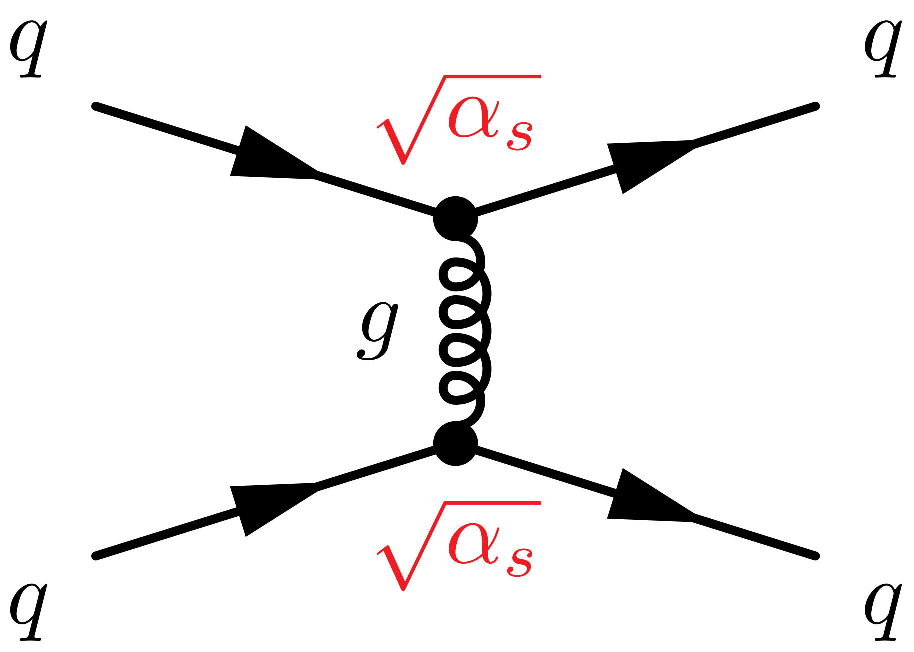
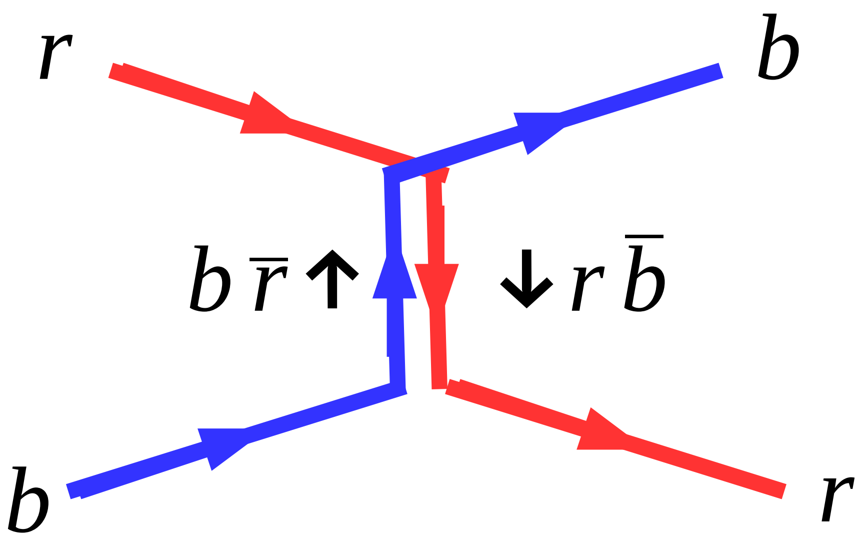
Hardons

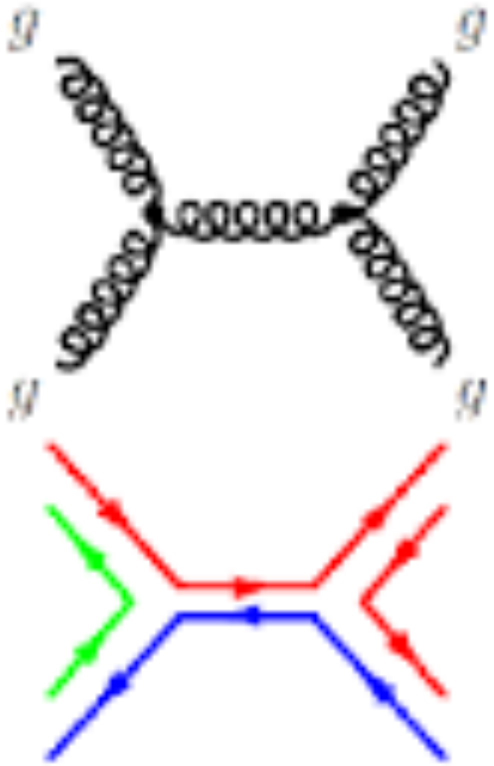
Mark Dalton

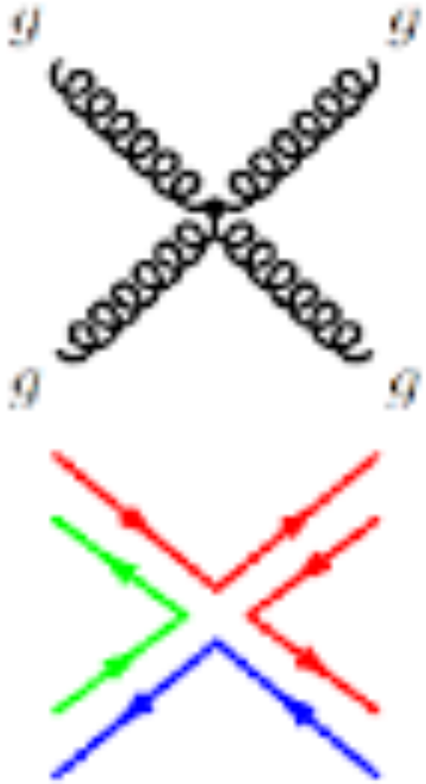
Jefferson Lab

Quantum Chromodynamics (QCD)



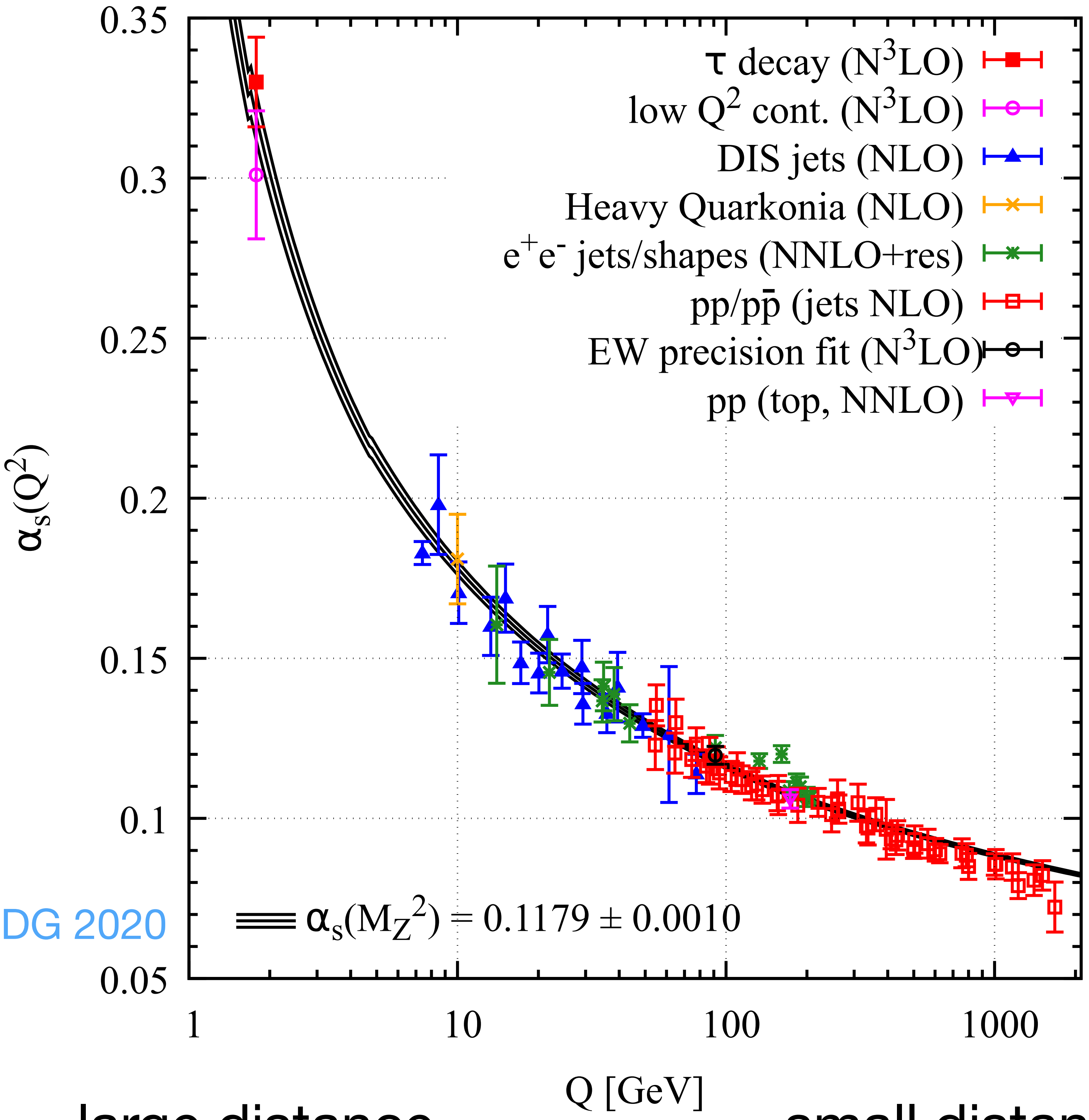






coupling is to 3 color charges
gluons carry color—anti-color
charges and self interact
color charge is conserved
QCD conserves flavor
QCD conserves parity

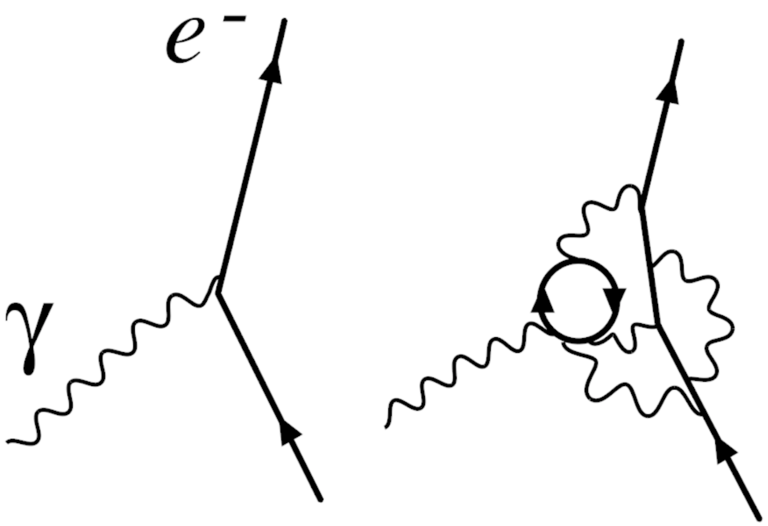
Running Coupling



PDG 2020

large distance

small distance



QED: screening of charge by fermion pairs.

QCD: screening by quarks—anitquark pairs

anti-screening by gluons (dominates)

QCD

Asymptotic Freedom

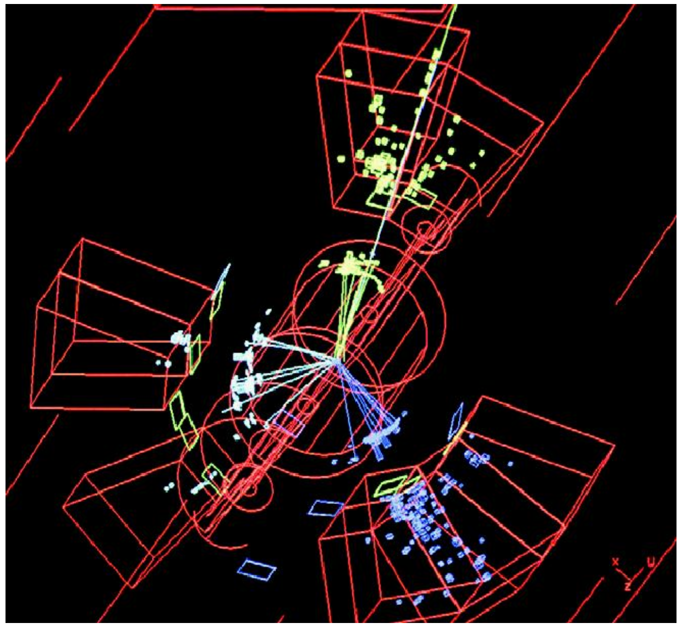
Small Distance
High Energy

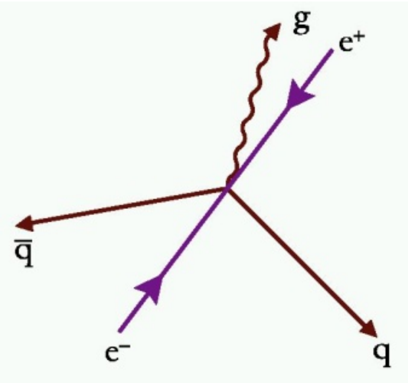
Confinement

Large Distance
Low Energy

Perturbative QCD

High Energy Scattering

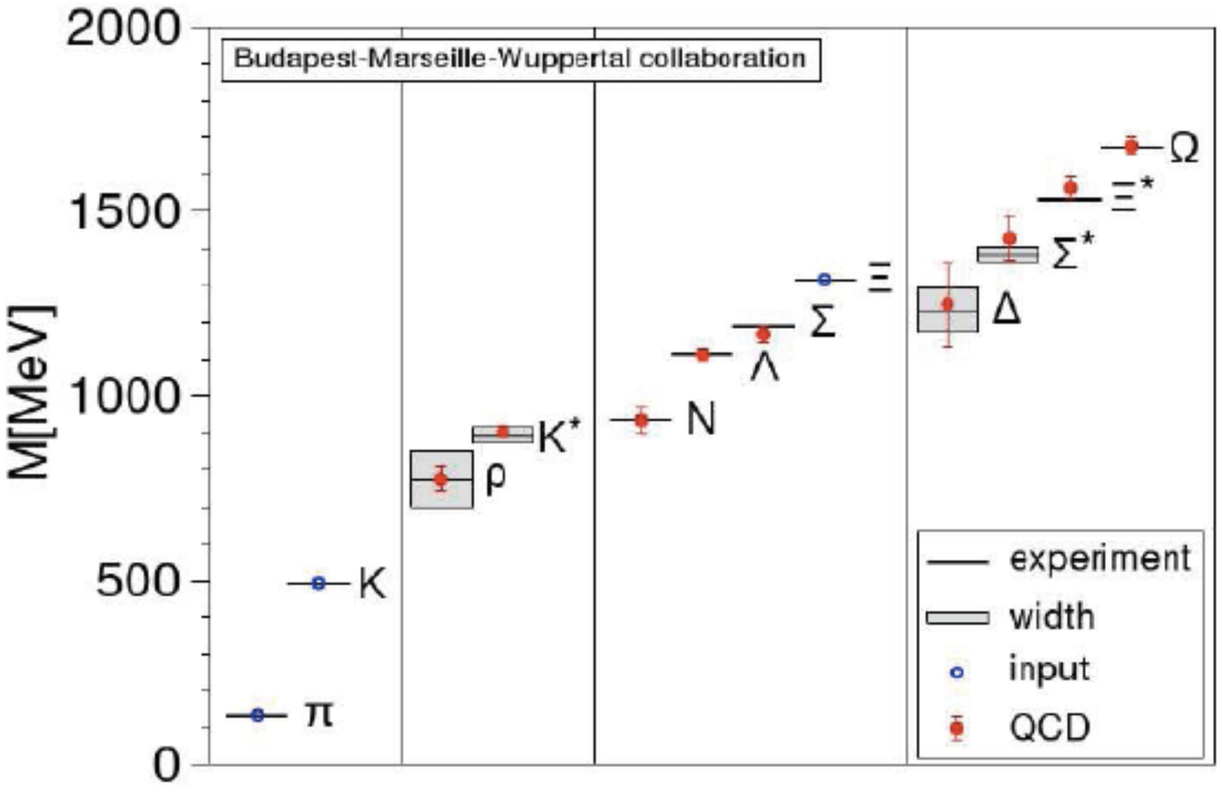


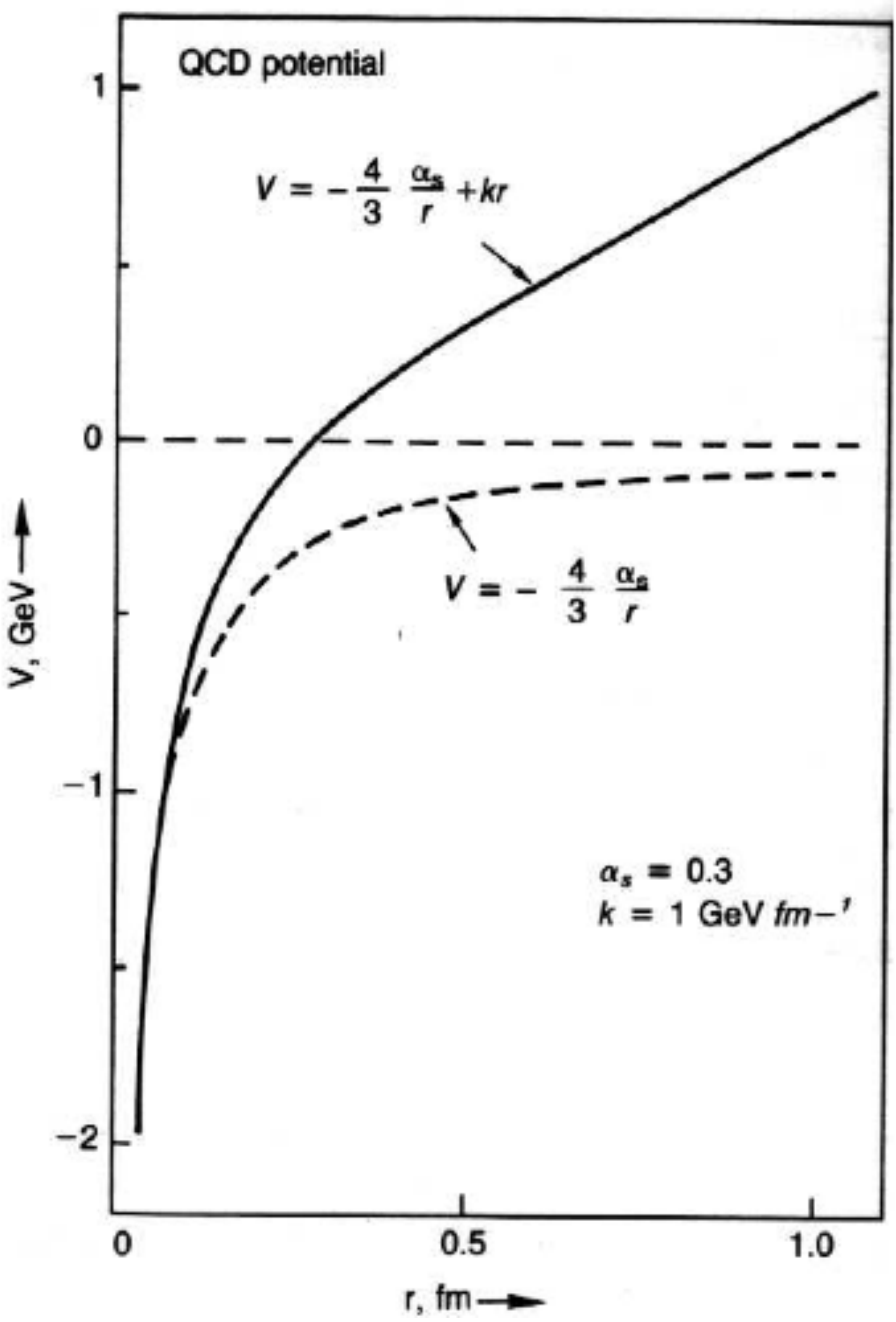


Gluon Jets Observed

Strong QCD

Hadron Spectrum - no signature of gluons?





QCD Potential

Short distance part (1/r term)
from quark-antiquark gluon exchange

$$V(q\bar{q}) = -\frac{4}{3}\frac{\alpha_s}{r} + k\,r$$

Long distance part (k r term)
is modelled on an elastic spring

k is known as the string tension

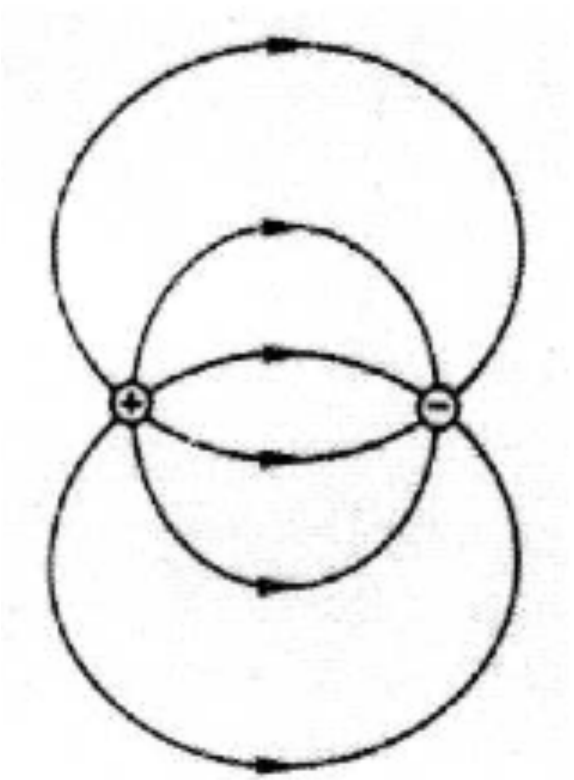
This model provides a good description
of the bound states of heavy quarks:
charmonium ($c\bar{c}$)
bottomonium ($b\bar{b}$)

Colour Flux-tube Model

QED

Field lines extend out to infinity with strength $1/r^2$

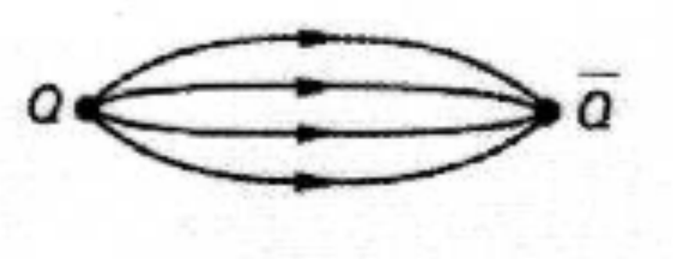
Electromagnetic flux conserved to infinity



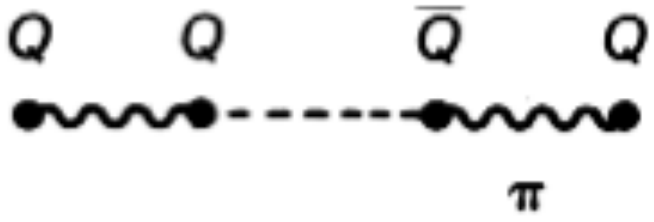
QCD

Field lines are compressed into region between quark and antiquark

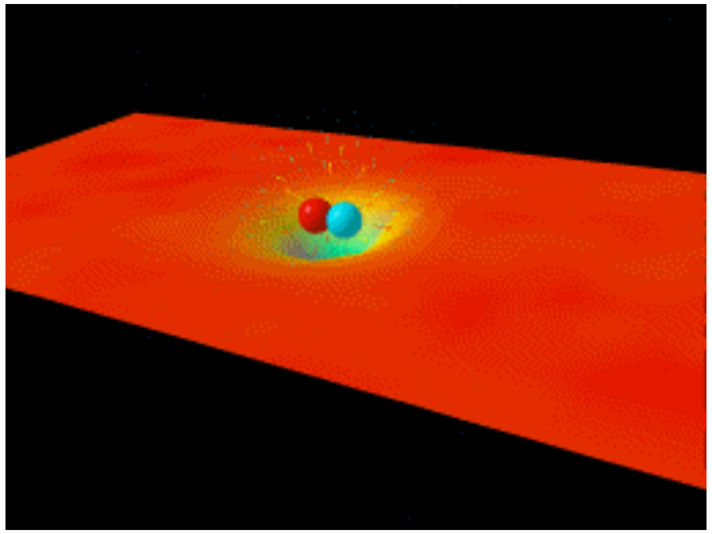
Colour flux is confined within a tube. No strong interactions outside the flux-tube .



Breaking a flux tube requires the creation of a quark-antiquark pair



Like breaking a string! Requires energy to overcome string tension



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Particle Physics Lecture 8 Steve Playfer

Leinweber flux tube visuals

Why Electron Scattering?

Well known

$$V_{int} = \rho\phi + \mathbf{J}\mathbf{A}$$

scaler potential

vector potential

calculable in SM using QED to high precision

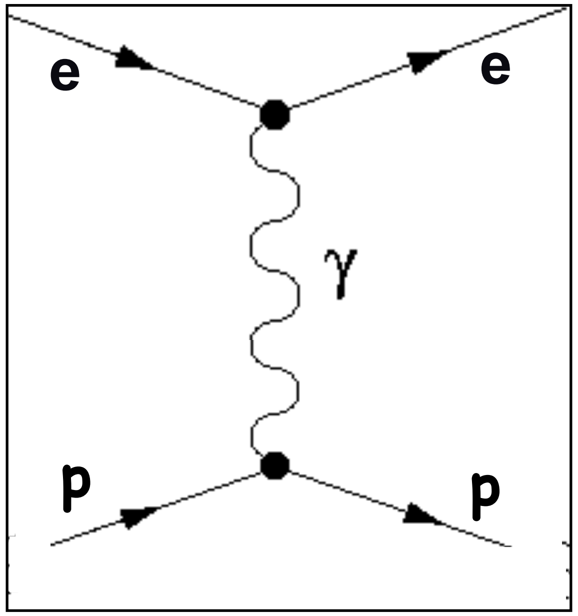
small cross section

Weak $\alpha \propto 1/137$

one photon exchange (simple)

penetrating

Except: charge elastic scattering of the Coulomb field of a heavy-Z nucleus



Energy and momentum transfer independent

Magnetic, electric and **charge** transitions

$M_\lambda, E_\lambda, C_\lambda$

Charged

Difficult to access neutrons, Beam heating of the target, Bremsstrahlung, causes radiative tails and potentially large corrections

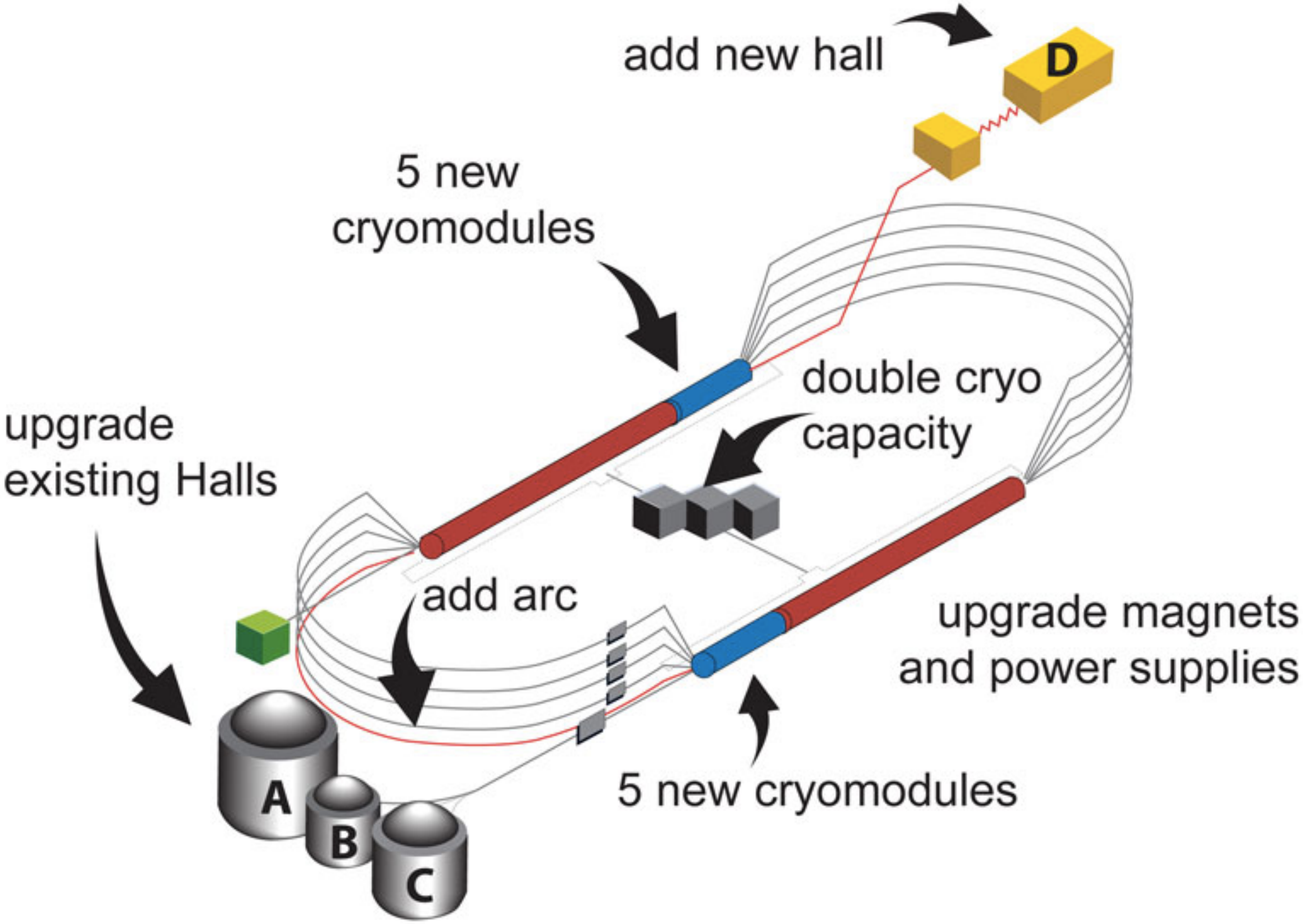
Light Mass

"Easy" experimentally

stable, pre-existing
high intensity, high duty cycle,
high energy, and high polarization

Jefferson Lab

CEBAF Accelerator, 12 GeV electron beam
4 experimental end stations
Newport News, Virginia, USA



Electron Scattering Kinematics

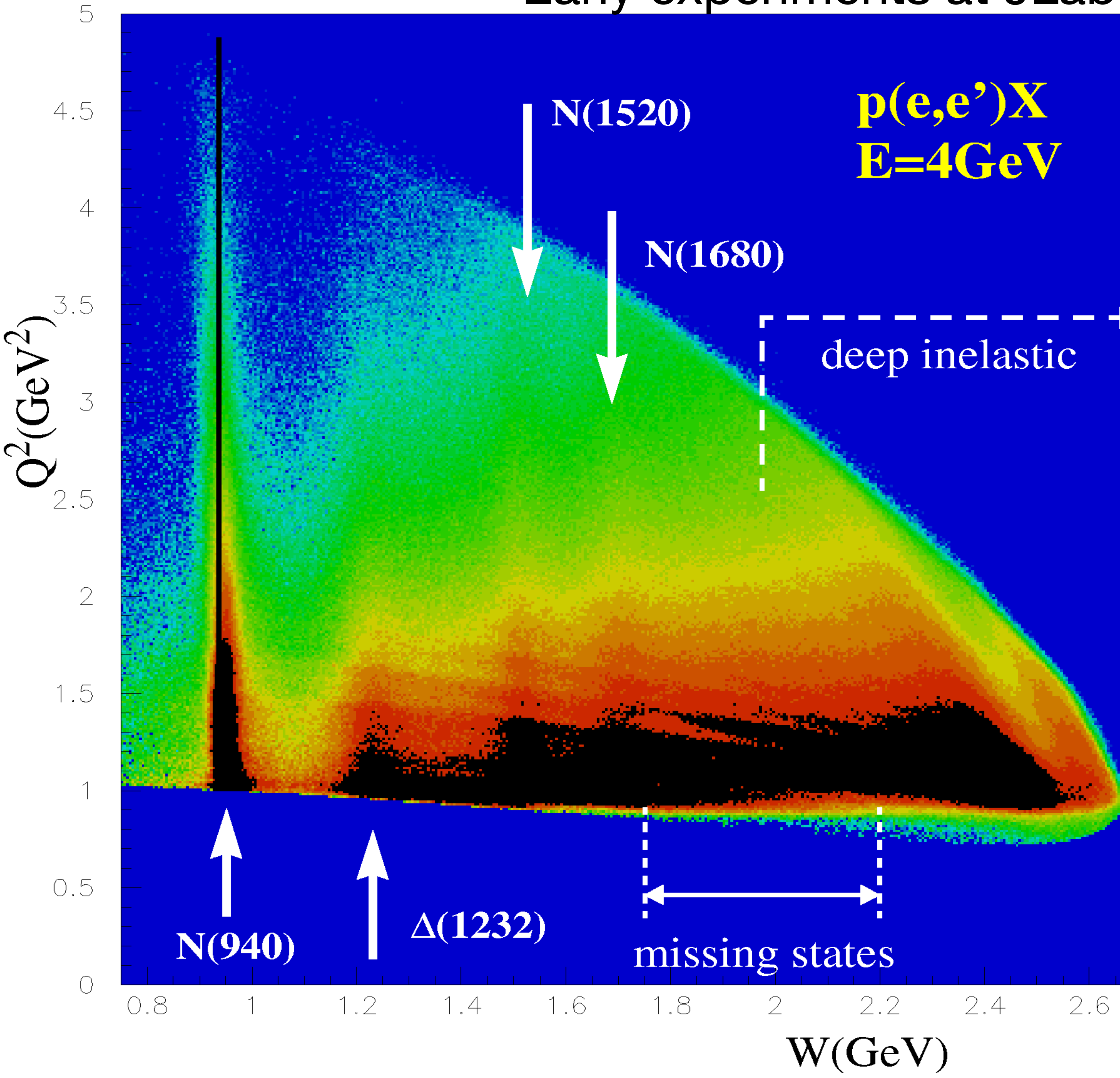
Scattering is a function of 2 variables, energy and angle

We choose to use other variables.

$$Q^2 = EE'\sin^2(\theta/2)$$

$$x = \frac{Q^2}{2M\nu}$$

Early experiments at JLab

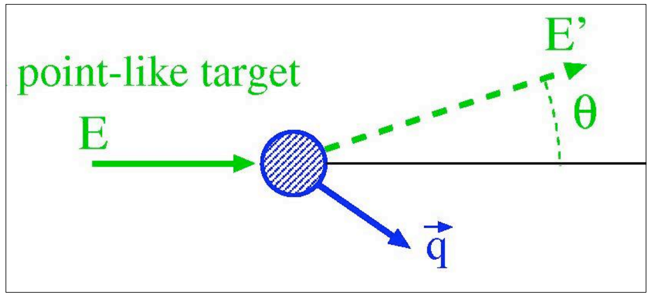


Electron Scattering

Matter wave $Q^2 = EE'\sin^2(\theta/2)$

De Broglie wavelength $\lambda = \frac{h}{\mathbf{p}}$

Q²: 4-momentum of the virtual photon



Photon is off mass shell

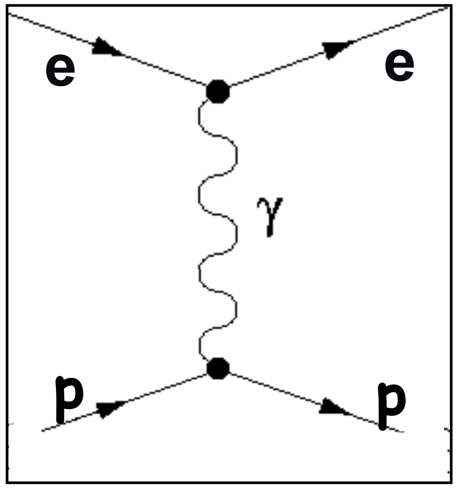
Q² measures

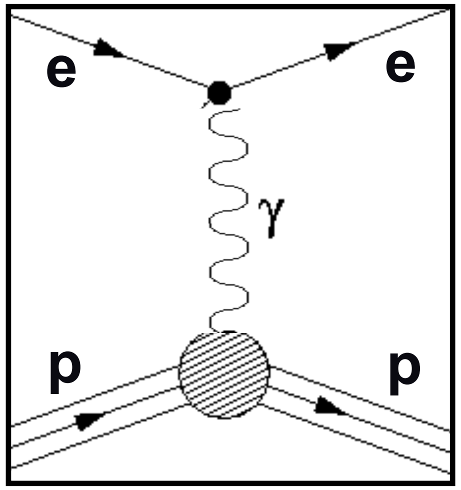
- virtuality or “mass” of the photon
- momentum transferred to the target

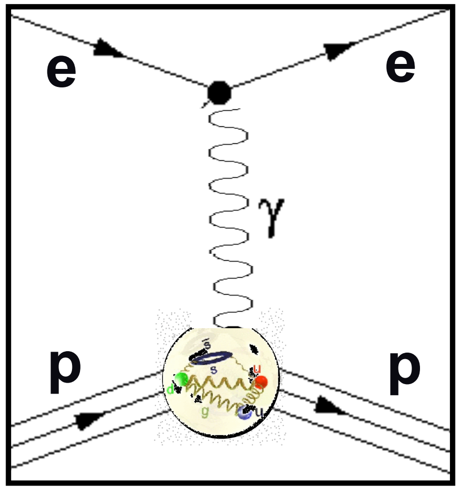
If photon carries low momentum

-> long wavelength

-> low resolution







Increasing momentum transfer

-> shorter wavelength

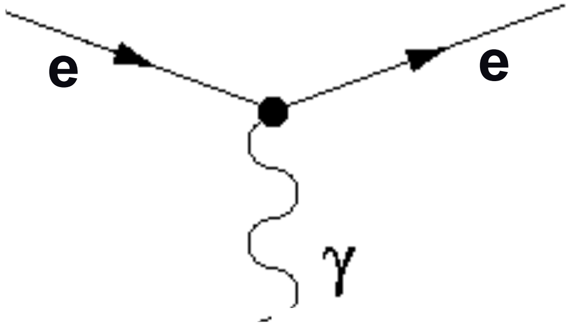
-> higher resolution to observe smaller structures

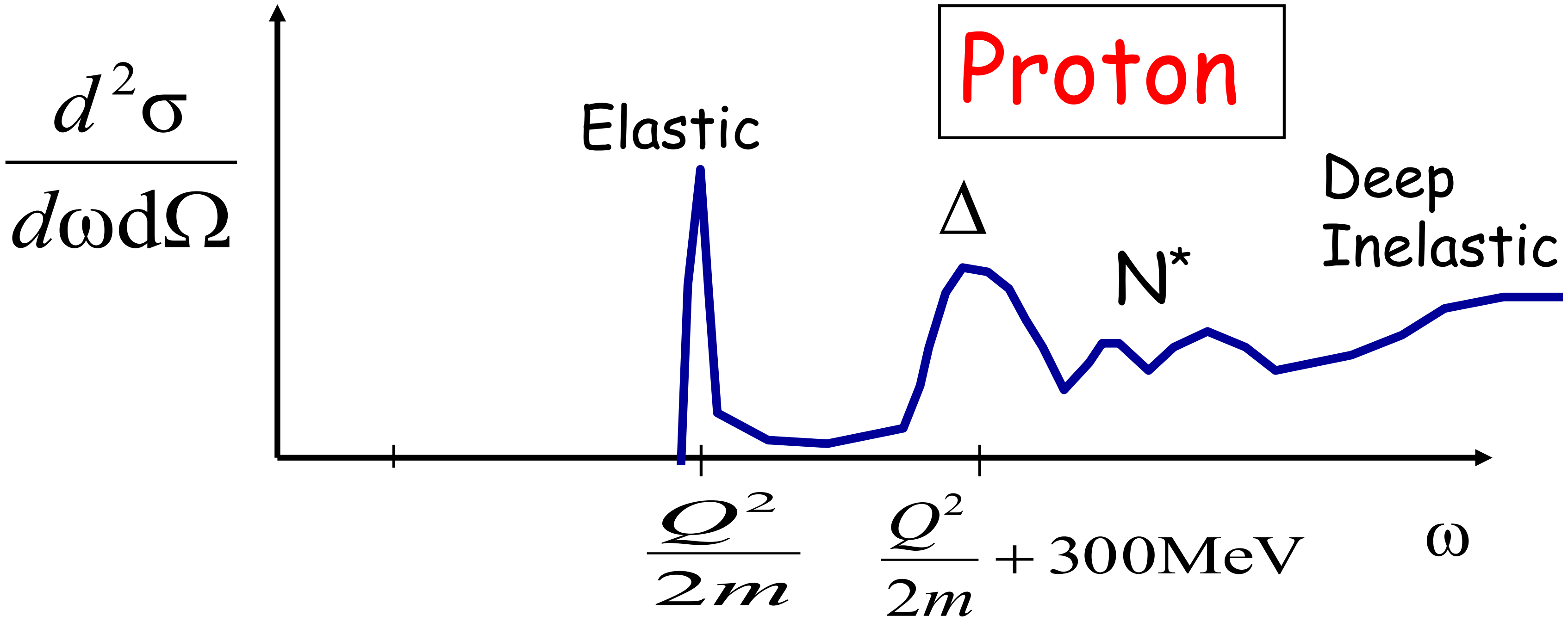
Electron Scattering

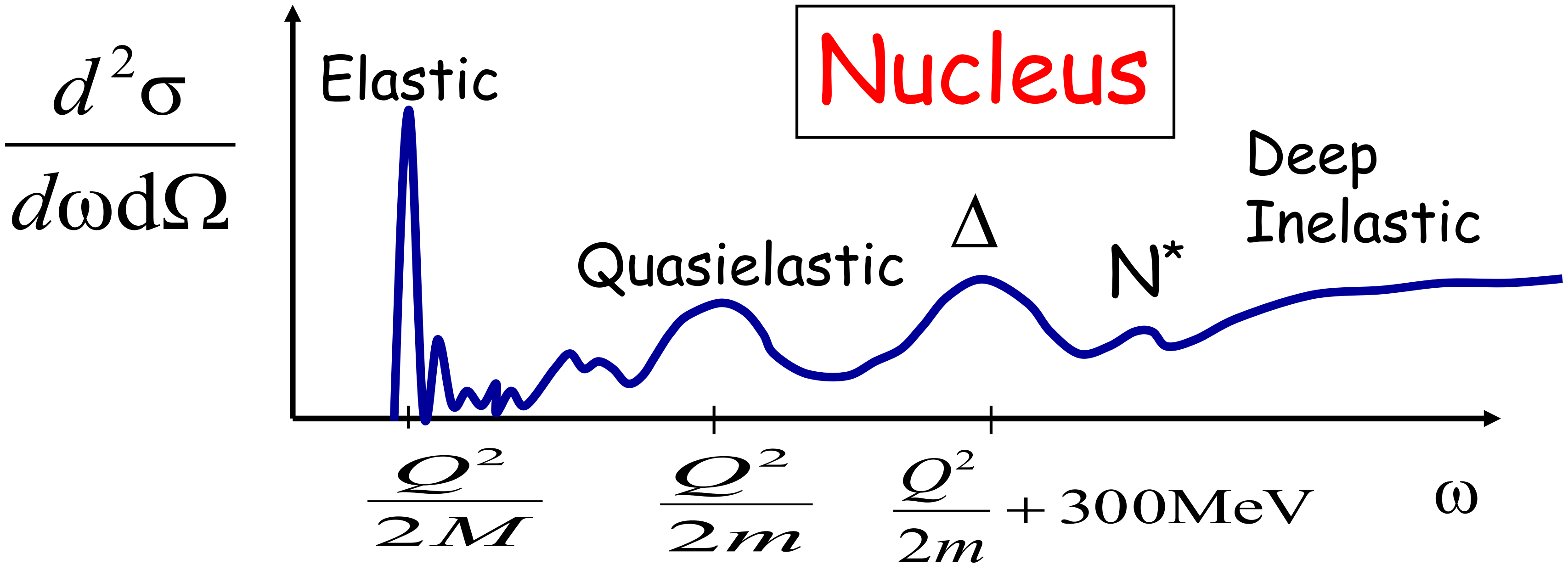
Vary energy transfer at constant momentum transfer

↓

achieved by varying the angle and energy of the scattered electron.



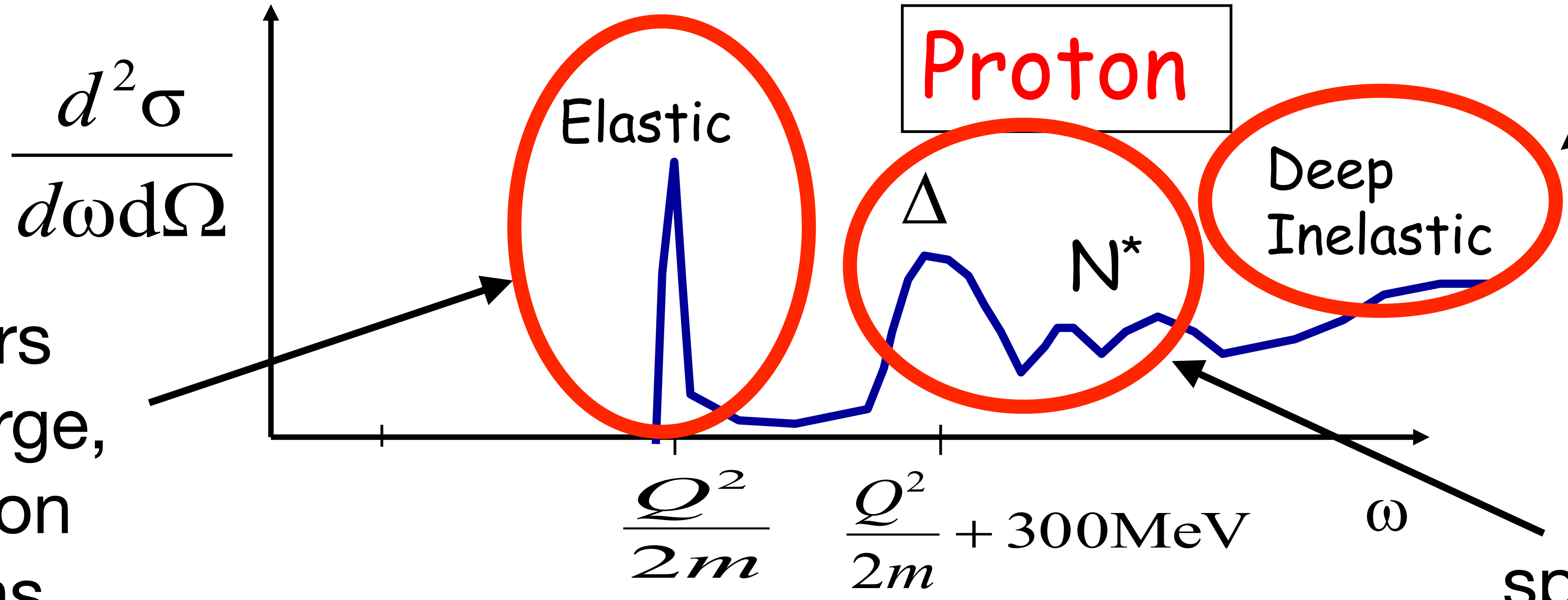




Fermi motion broadening

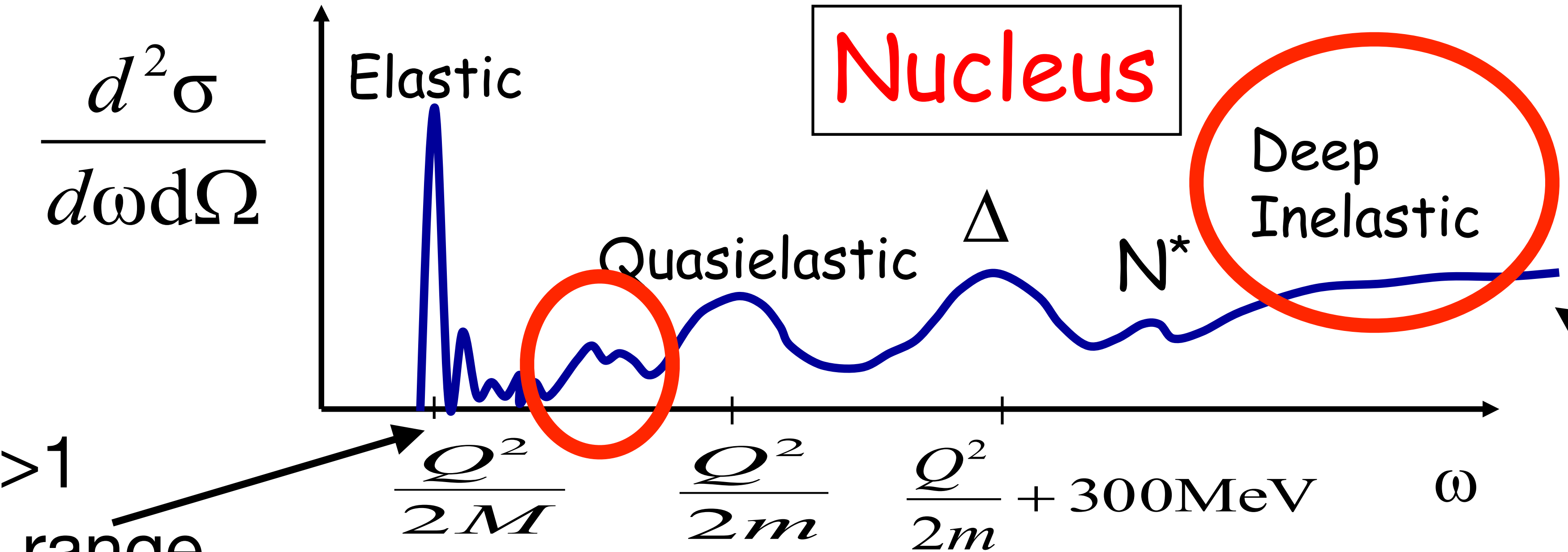
Electron Scattering

Partonic structure of nucleon



Form factors
Nucleon charge,
magnetization
distributions

Baryon
spectroscopy



EMC effect

x>1
short range
correlations

Spectroscopy and Structure

Spectroscopy	Structure
Map out the all states of QCD	Study internal structure of QCD states
determine properties such as charge, mass, quantum numbers (spin, parity conjugation, charge conjugation)	determine internal properties properties such as distribution of partons (flavor, momentum, spin) and correlations
partial wave analysis (PWA) to separate broad and overlapping states,	scattering from long-lived objects, scattering from virtual objects, transition from one object to another
phenomenological models, effective field theories and lattice QCD	Factorization of scales, lattice QCD

Structure

Elastic Scattering and Form Factors

The point-like scattering probability for elastic scattering is modified to account for finite target extent by introducing the "form factor"

Assuming spherically symmetric (spin-0) target

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \left| F(q) \right|^2$$

point-like target, electron spin

$$F(q) = \int e^{iqr} \rho(r) d^3r$$

Form factor is the Fourier transform of charge distribution

This is a non-relativistic picture

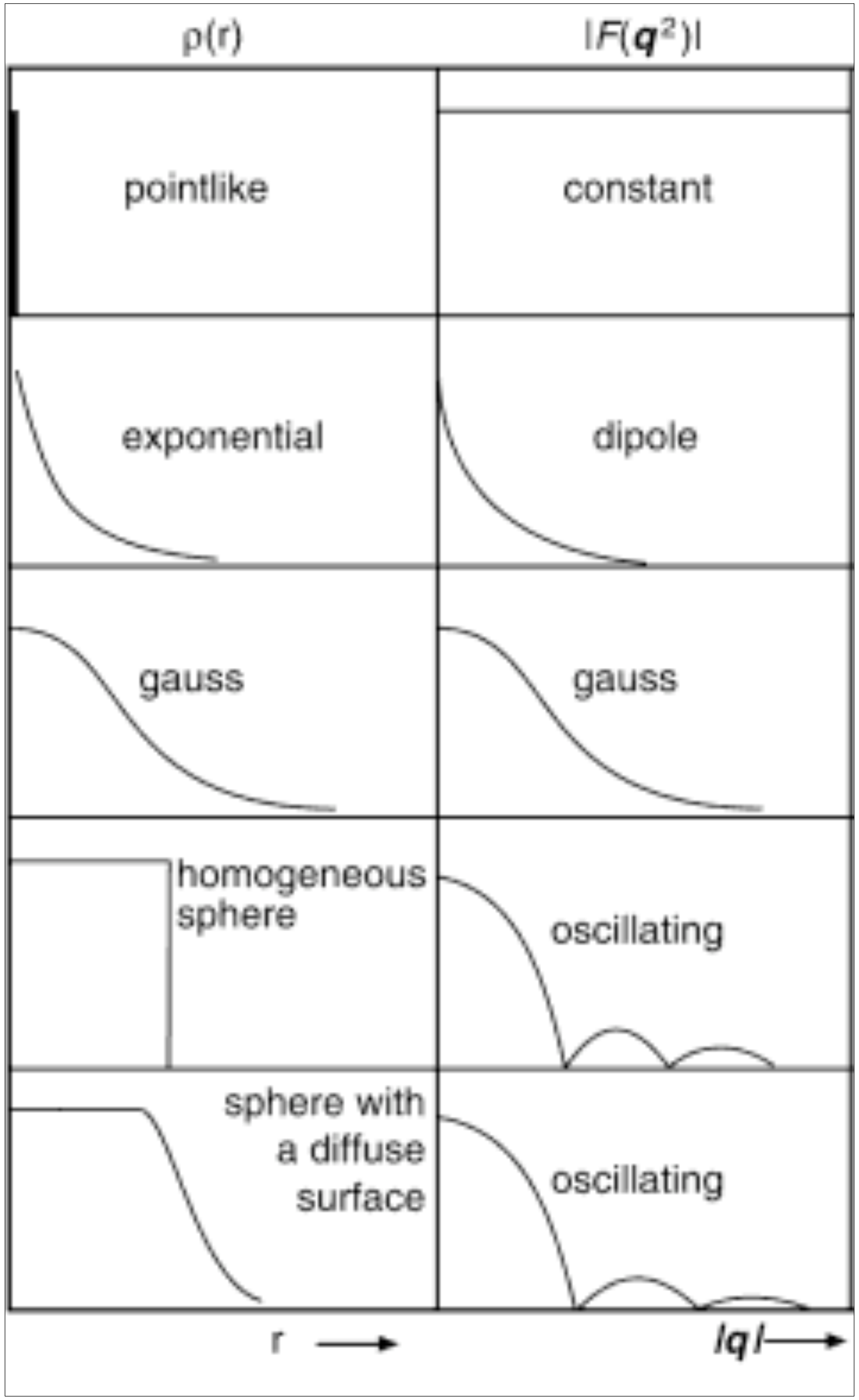
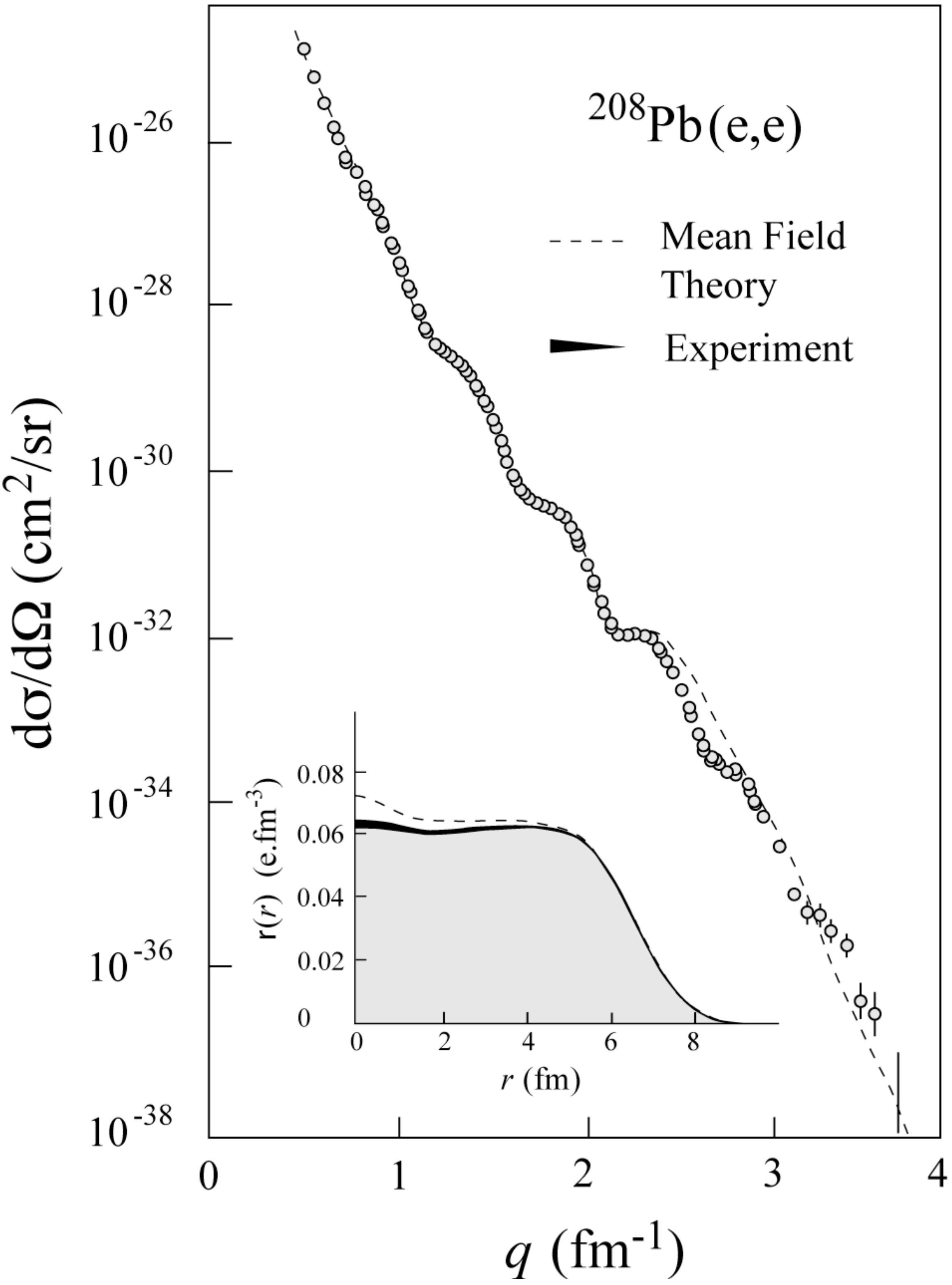
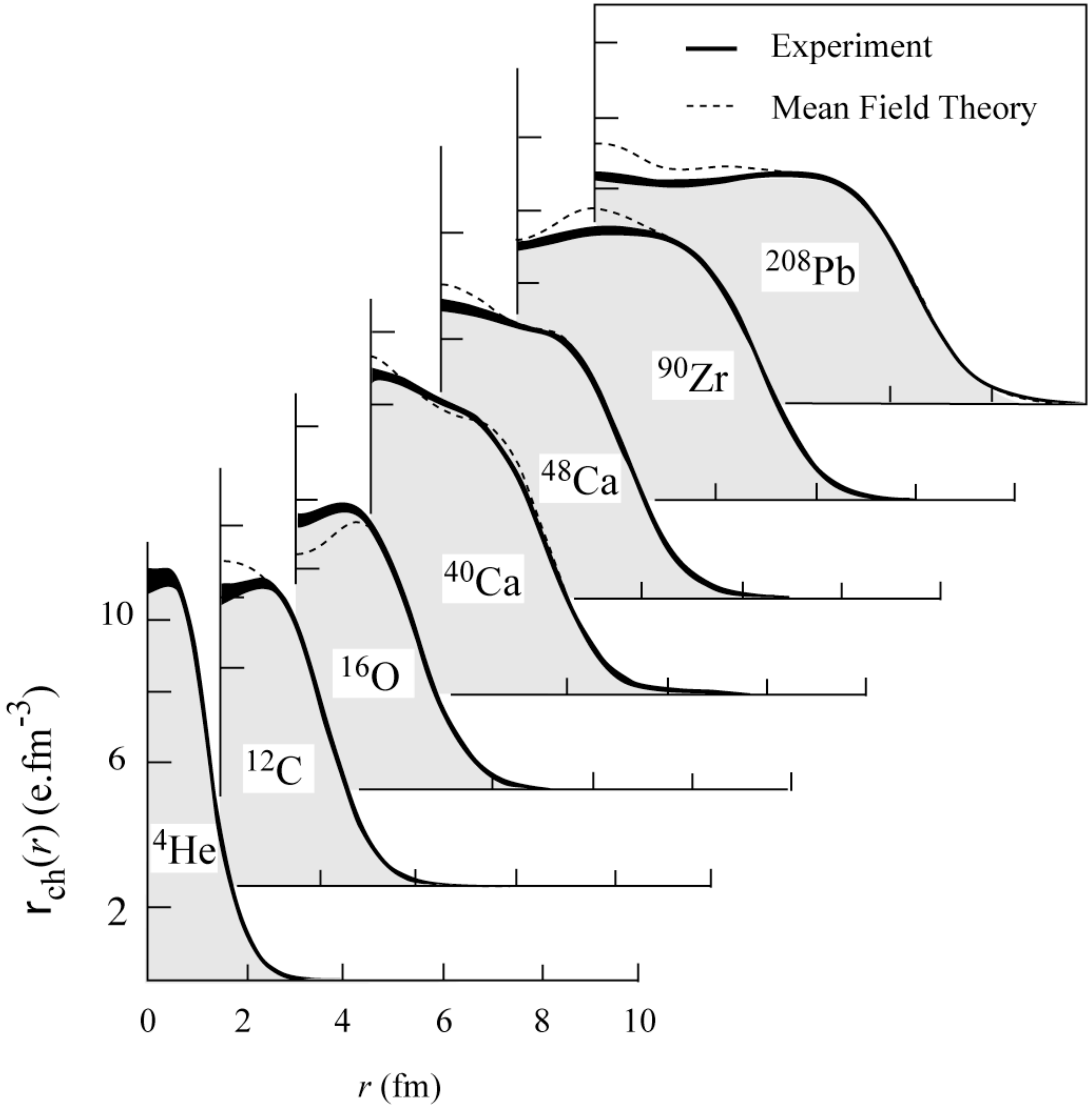


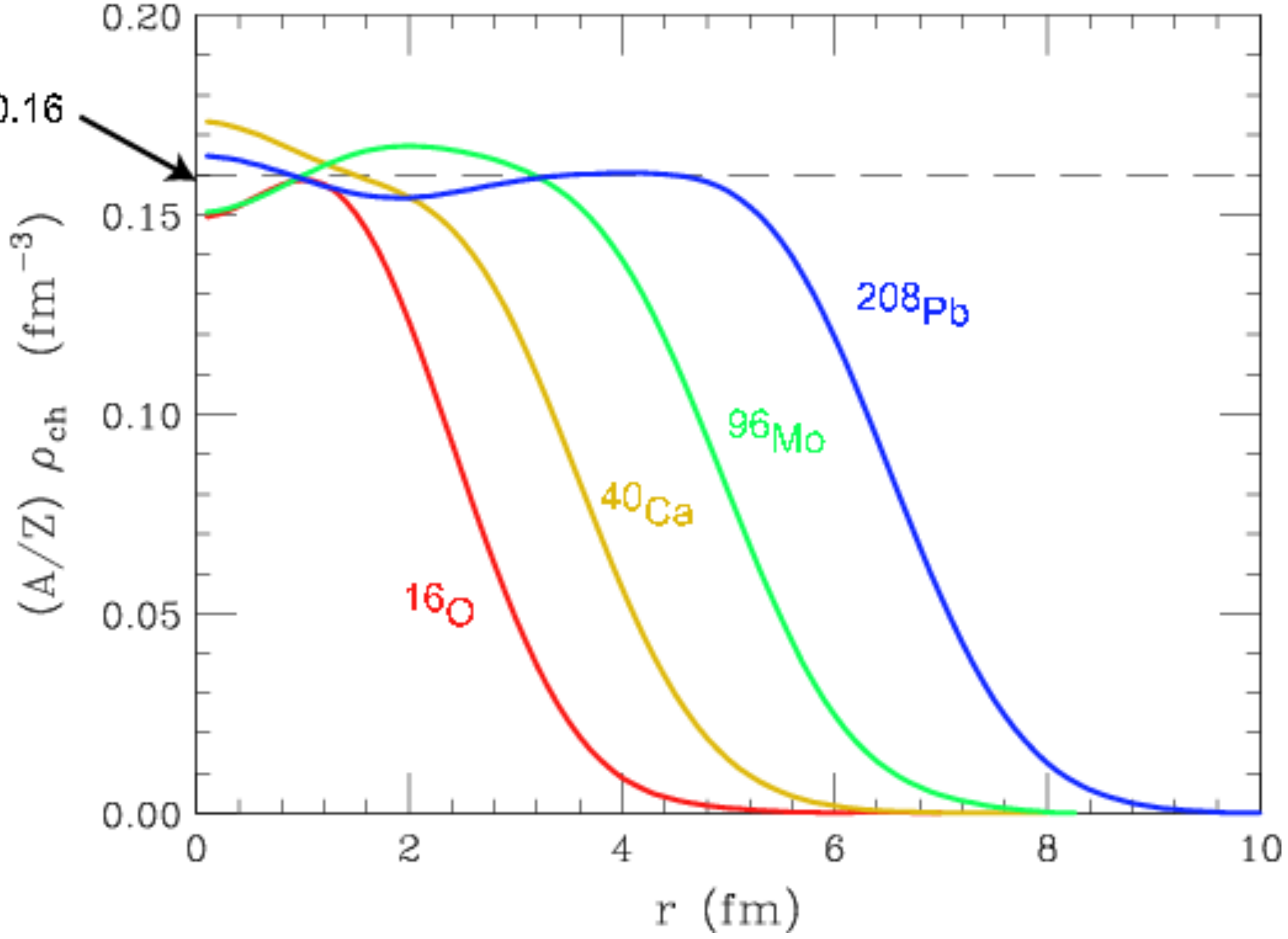
Figure from Particles and Nuclei, Povh *et al.*

Historical Nuclear Charge Distributions

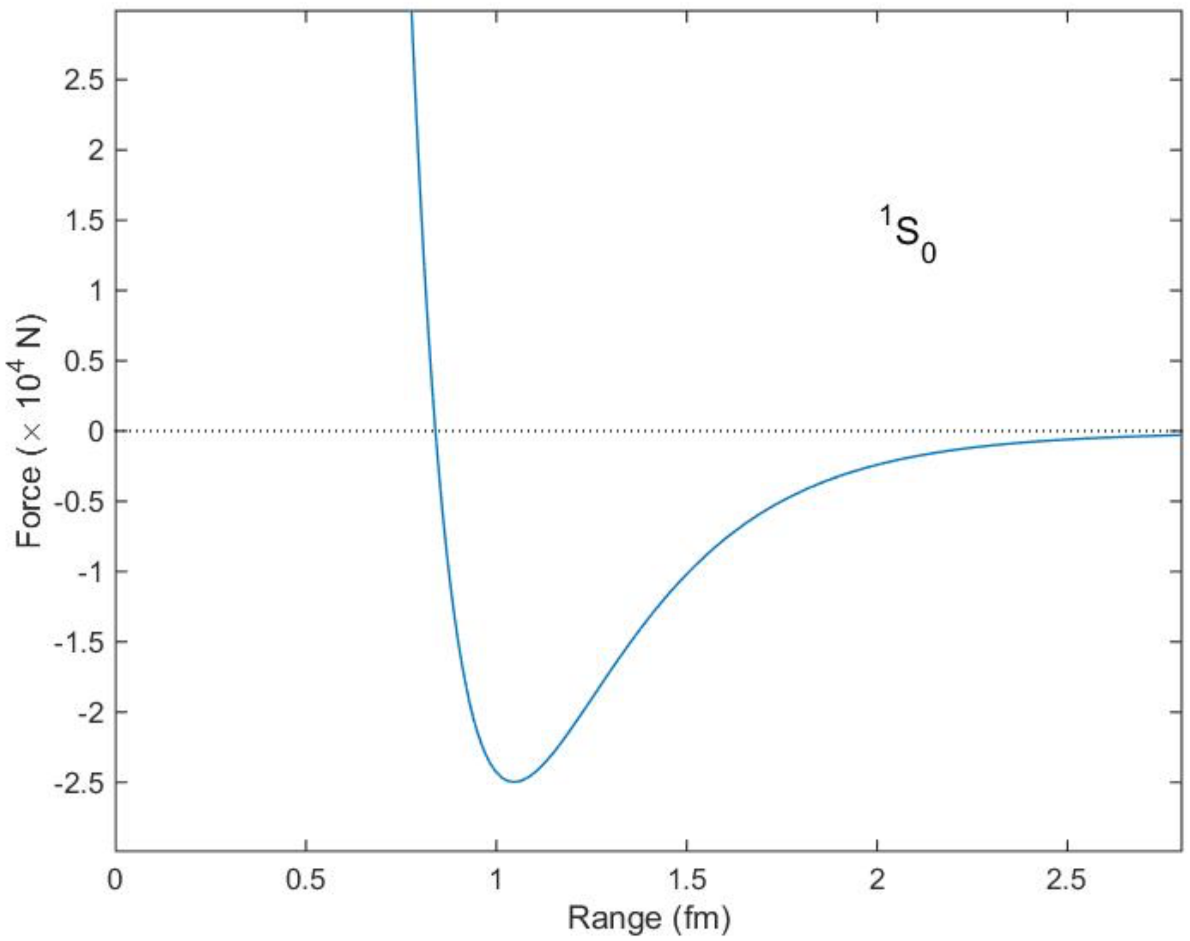




Nuclear Potential



Acta Phys.Polon.B 40 (2009) 2389-2404



depends on the nucleon spins, relative momentum of the nucleons

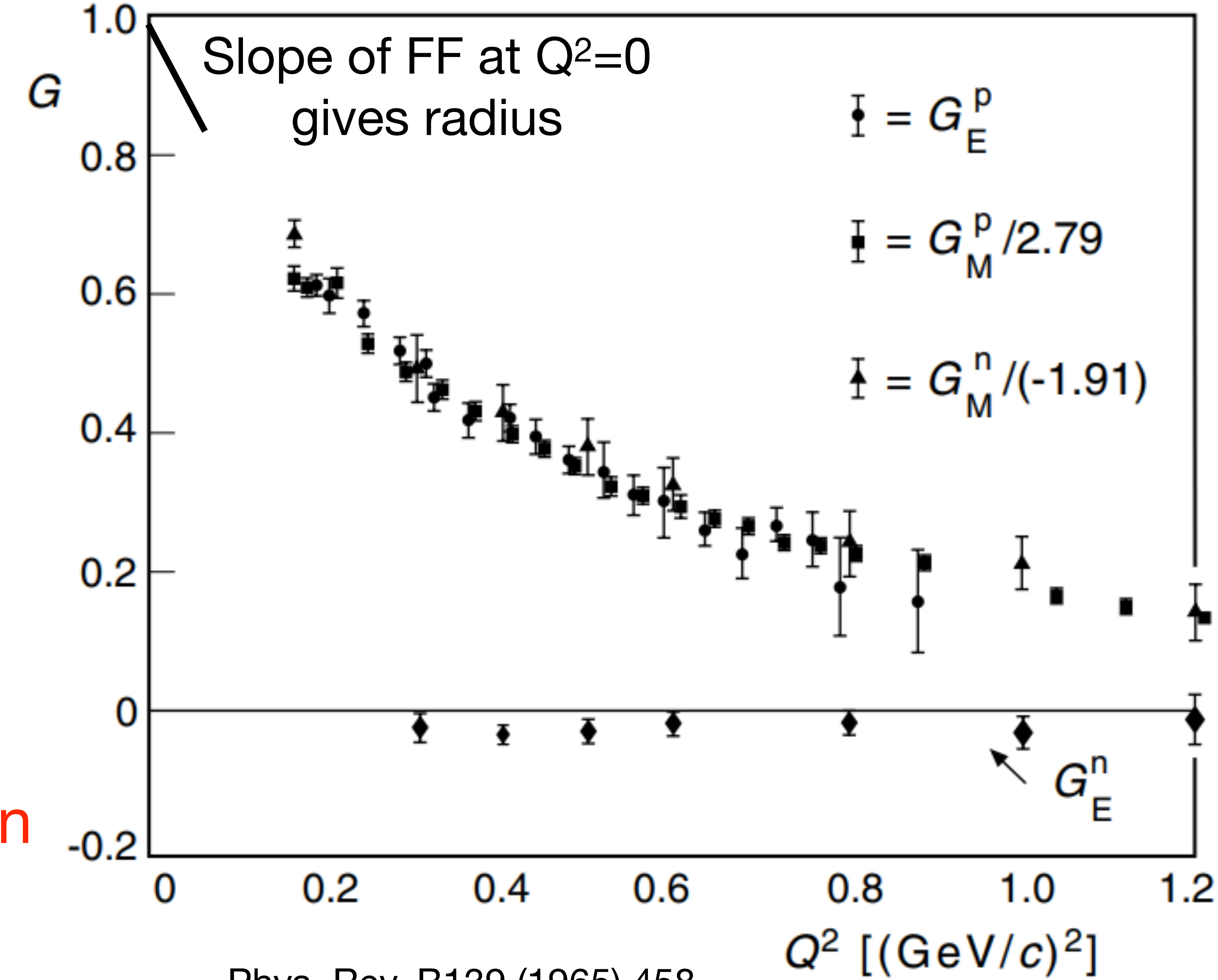
has a tensor component

Proton Form Factor

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \cdot \left[\frac{\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)}{\epsilon(1+\tau)}\right]$$

Kinematics make electric form factor difficult to measure at high Q^2

$$\frac{G_M^p(Q^2)}{\mu_p} \approx G_E^p(Q^2) \approx G^{\text{dipole}}(Q^2)$$



Slope of FF at Q^2=0 gives radius

Phys. Rev. B139 (1965) 458

Measurements using polarization can measure form factor ratio directly

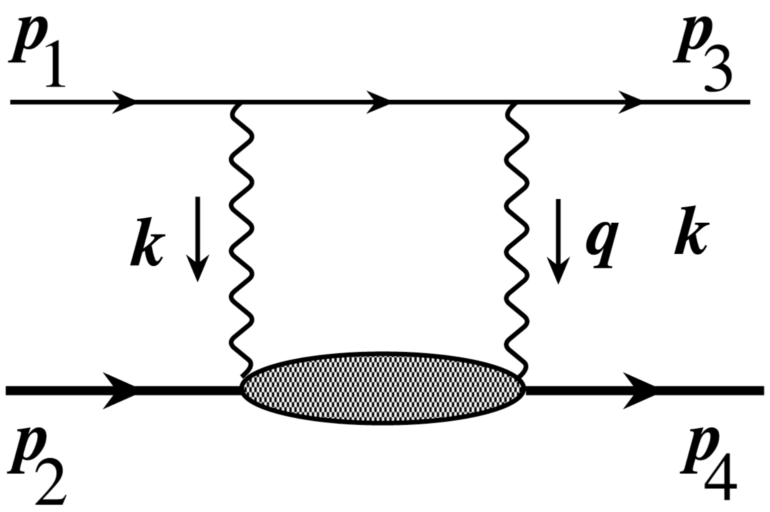
$$\frac{G_E}{G_M} = -\boxed{\frac{P_t}{P_l}}\sqrt{\frac{\tau(1+\epsilon}{2\epsilon}}$$

polarization of scattered proton

Many systematics cancel

Proton Form Factor

Polarization transfer measurements give different result.



2-photon exchange i.e. failure of the Born approximation

Charge & magnetization distributions in the proton are different

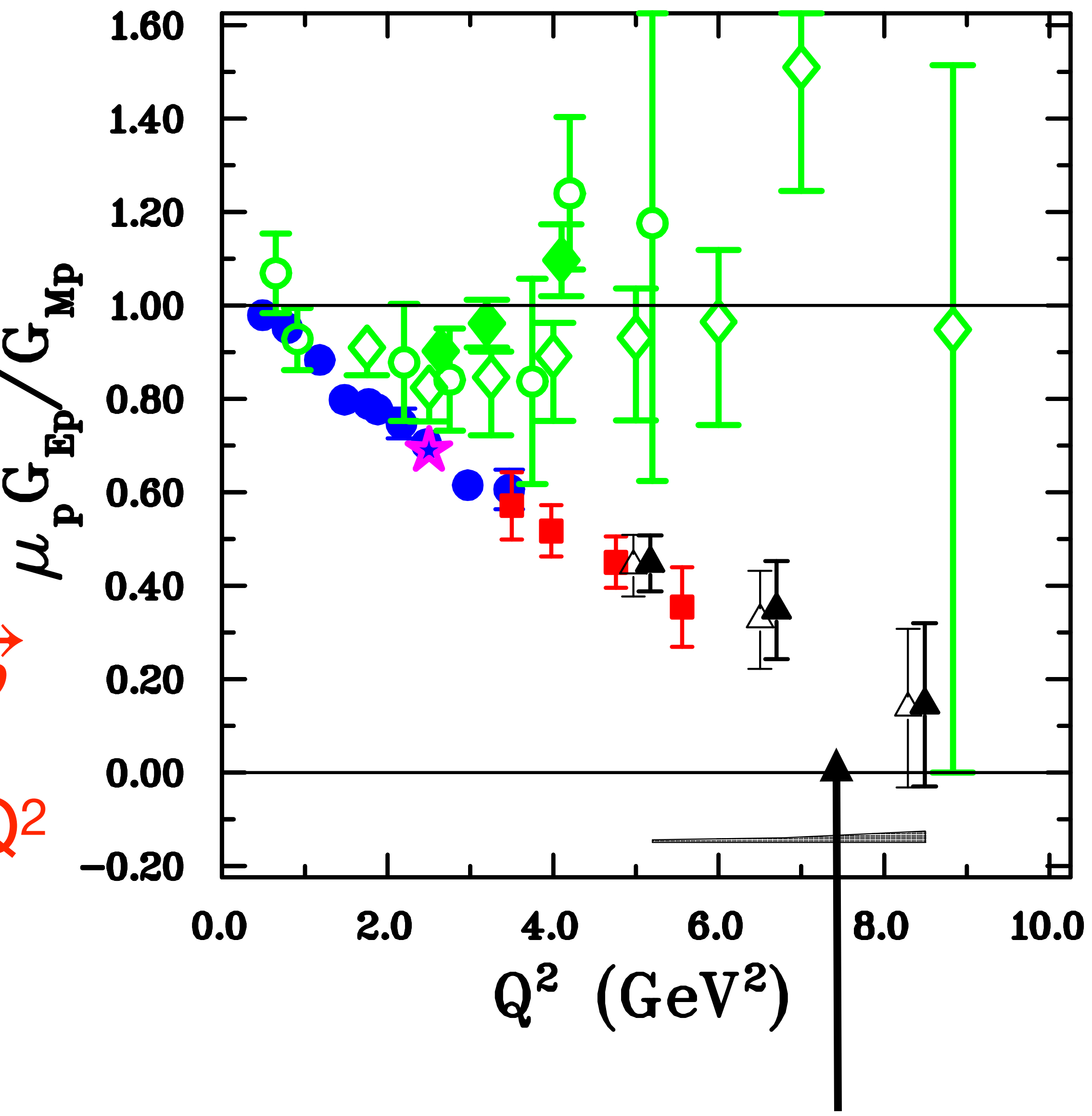
$$e + p \to e' + p$$

$\frac{G_E^p}{G_M^p}$ constant

$$\vec{e} + p \to e' + \vec{p}$$

$\frac{G_E^p}{G_M^p}$ drops with Q^2

PHYSICAL REVIEW C 96, 055203 (2017)

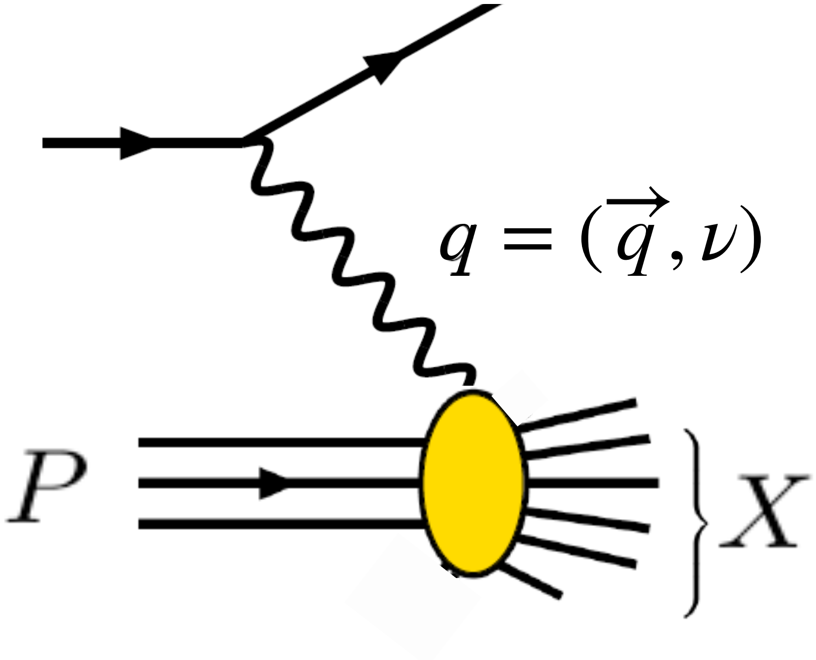


charge depletion in interior of proton

Orbital motion of quarks play a key role

(Belitsky, Ji + Yuan PRL 91 (2003) 092003)

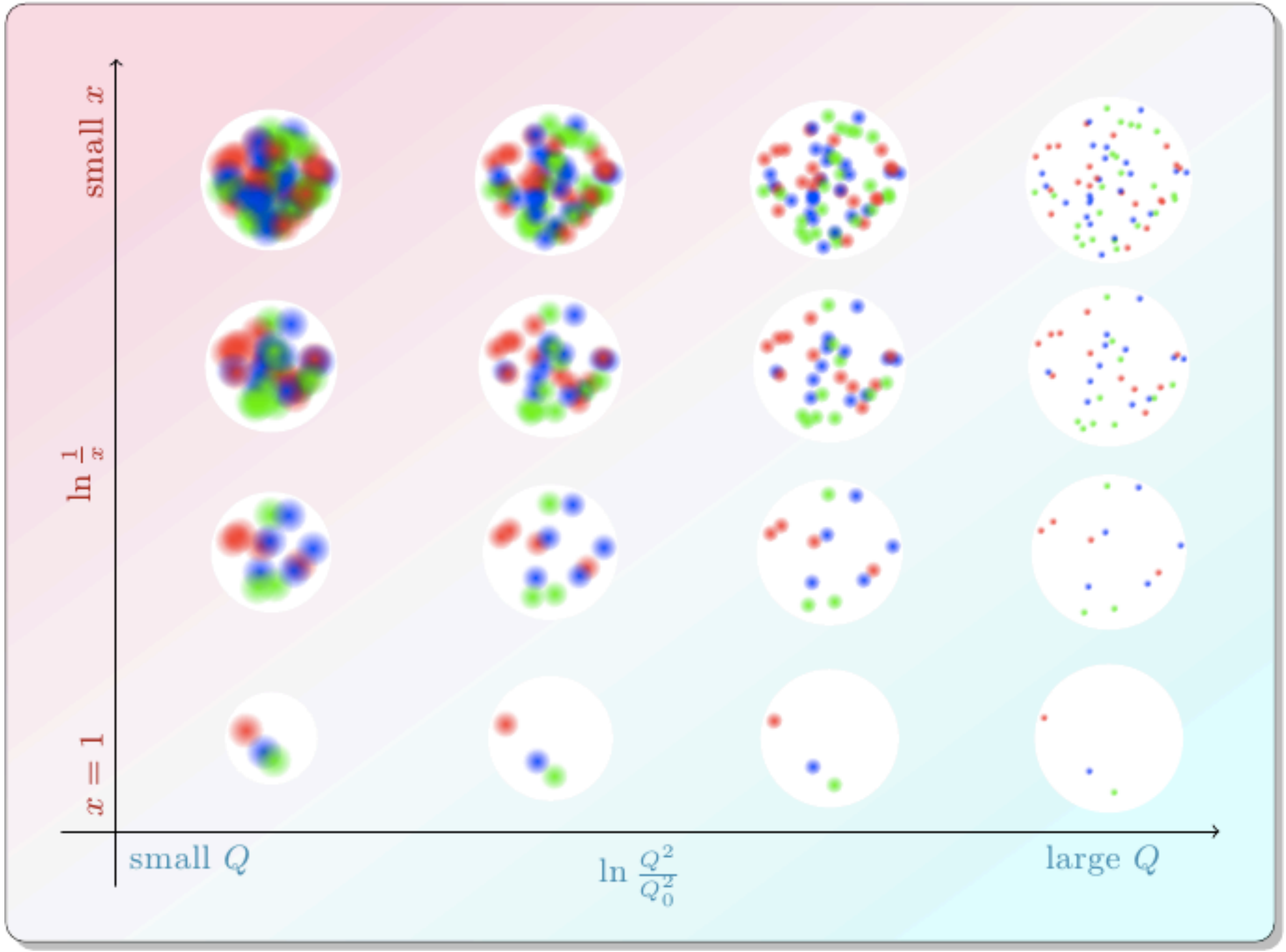
Deep **Inelastic** Scattering



Inelastic scattering requires 2 quantities to describe the kinematics

$$x = \frac{Q^2}{2M\nu}$$

Interpreted as the fraction of nucleon momentum of the parton that was struck.

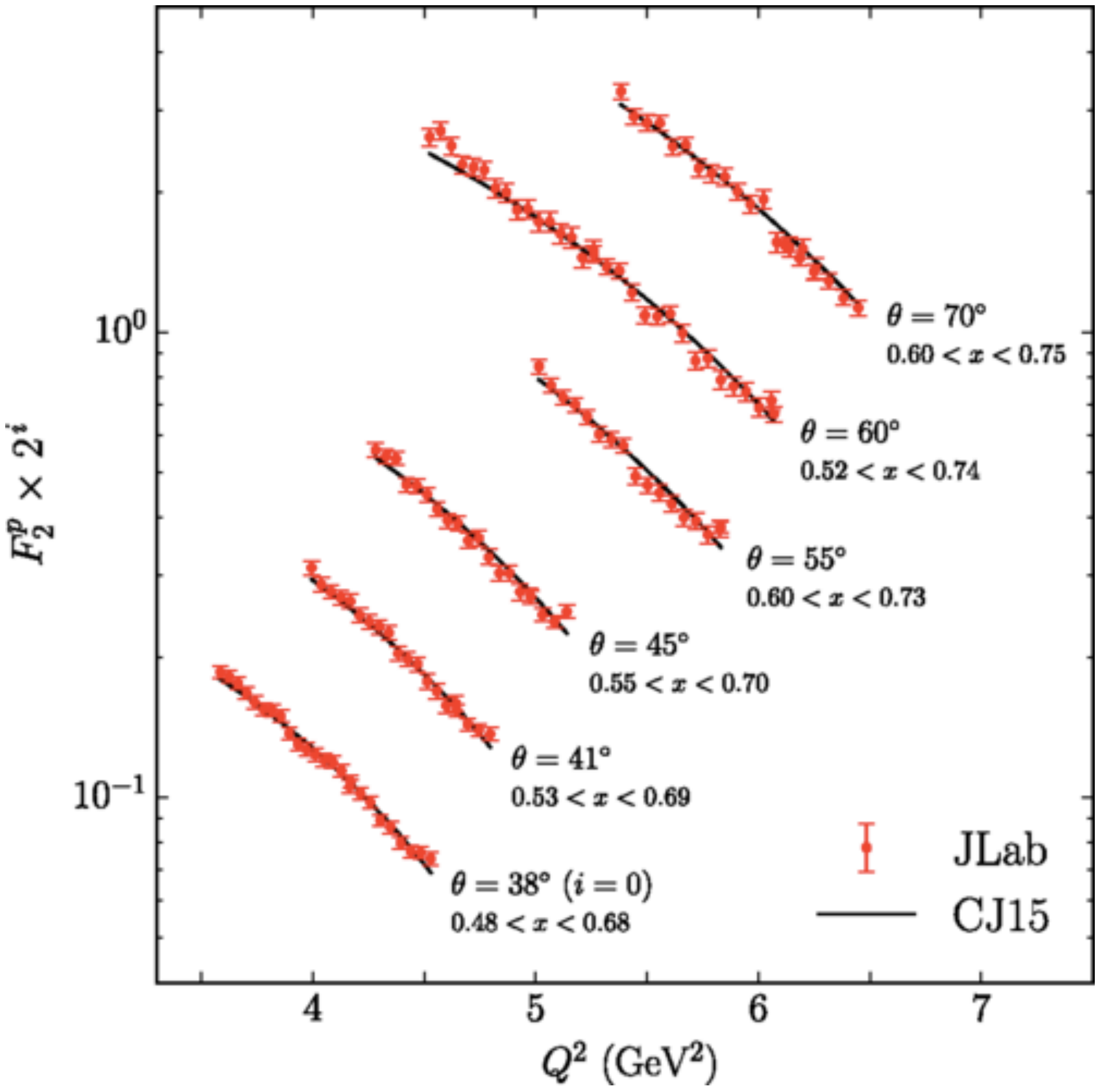


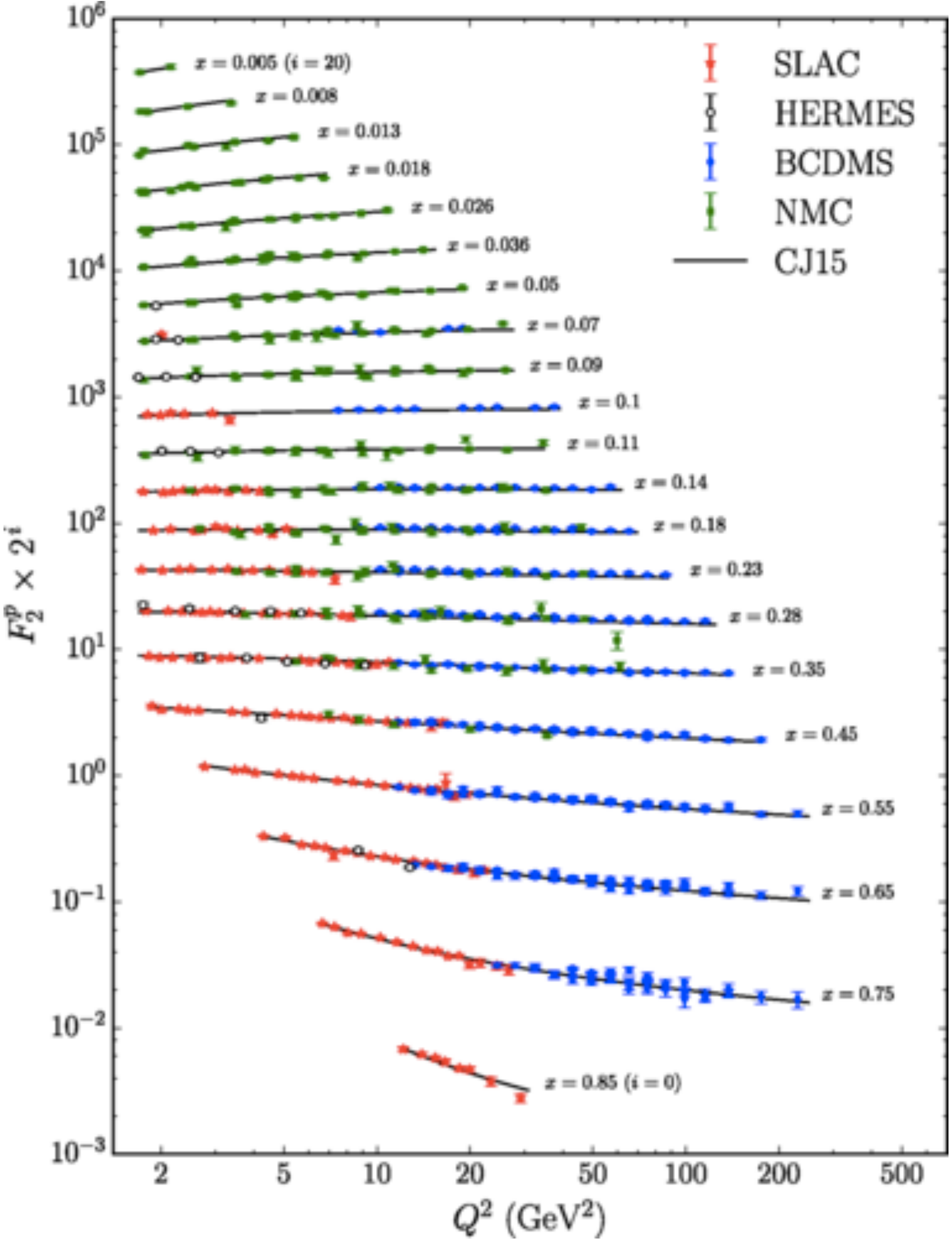
https://www.ellipsix.net/

Structure Functions

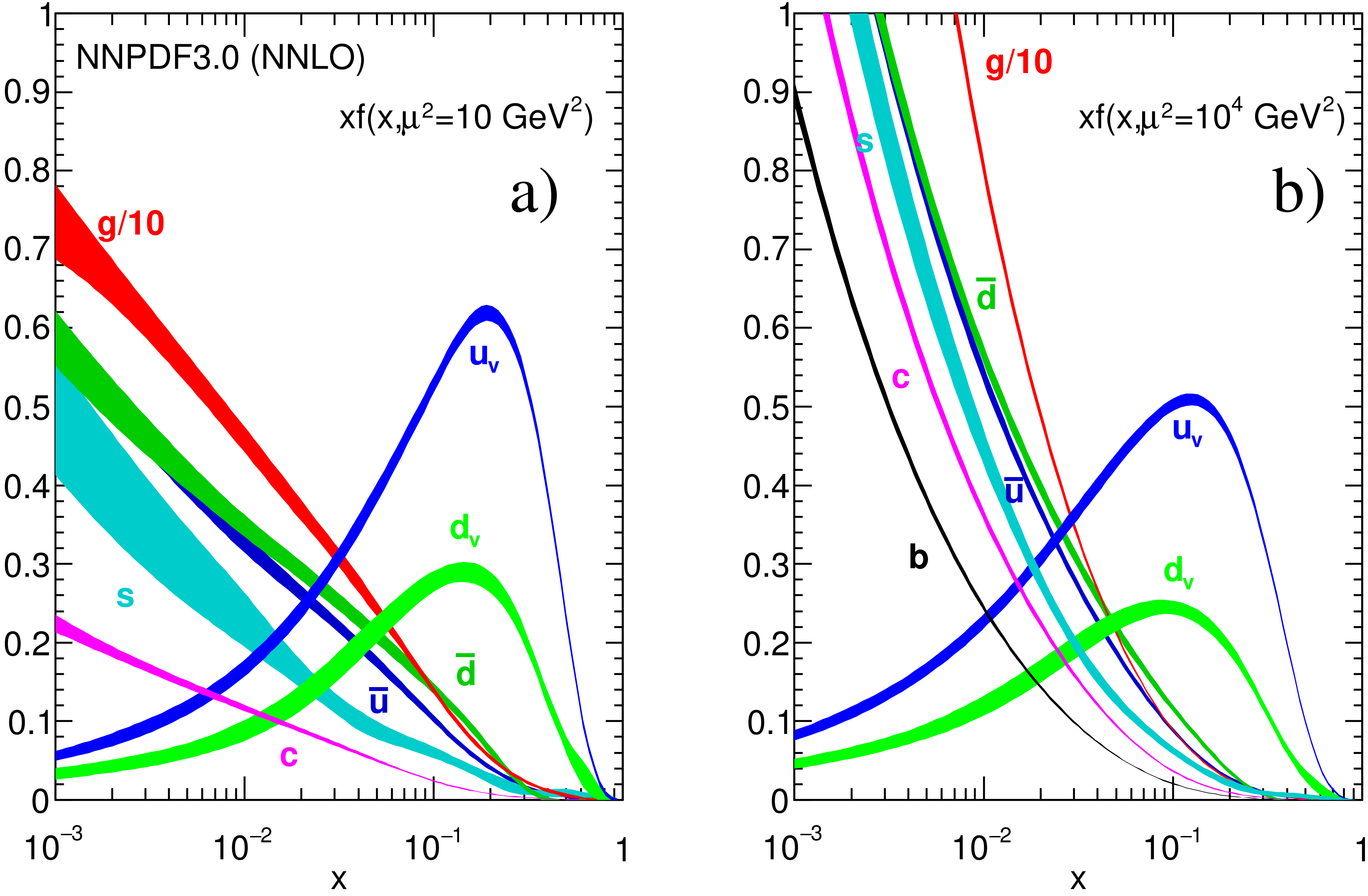
Independent of $Q^2 \Rightarrow$

quarks pointlike





Parton Distribution Function



Spectroscopy

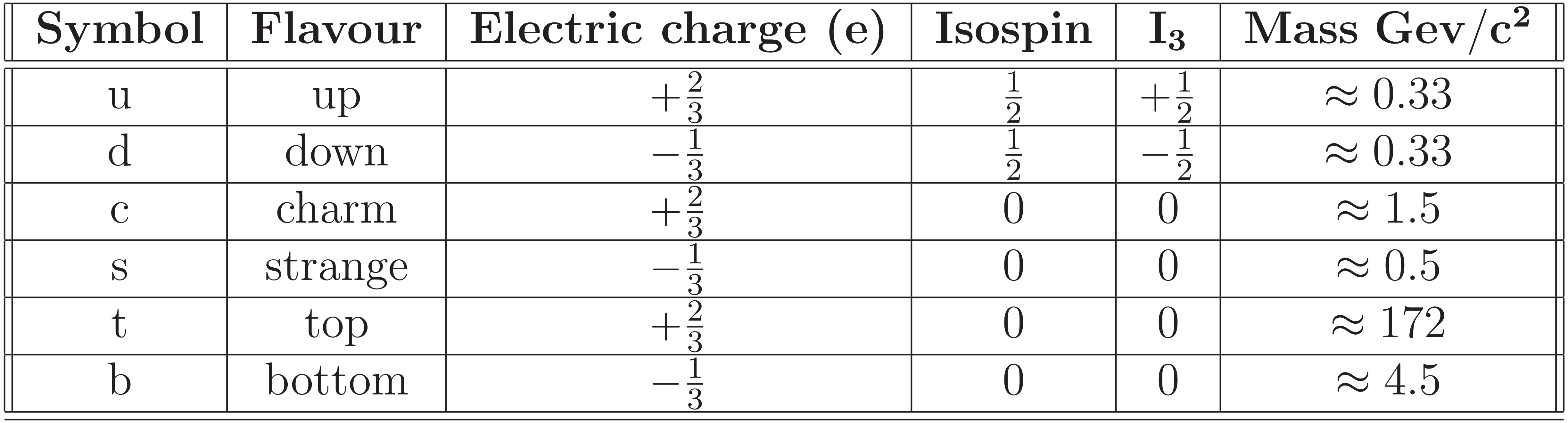
Constituent Quark Model

Classification scheme for hadrons in terms of “valence quarks” which give rise to the quantum numbers of hadrons.

J^{PC} J- total angular momentum, P-symmetry and C-symmetry

SU(3) flavour “Eightfold way”

Organizes a huge number of hadrons



Symbol	Flavour	Electric charge (e)	Isospin	I_3	Mass Gev/c^2
u	up	$+\frac{2}{3}$	$\frac{1}{2}$	$+\frac{1}{2}$	≈ 0.33
d	down	$-\frac{1}{3}$	$\frac{1}{2}$	$-\frac{1}{2}$	≈ 0.33
c	charm	$+\frac{2}{3}$	0	0	≈ 1.5
s	strange	$-\frac{1}{3}$	0	0	≈ 0.5
t	top	$+\frac{2}{3}$	0	0	≈ 172
b	bottom	$-\frac{1}{3}$	0	0	≈ 4.5

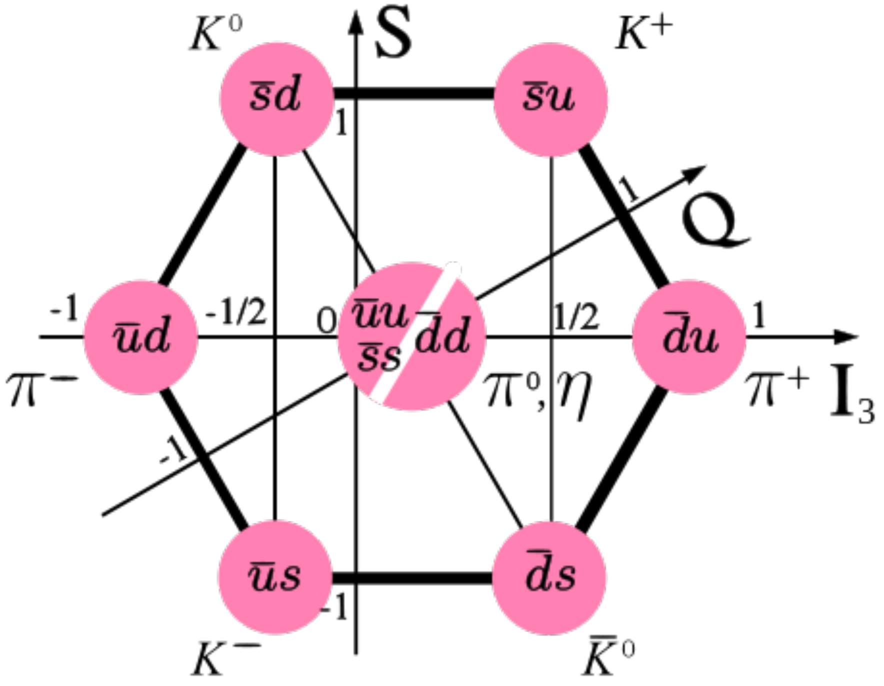
Baryon	**Quark content**	**Spin**	**Isospin**	$\mathbf{I_3}$	**Mass Mev/c^2**
p	uud	$\frac{1}{2}$	$\frac{1}{2}$	$+\frac{1}{2}$	938
n	udd	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	940
Δ^{++}	uuu	$\frac{3}{2}$	$\frac{3}{2}$	$+\frac{3}{2}$	1230
Δ^{+}	uud	$\frac{3}{2}$	$\frac{3}{2}$	$+\frac{1}{2}$	1230
Δ^{0}	udd	$\frac{3}{2}$	$\frac{3}{2}$	$-\frac{1}{2}$	1230
Δ^{-}	ddd	$\frac{3}{2}$	$\frac{3}{2}$	$-\frac{3}{2}$	1230

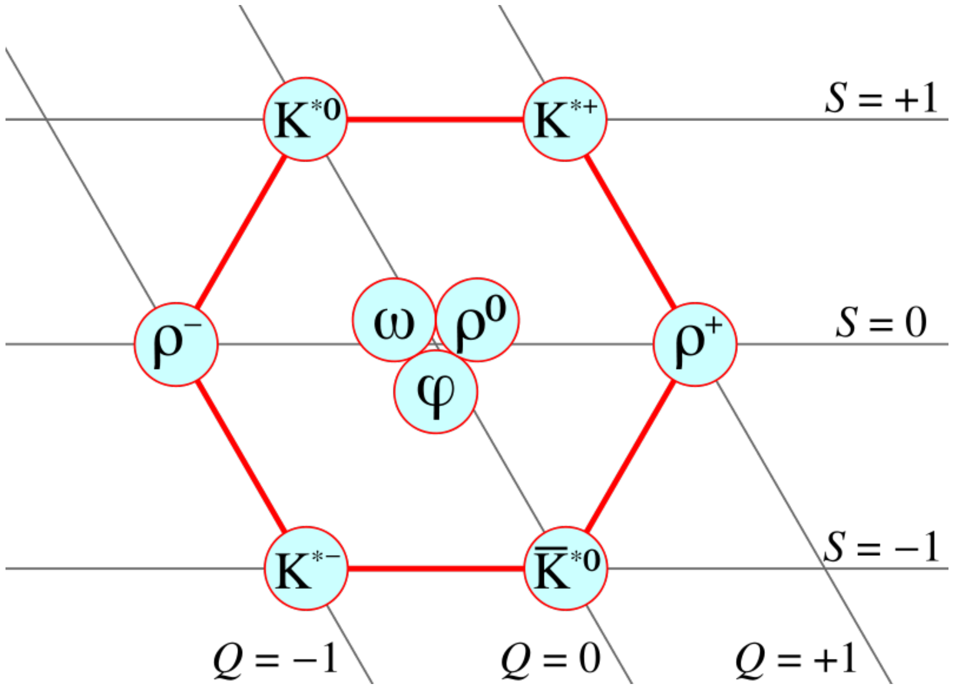
Meson	**Quark content**	**Spin**	**Isospin**	$\mathbf{I_3}$	**Mass Mev/c^2**
π^{+}	$u\bar{d}$	0	1	$+1$	140
π^{0}	$\frac{1}{\sqrt{2}}\left(u\bar{u}-d\bar{d}\right)$	0	1	0	135
π^{-}	$d\bar{u}$	0	1	-1	140
ρ^{+}	$u\bar{d}$	1	1	$+1$	770
ρ^{0}	$\frac{1}{\sqrt{2}}\left(u\bar{u}-d\bar{d}\right)$	1	1	0	770
ρ^{-}	$d\bar{u}$	1	1	-1	770
ω	$\frac{1}{\sqrt{2}}\left(u\bar{u}+d\bar{d}\right)$	1	0	0	782

Baryon	Quark content	Spin	Isospin	I_3	Mass Mev/c^2
Σ^+	uus	$\frac{1}{2}$	1	$+1$	1189
Σ^0	uds	$\frac{1}{2}$	1	0	1193
Σ^-	dds	$\frac{1}{2}$	1	-1	1189
Ξ^0	uss	$\frac{1}{2}$	$\frac{1}{2}$	$+\frac{1}{2}$	1314
Ξ^-	dss	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1321
Λ	uds	$\frac{1}{2}$	0	0	1115
Σ^{*+}	uus	$\frac{3}{2}$	1	$+1$	1385
Σ^{*0}	uds	$\frac{3}{2}$	1	0	1385
Σ^{*-}	dds	$\frac{3}{2}$	1	-1	1385
Ξ^{*0}	uss	$\frac{3}{2}$	$\frac{1}{2}$	$+\frac{1}{2}$	1530
Ξ^{*-}	dss	$\frac{3}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1530
Ω^-	sss	$\frac{3}{2}$	0	0	1672

Mesons

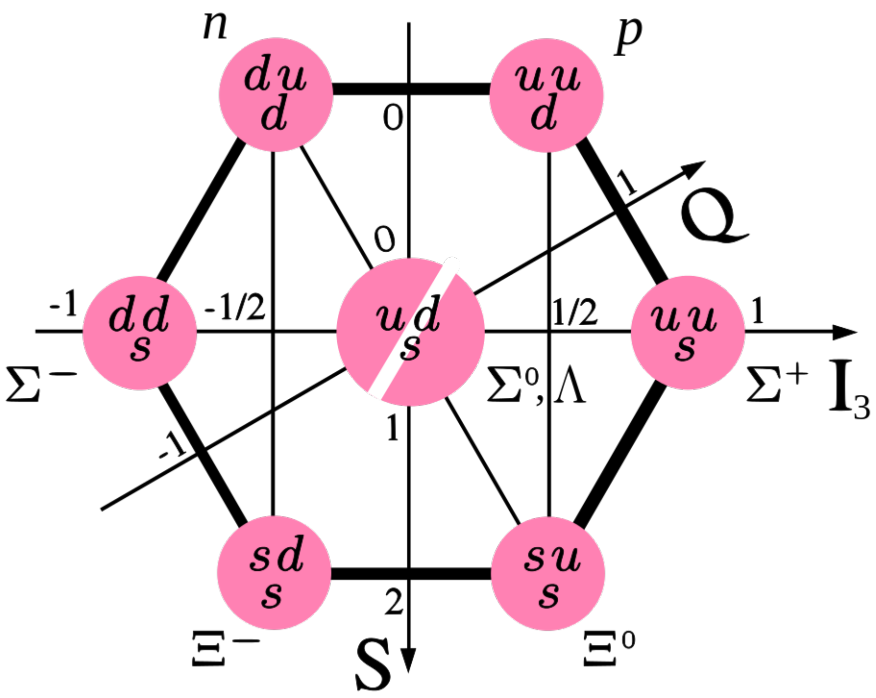
Ancient Greek μέσον (méson, “middle”)



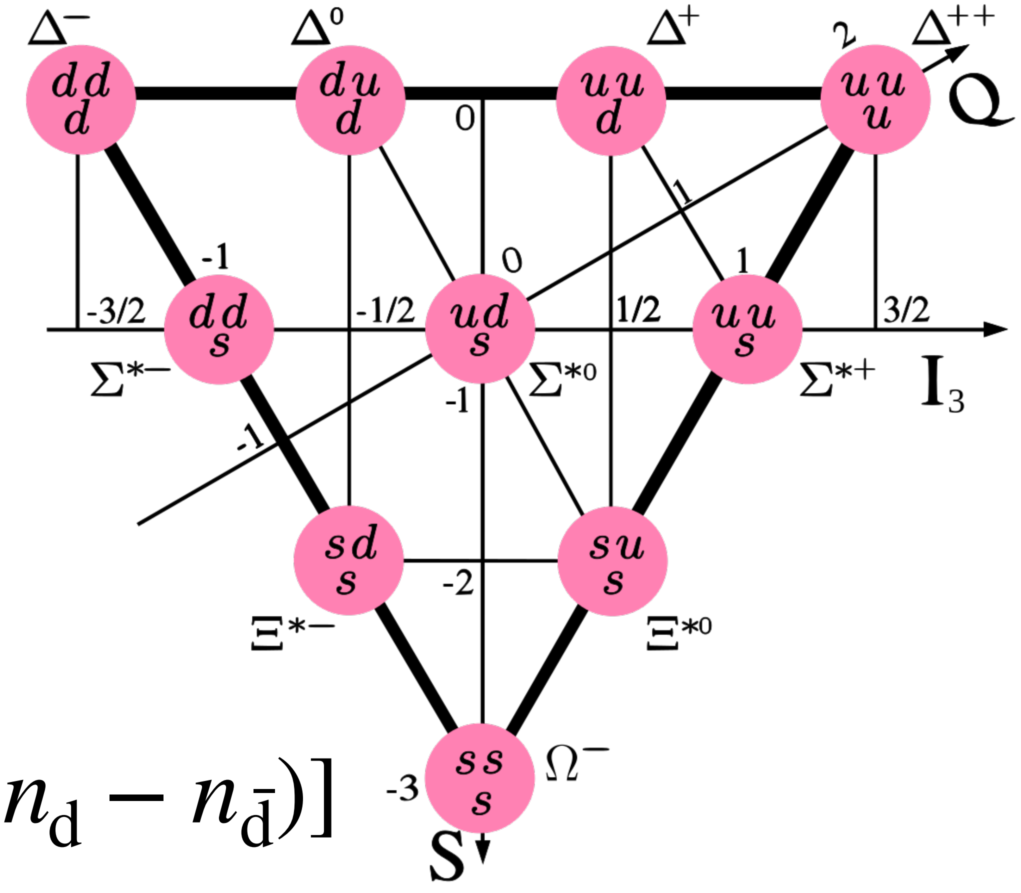


Baryons

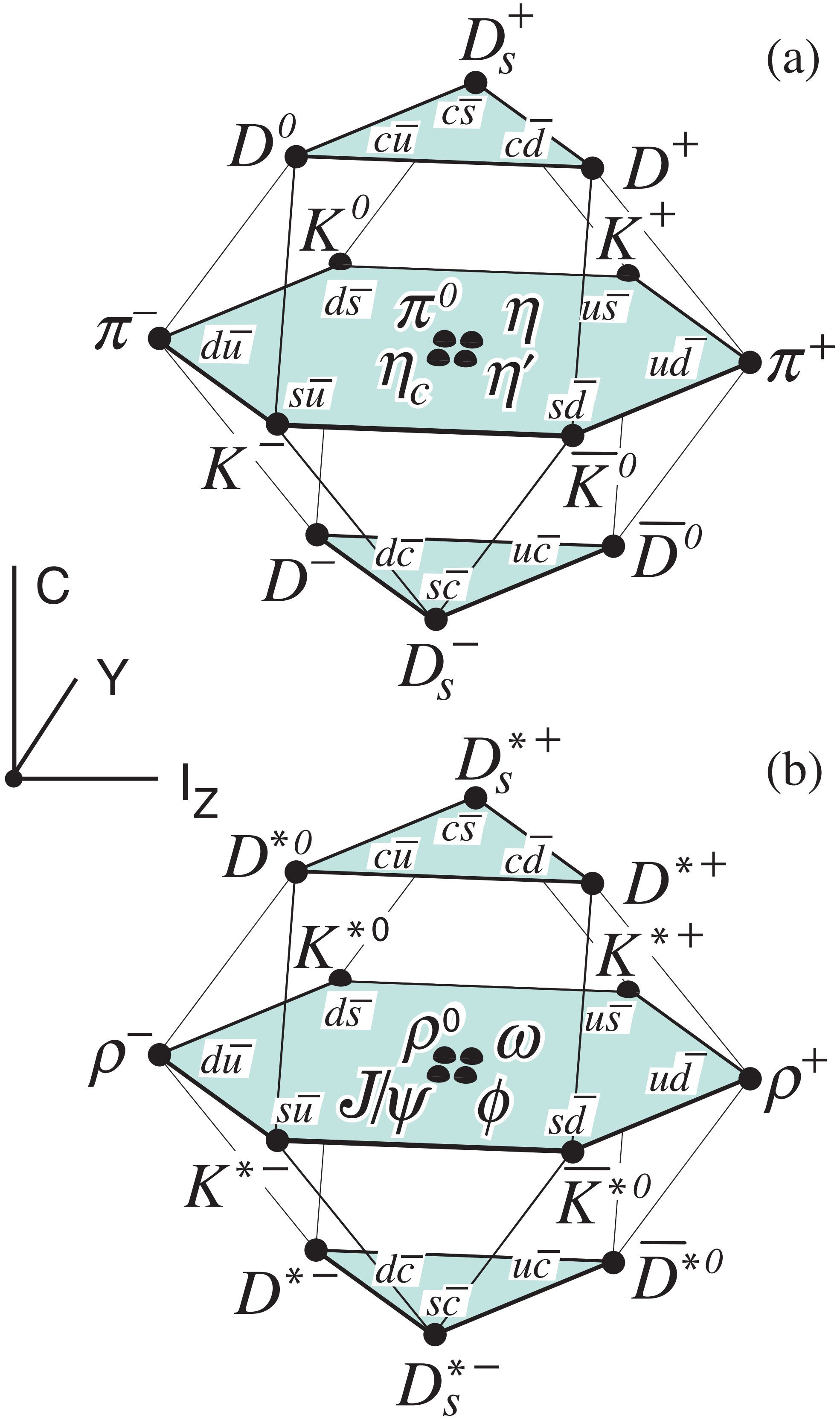
Greek word for "heavy" (βαρύς, barýs)

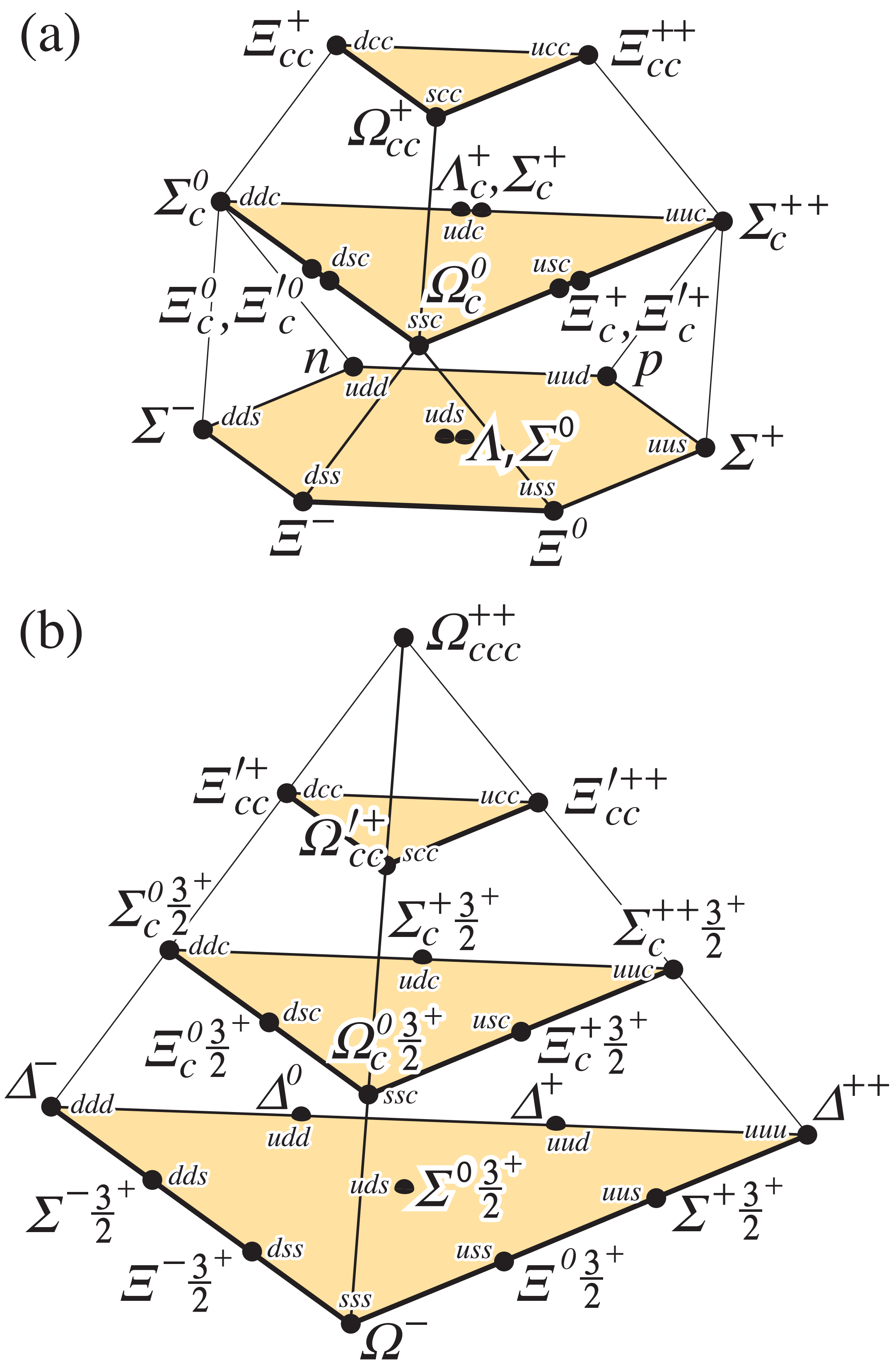


$$Q = I_3 + \frac{1}{2}(B + S)$$



$$I_3 = \frac{1}{2}[(n_{\mathrm{u}} - n_{\bar{\mathrm{u}}}) - (n_{\mathrm{d}} - n_{\bar{\mathrm{d}}})]$$

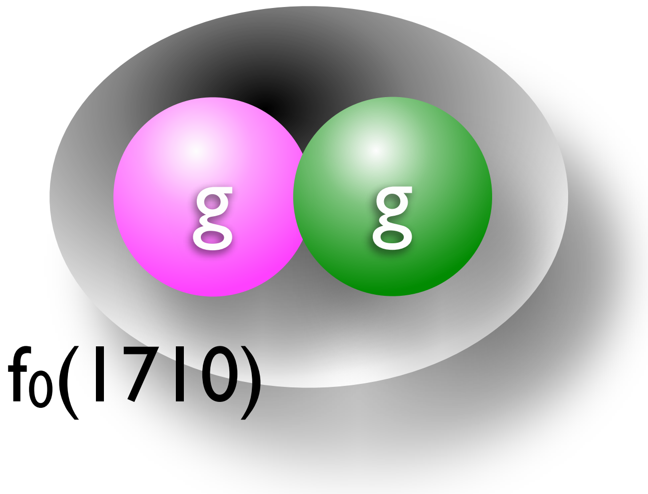

(a)
D_s^+
D^0
D^+
$c\bar{u}$
$c\bar{s}$
$c\bar{d}$
K^0
K^+
π^-
π^+
$d\bar{s}$
$u\bar{s}$
$d\bar{u}$
$u\bar{d}$
π^0
η
η_c
η'
$s\bar{u}$
$s\bar{d}$
K^-
$\bar{K}^0$
$d\bar{c}$
$u\bar{c}$
$s\bar{c}$
D^-
$\bar{D}^0$
D_s^-
C
Y
I_Z
(b)
D_s^{*+}
D^{*0}
D^{*+}
$c\bar{u}$
$c\bar{s}$
$c\bar{d}$
K^{*0}
K^{*+}
ρ^-
ρ^+
$d\bar{s}$
$u\bar{s}$
$d\bar{u}$
$u\bar{d}$
ρ^0
ω
J/ψ
ϕ
$s\bar{u}$
$s\bar{d}$
K^{*-}
$\bar{K}^{*0}$
$d\bar{c}$
$u\bar{c}$
$s\bar{c}$
D^{*-}
$\bar{D}^{*0}$
D_s^{*-}


(a)
Ξ_{cc}^+
Ξ_{cc}^{++}
dcc
ucc
scc
Ω_{cc}^+
Λ_c^+, Σ_c^+
Σ_c^0
Σ_c^{++}
ddc
uuc
udc
dsc
usc
Ω_c^0
ssc
$\Xi_c^0, \Xi_c'^0$
$\Xi_c^+, \Xi_c'^+$
n
p
udd
uud
Σ^-
Σ^+
dds
uus
uds
Λ, Σ^0
dss
uss
Ξ^-
Ξ^0
(b)
Ω_{ccc}^{++}
$\Xi_{cc}'^+$
$\Xi_{cc}'^{++}$
dcc
ucc
$\Omega_{cc}'^+$
scc
$\Sigma_c^{0\,\frac{3}{2}^+}$
$\Sigma_c^{+\,\frac{3}{2}^+}$
$\Sigma_c^{++\,\frac{3}{2}^+}$
ddc
udc
uuc
dsc
usc
$\Xi_c^{0\,\frac{3}{2}^+}$
$\Omega_c^{0\,\frac{3}{2}^+}$
$\Xi_c^{+\,\frac{3}{2}^+}$
ssc
Δ^-
Δ^0
Δ^+
Δ^{++}
ddd
udd
uud
uuu
dds
uds
uus
$\Sigma^{-\,\frac{3}{2}^+}$
$\Sigma^{0\,\frac{3}{2}^+}$
$\Sigma^{+\,\frac{3}{2}^+}$
dss
uss
$\Xi^{-\,\frac{3}{2}^+}$
$\Xi^{0\,\frac{3}{2}^+}$
sss
Ω^-

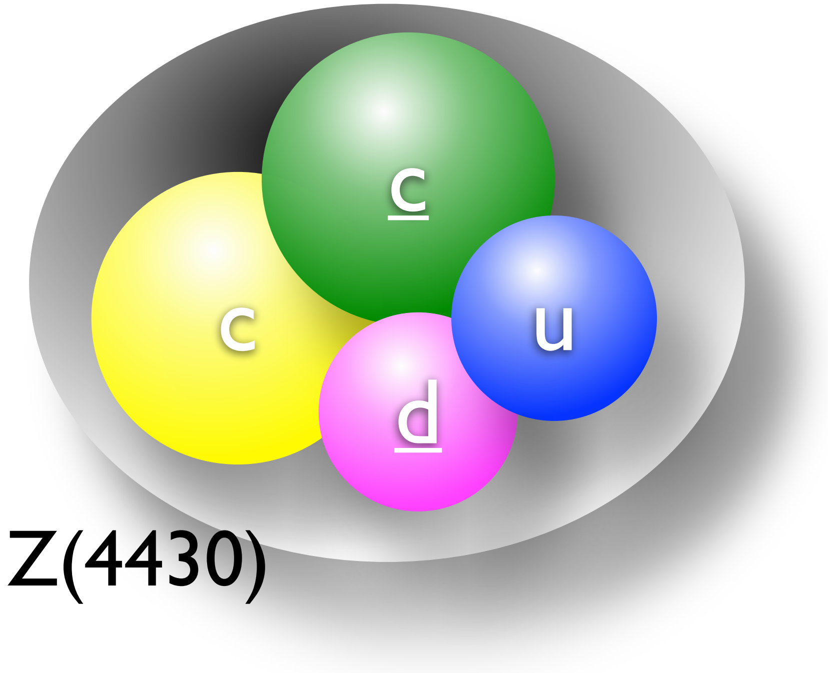
Exotic Hadrons

Why don't we find other color-singlets?
If they exist: what are their properties?
Why are they so rare?

glueball

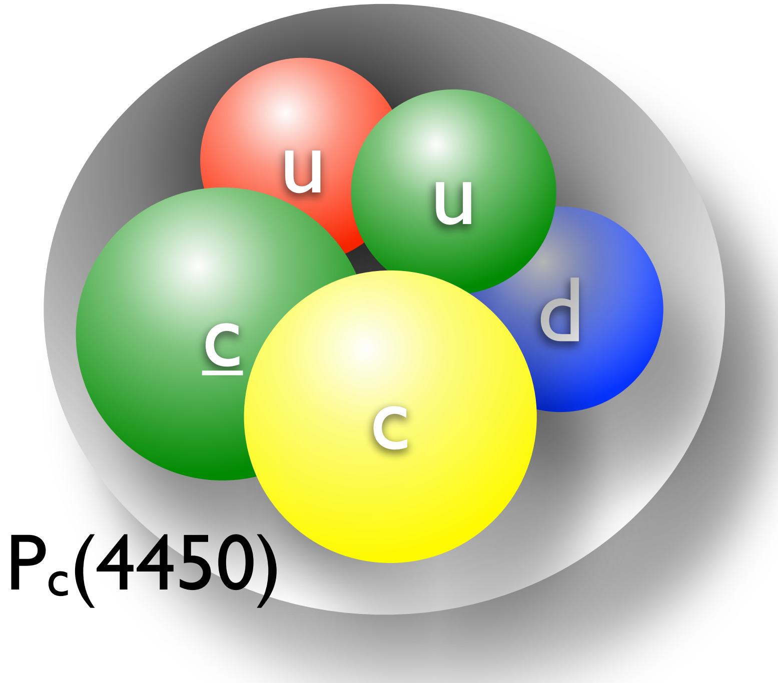


tetra-quark



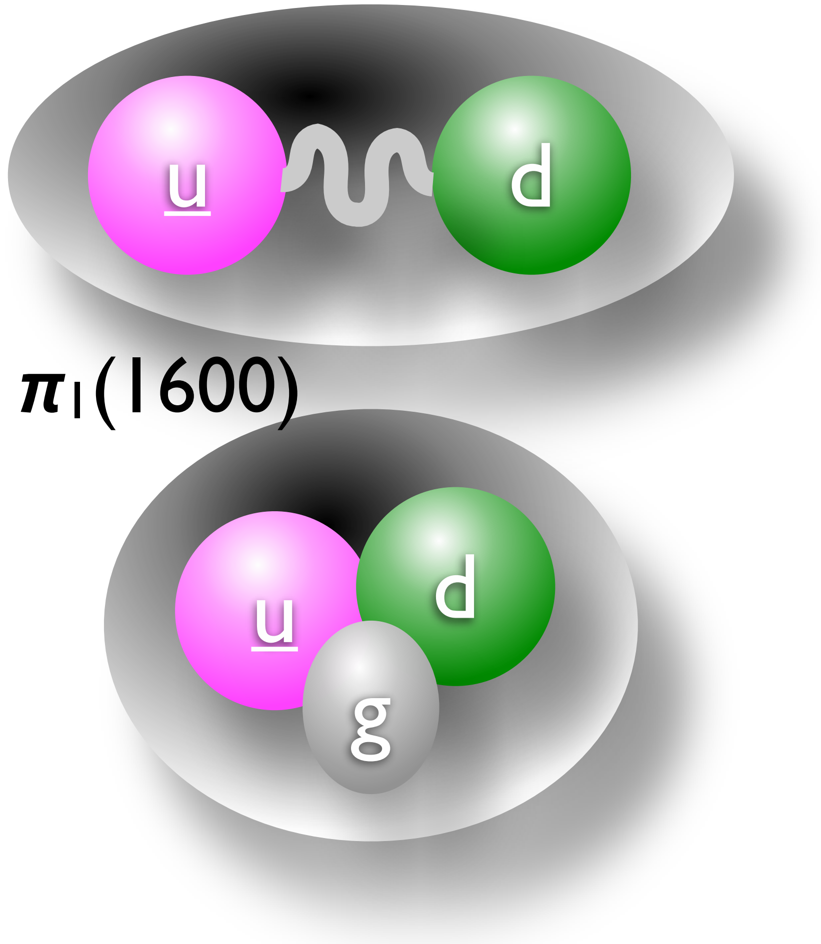
Evidence for resonant behavior
PRL 112 (2014) 222002

penta-quark



PRL 115, 072001 (2015)

hybrid meson

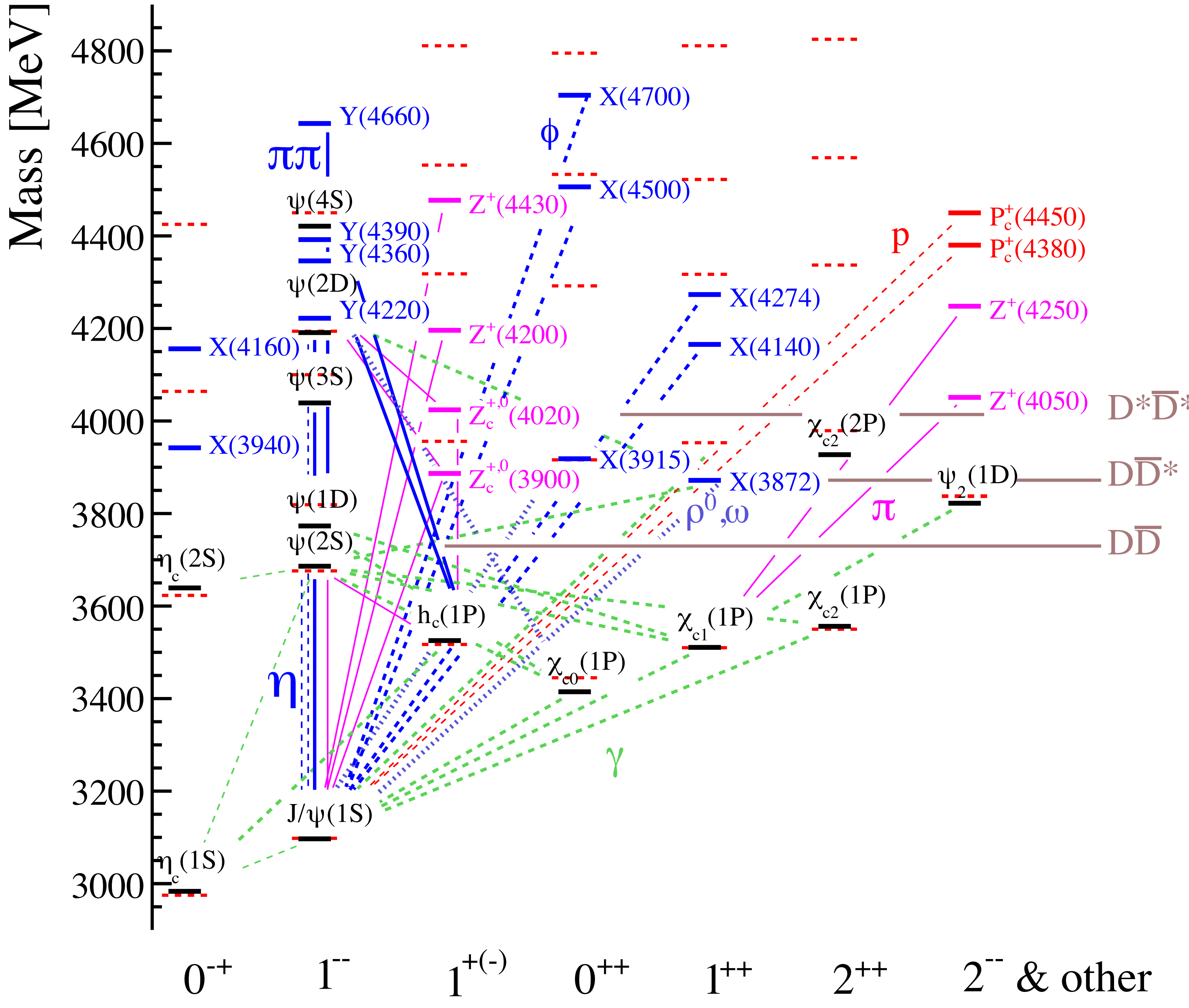


Heavy Exotics (XYZ states)

What are they?
Observations that don't fit with conventional quark model charmonium

Why called XYZ?
X: Everything else!
Y: JPC=1-- in e+e-
Z: Electrically charged

There are many!



As of 2017

https://doi.org/10.1103/RevModPhys.90.015003 Olsen

Meson Quantum Numbers

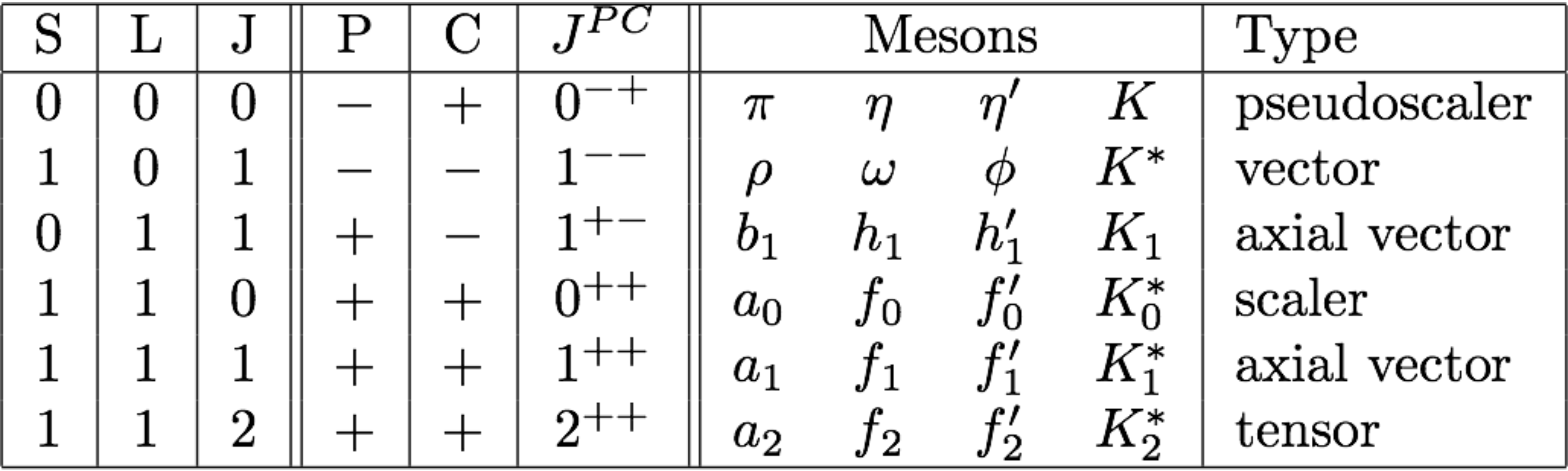
Mesons have well defined quantum numbers: total spin J, parity P, and C-parity C represented as J^{PC}

$$P(q\bar{q}) = (-1)^{L+1}$$

mirror

$$C(q\bar{q}) = (-1)^{L+S}$$

particle—anti-particle exchange

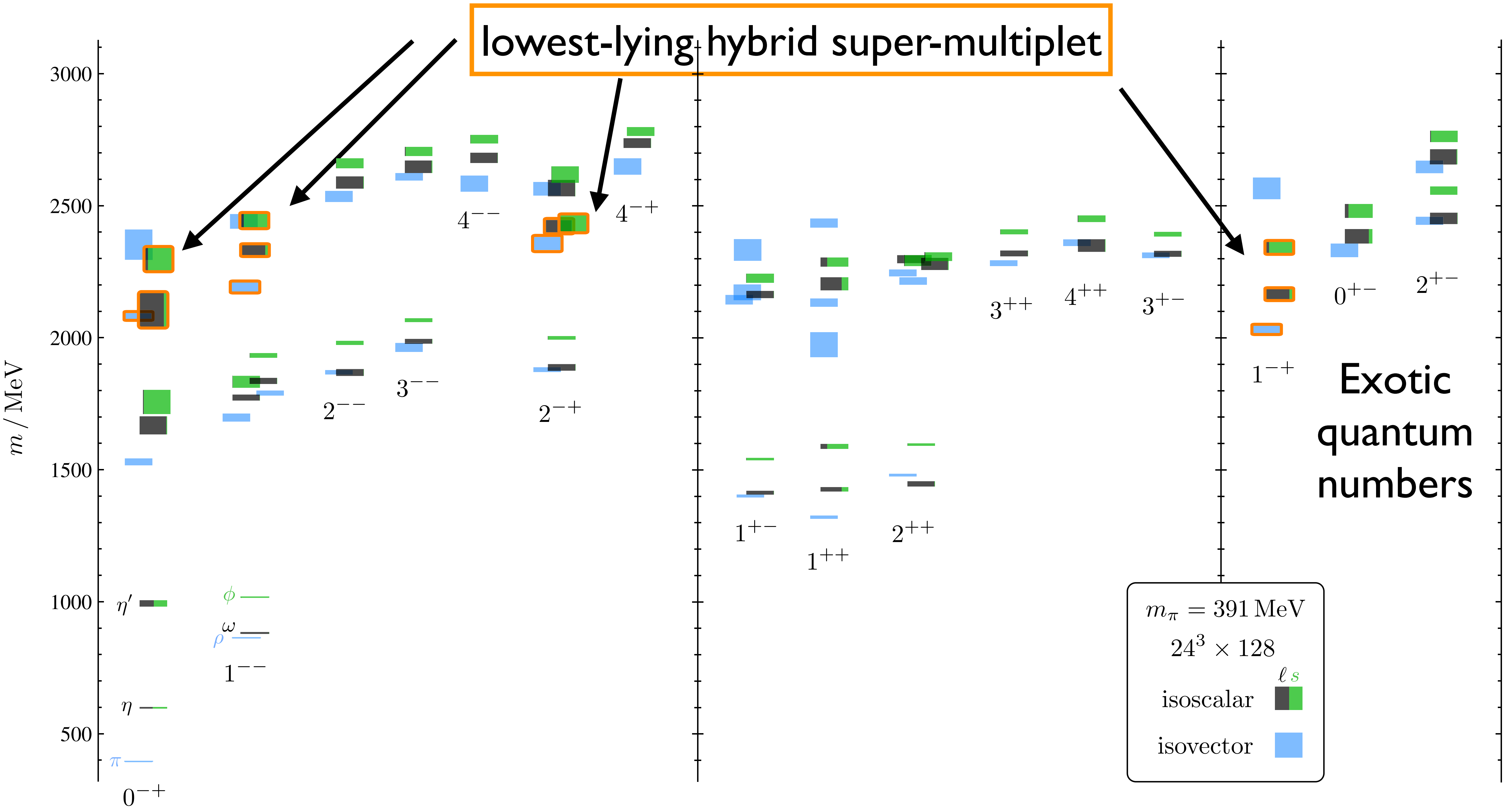


S	L	J	P	C	J^{PC}	Mesons				Type
0	0	0	$-$	$+$	0^{-+}	π	η	η'	K	pseudoscaler
1	0	1	$-$	$-$	1^{--}	ρ	ω	ϕ	K^*	vector
0	1	1	$+$	$-$	1^{+-}	b_1	h_1	h'_1	K_1	axial vector
1	1	0	$+$	$+$	0^{++}	a_0	f_0	f'_0	K^*_0	scaler
1	1	1	$+$	$+$	1^{++}	a_1	f_1	f'_1	K^*_1	axial vector
1	1	2	$+$	$+$	2^{++}	a_2	f_2	f'_2	K^*_2	tensor

explicitly exotic quantum numbers

$$0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$$

Light Quark Mesons from Lattice

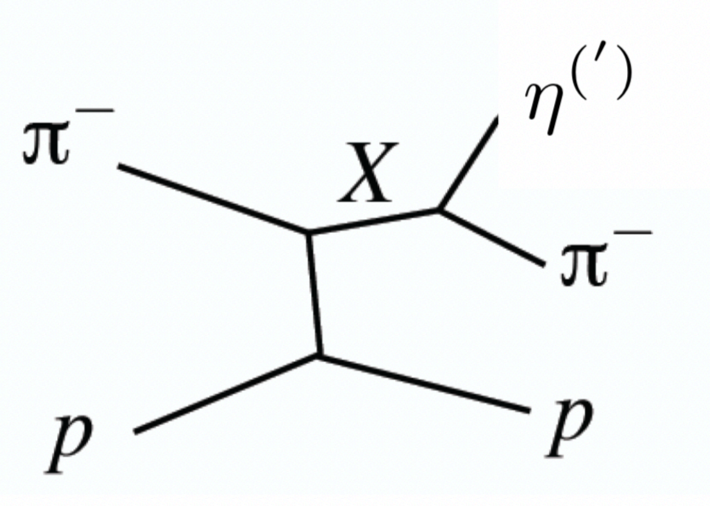


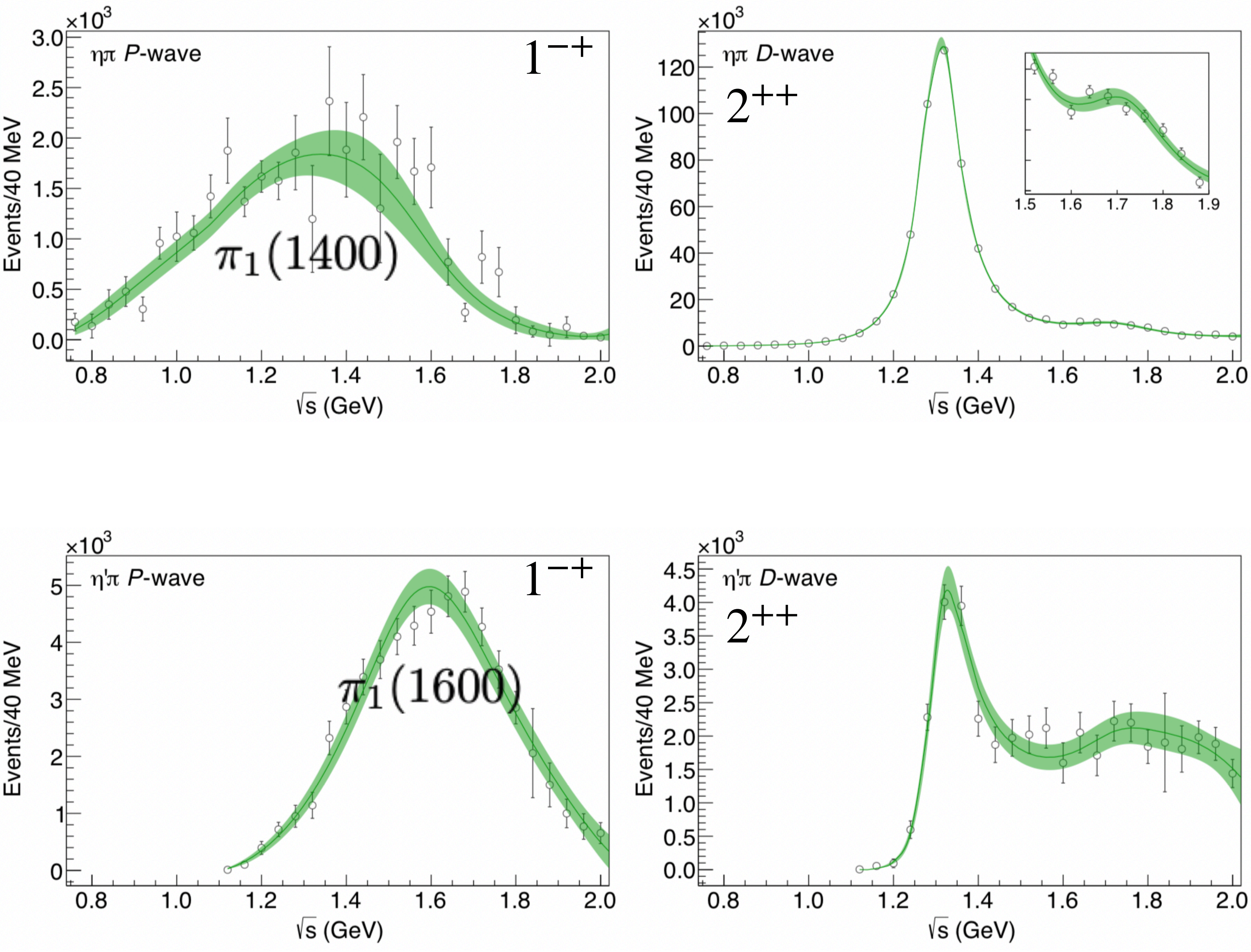
lowest-lying hybrid super-multiplet

Exotic quantum numbers

Dudek et al. PRD 88 (2013) 094505

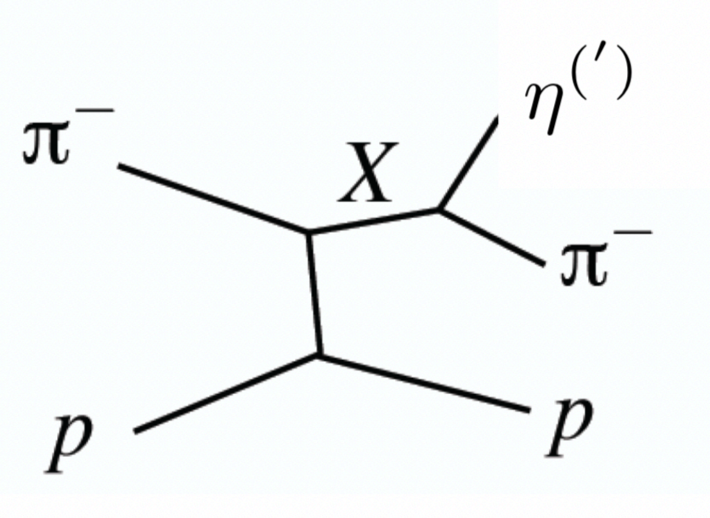
$\eta\pi / \eta'\pi$ spectroscopy



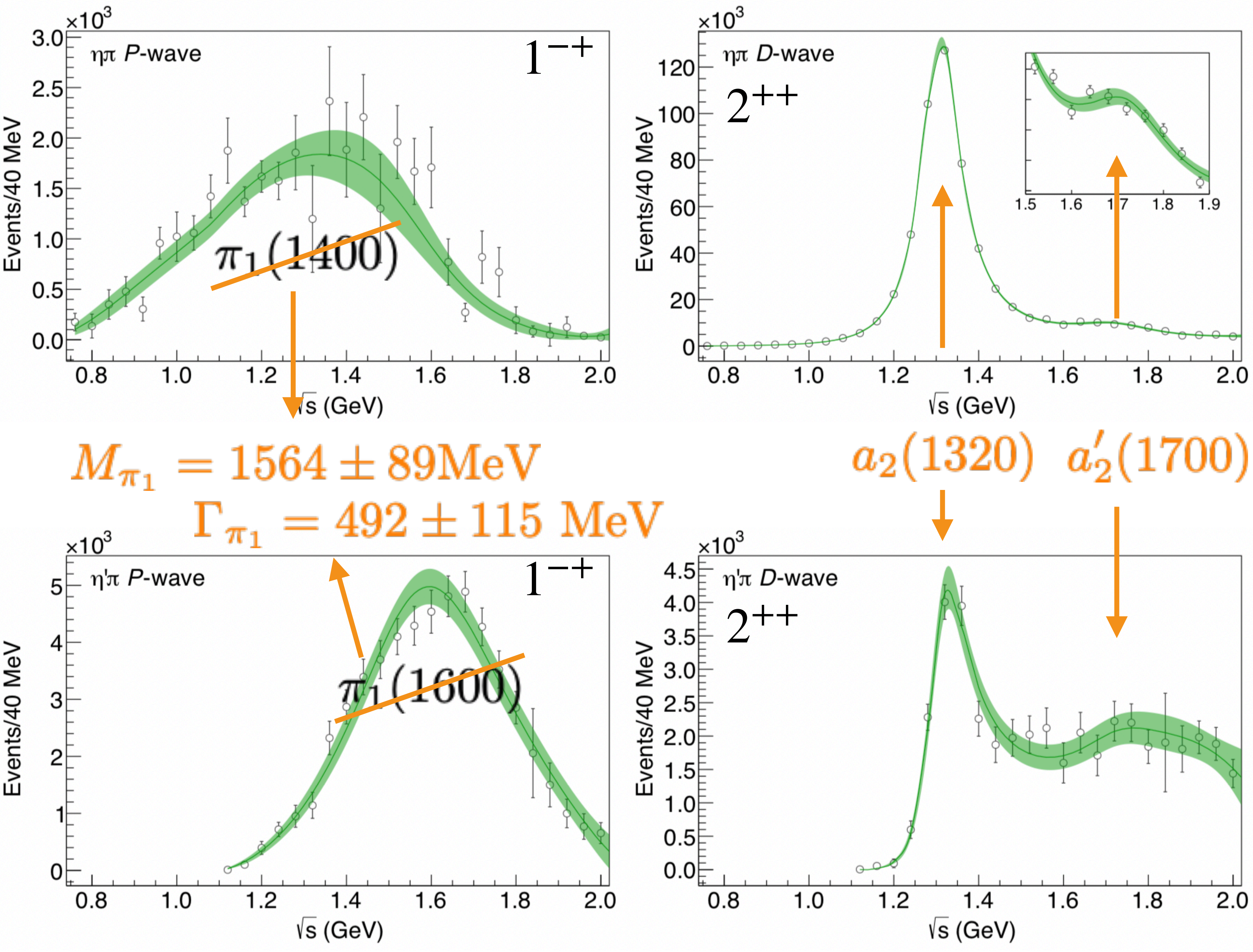


COMPASS:
PLB 740 (2015) 303
JPAC:
PRL 122 (2019) 042002

$\eta\pi / \eta'\pi$ spectroscopy



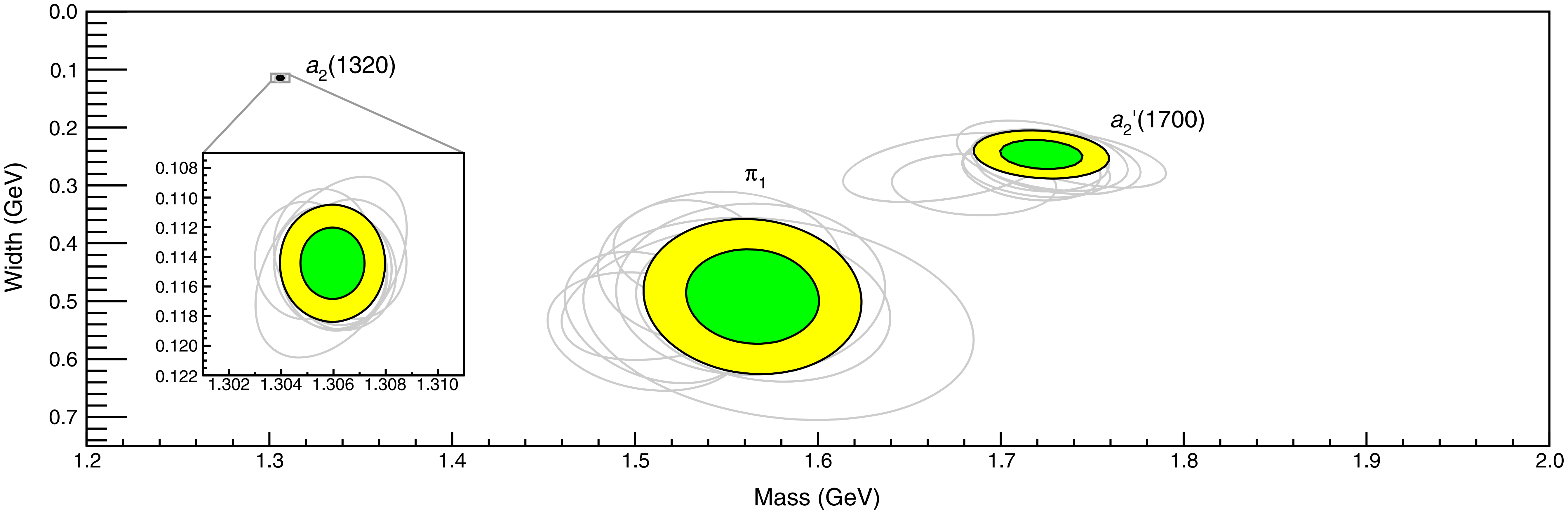
coupled channel fit to ηπ and η'π determine pole positions for a_2, a_2', and exotic π_1



$$M_{\pi_1} = 1564 \pm 89 \text{MeV}$$

$$\Gamma_{\pi_1} = 492 \pm 115 \text{ MeV}$$

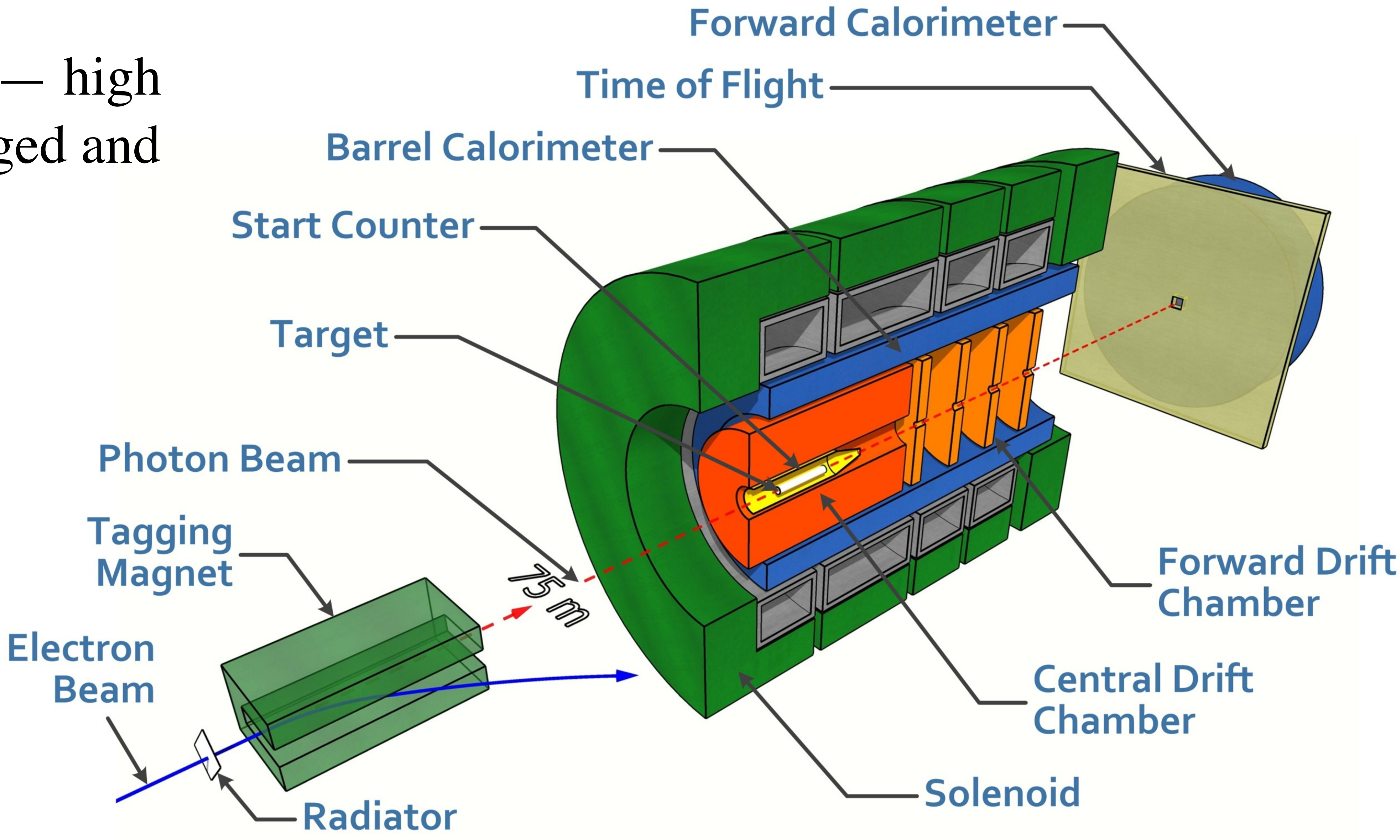
COMPASS:
PLB 740 (2015) 303
JPAC:
PRL 122 (2019) 042002


0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Width (GeV)
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Mass (GeV)
$a_2(1320)$
π_1
$a_2'(1700)$
0.108
0.110
0.112
0.114
0.116
0.118
0.120
0.122
1.302
1.304
1.306
1.308
1.310

Experiment and Detector

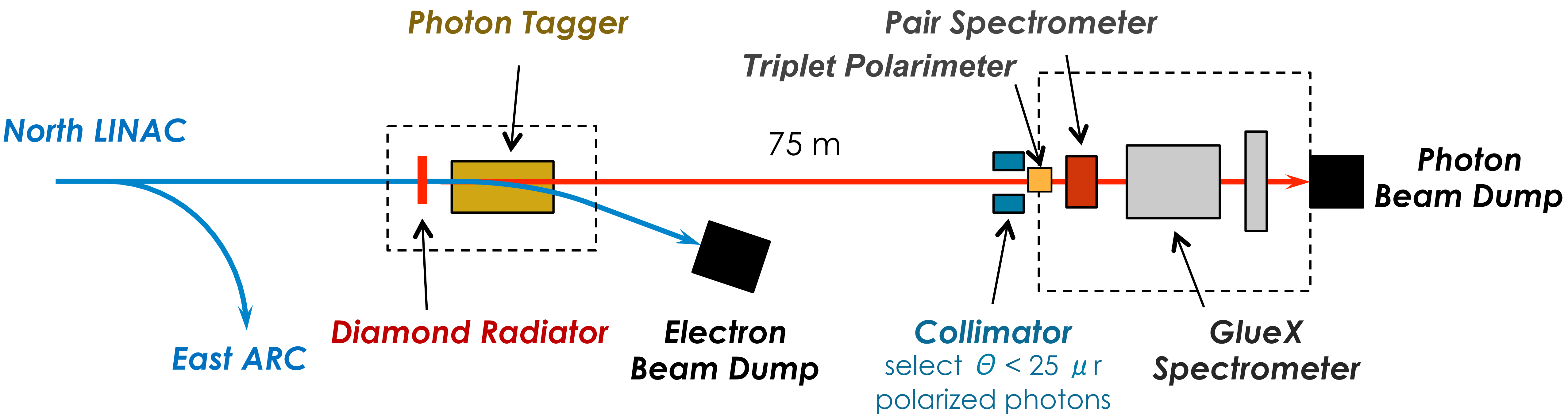
Hall D at Jefferson Lab

Linearly polarized photon beam
Proton target
Hermetic detector — high efficiency for charged and neutral particles



Nucl. Instrum. & Meth. A987, 164807 (2021)

Photon Beamline



~12 GeV electrons from CEBAF

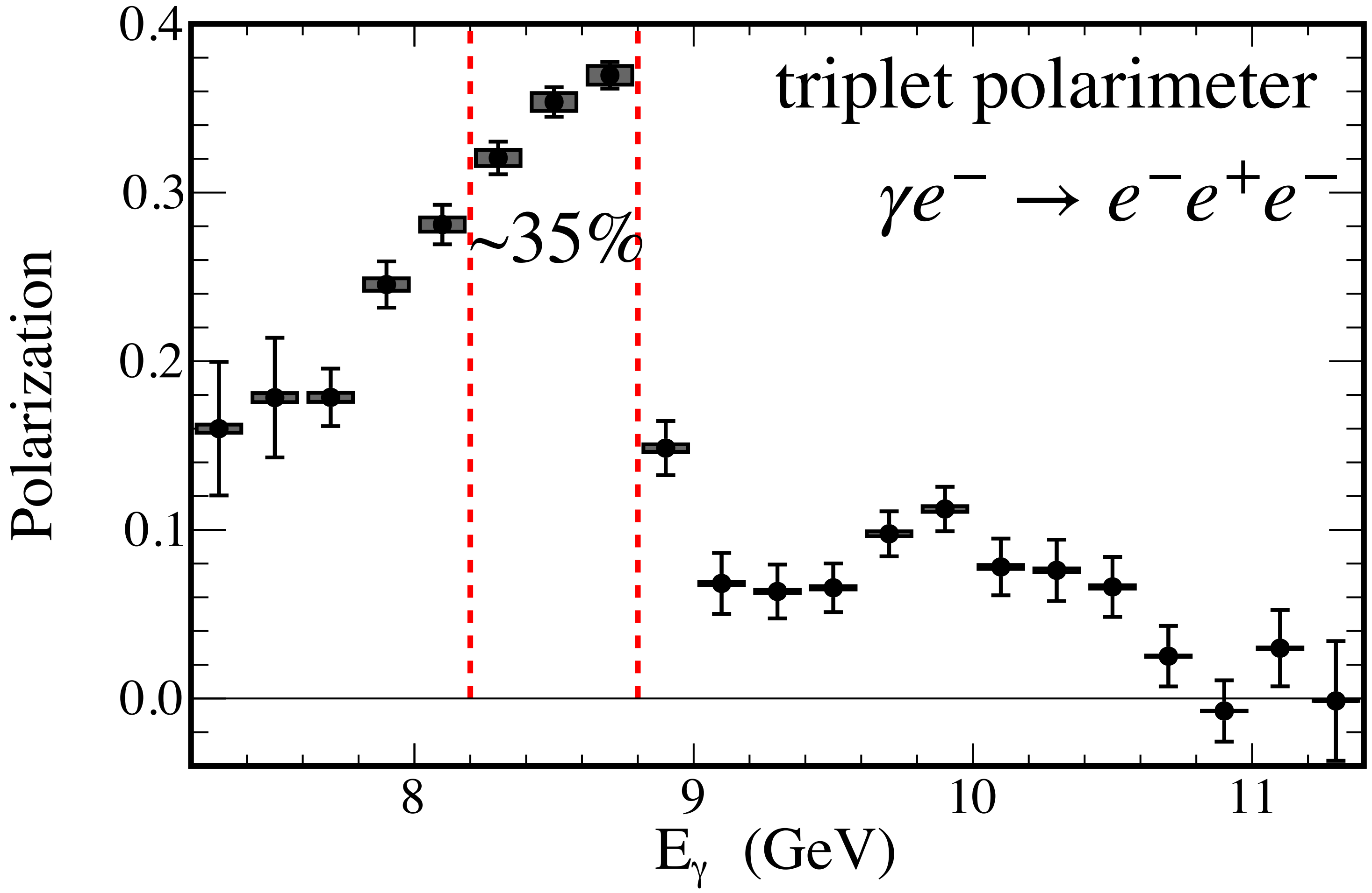
Coherent bremsstrahlung on thin diamond wafer

Linearly polarized in coherent peak ~35%

Tagged photon energy

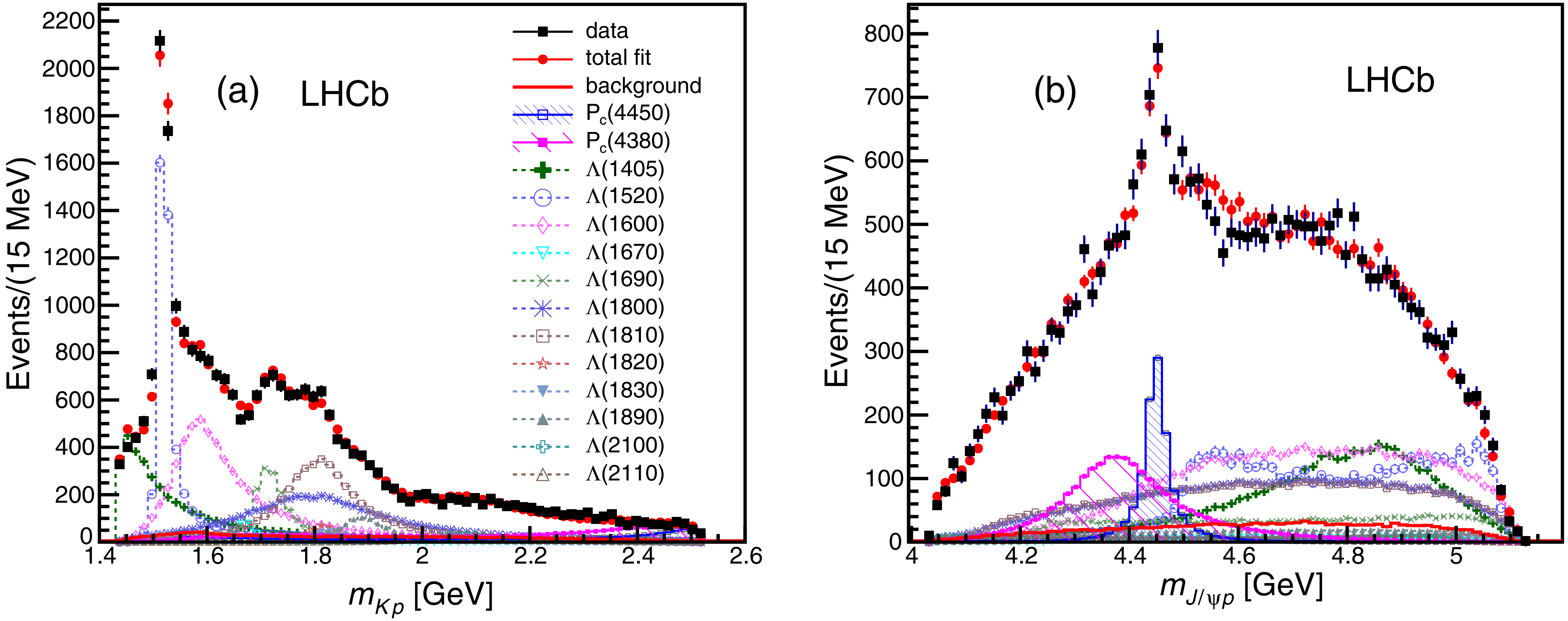
GlueX phase 1 tagged luminosity

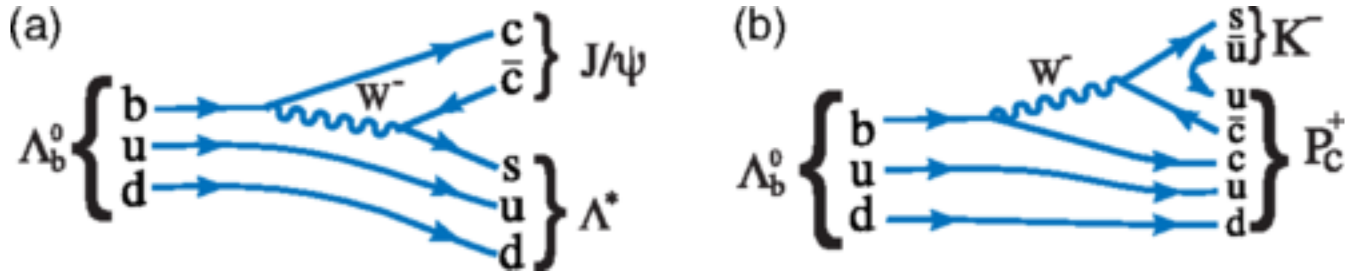
8.2 - 8.8 GeV	125 pb^{-1}
6.0 - 11.6 GeV	440 pb^{-1}

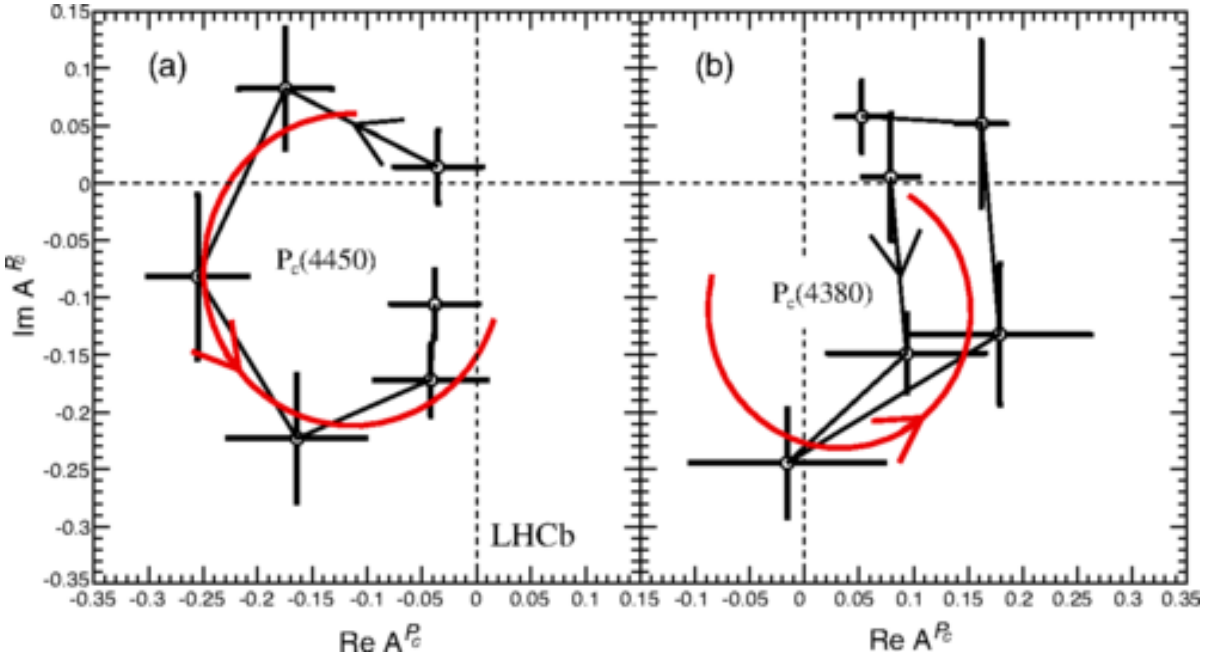


LHCb Pentaquarks (2015)

$$\Lambda_b^0 \to J/\psi p K^-$$





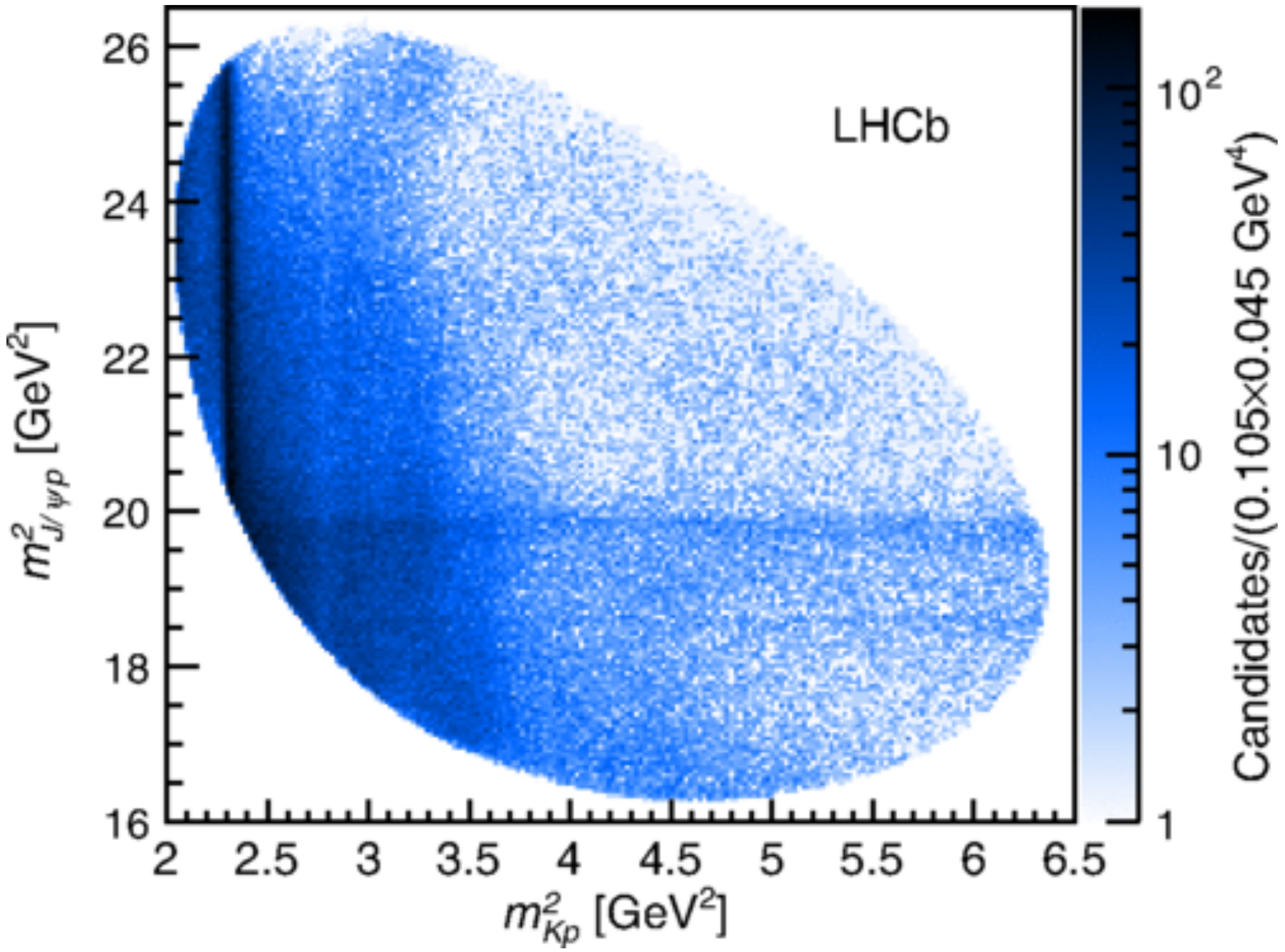


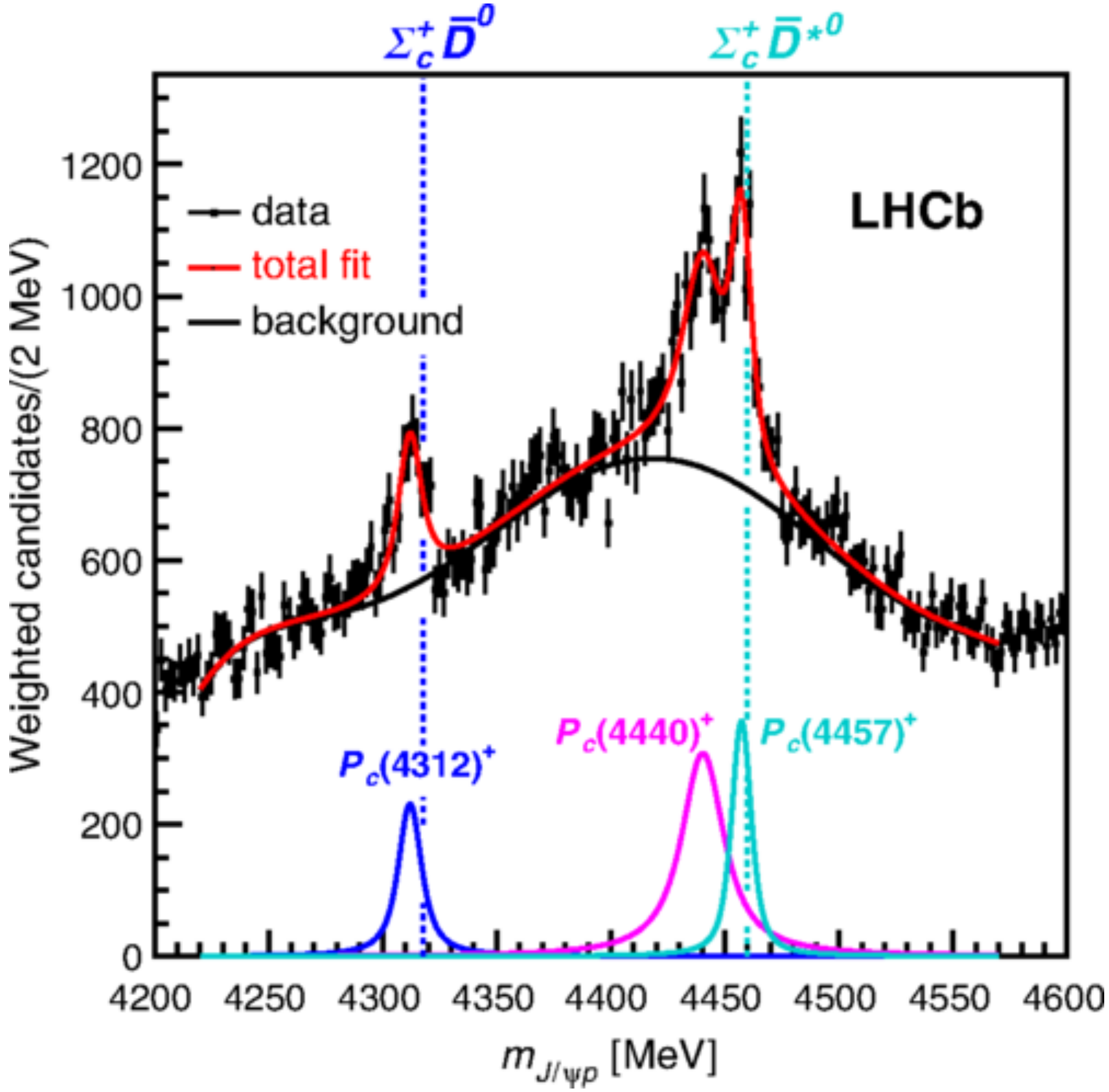
https://doi.org/10.1103/PhysRevLett.115.072001

LHCb Pentaquarks (2019)

$$\Lambda_b^0 \to J/\psi p K^-$$

9 times more data

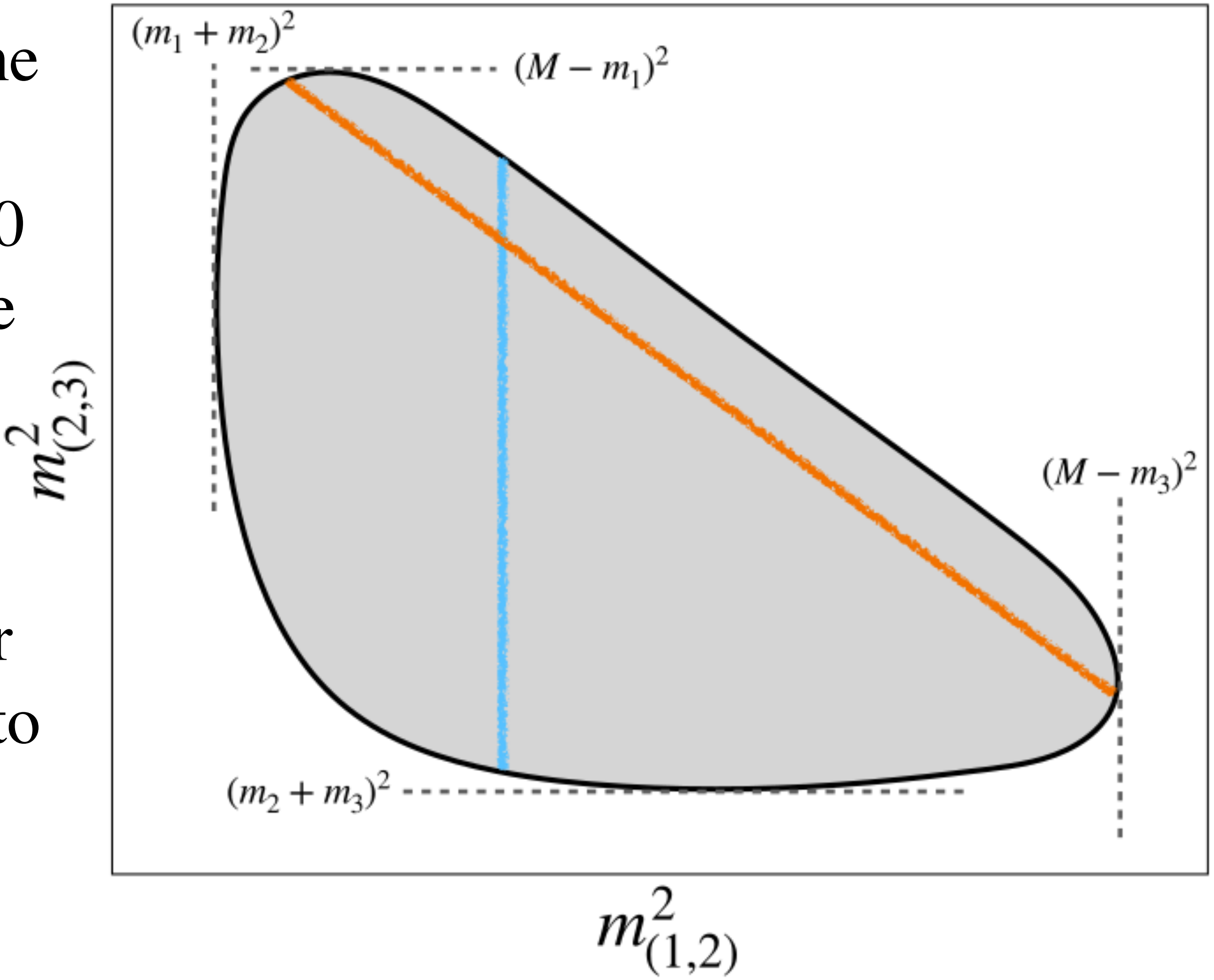




https://doi.org/10.1103/PhysRevLett.122.222001

Dalitz Plot

Dalitz plot for a three-body decay of a spin-0 particle of the mass M into three spin-0 particles of masses m_1, m_2, m_3. The grey area depicts the allowed kinematic region. The blue line shows a possible position of accumulation of events in case a spin-0 resonance is present as an intermediate state in this three-body decay, which then decays to particles 1 and 2. The orange line shows the position of accumulation of events in case another spin-0 resonance is present, decaying to particles 1 and 3.

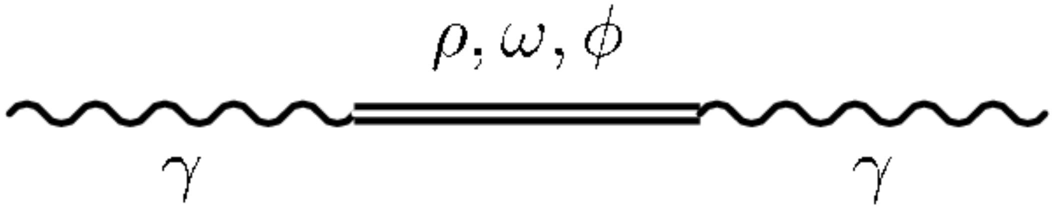


Vector Meson Dominance (VMD)

Predates QCD

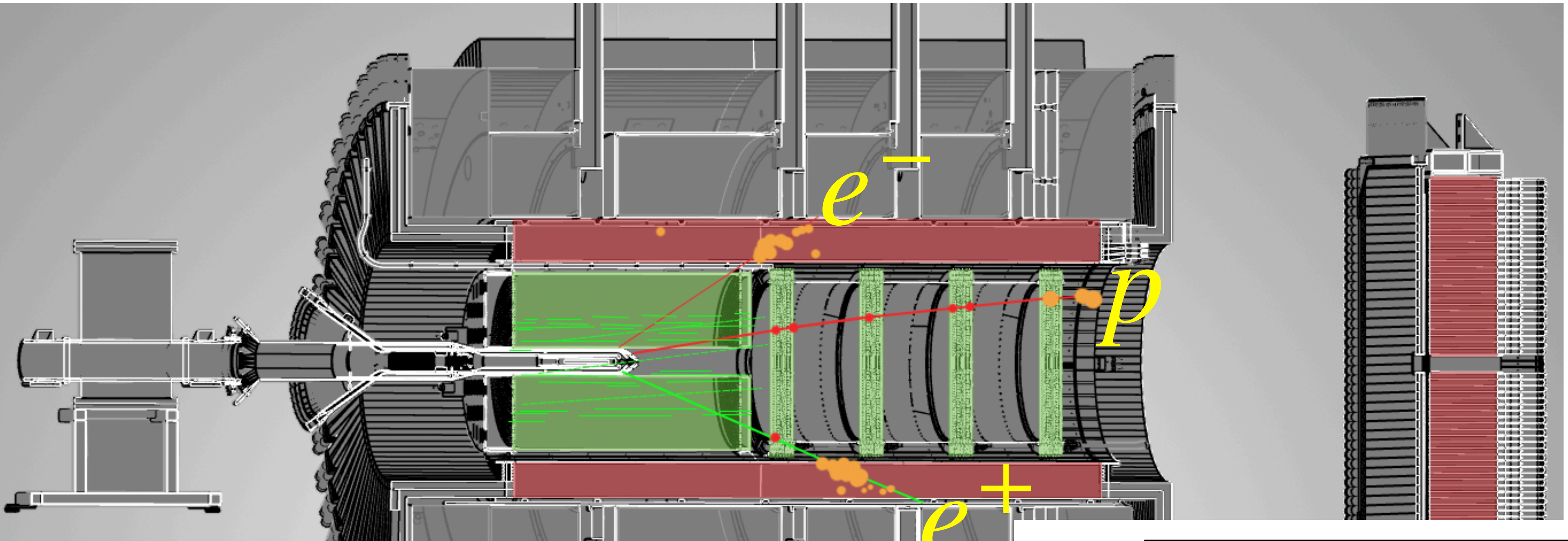
Vector mesons have the same quantum numbers (J^{PC}) as a photon

the hadronic components of the physical photon consist of the lightest vector mesons, ρ, ω, ϕ



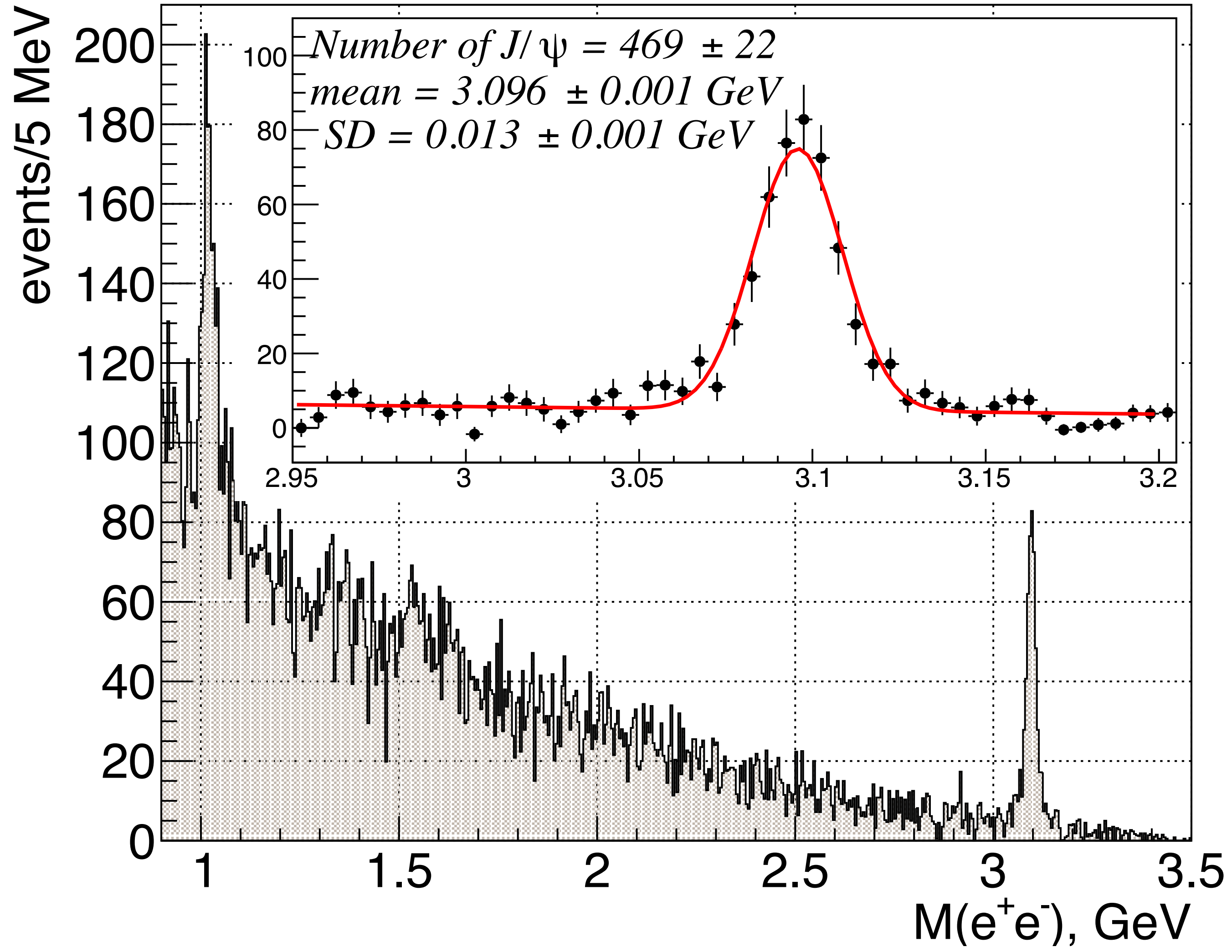
interactions between photons and hadronic matter occur by the exchange of a hadron between the dressed photon and the hadronic target

J/ψ Photoproduction at GlueX



$$\gamma p \to J/\psi p$$

$$J/\psi \to e^+e^-$$

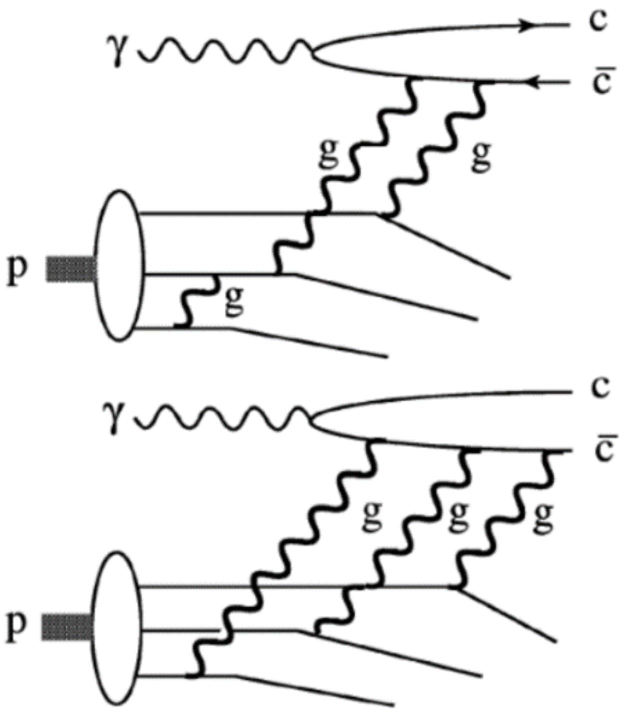


- Electron identification: E/p and E-dE in calorimeters, pion background suppression by 10^4
- Kinematic Fit with $0.2\,\%$ precision on photon beam energy

J/ψ Photoproduction at GlueX

First measurement of J/ψ photoproduction cross section at threshold

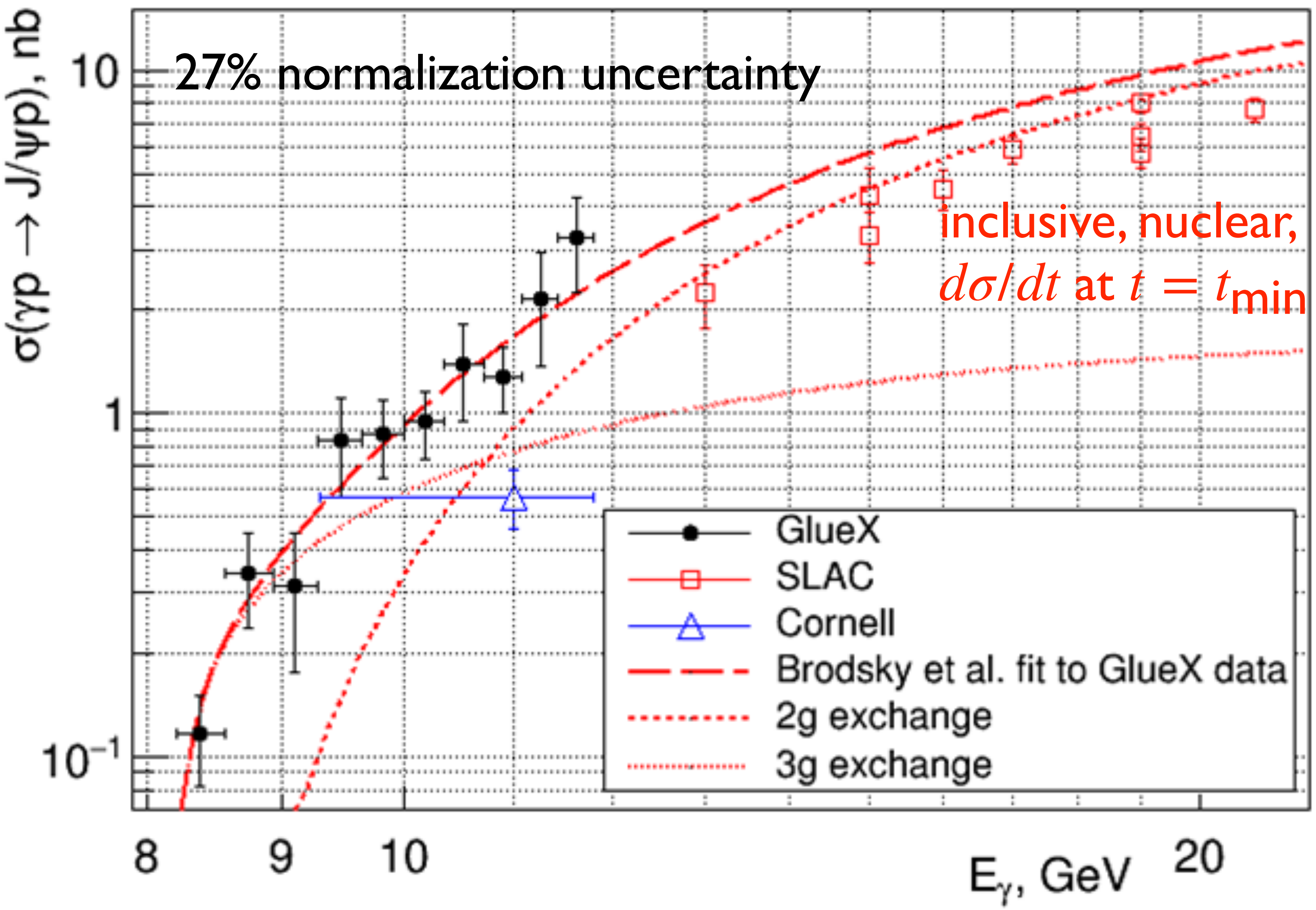
Heavy quarks $c\bar{c}$ system interacts with proton via gluon exchange.



Dimensional scaling rules, number of exchanged gluons
→energy dependence

3-gluon exchange needed to describe cross section at threshold

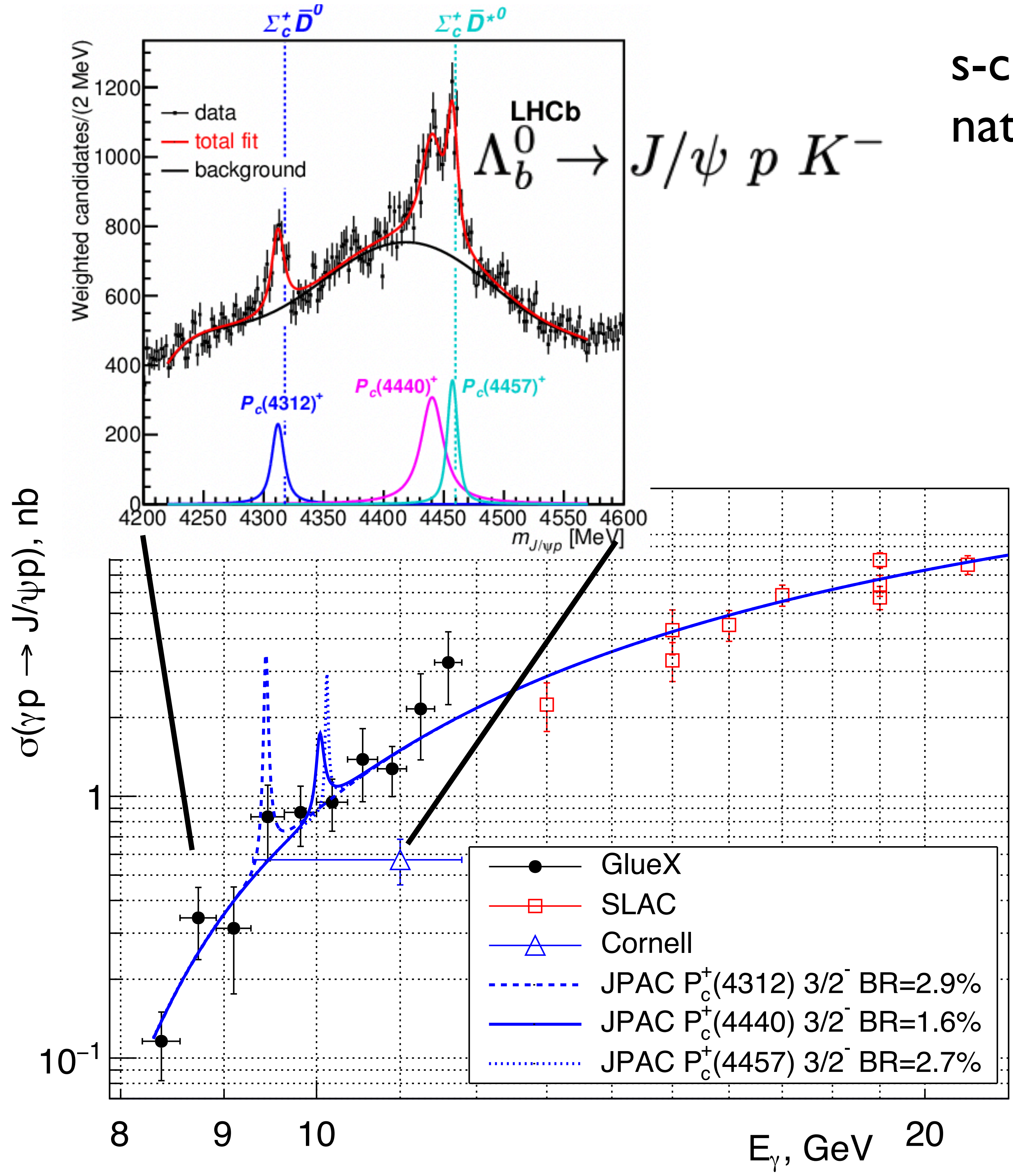
GlueX Phys. Rev. Lett. 123, 072001



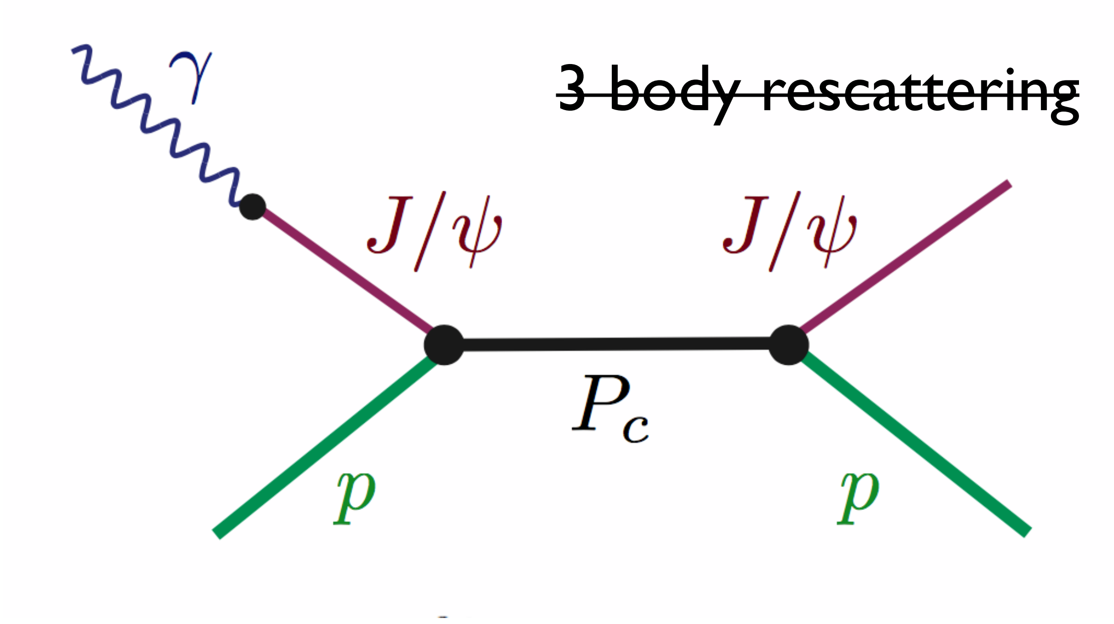
27% normalization uncertainty

inclusive, nuclear, $d\sigma/dt$ at $t = t_{\text{min}}$

J/ψ Photoproduction at GlueX



s-channel photoproduction probes nature of 5-quark interaction!



- Model-dependent upper limits at 90% CL: $J^p = 3/2^-, L = 0$
- Br(Pc(4312) → J/ψ p) < 4.6%
- Br(Pc(4440) → J/ψ p) < 2.3%
- Br(Pc(4457) → J/ψ p) < 3.8%

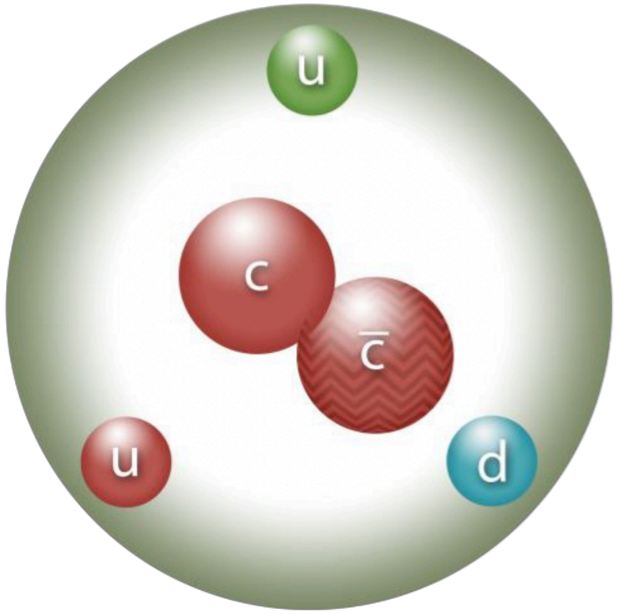
Full Phase-I under analysis:

- additional 300% stats
- unbinned analyses planned

J/ψ Photoproduction at GlueX

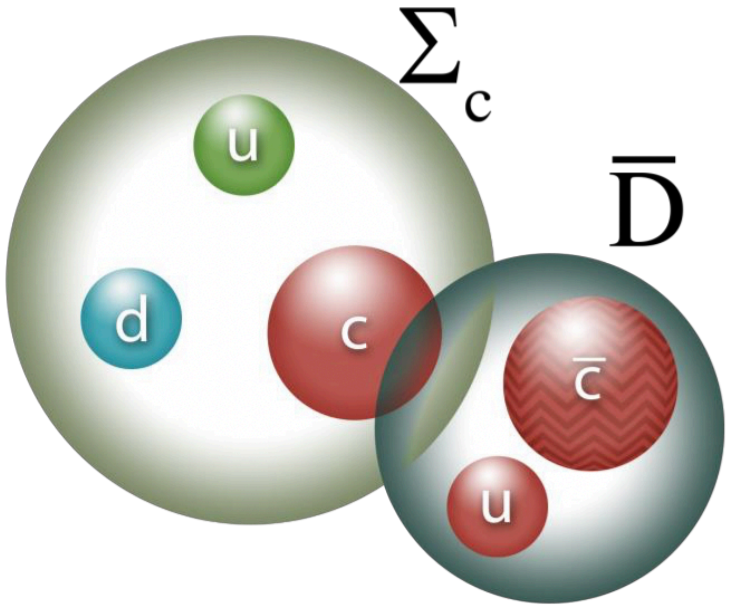
hadrocharmonium

Strongly disfavored
Model predicts large Br



molecular

Very close to threshold created with low relative momentum

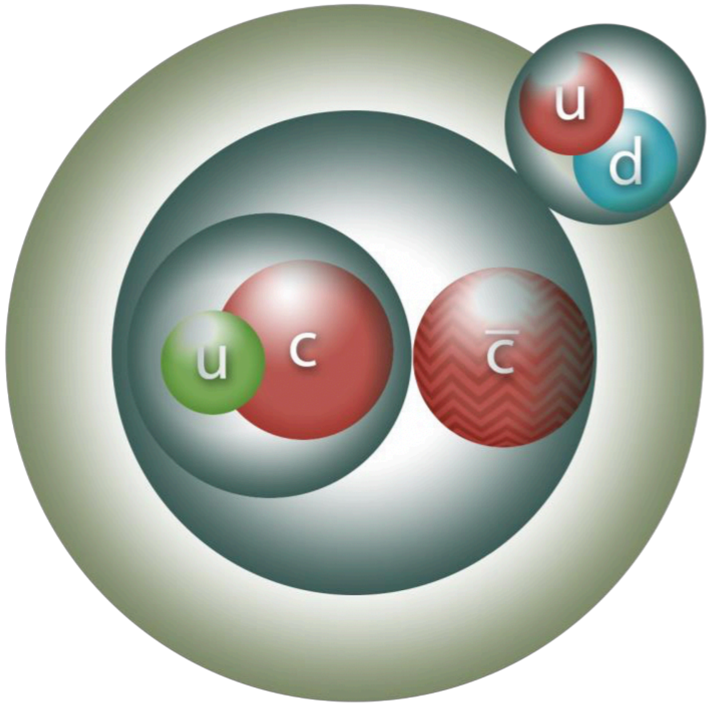


subsystems are color singlets

M.Eides and V.Petrov
Phys.Rev.D98,114037 and
M.Eides, V.Petrov, and M.Polyakov
arXiv:1904.11616

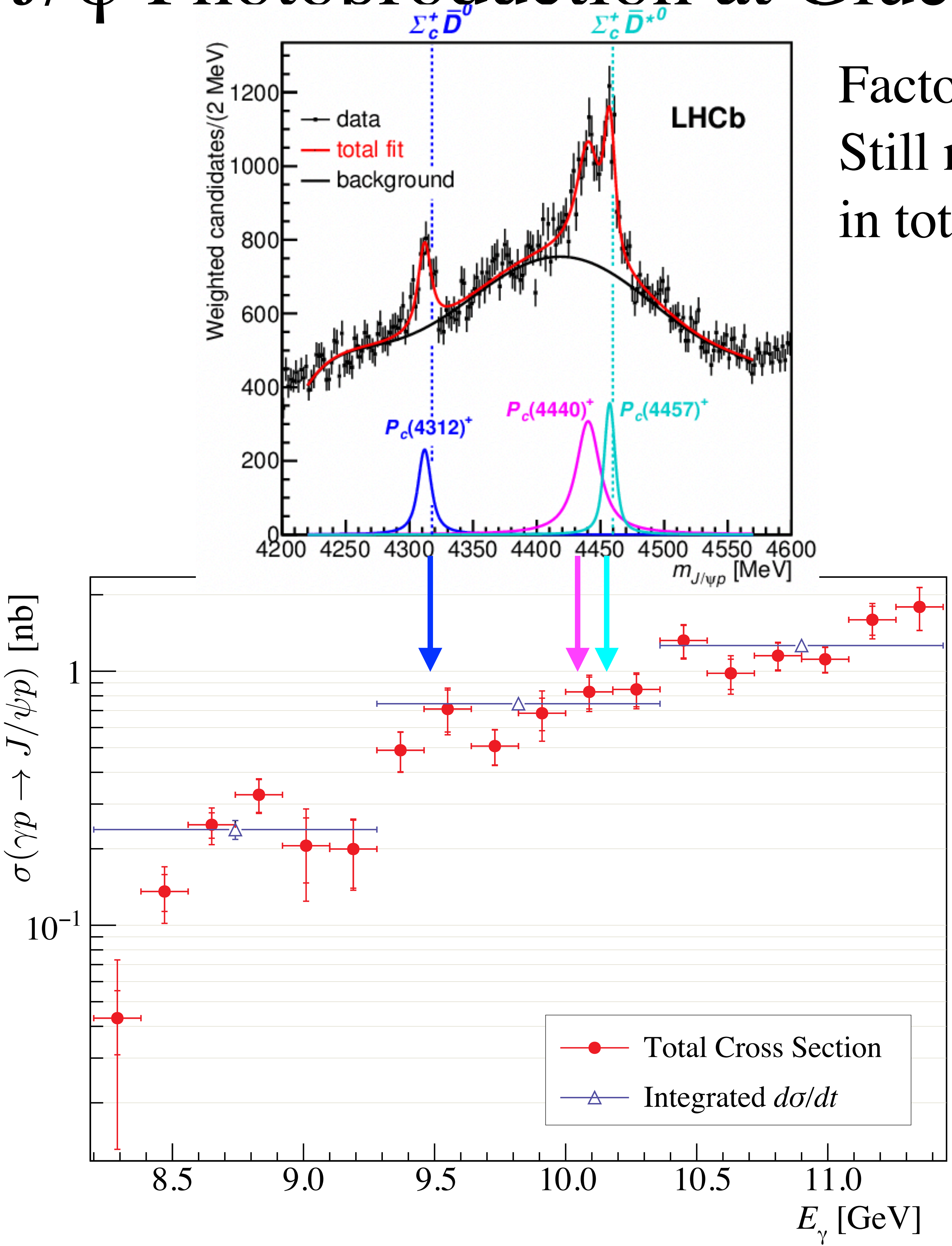
compact diquark

diquarks in color anti-triplet states uC-diquark reduces the probability to form $C\bar{C}$-state



A.Ali, A.Parkhomenko
Phys.Lett.B793, 365

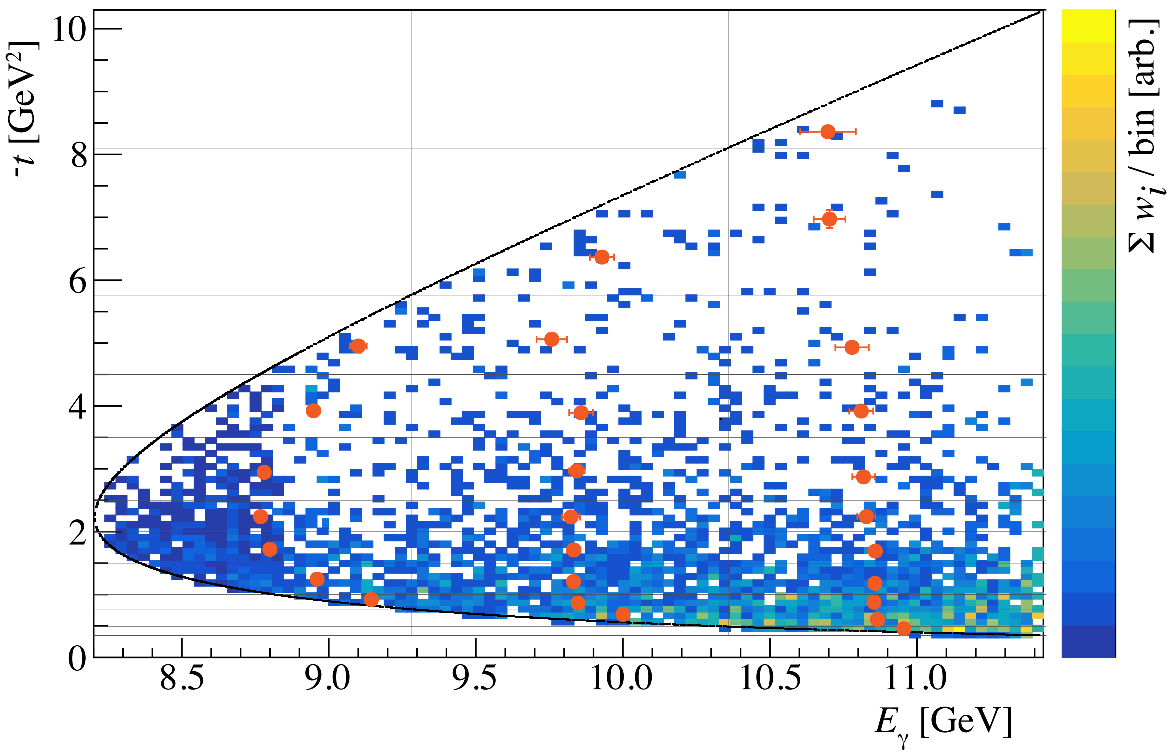
J/ψ Photoproduction at GlueX



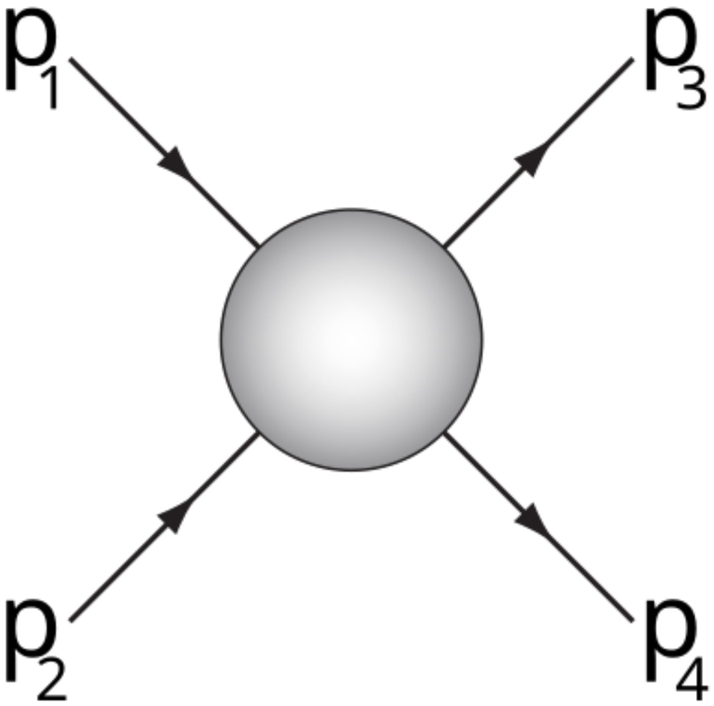
Factor of 5 more data.
Still no evidence of pentaquark enhancement in total cross section.

Full t-channel acceptance:
s-channel states have weaker t-dependence

GlueX PRC **108**, 025201 (2023)

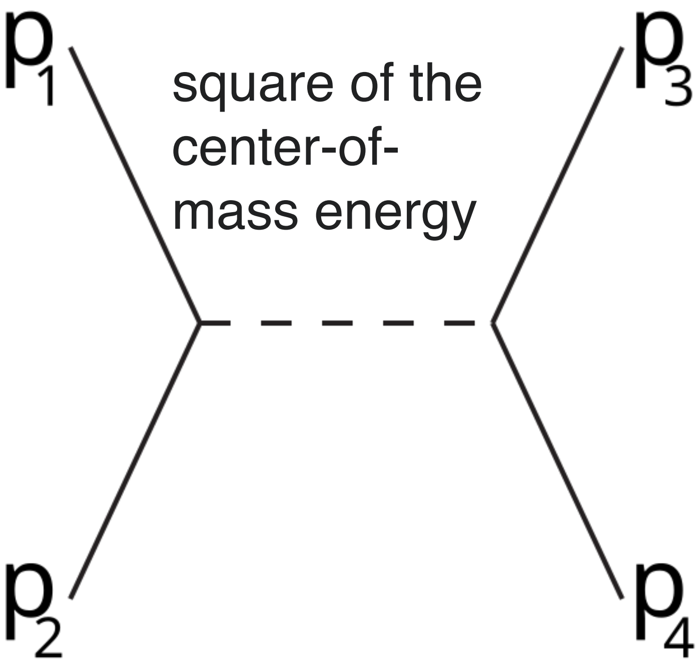


Mandelstam Variables



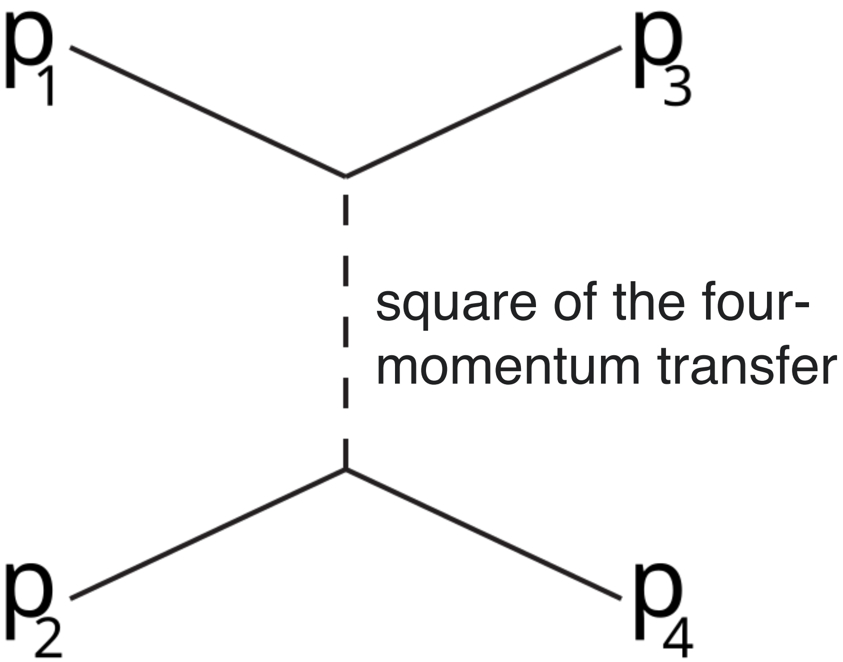
$$
\begin{aligned}
s &= (p_1 + p_2)^2 = (p_1 + p_2)^2 \\
t &= (p_1 - p_3)^2 = (p_4 - p_2)^2 \\
u &= (p_1 - p_4)^2 = (p_3 - p_2)^2
\end{aligned}
$$

s-channel (timelike)



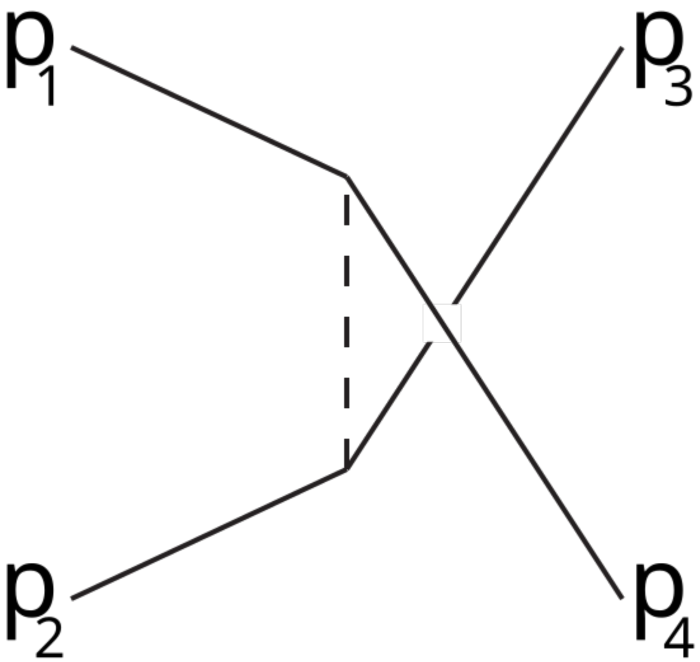
square of the center-of-mass energy

t-channel (spacelike)

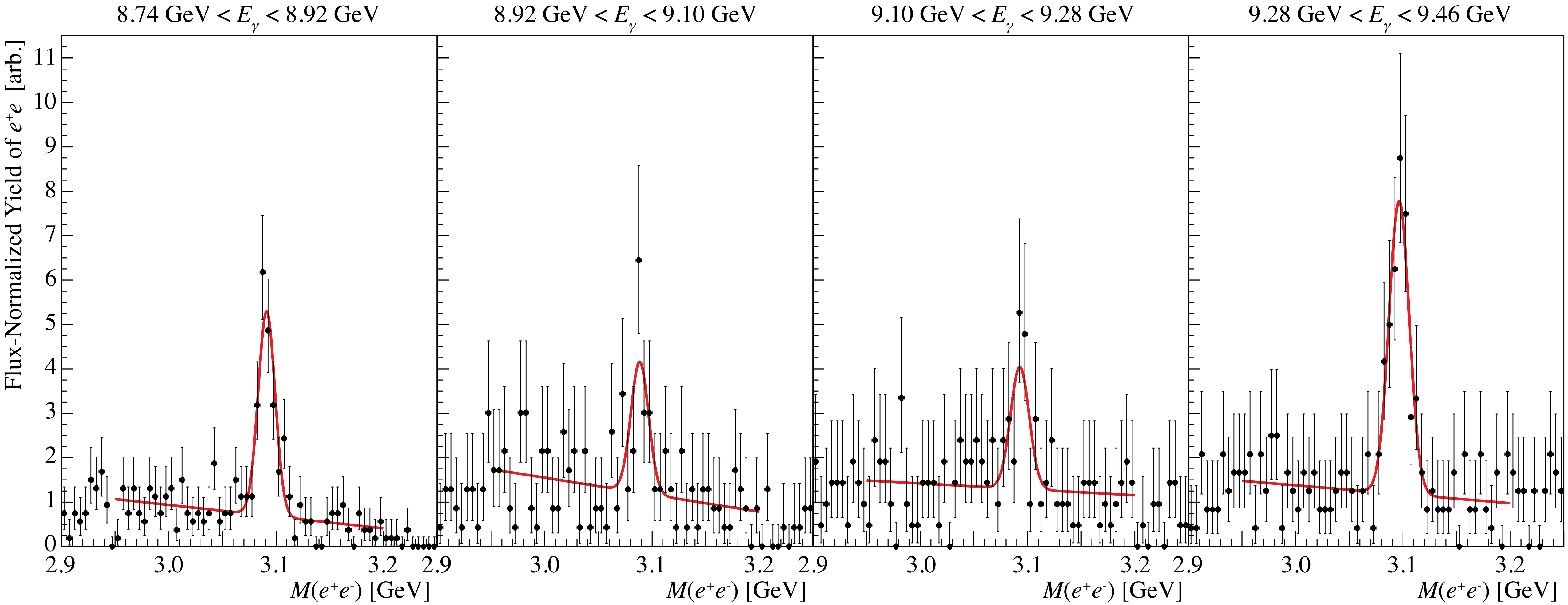


square of the four-momentum transfer

u-channel (spacelike)

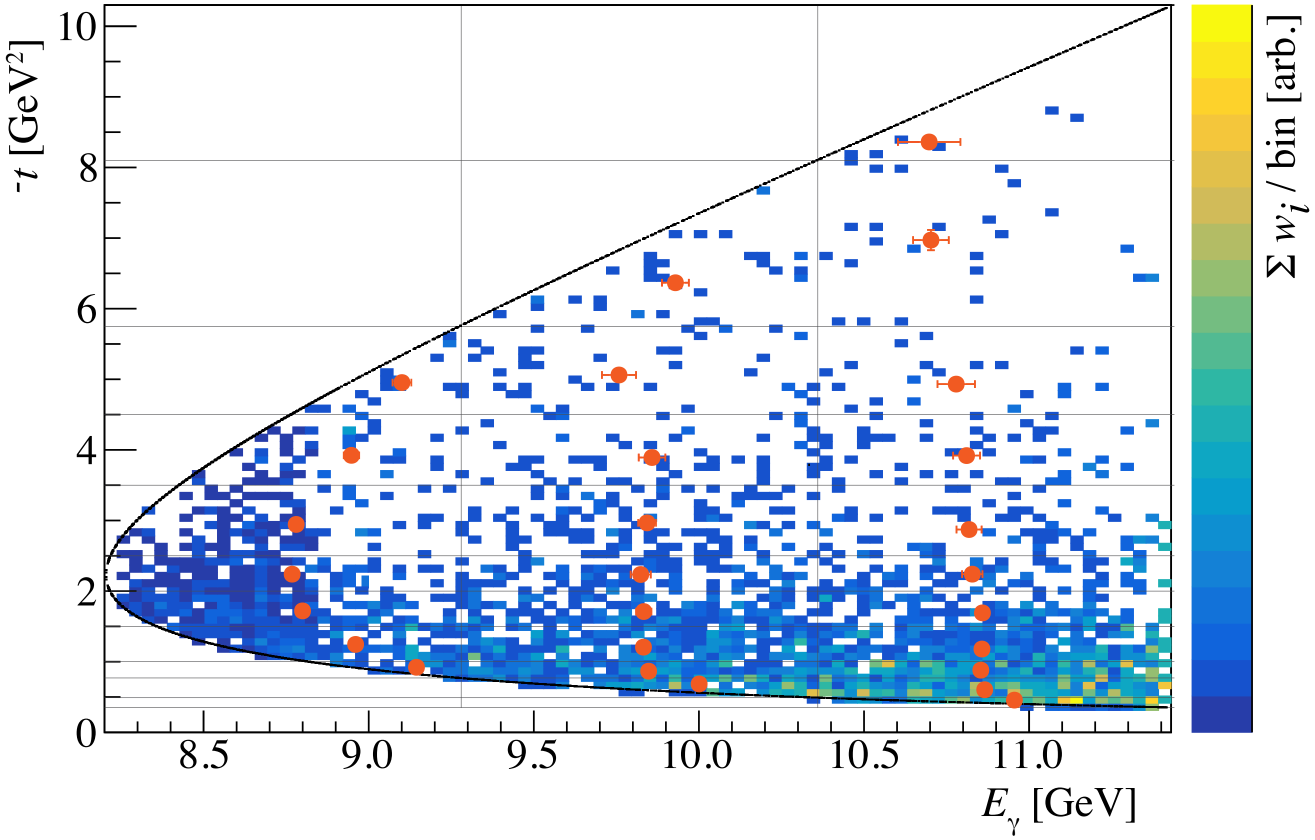


Dip Region in Data



GlueX PRC **108**, 025201 (2023)

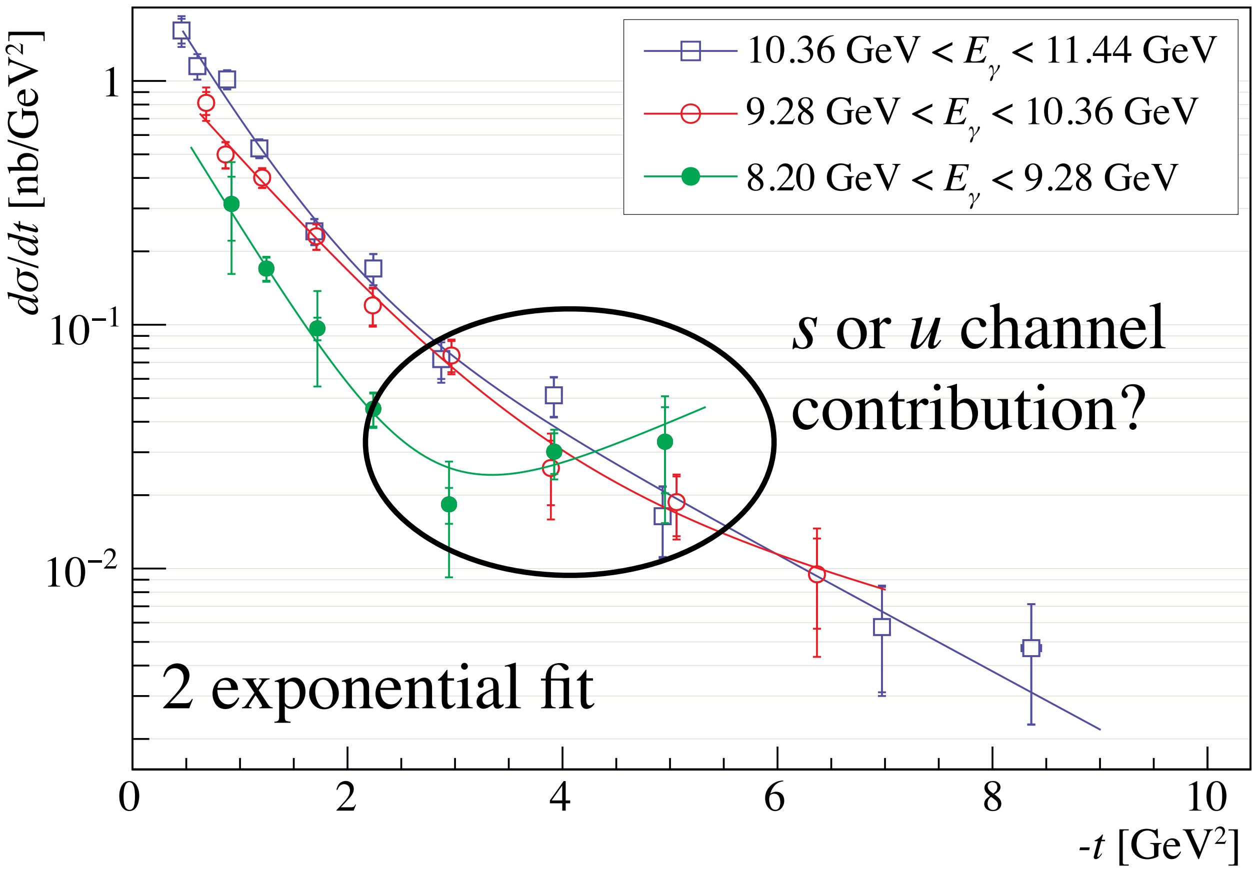
Dependence on *t*



Differential cross sections vs *t*

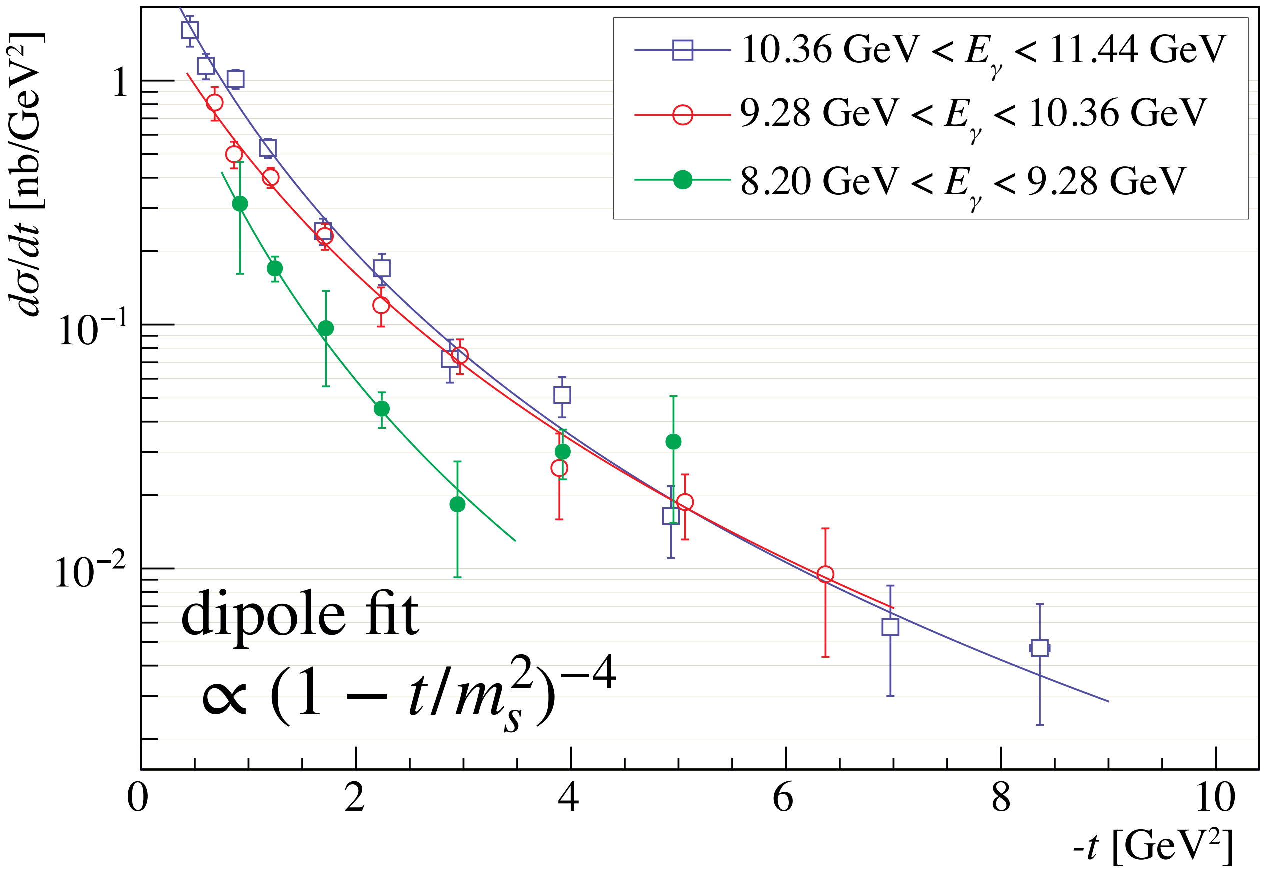
Expect exponentially decreasing t dependence in the differential cross sections

GlueX PRC **108**, 025201 (2023)



s or *u* channel contribution?

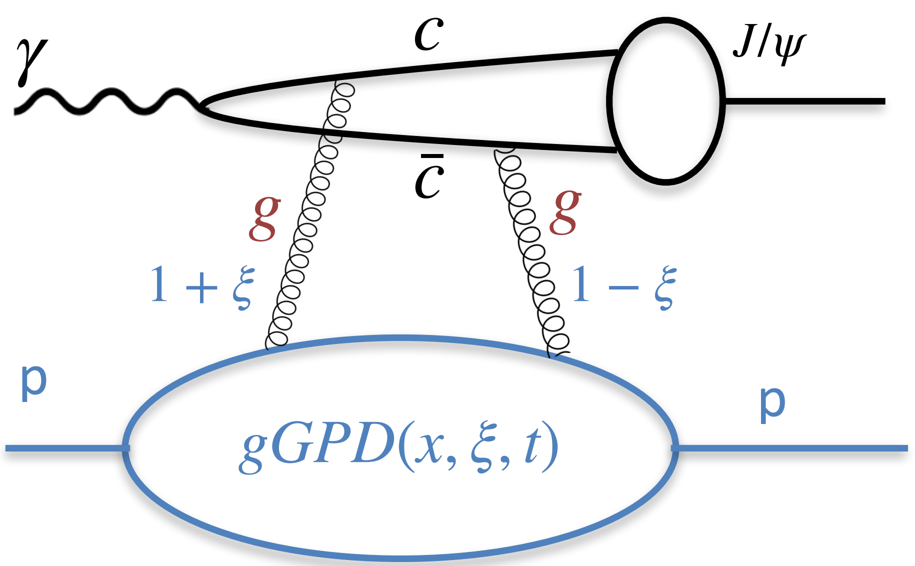
2 exponential fit



dipole fit

$\propto (1 - t/m_s^2)^{-4}$

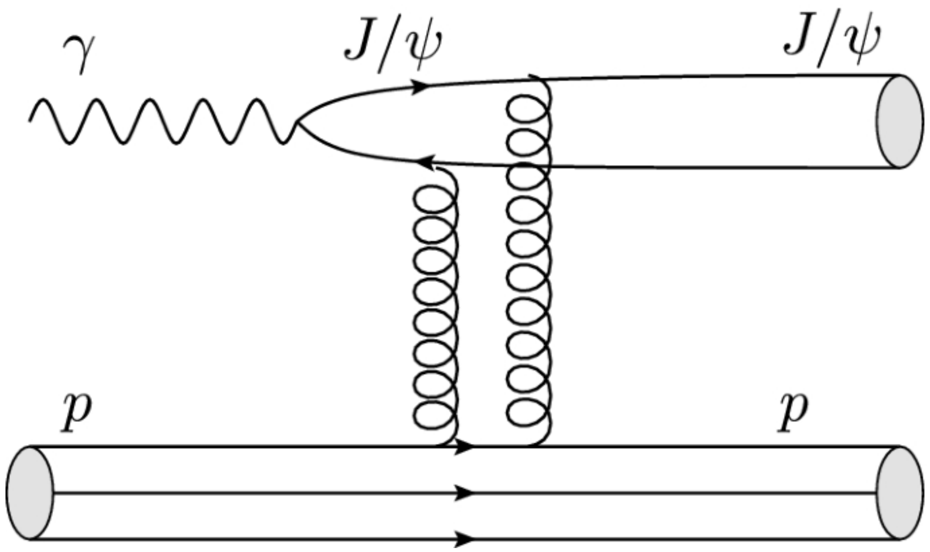
Target Structure

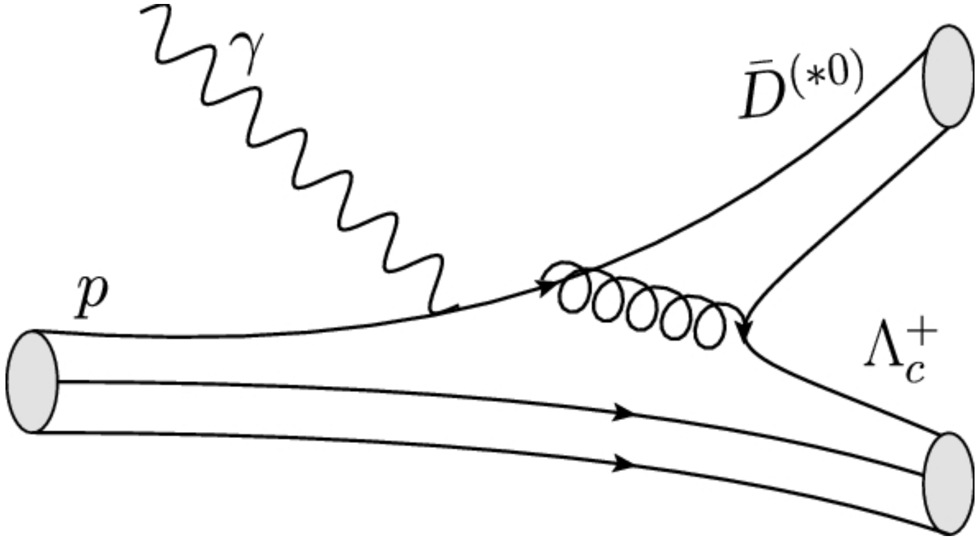


Charm is heavy so it’s production is a hard process.
Charm exchange (heavy)
Light exchange (OZI suppressed)
Then the scattering could give information about internal structure of the proton
(PDFs or GPDs) and can be used to extract gravitational form factors, the trace anomaly contribution to the proton mass, and the mass radius.
The data could also be used to extract the J/ψ-p scattering length.

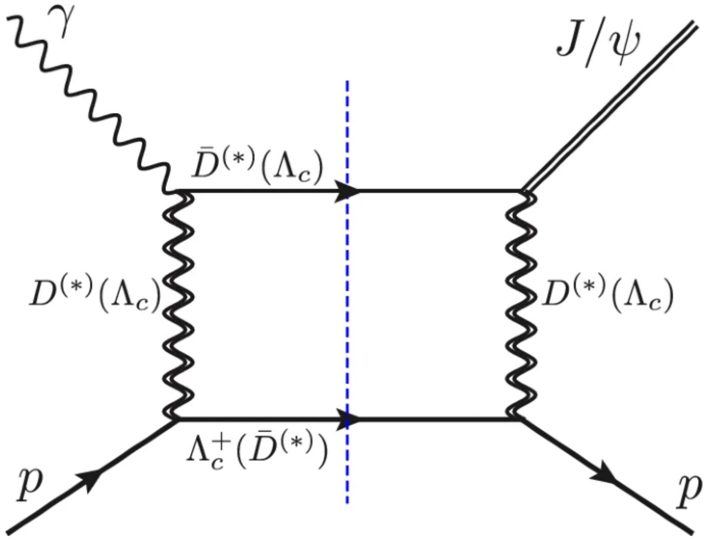
https://doi.org/10.1103/PhysRevD.109.014014 Guo

Open Charm Exchange





+ rescattering



1870 MeV

$D^+ = c\bar{d}$

$D^0 = c\bar{u}$

$\bar{D}^0 = \bar{c}u$

$D^- = \bar{c}d$

2287 MeV

$\Lambda_c^+ = udc$

direct relation between the trace anomaly contribution to the nucleon mass and the J/ψ near-threshold photoproduction, that is present in the VMD model

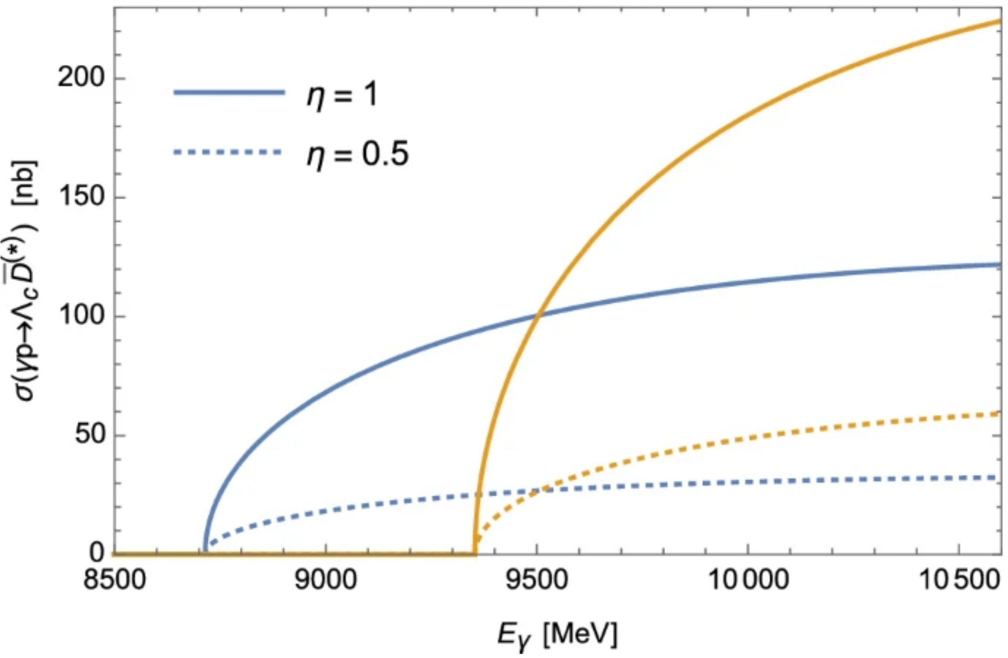
https://doi.org/10.1140/epjc/s10052-020-08620-5 Du

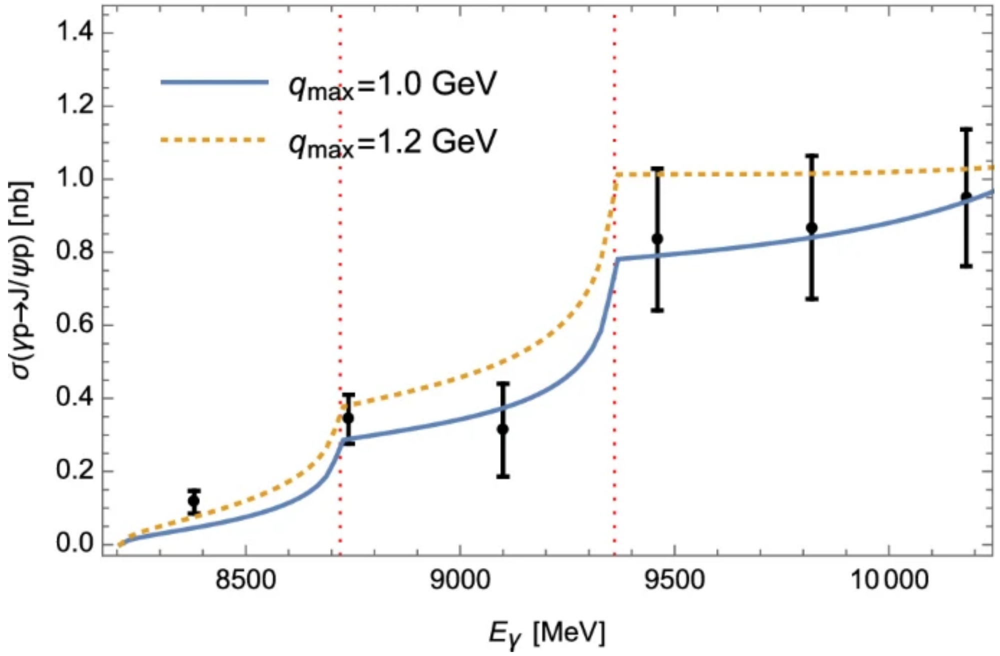
Open Charm Exchange

$$\gamma p \rightarrow K^{+}\Lambda / K^{+}\Sigma^{0} \gg \gamma p \rightarrow \varphi p$$

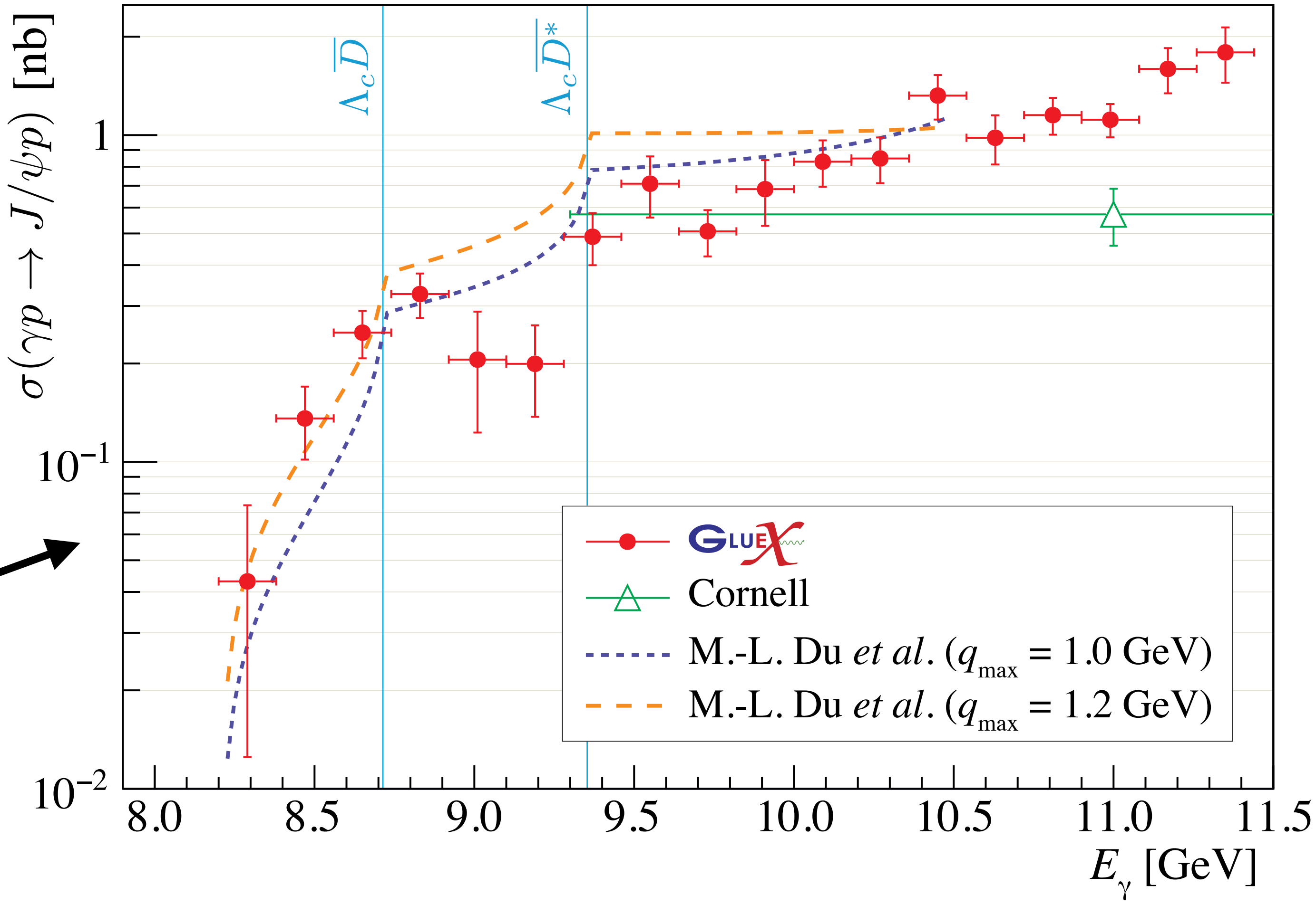
Cross sections for open charm expected to be much larger

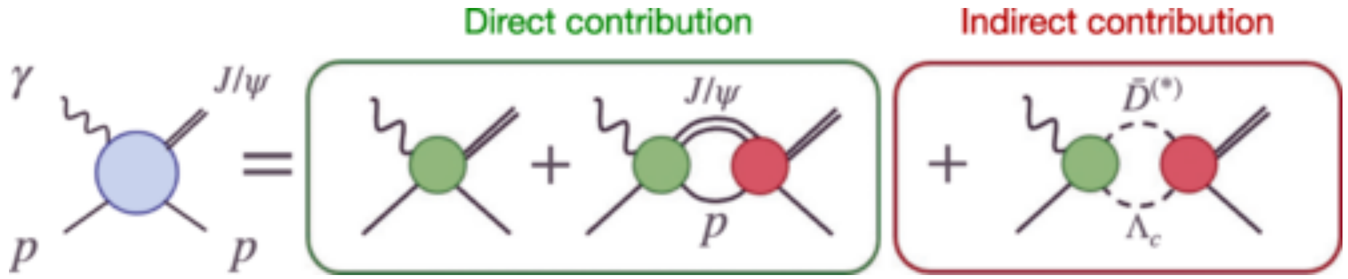
thresholds just 116 and 258 MeV above the J /ψ p threshold

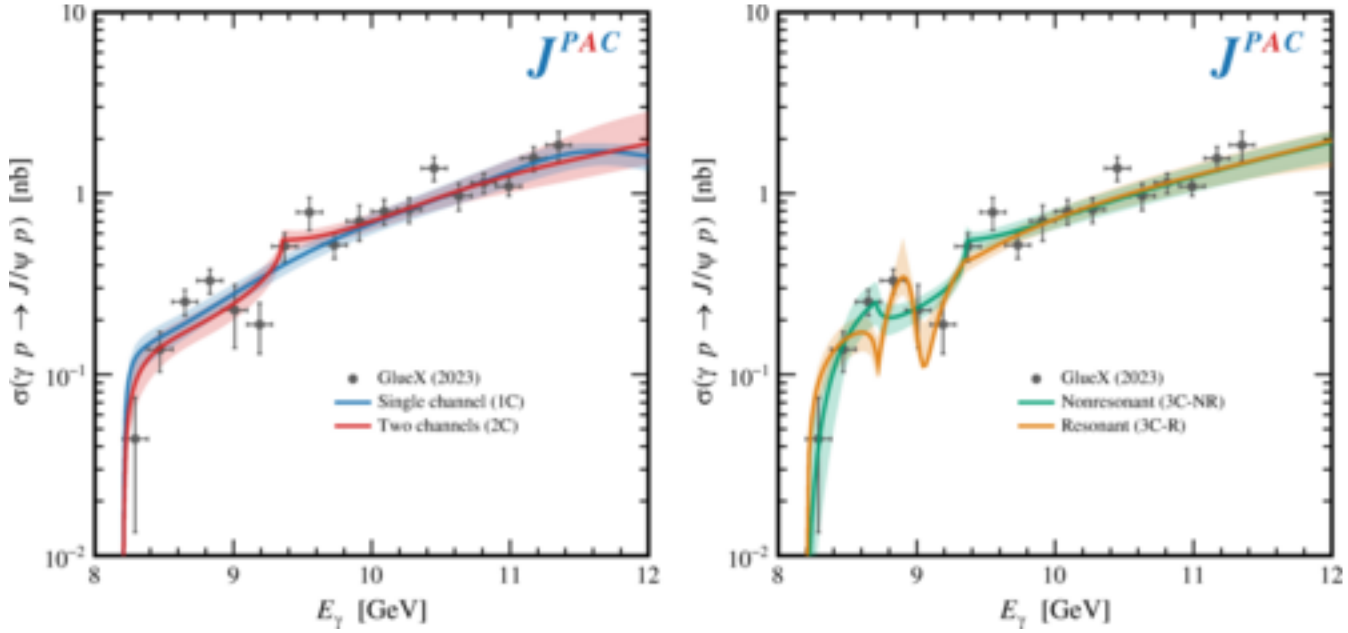


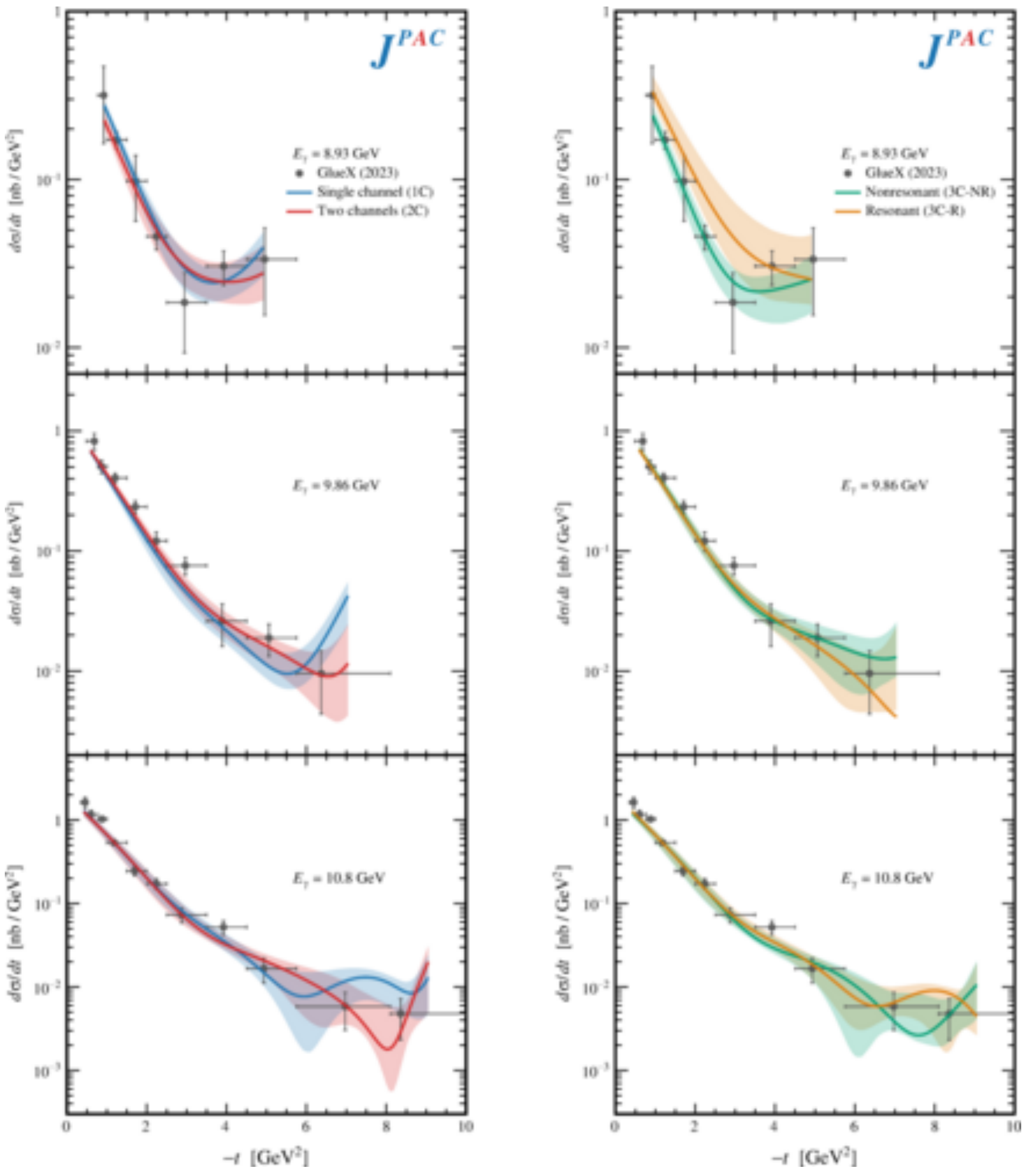


Clear prediction, cusps at the thresholds
cusp shape is a measure of the strength of the transition leading to the cusp









integrated and differential cross sections can be described with a small number of partial waves

incorporate effects of nearby open-charm thresholds

May violate factorization

https://doi.org/10.1103/PhysRevD.108.054018 JPAC

Summary

The study of hadrons is vital to understanding QCD.

Once can study the spectrum of states or the internal dynamics of states but everything is connected.

There are constant surprises and there is a lot left to be discovered.