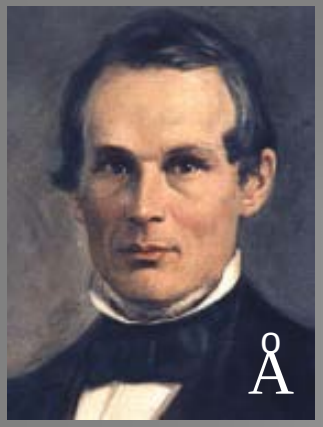
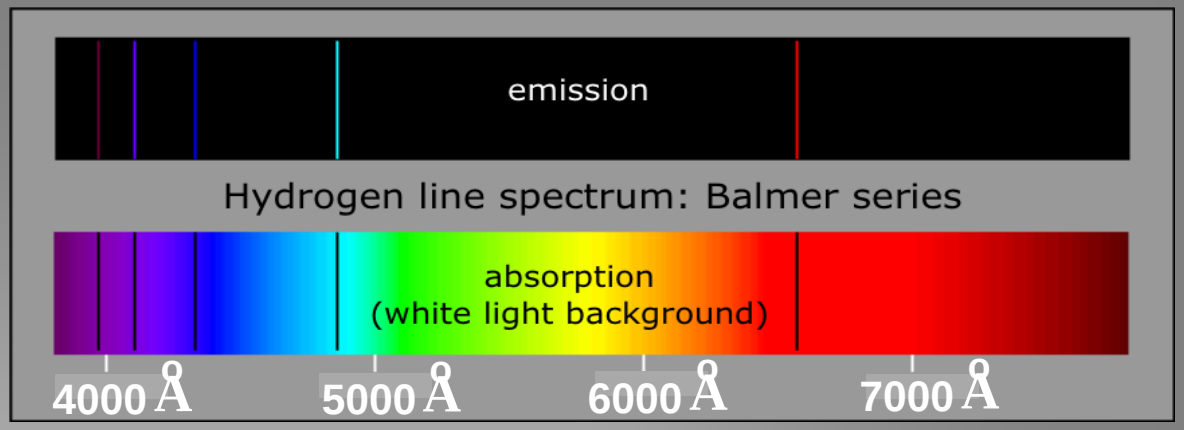




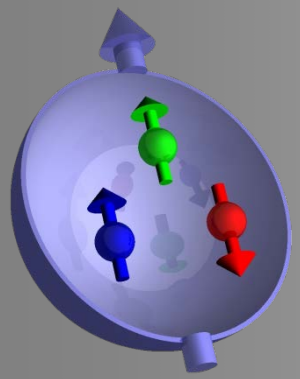
Why is GeV physics still interesting in the era of the LHC?

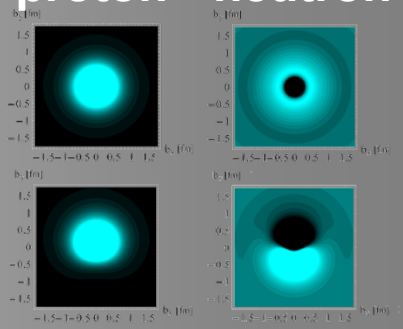
Michael Pennington
Jefferson Lab

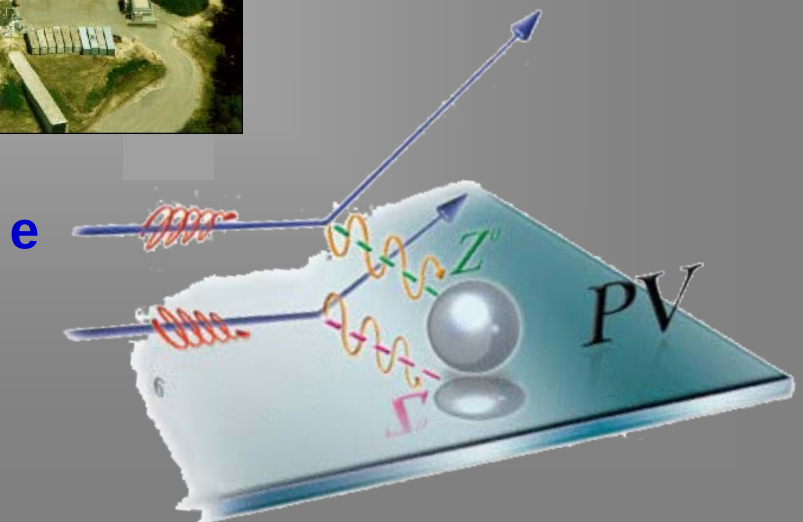
LEAP 2013
Uppsala

Jefferson Lab

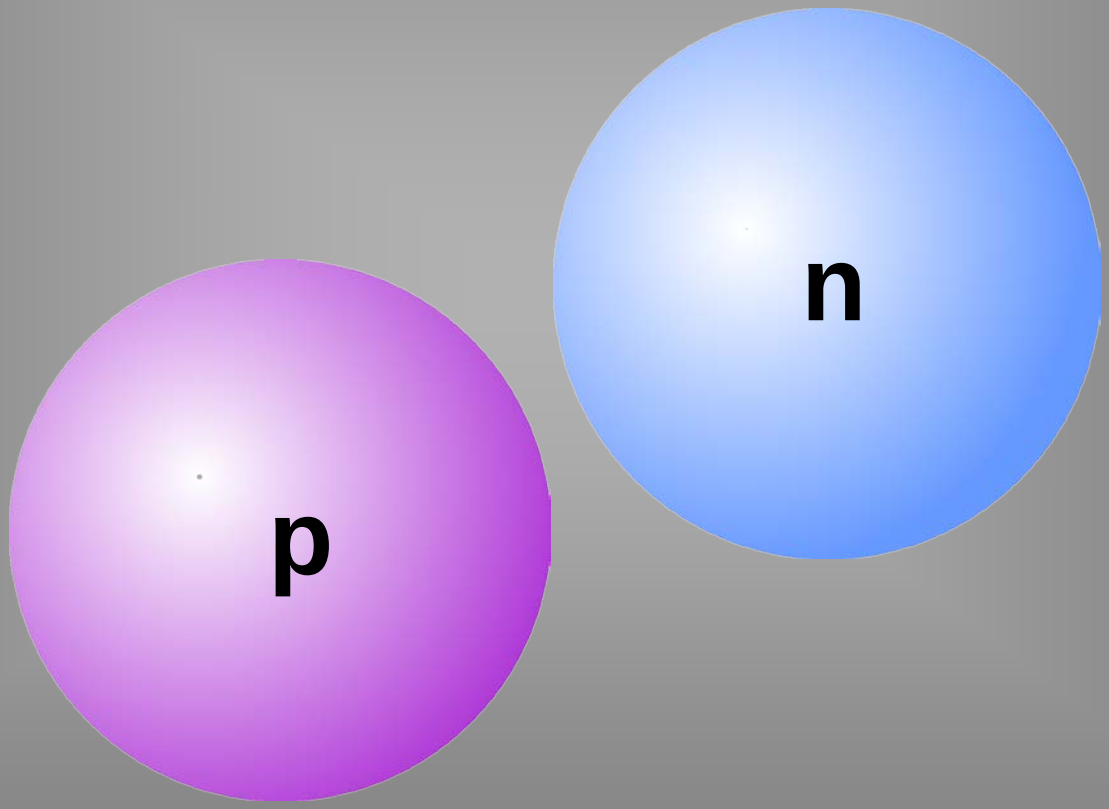
Exploring the Nature of Matter





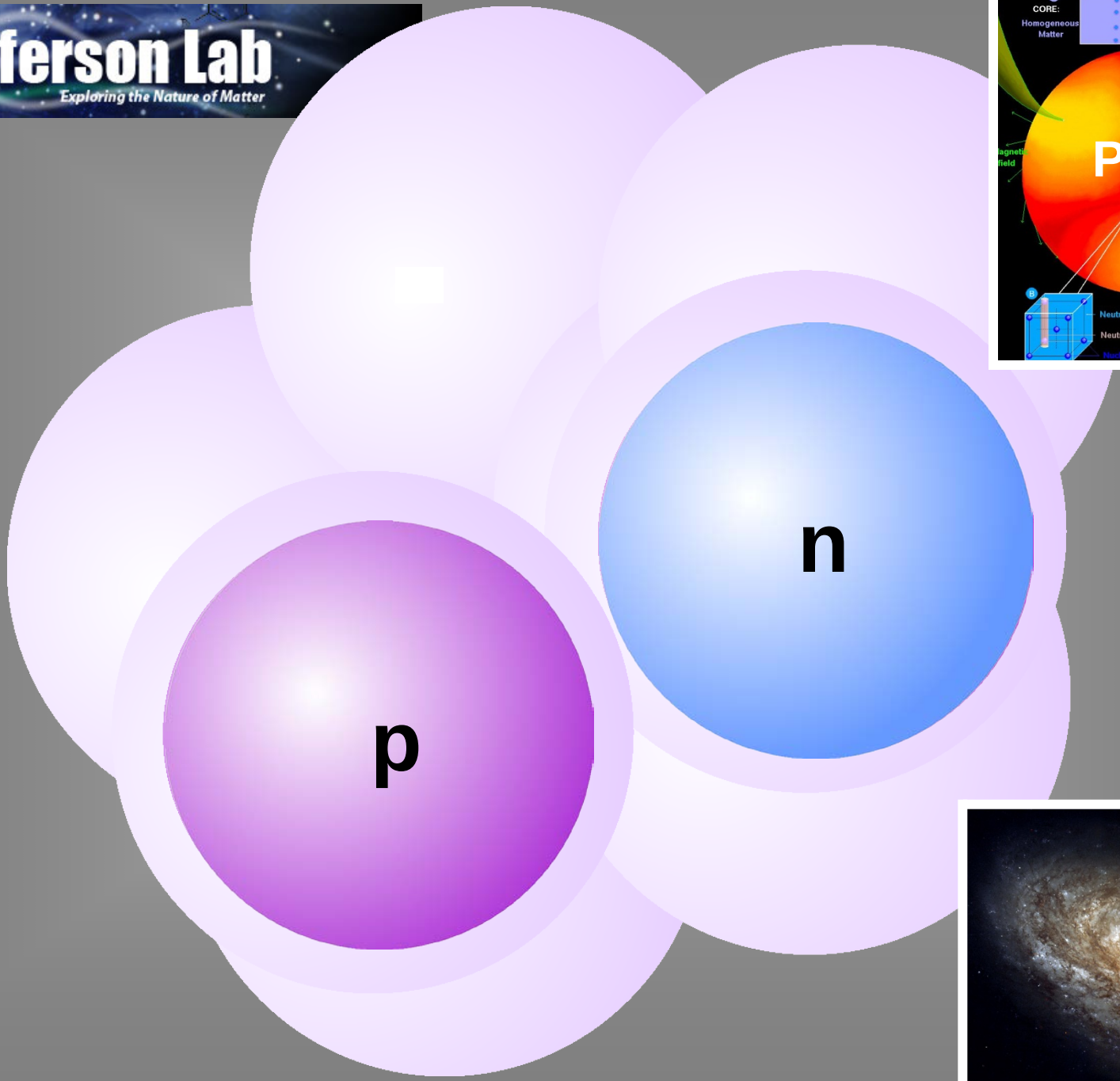


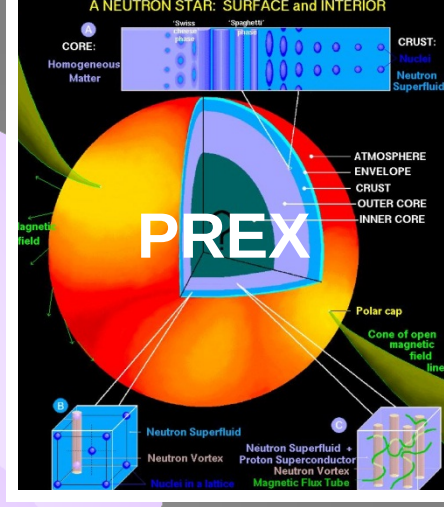
Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter


n
p

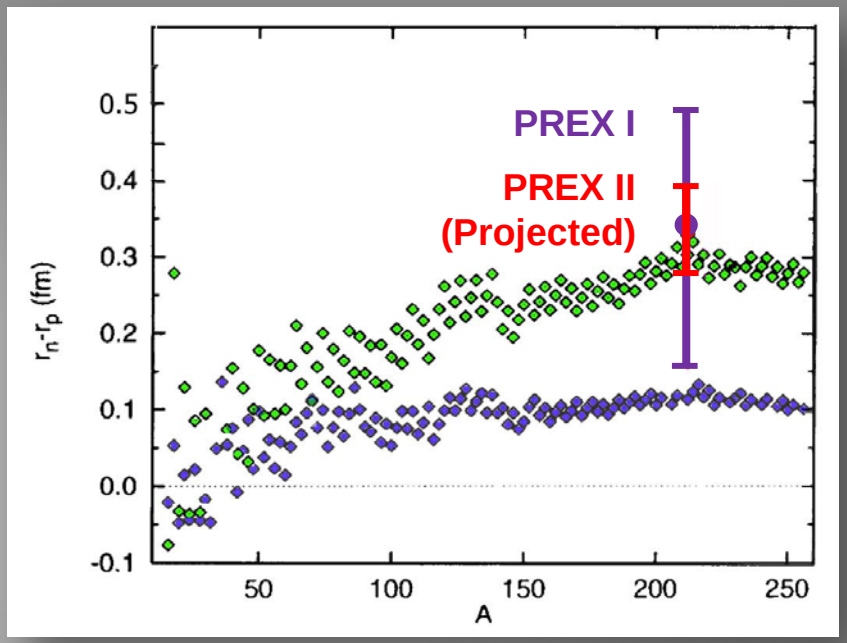
Jefferson Lab

Exploring the Nature of Matter



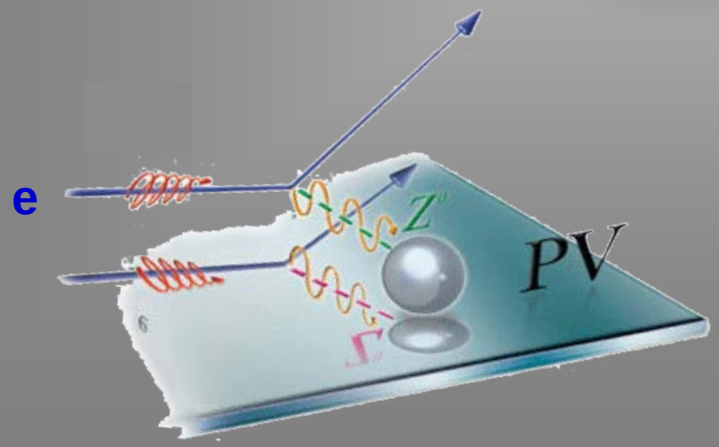


Parity violation at JLab

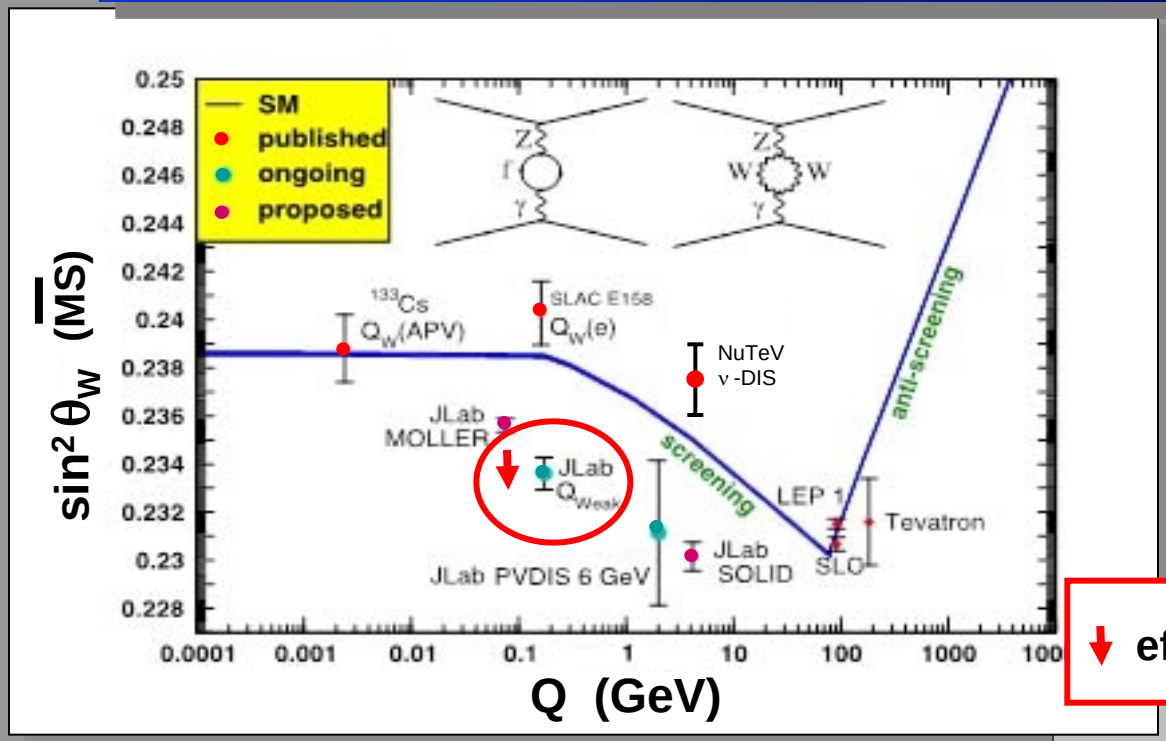


Relativistic mean field

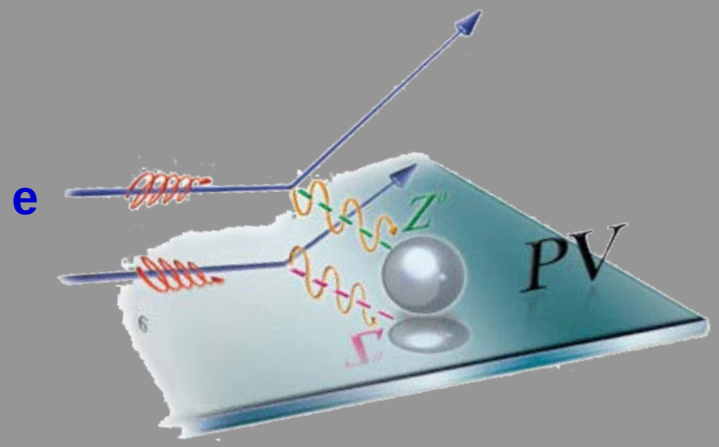
Nonrel. Skyrme

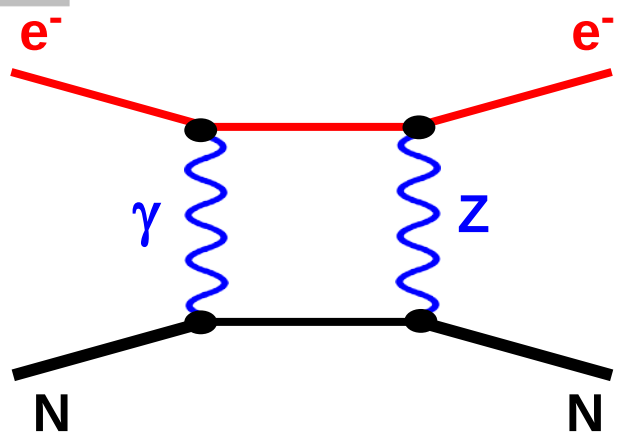


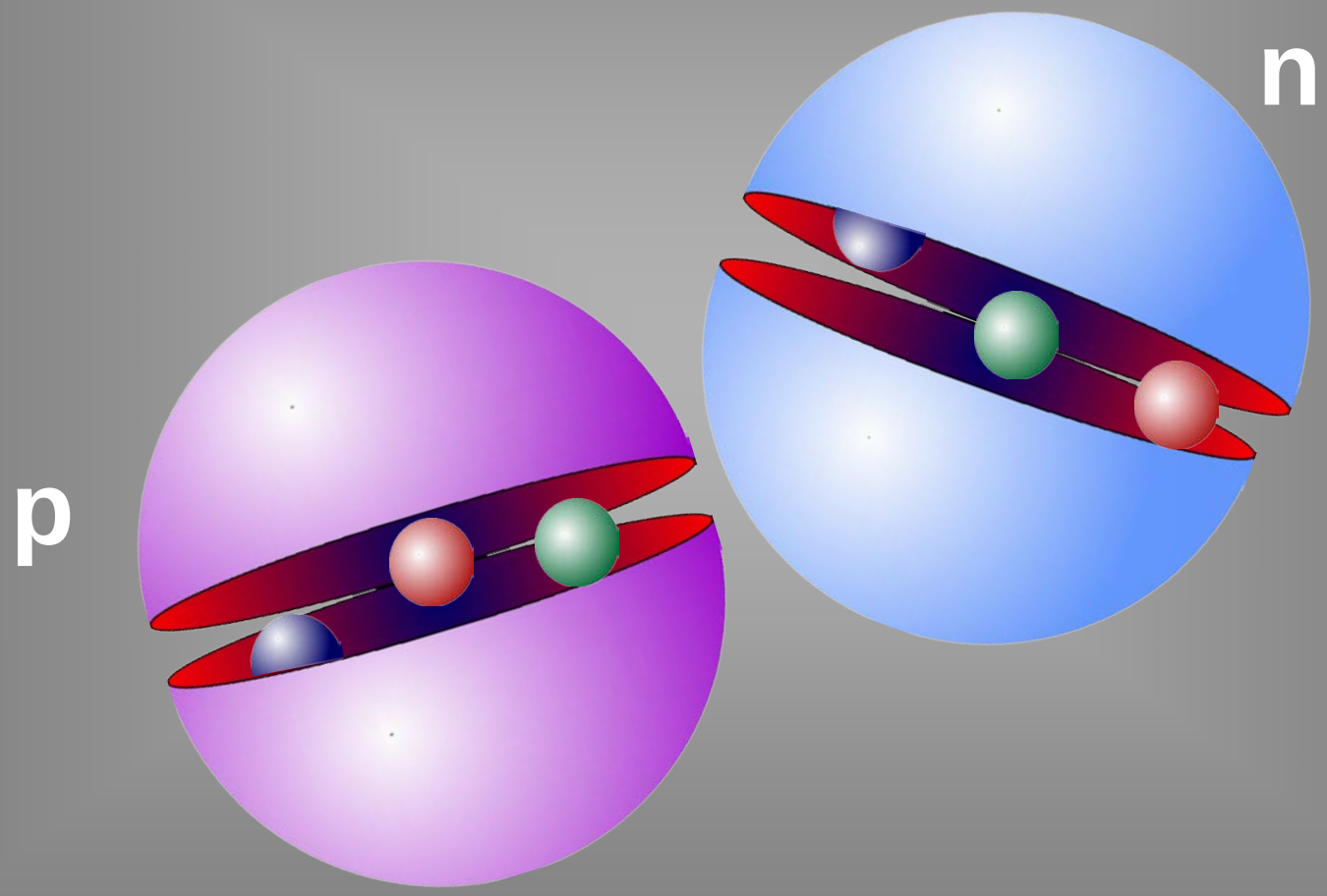
Parity violation at JLab



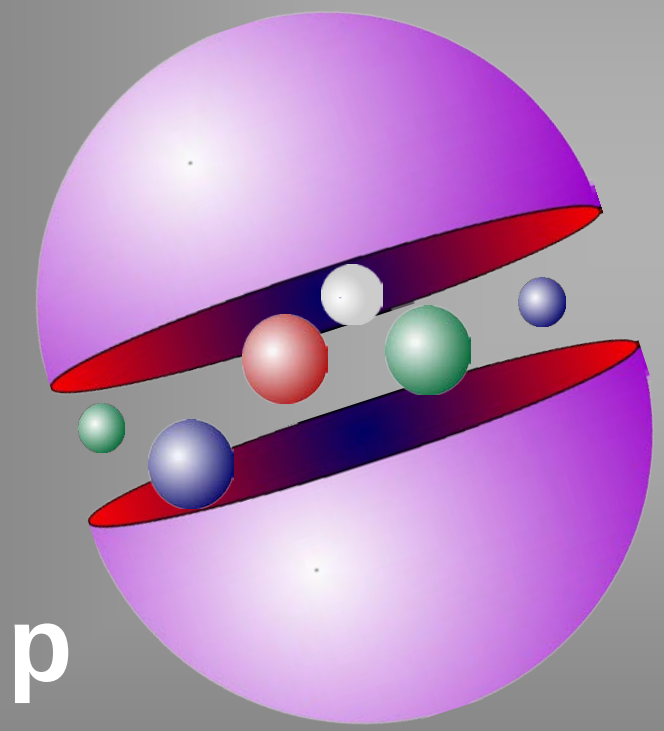
effect of V+A corrections at Q_W

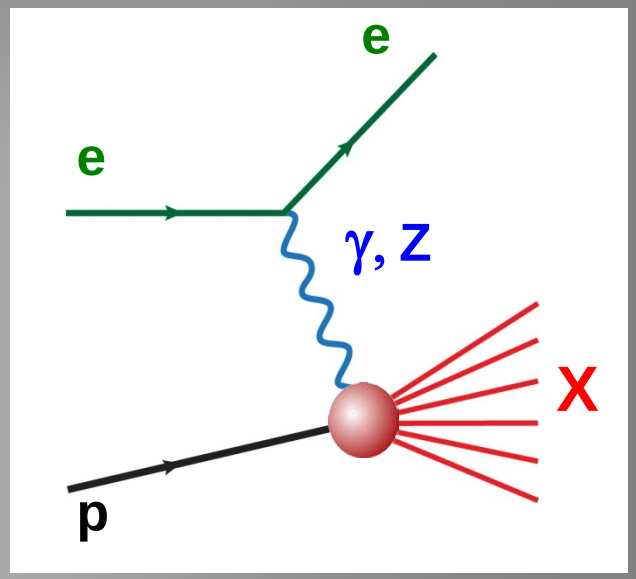




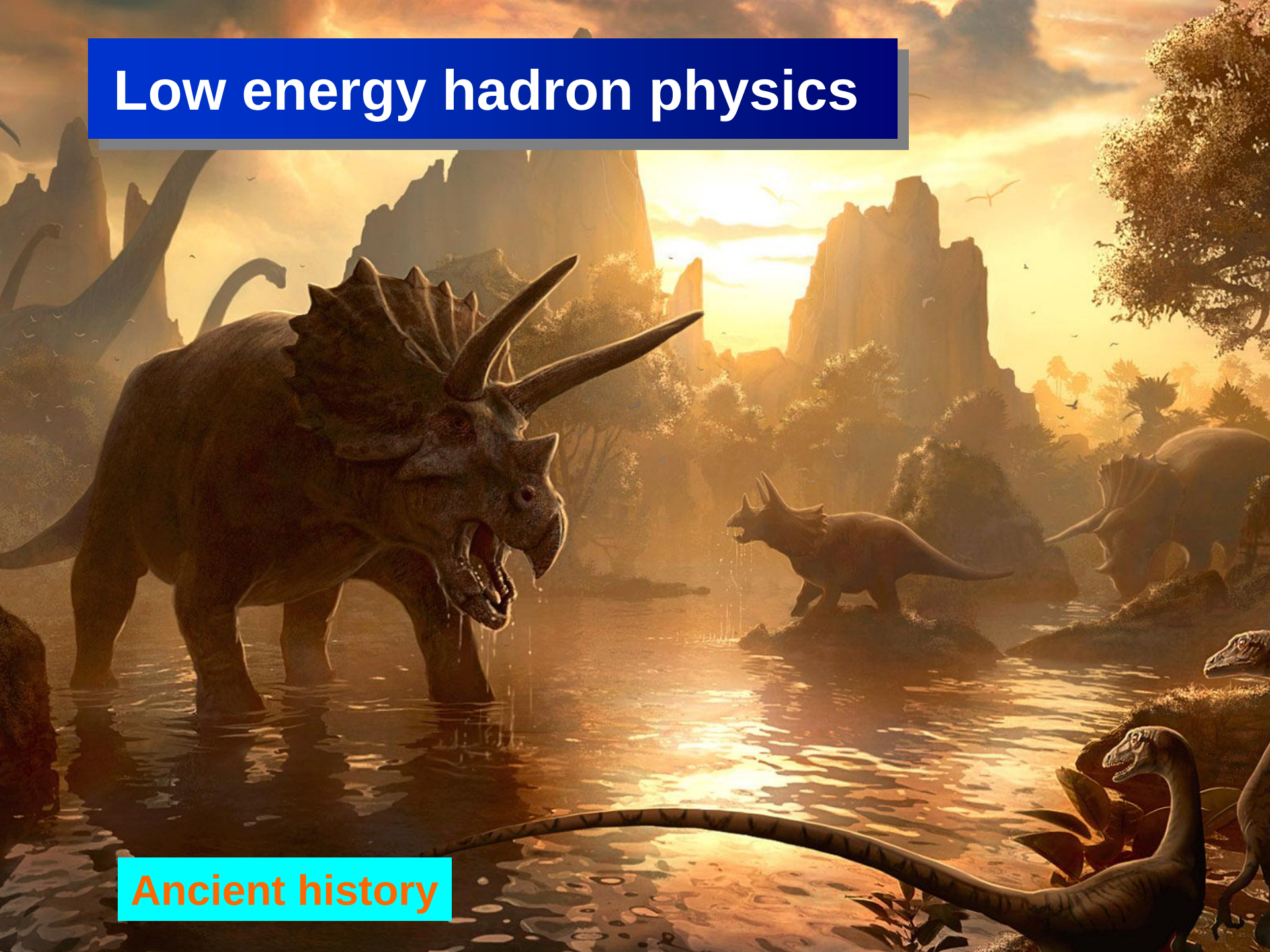

n
p

Deep inelastic scattering



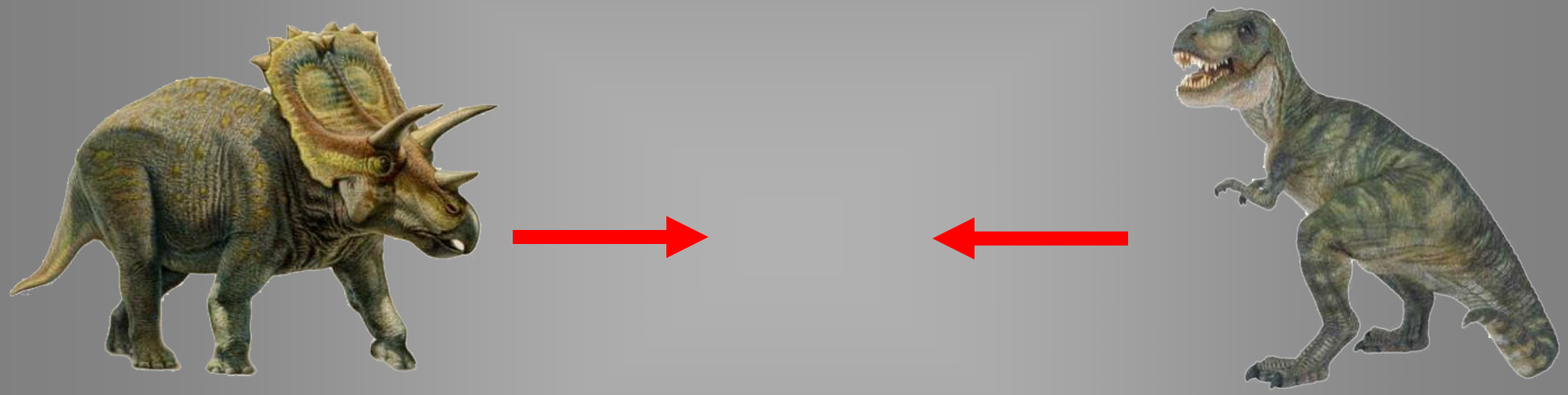


Low energy hadron physics

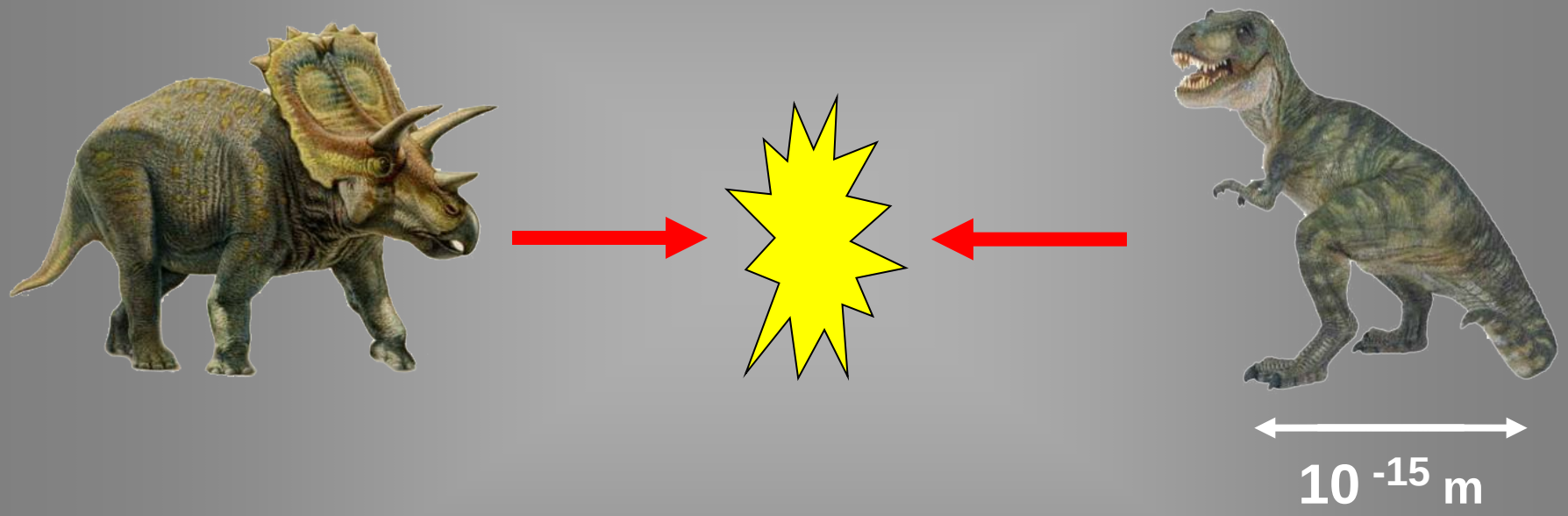


Ancient history

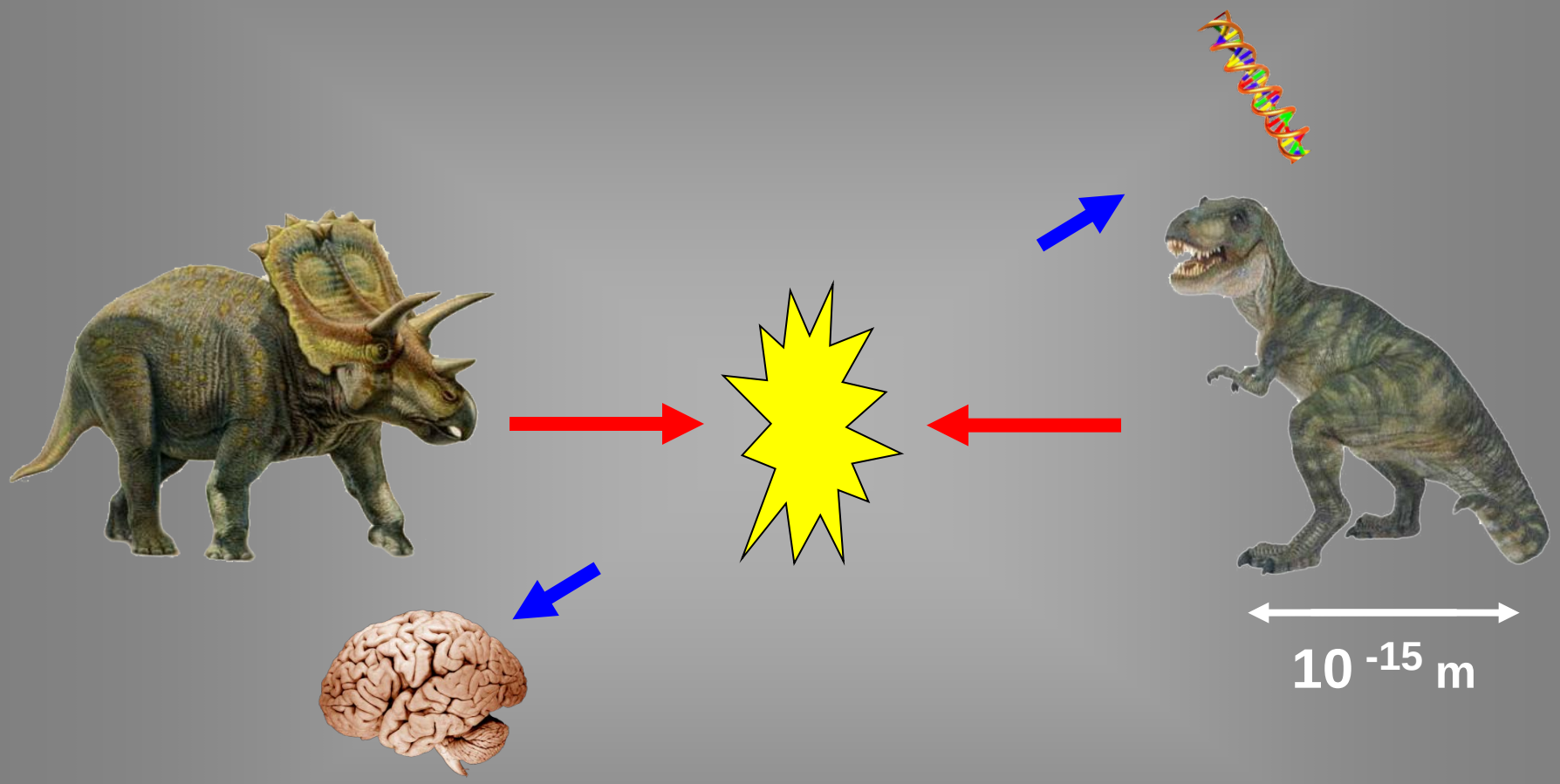
LHC collisions



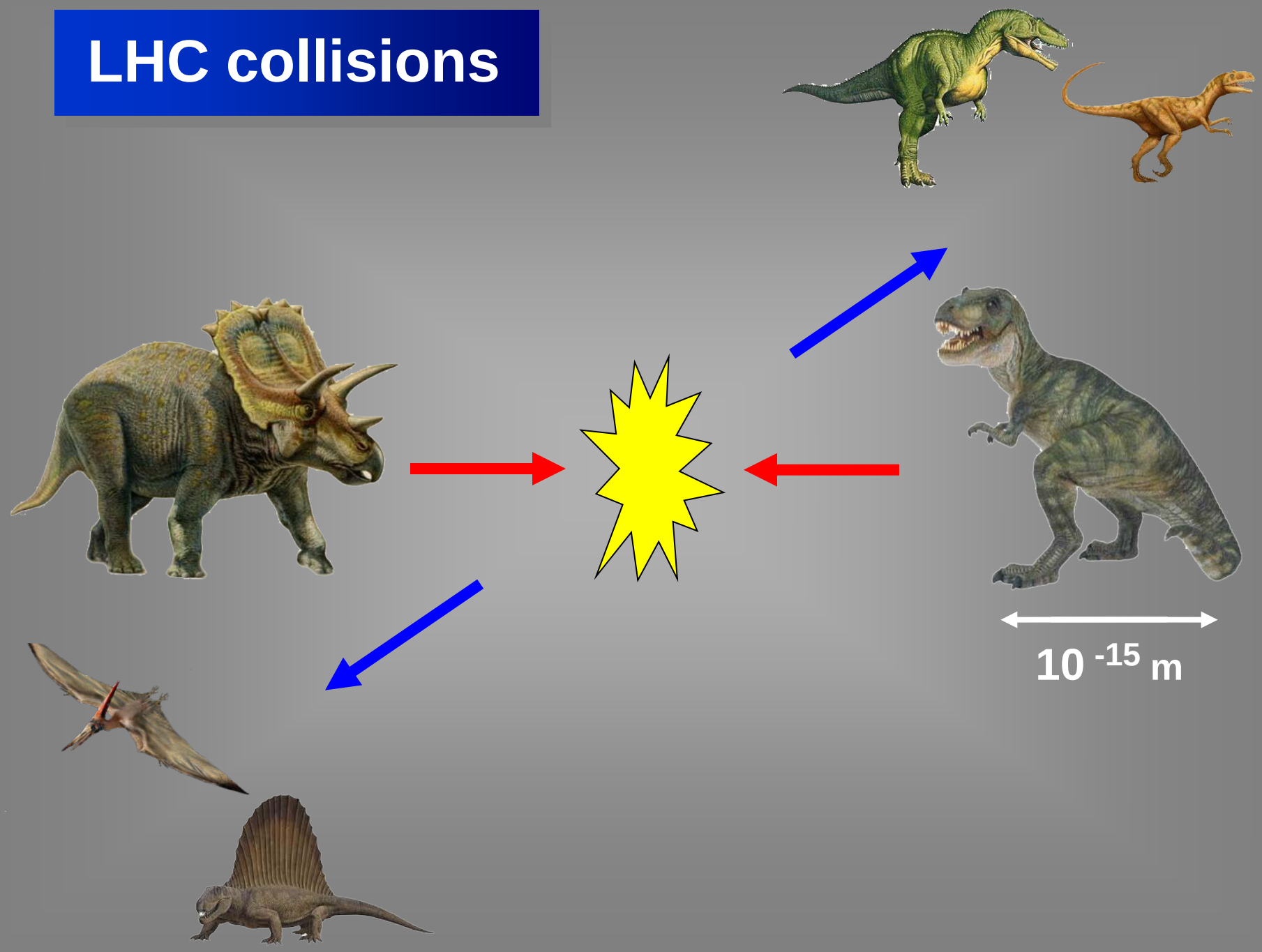
LHC collisions



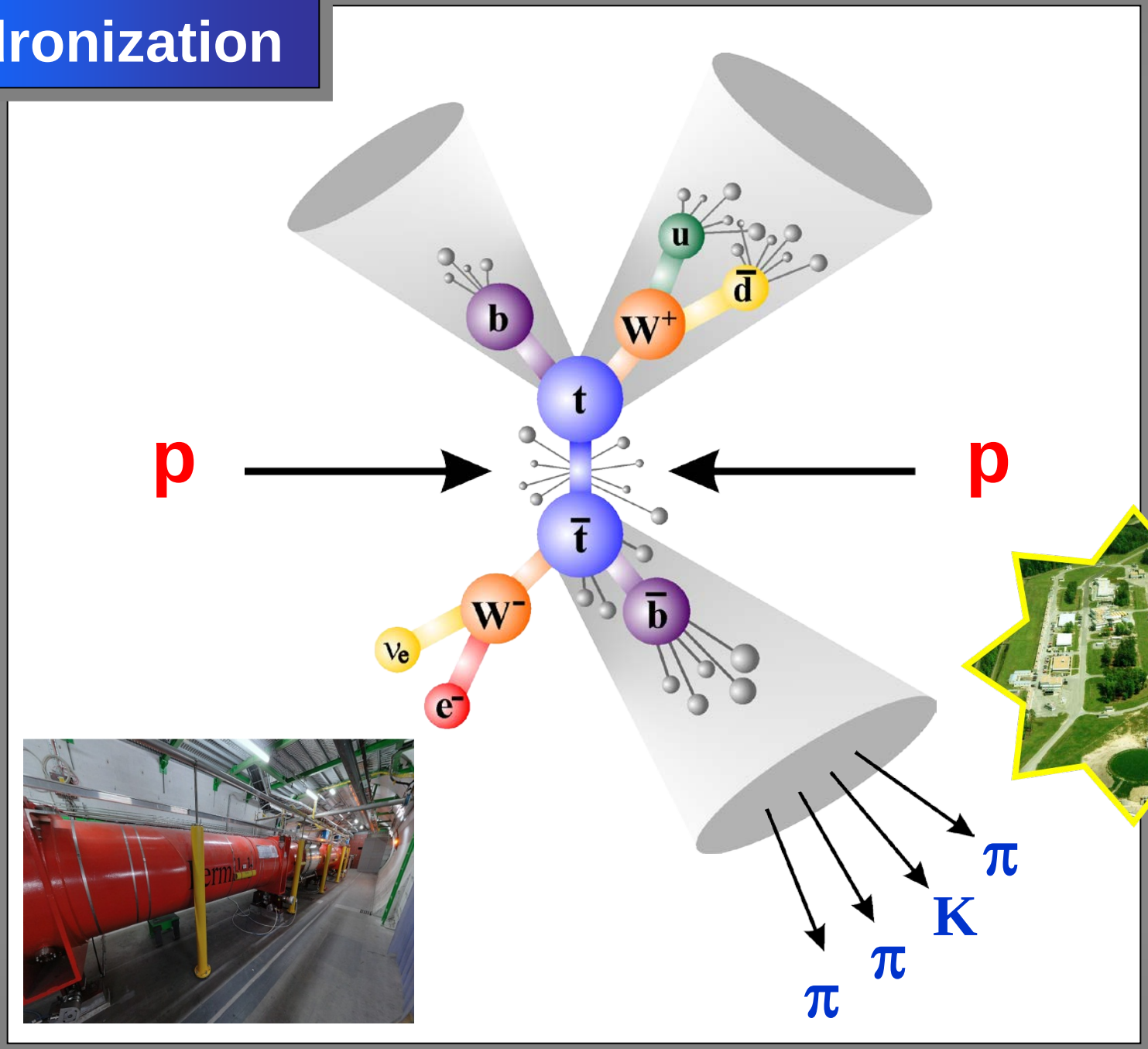
LHC collisions



LHC collisions



Hadronization



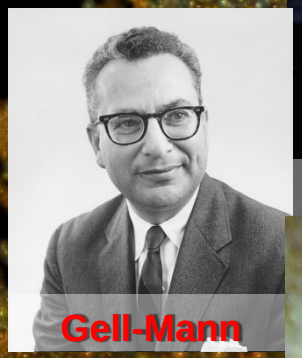
Glimpsing colour
in a world of black & white

understanding
the spectrum & structure
of hadrons

to reveal the workings of QCD

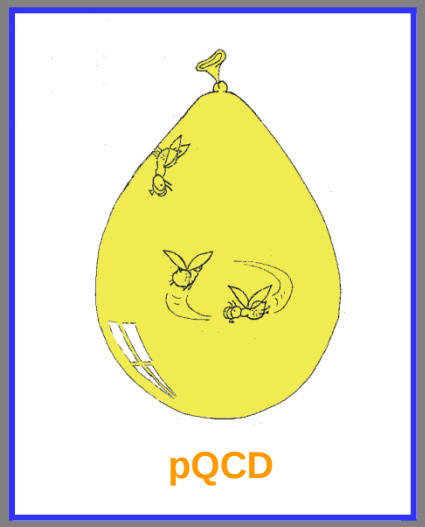
QCD

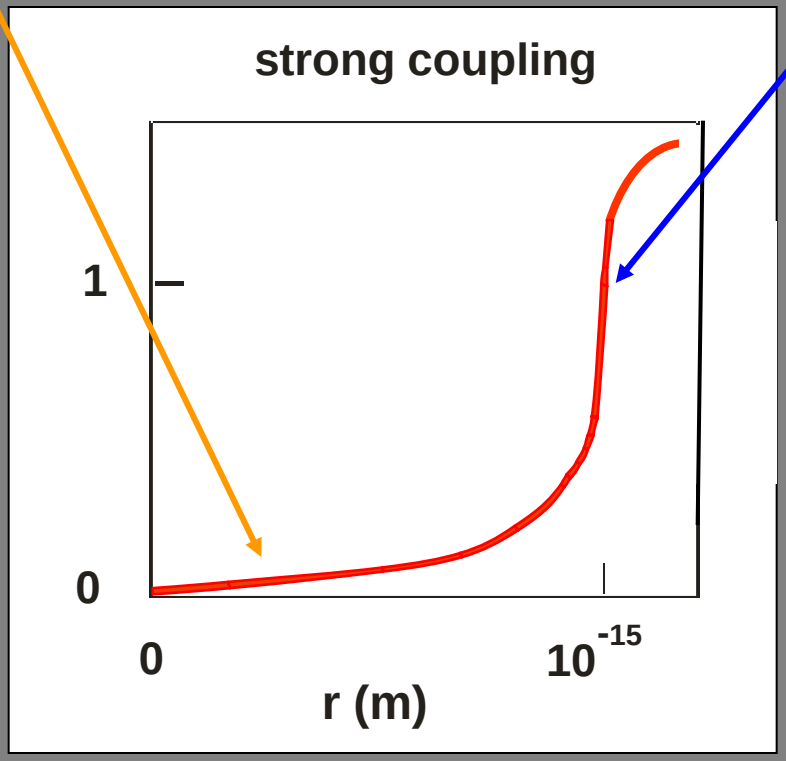
$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} \bar{q} \left(i \gamma_\mu D^\mu - m_q \right) q - \frac{1}{4} \mathcal{F}^{\mu\nu} \mathcal{F}_{\mu\nu}$$



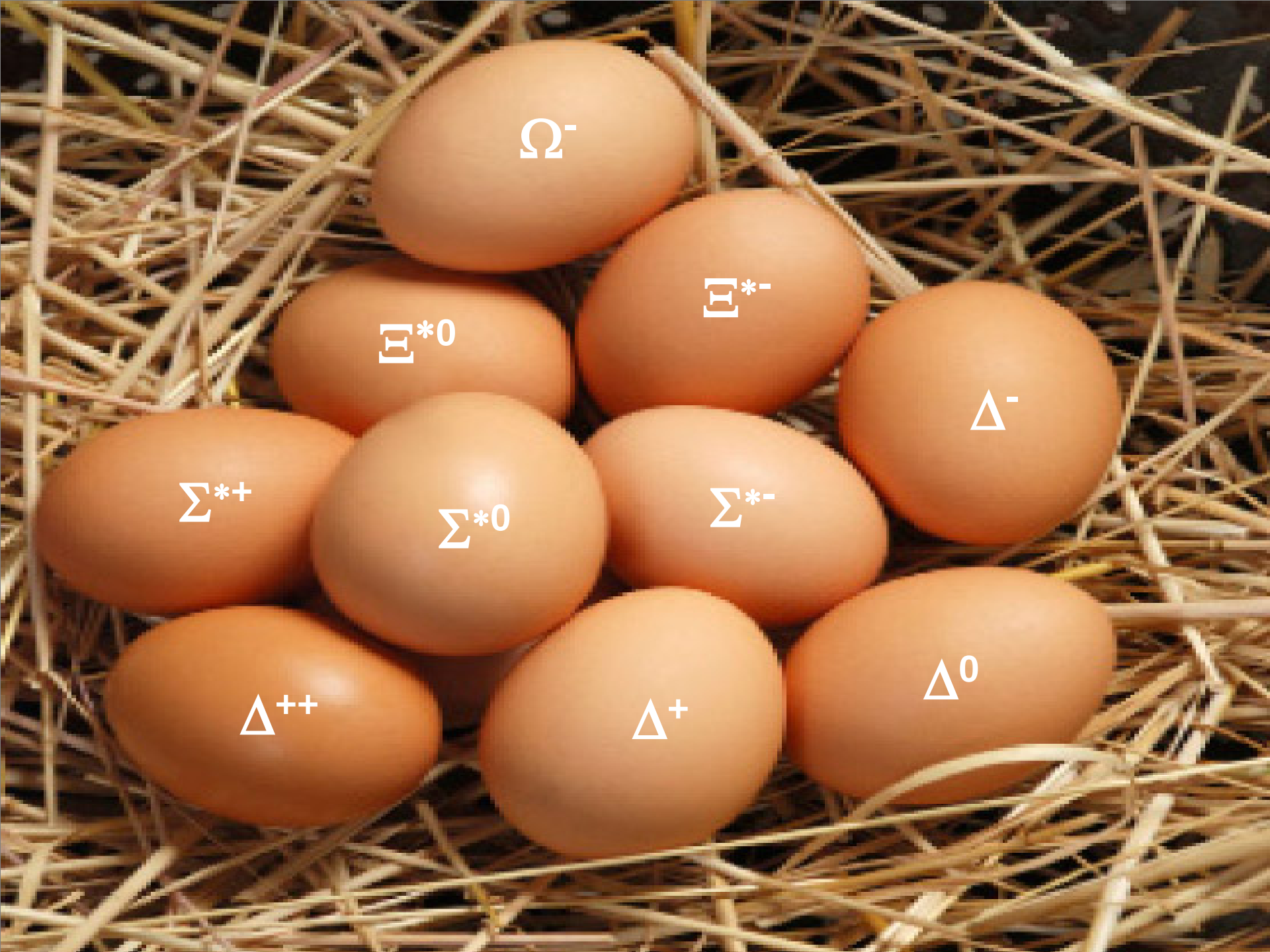
QCD

asymptotic freedom

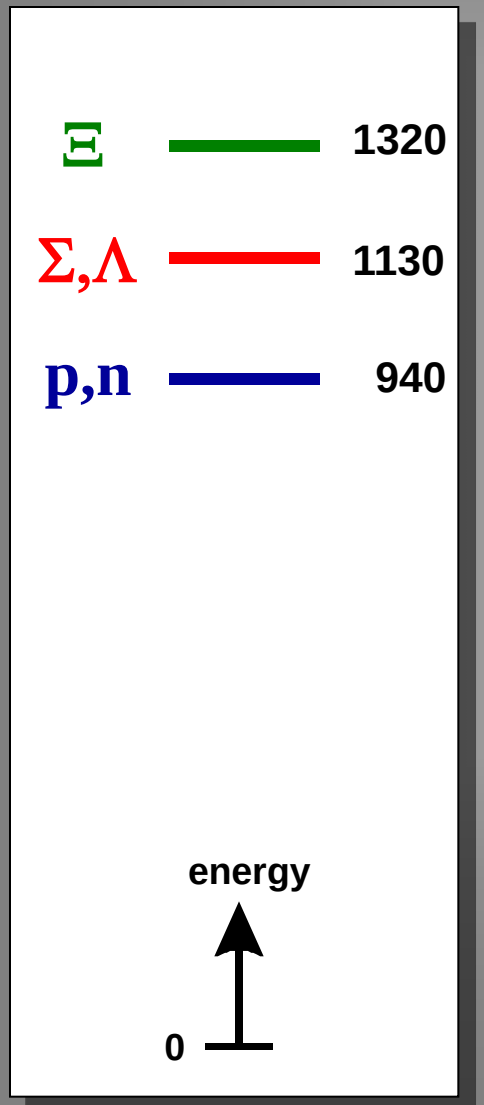


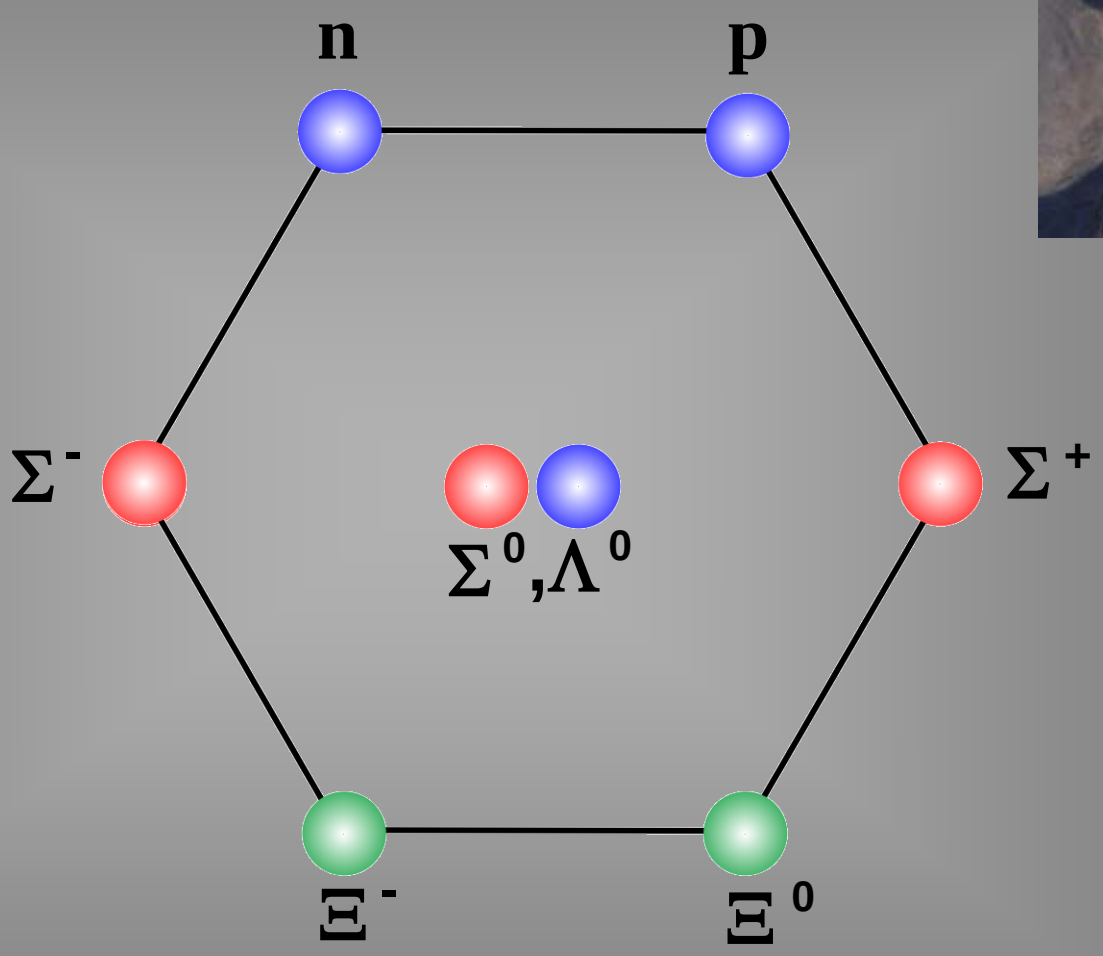


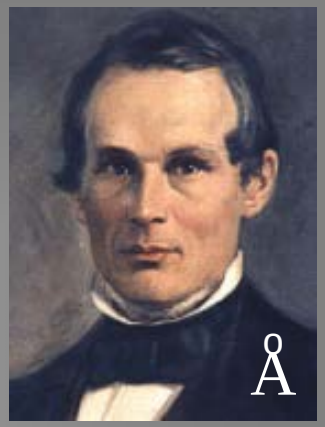
confinement


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

Baryon octet

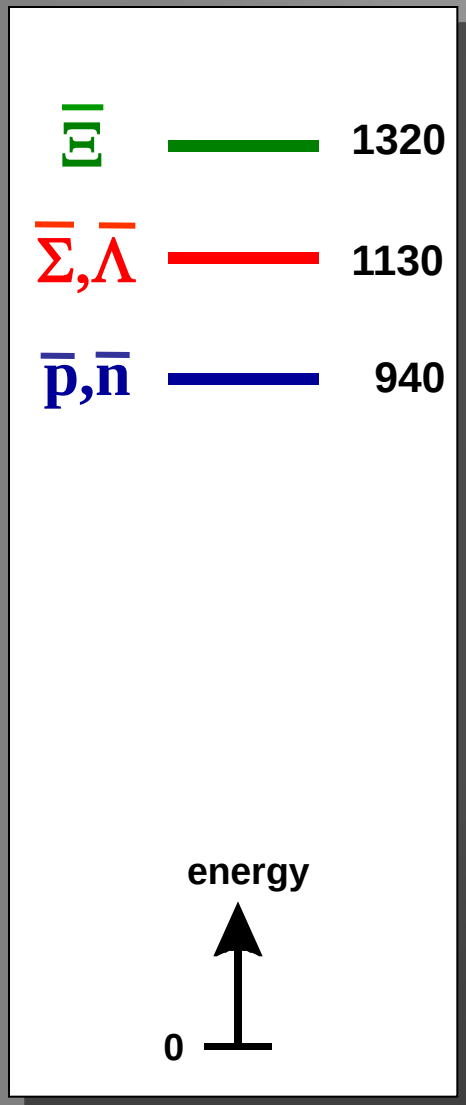


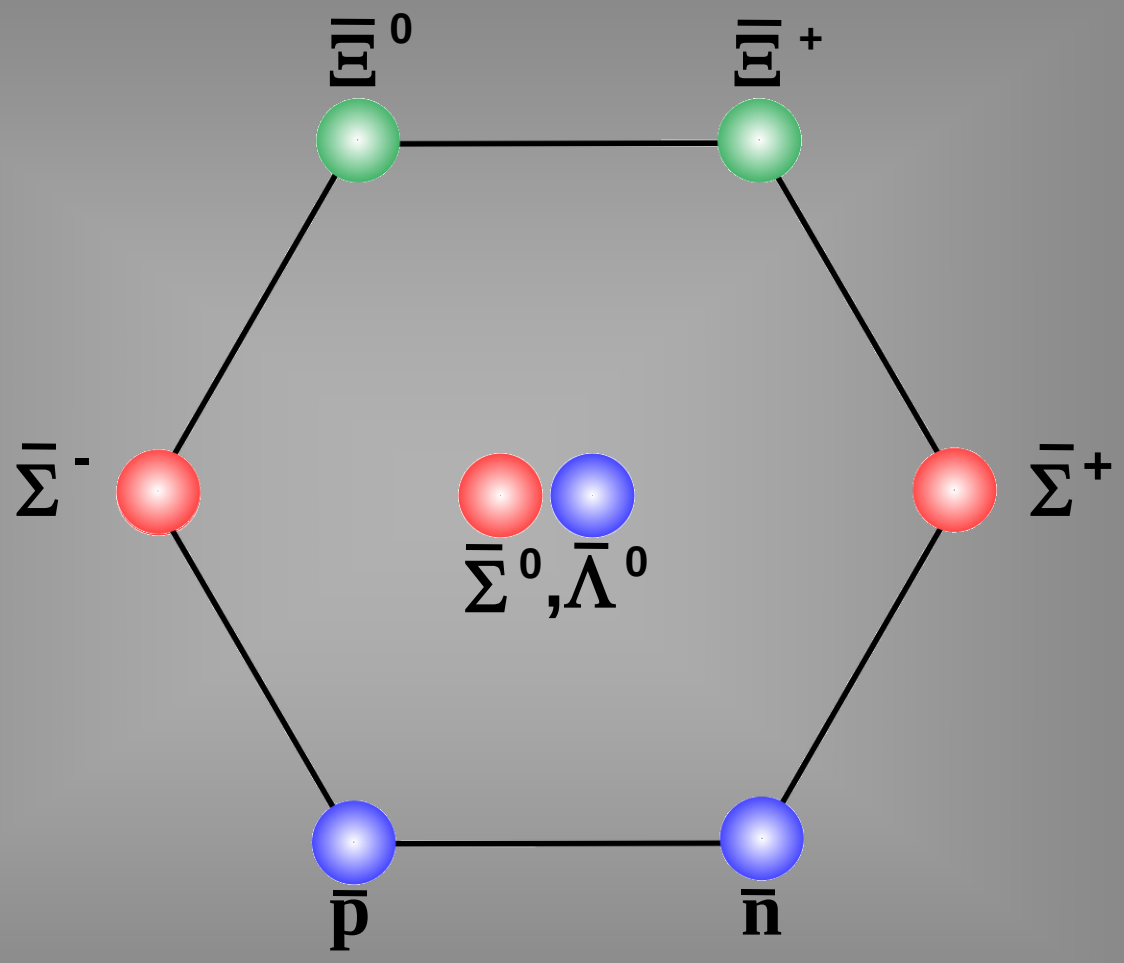




Ground States

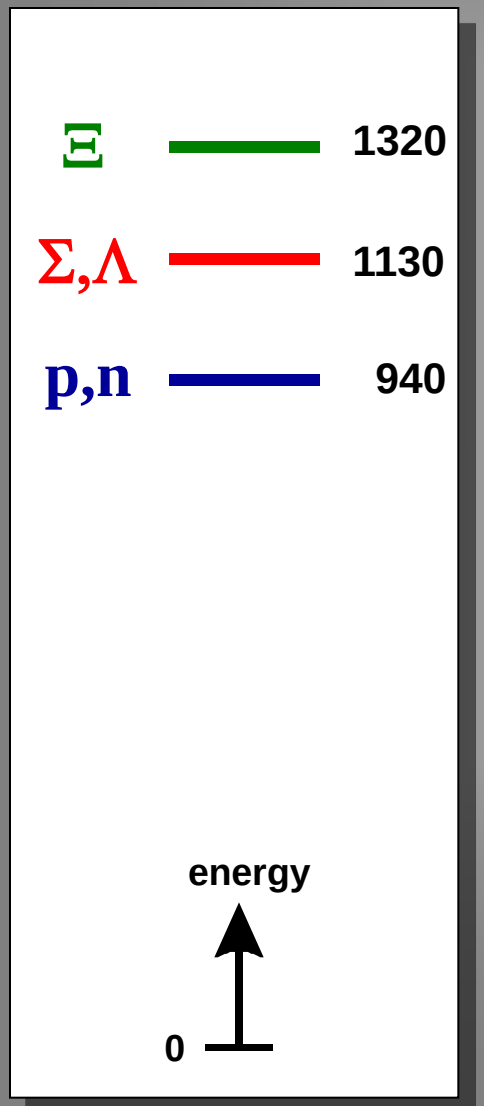
Anti-Baryon octet

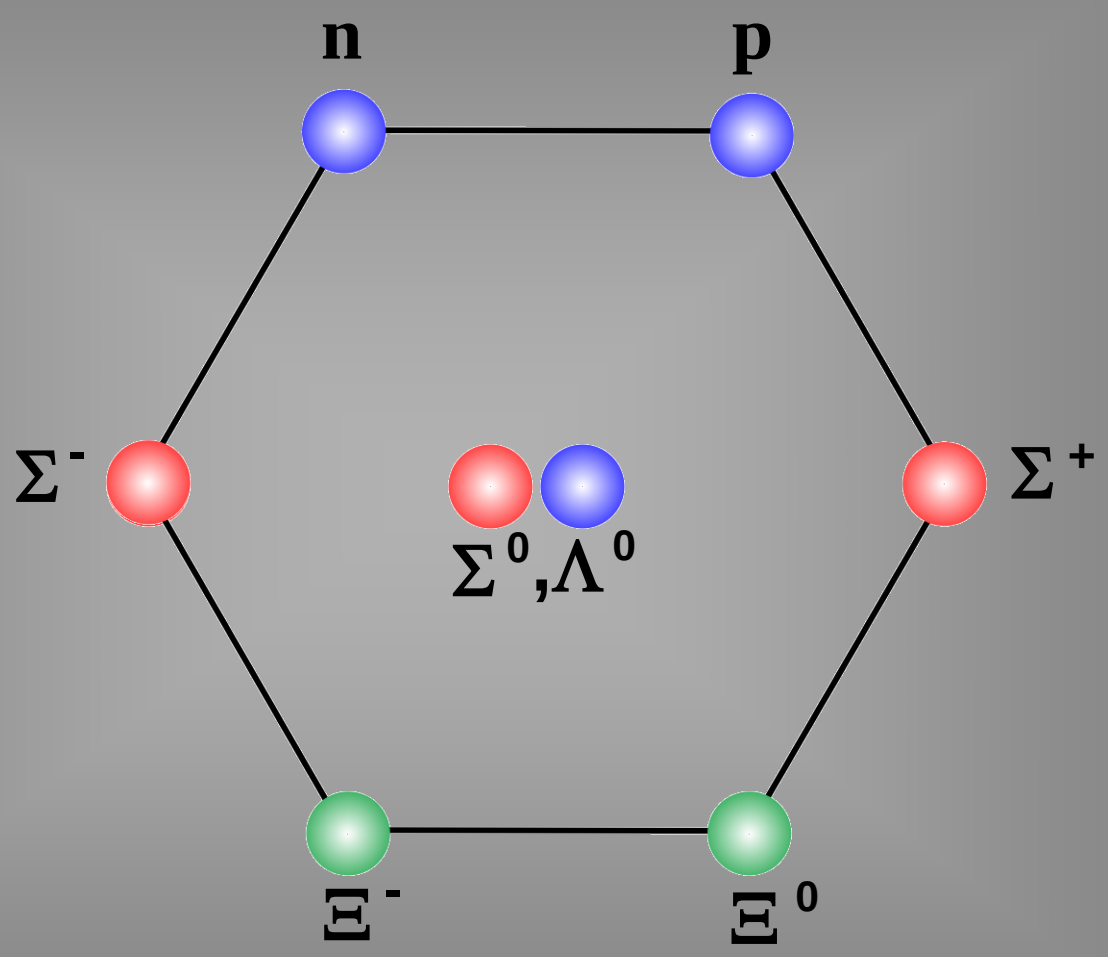




Ground States

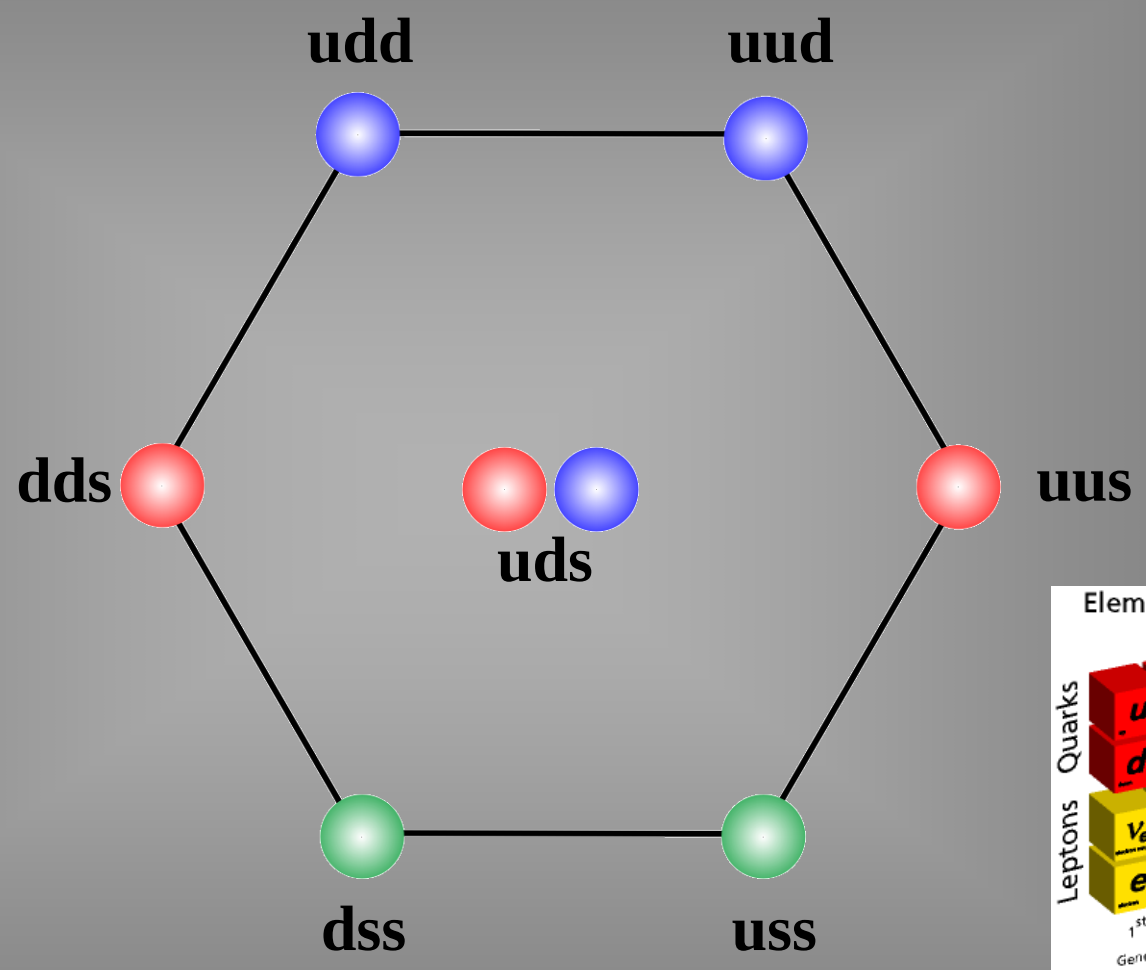
Baryon octet

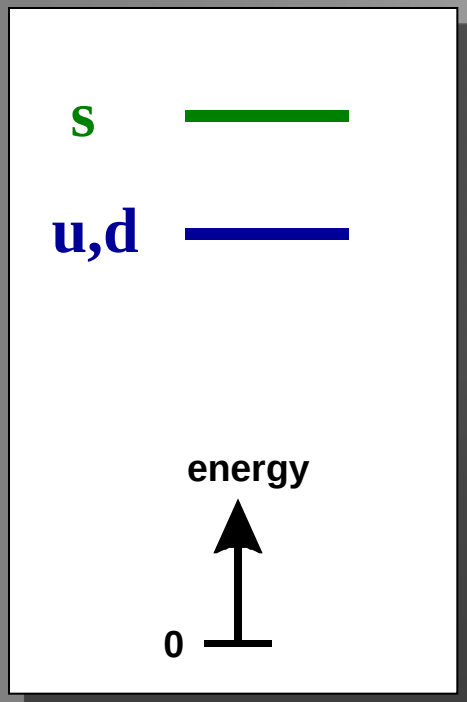


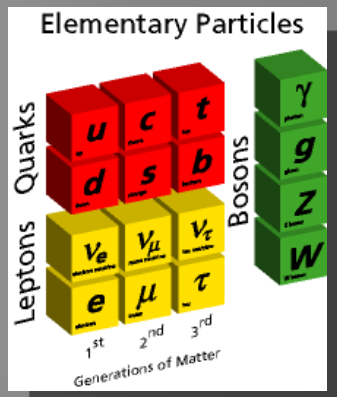


Ground States

Baryon octet







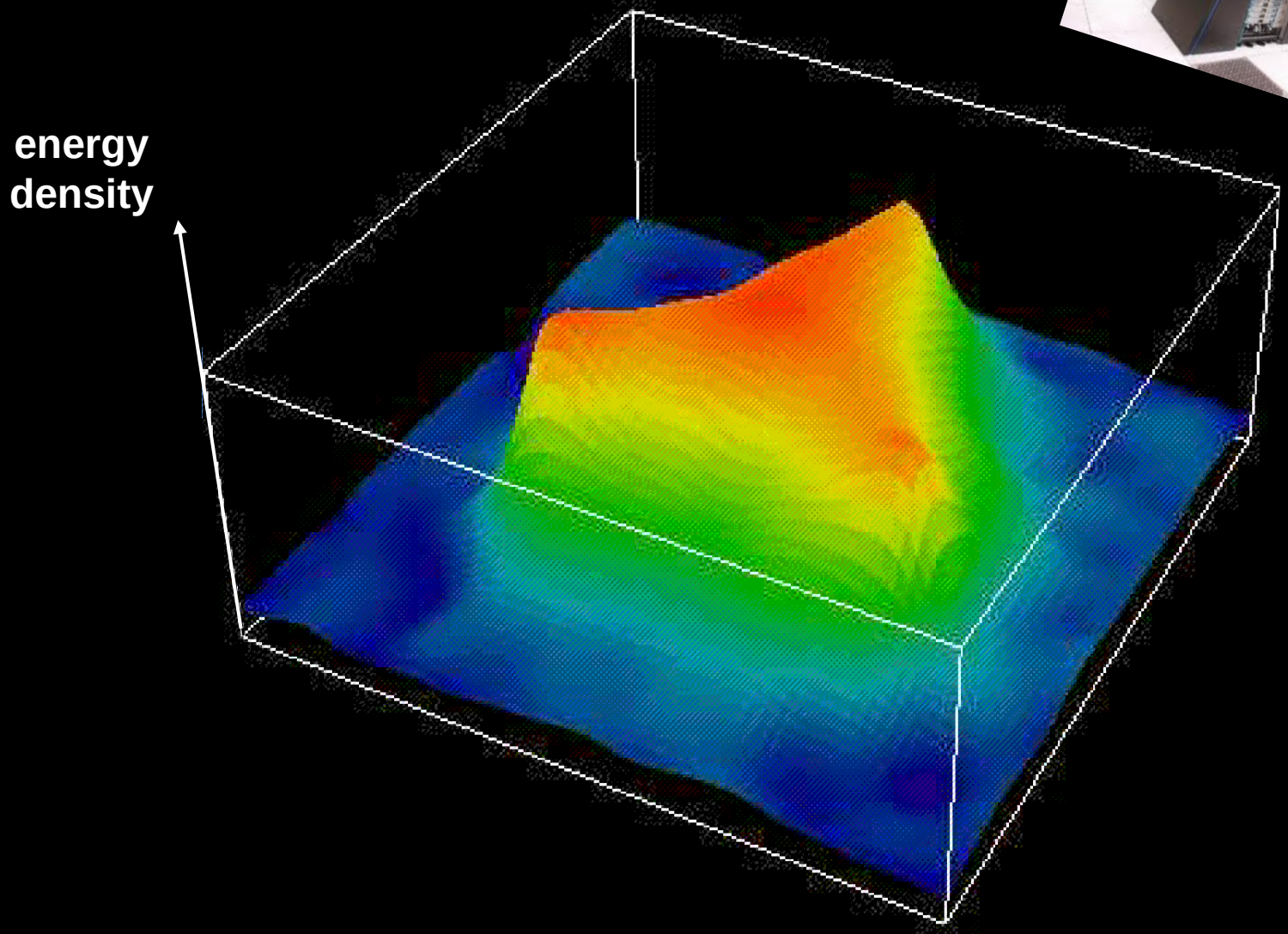
colour wave-functions

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

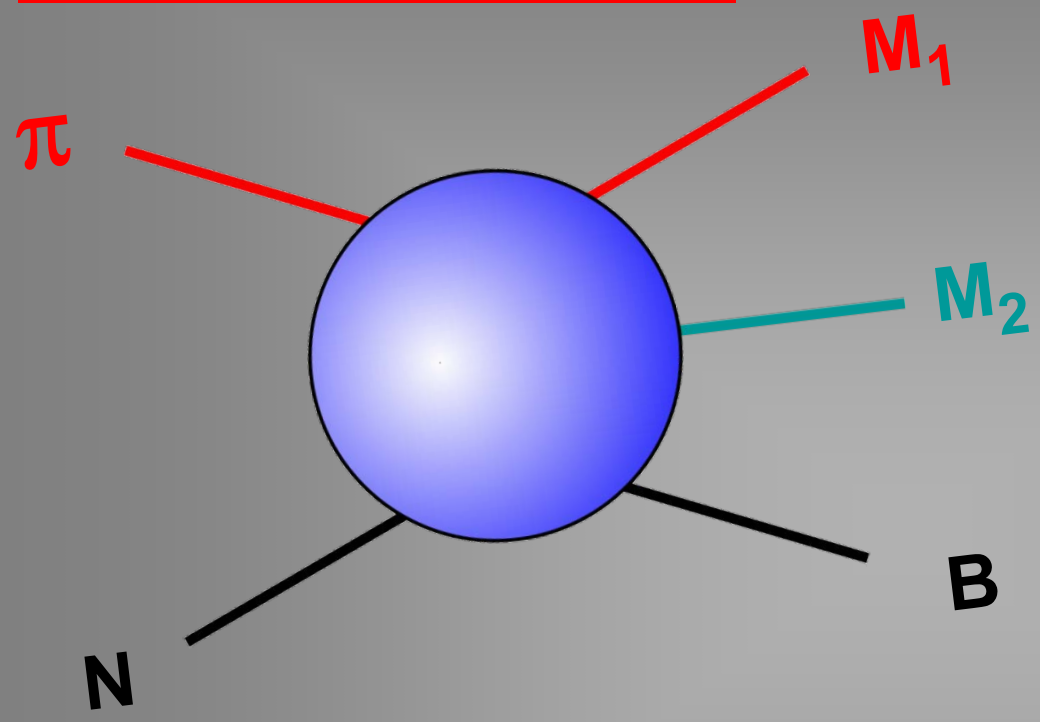
$N_c = 3$

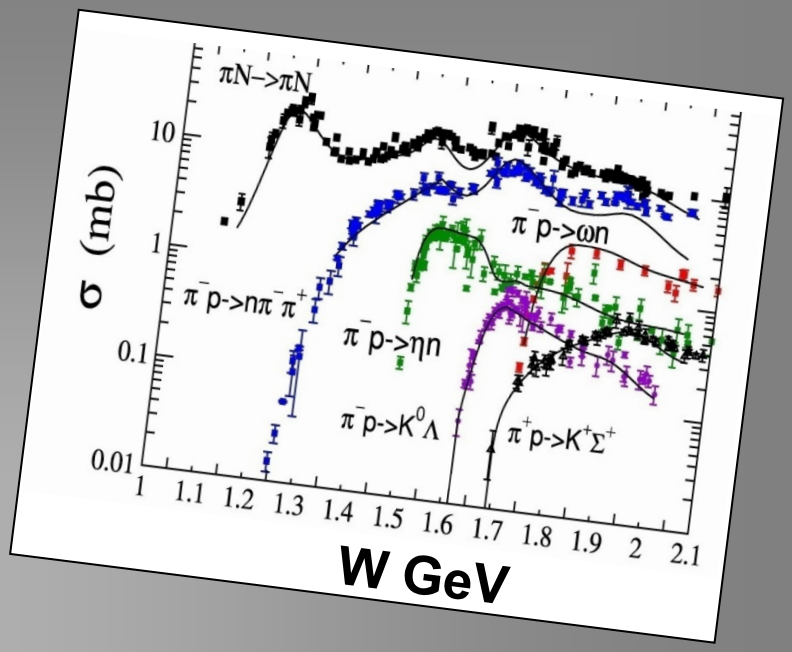
$$p = \frac{1}{\sqrt{6}} \left[uud + uud + uud - uud - uud - uud \right]$$

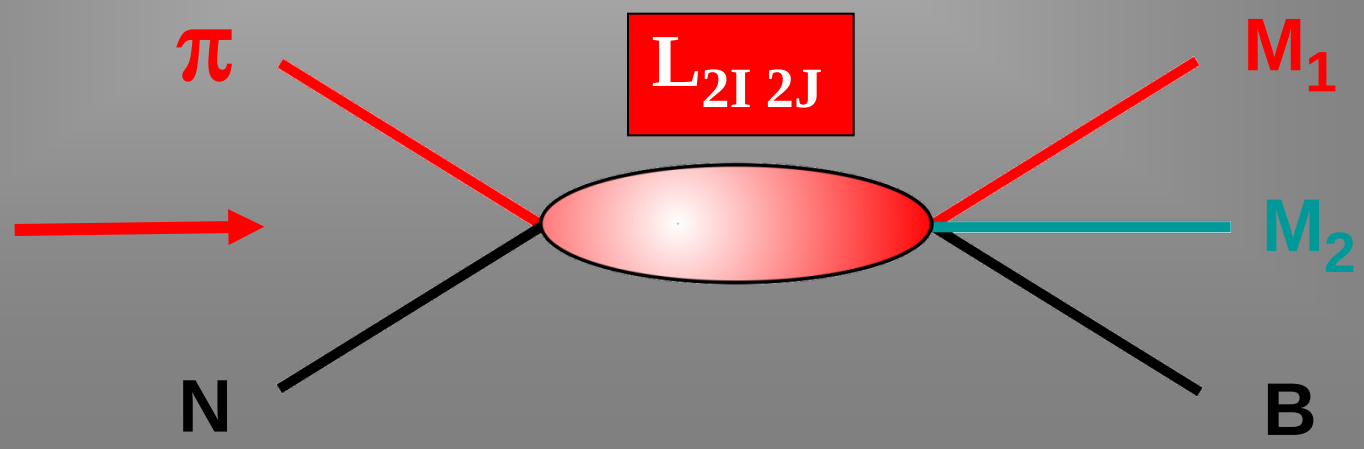
Colour Forces



πN scattering

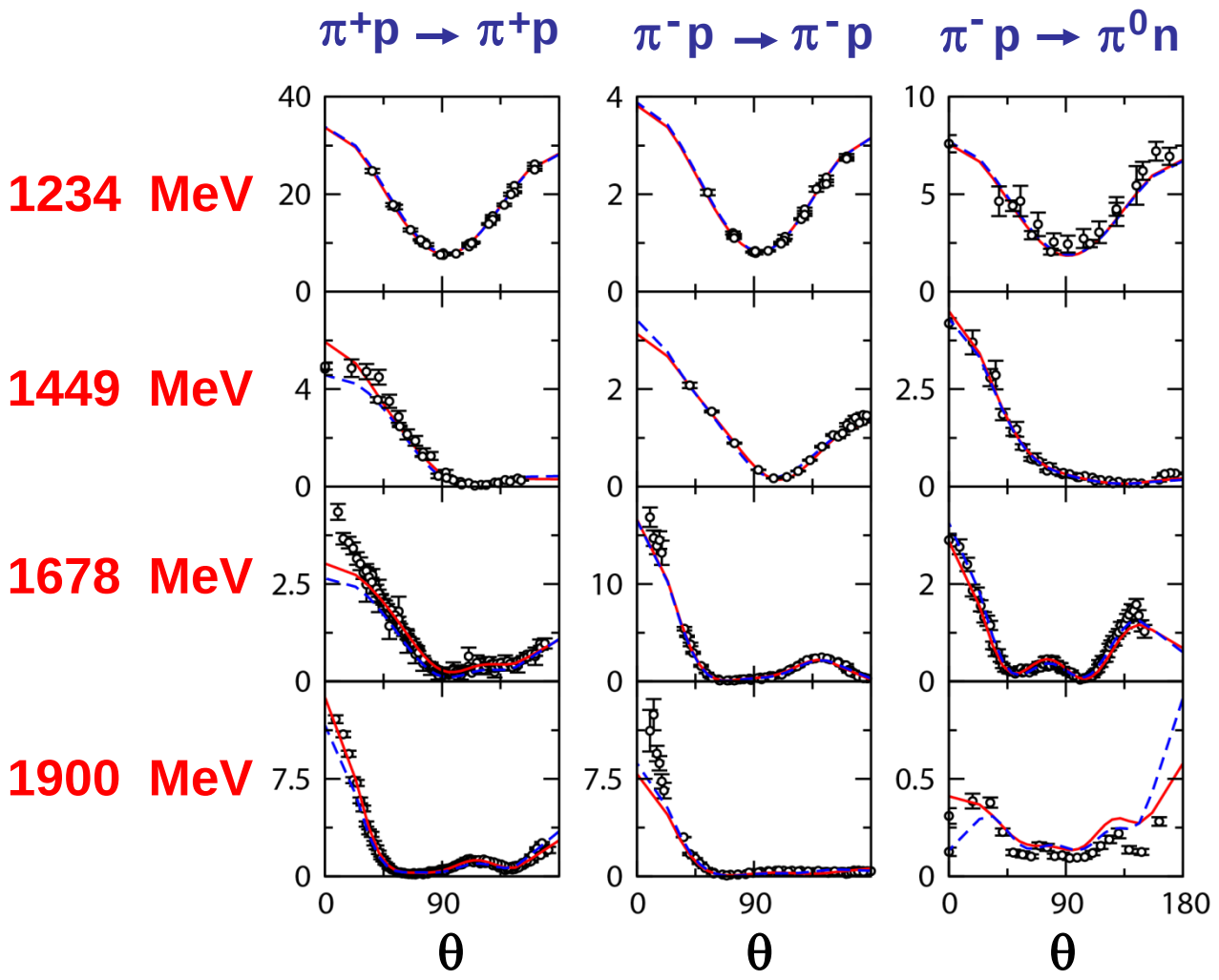






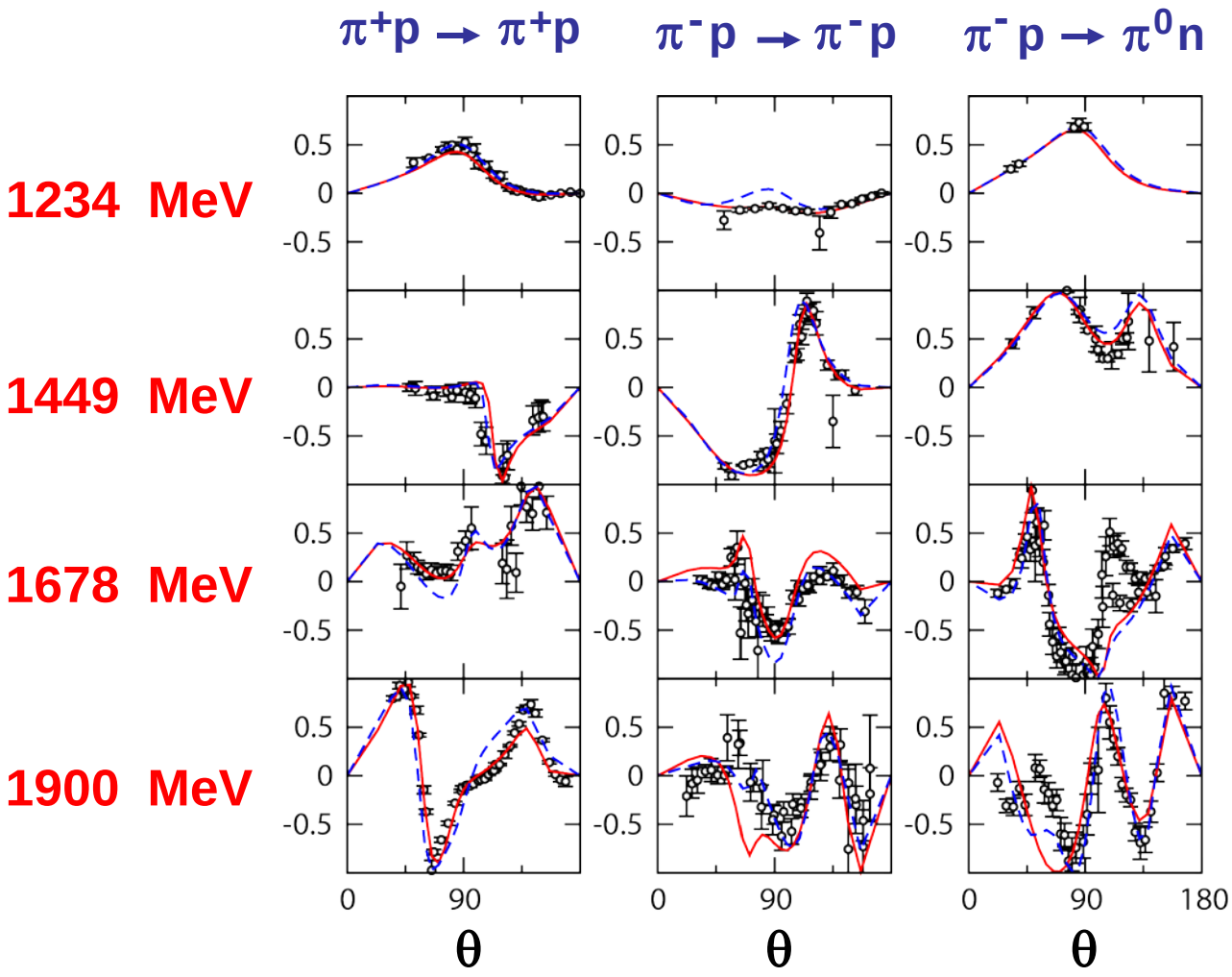
$\pi N \longrightarrow \pi N$ scattering

$d\sigma/d\Omega$

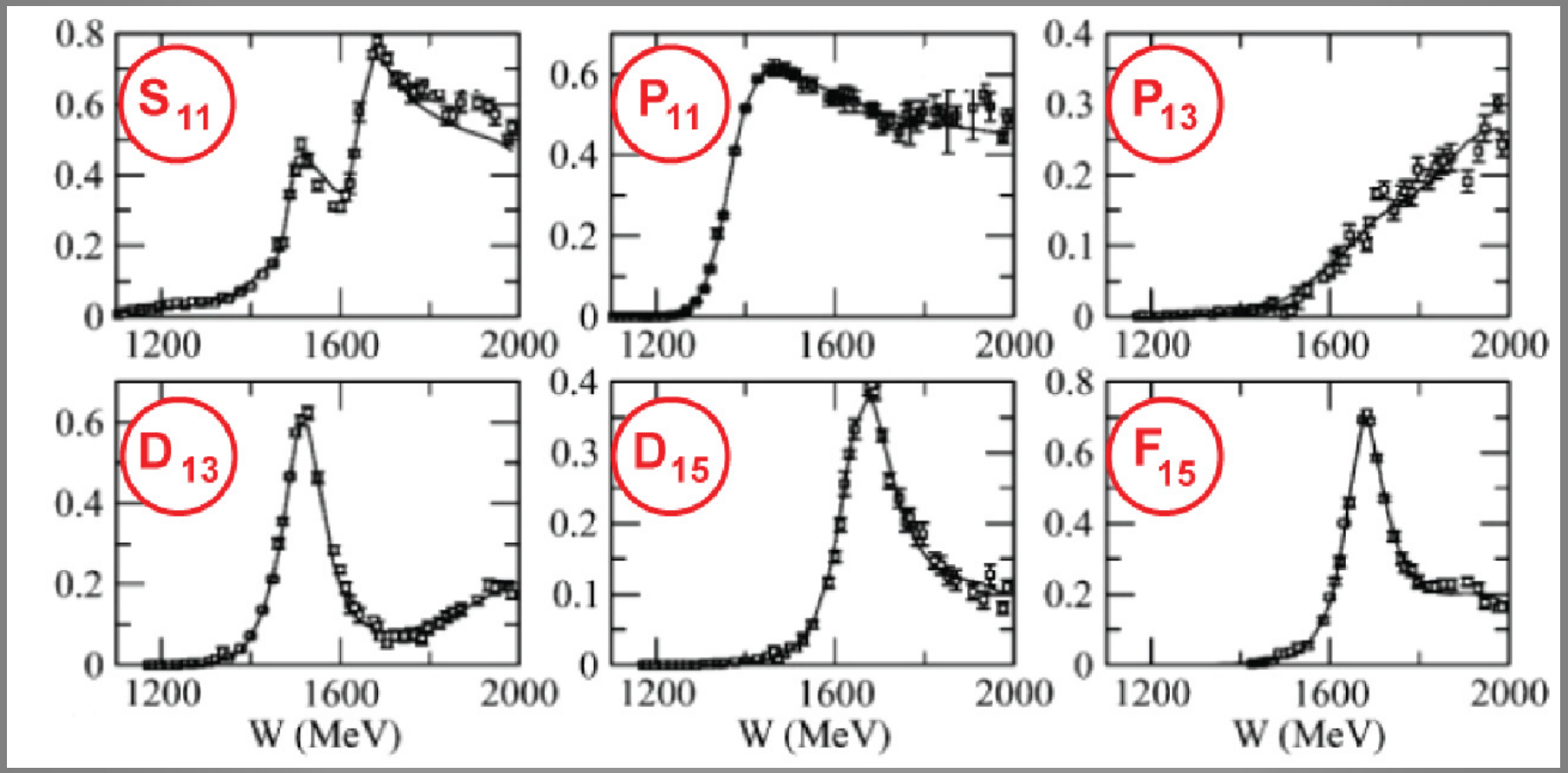


$\pi N \longrightarrow \pi N$ scattering

P



πN amplitudes



Isospin 1/2
Imaginary T

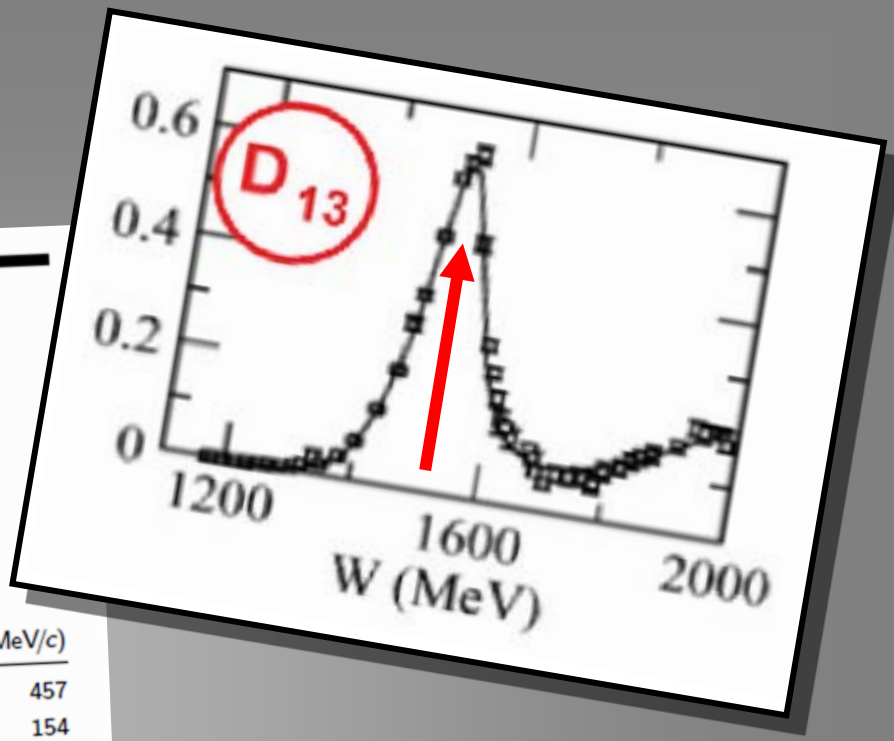
SAID: Workman *et al*

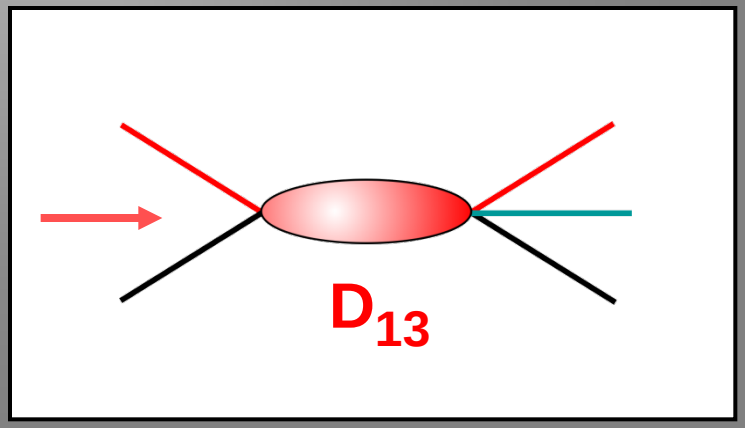
N*(1520) D_{13}

$N(1520)\ D_{13}$ $\quad I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$

Breit-Wigner mass = 1515 to 1525 (≈ 1520) MeV
Breit-Wigner full width = 100 to 125 (≈ 115) MeV
$p_{\text{beam}} = 0.74$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 23.5$ mb
Re(pole position) = 1505 to 1515 (≈ 1510) MeV
−2Im(pole position) = 105 to 120 (≈ 110) MeV

$N(1520)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	0.55 to 0.65	457
$N\eta$	$(2.3 \pm 0.4) \times 10^{-3}$	154
$N\pi\pi$	40–50 %	414
$\Delta\pi$	15–25 %	230
$N\rho$	15–25 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<8 %	–
$p\gamma$	0.46–0.56 %	470
$p\gamma$, helicity=1/2	0.001–0.034 %	470
$p\gamma$, helicity=3/2	0.44–0.53 %	470
$n\gamma$	0.30–0.53 %	470
$n\gamma$, helicity=1/2	0.04–0.10 %	470
$n\gamma$, helicity=3/2	0.25–0.45 %	470



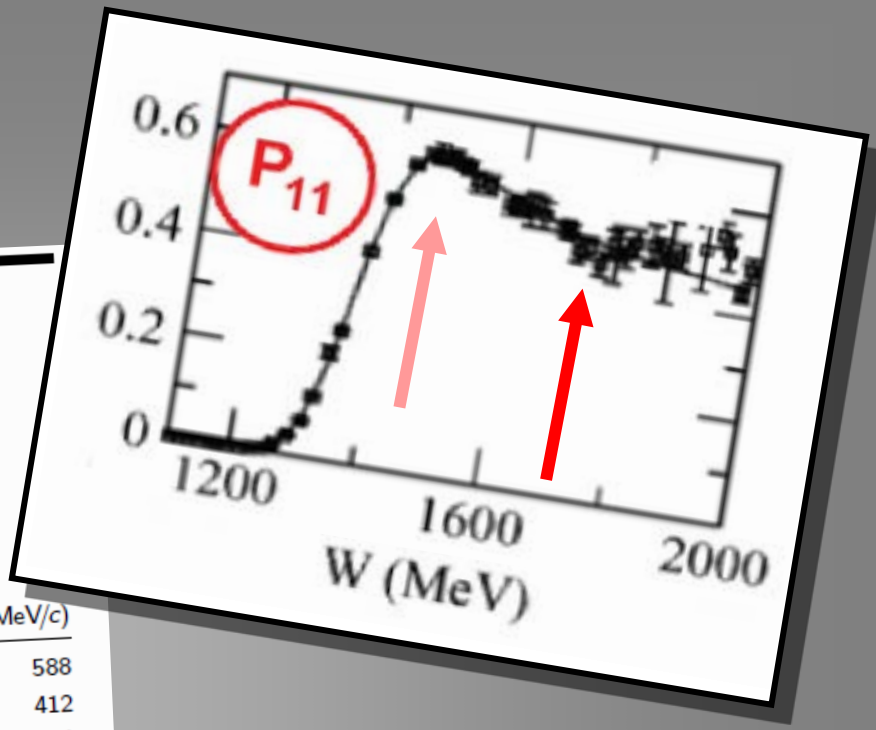


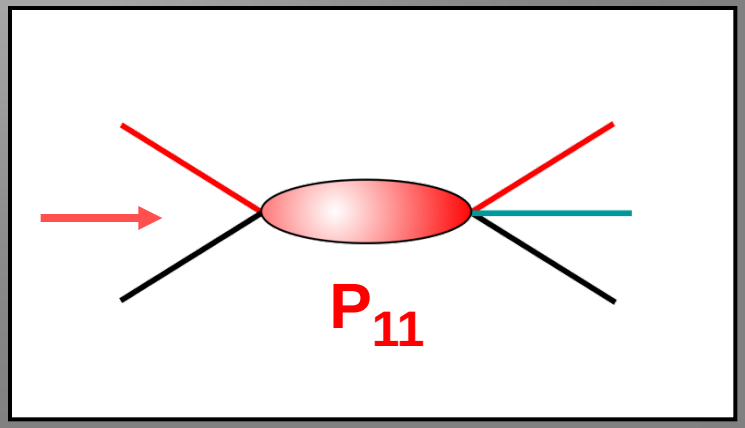
N*(1710) P_{11}

$N(1710)$ P_{11} $\quad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

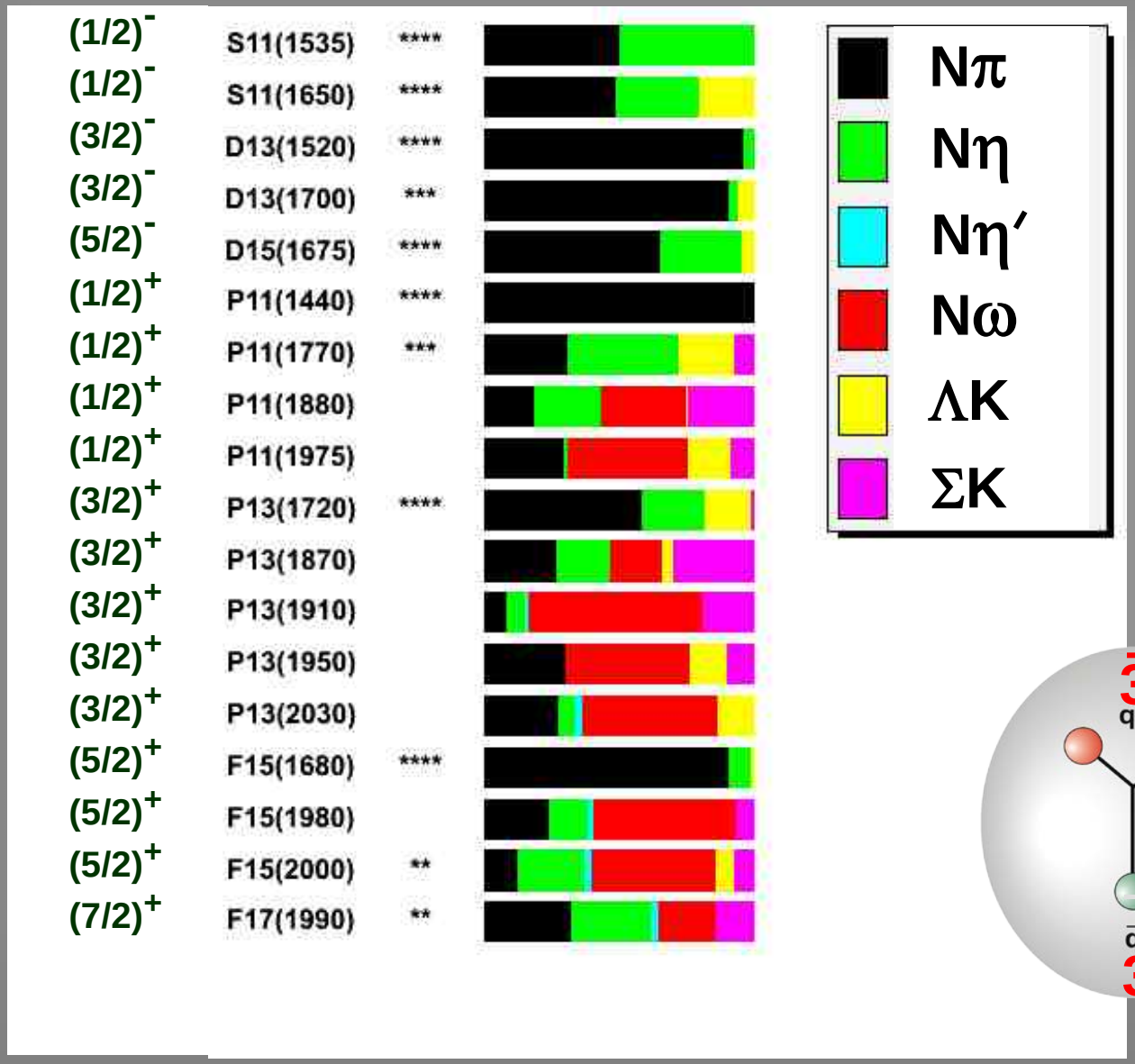
Breit-Wigner mass = 1680 to 1740 (≈ 1710) MeV
Breit-Wigner full width = 50 to 250 (≈ 100) MeV
$p_{\text{beam}} = 1.07$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 14.2$ mb
Re(pole position) = 1670 to 1770 (≈ 1720) MeV
−2Im(pole position) = 80 to 380 (≈ 230) MeV

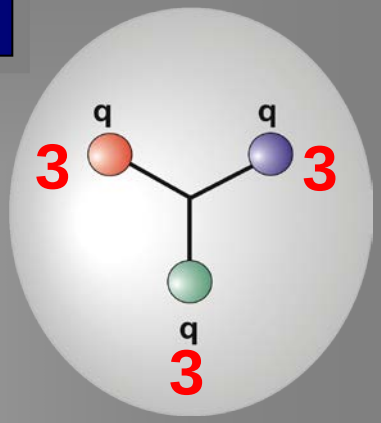
$N(1710)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	588
$N\eta$	(6.2±1.0) %	412
$N\omega$	(13.0±2.0) %	†
ΛK	5–25 %	269
$N\pi\pi$	40–90 %	557
$\Delta\pi$	15–40 %	394
$N\rho$	5–25 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	10–40 %	–
$p\gamma$	0.002–0.05%	598
$p\gamma$, helicity=1/2	0.002–0.05%	598
$n\gamma$	0.0–0.02%	597
$n\gamma$, helicity=1/2	0.0–0.02%	597

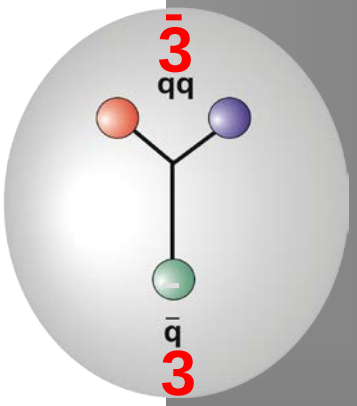




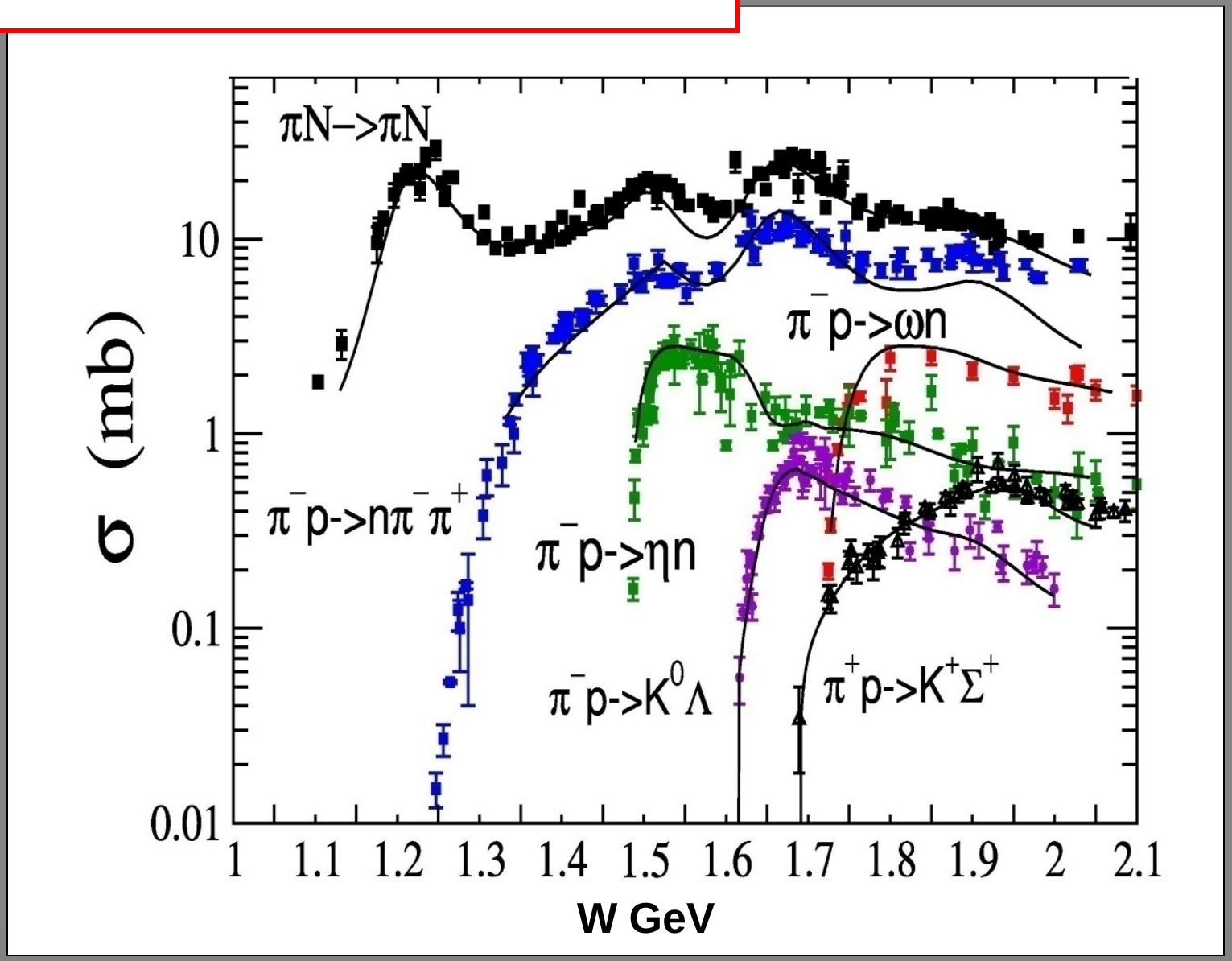
search all channels: not just πN





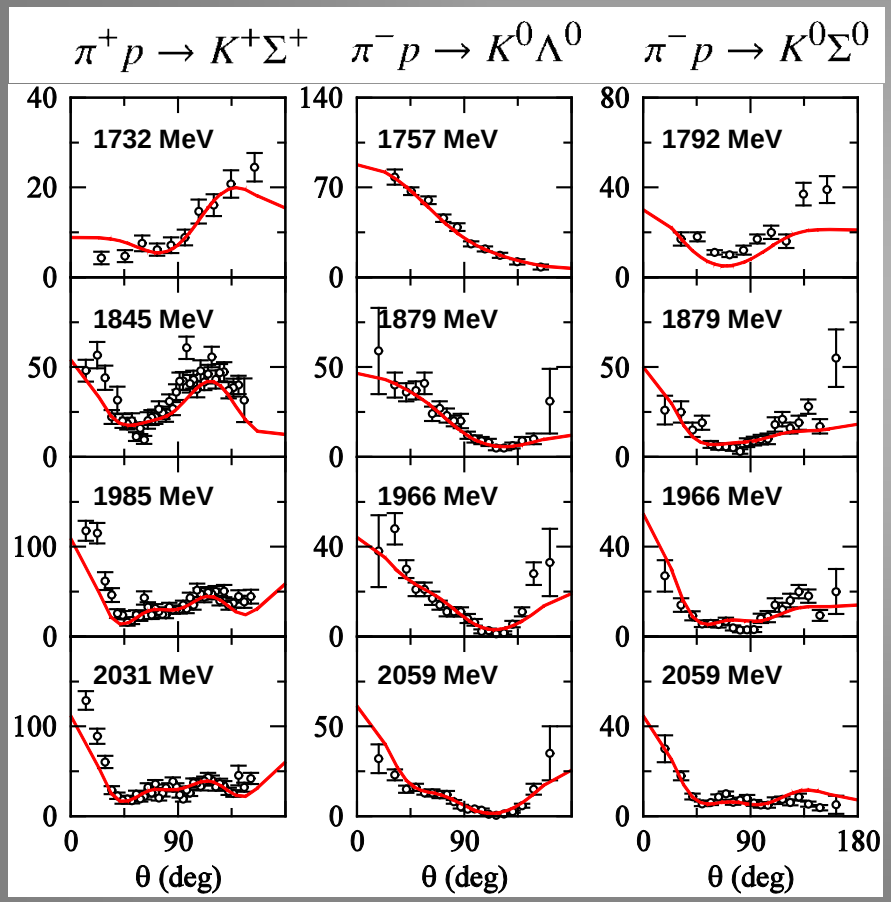


πN exclusive channels

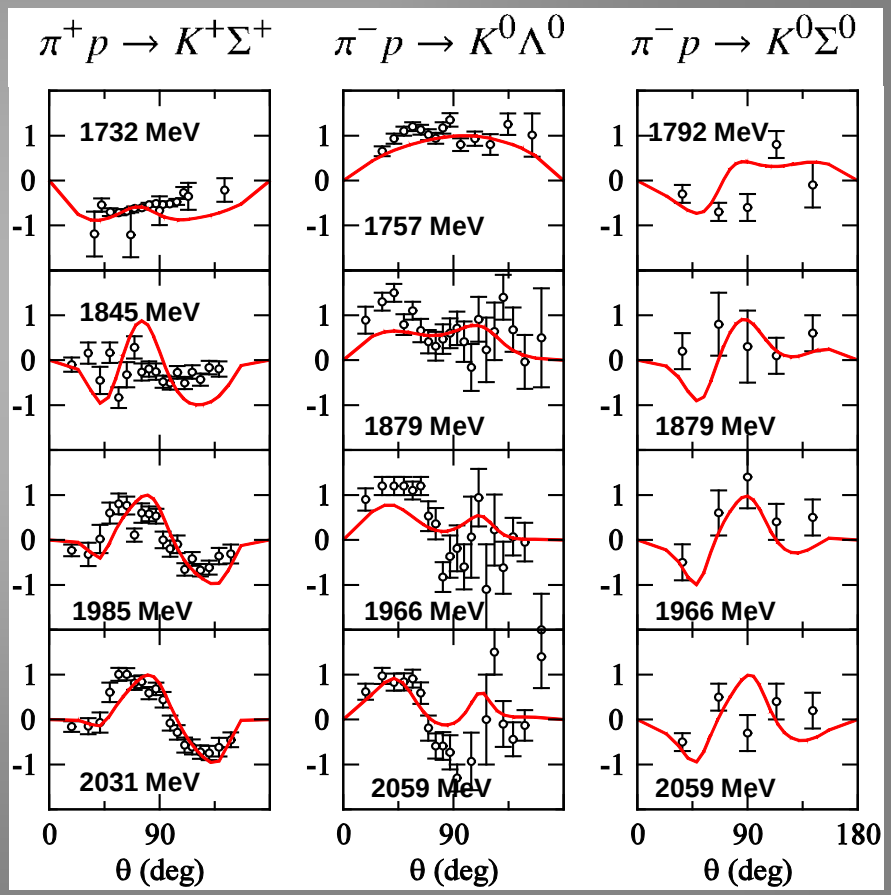


$\pi N \longrightarrow K\Lambda$

$d\sigma/d\Omega$



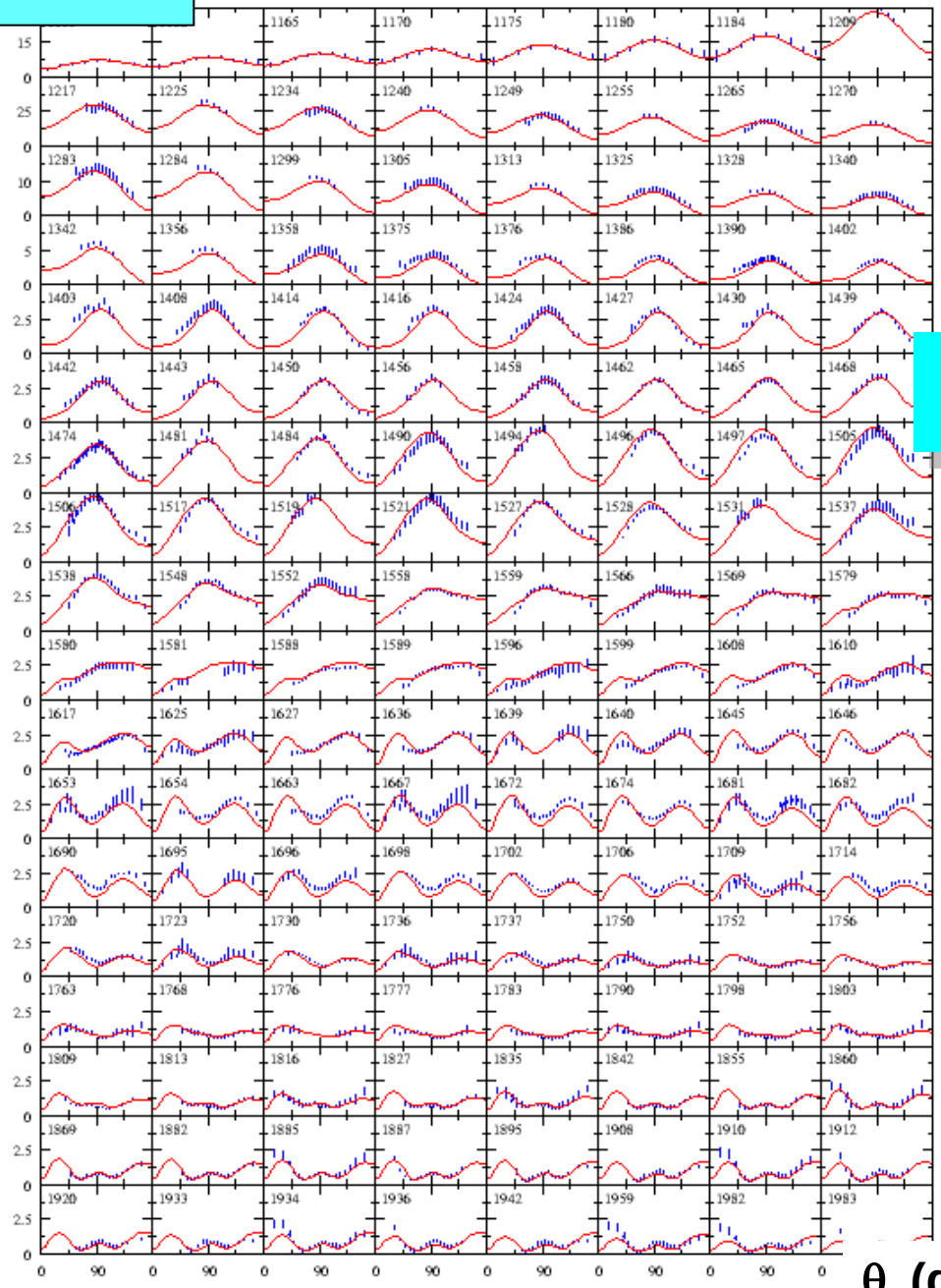
P



EBAC

$d\sigma/d\Omega$

Kamano
Nakamura
Lee &
Sato, 2012

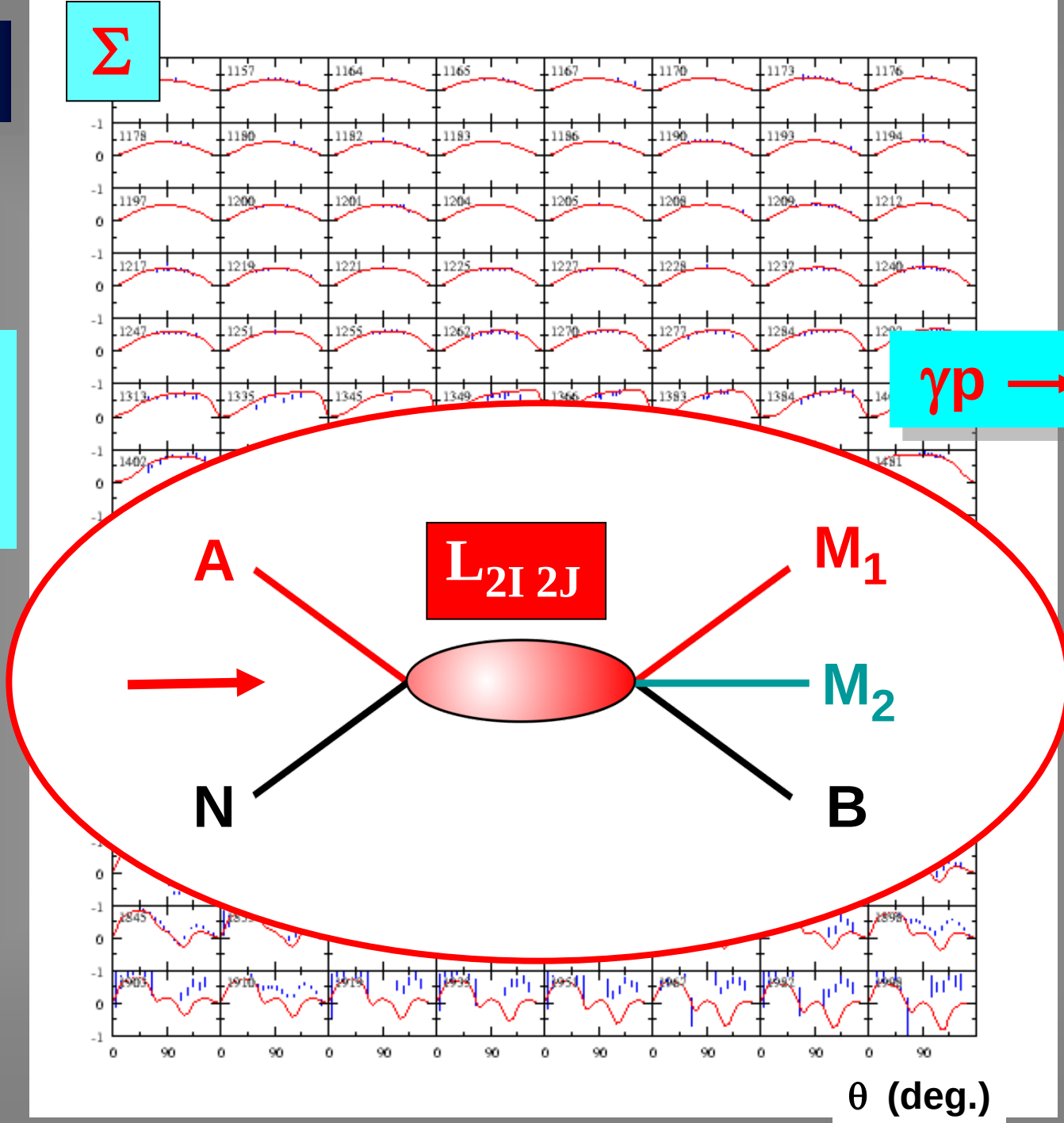


$\gamma p \longrightarrow \pi^0 p$

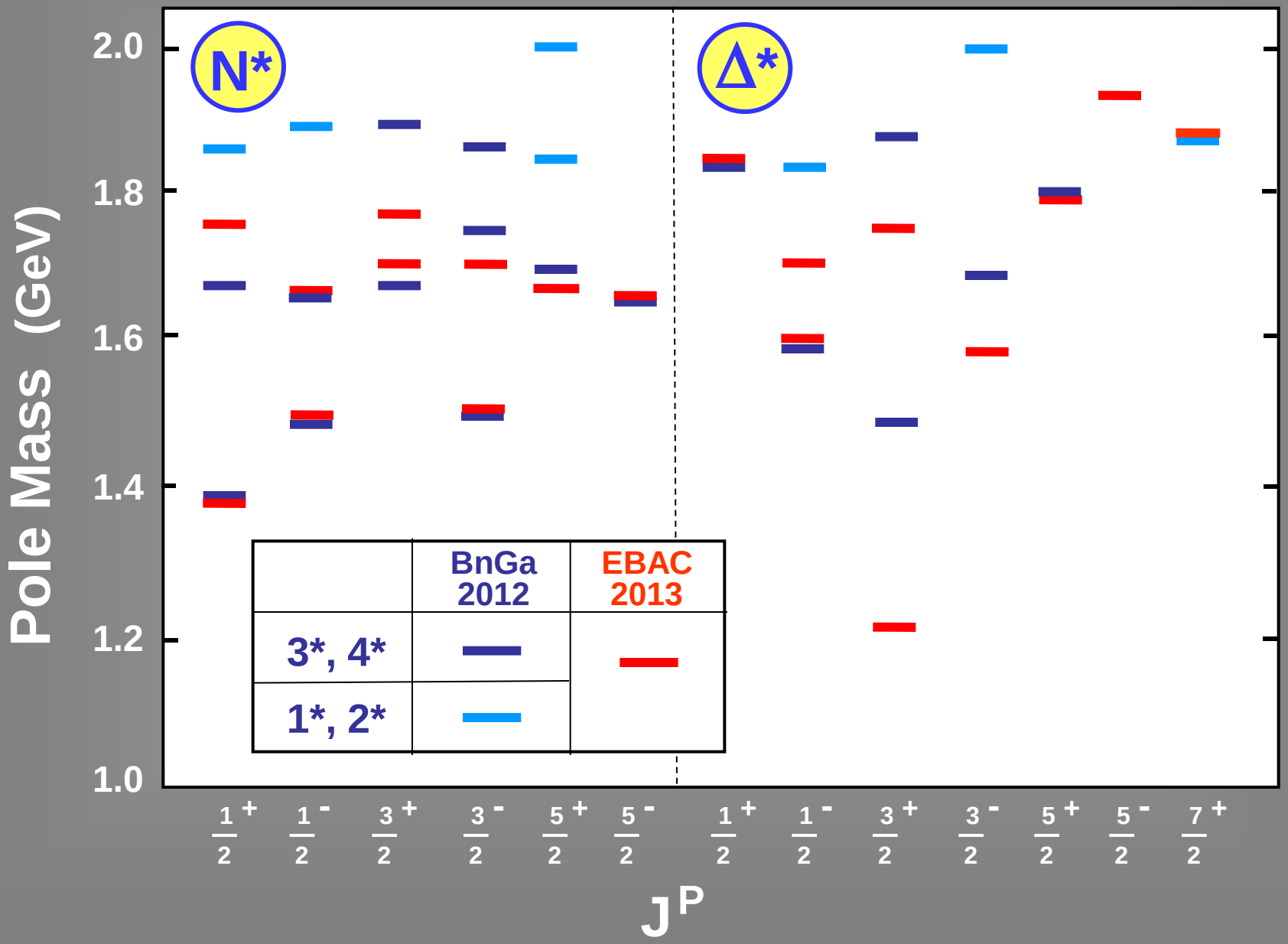
θ (deg.)

EBAC

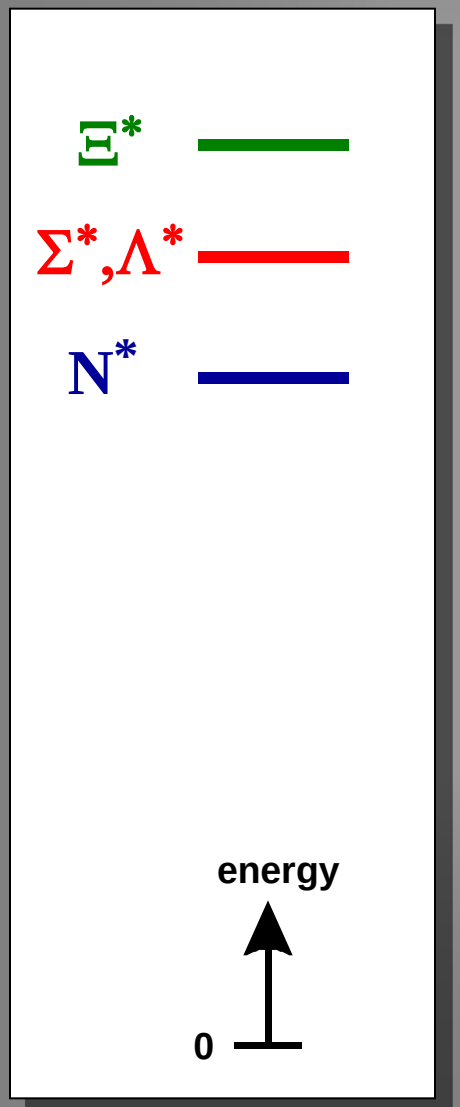
Kamano
Nakamura
Lee &
Sato, 2012

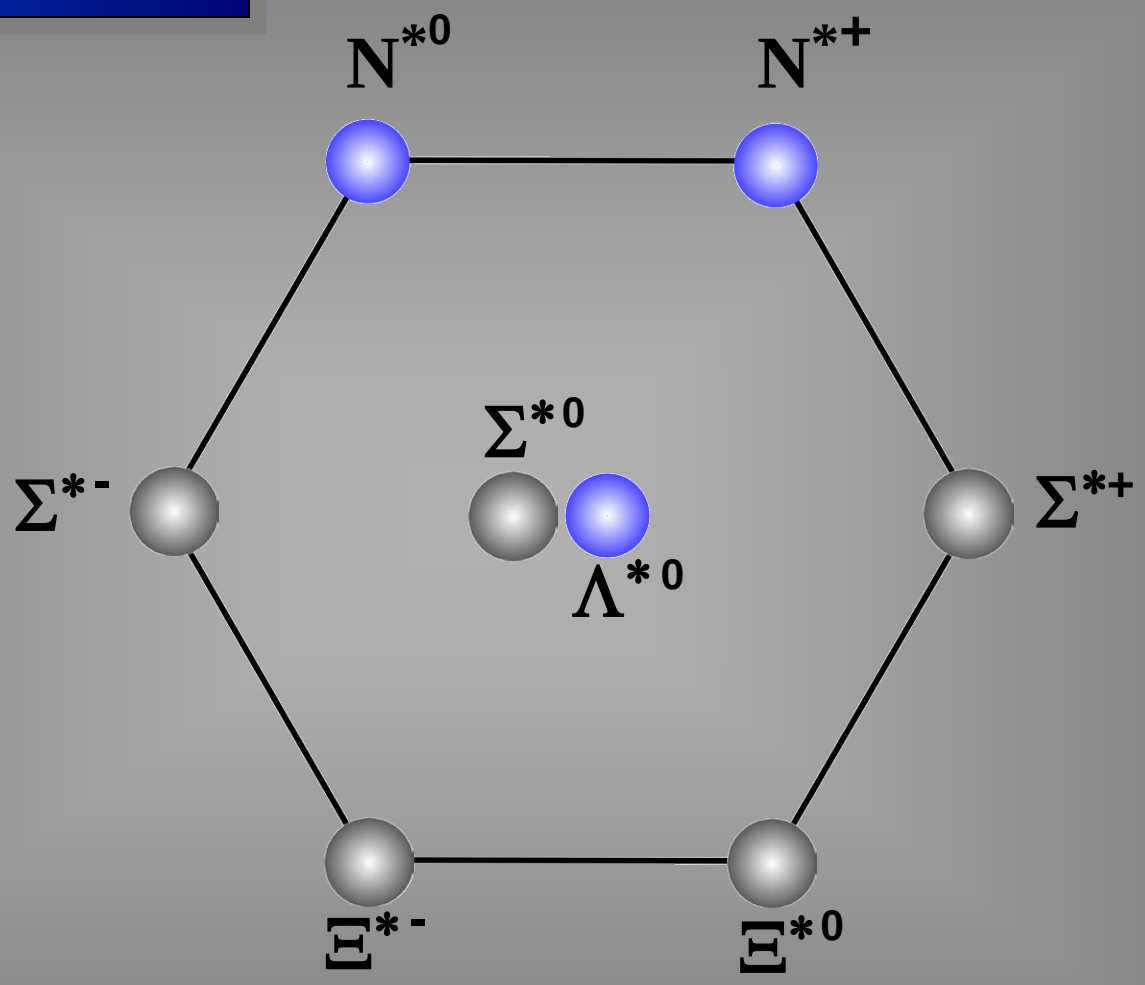


Baryon spectrum from EBAC & Bonn-Ga



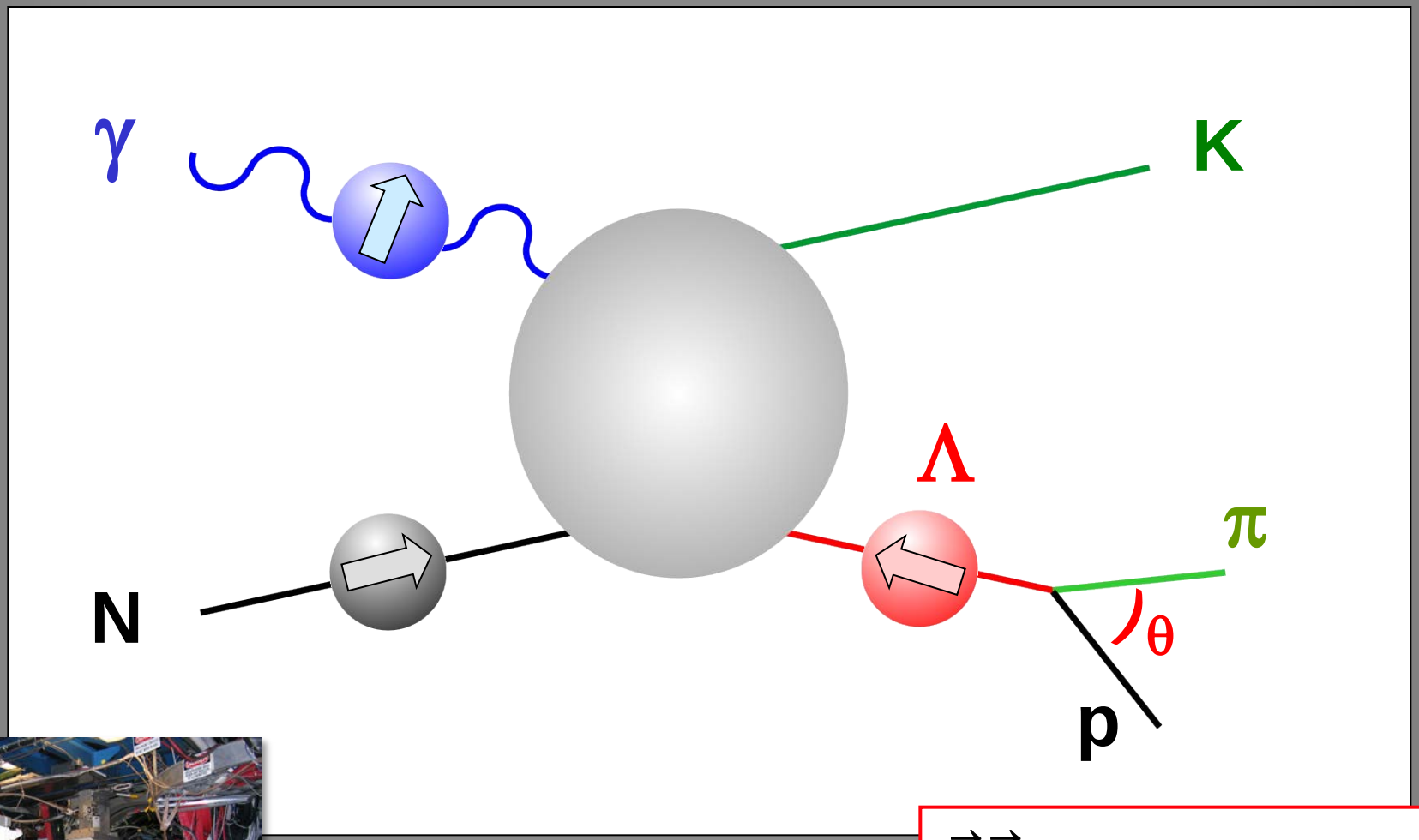
Baryon octet

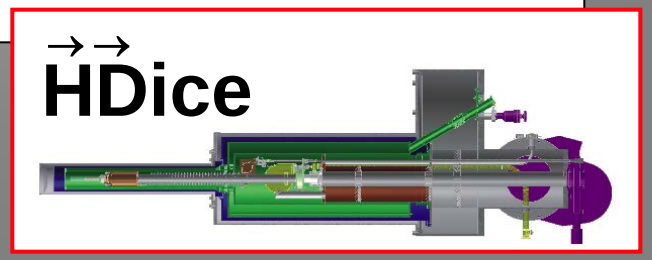




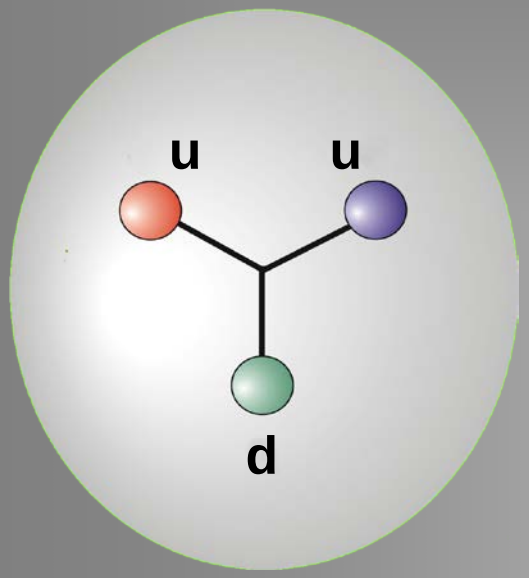
Excited States

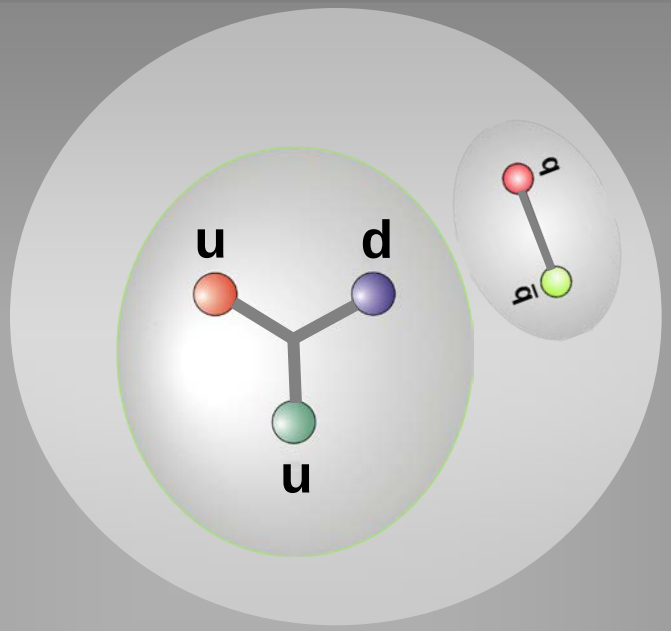
Complete experimental measurements

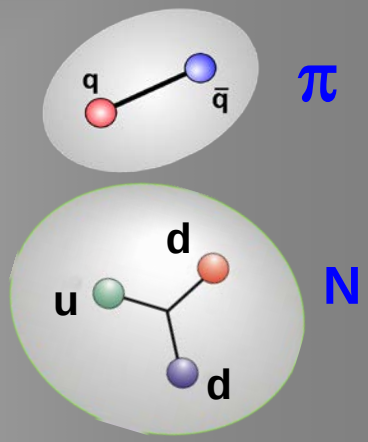




N*(1440) color wave-function



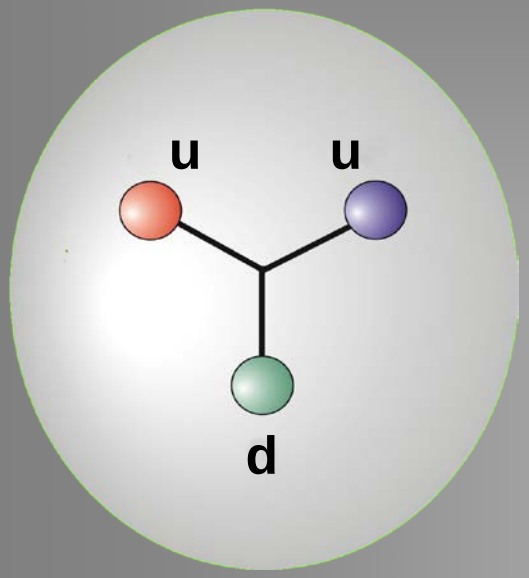


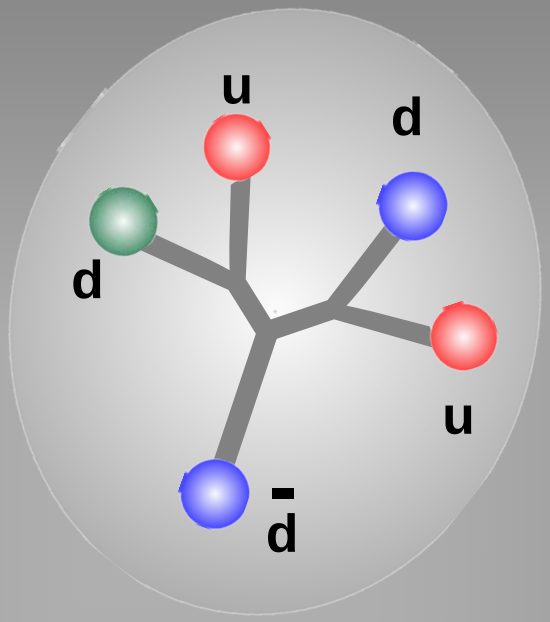


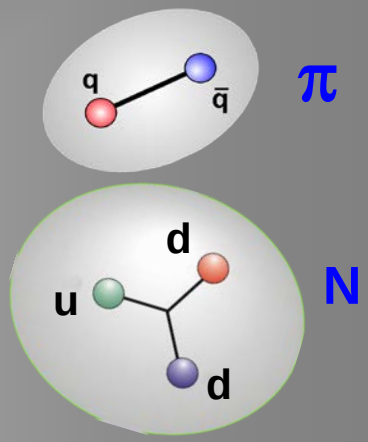
$N_c = 3$

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

N*(1440) color wave-function







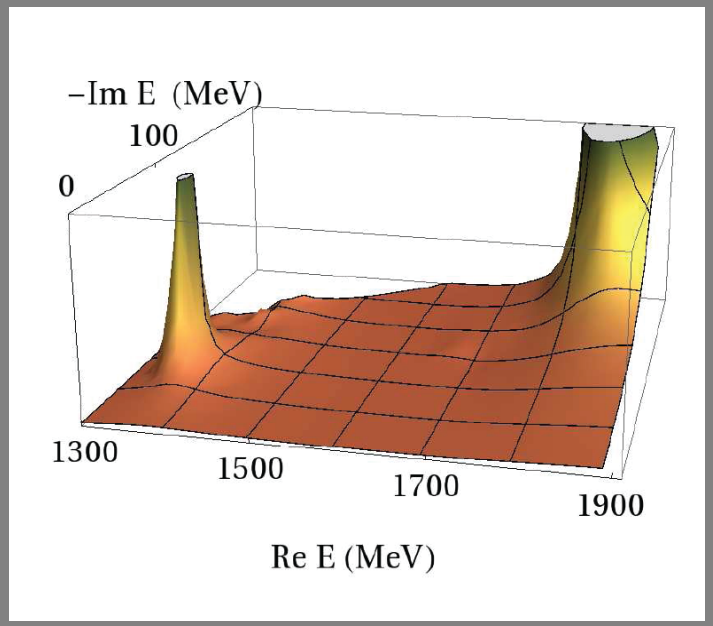
$N_c = 3$

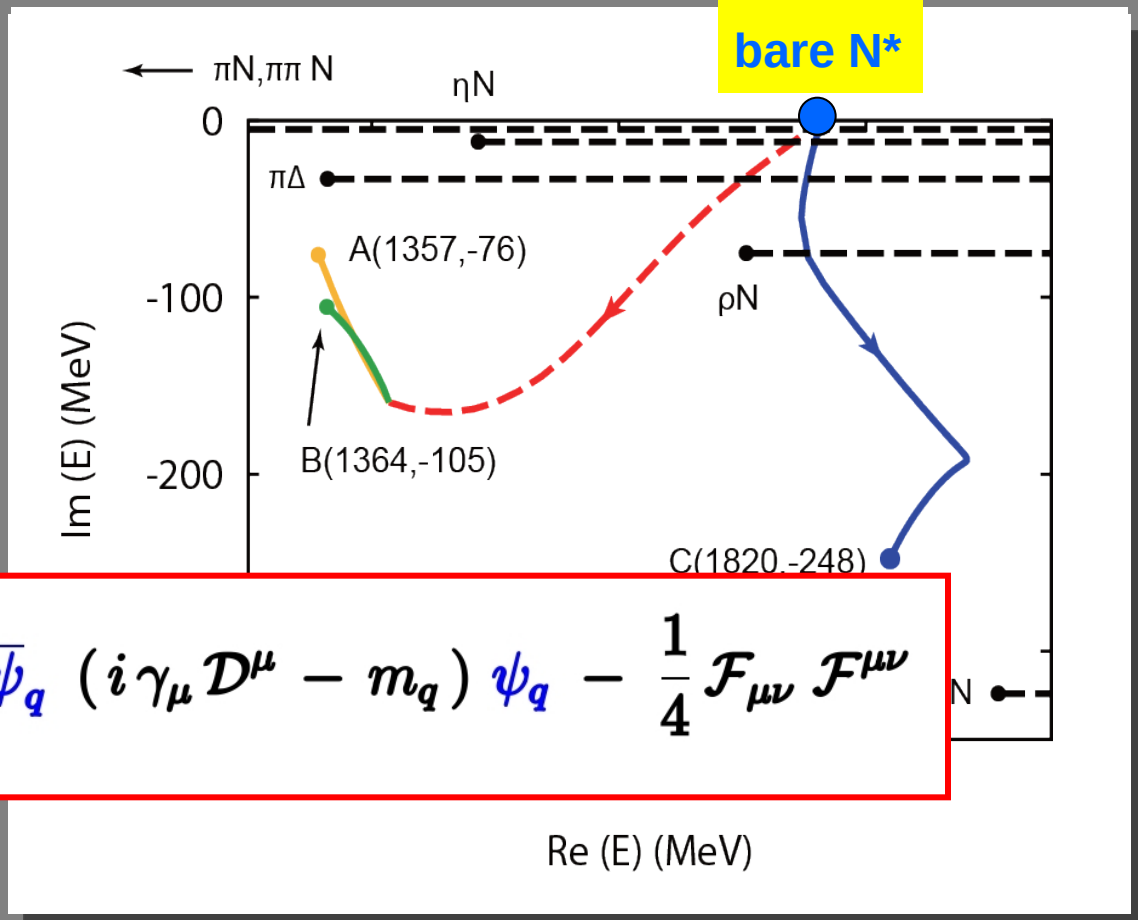
$$N^{*+} = \frac{1}{\sqrt{6}}\left[\, uud + uud + uud - uud - uud - uud \,\right]$$

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

EBAC

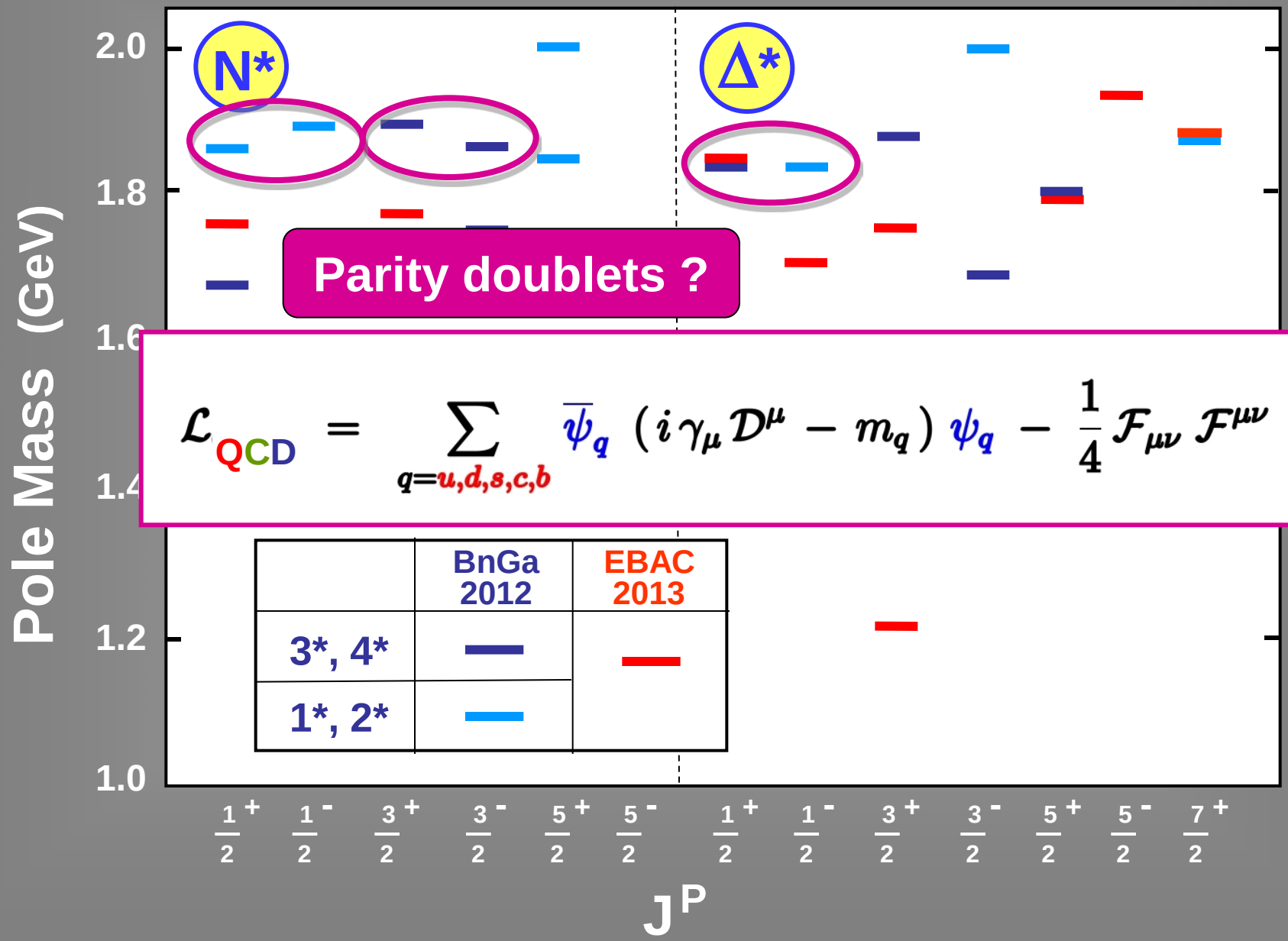
Suzuki *et al.*



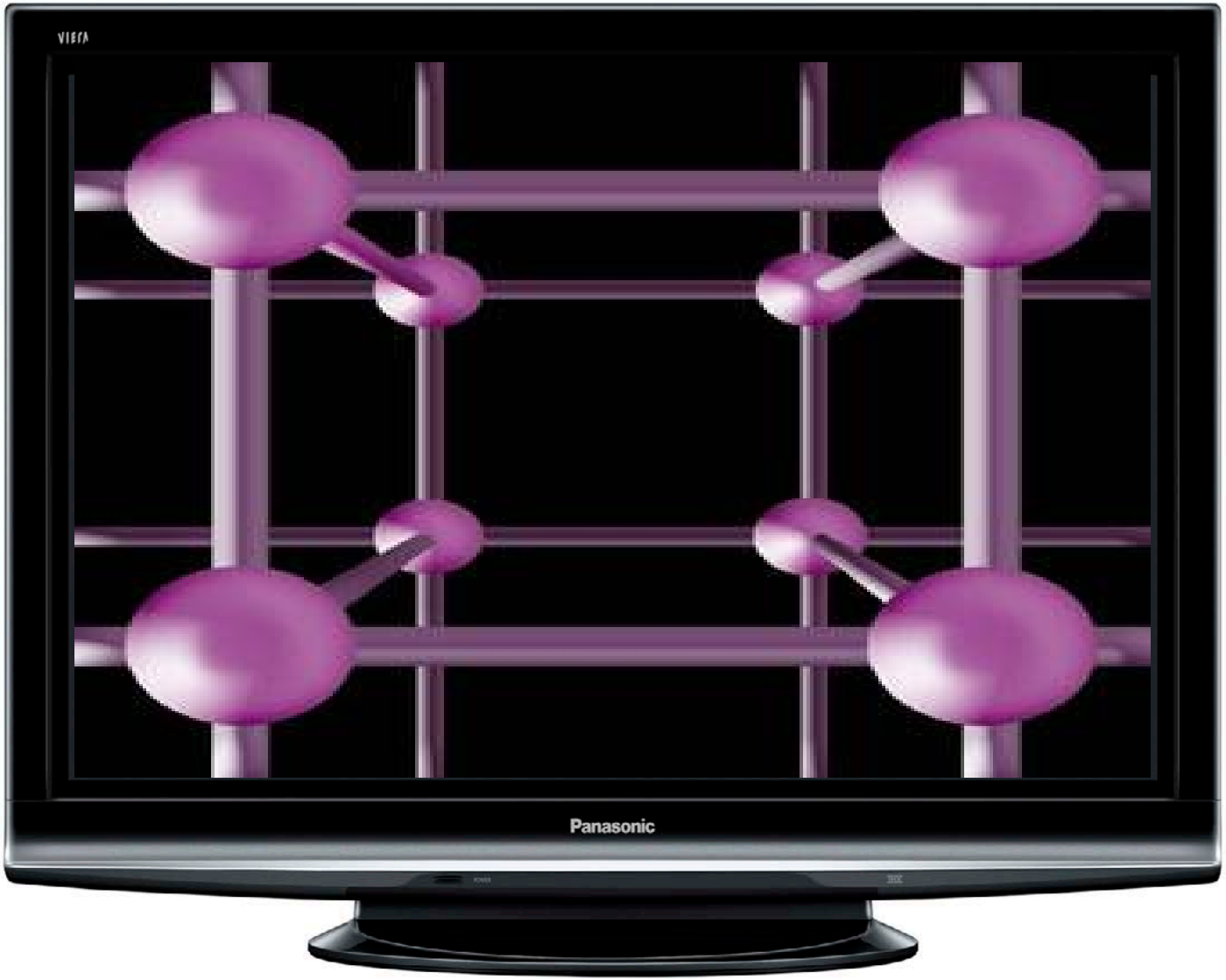


$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} \overline{\psi}_q \left(i \gamma_\mu \mathcal{D}^\mu - m_q \right) \psi_q - \frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}$$

Baryon spectrum from EBAC & Bonn-Ga

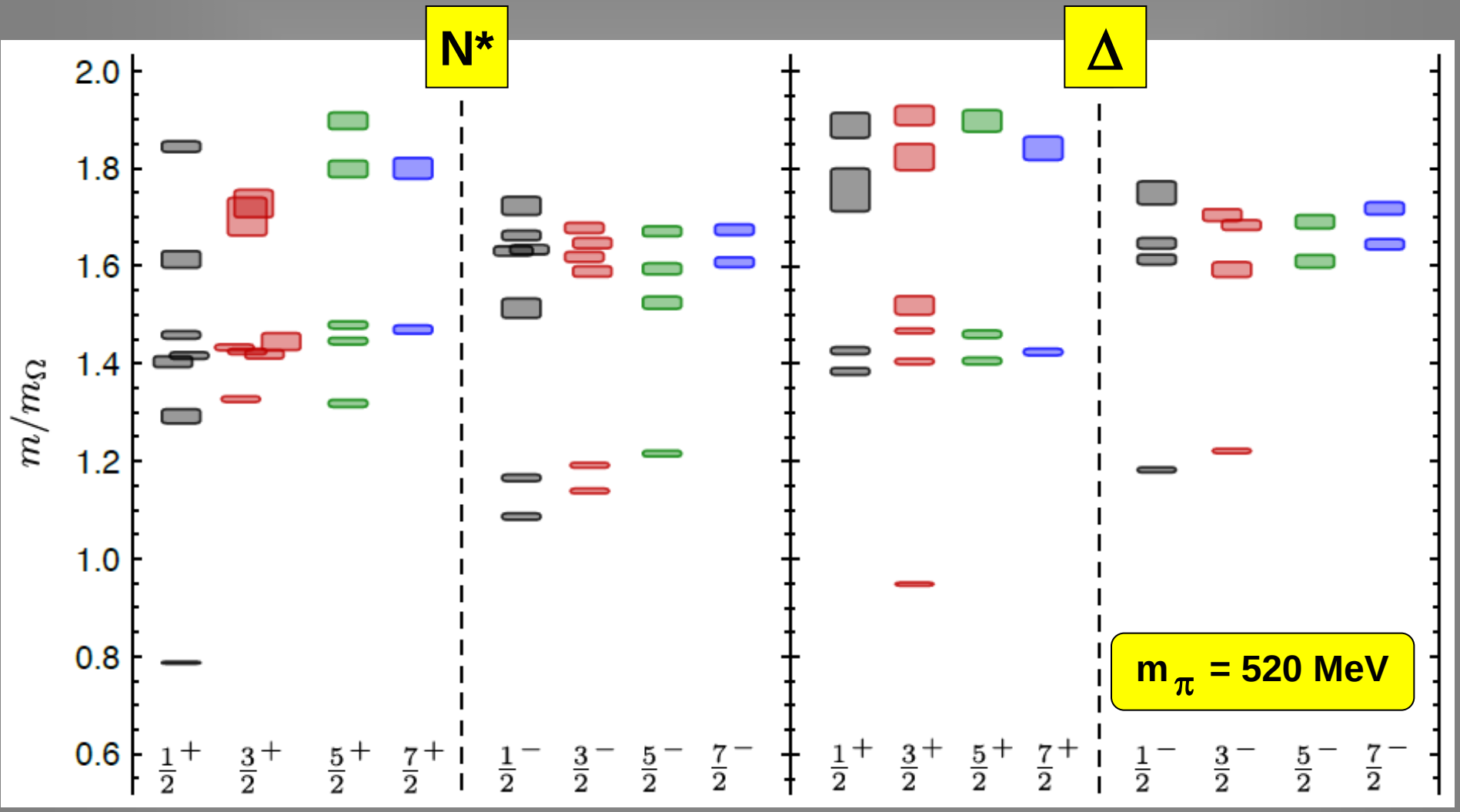


$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} \bar{\psi}_q \left(i \gamma_\mu \mathcal{D}^\mu - m_q \right) \psi_q - \frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}$$


VIERA
Panasonic

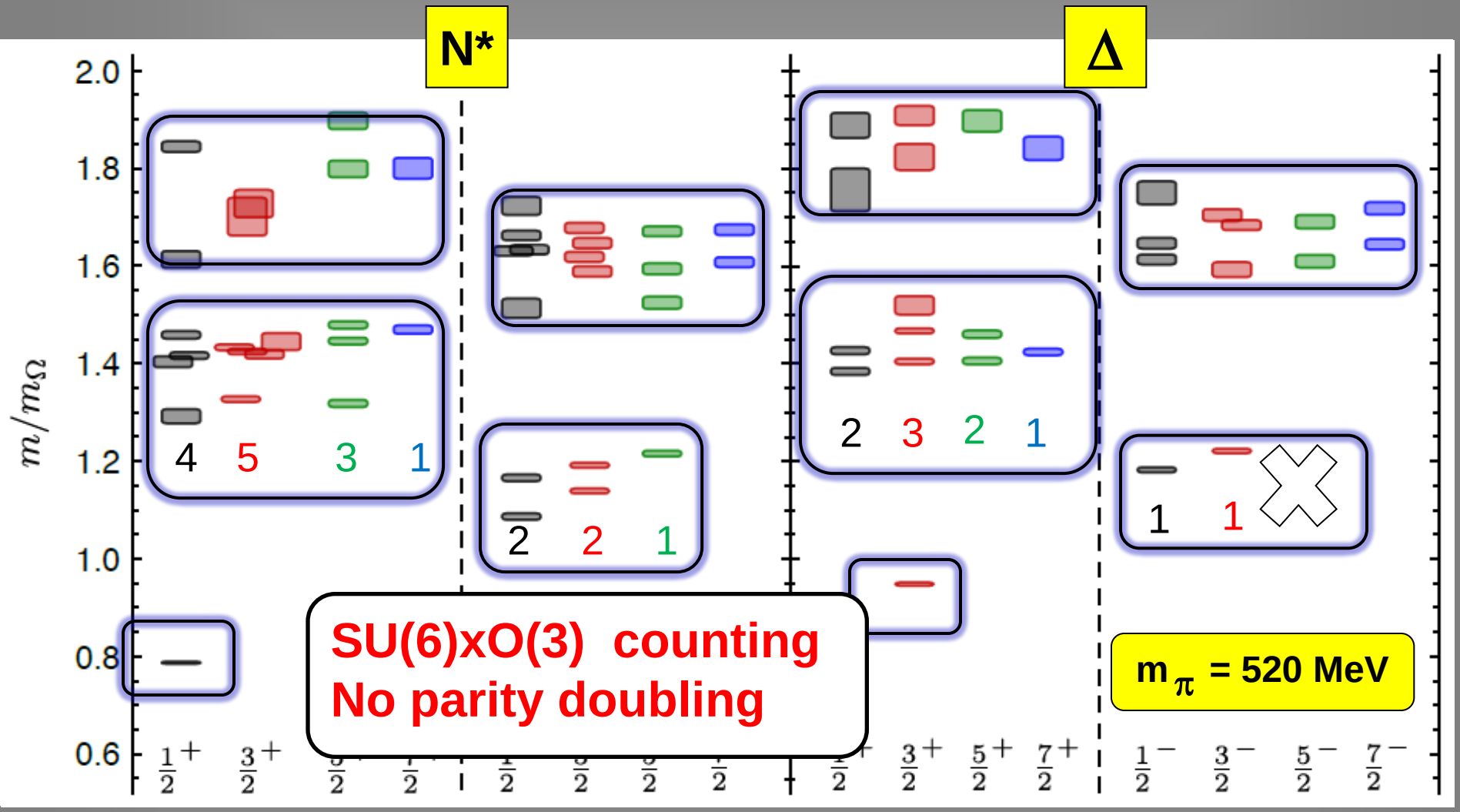
VIERA
Panasonic

Spin identified N* and Δ states



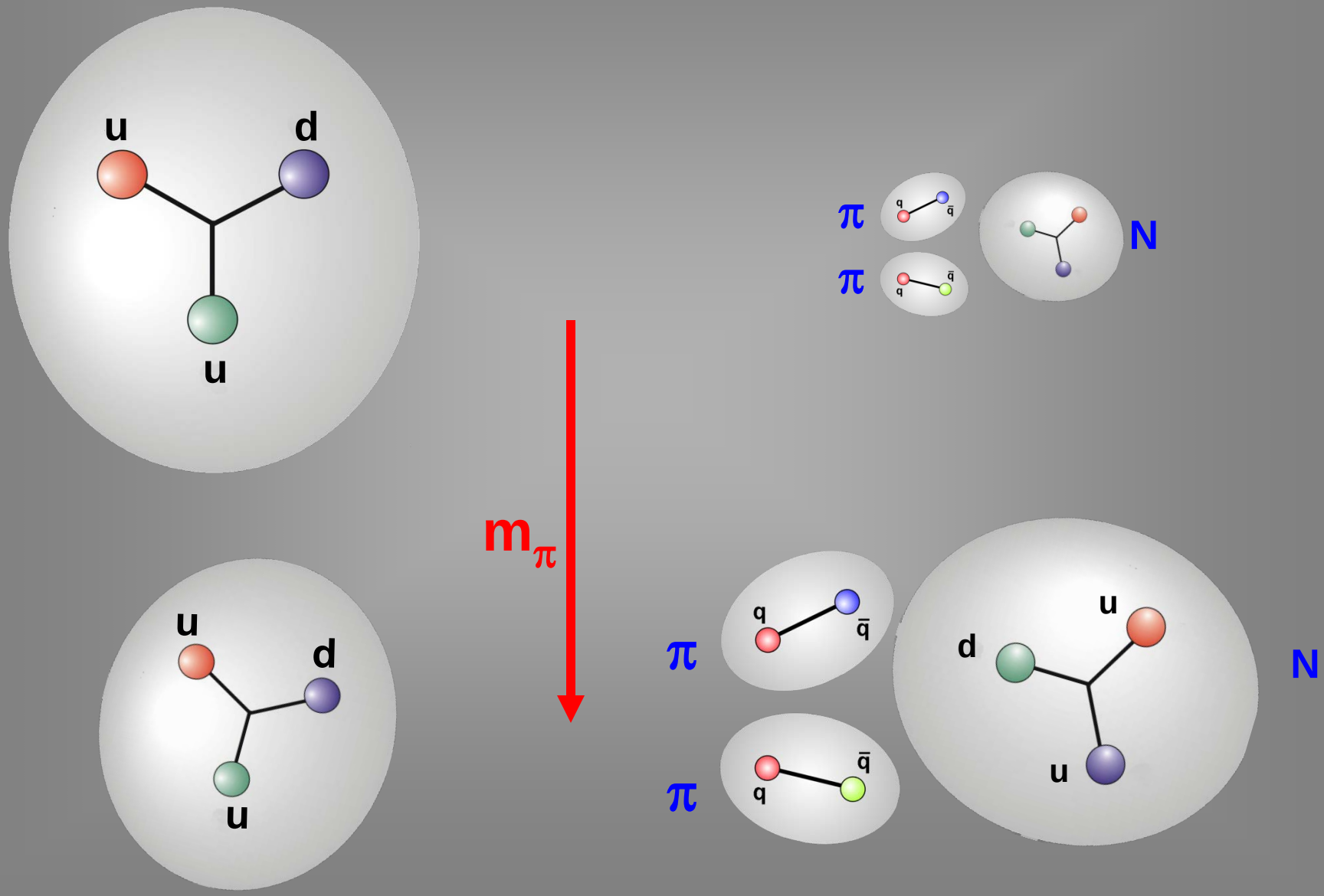
Edwards, Dudek, Wallace & Richards

Spin identified N* and Δ states

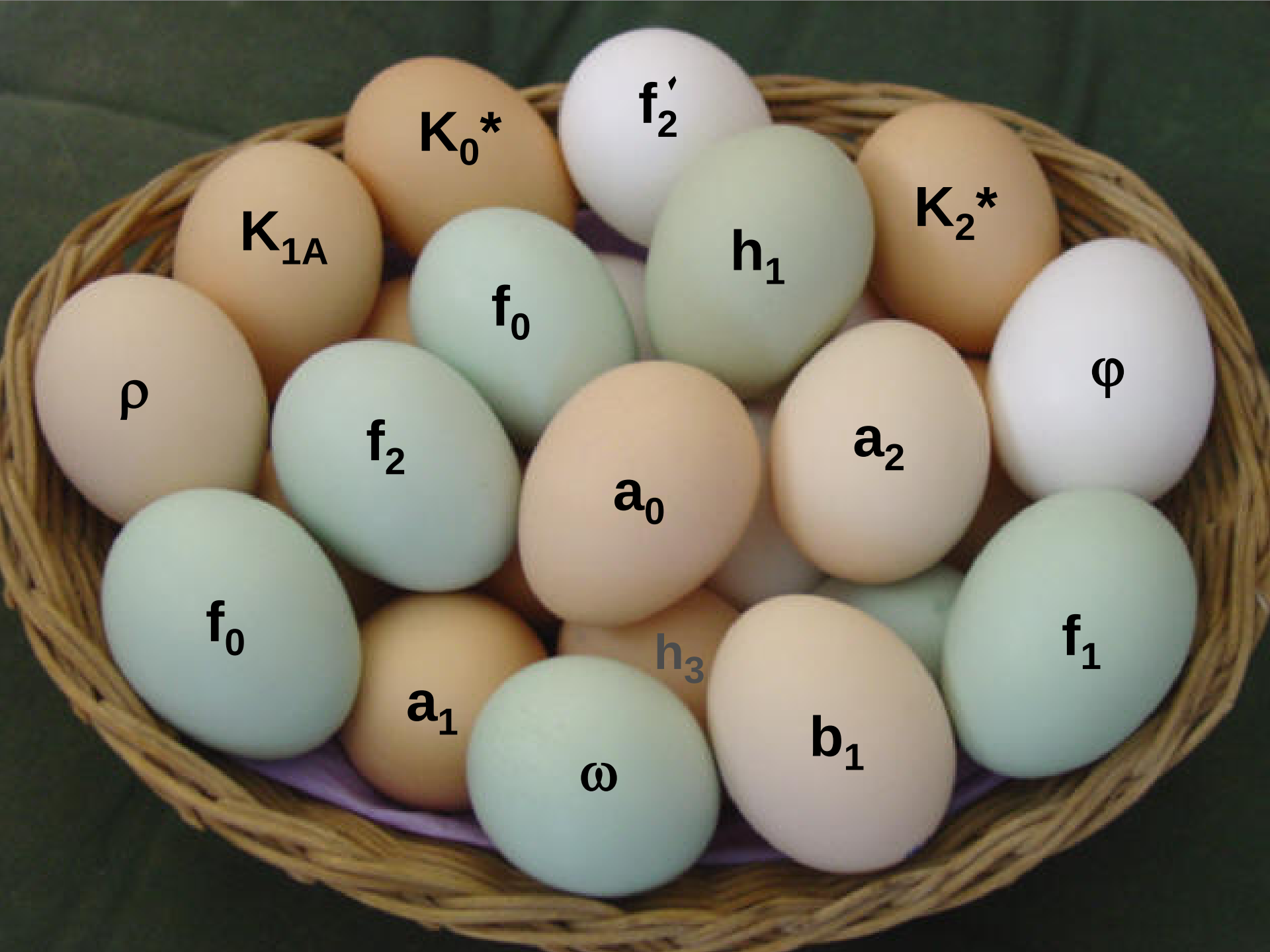


Edwards, Dudek, Wallace & Richards

N*(1xxx) Fock space



VIERA
Panasonic

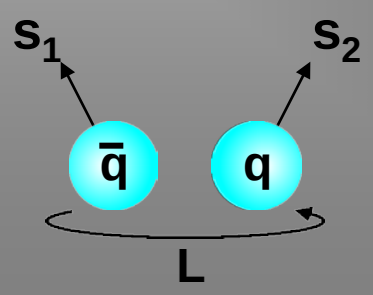

K_0^*
f_2'
K_{1A}
h_1
K_2^*
f_0
ρ
φ
f_2
a_2
a_0
f_0
h_3
f_1
a_1
b_1
ω

Meson spectrum

J^{PC}

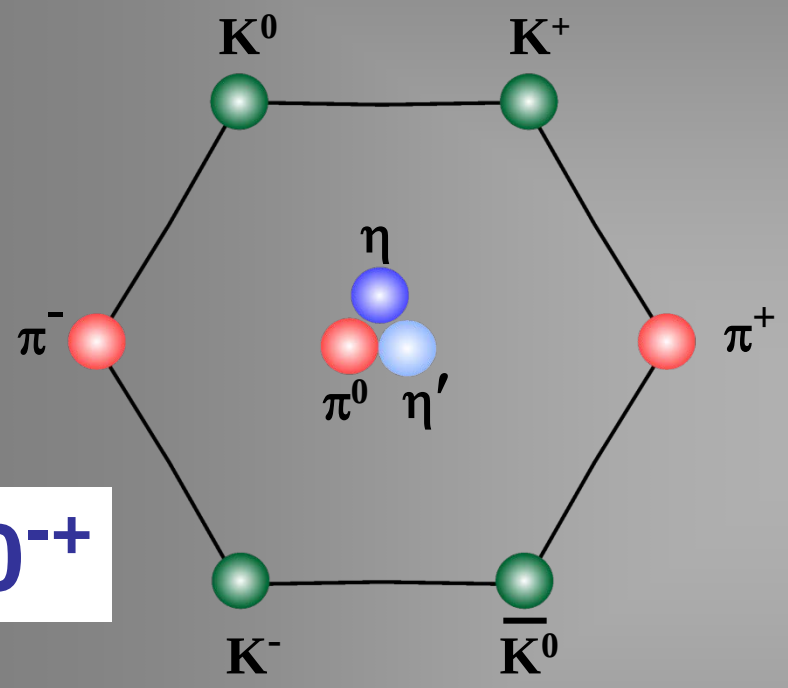
radial

L=3	4^{++}	
	3^{++}	
	2^{++}	
	3^{+-}	
L=2	3^{--}	
	2^{--}	
	1^{--}	
	2^{-+}	
L=1	2^{++}	
	1^{++}	
	0^{++}	
	1^{+-}	
L=0	1^{--}	
	0^{-+}	

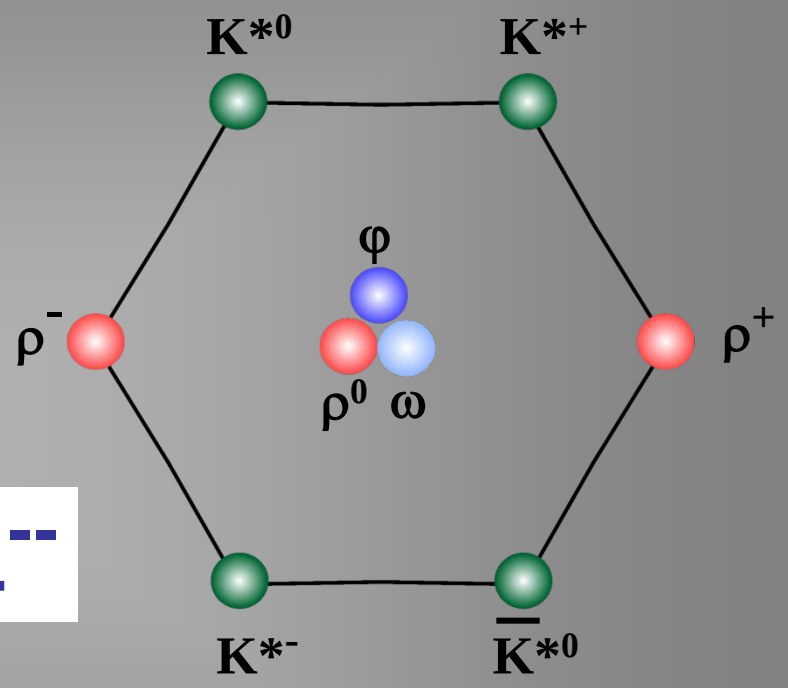


S = 0, 1

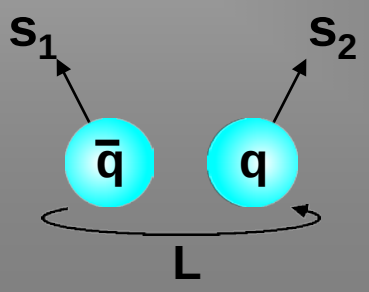
Meson spectrum



0^{-+}



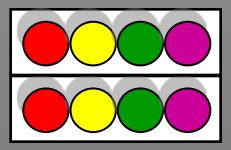
1^{--}



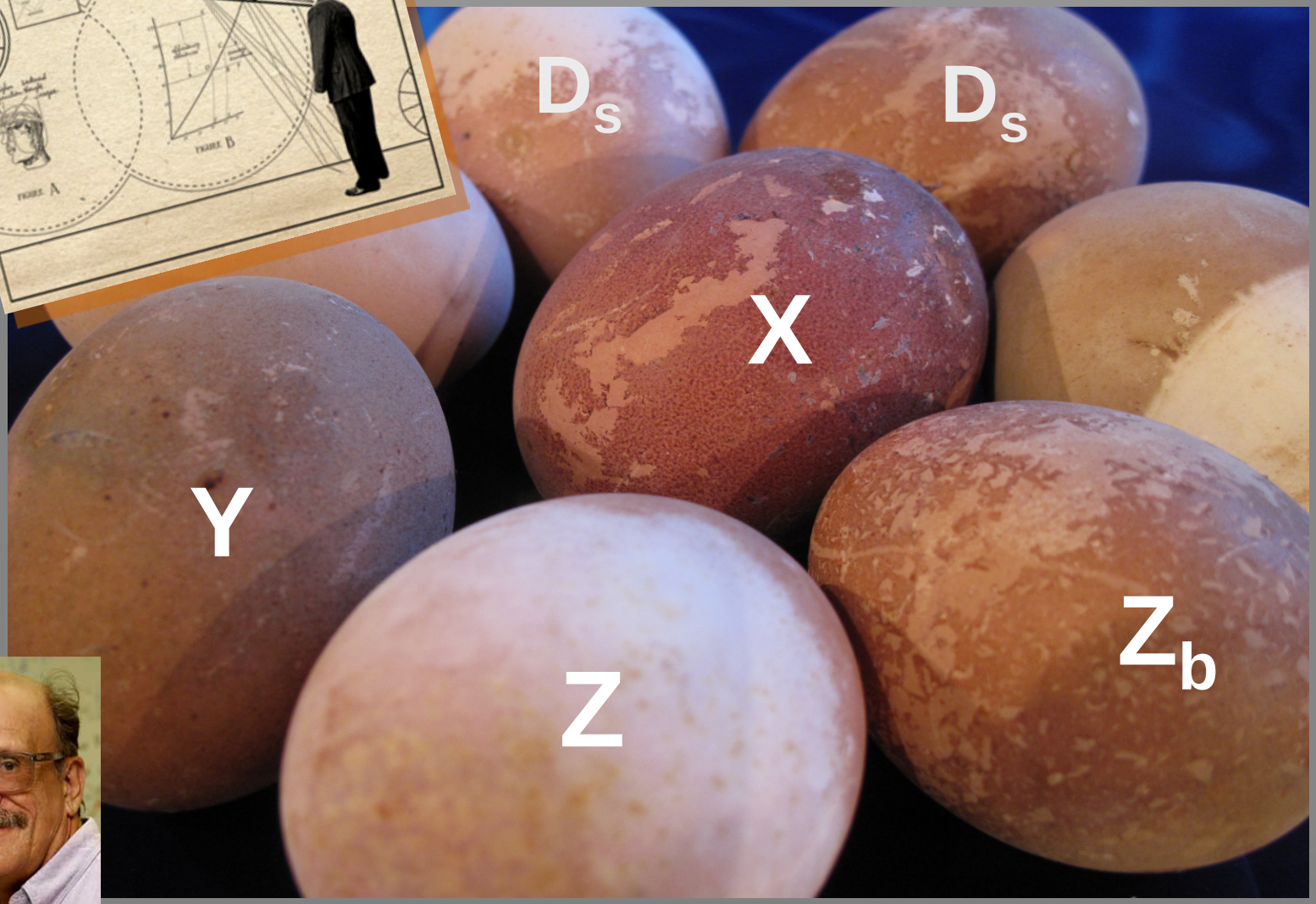
$S = 0, 1$

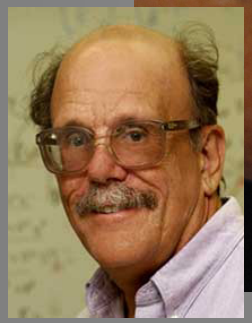
L=0

1^{--}
0^{-+}

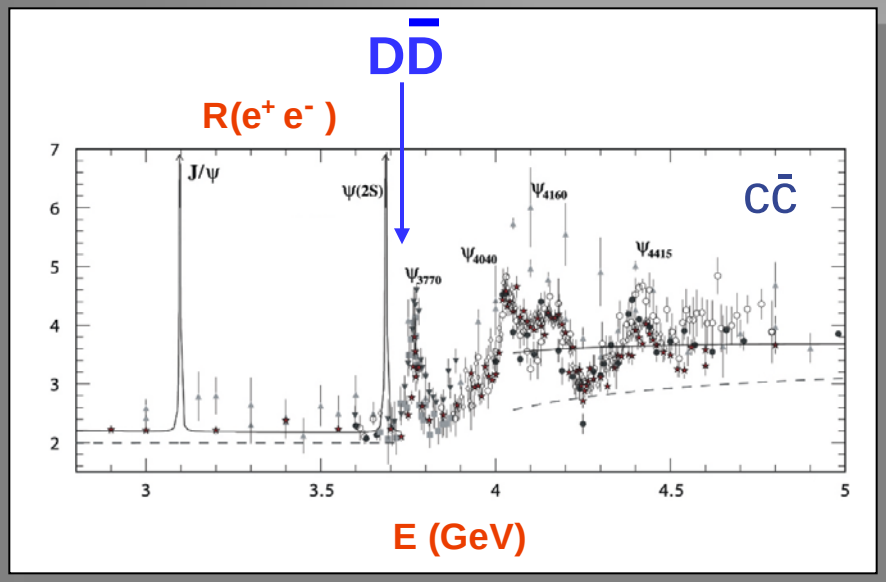


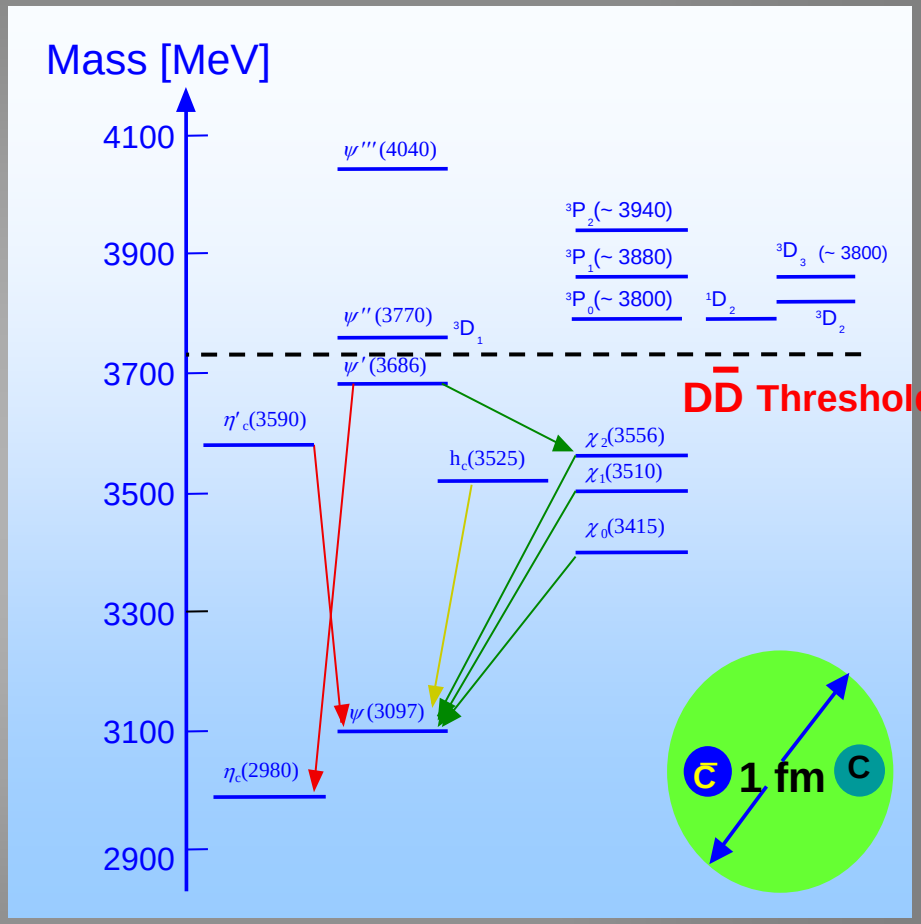
THE XYZ AFFAIR



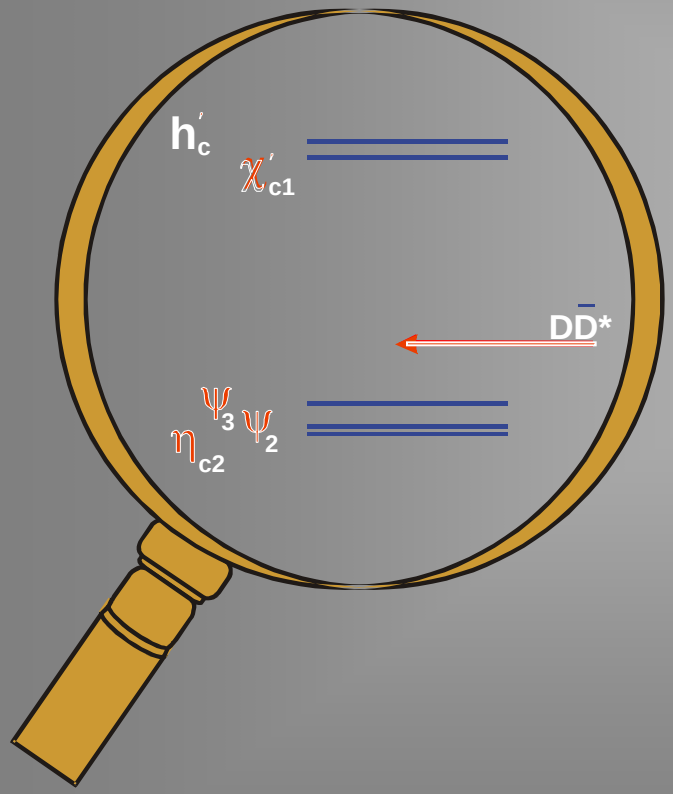


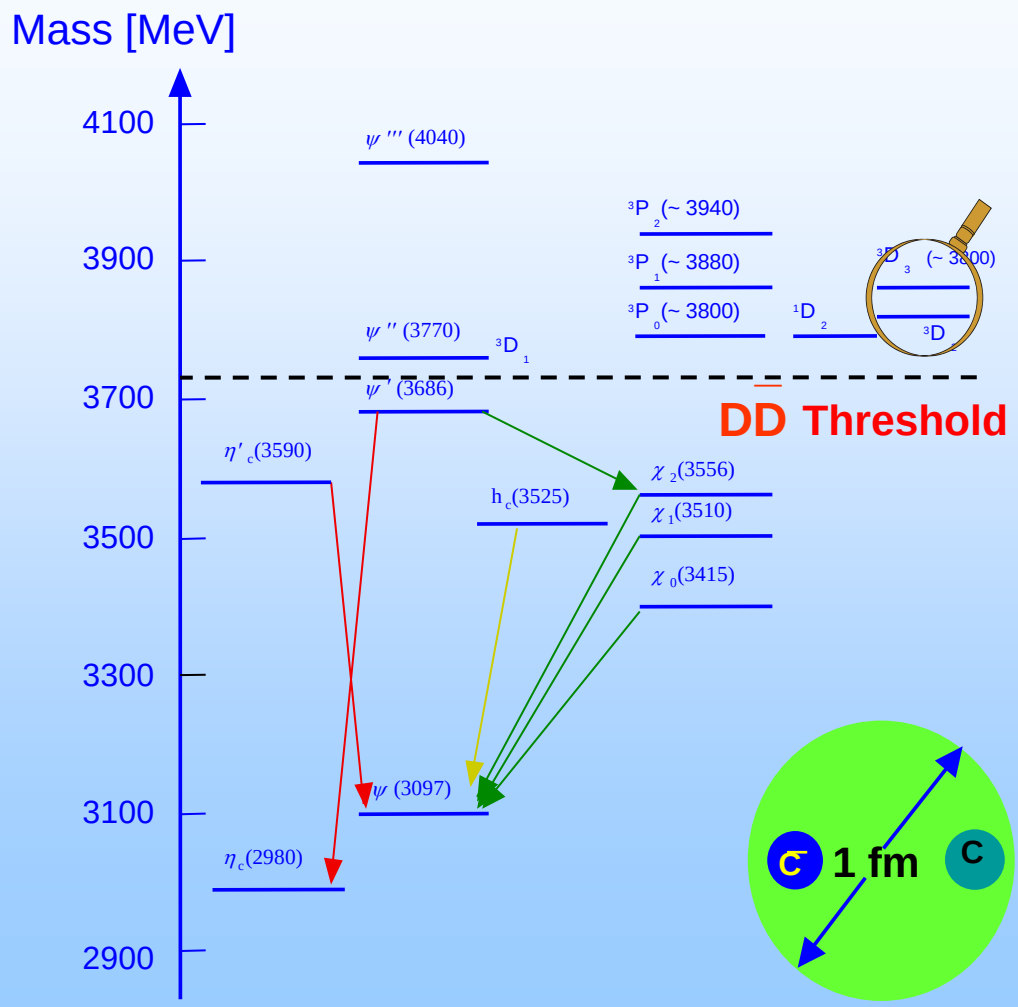
charmonium


$D\bar{D}$
$R(e^+ e^-)$
$c\bar{c}$
J/ψ
ψ(2S)
ψ_{3770}
ψ_{4040}
ψ_{4160}
ψ_{4415}
E (GeV)

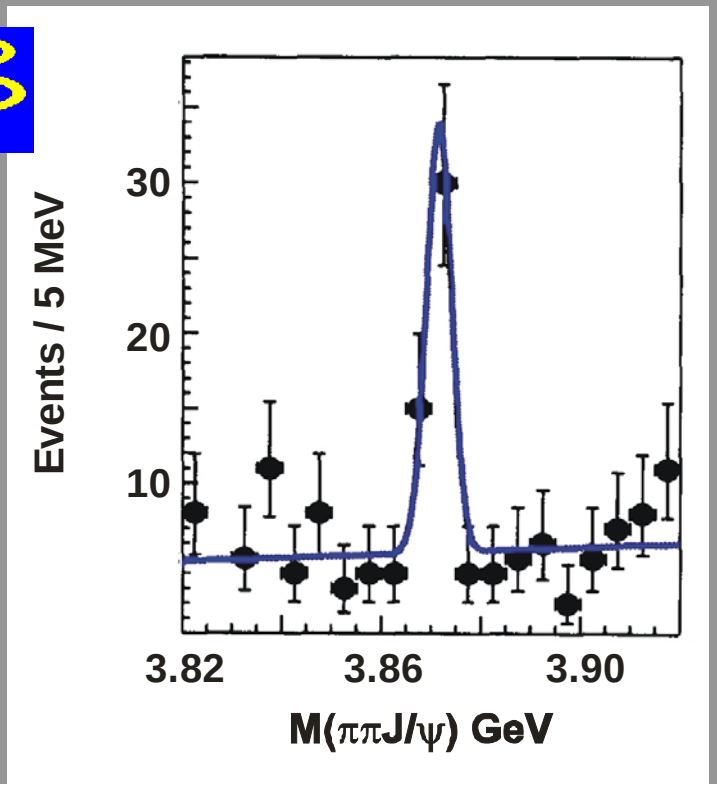

Mass [MeV]
4100
3900
3700
3500
3300
3100
2900
$\psi'''(4040)$
$^3P_2(\sim 3940)$
$^3P_1(\sim 3880)$
$^3P_0(\sim 3800)$
$^3D_3$ (~ 3800)
$^1D_2$
$^3D_2$
$\psi''(3770)$
$^3D_1$
$\psi'(3686)$
$D\bar{D}$ Threshold
$\eta'_c(3590)$
$h_c(3525)$
$\chi_2(3556)$
$\chi_1(3510)$
$\chi_0(3415)$
$\psi(3097)$
$\eta_c(2980)$
$\bar{c}$
1 fm
c

charmonium

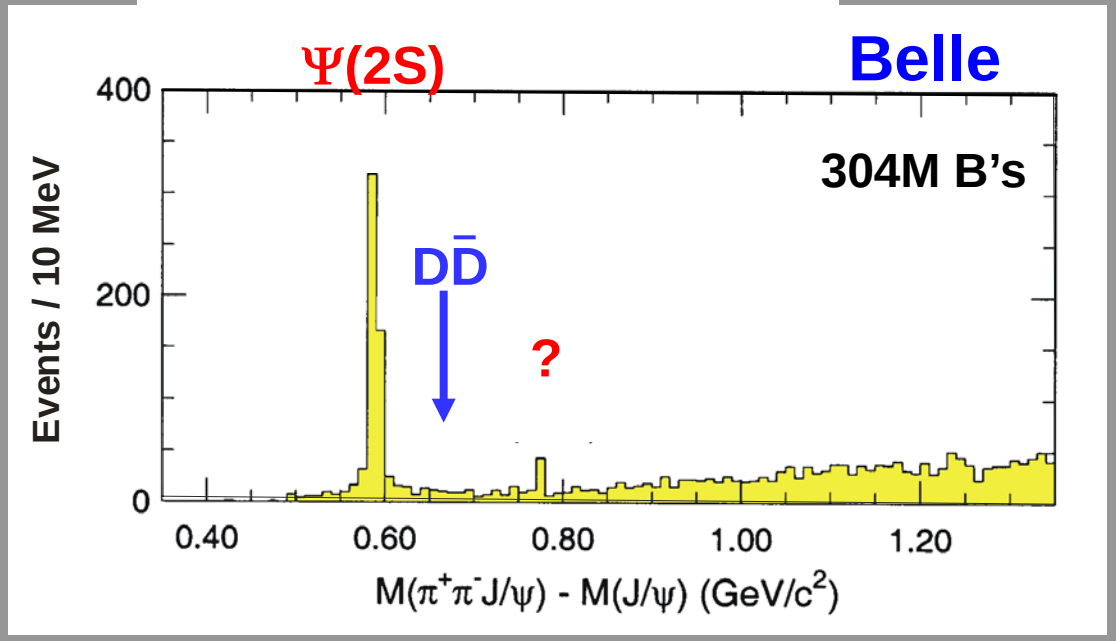

h'c
χ'c1
DD̄*
ψ3 ψ2
ηc2


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)
χ2(3556)
hc(3525)
χ1(3510)
χ0(3415)
ψ (3097)
ηc(2980)
c̄
1 fm
c

gifts from B-factories



X(3872)



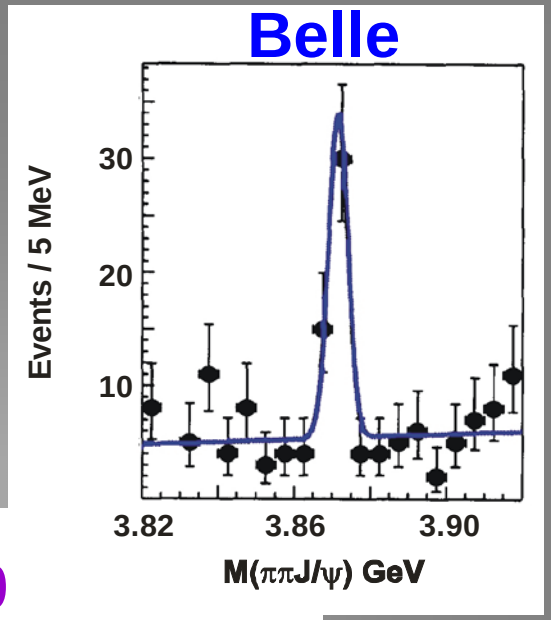
$B \rightarrow KX$

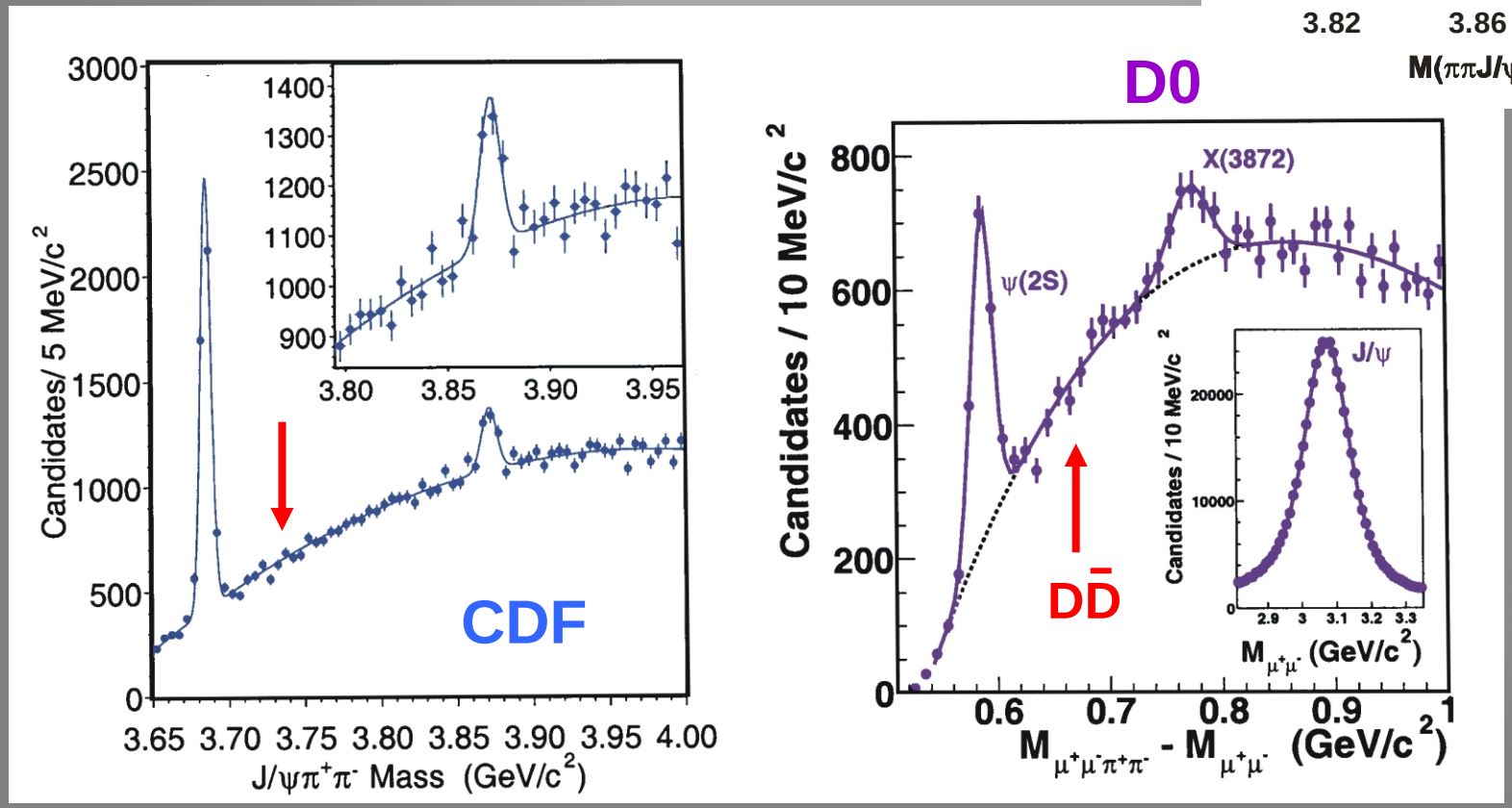
$X \rightarrow \pi^+ \pi^- J/\psi$

$\Gamma < 2.3$ MeV

X(3872)

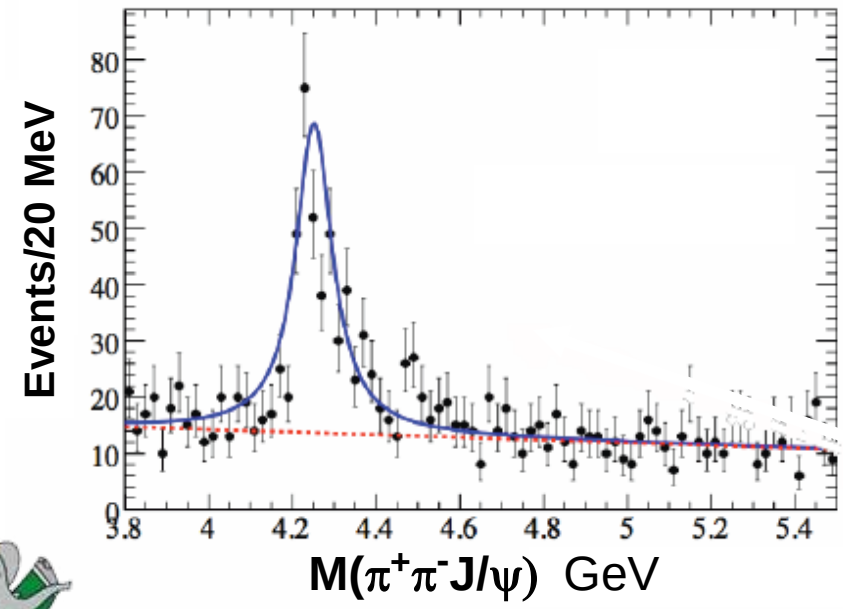
$J^{PC} = 1^{++}$ LHCb



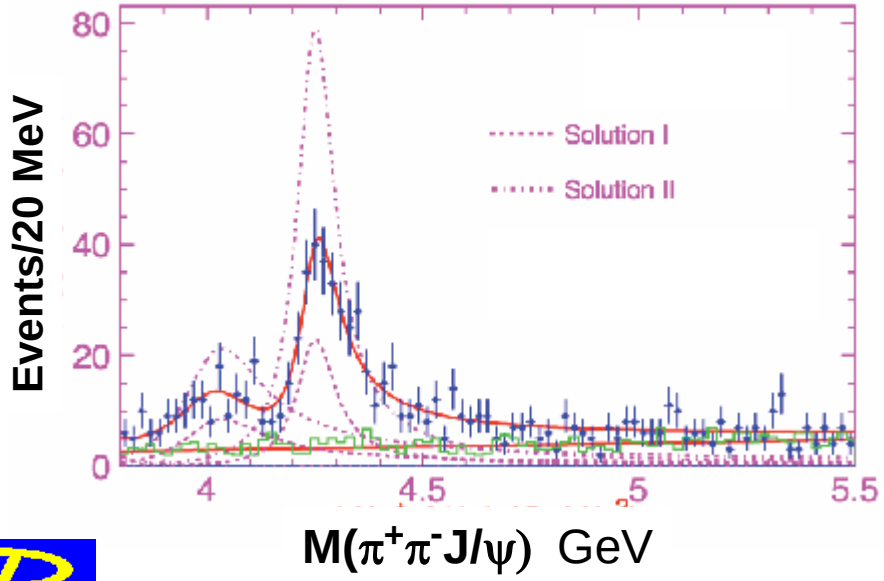


Y (4260)

$e^+e^- \longrightarrow \pi^+\pi^- J/\Psi$



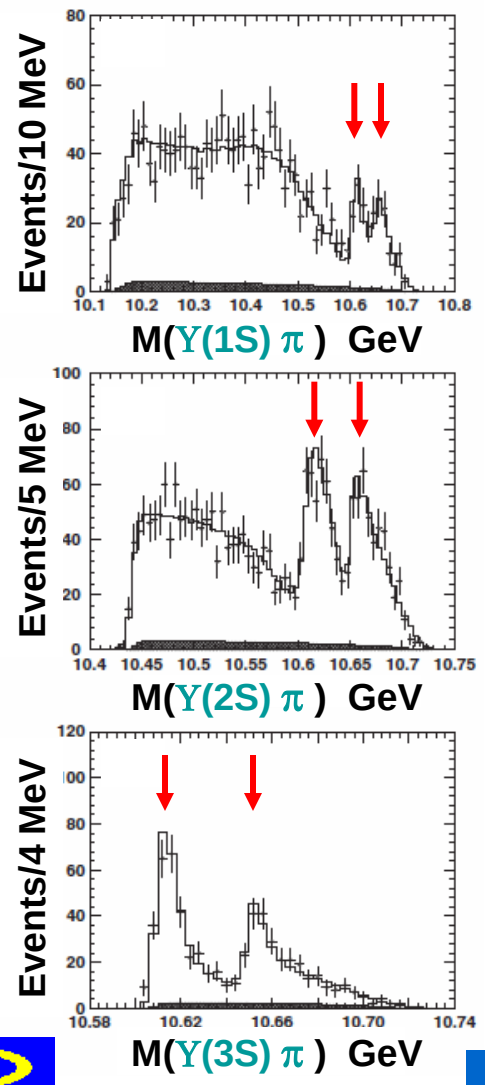
$e^+e^- \longrightarrow \pi^+\pi^- J/\Psi$



BELLE

Z_b 's

$\Upsilon(5S) \to (\Upsilon(nS)\pi)\pi$



M = 10607.2 ± 2.0 MeV
Γ = 18.4 ± 2.4 MeV

M = 10652.2 ± 1.5 MeV
Γ = 11.5 ± 2.2 MeV

n = 1,2,3
m = 1,2

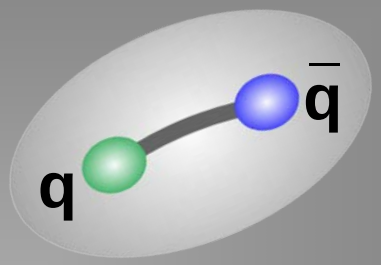
$\Upsilon(5S) \to (h_b(mP)\pi)\pi$

meson spectrum

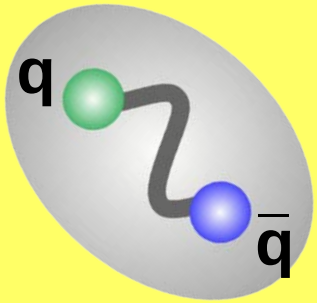
allowed J^{PC}

0^{--}	0^{-+}	0^{+-}	0^{++}
1^{--}	1^{-+}	1^{+-}	1^{++}
2^{--}	2^{-+}	2^{+-}	2^{++}
3^{--}	3^{-+}	3^{+-}	3^{++}
4^{--}	4^{-+}	4^{+-}	4^{++}

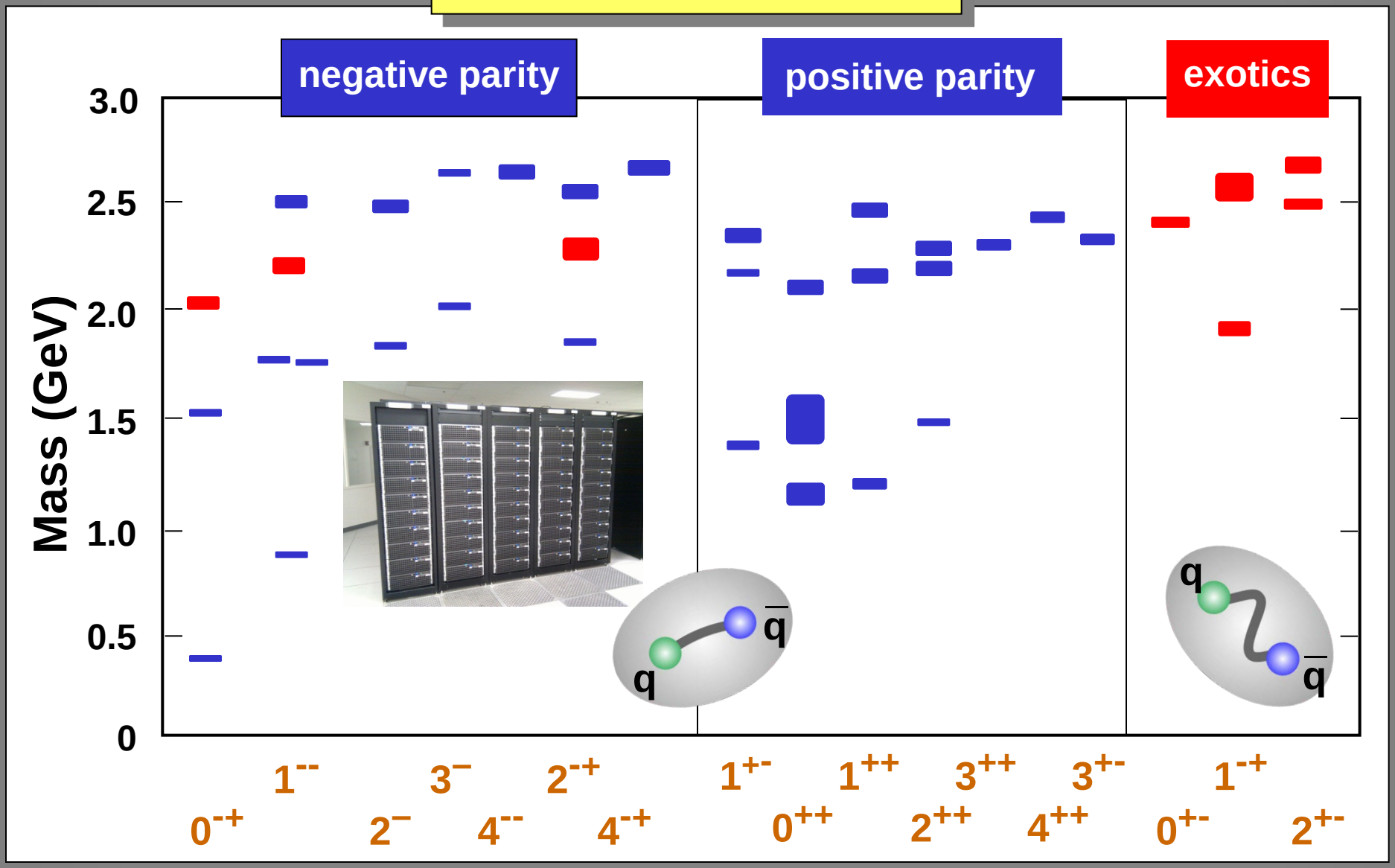
...



$J^{PC} \rightarrow$ not $\bar{q}q$



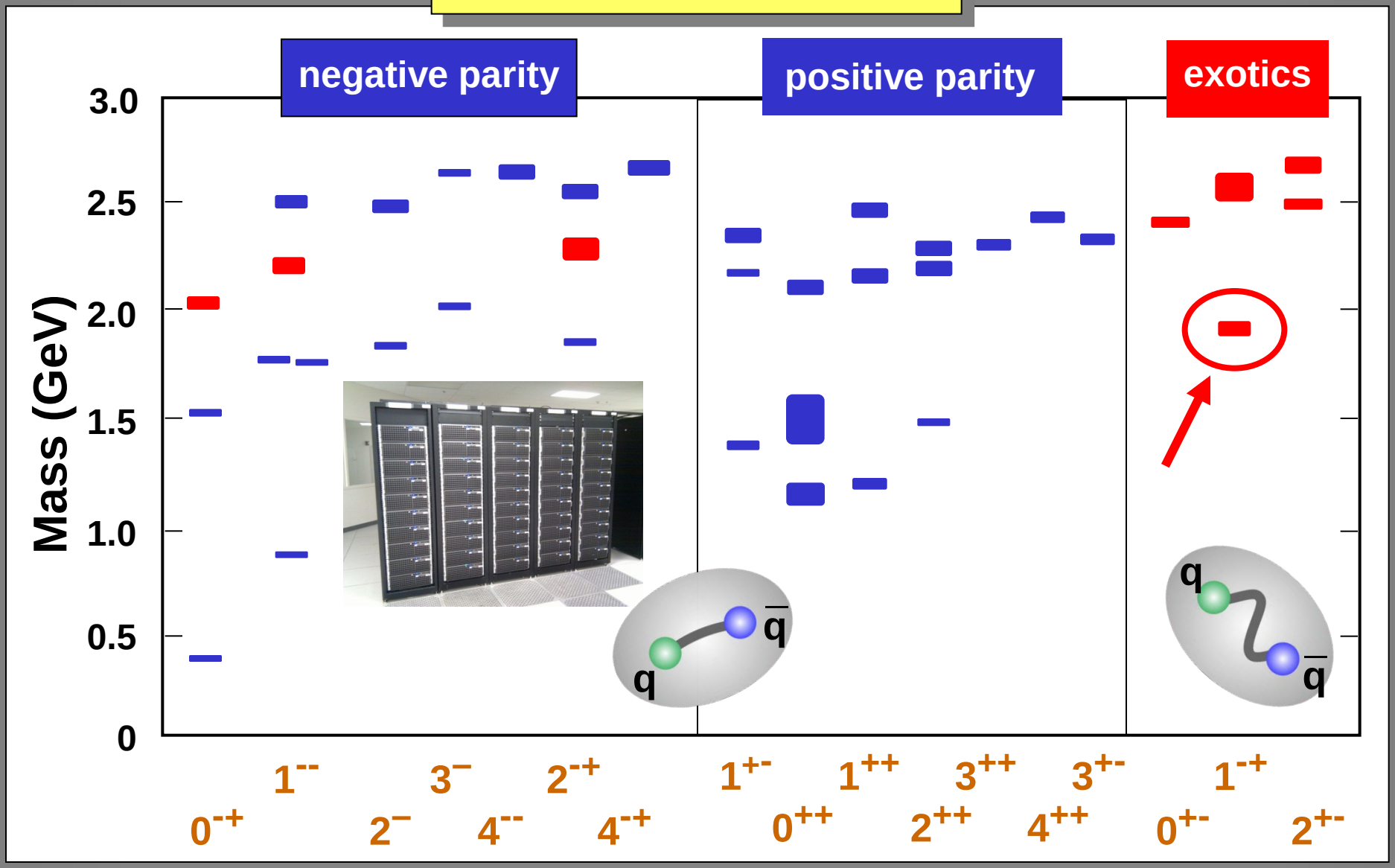
Meson spectrum



Dudek *et al*

m_π = 396 MeV

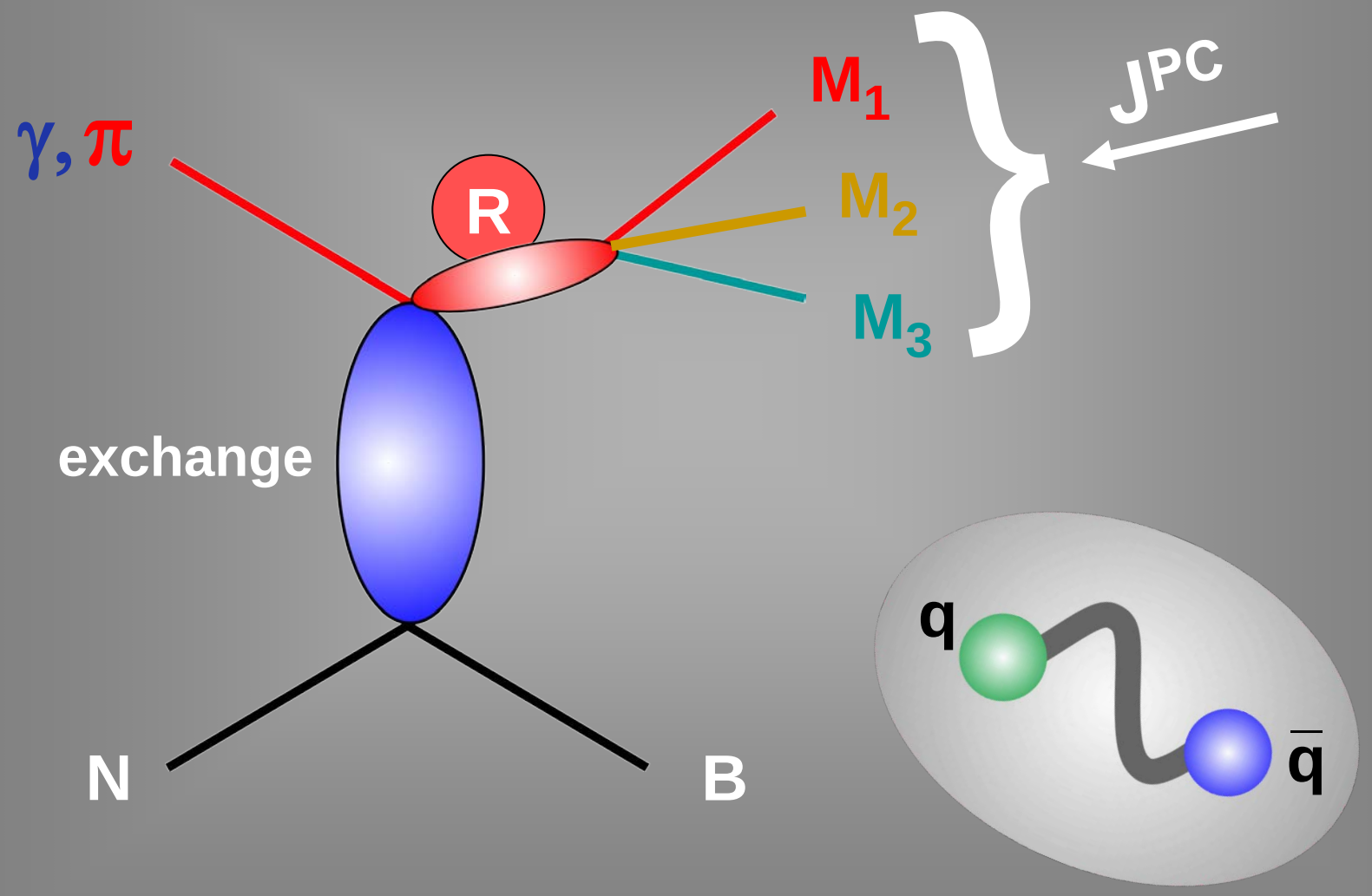
Meson spectrum



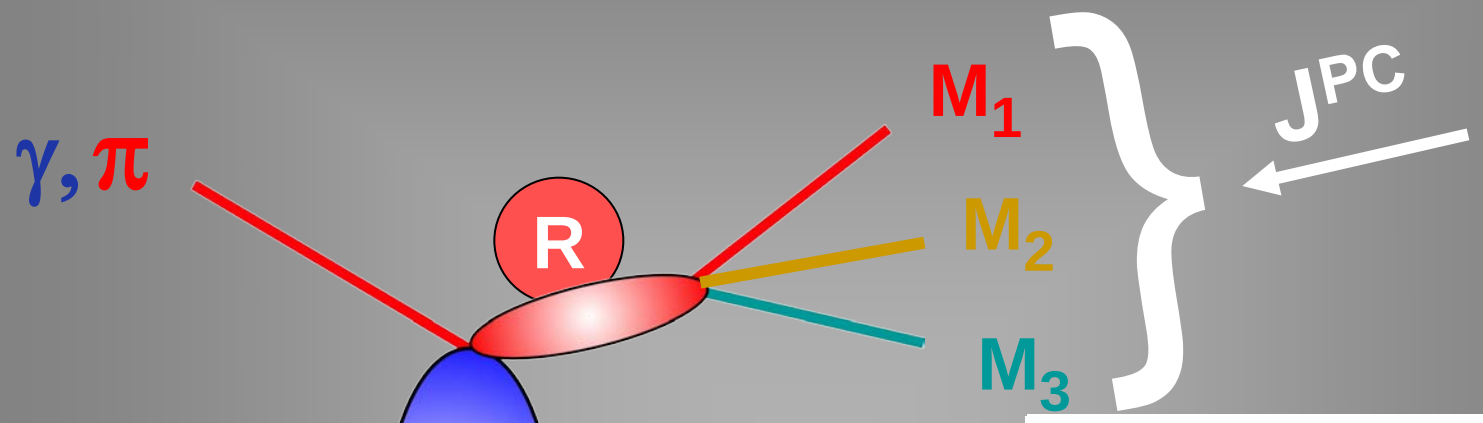
Dudek *et al*

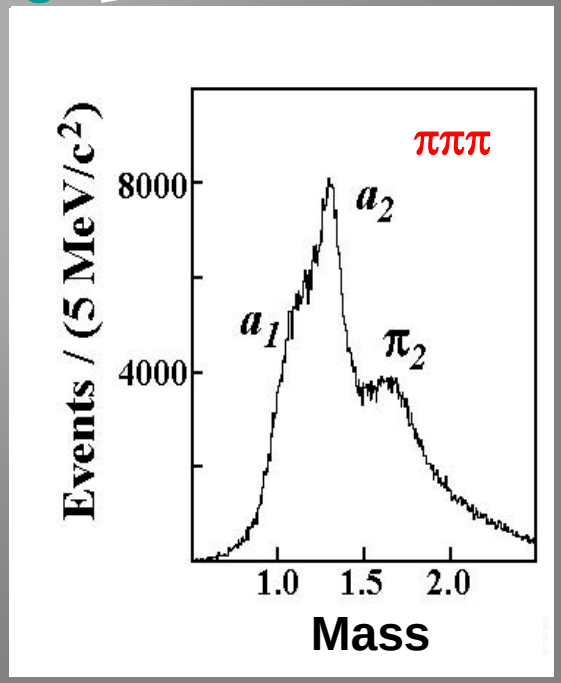
m_π = 396 MeV

Partial Wave Analysis

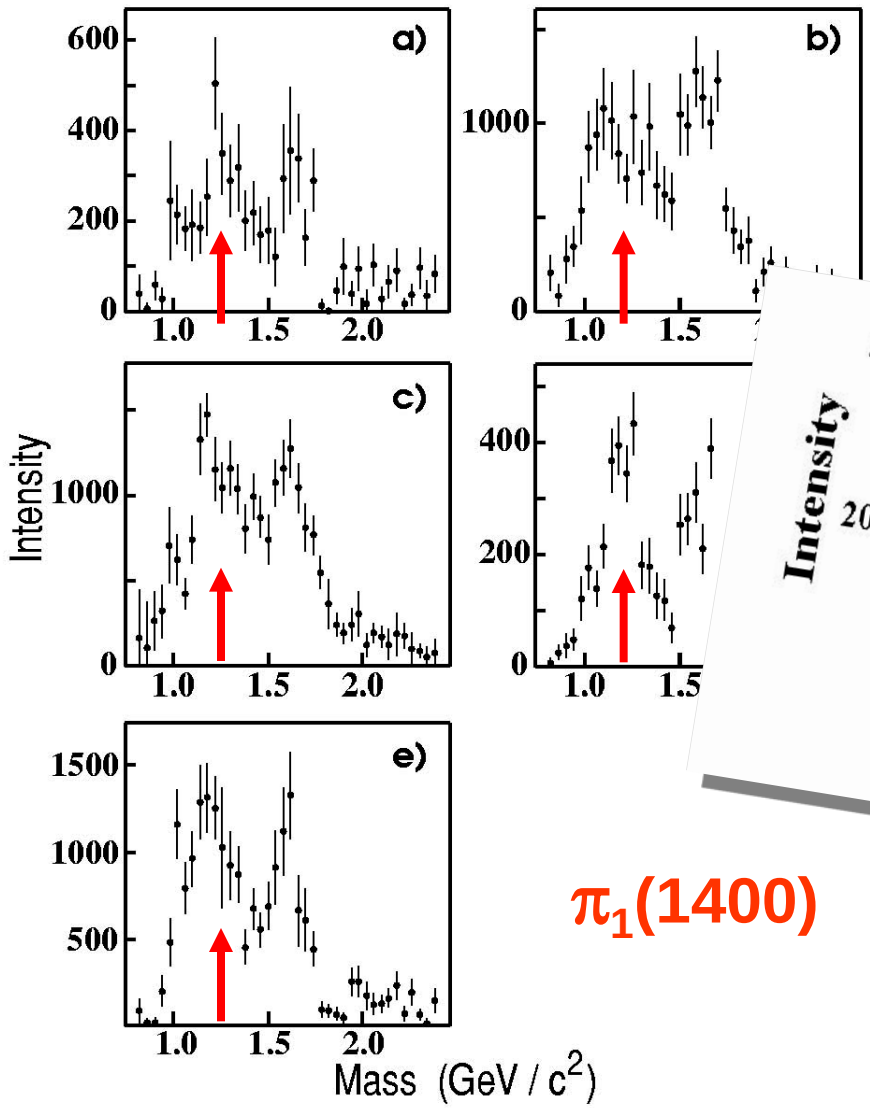


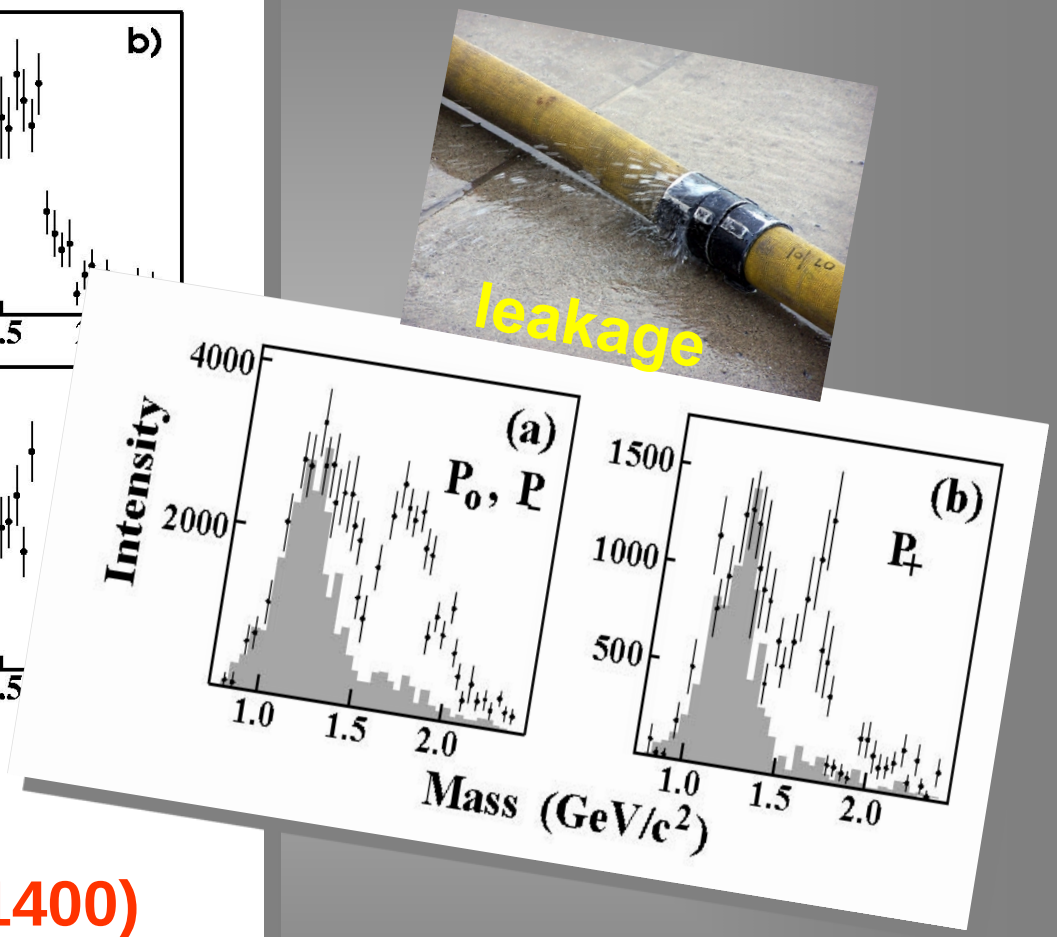
Partial Wave Analysis





BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^-\pi^- p$

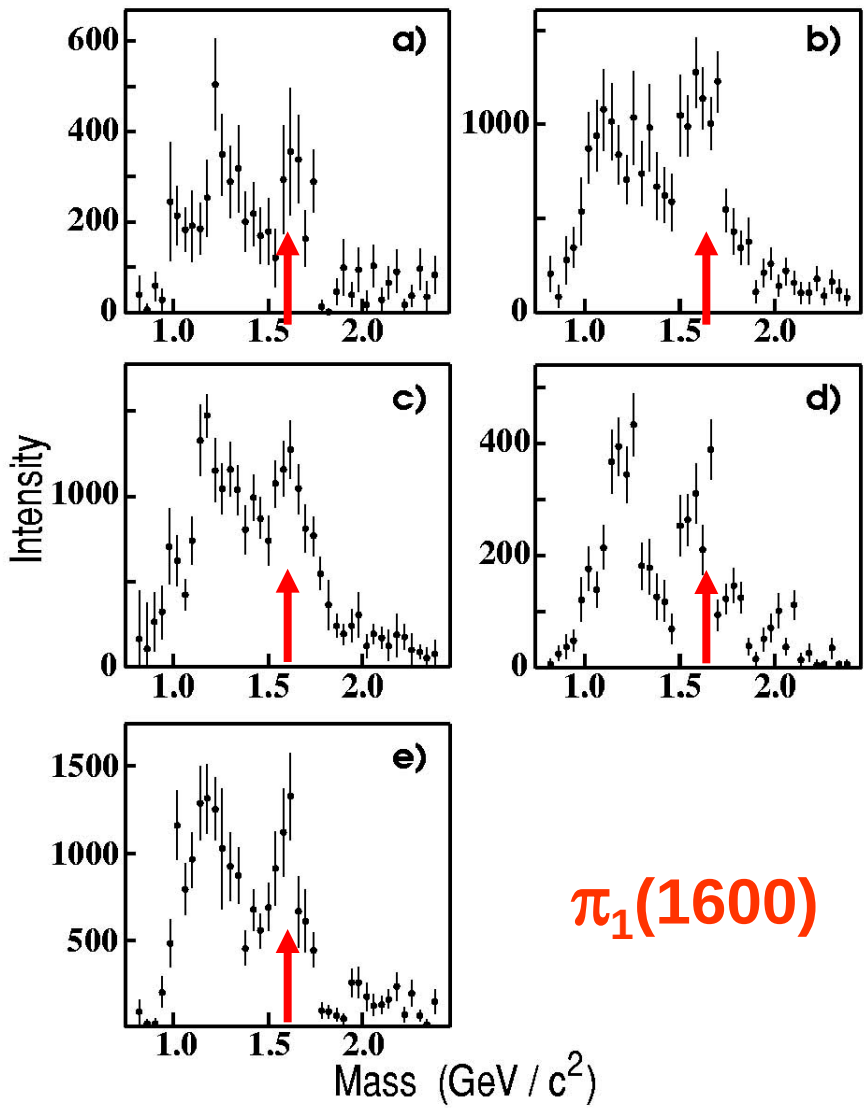




$\pi_1(1400)$

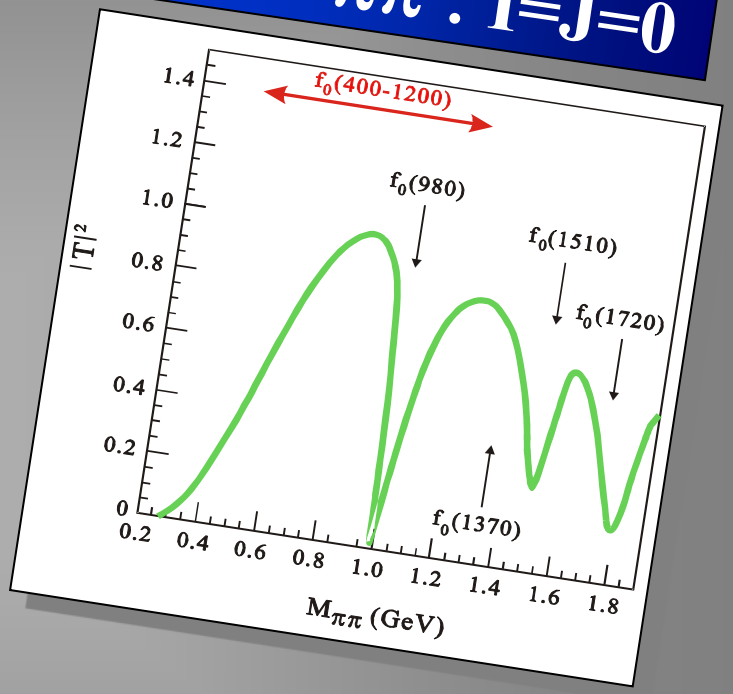
Chung et al.

BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^-\pi^- p$



$\pi_1(1600)$

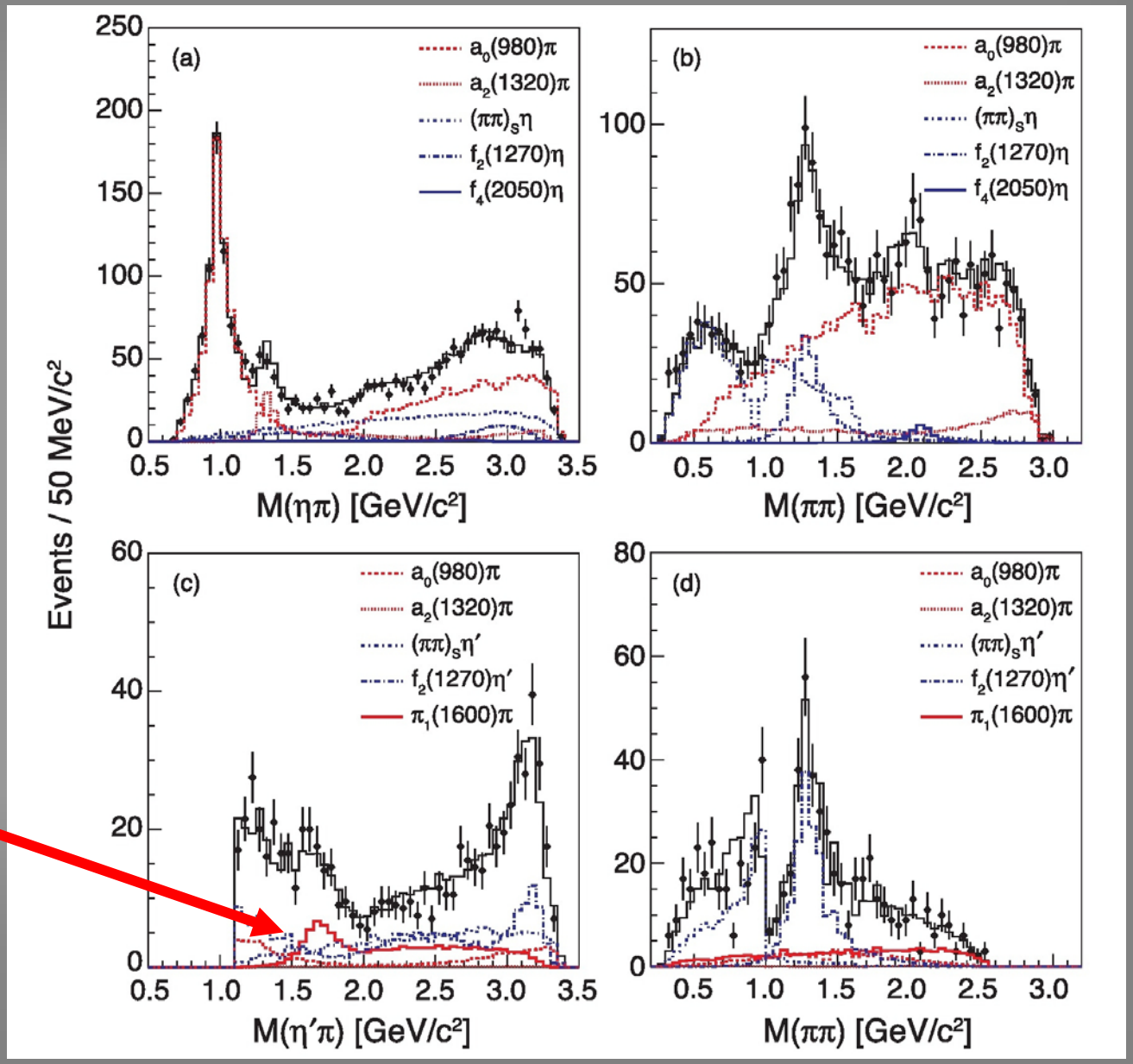
$\pi\pi \rightarrow \pi\pi$: I=J=0



variation of 1^{-+} with 0^{++}

Chung et al.

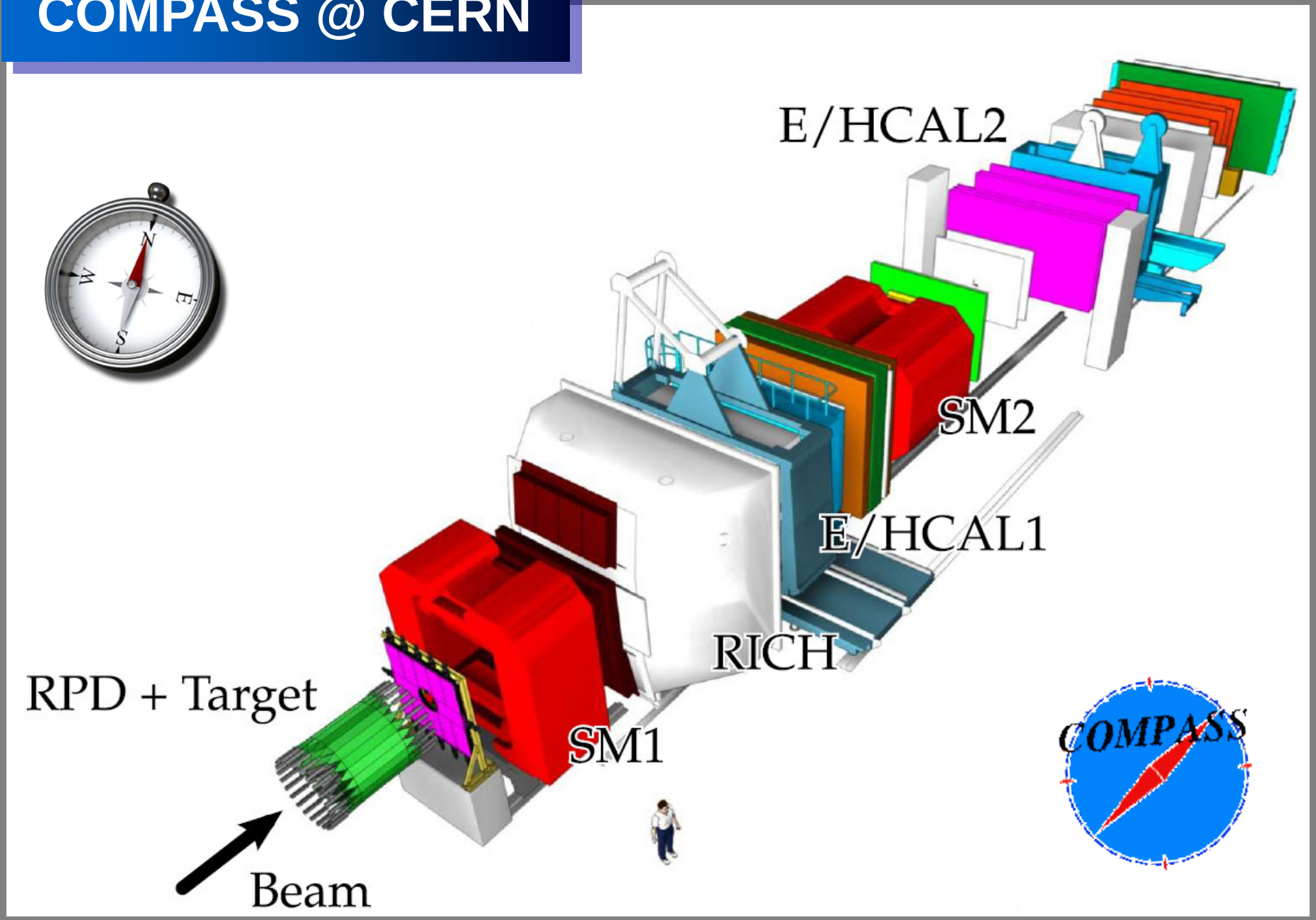
CLEO-c: $\chi_{c1} \longrightarrow \eta\,\pi^+\pi^-$, $\eta'\pi^+\pi^-$



$\pi_1(1600)$

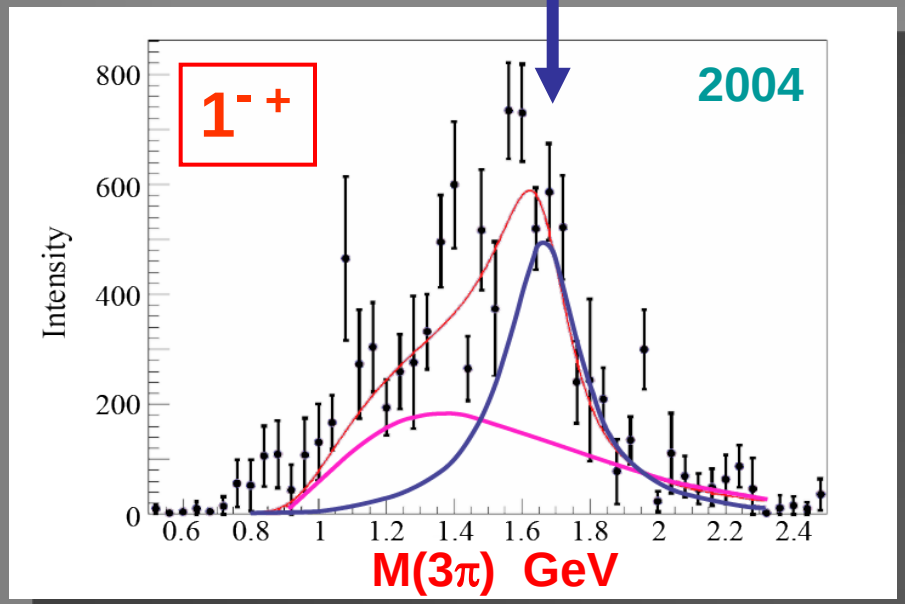
Adams *et al.*

COMPASS @ CERN

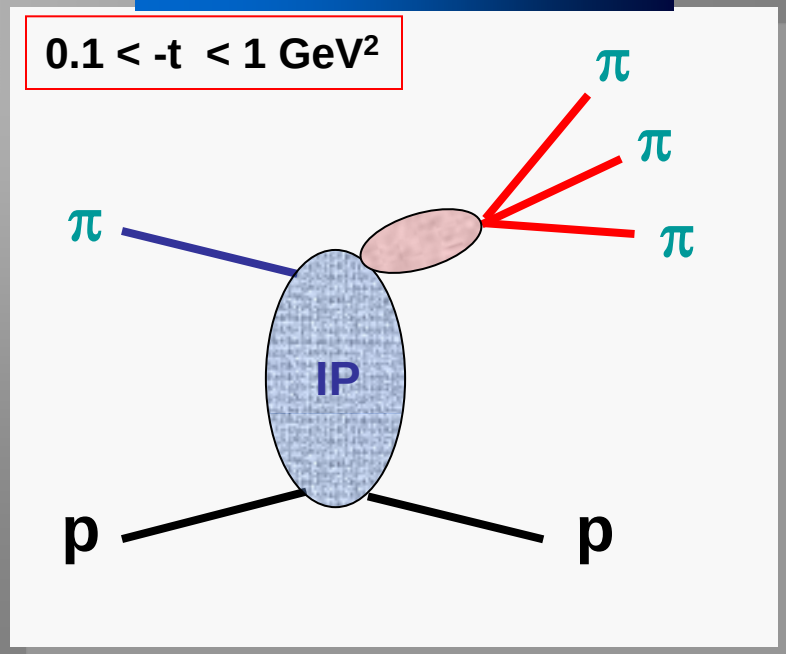


COMPASS @ CERN

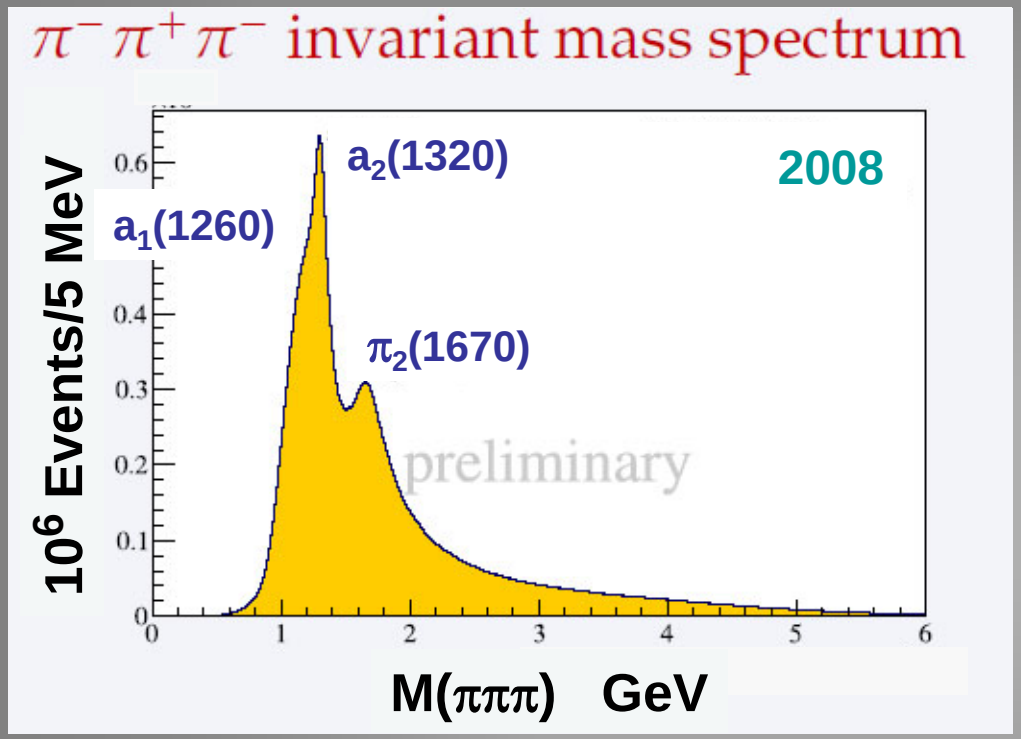
First analysis tools

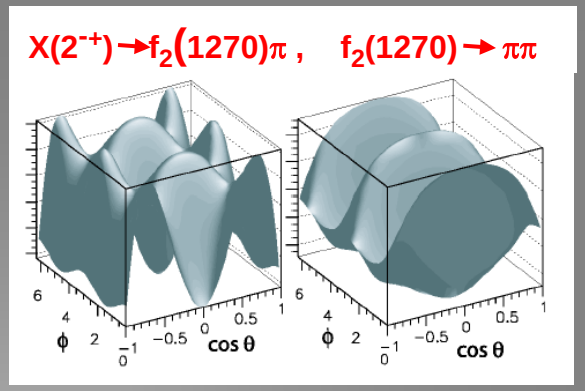


$\pi^- p \longrightarrow \pi^-\pi^+\pi^- p$

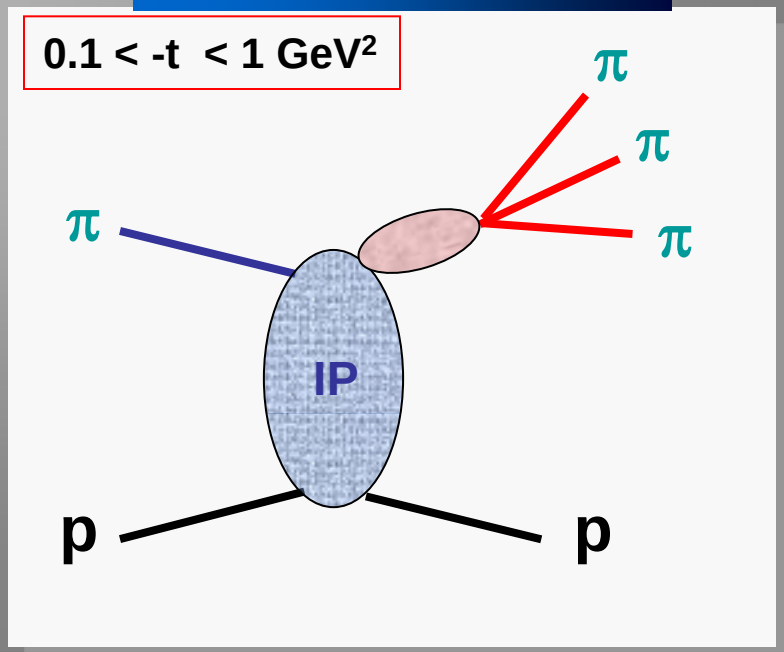


COMPASS @ CERN





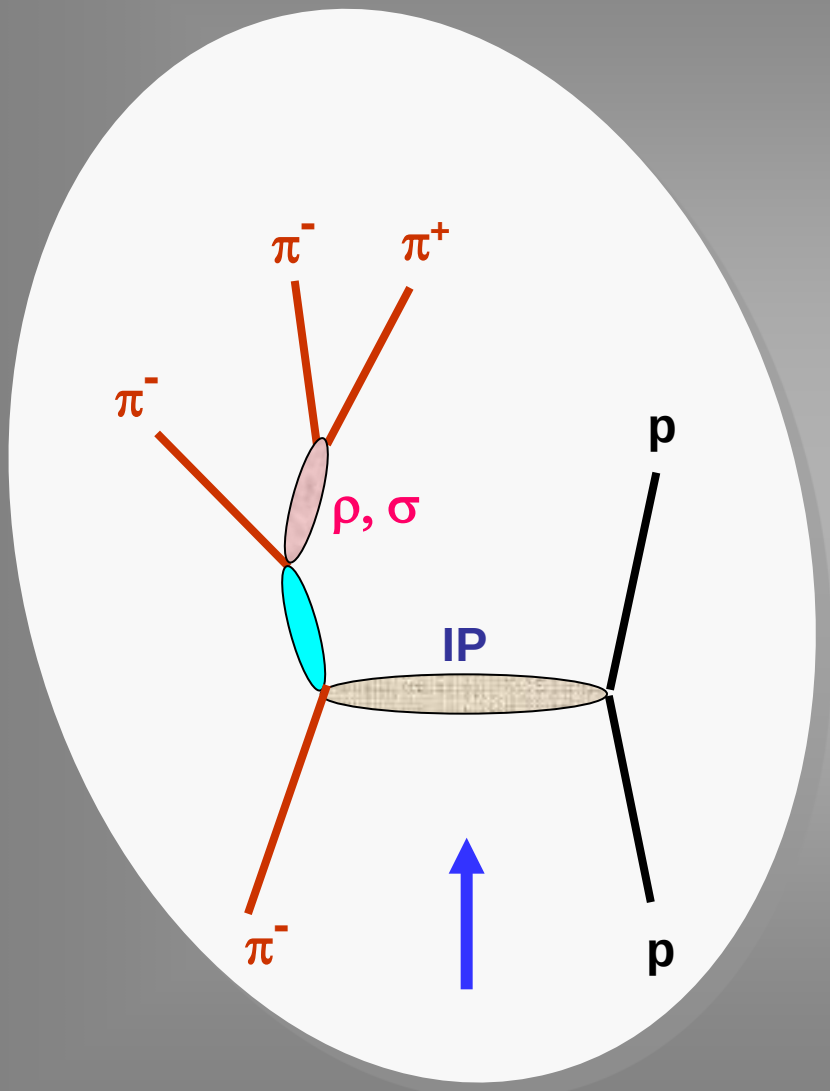
$\pi^- p \longrightarrow \pi^-\pi^+\pi^- p$

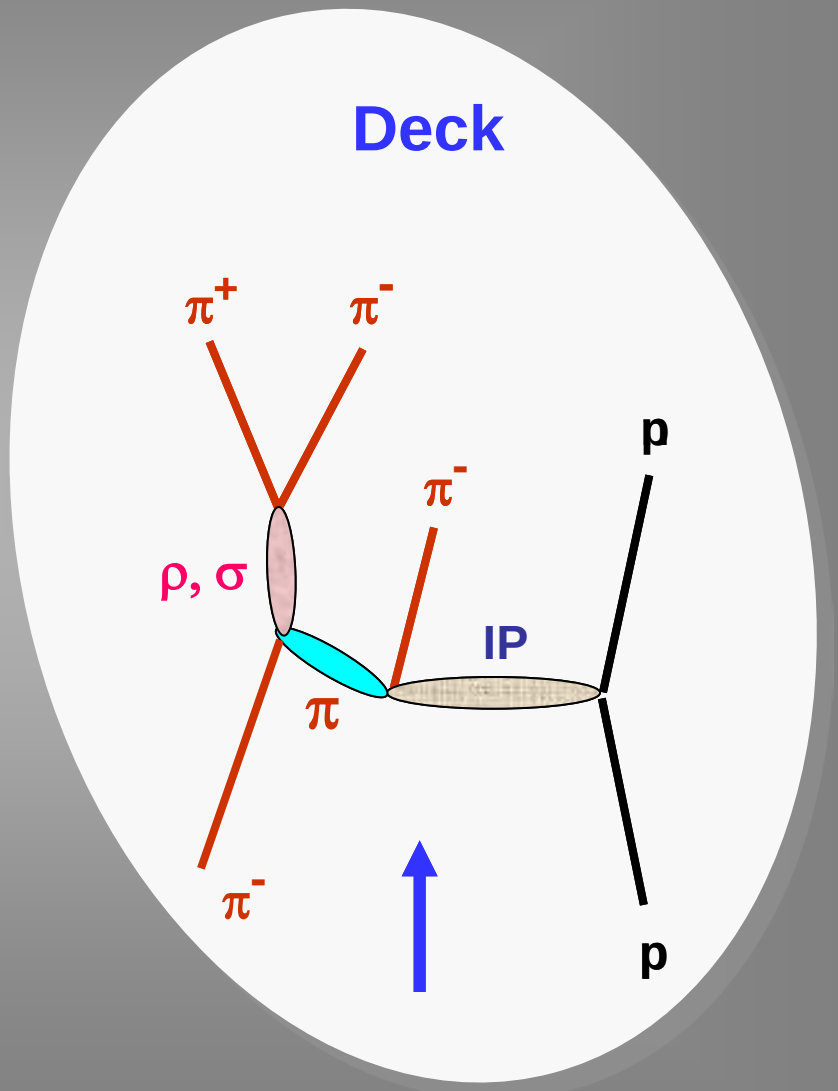


192 GeV beam 96M 3π events

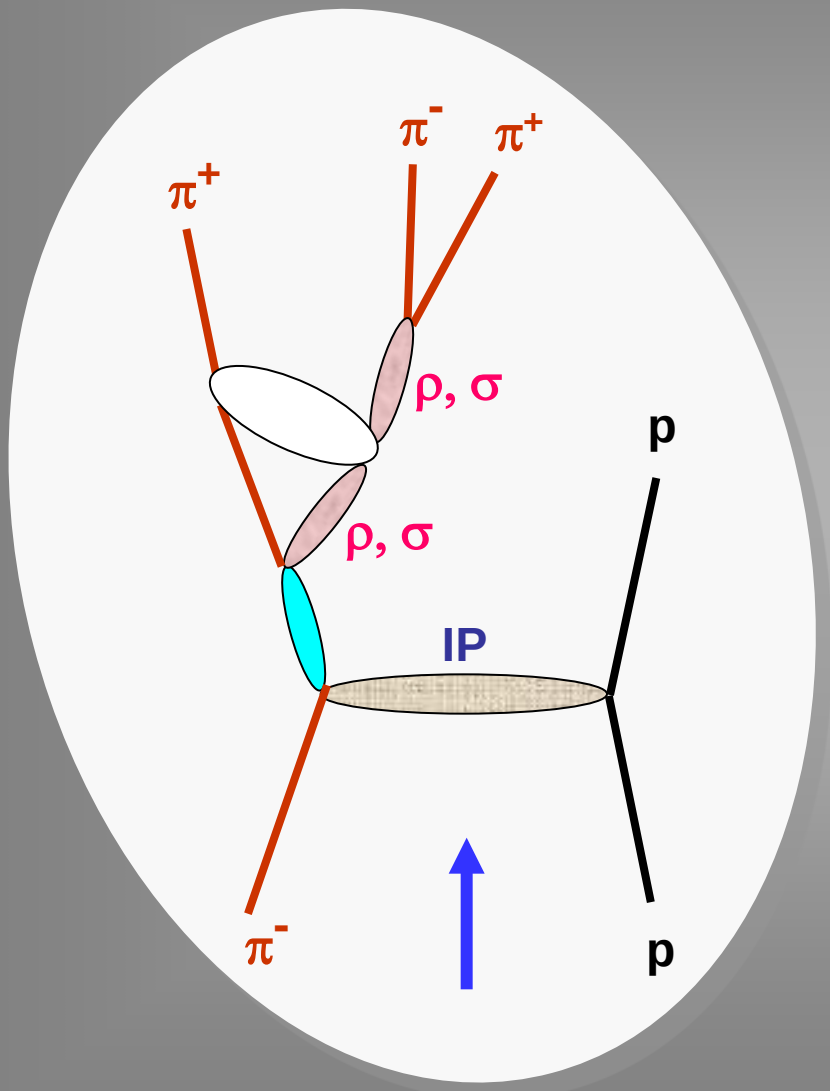
PWA: 52 waves

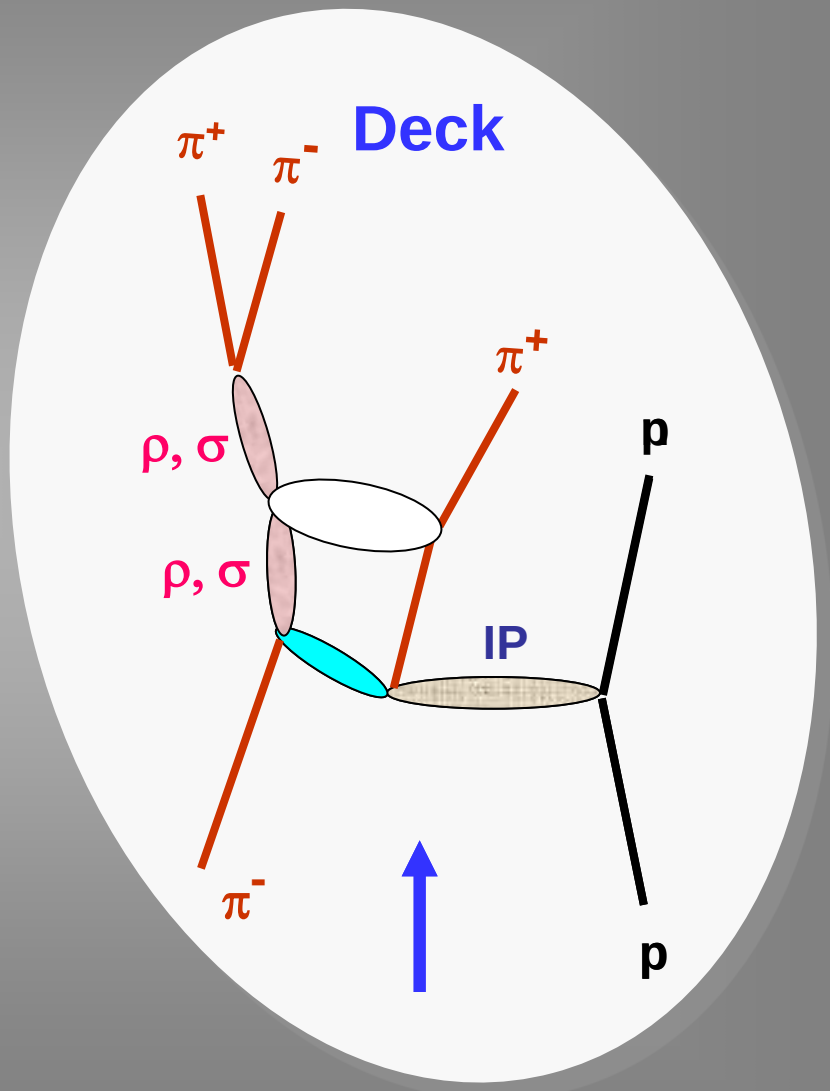
reaction mechanisms



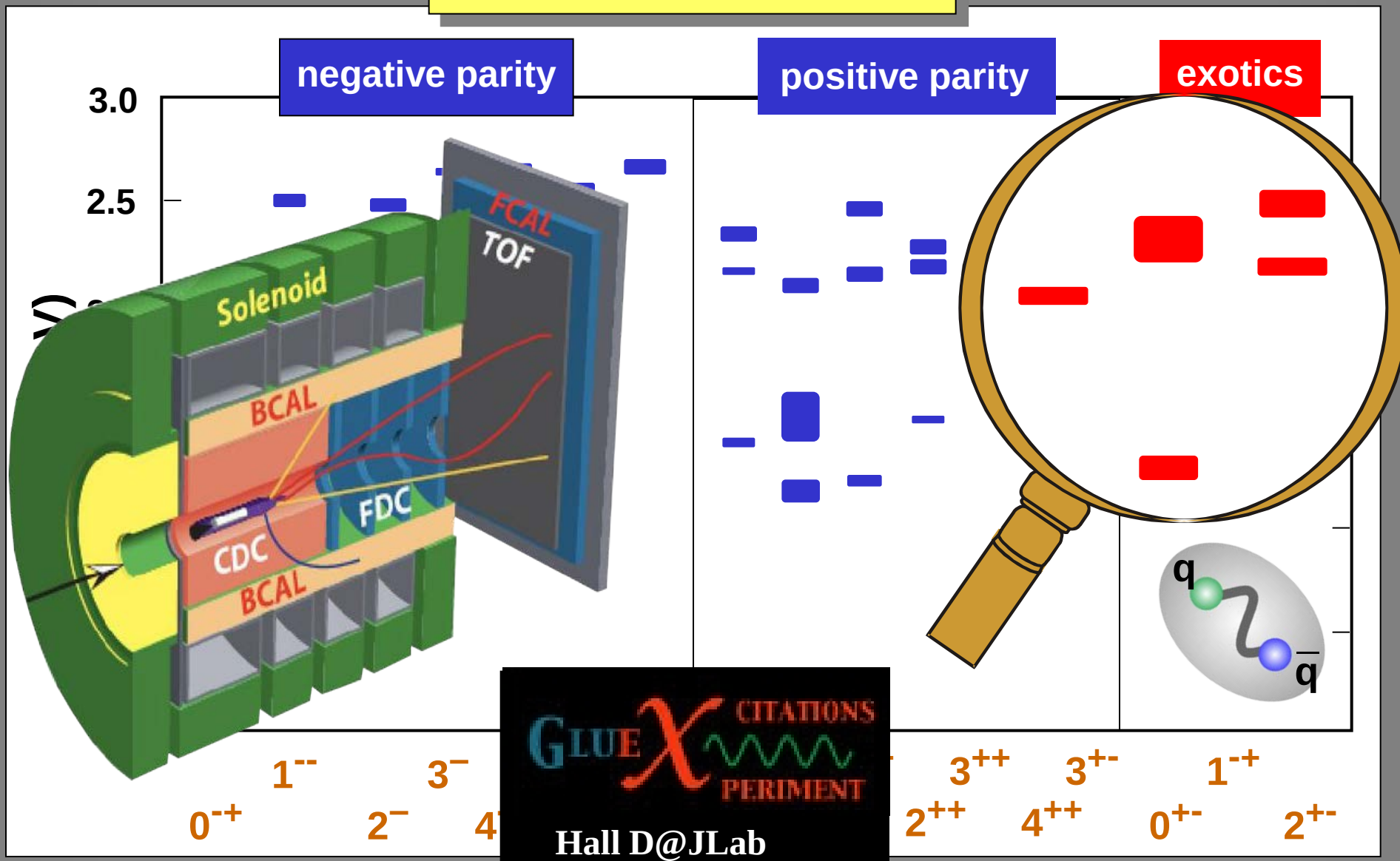


reaction mechanisms



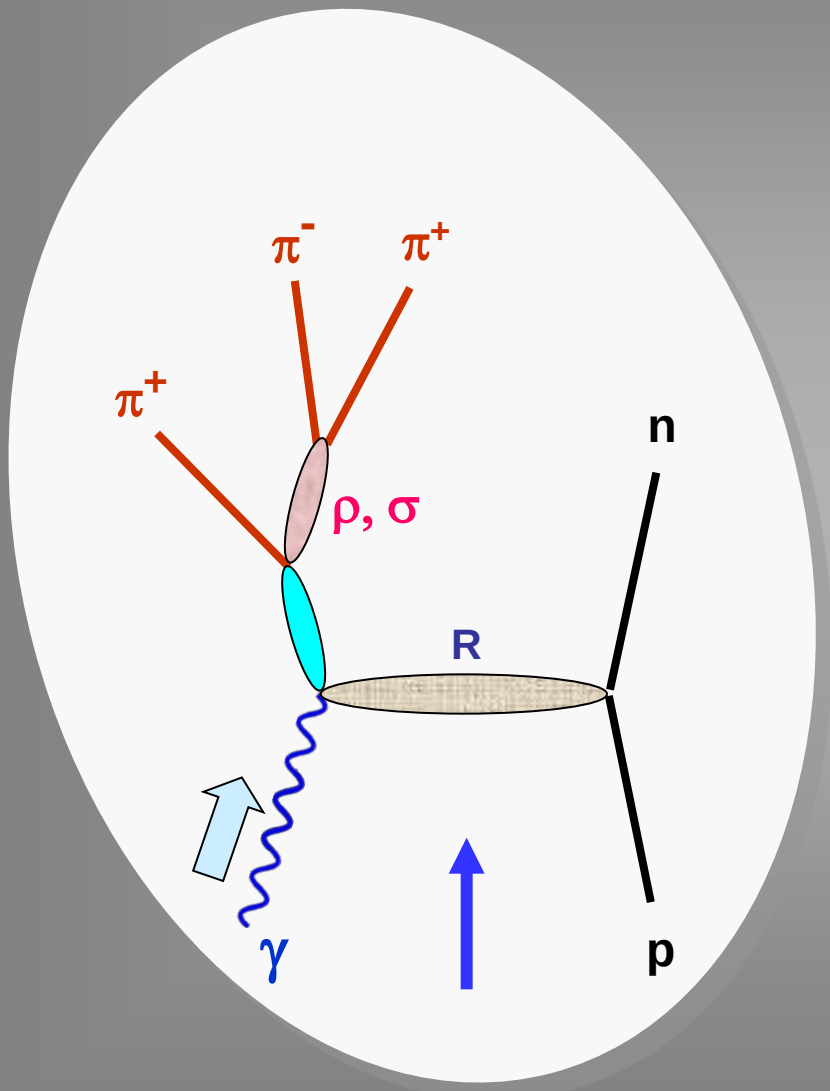


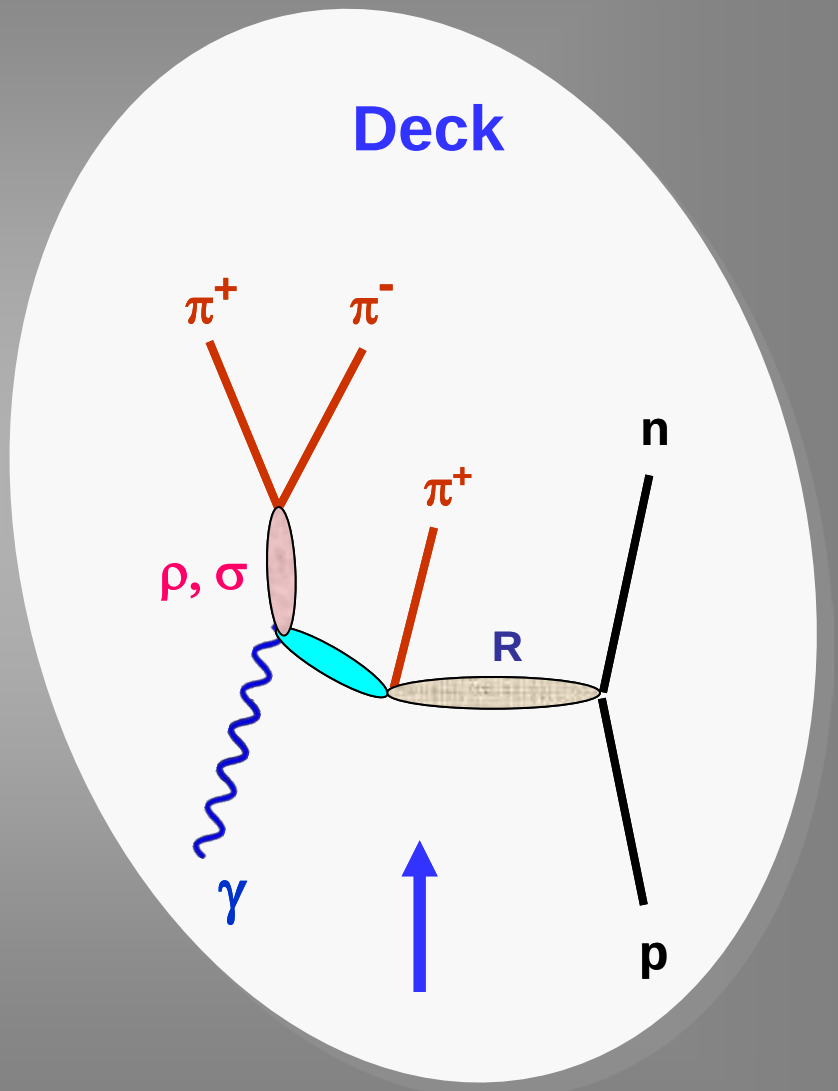
Meson spectrum



Dudek *et al*

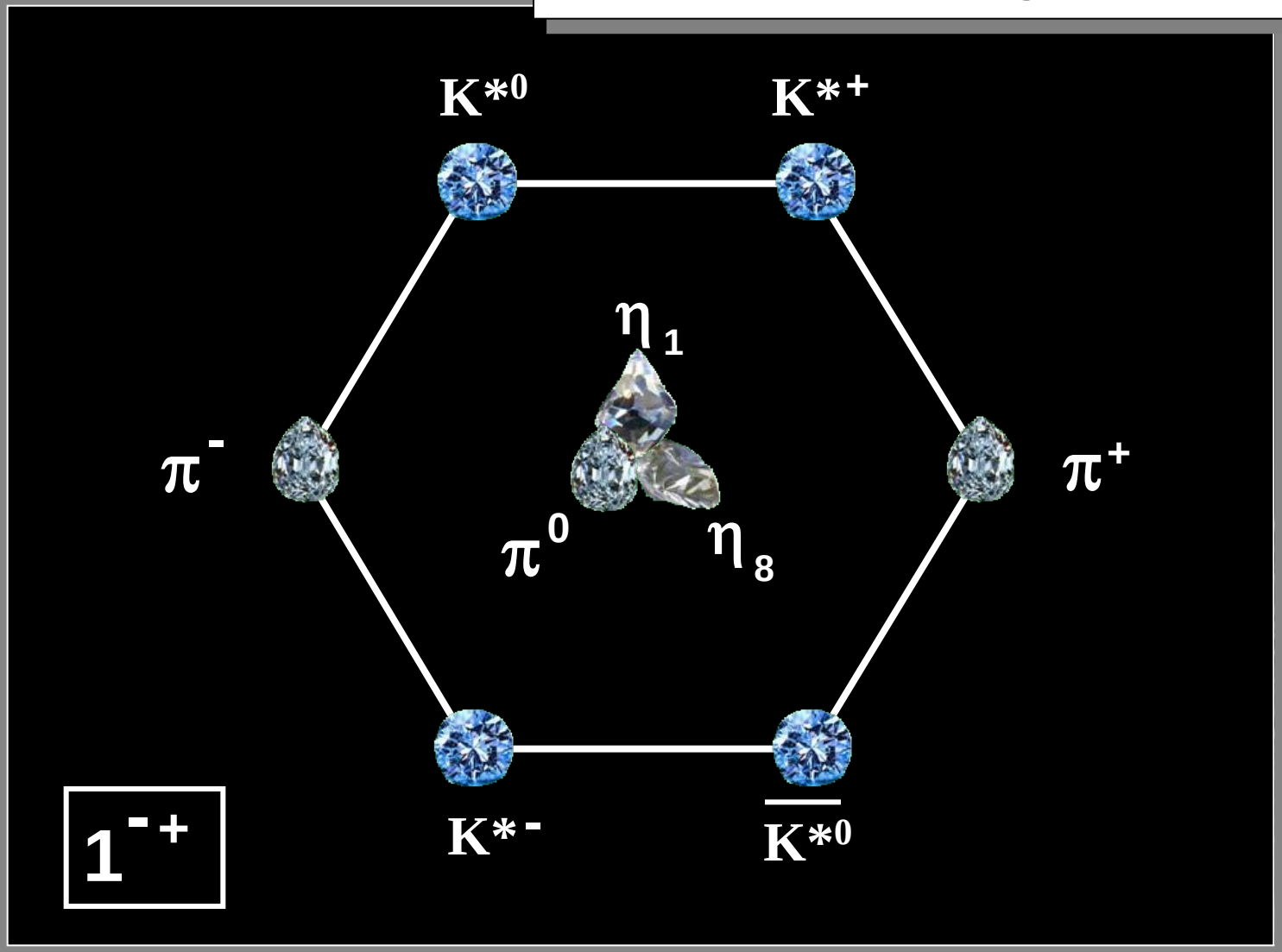
reaction mechanisms

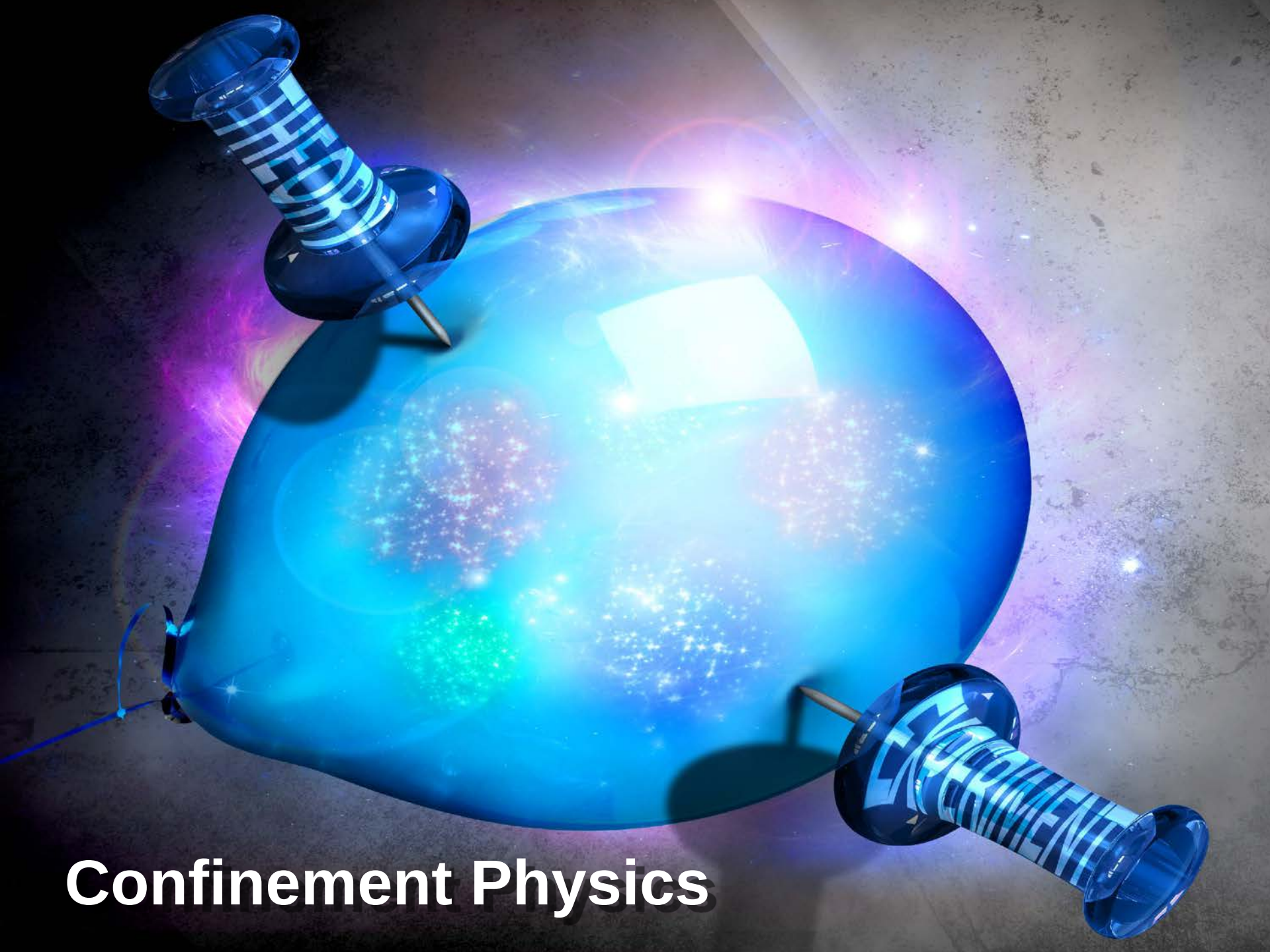




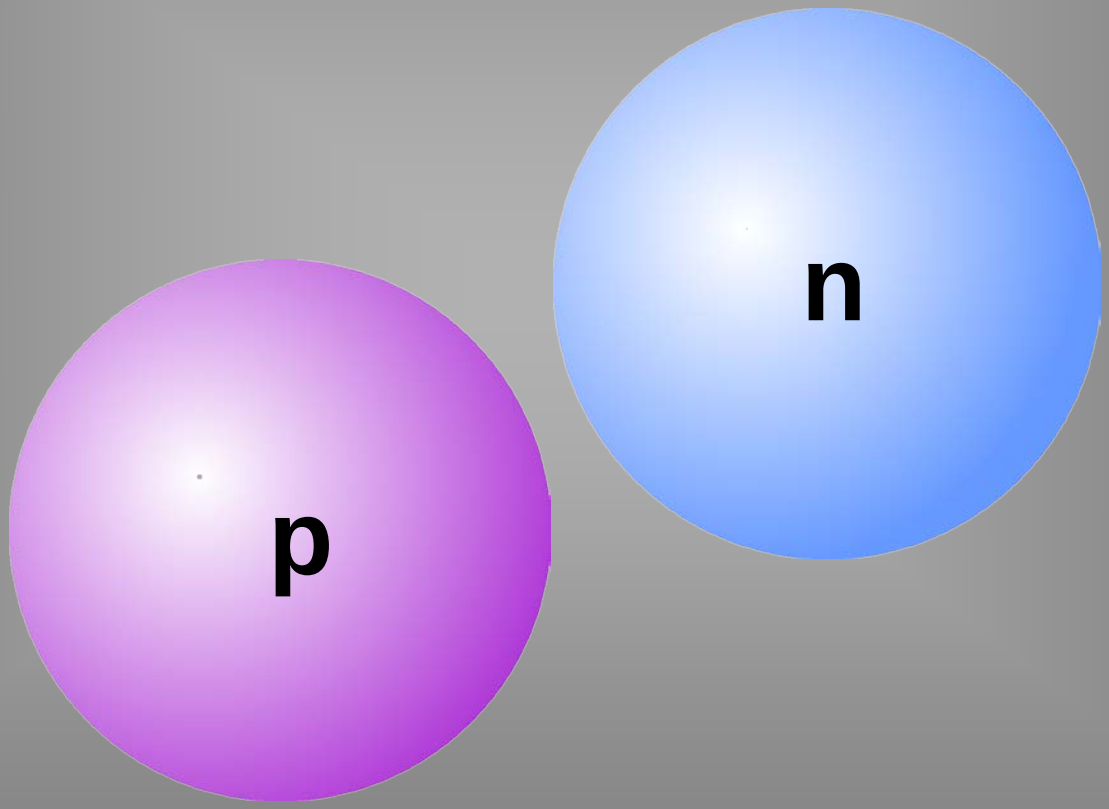
Global working

Precision analysis tools





Confinement Physics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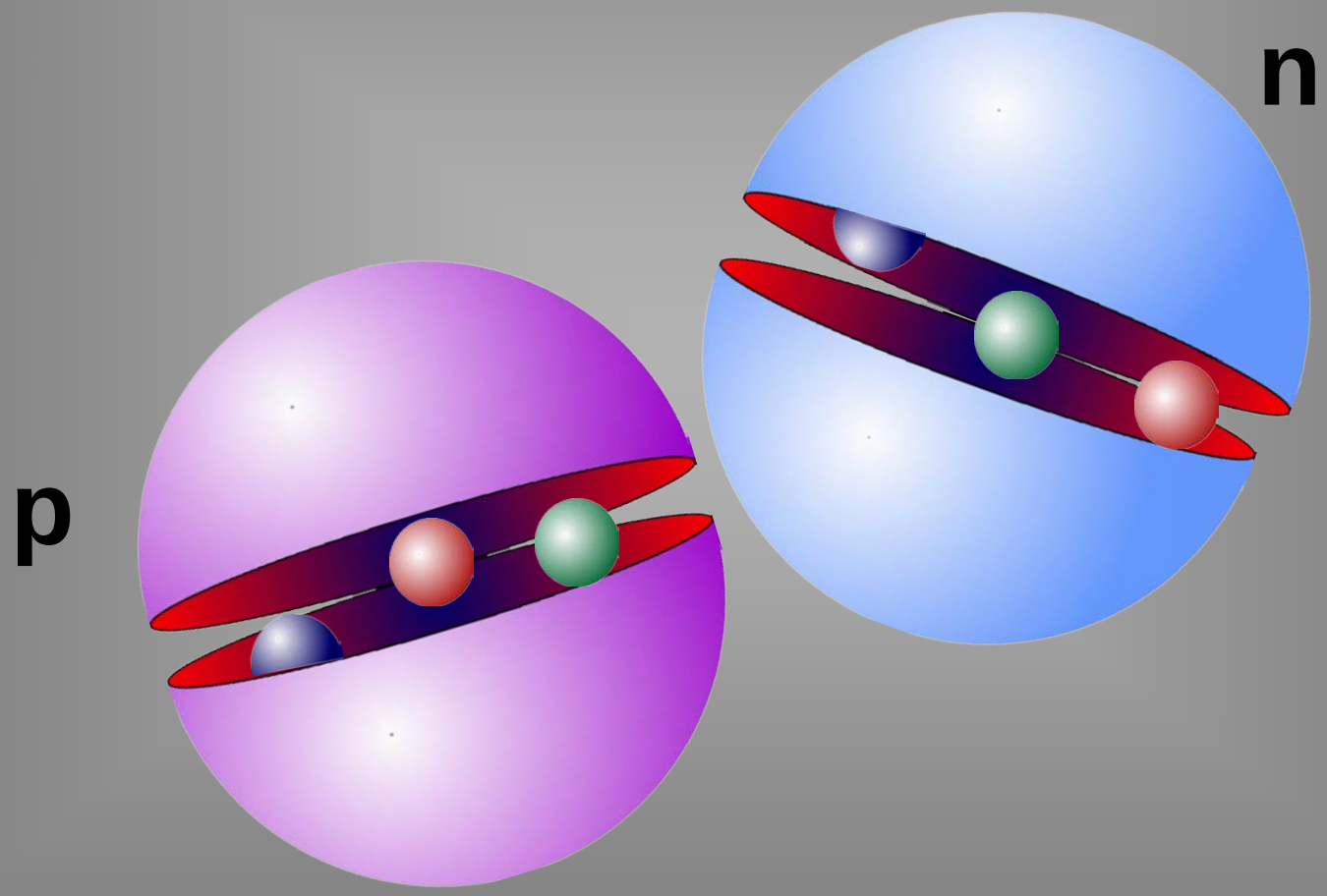
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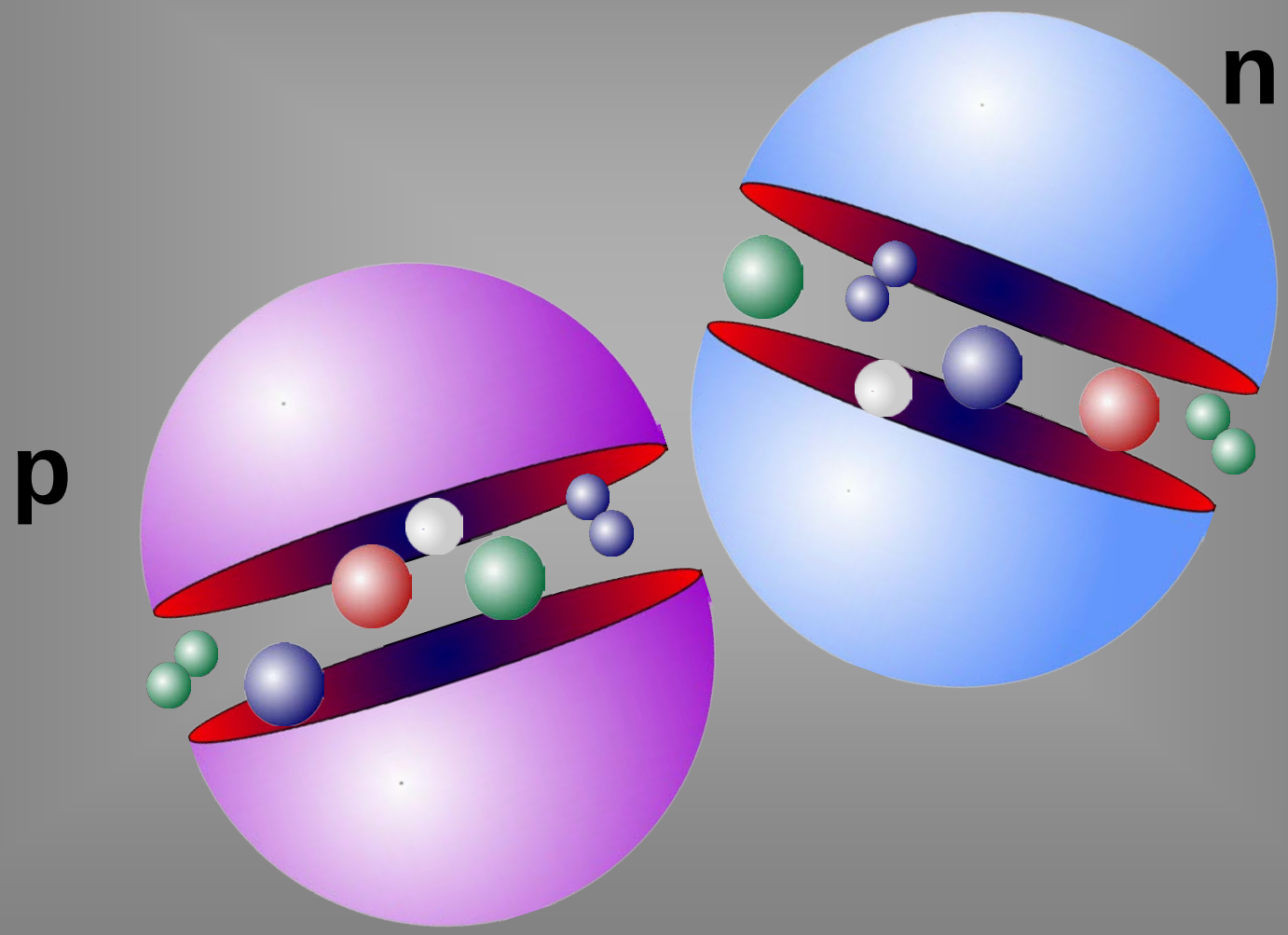
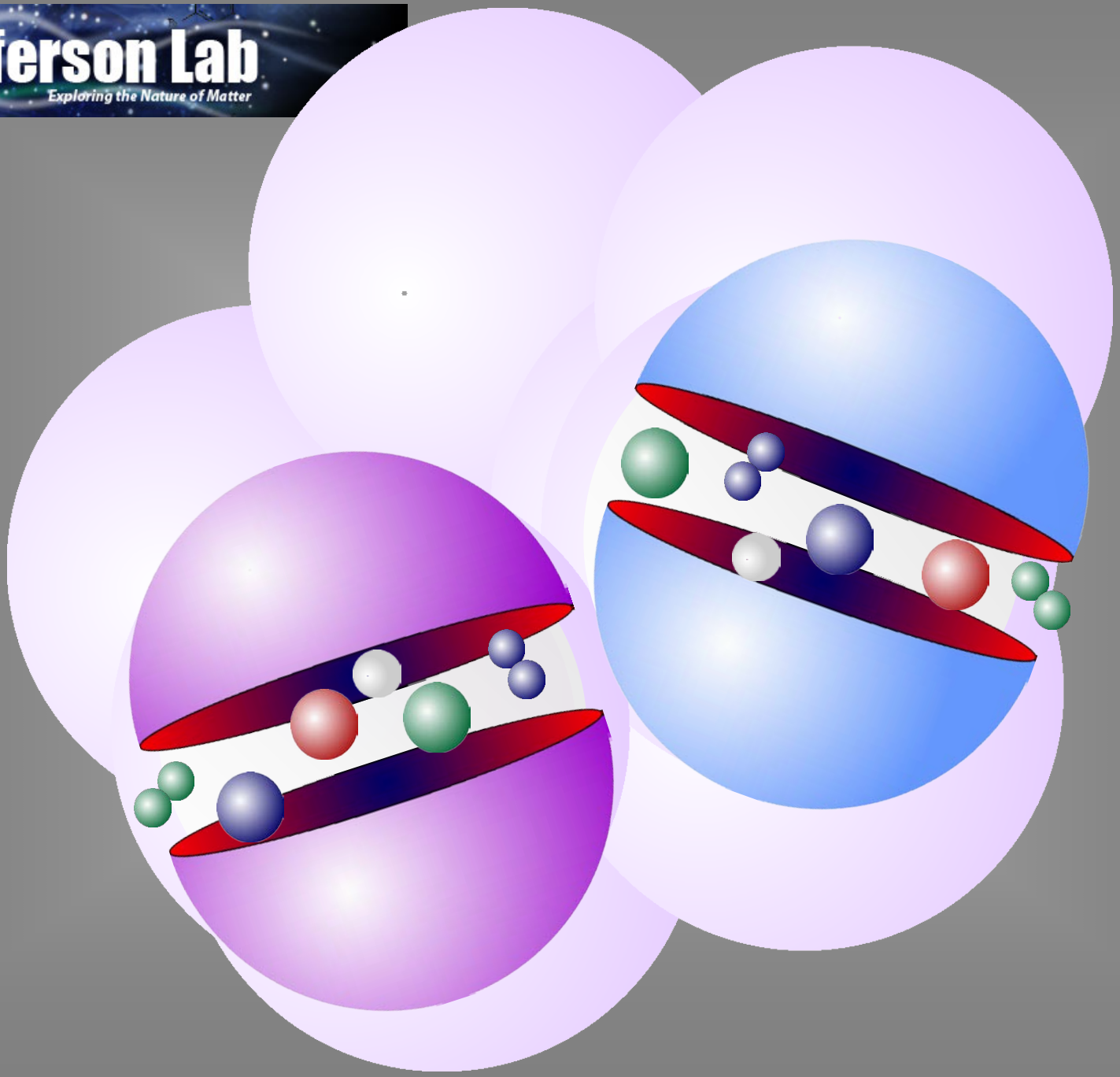
Jefferson Lab
Exploring the Nature of Matter

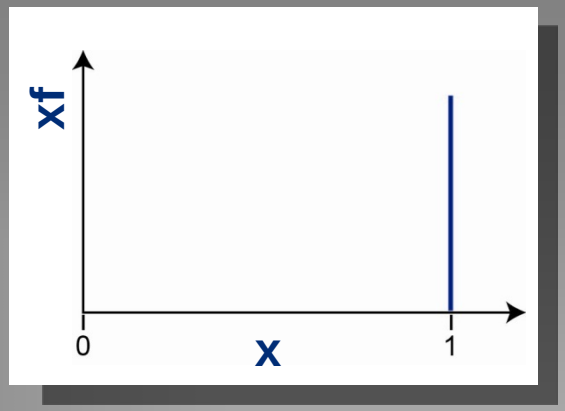


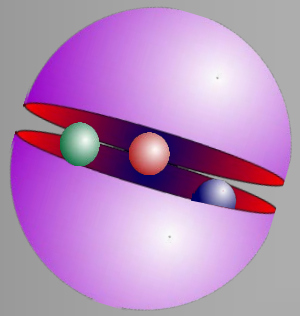
Jefferson Lab

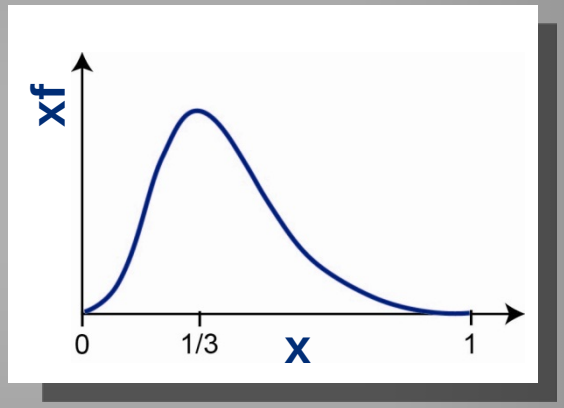
Exploring the Nature of Matter

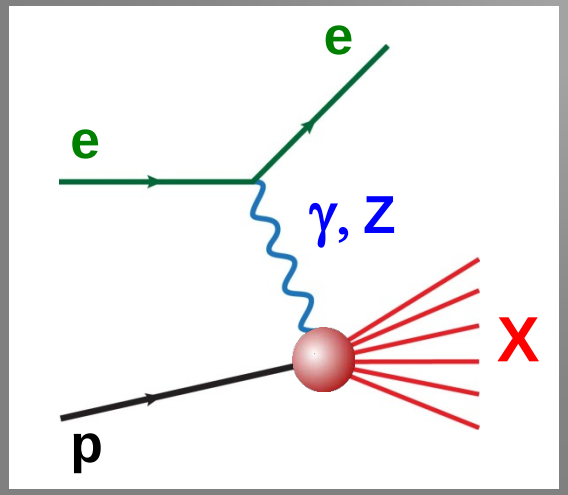


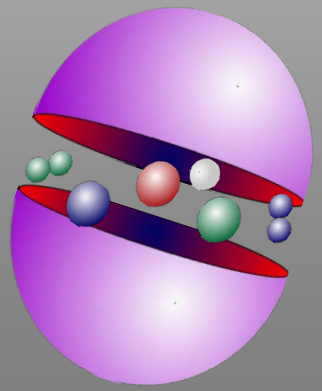
parton structure of the nucleon

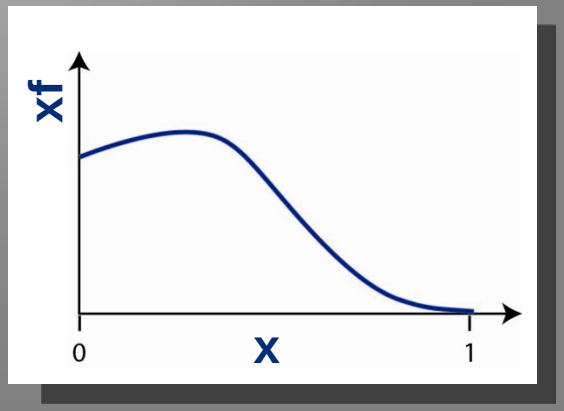




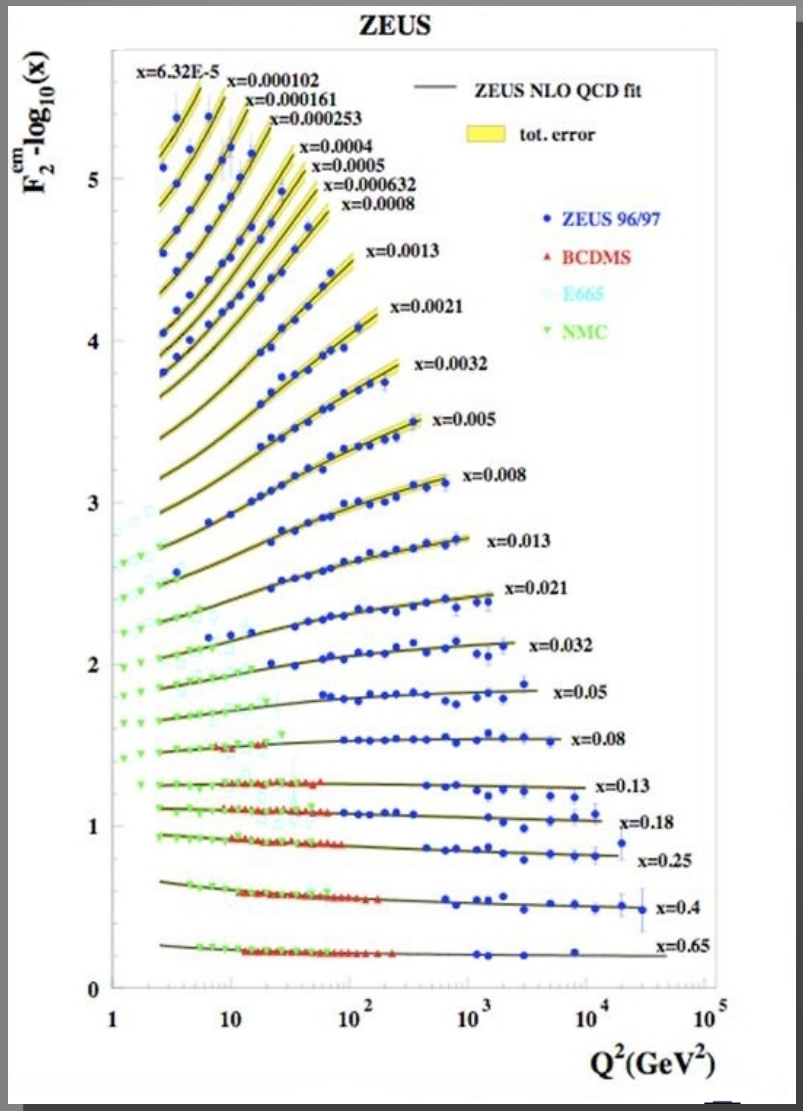


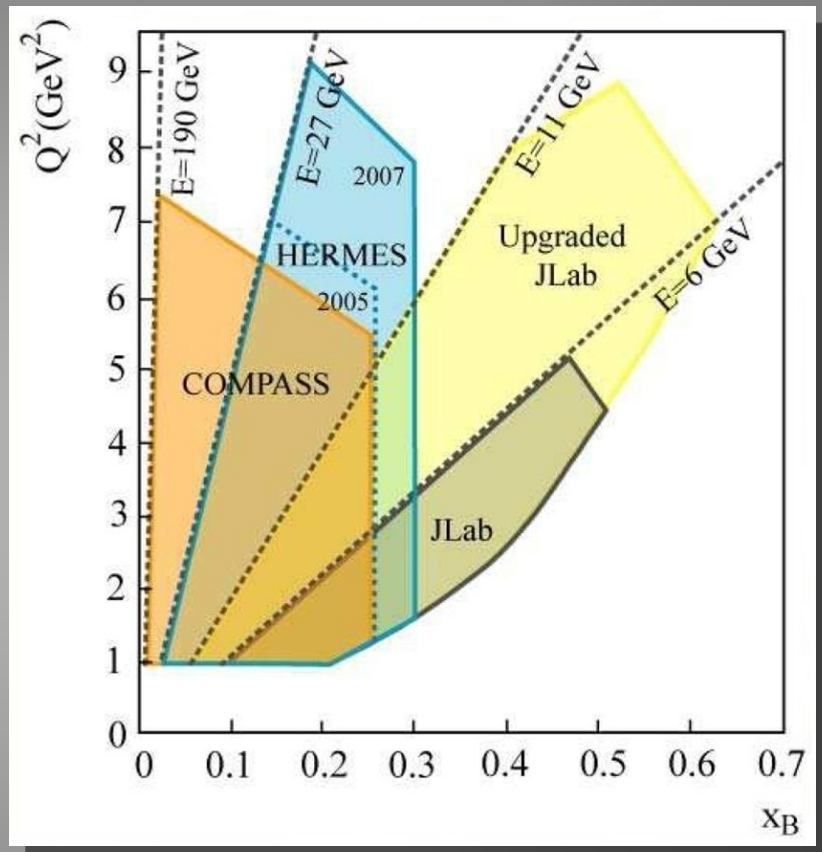




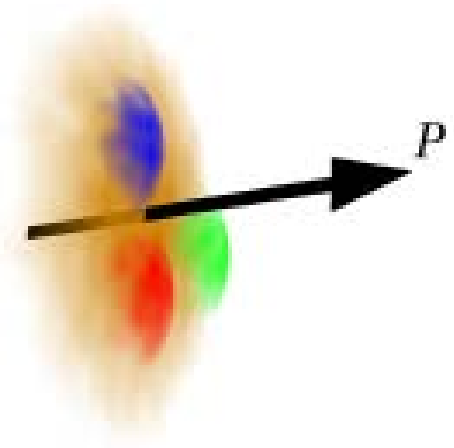


Parton Distribution Functions

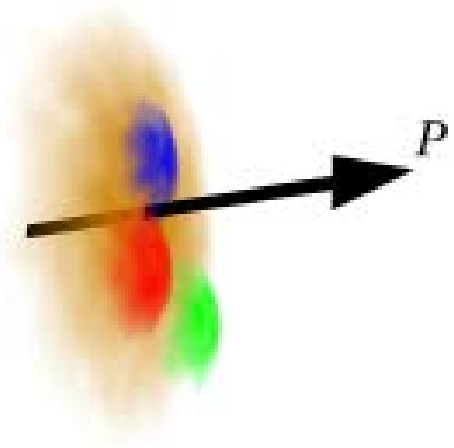




Parton densities



Parton densities



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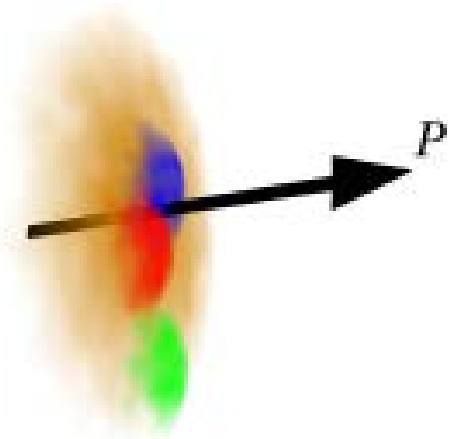

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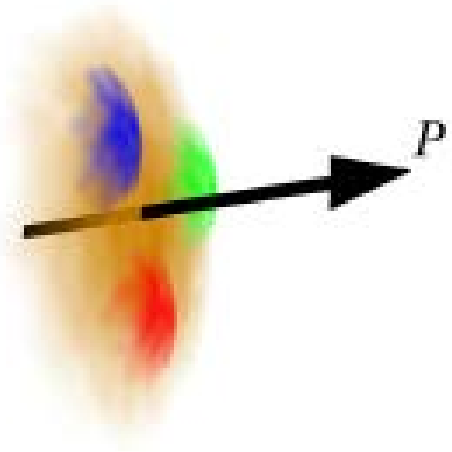

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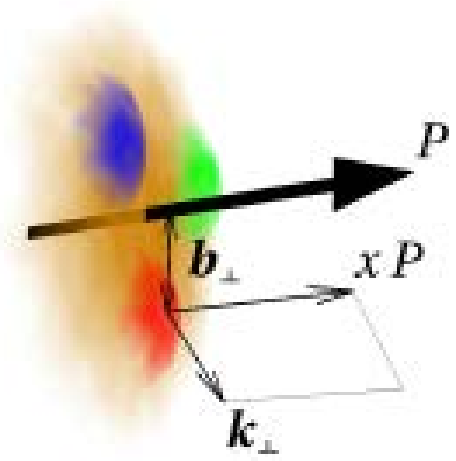
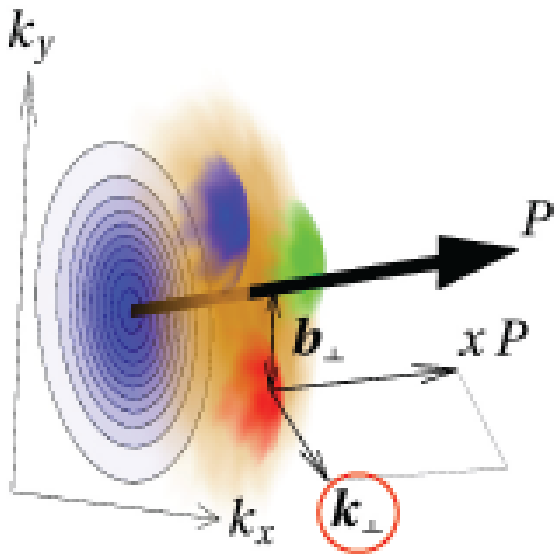
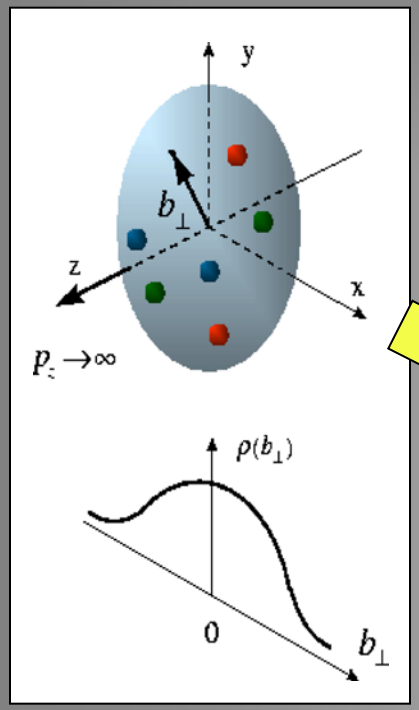


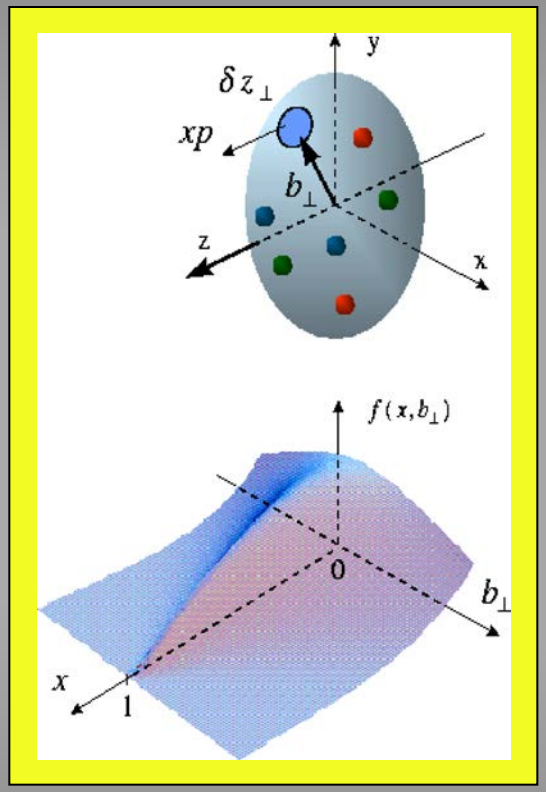
Parton densities

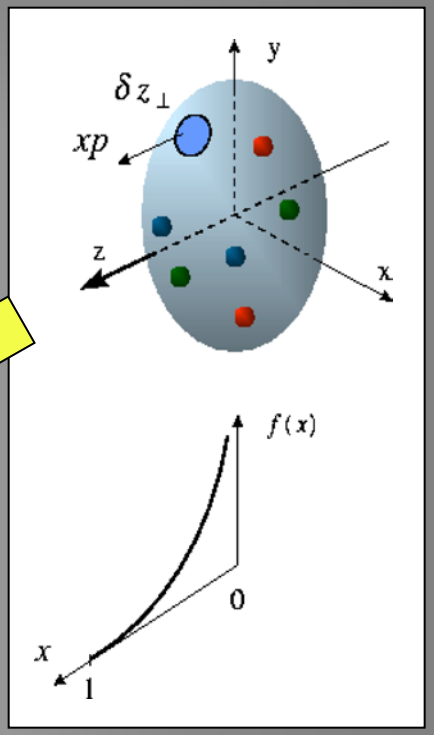


- x (longitudinal momentum fraction) ➡ **PDFs**
- $x, b_\perp$ (impact parameter) ➡ **GPDs**
- $x, k_\perp$ (intrinsic transverse momentum) ➡ **TMDs**

Internal Landscape of the Hadron







Form factors

transverse charge & current densities In coordinate space

GPDs, TMDs

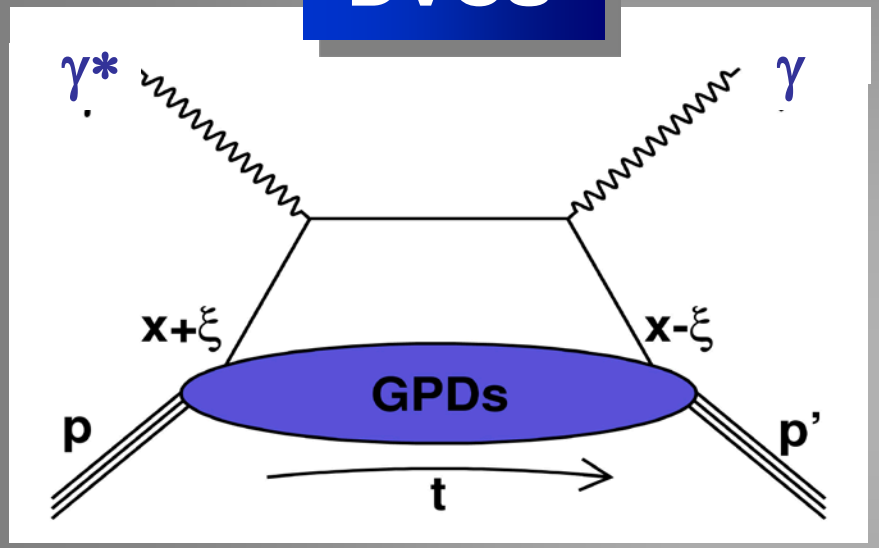
correlated quark distributions in longitudinal & transverse space

Structure fns

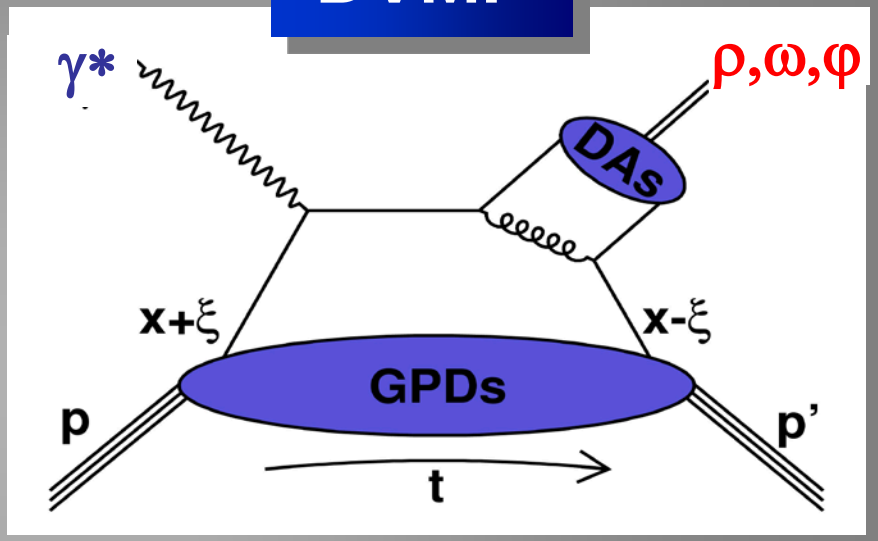
longitudinal quark momentum distributions

Accessing GPDs

DVCS

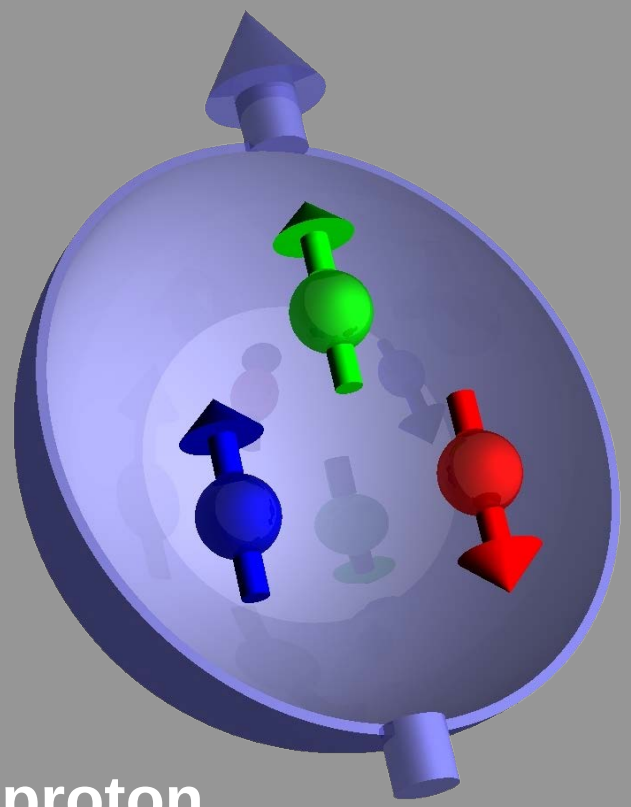


DVMP



$H(x, \xi, t, Q)$

Internal Landscape of the Hadron



proton

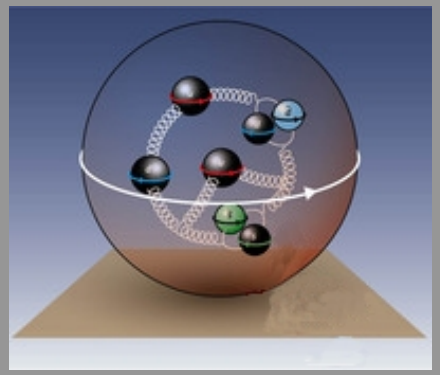
Spatial

Momentum

Flavor

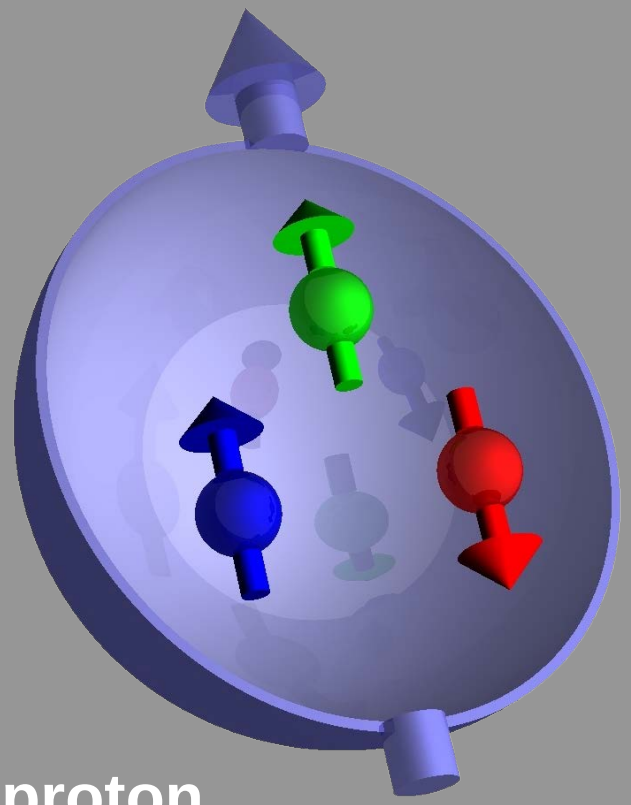
Angular momentum

Parton Distribution Functions

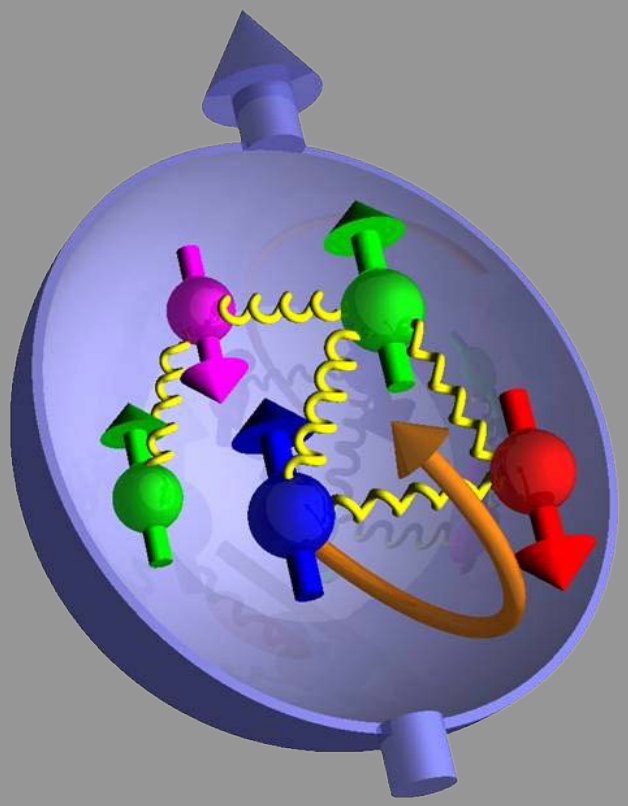


Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

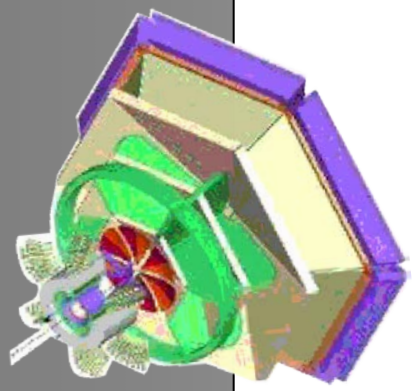
Spin of the proton



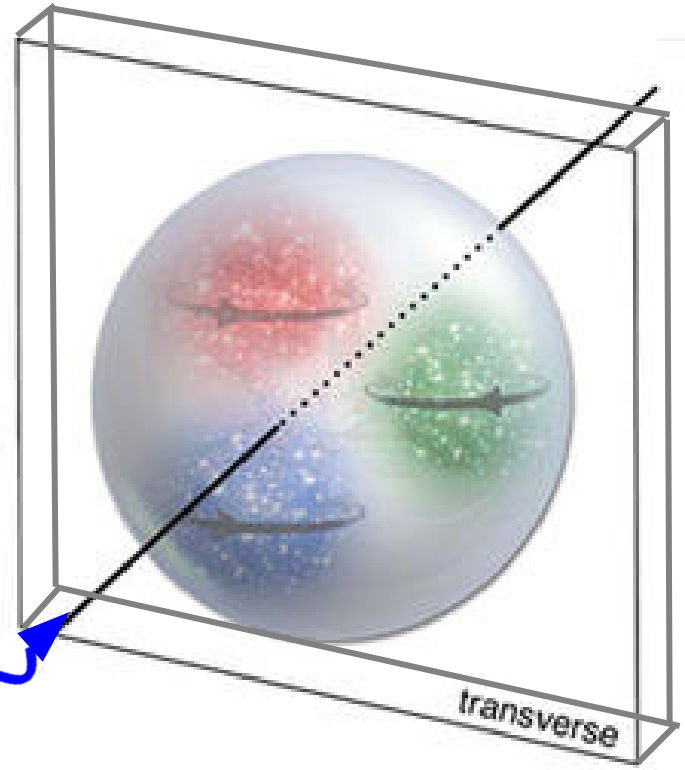
proton

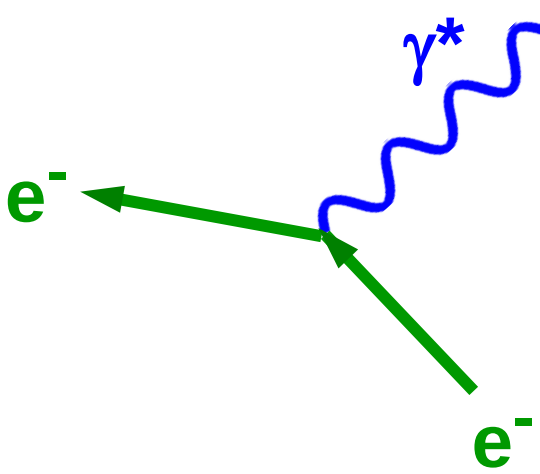


Revealing orbital motion



CLAS12

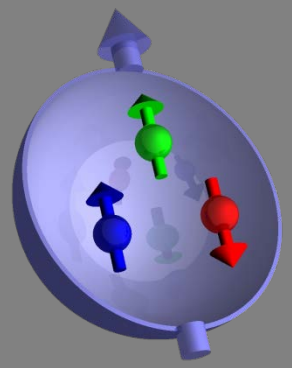




COMPASS

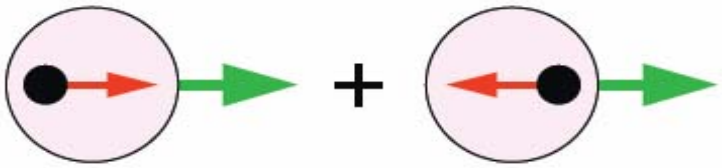
hermes

Spin of the proton

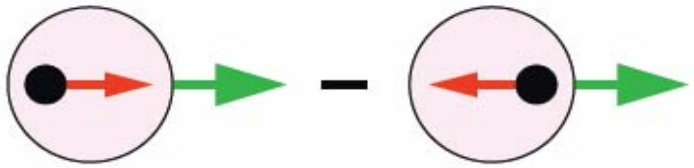


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

$$q(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$$



$$\Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$$

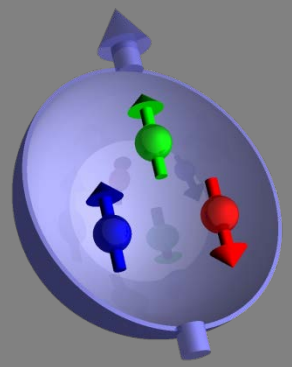


$$\Delta\Sigma \equiv \int dx\, \left(\Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta\bar{u}(x) + \Delta\bar{d}(x) + \Delta\bar{s}(x)\right)$$

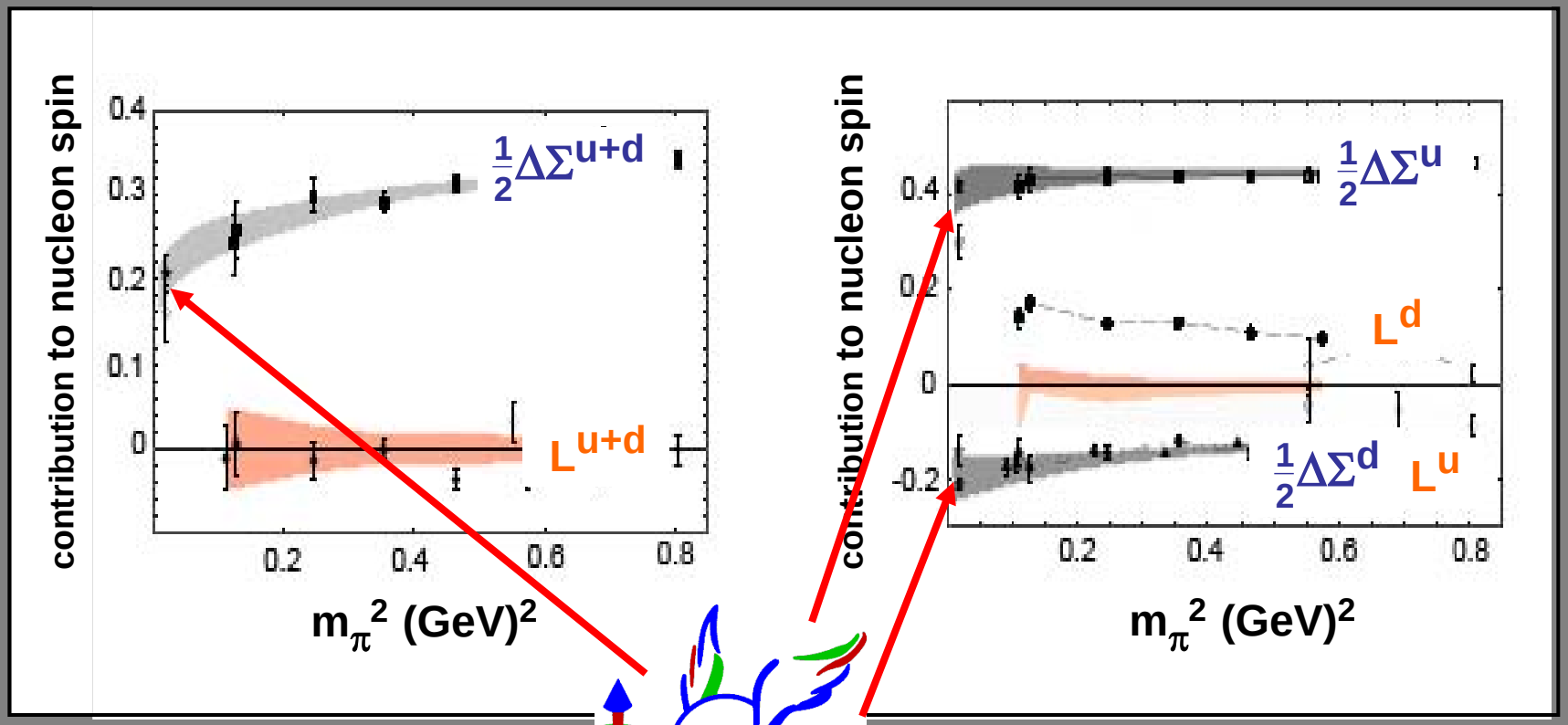
~ 20%

evolves with Q^2 : here $Q^2 > 5\ \mathrm{GeV}^2$

Spin of the proton: Lattice v Experiment



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$



LHPC, Haegler *et al.*

hermes

No disconnected contributions

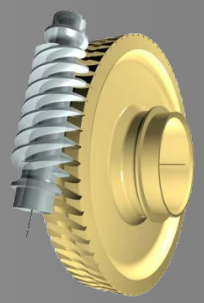
Transverse Momentum Distributions

nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

at leading twist

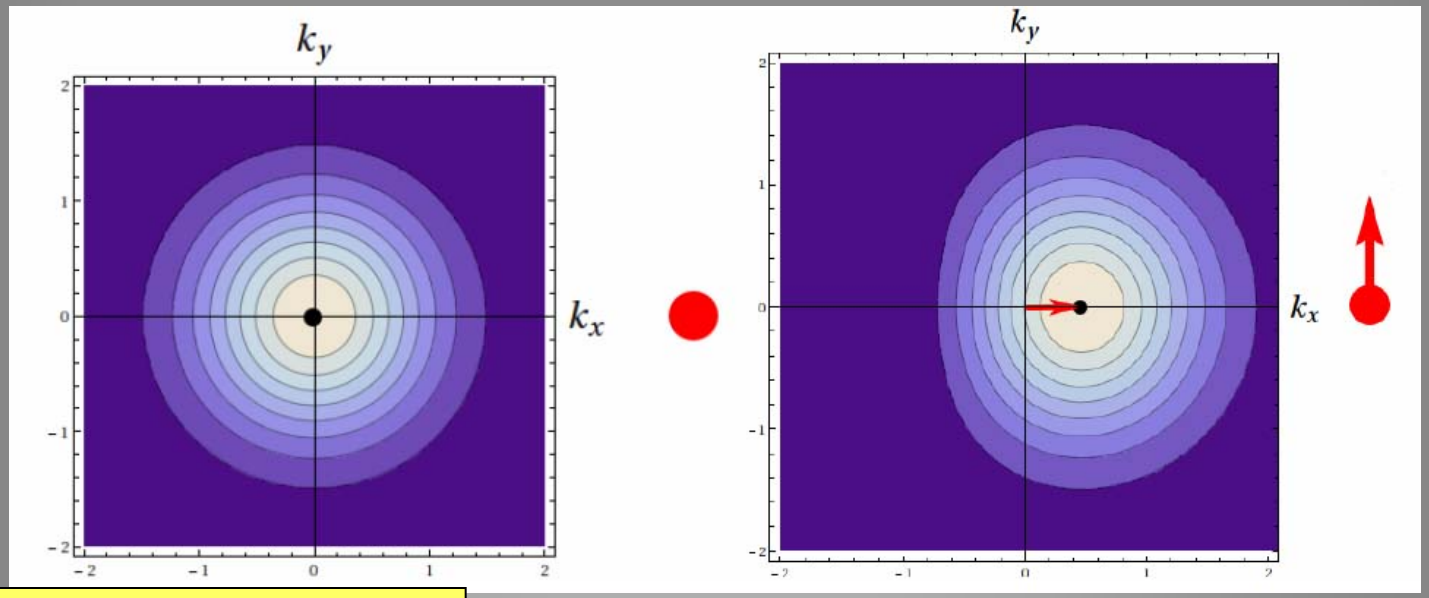
Transverse Momentum Distributions

nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 $h_{1T}^\perp$



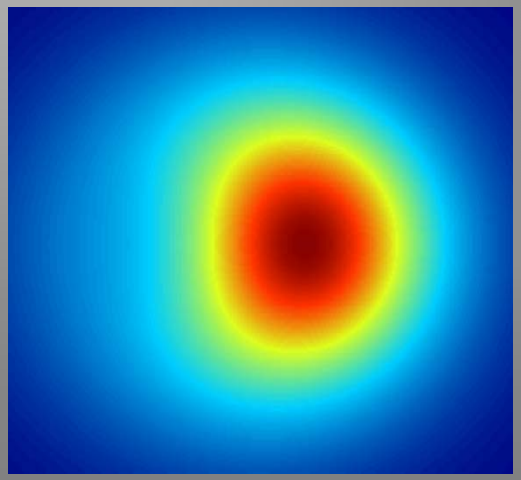
transversity pretzelosity

Tomographic scan of the nucleon

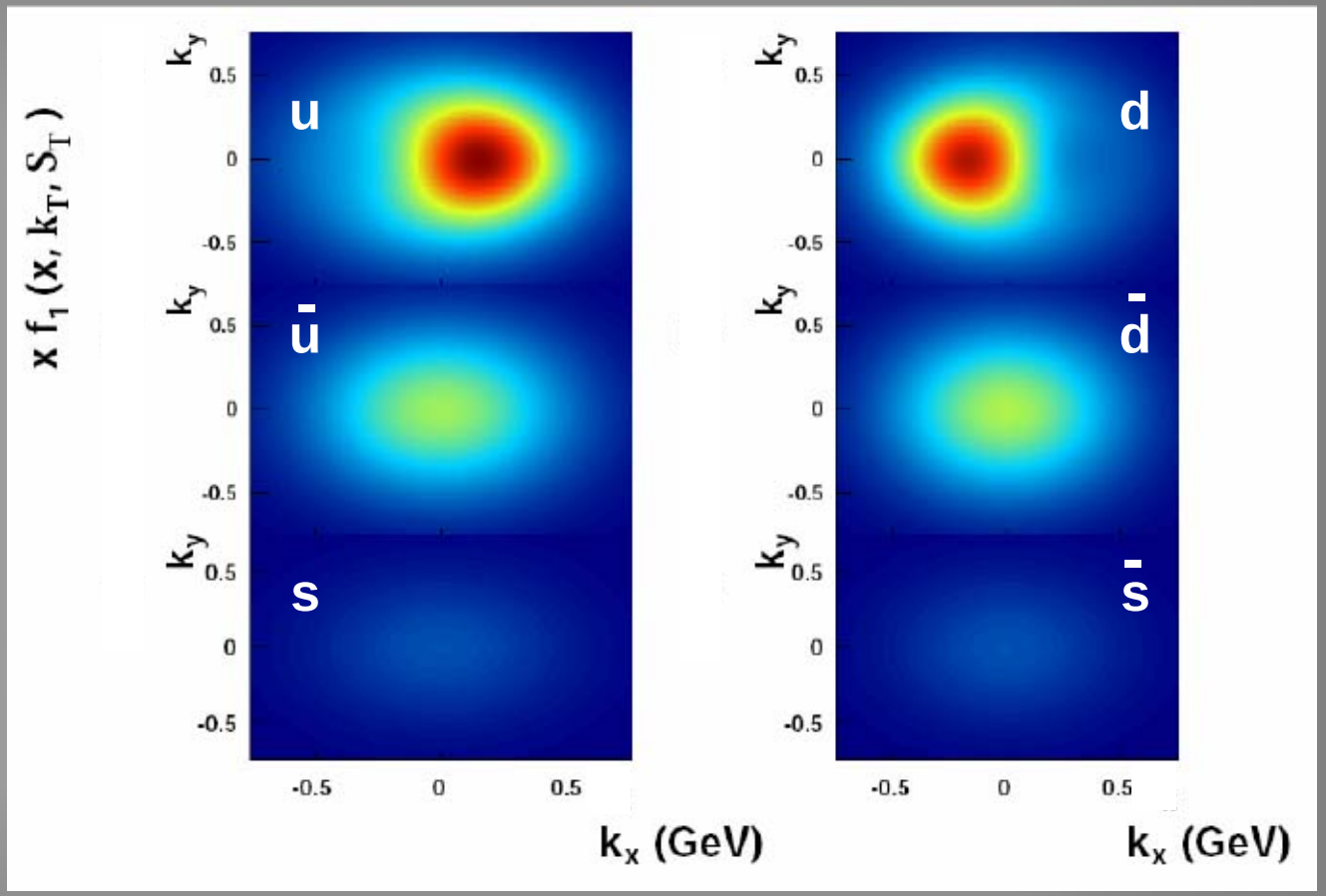


$$f\,(\,x,\,z,\,Q^2,\,p_T\,)$$

experiment

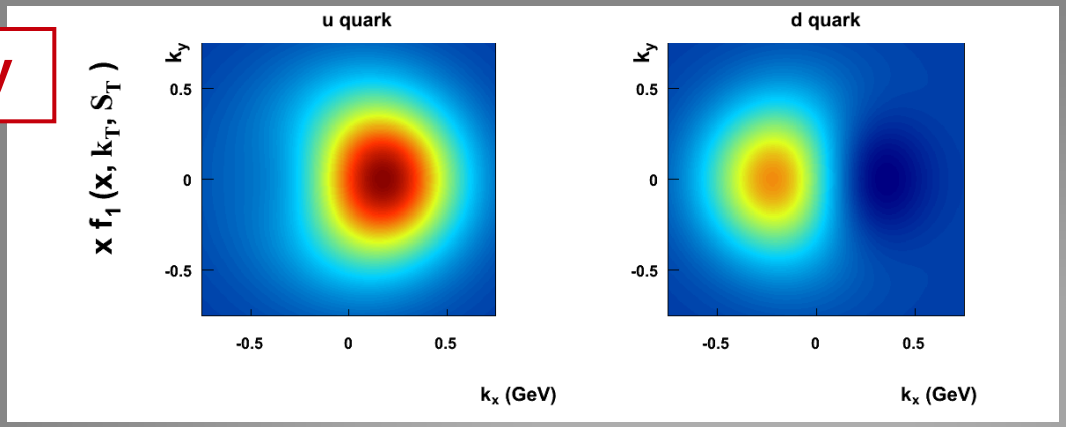


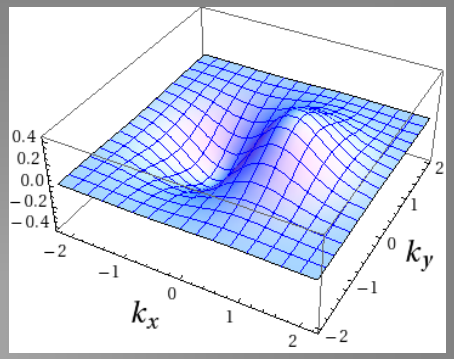
Tomographic scan of the nucleon



Tomographic scan of the nucleon

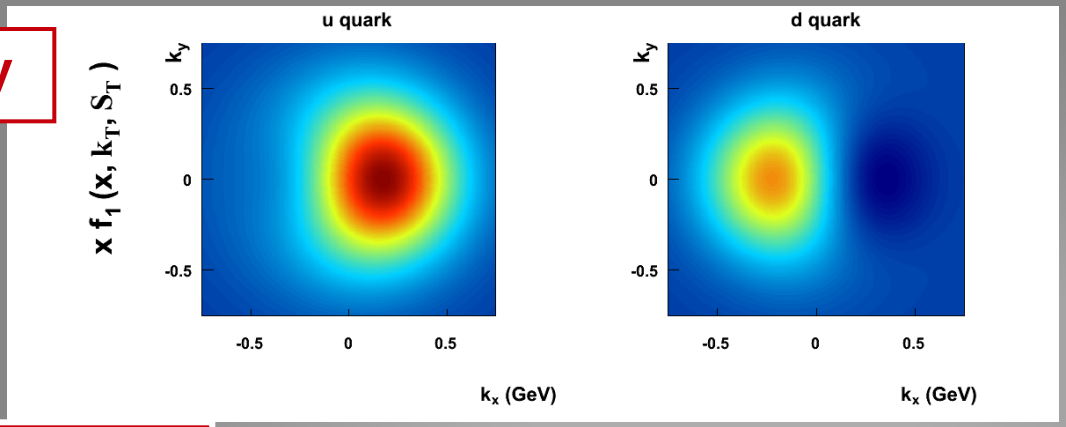
Theory

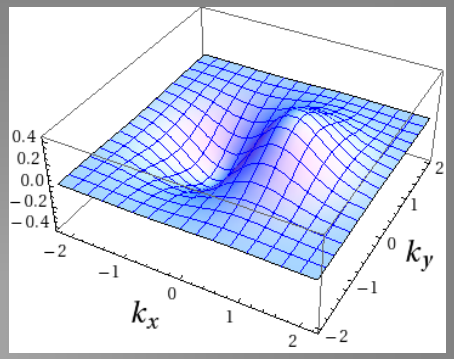




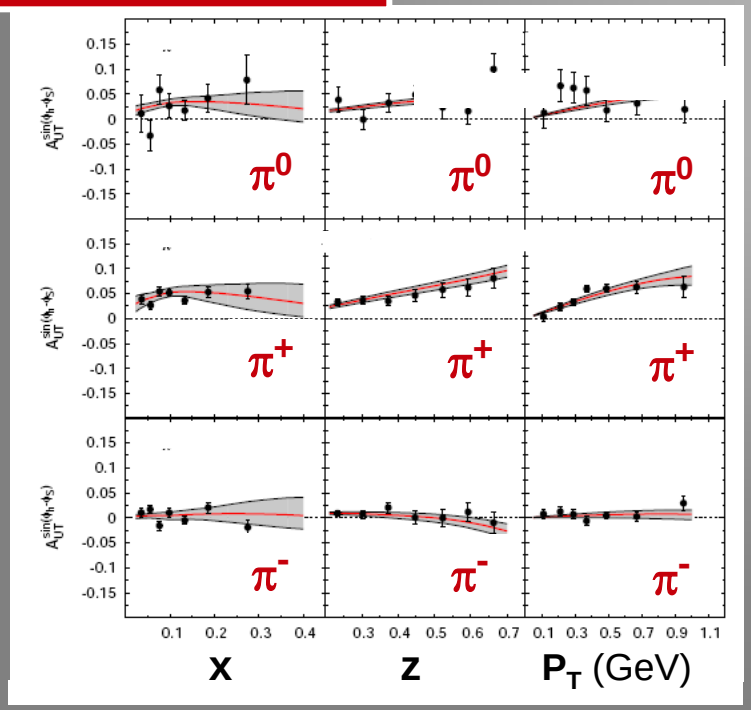
Tomographic scan of the nucleon

Theory



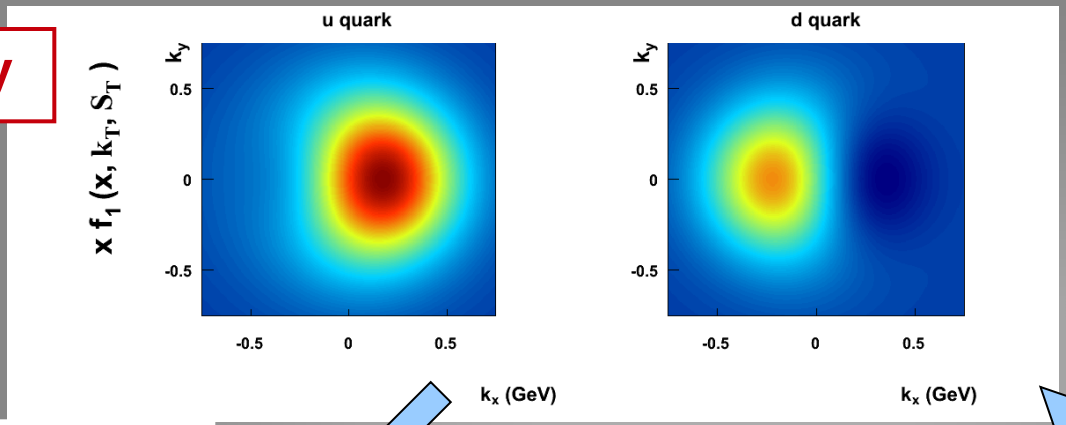


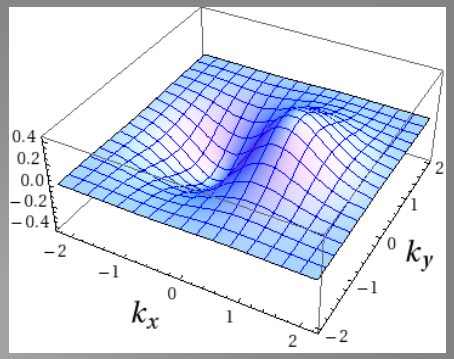
Measurement



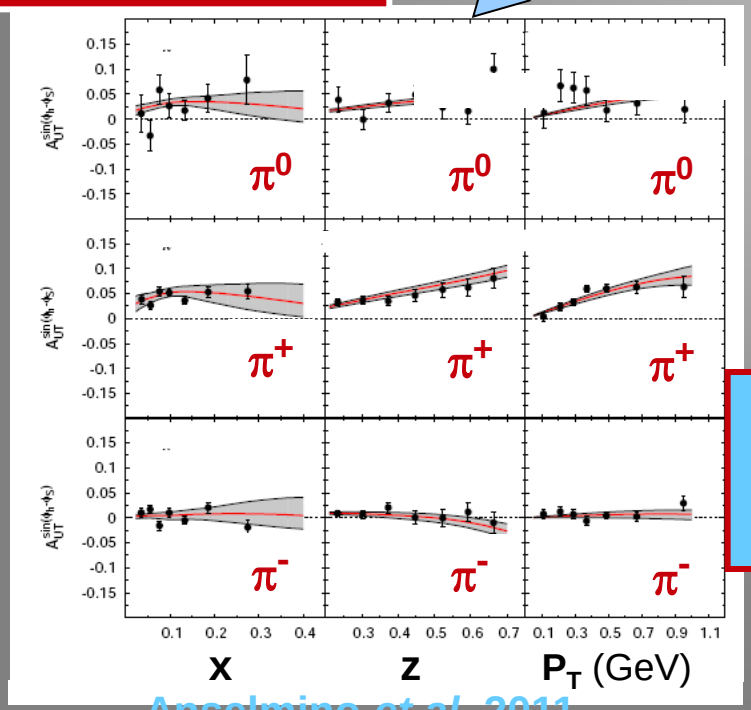
Tomographic scan of the nucleon

Theory





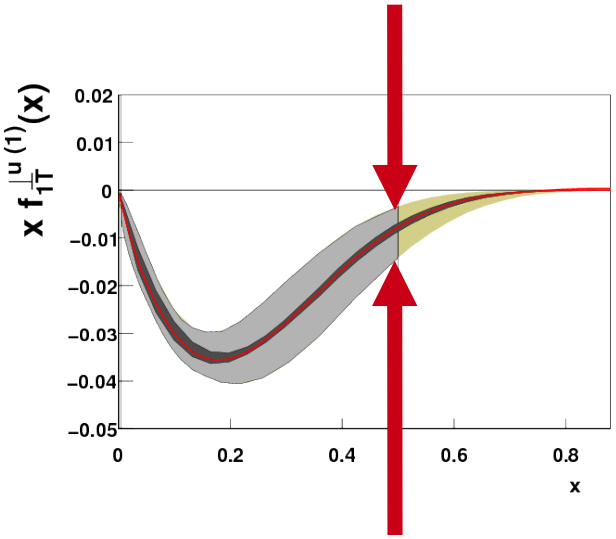
Measurement



Anselmino *et al* 2011

Global analysis of the data and projections

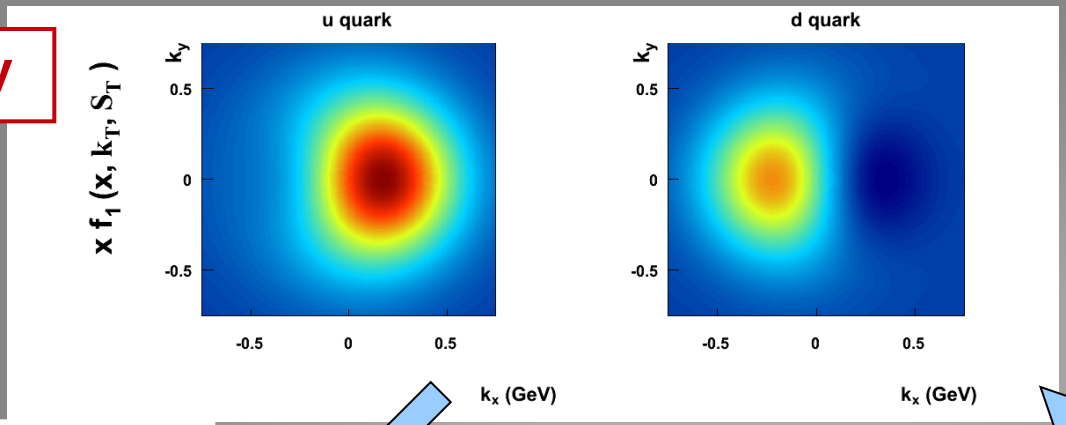
Results

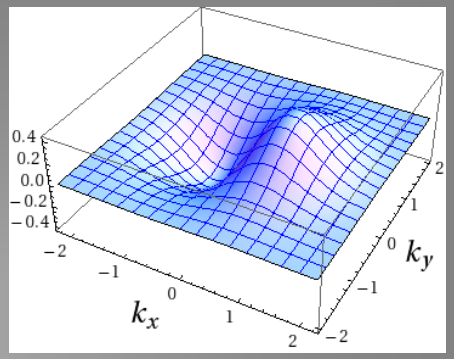


modern knowledge

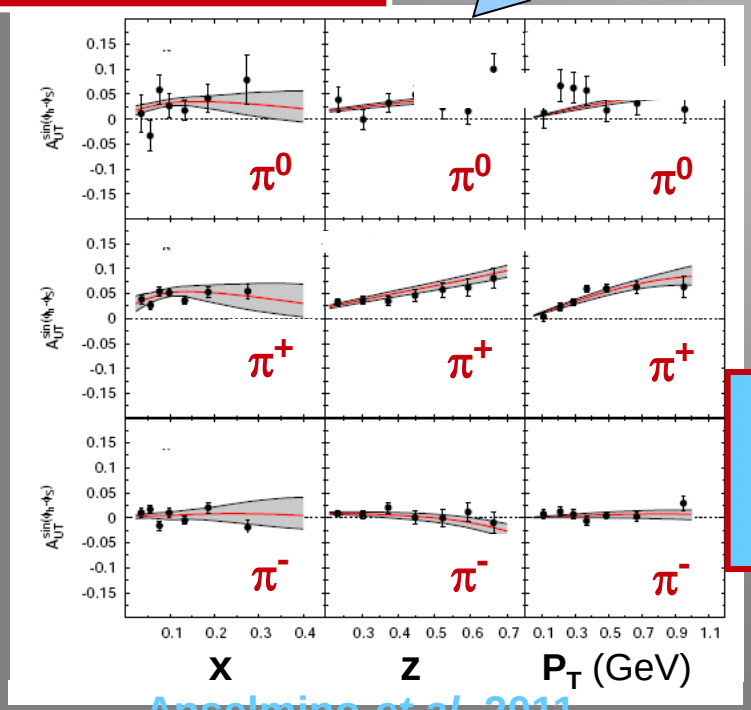
Tomographic scan of the nucleon

Theory





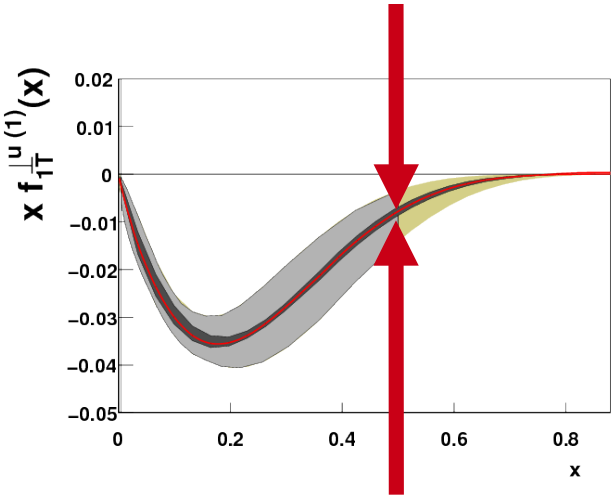
Measurement



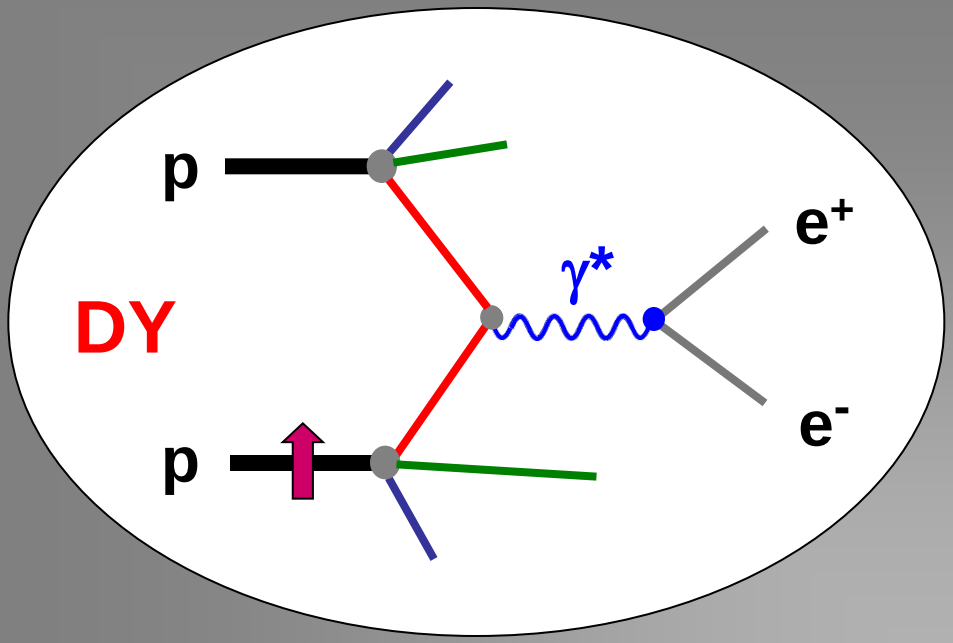
Anselmino *et al* 2011

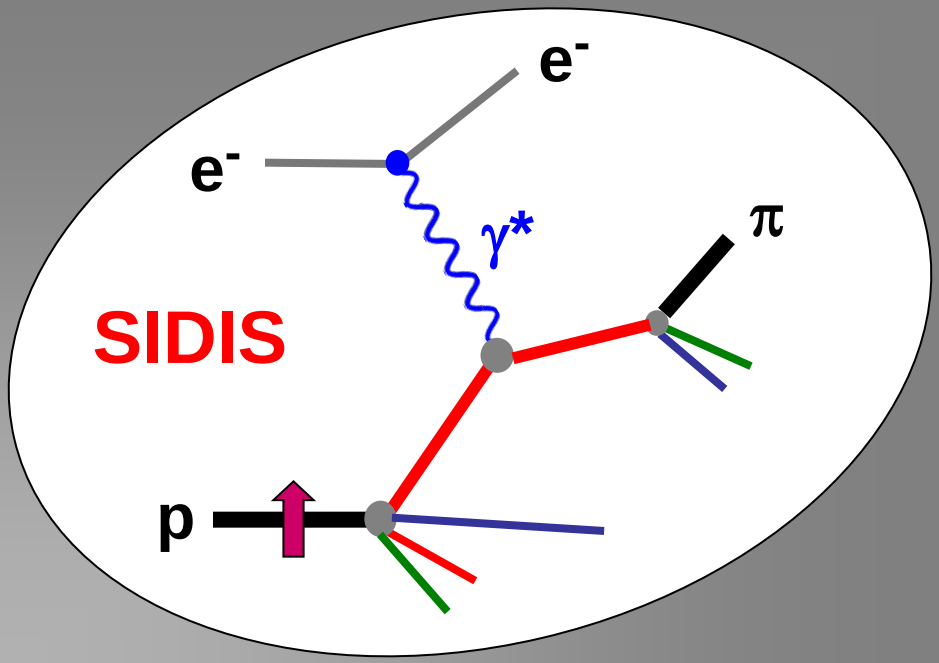
Global analysis of the data and projections

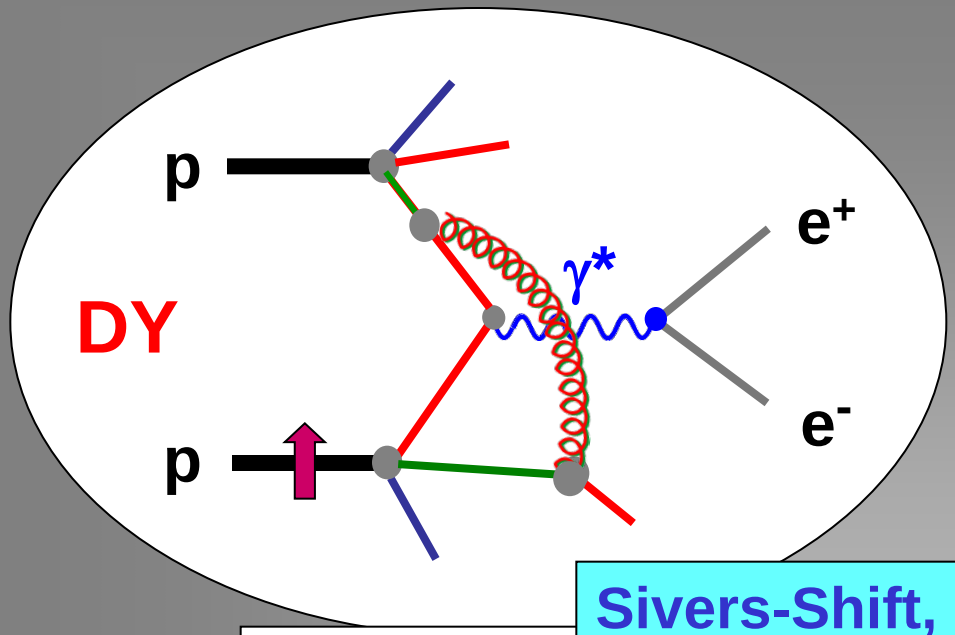
Results

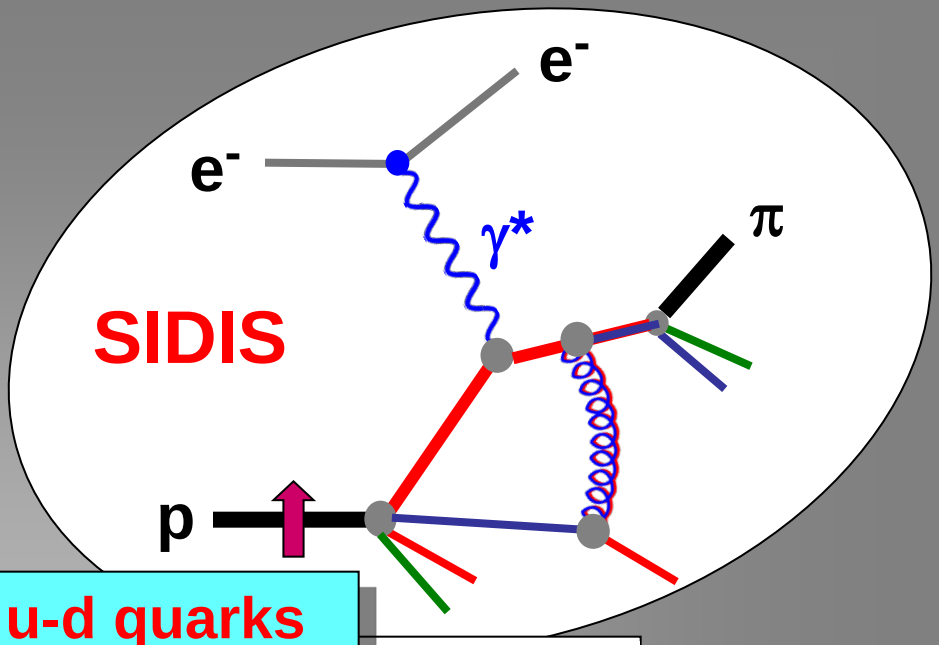


after 1 year of JLab 12

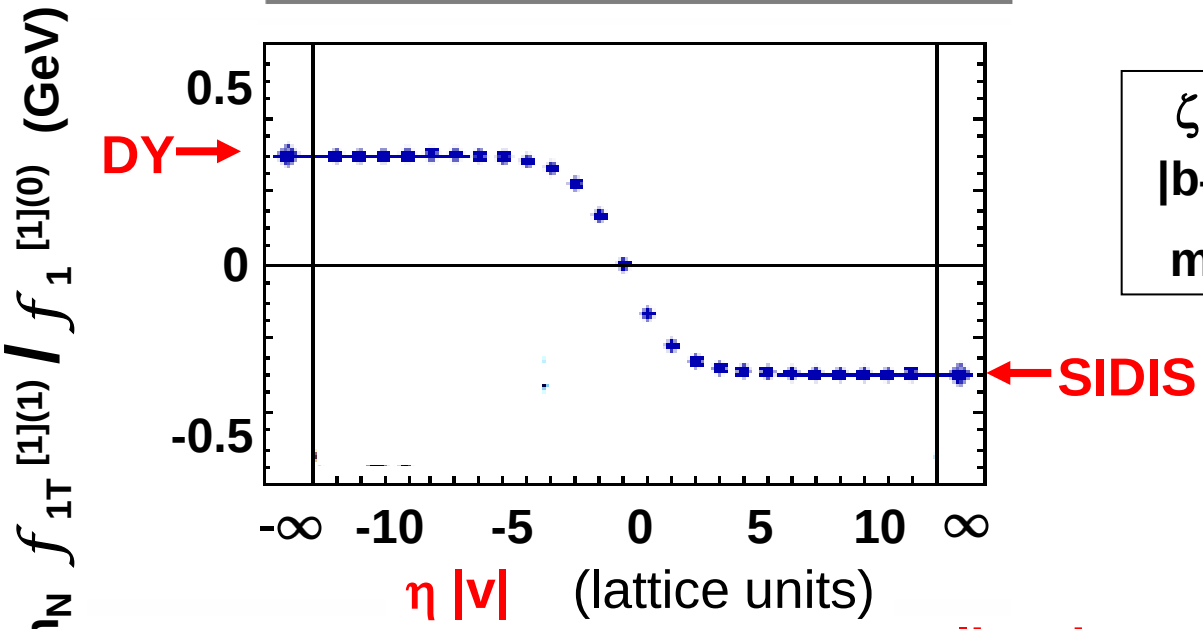

p
p
DY
γ*
e+
e-


e-
e-
γ*
π
SIDIS
p





Sivers-Shift, u-d quarks



$\zeta^2 = 0.39$

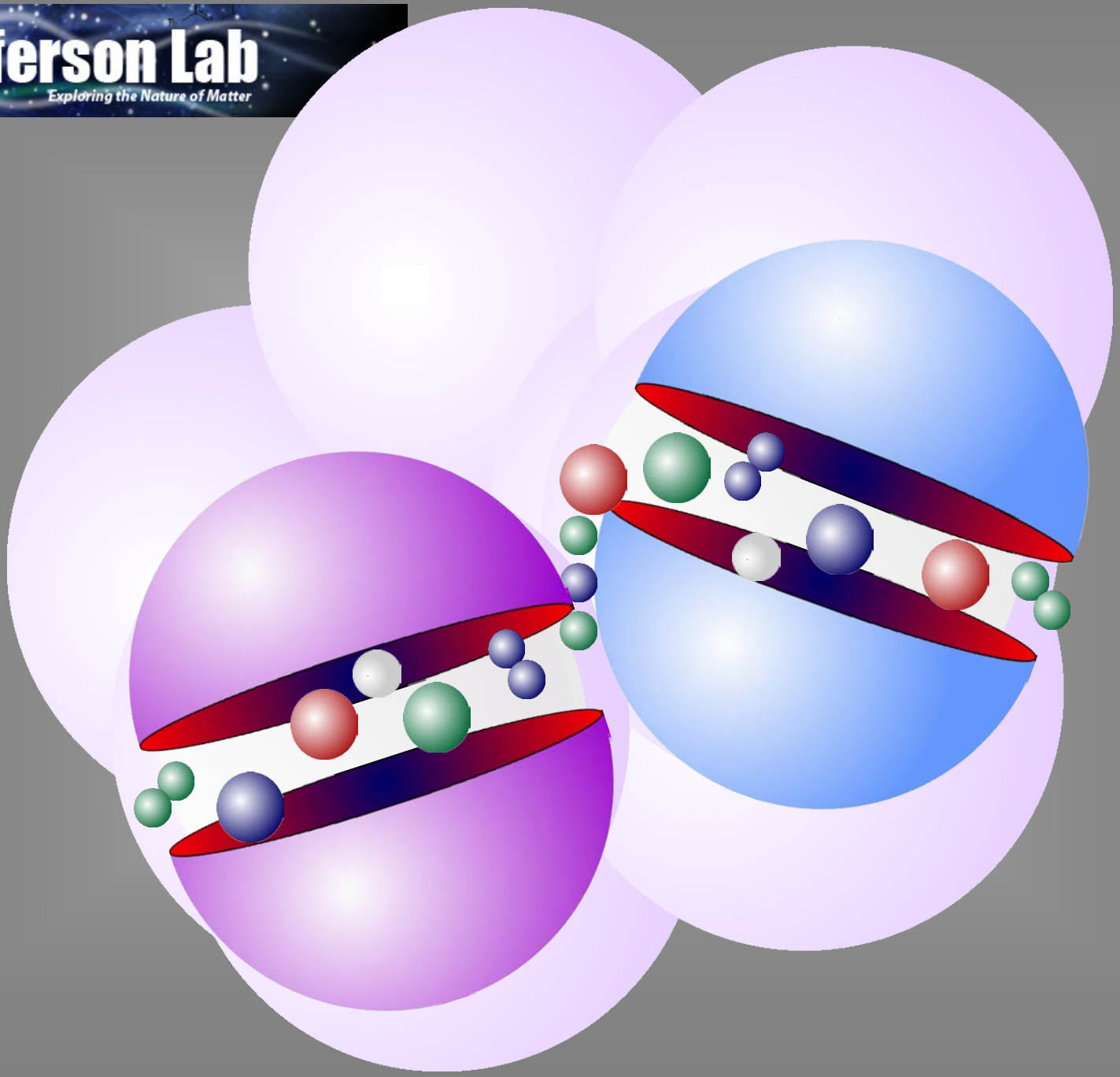
$|b_T| = 0.12$ fm

$m_\pi = 518$ MeV

Engelhardt *et al.*

Jefferson Lab

Exploring the Nature of Matter



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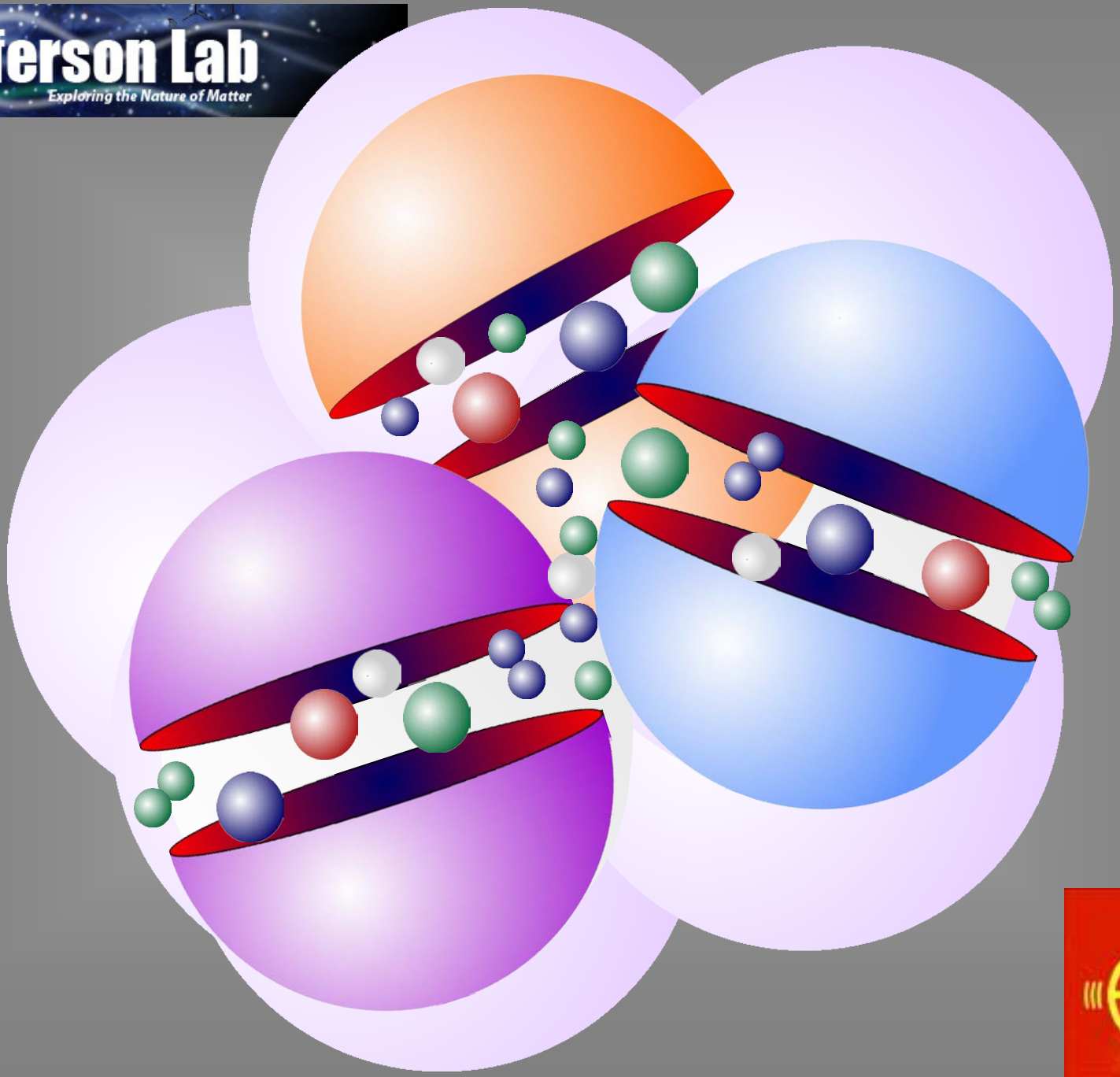
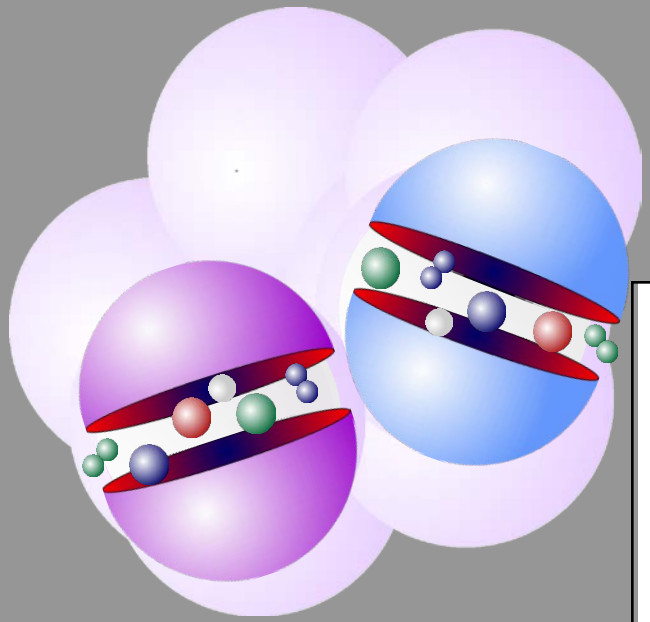
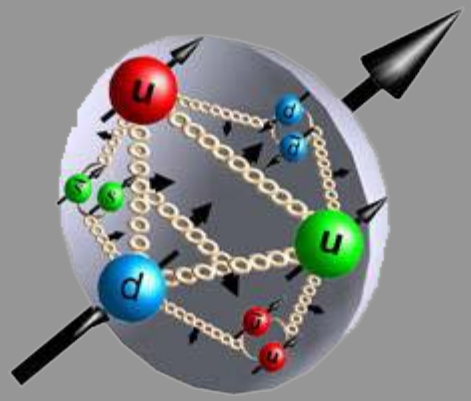
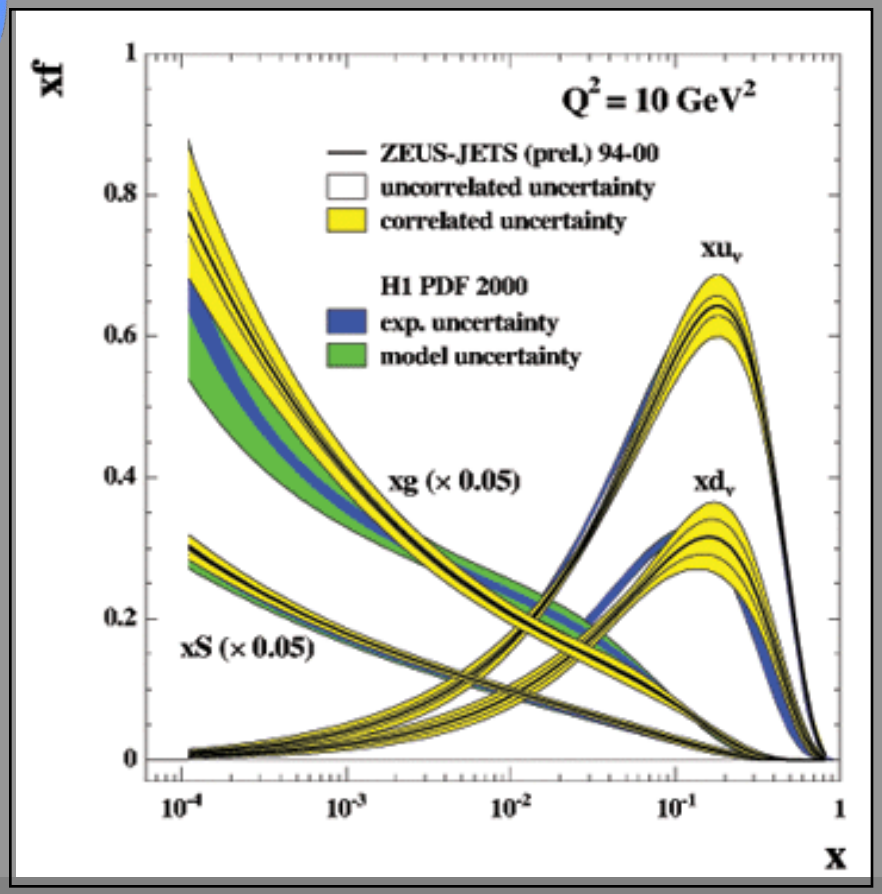
Exploring the Nature of Matter



Electron Ion Collider





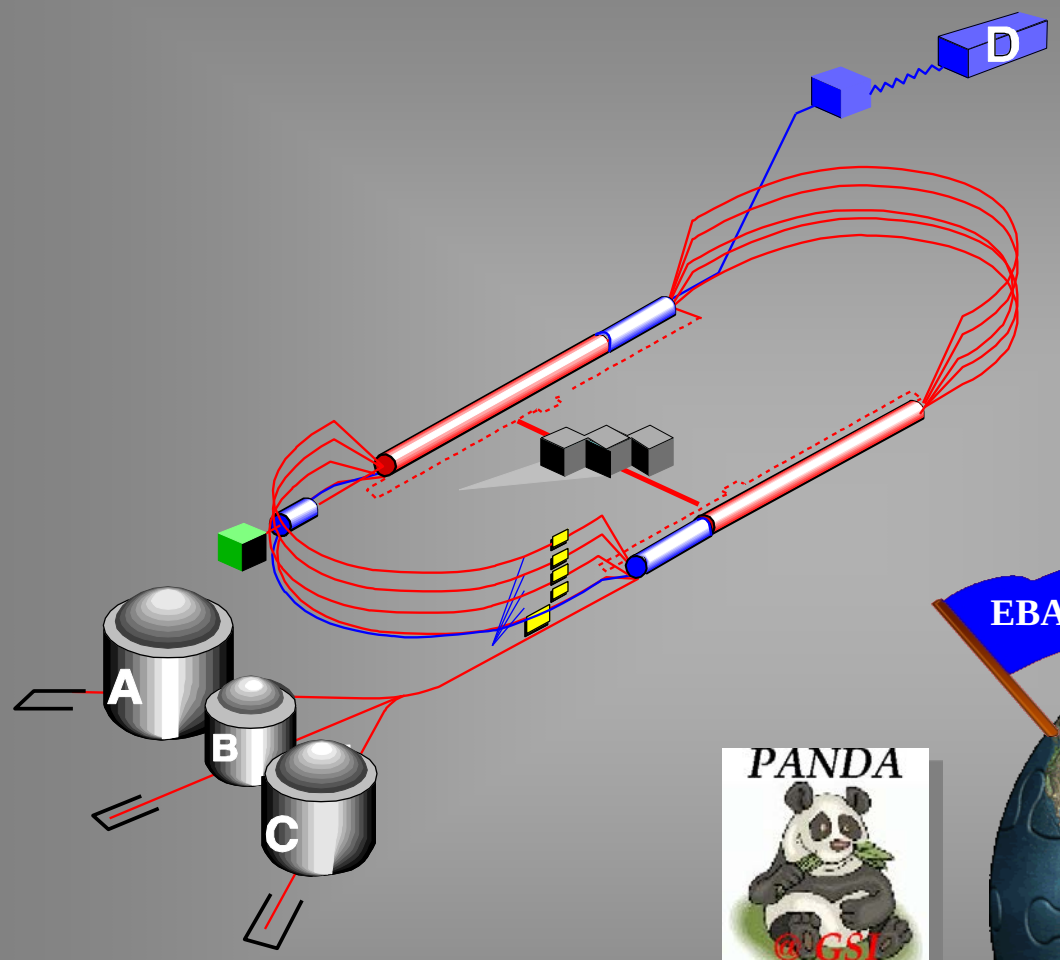


New states of matter

Color glass Condensate?

Jefferson Lab 12 GeV upgrade

Exploring the Nature of Matter



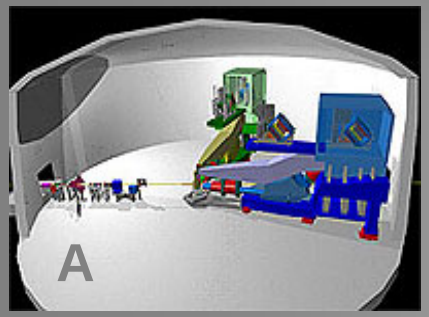
PANDA @ GSI

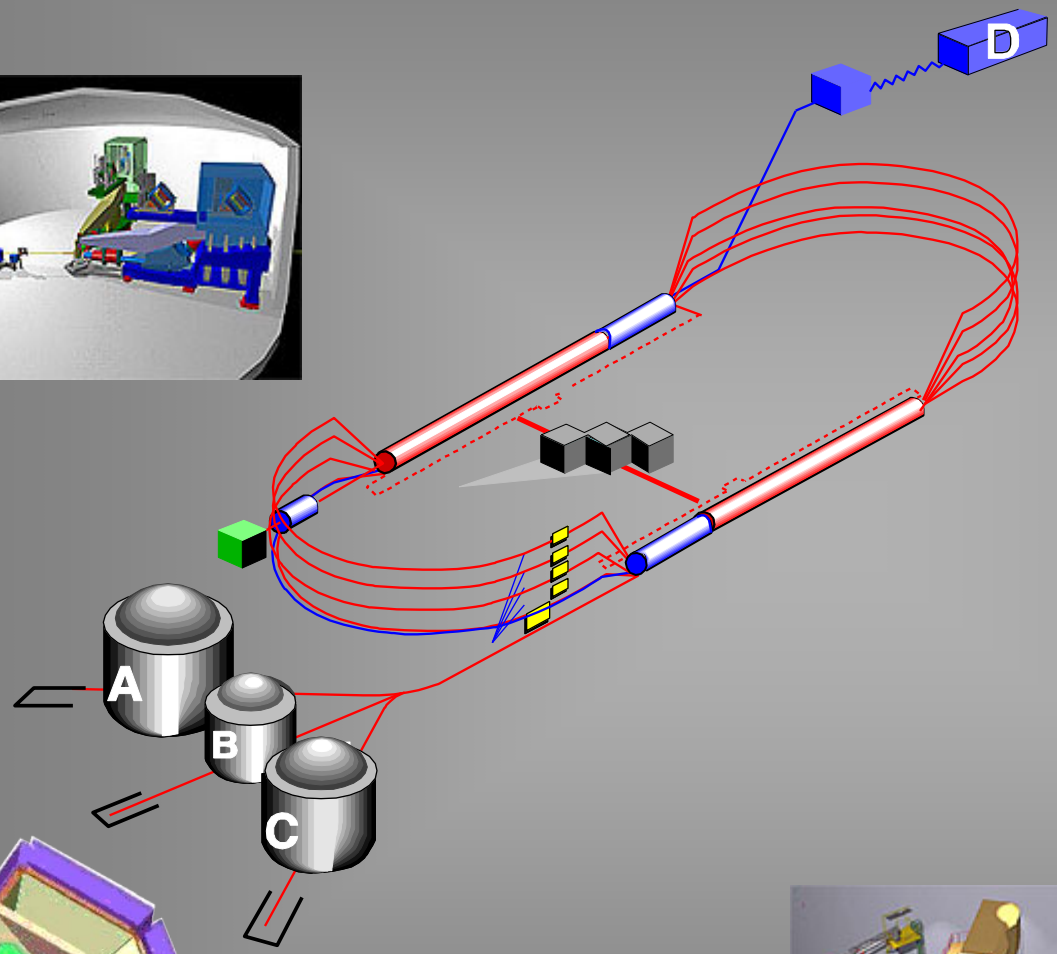
BESIII

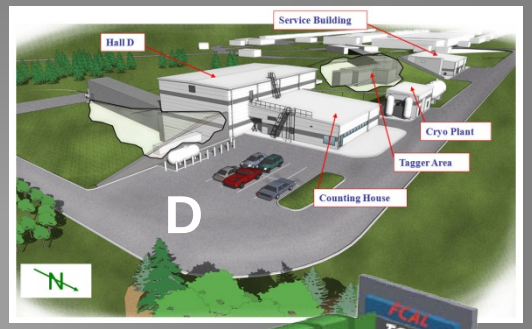
COMPASS

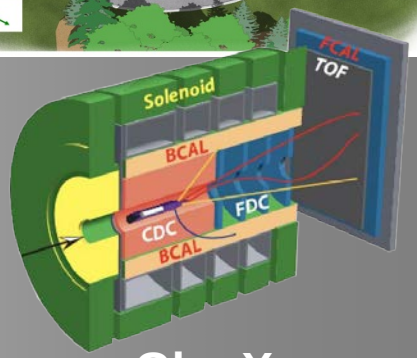
Jefferson Lab 12 GeV upgrade

Exploring the Nature of Matter

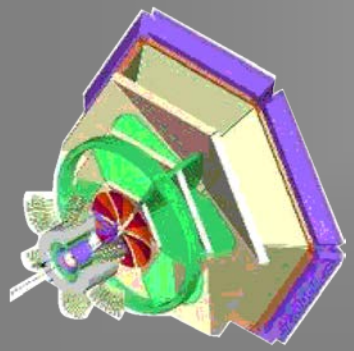




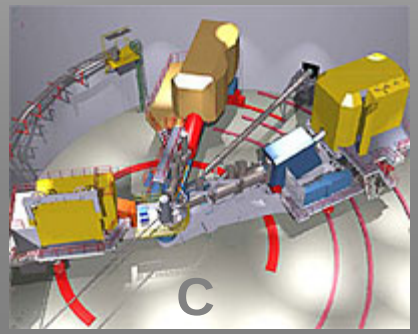




GlueX



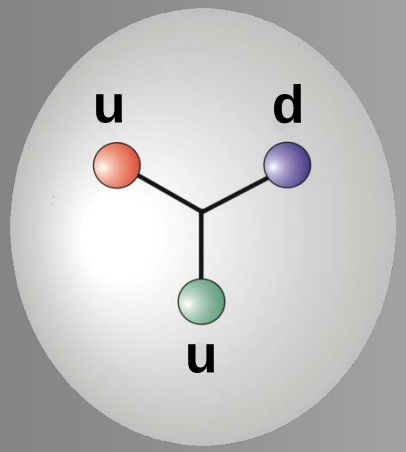
B CLAS12

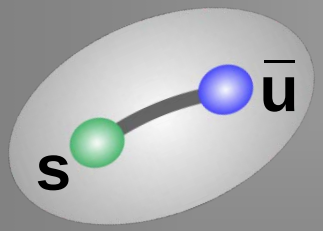


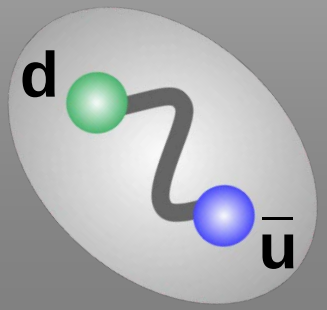
Glimpsing colour
in a world of black & white

Extra Slides

cool QCD







Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter