Standard Model and Beyond at colliders

JUL. 5 2017 **ROBERTO FRANCESCHINI (ROMA 3 UNIVERSITY)**





Open Questions on the "big picture" on fundamental physics circa 2020



EFT

EFT

- why QCD does not violate CP?
- how have baryons originated in the early Universe?
- what is the dark matter in the Universe?
- what originates flavor mixing and fermions masses?
- what gives mass to neutrinos?
- why gravity and weak interactions are so different?
- what fixes the cosmological constant?

end of "The Boltzmann Way"



COLLISIONS

AS PROBES OF THE MICROSCOPIC CHARACTER OF NATURE





SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE





SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE





SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE





Symmetries and particles



1973

SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE



a symmetry that relates bosons and fermions, supersymmetry



SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE



a symmetry that relates bosons and fermions, supersymmetry





SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE



a symmetry that relates bosons and fermions, supersymmetry





SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE







 $\begin{aligned} \chi &= -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ &+ i F \mathcal{D} \mathcal{V} + h.c. \\ &+ \mathcal{V}_i \mathcal{Y}_{ij} \mathcal{Y}_j \mathcal{P} + h.c. \end{aligned}$ $+ \left| \sum_{n} \varphi \right|^2 - V(\phi)$

SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE



?????



SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE







?????





How we get out of there?

SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE

 $C + \mu^2 F$ Fermi constant (periodic table)

Cosmological Constant (galaxy formation)

Steven Weinberg Phys. Rev. Lett. 59, 2607 - If $c > 200 c_{Misurato}$ galaxies would ne be able to form (matter-domination phase too short) arXiv:hep-ph/9707380 Agrawal et al. - If $\mu > 5 \cdot \mu_{SM}$ periodic table disappears! (neutron decay too fast) arXiv:1205.6497 - Degrassi et al. - If m_{Higgs} grew by 1%, Universe would be unstable (in the SM) Rev. Mod. Phys. 68, 951 - Cahn, Robert N. - The eighteen arbitrary parameters of the standard model in your everyday life

?????

Coincidences? $\mathcal{L} = c + \mu^2 H^2 + \lambda H^4$

Higgs boson mass (meta-)stability of the Universe

How we get out of there?

SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE

Fermi constant

Cosmological Constant (galaxy formation)

Steven Weinberg Phys. Rev. Lett. 59, 2607 - If $c > 200 c_{Misurato}$ galaxies wc β arXiv:hep-ph/9707380 Agrawal et al. - If $\mu > 5 \cdot \mu_{SM}$ periodic ta arXiv:1205.6497 - Degrassi et al. - If m_{Higgs} grew by 1% Rev. Mod. Phys. 68, 951 - Cahn, Robert N. - The eighteen arbitrary para

?????

Coincidences? $\mathcal{L} = c + \mu^2 H^2 + \lambda H^4$ (periodic table) 180 200 Instability Meta-stability Instability ivers > M_t in GeV Meta-stabi 150 ·Ħ 175 M_t $1,2,3\sigma$ **Stability** 100 rbativity lomii 🗗 170 bole fat oot 50 Stability h the 165 115 125 120 130 150 200 100 0 50 youi Higgs mass M_h in GeV

Higgs mass M_h in GeV



Beyond LO all the way

SYMMETRY

CURSE OR BLESSING?



Reference

PLB 761 (2016) 158 Nucl. Phys. B, 486-548 (2014) PLB 759 (2016) 60 EPJC 77 (2017) 367 JHEP 02 (2017) 117 JHEP 02 (2017) 117 JHEP 02 (2017) 117 PLB 761 (2016) 136 EPJC 74: 3109 (2014) EPJC 74: 3109 (2014) JHEP 04 (2017) 086 EPJC 77 (2017) 531 PRD 90, 112006 (2014) PLB 773 (2017) 354 PLB 763, 114 (2016) PRD 87, 112001 (2013) PRL 113, 212001 (2014 ATLAS-CONF-2017-047 EPJC 76, 6 (2016) EPJC 76. 6 (2016) JHEP 01 (2018) 63 JHEP 01, 064 (2016) PLB 716, 142-159 (2012) ATLAS-CONF-2018-034 PLB 761 (2016) 179 PRD 93, 092004 (2016) PLB 761 (2016) 179 JHEP 01, 099 (2017) PLB 756, 228-246 (2016 EPJC 77 (2017) 40 JHEP 11, 172 (2015) EPJC 77 (2017) 40 JHEP 11, 172 (2015)

PLB 780 (2018) 557

 Standard Model calculations have been improved beyond lowest order and can be automated in basically all cases at NLO (EW may still resist though).

•General agreement confirms SM in total rates

•Differential distributions may need NNLO, not easy but slowly coming

 In any event, amplitudes in a gauge theory beyond lowest order:

become too many

• develop complicated divergences structure

•play with/remove gauge principle seems to help to simplify these issues (the "too many" problem for sure)







effects in single Higgs processes and precision physics is actually very competitive with the present



BSM is missing

NEW

SYMMETRY OR ENERGY SCALE

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2019 Model Signature $\int \mathcal{L} dt \, [\mathbf{fb}^{-1}]$ Mass limit E_T^{miss} E_T^{miss} 36.1 36.1 0 e,µ 2-6 jets 1.55 $m(\tilde{\chi}_1^0) < 100 \, \text{GeV}$ $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ [2x, 8x Deger 1-3 jets [1x, 8x Degen.] mono-jet 0.43 0.71 $m(\tilde{q})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$ 2-6 jets $E_T^{\rm miss}$ 36.1 0 e,µ $m(\tilde{\chi}_1^0) < 200 \, GeV$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$ 0.95-1.6 Forbidden $m(\tilde{\chi}_1^0)=900 \, \text{GeV}$ 4 jets $m(\tilde{\chi}_1^0) < 800 \, GeV$ 3 e,µ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$ 36.1 $E_T^{\rm miss}$ $ee, \mu\mu$ 2 jets 36.1 1.2 $m(\tilde{g})-m(\tilde{\chi}_1^0)=50 \text{ GeV}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$ 0 e,µ 7-11 jets $E_T^{\rm miss}$ 36.1 $m(\tilde{\chi}_{1}^{0}) < 400 \, \text{GeV}$ 36.1 4 jets 0.98 3 e, µ $m(\tilde{g})-m(\tilde{\chi}_1^0)=200 \text{ GeV}$ $E_T^{\rm miss}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ 0-1 e,μ 3 b 79.8 $m(\tilde{\chi}_1^0) < 200 \, GeV$ 2.25 36.1 1.25 3 e,µ 4 jets $m(\tilde{g})-m(\tilde{\chi}_1^0)=300 \, \text{GeV}$ $\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^{\pm}$ Multiple 36.1 Forbidden 0.9 $m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}, BR(b\tilde{\chi}_{1}^{0})=1$ Multiple 0.58-0.82 36.1 Forbidden $m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}, BR(b\tilde{\chi}_{1}^{0})=BR(t\tilde{\chi}_{1}^{\pm})=0.5$ Multiple 36.1 Forbidden 0.7 $m(\tilde{\chi}_{1}^{0})=200 \text{ GeV}, m(\tilde{\chi}_{1}^{\pm})=300 \text{ GeV}, BR(t\tilde{\chi}_{1}^{\pm})=1$ E_T^{miss} 139 $\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$ $0 e, \mu$ 6 b 0.23-1.35 $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \,\text{GeV}, \, m(\tilde{\chi}_{1}^{0}) = 100 \,\text{GeV}$ Forbidde 0.23-0.48 $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ or $t \tilde{\chi}_1^0$ 0-2 e, μ 0-2 jets/1-2 $b E_T^{\text{miss}}$ 36.1 $m(\tilde{\chi}_1^0)=1 \text{ GeV}$ $\tilde{t}_1 \tilde{t}_1$, Well-Tempered LSP 0.48-0.84 Multiple 36.1 $\mathsf{m}(\tilde{\chi}_1^0)$ =150 GeV, $\mathsf{m}(\tilde{\chi}_1^{\pm})$ - $\mathsf{m}(\tilde{\chi}_1^0)$ =5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$ $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$ $1 \tau + 1 e, \mu, \tau$ 2 jets/1 b E_T^{miss} 36.1 $m(\tilde{\tau}_1)=800 \, GeV$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$ 0 e,µ 2 c 36.1 0.85 $m(\tilde{\chi}_1^0)=0$ GeV E_T^{miss} 0.46 0.43 $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$ 36.1 0 e, µ mono-iet $m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$ $\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$ 0.32-0.88 $E_T^{\rm miss}$ 36.1 1-2 e,μ 4 b $m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}, m(\tilde{t}_{1})-m(\tilde{\chi}_{1}^{0})=180 \text{ GeV}$ $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via WZ 2-3 e,µ $E_T^{
m miss}$ $E_T^{
m miss}$ 36.1 36.1 0.6 $m(\tilde{\chi}_1^0)=0$ 0.17 ≥ 1 $ee, \mu\mu$ $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=10 \text{ GeV}$ $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ via WW $E_T^{\rm miss}$ 139 0.42 2 e, µ $m(\tilde{\chi}_1^0)=0$ 36.1 $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via Wh0-1 e, µ E_T^{miss} $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 2 b 0.68 $m(\tilde{\chi}_1^0)=0$ $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L / \tilde{\nu}$ 2 e,µ E_T^{miss} 139 $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ 36.1 $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0, \tilde{\chi}_1^{+} \rightarrow \tilde{\tau}_1 \nu(\tau \tilde{\nu}), \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau(\nu \tilde{\nu})$ $m(\tilde{\chi}_1^0)=0, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ 2τ E_T^{miss} $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.76 0.22 $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=100 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ $E_T^{
m miss}$ $E_T^{
m miss}$ 2 e,µ 0 jets 0.7 $\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$ 139 $m(\tilde{\chi}_1^0)=0$ 0.18 36.1 2 e, µ ≥ 1 $m(\tilde{\ell})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$ $\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$ $E_T^{
m miss}$ $E_T^{
m miss}$ 0 e,µ $\geq 3 b$ 36.1 0.13-0.23 0.29-0.88 $BR(\tilde{\chi}_1^0 \to h\tilde{G})=1$ 0 jets 36.1 0.3 $BR(\tilde{\chi}_1^0 \to Z\tilde{G})=1$ 4 e,µ Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$ Disapp. trk 1 jet E_T^{miss} 36.1 0.46 Pure Wino 0.15 Pure Higgsino Stable g R-hadron Multiple 36.1 2.0 Multiple 2.05 2.4 36.1 Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_{1}^{0}$ $m(\tilde{\chi}_1^0)=100 \text{ GeV}$ LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$ $e\mu, e\tau, \mu\tau$ 3.2 1.9 $\lambda'_{311}=0.11, \lambda_{132/133/233}=0.07$ $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$ 4 e,µ 0 jets E_T^{miss} 36.1 0.82 1.33 $m(\tilde{\chi}_1^0)=100 \text{ GeV}$ $\lambda_{133}^{\circ} \neq \mathbf{0}, \lambda_{12k} \neq \mathbf{0}$ 4-5 large-R jets 36.1 ")=200 GeV, 1100 GeV] =2e-4, 2e-5] 1.3 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$ Large $\lambda_{11}^{\prime\prime}$ 1.9 Multiple 36.1 1.05 2.0 $m(\tilde{\chi}_1^0)=200 \text{ GeV}, \text{ bino-like}$ $\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$ Multiple [λ''_{222} =2e-4, 1e-2] 36.1 0.55 1.05 $m(\tilde{\chi}_1^0)=200 \text{ GeV}, \text{ bino-like}$ 2 jets + 2 *b* $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$ 0.42 0.61 36.7 $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$ 2 e, µ 2 b 36.1 0.4-1.45 $BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$ -10< λ'_{22} <1e-8, 3e-10< λ'_{22} <3e-9] 1μ DV 136 1.0 1.6 BR($\tilde{t}_1 \rightarrow q\mu$)=100%, cos θ_t =1

 10^{-1}

Mass scale [TeV]

1

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Tuning often quoted, but beware tuning is a plastic material shrinks under heat (unlike "normal" solid)





XX CENTURY

EXAMPLE FROM WEAK INTERACTIONS

SHORT-DISTANCE THEORY (which Today we know) n n p

 $\sigma \sim E^2 G_F^2 \sim \frac{E}{v^4}$



EFFECTIVE 4-FERMION INTERACTION

XXI CENTURY

EXAMPLE FROM HIGGS&WEAK INTERACTIONS

SHORT-DISTANCE THEORY (which Today we DON'T Know)







EFFECTIVE 4-PARTICLE IN FERACTION

XXI CENTURY

EXAMPLE FROM HIGGS&WEAK INTERACTIONS



XXI CENTURY

EXAMPLE FROM HIGGS&WEAK INTERACTIONS



$\sigma = \sigma_{SM} + \sigma_{BSM} \sim \sigma_{SM}$

*Light exceptional cases

SYMMETRY

AND ITS SUBTLE CONSEQUENCES





How to move forward?



- the least well known
- the highest mass scale
- the most central to the origin of EW scale

*of any shape

How to move forward?

● ● ● < > □

CERN Accelerating science



European Strategy Update



"The size of the Higgs boson"

it matters because being "point-like" is the source of all the theoretical questions on the Higgs boson and weak scale

... and if it is not ... well, that is physics beyond the Standard Model!





LOW ENERGY CIRCULAR COLLIDER





The size of the Higgs boson





LOW ENERGY LINEAR COLLIDER



Lots of material from



CLIC detector & physics + Theory community

Editors: J. De Blas, R. Franceschini, F. Riva, P. Roloff, U. Schnoor, M. Spannowsky, A. Wulzer, J. Wells, J. Zupan http://clicdp.web.cern.ch/content/wg-physics-potential



Lots of material from

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Lots of material from

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Mediator of Neutrino mass mechanism

DOUBLY CHARGED

in total rate $e^+e^- \rightarrow \ell^+ \ell^-$



$$\mathcal{L}_{\mathrm{UV}} = \mathcal{L}_{\mathrm{SM}} + \left(D_{\mu}S^{++}\right)^{\dagger} \left(D^{\mu}S^{++}\right) + \left(\lambda_{ab}\overline{(\ell_R)}_{a}^{c}(\ell_R)_{b}S^{++} + \mathrm{h.c.}\right) + \lambda_2\left(H^{\dagger}H\right)\left(S^{--}S^{++}\right) + \lambda_4\left(S^{--}S^{++}\right)^2 + [\ldots],$$





+

Lumivs. Energy

New Physics may fit well in a EFT (new contact interactions) • effects grow at larger energies like $ve \rightarrow ve^{-1}$ in Fermi Theory

$m_W, m_Z, \sin \theta_W, A_{FR}^{whatever}, h \to Z\gamma, h \to ZZ, t \to b\tau\nu$

measurements dominated by a single mass scale

- dominant energy scale is low
- measurement is simple to grasp

LESSON FROM LHC

EFT EPOCH

progress is easy to measure (in)significant digits





$$d\sigma$$

 dp_T

measurements sensitive to a range of mass scales

- sensitive to a range of energy scales
- measurement of a spectrum (not so?!?) simple to grasp
- progress is easy to measure: bounds on new Fermi constants

Lumivs. Energy

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HIGH-LUMI PROBES

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as NP effects may grow quadratically with energy $\sim - 2$ $\Delta O = O_{NP} - O_{SM} \sim \left(\frac{E}{v}\right)$ 1% at m_z is worse than 10% at 1 TeV

Effects of the size of the Higgs boson

h~π

STRONGLY INTERACTING LIGHT HIGGS

$$\begin{aligned} \mathcal{L}_{universal}^{d=6} &= c_{H} \frac{g_{*}^{2}}{m_{*}^{2}} \mathcal{O}_{H} + c_{T} \frac{N_{c} \epsilon_{q}^{4} g_{*}^{4}}{(4\pi)^{2} m_{*}^{2}} \mathcal{O}_{T} + c_{6} \lambda \frac{g_{*}^{2}}{m_{*}^{2}} \mathcal{O}_{6} + \frac{1}{m_{*}^{2}} [c_{W} \mathcal{O}_{W} + c_{B} \mathcal{O}_{B}] \\ &+ \frac{g_{*}^{2}}{(4\pi)^{2} m_{*}^{2}} [c_{HW} \mathcal{O}_{HW} + c_{HB} \mathcal{O}_{HB}] + \frac{y_{t}^{2}}{(4\pi)^{2} m_{*}^{2}} [c_{BB} \mathcal{O}_{BB} + c_{GG} \mathcal{O}_{GG}] \\ &+ \frac{1}{g_{*}^{2} m_{*}^{2}} \left[c_{2W} g^{2} \mathcal{O}_{2W} + c_{2B} g'^{2} \mathcal{O}_{2B} \right] + c_{3W} \frac{3! g^{2}}{(4\pi)^{2} m_{*}^{2}} \mathcal{O}_{3W} \\ &+ \frac{c_{y_{t}} \frac{g_{*}^{2}}{m_{*}^{2}} \mathcal{O}_{y_{t}} + c_{y_{b}} \frac{g_{*}^{2}}{m_{*}^{2}} \mathcal{O}_{y_{b}} \end{aligned}$$

$$1/f \sim g_{\star}/m_{\star}$$

 $1/(g_{\star}f) \sim 1/m_{\star}$

$$g_{SM}/(g_{\star}f) \sim g_{SM}/m_{\star}$$



Effects of the size of the Higgs boson

h~π

STRONGLY INTERACTING LIGHT HIGGS

$$\begin{aligned} \mathcal{L}_{universal}^{d=6} &= c_{H} \frac{g_{*}^{2}}{m_{*}^{2}} \mathcal{O}_{H} + c_{T} \frac{N_{c} \epsilon_{q}^{4} g_{*}^{4}}{(4\pi)^{2} m_{*}^{2}} \mathcal{O}_{T} + c_{6} \lambda \frac{g_{*}^{2}}{m_{*}^{2}} \mathcal{O}_{6} + \frac{1}{m_{*}^{2}} [c_{W} \mathcal{O}_{W} + c_{B} \mathcal{O}_{B}] \\ &+ \frac{g_{*}^{2}}{(4\pi)^{2} m_{*}^{2}} [c_{HW} \mathcal{O}_{HW} + c_{HB} \mathcal{O}_{HB}] + \frac{y_{t}^{2}}{(4\pi)^{2} m_{*}^{2}} [c_{BB} \mathcal{O}_{BB} + c_{GG} \mathcal{O}_{GG}] \\ &+ \frac{1}{g_{*}^{2} m_{*}^{2}} \left[c_{2W} g^{2} \mathcal{O}_{2W} + c_{2B} g'^{2} \mathcal{O}_{2B} \right] + c_{3W} \frac{3! g^{2}}{(4\pi)^{2} m_{*}^{2}} \mathcal{O}_{3W} \\ &+ \frac{c_{y_{t}} \frac{g_{*}^{2}}{m_{*}^{2}} \mathcal{O}_{y_{t}} + c_{y_{b}} \frac{g_{*}^{2}}{m_{*}^{2}} \mathcal{O}_{y_{b}} \end{aligned}$$

$$1/f \sim g_{\star}/m_{\star}$$

 $1/(g_{\star}f) \sim 1/m_{\star}$

$$g_{SM}/(g_{\star}f) \sim g_{SM}/m_{\star}$$

$$r_{Higgs} \sim f^{-1} \sim g_{\star}/m_{\star}$$



complementary bounds from:

Drell-Yan (high-pT probe) $\frac{d\sigma}{d\cos\theta} \text{ of } e^+e^- \to f\bar{f}$



$$W = 2\frac{g^2}{g_{\star}^2}\frac{M_W^2}{M_{\star}^2}, \quad Y = 2\frac{g'^2}{g_{\star}^2}\frac{M_W^2}{M_{\star}^2}.$$

$$c_{6}\lambda \frac{g_{*}^{2}}{m_{*}^{2}}\mathcal{O}_{6} + \frac{1}{m_{*}^{2}}\left[c_{W}\mathcal{O}_{W} + c_{B}\mathcal{O}_{B}\right] + \frac{g_{*}^{2}}{(4\pi)^{2}m_{*}^{2}}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_{t}^{2}}{(4\pi)^{2}m_{*}^{2}}\left[c_{BB}\mathcal{O}_{BB} - \frac{g_{*}^{2}}{(4\pi)^{2}m_{*}^{2}}\right]$$

$${}_{2B}\Big] + c_{3W} \frac{3!g^2}{(4\pi)^2 m_*^2} \mathcal{O}_{3W} + c_{y_t} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_t} + c_{y_b} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_t}$$

complementary bounds from:

Higgs boson (high-luminosity probe)









complementary bounds from:

• Drell-Yan (high-pT probe)

$$\frac{d\sigma}{d\cos\theta} \text{ of } e^+e^- \to f\bar{f}$$

$$(1,2,3)$$

$$W = 2\frac{g^2}{g_{\star}^2}\frac{M_W^2}{M_{\star}^2}, \quad Y = 2\frac{g'^2}{g_{\star}^2}\frac{M_W^2}{M_{\star}^2}.$$



$$c_{6}\lambda \frac{g_{*}^{2}}{m_{*}^{2}}\mathcal{O}_{6} + \frac{1}{m_{*}^{2}}\left[c_{W}\mathcal{O}_{W} + c_{B}\mathcal{O}_{B}\right] + \frac{g_{*}^{2}}{\left(4\pi\right)^{2}m_{*}^{2}}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_{t}^{2}}{\left(4\pi\right)^{2}m_{*}^{2}}\left[c_{BB}\mathcal{O}_{BB} - \frac{g_{*}^{2}}{\left(4\pi\right)^{2}m_{*}^{2}}\right] + \frac{g_{*}^{2}}{\left(4\pi\right)^{2}m_{*}^{2}}\left[c_{BB}\mathcal{O}_{BB} - \frac{g_{*}^{2}}{\left(4\pi\right)^{2}m_{*}^{2}}\right] + \frac{g_{*}^{2}}{\left(4\pi\right)^{2}m_{*}^{2}}\left[c_{B}\mathcal{O}_{B} - \frac{g_{*}^{2}}{\left(4\pi\right$$

$${}_{2B}\Big] + c_{3W} \frac{3!g^2}{(4\pi)^2 m_*^2} \mathcal{O}_{3W} + c_{y_t} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_t} + c_{y_b} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_b}$$

complementary bounds from:

Higgs boson (high-luminosity probe)









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complementary bounds from:



$$c_{6}\lambda \frac{g_{*}^{2}}{m_{*}^{2}}\mathcal{O}_{6} + \frac{1}{m_{*}^{2}}\left[c_{W}\mathcal{O}_{W} + c_{B}\mathcal{O}_{B}\right] + \frac{g_{*}^{2}}{(4\pi)^{2}m_{*}^{2}}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_{t}^{2}}{(4\pi)^{2}m_{*}^{2}}\left[c_{BB}\mathcal{O}_{BB} + \frac{g_{*}^{2}}{(4\pi)^{2}m_{*}^{2}}\right] + \frac{g_{*}^{2}}{(4\pi)^{2}m_{*}^{2}}\left[c_{BB}\mathcal{O}_{BB} + \frac{g$$

$${}_{2B}\Big] + c_{3W} \frac{3!g^2}{(4\pi)^2 m_*^2} \mathcal{O}_{3W} + c_{y_t} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_t} + c_{y_b} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_b}$$

complementary bounds from:









complementary bounds from:



High energy lepton colliders can probe the large set of dim-6 operators for universal theories (least flavor puzzling) bounds are improving one order or better w.r.t. HL-LHC

$$c_{6}\lambda \frac{g_{*}^{2}}{m_{*}^{2}}\mathcal{O}_{6} + \frac{1}{m_{*}^{2}}\left[c_{W}\mathcal{O}_{W} + c_{B}\mathcal{O}_{B}\right] + \frac{g_{*}^{2}}{(4\pi)^{2}m_{*}^{2}}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_{t}^{2}}{(4\pi)^{2}m_{*}^{2}}\left[c_{BB}\mathcal{O}_{BB} + \frac{g_{*}^{2}}{(4\pi)^{2}m_{*}^{2}}\right]$$

$${}_{2B}\Big] + c_{3W} \frac{3!g^2}{(4\pi)^2 m_*^2} \mathcal{O}_{3W} + c_{y_t} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_t} + c_{y_b} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_b}$$





Unstable and weak: our future

Unstable and weakly charged: our future beams

Challenges we can see already from here

A BALANCING PROBLEM



Challenges we can see already from here

A BALANCING PROBLEM



 $\mathscr{L} \sim E^2$



Challenges we can see already from here

A BALANCING PROBLEM



$\sigma(ab \to cd) \sim 1/E^2$ $\mathscr{L} \sim E^2$ $\mathscr{L} \circ (ab \to cd) \sim \text{const}$



Time-scale

HOW LONG

DOES IT TAKE TO GET THERE?



DOABLE WITHIN ONE GENERATION

Time-scale (time · 10^{±1}?)

FUTURE?

FUTURE COLLIDERS

- 1 billion Higgs bosons!
- High-energy probes at even higher energy!
- electroweak beam structure exposed
- WW scattering as a "ordinary" collision
- thoroughly explore weakly interacting physics one loop factor above weak scale
- WIMP in large SU(2) multiplets in reach
- directly access the scale of composite states or susy partners

https://indico.cern.ch/event/831718/

µµ→ new physics?

MUON COLLIDER

CHALLENGE

10-11 April 2019 CERN Europe/Zurich timezone

µµ→ new physics?

MUON COLLIDER

CHALLENGE

µµ→ new physics?

MUON COLLIDER

CHALLENGE

Muon Source

Goals

- **Neutrino Factories**: Rate > $10^{14} \mu$ /sec within the acceptance of a μ ring
- luminosities >10³⁴/cm⁻²s⁻¹ at TeV-scale ($\approx N_{\parallel}^2 1/\epsilon_{\parallel}$) Muon Collider:

Options

Tertiary production through proton on target: cooling needed, baseline for Fermilab design study production Rate > $10^{13}\mu$ /sec N_µ = $2 \cdot 10^{12}$ /bunch (5 10⁸ μ /sec today @PSI)

- e⁺e⁻ annihilation: positron beam on target: very low emittance and no cooling needed, baseline for our proposal here production Rate $\approx 10^{11} \,\mu/\text{sec}$ N_{II} $\approx 5.10^9/\text{bunch}$ **10-20Hz cycle**
- **by Gammas (** $\gamma N \rightarrow \mu^+ \mu^- N$ **): GeV-scale Compton** γs not discussed here production Rate $\approx 5.10^{10} \,\mu/\text{sec}$ N₁₁ $\approx 10^{6}$ (Pulsed Linac) production Rate >10¹³ μ /sec N_{II} \approx few·10⁴ (High Current ERL) see also: W. Barletta and A. M. Sessler NIM \overrightarrow{A} 350 (1994) 36-44 ($e^-N \rightarrow \mu^+\mu^-e^-N$)

Buttazzo, RF, Wulzer

Order of magnitude improvement of the bunds on mass scale of new physics is possible

Even higher energy colliders can exploit "precise" measurements at the 10% level

ZH	Cross-Section	m 95% CL
3 TeV	1362 ab	12 TeV
14 TeV	62 ab	57 TeV
30 TeV	13 ab	120 TeV

 $d\sigma$ [ab] $d\theta_1^{\star}d\theta_2^{\star}$ $\bar{\theta}_{1,2}$

High-Energy lepton collider has large flux of "partonic" W bosons

less powerful than Zh in general on m* but tests different operators, e.g. OH

 $m_{\star} \gtrsim 14 \cdot g_{\star} \text{ TeV}$

EFT EPOCH

LESSON FROM LHC

Amplitude	High-energy primaries	Low-energy primaries
$\boxed{\bar{u}_L d_L \to W_L Z_L, W_L h}$	$\sqrt{2}a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2} \left[c_{\theta_W} (\delta g_{uL}^Z - \delta g_{dL}^Z) / g - c_{\theta_W}^2 \delta g_1^Z \right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2} \left[Y_L t_{\theta_W}^2 \delta \kappa_\gamma + T_Z^{u_L} \delta g_1^Z + c_{\theta_W} \delta g_{dL}^Z / g \right]$
$ \begin{array}{c} \bar{d}_L d_L \to W_L W_L \\ \bar{u}_L u_L \to Z_L h \end{array} $	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2} \left[Y_L t_{\theta_W}^2 \delta \kappa_\gamma + T_Z^{d_L} \delta g_1^Z + c_{\theta_W} \delta g_{uL}^Z / g \right]$
$\overline{f_R f_R \to W_L W_L, Z_L h}$	a_f	$-\frac{2g^2}{m_W^2} \left[Y_{f_R} t_{\theta_W}^2 \delta \kappa_\gamma + T_Z^{f_R} \delta g_1^Z + c_{\theta_W} \delta g_{fR}^Z / g \right]$

All-round progress up to $m^* \sim 10^2 m_{Higgs}$ (call it 16 $\pi^2 m_{Higgs}$)

Even higher energy colliders can exploit "precise" measurements at the 10% level

on mass scale of new physics is possible

m* 95% CL	
60 TeV (g*/4)	\mathcal{O}_H
84 ⊕ 76 TeV ≃113 TeV	$a_q^{(3)}$
120 TeV	$a_{q}^{(1)}$
120 TeV (4/g*)	W,Y

The size of the Higgs boson

LOW ENERGY LINEAR COLLIDER

LOW ENERGY LINEAR COLLIDER

$\sigma \cdot \mathscr{L} \simeq 10^9 \,\mathrm{H}$

- ultra-rare Higgs decays
- differential distribution
- off-shell Higgs bosons
- rare production modes

Buttazzo, RF, Wulzer

Direct Measurement of Y_b

if $\chi \sim 10^2 \chi_{boseline} \rightarrow \delta \gamma_{s} \sim 2\%$

$\ell^+\ell^- \rightarrow new physics$ LEPTONS VALENCE

Can produce heavy new physics (colored or not)

in principle can probe directly new states at O(10) TeV scale!

Compares pretty well with a pp collider

14 TeV µµ roughly equivalent to 100 TeV pp

probed and are under a fair amount of pressure

Motivations for new physics to be out there are stronger • than ever

Standard "targets" such as vanilla SUSY, compositeness of Higgs and other states, sub-TeV WIMPs are all being

- Searches for new physics at colliders are shifting towards •
- heavy and light new physics signals
- •

increasingly *heavier* and *subtler* signals (both direct and indirect)

multi-TeV leptonic colliders can cope well with the ever subtler

multi-TeV leptonic colliders, e.g. CLIC, can deliver high-energy and high-luminosity \Rightarrow provide both *precision* and *mass reach* for BSM

• their interactions

- a multi-10-TeV muon collider appears as a fantastic chance to put high energy physics on a fast lane towards substantial advancement of our understanding of
- fundamental properties of constituents of matter and

Thank You!

WITHIN 2:30PM - 3:00PM ???

20+X MIN.?

