Darkonia at Colliders

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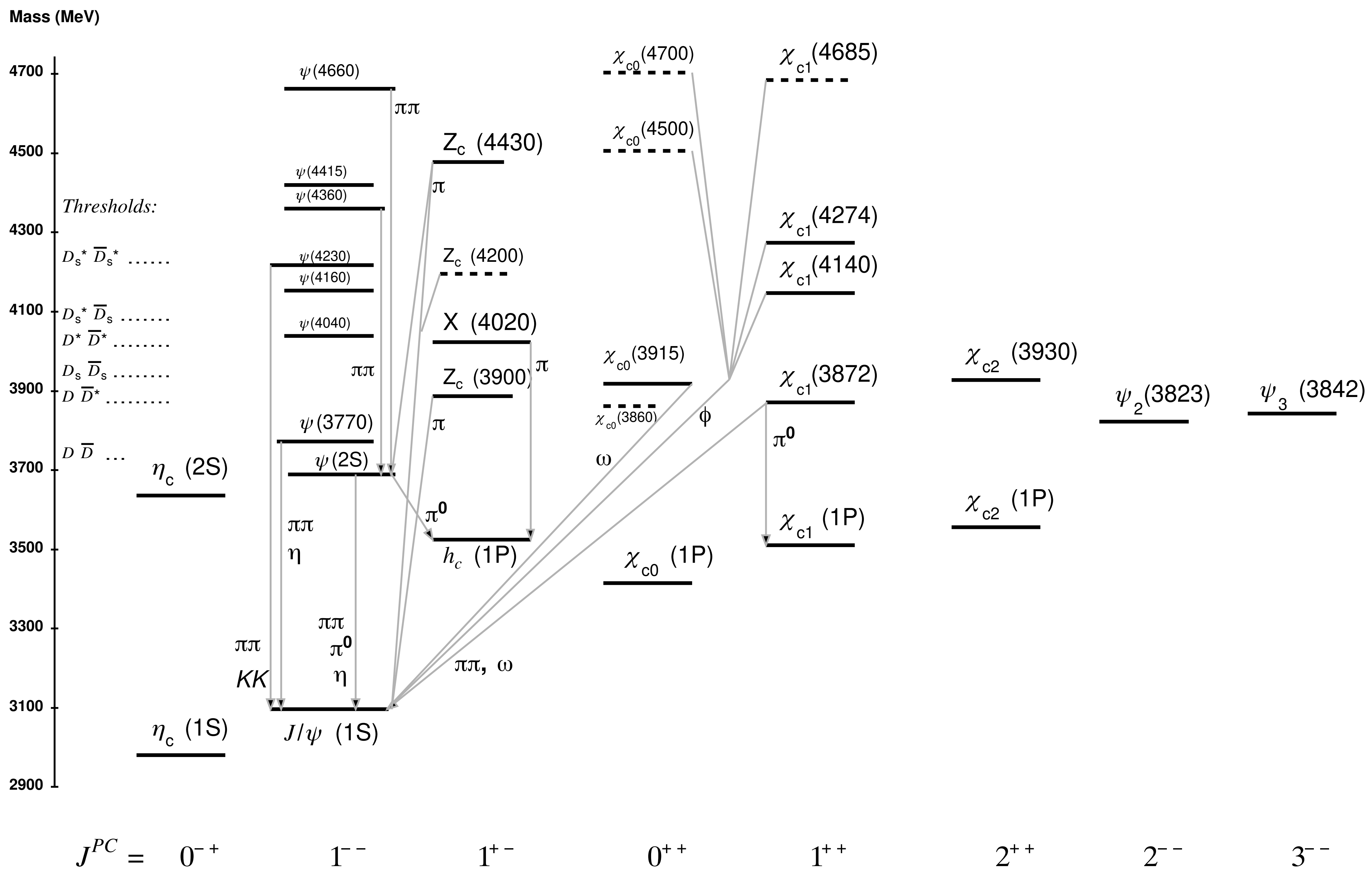
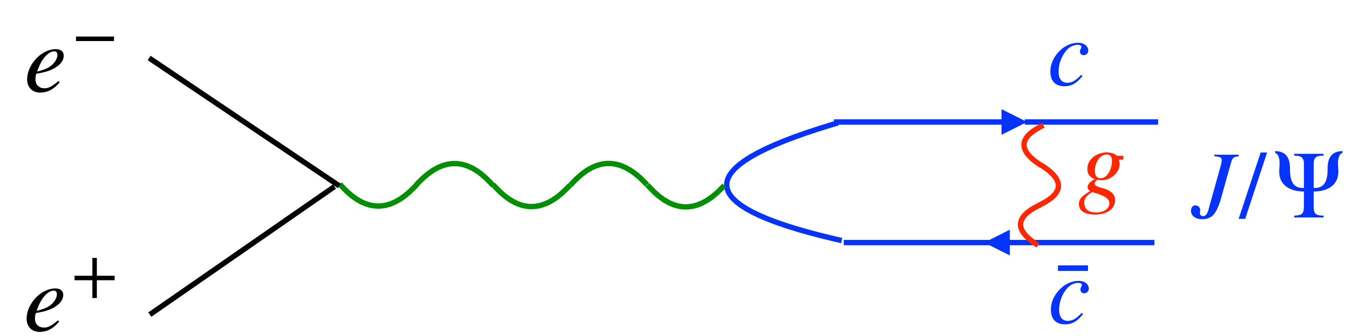
Charmonium

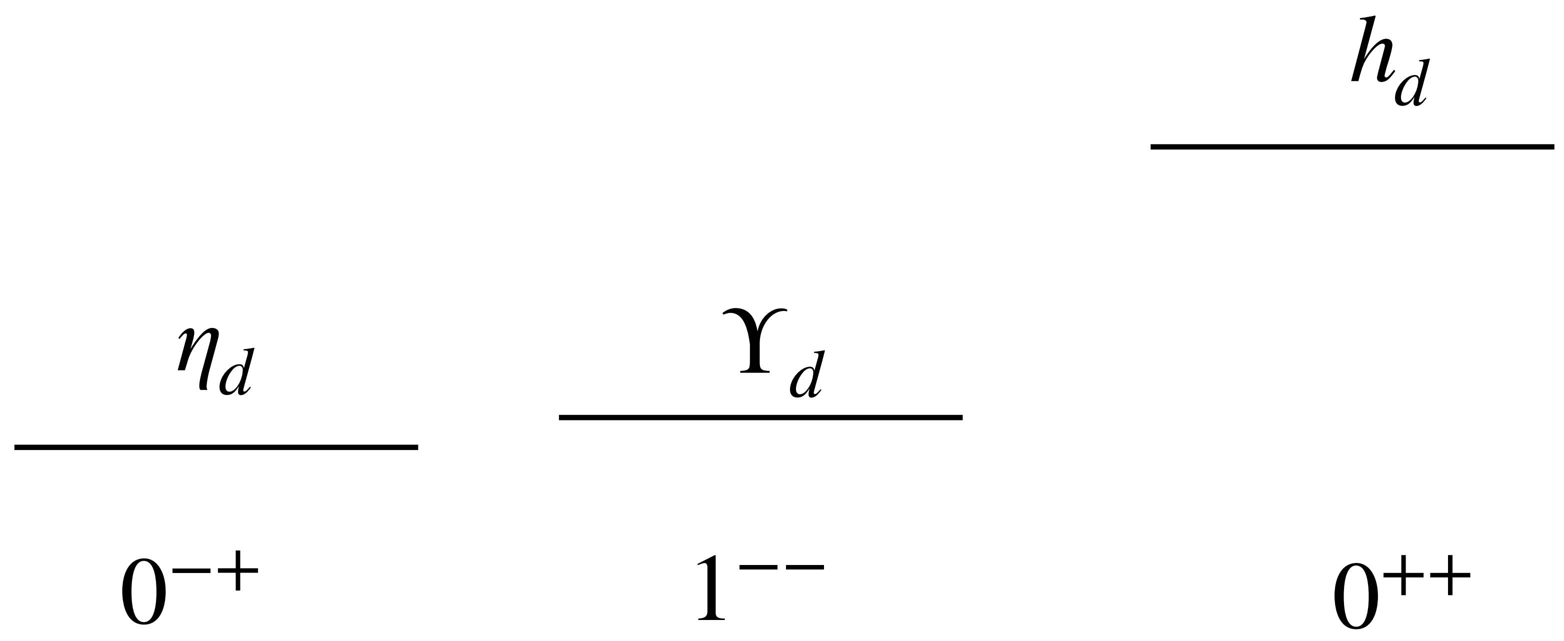




Appelquist and Politzer, PRL 34, 43 (1975)

Darkonia

- **3 unknowns: dark matter spin, binding force, mediator**
- **We choose dark matter to be a Dirac fermion. The scalar dark matter case can be worked out in a similar way.**
- **The three lightest darkonia are**



Dark force

- **The mediator could be scalar, pseudo-scalar or vector boson**

$$\mathscr{L}_{\rm dark} \supset -\, m_\chi \bar{\chi}\chi - \frac{1}{2} m_d^2 S^2 - g_d\, S\, \bar{\chi}\chi \,, \qquad (\mathrm{F_S\ Model})$$

$$\mathscr{L}_{\rm dark} \supset -\, m_\chi \bar{\chi}\chi - \frac{1}{2} m_d^2 P^2 - g_{d5}\, P\, \bar{\chi} i\gamma_5 \chi \,, \qquad (\mathrm{F_P\ model})$$

$$\mathscr{L}_{\rm dark} \supset -\, m_\chi \bar{\chi}\chi - \frac{1}{2} m_d^2 A_d^\mu A_{d\,\mu} - g_d\, A_d^\mu\, \bar{\chi}\gamma_\mu \chi \,, \qquad (\mathrm{F_V\ model})$$

$$\alpha_d \equiv g_d^2/(4\pi) \quad (\mathrm{F_S}, \mathrm{F_V}) \qquad \eta_d \quad \Upsilon_d \quad h_d$$

$$V(r) = -\frac{\alpha_d}{r}\, e^{-m_d r}$$

$$\alpha_d \equiv \frac{g_{d5}^2}{4\pi} \times \frac{m_d^2}{4 m_\chi^2} \quad (\mathrm{F_P}) \qquad \eta_d$$

Dark P & C

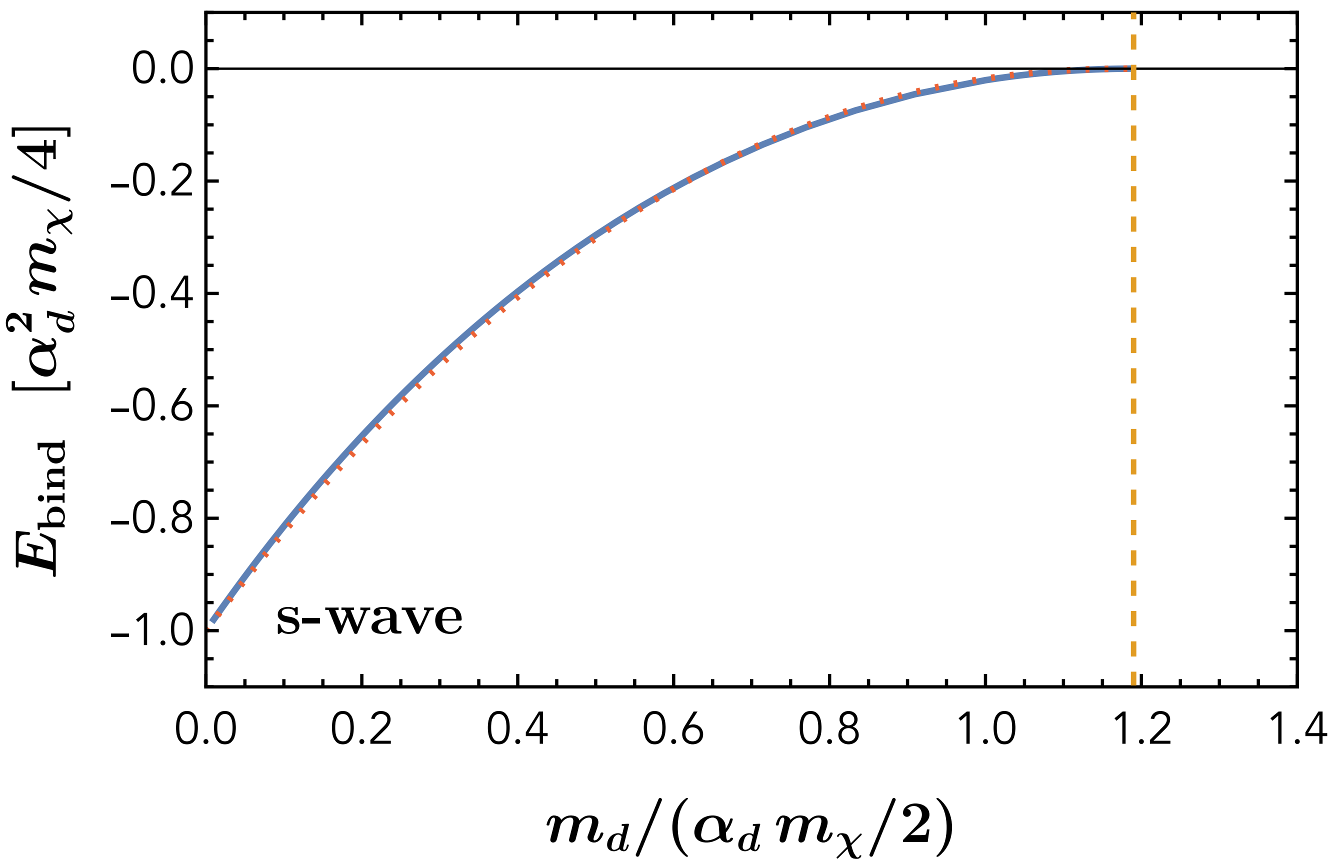
- **The minimal models have dark parity and dark charge conjugation symmetries (similar to G-parity for pion)**

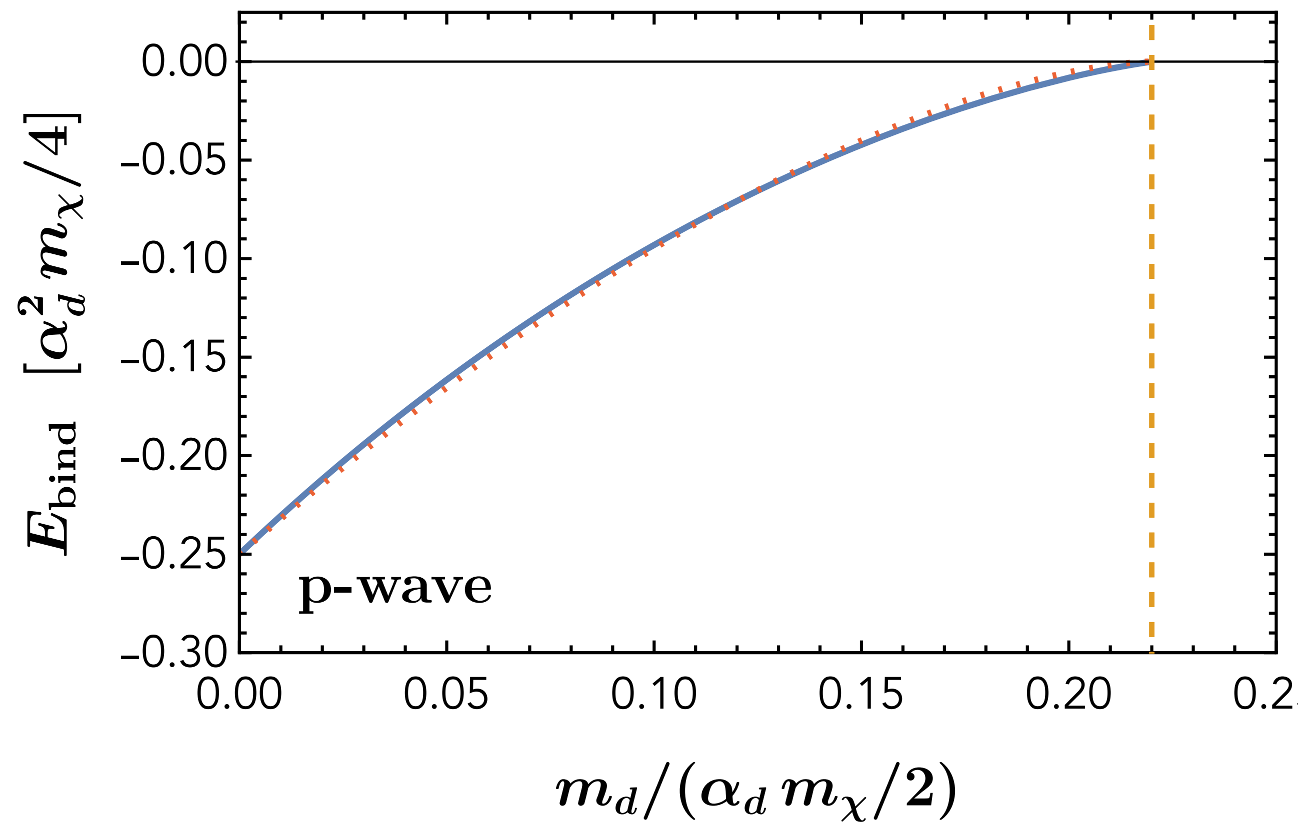
$$P_d\, \chi_L P_d = -\chi_R \qquad\qquad P_d\, \chi_R P_d = -\chi_L$$

$$C_d\, \chi\, C_d = i\gamma^2\, \chi^*$$

- **For the $\mathrm{F_S}$ model, η_d is P_d-odd and Υ_d is C_d-odd**
- **For the $\mathrm{F_P}$ model, η_d and P are P_d-odd**
- **For the $\mathrm{F_V}$ model, P_d and C_d will not play a role for phenomenology**

Binding energies

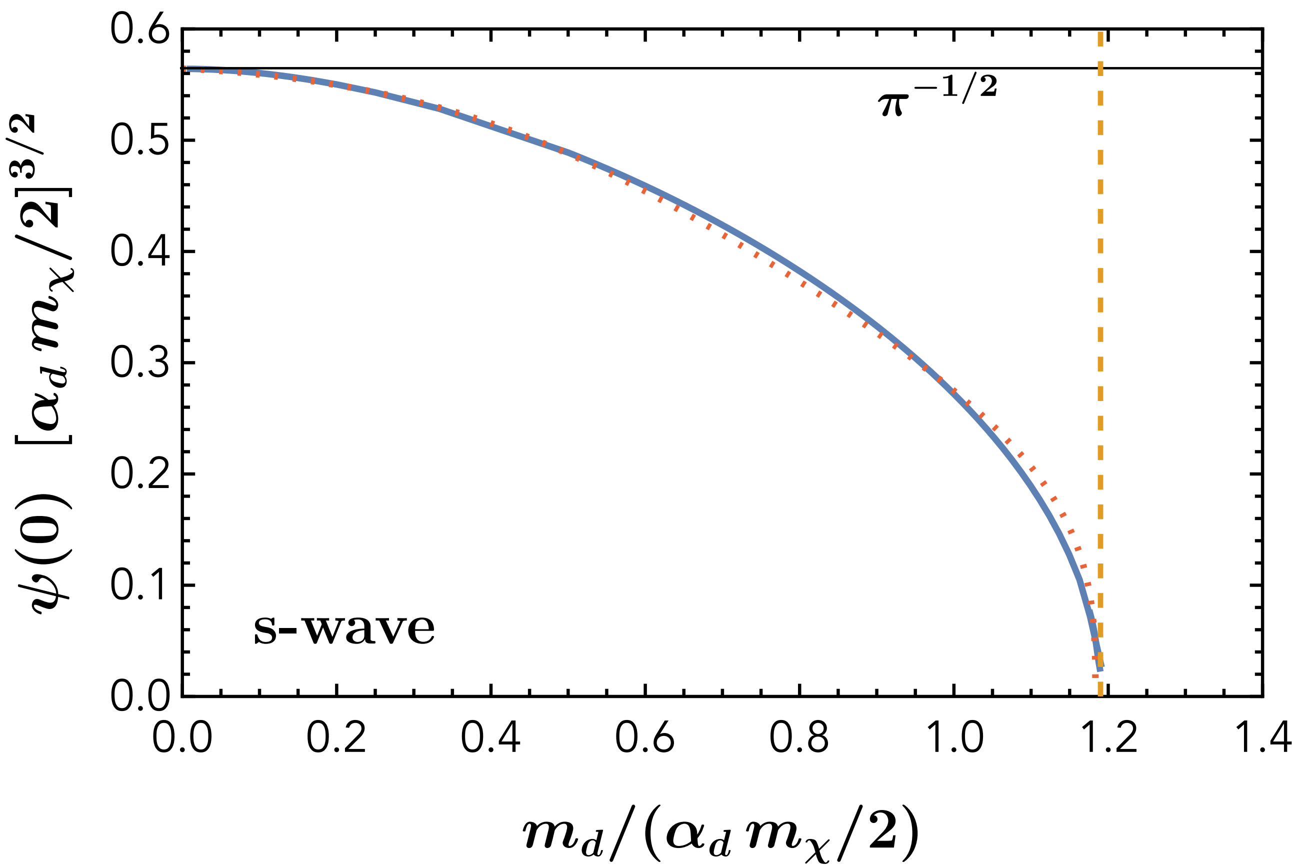


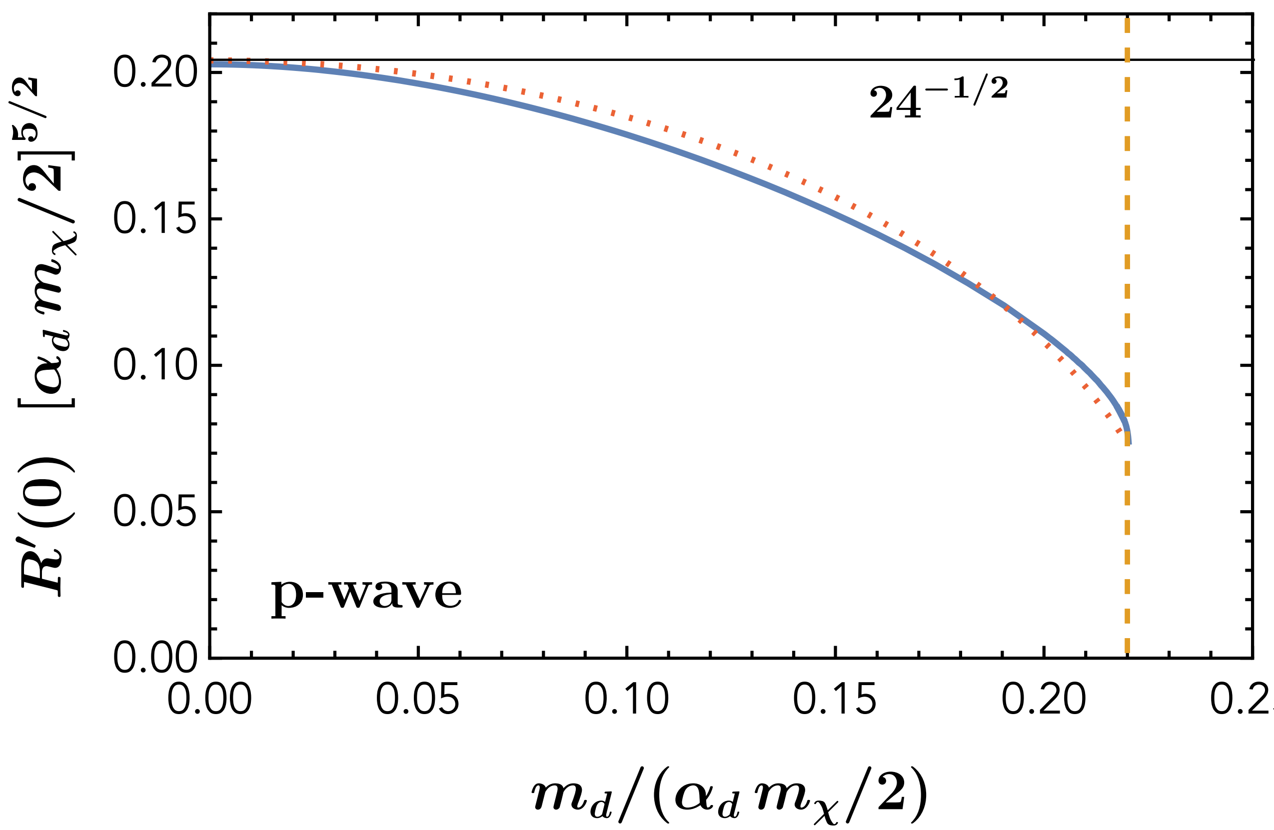


$$\frac{m_d}{\alpha_d m_\chi/2} < 1.19$$

$$\frac{m_d}{\alpha_d m_\chi/2} < 0.22$$

Wave functions





Portal interactions

- **In general, the mediator particle to the SM may not be the force carrier. For simplicity, we assume that the force carrier can couple to the SM**

$$\mathscr{L}_{\rm portal} = -\,\mu_S\, S\, H^\dagger H - \lambda_S\, S^2\, H^\dagger H \;+ \mu^2 H^\dagger H - \lambda (H^\dagger H)^2, \qquad (\mathrm{F_S})$$

$$\mathscr{L}_{\rm portal} = -\,\lambda_P\, P^2\, H^\dagger H\;, \qquad (\mathrm{F_P})$$ **[conserving dark parity]**

$$\mathscr{L}_{\rm portal} = -\,\frac{1}{2}\frac{\epsilon}{c_W} B_{\mu\nu} F_d^{\mu\nu} \qquad (\mathrm{F_V})$$

Bound State EFT (BSEFT)

- **Similar to NRQCD, one has an EFT with the cutoff scale**

$$m_\chi\, v \sim \alpha_d\, m_\chi \ll \Lambda_d \ll m_\chi$$

- P_d**- and** C_d**-conserving interactions up to three boundstates**

$$\mathscr{L}_{\mathrm{F_S,eff}} = \frac{1}{2}\partial_\mu\eta_d\partial^\mu\eta_d - \frac{m^2_{\eta_d}}{2}\eta_d^2 - \frac{1}{4}\Upsilon_d^{\mu\nu}\Upsilon_{d,\mu\nu} + \frac{m^2_{\Upsilon_d}}{2}\Upsilon_d^\mu\Upsilon_{d,\mu}$$
$$+\frac{1}{2}\partial_\mu S\partial^\mu S + \frac{1}{2}\partial_\mu h_d\partial^\mu h_d - \frac{m_S^2}{2}SS - \mu_d^2\, g_d\, h_d\, S - \frac{m^2_{h_d}}{2}\, h_d^2$$
$$+\lambda_h SSh_d + \lambda'_h Sh_dh_d + \omega_h SSh_dh_d + \lambda'_\eta S\eta_d\eta_d + \omega_\eta SS\eta_d\eta_d + \omega_{h\eta}Sh_d\eta_d\eta_d + \xi_\eta h_d\eta_d\eta_d$$
$$+\lambda'_\Upsilon S\Upsilon_d^\mu\Upsilon_{d,\mu} + \omega_\Upsilon SS\Upsilon_d^\mu\Upsilon_{d,\mu} + \xi_\Upsilon h_d\Upsilon_d^\mu\Upsilon_{d,\mu}$$

Both η_d and Υ_d are stable

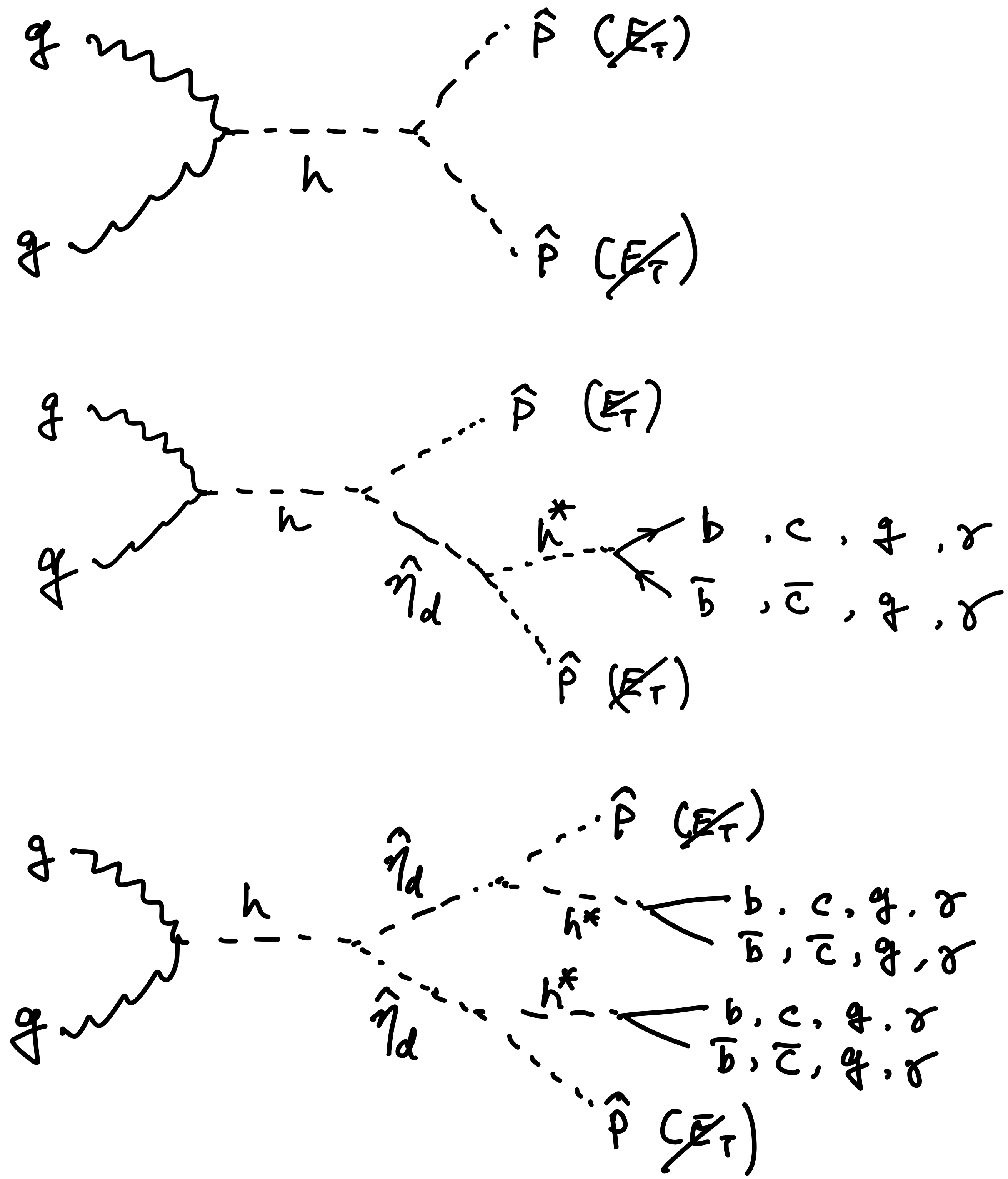
Bound State EFT (BSEFT)

$$\mathscr{L}_{\mathrm{F_P,eff}} = \frac{1}{2}\partial_\mu \eta_d \partial^\mu \eta_d - \frac{m_\eta^2}{2}\eta_d \eta_d + \frac{1}{2}\partial_\mu P \partial^\mu P - \frac{1}{2} m_P^2 P^2 - \mu_d^2\, g_d\, \eta_d\, P$$

$$\mathscr{L}_{\mathrm{portal}} \supset -\lambda_P (\cos\theta\, \hat{P} + \sin\theta\, \hat{\eta}_d)^2 \left(v\, h + \frac{1}{2} h^2 \right)$$

The lighter one of $\hat{P}$ and $\hat{\eta}_d$ is stable

Signatures at the LHC: $\mathrm{F_P}$



Signatures at the LHC: $\mathrm{F_S}$

$$pp \to h \xrightarrow{\hat{S}^*} \hat{S}\hat{h}_d\hat{h}_d \to (\mathrm{SM})_{\hat{S}}[\hat{S}\hat{S}]_{h_d}[\hat{S}\hat{S}]_{h_d} \to (\mathrm{SM})_{\hat{S}}\big[(\mathrm{SM})_{\hat{S}}(\mathrm{SM})_{\hat{S}}\big]_{\hat{h}_d}\big[(\mathrm{SM})_{\hat{S}}(\mathrm{SM})_{\hat{S}}\big]_{\hat{h}_d}$$

$$pp \to h \xrightarrow{\hat{S}^*} \hat{S}\hat{h}_d\hat{h}_d \to (\mathrm{SM})_{\hat{S}}[\eta_d\eta_d]_{h_d}[\eta_d\eta_d]_{h_d} \to (\mathrm{SM})_{\hat{S}} + \not{E}$$

$$pp \to h \xrightarrow{\mathrm{mix}} \hat{S}\hat{h}_d \to (\mathrm{SM})_{\hat{S}}[\hat{S}\hat{S}]_{h_d} \to (\mathrm{SM})_{\hat{S}}\big[(\mathrm{SM})_{\hat{S}}(\mathrm{SM})_{\hat{S}}\big]_{\hat{h}_d}$$

$$pp \to h \xrightarrow{\mathrm{mix}} \hat{S}\hat{h}_d \to (\mathrm{SM})_{\hat{S}}[\eta_d\eta_d]_{h_d} \to (\mathrm{SM})_{\hat{S}} + \not{E}$$

$$pp \to h \xrightarrow{s_\beta} \hat{h}_d\hat{h}_d \to [\hat{S}\hat{S}]_{h_d}[\hat{S}\hat{S}]_{h_d} \to \big[(\mathrm{SM})_{\hat{S}}(\mathrm{SM})_{\hat{S}}\big]_{\hat{h}_d}\big[(\mathrm{SM})_{\hat{S}}(\mathrm{SM})_{\hat{S}}\big]_{\hat{h}_d}$$

$$pp \to h \xrightarrow{s_\beta} \hat{h}_d\hat{h}_d \to [\hat{S}\hat{S}]_{h_d}[\eta_d\eta_d]_{h_d} \to \big[(\mathrm{SM})_{\hat{S}}(\mathrm{SM})_{\hat{S}}\big]_{\hat{h}_d} + \not{E},$$

$$(\mathrm{SM})_{\hat{S}} = \{\ell^+\ell^-, jj, \gamma\gamma\}$$

Signatures at the LHC: $\mathrm{F_V}$

$$pp \xrightarrow{1/\Lambda_d} \eta_d \gamma_d \to [(\mathrm{SM})_{\gamma_d} (\mathrm{SM})_{\gamma_d}]_\eta (\mathrm{SM})_{\gamma_d}$$

$$pp \xrightarrow{\epsilon} \Upsilon_d\, j \to [(\mathrm{SM})_{\gamma_d} (\mathrm{SM})_{\gamma_d} (\mathrm{SM})_{\gamma_d}]_\Upsilon\, j$$

$$pp \xrightarrow{\epsilon} \Upsilon_d\, j \xrightarrow{\Delta_{\Upsilon\eta}} [\eta_d \gamma_d^*]_\Upsilon\, j \to \big[[(\mathrm{SM})_{\gamma_d} (\mathrm{SM})_{\gamma_d}]_\eta\, \mathrm{SM}\big]_\Upsilon\, j,$$

$$(\mathrm{SM})_{\gamma_d} = \{\ell^+\ell^-, jj\}$$

- **Some light mass parameter space has been searched for at low-energy linear colliders** BABAR, PRL 128 (2022) 2, 021802

Conclusions

- Dark matter could form bound states if it interacts through additional dark forces.
- Some models suggest that darkonia could remain stable not only at colliders but also on cosmological time scales.
- There are still many intriguing signatures at the LHC waiting to be explored.

Thanks!