Teoria – Alte Energie
progetti a Roma 1

Marco Bonvini

INFN, Rome 1 unit

Assisi, 16 Giugno 2019

Definition of High Energy

High with respect to what?

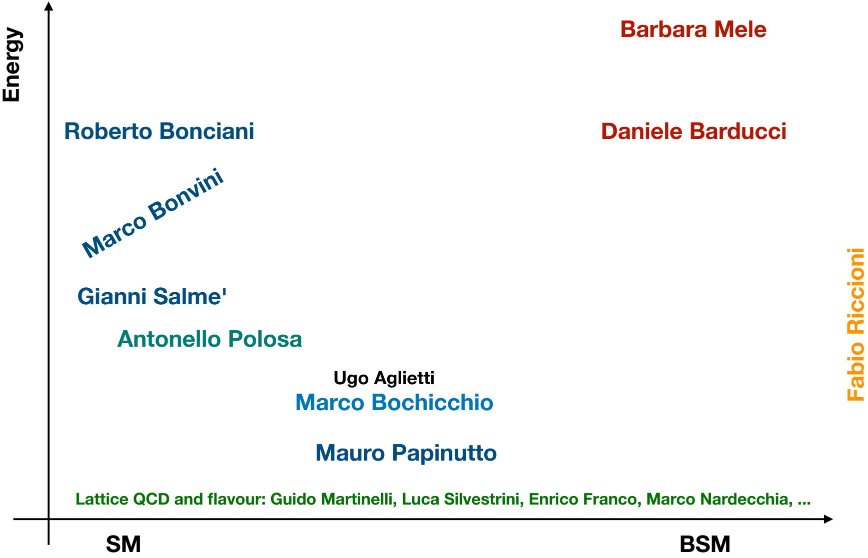
My own answer: wrt to the "scale of the theory":

- QCD: $\boldsymbol{Q \gg \Lambda_{\mathrm{QCD}} \sim 0.2}$ GeV
- EW: $\boldsymbol{Q \gg v \sim 250}$ GeV

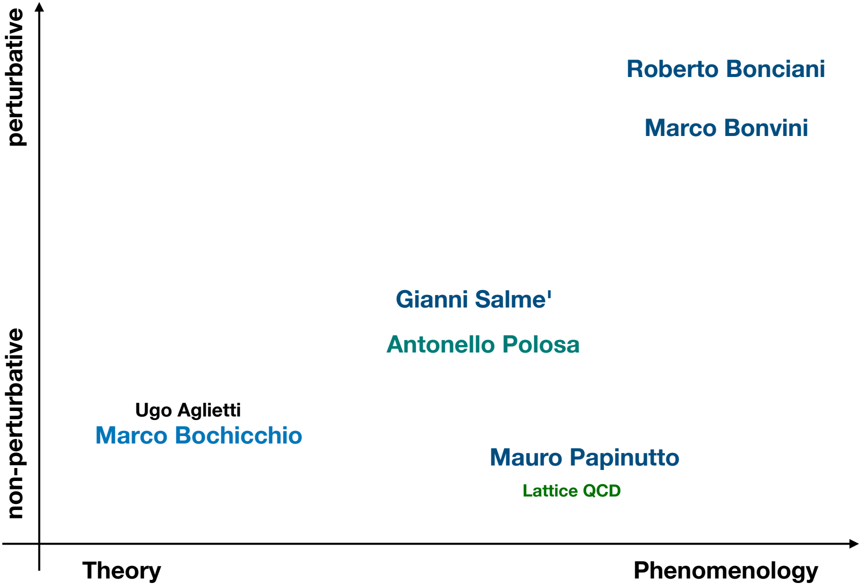
This allows me to include the activity of more people in Rome

Flavour physics is excluded (tomorrow morning's session)

Overview of the theorists in Rome 1 + Sapienza

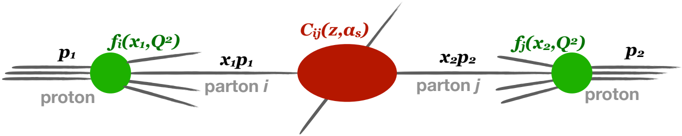


QCD (mostly SM)



Collinear factorization theorem in QCD:

$$\frac{d\sigma}{dQ^2 dy dp_t \ldots} \simeq \sum_{i,j=g,q} \int_0^1 dx_1\, dx_2\, f_i(x_1, Q^2) f_j(x_2, Q^2)\, C_{ij}(x_1, x_2, y, p_t, \ldots, \alpha_s(Q^2))$$



- partonic cross sections $C_{ij}(\ldots, \alpha_s)$ (observable-dependent, perturbative)
- parton distribution functions (PDFs) $f_i(x, Q^2)$ (universal, non-perturbative)

There exist generalizations (transverse momentum dependent factorization, double parton scattering, ...)

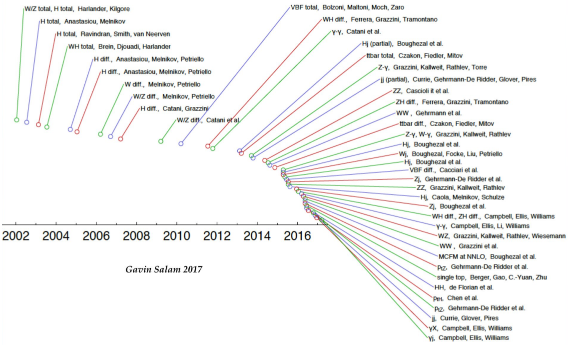
Perturbative computations of the partonic cross sections

$$C(\ldots,\alpha_s) = \underbrace{C^{(0)}(\ldots)}_{\text{LO}} + \underbrace{\alpha_s C^{(1)}(\ldots)}_{\text{NLO}} + \underbrace{\alpha_s^2 C^{(2)}(\ldots)}_{\text{NNLO}} + \underbrace{\alpha_s^3 C^{(3)}(\ldots)}_{\text{N}^3\text{LO}} + \ldots$$

LO: trivial

NLO revolution: automation (MG5_aMC@NLO and others, matching to parton showers)

NNLO revolution:

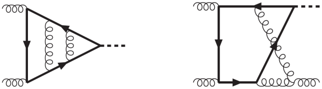


N^{3}LO: inclusive total cross section for Higgs production in gluon fusion

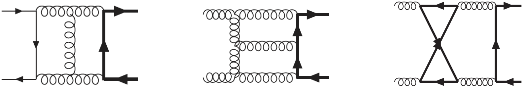
Analytic computations are faster and more powerful than numerical ones

Need to reduce to master integrals, and solve differential equations (sometimes elliptic)

- Higgs production: mass corrections to total XS at NNLO or to $H + j$ at NLO (sensitive to new physics in loop at medium/high p_t)



- top pair production at NNLO (asymmetries and top properties, constraints on the gluon PDF at large x)



- di-jet production at NNLO (determination of α_s and constraints on PDFs at medium-large x)

All-order resummation of logarithmically enhanced contributions

In general, perturbative coefficients contain logarithms of dimensionless ratios

$$L = \log(\text{something})$$

Sometimes, they are logarithmically enhanced:

$$\begin{aligned} C(\ldots, \alpha_s) = \quad & a_0 \\ & + \alpha_s \left[a_1 L + b_1\right] \\ & + \alpha_s^2 \left[a_2 L^2 + b_2 L + c_2\right] \\ & + \alpha_s^3 \left[a_3 L^3 + b_3 L^2 + c_3 L + d_3\right] \\ & + \alpha_s^4 \left[a_4 L^4 + b_4 L^3 + c_4 L^2 + d_4 L + e_4\right] \\ & + \ldots \end{aligned}$$

If/when $\alpha_s L \sim 1$ the fixed-order expansion is no longer predictive!

Resum the logs, and convert to a "logarithmic-order" expansion:

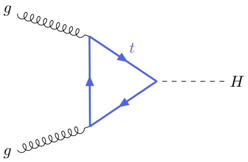
$$g_{\rm LL}(\alpha_s L) + \alpha_s\, g_{\rm NLL}(\alpha_s L) + \alpha_s^2\, g_{\rm NNLL}(\alpha_s L) + \alpha_s^3\, g_{\rm N^3LL}(\alpha_s L) + \ldots$$

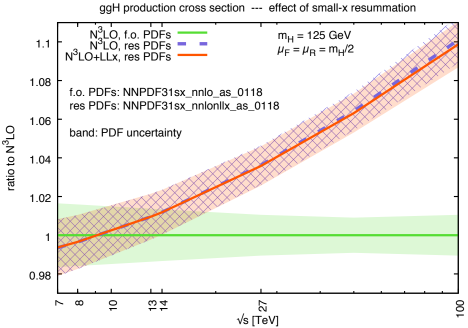
Leading log (LL), next-to-leading log (NLL), next-to-next-to-leading log (NNLL)...

Past and current activities:

- threshold logarithms
- small p_t logarithms
- collinear logarithms in presence of massive (heavy) quarks
- small-x (high-energy) resummation

Applications e.g. to Higgs physics





M.Bonvini: also interested in theoretical uncertainties

... with DGLAP evolution

$$Q^2 \frac{d}{dQ^2} f_i(x, Q^2) = \sum_{j=g,q} \int_x^1 \frac{dz}{z} P_{ij}(z, \alpha_s(Q^2)) f_j\left(\frac{x}{z}, Q^2\right)$$

Splitting functions $P_{ij}(x, \alpha_s)$ (universal, perturbative)

PDFs at a given scale Q_0 + DGLAP evolution $\to$ PDFs at any scale Q

$f_i(x, Q_0^2)$ at low $Q_0 \sim 1$ GeV is non-perturbative: how to determine?

Standard approach: determine PDFs by comparison with (many) data

parametrize PDFs at initial scale Q_0 $f_i(x, Q_0^2)$ $\to$ **evolve with DGLAP to the data scale Q** $f_i(x, Q^2_{\text{data}})$ $\to$ **compute the cross section** σ_{theo} $\to$ **compare with actual data** $(\sigma_{\text{theo}} - \sigma_{\text{data}}) \to \chi^2$

Activity [M.Bonvini]: include all-order resummations in PDF fits

Can we determine PDFs from the theory? [G.Salme']

Non-perturbative problem → numerical simulations on a discretized spacetime
However, the field-theoretic definition of PDFs involves light-cone distances:

$$f_q(x,Q^2) = \int \frac{d\xi}{4\pi}\, e^{-ix\xi P^+} \langle P|\bar\psi_q(\xi)\not{n} U_n(\xi,0)\psi_q(0)|P\rangle \qquad \xi^2 = 0$$

but in lattice QCD simulation the spacetime is Euclidean, where light-cone separations are only trivial ($\xi = 0$) → **PDFs cannot be computed in lattice QCD!**

Need to work directly in Minkowski space

A possible approach makes use of the Bethe-Salpeter equation to study a relativistic bound state, which can account for non-perturbative effects

$$G_{\text{4pt}}(k,q;p) \sim \frac{\chi(k,p)\chi(q,p)}{2\omega(p^0-\omega+i\epsilon)} \qquad \chi(k,p) = G_0(k,p)\int d^4k'\, I(k,k',p)\chi(k',p)$$

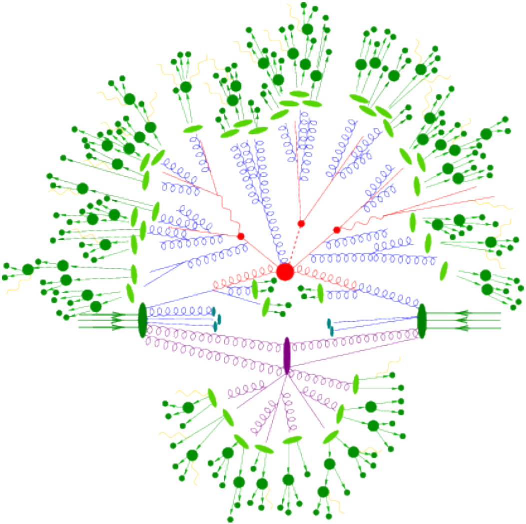
Working in the Euclidean is simpler, but staying in Minkowski, though more difficult, is now achievable thanks to the so-called Light-Front framework

Obtaining the PDFs is the ultimate goal of such a business
(transverse momentum dependent PDFs could be obtained similarly)

So far:
PDFs and hard scattering

Afterwards:
parton shower

Finally:
hadronization and decays



Exotic final states

[A.Polosa+L.Maiani]

Belle, BES, BaBar, LHCb,... have found a large number of exotic resonances, which appear to be composed of 4 or 5 quarks

Interpretation as bound states of di-quarks explains:

- mixing
- degeneracies
- decay rates
- spin interactions

Dynamical description of how QCD produces these bounds states

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	References
$X(3872)$	3871.69±0.17	<1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [10,32], BaBar [36], LHCb [34,73]
				$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$	CDF [31,74,75], D0 [76]
				$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BES III [77]
				$B \to K(\omega J/\psi)$	Belle [78], BaBar [33]
				$B \to K(D^{*0}\bar{D}^0)$	Belle [38,79], BaBar [37]
				$B \to K(\gamma J/\psi)$ and	Belle [29], BaBar [30],
				$B \to K(\gamma\psi(2S))$	LHCb [40]
$Z_c(3900)^+$	3888.7 ± 3.4	35±7	1^+	$e^+e^- \to (J/\psi\,\pi^+)\pi^-$	Belle [43], BES III [55]
				$e^+e^- \to (D\bar{D}^*)^+\pi^-$	BES III [56]
$X(3915)$	3915.6 ± 3.1	28±10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [80], BaBar [33]
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [81], BaBar [82]
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(DD^*)$	Belle [83]
				$e^+e^- \to J/\psi\ (\ldots)$	Belle [84]
$Y(4008)$	3891 ± 42	255±42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [42,43]
$Z_c(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [53], BaBar [54]
$X(4050)^+$	4054 ± 3	45	?	$e^+e^- \to (\pi^+\psi(2S))\pi^-$	Belle [85]
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [72],D0 [86]
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [83]
$Z_c(4200)^+$	4196^{+35}_{-32}	370^{+99}_{-149}	?	$B \to K(\pi^+ J/\psi)$	Belle [87]
$Z_c(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [53], BaBar [54]
$Y(4260)$	4263 ± 5	108±14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BaBar [41,88], CLEO [89], Belle [42,43]
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [47], BES III [56]
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [47]
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$?^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [90]
$Y(4360)$	4361 ± 13	74±18	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	BaBar [44], Belle [45,85]
$Z_c(4430)^+$	4485^{+36}_{-25}	200^{+49}_{-58}	1^+	$B \to K(\pi^+\psi(2S))$	Belle [49,51,52], BaBar [50], LHCb [21]
				$B \to K(\pi^+ J/\psi)$	Belle [87], BaBar [50]
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [91]
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [45]
$Z_b(10610)^+$	10607.2±2.0	18.4±2.4	1^+	$e^+e^- \to (b\bar{b}\,\pi^+)\pi^-$	Belle [20]
$Z_b(10610)^0$	10609±4±4	NA	1^{+-}	$e^+e^- \to (\Upsilon(2,3S)\pi^0)\pi^0$	Belle [23]
$Z_b(10650)^+$	10652.2±1.5	11.5±2.2	1^+	$e^+e^- \to (b\bar{b}\,\pi^+)\pi^-$	Belle [20]
$Y_b(10888)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [60,62]

A.Polosa: also carbon nanotubes and graphene as directional detectors of light Dark Matter and effective theories of liquid helium for Dark Matter detectors

[+M.Papinutto+U.Aglietti]

Find solution of the large-N limit of QCD

- theory of quark and gluons $\rightarrow$ theory of glueballs and mesons
- strong coupling α_s $\rightarrow$ weak coupling $1/N$

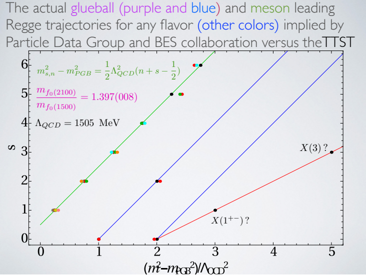
The solution must possess two fundamental properties:

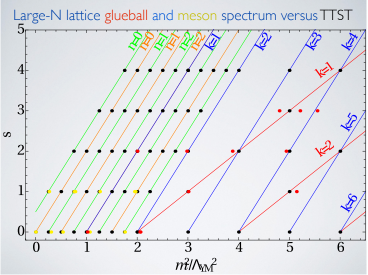
- asymptotic freedom
- renormalizability (renormalization group)

Canonical string theory (glueballs:closed mesons:open strings) cannot be a solution

$\rightarrow$ **Non-canonical string solutions** (twistor strings)

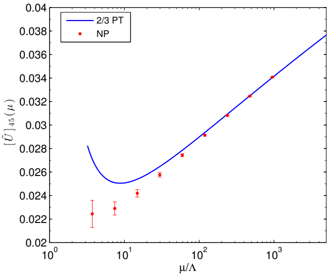
It is the only presently known string theory that may be consistent, both for the ultraviolet asymptotics and the spectrum, with the fundamental principles of QCD





In Rome1 + Rome3 a strong lattice QCD group, mostly interested in flavour physics
I assume it will be covered tomorrow morning

Important: non-perturbative renormalization [M.Papinutto]
At low scales computing Wilson coefficients perturbatively can miss important higher-order and non-perturbative effects



Future project: lattice simulations of large-N QCD [M.Papinutto+M.Bochicchio]

String theory is a consistent quantum theory that contains gravity
General relativity arises in string theory as a Wilsonian effective theory

Local activity:

- understanding the general structure of the low energy theories in four dimensions (new results have been obtained in this directions in the past couple of years — fluxes and exotic branes)
- how to obtain inflation and a vacuum with a positive cosmological constant
- a microscopic understanding of the Bekenstein-Hawking entropy of black holes

Many theoretic ideas were born in this field of research, like large extra dimensions, holography, techniques to compute scattering amplitudes, ... and in this sense this line of research is very fruitful although not in direct contact with experiments

Two classes of motivations for BSM

- internal consistency issues of the SM (hierarchy, naturalness, strong CP, ...)
- experimental facts (dark matter, baryon asymmetry, neutrino masses, ...)

Two approaches to BSM

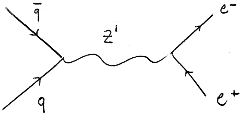
- model building (to address some of the above issues)
- phenomenology (either of a single model, or using SM-EFT)

Activities and expertise:

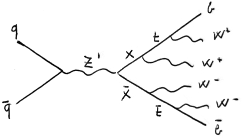
- (non-minimal) composite Higgs [hierarchy/naturalness]
- (non-minimal) SUSY [hierarchy/naturalness]
- WIMPs [DM + hierarchy/naturalness]
- hidden sector [DM + hierarchy/naturalness]
- technicolor [DM + neutrino mass]
- ....
- and of course flavour...

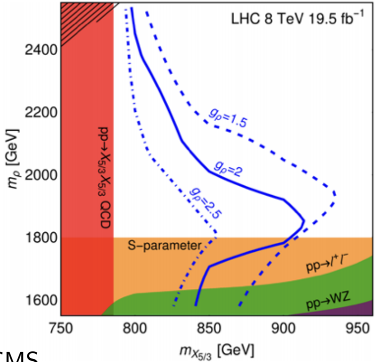
Non-minimal signatures in composite Higgs model [D.Barducci]

Conventional signature, $\sim g_w/g_\rho$ (suppressed)



Non-conventional signature, $\sim g_\rho$ (enhanced)





This work triggered an experimental analysis in CMS

Current interests:

- BSM models for dark matter and/or baryogenesis and/or neutrino masses, with interests to theories with first-order phase transitions leading to gravitational waves
- SM-EFT in EW and top sectors, with interests on the recent flavour anomalies

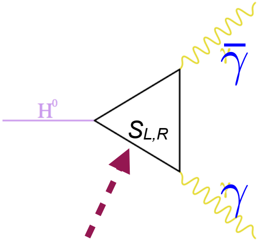
Member of CMS as theory collaborator, participating to light ($\lesssim 30$ GeV) scalar searches

A Dark Photon BSM model

A model of dark fermions with an unbroken $U(1)$ symmetry to explain

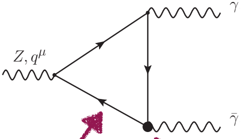
- dark matter
- flavour hierarchies

Mono-photon signatures in Higgs and Z decays



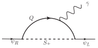
heavy scalar messengers
(squark/slepton-like)
connecting SM to HS

$$Z \to \gamma\bar{\gamma}$$



$$\mathcal{L} \sim \bar{\psi}\,\sigma_{\mu\nu}\,(d_M + i\gamma_5\, d_E)\,\psi\, B^{\mu\nu}$$

SM fermions



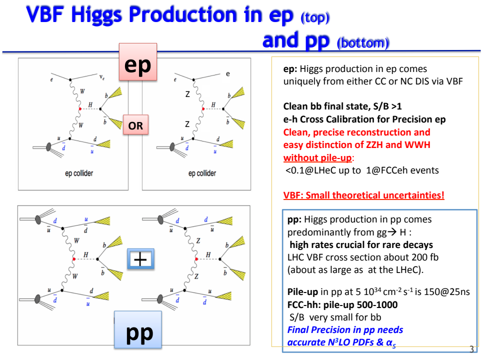
Also new Higgs signatures at e^+e^- colliders

Several options:

- e^+e^-: ILC, CLIC (linear), FCC-ee (circular) [B.Mele, D.Barducci]
- $e^\pm p$: LHeC, FCC-eh [M.Bonvini]
- pp: HE-LHC, FCC-hh [B.Mele, D.Barducci, M.Bonvini]
- $\mu^+\mu^-$: muon collider [B.Mele]

$e^\pm p$ collider very important for PDF determination
(functional to pp colliders)

Also very interesting physics cases!
[slide from Uta Klein]



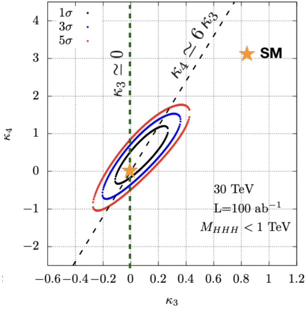
Can reach very high energies $\sqrt{s} \sim \mathbf{10 \div 30}$ TeV (negligible synchrotron radiation), but high luminosity is a challenge

Super clean: $\mu^+\mu^- \to f\bar{f}$ with $m_f \lesssim \sqrt{s}/2$

Higgs self-interaction measurements at a new level of precision

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \boxed{\lambda_3} \frac{m_h^2}{2v} h^3 - \boxed{\lambda_4} \frac{m_h^2}{8v^2} h^4$$

$$\lambda_3^{SM} = \lambda_4^{SM} = 1$$



For instance the quartic coupling λ_4 (assuming $\lambda_3 = 1$)

- FCC-hh at $\sqrt{s} = 100$ TeV for 30/ab: $\lambda_4 \in [-4, 16]$ at 68% c.l.
- muon coll at $\sqrt{s} = 30$ TeV for 100/ab: $\lambda_4 \in [0.8, 1.5]$ at 68% c.l.

Final considerations

Pros of the group:

- we cover various expertises
- various (inter)national connections

Cons of the group:

- we are quite disconnected/isolated locally
- very few students and post-docs

Suggestions/requests:

- improve communication among us, perhaps with a common room, a better seminar organization (e.g. with food after seminars), journal club(s), ...
- from M.Bochicchio: access to CPU hours at CINECA (issues related to assignments to iniziative specifiche)