[238-136]

March, 2018

The Galileo Galilei Institute for Theoretical Physics

Bound States in Strongly Coupled Systems, GGI

Pentaquarks and Hadronic Interactions

Eric Swanson

$$\boxed{\begin{array}{l}P_c(4450)\\ P_c(4380)\end{array}}$$

5/2+ preferred for 4450

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

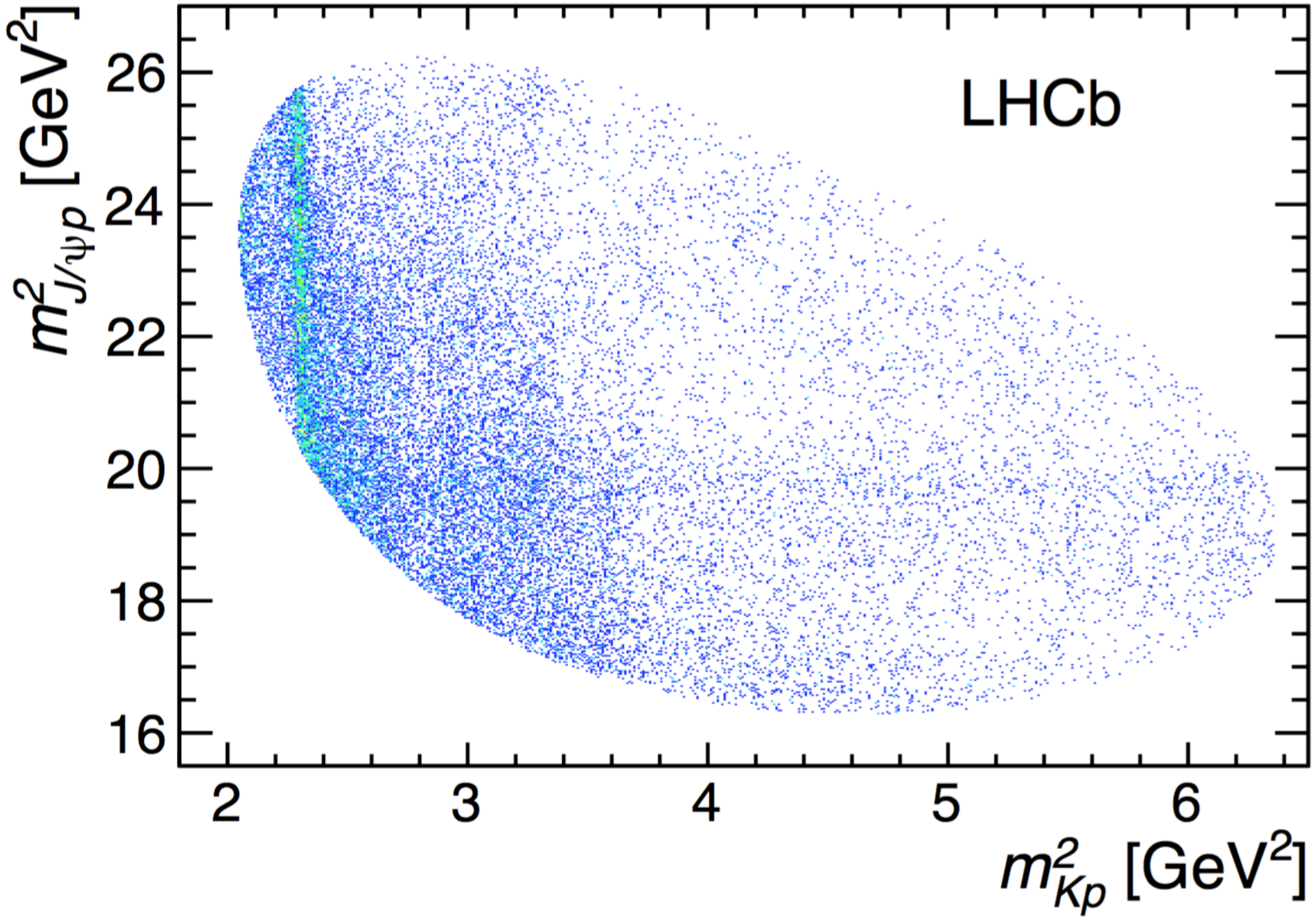
$$P_c(4450) \qquad \Gamma = 39 \pm 5 \pm 19 \ \mathrm{MeV}$$

$$P_c(4380) \qquad \Gamma = 205 \pm 18 \pm 86 \ \mathrm{MeV}$$

LHCb 1507.03414v2

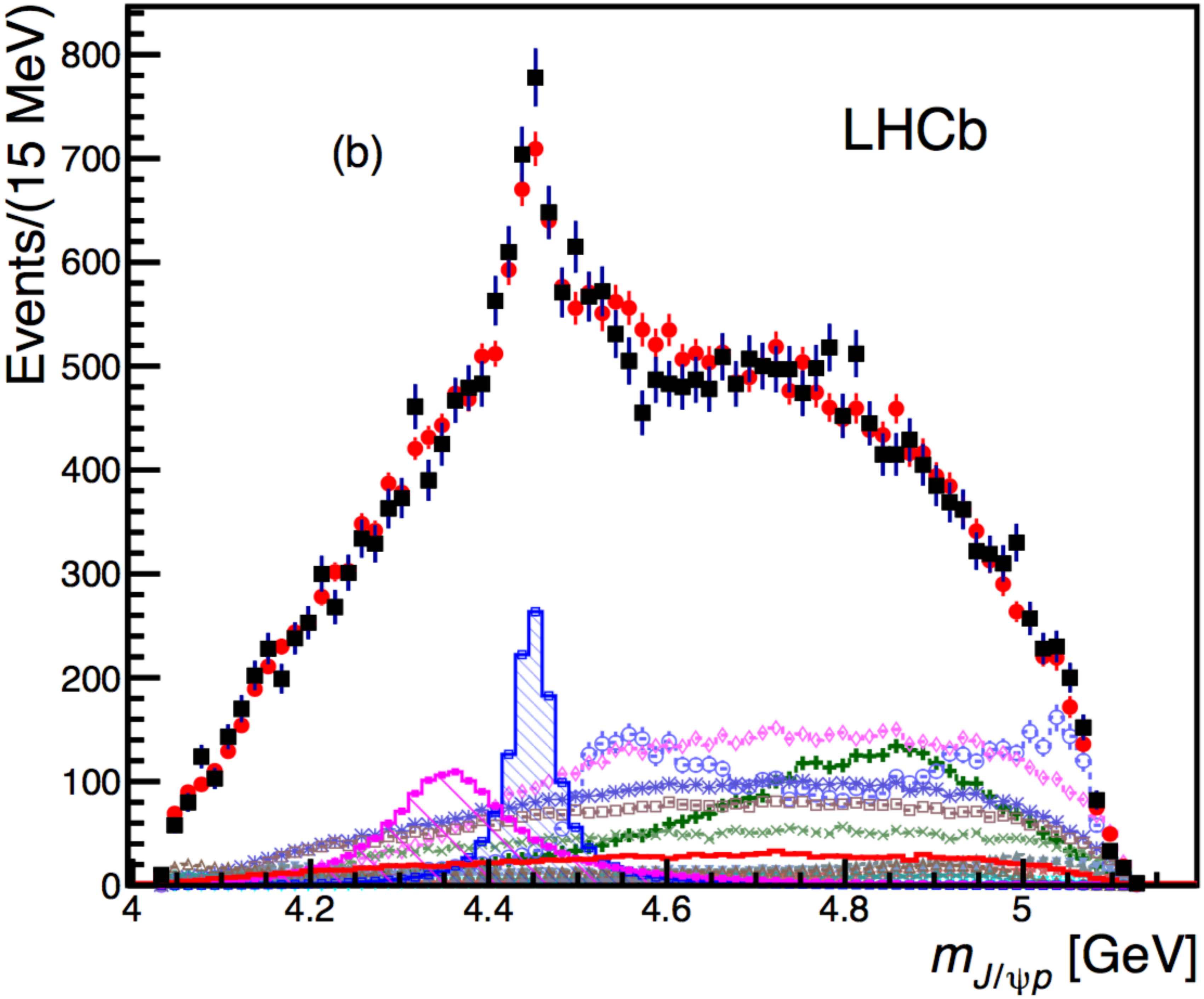
$$J^P = \frac{3}{2}^{\pm}$$

$$J^P = \frac{5}{2}^{\mp}$$



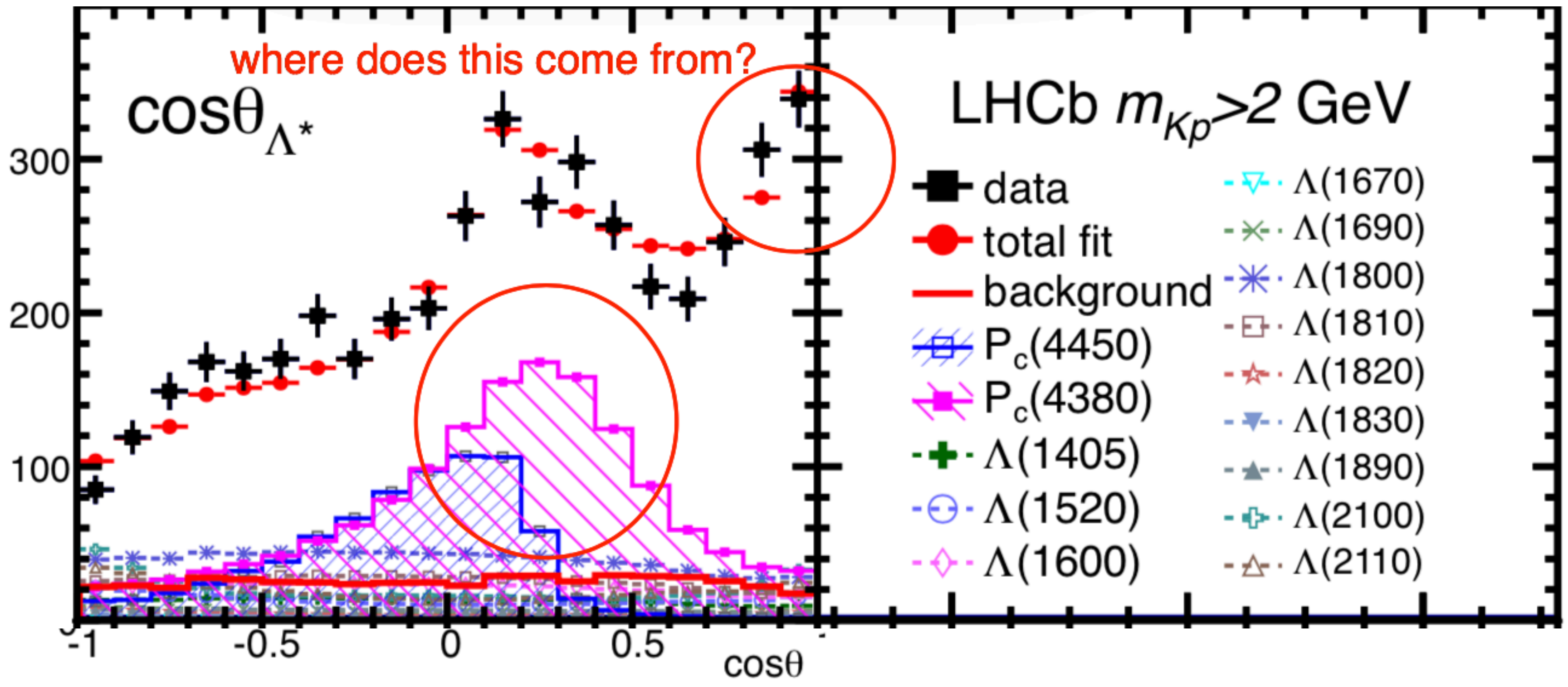
$P_c(4450)$
$P_c(4380)$

blue = 4450
purple = 4380



$P_c(4450)$
$P_c(4380)$

NB: evidence for 4380 does not just come from the projection



$P_c(4450)$
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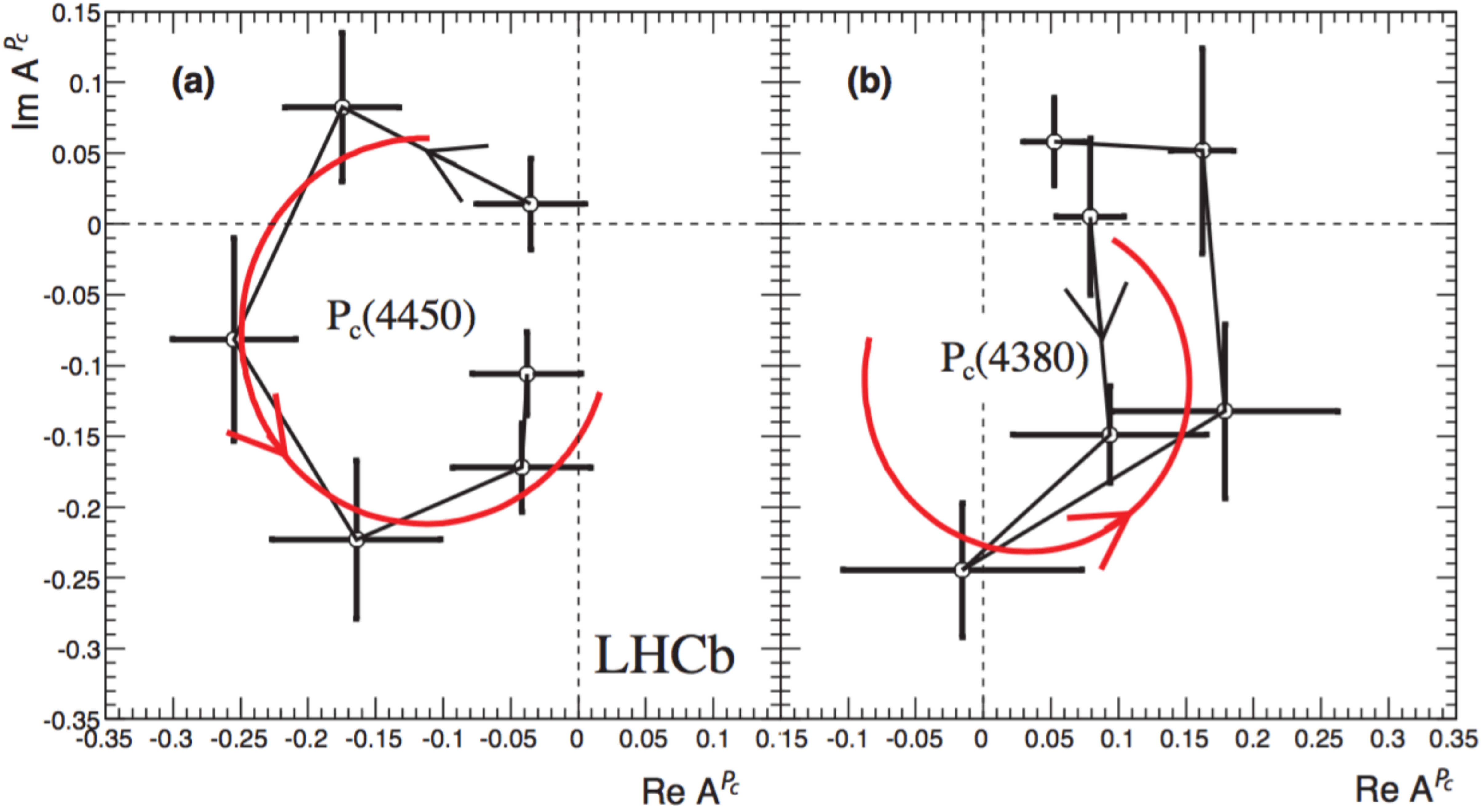
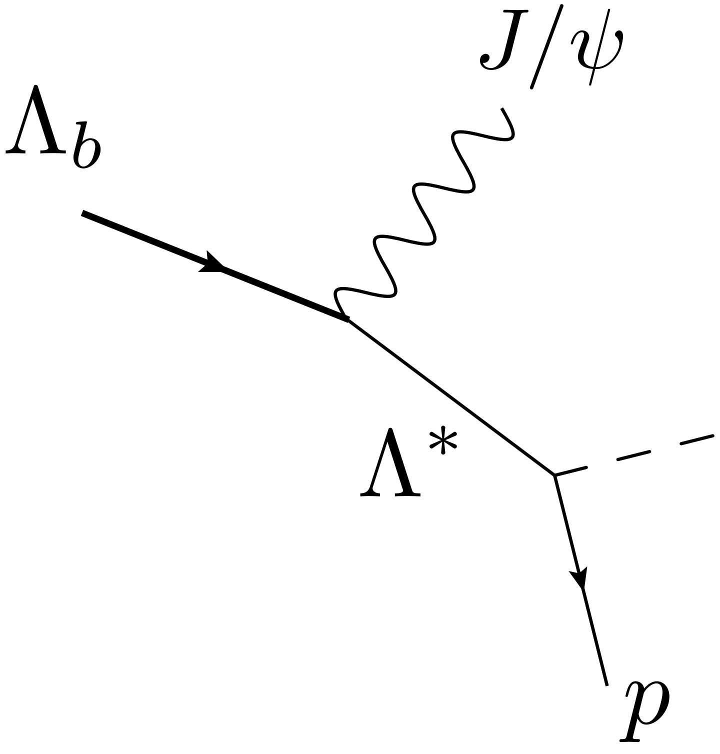
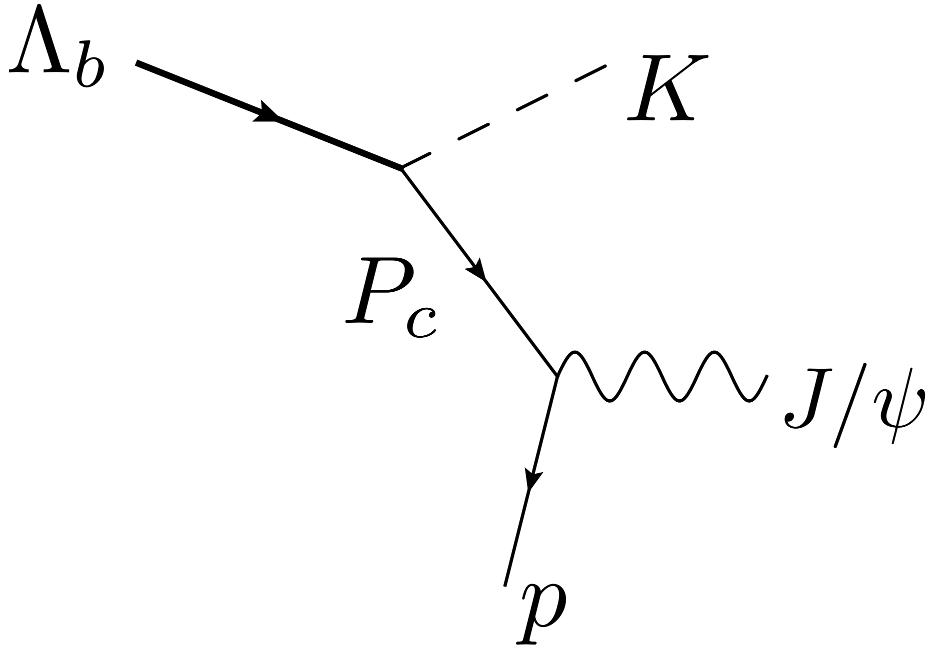


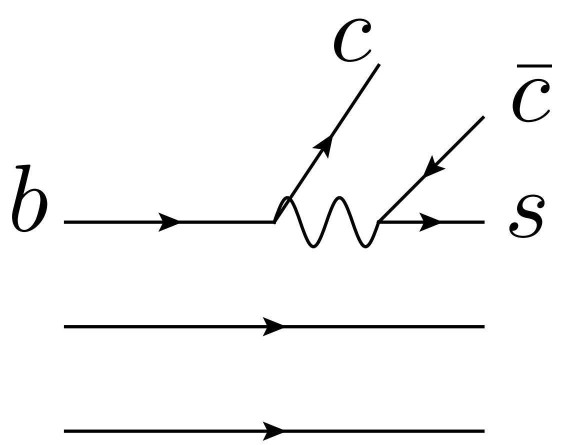
T. J. Burns
Phenomenology of Pc(4380)+, Pc(4450)+ and related states
arXiv:1509.02460v1 [hep-ph]

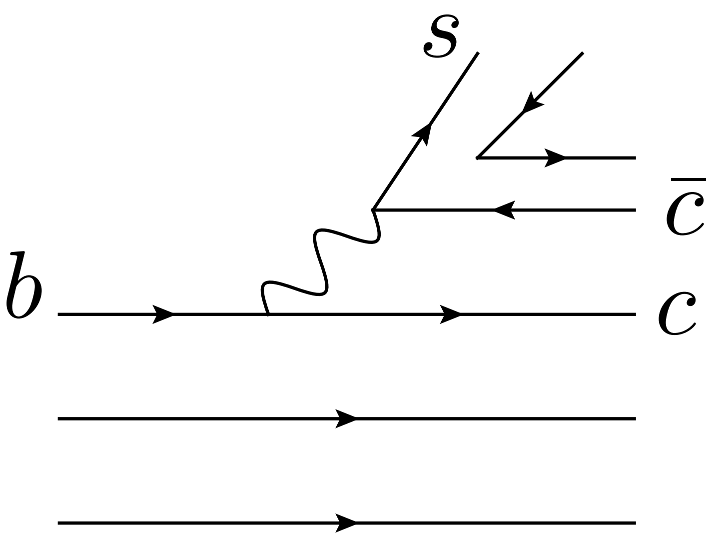
		$P_c(4380)^+$	$P_c(4450)^+$
Mass		$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width		$205 \pm 18 \pm 86$	$35 \pm 5 \pm 19$
Assignment 1		$3/2^-$	$5/2^+$
Assignment 2		$3/2^+$	$5/2^-$
Assignment 3		$5/2^+$	$3/2^-$
Assignment 4		$5/2^-$	$3/2^+$
$\Sigma_c^{*+}\bar{D}^0$	$(udc)(u\bar{c})$	4382.3 ± 2.4	
$\Sigma_c^+\bar{D}^{*0}$	$(udc)(u\bar{c})$		4459.9 ± 0.5
$\Lambda_c^+(1P)\bar{D}^0$	$(udc)(u\bar{c})$		4457.09 ± 0.35
$\chi_{c1}p$	$(udu)(c\bar{c})$		4448.93 ± 0.07

Production Mechanisms (tree)

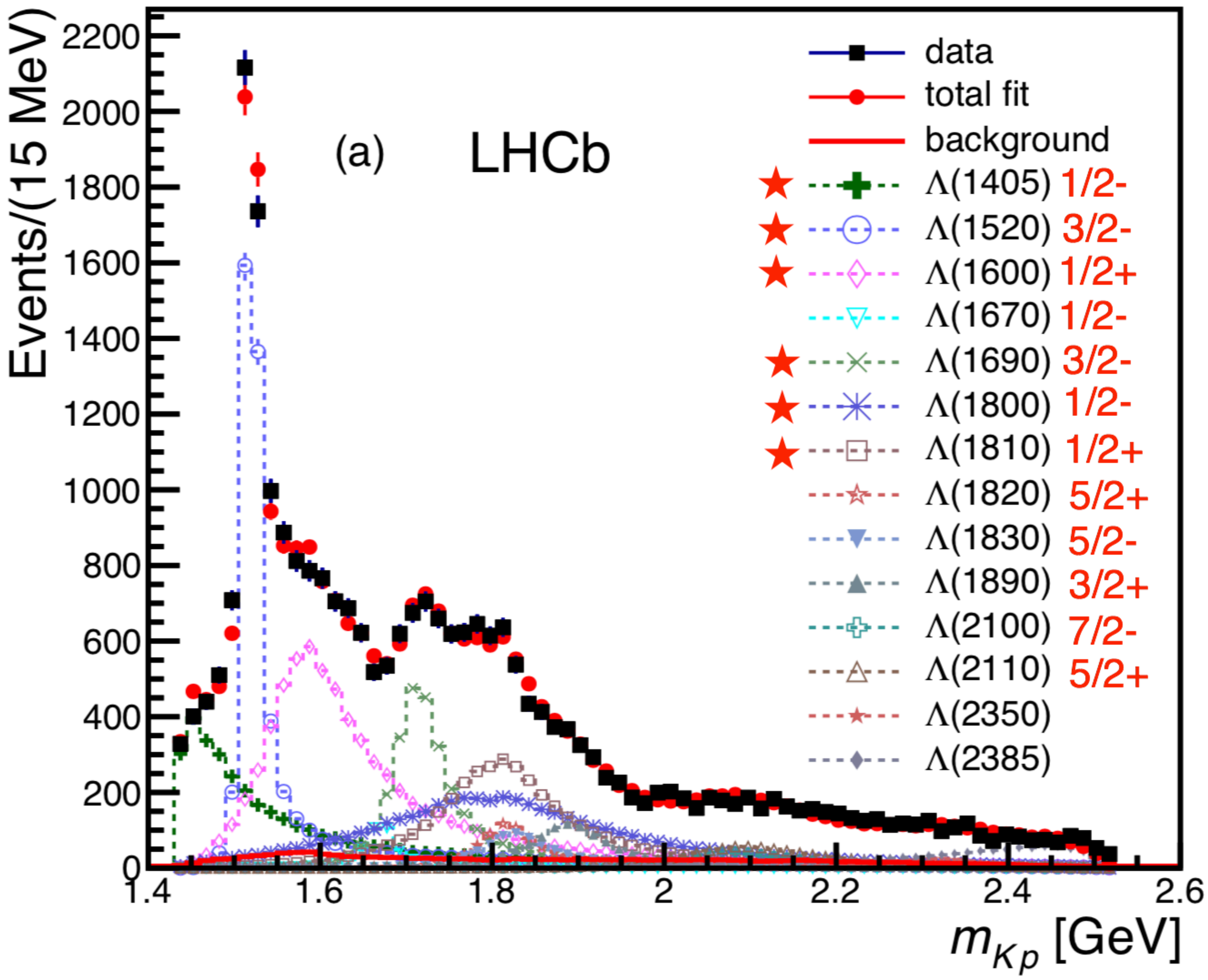




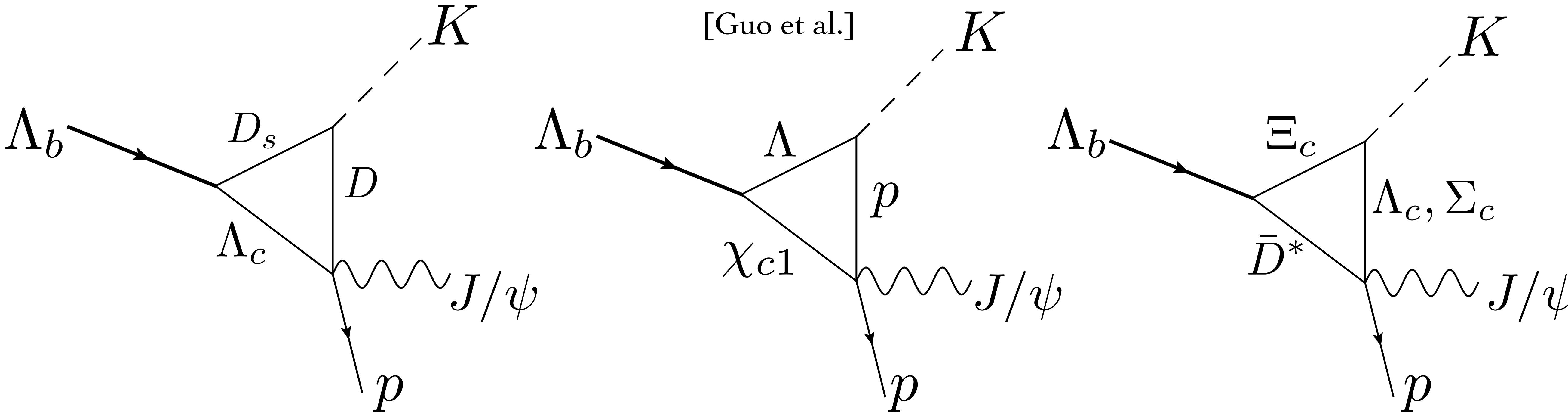




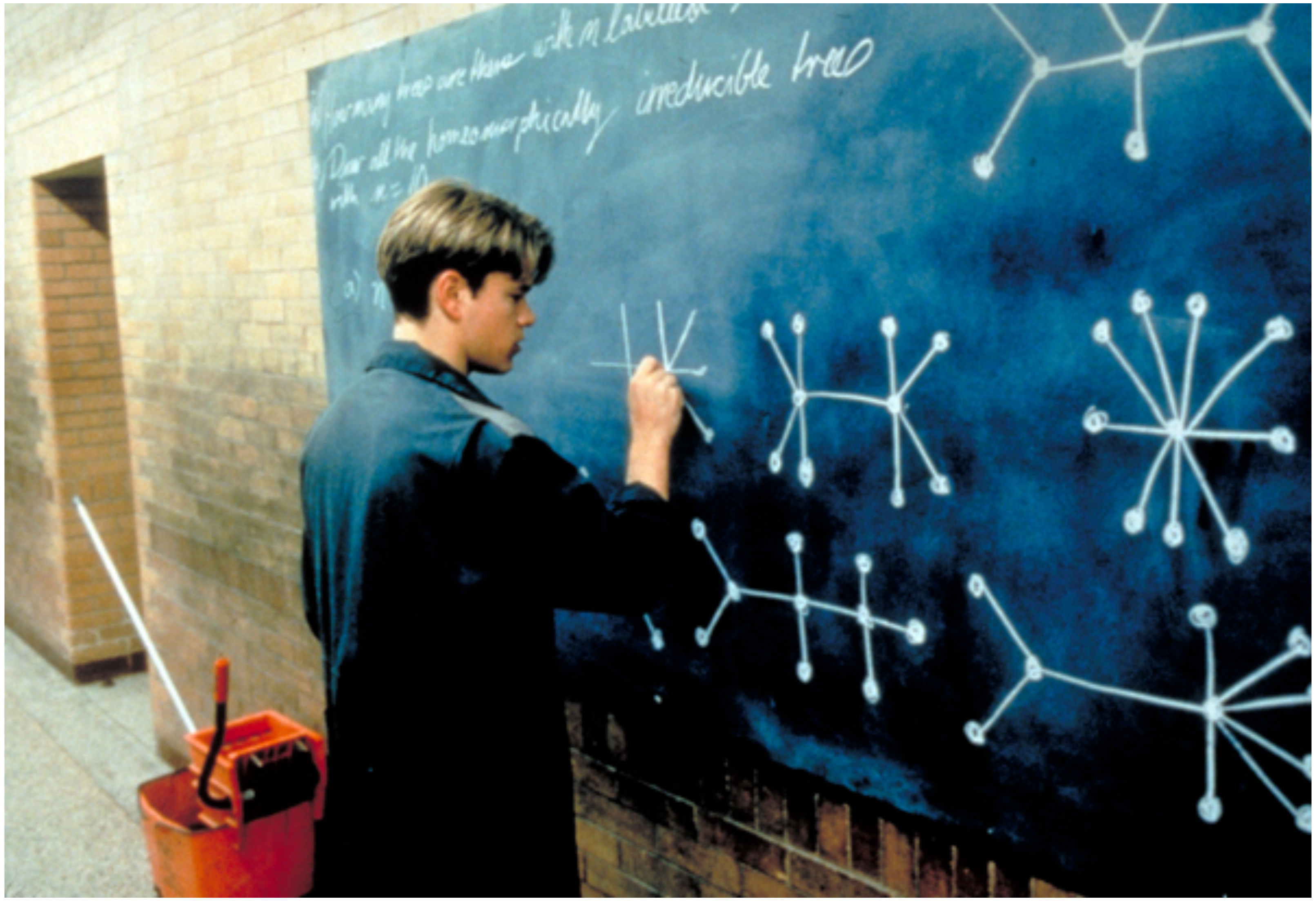
LHC is a baryon factory!



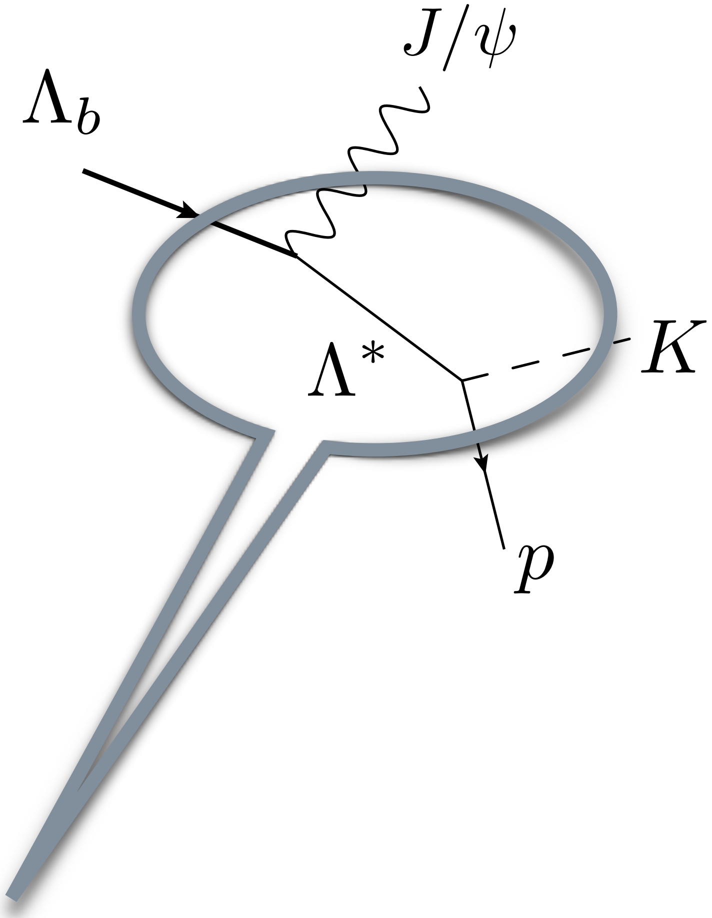
Production Mechanisms (loop)


[Guo et al.]

A Calculation

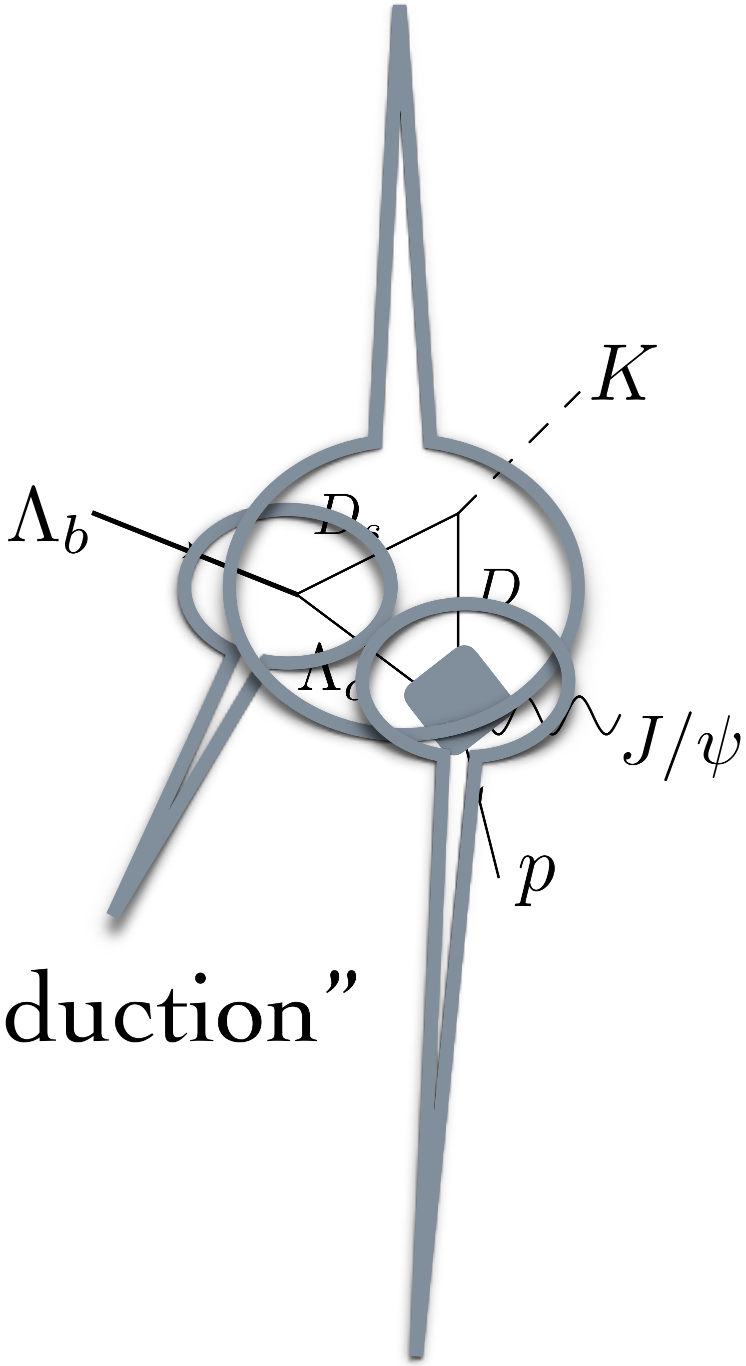


Organization



(0) “background”

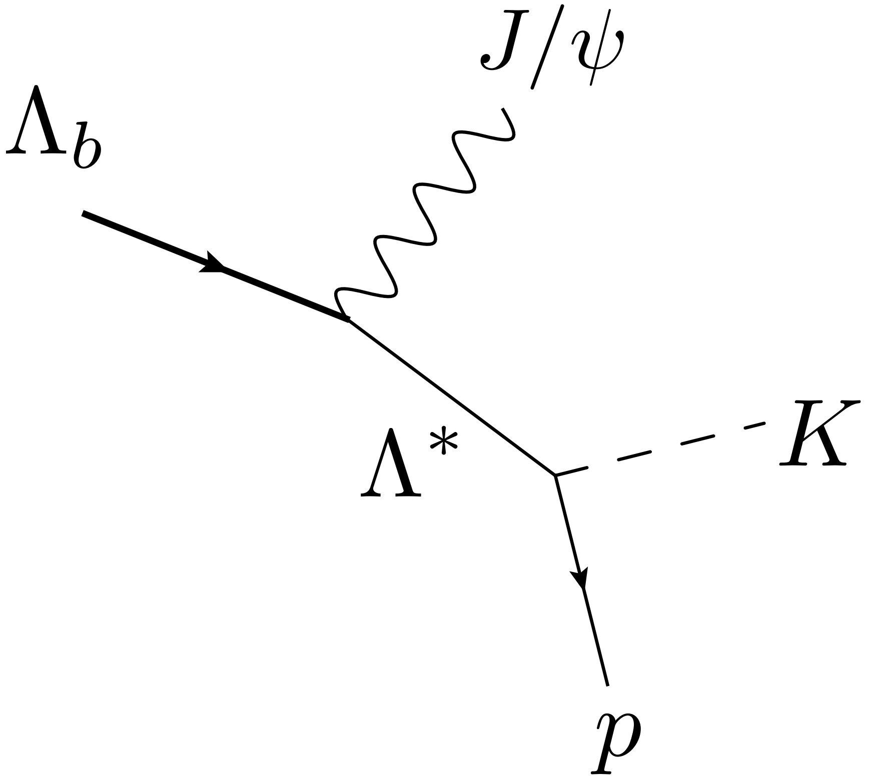
(ii) “dynamics”

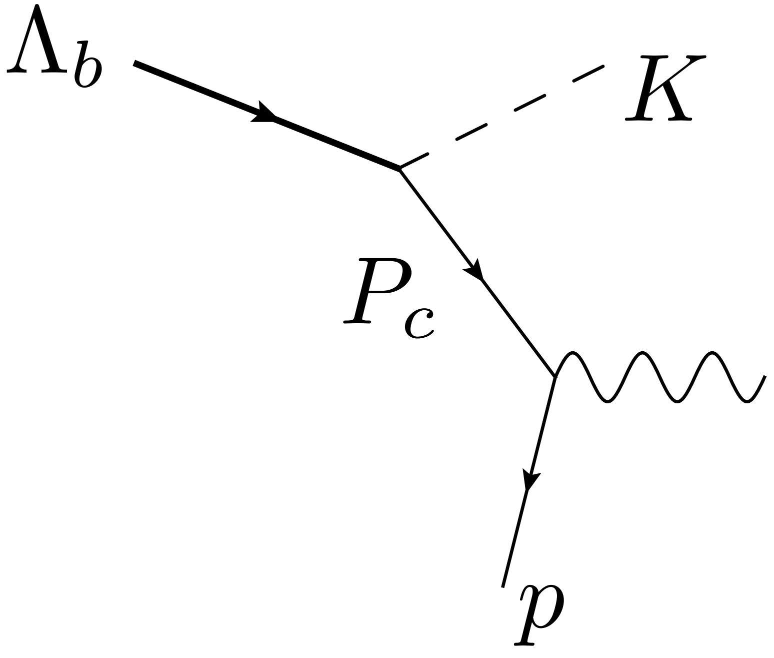


(i) “production”

(iii) soft dynamics/ final state interactions

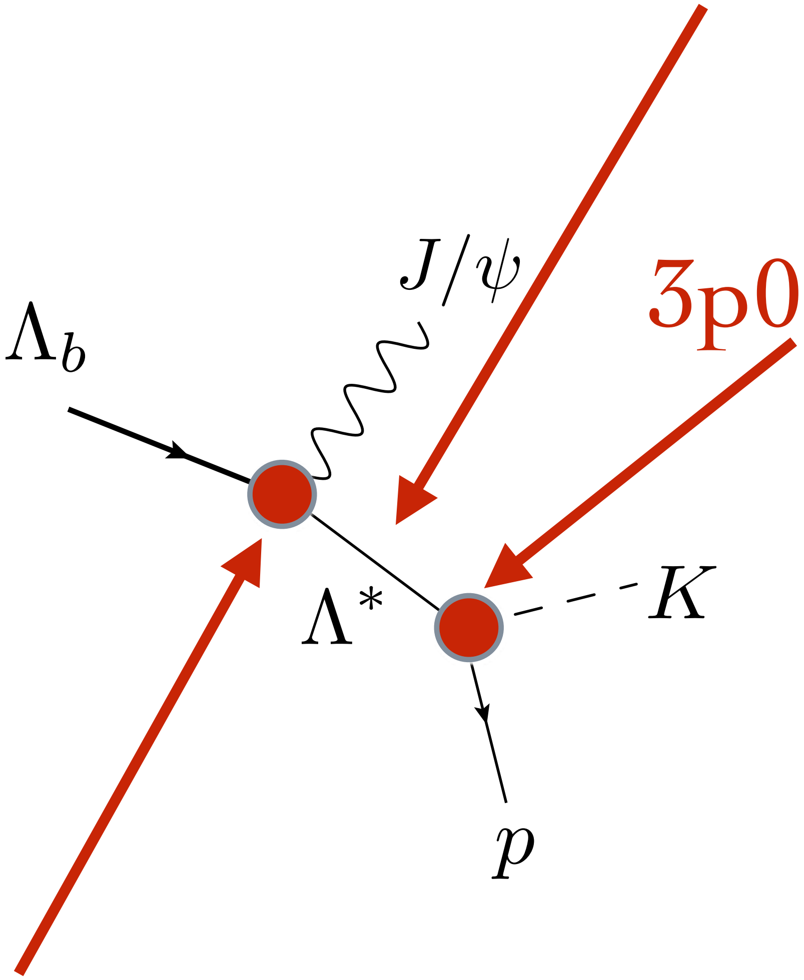
(0) Background – Lambda spectrum





(0) Background — Lambda spectrum

$\Lambda(1/2^-;1405)+\Lambda(1/2+;1600)$



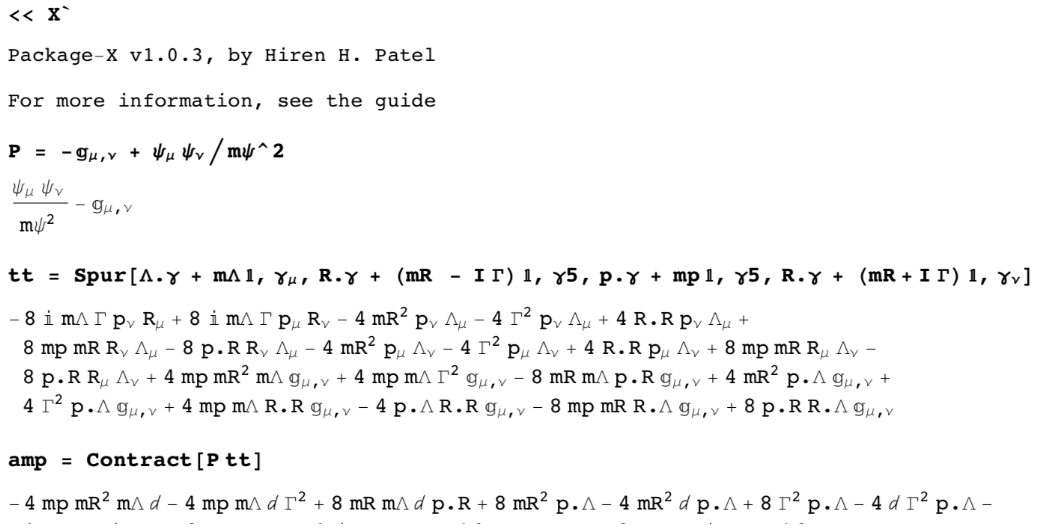
3p0 model

$$G_F V_{bc} V_{cs} \frac{f_{J/\psi} m_{J/\psi}}{\sqrt{2} N_c} \cdot 4 m_{\Lambda_b} \frac{\sqrt{s}}{(\sqrt{s}+m_{\Lambda_b})^2 - m_{J/\psi}^2}$$

$\Lambda_b \to \psi K p$

via *a* simple covariant model

(what's with the font change??)



```
<< X`

Package-X v1.0.3, by Hiren H. Patel

For more information, see the guide

P = -g_{μ,ν} + ψ_μ ψ_ν / mψ^2
```

$$\frac{\psi_\mu \psi_\nu}{m\psi^2} - g_{\mu,\nu}$$

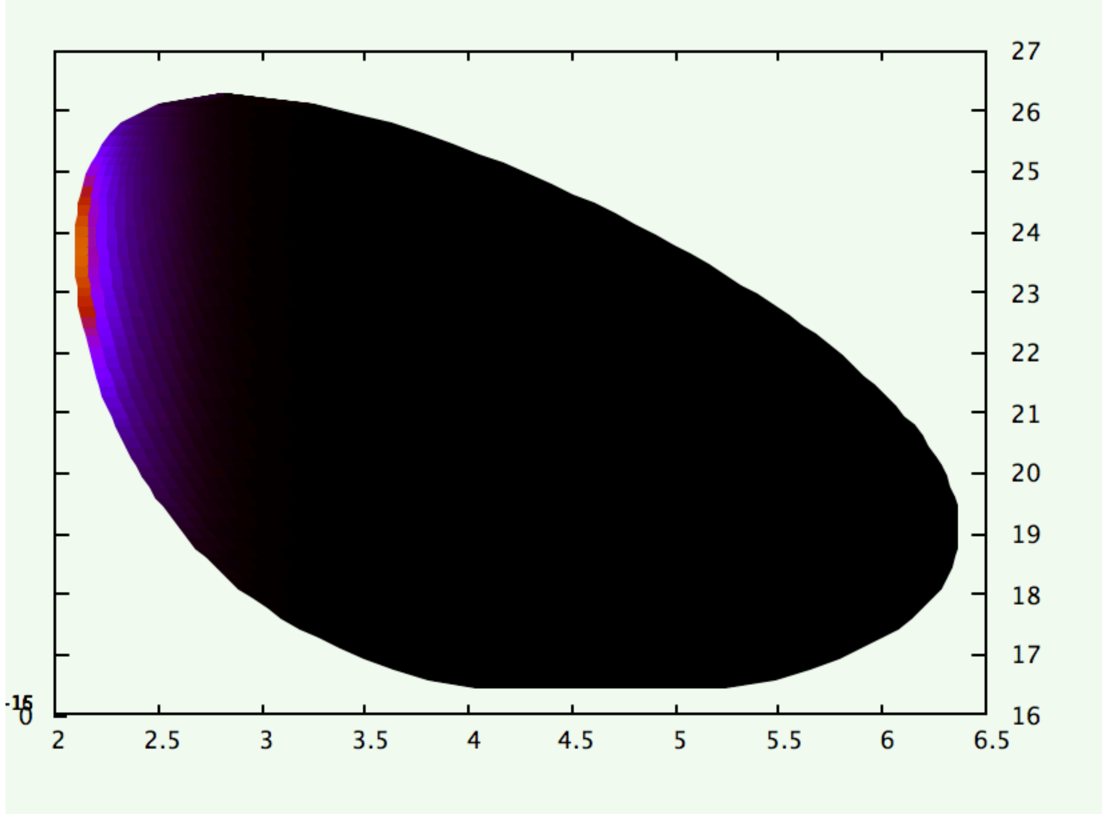
```
tt = Spur[Λ.γ + mΛ 𝟙, γ_μ, R.γ + (mR - I Γ) 𝟙, γ5, p.γ + mp 𝟙, γ5, R.γ + (mR + I Γ) 𝟙, γ_ν]
```

$$-8\, i\, m\Lambda\, \Gamma\, p_\nu R_\mu + 8\, i\, m\Lambda\, \Gamma\, p_\mu R_\nu - 4\, mR^2\, p_\nu \Lambda_\mu - 4\, \Gamma^2\, p_\nu \Lambda_\mu + 4\, R.R\, p_\nu \Lambda_\mu + 8\, mp\, mR\, R_\nu \Lambda_\mu - 8\, p.R\, R_\nu \Lambda_\mu - 4\, mR^2\, p_\mu \Lambda_\nu - 4\, \Gamma^2\, p_\mu \Lambda_\nu + 4\, R.R\, p_\mu \Lambda_\nu + 8\, mp\, mR\, R_\mu \Lambda_\nu - 8\, p.R\, R_\mu \Lambda_\nu + 4\, mp\, mR^2\, m\Lambda\, g_{\mu,\nu} + 4\, mp\, m\Lambda\, \Gamma^2\, g_{\mu,\nu} - 8\, mR\, m\Lambda\, p.R\, g_{\mu,\nu} + 4\, mR^2\, p.\Lambda\, g_{\mu,\nu} + 4\, \Gamma^2\, p.\Lambda\, g_{\mu,\nu} + 4\, mp\, m\Lambda\, R.R\, g_{\mu,\nu} - 4\, p.\Lambda\, R.R\, g_{\mu,\nu} - 8\, mp\, mR\, R.\Lambda\, g_{\mu,\nu} + 8\, p.R\, R.\Lambda\, g_{\mu,\nu}$$

```
amp = Contract[P tt]
```

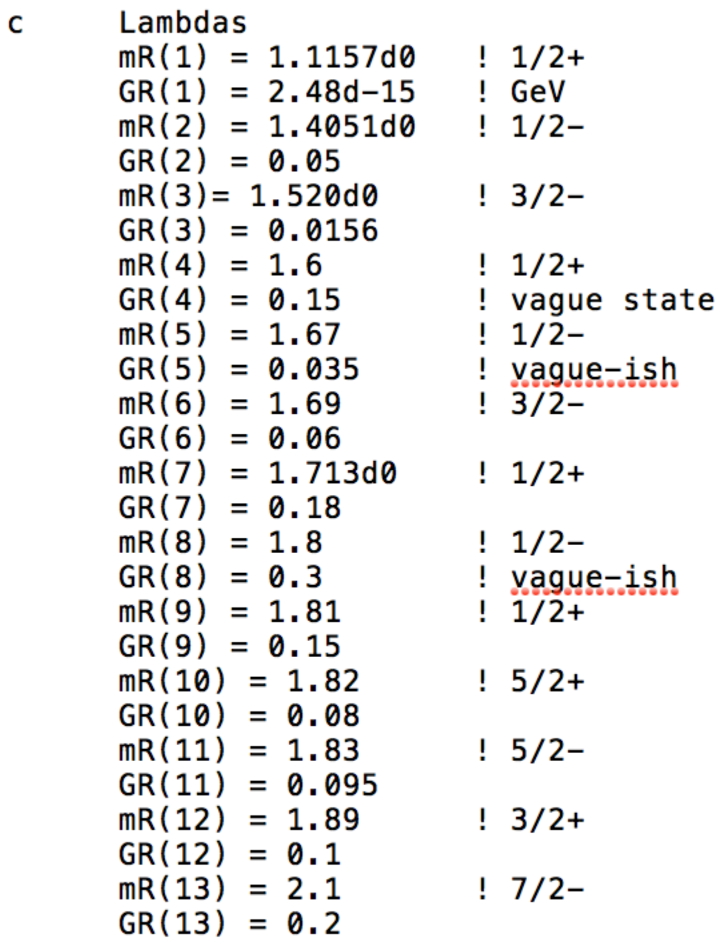
$$-4\, mp\, mR^2\, m\Lambda\, d - 4\, mp\, m\Lambda\, d\, \Gamma^2 + 8\, mR\, m\Lambda\, d\, p.R + 8\, mR^2\, p.\Lambda - 4\, mR^2\, d\, p.\Lambda + 8\, \Gamma^2\, p.\Lambda - 4\, d\, \Gamma^2\, p.\Lambda -$$

• • •

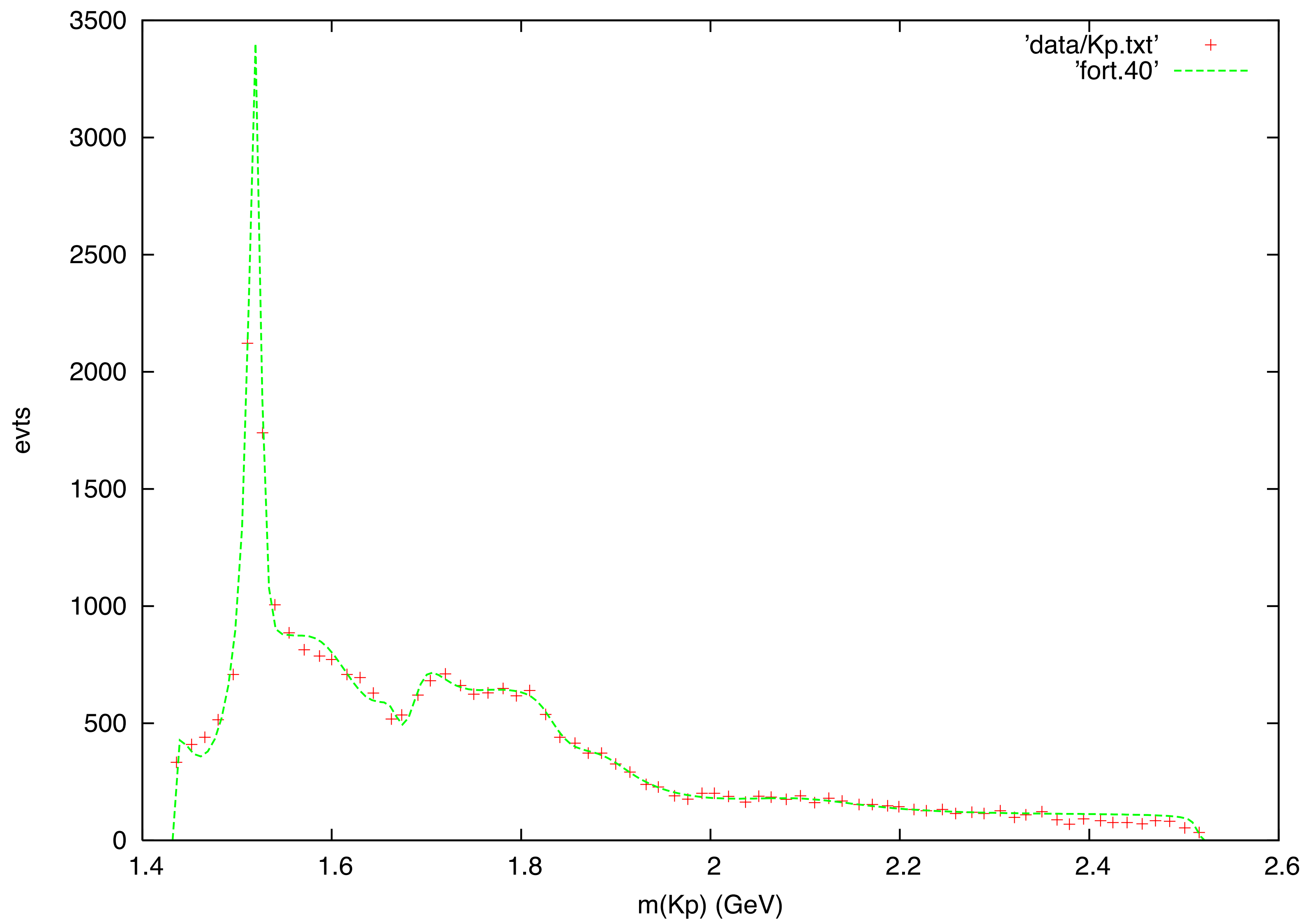


(0) Background – Lambda spectrum

try a fit to the Kp
and J/ψp
projections with Λs

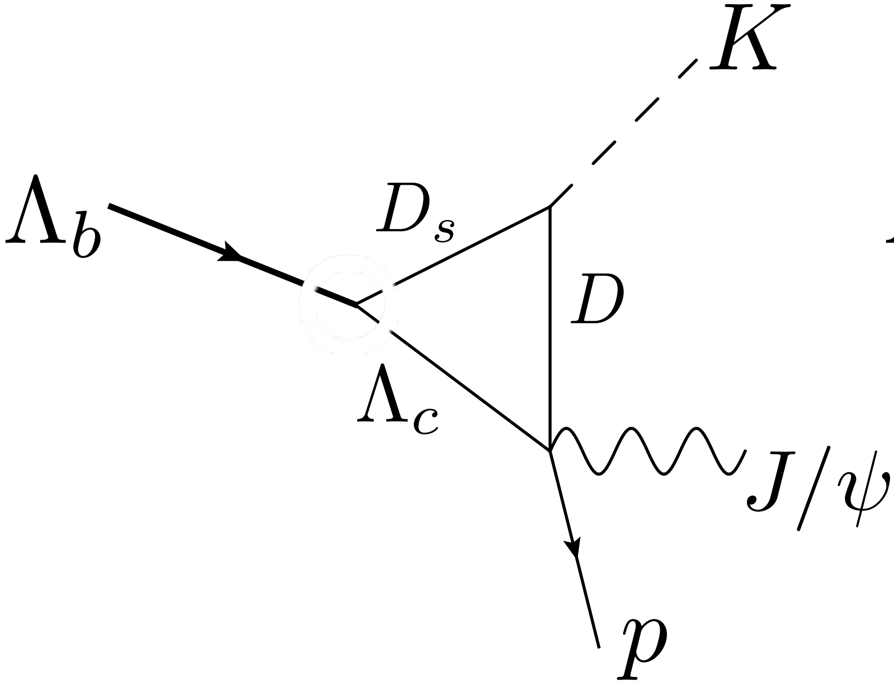


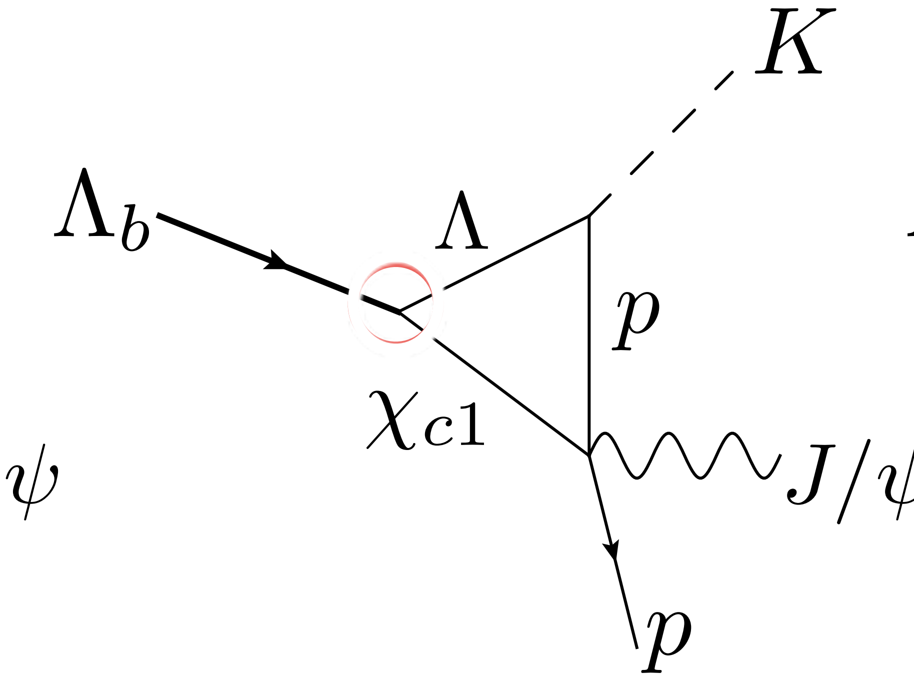
```
c       Lambdas
        mR(1) = 1.1157d0    ! 1/2+
        GR(1) = 2.48d-15    ! GeV
        mR(2) = 1.4051d0    ! 1/2-
        GR(2) = 0.05
        mR(3)= 1.520d0      ! 3/2-
        GR(3) = 0.0156
        mR(4) = 1.6         ! 1/2+
        GR(4) = 0.15        ! vague state
        mR(5) = 1.67        ! 1/2-
        GR(5) = 0.035       ! vague-ish
        mR(6) = 1.69        ! 3/2-
        GR(6) = 0.06
        mR(7) = 1.713d0     ! 1/2+
        GR(7) = 0.18
        mR(8) = 1.8         ! 1/2-
        GR(8) = 0.3         ! vague-ish
        mR(9) = 1.81        ! 1/2+
        GR(9) = 0.15
        mR(10) = 1.82       ! 5/2+
        GR(10) = 0.08
        mR(11) = 1.83       ! 5/2-
        GR(11) = 0.095
        mR(12) = 1.89       ! 3/2+
        GR(12) = 0.1
        mR(13) = 2.1        ! 7/2-
        GR(13) = 0.2
```

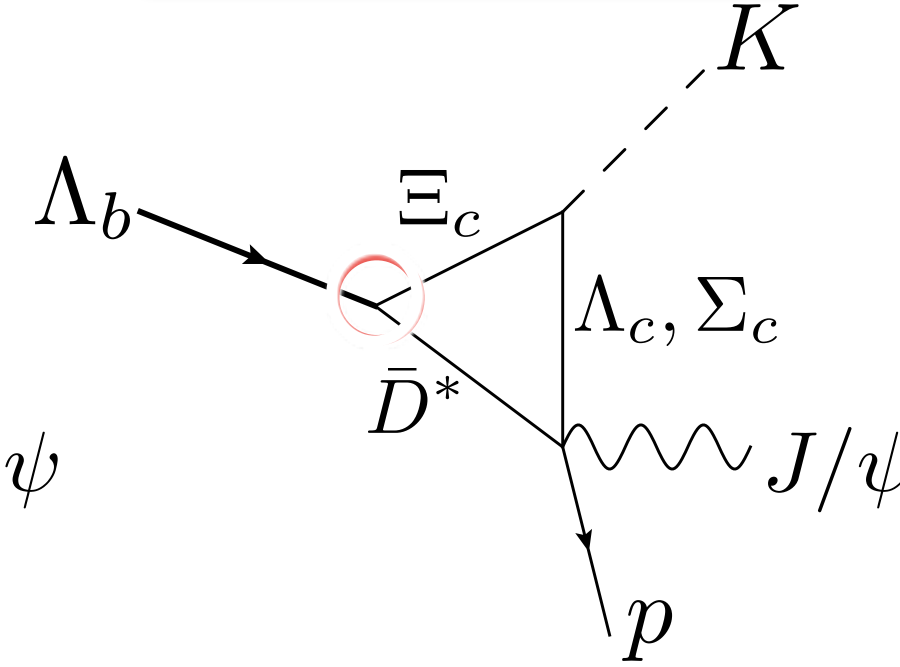


(i) Electroweak Production Vertex

novel (first ever?) non-factorizable decay!







note that flavour-spin structure gets preserved in the spectator lines

first is strongly preferred, need to argue for who dominates…

(i) Electroweak Production Vertex

use heavy quark formalism

- $$i\mathcal{M}(\Lambda_b \to D_s \Lambda_c) = \frac{G_F}{\sqrt{2}} V_{bc} V_{cs}^* \, i f_{D_s} p_{D_s}^{\mu} \, \xi(w) \, \bar{u}_c \gamma_\mu u_b$$

$$\Gamma = 5.8 \cdot 10^{-15} \text{ GeV}$$

$$\Gamma_{expt} = 4.95 \cdot 10^{-15} \text{ GeV}$$

(i) Electroweak Production Vertex

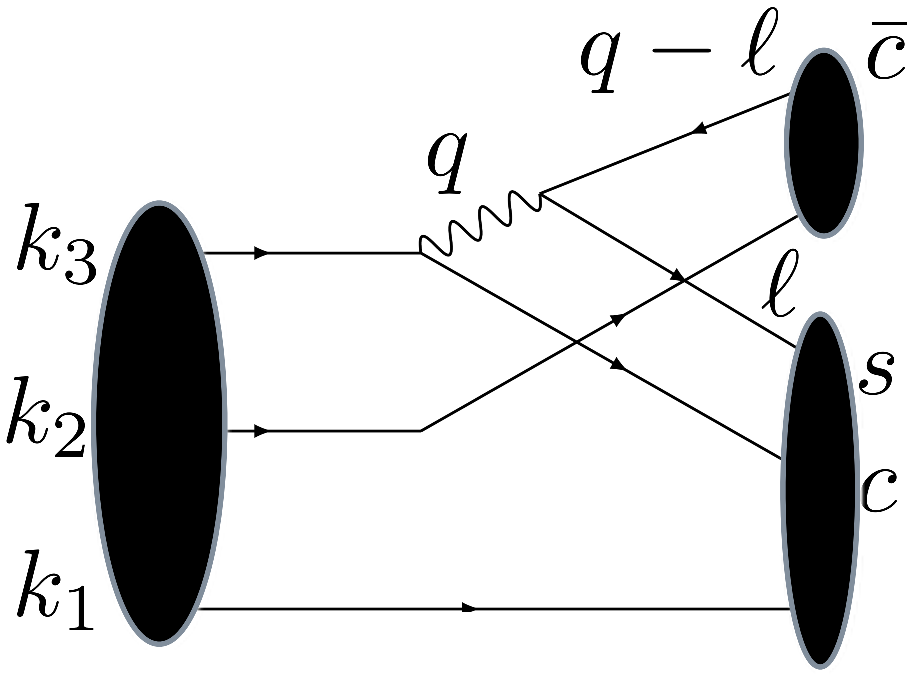
- $$i\mathcal{M}(\Lambda_b \to \chi_{c1} \Lambda) = \frac{G_F}{\sqrt{2}} V_{bc} V_{cs}^* \frac{1}{N_c} \, m_\chi f_\chi \epsilon^\mu (p_\chi, \lambda_\chi) \, \xi(w) \, \bar{u}_s \gamma_\mu u_b$$

$$\Gamma = 4.6 \cdot 10^{-16} \text{ GeV}$$

This is colour-suppressed. Comparing other predictions to experiment indicates that about 1/2 of the amplitude is due to rescattering from colour enhanced decay modes.

(i) Electroweak Production Vertex

Quark model computation



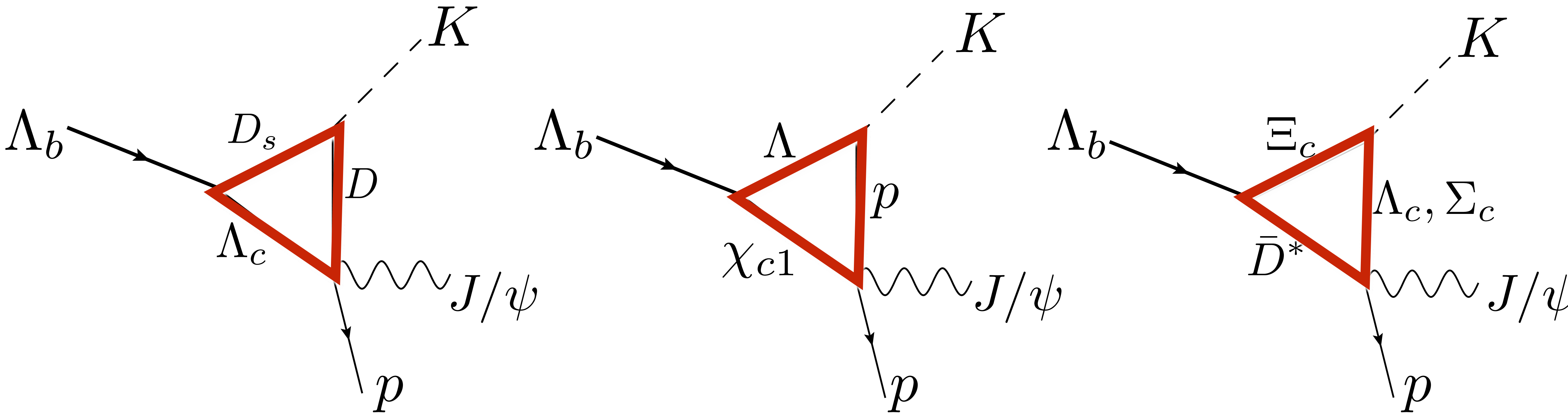
- $$i\mathcal{M} \approx \frac{G_F}{\sqrt{2}}\frac{1}{N_c}V_{bc}V_{cs}\int\frac{d^3q}{(2\pi)^3}\frac{d^3\ell}{(2\pi)^3}\frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3}\frac{d^3k_3}{(2\pi)^3}\cdot\ \phi_{\Lambda_b}(k_1,k_2,k_3)$$

$$\bar{u}_b(k_3)\Gamma^\mu u_c(k_3-q)\,\phi^*_{\Lambda_c}(k_1,k_3-q,\ell)\bar{v}_c(q-\ell)\Gamma^\mu u_s(\ell)\,\phi^*_D(k_2,q-\ell)\cdot$$

$$(2\pi)^3\delta(Q-q+\ell-k_2)\,(2\pi)^3\delta(-Q-\ell-k_3+q-k_1)$$

$$\Gamma \approx 1.1\cdot 10^{-16}\ \text{GeV}$$

(ii) Loop Dynamics



E.P. Wigner, Phys. Rev. 73 (1948) 1002

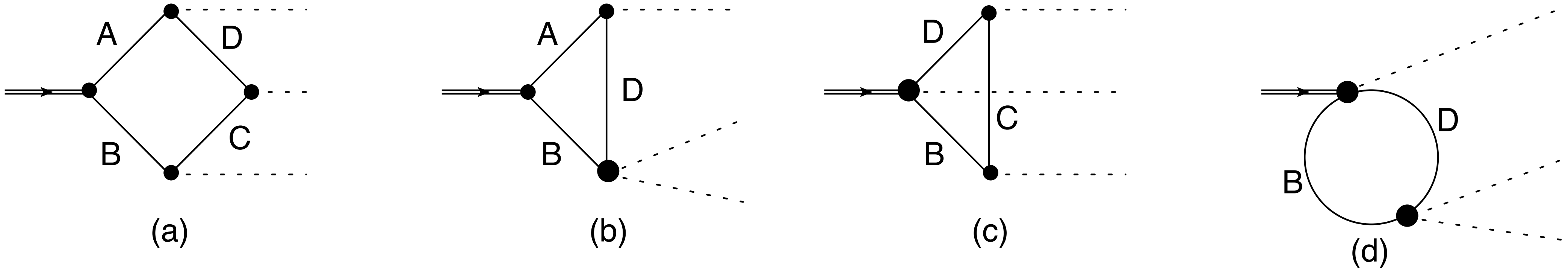
D. V. Bugg, Europhys. Lett. 96, 11002 (2011)

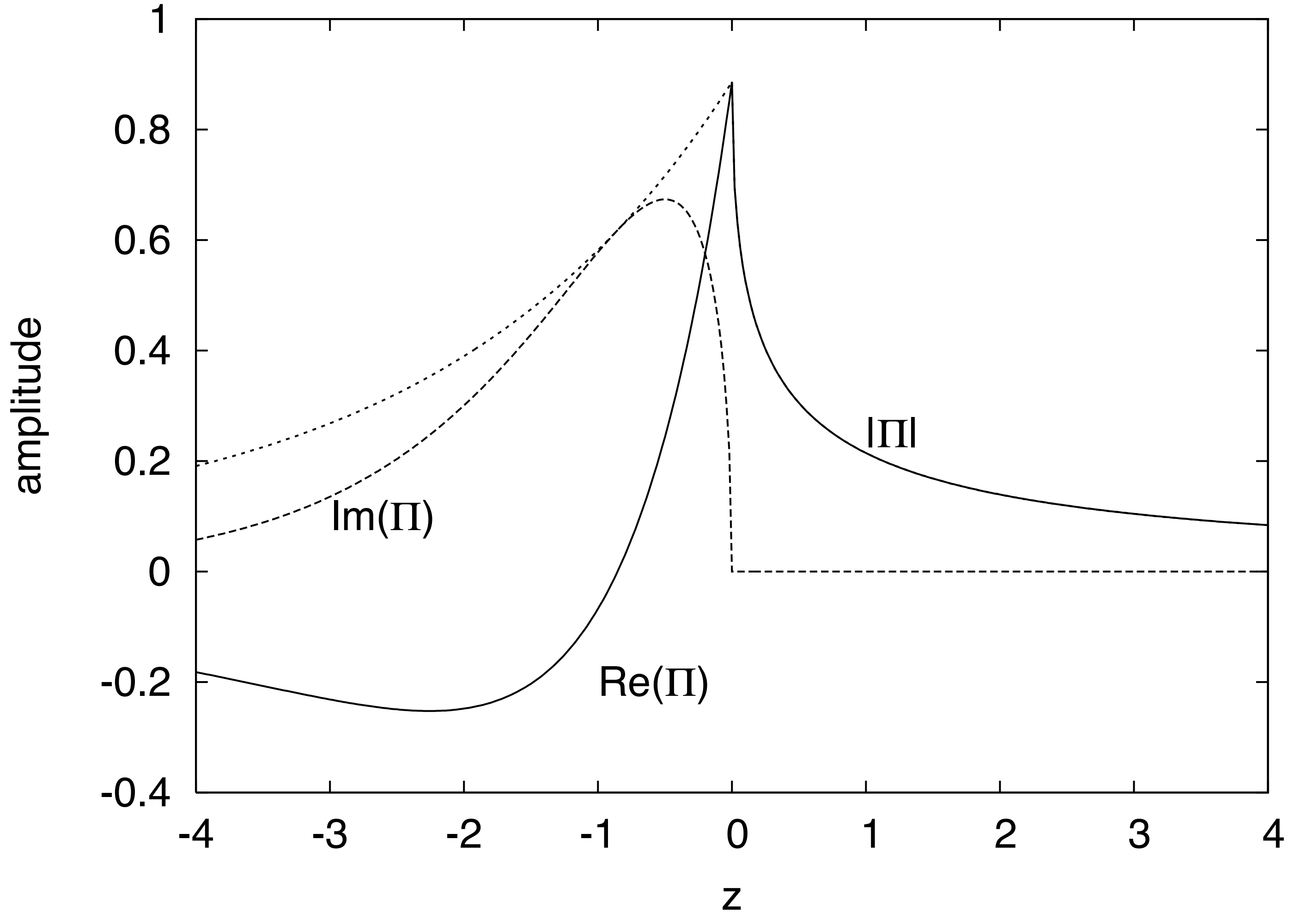
D. V. Bugg, Int. J. Mod. Phys. A 24, 394 (2009)

E.S. Swanson, arXiv:1409.3291; arXiv:1504.07952

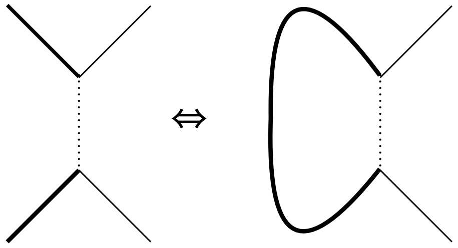
(ii) Loop Dynamics

Loops create cusps





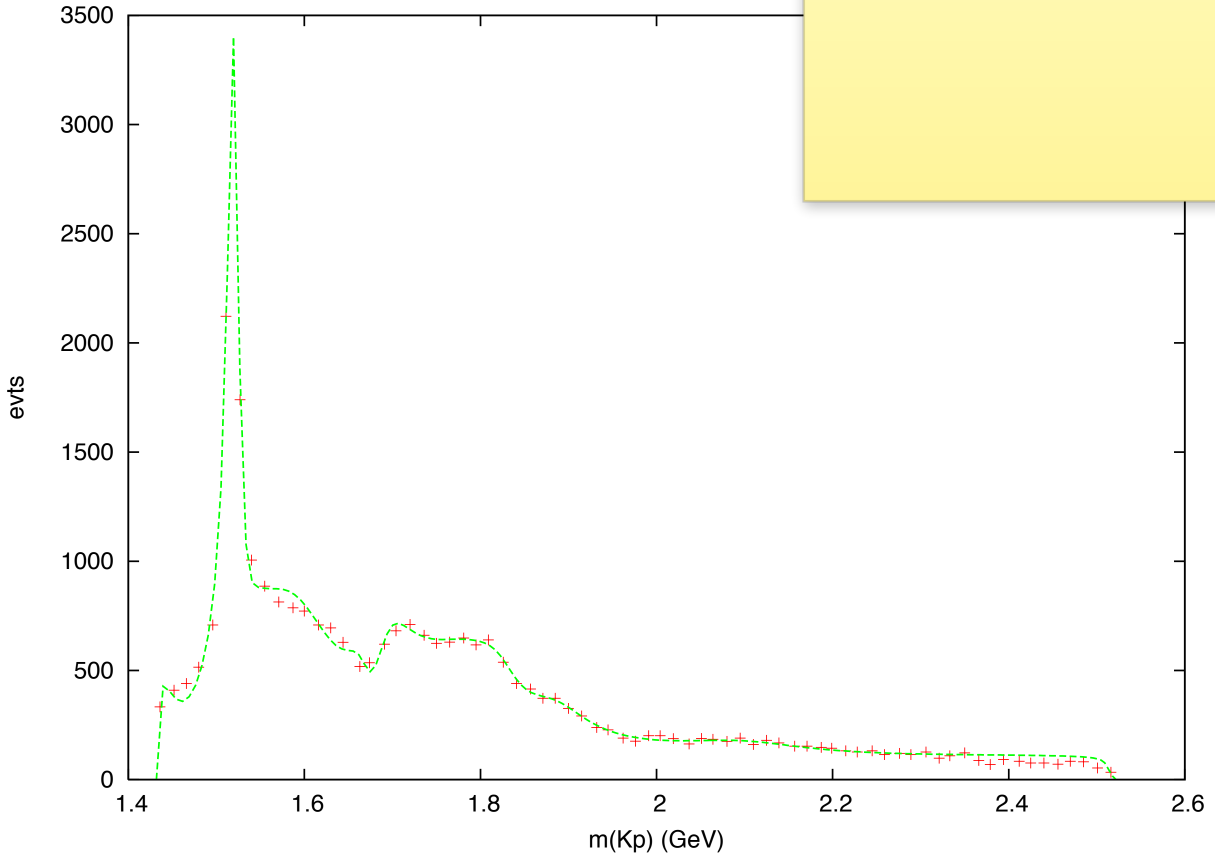
and are related to thresholds

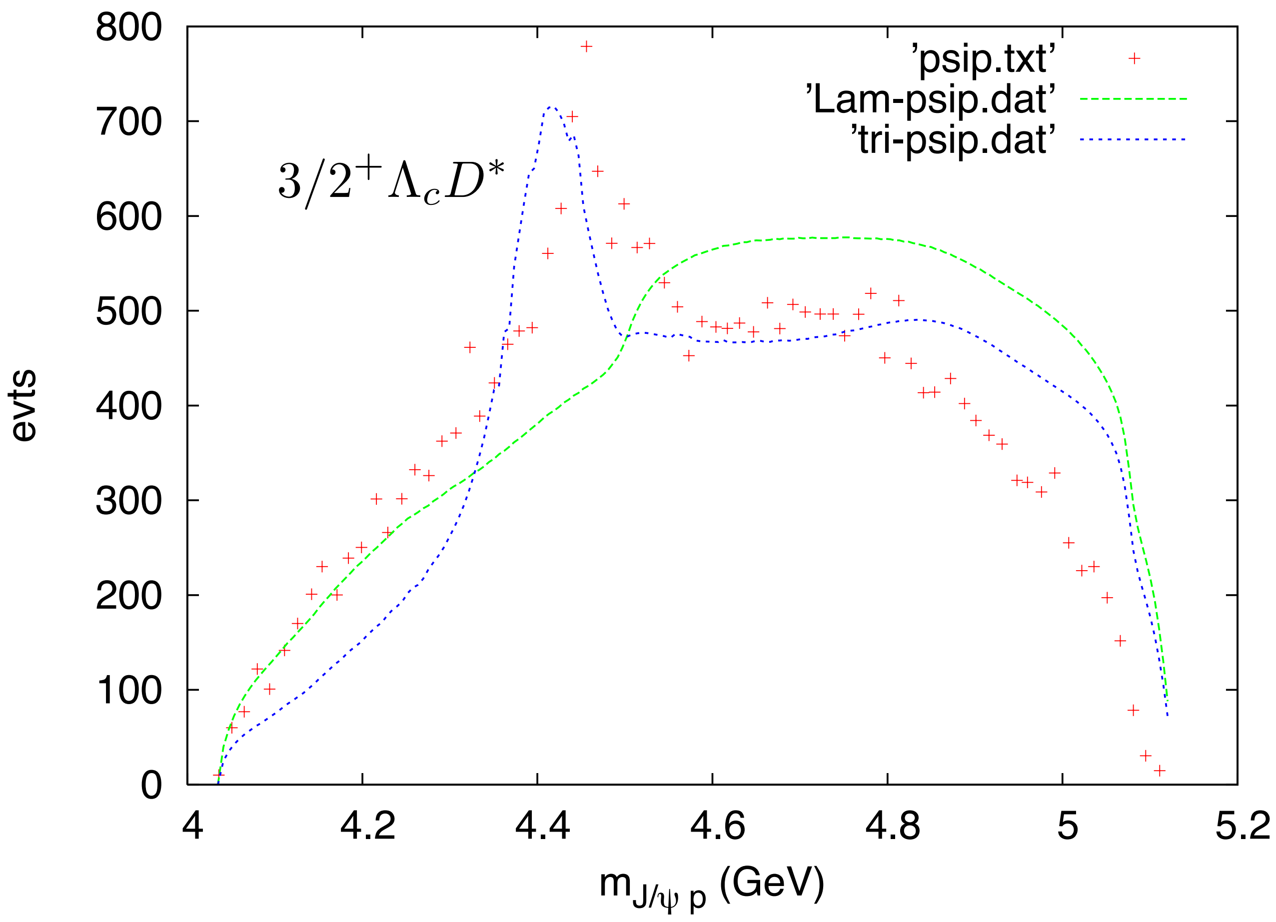


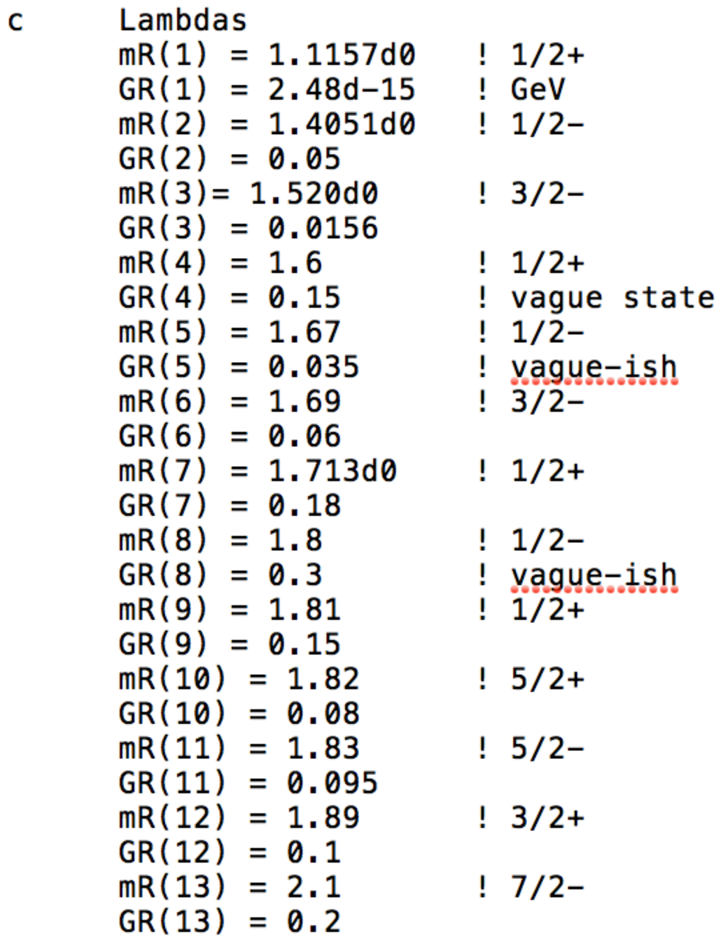
(ii) Loop Dynamics

try a fit to the Kp and J/ψp projections with Λs

blue curve include a triangle diagram







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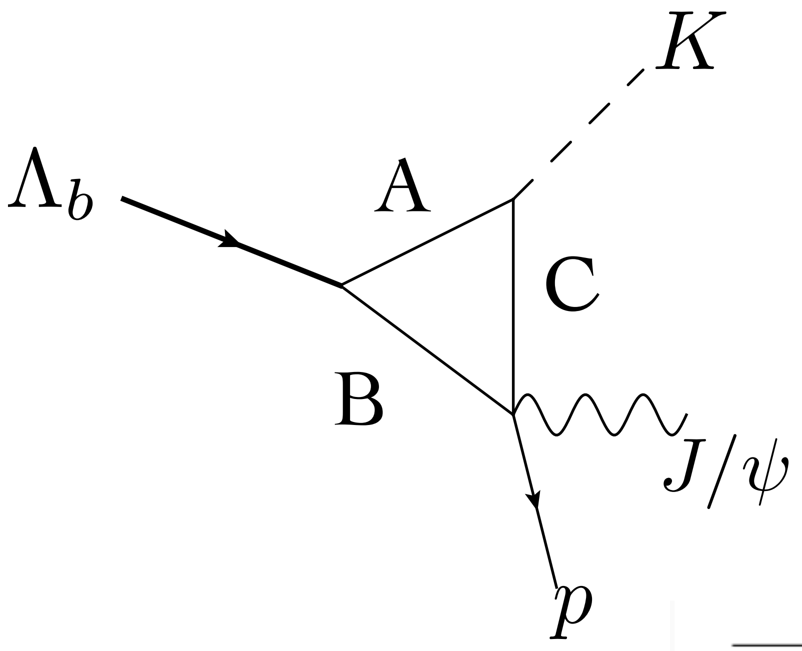
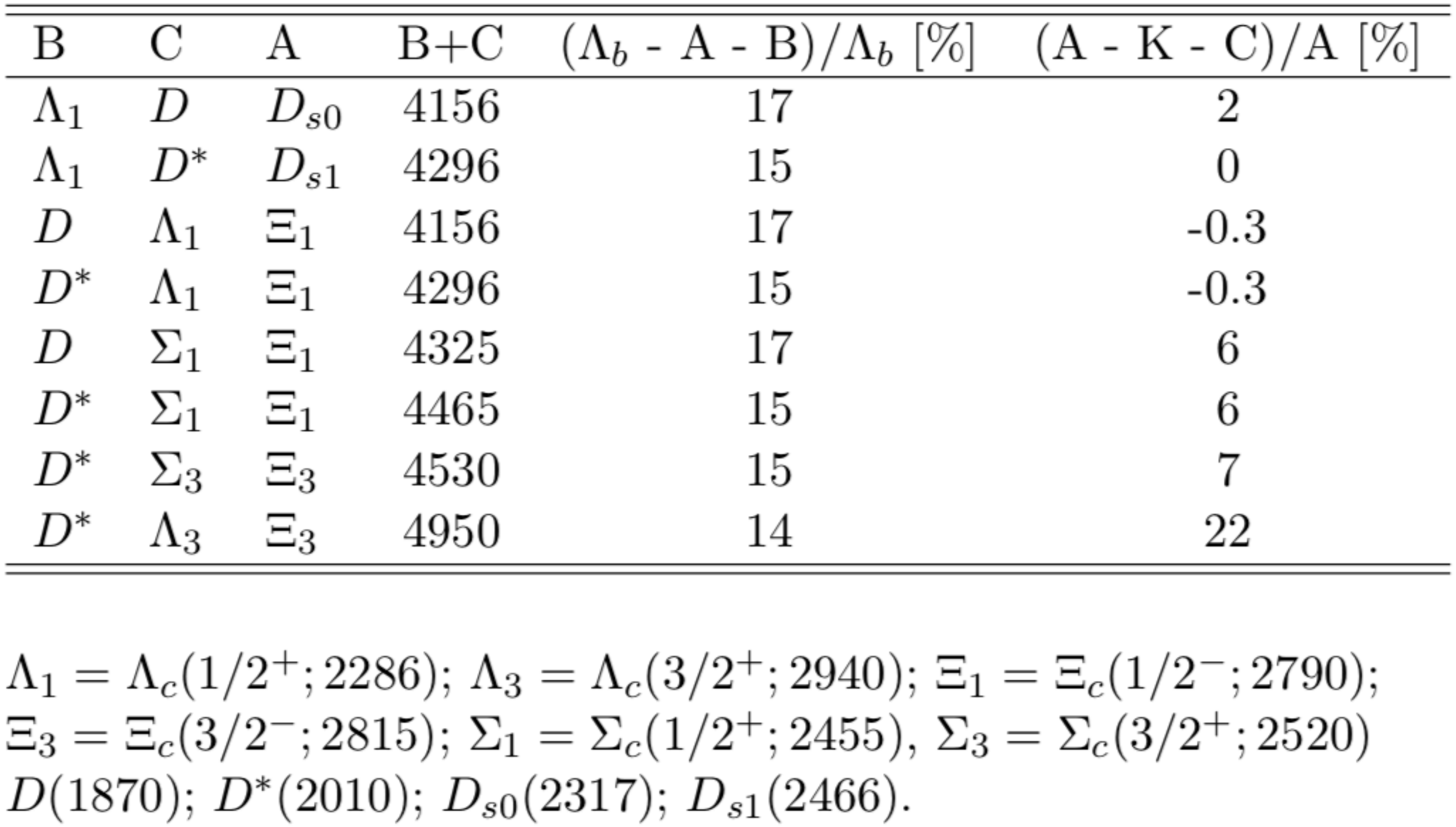
```

(ii) Loop Dynamics



- S-waves only
- ground states only
- narrow states only

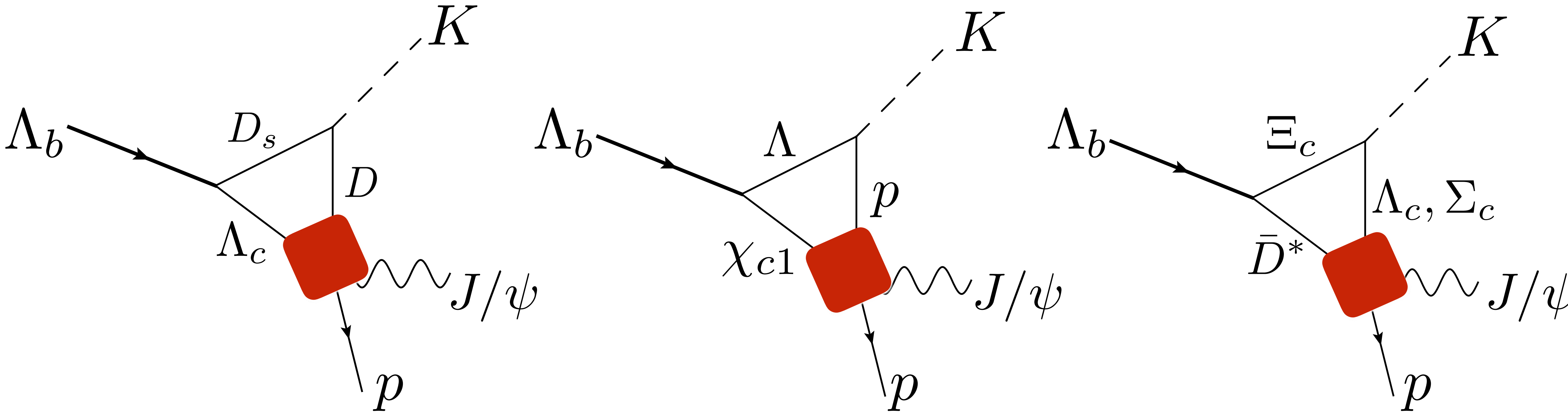


B	C	A	B+C	(Λ_b - A - B)/Λ_b [%]	(A - K - C)/A [%]
Λ_1	D	D_{s0}	4156	17	2
Λ_1	D^*	D_{s1}	4296	15	0
D	Λ_1	Ξ_1	4156	17	-0.3
D^*	Λ_1	Ξ_1	4296	15	-0.3
D	Σ_1	Ξ_1	4325	17	6
D^*	Σ_1	Ξ_1	4465	15	6
D^*	Σ_3	Ξ_3	4530	15	7
D^*	Λ_3	Ξ_3	4950	14	22

$\Lambda_1 = \Lambda_c(1/2^+; 2286)$; $\Lambda_3 = \Lambda_c(3/2^+; 2940)$; $\Xi_1 = \Xi_c(1/2^-; 2790)$; $\Xi_3 = \Xi_c(3/2^-; 2815)$; $\Sigma_1 = \Sigma_c(1/2^+; 2455)$, $\Sigma_3 = \Sigma_c(3/2^+; 2520)$ $D(1870)$; $D^*(2010)$; $D_{s0}(2317)$; $D_{s1}(2466)$.

Who wins?

(iii) Final State Interactions



what's in the box??

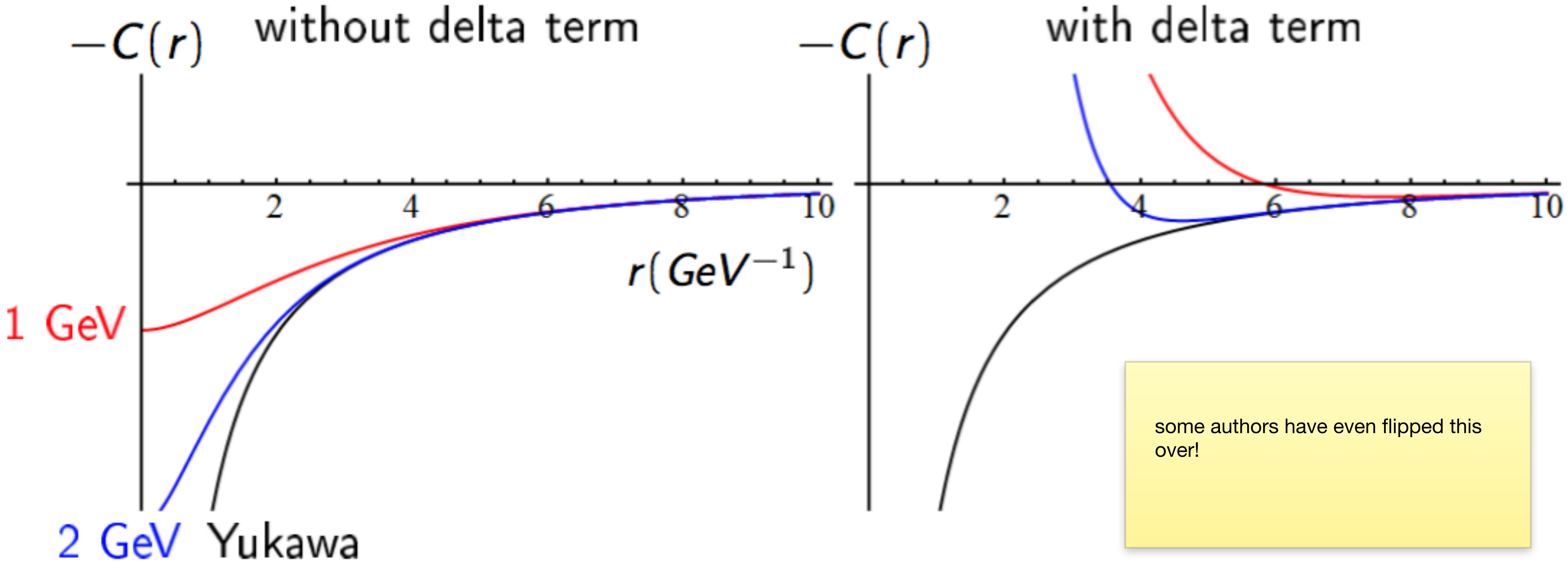
-> one pion exchange/ short range dynamics

(iii) Final State Interactions

For point-like constituents:

$$C(r) = \frac{g^2 m^3}{12\pi f_\pi^2}\left(\frac{e^{-mr}}{mr} - \frac{4\pi}{m^3}\delta^3(\vec{r})\right)$$

For extended hadrons, use dipole form factors with cutoff Λ. The limit $\Lambda \to \infty$ recovers the point-like case.



some authors have even flipped this over!

(iii) Final State Interactions

diagonal only

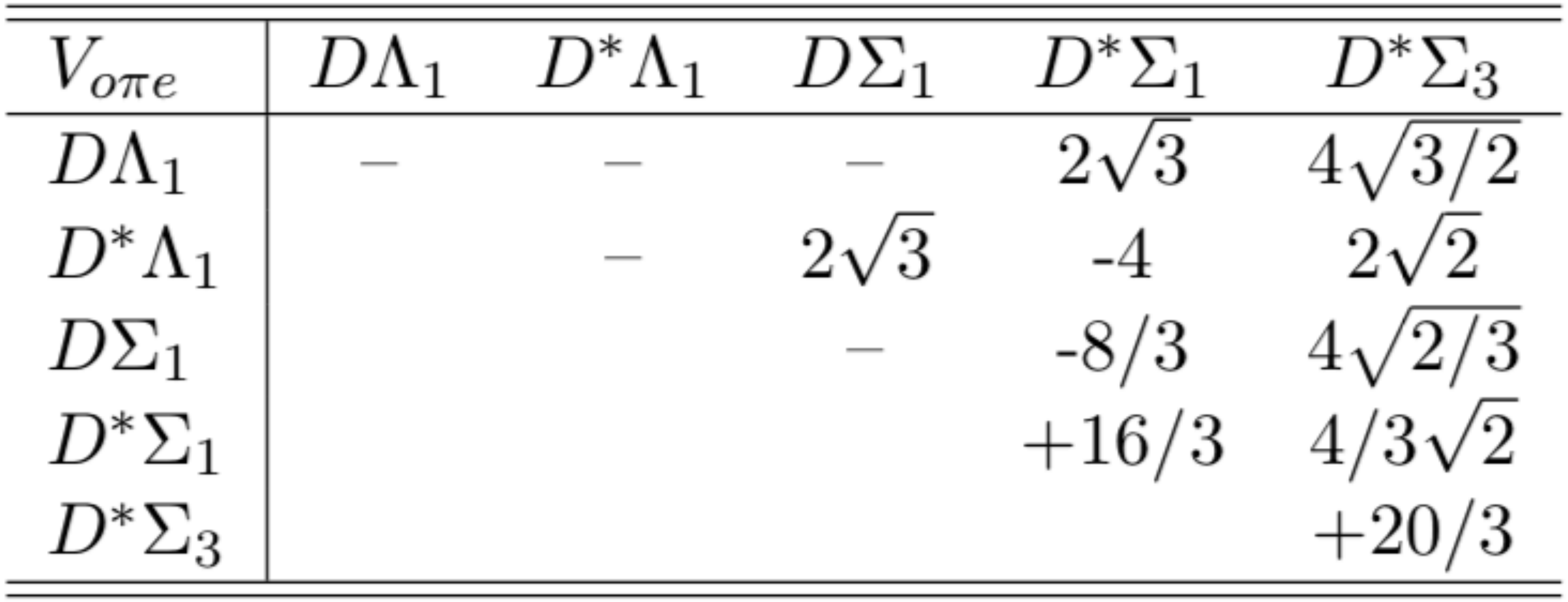
Potential without the delta term.
(Deuteron binding requires $\Lambda = 0.8$ GeV.)

	$\Lambda_c\bar{D}$	$\Lambda_c\bar{D}^*$	$\Sigma_c\bar{D}$	$\Sigma_c^*\bar{D}$	$\Sigma_c\bar{D}^*$	$\Sigma_c^*\bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		$+16/3$	$+20/3$
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	$-8/3$	$+8/3$
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						-4
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		$-8/3$	$-10/3$
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	$+4/3$	$-4/3$
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						$+2$

(iii) Final State Interactions

C only

$$I\,J^P = \frac{1}{2}\,\frac{1}{2}^-$$



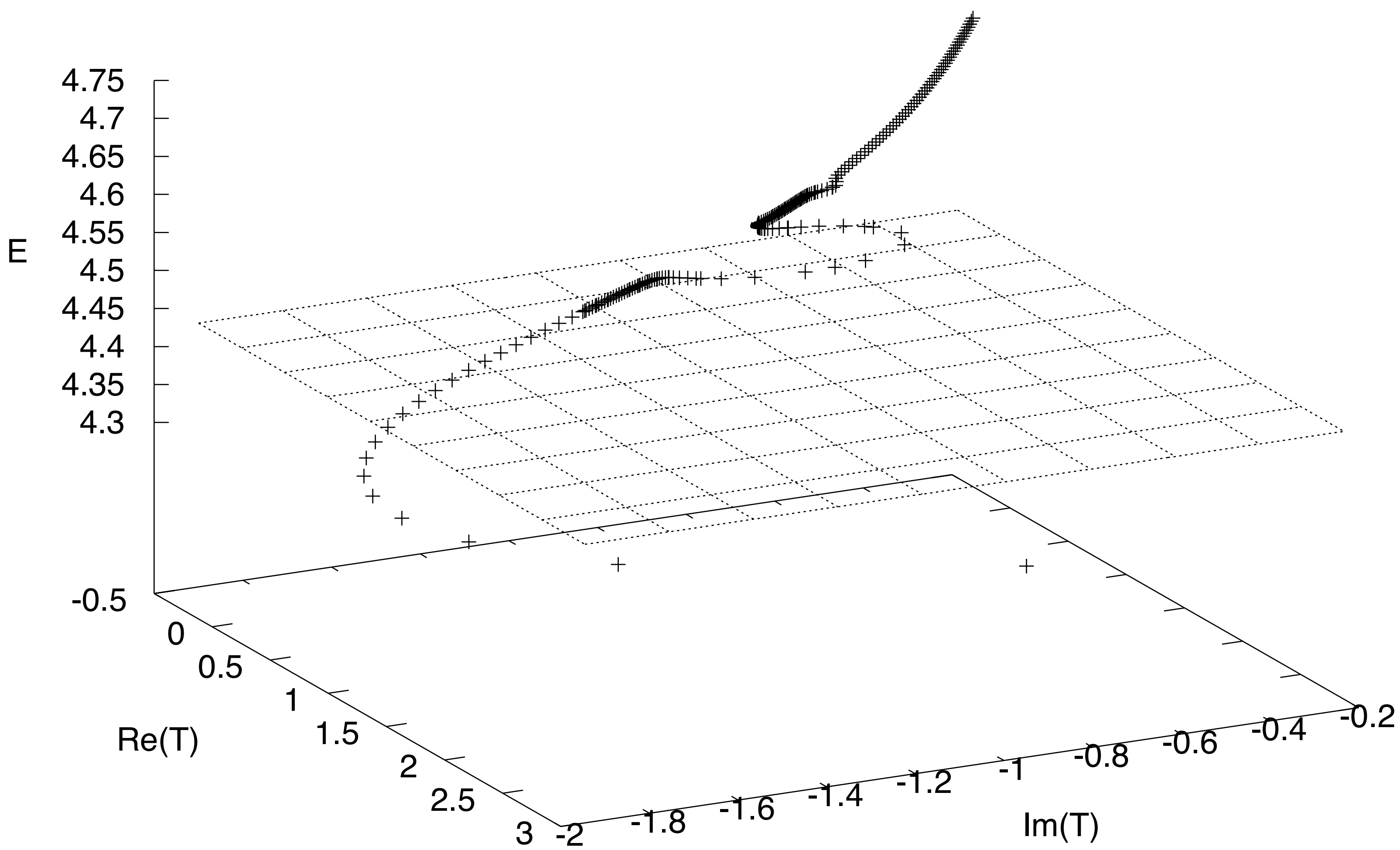
$V_{o\pi e}$	$D\Lambda_1$	$D^*\Lambda_1$	$D\Sigma_1$	$D^*\Sigma_1$	$D^*\Sigma_3$
$D\Lambda_1$	–	–	–	$2\sqrt{3}$	$4\sqrt{3/2}$
$D^*\Lambda_1$		–	$2\sqrt{3}$	-4	$2\sqrt{2}$
$D\Sigma_1$			–	-8/3	$4\sqrt{2/3}$
$D^*\Sigma_1$				$+16/3$	$4/3\sqrt{2}$
$D^*\Sigma_3$					$+20/3$

(iii) Final State Interactions

large phase motion at 4450
near Sigma D*

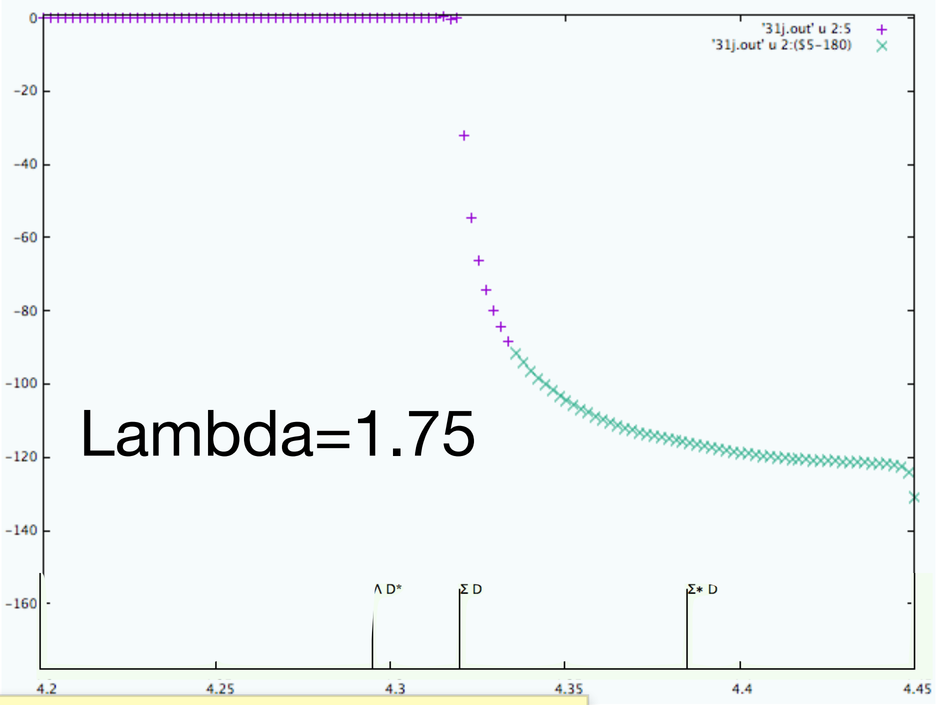
$I\,J^P = 3/2\,1/2^-$ 7 channels (central + tensor)

Sigma D 32/(1/2-) Lambda=1.9, sr=0



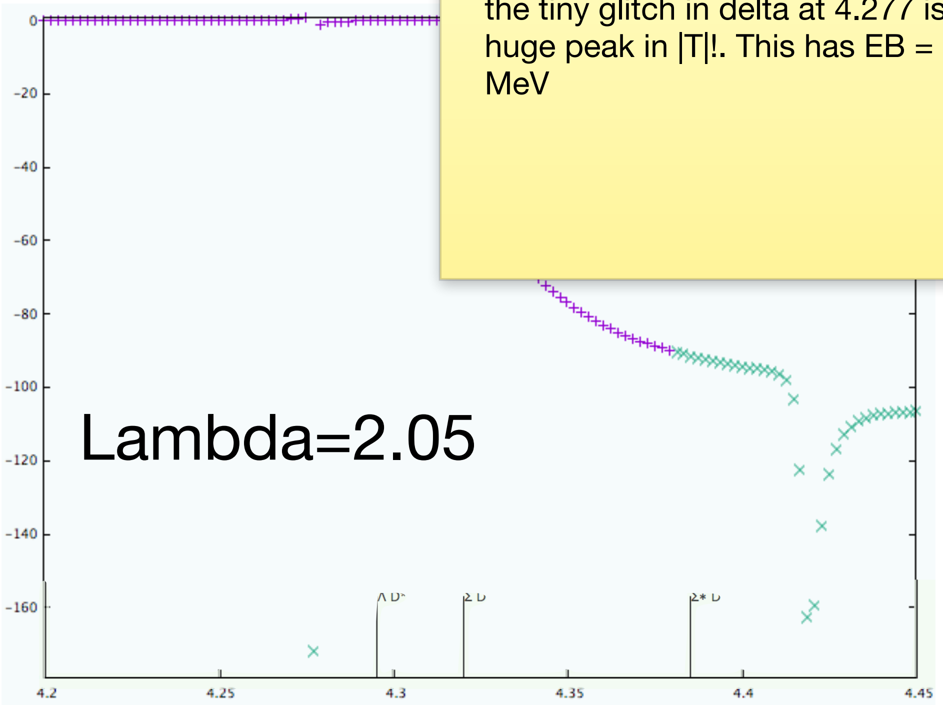
(iii) Final State Interactions

$I\,J^P = 3/2\,1/2^-$ 7 channels (central + tensor)



Lambda=1.75

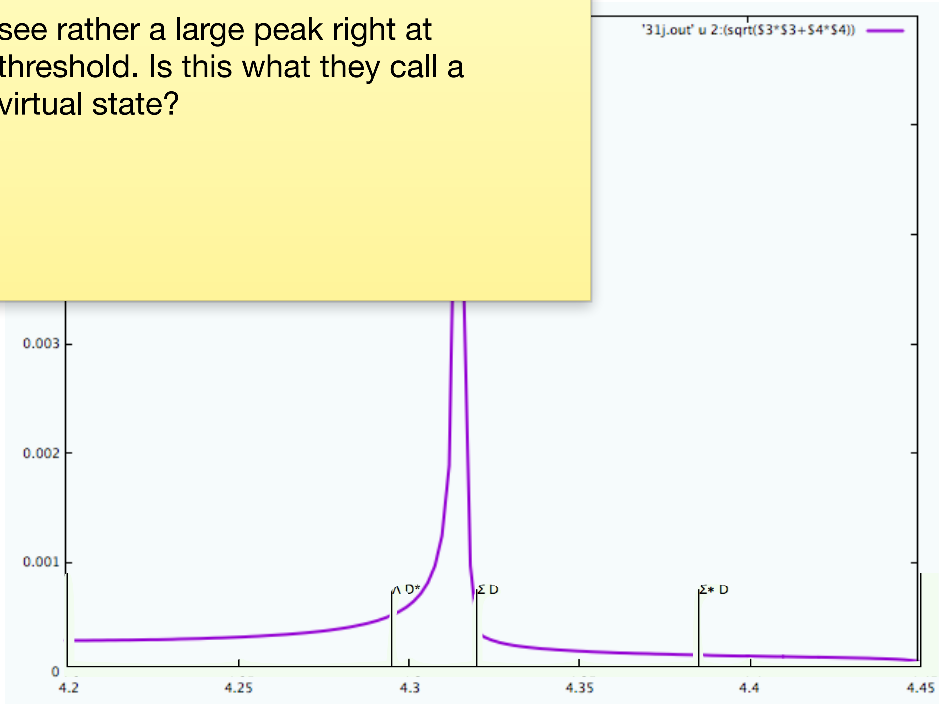
probe delta



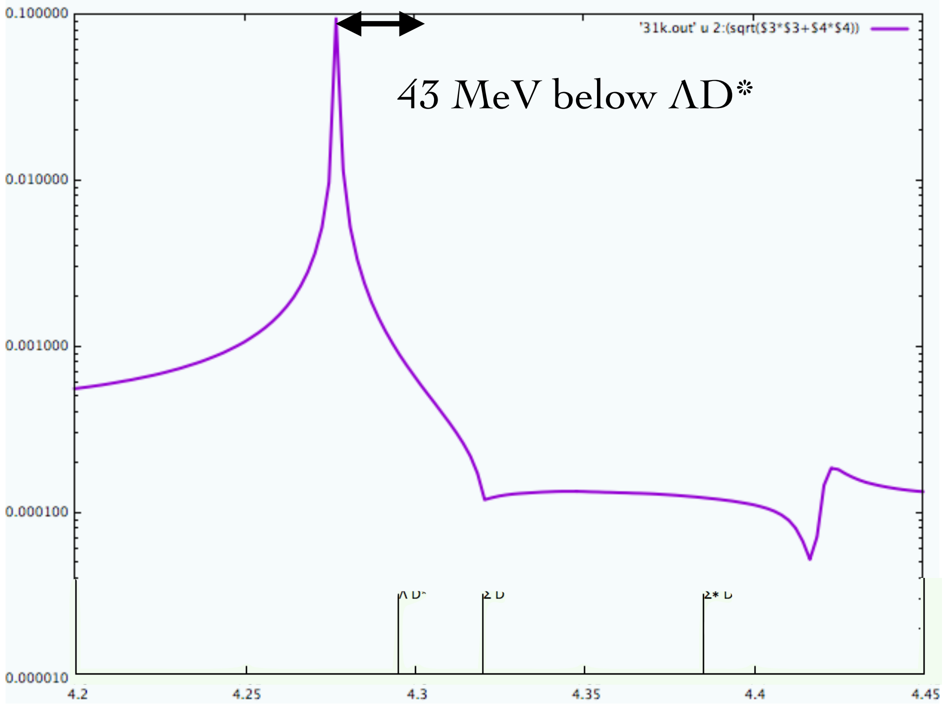
Lambda=2.05

the tiny glitch in delta at 4.277 is the huge peak in |T|!. This has EB = 43 MeV

see rather a large peak right at threshold. Is this what they call a virtual state?



|T|

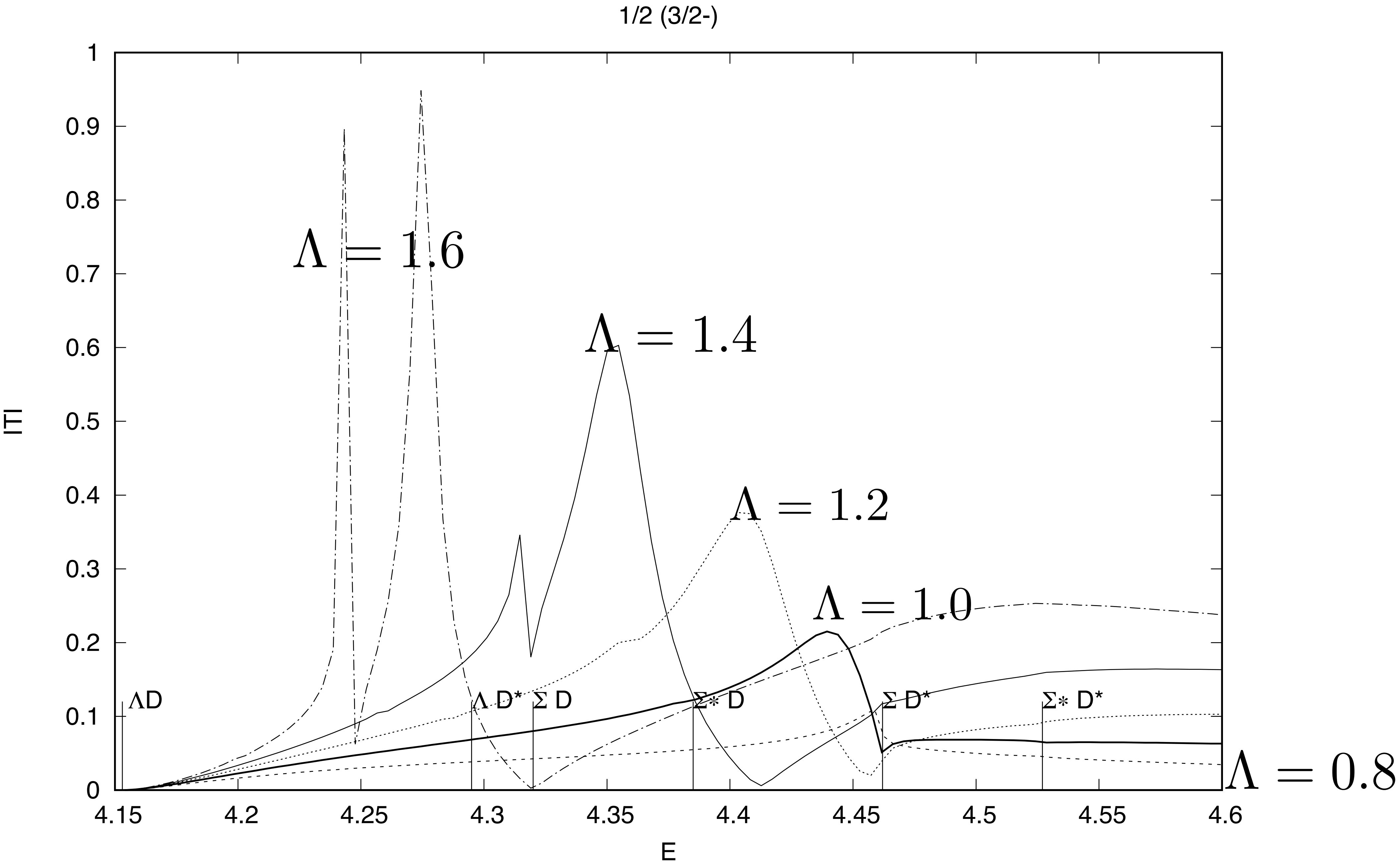


43 MeV below ΛD*

(iii) Final State Interactions

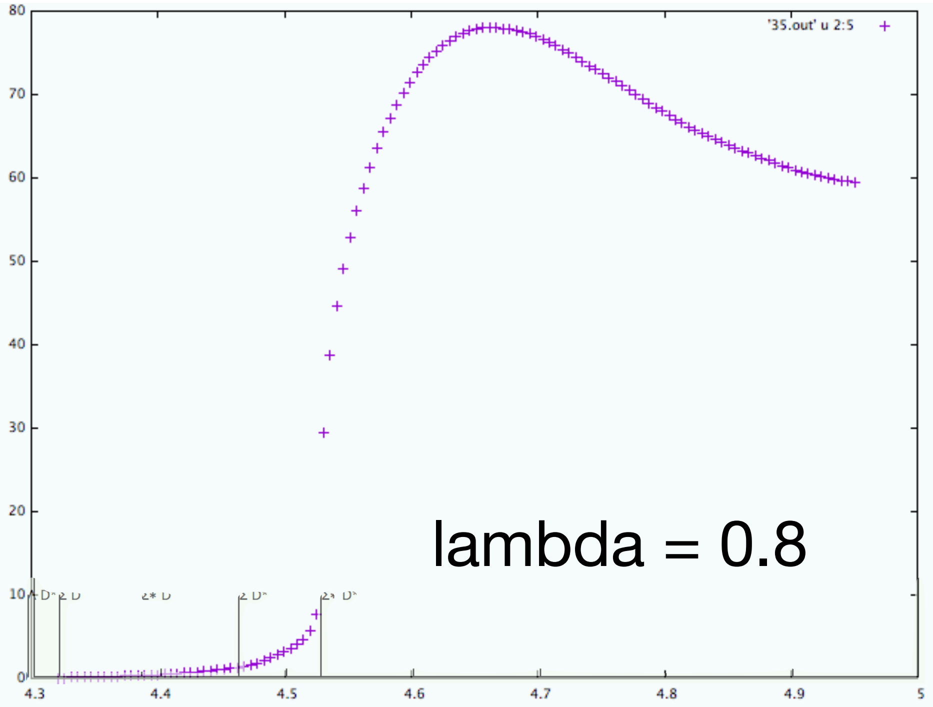
small glitch at SD* L=0.8

$I\,J^P = 1/2\,3/2^-$ 14 channels (central + tensor)



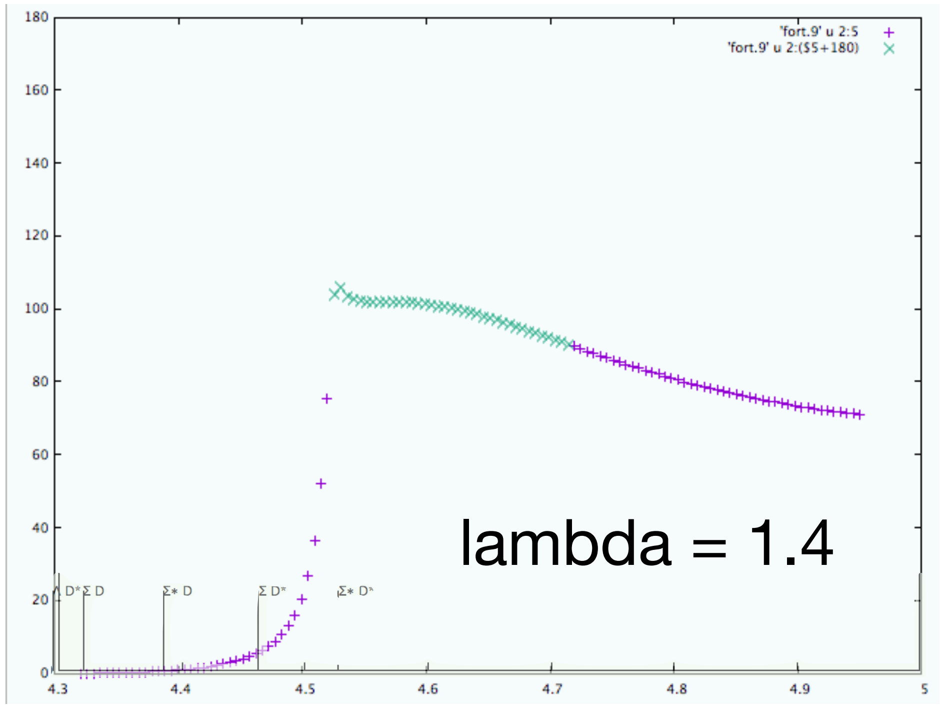
(iii) Final State Interactions

$I\,J^P = 3/2\,5/2^-$ 8 channels (central + tensor)

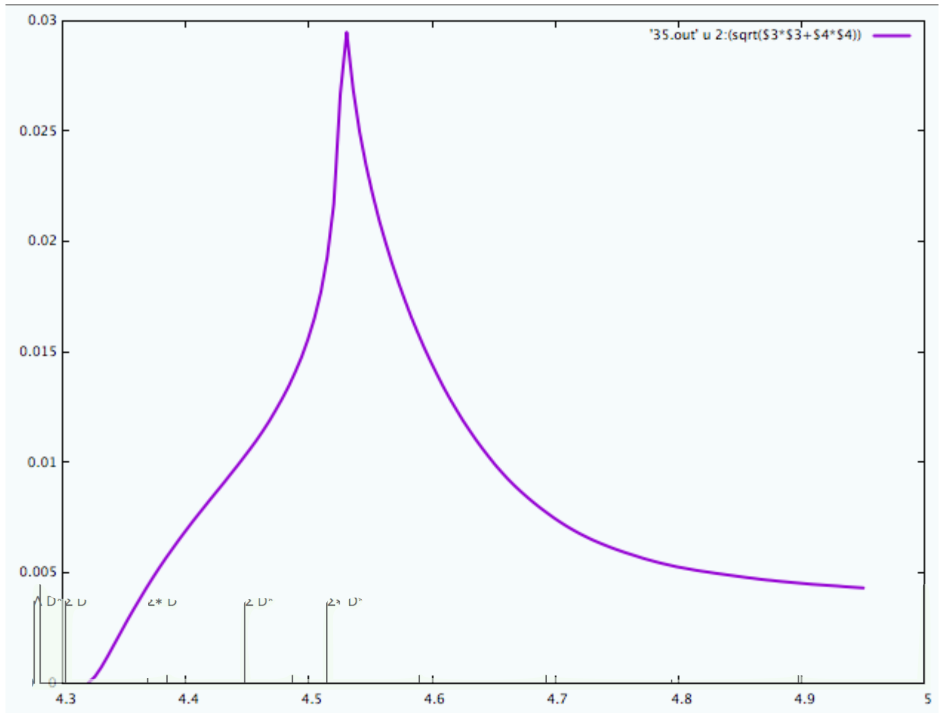


lambda = 0.8

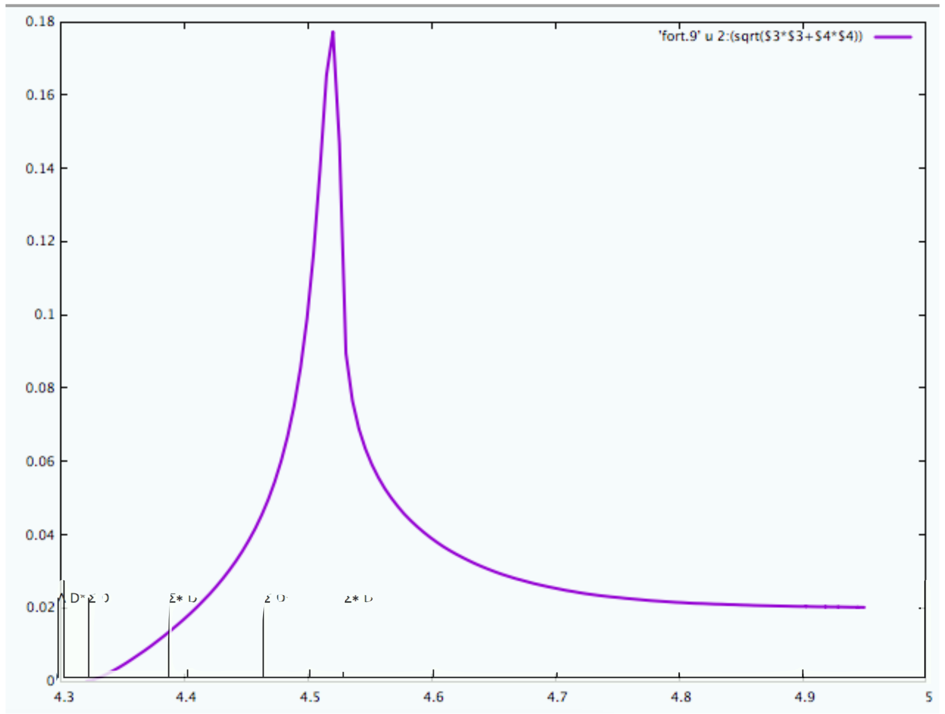
delta



lambda = 1.4

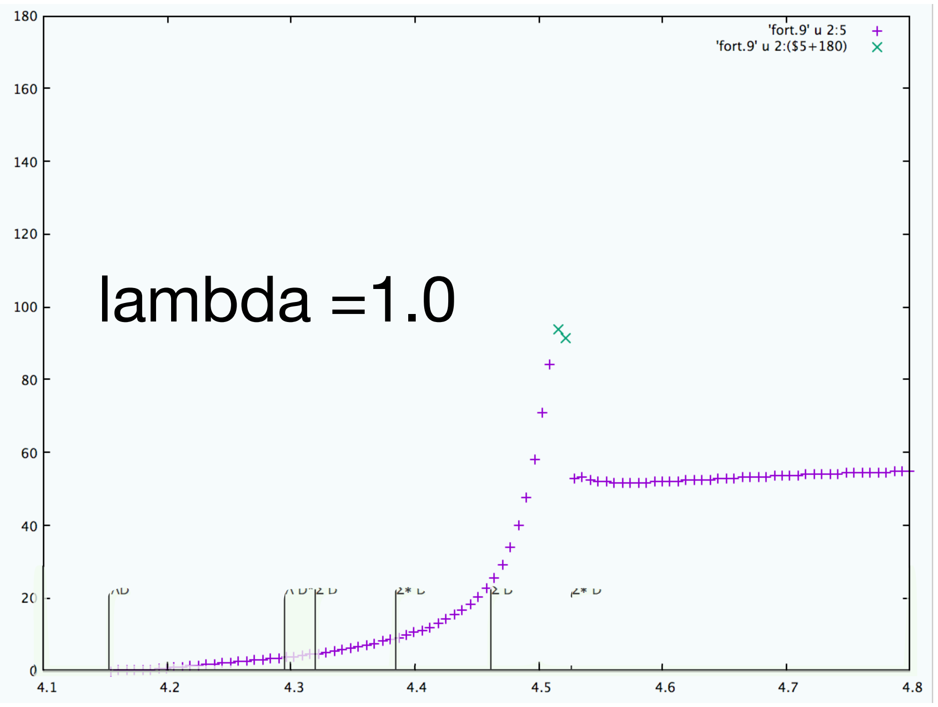


|T|



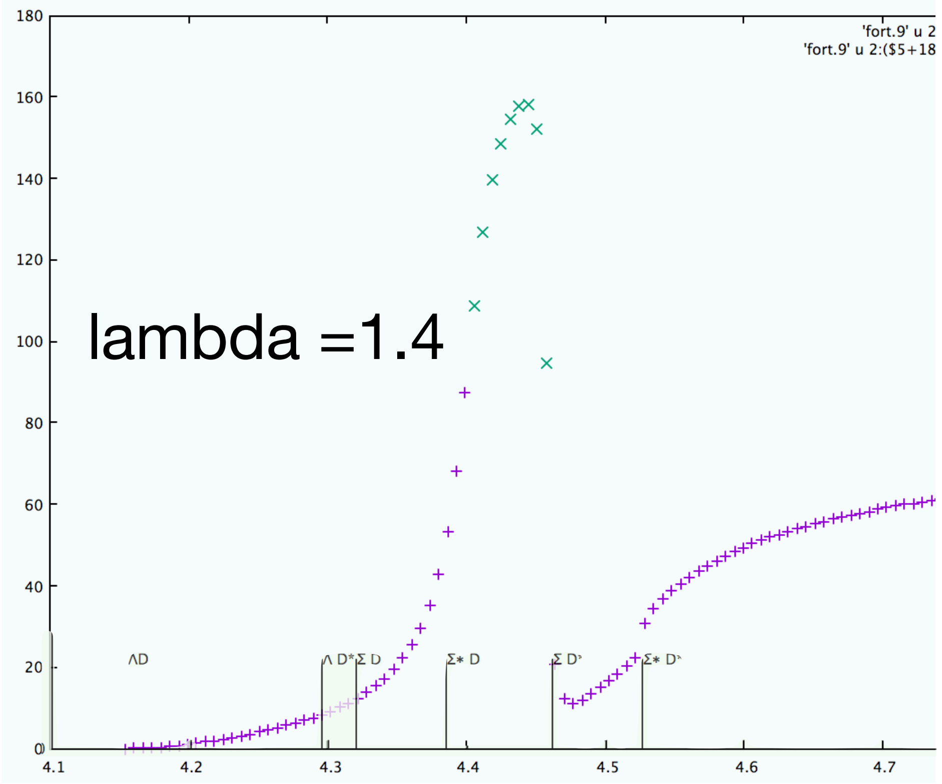
(iii) Final State Interactions

$I\,J^P = 1/2\,5/2^-$ 11 channels (tensor & central)

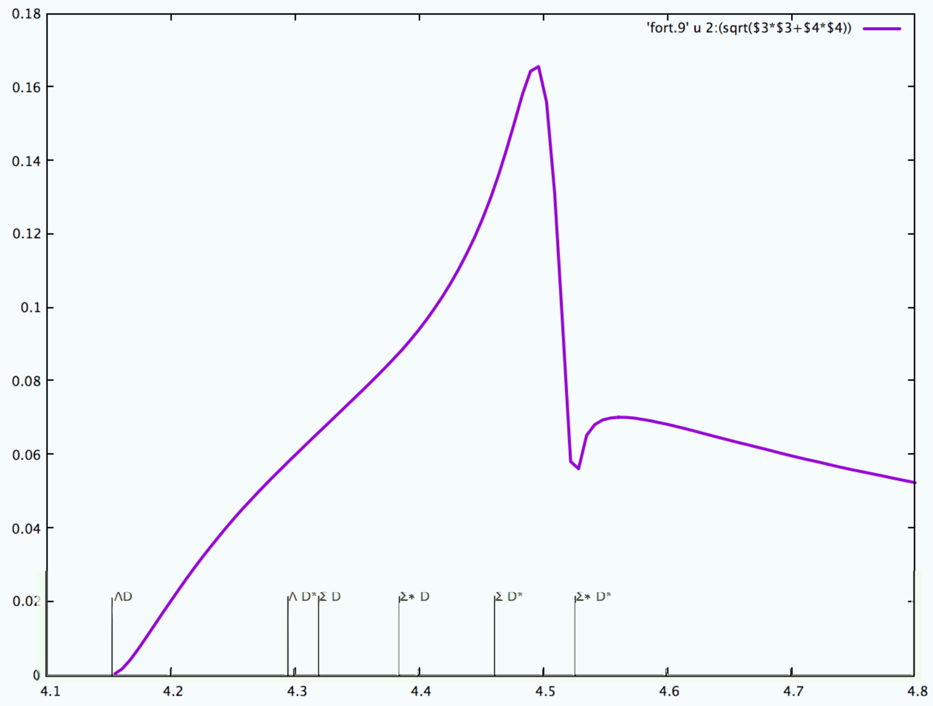


lambda =1.0

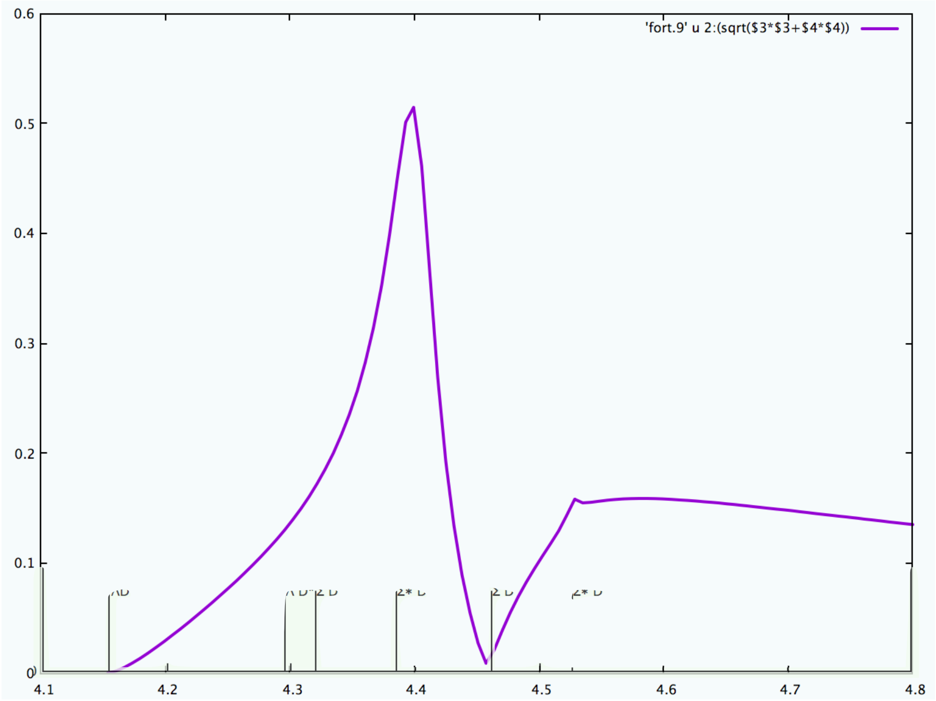
delta



lambda =1.4



|T|

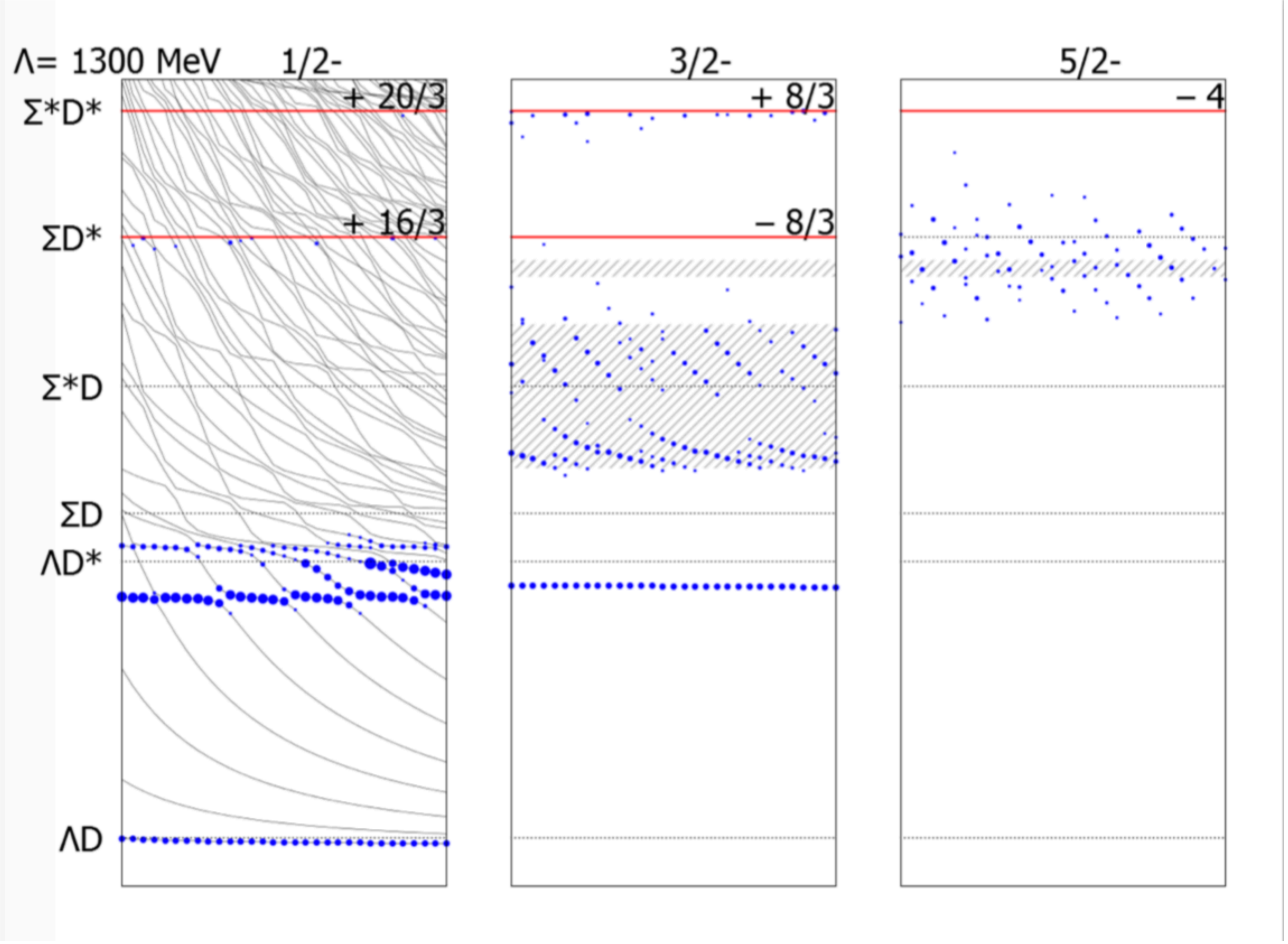


(iii) Final State Interactions

dots indicate significant components with higher mass states

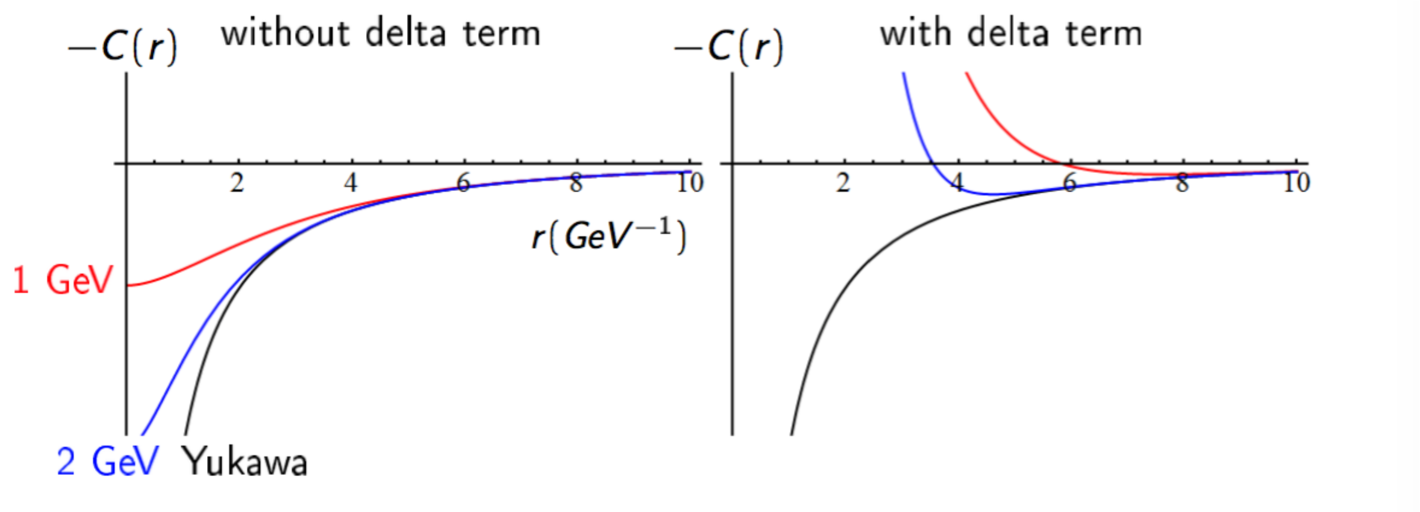
Also, the size of the state provides information!

Amusing to try box quantisation a la Luescher for this stuff…



(iii) Final State Interactions

disambiguating the short range οπε



- Effective field theory: cutoff where we no longer trust the long range dynamics and fit a constant to the short range. NB: long range observables can be sensitive to SR dynamics!

$$V_{LR}(r) \to$$
$$c(\Lambda)\delta(r) + V_{LR}(r;\Lambda)$$

- There are a *lot* of contact terms in the Pc system!

(iii) Final State Interactions
disambiguating the short range οπε

- There is no guarantee that a consistent power counting exists!

  Bedaque and van Kolck, ARNPS 52, 339 (2002)

- Strong UV divergence in ope tensor interaction can ruin naive power counting.

- The correct renormalization of singular potentials is intrinsically nonperturbative.

(iii) Final State Interactions

disambiguating the short range oπe

$$V = f(p/\Lambda) c_0 f(p/\Lambda) \qquad\qquad Q \sim (p, m_\pi, 1/a, \ldots)$$

$$-\frac{1}{c_0} = \int \frac{d^3q}{(2\pi)^3} f^2(q/\Lambda) \frac{2\mu}{q^2 - 2\mu E_B}$$

Q are the light scales in the problem

c ~ 1/Q rather than the naively expected Q^0

$$-\frac{1}{c_0} \approx \frac{\mu}{2\pi}(\underset{\underset{O(Q)}{\uparrow}}{\sqrt{-2\mu E_B}} - \frac{2}{\pi}\underset{\underset{\Lambda \sim O(Q)}{\uparrow}}{\Lambda})$$

thus $c_0 \sim 1/Q$

(iii) Final State Interactions
disambiguating the short range οπε

XEFT

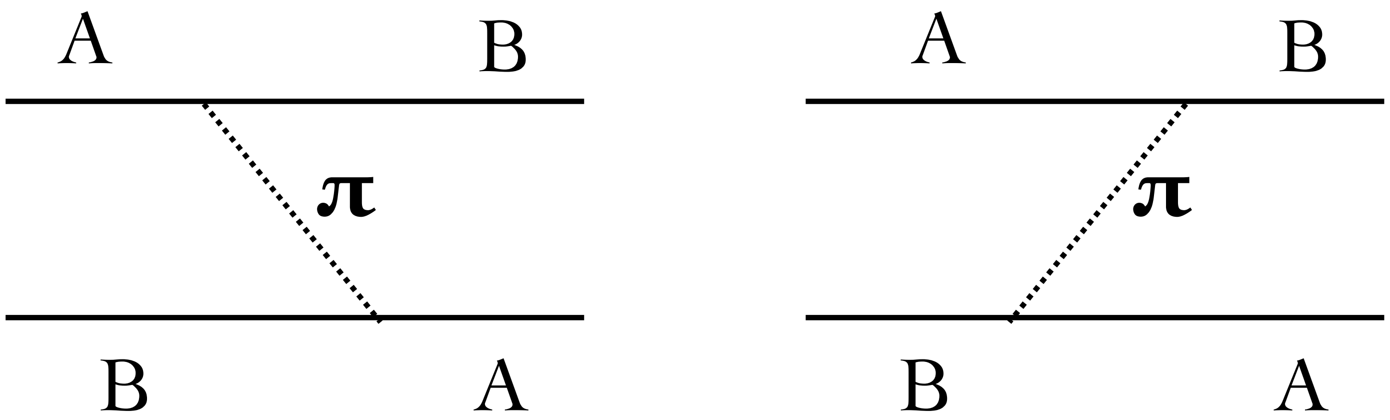
- X-χ mixing is O(Q) and therefore subleading.

- "For weakly bound systems the addition of coupled channels seems not justified from the effective field theory point of view."
  Lu, Geng, and Valderrama, arXiv:1706.02588

- *But*: quark-based model is a subset of effective field theories in which X-chi coupling and coupled channel effects are comparable in strength to the SR interactions.

- Thus the power counting can be confounded by ambiguous scales or large anomalous dimensions.

(iii) Final State Interactions on-shell pions



$$\Omega_A = \langle B\pi|H|A\rangle$$

$$\begin{aligned} K_{AB}\psi_{AB} + \Omega_A\,\varphi_{BB\pi} + \Omega_B\,\varphi_{AA\pi} &= E\psi_{AB} \\ \Omega_A^\dagger\,\psi_{AB} + K_{BB\pi}\varphi_{BB\pi} &= E\varphi_{BB\pi} \\ \Omega_B^\dagger\,\psi_{AB} + K_{AA\pi}\varphi_{AA\pi} &= E\varphi_{AA\pi}. \end{aligned}$$

$$K_{AB}\psi_{AB} + V_{eff}\psi_{AB} = E\psi_{AB}$$

$$V_{eff} = \Omega_A^\dagger \frac{1}{E - K_{BB\pi} + i\epsilon}\Omega_A + \Omega_B^\dagger\ \frac{1}{E - K_{AA\pi} + i\epsilon}\Omega_B.$$

(iii) Final State Interactions

on-shell pions

$$V_{eff} = \Omega_A^\dagger \frac{1}{E - K_{BB\pi} + i\epsilon} \Omega_A + \Omega_B^\dagger \frac{1}{E - K_{AA\pi} + i\epsilon} \Omega_B.$$

assume a point-like vertex, weak binding, and approximate K's as m's

$$\frac{k^2}{2\mu_{AB}} \psi_{AB}(k) + \frac{g^2}{4m_A m_B} \int \frac{d^3q}{(2\pi)^3} \frac{1}{2\omega(q)} \left(\frac{1}{m_A - m_B - \omega + i\epsilon} + \frac{1}{m_B - m_A - \omega + i\epsilon} \right) \psi_{AB}(k-q) = (\varepsilon - i\Gamma/2)\psi_{AB}(k)$$

can go on-shell, evaluate the imaginary part: $\Gamma = \frac{g^2}{8\pi m_A m_B} \bar{q}_*$

$$m_B = m_A + \omega(\bar{q}_*)$$

compare to the perturbative relativistic result: $\Gamma = \frac{g^2}{8\pi m_B^2} q_*$ ✓

$$m_B = E_A(q_*) + \omega(q_*).$$

(iii) Final State Interactions on-shell pions

Lastly, Fourier transform:

$$-\frac{\nabla^2}{2\mu_{AB}}\psi_{AB}(r) - \frac{g^2}{4m_A m_B}V(r)\psi_{AB} = (\varepsilon - i\Gamma/2)\psi_{AB}(r).$$

$$V(r) = \int \frac{d^3q}{(2\pi)^3}\frac{\exp(i\vec{q}\cdot\vec{r})}{\vec{q}^2 + m_\pi^2 - (m_B - m_A)^2 - i\epsilon}. \qquad = \frac{1}{4\pi r}\exp(i\bar{\mu}r)$$

$$\bar{\mu}^2 = m_\pi^2 - (m_B - m_A)^2.$$

Evaluate the perturbative imaginary shift in the energy:

$$\Gamma = 2\frac{g^2}{4m_A m_B}\langle\psi_0|\frac{\sin(\bar{\mu}r)}{4\pi r}|\psi_0\rangle. \qquad \bar{\mu} \ll \mu_{AB}e^2$$

$$\Gamma = \frac{32\mu_{AB}^4 e^{10}\bar{\mu}}{((2\mu_{AB}e^2)^2 + \bar{\mu}^2)^2} \to 2\bar{\mu}e^2 + O(\bar{\mu}^3).$$

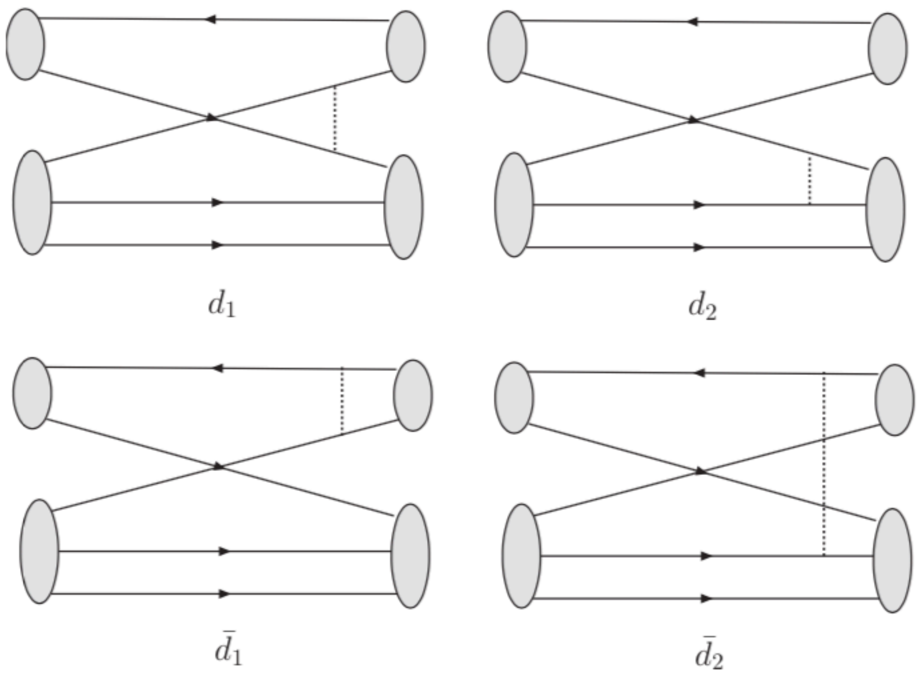
✓

nearly Coulombic wavefunction, mu-bar = q*

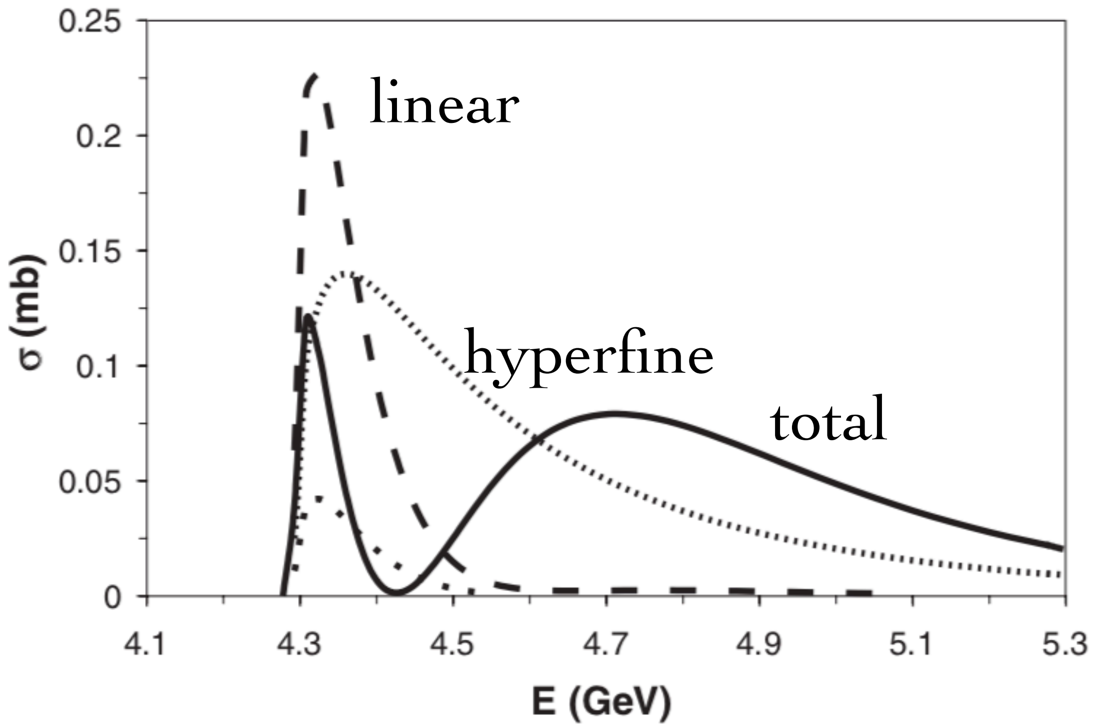
(iii) Final State Interactions

short range

ie. try to pin down the LE constants



$$J/\psi p(J=1/2) \to \bar{D}^0 \Lambda_c^+$$



J. P. Hilbert, N. Black, T. Barnes, and E. S. Swanson
Phys Rev C 75, 064907 (2007)

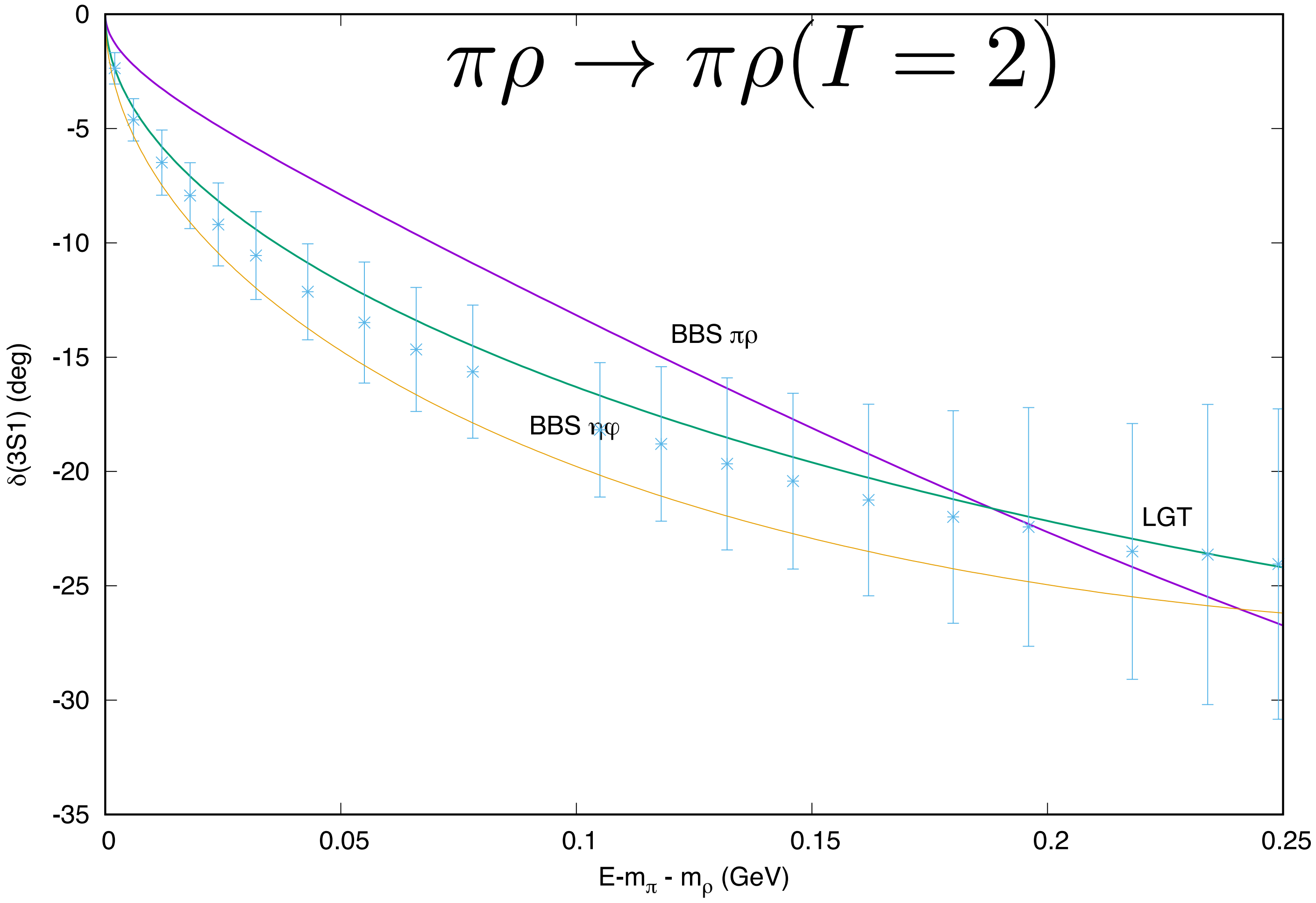
(iii) Final State Interactions short range

does it work?

lattice scattering from Woss at ~ s quark masses
purple = pi-rho physica;
orange = pi-rho scaled to s-quark

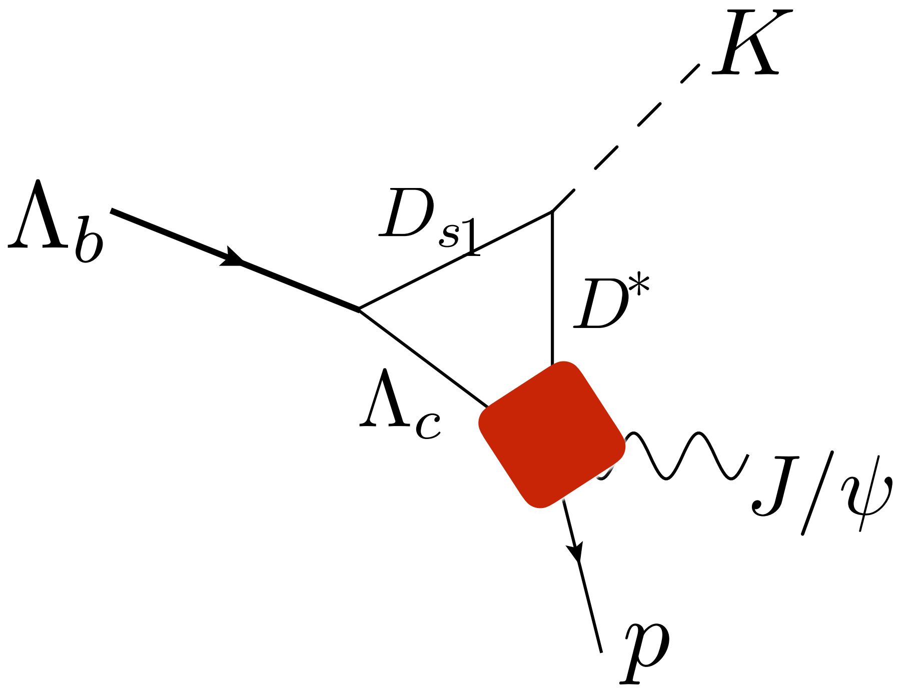
Woss, Thomas, Dudek, Edwards, Wilson, arXiv:1802.05580

Barnes, Black, and Swanson Phys.Rev. C63 (2001) 025204



Conclusions

my best bet:



- Use the strongest EW vertex:

  B -> DsJ D(*), Ds1 >> Ds0 >> Ds1(H) >> Ds2

- Ds1 -> D*K is large.

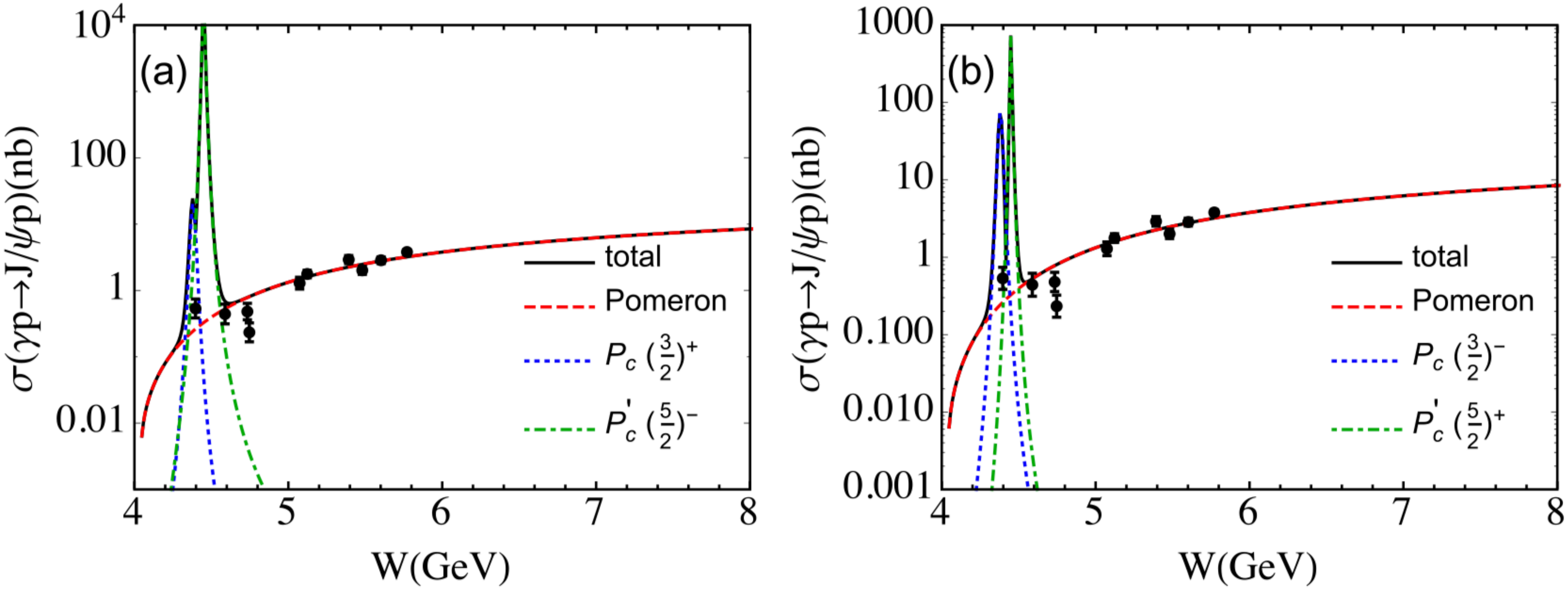
- D* Λ (1/2 3/2-) scattering“glitches” just below 4450

- $\sigma(D^*\Lambda_c \to J/\psi p)|_{J=3/2} \approx 10\sigma(D^*\Lambda_c \to J/\psi p)|_{J=1/2}$

- **The Pc(4450) is a 1/2 3/2- rescattering effect**

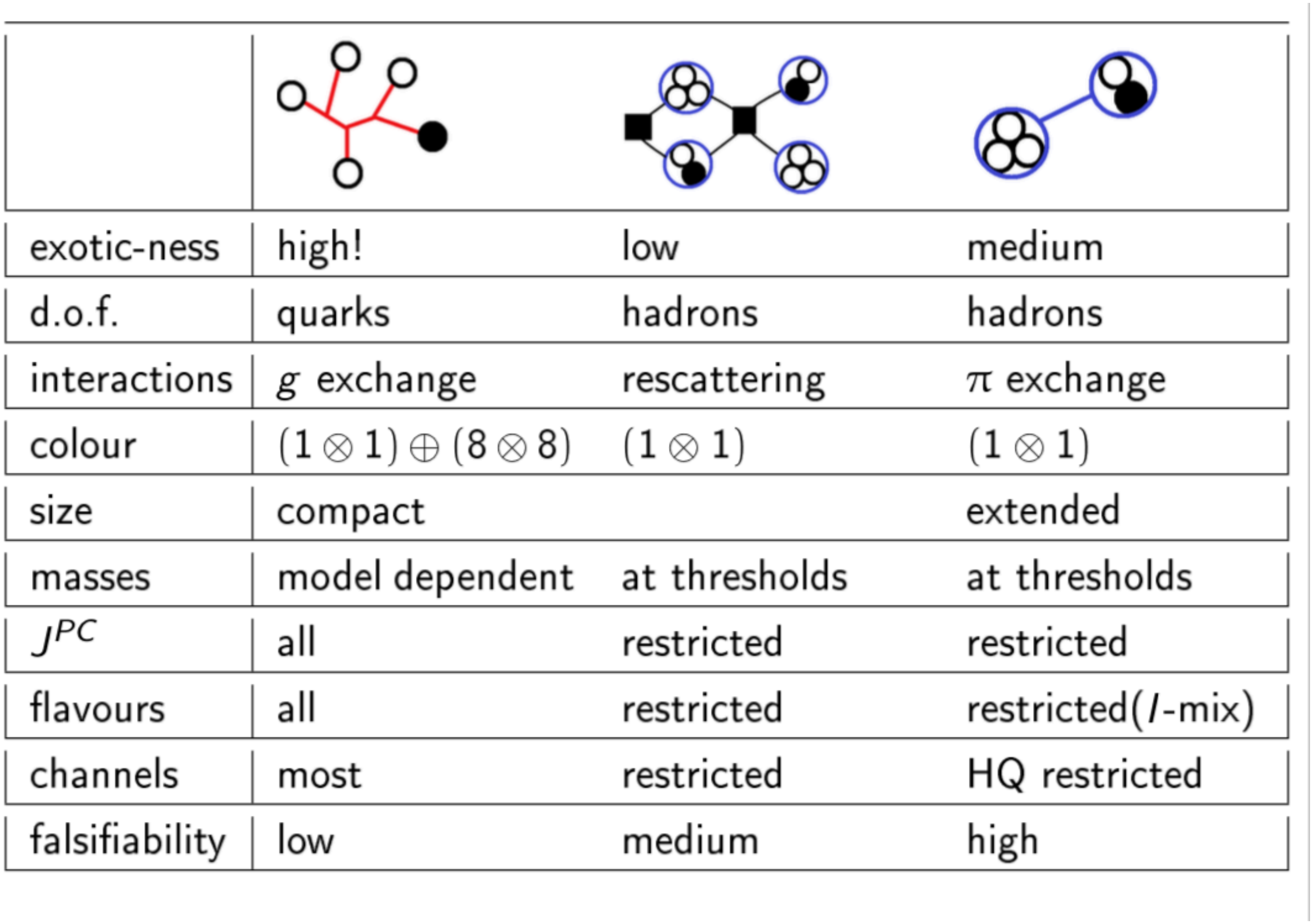
Conclusions

Search at JLab will be interesting.



Wang, Liu, Zhao, arXiv:1508.00339

Conclusions



exotic-ness	high!	low	medium
d.o.f.	quarks	hadrons	hadrons
interactions	g exchange	rescattering	π exchange
colour	$(1 \otimes 1) \oplus (8 \otimes 8)$	$(1 \otimes 1)$	$(1 \otimes 1)$
size	compact		extended
masses	model dependent	at thresholds	at thresholds
J^{PC}	all	restricted	restricted
flavours	all	restricted	restricted(I-mix)
channels	most	restricted	HQ restricted
falsifiability	low	medium	high

✢ ÆRIC MEC HEHT GEWYRCAN✢