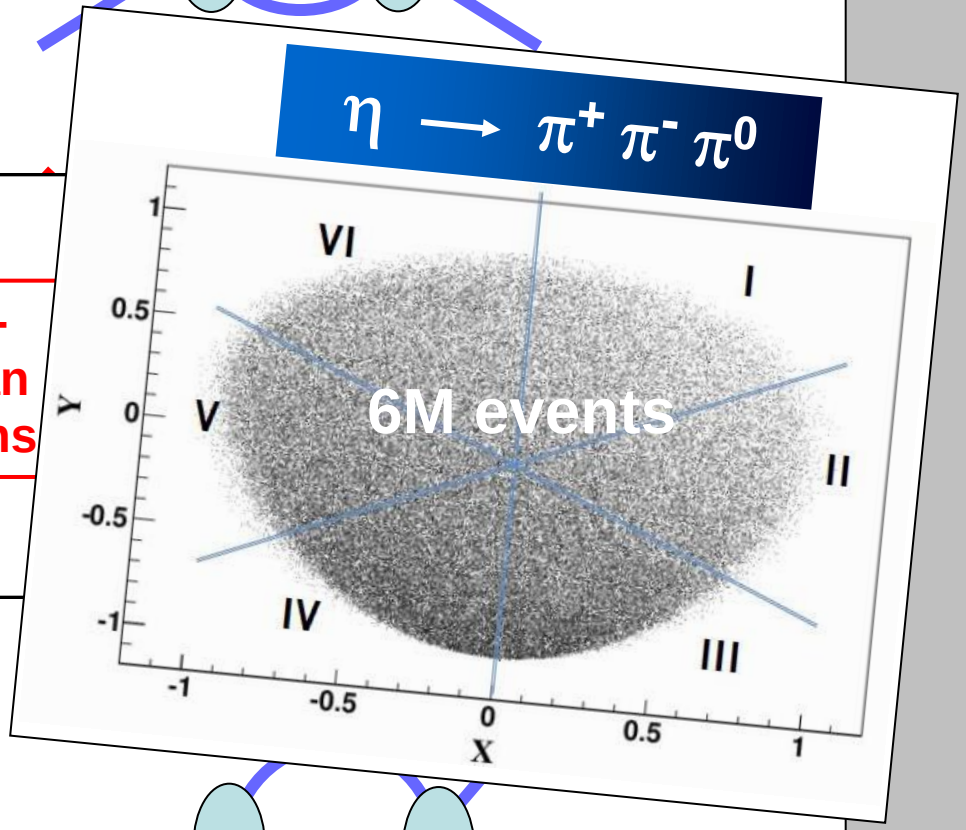
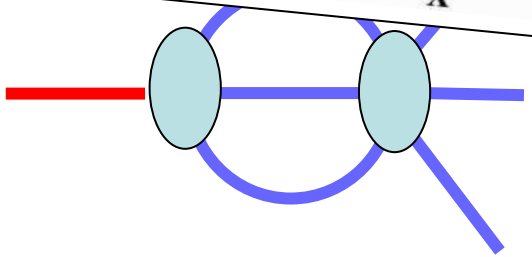
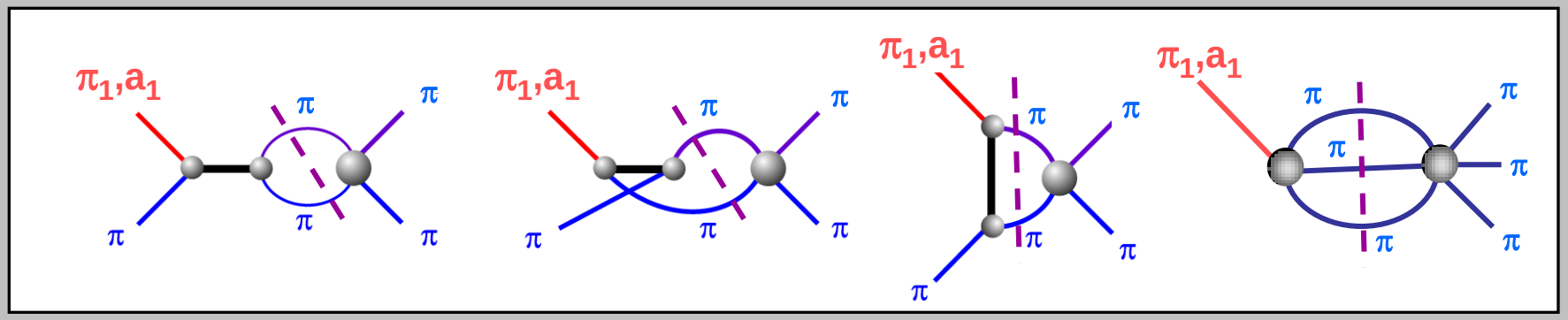


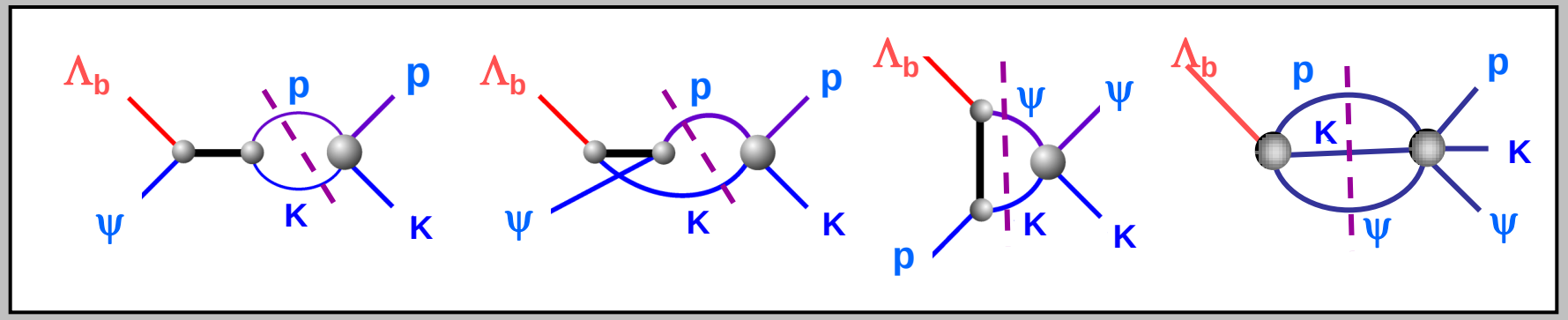


2-body unitarity

$\pi_1/a_1 \rightarrow \pi\pi\pi$



$\Lambda_b \rightarrow K^- J/\psi\, p$



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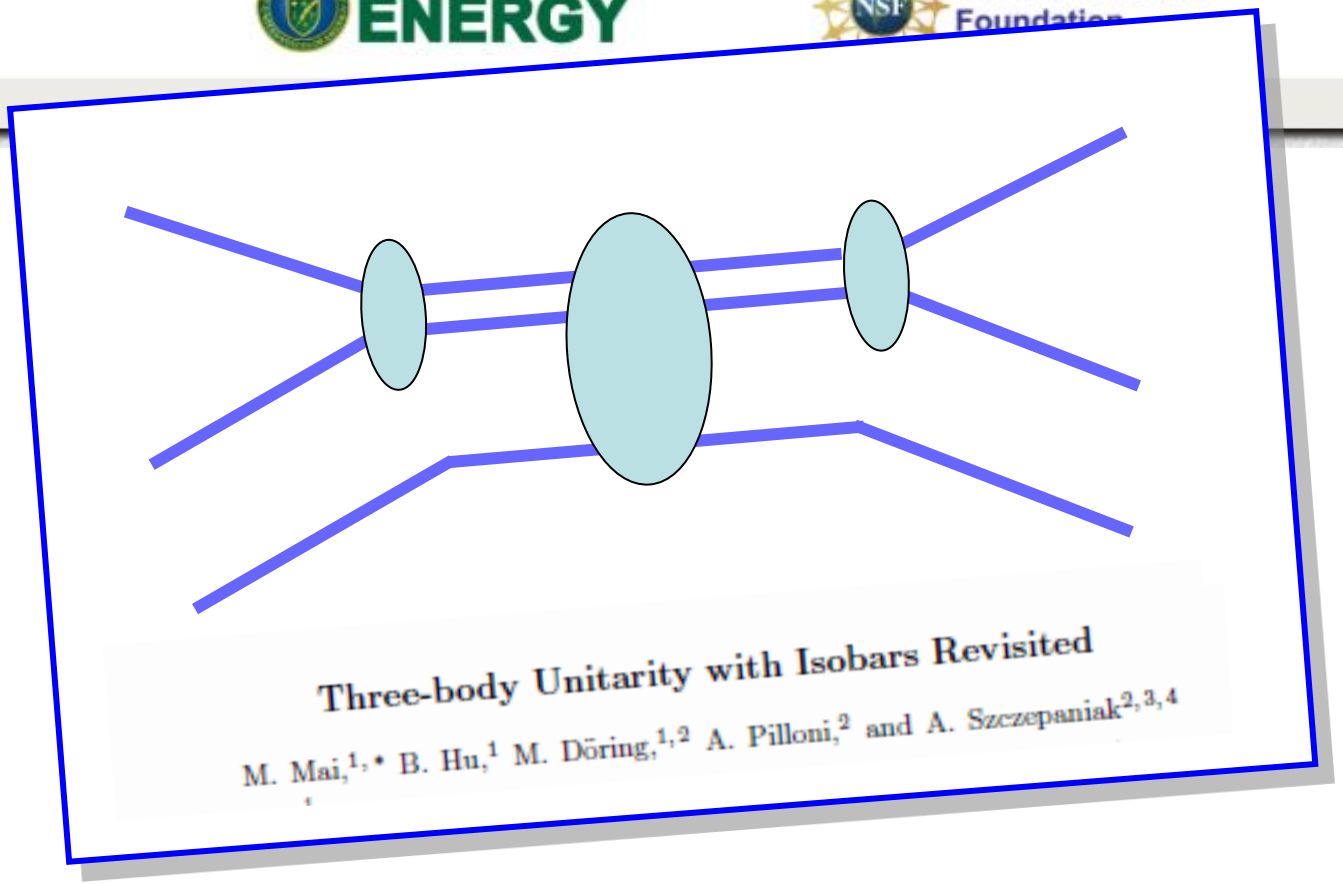

Three-body Unitarity with Isobars Revisited

M. Mai,[1,*] B. Hu,[1] M. Döring,[1,2] A. Pilloni,[2] and A. Szczepaniak[2,3,4]

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NEWS

Photoproduction:

- High energy model for η' beam asymmetry photoproduction: $\gamma p \to \eta(')p$
- High energy model for η photoproduction: $\gamma p \to \eta p$
- High energy model for π^0 photoproduction: $\gamma p \to \pi 0 p$
- High energy model for J/ψ photoproduction: $\gamma p \to J/\psi p$

Hadroproduction:

- Pion-nucleon scattering: $\pi N \to \pi N$ amplitude
- Finite energy sum rules $\pi N \to \pi N$ FESR page
- Kaon-nucleon scattering: $\bar{K} N \to \bar{K} N$

Light meson Decay:

- η meson into three pions: $\eta \to 3\pi$
- vector meson into three pions: $\omega, \phi \to 3\pi$

Joint Physics Analysis Center Team

Indiana University

- **Adam Szczepaniak** Professor
- **Geoffrey Fox** Professor
- **Emilie Passemar** Professor
- **Tim Londergan** Professor
- **Vincent Mathieu** Postdoctoral researcher
- **Ina Lorenz** Postdoctoral researcher
- **Andrew Jackura** PhD student

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- **Alessandro Pilloni** Postdoctoral researcher

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CDC
BCAL
COMPASS
LHCb

Exposing QCD

- what are the relevant degrees of freedom?

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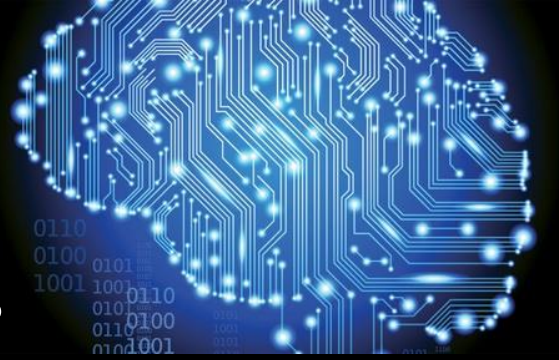
  - what are their patterns -- flavour, spin, …?
  - what does this reveal about the internal dynamics?

Exposing QCD



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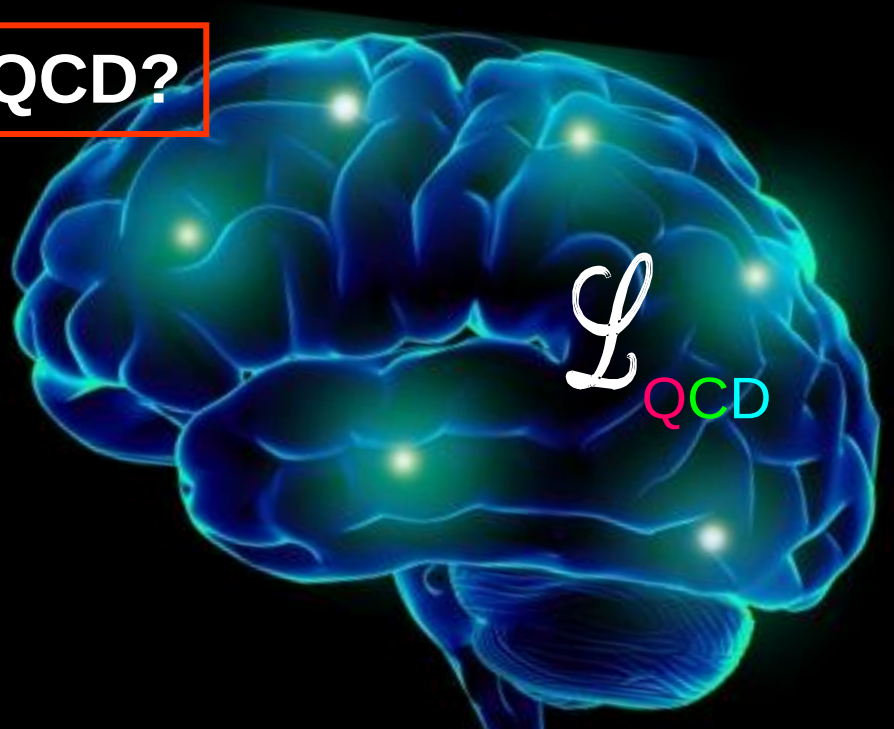
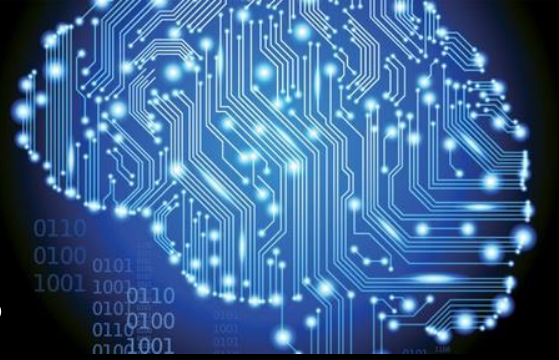


Exposing QCD



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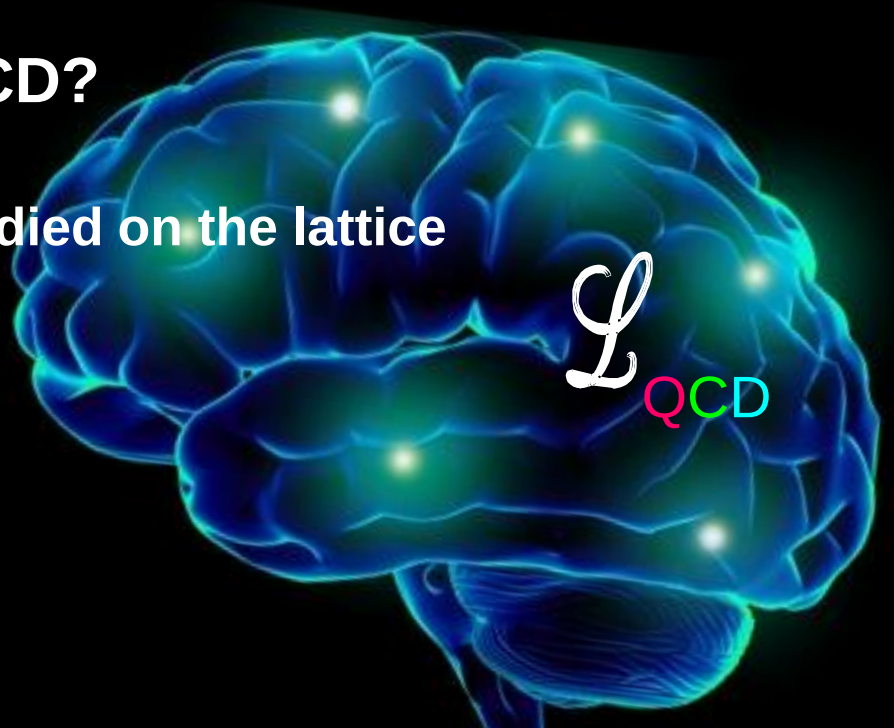
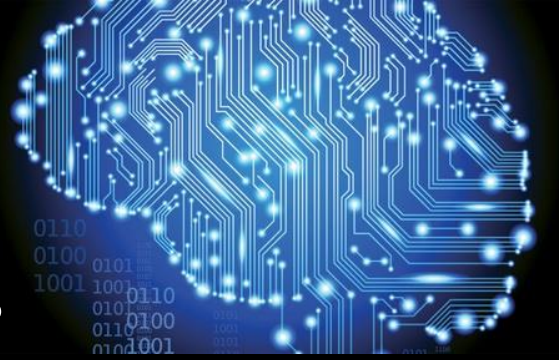


Exposing QCD



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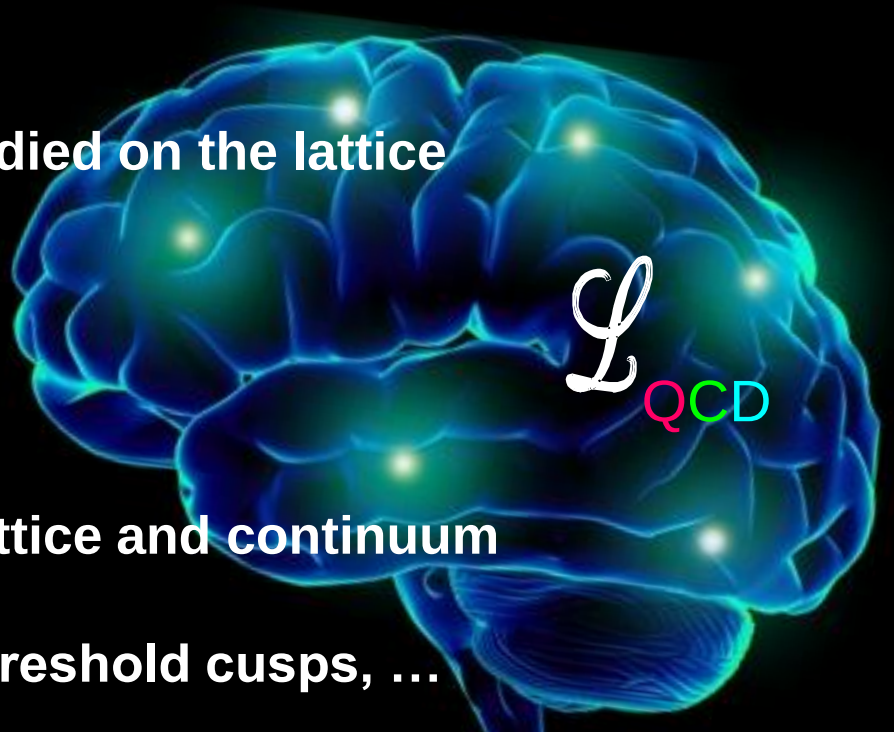
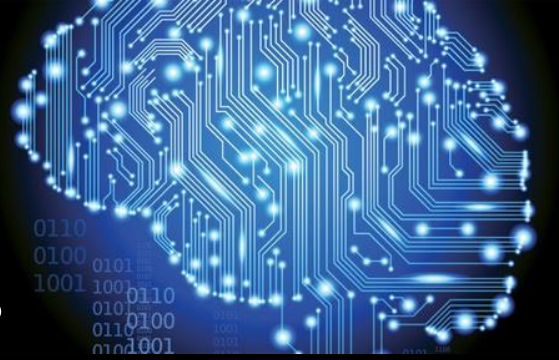


- multi-particle scattering on the lattice and continuum
- methods of S-matrix theory
  - poles, triangle singularities, threshold cusps, …

Exposing QCD



- what are the relevant degrees of freedom?

- **how are hadrons *really* connected to QCD?**

BESIII

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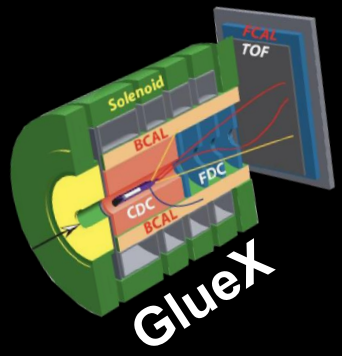

LHCb

Belle II