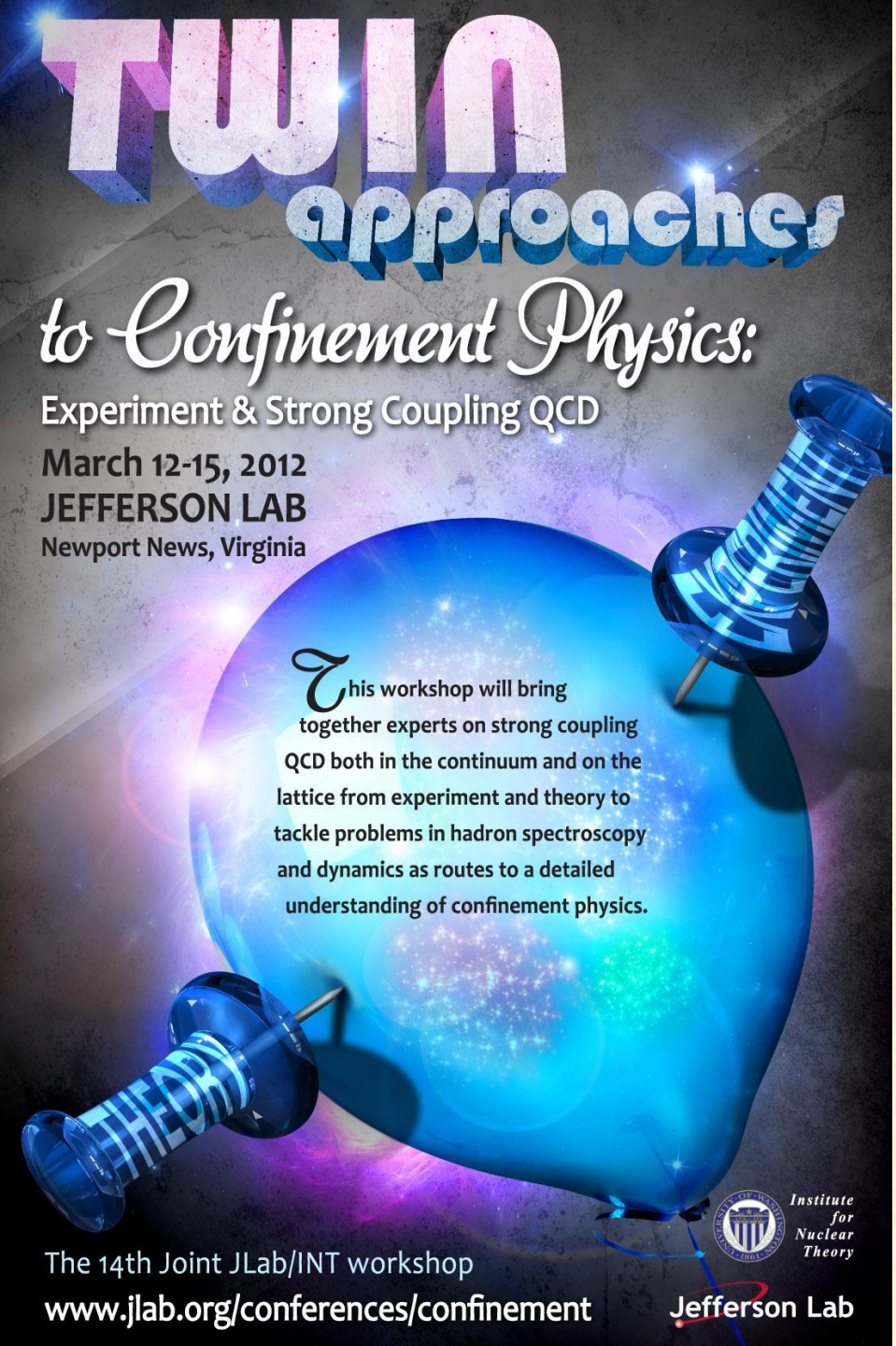
TWIN approaches
to Confinement Physics:
Experiment & Strong Coupling QCD
March 12-15, 2012
JEFFERSON LAB
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This workshop will bring together experts on strong coupling QCD both in the continuum and on the lattice from experiment and theory to tackle problems in hadron spectroscopy and dynamics as routes to a detailed understanding of confinement physics.
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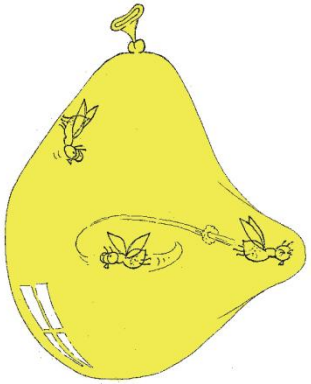

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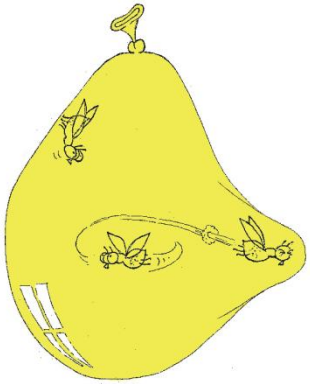
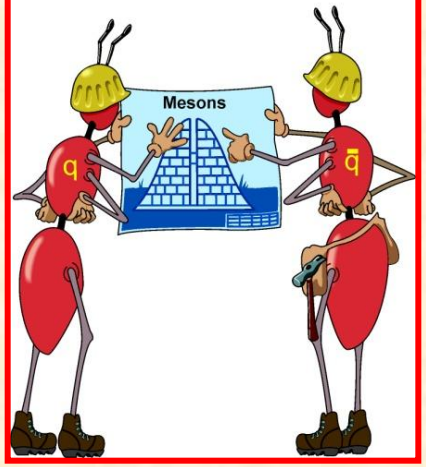
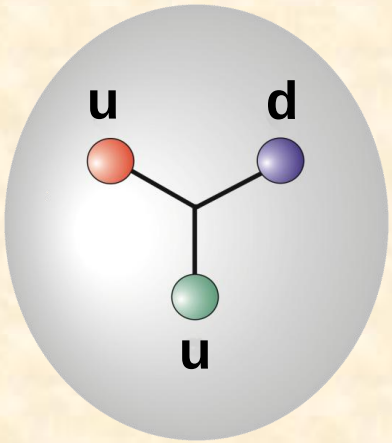
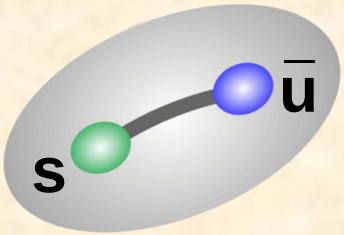


confinement

bound states







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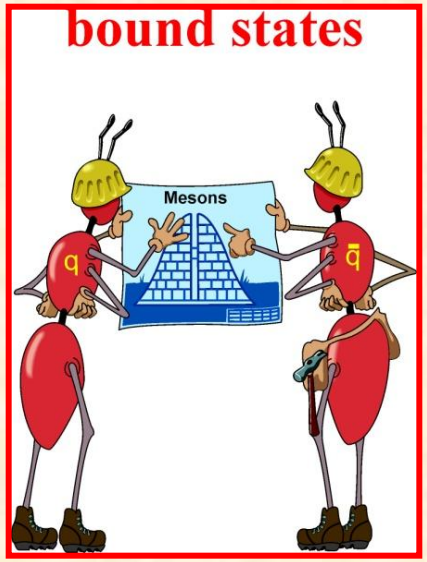

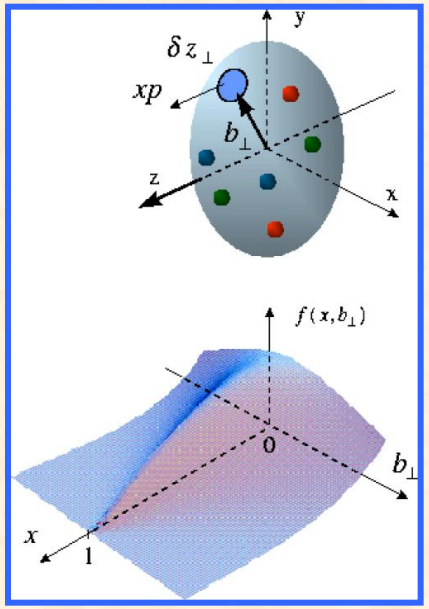

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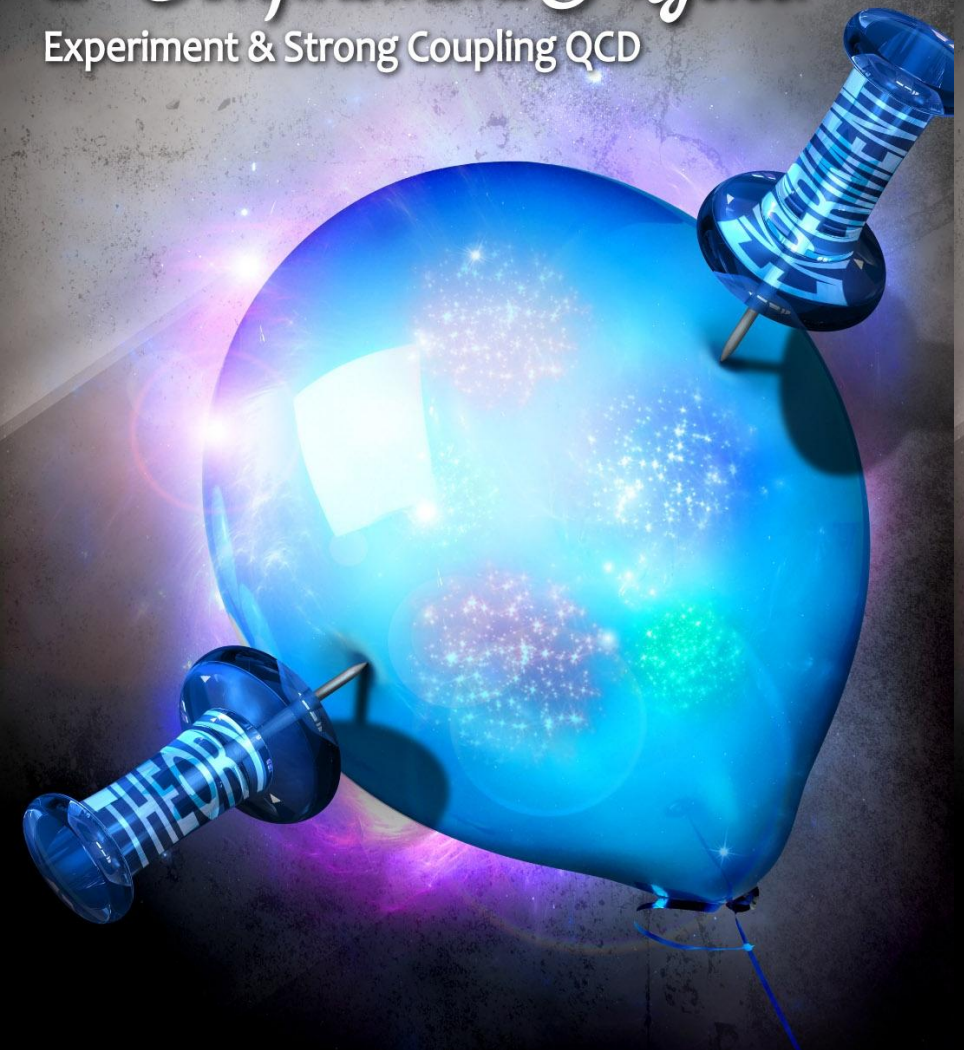

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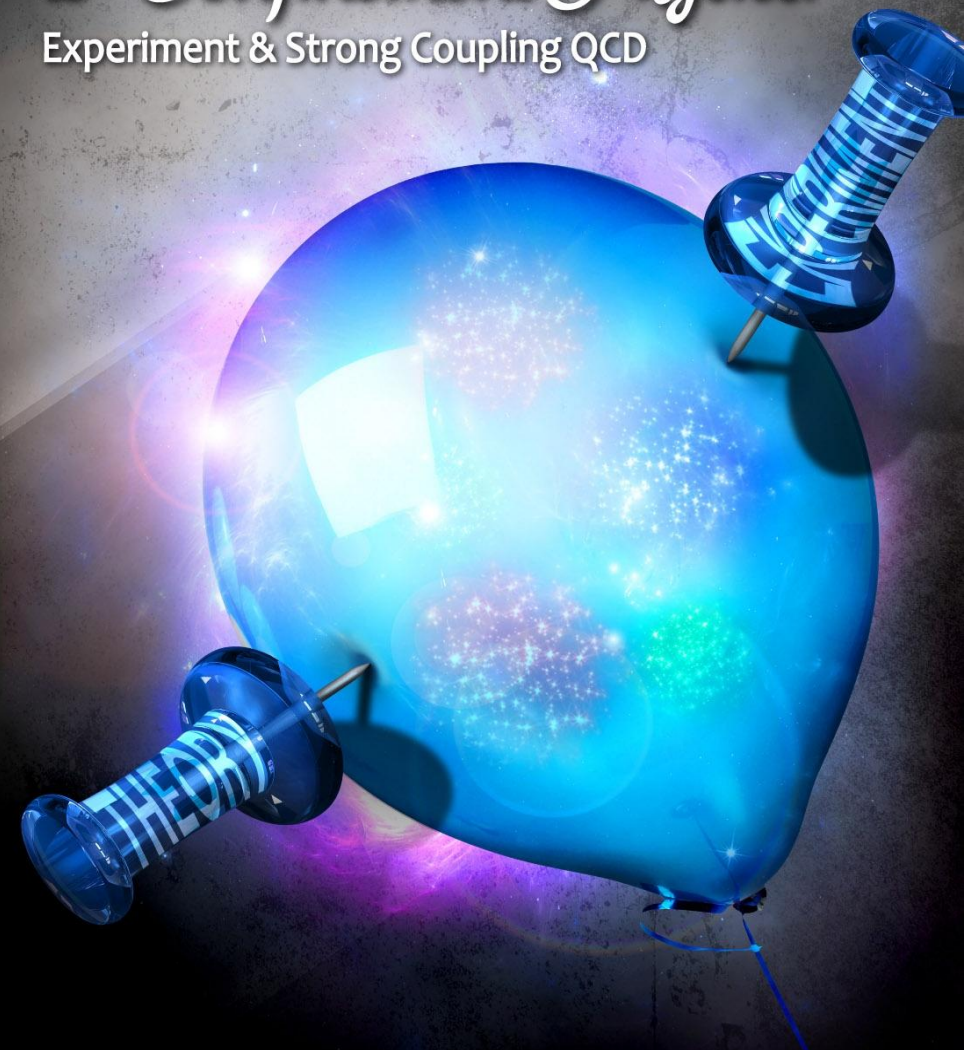

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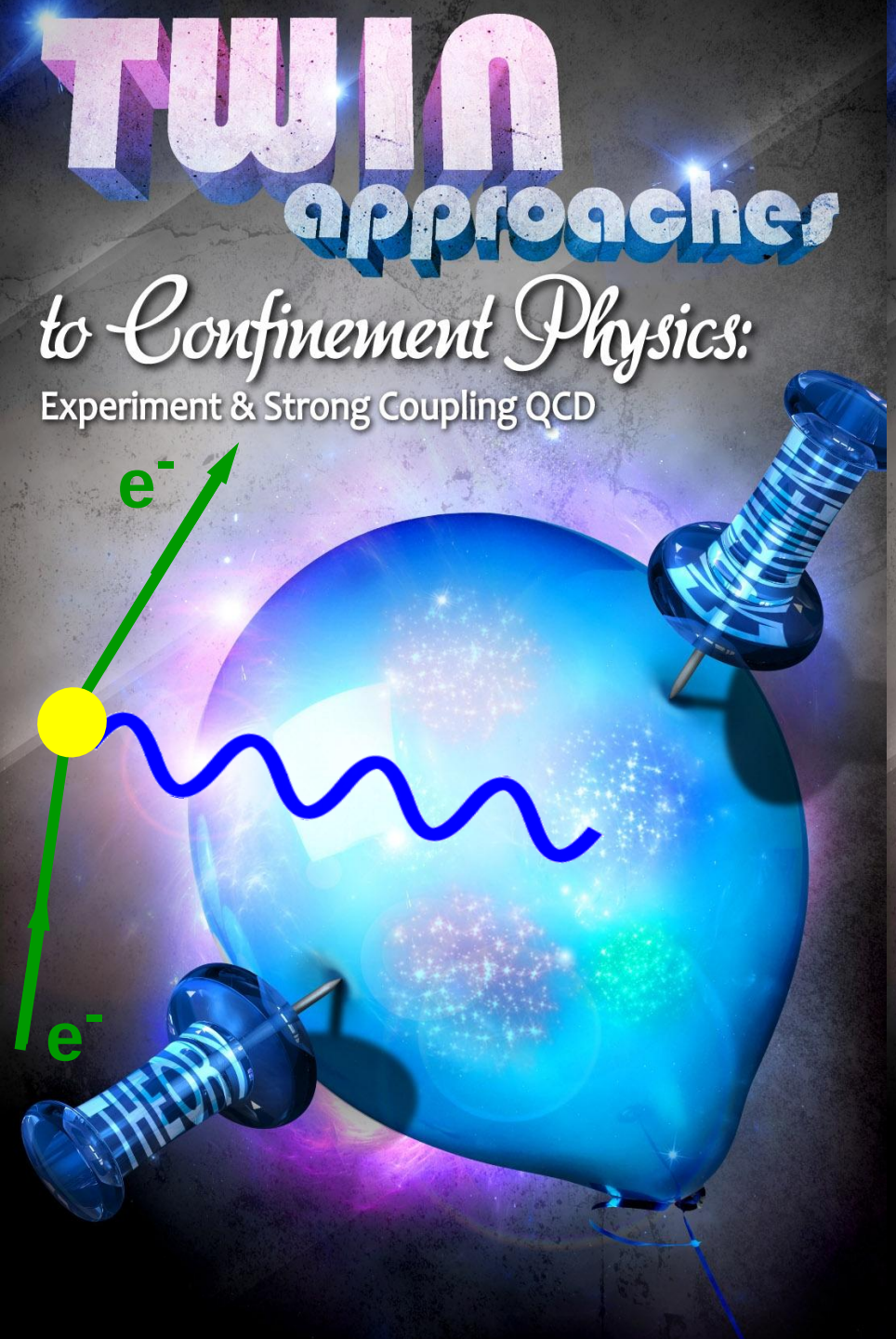

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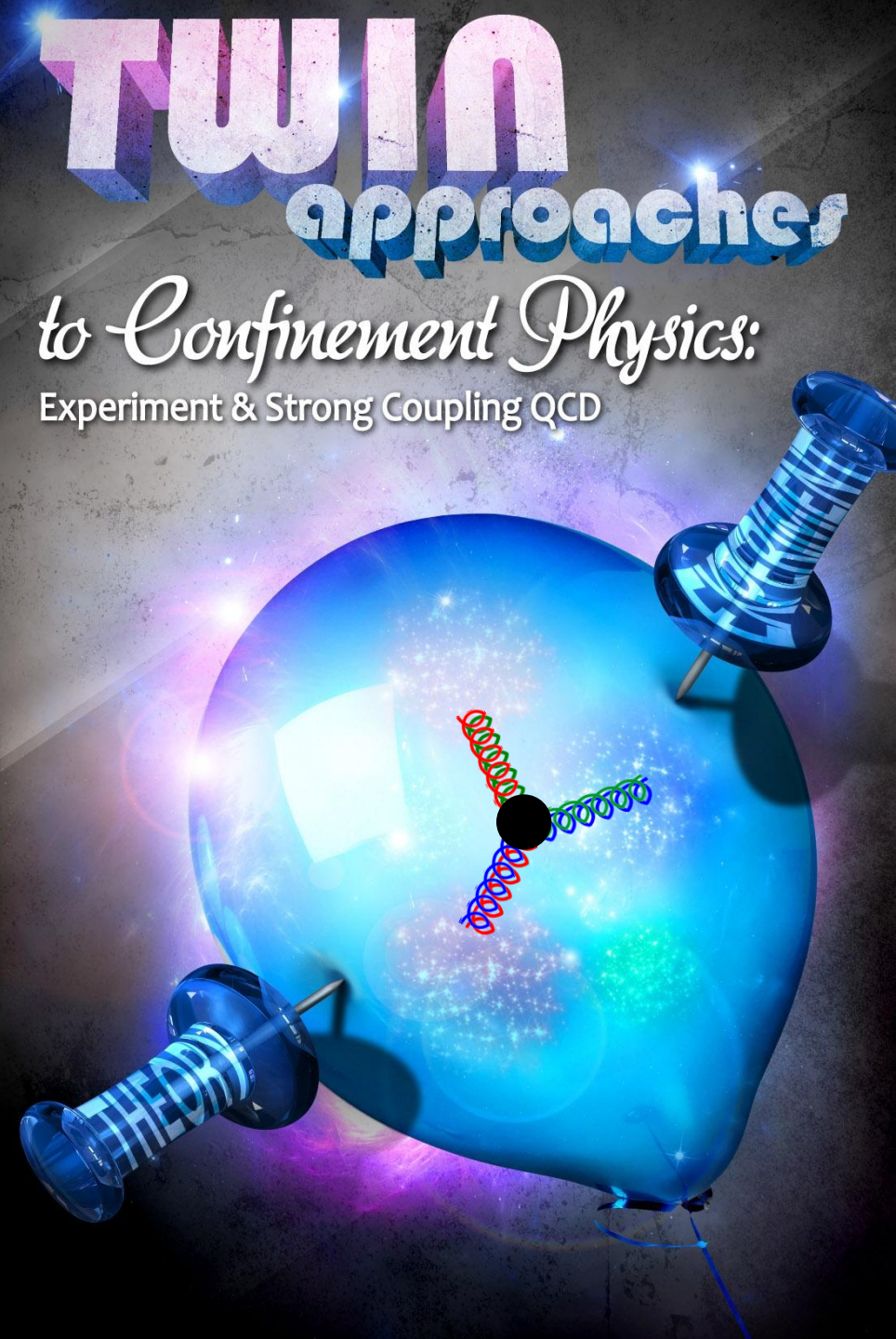
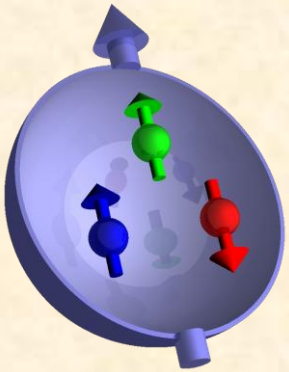
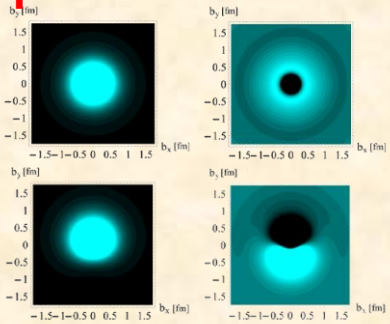


Jefferson Lab

Exploring the Nature of Matter

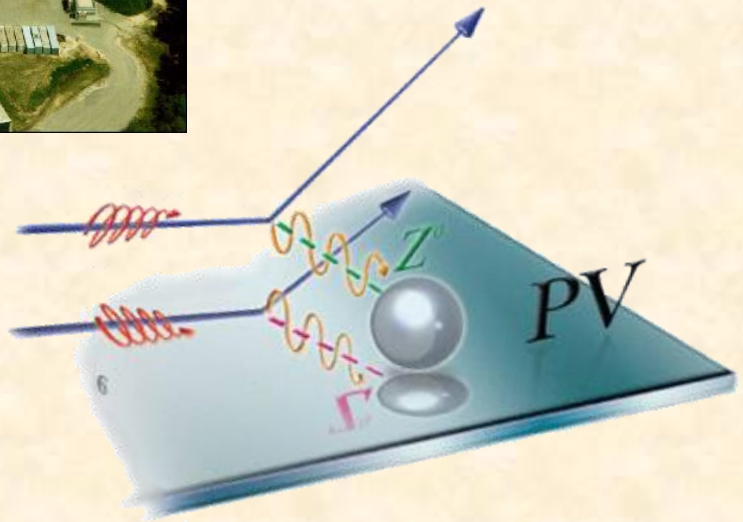


proton neutron



Jefferson Science Associates, LLC

a SURA/CSC Company



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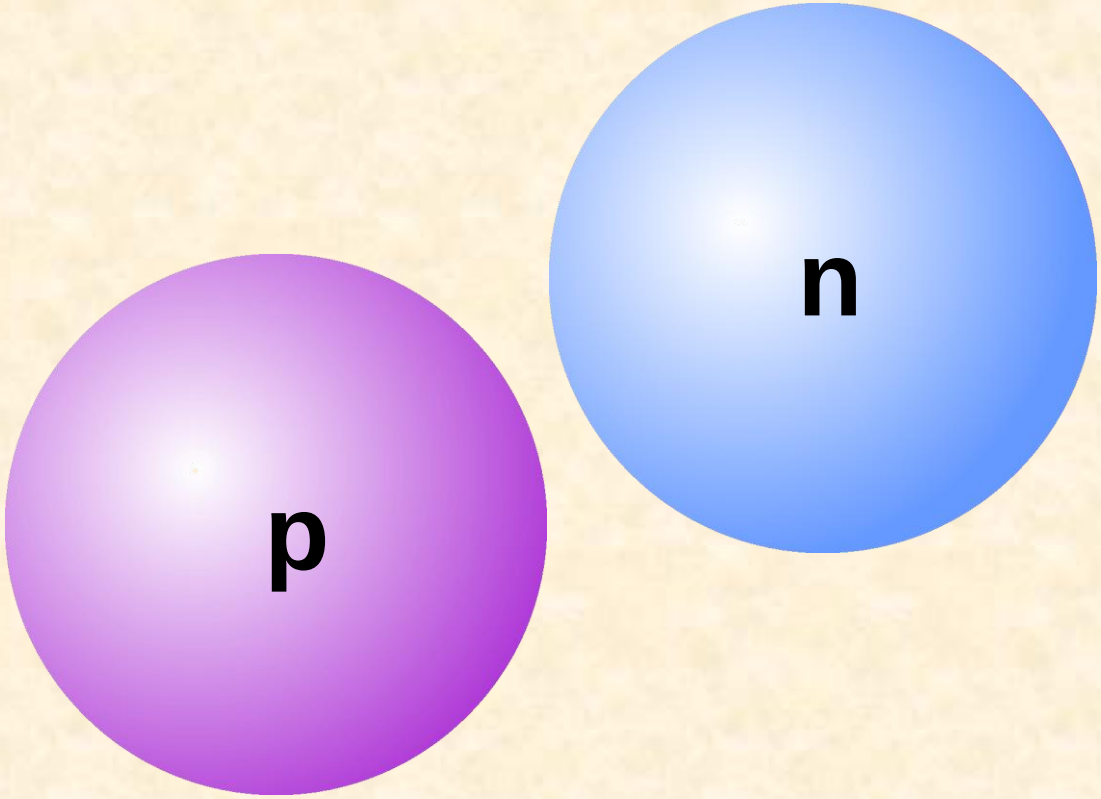

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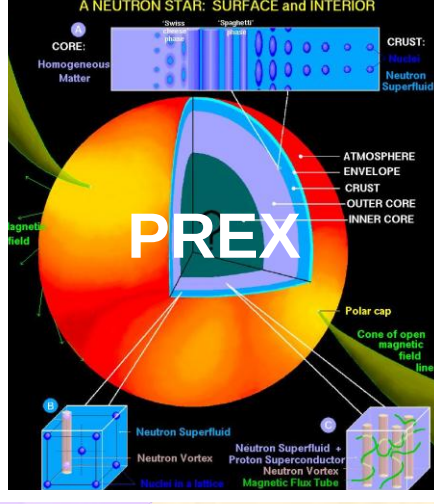

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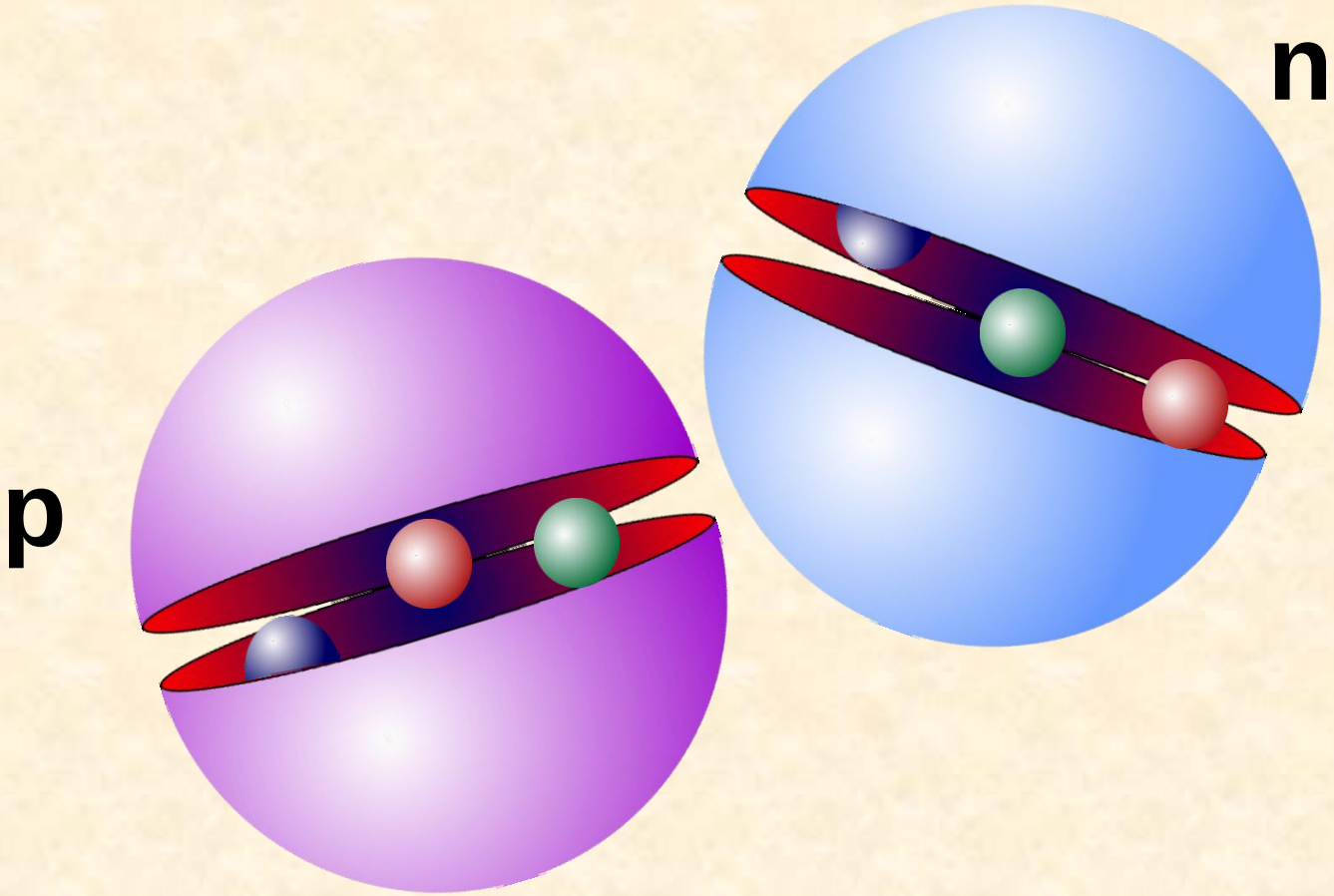

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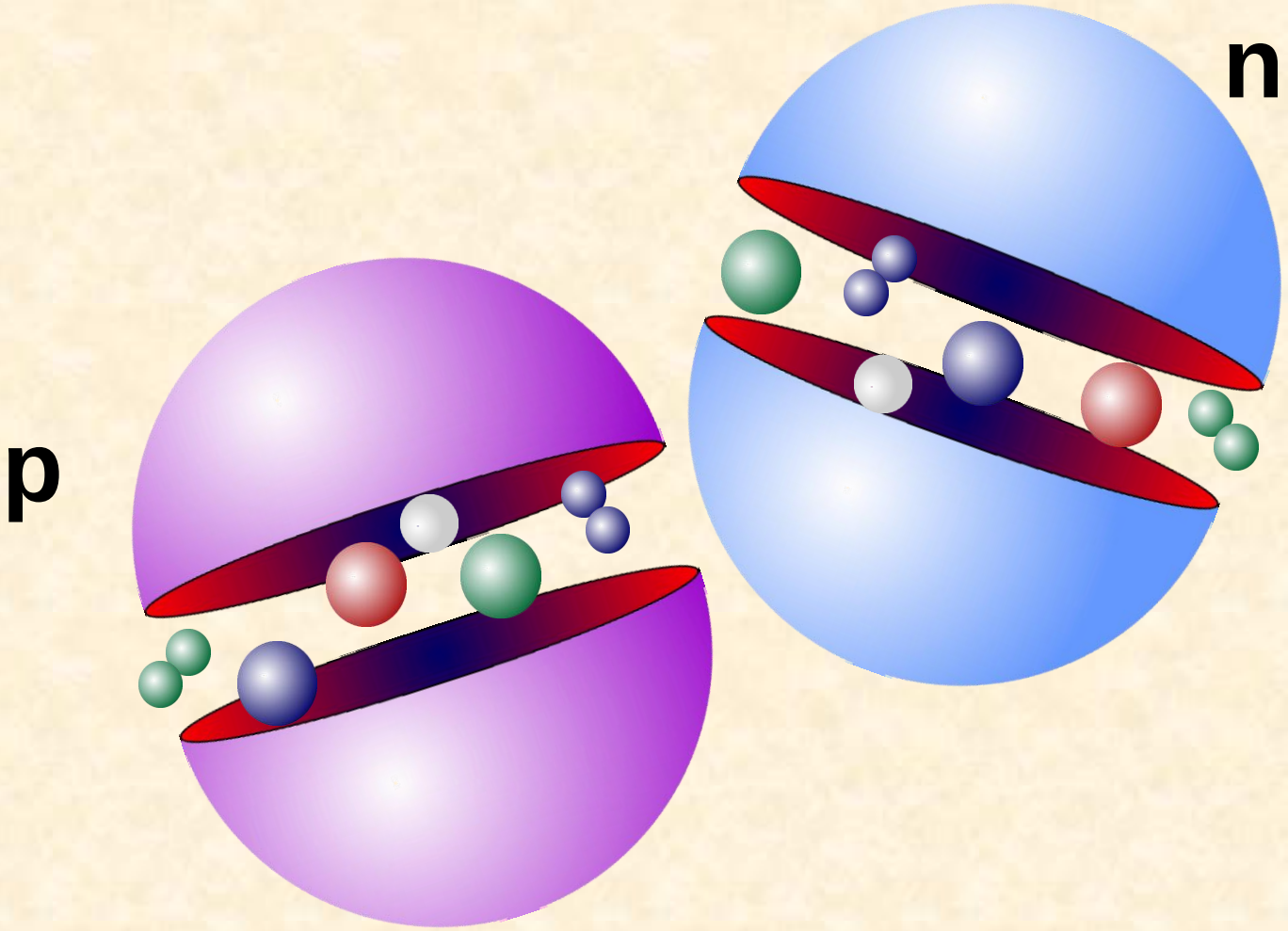
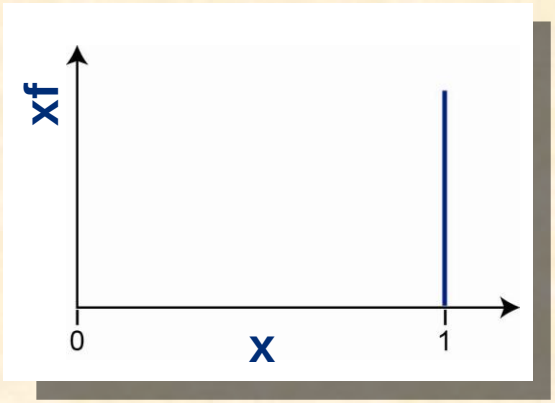
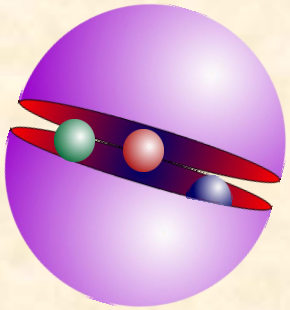
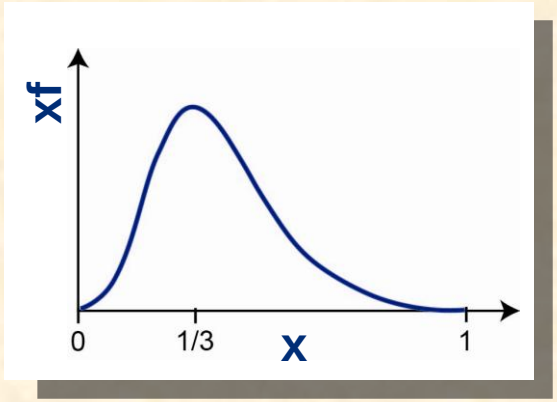
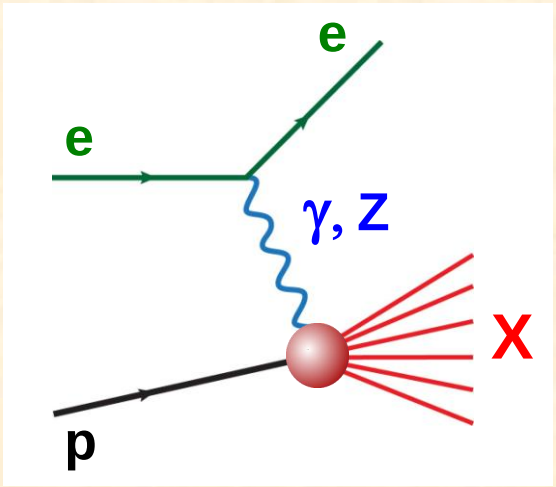


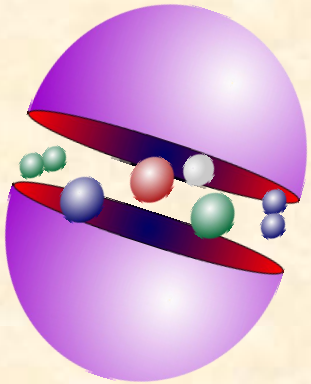
parton structure of the nucleon

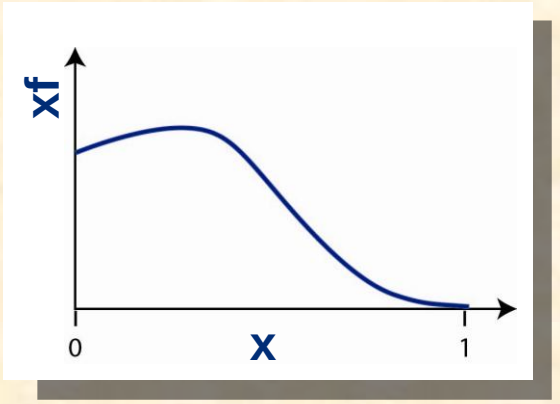




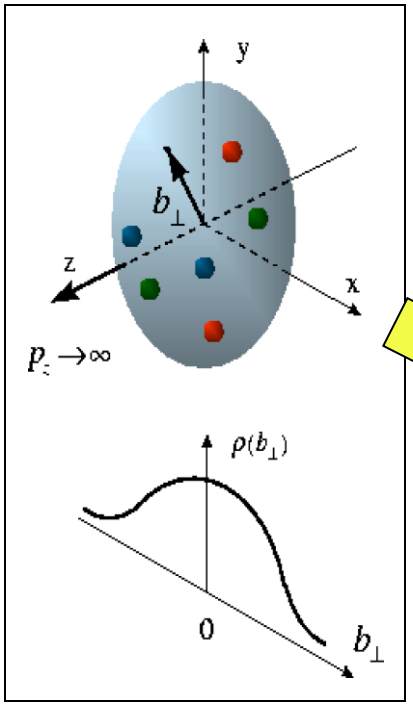






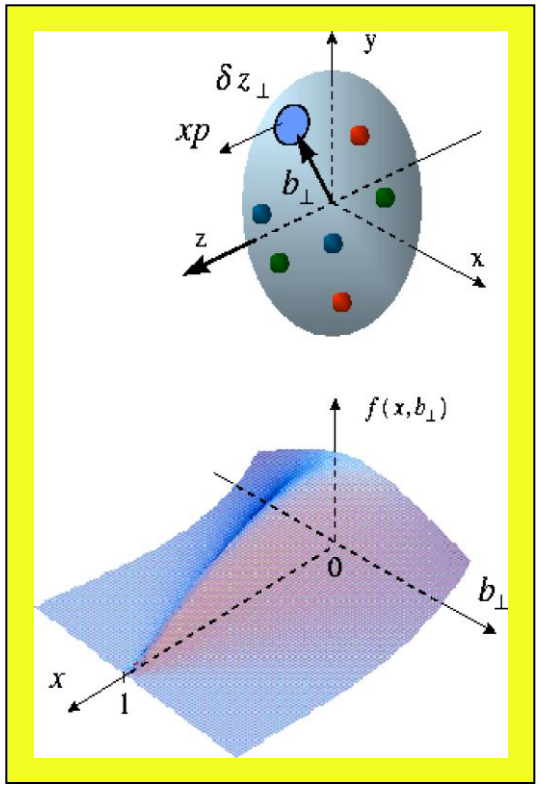


Internal Landscape of the Hadron



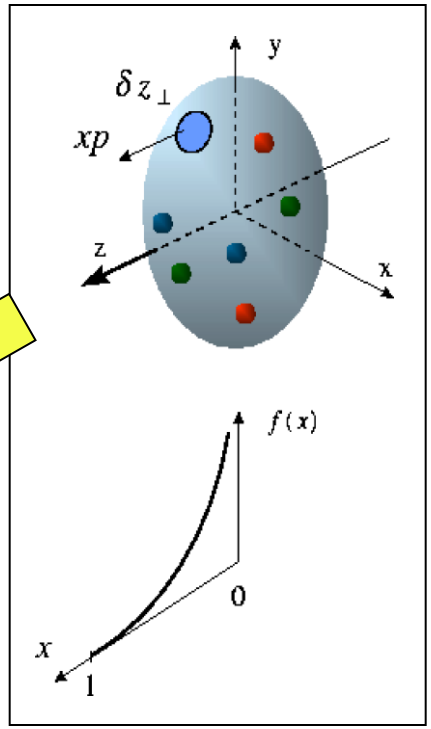
Form factors

transverse charge & current densities In coordinate space



GPDs, TMDs

correlated quark distributions in longitudinal & transverse space

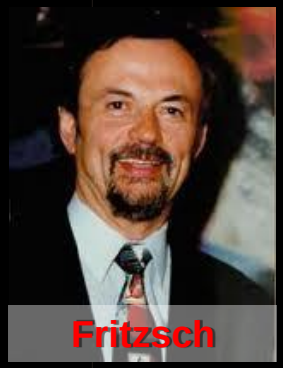


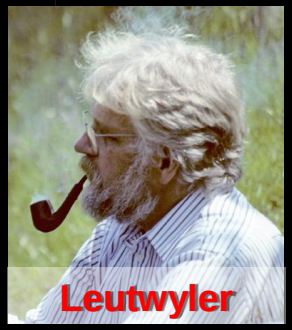
Structure fns

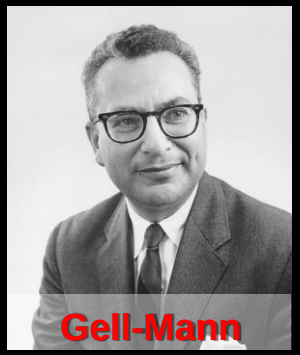
longitudinal quark momentum distributions

QCD

1971


Fritzsch


Leutwyler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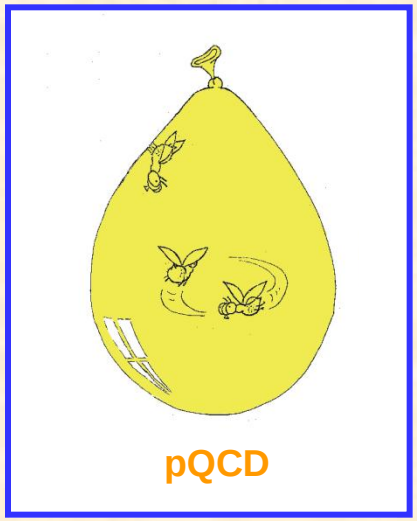
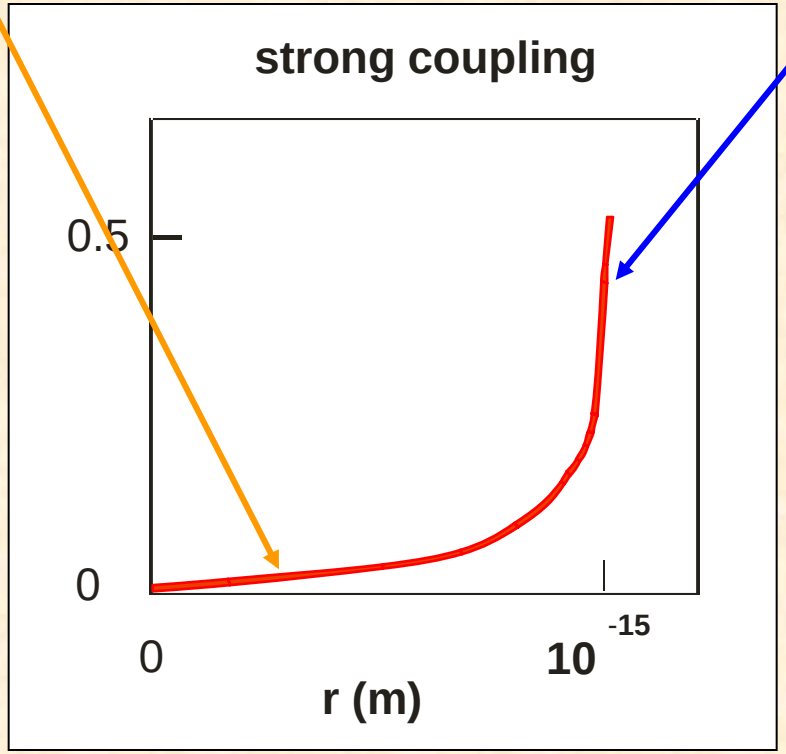
QCD

asymptotic freedom

confinement



pQCD



strong QCD

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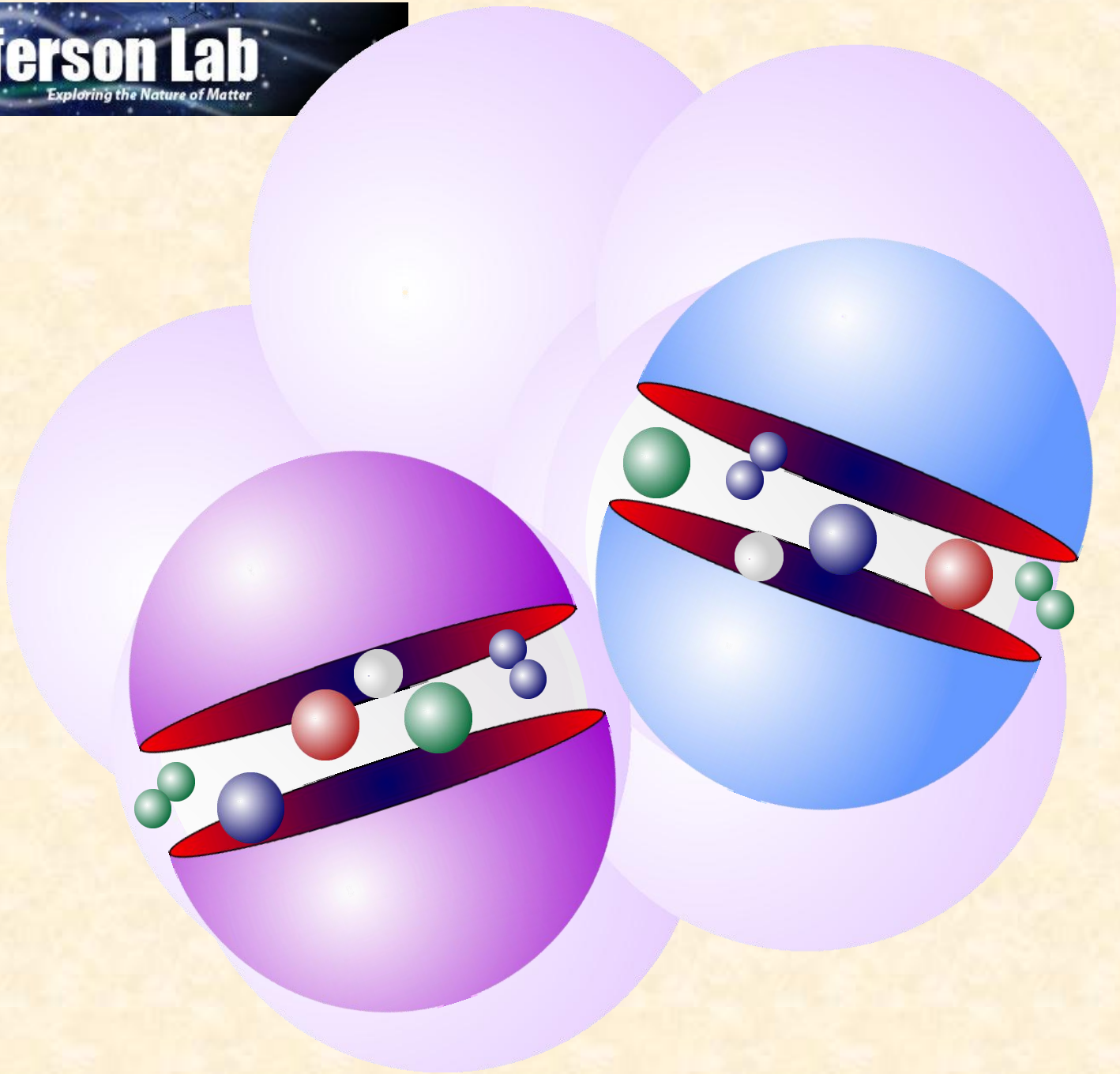
Exploring the Nature of Matter



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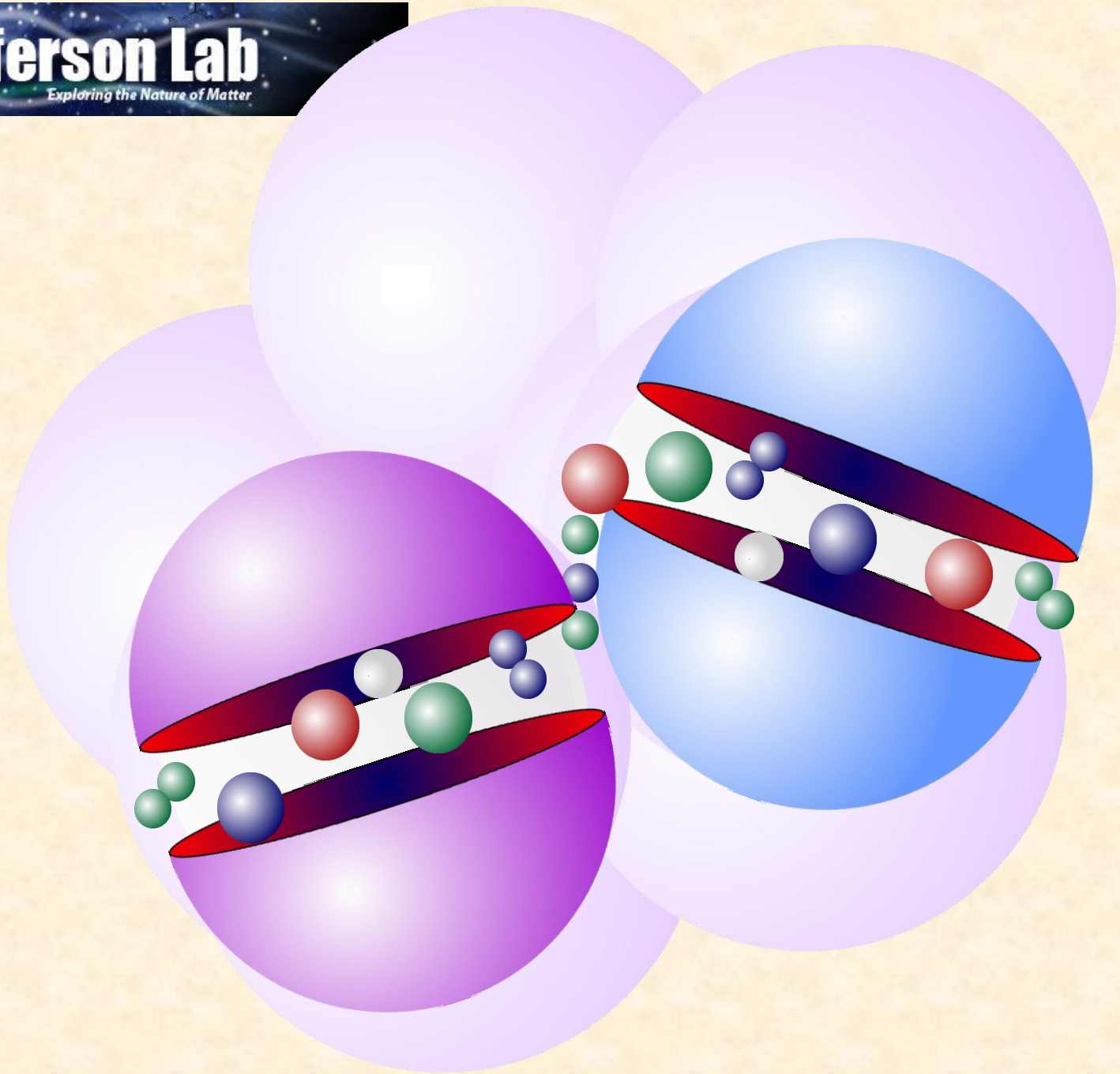

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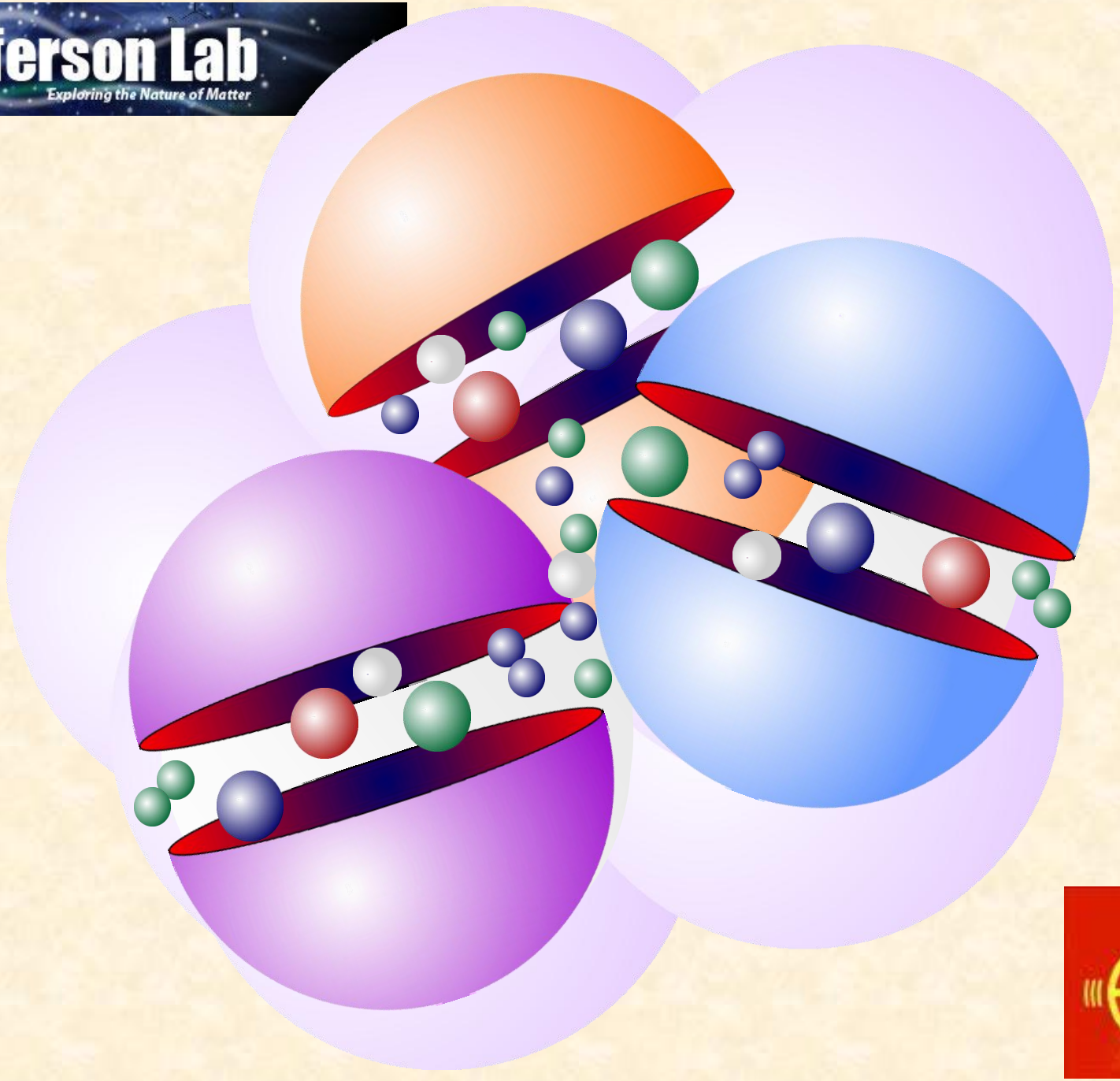
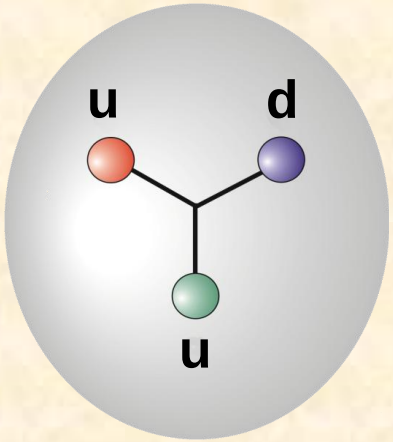
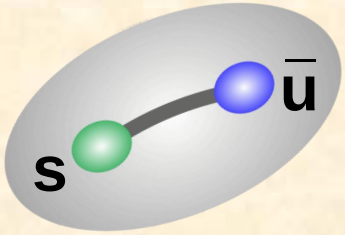
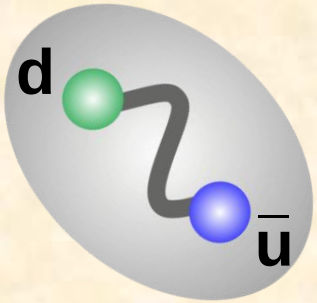


cool QCD







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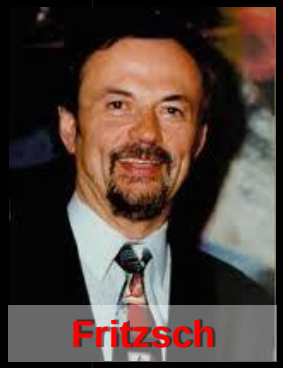
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

QCD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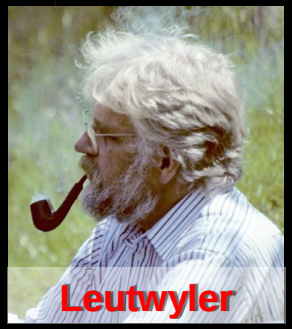
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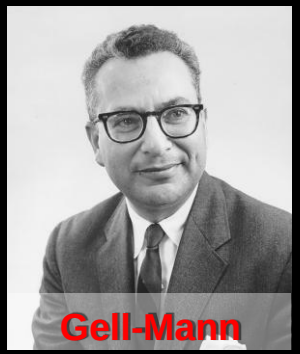
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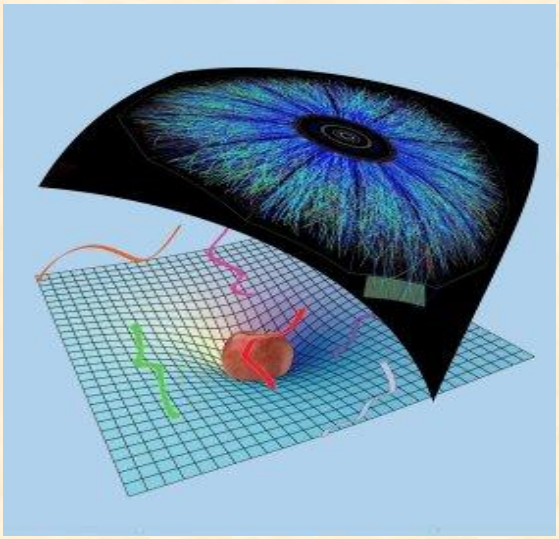
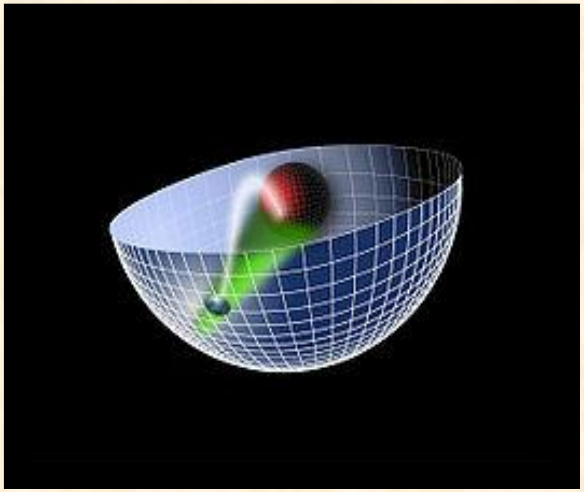
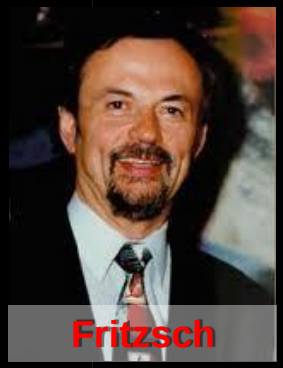


AdS/CFT

QCD





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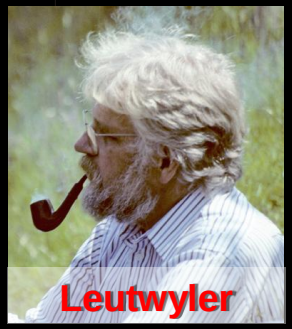

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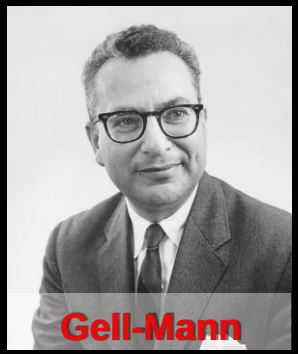
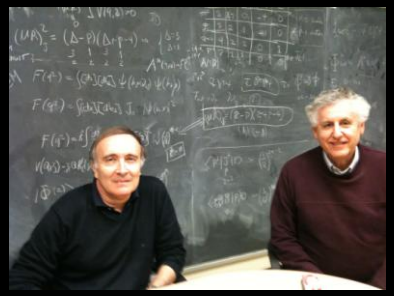
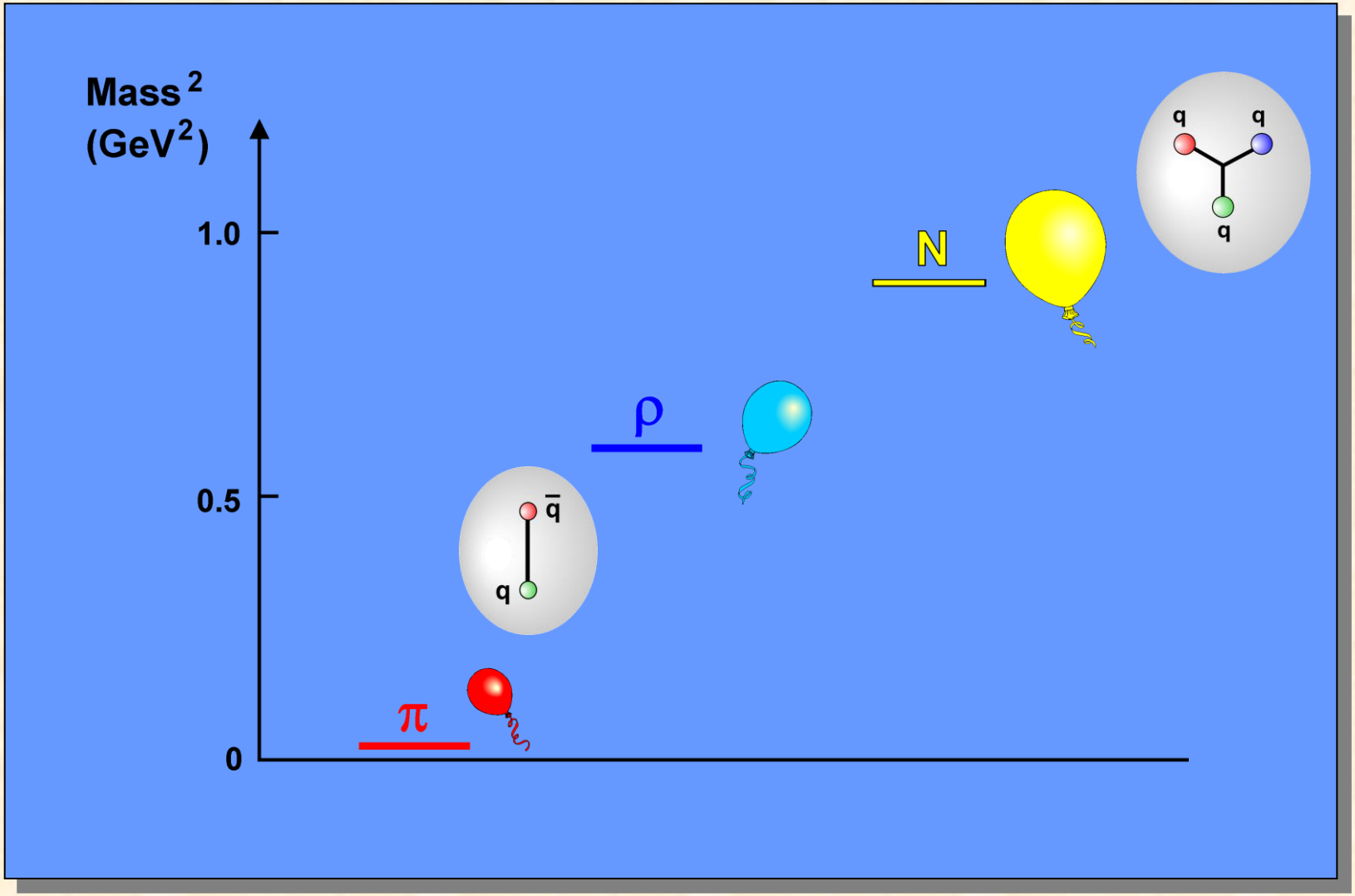


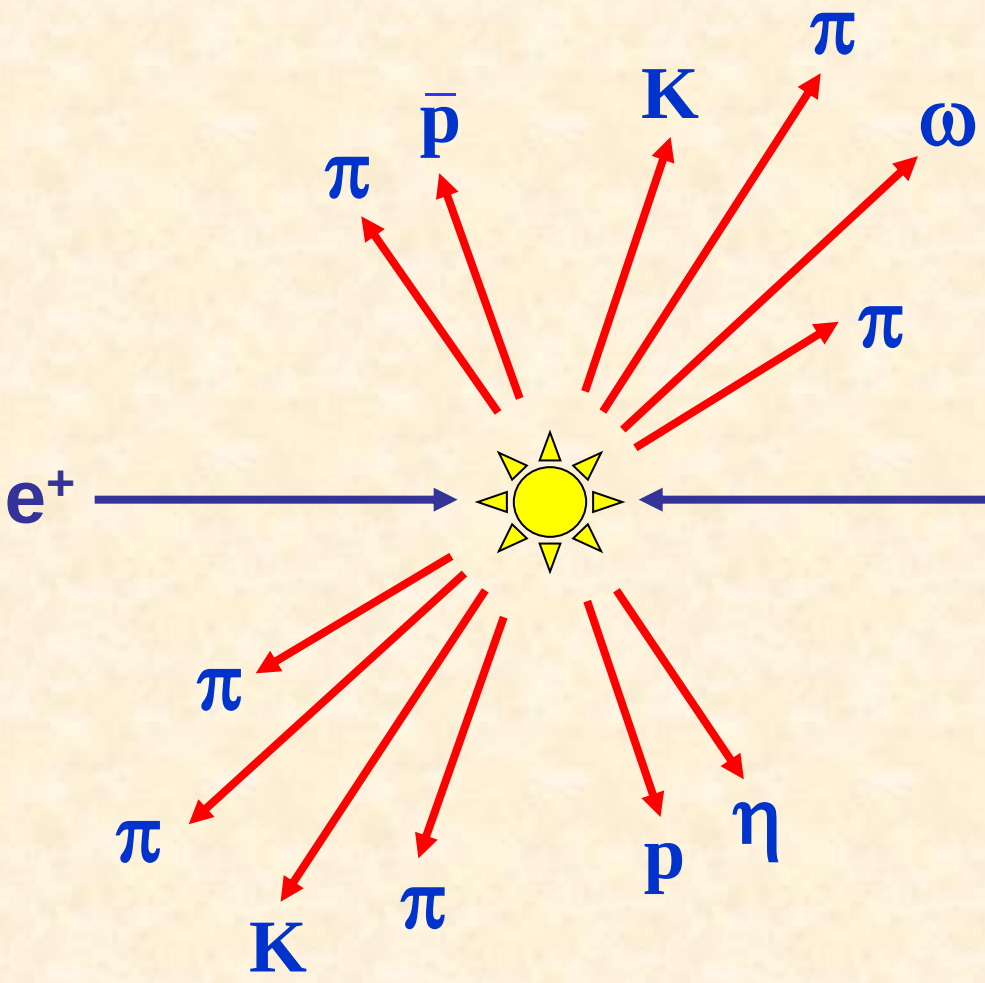
Gell-Mann



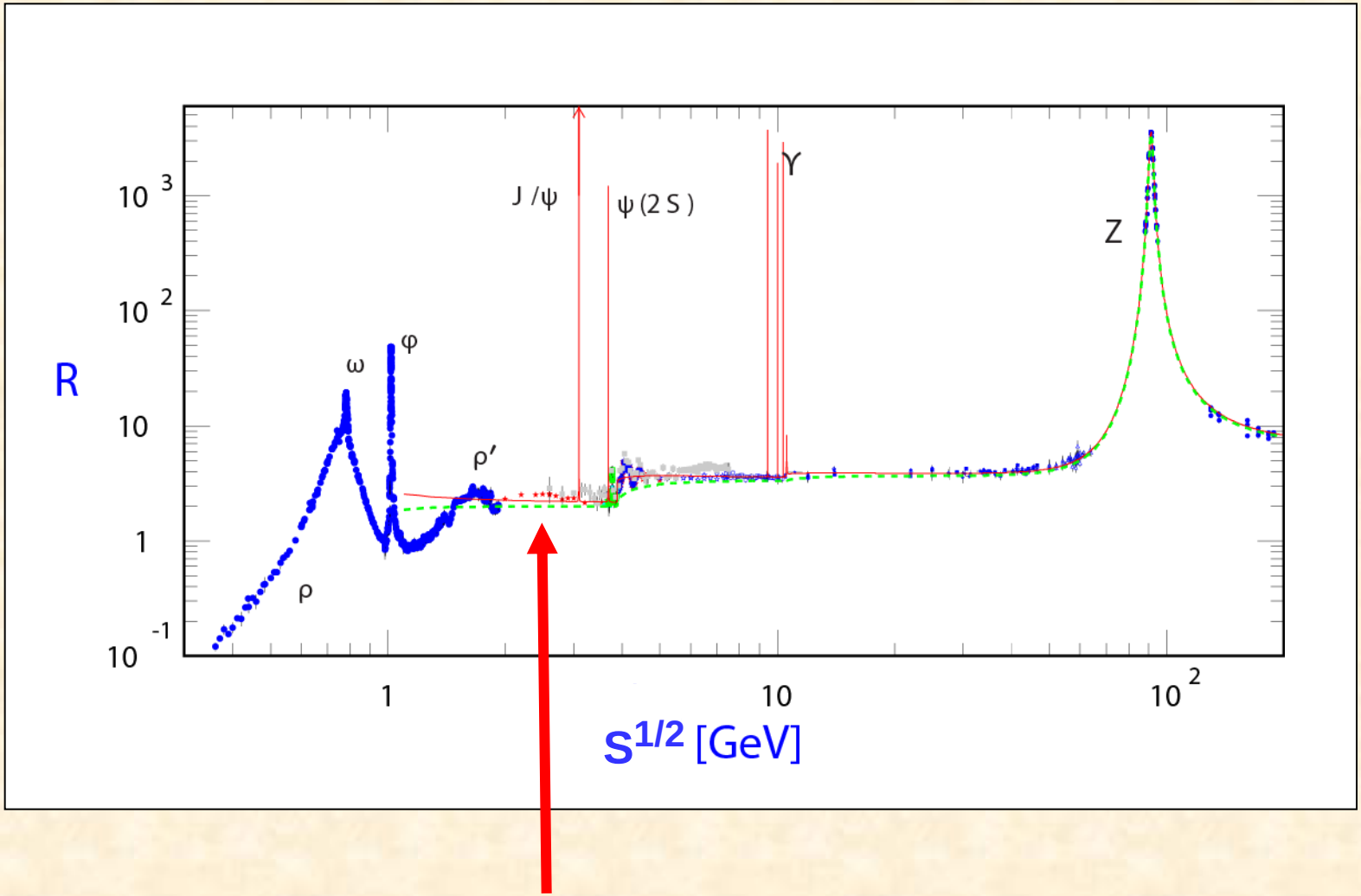
Hadron masses [2]



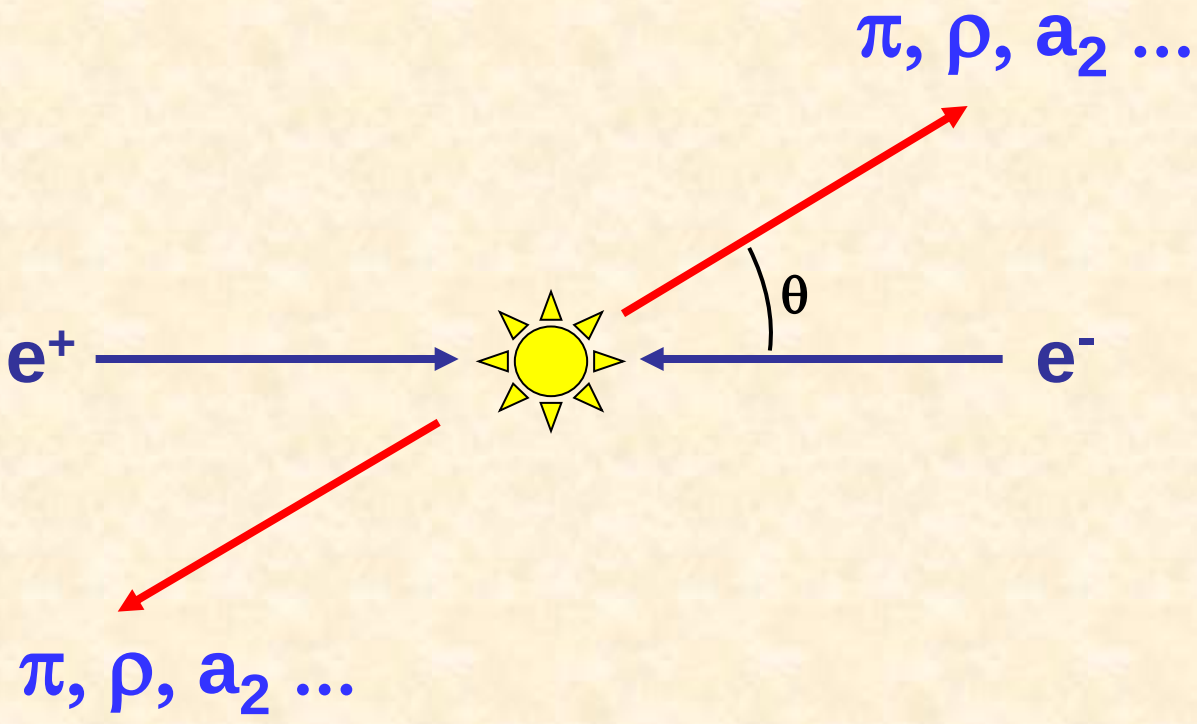
e^+e^- annihilation into hadrons



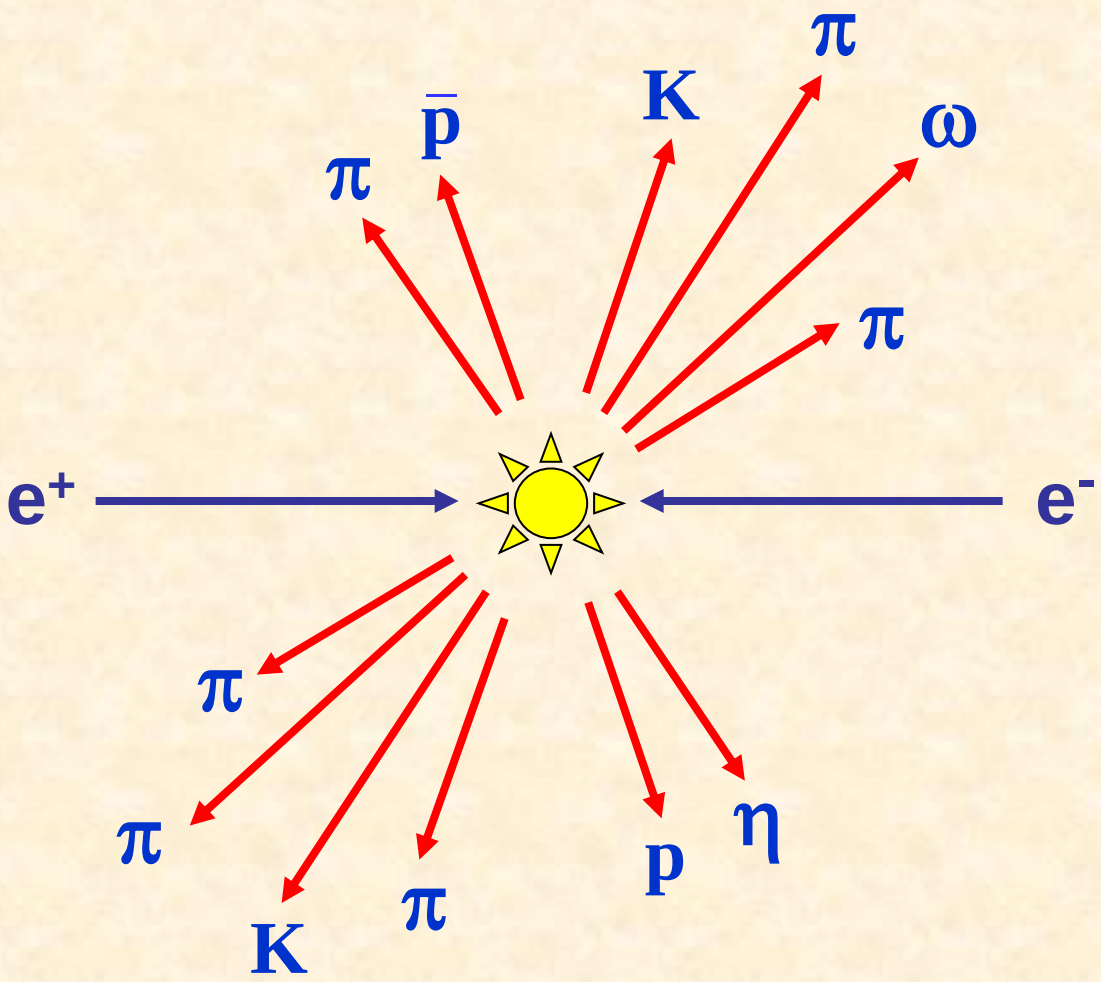
e^+e^- annihilation into hadrons



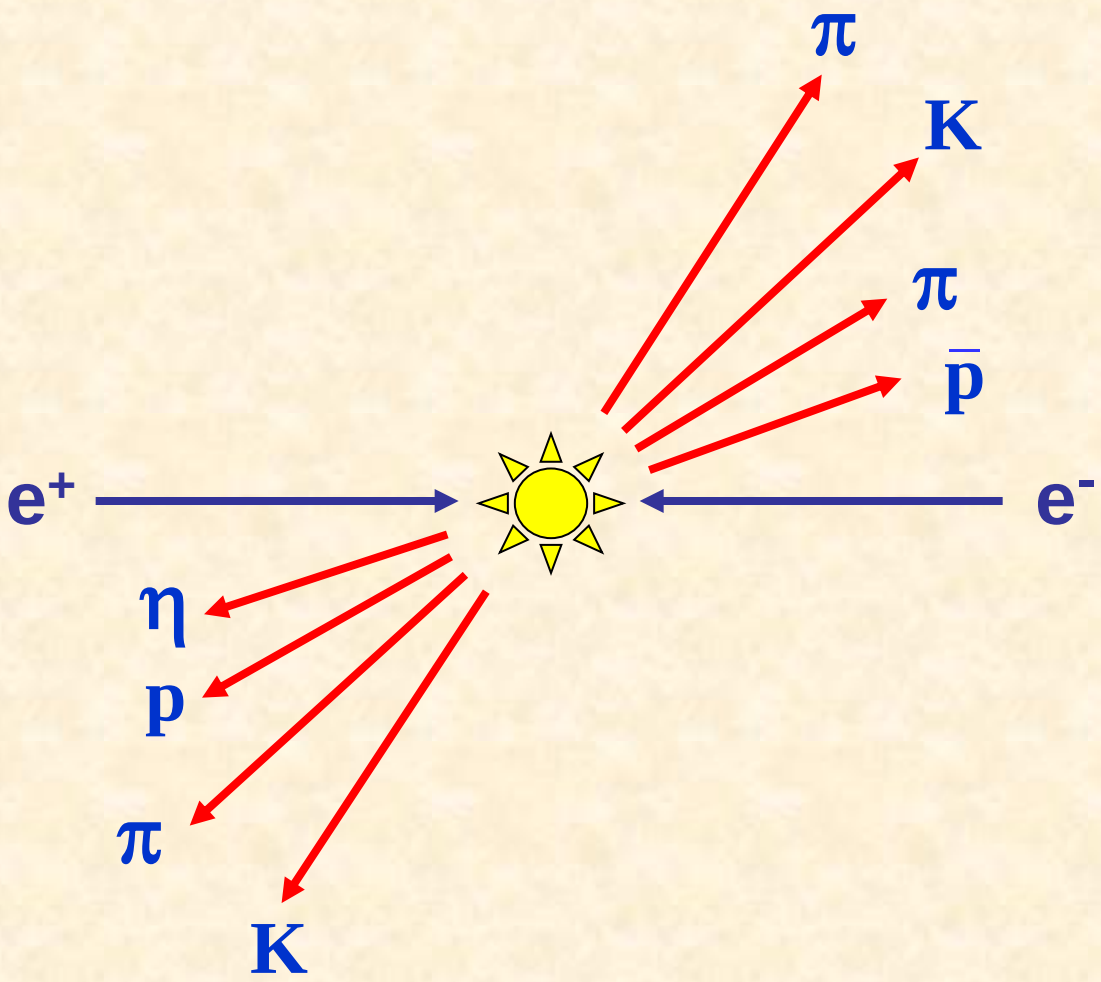
e^+e^- annihilation into hadrons



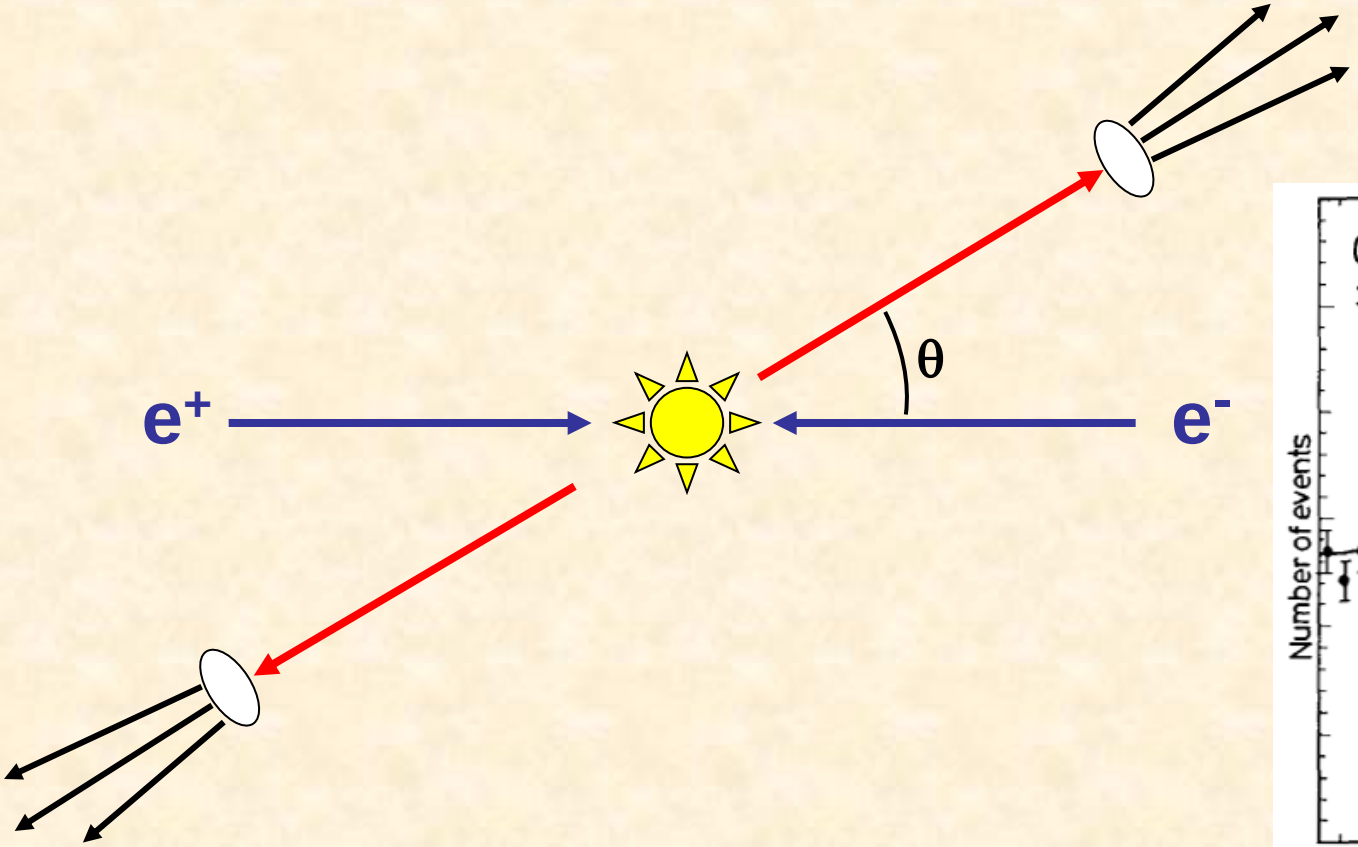
e^+e^- annihilation into hadrons

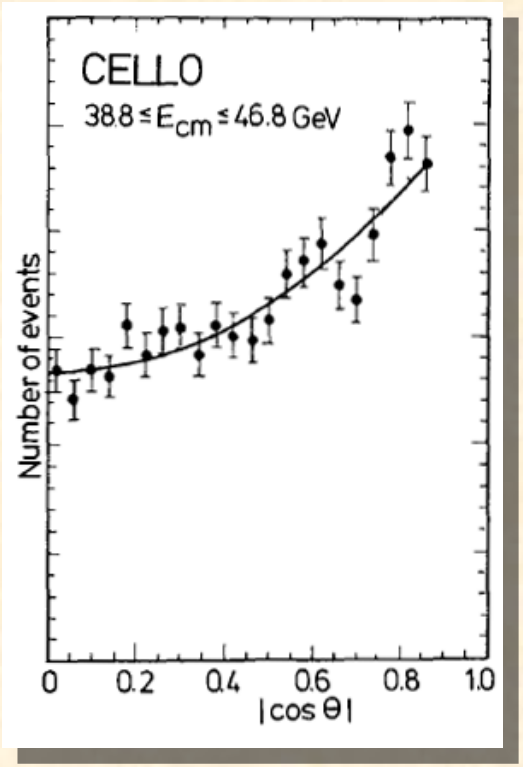


e^+e^- annihilation into hadrons



e^+e^- annihilation into hadrons

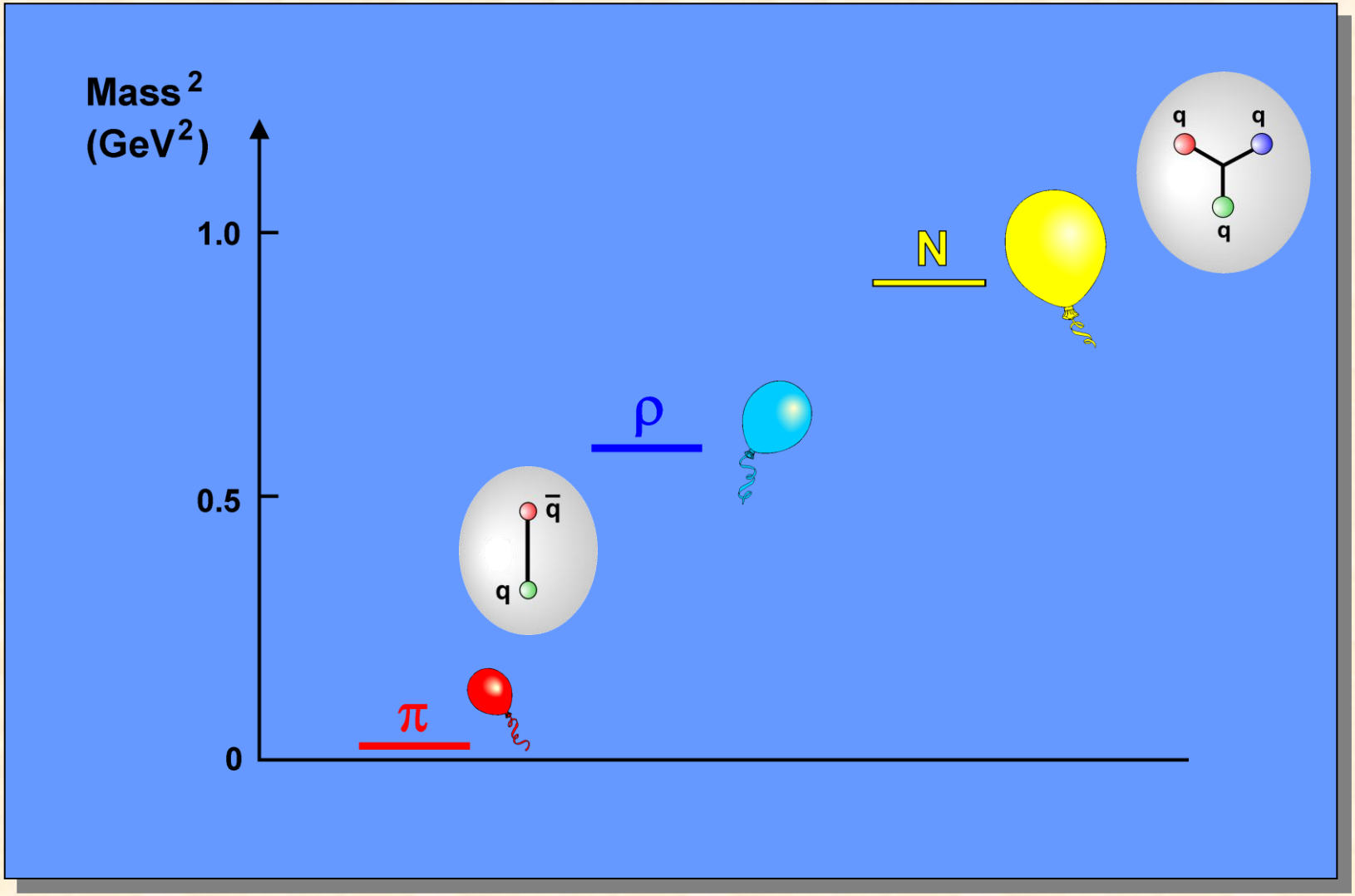




$$\frac{d\sigma}{d\Omega} \sim \rho_T (1 + \cos^2\theta) + \rho_L \sin^2\theta$$

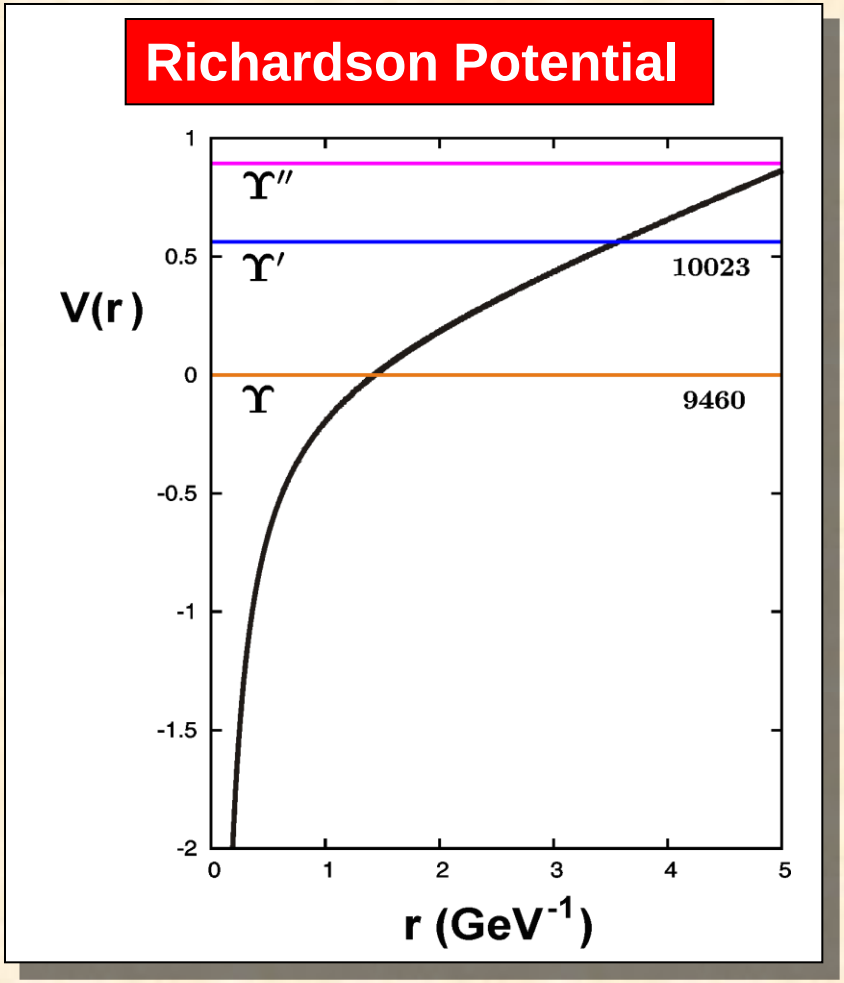
$\rho_L/\rho_T << 1$

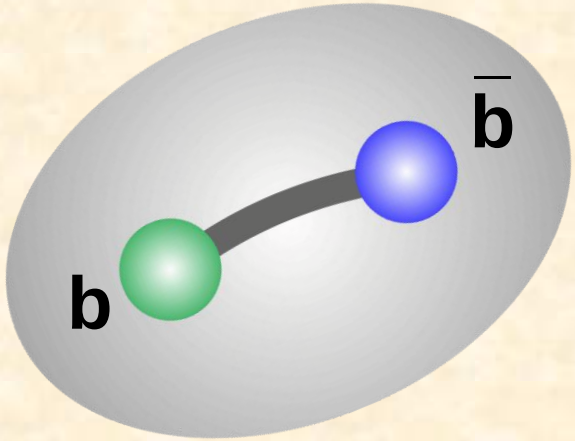
Hadron masses [2]



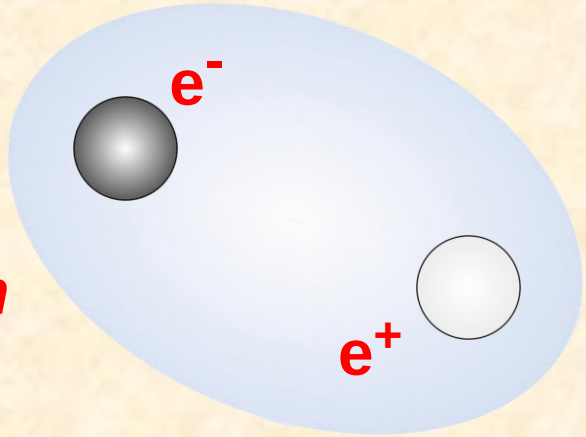
b

heavy quark potential — spectrum

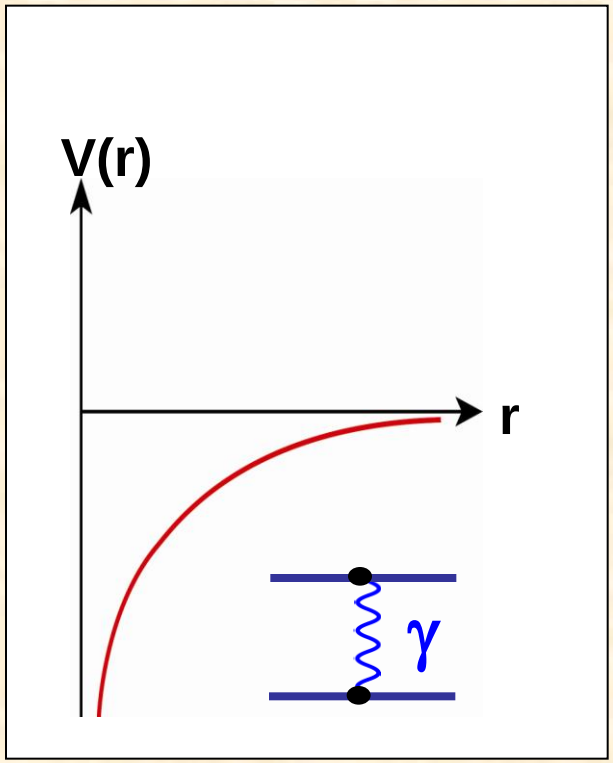




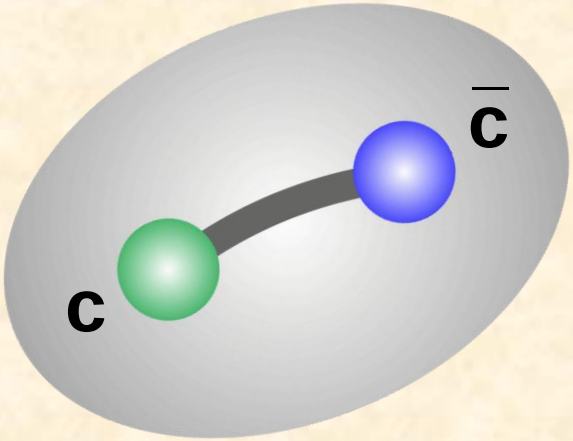
positronium



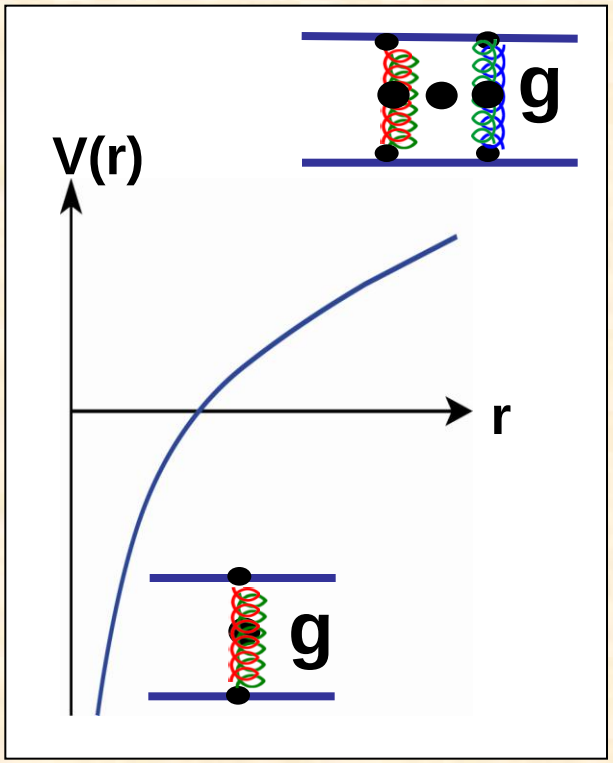
0.1 *nm*



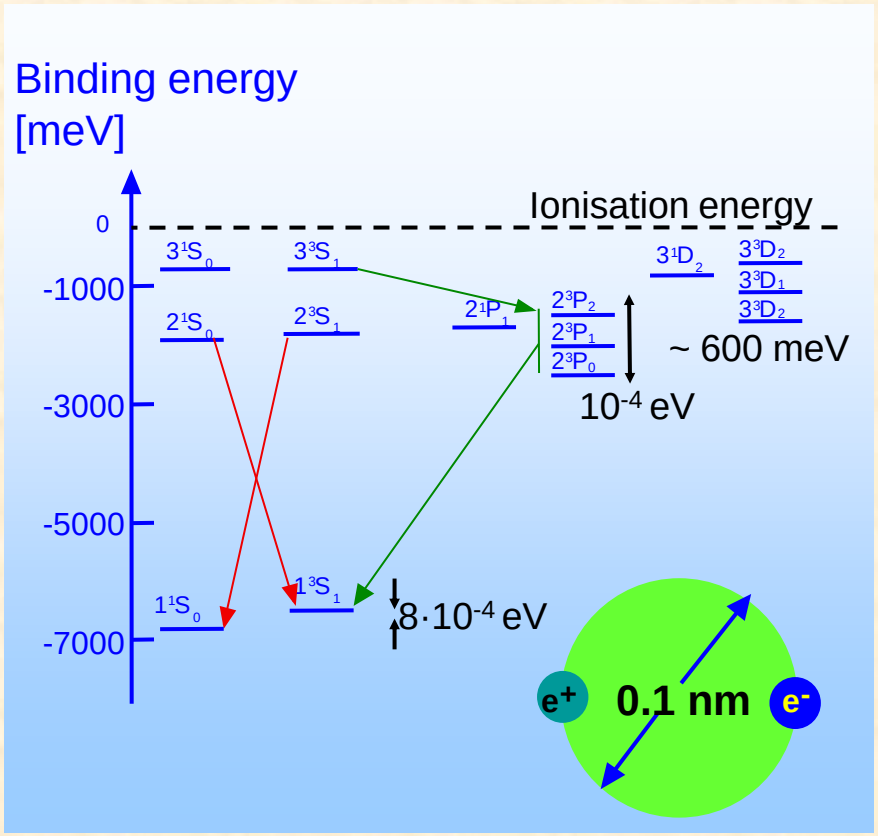
charmonium



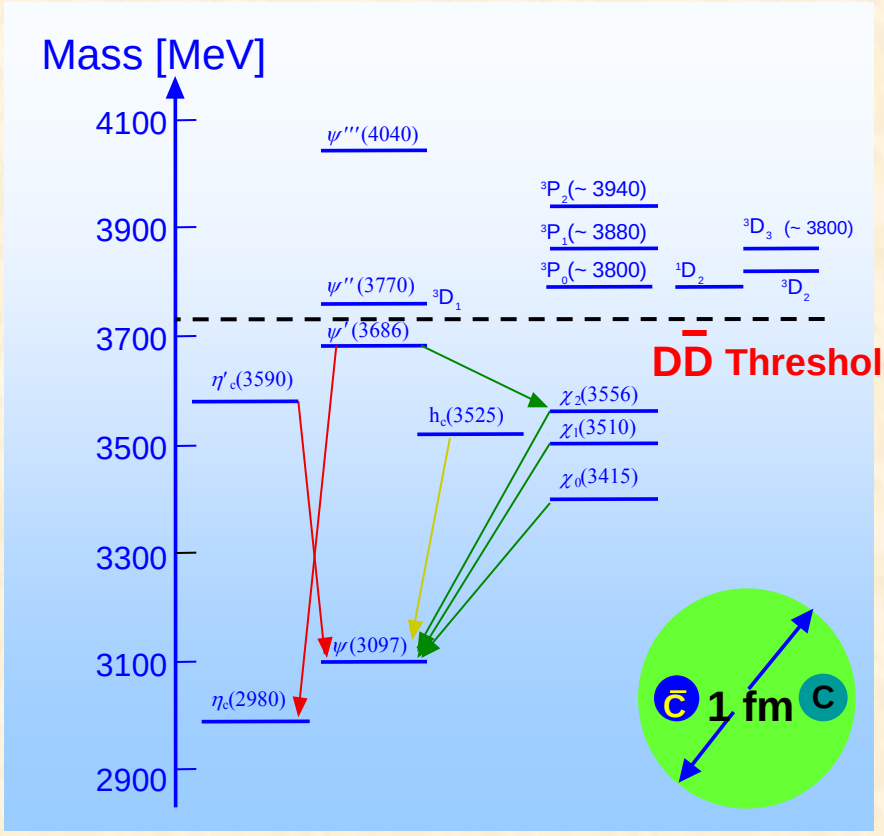
1 *fm*



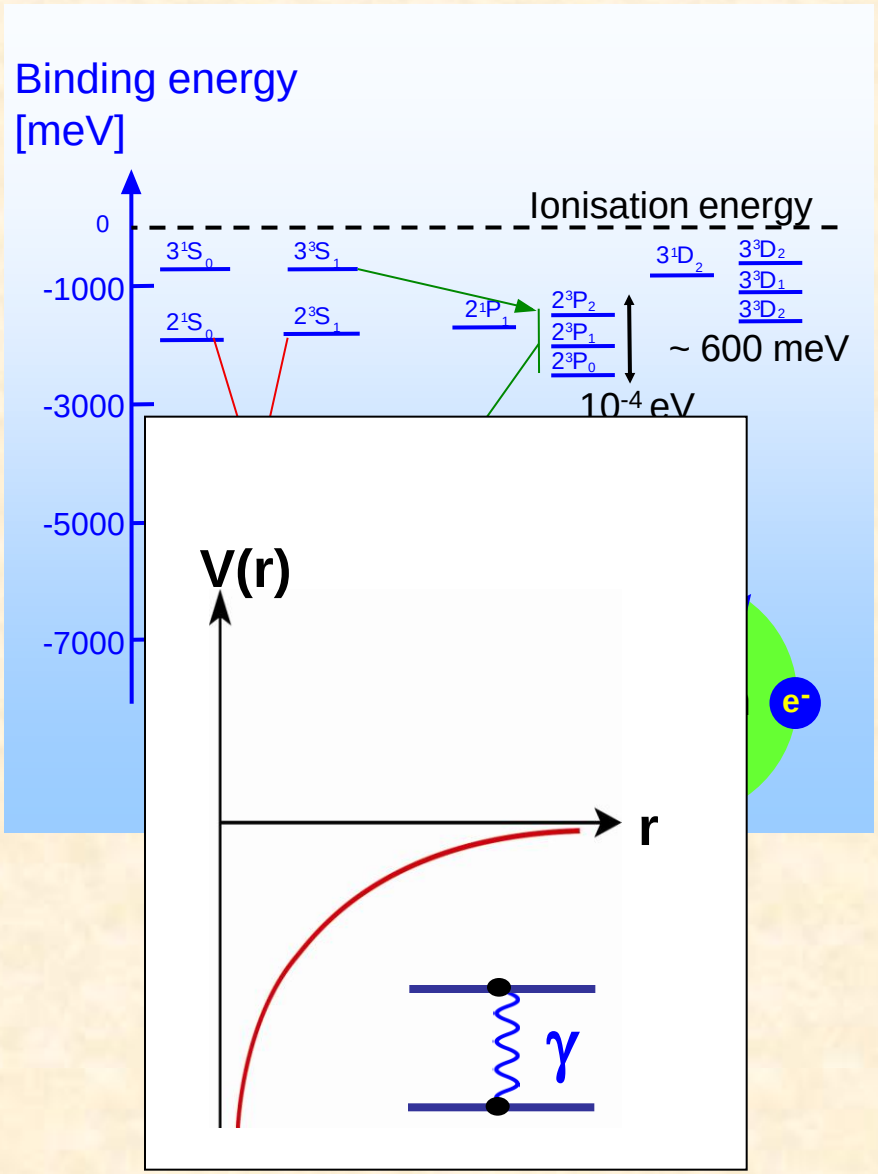
positronium



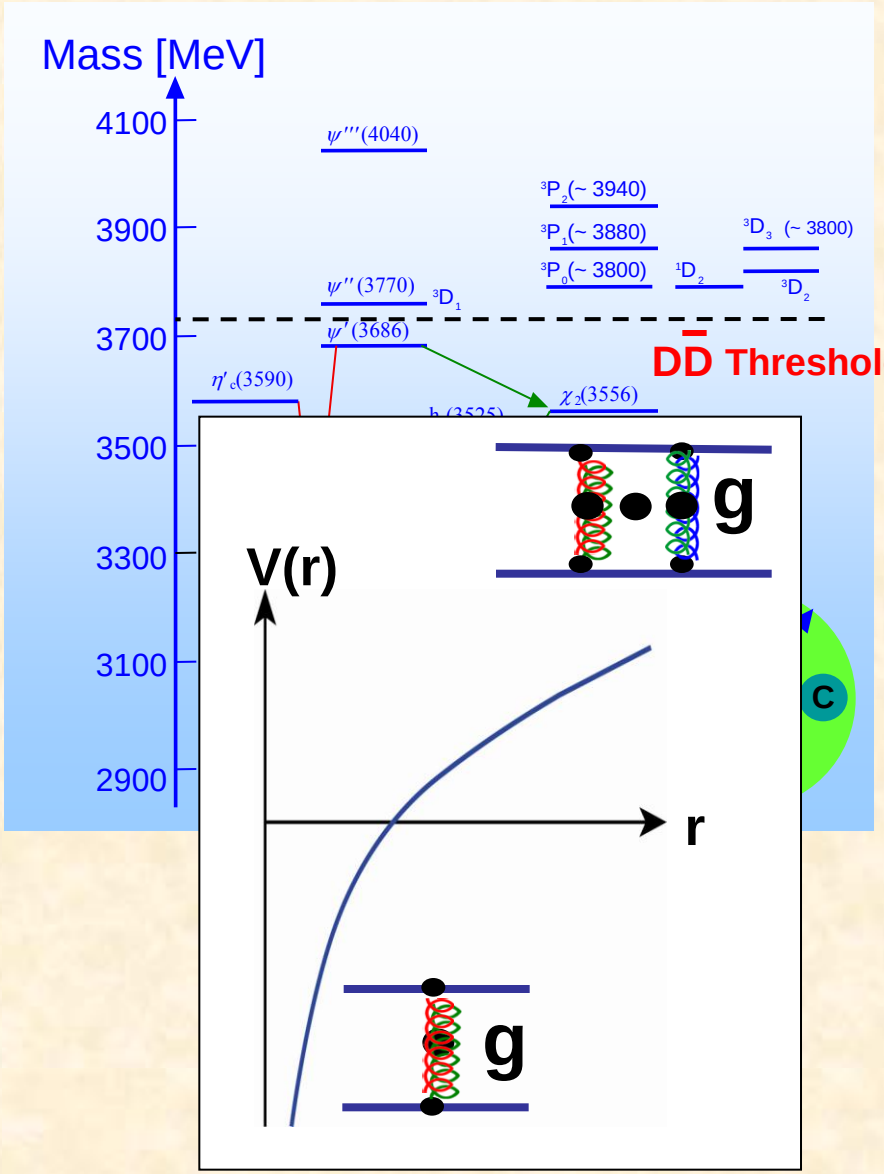
charmonium



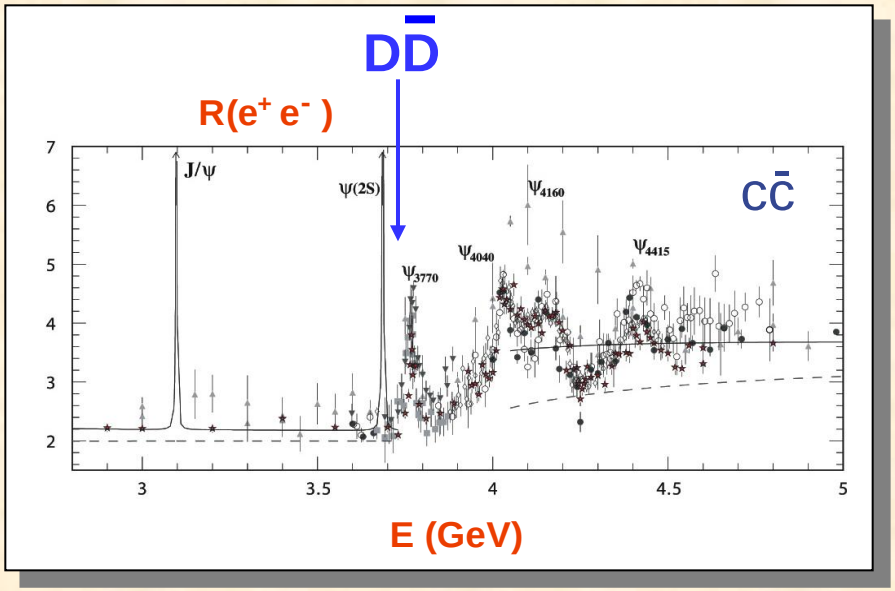
positronium

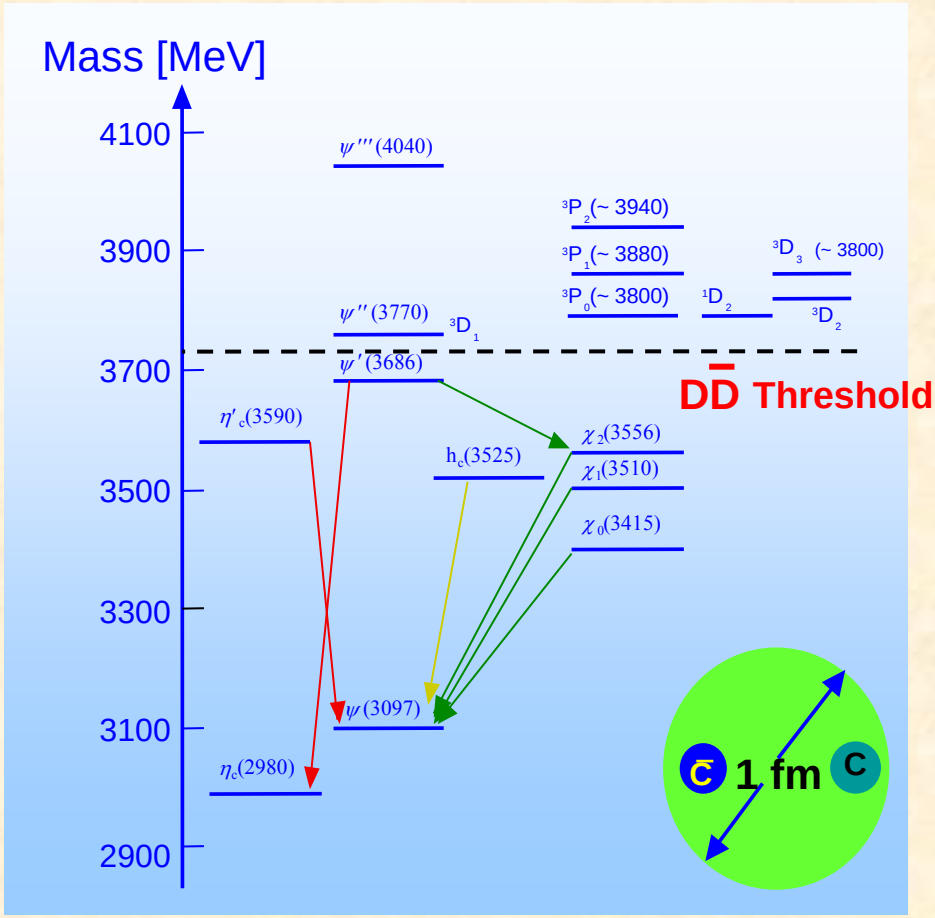


charmonium



charmonium


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

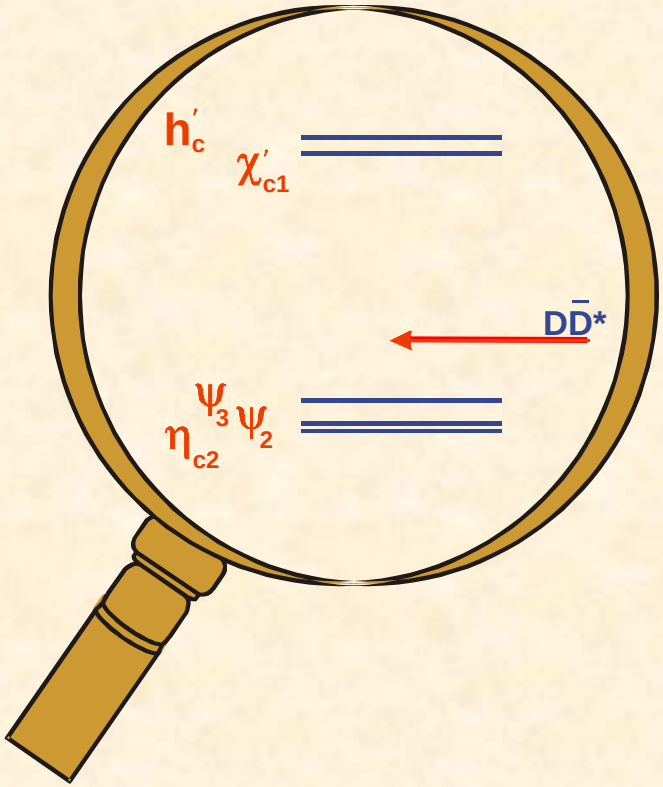

Mass [MeV]
4100
3900
3700
3500
3300
3100
2900
ψ'''(4040)
3P2(~ 3940)
3P1(~ 3880)
3P0(~ 3800)
1D2
3D3 (~ 3800)
3D2
ψ''(3770)
3D1
ψ'(3686)
DD̄ Threshold
η'c(3590)
hc(3525)
χ2(3556)
χ1(3510)
χ0(3415)
ψ(3097)
ηc(2980)
c̄
1 fm
c

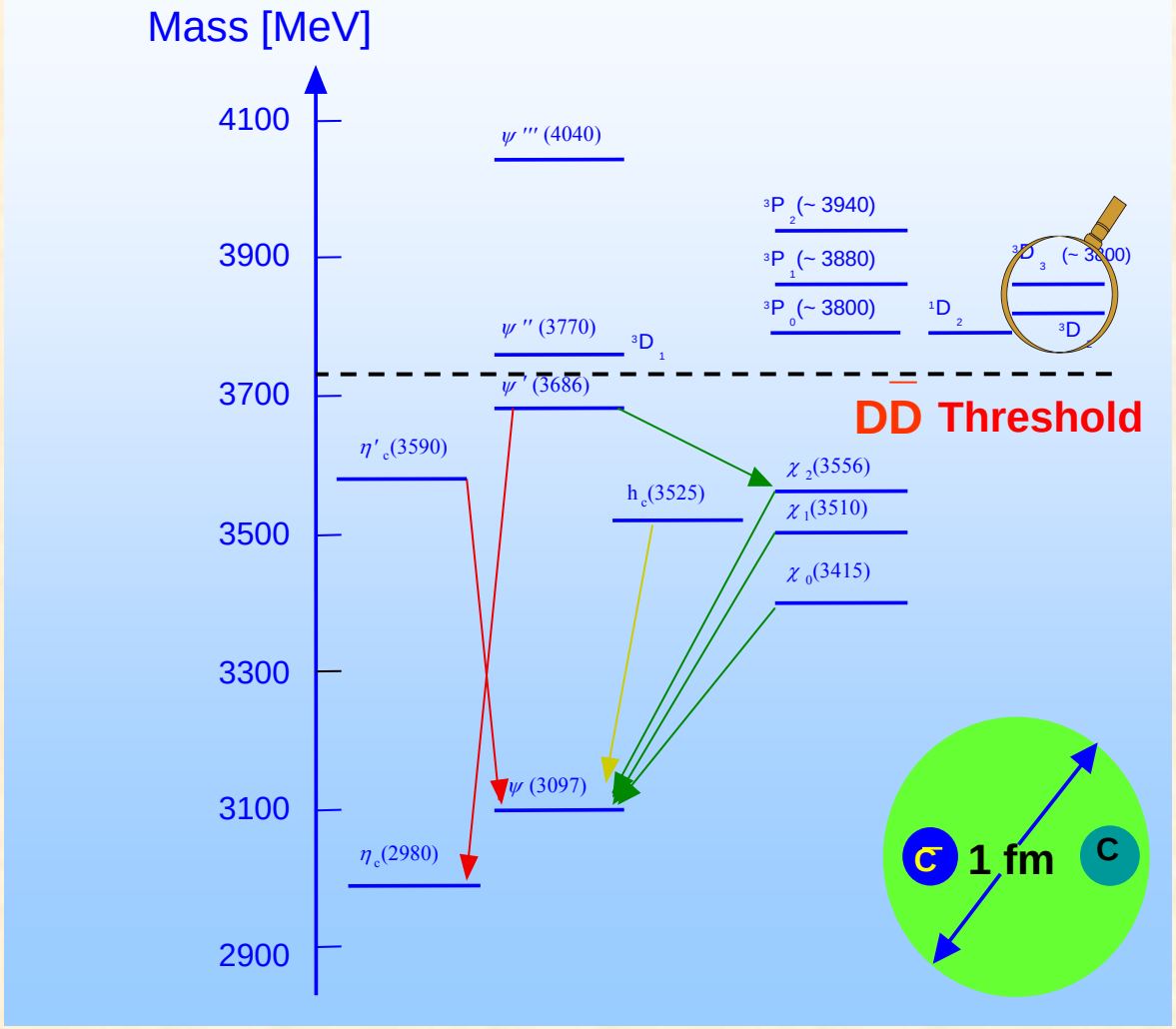
Hadrons and confinement

Hadrons and de-confinement

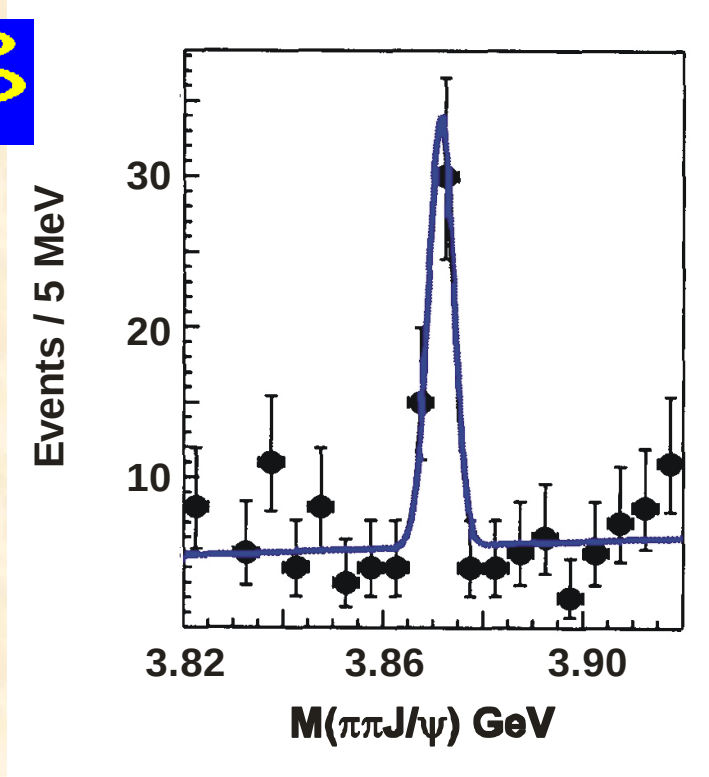
Hadrons and de-confinement

charmonium

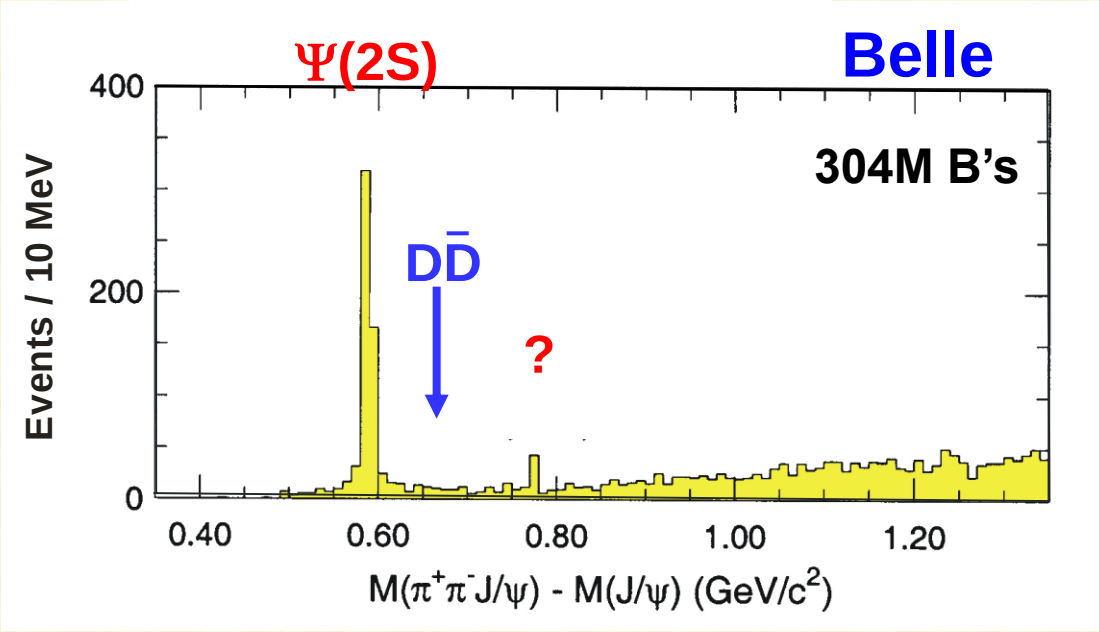

h'c
χ'c1
DD̄*
ψ3 ψ2
ηc2


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

gifts from B-factories



X(3872)

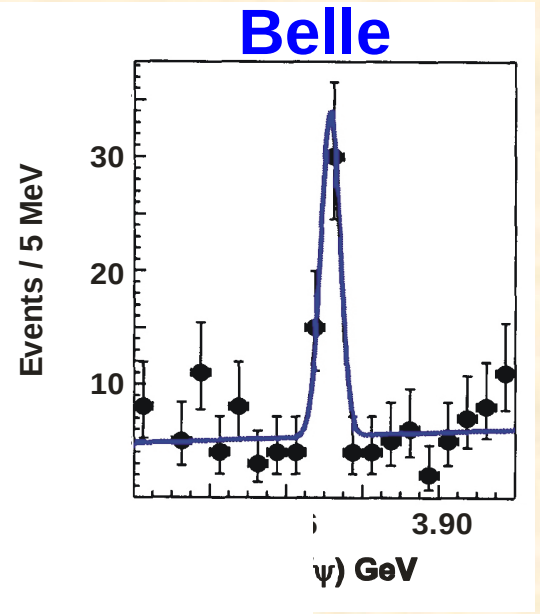


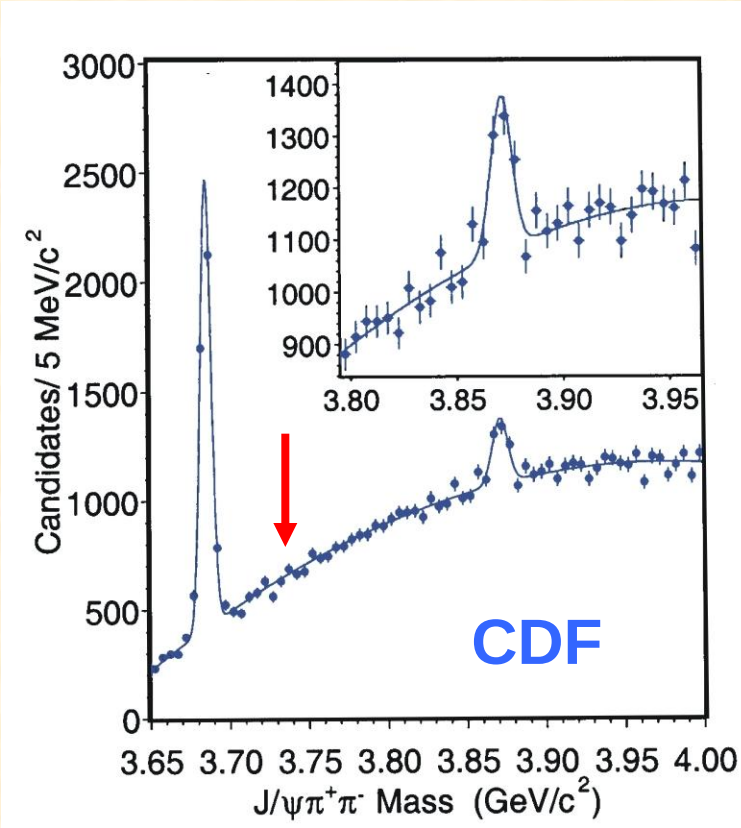
$B \rightarrow K X$

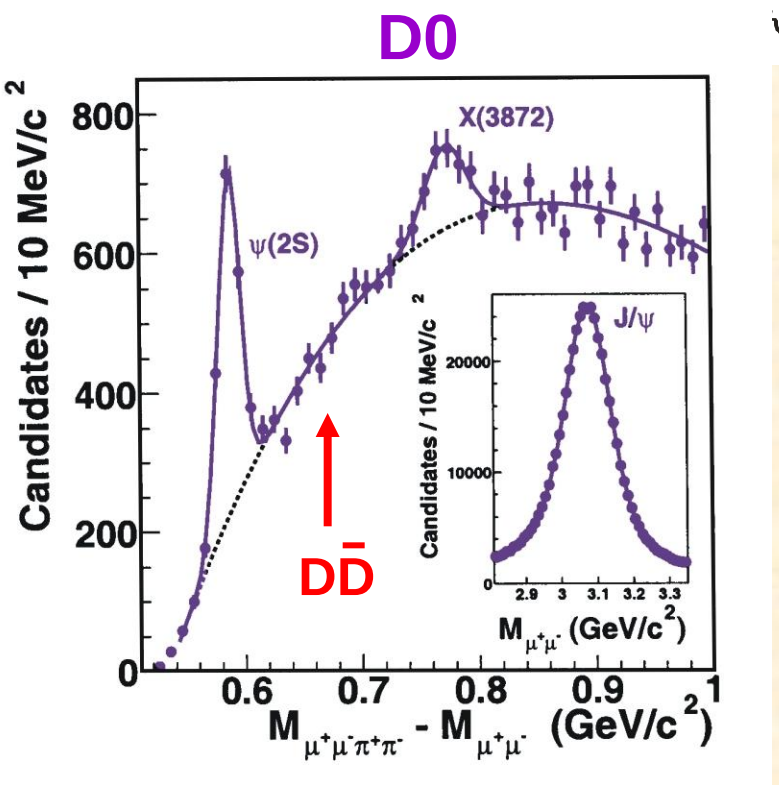
$X \rightarrow \pi^+ \pi^- J/\psi$

$\Gamma < 2.3$ MeV

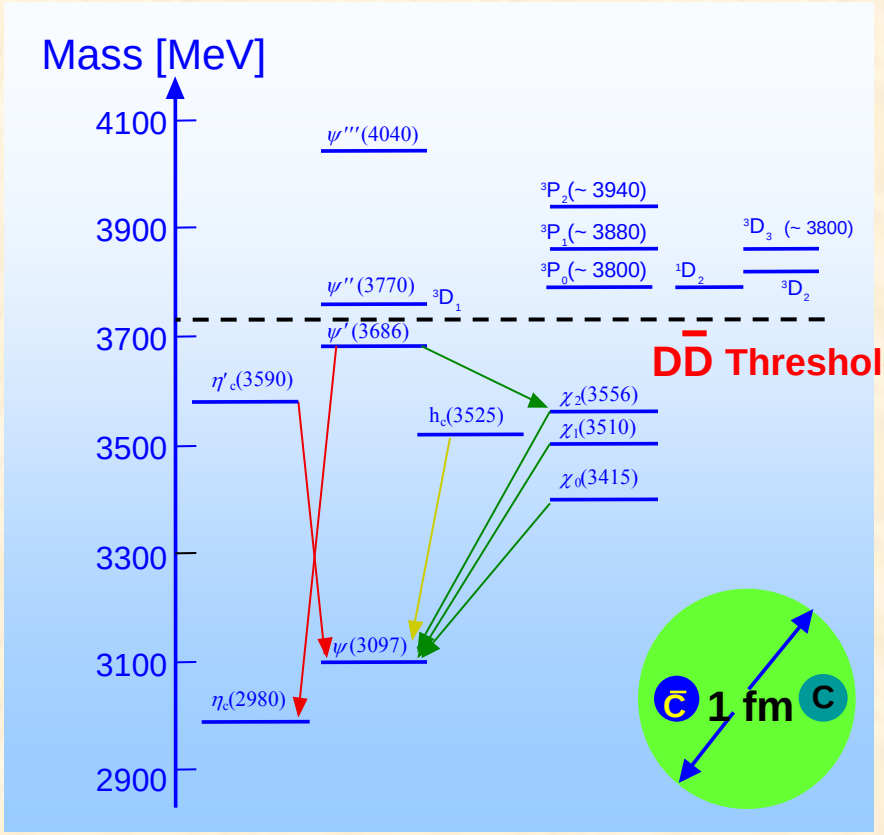
X(3872) confirmed

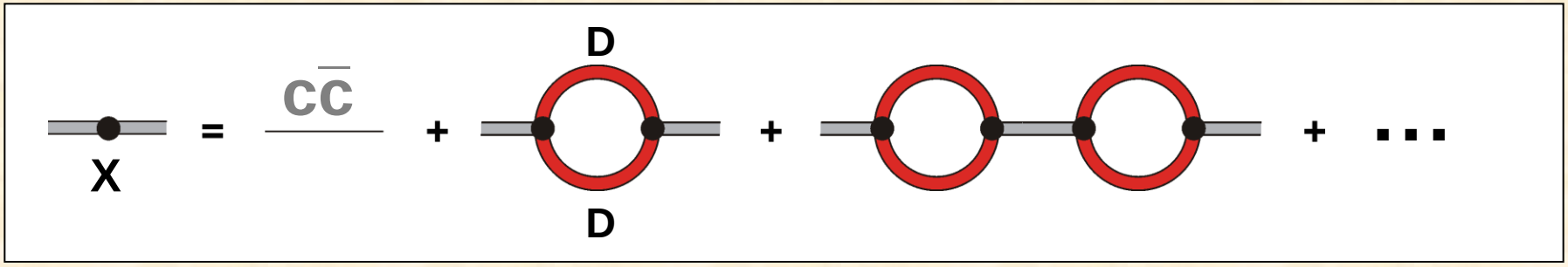


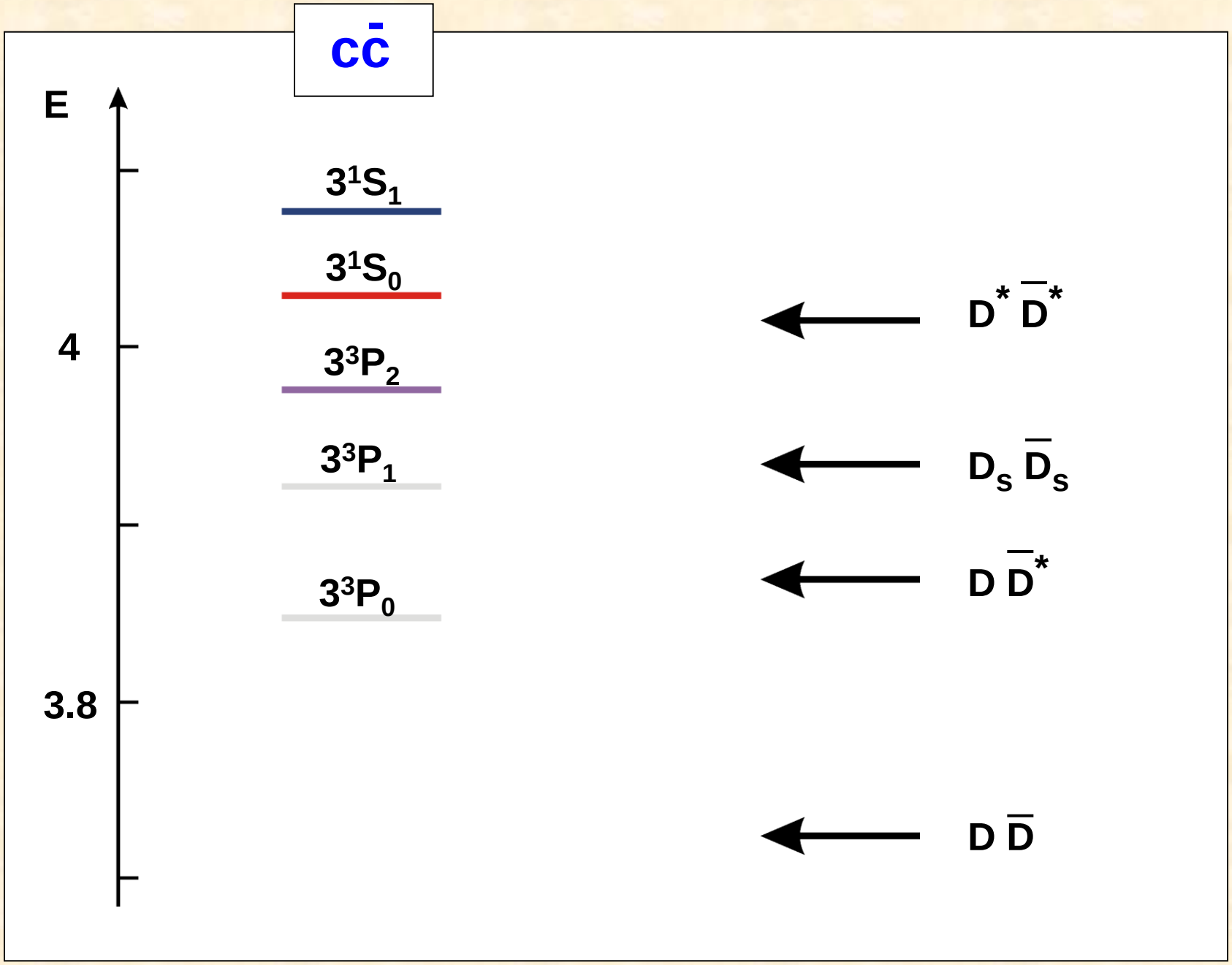


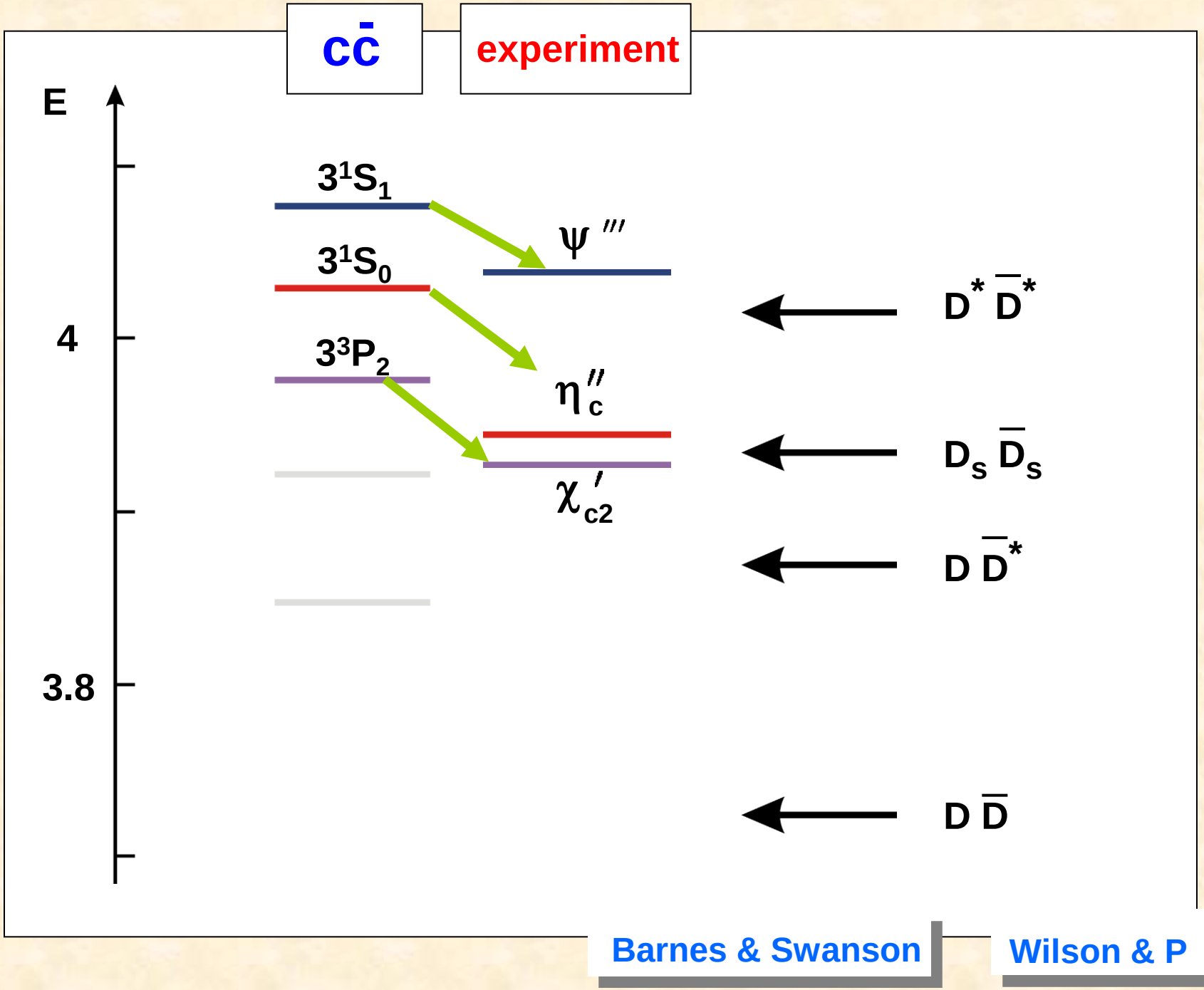


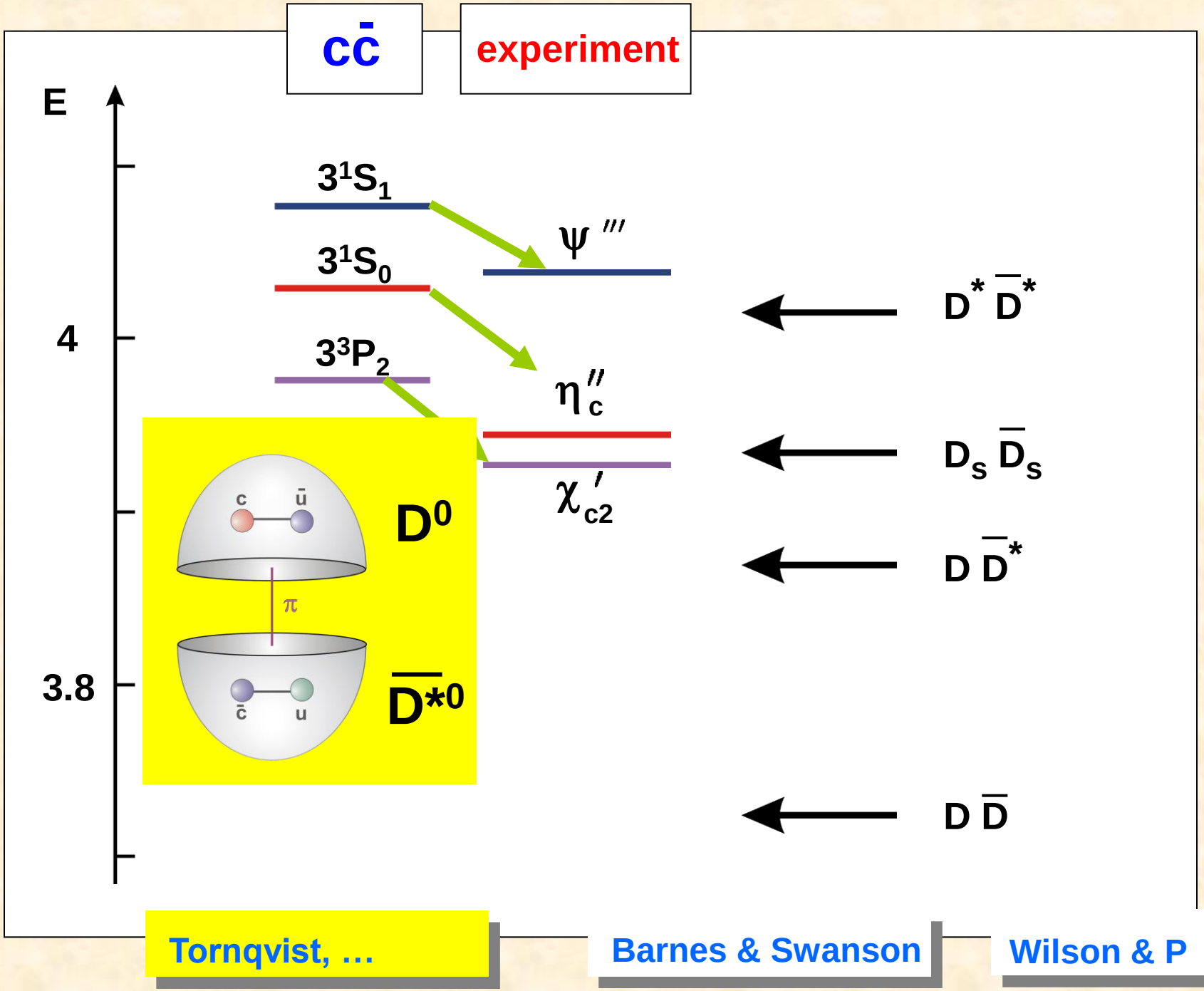
Effect of Decay channels






$c\bar{c}$
E
4
3.8
3^1S_1
3^1S_0
3^3P_2
3^3P_1
3^3P_0
$D^* \bar{D}^*$
$D_s \bar{D}_s$
$D \bar{D}^*$
$D \bar{D}$


cc̄
experiment
E
4
3.8
3^1S_1
3^1S_0
3^3P_2
ψ'''
η_c''
χ_{c2}'
$D^* \bar{D}^*$
$D_s \bar{D}_s$
$D \bar{D}^*$
$D \bar{D}$
Barnes & Swanson
Wilson & P

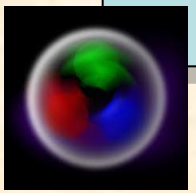

cc̄
experiment
E
4
3.8
3^1S_1
3^1S_0
3^3P_2
ψ'''
η_c''
χ_{c2}'
D^0
$\overline{D}^{*0}$
c
ū
c̄
u
π
$D^* \overline{D}^*$
$D_s \overline{D}_s$
$D \overline{D}^*$
$D \overline{D}$
Tornqvist, …
Barnes & Swanson
Wilson & P

color wave-functions

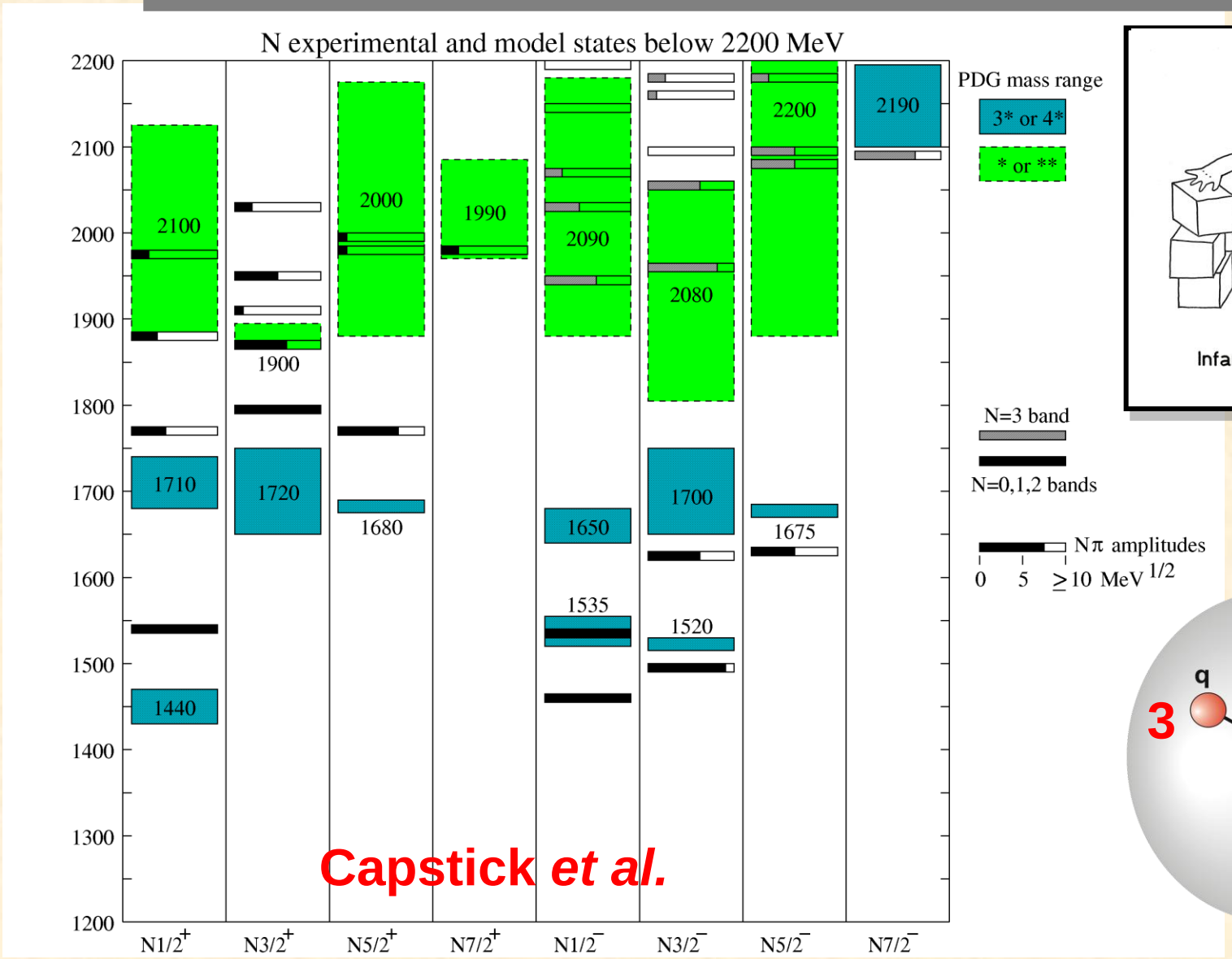
$$\pi^+ = \frac{1}{\sqrt{N_c}} \left[u\bar{d} + u\bar{d} + u\bar{d} + u\bar{d} + \ldots \right]$$

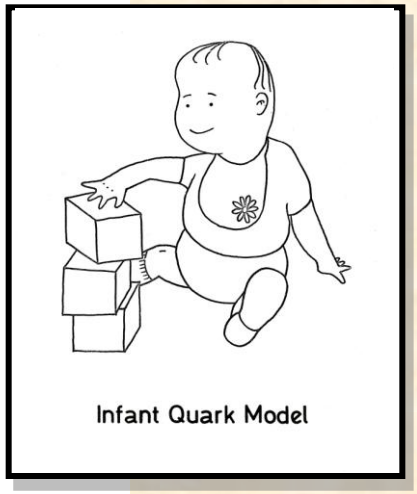
$N_c = 3$

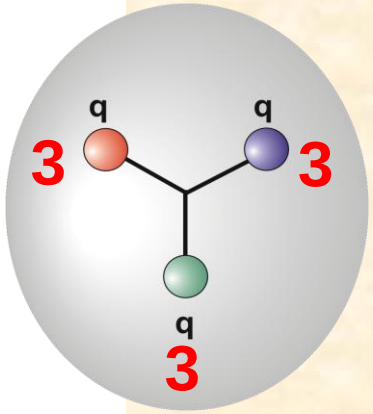
$$p = \frac{1}{\sqrt{6}} \left[uud + uud + uud - uud - uud - uud \right]$$



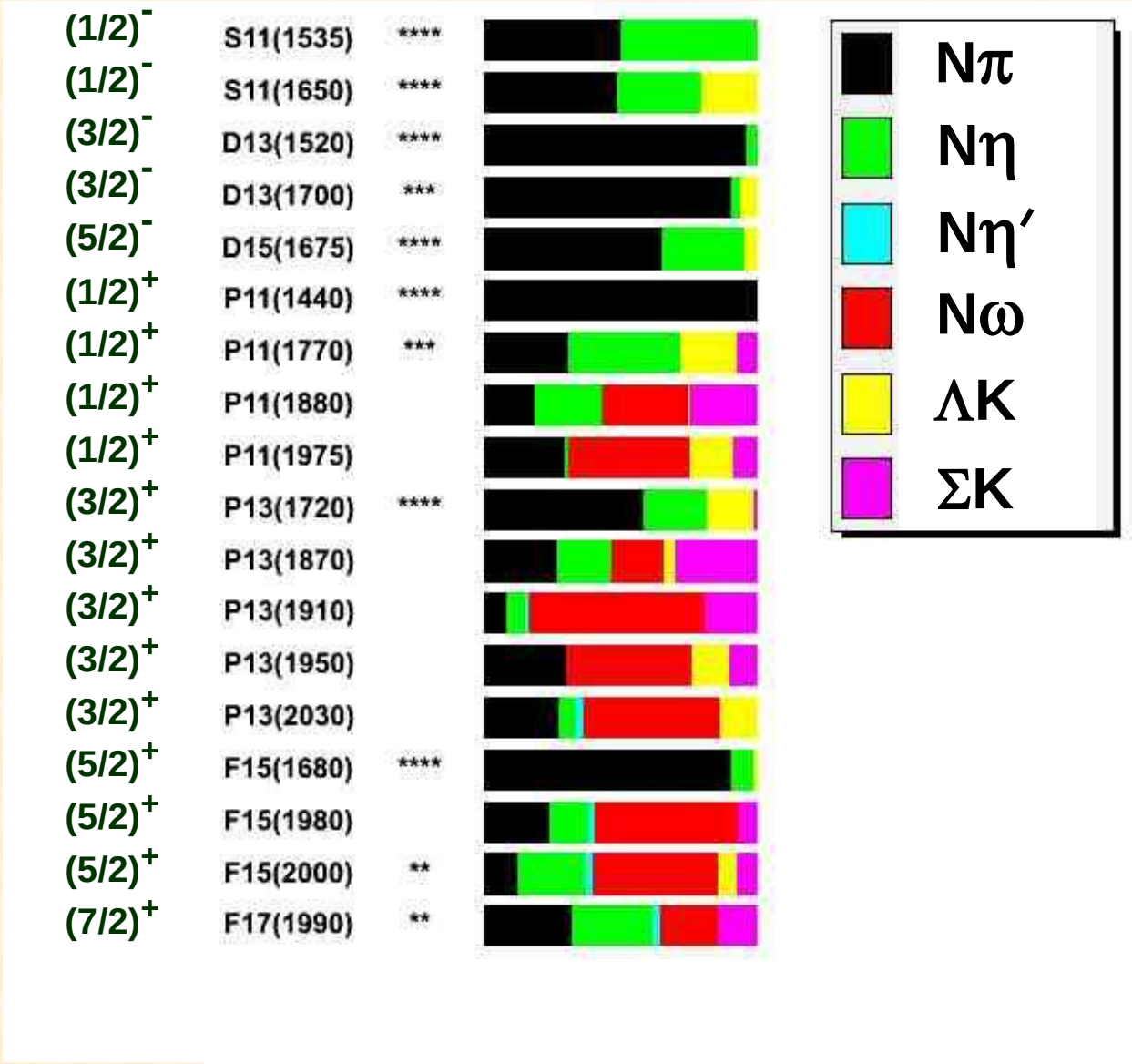
Nucleon model states (πN couplings)



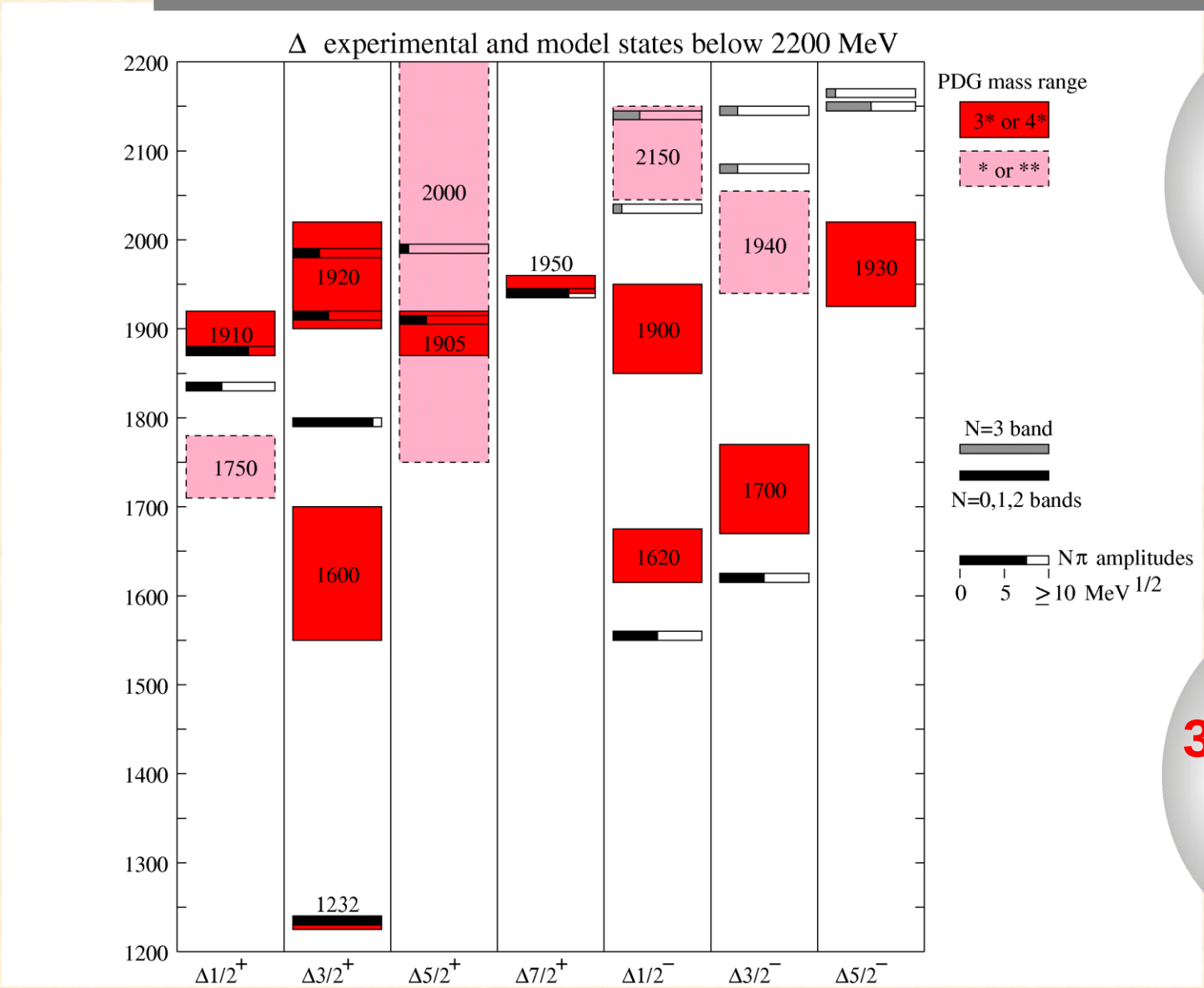


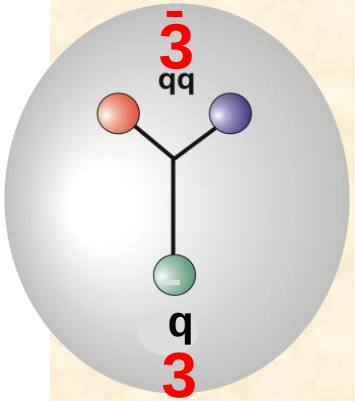


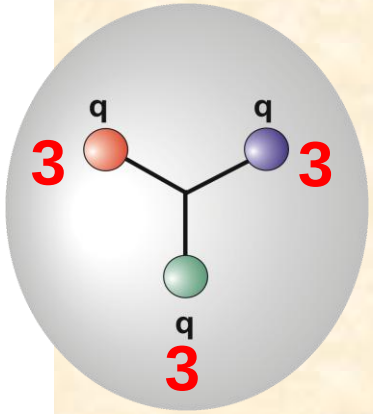
search all channels: not just πN



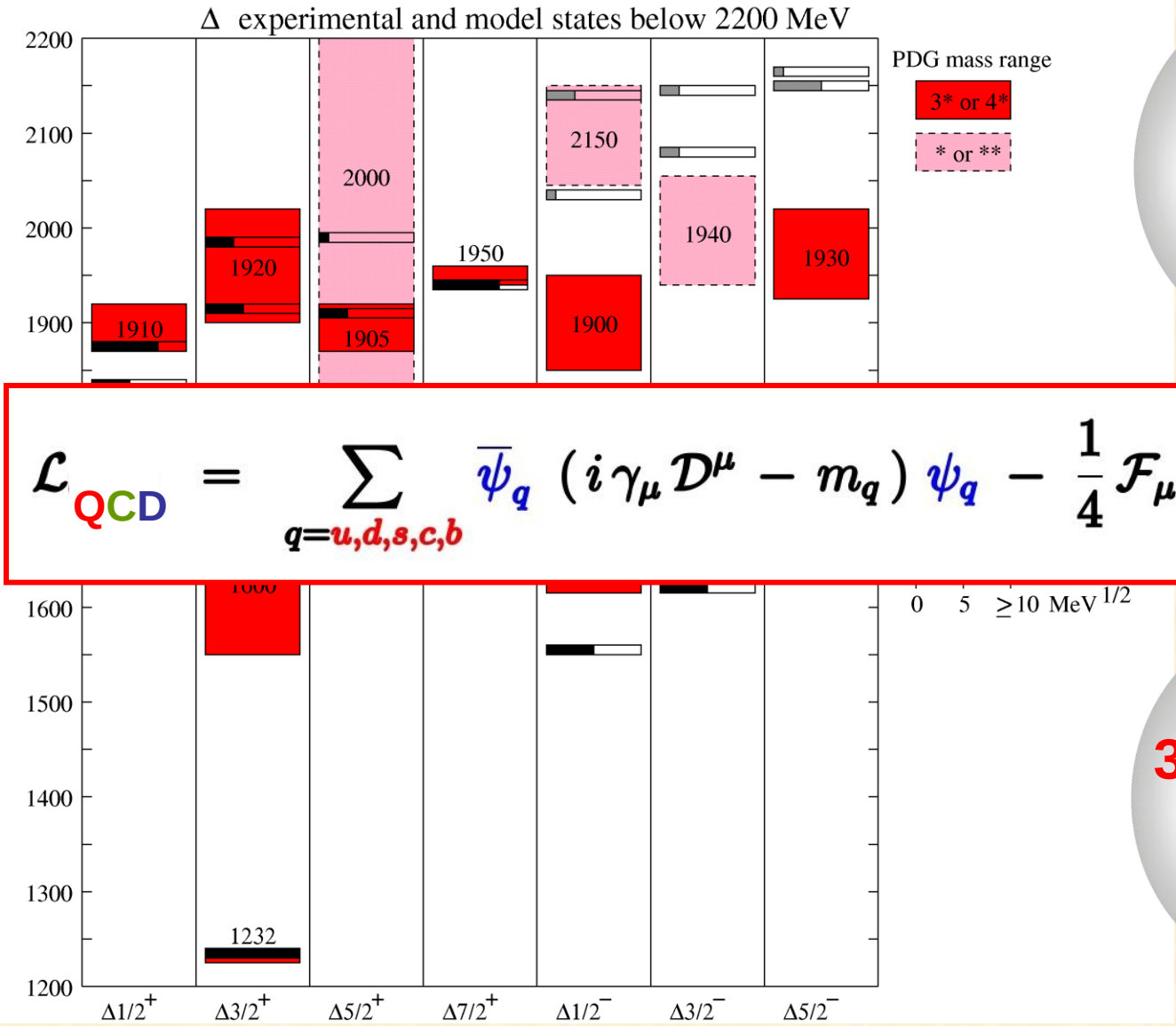
Δ model states (πN couplings)



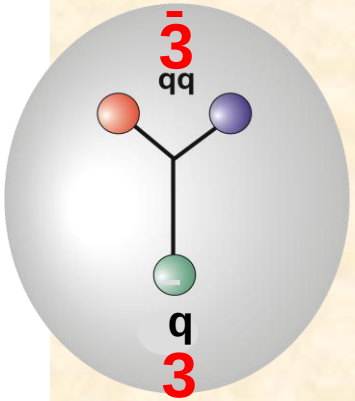


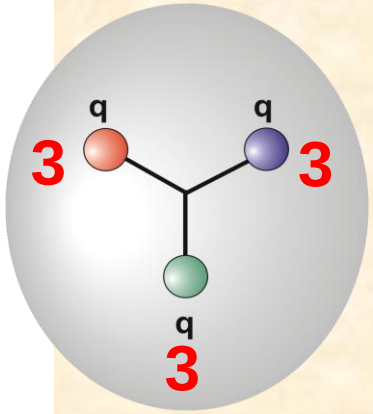


Δ model states (πN couplings)



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

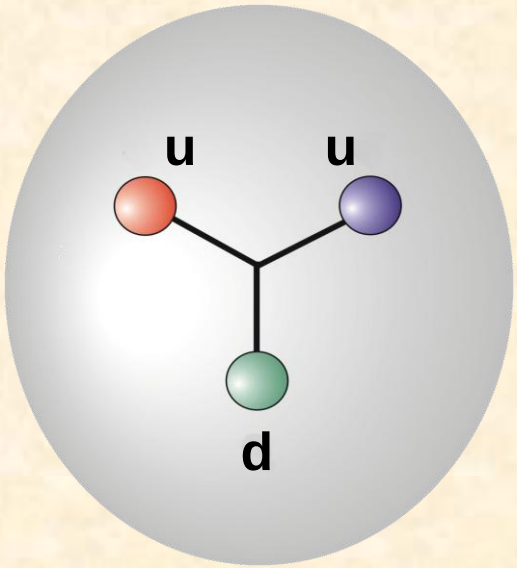


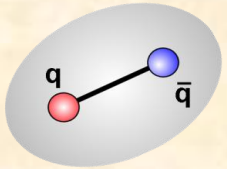


Δ(1232) color wave-function

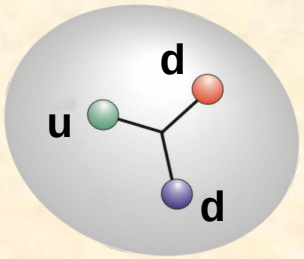
$N_c = 3$

$$\Delta^+ = \frac{1}{\sqrt{6}} [\, uud + uud + uud - uud - uud - uud \,]$$





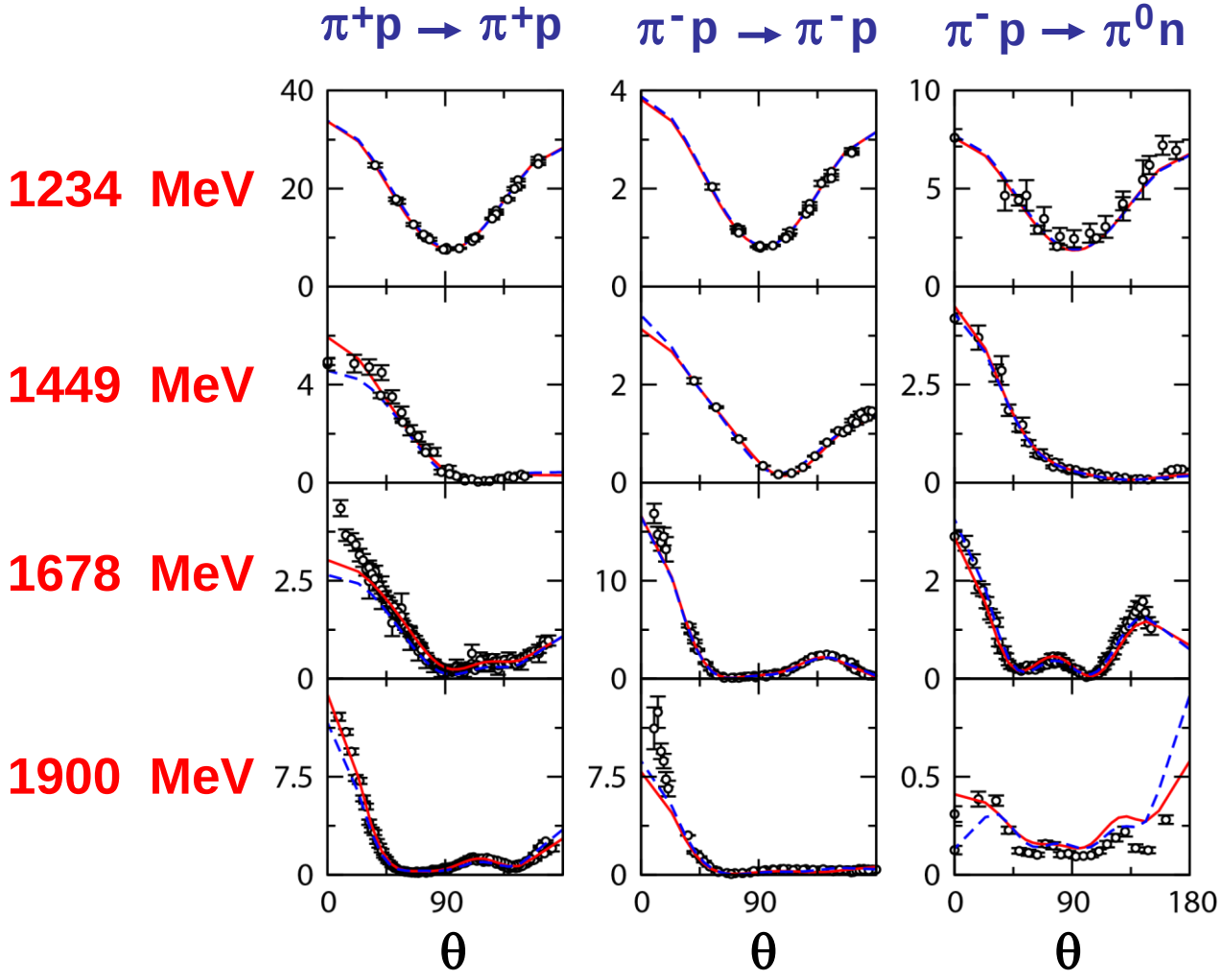
π



N

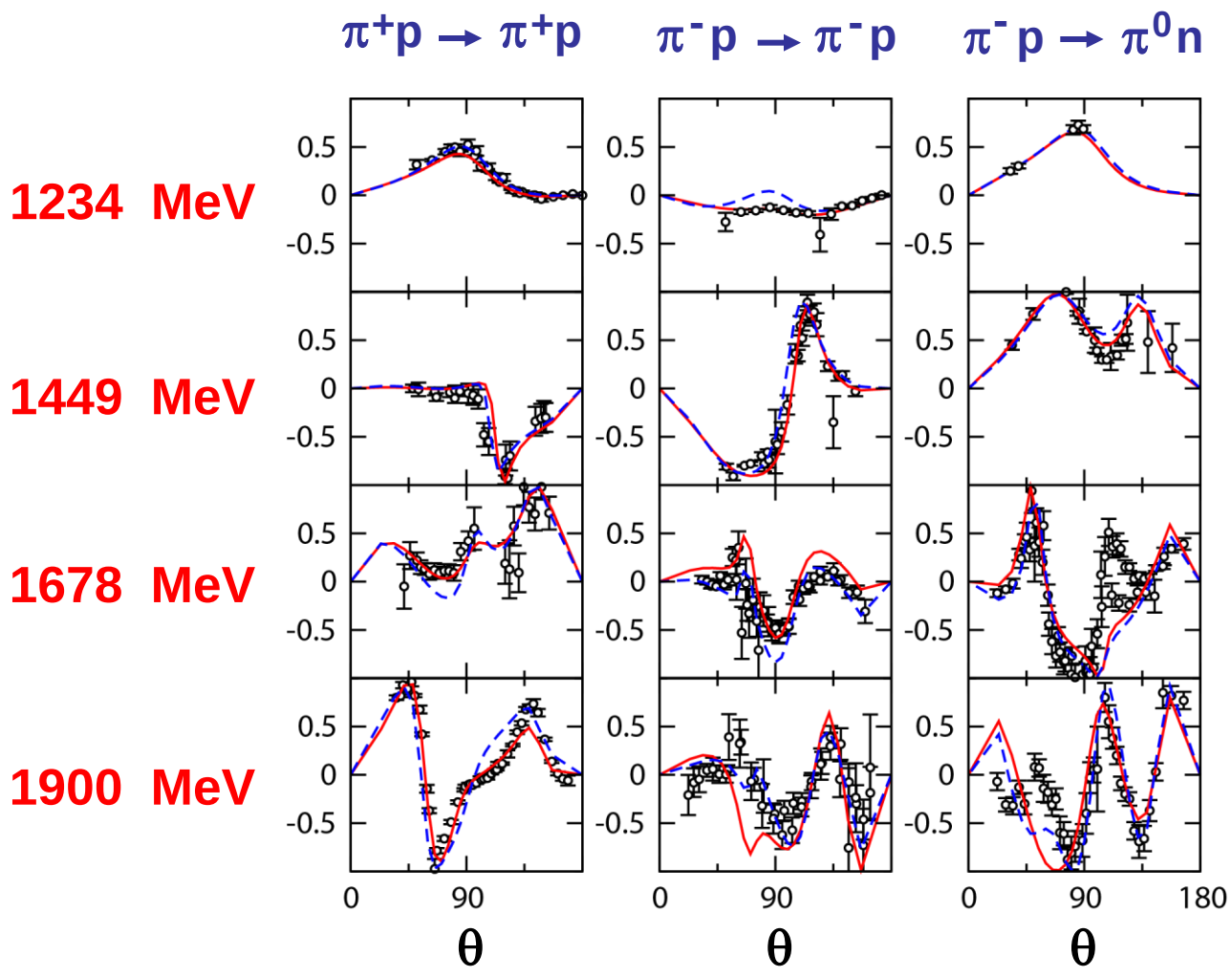
$\pi N \longrightarrow \pi N$ scattering

$d\sigma/d\Omega$

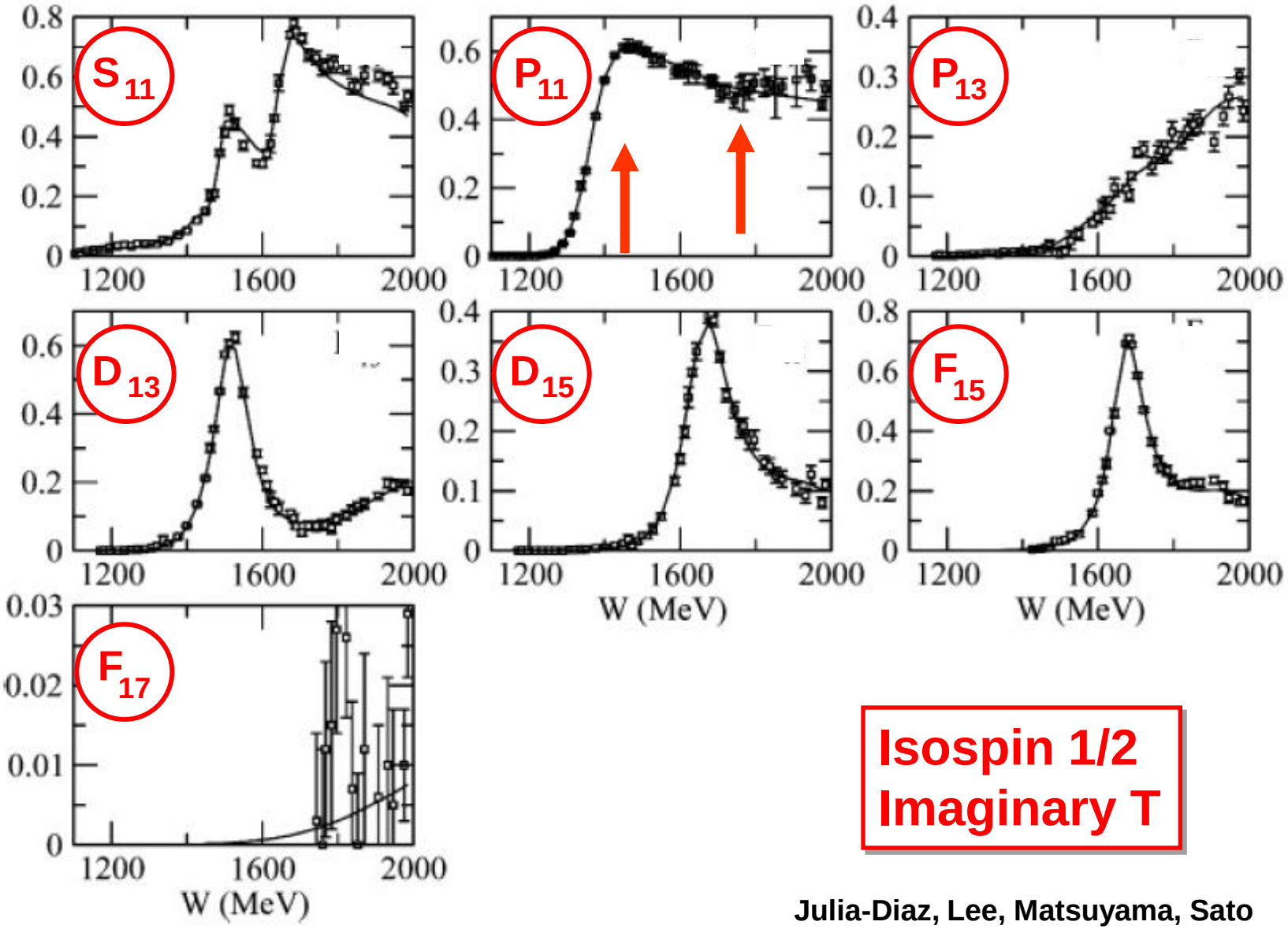


$\pi N \longrightarrow \pi N$ scattering

P



πN amplitudes

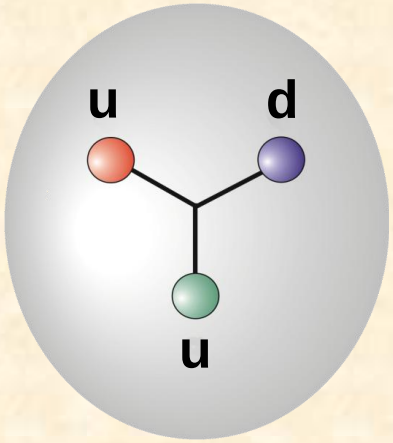


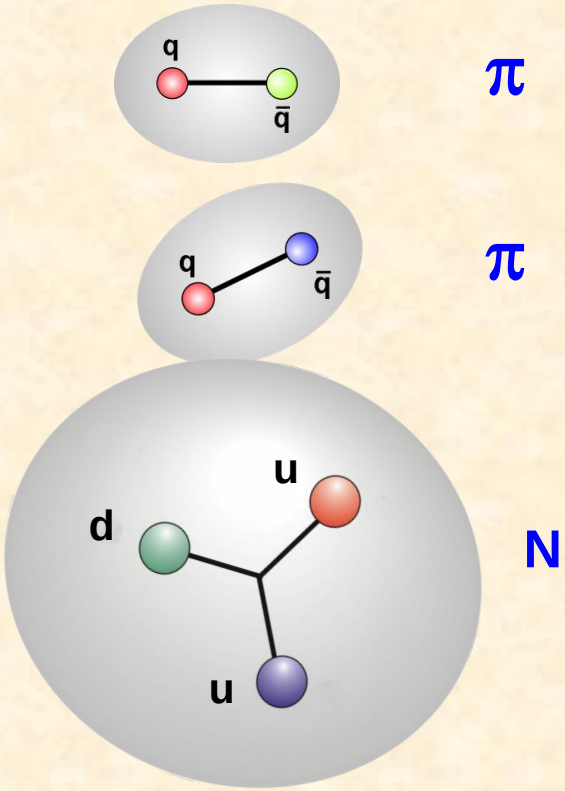
Isospin 1/2
Imaginary T

Julia-Diaz, Lee, Matsuyama, Sato

N*(1xxx)

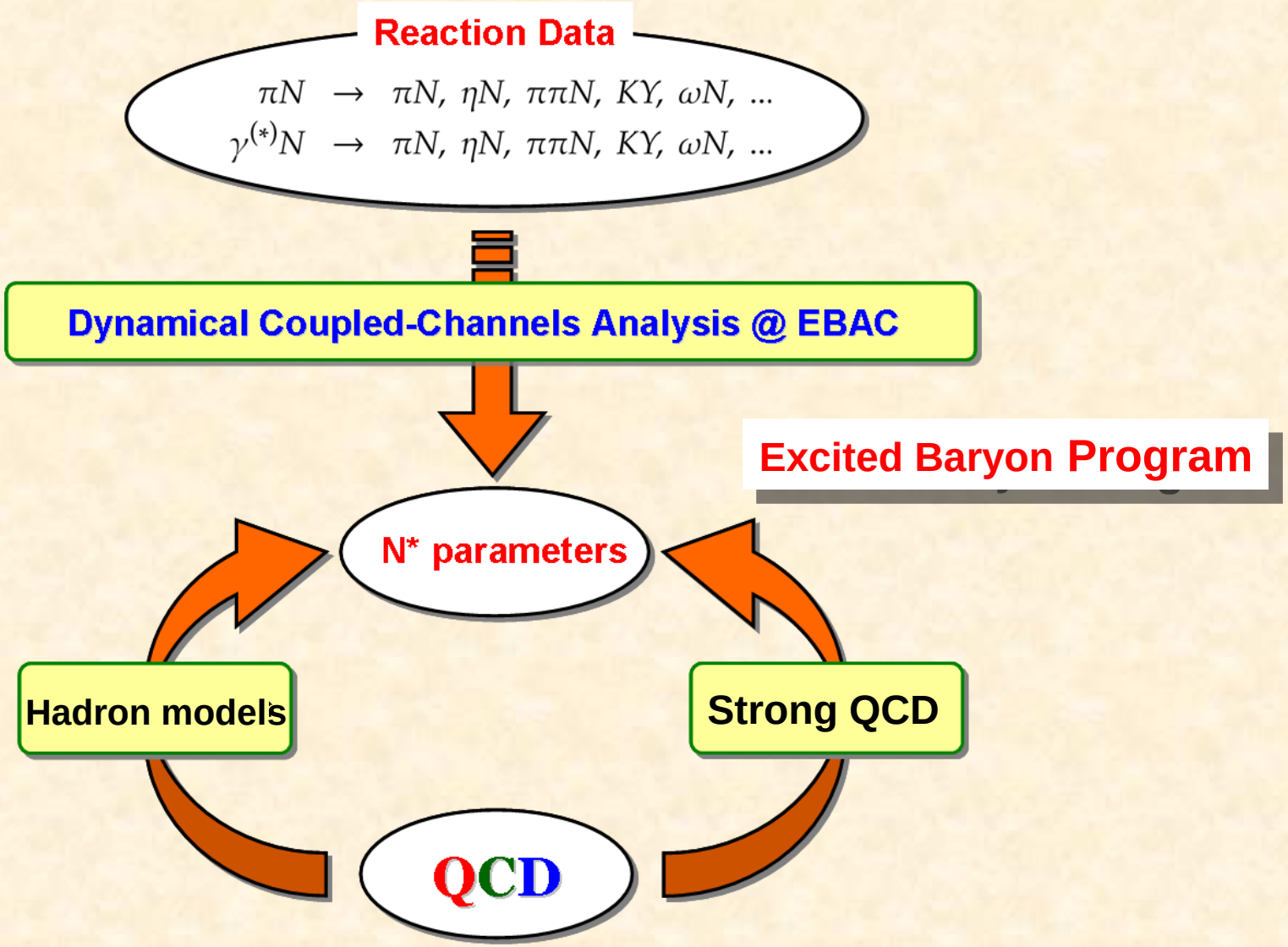
?





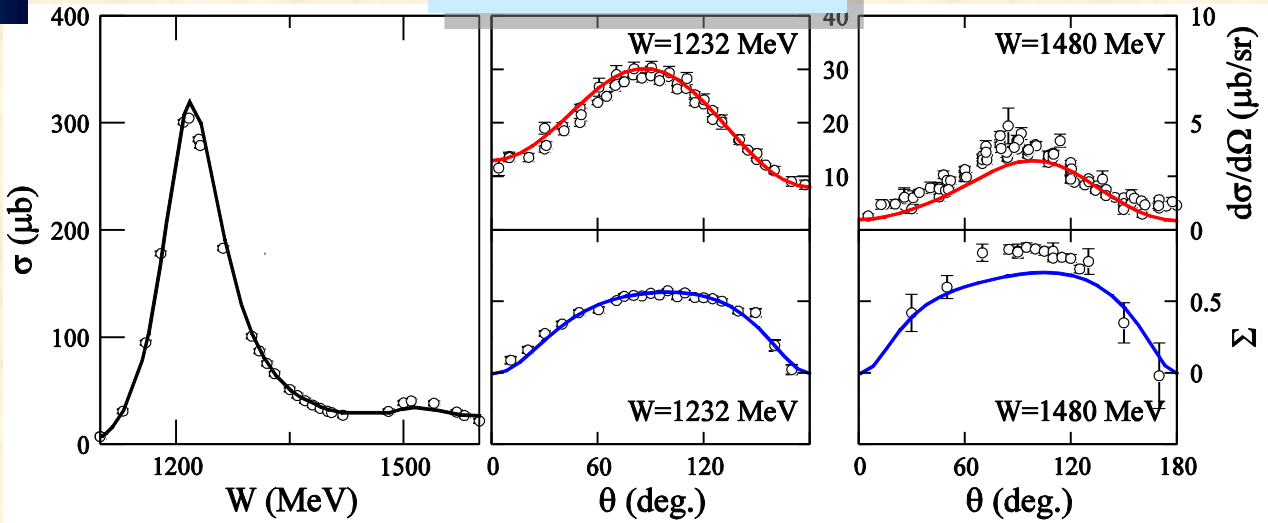
Coupled channels
Coupled channels

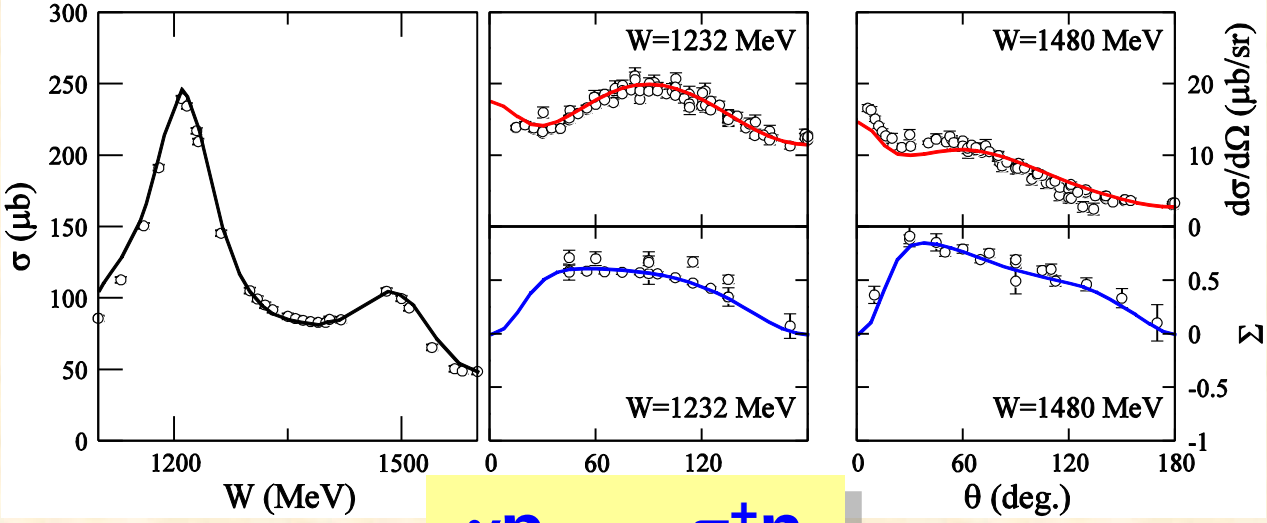
Properties of Excited Baryons



EBAC

$\gamma p \rightarrow \pi^0 p$





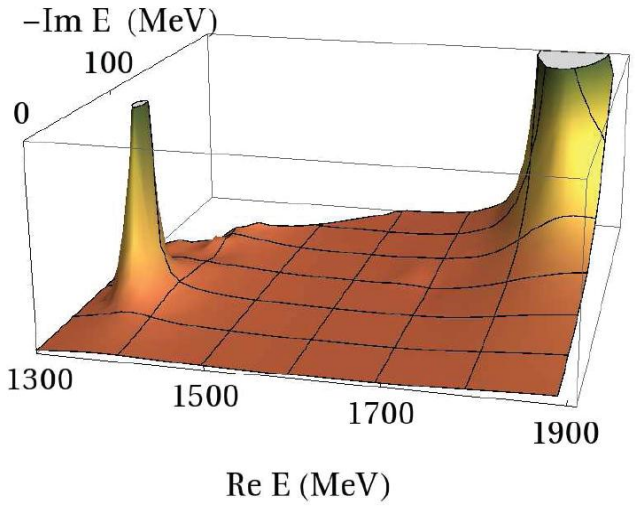
$\gamma p \rightarrow \pi^+ n$

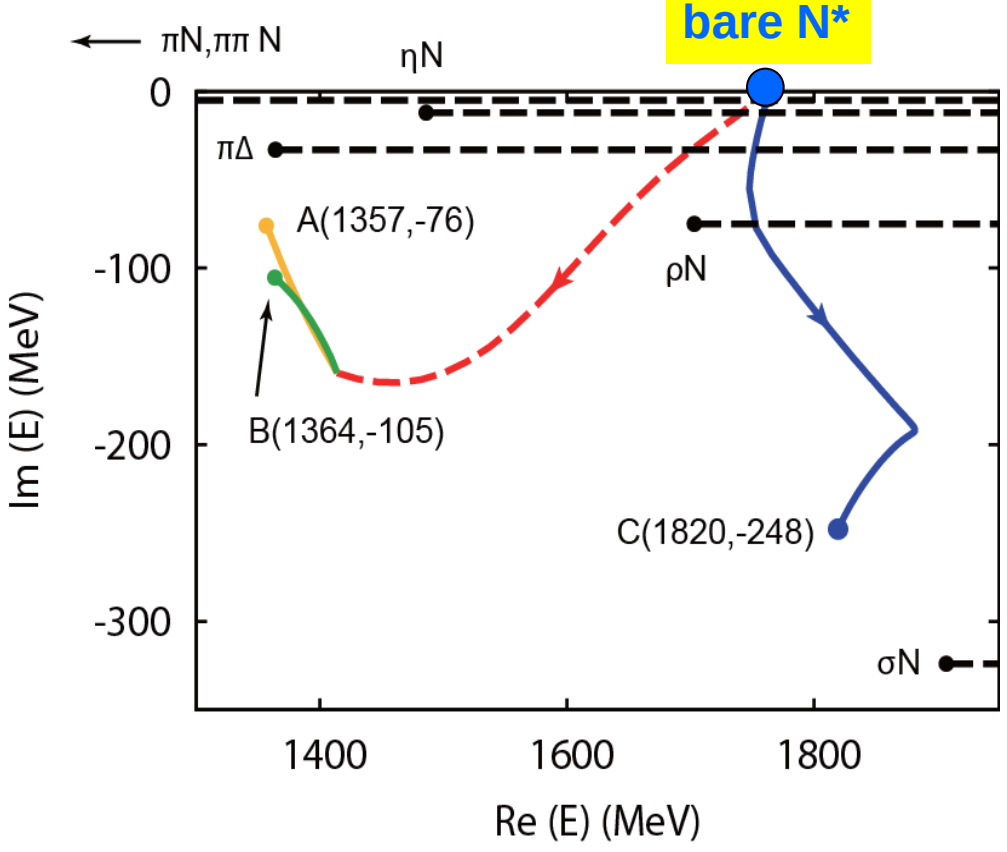
Kamano et al.

$P_{11}(1360)$, $P_{11}(1820)$

EBAC

Suzuki et al.

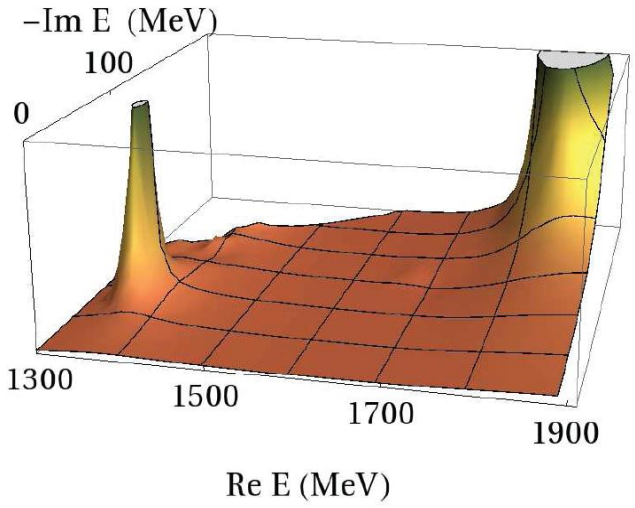


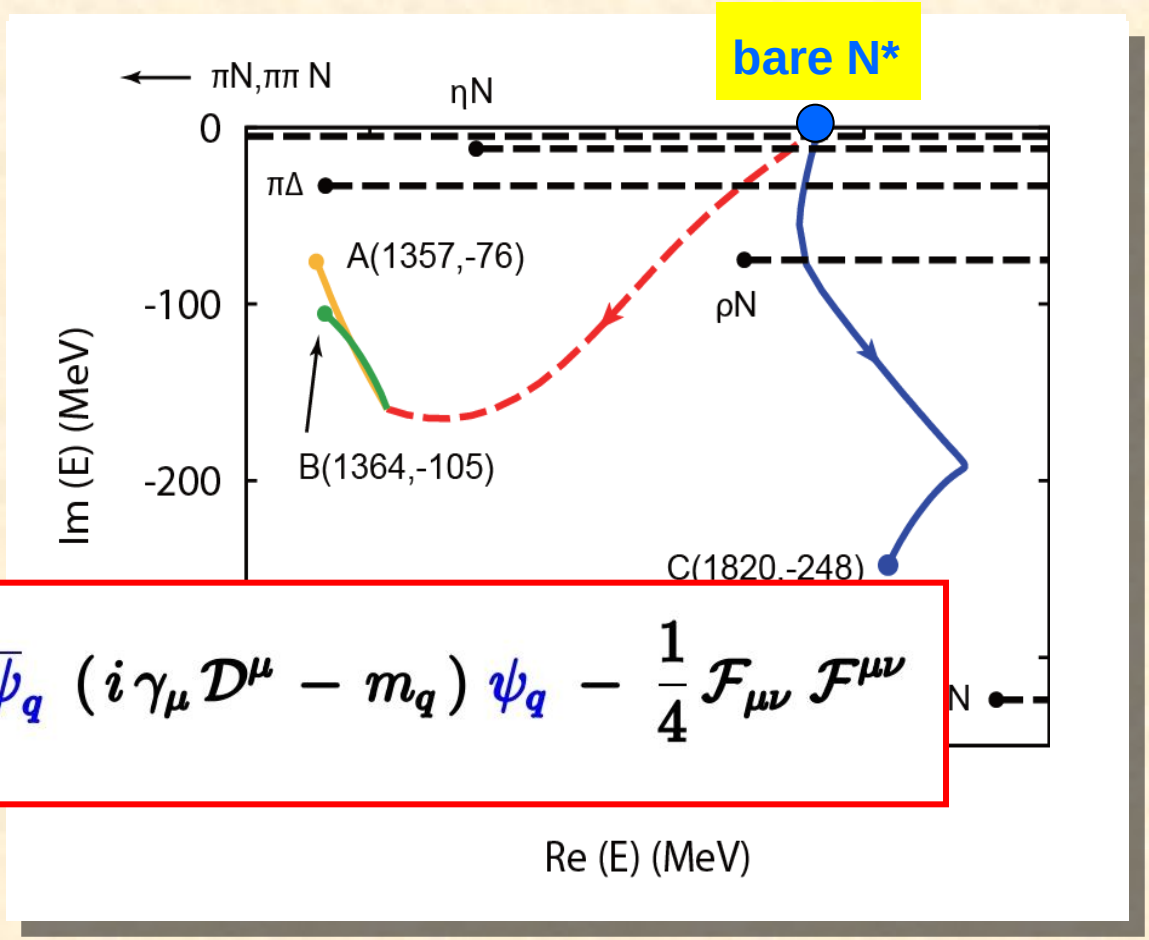


$P_{11}(1360)$, $P_{11}(1820)$

EBAC

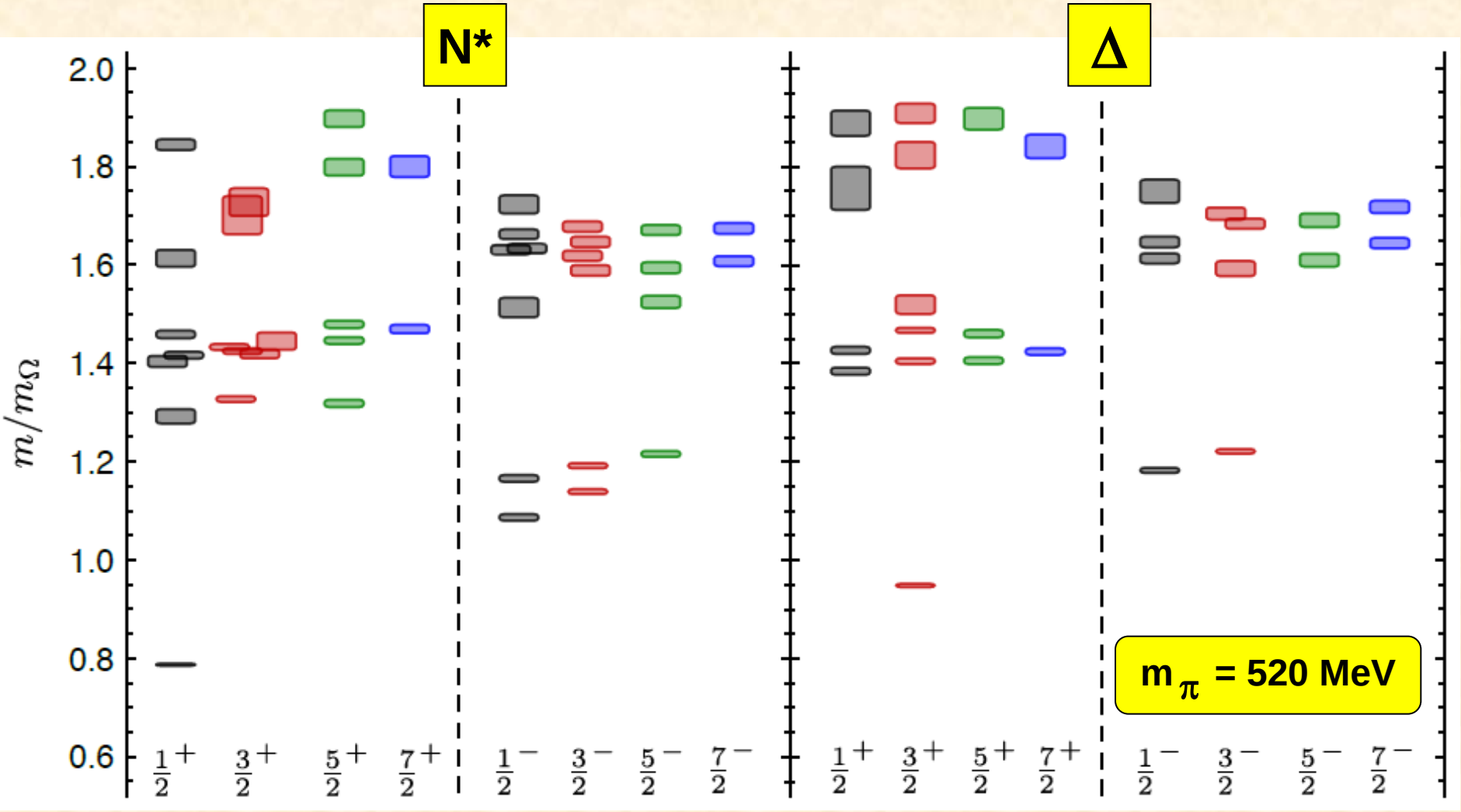
Suzuki et al.





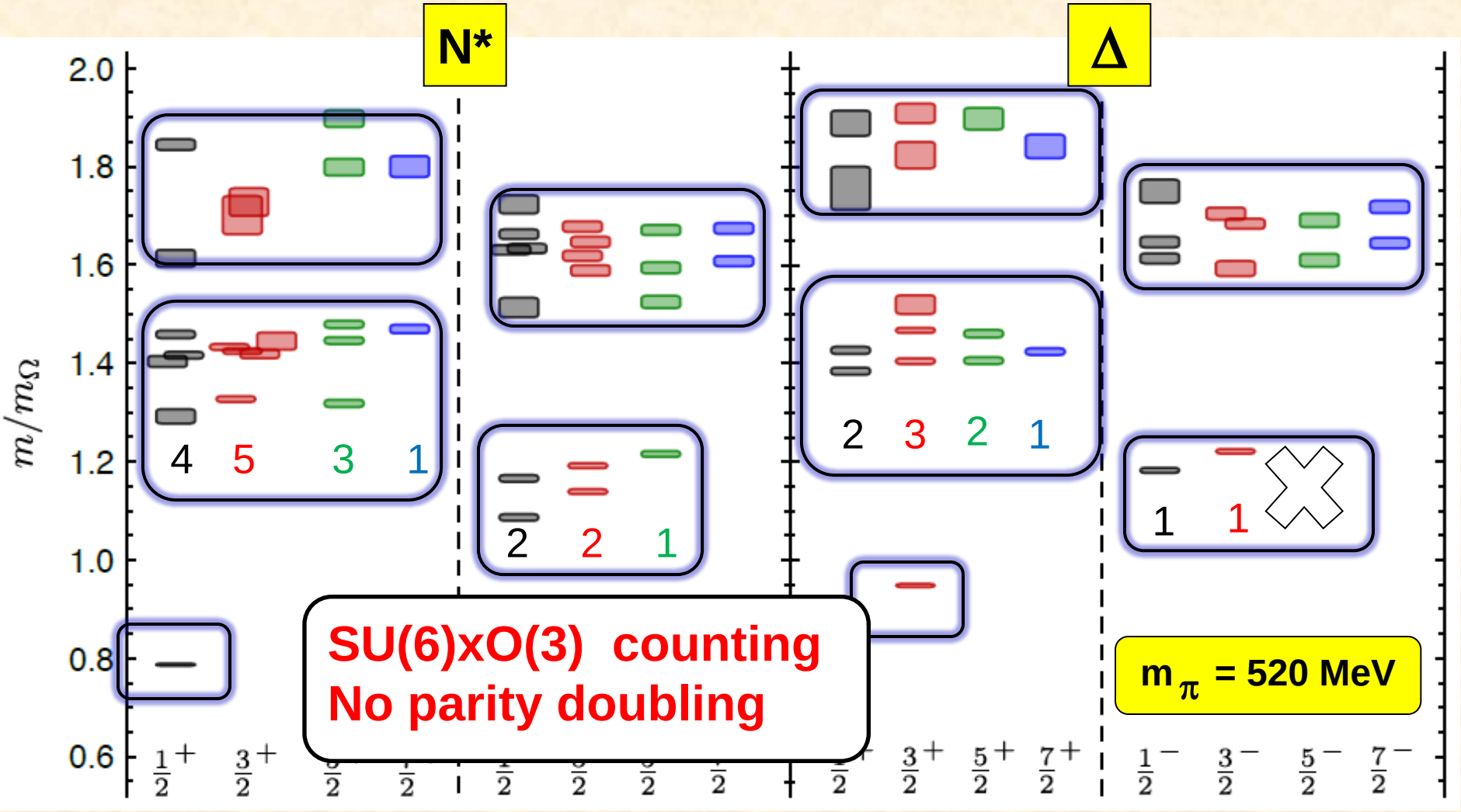
$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} \bar{\psi}_q \left(i \gamma_\mu \mathcal{D}^\mu - m_q \right) \psi_q - \frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}$$

Spin identified N* and Δ states



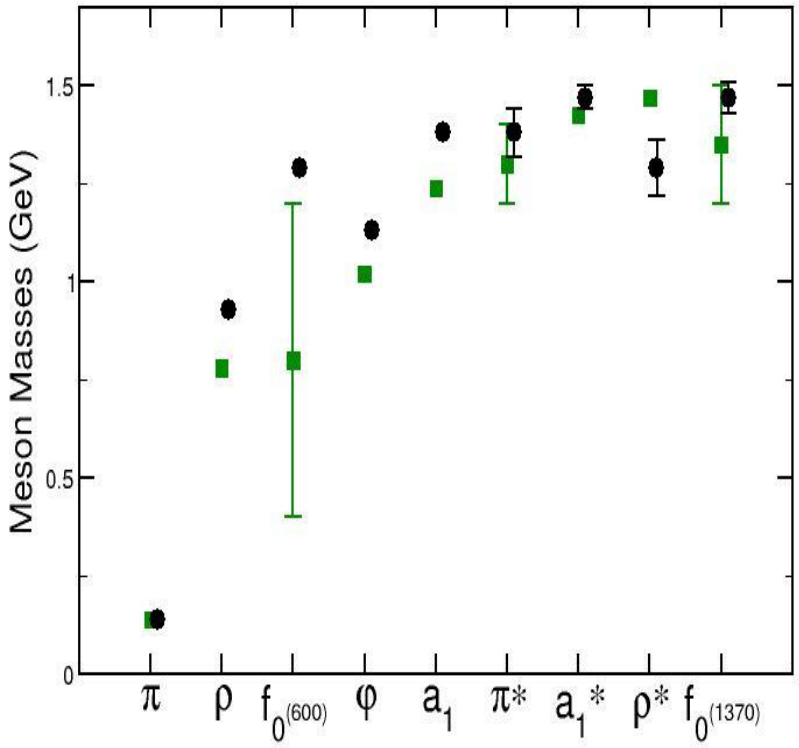
Edwards, Dudek, Wallace & Richards

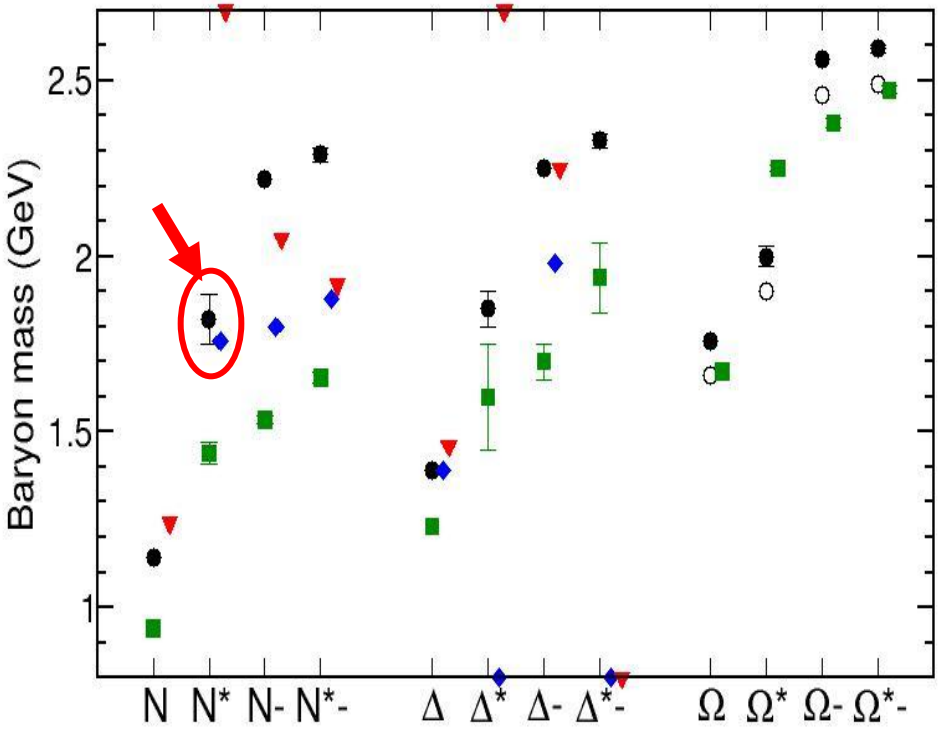
Spin identified N* and Δ states

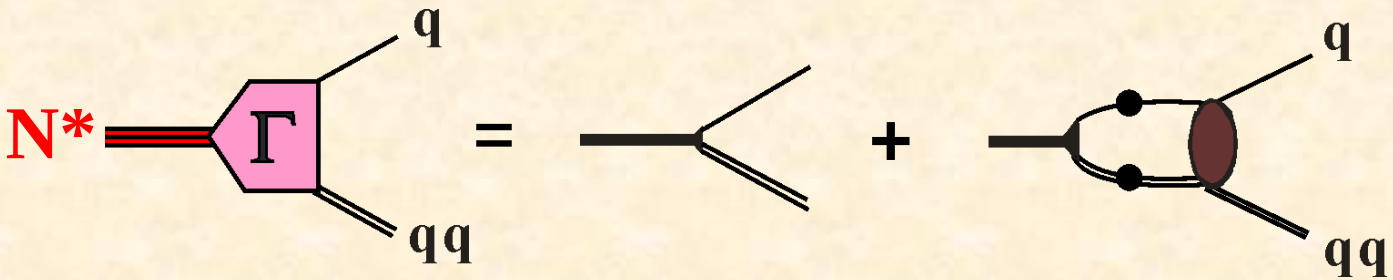


Edwards, Dudek, Wallace & Richards

Hadron Spectrum in ANL BS model



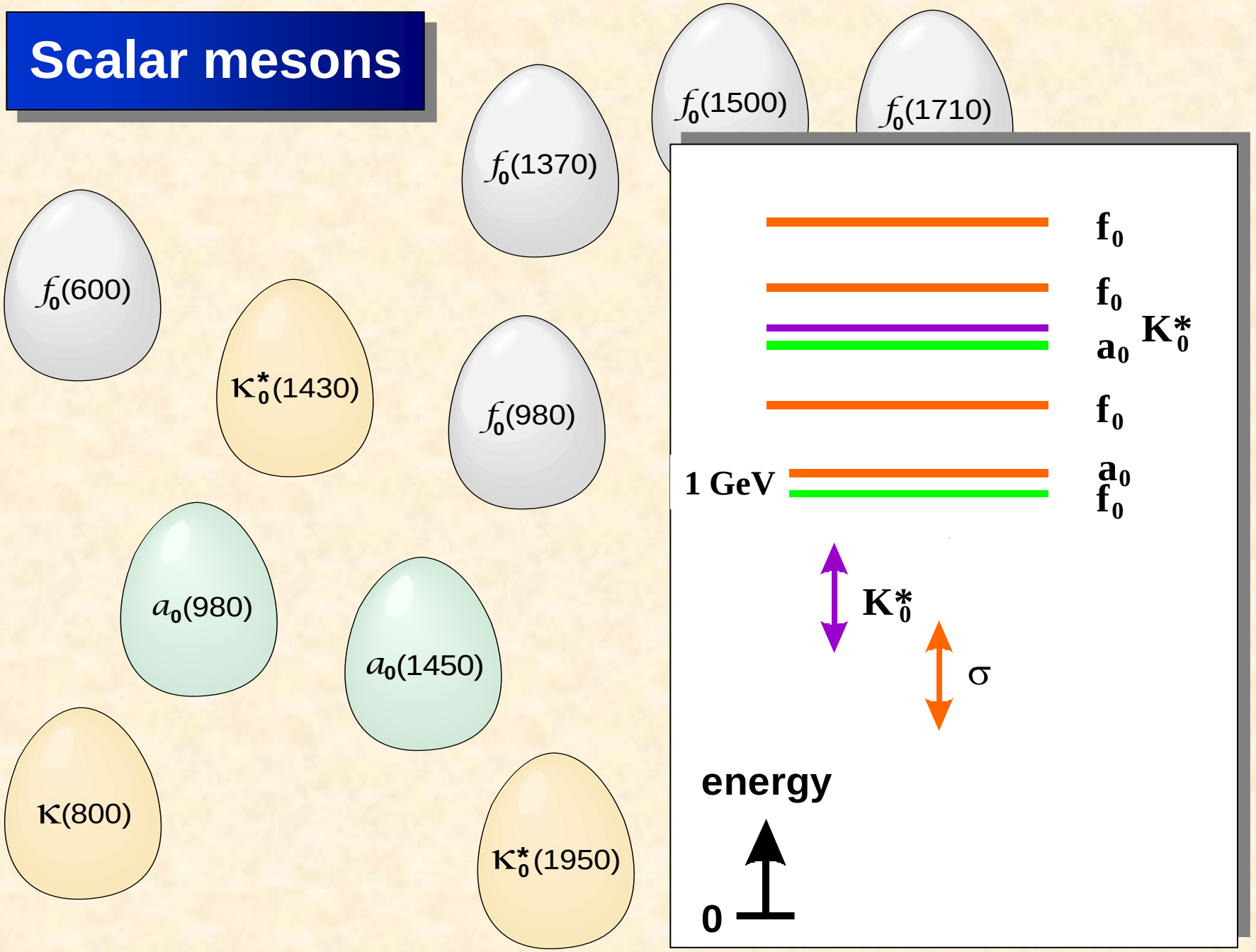




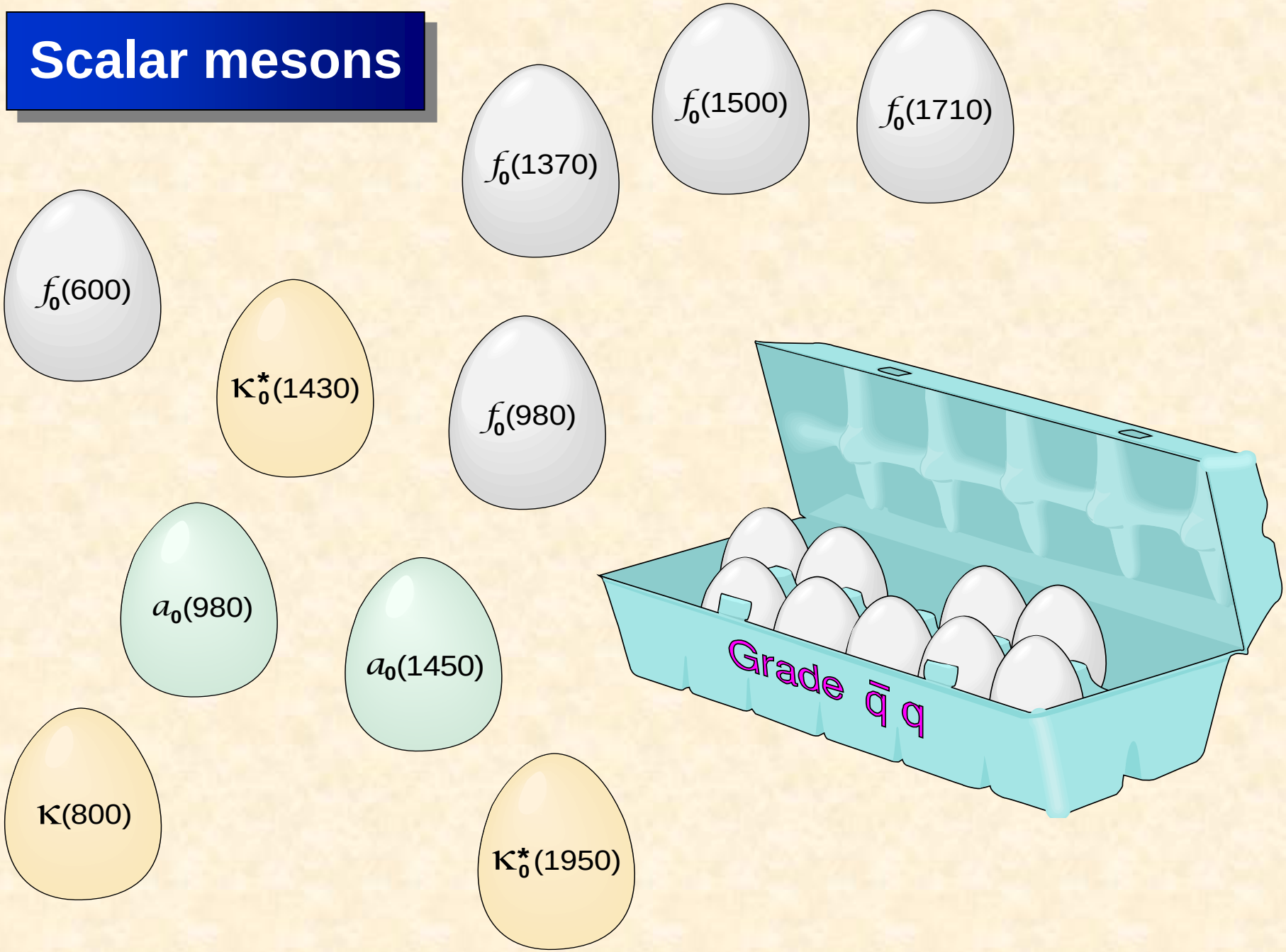
Legend:

- Particle Data Group
- H.L.L. Roberts *et al.*
- EBAC
- Jülich

Scalar mesons

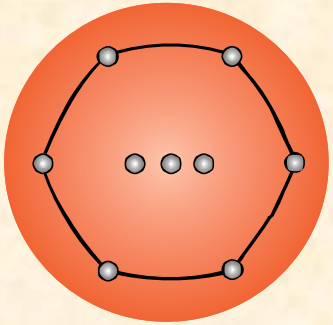


Scalar mesons



Scalar meson multiplets

$q\bar{q}$

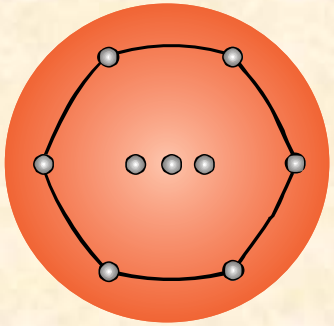


$\bar{s}s$ — f_0

$\bar{s}n$ — K_0

$\bar{n}n$ — a_0 / f_0

$q\bar{q}q\bar{q}$



$\bar{s}s\bar{n}n$ — a_0 / f_0

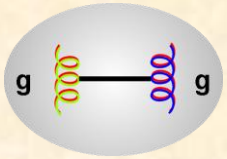
$\bar{s}n\bar{n}n$ — K_0 κ

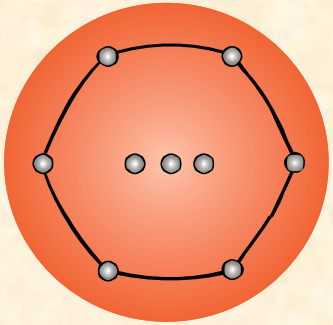
$\bar{n}n\bar{n}n$ — f_0 σ

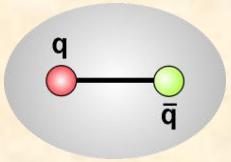
n = u,d

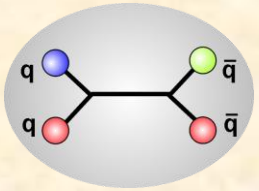
Jaffe

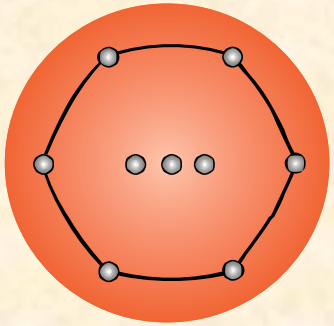
Scalar mesons











gg — f_0

$\bar{s}s$ — f_0

$\bar{s}n$ — K_0

$\bar{n}n$ — a_0 / f_0

$\bar{s}s\bar{n}n$ — a_0 / f_0

$\bar{s}n\bar{n}n$ — K_0 κ

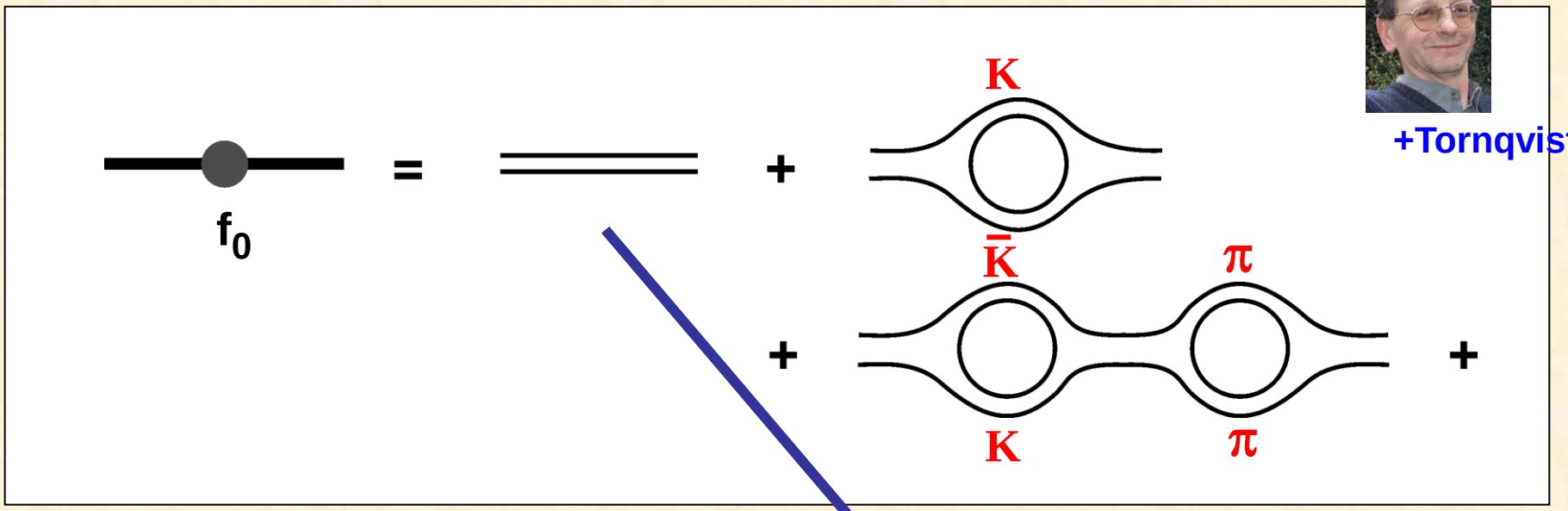
$\bar{n}n\bar{n}n$ — f_0 σ

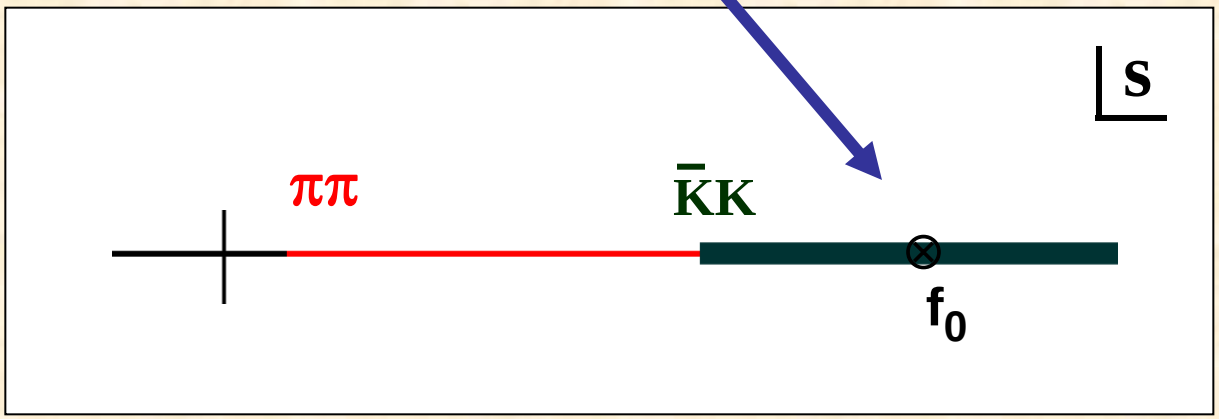
$n = u,d$

Scalar multiplet

van Beveren
Rupp

+Tornqvist



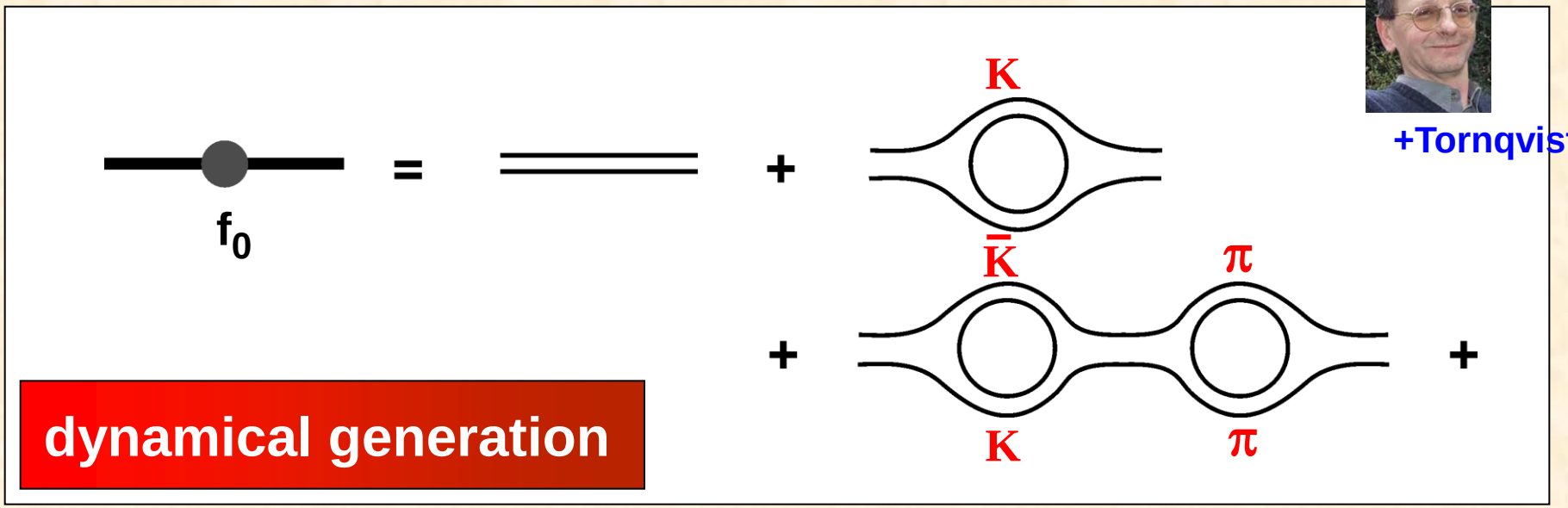


s̄s

Scalar multiplet

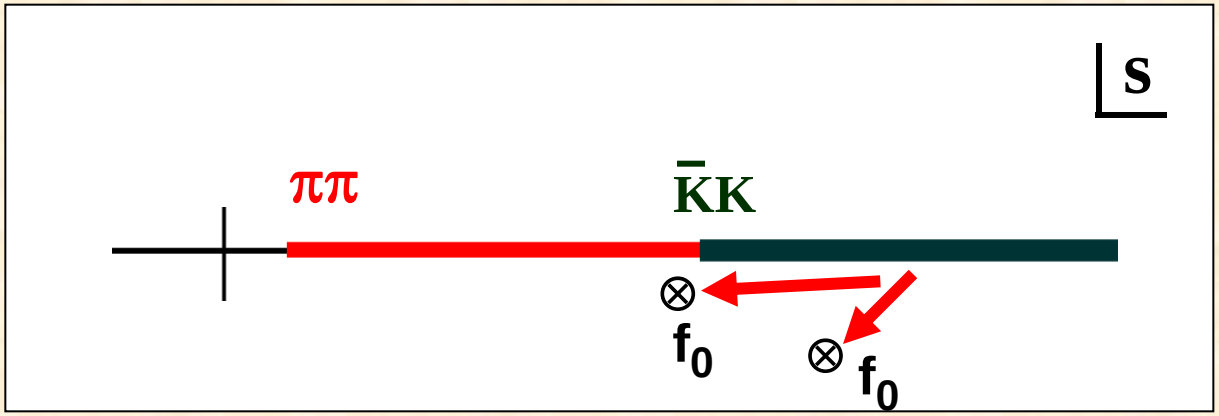
van Beveren
Rupp

+Tornqvist

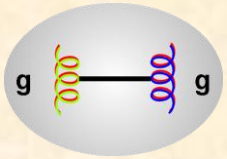


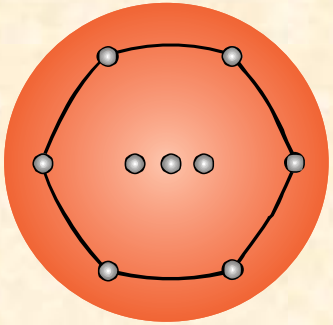
dynamical generation

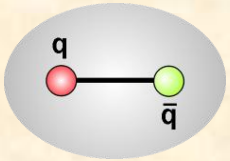
$\bar{s}s$

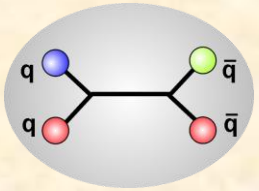


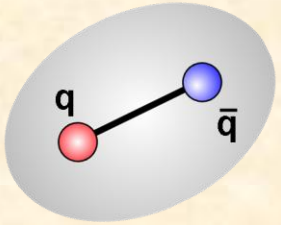
Scalar mesons

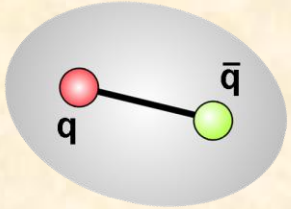


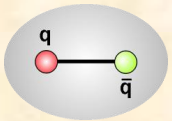


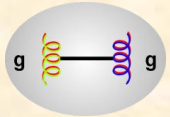












gg — f_0

$\bar{s}s$ — f_0

$\bar{s}n$ — K_0

$\bar{n}n$ — a_0 / f_0

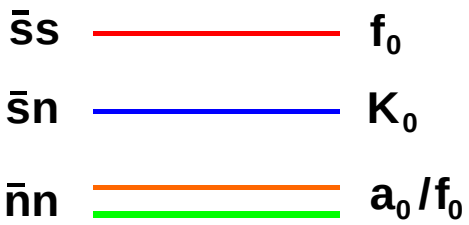
$\bar{s}s\bar{n}n$ — a_0 / f_0

$\bar{s}n\bar{n}n$ — K_0 κ

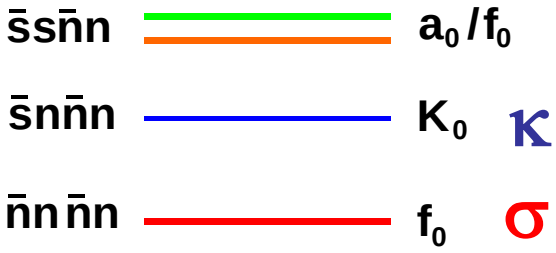
$\bar{n}n\bar{n}n$ — f_0 σ

Scalar mesons

$q\bar{q}$



$q\bar{q}q\bar{q}$

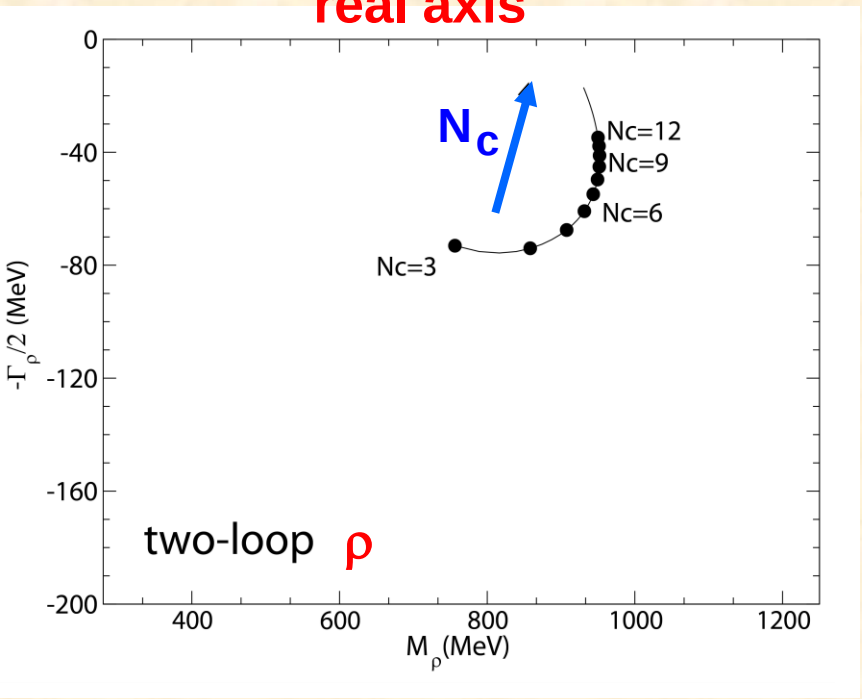


N_c large → stable

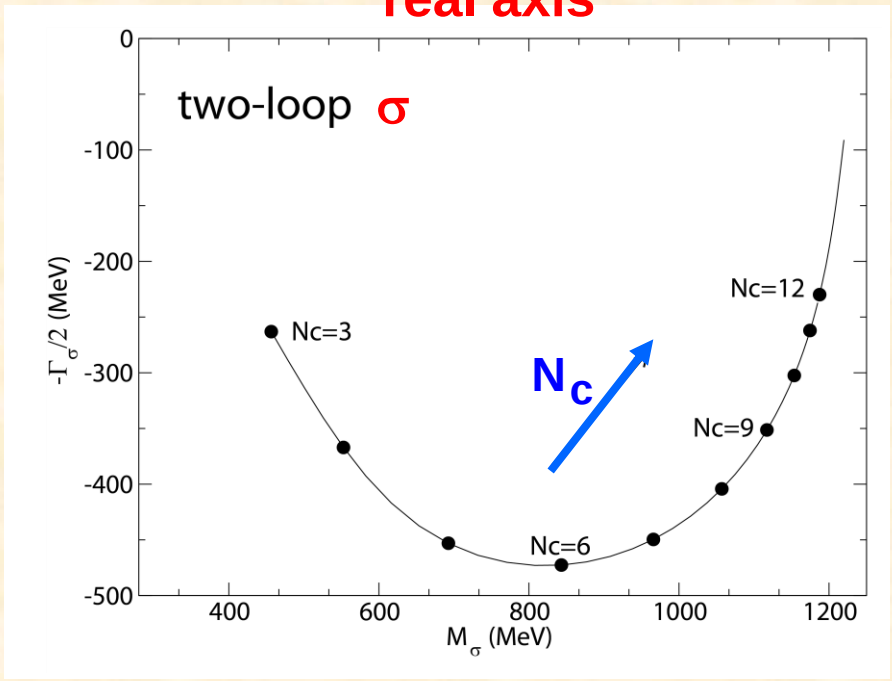
N_c large → meson continuum

1 / N_c @ two loops

real axis



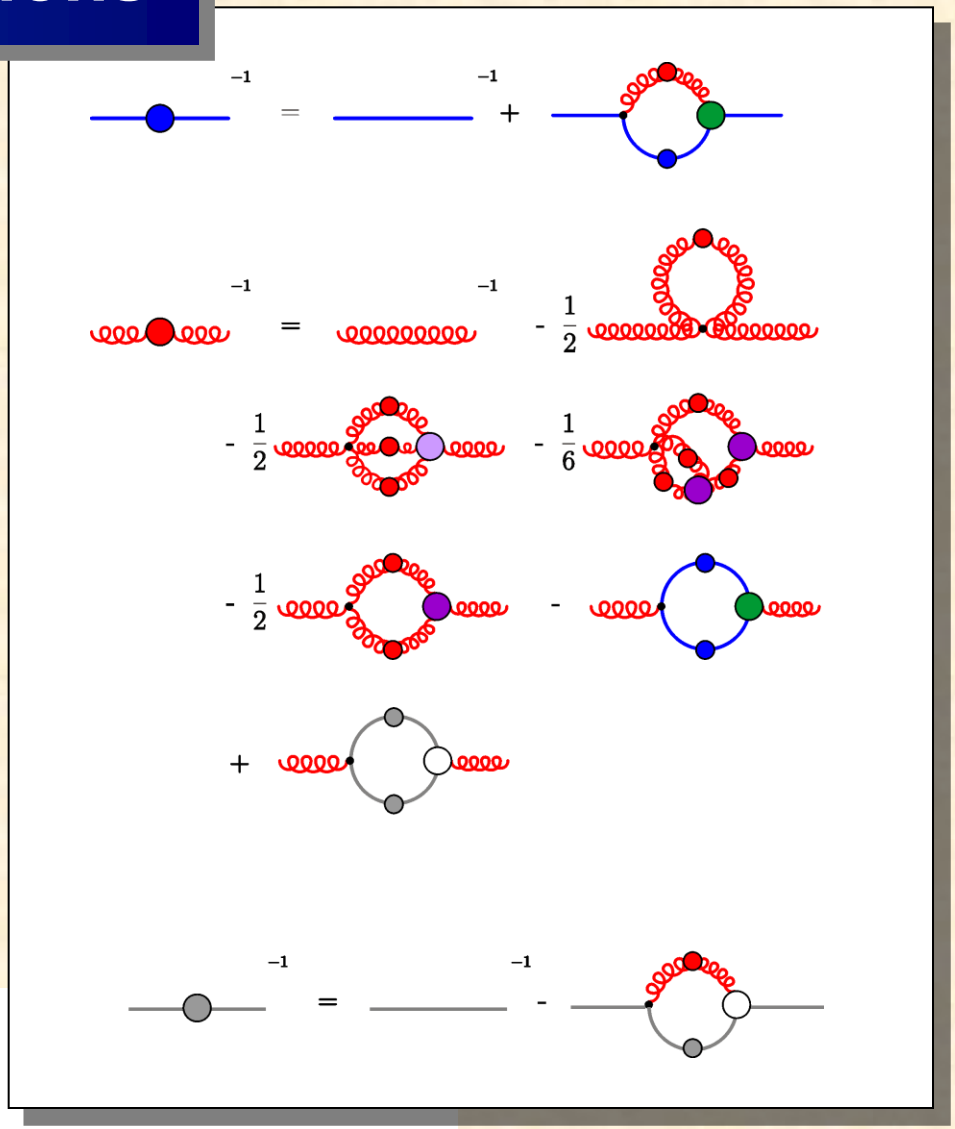
real axis



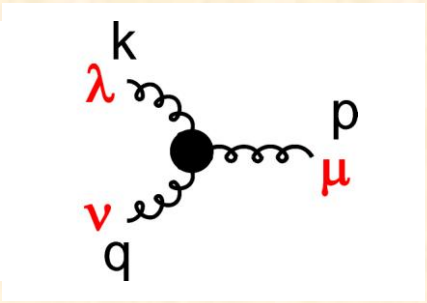
Pelaez, Ruiz de Elvira, Wilson & P

Schwinger-Dyson Equations

QCD



Slavnov-Taylor Identity



covariant gauges

$$k_\lambda \, \Gamma^{\lambda\mu\nu}(k,p,q) \; =$$

$$H(k^2) \; \left[G_{\mu,\sigma}(q,-k) \; \Pi^T_{\sigma,\nu}(p) \; - \; G_{\nu\sigma}(p,-k) \; \Pi^T_{\sigma\mu}(q) \right]$$

Schwinger-Dyson Equations

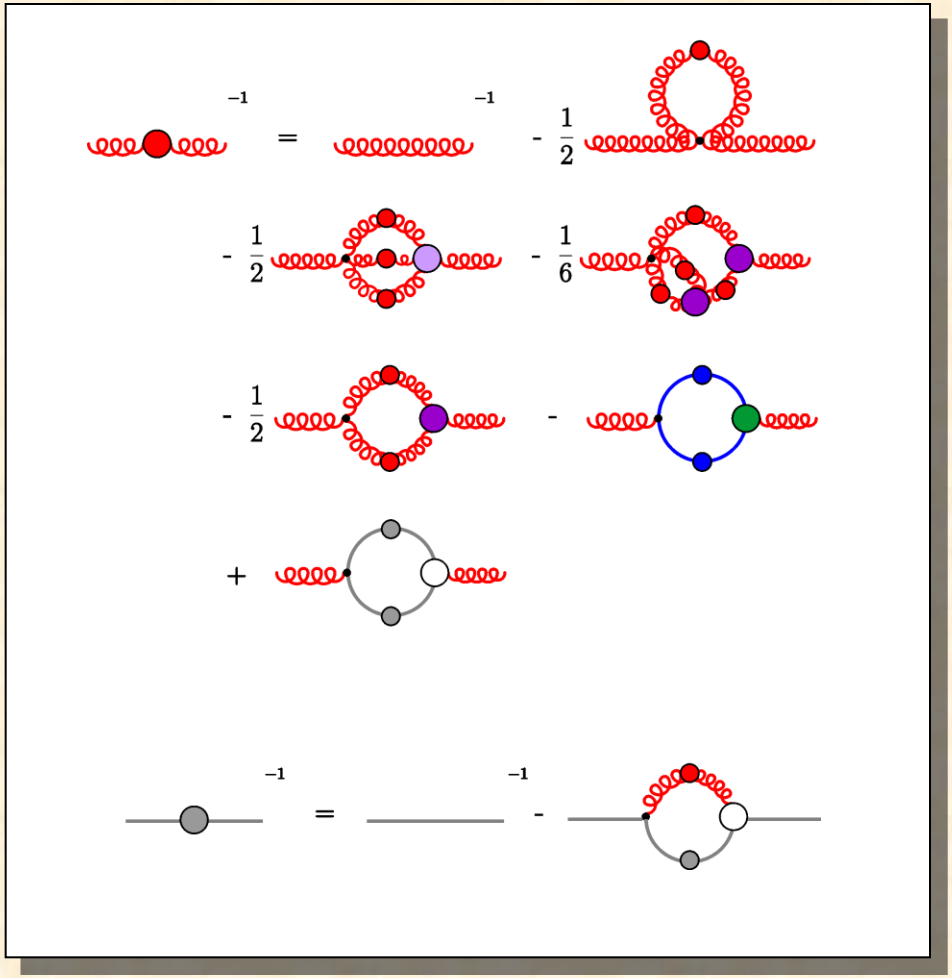
gluons & ghosts

QCD

$$\Delta^{\mu\nu}(p) = \frac{\mathcal{G}\ell(p^2)}{p^2} T^{\mu\nu}(p)$$

$$D(p) = \frac{\mathcal{G}h(p^2)}{p^2}$$

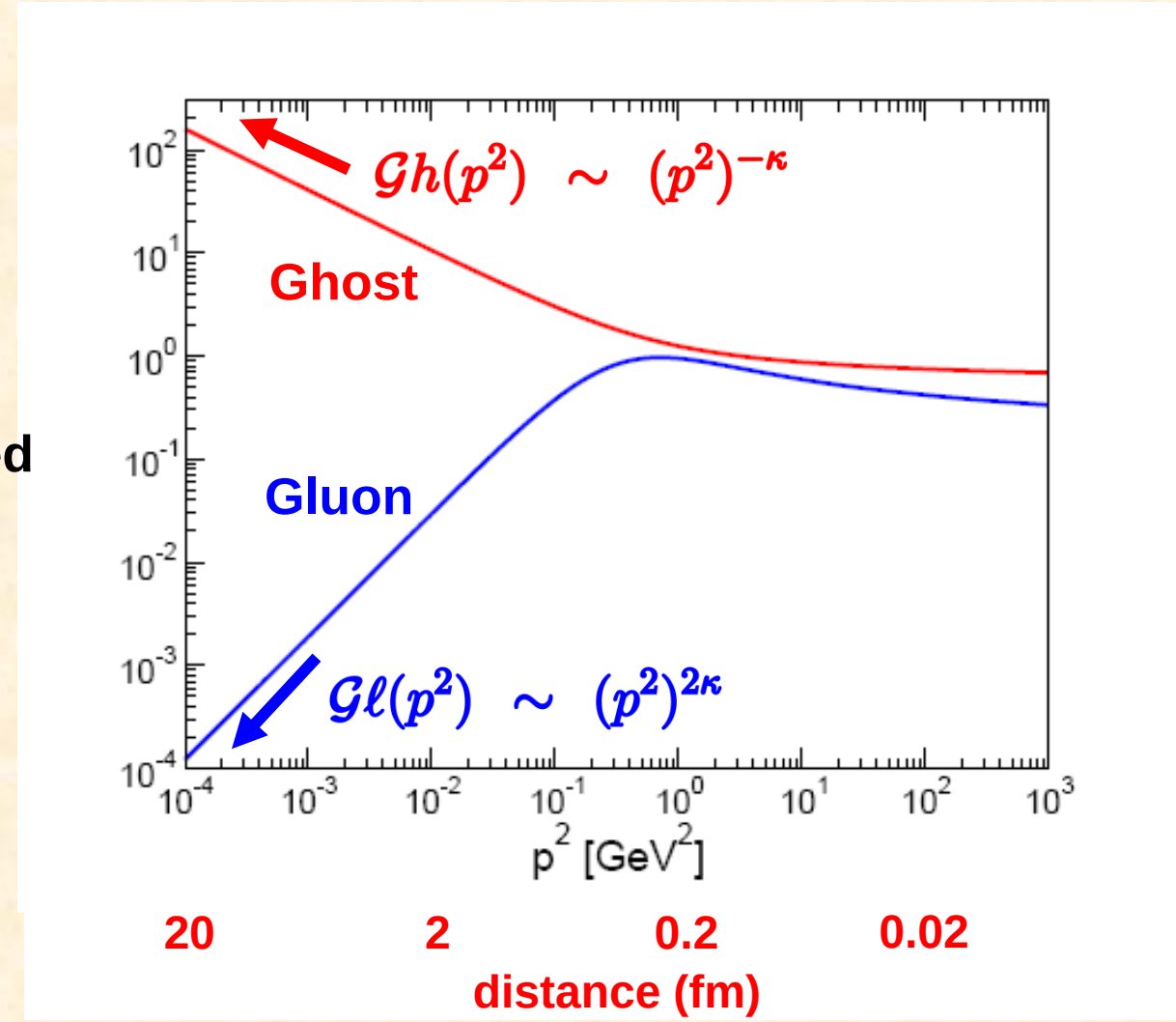
$$T^{\mu\nu}(p) = g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}$$



Landau gauge

Tübingen, Graz, Darmstadt

scaling solution



Deep Infrared

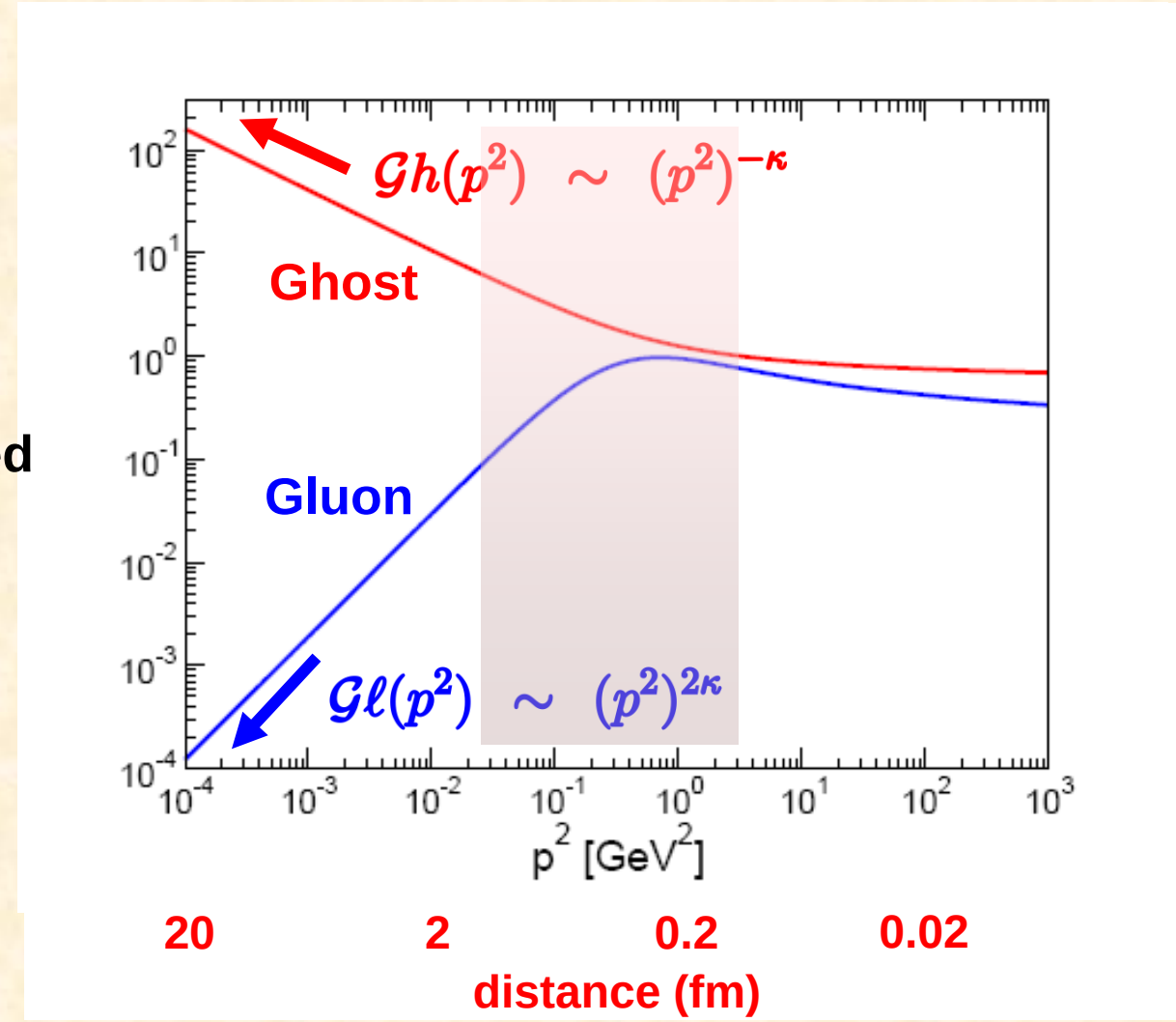
$\kappa \simeq 0.6$

von Smekal
Fischer

Landau gauge

Tübingen, Graz, Darmstadt

scaling solution



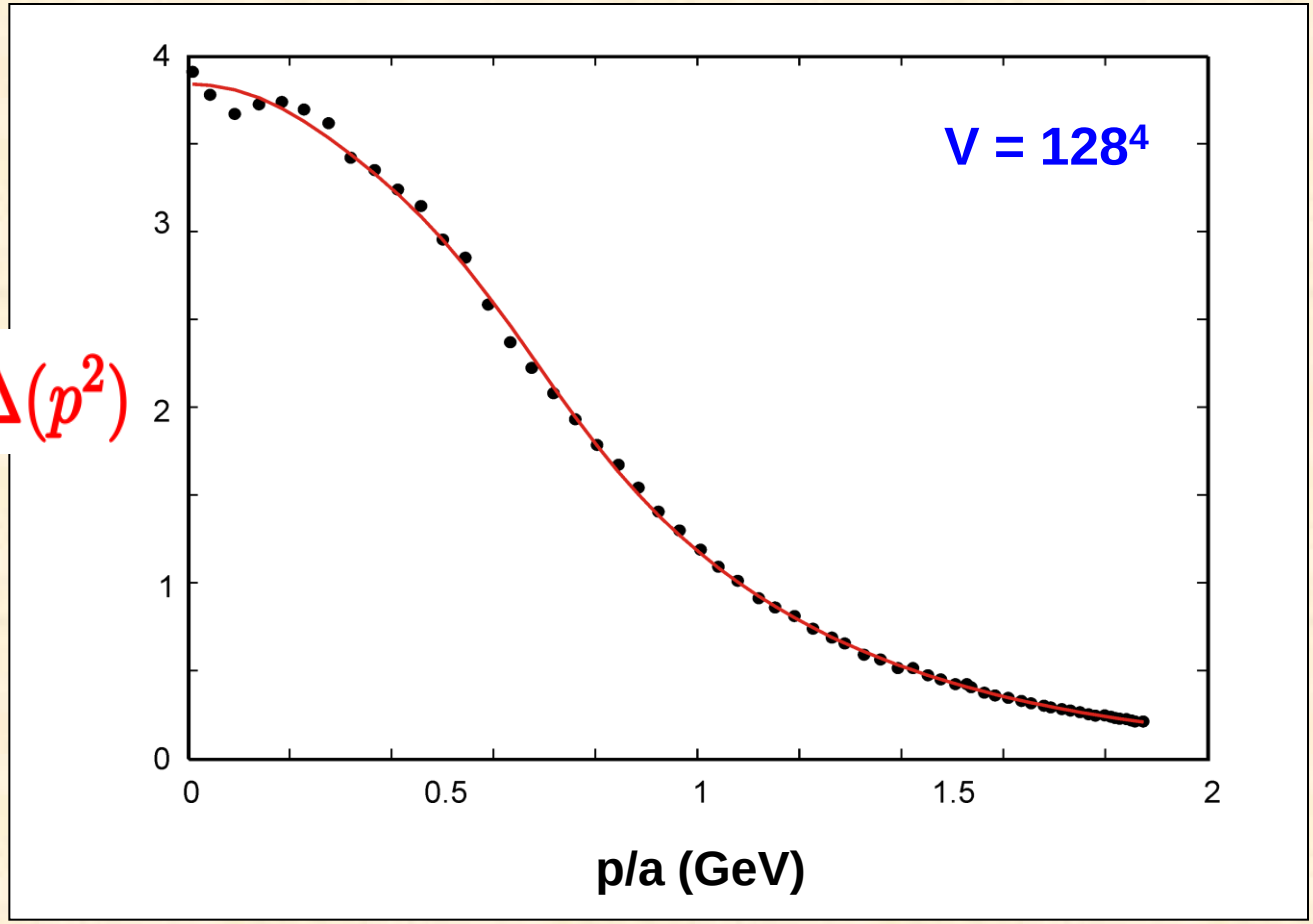
Deep Infrared

$\kappa \simeq 0.6$

von Smekal
Fischer

Landau gauge

Lattice Results: Cucchieri, Mendes

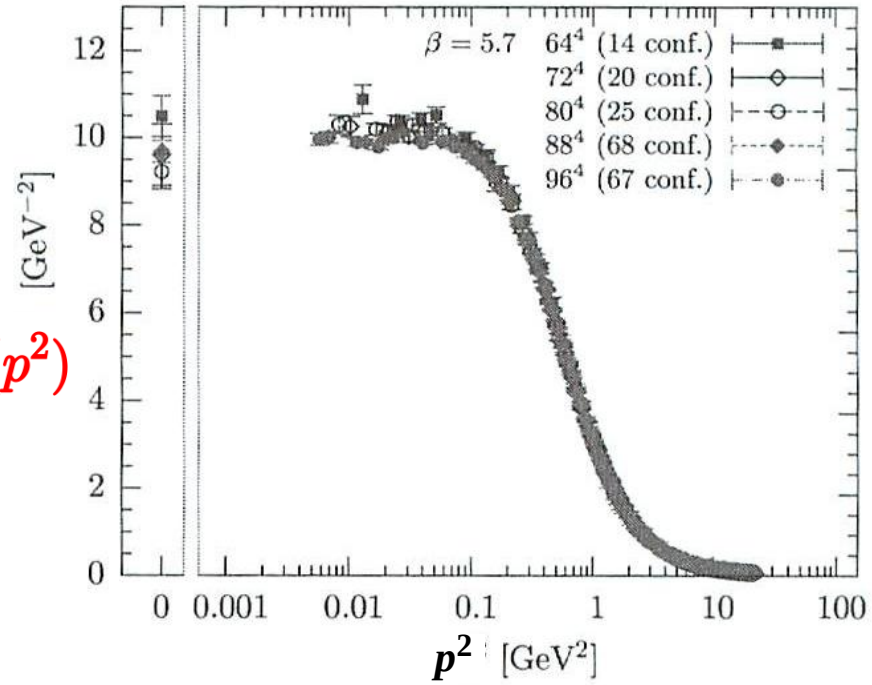


Landau gauge

$$\Delta(p^2) = \frac{\mathcal{G}\ell(p^2)}{p^2}$$

Bogolubsky et al. 2009

$\Delta(p^2)$



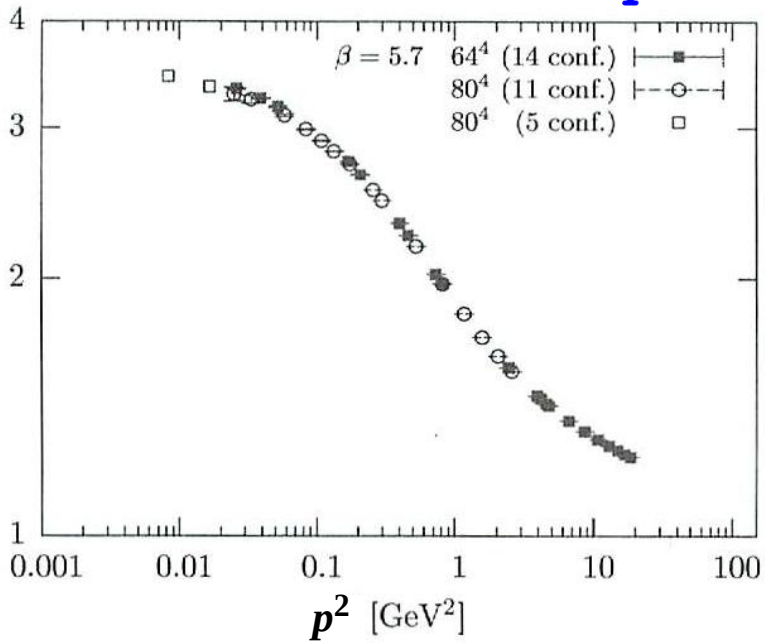
gluon

$$\Delta(p^2) = \frac{\mathcal{G}\ell(p^2)}{p^2}$$

ghost

$$D(p) = \frac{\mathcal{G}h(p^2)}{p^2}$$

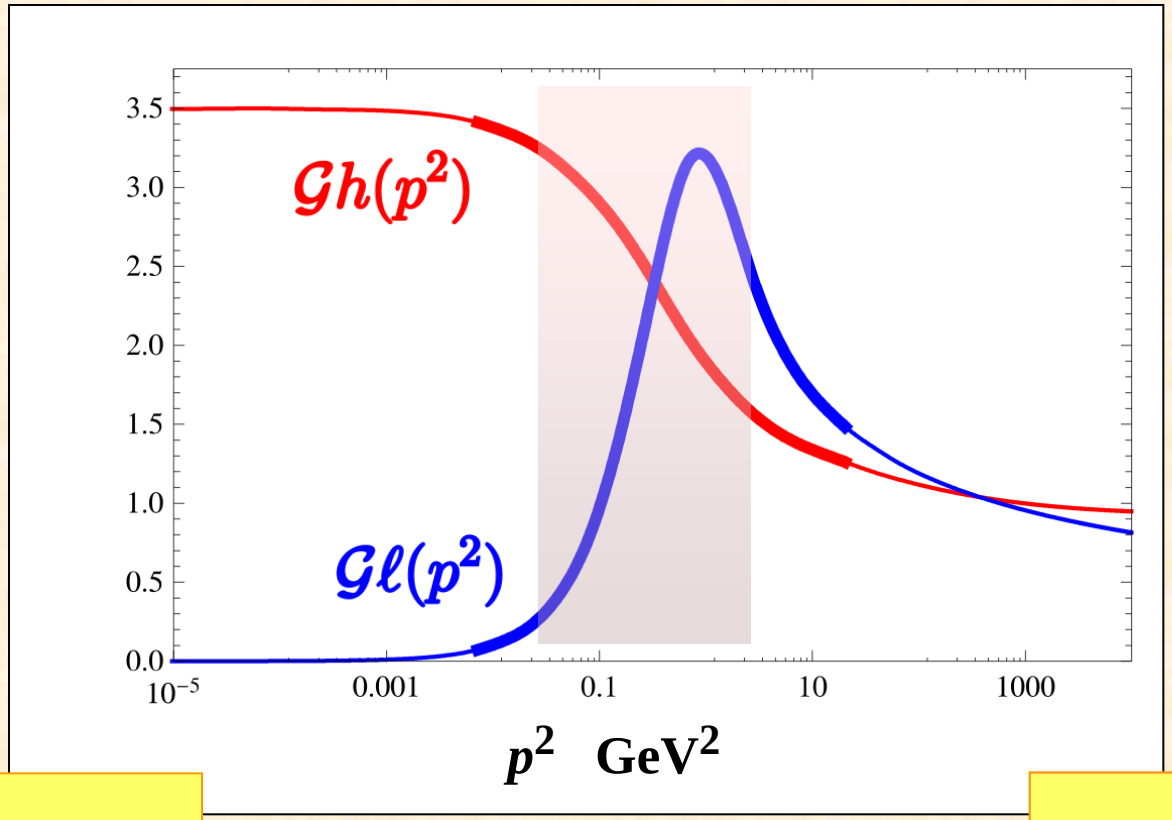
$\mathcal{G}h(p^2)$

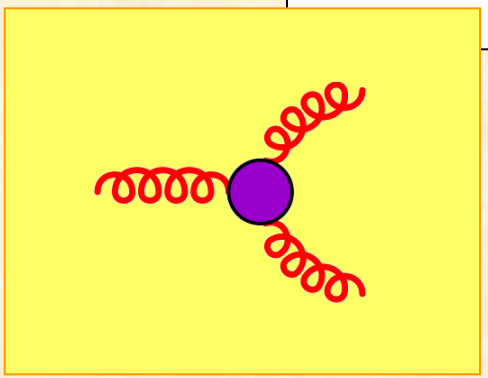


Oliveira & Silva

Solution of Gluon & Ghost SDEs

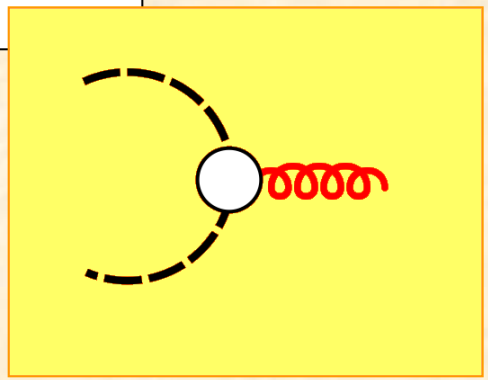
"massive"



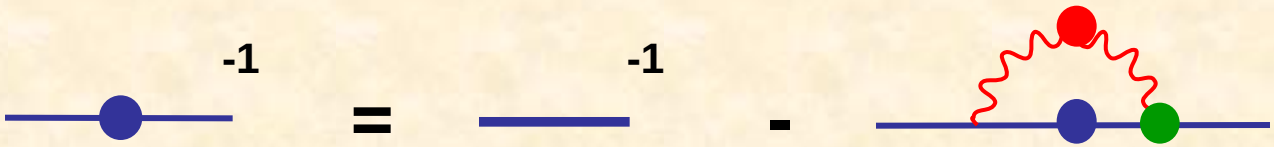


Aguilar, Papavassiliou, Binosi
Boucaud *et al*
Rodriguez Quintero

Wilson & P



Fermion mass generation



$$S_F(p) = \frac{\mathcal{F}(p)}{\not{p} - \mathcal{M}(p)}$$

wavefunction renormalisation

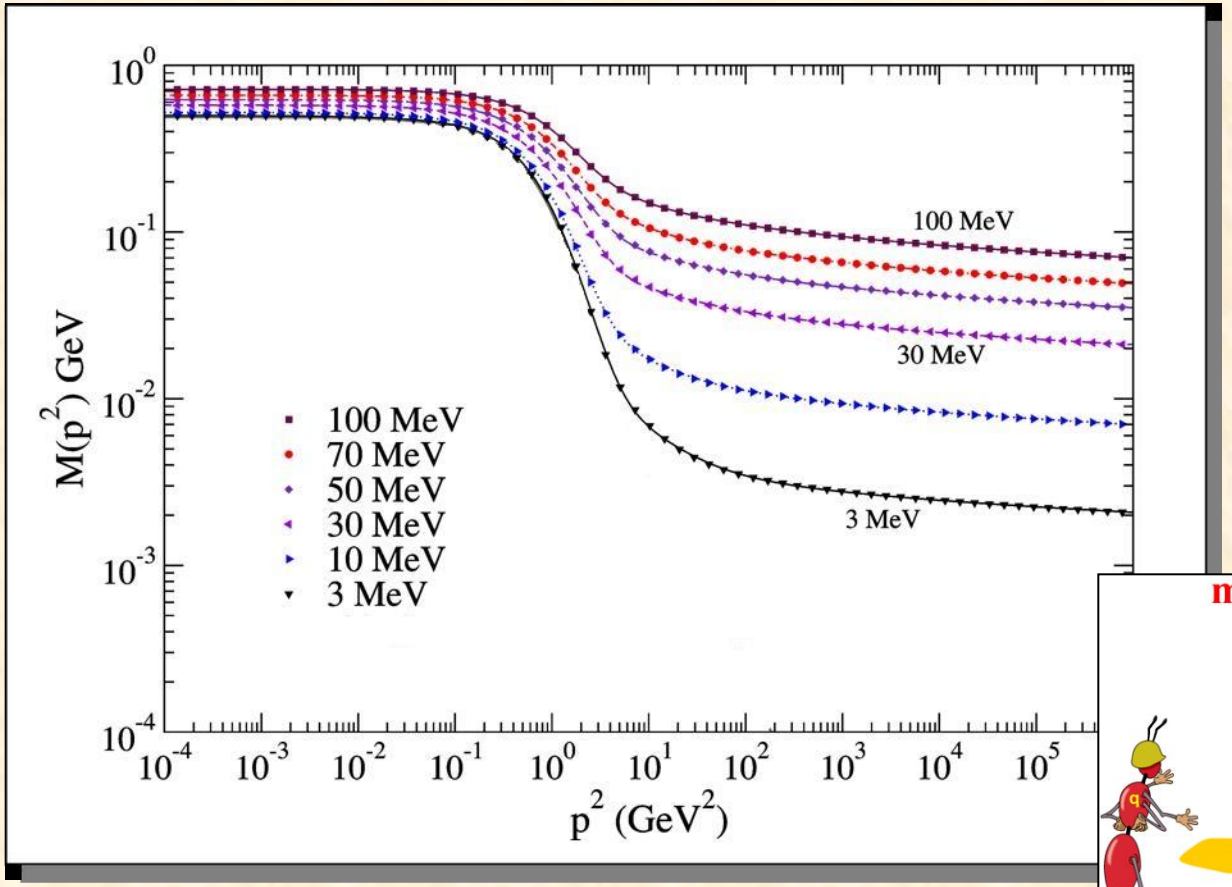
mass function

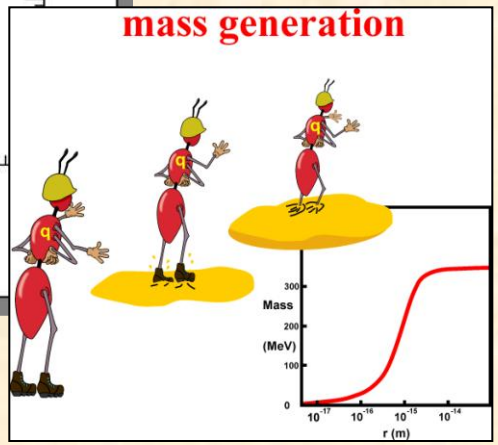
$$S_F(p)^{-1} = \not{p} - m_0 - \frac{\alpha}{4\pi}\int d^4k\, \gamma_\mu S_F(k) \Gamma_\nu(k,p) \Delta^{\mu\nu}(q)$$

Quark mass function

$\alpha_s > 1 \Longrightarrow \chi SB$

Williams, Fischer, P



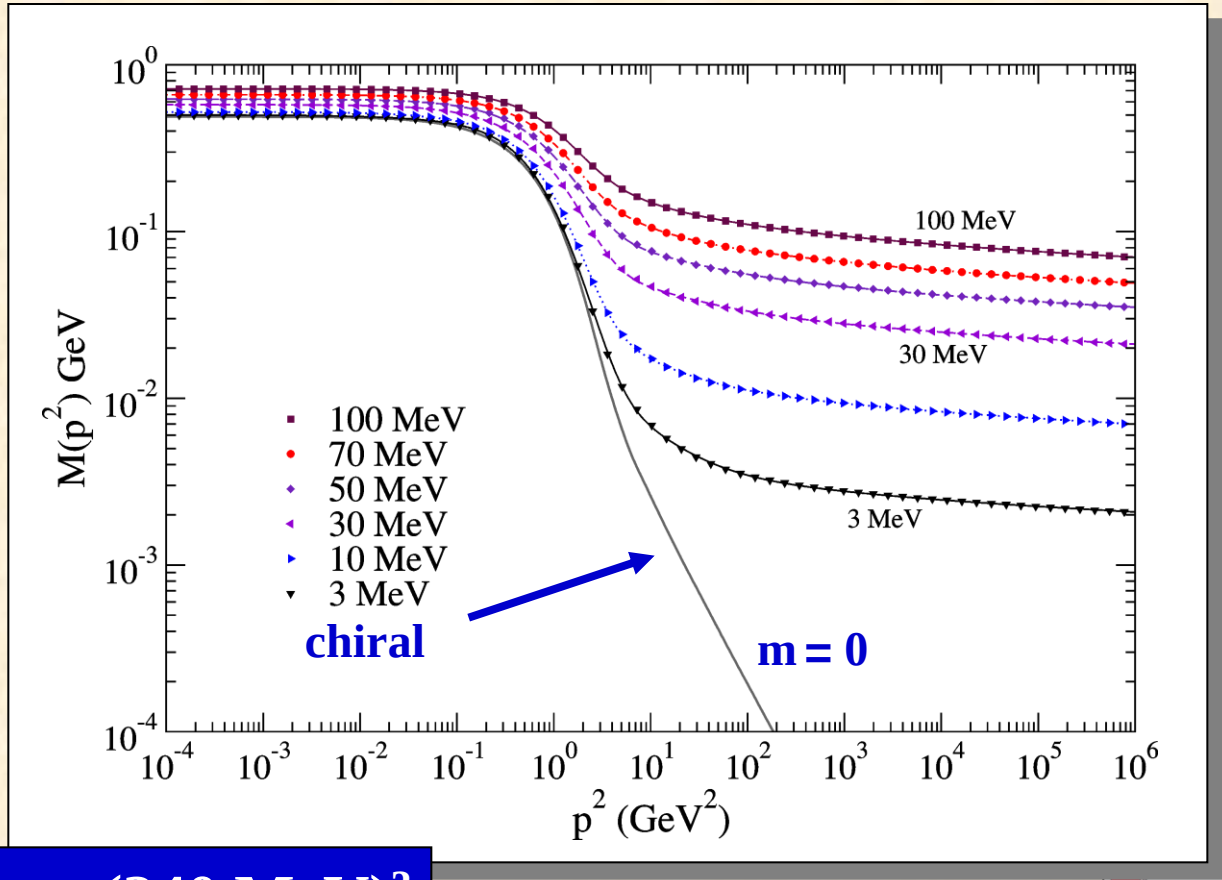


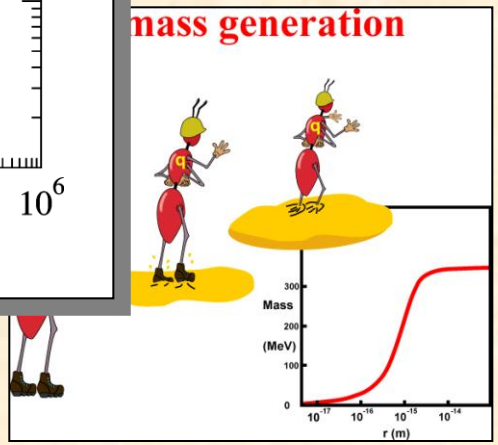
Quark mass function

$\alpha_s > 1 \Longrightarrow \chi SB$

Williams, Fischer, P

Maris & Roberts

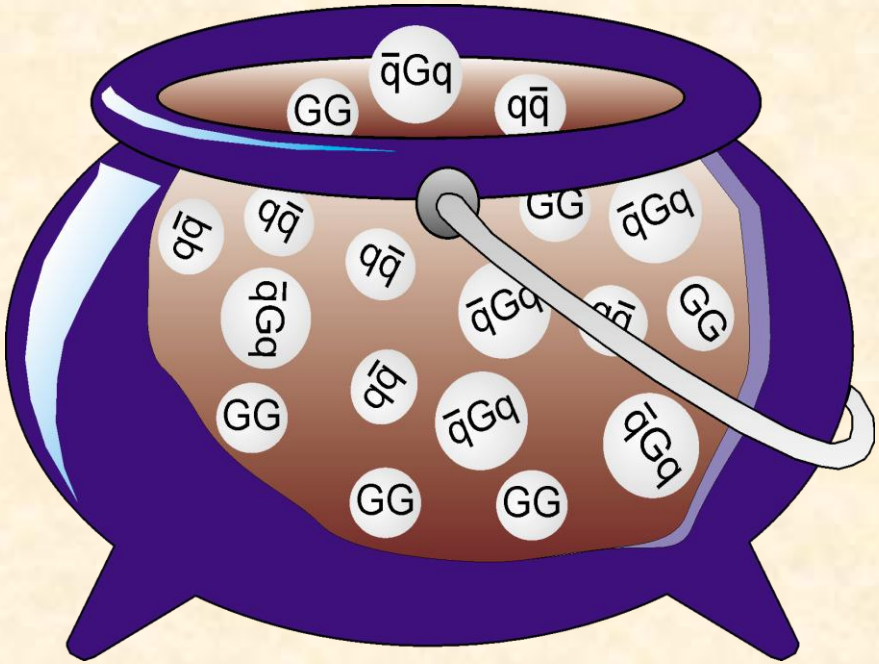




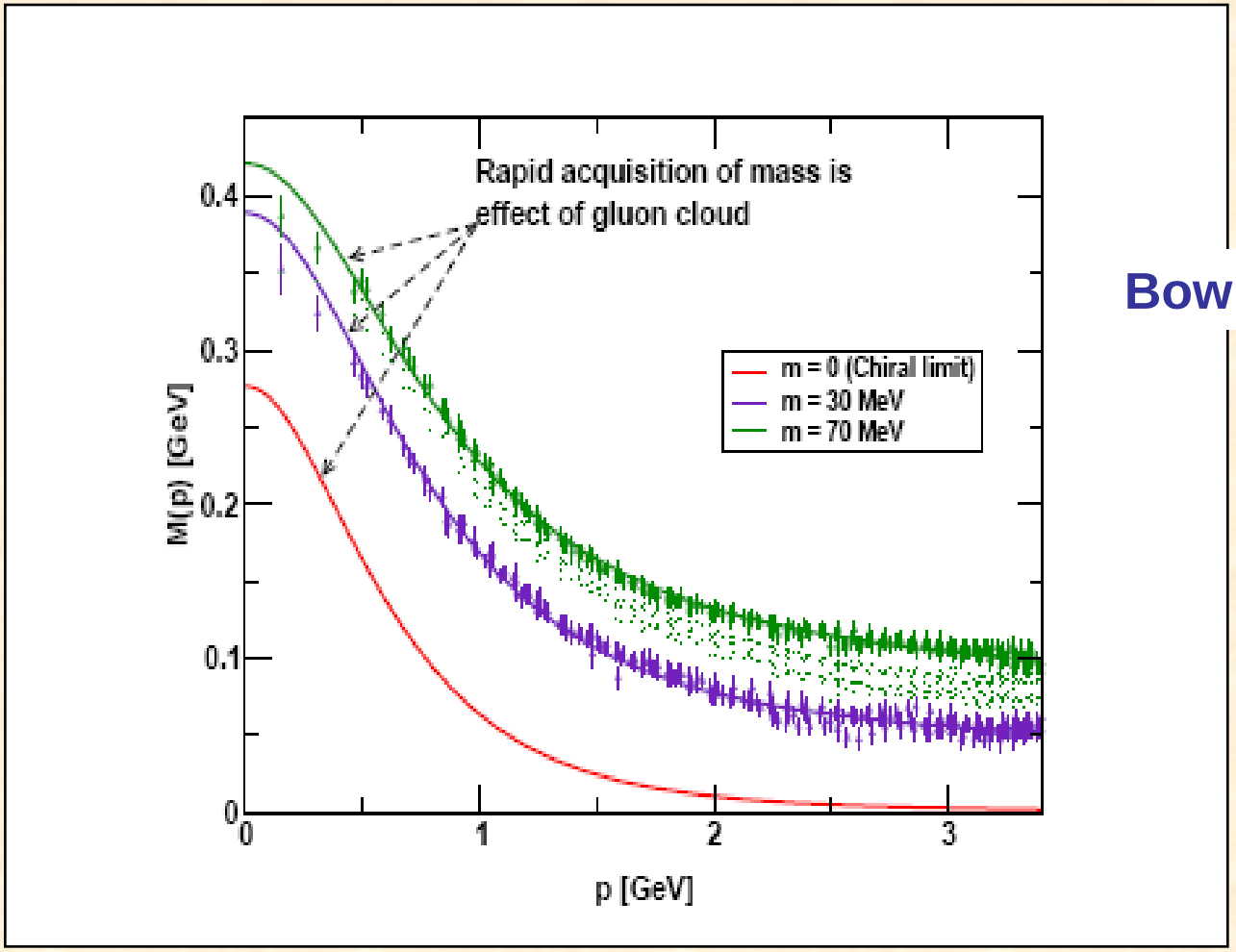
$< \bar{q}q >_0 \sim -(240\ \text{MeV})^3$

QCD vacuum

q̄Gq
GG
qq̄
qq̄
GG
q̄Gq
qq̄
q̄Gq
GG
qq̄
q̄Gq
GG
q̄Gq
GG
GG
q̄Gq


q̄Gq
GG
qq̄
qq̄
GG
q̄Gq
qq̄
q̄Gq
GG
qq̄
q̄Gq
GG
q̄Gq
GG
GG
q̄Gq

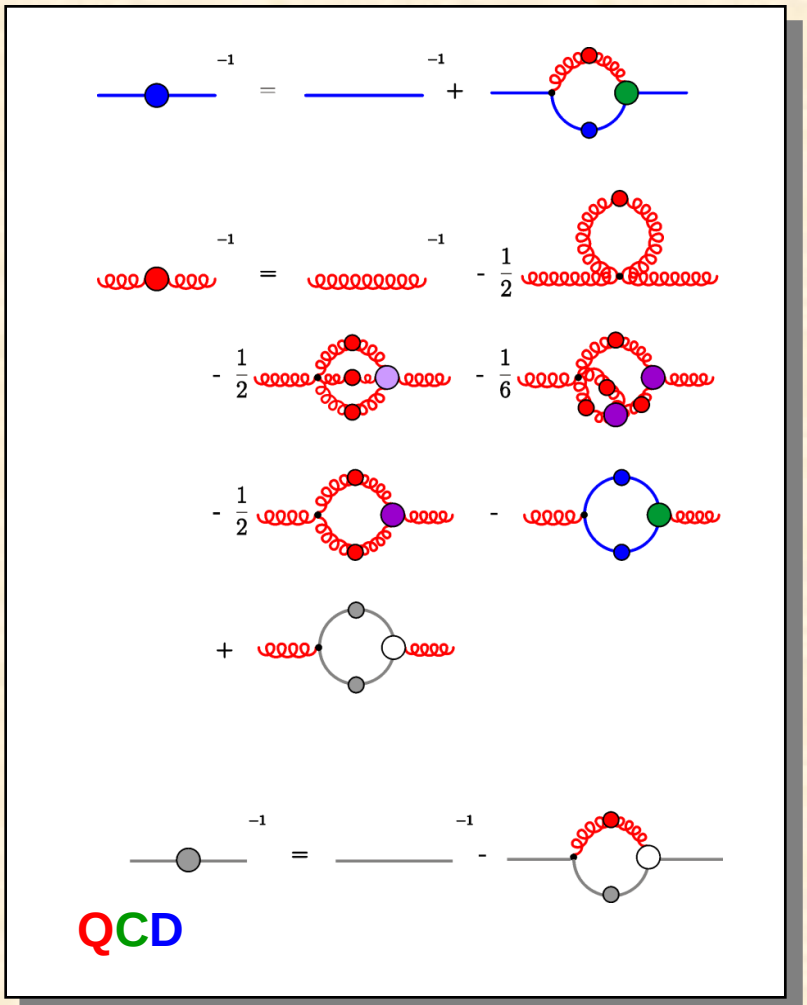
Lattice and SDE results



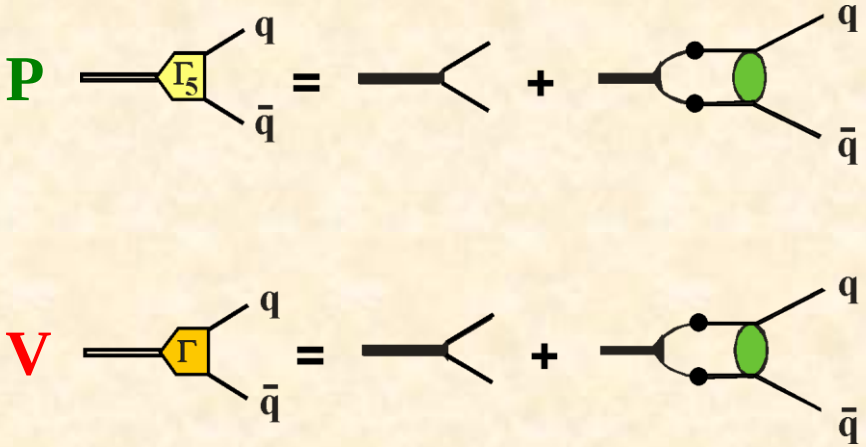
Bowman et al

Bhagwat & Tandy / Roberts et al

Schwinger-Dyson Equations

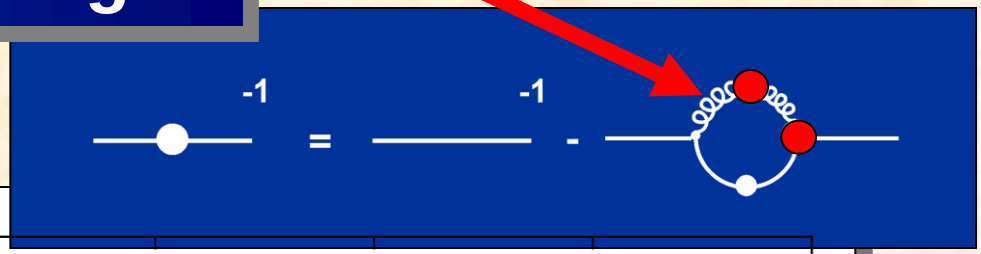


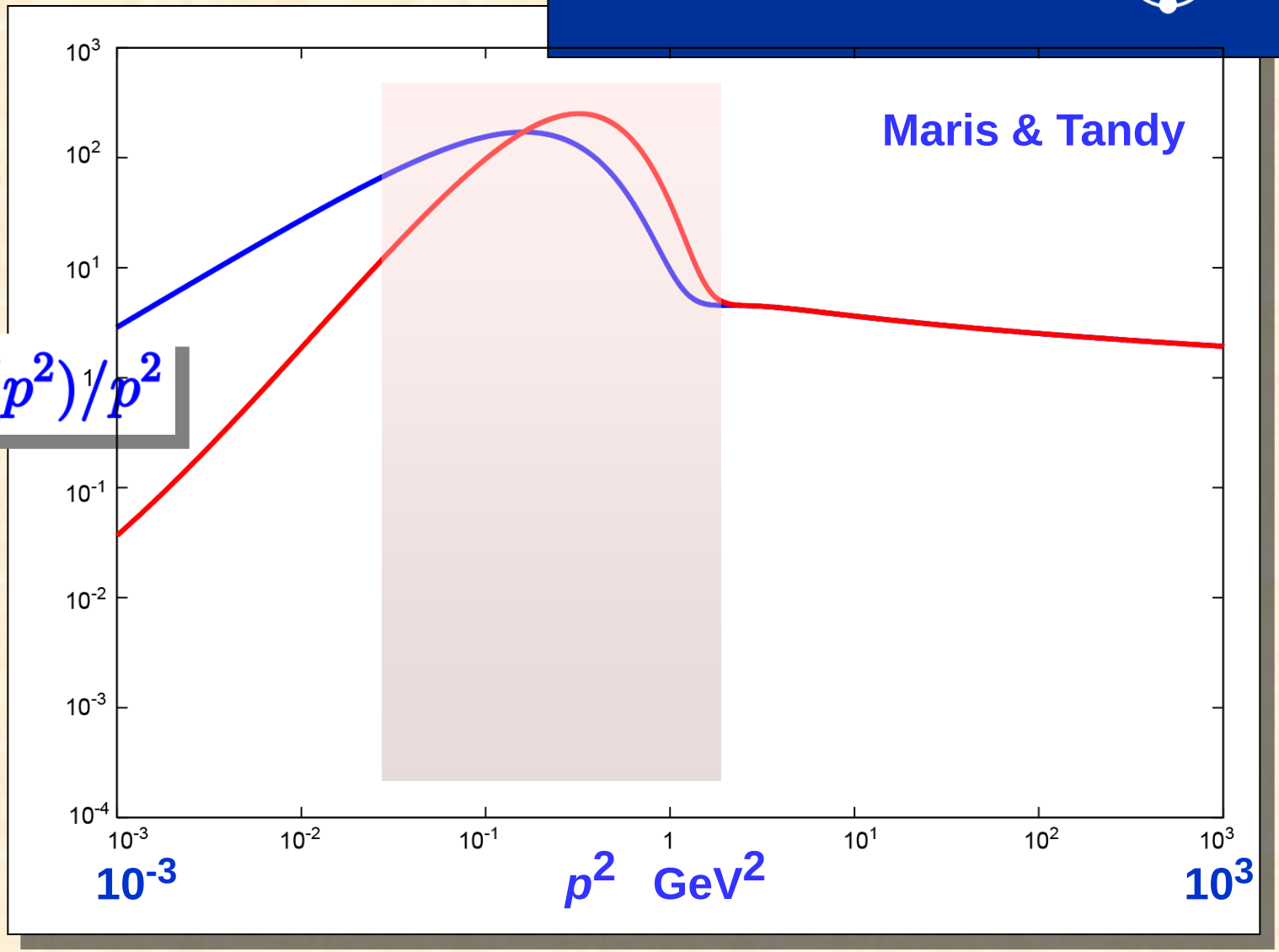
Bound State Equations



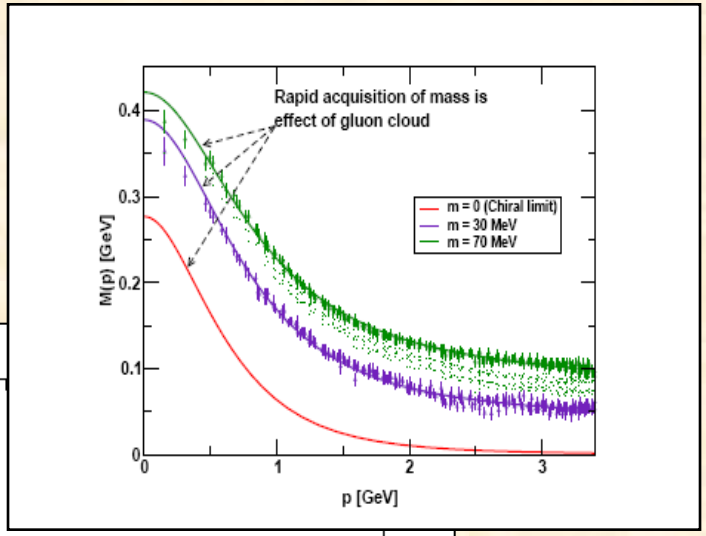
f_π , m_π

effective interaction strength





quark propagator



quark propagator

constant mass

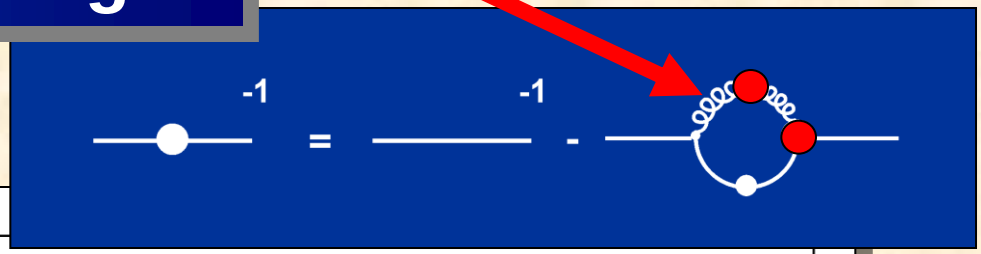
running mass

4
3
2
1
0

10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3}

10^{-3} p^2 (GeV)^2 10^{3}

effective interaction strength

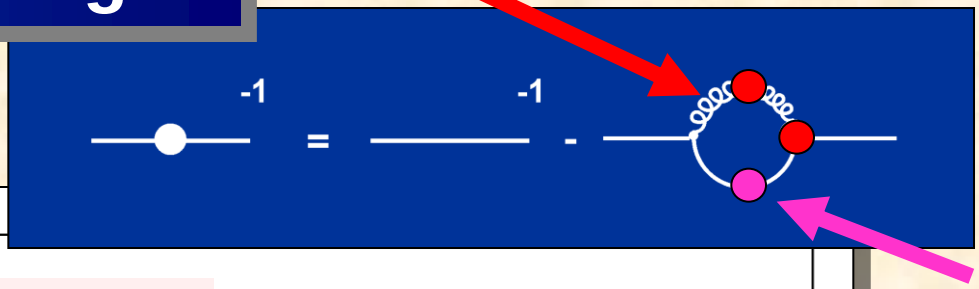


$4\pi\,\alpha_{\rm eff}(p^2)/p^2$

Qin, Chang, Liu, Roberts, Wilson

10^{-3} p^2 GeV^2 10^3

effective interaction strength



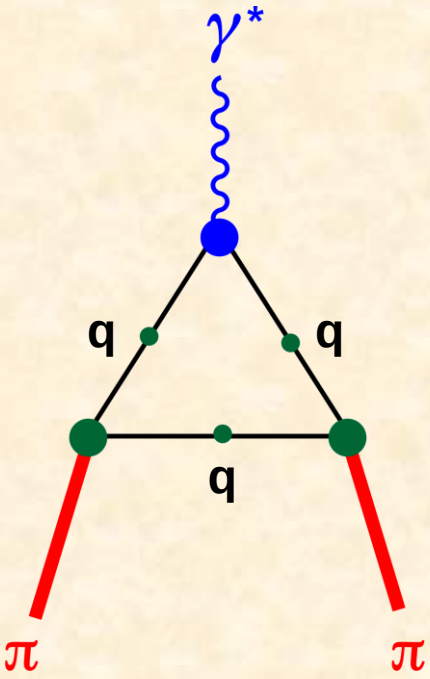
$4\pi\,\alpha_{\mathrm{eff}}(p^2)/p^2$

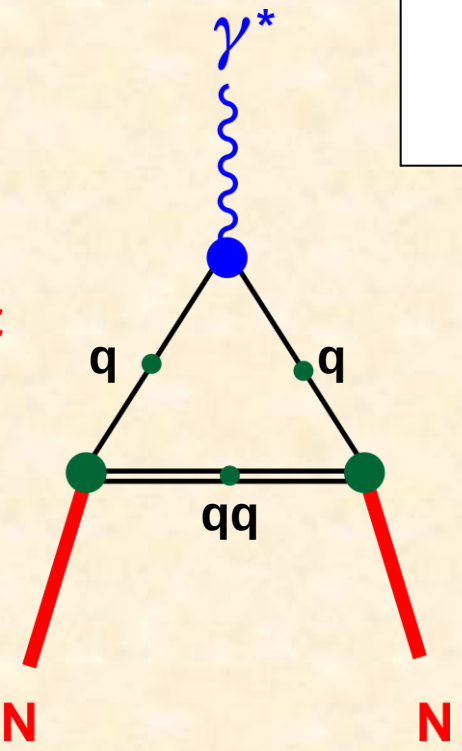
constant mass

running mass

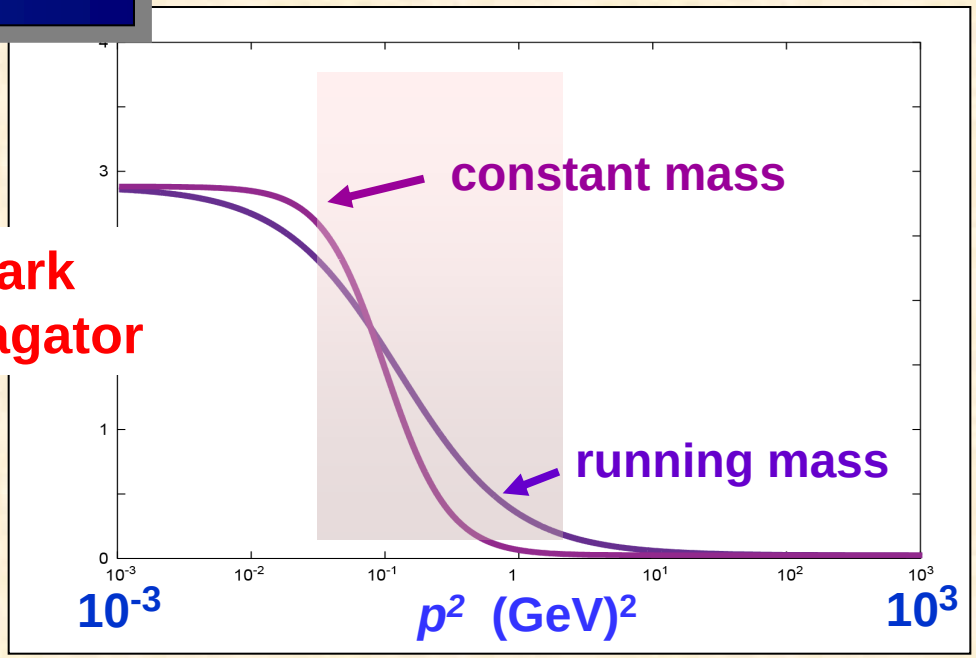
10^{-3} p^2 GeV^2 10^3

electromagnetic formfactors



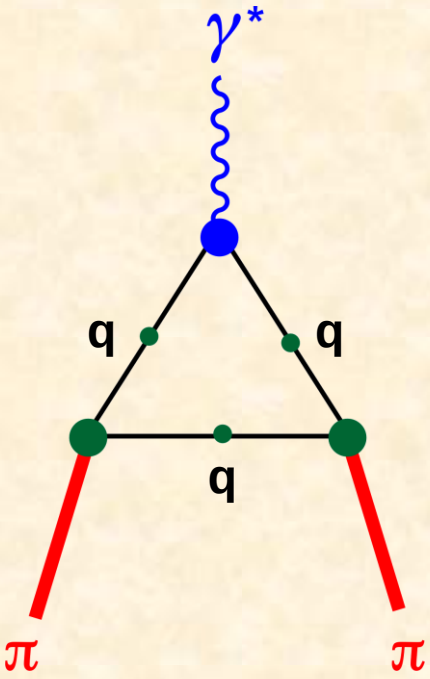


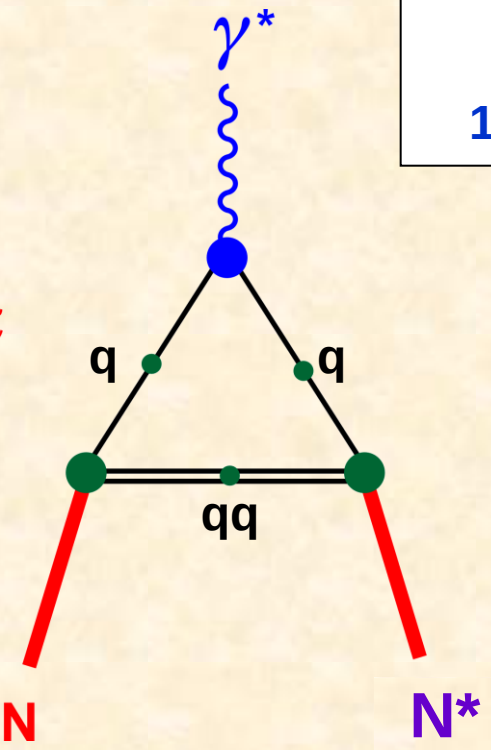
quark propagator



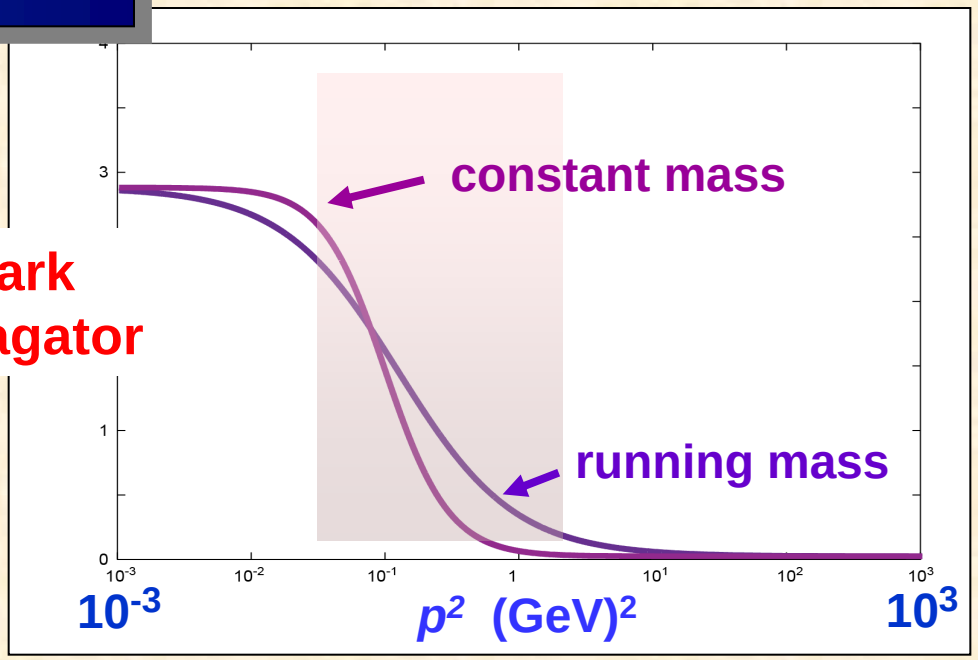
Jefferson Lab
Exploring the Nature of Matter

electromagnetic formfactors



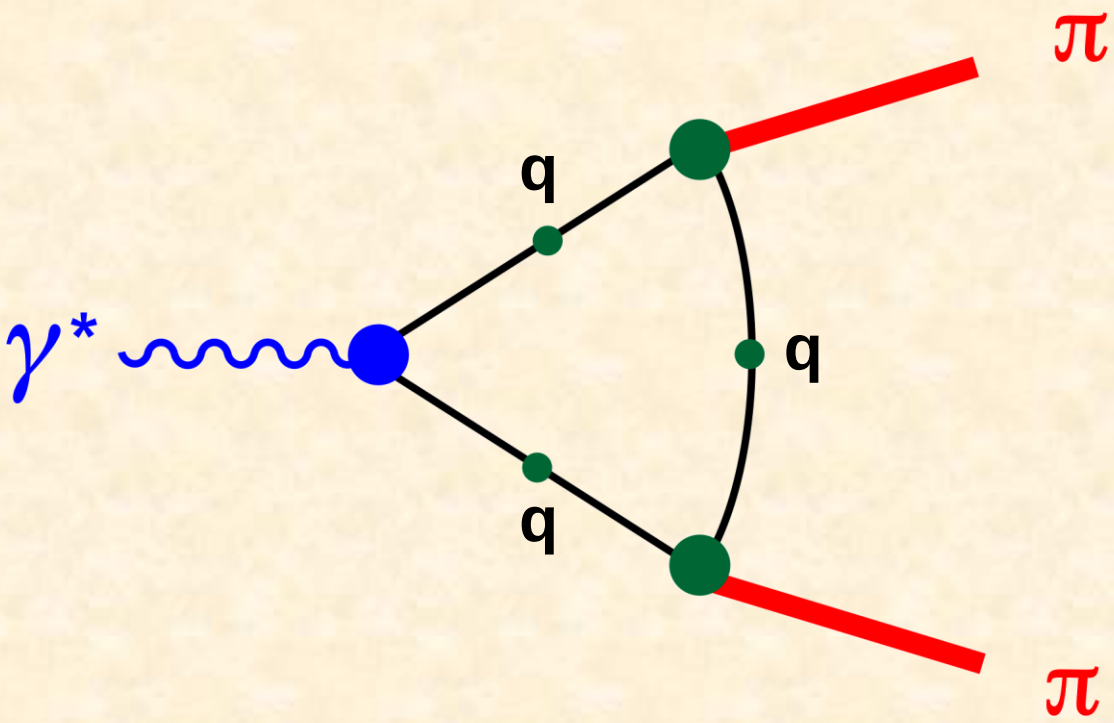


quark propagator

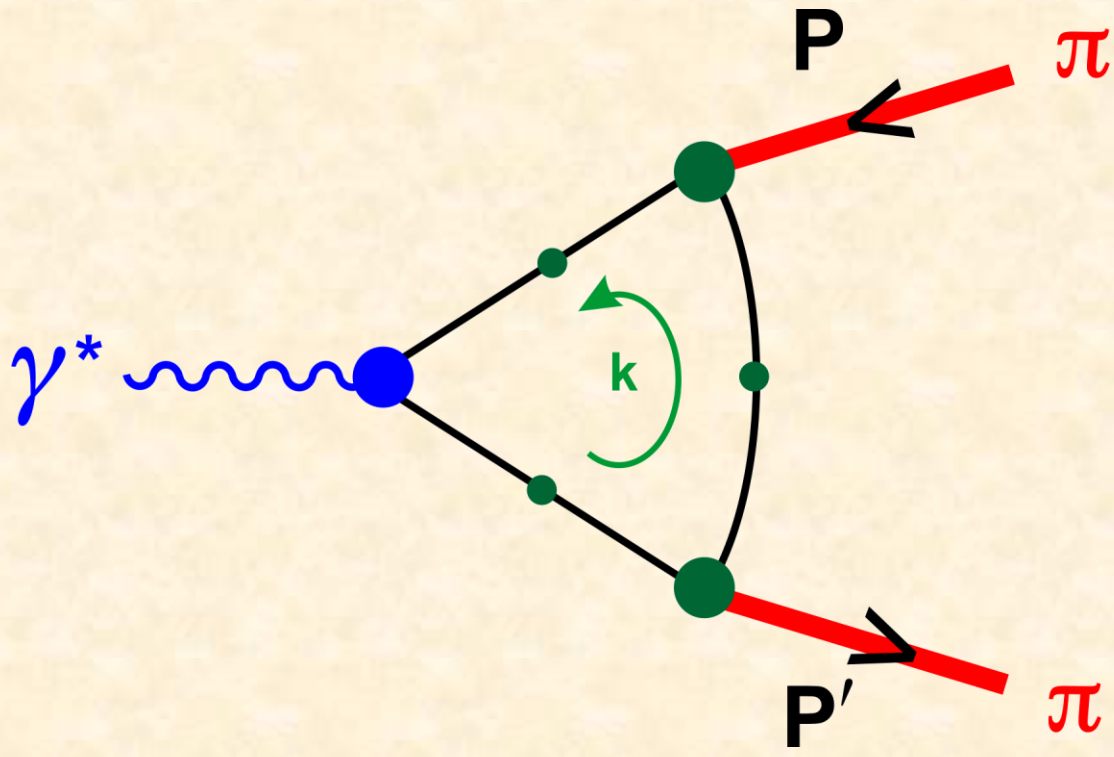


Jefferson Lab
Exploring the Nature of Matter

Pion electromagnetic formfactor

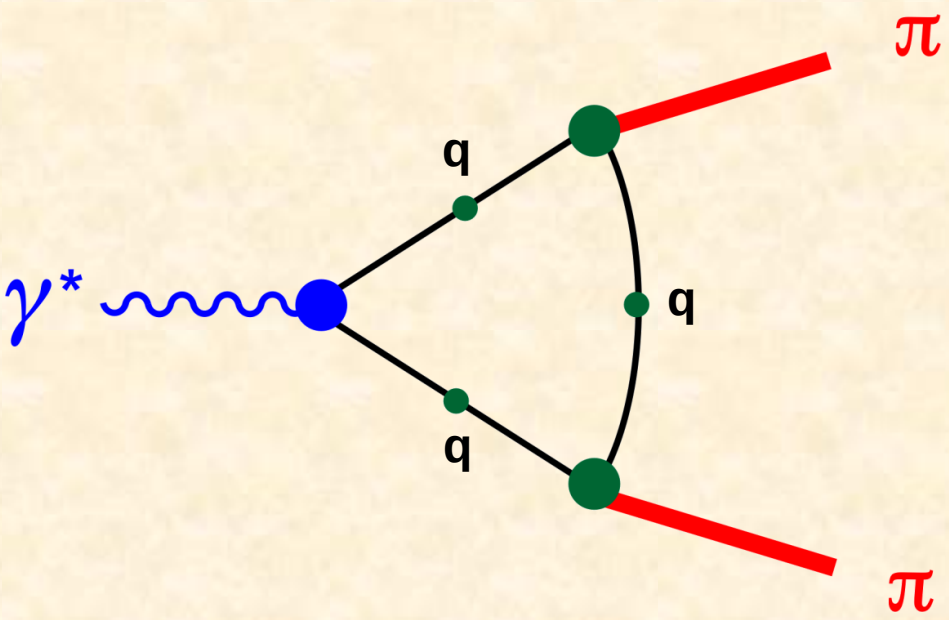


Pion electromagnetic formfactor

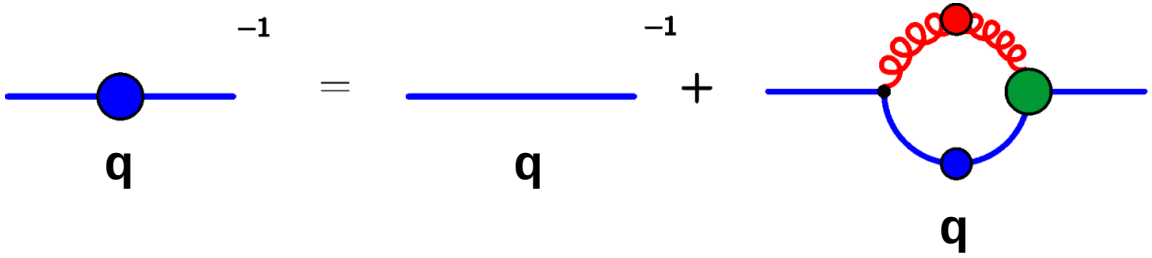


$$\Lambda_\mu = (P' + P)_\mu \, F_\pi(Q^2) = N_c \int \frac{d^4k}{(2\pi)^4} \, \mathrm{Tr}\left[\overline{\Gamma}^\pi \, S \, i\Gamma_\mu \, S \, \Gamma^\pi \, S\right]$$

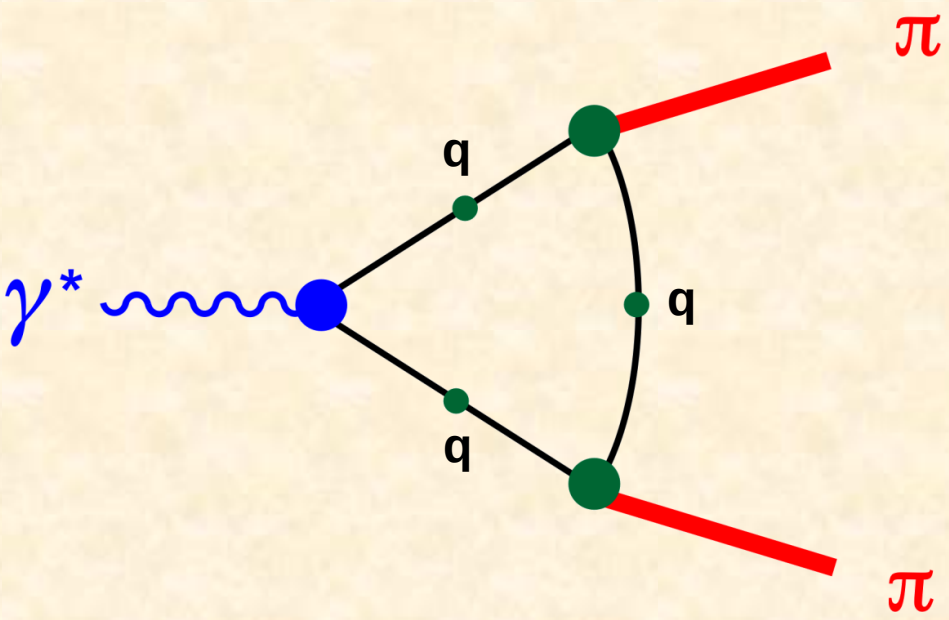
Pion electromagnetic formfactor



Maris, Tandy

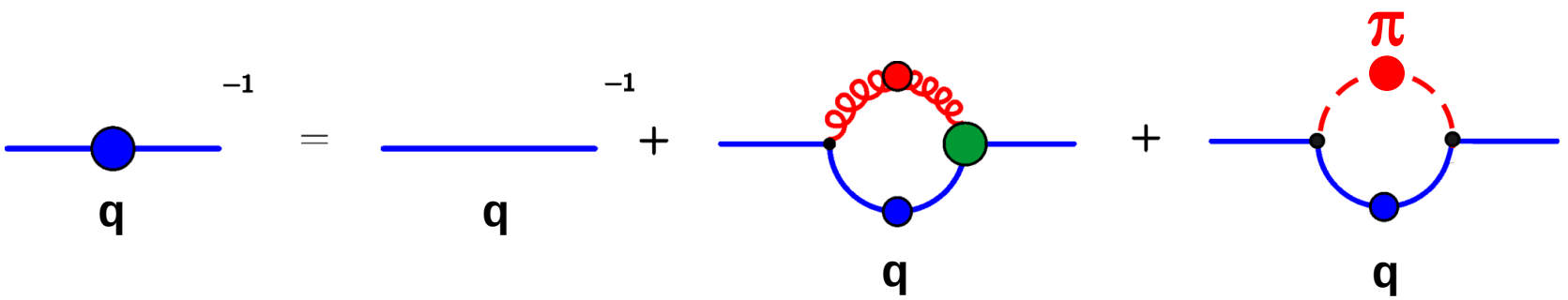


Pion electromagnetic formfactor

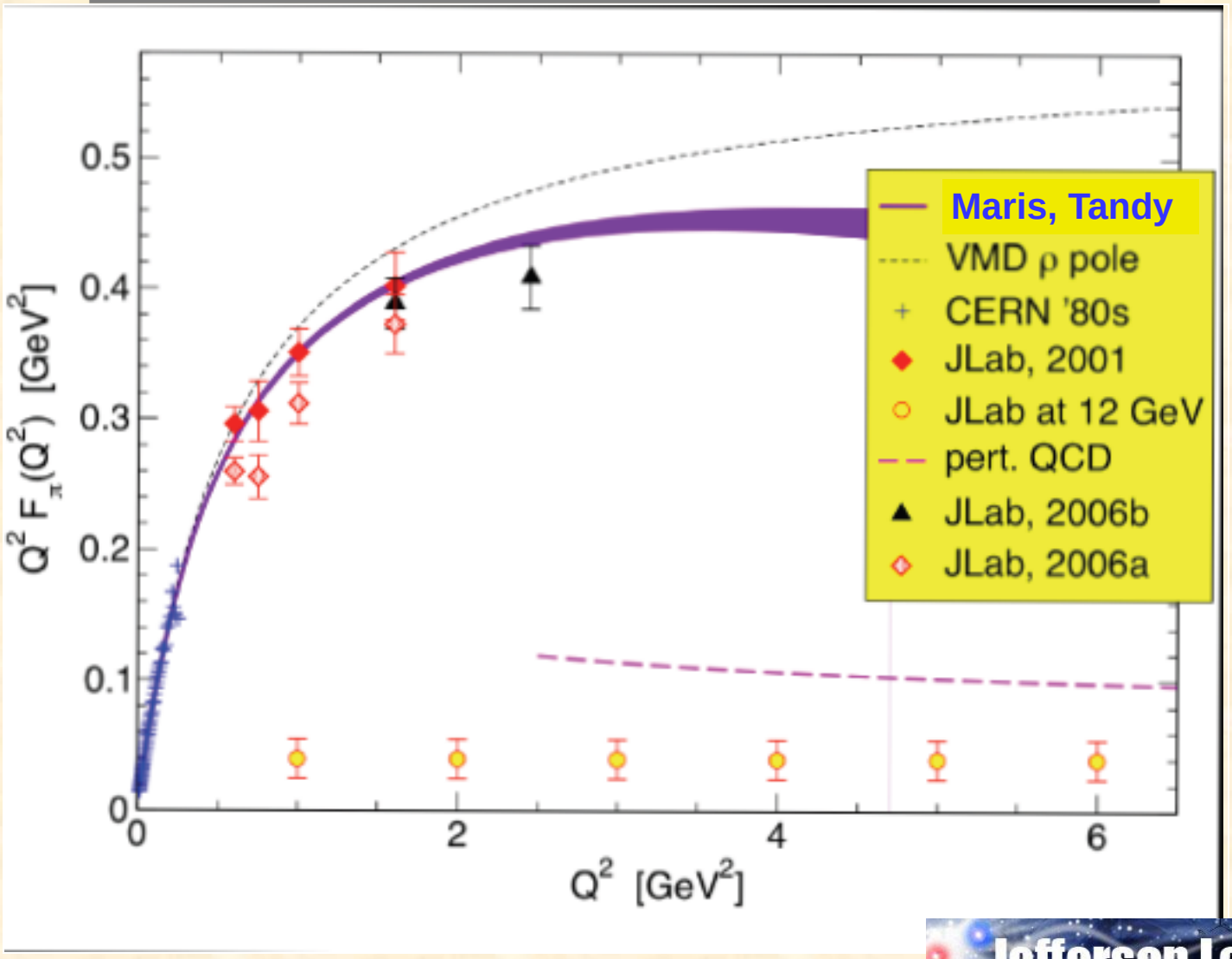


Maris, Tandy

Fischer, Williams



Pion electromagnetic formfactor



Jefferson Lab
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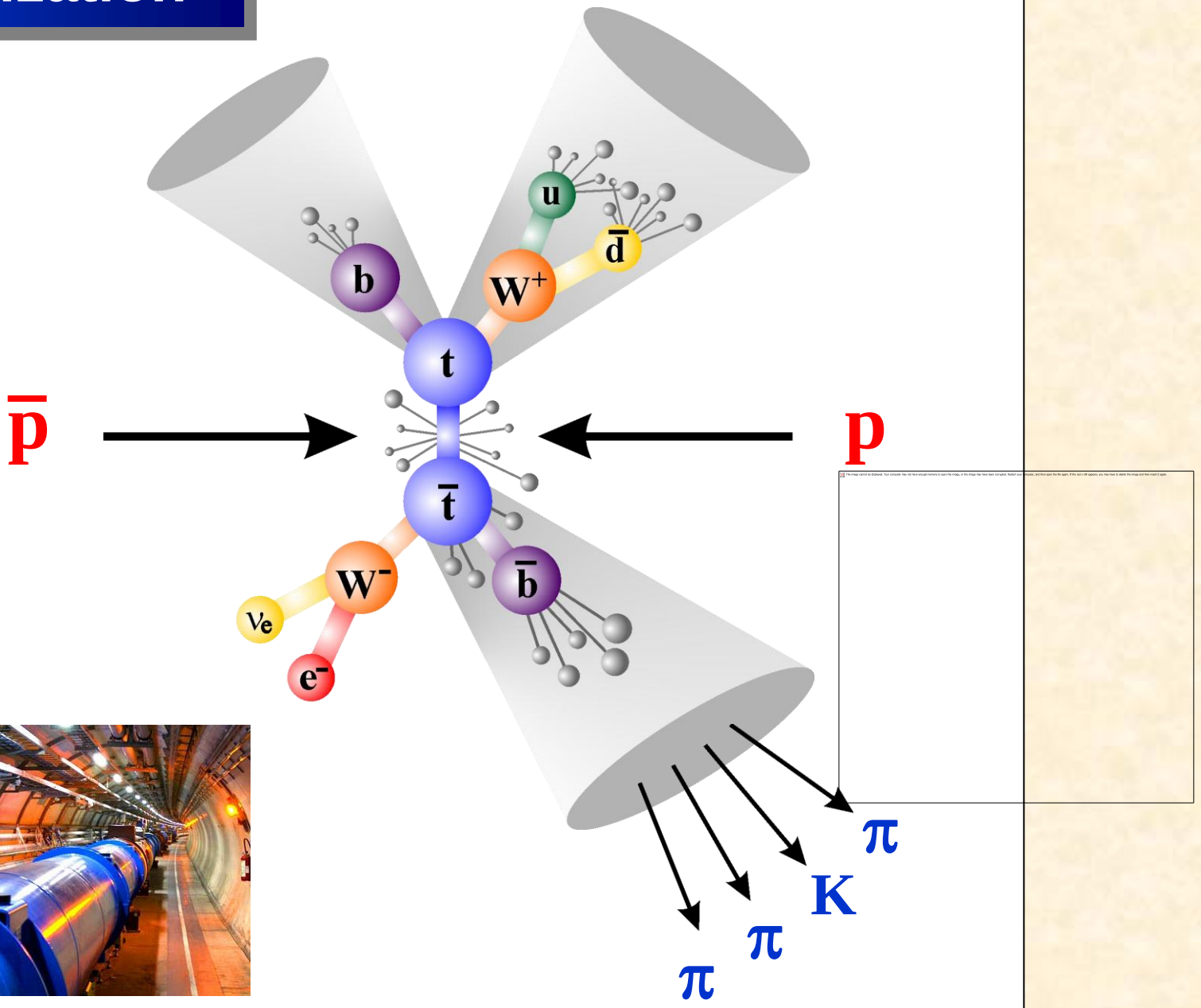
Hadronization



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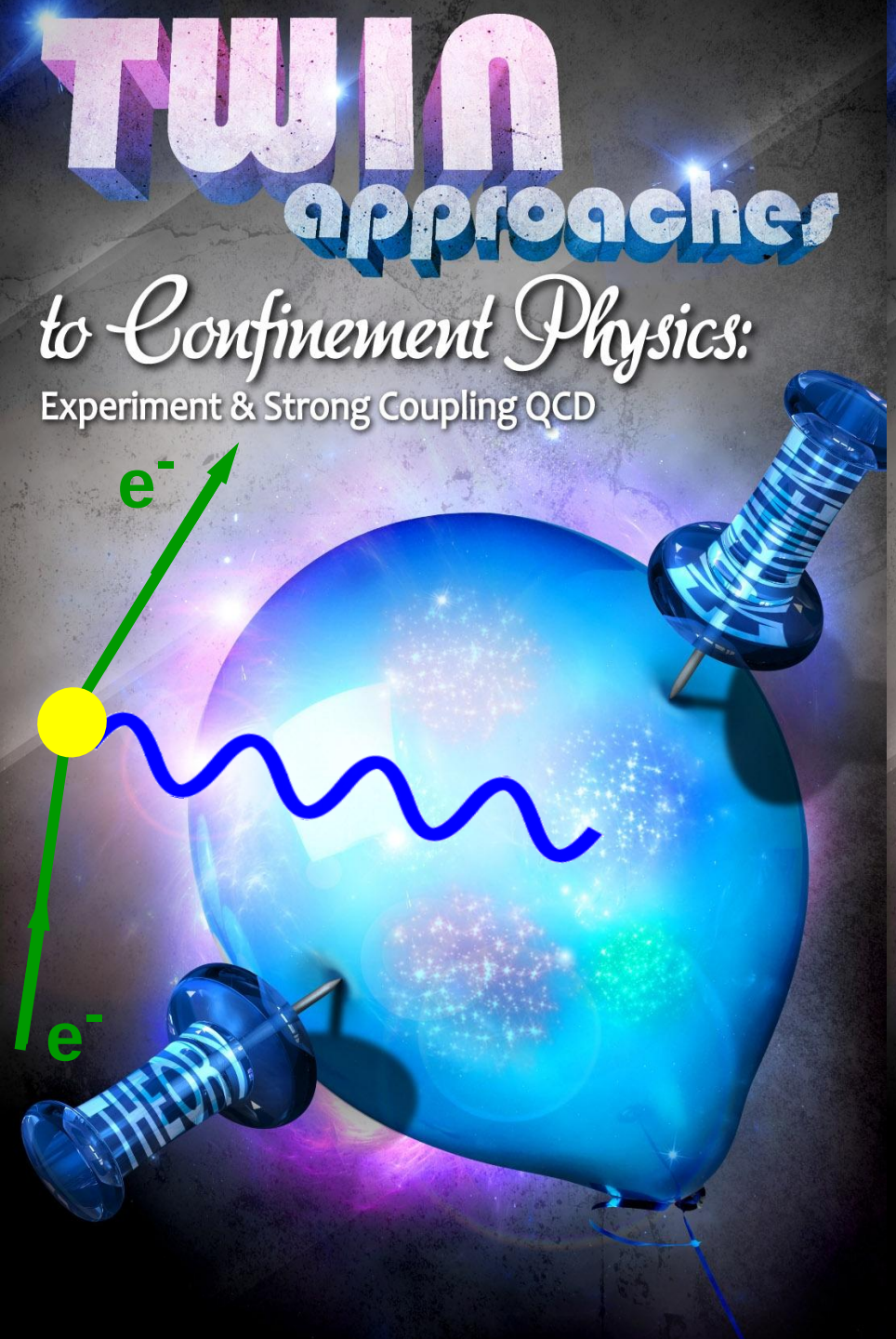
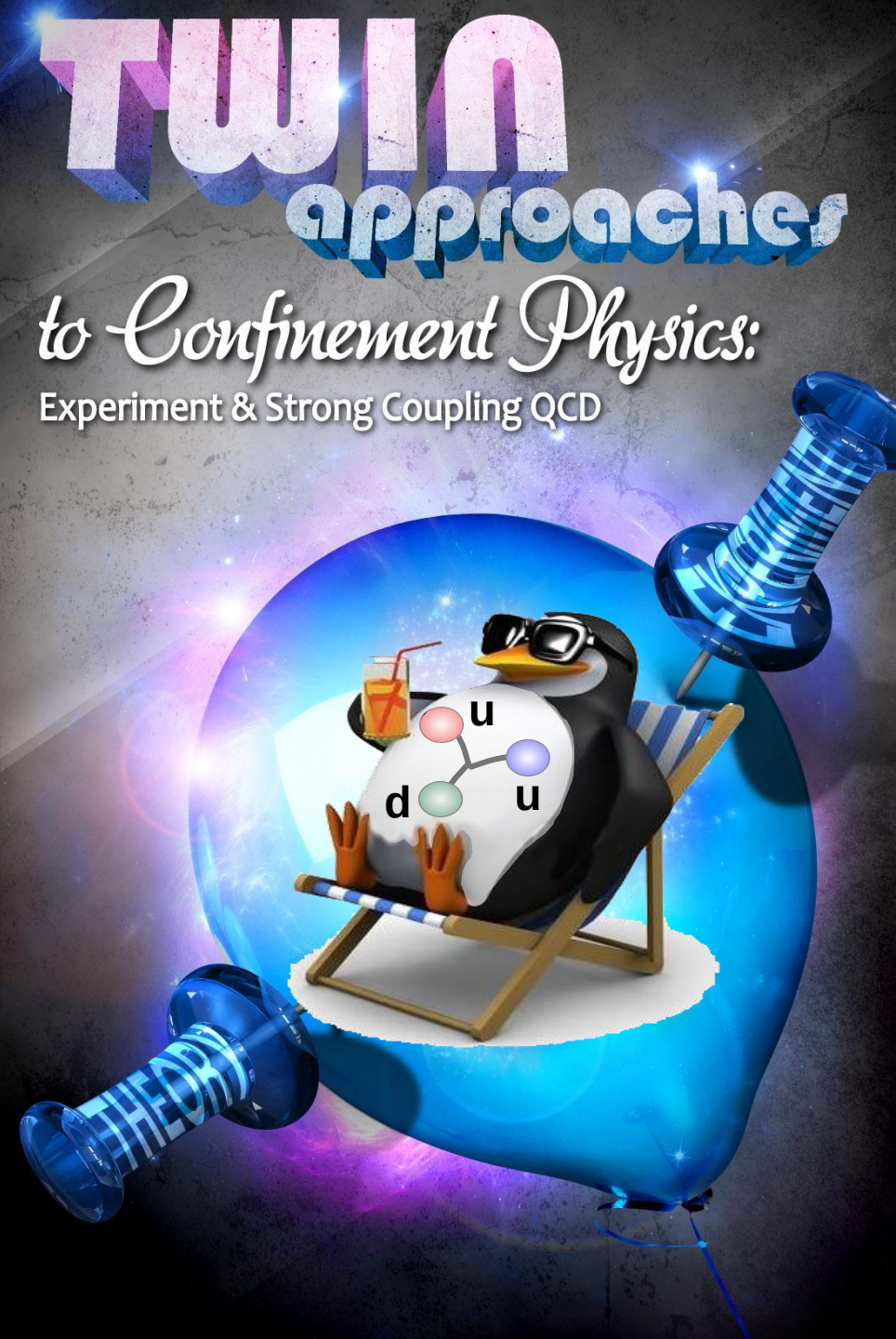
TWIN approaches to Confinement Physics:

Experiment & Strong Coupling QCD



TWIN approaches to Confinement Physics:

Experiment & Strong Coupling QCD