CSN4: theoretical physics

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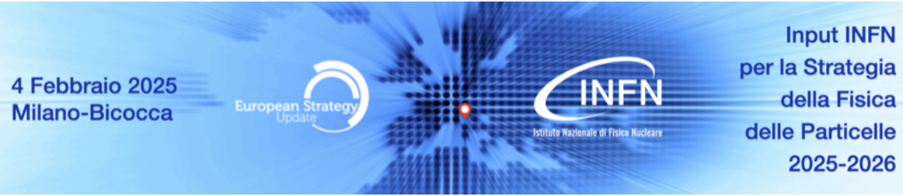
INFN, Sezione di Pavia and GGI



Dedicated events during 2024-2025

- L'INFN e la Strategia Europea per la Fisica delle Particelle, Rome, 6-7 May, 2024
  https://agenda.infn.it/event/39747/
- LFC24: Fundamental Interactions at Future Colliders, SISSA, 16-20 September, 2024
  https://agenda.infn.it/event/41113/
- Workshop on HighLumi-LHC and Hadron Colliders, 1-4 October 2024, LNF
  https://agenda.infn.it/event/42594/
- Workshop on FCC-ee and Lepton Colliders, 22-24 January 2025, LNF
  https://agenda.infn.it/event/43779/

and also many inspiring discussions with two Workshops celebrating the 50 years from J/Ψ discovery

- The Rise of Particle Physics, Roma Sapienza, 23-24 September, 2024
  https://agenda.infn.it/event/41258/

- The November J/ψ Fifty Years Later with a Look to the Future, 18 November 2024, LNF
  https://agenda.infn.it/event/42751/

- **Draft document in preparation together with**
  - the present CSN4 Chair Giuseppe Degrassi
  - the CSN4 Referees
    - Domenico Orlando, Dimitri Sorokin
    - Dario Buttazzo, Francesco Sanfilippo
    - Umberto D’Alesio, Isaac Vidana
    - Francesco Bigazzi, Roberto Casadio
    - Martina Gerbino, Daniele Montanino
    - Domenico Giuliano, Mario Nicodemi

present knowledge of fundamental interactions based on two pillars

- **Standard Model of particle physics**
  (microscopic world, strong/electroweak forces)

$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{4}\sum_a F^a_{\mu\nu}F^{a,\mu\nu} + \sum_f i\bar{\psi}_f D_\mu \gamma^\mu \psi_f \\
&+ (D_\mu H^\dagger D^\mu H) - V(H) - (\bar{\psi}^i_f y^{ij}_f \psi_f H + h.c.)
\end{aligned}
$$

- **General Relativity and Standard Cosmological Model**
  (macroscopic world, gravity)

$$
R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} - \Lambda g_{\mu\nu} = -\kappa T_{\mu\nu}
$$

The SM of particle physics in brief

- gauge symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$
- spontaneously broken to $U(1)_{em}$ through the Higgs mechanism
- fermion masses through Yukawa interactions
- Higgs boson is (the only one) pointlike scalar

Accidental properties/simmetries of the SM

Symmetries & conservation laws: conservation of B, L_e, L_μ, L_τ

Custodial symmetry: An approximate global $SU(2)_C$ symmetry in the Higgs sector. Protects the ratio $m_W / (\cos\theta_W\, m_Z) \approx 1$.

Absence of FCNC at tree-level: Z boson, photon and gluon couple in a flavour-conserving way + Higgs Yukawa couplings are small.

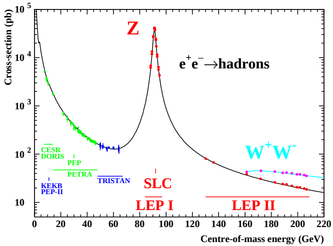
Small CP-violation effects, even though the CP-phase is large: small quark masses and mixing angles.

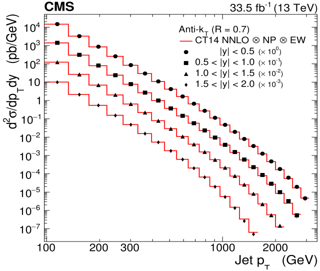
Lepton-Flavour Universality: SM gauge couplings are generation-independent + Yukawa couplings are small and hierarchical (e.g. $m_{e,\mu} \ll m_b$)

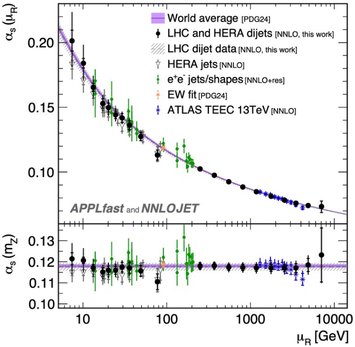
Massless neutrinos: a neutrino mass term is forbidden by gauge symmetries.

D. Marzocca, LNF Workshop, October 2024

Tests of the SM from LEP to LHC: the gauge structure

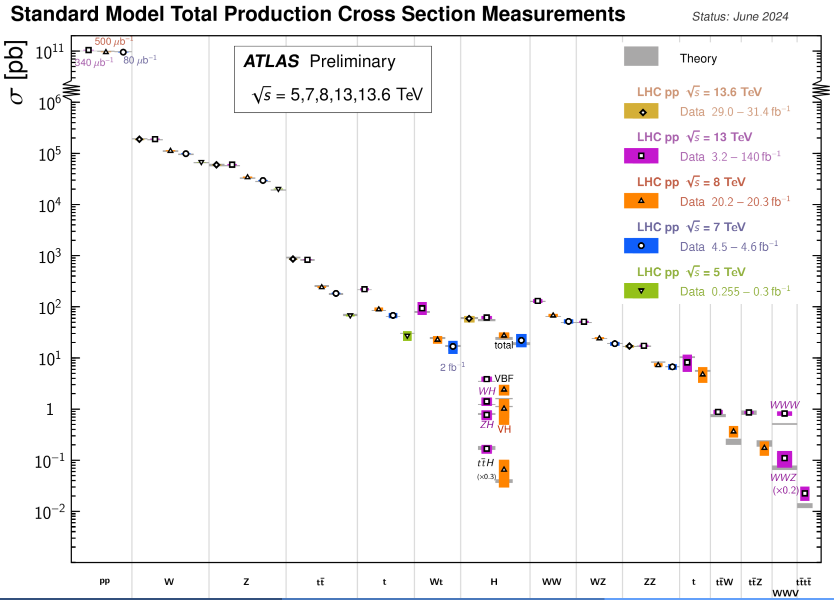




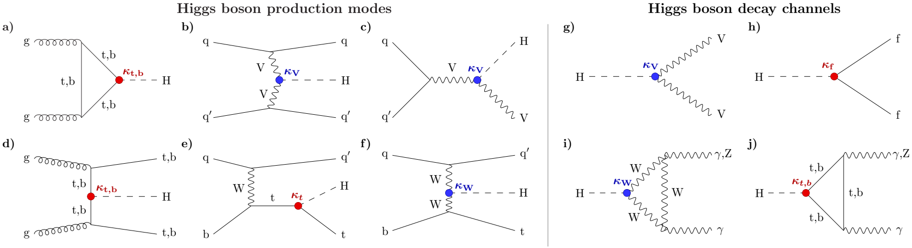


plots from G. Dissertori @ Stefano Catani Memorial Symposium, GGI, 09/01/2025

Tests of the SM @ LHC: adding the Higgs

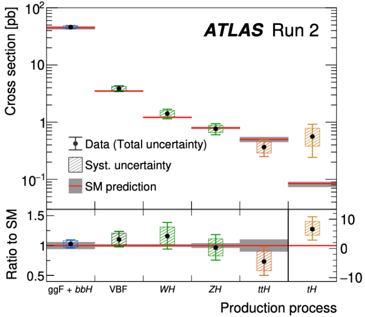


Higgs production and decay in hadronic collisions

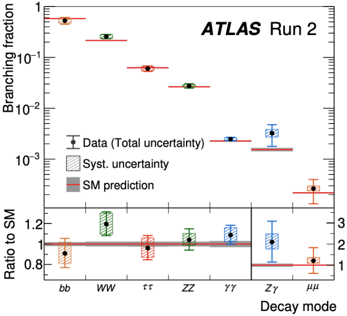


- **production (and decay) measured in several channels**
- for some channel th. uncertainties of same order of exp systematics

Production



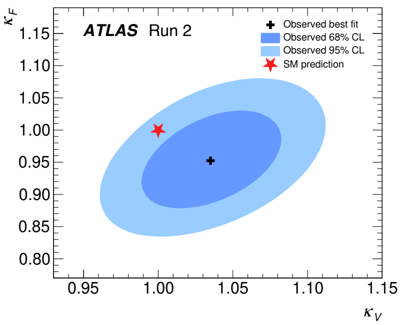
Decay



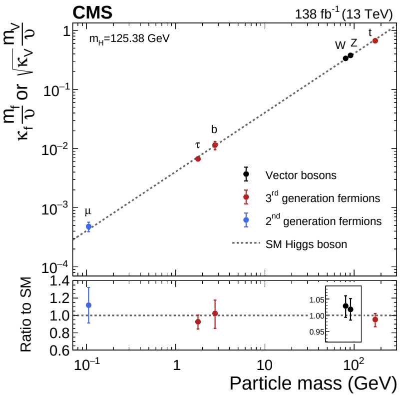
ATLAS Coll., Nature 607 (2022) 7917, 52

- **agreement with th. predictions**

Higgs boson after a decade from discovery



ATLAS Coll., Nature 607 (2022) 7917, 52

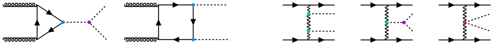


CMS Coll., Nature 607 (2022) 7917, 60

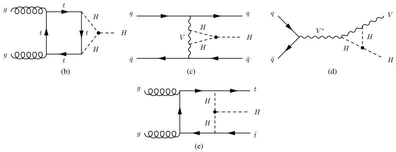
- $m_H = 125.20 \pm 0.11$ GeV (PDG); $\Gamma_H \sim 4$ MeV

Higgs self-coupling: sensitivity through

- **double Higgs production** (at NLO or LO in associated production)

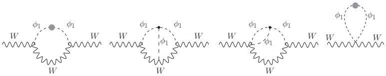


- **single Higgs production** (at NNLO or NLO in associated production) and decay (at NLO or NNLO for $H \to \gamma\gamma$)

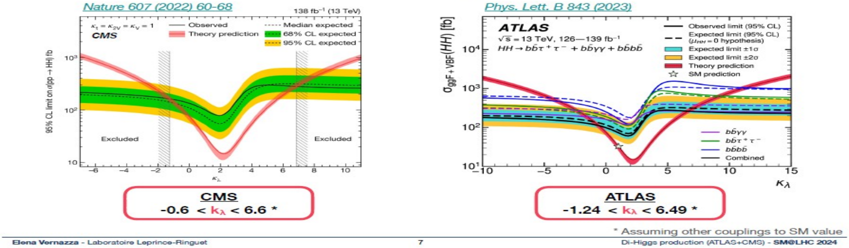


- **EW precision observables at two loops can help**

Degrassi et al., arXiv:1702.01737; Kribs et al., arXiv:1702.07678



- $k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$

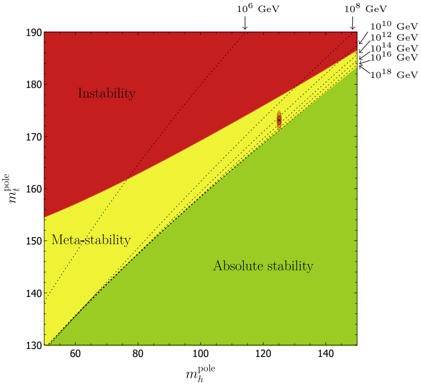


- important correlations of k_λ with k_V, k_{2V} and k_t

Summarizing the present status

- SM gauge sector tested with $\mathcal{O}(0.1\%)$ precision
- SM Higgs interaction with 3rd-generation fermions tested with $\mathcal{O}(10\%)$ level
- SM Higgs interaction with W-Z gauge boson tested at the $\mathcal{O}(10\%)$ level
- hardly constrained SM Higgs self-coupling
- negative searches of New Physics at high energy

- Even if technically the SM could be valid up to very high scales



Andreassen, Frost, Schwartz, arXiv:1707.08124; Buttazzo et al., arXiv:1307.3536

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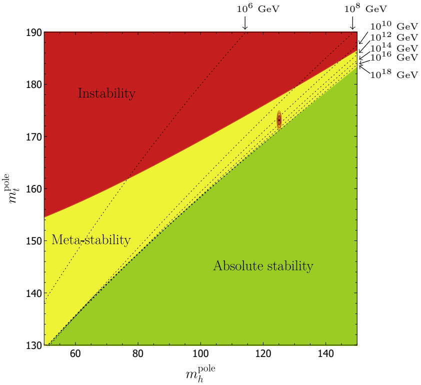


Andreassen, Frost, Schwartz, arXiv:1707.08124; Buttazzo et al., arXiv:1307.3536

- several hints suggest that the limiting scale of validity of the SM could be much lower

Old unanswered questions, e.g.

- Unnaturally light Higgs
- Unnaturally suppressed strong CP violation
- Fermion mass hierarchy
- Nature and origin of neutrino masses
- Dark Matter
- Baryon asymmetry in the Universe
- Gravity
- ...

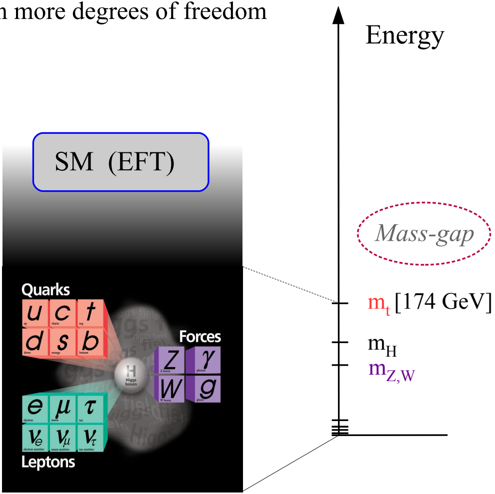
Despite all its phenomenological successes, as for any QFT, it is natural to consider the SM as an Effective Field Theory, i.e. the low energy limit of a more complete theory with more degrees of freedom

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \ \dots$$

We identified the *long-range* properties of this EFT

The key message following from run-II LHC results is that there is a mass-gap above the Fermi scale

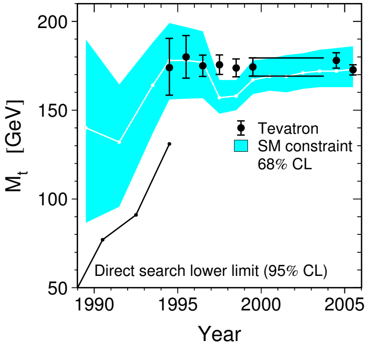
N.B.: *the existence of a mass gap, albeit not as large, was quite clear even before the LHC started, via EW and flavor physics*

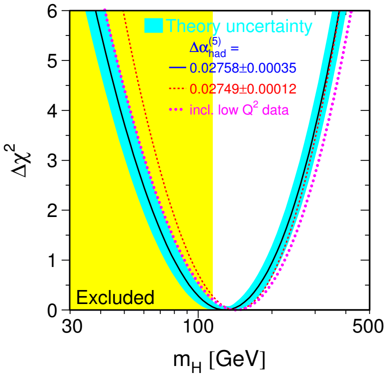


from talk by G. Isidori at LFC24

New threshold scale from lower energy?

- "easy" if you have a well defined model, as for instance for m_t and m_h in the SM through LEP data at $\sqrt{s} = M_Z$





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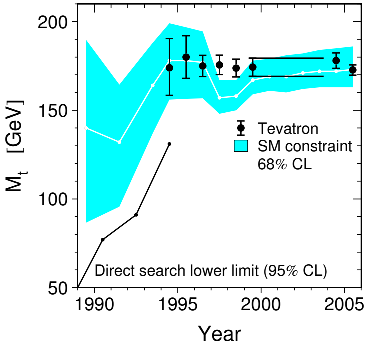
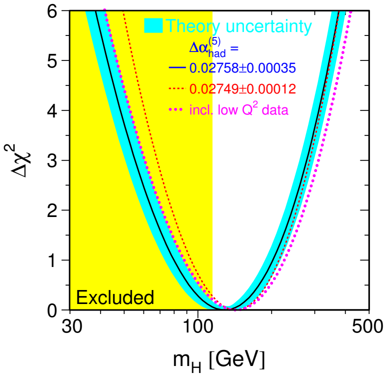




- more difficult if we don't have a definite model

SM as an Effective Theory

- consider the SM as an effective theory valid up to the NP scale Λ

- the effects of decoupling heavy NP can be described by higher dimensional gauge-invariant operators built with SM fields and suppressed by inverse powers of Λ

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i \mathcal{O}_i}{\Lambda^i}$$

- higher dim operators violate accidental symmetries of the SM
- $\Longrightarrow$ flavour physics observables are very sensitive to higher dim contributions

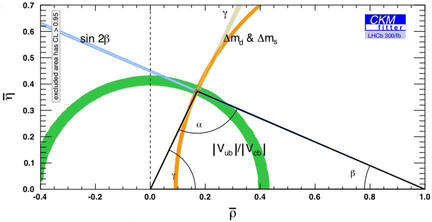
- **Significant improvement** in flavor measurements in the next (few) years!

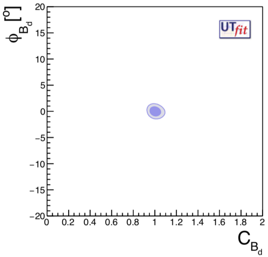
(upgrade 2)

- $O(10^{14})$ b and c hadrons
- $O(10^{11})$ τ leptons

- $O(10^{10})$ B mesons
- $O(10^{10})$ τ's

in clean environment





- Precision on CKM matrix elements < 1% (tree-level and loop)
  - Needed as input of SM predictions in all other observables!
- CPV in Bs system. CPV in charm with extreme precision.

O(15 y) timescale!

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by D. Buttazzo, Rome, 6-7 May 2024

The next 15 years: Flavor

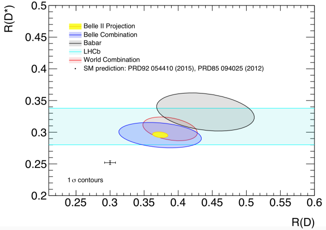
- **Significant improvement** in flavor measurements in the next (few) years!

LHCb (upgrade 2)

- O(10^{14}) b and c hadrons
- O(10^{11}) τ leptons

Belle II

- O(10^{10}) B mesons
- O(10^{10}) τ's in clean environment



O(15 y) timescale!

- Semi-leptonic decays $b \to q\ell\nu$
- Semi-tauonic decays @ few %

$\Rightarrow$ $M_{\rm NP} > 5\,{\rm TeV} \times g_\star$

(today below 1 TeV)

- Rare leptonic & semi-leptonic B decays
  - Access to b → dll transitions
  - LFU below 1% precision
- Rare tau decays and LFV

For the first time precise measurements of rare processes for different flavors:
$b \to s$ vs $b \to d$; τ vs μ, e; $\ell^\pm$ vs ν_ℓ

Ultimate precision on all ‘visible’ B and D decay modes

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by D. Buttazzo, Rome, 6-7 May 2024

The next 15 years: Flavor

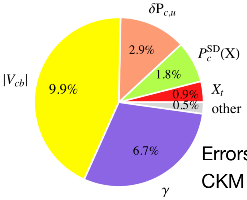
- Access to FCNC decays with neutrinos and taus for the first time!
  crucial to determine up vs. down aligment of NP: can suppress only one!

- Belle II will measure $B \to K^{(*)}\nu\nu$ to 10%

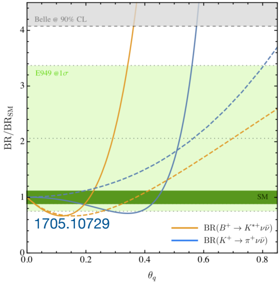
O(10 y) timescale!

Observables	Belle II 50 ab^{-1}
$\text{Br}(B^+ \to K^+\nu\bar{\nu})$	11%
$\text{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	9.6%
$\text{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	9.3%

- $K^+ \to \pi^+\nu\nu$ to 10% from NA62 and below 5% from HIKE



Errors dominated by CKM (will improve a lot!)



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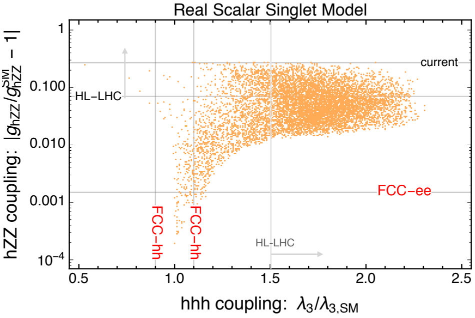
- $K_L \to \pi^0\nu\nu$ one of the few *very* clean modes (like $B_s \to \mu\mu$, or CP asymmetry in $B \to \psi K_S$).

by D. Buttazzo, Rome, 6-7 May 2024

Impact of extended Higgs sectors on nature of the EW phase transition

Extra-singlet models with potential strong 1st order phase transition

$$V(H,S) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 .$$



Experimental signature: deviation in the Higgs coupling to the Z (g_{hZZ}) and in the Higgs self-coupling λ_3

Scan of model parameters a_i and b_i, and impact on g_{hZZ} and λ_3 for parameter points with strong FOPT

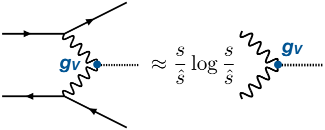
from talk by M.L. Mangano, LFC24, September 2024

Higgs factories

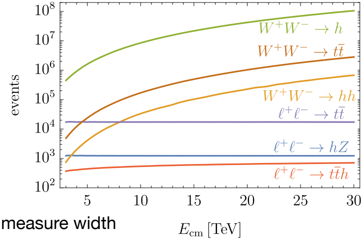
- Low-energy e+e- factories: $e^+e^- \to Zh$ @ 240 GeV

- measure the recoil (missing mass) of h against Z
- *direct* measurement of gV ⟶ other couplings + width

- A high-energy lepton collider is a “vector boson collider”



For “soft” SM final state $\hat{s} \sim m^2_{\rm EW}$ cross-section is enhanced



- potentially huge single H production (10^7-10^8 at 10-30 TeV)
- hard neutrinos from W-fusion not seen

  ZZ fusion (forward lepton tagging) could still measure width

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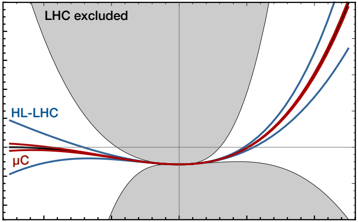
by D. Buttazzo, Rome, 6-7 May 2024

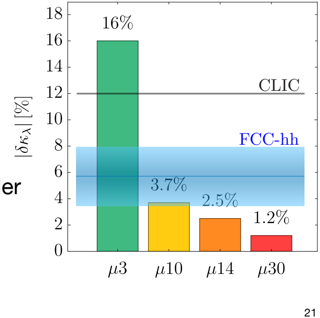
Double Higgs production

- Measurement of trilinear coupling: access to the Higgs potential



credits: Craig, Petrossian-Byrne

- very poorly known today!
- HL-LHC will only reach 50% precision on SM value



- Precise determination *only* possible at high-energy machines: 100 TeV FCC-hh or multi-TeV Muon collider

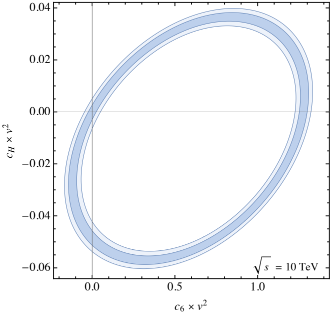
Mangano et al. 2004.03505
B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289
Han et al. 2008.12204
CLIC 1901.05897

by D. Buttazzo, Rome, 6-7 May 2024

Double Higgs production

- Double Higgs production depends on trilinear coupling κ_3 but also on W-boson couplings κ_W, κ_{WW} that enter the production cross-section
- Two dim. 6 operators: $\mathcal{O}_6 = -\lambda|H|^6$ $\quad \mathcal{O}_H = \frac{1}{2}\left(\partial_\mu|H|^2\right)^2$

$$\kappa_3 = 1 + v^2\left(C_6 - \frac{3}{2}C_H\right) \qquad \kappa_W = 1 - v^2 C_H/2 \qquad \kappa_{WW} = 1 - 2v^2 C_H$$



large degeneracy in total cross-section: coefficients not determined in general

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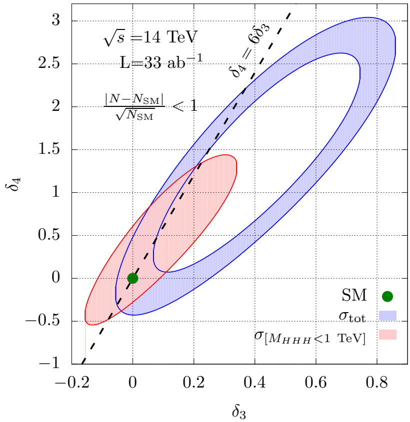
by D. Buttazzo, Rome, 6-7 May 2024

Quartic Higgs self-coupling



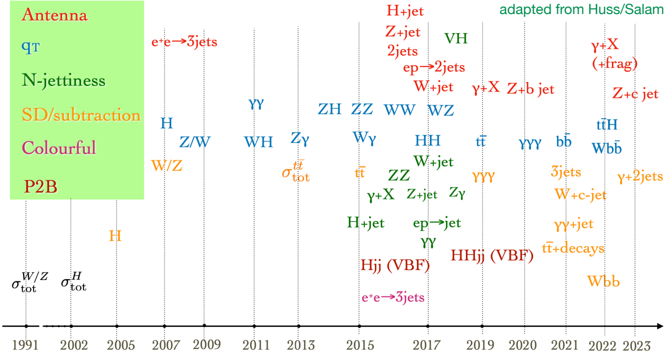
M. Chiesa et al., arXiv:2003.13628

- difficult, first explorations at μ-collider

The need for precision SM calculations

- **Impressive development during LHC era**
  - automatic codes for event generation at NLO (QCD and EW) precision matched to all order resummation of logarithmic enhanced corrections
  - $2 \to 2$@NNLO QCD perturbative accuracy for many processes
  - $2 \to 3$@NNLO QCD accuracy becoming available for selected processes
  - first complete mixed QCD-EW NNLO corrections
  - N3LO QCD calculations for Higgs and DY production
  - different approaches for matching NNLO calculation and resummation of logs
- recent work started to prepare for precise event generation in e^+e^- collisions

NNLO timeline



Different colour: different way to handle intermediate divergences

The dream is to have NNLO fully automated for generic processes [Sotnikov] 13

(from Zanderighi LHCP 2024)

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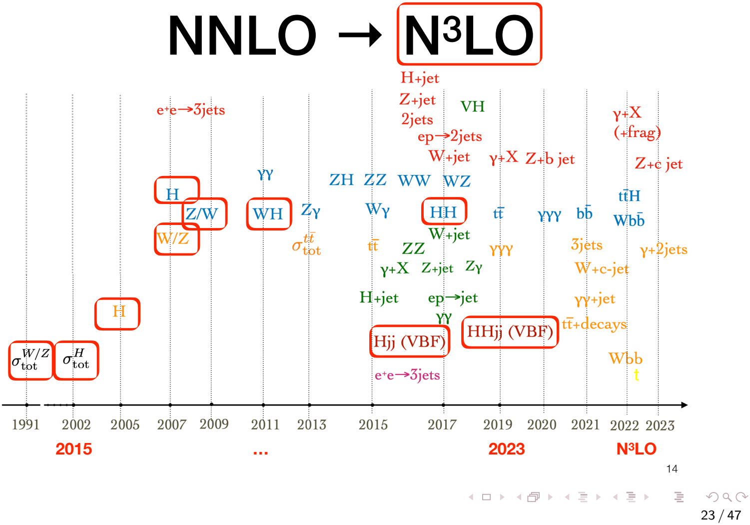
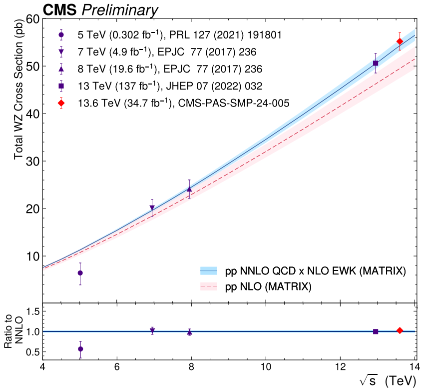
form talk by P. Nason at LNF, October 2024

N^3LO



form talk by P. Nason at LNF, October 2024

Improved agreement with experiments



$$55.2 \pm 1.2(\mathrm{stat}) \pm 1.2(\mathrm{syst}) \pm 0.8(\mathrm{lumi}) \pm 0.1(\mathrm{Theo})$$

$$54.7 + 1.2 - 1.1(\mathrm{scale})\ \text{NNLO QCD} \times \text{NLO EW (MATRIX)}.$$

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form talk by P. Nason at LNF, October 2024

What are EW Sudakov logarithms?

QCD: virtual and real terms are separately IR divergent ($1/\epsilon$ poles). In physical cross sections the contributions are combined and poles cancel.

QED: same story, but I can also regularise IR divergencies via a photon-mass λ. So $1/\epsilon$ poles $\rightarrow \log(Q^2/\lambda^2)$, where Q is a generic scale.

EW: with weak interactions $\lambda \rightarrow m_W, m_Z$ and W and Z radiation are typically not taken into account, which is anyway IR-safe.

Therefore, at high energies EW loops induce corrections of order

$$-\alpha^k \log^n(s/m_W^2)$$

where k is the number of loops and $n \leq 2k$. These logs are physical. Even including the real radiation of W and Z, there is not the full cancellation of this kind of logarithms.

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from talk by D. Pagani at LFC24, September 2024

Summary

- Strategic will be a wide future program of physics at accelerators, both at the intensity and the energy frontiers, with the aim of exploring with unprecedented precision the electroweak scale and the highest possible energies with conceivable technologies
- In the future increasing complementarities and synergies between intensity/energy and cosmological frontiers
- In various aspects of precision physics, non-perturbative contributions play an important role. Their quantitative estimate needs HPC resources and developments (see e.g. the ongoing effort on the muon $g - 2$ theoretical prediction)
- Continuous commitment for the development of challenging precision calculations and simulation tools, both for hadronic as well as leptonic collisions (theory systematics will be relevant)