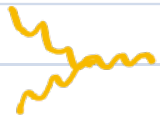
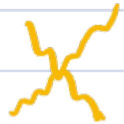
THE STANDARD MODEL (without Higgs)

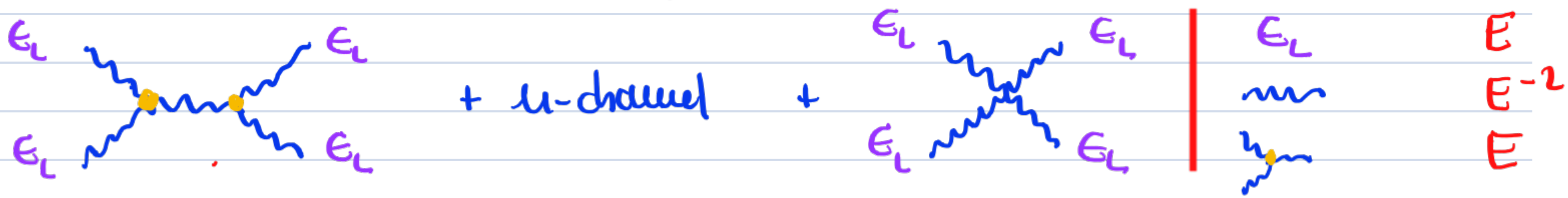
- $\mathcal{L}: \ \bar{\Psi}\, i\gamma^\mu D_\mu \Psi \ - \frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu}$

- $SU(2)_L \times U(1)_Y$: 4 gauge bosons $\{W_1^\mu \ W_2^\mu \ W_3^\mu \ B^\mu\}$
- With proper rotation $(W_3^\mu, B^\mu) \to (Z^\mu, A^\mu)$
- Above $\mathcal{L}$ (+ quark sector) (+ 3 families) looks "perfect"
- What's missing?
  - masses for gauge bosons $\sim M^2 V_\mu V^\mu$ GAUGE INVARIANCE !
  - masses for fermions $\sim m(\bar{e}_L e_R + \bar{e}_R e_L)$ GAUGE INVARIANCE !

MASSIVE GAUGE BOSONS (WITHOUT HIGGS)

- Let's forget all the TH conceptual issues: mass by hand?
- Massive vector boson: 2 TRANSVERSE $\oplus$ 1 LONG Pol's
- $p^\mu = (E, 0, 0, |\vec{p}|)$ $\quad \epsilon_L^\mu = \frac{1}{M}(|\vec{p}|, 0, 0, E)$
- $W_L Z_L \to W_L Z_L$ "Longitudinal Vector Boson Scattering"



- $\mathcal{M} \sim E^4 + E^2$ $\quad$ • E^4 cancel (gauge sym)
- E^2 remains $\Rightarrow$ Unitary violation @ $E \simeq 800$ GeV

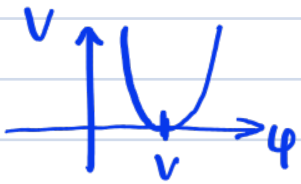
HIGGS MECHANISM : SSB

- Main goal: GAUGE BOSONS MASSIVE (← allows also fermion masses)
- VEV (Vacuum Expectation Value)

$$\varphi(x) = \int [dk] \left(a(k)\, e^{-ikx} + a^\dagger(k)\, e^{ikx} \right) \qquad \text{VEV} = \langle 0|\varphi|0\rangle = 0$$

- Interested in quantum fluctuations around VEV : φ : fluctuations about VEV
- VEV ← minimum of classical potential

a) $\mathcal{L}_{KG} = \frac{1}{2}\partial_\mu\varphi\, \partial^\mu\varphi - \frac{m^2}{2}\varphi^2$ ← $V = \frac{m^2}{2}\varphi^2$ ← minimum $\varphi = 0$

b)  ← expand around v: $\varphi(x) = v + h(x)$

← physical DoF

- Vacuum is unique.
- SPONTANEOUS SYMMETRY BREAKING ≡ $\mathcal{L}$ has a symmetry BUT VACUUM IS NOT SYMMETRIC

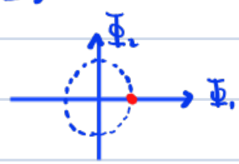
HIGGS MECHANISM: ABELIAN GAUGE THEORY I

- SSB of gauge symmetry → Higgs mechanism → massive vectors

- Abelian U(1) gauge theory $\quad D_\mu = \partial_\mu + ie A_\mu$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + (D_\mu \Phi)(D^\mu \Phi)^* - V(\Phi) \qquad V(\Phi) = \lambda\left(|\Phi|^2 - \frac{v^2}{2}\right)^2 \qquad \langle 0|\Phi|0\rangle = \frac{v}{\sqrt{2}}$$

$\Phi = \frac{1}{\sqrt{2}}(\Phi_1 + i\Phi_2)$ complex scalar field



- $\mathcal{L}$ invariant if $\Phi \to e^{ie\alpha(x)}\Phi$. VEV not invariant under U(1) local

- $\Phi = \frac{v}{\sqrt{2}} + \varphi(x) \qquad \varphi(x) = \frac{1}{\sqrt{2}}(\varphi_1 + i\varphi_2)$

- $|D_\mu \Phi|^2 = \frac{1}{2}\sum_i (\partial_\mu \varphi_i)(\partial^\mu \varphi_i) + ev A_\mu \partial^\mu \varphi_2 + \frac{e^2 v^2}{2} A_\mu A^\mu + \dots$

  ↑ massive vector boson ☺ $M = ev$

- $V(\Phi) = \lambda v^2 \varphi_1^2 + \dots$

  ↑ massive scalar (HIGGS) $\quad m^2 = 2\lambda v^2$

HIGGS MECHANISM: ABELIAN GAUGE THEORY II

- Change of variables: $B^\mu = A^\mu + \frac{1}{ev}\partial^\mu \varphi_2$
- Rewrite $\mathcal{L}$ using B^μ: $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$ is invariant: $F^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu$

$$\mathcal{L} = -\frac{1}{4}\left(\partial_\mu B_\nu - \partial_\nu B_\mu\right)^2 + \underline{\frac{1}{2}\left(\partial_\mu \varphi_1\right)^2} + \underline{\frac{e^2 v^2}{2} B_\mu B^\mu} + \underline{\lambda v^2 \varphi_1^2}$$

  - B^μ: massive, $\partial_\mu \varphi_2$ absorbed in B ← LONGIT. POLARIZATION
  - φ_2 : disappeared from $\mathcal{L}$ (Goldstone boson eaten)
  - φ_1 : massive (Higgs field)
- DoF : A^μ massless + (φ_1, φ_2) 2+2 DoF [before SSB]

  A^μ massive + φ_1 3+1 DoF [after SSB]
- VEV $\neq 0$ + SSB $\Rightarrow$ massive gauge bosons + Higgs field

HIGGS MECHANISM IN THE SM I

- Add to $\mathcal{L}$ a scalar field, doublet $SU(2)_L$ and charged $U(1)_Y$
- $\phi = \begin{vmatrix} \varphi_1 + i\varphi_2 \\ \varphi_3 + i\varphi_4 \end{vmatrix}$ 4 DoF $\dashrightarrow$ 3 eaten by $\{W^\pm, Z\}$ + 1 Higgs boson
- $V(\phi)$ such that $\langle 0|\phi|0\rangle$ $\to$ Mexican Hat potential

$$\Rightarrow \quad V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4 \qquad |\phi_{min}| = \sqrt{\frac{\mu^2}{2\lambda}} = \frac{v}{\sqrt{2}}$$

- vacuum $\phi_{min} = \frac{1}{\sqrt{2}} \begin{vmatrix} 0 \\ v \end{vmatrix}$ $\qquad \phi = e^{i\left(\tau^a \frac{\theta^a(x)}{v}\right)} \begin{vmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{vmatrix}$

- After SSB $\Rightarrow$ $\left.\begin{matrix} \text{3 massive bosons } W^\pm, Z \\ \text{1 massless boson } \gamma \end{matrix}\right\}$ $\qquad \boxed{SU(2)_L \times U(1)_Y \to U(1)_{em}}$

  $\hookrightarrow U(1)_{em}$ UNBROKEN $\leftarrow$ QED reproduced

  1 massive scalar field $H(x)$ HIGGS BOSON !!

The Higgs Mechanism

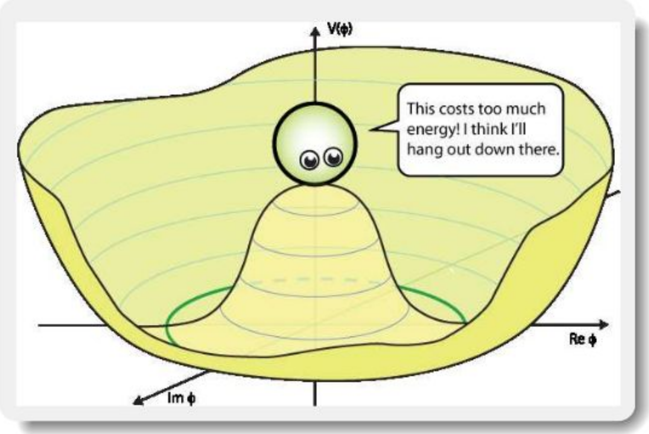
[Brout,Englert,Higgs 1964]

- One complex (doublet) scalar field Φ [4 d.o.f.]

potential: $V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$

- ▸ spontaneously broken symmetry

$$\mu^2 < 0: \quad \langle\Phi\rangle \neq 0$$



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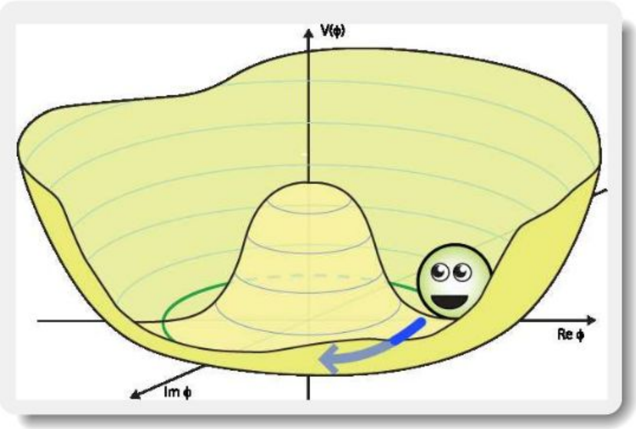
- 3 "angular" modes
  $\Rightarrow$ longitudinal W and Z



The Higgs Mechanism

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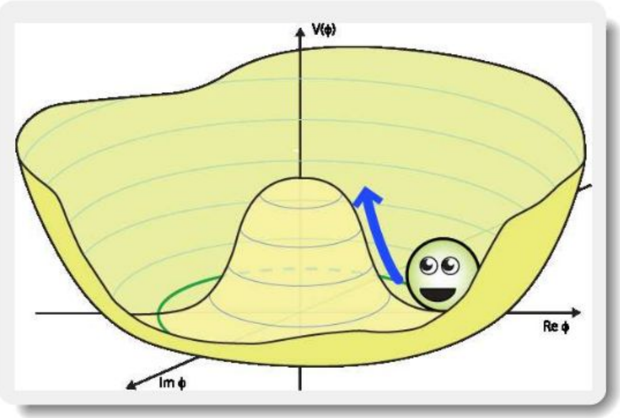
potential: $V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$

- spontaneously broken symmetry

  $\mu^2 < 0: \quad \langle\Phi\rangle \neq 0$

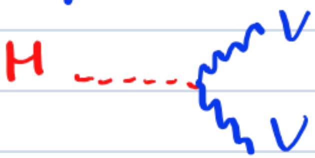
- 3 "angular" modes
  $\Rightarrow$ longitudinal W and Z

- radial mode: massive
  $\Rightarrow$ the "Higgs boson"



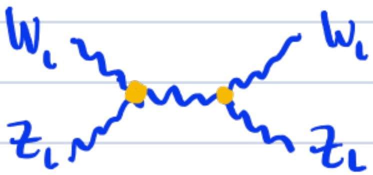
HIGGS MECHANISM IN SM II

- Higgs boson mass: $m_H^2 = 2\lambda v^2$
- Higgs couplings to gauge bosons

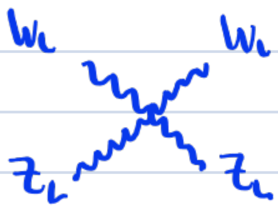


$\sim i g M_V$ "H-SM-SM" coupling $\sim M_{SM}$

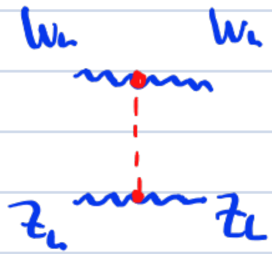
- Higgs unitarizes $V_L V_L$ x-section



\+ u-channel +

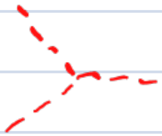


\+



$\sim E^2$

- Higgs potential ⋯→ Higgs self couplings



$\sim \lambda v$

$\sim \lambda$

YUKAWA LAGRANGIAN & FERMION MASSES

- We need to include a Dirac mass, keeping gauge invariance
- Focus on leptons for simplicity, and 1 family only
- $\mathcal{L}_{YUK}$: only possible extra term to $\mathcal{L}_{SM}$ that is gauge invariant & renormalizable

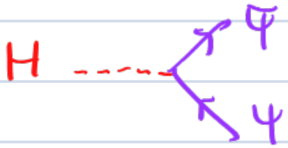
$$\mathcal{L}_{YUK} = -h_e \bar{L}(x)\,\phi(x)\,e_R(x) + h.c. \xrightarrow[EWSB]{} -h_e \bar{L} \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix} e_R + h.c. = -h_e \frac{v+H}{\sqrt{2}} \left(\bar{e}_L e_R + \bar{e}_R e_L \right)$$

$$\mathcal{L}_{YUK} = -h_e \frac{v}{\sqrt{2}} \left(1 + \frac{H}{v} \right) \bar{\Psi}_e \Psi_e$$

mass term ☺

coupling

$$h_e \frac{v}{\sqrt{2}} = m_e$$

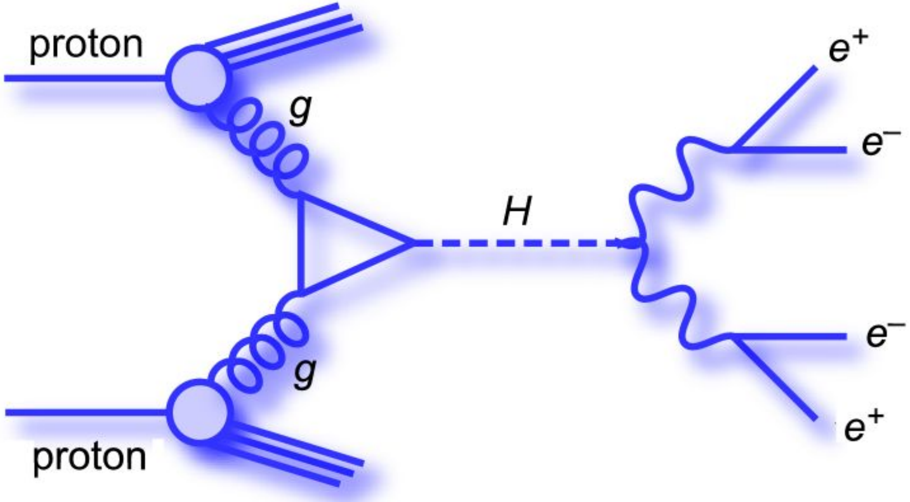


$$\sim -i \frac{m_\Psi}{v}$$

YUKAWA COUPLING (proportional to fermion mass)

- Yukawa Lagrangian ⊕ 3 families (of quarks) $\dashrightarrow$ $\left\{ \begin{array}{l} \text{CKM matrix} \\ \cancel{CP} \end{array} \right.$

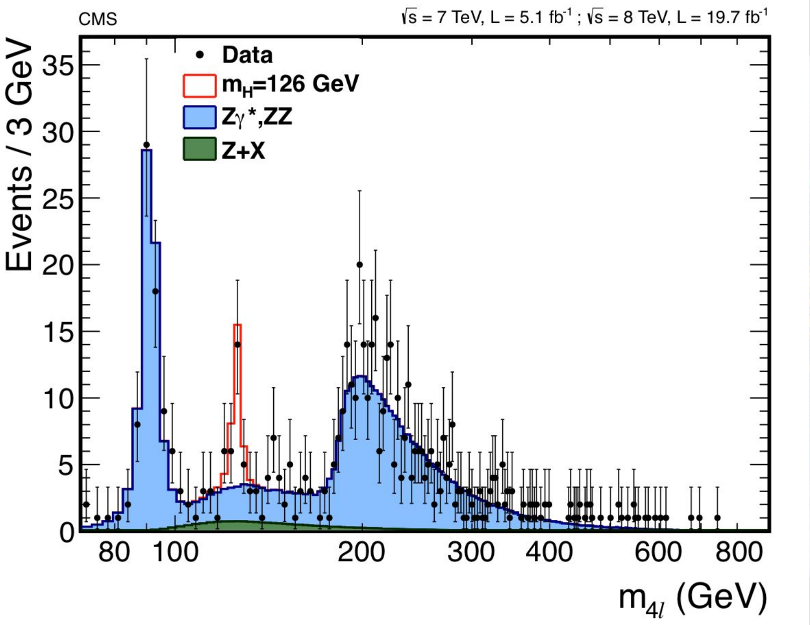
The Higgs boson discovery

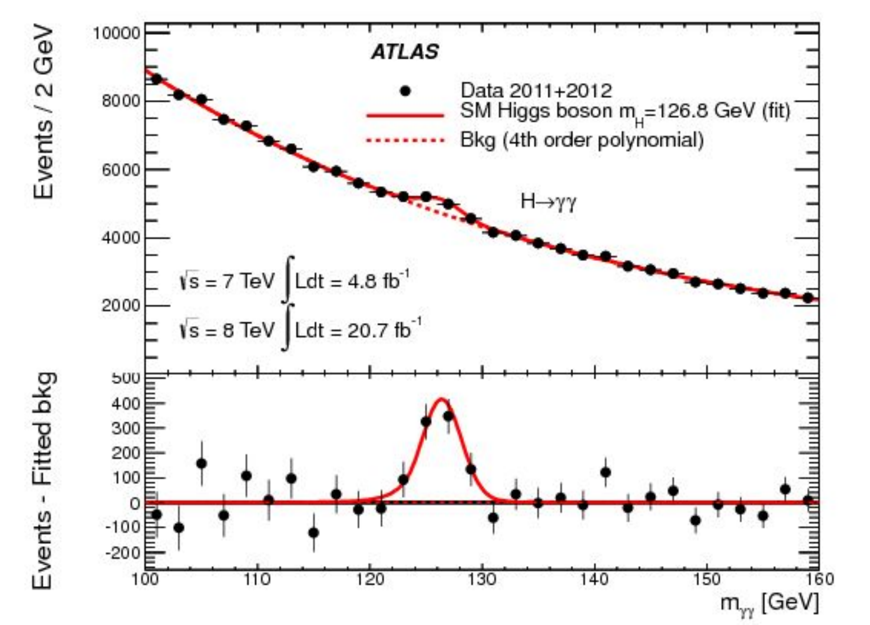


ultimately the Higgs boson discovery was an experimental challenge, but with a lot of cross-talk between theorists and experimentalists

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354

The Higgs boson discovery

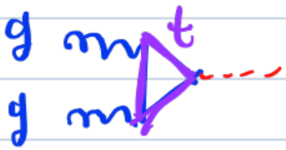




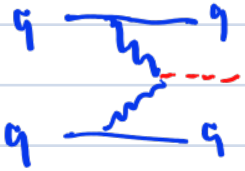
m_H = 125 GeV

HIGGS AT THE LHC I

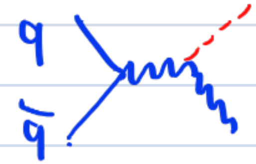
(main) production channels



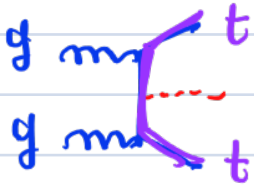
Gluon Fusion



Vector Boson Fusion

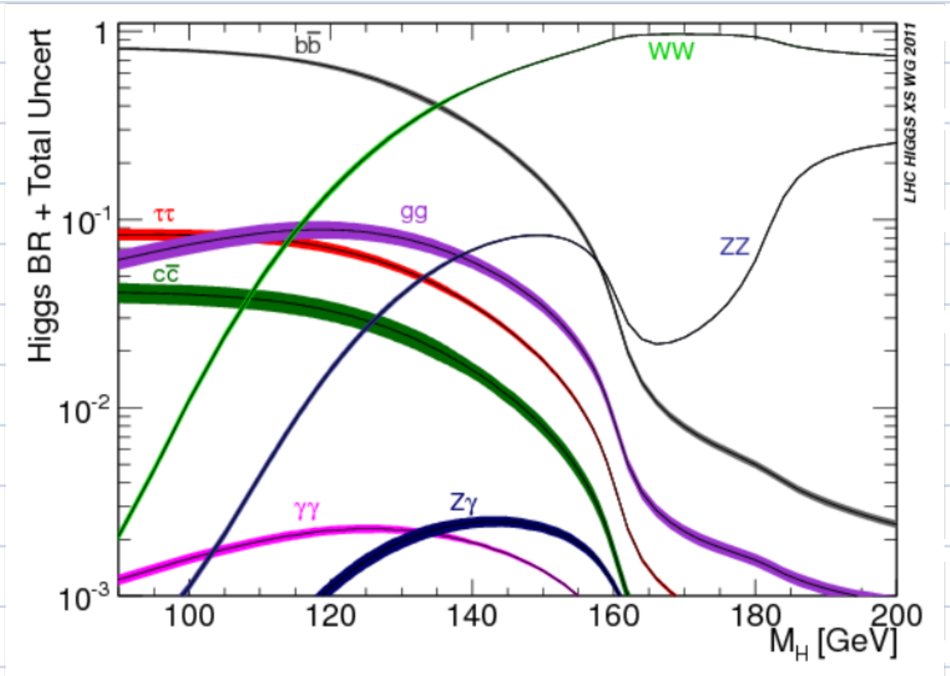


VH



$t\bar{t} + H$

Decay channels

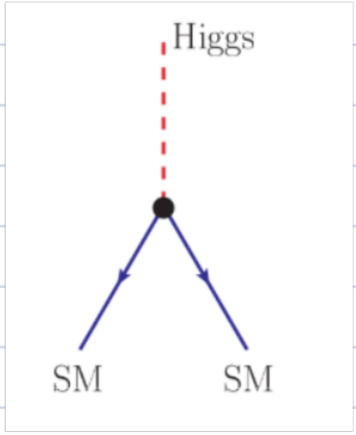


$\Rightarrow$ study its properties : · exactly as in the SM ?

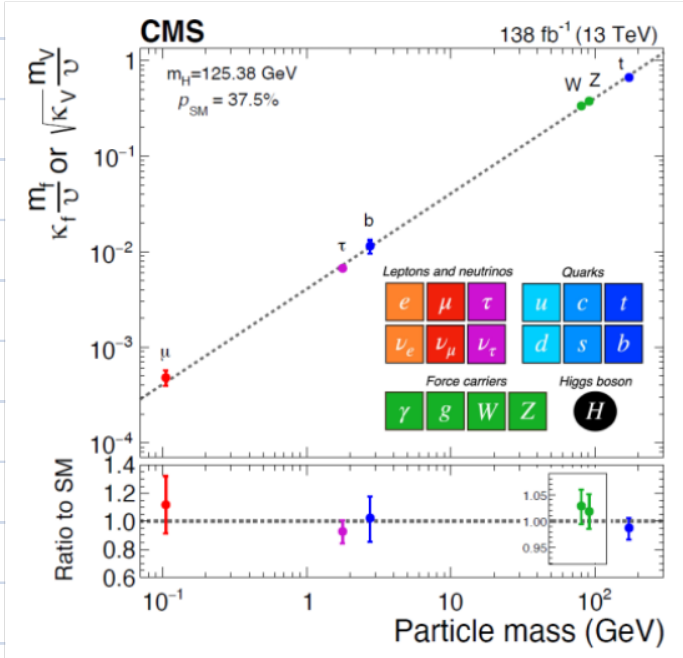
· deviations ?

HIGGS AT THE LHC II [STATUS]

- Higgs couplings with SM particles



H-SM-SM $\sim M_{SM}$ $\Rightarrow$



HIGGS : · SM-like within ~ 10-15 % accuracy

· Some tensions in some channel, no smoking gun!

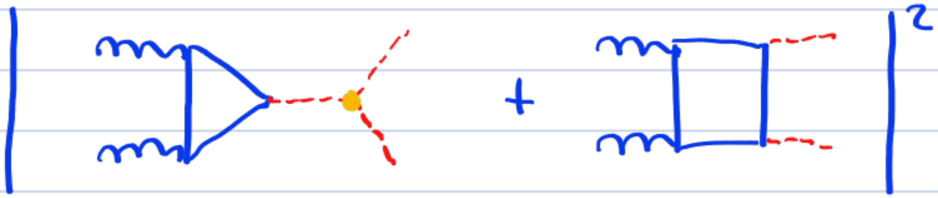
HIGGS TRILINEAR COUPLING

- $V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4 = \lambda \left(|\phi|^2 - \frac{v^2}{2} \right)^2$ $\quad [\mu^2 = \lambda v^2]$

  $m_H^2 = 2 \lambda v^2$ $\quad$ v known from G_F $(v = 246$ GeV$)$ $\quad \rightarrow \lambda$ extracted (assuming SM)

   $= i \lambda v$ $\quad \rightarrow$ Measure λ directly

- Process : $pp \rightarrow HH$

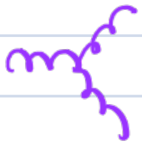
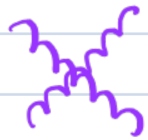


challenging : { small x-section
distructive interference
large backgrounds } $\Rightarrow$ HL-LHC !

QCD SECTOR

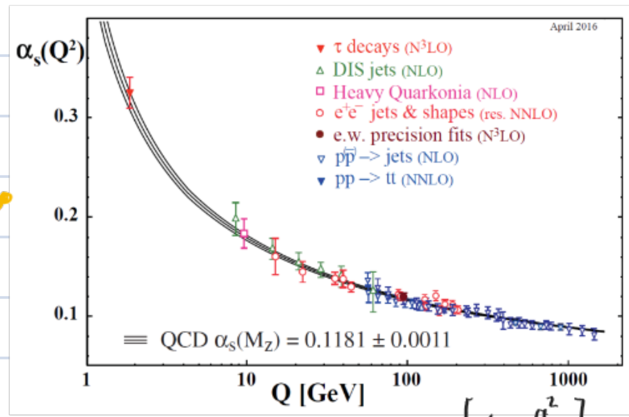
- strong force : $SU(3)_c$. NOT BROKEN $\Rightarrow$ carriers are massless

$$\boxed{\begin{array}{lll} \bullet\ \text{COUPLING} & g_s & \\ \bullet\ \text{GLUON FIELDS} & G^a_\mu & a = 1,\dots,8 \\ \bullet\ \text{QUARK FIELDS} & \psi_c(x) = (\psi_1, \psi_2, \psi_3) & \end{array}}$$

- Interactions :  $\sim g_s$  $\sim g_s$  $\sim g_s^2$

- Running coupling ["ASYMPTOTIC FREEDOM"]

high energy $\rightarrow$ small coupling $\rightarrow$ PERTURBATION THEORY

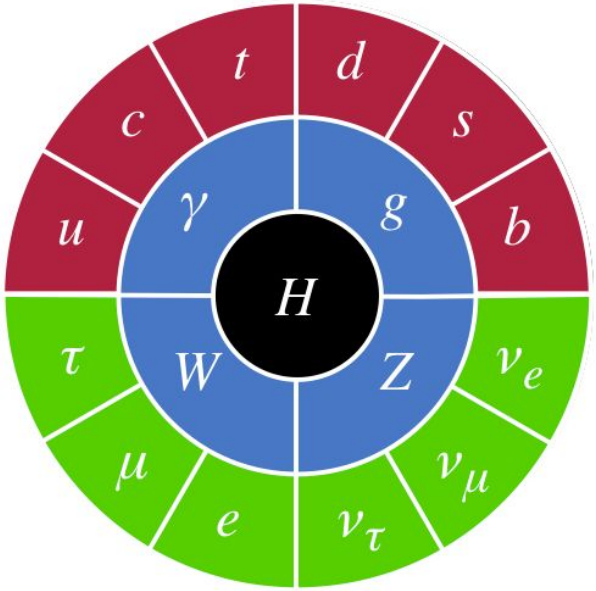


$\left[\alpha_s = \frac{g_s^2}{4\pi}\right]$

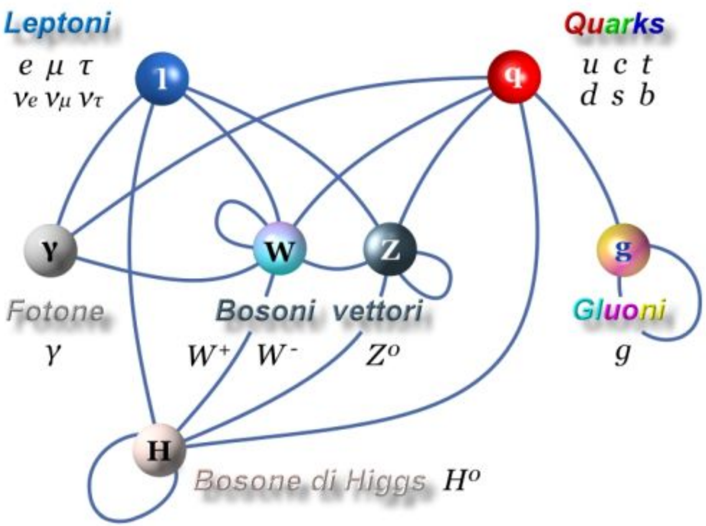
- (Perturbative) QCD
  - proton structure $\rightarrow$ needed for LHC predictions
  - $g_s > g_{EW}$ $\rightarrow$ subleading corrections more important in QCD

SM recap

Field Content



Interactions



SM SHORTCOMINGS

- SM with Higgs boson : successful BUT NOT THE FINAL THEORY
  - Why masses are so different? Flavour mixing?
  - Neutrinos: mass, Dirac vs Majorana
  - Dark Matter?
  - Matter - Antimatter asymmetry
  - Why Higgs is "light"? [hierarchy problem]
  - Explanation of Higgs potential
  - Gravity $\leftrightarrow$ QFT

Beyond the Standard Model (BSM)

- SM: effective theory valid at low energy:
  higher energy → new d.o.f. (particles), yet unseen

- for BSM theories addressing the above issues: there were (theoretical) reasons to expect BSM signatures at the LHC

- LHC main goals:

  - Understand EWSB, by looking for the Higgs boson
    → SM particle content finally established [✅]
    → not yet all its interactions (Higgs sector)

  - Search for new Physics beyond the SM
    → LHC is the current energy frontier (in a lab)

SM Phenomenology at the LHC and QCD

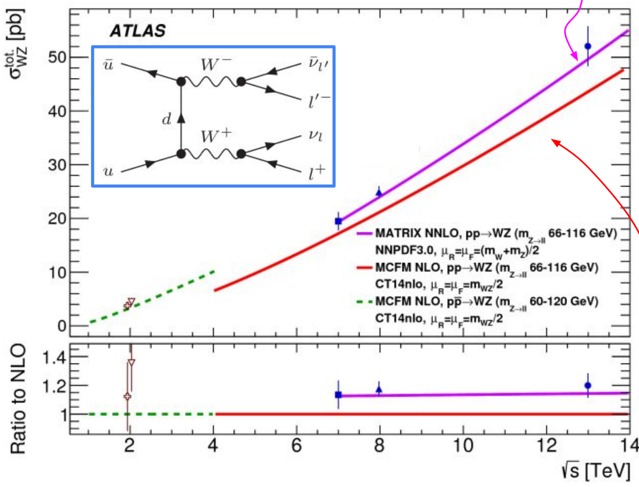
- TH computations enter in ~ all experimental analysis

$$d\sigma = d\sigma_{\mathrm{LO}} + \left(\frac{\alpha_S}{2\pi}\right) d\sigma_{\mathrm{NLO}} + \left(\frac{\alpha_S}{2\pi}\right)^2 d\sigma_{\mathrm{NNLO}} + \ldots$$

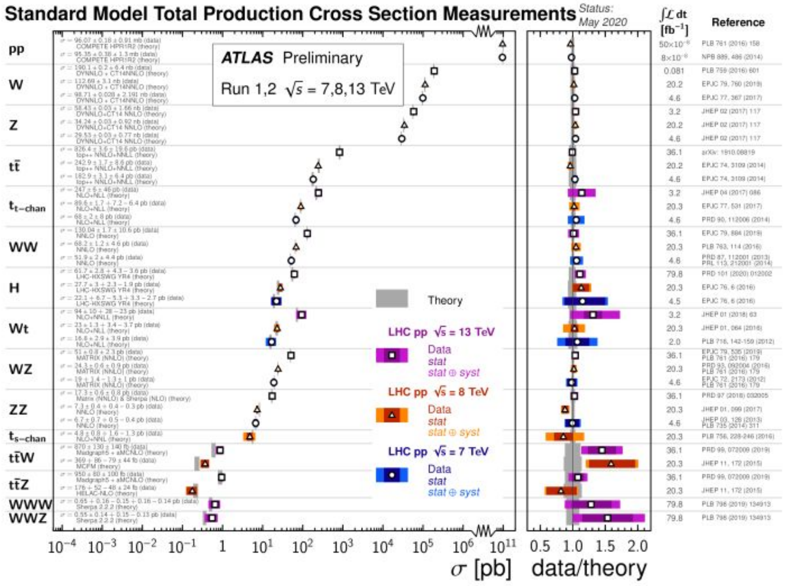
Feynman diagrams, at times advanced mathematics, analytical+numerical

$\mu \gg \Lambda_{\mathrm{QCD}}, \alpha_S \sim 0.1$
$\Leftarrow$ perturbation theory

NNLO: match data

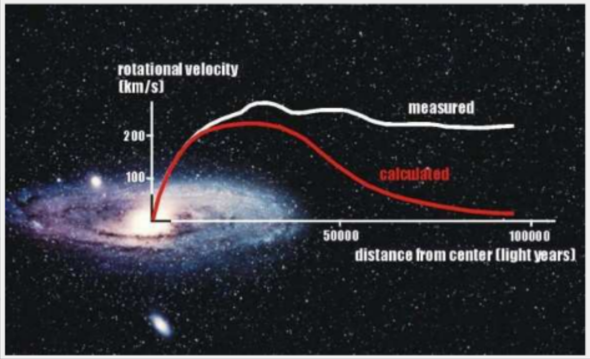


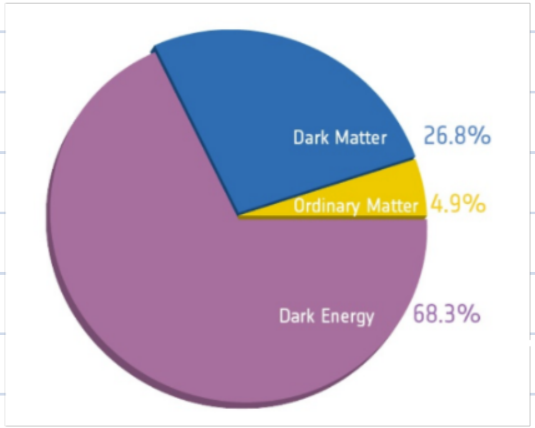
NLO: disagree with data



DARK MATTER [more details in DM lectures]

• Astrophysical Observations: ENERGY BUDGET OF THE UNIVERSE





• No SM particle can be a DM candidate

• DM: presumably, NEW PARTICLE(s)

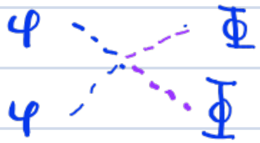
DM ↔ SM fields ⟶ gravitationally [this is sure]
⟶ other interactions ?

• Historically, good candidate: "WIMP" ↔ many years of direct searches
no signatures
.... other ideas being studied ...

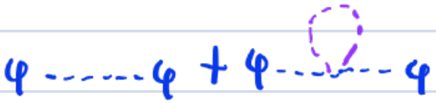
HIERARCHY PROBLEM [with some oversimplified explanation]

- SM: Higgs mass is an input parameter: m_H
- SM valid up to scale Λ (i.e. New Physics at scale Λ) ex: new particle $M \sim \Lambda$
- If New Physics coupled to SM Higgs $\Rightarrow$ quantum corrections DESTABILIZE m_H
- TOY MODEL: SM Higgs + heavy scalar, coupled to φ:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \varphi)(\partial^\mu \varphi) - \frac{m^2}{2}\varphi^2 + \frac{1}{2}(\partial_\mu \Phi)(\partial^\mu \Phi) - \frac{M^2}{2}\Phi^2 + \lambda \varphi^2 \Phi^2$$



Assume $M^2 \gg m^2$



$$\Rightarrow m^2_{PHYSICAL} = m^2 + \frac{\lambda}{8\pi^2} M^2$$

$\rightarrow m^2_{PHY}$ remains "light" ONLY IF $\lambda \ll \dfrac{m^2}{M^2}$ $\longleftrightarrow$ FINE TUNING OF λ

- Often stated as: $\delta m_H^2 \sim \Lambda^2$ Λ = new physics scale
- If $\Lambda = M_{PLANCK}$ $\rightarrow$ fine tuning $\sim 10^{-32}$
  (10^{19} GeV)

$$\boxed{\begin{array}{l}\text{NEVER HAPPENS IN NATURE:} \\ \text{low energies phenomena DO NOT DEPEND} \\ \text{on details at much larger energies !!}\end{array}}$$

NATURALNESS & WHERE TO EXPECT NEW PHYSICS

- Higgs mass $\sim \Lambda^2$ because NO SYMMETRY TO PROTECT IT
- technical naturalness ('t Hooft, 1979): parameter m naturally small if, when $m \to 0$, $\mathcal{L}$ is more symmetric

  → Ex: photon mass is 0. Natural because, with $m_\gamma \to 0$, there is gauge invariance
  $\Updownarrow$
  GAUGE INVARIANCE protects $m_\gamma = 0$

  → setting scalar mass to 0 : NO EXTRA SYMMETRY

- Consequences : a) $\delta m_H^2 \sim \lambda \Lambda^2$ ⇒ expect $\Lambda \sim$ TeV if $\lambda \simeq 0.01 - 0.1$

  LHC reach

  b) BSM models such that some mechanism protects Higgs boson mass

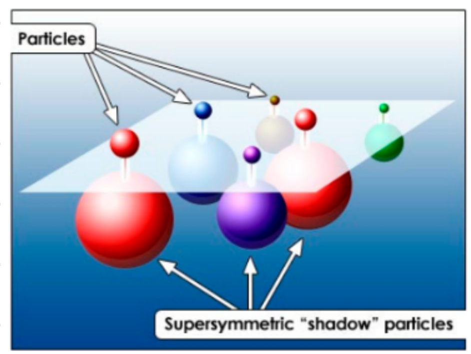
BSM: SUPERSYMMETRY

- New spacetime symmetry, relating bosons & fermions
  - Coleman-Mandula Theorem: internal & external symmetries commute [generators are not in the same algebra]
  - SUSY : only exception → requires fermionic generator

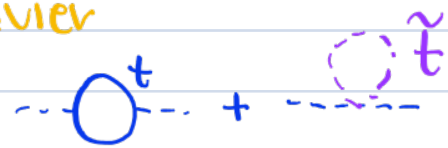
Q: SUSY GENERATOR $Q|B\rangle = |F\rangle$ $Q|F\rangle = |B\rangle$

-

SM PARTICLE				SUSY PARTNER		
quark	q	$1/2$	--→	squark	$\tilde{q}$	0
lepton	ℓ	$1/2$	--→	slepton	$\tilde{\ell}$	0
gluon	g	1	--→	gluino	$\tilde{g}$	$1/2$
Higgs	H	0	--→	Higgsino	$\tilde{H}$	$1/2$



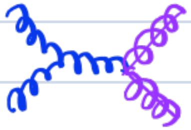
- Not observed ⇒ SUSY broken ← sparticles heavier
- Why? Higgs mass stable [HIERARCHY PROBLEM]

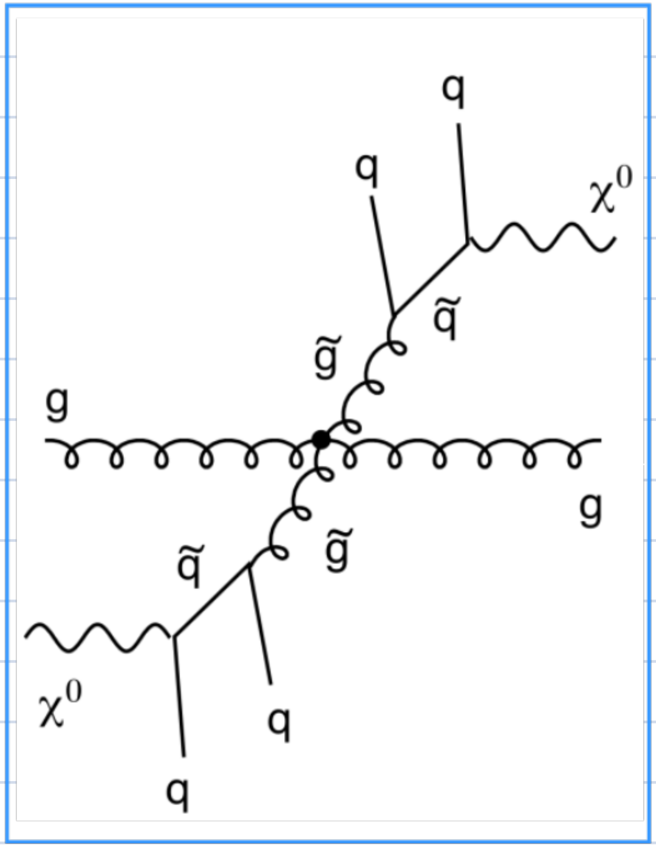


ALMOST CANCEL!!

  LIGHTEST SUSY PARTICLE STABLE [DM CANDIDATE]
  Gauge coupling unification

SUSY AT THE LHC

- largest x-section; STRONG PRODUCTION : $pp \to \tilde{g}\,\tilde{g}$ 
- typical signature : LSP (neutralino) not detected $\rightarrow$ $\not{E}_T$ + jets



SUSY AT THE LHC

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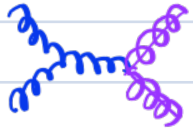

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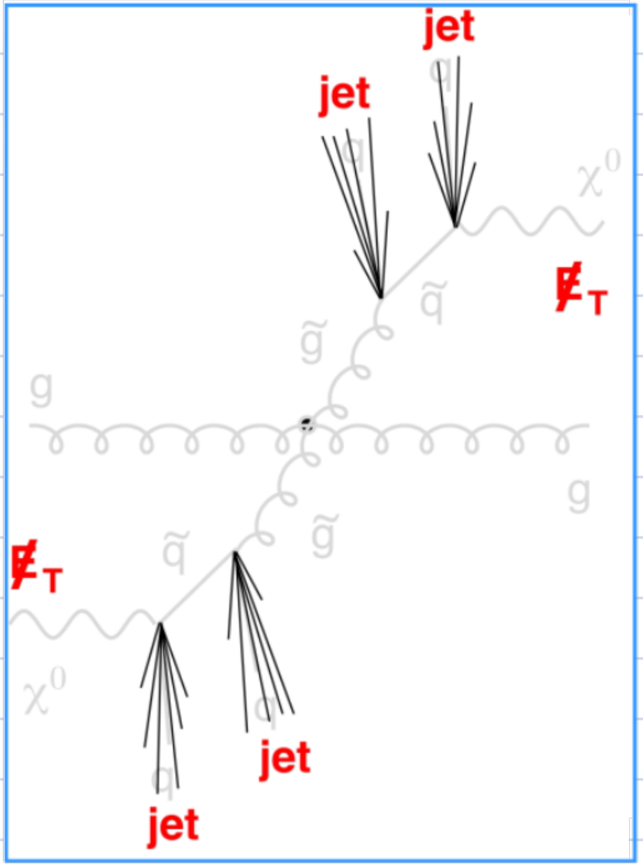
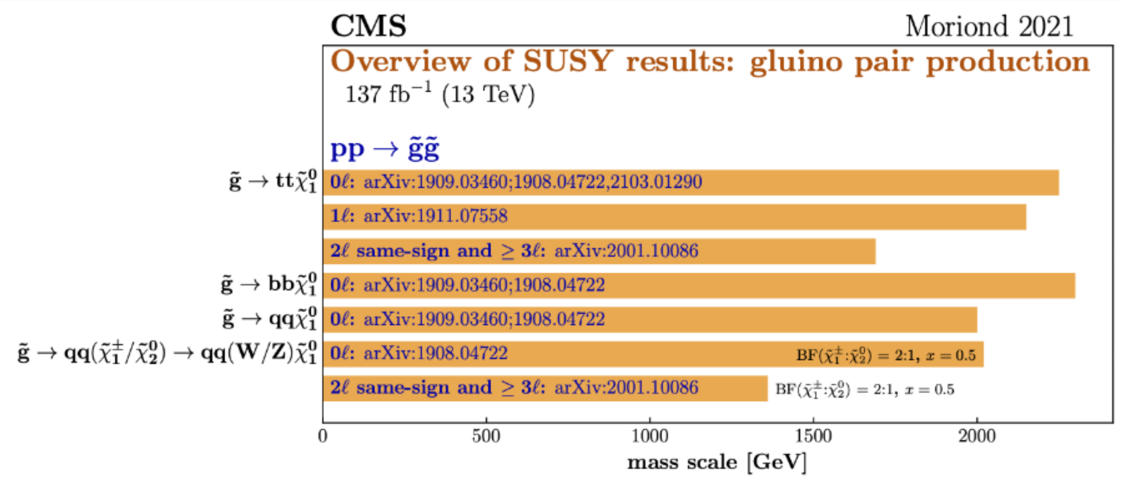


- CURRENT STATUS :

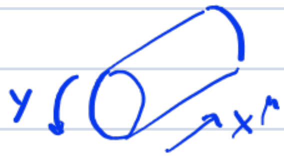


Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

OTHER BSM MODELS

- Grand Unified Theories [GUT] $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \subset G_{GUT}$ $\begin{cases} SU(5) \\ SO(10) \end{cases}$
  - only one coupling $\rightsquigarrow$ unification
  - larger multiplets $\rightsquigarrow$ proton decay
  - new bosons Z', W' ; leptoquarks

- Extra dimensions
  - several possible scenarios



  - Fields: $X^M = (x^\mu, y)$ $\quad p^M = (p^\mu, p_5)$

$y \in [0, L] \rightarrow p_5$ quantized : $p_5 = \frac{n}{L} \rightarrow p^M p_M = p^2 - p_5^2 = 0$

$\Rightarrow p^2 = (\text{mass})^2 = n^2/L^2$

  - Massless 5d fields $\Rightarrow$ tower of massive Kaluza-Klein fields
    - find them, check mass spectrum
  - $A^M = \begin{pmatrix} A^\mu \\ H \end{pmatrix}$: if $E \gg \frac{1}{L} \Rightarrow$ 5d symmetry restored

5d gauge symmetry $\rightsquigarrow A^M$ massless $\rightsquigarrow H$ "massless"

BSM: EXTENDED HIGGS SECTOR

- SUSY: UV-complete model, solves several problems
- less ambitious: Extended Higgs Sectors
- Why? ... Why not?
  - EWSB in SM: minimal realization: just $\phi = \begin{vmatrix} \varphi_1 + i\varphi_2 \\ \varphi_3 + i\varphi_4 \end{vmatrix}$
  - Why not other realization?
    → proxy for Higgs sector from more complete models....
- Example: 2HDM

$$\phi_1 = \begin{vmatrix} \varphi_1^+ \\ \varphi_1^0 \end{vmatrix} \overset{SSB}{\rightsquigarrow} \phi_1 = \begin{vmatrix} \varphi_1^+ \\ (h_1 + v_1 + i a_1)/\sqrt{2} \end{vmatrix}$$

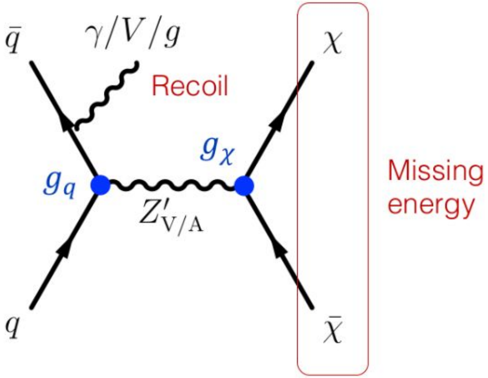
$$\phi_2 = \begin{vmatrix} \varphi_2^+ \\ \varphi_2^0 \end{vmatrix} \rightsquigarrow \phi_2 = \begin{vmatrix} \varphi_2^+ \\ (h_2 + v_2 + i a_2)/\sqrt{2} \end{vmatrix} \qquad (v_1^2 + v_2^2 = v^2)$$

- 8 real DOF ⟹ after Higgsing $H^\pm, h_0, H_0, A_0$ ⊕ $h_0 VV$, $H_0 VV$ couplings different than in SM.....

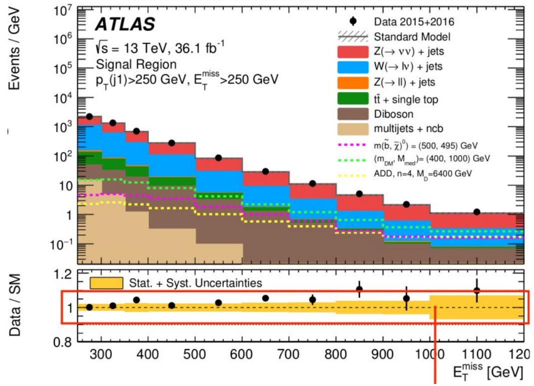
charged scalar → $H^\pm$; heavy Higgs → H_0; CP-odd scalar → A_0

DM@LHC

- Assume there is a mediator DM – SM
- Signature: “mono-jet” (DM is not detected!)



ATLAS : JHEP 01 (2018) 126

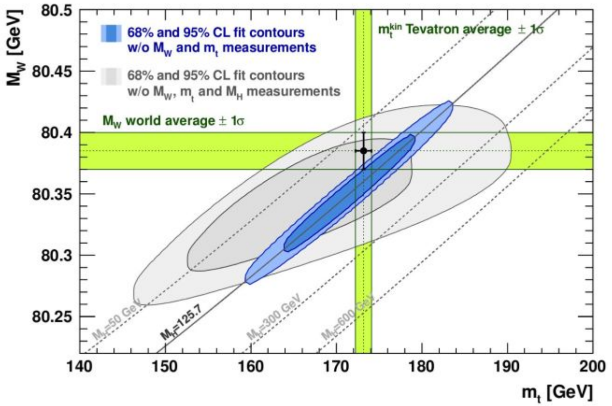


- In order to establish whether there’s a BSM excess, one must be sure to know the SM signal very well
- QCD (and EW) corrections crucial!

Indirect searches (LHC as a precision machine)

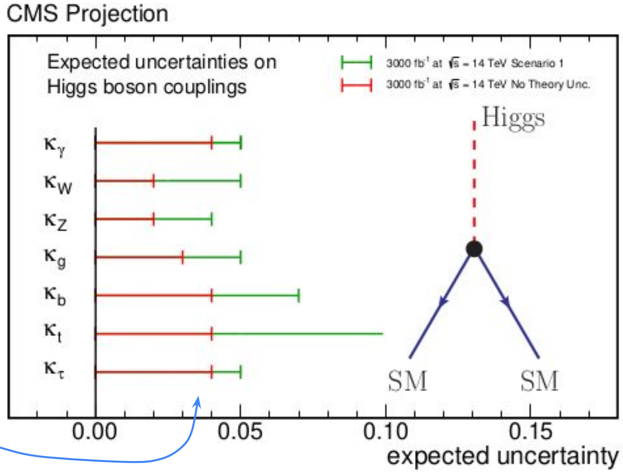
- SM is a QFT: self-consistency requires different parameters to be related (radiative corrections)

  ⇒ precise measurements might unveil tensions → BSM



- All Higgs couplings (in the SM) fixed once masses known

  ⇒ deviation in the expected Higgs couplings → BSM



TH uncertainties play a role

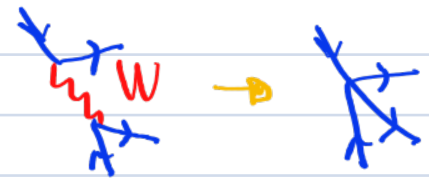
SM EFFECTIVE FIELD THEORY : MODEL INDEPENDENT BSM

- SM: NOT a TRULY FUNDAMENTAL THEORY BUT works well up to the ~TeV scale
- Consider it an EFFECTIVE THEORY $\Rightarrow$ no strict requirement of RENORMALIZABILITY

$\Rightarrow \mathcal{L} = \mathcal{L}_{SM} +$ "higher dimensional operators"

- $\mapsto$ ONLY SM fields [so far, NO NEW PARTICLES]
- $\mapsto$ respect gauge symmetry
- $\mapsto$ more general structure arising when "INTEGRATING OUT" heavier DOFs

~ Fermi theory



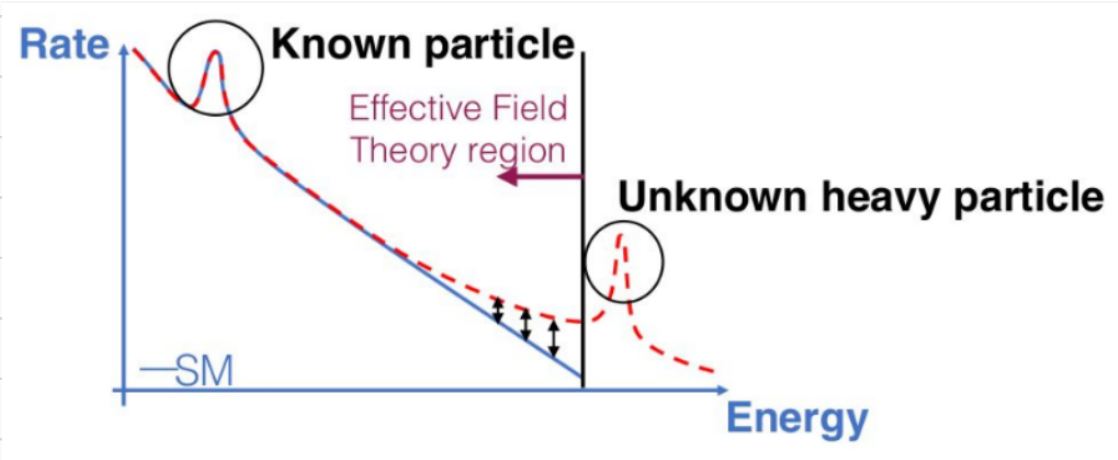
- AGNOSTIC ABOUT UV-THEORY $\Rightarrow$ BOTTOM-UP

- $$\boxed{\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \mathcal{O}(\Lambda^{-4})}$$

unknown Wilson coefficient $c_i^{(6)}$

- Name of the game : Constrain $c_i^{(6)}$ ---→ find some $\frac{c_i}{\Lambda^2} \approx 1$

SM EFFECTIVE FIELD THEORY : validity & examples

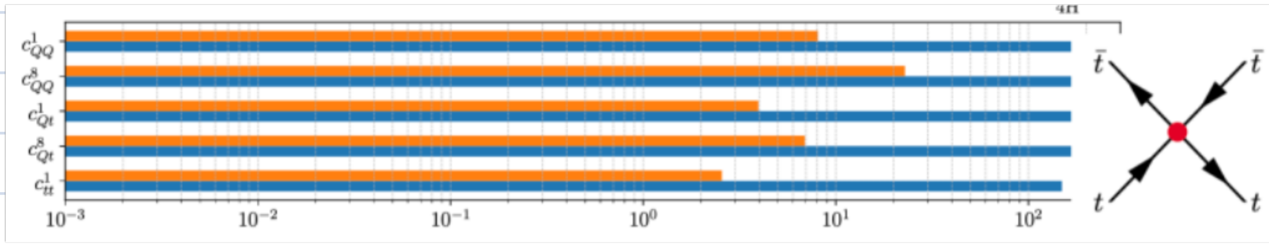


[figure: E. Vryonidou]

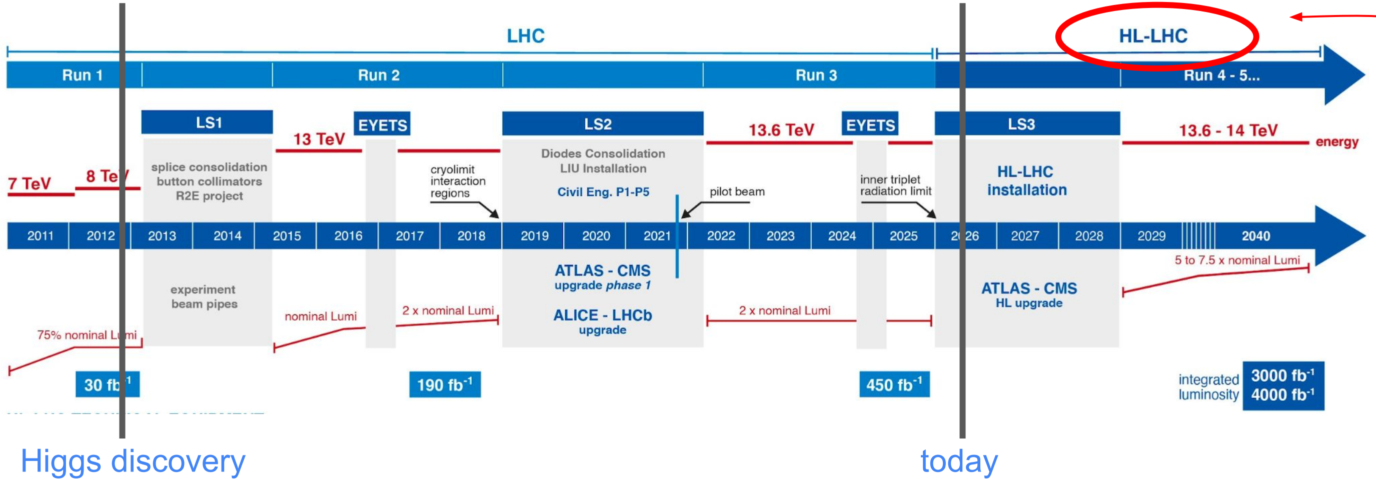
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

- Challenge: dimension 6 $\sim$ 59 operators (after some assumptions...)
- Example: bounds on 4-tops operators [2604.16595]

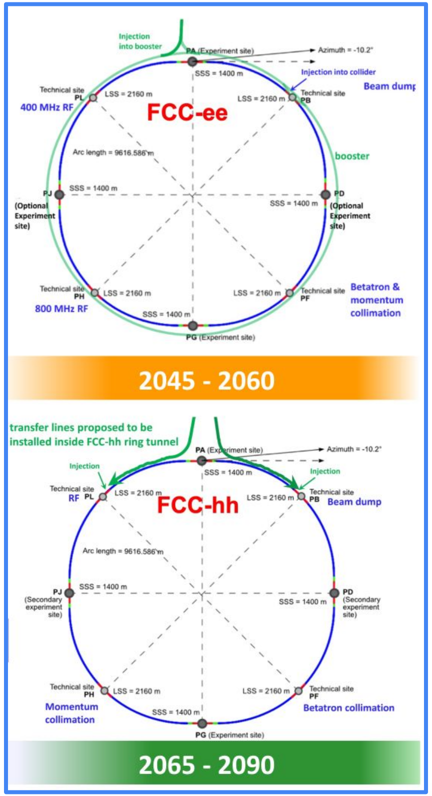


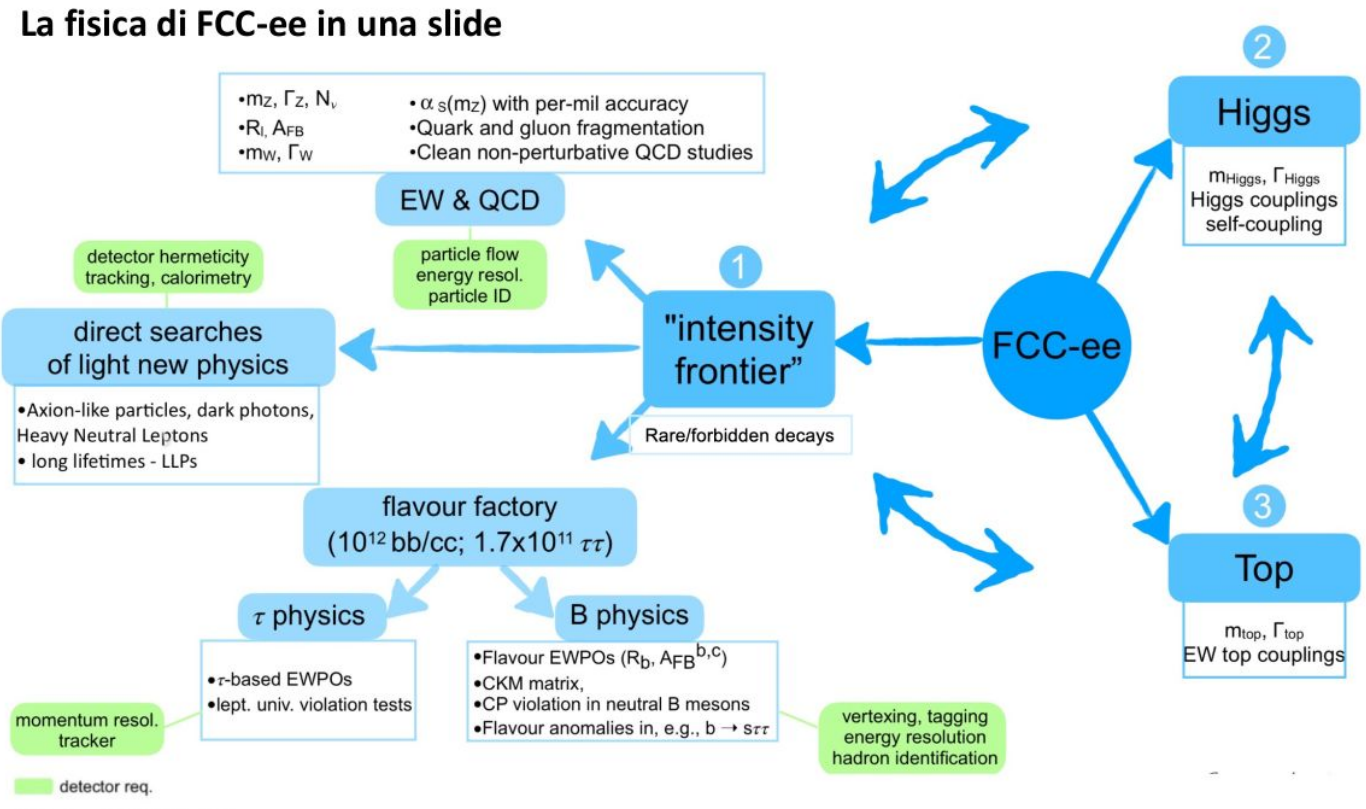
The path ahead



- High-Luminosity LHC: 15 years of data to come, ~10 times more statistics
- Increasingly clear that hints of new Physics at the LHC, if there, are difficult to be found
    - More and more ingenuity and advanced techniques in EXP analysis
    - Role of precise computations in the SM become more and more important

Beyond the LHC (>2040)





Slide from C. Grojean @ FCC Week'22

Extraordinary stat → precision ⊕ 100 TeV → higher mass reach

Conclusions

- SM (←QFT) is extremely successful in describing fundamental interactions
- SM: not the ultimate theory → BSM → explicit models / bottom up approach
- Path to New Physics: Direct vs Indirect searches
- Both ways: impressive progress in understanding and exploiting QFT (e.g. QCD)

Ultimate goal: find hints of new Physics

- Scale of New Physics not clear; precision measurements might give hints

- The LHC will continue (~20 years) probing fundamental physics at energies never explored before + other smaller experiments
- Large and lively TH communities, new ideas, interactions with EXP colleagues
- Many intense years ahead of us ……………………(ahead of YOU!)