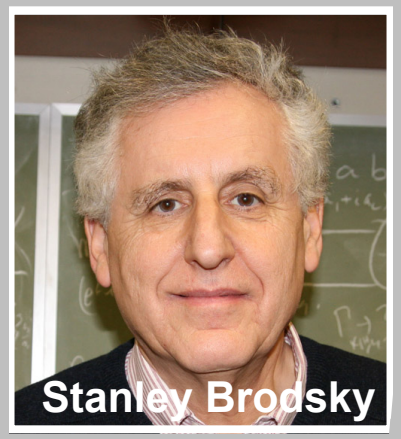
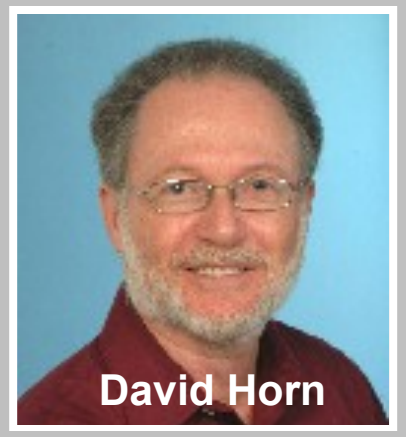

Summer School on Reaction Theory
INDIANA UNIVERSITY
Michael Pennington
Jefferson Lab


Edmond Berger


Stanley Brodsky


Geoffrey Fox


David Horn

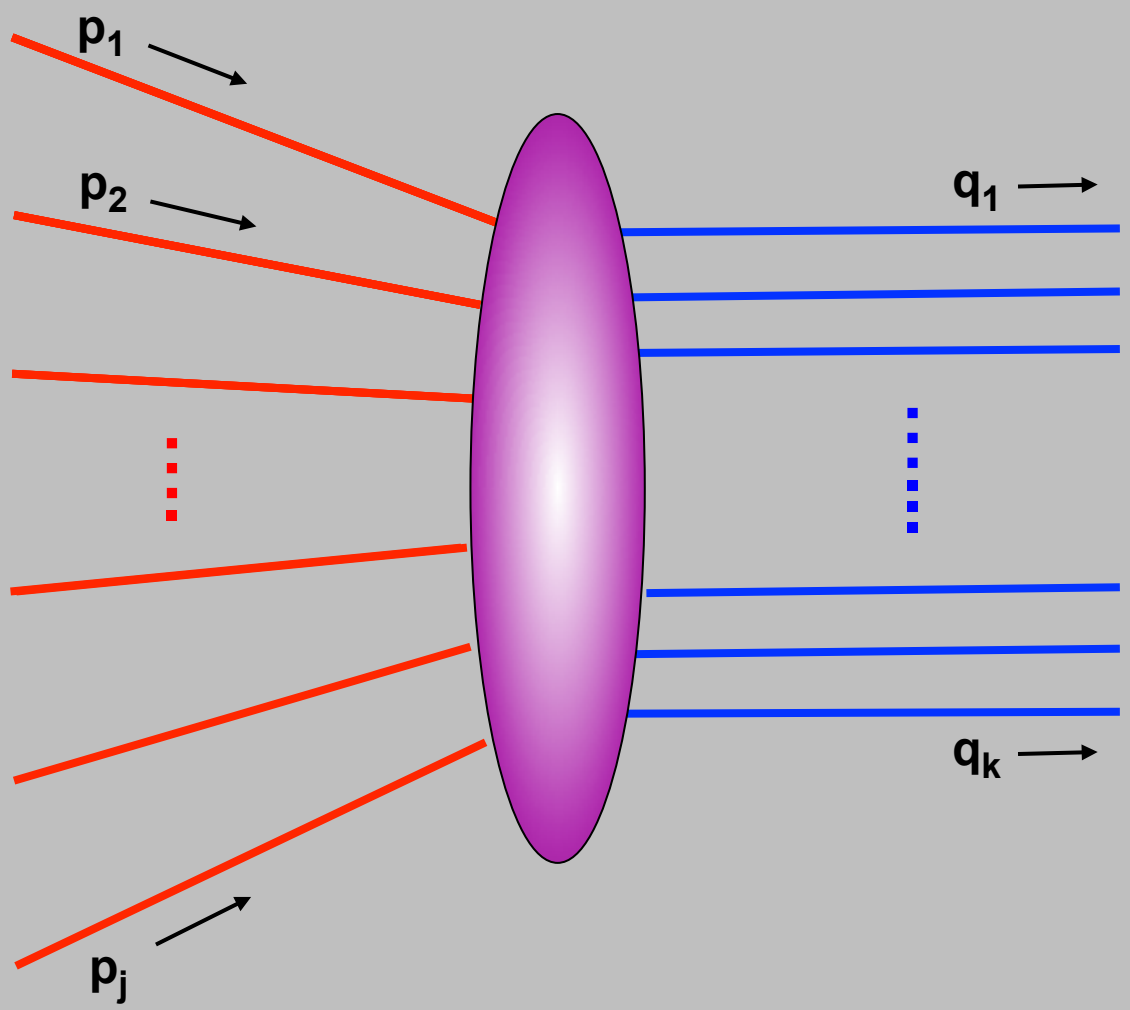

Jonathon Rosner


Michael Pennington


Timothy Londergan


Peter Landshoff

$$S(p_1,p_2,\ldots,p_j;\ \sigma_1,\sigma_2\ldots,\sigma_j;\ q_1,\ldots,q_k;\ \tau_1,\ldots,\tau_k)$$



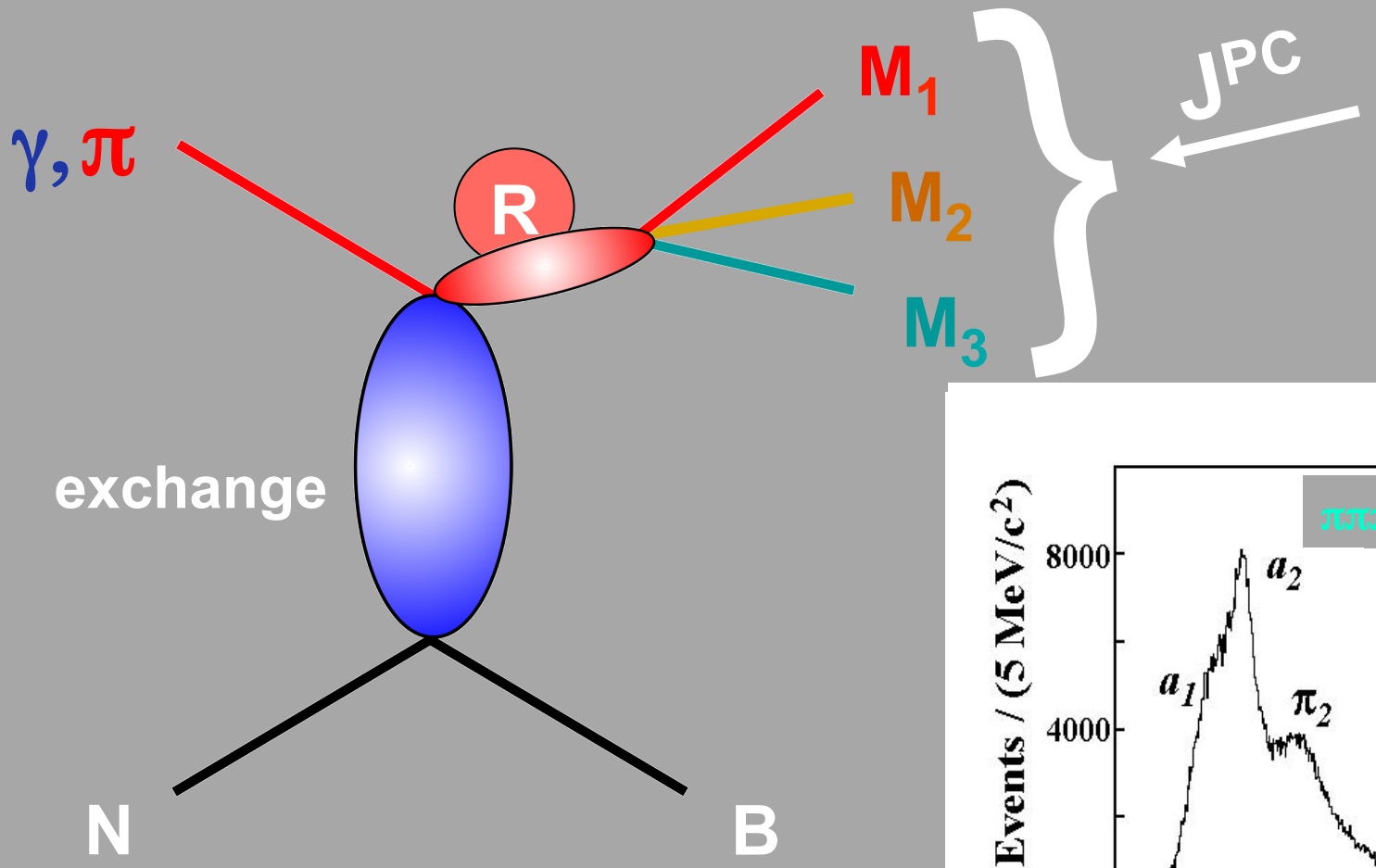
$2 \to 2$

$2 \to 3$

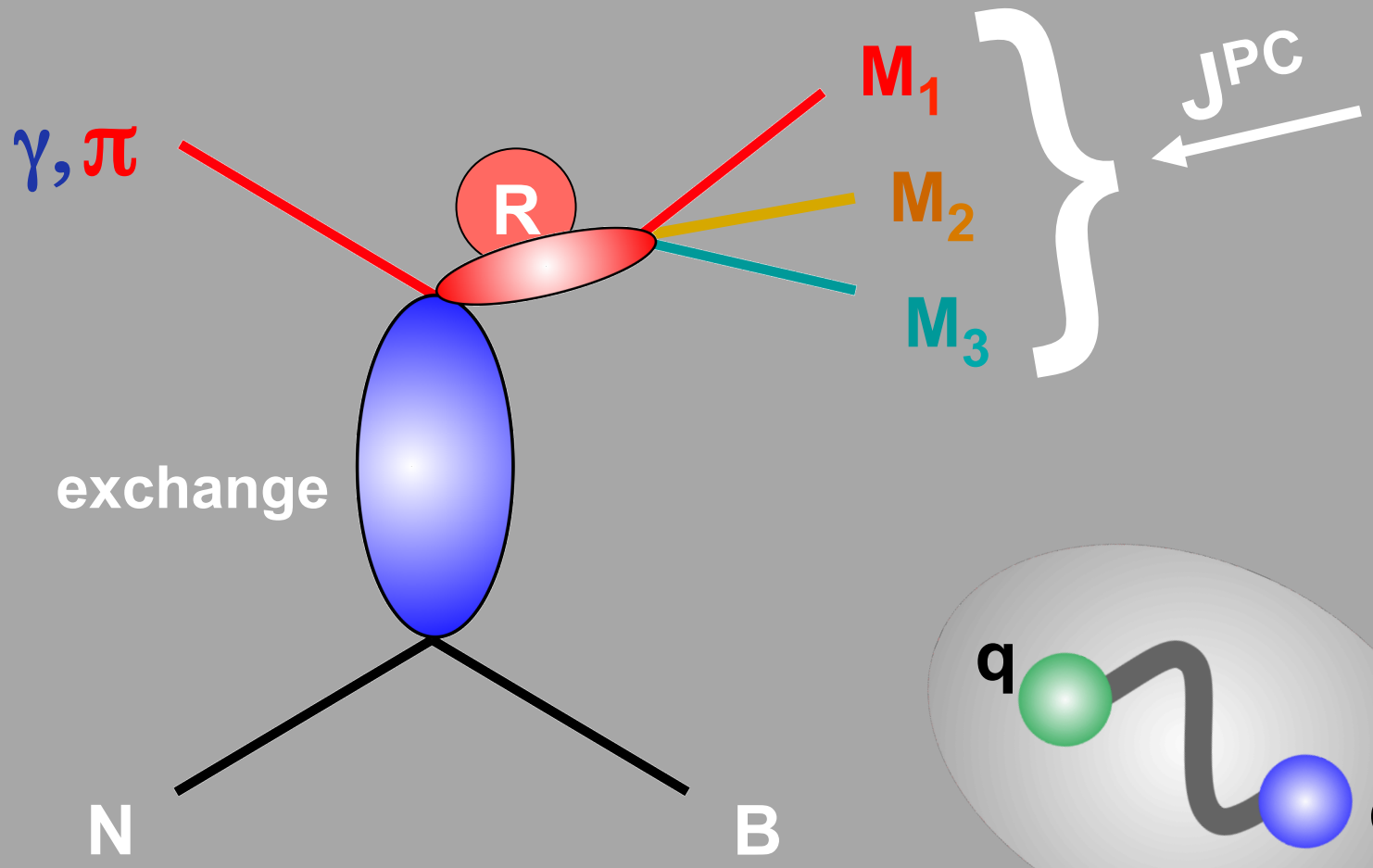
$3 \to 3$

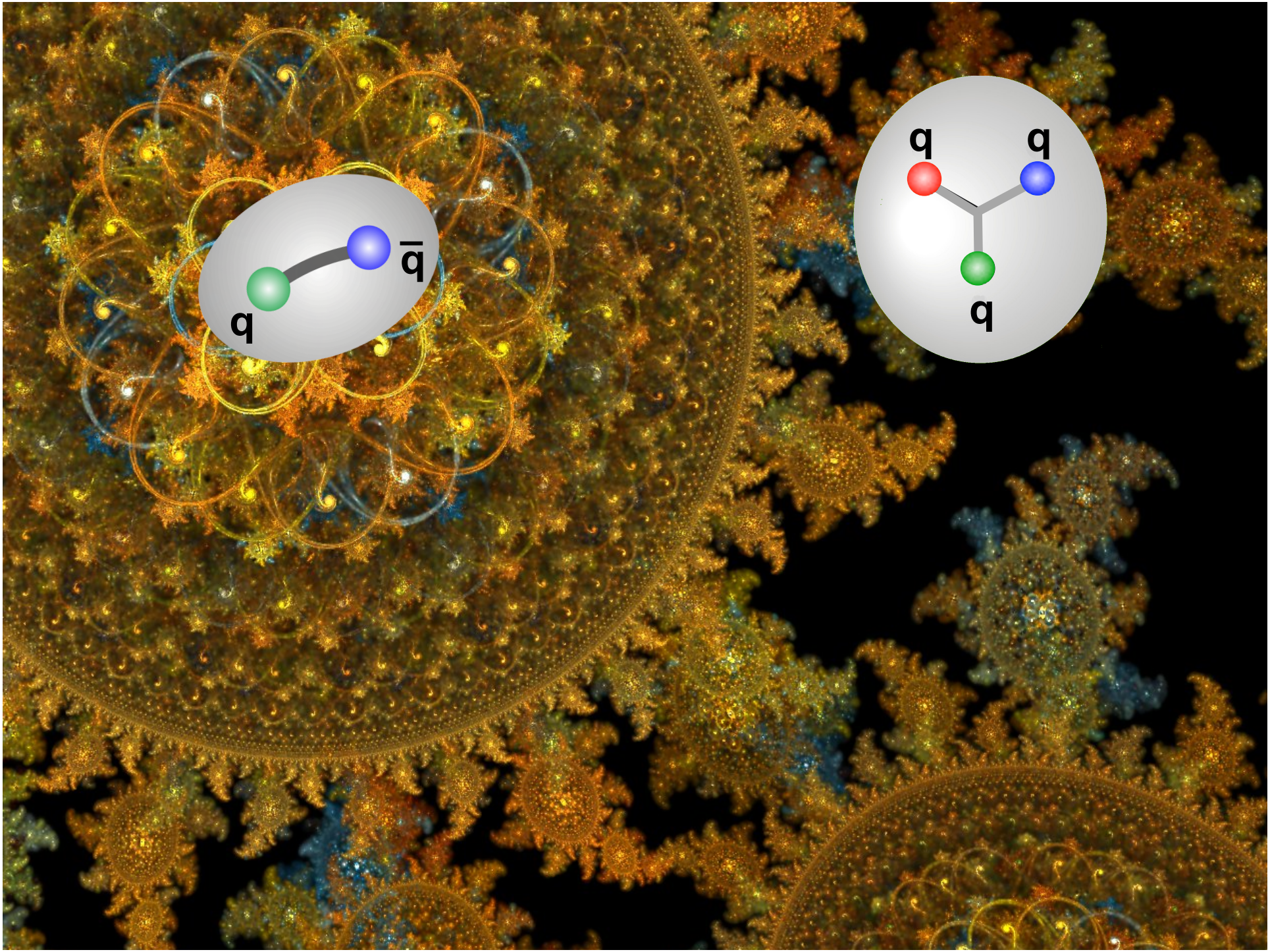
$\vdots$

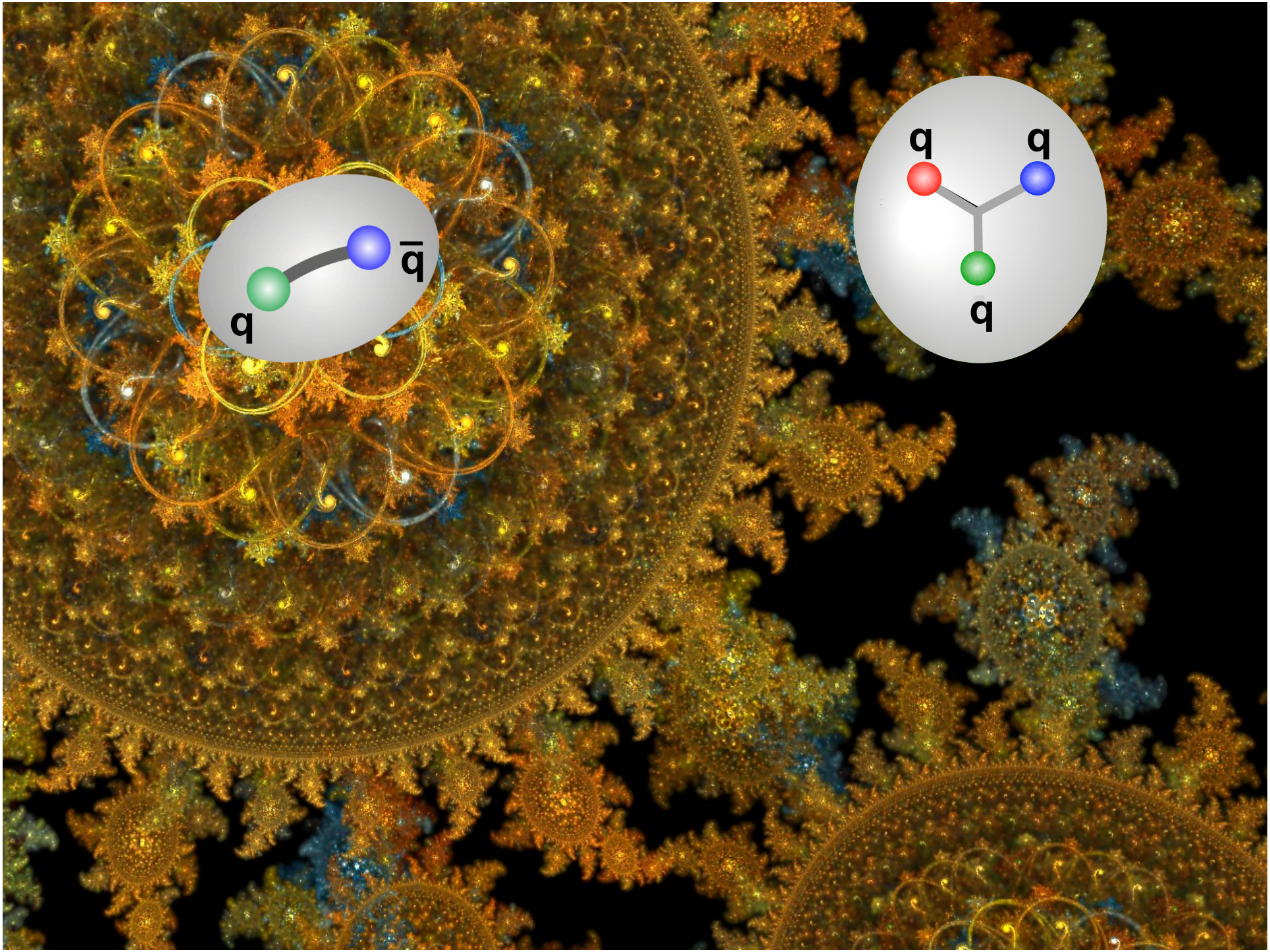
Amplitude Analysis

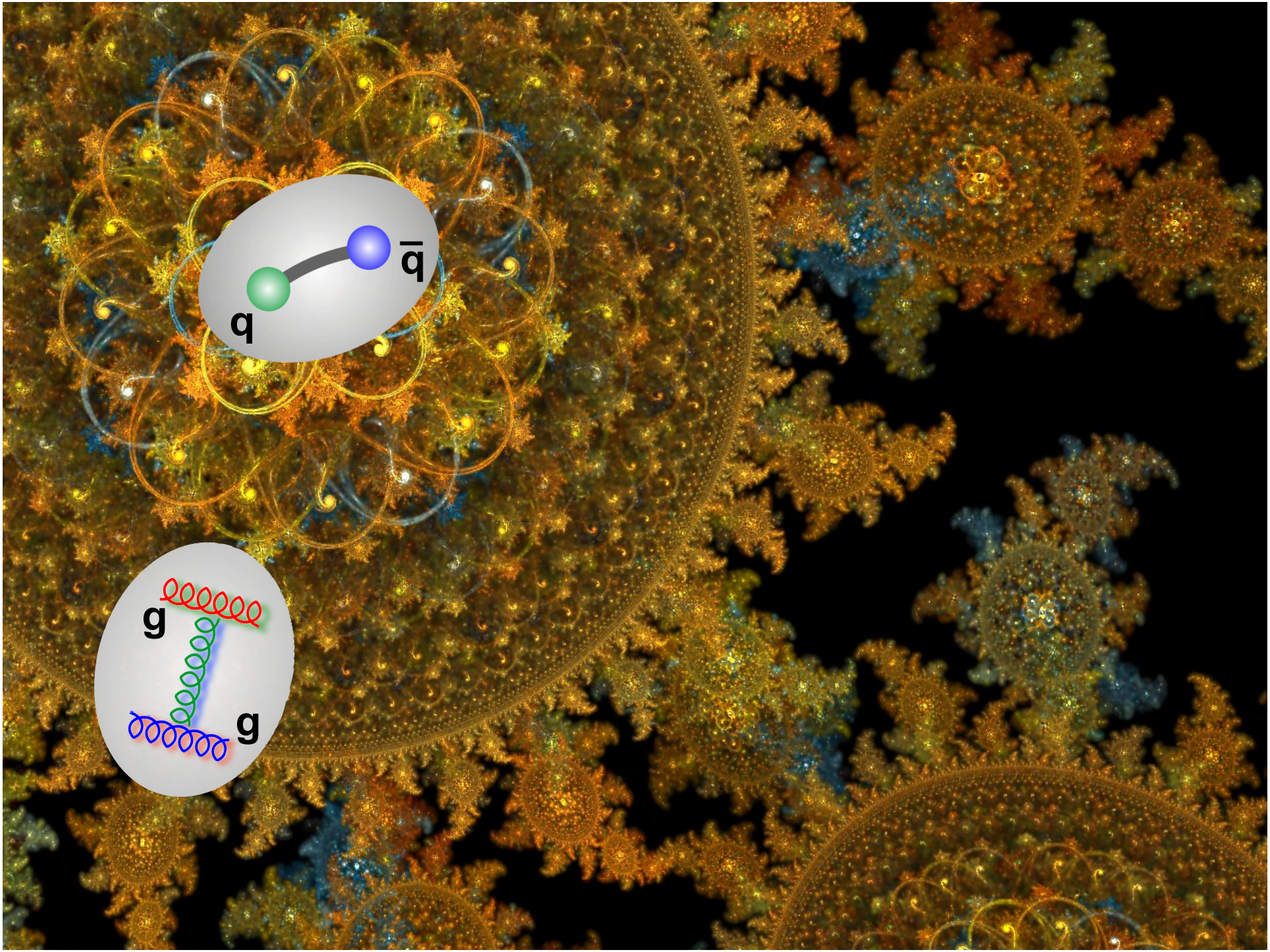


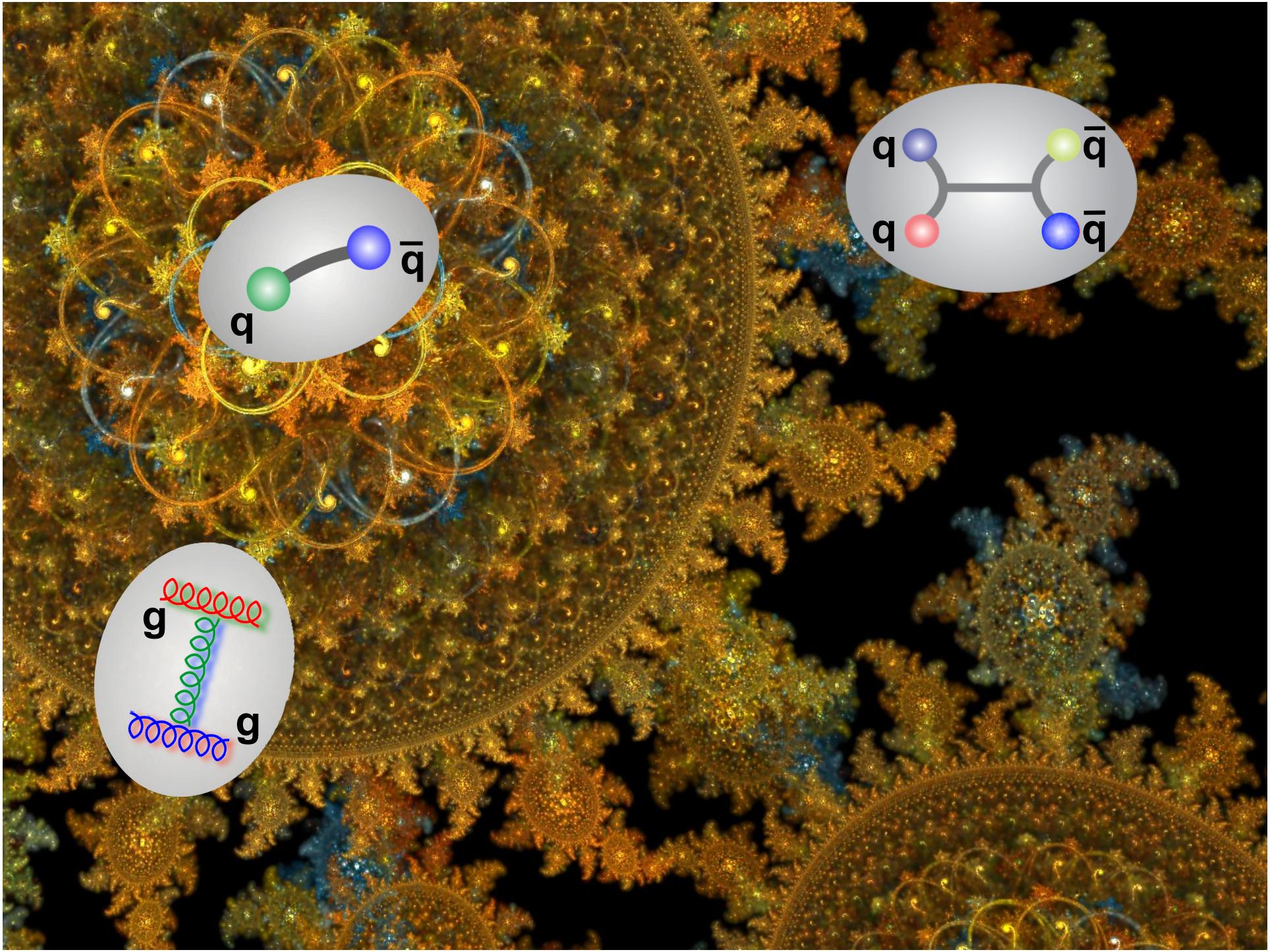
Amplitude Analysis

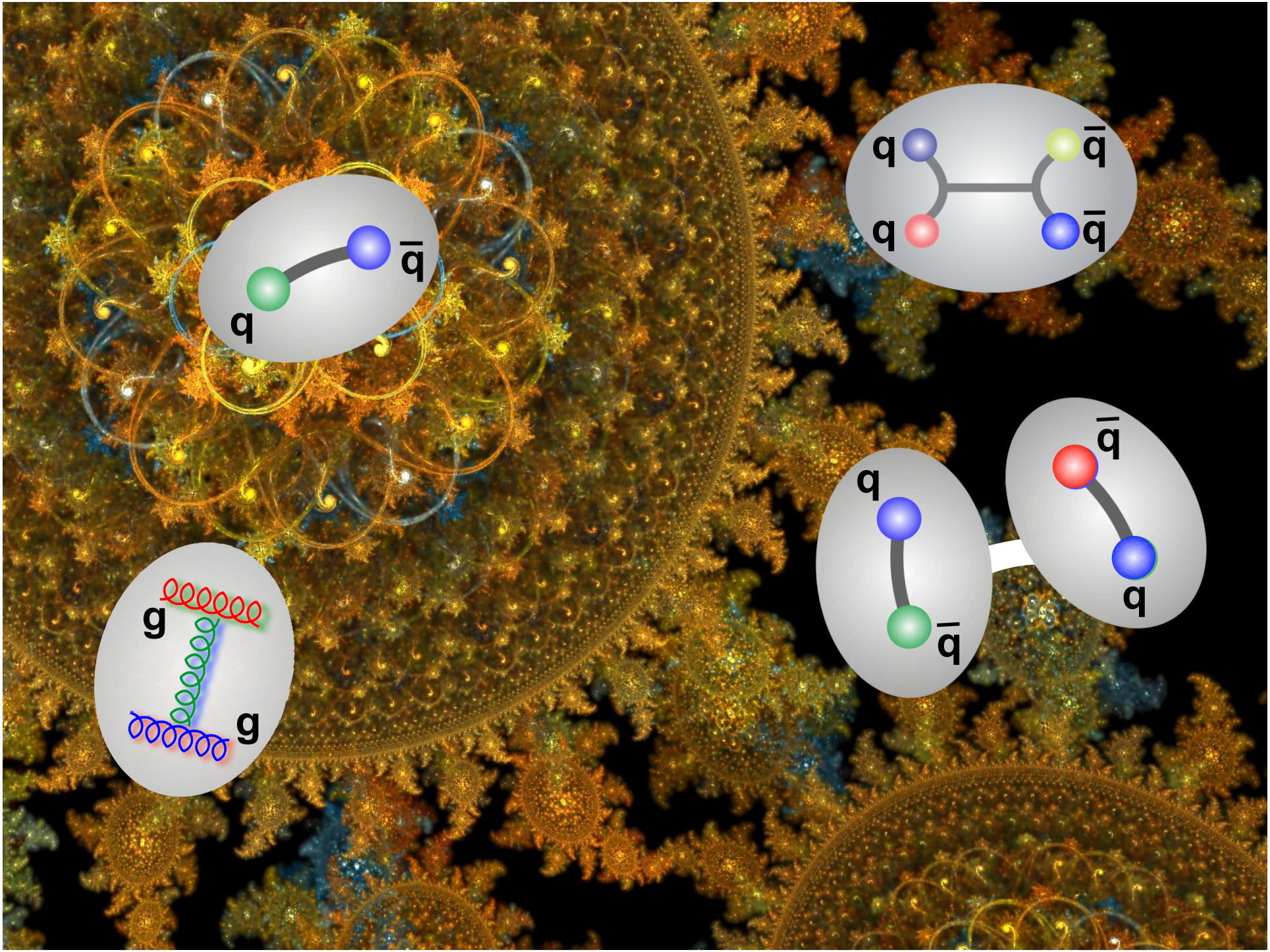


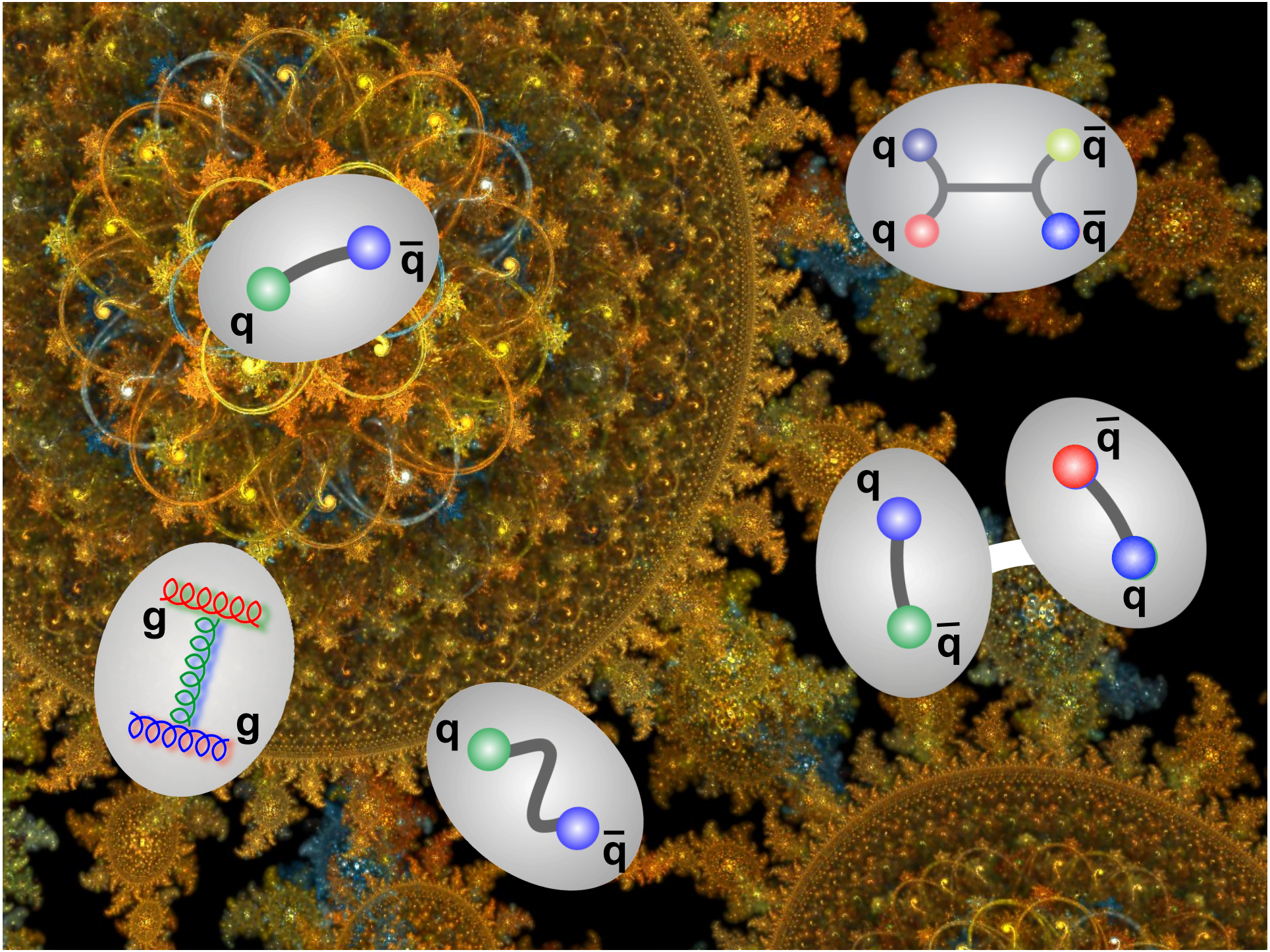

q
$\bar{q}$
q
q
q


q
$\bar{q}$
q
q
q

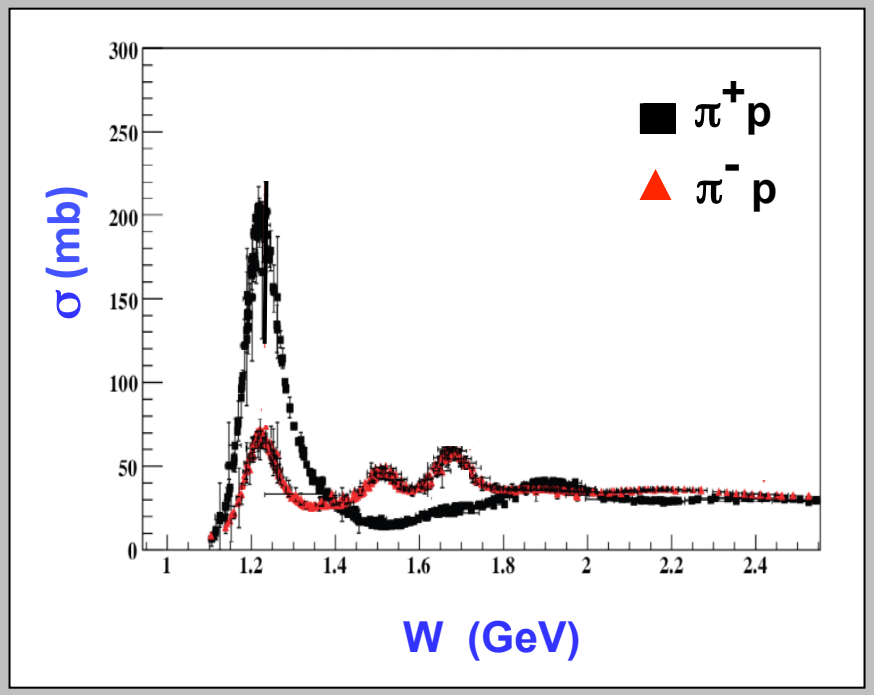

q
$\bar{q}$
g
g

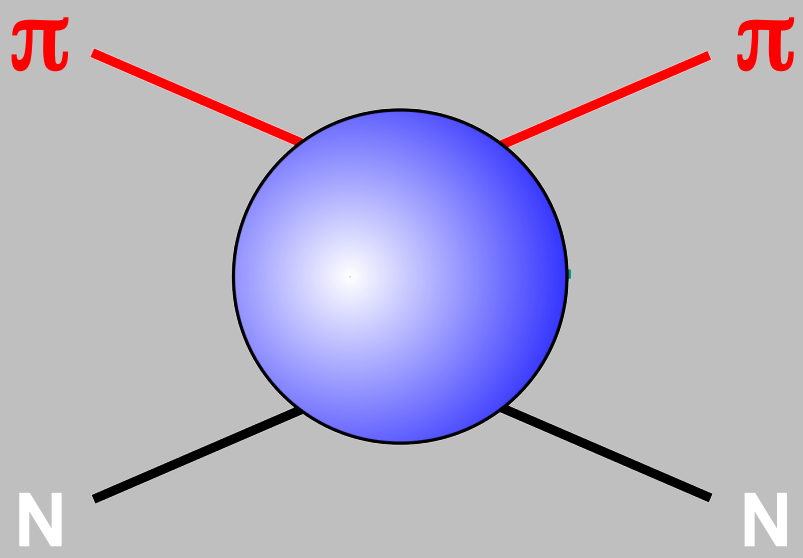

q
q̄
q
q̄
q̄
g
g


q
q̄
q
q̄
q̄
q
q̄
q
g
g

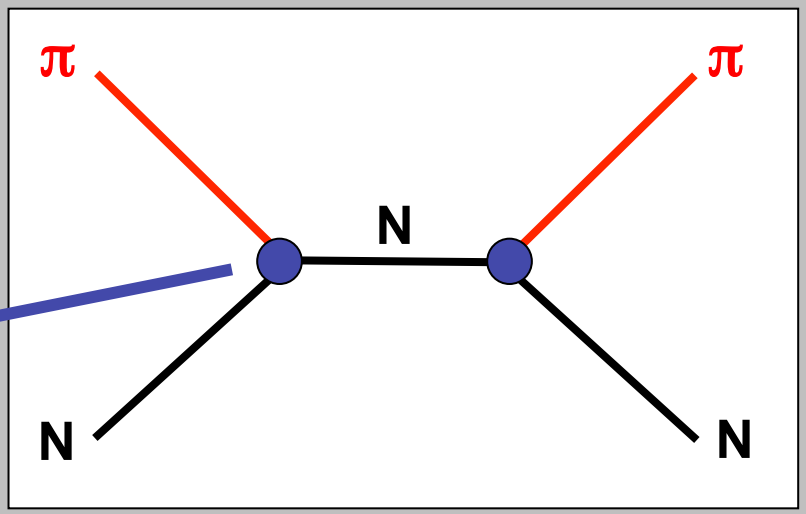

q
q̄
q
q̄
q̄
q
q̄
q
g
g
q
q̄

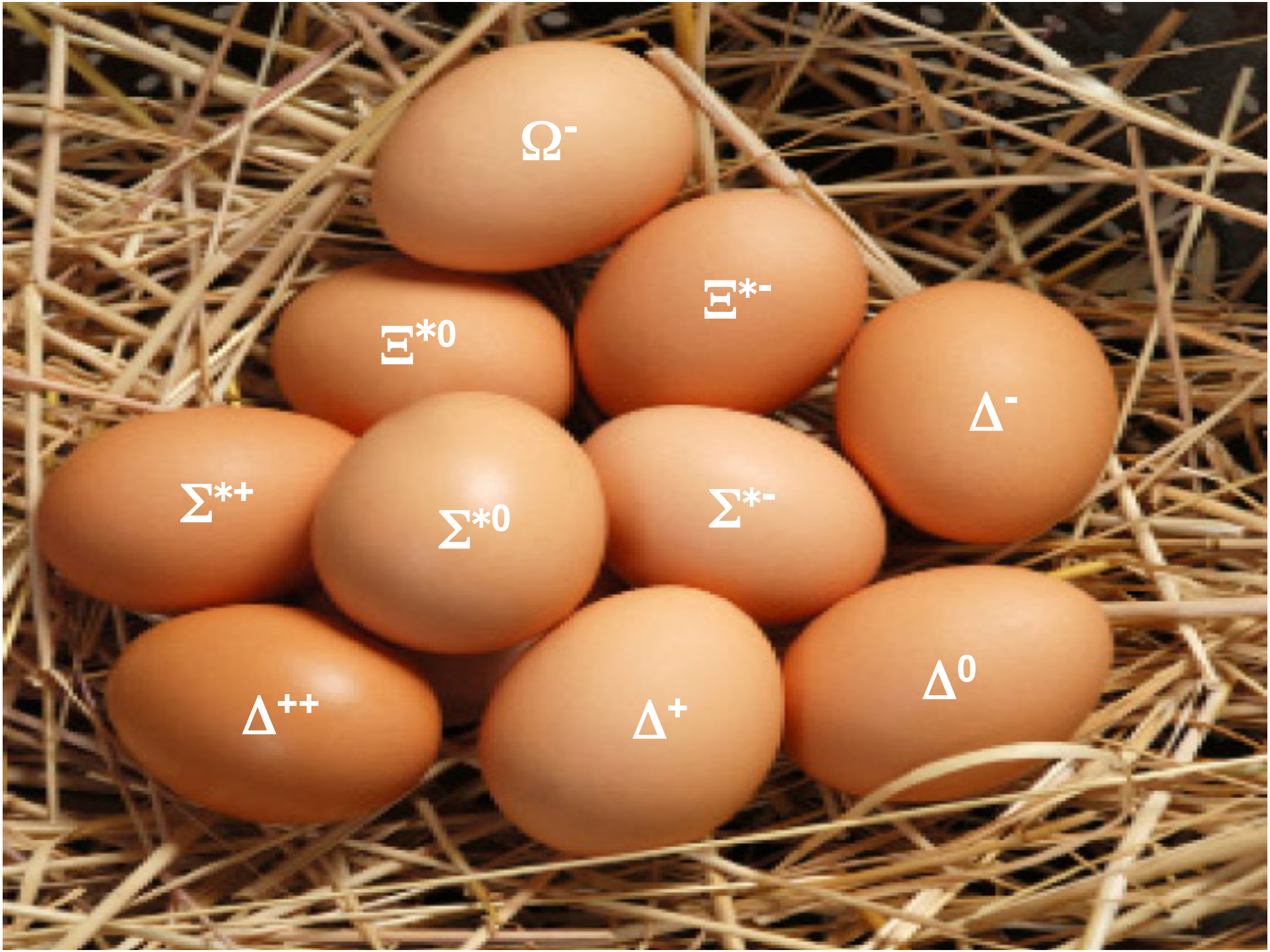
πN scattering



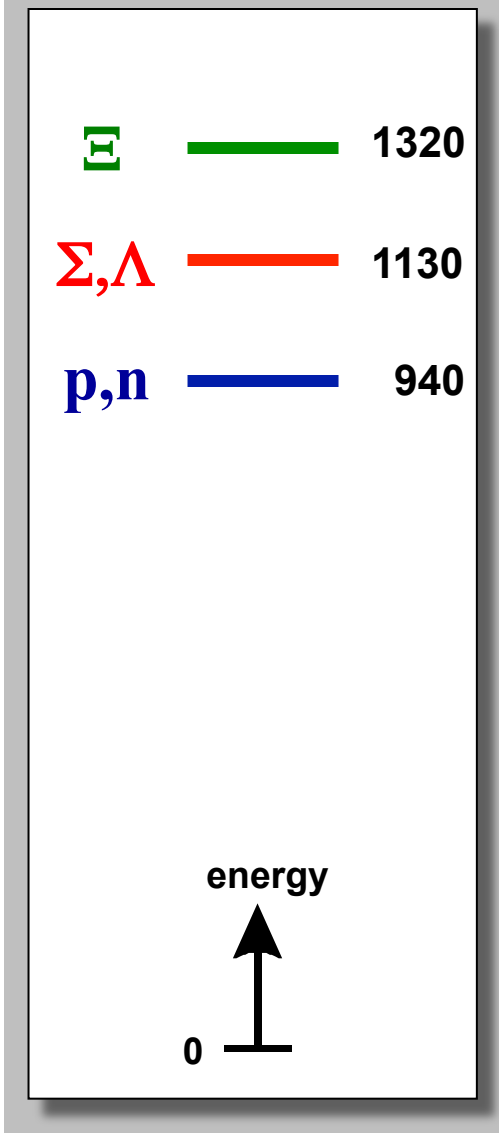


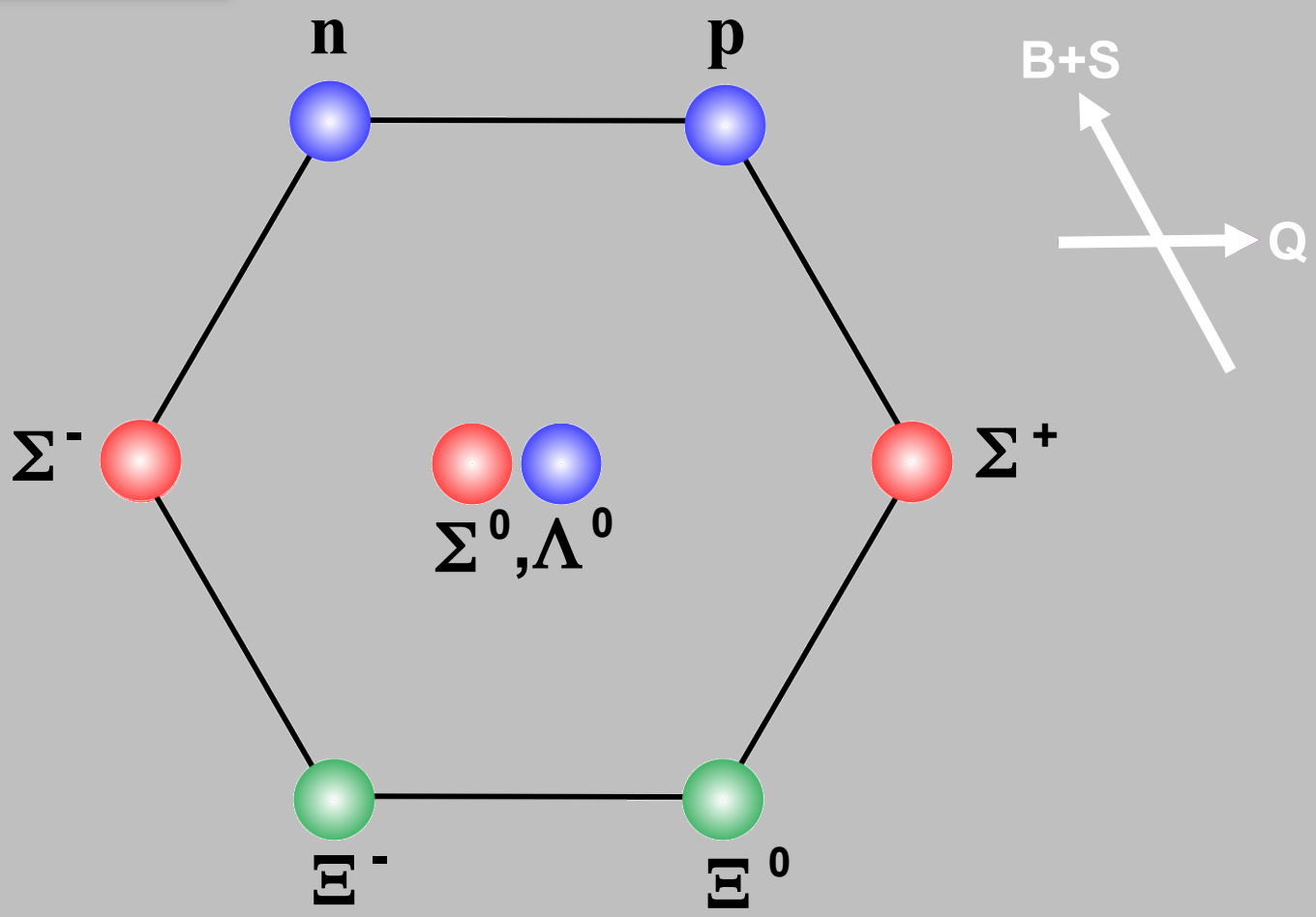
$$\frac{g^2_{\pi NN}}{4\pi} \simeq 14$$




Ω^-
Ξ^{*-}
Ξ^{*0}
Δ^-
Σ^{*+}
Σ^{*0}
Σ^{*-}
Δ^{++}
Δ^+
Δ^0

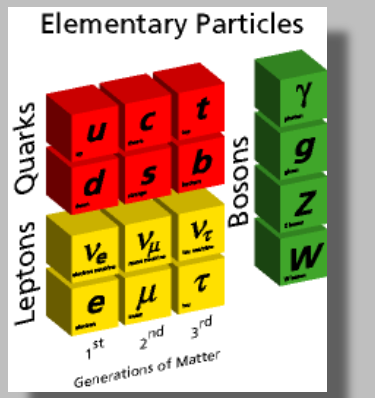
Baryon octet





Ground States

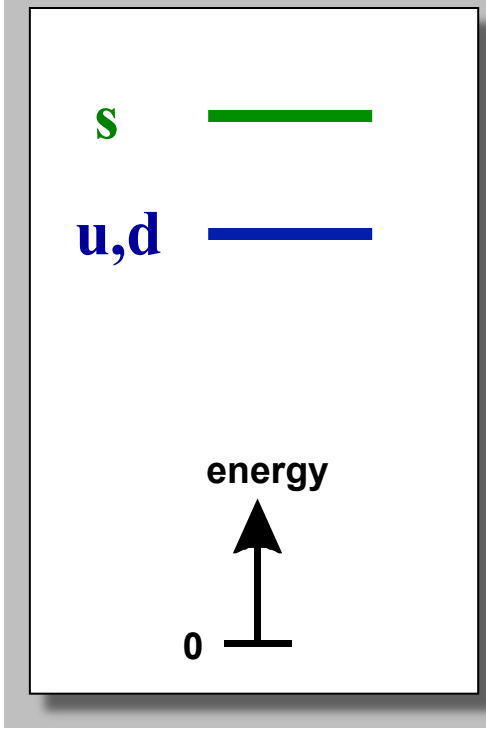
Baryon octet



udd uud

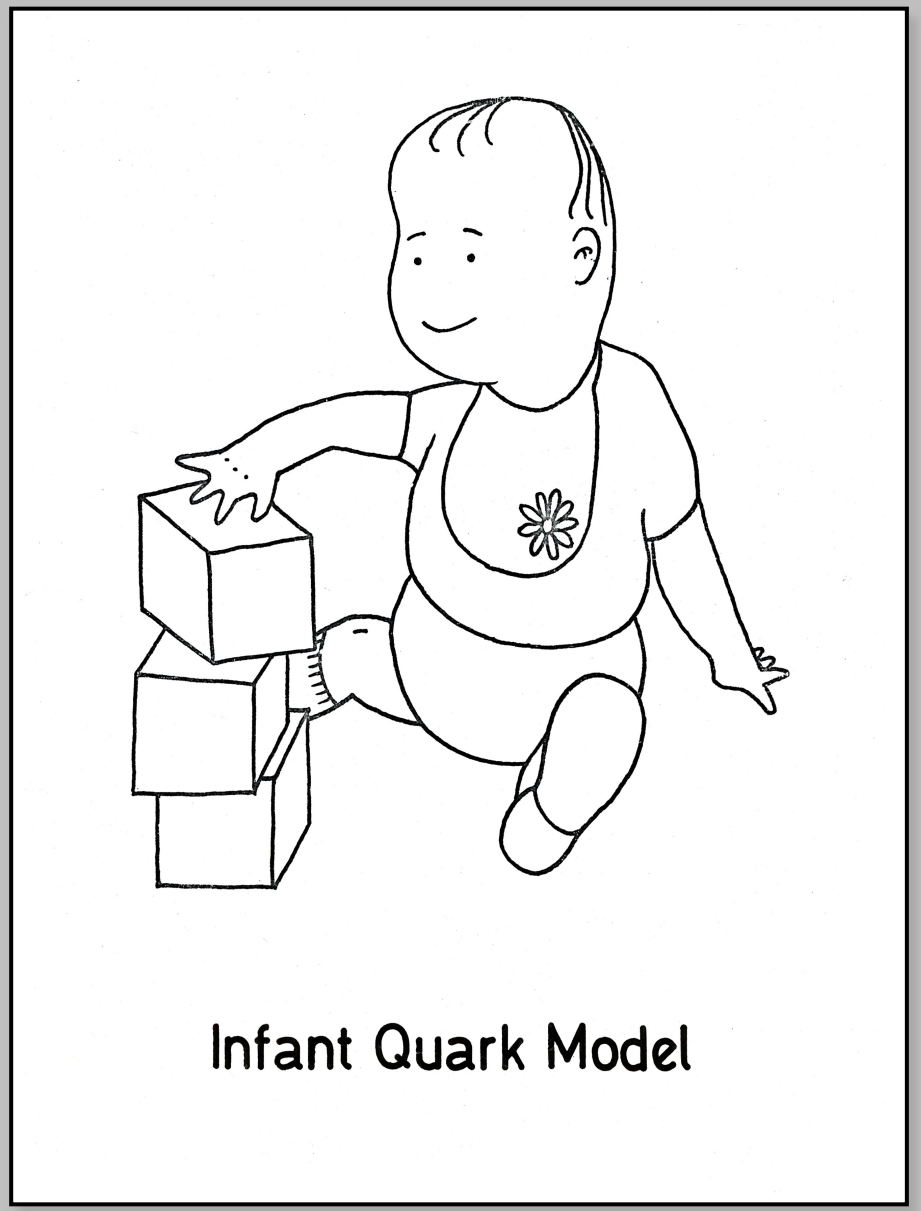
dds uds uus

dss uss

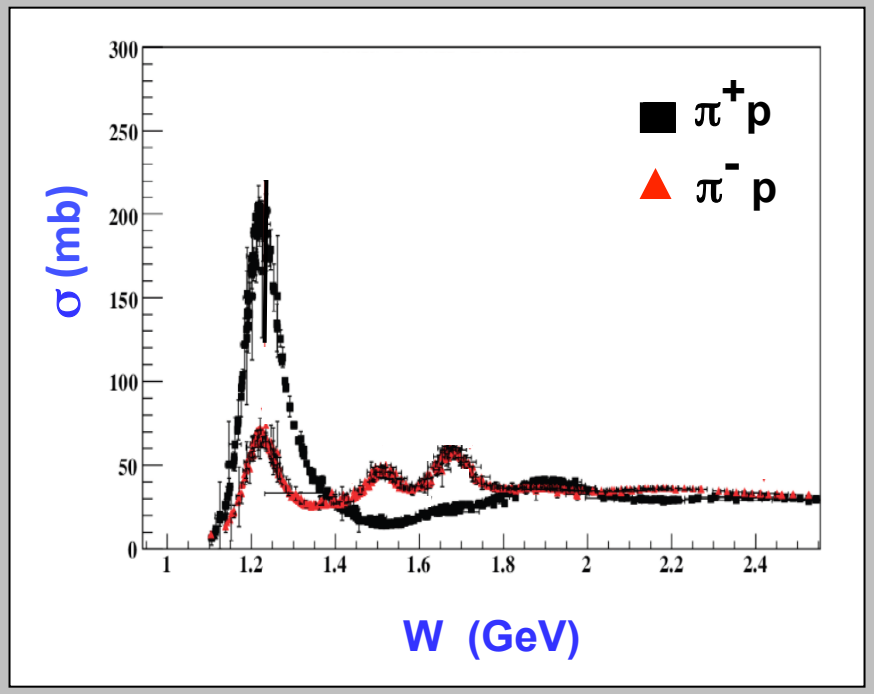


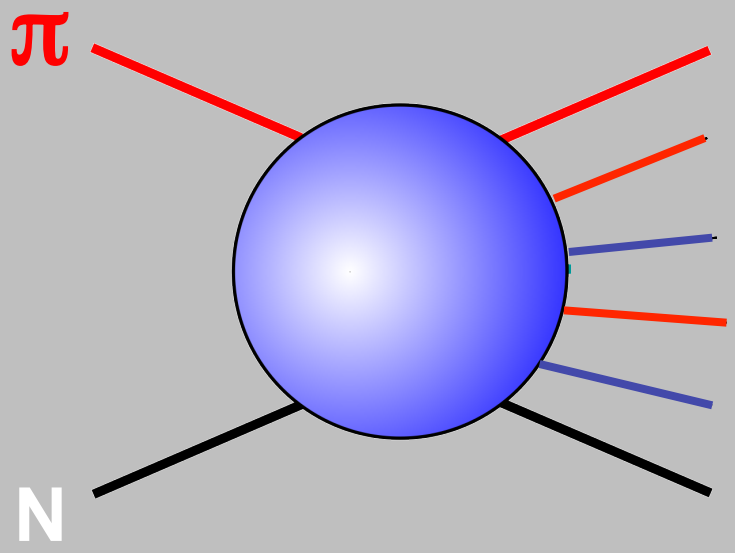
Ground States

Quark model



Strong Nuclear Force : 10

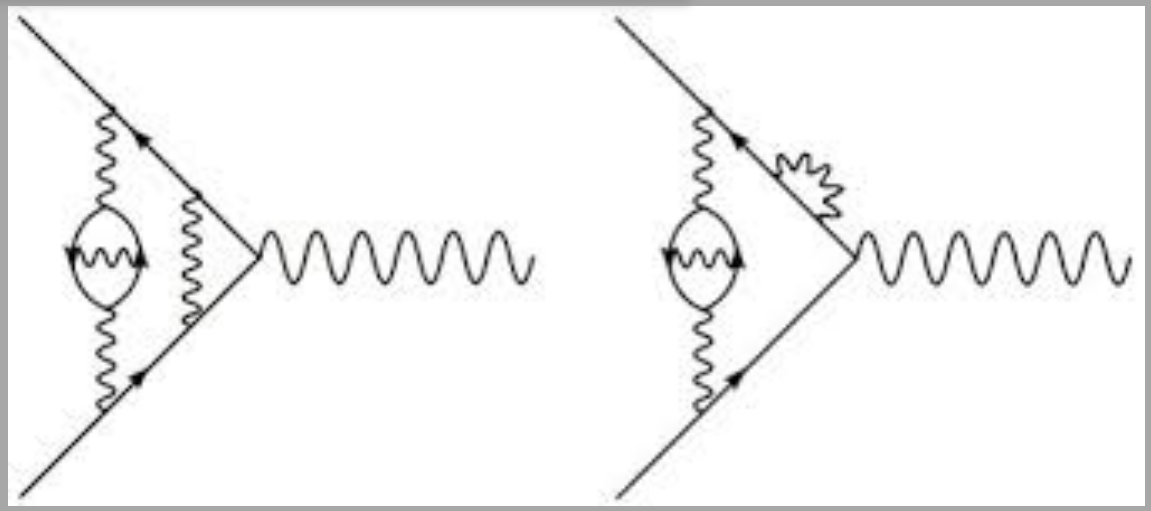




$$\frac{g^2_{\pi NN}}{4\pi} \simeq 14$$

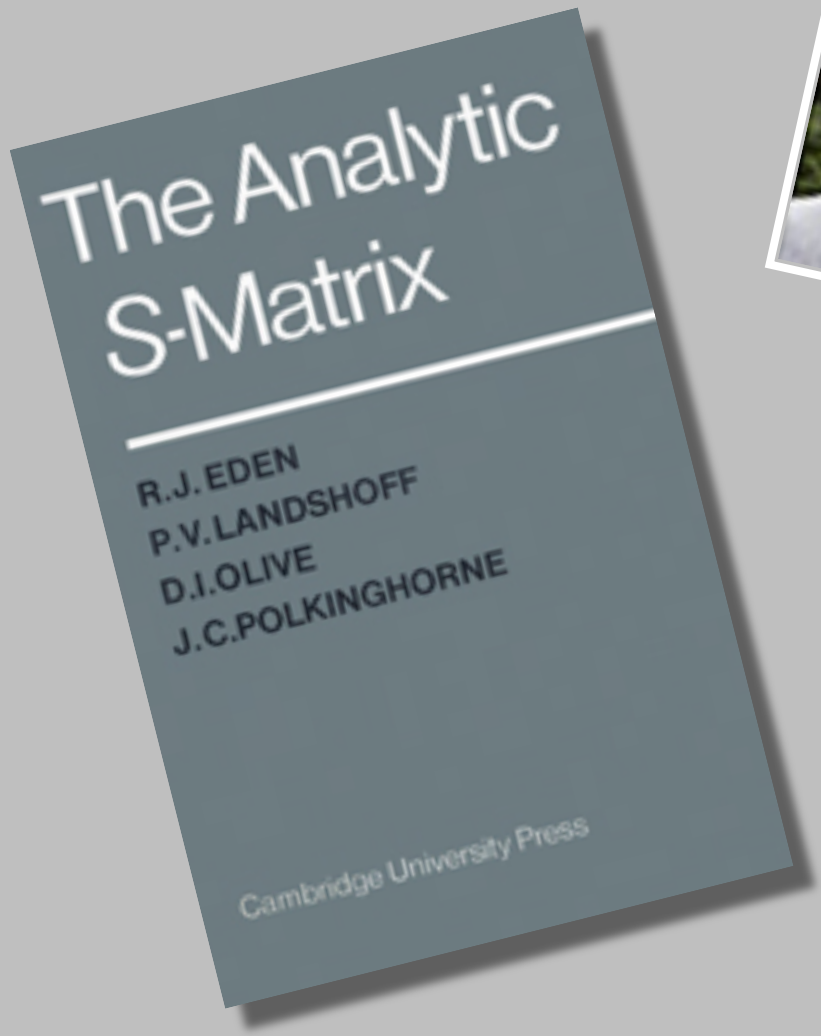
Electromagnetism: QED 10^{-2}

$$\frac{e^2}{4\pi} = \frac{1}{137}$$



$$\mathcal{L}_{QED} = \bar{\psi}\,(i \gamma_\mu D^\mu - m)\,\psi - \frac{1}{4} \mathcal{F}^{\mu\nu} \mathcal{F}_{\mu\nu}$$


Richard Eden

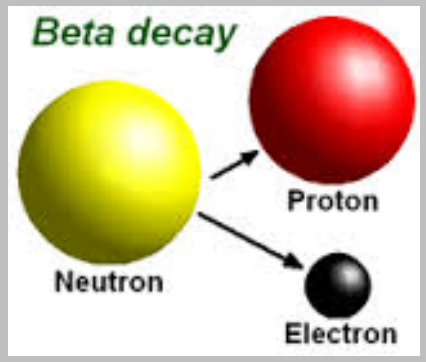

The Analytic S-Matrix
R.J. EDEN
P.V. LANDSHOFF
D.I. OLIVE
J.C. POLKINGHORNE
Cambridge University Press

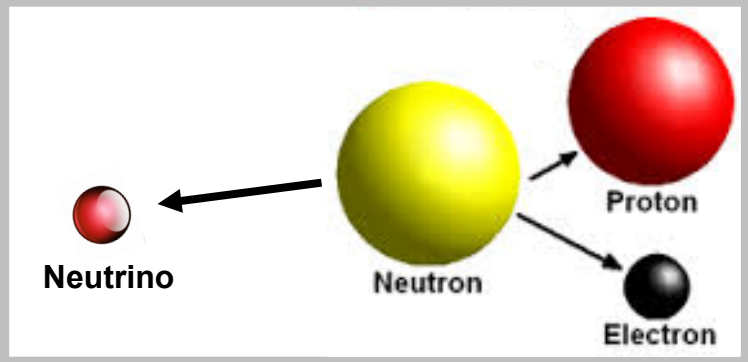

Peter Landshoff

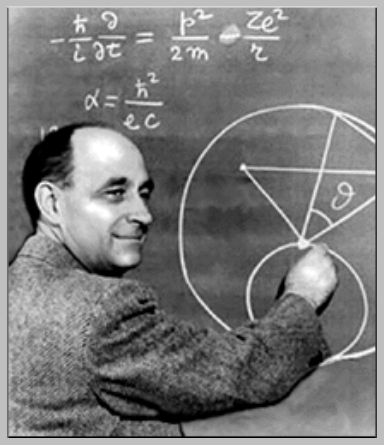

David Olive

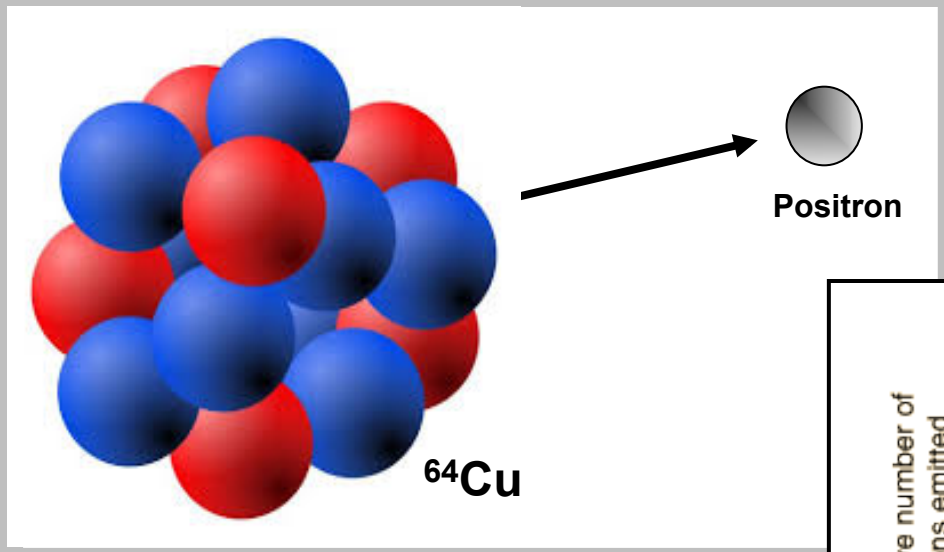

John Polkinghorne

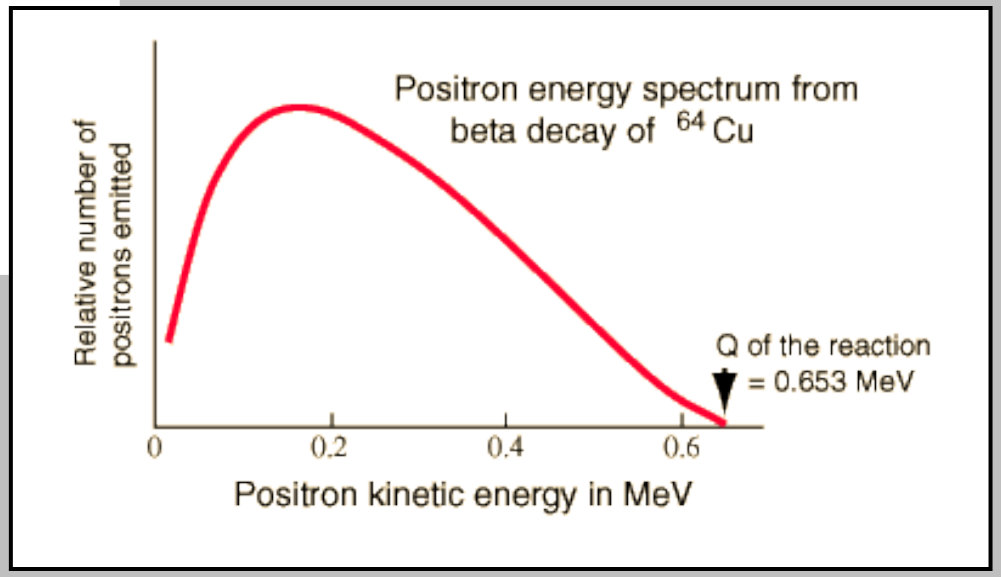
STANDARD MODEL OF ELEMENTARY PARTICLES


Beta decay
Proton
Neutron
Electron


Neutrino
Neutron
Proton
Electron

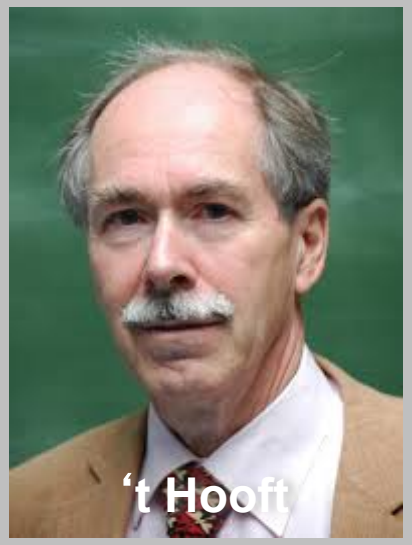


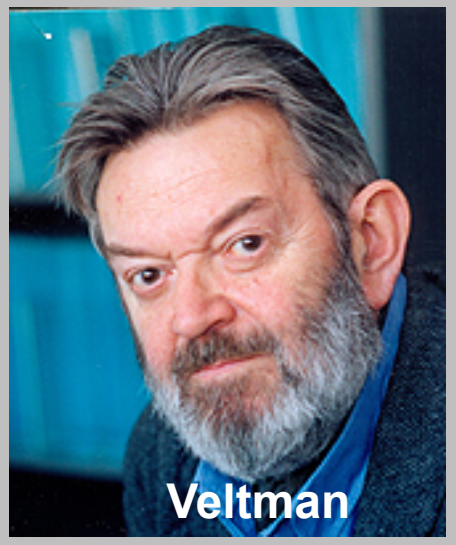

Positron
64Cu


Positron energy spectrum from beta decay of 64 Cu
Relative number of positrons emitted
Q of the reaction = 0.653 MeV
0
0.2
0.4
0.6
Positron kinetic energy in MeV

$G_F \sim 10^{-5}$

Non-Abelian gauge theories





Electroweak Lagrangian

SU(2) x U(1)

$$\mathcal{L}_{GWS} = \mathcal{L}_1 + \mathcal{L}_2 + \mathcal{L}_3$$

$$\mathscr{L}_1 = -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$\mathscr{L}_2 = i\bar{R}\gamma^\mu D_\mu R + i\bar{L}\gamma^\mu D_\mu L$$

$$\mathscr{L}_3 = D_\mu \phi^\dagger D^\mu \phi - m^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2 + G_e(\bar{L}\phi R + \bar{R}\phi^\dagger L)$$

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g f^{abc} W^b_\mu W^c_\nu$$

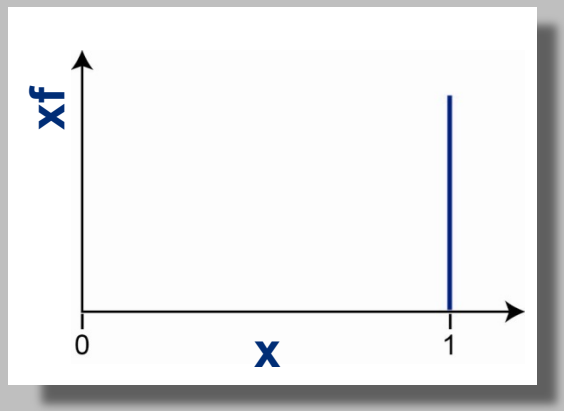
$$F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

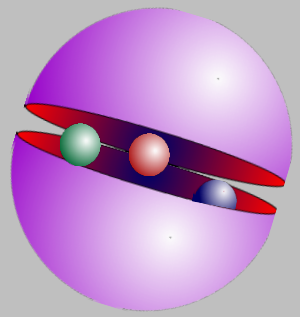
$$D_\mu R = (\partial_\mu + i g' B_\mu) R$$

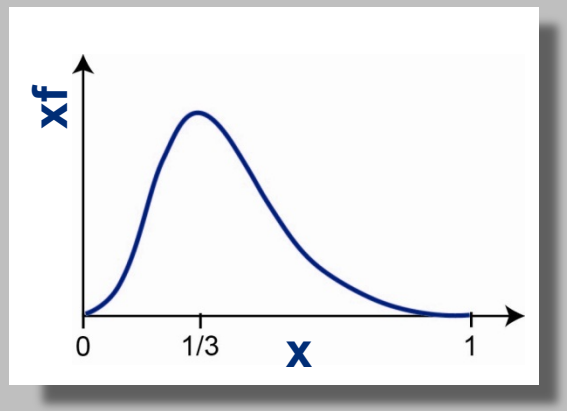
$$D_\mu L = \left[\partial_\mu + (i/2) g' B_\mu - (i/2) g \sigma_i W^i_\mu\right] L$$

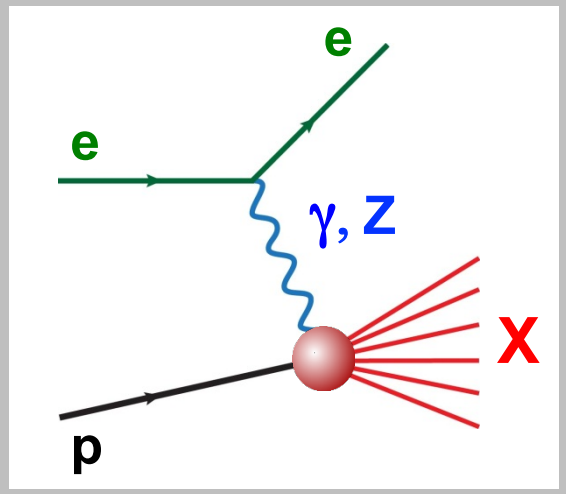
$$D_\mu \phi = \left[\partial_\mu - (i/2) g \sigma_i W^i_\mu - (i/2) g' B_\mu\right] \phi$$

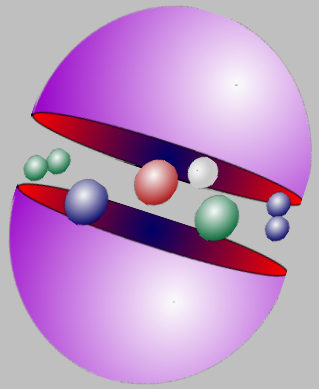
parton structure of the nucleon

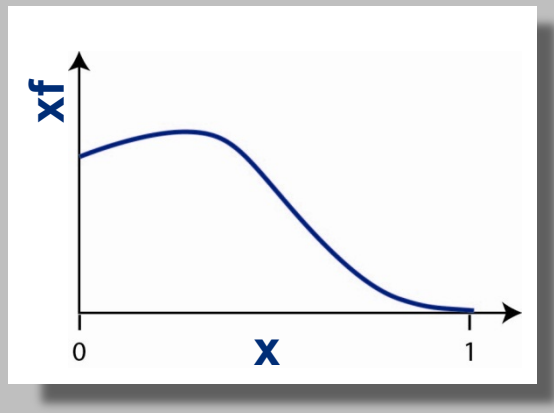




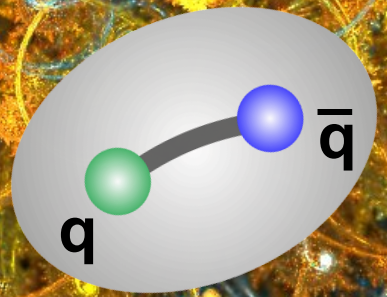


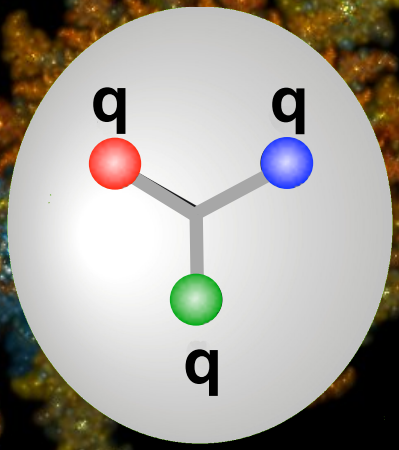






QCD Lagrangian

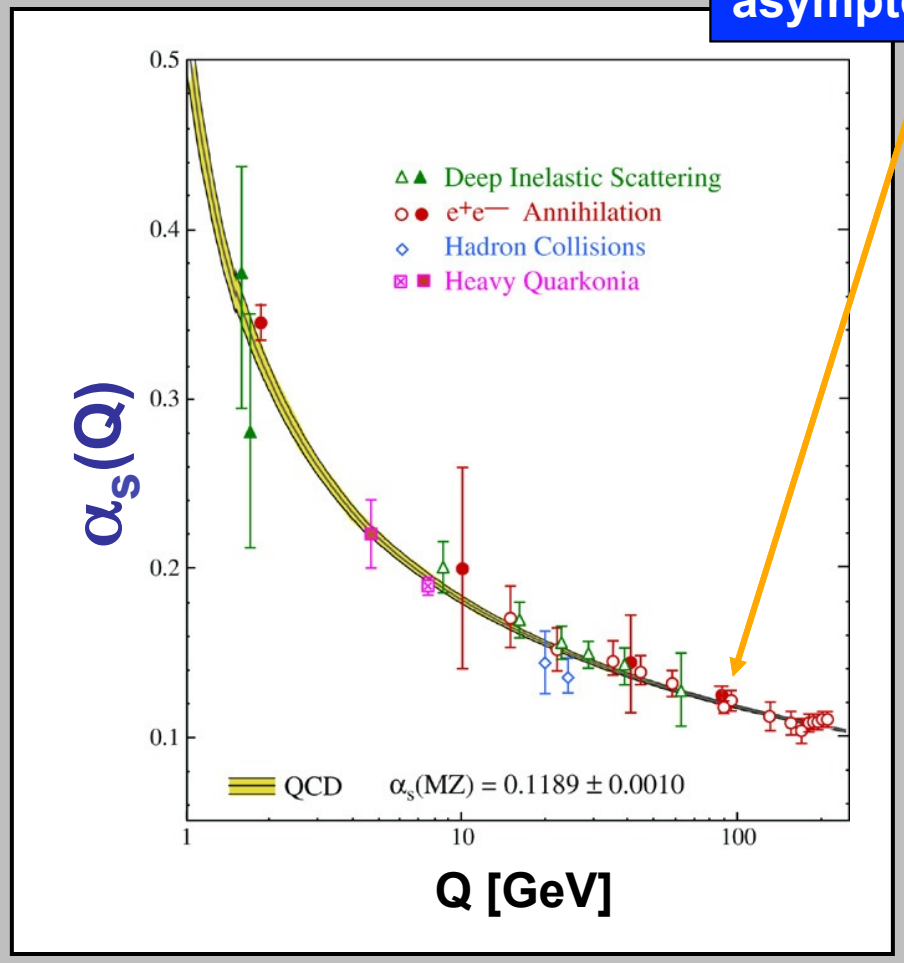


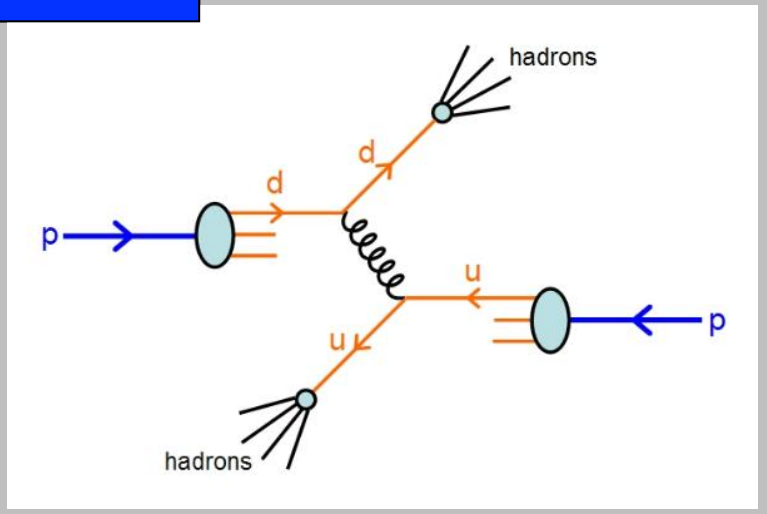


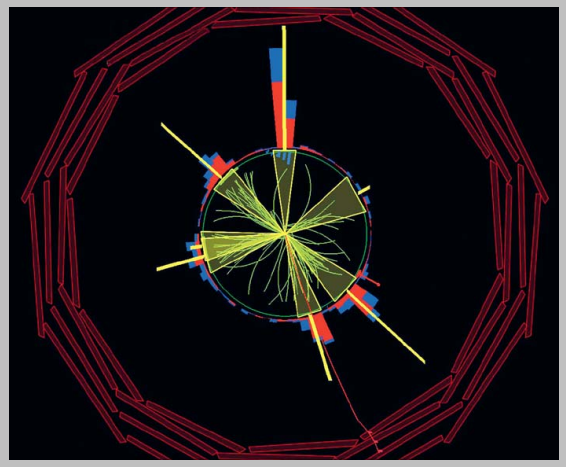
$$\mathcal{L}_{QCD} = \sum_{\substack{q=u,d,s,\\ c,b,t}} \bar{q} \left(i\gamma_\mu D^\mu - m_q \right) q \; - \frac{1}{4} \mathcal{F}^{\mu\nu} \mathcal{F}_{\mu\nu}$$

QCD coupling

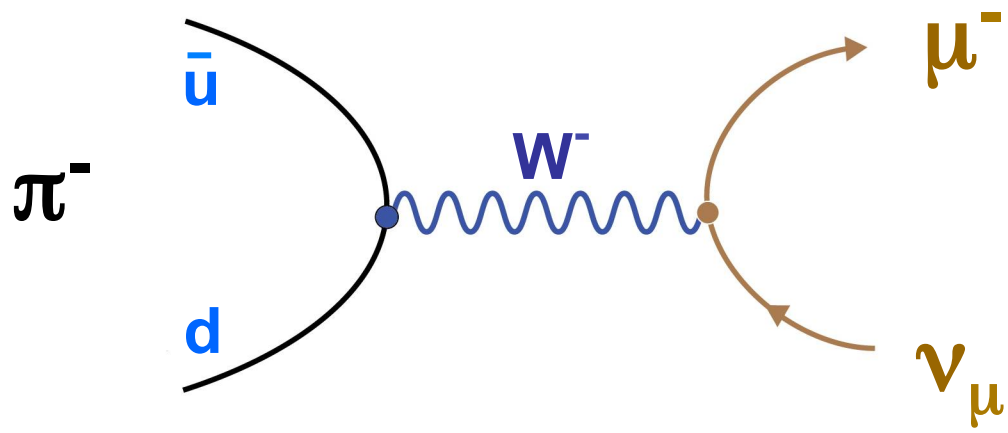
asymptotic freedom

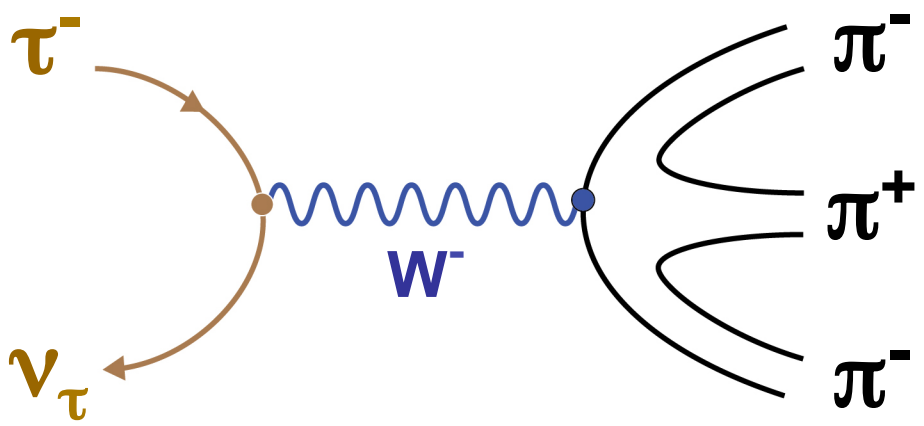




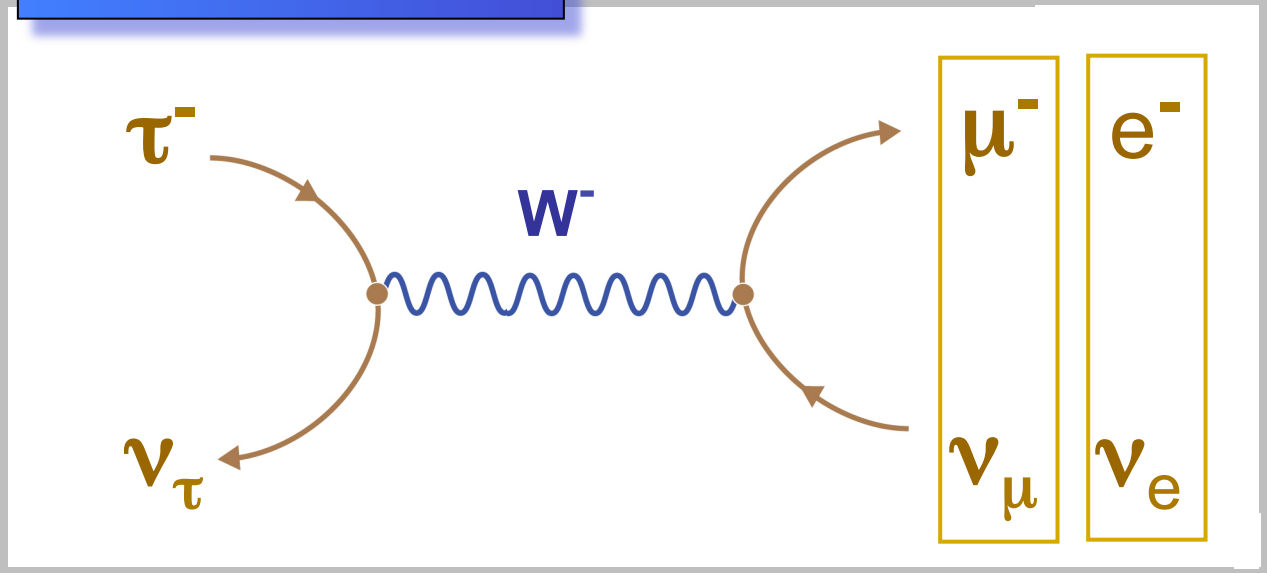


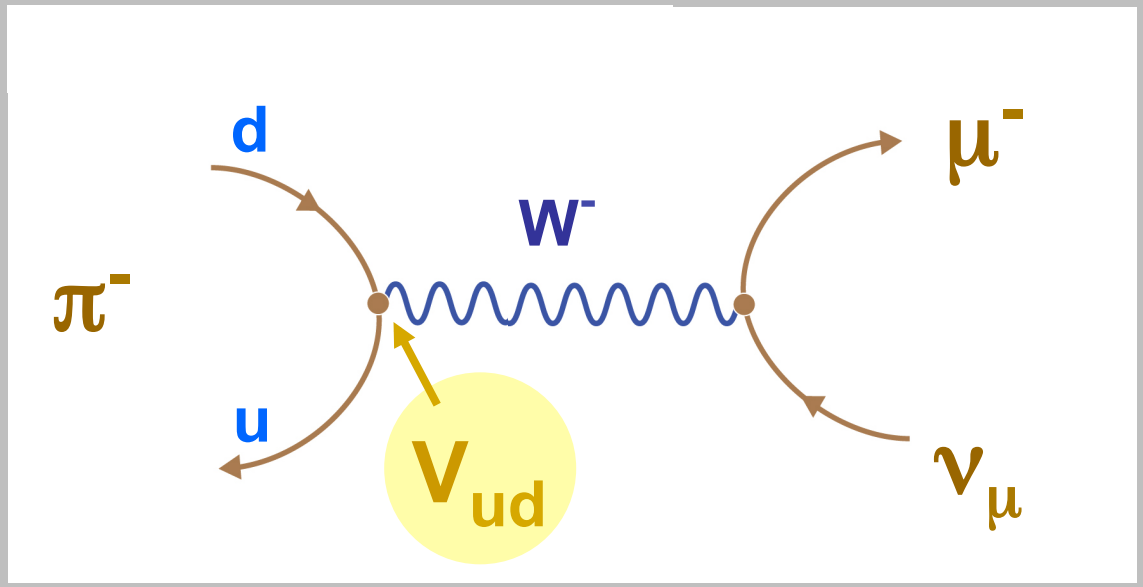
$\tau^- \longrightarrow \nu_\tau \pi\pi\pi$ decay





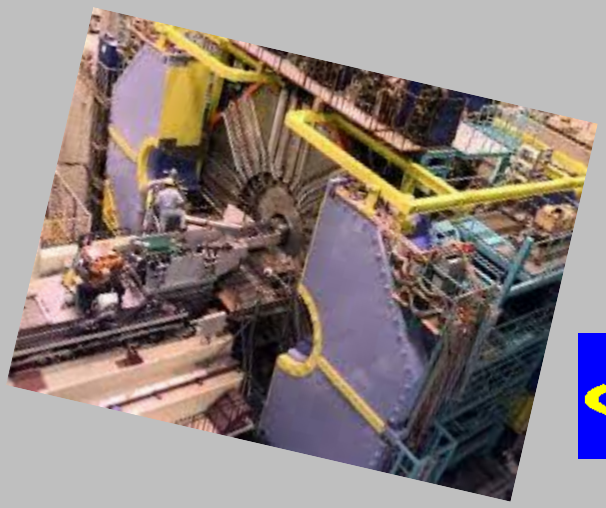
weak decays

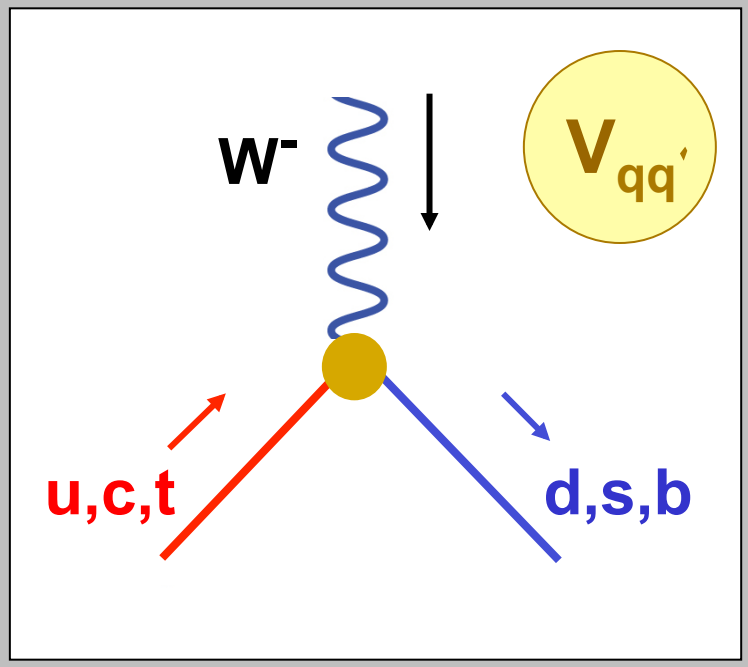




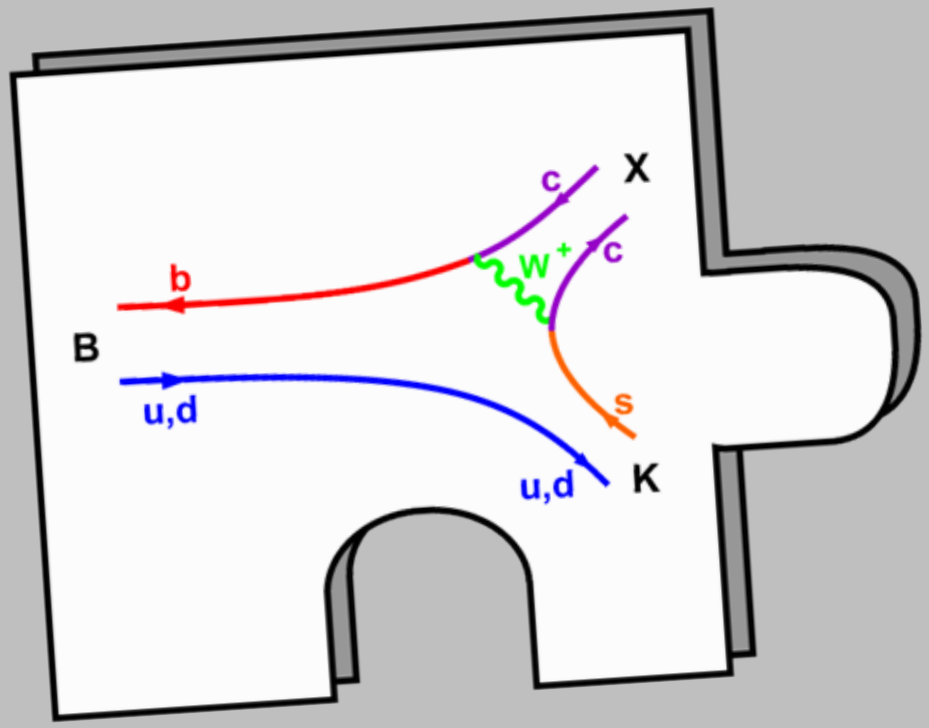
CKM matrix elements

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$



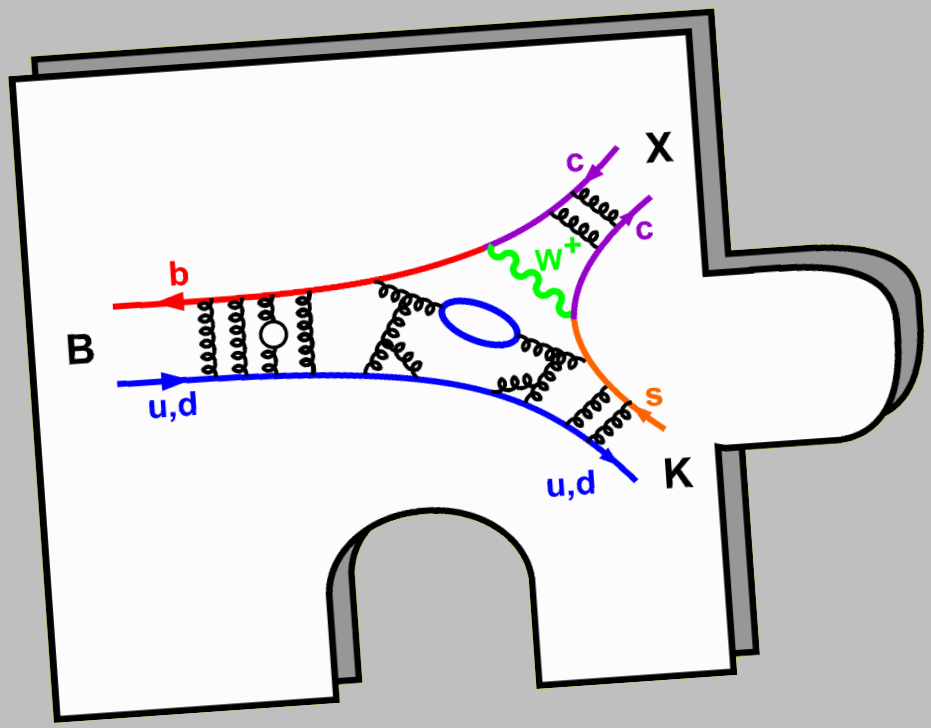


Physics Puzzle



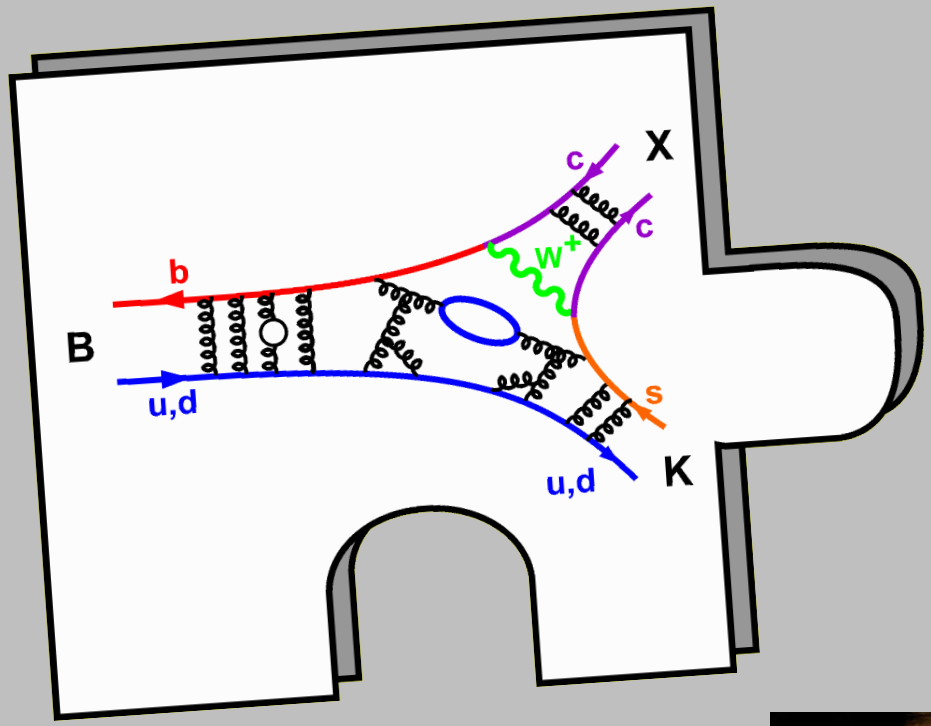
CP

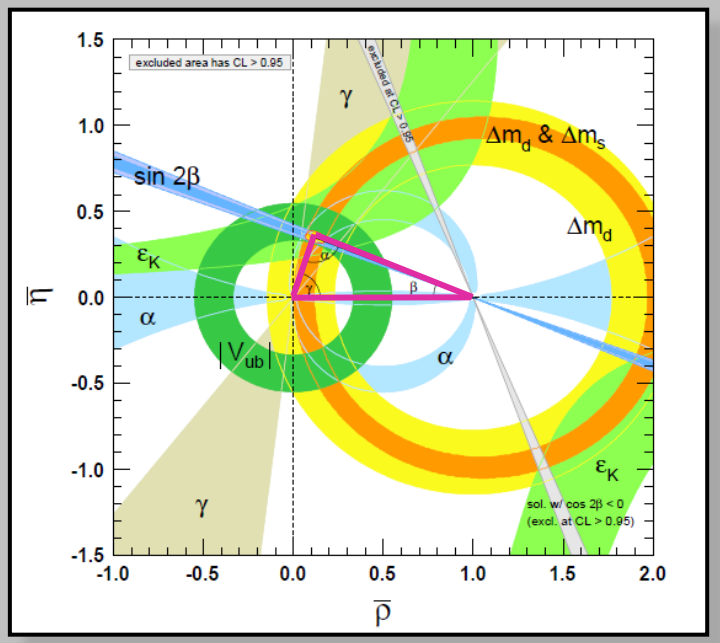
Physics Puzzle



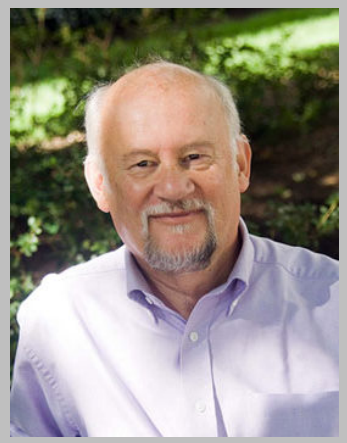
CP

CKM matrix elements

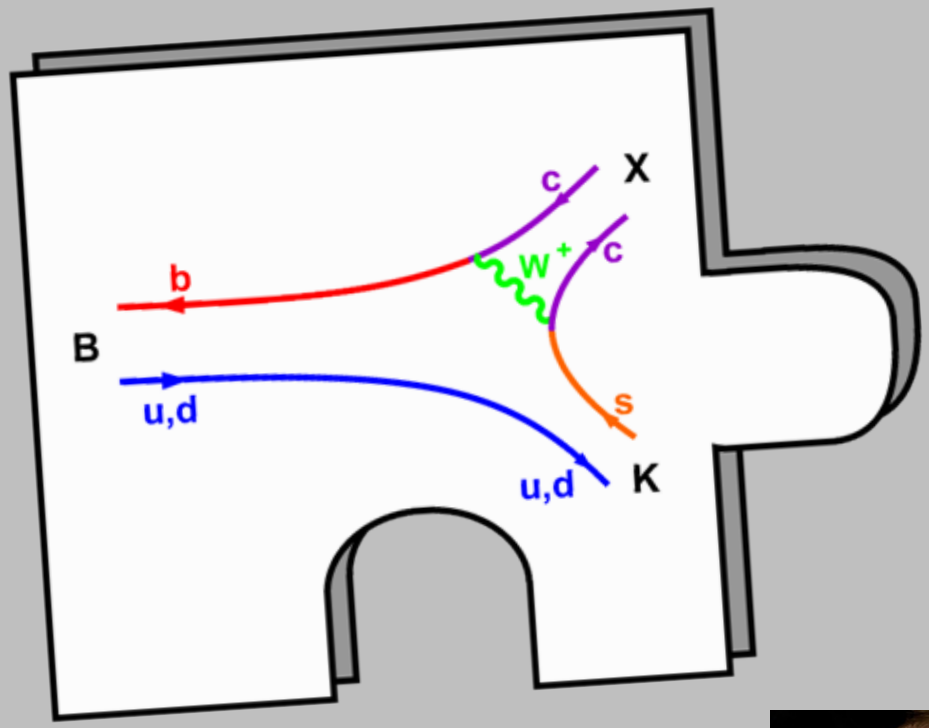


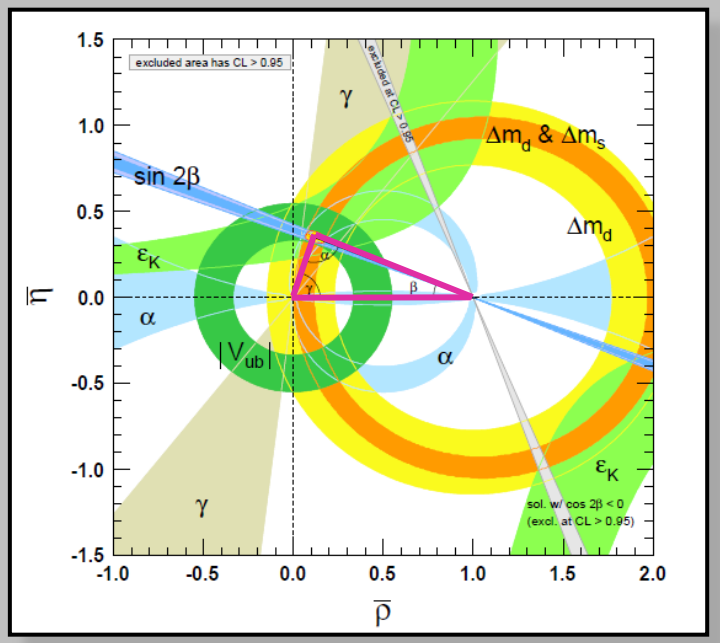


CP



CKM matrix elements





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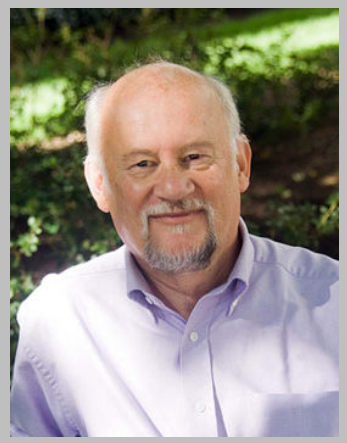
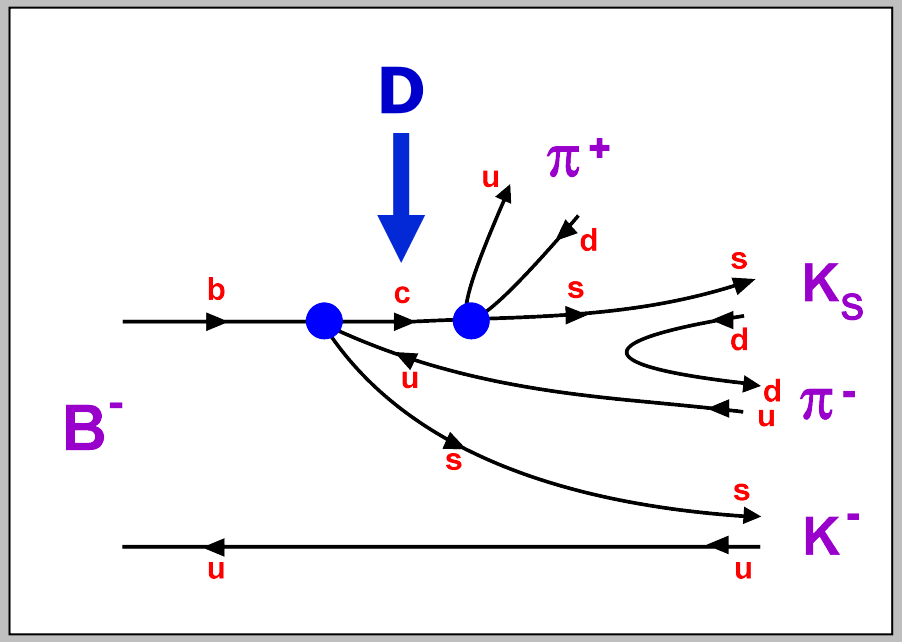
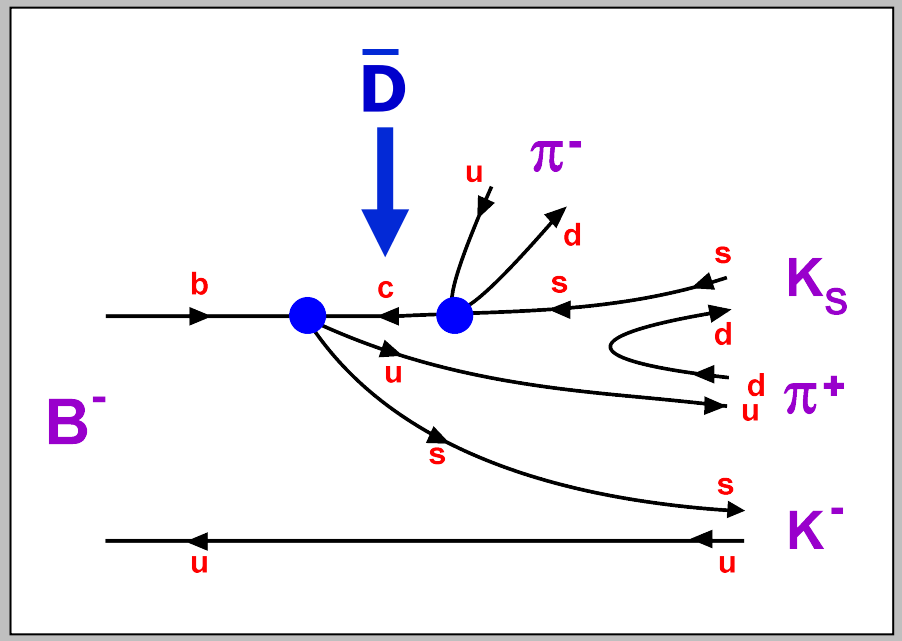


$B \to D\bar{K} \to \bar{K}K\pi\pi$



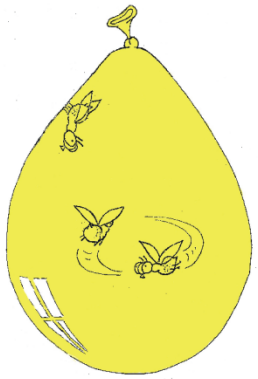
$B \to \bar{D}K \to \bar{K}K\pi\pi$



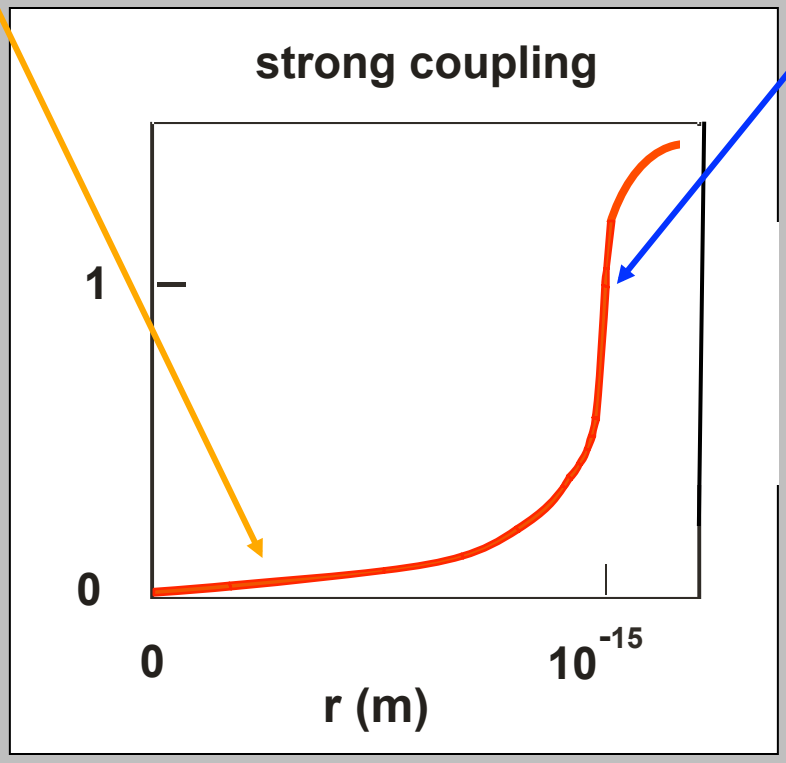
CP

QCD

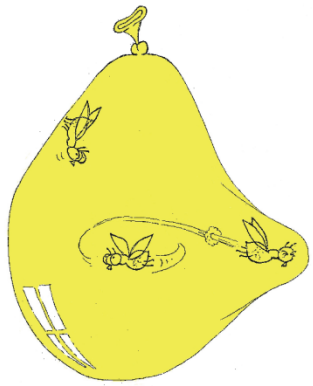
asymptotic freedom



pQCD

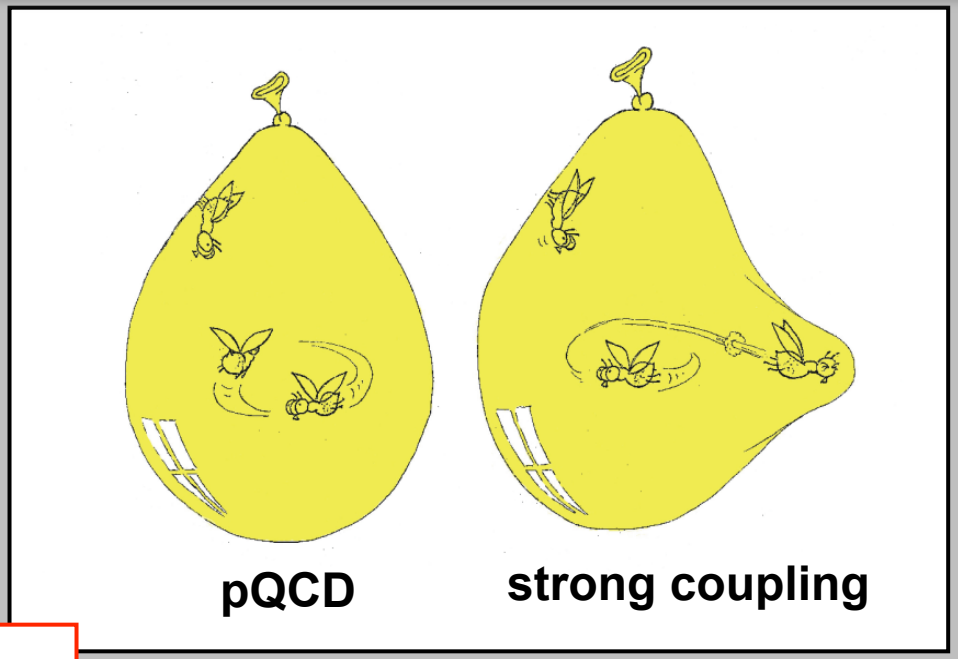


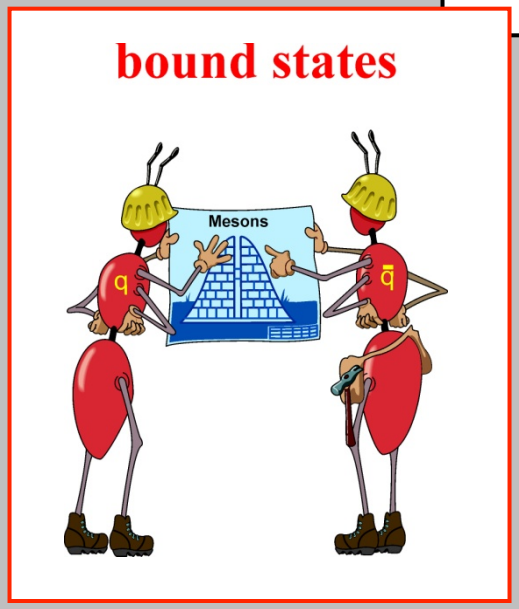
confinement

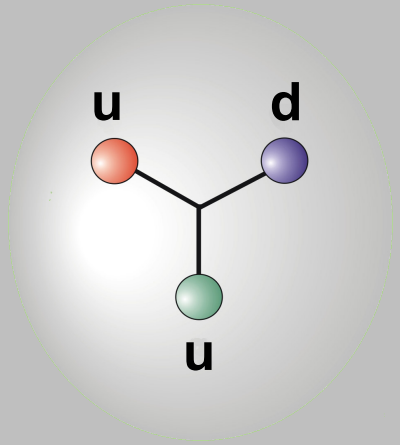


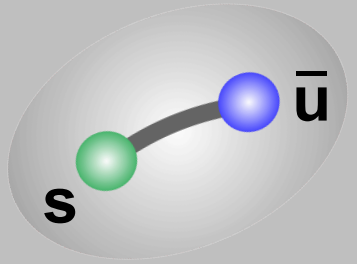
strong QCD

Strong physics problems





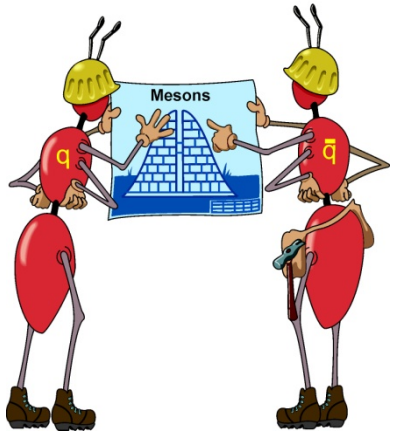




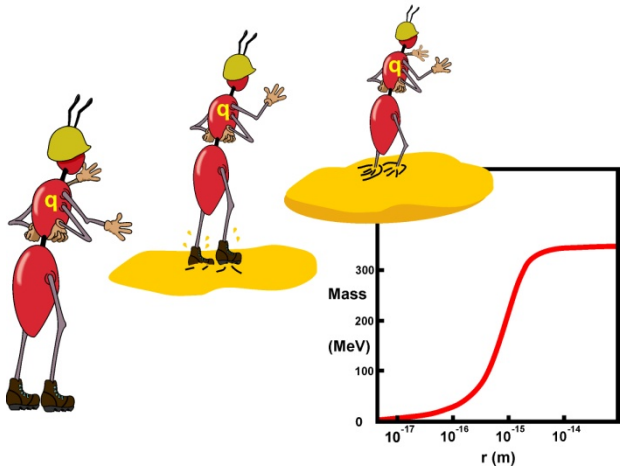
Strong physics problems

pQCD strong coupling

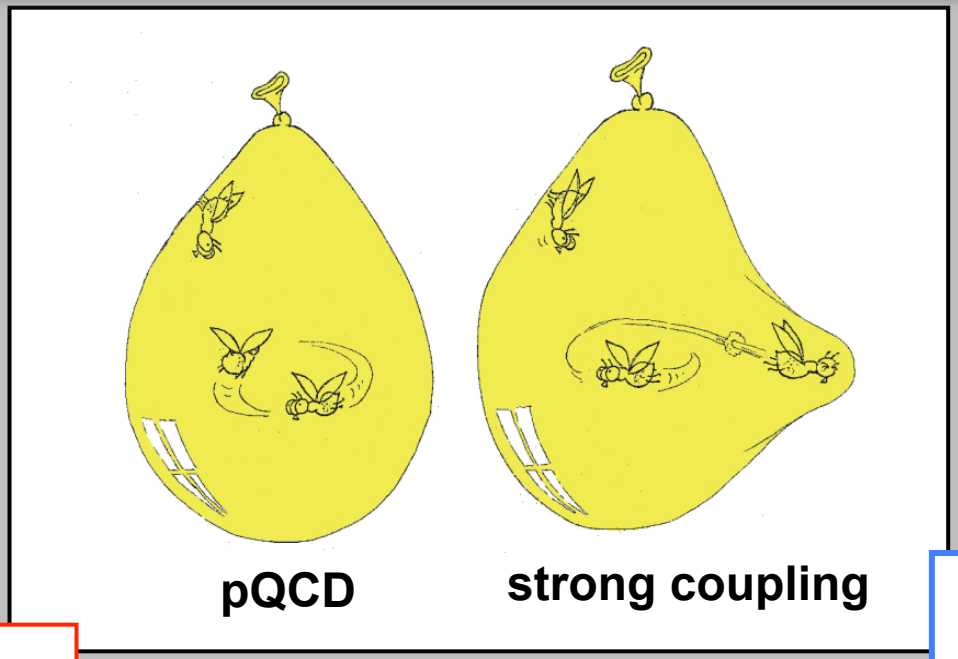
bound states



mass generation

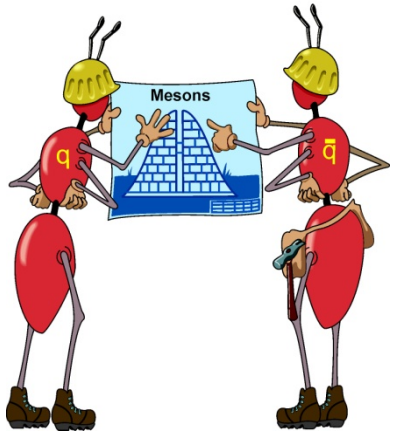


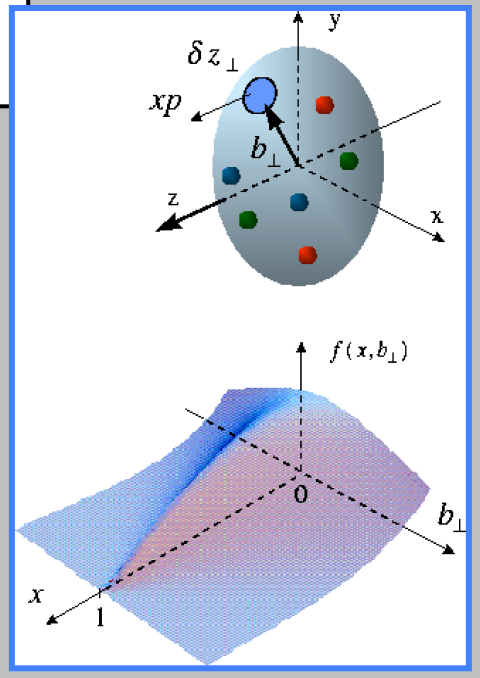
Strong physics problems



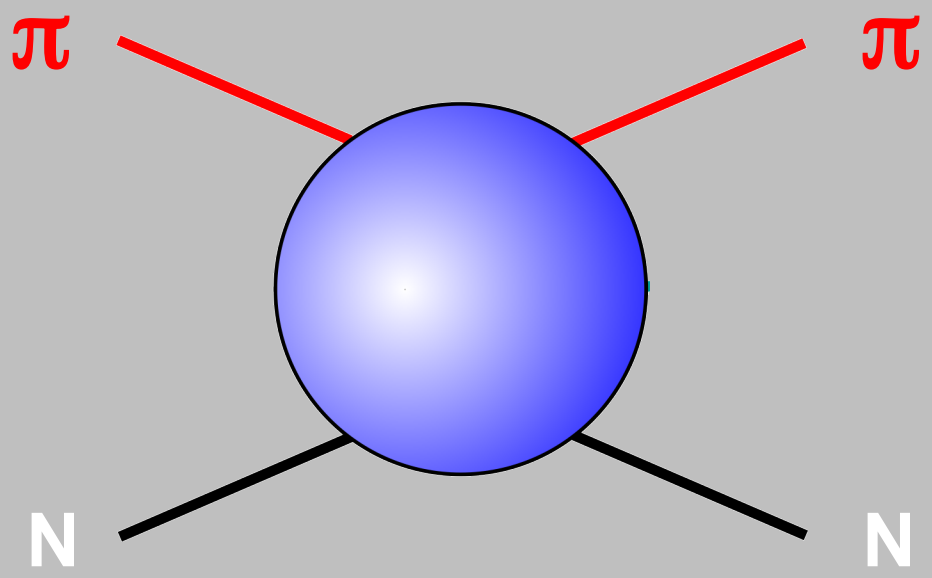
pQCD strong coupling

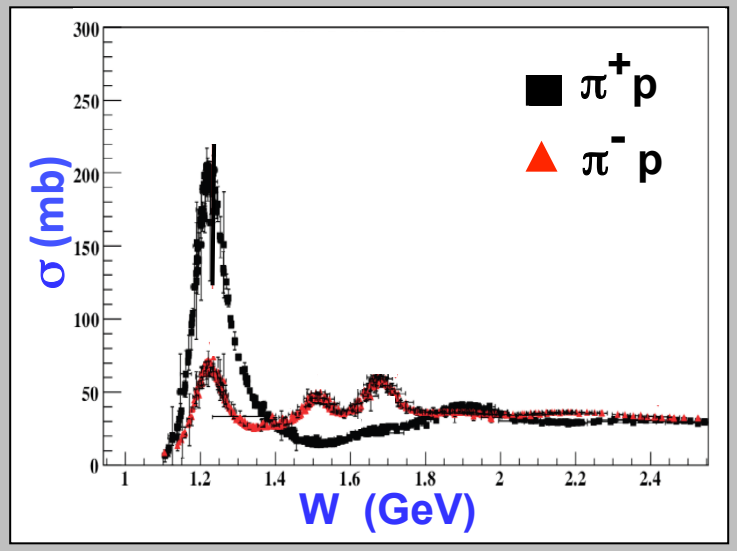
bound states

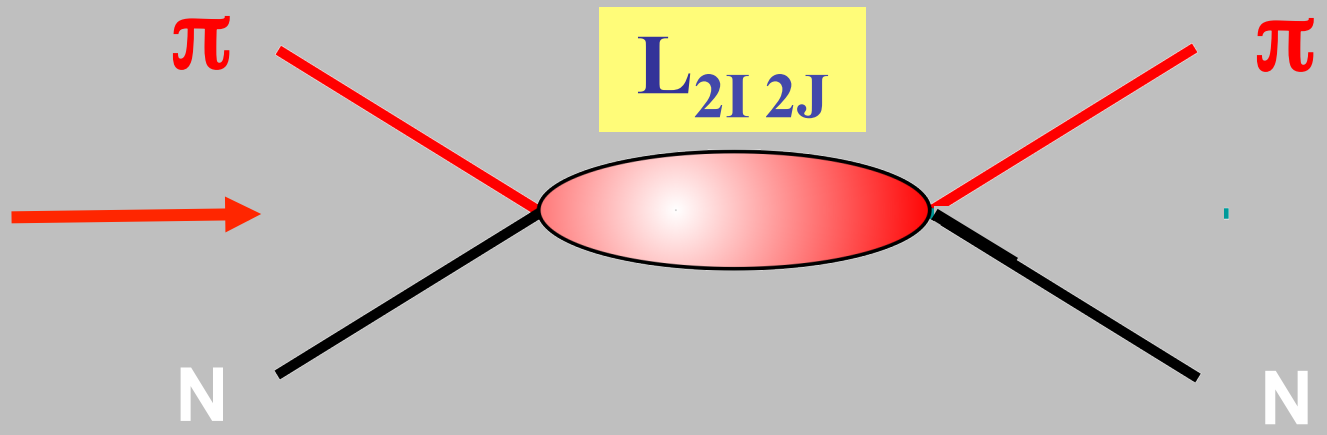




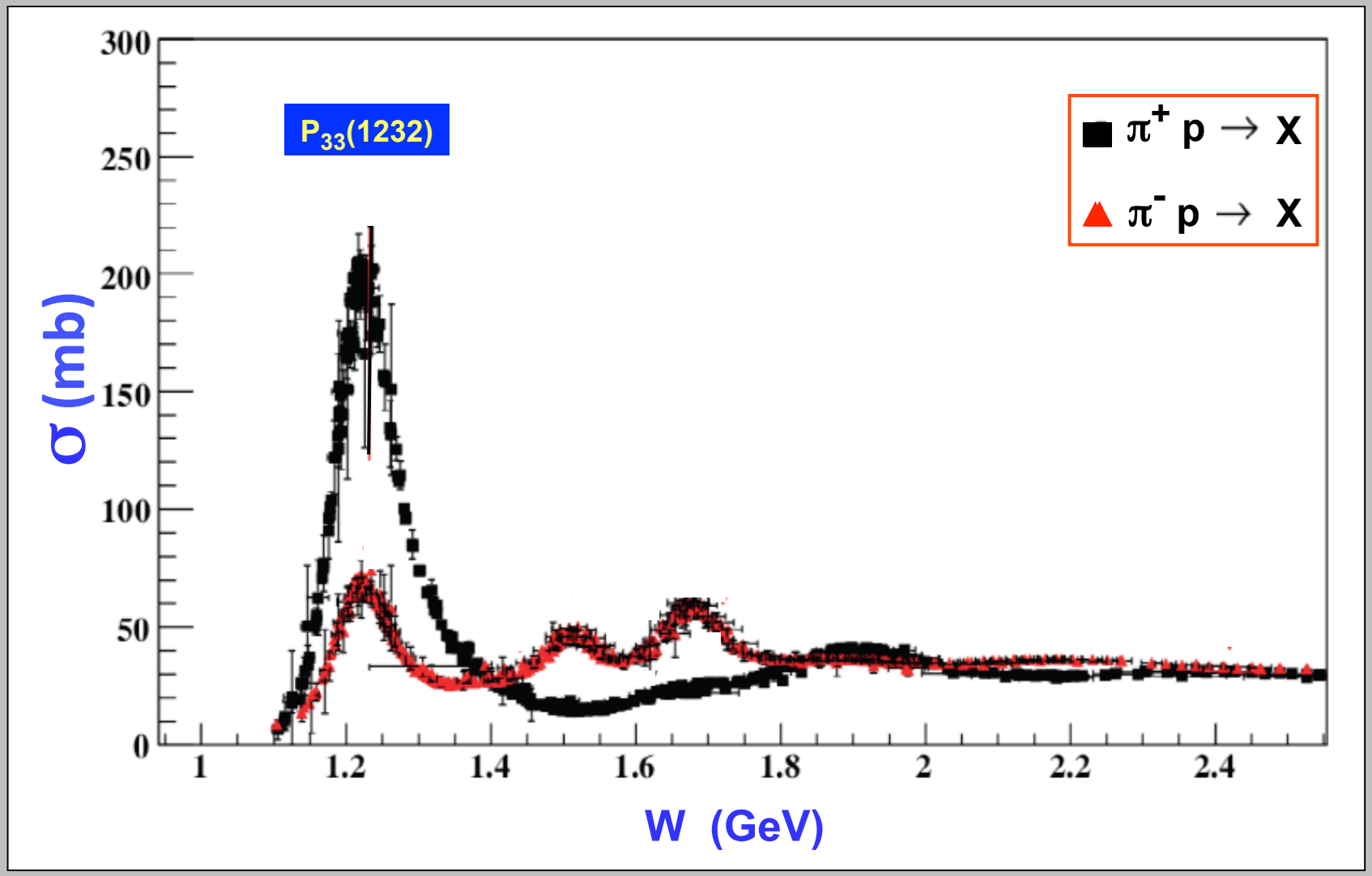
πN scattering



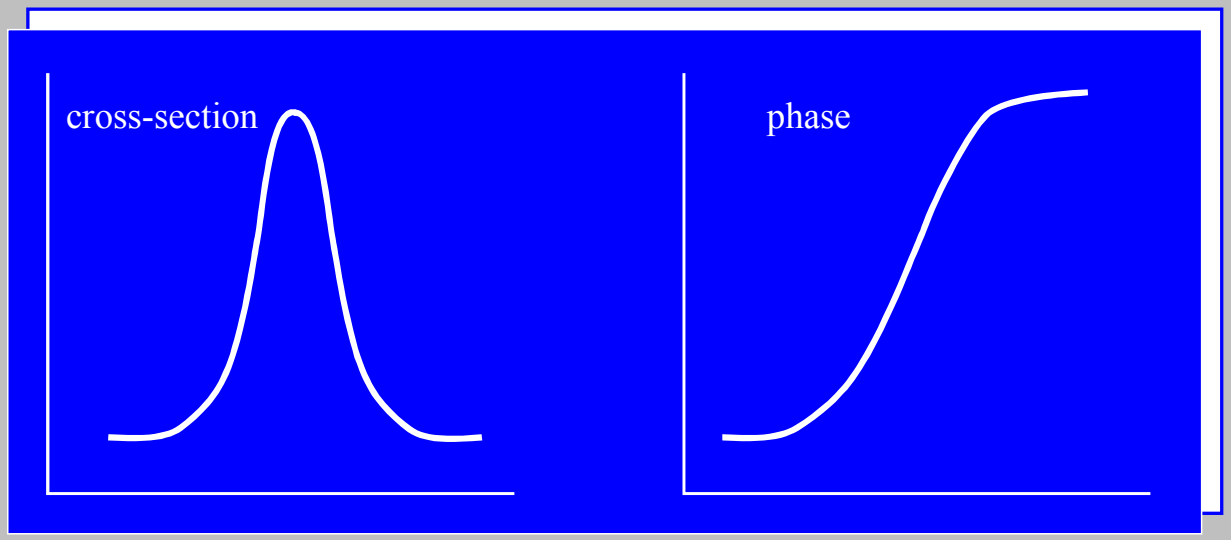


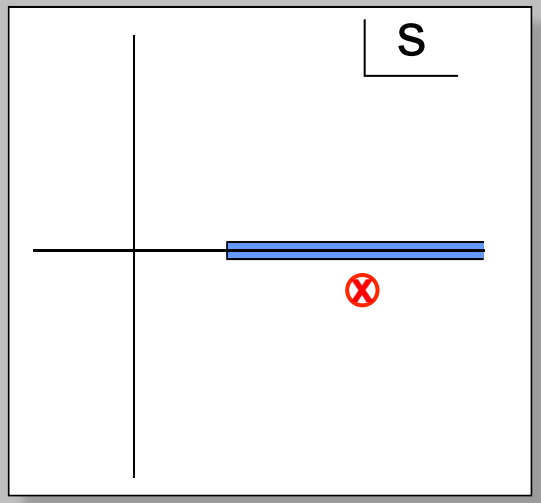


Baryon resonances (N*s and Δ*s)



hadron states

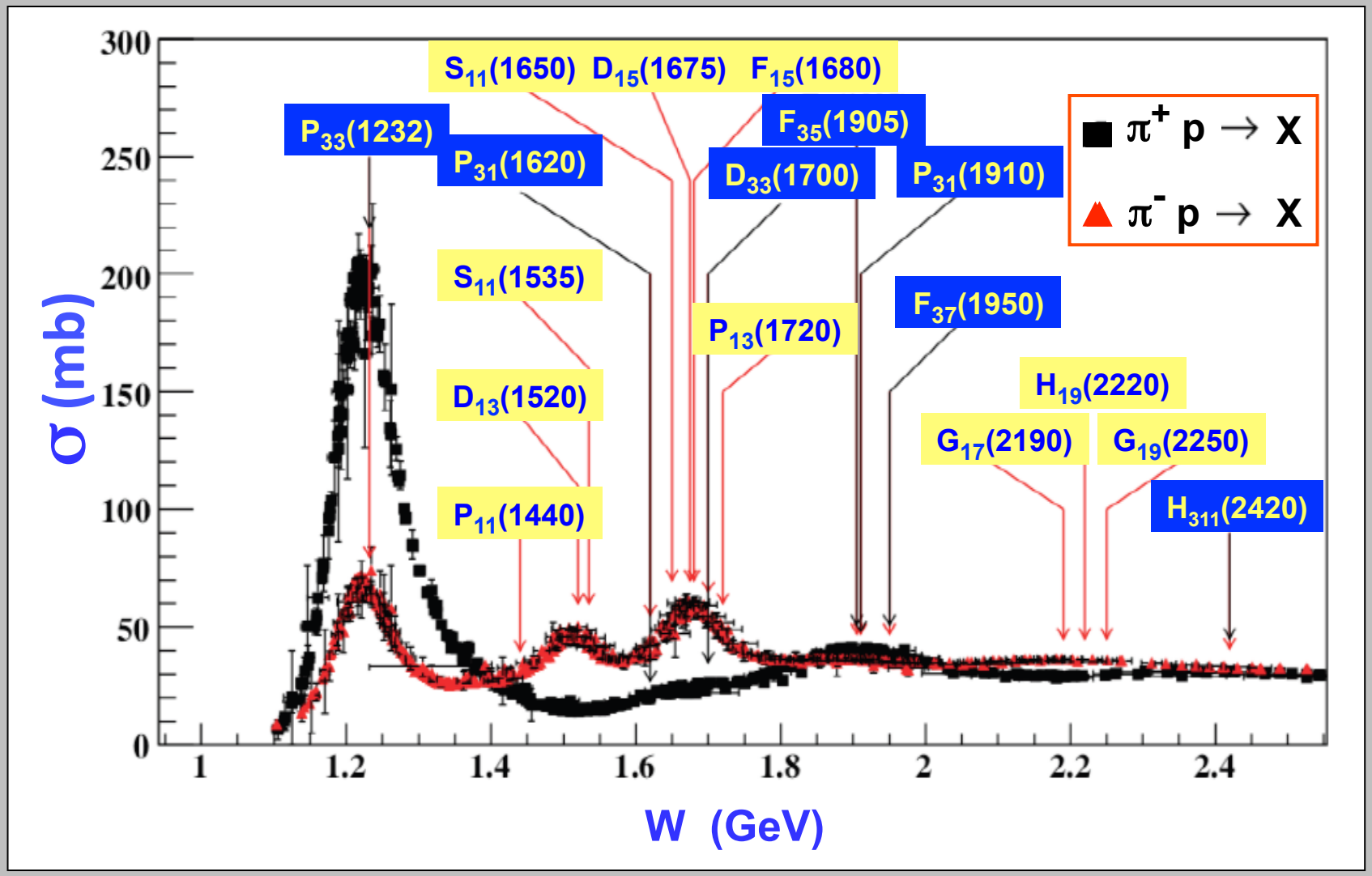




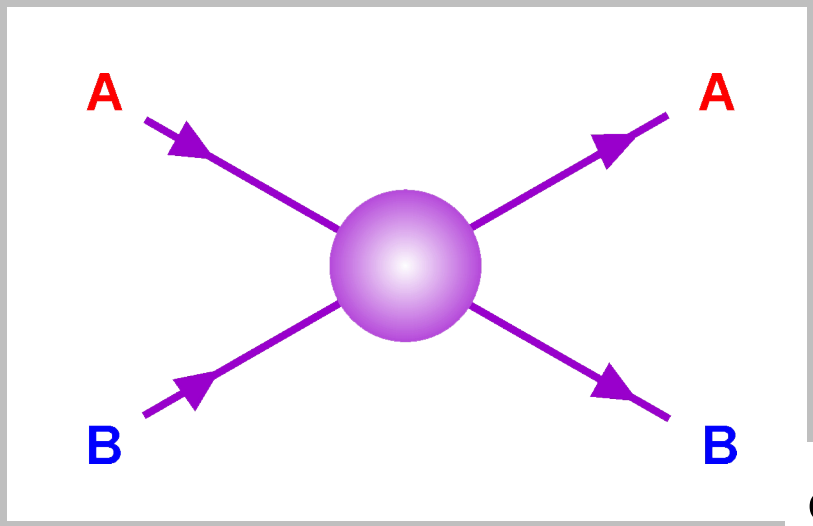
$$\frac{1}{M^2 - s - iM\Gamma}$$

$s = E^2$

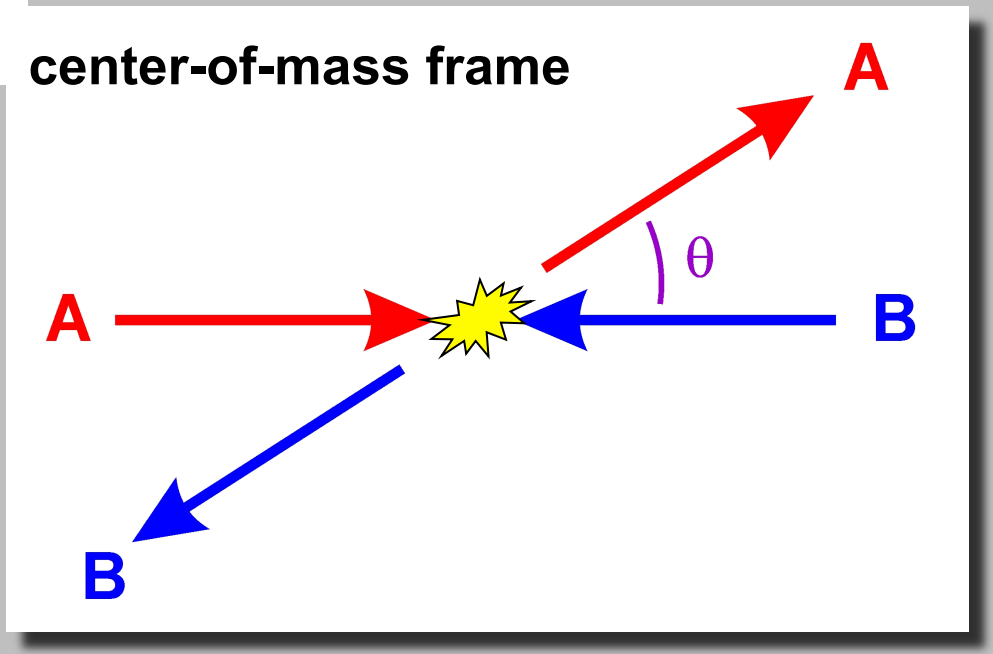
Baryon resonances (N*s and Δ*s)

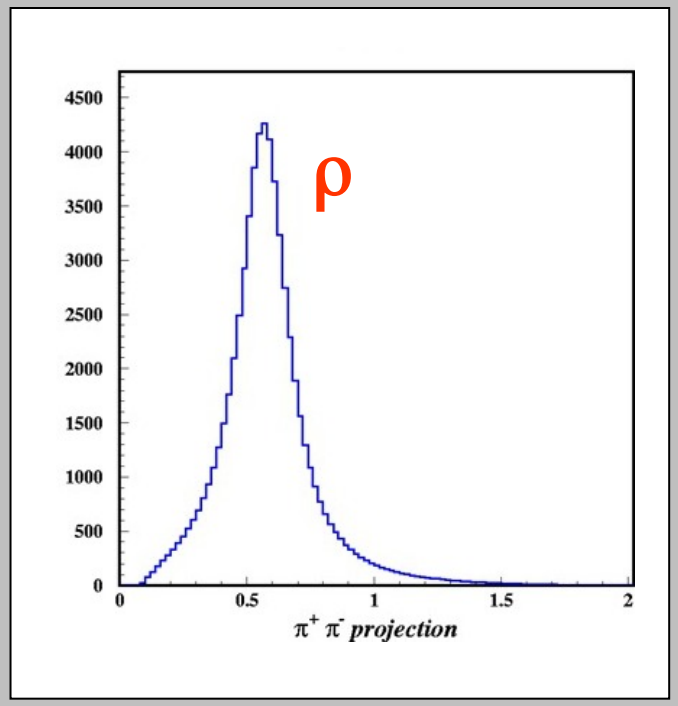


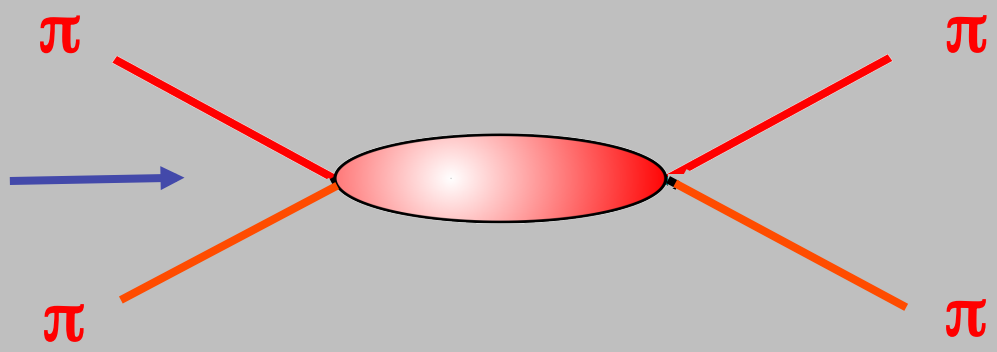
spinless particle scattering



variables: $E = \sqrt{s}$, ϑ

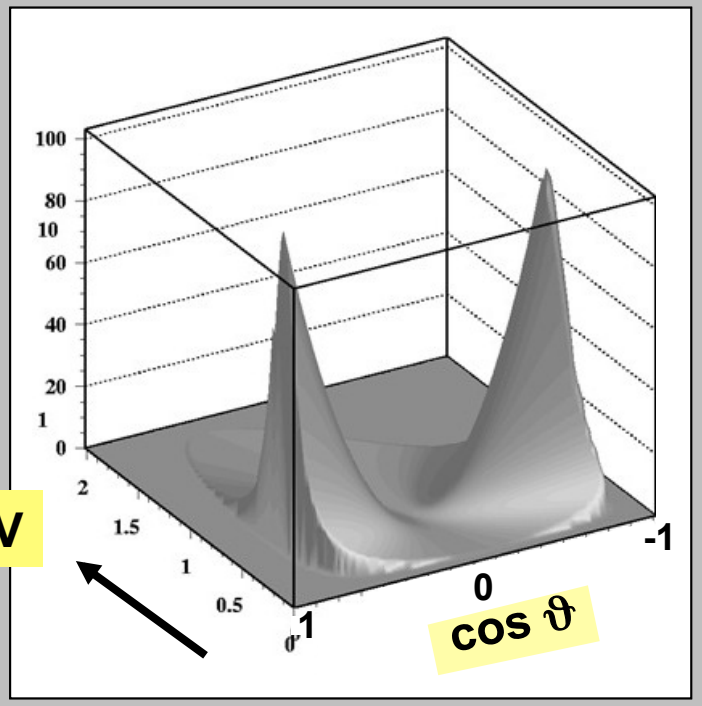




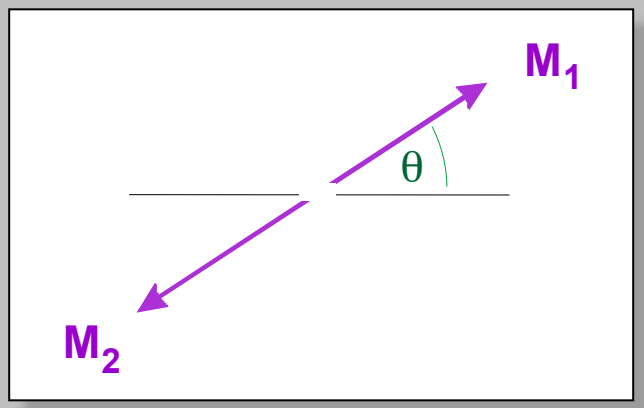


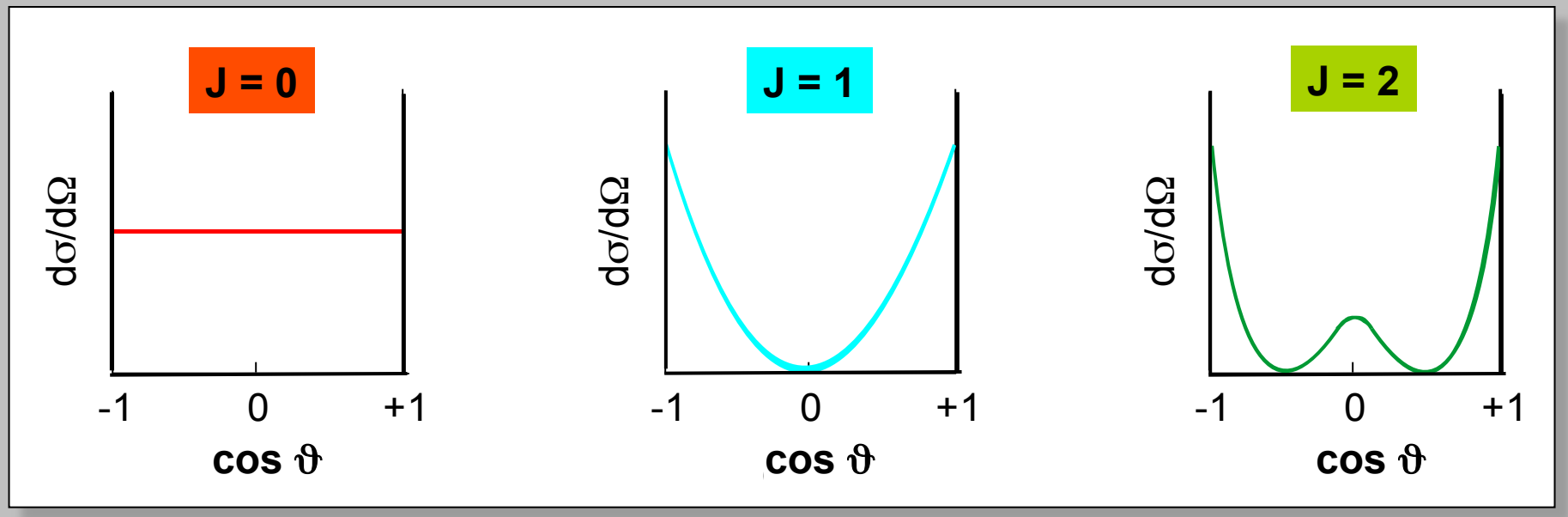
$$F(s,\vartheta) = 3\, f_1(s) \cos\vartheta$$

$s = M^2(\pi\pi)$



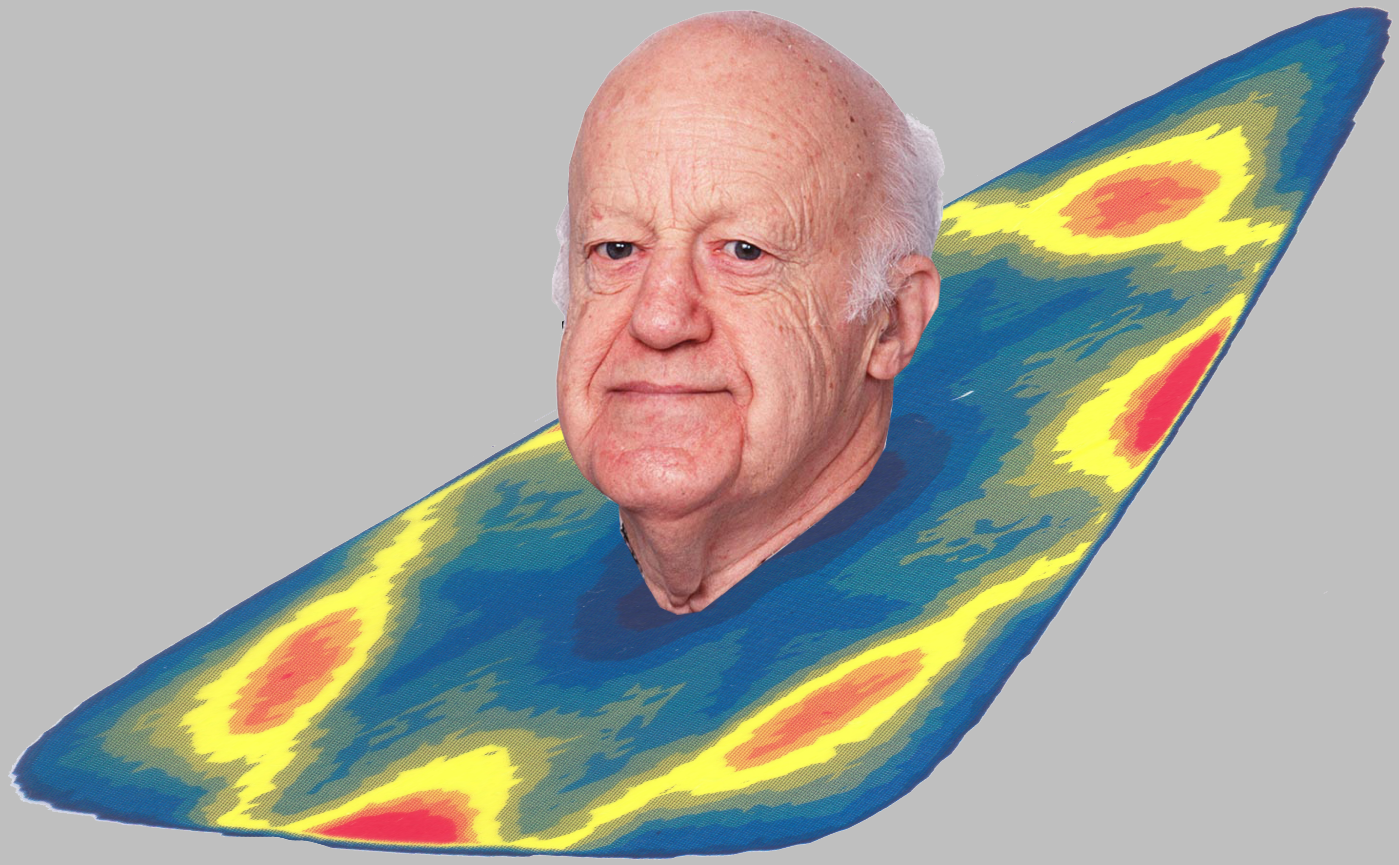
Spin analysis

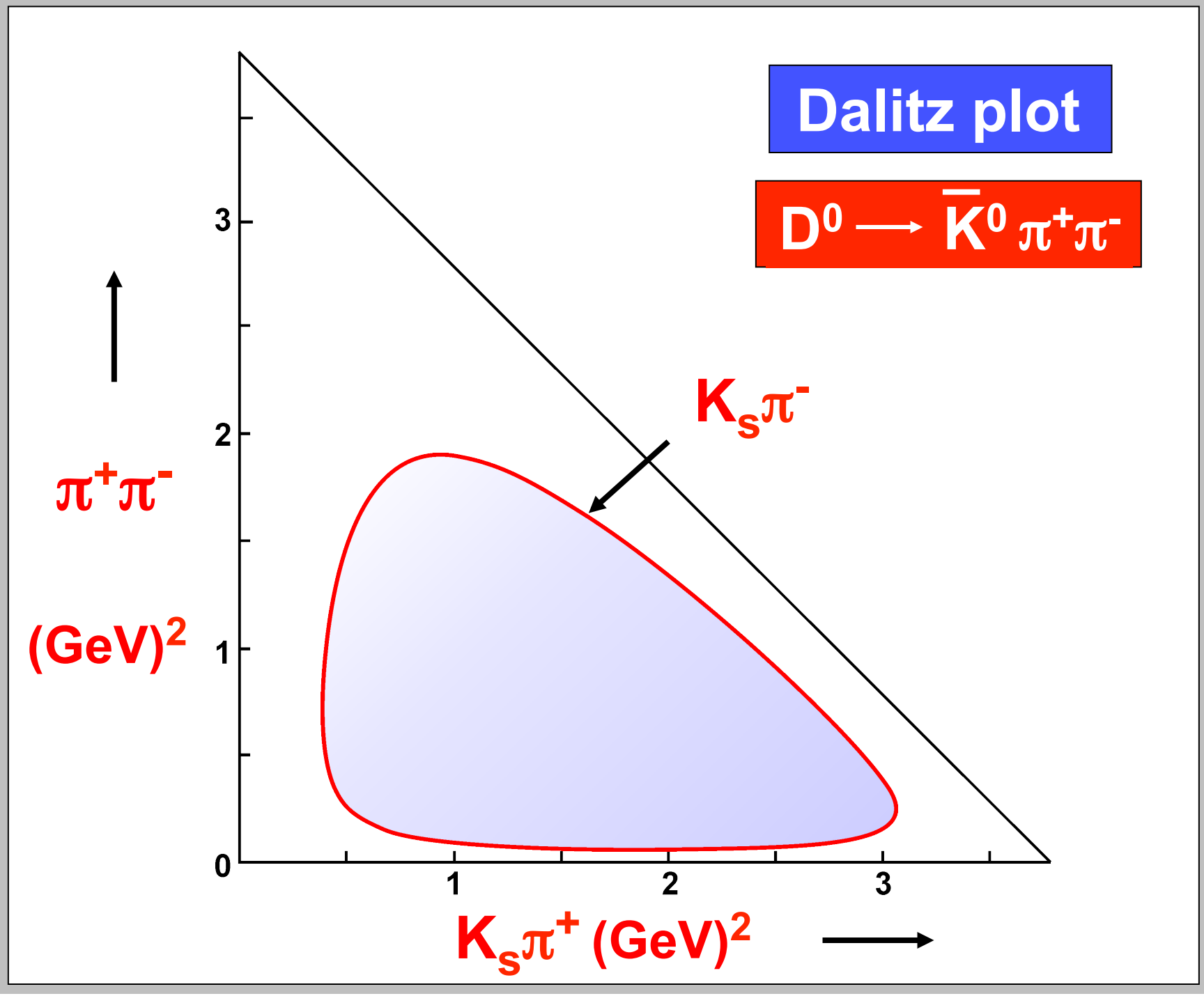




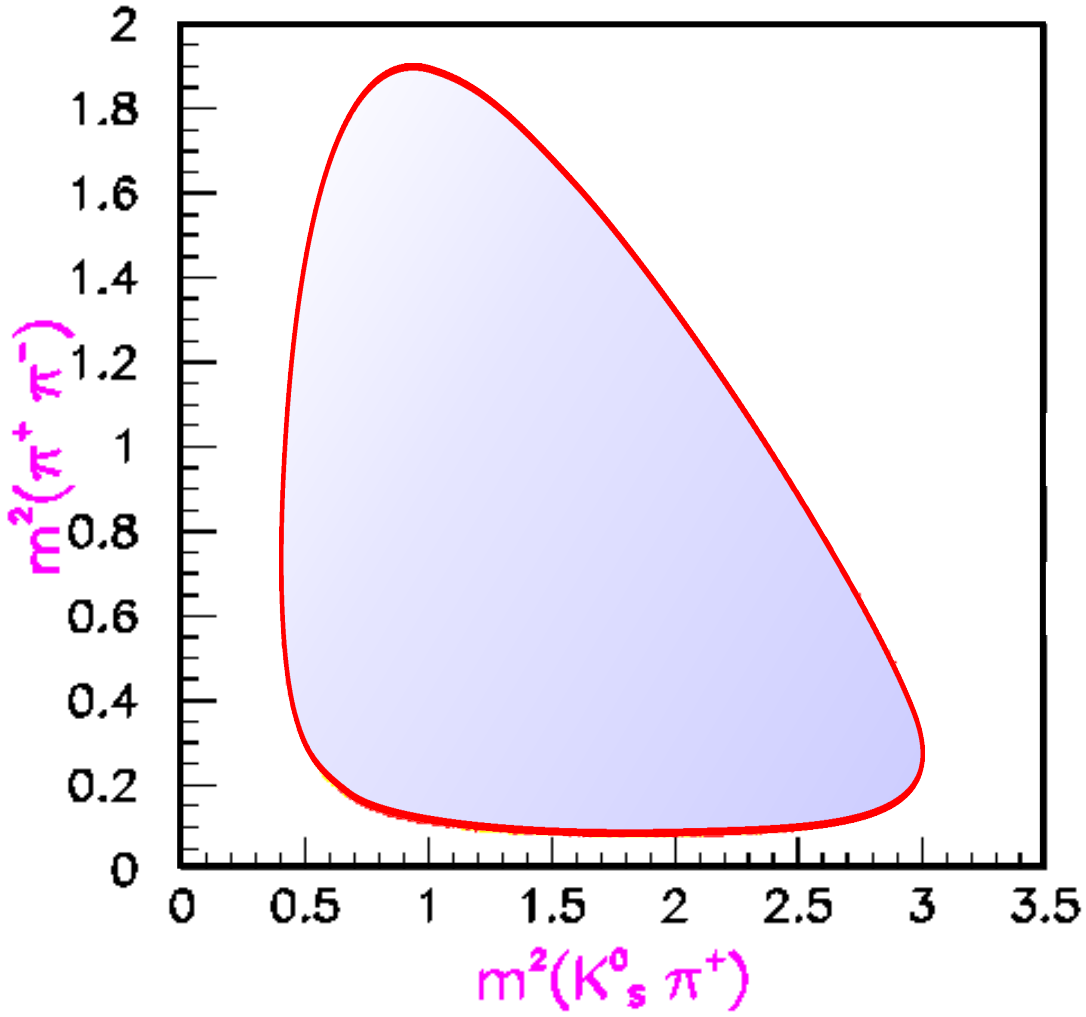
Spectroscopy: interplay of poles & zeros

Dalitz Analysis

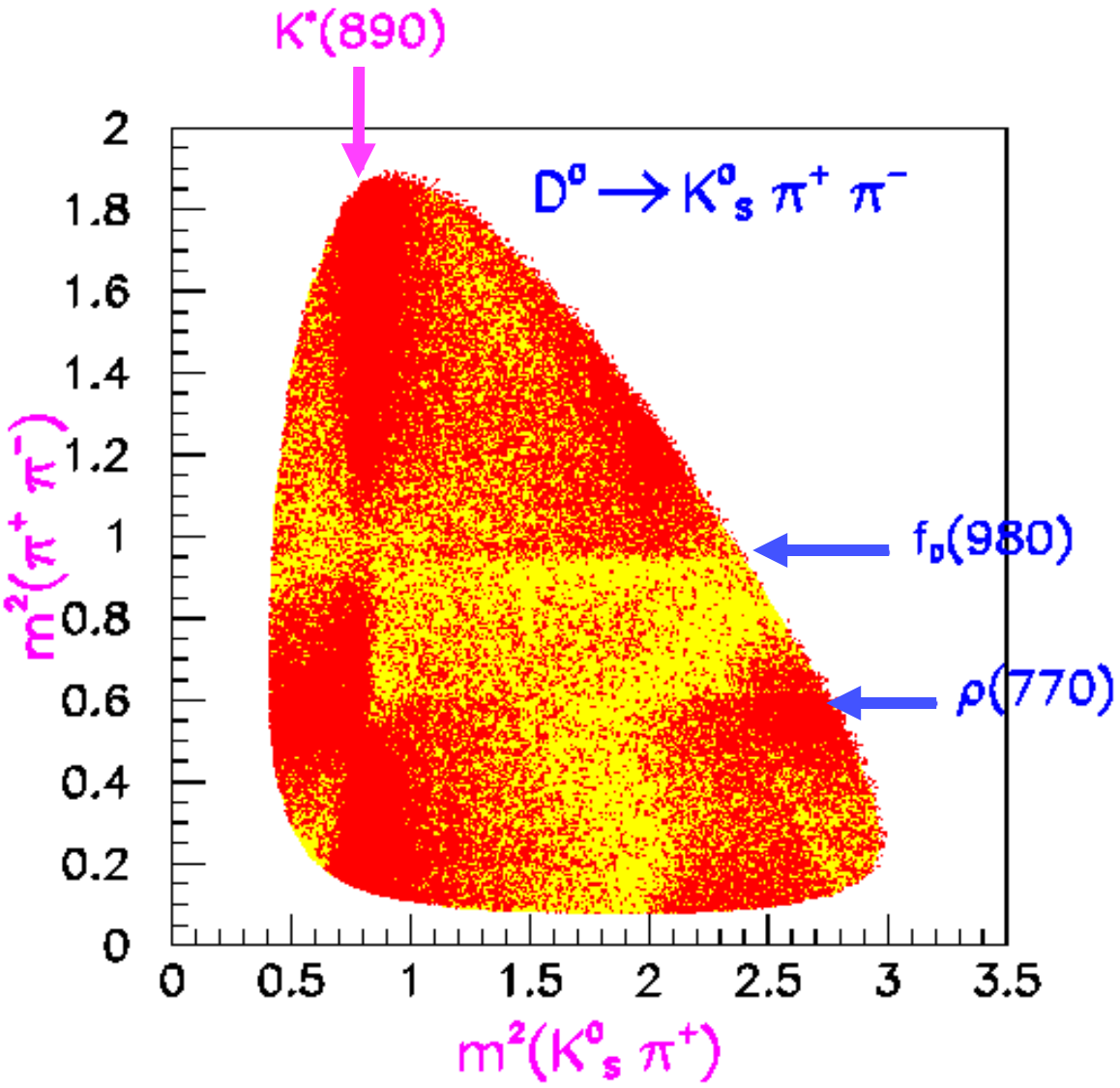



Dalitz plot
$D^0 \longrightarrow \bar{K}^0 \pi^+\pi^-$
$K_s\pi^-$
$\pi^+\pi^-$
$(GeV)^2$
0
1
2
3
1
2
3
$K_s\pi^+ (GeV)^2$

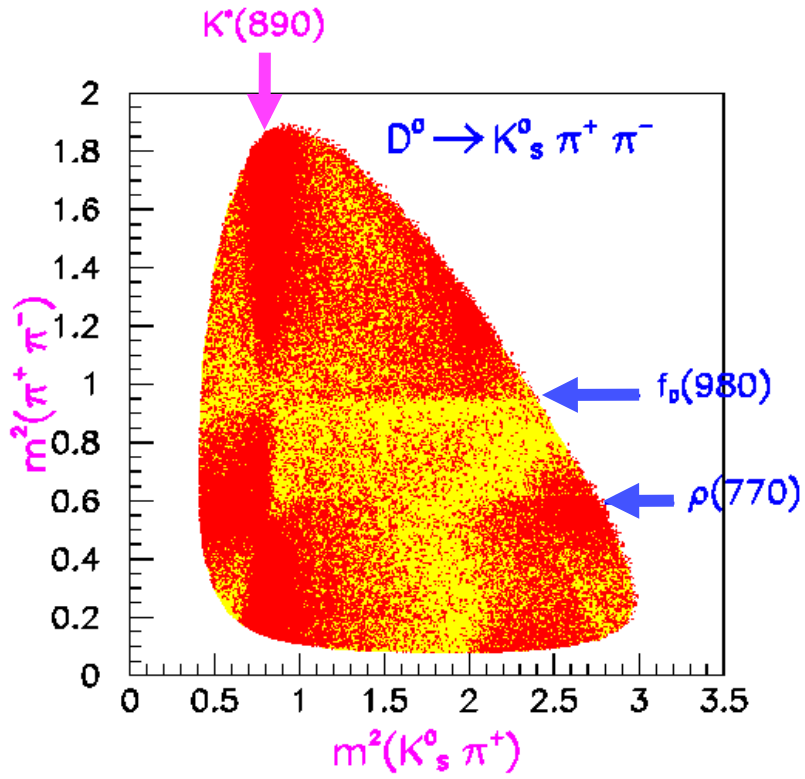
Dalitz plot of $D^0 \to \bar{K}^0\pi^+\pi^-$.

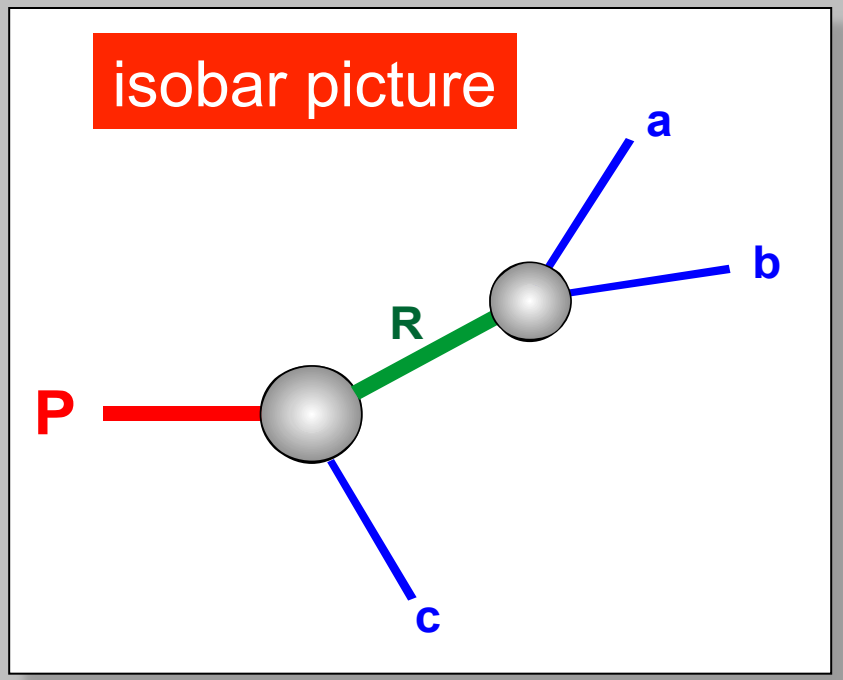


Dalitz plot of $D^0 \to \bar{K}^0\pi^+\pi^-$.

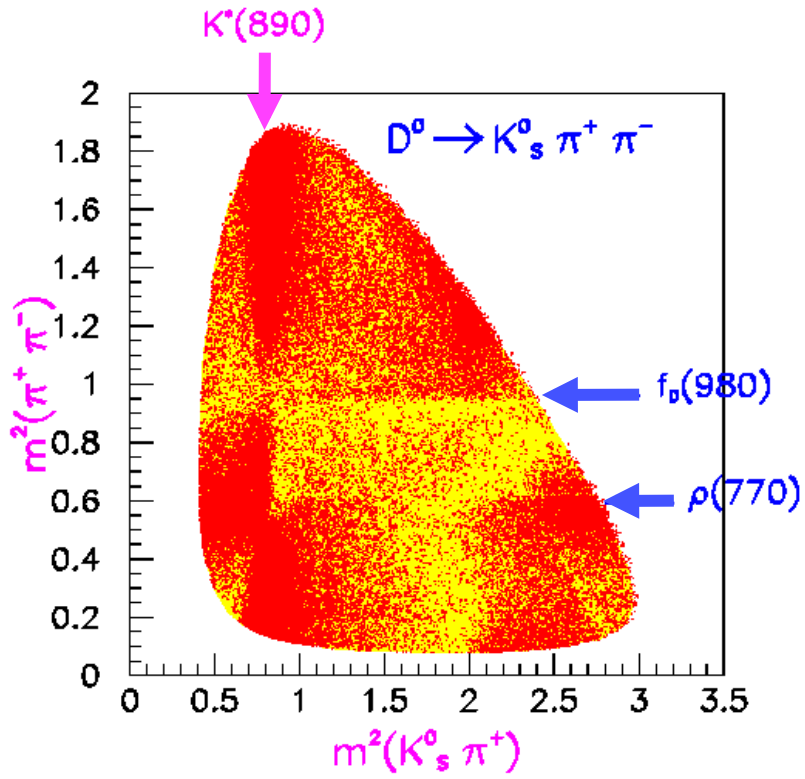


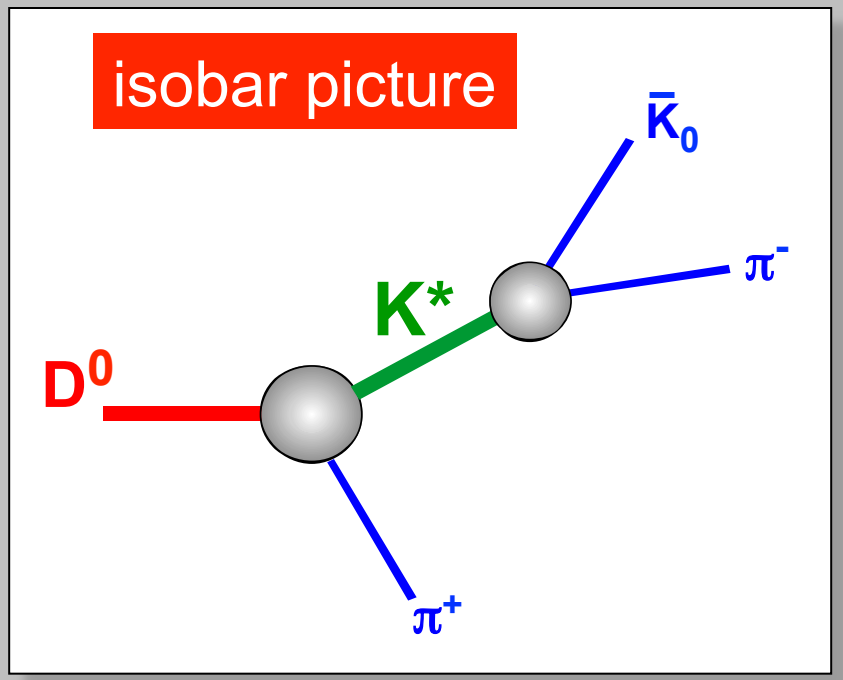
Dalitz plot of $D^0 \to \bar{K}^0\pi^+\pi^-$.



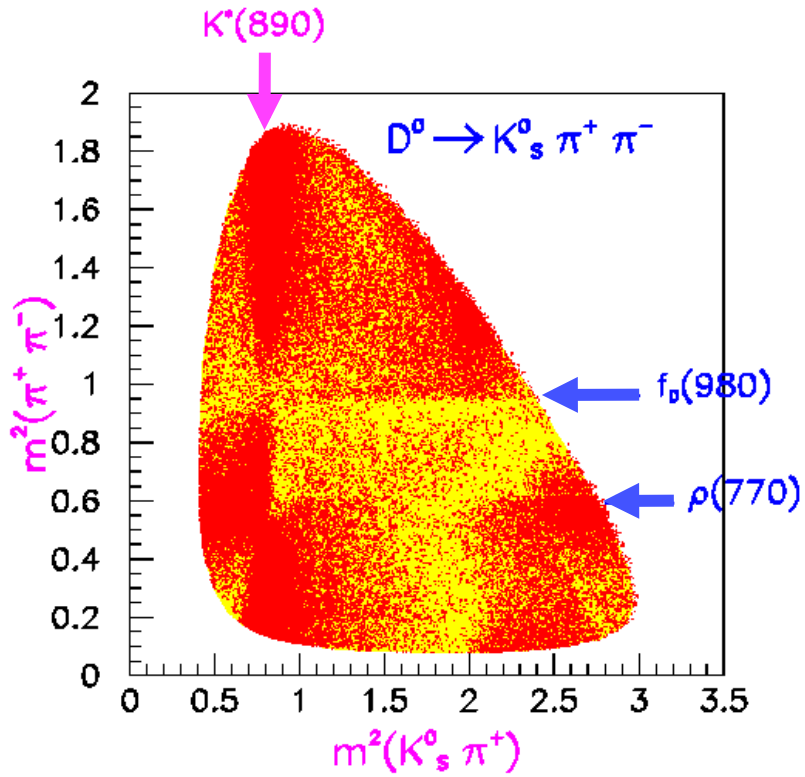


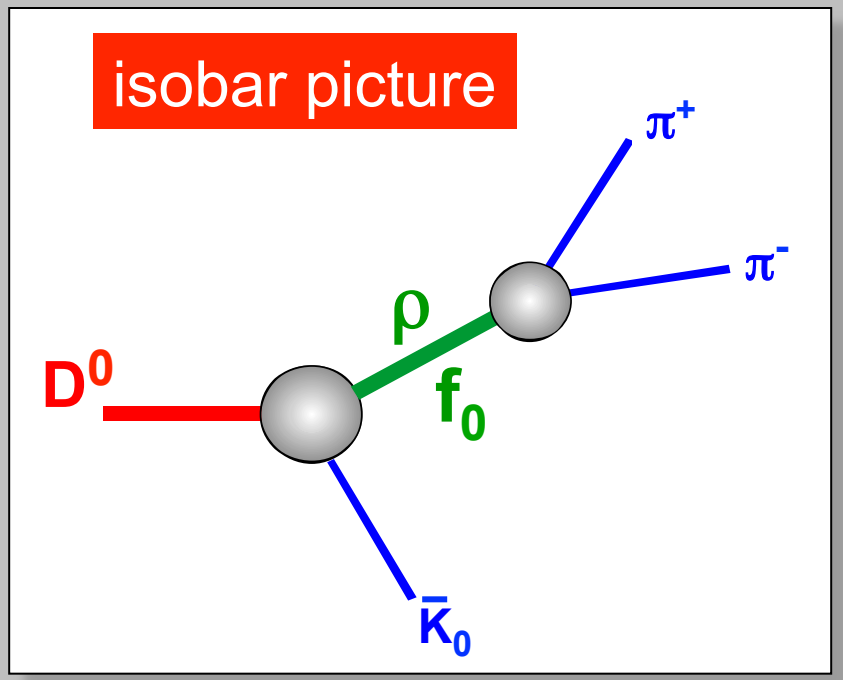
Dalitz plot of $D^0 \to \bar{K}^0\pi^+\pi^-$.

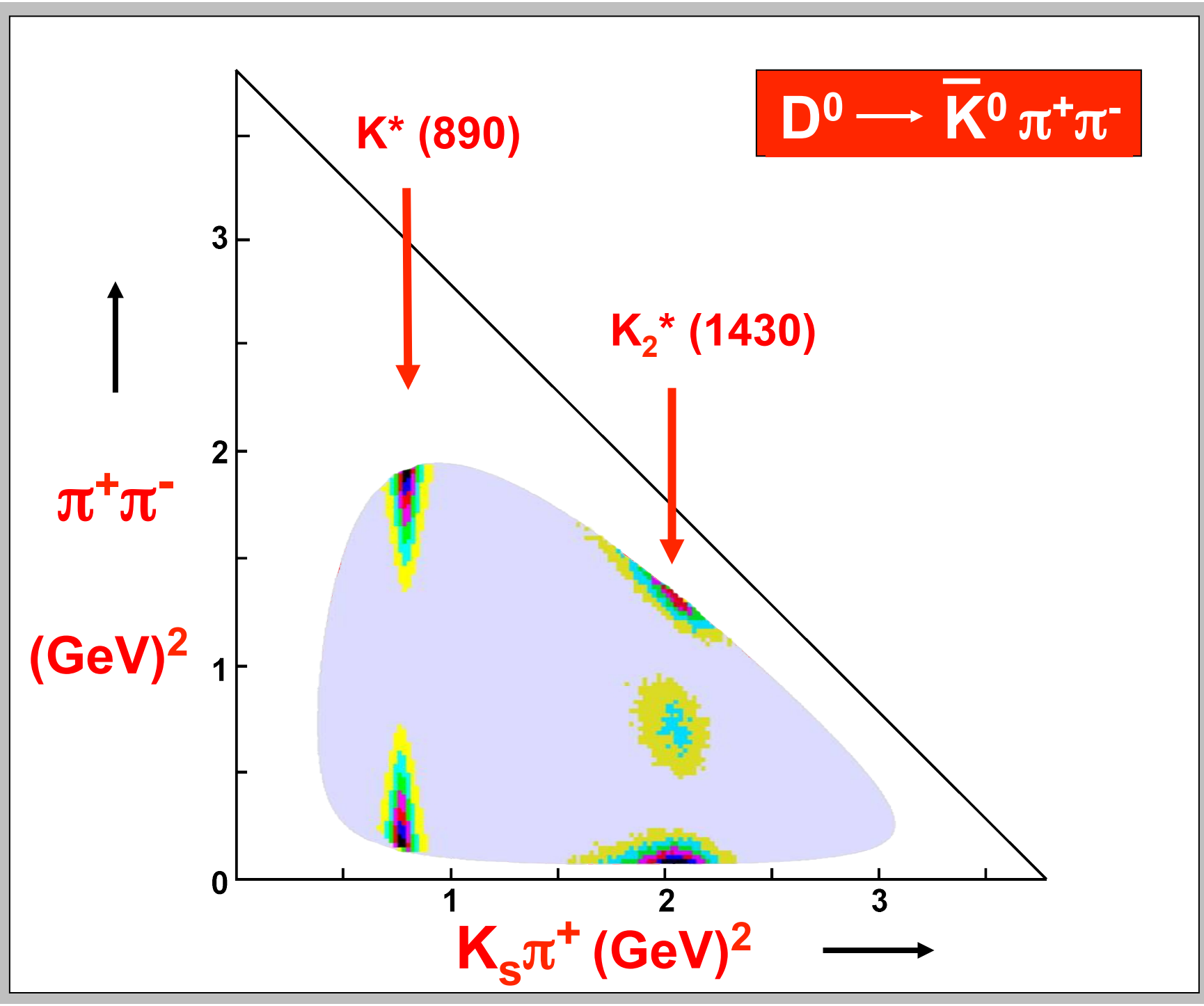




Dalitz plot of $D^0 \to \bar{K}^0\pi^+\pi^-$.

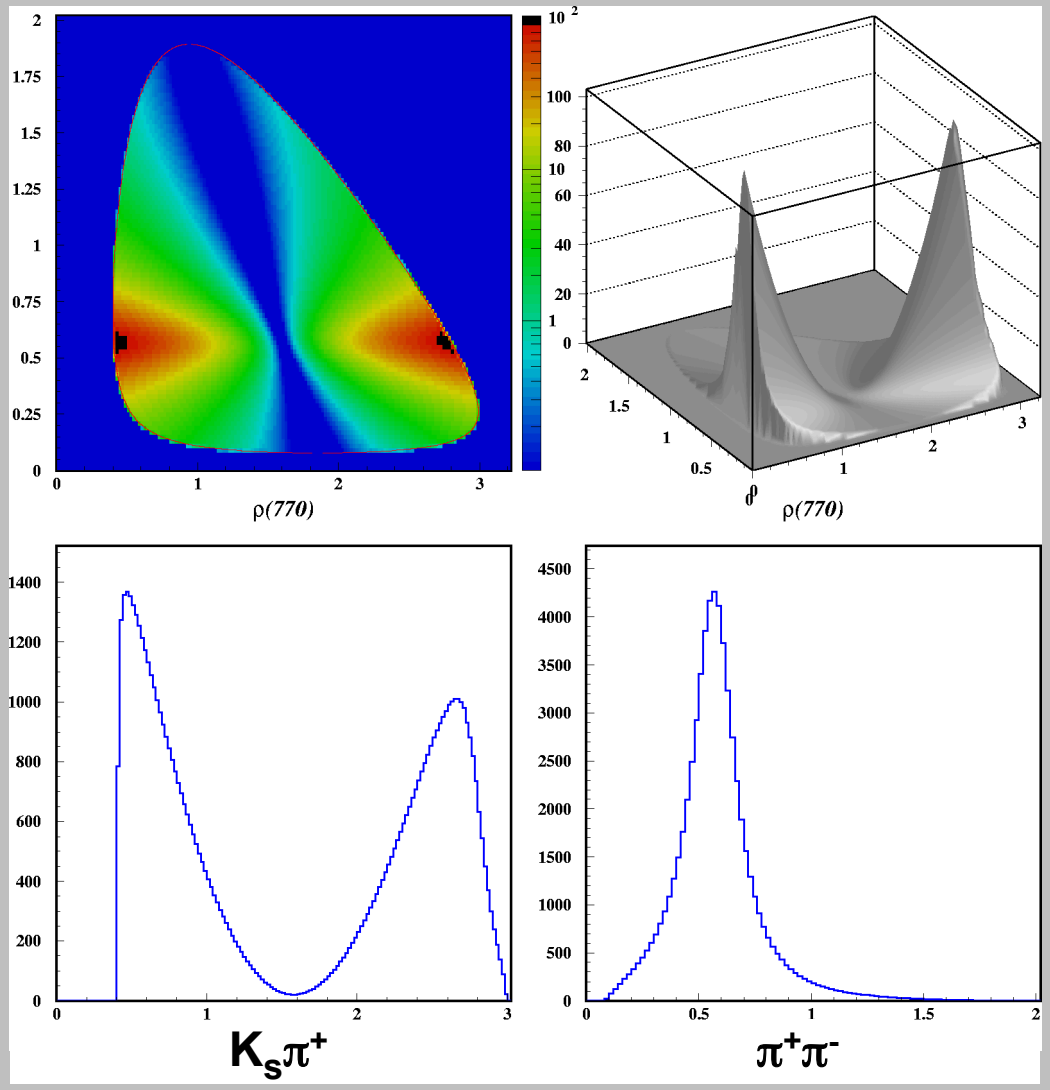





$D^0 \longrightarrow \bar{K}^0 \pi^+\pi^-$
K* (890)
K_2* (1430)
$\pi^+\pi^-$
$(GeV)^2$
0
1
2
3
1
2
3
$K_s\pi^+ (GeV)^2$

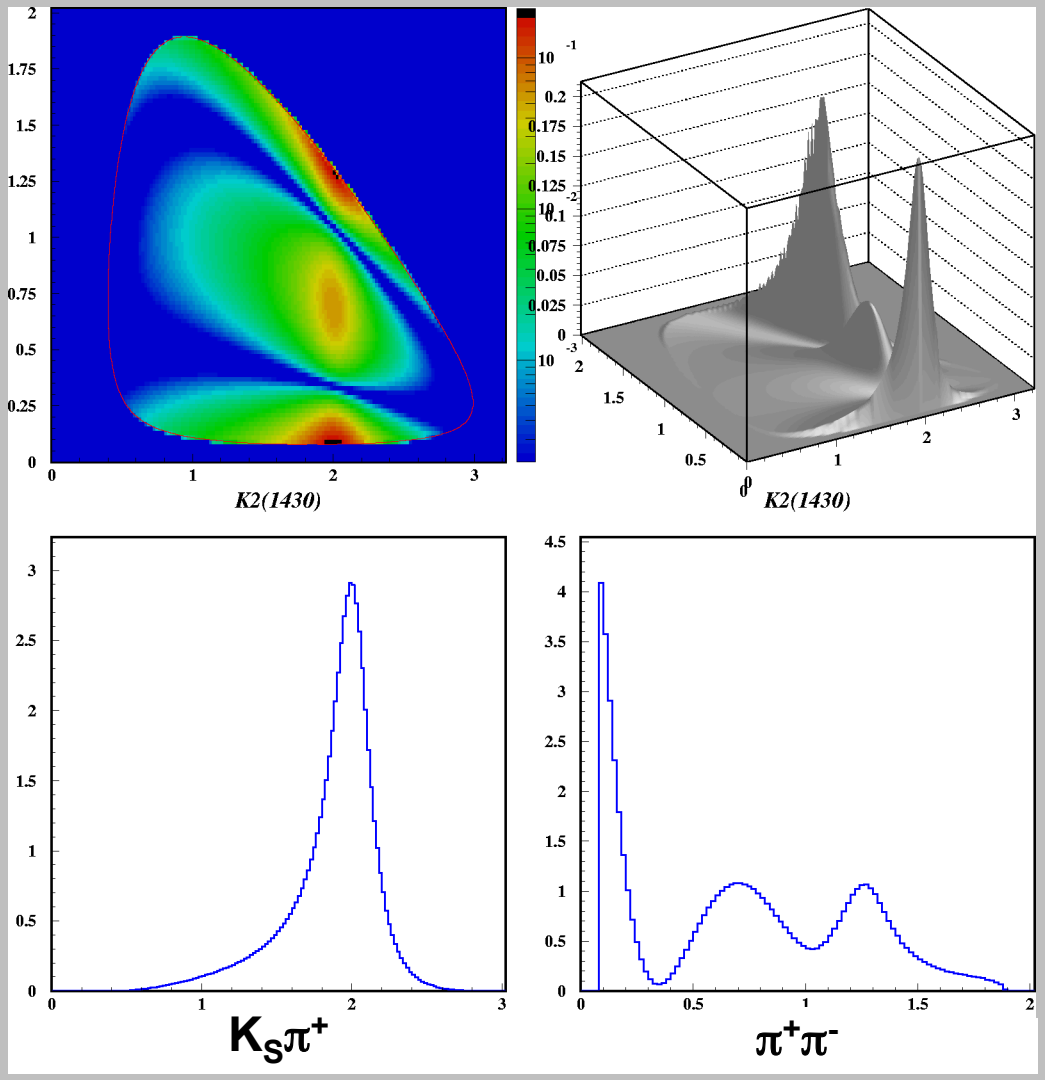
$D^0 \longrightarrow \bar{K}^0\pi^+\pi^-$

ρ(770)



$D^0 \longrightarrow \bar{K}^0\pi^+\pi^-$

$K_2^*(1430)$

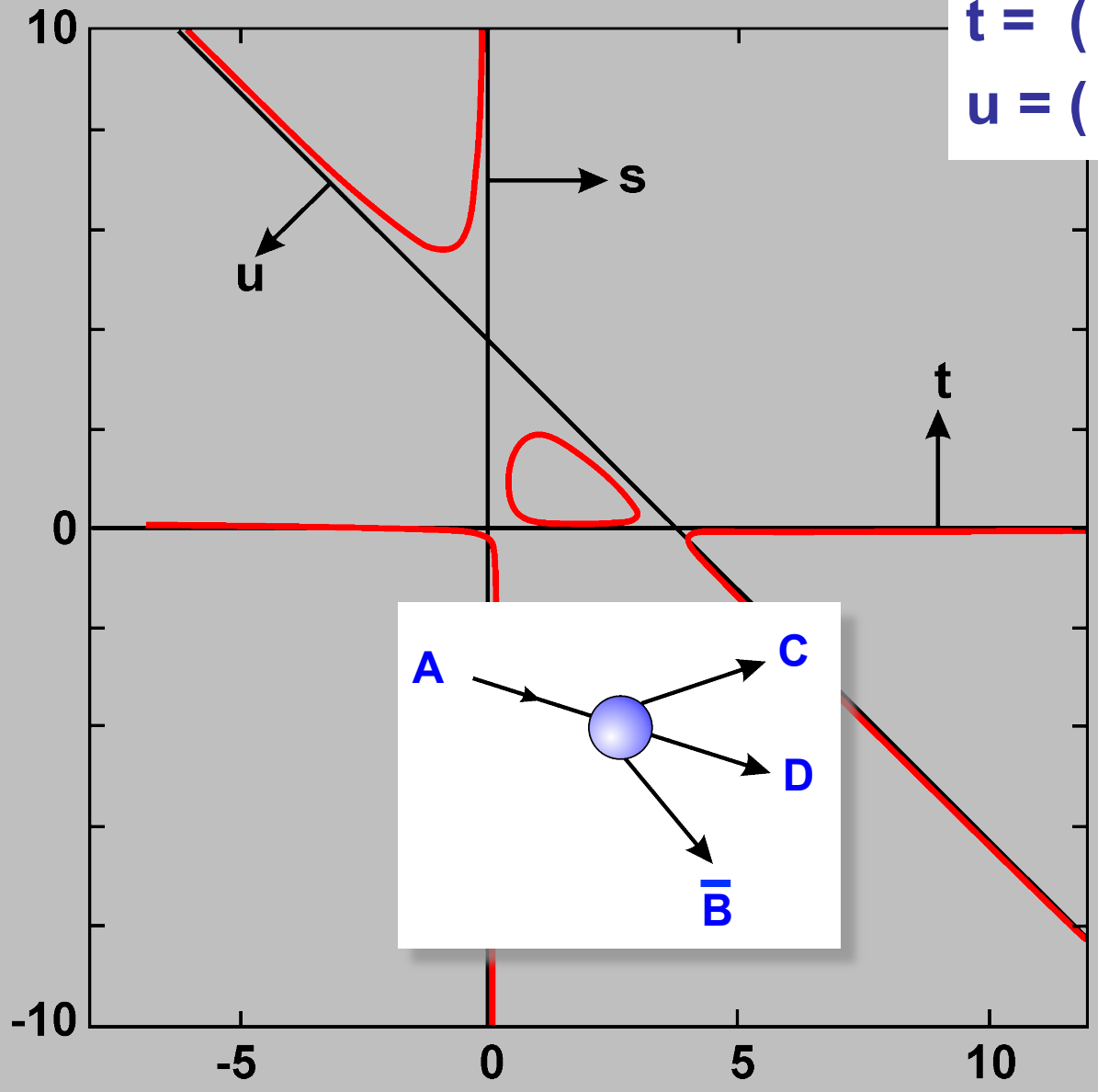


decay region

$s = (p_A + p_B)^2$

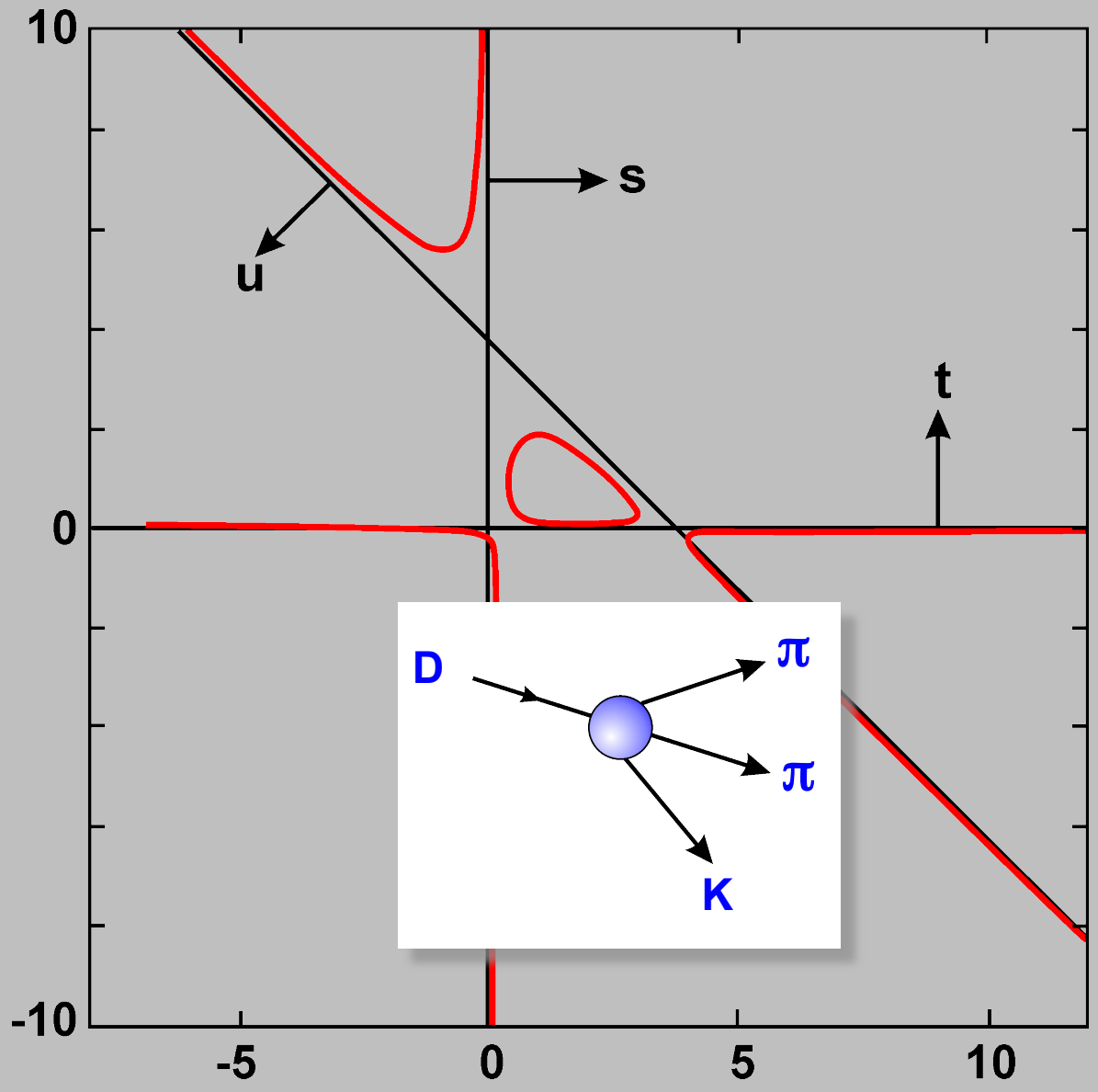
$t = (p_A - p_C)^2$

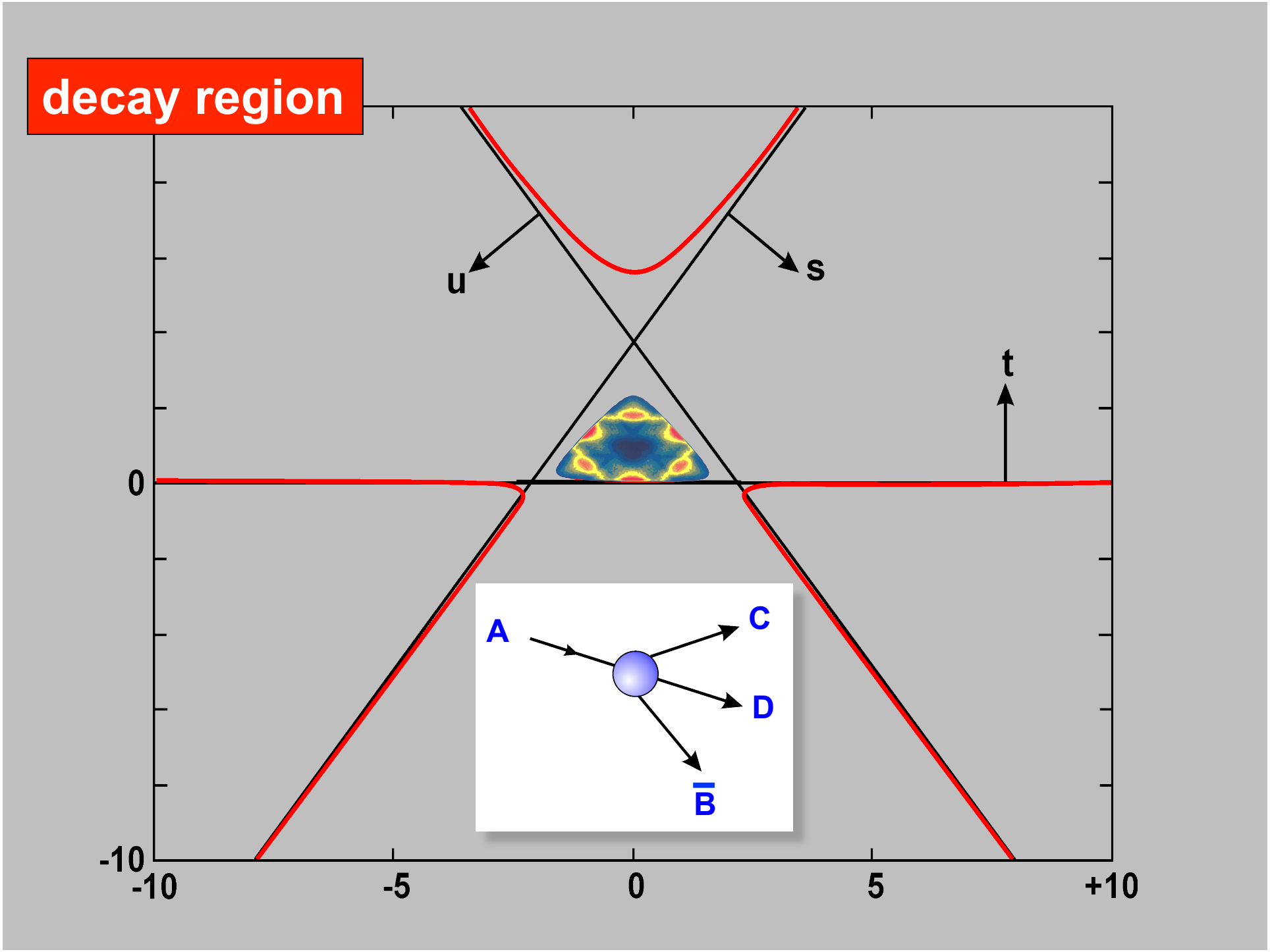
$u = (p_A - p_D)^2$

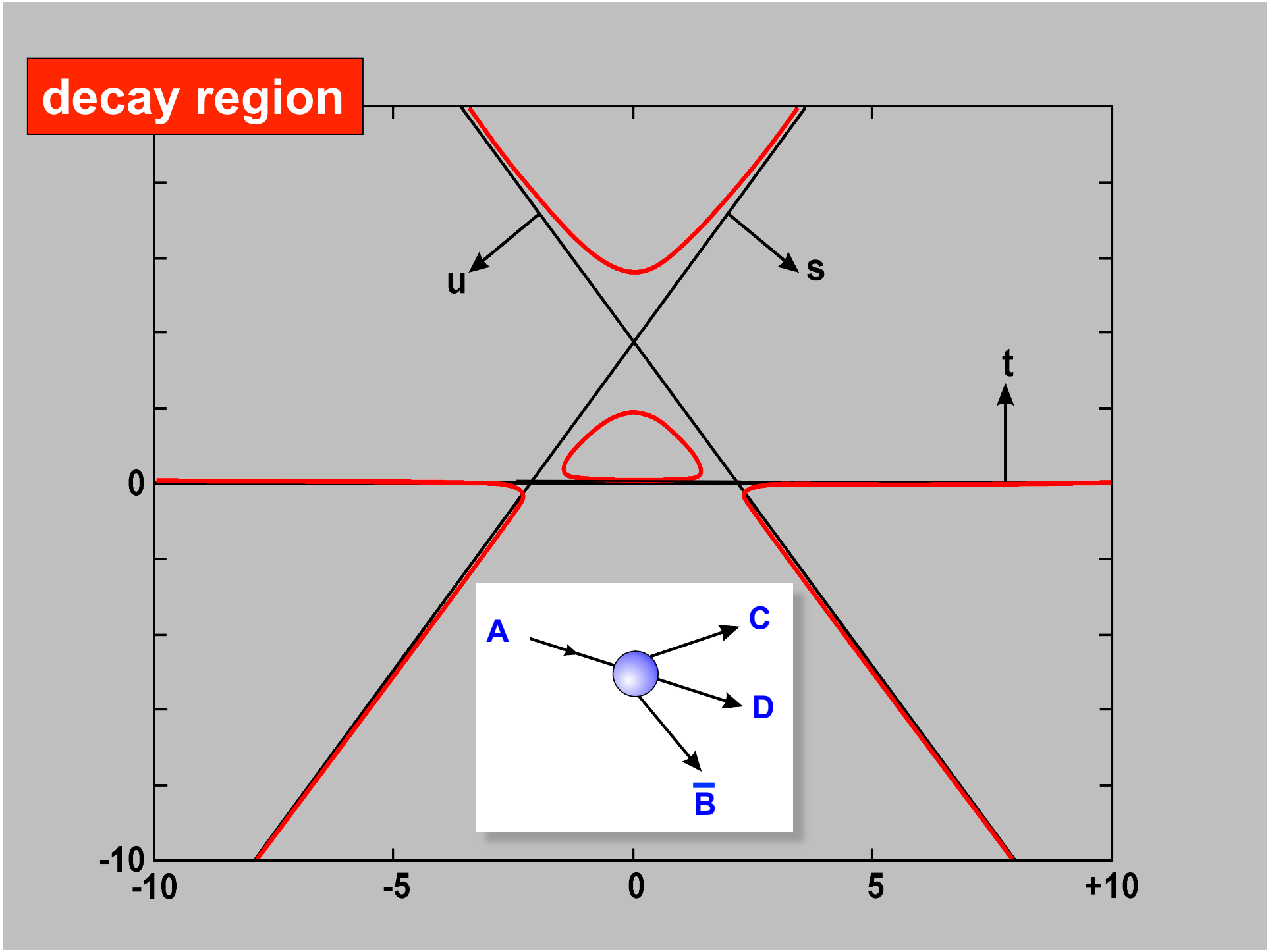


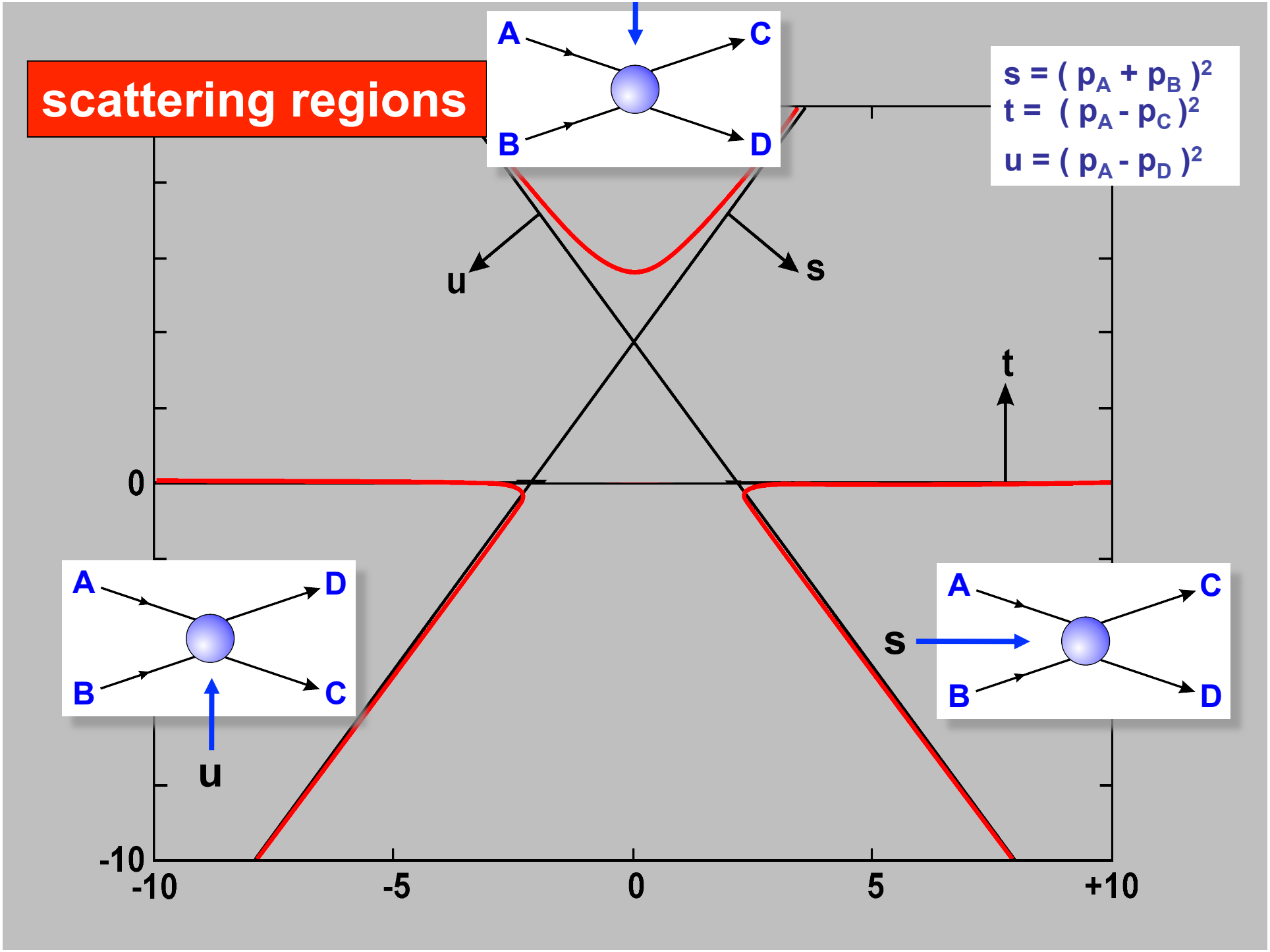
decay region

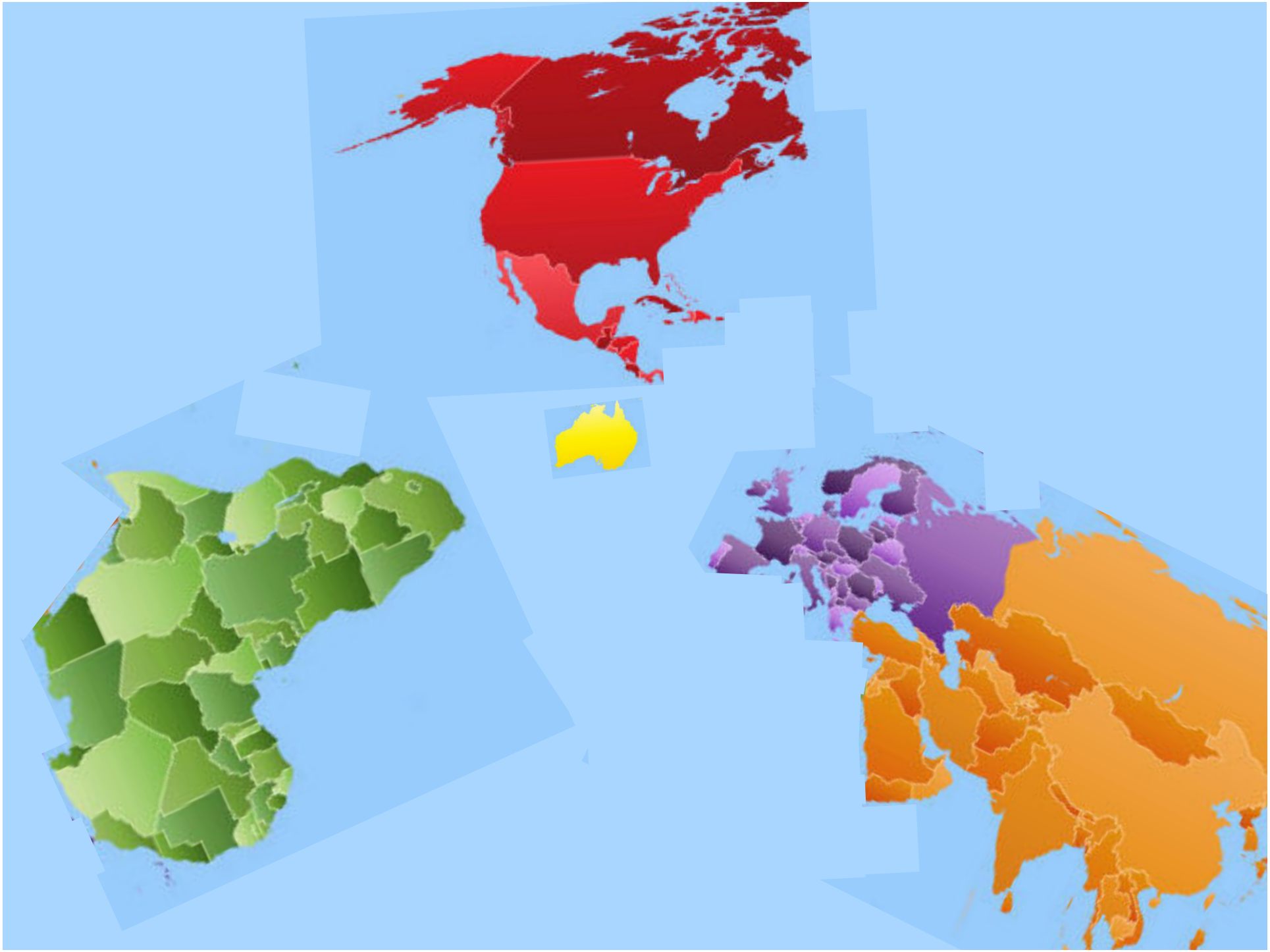
$D^0 \longrightarrow \bar{K}^0 \pi^+\pi^-$

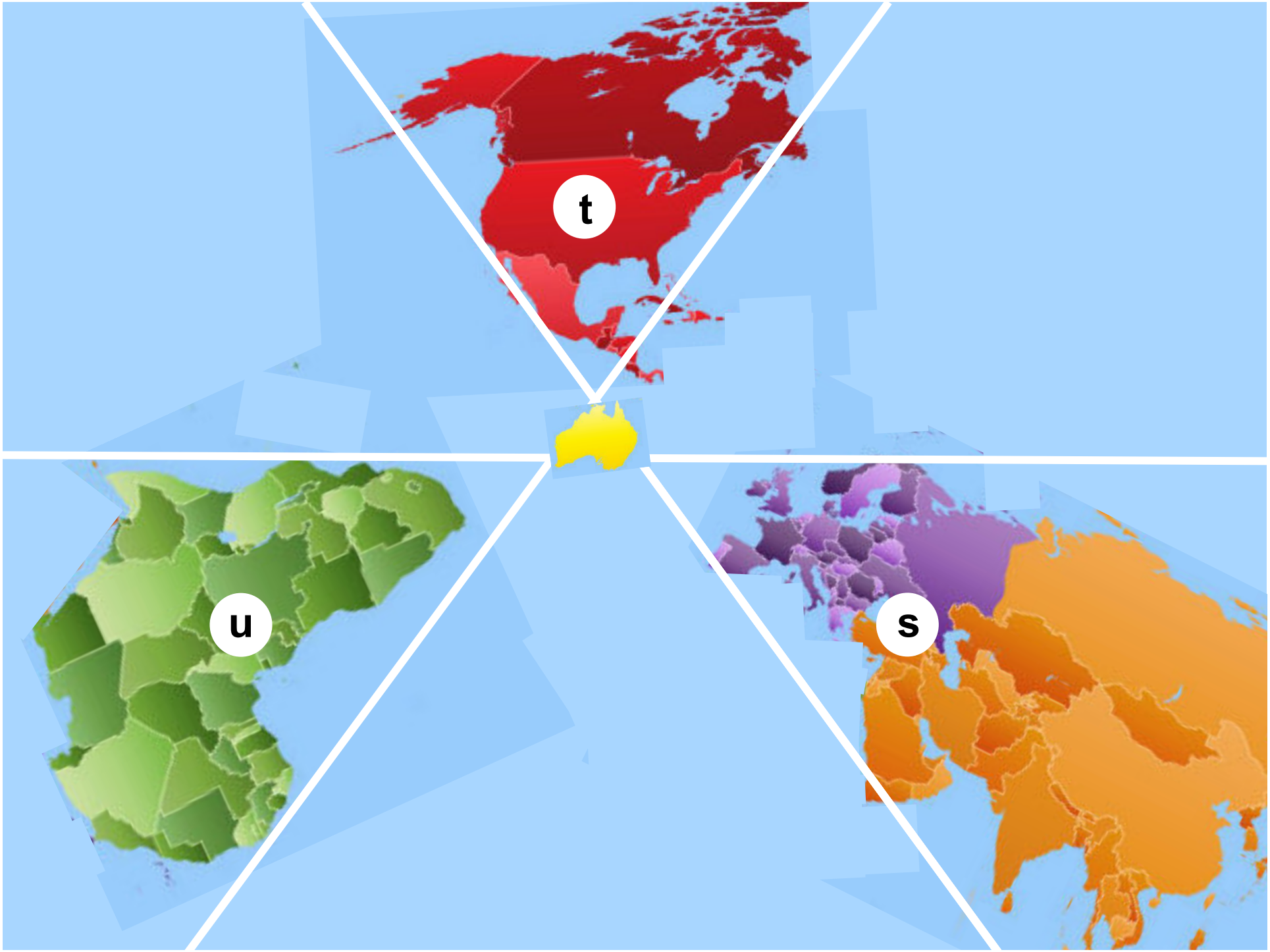



decay region
u
s
t
0
-10
-10
-5
0
5
+10
A
C
D
B

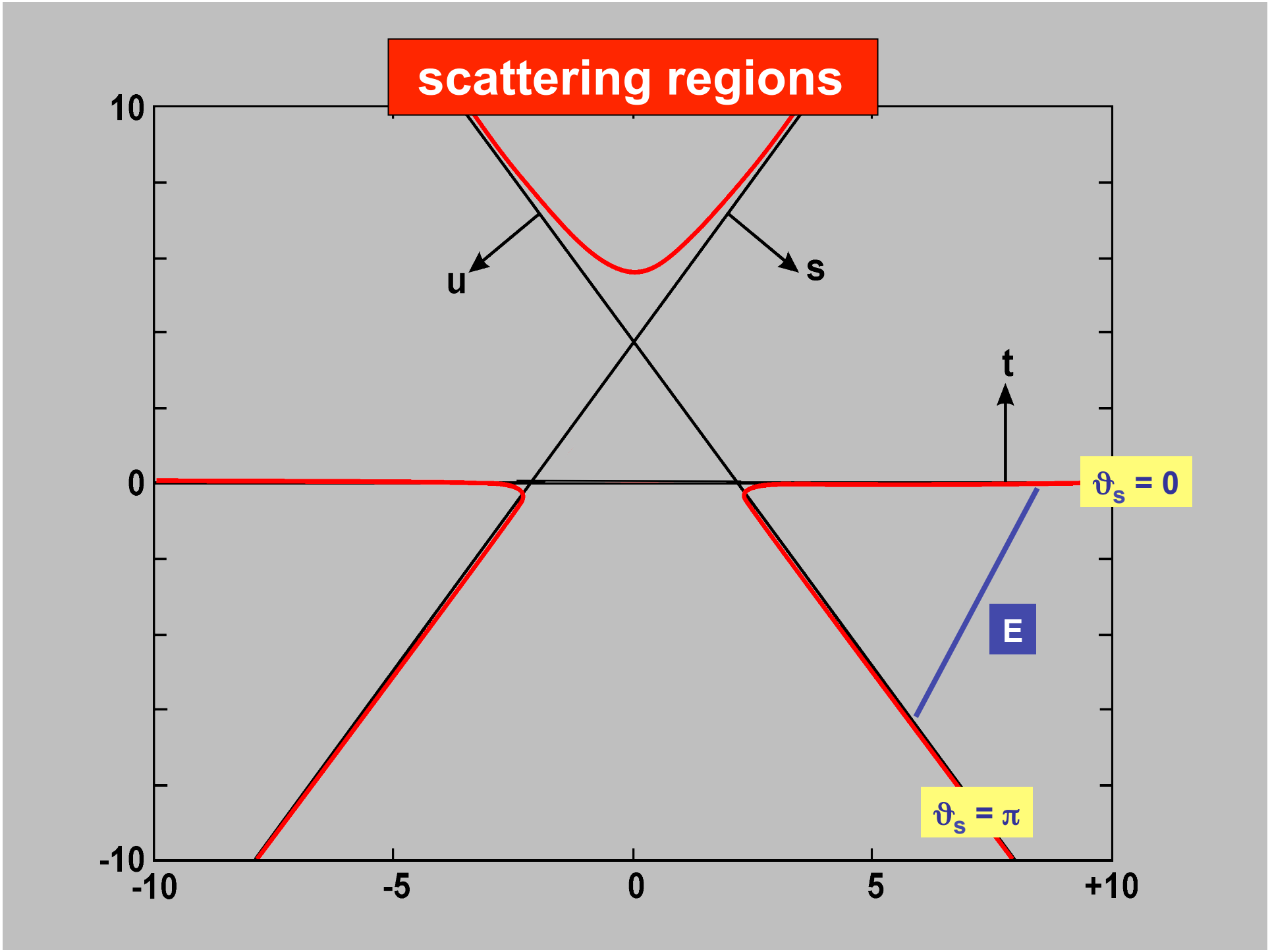

decay region
u
s
t
0
-10
-10
-5
0
5
+10
A
C
D
B

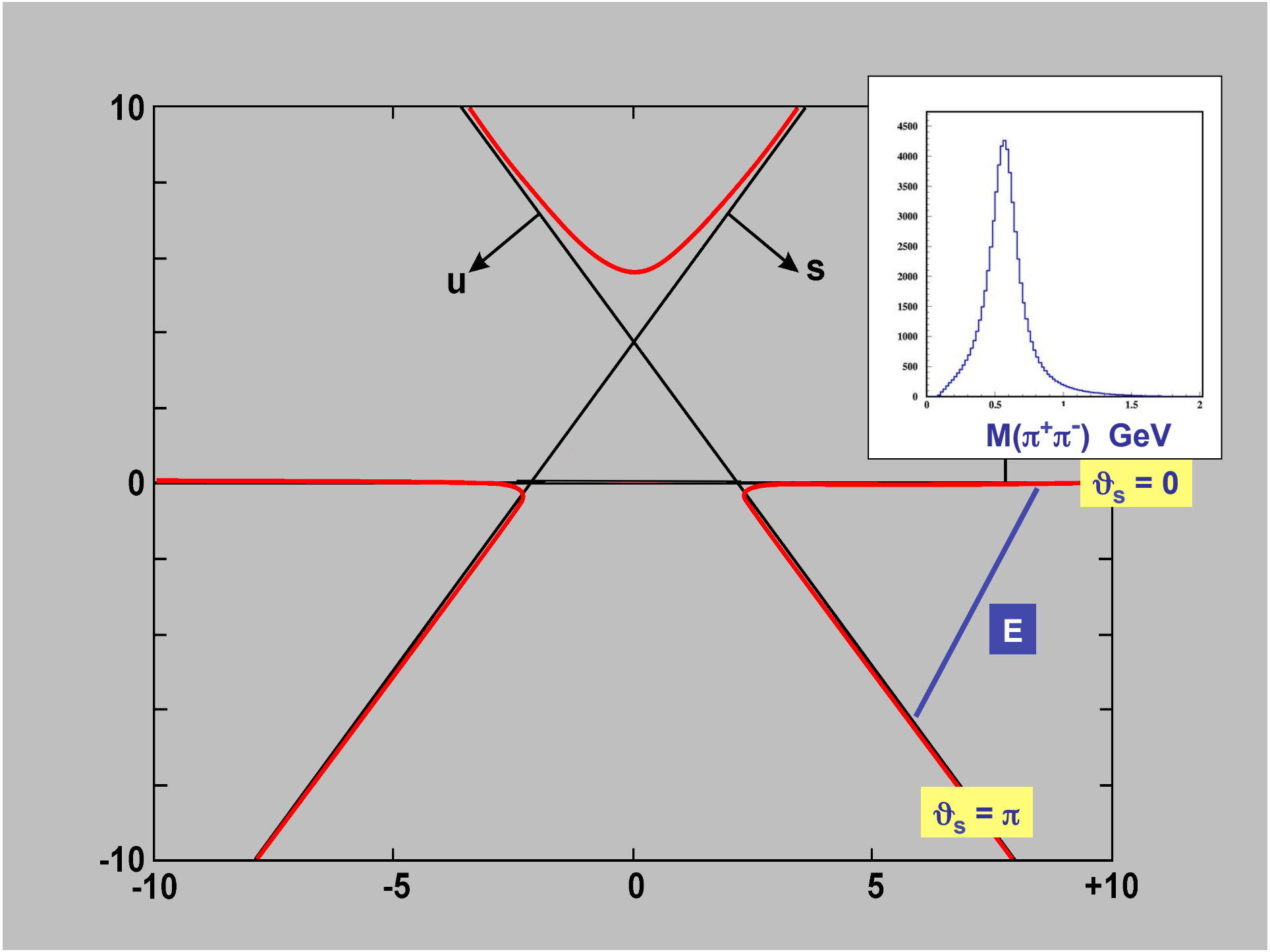

scattering regions
A
C
B
D
$s = (p_A + p_B)^2$
$t = (p_A - p_C)^2$
$u = (p_A - p_D)^2$
u
s
t
0
A
D
B
C
u
s
A
C
B
D
-10
-10
-5
0
5
+10

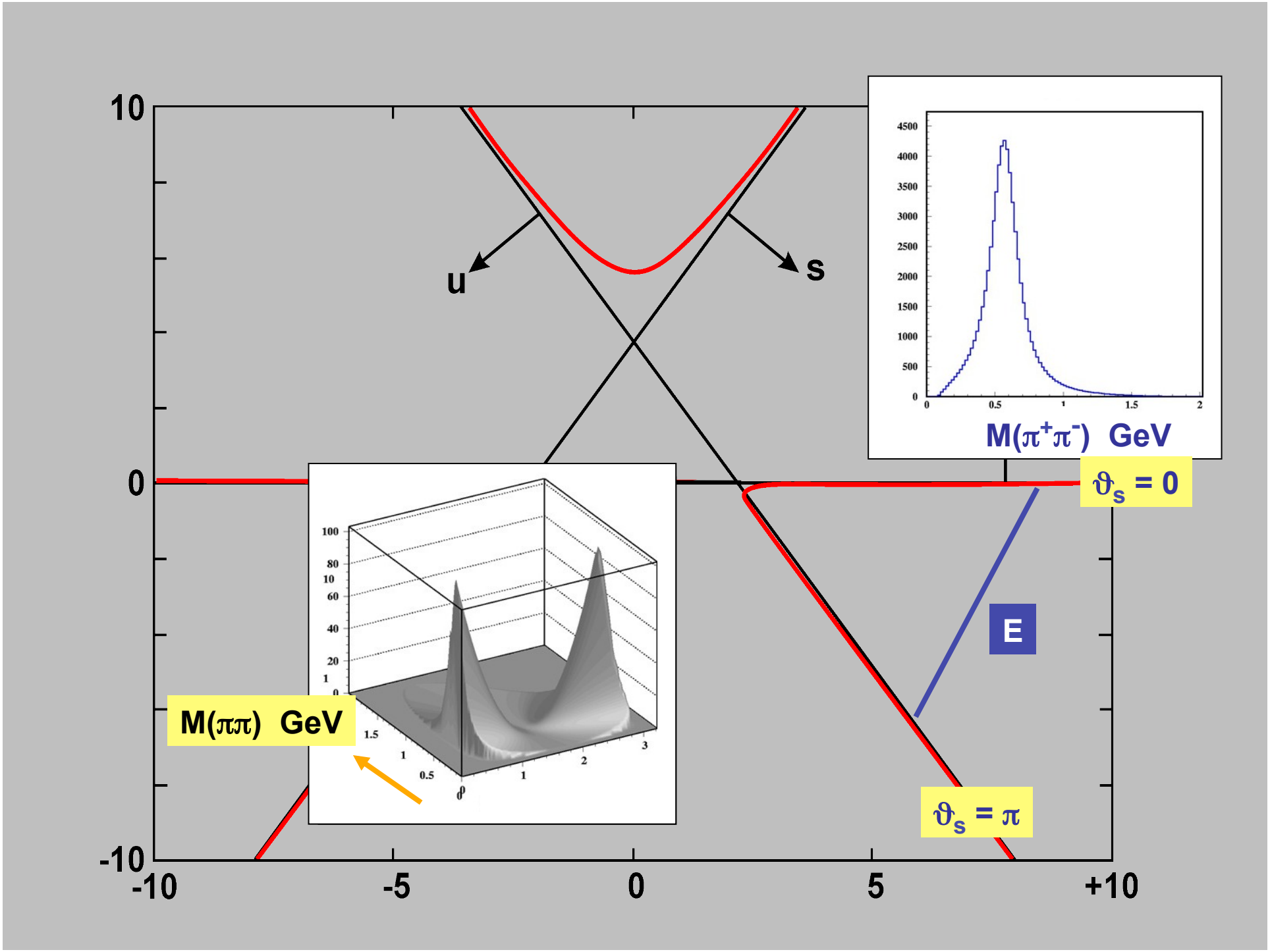


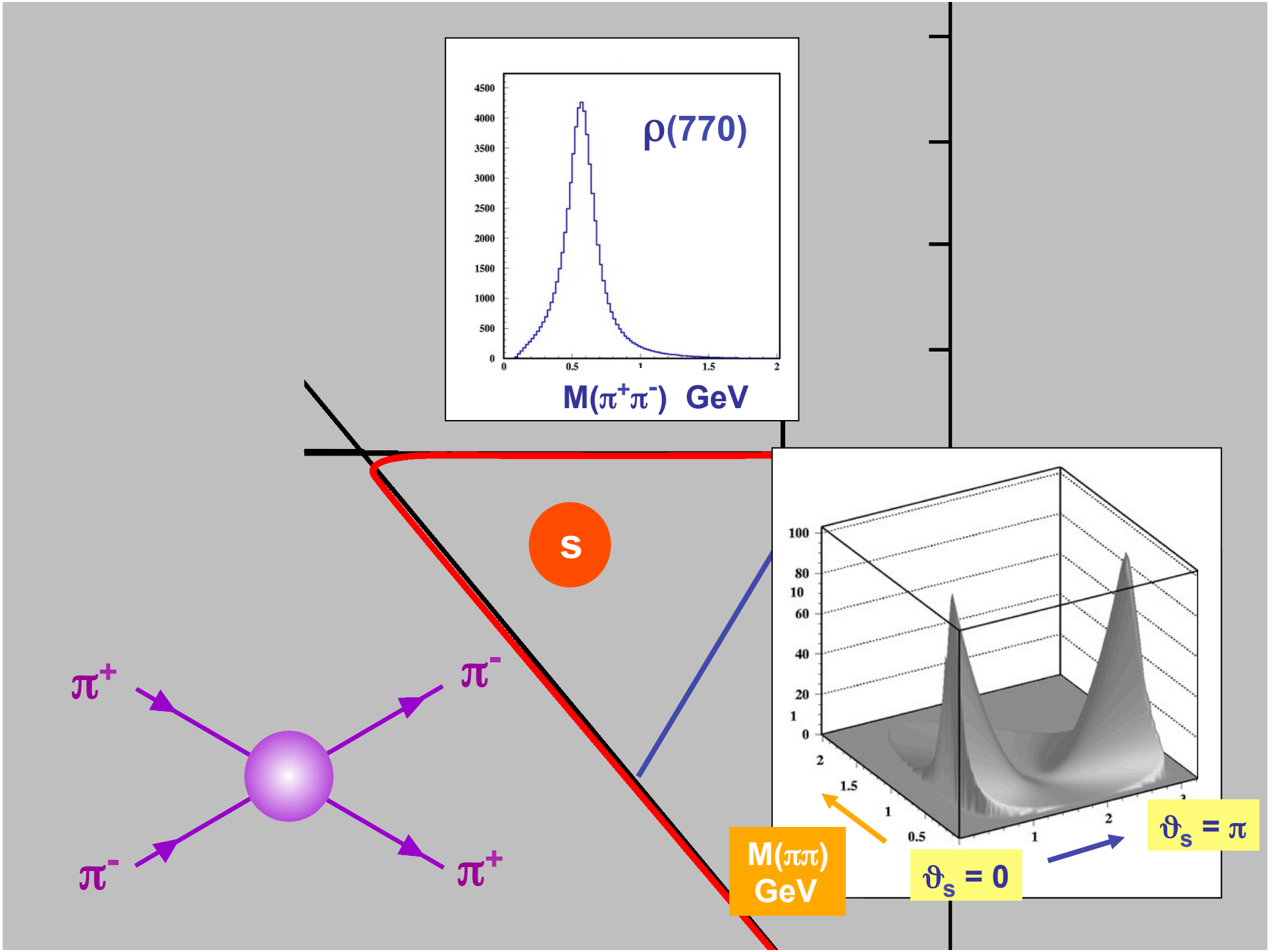

t
u
s


Crossing
Continents
t
u
s

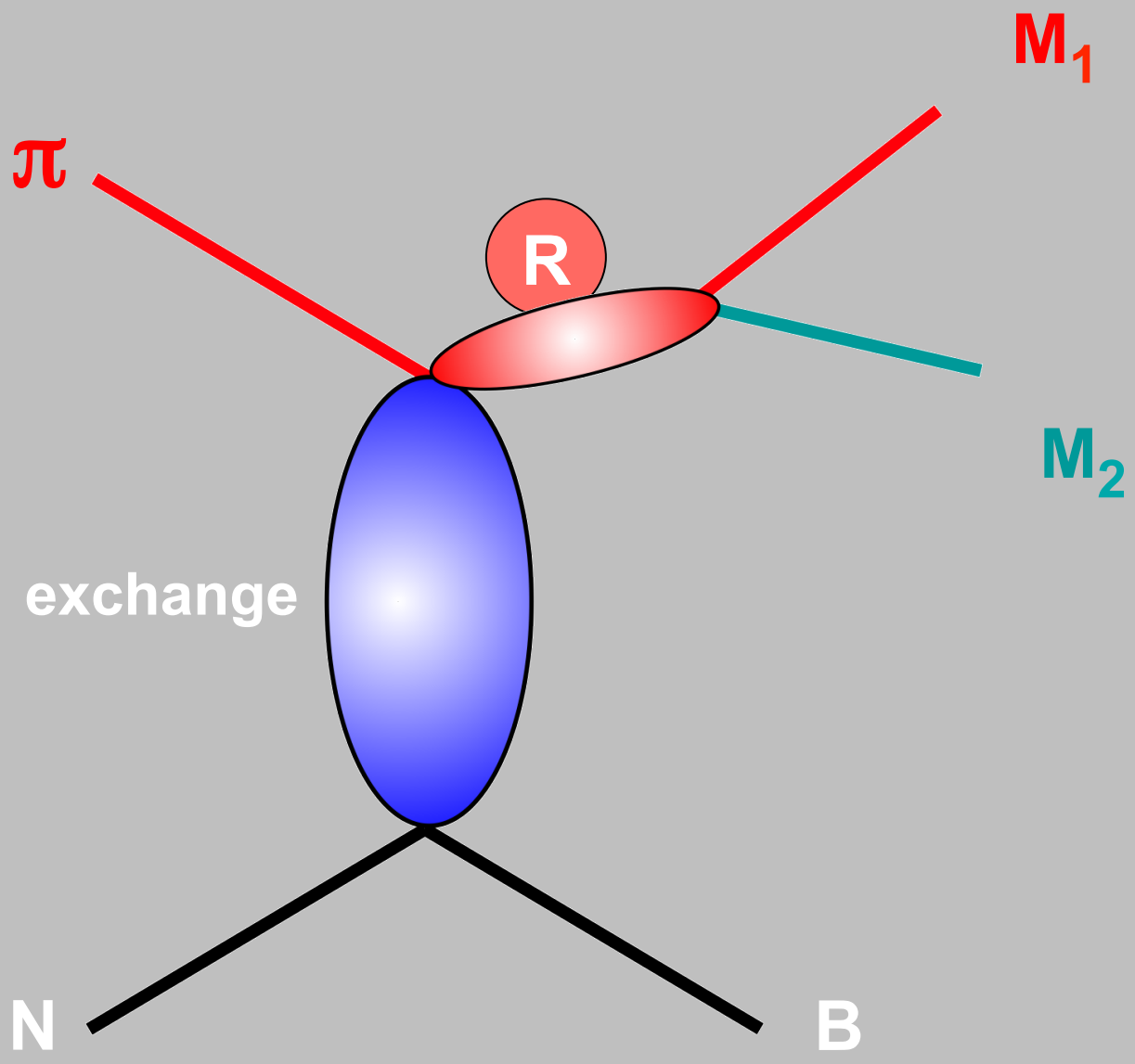

scattering regions
10
0
-10
-10
-5
0
5
+10
u
s
t
$\vartheta_s = 0$
E
$\vartheta_s = \pi$

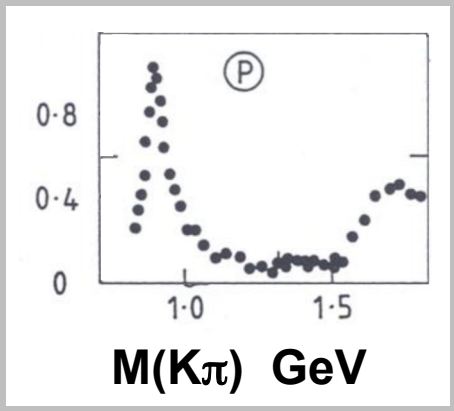

10
0
-10
-10
-5
0
5
+10
u
s
E
$\vartheta_s = 0$
$\vartheta_s = \pi$
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
$M(\pi^+\pi^-)$ GeV


10
0
-10
-10
-5
0
5
+10
u
s
M(ππ) GeV
M(π+π-) GeV
ϑs = 0
ϑs = π
E


ρ(770)
M(π+π-) GeV
s
π+
π-
π-
π+
M(ππ) GeV
ϑs = 0
ϑs = π

Hadroproduction





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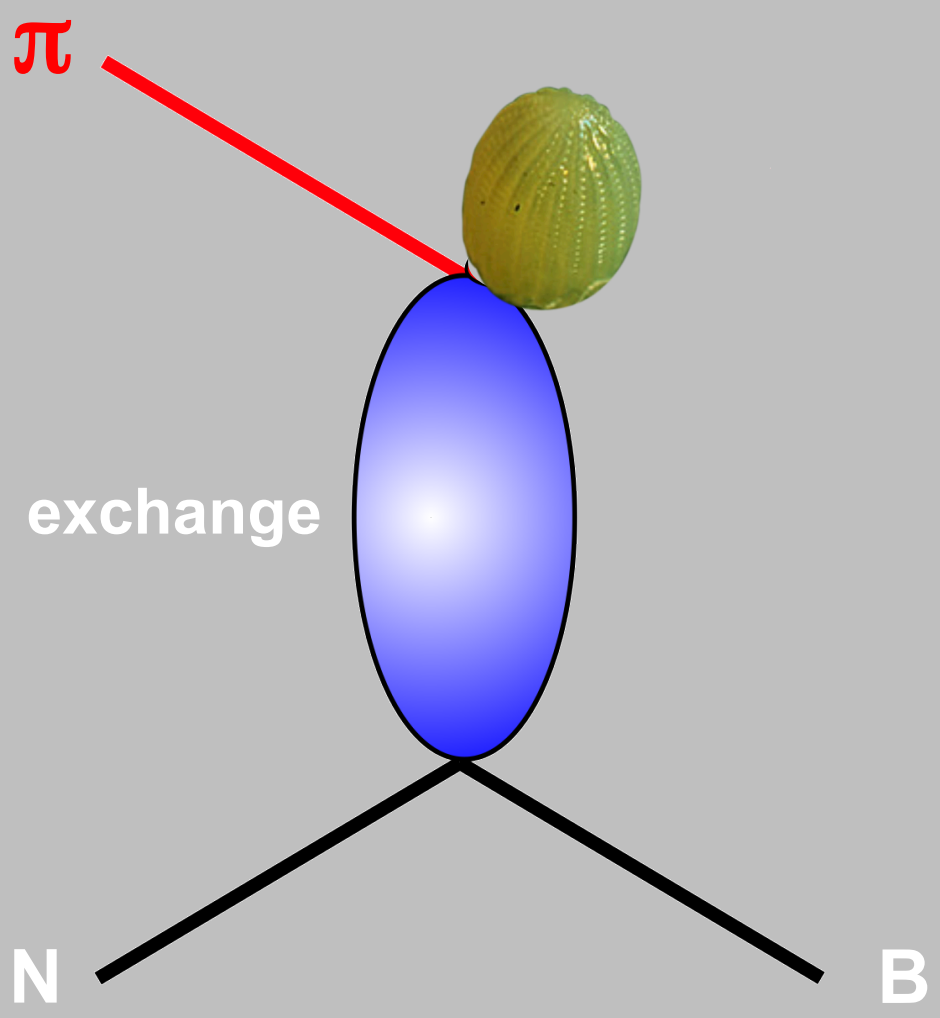

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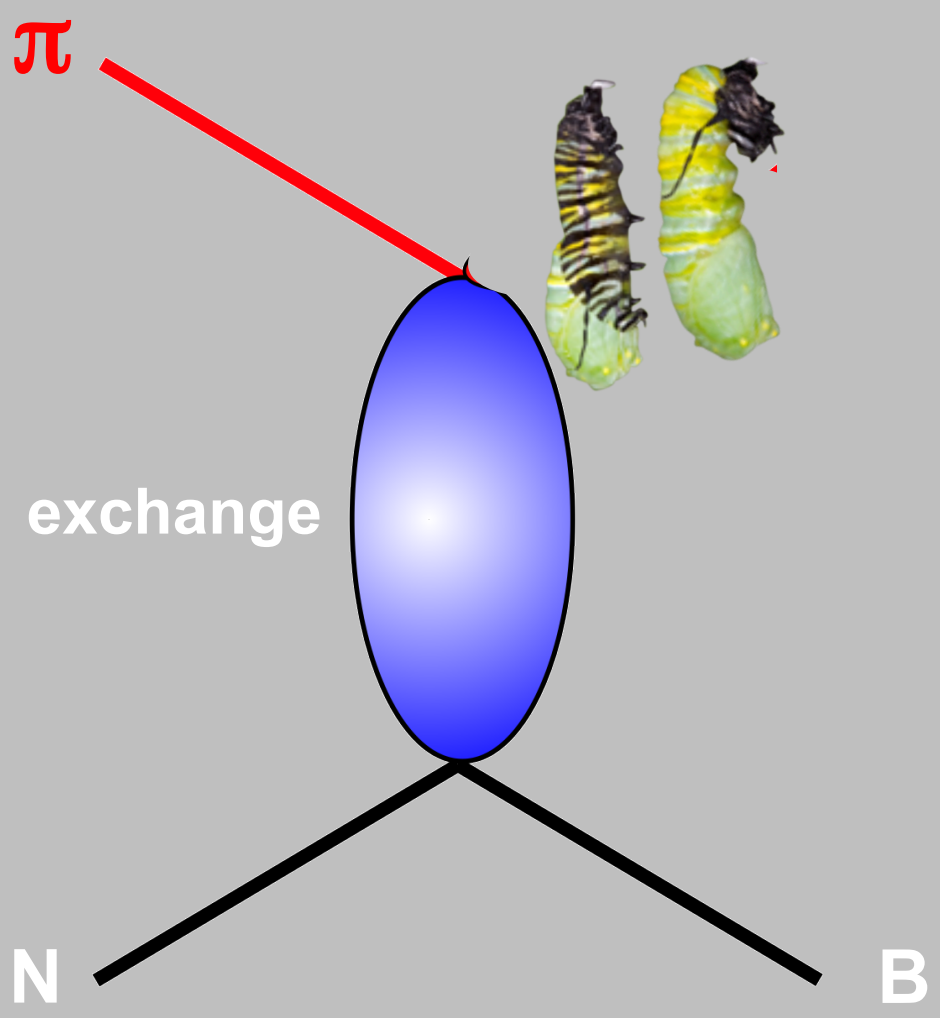

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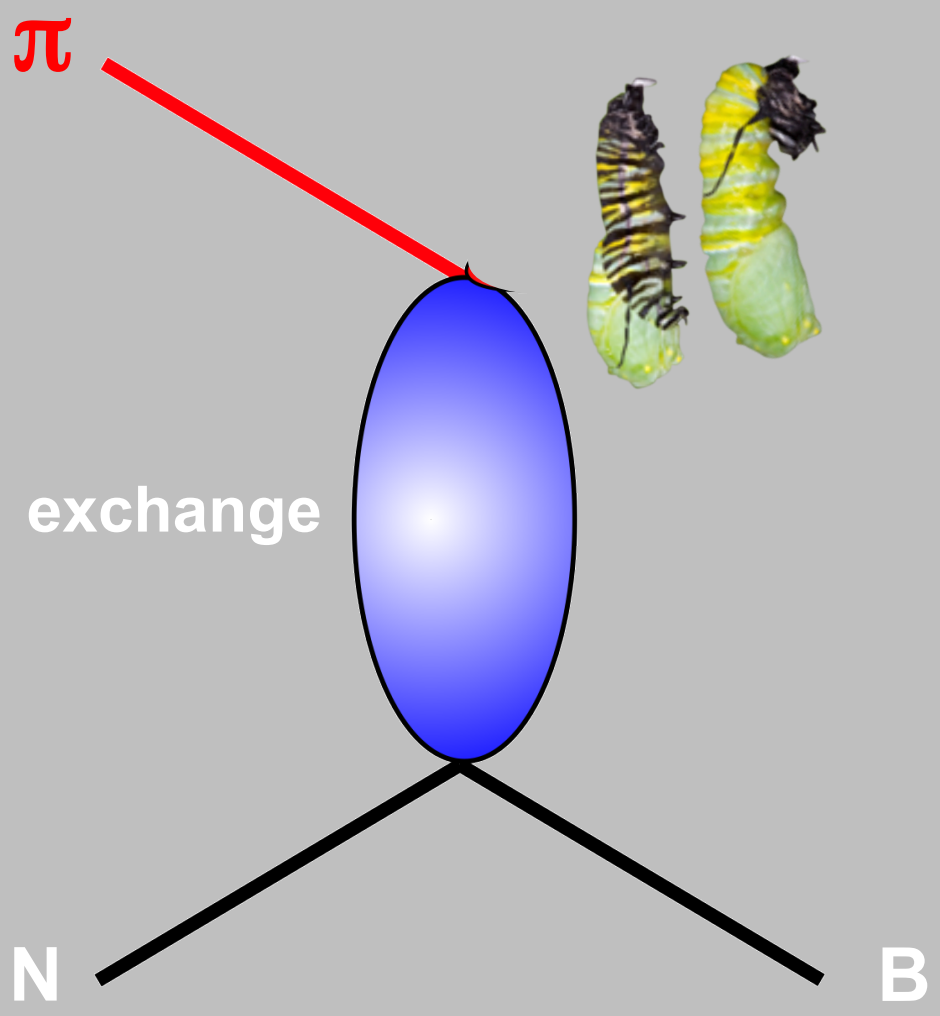

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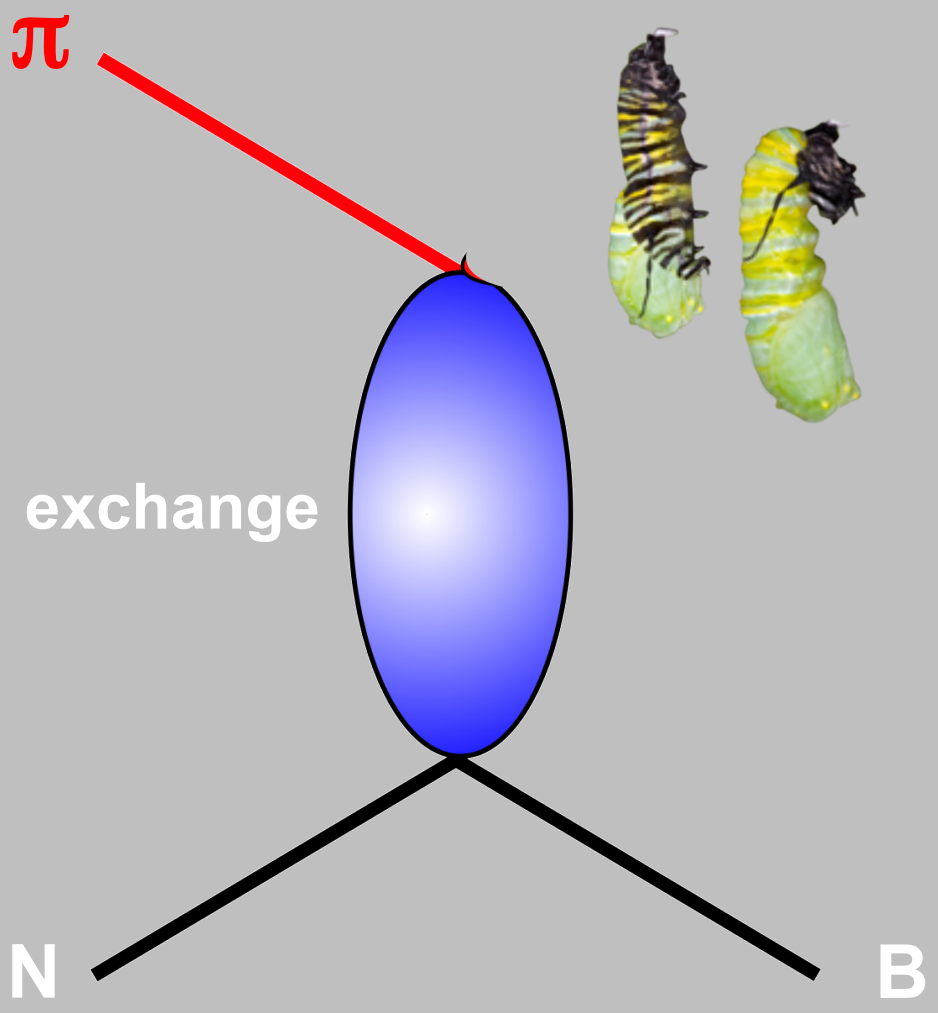

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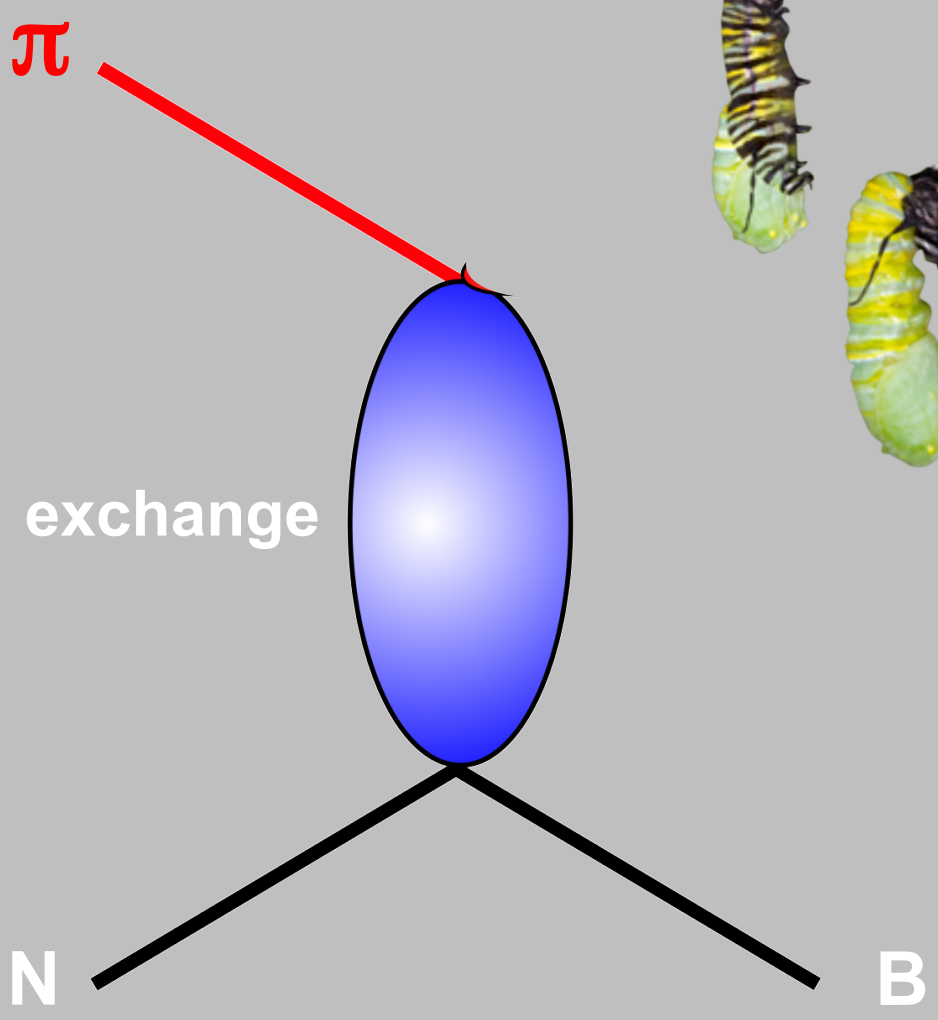

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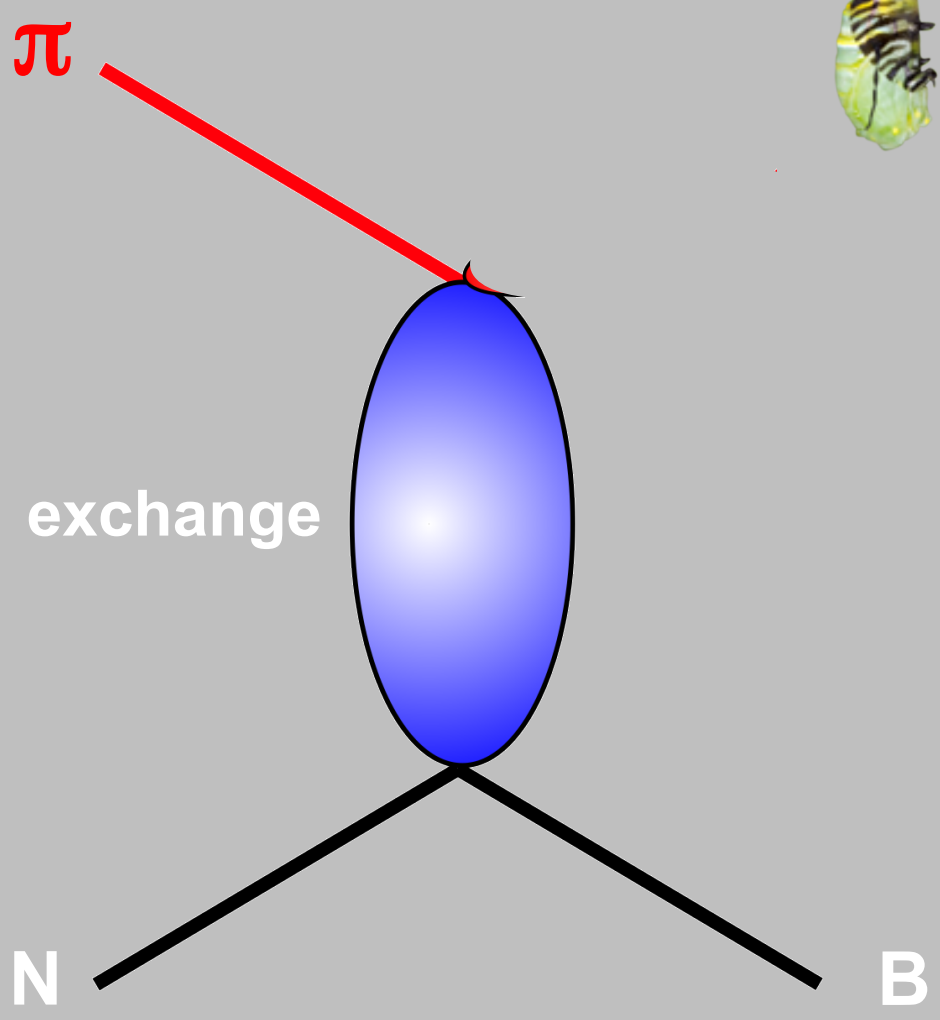

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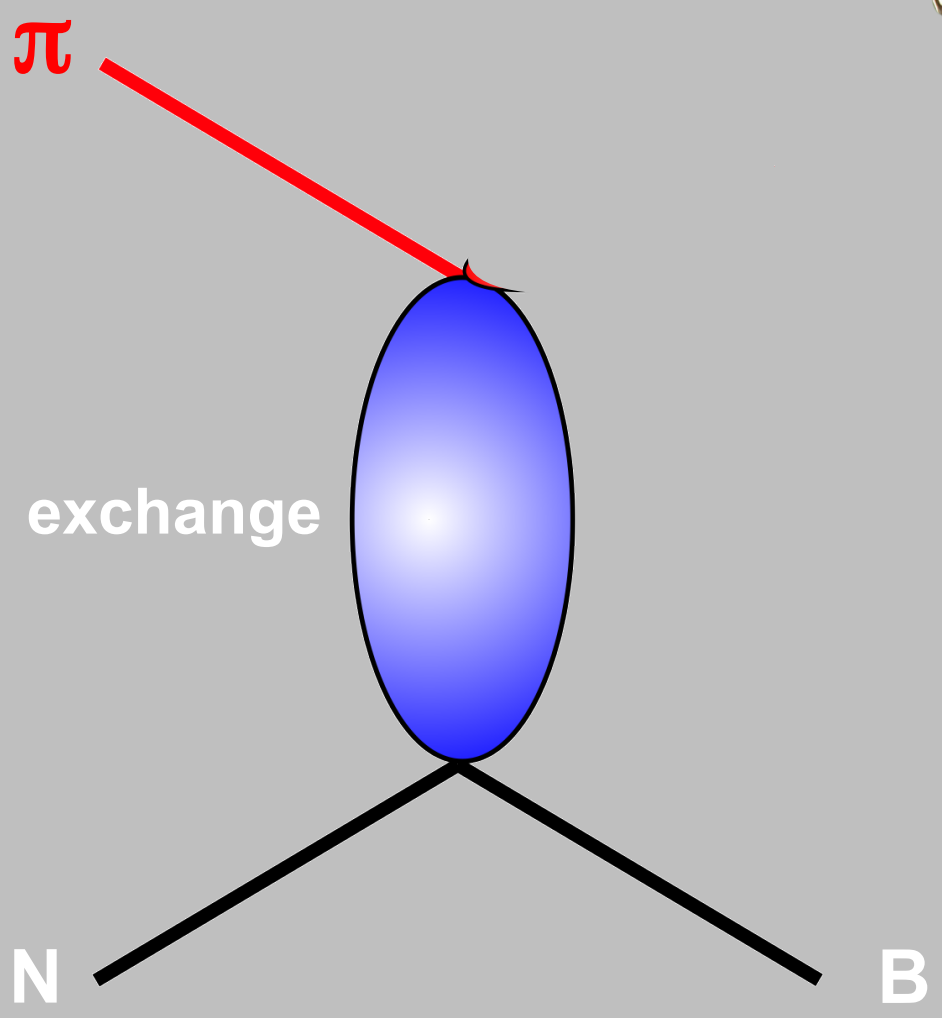

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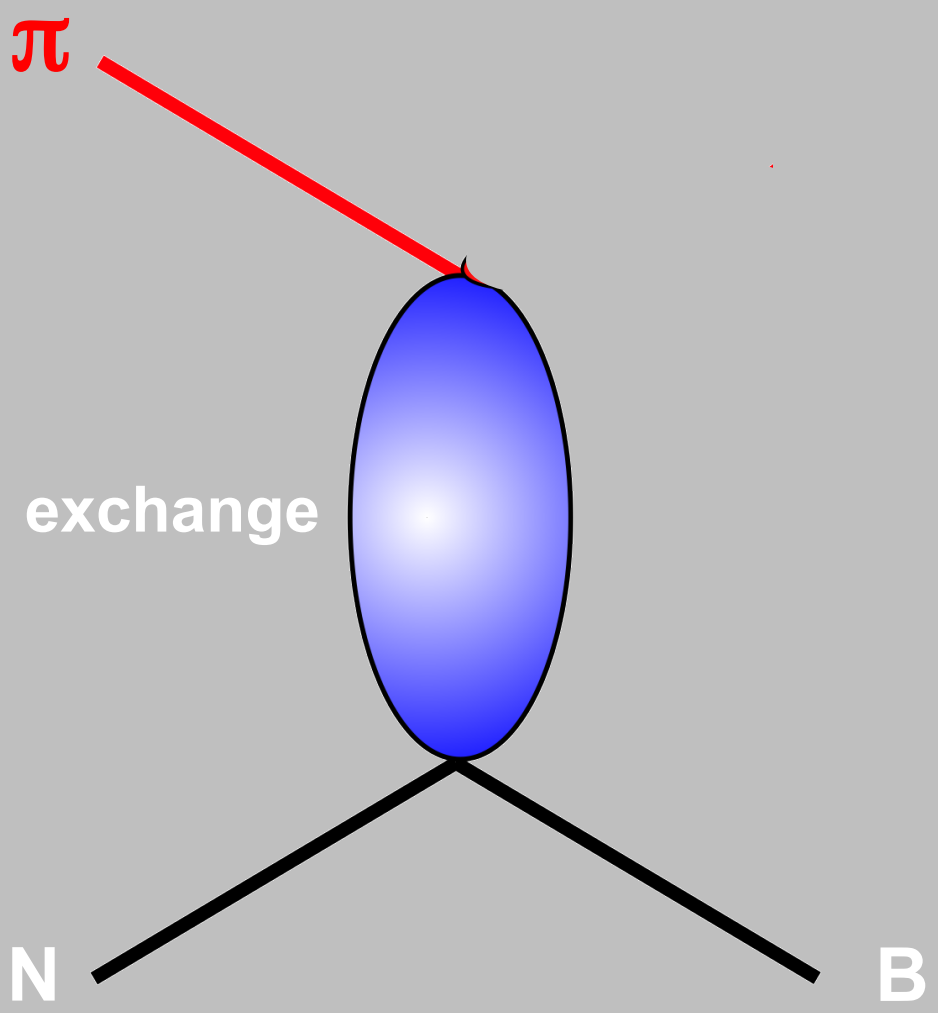
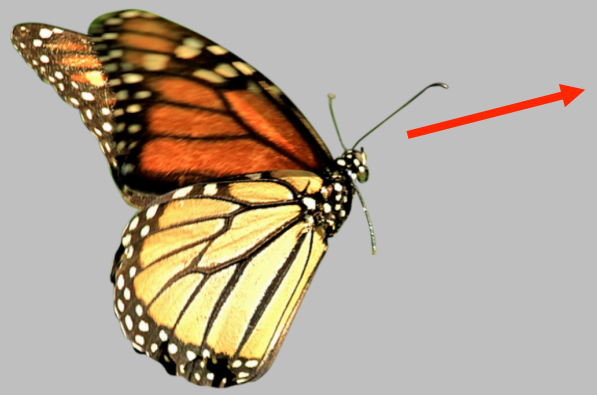
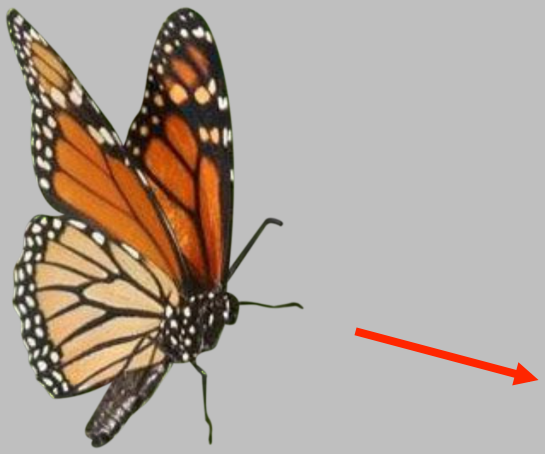
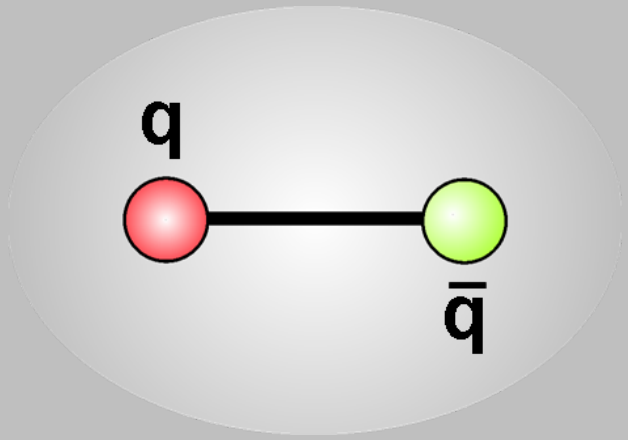


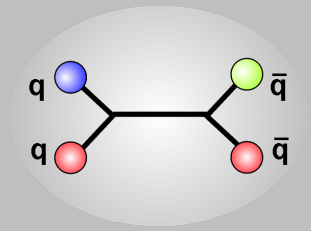


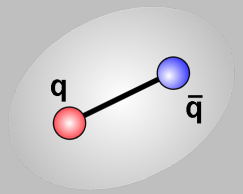


ρ(770)

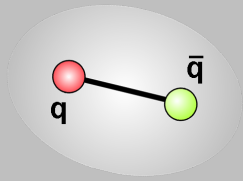
$J^{PC} = 1^{--}$







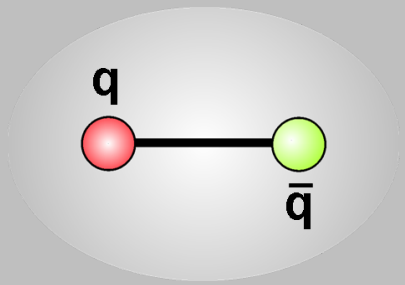
π^+

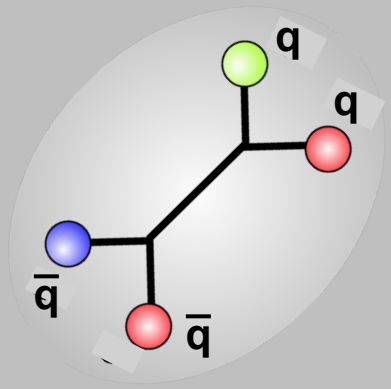


π^-

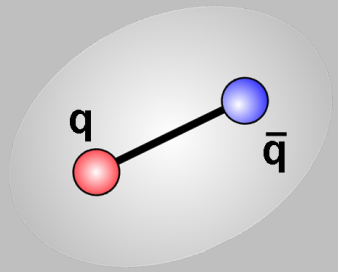
$a_1(1260)$

$J^{PC} = 1^{++}$

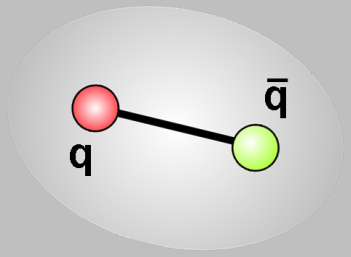




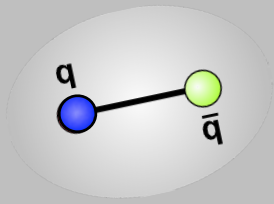
ρ^+



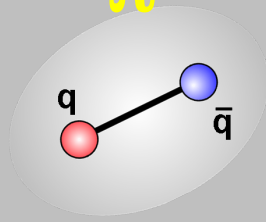
π^-

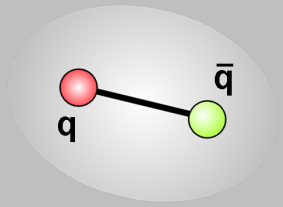


π



π





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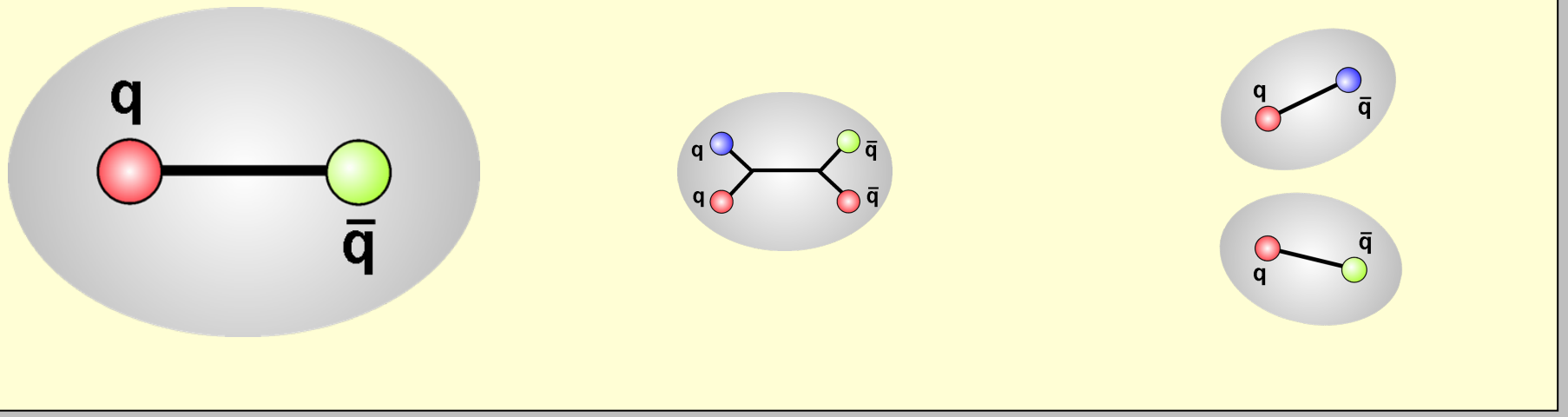
q
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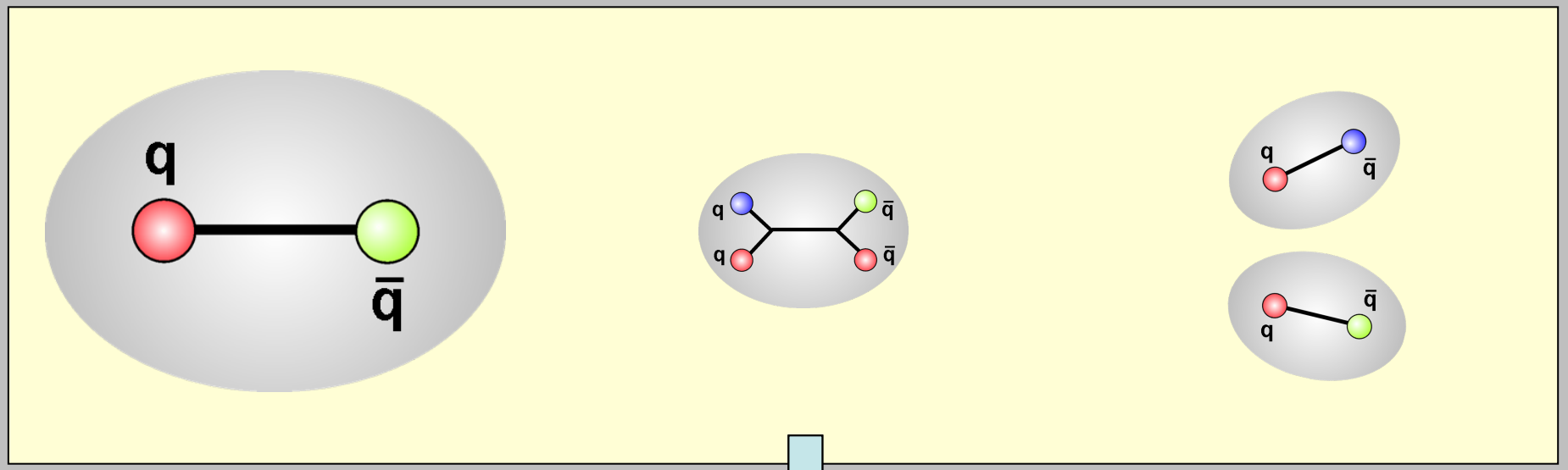
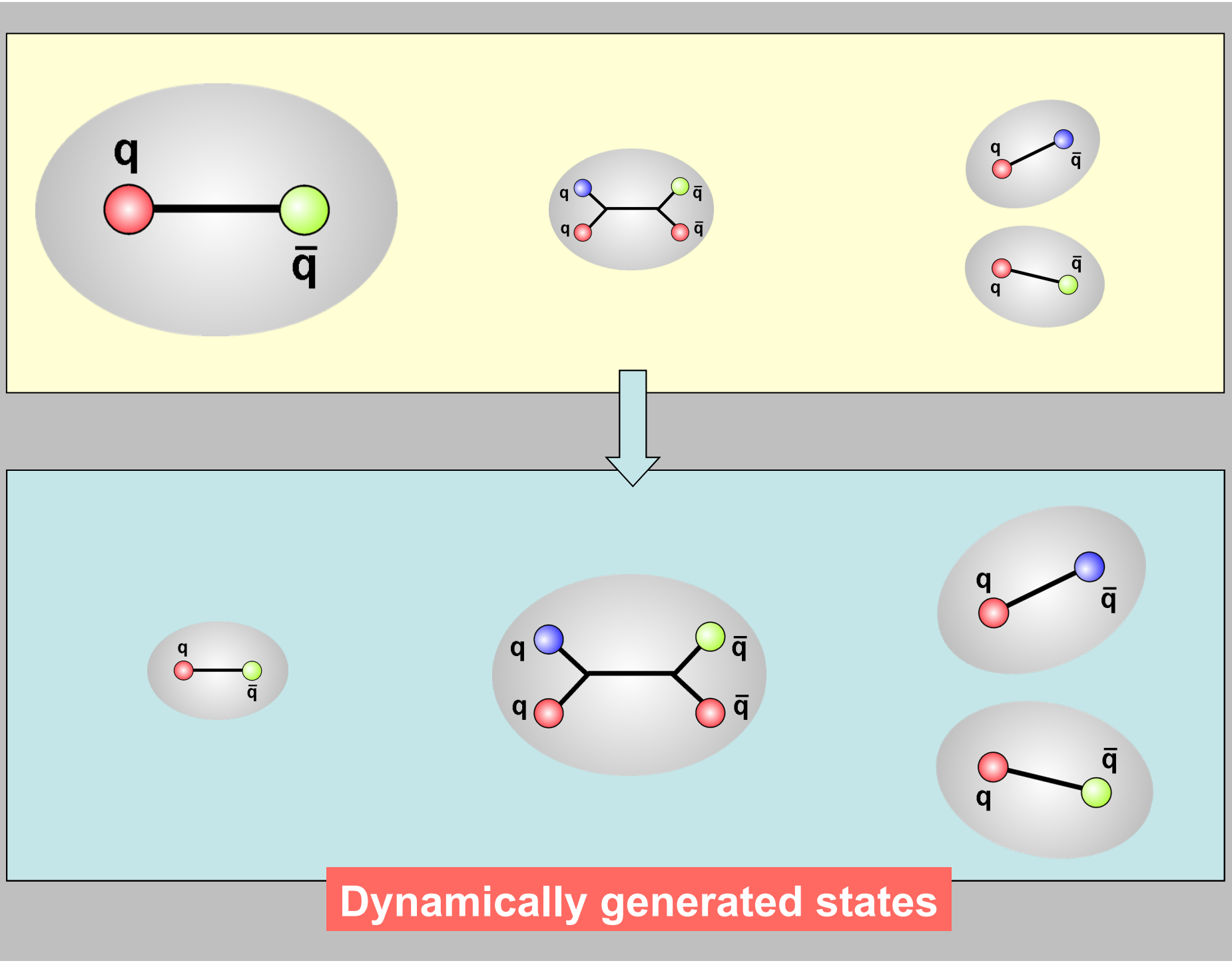


Degrees of freedom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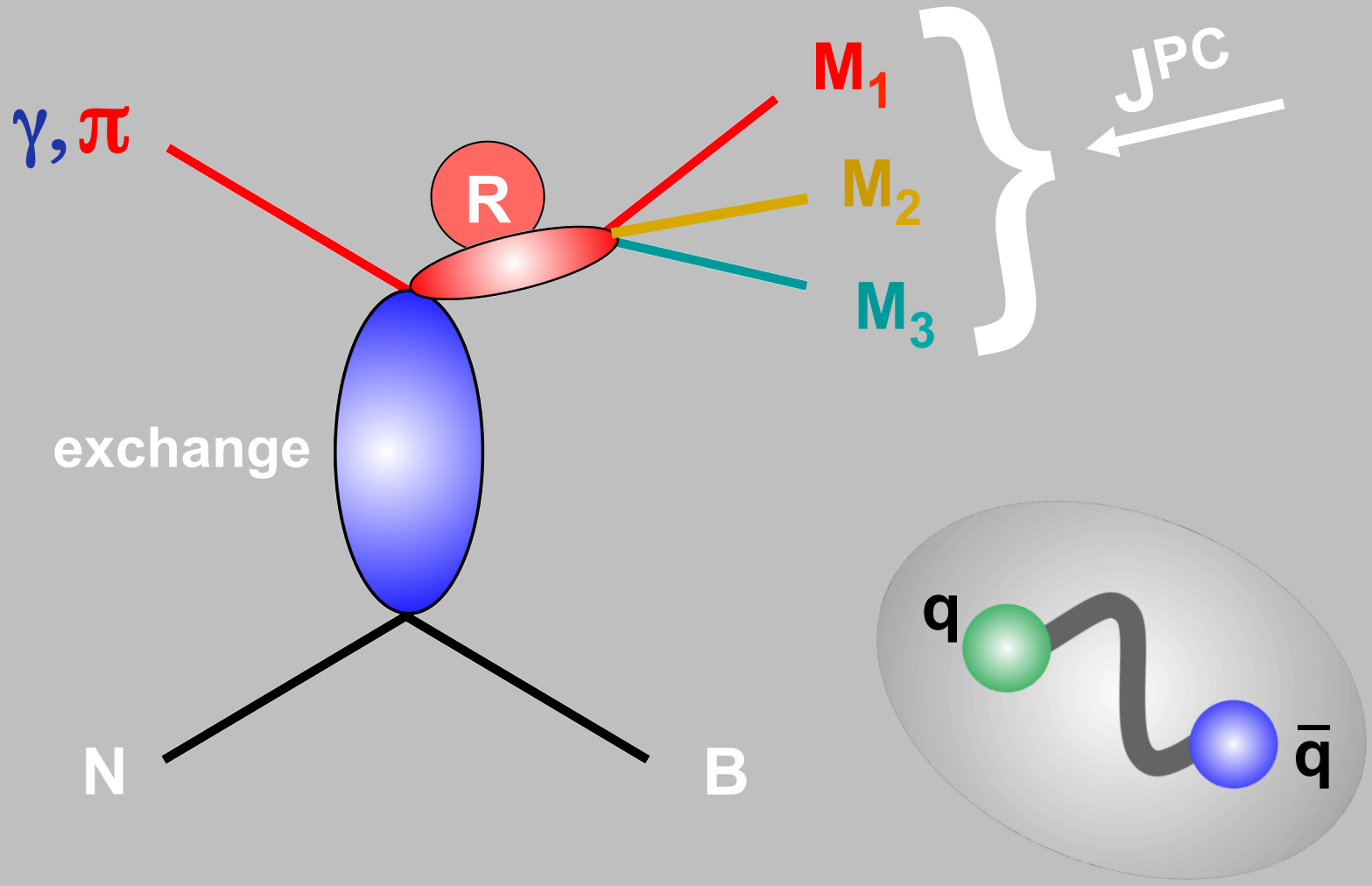
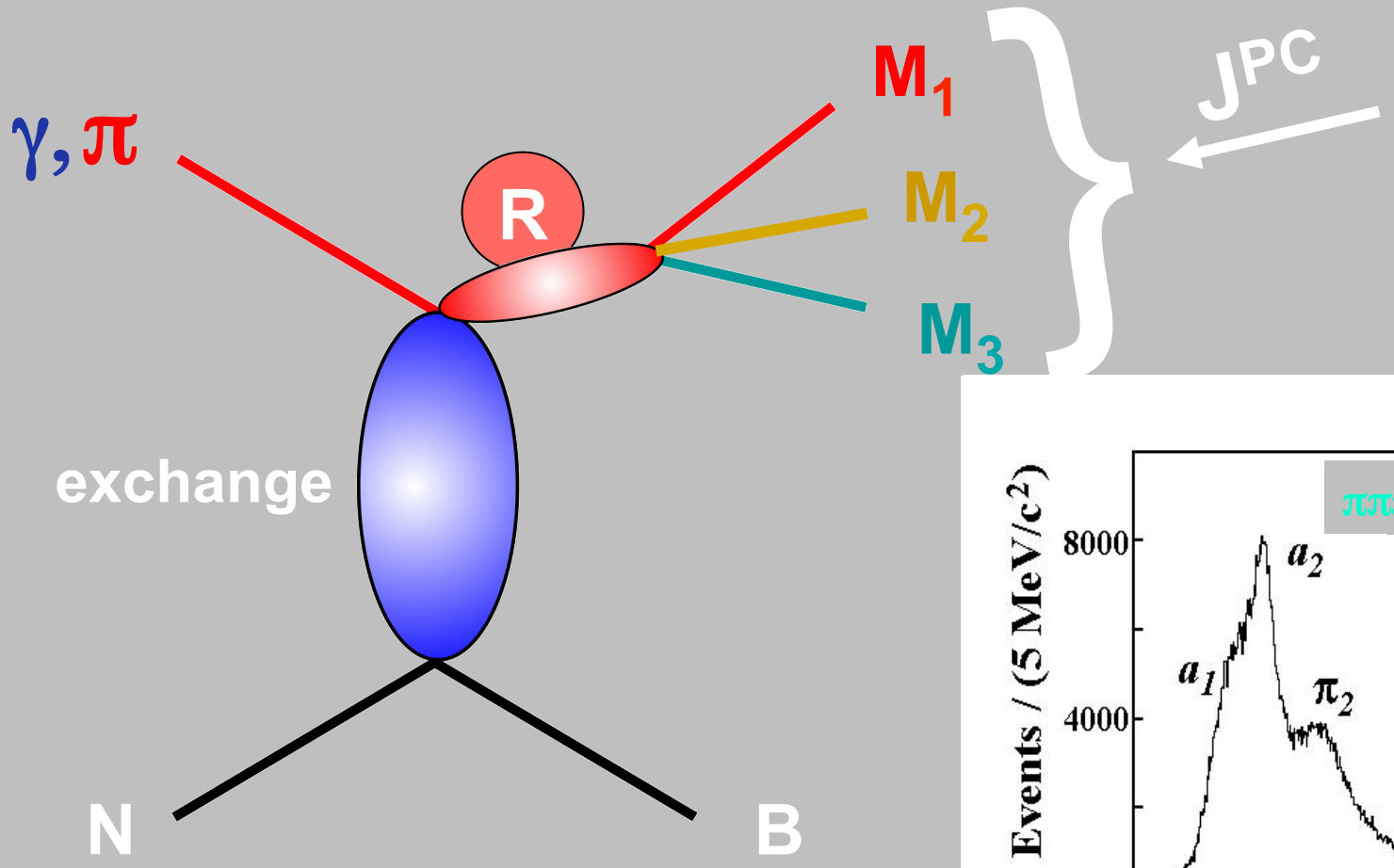
Dynamically generated states

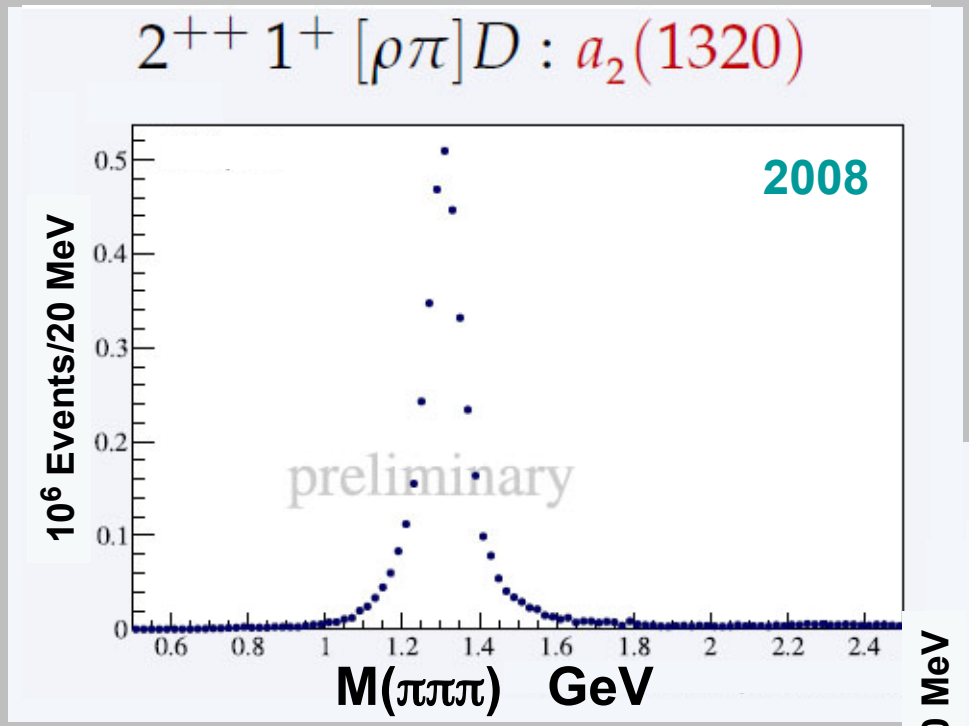
Amplitude Analysis

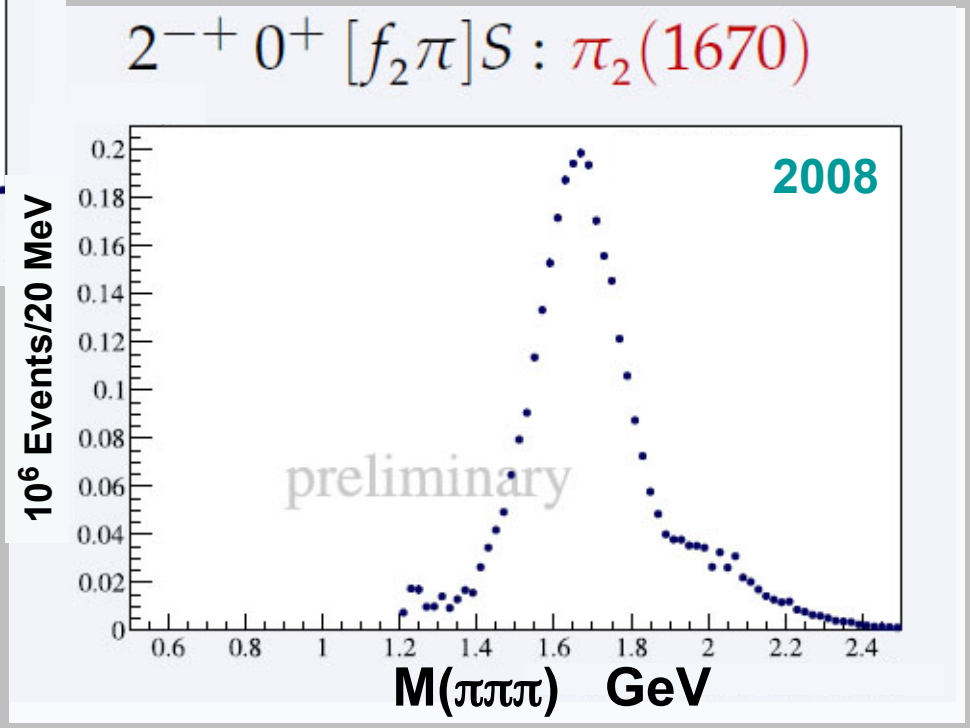


Amplitude Analysis



COMPASS @ CERN





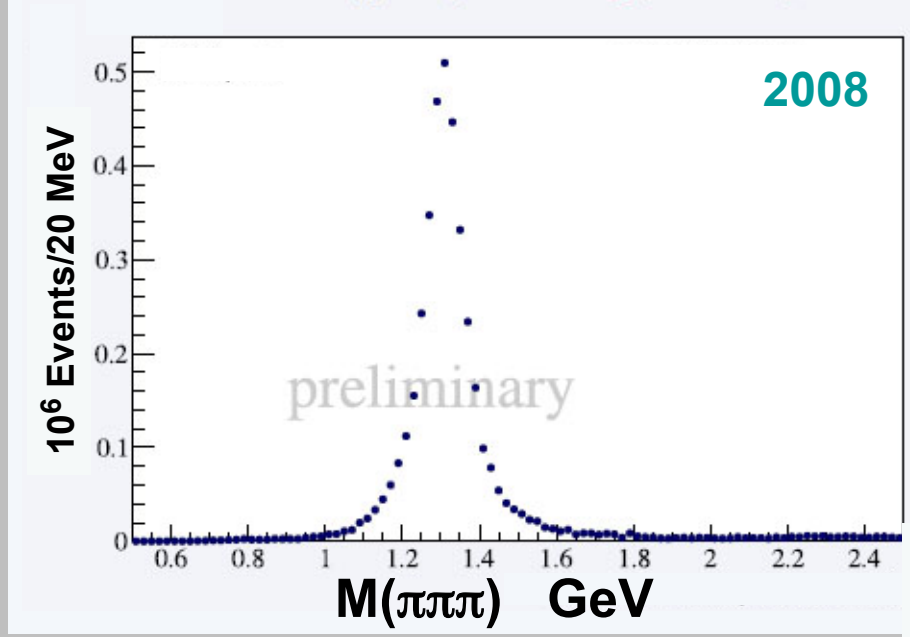
PWA: 2 of 88 waves

COMPASS @ CERN

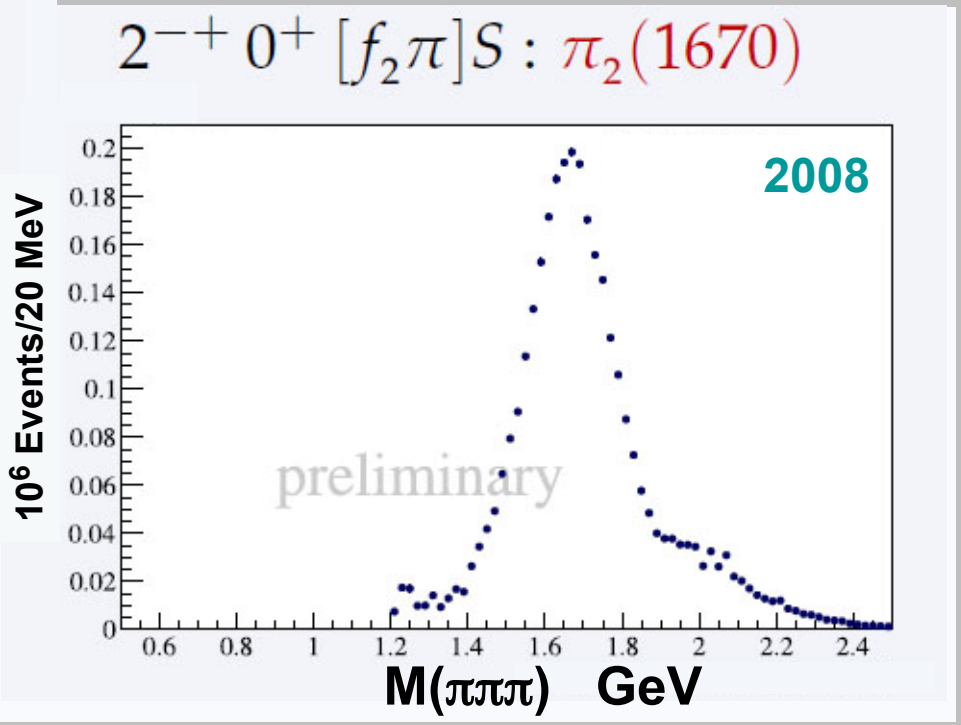
Robust 1^{-+} results awaited

impact of limiting number of waves

$2^{++}\,1^{+}\,[\rho\pi]D : a_2(1320)$



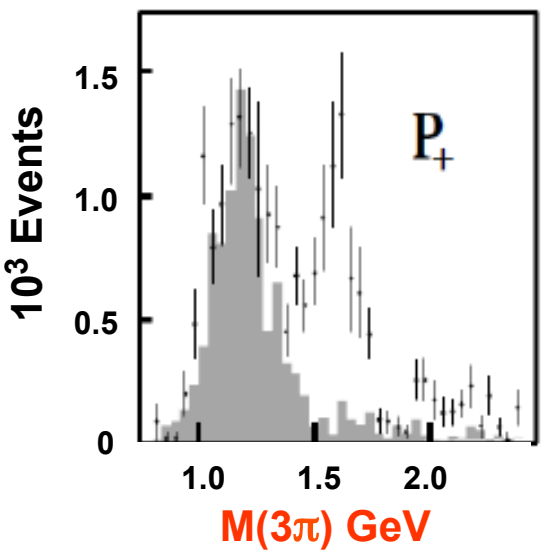
$2^{-+}\,0^{+}\,[f_2\pi]S : \pi_2(1670)$

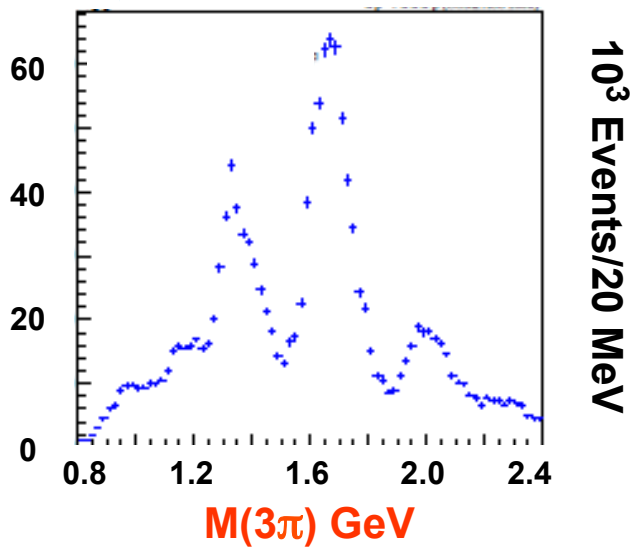


PWA: 2 of 88 waves

P-wave $\rho\pi$ 1^{-+}

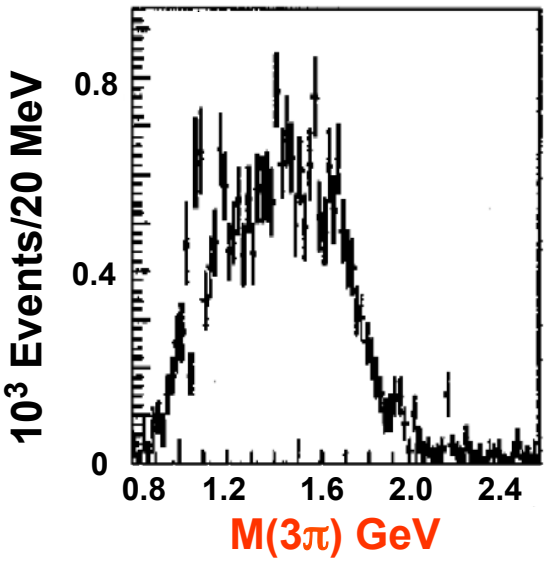
BNL-E852-I
21 waves

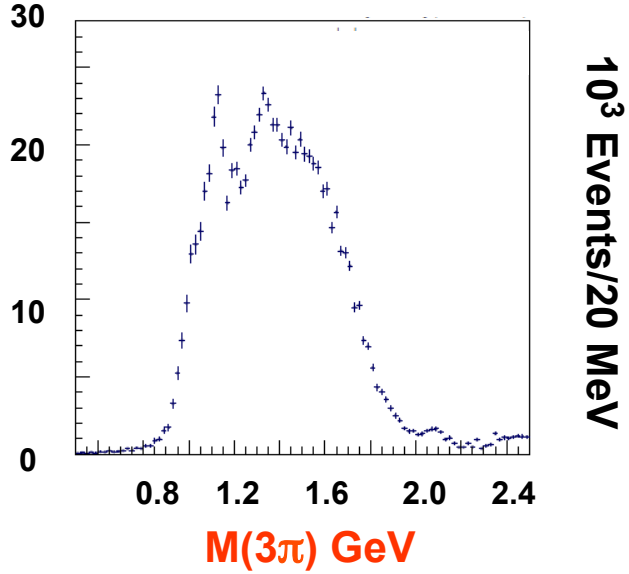




COMPASS
21 waves

VES
42 waves

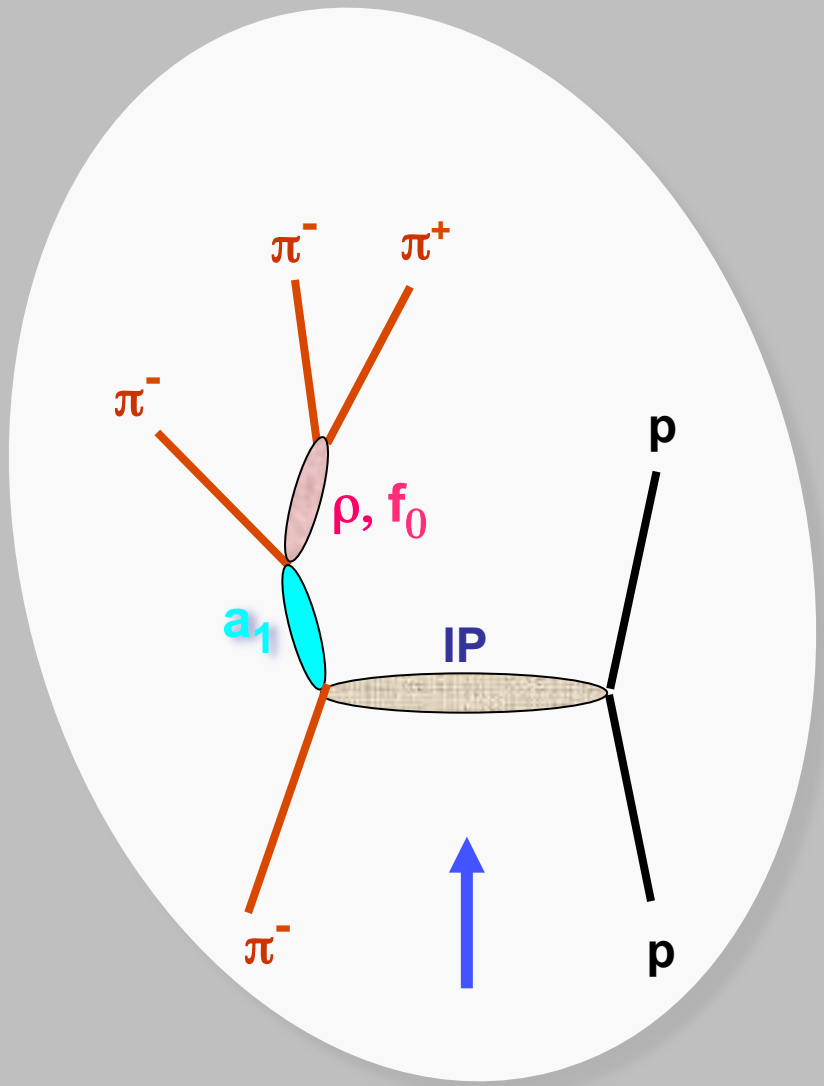


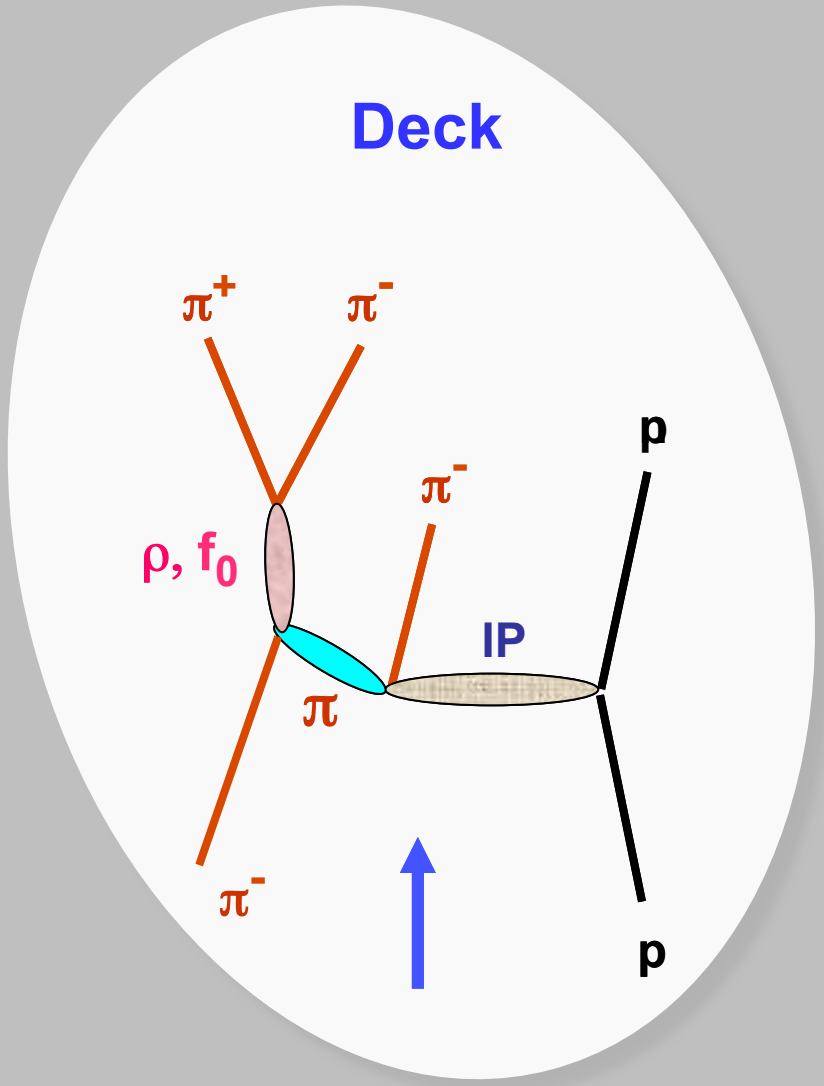


COMPASS
44 waves

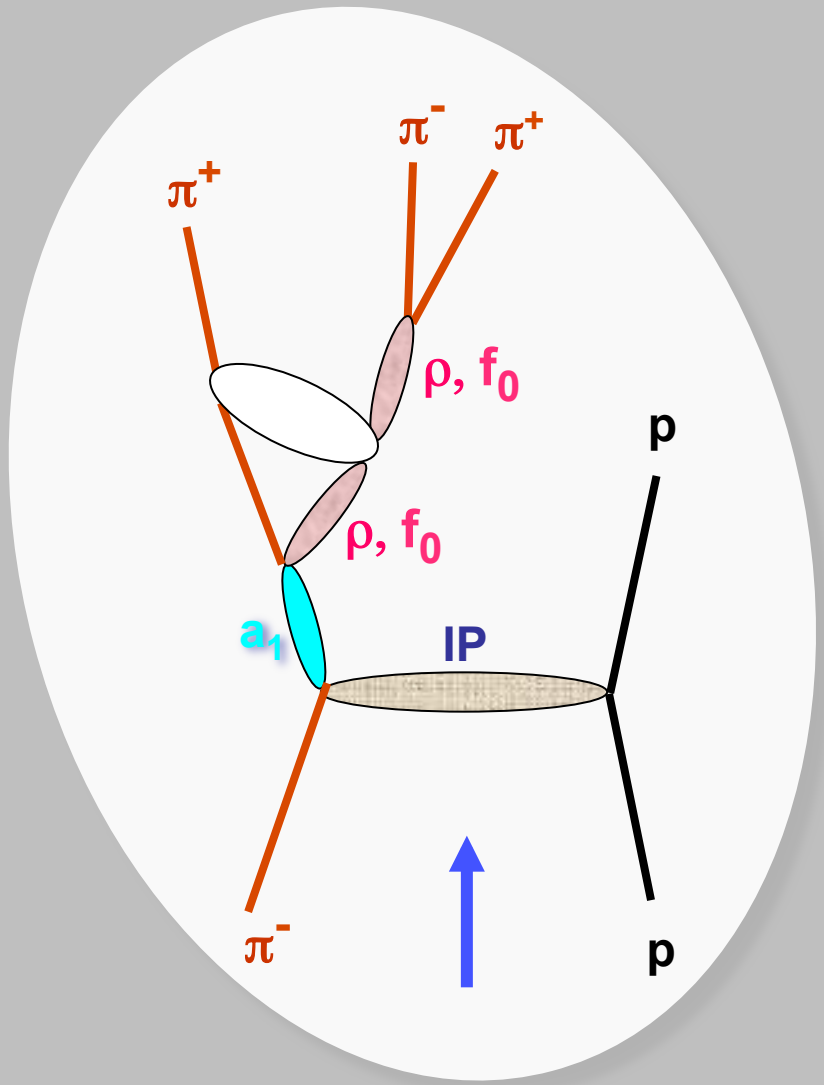
- **essential to eliminate partial wave truncation**

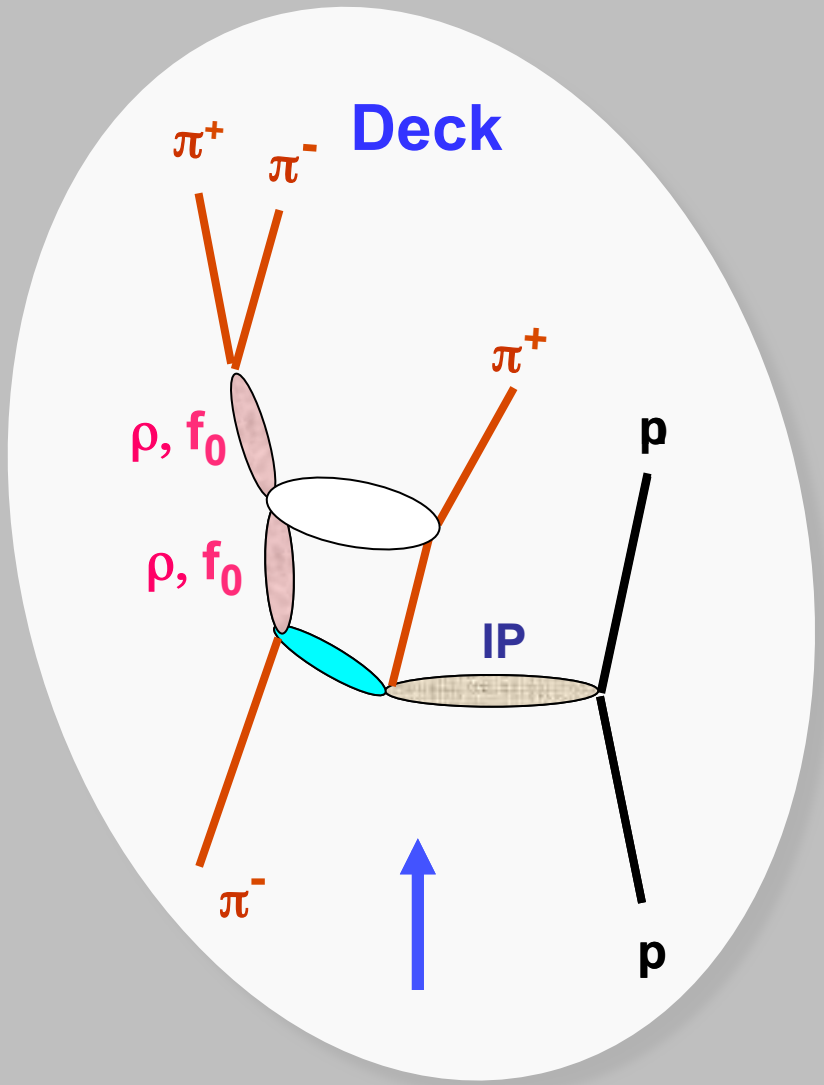
reaction mechanisms





reaction mechanisms

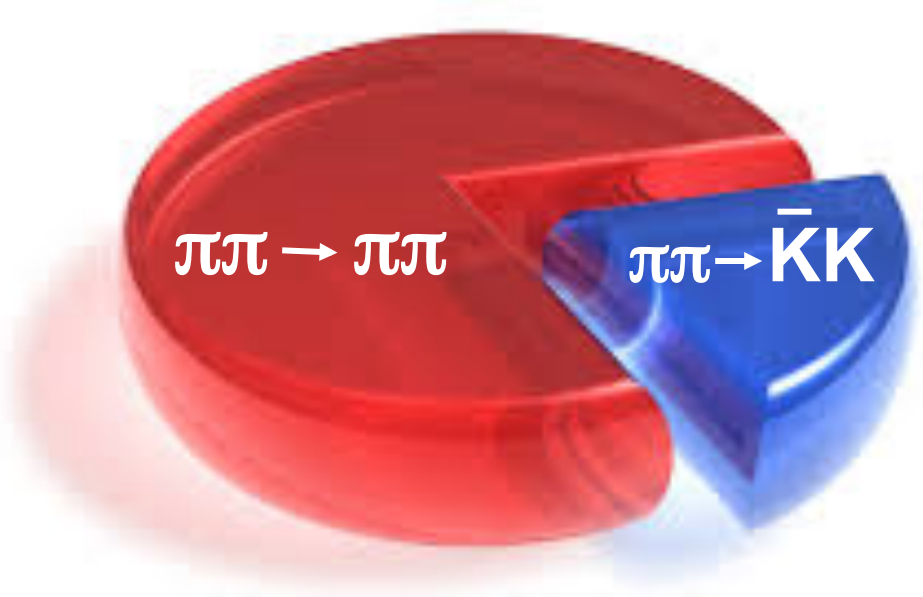




Unitarity

Sum of probabilities $= \sum_i P_i = 1$

Conservation of probability



Sum of probabilities $= \sum_i P_i = 1$

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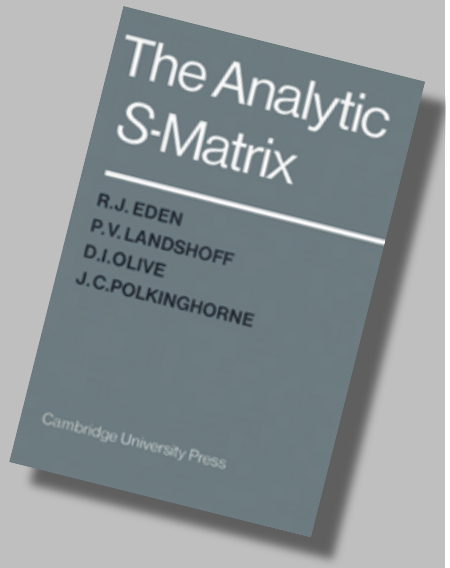
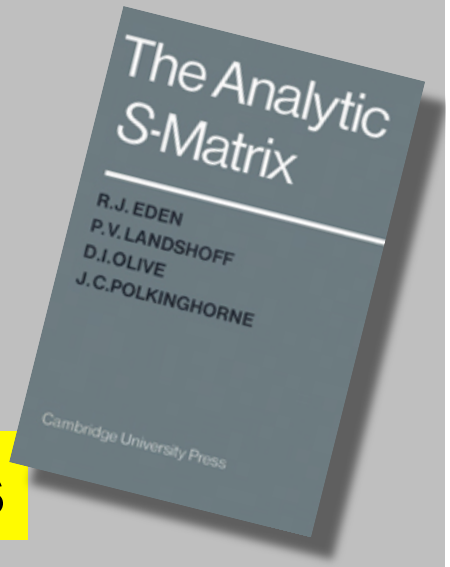
Outstanding theory issues

- **Techniques of Amplitude Analysis**

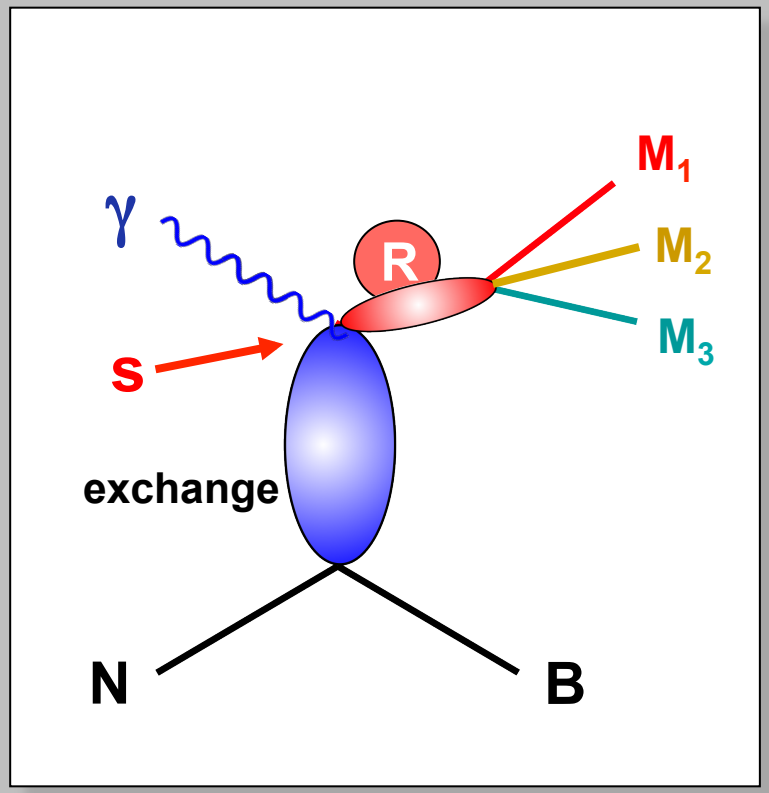
synergy with scattering on the lattice



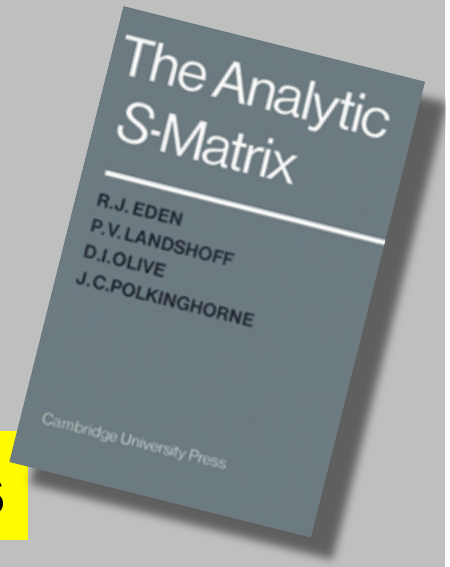
Outstanding theory issues



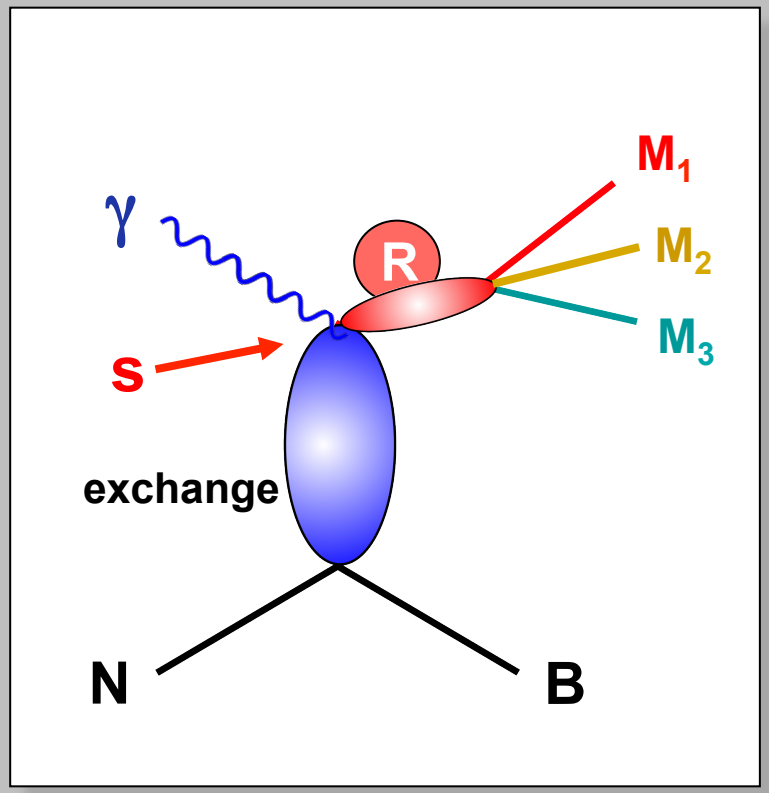
- Techniques of **Amplitude Analysis**
- **Understand reaction mechanisms**

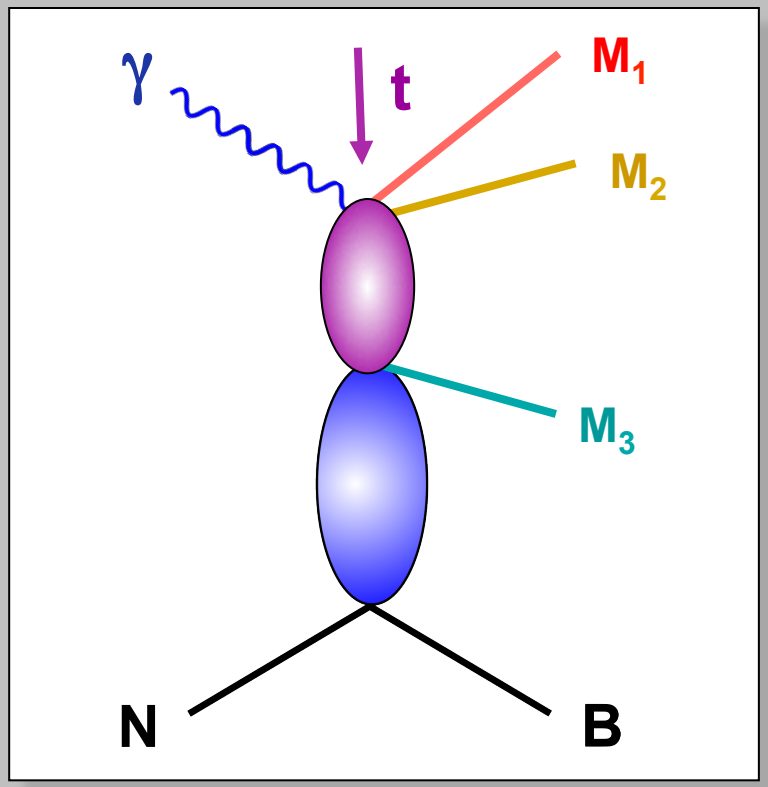


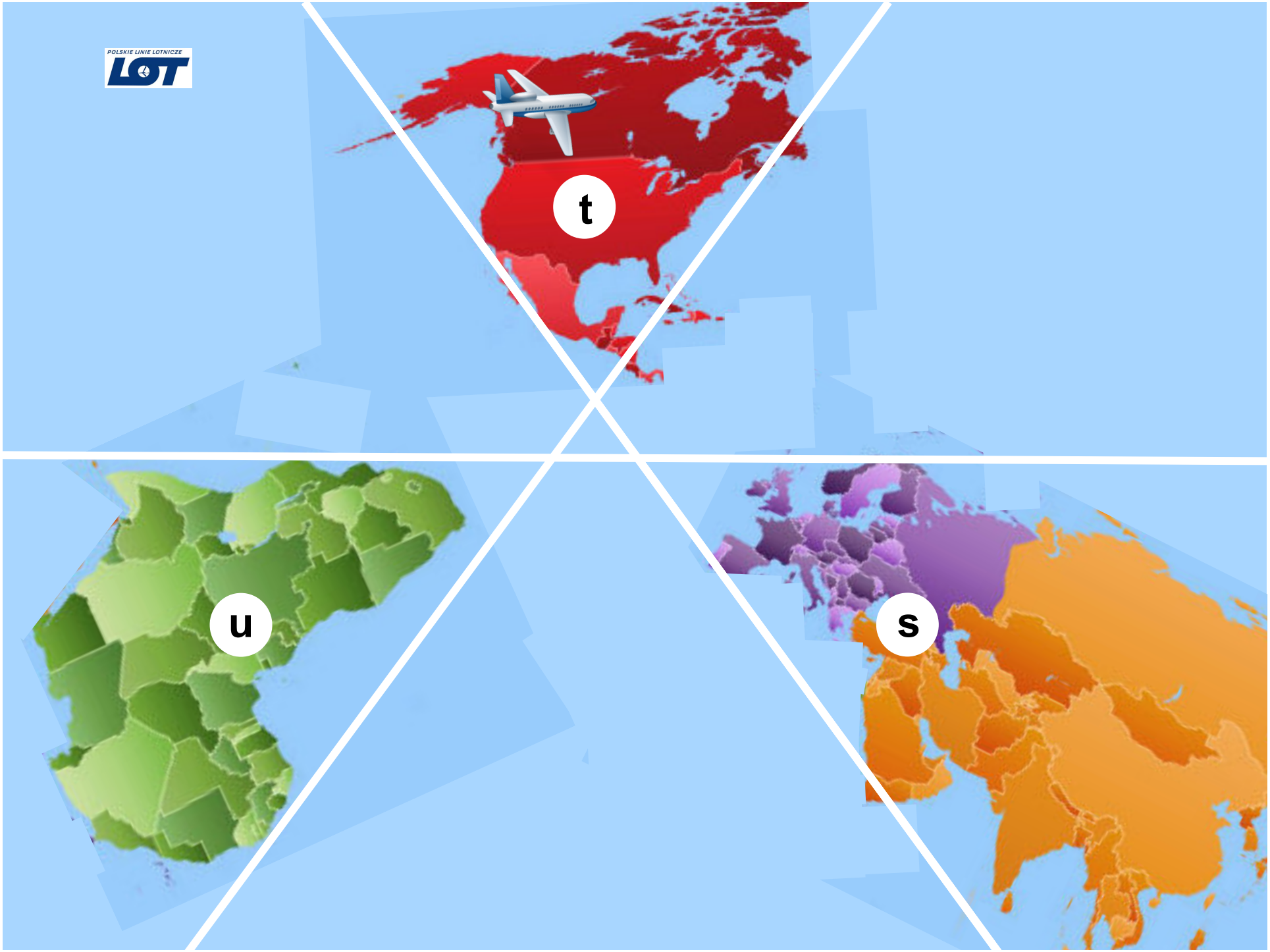
Outstanding theory issues



- Techniques of **Amplitude Analysis**
- **Understand reaction mechanisms**



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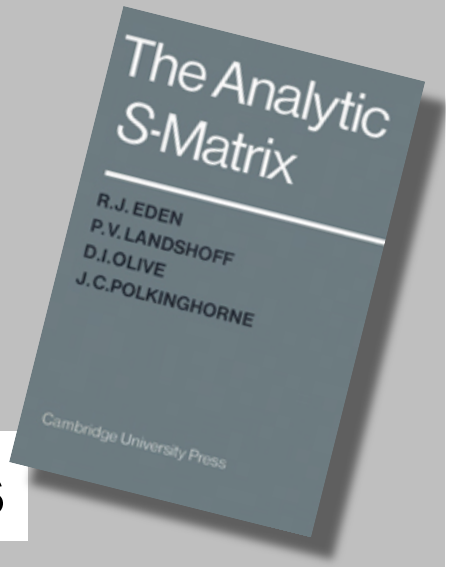
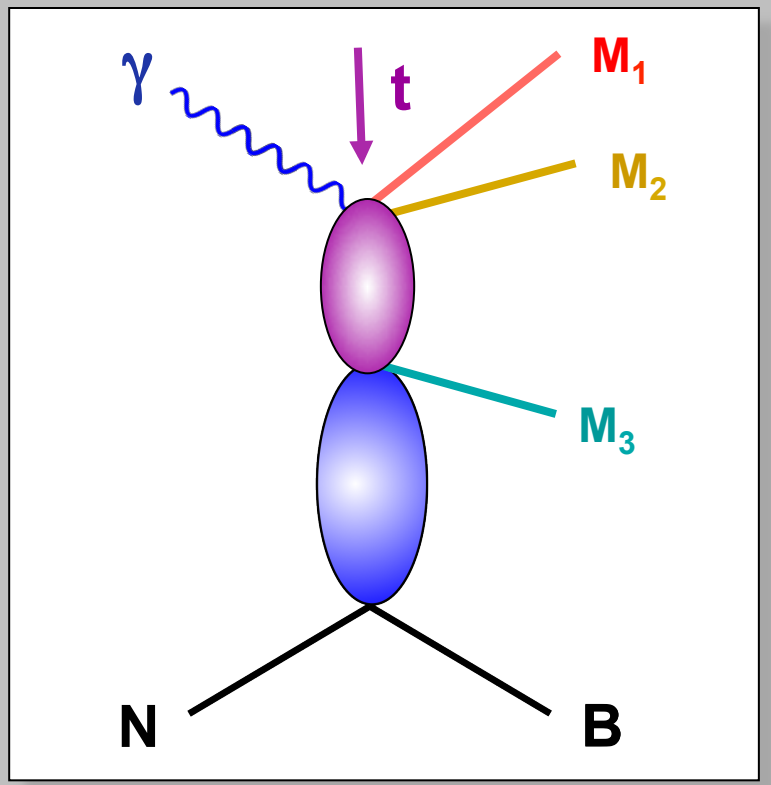
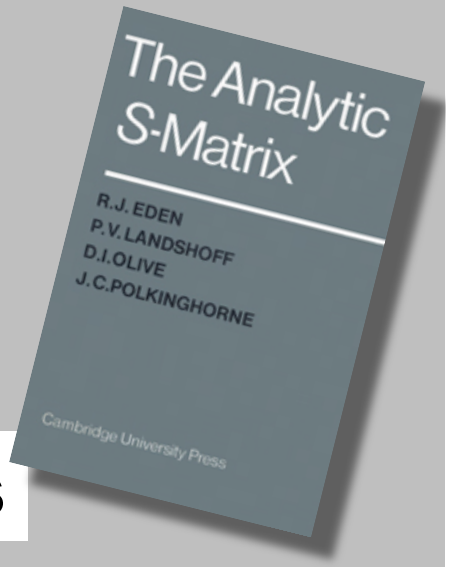
Outstanding theory issues



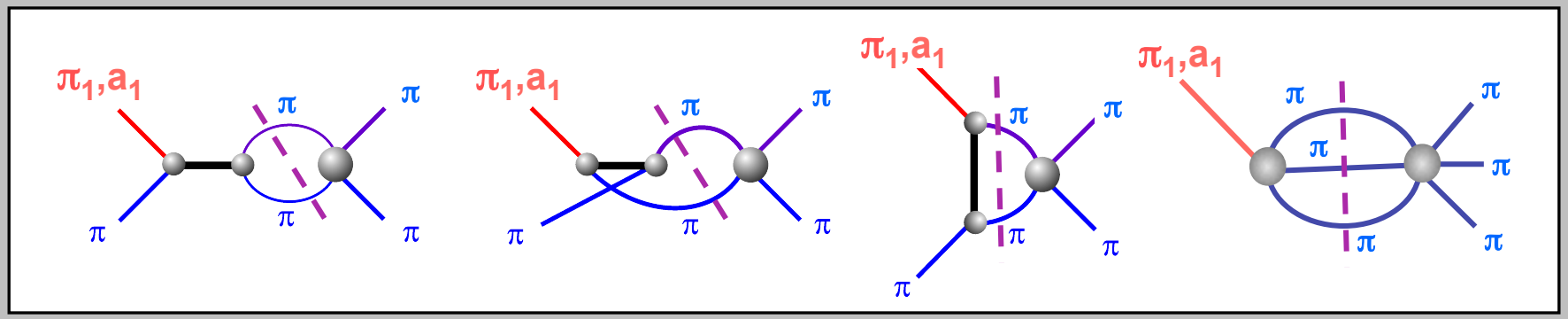
- Techniques of **Amplitude Analysis**
- Understand reaction mechanisms
- **Crossing:** eliminates partial wave truncation



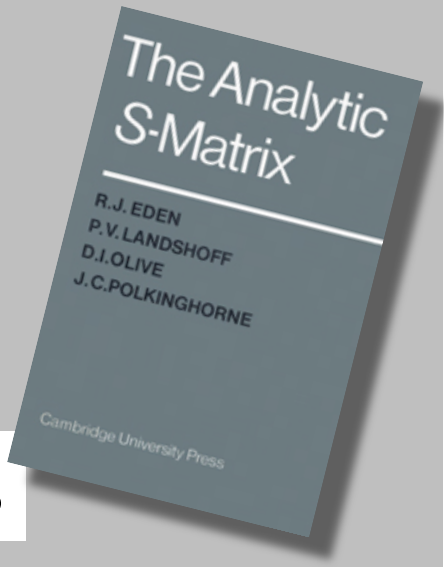
Outstanding theory issues



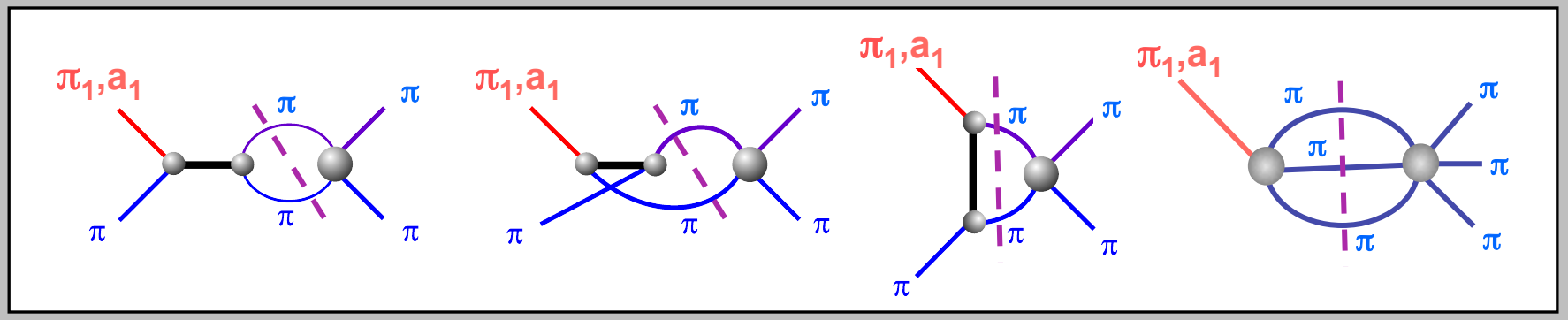
- Techniques of **Amplitude Analysis**
- Understand reaction mechanisms
- Unitarity and final state interactions

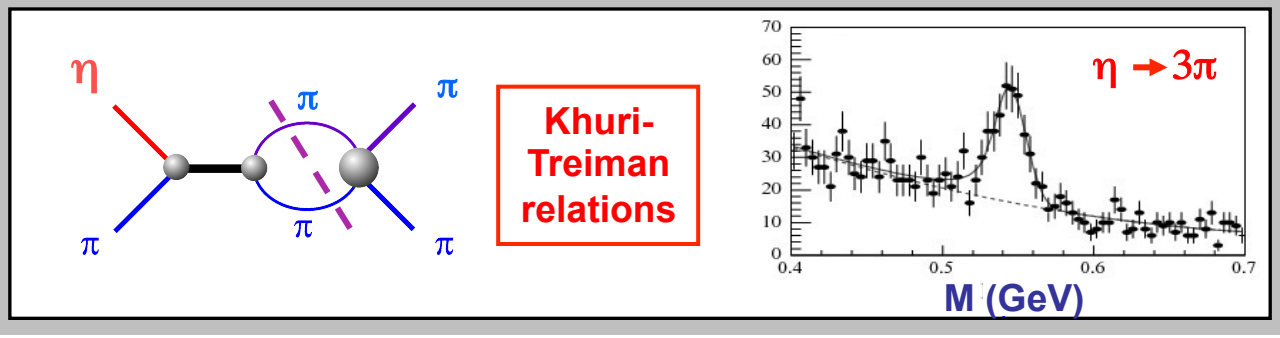


Outstanding theory issues

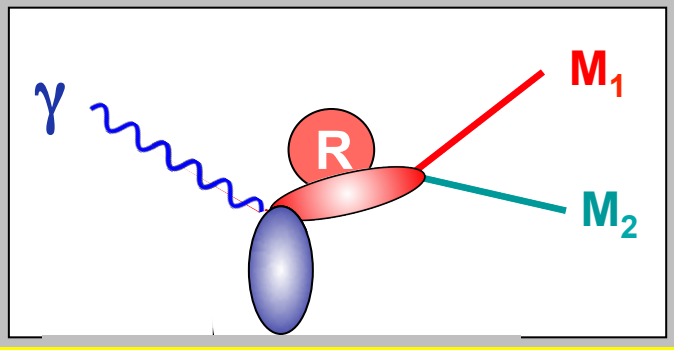


- Techniques of **Amplitude Analysis**
- Understand reaction mechanisms
- **Unitarity and final state interactions**



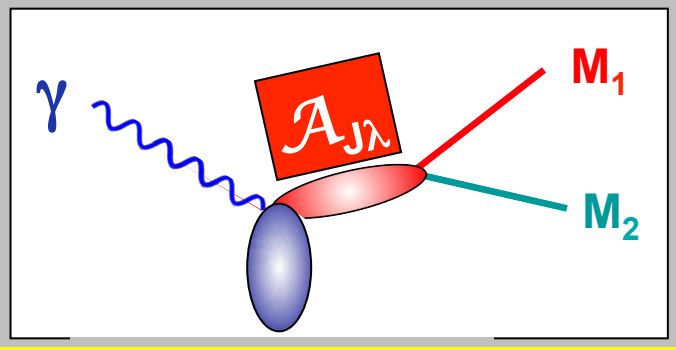


Model Analyses



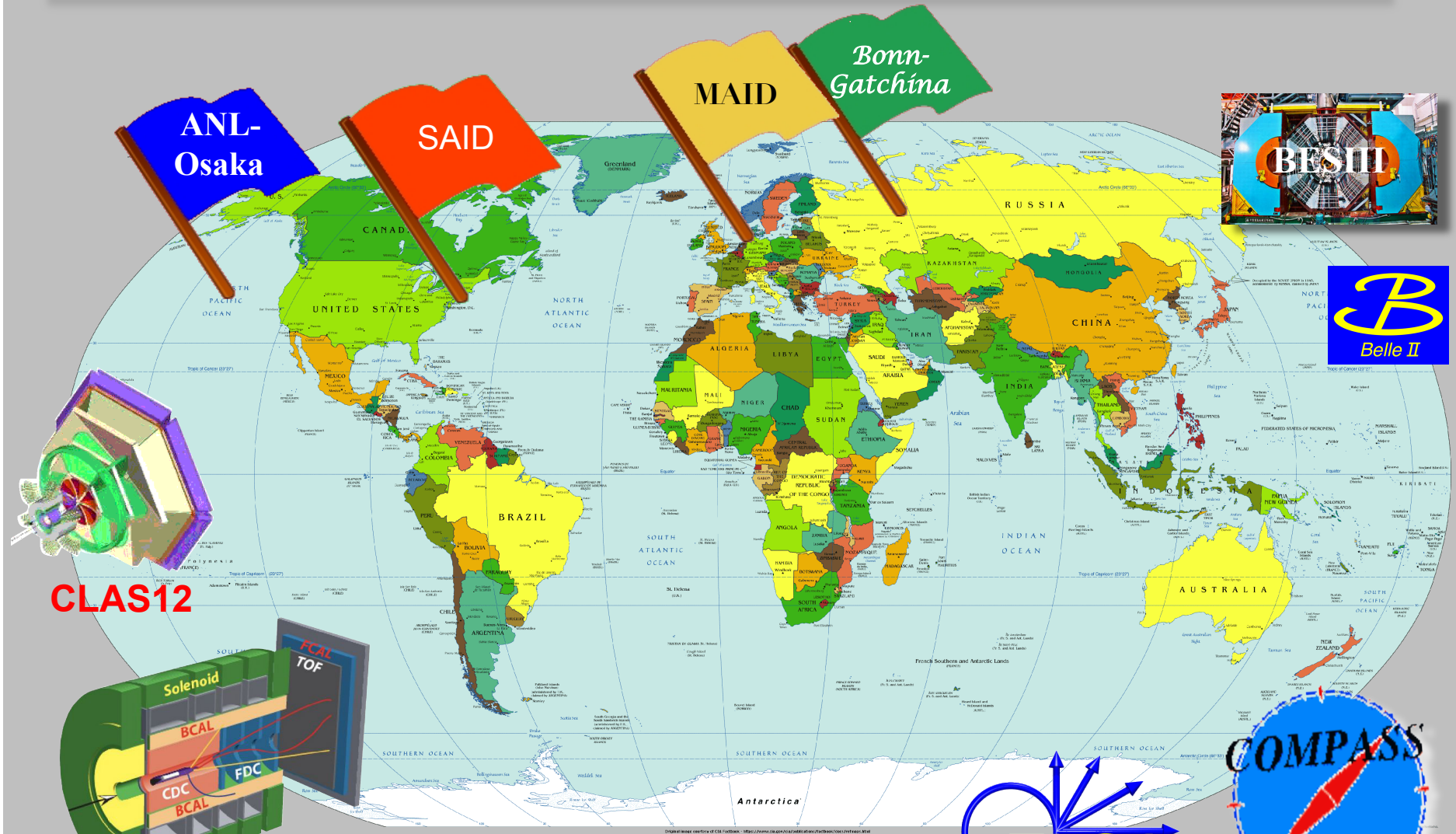
- **Isobar Model**

Model-independent Analyses



- **Beyond the Isobar**

Global working : Amplitude Analyses & Spectroscopy



Joint Physics Analysis Center program

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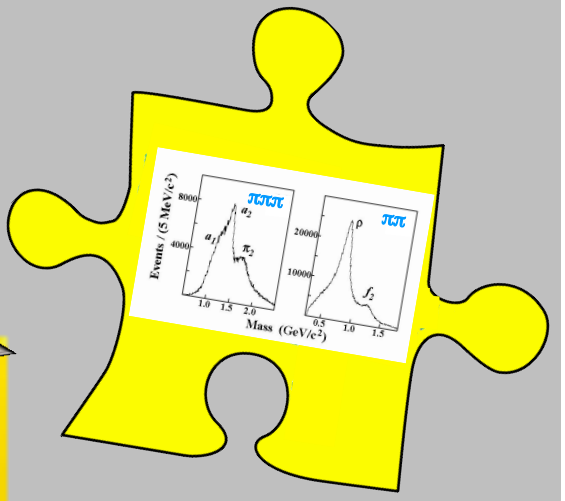
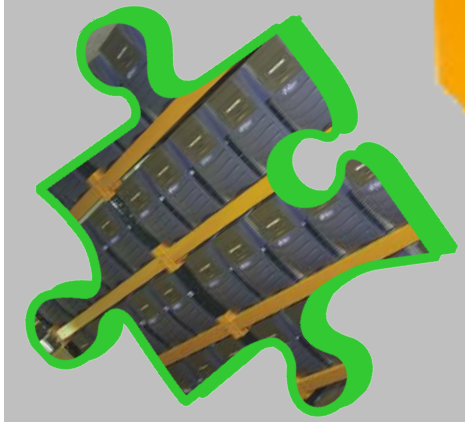
Joint Physics Analysis Center program





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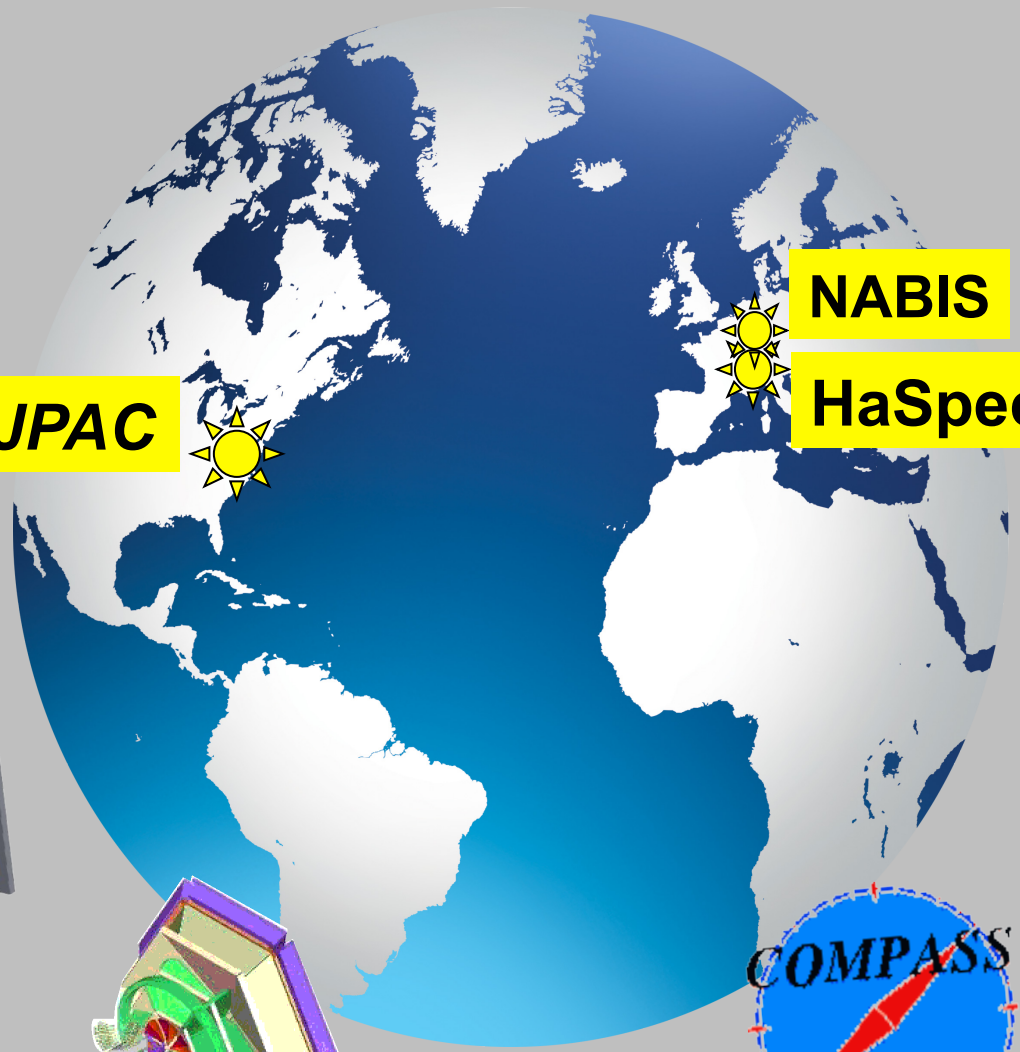
12 GeV



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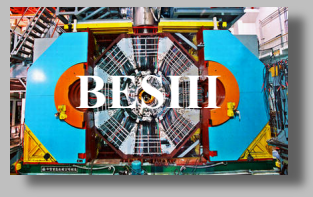
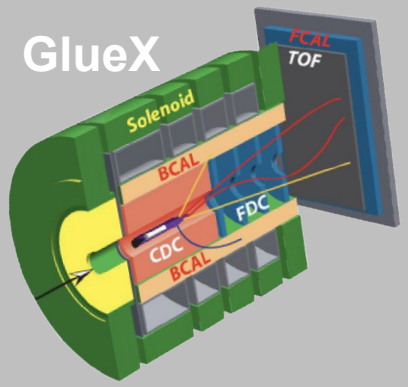
NABIS

HaSpect



GlueX



CLAS12

cool QCD