Open questions in hadron spectroscopy and dynamics

Adam Szczepaniak
Indiana University
Jefferson Lab

What can we learn about QCD from studying hadron spectrum

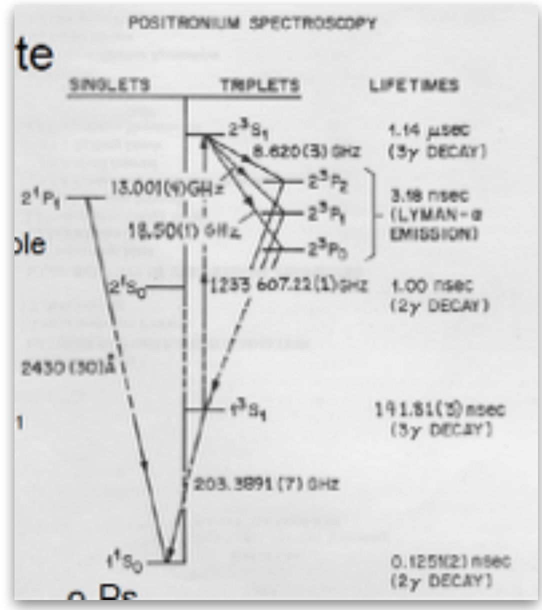
What are the “effective” constituents of hadrons (focus on glue)

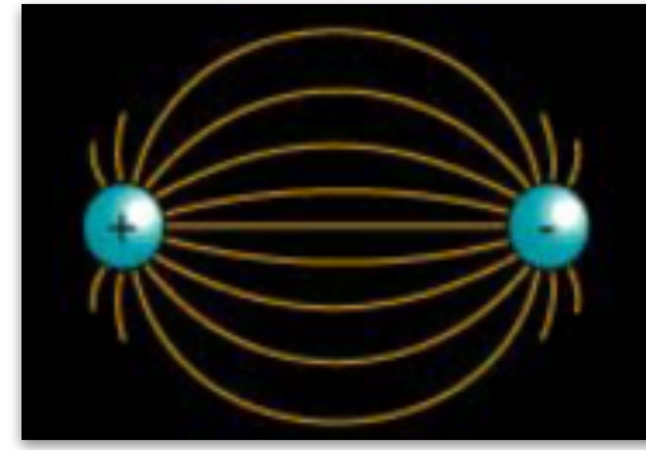
How to identify new phenomena in hadron spectrum

QED bound states

“weak” + “few”

→ complex



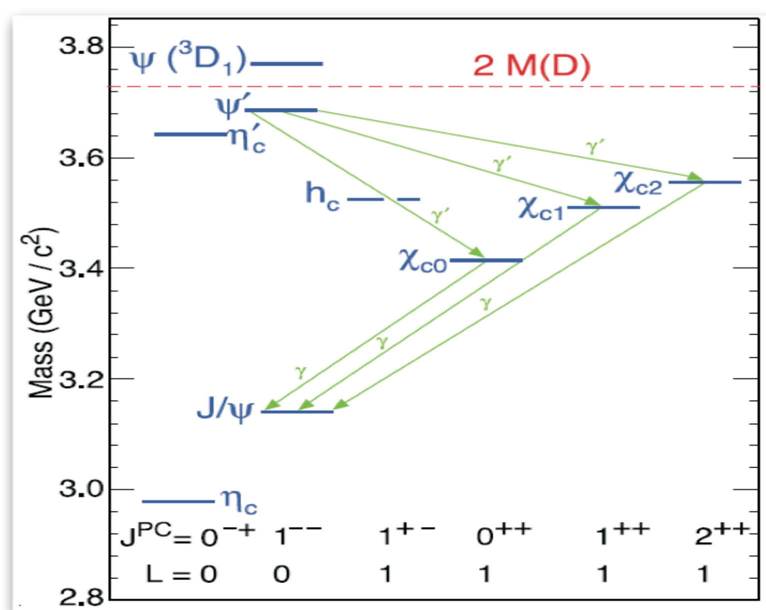


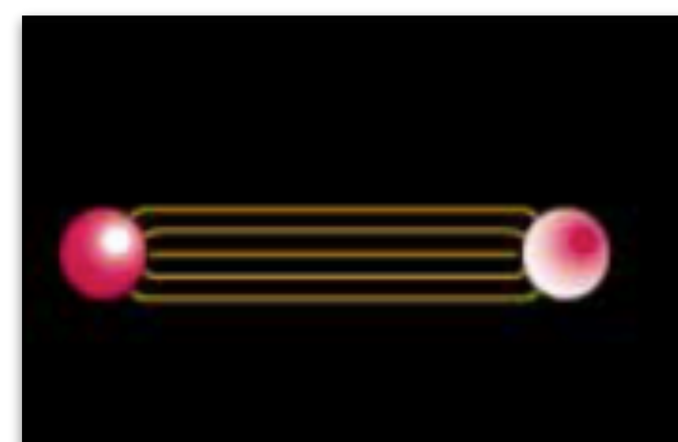
Spectrum “solves” QCD: H|Ψ> = E|Ψ>

QCD bound states

“strong” + “many”

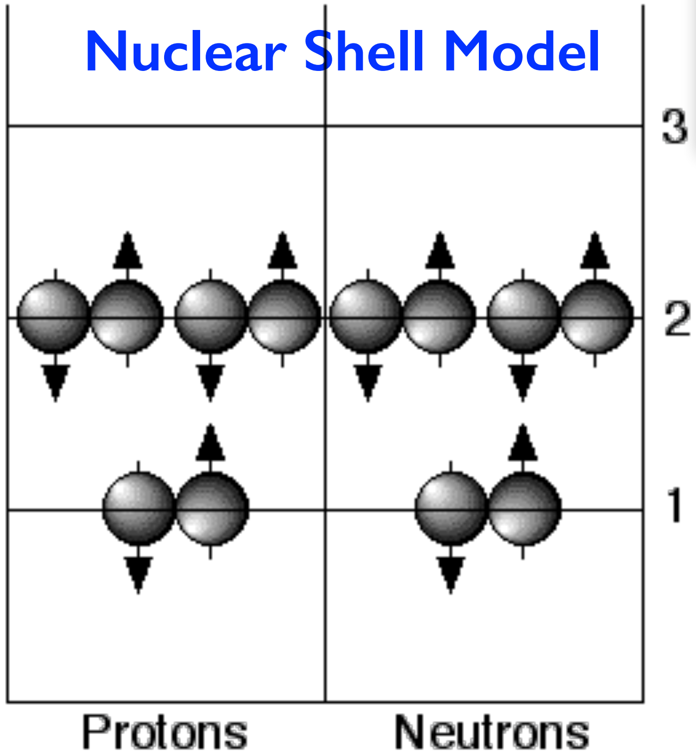
→ complex++

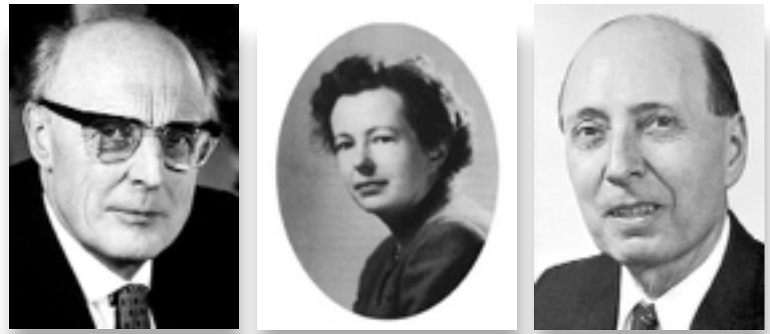




Models

Nuclear Shell Model

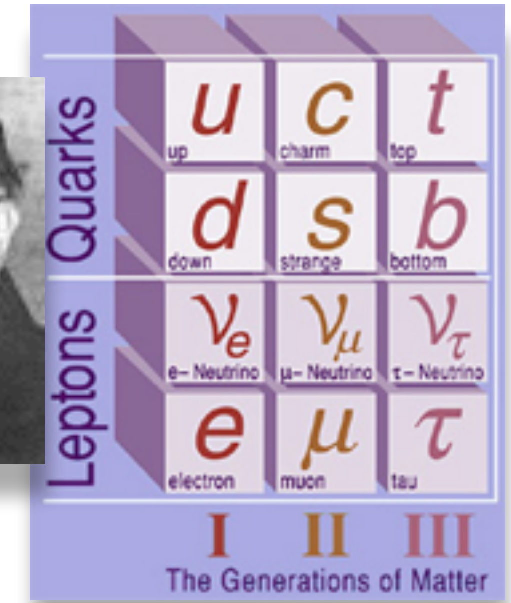




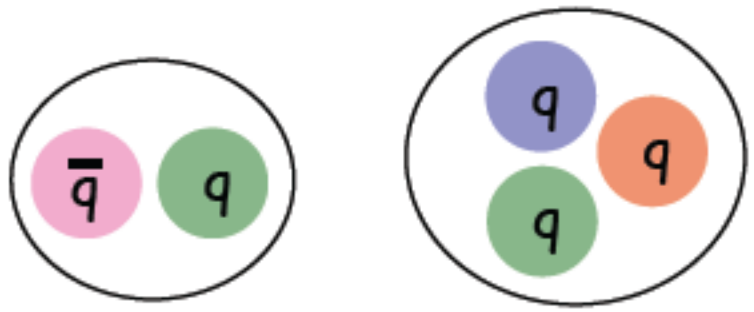
Jensen,Geoppert-Meyer,Wigner
Nobel-1963

Glashow,Salam,Weinberg
Nobel-1979

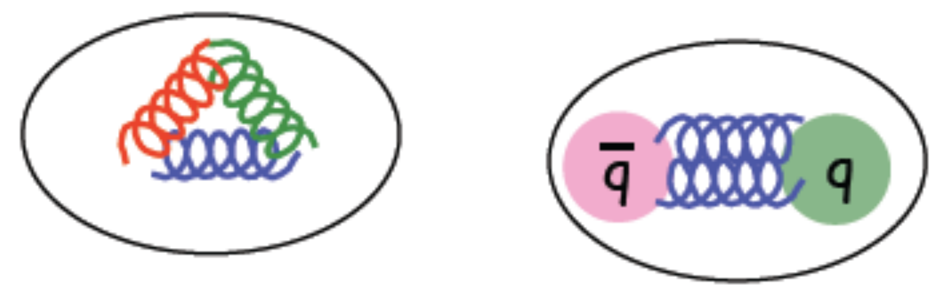
Standard Model



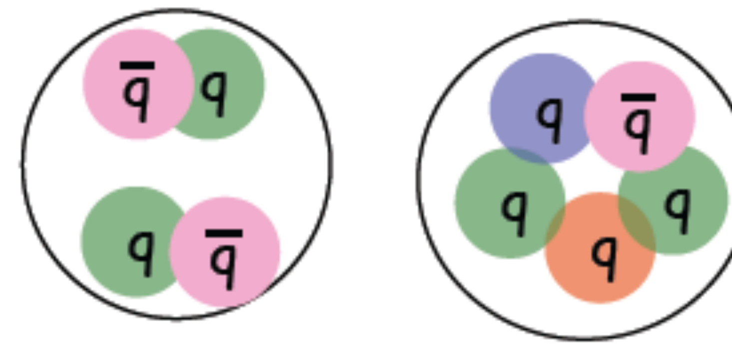
Quark Model
Gell-Mann, Zweig



mesons baryons



glueball meson hybrid meson



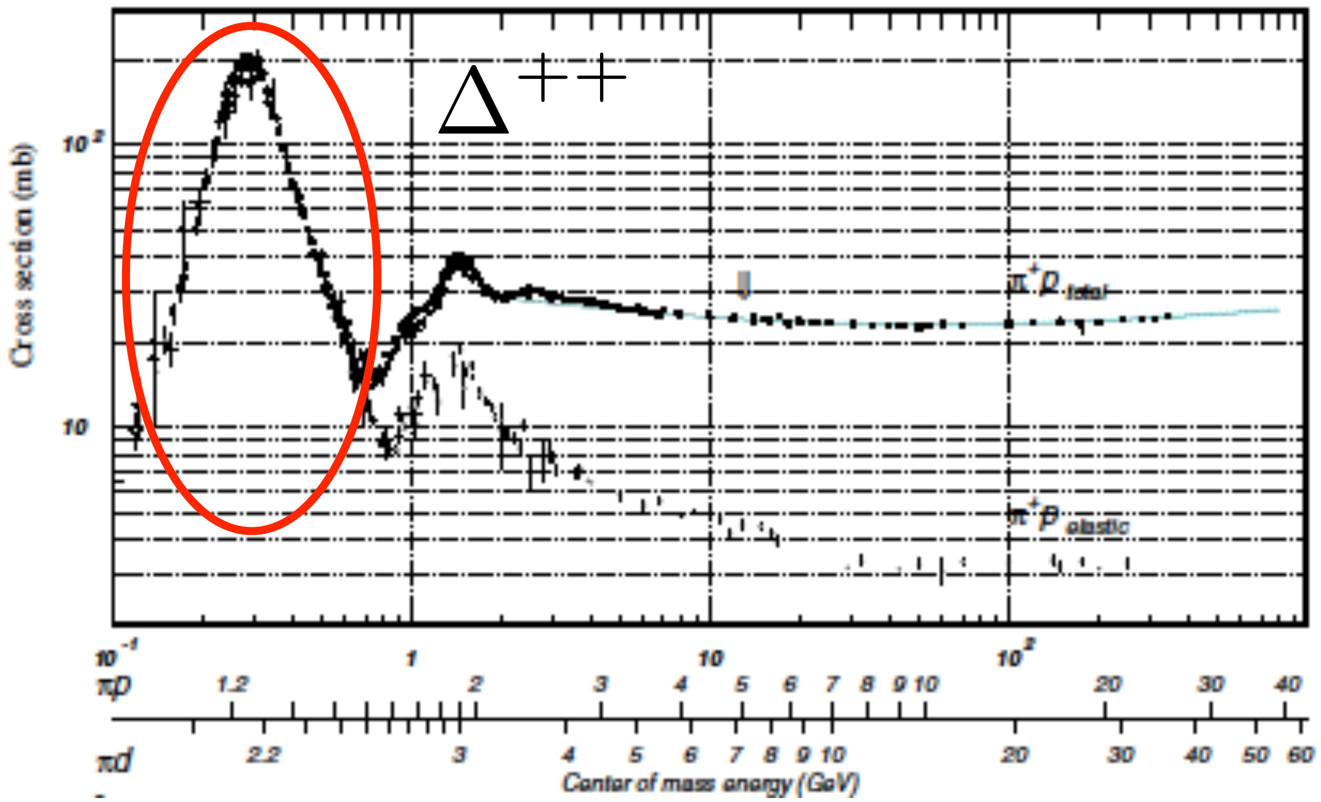
molecules pentaquark

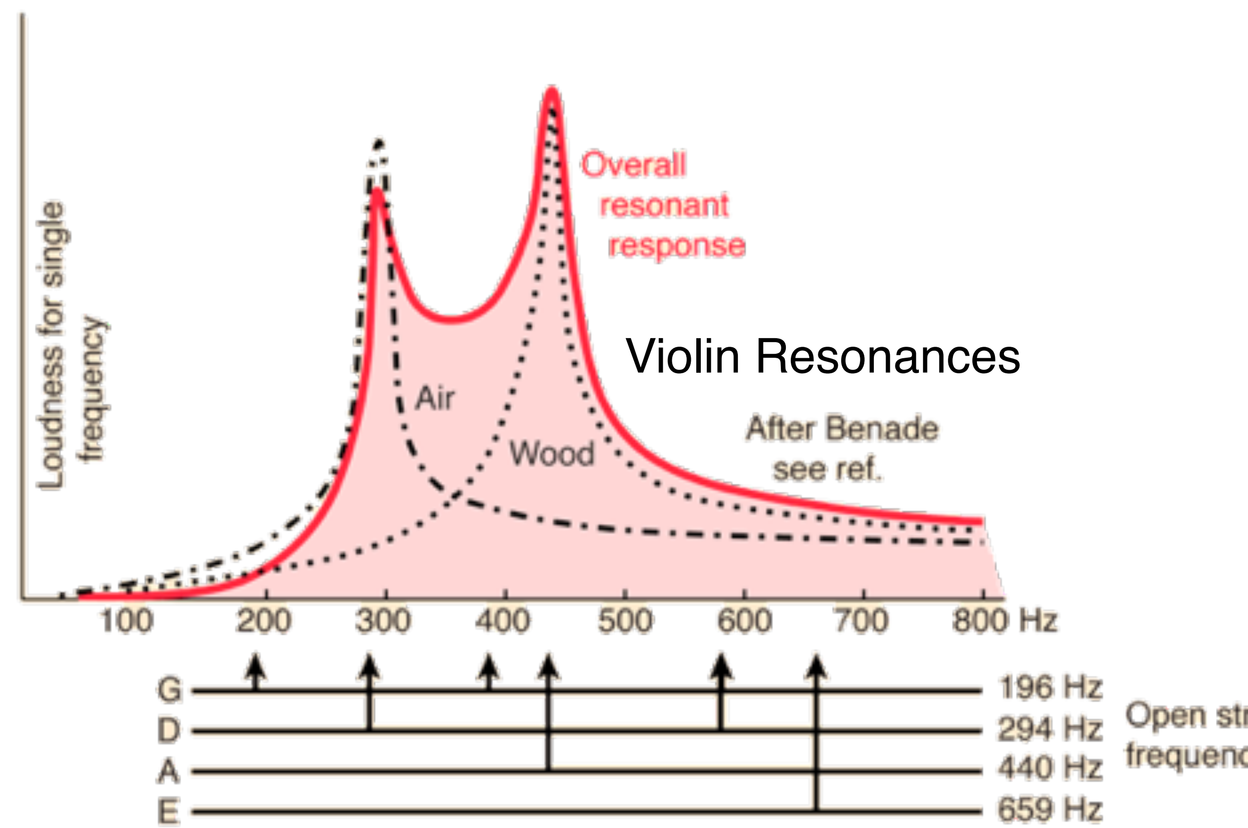
Hadrons
small world (10^{-15}m)
of fast (v/c~1)
confined particles
exerting ~1T forces !!!

Emergent degrees of freedom should be different from the “bare” constituent

peak in intensity
(cross section)

180^0 phase change
in the amplitude



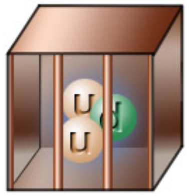


Two key issues:

1. How to identify resonance in the data

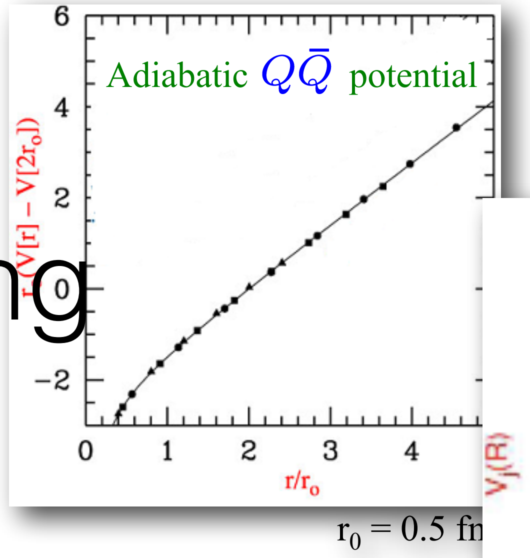
2. How to connect with QCD

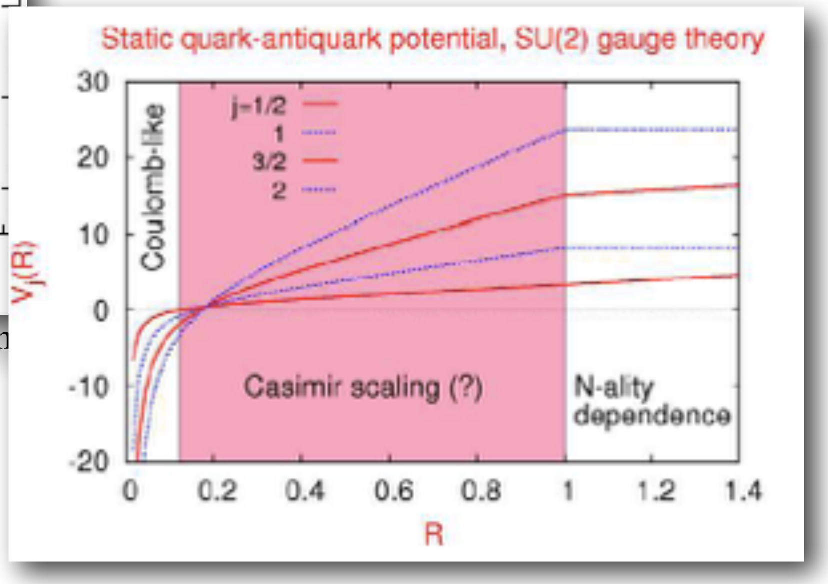
2.Connection with QCD

Confinement in QCD 

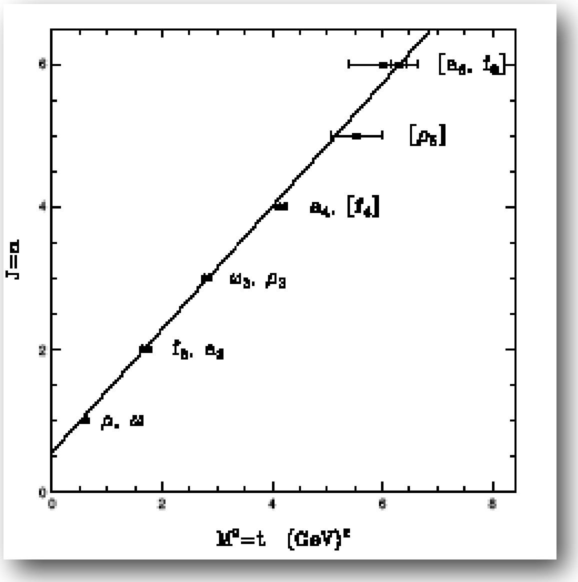
in absence of isolated quarks we have to content with emergent properties of confinement

- linearly rising potential
- Casimir and N-ality scaling

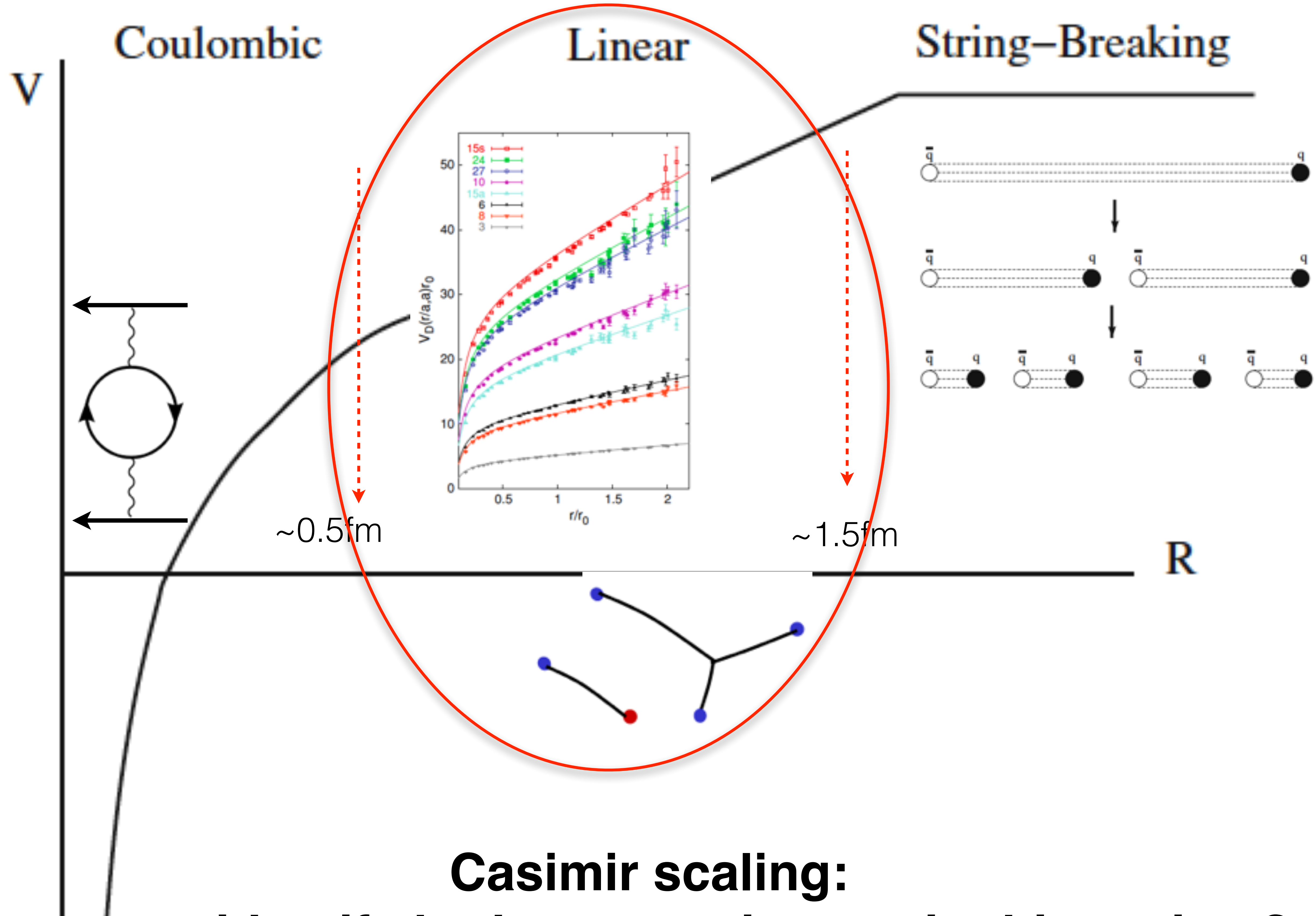




- Regge trajectories



Anatomy of Confinement

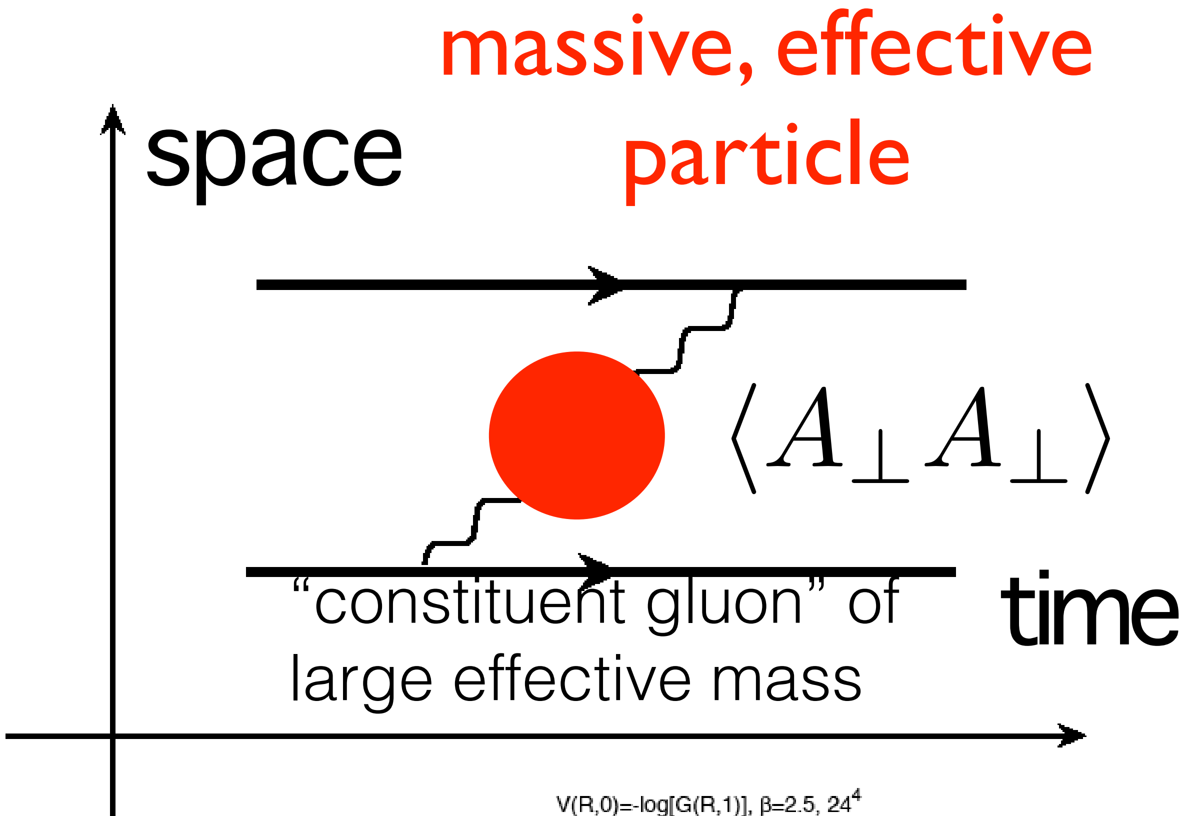


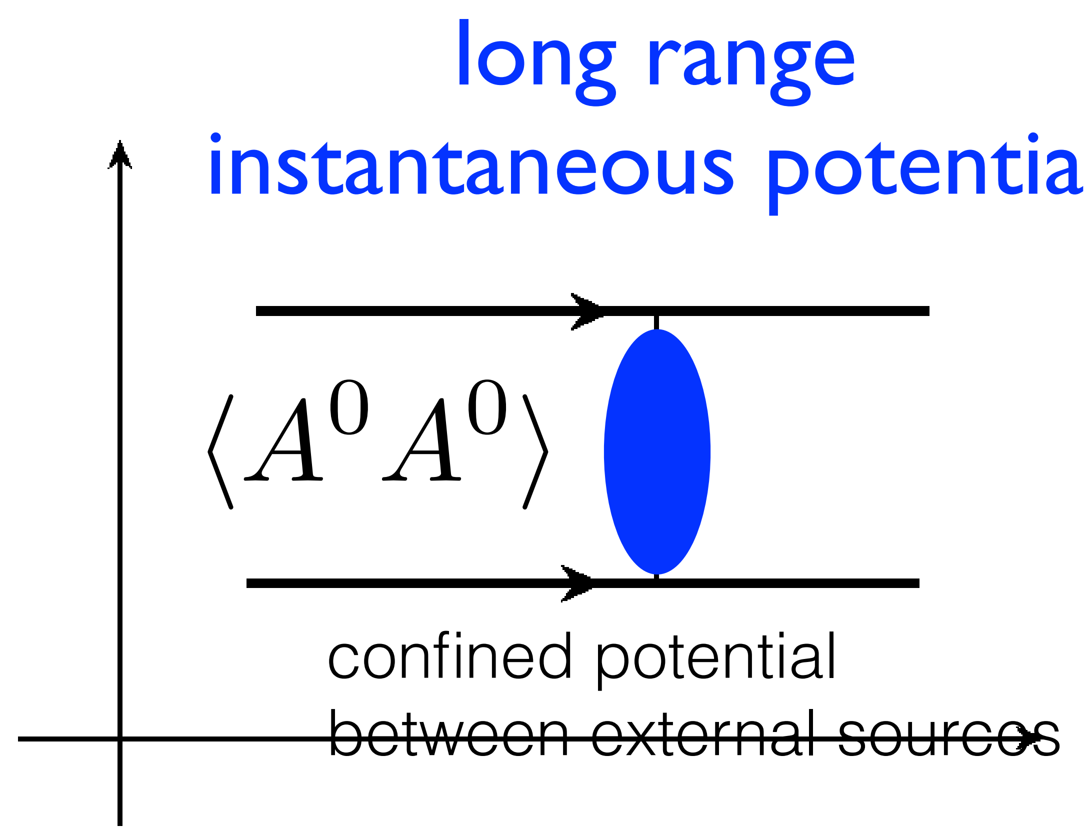
Casimir scaling:
can one identify hadron constituents in this regime?

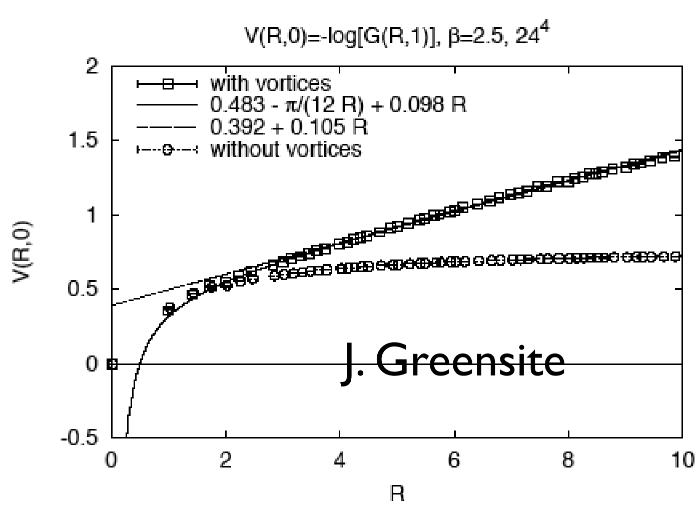
All gluons are equal but some are more equal than others:

provide confinement => long range correlations

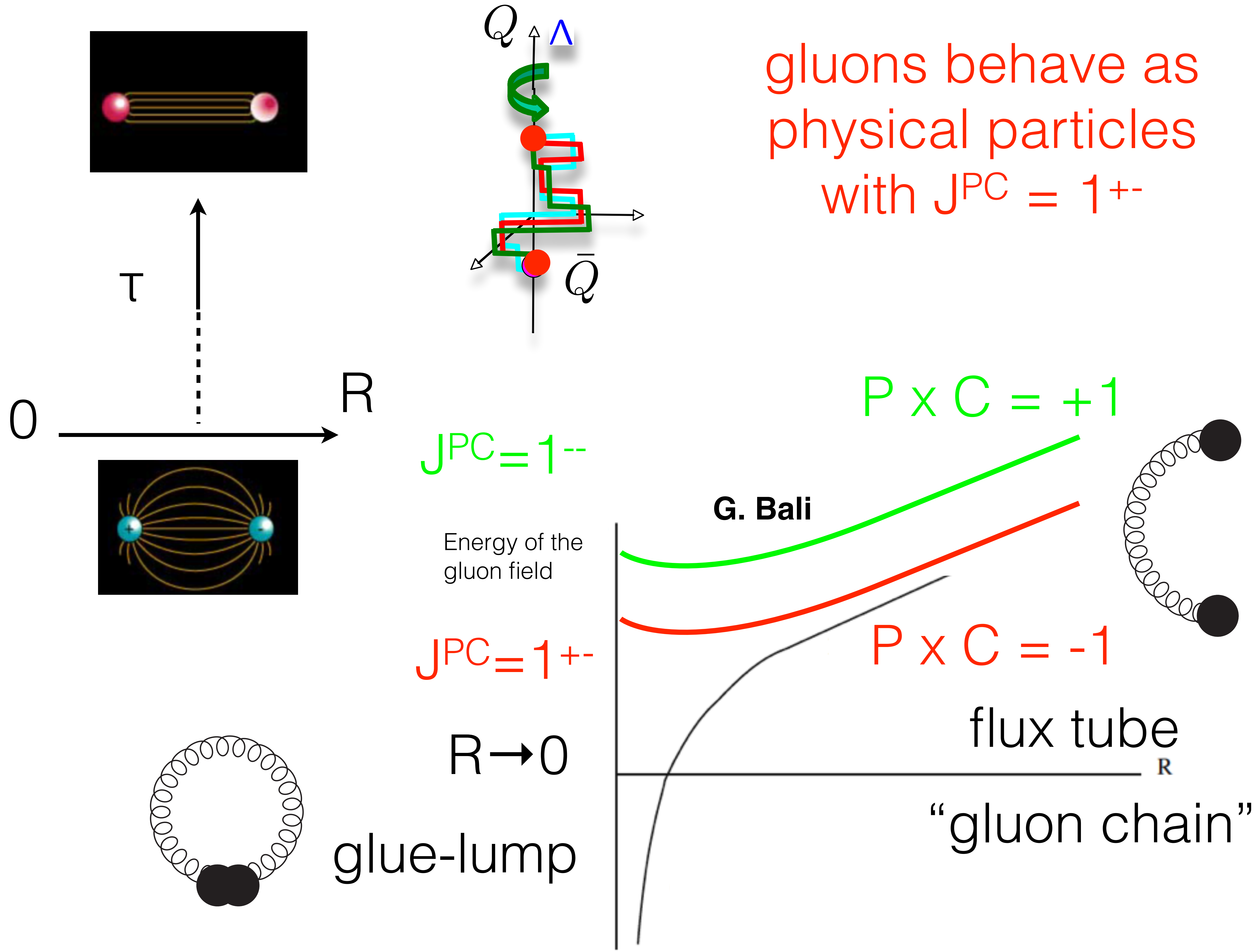
are confined => short range correlations



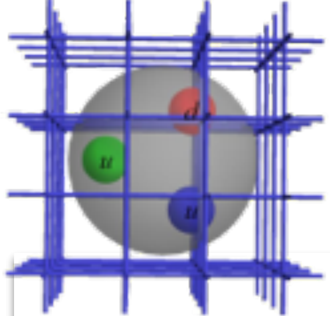




$$\int dy \frac{\rho(y)}{|x-y|} \to \int dy \frac{\rho(y)}{\nabla D}(x,y,A)$$



gluons behave as physical particles with $J^{PC} = 1^{+-}$
Q
Λ
$\bar{Q}$
τ
0
R
$J^{PC}=1^{--}$
P x C = +1
G. Bali
Energy of the gluon field
$J^{PC}=1^{+-}$
P x C = -1
flux tube
R→0
R
glue-lump
"gluon chain"



Charmonium spectrum form lattice

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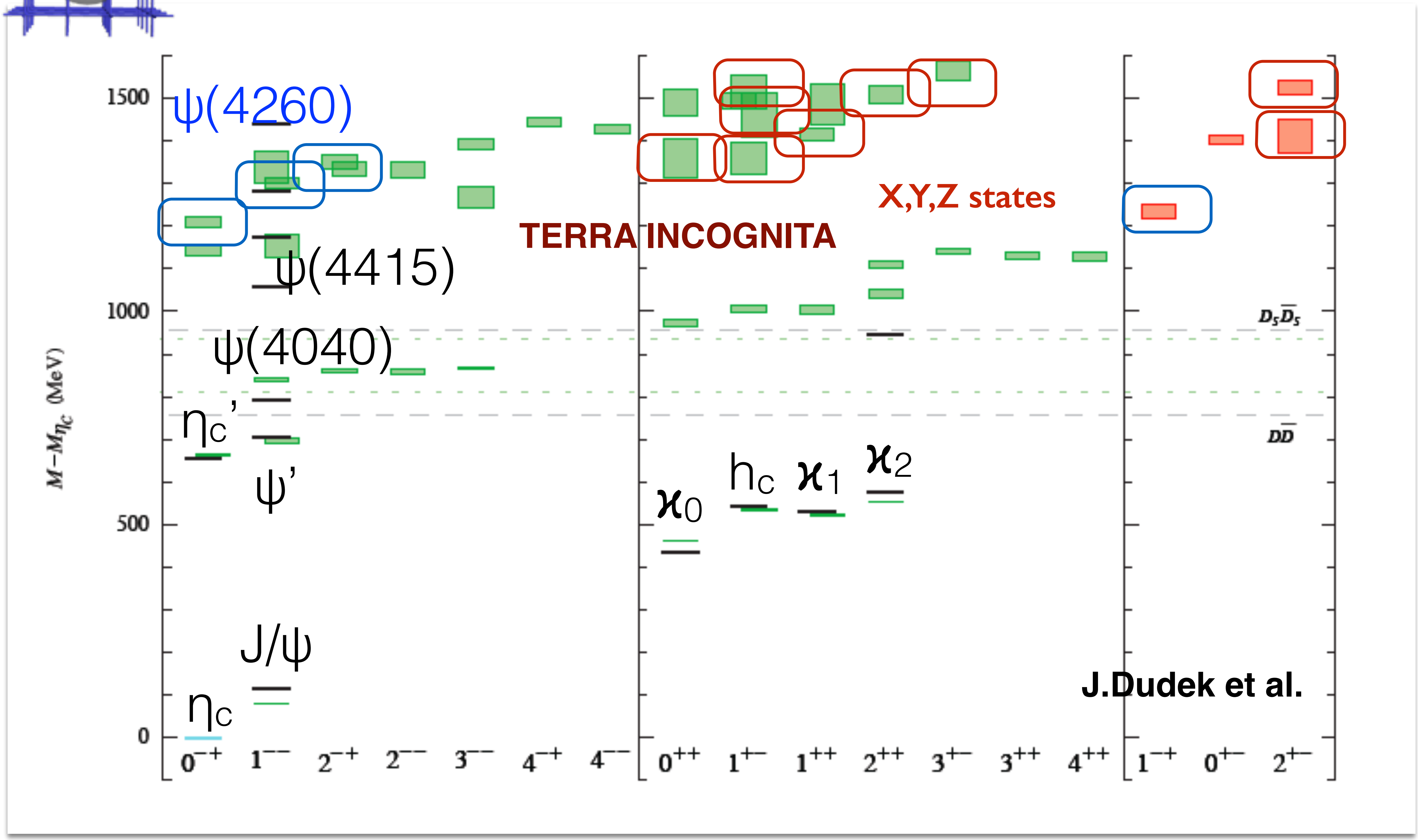
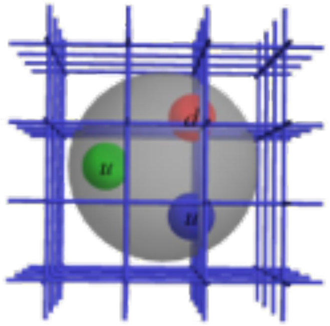
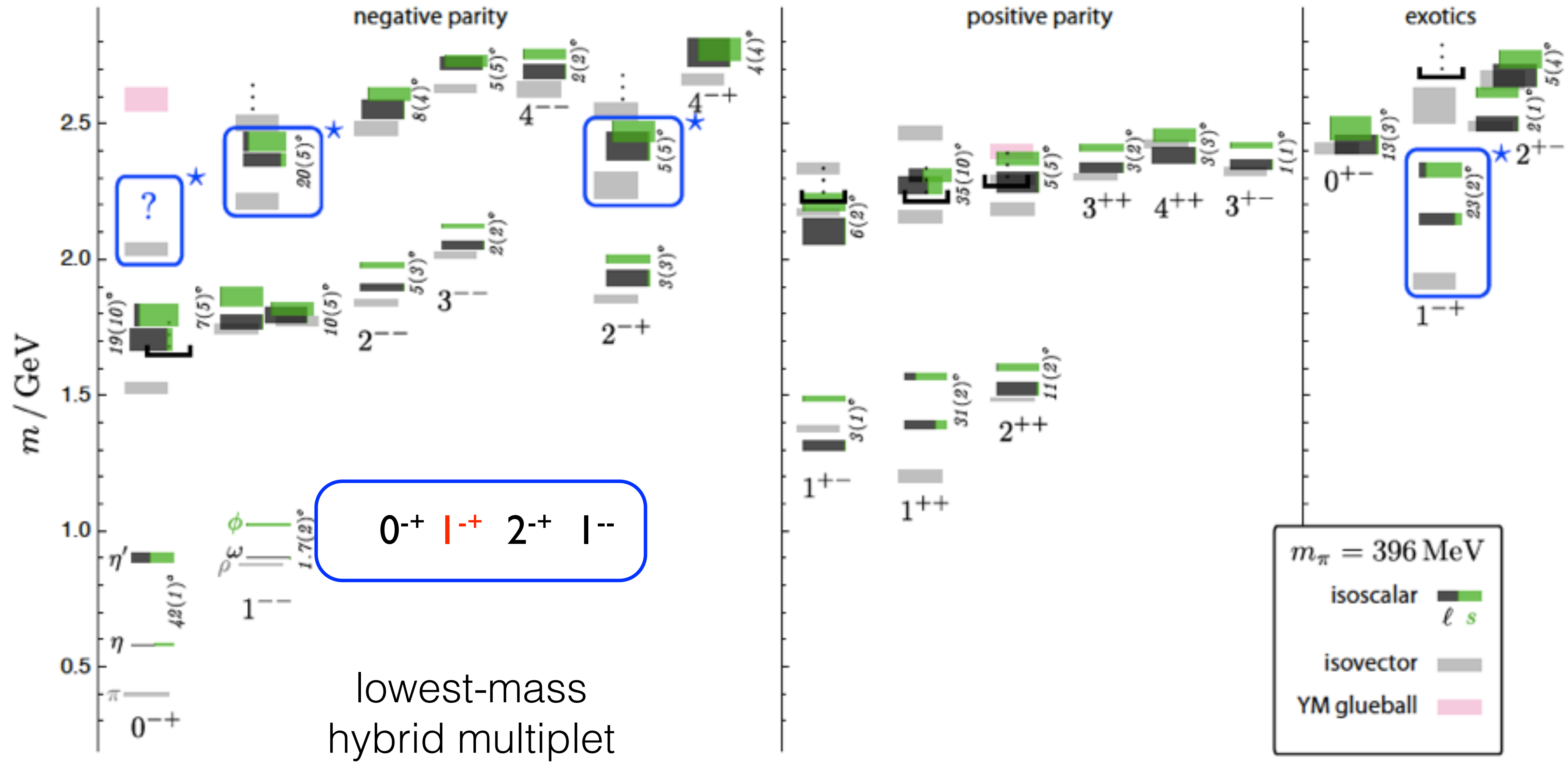


0-+ 1-+ 2-+ 1- -

0++ 1++ 2++ 0+- 1+- 1+- 1+- 2+- 2+- 3+-





negative parity
positive parity
exotics
m / GeV
0⁻⁺ 1⁻⁺ 2⁻⁺ 1⁻⁻
lowest-mass
hybrid multiplet
$m_\pi = 396$ MeV
isoscalar
isovector
YM glueball

J.Dudek et al.

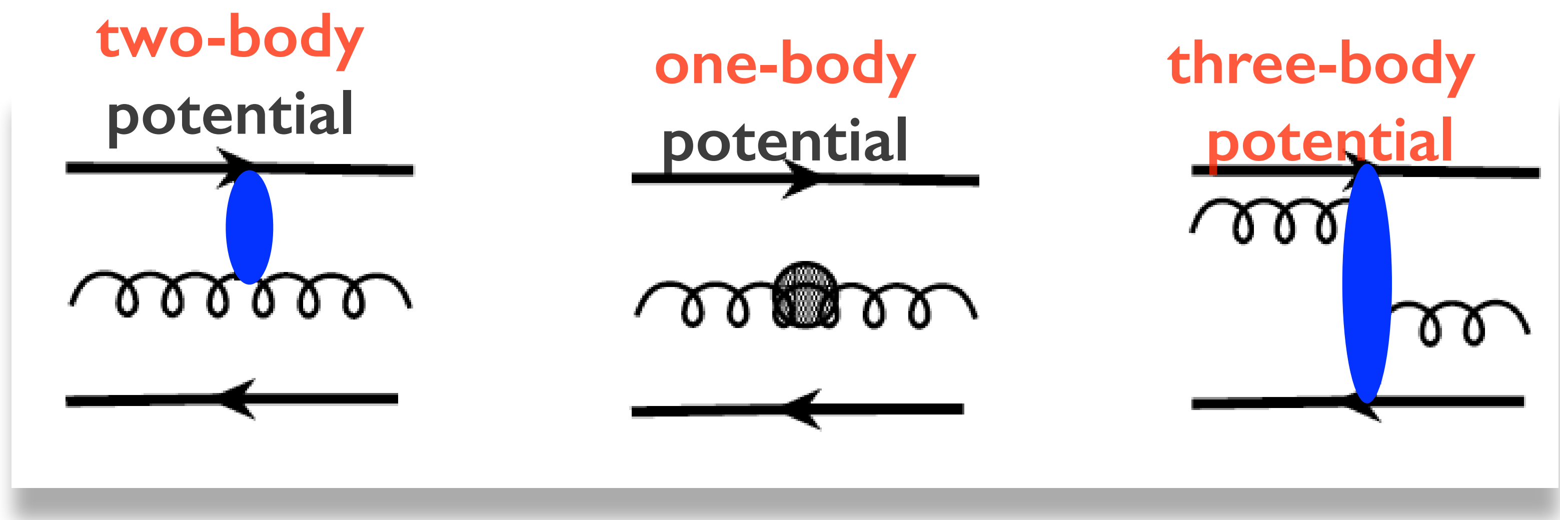
QCD Hamiltonian

$$H = H_D + H_{YM} + H_C$$

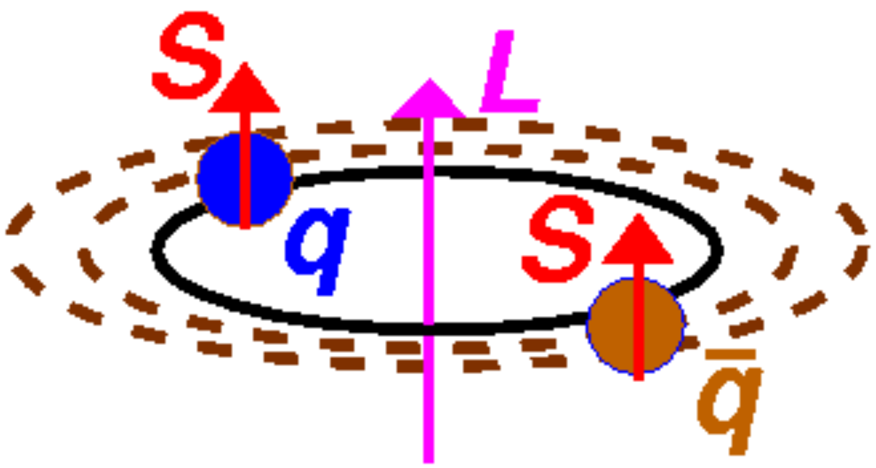
$$K = \frac{1}{2}\frac{g}{\nabla \cdot D}(-\nabla^2)\frac{g}{\nabla \cdot D}$$

$$H_C = \int d\mathbf{x} d\mathbf{y}\, \rho^a(\mathbf{x}) K[\mathbf{x},\mathbf{y},\mathbf{A}]_{ab}\rho^b(\mathbf{y})$$

Casimir Scaling and Constituent particles



$$J_g^{P_g C_g} \times L_{Q\bar{Q}} \times S_{Q\bar{Q}}$$



J^{PC} glue

J^{PC} $Q\bar{Q}$

$$1^{+-} \times 0^{-+}_{S_{Q\bar{Q}}} = \boxed{1^{--}}$$

$$1^{+-} \times 1^{--}_{S_{Q\bar{Q}}=1} = \boxed{0^{-+}, 1^{-+}, 2^{-+}}$$

gluons behave as 1^{+-} quasi-particle

Prediction of (Coulomb gauge) QCD

radiative decays

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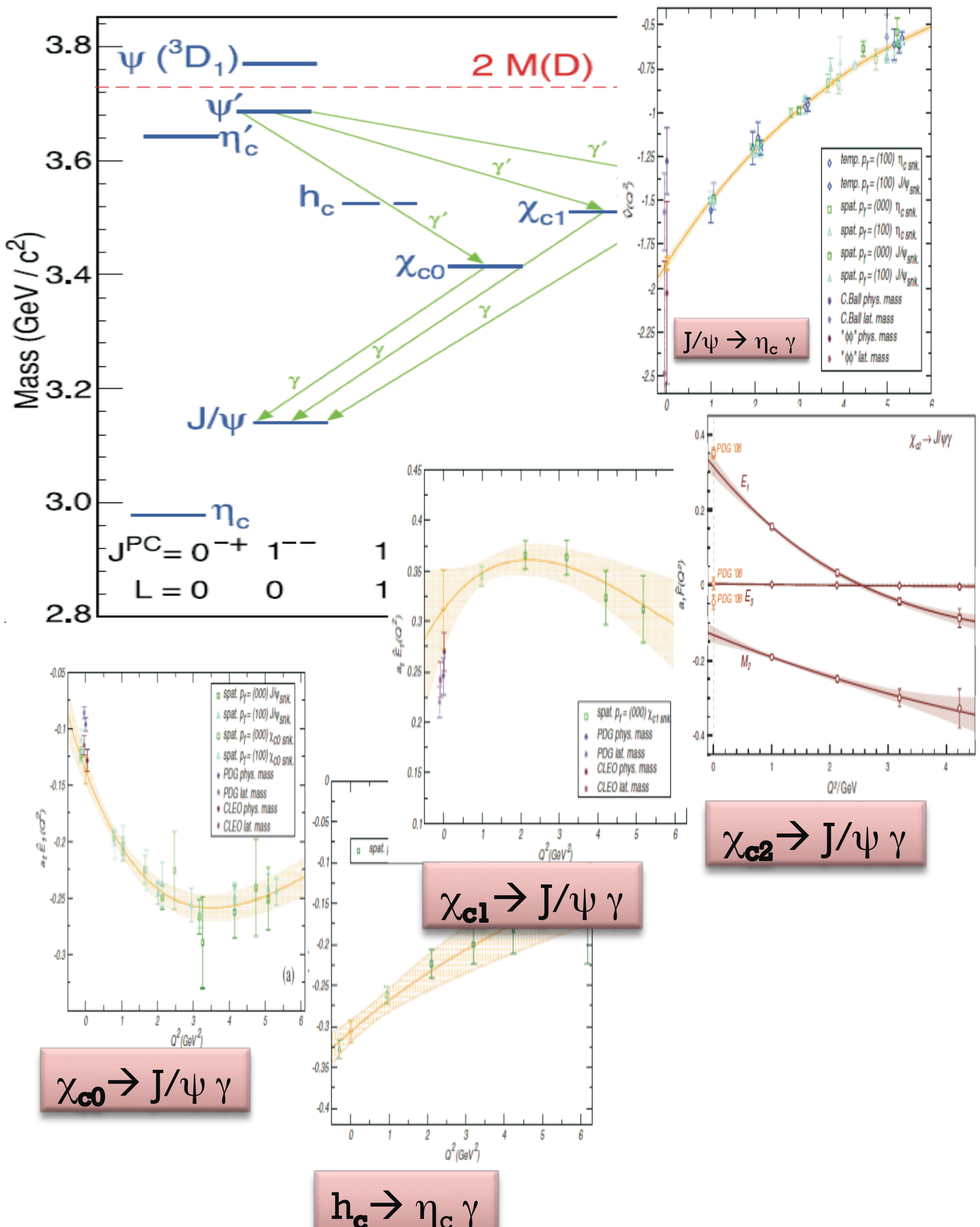
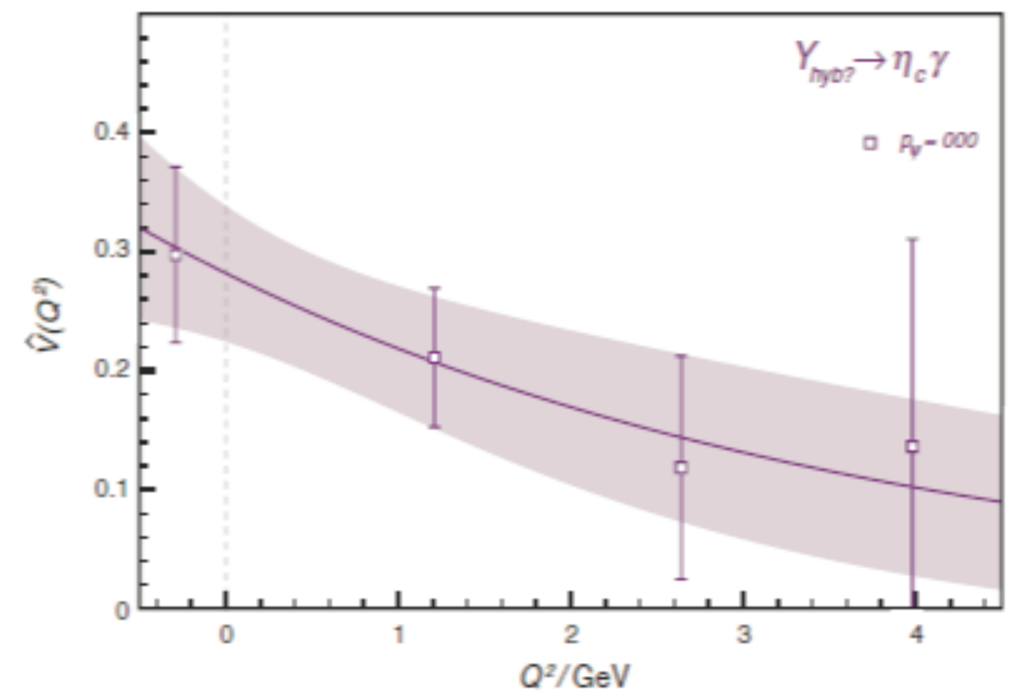
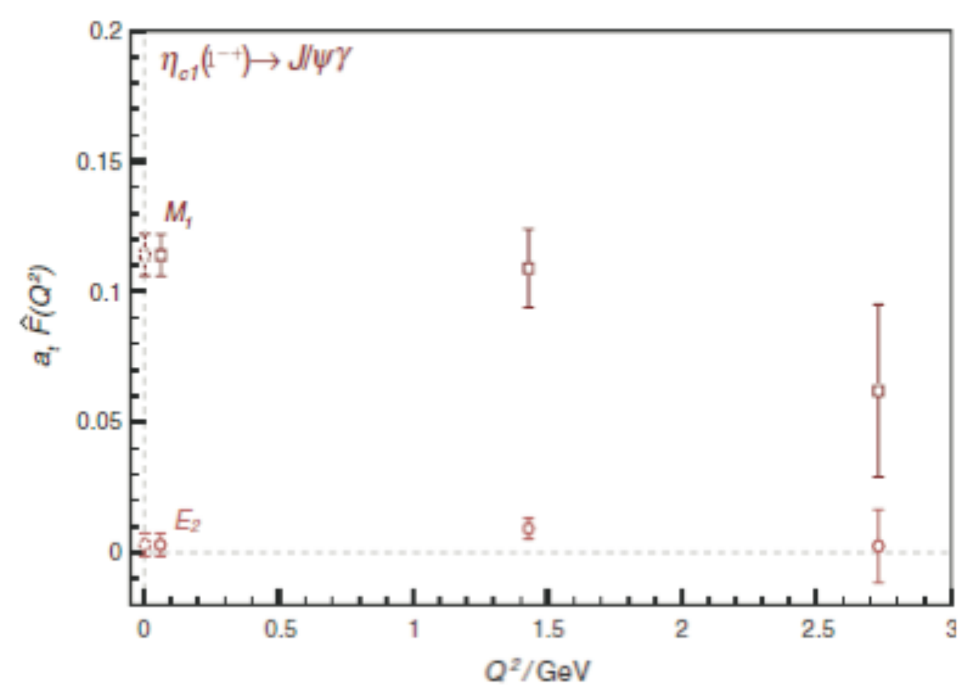


hybrid → γ meson

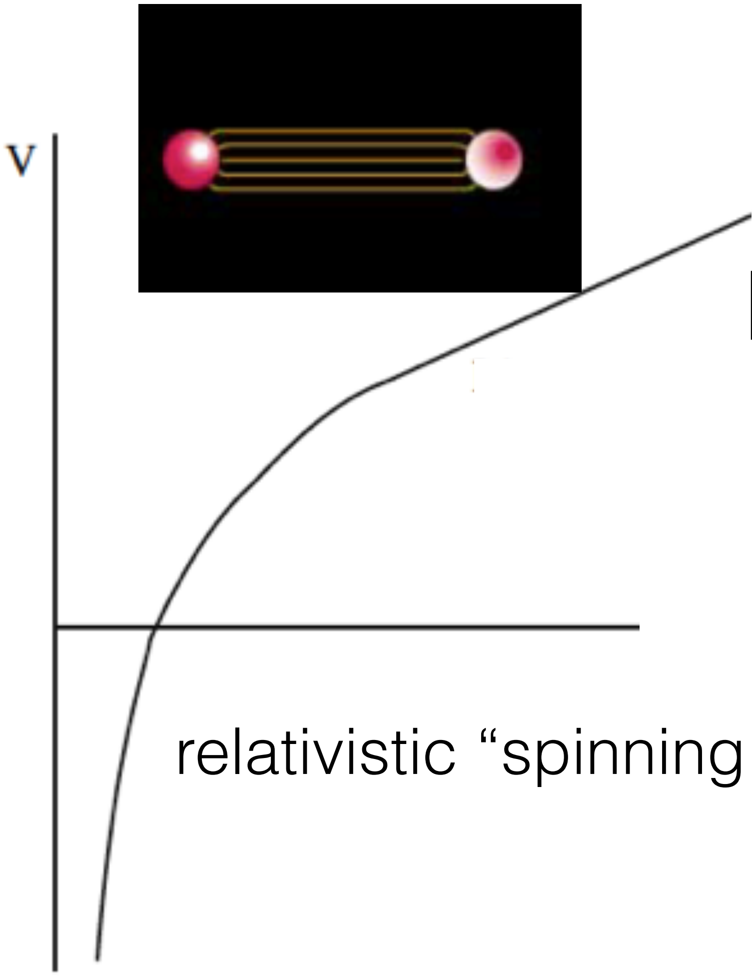




0⁻⁺ 1⁻⁺ 2⁻⁺ 1⁻⁻ have comparable decays rates O(100keV)

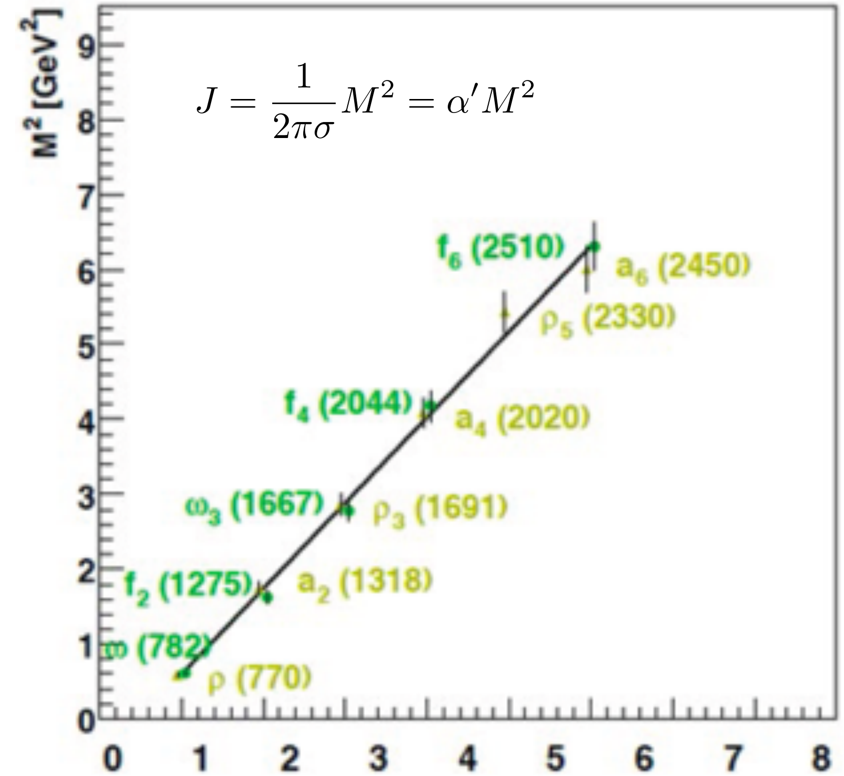
Hadrons Beyond Confinement

String-like properties and Regge behavior

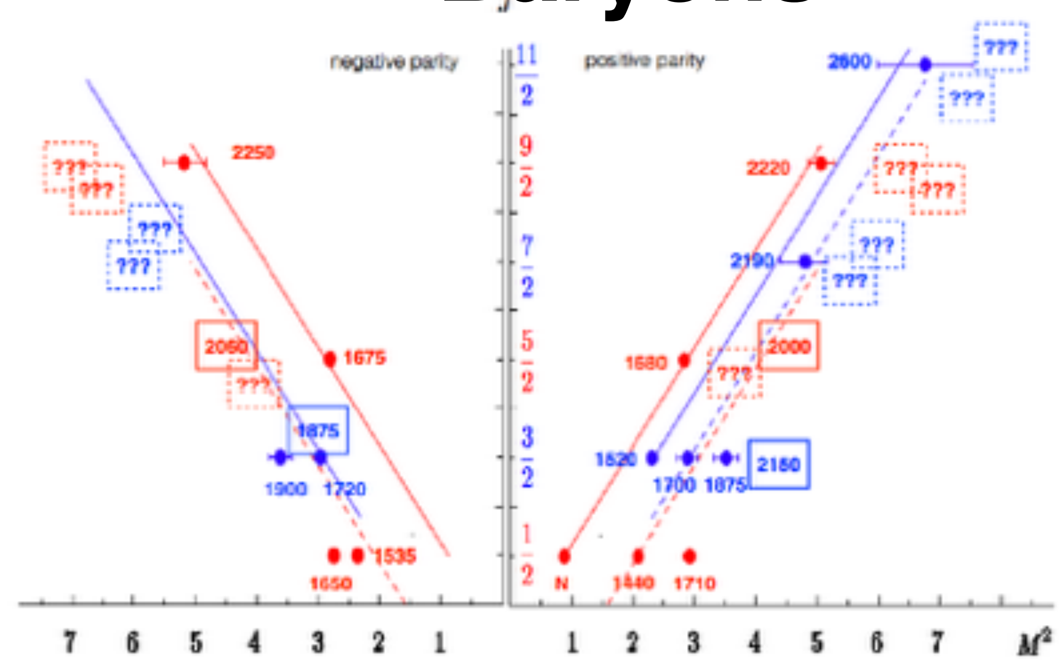


Normal ("Casimir" hadrons) follow linear Regge trajectories (J vs M²).

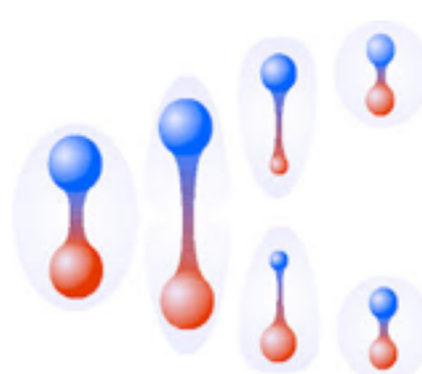
Mesons



Baryons



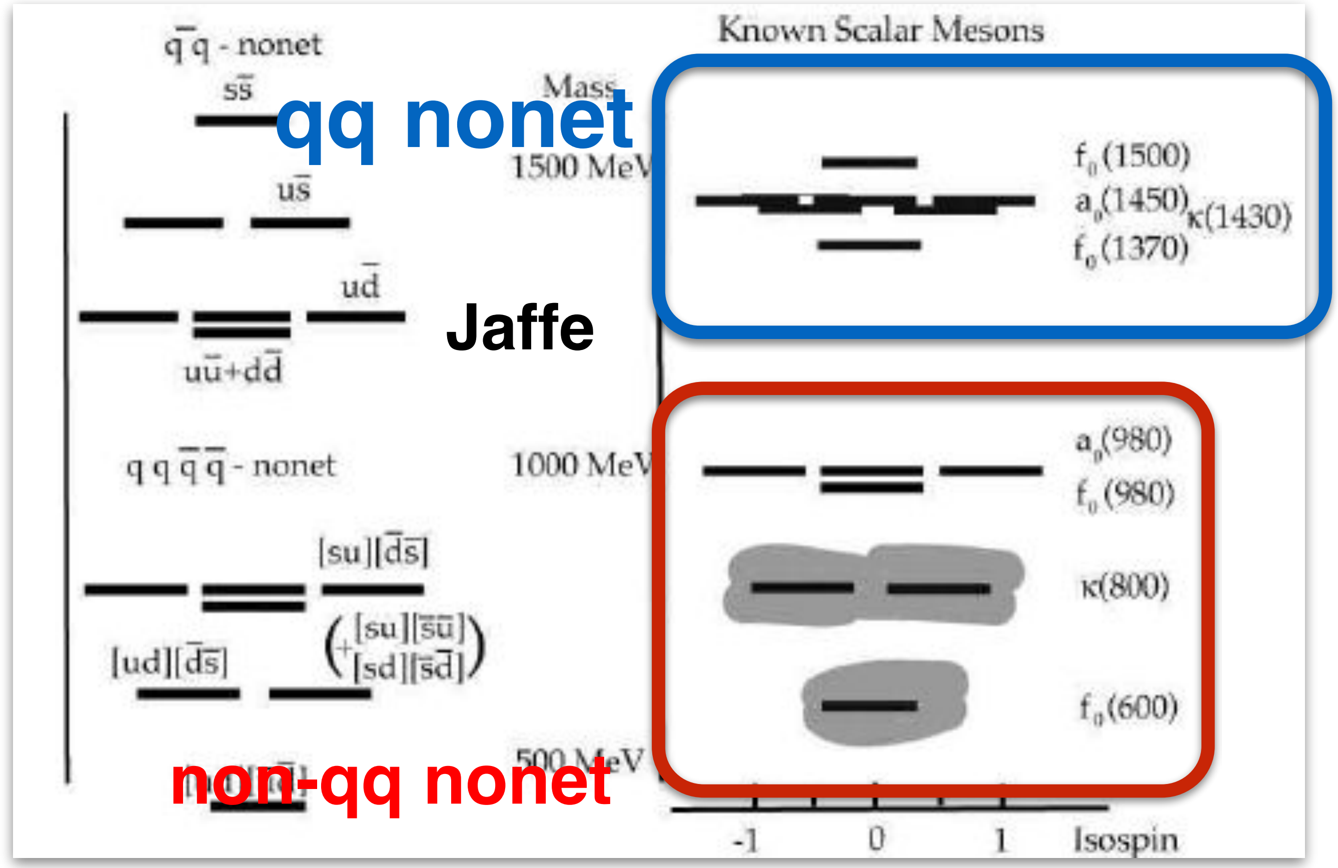
They survive even in presence of open decay channels



But there are known exceptions

Example of known non-ordinary: σ

Possible evidence for non-qq nature of light scalars



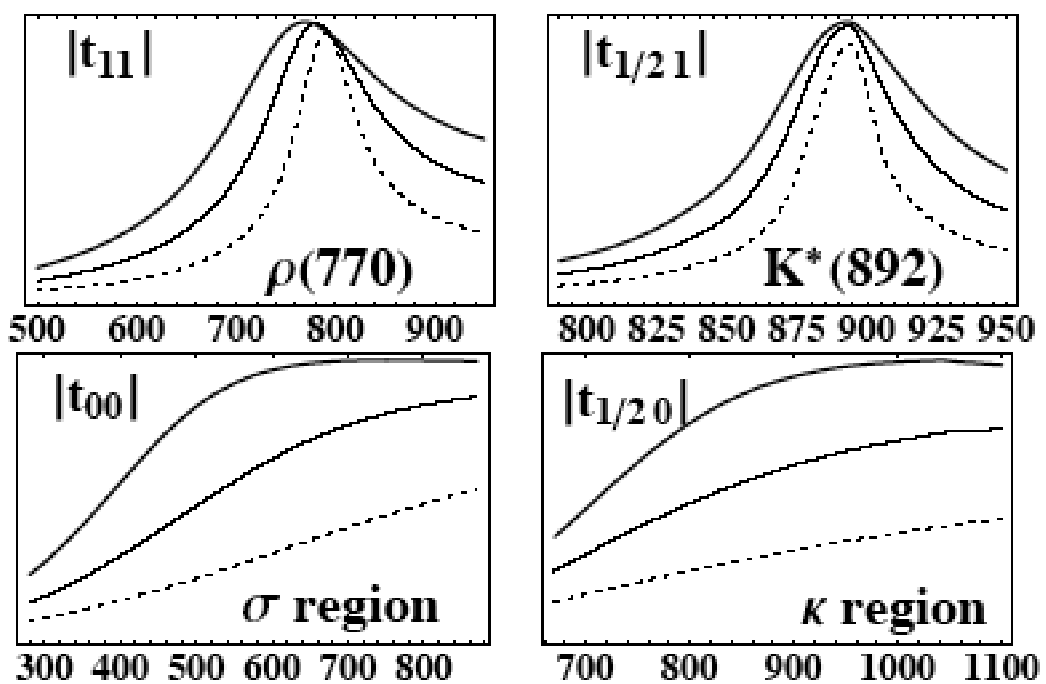
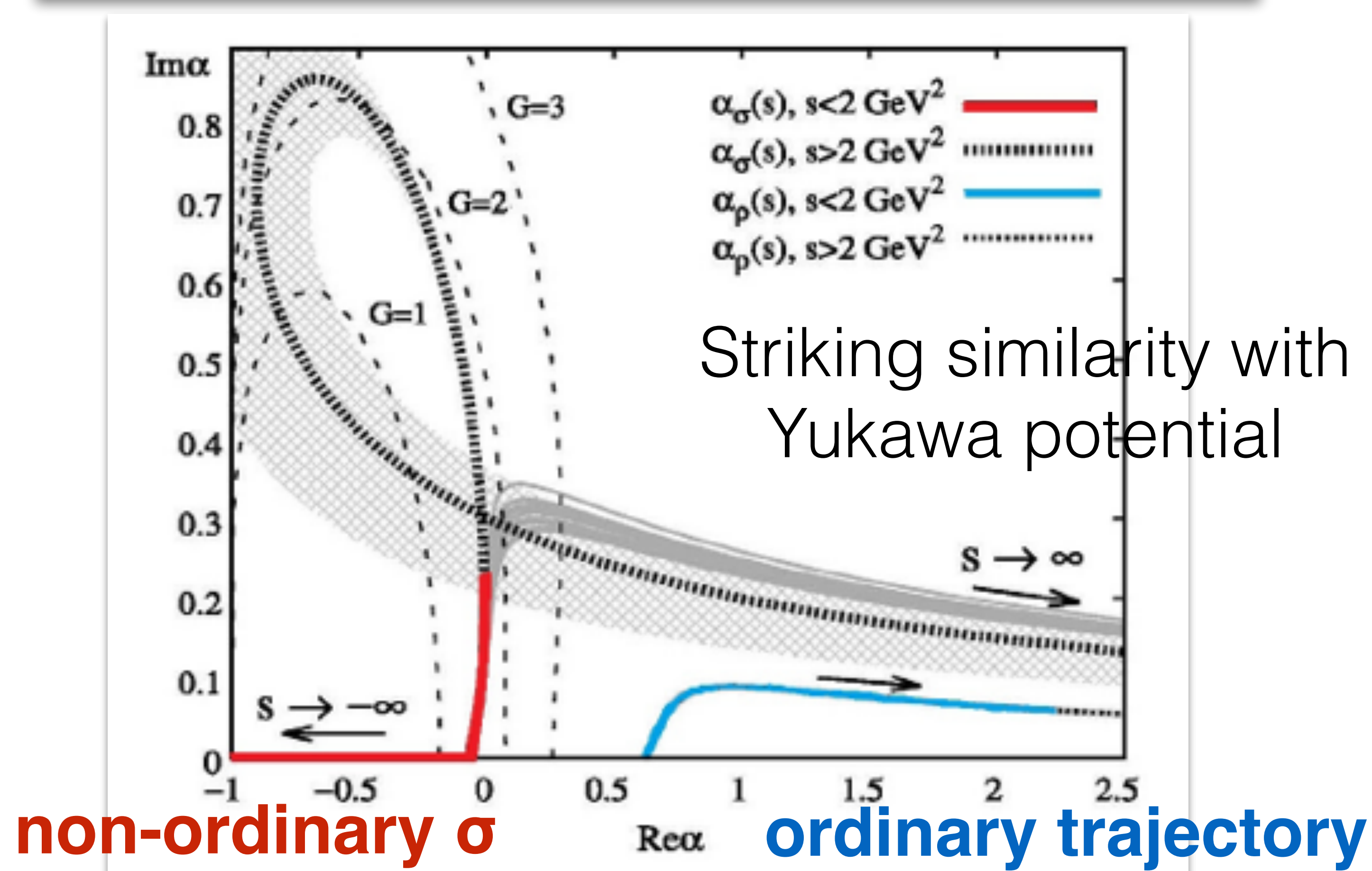
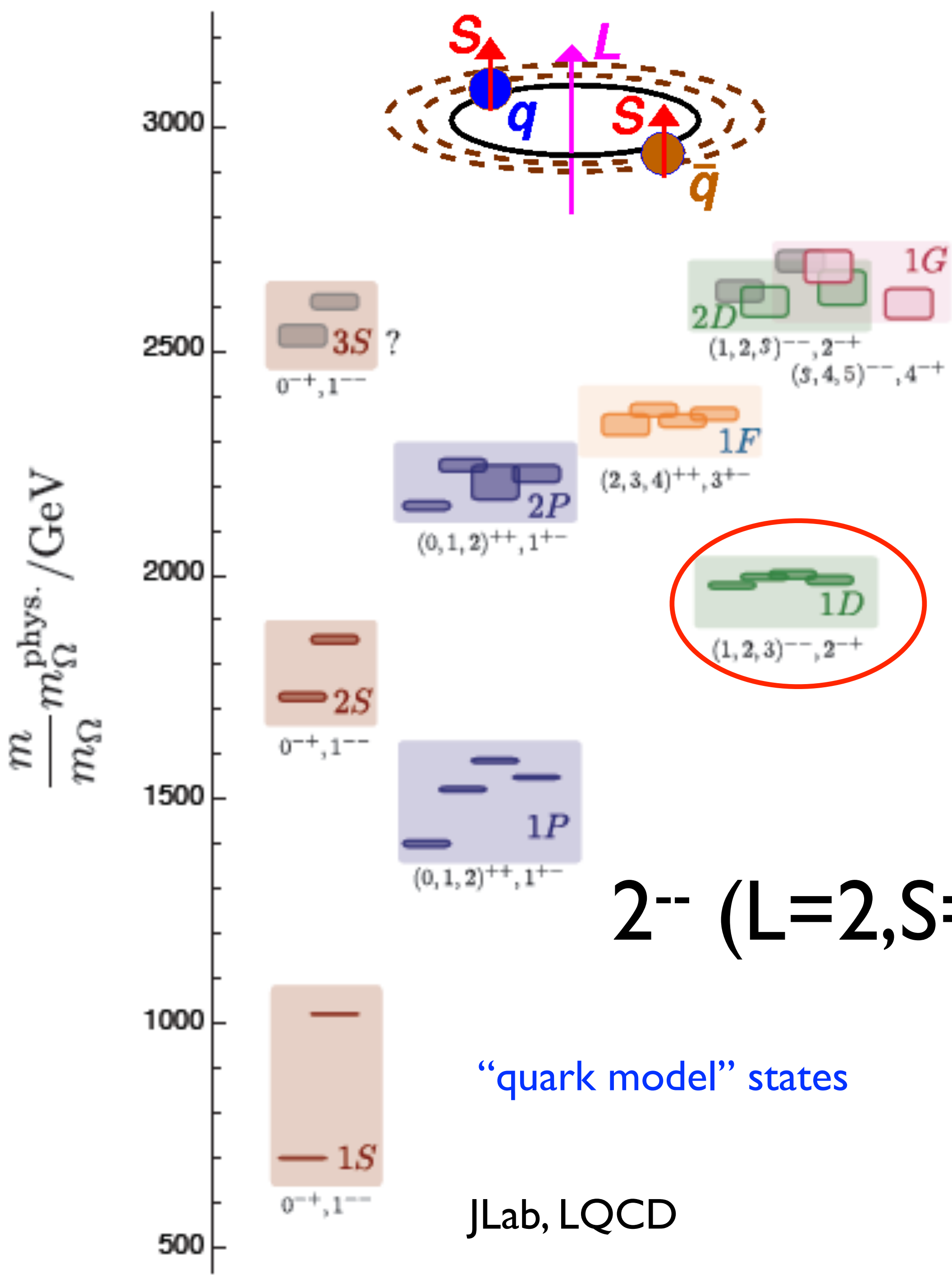


FIG. 1: Modulus of amplitudes in different meson-meson channels for $N_c = 3$ (thick line) $N_c = 5$ (thin continuous line) and $N_c = 10$ (thin dotted line), scaled at $\mu = 770$ MeV.

Pelaez



Quark model vs Regge classification



2^{--} (L=2,S=1)

"quark model" states

JLab, LQCD

I^G	naturality $=P(-1)^J$	twist =+1 if J=0,2,.. =-1 if J=1,3...	name
0^+	+1	+1	$f_0, f_2, \ldots$
0^+	+1	-1	$\eta/\eta'_1, \eta/\eta'_3, \ldots$ $(1^{-+}, 3^{-+}, \ldots)$
0^+	-1	+1	$\eta/\eta'_0, \eta/\eta'_2, \ldots$
0^+	-1	-1	$f_1, f_3, \ldots$
0^-	+1	+1	$h_0, h_2, \ldots$ $(0^{+-}, 2^{+-}, \ldots)$
0^-	+1	-1	$\omega/\phi_1, \omega/\phi_3, \ldots$
0^-	-1	+1	$\omega/\phi_0, \omega/\phi_2, \ldots (0^{--}, 2^{--}, \ldots$:not seen)
0^-	-1	-1	$h_1, h_3, \ldots$
1^+	+1	+1	$b_0, b_2, \ldots$ $(0^{+-}, 2^{+-}, \ldots)$
1^+	+1	-1	$\rho_1, \rho_3, \ldots$
1^+	-1	+1	$\rho_0, \rho_2, \ldots$ $(0^{--}, 2^{--}, \ldots$:not seen)
1^+	-1	-1	$b_1, b_3, \ldots$
1^-	+1	+1	$a_0, a_2, \ldots$
1^-	+1	-1	$\pi_1, \pi_3, \ldots$ $(1^{-+}, 3^{-+}, \ldots)$
1^-	-1	+1	$\pi, \pi_2, \ldots$
1^-	-1	-1	$a_1, a_3, \ldots$

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$$p\bar{p} \to 2^{--} \to \gamma\eta_c$$
$$p\bar{p} \to 2^{--} \to D\bar{D}^*$$

Same question in charmonium where is J/ψ_2 $J^{PC} = 2^{--}$

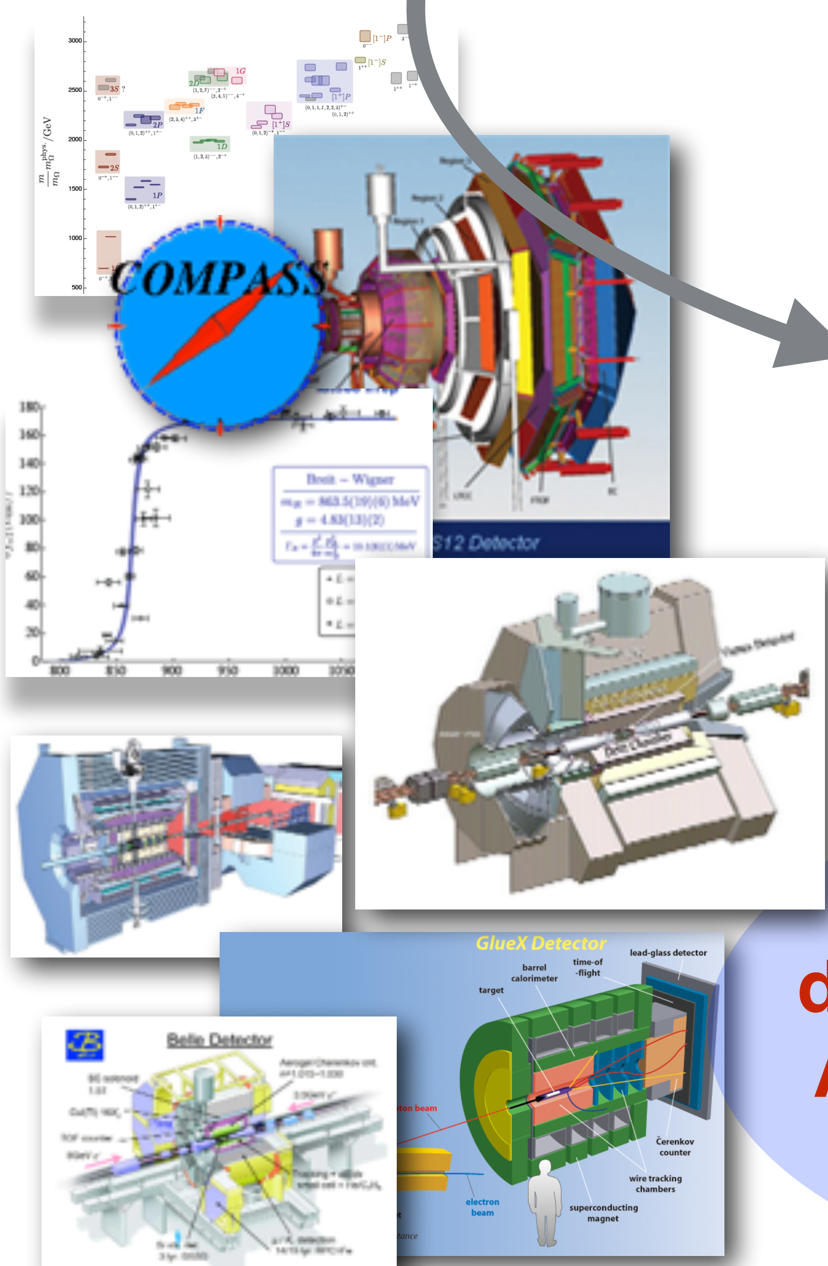
1. How to identify resonances in the data

Why Amplitude Analysis

Experimental Measurement

QCD Measurement

Physics quantities: form factors, resonance parameters masses, etc.



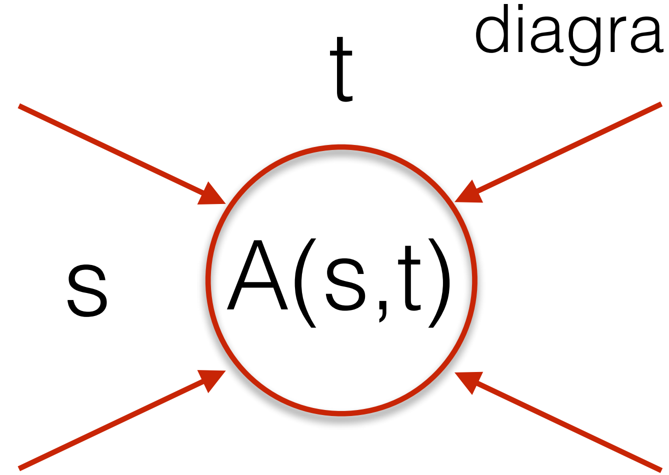
Reaction amplitudes

dσMeasured = Detector Acceptance ⊗ dPS |A|²

Amplitude construction

Axiomatic S-matrix principles: (not the same as based on a a microscopic model/theory, e.g. unitary diagrams vs Feynman diagrams)

- Crossing relations:



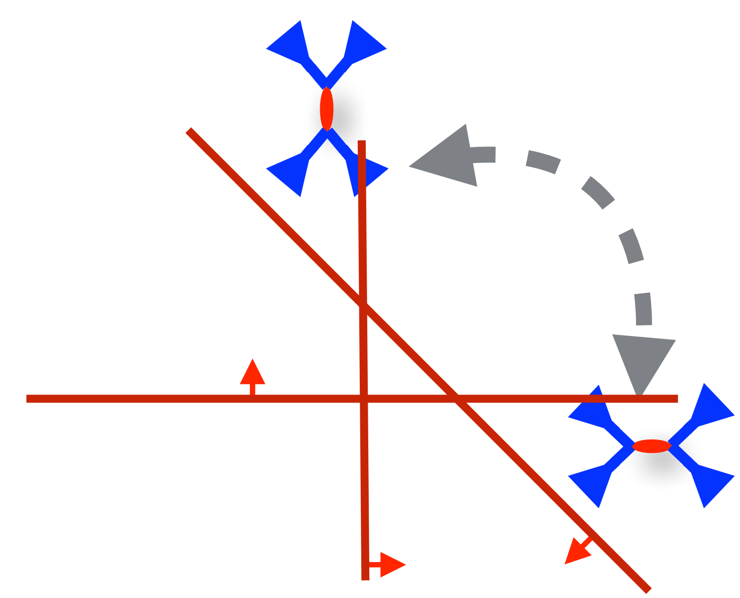
A(s,t) describes all processes related by line reversal

- Analyticity: Cuts determined by unitarity (i.e. in the physical region, continuation is complicated, Mandelstam representation known only for 4-point function)

  Asymptotic behavior ($A(s_i) < s_i\, O(\log s_j)$)

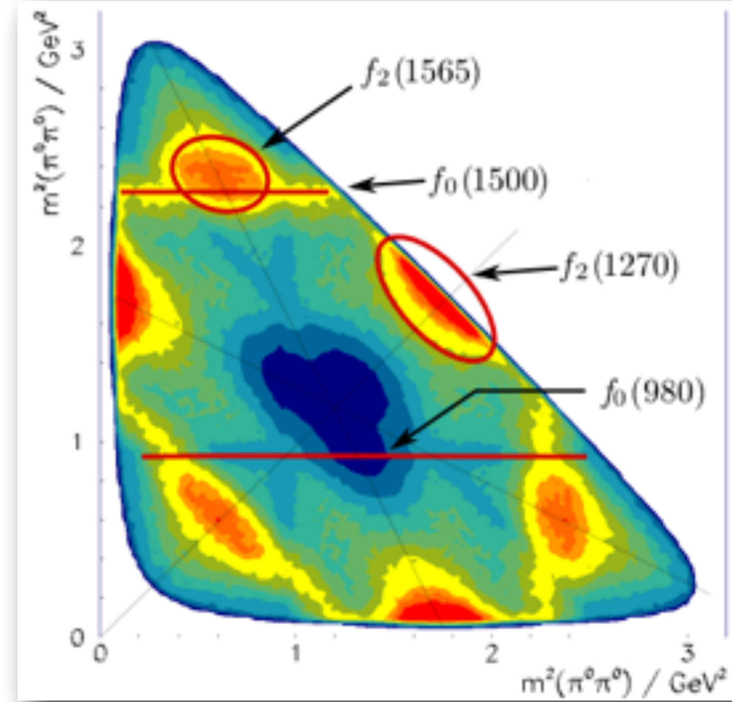
  Bound state poles : **Anomalous Thresholds (the XYZ's)**

- **Regge behavior: Analyticity**
- **of "the second kind"**



- Global symmetries: EM, chiral, …

- When cross-channel channel singularities are all nearby, there are no known amplitudes that satisfy all S-matrix constraints



(except perturbatively, e.g. chiral p.t.)

Two general class of models

- **Two-body unitarization, of low partial waves**

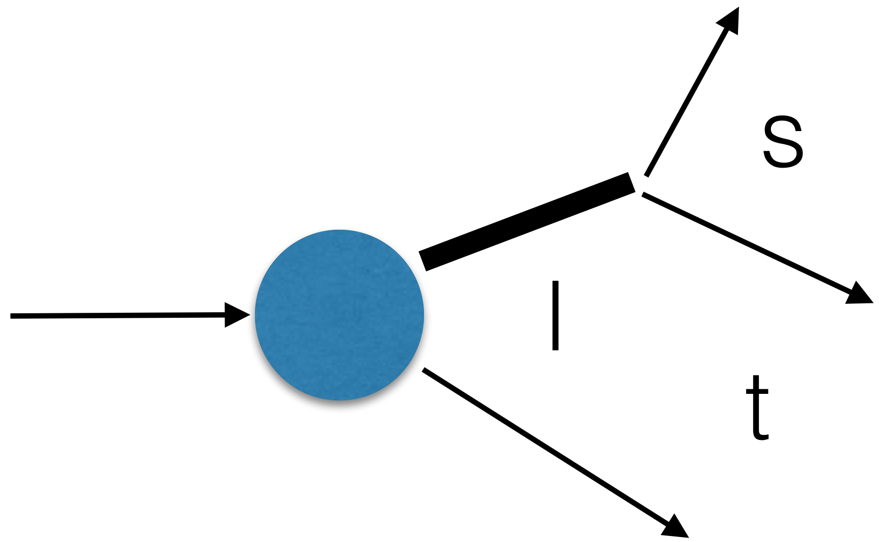
violate analyticity of the 2nd kind

Isobar model

- **Resonance/Regge Duality**

Dual Models

violate analyticity of individual partial waves



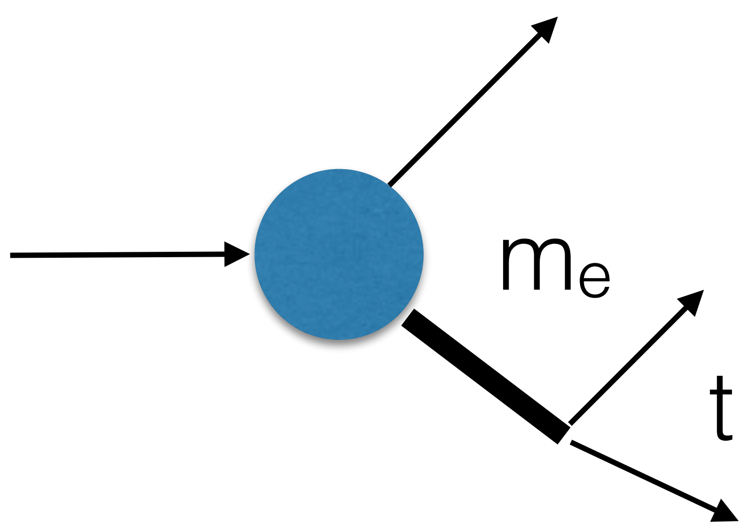
Isobar model

$$\sum_{l}^{L_{max}} (2l+1) f_l(s) P_l(z_s \sim t)$$

(s-channel break up momentum)^2 / nearest singularity in exchange channel

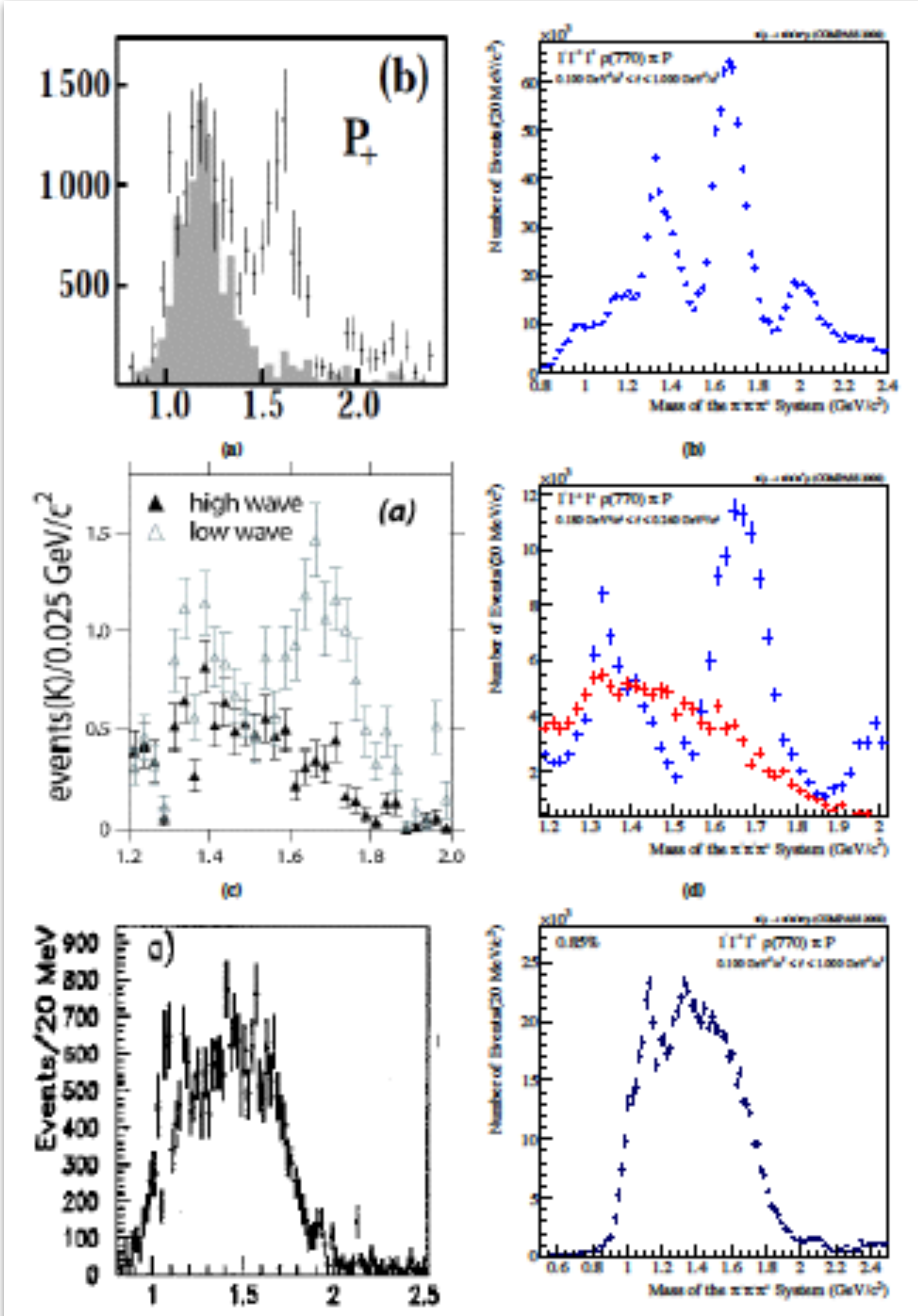
OK if

$$(s-4)R^2 \sim \frac{s-4}{m_e^2} << 1$$

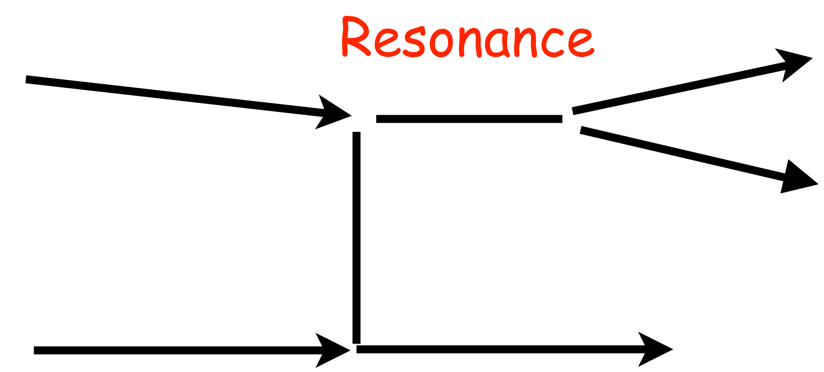


if s and t -channel singularities are close by truncation leads to unphysical dependence on cross-channel variable

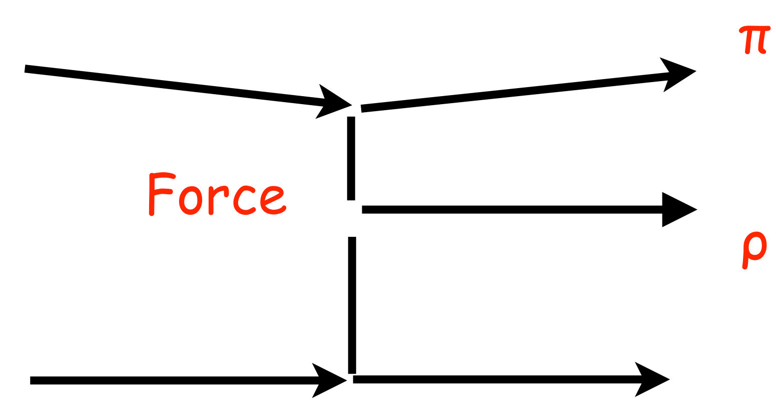
then adding s and t channel "diagrams" results in double counting …



Isobars represent a finite set of terms in p.w. expansion

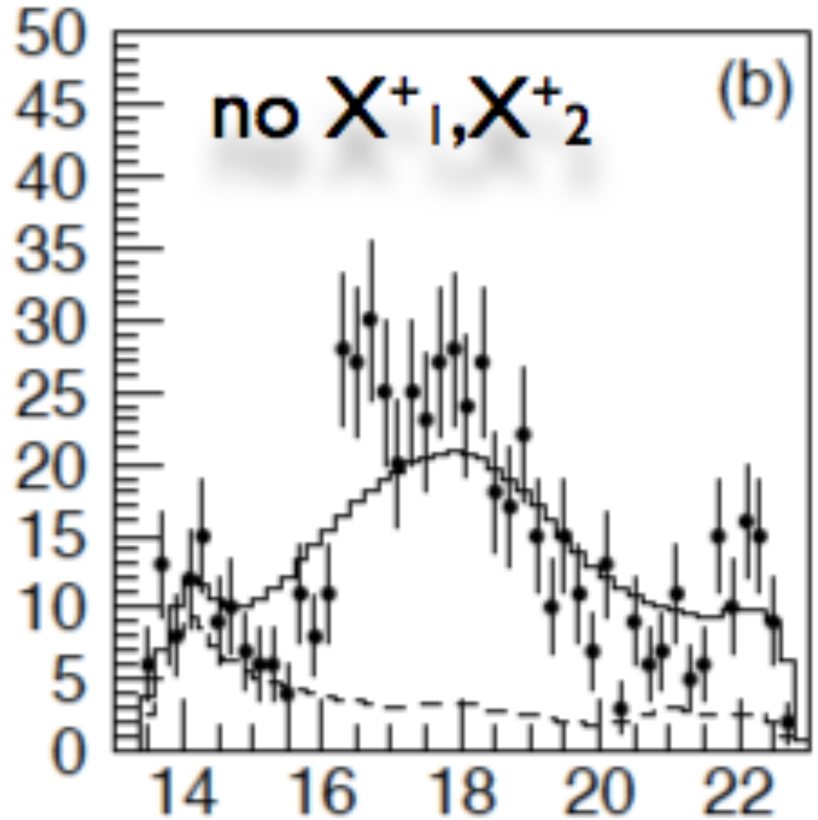


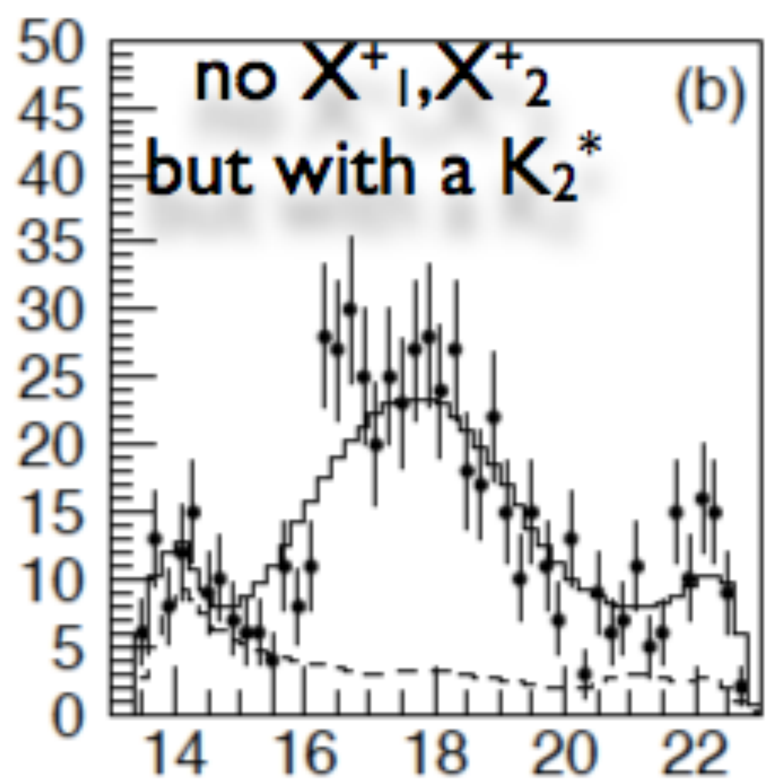
“Forces” contribute to infinite number of p.w. not including them makes analysis truncation dependent

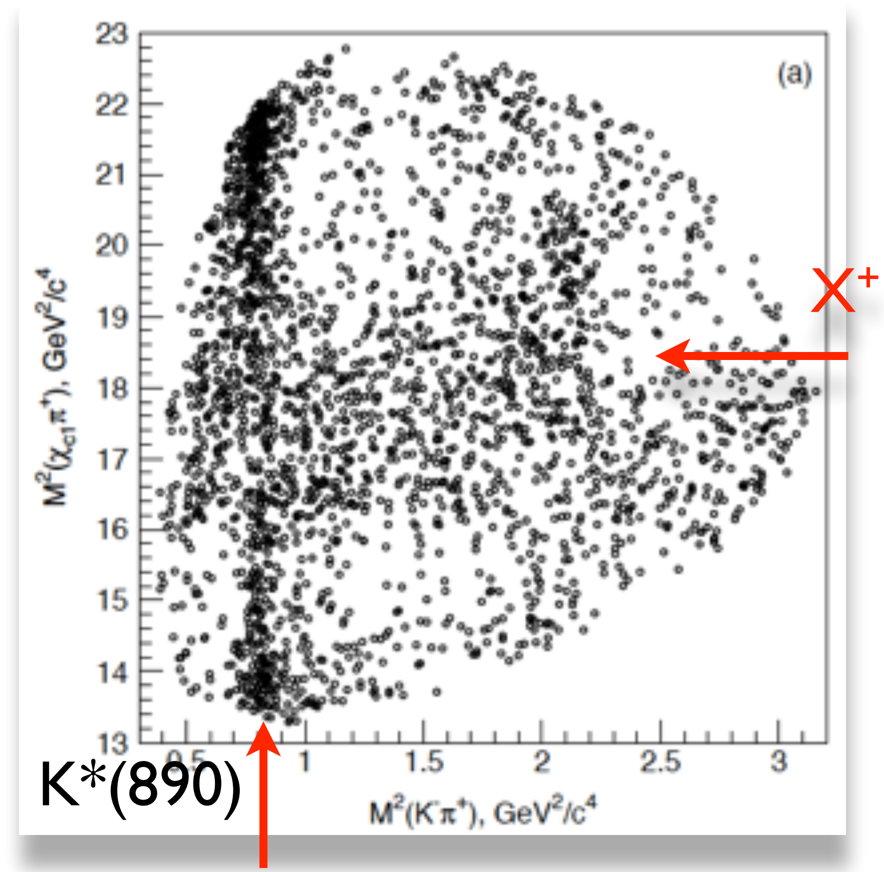


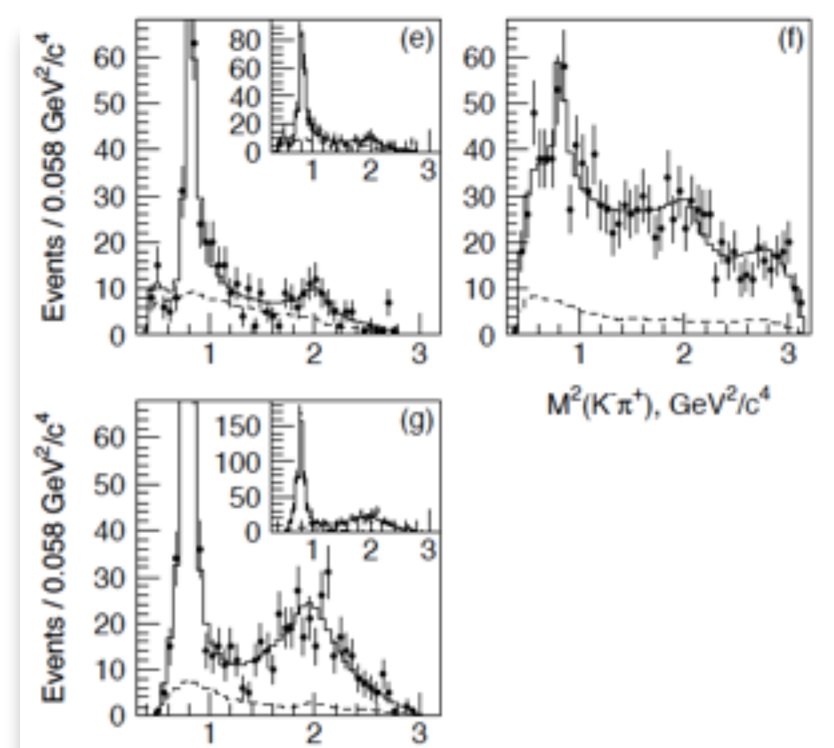
What may happen when amplitudes are unconstrained

- X^+ (4050,4250) Belle (2009) $\bar{B}^0 \to K^-(\chi_{c1}\pi^+)$





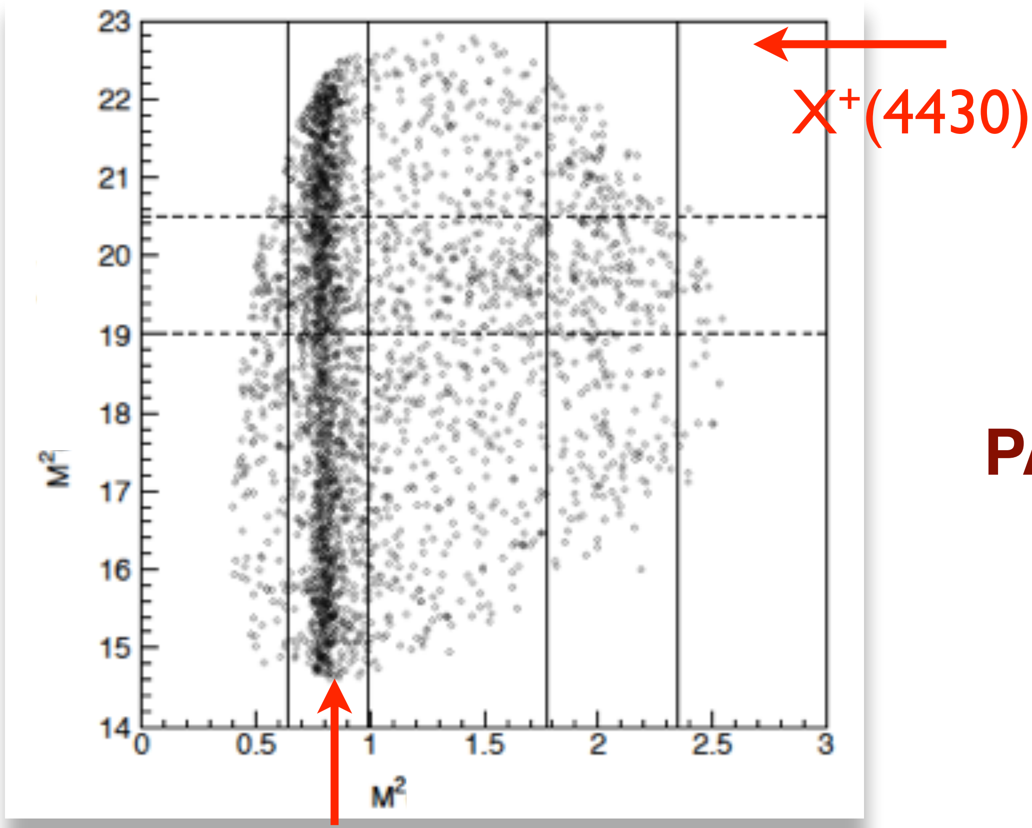




higher K* spins produced more “wiggles” in cross-channel

- $X^{\pm}$ (4430) Belle (2009) $\bar{B}^0 \to K^-(\psi'\pi^+), B^+ \to K^0_s\,(\psi'\pi^+)$

not seen in BaBar (also in $J/\psi\ \pi^-$)



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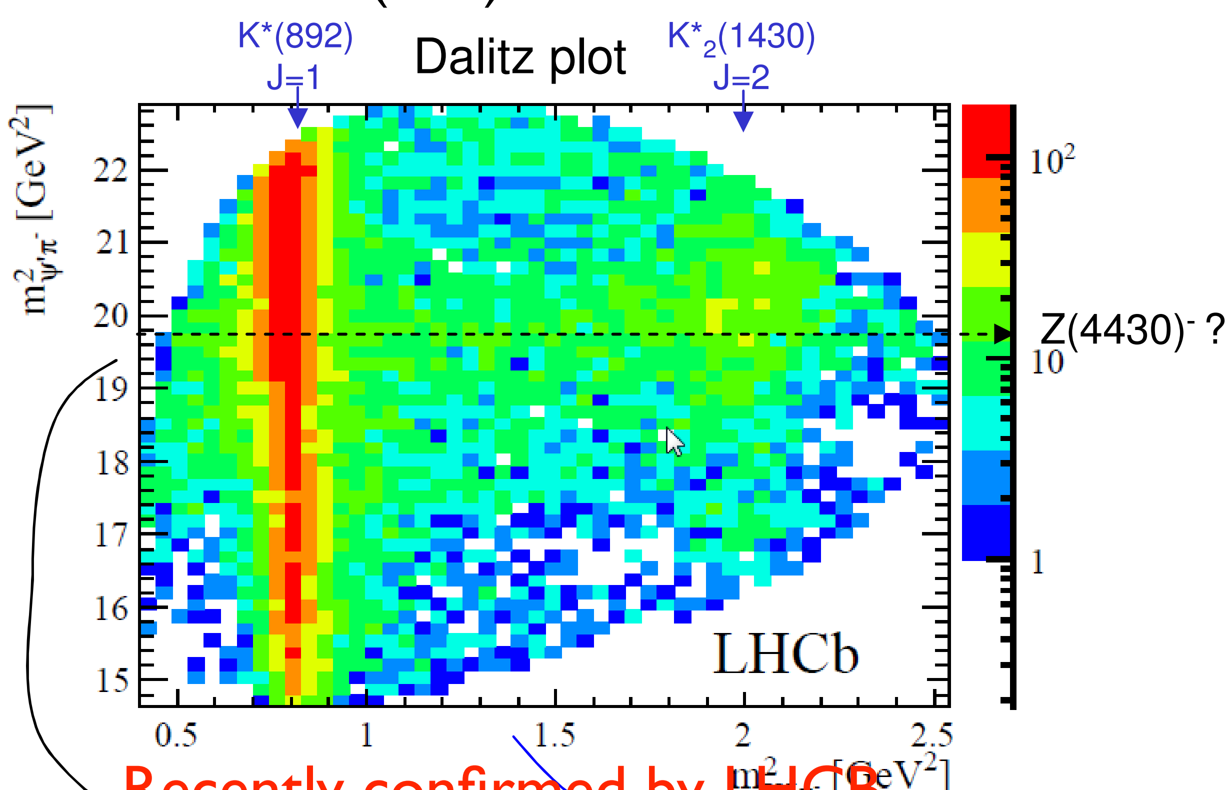
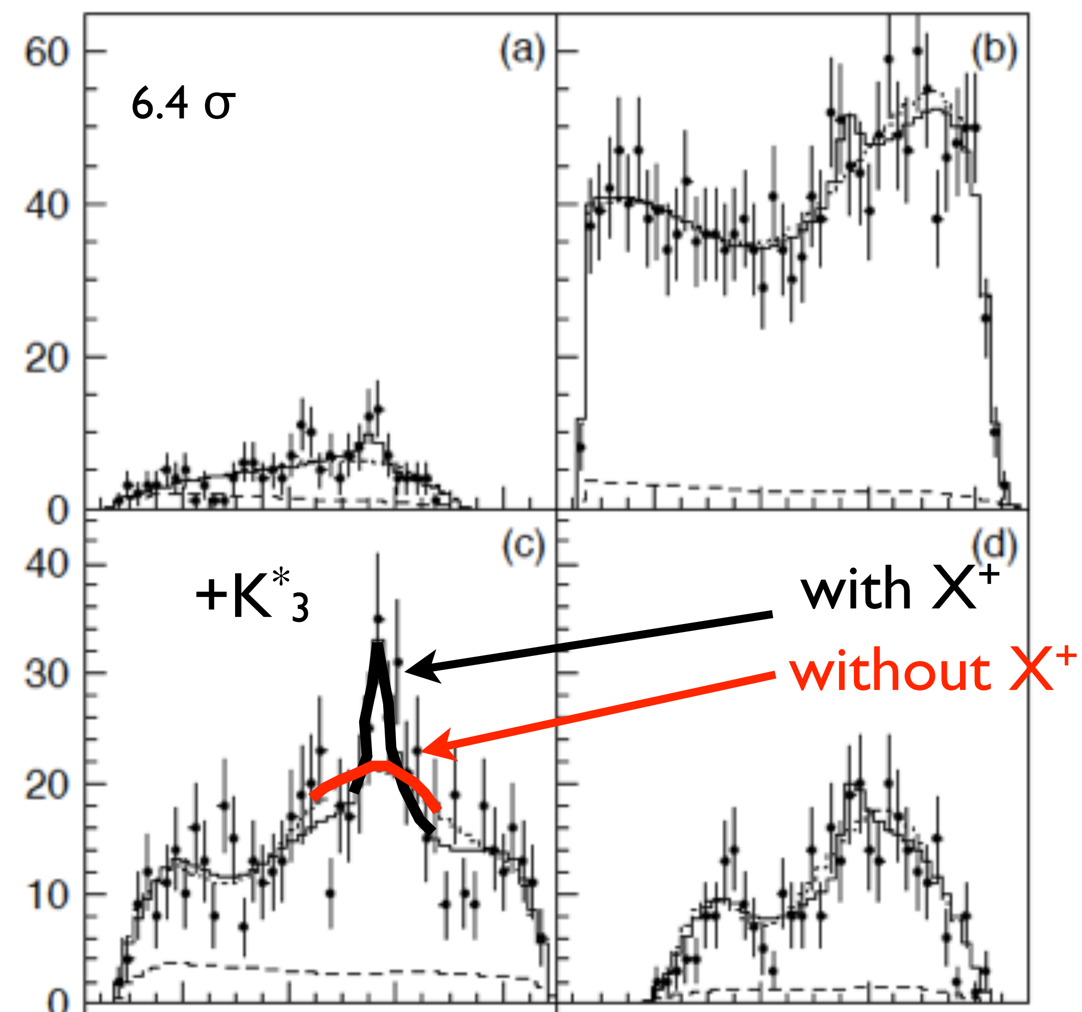


Recently confirmed by LHCB



constraints from duality

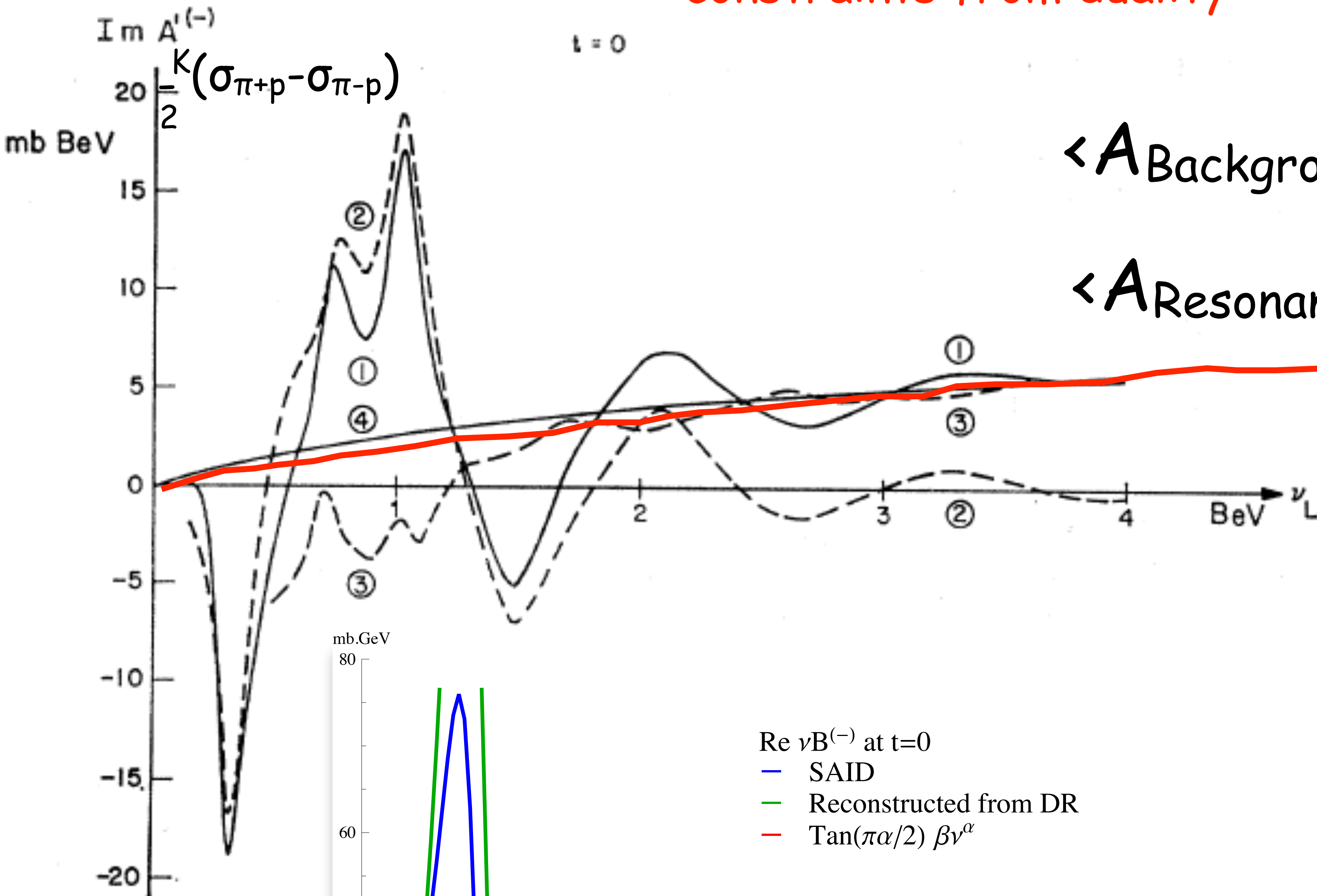
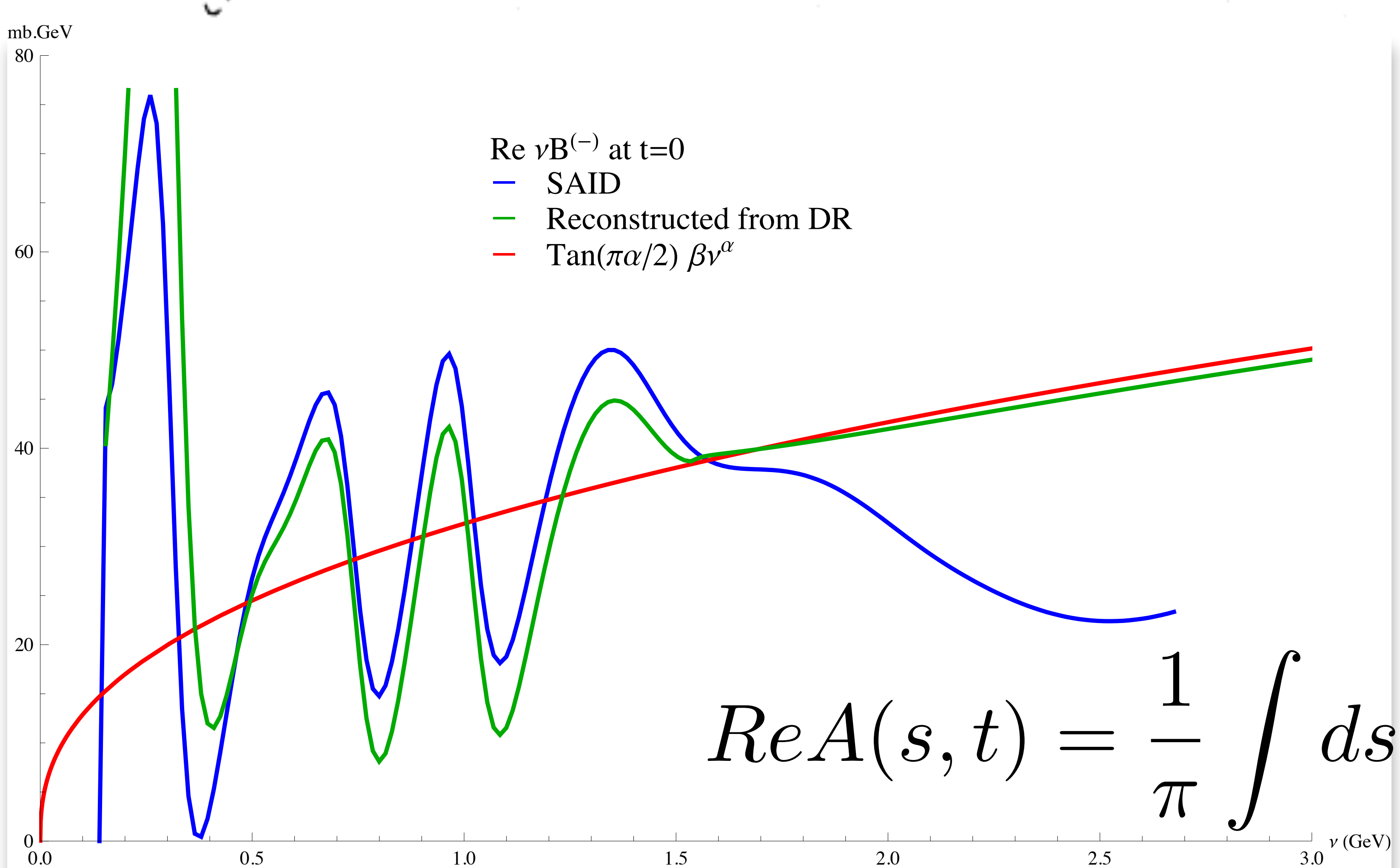


FIG. 7. Plot of $\mathrm{Im}A'^{(-)}$ at $t=0$. Comparison between different models.

$\langle A_{Backgrond} \rangle \sim \langle A_{Pomeron} \rangle$

$\langle A_{Resonance} \rangle \sim \langle A_{Regge} \rangle$

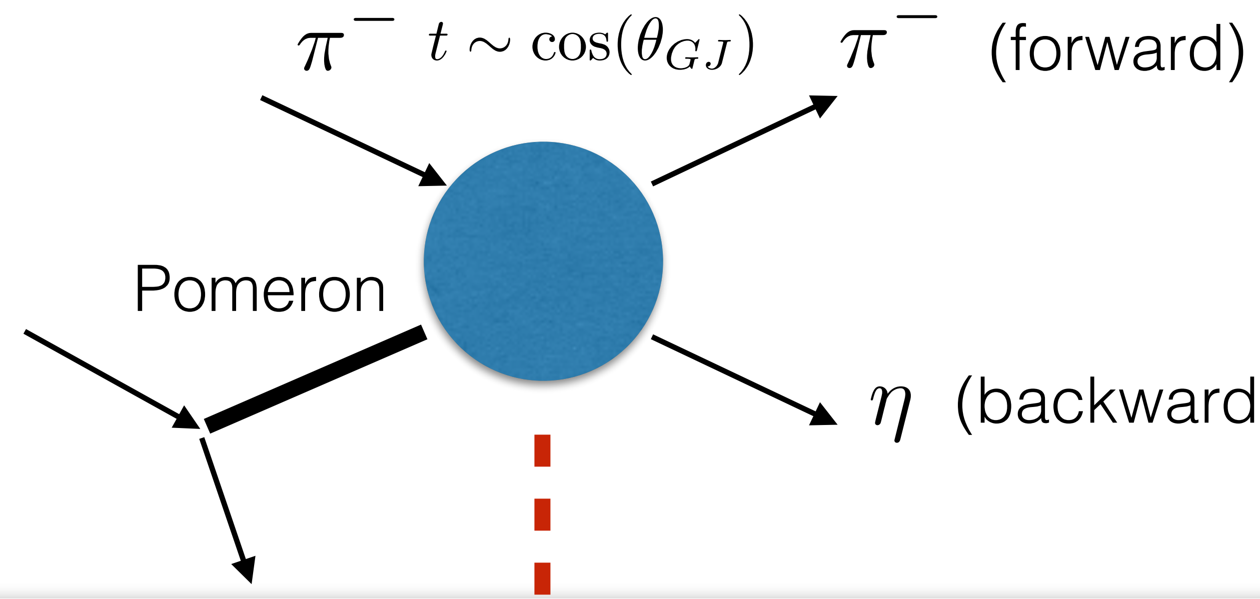


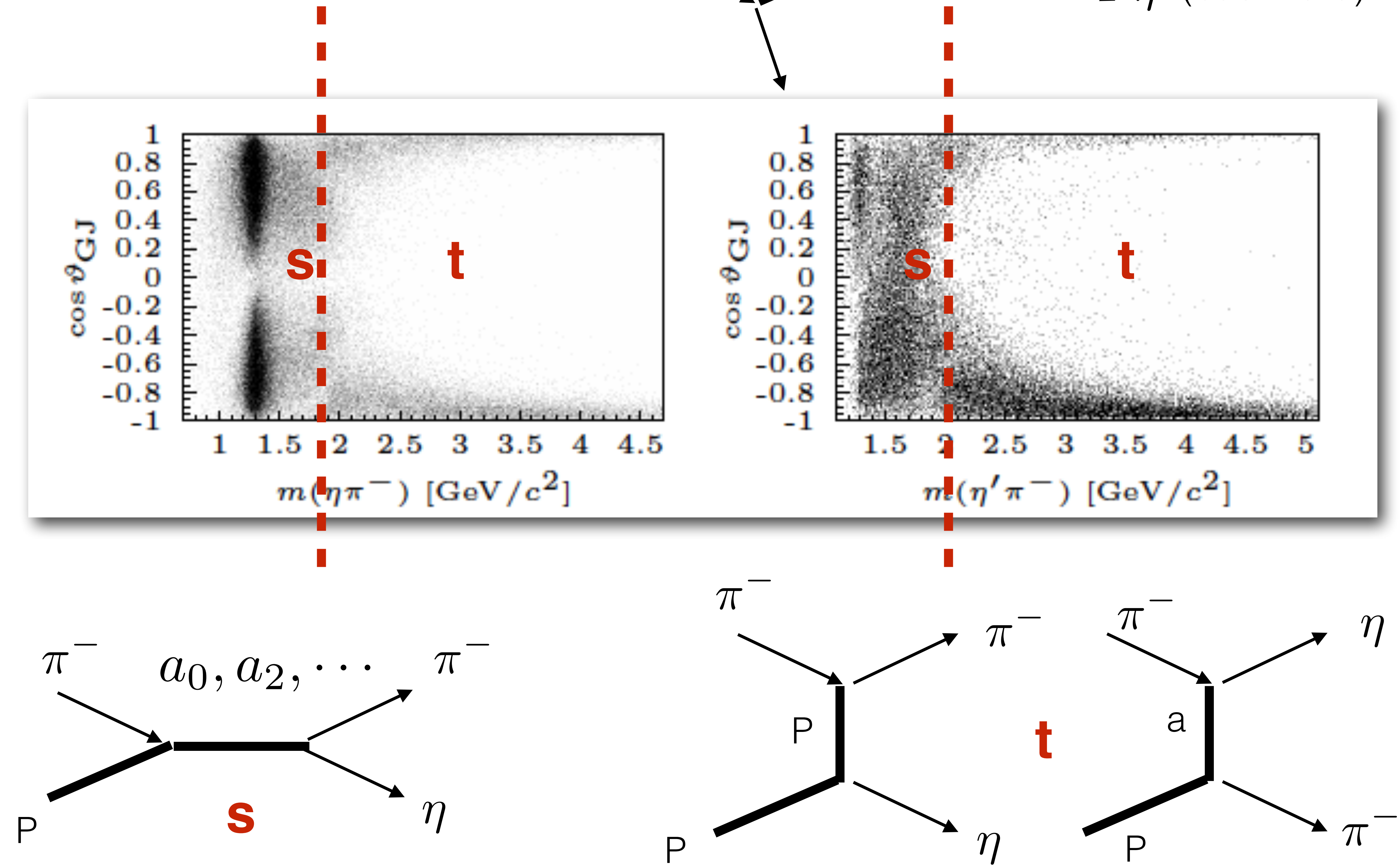
$$ReA(s,t) = \frac{1}{\pi}\int ds' \frac{ImA(s',t)}{s'-s}$$

V. Mathieu et al.

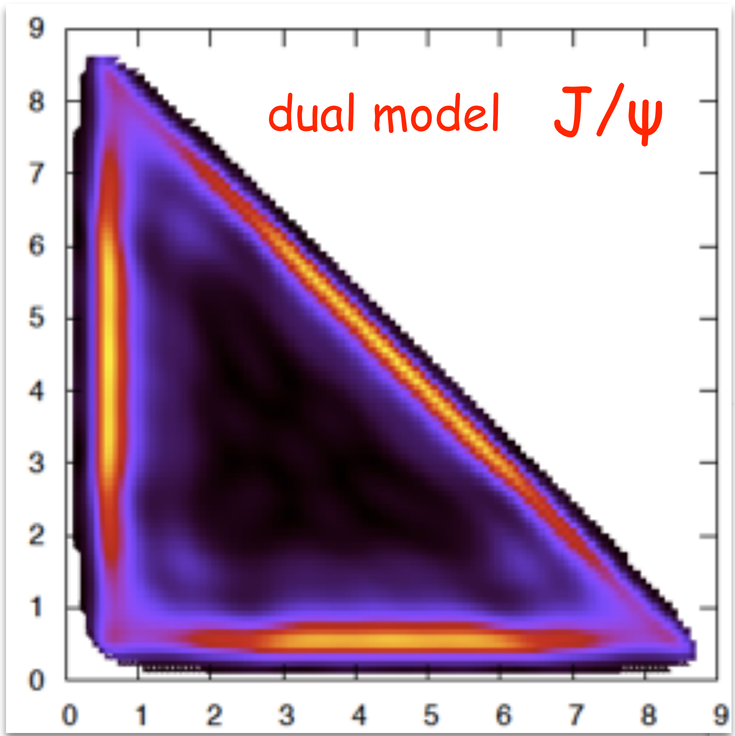
COMPASS

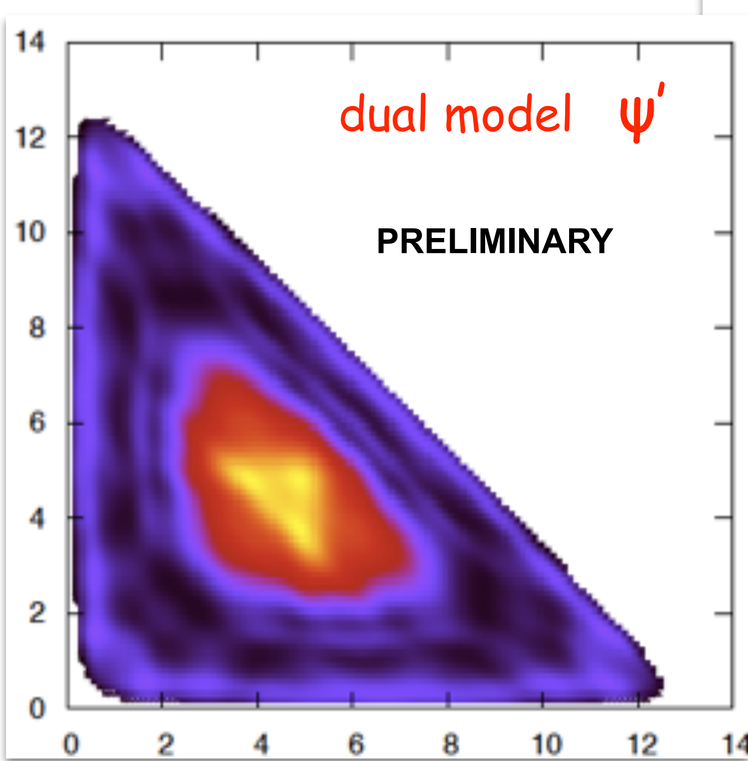
$$\pi^-(190\mathrm{GeV}^2)p \to \eta(')\pi^- p$$



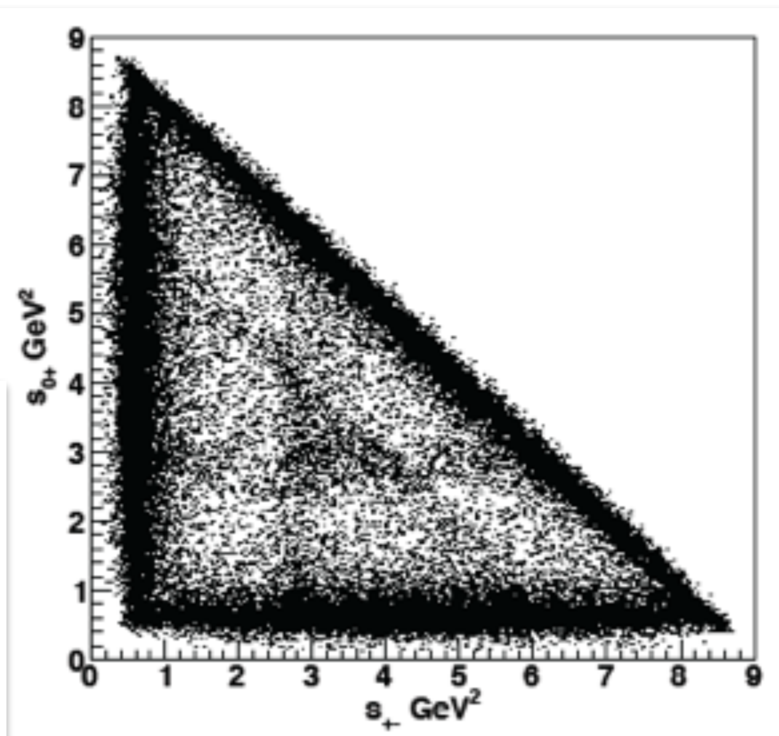


Regge

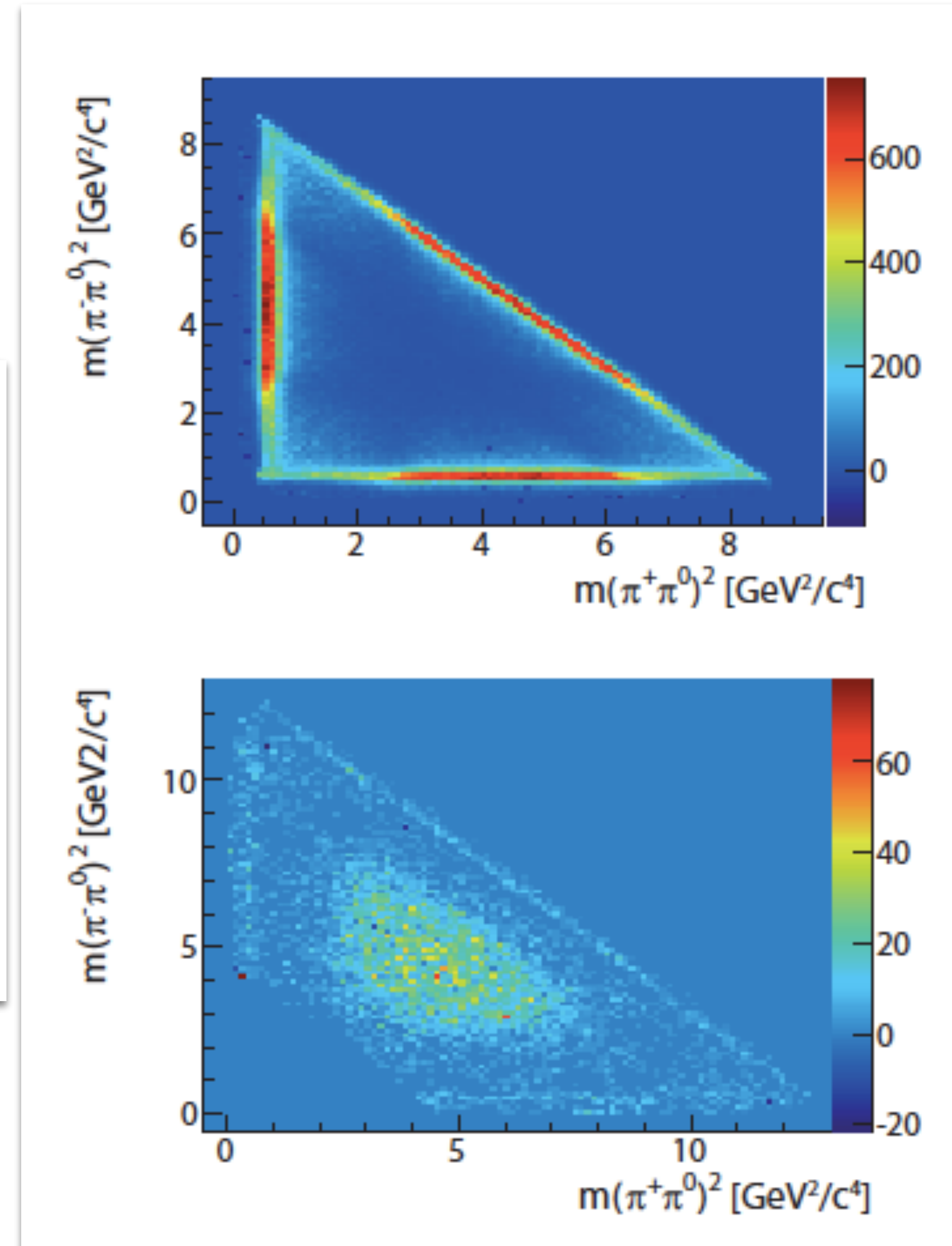




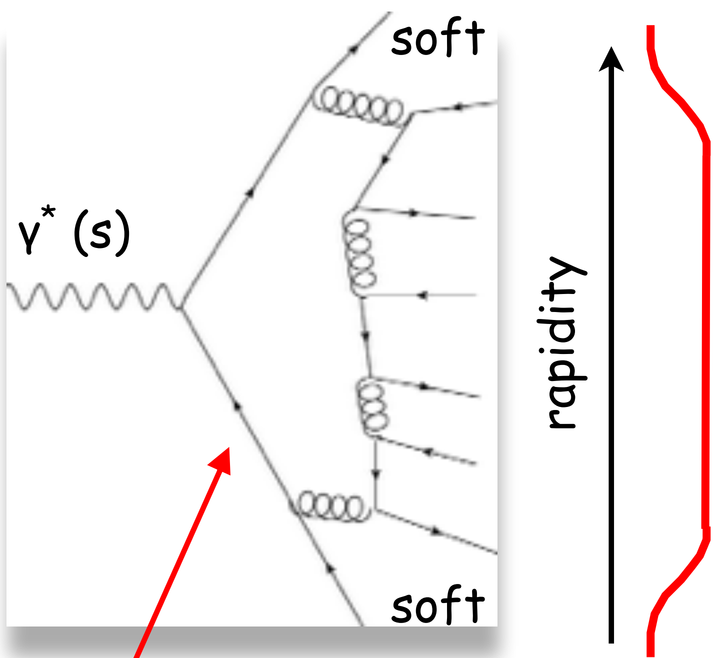
standard
isobar



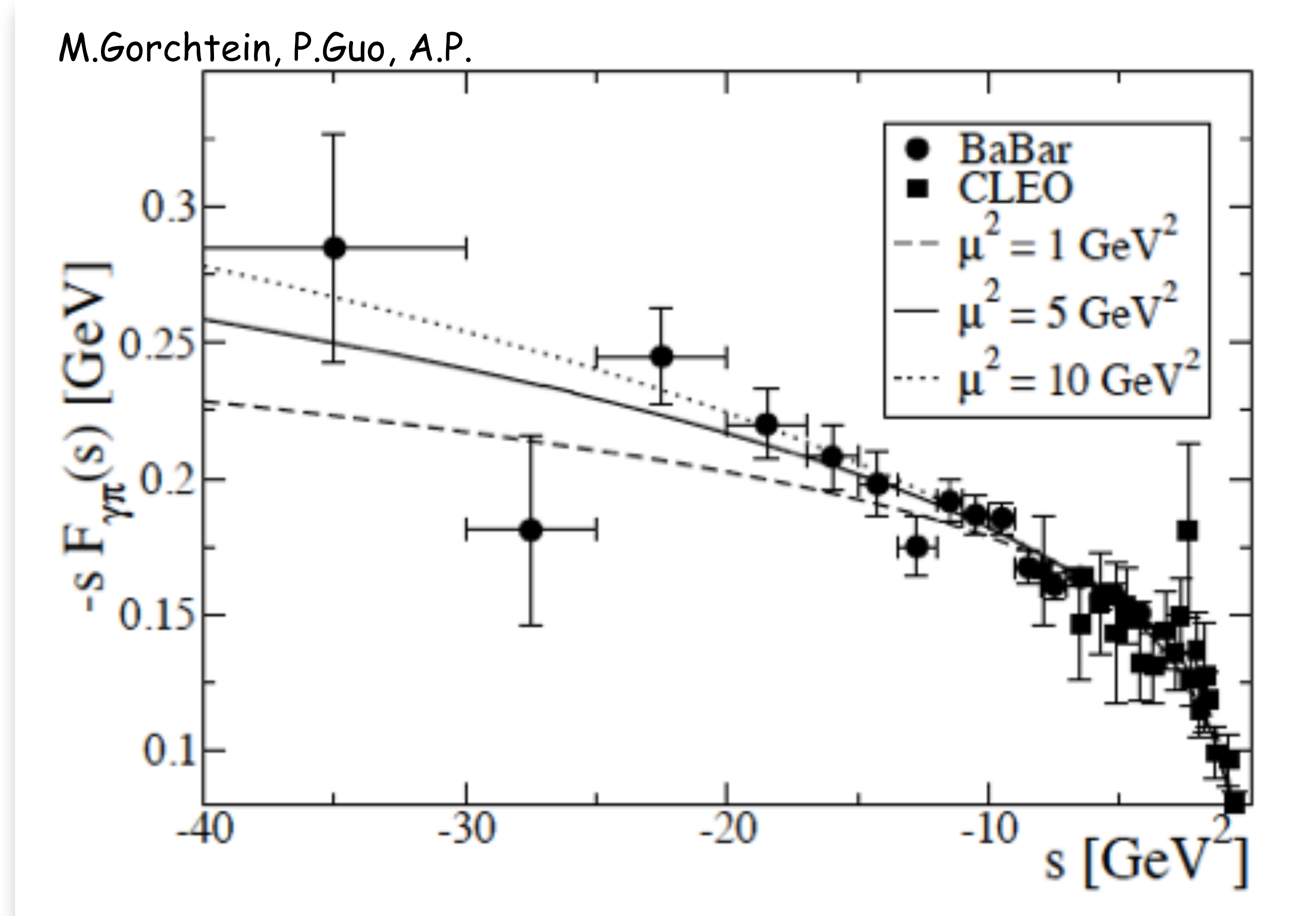
PANDA@FAIR



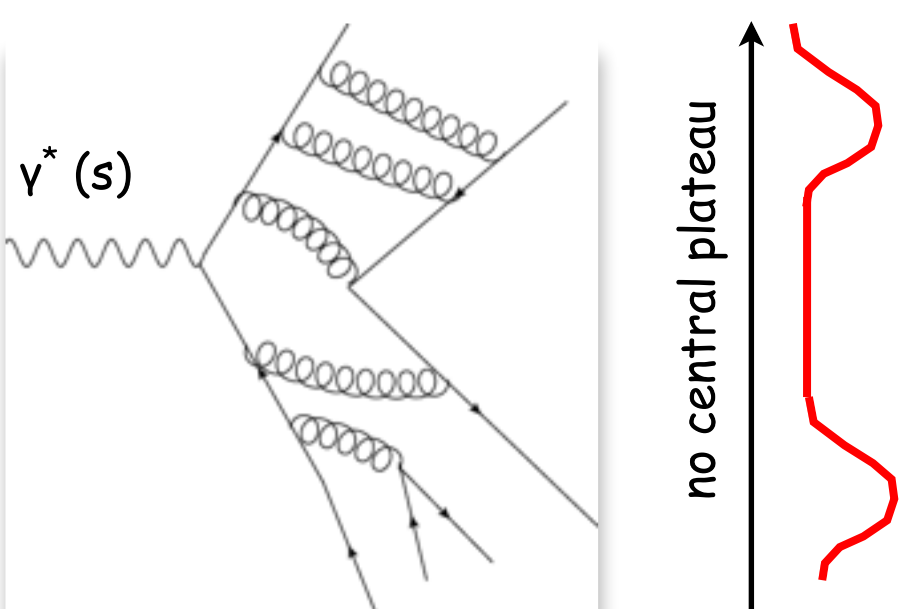
Form Factors : Regge manifestations in multi-particle production in e^+e^- / $\bar{p}p$ and F.Factors ?

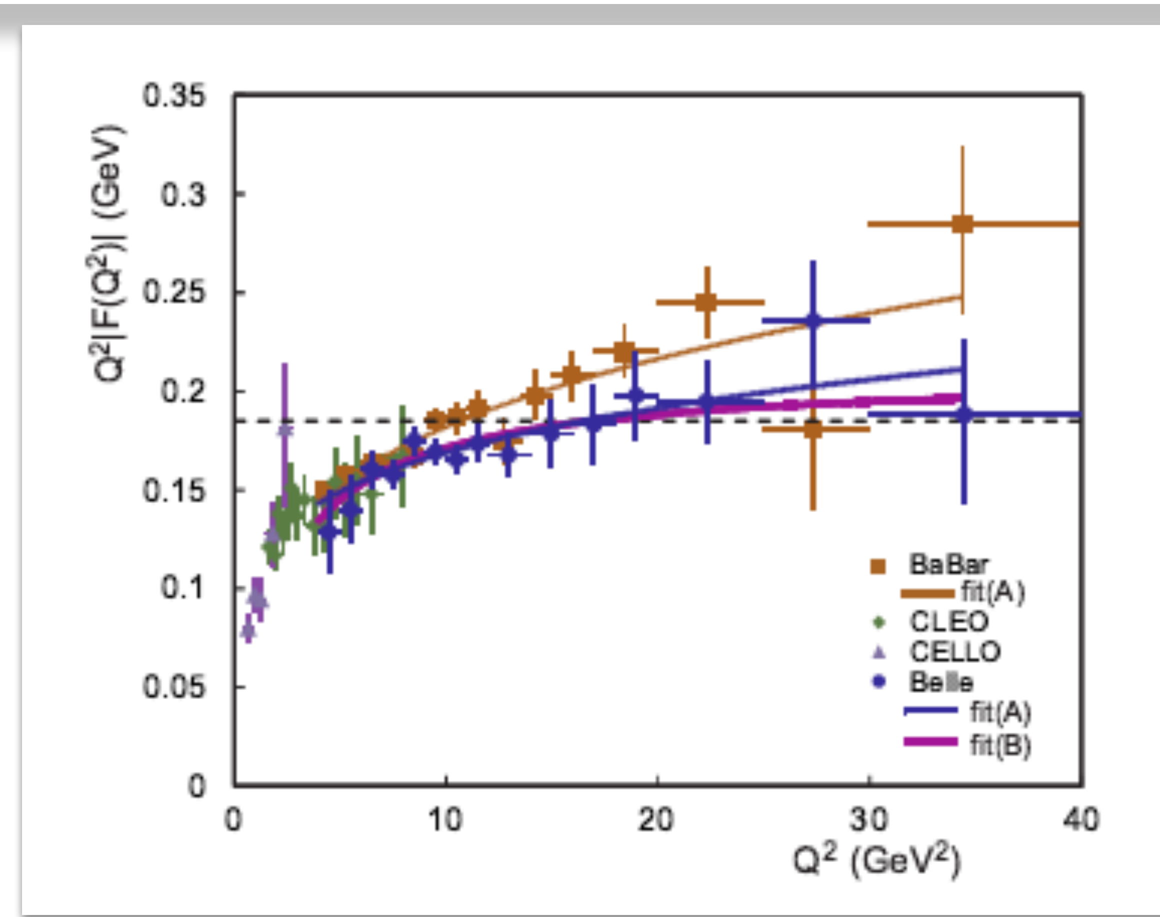


multi-particles production reggizes quark an/or adds Pomeron cut



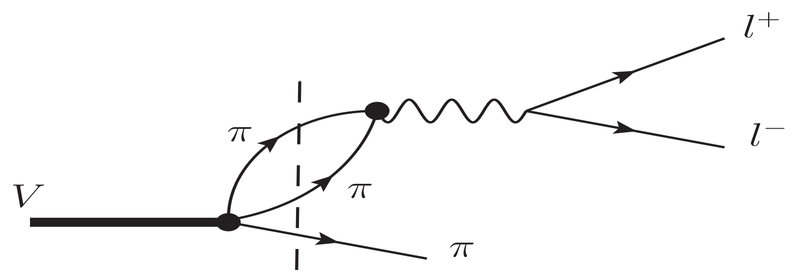
"leading Fock components"



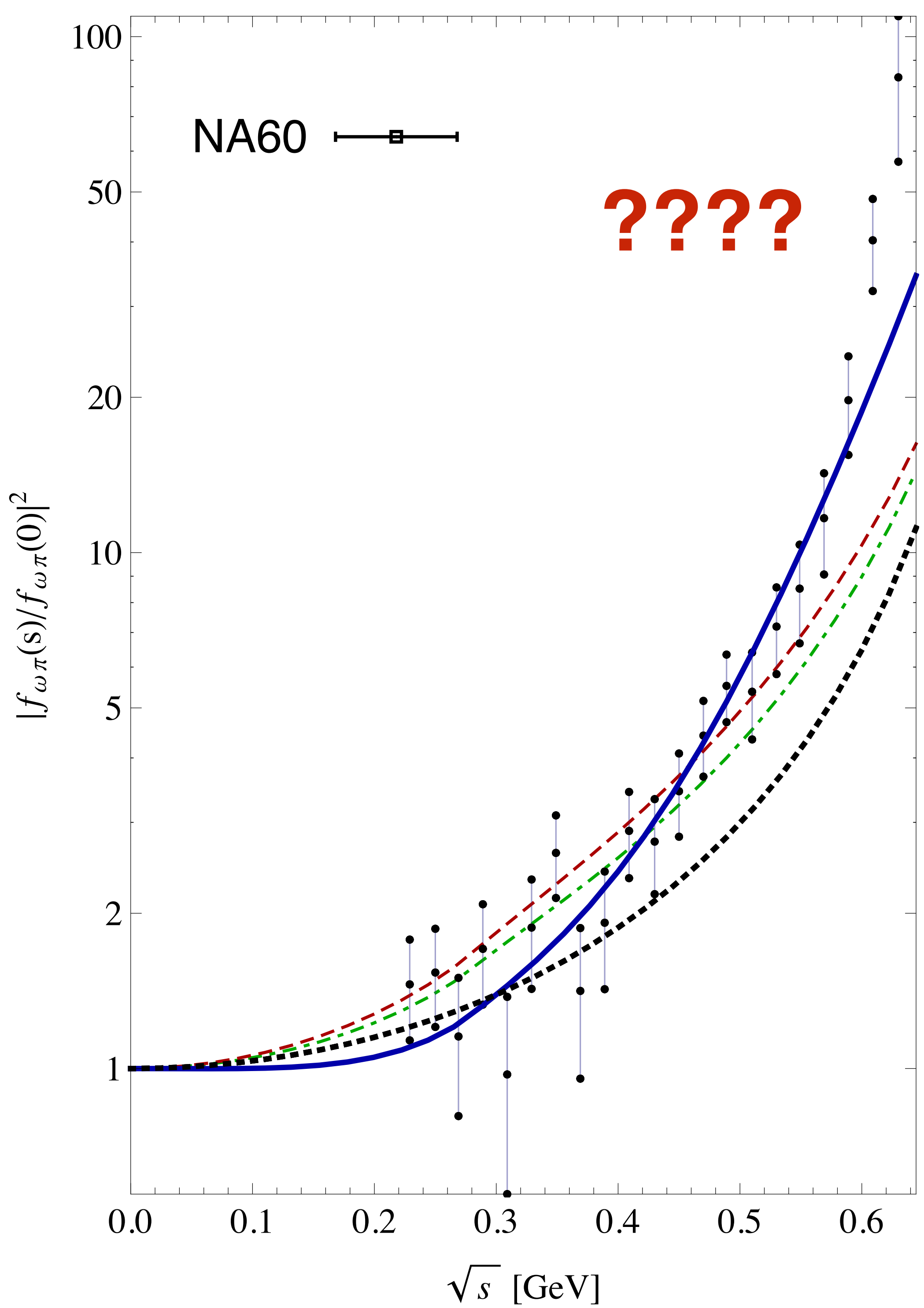


S. Brodsky P. Lapage

Electromagnetic Form Factors



$$f_{V\pi}(s) = \int_{4m^2}^{s_i} \frac{ds'}{\pi} \frac{\Delta f_{V\pi}(s')}{s'-s} + \sum_{i=0}^{N} C_i \omega^i(s)$$



- **Black**: standard VMD (fails to describe the data)
- **Blue**: N=0 (C_0 from $\Gamma_{exp}(V\to\pi\gamma)$)
  Red: N=1
  Green: N=2
  (fit to the data)
- Nature of the steep rise? Exp. analysis of $\phi\to\pi\gamma$ is very important

I. Danilkin et al.

Theory + Phenomenology + Data Analysis Synergy

theory

```
double complex function A(gamma,target,recoil,pip,pim,
                          ,lambda_g,lambda_t,lambda_r,
                           params)
implicit double precision (a-h,o-z)
dimension gamma(4)
dimension target(4)
dimension recoil(4)
dimension pip(4),pim(4)
dimension params(100)

 double complex Ampl

s = (gamma(4)+target(4))**2 - (gamma(1)+target(1))**2
$  - (gamma(2)+target(2))**2 - (gamma(3)+target(3))**2

s1 = (pip(4)+pim(4))**2 - (pip(1)+pim(1))**2
$   - (pip(2)+pim(2))**2 - (pip(3)+pim(3))**2

s2 = (pip(4)+recoil(4))**2 - (pip(1)+recoil(1))**2
$   - (pip(2)+recoil(2))**2 - (pip(3)+recoil(3))**2

t1 = (gamma(4)-pim(4))**2 - (gamma(1)-pim(1))**2
$   - (gamma(2)-pim(2))**2 - (gamma(3)-pim(3))**2

t2 = (target(4)-recoil(4))**2 - (target(1)-recoil(1))**2
$   - (target(2)-recoil(2))**2 - (target(3)-recoil(3))**2

call Ath(s,s1,s2,t1,t2,lambda_g,lambda_t,lambda_r,params,Ampl)

A = Ampl

return
end
```

experiment

Name	Last modified	Size	Description
Parent Directory		-	
g12_data_EBin26_95.txt.gz	05-Aug-2014 08:27	349M	
g12_mc_gen.txt.gz	05-Aug-2014 12:13	385M	
g12_mc_rec.txt.gz	05-Aug-2014 12:13	82M	

AmpTools

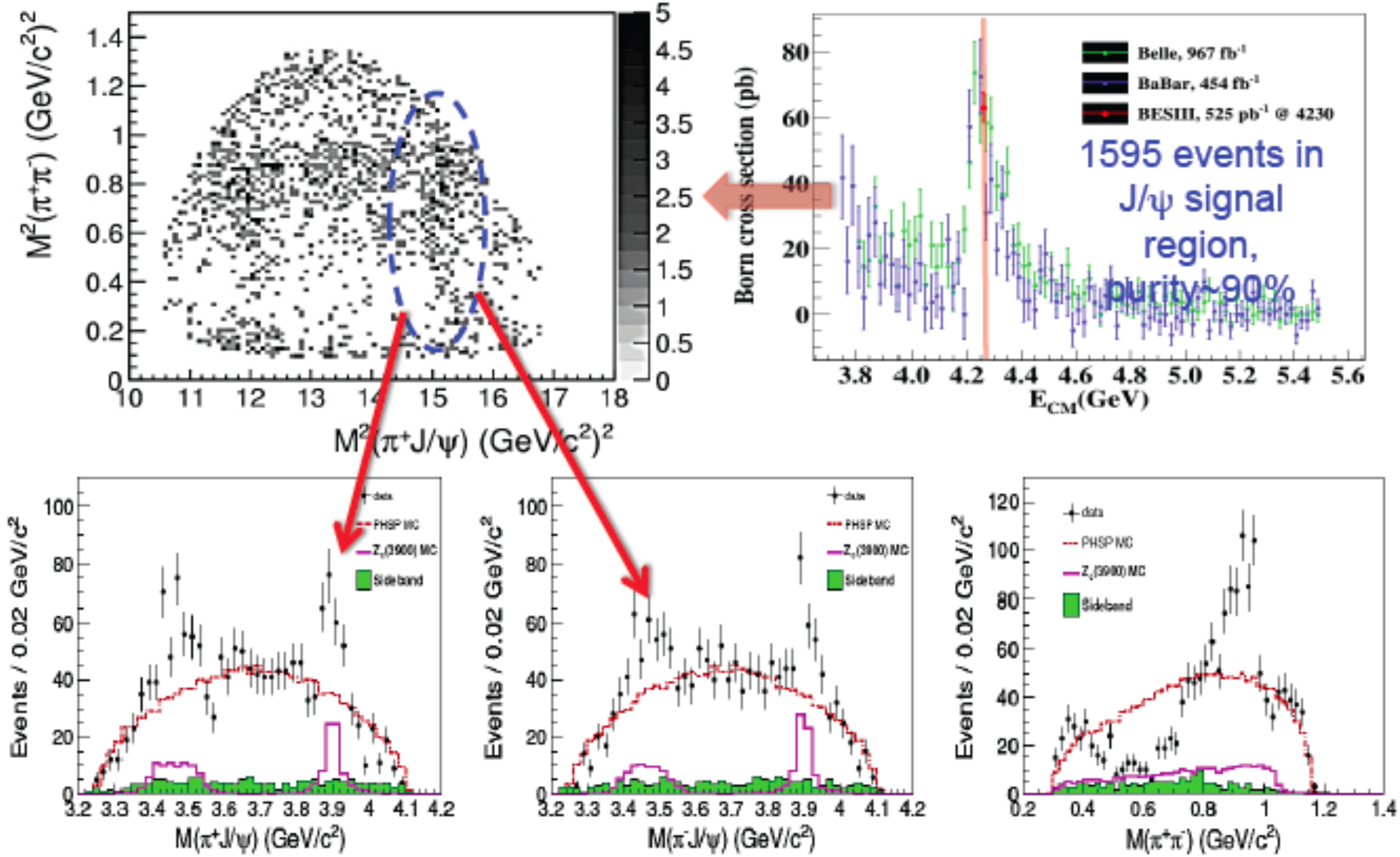
Brought to you by: mashephe

Joint Physics Analysis Center

$e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII

[PRL110, 252001(2013)]

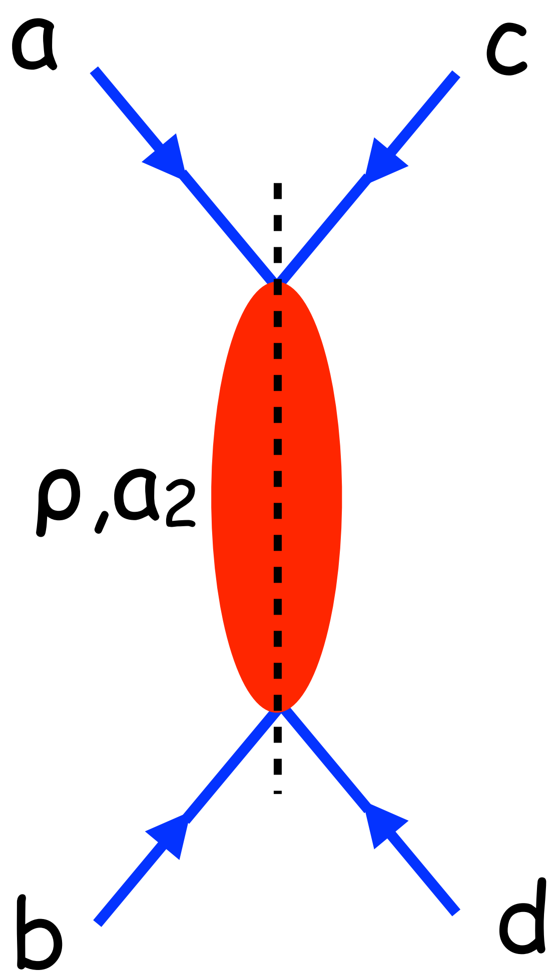
525 pb^{-1} data at 4.260 GeV



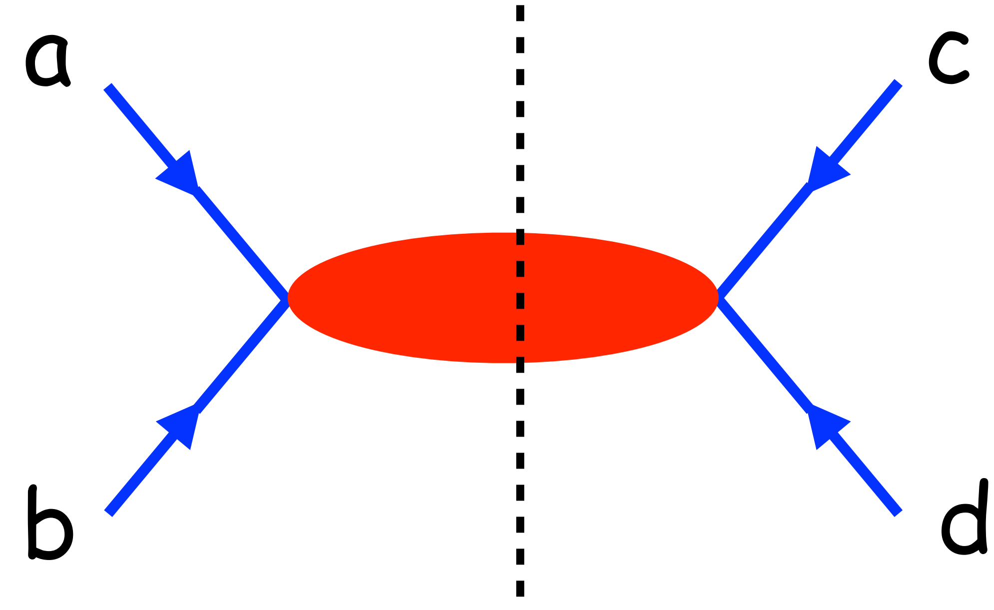
make a slide about p \bar p annihilation vs resonacnes

Backups

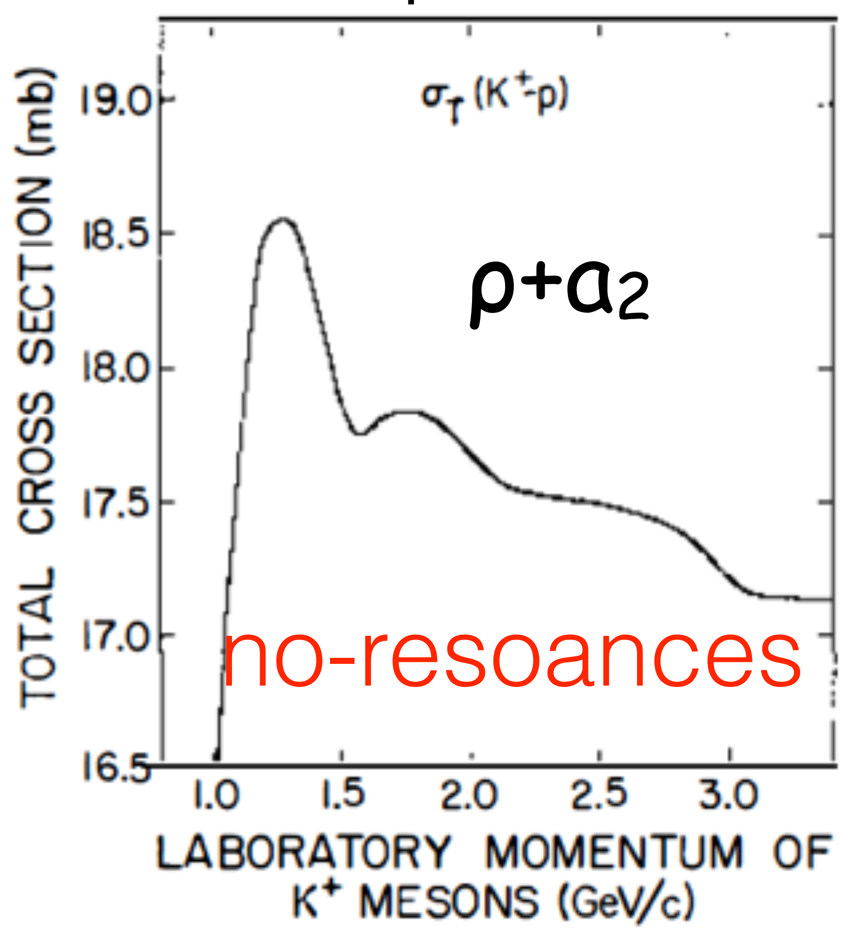
$$\int^{N} ds \, \mathrm{Im}\, A(s,t) = \mathrm{Im}\, A_{Regge}(N,t)$$



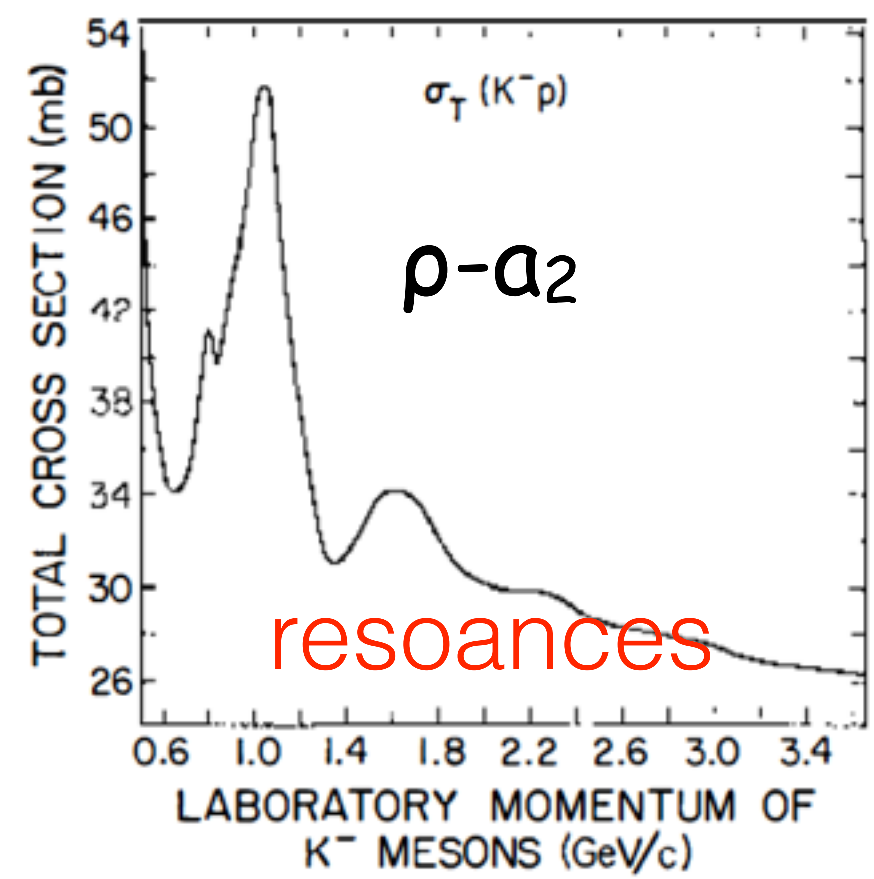
If r.h.s $\neq 0$ then
A(s,t) has a non-zero
phase at low energy
> resonances <



$K^{+}p$



$K^{-}p$

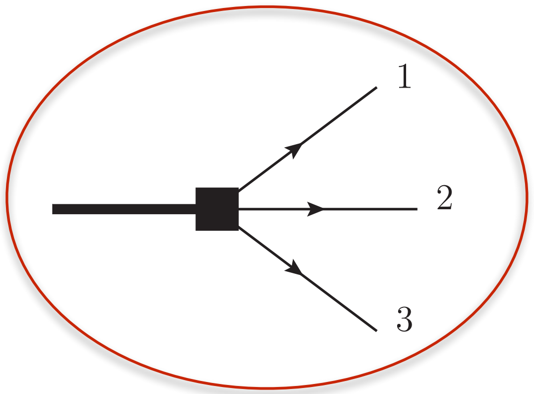


$a_2 \sim 1 + \exp(i\,\pi\,\alpha(t))$

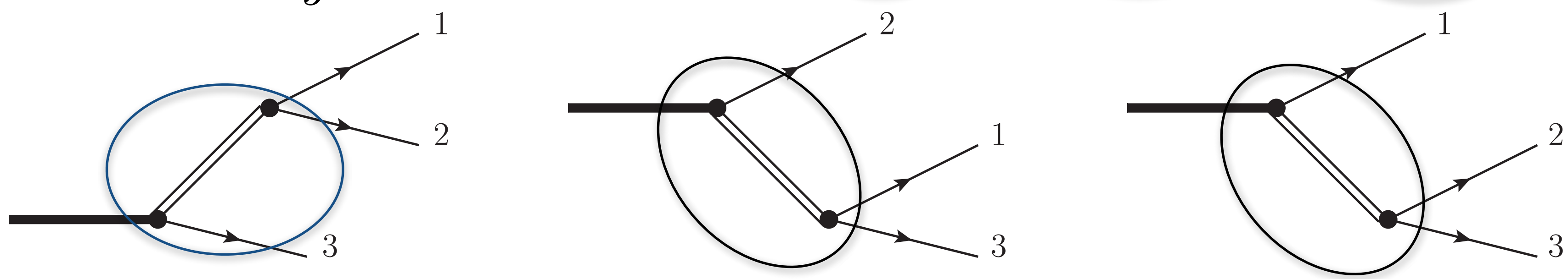
$\rho \sim 1 - \exp(i\,\pi\,\alpha(t))$

Dispersive analysis of ω/φ→3π

$$A(s,t) = \sum_{J}^{J_{max}} (2J+1) d^J_{1,0}(z_s) a^R_J(s) + (s \to t) + (s \to u)$$



=



$$A^L(s) = 3 \int_{-1}^{1} dz_s \frac{1-z_s^2}{2} a^R(t(s,z_s))$$

$$A(s,t) = \sum_{J}^{J_{max}} (2J+1) d^J_{1,0}(z_s) A_J(s)$$

Solution: (e.g. P-waves only)

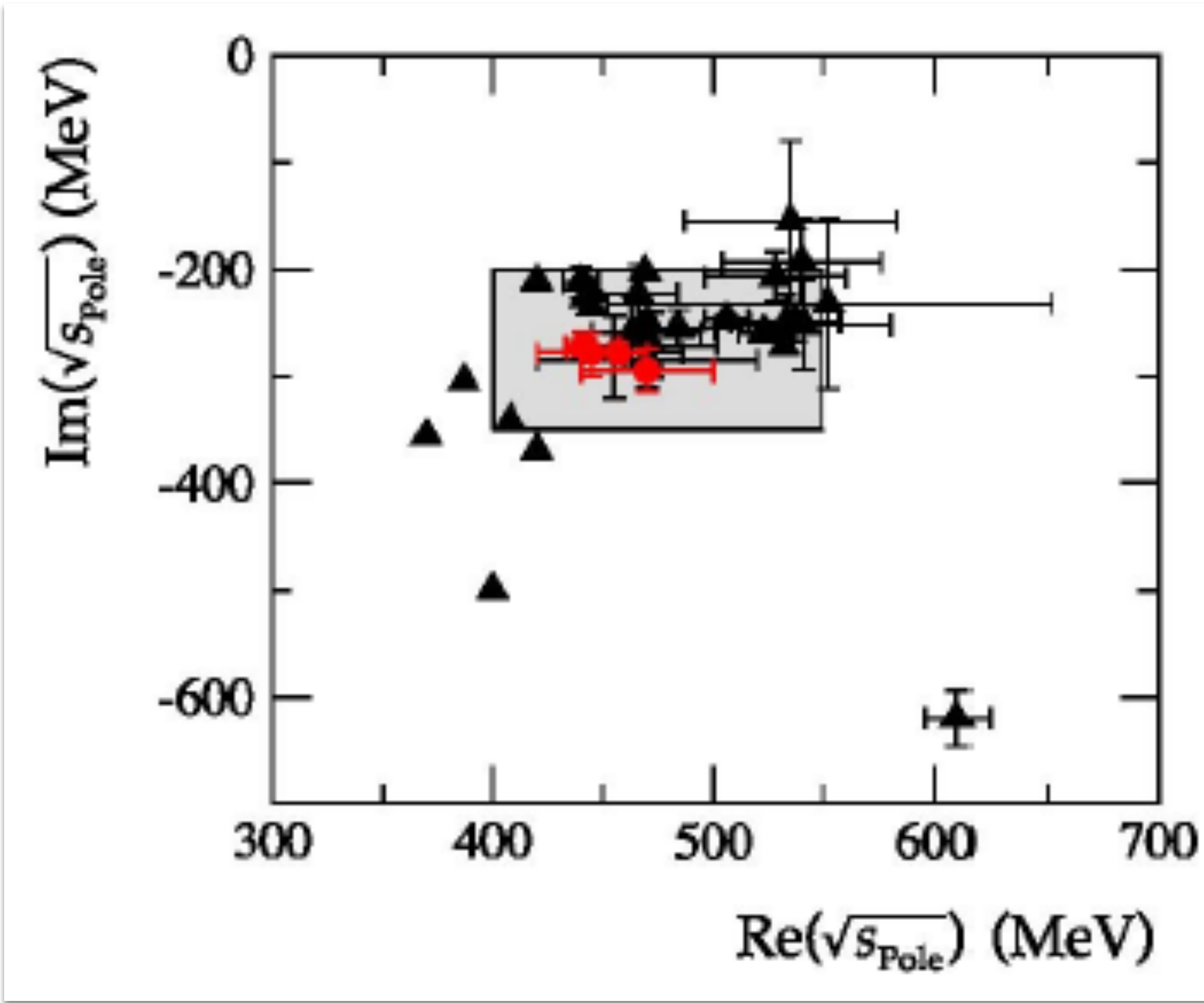
$$a^R(s) = \frac{1}{D(s)} \int_{4m^2} \frac{ds'}{\pi} \frac{\rho(s')N(s')A^L(s')}{s'-s}$$

Easily generalized to inelastic case

$$a^R(s) = \frac{1}{D^{el}(s)} \left(\int_{4m^2}^{s_i} \frac{ds'}{\pi} \frac{\rho(s')N(s)(s')A^L(s')}{s'-s} + A^{in}(s) \right)$$

el = only elastic cut   in = only inelastic cut

$$\sqrt{s^{\sigma}_{\text{Pole}}} = (446 \pm 6) - i(276 \pm 5)\ \text{MeV}\ .$$



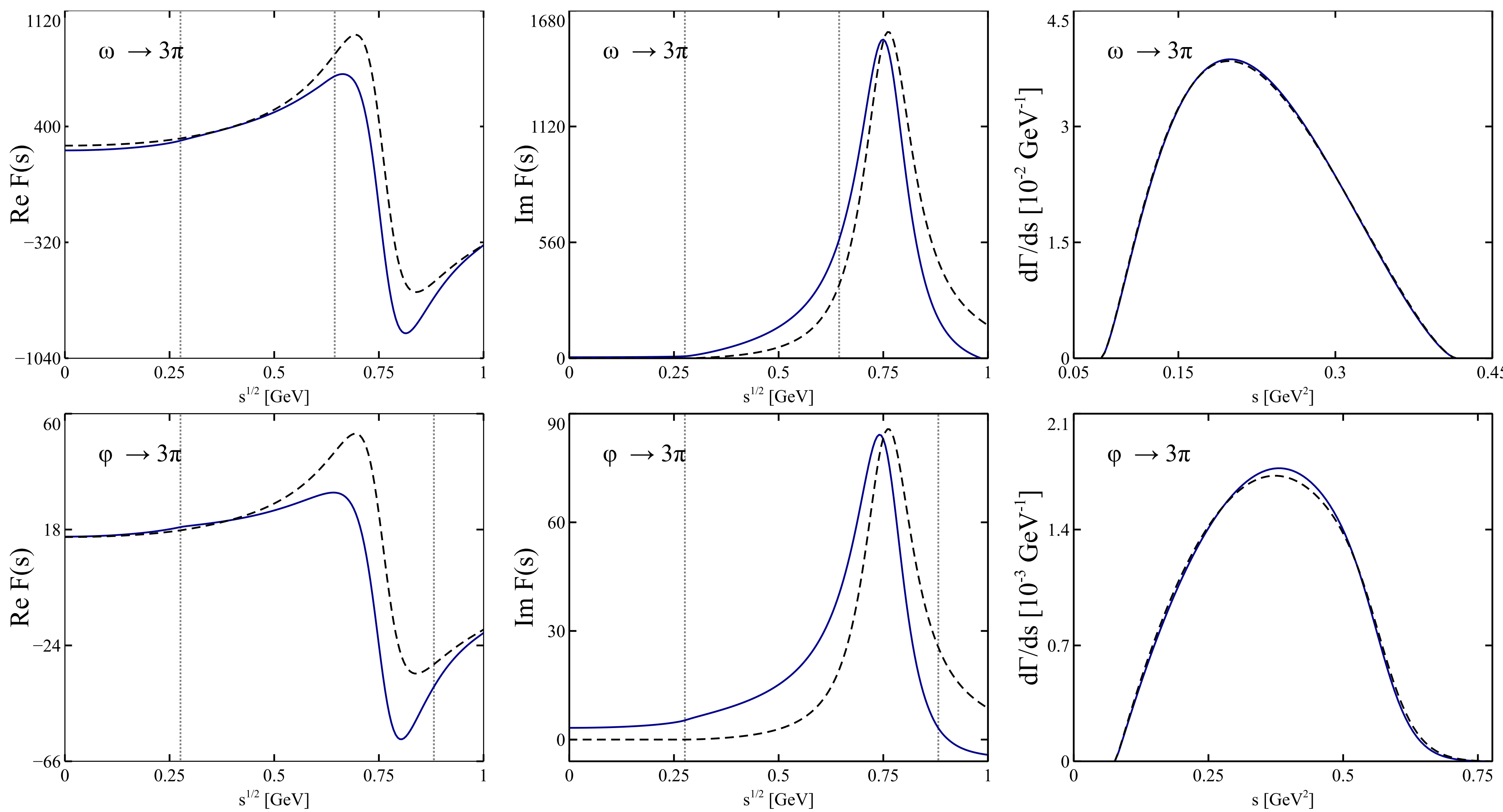
Dispersive analysis of ω/ϕ→3π

Integral equation

$$a^R(s) = \frac{1}{D^{el}(s)}\left(\int_{4m^2}^{s_i} \frac{ds'}{\pi}\, \frac{\rho(s')N(s)(s')A^L(s')}{s'-s} + \sum_{i=0}^{N} a_i \omega^i(s)\right)$$

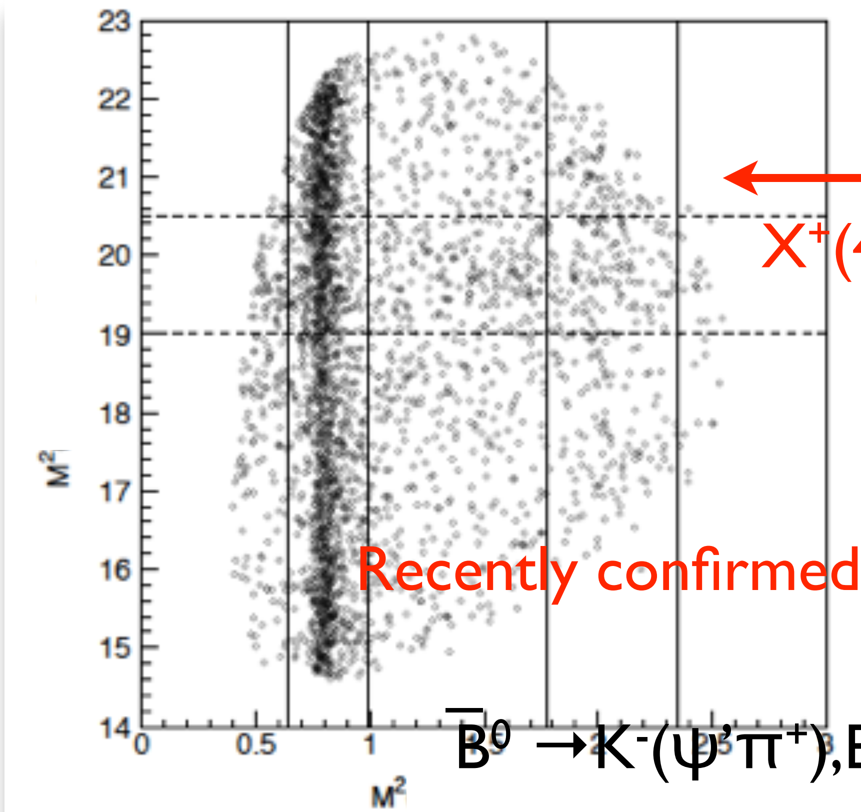
- w(s) is the conformal map of inelastic contributions: Coefficients a_i play the role of improved subtraction constants

different from
Niecknig et. al. 2012
Anisovich et. al. 1998



all details in: I. Danilkin et al., arXiv1076363

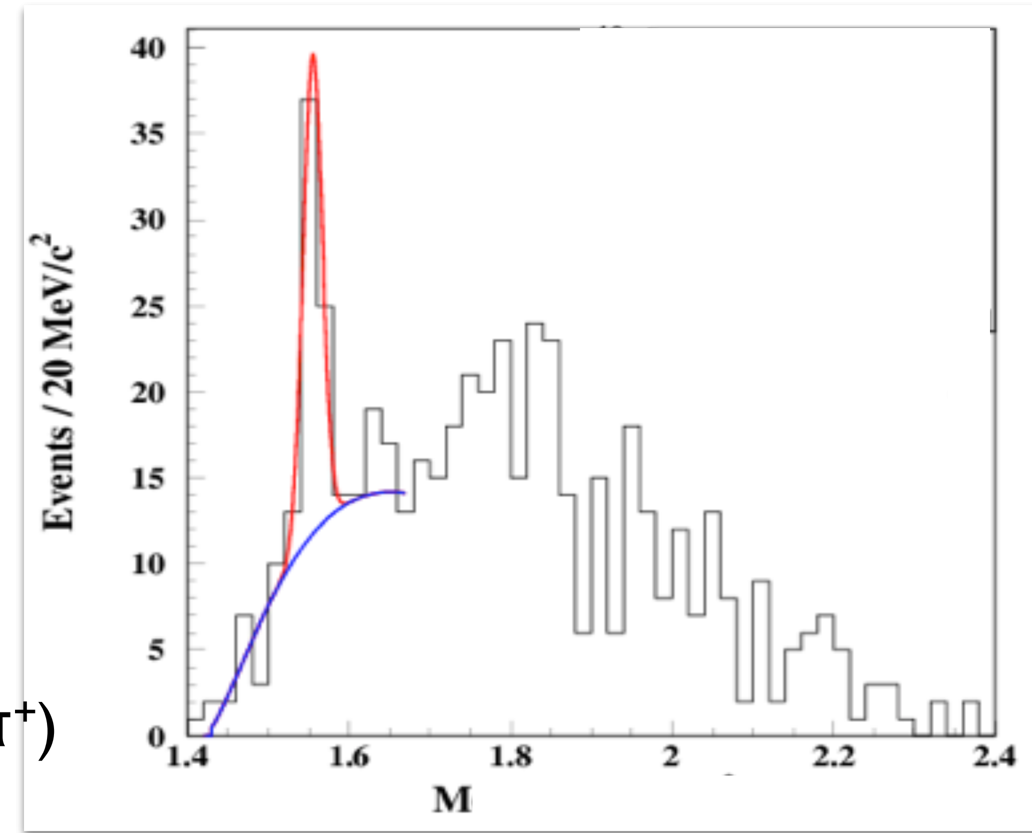
What may happen when amplitudes are unconstrained



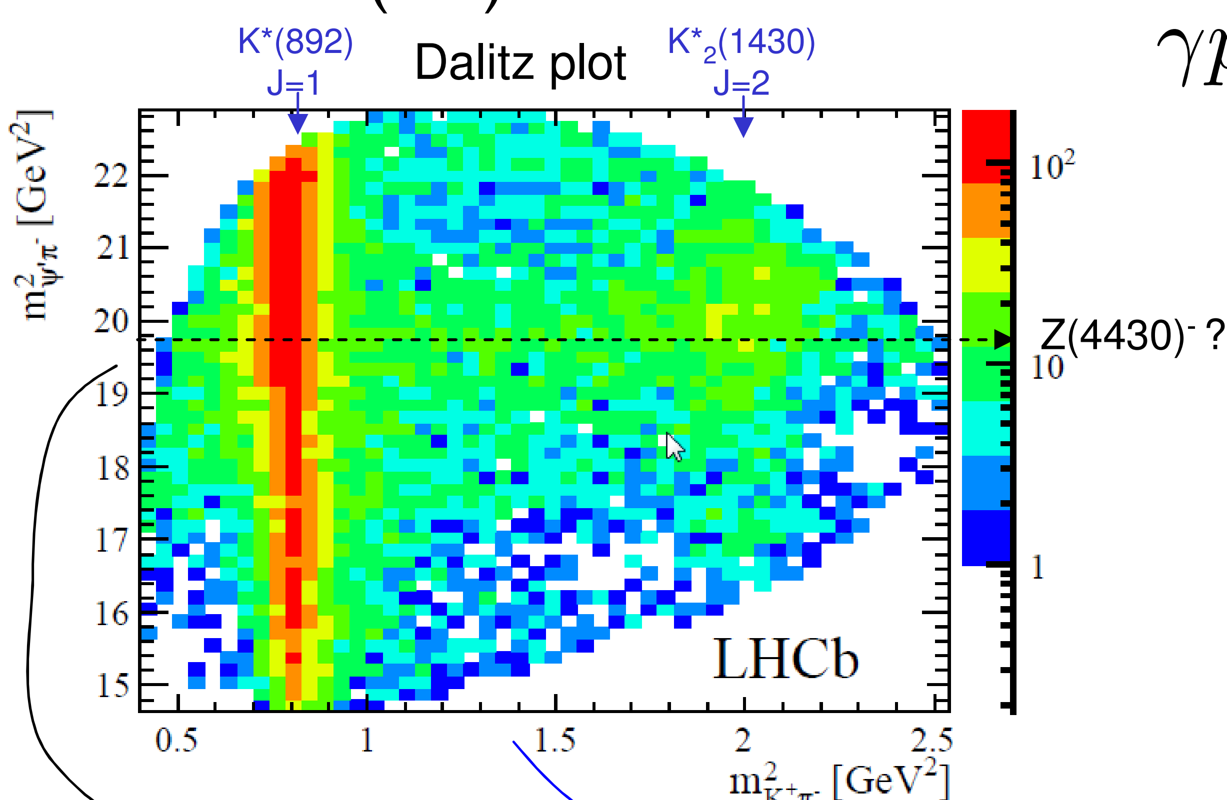
$X^+(4430)$

Recently confirmed by LHCB

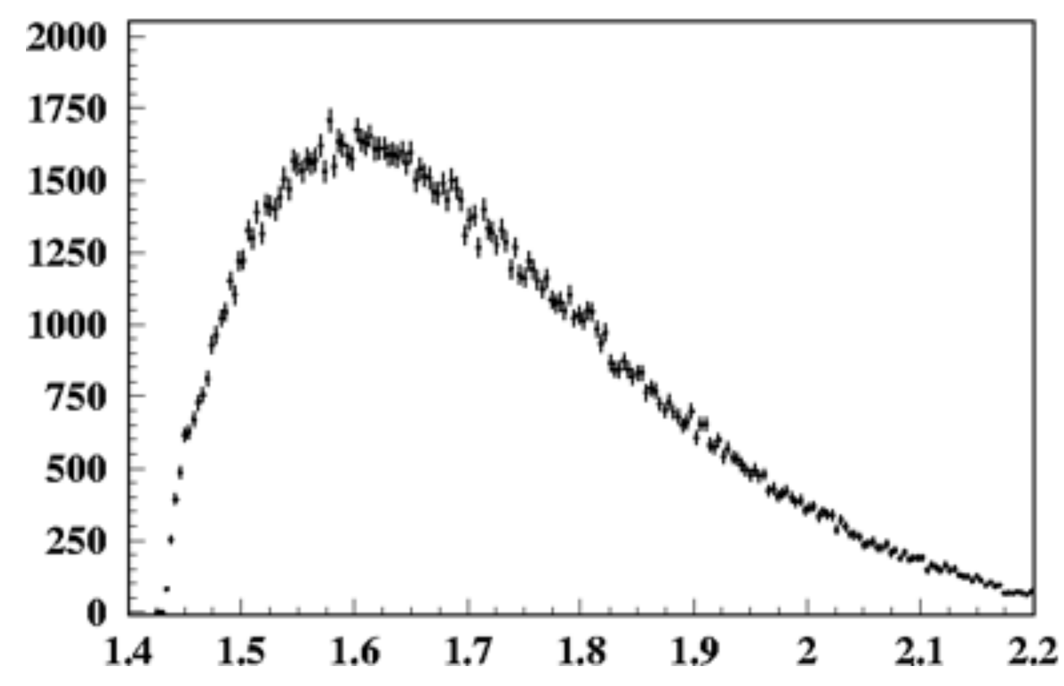
$\overline{B}^0 \to K^-(\psi'\pi^+), B^+ \to K^0_s\ (\psi'\pi^+)$



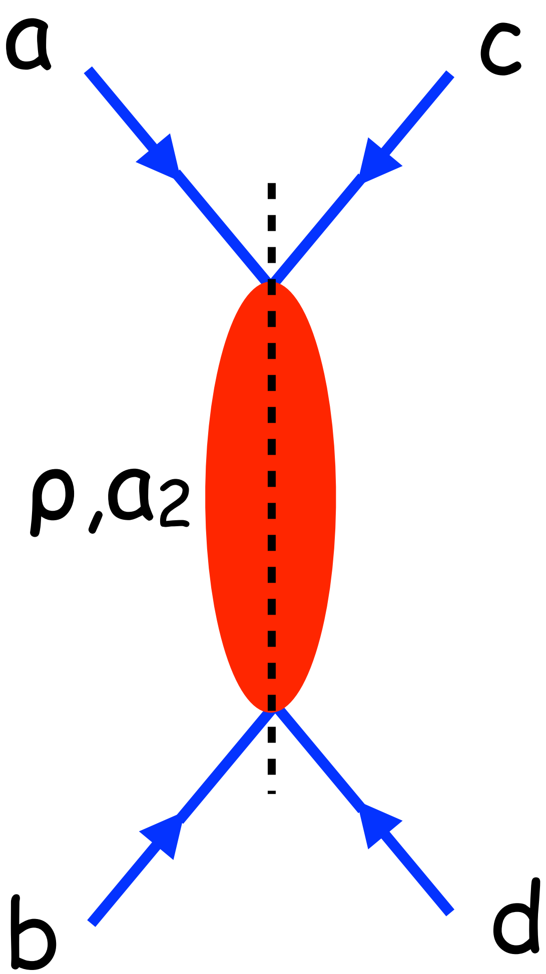
K*(890)



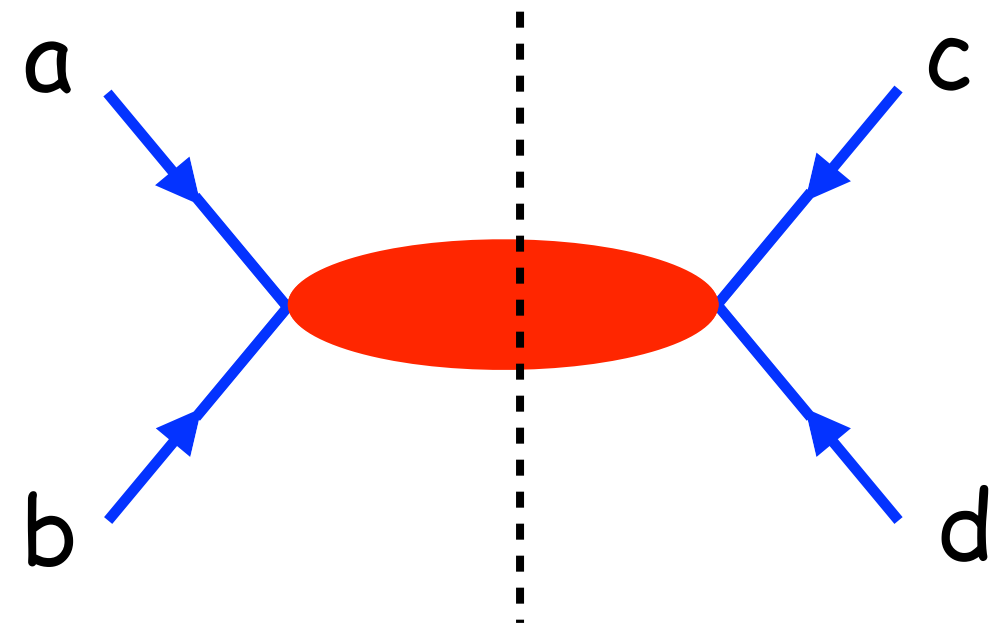
$$\gamma p \to \Theta^+ K^- \pi^+ \to (K^+ n) K^- \pi^+$$



$$\int^N ds \; \mathrm{Im}\, A(s,t) = \mathrm{Im}\, A_{Regge}(N,t)$$

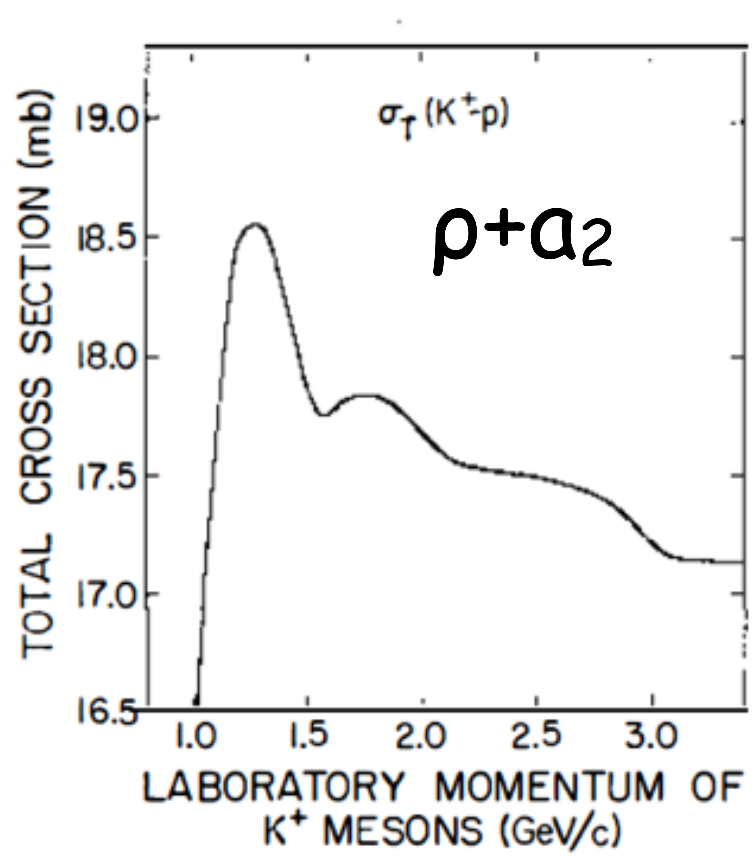


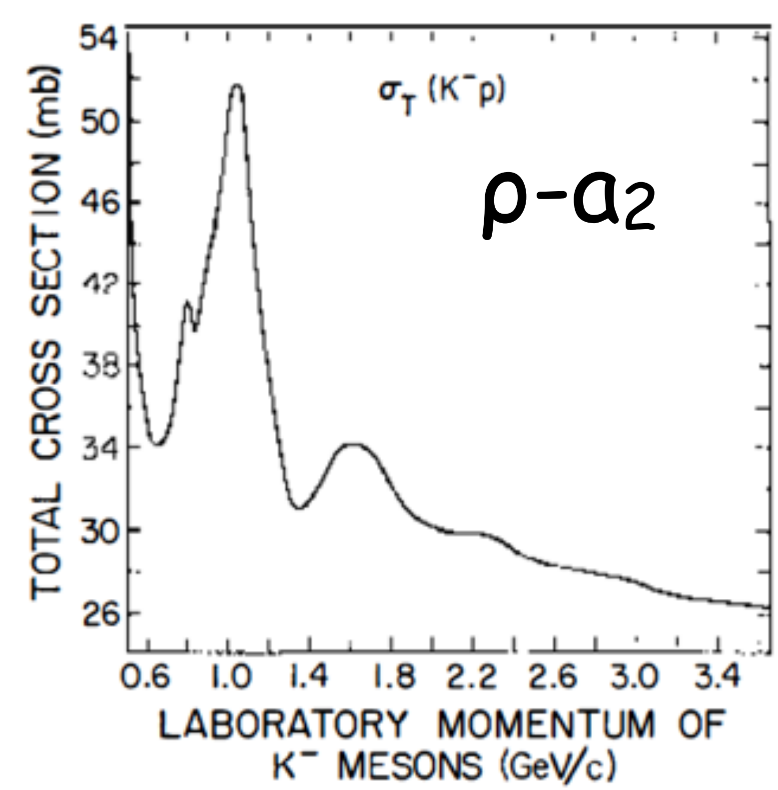
If r.h.s $\neq 0$ then
A(s,t) has a non-zero
phase at low energy
> resonances <

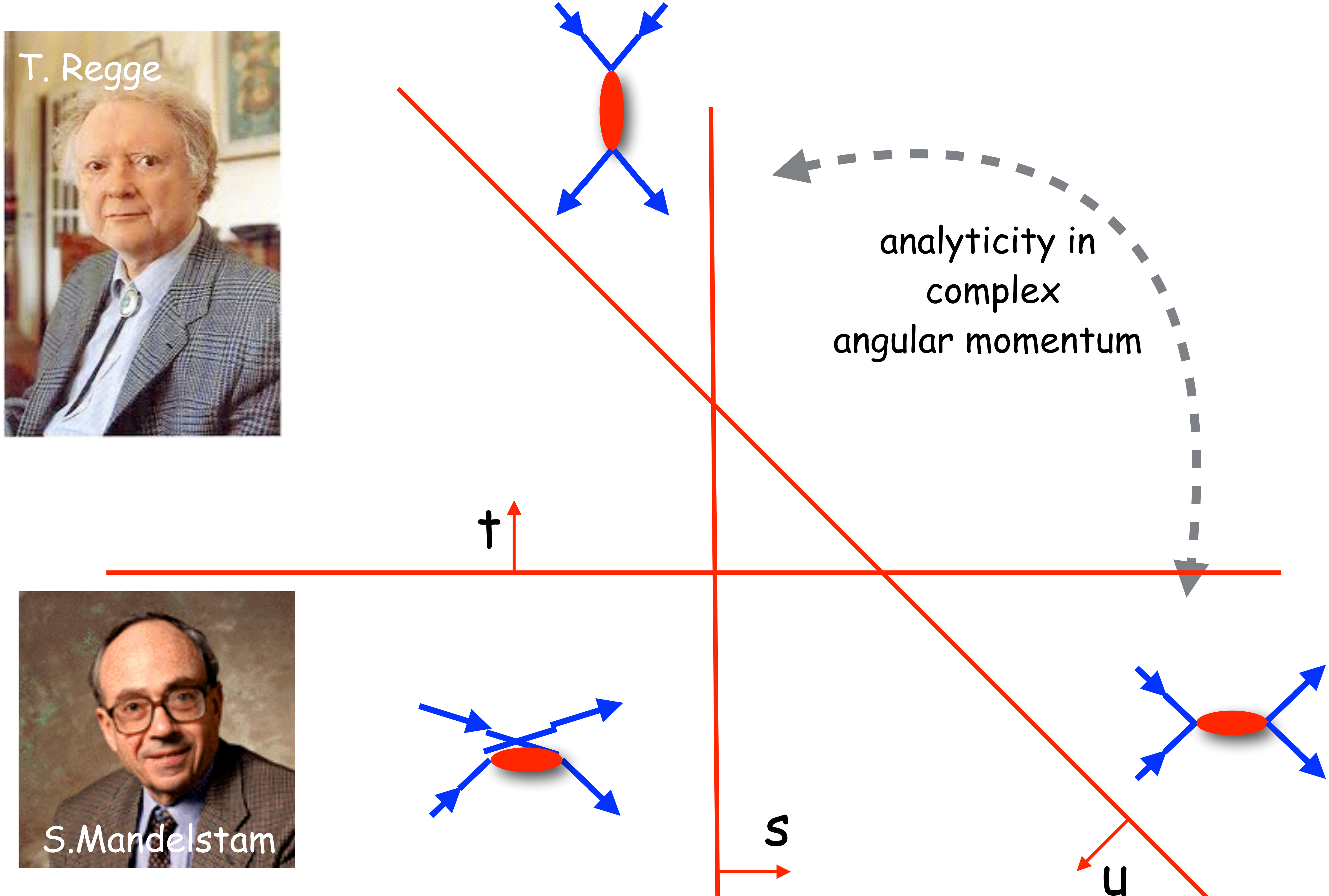


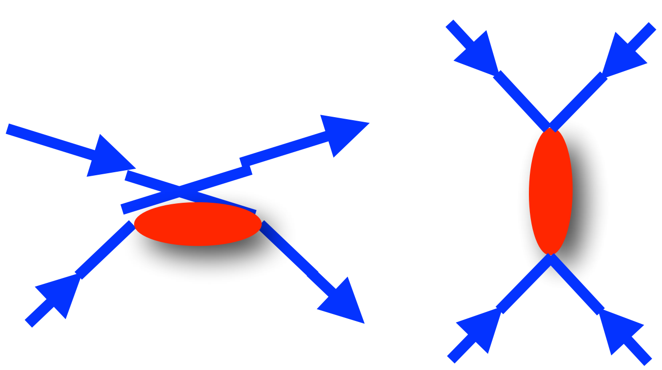
$a_2 \sim 1 + \exp(i\,\pi\,\alpha(t))$

$\rho \sim 1 - \exp(i\,\pi\,\alpha(t))$

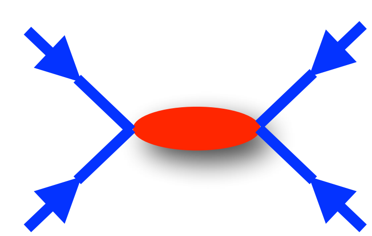




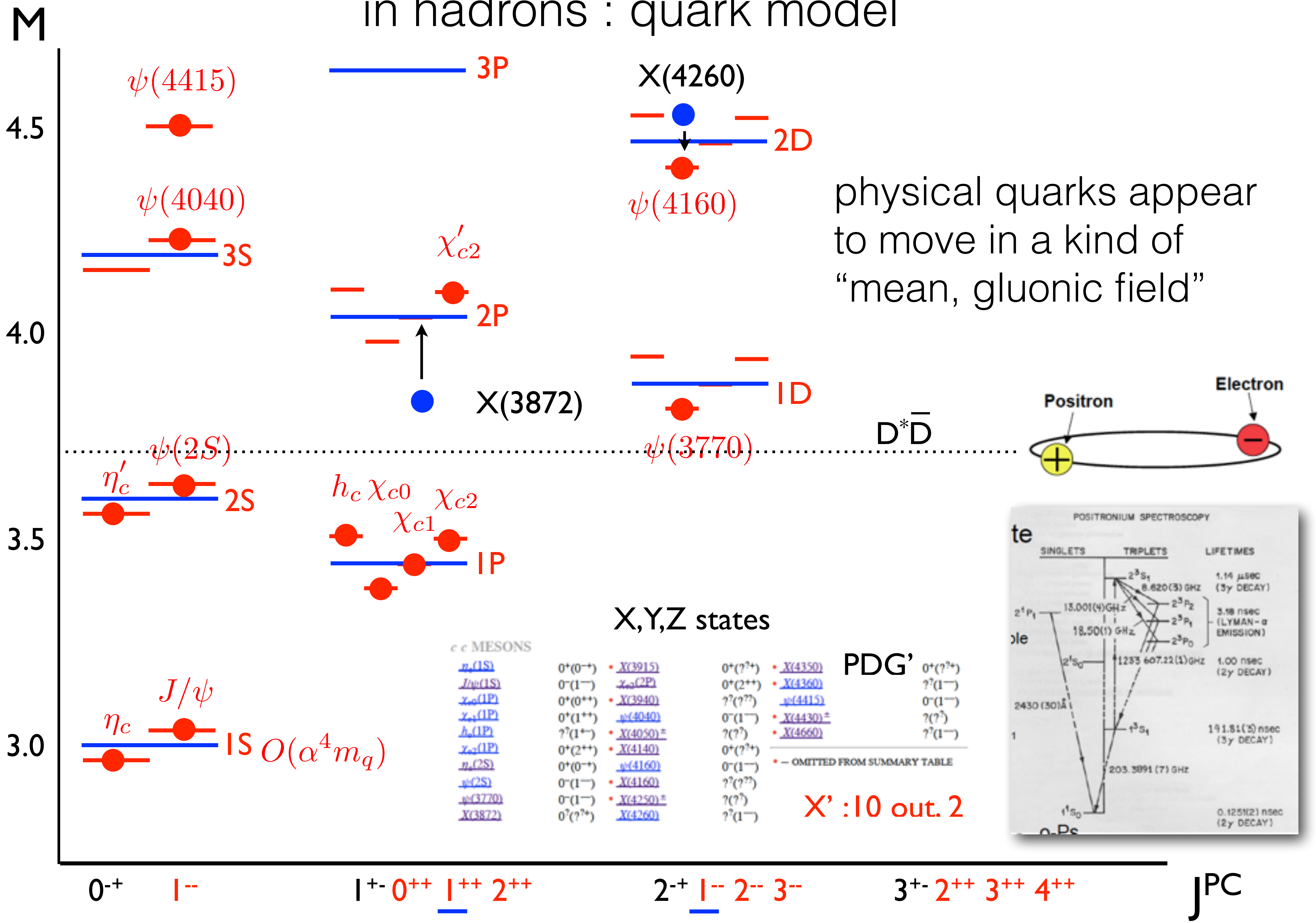




“force” <duality>“particle”



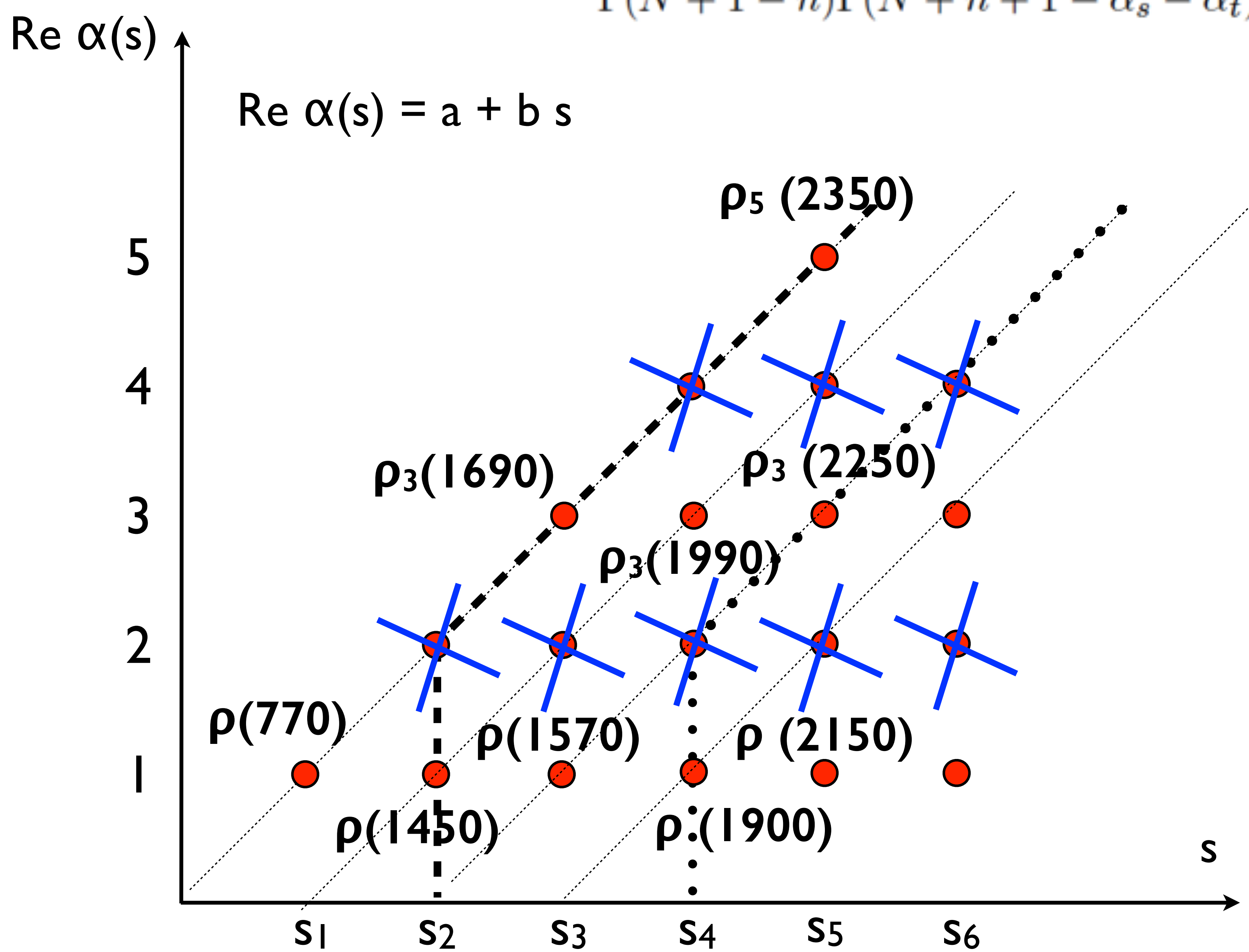
old (but still surprisingly adequate) description of quarks in hadrons : quark model



- Dual models (Veneziano) $A(s,t) = \dfrac{\Gamma(1-\alpha(s))\Gamma(1-\alpha(t))}{\Gamma(2-\alpha(s)+\alpha(t))}$

$$A(s,t) = \sum_k \frac{\beta_k(t)}{k-\alpha(s)} = \sum_k \frac{\beta_k(s)}{k-\alpha(t)}$$

$$\mathcal{A}_n(s,t;N) = \frac{2n-\alpha_s-\alpha_t}{(n-\alpha_s)(n-\alpha_t)} \sum_{i=1}^{n} a_{n,i}(-\alpha_s-\alpha_t)^{i-1} \times \frac{\Gamma(N+1-\alpha_s)\Gamma(N+1-\alpha_t)}{\Gamma(N+1-n)\Gamma(N+n+1-\alpha_s-\alpha_t)}.$$



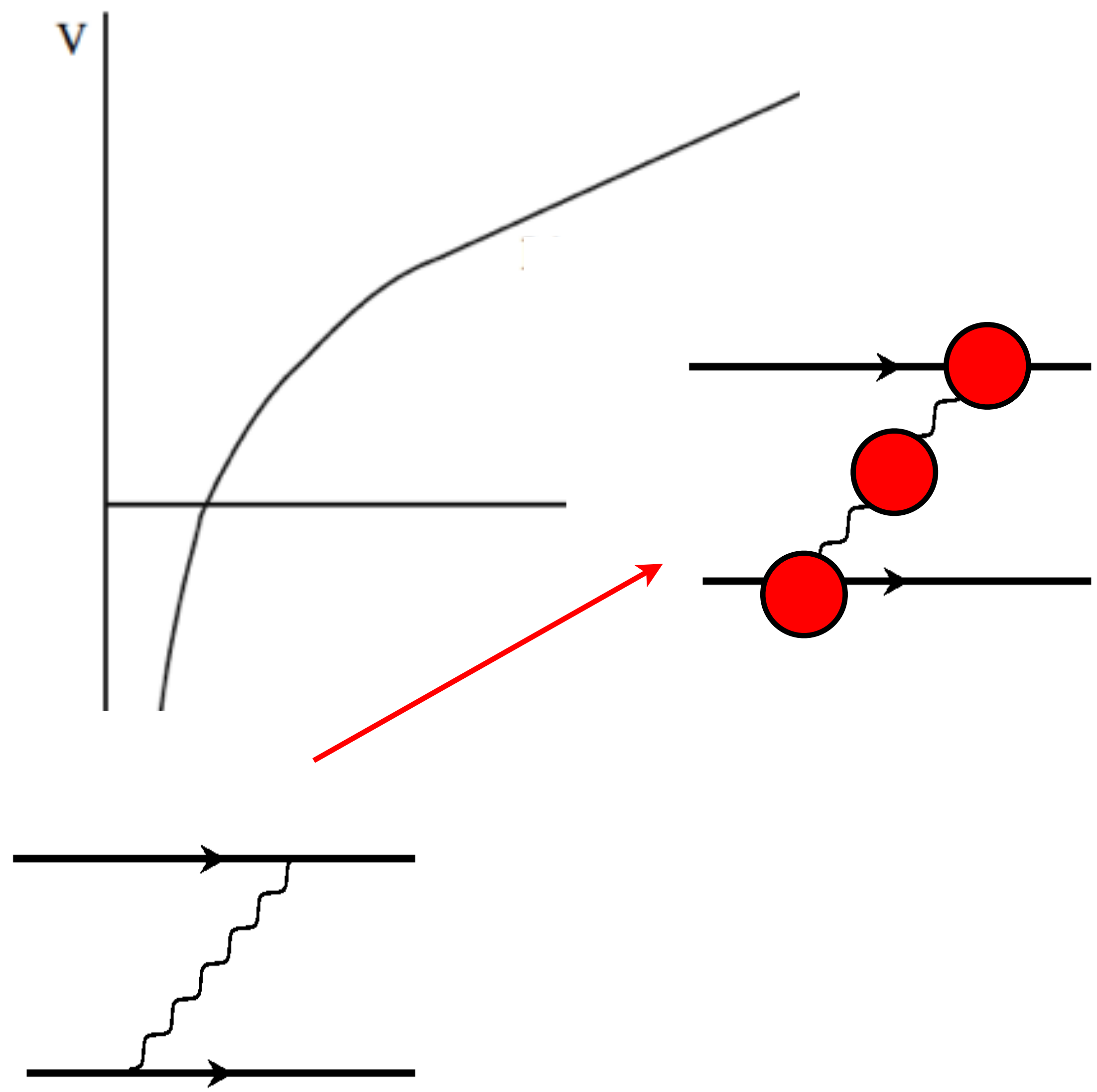
Regge/Resonance duality

Can be generalized to any number of external particles

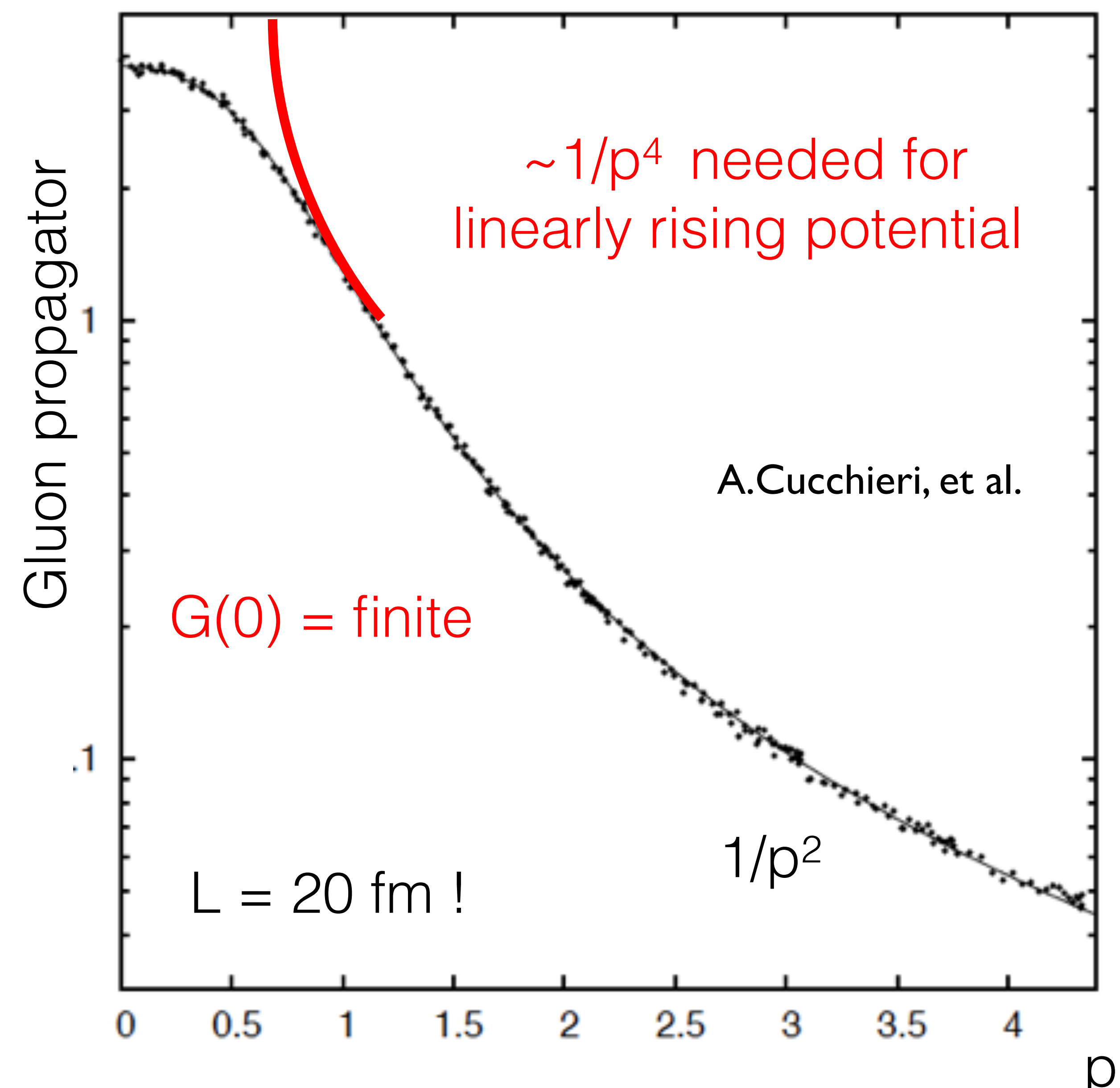
Can be extend to satisfy Mandelstam duality, but not known extensions to several trajectories

Early ideas about the origin of confinement

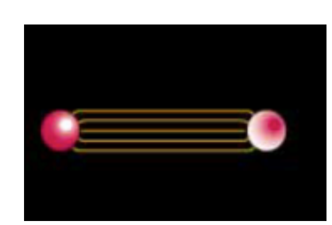
“One-gluon” exchange



Landau gauge gluon propagator



Not compatible with current understanding (in terms of condensation of chromo-magnetic charges)



Strong, theoretical evidence (lattice) for gluon field excitations in hadron spectrum

Phenomenologically, gluons behave as axial vector, quasiparticles $J^{PC}=1^{+-}$

Lowest multiplet of "hybrid mesons" has $J^{PC} = 0^{-+}$, 1^{-+}, 2^{-+}, 1^{--} states

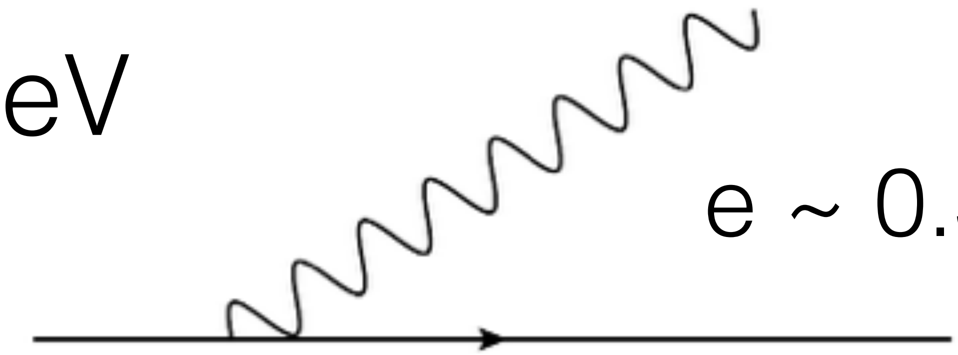
What about other non-quark model possibilities ?

Can these be detected and distinguished ?

In QED “bare particle” ~ observed particle

$$H_{QED} = H_{c.h.o.} + eV$$

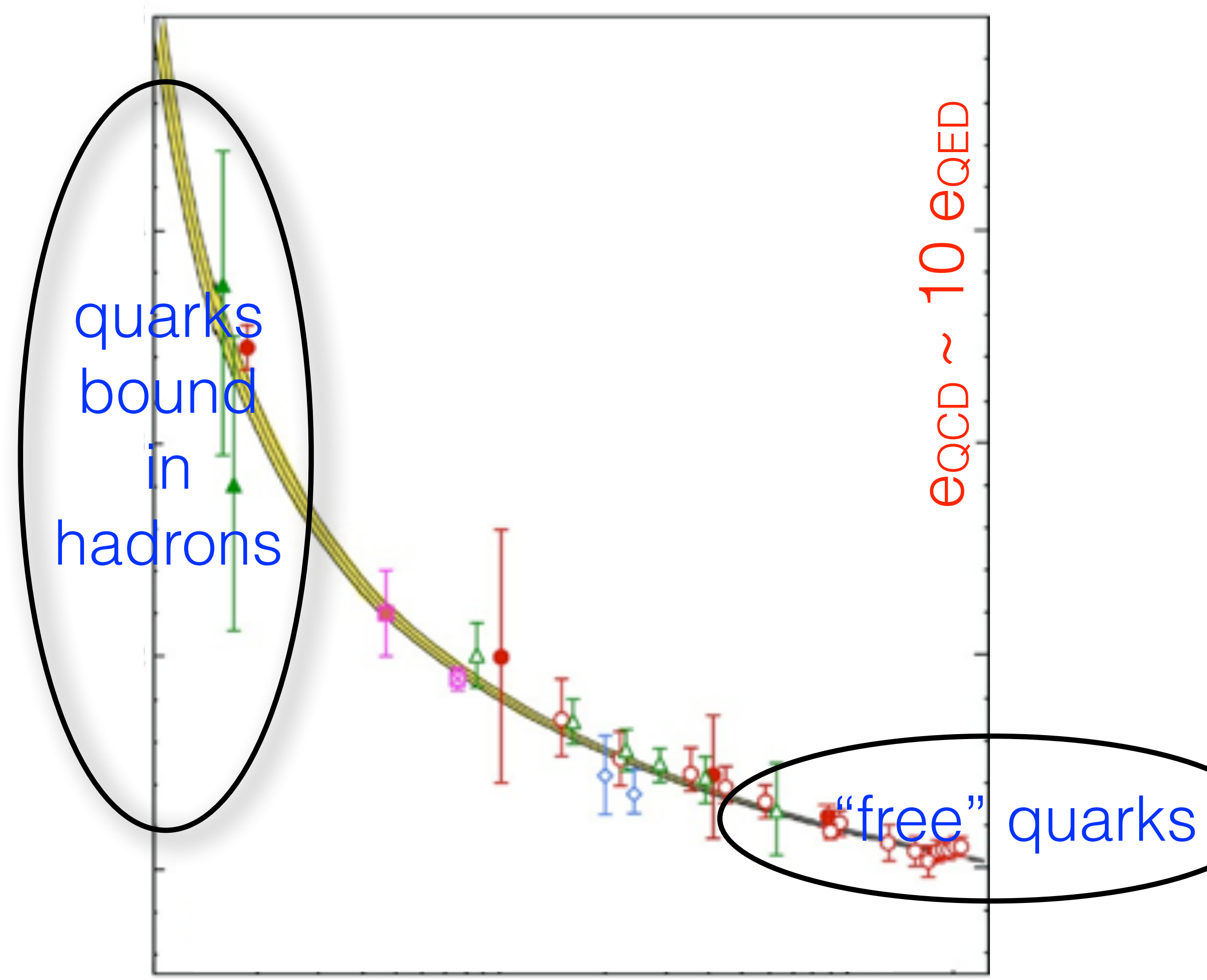
e ~ 0.3

|electron> =  +  + $O(e^2)$

|bare electron>   eV|bare electron>

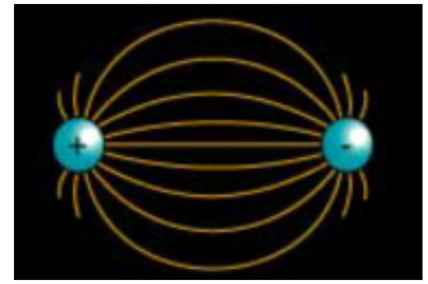
but in QCD e > 1

the nature of physical quarks and gluons remains a mystery

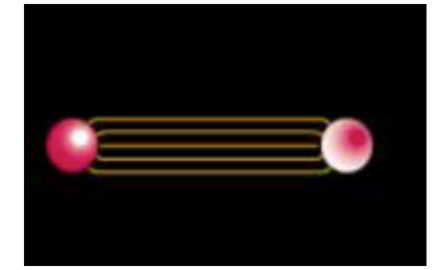


Monopole confinement scenario

in “empty vacuum”



in “magnetic condensate”



Type-II supper conductor

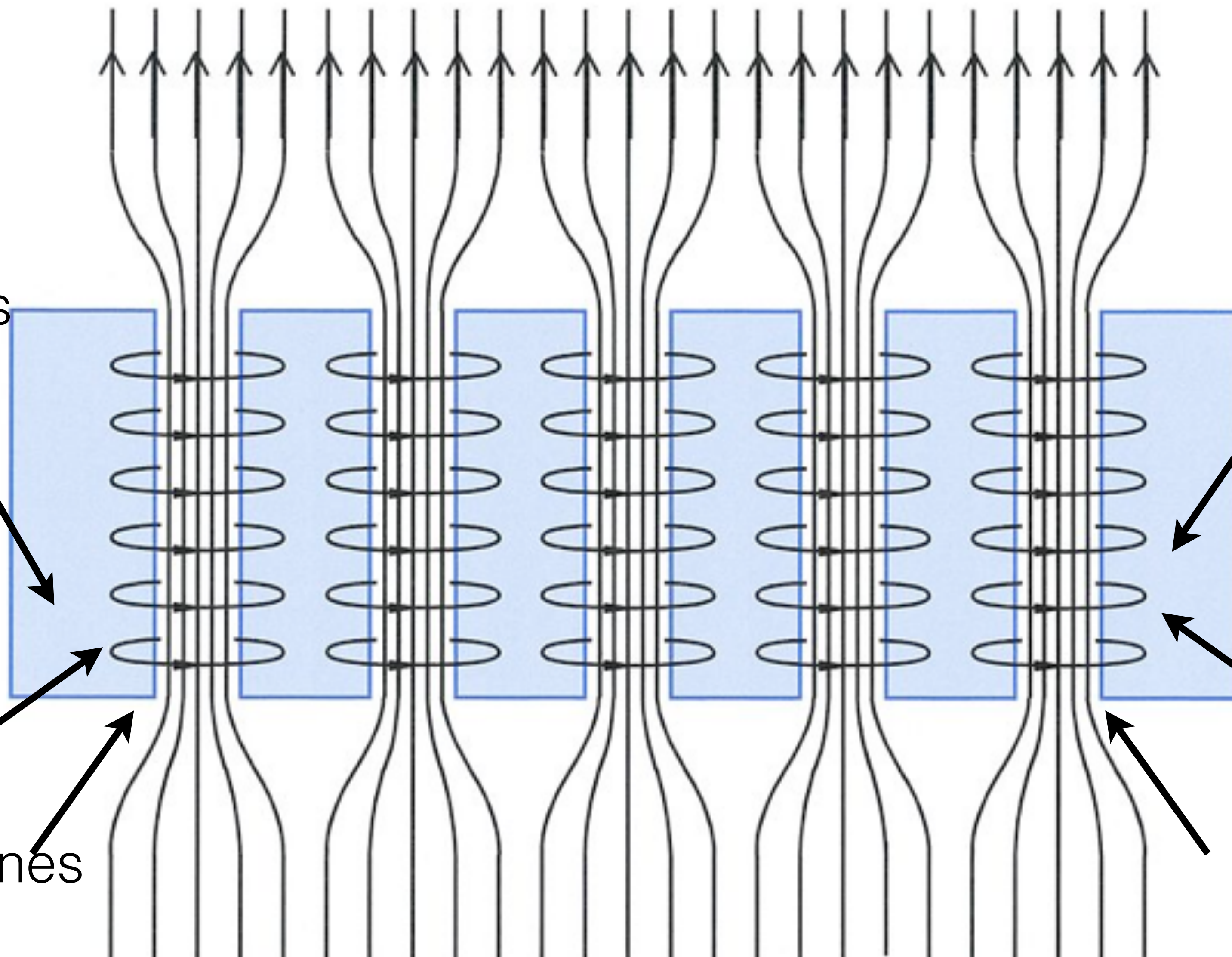
Dual Type-II supper conductor

QED

QCD

condensate of electric charges

condensate of magnetic charges



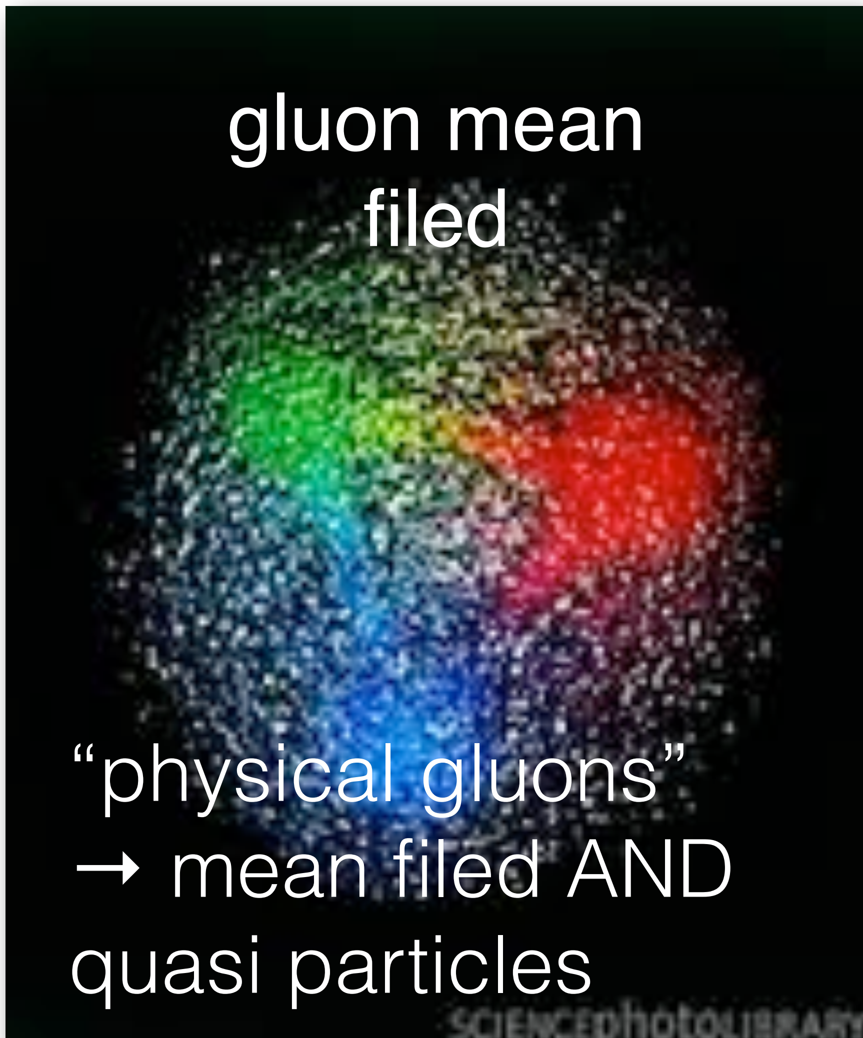
electric current screens magnetic lines

magnetic current screens electric lines

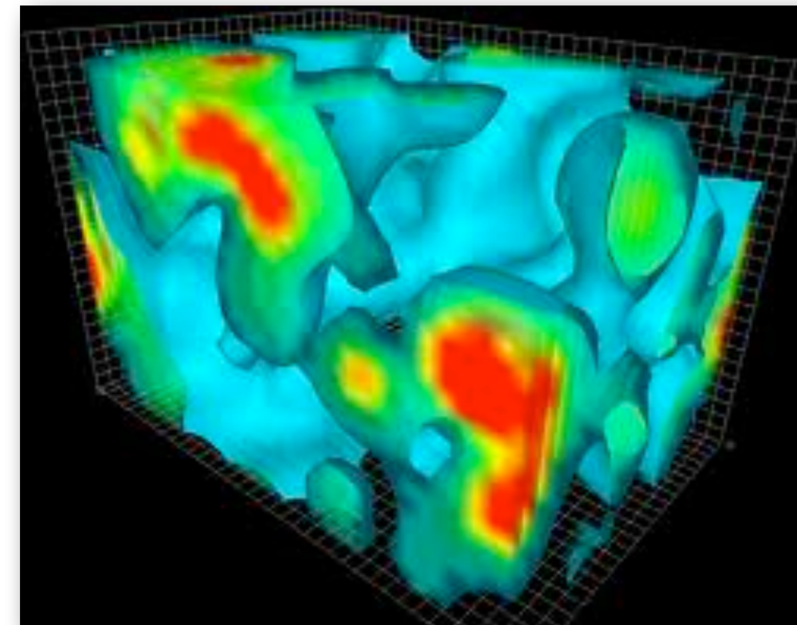
Plausible scenario: $H_{QCD} = H_{c.h.o.} +$ non-linear

~~"physical quarks"~~ →
quasi particles in gluon mean filed

finite energy, localized solutions:
solitons (monopoles, vortices , ...)



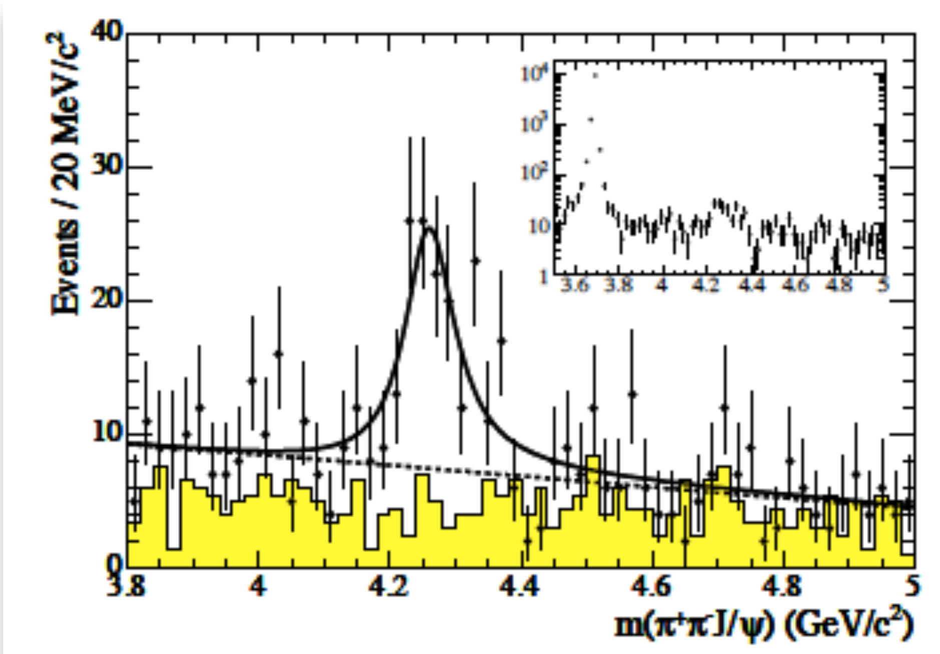
The QCD vacuum is not empty. Rather it contains quantum fluctuations in the gluon field at all scales. (Image: University of Adelaide)

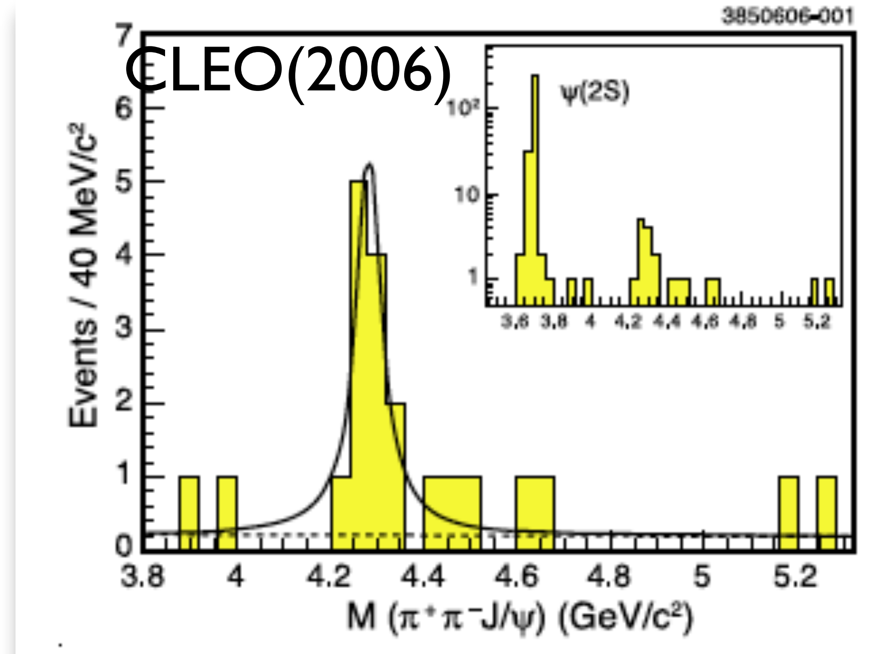


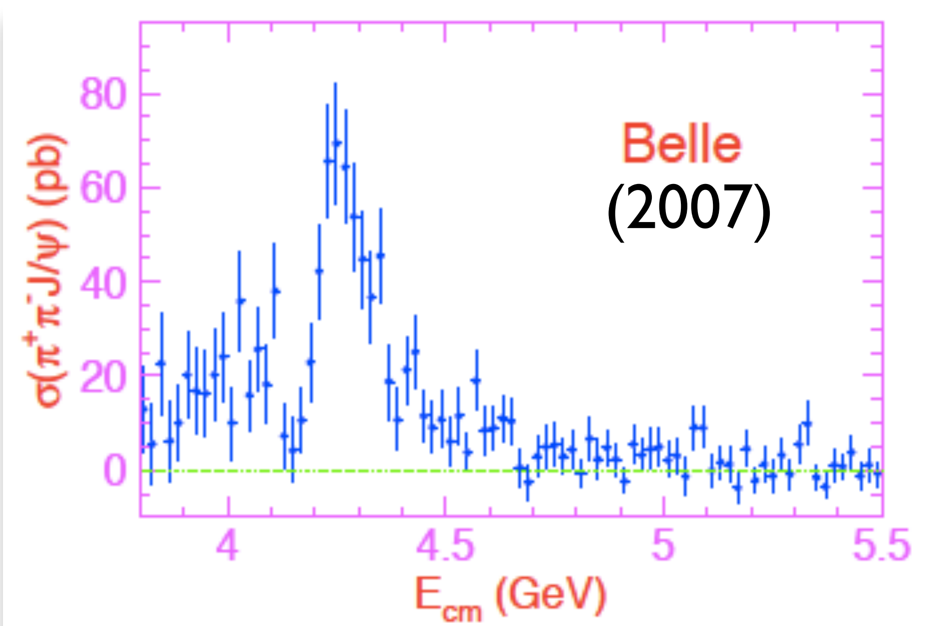
Monopoles and vortices have been long speculated to be candidate gluon field configurations responsible for confinement

"Can we quantitatively understand quark and gluon confinement in quantum chromodynamics and the existence of a mass gap" (in 10 Physics Questions to Ponder for a Millennium or Two)

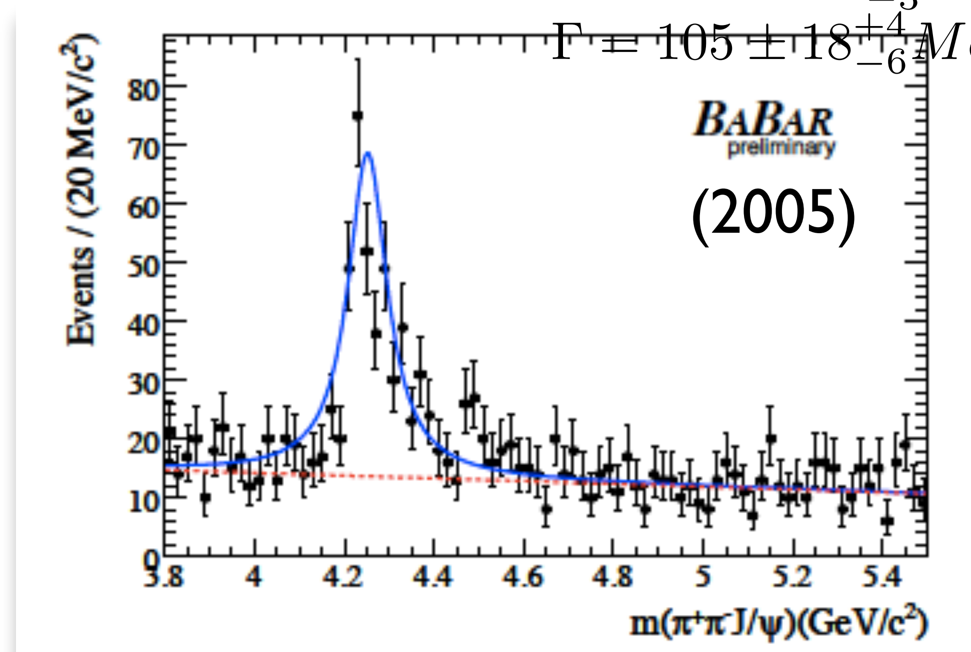
- **Y(4260)** discovered by BaBar in J/ψ $\pi^+\pi^-$ (2005) confirmed by CLEO,Belle other modes from BaBar
  $J^{PC}=1^{--}$ (from e^+e^-) width O(100MeV)







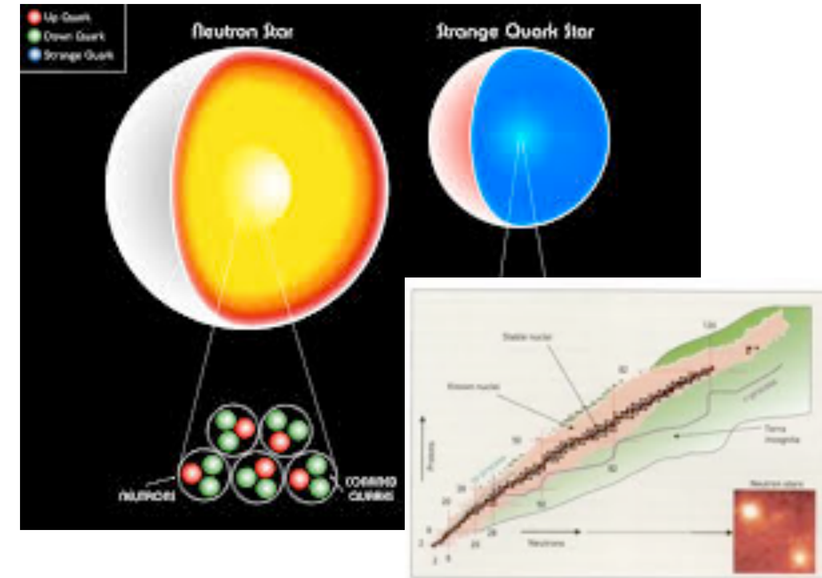
$$M = 4252 \pm 6^{+2}_{-3} MeV$$
$$\Gamma = 105 \pm 18^{+4}_{-6} MeV$$



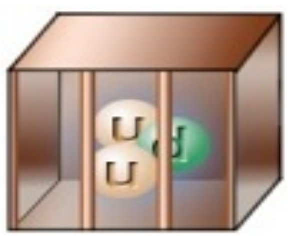
PANDA@FAIR Theory: Hybrid candidate

Quantum Chromodynamics (QCD) = physics of quarks and gluons

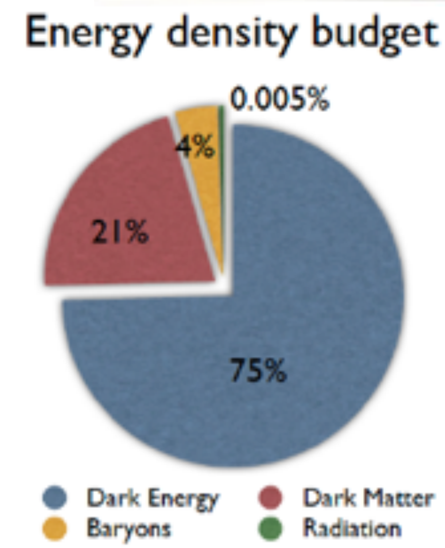
Why is QCD special ?



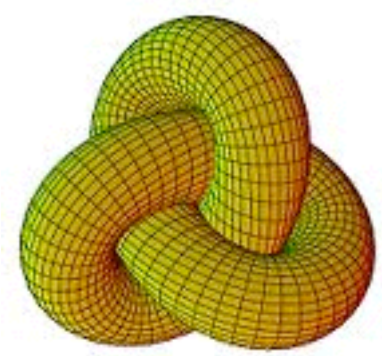
✓ A single theory is responsible for phenomena at distance scales of the order of 10^{-15}m as well as of the order 10^{4}m.

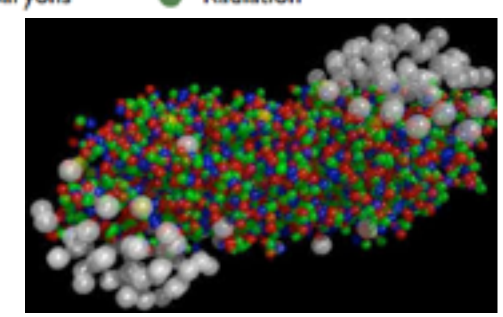


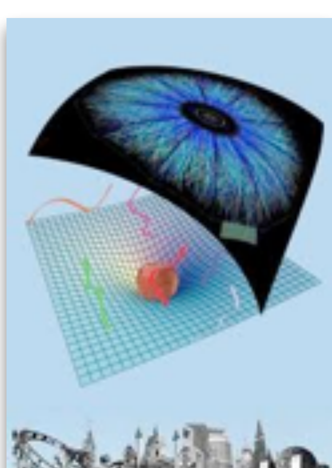
✓ It builds from objects (quarks and gluons) that do not exist in a common sense, >95% mass comes from interactions!



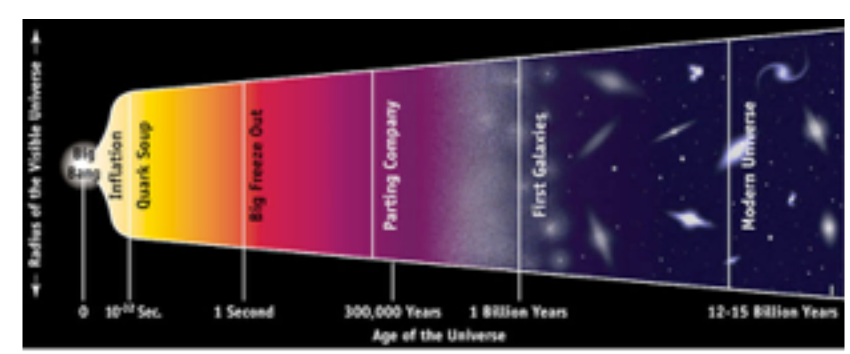
✓ Predicts existence of exotic matter, e.g. made from radiation (glue balls,hybrids) or novel plasmas.







✓ A possible template for physics beyond the Standard Model



Cosmologists believe that the Quark Soup, a perfect liquid, was the first form of matter which appeared in the universe.