On a possible Interpretation of the 5q signal

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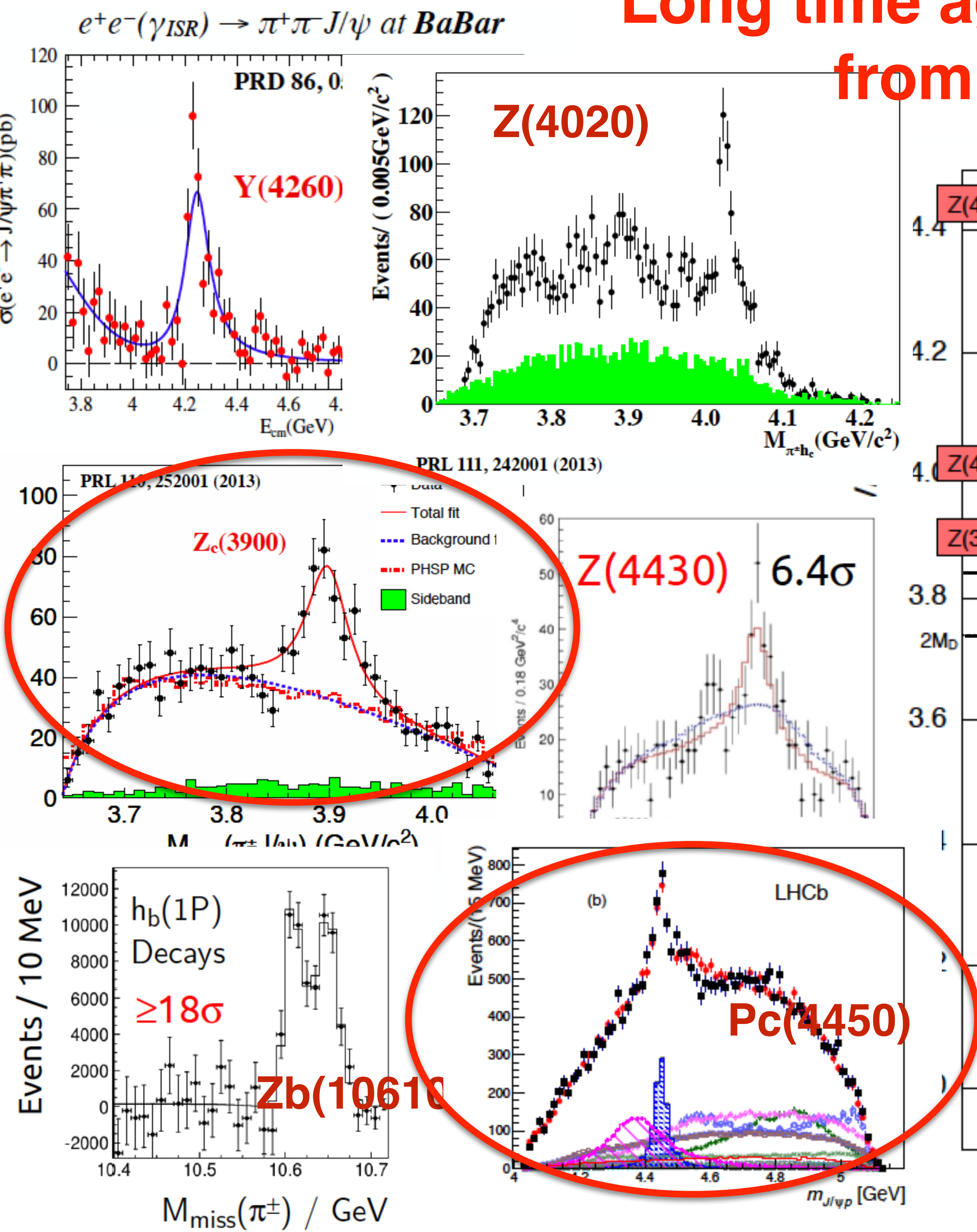
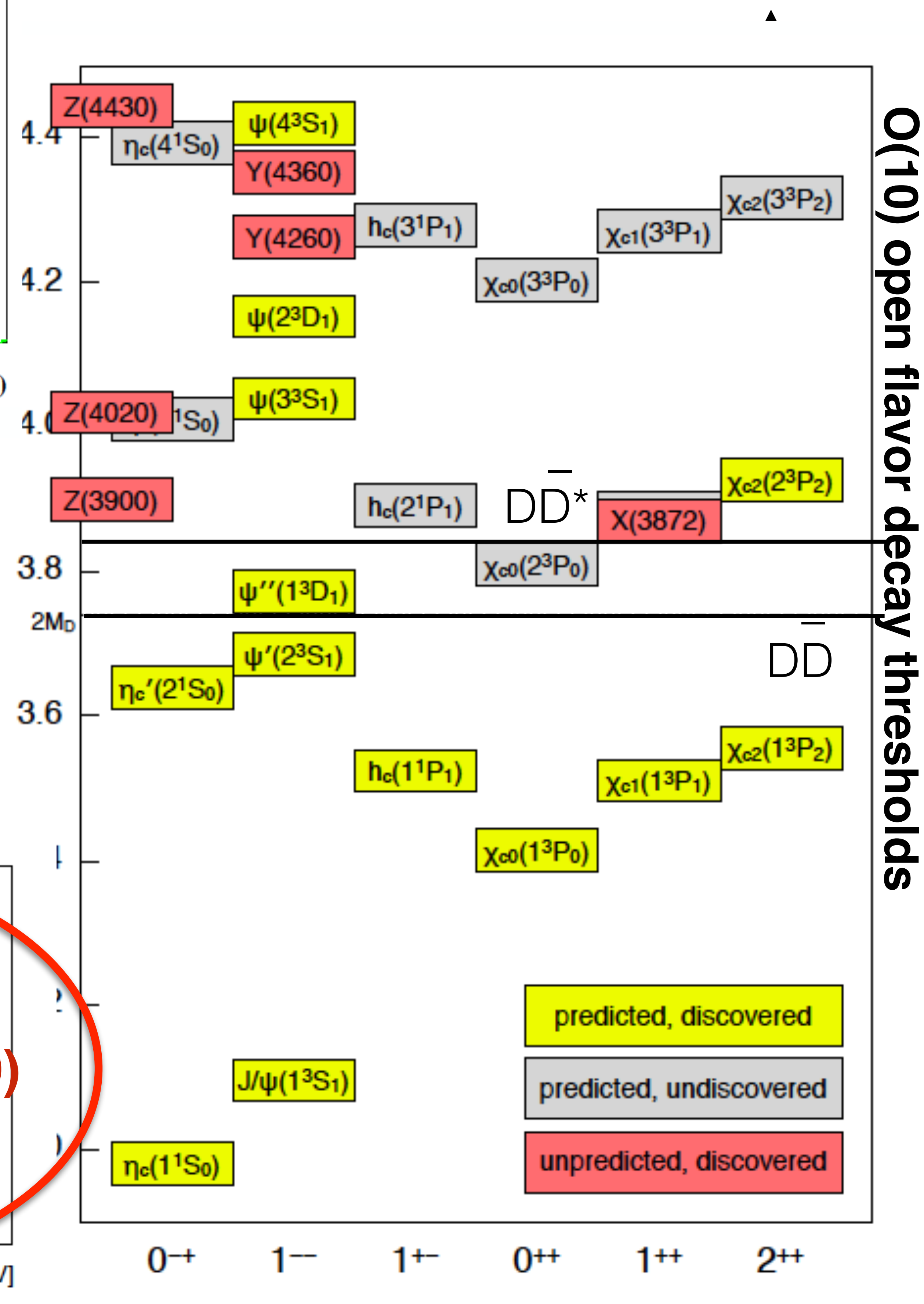
Evidence of new hadrons

Role of reaction theory

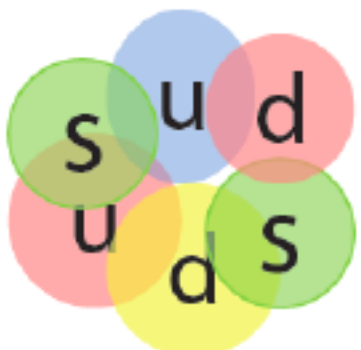
The Pc and the Z's

Long time ago hadrons were made from valence quarks





before we can address the following question…

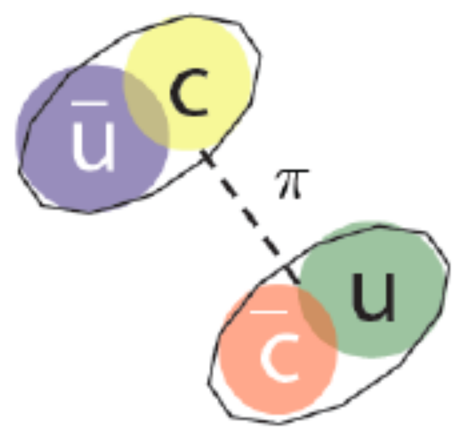


dibaryon

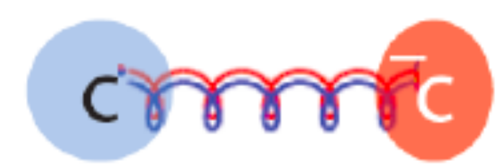
pentaquark

glueball

diquark + di-antiquark

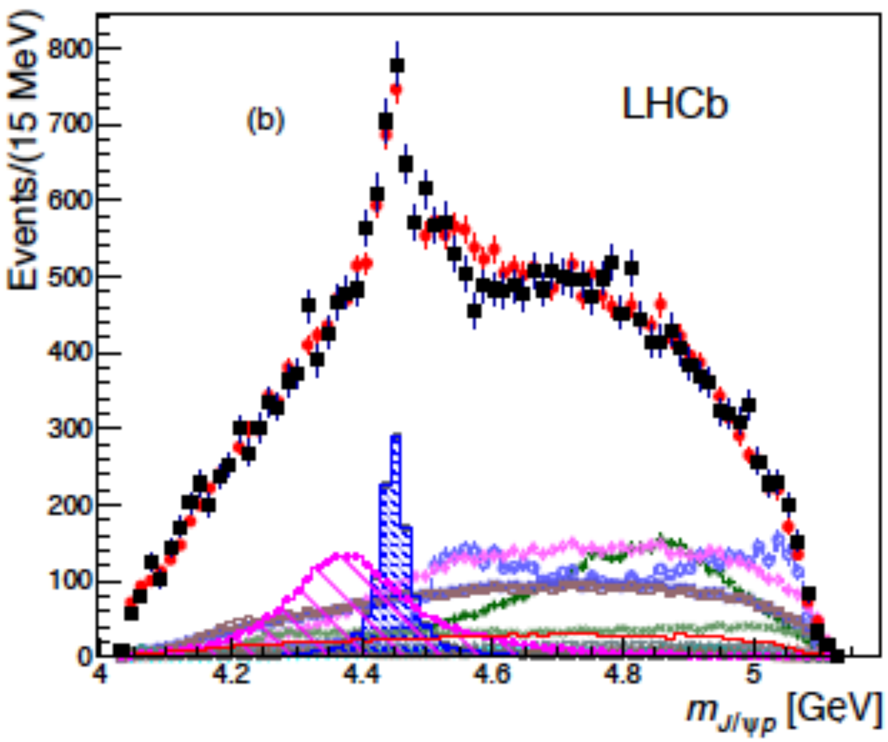


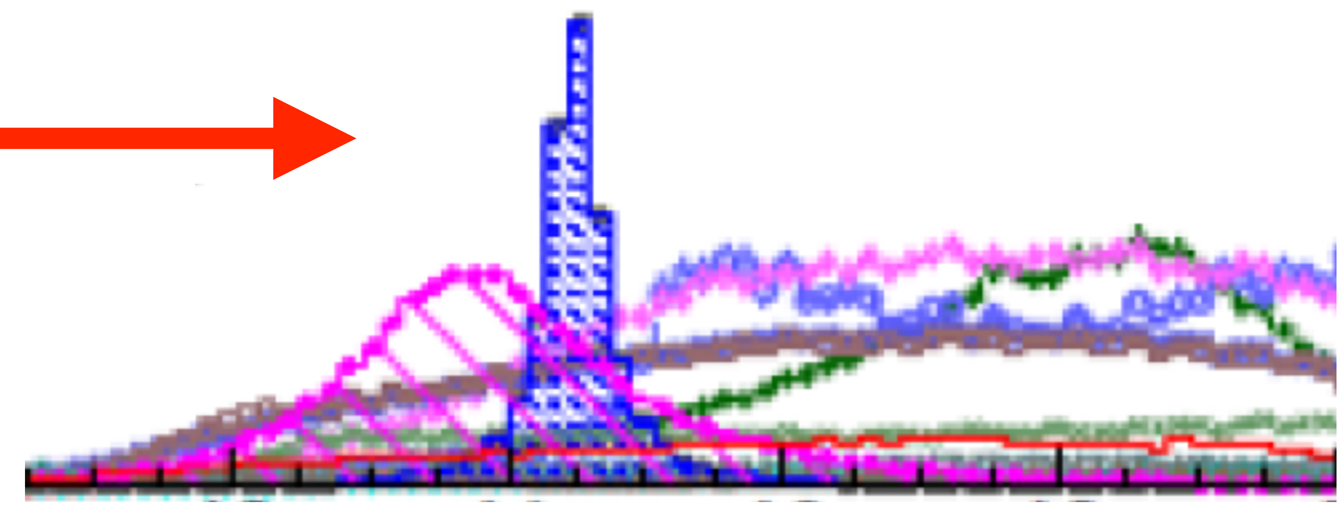
dimeson molecule



$q\,\bar{q}\,g$ hybrid

…we need to know how to interpret "peaks"

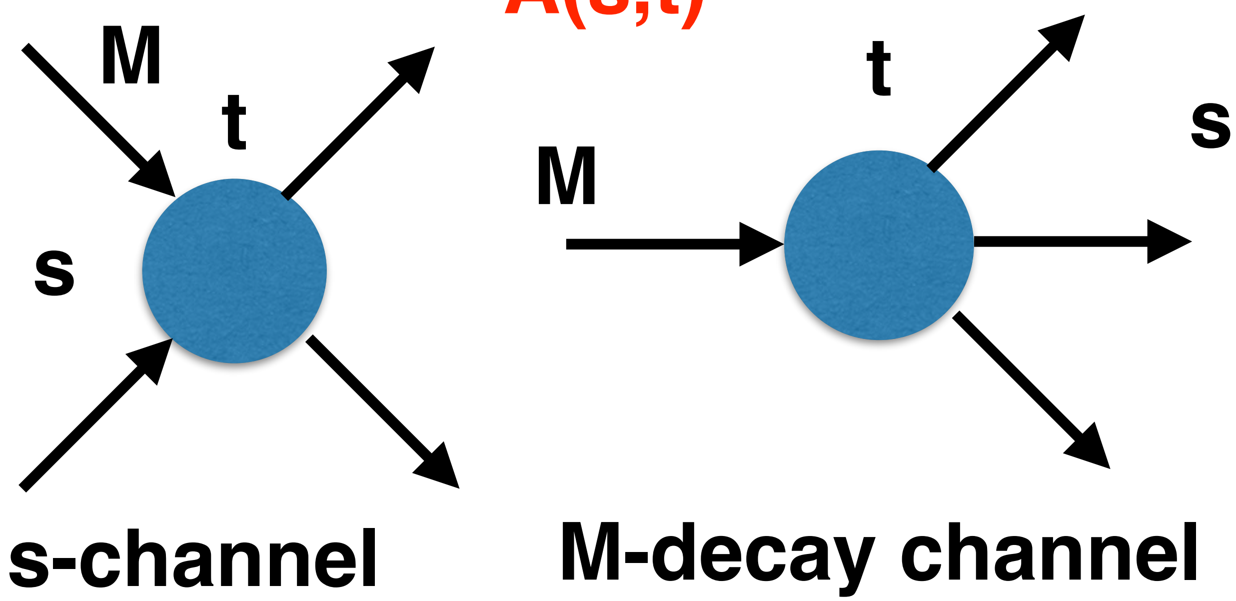




is it always a direct channel resonance ?

S-matrix principles: Crossing, Analyticity, Unitarity

A(s,t)



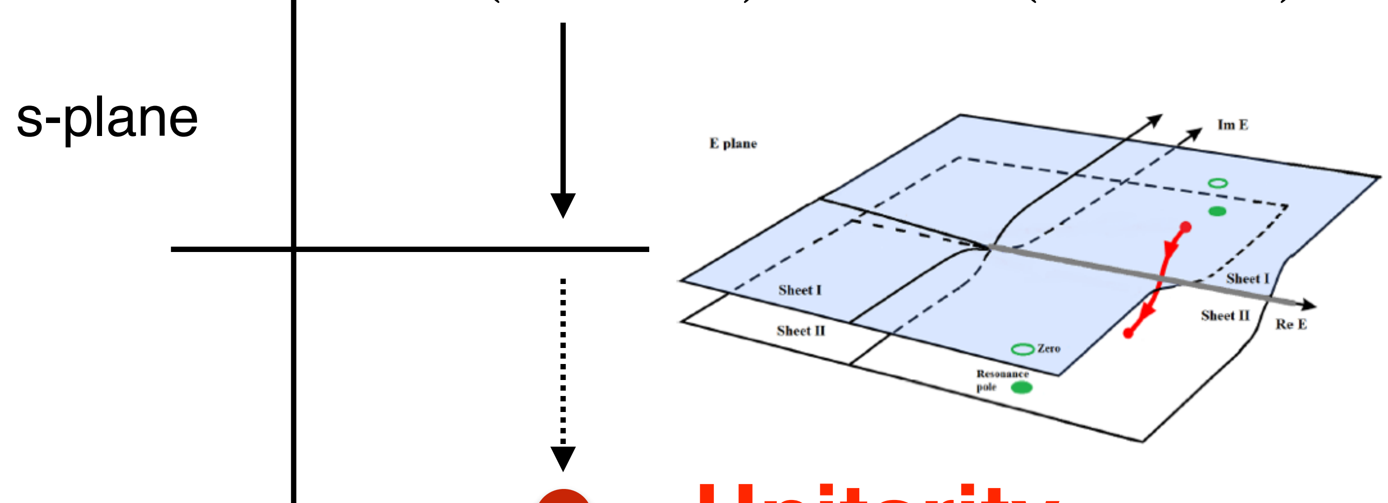
Crossing

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

Analyticity

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

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



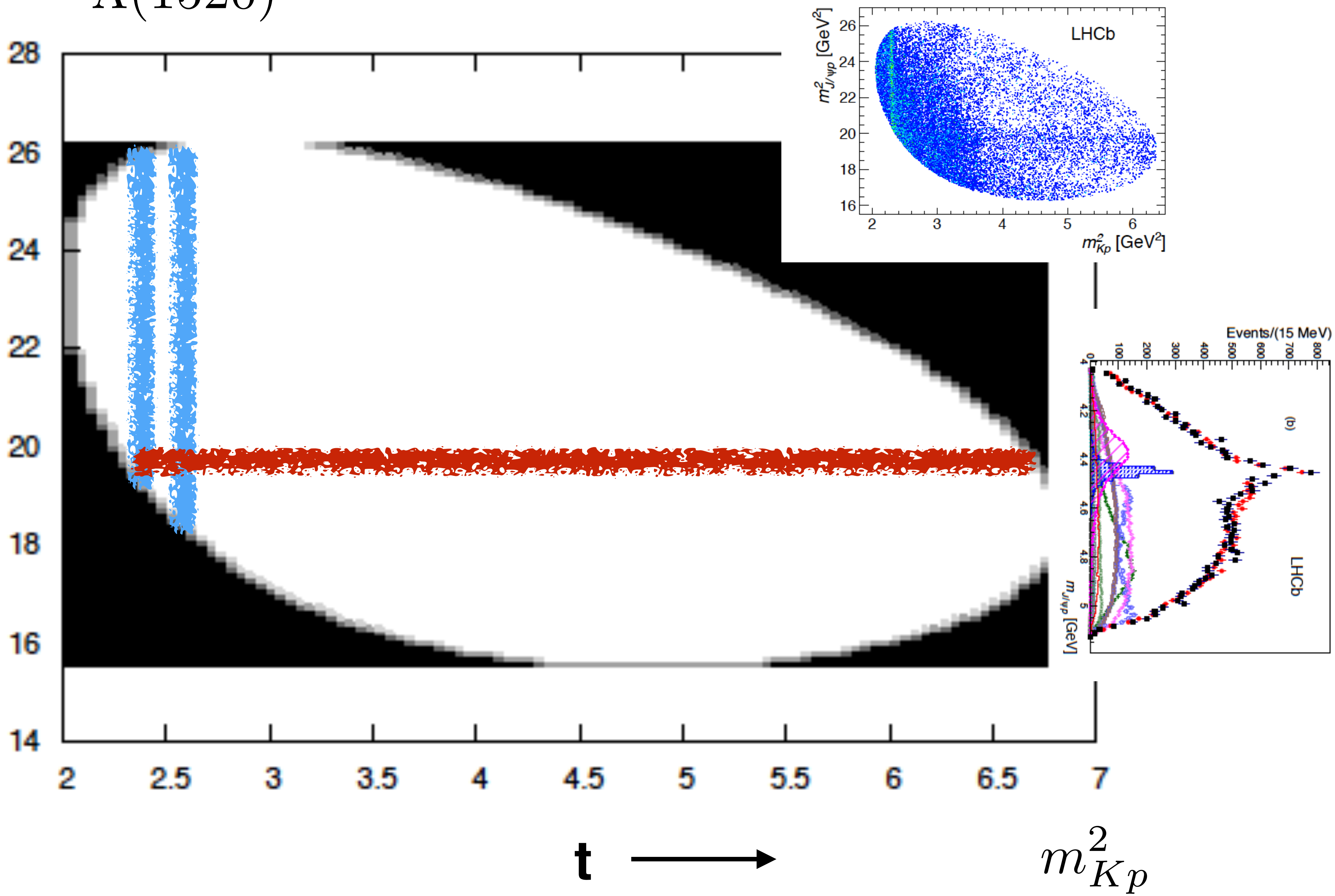
Unitarity

bumps/peaks on the real axis (experiment) come from singularities in the complex domain.

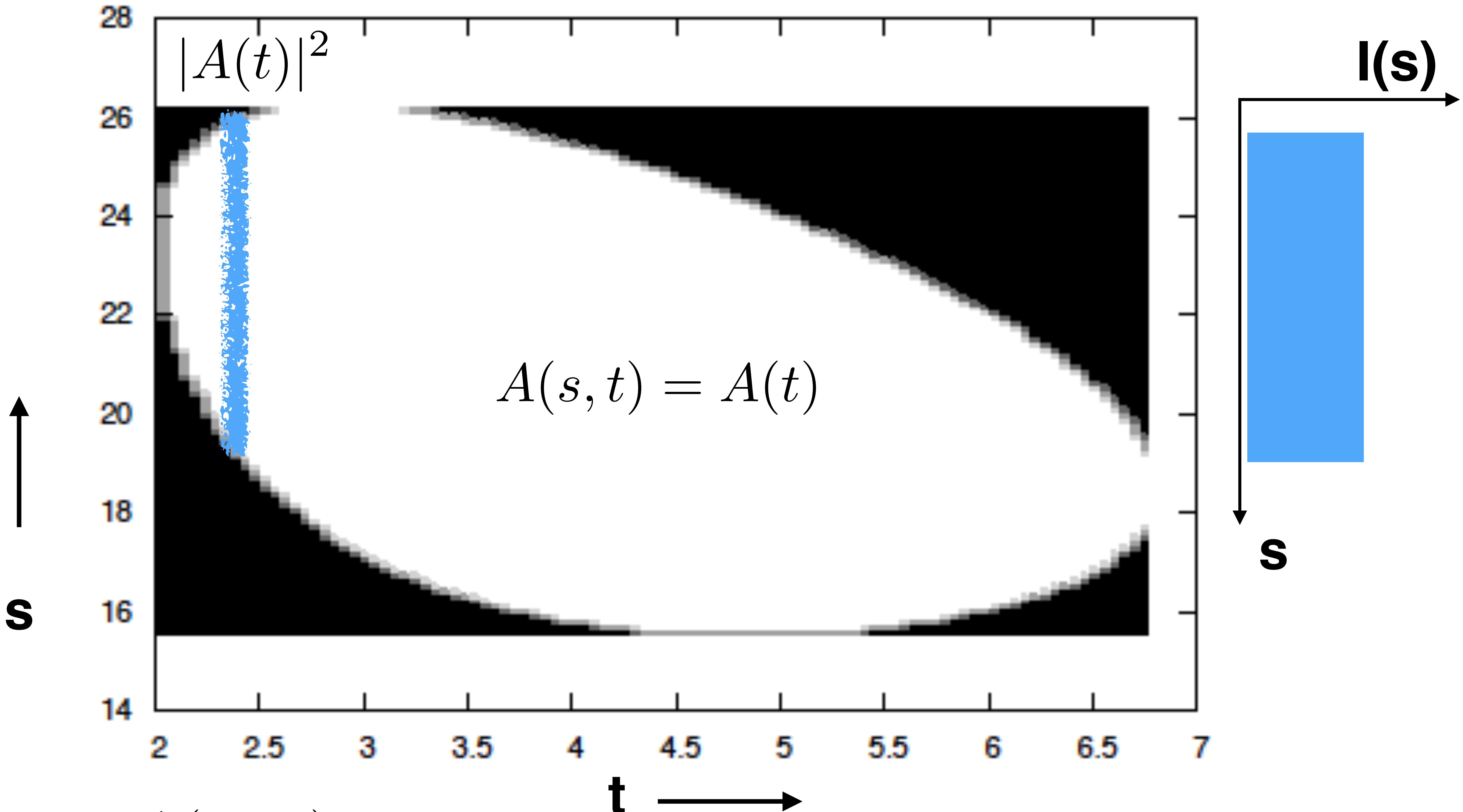
$\Lambda_b \to K^- p J/\psi$

Can the s-channel band originate from a non-s-channel pole

$\Lambda(1520)$

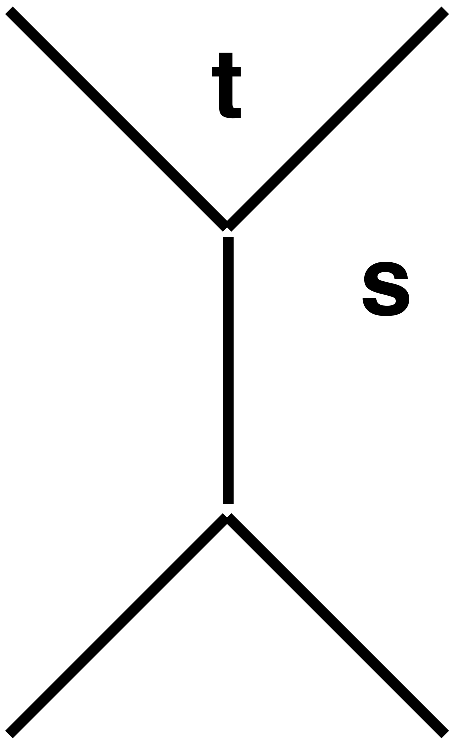


$$I(s) = \int_{P.S.(s)} dt |A(t)|^2$$



$\Lambda(1520)$

anatomy of the full, A(s,t) amplitude and its partial waves
-> an s-channel singularity out-of a t-channel pole

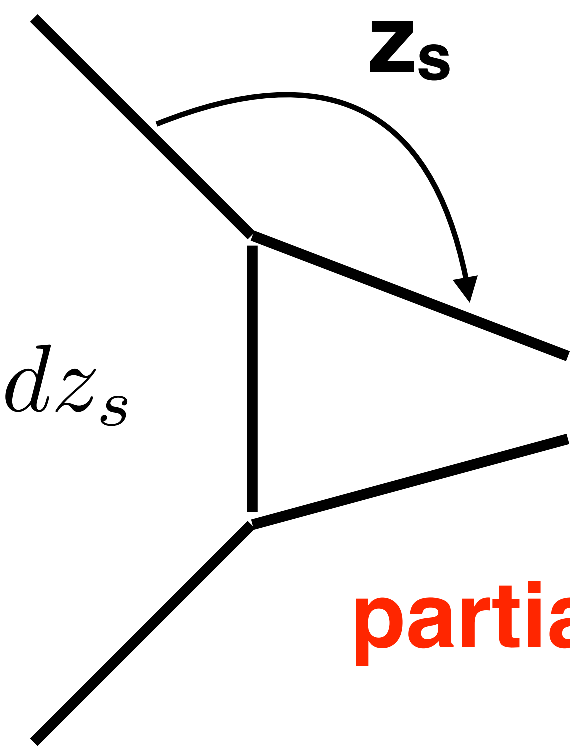


$$A(s,t) = A(t)$$ **pole (peak) in t**

$$= b(s) + \sum_{l>0} (2l+1) b_l(s) P_l(z_s)$$

t = t(s,z_s) kinematical relation

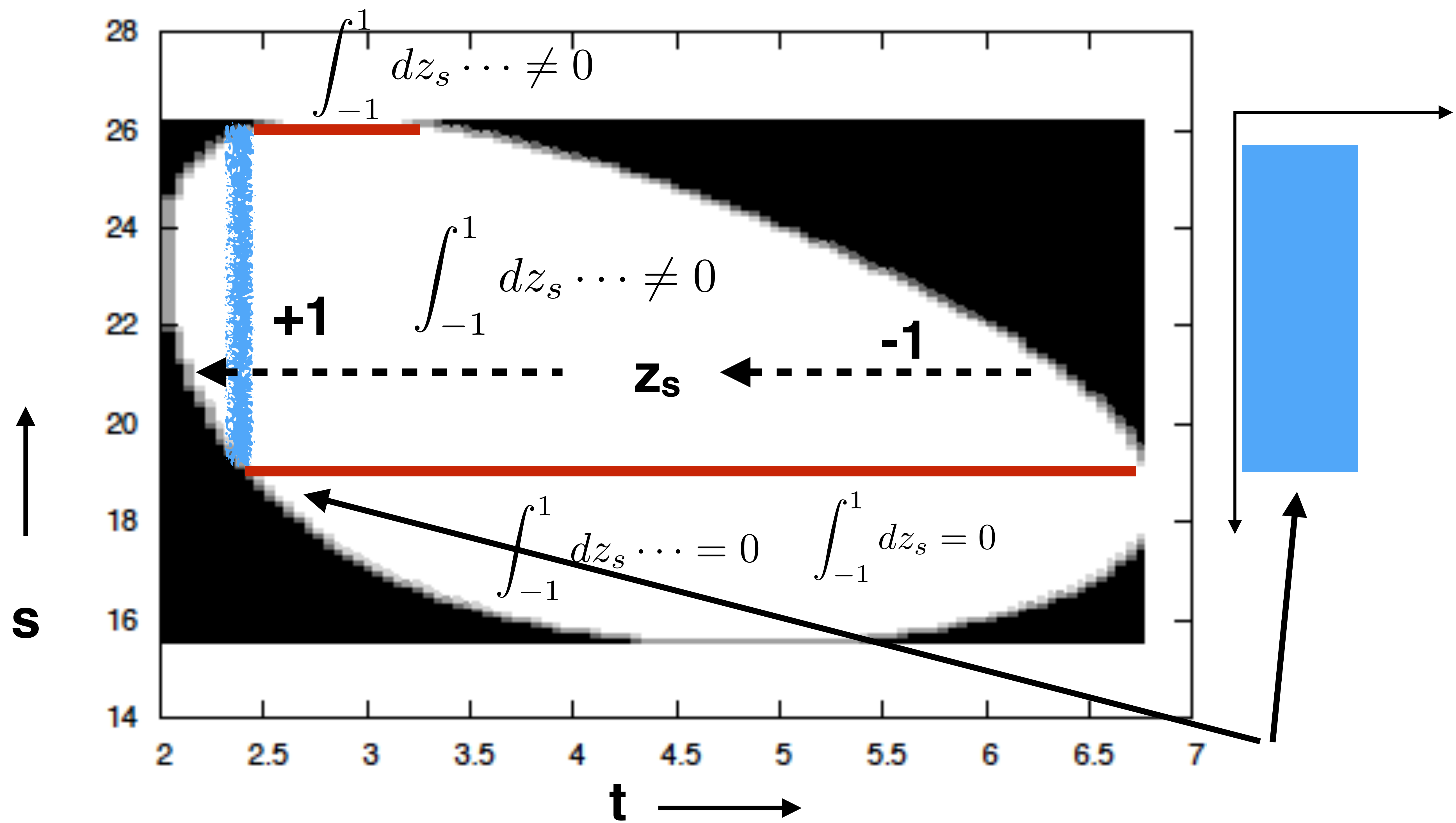
$\int dz_s$



$$= \qquad b(s) = \frac{1}{2}\int_{-1}^{1} dz_s \frac{\beta}{m_t^2 - t(s,z_s)}$$

partial wave projection induces singularities in s (aka. left cuts)

$$b(s) = \frac{1}{2}\int_{-1}^{1} dz_s A(t) \qquad I(s) = \sum_{l>0} |b_l(s)|^2 + |b(s)|^2$$



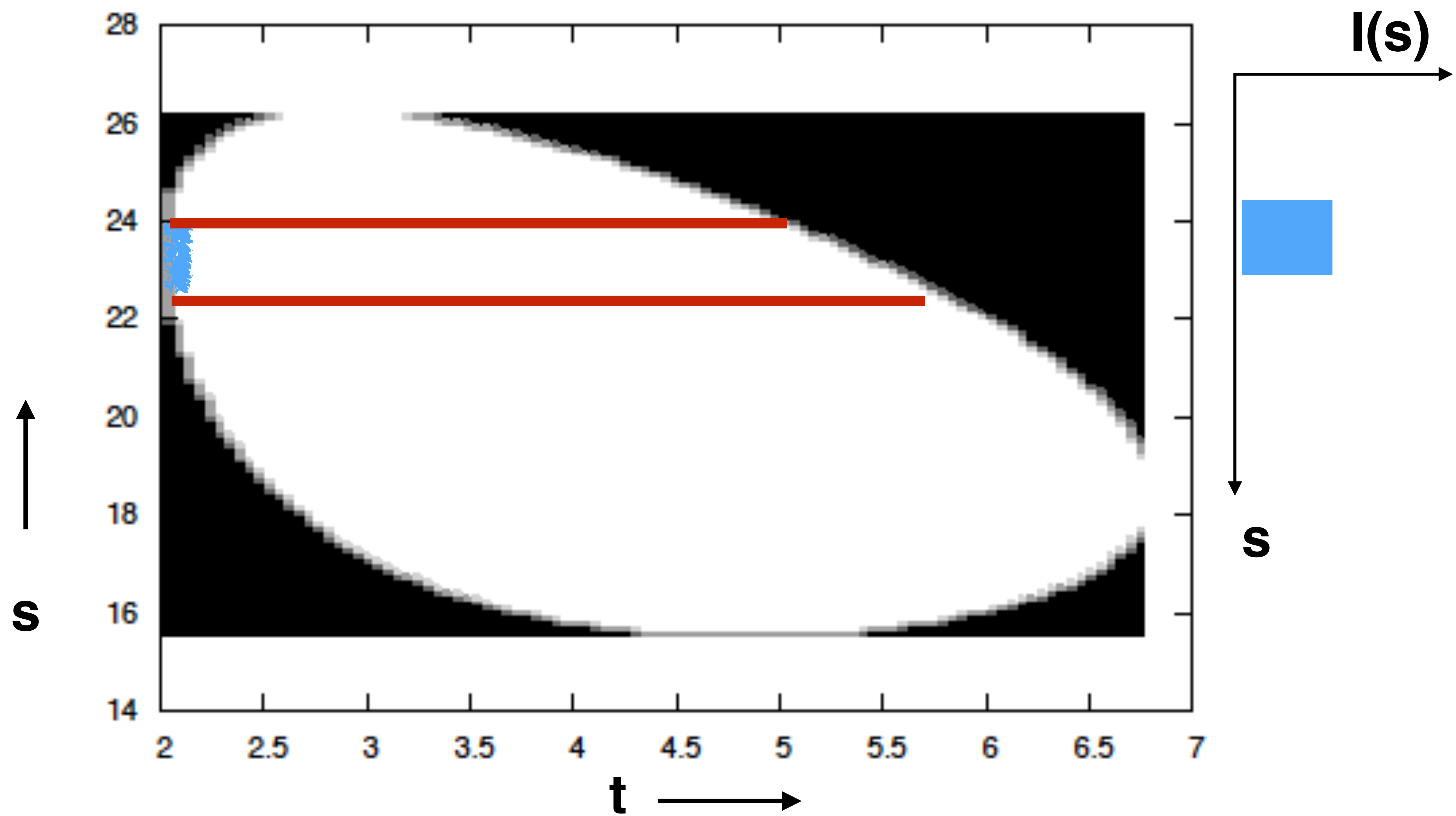
singularity in each partial wave manifests in more or less abrupt "edge"

coherent

$$|A(t)|^2 = |b(s) + \sum_{l>0} \cdots |^2$$

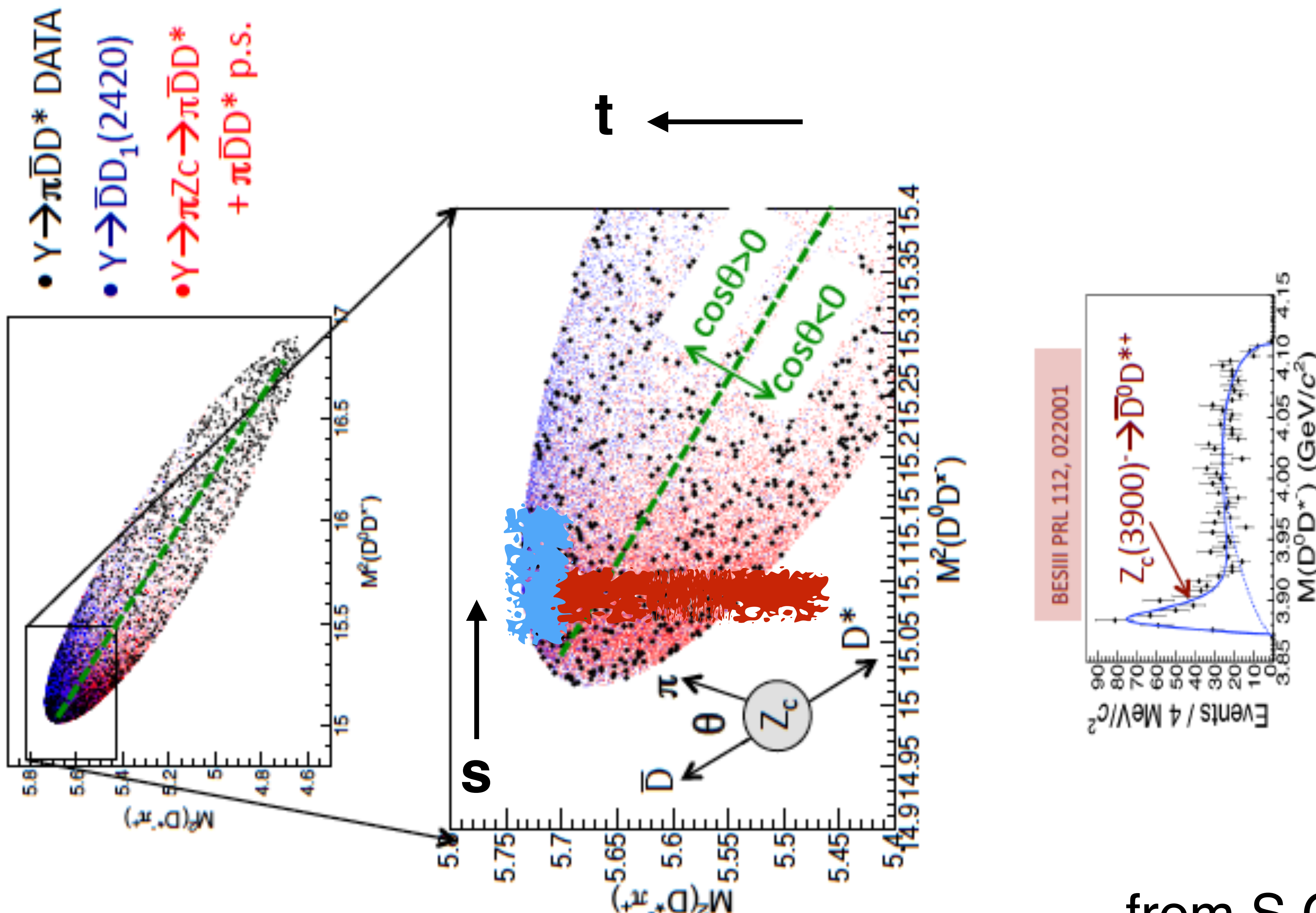
incoherent

$$I(s) = \sum_{l>0} |b_l(s)|^2 + |b(s)|^2$$



$D_1(2420)$ (t-channel)
or
$Z_c(3900)$ (s-channel)

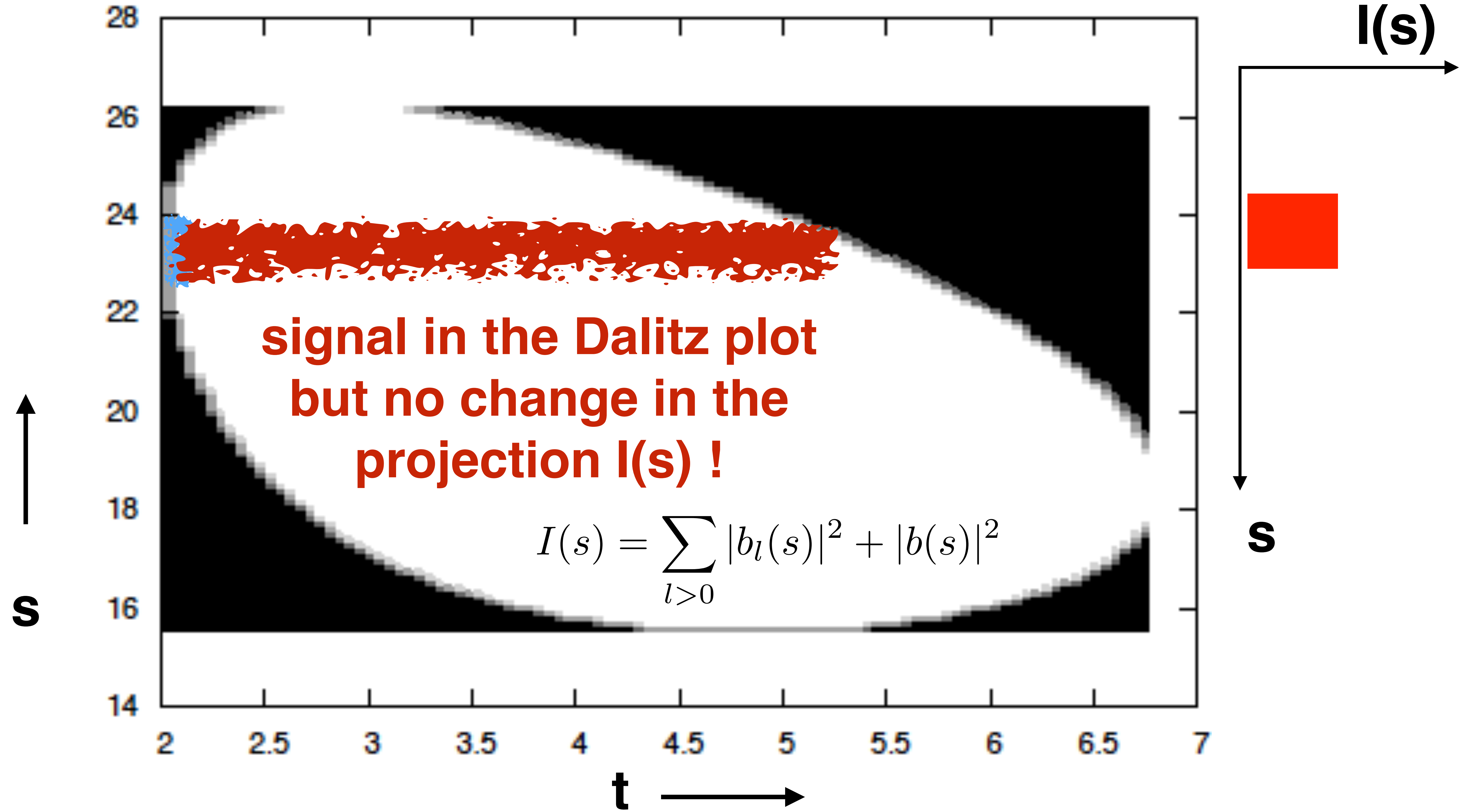
$e^+e^- \rightarrow Y(4260) \rightarrow \pi^- \bar{D}^0 D^{*+}$



from S.Olsen

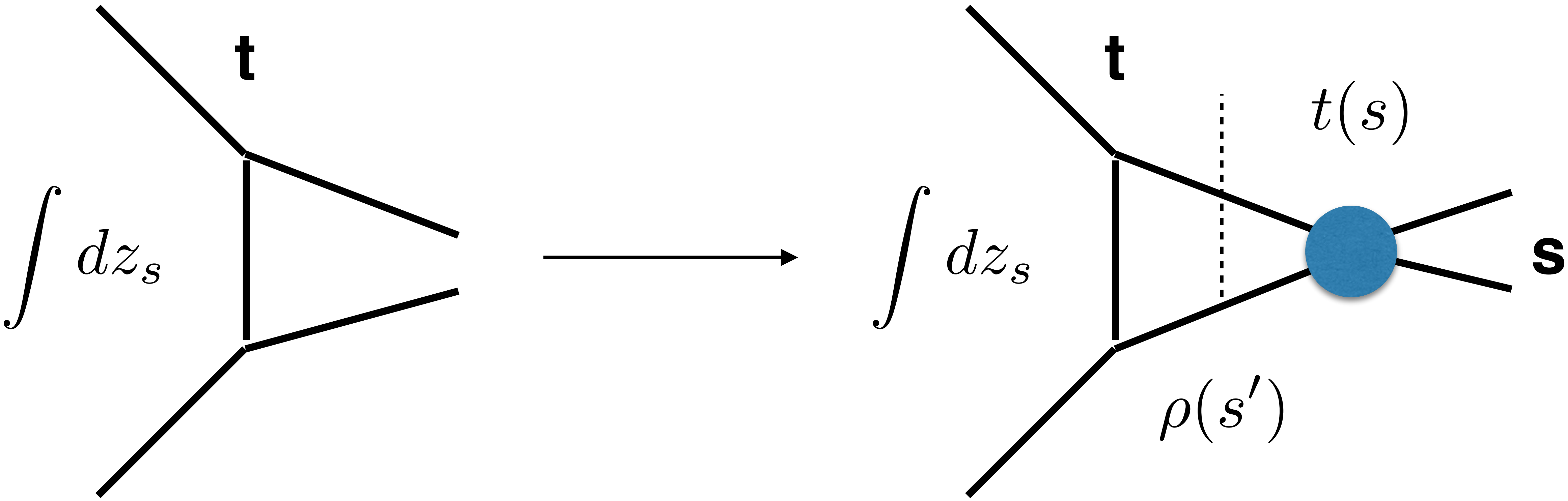
suppose coherence between partial waves is broken

$$|A(t)|^2 \to |\sum_{l>0} \cdots|^2 + |b(s)|^2 = |A(s,t)|^2$$

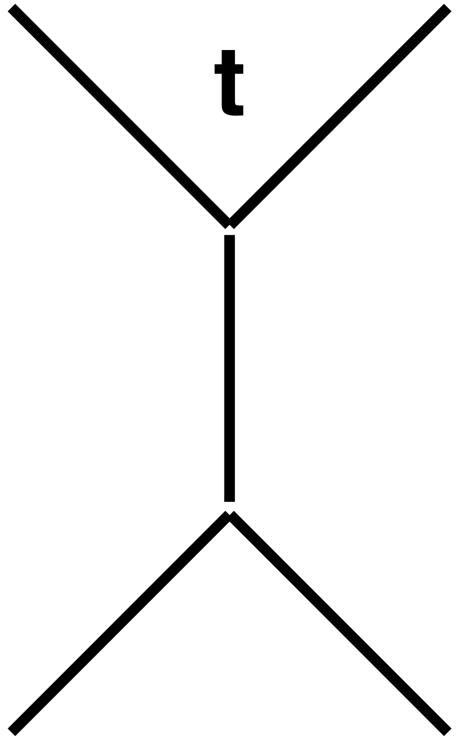


$$|A(s,t)|^2 = |A(t)|^2 - 2Re[A^*(t)b(s)] + 2|b(s)|^2$$

coherence between t-channel partial waves will be distorted if there are s-channel interactions. e.gin the I=0 wave

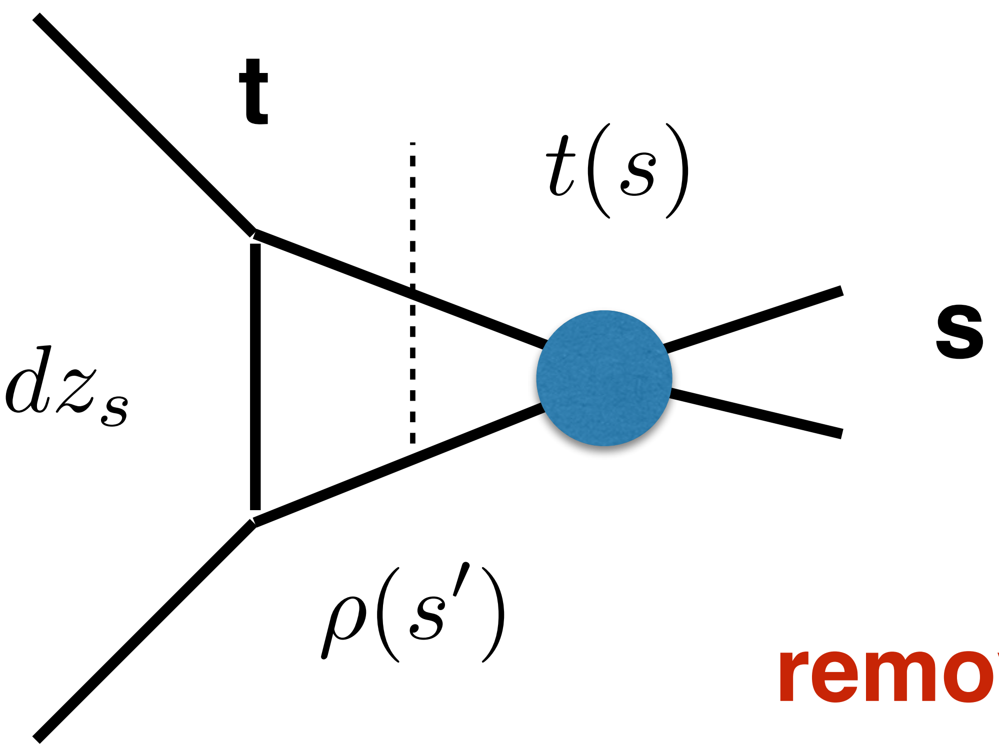


$$b(s) \to t(s)\left[\frac{1}{\pi}\int_{s_{tr}} ds'\rho(s')\frac{b(s')}{s'-s}\right]$$



$$= b(s) + \sum_{l>0} (2l+1) b_l(s) P_l(z_s)$$

$$\int dz_s$$



$$+t(s)\left[\frac{1}{\pi}\int_{s_{tr}} ds' \rho(s') \frac{b(s')}{s'-s}\right]$$

remove b(s) and replace it b'(s)

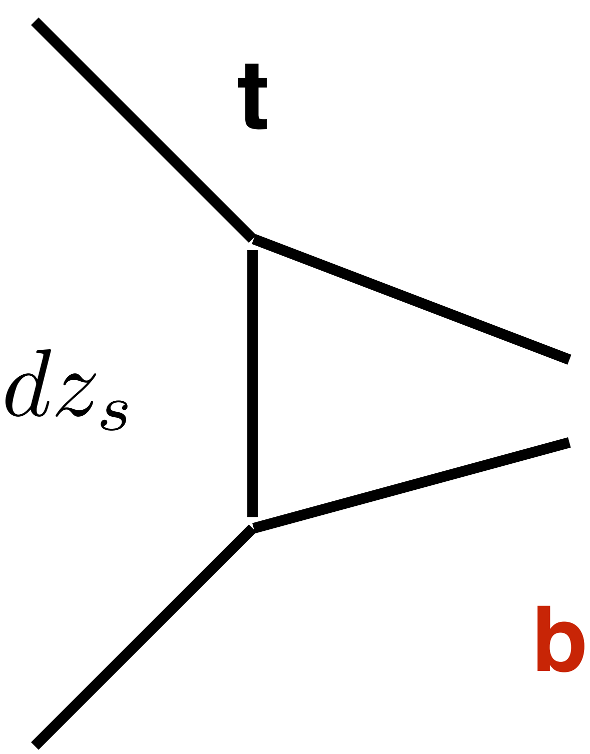
$$b(s) \to b'(s) = b(s) + t(s)\left[\frac{1}{\pi}\int_{s_{tr}} ds' \rho(s') \frac{b(s')}{s'-s}\right]$$

can the s-channel interaction, (though de-coherence) generate narrow s-bands?

$$b'(s) - b(s) = t(s)\left[\frac{1}{\pi}\int_{s_{tr}} ds' \rho(s') \frac{b(s')}{s'-s}\right]$$

- t(s) has a peak in s (e.g. J/psi + p -> J/psi + p resonate)
- [...] has a peak as a function of s

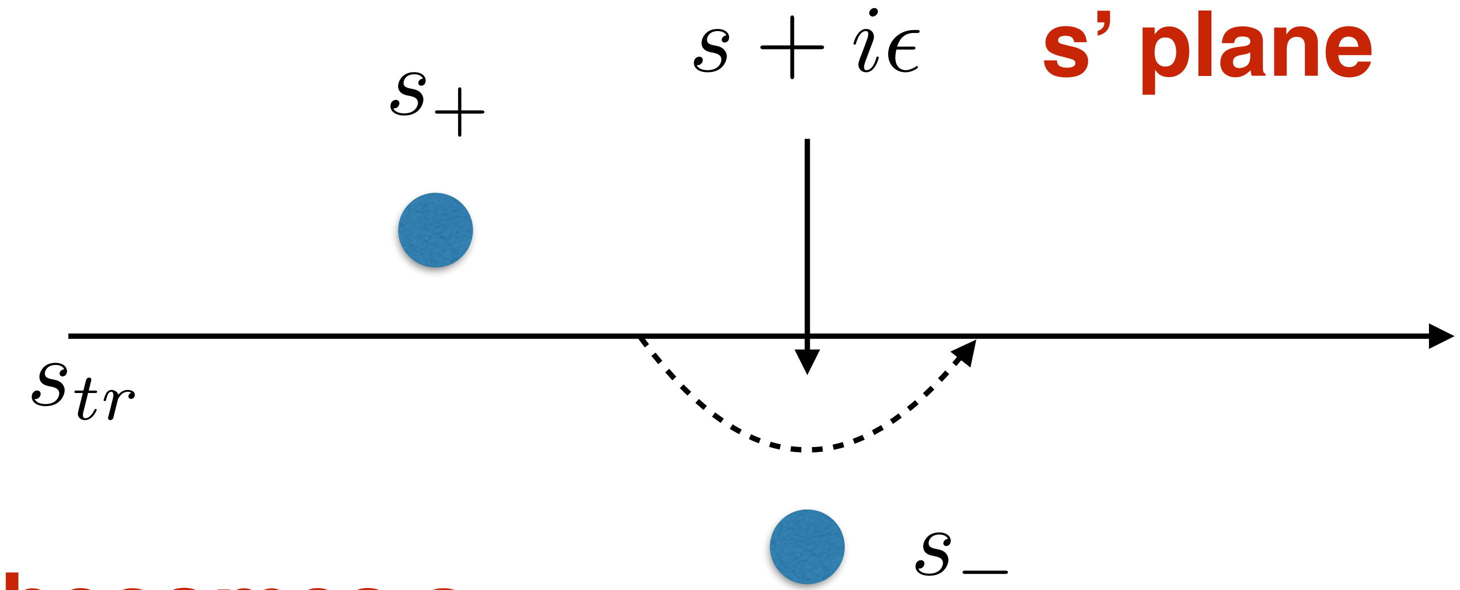
$$\int dz_s$$



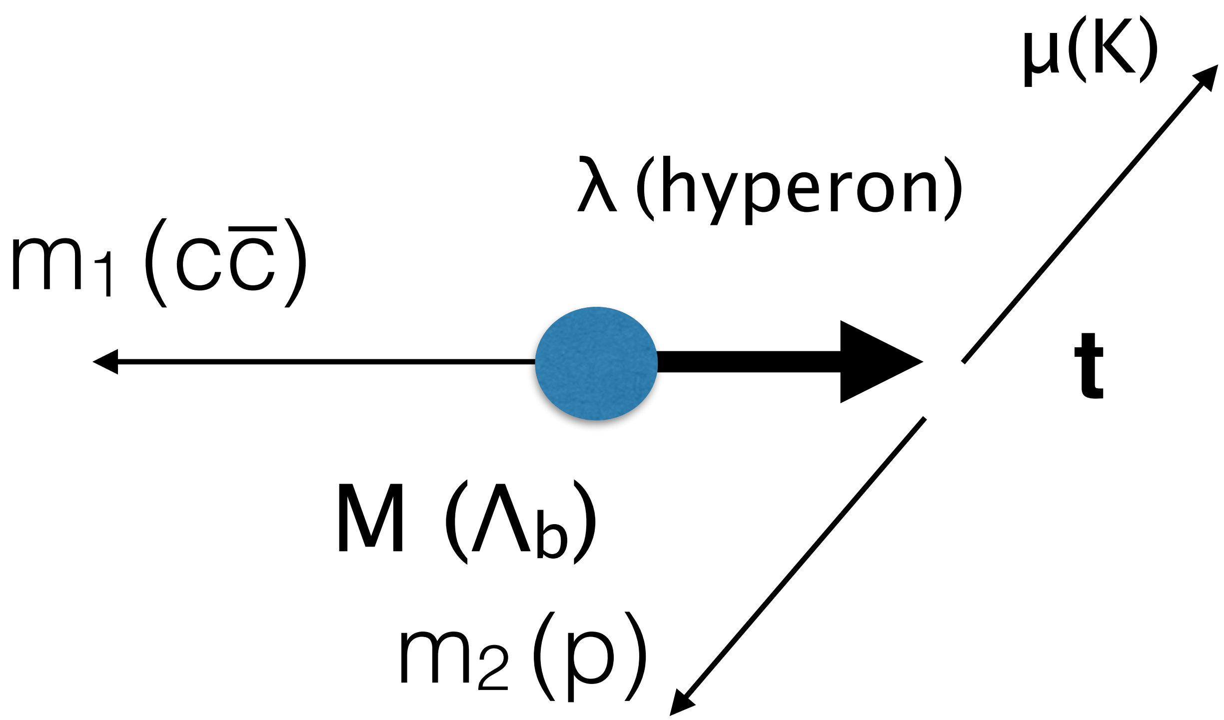
$$= \quad b(s) = \frac{1}{2}\int_{-1}^{1} dz_s \frac{\beta}{m_t^2 - t(s, z_s)}$$

b(s) has singularities for complex s

$$\frac{1}{\pi}\int_{s_{tr}} ds'\rho(s')\frac{b(s')}{s'-s}$$



s_- singularity of b(s) becomes a second sheet singularity of the integral (i.e. physical amplitude) —> very much like a resonance



Coleman-Norton theorem

t-channel resonance can produce s-channel "band" if:

all particles on-shell

m_2 and m_1 collinear

$v(m_2) > v(m_1)$

$$A(t) \to A(s,t) = [A(t) - b(s)] + b'(s)$$

$$= \sum_{l>0} (2l+1) b_l(s) P_l(z_s) + b'(s)$$

- **Dalitz plot distribution changes**

$$|A(t)|^2 \neq |A(s,t)|^2$$

- **Projection changes if** $|b'(s)|^2 \neq |b(s)|^2$

$$I(s) = \int_{P.S.(s)} dt |A(t)|^2 = \sum_{l>0} |b_l(s)|^2 + |b(s)|^2$$

$$\to \sum_{l>0} |b_l(s)|^2 + |b'(s)|^2$$

(C.Schmidt)

in the single channel case |b'(s)|² = |b(s)|²

for s ~ s-

$$\left[\frac{1}{\pi}\int_{s_{tr}} ds'\rho(s')\frac{b(s')}{s'-s}\right] \sim 2i\rho(s)b(s)$$

$$b'(s) = b(s) + t(s)[\cdots] \to [1 + 2i\rho(s)t(s)]b(s)$$

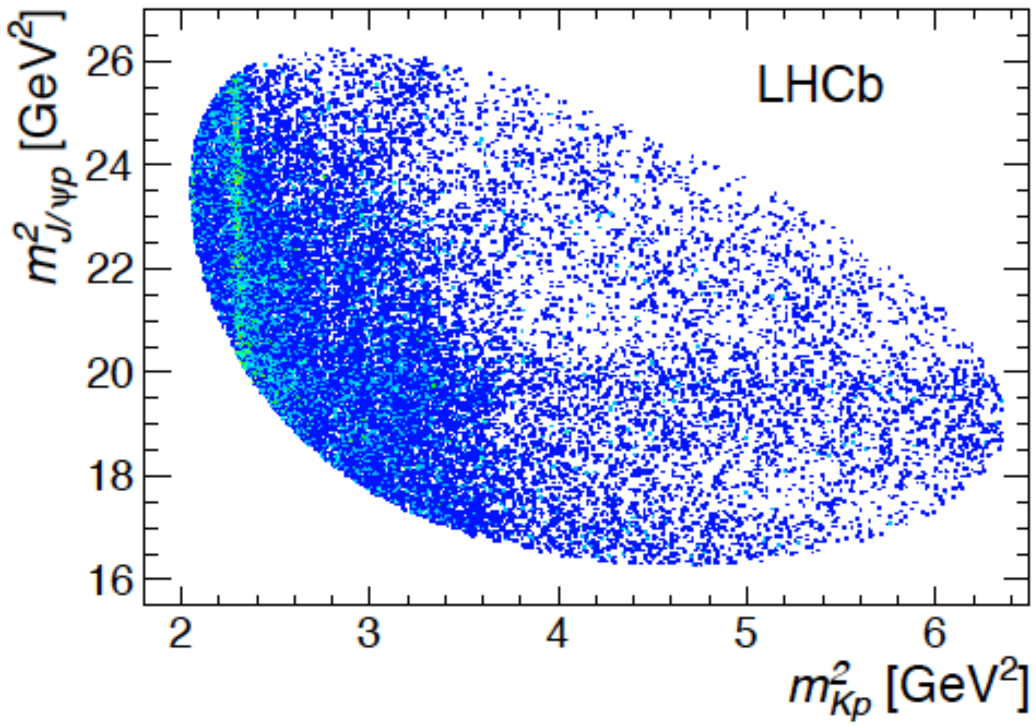
$$= S(s)b(s)$$

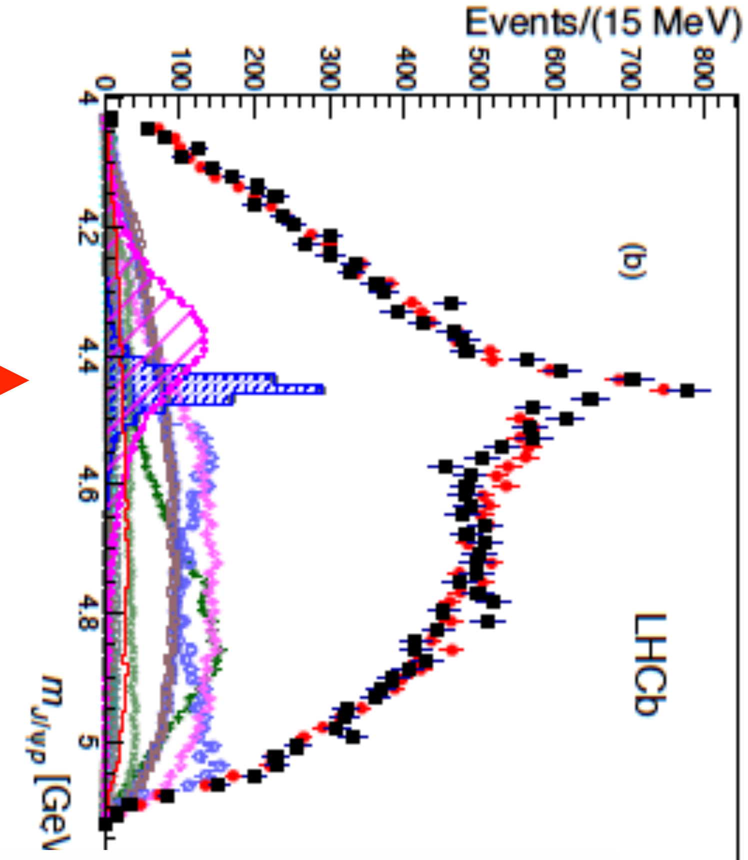
S(s) = unitary S-matrix element

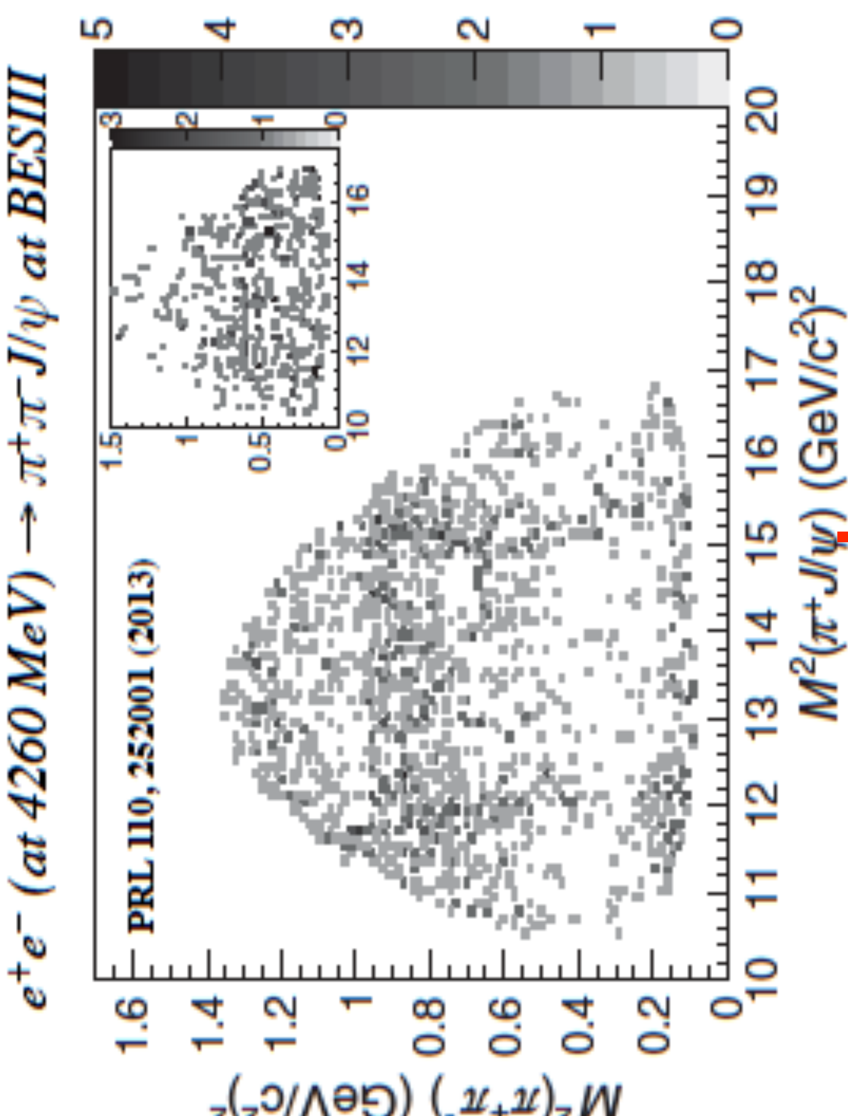
- and projection does NOT change

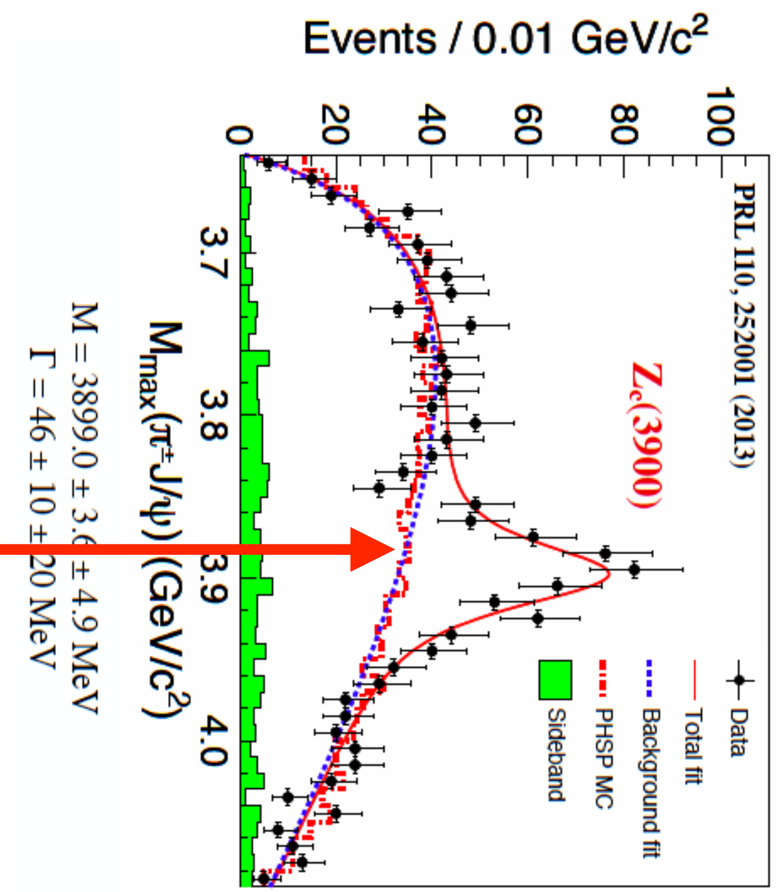
$$I(s) = \int_{P.S.(s)} dt|A(t)|^2 = \sum_{l>0} |b_l(s)|^2 + |b(s)|^2$$

$$\to \sum_{l>0} |b_l(s)|^2 + |b'(s)|^2$$


LHCb
$m^2_{J/\psi p}$ [GeV^2]
m^2_{Kp} [GeV^2]


(b)
LHCb
Events/(15 MeV)
$m_{J/\psi p}$ [GeV]


e^+e^- (at 4260 MeV) $\to \pi^+\pi^- J/\psi$ at BESIII
PRL 110, 252001 (2013)
$M^2(\pi^+ J/\psi)$ (GeV/c^2)^2
$M^2(\pi^+\pi^-)$ (GeV/c^2)^2


PRL 110, 252001 (2013)
$Z_c(3900)$
Data
Total fit
Background fit
PHSP MC
Sideband
Events / 0.01 GeV/c^2
$M_{max}(\pi^\pm J/\psi)$ (GeV/c^2)
M = 3899.0 ± 3.6 ± 4.9 MeV
Γ = 46 ± 10 ± 20 MeV

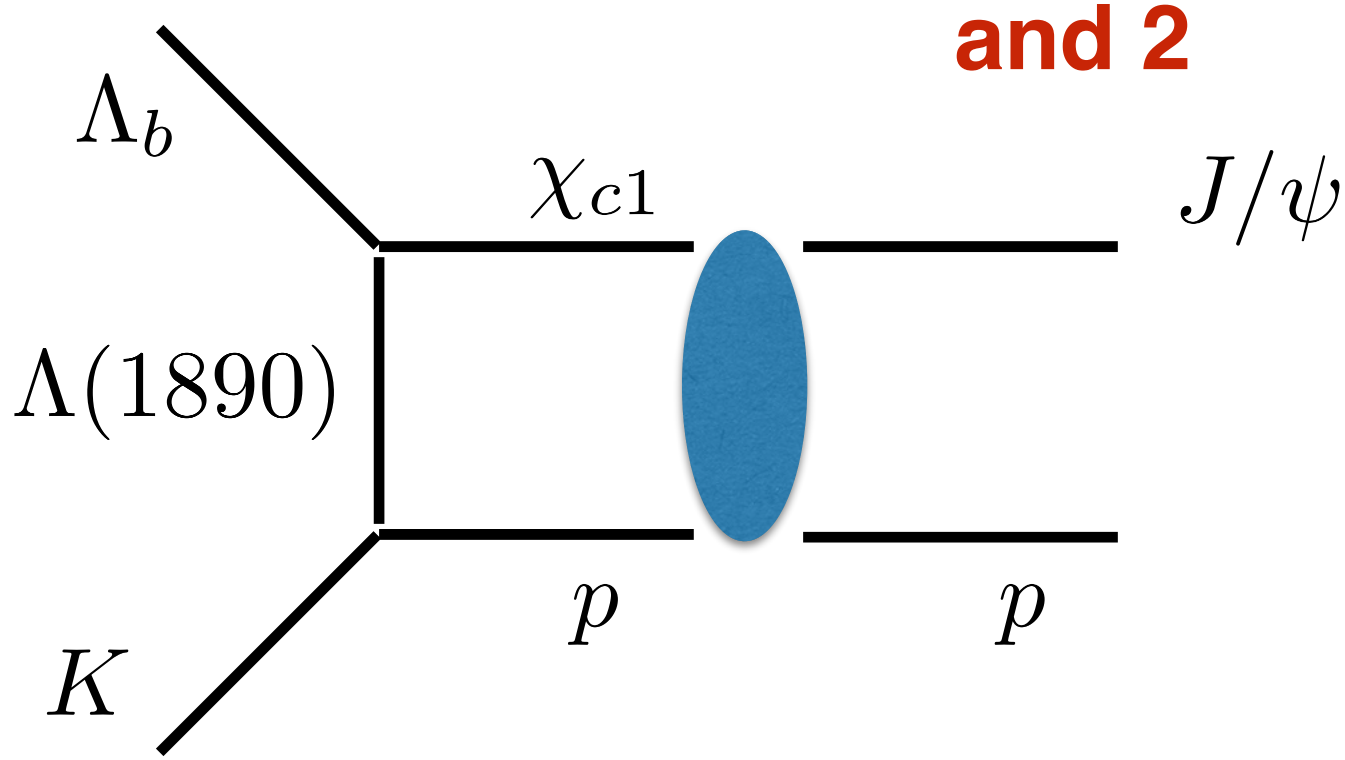
Projection changes if interactions are inelastic

$$A_\alpha(s) = b'_\alpha(s) + \sum_{l>0} \cdots$$

$$\alpha = 1, 2, \cdots = (J/\psi p), (\chi_{c1} p) \cdots$$ **P_c**

$$= (J/\psi \pi), (\bar{D} D^* + c.c) \cdots$$ **Z_c(3900) in Y-> π π J/ψ**

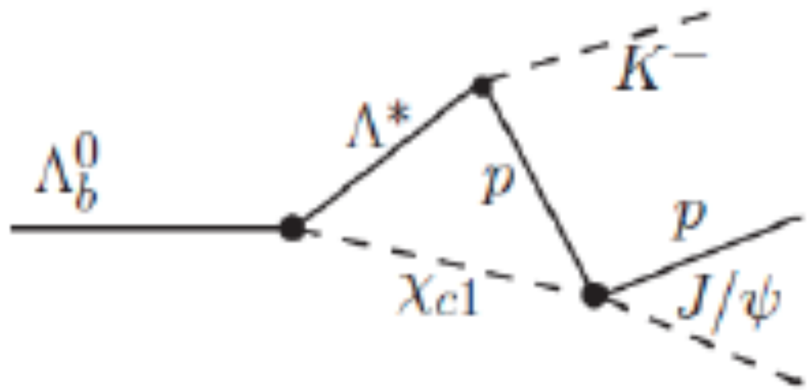
suppose there is peak from projection of a t-channel resonance in channel 2 and inelastic interaction between 1 and 2



$$b'_1(s) \sim S_{1,2} b_2(s)$$

$$|S_{1,2}| < 1$$

The key to the XYZ phenomena are the many nearby channels



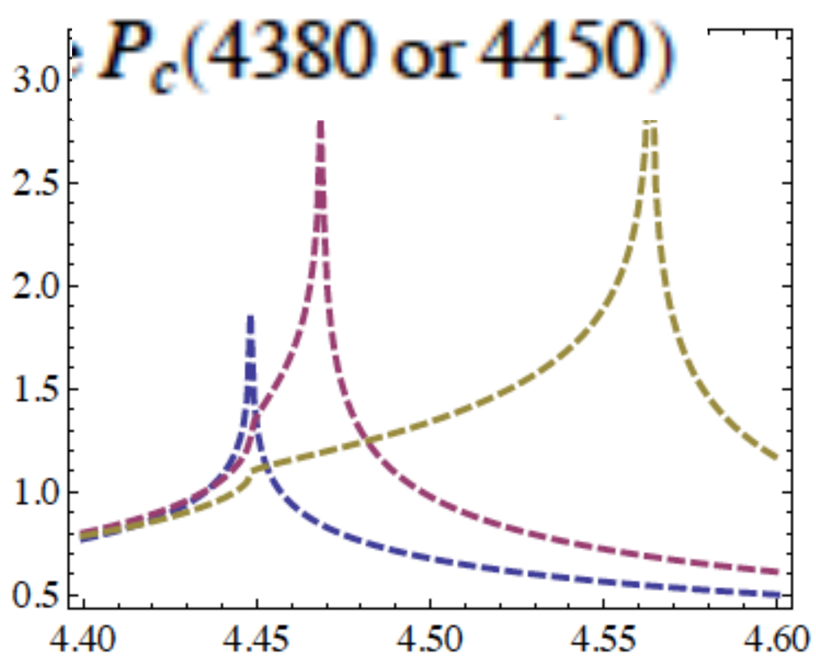
$$M_{\Lambda_b^0} = 5.6195,\ \mu_{K^-} = 0.4937,\ m_1 = m_{\chi_{c1}} = 3.510,\ m_2 = m_p = 0.93827$$

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

Coleman-Norton requires

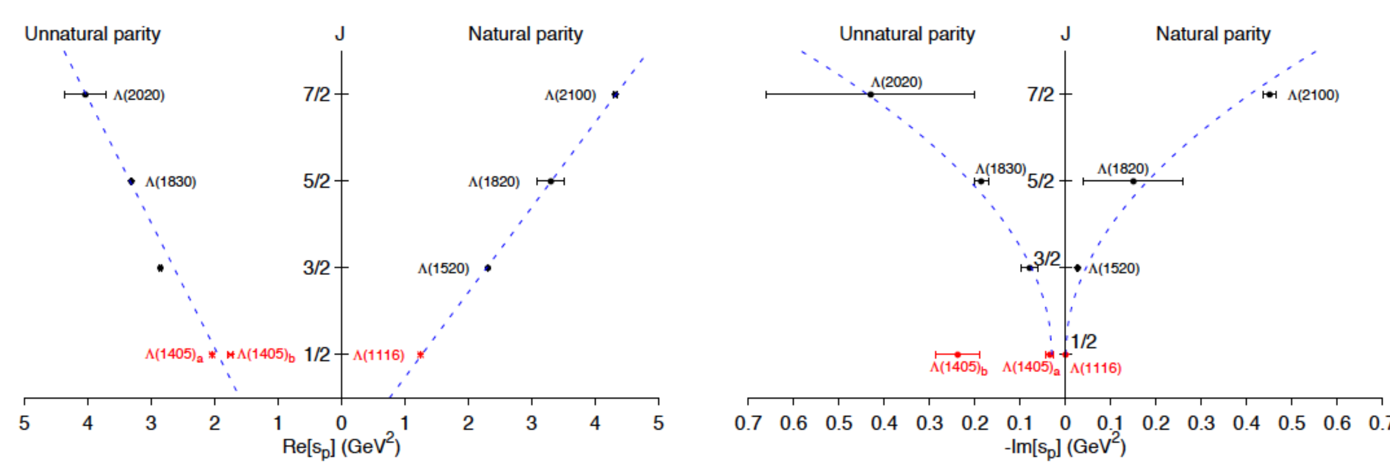
$$1.89 < \lambda < 2.11 \text{ GeV}$$

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

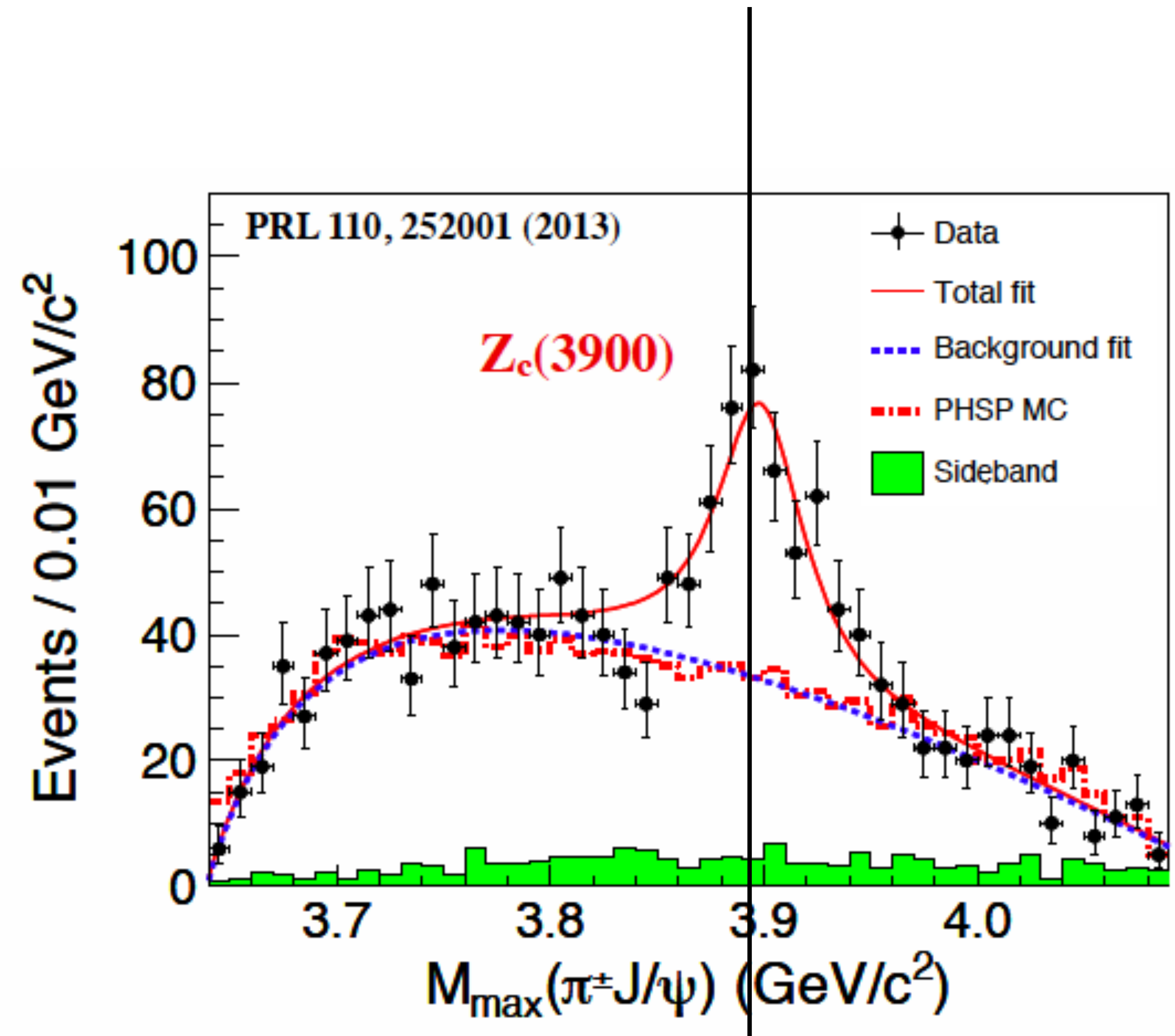


Axes : Abs[$T(s)$], $\sqrt{s}$

Lines : blue ($\lambda = 1.89$ GeV), red ($\lambda = 1.99$ GeV), yellow ($\lambda = 2.0$



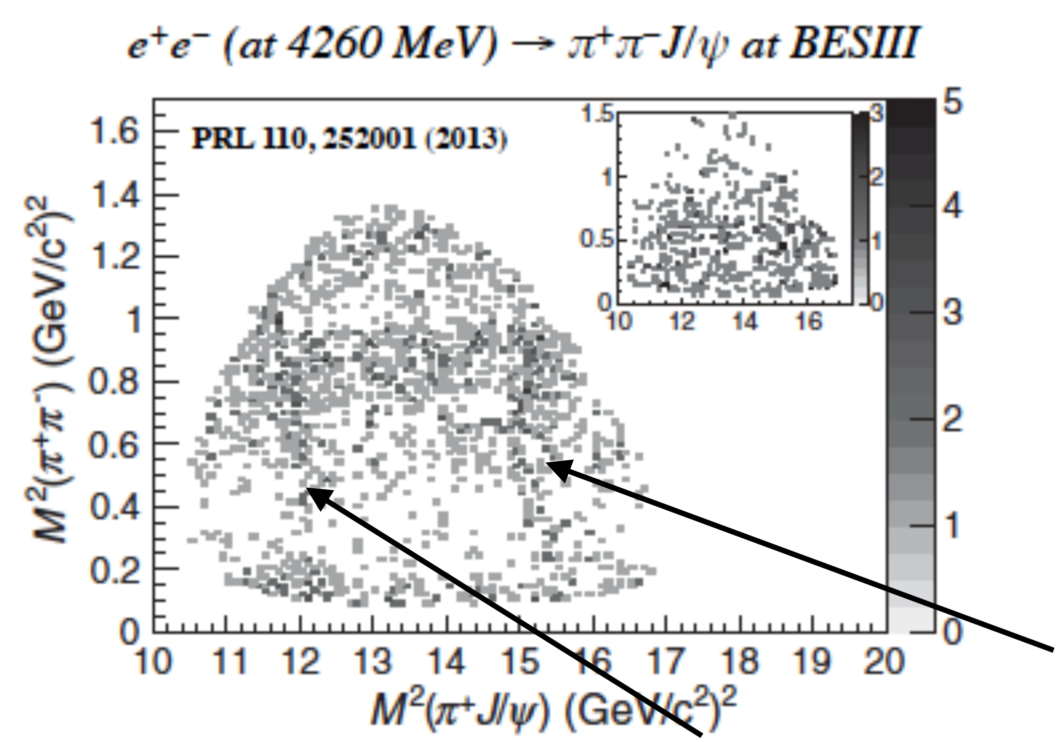
$Z_c(3900)$ Charged charmonium ?



$$e^+e^- \to Y(4260)$$
$$\to \pi^+ Z_c^-(3900)$$
$$\to \pi^+\pi^- J/\psi$$

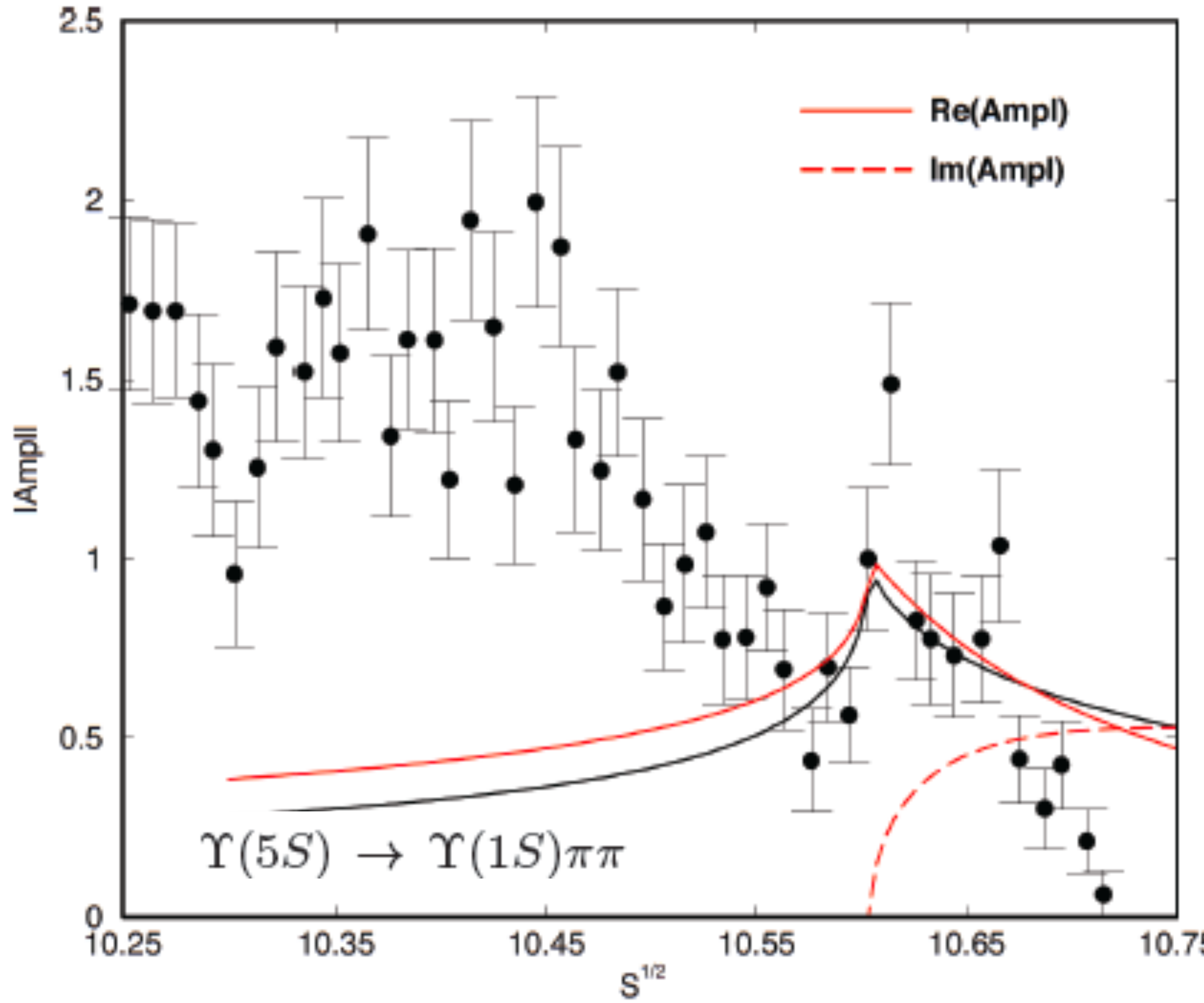
M = 3899.0 ± 3.6 ± 4.9 MeV
Γ = 46 ± 10 ± 20 MeV

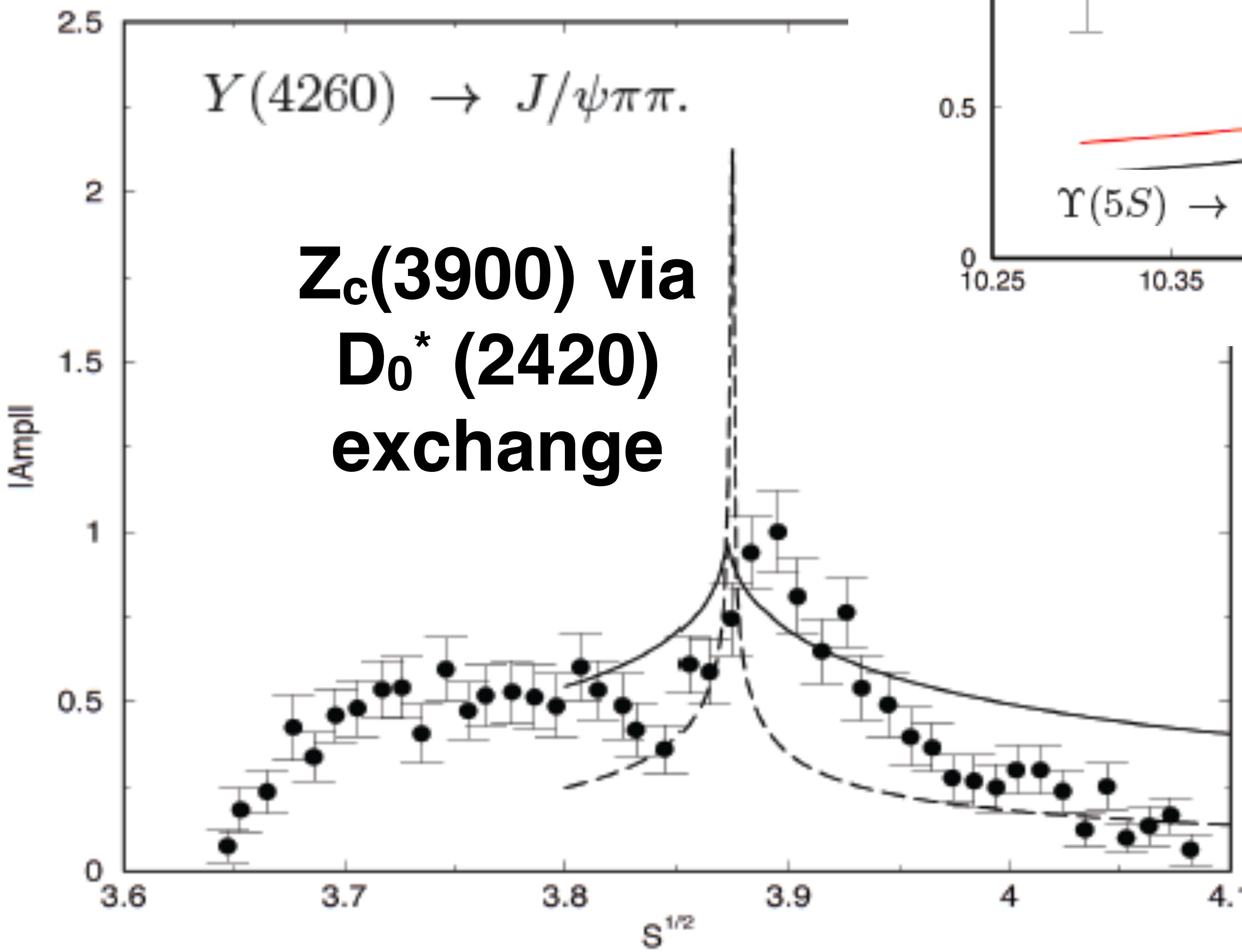
Breit-Wigner model fit



close to D*D threshold

coupling to DD*





$Z_c(3900)$ via D_0^* (2420) exchange

$Z_b(10610)$ via $B_J^{**}(5698)$ exchange

XYZ phenomena are seem to occur near inelastic thresholds

For the non-resonant [(t-channel) induced singularities] interpretation there needs to be significant coupling between channels

Specific predictions for “the other” Dalitz plot distribution e.g.

$$\Lambda_b \to K^- p \chi_{c1}$$

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

Origin of singularities (exchanges constrained by unitarity)