Real(Complex) Calculations in the Standard Model

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Higgs XS WG

Veltman80, 24 June 2011

Real or Complex?

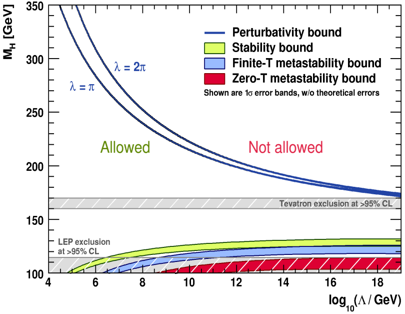
The real discovery is the one which enables me to stop doing philosophy when I want to.

Ludwig Wittgenstein

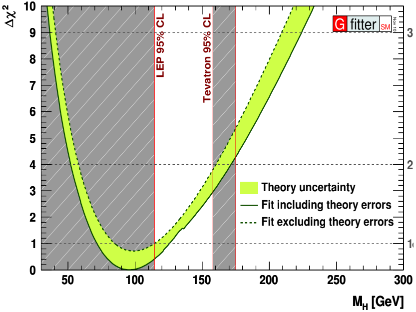
Theoretical and indirect exp. Higgs constr

The Higgs boson should be light but not too light…

Perturbativity and (meta)stability bounds versus the SM cut-off scale ∃%



EW fit **not including** direct Higgs searches



The SM Higgs must steer a narrow course between two disastrous situations if it is to survive up to the Planck scale M_P ~ 2"10 ^{18} GeV

Central value ±1#: $M_H = 96^{+30}_{!25}$ GeV

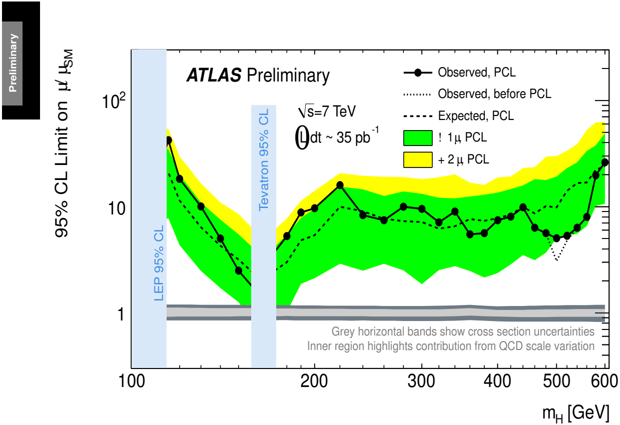
95% CL upper limit: 170 GeV

J. Ellis et al., arXiv:0906.0954

http://cern.ch/gfitter

SM Higgs Exclusion Potential

ATLAS combination of individual channels for 2010 data



Combination using maximum likelihood fit taking into account correlated nuisance parameters

Uncertainty on cross section included in SM expectation#

Not yet reached at Tevatron who exclude 158–173 GeV at 95% CL [arXiv:1103.3233]#

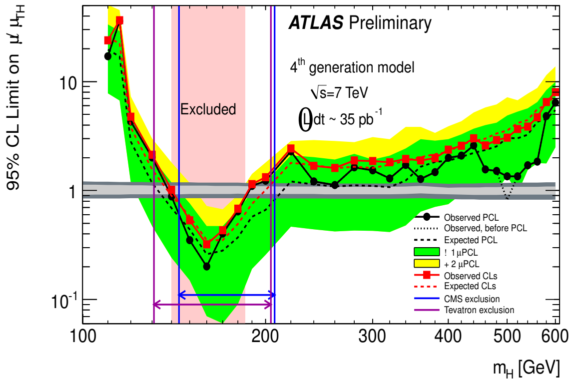
Power-constrained* limits (PCL) computed from CL_{s+b} of test statistics using toy MC

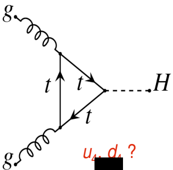
*Fluctuations below –1# wrt. median of expected limits are not allowed
Corresponding CL_s limits provide reduced exclusion (overcoverage)

4-Gen SM Higgs Exclusion Potential

Gluon fusion to Higgs via triangular heavy-quark loop sensitive to 4th generation

Preliminary





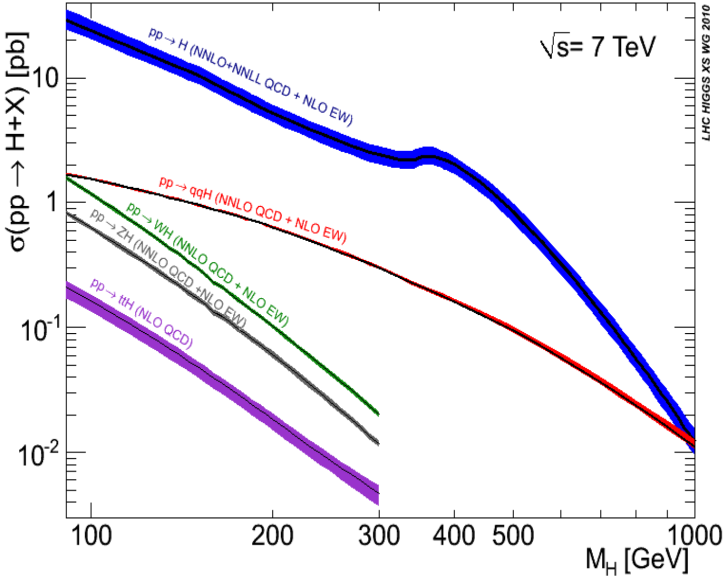
u_4, d_4 ?

4th generation ?

K-factor of ~3^2 = 9

using sequential model

95% CL exclusion of 140 < M_H < 185 GeV in SM4


√s= 7 TeV
LHC HIGGS XS WG 2010
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
σ(pp → H+X) [pb]
10
1
10^-1
10^-2
100
200
300
400
500
1000
M_H [GeV]

Veltman, M. Physica 29
1963 186–207

UNITARITY AND CAUSALITY IN A RENORMALIZABLE FIELD THEORY WITH UNSTABLE PARTICLES

M. VELTMAN *)

Instituut voor theoretische fysica der Rijksuniversiteit, Utrecht, Nederland

Synopsis

The problems of unitarity, causality and renormalizability are treated in a field theory containing an unstable particle. Perturbation theory is suitably modified and leads to an implicit equation for complete propagators. The *S*-matrix constructed with these propagators and connecting stable particle states only is shown to be unitary, renormalizable and causal. It is also shown to give rise to interpolating Heisenberg fields which verify the original field equations.

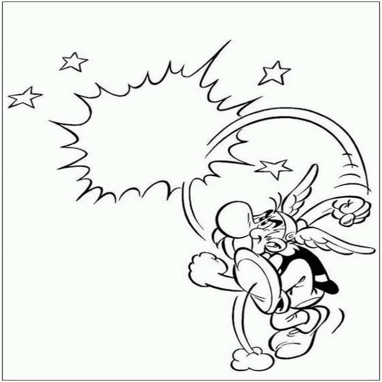
1. *Introduction.* In recent years many auth
particles in the framework of quantum field theory.
and Salam[1]) gave suitable definitions of mass an
particle in terms of its field theoretical propagat
and Sachs[2]) these definitions are in agreement
situation.

In the present paper we study another aspec
unstable particles, namely the questions of uni
normalization in perturbation theory. To be more
have a situation where an unstable scalar particle,
into two identical stable scalar particles, say φ
perturbation theory for such a model one starts by
fields A and φ, obeying the Klein-Gordon equat
other in some way specified by an interaction Lag
bation theory leads then, however, to a very undes
unstable A-particles appear at infinite times in
states. A realistic theory cannot have this feature
the unstable particle states from the in- and out
the problem of unitarity of the resulting truncate
can now be stated as follows: consider the Hilber
states. Is it then possible to construct by suitable m
theory an S-matrix which is unitary in this Hilb

*) Present address: CERN, Genève.

Last few years

Feynmanians versus Unitarians



Contentious Matters

Melrose, Veltman et al.

$$
\begin{aligned}
I_N\,(4\,\mathrm{dim}) &= \sum_{B\in I_N} C_B\, D_0(B) + \sum_{V\in I_N} C_T\, C_0(V) \\
&+ \sum_{S\in I_N} C_S\, B_0(S) + \sum_{T\in I_N} C_T\, A_0(T)
\end{aligned}
$$

Find the most efficient algorithm to compute coefficients

($\oplus$ find the analogous two-loop basis).

Highlingths in Loops

- **NNLO QCD**: Catani, Grazzini, DeFlorian, Anastasiou, Petriello, . . .
- **Mostly QCD** (Unitarians): Bern, Dixon, Kosower, Kunszt, Zanderighi, K. Ellis, . . .
- **Mostly QCD** (Numerical): Ossola, Papadopolous, Pittau, . . .
- **Mostly EW** (Feynmanians): Denner, Dittmaier, Binoth . . .
- **Two-Loop EW**: Actis, Passarino, Uccirati, Sturm, . . .

Feynmanians

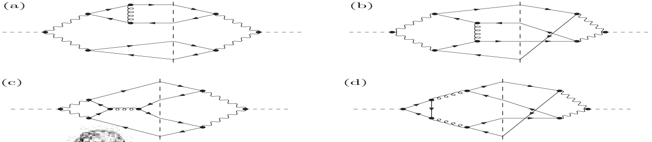
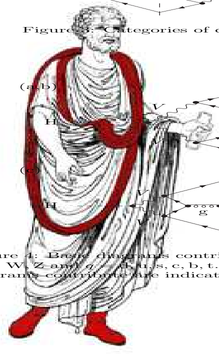


Figure 3: Categories of cut diagrams contributing to the QCD corrections.



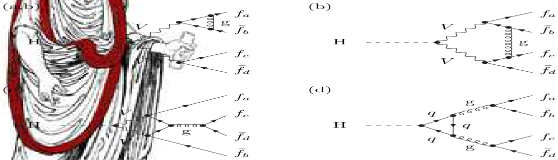
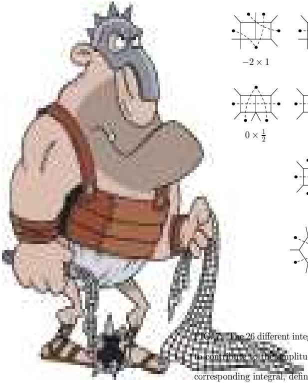


Figure 4: Basic diagrams contributing to the virtual QCD corrections for H $\longrightarrow$ $4f$ where V = W, Z and q = d, u, s, c, b, t. The categories of QCD corrections, (a)–(d), to which the diagrams contribute are indicated.

5

Unitarians



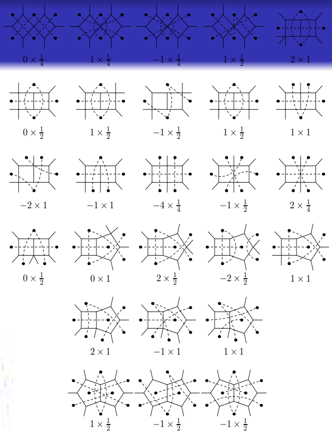


FIG. 7: The 26 different integrals which are allowed, by the hypothesis of dual conformal symmetry, to contribute to the amplitude $M_6^{(2),D=4}$. Beneath each diagram is the coefficient with which the corresponding integral, defined according to the rules reviewed in fig. 1, enters into our result for $M_6^{(2),D=4}$. An overall factor of 1/16 is suppressed and it is understood that one should sum over the 12 cyclic and reflection permutations of the external legs. In each coefficient, the second factor is a symmetry factor that accounts for overcounting in this sum.

Anatomy of a Two−Loop EW Calculation

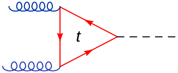
with unstable particles

Calculation & Techniques

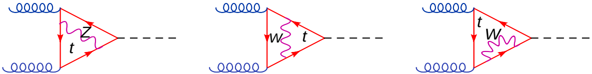
...some diagrams contributing to the EW 2-loop corrections

- $gg \to H$:

LO



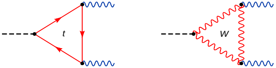
NLO



, . . .

- $H \to \gamma\gamma$:

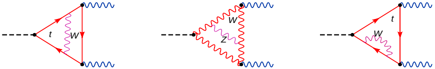
LO



fermionic bosonic

, . . .

NLO



, . . .

Calculation & Techniques

...some diagrams contributing to the EW 2-loop corrections

- $gg \to H$:

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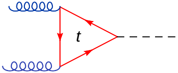
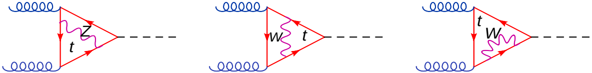


NLO



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- $H \to \gamma\gamma$:

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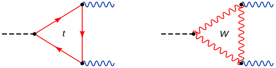

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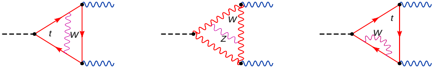
NLO



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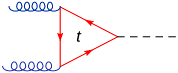
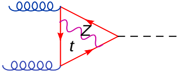
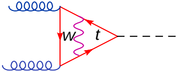
Calculation & Techniques

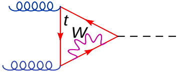
...some diagrams contributing to the EW 2-loop corrections

- $gg \to H$:

LO 

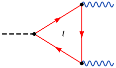
NLO 

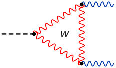




, . . .

- $H \to \gamma\gamma$:

LO 



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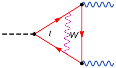
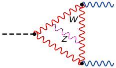
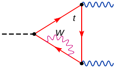
fermionic bosonic

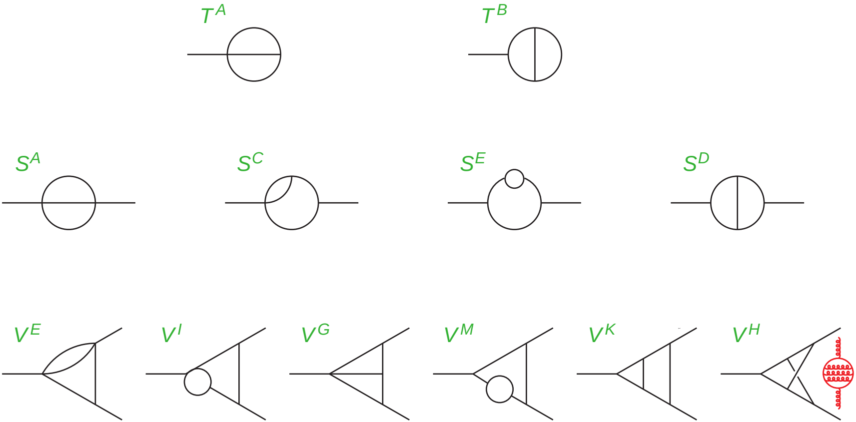
NLO 





, . . .

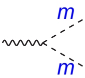
List-of-diagrams: all what is needed

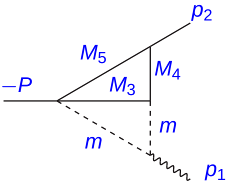


Extracting Collinear divergencies

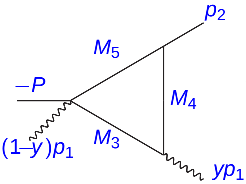
Theorem

Coefficients of collinear logarithms are integrals of one-loop functions





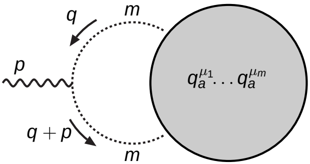
$$= \ln\frac{m^2}{s}\int_0^1 dy$$



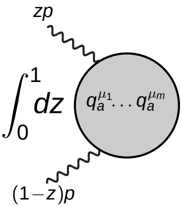
$$+ \text{ finite part}$$

General results I

Coll. behavior of arbitrary two-loop q -scalar, UV-finite diagrams



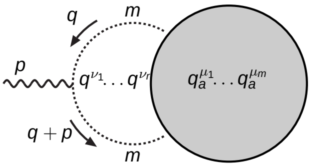
$$= \ln \frac{m^2}{s} \int_0^1 dz$$



$$+ \text{ coll. fin.}$$

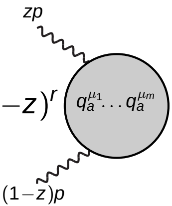
General results II

Generalization to tensor integrals



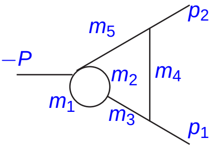
$$= \ln\frac{m^2}{s}\left[1-\frac{\epsilon}{2}\Delta_{UV}(s)-\frac{\epsilon}{4}\ln\frac{m^2}{s}\right]$$

$$\times \int_0^1 dz\,(-z)^r$$



$$p^{\nu_1}\ldots p^{\nu_r} + \text{c. f.}$$

Extracting Ultraviolet divergencies

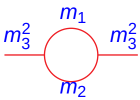
$V^l =$ 

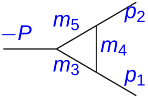
$$= \frac{1}{\pi^4} \int \frac{d^n q_1\, d^n q_2}{\underbrace{\underbrace{[1]\,[2]}_{x}\,[3]\,[4]\,[5]}_{y_1, y_2, y_3}},$$

$$[1] = q_1^2 + m_1^2$$
$$[2] = (q_1 - q_2)^2 + m_2^2$$
$$[3] = q_2^2 + m_3^2$$
$$[4] = (q_2 + p_1)^2 + m_4^2$$
$$[5] = (q_2 + P)^2 + m_5^2$$

$$= C_\epsilon \int_0^1 dx \int dS_3(y_1, y_2, y_3)\, [x\,(1-x)]^{-\epsilon/2}\, (1 - y_1)^{\epsilon/2 - 1}\, V^{-1-\epsilon}$$

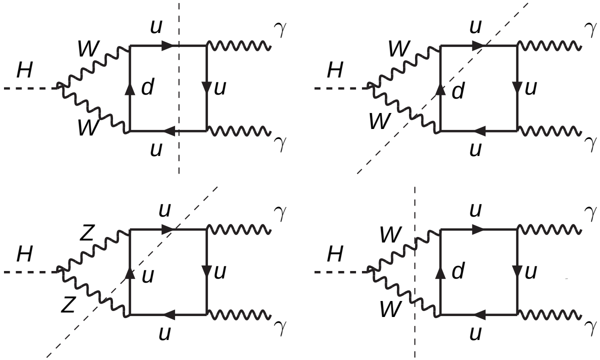
The single pole can always be expressed in terms of 1L.

$V^l =$ 

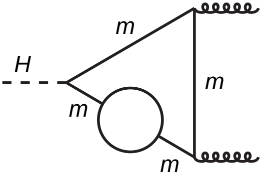
$\times$ 

$+$ finite part.

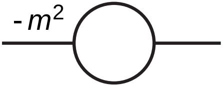
Around threshold



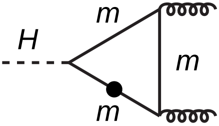
$1/\beta$-behavior



$= \; -$



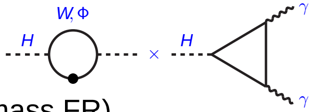
$\times$



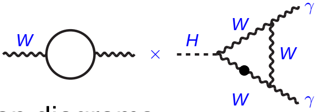
$+ \left(\begin{array}{l} \text{reg. part} \\ \text{at } \beta = 0 \end{array} \right)$

Origin of $1/\beta$

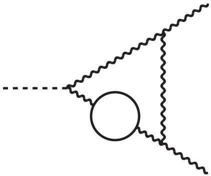
- (1-loop diagrams) $\otimes$ (H wave-function FR)



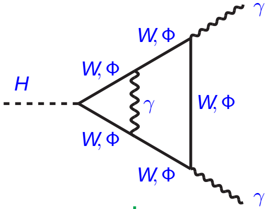
- (1-loop diagrams) $\otimes$ (W mass FR)



- Pure 2-loop diagrams

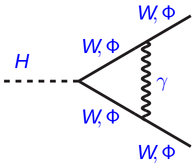


Logarithmic singularities



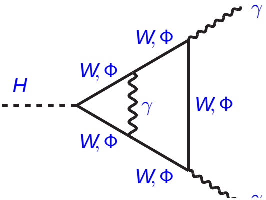
$\sim \ln \beta_W$

Remnant of Coulomb singularity

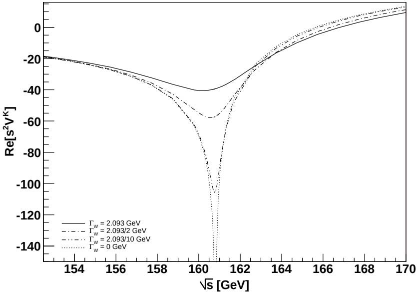


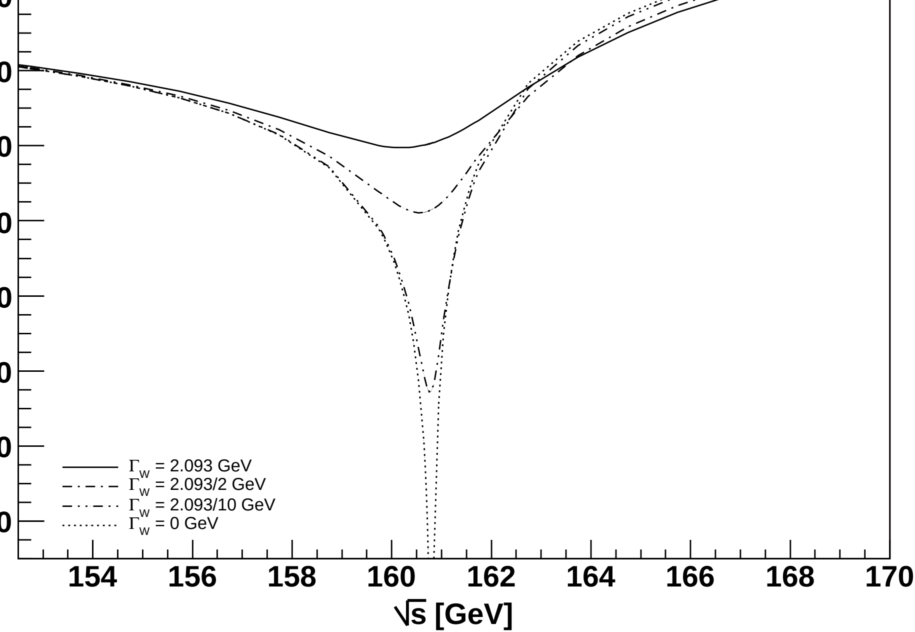
$\sim 1/\beta_W$

Cure for logarithmic singularities



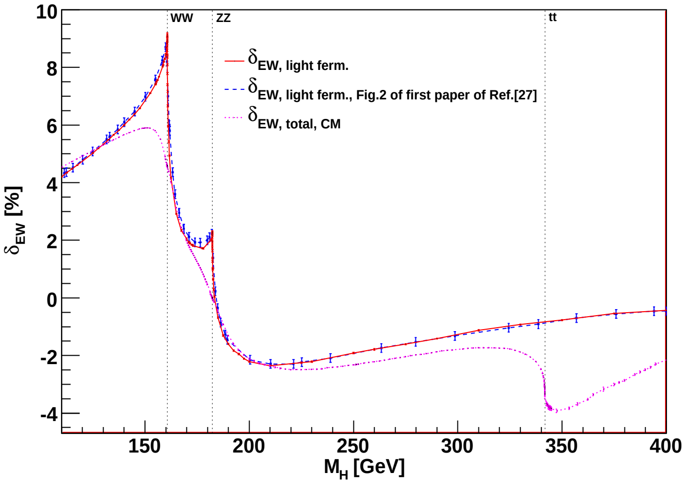
Complex W Mass

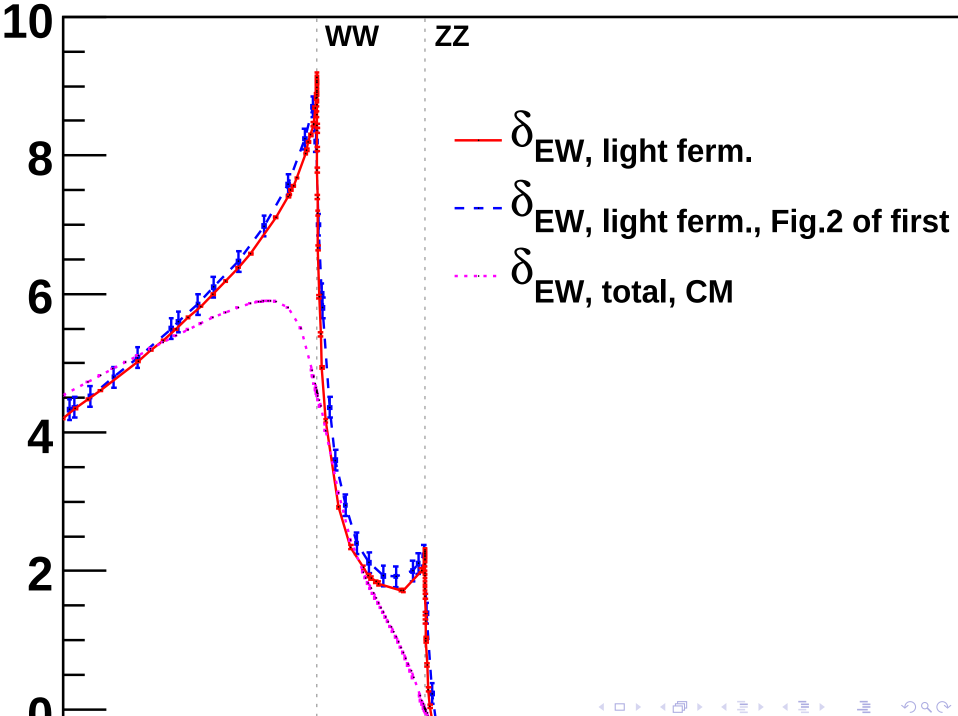




Γ_W = 2.093 GeV
Γ_W = 2.093/2 GeV
Γ_W = 2.093/10 GeV
Γ_W = 0 GeV
154
156
158
160
162
164
166
168
170
√s [GeV]

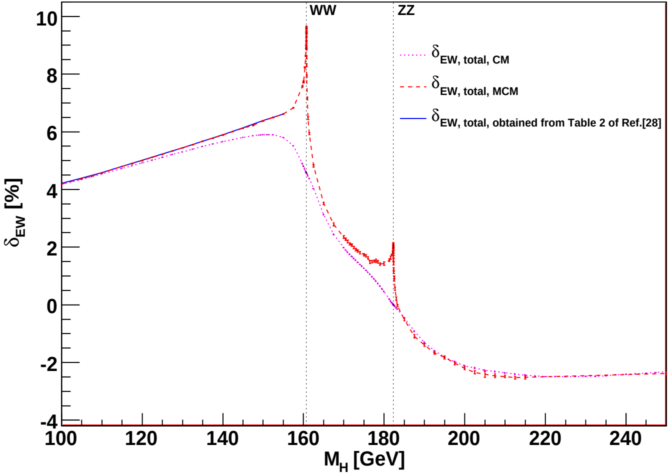
Comparing


WW
ZZ
tt
$\delta_{EW, light\ ferm.}$
$\delta_{EW, light\ ferm., Fig.2\ of\ first\ paper\ of\ Ref.[27]}$
$\delta_{EW, total, CM}$
δ_{EW} [%]
M_H [GeV]
10
8
6
4
2
0
-2
-4
150
200
250
300
350
400



10
8
6
4
2
0
WW
ZZ
δ EW, light ferm.
δ EW, light ferm., Fig.2 of first
δ EW, total, CM

Comparing



WW
ZZ
$\delta_{EW, total, CM}$
$\delta_{EW, total, MCM}$
$\delta_{EW, total, obtained from Table 2 of Ref.[28]}$
δ_{EW} [%]
M_H [GeV]
10
8
6
4
2
0
-2
-4
100
120
140
160
180
200
220
240

Dealing with experimenters today

Dialogue Concerning the Two Chief World Systems: Salviati, Sagredo, Simplicio

TH How do you want to proceed? Full scenario?

EX No, we separate Higgs production and decay, and MCs implement an ad-hoc Breit-Wigner

TH Hope you are not going for high-mass!

EX Up to 600 GeV via ggF(+VBF) ($H \to WW \to l\nu qq$)

TH Then you got problems, the three bricks need a proper definition:

1. The full $\mathcal{S}$-matrix element is $S \oplus B$
2. S is $\left[\text{ production } \otimes \text{ propagation } \otimes \text{ decay }\right]$
3. each of them must be defined consistently

EX We are working with a mass spectrum peak, but what about the on-shell mass peak? Are there other definitions?

TH This I told you before

Conclusion?

- What is the best way of dealing with experimeters? Well,

> *that all true believers break their eggs at the convenient end.*

Jonathan Swift's Travels into Several Remote Nations of the World

- Exclusions are approaching

> *Good tests kill flawed theories; we remain alive to guess again.*

Karl Popper

> *El sueño de la razõn produce monstruos*

Francisco Goya

Moving towards modernity

Which

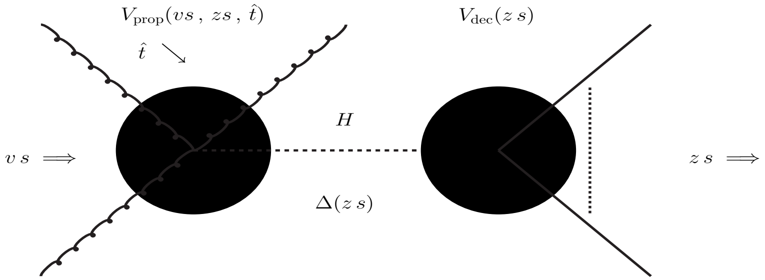
best language to simulate intuition?

- production of on-shell Higgs
- intermediate Breit–Wigner
- Higgs on-shell decay

- *production* of a Higgs at its complex pole
- Dyson resummed propagator
- Higgs *decay* at its complex pole

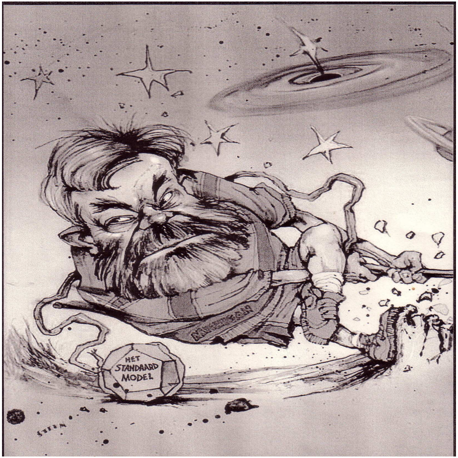
Right column

cannot yet produce fast answers, that's why the PO oblivion



$$\Longrightarrow \quad \sigma_{gg\to H+X}(vs\,,\ \hat{t}\,,\ zs)\,\frac{(zs)^2}{\left|zs - s_H\right|^2}\,\frac{\Gamma_{H\to f}(zs)}{(zs)^{1/2}} + \mathrm{NR}$$

$$= \quad \sigma_{gg\to H+X}(vs\,,\ \hat{t}\,,\ s_H)\,\frac{\left|s_H\right|^2}{\left|zs - s_H\right|^2}\,\frac{\Gamma_{H\to f}(s_H)}{\left|s_H\right|^{1/2}} + \mathrm{NR}'$$



Age is an issue
of mind
over matter.
If you don't
mind, it
doesn't
matter.

Mark Twain