Effective theories and dark matter

RICHARD HILL

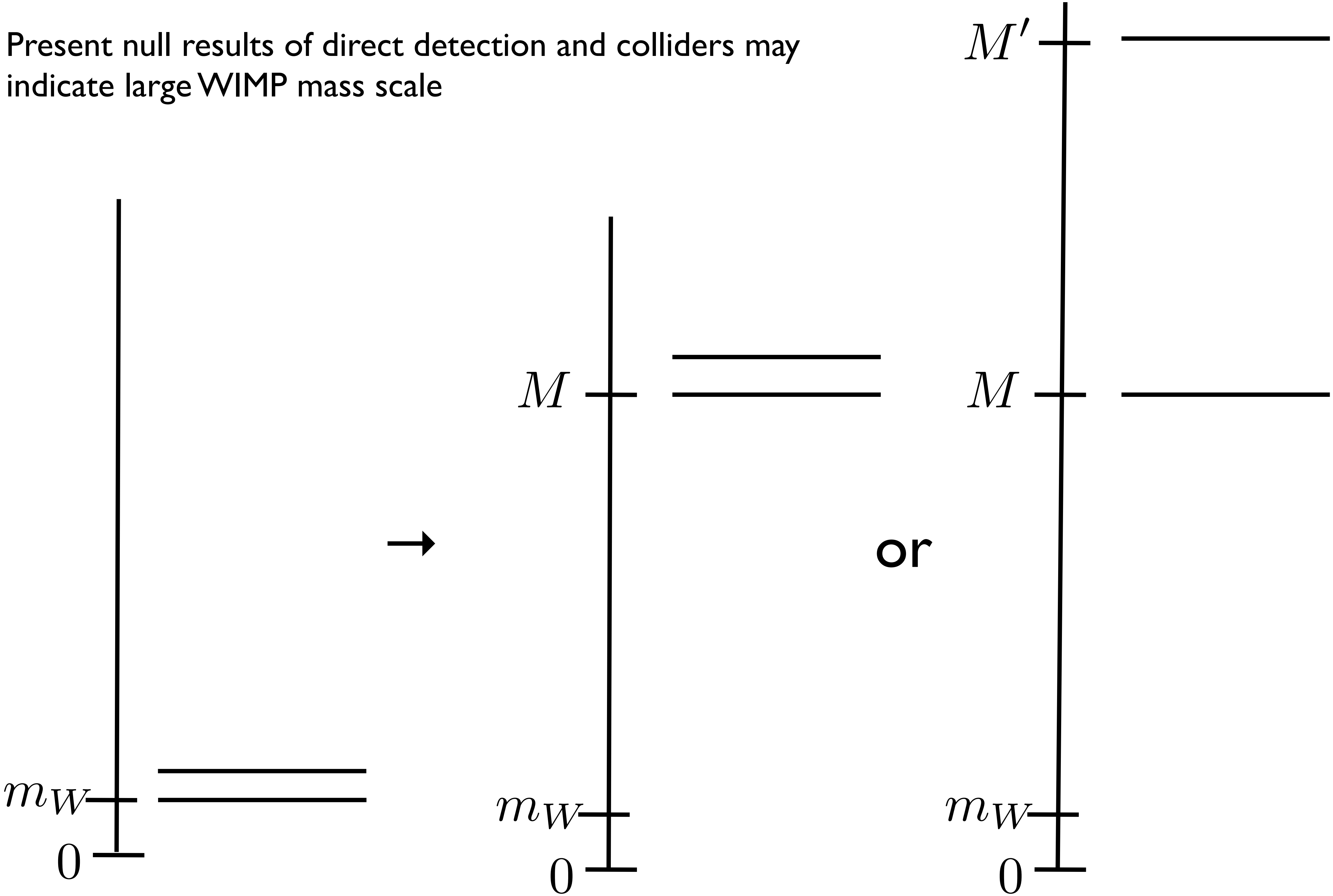
THE UNIVERSITY OF CHICAGO

SUSY 2014
Manchester

25 July 2014

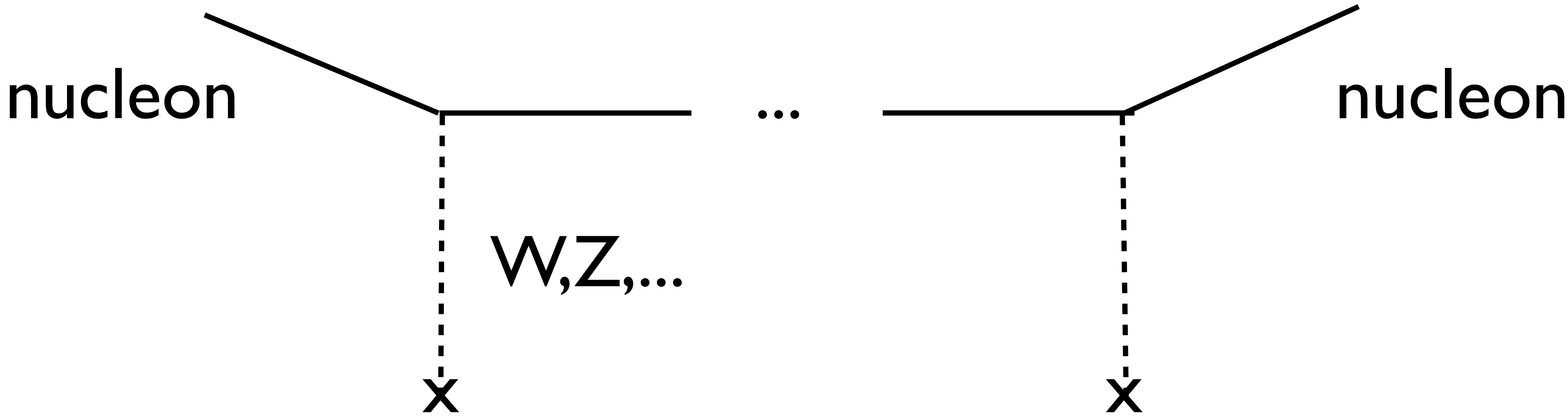
based on work with M. Solon, 1111.0016, 1309.4092(PRL), 1401.3339, and work to appear

Present null results of direct detection and colliders may indicate large WIMP mass scale



If WIMP mass M >> m_W , isolation (M'-M >> m_W) becomes generic.   Expand in m_W/M, m_W/(M'-M)

This regime is a focus of future experiments in direct, indirect and collider probes



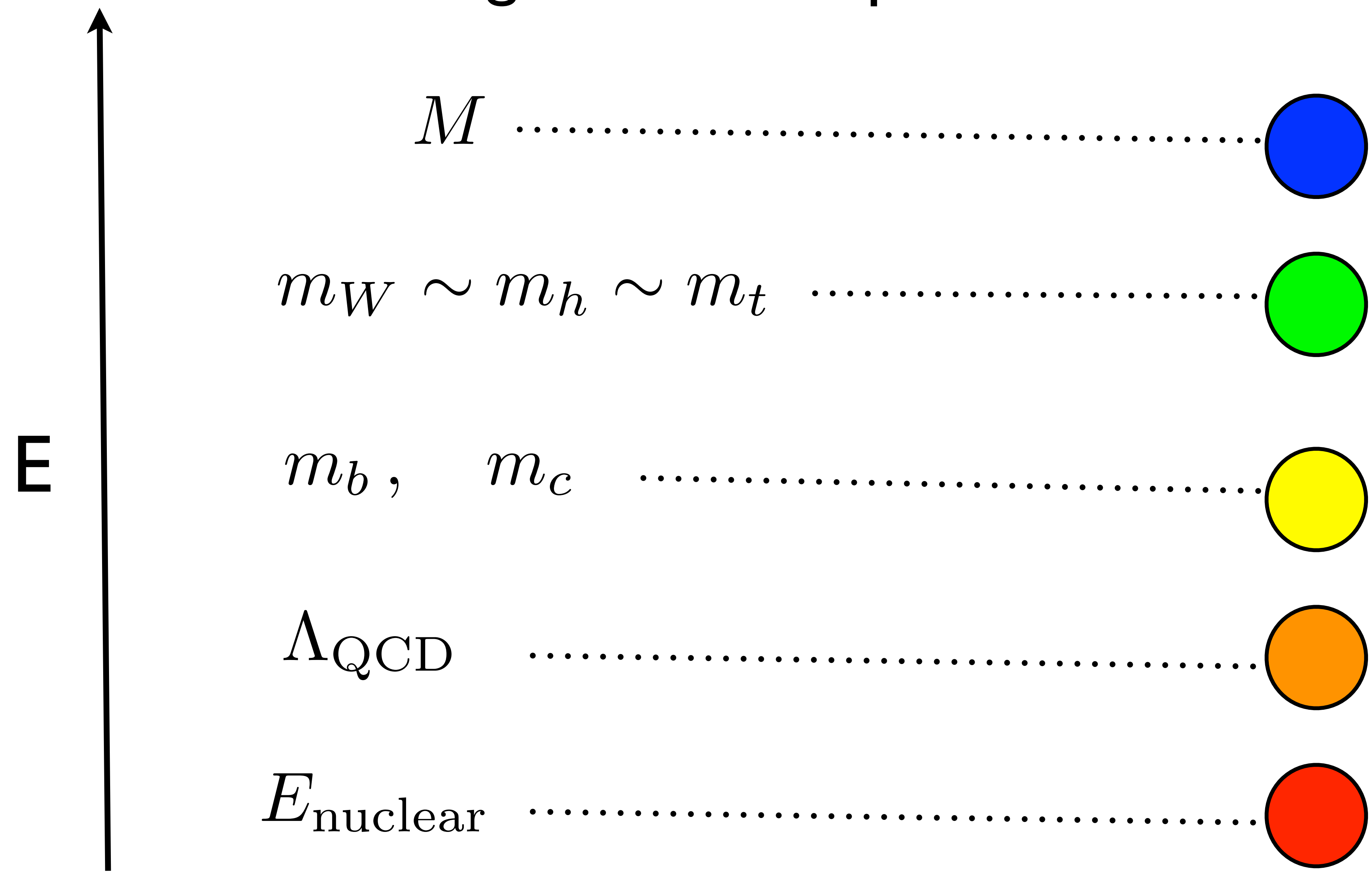
basic problem in SM physics: scattering of nucleon from SU(2)xU(1) source

- discovery of SM-like higgs boson + necessary hadronic matrix elements: complete answer to this problem in principle, but a loop-mediated, multi-scale problem

- $M_{WIMP} >> m_W$: WIMP phenomenology highly constrained and universal (analog of heavy quark spin-flavor symmetries). Interesting features, e.g., heavy WIMP "transparency" to nucleon scattering

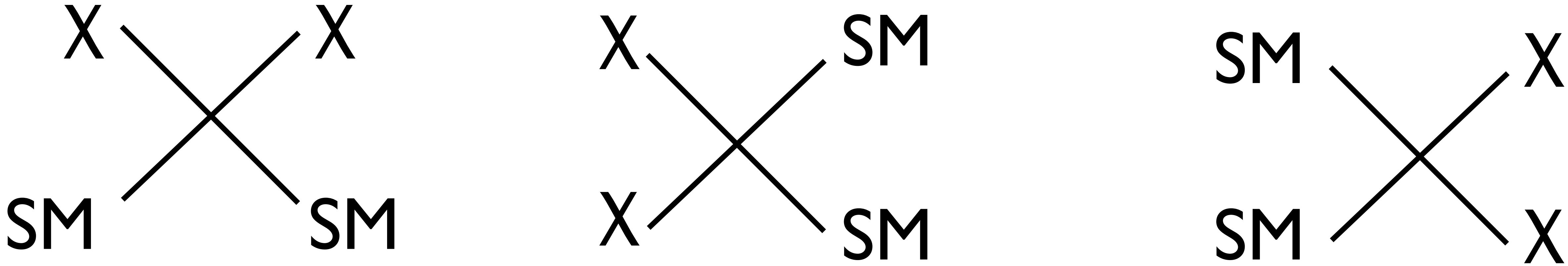
- complications in addition to QED/QCD analogs: EWSB, and SU(3)xSU(2)xU(1) vs. U(1) or SU(3)

DM-nucleus scattering: multi-scale problem



Standard model anatomy well studied in quark flavor and EDM problems. *[cf. morning talks of Buras, Lee]*

Dark matter still in a relatively nascent stage. Naively subleading corrections can have large effects, e.g. determining observability of motivated candidates.



HQET   HQET, NRQCD, SCET

Very active field. Focus here on physics of direct detection above nuclear scale. Other applications of effective theories:

- Derivative suppressed single nucleon operators and nuclear responses. *Lorentz invariance constraints*
- Collider production via contact interactions and extensions. *Relate constraints in high scale theory (n_f=5 or 6) to low scale theory (n_f=3 or 4) where direct detection and other observables are evaluated*
- Annihilation, indirect detection. *Large logs from SCET and consistent merging with nonperturbative enhancments*
- ...

[work with M. Bauer, T. Cohen and M. Solon (not this talk)]

[cf. Thurs. talk of Hellmann]

SM + X

- consider one or two SU(2)xU(1) multiplets

- expand in $m_W/(m_{X'}-m_X)$

- convergence may be good (cf. Λ/m_b) or less good (cf. Λ/m_c), but a powerful handle on unknown dynamics

M ....

$m_W \sim m_h \sim m_t$ ....

$m_b\,,\quad m_c$ ....

$\Lambda_{\rm QCD}$ ....

$E_{\rm nuclear}$ ....

- hydrogen spectroscopy

$$E_n(H) = -\frac{1}{2} m_e (Z\alpha)^2 + \dots \qquad (m_e Z\alpha) \ll m_e$$

- heavy meson transitions

$$F^{B\to D}(v'=v) = 1 + \dots \qquad \Lambda_{\rm QCD} \ll m_{b,c}$$

- DM interactions

$$\sigma(\chi N \to \chi N) = ? \qquad m_W \ll m_\chi$$

Setup

$$\psi = \begin{pmatrix} Q \\ \bar{u} \\ \bar{d} \\ L \\ \bar{e} \end{pmatrix}$$

	$SU(3)$	$SU(2)$	$U(1)$
Q	3	2	$1/6$
$\bar{u}$	$\bar{3}$	1	$-2/3$
$\bar{d}$	$\bar{3}$	1	$1/3$
L	1	2	$-1/2$
$\bar{e}$	1	1	1
H	1	2	$\frac{1}{2}$
e.g. X	1	0	0
X	1	3	0
X	1	2	1/2

- consider 1 or 2 multiplets, lightest neutral component stabilized by Z_2 symmetry (e.g., R parity, G parity)

$$\mathcal{L} = \bar{h}\Big[iv\cdot\partial + eQv\cdot A + \frac{g_2}{c_W}v\cdot Z(T^3 - s_W^2 Q) + \frac{g_2}{\sqrt{2}}(v\cdot W^+T^+ + v\cdot W^-T^-) - \delta M(v_{\rm wk}) - f(\phi)\Big]h + \mathcal{O}(1/M)$$

Low energy theory

Operator basis

$$\mathcal{L} = \mathcal{L}_{\phi_0} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\phi_0,\rm SM} + \dots \,,$$

Heavy neutral scalar:

$$\mathcal{L}_{\phi_0} = \phi^*_{v,Q=0}\left\{ iv\cdot\partial - \frac{\partial_\perp^2}{2M_{(Q=0)}} + \mathcal{O}(1/m_W^3) \right\}\phi_{v,Q=0}$$

c_D=0 (reality constraint)

SM interactions:

$$\mathcal{L}_{\phi_0,\rm SM} = \frac{1}{m_W^3}\phi_v^*\phi_v\left\{ \sum_q \left[c_{1q}^{(0)} O_{1q}^{(0)} + c_{1q}^{(2)} v_\mu v_\nu O_{1q}^{(2)\mu\nu}\right] + c_2^{(0)} O_2^{(0)} + c_2^{(2)} v_\mu v_\nu O_2^{(2)\mu\nu} \right\} + \dots$$

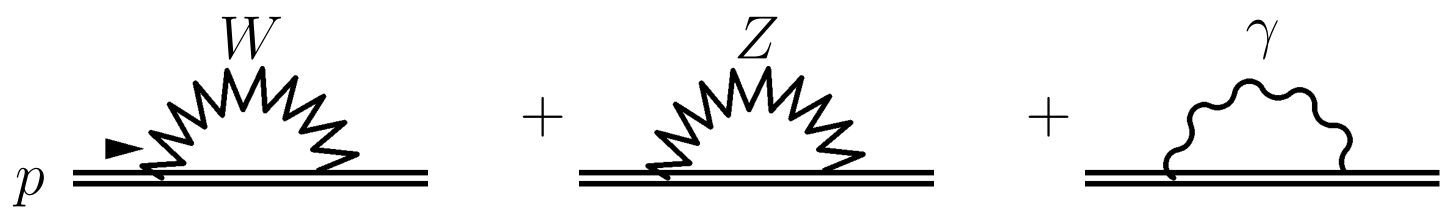
Convenient to choose basis of definite spin

$$O_{1q}^{(0)} = m_q \bar{q} q \,, \qquad O_2^{(0)} = (G^A_{\mu\nu})^2 \,,$$

$$O_{1q}^{(2)\mu\nu} = \bar{q}\left(\gamma^{\{\mu} iD^{\nu\}} - \frac{1}{d} g^{\mu\nu} i\not{D} \right) q \,, \qquad O_2^{(2)\mu\nu} = -G^{A\mu\lambda}G^{A\nu}{}_\lambda + \frac{1}{d} g^{\mu\nu}(G^A_{\alpha\beta})^2 \,.$$

Universal mass shift induced by EWSB

$-i\Sigma(p) =$



$+ \dots .$

$$-i\Sigma_2(v\cdot p) = -g_2^2 \int \frac{d^dL}{(2\pi)^L}\frac{1}{v\cdot(L+p)}\left[J^2\frac{1}{L^2-m_W^2} + J_3^2\left(\frac{c_W^2}{L^2-m_Z^2} - \frac{1}{L^2-m_W^2} + \frac{s_W^2}{L^2}\right)\right] + \mathcal{O}(1/M)$$

heavy particle Feynman rules

$$\delta M = \Sigma(v\cdot p = 0) = \alpha_2 m_W \left[-\frac{1}{2}J^2 + \sin^2\frac{\theta_W}{2}J_3^2\right]$$

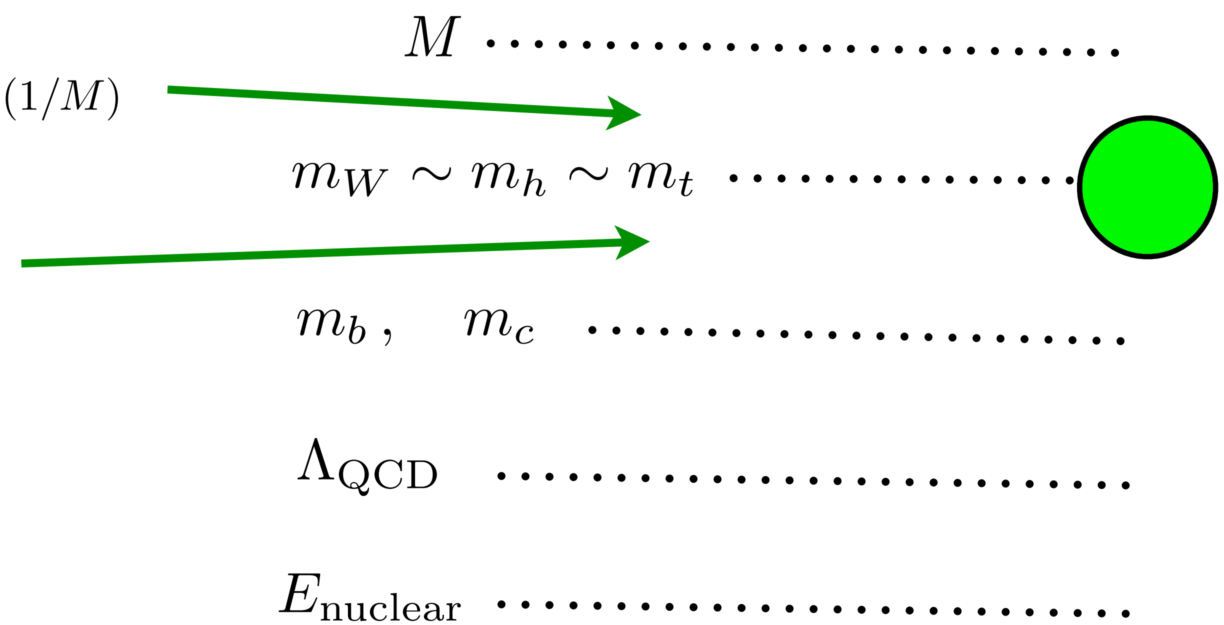
$$M_{(Q)} - M_{(Q=0)} = \alpha_2 Q^2 m_W \sin^2\frac{\theta_W}{2} + \mathcal{O}(1/M) \approx (170\,\mathrm{MeV})Q^2$$

Different pole masses for each charge eigenstate in low-energy theory (residual mass terms)

Matching (μ≈mw)

$$\mathcal{L} - \mathcal{L}_{\rm SM} \to \bar{h}(iv\cdot\partial - \delta M + g_2 t^a v\cdot W^a + g_1 Y v\cdot B - f(H))h + \mathcal{O}(1/M)$$

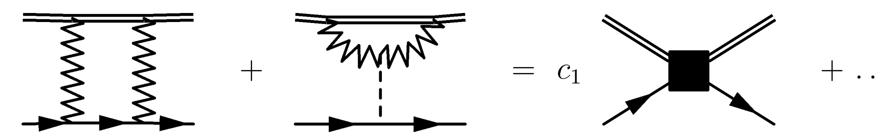
$$\mathcal{L}_{\rm WIMP-SM} = \bar{h}_v h_v \Big\{ \sum_{q=u,d,s,c,b} \Big[c_{1q}^{(0)} O_{1q}^{(0)} + c_{1q}^{(2)} v_\mu v_\nu O_{1q}^{(2)\mu\nu} \Big] + c_2^{(0)} O_2^{(0)} + c_2^{(2)} v_\mu v_\nu O_2^{(2)\mu\nu} \Big\} + \dots ,$$



quark operators

$$c_{1U}^{(0)}(\mu_t) = \mathcal{C}\left[-\frac{1}{x_h^2}\right]\,, \qquad c_{1D}^{(0)}(\mu_t) = \mathcal{C}\left[-\frac{1}{x_h^2} - |V_{tD}|^2 \frac{x_t}{4(1+x_t)^3}\right]\,,$$

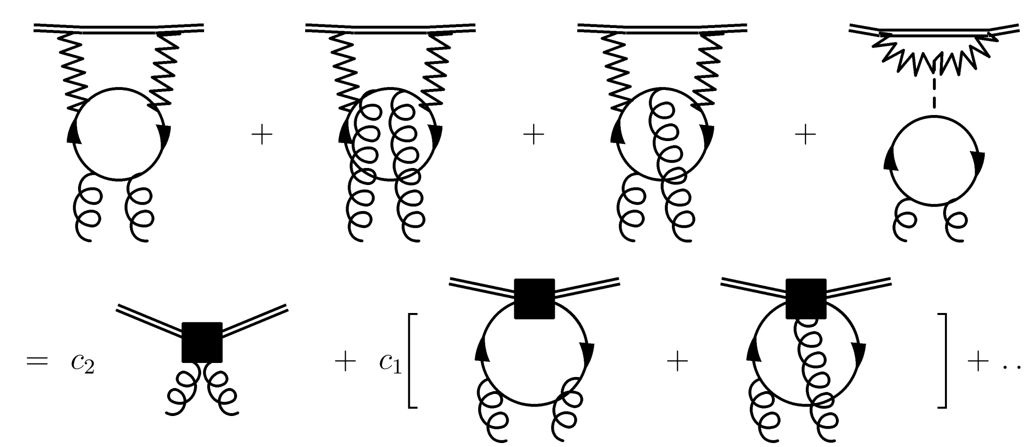
$$c_{1U}^{(2)}(\mu_t) = \mathcal{C}\left[\frac{2}{3}\right]\,, \qquad c_{1D}^{(2)}(\mu_t) = \mathcal{C}\left[\frac{2}{3} - |V_{tD}|^2 \frac{x_t(3+6x_t+2x_t^2)}{3(1+x_t)^3}\right]\,,$$



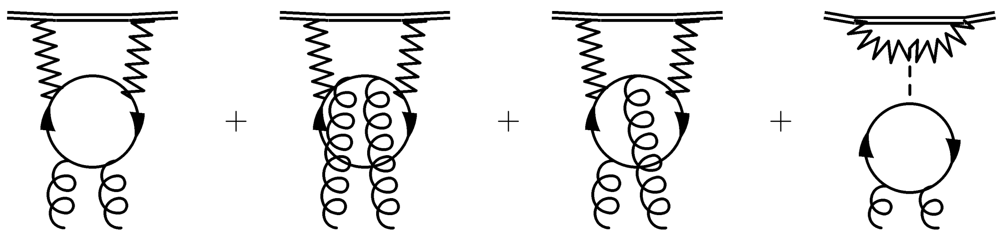
gluon operators

$$c_2^{(0)}(\mu_t) = \mathcal{C}\frac{\alpha_s(\mu_t)}{4\pi}\left[\frac{1}{3x_h^2} + \frac{3+4x_t+2x_t^2}{6(1+x_t)^2}\right]\,,$$

$$\begin{aligned} c_2^{(2)}(\mu_t) = \mathcal{C}\frac{\alpha_s(\mu_t)}{4\pi}\Bigg[& -\frac{32}{9}\log\frac{\mu_t}{m_W} - 4 - \frac{4(2+3x_t)}{9(1+x_t)^3}\log\frac{\mu_t}{m_W(1+x_t)} \\ & - \frac{4(12x_t^5 - 36x_t^4 + 36x_t^3 - 12x_t^2 + 3x_t - 2)}{9(x_t-1)^3}\log\frac{x_t}{1+x_t} - \frac{8x_t(-3+7x_t^2)}{9(x_t^2-1)^3}\log 2 \\ & - \frac{48x_t^6 + 24x_t^5 - 104x_t^4 - 35x_t^3 + 20x_t^2 + 13x_t + 18}{9(x_t^2-1)^2(1+x_t)}\Bigg]\,. \end{aligned}$$



E.g. full theory:



$$iM = -g_2^2 \int (dL) \left[\frac{1}{-v\cdot L + i0} + \frac{1}{v\cdot L + i0} \right] \frac{1}{(L^2 - m_W^2 + i0)^2} v_\mu v_\nu \Pi^{\mu\nu}(L)$$

electroweak polarizability tensor
in background gluon field

Electroweak gauge invariance is immediate:

$$v^\mu \left[g_{\mu\mu'} - (1-\xi)\frac{L_\mu L_{\mu'}}{L^2 - \xi m_W^2} \right] = v_{\mu'} + \mathcal{O}(v\cdot L)$$

crossed and uncrossed diagrams cancel

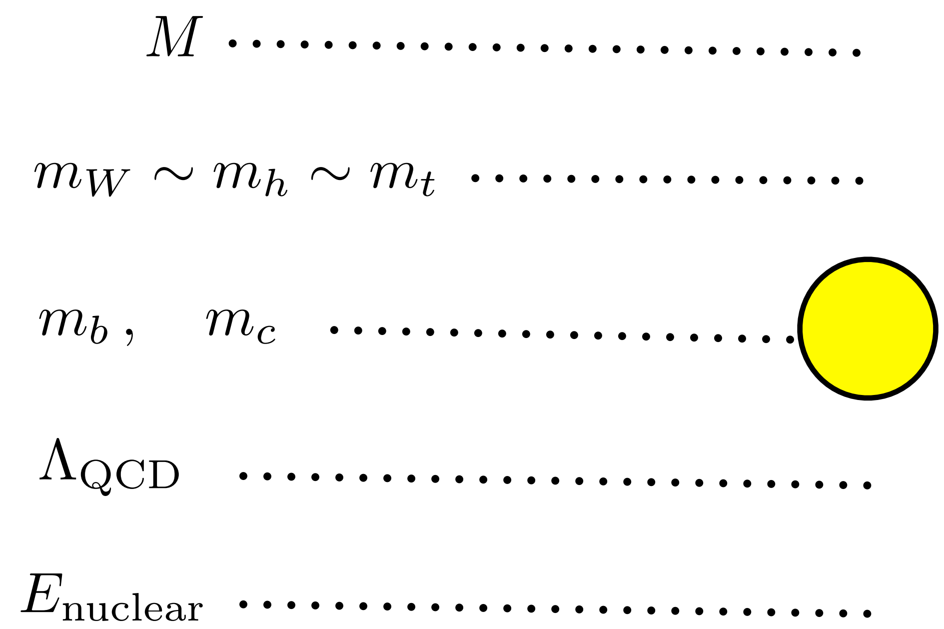
Background gluon and Fock-Schwinger gauge (x.A=0):

$$A\!\!\!/(q) = t^a \gamma^\alpha \left[\frac{-i}{2} \frac{\partial}{\partial q_\rho} G^a_{\rho\alpha}(0)(2\pi)^d \delta^d(q) + \dots \right]$$

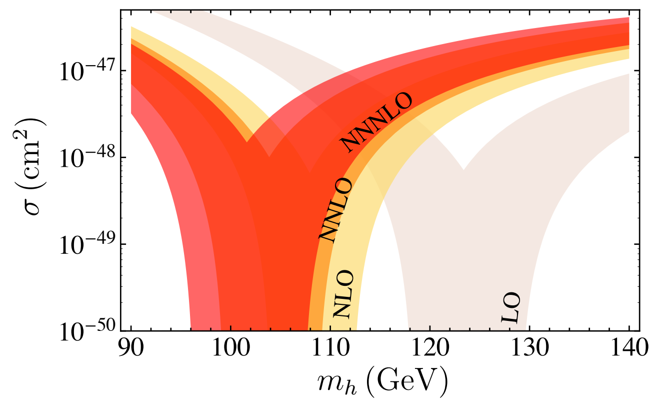
$$iS(p) = \frac{i}{p\!\!\!/ - m} + g\int (dq) \frac{i}{p\!\!\!/ - m} iA\!\!\!/(q) \frac{i}{p\!\!\!/ - q\!\!\!/ - m}$$

$$+ g^2 \int (dq_1)(dq_2) \frac{i}{p\!\!\!/ - m} iA\!\!\!/(q_1) \frac{i}{p\!\!\!/ - q\!\!\!/_1 - m} iA\!\!\!/(q_2) \frac{i}{p\!\!\!/ - q\!\!\!/_1 - q\!\!\!/_2 - m} + \dots$$

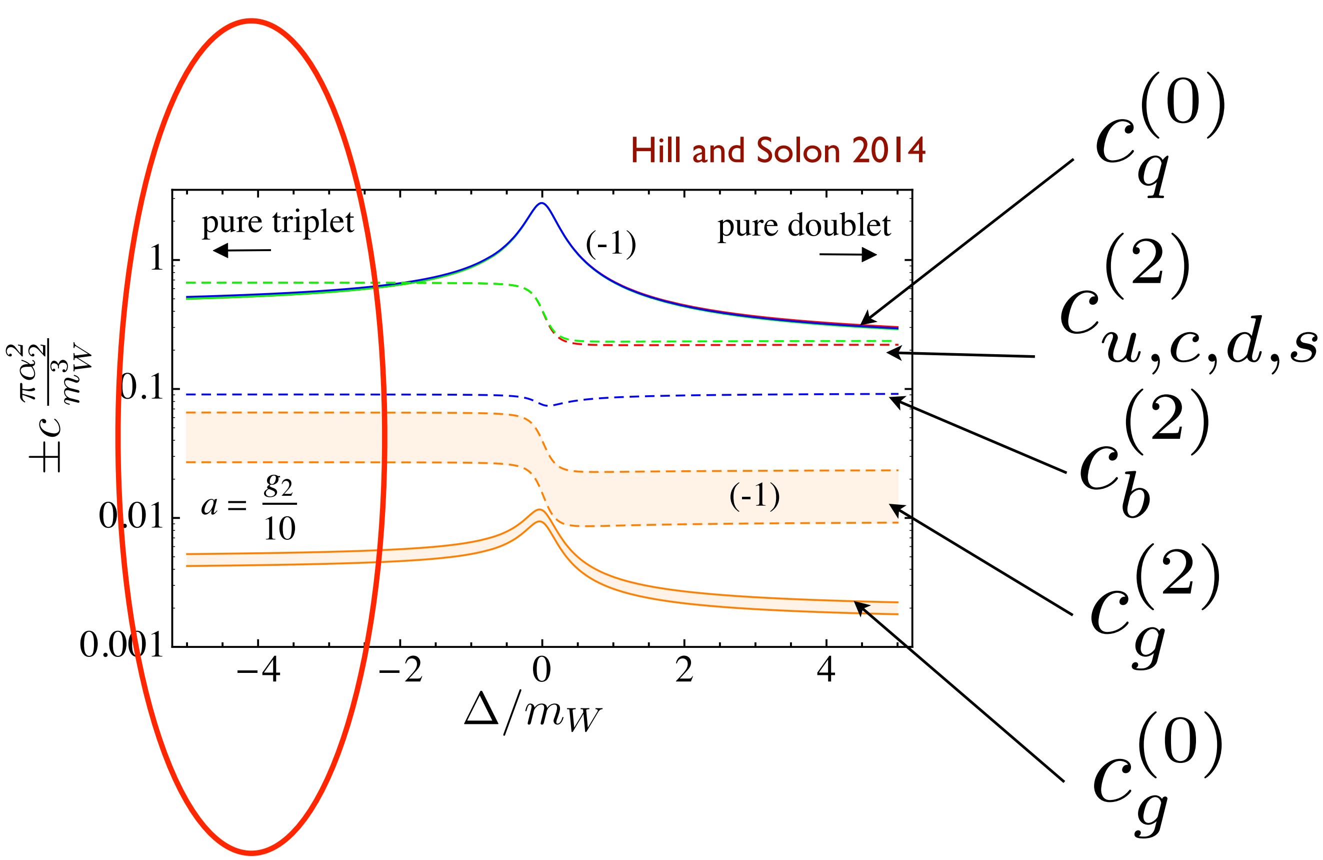
QCD evolution and threshold matching

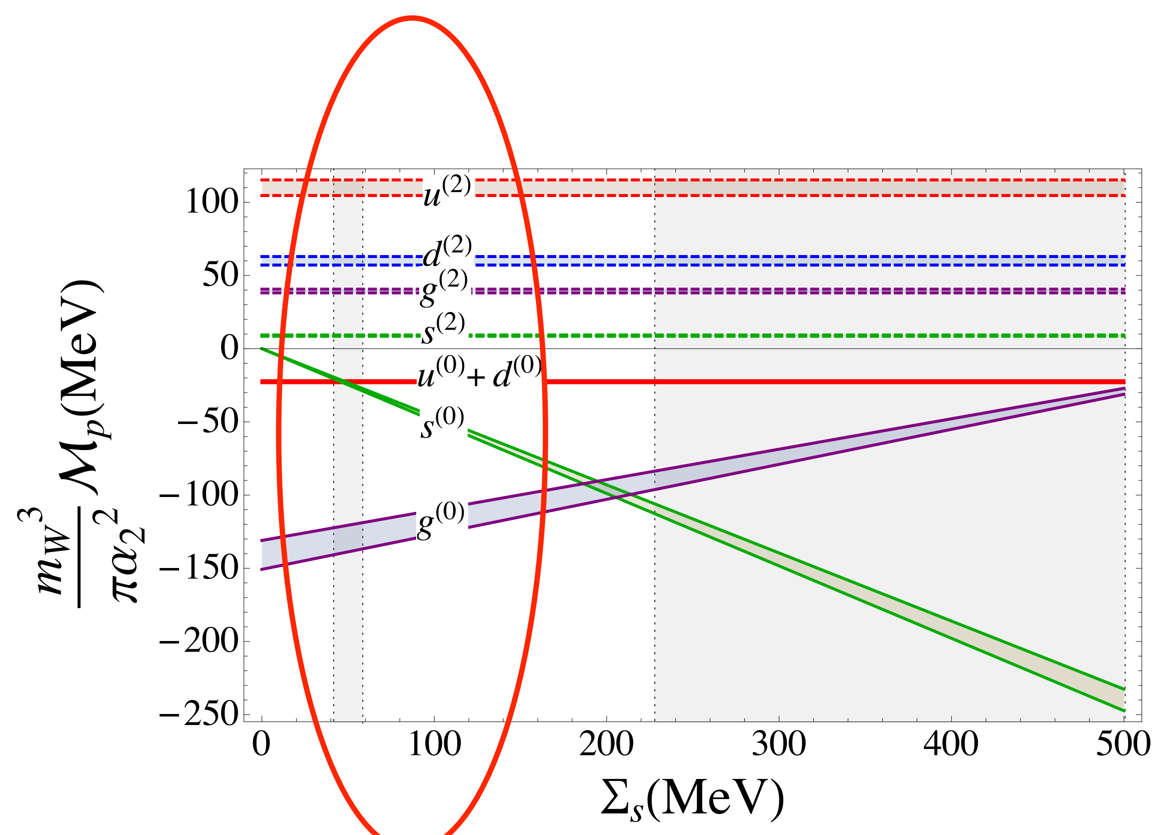


- large effects of QCD renormalization and threshold matching



- nontrivial mapping from high-scale coefficients to hadronic amplitudes





Solution to RG equations

$$O_{1q}^{(0)} = m_q \bar{q} q \,, \qquad O_2^{(0)} = (G^A_{\mu\nu})^2 \,,$$

$$O_{1q}^{(2)\mu\nu} = \bar{q}\left(\gamma^{\{\mu} iD^{\nu\}} - \frac{1}{d} g^{\mu\nu} i\not{D}\right) q \,, \qquad O_2^{(2)\mu\nu} = -G^{A\mu\lambda} G^{A\nu}{}_{\lambda} + \frac{1}{d} g^{\mu\nu} (G^A_{\alpha\beta})^2$$

$$\frac{d}{d\log\mu} O_i^{(S)} = -\sum_j \gamma_{ij}^{(S)} O_j \qquad \frac{d}{d\log\mu} c_i^{(S)} = \sum_j \gamma_{ji}^{(S)} c_j^{(S)}$$

Spin 0:

$$c_2^{(0)}(\mu) = c_2^{(0)}(\mu_t) \frac{\frac{\beta}{g}[\alpha_s(\mu)]}{\frac{\beta}{g}[\alpha_s(\mu_t)]}$$

$$\hat{\gamma}^{(0)} = \left(\begin{array}{ccc|c} 0 & & & 0 \\ & \ddots & & \vdots \\ & & 0 & 0 \\ \hline -2\gamma_m' & \cdots & -2\gamma_m' & (\beta/g)' \end{array}\right)$$

$$c_1^{(0)}(\mu) = c_1^{(0)}(\mu_t) - 2[\gamma_m(\mu) - \gamma_m(\mu_t)] \frac{c_2^{(0)}(\mu_t)}{\frac{\beta}{g}[\alpha_s(\mu_t)]}$$

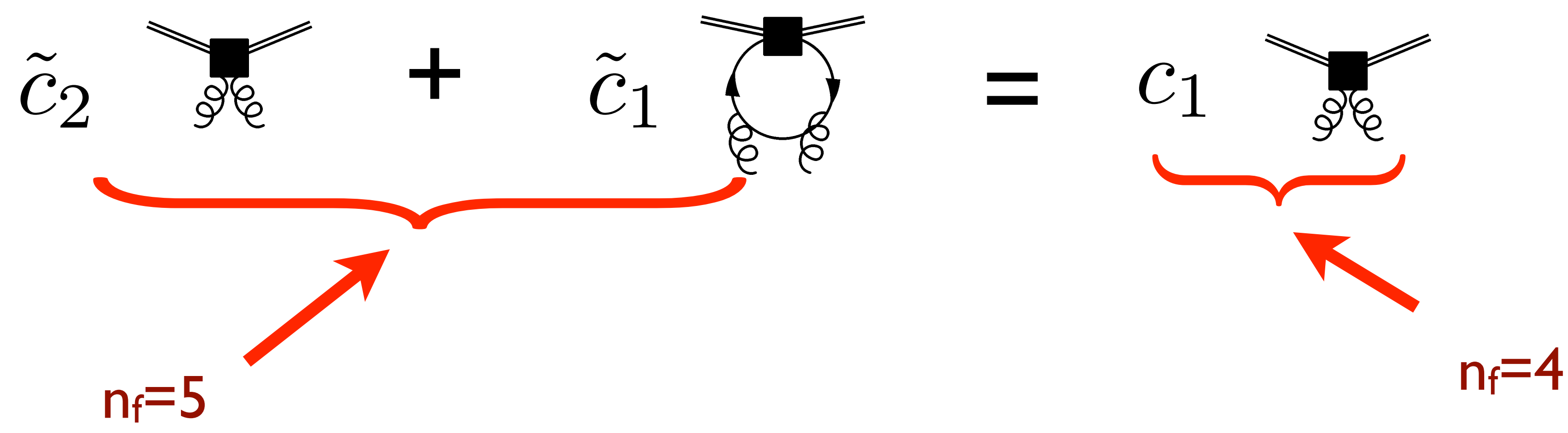
Spin 2:

Diagonalize anomalous dimension matrix
(familiar from PDF analysis)

$$\hat{\gamma}^{(2)} = \frac{\alpha_s}{4\pi} \left(\begin{array}{ccc|c} \frac{64}{9} & & & -\frac{4}{3} \\ & \ddots & & \vdots \\ & & \frac{64}{9} & -\frac{4}{3} \\ \hline -\frac{64}{9} & \cdots & -\frac{64}{9} & \frac{4n_f}{3} \end{array}\right) + \ldots$$

As check, can evaluated spin-2 matrix elements at high scale (spin-0 and spin-2 decoupled)

Integrate out heavy quarks



$$c_2^{(0)}(\mu_b) = \tilde{c}_2^{(0)}(\mu_b)\left(1 + \frac{4\tilde{a}}{3}\log\frac{m_b}{\mu_b}\right) - \frac{\tilde{a}}{3}\tilde{c}_{1b}^{(0)}(\mu_b)\left[1 + \tilde{a}\left(11 + \frac{4}{3}\log\frac{m_b}{\mu_b}\right)\right] + \mathcal{O}(\tilde{a}^3)$$

$$c_{1q}^{(0)}(\mu_b) = \tilde{c}_{1q}^{(0)}(\mu_b) + \mathcal{O}(\tilde{a}^2),$$

$$c_2^{(2)}(\mu_b) = \tilde{c}_2^{(2)}(\mu_b) - \frac{4\tilde{a}}{3}\log\frac{m_b}{\mu_b}\tilde{c}_{1b}^{(2)}(\mu_b) + \mathcal{O}(\tilde{a}^2),$$

$$c_{1q}^{(2)}(\mu_b) = \tilde{c}_{1q}^{(2)}(\mu_b) + \mathcal{O}(\tilde{a}),$$

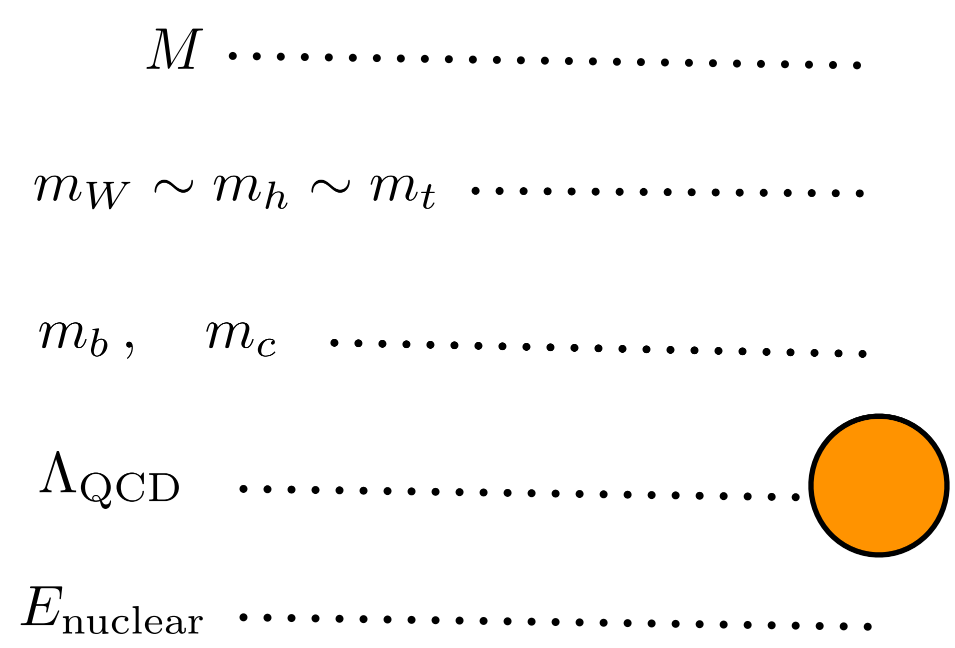
Contribution to gluon operators familiar from h→gg

Heavy quark mass scheme enters at higher order

Charm quark treated similarly (after running to m_c)

Nucleon matrix elements

- having evolved to 3-flavor QCD, appeal to lattice QCD or SU(3) chiral perturbation theory for matrix elements



$$m_N = (1-\gamma_m)\sum_q \langle N|m_q\bar{q}q|N\rangle + \frac{\beta}{2g}\langle N|(G^a_{\mu\nu})^2|N\rangle$$

$$\Sigma_{\pi N} = \frac{m_u+m_d}{2}\langle p|(\bar{u}u+\bar{d}d)|p\rangle \qquad \Sigma_0 = \frac{m_u+m_d}{2}\langle p|(\bar{u}u+\bar{d}d-2\bar{s}s)|p\rangle$$

$$m_N(f^{(0)}_{u,N}+f^{(0)}_{d,N}) \approx \Sigma_{\pi N} \qquad m_N f^{(0)}_{s,N} = \frac{m_s}{m_u+m_d}(\Sigma_{\pi N}-\Sigma_0) = \Sigma_s$$

$$\langle N|O^{(2)\mu\nu}_{1q}(\mu)|N\rangle \equiv \frac{1}{m_N}\left(k^\mu k^\nu - \frac{g^{\mu\nu}}{4}m_N^2\right) f^{(2)}_{q,N}(\mu)$$

$$\langle N|O^{(2)\mu\nu}_{2}(\mu)|N\rangle \equiv \frac{1}{m_N}\left(k^\mu k^\nu - \frac{g^{\mu\nu}}{4}m_N^2\right) f^{(2)}_{G,N}(\mu)$$

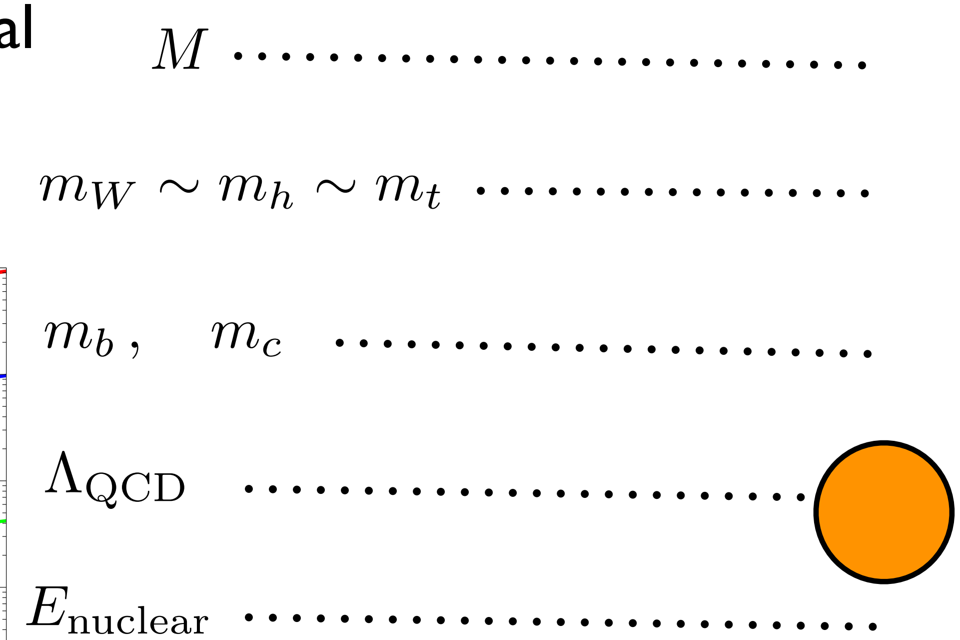
$$f^{(2)}_{q,p}(\mu) = \int_0^1 dx\, x[q(x,\mu)+\bar{q}(x,\mu)]$$

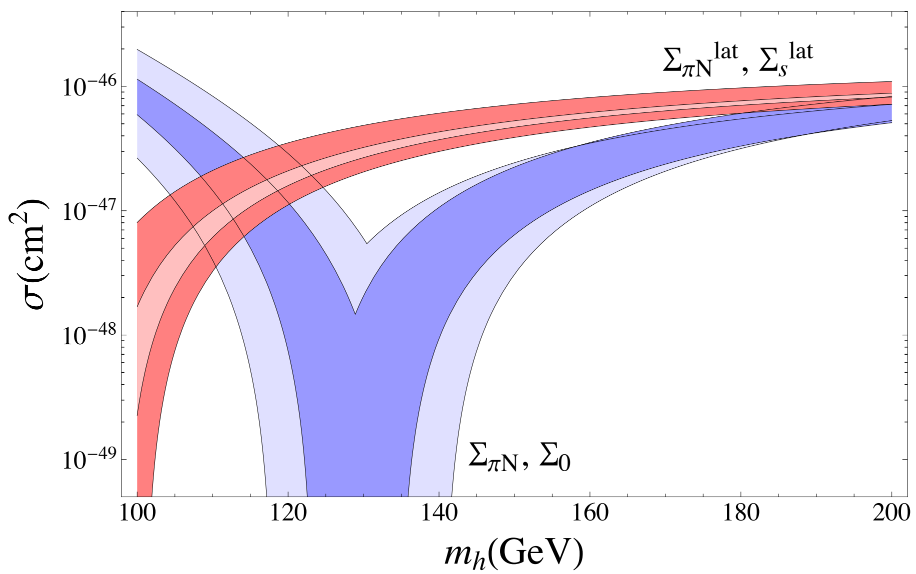
μ(GeV)	$f^{(2)}_{u,p}(\mu)$	$f^{(2)}_{d,p}(\mu)$	$f^{(2)}_{s,p}(\mu)$	$f^{(2)}_{G,p}(\mu)$
1.0	0.404(6)	0.217(4)	0.024(3)	0.36(1)
1.2	0.383(6)	0.208(4)	0.027(2)	0.38(1)
1.4	0.370(5)	0.202(4)	0.030(2)	0.40(1)

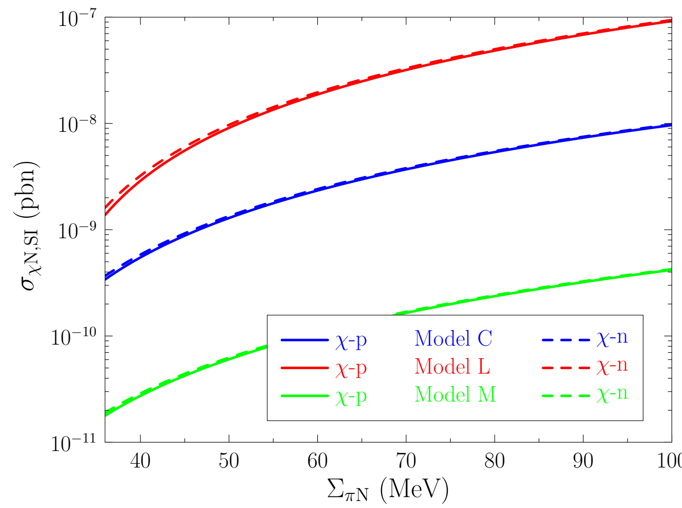
MSTW 0901.0002

$$f^{(2)}_{u,n} = f^{(2)}_{d,p}\,,\quad f^{(2)}_{d,n} = f^{(2)}_{u,p}\,,\quad f^{(2)}_{s,n} = f^{(2)}_{s,p}$$

- strange quark scalar matrix element overestimated (central value) by SU(3) ch.p.t.

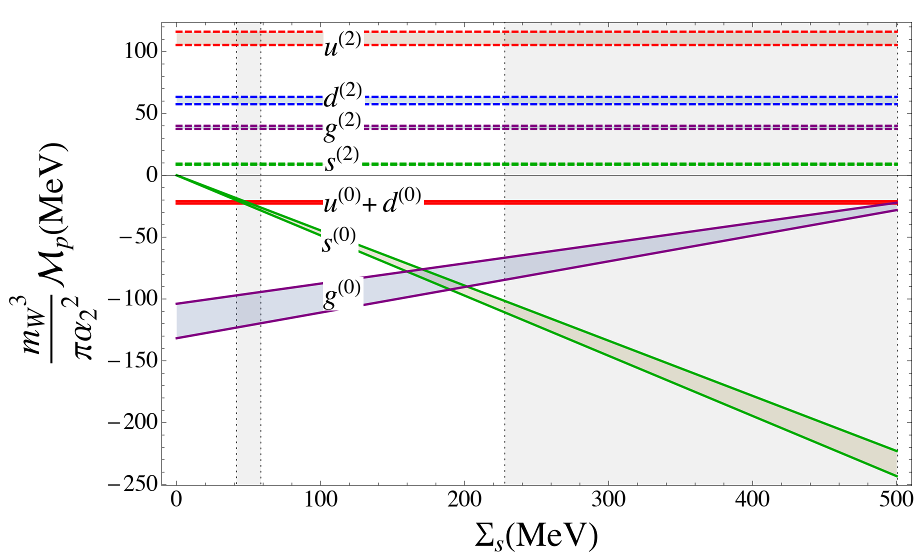


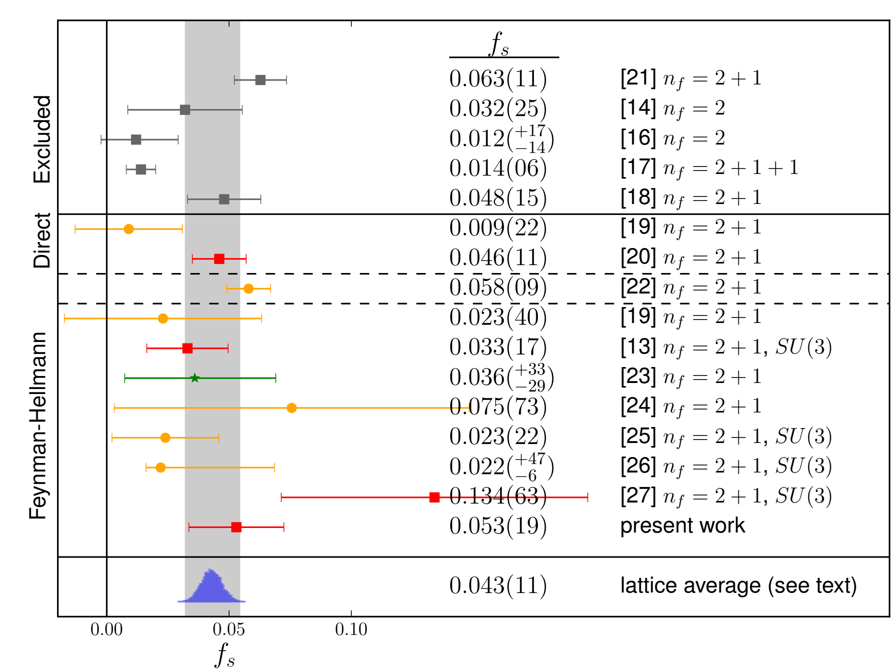




Ellis, Olive, Savage, PRD 77 065026 (2008)

- important impact on cross sections

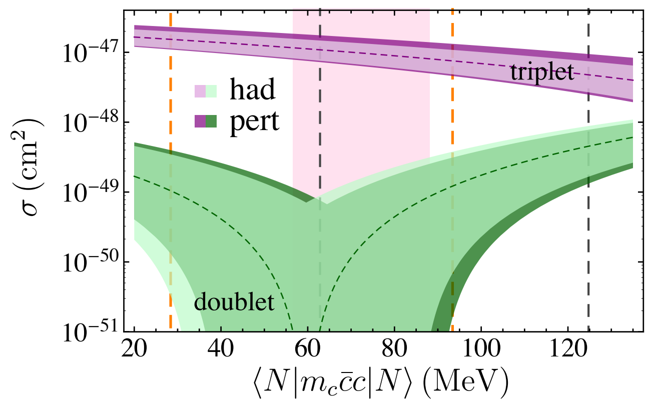


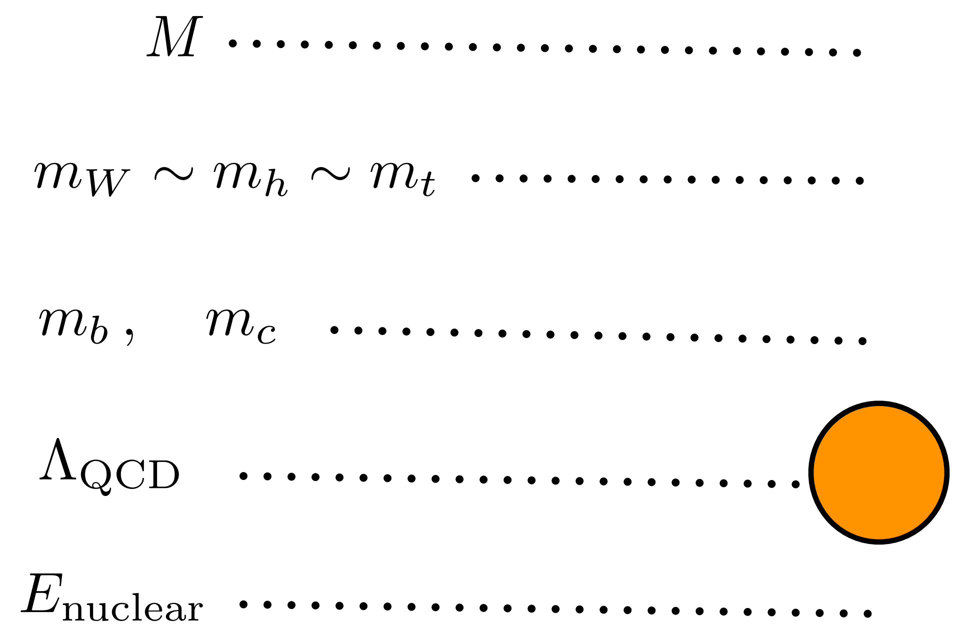


summary plot: Junnarkar and Walker-Loud, 1301.1114

- lattice still converging, but indicate small value

- new frontier: charm scalar matrix element





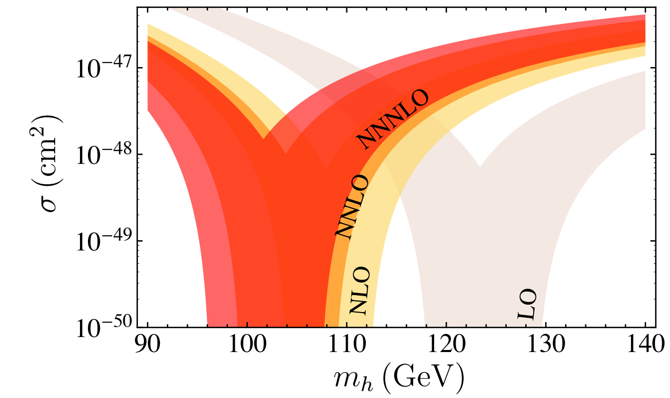
Freeman et al [MILC] 1204.3866

Gong et al. 1304.1194

- upper-bound ↔ prediction for some cross sections

Some results

(benchmark zero-velocity, heavy particle limit of single-nucleon cross section)



Triplet (e.g., wino)

$$\sigma^T_{\rm SI} = 1.3^{+1.2+0.4}_{-0.5-0.3} \times 10^{-47}\,{\rm cm}^2$$

perturbative uncertainty

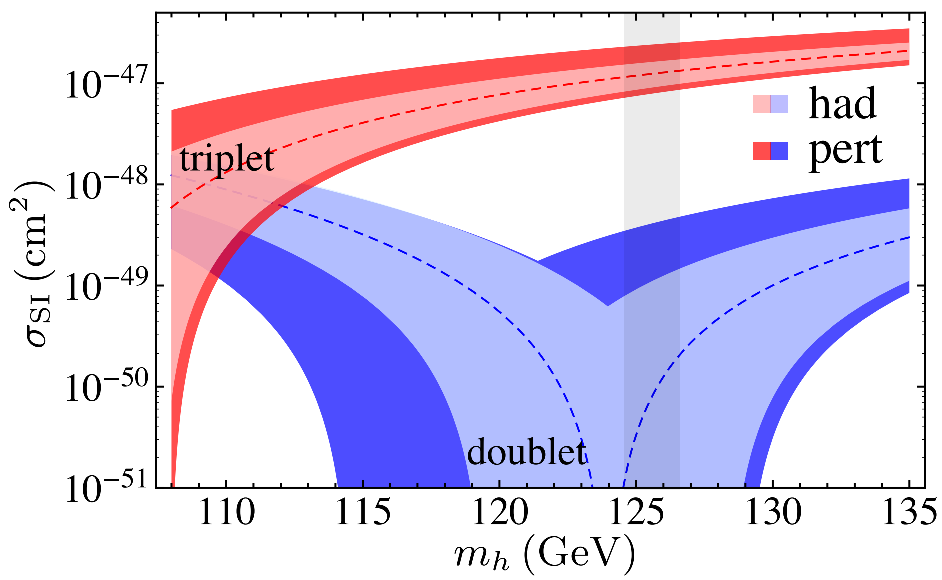
hadronic uncertainty

Parameter	Value
$\lvert V_{td}\rvert$	~ 0
$\lvert V_{ts}\rvert$	~ 0
$\lvert V_{tb}\rvert$	~ 1
m_u/m_d	$0.49(13)$
m_s/m_d	$19.5(2.5)$
$\Sigma^{\rm lat}_{\pi N}$	$0.047(9)$ GeV
$\Sigma^{\rm lat}_{s}$	$0.050(8)$ GeV
$\Sigma_{\pi N}$	$0.064(7)$ GeV
Σ_0	$0.036(7)$ GeV
m_W	80.4 GeV
m_t	172 GeV
m_b	4.75 GeV
m_c	1.4 GeV
m_N	0.94 GeV
$\alpha_s(m_Z)$	0.118
$\alpha_2(m_Z)$	0.0338

cf. dimensional estimate: $$\sigma_{\rm SI} \sim \frac{\alpha_2^4 m_N^4}{m_W^2}\left(\frac{1}{m_W^2}, \frac{1}{m_h^2}\right)^2 \sim 10^{-45}\,{\rm cm}^2$$

By heavy WIMP spin symmetry, same result for self-conjugate fermion (wino) as real scalar (e.g. weakly interacting stable pion)

Doublet (e.g. higgsino)



$$\sigma_{\rm SI}^D \lesssim 10^{-48}\,{\rm cm}^2 \quad (95\%\,{\rm C.L.})$$

By heavy WIMP spin symmetry, same result for fermion (higgsino) as scalar (e.g. "inert higgs")

Mixed cases

With the scale separation M ≫ m_W, "pure states" are generic: effects of higher states suppressed by m_W/(M'-M)

Intricate interplay of m_W/(M'-M) suppressed higgs exchange versus pure-state loop corrections

Again, analyze in the M,M' ≫ m_W limit.

Inclusion of additional multiplets allows nontrivial residual mass and direct Higgs coupling

$$\mathcal{L} = \bar{h}_v \left[iv\cdot D - \delta m - f(H) \right] h_v + \mathcal{O}(1/M)$$

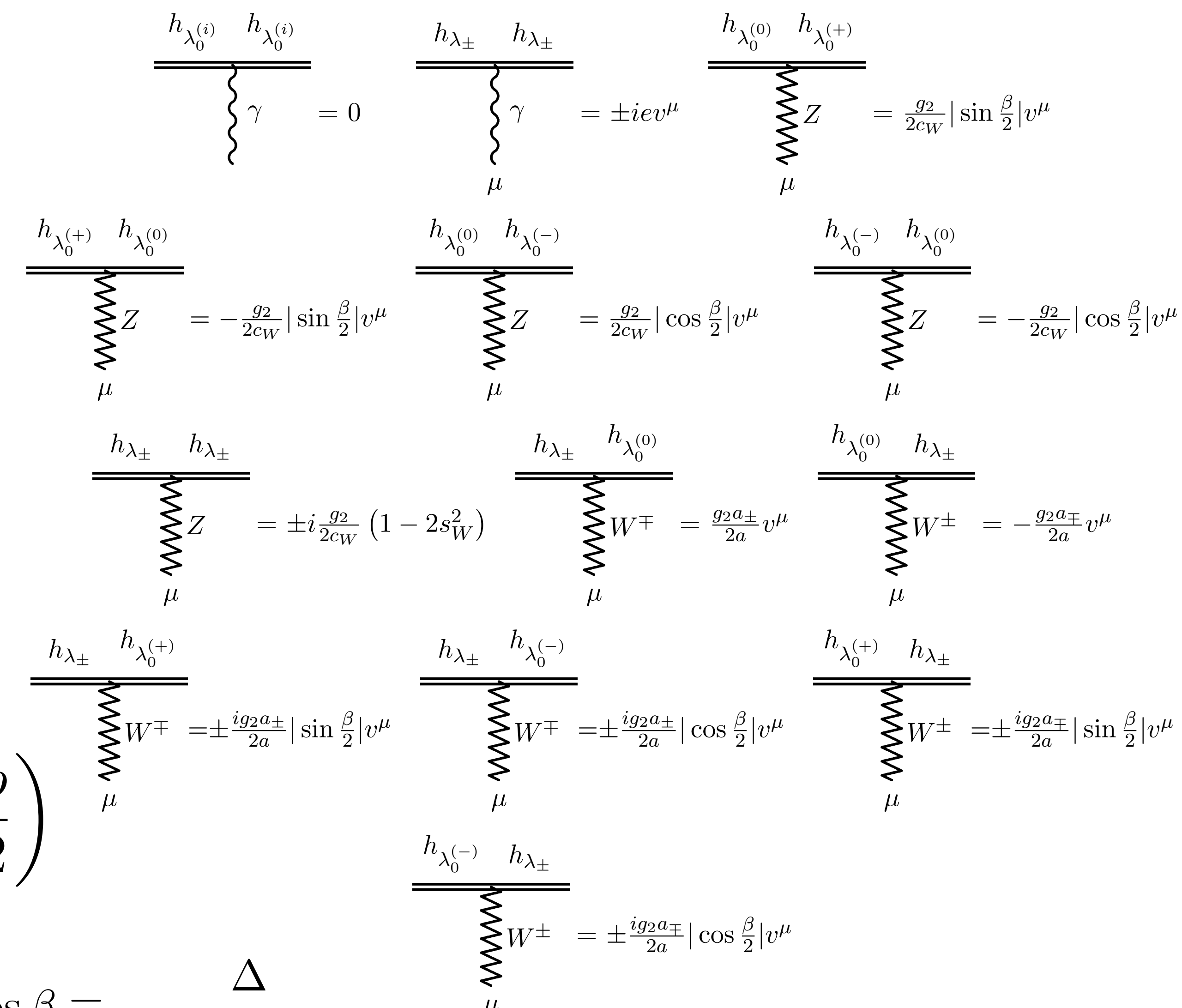
$$T^a = \begin{pmatrix} 0 & \cdot & \cdot \\ \cdot & \frac{\tau^a}{4} & \frac{-i\tau^a}{4} \\ \cdot & \frac{i\tau^a}{4} & \frac{\tau^a}{4} \end{pmatrix} - \text{c.c.}\,, \quad Y = \begin{pmatrix} 0 & \cdot & \cdot \\ \cdot & \mathbb{0}_2 & \frac{-i\mathbb{1}_2}{2} \\ \cdot & \frac{i\mathbb{1}_2}{2} & \mathbb{0}_2 \end{pmatrix}; \quad f(H) = \frac{g_2\kappa_1}{\sqrt{2}} \begin{pmatrix} 0 & H^T & iH^T \\ H & \mathbb{0}_2 & \mathbb{0}_2 \\ iH & \mathbb{0}_2 & \mathbb{0}_2 \end{pmatrix} + \begin{bmatrix} iH \to H \\ \kappa_1 \to \kappa_2 \end{bmatrix} + \text{h.c.}$$

Tree level mass diagonalization

$$\delta m(v_{\rm wk}) = \delta m + v_{\rm wk} \begin{pmatrix} 0 & a_1(0,1) & a_2(0,1) \\ a_1 \begin{pmatrix} 0 \\ 1 \end{pmatrix} & \mathbb{0}_2 & \mathbb{0}_2 \\ a_2 \begin{pmatrix} 0 \\ 1 \end{pmatrix} & \mathbb{0}_2 & \mathbb{0}_2 \end{pmatrix}$$

mass eigenstate basis:

$$h = \begin{pmatrix} h_0^{(0)} \\ h_0^{(+)} \\ h_0^{(-)} \\ h_+ \\ h_- \end{pmatrix}$$



$$\delta m = \text{diag}\left(av\tan\frac{\rho}{2}, av\frac{2}{\sin\rho}, 0, av\tan\frac{\rho}{2}, av\tan\frac{\rho}{2}\right)$$

$$\Delta \equiv \frac{M_S - M_D}{2}, \quad a \equiv \sqrt{a_1^2 + a_2^2} \qquad \sin\rho \equiv \frac{av}{\sqrt{(av)^2 + \Delta^2}}, \quad \cos\beta \equiv \frac{\Delta}{\sqrt{(av)^2 + \Delta^2}}$$

Onshell renormalization

$$\mathcal{L} = \bar{h}^{\text{bare}} \left[iv \cdot D - \mu^{\text{bare}} - f^{\text{bare}}(H) \right] h^{\text{bare}}$$

$$= \bar{h} \left[iv \cdot D - \mu - f(H) \right] h + \bar{h} \left[\delta Z_h iv \cdot D - \delta\mu - \delta f(H) \right] h$$

$$\mu^{\text{bare}} = \text{diag}(\mu_S^{\text{bare}}, \mu_D^{\text{bare}}, \mu_D^{\text{bare}}, \mu_D^{\text{bare}}, \mu_D^{\text{bare}}),$$

$$f^{\text{bare}} = \frac{a_1^{\text{bare}}}{\sqrt{2}} \begin{pmatrix} 0 & H^\dagger + H^T & i(H^T - H^\dagger) \\ H + H^* & \mathbb{0}_2 & \mathbb{0}_2 \\ i(H - H^*) & \mathbb{0}_2 & \mathbb{0}_2 \end{pmatrix}$$

Compute loop corrections Σ_2(v.k)

$$[\delta\mu]_{22} + \text{Re}[\Sigma_2(\delta m(v)_0^{(+)})]_{22} - \delta m(v)_0^{(+)} [\delta Z_h]_{22} = 0$$

$$[\delta\mu]_{33} + \text{Re}[\Sigma_2(0)]_{33} = 0$$

$$[\delta\mu]_{11} + \text{Re}[\Sigma_2(\delta m(v)_\pm)]_{11} - \delta m(v)_0^{(0)} [\delta Z_h]_{11} = 0$$

} renormalized lagrangian parameters = physical masses

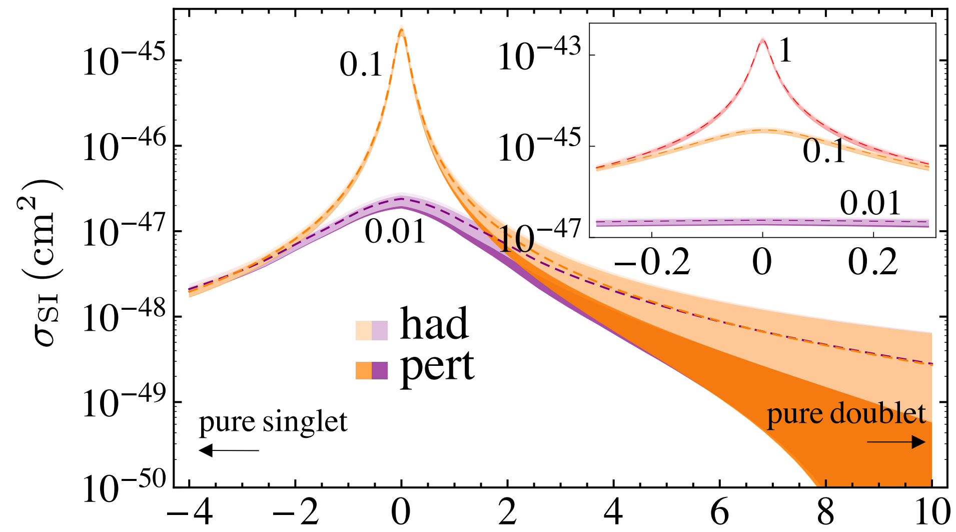
$$[\delta M]_{13} + \text{Re}[\Sigma_2(0)]_{13} = 0$$

$$[\delta M]_{23} + \text{Re}[\Sigma_2(0)]_{23} = 0$$

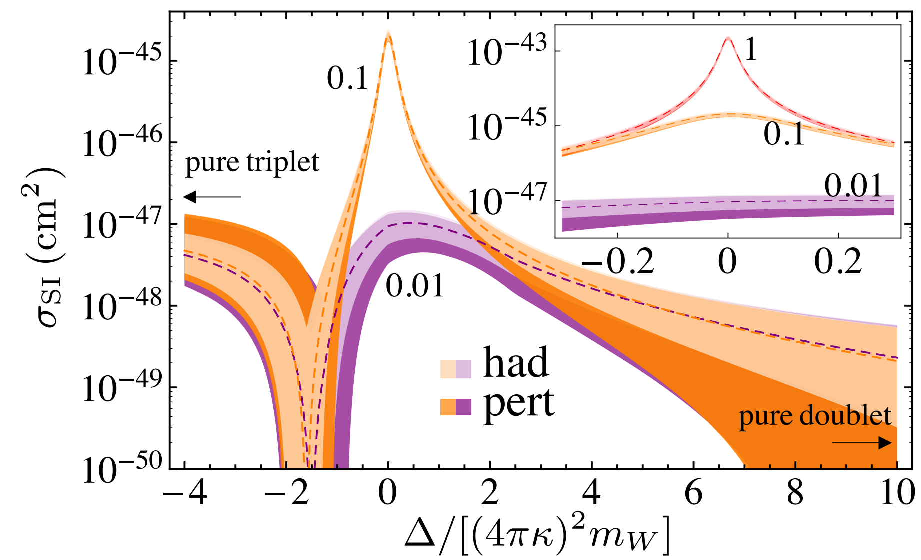
} lightest state remains eigenstate

Additional states in the dark sector

singlet-doublet (e.g., bino-higgsino)



triplet-doublet (e.g., wino-higgsino)



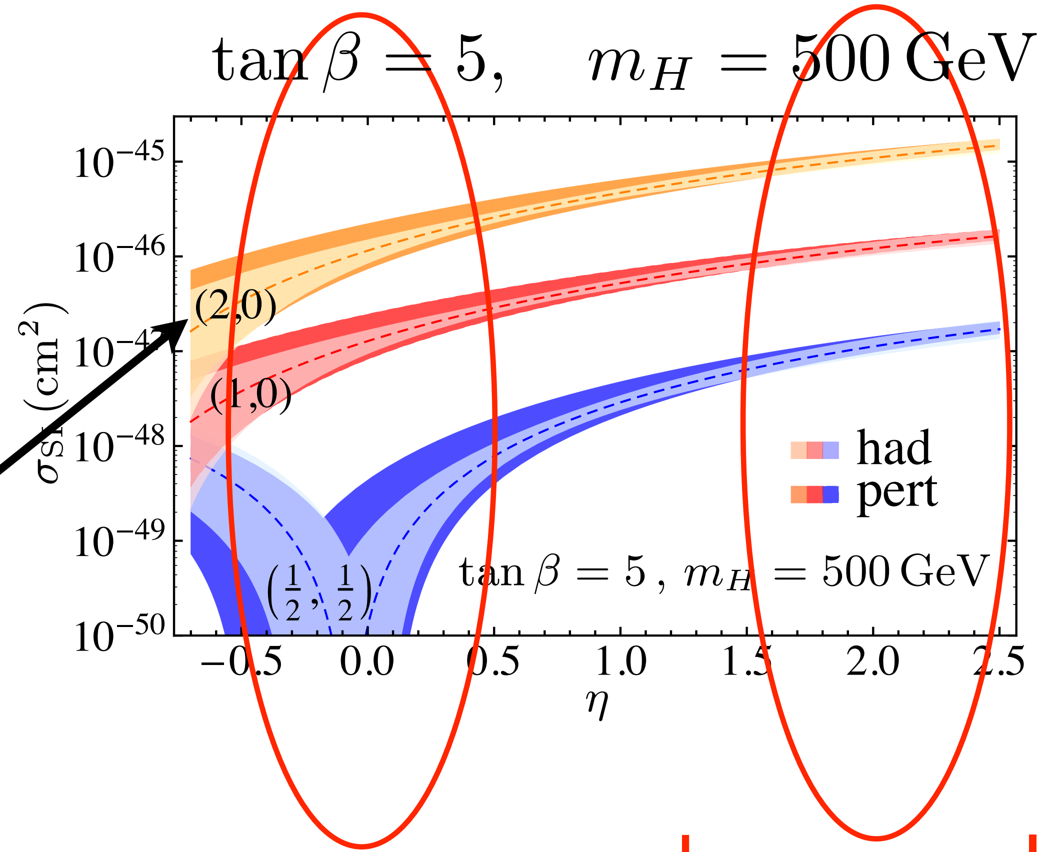
Δ: mass splitting of multiplets, in units where tree/loop crossover occurs at ~1

interplay of mass-suppressed (tree level) and loop suppressed contributions

Additional states in the Higgs sector

can the amplitude cancellation be avoided ?

E.g., 2HDM



(J,Y) of SU(2)xU(1)

phenomenologically allowed

coupling of h to W,Z,u,c,t : $1 + \mathcal{O}(1/t_\beta^2)$

coupling of h to d,s,b : $1 - \eta + \mathcal{O}(1/t_\beta^2)$

$\eta \equiv t_\beta \cos(\beta - \alpha)$: departure from "alignment" limit

cf. Carena et al. 1310.2248

Summary

• Indications of $M_{New\ Physics} >> m_W$ imply constrained but challenging WIMP phenomenology

• Heavy WIMP effective theory used to give first complete matching onto full basis of operators at the weak scale at leading order in perturbation theory: application to SM extensions consisting of 1 and 2 electroweak multiplets

• Systematic treatment of QCD perturbation theory and scale uncertainties (significant residual perturbative uncertainty)

• Important inputs from lattice (strange scalar matrix element), and potential impact of charm scalar matrix element

• Much work to do: power corrections, detailed nuclear modeling, interface with indirect detection