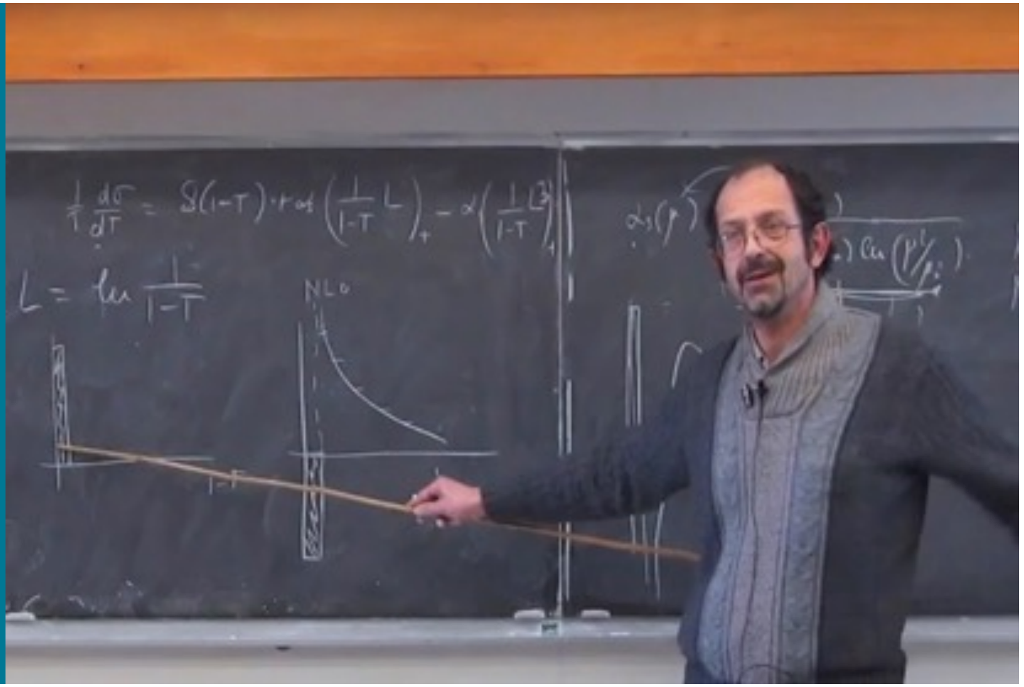
Precision is important

Prof. Dr. Günther Dissertori
ETH Zurich

9 January 2025, S. Catani Memorial Symposium
Firenze



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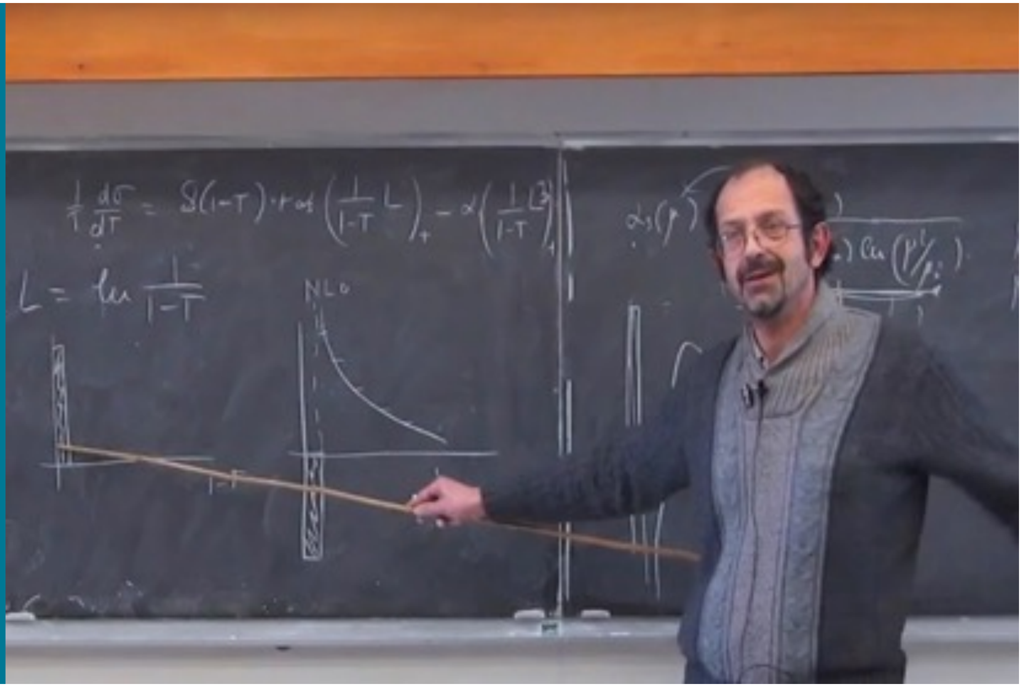
Precision of measurements and **Accuracy** of theoretical predictions are important

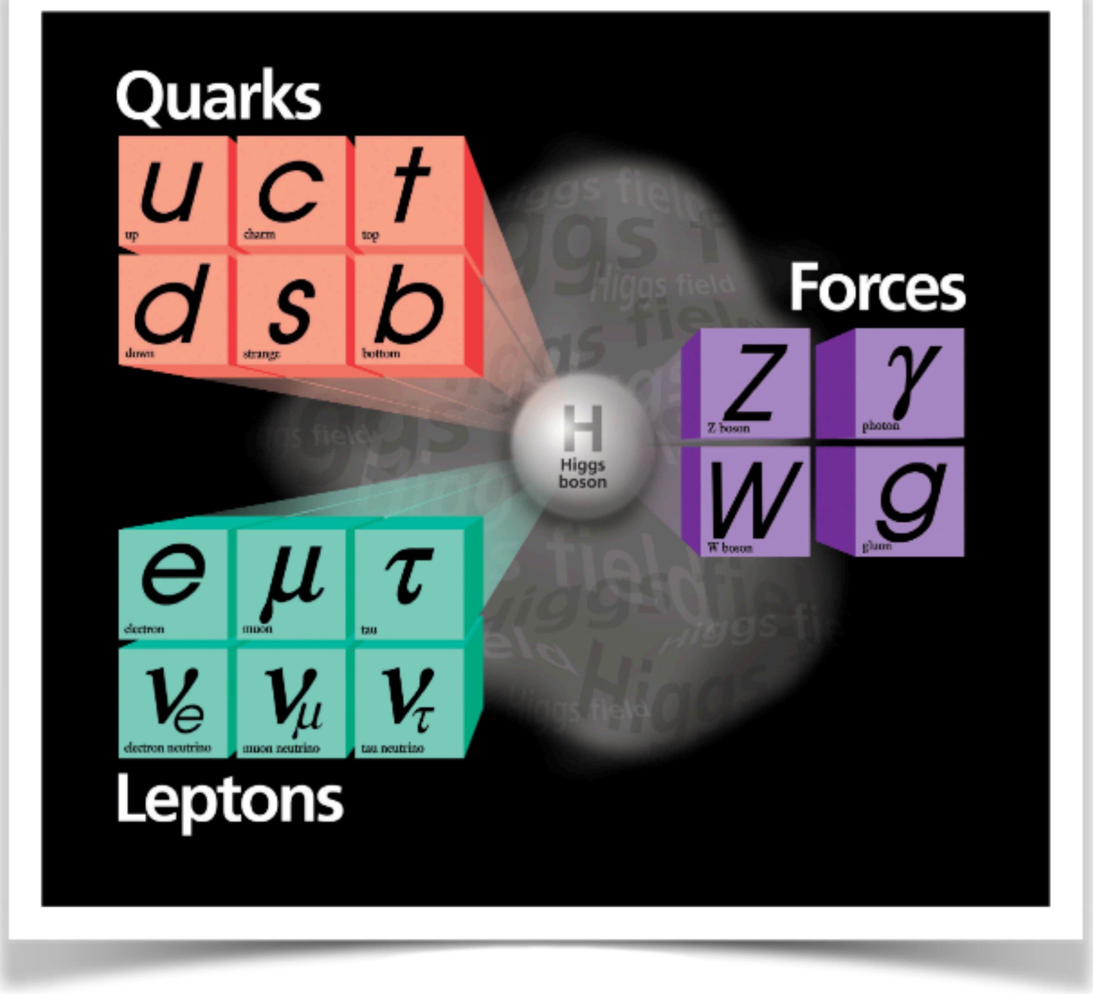


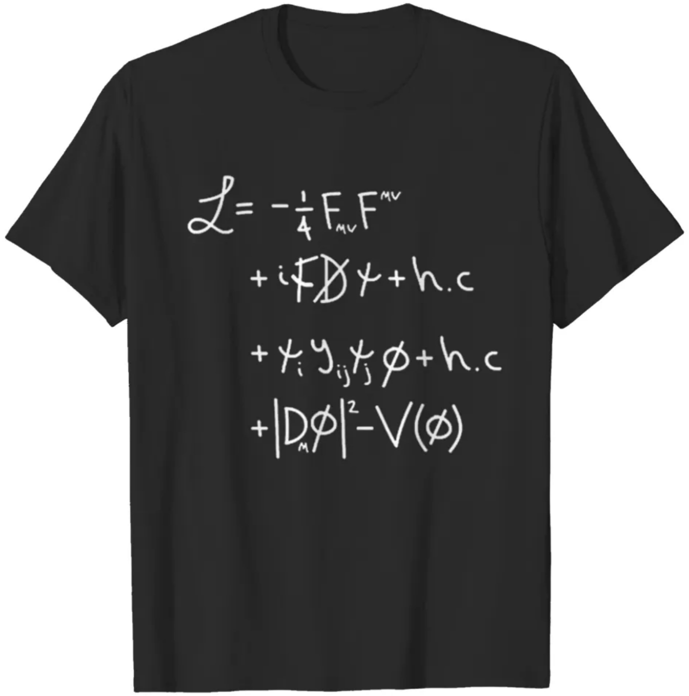
Some preliminary remarks

The state of the nation

The Standard Model of Particle Physics

http://www.ph.ed.ac.uk/higgs/searches





A renormalizable **Quantum Field Theory**,
built on the powerful principle of **gauge theories**,
with great predictive power

“It works”

as shown, eg. by the results from the first decade of the LHC

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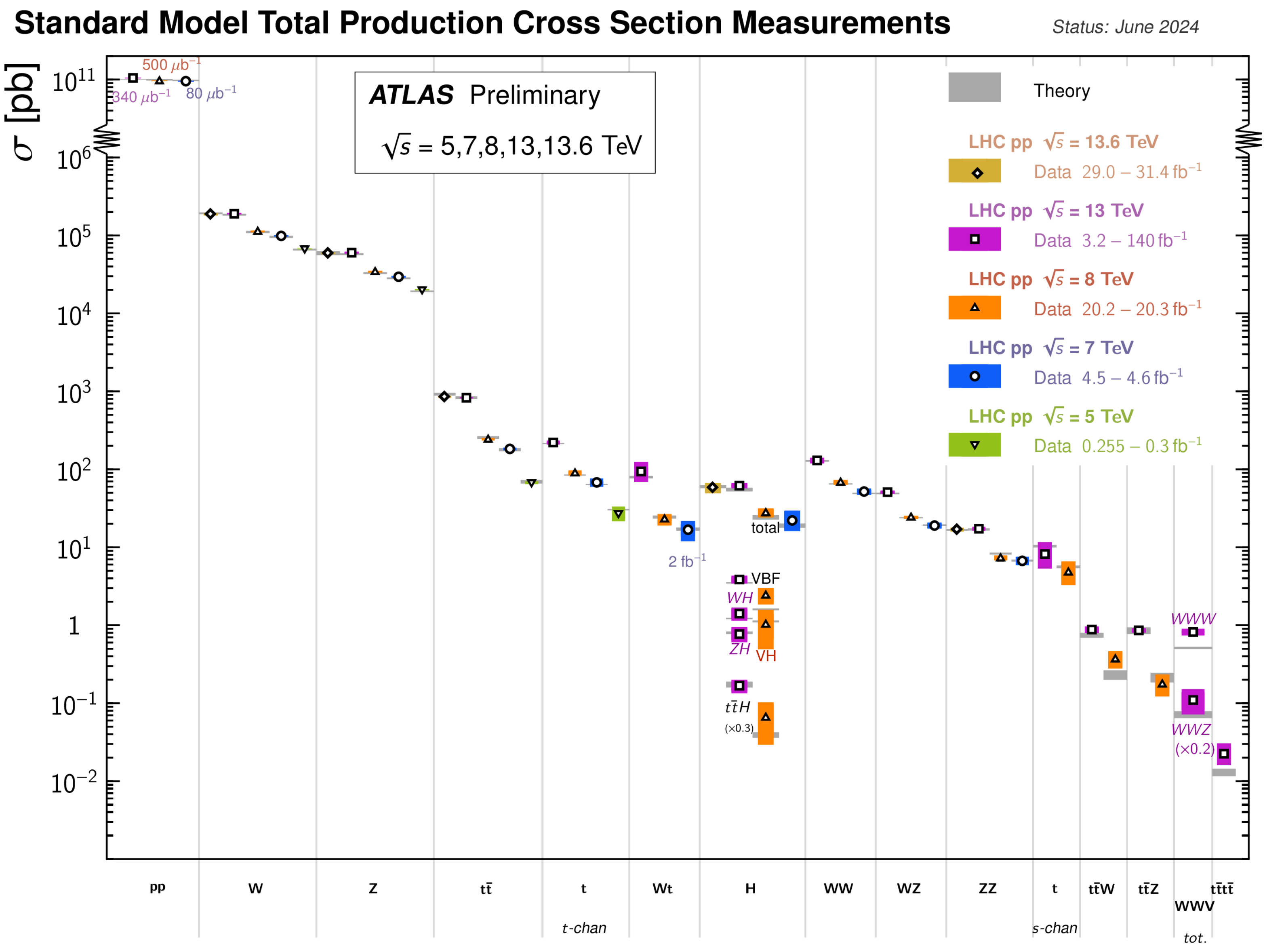
The SM: Tested to greatest precision (EW sector)



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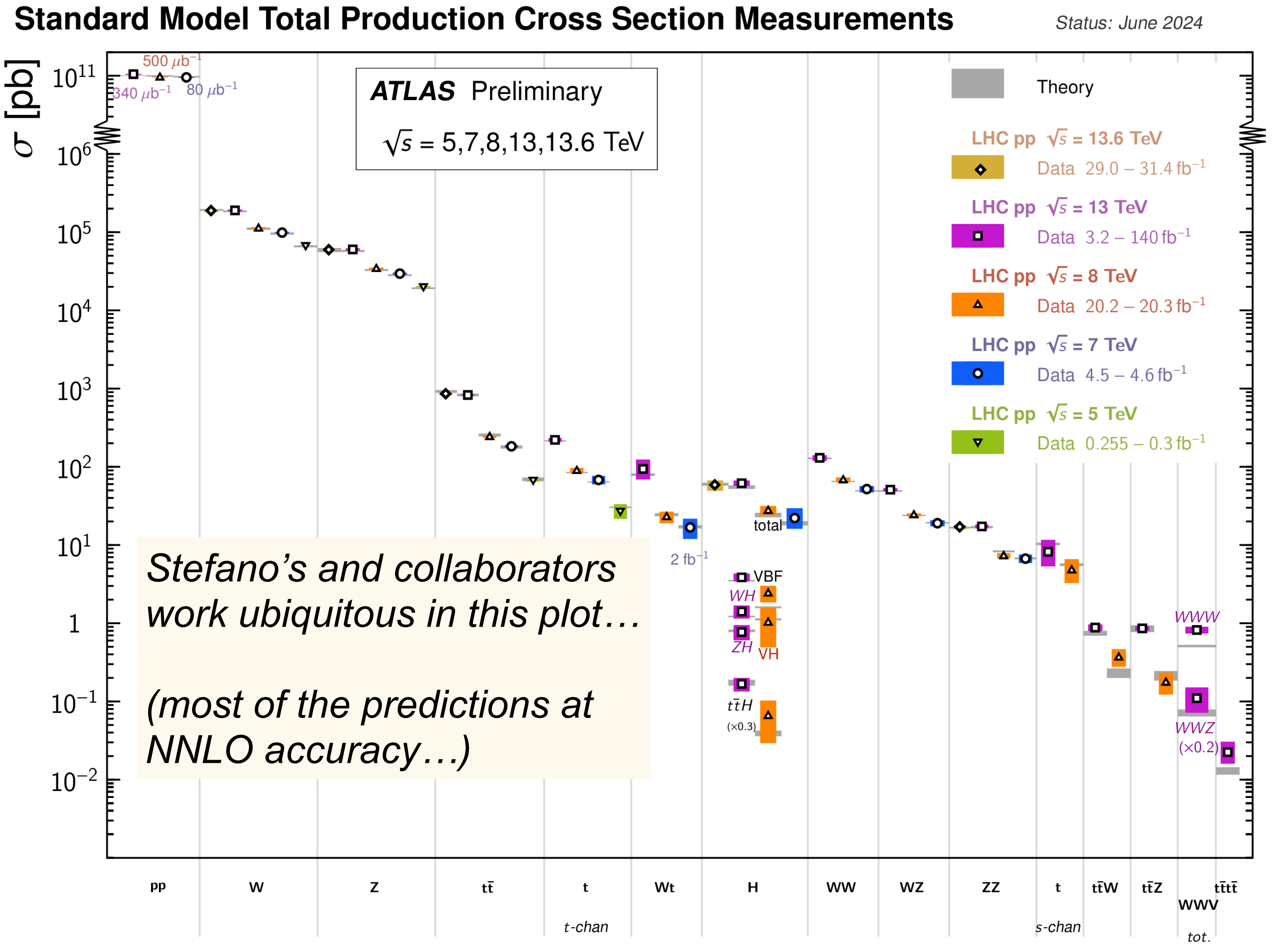

Stefano's and collaborators work ubiquitous in this plot…

(most of the predictions at NNLO accuracy…)

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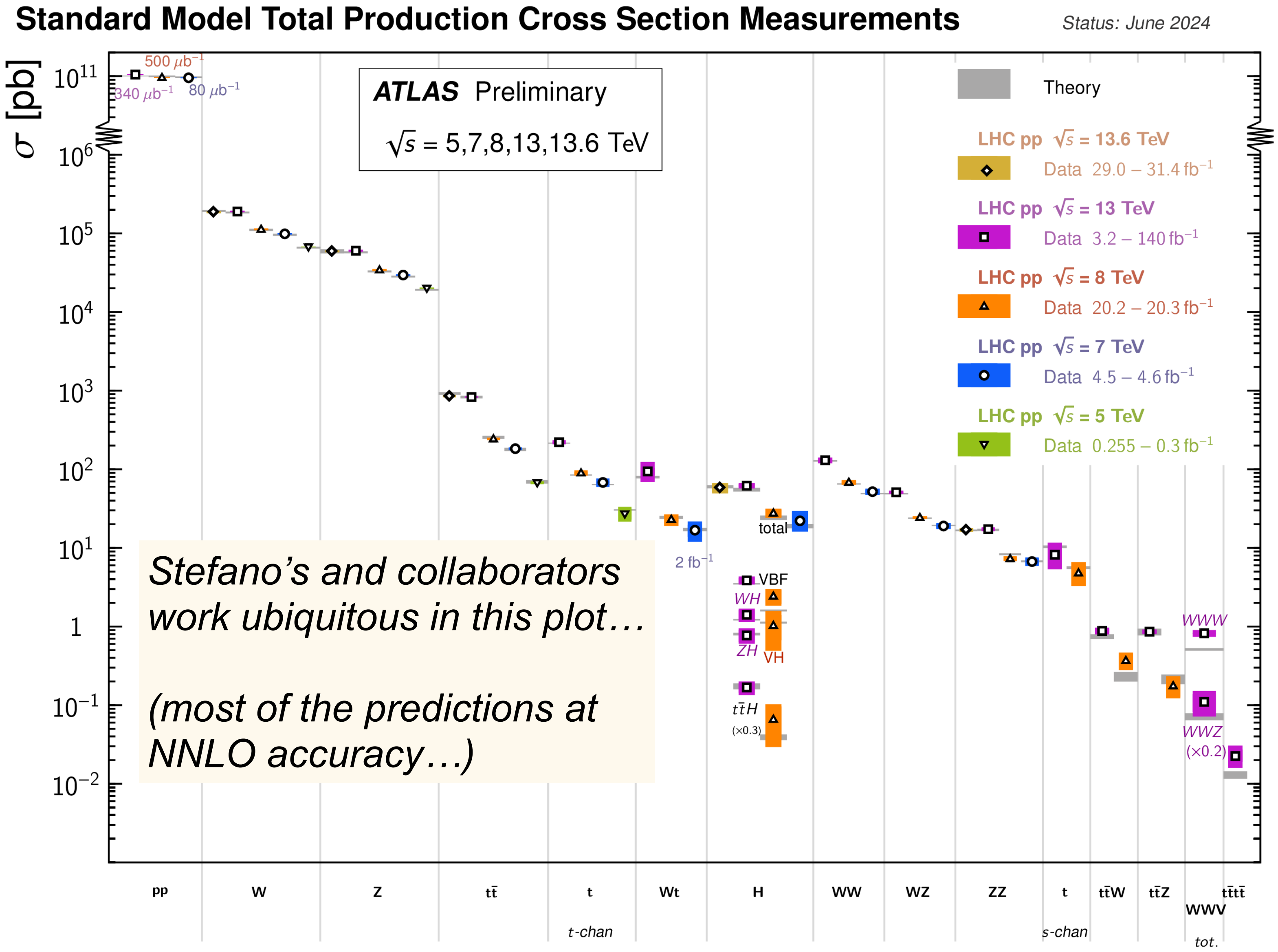

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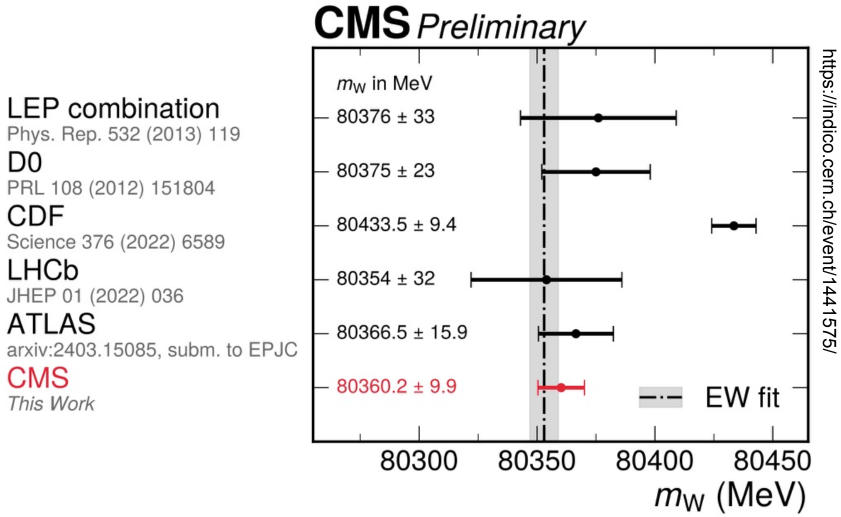

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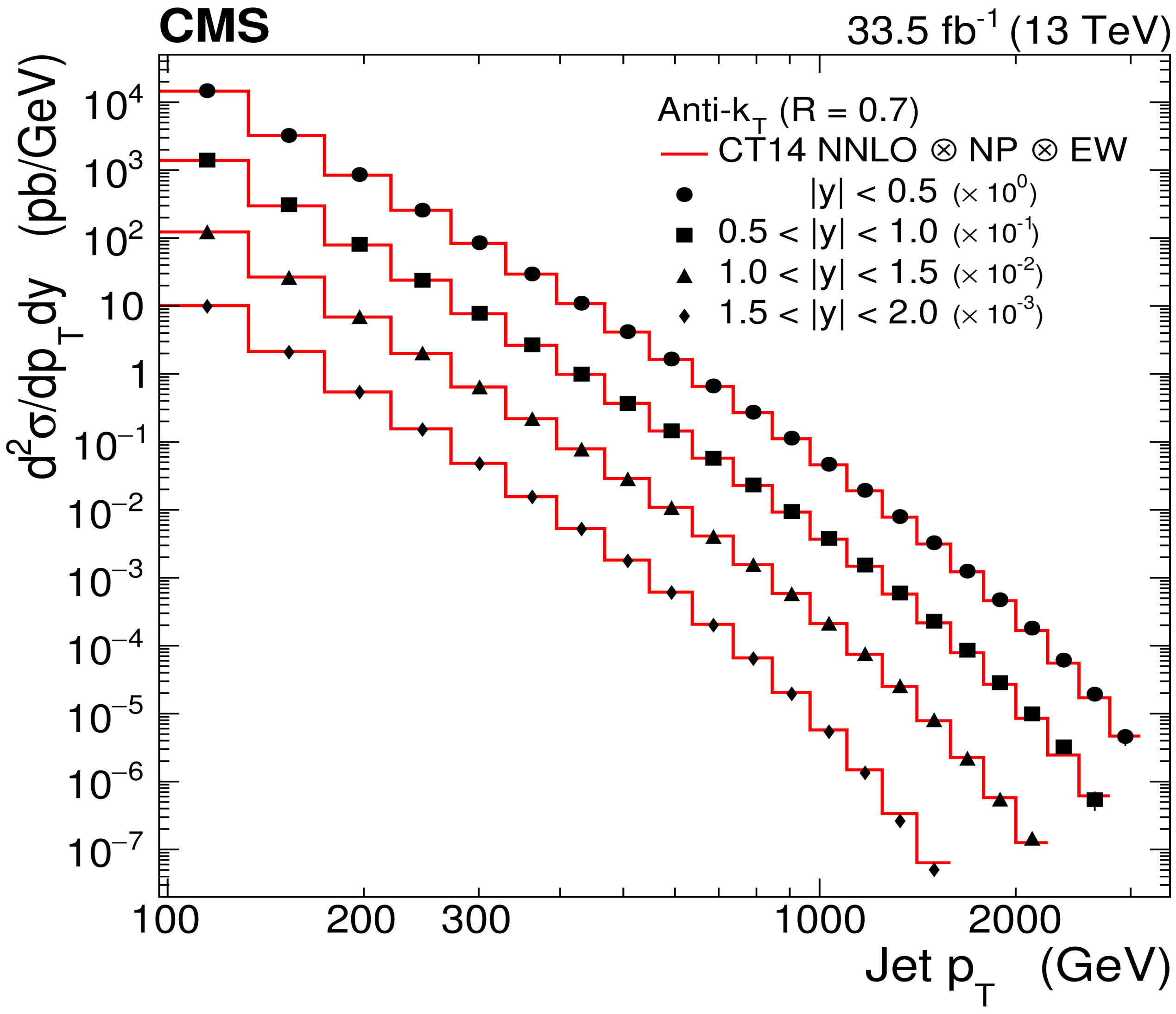

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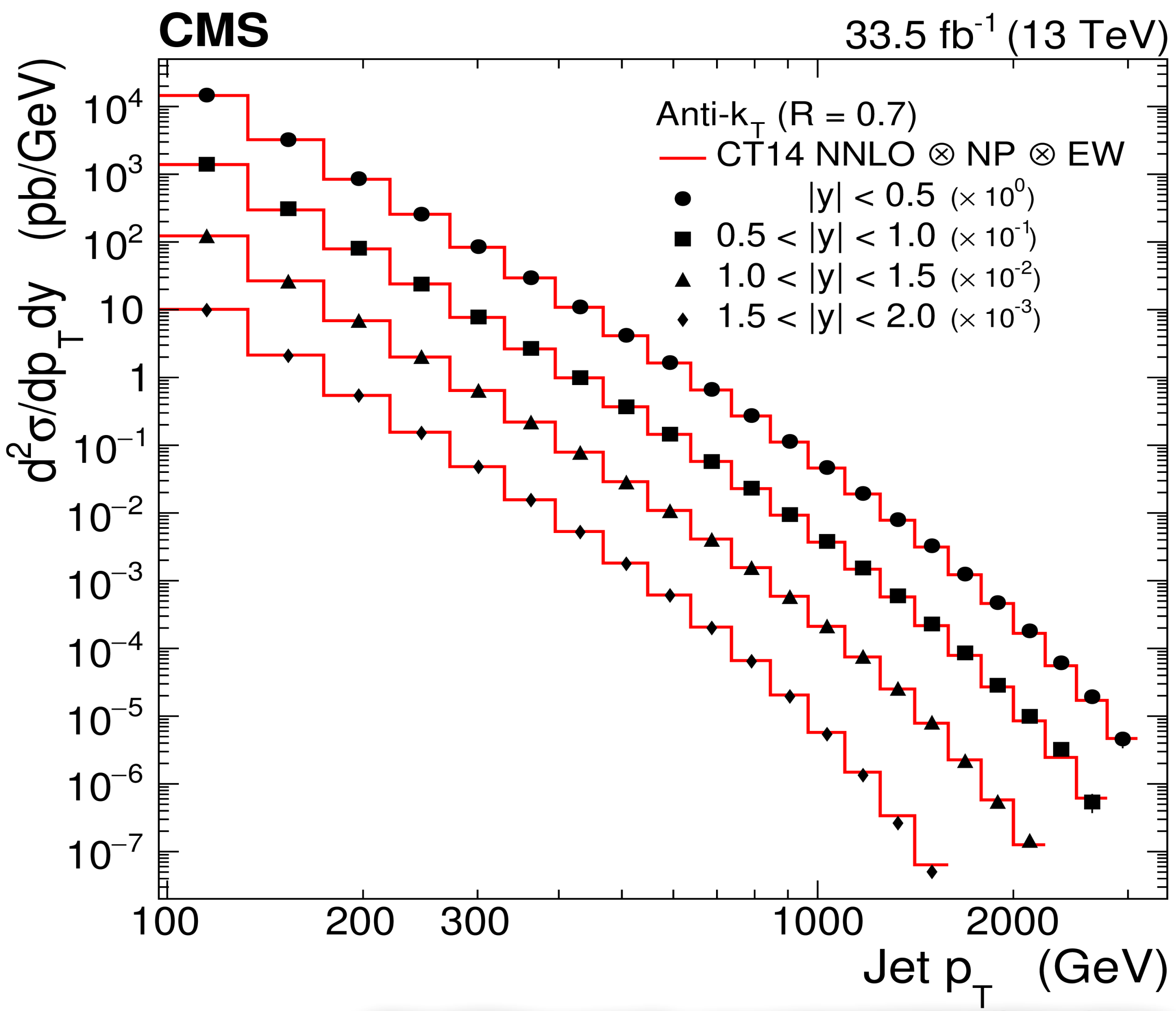

probing distance scales of 10^{-19} m !

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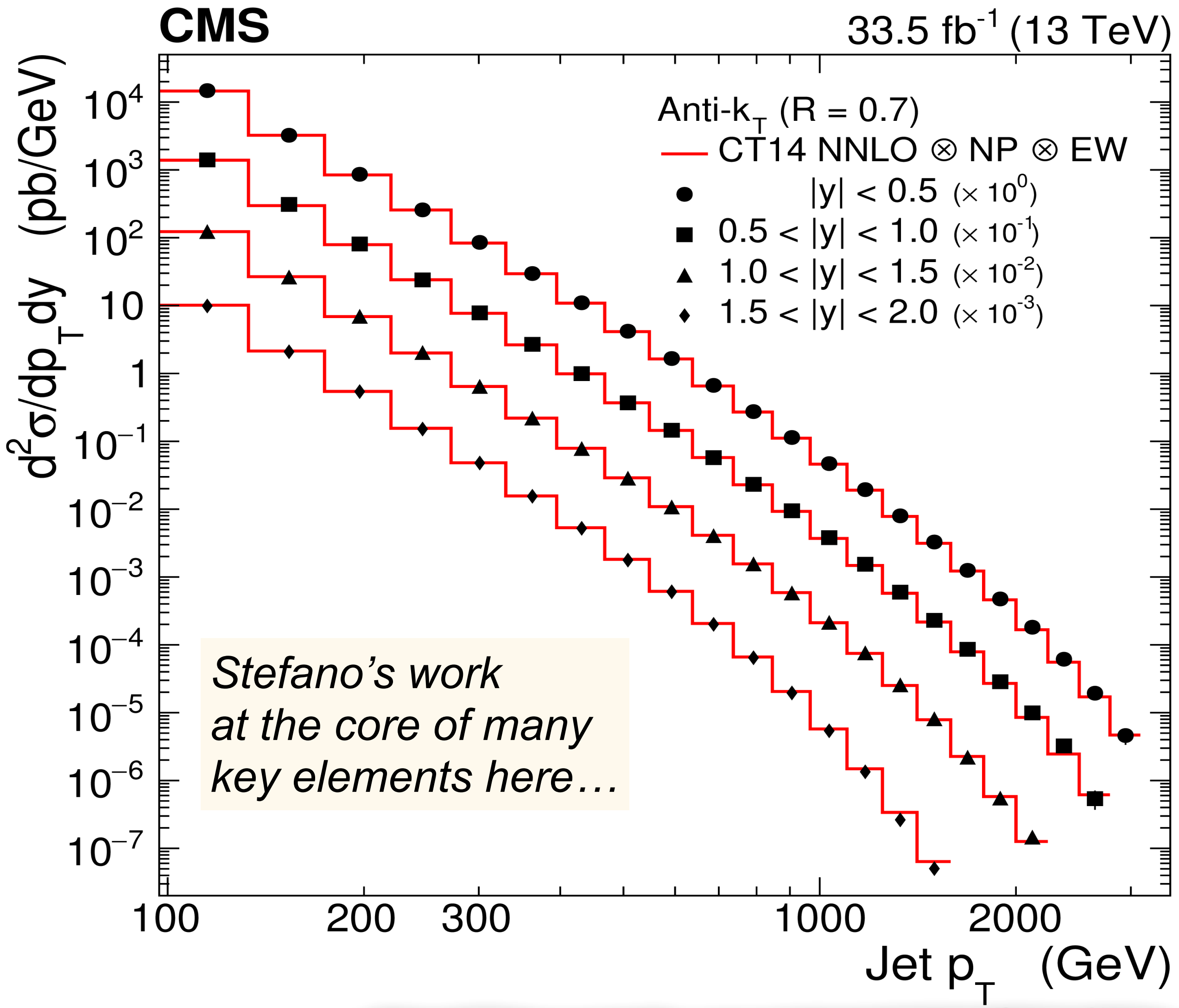

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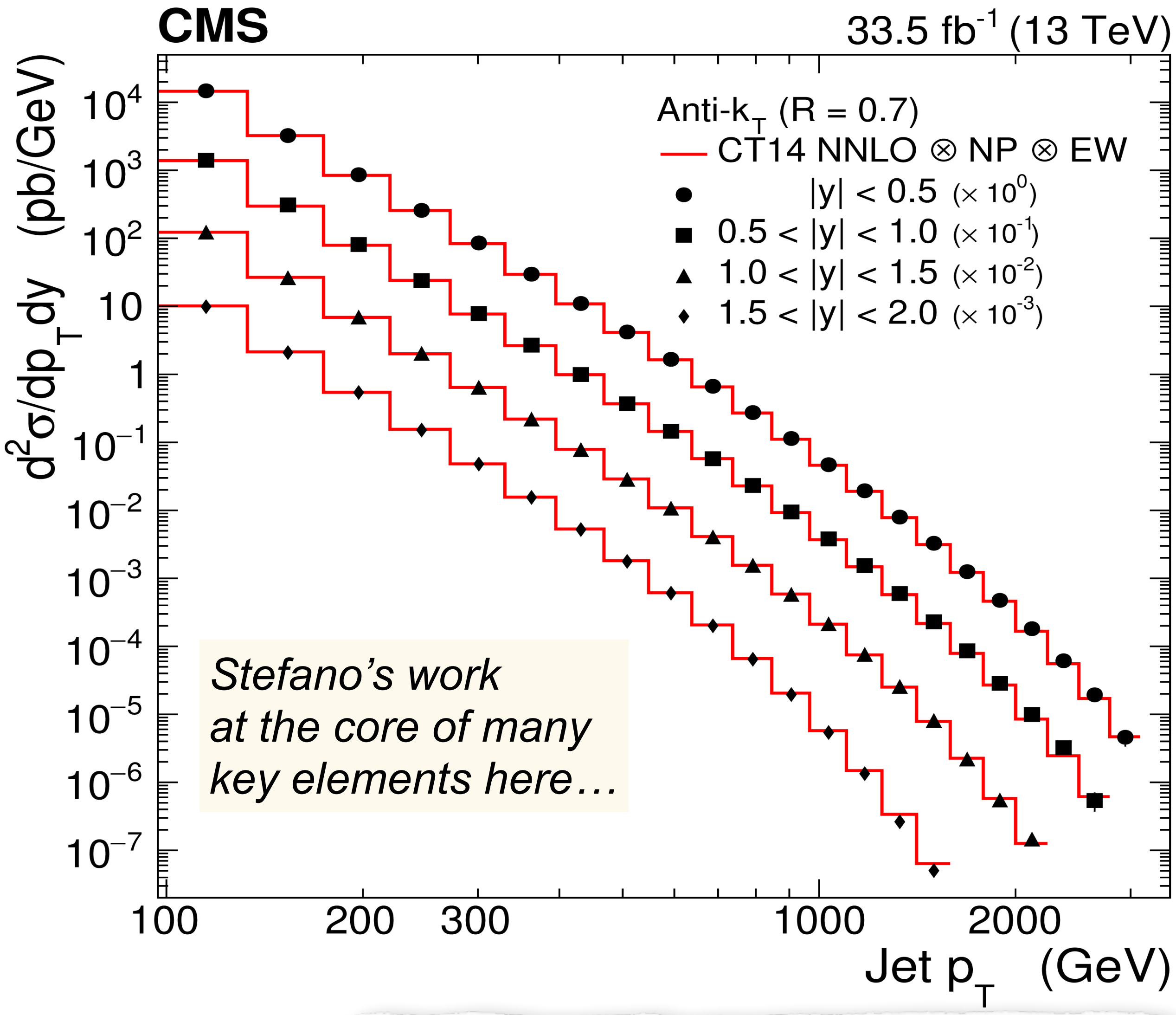
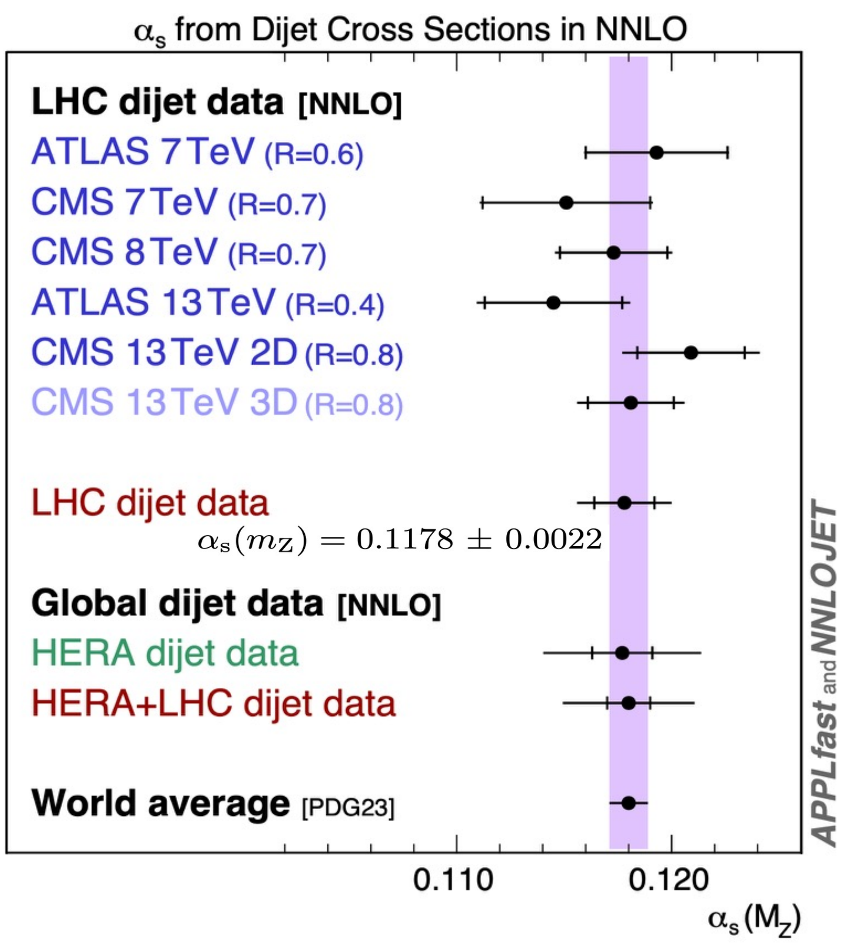


https://arxiv.org/pdf/2412.21165



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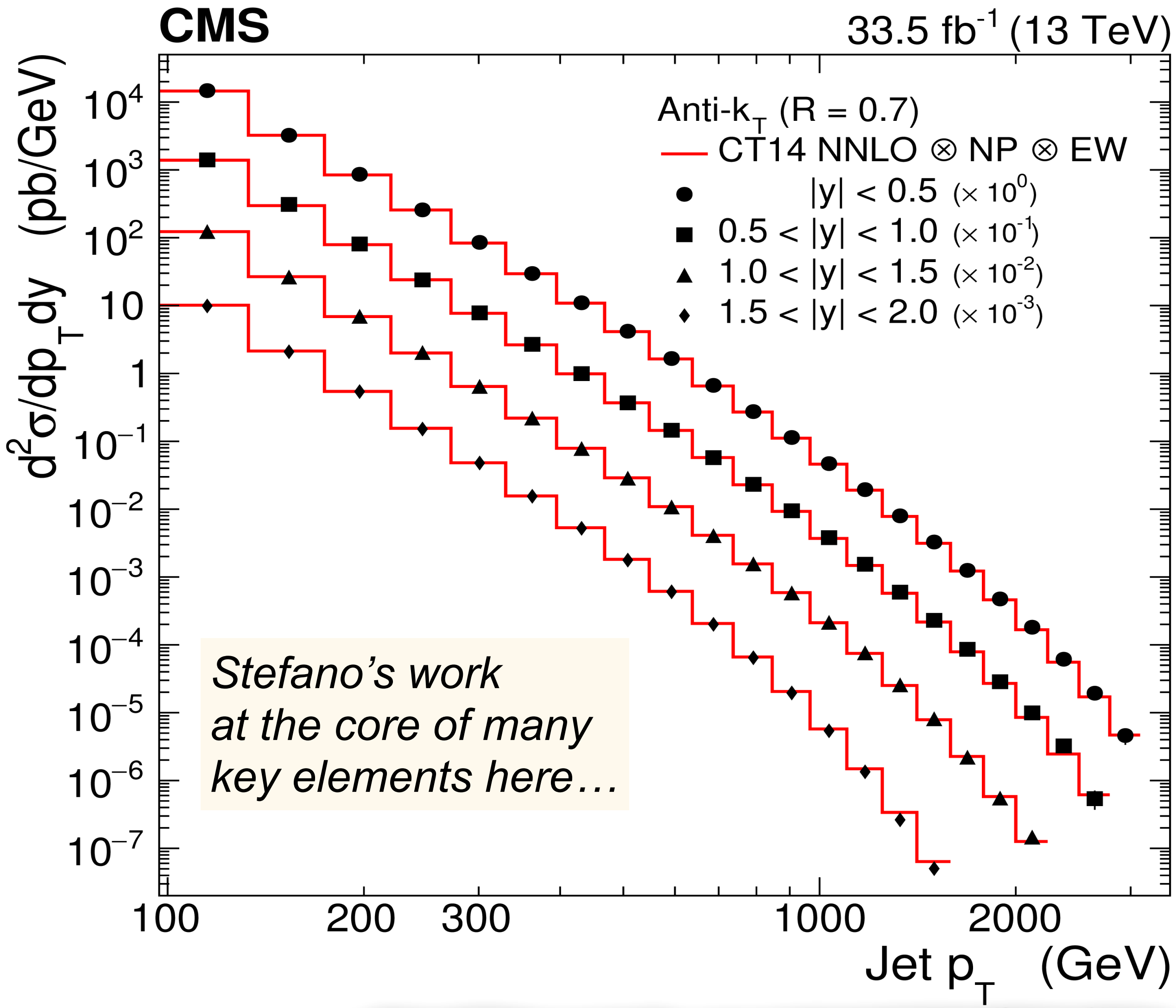

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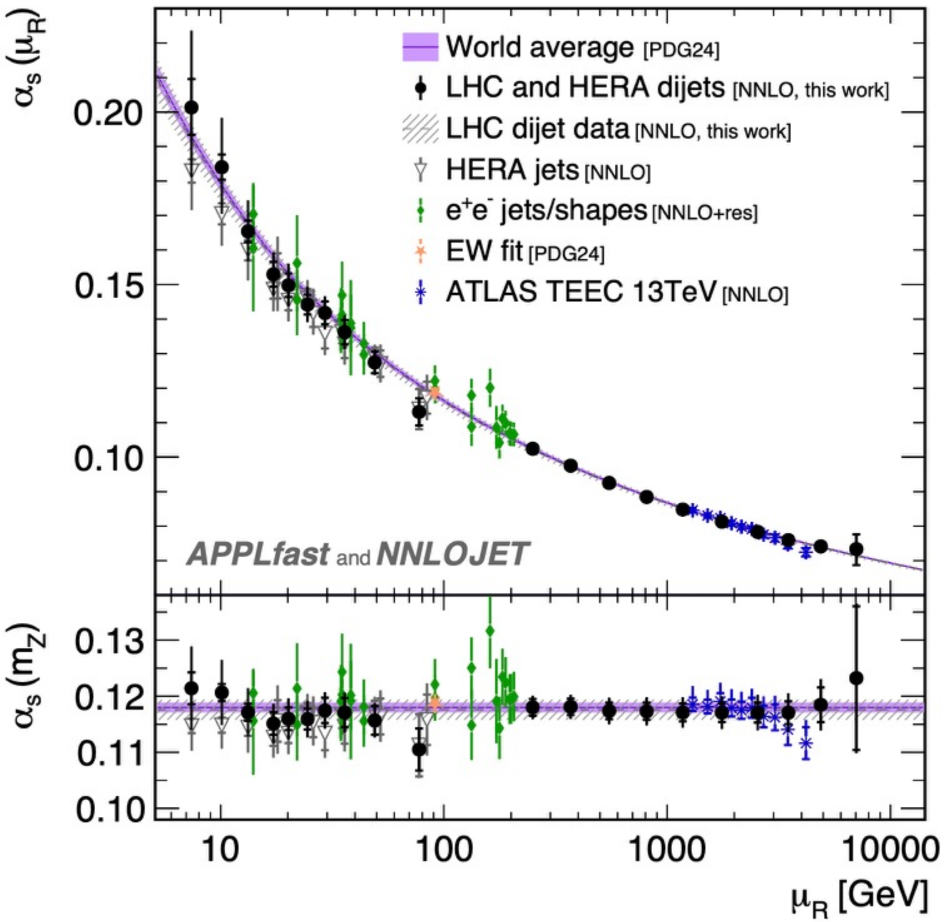

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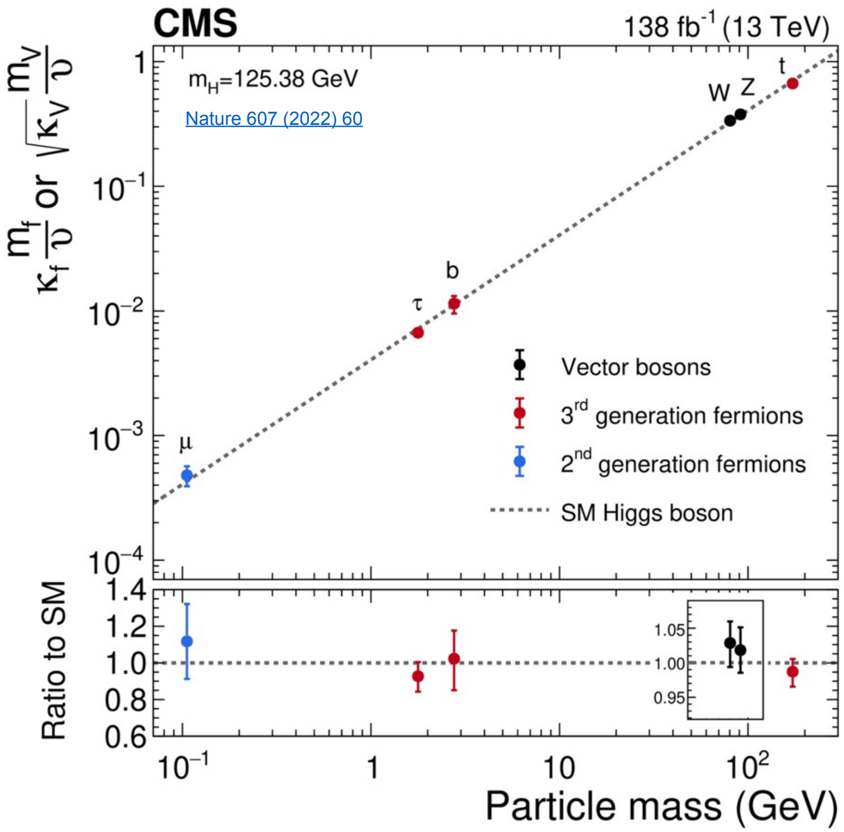
The Higgs boson: a fundamentally new tool and future “precision probe“

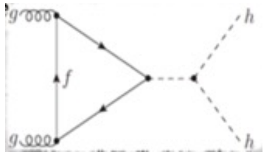
$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \qquad + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

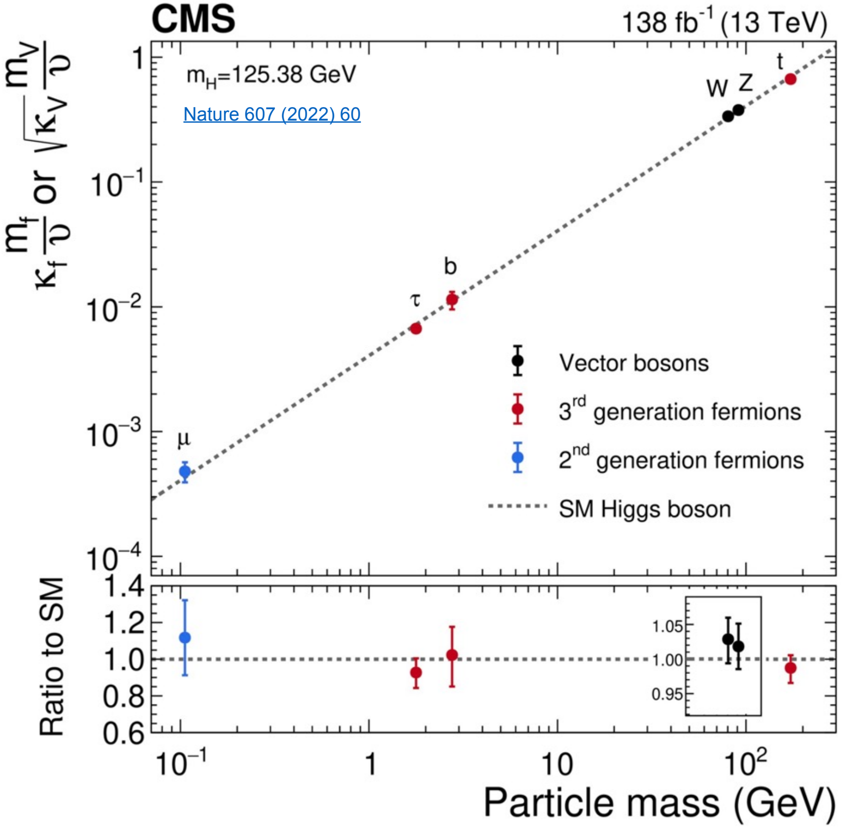


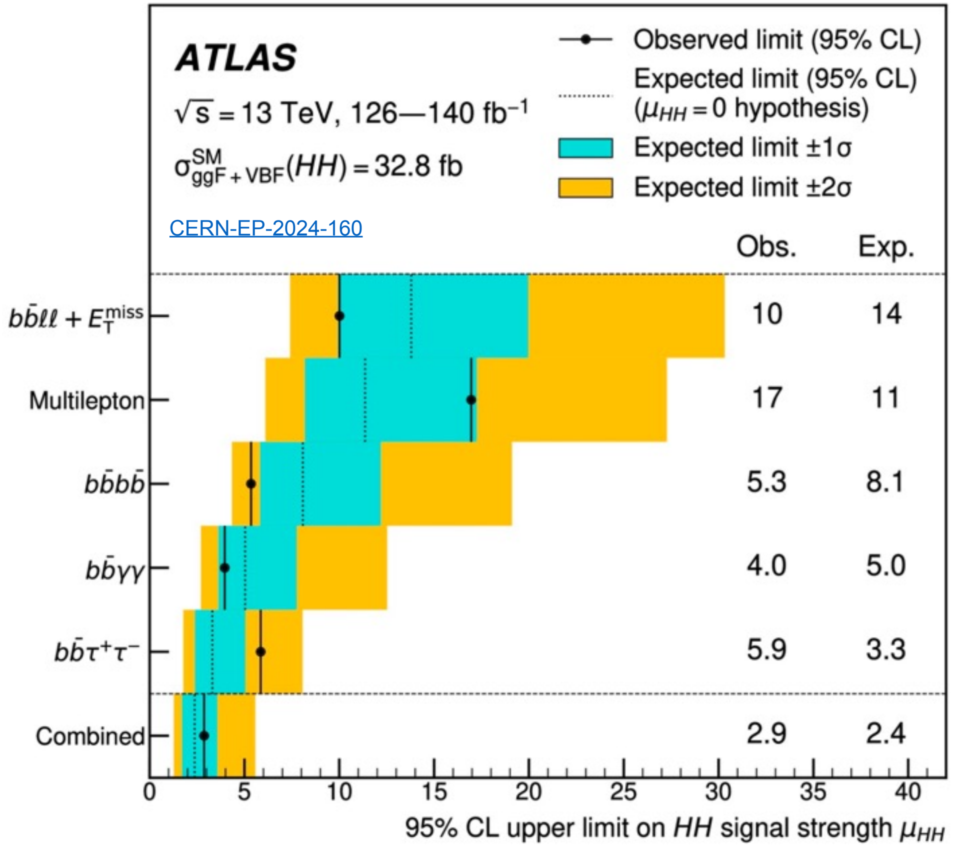
Again, the amazing precision and accuracy achieved “already” at this stage is also thanks to Stefano’s (and collaborators) work

The Higgs boson: a fundamentally new tool and future “precision probe“

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad + \chi_i y_{ij} \chi_j \phi + h.c \quad + |D_\mu \phi|^2 - V(\phi)$$







	Obs.	Exp.
$b\bar{b}\ell\ell + E_T^{miss}$	10	14
Multilepton	17	11
$b\bar{b}b\bar{b}$	5.3	8.1
$b\bar{b}\gamma\gamma$	4.0	5.0
$b\bar{b}\tau^+\tau^-$	5.9	3.3
Combined	2.9	2.4

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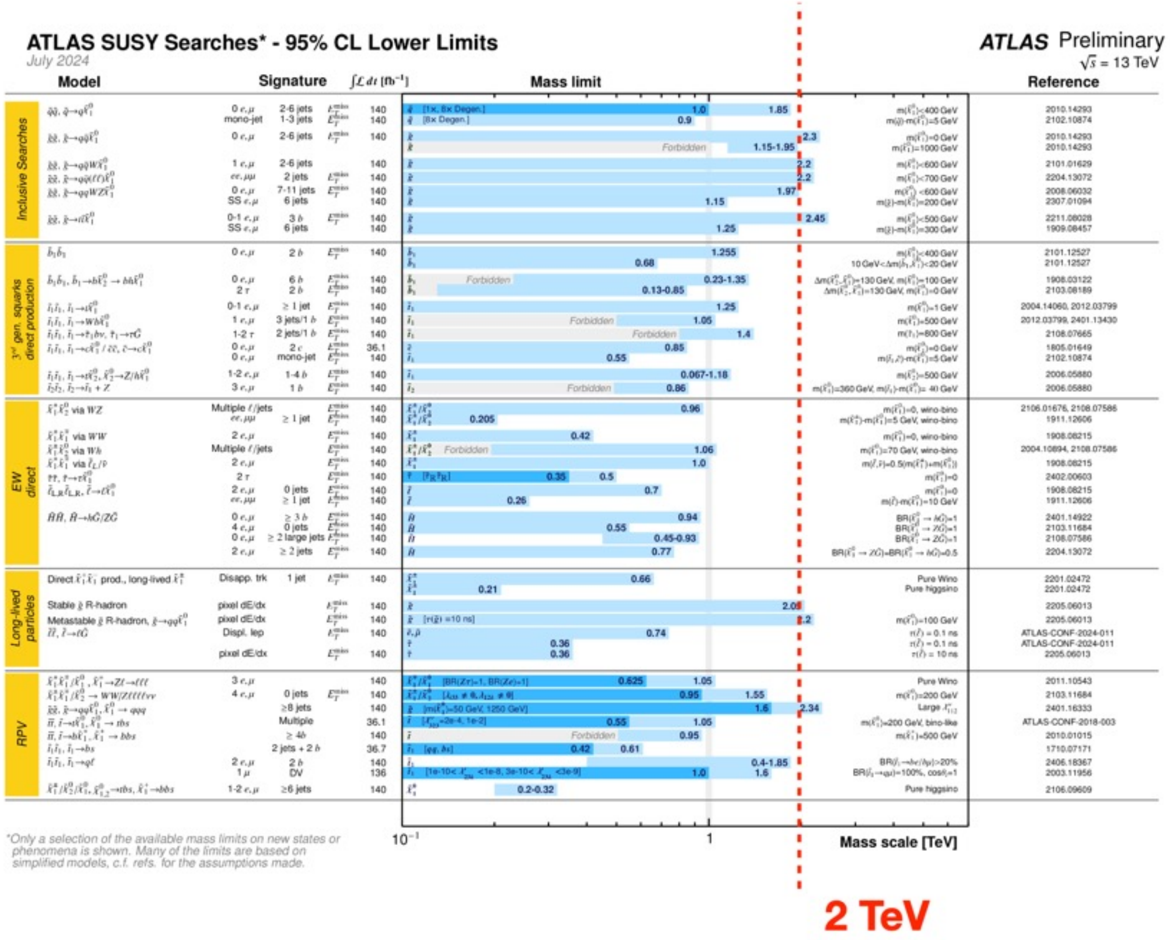
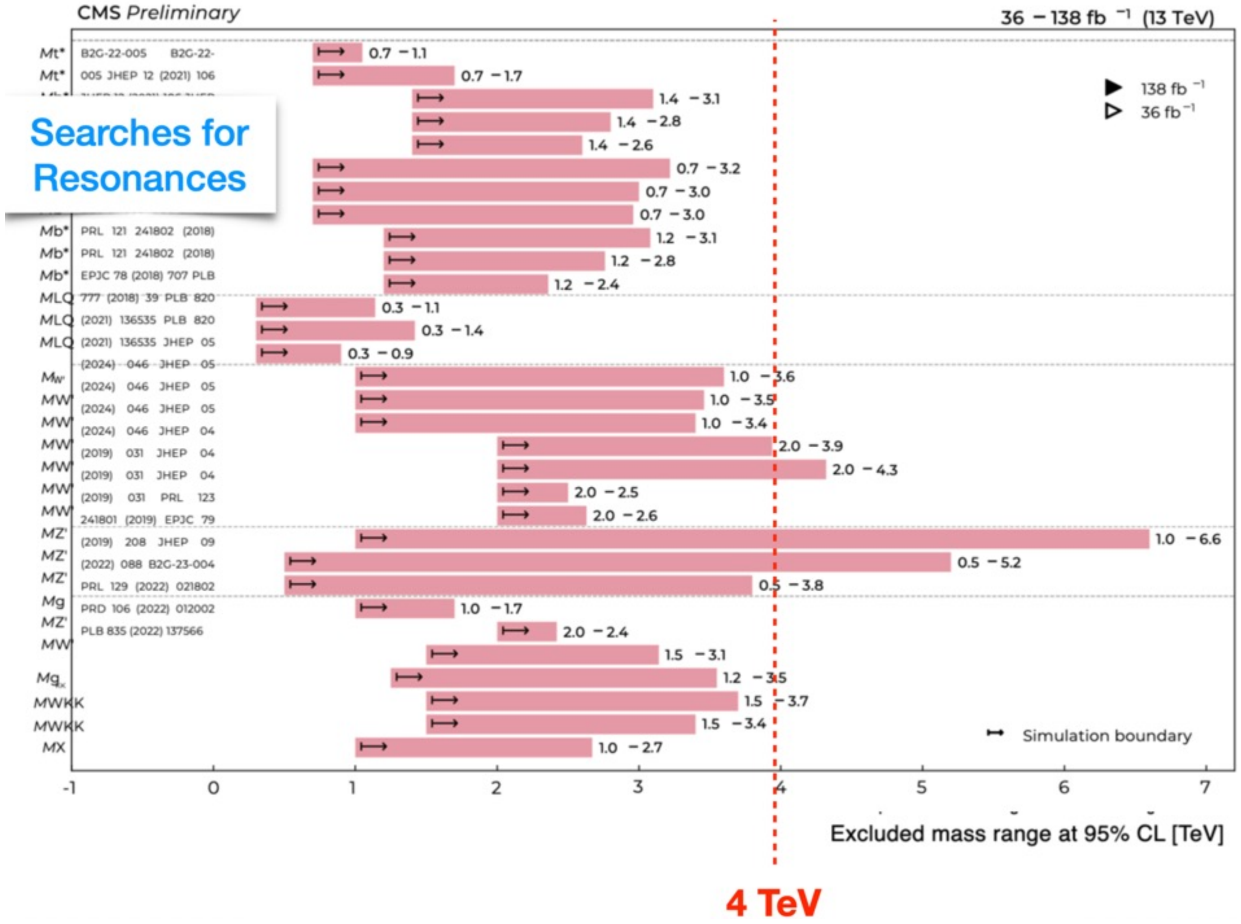
Enormous „clean up“ of Beyond-SM model/parameter space: an achievement probably not valued enough

See talks by Livia Soffi and Marumi Kado, ICHEP 2024





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The SM: Highly successful, **but**….

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c$$

Simplicity, governed by symmetries, few free parameters

$$+\psi_i y_{ij}\psi_j\phi + h.c + |D_\mu\phi|^2 - V(\phi)$$

Not governed by symmetries
many (!) parameters
set by the “hand” of experiments!

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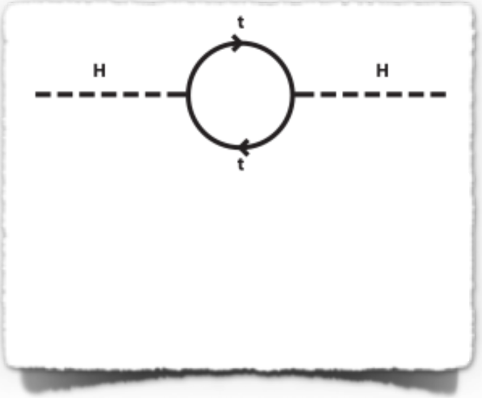
Why is the Higgs boson so light?



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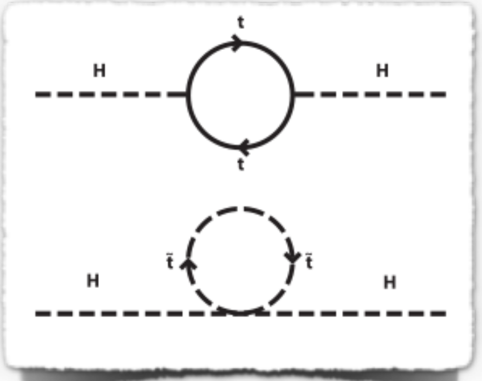

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No dark matter candidate in the model on the left !

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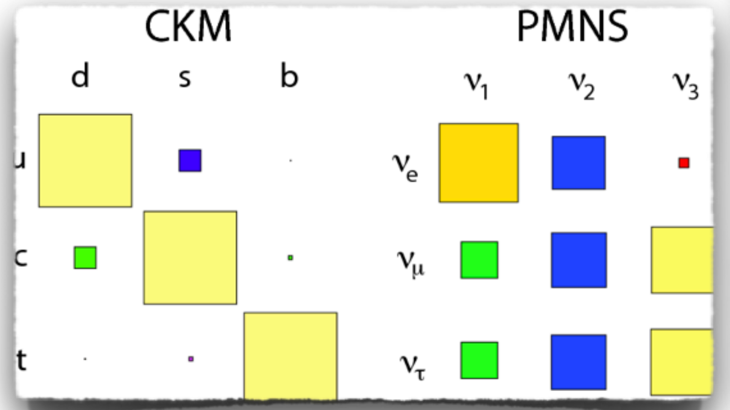

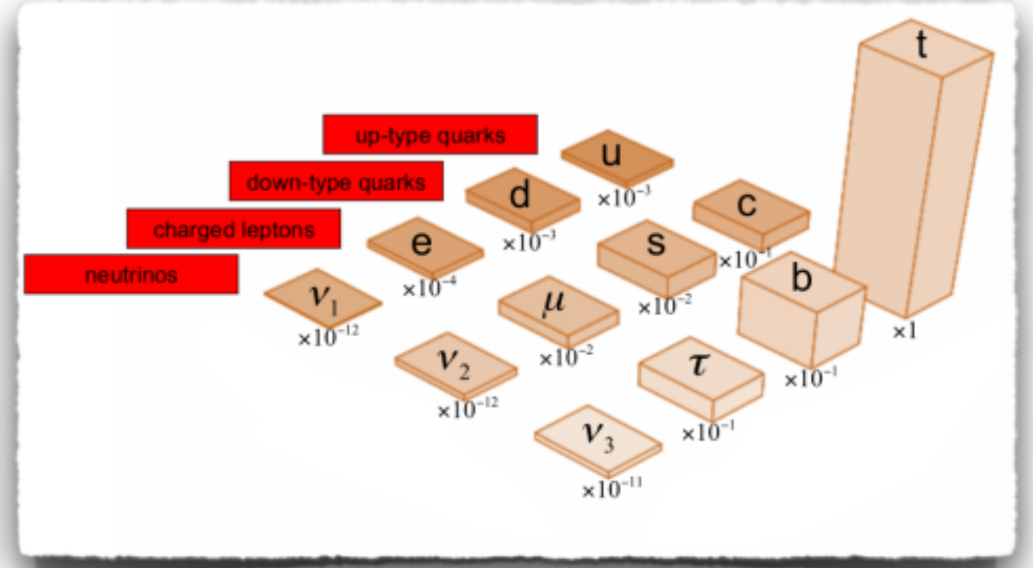

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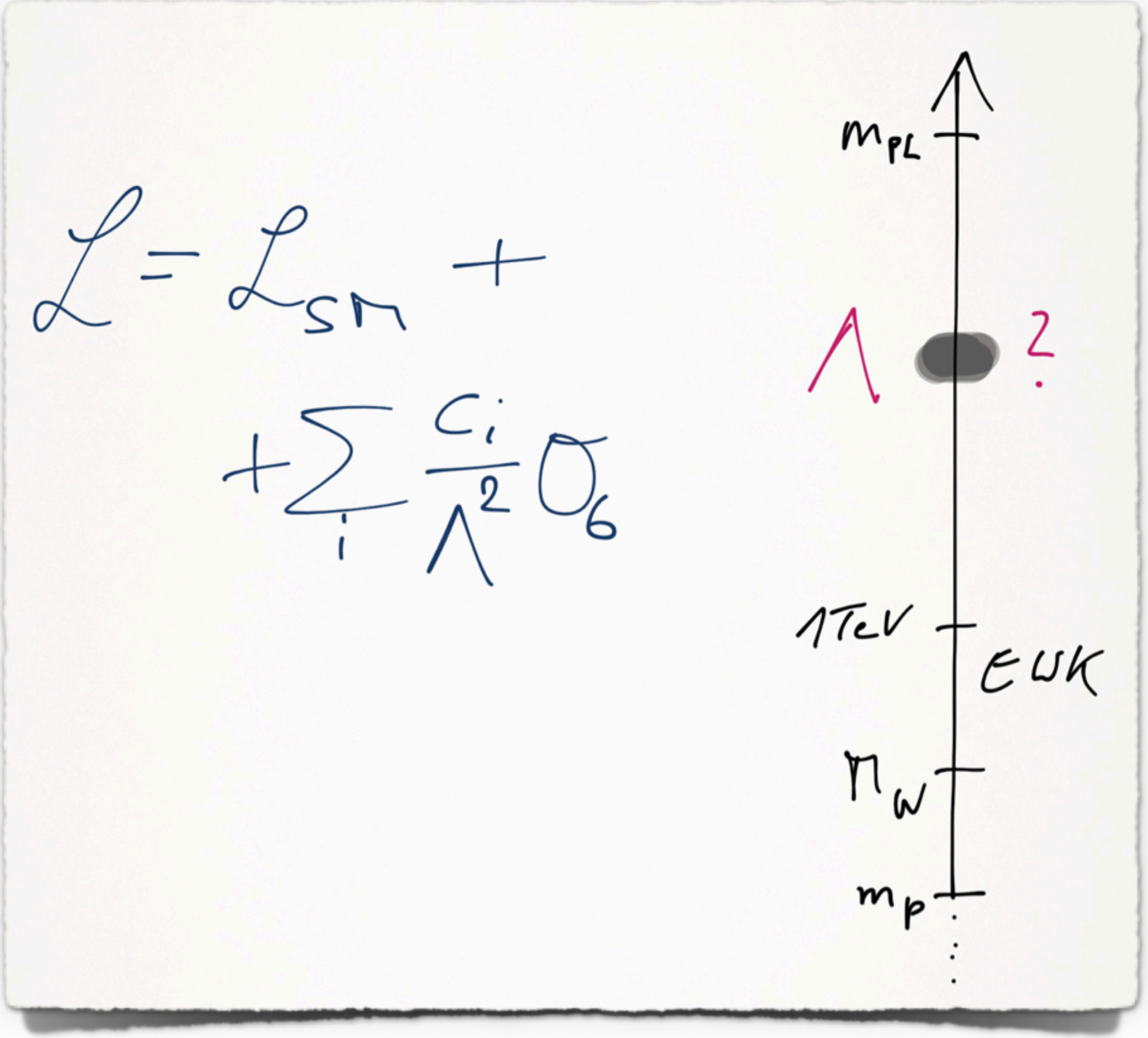
Why are neutrinos so light?

Matter-Antimatter asymmetry?

New physics needed, but where is it?

i.e. what is the scale of New Physics?



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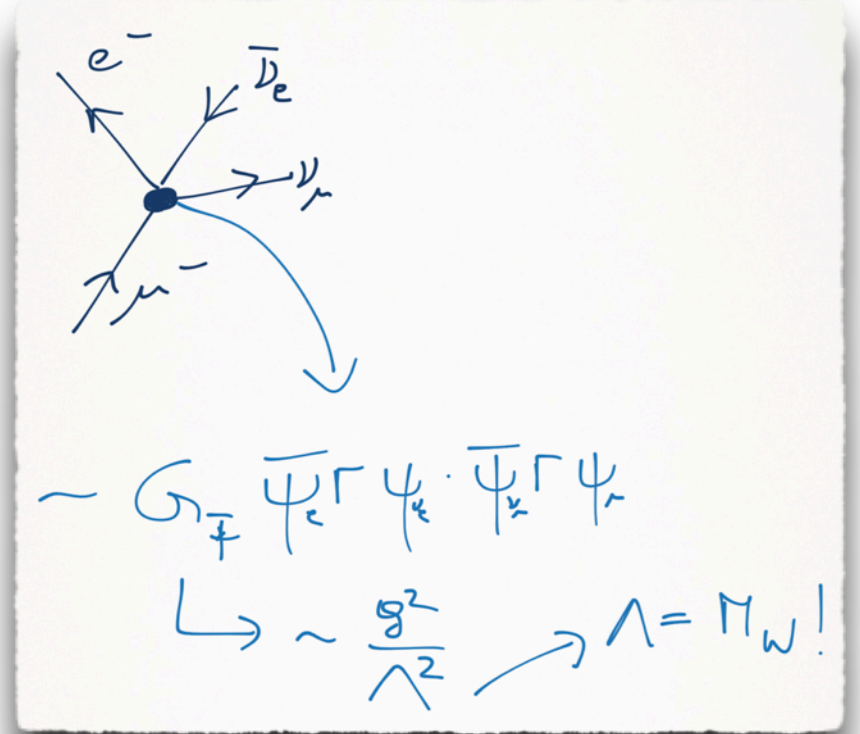

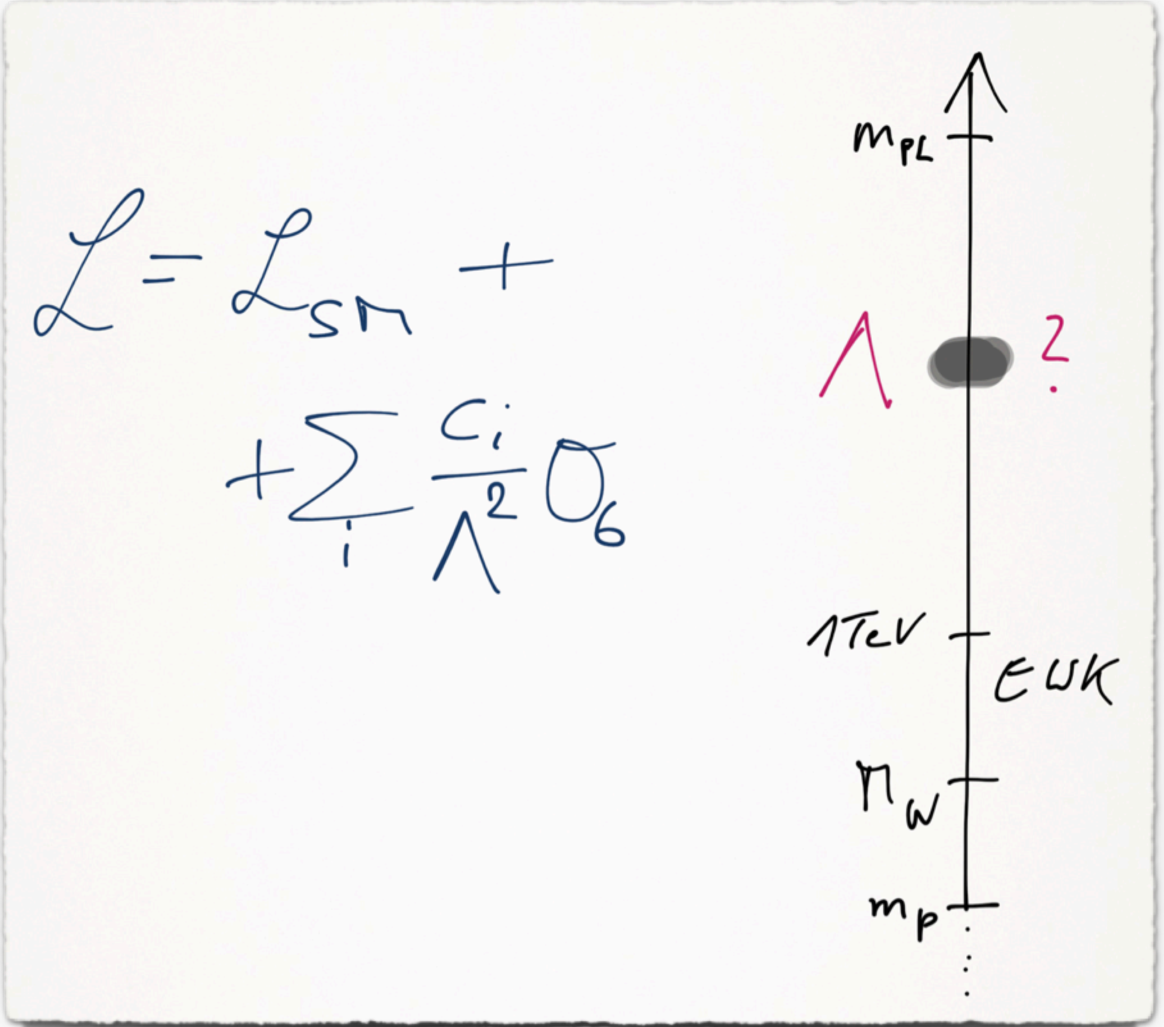

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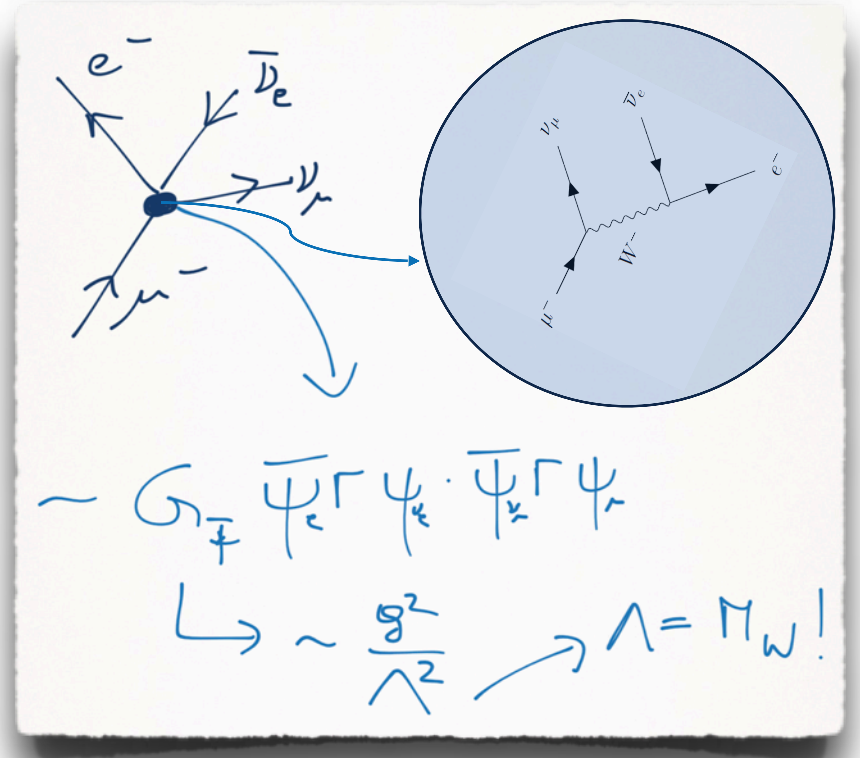

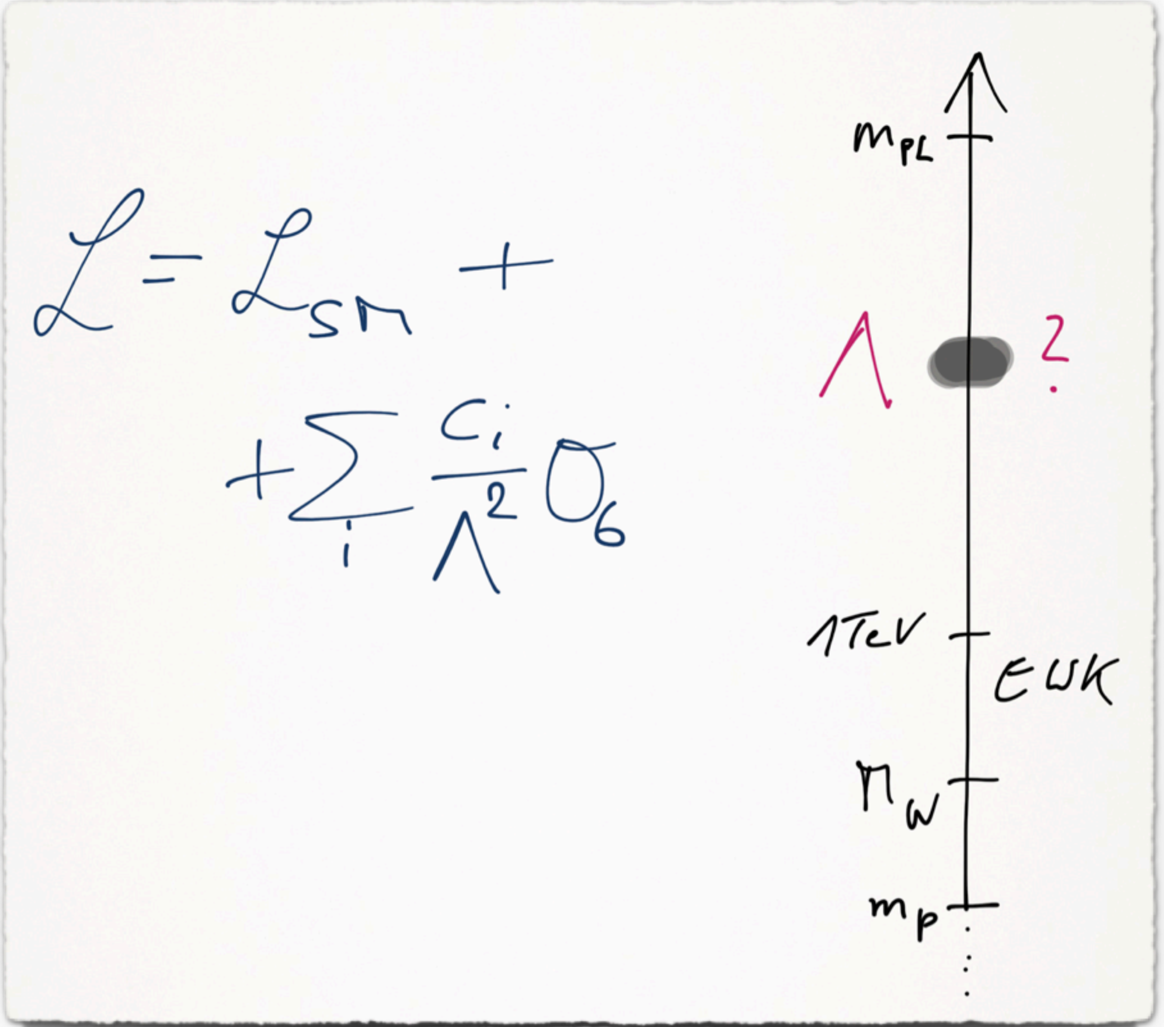

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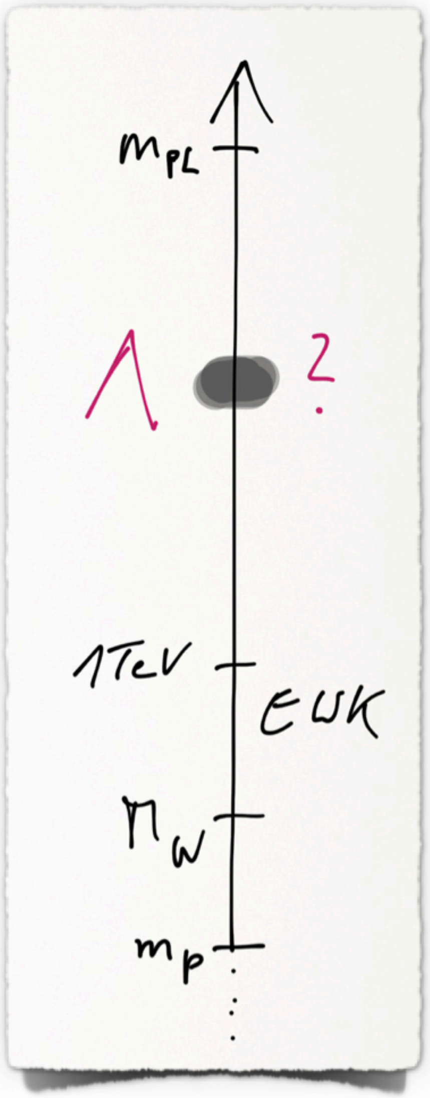

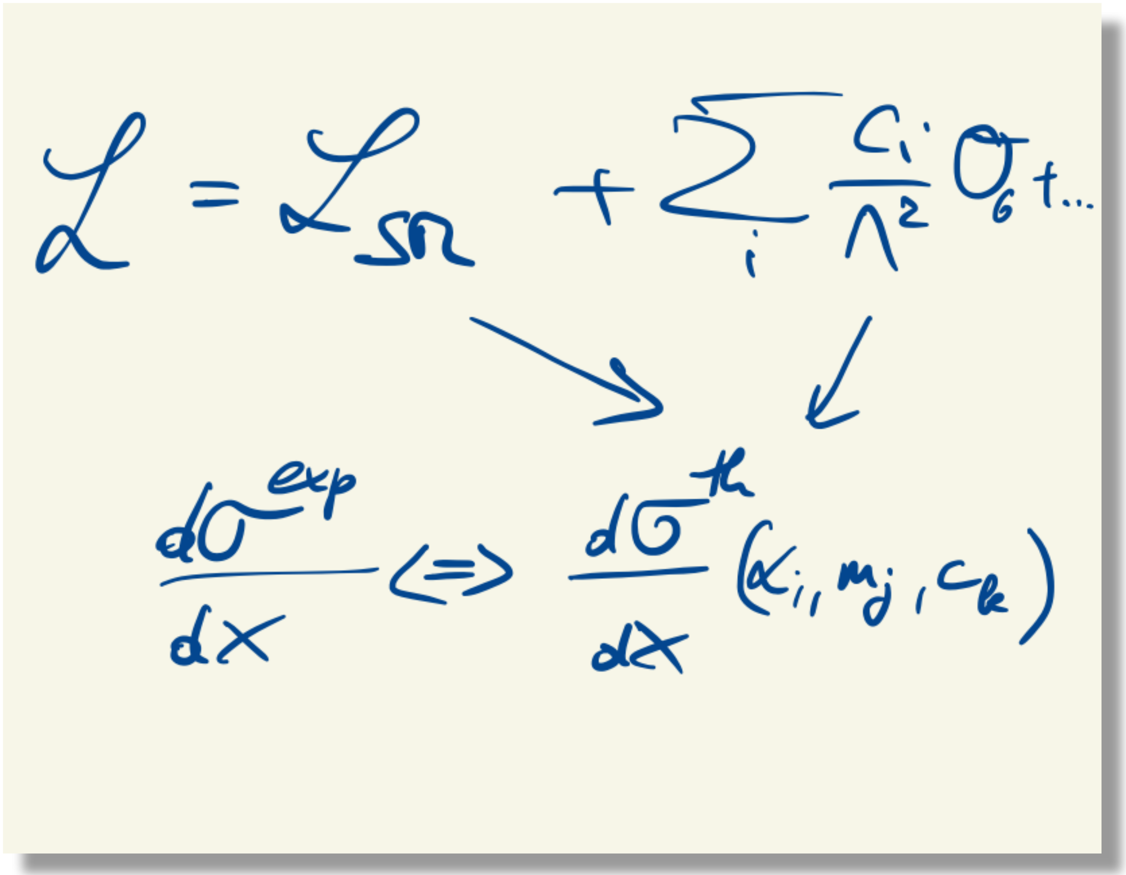

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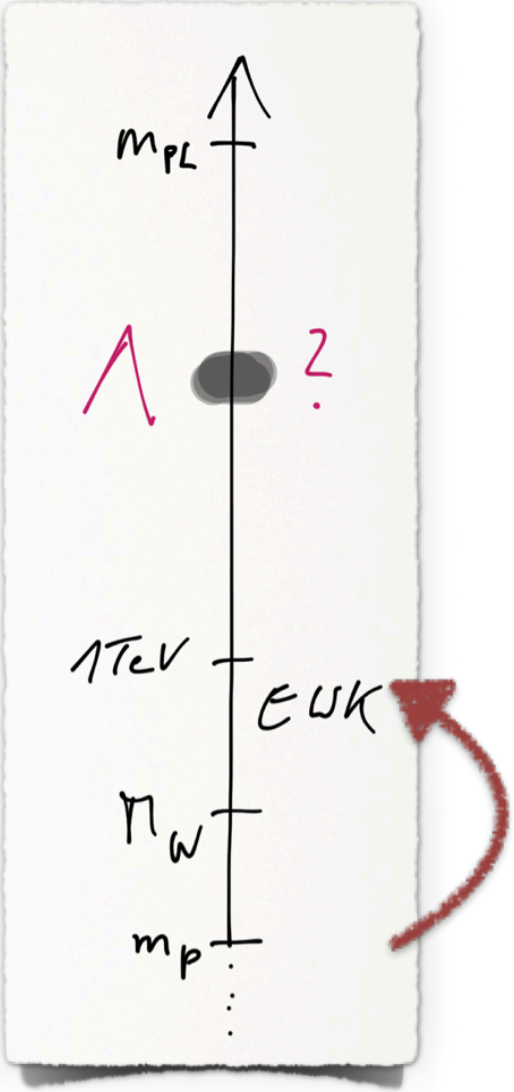
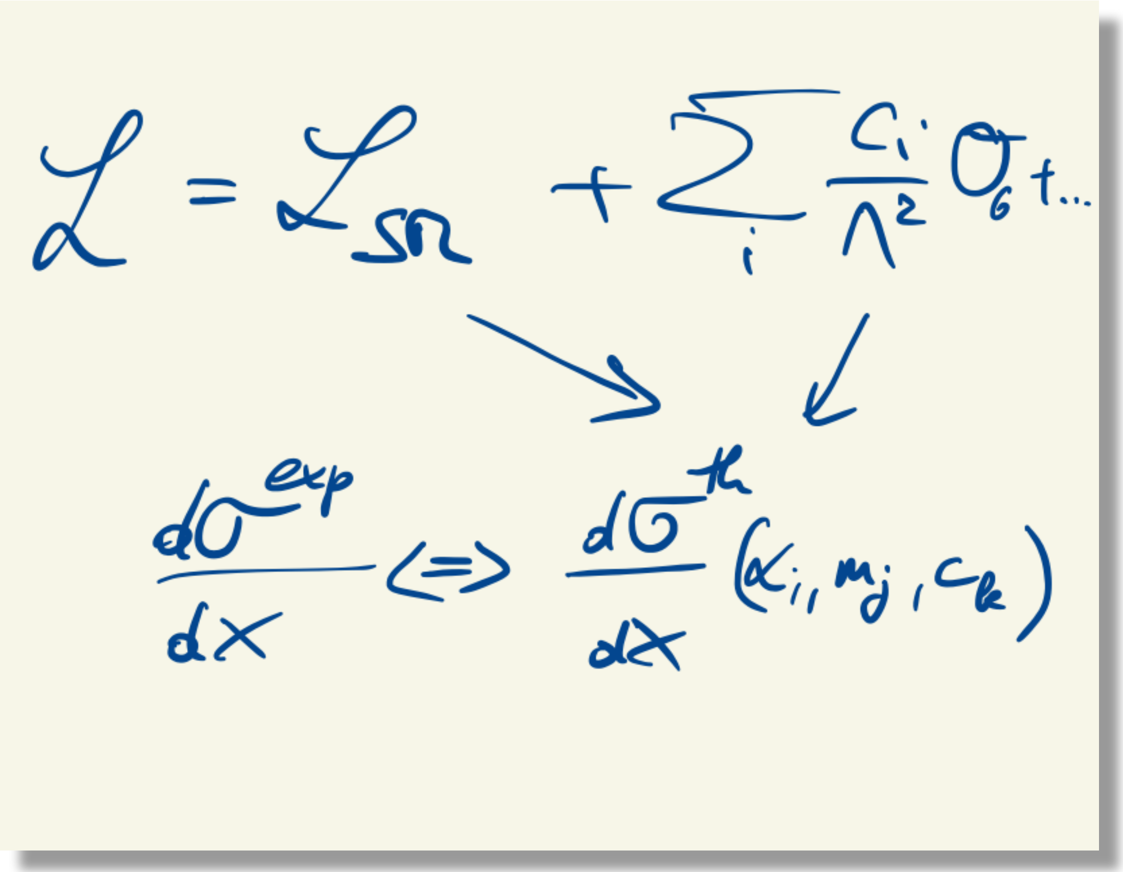


precision
measurements
and higher energy



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New physics needed, but where is it?

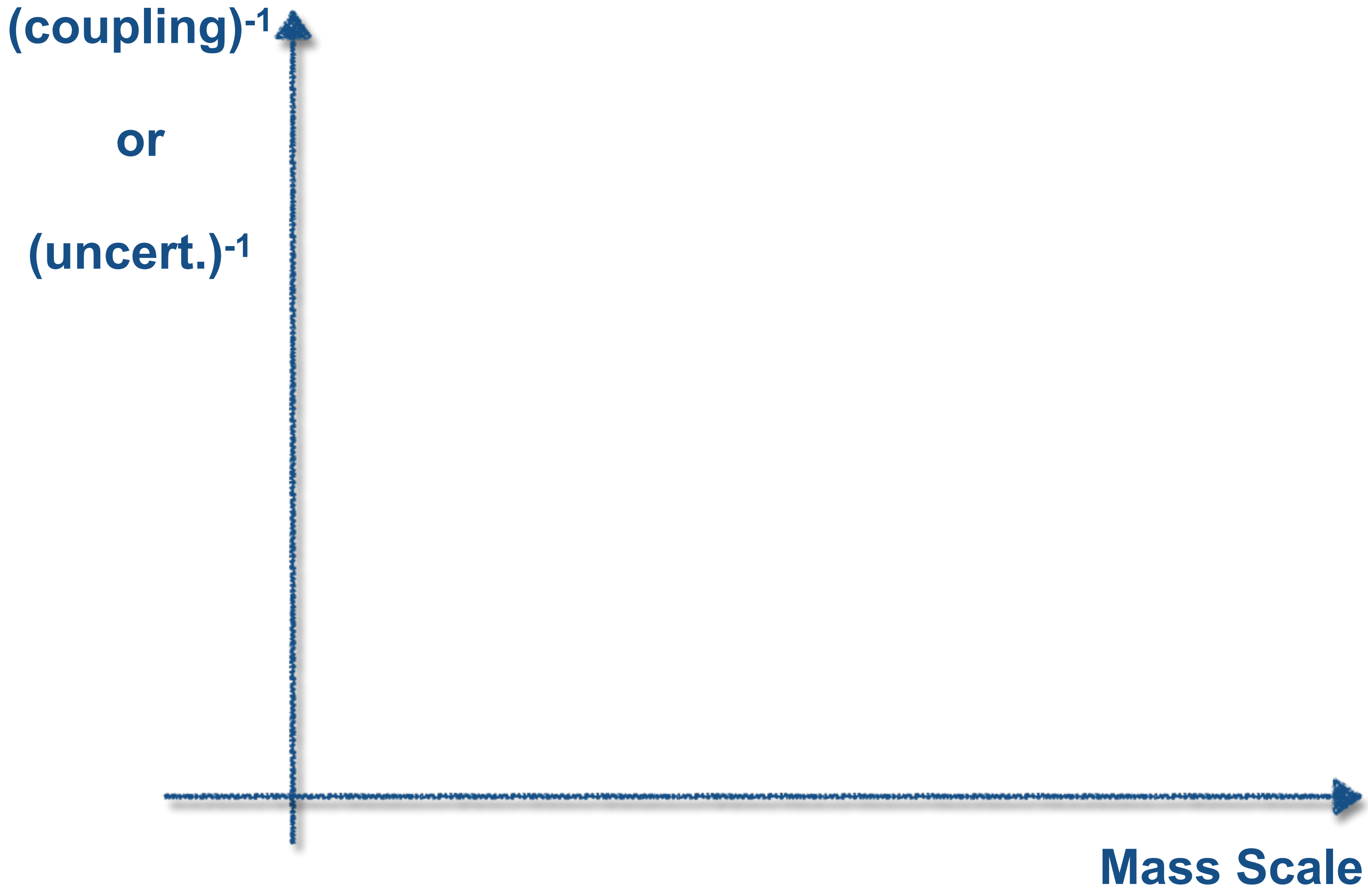
combination of
precision and
higher energy

precision
measurements
and higher energy

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_6 + \ldots$$

$$\frac{d\sigma^{exp}}{dx} \Longleftrightarrow \frac{d\sigma^{th}}{dx}(\alpha_i, m_j, c_k)$$

How to explore the unknown



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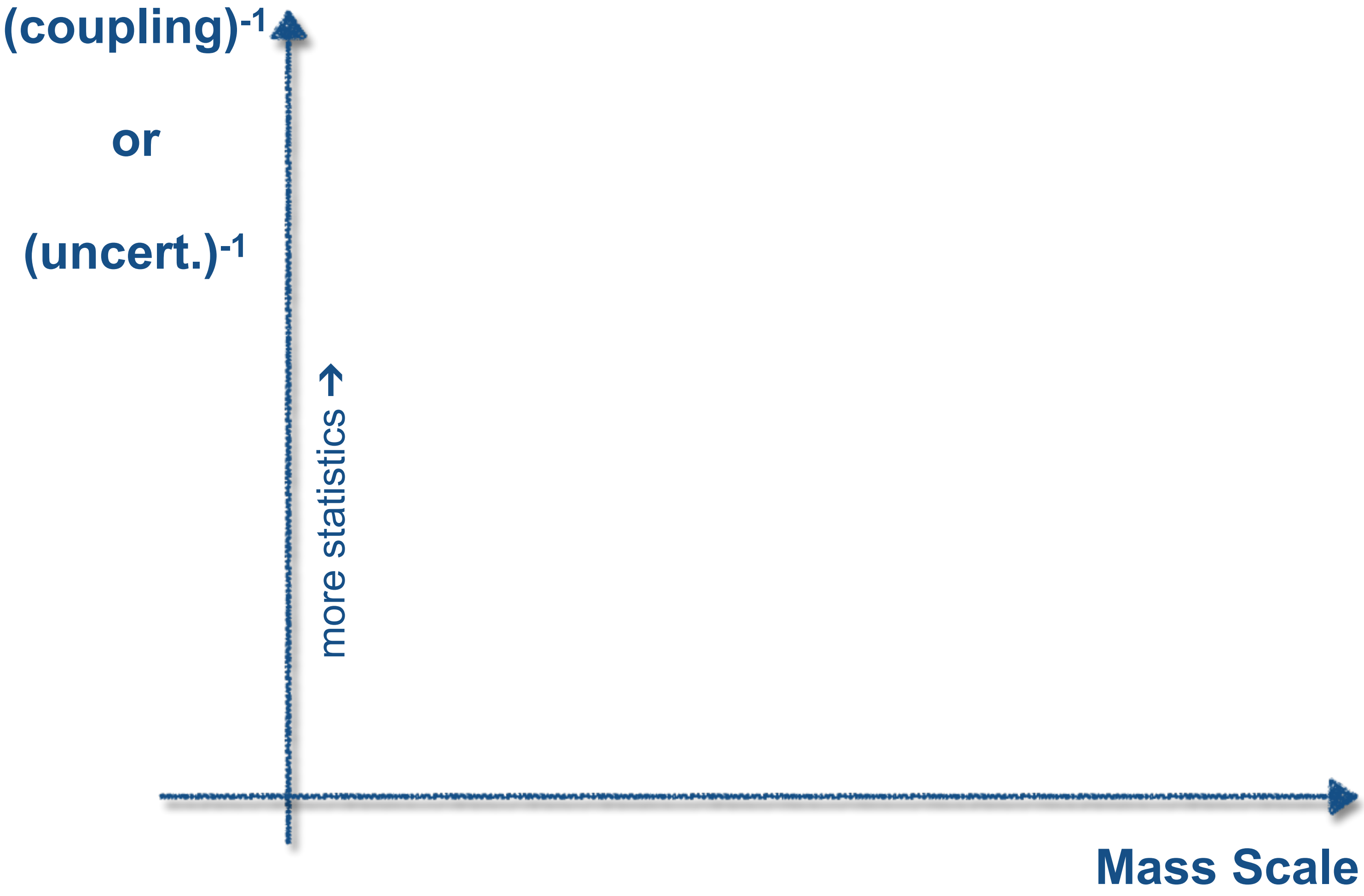

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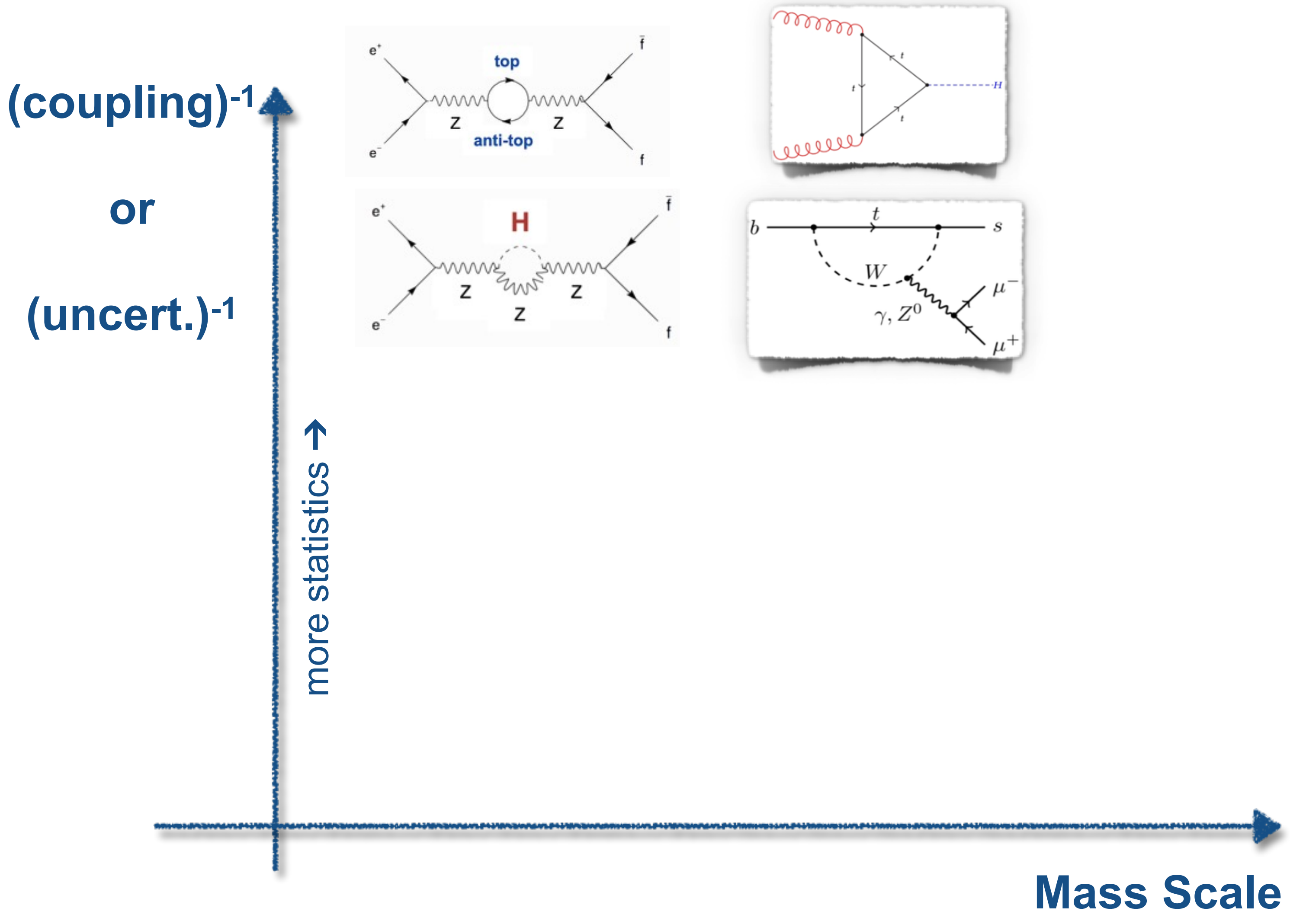

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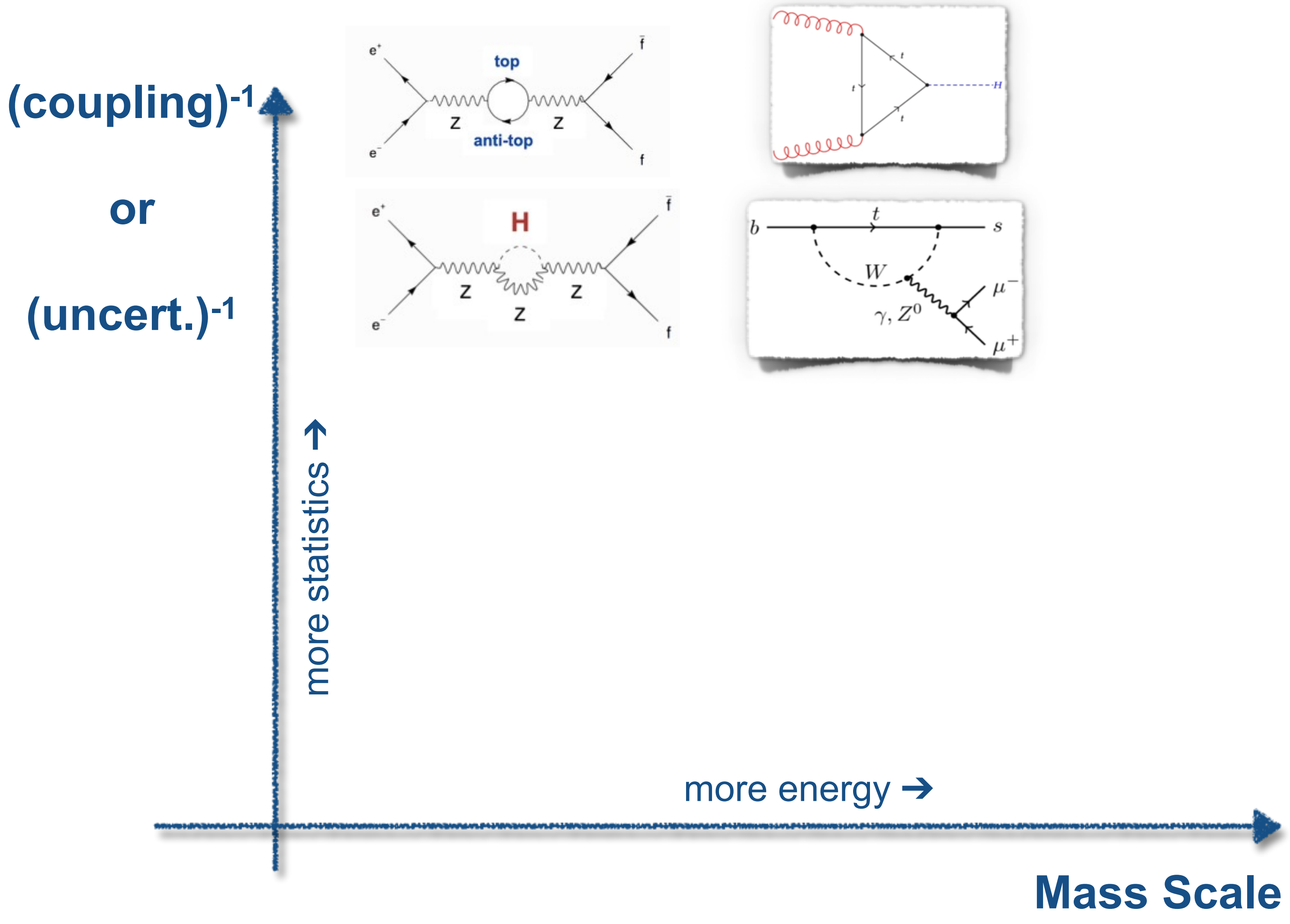

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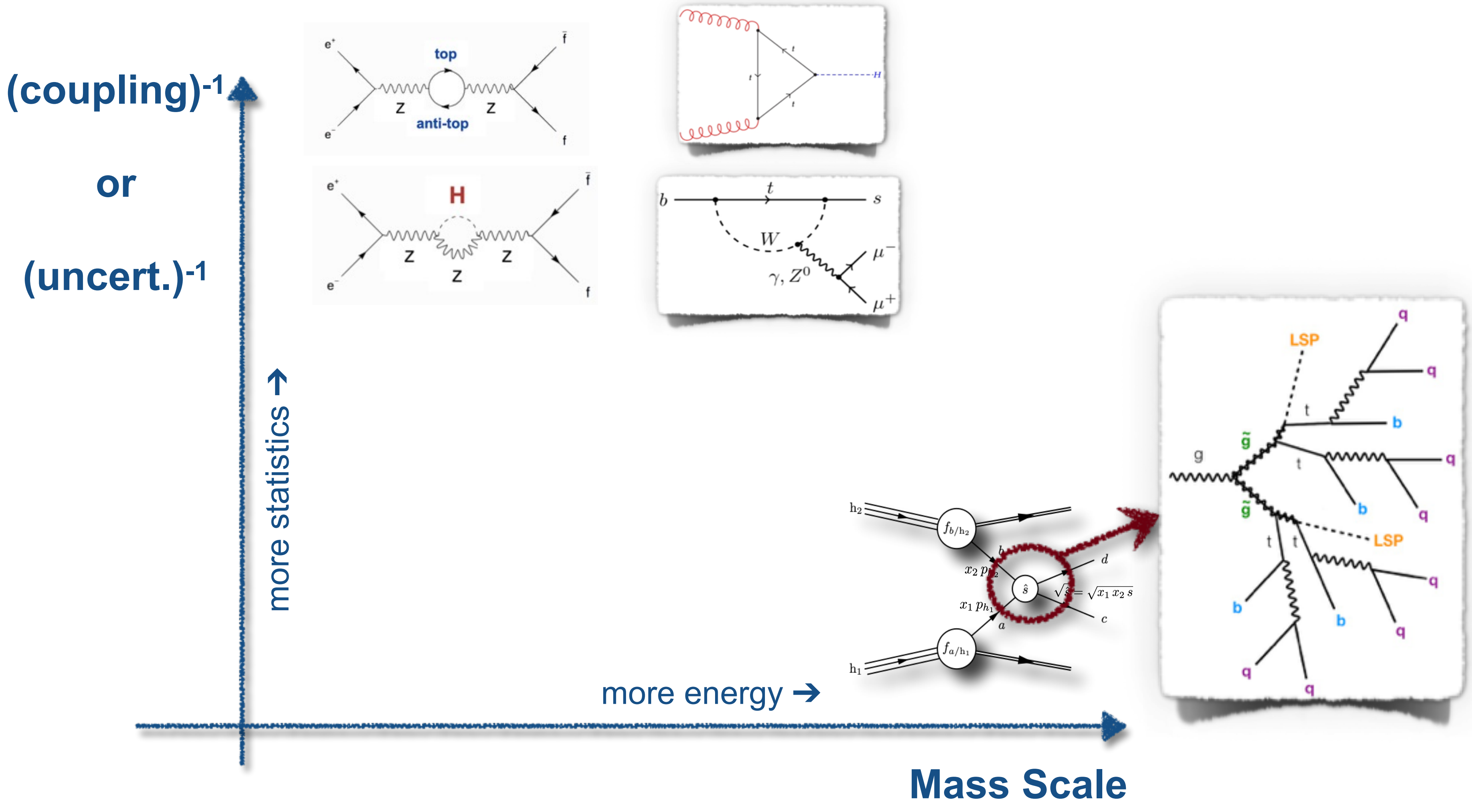

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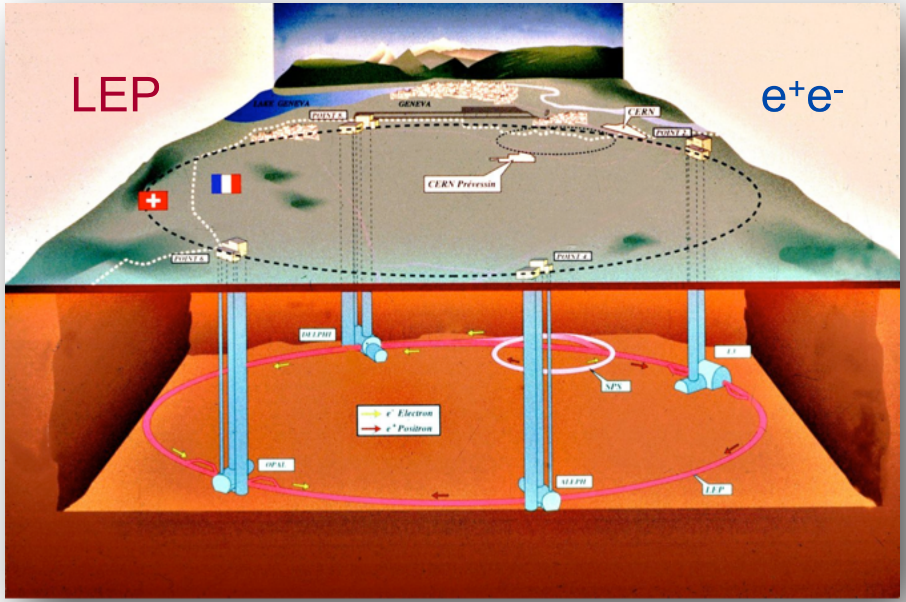
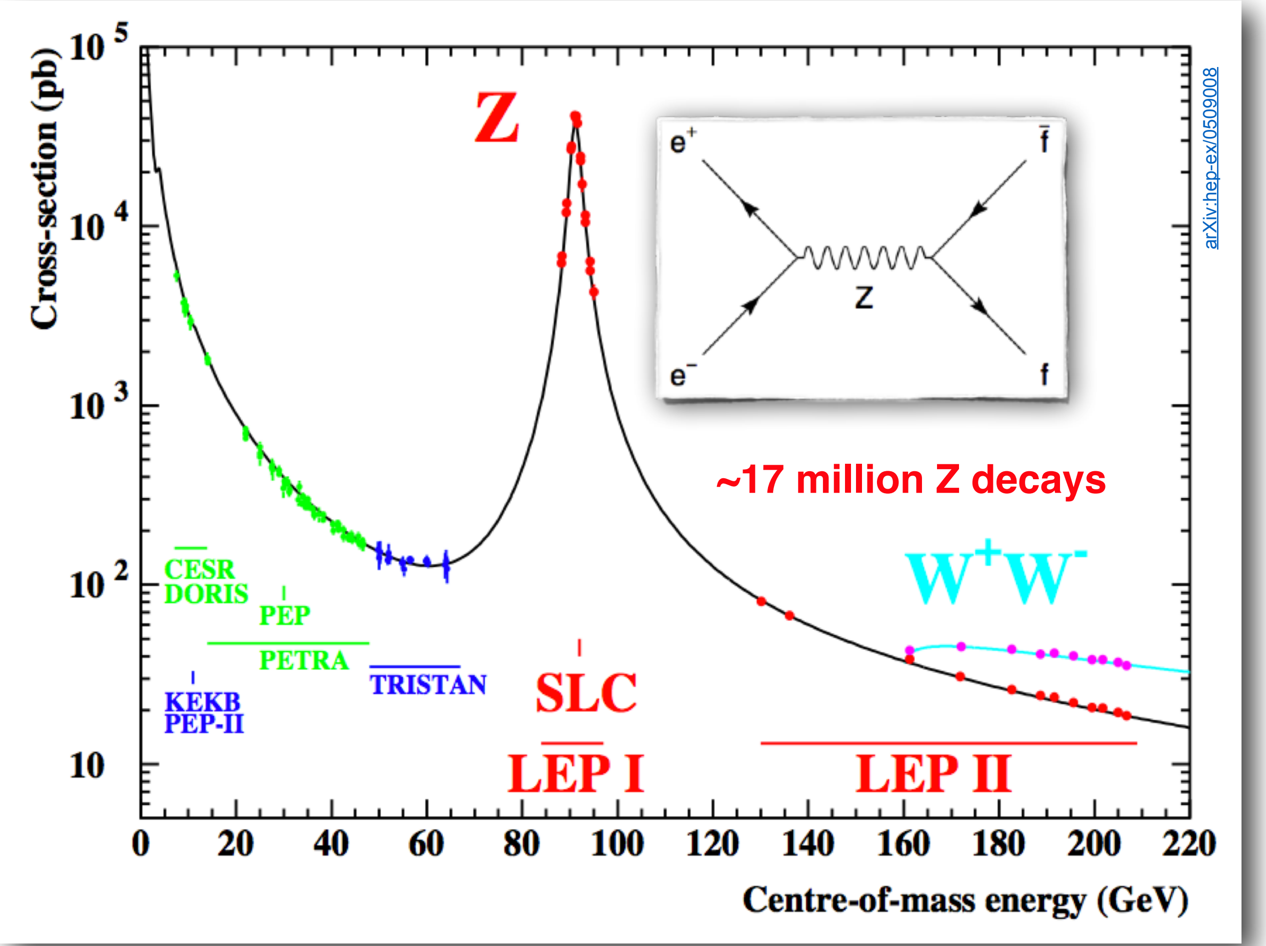
A look back at the ”good old” LEP times

Physics at LEP



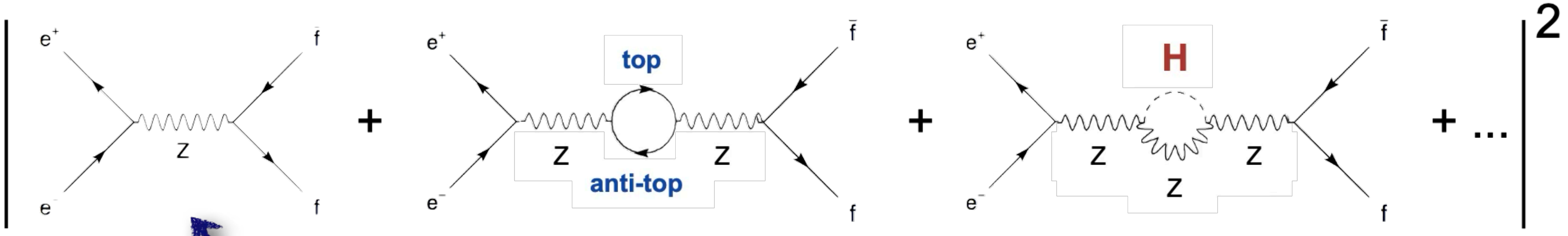


Z mass: relative precision of **0.02 per-mille**

“Height” of the Z resonance : ~ **1 per-mille**

Sensitivity to quantum loops, thanks to precision and accuracy

$$\sigma(e^+e^- \to f\bar{f}) =$$



$\propto \; M_t^2$

% level correction

$\propto \; \log M_H^2$

sub-% level correction

Observable $\mathcal{O}$

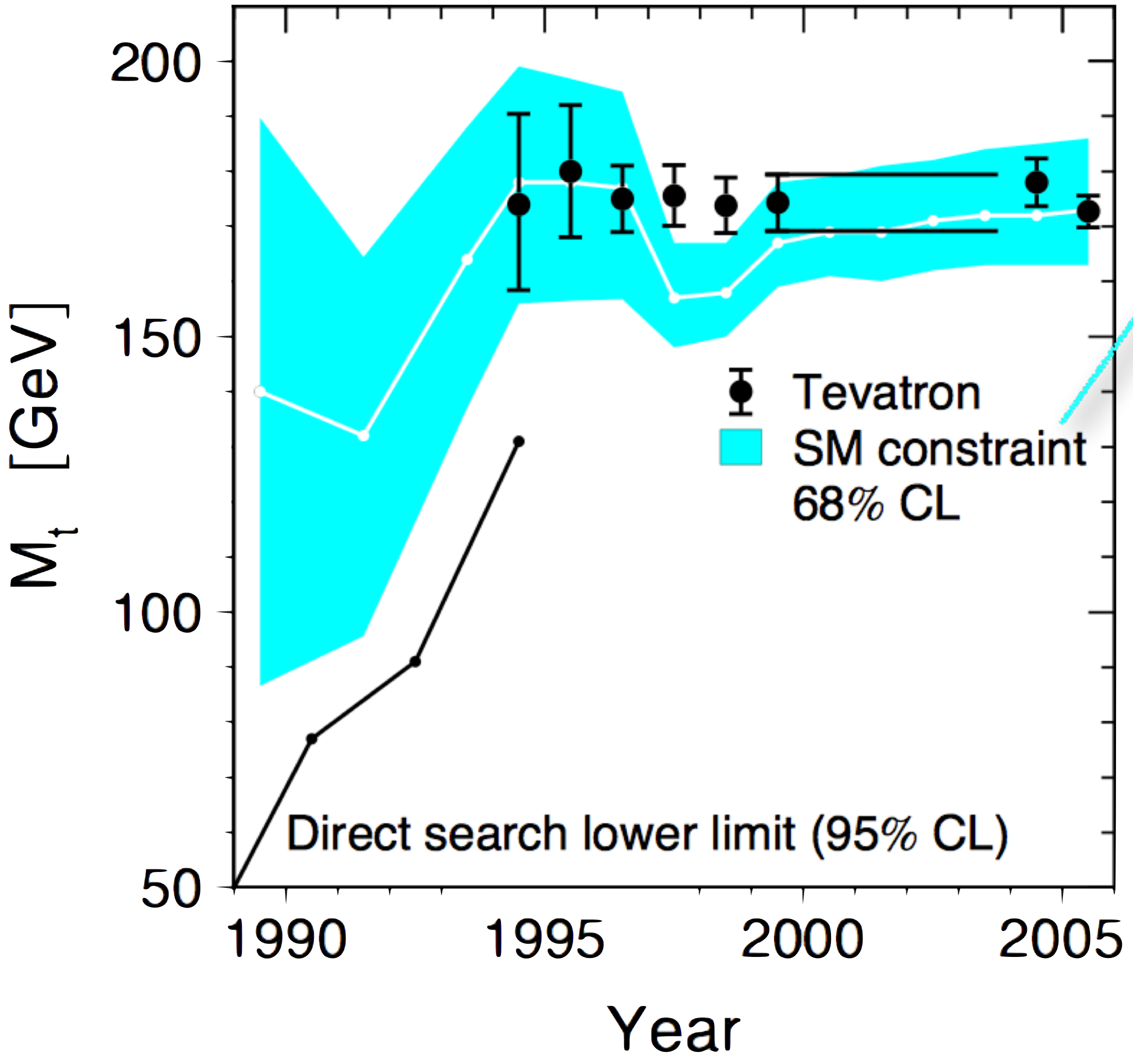
$$\Rightarrow \quad \mathcal{O}_{\mathrm{theo}} = \mathcal{O}_{\mathrm{LO}} \times (1 + \Delta r) \quad \overset{\text{compare}}{\longleftrightarrow} \quad \mathcal{O}_{\mathrm{meas}}$$

"loop" corrections: $\Delta r = f(M_t^2, \log M_H^2)$

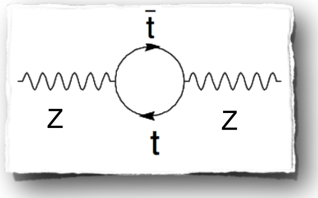
☞ with per-mille level precision measurements sensitivity to heavy particles in the loops!

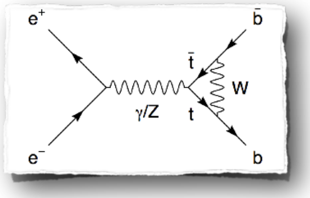
Proof of principle

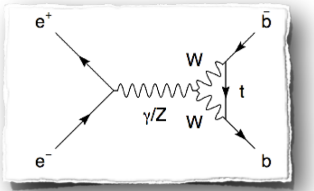
"prediction" of the top quark mass and comparison to the direct measurement from arXiv:hep-ex/0509008



$M_t = 173^{+13}_{-10}$ GeV







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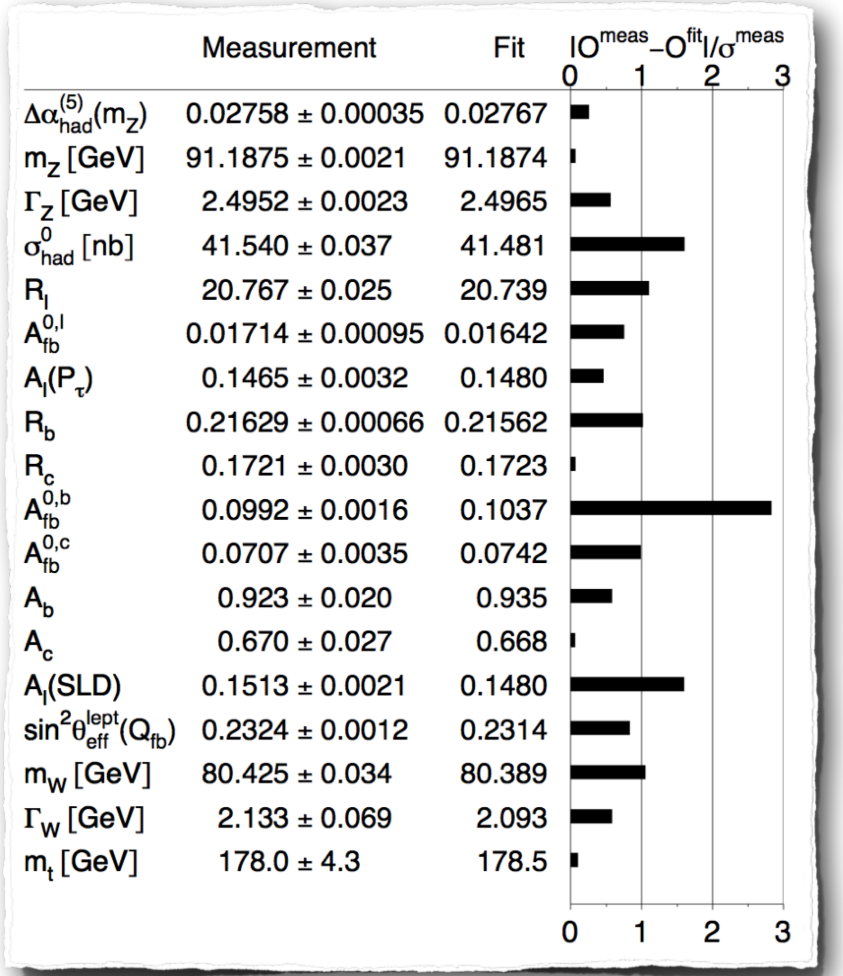
And then the "Higgs prediction"….

Vary a few input parameters, including M_H, in a global fit to:

Z-pole data, direct measurements of m_W, Γ_W, m_{top} and the hadr. vac. pol.



	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965	
σ^0_{had} [nb]	41.540 ± 0.037	41.481	
R_l	20.767 ± 0.025	20.739	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480	
R_b	0.21629 ± 0.00066	0.21562	
R_c	0.1721 ± 0.0030	0.1723	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1480	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.425 ± 0.034	80.389	
Γ_W [GeV]	2.133 ± 0.069	2.093	
m_t [GeV]	178.0 ± 4.3	178.5	

Number of standard deviations

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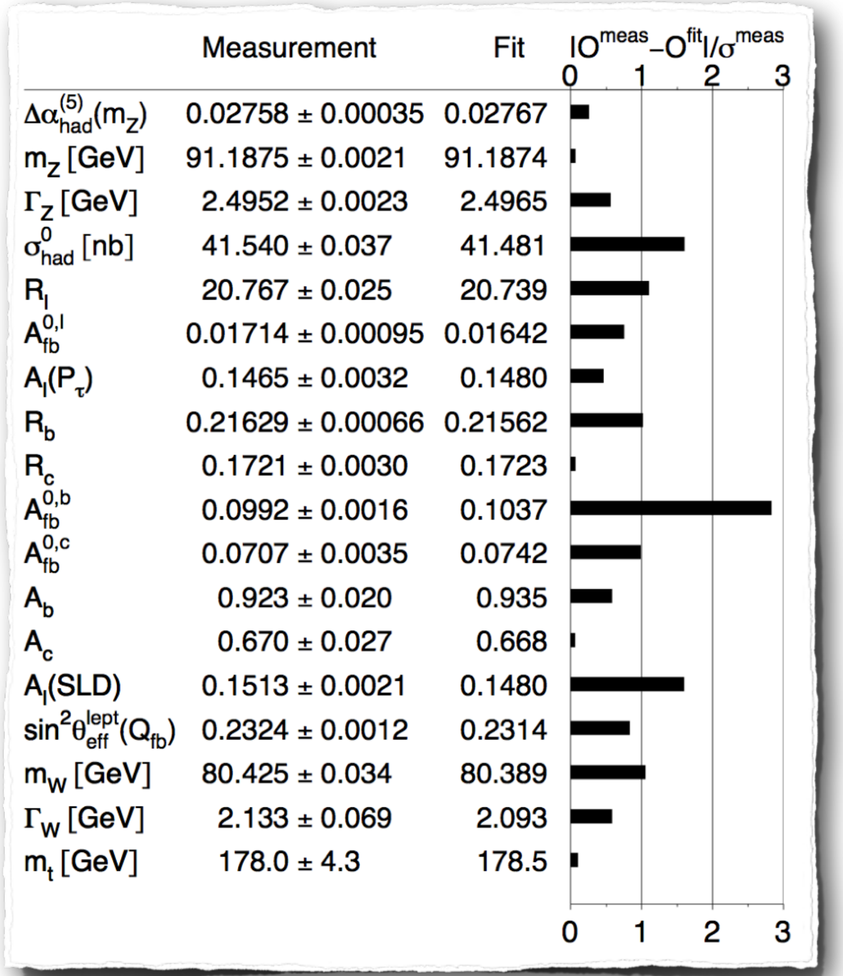
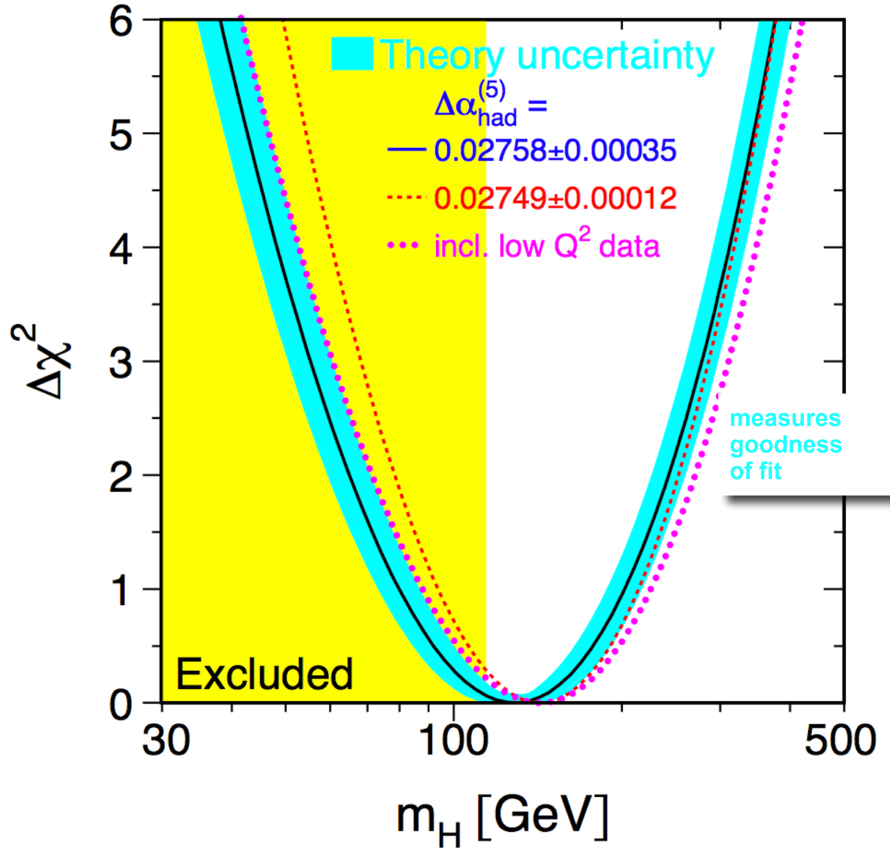
Example taken from LEP EWK combination **early 2006**

https://arxiv.org/abs/hep-ex/0509008v3



	Measurement	Fit	$\lvert O^{meas} - O^{fit} \rvert / \sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965	
σ_{had}^0 [nb]	41.540 ± 0.037	41.481	
R_l	20.767 ± 0.025	20.739	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480	
R_b	0.21629 ± 0.00066	0.21562	
R_c	0.1721 ± 0.0030	0.1723	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037	
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1480	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.425 ± 0.034	80.389	
Γ_W [GeV]	2.133 ± 0.069	2.093	
m_t [GeV]	178.0 ± 4.3	178.5	

Number of standard deviations



measures goodness of fit

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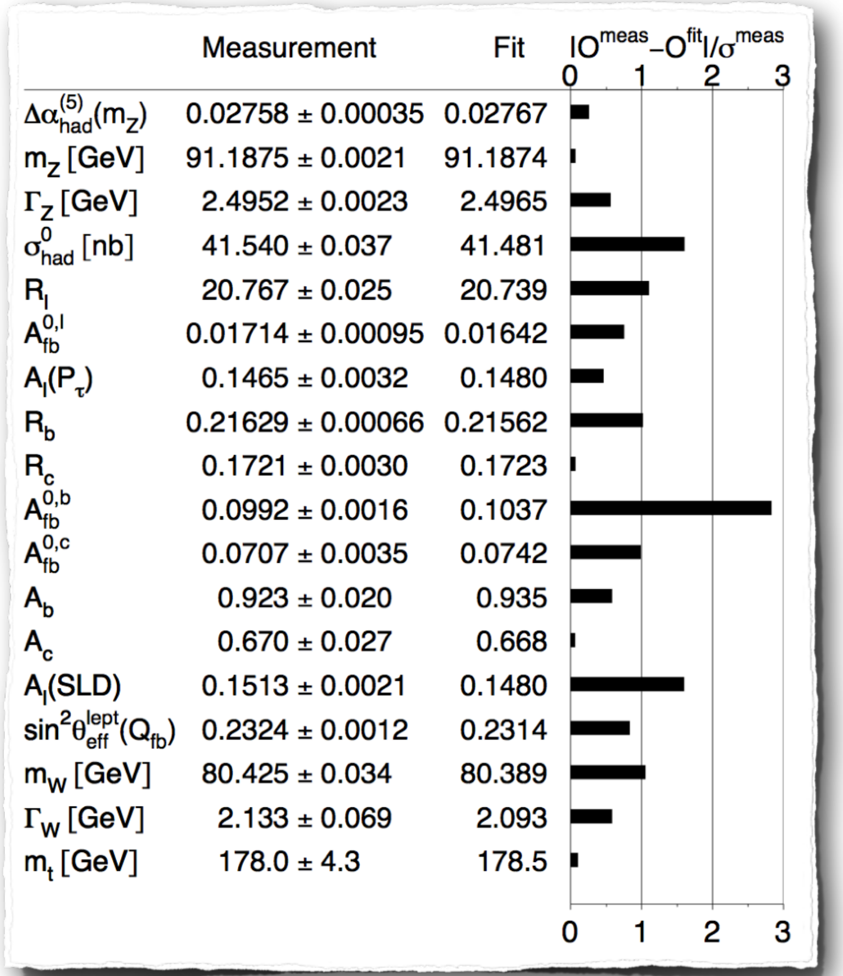
And then the “Higgs prediction”….

Vary a few input parameters, including M_H, in a global fit to:

Z-pole data, direct measurements of m_W, Γ_W, m_{top} and the hadr. vac. pol.

Example taken from LEP EWK combination **early 2006**

https://arxiv.org/abs/hep-ex/0509008v3



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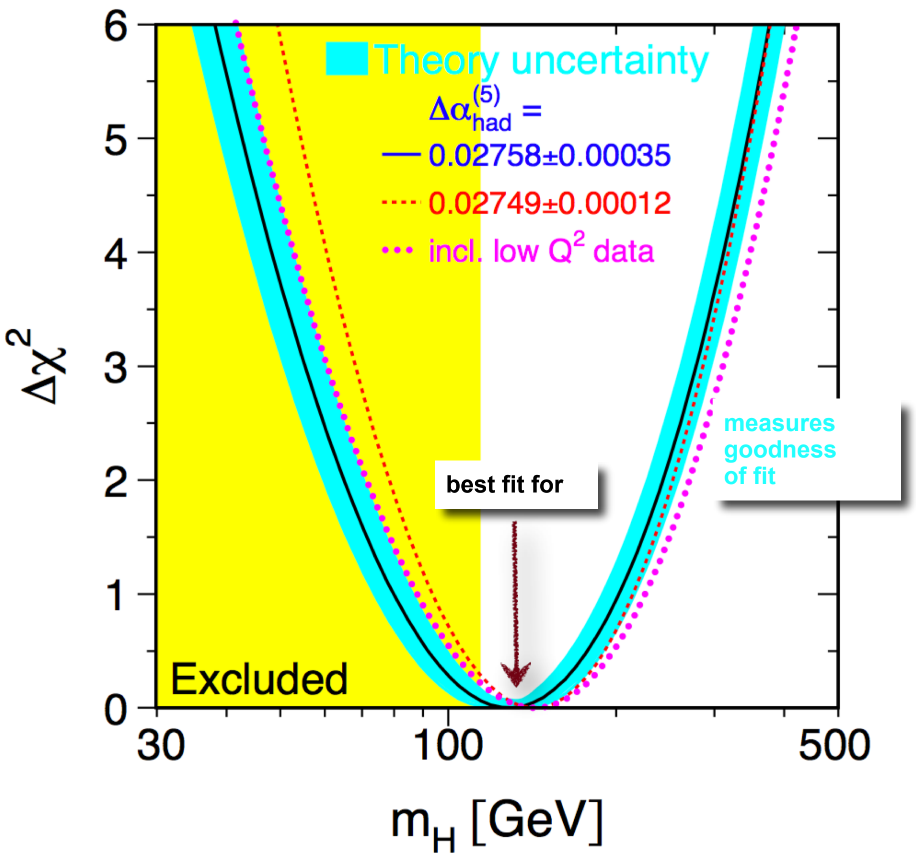
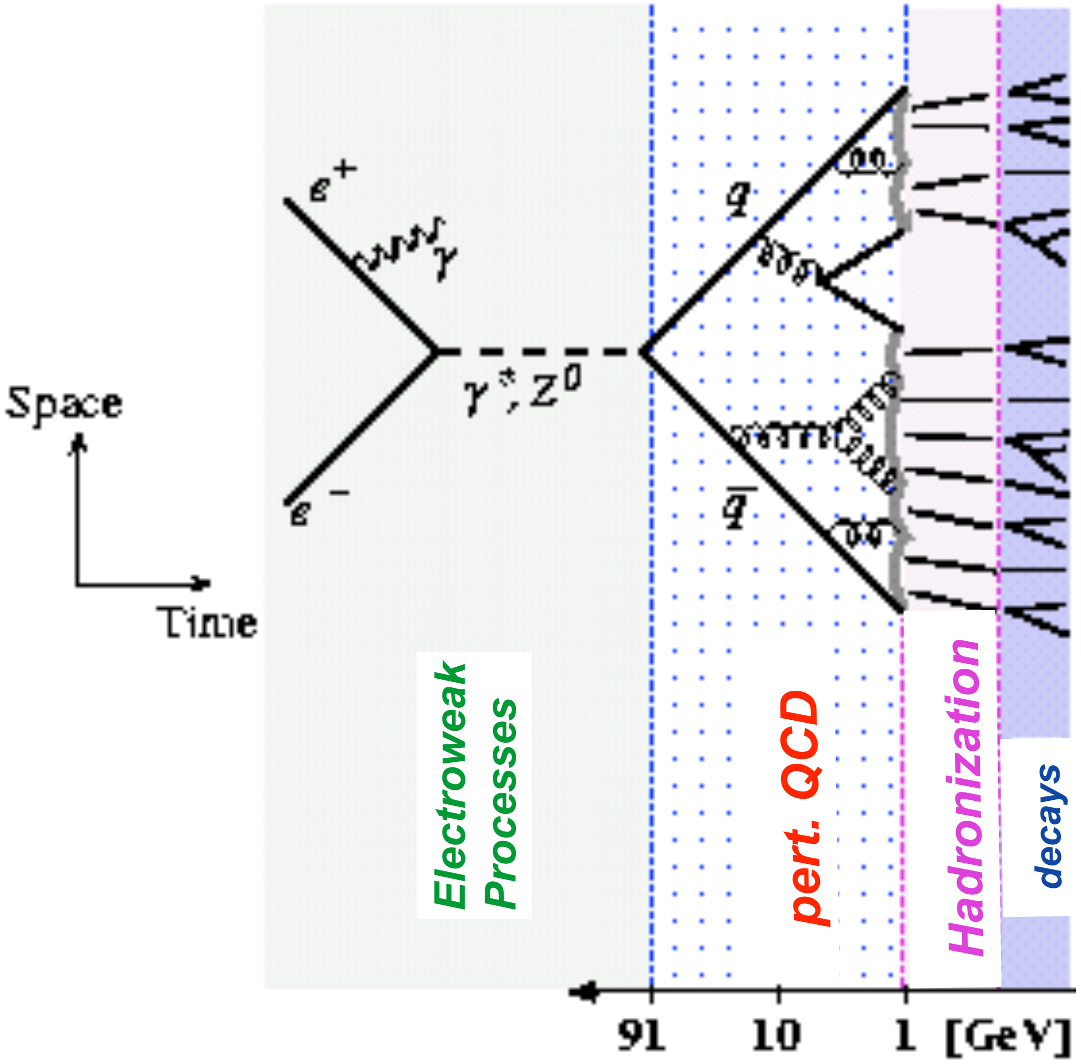


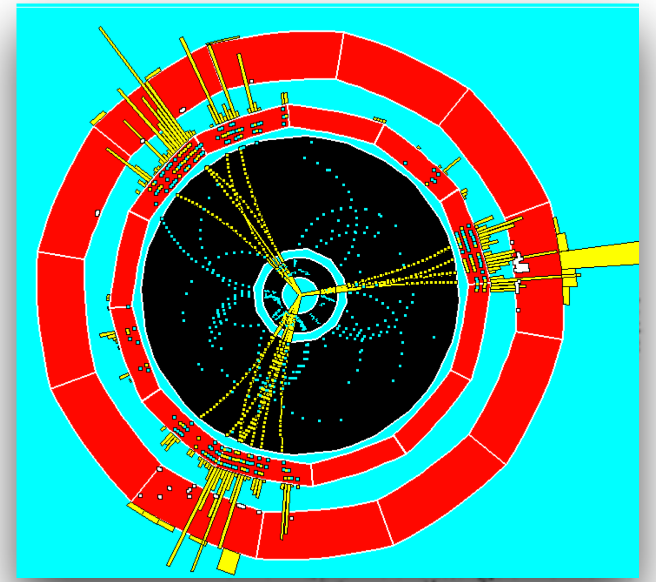
$$M_H = 129^{+74}_{-49}\ \text{GeV}$$

$$M_H < 285\,\text{GeV} \quad \text{at} \quad 95\%\ \text{C.L.}$$

ETH zürich

LEP: Also a wonderful tool for precision QCD studies…





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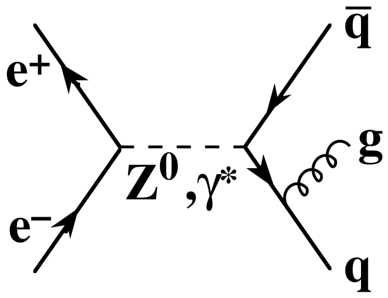
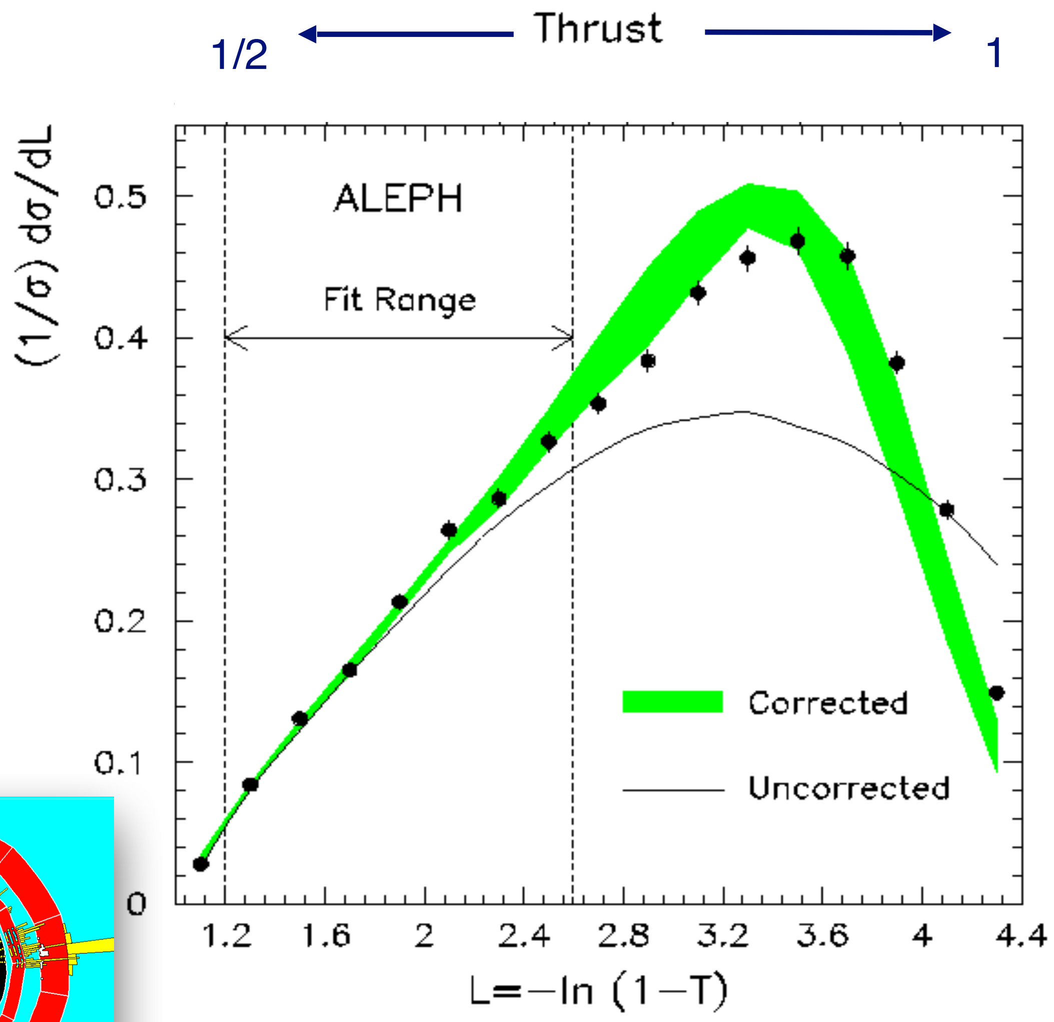
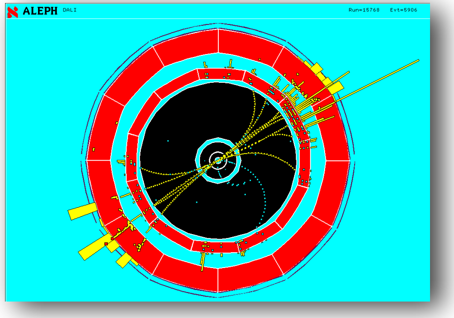
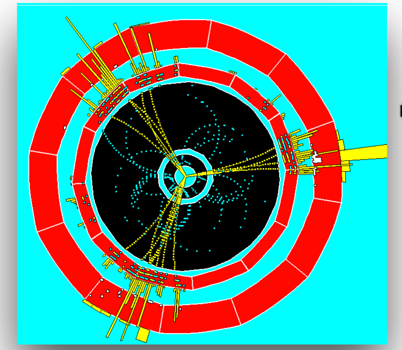
Measurements of the strong coupling









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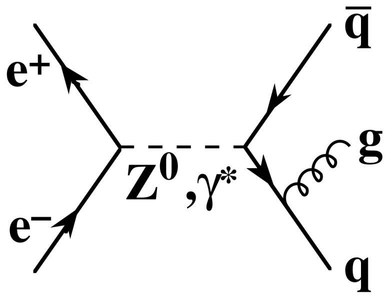

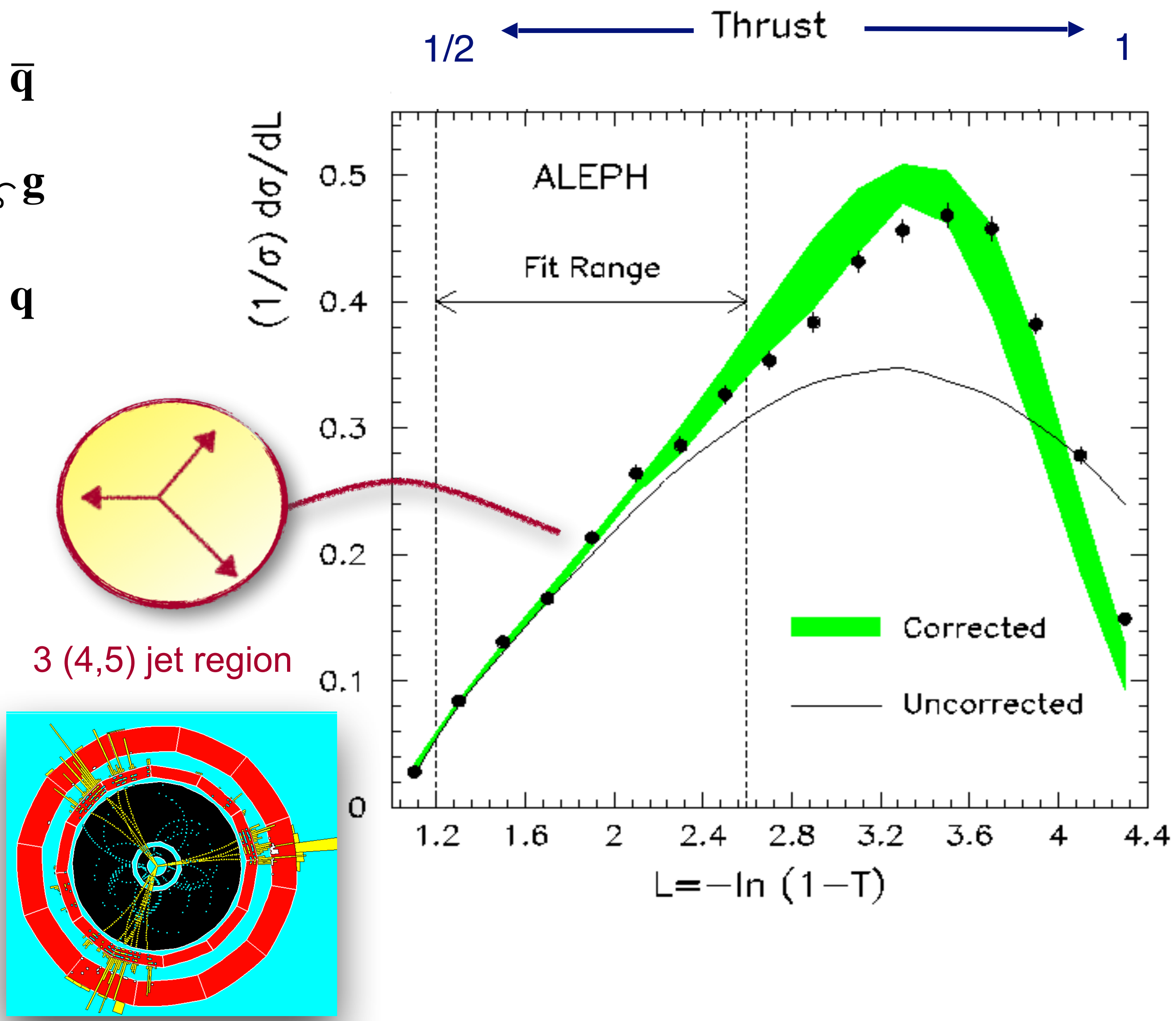

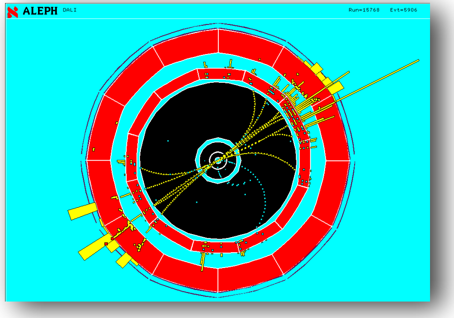

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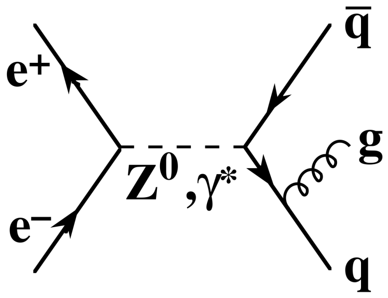

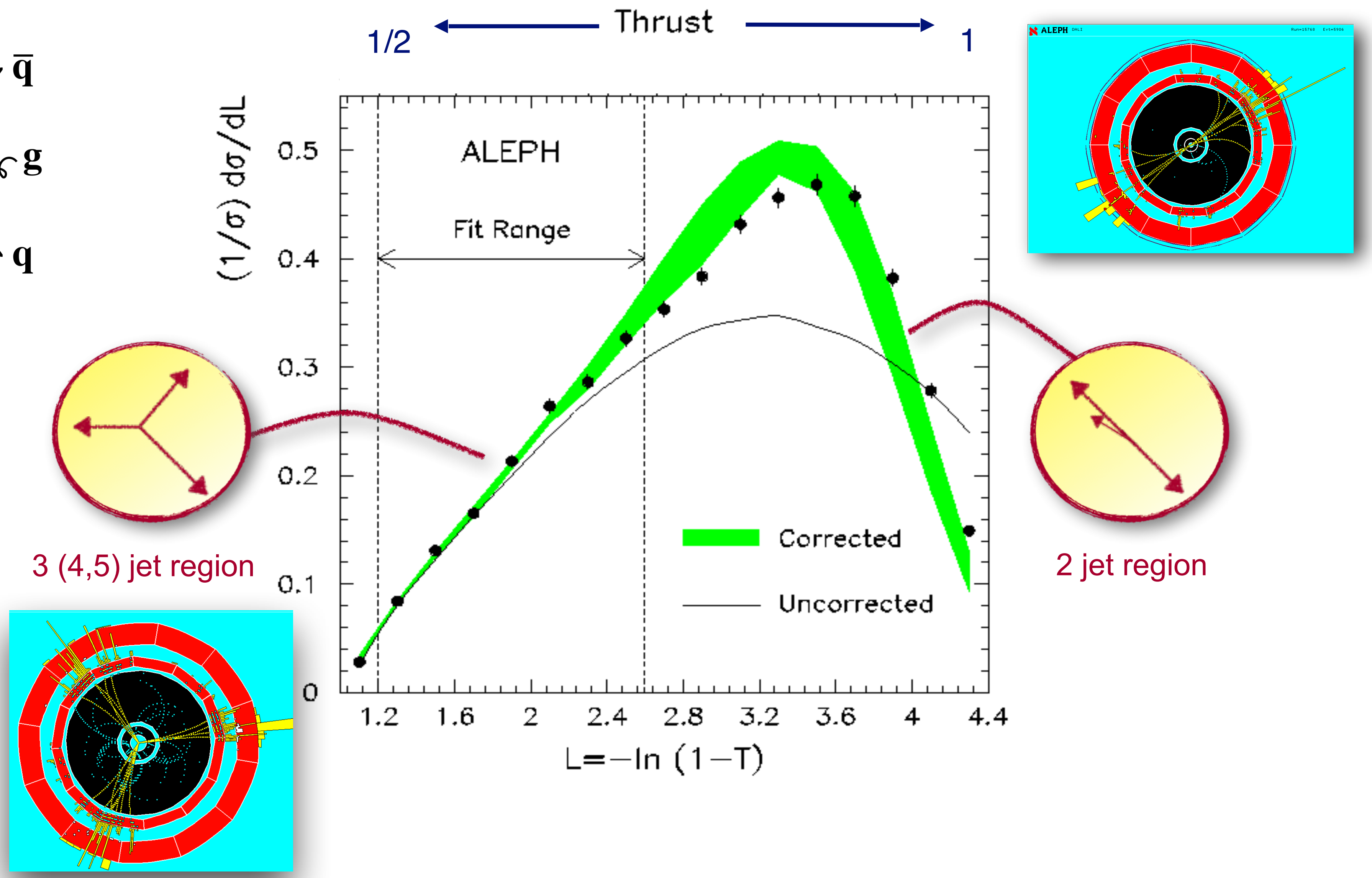

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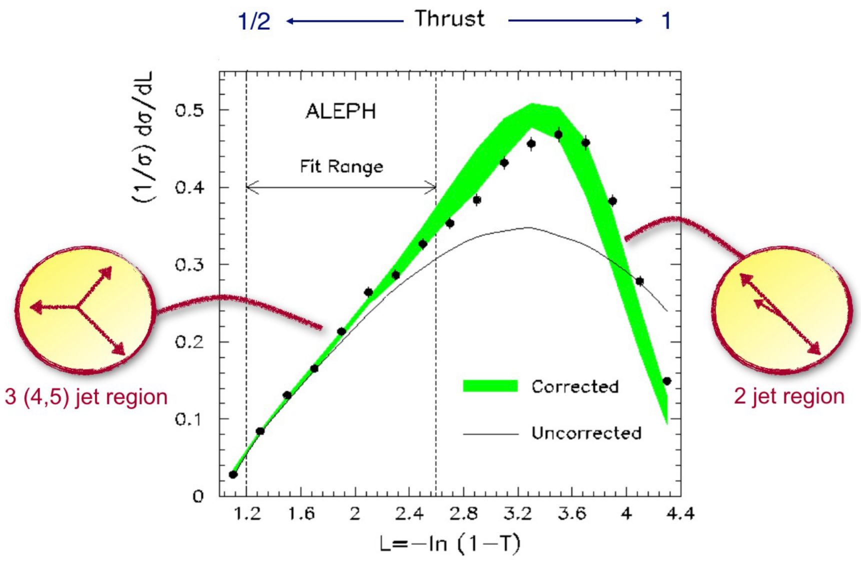

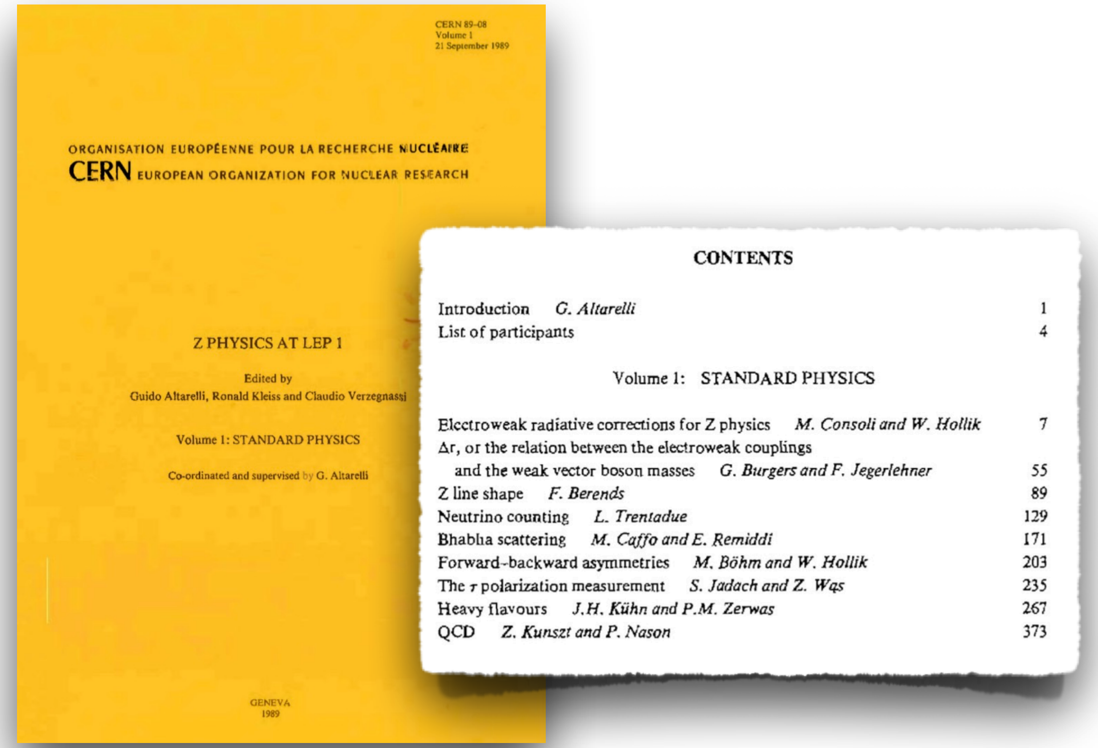
CERN 89-08
Volume 1
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ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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Z PHYSICS AT LEP 1

Edited by
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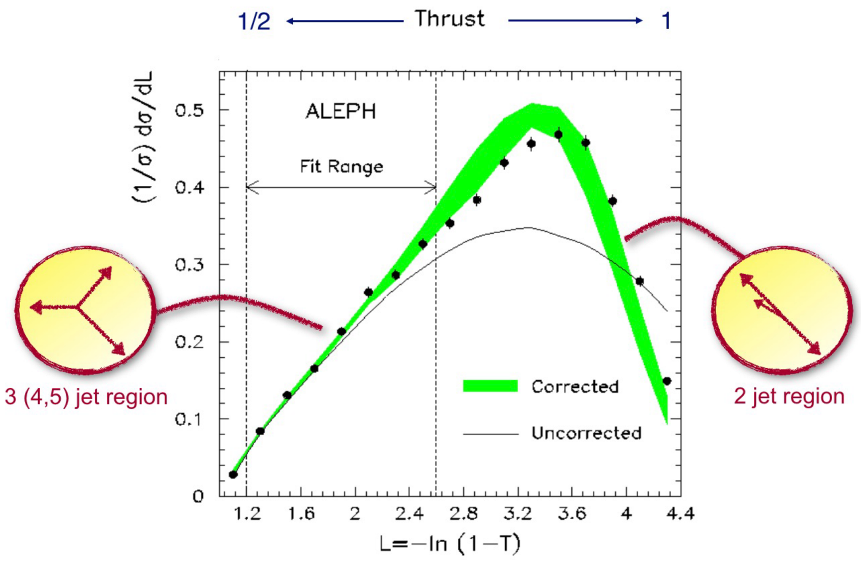

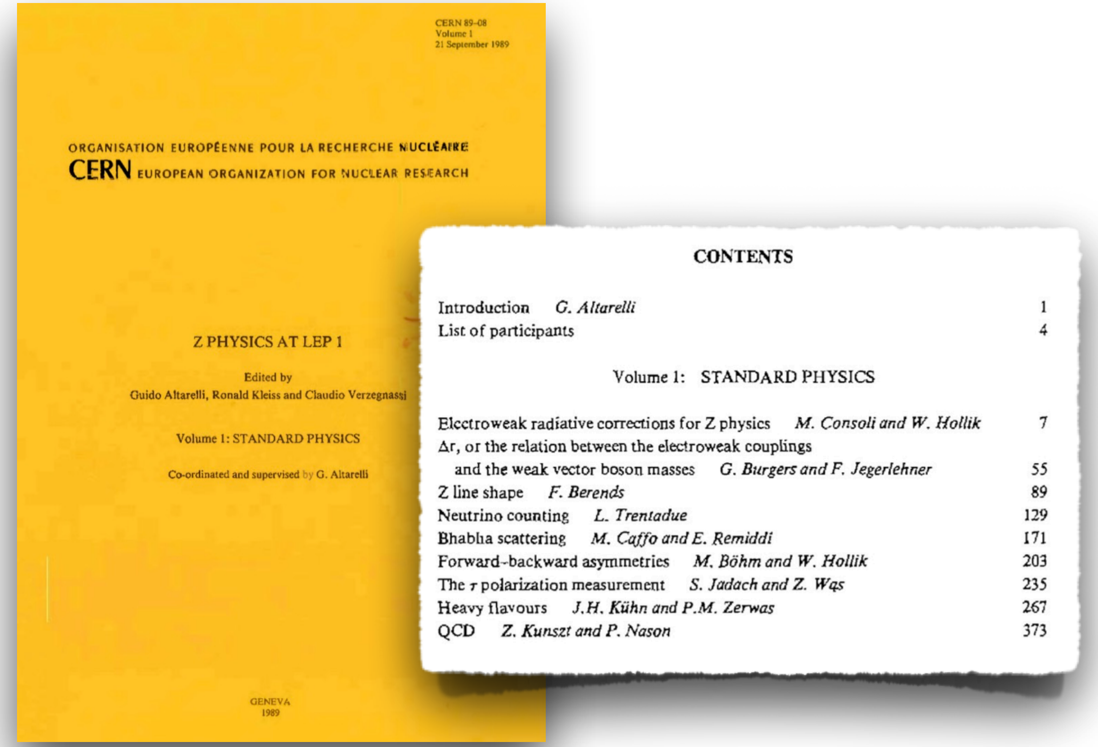
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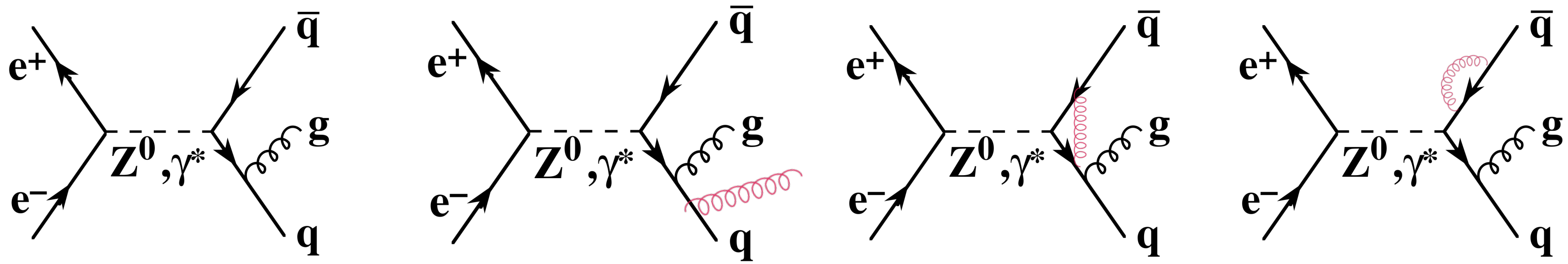

$$\sigma^{\text{pert}}_{\text{NLO}} = \alpha_s(\mu^2)\,A + \alpha_s^2(\mu^2)\left[B + \beta_0\,A\,\ln\frac{\mu^2}{Q^2}\right]$$

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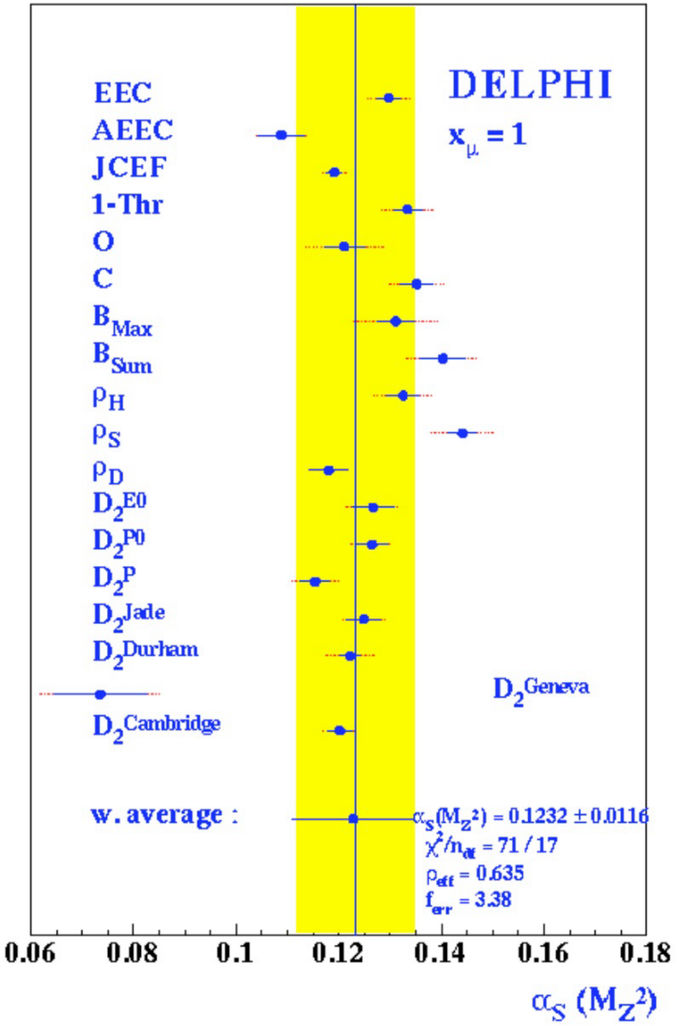
The path from NLO to NLO+NLL



NLO only, typical results

$\alpha_s(M_Z) \approx 0.125 \pm$ **0.010**

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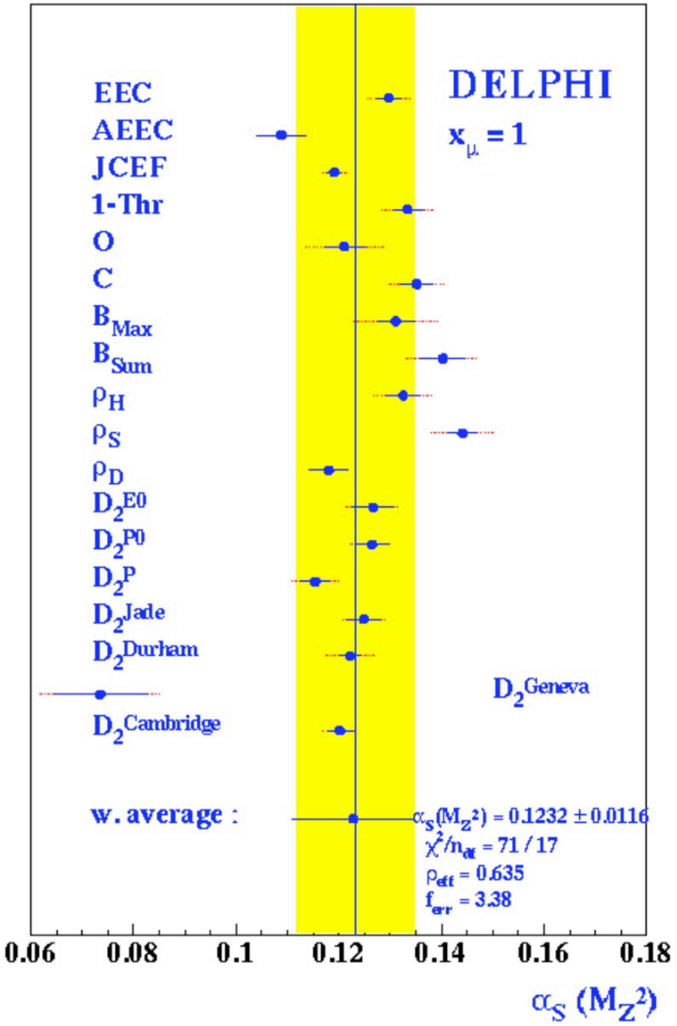

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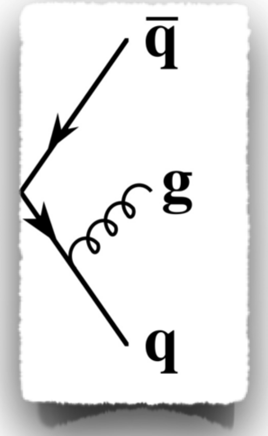

$$\frac{\alpha_s}{E_G\,(1-\cos\theta_{QG})}$$

$$\Rightarrow \alpha_s \ln^2 y_{cut}$$

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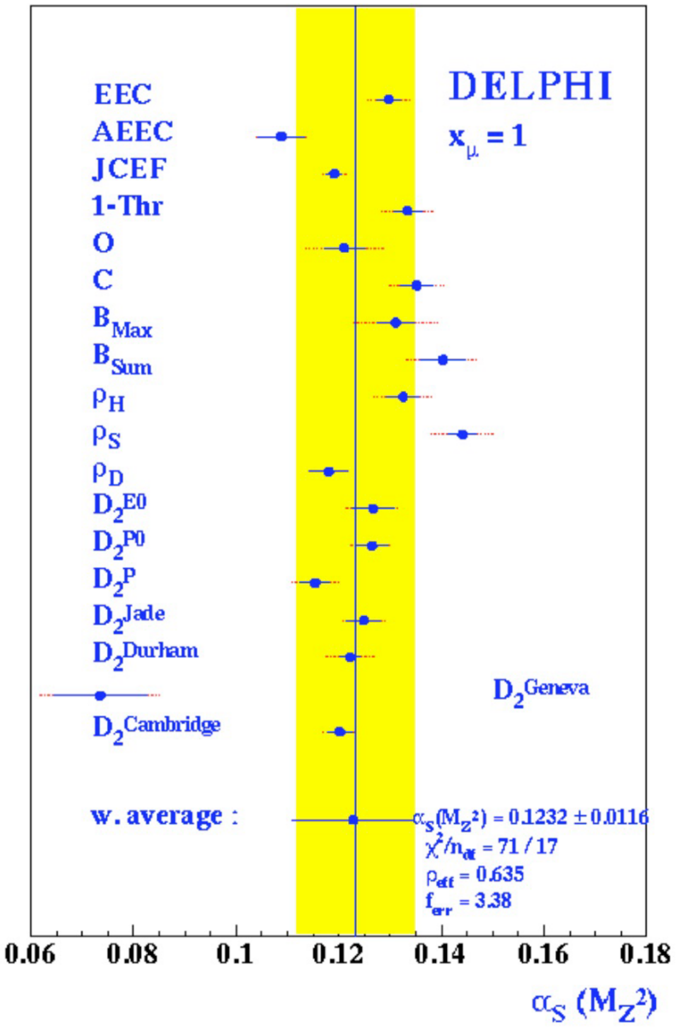
The path from NLO to NLO+NLL



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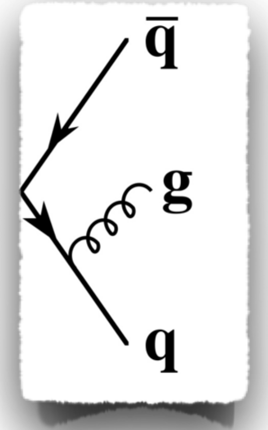

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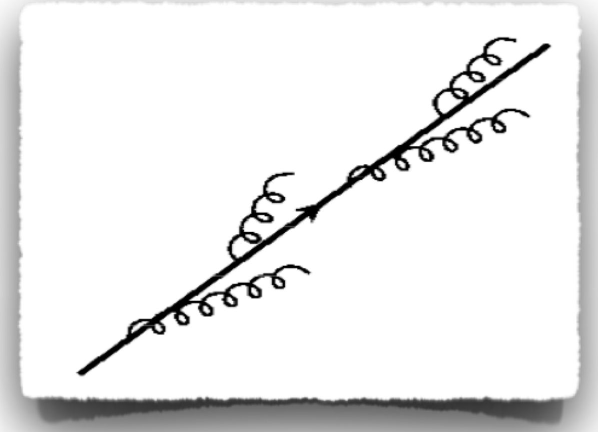

$$\alpha_s^n \ln^{2n} y_{\text{cut}}$$

$$\sigma \propto \sigma_{\text{NLO}} + \sum_{n,m} c_{n,m}\, \alpha_s^n \ln^m y_{\text{cut}}$$

"the rise of resummation"

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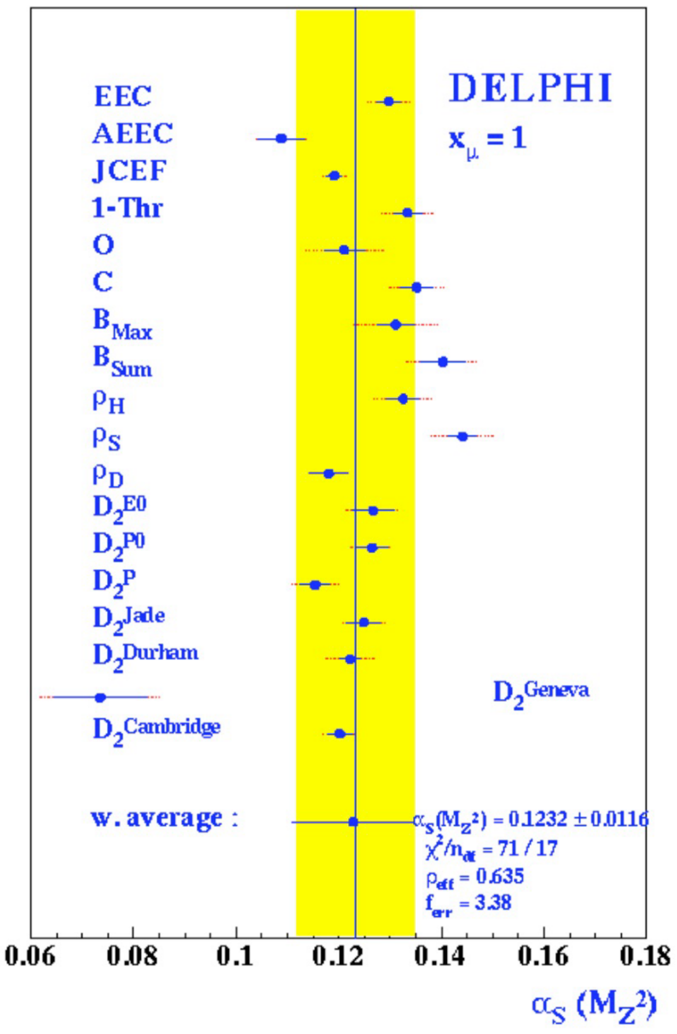
The path from NLO to NLO+NLL



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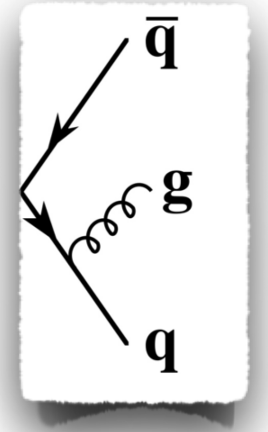

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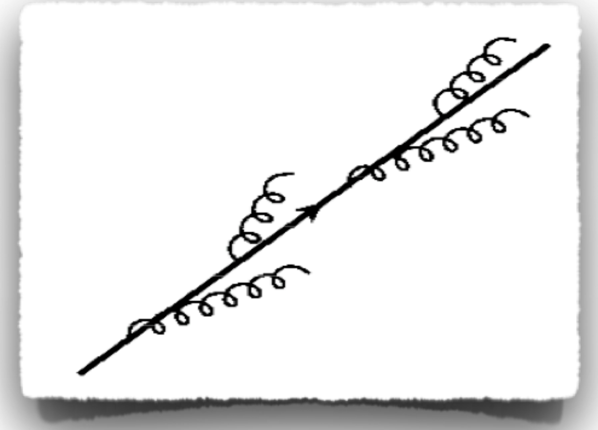

$$\alpha_s^n \ln^{2n} y_{cut}$$

$$\sigma \propto \sigma_{NLO} + \sum_{n,m} c_{n,m}\, \alpha_s^n \ln^m y_{cut}$$

"the rise of resummation"

$$R_2(y_{cut}) = \frac{\sigma_2(y_{cut})}{\sigma_{tot}}$$

$$R_2 = \exp\left\{-\int_{sy_{cut}}^{s} \frac{dq^2}{q^2} \frac{C_F\alpha_s(q^2)}{2\pi}\left[\ln\frac{s}{q^2} - \frac{3}{2}\right]\right\} \approx 1 - \int_{sy_{cut}}^{s} \frac{dq^2}{q^2} \frac{C_F\alpha_s(q^2)}{2\pi} \ln \ldots + \ldots \approx 1 - \frac{C_F\alpha_s}{2\pi} \ln^2 y_{cut} + \ldots.$$

$$R_2(y_{cut} \to 0) = 0$$

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Resummation

Thrust distribution in e^+e^- annihilation ☆

S. Catani [a,b], G. Turnock [a], B.R. Webber [a] and L. Trentadue [c]

[a] Cavendish Laboratory, University of Cambridge, Madingley road, Cambridge CB3 0HE, UK
[b] INFN, Sezione di Firenze, Largo Fermi 2, I-50125 Florence, Italy
[c] Dipartimento di Fisica, Università di Parma, and INFN, Gruppo Collegato di Parma, I-43100 Parma, Italy

Received 18 April 1991

We calculate the thrust distribution in e^+e^- annihilation including resummation of leading and next-to-leading logarithms of $1-T$ to all orders in QCD perturbation theory. This enables us to predict the distribution up to the largest values of T and reduces the renormalization scale dependence relative to the leading order at both large and small T. From a comparison with experimental data, we find $\Lambda^{(5)}_{\overline{MS}} = 200 \pm 140$ MeV, corresponding to $\alpha_s(m_Z^2) = 0.116 \pm 0.012$.

1. Introduction

The detailed experimental data on event shapes in e^+e^- annihilation at LEP energies [1] and below [2–5] provide both a challenge to QCD and a good opportunity for accurate determinations of the strong coupling constant α_s. Of the various possible event shape measures (see ref. [6] for a recent review), one of the earliest and most widely-used is the thrust, T [7], defined as

$$T = \mathrm{Max}\,\frac{\sum_i |\boldsymbol{p}_i \cdot \boldsymbol{n}|}{\sum_i |\boldsymbol{p}_i|}\,, \qquad (1)$$

where the sum is over all final-state particles i and the maximum is with respect to the direction of the vector $\boldsymbol{n}$ (the thrust axis). It can be seen from this definition that the thrust is an infrared and collinear safe quantity, that is, it is insensitive to the emission of zero-momentum particles and to the splitting of one particle into two collinear ones. Thus the cross section

$$\sigma(\tau) = \int_{1-\tau}^{1} \frac{d\sigma}{dT}\,dT \qquad (2)$$

is finite order-by-order in QCD perturbation theory, and the experimental data on this quantity should be directly comparable with perturbative calculations at the parton level, after small corrections for non-perturbative hadronization effects.

So far, comparisons between the theoretical and experimental thrust distributions have been performed [1–8] using theoretical predictions based on the relevant QCD matrix elements evaluated to second order in the strong coupling α_s [9]. As long as the thrust is not too large, the fixed-order perturbative calculations should be reliable. At large values of T, however, there are terms in higher order that become enhanced by powers of $\ln(1-T)$. In this kinematical region the real expansion parameter is the large effective coupling $\alpha_s \ln^2(1-T)$ and therefore *any* finite-order perturbative calculation cannot give an accurate evaluation of the cross section. The logarithmic terms need to be identified and resummed to all orders in α_s before a reliable prediction can be made.

The appearance of large double logarithmic terms is a common feature of any hard process in the semi-inclusive or Sudakov region, where emission of radiation is inhibited by the kinematics. In the case of jet cross sections at $1-T \ll 1$, the jet invariant masses are constrained to be so small as to allow only emission of gluons that are soft and collinear with respect to the parton generating the jet. The double logarithmic terms $\alpha_s \ln^2(1-T)$ are due to such soft and collinear gluons.

☆ Research supported in part by the UK Science and Engineering Research Council and in part by the Italian Ministero della Pubblica Istruzione.

… α_s). These are normally classified as *leading* logarithms when $n < m \leqslant 2n$, *next-to-leading* when $m = n$, and *sub-dominant* when $m < n$. In the next section we resum all leading and next-to-leading terms, neglecting only the sub-dominant logarithms.

2. Calculation

For a final-state configuration corresponding to a large value of the thrust, eq. (1) can be approximated by

$$1 - T \simeq (k_1^2 + k_2^2)/Q^2\,, \qquad (5)$$

where k_1^2 and k_2^2 are the invariant masses-squared of two back-to-back jets. Thus the key to the evaluation of the thrust distribution is its relation to the jet mass distribution, which was introduced in refs. [11,12] and calculated to next-to-leading logarithmic accuracy in ref. [17]. If $J(Q^2, k^2)$ denotes the probability distribution of jet invariant mass-squared k^2 at scale Q^2, then to this accuracy the thrust fraction R takes the form

$$R(\tau, \alpha_s(Q^2)) \underset{\tau \ll 1}{=} \Sigma(\tau, \alpha_s(Q^2))$$
$$= \int_0^\infty dk_1^2\, dk_2^2\, J(Q^2, k_1^2) J(Q^2, k_2^2) \times \Theta(\tau Q^2 - k_1^2 - k_2^2)\,, \qquad (6)$$

where Θ is the Heaviside step function. It can be shown [18] that corrections to eq. (5), as well as kinematic correlations between the jet masses and overlap between the jets, give only contributions that are sub-dominant in the sense defined above. Introducing the Laplace transform of the jet mass distribution,

$$\tilde{J}_\nu(Q^2) = \int_0^\infty dk^2\, J(Q^2, k^2)\, e^{-\nu k^2}\,, \qquad (7)$$

and using the integral representation

$$\Theta(\tau Q^2 - k^2) = \int_{\epsilon - i\infty}^{\epsilon + i\infty} \frac{dN}{2\pi i} \frac{e^{N\tau}}{N}\, e^{-Nk^2/Q^2}\,, \qquad (8)$$

we find that

$$\Sigma(\tau, \alpha_s(Q^2)) = \int_{\epsilon - i\infty}^{\epsilon + i\infty} \frac{dN}{2\pi i} \frac{e^{N\tau}}{N} [\tilde{J}_{N/Q^2}(Q^2)]^2\,, \qquad (9)$$

Nuclear Physics B407 (1993) 3–42
North-Holland
NUCLEAR PHYSICS B

Resummation of large logarithms in e^+e^- event shape distributions *

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Received 29 January 1993
Accepted for publication 27 May 1993

We describe a method for the resummation of leading and next-to-leading large logarithms to all orders in QCD perturbation theory, applicable to e^+e^- event shape distributions that have the property of exponentiation near the two-jet region. After a general discussion of the conditions for exponentiation and the evaluation of matrix elements and phase space to next-to-leading logarithmic accuracy, we give details of the application of the method to the thrust and heavy jet mass distributions. We show how the resummed expressions can be matched with known second-order results to obtain improved predictions throughout the whole of phase space, and how to suppress spurious higher-order terms generated by resummation outside the physical region. We also give the necessary ingredients for the improvement of third-order predictions by resummation when they become available.

1. Introduction

The measurement of hadronic event shape parameters in e^+e^- annihilation is one of the most important ways in which QCD can be tested and its coupling constant α_S determined. The recent flood of very accurate data from the LEP experiments has brought about a situation in which the theoretical uncertainties

* Research supported in part by the UK Science and Engineering Research Council and in part by the Italian Ministero dell'Università e Ricerca Scientifica.
[1] On leave of absence from INFN, Sezione di Firenze, Italy.
[2] On leave of absence from Cavendish Laboratory, University of Cambridge, UK

0550-3213/93/$06.00

…en when α_S is small, a perturbative treatment of the shape distribution …nly appear to make sense when $\alpha_S L^2$ is also small, which excludes a large …ear the two-jet configuration, where most of the events occur. Whenever …ge, even if $\alpha_S L^2$ is still small, we can improve the range and accuracy …rbative predictions by identifying these logarithmically-enhanced terms …ematically resumming them to all orders.

…ailed understanding of logarithmically-enhanced terms now exists for a …class of shape variables, namely those for which the leading logarithmic …tions *exponentiate*. By this we mean that at small y the logarithm of the …oss section takes the form

$$\ln R(y) \sim L g_1(\alpha_S L)\,, \qquad (4)$$

…e function g_1 has a power series expansion in $\alpha_S L$. More precisely, the …ation of QCD matrix elements in the two-jet region implies that, pro… …e phase space by which $R(y)$ is defined also has factorization properties …shall specify, then

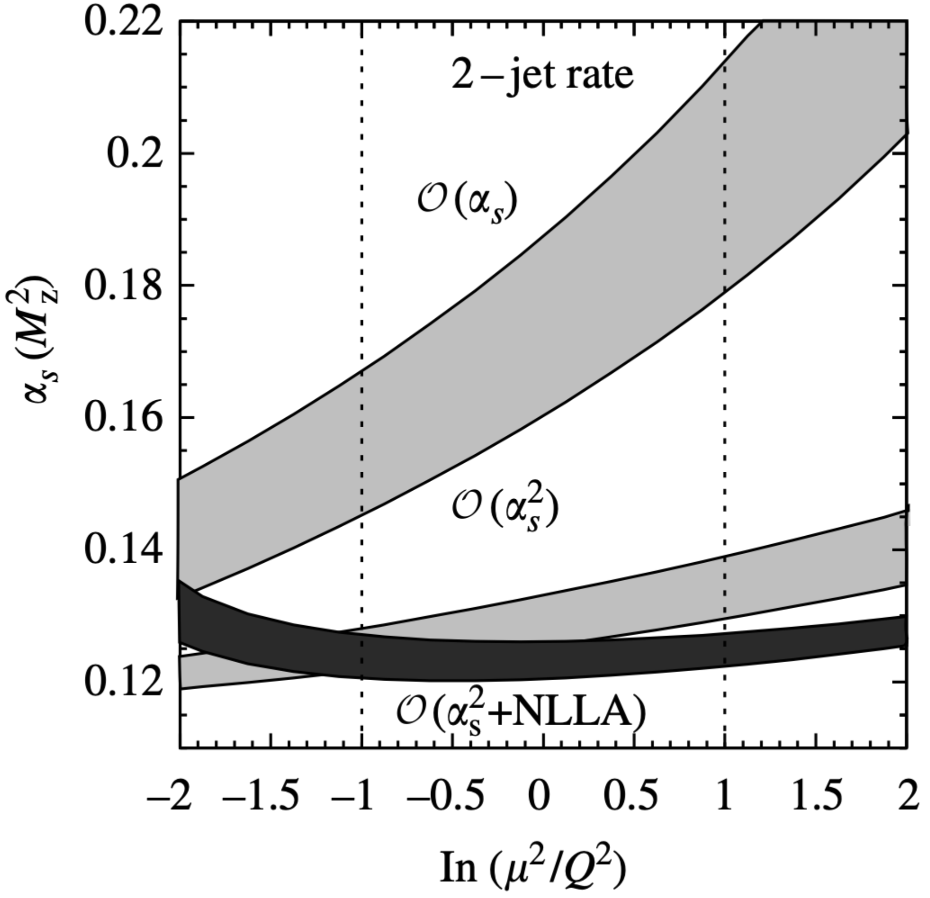
$$R(y) = C(\alpha_S)\Sigma(y, \alpha_S) + D(y, \alpha_S)\,, \qquad (5)$$

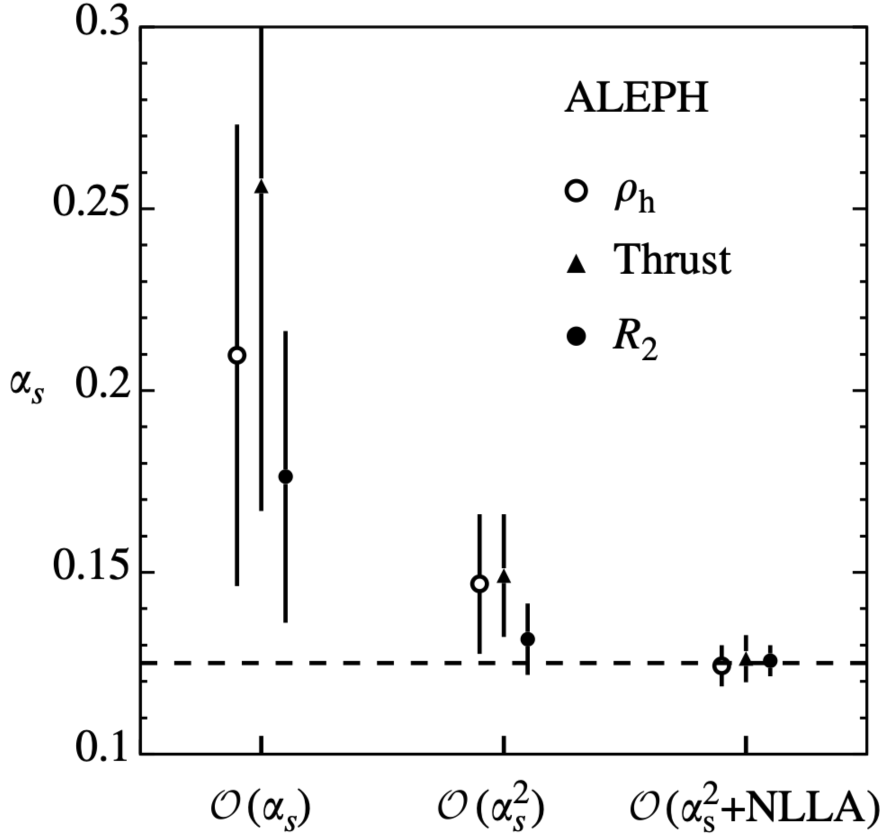
$$C(\alpha_S) = 1 + \sum_{n=1}^{\infty} C_n \bar{\alpha}_S^n\,,$$
$$\ln \Sigma(y, \alpha_S) = \sum_{n=1}^{\infty} \sum_{m=1}^{n+1} G_{nm} \bar{\alpha}_S^n L^m \qquad (6)$$
$$= L g_1(\alpha_S L) + g_2(\alpha_S L) + \alpha_S g_3(\alpha_S L) + \dots\,,$$

…y, α_S) vanishes as $y \to 0$ order-by-order in perturbation theory. For later …ence we have defined $\bar{\alpha}_S = \alpha_S/2\pi$ in the expansions. The word expo…on refers to the fact that the terms $\alpha_S^n L^m$ with $m > n+1$ are absent from …, whereas they do appear in $R(y)$ itself. The function g_1 resums all the …contributions $\alpha_S^n L^{n+1}$, while g_2 contains the *next-to-leading* logarithmic …terms $\alpha_S^n L^n$, and g_3 etc. represent the remaining *subdominant* logarithmic corrections $\alpha_S^n L^m$ with $0 < m < n$. All the functions g_i vanish at $L = 0$ since they resum terms with $m > 0$.

Eq. (6) represents an improved perturbative expansion in the small-y region. If we can find the form of the functions g_i, then we shall have a systematic perturbative treatment of the shape distribution throughout the region of y in which $\alpha_S L \lesssim 1$, which is much larger than the domain $\alpha_S L^2 \ll 1$ in which the non-exponentiated perturbation series was applicable. Furthermore, the resummed expression (6) can be consistently matched with fixed-order calculations. In particular, one can evaluate the leading and next-to-leading functions g_1 and g_2 and combine them with the known order-α_S^2 results on the shape cross section,

The path from NLO to NLO+NLL

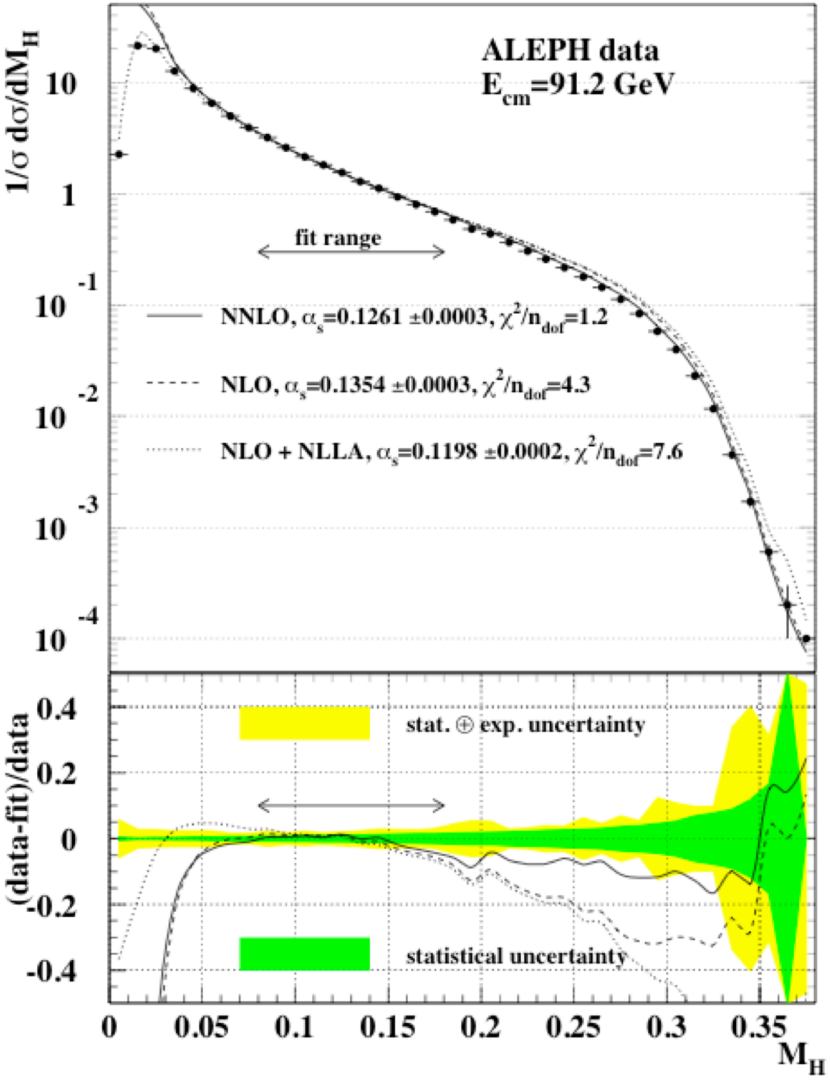




Resummation matched to NLO, typical results

$\alpha_s(M_Z) \approx 0.120 \pm \mathbf{0.005}$

The path from NLO to NLO+NLL, and the dawn of the NNLO era



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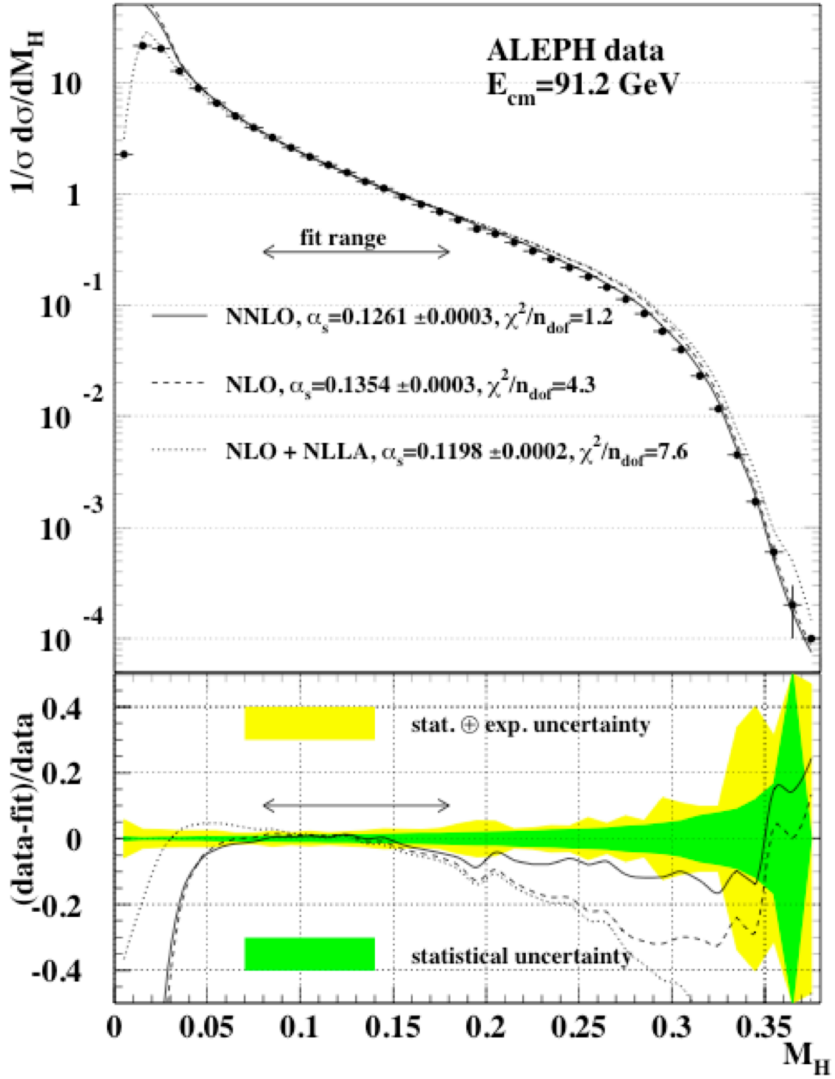

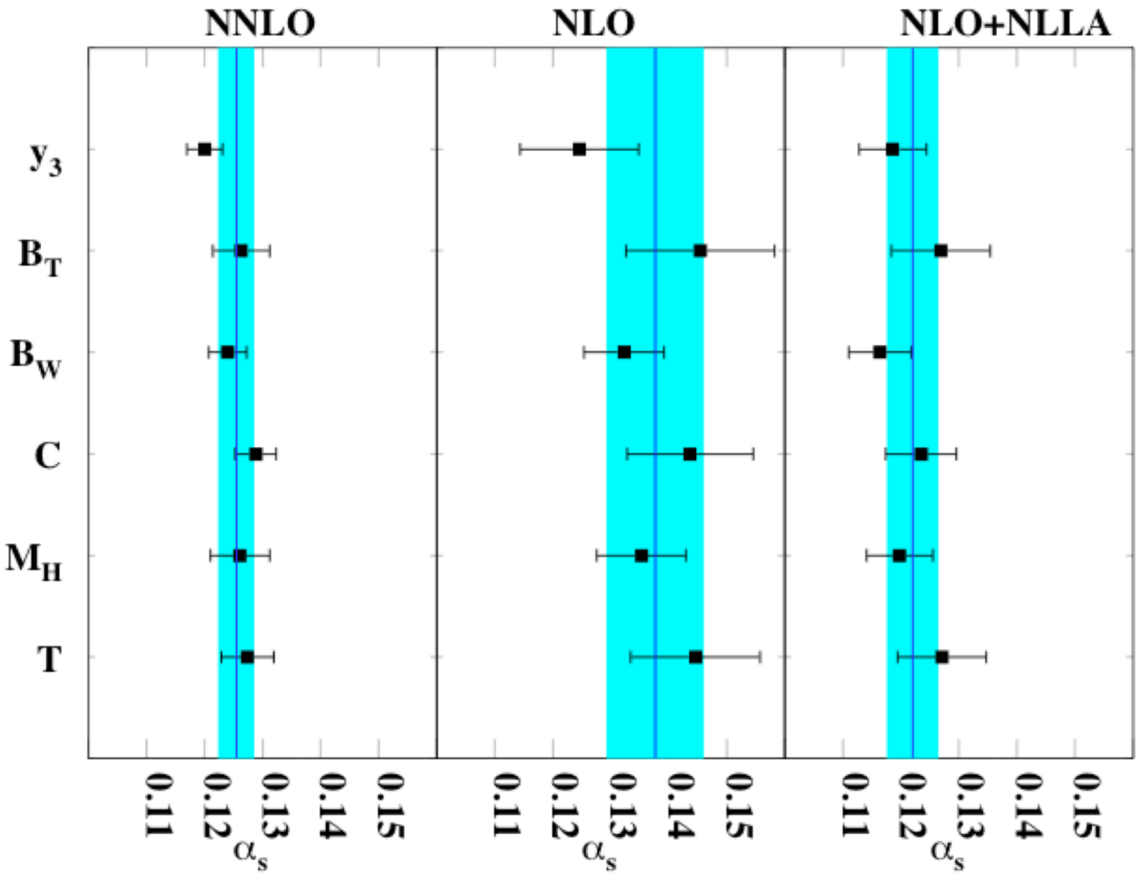

much less scatter at NNLO, reduced pert. uncertainty : 0.003

$$\alpha_s(M_Z^2) = 0.1240 \pm 0.0008\,(\text{stat}) \pm 0.0010\,(\text{exp}) \pm 0.0011\,(\text{had}) \pm 0.0029\,(\text{theo})$$

Th. Gehrmann, A. Gehrmann-DeRidder, G. Heinrich, N. Glover, H. Stenzel, GD, JHEP 2008, 040, arXiv:0712.0327

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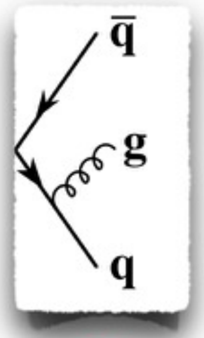
Jet algorithms



$$\frac{\alpha_s}{E_G\,(1-\cos\theta_{QG})}$$

$$y_{ij} = \frac{2\,\min(E_i^2, E_j^2)\,(1-\cos\theta_{ij})}{E_{cm}^2} \approx \frac{k_\perp^2}{E_{cm}^2}$$

"Durham" Jet Algo

1420 citations

Physics Letters B 269 (1991) 432–438
North-Holland

PHYSICS LETTERS B

New clustering algorithm
for multijet cross sections in e^+e^- annihilation ☆

S. Catani [a,b,1], Yu.L. Dokshitzer [c,d], M. Olsson [d], G. Turnock [a] and B.R. Webber [a]

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[c] *Leningrad Nuclear Physics Institute, Gatchina, SU-188 350 Leningrad, USSR*
[d] *Department of Theoretical Physics, University of Lund, Sölvegatan 14A, S-22362 Lund, Sweden*

Received 2 August 1991

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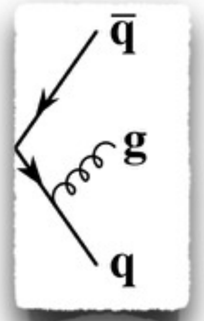

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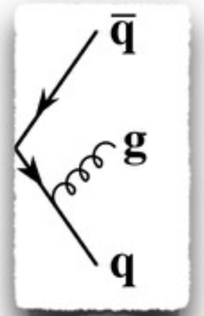

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Nuclear Physics B
Volume 406, Issues 1–2, 27 September 1993, Pages 187-224

Longitudinally-invariant $k_\perp$-clustering algorithms for hadron-hadron collisions ☆

S. Catani **, Yu.L. Dokshitzer a b, M.H. Seymour, B.R. Webber ***

$$y_{ij} = \frac{2\,\min(E_i^2, E_j^2)\,(1-\cos\theta_{ij})}{E_{\rm cm}^2} \approx \frac{k_\perp^2}{E_{\rm cm}^2}$$

"Durham" Jet Algo

We propose a version of the QCD-motivated "$k_\perp$" jet-clustering algorithm for hadron-hadron collisions which is invariant under boosts along the beam directions. This leads to improved factorization properties and closer correspondence to experimental practice at hadron colliders. We examine alternative definitions of the resolution variables and cluster recombination scheme, and show that the algorithm can be implemented efficiently on a computer to provide a full clustering history of each event. Using simulated data at $\sqrt{S}$ = 1.8 TeV, we study the effects of calorimeter segmentation, hadronization and the soft underlying event, and compare the results with those obtained using a conventional cone-type algorithm.

In the past few years, a suite of IRC safe algorithm has become widely used

k_t	SR $d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2$ hierarchical in rel p_t	Catani et al '91 Ellis, Soper '93
Cambridge/Aachen	SR $d_{ij} = \Delta R_{ij}^2/R^2$ hierarchical in angle	Dokshitzer et al '97 Wengler, Wobish '98
anti-k_t	SR $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\Delta R_{ij}^2/R^2$ gives perfectly conical hard jets	MC, Salam, Soyez '08 (Delsart, Loch)
SISCone	Seedless iterative cone with split-merge gives 'economical' jets	Salam, Soyez '07

Matteo Cacciari - LPTHE   CMS Week - May 19, 2010   25

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PHYSICS LETTERS B

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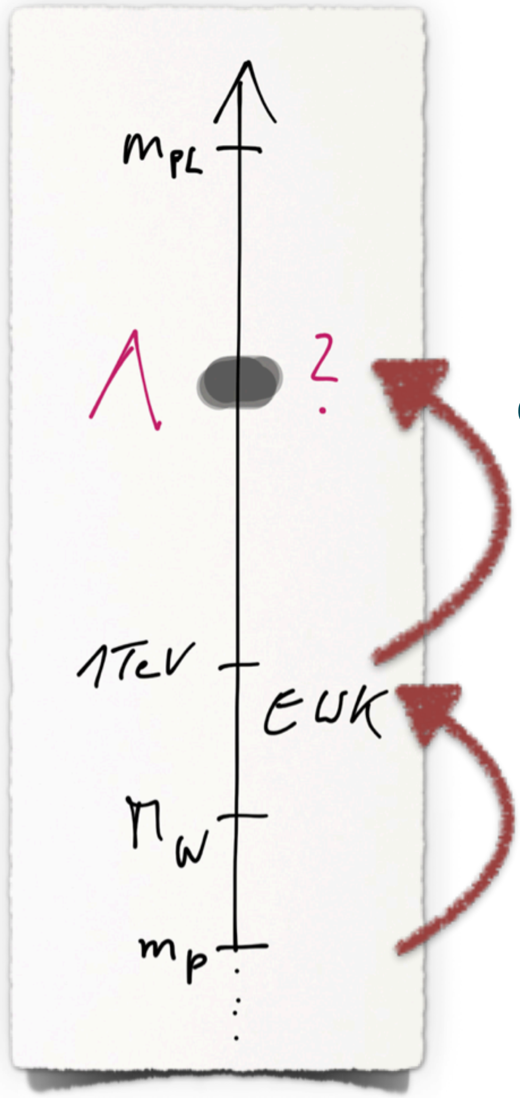
Now back to our current LHC times…

New physics needed, but where is it?



combination of
precision and
higher energy

precision
measurements
and higher energy

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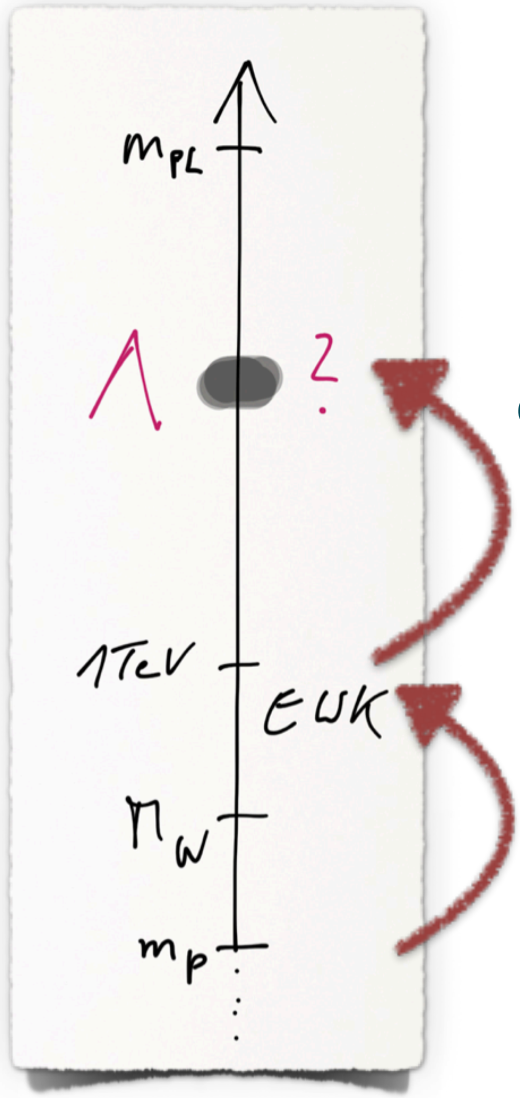
New physics needed, but where is it?



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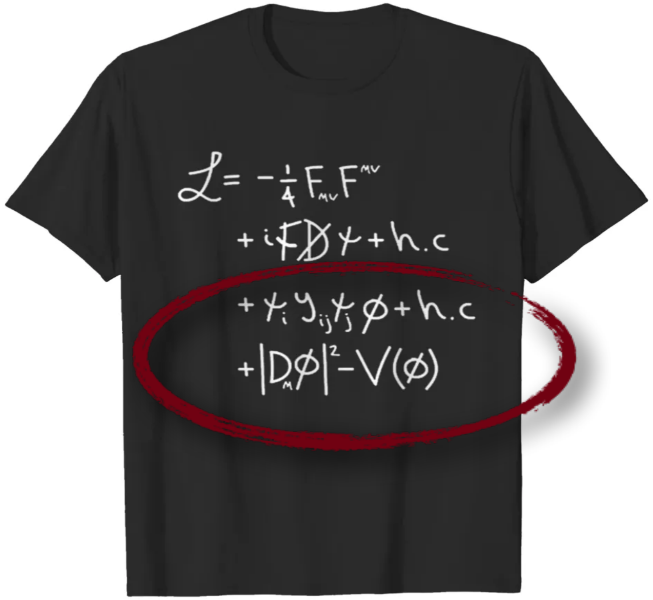
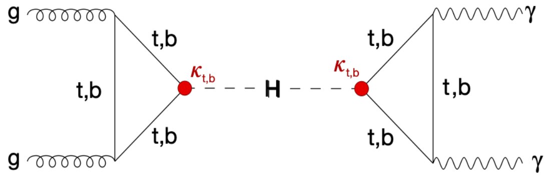
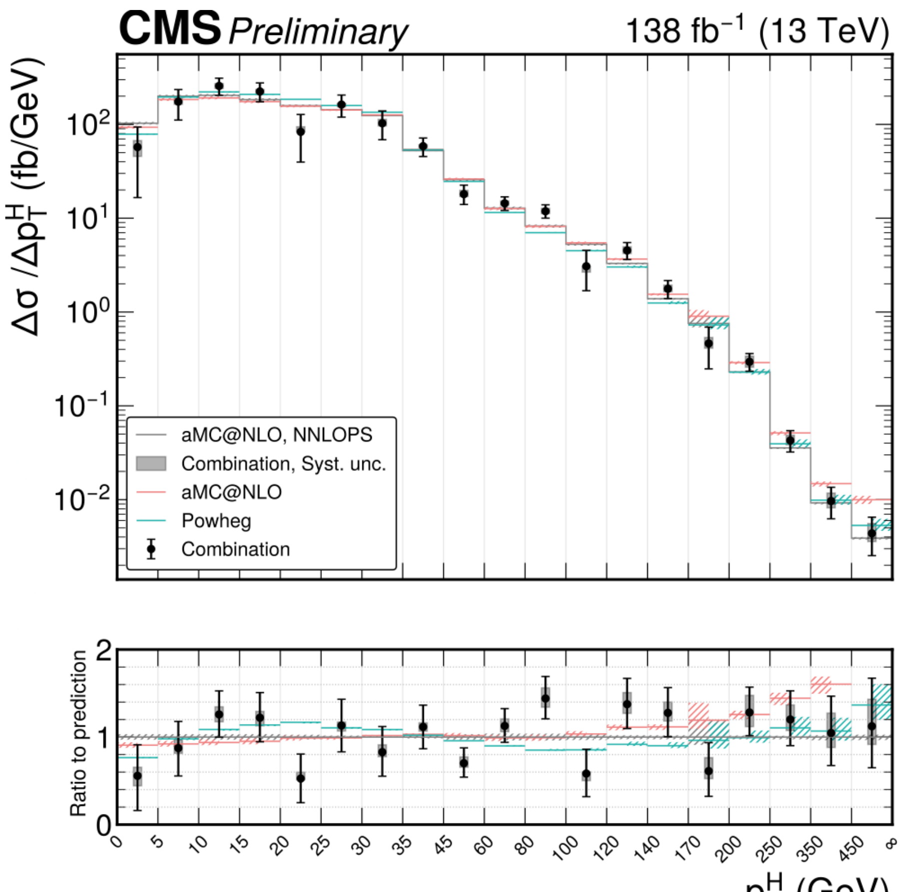


Could the Higgs boson be a gateway to it?

Differential cross sections and importance of exp. precision and tools

Besides incl. cross sections/couplings, new physics could also modify the *differential* cross sections





https://cds.cern.ch/record/2905139/files/HIG-23-013-pas.pdf

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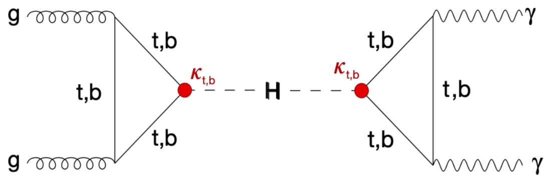

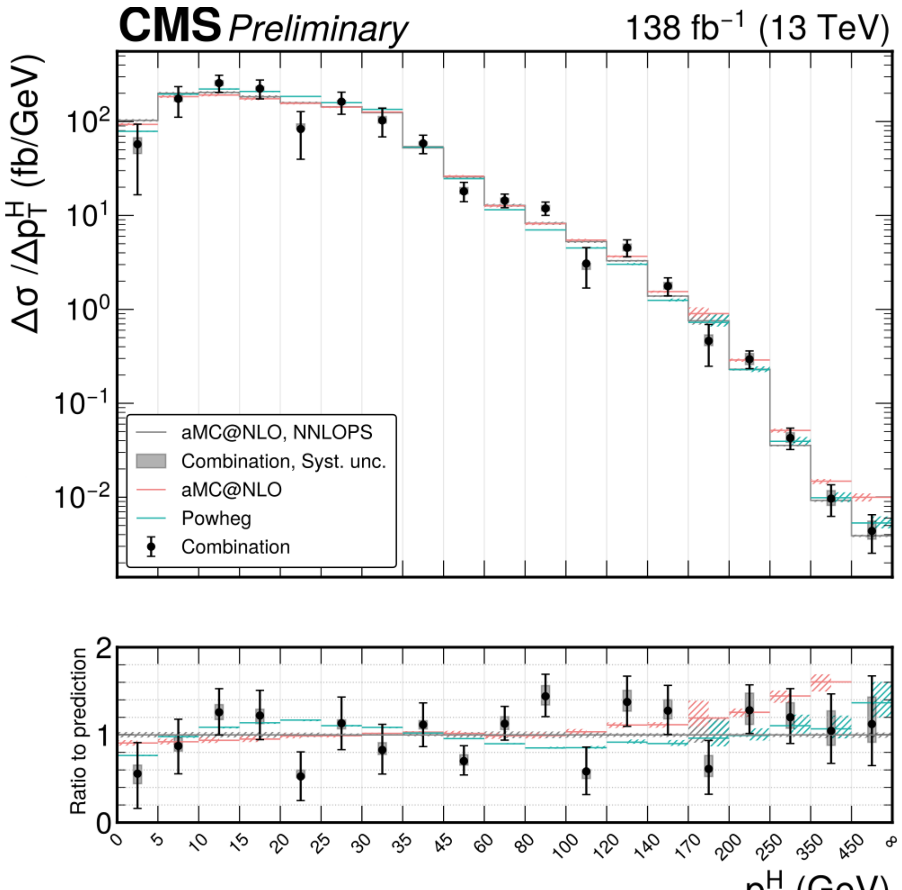

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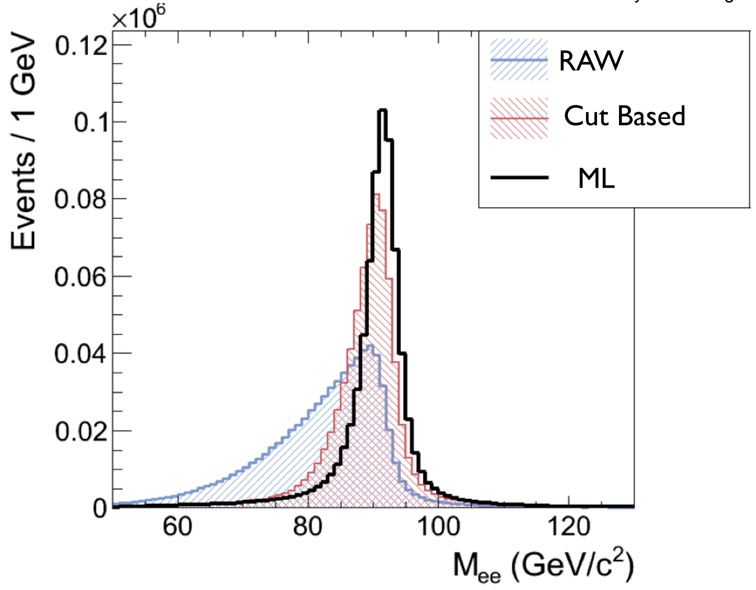
Courtesy: M. Donega



Thanks to **Machine Learning tools**:
improvements in resolution → increases S/sqrt(B), that can be directly translated to a luminosity gain:

- improve the resolution by 20%
- equivalent to a gain in sensitivity of 10%
- equivalent to a gain in luminosity of 20%

i.e. equivalent to running the LHC for 20% longer time

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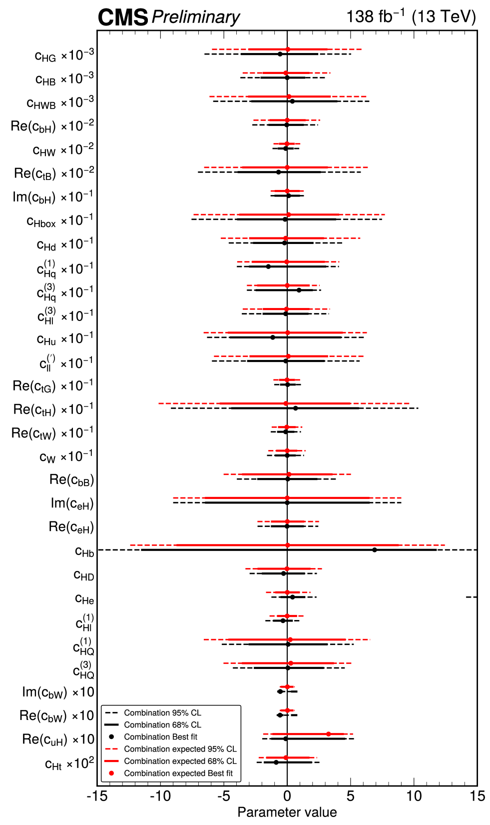
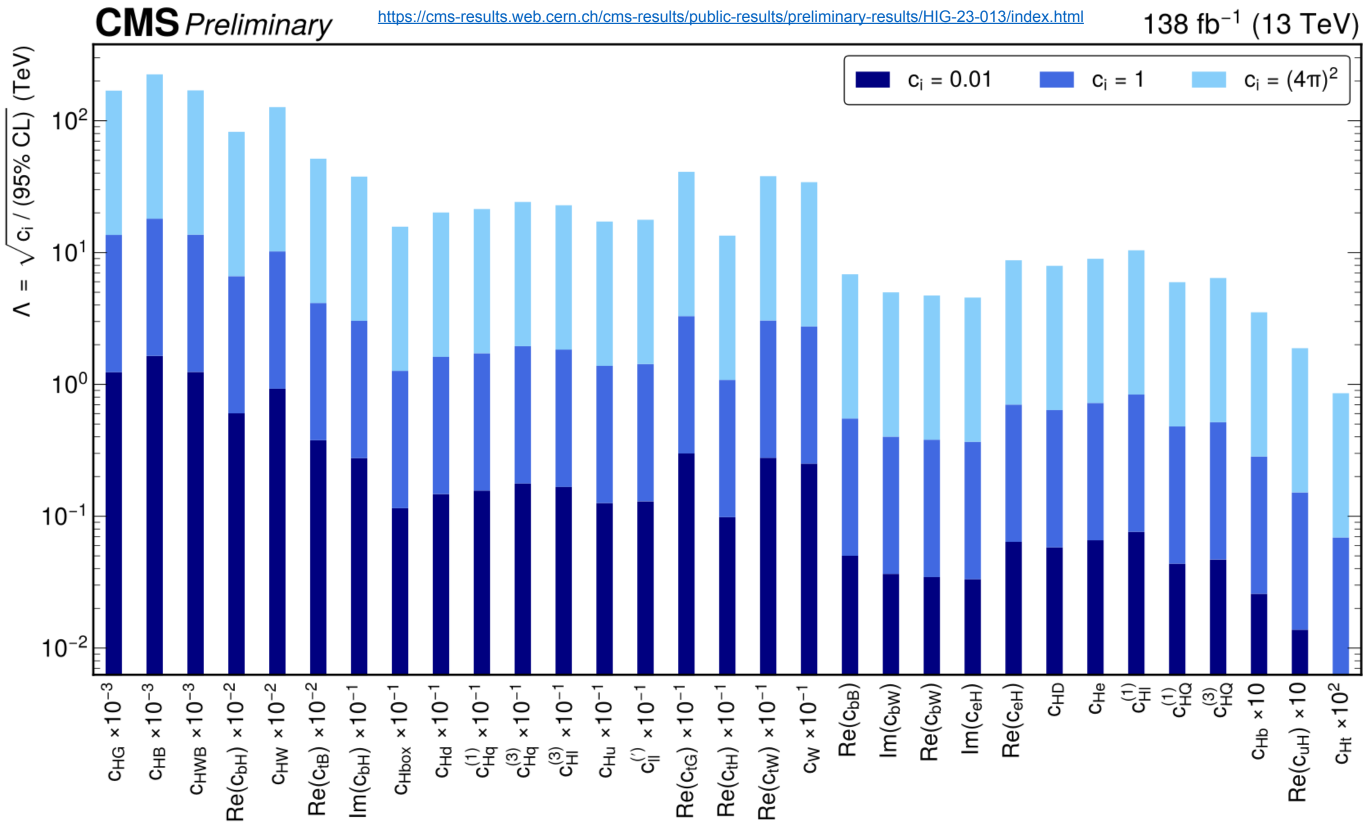
The Higgs boson is used as a „search tool“, already now

Example from CMS PAS HIG-23-013

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{j=0}^{2499} \frac{c_j^{(6)}}{\Lambda^2} O_j^{(6)}$$

$$L(\vec{x}|\vec{\mu},\vec{\nu}) = \prod_n p\left(\vec{x} \,\middle|\, \sum_{if} \mu_{if}(\vec{c}) S_{if,n}(\vec{\nu}) + B(\vec{\nu})\right) \cdot \prod_j p(\vec{y}_j|\vec{\nu}_j)$$





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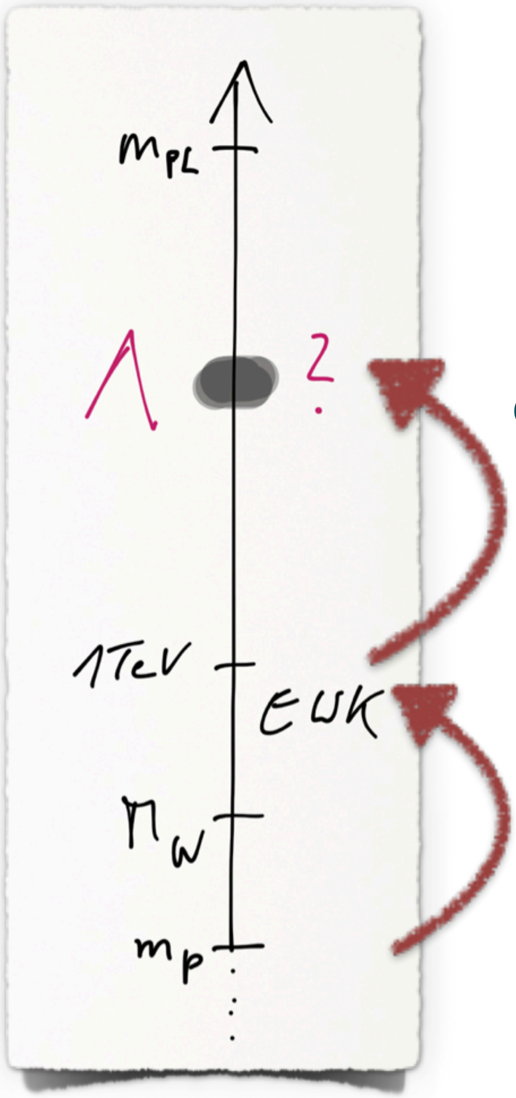

combination of
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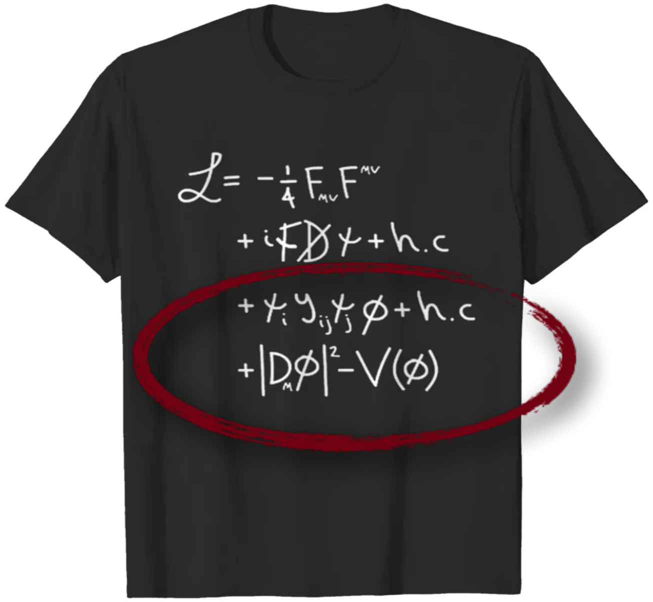

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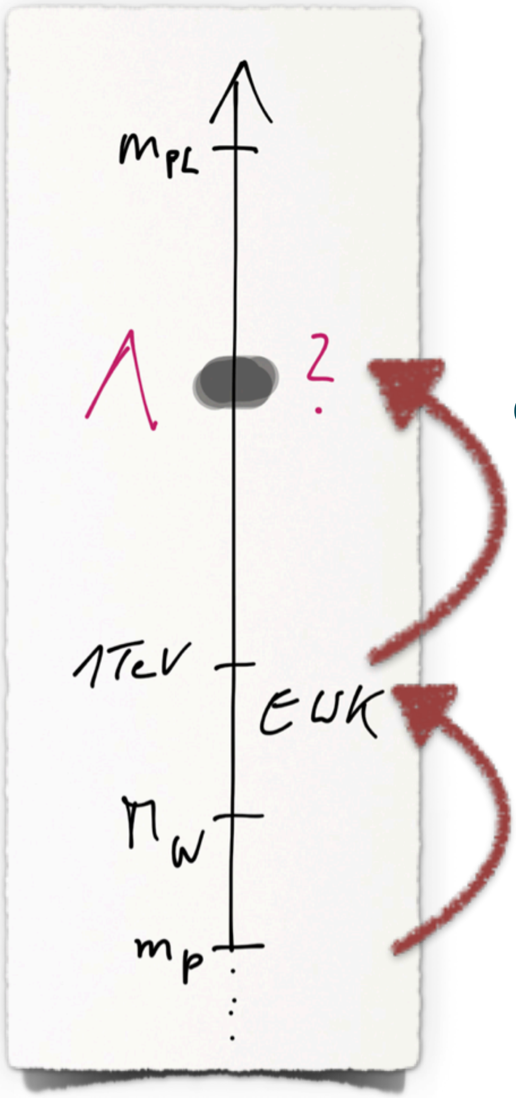

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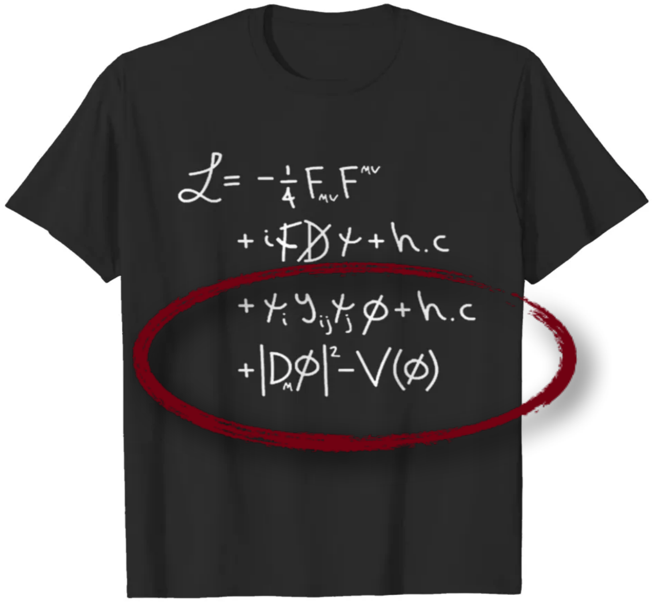

Could the Higgs boson be a gateway to it?

Consensus (?) regarding a

e^+e^- Higgs factory as next step, beyond HL-LHC

In any case: We are in an exploratory phase!

Actually, this is the “normal” case…

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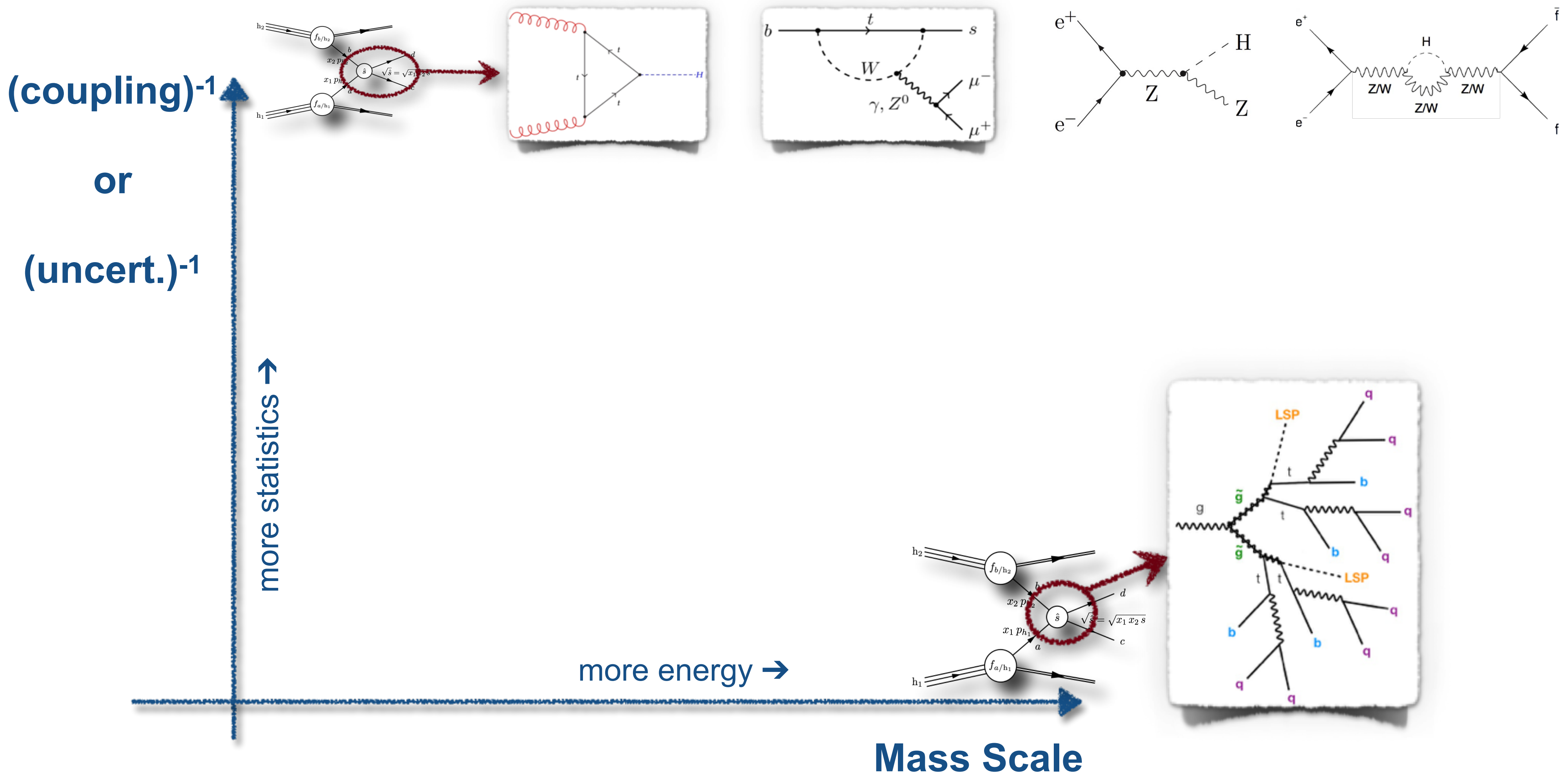
Remember: How to explore the unknown



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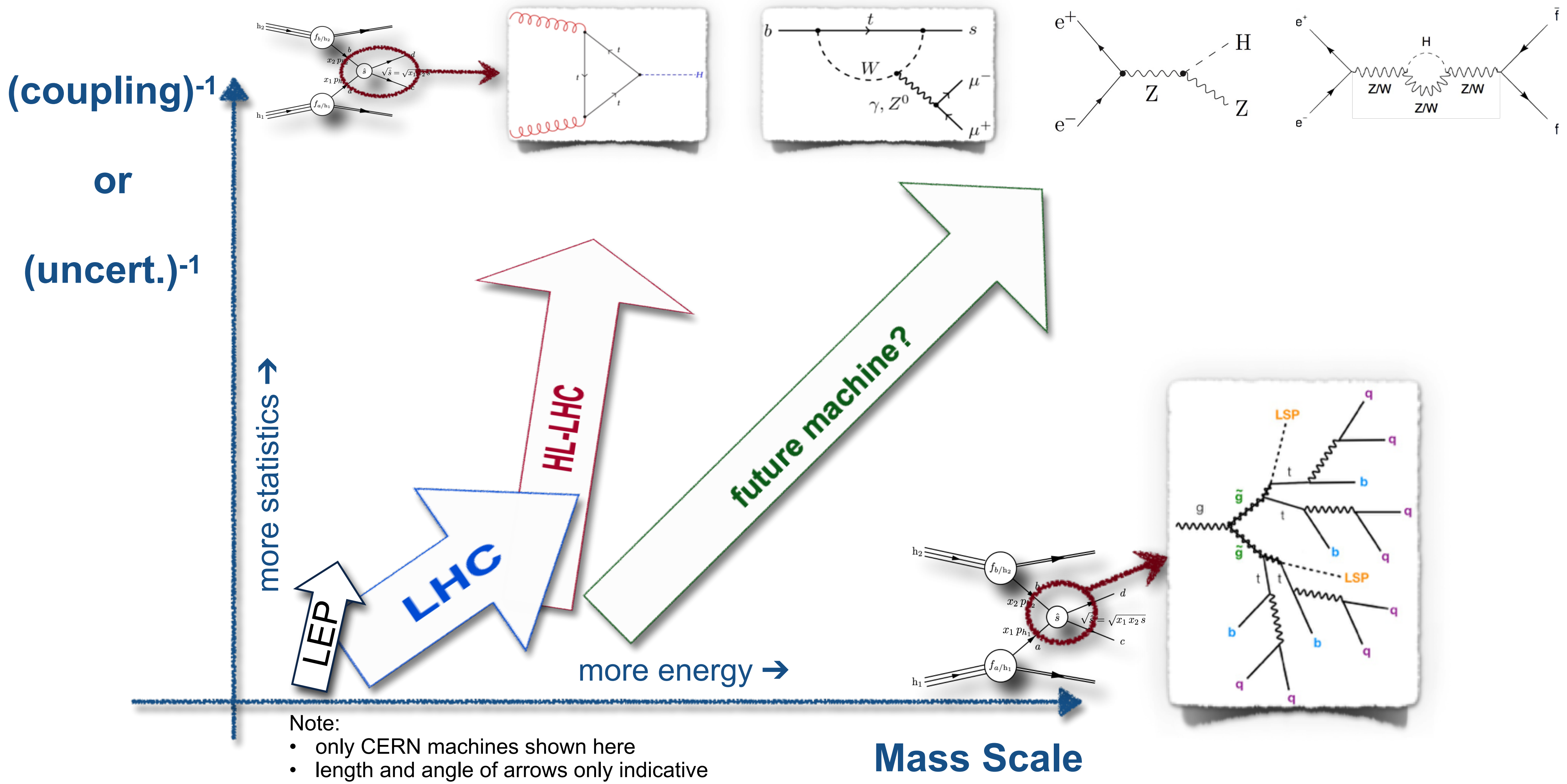
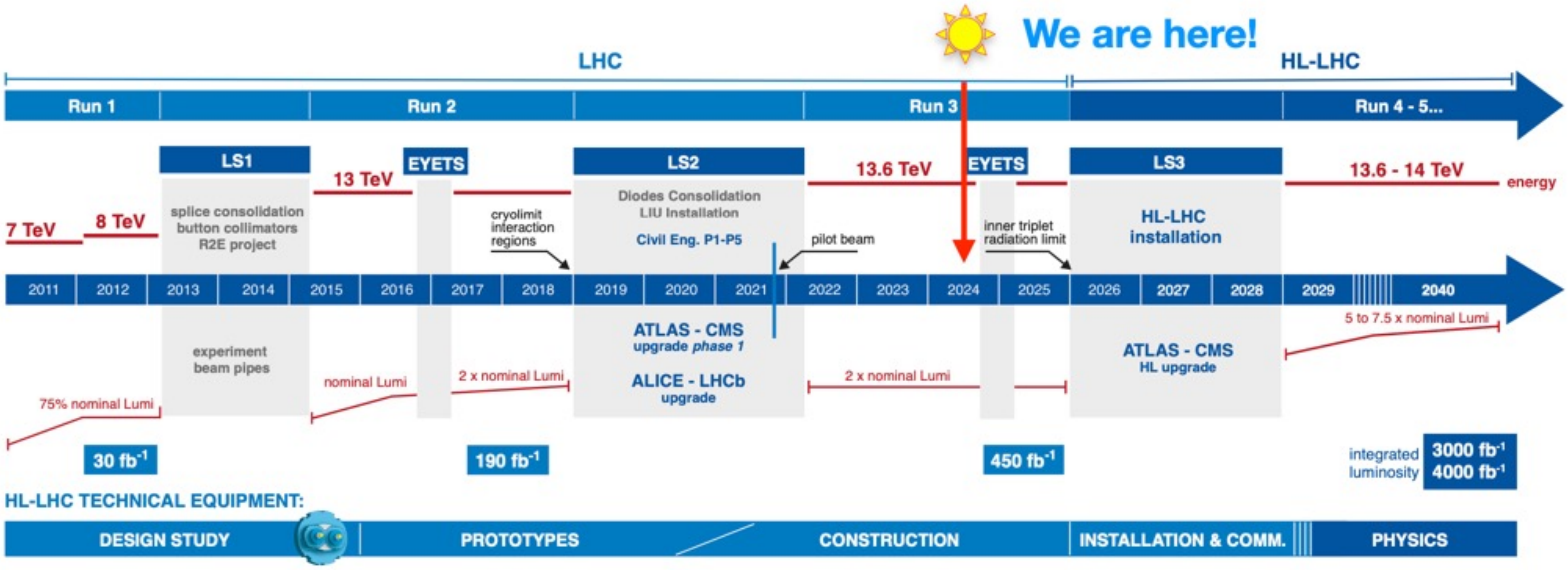


Note:
- only CERN machines shown here
- length and angle of arrows only indicative

The future (?)

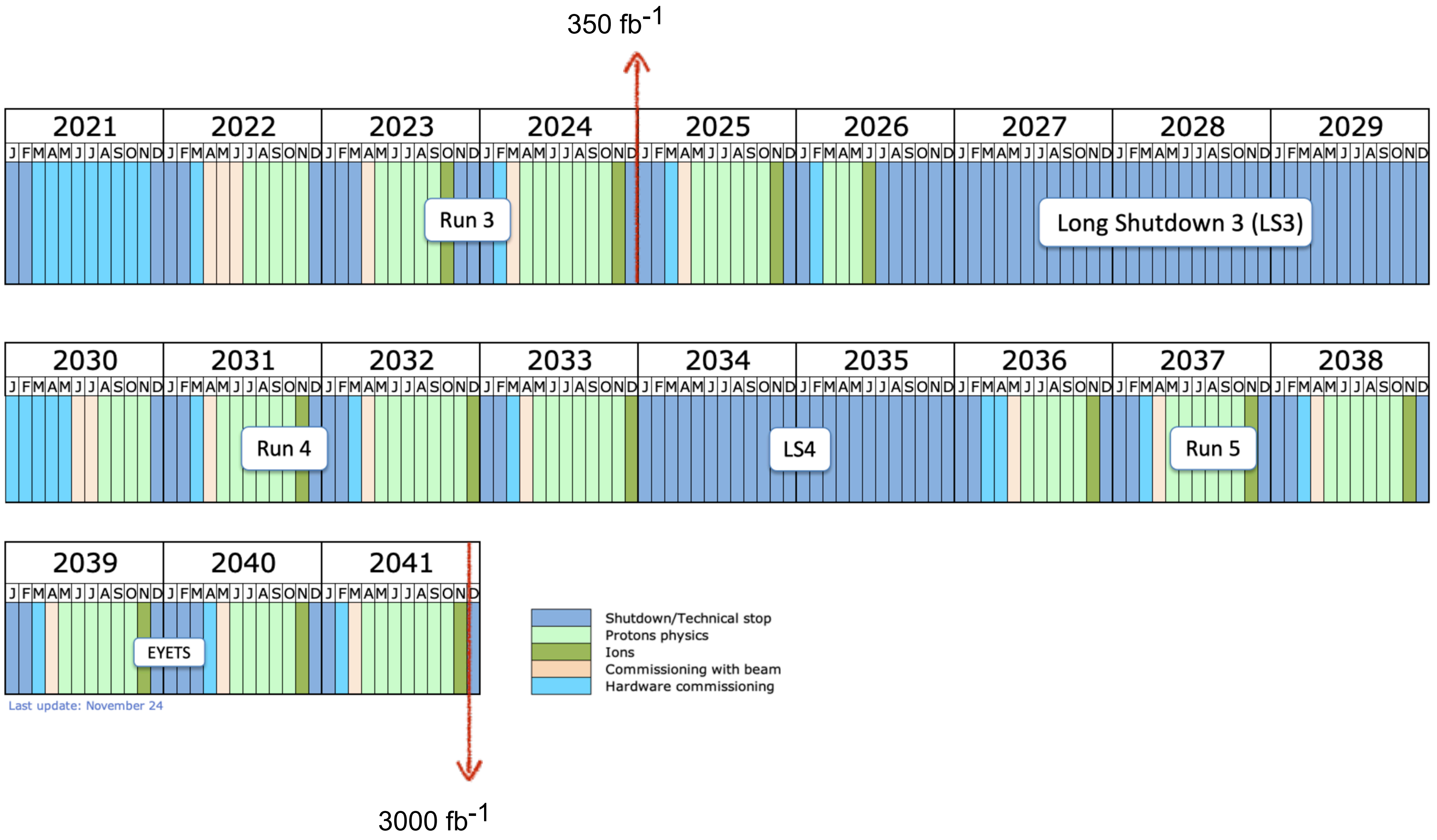
The imminent future, HL-LHC: Failure is not an option….



Marumi Kado, ICHEP 2024

Current challenge: in parallel data taking, data analyses and upgrades

The imminent future, HL-LHC: Latest schedule update



(160M H + 120k HH)

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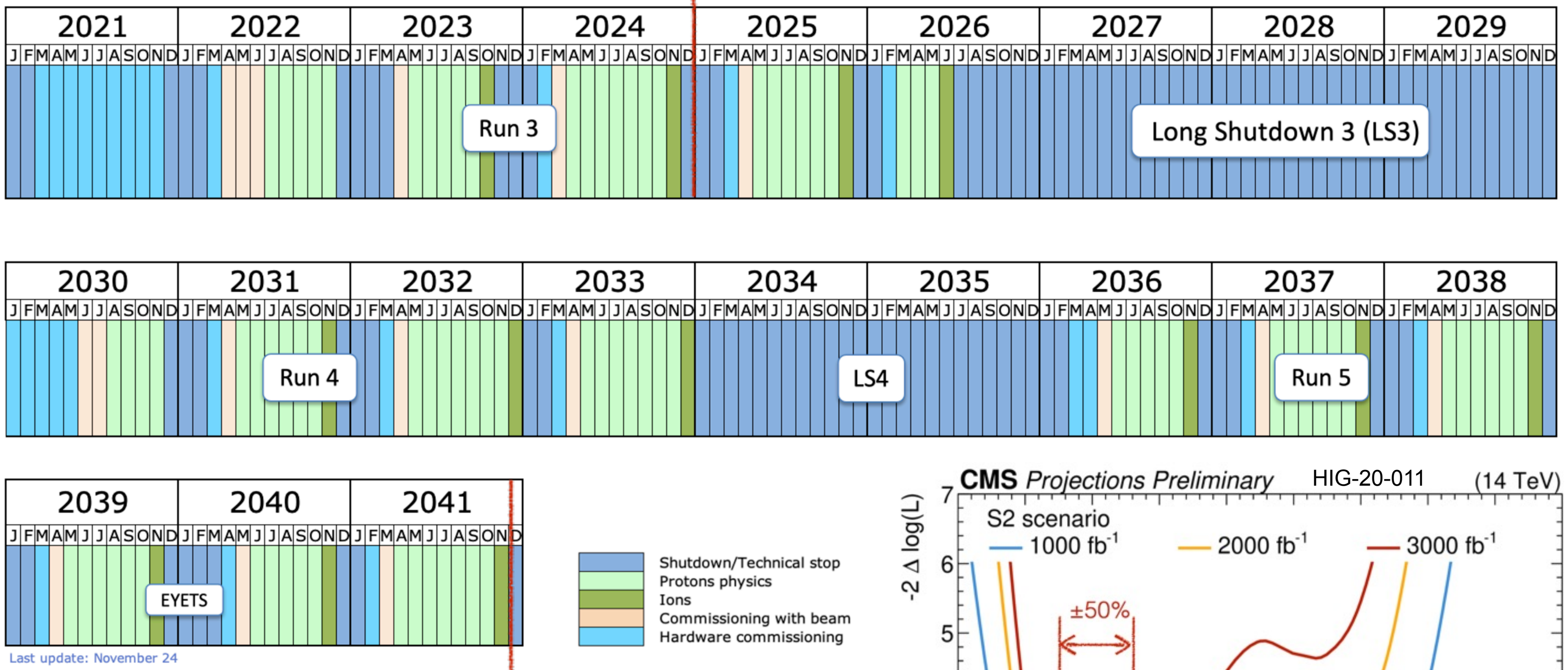
The imminent future, HL-LHC: Latest schedule update

350 fb^{-1}



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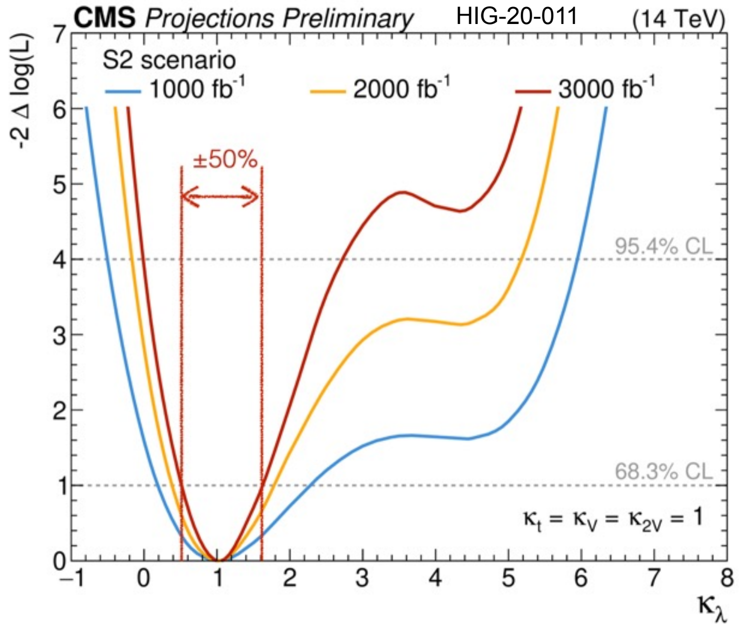

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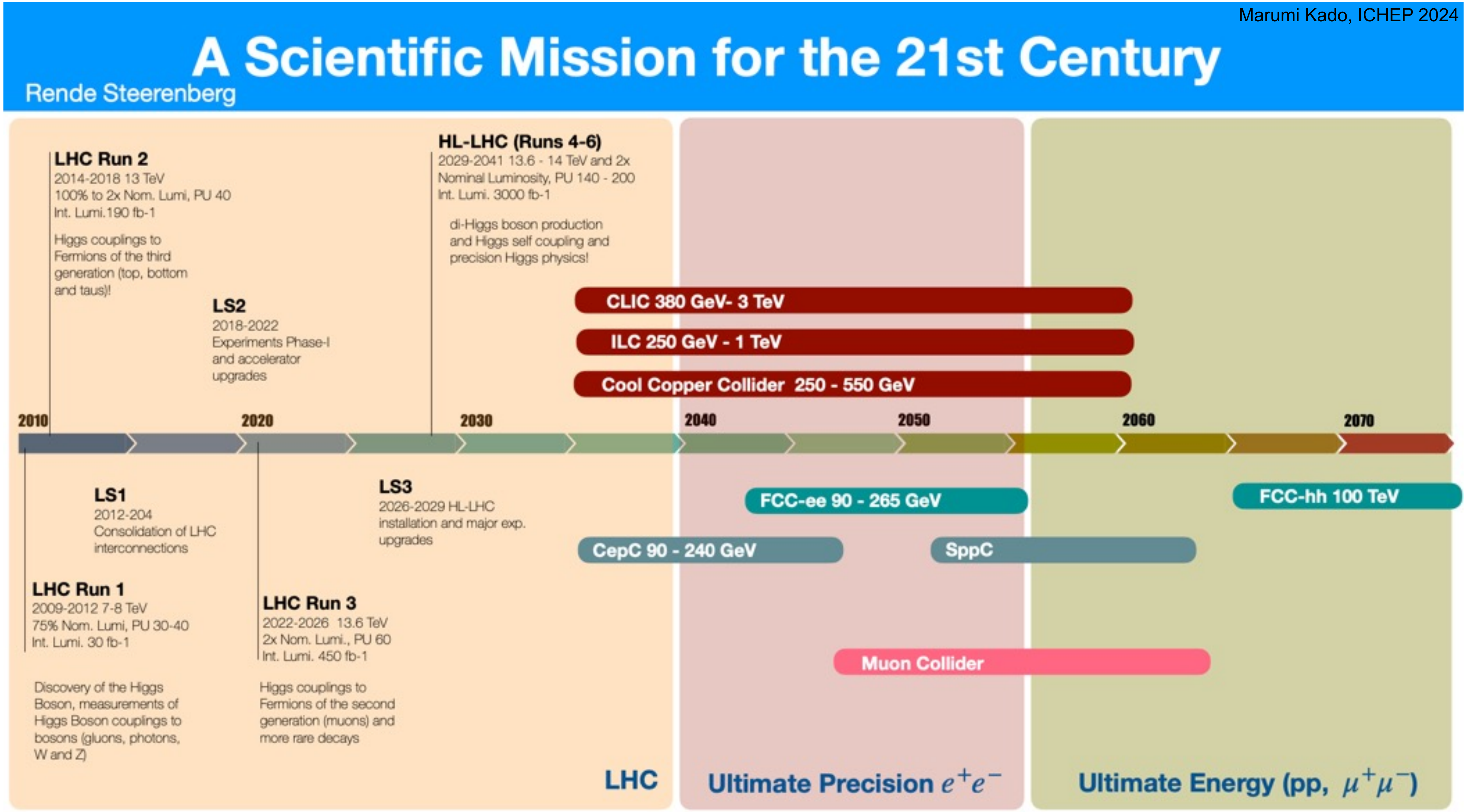

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If you are in an exploratory regime….

If you are in an exploratory regime….

or

?

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If you are in an exploratory regime….

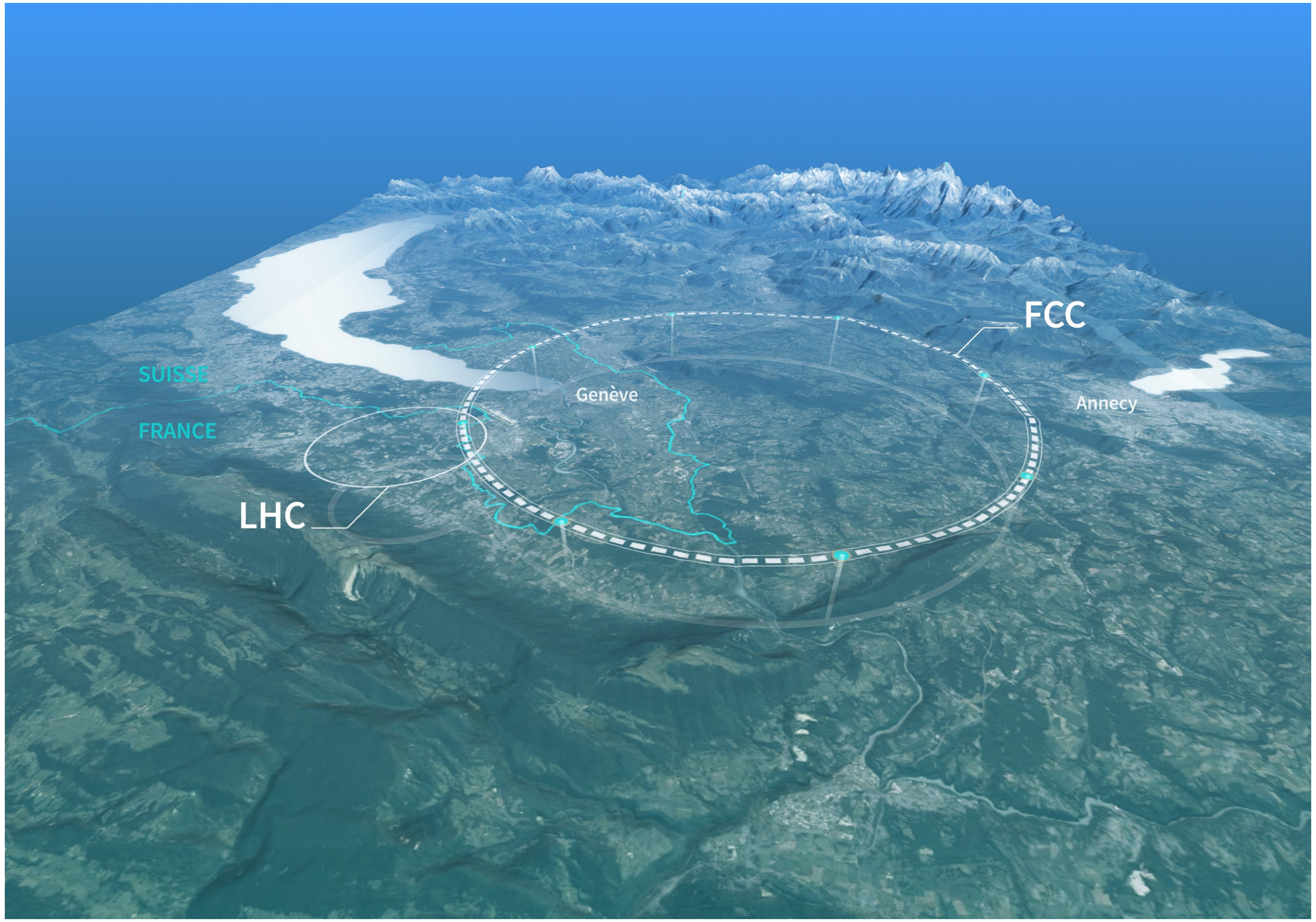
or

?

The **full FCC programme** (ee then hh, and more than one experiment) is the most versatile toolbox among all options on the table!

The FCC programme

https://home.cern/science/accelerators/future-circular-collider



FCC IN A NUTSHELL

Timeline

- **2025**: Completion of the FCC Feasibility Study
- **2027–2028**: Decision by CERN Member States and international partners

Tunnel

- **90.7 km** circumference
- **200 m** average depth
- **8 surface points** (7 in France, 1 in Switzerland)

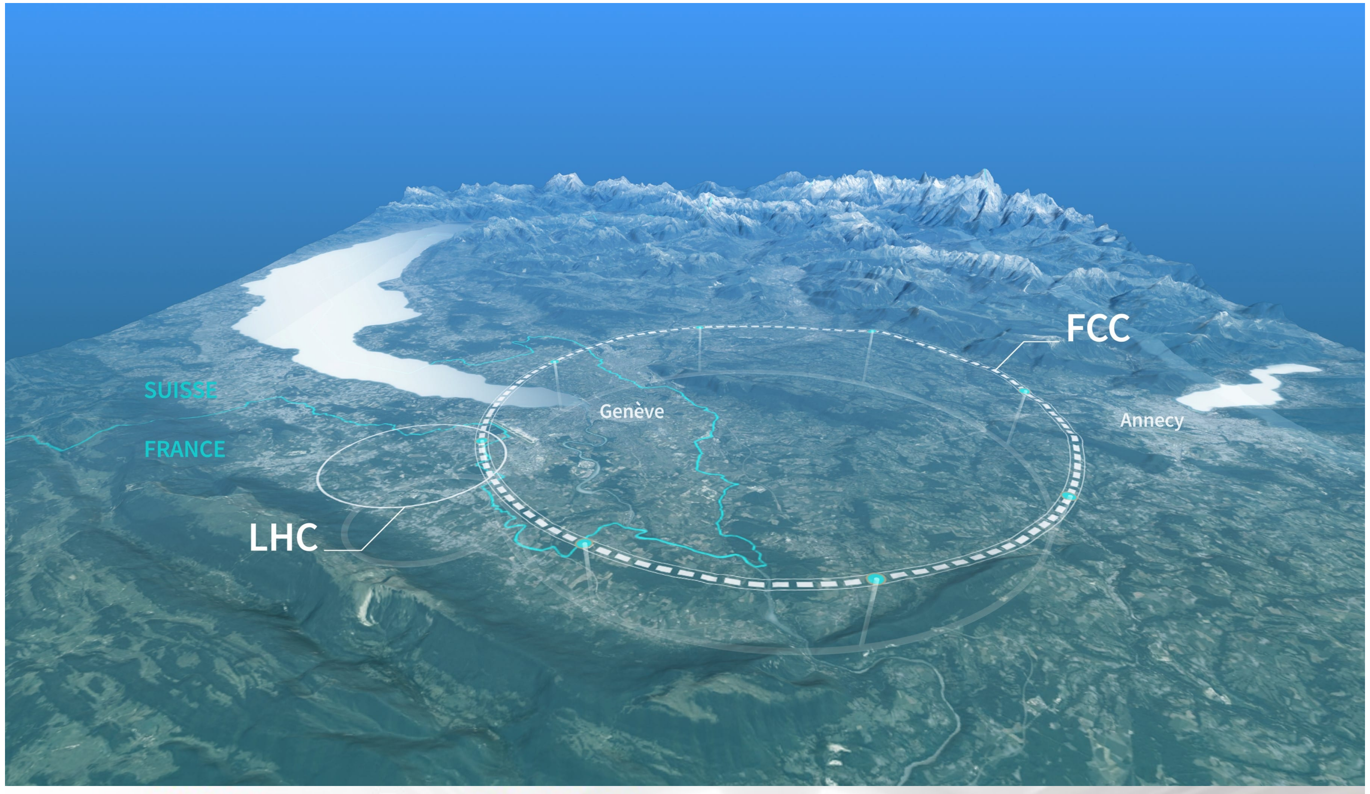
Two stages

- **FCC-ee** (precision measurements) about 15 years from the **mid-2040s**
- **FCC-hh** (high energy) about 25 years from the **2070s**

Costs/benefits

- **15 billion CHF**, spread over at least **15 years** for FCC-ee with four experiments
- Estimated benefit–cost ratio of **1.66**
- About **800 000** person-years of employment created

The FCC programme



- **Stage 1: FCC-ee** (Z, W, H, $t\bar{t}$) as a **Higgs factory,** electroweak & top factory at highest luminosities
- **Stage 2: FCC-hh** (~100 TeV) as natural continuation at energy frontier, **proton-proton** with options

Rende Steernberg, ICHEP 2024

https://home.cern/science/accelerators/future-circular-collider

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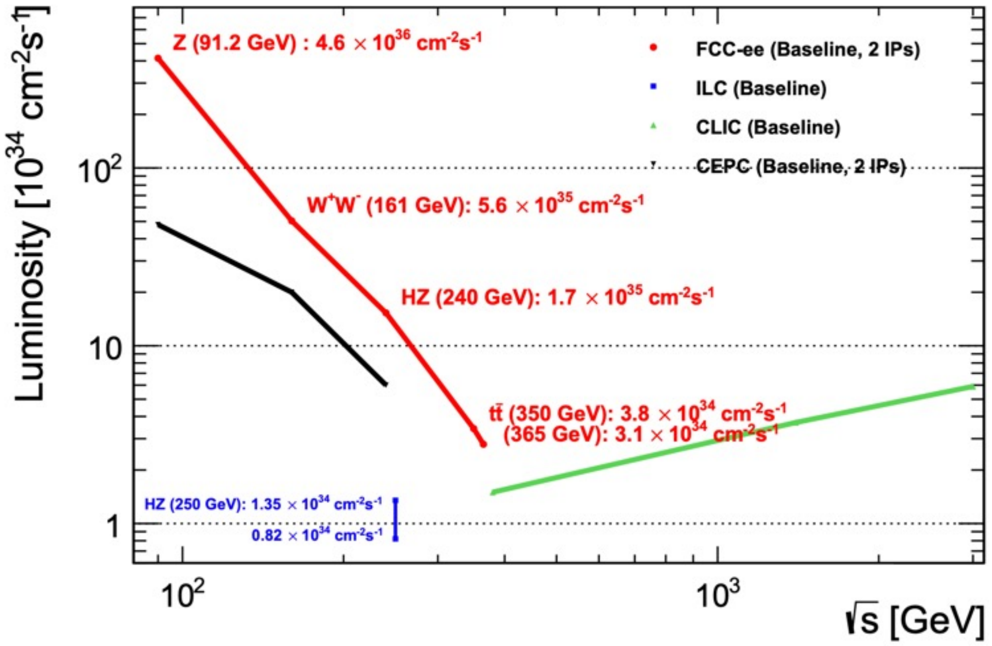
FCC: promises and challenges

Some examples taken from
Blondel & Janot, https://inspirehep.net/literature/1870513



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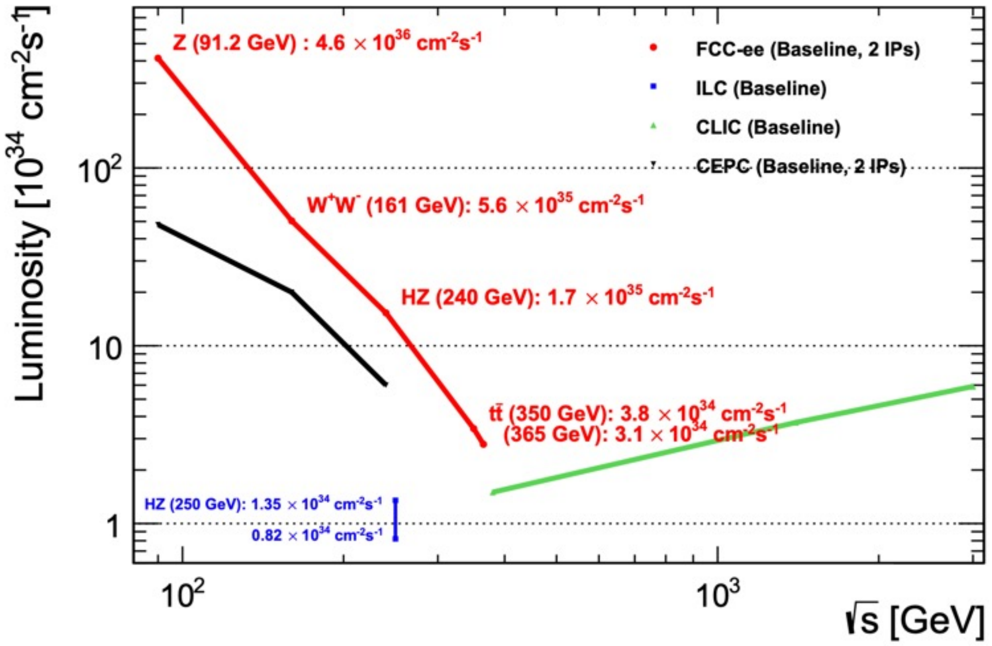

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30
Years	10	3 + 1 + 4	25
g_{HZZ} (%)	1.5	0.18/0.17	0.17/0.16
g_{HHH} (%)	50	44/33 27/24	3–4
Γ_H (%)	SM	1.1	0.91

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FCC: promises and challenges

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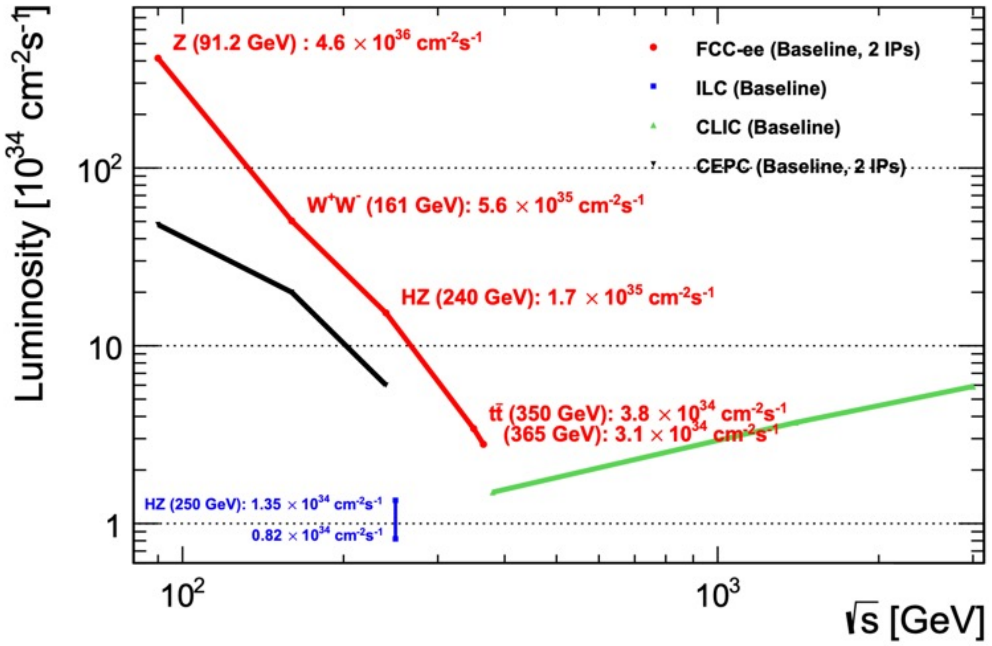

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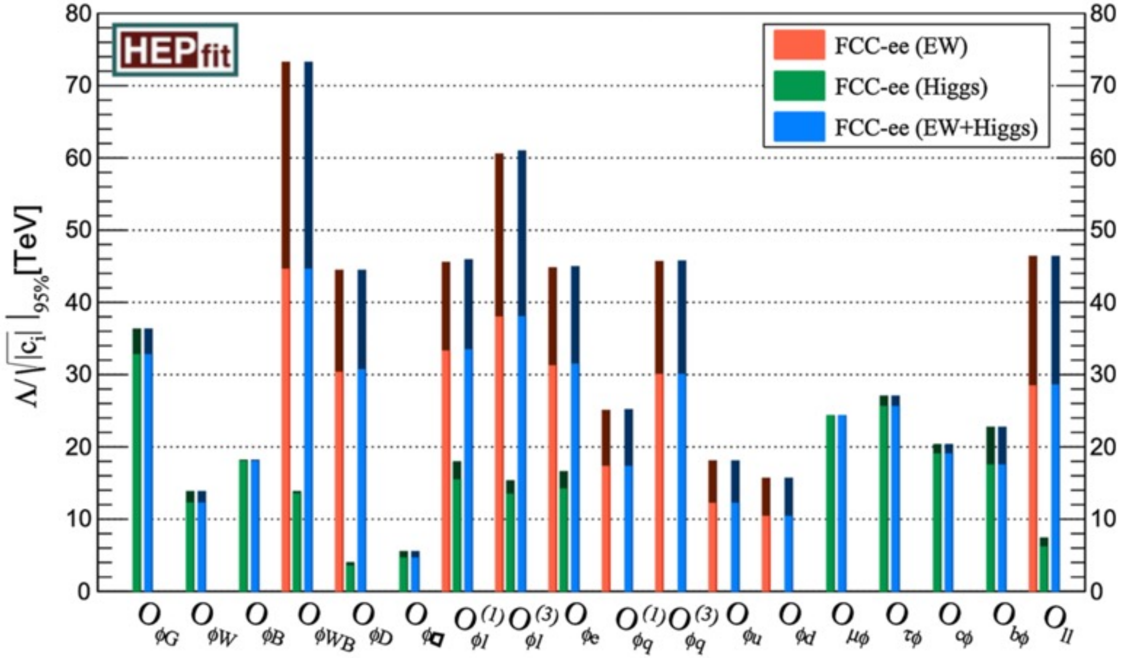

Fig. 5 Electroweak (red) and Higgs (green) constraints from FCC-ee, and their combination (blue) in a global EFT fit. The constraints are presented as the 95% probability bounds on the interaction scale, $\Lambda/\sqrt{c_i}$, associated to each EFT operator. Darker shades of each colour indicate the results when neglecting all SM theory uncertainties

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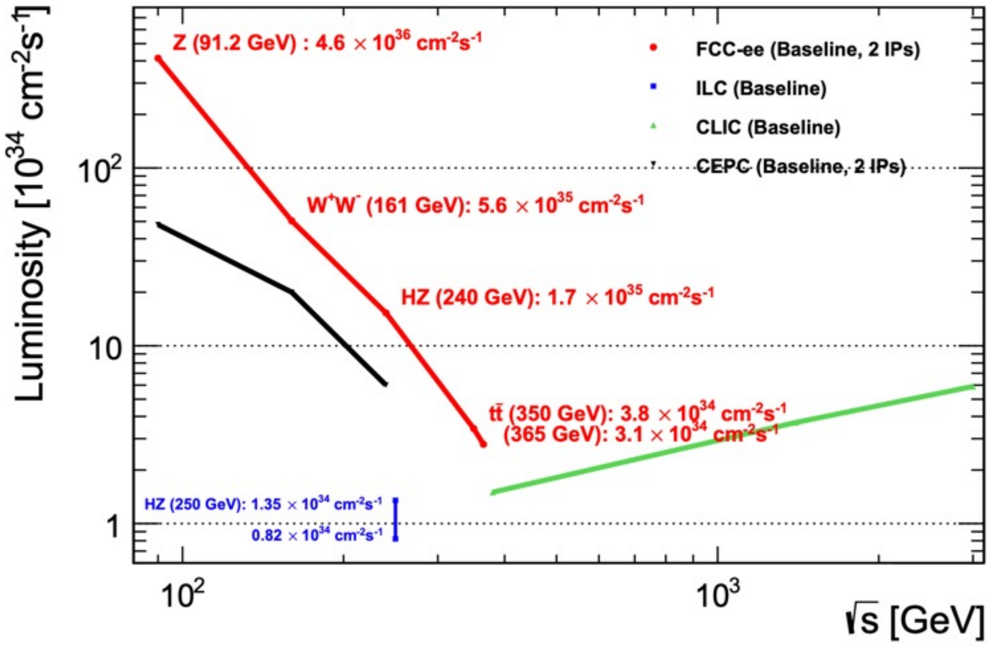
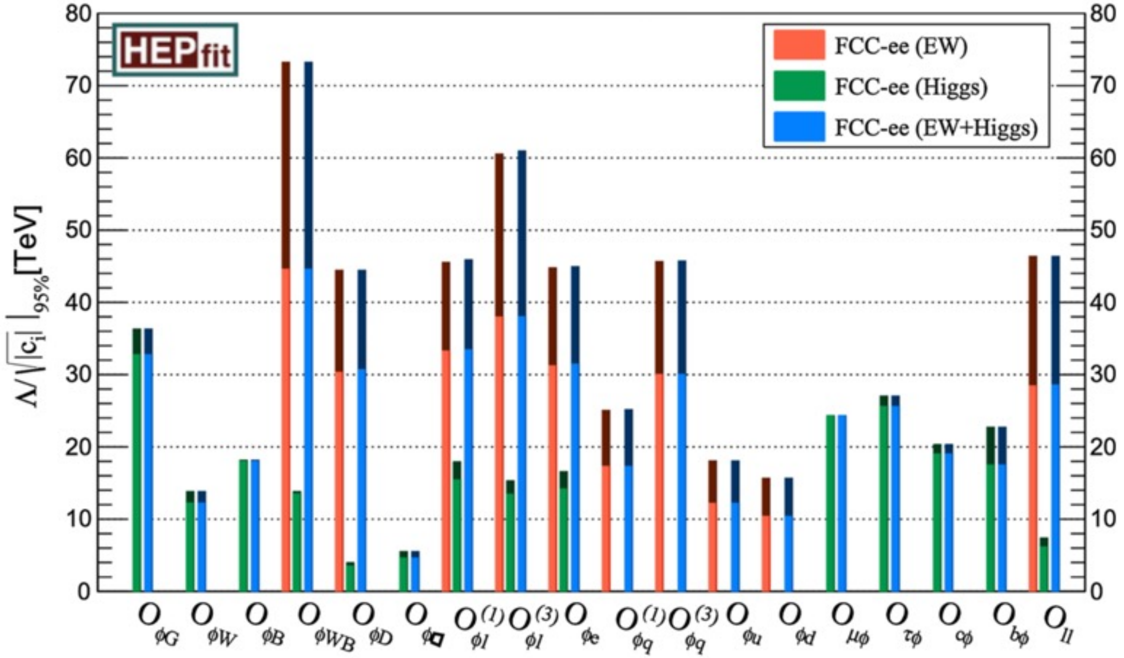
FCC: promises and challenges

Some examples taken from
Blondel & Janot, https://inspirehep.net/literature/1870513



Call for new generation(s) of brave theorists to tackle the new challenges…

Collider	HL-LHC	$FCC\text{-}ee_{240\to365}$	FCC-INT
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30
Years	10	3 + 1 + 4	25
g_{HZZ} (%)	1.5	0.18/0.17	0.17/0.16
g_{HHH} (%)	50	44/33	3–4
		27/24	
Γ_H (%)	SM	1.1	0.91



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- Make sure that, besides such a (timely) flagship project, there remains an **attractive portfolio of other projects at CERN** (like in the past).

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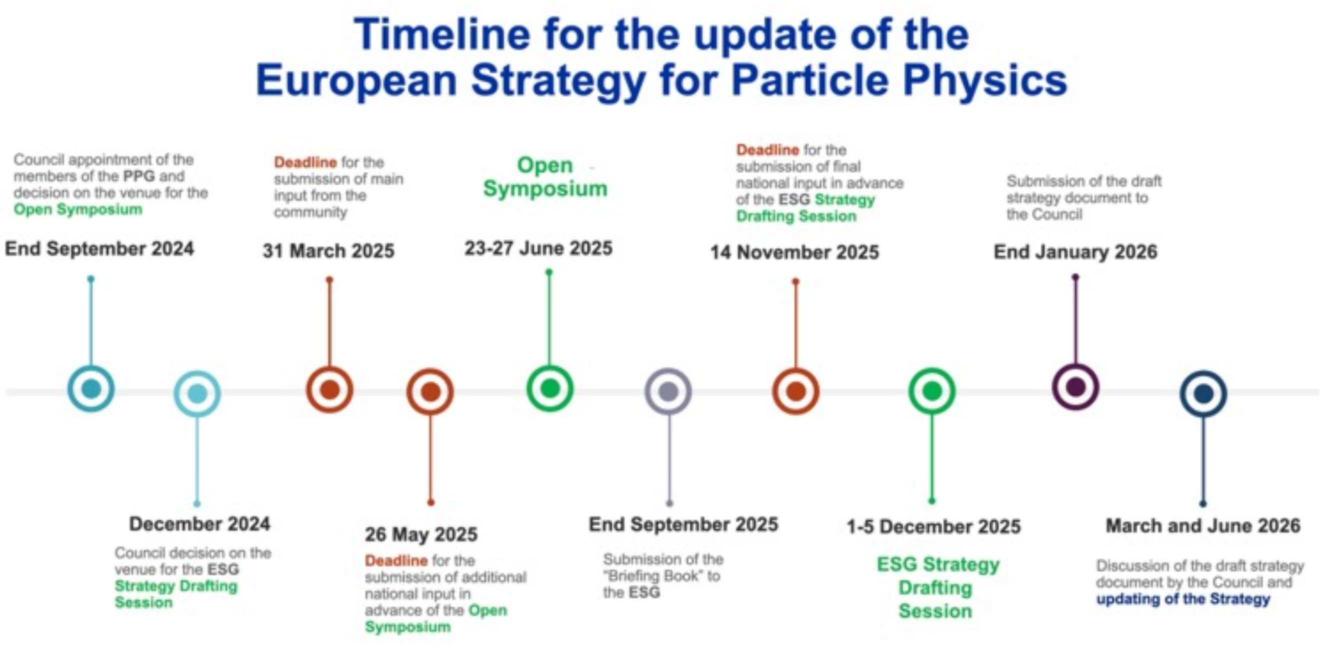

https://home.cern/news/news/knowledge-sharing/updating-european-strategy-particle-physics

A remark regarding the upcoming **European Strategy exercise**:

There is only one question to be answered: **do you envision a bright future for CERN?** No need to repeat the entire discussions of the last time – the physics situation is clear, basically no change since last time. Fight the entropy.

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Conclusion(s)

Concluding statements

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Thank you for the invitation!