Higgs production via gluon fusion

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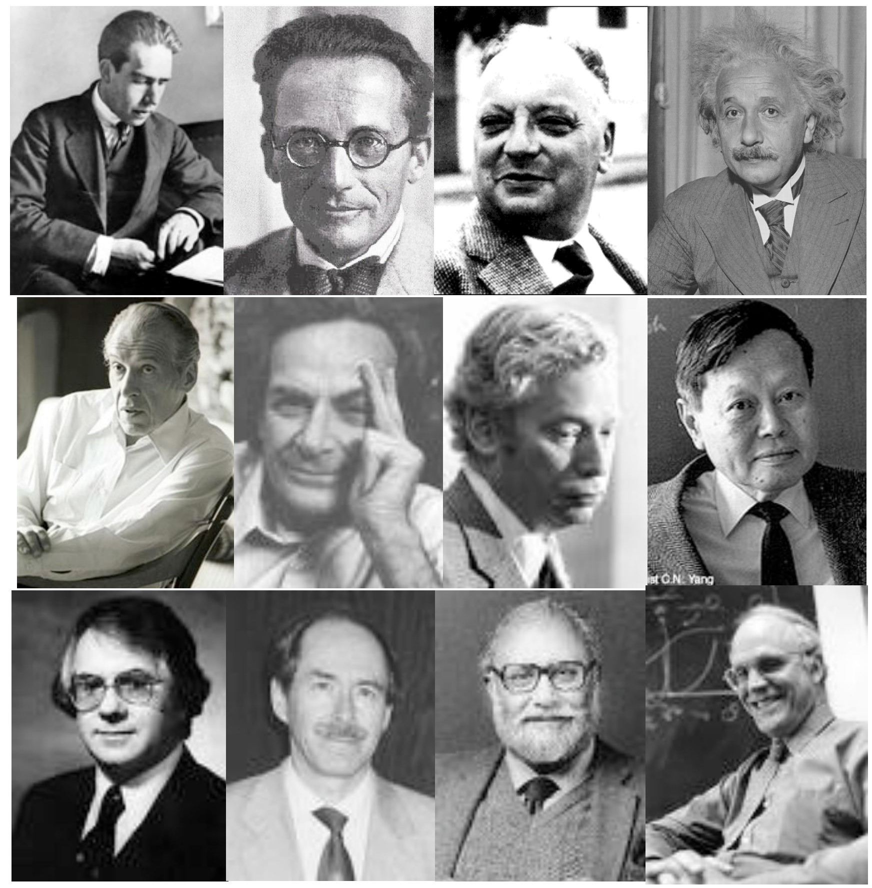
Orsay, June 2009

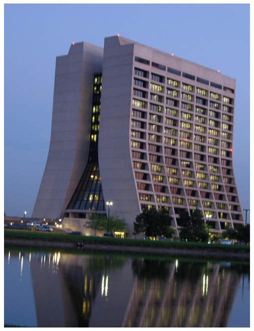
Particle physicists of the 20th century

- Pieced together an almost perfect theory of particle interactions
- Guided by symmetry and mathematical consistency
- Predicted new particles to be found many years later!



"Last" mystery

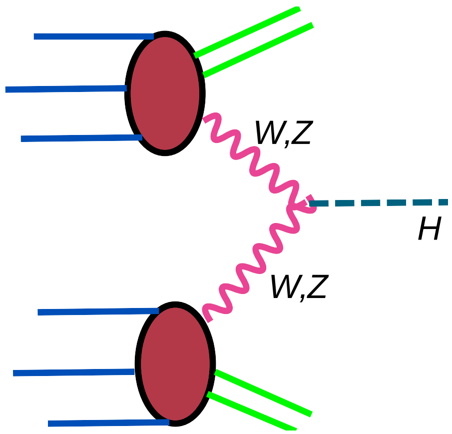
- Why do elementary particles have mass?
- Rudimentary theoretical answer given in 1964: *"Mass is the potential energy due to an unknown force".*



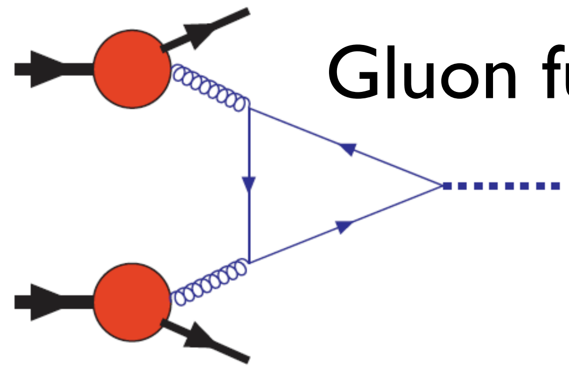
- *Unknown Force = Undiscovered particle (Higgs)!*
- Elusive particle! Bulk of its interaction creates mass, leaving pale experimental traces.

- *Holy Grail of particle physics.* The most sought after particle in history: LEP, TEVATRON, LHC accelerators.

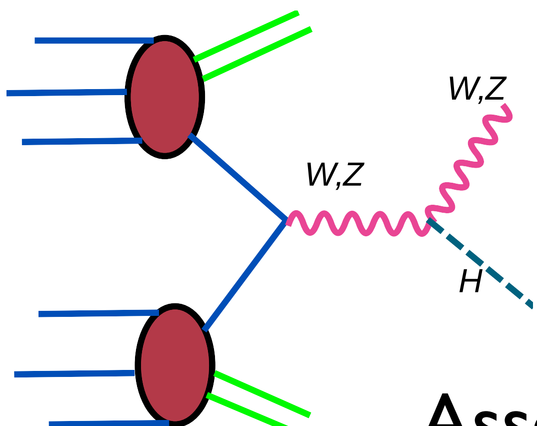
Higgs hadroproduction



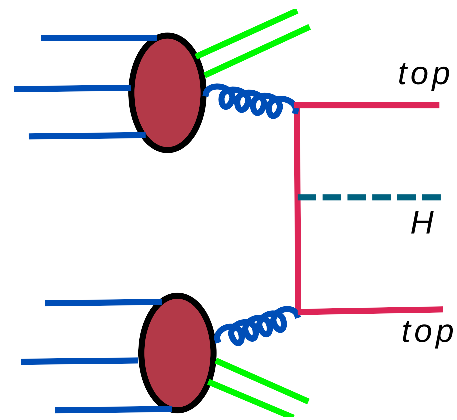
Weak boson fusion



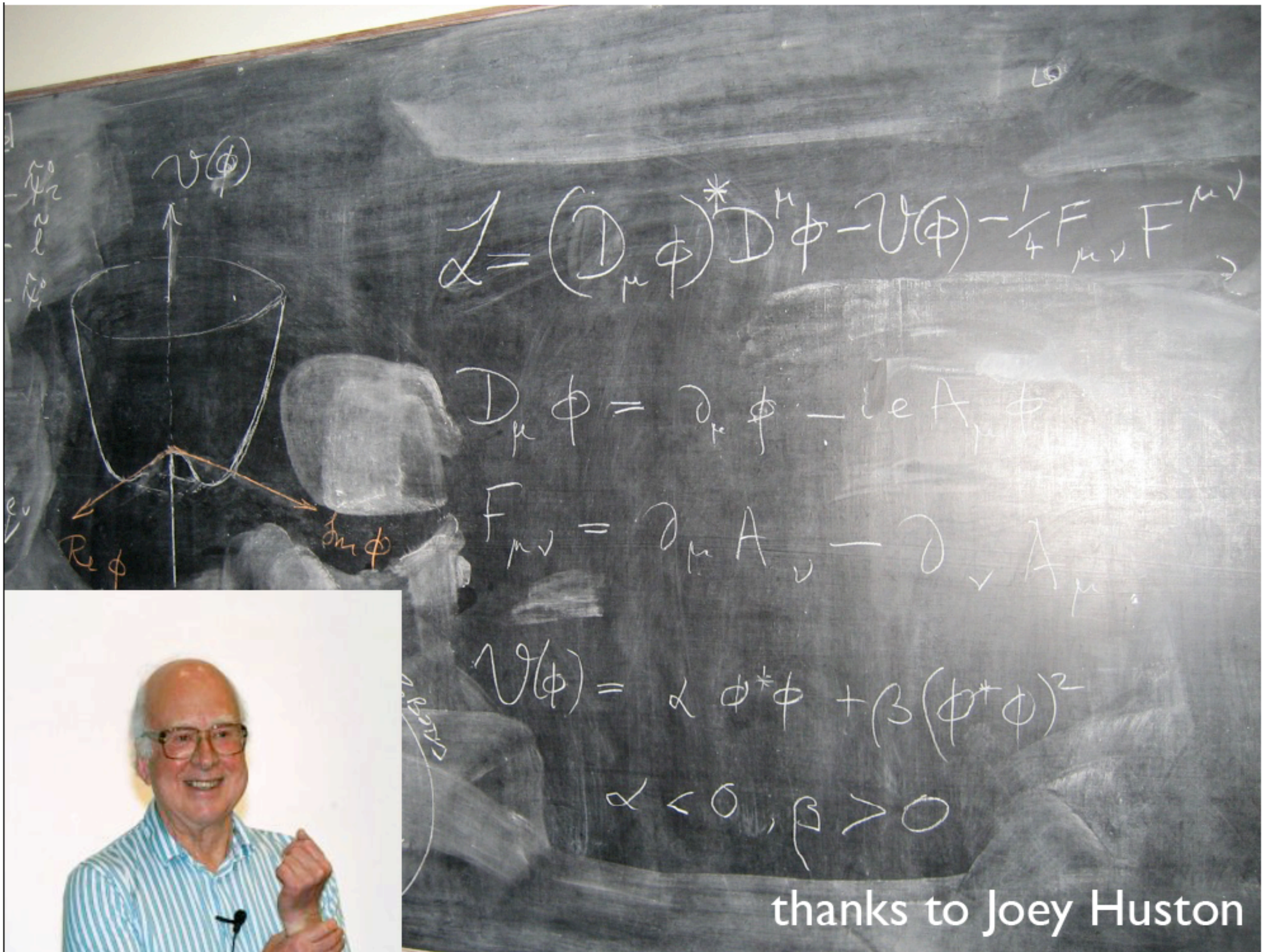
Gluon fusion



Associated Drell-Yan



Associated Top pair


V(φ)
Re φ
Im φ
L = (D_μ φ)* D^μ φ − V(φ) − 1/4 F_μν F^μν
D_μ φ = ∂_μ φ − ieA_μ φ
F_μν = ∂_μ A_ν − ∂_ν A_μ
V(φ) = α φ*φ + β(φ*φ)²
α < 0, β > 0
thanks to Joey Huston

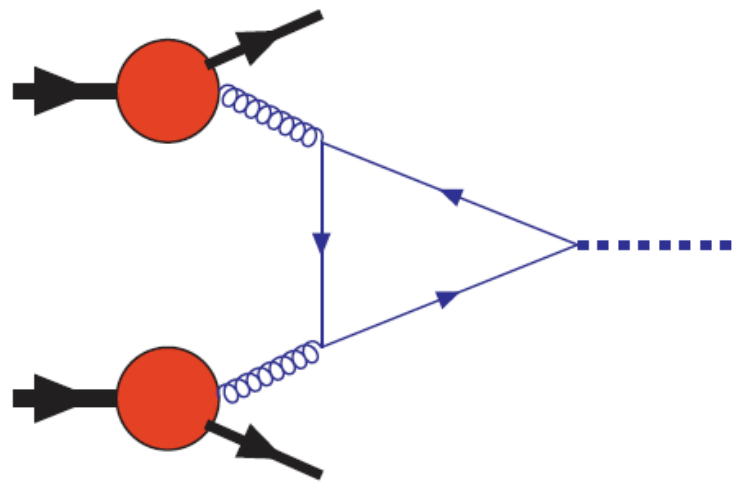
$$M_{HIGGS} = ?$$

Just a number away...

- The mass of the Higgs boson may be the only parameter missing to explain everything that we will see at the LHC!
- If the SM is true, this will be the most spectacular triumph of the physicists of the 20th century.

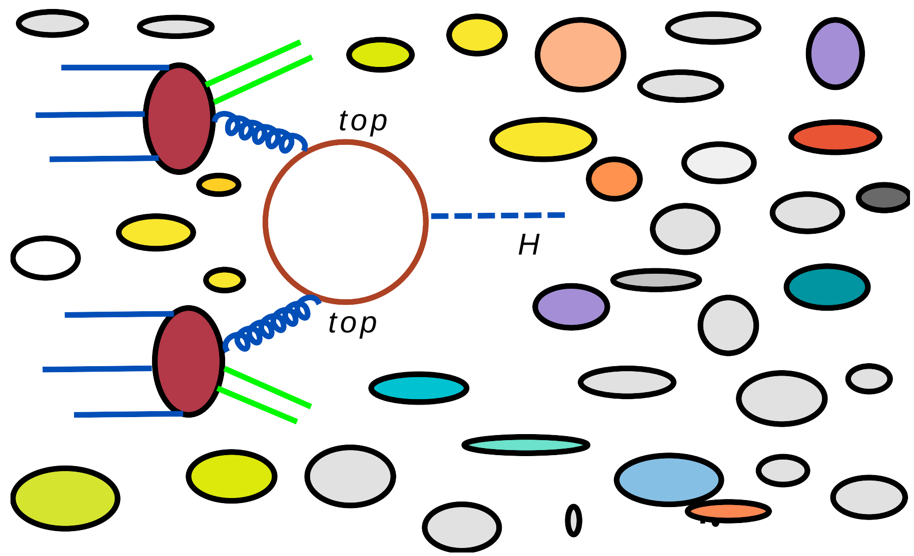
The gluon-fusion cross-section

- The Higgs boson couples to gluons through heavy quarks.
- Large gluon density at LHC
- Large Born cross-section (~ 20 pb); this is the best production channel to discover a SM Higgs boson.
- Reliable estimate of the cross-section is a challenge.



Probing the vacuum!

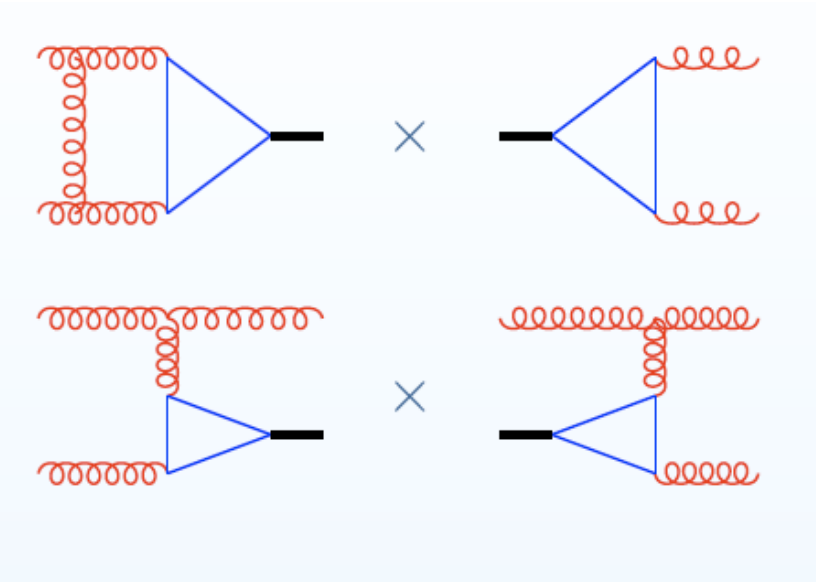
Everything that couples to a Higgs boson contributes. Heavy quarks (in SM) do not decouple!



PRICE: Energy = Higgs mass

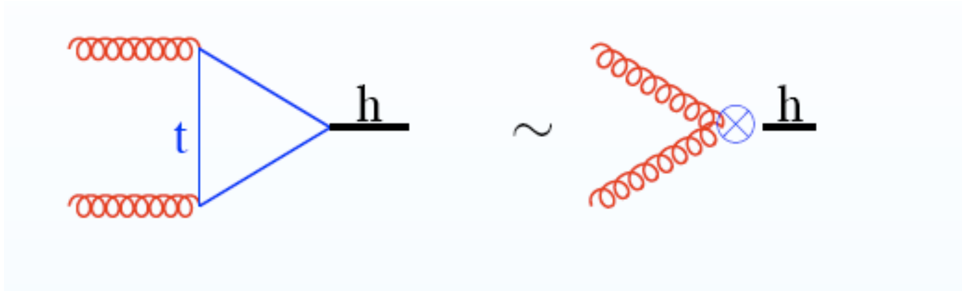
Two powers of the strong coupling α_s

NLO QCD cross-section in the SM



- A two-loop computation
  Spira, Djouadi, Gradenz, Zerwas
- Large scale uncertainty
  (~ 25 %)
- a very big correction
  (~70% -100 %)
  Spira et al; Dawson
- Is perturbation theory valid?

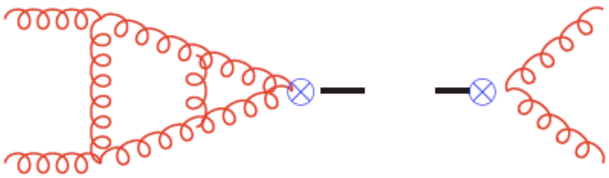
Heavy quark effective theory



- Light Higgs-boson in comparison to the mass of a top-pair produced at threshold.
- The effective theory was the only means to make progress in computing the NNLO cross-section (simpler calculations: from 3 to 2 loops).
- NNLO Wilson coefficients (Chetyrkin, Kniehl, Steinhauser)
- Massive loop integrals reach very quickly their asymptotic value: a very good approximation!

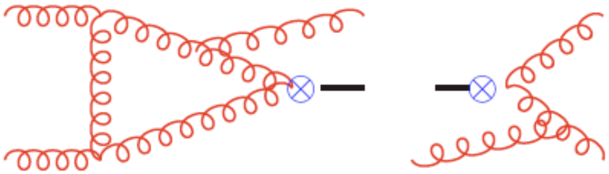
Still, a formidable calculation

- Double Virtual (V-V)



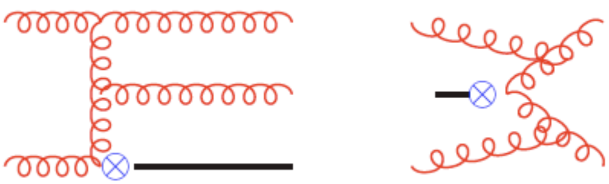
+ 148 diagrams

- Real - Virtual (V-R)



+ 559 diagrams

- Double Real (R-R)



+ 675 diagrams

A laboratory of new computational methods

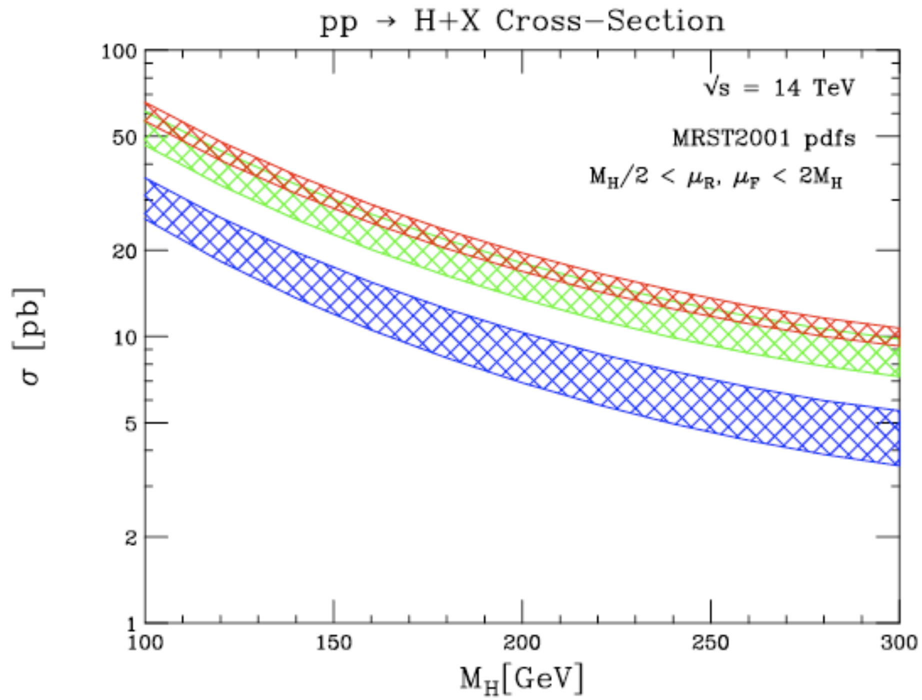
- Expansion around threshold (Harlander, Kilgore 2002)

- Dual reductions and differential equations for phase-space and loop integrations (CA, Melnikov 2002)

$$2\pi i\delta(k^2 - m^2) \rightarrow \frac{1}{k^2 - m^2 + i0} - \frac{1}{k^2 - m^2 - i0}$$

- Recursion properties of hypergeometric functions (Ravindran, Smith, van Neerven 2003)

Total cross-section through NNLO



- Slowly converging perturbative series

$$\sigma\,(\mathrm{NNLO}) = \mathrm{LO}\,(1 + 0.7 + 0.3)$$

- Scale variation of about 15% at NNLO

Beyond the Standard Model

- We have achieved a very good theoretical precision of about 10% in all viable gluon-fusion signal cross-sections at the LHC.
- Higgs boson = New physics! Every model-builder believes that the Higgs sector of the SM is not right!
- The measurements of the Higgs mass and the gluon-fusion cross-section will be a serious precision test for any model which aspires to explain LHC data.

What if

$$\sigma_{HIGGS}^{TRUE} = 75\% \sigma_{HIGGS}^{SM}???$$

Higgs cross-sections

- Precision test for ALL models which aspire to explain LHC data...
- If SM cross-section estimate is roughly correct, then they may be measured with a 10-15% precision. Comparable to theory!
- We should be prepared for surprises in the Higgs sector! All SM extensions modify this one way or another!

Higgs boson: a pseudo-Goldstone?

Hard to satisfy Electroweak Precision Tests and associate the Electroweak Symmetry Breaking with

strong dynamics at Mw

Strong dynamics and an ``effective'' Higgs boson is possible:

- Little Higgs
- Warped extra dimension

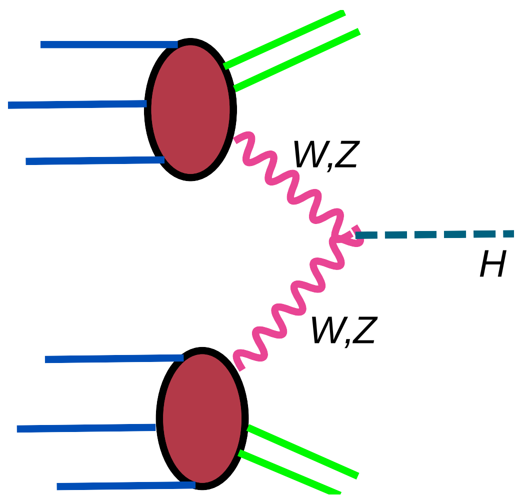
Common effective theory for Higgs and SM gauge boson/fermion interactions

Giudice, Grojean, Pomarol, Rattazzi

Strong dynamics at a (not so high) scale with a global symmetry.
This is broken spontaneously: Goldstone boson
A subgroup is gauged under SU(2) x U(1) + Yukawa interactions of SM and strong sector particles: massive (pseudo) Goldstone

Common phenomenology

Giudice, Grojean, Pomarol, Rattazzi



All couplings of the Higgs boson to other SM particles may be suppressed by a factor:

$$\sqrt{1 - \frac{v^2}{f^2}}$$

$f \simeq 500\mathrm{GeV} \qquad \sigma_{WBF} \approx 75\% \quad \sigma_{WBF}^{SM}$

Going beyond the SM

Let's extend the SM naively, without symmetry protections

$$\mathcal{L} \ni \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{m_\phi^2}{2}\phi^2$$

$$+\frac{1}{2}\left(\partial_\mu S\right)^2 - \frac{m_S^2}{2}S^2$$

$$+\bar{\psi}\left(i\not{\partial} - m_f\right)\psi$$

$$-\frac{1}{4}\lambda\phi^2 S^2 - y_\phi \phi\bar{\psi}\psi - y_S S\bar{\psi}\psi$$

Heavy-Light Interactions

The hierarchy problem

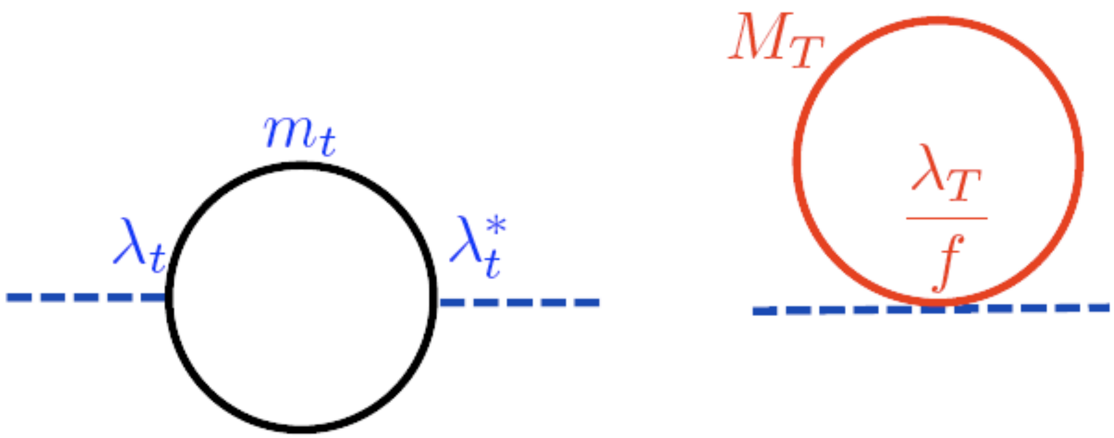
$$\delta m_\phi^2 = \frac{y_\phi^2}{4\pi^2} m_\psi^2 \Big[1 - 2\ln\frac{m_\psi^2}{\mu^2} + \mathcal{O}(m_\phi^2/m_\psi^2)\Big]$$
$$- \frac{\lambda}{32\pi^2} m_\Phi^2 \Big[1 - \ln\frac{m_\Phi^2}{\mu^2}\Big]$$

Large redefinitions of scalar masses at each order in perturbation theory

$$\delta m_\psi = m_\psi \Big[\frac{5}{4} - \frac{3}{2}\ln\frac{m_\Phi^2}{\mu^2} + \mathcal{O}(m_\psi^2/m_\Phi^2)\Big] + (\Phi \to \phi)$$

Hard to satisfy electroweak precision and other tests.

Canceling the UV sensitivity

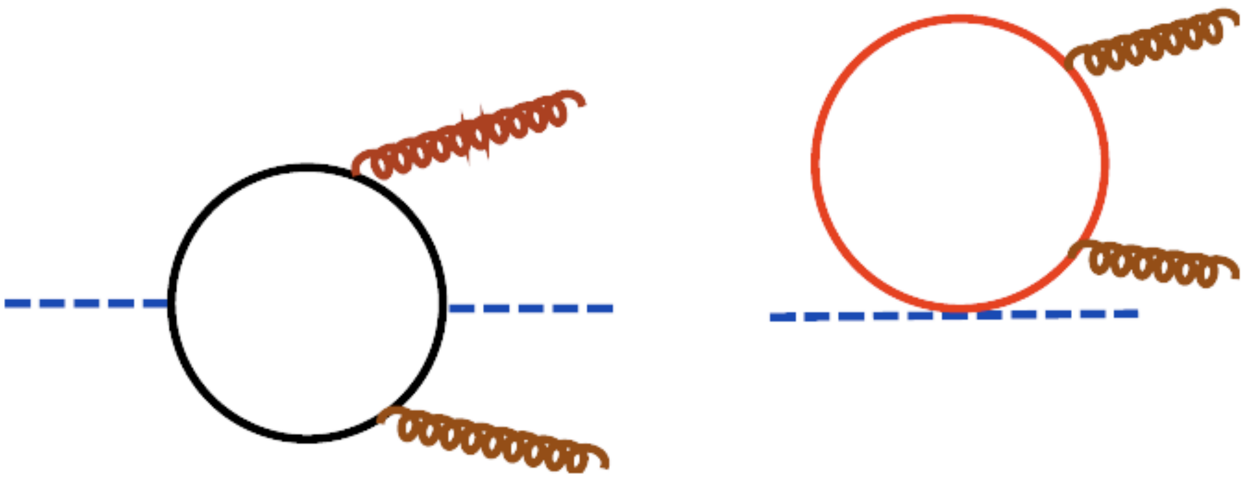


$$-\frac{3}{8\pi^2}\left|\lambda_t\right|^2\Lambda_{NP}^2 \qquad -\frac{3}{8\pi^2}\left(-M_T\frac{\lambda_T}{f}\right)\Lambda_{NP}^2$$

Such cancelations can be passed onto the gluon fusion cross-section *(Rattazzi, Low; Falkowski)*

Cancelation and gluon fusion

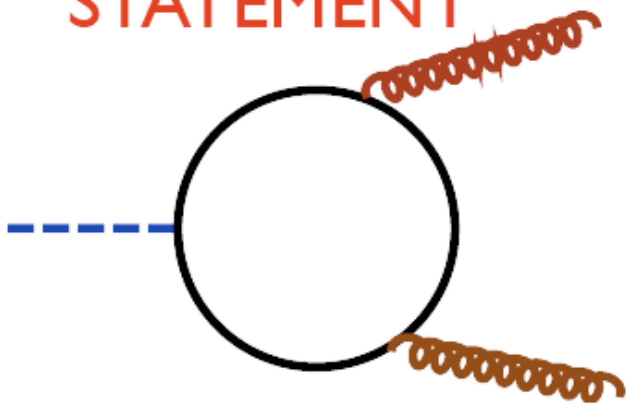
Low,Rattazi

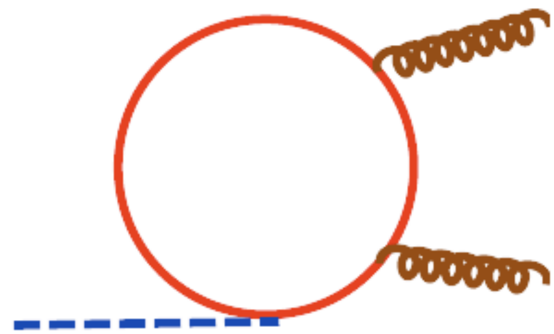


ADDING TWO GLUONS DOES NOT CHANGE THE RELATIVE SIGN

Cancelation also in gluon fusion

MODEL INDEPENDENT STATEMENT





ADDING TWO GLUONS DOES NOT CHANGE THE RELATIVE SIGN

(Take momentum of second Higgs to zero)

Natural MSSM

Low, Rattazi; Dermisek, Low; Cho; Kitano, Nomura; Perelstein;...

- A light stop quark is required to cut-off the quadratic divergence from the top-loop.
- The second stop quark must be heavier, as it is required from the LEP bound on the Higgs mass.

LHC Olympics...

@Zurich!

- Can we compute the gluon fusion cross-section in the toughest BSM scenario that we can think of?
- Are known multi-loop methods up to the task?
- How well do we understand field theory aspects of new models and their symmetries which are relevant at higher orders? Renormalization?

LHC Olympics...

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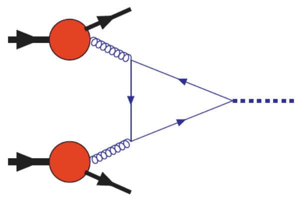
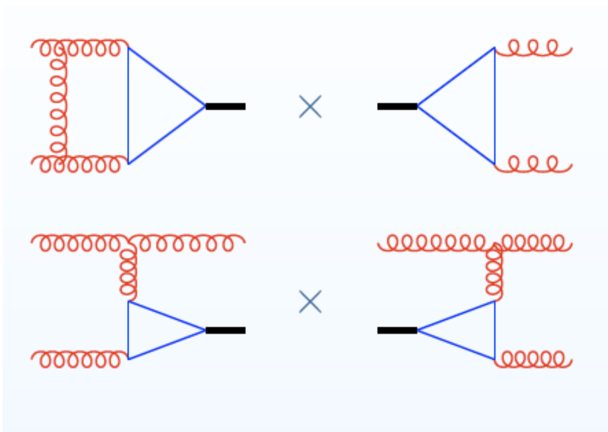
How tough was the SM?

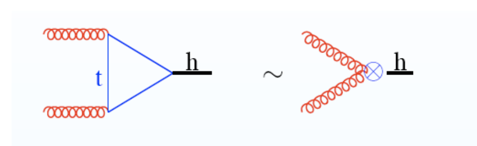


Starting with a loop
already at leading order!



A really tough two-loop
calculation at NLO.
Pioneering work by Spira,
Djouadi, Gradenz, Zerwas.
Large: (70-100%) x LO
(Spira et al, Dawson)

NNLO only in the heavy top
approximation



How tough is BSM?

- New colored and massive particles will circulate in the gluon-fusion loops
- Very heavy ones may decouple (not always)
- For topologically equivalent Feynman diagrams, results can be lifted from (or be computed a la) SM.
- BSM models can though be more complicated....

MSSM: a computing nightmare

- QCD corrections should be large
- More than one massive particles may circulate in the loops.
- Consistent regularization/renormalization
- A challenge for any analytic computational method already at NLO
- Disparate mass-scales e,g, Mbottom, Mhiggs, Mgluino

First attempts

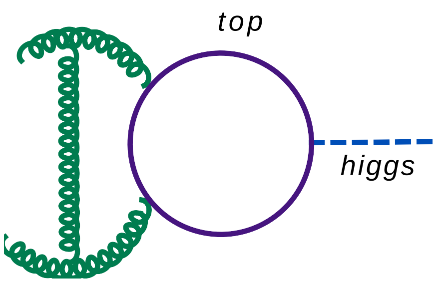
- Effective Theory at NLO for light Higgs boson with respect to quarks, squarks and gluino. Harlander, Steinhauser
- Effective Theory is not valid for a heavy Higgs, large tanb.
- Two-loop amplitude with squarks and quarks only. CA, Beerli, Bucherer, Daleo, Kunszt; Aglieti, Bonciani, Degrassi, Vicini
- NLO cross-section with squark and quarks only Muhlleitner, Spira; Bonciani, Degrassi, Vicini

Numerical N...LO fully differential cross-sections

Lazopoulos, Melnikov, Petriello; CA, Beerli, Daleo

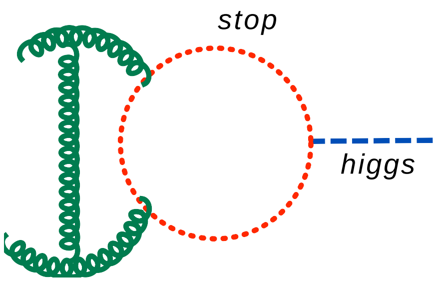
- Works in dimensional regularization and uses sector decomposition to disentangle overlapping singularities *(Binoth, Heinrich;Denner,Roth,Hepp)*
- Infrared divergences in phase-space integrals are found and simplified automatically. Integration boundaries are arbitrary *(CA, Melnikov, Petriello)*.
- Loop amplitudes are computed in the physical region. NEW: automated contour (*Nagy,Soper*) deformation to avoid threshold singularities.

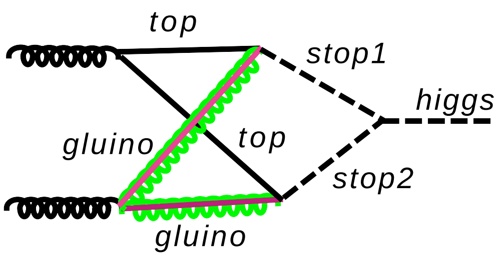
SUSY gluon fusion amplitude



Spira, Djouadi, Graudez, Zerwas

CA, Beerli, Bucherer,Daleo, Kunszt
Aglieti,Bonciani,Degrassi,Vicini
Spira, Muhlleitner

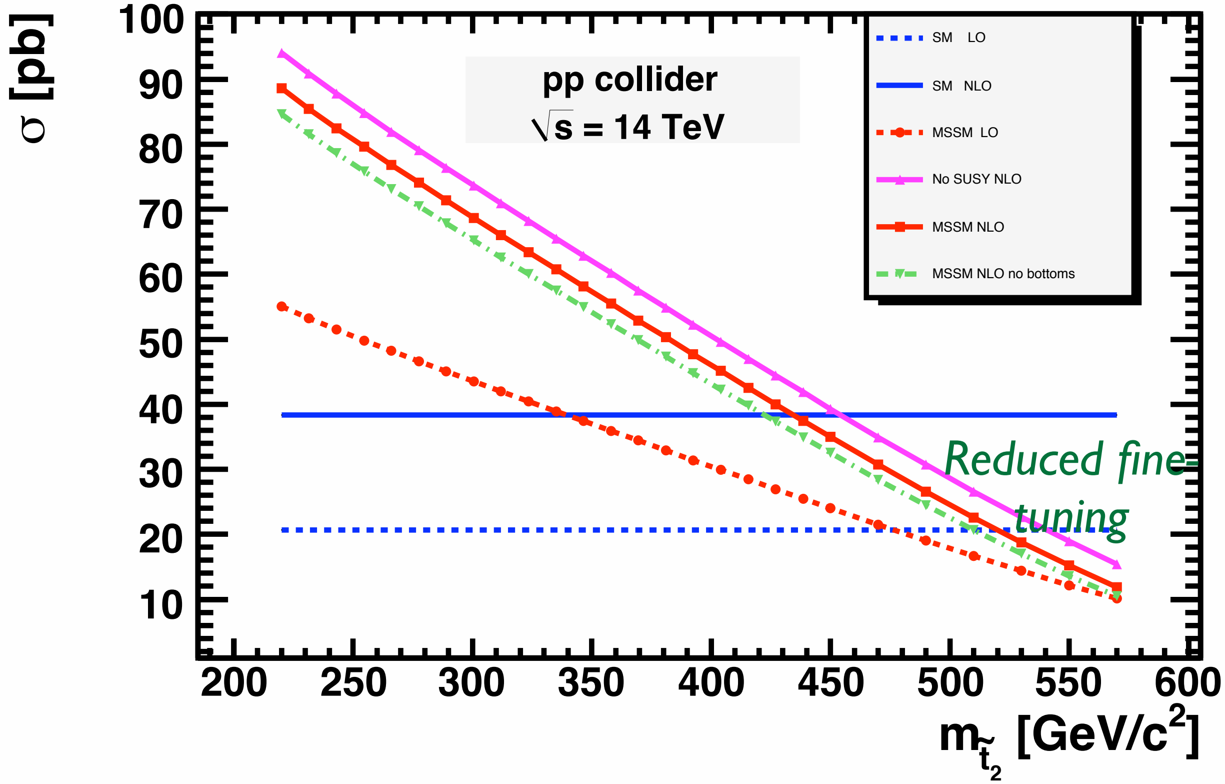




CA, Beerli, Daleo

New numerical method for multi-loop amplitudes

NLO Higgs cross-section in the MSSM



First complete computation of the gluon fusion cross-section at NLO in the MSSM

CA, Beerli, Bucherer, Daleo, Kunszt

Some more effort is required for precise NNLO MSSM or BSM Higgs phenomenology

Back to the SM!

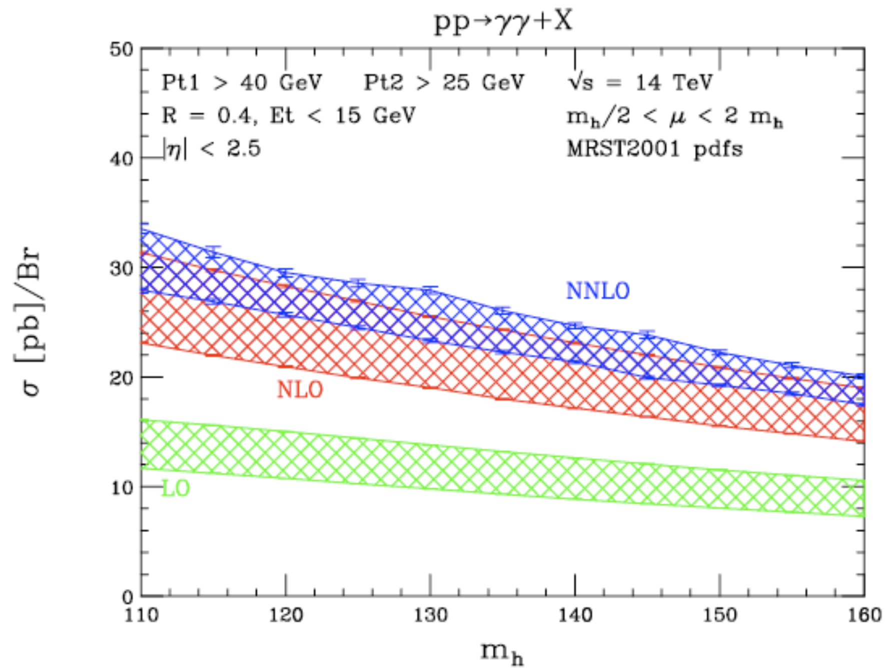
- Include all known effects at the 10% level (pdf, alphas, EWK corrections)
- Full description of kinematics. A total cross-section is too little information, and often misleading!

Fully differential NNLO cross-sections

- New methods for fully differential cross-sections at NNLO
- Two independent Monte-Carlo programs with a different treatment of infrared radiation at NNLO
- \- $pp \to H+X$ CA, Melnikov, Petriello (04)
  \- $pp \to H+X \to \gamma\gamma+X$ CA, Melnikov, Petriello (04), Catani, Grazzini (07)
  \- $pp \to H+X \to WW+X \to ll\nu\nu+X$ CA, Dissertori, Stoeckli (07), Grazzini (08)
  \- $pp \to H+X \to ZZ+X \to ll\nu\nu+X$ Grazzini (08)
- Realistic studies of accepted cross-sections after cuts for all basic channels
- Validation against MC@NLO and Herwig for the acceptances of cuts which are envisaged at the LHC. CA, Dissertori, Stoeckli, Webber (08)
- Studies for the Tevatron search CA, Dissertori, Grazzini, Stoeckli, Webber (09)

The di-photon signal

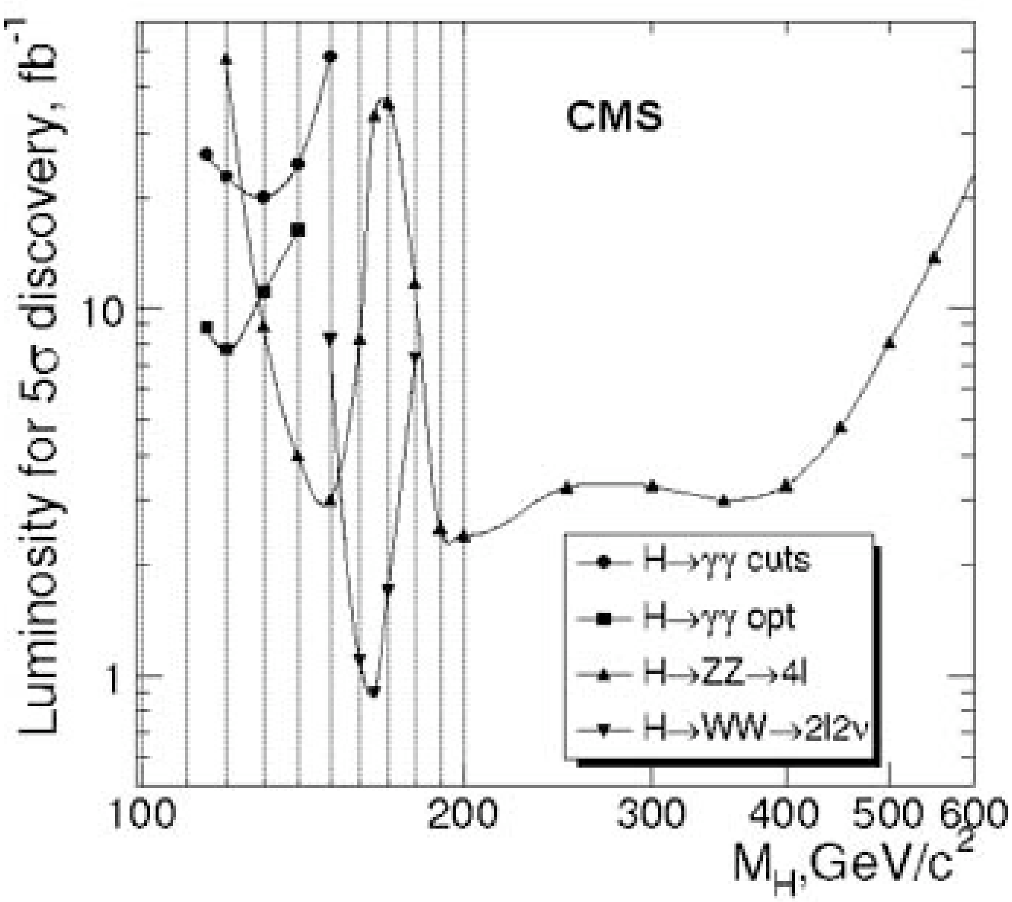
- pp→H+X→γγ+X *CA, Melnikov, Petriello*



All cuts envisaged from CMS/ ATLAS applied

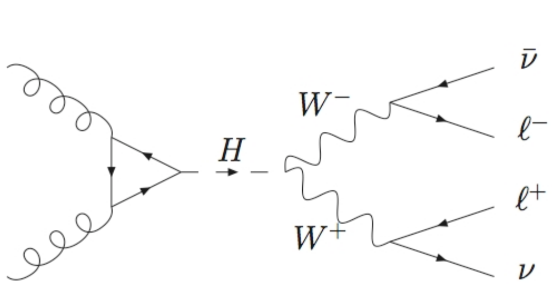
$$\sigma\left(\mu = 2M_h\right) \;=\; \mathrm{LO}\left(1 + 0.9 + 0.35\right)$$
$$\sigma\left(\mu = M_h/2\right) \;=\; \mathrm{LO}\left(1 + 0.75 + 0.13\right)$$

Higgs boson discovery in the WW channel

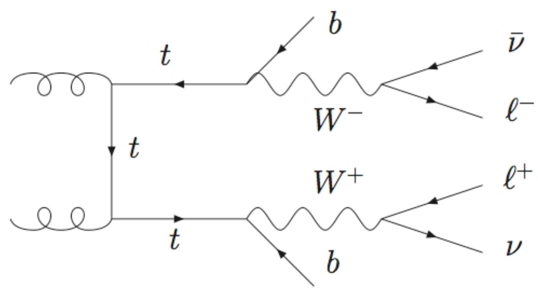


For a Higgs mass ~2 m_W the H→WW channel is dominant BR(H→WW)~1

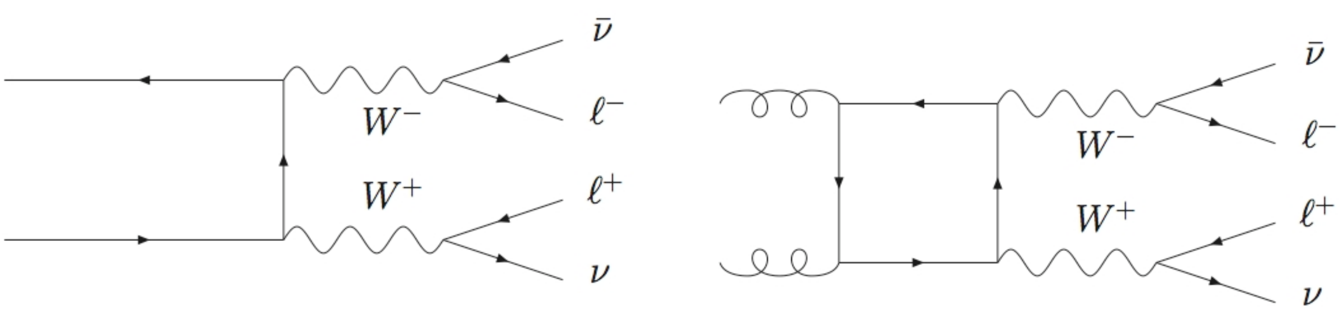
Signal and background



Gluon fusion signal



Top pair background



Direct W-pair production

WW channel

After trigger and some basic cuts on the leptons:

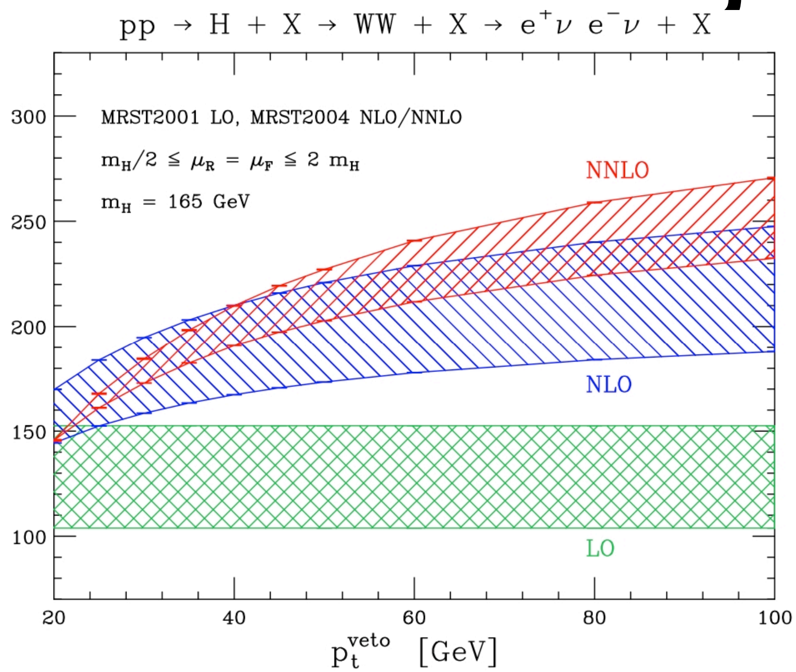
process	m_H=165 GeV	tt	qq→WW	gg→WW
σ [pb]	0.4	15.7	1.4	0.1

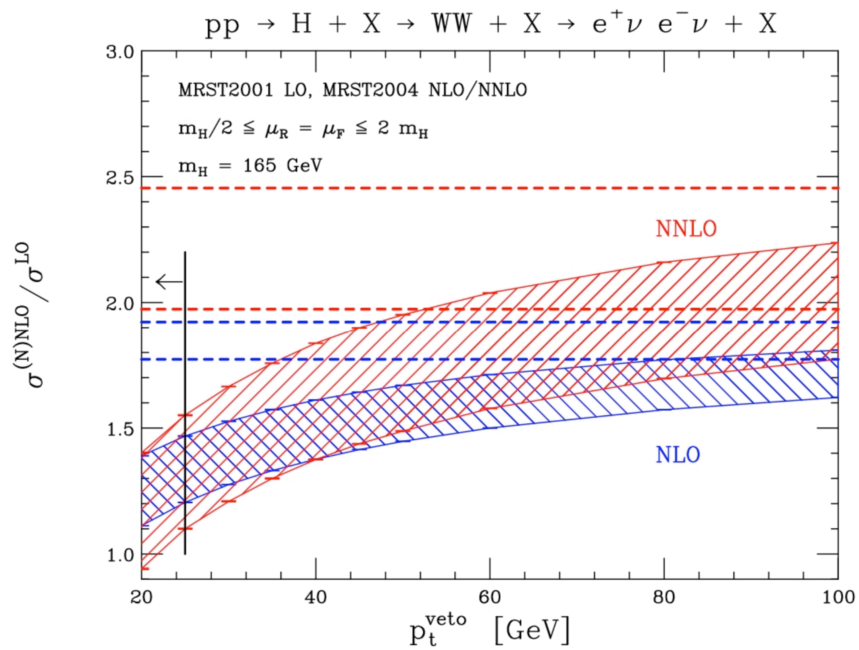
After signal selection cuts (jet-veto, lepton angle, missing energy, ...):

process	m_H=165 GeV	tt	qq→WW	gg→WW
σ [fb]	46	10	12	4

At what order in perturbation theory are these cut efficiencies accurately predicted?

Jet Veto





Jet-veto has no impact at LO

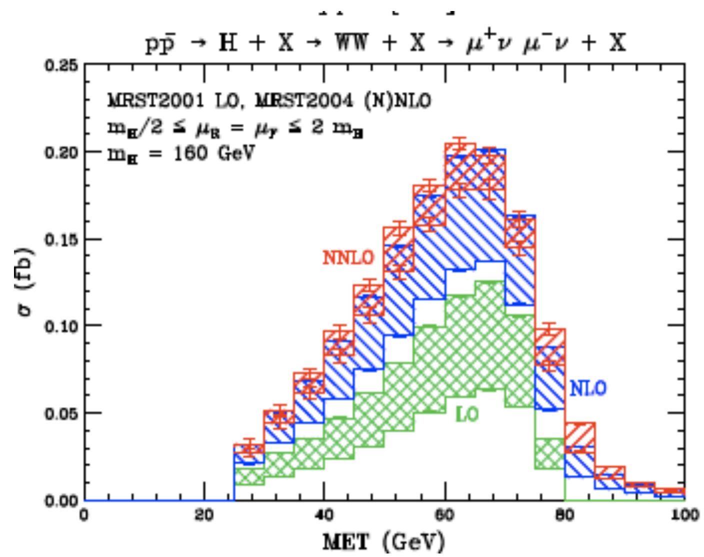
At NLO corresponds to a cut on the Higgs pt.

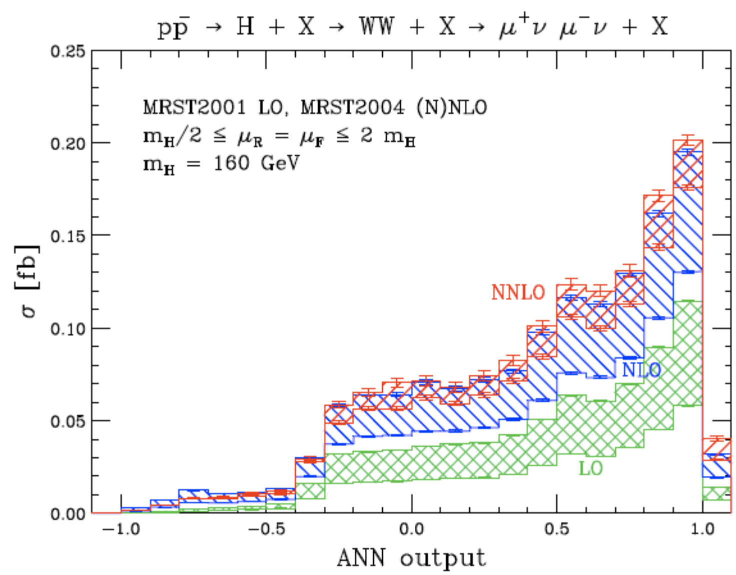
K-factors ($\sigma^{(N)NLO}/\sigma^{LO}$) depend heavily on cut-value

Inclusive K-factors would fail to predict the cross-section reliably

Cross-sections after jet-veto have a better perturbative series than the inclusive cross-section.

How detailed can be NNLO computations?





CA,Dissertori,Grazzini,Stoeckli,Webber

For the ongoing Tevatron analysis: various distributions including a Artificial Neural Network: using FEHiP and HNNLO

“Inclusive wrong impression”!

σ [fb]	LO (pdfs, α_s)	NLO (pdfs, α_s)	NNLO (pdfs, α_s)	
0-jets	$3.452^{+7\%}_{-10\%}$	$2.883^{+4\%}_{-9\%}$	$2.707^{+5\%}_{-9\%}$	66.5%
1-jet	$1.752^{+30\%}_{-26\%}$	$1.280^{+24\%}_{-23\%}$	$1.165^{+24\%}_{-22\%}$	28.6%
$\geq$ 2-jets	$0.336^{+91\%}_{-44\%}$	$0.221^{+81\%}_{-42\%}$	$0.196^{+78\%}_{-41\%}$	4.9%

NNLO scale variation: $\pm 14\%$

Jet binning and multiplicity dependent analysis

$$\frac{\Delta N_{\text{signal}}(\text{scale})}{N_{\text{signal}}} = 60\% \cdot \binom{+5\%}{-9\%} + 29\% \cdot \binom{+24\%}{-22\%} + 11\% \cdot \binom{+78\%}{-41\%} = \binom{+18.5\%}{-16.3\%}$$

$$\frac{\Delta N_{\text{signal}}(\text{scale})}{N_{\text{signal}}} = 60\% \cdot \binom{+5\%}{-9\%} + 29\% \cdot \binom{+24\%}{-23\%} + 11\% \cdot \binom{+91\%}{-44\%} = \binom{+20.0\%}{-16.9\%}$$

CA, Dissertori, Grazzini, Stoeckli, Webber

Conclusions

- Natural theories tend to have a light spectrum of new particles
- Light colored particles may change significantly the gluon fusion cross-sections
- Cutting edge methods are required to compute BSM effects.
- QCD corrections are important through NNLO.
- Higher order corrections are not just a “K-factor”
- The Higgs boson can be more interesting than its mass!