From theorists dreams to reality
My (physics) adventures with AGW

Tony an Jan (on US hwy 10, 1992)

one, two, …∞ gluons

solitons and bags

confinement, dynamical χ-sym. breaking

poles, cuts and covariant amplitudes

pion form factor

ρ-ω mixing

Dyson-Schwinger eqs.

strangeness in proton

ϕ-production

one, two, …∞
gluons

poles, cuts and
covariant
amplitudes

pion
form factor

ρ-ω mixing

Exclusive processes in perturbative quantum chromodynamics

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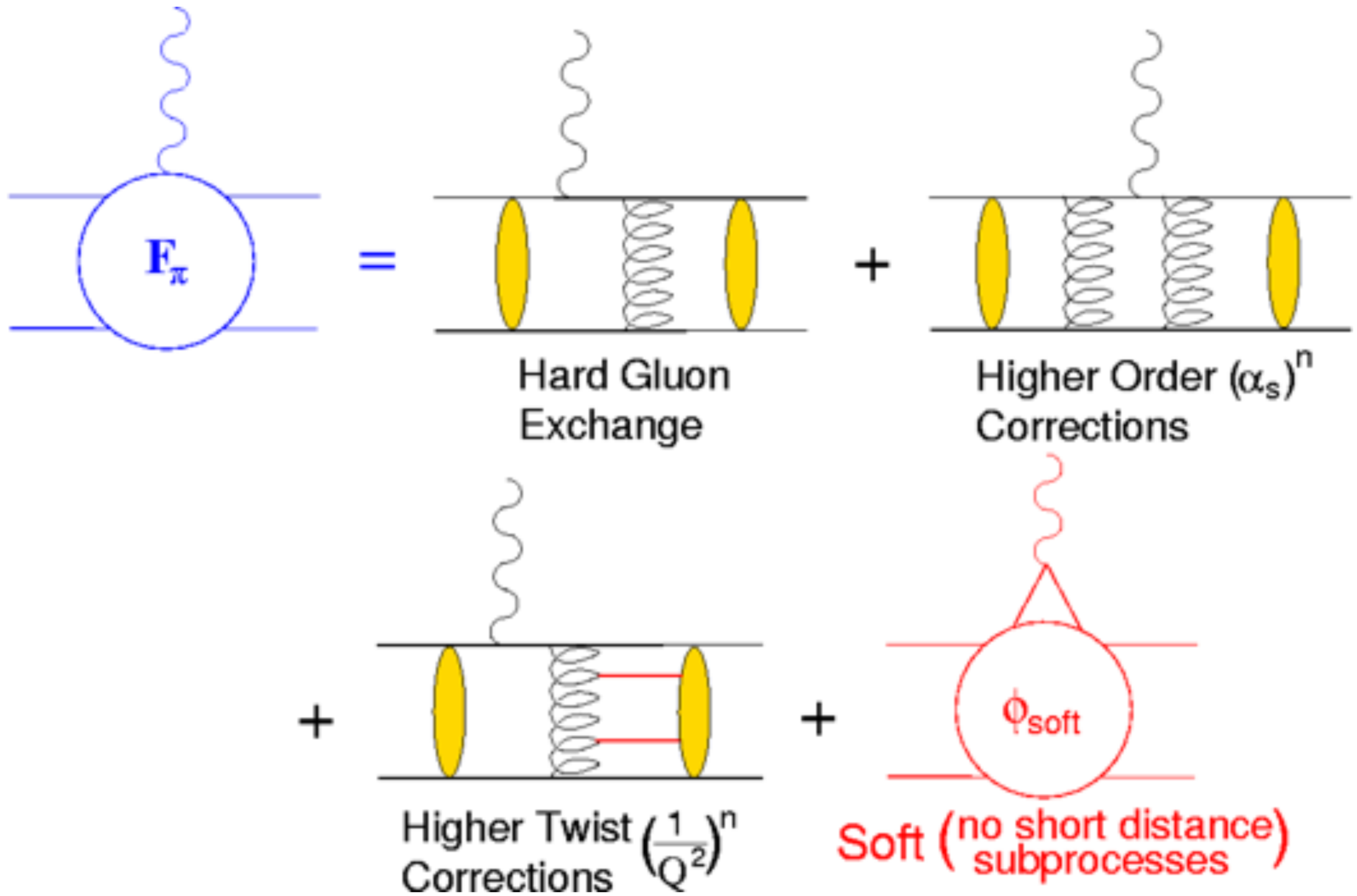
Stanley J. Brodsky
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 27 May 1980)



Asymptotic Q^2 for Exclusive Processes in Quantum Chromodynamics

Nathan Isgur[(a)] and C. H. Llewellyn Smith
Department of Theretical Physics, University of Oxford, Oxford OX1 3NP, England, United Kingdom
(Received 19 October 1983)

Model analysis of the nonleading twist contributions to the pion electromagnetic form factor

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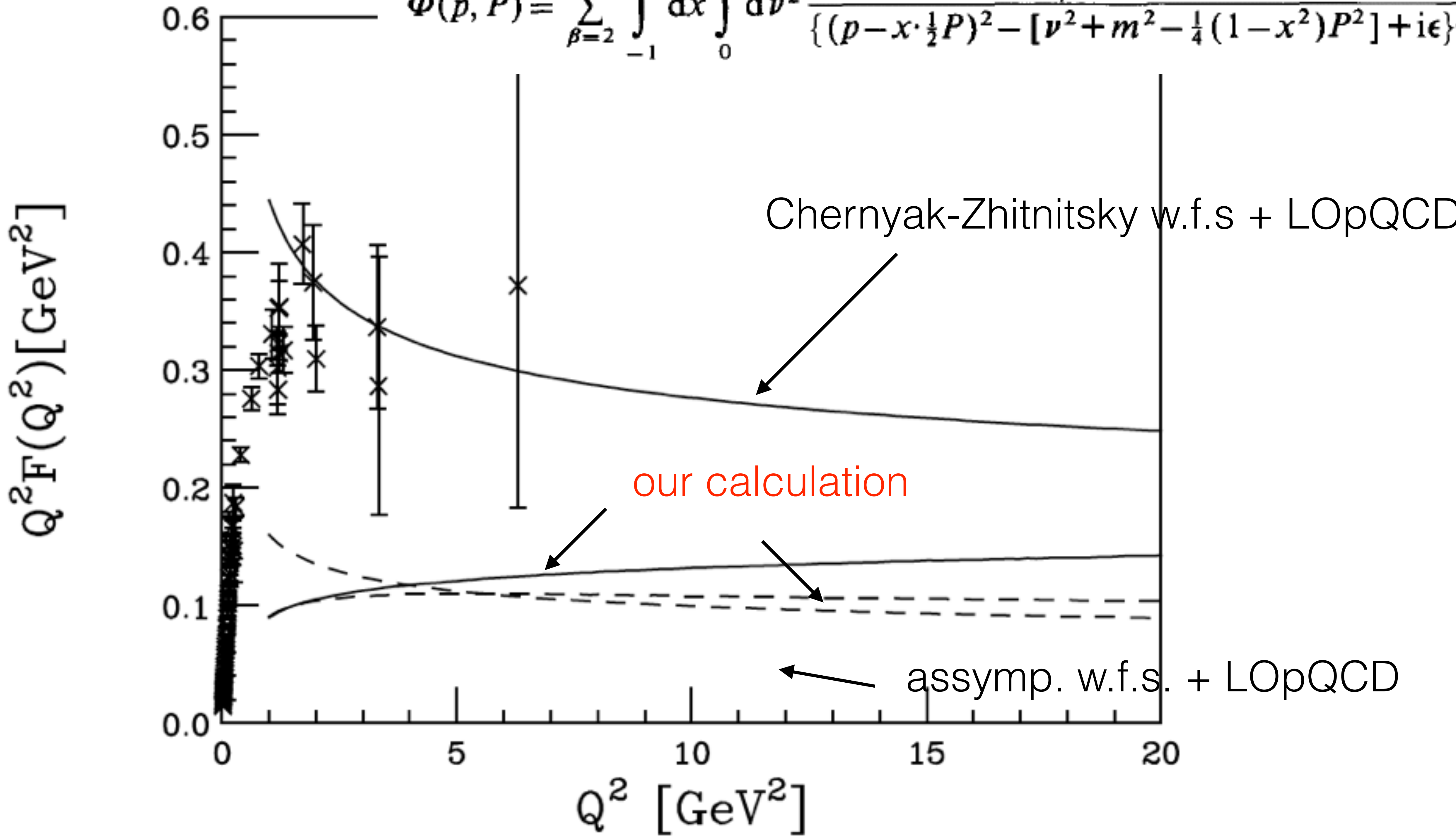
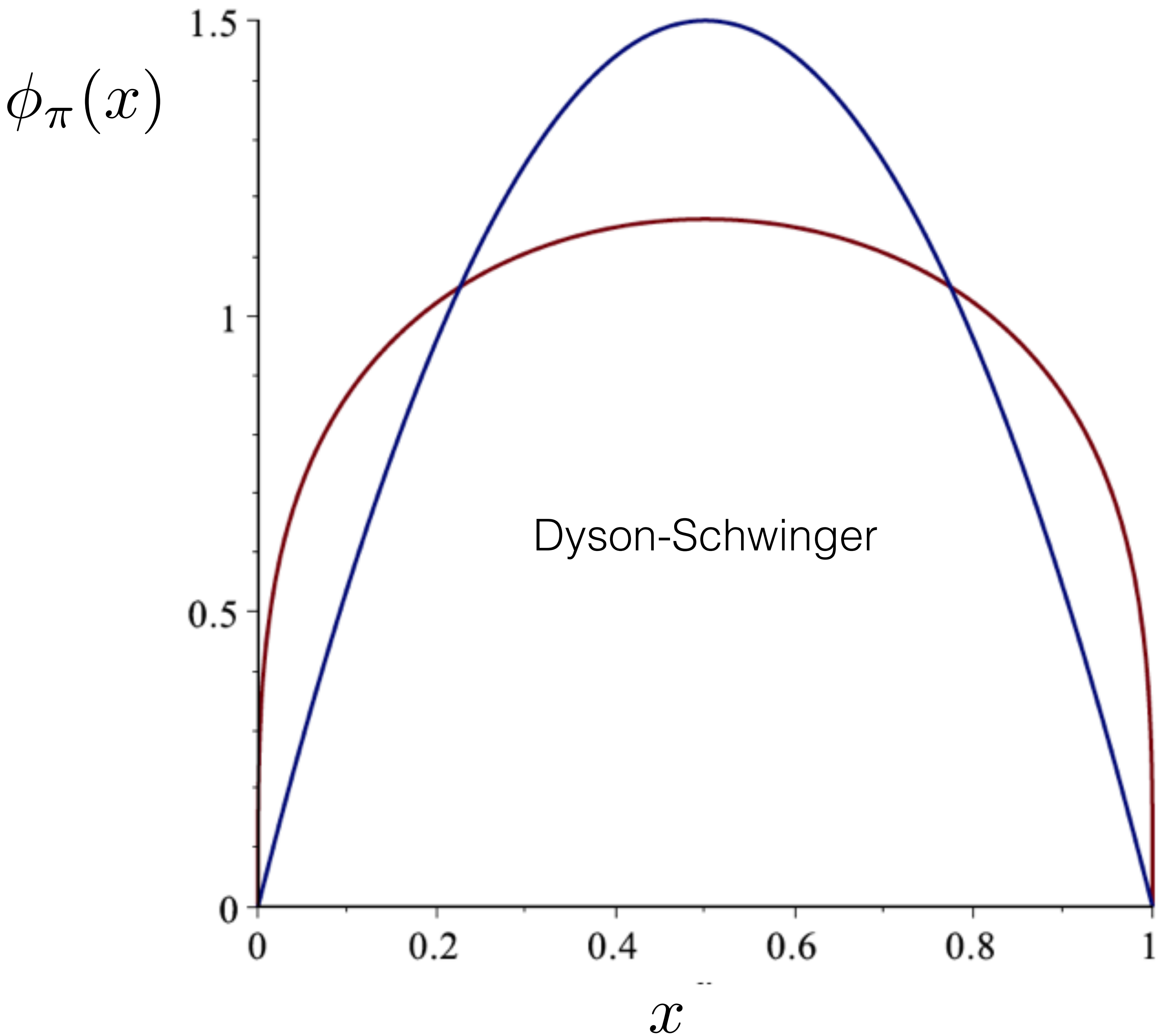
[b] *Supercomputer Computations Research Institute, Florida State University, Tallahassee, FL 32306, USA*

$$\Phi(p,P)=\sum_{\beta=2}^{\infty}\int_{-1}^{1}\mathrm{d}x\int_{0}^{\infty}\mathrm{d}\nu^2\,\frac{\bar{g}_\beta(x,\nu;p,P)}{\{(p-x\cdot\frac{1}{2}P)^2-[\nu^2+m^2-\frac{1}{4}(1-x^2)P^2]+\mathrm{i}\epsilon\}^\beta}$$



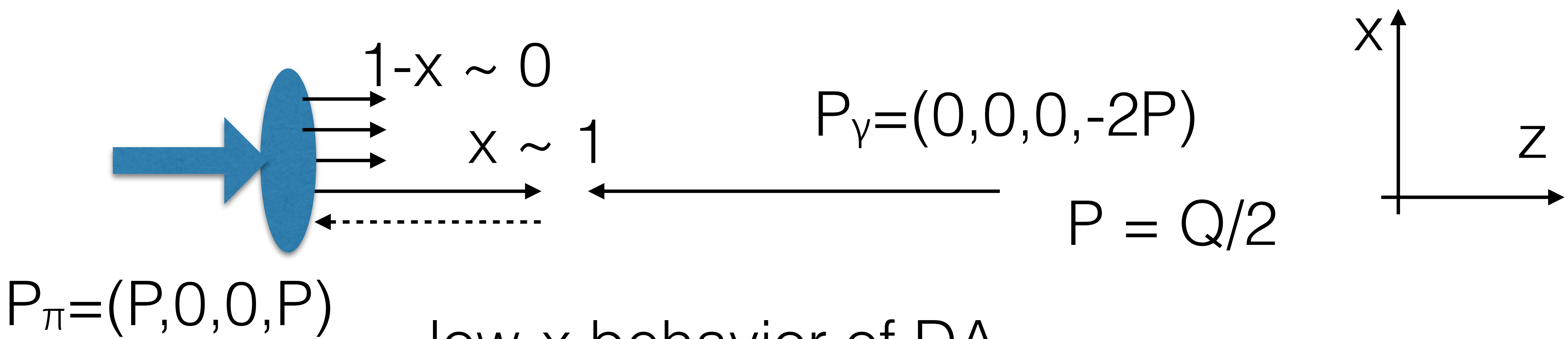
asymptotic $6x(1-x)$



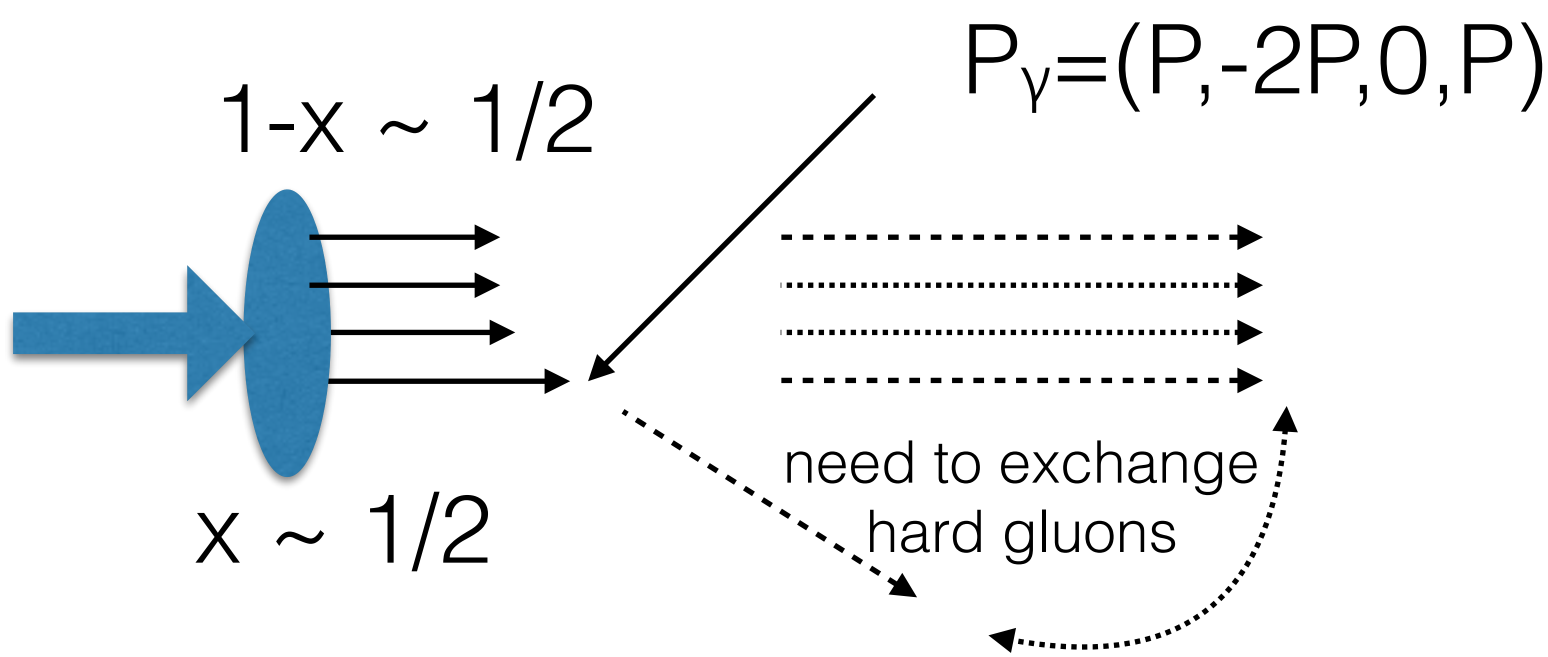
L.Chang, C.D.Roberts, I.Cloet, P.Tandy et al, (2013)

wee or valence quarks ?

"longitudinal or transverse kick ? "



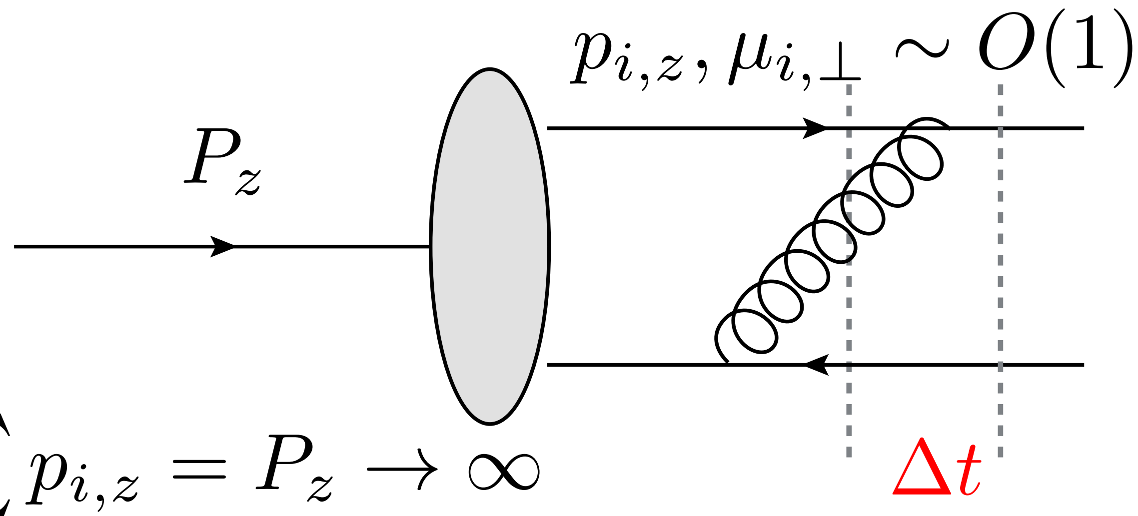
low-x behavior of DA



"hardness" of the gluon

OGE or else ?

$$\frac{1}{\Delta t} \sim \Delta E$$



$$\sum_i p_{i,z} = P_z \to \infty$$

$$\Delta E \sim P_z - \sum_i \sqrt{\mu_{i\perp}^2 + p_{i,z}^2}$$

$$\sqrt{\mu_{i\perp}^2 + p_{i,z}^2} \to p_{i,z} + \frac{\mu_{i\perp}^2}{2p_{i,z}}$$

$$\to \sum_i \frac{\mu_{i\perp}^2}{2p_{i,z}}$$

perturbative tail of the
wave function suppressed
at the end-points $p_{zi} \sim 0$

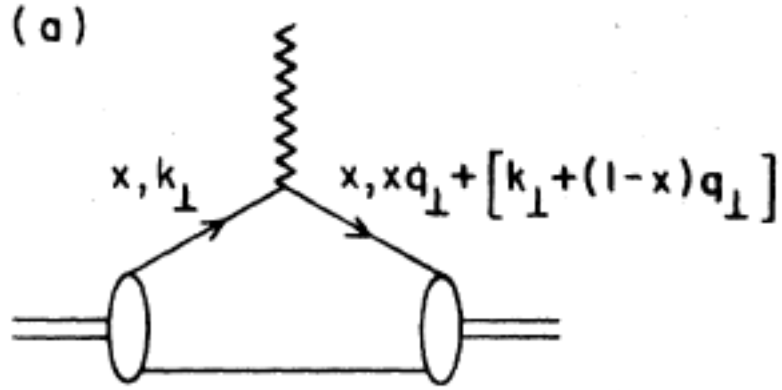
$$\Psi \sim \frac{1}{\Delta E} \sim \frac{p_{i,z}}{\mu_{i,\perp}^2}$$

but for $p_{iz} \sim 0$

$$\sqrt{\mu_{i\perp}^2 + p_{i,z}^2} \not\to p_{i,z} + \frac{\mu_{i\perp}^2}{2p_{i,z}} \qquad \Delta E \sim \text{finite}$$

wave function not
suppressed and non-
perturbative !

L.Mankiewicz,APS
P.Hoyer



S.J.Brodsky, G.P.Lepage, Phys.Rev. (1980)

$$F(Q^2) = \int_0^1 dx \int \frac{d^2k_\perp}{16\pi^3} \psi(x, k_\perp)\psi^*(x, k_\perp + (1-x)q_\perp),$$

$$\sim \int_{1-\lambda/Q}^1 dx \, |\psi(x, \lambda)|^2$$

$$\to (\lambda/Q)^{1+2\delta},$$

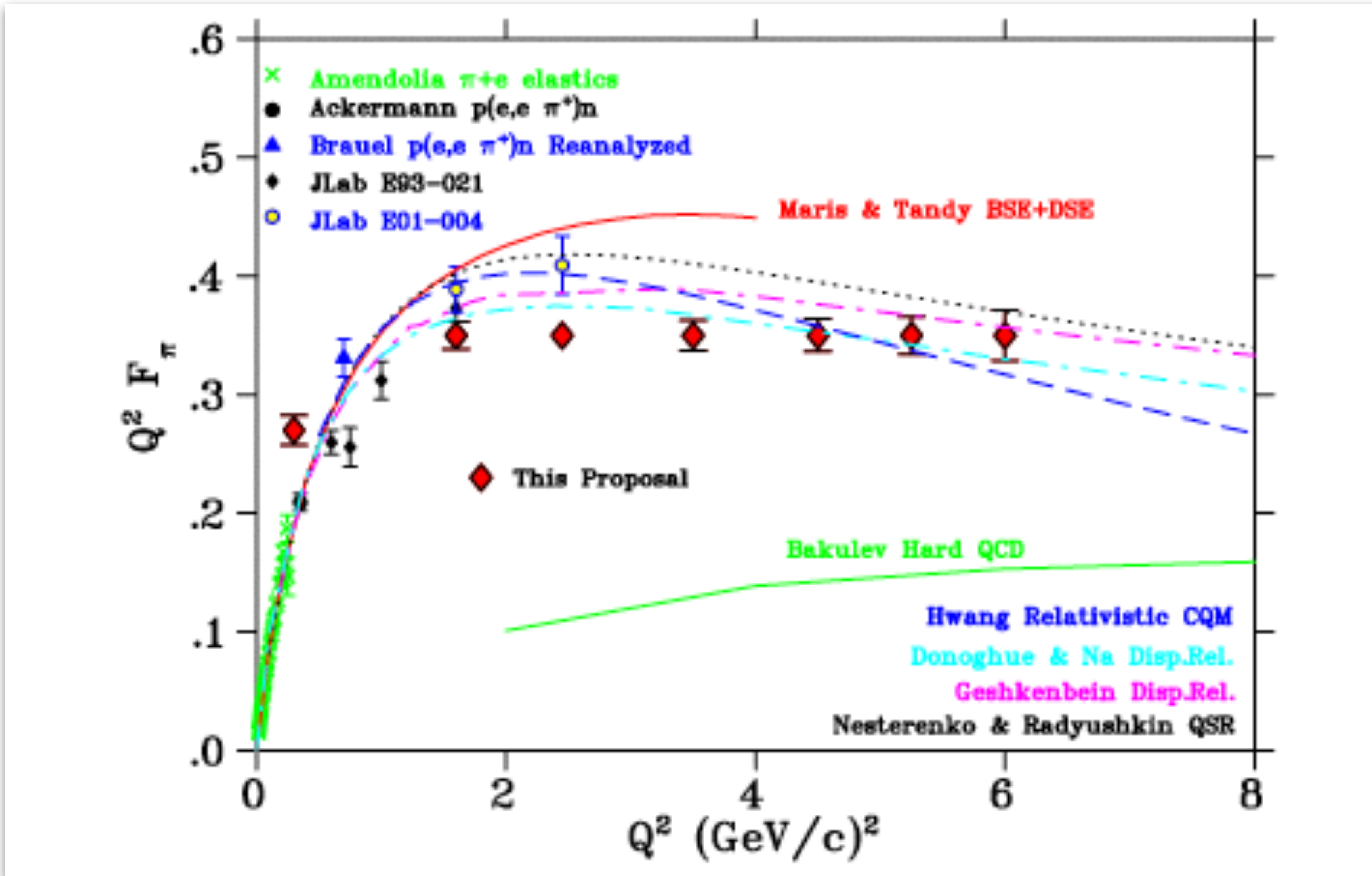
where $\psi(x, \lambda) \sim (1-x)^\delta$.

$$F_\pi(Q^2) \sim \frac{\alpha(Q^2)}{Q^2}$$

vs

$$F_\pi(Q^2) \sim \frac{(Q^2)^{(0.5-\delta)}}{Q^2}$$

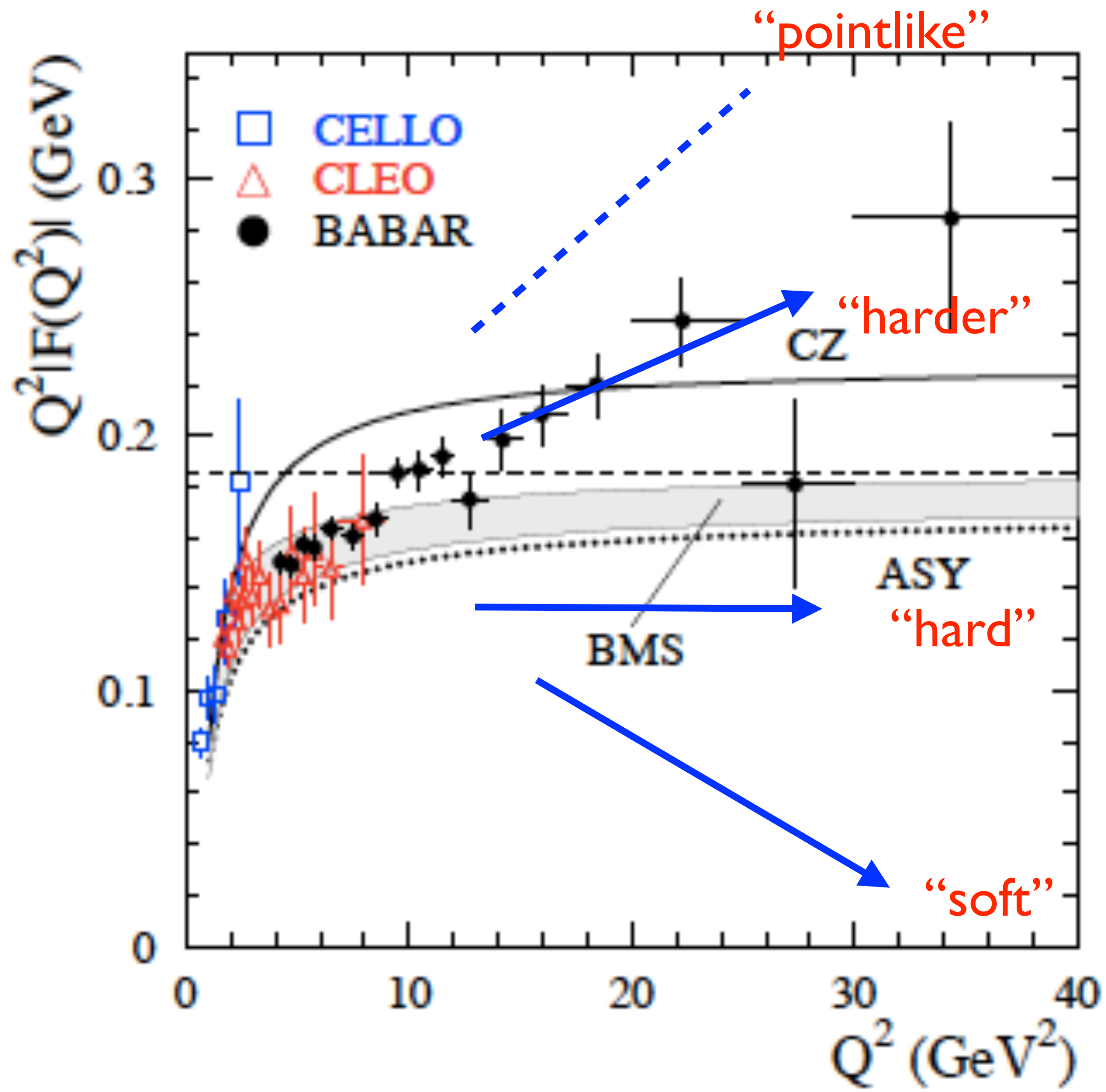
e.g. δ ~ 0.25 (~ 0.29 in DS) solves BaBar anomaly and is consistent with the Regge picture of a quark exchange

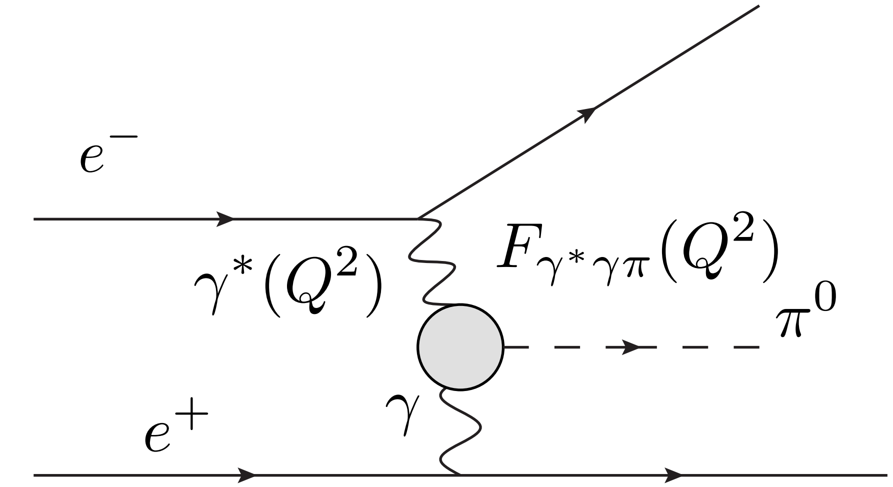


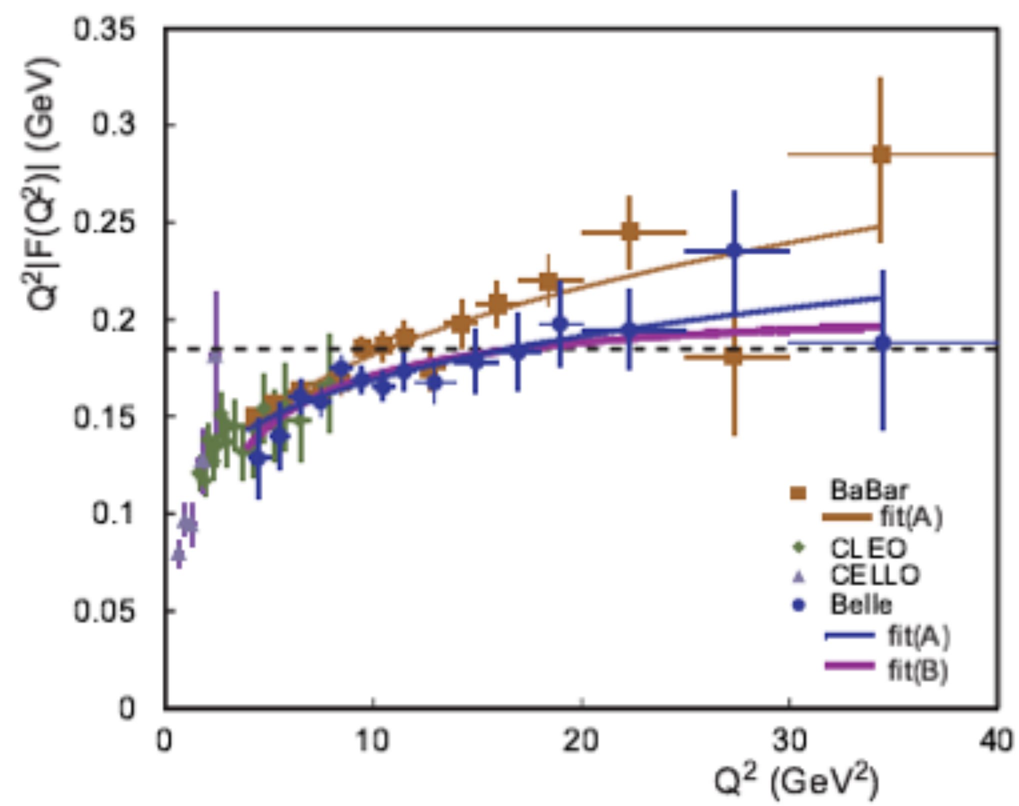
E12-06-101 D.Gaskell, G.M.Huber,
"Measurement of the Charged Pion From Factors to High-Q^2"

BaBar anomaly $e^+e^- \to \pi^0 e^+ e^-$

B.Aubert et al. Phys.Rev. (2009)

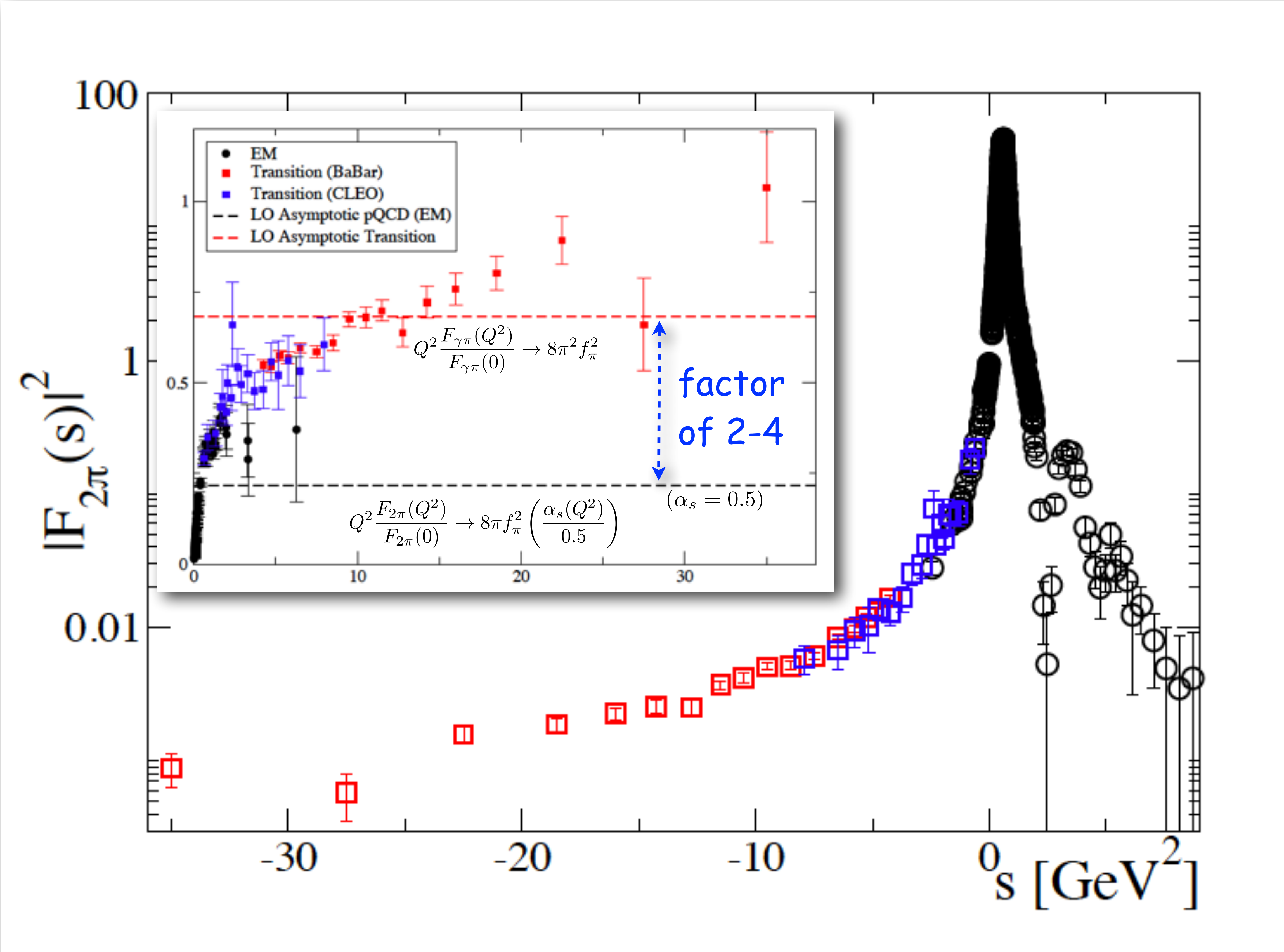






S. Uehara, et al. Belle (2012)

theory: G.P.Lepage, S.Brodsky
A.Radyushkin



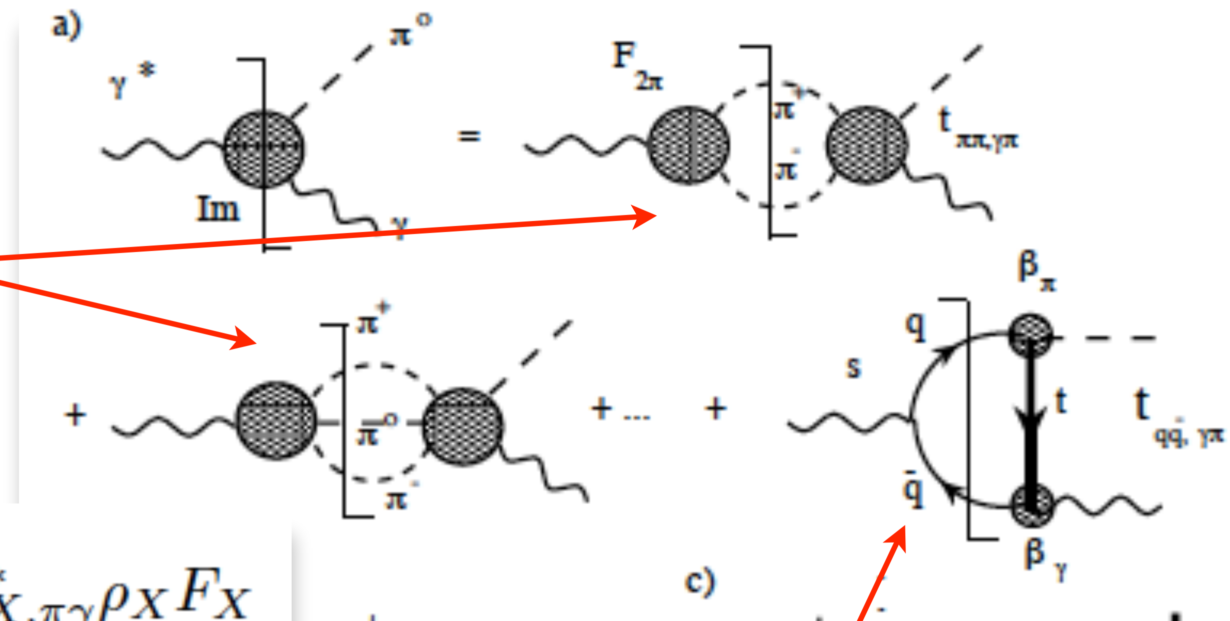
$|F_{2\pi}(s)|^2$
100
1
0.01
-30
-20
-10
0
s [GeV^2]
EM
Transition (BaBar)
Transition (CLEO)
LO Asymptotic pQCD (EM)
LO Asymptotic Transition
$Q^2 \frac{F_{\gamma\pi}(Q^2)}{F_{\gamma\pi}(0)} \to 8\pi^2 f_\pi^2$
$Q^2 \frac{F_{2\pi}(Q^2)}{F_{2\pi}(0)} \to 8\pi f_\pi^2 \left(\frac{\alpha_s(Q^2)}{0.5}\right)$
$(\alpha_s = 0.5)$
factor of 2-4

From the s-channel:

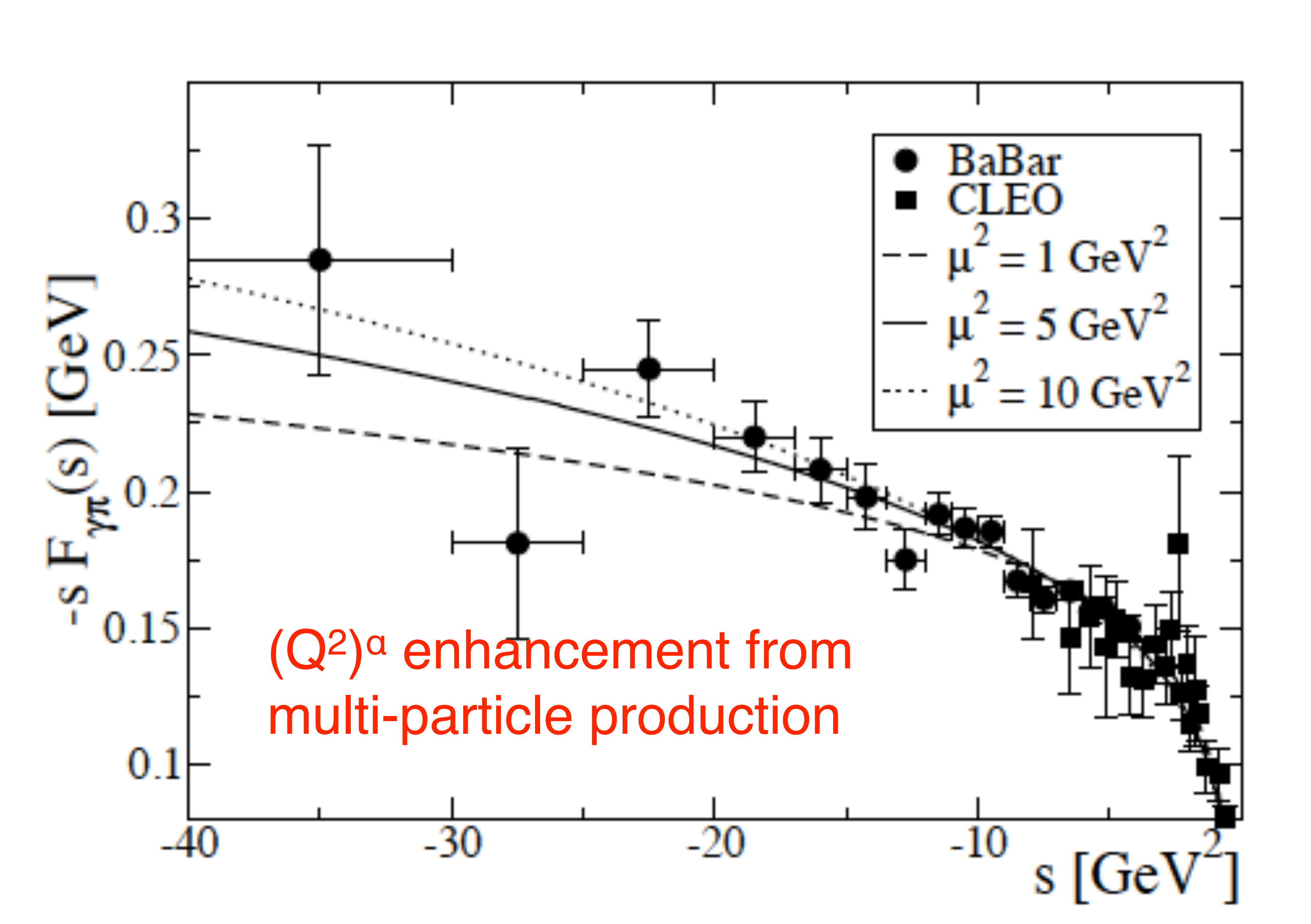
resonances (ρ,ω) at low energies

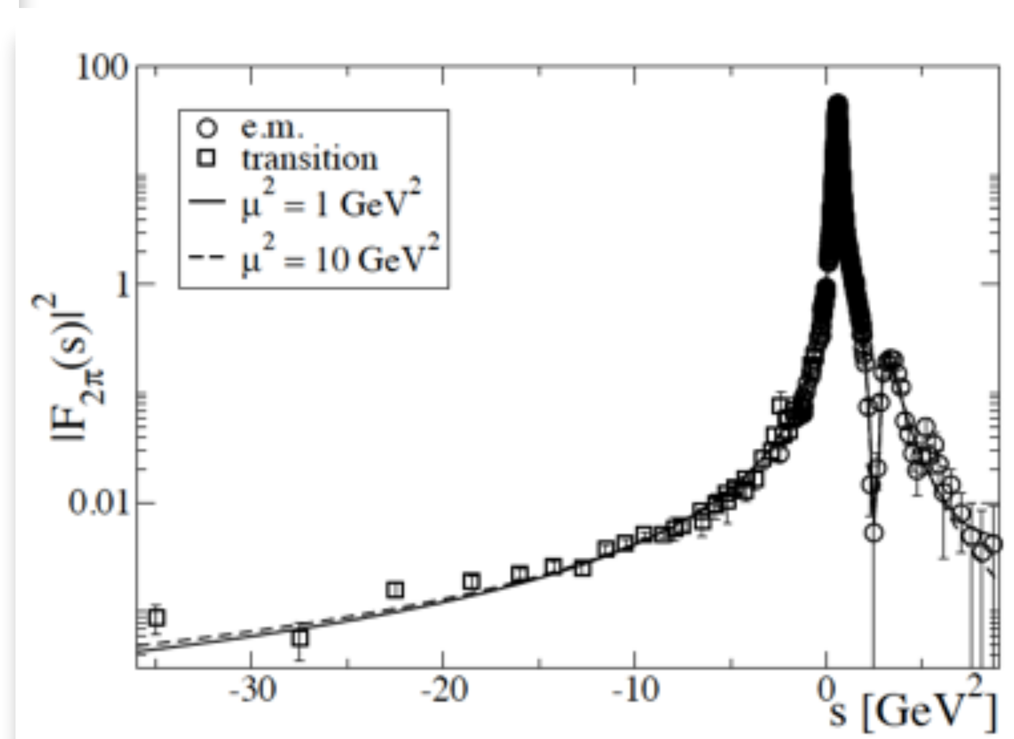
$$ImF(s) = \sum_X t_X^*(s)\rho_X(s)F_X(s)$$

$$ImF_{\pi\gamma} = t^*_{2\pi,\pi\gamma}\rho_{2\pi}F_{2\pi} + t^*_{3\pi,\pi\gamma}\rho_{3\pi}F_{3\pi} + \sum_X t^*_{X,\pi\gamma}\rho_X F_X$$



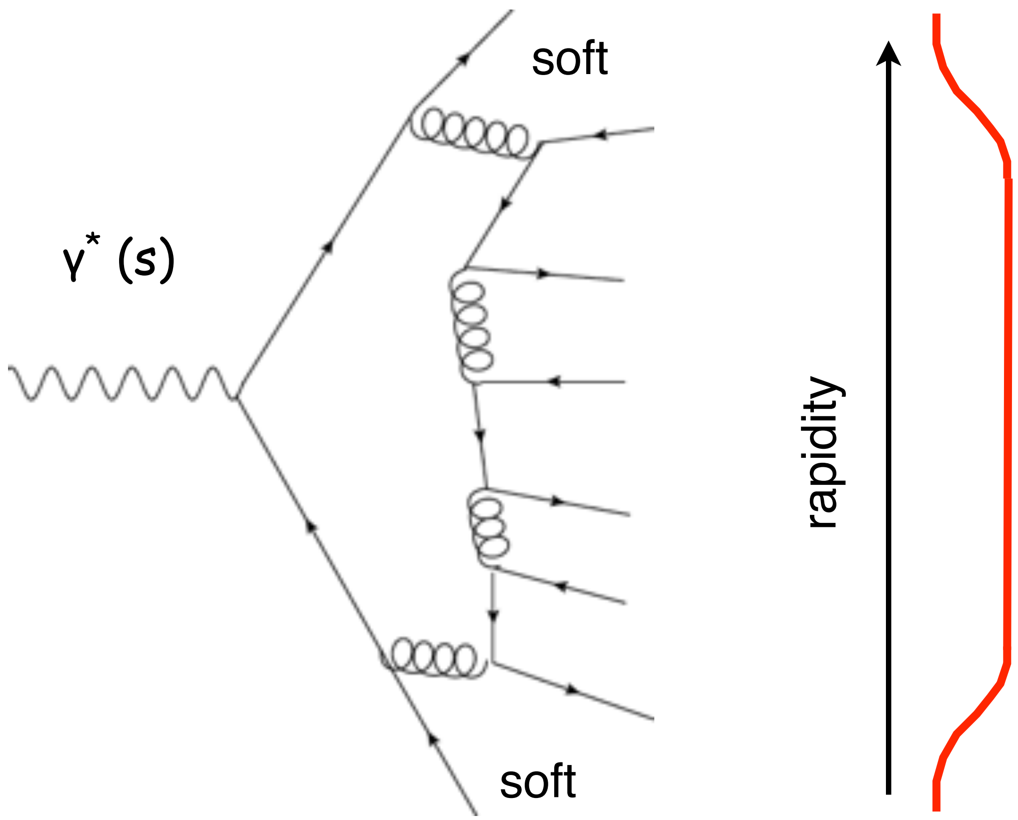
multi-particle ladder
-- Reggized quark

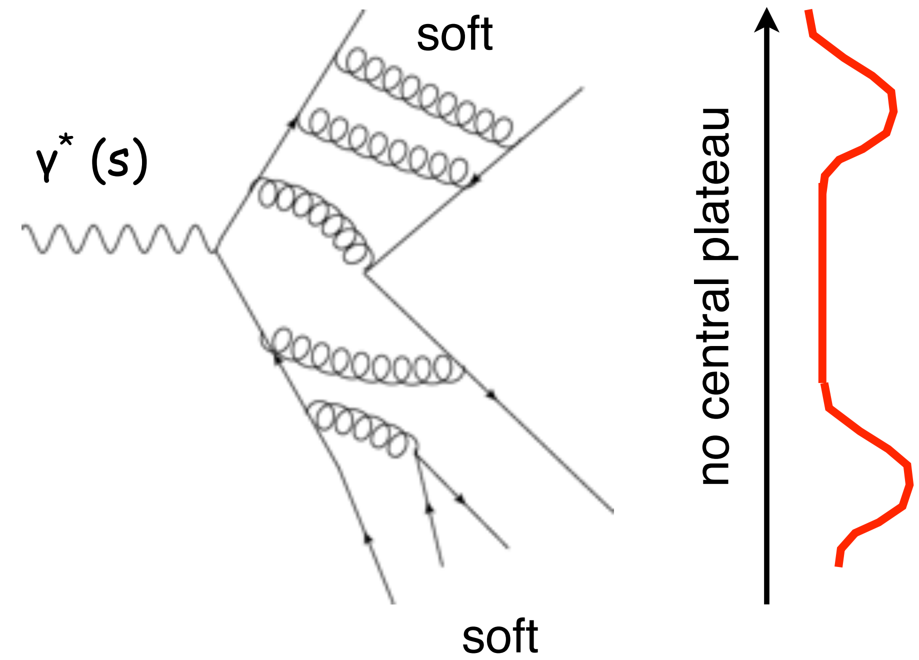


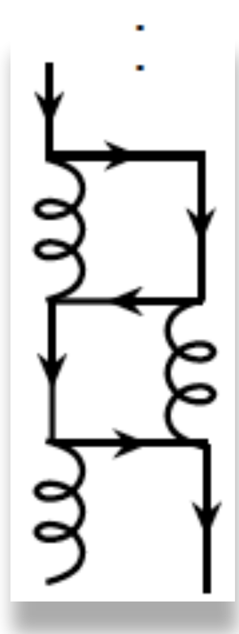


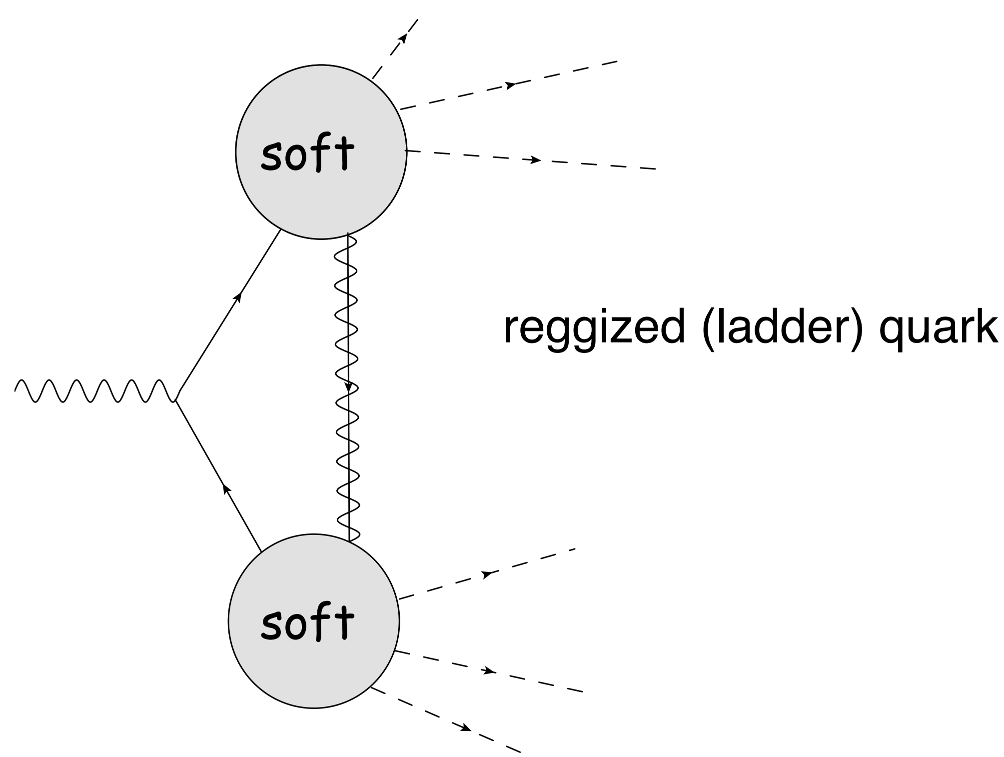
M.Gorchtein, P.Guo, AS (2012)

reggized vs single quark exchange









one, two, ...∞
gluons

solitons
and bags

confinement,
dynamical χ-sym
breaking

Dyson-Schwinger
eqs.

poles, cuts and
covariant
amplitudes

pion
form factor

ρ-ω mixing

strangeness in proton

ϕ-production

one, two, ...∞ gluons

solitons and bags

confinement, dynamical χ-sym. breaking

Dyson-Schwinger eqs.

Early ideas about the origin of confinement

On the Implications of Confinement

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PACS numbers: 12.38.Aw, 11.30.Qc, 11.30.Rd

Dyson–Schwinger Equations and their Application to Hadronic Physics

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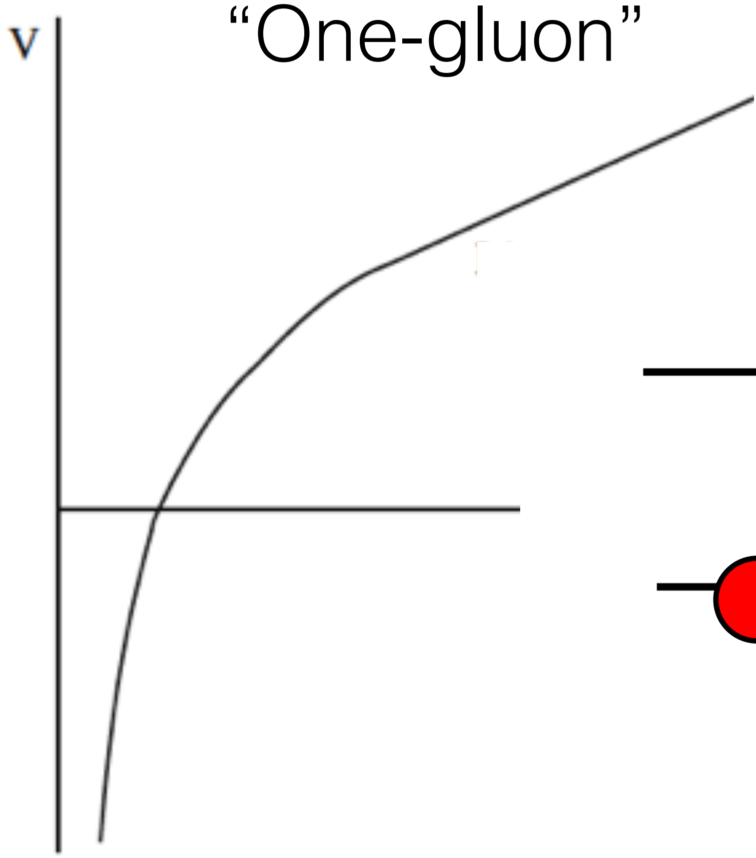
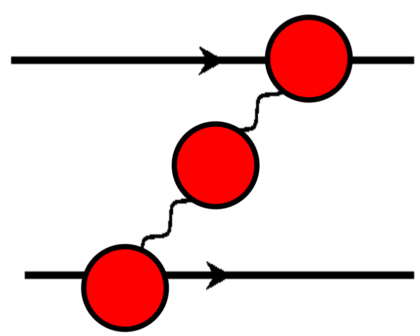
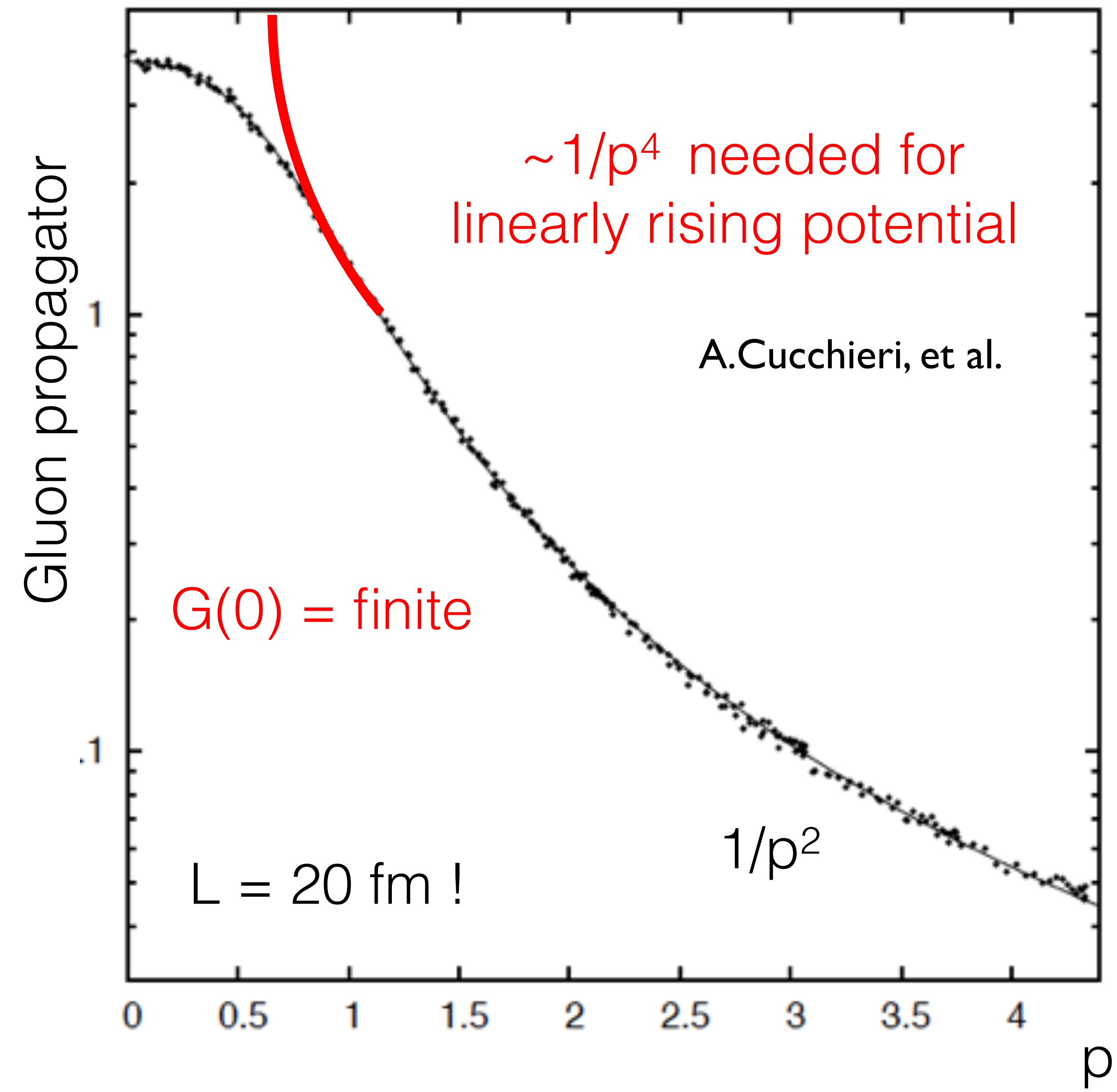




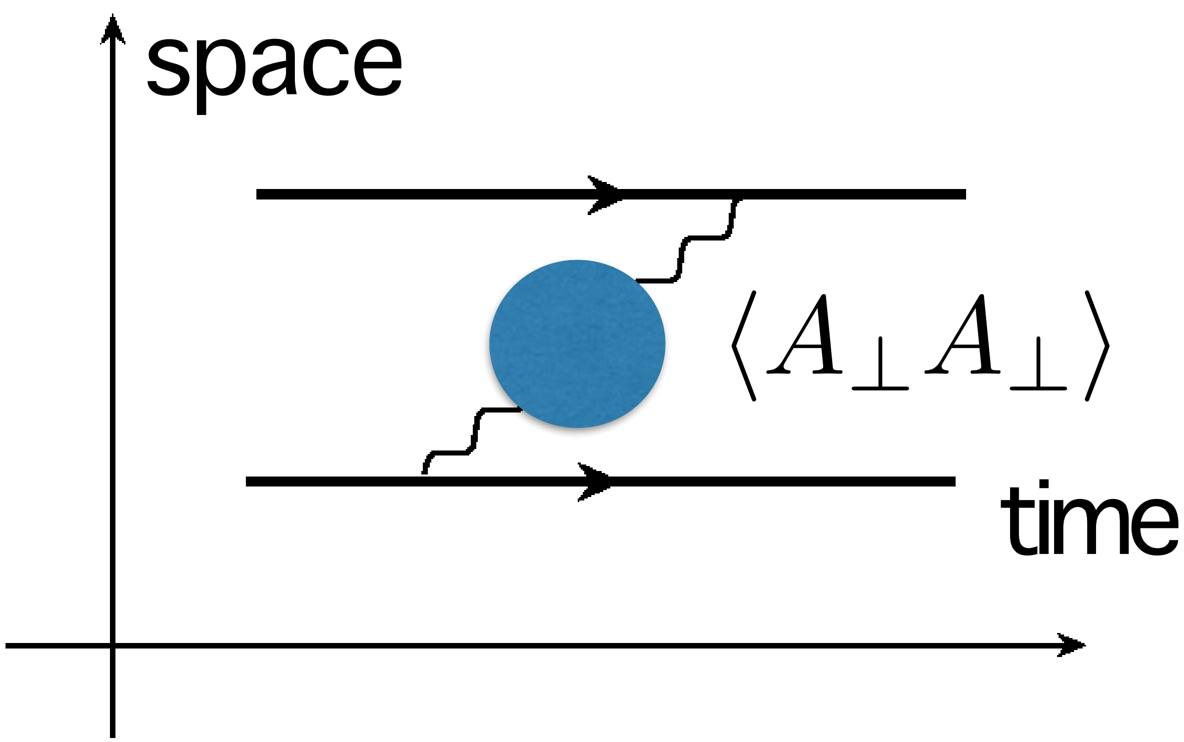


How does this relate to Regge trajectories ?

Dual role of gluons

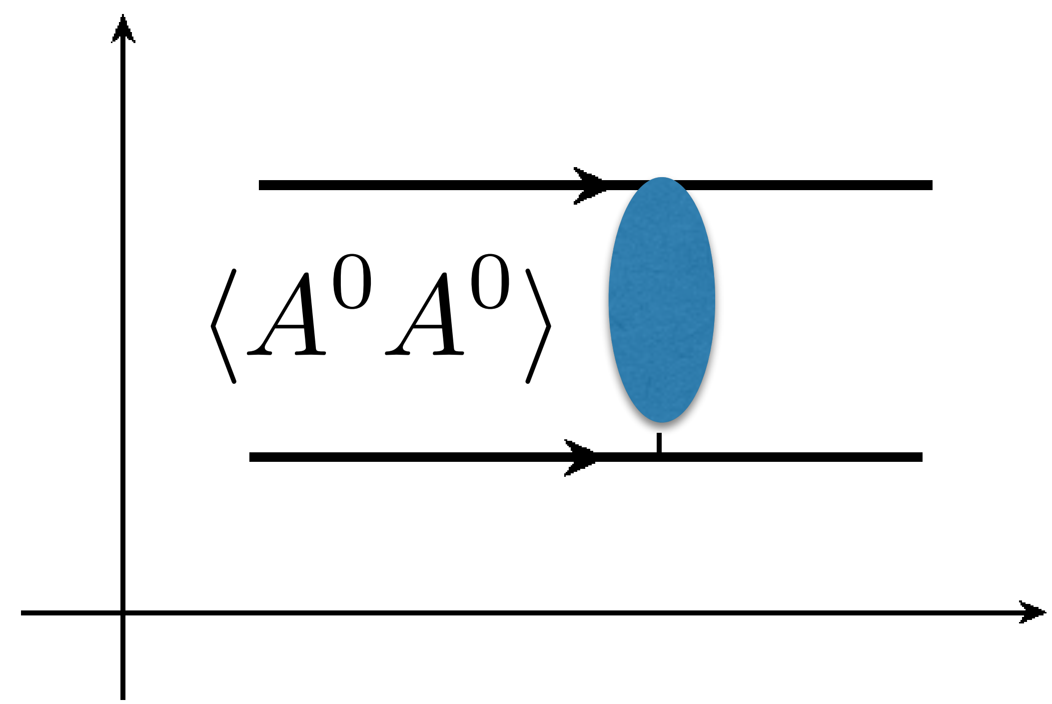
(all gluons are equal but some are more equal than others)

IR suppressed



are confined
("constituent gluon" of
large effective mass)

IR enhanced

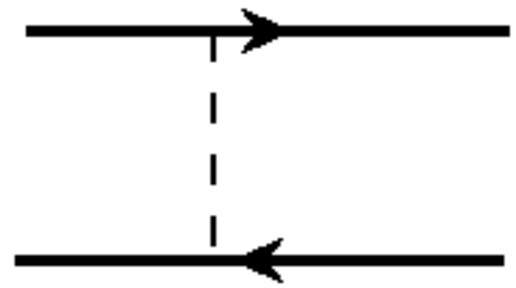


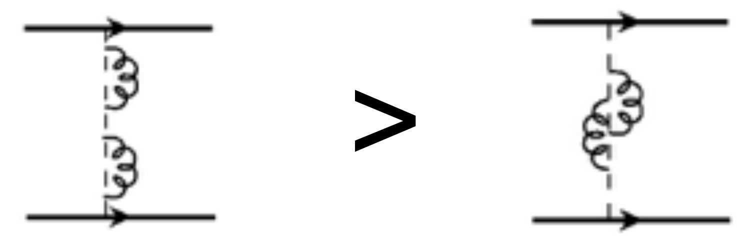
lead to confinement

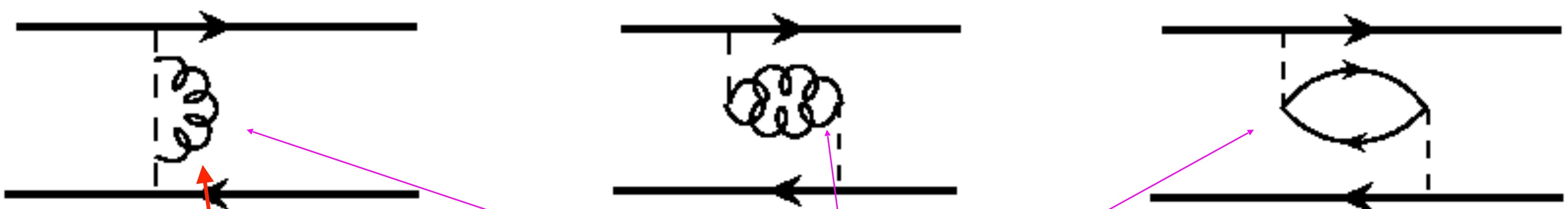
Onset of confinement

QED $-\frac{1}{\nabla^2} \to -\frac{1}{\nabla D}\nabla^2\frac{1}{\nabla^2}$ QCD

$\frac{4\pi\alpha}{k^2}$







$\beta = 12 - 1 - \frac{2}{3}n_f$ $\alpha \to \alpha(k^2) = \frac{\alpha(\Lambda)}{1 - \frac{\alpha(\Lambda)\beta}{4\pi}\log\left(\frac{\Lambda}{k}\right)^2}$

equal-time gluon propagator

If $\omega(k) \neq k$ **then** $\log\left(\frac{\Lambda}{k}\right)^2 \to \log\frac{\Lambda^2}{k^2 + m_g^2}$

$\alpha(\Lambda) \to \frac{4\pi}{\beta \log\frac{\Lambda^2}{m_g^2}}$ $\alpha(k) \sim \frac{4\pi}{\beta k^2}$

$$\omega_p \equiv \sqrt{\boldsymbol{p}^2 + M^2(\boldsymbol{p})}\ .$$

$$V(\boldsymbol{k}) = -\frac{64}{3} e^{21/22} \frac{\Lambda_{\overline{MS}}}{|\boldsymbol{k}|^3}\ .$$

$$M^2(\boldsymbol{k}) = \begin{cases} m^4/\boldsymbol{k}^2 & \text{Gribov propagator} \\ m^2 & \text{massive propagator} \end{cases}$$

$$V(k) = -\frac{48\pi^2 m^2}{k^4\left(\frac{41}{20}\log\frac{m^2}{k^2} - \frac{\log 2}{4} + \frac{219}{25}\right)}\ ,$$

equal-time gluon propagator

$$V_C(R) \overset{R\to\infty}{=} \frac{C_r}{N}\left(\frac{120\pi}{41}\frac{m^2}{\log(8.12mR/3)^2}\right.$$

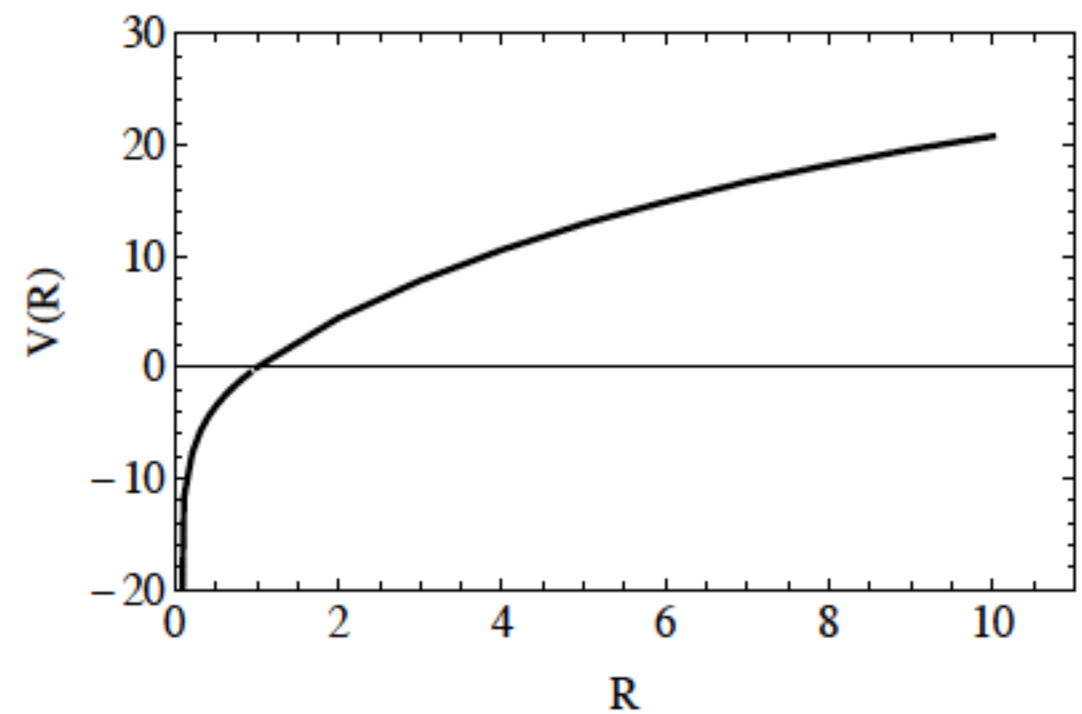
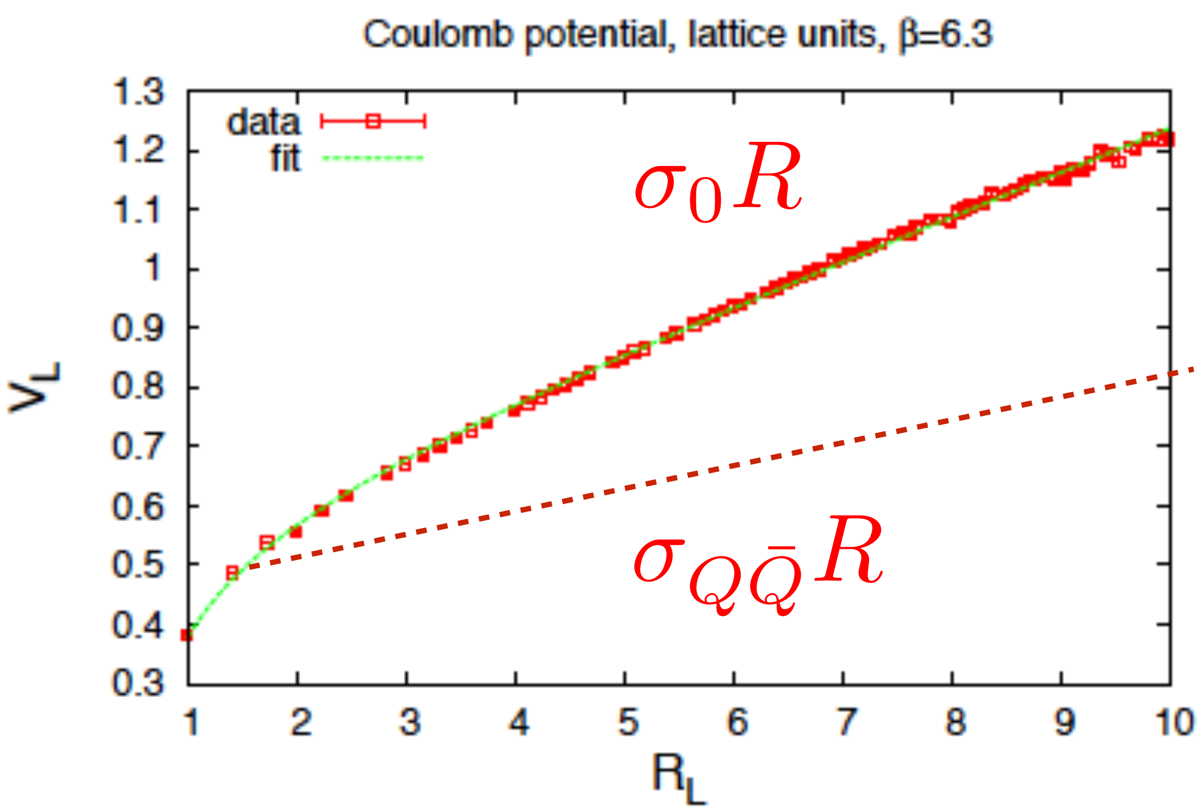


FIG. 2. Potential $V(R)$ vs. R, obtained from a Fourier transform to position space of the numerical solution for $V(k)$. The result includes the self-energy, which is both ultraviolet and infrared divergent. The infrared divergence is cancelled, for a color singlet, by a corresponding term in the interaction, as explained in the text. To regulate the ultraviolet divergence we have made an arbitrary subtraction such that $V(R)$ passes through zero at $R = 1$. $V(R)$ is in units of m, R in units of $1/m$.

Golterman Greensite, Peris, AS (2012)

string-less state is not a QCD eigenstate

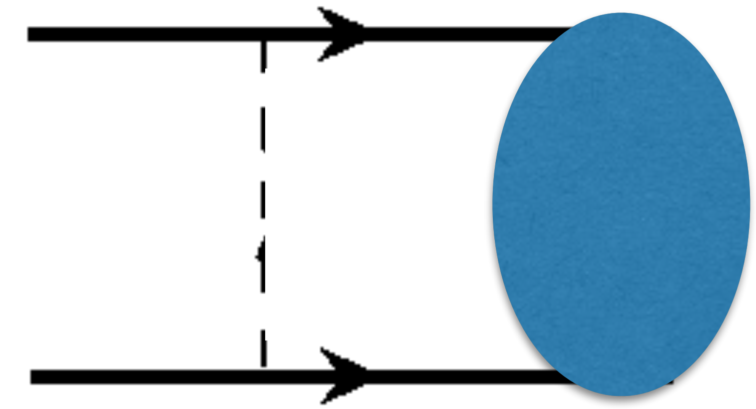
$$|Q\bar{Q}, R\rangle = Q(\vec{R}/2)\bar{Q}(\vec{R}/2)|\Psi_0[A]\rangle$$



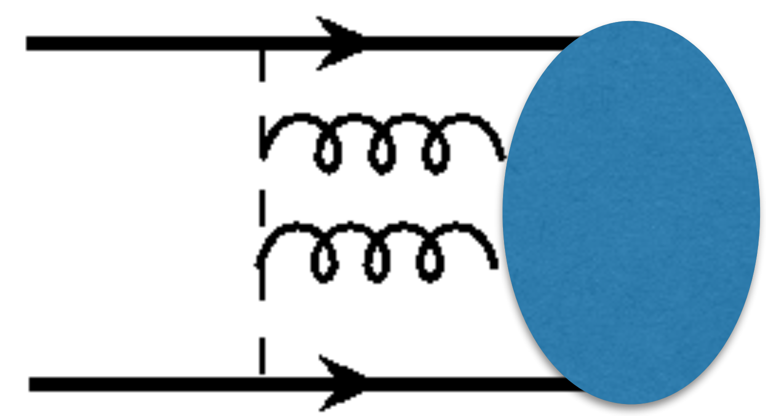
$$\sigma_0 \sim 3\sigma_{Q\bar{Q}}$$

QCD: No-confinement without Coulomb confinement (Zwanziger)

Greensite, Olejnik (2009)

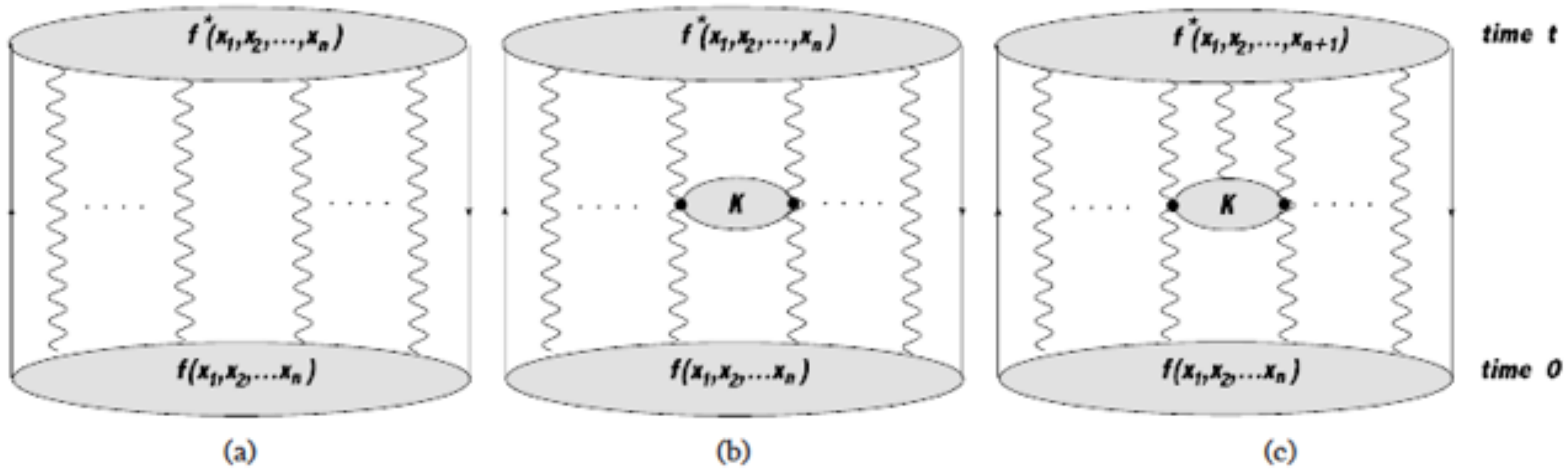


$\Psi_0[A]$

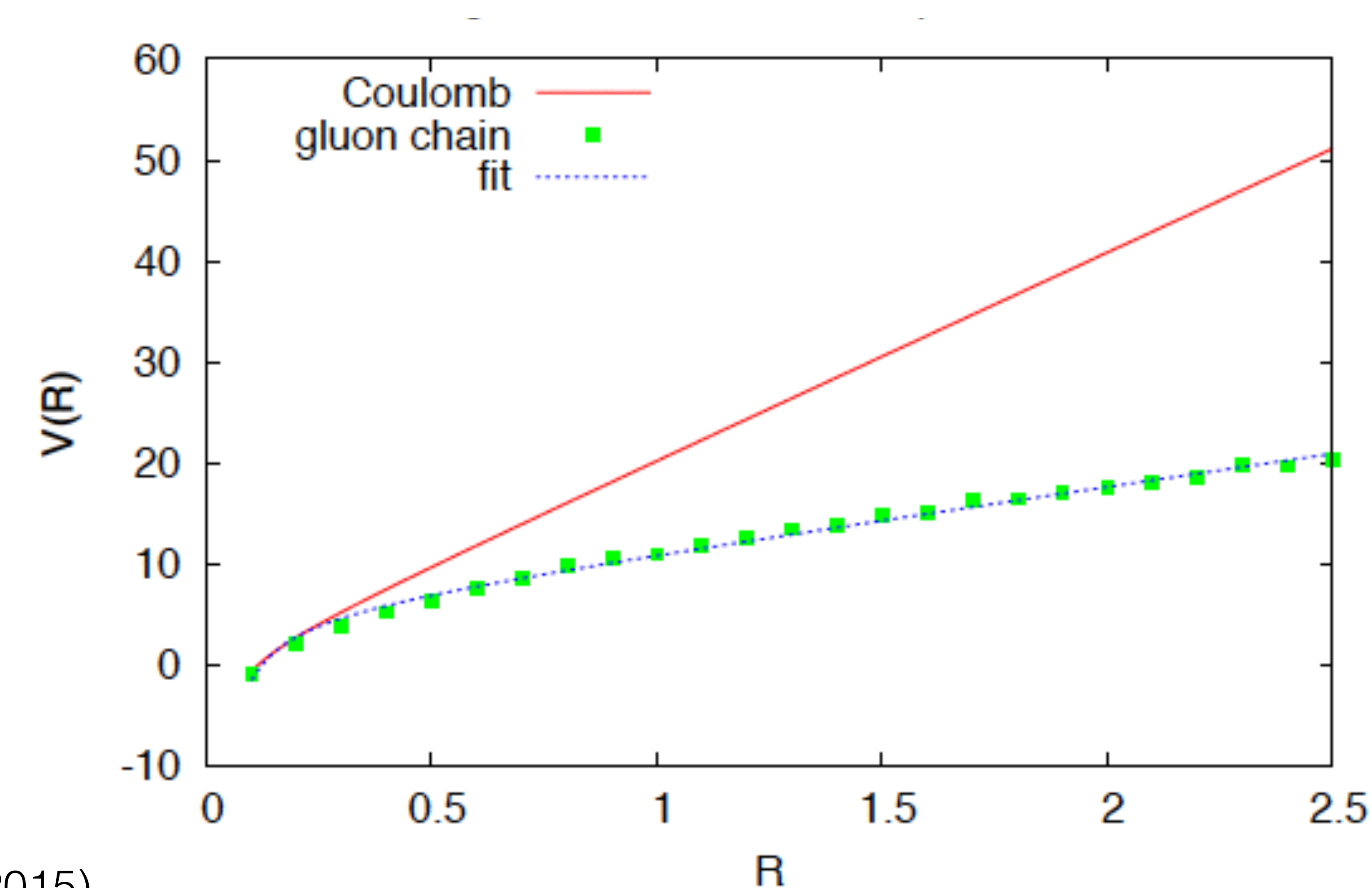


$\Psi_{Q\bar{Q}}[A]$

From stringless state to flux tubes



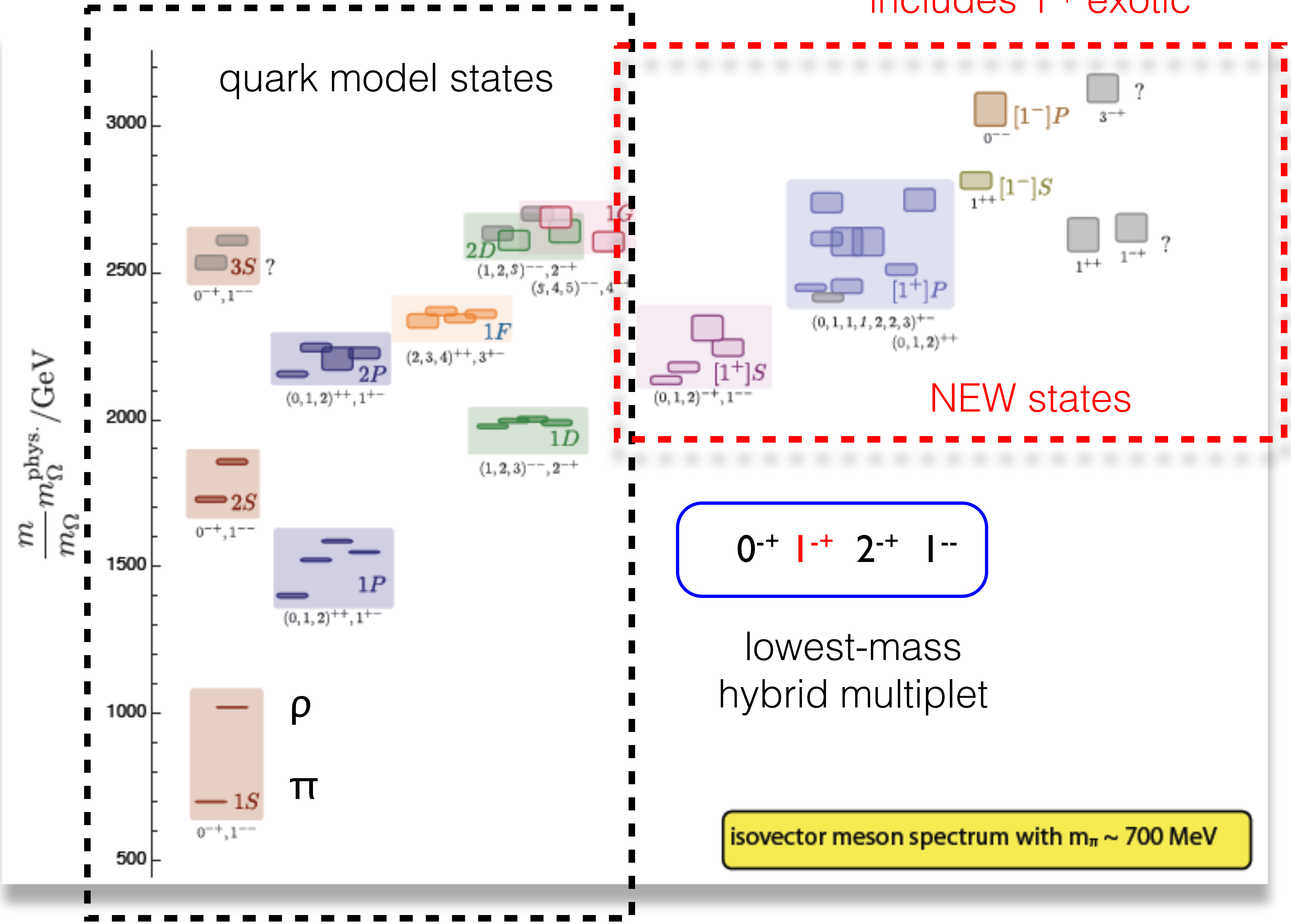
in 1-gluon (variational) approximation



Greensite, AS (2015)

new multiplets from lattice

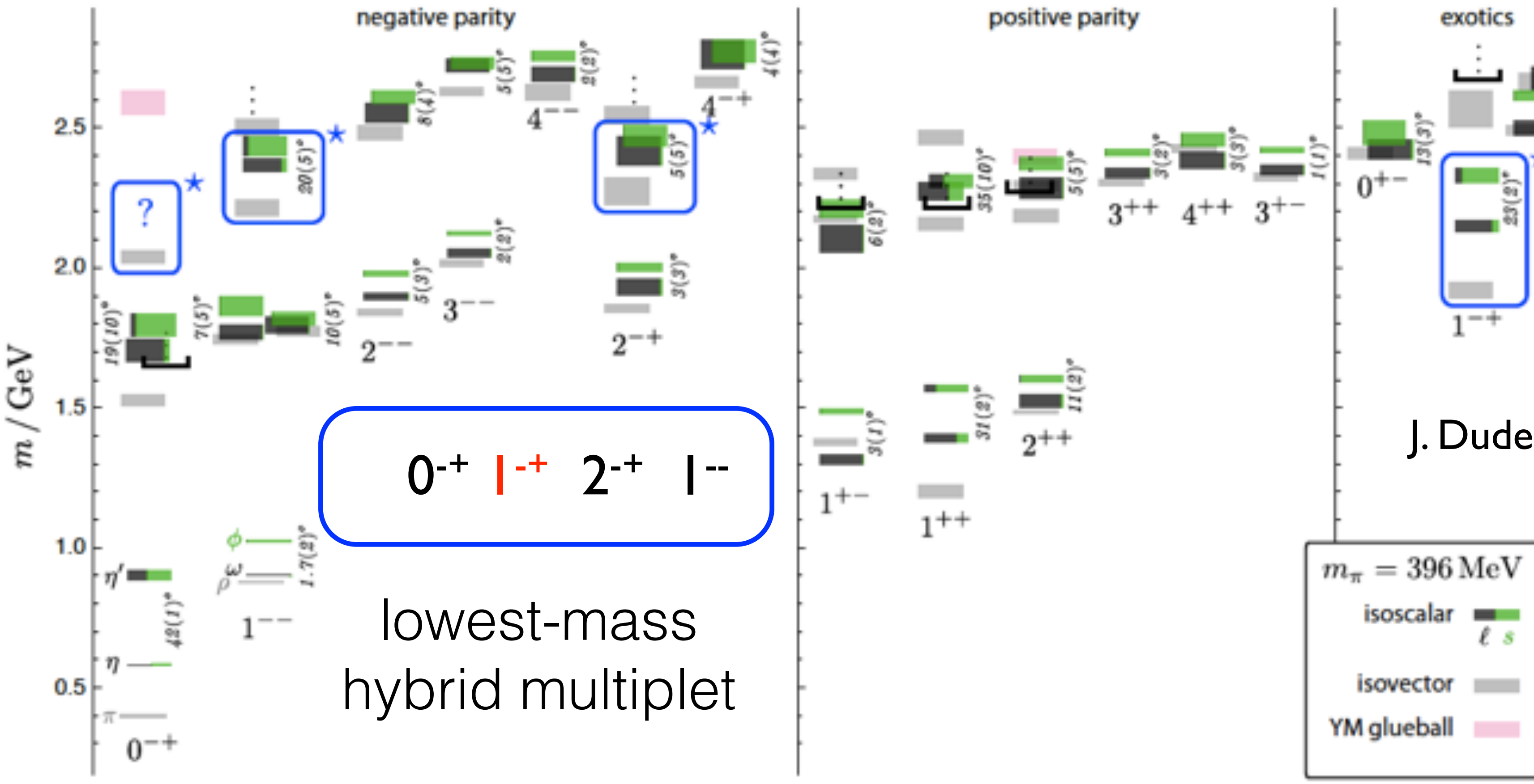
large overlap with gluonic operators includes 1^{-+} exotic

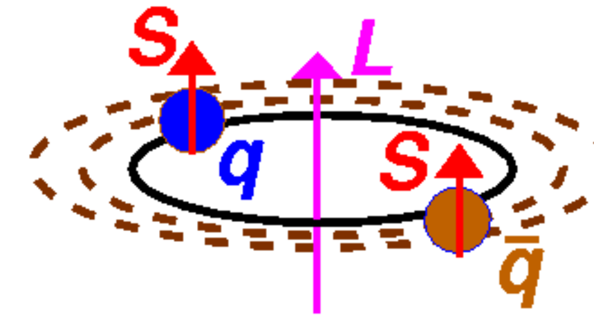


same pattern in $s\bar{s}$, $c\bar{c}$

hybrid interpretation of the **Y(4260)**

Dudek, et al.





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

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

$$J_g^{PC} = 1^{+-}$$

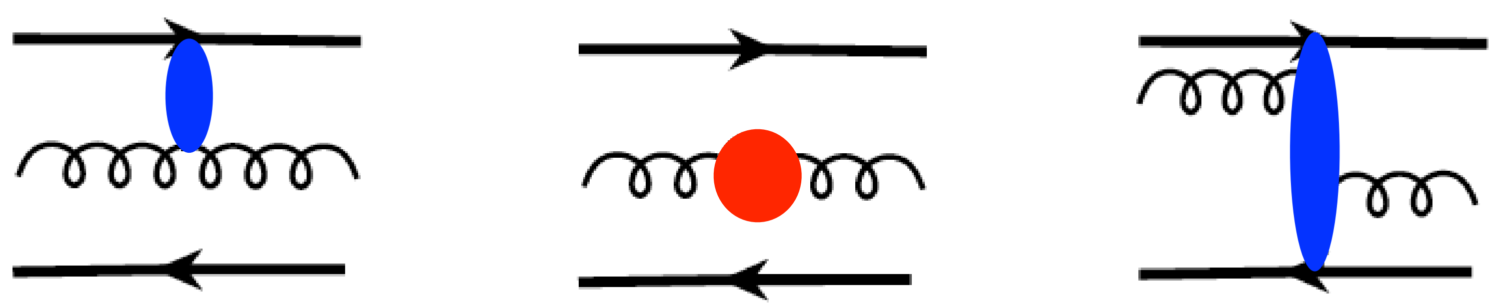
Physical gauge QCD (Hamiltonian)

J^{PC} glue ↓

J^{PC} $Q\bar{Q}$ ↓

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

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



two-body potential

one-body (kinetic + self-energy)

three-body potential

Krupinski, AS (2006)

Guo, Galata, Santopinto, AS (2008)

one, two, …∞ gluons

solitons and bags

confinement, dynamical χ-sym. breaking

Dyson-Schwinger eqs.

poles, cuts and covariant amplitudes

pion form factor

ρ-ω mixing

strangeness in proton

ϕ-production

strangeness in proton

ϕ-production

Phi production as a measure of the strangeness content of the nucleon

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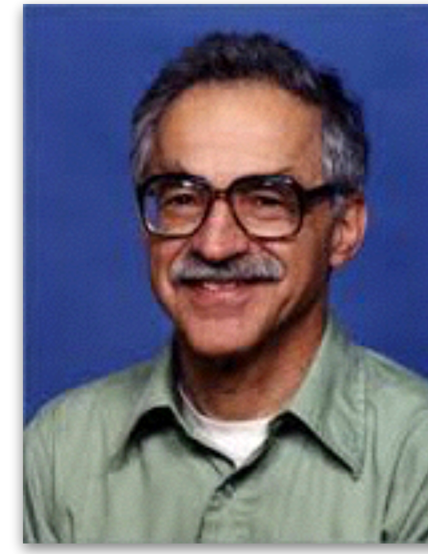
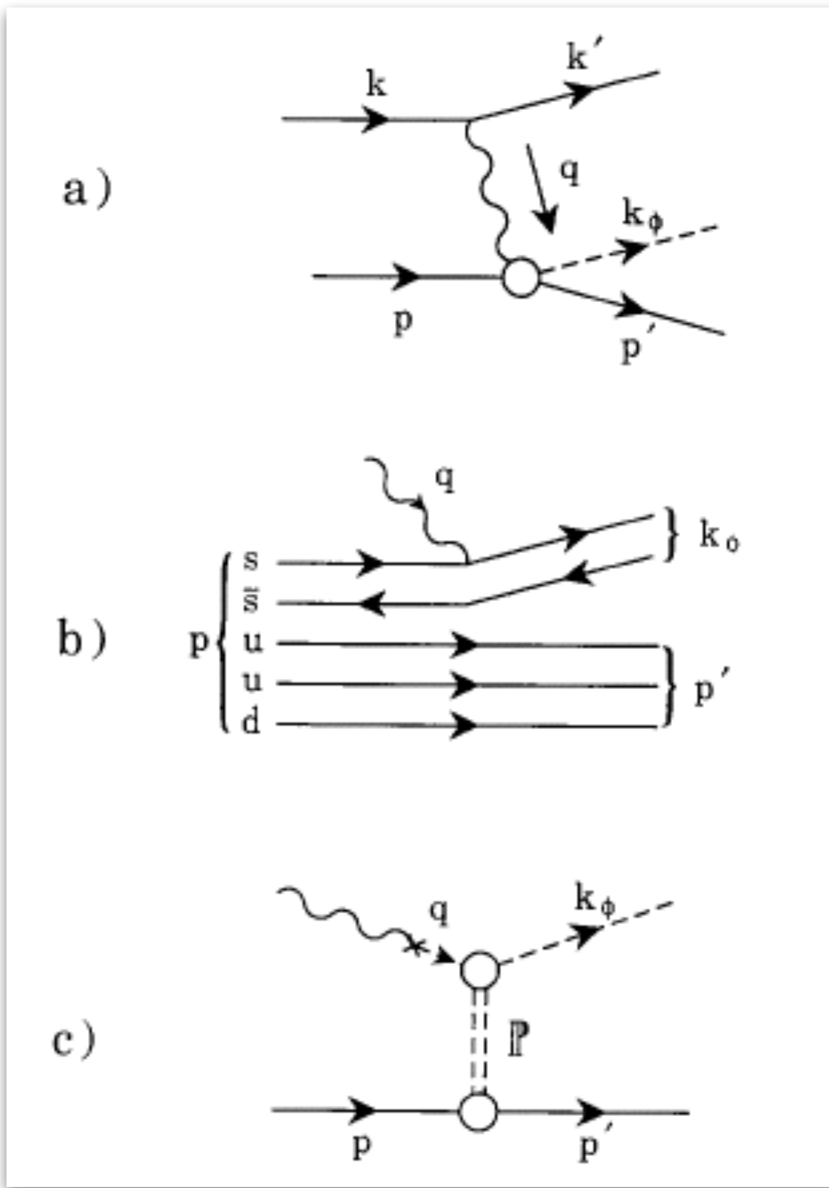
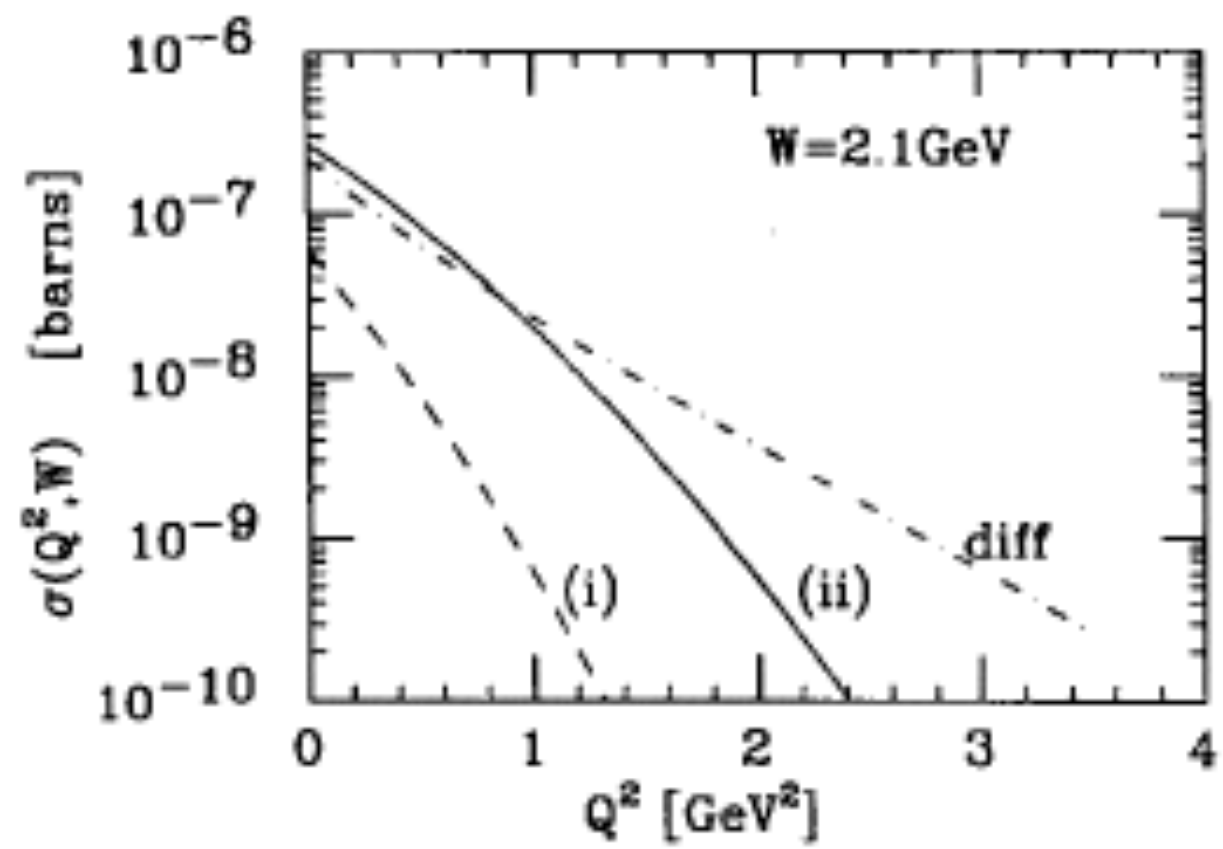
[b] *Institute for Nuclear Theory, HN-12, University of Washington, Seattle, WA 98195, USA*
[c] *Instituto de Fisica Téorica, 01405 São Paulo, SP, Brazil* [1]
[d] *Physics Department and Supercomputer Computations Research Institute* [1]*, Florida State University, Tallahassee, FL 32306-3016, USA*

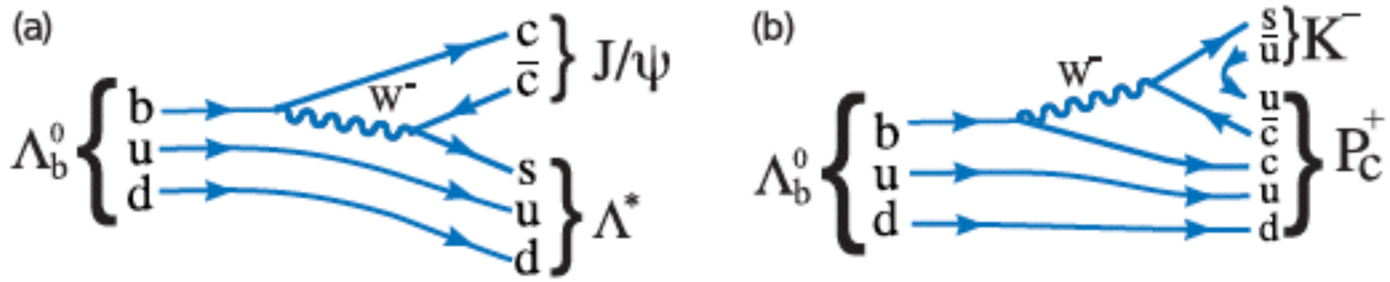




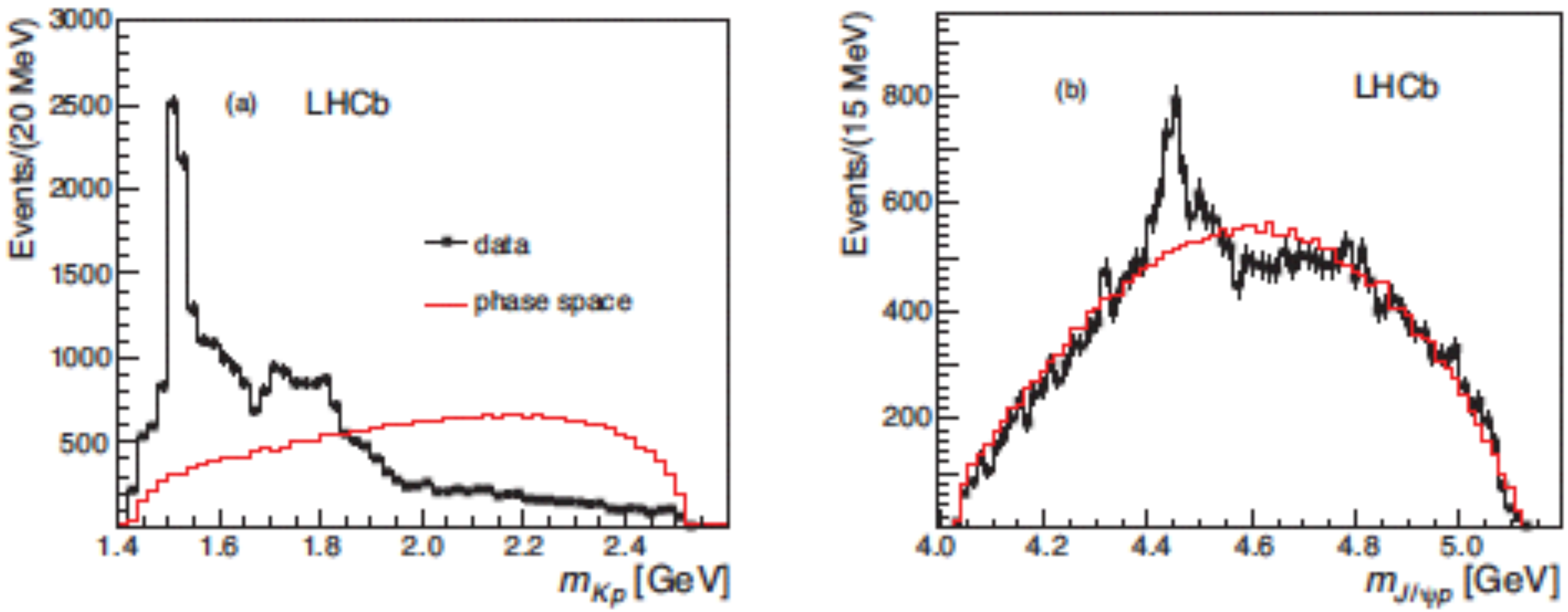


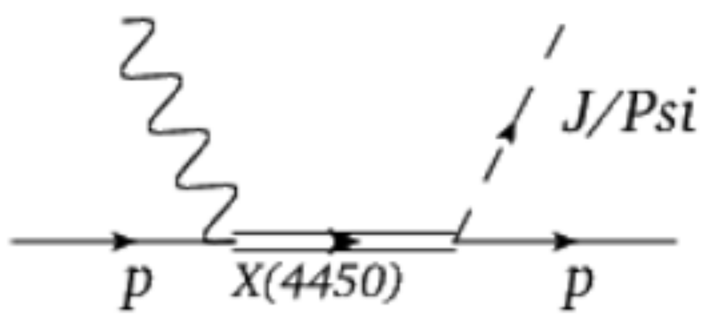
LHCb Pentaquark(s)

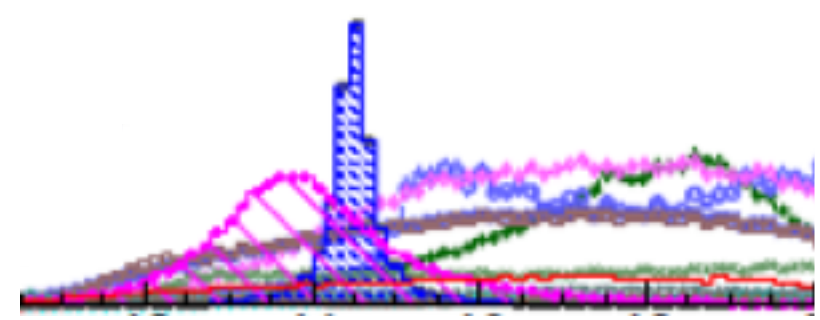
$\Lambda_b \to K^- p J/\psi$



Aaij,,et al., LHCb (2015)



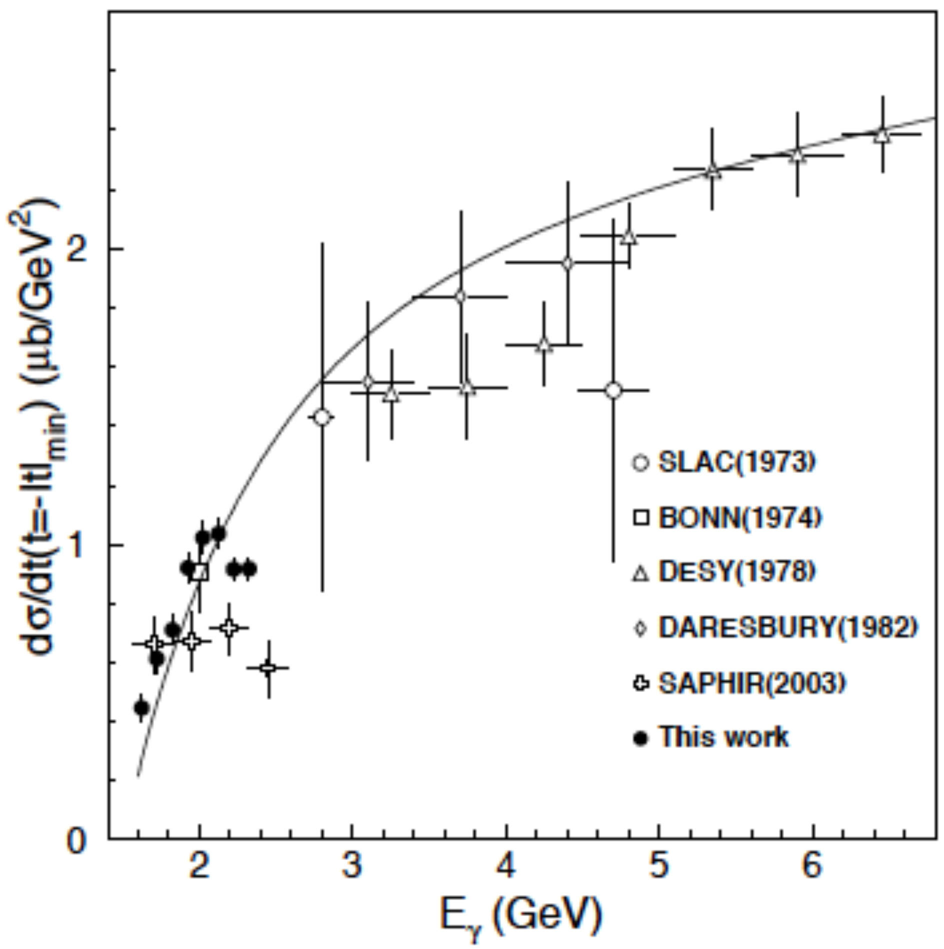




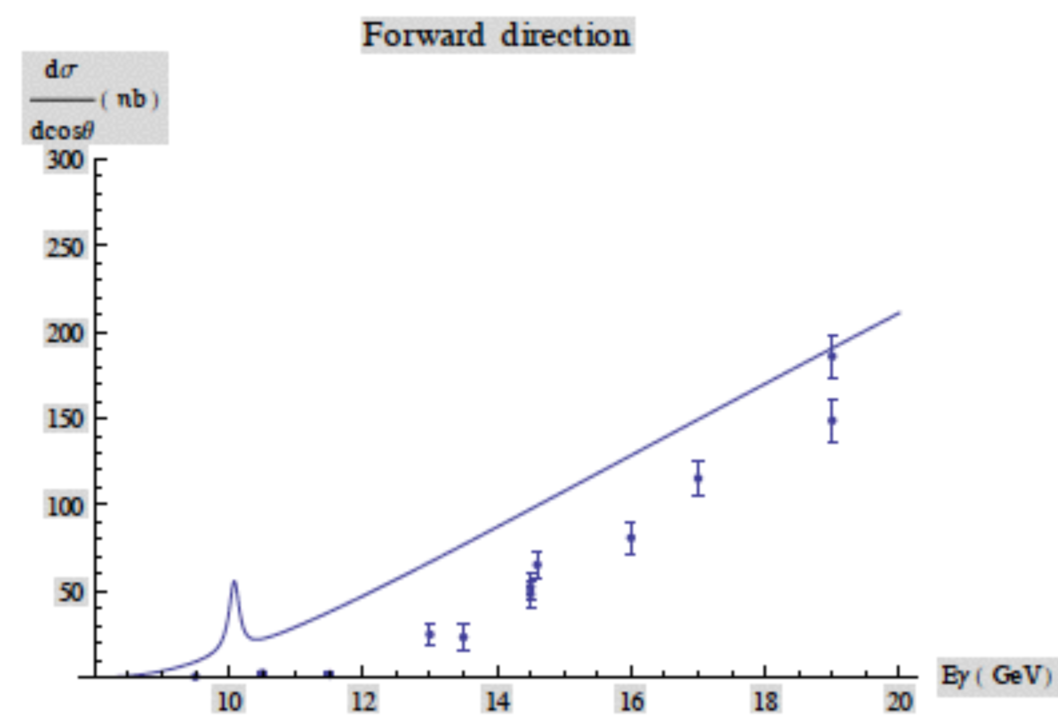
M.Karliner, J.Rosner (2015)

Nucleon bound meson atoms?

Possible signal at Jlab12 ?



$\gamma p \to \phi p$

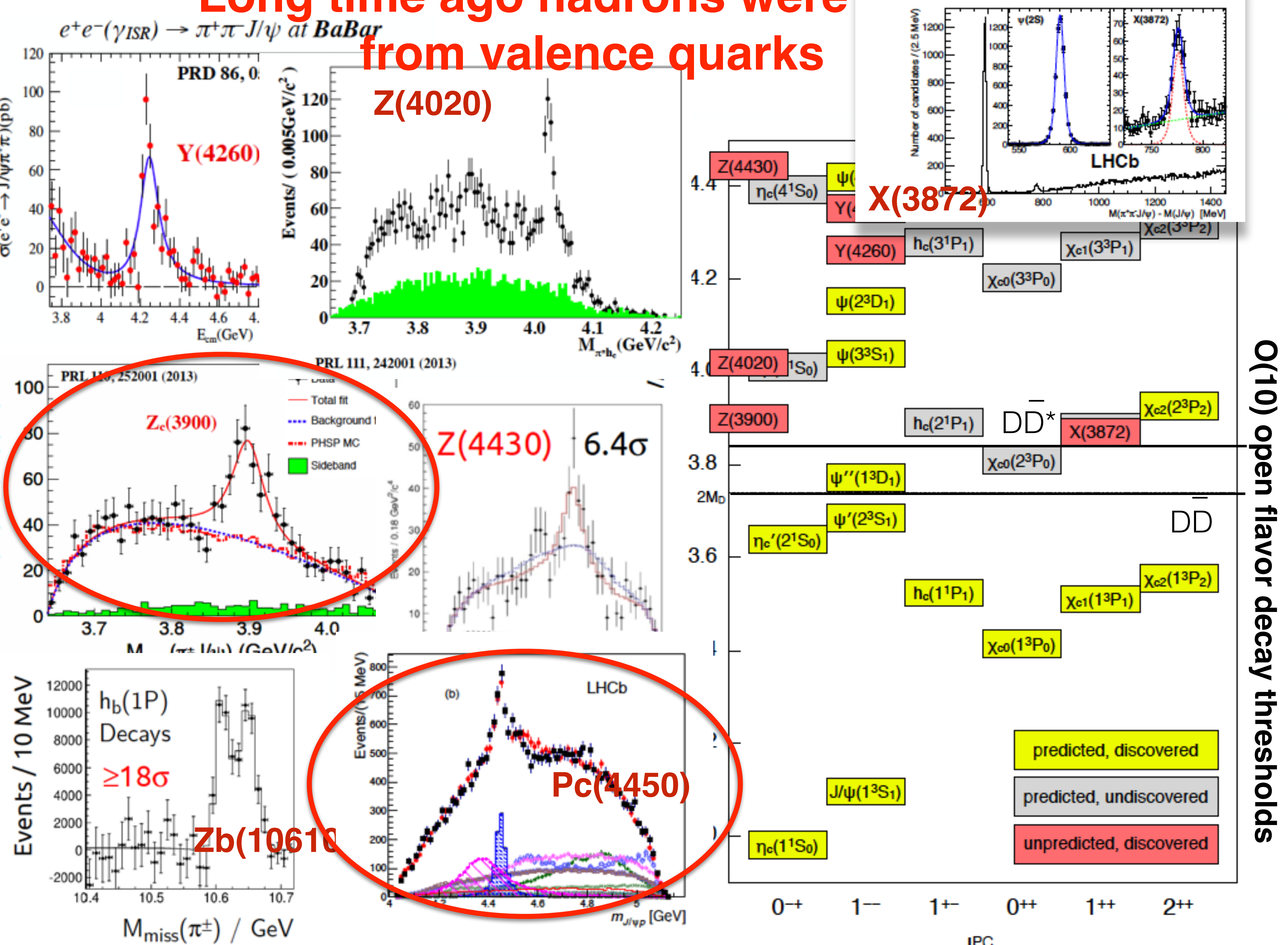


$\gamma p \to J/\psi p$

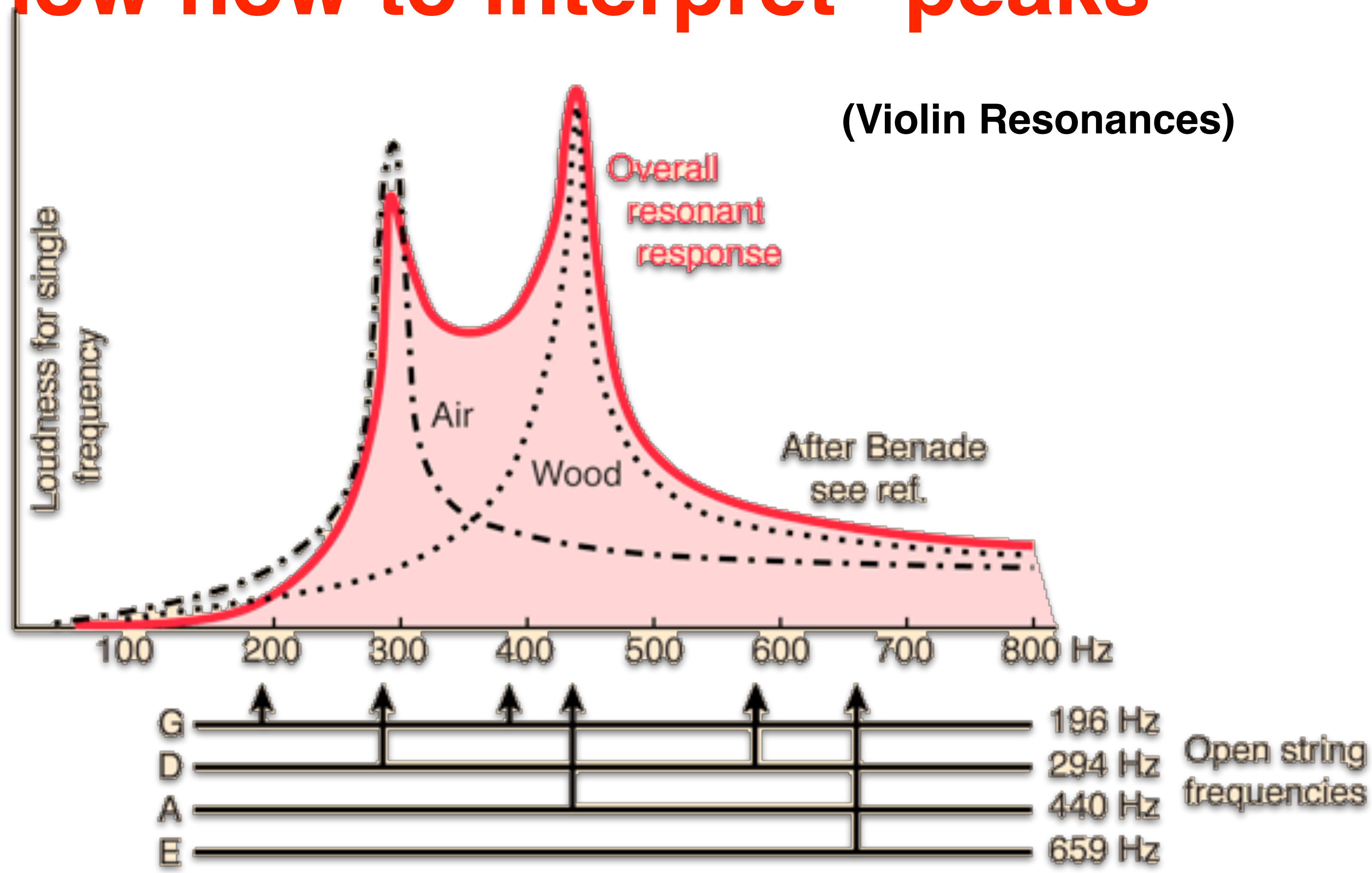
T.Mibe,et al. LEPS (2005)

A.Blin et al. JPAC (in preparation)

Long time ago hadrons were from valence quarks

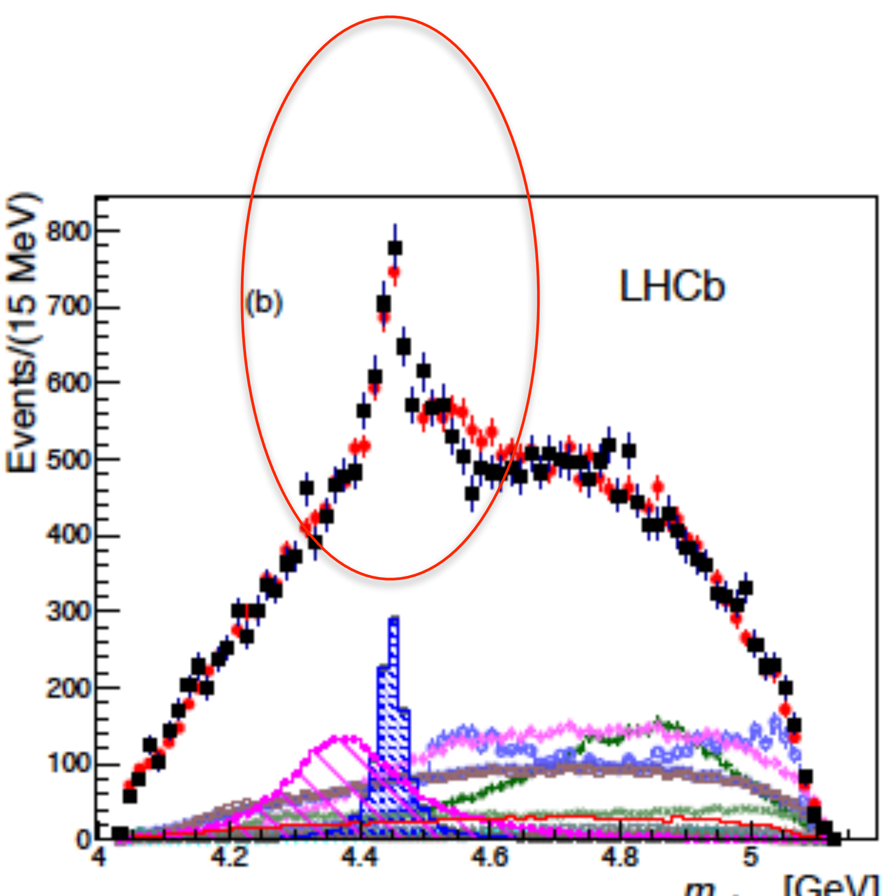


…we need to know how to interpret "peaks"



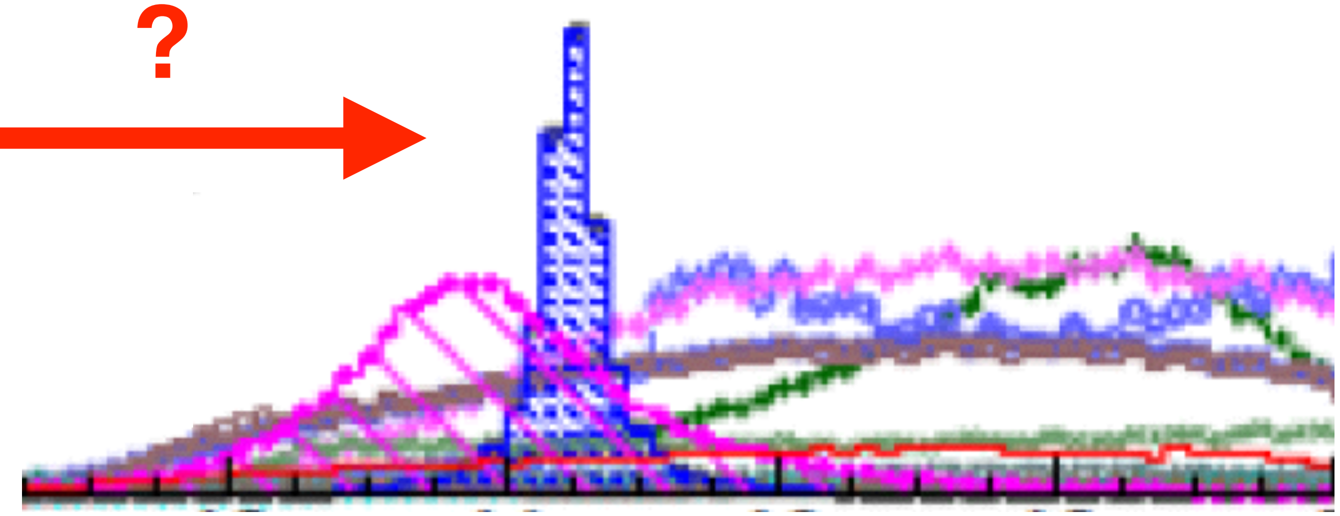
$$\Lambda_b \to K^- p J/\psi$$

a resonance in pJ/ψ ?



?

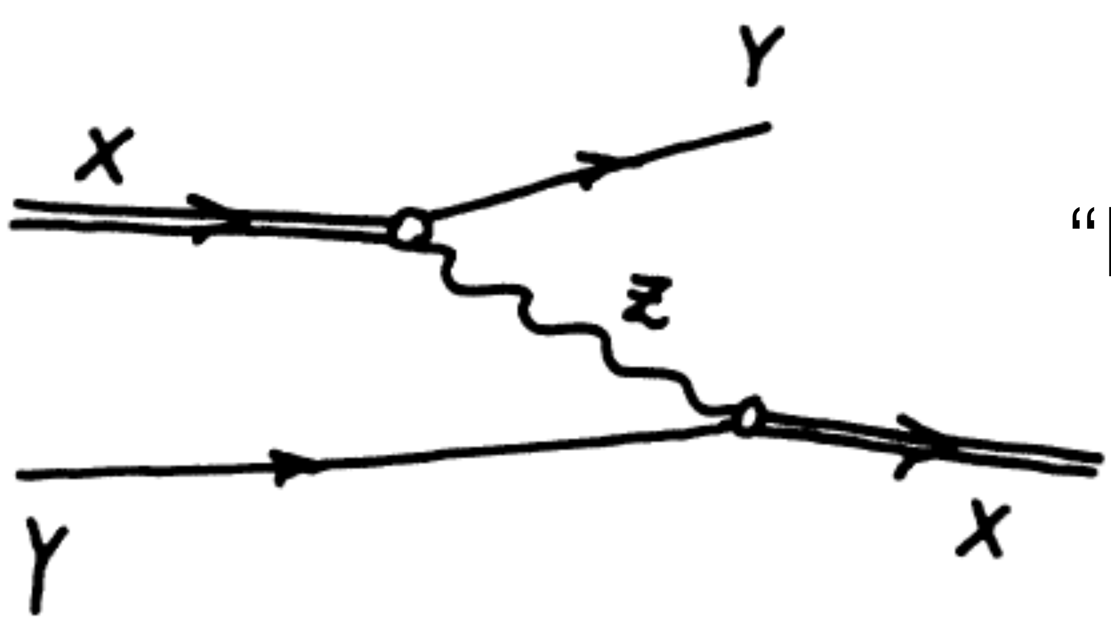
… or a $\overline{K}\, p$ reflection ?



REMARK ON ENERGY PEAKS IN MESON SYSTEMS

M. Nauenberg A. Pais

If the width of particle X is not very large we will stay close to the physical region. This almost singular behavior of $A(s)$ for certain physical s causes the peaking effect to which we refer as an (X, Y, Z) peak.

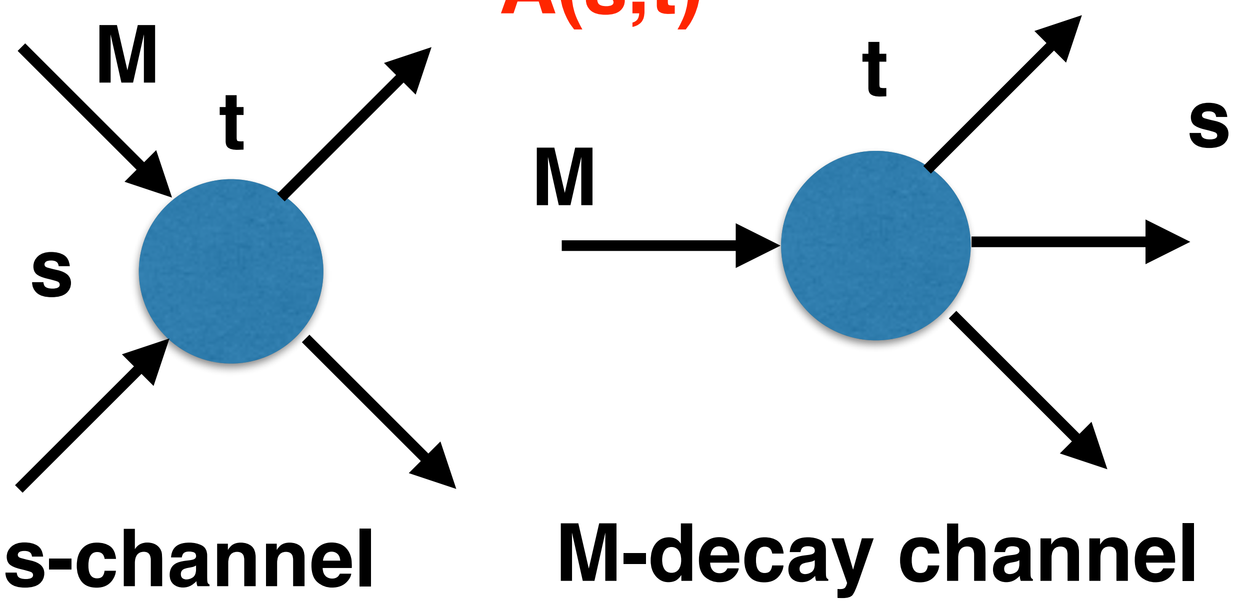


"Peierls mechanism"

XYZ
“dynamics”

S-matrix principles: Crossing, Analyticity, Unitarity

A(s,t)



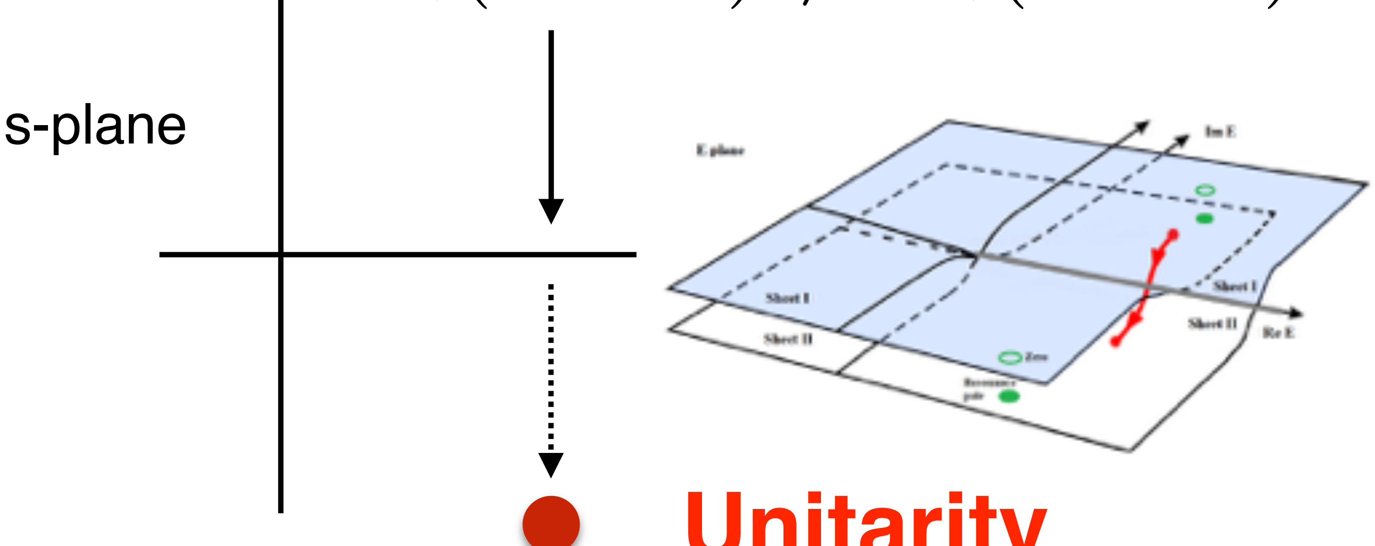
Crossing

$$A(s,t) = \sum_l A_l(s) P_l(z_s)$$

Analyticity

$$A_l(s) = \lim_{\epsilon \to 0} A_l(s + i\epsilon)$$

$$A_l(s+i\epsilon) \neq A_l(s-i\epsilon)$$

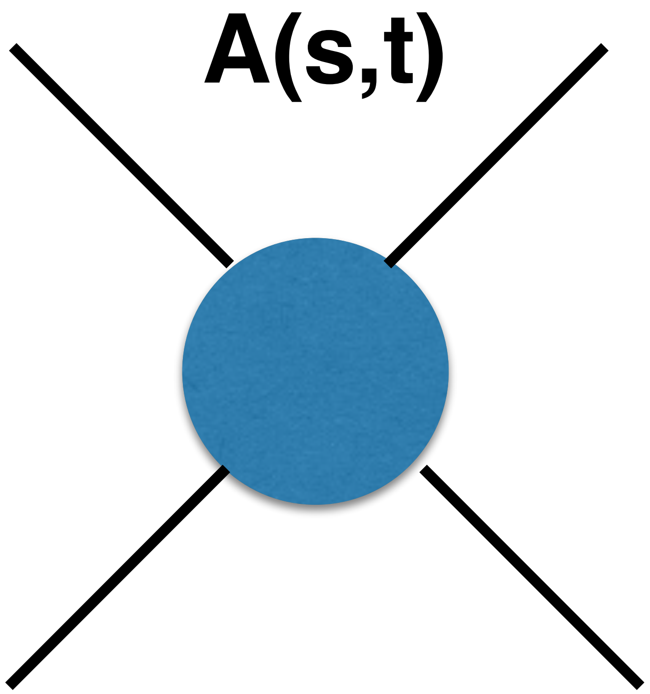


Unitarity

bumps/peaks on the real axis (experiment) come from singularities in physical sheets: cuts and unphysical sheets :poles

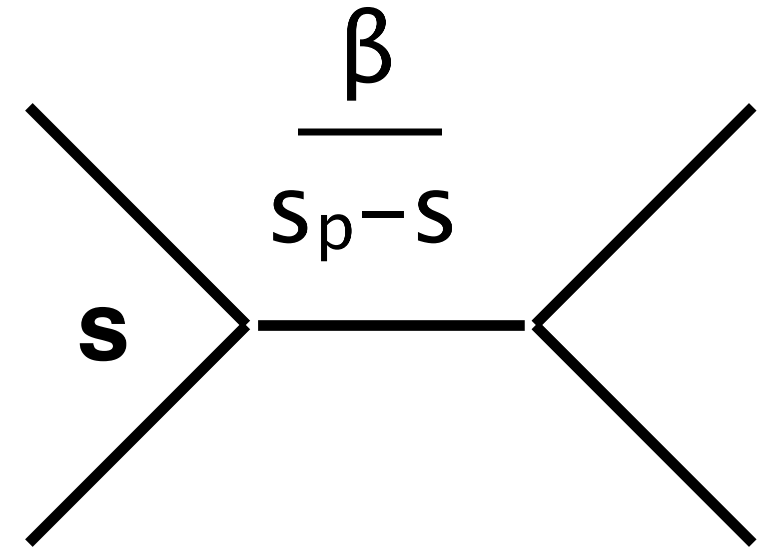
poles come from QCD

Origin of singularities (exchanges constrained by unitarity)

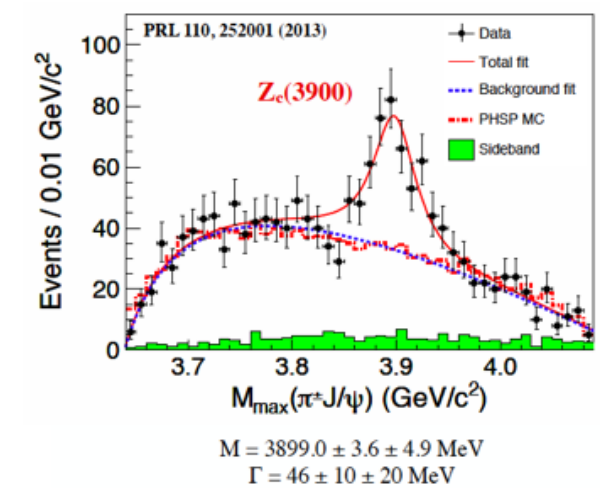


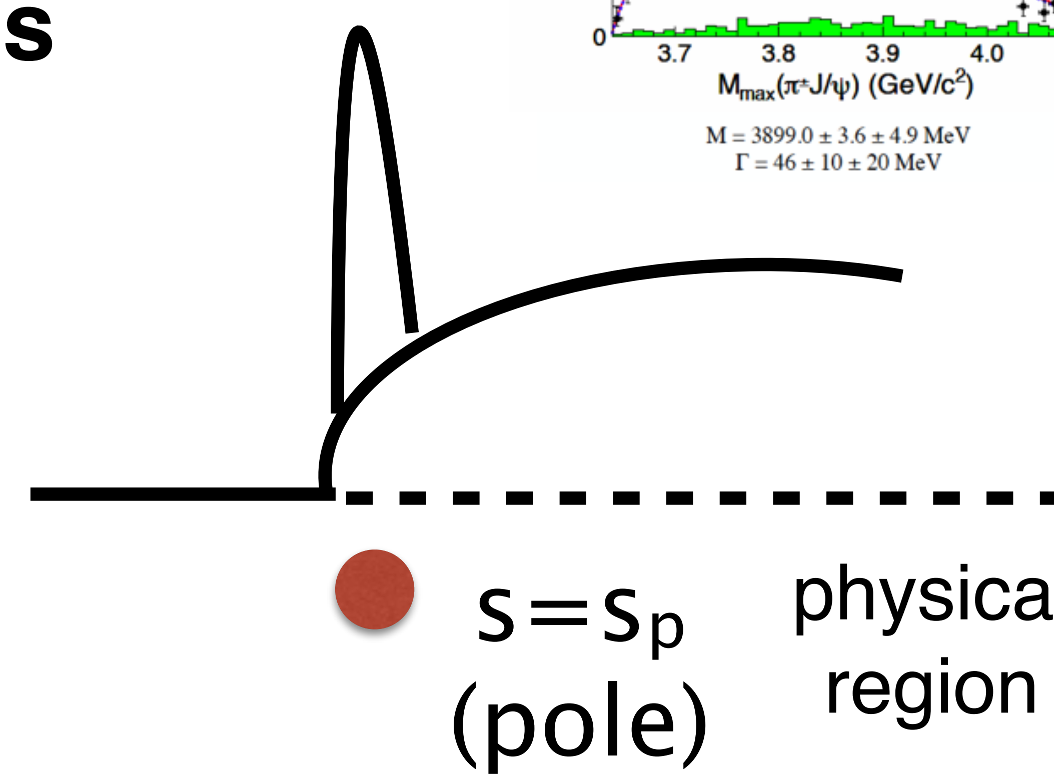
$$\overbrace{\Lambda_b \to \underbrace{K^- p J/\psi}_{s}}^{t}$$

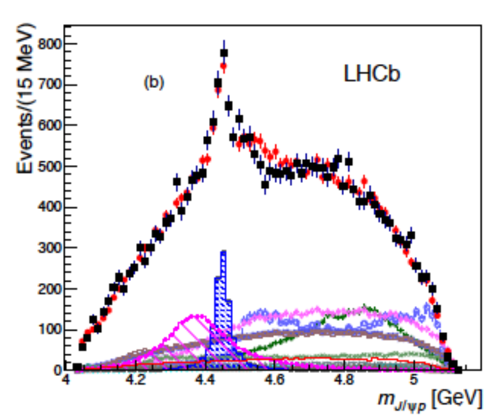
$$\overbrace{Y(4260) \to \underbrace{\pi^+\pi^- J/\psi}_{s}}^{t}$$



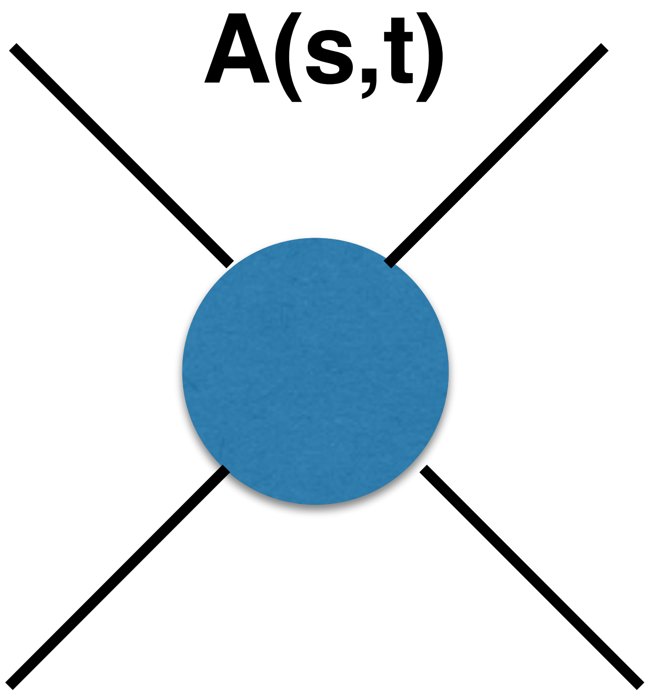
$A_l(s)$







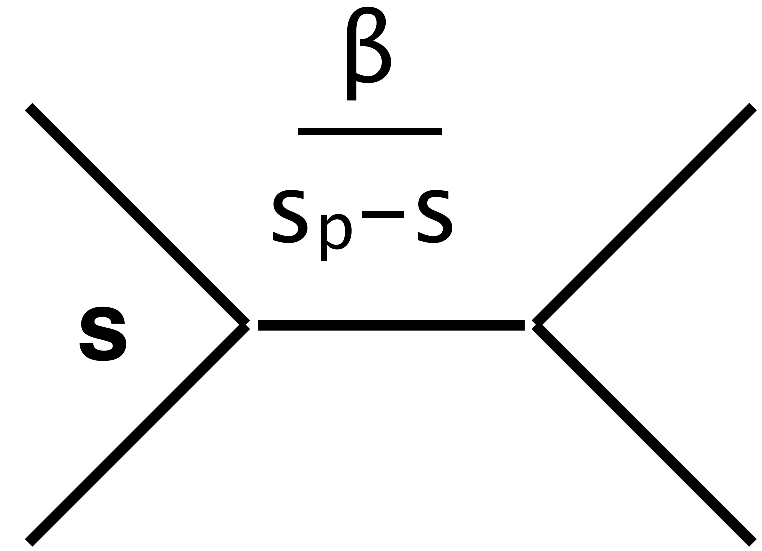
Origin of singularities (exchanges constrained by unitarity)



t

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

s

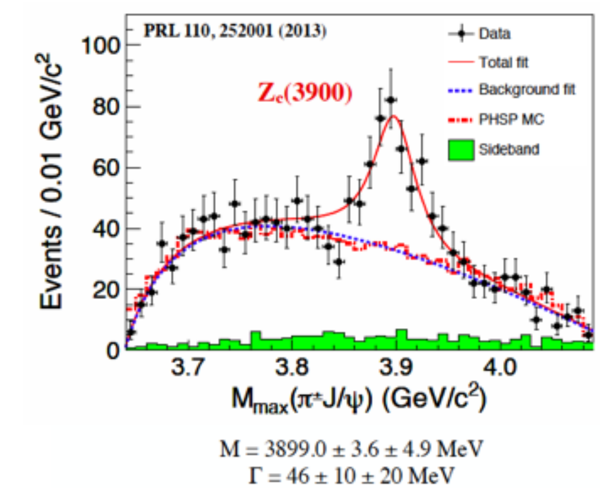


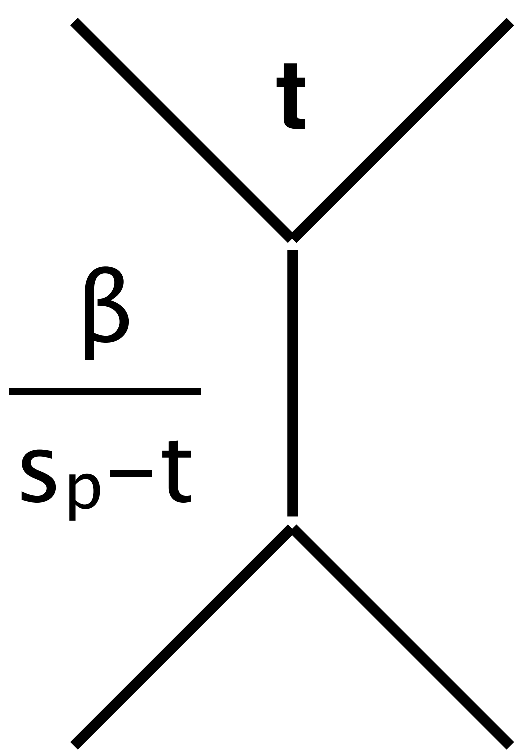
t

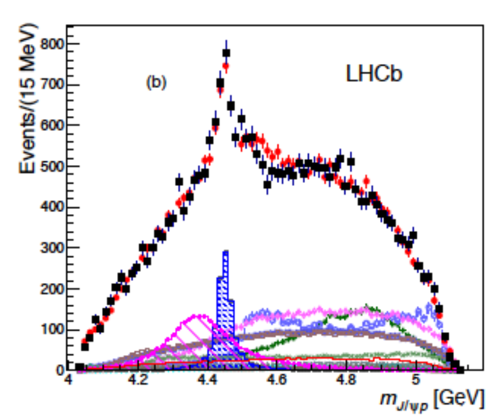
$$Y(4260) \to \pi^+ \pi^- J/\psi$$

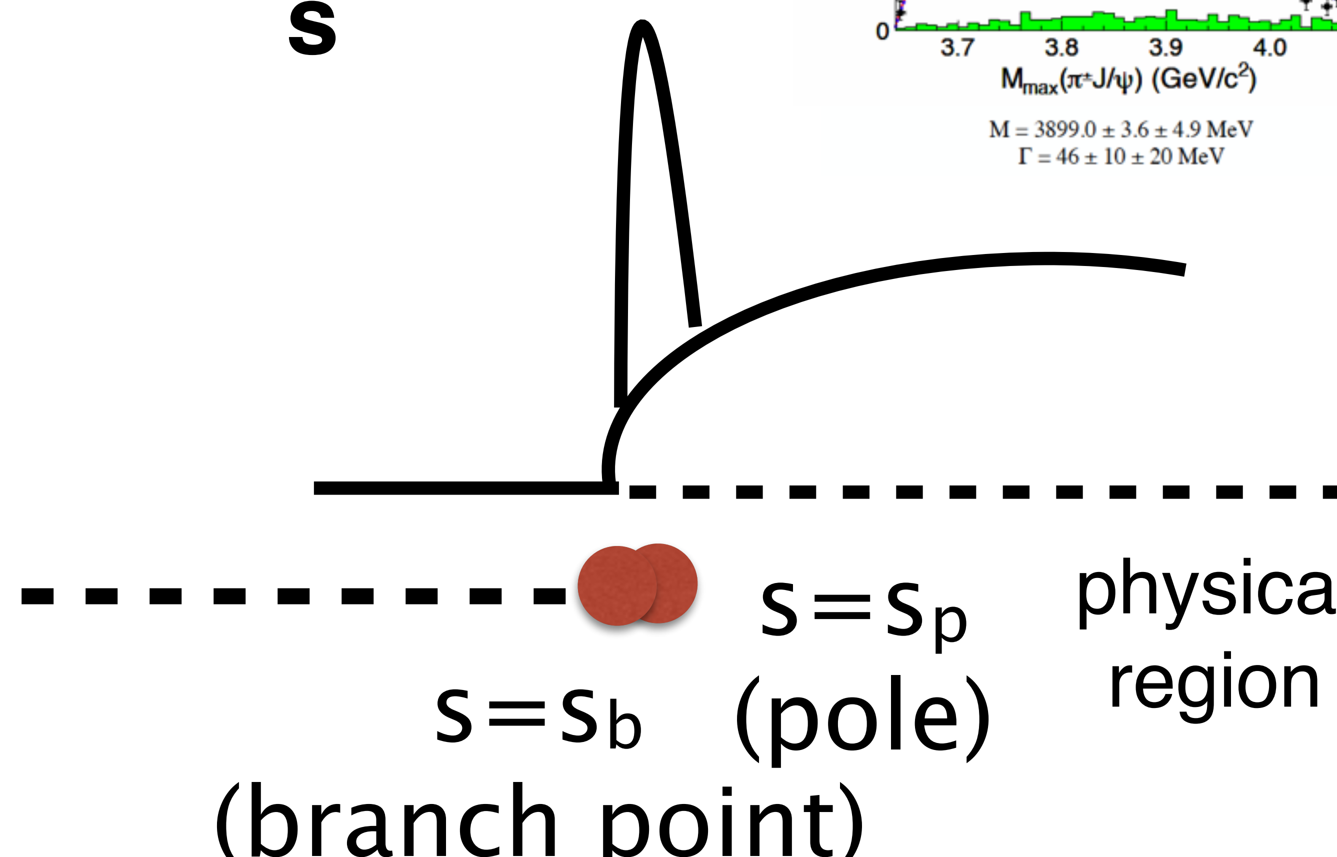
s

A$_l$(s)

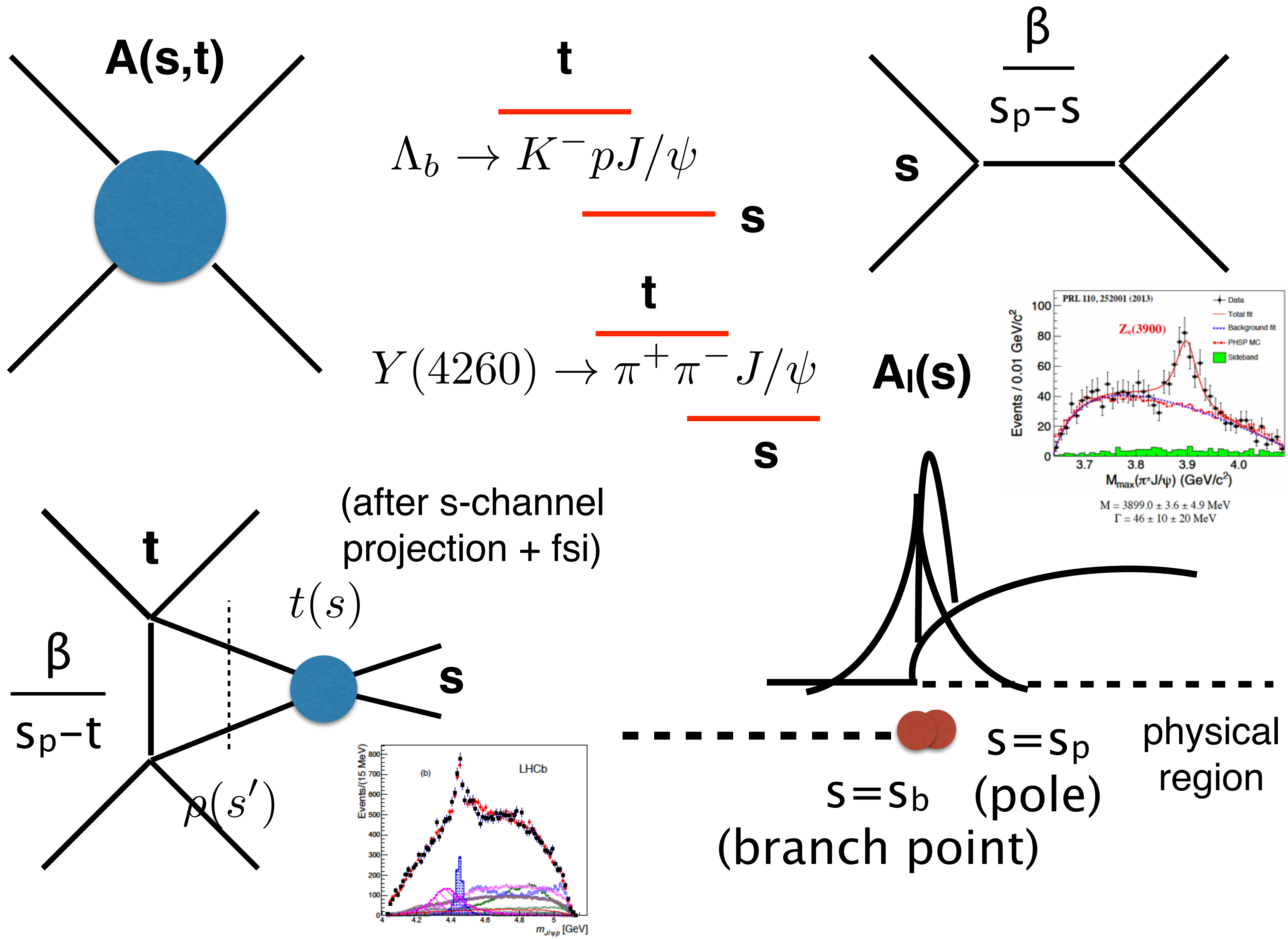








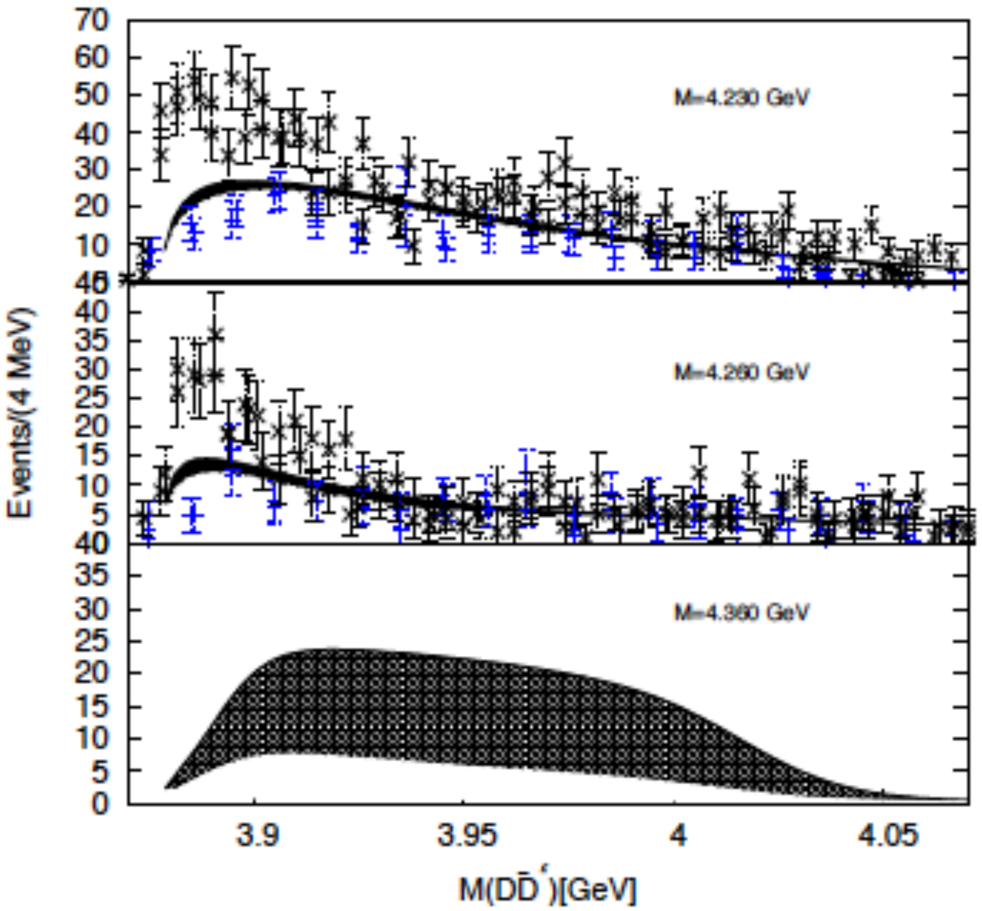
Origin of singularities (exchanges constrained by unitarity)

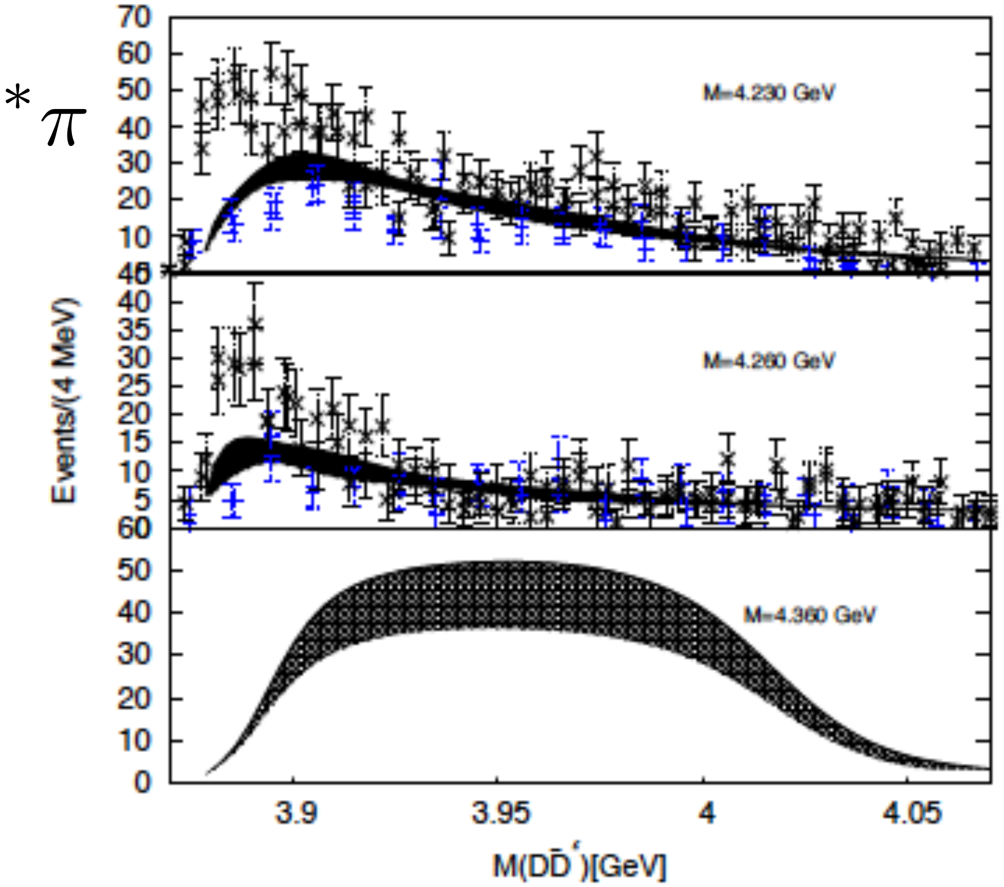


with resonance

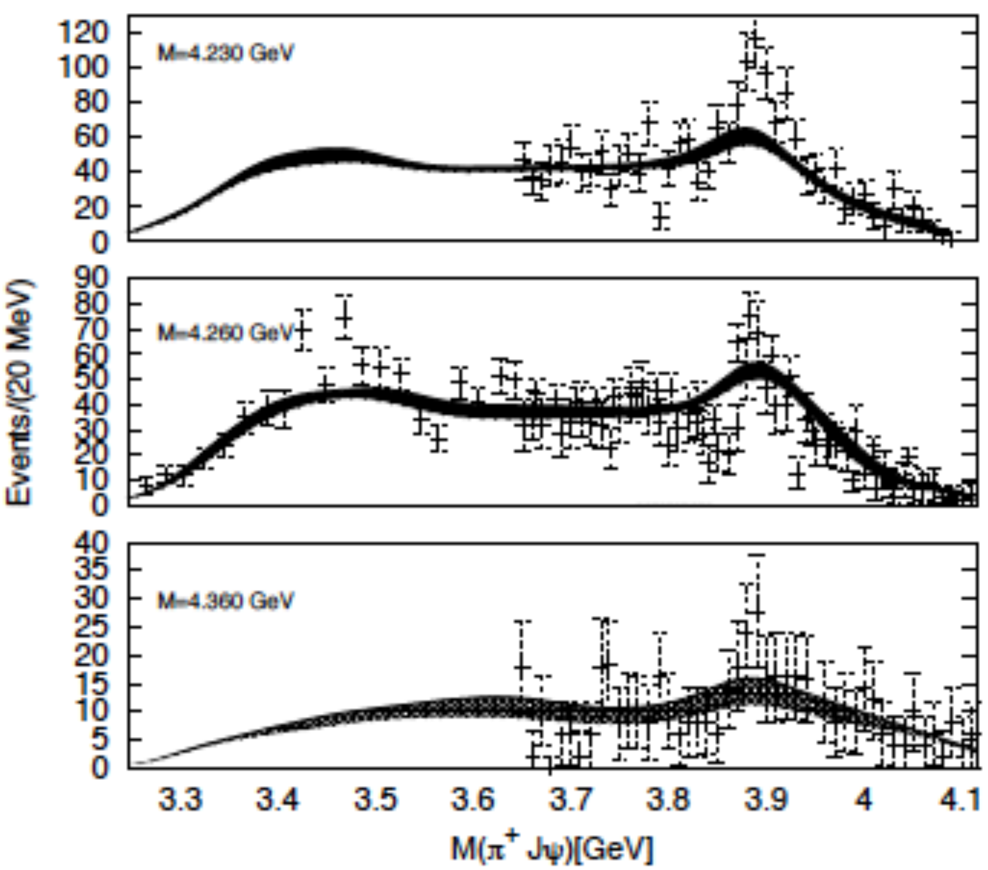
without resonance

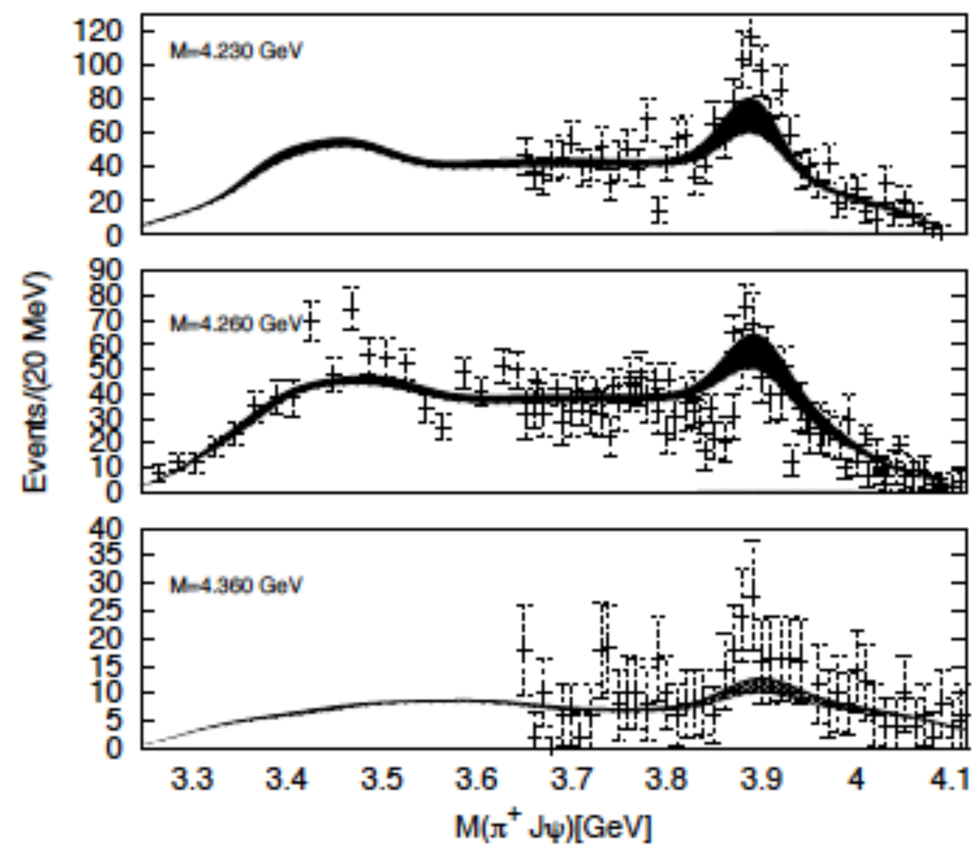
$$Y(4260) \to D\bar{D}^*\pi$$



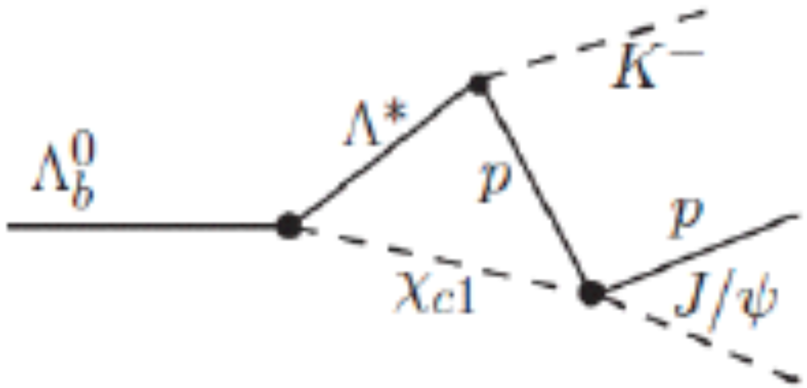


$$Y(4260) \to \pi\pi J/\psi$$





The key to the XYZ phenomena are the many nearby channels



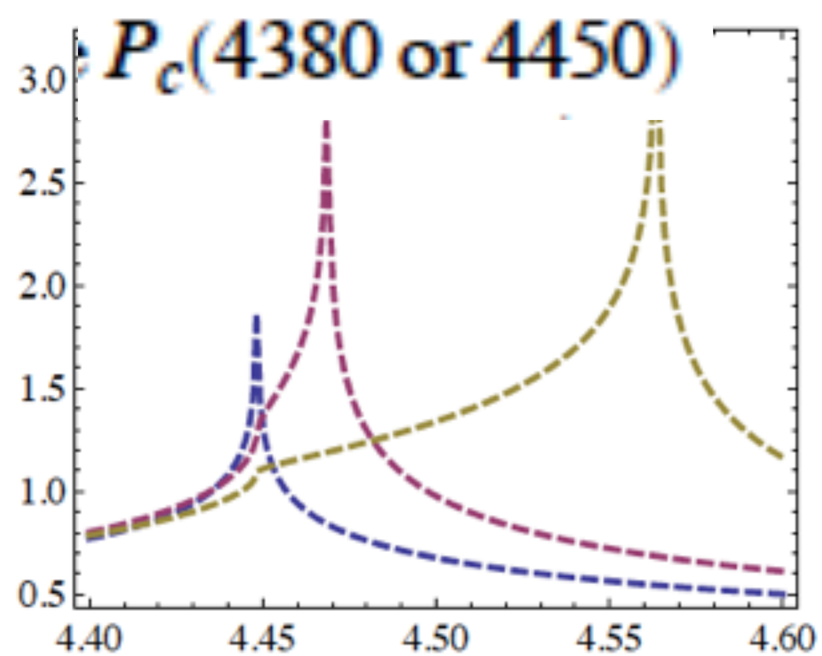
$$M_{\Lambda_b^0} = 5.6195,\ \mu_{K^-} = 0.4937,\ m_1 = m_{\chi_{c1}} = 3.510,\ m_2 = m_p = 0.93827$$

$\lambda = m_{\Lambda^*} = 1.89$ (they take)

Coleman-Norton requires

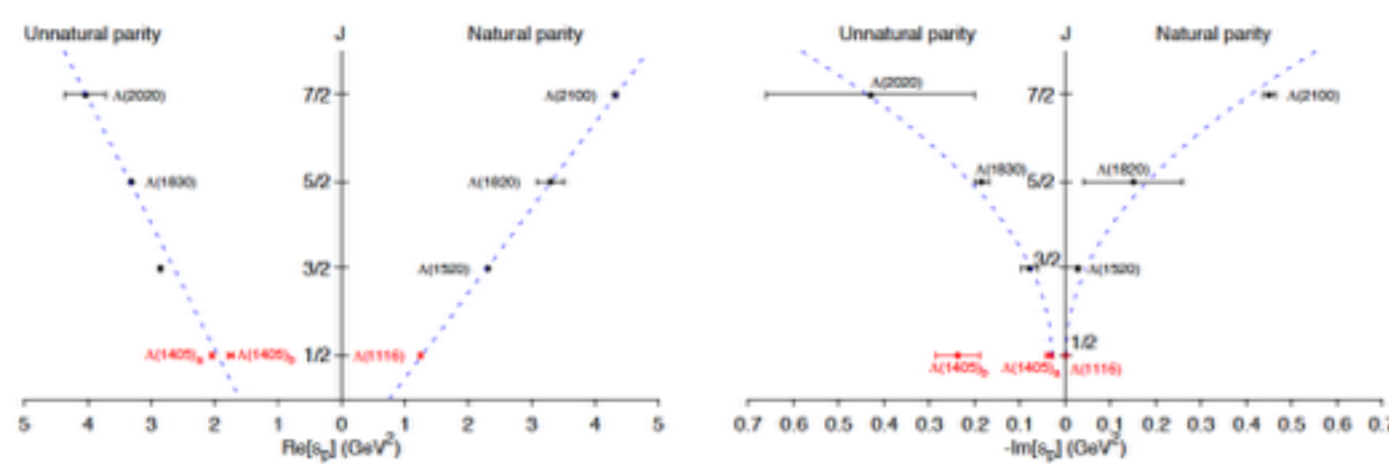
$$1.89 < \lambda < 2.11\ \text{GeV}$$

$$4.45 < \sqrt{s_{\text{peak}}} < 4.65\ \text{GeV}$$



Axes : Abs[$T(s)$], $\sqrt{s}$

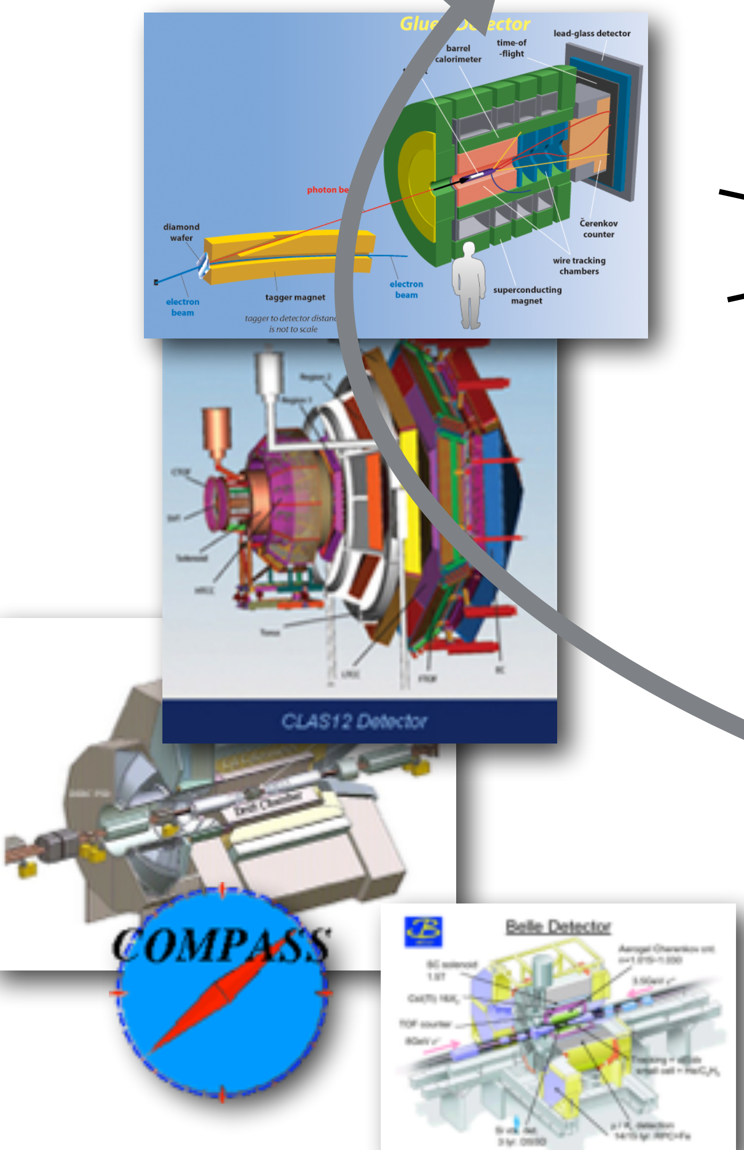
Lines : blue ($\lambda = 1.89$ GeV), red ($\lambda = 1.99$ GeV), yellow ($\lambda = 2.09$

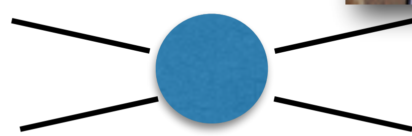


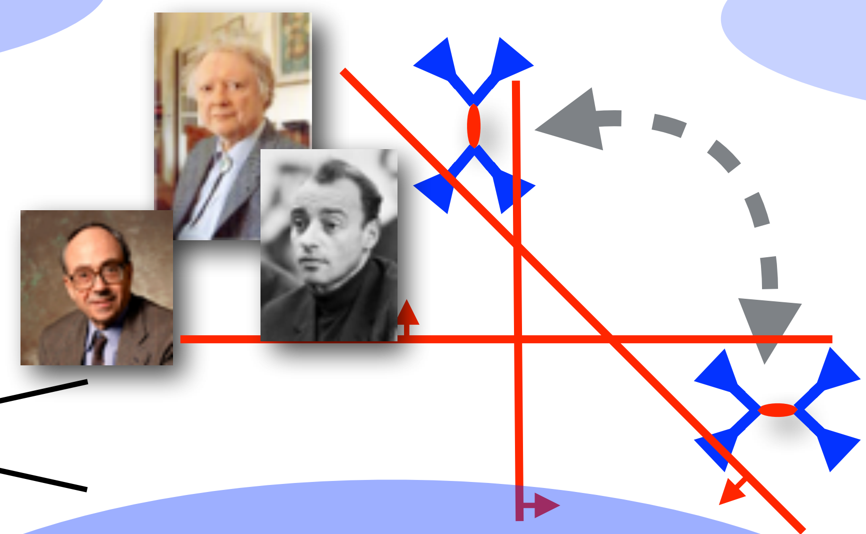
Joint Physics Analysis Center

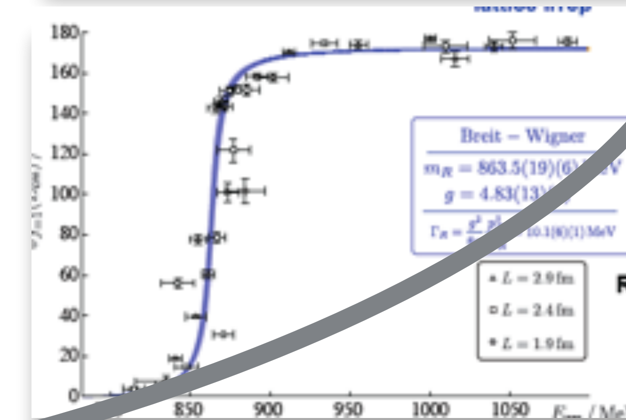
Events, X-sections,MC

QCD Predictions









Amplitude analysis:
based on S-matrix principles

JPAC : Example of Analysis Projects

Light meson decays and light quark resonance

- **$\omega/\phi \to 3\pi, \pi\gamma$ (dispersive)**
- $\omega \to 3\pi$ (Veneziano, B4)
- $\eta \to 3\pi$, $\eta'/f1 \to \eta\pi\pi$, (Khuri-Treiman, B4)
- $J/\Psi \to \gamma\pi0\pi0$

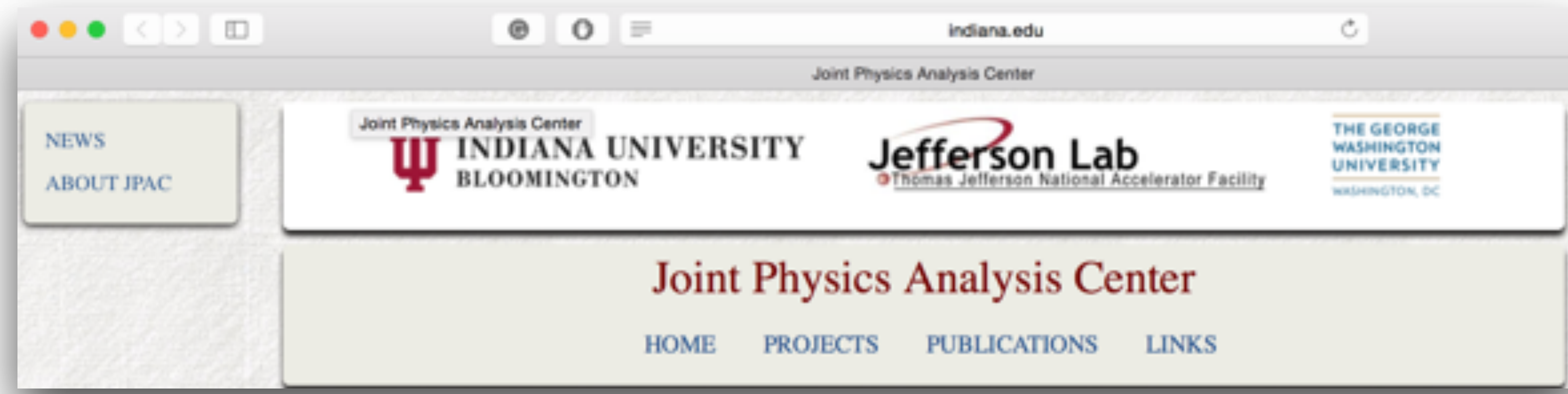
Photo-production: (production models, FESR and duality)

- $\gamma p \to \pi0p$
- $\gamma p \to$ pK+K- (and Kp)
- $\gamma p \to \pi+\pi-p$, $\pi0\eta p$, ωp

Launched in the Fall of 2013
>20 analysis/papers published

Exotica and XYZ's:

- **$\pi-p \to \pi-\eta p$ & $\pi-p \to \pi-\eta' p$ (FESR)**
- **$B^0 \to \Psi'\ \pi-\ K^+\ u$, $\Psi(4260) \to J/\Psi\ \pi+\pi-$, $\Lambda_b \to K-\ pJ/\Psi$**
- $J/\Psi \to 3\pi$, $KK\pi$ (Veneziano, B4)



http://www.indiana.edu/~jpac/

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Mike Pennington (JLab)
Tim Londergan (IU)
Geoffrey Fox (IU)
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GlueX collaboration
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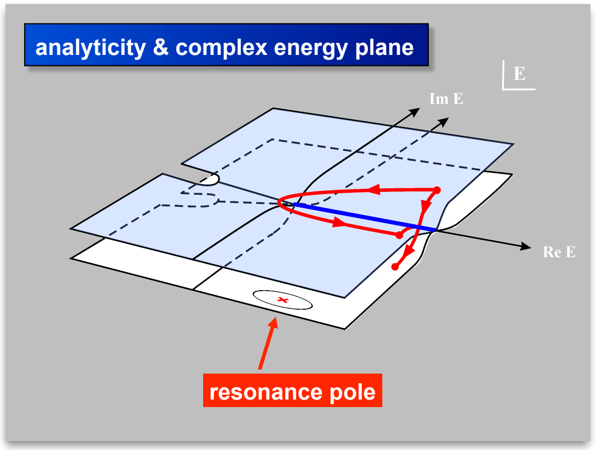


special thanks to Vincent Mathieu

```
      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

      t1 = (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
```

$\gamma p \to \pi^0 p$
- Formalism
- Model
- Resources
- Run

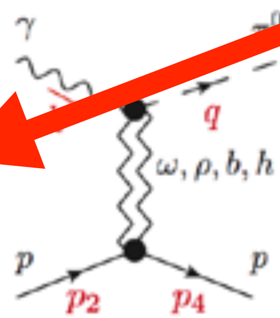
Joint Physics Analysis Center

HOME PROJECTS PUBLICATIONS LINKS

INDIANA UNIVERSITY BLOOMINGTON — Jefferson Lab, Thomas Jefferson National Accelerator Facility — THE GEORGE WASHINGTON UNIVERSITY, WASHINGTON, DC

$\gamma p \to \pi^0 p$

We present the model published in [Mat15a] .
The differential cross section for $\gamma p \to \pi^0 p$ is computed with Regge amplitudes in the domain $E_\gamma \geq 4$ GeV and $0.01 \leq |t| \leq 3$ (in GeV^2).
The formulas can be extrapolated outside these intervals.
We use the CGLN invariant amplitudes A_i defined in [Chew57a].
See the section Formalism for the definition of the variables.
The fitting procedure is detailed in [Mat15a] . We report here only the main feature of the model.



Formalism

The differential cross section is a function of 2 variables. The first is the beam energy in the laboratory frame E_γ (in GeV) or the total energy squared s (in GeV^2). The second is the cosine of the s... ...ng angle in the rest frame $\cos\theta$ or the momentum transfered squared t (in GeV^2).
The momenta of the particles are k (photon), q (pion), p_2 (target) and p_4 (recoil). The pion mass is μ and the proton mass is M.
The Mandelstam variables, $s = (k+p_2)^2, t = (k-q)^2, u = (k-p_4)^2$ are related through $s+t+u = 2M^2 + \mu^2$.

The differential cross section is expressed in term of the parity conserving helicity invariant amplitudes in the t −channel F_i

$$\frac{d\sigma}{dt} = \frac{389.4}{64\pi}\frac{k_t^2}{4M^2E_\gamma^2}\left[2\sin^2\theta_t\left(t|F_1|^2 + 4p_t^2|F_2|^2\right) + (1 - \cos \ldots\right.$$

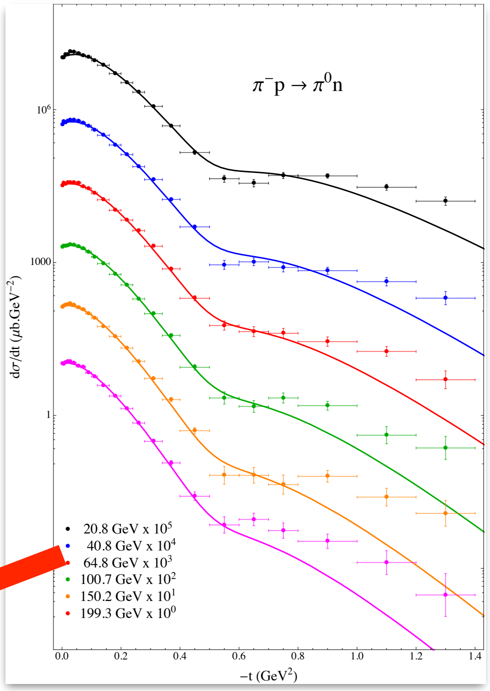
The differential cross section is expressed in μb/GeV^2. We used $(\hbar c)^2$ ...
The t −channel is the rest frame of the process $\gamma\pi^0 \to p\bar{p}$.
In the t −channel, the momenta of the nucleon p_t and the pion k_t and ...

$$k_t = \frac{1}{2}\sqrt{t - 4M^2}, \qquad q_t = \frac{t - \ldots}{2\ldots}$$

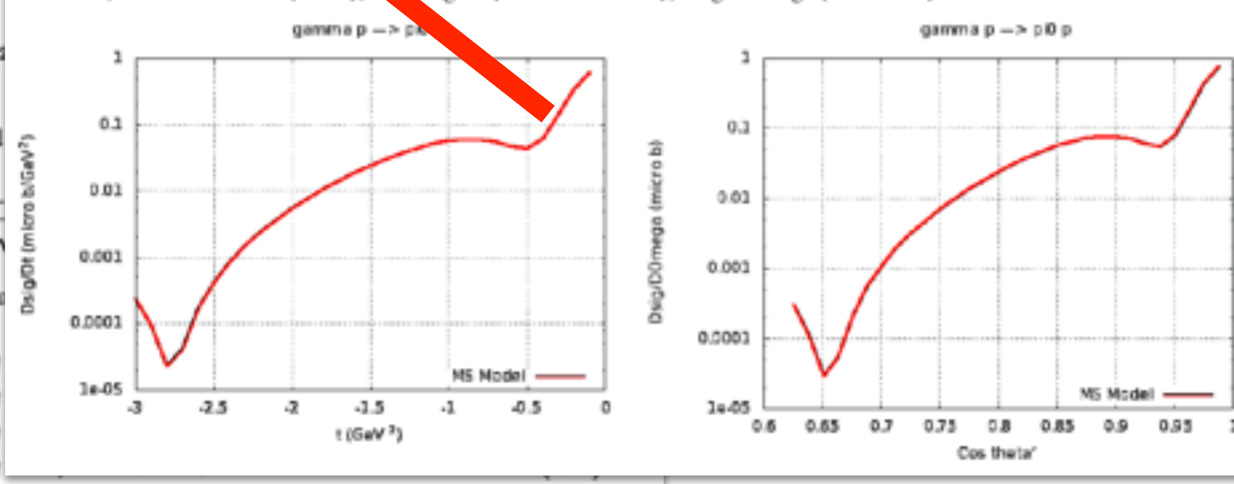
The invariant amplitudes F_i are related through the CGLN A_i amplitu...

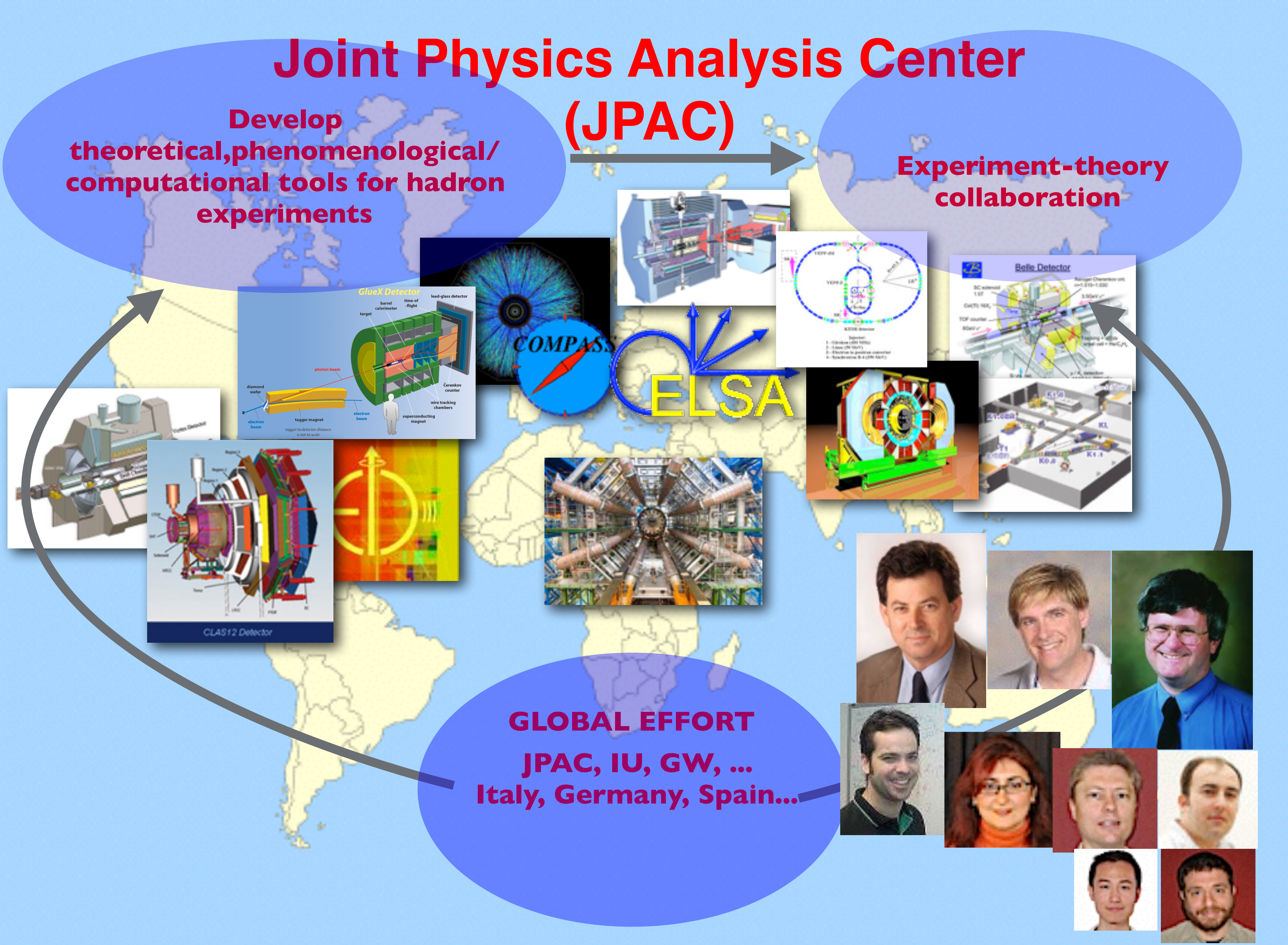
$$F_1 = -A_1 + 2MA_4, \quad \eta \ldots$$
$$F_2 = A_1 + tA_2, \quad \eta \ldots$$
$$F_3 = 2MA_1 - tA_4, \quad \eta \ldots$$
$$F_4 = A_3 \quad \eta \ldots$$

The F_i amplitudes have good quantum numbers of the t −channel, the naturality $\eta = P(-1)^J$ and the product CP.



Download the output file, the plot with Ox=t , the plot with Ox=cos .
In the file, the columns are: t (GeV^2), ..., Dsig/Dt (micro barn/GeV^2), Dsig/DOmega (micro barn)

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computational tools for hadron
experiments
Experiment-theory
collaboration
GlueX Detector
COMPASS
ELSA
Belle Detector
CLAS12 Detector
GLOBAL EFFORT
JPAC, IU, GW, ...
Italy, Germany, Spain...

Thank you

and happy birthday Tony !