

Discovery of T_{cc}^+ , new species of hadronic matter

[LHCb, arXiv:2109.01038]

[LHCb, arXiv:2109.01056]

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LHCb collaboration

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Particle physics colloquium

Standard model of particle physics

One of the most beautiful and elegant(!) theory in physics

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$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\mu g_\nu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}\partial_\mu^2 M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\nu A_\nu - ig c_w (\partial_\nu Z_\mu^0 (W_\mu^+ W_\mu^- \\
 & W_\nu^+ W_\mu^-) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)) - \\
 & ig s_w (\partial_\nu A_\mu (W_\nu^+ W_\mu^- - W_\nu^- W_\mu^+) - A_\mu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- \\
 & - W_\nu^- \partial_\nu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\nu^+ W_\nu^- W_\mu^+ W_\mu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\mu^0 W_\mu^- \\
 & Z_\mu^0 Z_\nu^0 (W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- \\
 & W_\nu^+ W_\mu^-) - 2 A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\nu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^\dagger \partial_\mu \phi - \frac{1}{2}\lambda \phi^\dagger \partial_\mu \phi^\dagger - \\
 & \beta_h \left(\frac{24t^2}{\pi^2} + \frac{2M}{\pi} H + \frac{1}{2}H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^- \right) + \frac{24t^4}{\pi^2} \alpha_h - \\
 & g_{0,h} M (H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-) - \\
 & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2}\frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \\
 & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
 & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}\frac{M}{c_w} Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w^2} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
 & \frac{1}{2}g^2 \frac{s_w^2}{c_w^2} Z_\mu^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}\frac{g^2 s_w^2}{c_w^2} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) D_\mu^0 A_\mu \phi^1 \phi^- - \\
 & g^2 s_w^2 A_\mu A_\nu \phi^1 \phi^- + \frac{1}{2}ig \lambda_\mu^0 (\bar{q}_j^\mu \gamma^\nu q_j^\nu) g_\mu^\mu - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{u}_j^\lambda (\gamma \partial + \\
 & m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu (-(\bar{e}^\lambda \gamma^\mu e^\mu) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\mu) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\mu))) + \\
 & \frac{ig}{6c_w} Z_\mu^0 ((\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{2}{3}u_0^\lambda - 1 - \gamma^5) d_j^\lambda) + \\
 & (u_j^\lambda \gamma^\mu (1 - \frac{2}{3}s_w^2 + \gamma^5) u_j^\lambda)) + \frac{ig}{2} W_\mu^- ((\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) U^{1\mu}{}_{\lambda\kappa} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)) + \\
 & \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\mu U^{1\mu}{}_{\lambda\kappa} (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda C_{\lambda\kappa} \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_u^0 (\bar{v}^\mu U^{1\mu}{}_{\lambda\kappa} (1 - \gamma^5) \nu^\lambda) + m_u^0 (\bar{v}^\mu U^{1\mu}{}_{\lambda\kappa} (1 + \gamma^5) e^\kappa)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_u^0 (\bar{v}^\lambda U^{1\mu}{}_{\lambda\kappa} (1 + \gamma^5) \nu^\kappa) - m_u^0 (\bar{v}^\lambda U^{1\mu}{}_{\lambda\kappa} (1 - \gamma^5) \nu^\kappa)) - \frac{s}{M} \frac{m_b^\lambda}{M} H (\bar{b}^\lambda \nu^\lambda) - \\
 & \frac{s}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} M^2 \phi^0 (\bar{e}^\lambda \gamma^\mu \nu^\lambda) - \frac{ig}{2} M^2 \phi^0 (\bar{e}^\lambda \gamma^\mu e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa - \\
 & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_u^0 (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^0 (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)) + \\
 & \frac{ig}{2M} \phi^- (m_d^0 (d_j^\lambda C_{\lambda\kappa}^1 (1 + \gamma^5) u_j^\kappa) - m_u^0 (d_j^\lambda C_{\lambda\kappa}^1 (1 - \gamma^5) u_j^\kappa)) - \frac{s}{2} \frac{m_b^\lambda}{M} H (\bar{u}_j^\lambda u_j^\kappa) - \\
 & \frac{g}{2} \frac{m_b^\lambda}{M} H (\bar{d}_j^\lambda d_j^\kappa) + \frac{ig}{2} \frac{m_b^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^\kappa u_j^\kappa) - \frac{ig}{2} \frac{m_b^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^\kappa d_j^\kappa) + \bar{G}^\alpha \bar{J}^\mu G^\alpha + g_s f^{abc} \partial_\mu \bar{G}^\alpha G^\alpha g_\mu^c + \\
 & \bar{X}^+ (\partial^\mu - M^2) X^+ + \bar{X}^- (\partial^\mu - M^2) X^- + X^0 (\partial^\mu - \frac{M^2}{c_w^2}) X^0 + Y \partial^\mu Y + ig c_w W_\mu^- (\partial_\mu \bar{X}^0 X^- - \\
 & \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^- X^- - \\
 & \partial_\mu \bar{X}^+ X^-) - \frac{1}{2}g M (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} ig M (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
 & \frac{1}{2c_w} ig M (\bar{X}^0 X^- \phi^- - \bar{X}^0 X^+ \phi^+) + ig M s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
 & \frac{1}{2}ig M (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
 \end{aligned}$$

SM: Electroweak-Higgs & QCD

Standard model of particle physics

One of the most beautiful and elegant(!) theory in physics

$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\mu g_\nu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_\nu^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}\partial_\nu^2 M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\mu A_\mu - ig s_w (\partial_\mu Z_\mu^0 (W_\mu^+ W_\mu^- \\
 & W_\nu^+ W_\mu^-) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)) - \\
 & ig s_w (\partial_\mu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\mu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\mu^+ \partial_\nu W_\mu^- \\
 & - W_\nu^- \partial_\nu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^+ W_\mu^- W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\mu^0 W_\nu^- \\
 & Z_\mu^0 Z_\nu^0 (W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\mu^0 (W_\mu^+ W_\nu^- \\
 & W_\nu^+ W_\mu^-) - 2 A_\mu Z_\mu^0 W_\nu^+ W_\mu^-) - \frac{1}{2}\partial_\mu \phi^\dagger H \partial_\mu \phi - \frac{1}{2}\partial_\mu \phi^\dagger \partial_\mu \phi^\dagger - \frac{1}{2}\partial_\mu \phi^\dagger \partial_\mu \phi^\dagger - \\
 & \beta_h \left(\frac{24t^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^- \right) + \frac{24t^4}{g^2} \alpha_h - \\
 & g_{obh} M (H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-) - \\
 & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^0 \phi^+)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{Z_\mu^0} Z_\mu^0 Z_\mu^0 H - \\
 & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
 & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
 & M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^+ + W_\mu^- \partial_\mu \phi^-) - ig \frac{s_w}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w A_\mu (W_\mu^+ \phi^- \\
 & - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w^2} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) + \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
 & \frac{1}{2}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}g^2 \frac{1}{c_w^2} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{1}{c_w^2} (2c_w^2 - 1)^2 \frac{1}{2}g^2 A_\mu \phi^1 \phi^0 - \\
 & g^2 s_w^2 A_\mu A_\nu \phi^1 \phi^0 + \frac{1}{2}ig \lambda_\mu^0 (\bar{q}_i^0 \gamma^\mu q_j^0) g_\mu^a - \bar{e}^\lambda (\gamma \partial + m_e^2) e^\lambda - \bar{e}^\lambda (\gamma \partial + m_e^2) e^\lambda - \bar{u}_j^3 (\gamma \partial + \\
 & m_u^2) u_j^3 - \bar{d}_j^3 (\gamma \partial + m_d^2) d_j^3 + ig s_w A_\mu (\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^3 \gamma^\mu u_j^3) - \frac{1}{3}(\bar{d}_j^3 \gamma^\mu d_j^3)) + \\
 & \frac{ig}{2M} Z_\mu^0 ((\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\kappa) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^3 \gamma^\mu (\frac{1}{3} \bar{u}_0^6 - 1 - \gamma^5) d_j^3) + \\
 & (u_j^3 \gamma^\mu (1 - \frac{2}{3}s_w^2 + \gamma^5) u_j^3)) + \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{d}_j^3 \gamma^\mu (1 + \gamma^5) U^{lep} \lambda_\kappa e^\kappa) + (u_j^3 \gamma^\mu (1 + \gamma^5) C_{\lambda \kappa} d_j^3)) + \\
 & \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\nu U^{lep \dagger} \lambda_\kappa (1 + \gamma^5) \nu^\kappa) + (\bar{d}_j^3 C_{\lambda \kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^3)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_u^2 (\bar{e}^\nu U^{lep \dagger} \lambda_\kappa (1 - \gamma^5) e^\kappa) + m_u^2 (\bar{e}^\nu U^{lep \dagger} \lambda_\kappa (1 + \gamma^5) e^\kappa)) + \\
 & -\frac{ig}{2M\sqrt{2}} \phi^- (m_u^2 (\bar{e}^\lambda U^{lep \dagger} \lambda_\kappa (1 + \gamma^5) \nu^\kappa) - m_u^2 (\bar{e}^\lambda U^{lep \dagger} \lambda_\kappa (1 - \gamma^5) \nu^\kappa)) - \frac{s}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
 & \frac{s}{M} H (\bar{e}^\lambda e^\lambda) + \frac{i g m_e^2}{2} \phi^0 (\bar{e}^\lambda \gamma^\mu \nu^\lambda) - \frac{i g m_e^2}{2} \phi^0 (\bar{e}^\lambda \gamma^\mu e^\lambda) - \frac{1}{2} \bar{\nu}_\lambda M_{\lambda \kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa - \\
 & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda \kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_u^2 (\bar{u}_j^3 C_{\lambda \kappa} (1 - \gamma^5) d_j^3) + m_u^2 (\bar{u}_j^3 C_{\lambda \kappa} (1 + \gamma^5) d_j^3)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_d^2 (d_j^3 C_{\lambda \kappa}^\dagger (1 + \gamma^5) u_j^3) - m_u^2 (d_j^3 C_{\lambda \kappa}^\dagger (1 - \gamma^5) u_j^3)) - \frac{s}{M} H (\bar{u}_j^3 u_j^3) - \\
 & \frac{g}{2M} H (\bar{d}_j^3 d_j^3) + \frac{ig}{2M} \phi^0 (\bar{u}_j^3 \gamma^\lambda u_j^3) - \frac{ig}{2M} \phi^0 (\bar{d}_j^3 \gamma^\lambda d_j^3) + \bar{G}^\alpha \bar{J}^\mu G^\alpha + g_s f^{abc} \partial_\mu \bar{G}^\alpha G^\alpha g_\mu^c + \\
 & \bar{X}^+ (\partial^\mu - M^2) X^+ + \bar{X}^- (\partial^\mu - M^2) X^- + \bar{X}^0 (\partial^\mu - \frac{M^2}{c_w}) X^0 + \bar{Y} \partial^\mu Y + ig c_w W_\mu^- (\partial_\mu \bar{X}^0 X^- - \\
 & \partial_\mu \bar{X}^0 X^+ + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ \bar{Y}) + ig c_w W_\mu^- (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ \bar{Y}) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} ig M (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
 & \frac{1}{2c_w} ig M (\bar{X}^0 X^- \phi^- - \bar{X}^0 X^+ \phi^+) + ig M s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
 & \frac{1}{2}ig M (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0).
 \end{aligned}$$

SM: Electroweak-Higgs & QCD



QCD: Self-couplings of gluons,
— color confinement

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$$\begin{aligned} \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\mu g_\nu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- \\ & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}\partial_\nu^2 M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\mu A_\mu - ig s_w (\partial_\mu Z_\mu^0 (W_\mu^+ W_\mu^- \\ & W_\nu^+ W_\mu^-) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^+ \partial_\nu W_\mu^+) - \\ & ig s_w (\partial_\mu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\mu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\mu^+ \partial_\nu W_\mu^- \\ & - W_\nu^+ \partial_\nu W_\mu^+) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^+ W_\mu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\mu^0 W_\nu^- \\ & Z_\mu^0 Z_\nu^0 (W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\mu^0 (W_\mu^+ W_\nu^- \\ & W_\nu^+ W_\mu^-) - 2 A_\mu Z_\nu^0 (W_\mu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2 M^2 \partial_\mu H^2 - \partial_\mu \phi^\dagger \partial_\mu \phi - \frac{1}{2}\partial_\mu \phi^\dagger \partial_\mu \phi^0 - \\ & \beta_h \left(\frac{24t^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}H^2 + \phi^0 \partial_\mu \phi^0 + 2\phi^+ \partial_\mu \phi^- \right) + \frac{24t^4}{g^2} \alpha_h - \\ & g_{\phi h} M (H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-) - \end{aligned}$$

$$\begin{aligned} & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^0 \phi^+)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\ & g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \\ & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\ & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\ & M \left(\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^+ + W_\mu^- \partial_\mu \phi^- \right) - ig \frac{s_w}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w A_\mu (W_\mu^+ \phi^- \\ & - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w^2} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) + \frac{1}{2}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)\phi^+ \phi^-) - \\ & \frac{1}{2}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}g^2 \frac{1}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{1}{c_w} (2s_w^2 - 1) Z_\mu^0 A_\mu \phi^1 \phi^- - \\ & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2}ig \lambda_\mu^0 (\bar{q}_j^0 \gamma^\mu q_j^0) g_\mu^\mu - \bar{e}^\lambda (\gamma \partial + m_e^2) e^\kappa - \bar{e}^\lambda (\gamma \partial + m_e^2) e^\lambda - \bar{u}_j^3 (\gamma \partial + \\ & m_u^2) u_j^3 - \bar{d}_j^3 (\gamma \partial + m_d^2) d_j^3 + ig s_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\kappa) + \frac{2}{3}(\bar{u}_j^3 \gamma^\mu u_j^3) - \frac{1}{3}(\bar{d}_j^3 \gamma^\mu d_j^3)) + \\ & \frac{ig}{2M} Z_\mu^0 ((\bar{u}_j^3 \gamma^\mu (1 + \gamma^5) u_j^3) + (\bar{d}_j^3 \gamma^\mu (1 + \gamma^5) d_j^3) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\kappa) + (\bar{d}_j^3 \gamma^\mu (\frac{2}{3}s_w^2 - 1 - \gamma^5) d_j^3) + \\ & (\bar{u}_j^3 \gamma^\mu (1 - \frac{2}{3}s_w^2 + \gamma^5) u_j^3)) + \frac{ig}{2M} W_\mu^- \{(\bar{u}_j^3 \gamma^\mu (1 + \gamma^5) U^{lep} \lambda_\kappa e^\kappa) + (\bar{u}_j^3 \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^3) + \\ & \frac{ig}{2M} W_\mu^- \left((\bar{e}^\lambda U^{lep \dagger} \lambda_\kappa (1 + \gamma^5) \nu^\kappa) + (\bar{d}_j^3 C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^3) \right) + \\ & \frac{ig}{2M\sqrt{2}} \phi^+ \left(-m_u^2 (\bar{p}^\nu U^{lep} \lambda_\kappa (1 - \gamma^5) e^\kappa) + m_u^2 (\bar{p}^\nu U^{lep \dagger} \lambda_\kappa (1 - \gamma^5) e^\kappa) + \right. \\ & \left. - \frac{ig}{2M} \left(m_u^2 (\bar{e}^\lambda U^{lep \dagger} \lambda_\kappa (1 + \gamma^5) \nu^\kappa) + m_u^2 (\bar{e}^\lambda U^{lep} \lambda_\kappa (1 - \gamma^5) \nu^\kappa) \right) - \frac{s}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \right. \\ & \left. - \frac{s}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2M} \phi^0 (\bar{p}^\lambda \gamma^\mu p^\lambda) + \frac{ig}{2M} \phi^0 (\bar{e}^\lambda \gamma^\mu e^\lambda) - \frac{i}{2} \bar{\nu}_\kappa M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa - \right. \\ & \left. - \frac{1}{4} \bar{\nu}_\kappa M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ \left(-m_u^2 (\bar{u}_j^3 \lambda_\kappa (1 - \gamma^5) d_j^3) + m_u^2 (\bar{u}_j^3 C_{\lambda\kappa} (1 + \gamma^5) d_j^3) + \right. \right. \\ & \left. \left. - \frac{ig}{2M} \phi^+ \left(m_d^2 (d_j^3 C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^3) - m_u^2 (d_j^3 C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^3 \right) \right) - \frac{s}{M} H (\bar{u}_j^3 u_j^3) - \right. \\ & \left. - \frac{g}{2M} H (\bar{d}_j^3 d_j^3) + \frac{ig}{2M} \phi^0 (\bar{u}_j^3 \gamma^\lambda u_j^3) - \frac{ig}{2M} \phi^0 (\bar{d}_j^3 \gamma^\lambda d_j^3) + \bar{G}^\alpha \bar{J}^\mu G^\alpha + g_s f^{abc} \partial_\mu \bar{G}^\alpha G^\alpha g_\mu^c + \right. \\ & \left. \bar{X}^+ (\partial^\mu - M^2) X^+ + \bar{X}^- (\partial^\mu - M^2) X^- + \bar{X}^0 (\partial^\mu - \frac{M^2}{c_w}) X^0 + \bar{Y} \partial^\mu Y + ig c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \right. \\ & \left. \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{X}^+ \bar{Y}) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \right. \\ & \left. \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^- X^- - \right. \\ & \left. - \frac{1}{2}g M (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} ig M (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \right. \\ & \left. - \frac{1}{2c_w} ig M (\bar{X}^0 X^- \phi^- - \bar{X}^0 X^+ \phi^+) + ig M s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \right. \\ & \left. \frac{1}{2}ig M (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) . \right) \end{aligned}$$

SM: Electroweak-Higgs & QCD



QCD: Self-couplings of gluons,
— color confinement



Hadronic matter

Standard model of particle physics

One of the most beautiful and elegant(!) theory in physics

$$\begin{aligned} \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\mu g_\nu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- \\ & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}\partial_\nu^2 M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\mu A_\mu - ig s_w (\partial_\mu Z_\mu^0 (W_\mu^+ W_\mu^- \\ & W_\nu^+ W_\mu^-) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)) - \\ & ig s_w A_\mu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) - A_\mu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\mu^+ \partial_\nu W_\mu^- \\ & - W_\nu^- \partial_\nu W_\mu^+) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\mu^0 W_\mu^- \\ & Z_\mu^0 Z_\mu^0 (W_\mu^+ W_\mu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\mu W_\mu^- - A_\mu A_\mu W_\mu^+ W_\mu^-) + g^2 s_w c_w (A_\mu Z_\mu^0 (W_\mu^+ W_\mu^- \\ & W_\nu^+ W_\mu^-) - 2 A_\mu Z_\mu^0 (W_\mu^+ W_\mu^-) - \frac{1}{2}\partial_\mu \phi H \partial_\mu H - 2M^2 \partial_\mu H^2 - \partial_\mu \phi \partial_\mu \phi - \frac{1}{2}\partial_\mu \phi \partial_\mu \phi^2 - \\ & \beta_h \left(\frac{24t^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^- \right) + \frac{24t^4}{g^2} \alpha_h - \\ & g_{Qh} M (H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-) - \end{aligned}$$

$$\begin{aligned} & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^0 \phi^+)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\ & g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \\ & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0)) + \\ & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^- - \phi^- \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\ & M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^+ + W_\mu^- \partial_\mu \phi^+) - ig \frac{s_w}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w A_\mu (W_\mu^+ \phi^- \\ & - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w^2} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) + \frac{1}{4}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)\phi^+ \phi^-) - \\ & \frac{1}{2}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}g^2 \frac{1}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{1}{c_w} (2s_w^2 - 1) Z_\mu^0 A_\mu \phi^1 \phi^- - \\ & g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- + \frac{1}{2}ig \lambda_j^0 (\bar{q}_j^0 \gamma^\mu q_j^0) g_\mu^\mu - \bar{e}^\lambda (\gamma \partial + m_e^2) e^\alpha - \bar{e}^\lambda (\gamma \partial + m_e^2) e^\lambda - \bar{u}_j^3 (\gamma \partial + \\ & m_u^2) u_j^3 - \bar{d}_j^3 (\gamma \partial + m_d^2) d_j^3 + ig s_w A_\mu ((\bar{e}^\lambda \gamma^\mu e^\nu) + \frac{2}{3}(\bar{u}_j^3 \gamma^\mu u_j^3) - \frac{1}{3}(\bar{d}_j^3 \gamma^\mu d_j^3)) + \\ & \frac{ig}{2M} Z_\mu^0 ((\bar{u}_j^3 \gamma^\mu (1 + \gamma^5) u_j^3) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\nu) + (\bar{d}_j^3 \gamma^\nu (\frac{2}{3}u_0^6 - 1 - \gamma^5) d_j^3) + \\ & (u_j^3 \gamma^\mu (1 - \frac{2}{3}s_w^2 + \gamma^5) u_j^3)) + \frac{ig}{2M} W_\mu^- \{(\bar{u}_j^3 \gamma^\mu (1 + \gamma^5) U^{1\mu}{}_{\lambda\kappa} e^\kappa + (u_j^3 \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^3)) + \\ & \frac{ig}{2M} W_\mu^- \left((\bar{e}^\nu U^{1\mu}{}_{\lambda\kappa} (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^3 C_{\lambda\kappa}^1 \gamma^\mu (1 + \gamma^5) u_j^3) \right) + \\ & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_u^6 (\bar{p}^\nu U^{1\mu}{}_{\lambda\kappa} (1 - \gamma^5) \nu^\lambda) + m_u^6 (\bar{p}^\nu U^{1\mu}{}_{\lambda\kappa} (1 - \gamma^5) \nu^\lambda) + \\ & - \frac{ig}{2M\sqrt{2}} \phi^- (m_u^6 (\bar{e}^\lambda U^{1\mu}{}_{\lambda\kappa}^1 (1 + \gamma^5) \nu^\lambda) - m_u^6 (\bar{e}^\lambda U^{1\mu}{}_{\lambda\kappa} (1 - \gamma^5) \nu^\lambda) - \frac{s}{M} H (\bar{p}^\lambda \nu^\lambda) - \\ & \frac{s}{M} H (\bar{e}^\lambda e^\lambda) + \frac{1}{2}M \phi^0 (\bar{p}^\lambda \gamma^\mu \nu^\lambda) - \frac{ig}{M} \phi^0 (\bar{e}^\lambda \gamma^\mu e^\lambda) - \frac{1}{2} \bar{p}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa - \\ & \frac{1}{4} \bar{p}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^6 (\bar{u}_j^3 \gamma^\mu (1 - \gamma^5) d_j^3) + m_u^6 (\bar{u}_j^3 \gamma^\mu C_{\lambda\kappa} (1 + \gamma^5) d_j^3) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_d^6 (\bar{d}_j^3 C_{\lambda\kappa}^1 (1 + \gamma^5) \nu^\lambda) - m_u^6 (\bar{d}_j^3 C_{\lambda\kappa}^1 (1 - \gamma^5) \nu^\lambda) - \frac{s}{M} H (\bar{u}_j^3 u_j^3) - \\ & \frac{g}{2M} H (\bar{d}_j^3 d_j^3) + \frac{ig}{M} \phi^0 (\bar{u}_j^3 \gamma^\lambda u_j^3) - \frac{ig}{M} \phi^0 (\bar{d}_j^3 \gamma^\lambda d_j^3) + \bar{G}^\alpha \bar{J}^\mu G^\alpha + g_s f^{abc} \partial_\mu \bar{G}^\alpha G^\alpha g_\mu^c + \\ & \bar{X}^+ (\partial^\mu - M^2) X^+ + \bar{X}^- (\partial^\mu - M^2) X^- + \bar{X}^0 (\partial^\mu - \frac{M^2}{c_w}) X^0 + \bar{Y} \partial^\mu Y + ig c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\ & \partial_\mu \bar{X}^0 X^+ + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ \bar{Y}) + ig c_w W_\mu^- (\partial_\mu \bar{X}^+ X^- - \\ & \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ \bar{Y}) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \\ & \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^- - \end{aligned}$$

$$\begin{aligned} & \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} ig M (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\ & \frac{1}{2c_w} ig M (\bar{X}^0 X^- \phi^- - \bar{X}^0 X^+ \phi^+) + ig M s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\ & \frac{1}{2}ig M (\bar{X}^+ X^+ \phi^+ - \bar{X}^- X^- \phi^0) . \end{aligned}$$

SM: Electroweak-Higgs & QCD



QCD: Self-couplings of gluons,
— color confinement

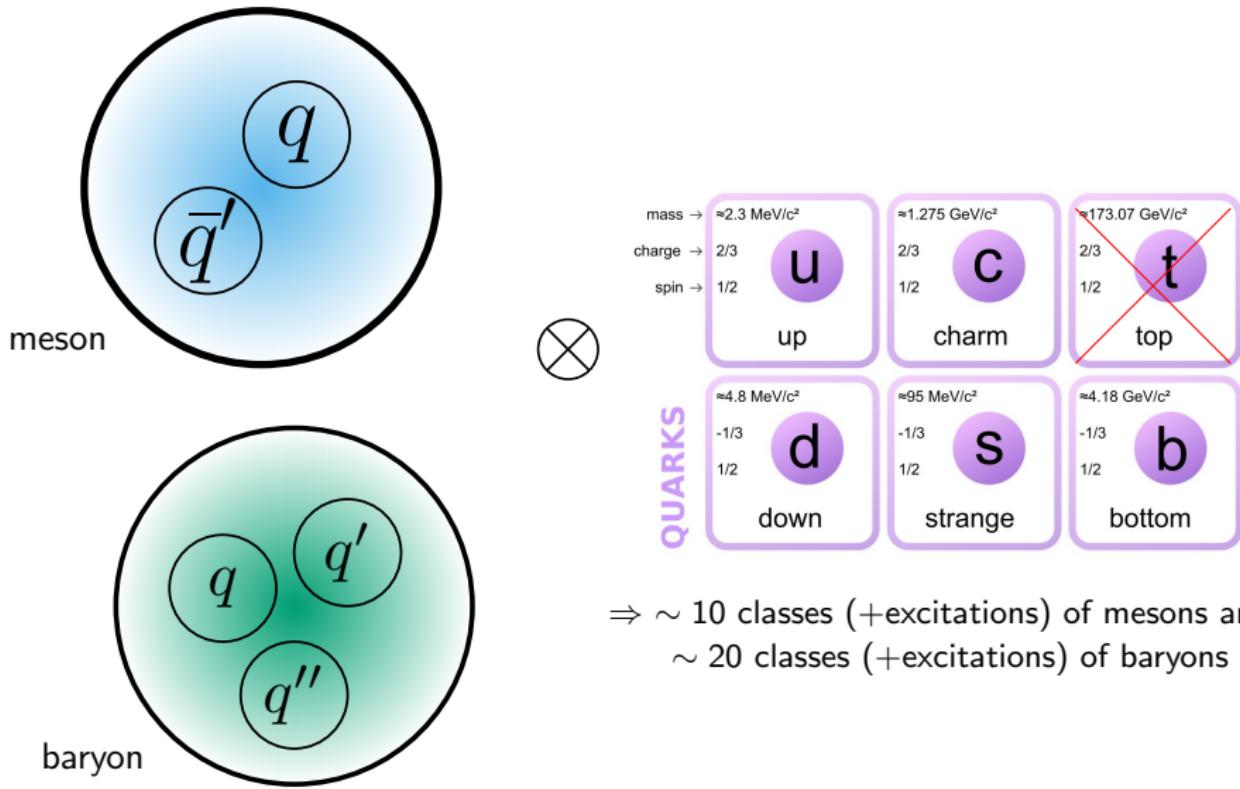


Hadronic matter



Conscious life

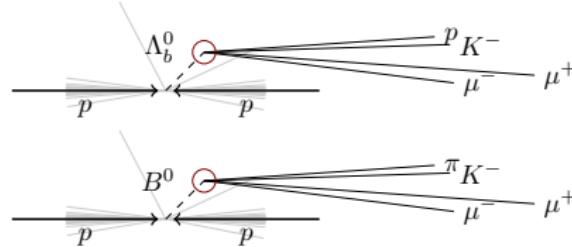
Conventional hadrons



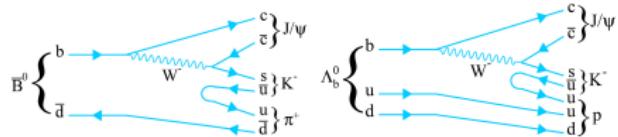
Almost-stable hadrons

Lifetime measurements of Λ_b^0 and B^0

- identification of displaced vertex



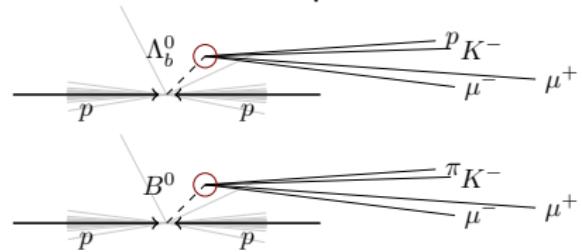
- similar decay chains



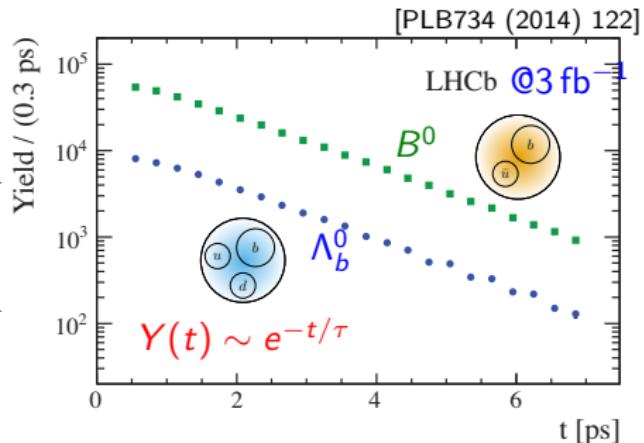
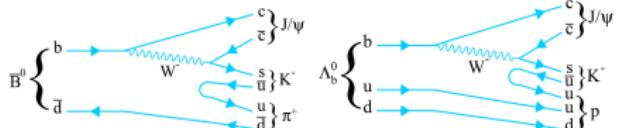
Almost-stable hadrons

Lifetime measurements of Λ_b^0 and B^0

- identification of displaced vertex



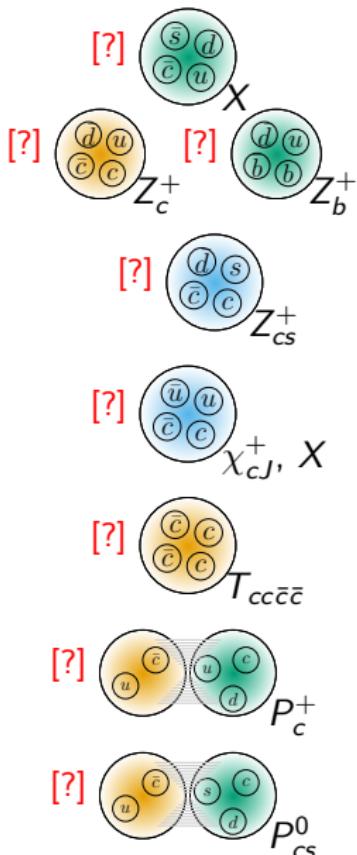
- similar decay chains



$$\tau_{\Lambda_b^0}/\tau_{B^0} = 0.974 \pm 0.006 \pm 0.004,$$

$$\tau_{\Lambda_b^0} = 1.479 \pm 0.009 \pm 0.010 \text{ ps},$$

Growing evidence of exotic states



- All but one with hidden flavor: $(c\bar{c})$ or $(b\bar{b})$
- Complex discovery, controversial interpretation

States

$X_0(2900)$, $X_1(2900)$ [22,23]

$\chi_{c1}(3872)$ [7]

$Z_c(3900)$ [24], $Z_c(4020)$ [25,26], $Z_c(4050)$ [27], $X(4100)$ [28], $Z_c(4200)$ [29], $Z_c(4430)$ [30,31,32,33], $R_{c0}(4240)$ [32]

$Z_{cs}(3985)$ [34], $Z_{cs}(4000)$, $Z_{cs}(4220)$ [35]

$\chi_{c1}(4140)$ [36,37,38,39], $\chi_{c1}(4274)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$ [39], $X(4630)$, $X(4685)$ [35], $X(4740)$ [40]

$X(6900)$ [15]

$Z_b(10610)$, $Z_b(10650)$ [41]

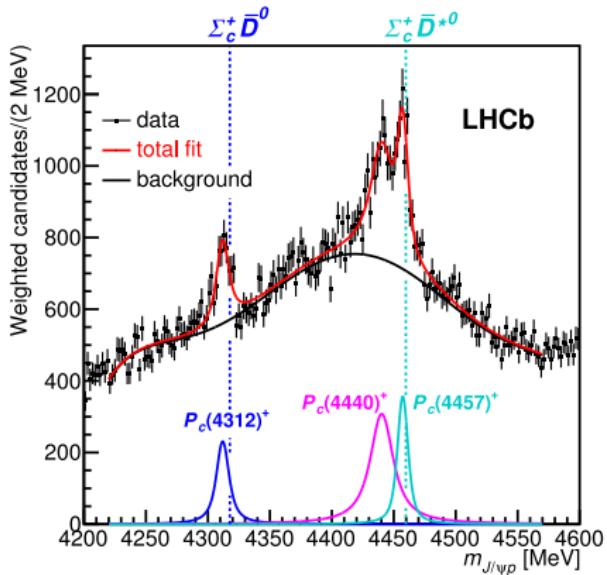
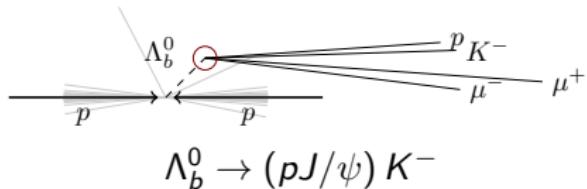
$P_c(4312)$ [42], $P_c(4380)$ [43], $P_c(4440)$, $P_c(4457)$ [42], $P_c(4357)$ [44]

$P_{cs}(4459)$ [45]

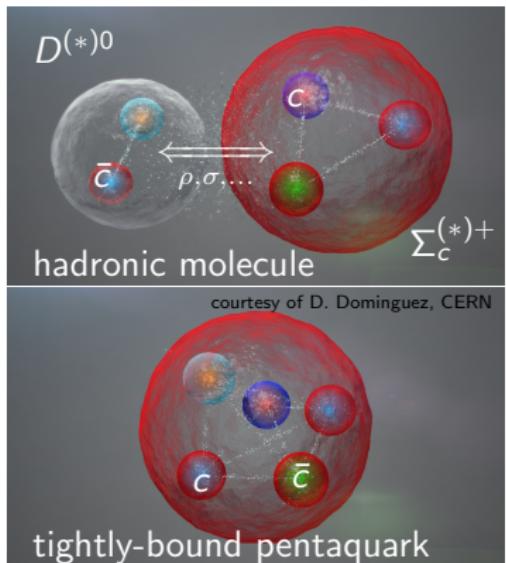
Milestones: 1) XYZ 2) P_c^+ 3) T_{cc}^+

Pentaquarks in pJ/ψ mass spectrum

[PRL 122 (2019) 22, 222001]

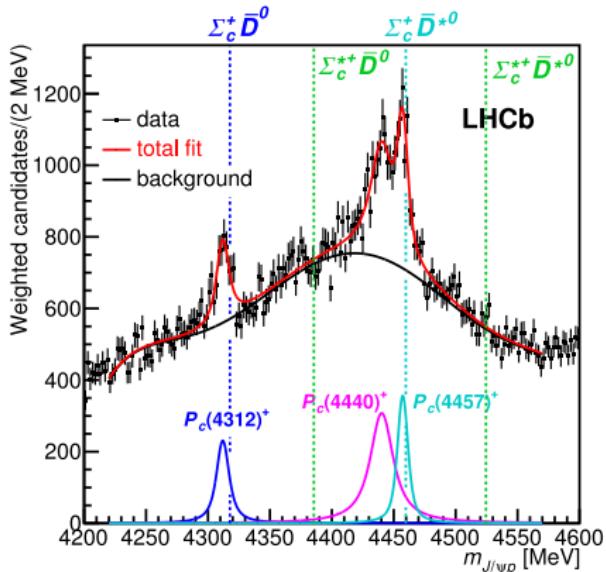
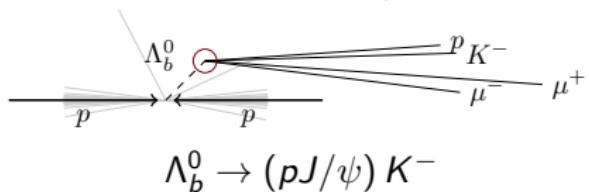


- Narrow peaks in $\rightarrow pJ/\psi$
- Right near $\Sigma_c^{*+} \bar{D}^{*0}$ threshold



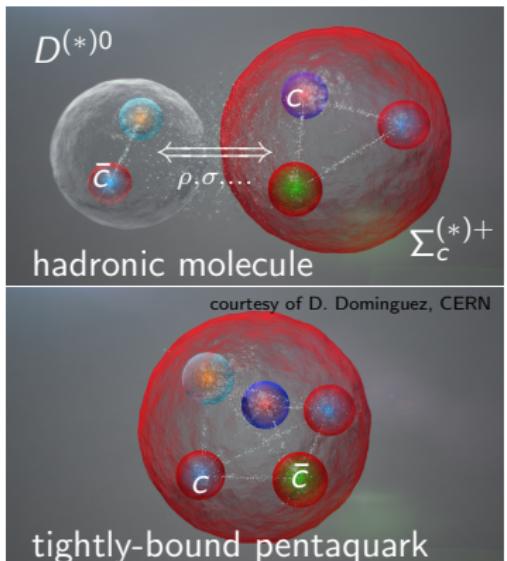
Pentaquarks in pJ/ψ mass spectrum

[PRL 122 (2019) 22, 222001]



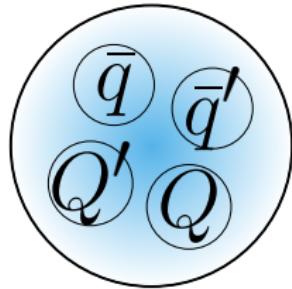
Fit with 7 P_c^+ [Meng-Lin Du et al., PRL124 (2020) 7, 072001]

- Narrow peaks in $\rightarrow pJ/\psi$
- Right near $\Sigma_c^{*+} \bar{D}^{*0}$ threshold



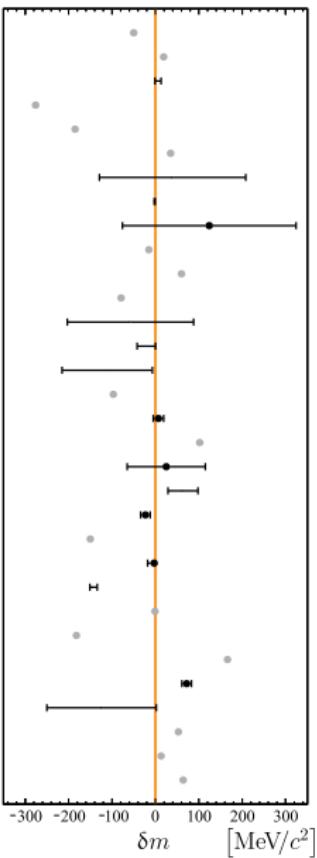
Meet $T_{QQ'}$: new class

"hypothetical" before August 2021



- Ground state: $(QQ'\bar{u}\bar{d})$, $J^P = 1^+$, isospin 0
- Exists?
 - ▶ T_{bb}^- : most theorists believe that it exists.
 - ▶ T_{cc}^+ : no consensus
- in experiment: it does not exist before observed

Mass of T_{cc}^+ wrt $D^{*0}D^+$

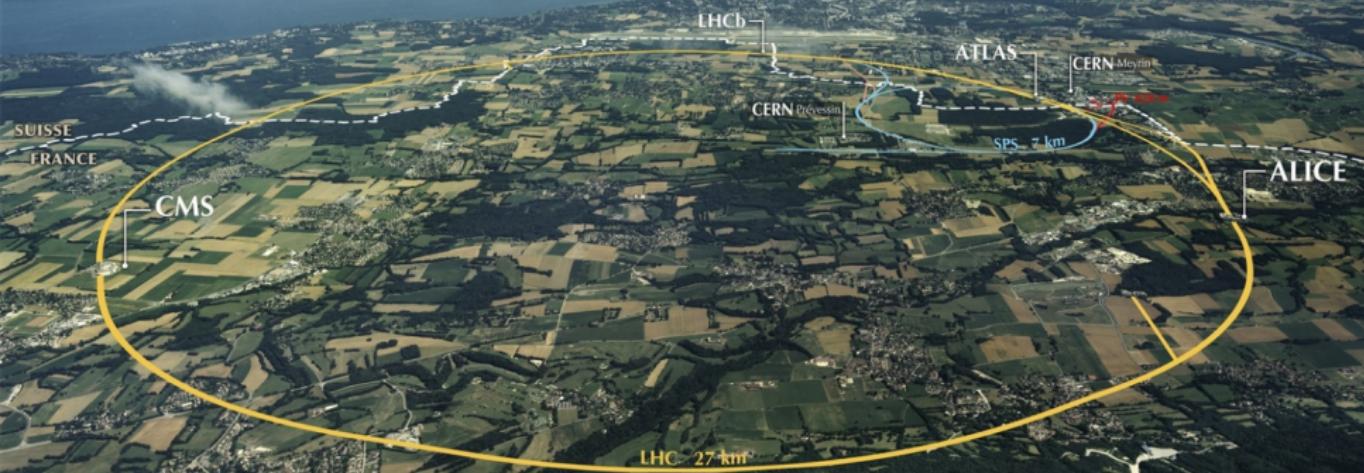


J. Carlson <i>et al.</i>	1987
B. Silvestre-Brac and C. Semay	1993
C. Semay and B. Silvestre-Brac	1994
M. A. Moinester	1995
S. Pepin <i>et al.</i>	1996
B. A. Gelman and S. Nussinov	2003
J. Vijande <i>et al.</i>	2003
D. Janc and M. Rosina	2004
F. Navarra <i>et al.</i>	2007
J. Vijande <i>et al.</i>	2007
D. Ebert <i>et al.</i>	2007
S. H. Lee and S. Yasui	2009
Y. Yang <i>et al.</i>	2009
N. Li <i>et al.</i>	2012
G.-Q. Feng <i>et al.</i>	2013
S.-Q. Luo <i>et al.</i>	2017
M. Karliner and J. Rosner	2017
E. J. Eichten and C. Quigg	2017
Z. G. Wang	2017
W. Park <i>et al.</i>	2018
P. Junnarkar <i>et al.</i>	2018
C. Deng <i>et al.</i>	2018
M.-Z. Liu <i>et al.</i>	2019
L. Maiani <i>et al.</i>	2019
G. Yang <i>et al.</i>	2019
Y. Tan <i>et al.</i>	2020
Q.-F. Lü <i>et al.</i>	2020
E. Braaten <i>et al.</i>	2020
D. Gao <i>et al.</i>	2020
J.-B. Cheng <i>et al.</i>	2020
S. Noh <i>et al.</i>	2021
R. N. Faustov <i>et al.</i>	2021

Observation of T_{cc}^+

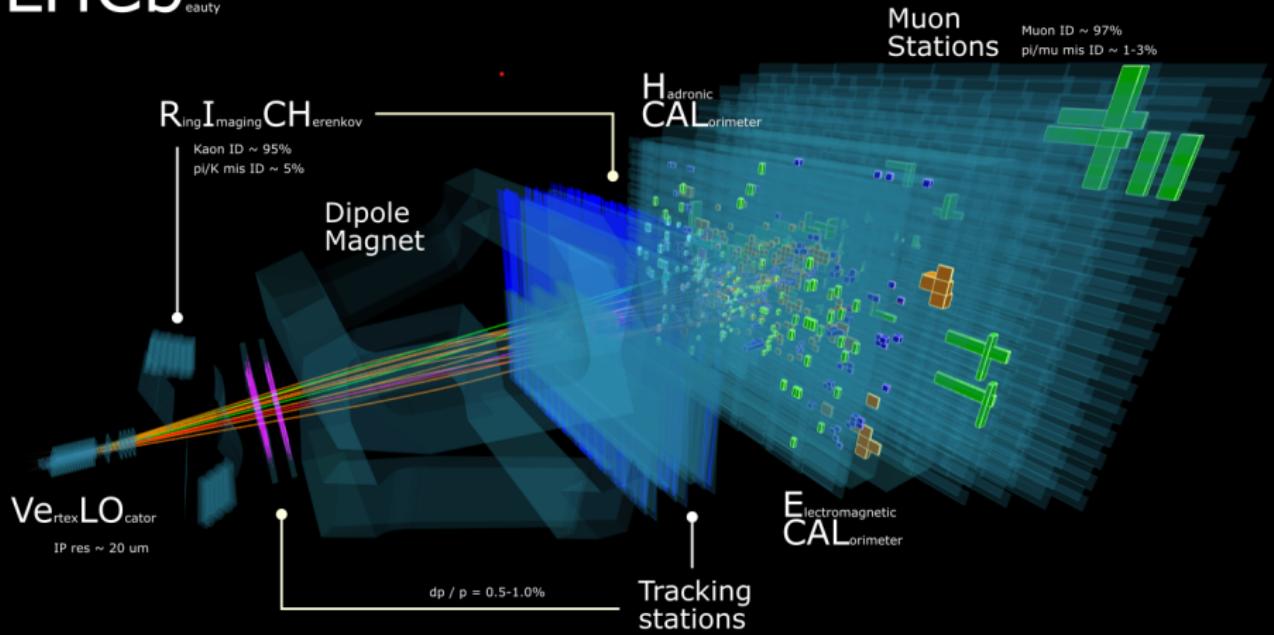
[LHCb, arXiv:2109.01038]

[Image: Maximilien Brice/CERN]



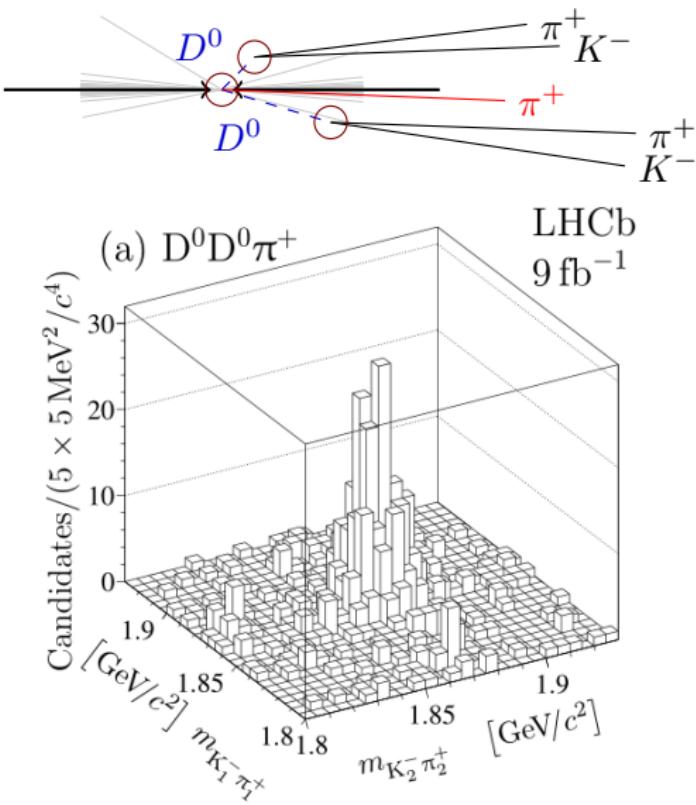
[display]

LHCb_{eauty}



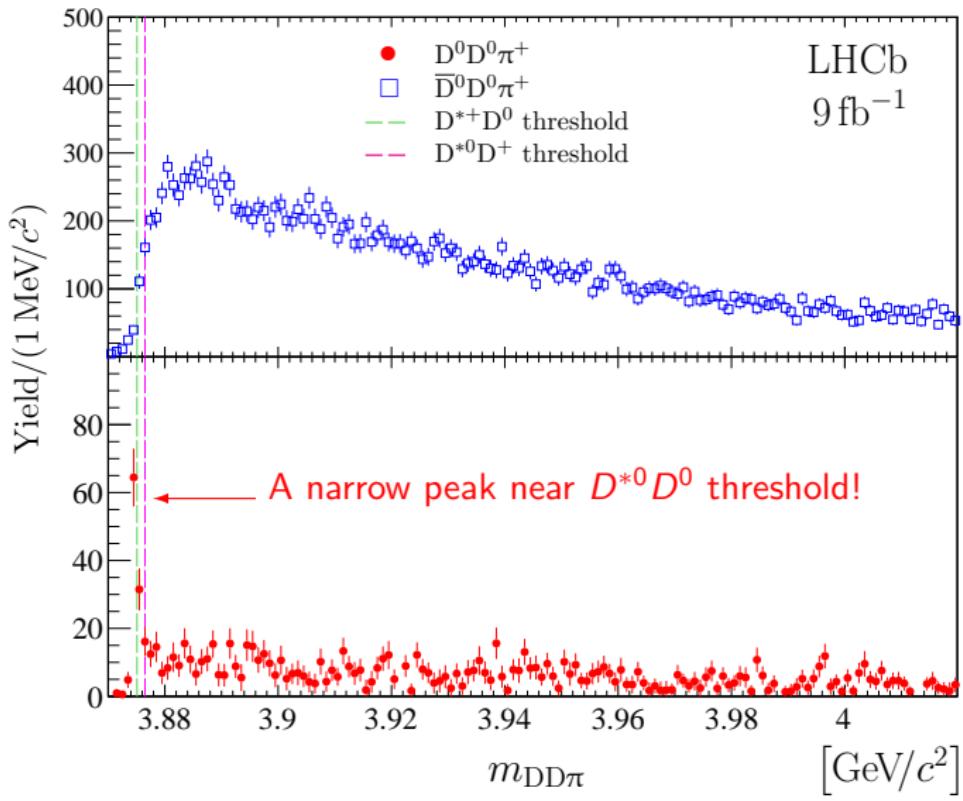
pp collider (7+7 TeV)

Selection of T_{cc}^+ in prompt decays to $D^0 D^0 \pi^+$



- Select $D^0 D^0 \pi^+$ candidates from primary vertex with detached $D^0 \rightarrow K^- \pi^+$
- Require detached $K^- \pi^+$ with high p_T
- Require good quality of tracks, vertexes, and particle ids.
- Ensure no K/π candidates belong to one track (clones)
- Ensure no reflections via mis-ID
- Subtract fake-D background using 2d fit to $(m_{K\pi} \times m_{K\pi})$

The first hint of the signal: $D^0 D^0 \pi^+$ and $D^0 \bar{D}^0 \pi^+$



Spectrum fit and significance

Breit-Wigner model

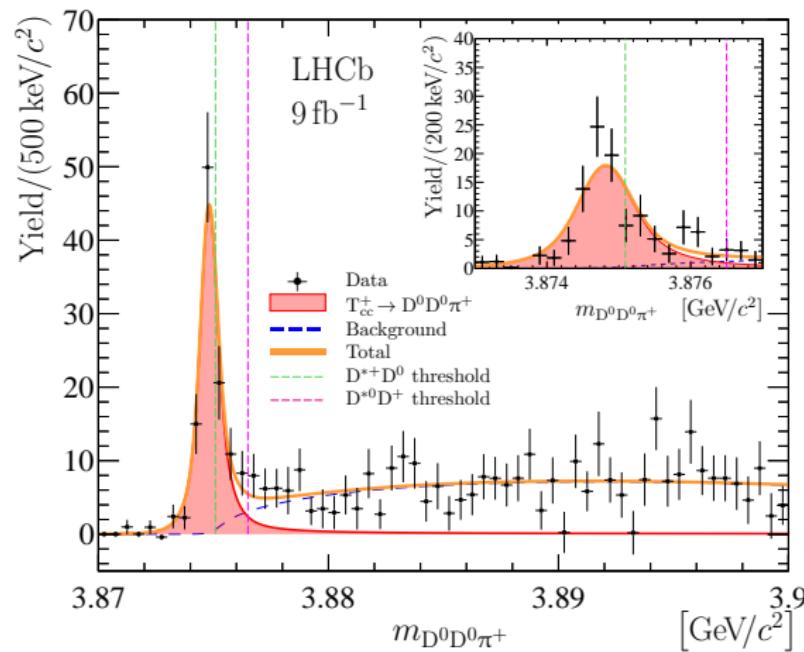
Too naive model

BW signal $[(DD)_S \pi P\text{-wave}]$

+ ph.sp. background

- significance $> 10\sigma$
- peak below (4.3σ)

Parameter	Value
N	117 ± 16
δm_{BW}	$-273 \pm 61 \text{ keV}/c^2$
Γ_{BW}	$410 \pm 165 \text{ keV}$

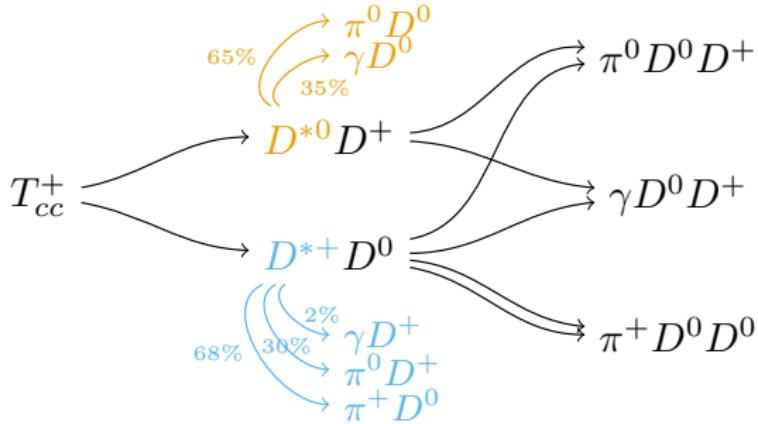


Fundamental properties? Need better model (D^*D threshold)

Extracting T_{cc}^+ parameters

[LHCb, arXiv:2109.01056]

T_{cc}^+ decay amplitude



Model assumptions:

- $J^P = 1^+$: S-wave decay to D^*D
- T_{cc}^+ is an isoscalar: $|T_{cc}^+ \rangle_{I=0} = \{ |D^{*0}D^+ \rangle - |D^{*+}D^0 \rangle \} / \sqrt{2}$
- No isospin violation in couplings to $D^{*+}D^0$ and $D^{*0}D^+$

T_{cc}^+ self-energy and hadronic reaction amplitude

Three-body unitarity [MM et al. (JPAC), JHEP 08 (2019) 080]

Dynamic amplitude of $D^*D \rightarrow D^*D$ scattering:

$$T_{2 \times 2}(s) = K + K \Sigma K + K \Sigma K \Sigma K + \dots$$

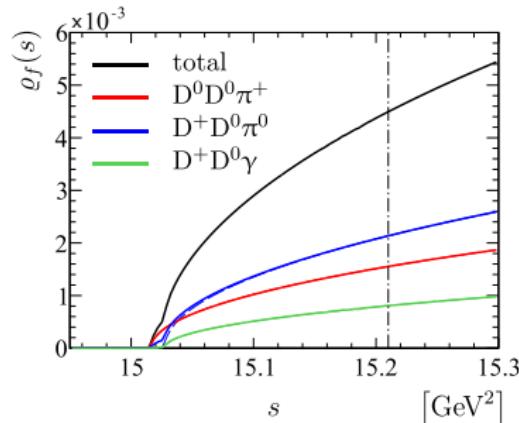
where K is the isoscalar potential:

$$K = \frac{1}{m^2 - s} \begin{pmatrix} g \cdot g & -g \cdot g \\ -g \cdot g & g \cdot g \end{pmatrix},$$

and Σ is the loop function:

$$\begin{aligned} \Sigma(s) &= [D^*D \rightarrow DD\pi(\gamma) \rightarrow D^*D] \\ &= \left[\text{---} \circlearrowleft \text{---} + \text{---} \circlearrowright \text{---} \right]. \end{aligned}$$

$$\text{Im} \left[\begin{pmatrix} g \\ -g \end{pmatrix}^\dagger \Sigma(s) \begin{pmatrix} g \\ -g \end{pmatrix} \right] = \rho(s)$$



D^* decays are accounted for.

Unitarity and Analyticity principles are fulfilled.

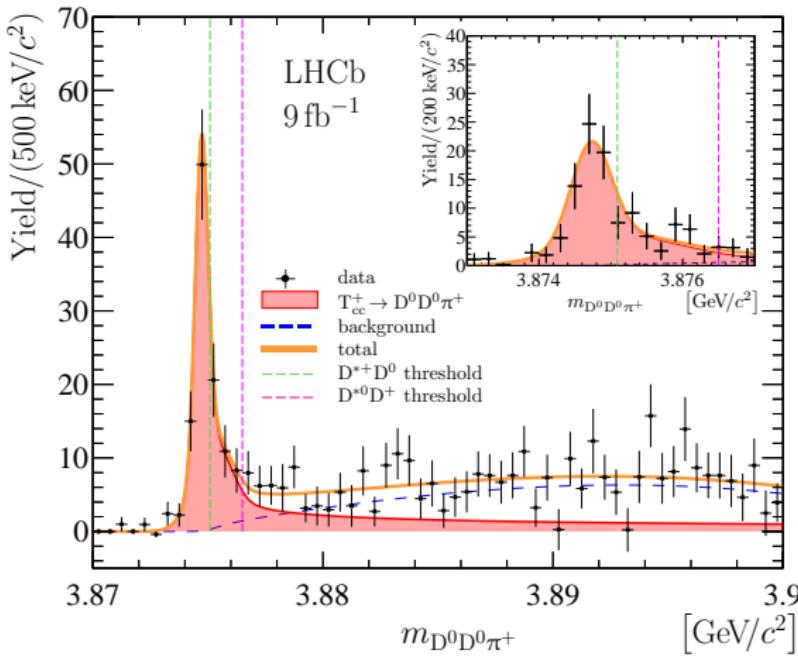
Model parameters: $|g|^2$ and m^2 – bare mass and coupling

Fit to the spectrum

Unitarized model

- The signal shape does not depend on $|g|$ for $|g| \rightarrow \infty$.
- The lower limit: $|g| > 7.7(6.2)$ GeV at 90(95)% CL
- δm_U is the only parameter

Parameter	Value
N	186 ± 24
δm_U	-359 ± 40 keV/ c^2
$ g $	3×10^4 GeV (fixed)



Excellent agreement with the data. Reaction amplitude is fully fixed.

Predicted mass spectrum

resolution removed

Visible
characteristics:

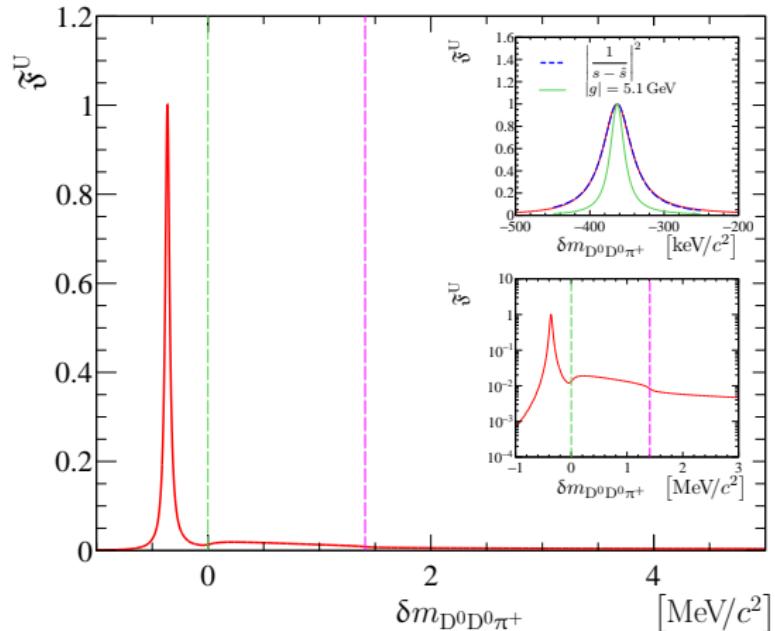
- Peak position:
 $-359 \pm 40 \text{ keV}$

(The most precise ever wrt to
the threshold)

- FWHM:
 $47.8 \pm 1.9 \text{ keV}$,

- Lifetime:
 $\tau \approx 10^{-20} \text{ s.}$

(Unprecedented for exotic
hadrons)



- Nearly-isolated resonance below $D^{*+}D^0$ threshold
- Long tail with cusps on $D^{*+}D^0$ and $D^{*0}D^+$ thresholds

Fundamental resonance parameters

[interactive]

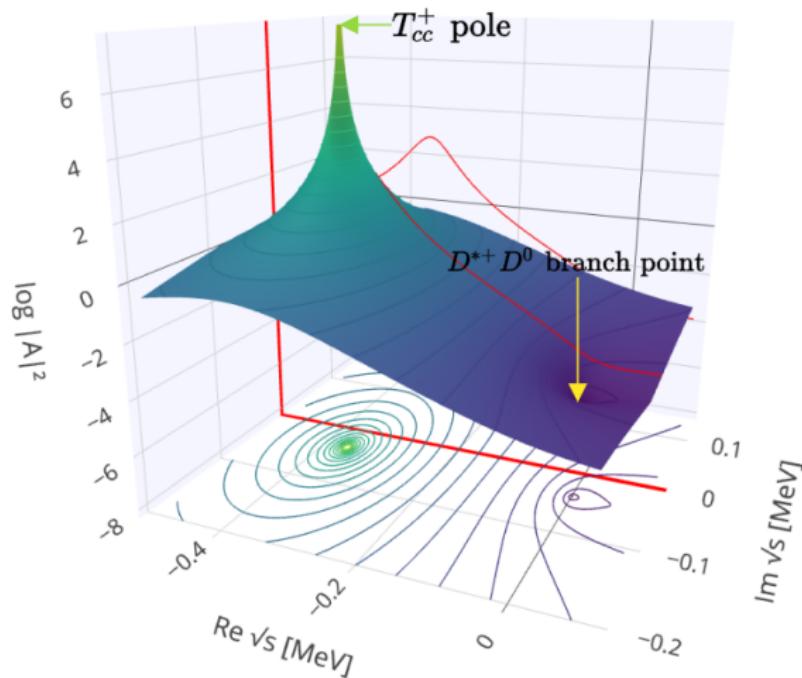
Mass and width – position of the complex pole of the reaction amplitude

- Analytic continuation is non-trivial due to three-body decays [MM et al. (JPAC), PRD 98 (2018) 096021]

The pole parameters:

$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0} \text{ keV},$$

$$\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14} \text{ keV}.$$



How the width is made

Components of the model:

- Coupled $D^{*+}D^0/D^{*0}D^+$ channels
- One-particle exchange
- $D^* \rightarrow D\pi$ decay

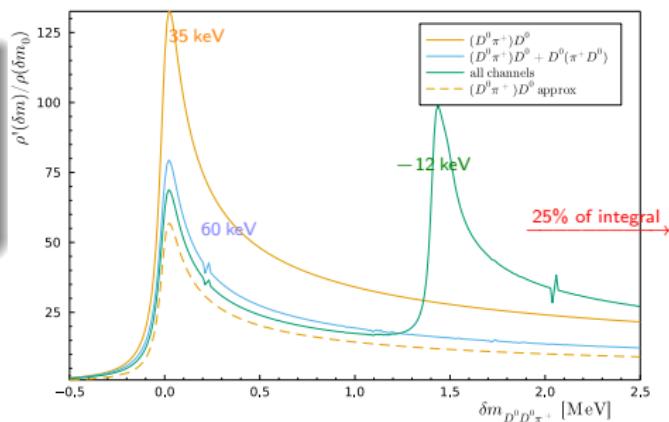
Analytic expression for the width:

$$\frac{1}{\Gamma} = \frac{1}{2\pi} P \int_{th}^{\infty} \frac{\rho'(e)/\rho(\delta m_0)}{e - \delta m_0} de$$

- 48 keV: default model
- -12 keV if not consider the $D^{*0}D^+$
- ~ 15 keV is controlled by the tail

$$48 \text{ keV} \xrightarrow[\text{OPE}]{\text{remove}} 30 \text{ keV} \xrightarrow[D^* \rightarrow D\pi]{\text{remove}} 75 \text{ keV}$$

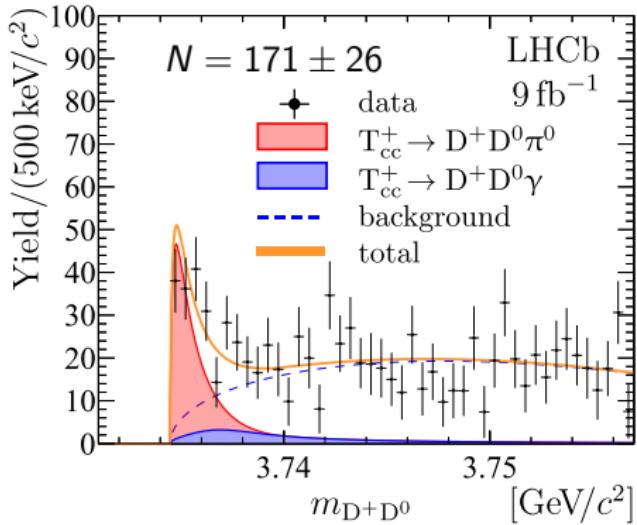
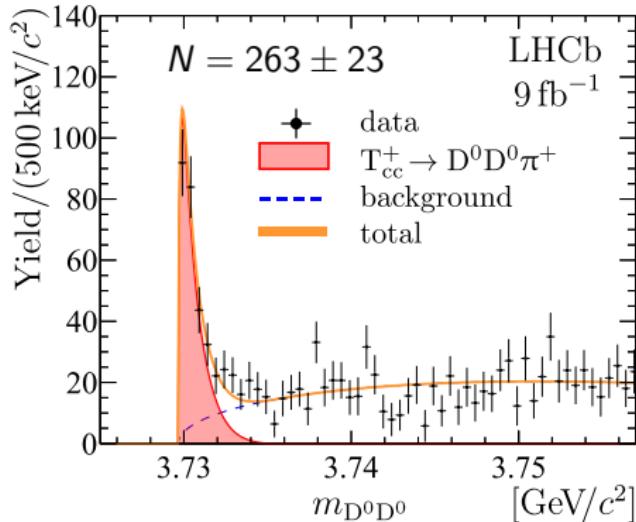
Two-body approx. [Albaladejo, M. (2021)]



Complete of the three-body effects gives 56 keV [Meng-Lin Du et al. (2021)]

Partially-reconstructed decays

Independent selection of the prompt D^0D^0 and D^+D^0 events.



- Lineshape of D^0D^0 and D^+D^0 spectra are predicted well by the model
- Relative yields of D^0D^0 and D^0D^+ is in good agreement with the model predictions

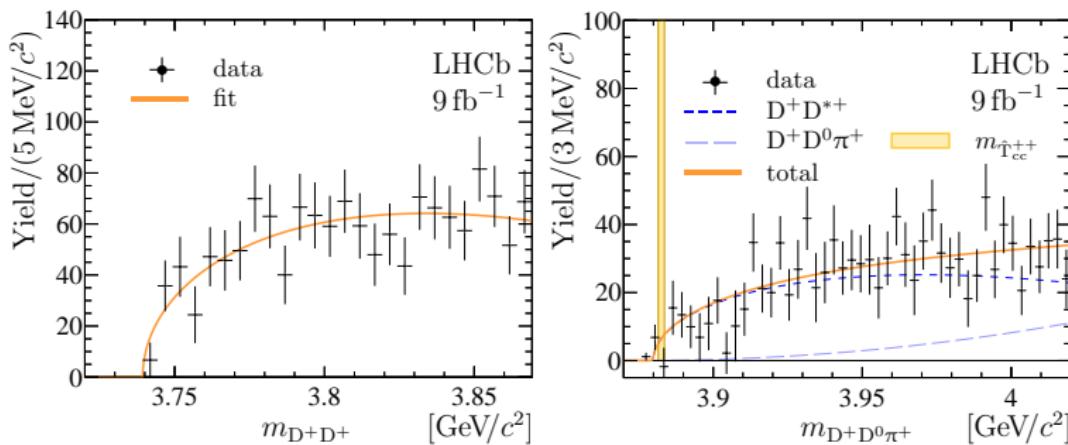
Isospin partners?

What if the T_{cc}^+ is a part of the isospin-1 triplet

$$\begin{array}{ll}
 T_{cc}^0 : & cc\bar{d}\bar{d} \\
 T_{cc}^+ : & cc\bar{u}\bar{d} \\
 T_{cc}^{++} : & cc\bar{u}\bar{u} \quad \rightarrow D^+ D^{*+}
 \end{array}$$

The partners should be roughly of the same mass, more precise

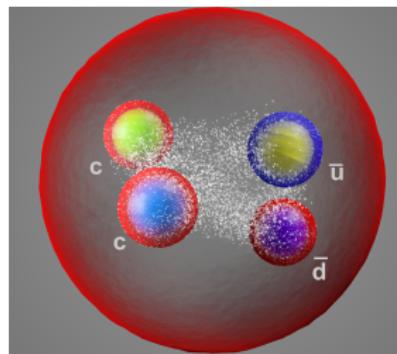
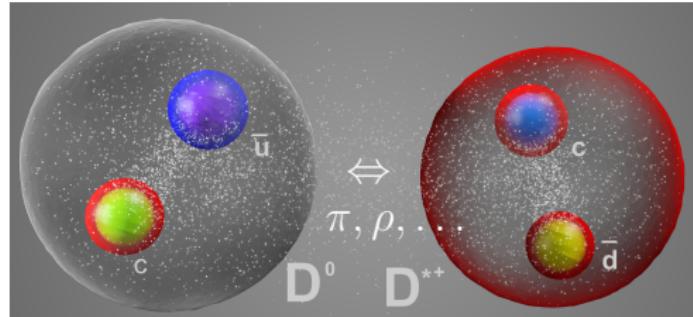
$$m_{T_{cc}^{++}} - (m_{D^+} + m_{D^{*+}}) = 2.7 \pm 1.3 \text{ MeV} (\text{using mass of } \Sigma_c^0, \Sigma_c^+, \Sigma_c^{++})$$



No indication of $I = 1$ family.

Interpretation

Two extreme spatial configurations



"Molecule" configuration:

- two mesons are well separated,
- bound by forces similarly to el.mag. van der Waals,
- entirely coupled to $D^{*+}D^0$,
- ~ T_{cc}^+ lives until D^{*0} decays,
- ? spatially-extended object.

"Atomic" configuration:

- genuine QCD state,
- bound by direct color forces
- ~ T_{cc}^+ cannot live shorter than D^{*0} , width can be as arbitrary large (uncoupled from continuum)
- ? typical hadronic size of 1 fm.

Effective range and Weinberg compositeness

Non-relativistic expansion near the threshold:

$$\mathcal{A}_{\text{NR}} = \frac{1}{a} + r \frac{k^2}{2} + O(k^4) - ik$$

Scattering length, a

- a characteristic size of the state
- $a > 0$: moderate interaction
- $a < 0$: strong attraction forming a bound state

Effective range, r

- is the second order term
 - ! always positive in potential scattering
- [Landau-Smorodinsky(1944), Esposito(2021)]

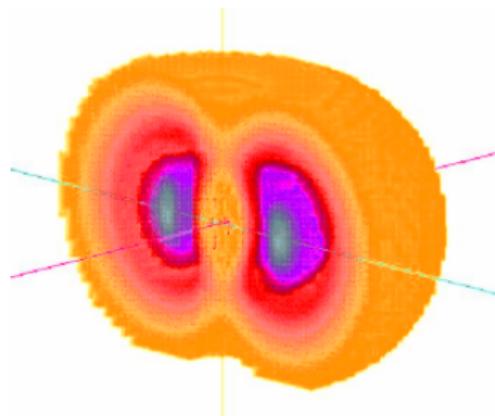
$$\text{Weinberg compositeness: } 1 - Z = \sqrt{\frac{1}{1 + 2r/\Re a}}$$

$$1 - Z = 1 : \text{composite (molecule)} \quad 1 - Z = 0 : \text{elementary}$$

- T_{cc}^+ : $a = (-7.16 \pm 0.51) + i(1.85 \pm 0.28) \text{ fm}$
- T_{cc}^+ : r is negative in the model: $0 < -r < 11.9(16.9) \text{ fm}$ at 90(95) % CL
- T_{cc}^+ : $1 - Z > 0.48(0.42)$. T_{cc}^+ is consistent with the molecule

Comparison to the deuteron

Deuteron [Garcon, Van Orden(2001)]



Tetraquark T_{cc}^+ [LHCb, arXiv:2109.01056]

[compact cc core]

[$\bar{u}\bar{d}$ cloud]

- Presumably molecule
- $1 - Z \approx 1$
- $R_{\text{charge}} = 2.1 \text{ fm}$
- $R_{\text{matter}} = 1.9 \text{ fm}$
- $a = -5.42 \text{ fm}$
- $r = 1.75 \text{ fm}$
- Expected to be atomic
- $1 - Z \geq 0.48$ at 90% CL
- $R_{\text{charge}} = ??$
- $R_{\text{matter}} = ??$
- $a = -7.16 \text{ fm}$
- $r > -11.9 \text{ fm}$ at 90% CL

Non-relativistic quark model. T_{cc}^+ wave function

- Solve Heisenberg equation. Interaction between **every pair** of quarks

$$H = \sum_i \left(m_i + \frac{p^2}{2m_i} \right) - \frac{3}{16} \sum_{i < j} v_{ij}(r_{ij}), \text{ with } r_{ij} = |\vec{r}_i - \vec{r}_j|$$

- Different **variants** for potential are used ("Bhaduri" and "Grenoble")

$$v_{ij}^{(\text{Bhaduri})}(r_{ij}) = \overline{\tilde{\lambda}_i^C \tilde{\lambda}_j^C} \left[\Lambda - \underbrace{\frac{\kappa}{r}}_{\text{Columnb}} + \underbrace{\lambda r}_{\text{confinement}} + \underbrace{\frac{\kappa}{m_i m_j} \frac{\exp(-r/r_0)}{r r_0^2} \sigma_i \sigma_j}_{\text{spin-spin interaction}} \right],$$

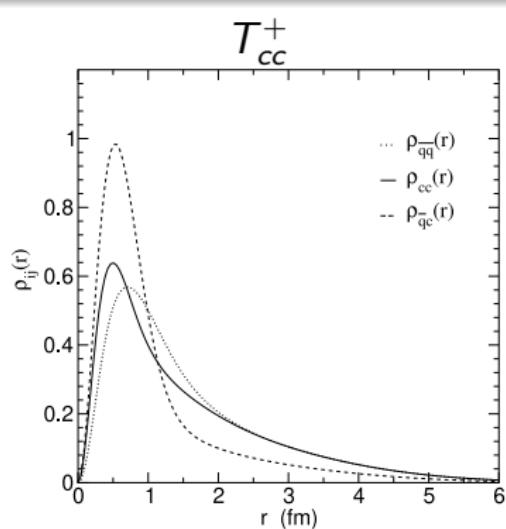
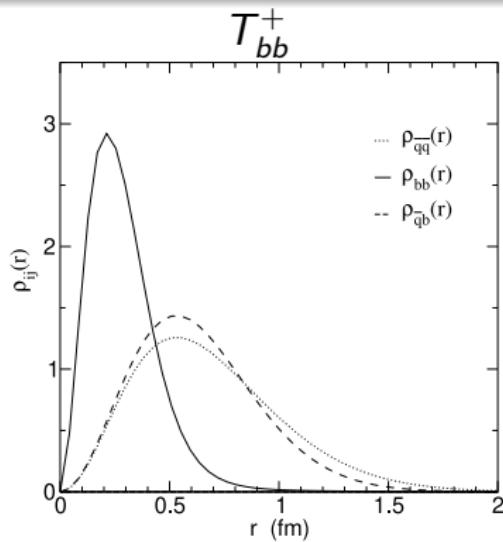
with parameters adjusted by fit to conv. states.

- T_{bb}^- is bound well below the lowest threshold. Stable (bb) in triplet, $J_{(bb)} = 1$.
- T_{cc}^+ is near the threshold: (cc) in (sixt.), $J_{(cc)} = 0, 1$.
 - $\delta m \in \{-1, 0, 11, 13\}$ MeV [Semay, Silvestre-Brac (1993)]
 - $\delta m \in \{-2.7, -0.6\}$ MeV [Janc, Rosina (2004)]

Distributions of QQ component

[[Janc, Rosina (2004)]]

- Matter w.f.: ρ_{QQ} shows how close QQ together
- Color w.f.: $3 \otimes 3 = \bar{3} \oplus 6$
 - ▶ compact (QQ) is in triplet $\sim \bar{Q}$.
 - ▶ ($\text{Meson}_Q \text{ Meson}_Q$) has QQ in sextet



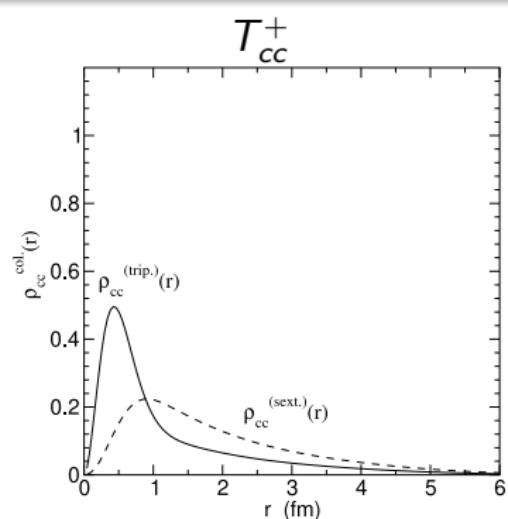
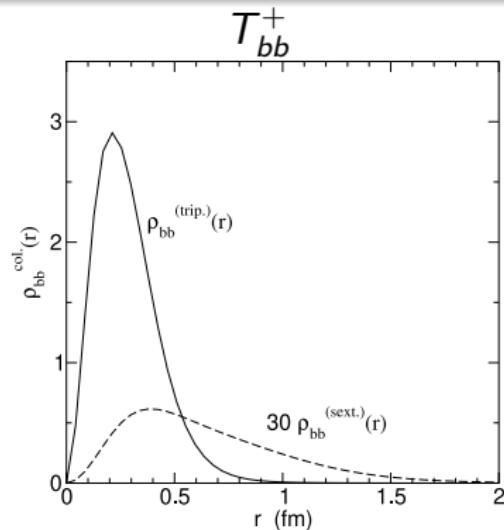
T_{bb}^+ looks atomic like Λ_b ,

while T_{cc}^+ has large $D\bar{D}^*$ component

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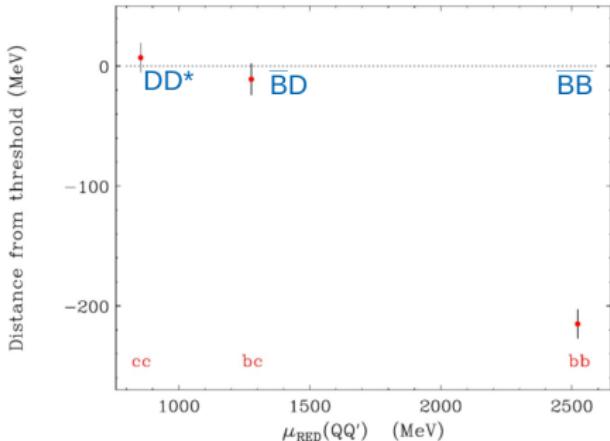


T_{bb}^+ looks atomic like Λ_b , while T_{cc}^+ has large $D\bar{D}^*$ component

Do other hadrons of the $(QQ'qq')$ family exist?

- Exists? Now, we are sure they do, all of them.
- Can be observed? Certainly some. Some might be too broad.

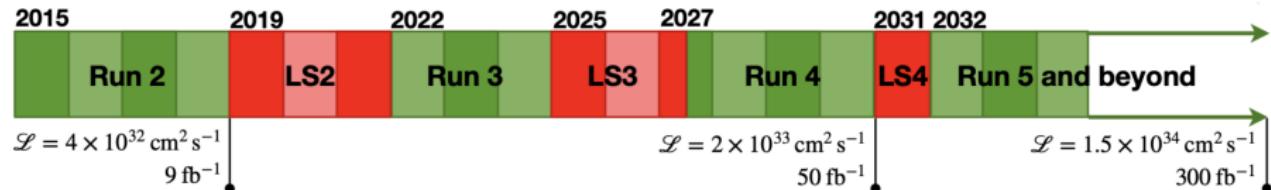
- $T_{bb}^-(bb\bar{u}\bar{d})$ are likely stable wrt QCD
- $T_{cb}^0(cb\bar{u}\bar{d})$ is either stable or almost, like T_{cc}^+
- ? Radial and orbital excitations of isoscalar T_{QQ}^*
- ? Isovector T_{QQ} and its family



[Karliner, Rosner (2017)]

Exotic hadrons in the future plans of LHCb

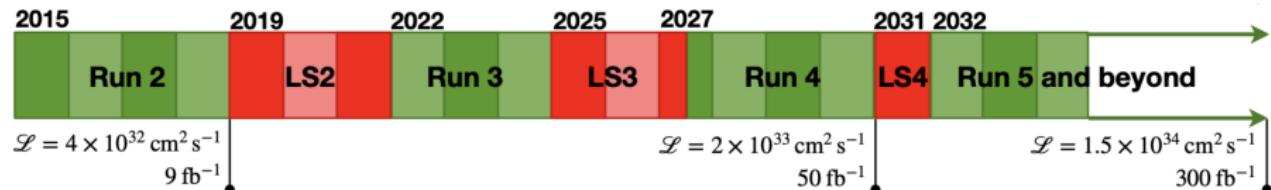
Major LHCb upgrade during LS2 is nearly finished



		P_c^+	T_{cc}^+
Run 1 (2011-2015) :	$+3 \text{ fb}^{-1}$ @7 TeV	~ 100	~ 60
+Run 2 (2015-2019) :	$+6 \text{ fb}^{-1}$ @13 TeV	$\sim 1.5k$	~ 200
+Run 3 (2022-2025) :			
+Run 4 (2027-2030) :	$+40 \text{ fb}^{-1}$ @14 TeV	$> 8k$	$> 1k$

Exotic hadrons in the future plans of LHCb

Major LHCb upgrade during LS2 is nearly finished



	P_c^+	T_{cc}^+
Run 1 (2011-2015) :	$+3 \text{ fb}^{-1} @ 7 \text{ TeV}$	~ 100
+Run 2 (2015-2019) :	$+6 \text{ fb}^{-1} @ 13 \text{ TeV}$	$\sim 1.5k$
+Run 3 (2022-2025) :		
+Run 4 (2027-2030) :	$+40 \text{ fb}^{-1} @ 14 \text{ TeV}$	$> 8k$
		$> 1k$

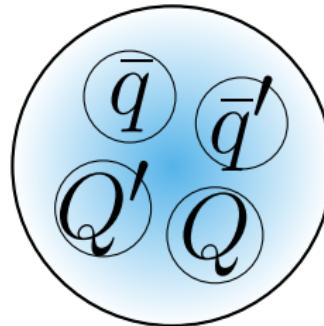
Run 3 is about to start (2022):

- Same energy, but $\times 4$ intensity: $1.5 \rightarrow 5.5 \text{ PV per } \times\text{-ing}$
- Uncertainty due to new tracking system, new software trigger

Optimistically, we will be doing 4 years in 1!

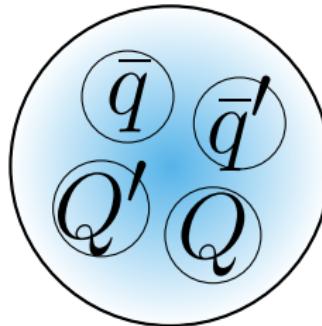


Summary



- T_{cc}^+ is the first representee of $(QQ'\bar{q}\bar{q}')$ hadrons
- Undoubted proof of hadrons beyond conventional $(q\bar{q})$ and (qqq) scheme
- Almost stable with respect to the strong interaction

Summary



- T_{cc}^+ is the first representee of $(QQ'\bar{q}\bar{q}')$ hadrons
- Undoubted proof of hadrons beyond conventional $(q\bar{q})$ and (qqq) scheme
- Almost stable with respect to the strong interaction

Outlook

- Model assumption are consistent with the data, but need to be proven:
 - ▶ Accurate accounting for three-body effects
 - ▶ Dalitz-plot analysis and test of J^P
- Analysis of the production cross sections

New hadrons observed at LHCb

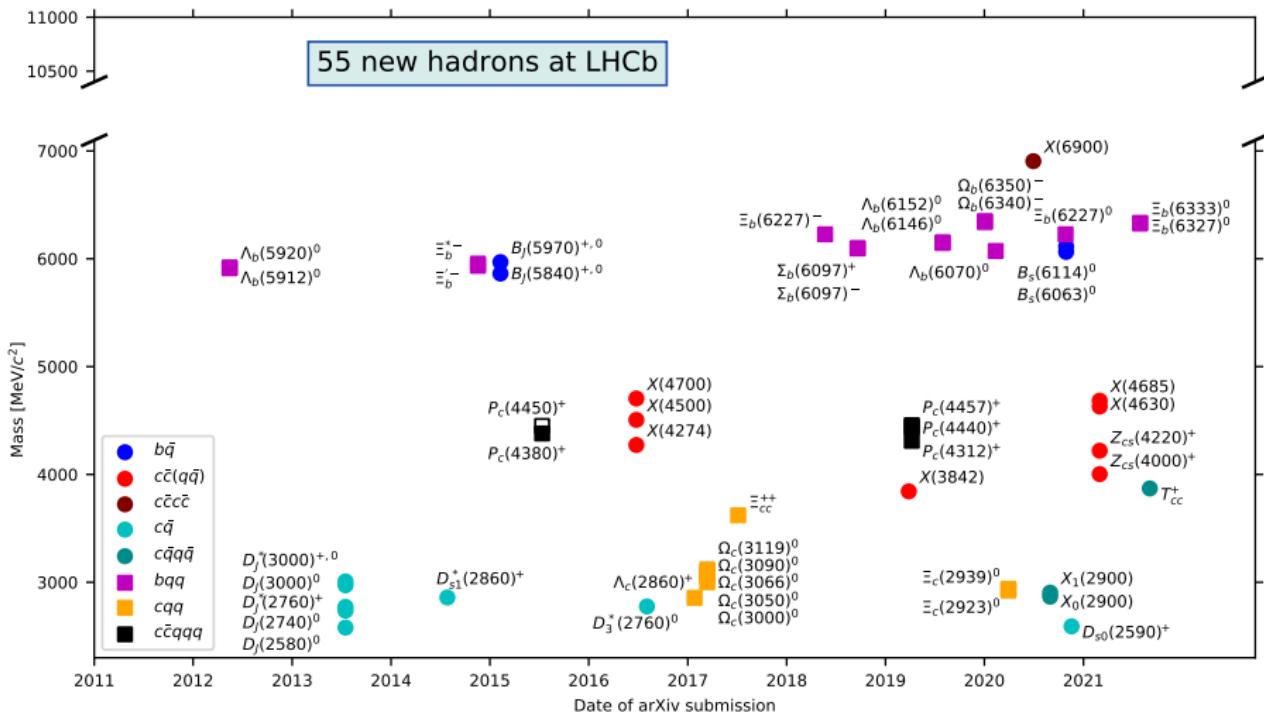
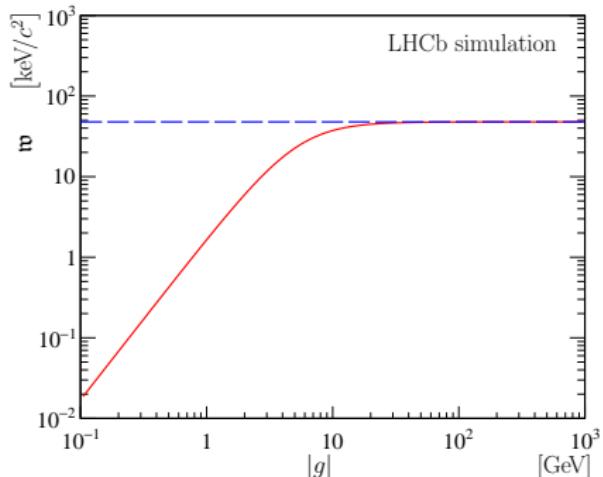
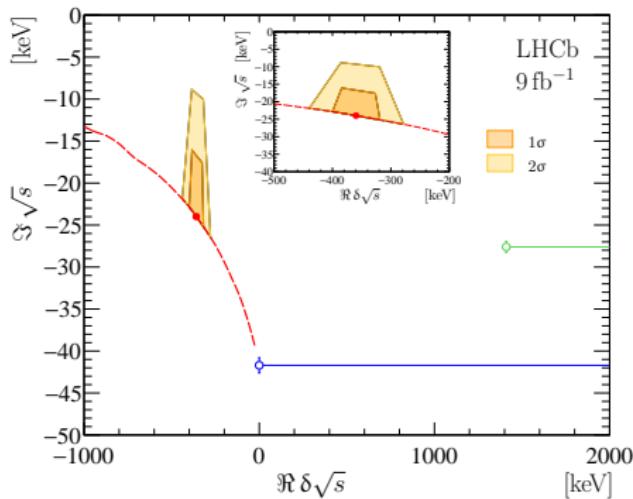


image credit: Patrick Koppenburg / LHCb

Thank you for the attention

Width saturation

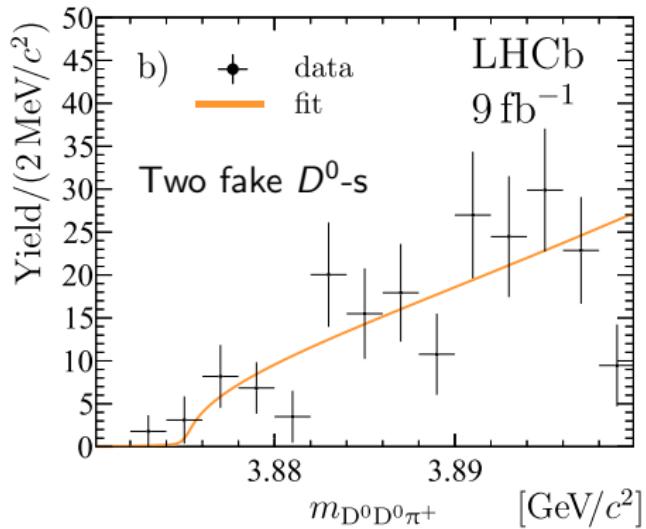
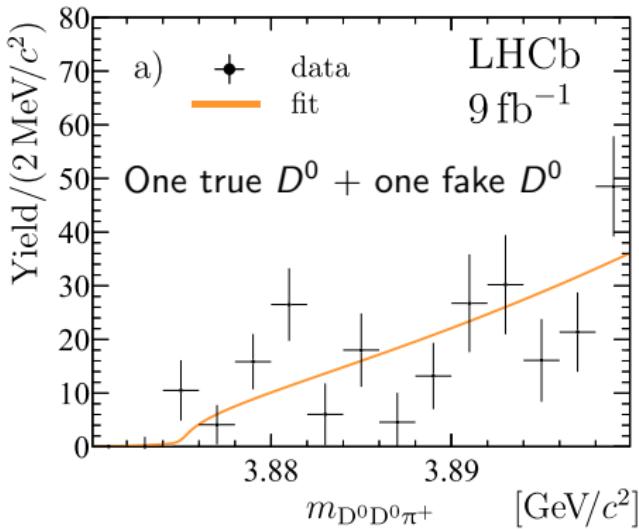
Complex plane



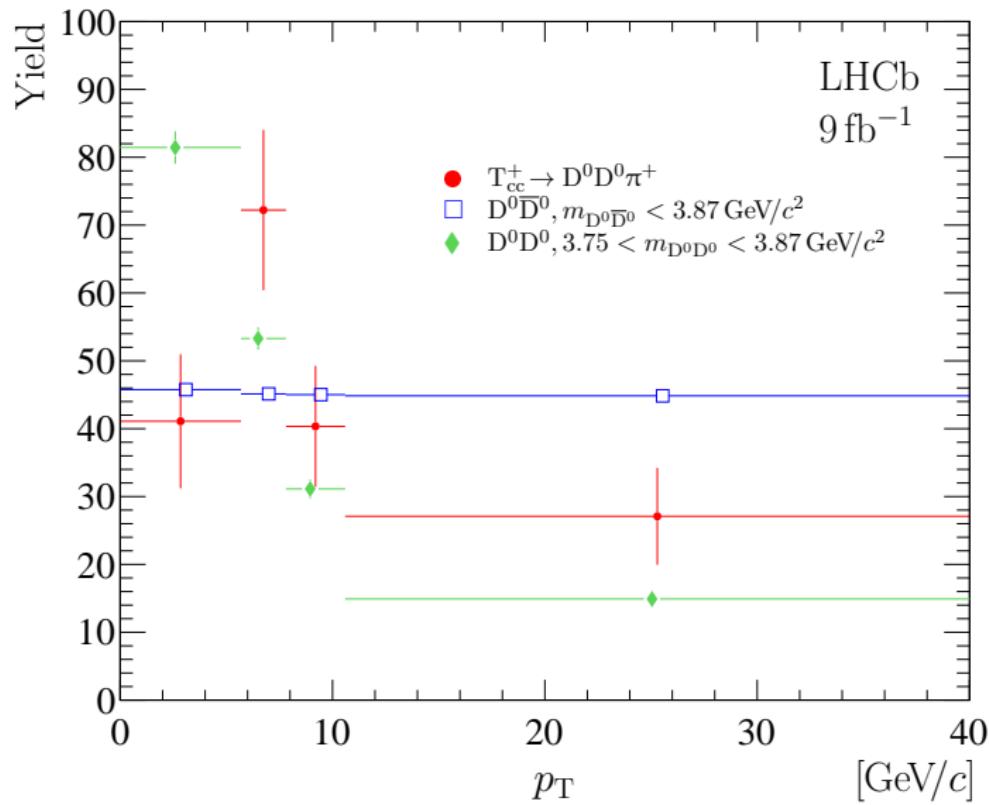
- The D^* width gives the limit to T_{cc}^+ width, $< \Gamma_{T_{cc}^+}^{(\max)}$
- Parameter $|g|$ sets the value in the range $[0, \Gamma_{T_{cc}^+}^{(\max)}]$
- The fit prefers the limit value

Cross-checks

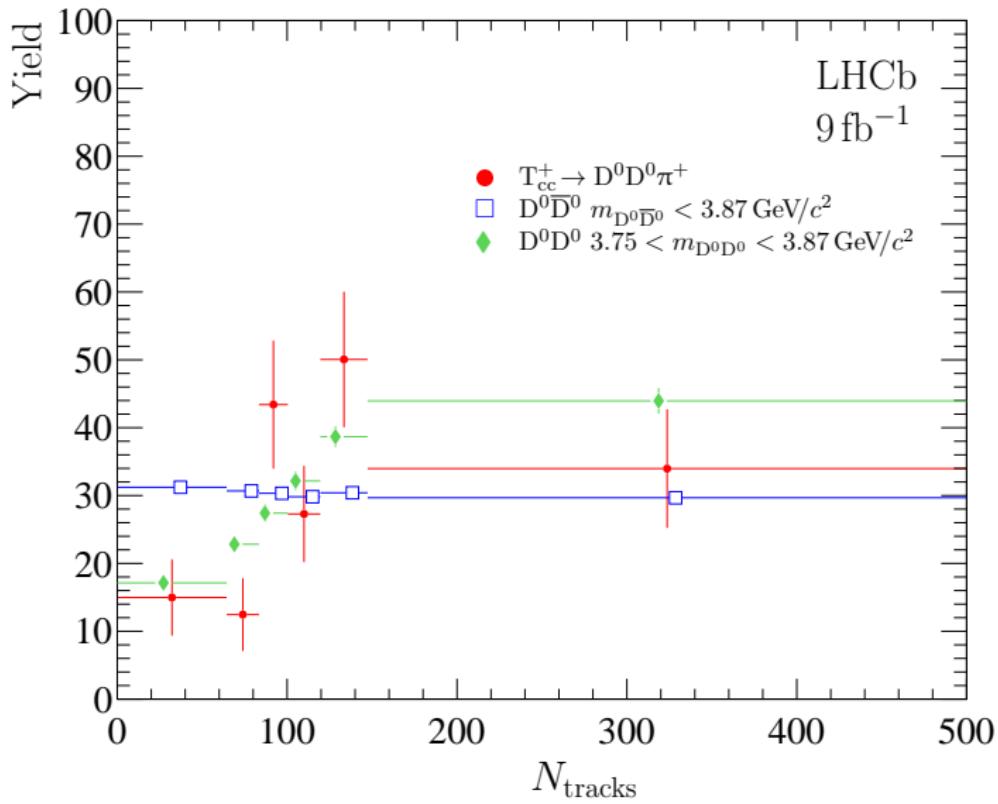
- Different years (2011-2018)
- Different data-taking conditions (magnet polarity)
- No signal when using fake D^0



p_t spectrum for T_{cc}^+



Multiplicity dependence of T_{cc}^+ yield



Surprisingly similar to uncorrelated $D^0 D^0$ production (DPS)

Observation of T_{cb}^0 , T_{bb}^-

Based on Steve Blusk estimation [Tcc & beyond workshop]

$$N_{\text{signal}} = \overbrace{\mathcal{L}}^{\text{luminosity}} \times \underbrace{\sigma_{\text{prod}}}_{\text{cross section}} \times \overbrace{\text{Br}}^{T_{QQ} \rightarrow B(D)B(D)} \times \prod_{B/D \text{ decays}} \underbrace{\text{Br}}_{\text{B/D decays}} \times \overbrace{\varepsilon}^{\text{efficiency}}$$

Observation of T_{cb}^0 , T_{bb}^-

Based on Steve Blusk estimation [Tcc & beyond workshop]

$$N_{\text{signal}} = \overbrace{\mathcal{L}}^{\text{luminosity}} \times \underbrace{\sigma_{\text{prod}}}_{\text{cross section}} \times \overbrace{\text{Br}}^{T_{QQ} \rightarrow B(D)B(D)} \times \prod_{B/D \text{ decays}} \underbrace{\text{Br}}_{B/D \text{ decays}} \times \overbrace{\epsilon}^{\text{efficiency}}$$

$$\begin{aligned}\varepsilon(D^+) \varepsilon(D^{*+}) &\approx 0.08 \\ \varepsilon(D^0 \rightarrow K^- \pi^+) &\approx 0.17\end{aligned}$$

$$\epsilon(B^-) \approx 0.1$$

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Observing T_{cb}^0

- Cross-section: $\sigma \approx 100 \text{ nb}$
[Ali et al., PLB785 (2018) 605]
- Rough expectations with 50 fb^{-1} (by 2030):
 - ▶ Strong decay

$$N_{\text{signal}}(T_{cb}^0 \rightarrow B^- D^+) \sim 300$$

- ▶ Weak decay

$$N_{\text{signal}}(T_{cb}^0 \rightarrow J/\psi D^+ K^-) \sim 7k$$

Observing T_{bb}^-

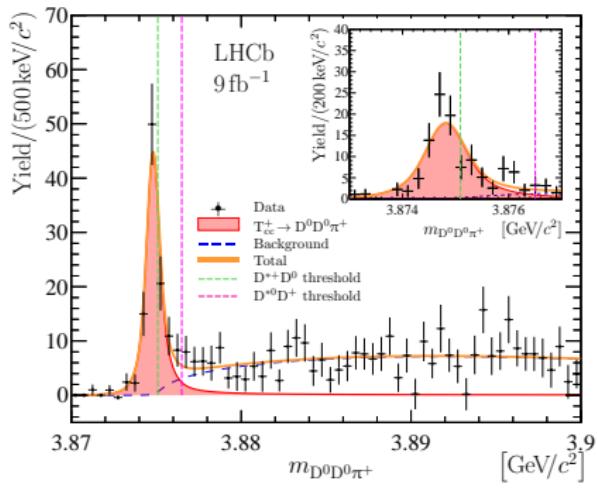
- Cross-section: $\sigma \approx 1 \text{ nb}$
- lifetime: $\tau \approx 0.6 \text{ ps} - 7.6 \text{ ps}$
[Agaev et al., EPJA 56, 177 (2020)]
[Hernandez et al., PLB800, 135073 (2020)]
- Rough expectations with 50 fb^{-1} (by 2030):
 - ▶ Weak decay

$$N_{\text{signal}}(T_{bb}^- \rightarrow B_c^- D^+ K^-) \sim 0.2$$

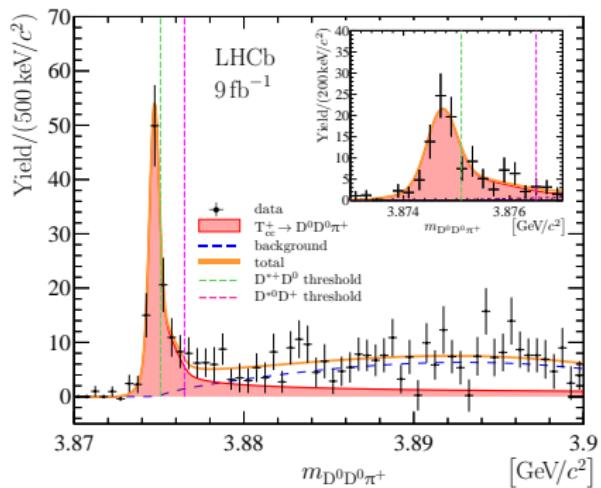
Two models

Naive model is of similar quality but yeilds incorrect parameters

Naive model ($\Gamma_{\text{BW}} = 410 \pm 165 \text{ MeV}$)



Complete model
($\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14} \text{ MeV}$)



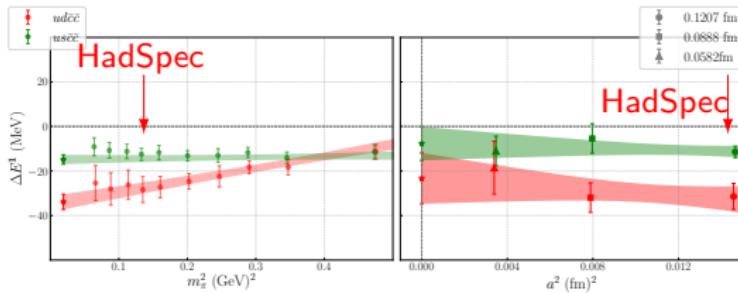
The reason: background and resolution. Confirmed by MC studies.

Lattice QCD

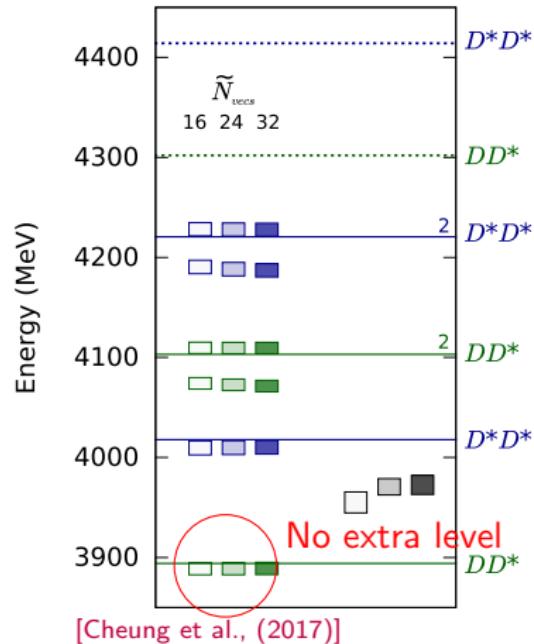
First-principles theoretical (numerical) approach to QCD.

Several calculations are done. The situation is puzzling

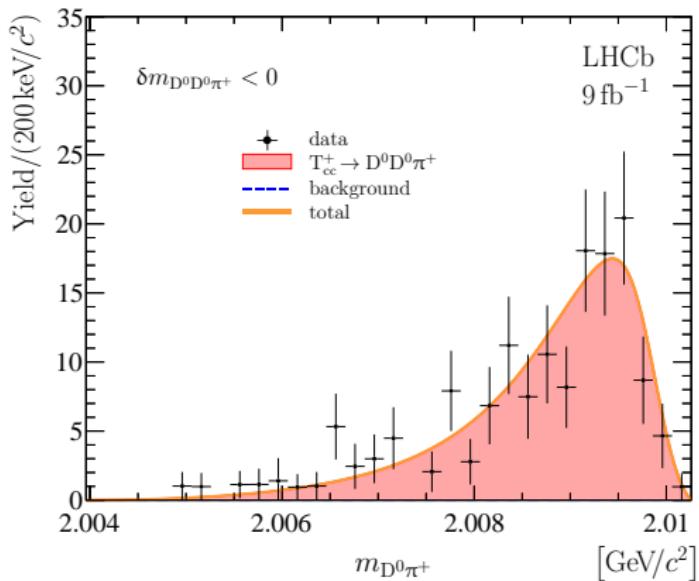
- HAL QCD Collaboration (2014):
attraction but **no binding**
- Hadron Spectrum Collaboration (2017):
no binding
- Junnarkar et al. (2018):
 -23 ± 11 MeV **binding**



[Junnarkar et al. (2018)]



Does T_{cc}^+ decay via off-shell D^* ?



- Peak at high mass requires D^* propagator
- P -wave behavior on the left limit
- S -wave behavior on the right limit