Precision Physics and the BEH boson

Fabio Maltoni
Center for Particle Physics and Phenomenology (CP3)
Université Catholique de Louvain

A simple plan

- Precision QCD
- LHC BEH pheno in a nutshell

Anatomy of pp→Higgs at NLO

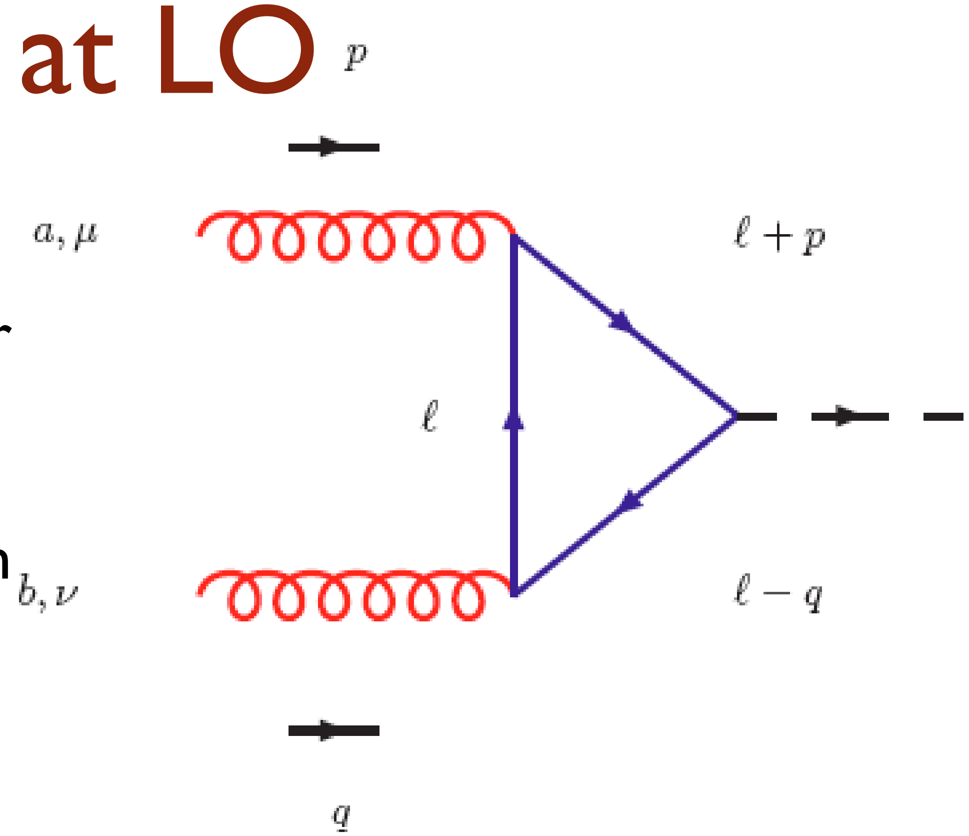
- LO : 1-loop calculation and HEFT
- NLO in the HEFT
  - Virtual corrections and renormalization
  - Real corrections and IS singularities
- Cross sections at the LHC

pp→H at LO

This is a "simple" 2→1 process.

However, at variance with pp→W, the LO order process already proceeds through a loop.

In this case, this means that the loop calculation has to give a finite result!



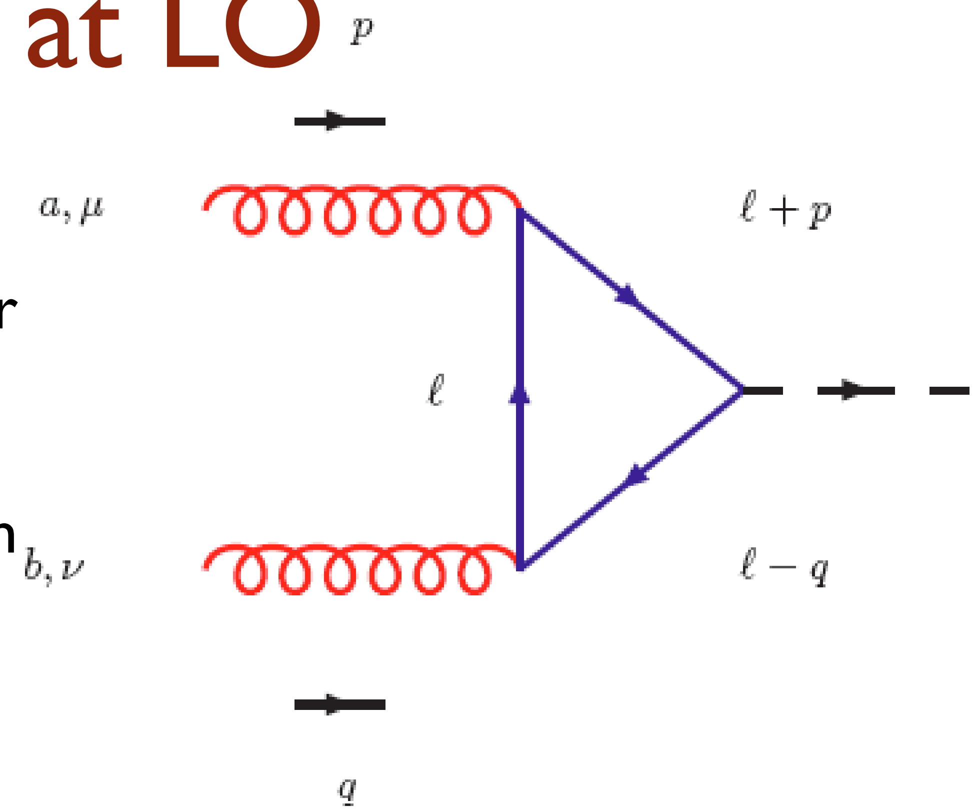
pp→H at LO

This is a "simple" 2→1 process.

However, at variance with pp→W, the LO order process already proceeds through a loop.

In this case, this means that the loop calculation has to give a finite result!

Let's do the calculation!

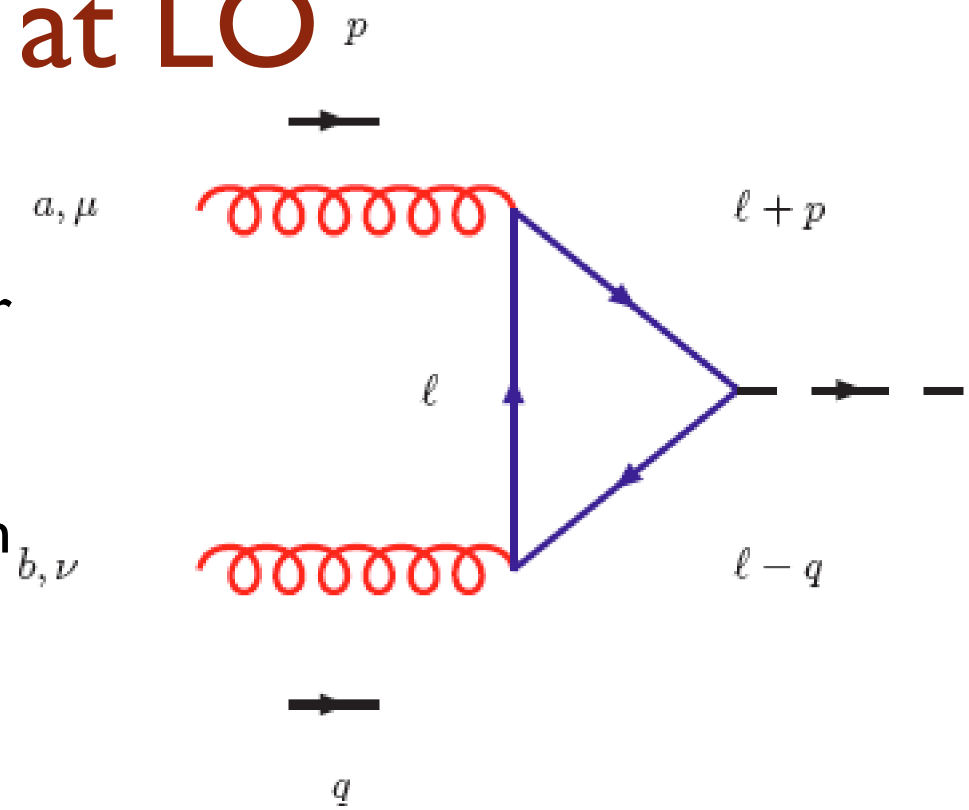


pp→H at LO

This is a "simple" 2→1 process.

However, at variance with pp→W, the LO order process already proceeds through a loop.

In this case, this means that the loop calculation has to give a finite result!



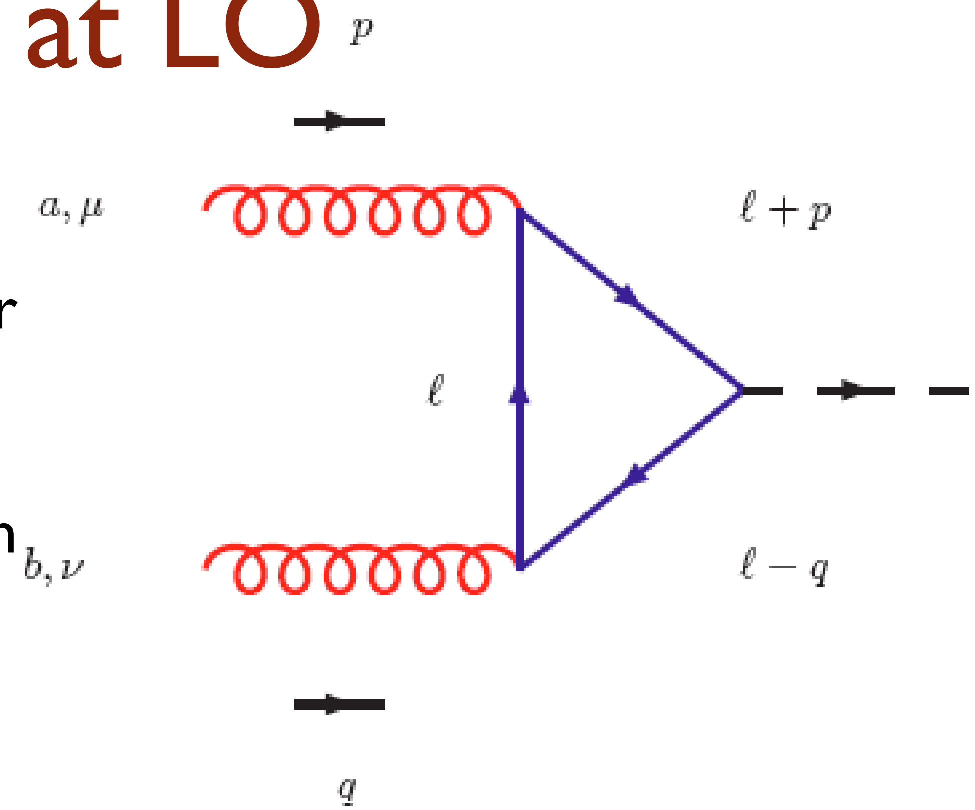
Let's do the calculation!

$$i\mathcal{A} = -(-ig_s)^2 \mathrm{Tr}(t^a t^b) \left(\frac{-im_t}{v} \right) \int \frac{d^d \ell}{(2\pi)^n} \frac{T^{\mu\nu}}{\mathrm{Den}} (i)^3 \epsilon_\mu(p) \epsilon_\nu(q)$$

where

$$\mathrm{Den} = (\ell^2 - m_t^2)[(\ell + p)^2 - m_t^2][(\ell - q)^2 - m_t^2]$$

pp→H at LO



This is a "simple" 2→1 process.

However, at variance with pp→W, the LO order process already proceeds through a loop.

In this case, this means that the loop calculation has to give a finite result!

Let's do the calculation!

$$i\mathcal{A} = -(-ig_s)^2 \mathrm{Tr}(t^a t^b)\left(\frac{-im_t}{v}\right)\int \frac{d^d\ell}{(2\pi)^n}\frac{T^{\mu\nu}}{\mathrm{Den}}(i)^3 \epsilon_\mu(p)\epsilon_\nu(q)$$

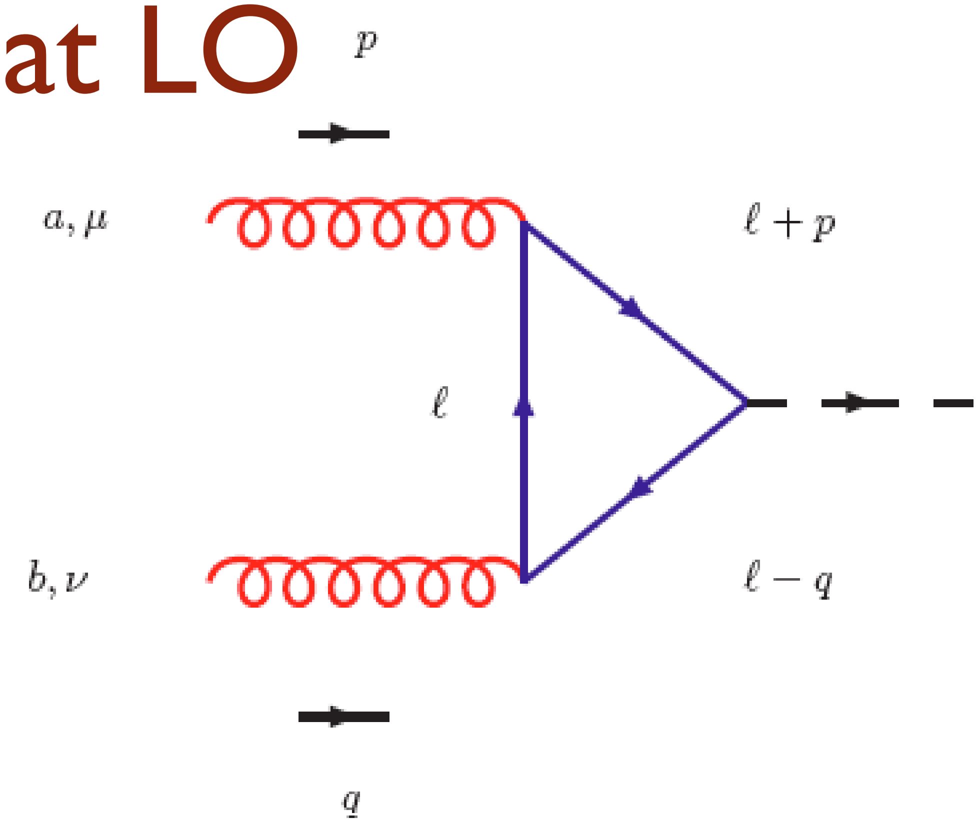
where

$$\mathrm{Den} = (\ell^2 - m_t^2)[(\ell+p)^2 - m_t^2][(\ell-q)^2 - m_t^2]$$

We combine the denominators into one by using $\frac{1}{ABC} = 2\int_0^1 dx \int_0^{1-x} \frac{dy}{[Ax + By + C(1-x-y)]^3}$

$$\frac{1}{\mathrm{Den}} = 2\int dx\ dy \frac{1}{[\ell^2 - m_t^2 + 2\ell\cdot(px - qy)]^3}.$$

pp→H at LO



$$\int \frac{d^dk}{(2\pi)^d}\frac{k^2}{(k^2-C)^3} = \frac{i}{32\pi^2}(4\pi)^\epsilon \frac{\Gamma(1+\epsilon)}{\epsilon}(2-\epsilon)C^{-\epsilon}$$

$$\int \frac{d^dk}{(2\pi)^d}\frac{1}{(k^2-C)^3} = -\frac{i}{32\pi^2}(4\pi)^\epsilon \Gamma(1+\epsilon)C^{-1-\epsilon}.$$

where d=4-2eps. By substituting we arrive at a very simple final result!!

$$\mathcal{A}(gg\to H) = -\frac{\alpha_S m_t^2}{\pi v}\delta^{ab}\left(g^{\mu\nu}\frac{M_H^2}{2} - p^\nu q^\mu\right)\int dxdy\left(\frac{1-4xy}{m_t^2 - m_H^2 xy}\right)\epsilon_\mu(p)\epsilon_\nu(q).$$

Comments:

* The final dependence of the result is mt^2 : one from the Yukawa coupling, one from the spin flip.
* The tensor structure could have been guessed by gauge invariance.
* The integral depends on mt and mh.

LO cross section

$$\sigma(pp \to H) = \int_{\tau_0}^{1} dx_1 \int_{\tau_0/x_1}^{1} dx_2\, g(x_1,\mu_f) g(x_2,\mu_f)\, \hat{\sigma}(gg \to H)$$

$$x_1 \equiv \sqrt{\tau} e^{y} \quad x_2 \equiv \sqrt{\tau} e^{-y} \quad \tau = x_1 x_2 \qquad \tau_0 = M_H^2/S \quad z = \tau_0/\tau$$

$$= \frac{\alpha_S^2}{64\pi v^2} \mid I\left(\frac{M_H^2}{m^2}\right) \mid^2 \tau_0 \int_{\log\sqrt{\tau_0}}^{-\log\sqrt{\tau_0}} dy g(\sqrt{\tau_0} e^{y}) g(\sqrt{\tau_0} e^{-y})$$

The hadronic cross section can be expressed a function of the gluon-gluon luminosity.

LO cross section

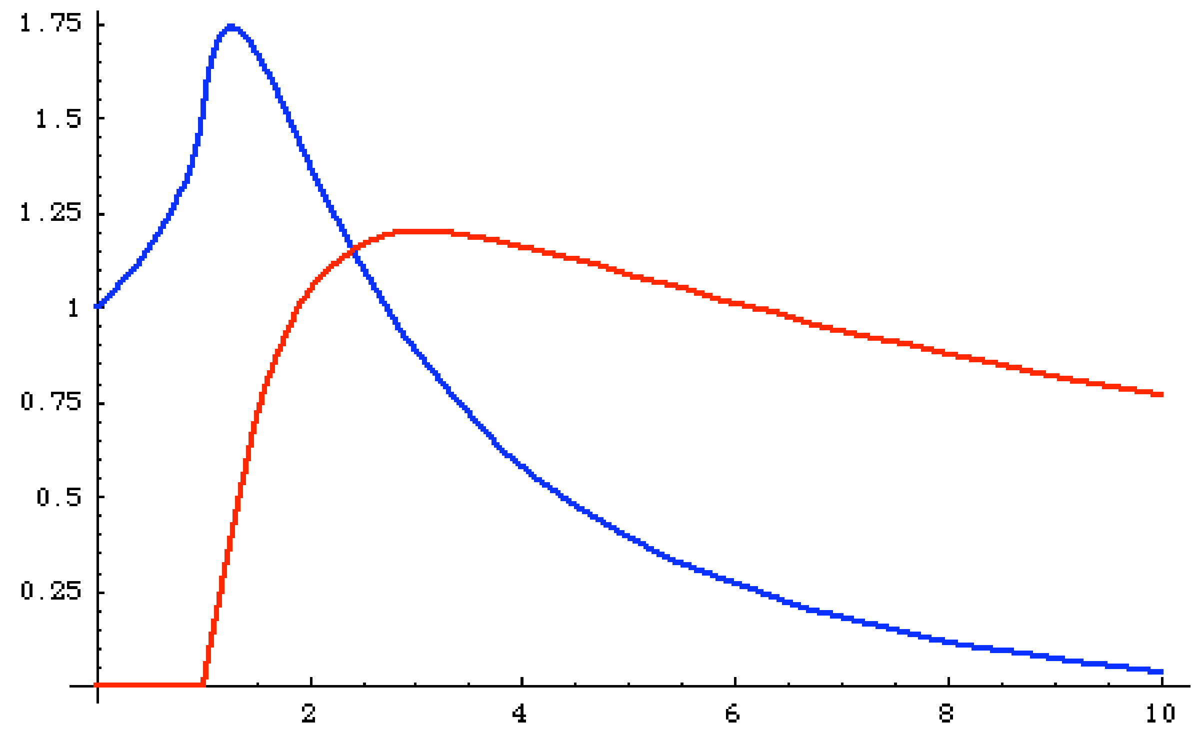
$$\sigma(pp \to H) = \int_{\tau_0}^{1} dx_1 \int_{\tau_0/x_1}^{1} dx_2\, g(x_1,\mu_f) g(x_2,\mu_f)\, \hat{\sigma}(gg \to H)$$

$$x_1 \equiv \sqrt{\tau} e^{y} \quad x_2 \equiv \sqrt{\tau} e^{-y} \quad \tau = x_1 x_2 \qquad \tau_0 = M_H^2/S \quad z = \tau_0/\tau$$

$$= \frac{\alpha_S^2}{64\pi v^2} \mid I\left(\frac{M_H^2}{m^2}\right) \mid^2 \tau_0 \int_{\log\sqrt{\tau_0}}^{-\log\sqrt{\tau_0}} dy g(\sqrt{\tau_0}e^{y}) g(\sqrt{\tau_0}e^{-y})$$

The hadronic cross section can be expressed a function of the gluon-gluon luminosity.

I(x) has both a real and imaginary part, which develops at mh=2mt.



LO cross section

$$\sigma(pp \to H) = \int_{\tau_0}^{1} dx_1 \int_{\tau_0/x_1}^{1} dx_2\, g(x_1,\mu_f) g(x_2,\mu_f)\, \hat{\sigma}(gg \to H)$$

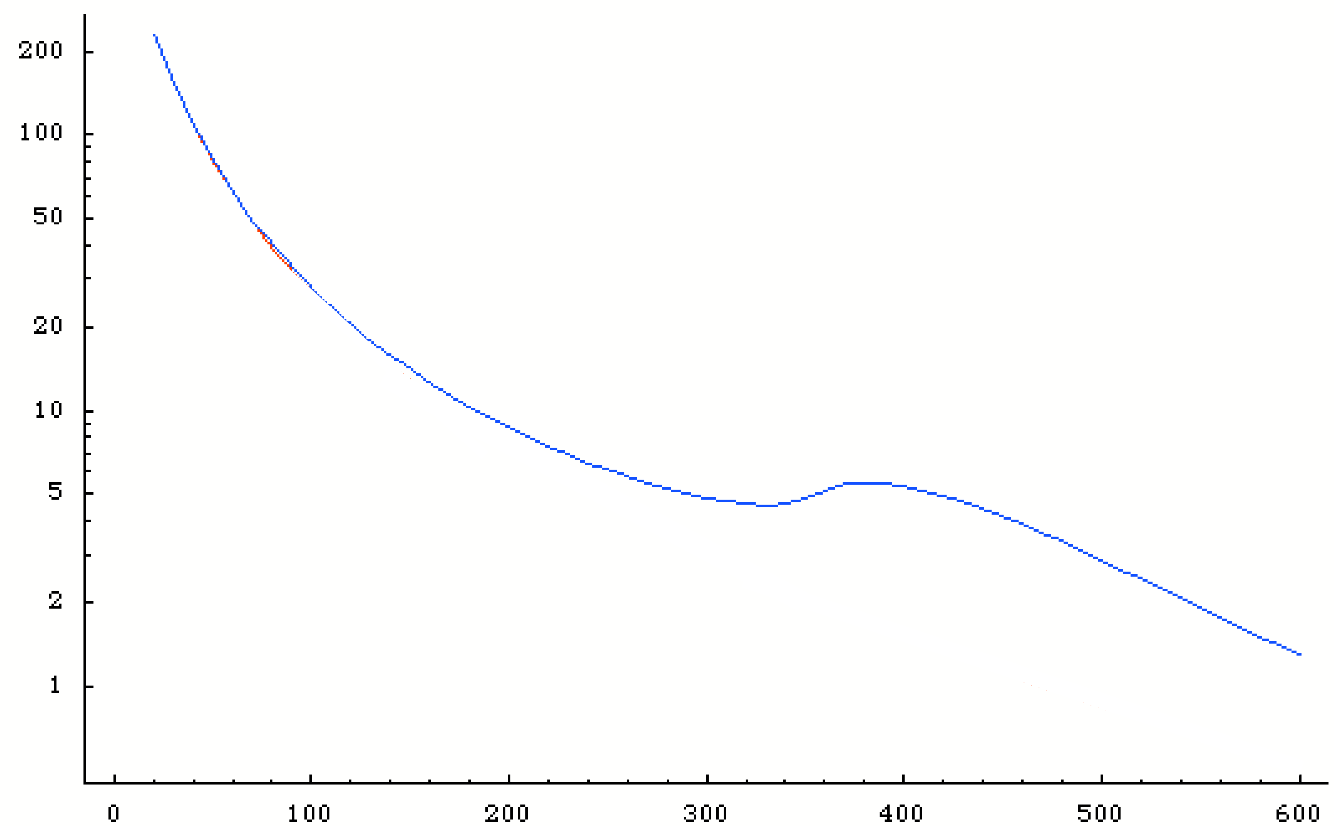
$$x_1 \equiv \sqrt{\tau} e^{y} \quad x_2 \equiv \sqrt{\tau} e^{-y} \quad \tau = x_1 x_2 \qquad \tau_0 = M_H^2/S \quad z = \tau_0/\tau$$

$$= \frac{\alpha_S^2}{64\pi v^2} \mid I\left(\frac{M_H^2}{m^2}\right) \mid^2 \tau_0 \int_{\log \sqrt{\tau_0}}^{-\log \sqrt{\tau_0}} dy g(\sqrt{\tau_0} e^{y}) g(\sqrt{\tau_0} e^{-y})$$

The hadronic cross section can be expressed a function of the gluon-gluon luminosity.

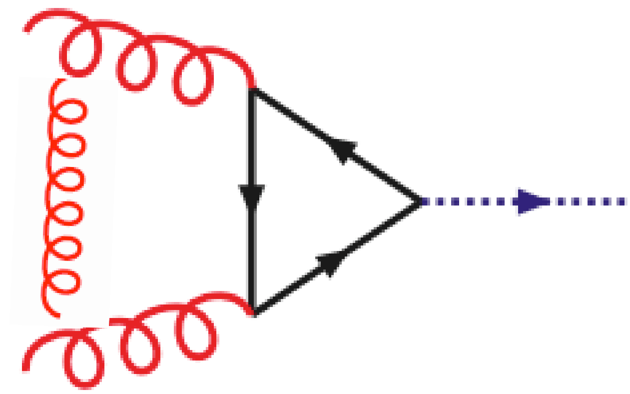
I(x) has both a real and imaginary part, which develops at mh=2mt.

This causes a bump in the cross section.



pp → H @ NLO

At NLO we have to include an extra parton (virtual or real).

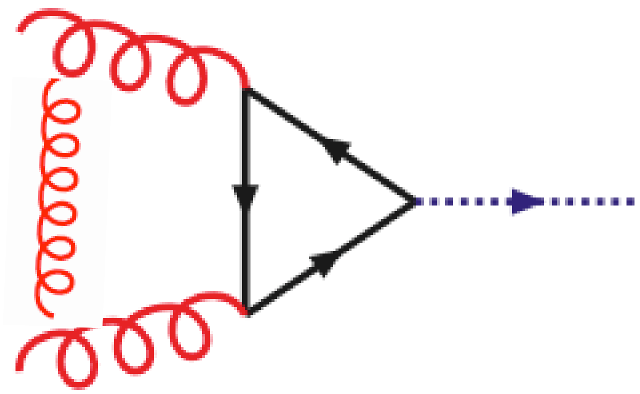


The virtuals will become a two-loop calculation!!

Can we avoid that?

pp →H @ NLO

At NLO we have to include an extra parton (virtual or real).



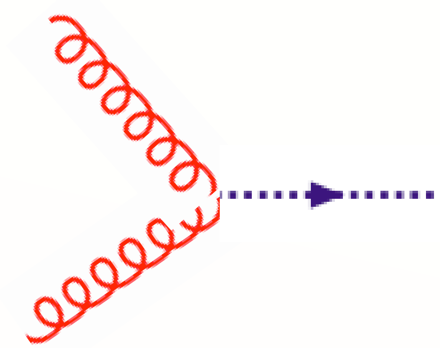
The virtuals will become a two-loop calculation!!

Can we avoid that?

Let's consider the case where the Higgs is light:

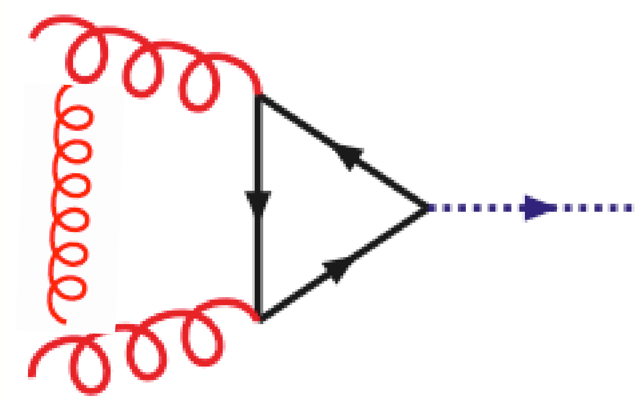
$$\mathcal{A}(gg \to H) = -\frac{\alpha_S m_t^2}{\pi v}\delta^{ab}\left(g^{\mu\nu}\frac{M_H^2}{2} - p^\nu q^\mu\right)\int dxdy\left(\frac{1-4xy}{m_t^2 - m_H^2 xy}\right)\epsilon_\mu(p)\epsilon_\nu(q).$$

$$\stackrel{m \gg M_H}{\longrightarrow} \; -\frac{\alpha_S}{3\pi v}\delta^{ab}\left(g^{\mu\nu}\frac{M_H^2}{2} - p^\nu q^\mu\right)\epsilon_\mu(p)\epsilon_\nu(q).$$



pp → H @ NLO

At NLO we have to include an extra parton (virtual or real).



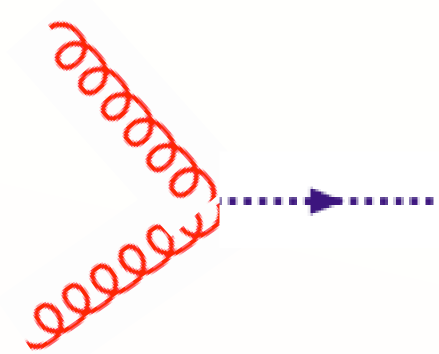
The virtuals will become a two-loop calculation!!

Can we avoid that?

Let's consider the case where the Higgs is light:

$$\mathcal{A}(gg \to H) = -\frac{\alpha_S m_t^2}{\pi v}\delta^{ab}\left(g^{\mu\nu}\frac{M_H^2}{2} - p^\nu q^\mu\right)\int dxdy\left(\frac{1-4xy}{m_t^2 - m_H^2 xy}\right)\epsilon_\mu(p)\epsilon_\nu(q).$$

$$\xrightarrow{m \gg M_H} -\frac{\alpha_S}{3\pi v}\delta^{ab}\left(g^{\mu\nu}\frac{M_H^2}{2} - p^\nu q^\mu\right)\epsilon_\mu(p)\epsilon_\nu(q).$$



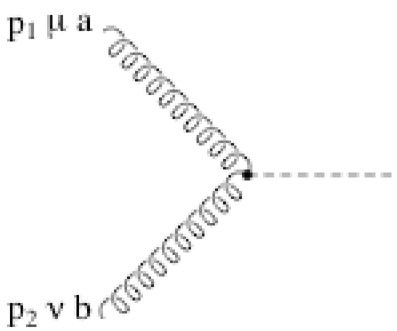
This looks like a local vertex, ggH.

The top quark has disappeared from the low energy theory but it has left something behind (non-decoupling).

Higgs effective field theory

$$\mathcal{L}_{\rm eff} = -\frac{1}{4}\left(1-\frac{\alpha_S}{3\pi}\frac{H}{v}\right) G^{\mu\nu}G_{\mu\nu}$$

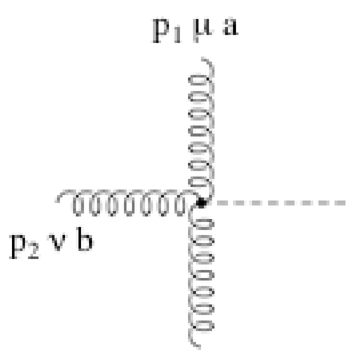
This is an effective non-renormalizable theory (no top) which describes the Higgs couplings to QCD.



(a)

$iA\delta^{ab}H^{\mu\nu}(p_1,p_2)$

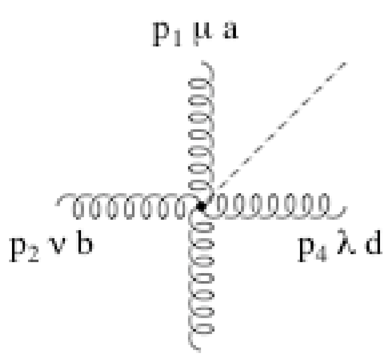
$$H^{\mu\nu}(p_1,p_2) = g^{\mu\nu}\,p_1\cdot p_2 - p_1^\nu p_2^\mu .$$



(b)

$-Agf^{abc}V^{\mu\nu\sigma}(p_1,p_2,p_3)$

$$V^{\mu\nu\rho}(p_1,p_2,p_3) = (p_1-p_2)^\rho g^{\mu\nu} + (p_2-p_3)^\mu g^{\nu\rho} + (p_3-p_1)^\nu g^{\rho\mu},$$



(c)

$-iAg^2X^{abcd}_{\mu\nu\sigma\lambda}$

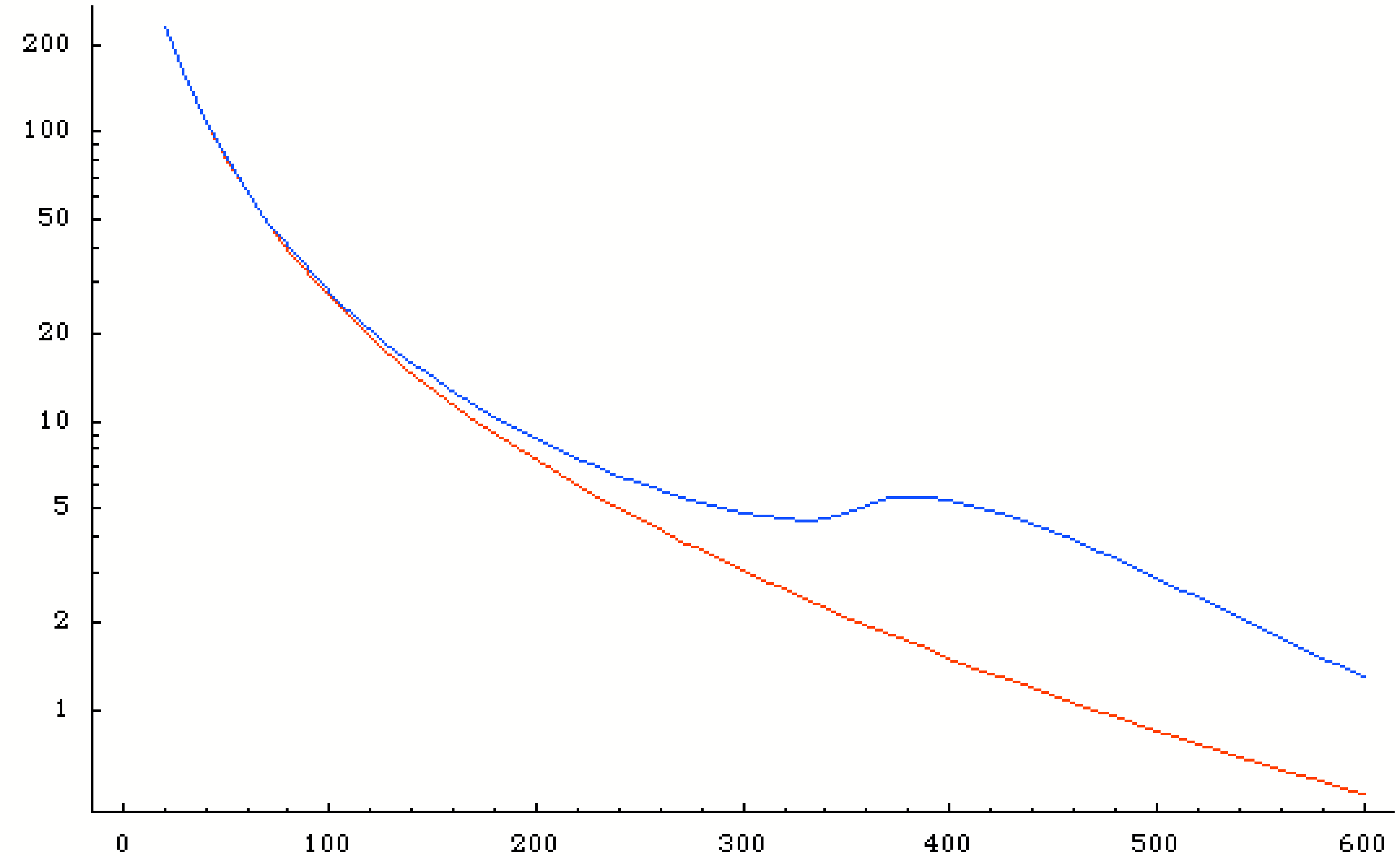
$$\begin{aligned} X^{\mu\nu\rho\sigma}_{abcd} &= f_{abe}f_{cde}(g^{\mu\rho}g^{\nu\sigma} - g^{\mu\sigma}g^{\nu\rho}) \\ &+ f_{ace}f_{bde}(g^{\mu\nu}g^{\rho\sigma} - g^{\mu\sigma}g^{\nu\rho}) \\ &+ f_{ade}f_{bce}(g^{\mu\nu}g^{\rho\sigma} - g^{\mu\rho}g^{\nu\sigma}). \end{aligned}$$

LO cross section: full vs HEFT

$$\sigma(pp \to H) = \int_{\tau_0}^{1} dx_1 \int_{\tau_0/x_1}^{1} dx_2\, g(x_1,\mu_f) g(x_2,\mu_f)\, \hat{\sigma}(gg \to H)$$

The accuracy of the calculation in the HEFT calculation can be directly assessed by taking the limit m→∞.

For light Higgs is better than 10%.

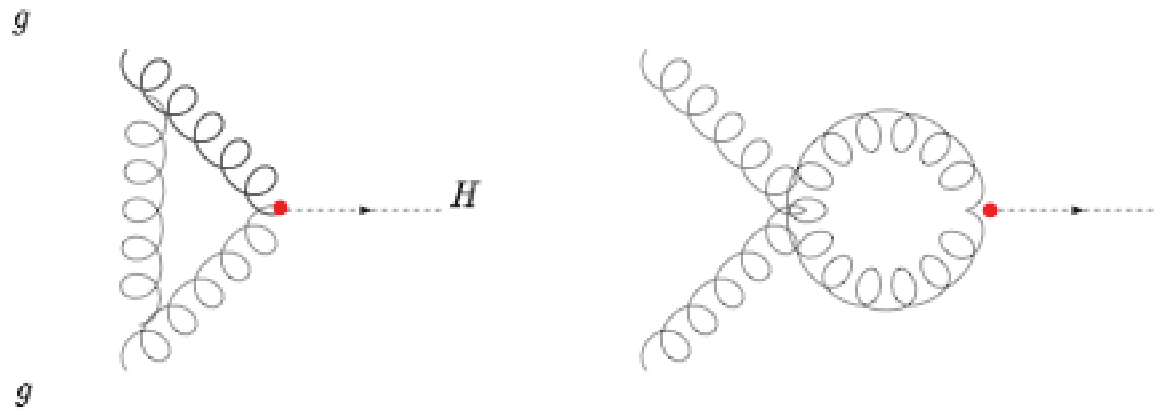


So, if we are interested in a light Higgs we use the HEFT and simplify our life.
If we do so, the NLO calculation becomes a standard 1-loop calculation, similar to Drell-Yan at NLO.

We can do it!!

Virtual contributions

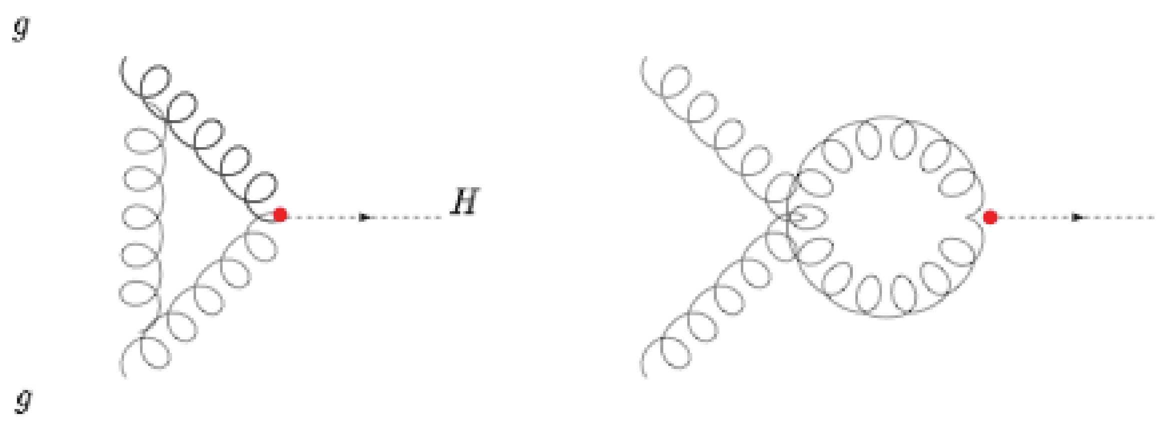
Virtual contributions



Out of 8 diagrams, only two are non-zero (in dimensional regularization), a bubble and a triangle.

They can be easily written down by hand.

Virtual contributions

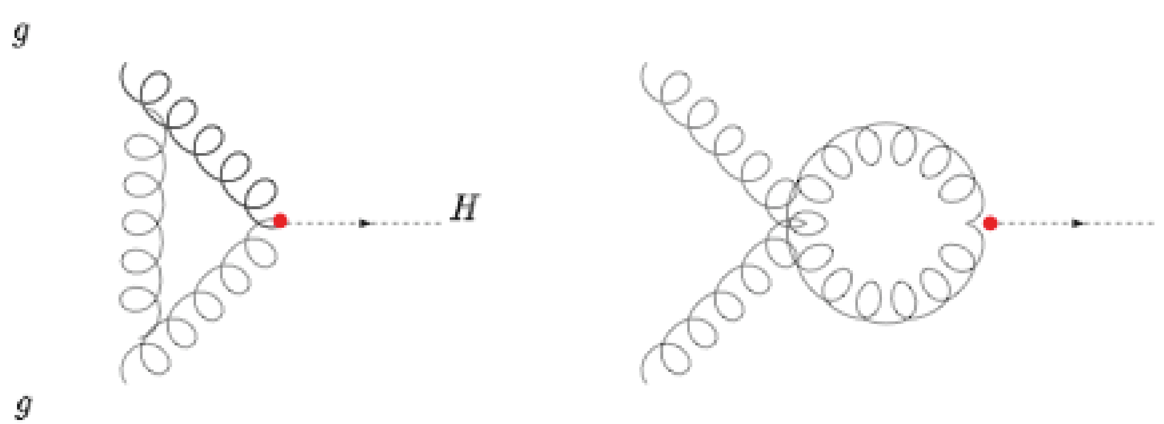


Out of 8 diagrams, only two are non-zero (in dimensional regularization), a bubble and a triangle.

They can be easily written down by hand.

Then the integration over the tensor decomposition into scalar integrals and loop integration has to be performed.

Virtual contributions



Out of 8 diagrams, only two are non-zero (in dimensional regularization), a bubble and a triangle.

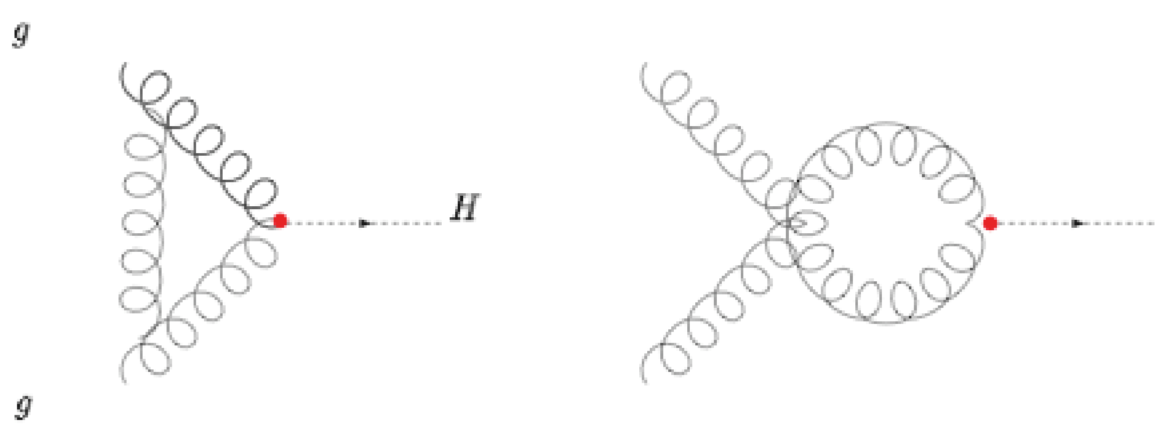
They can be easily written down by hand.

Then the integration over the tensor decomposition into scalar integrals and loop integration has to be performed.

$$\mathcal{L}_{\rm eff}^{\rm NLO} = \left(1 + \frac{11}{4}\frac{\alpha_S}{\pi}\right)\frac{\alpha_S}{3\pi}\frac{H}{v}G^{\mu\nu}G_{\mu\nu}$$

One also have to consider that the coefficient of the HEFT receive corrections which have to be included in the result.

Virtual contributions



Out of 8 diagrams, only two are non-zero (in dimensional regularization), a bubble and a triangle.

They can be easily written down by hand.

Then the integration over the tensor decomposition into scalar integrals and loop integration has to be performed.

One also have to consider that the coefficient of the HEFT receive corrections which have to be included in the result.

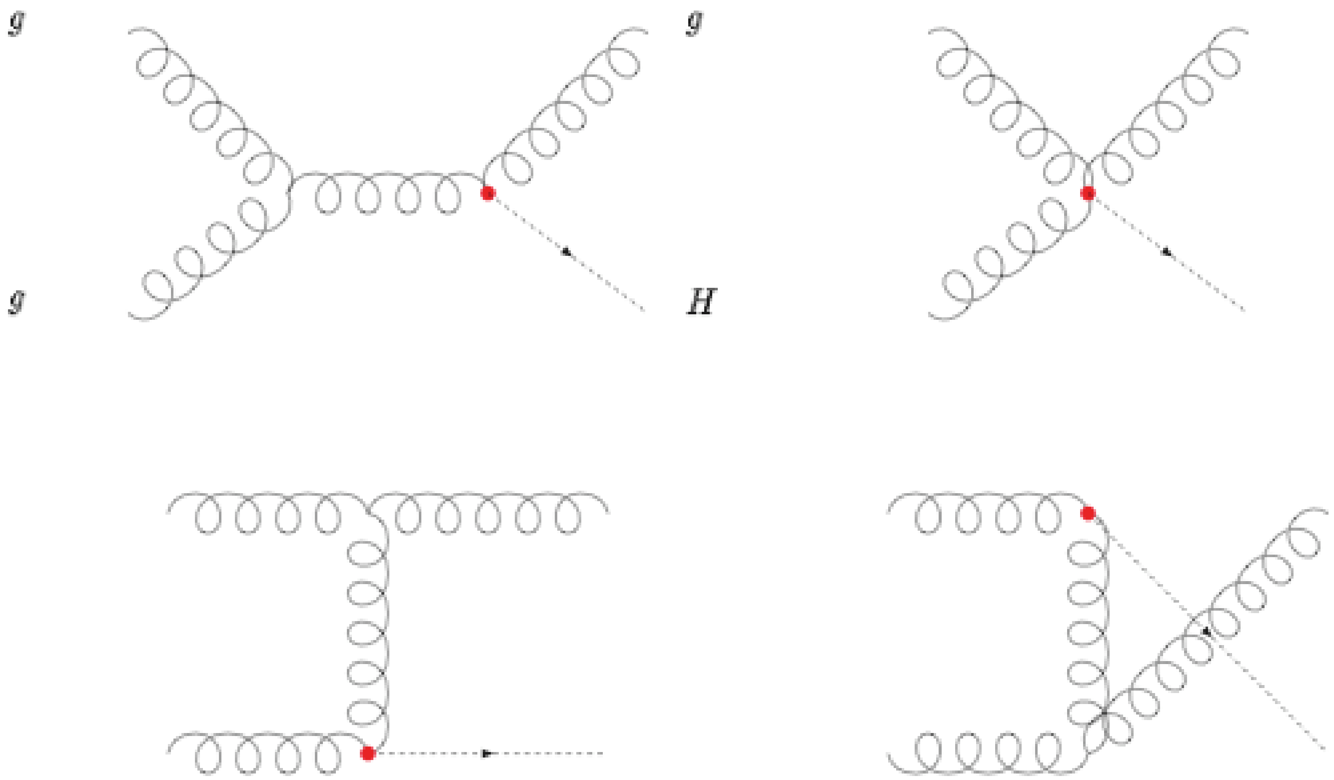
$$\mathcal{L}_{\rm eff}^{\rm NLO} = \left(1 + \frac{11}{4}\frac{\alpha_S}{\pi}\right)\frac{\alpha_S}{3\pi}\frac{H}{v}G^{\mu\nu}G_{\mu\nu}$$

The result is:

$$\sigma_{\rm virt} = \sigma_0\,\delta(1-z)\,\left[1 + \frac{\alpha_S}{2\pi}C_A\left(\frac{\mu^2}{m_H^2}\right)^{\epsilon} c_\Gamma\left(-\frac{2}{\epsilon^2} + \frac{11}{3} + \pi^2\right)\right],$$

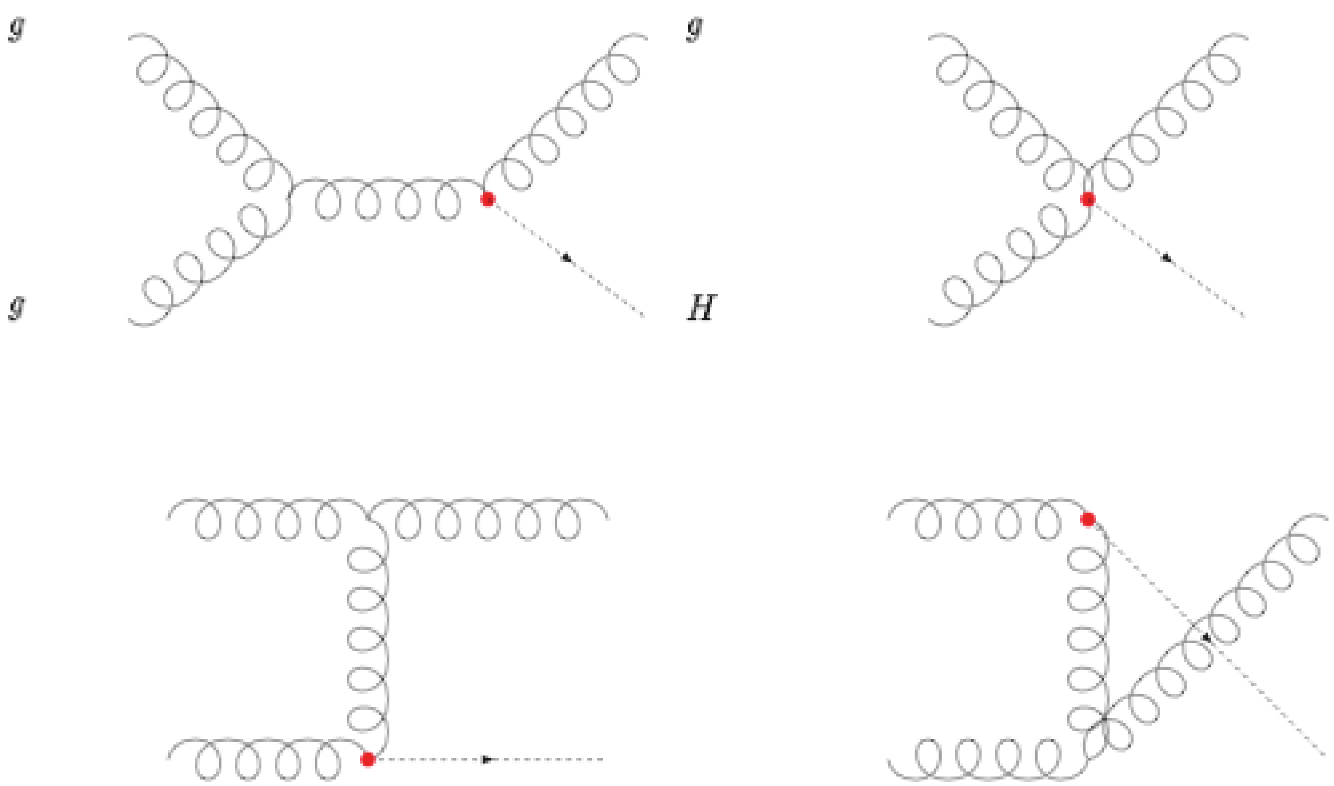
$$\sigma_{\rm Born} = \frac{\alpha_S^2}{\pi}\frac{m_H^2}{576 v^2 s}(1+\epsilon+\epsilon^2)\mu^{2\epsilon}\,\delta(1-z) \equiv \sigma_0\,\delta(1-z) \qquad z = m_H^2/s$$

Real contributions



This is the last piece: the result at the end must be finite!

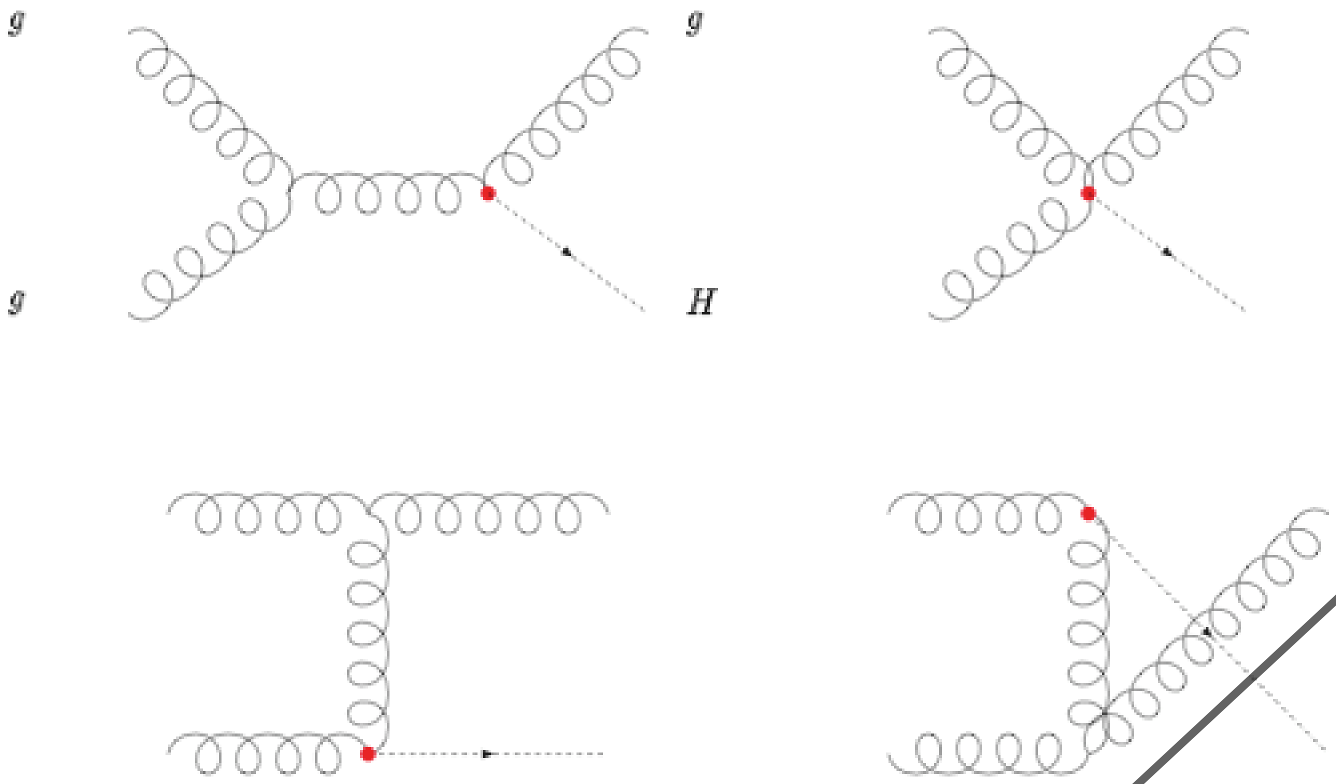
Real contributions



This is the last piece: the result at the end must be finite!

$$
\begin{aligned}
\sigma_{\rm real} \;=\;& \sigma_0 \frac{\alpha_S}{2\pi} C_A \left(\frac{\mu^2}{m_H^2}\right)^{\epsilon} c_\Gamma \left[\left(\frac{2}{\epsilon^2} + \frac{2}{\epsilon}\frac{b_0}{C_A} - \frac{\pi^2}{3} \right) \delta(1-z) \right. \\
& - \frac{2}{\epsilon} p_{gg}(z) - \frac{11}{3}\frac{(1-z)^3}{z} - 4 \frac{(1-z)^2(1+z^2)+z^2}{z(1-z)} \log z \\
& \left. + \, 4 \frac{1+z^4+(1-z)^4}{z} \left(\frac{\log(1-z)}{1-z} \right)_+ \right] .
\end{aligned}
$$

Real contributions

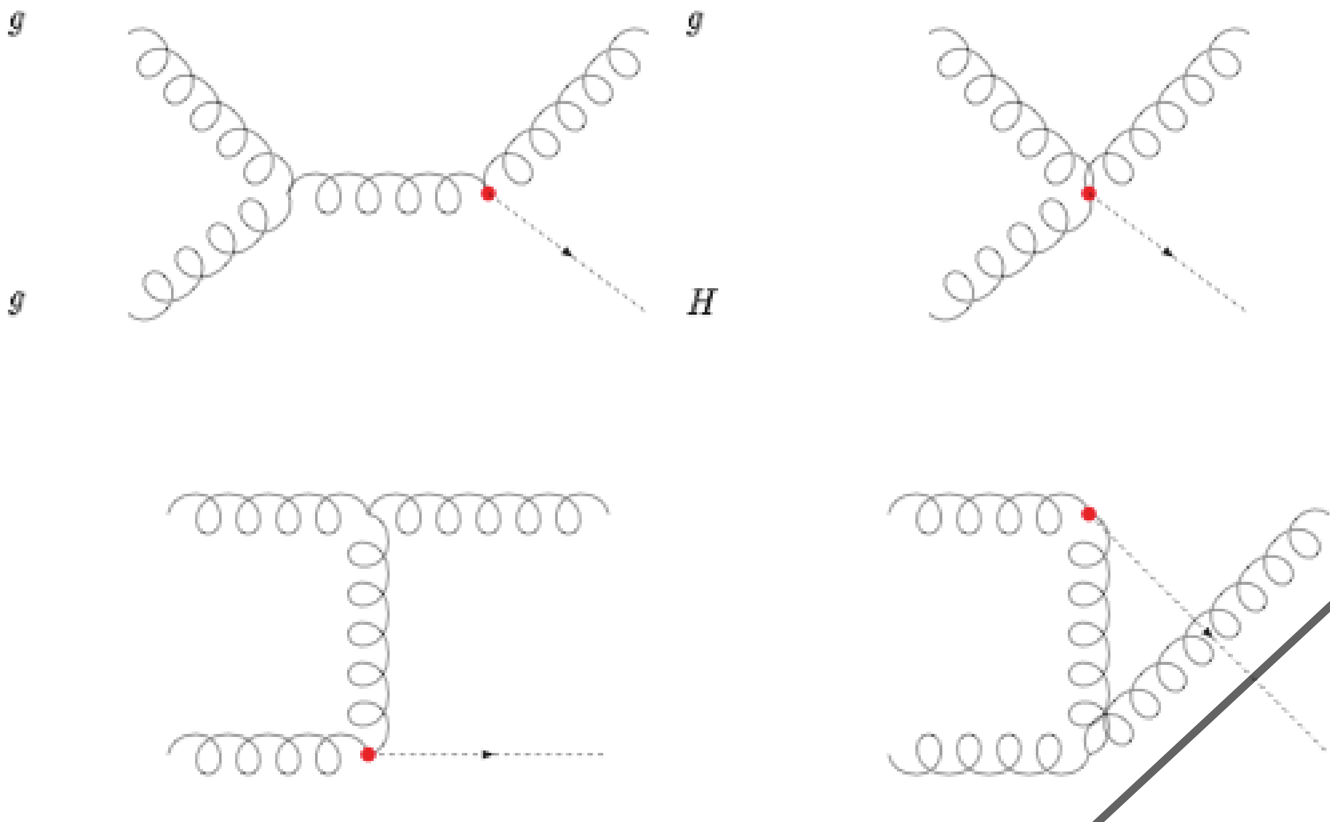


This is the last piece: the result at the end must be finite!

2/eps cancels with the virtual contribution ✓

$$\sigma_{\rm real} = \sigma_0 \frac{\alpha_S}{2\pi} C_A \left(\frac{\mu^2}{m_H^2}\right)^{\epsilon} c_\Gamma \left[\left(\frac{2}{\epsilon^2} + \frac{2}{\epsilon}\frac{b_0}{C_A} - \frac{\pi^2}{3}\right)\delta(1-z) - \frac{2}{\epsilon} p_{gg}(z) - \frac{11}{3}\frac{(1-z)^3}{z} - 4\frac{(1-z)^2(1+z^2)+z^2}{z(1-z)}\log z + 4\frac{1+z^4+(1-z)^4}{z}\left(\frac{\log(1-z)}{1-z}\right)_+\right].$$

Real contributions



This is the last piece: the result at the end must be finite!

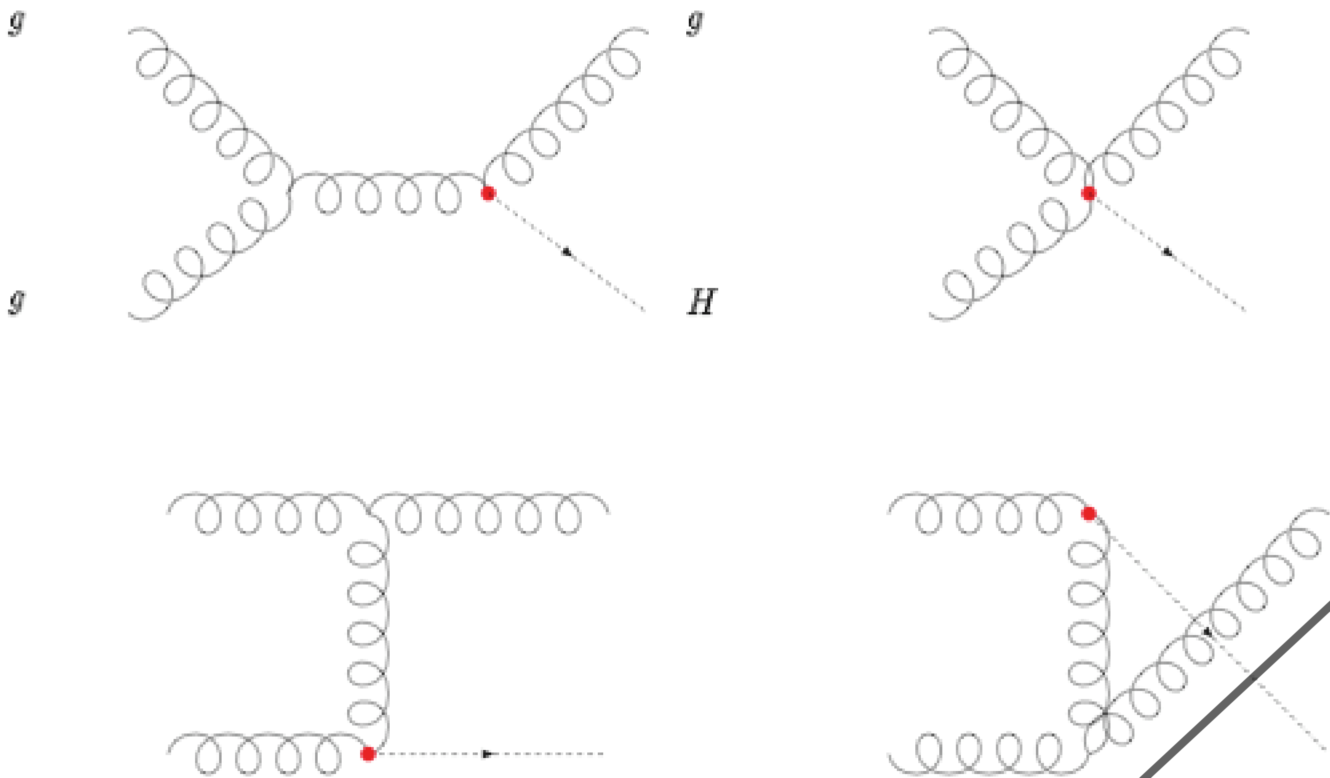
2/eps cancels with the virtual contribution ✓

This is the renormalization of the coulping!!

$$\sigma^{\rm UV}_{\rm c.t.} = 2\,\sigma_{\rm Born}\frac{\alpha_S}{2\pi}\left[-\left(\frac{\mu^2}{\mu^2_{\rm UV}}\right)^{\epsilon} c_\Gamma \frac{b_0}{\epsilon}\right] \checkmark$$

$$\begin{aligned}\sigma_{\rm real} \;=\; & \sigma_0\,\frac{\alpha_S}{2\pi}C_A\left(\frac{\mu^2}{m_H^2}\right)^{\epsilon} c_\Gamma\,\left[\left(\frac{2}{\epsilon^2}+\frac{2}{\epsilon}\frac{b_0}{C_A}-\frac{\pi^2}{3}\right)\delta(1-z)\right.\\ & -\frac{2}{\epsilon}p_{gg}(z)-\frac{11}{3}\frac{(1-z)^3}{z}-4\frac{(1-z)^2(1+z^2)+z^2}{z(1-z)}\log z\\ & \left.+\,4\frac{1+z^4+(1-z)^4}{z}\left(\frac{\log(1-z)}{1-z}\right)_+\right].\end{aligned}$$

Real contributions



$$\sigma_{\text{real}} = \sigma_0 \frac{\alpha_S}{2\pi} C_A \left(\frac{\mu^2}{m_H^2}\right)^{\epsilon} c_\Gamma \left[\left(\frac{2}{\epsilon^2} + \frac{2}{\epsilon}\frac{b_0}{C_A} - \frac{\pi^2}{3} \right) \delta(1-z) - \frac{2}{\epsilon} p_{gg}(z) - \frac{11}{3}\frac{(1-z)^3}{z} - 4\frac{(1-z)^2(1+z^2)+z^2}{z(1-z)} \log z + 4\frac{1+z^4+(1-z)^4}{z}\left(\frac{\log(1-z)}{1-z}\right)_+ \right].$$

This is the last piece: the result at the end must be finite!

2/eps cancels with the virtual contribution ✓

This is the renormalization of the coulping!!

$$\sigma^{\text{UV}}_{\text{c.t.}} = 2\,\sigma_{\text{Born}} \frac{\alpha_S}{2\pi} \left[- \left(\frac{\mu^2}{\mu^2_{\text{UV}}}\right)^{\epsilon} c_\Gamma \frac{b_0}{\epsilon} \right] ✓$$

This is an initial-state divergence to be reabsorbed in the pdf

$$\sigma^{\text{coll.}}_{\text{c.t.}} = 2\,\sigma_0 \frac{\alpha_S}{2\pi} \left[\left(\frac{\mu^2}{\mu^2_F}\right)^{\epsilon} \frac{c_\Gamma}{\epsilon} P_{gg}(z) \right] ✓$$

Final results = we made it!!

$$\sigma(pp \to H) = \sum_{ij} \int_{\tau_0}^{1} dx_1 \int_{\tau_0/x_1}^{1} dx_2 f_i(x_1, \mu_f) f_j(x_2, \mu_f) \hat{\sigma}(ij)[\mu_f/m_h, \mu_r/m_h, \alpha_S(\mu_r)]$$

The final cross section is the sum of three channels: q qbar, q g, and g g.

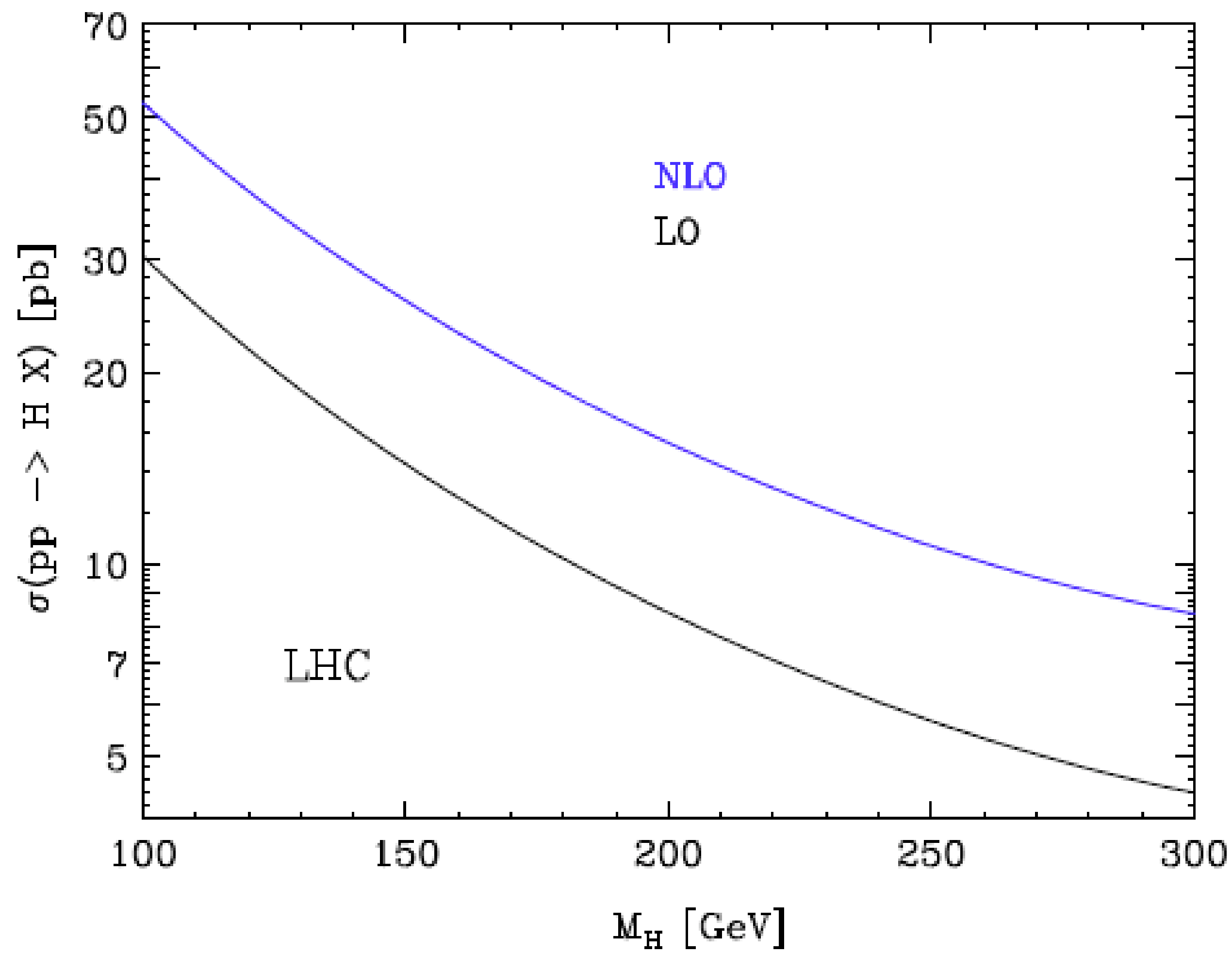
The short distance cross section at NLO depends explicitly on the subtraction scales (renormalization and factorization).

The explicit integration over the pdf's is trivial (just mind the plus distributions).

The result is that the corrections are huge!

K factor is ~2 and scale dependence not really very much improved.

Is perturbation theory valid?
NNLO is mandatory...



Final results = we made it!!

$$\sigma(pp \to H) = \sum_{ij} \int_{\tau_0}^{1} dx_1 \int_{\tau_0/x_1}^{1} dx_2 f_i(x_1,\mu_f) f_j(x_2,\mu_f) \hat{\sigma}(ij)[\mu_f/m_h, \mu_r/m_h, \alpha_S(\mu_r)]$$

The final cross section is the sum of three channels: q qbar, q g, and g g.

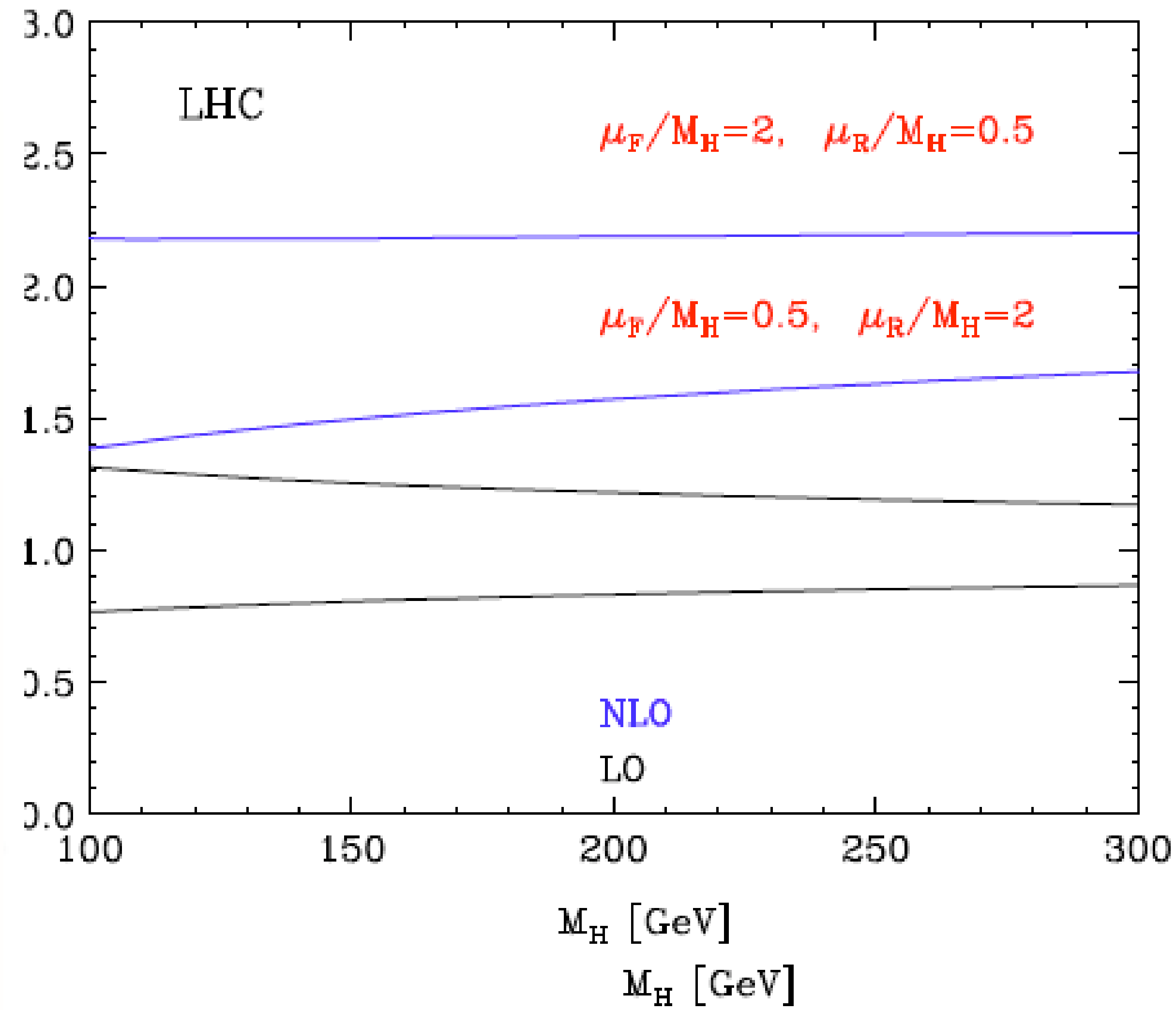
The short distance cross section at NLO depends explicitly on the subtraction scales (renormalization and factorization).

The explicit integration over the pdf's is trivial (just mind the plus distributions).

The result is that the corrections are huge!

K factor is ~2 and scale dependence not really very much improved.

Is perturbation theory valid?
NNLO is mandatory...



General algorithm for calculations of observables at NLO

As we discussed, the form of the soft and collinear terms are UNIVERSAL, i.e., they don't depend on the short distance coefficients, but only on the color and spin of the partons partecipating soft or collinear limit.

Therefore it is conceivable to have an algorithm that can handle any process, once the real and virtual contributions are computed.

There are several such algorithms avaiable, but the conceptually simplest is the Subtraction Method [Catani & Seymour ; Catani, Dittmaier, Seymour, Trocsanyi]

$$\sigma_{ab}^{LO} = \int_m d\sigma_{ab}^B$$

$$\sigma_{ab}^{NLO} = \int_{m+1} d\sigma_{ab}^R + \int_m d\sigma_{ab}^V$$

General algorithm for calculations of observables at NLO

One can use the universality to construct a set of counterterms

$$d\sigma^{ct} = \sum_{ct} \int_m d\sigma^B \otimes \int_1 dV_{ct}$$

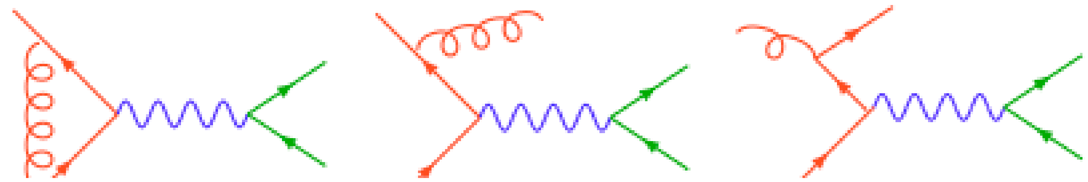
which only depend on the partons involved in the divergent regions, dσ^B denotes the approriate colour and spin projection of the Born-level cross section and the counter terms are independent on the process under considerations.
These counter terms cancell all non-integrable singularities in dσ^R, so that one can write

$$\sigma_{ab}^{NLO} = \int_{m+1} [d\sigma_{ab}^R - d\sigma_{ab}^{ct}] + \int_{m+1} d\sigma_{ab}^{ct} + \int_m d\sigma_{ab}^V$$

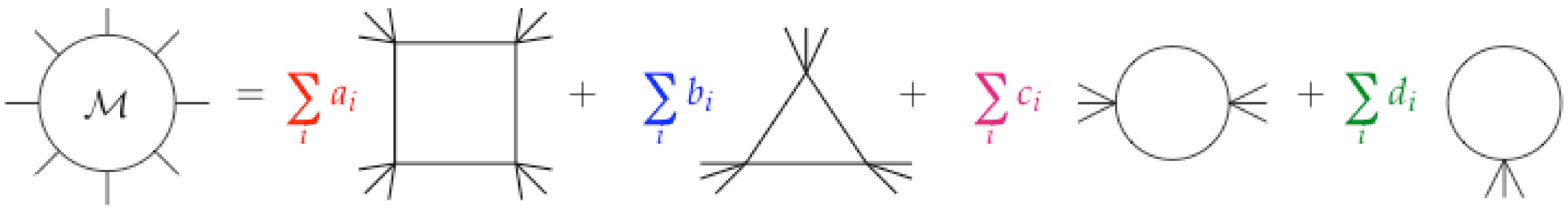
where the space integration in the first term can be performed numerically in four dimensions and the integral of the counter terms can be done once for all.

Next-to-leading order : Loops

$\hat{\sigma}^{(1)}$



Any one-loop amplitude can be written as (PV decomposition):



$$\mathcal{M} = \sum_i a_i(D)\,\text{Boxes}_i + \sum_i b_i(D)\,\text{Triangles}_i + \sum_i c_i(D)\,\text{Bubbles}_i + \sum_i d_i(D)\,\text{Tadpoles}_i$$

* All the scalar loop integrals are known and now easily available [Ellis, Zanderighi]

* Open issue is to compute the D-dimensional coefficient in the expansion: large number of terms forbid a direct evaluation with symbolic algebra. In addition normally large gauge cancellation, inverse Gram determinants, spurious phace-space singularities lead to numerical instabilities.

Sometimes it is better to calculate

$$\mathcal{M} = \sum_i a_i(4)\,\text{Boxes}_i + \sum_i b_i(4)\,\text{Triangles}_i + \sum_i c_i(4)\,\text{Bubbles}_i + \sum_i d_i(4)\,\text{Tadpoles}_i + R$$

Where R is a rational function

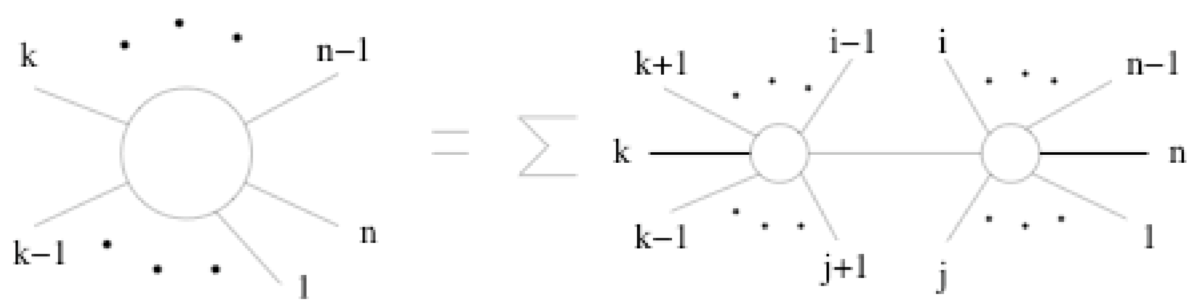
Progress in loops

Several new developments coming from the idea

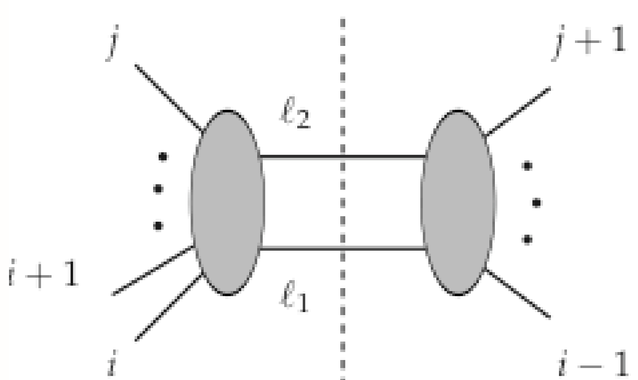
> A scattering amplitude is an analytic function of the external momenta and (most) its structure can be reconstructed from the poles and the branch cuts.
>
> LOOPS can be calculated from tree-level amplitudes

✓ POLES : lower number of external lines. Cauchy residue theorem

[Cachazo, Svreck, Witten]
[Witten]
[Britto, Cachazo, Feng]



✓ BRANCH CUTS : lower number of loops



$$\text{Disc} = \int d^4\Phi \, A^{\text{tree}}(\ell_1, i, \ldots, j, \ell_2) \, A^{\text{tree}}(-\ell_2, j+1, \ldots, i-1, -\ell_1)$$

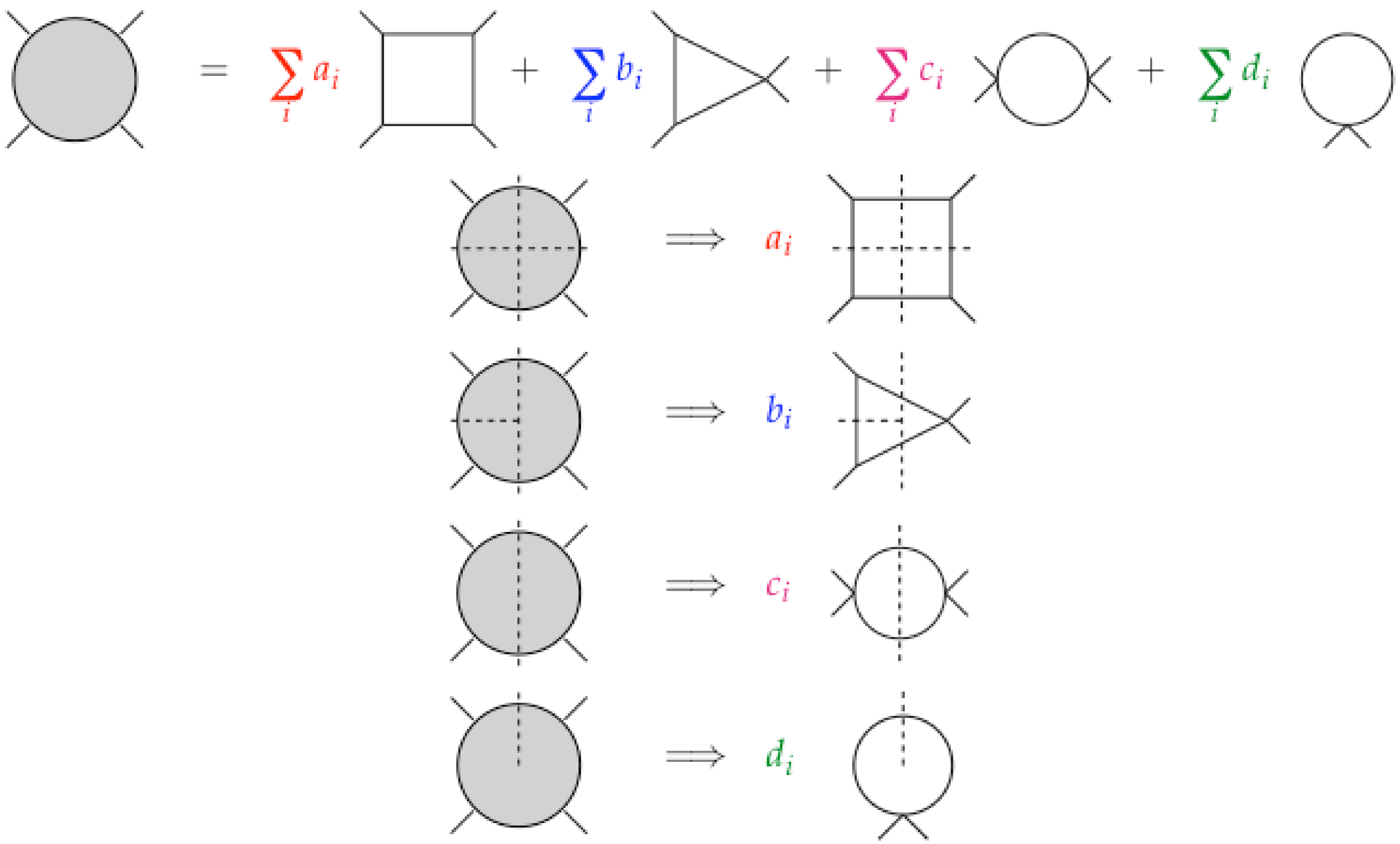
$$d^4\Phi = d^4\ell_1 \, d^4\ell_2 \, \delta^{(4)}(\ell_1 + \ell_2 - P_{ij}) \, \delta^{(+)}(\ell_1^2) \, \delta^{(+)}(\ell_2^2)$$

$$\delta^{(+)}(p^2) = \delta(p^2)\, \theta(p_0)$$ on-shell condition

[Vermaseren, van Neerven]
[Bern, Dixon, Dunbar, Kosower]
[Britto, Cachazo, Feng]

Generalized unitarity

[Bern, Dixon, Kosower]
[Britto, Cachazo, Feng]
[Anastasiou, Kunszt, Mastrolia]



Three and four particle cuts are non zero due to the continuation of momenta into complex values!

What about NNLO?

- At present only 2→1 calculations available, all of them (parton) exclusive final state.
- From loop integrals to phase space integrals...all of them are an art!
- General algorithms and checked only in e+e- →3j

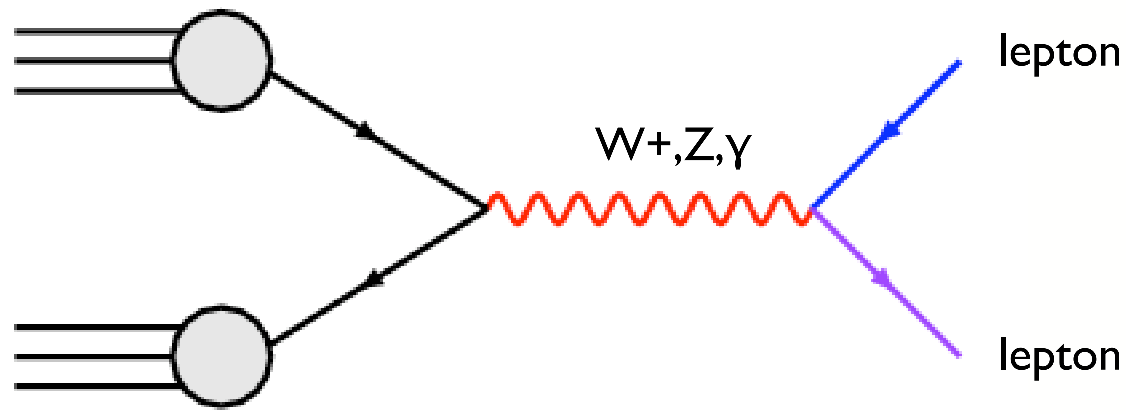
What about NNLO?

- At present only $2 \to 1$ calculations available, all of them (parton) exclusive final state.
- From loop integrals to phase space integrals...all of them are an art!
- General algorithms and checked only in e+e- $\to$3j

Let's consider two physics cases:

a. Drell-Yan
b. Higgs

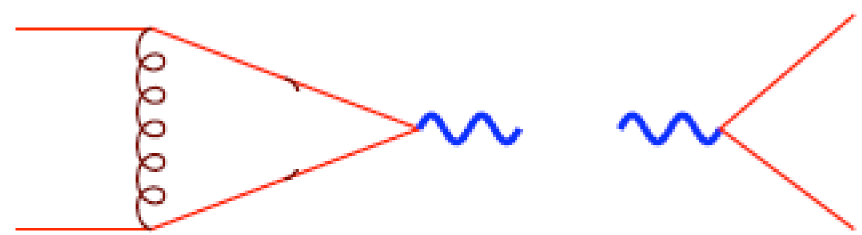
Drell-Yan



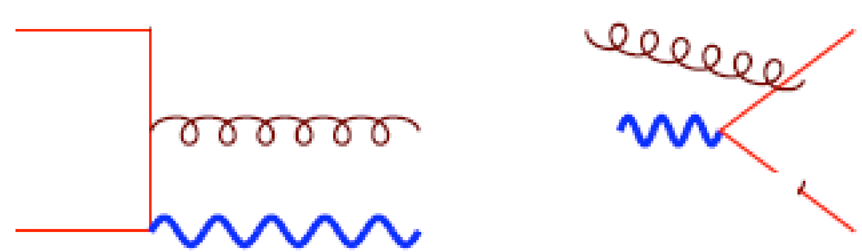
- Clean final state (no hadrons from the hard process).
- Nice test of QCD and EW interactions. The cross sections are known up to NNLO (QCD) and at NLO (EW).
- Measure m_W to be used in the EW fits together with the top mass to guess the Higgs mass.
- Constraint the PDF
- Channel to search for new heavy gauge bosons or new kind of interactions

Elements of pp→W NLO calculation

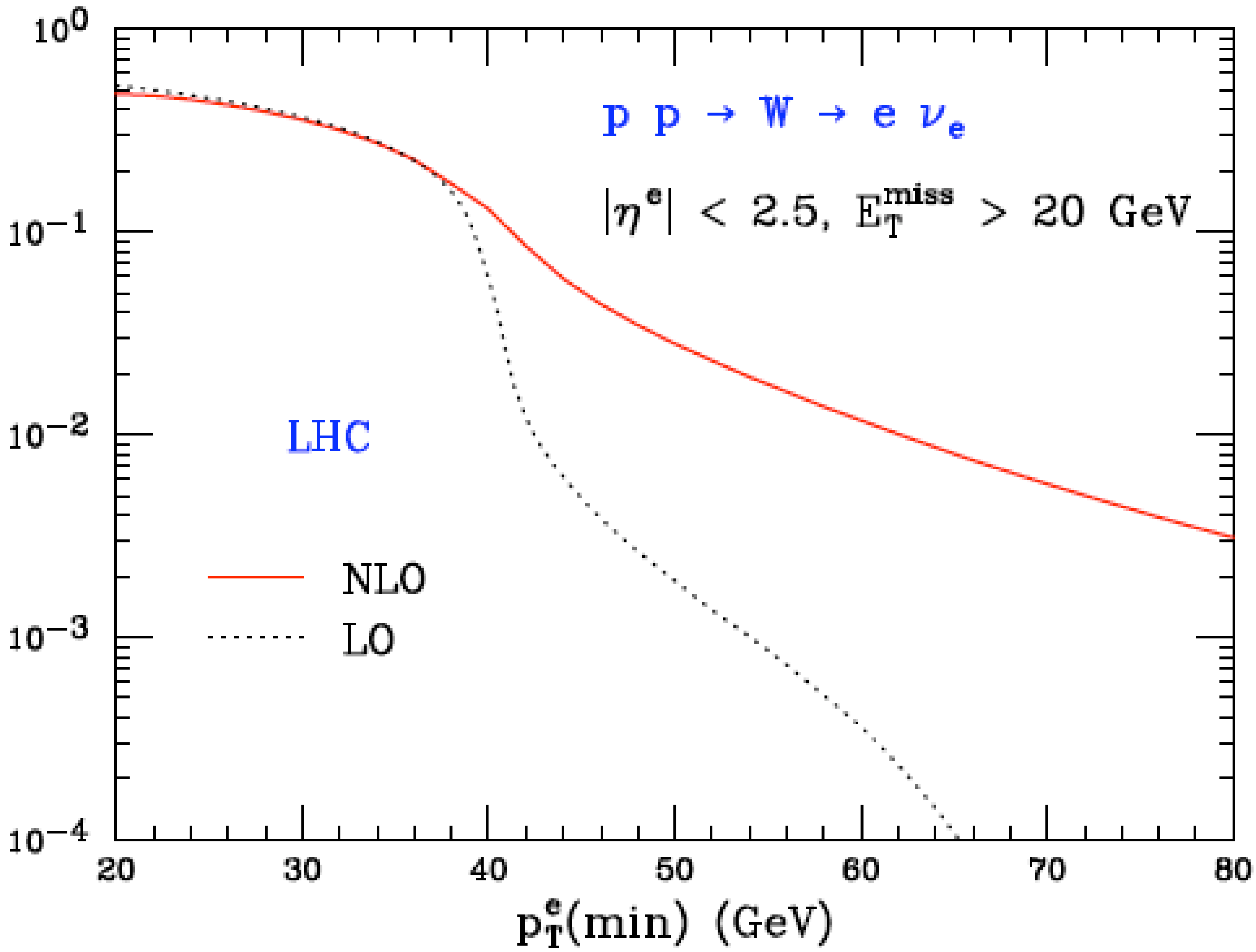
- Virtual



- Real



Drell-Yan @ NLO



✓ $A_W = \frac{1}{\sigma^{(tot)}} \int_{p_T^e(\mathrm{min})}^{\sqrt{S}/2} dp_T^e \frac{d\sigma}{dp_T^e}(\mathrm{cuts})$

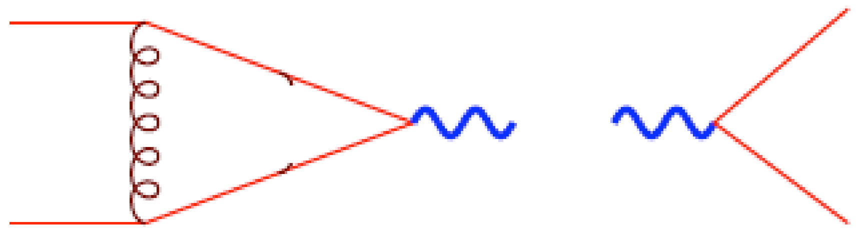
✓ $K(x) = \frac{d\sigma_{NLO}/dx}{d\sigma_{LO}/dx}$

K factors STRONGLY phase-space dependent.

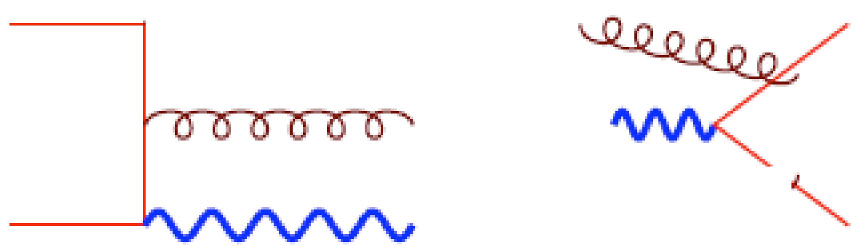
Lepton spin correlations have to be taken account correctly!

Elements of pp→W NLO calculation

- Virtual

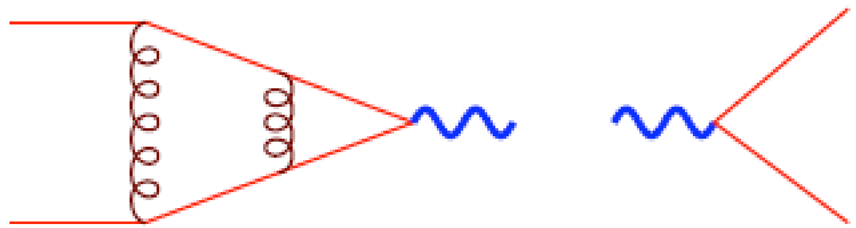


- Real



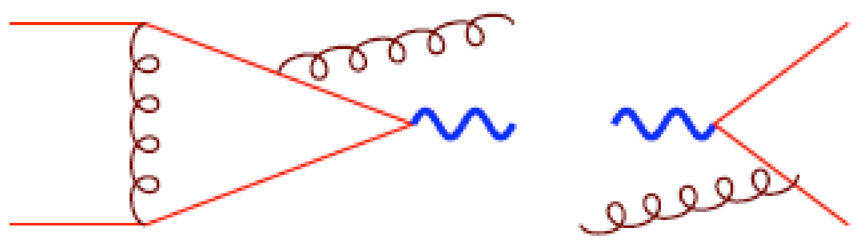
Elements of pp→W NNLO calculation

- Virtual-Virtual



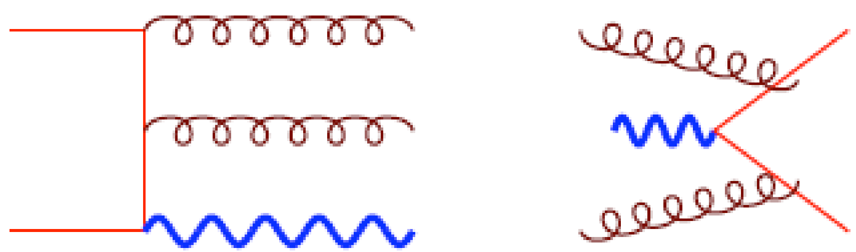
+ 100 terms

- Real-Virtual



+ 300 terms

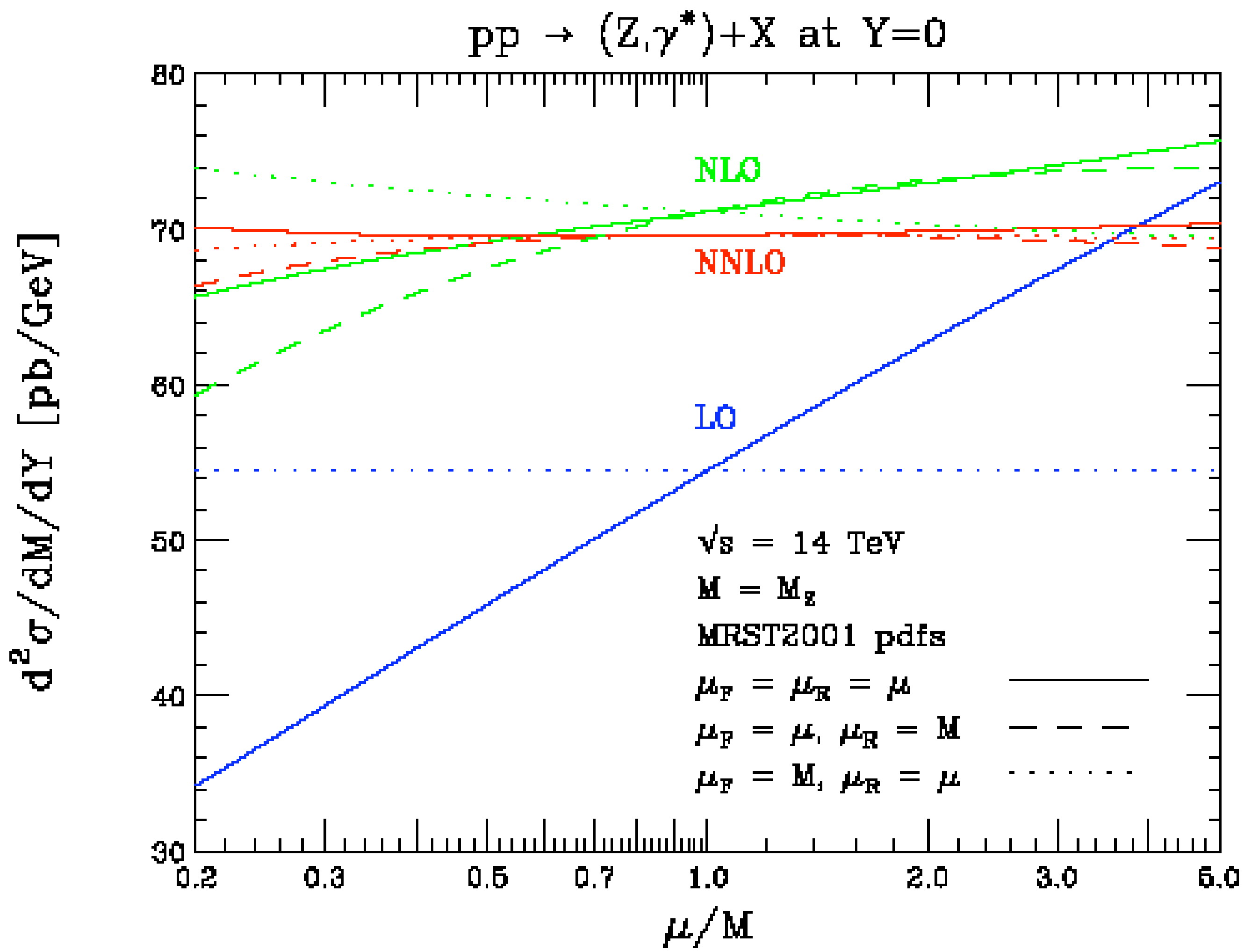
- Real-Real



+ 500 terms

⇒ Need clever algorithms to handle!

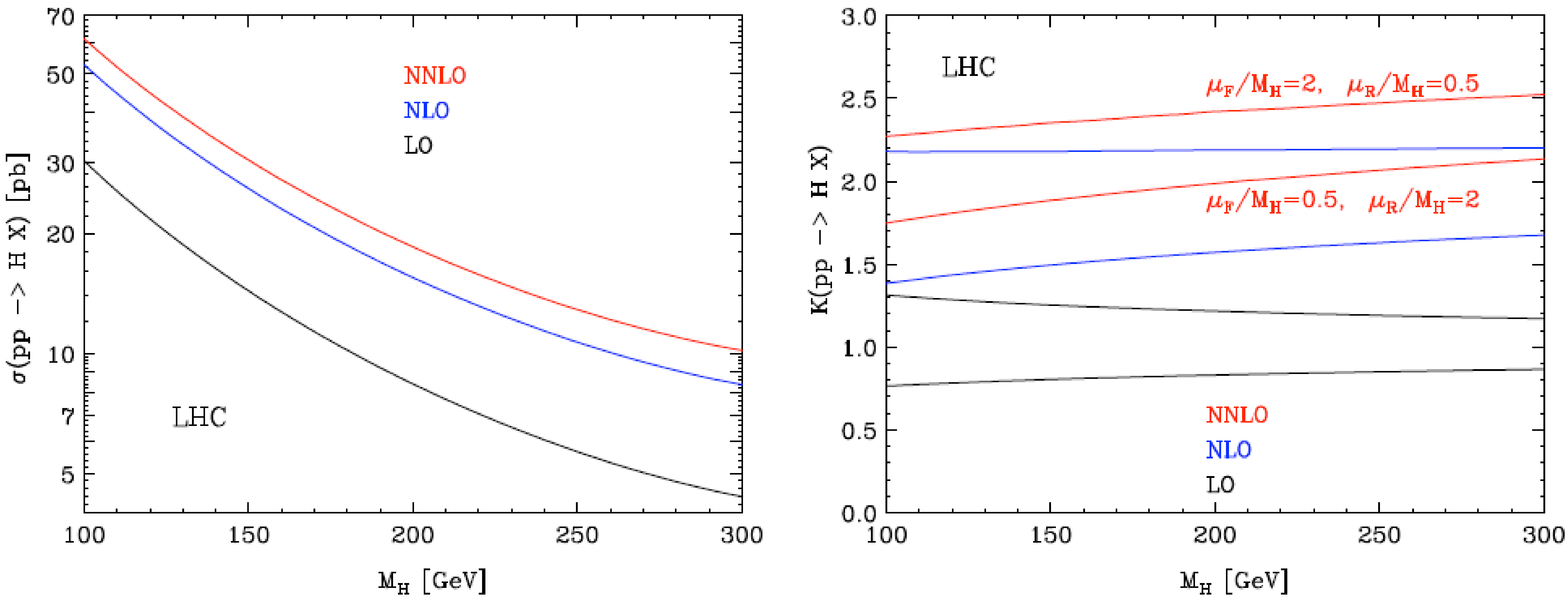
The NNLO result



- Precision predictions at NNLO
- Also miss qualitative effects at lower orders
  - Few initial channels open; sensitivity to pdfs underestimated
  - Few jets in final state
  - Jets modeled by too few partons
  - Incorrect kinematics, e.g., no p_T

[Anastasiou, Dixon, Melnikov, Petriello. 2004]

pp→H at NNLO



Is the series well behaved? $\Longrightarrow$ YES NNLO 15%

The current TH QCD uncertainty on the total cross section is about 10%.

What about our predictions for limited areas of the phase space?

NNLO : summary

NNLO : summary

- Frontier of precision QCD calculations.

NNLO : summary

- Frontier of precision QCD calculations.
- NNLO calculations are needed for very special cases, such as standard candles and/or precision physics.

NNLO : summary

- Frontier of precision QCD calculations.
- NNLO calculations are needed for very special cases, such as standard candles and/or precision physics.
- Still an art. General algorithm not yet in place.

NNLO : summary

- Frontier of precision QCD calculations.
- NNLO calculations are needed for very special cases, such as standard candles and/or precision physics.
- Still an art. General algorithm not yet in place.
- Handful of results available, mostly in private codes (few exceptions!).

Summary
of the status of the
theoretical predictions
for the LHC

Status : before 2003

$pp \rightarrow$ n particles

Status : before 2003

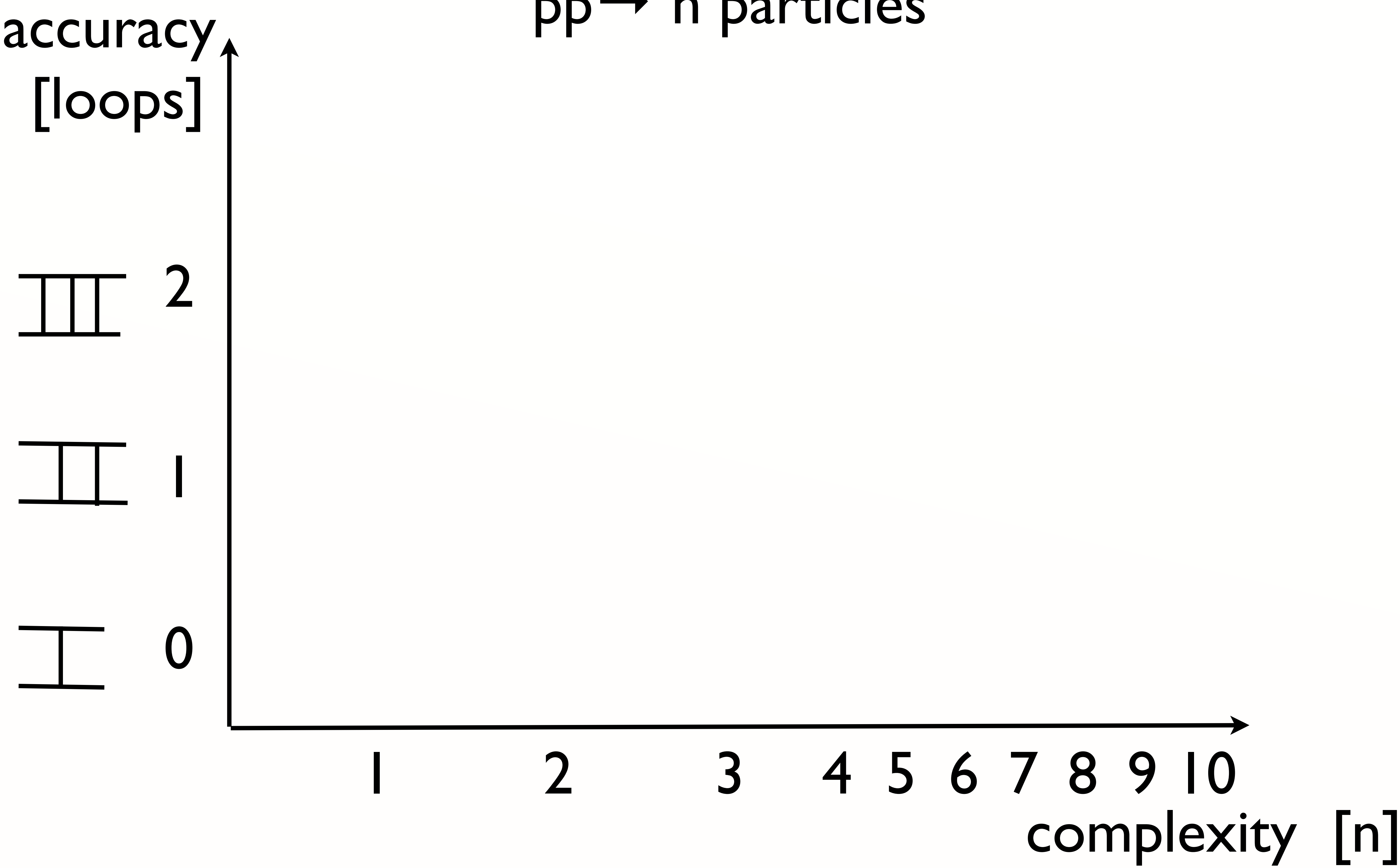
$pp \rightarrow$ n particles

1 2 3 4 5 6 7 8 9 10

complexity [n]

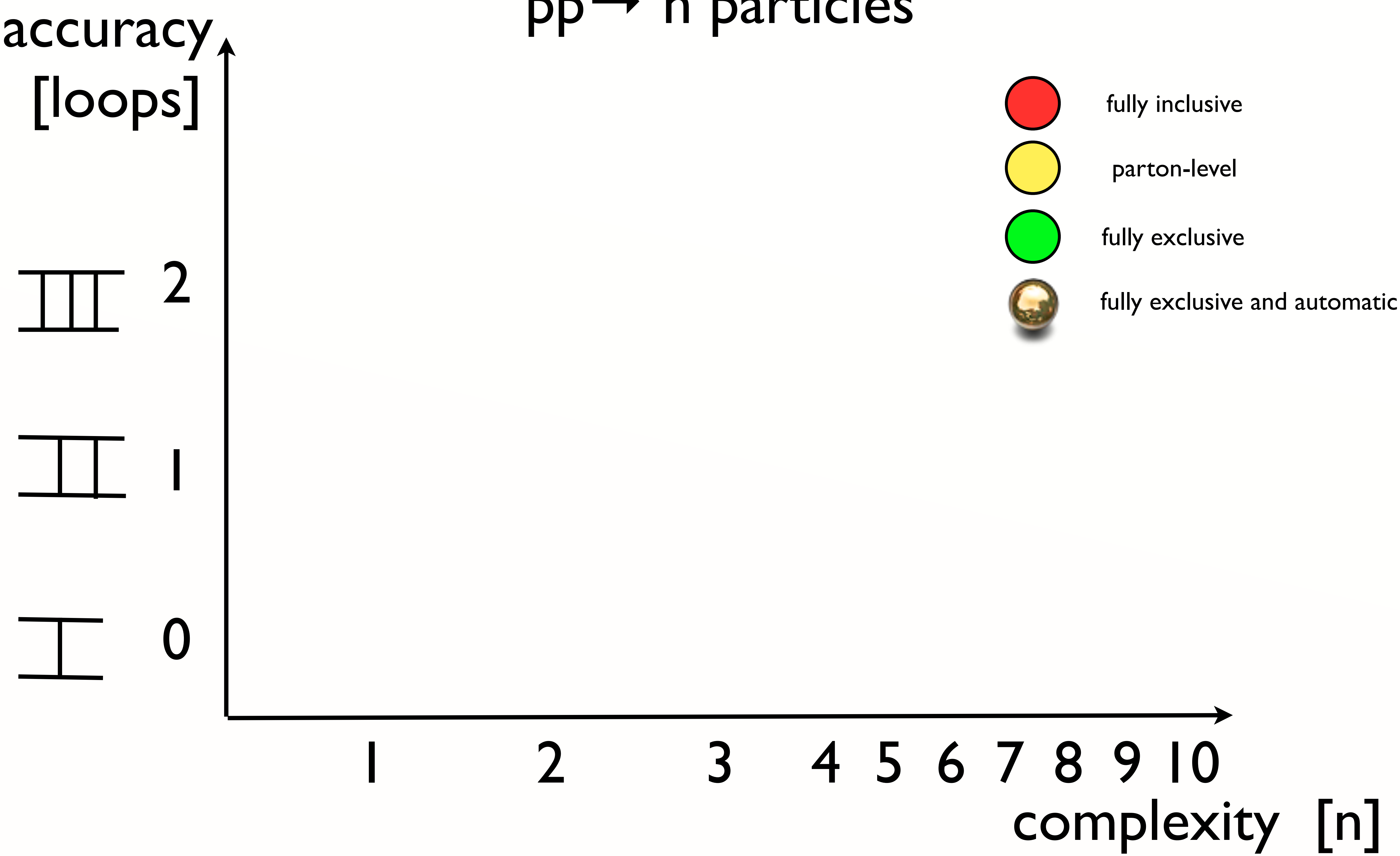
Status : before 2003

pp → n particles



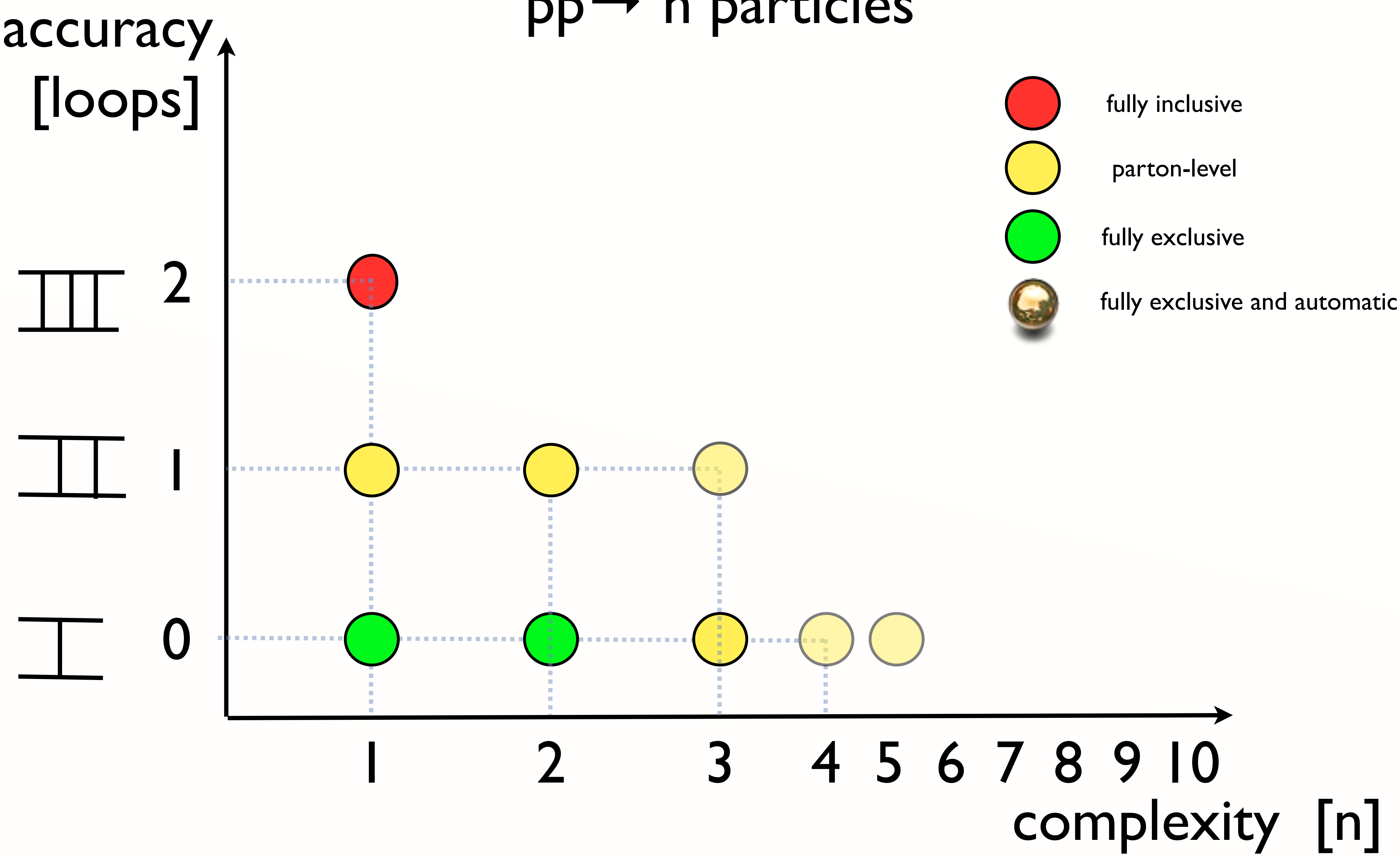
Status : before 2003

pp → n particles



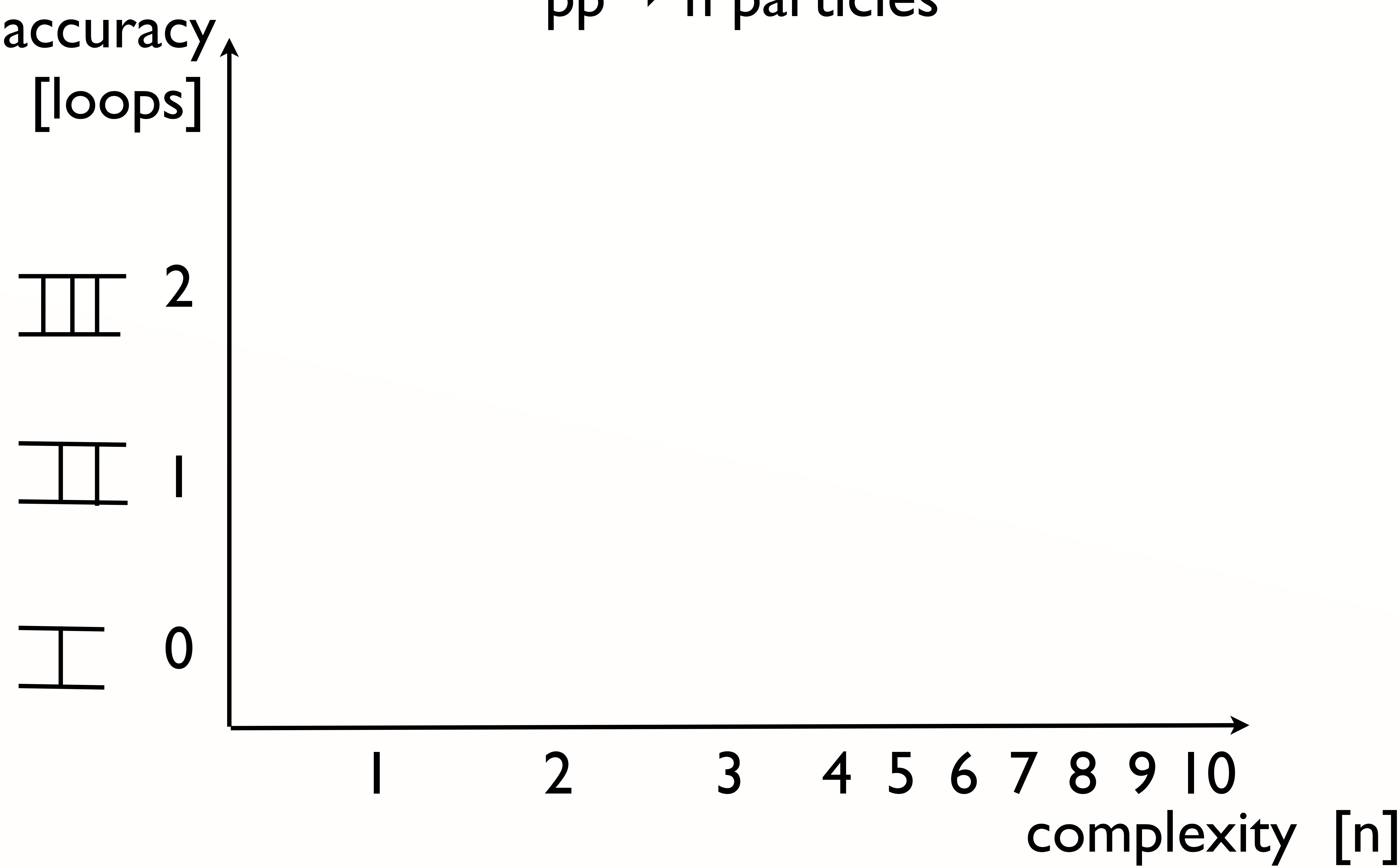
Status : before 2003

pp→ n particles

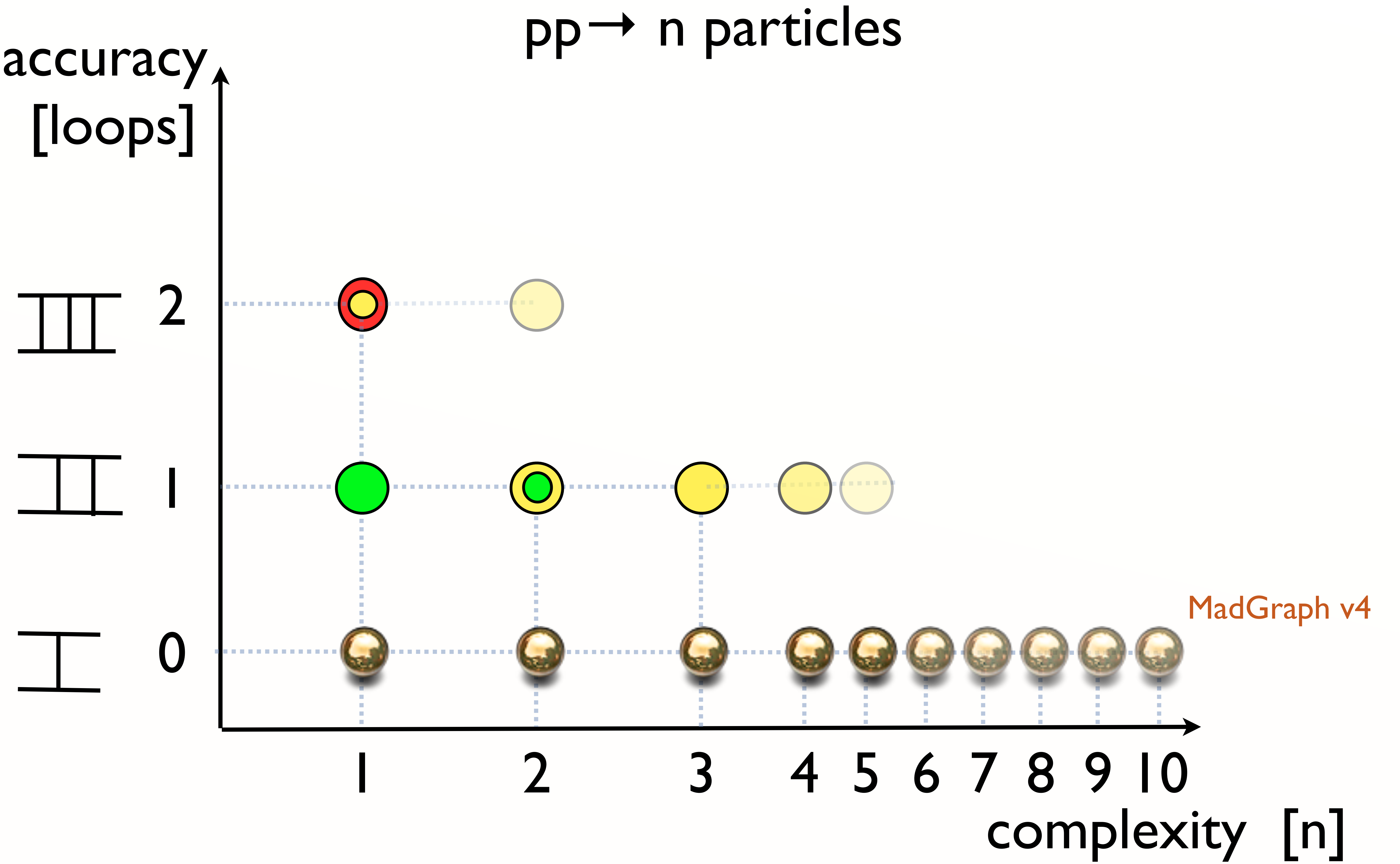


Status : since 2006

pp→ n particles

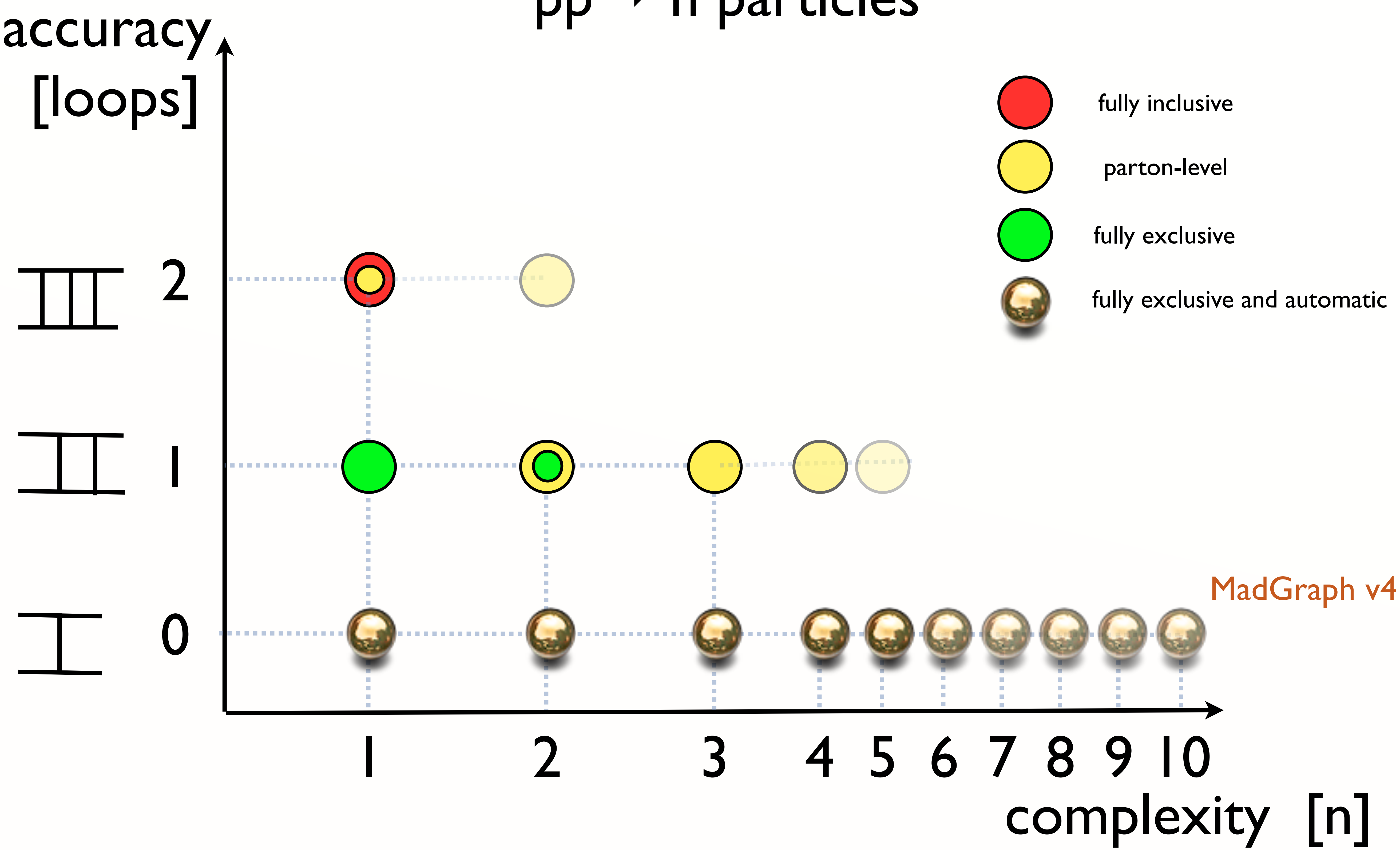


Status : since 2006



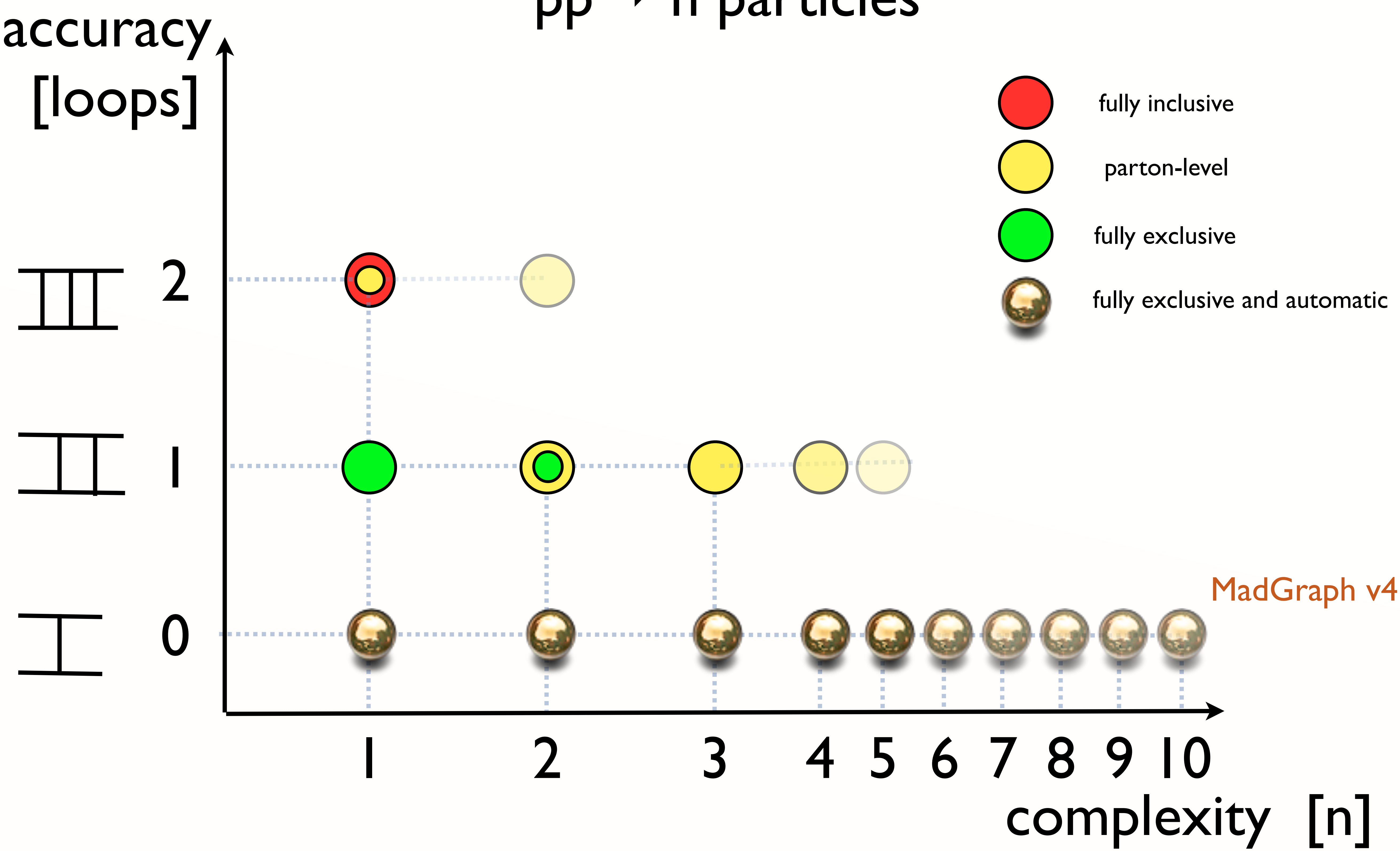
Status : since 2006

pp→ n particles



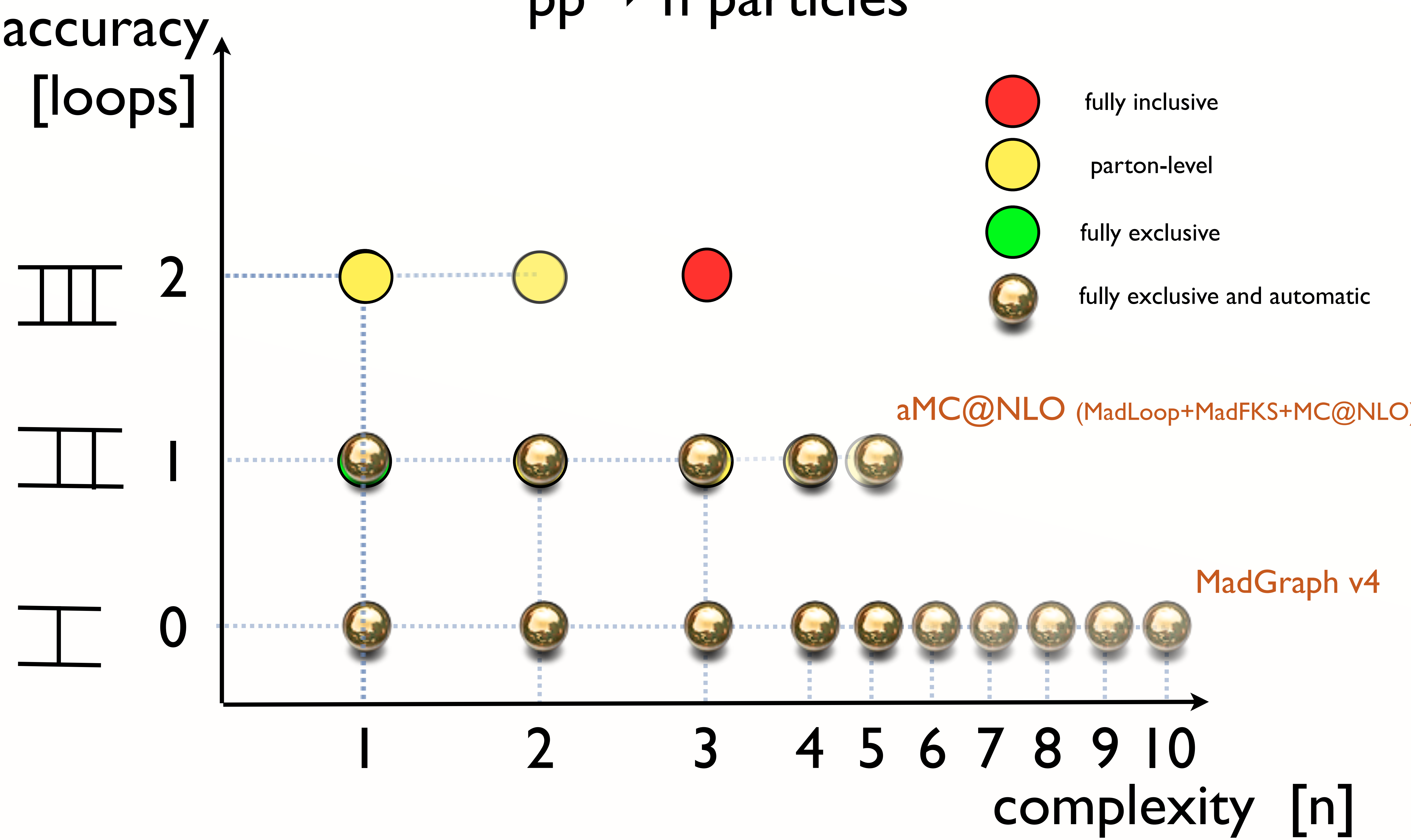
Status : since last week

pp→ n particles



Status : since last week

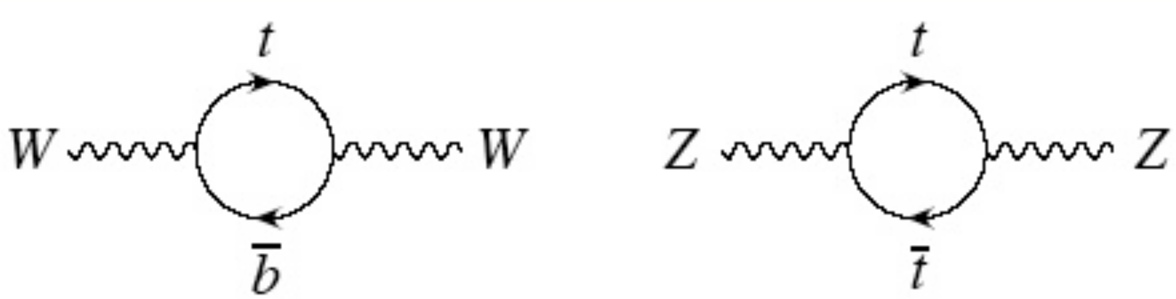
pp→ n particles



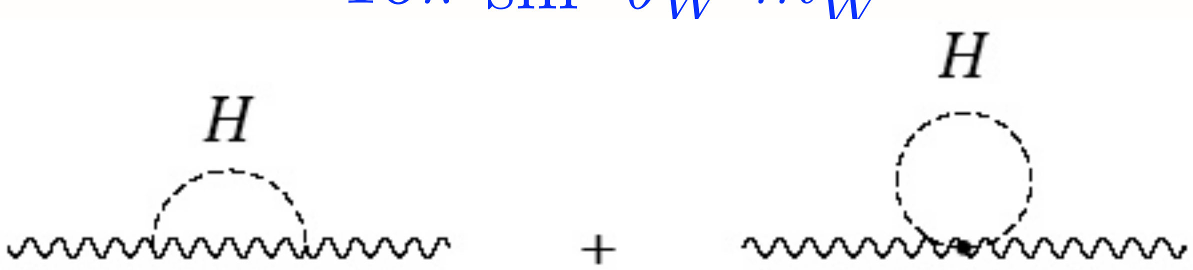
Precision EW, m_t & $m_W \Rightarrow m_H$

Indirect evidence for the existence of particles not yet detected can be inferred from quantum corrections. At tree level $m_W = m_Z \cos\theta_W$. At one loop:

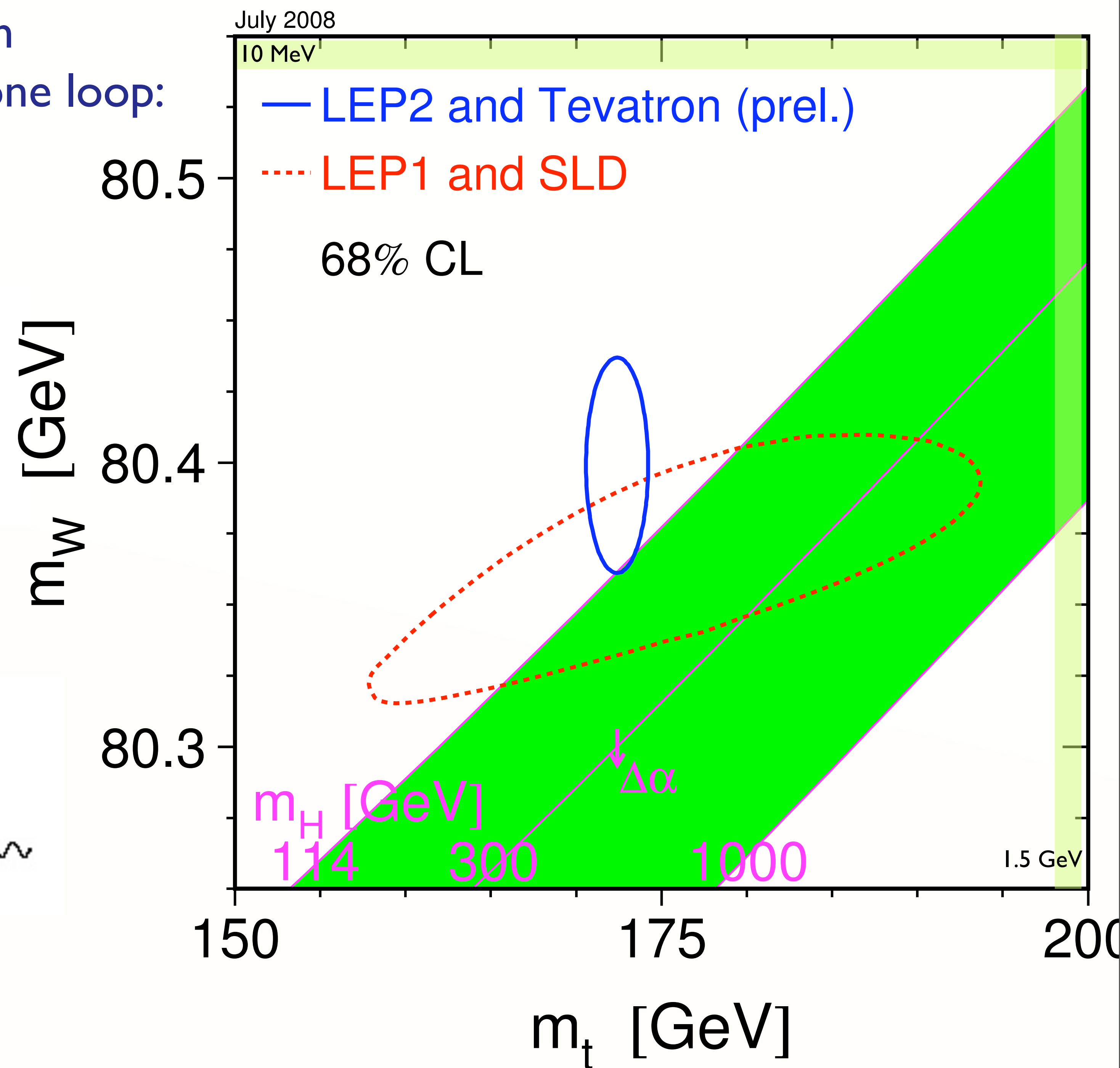
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



$$\Delta r_{\rm top} = -\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$



$$\Delta r_{\rm Higgs} = +\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$

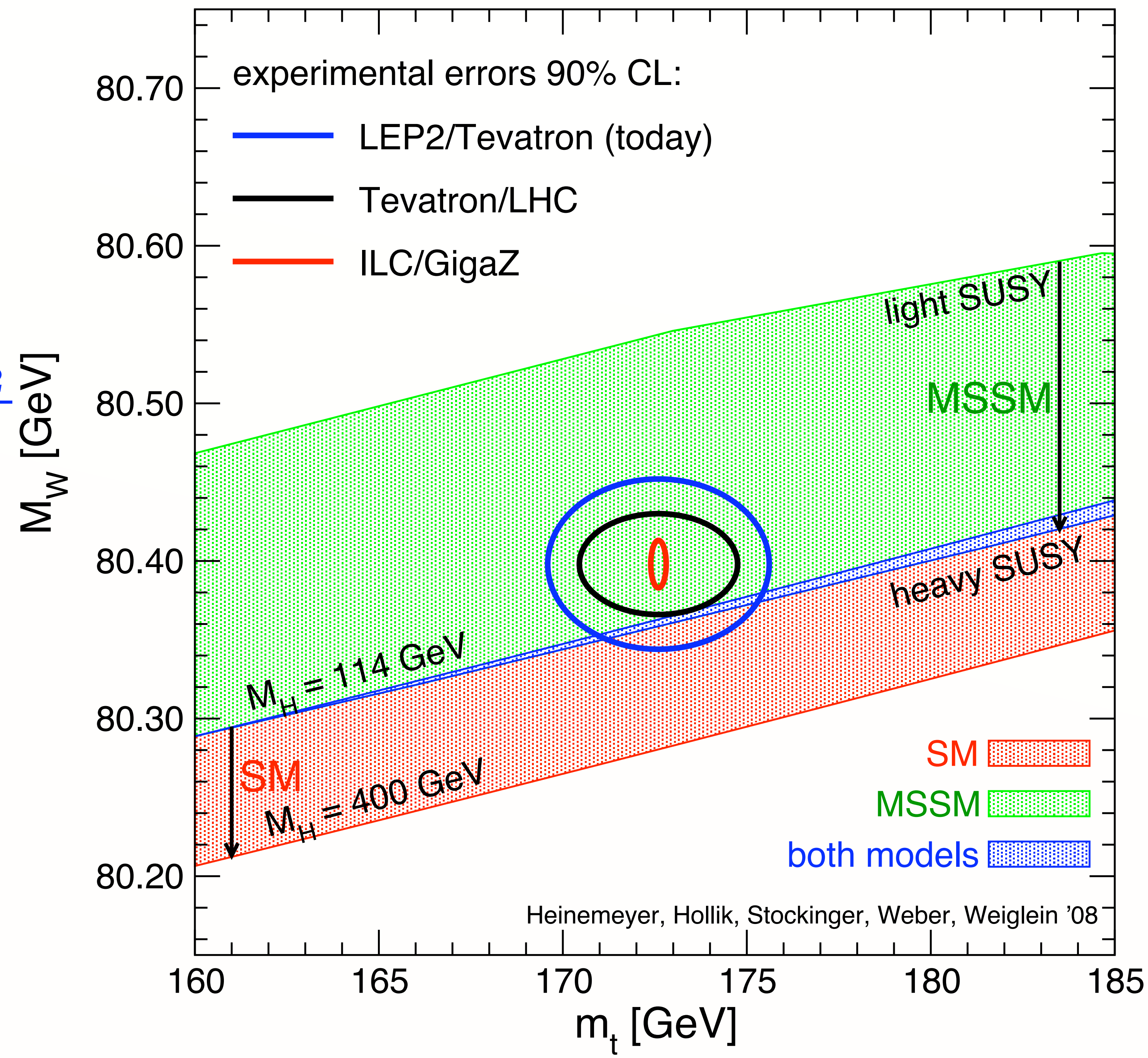


Precision EW and SUSY

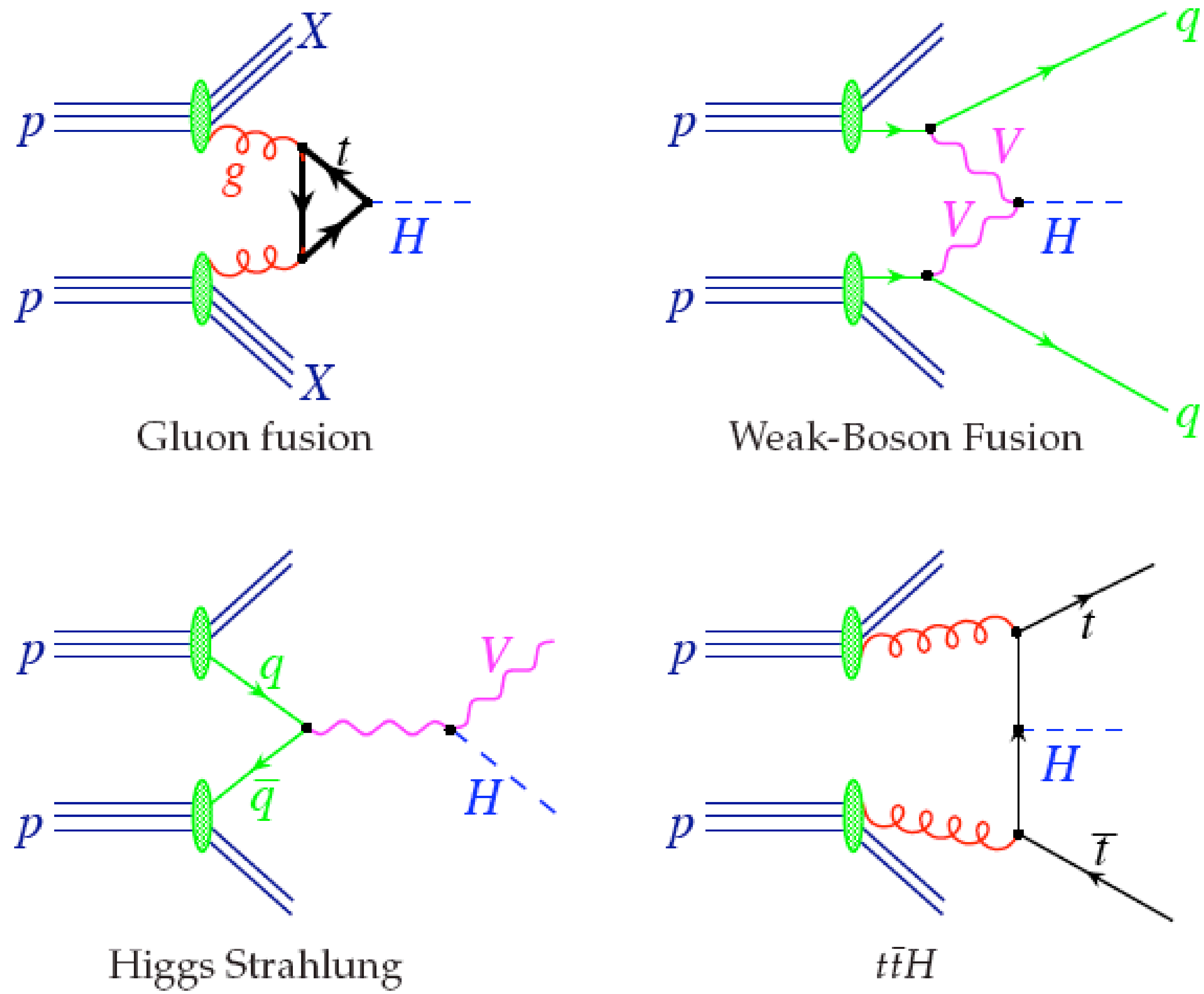
Beyond the SM precision measurements can be also very useful. For instance in SUSY, the corrections to the Higgs mass are given by:

$$\Delta M^2 \simeq G_F m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$$

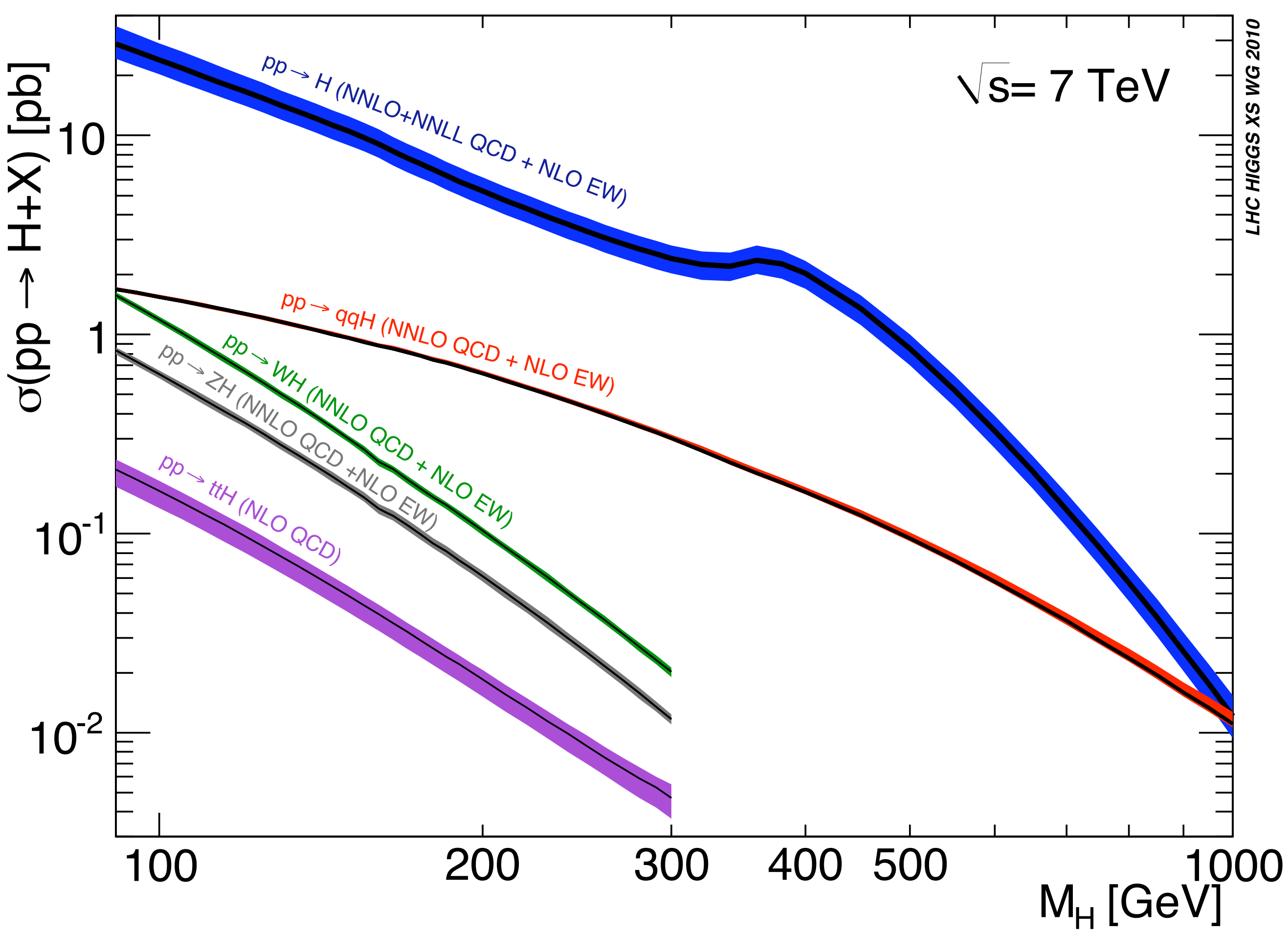
In fact top effects can be really important in theories like SUSY: Large and negative 1-loop corrections can turn the Higgs mass parameters negative and even trigger ESWB.

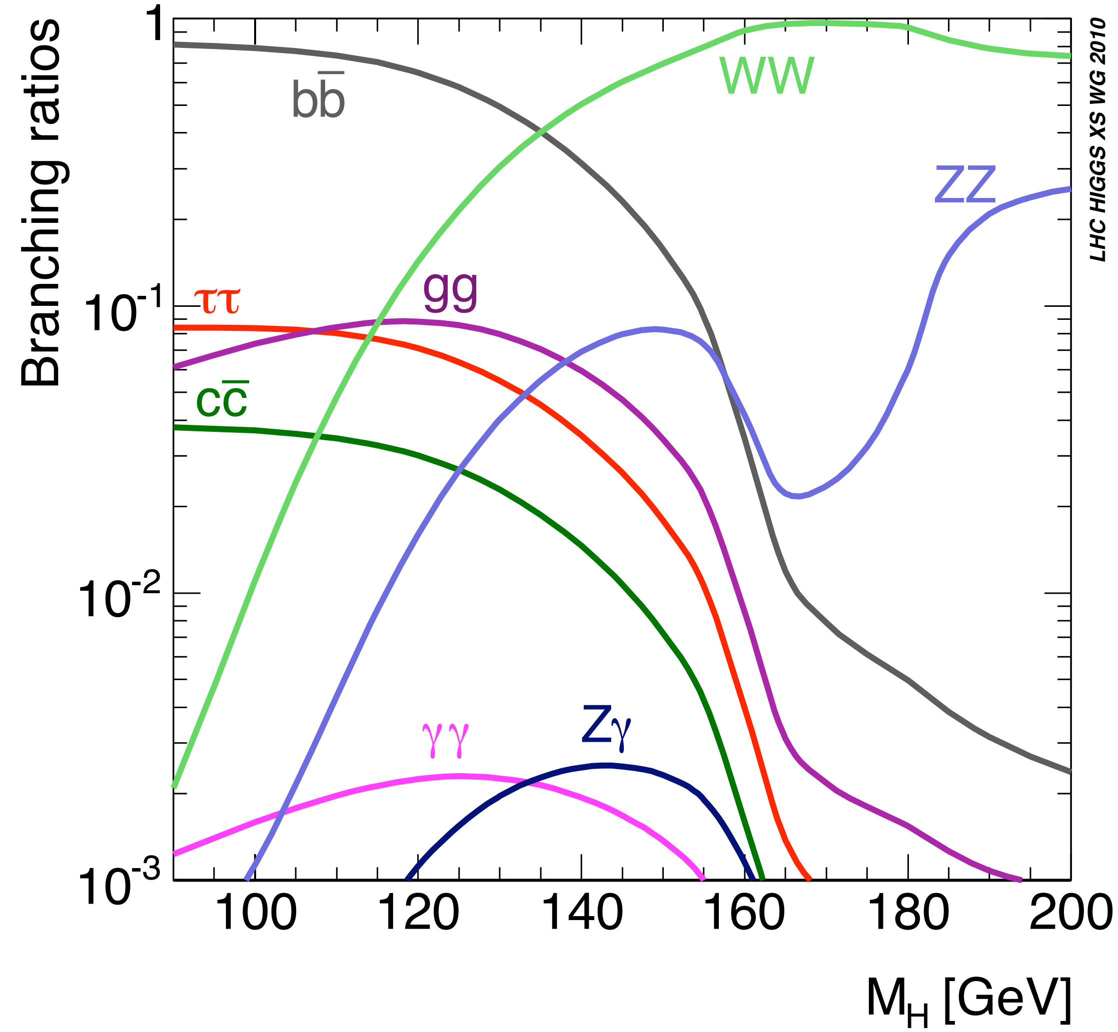


Higgs production at hadron colliders



The Higgs XS working group

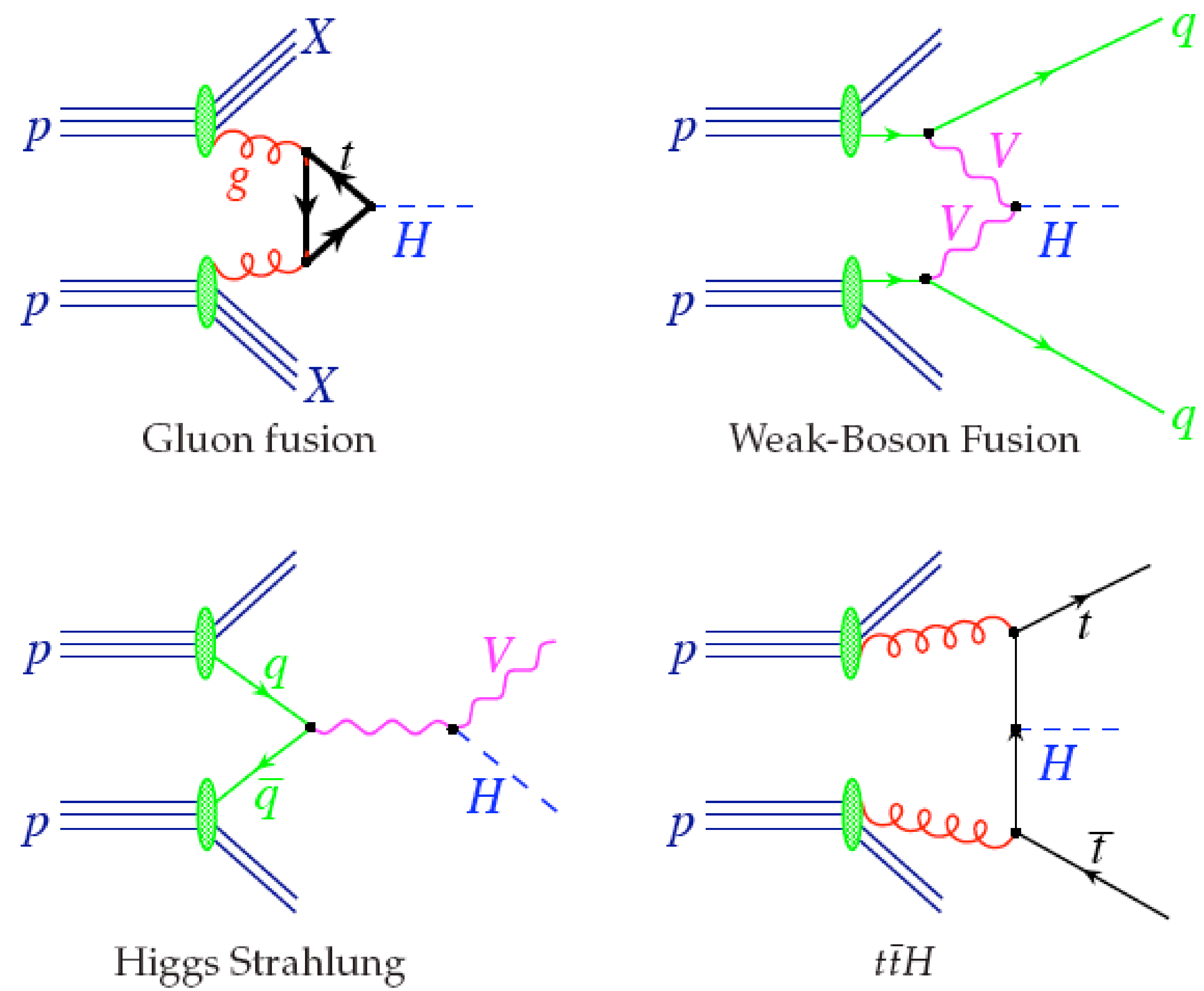




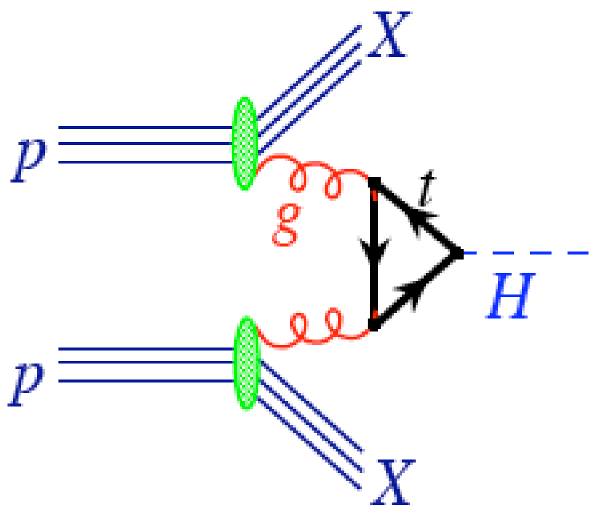
To keep in mind

- The organization of the Higgs production into channels is an handy and pragmatic idea.
- However, always keep in mind that is an approximation!!

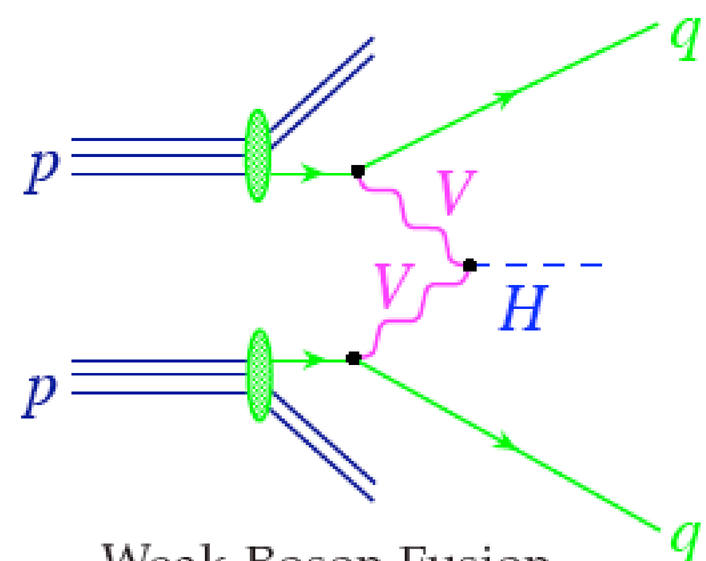
Higgs production at hadron colliders



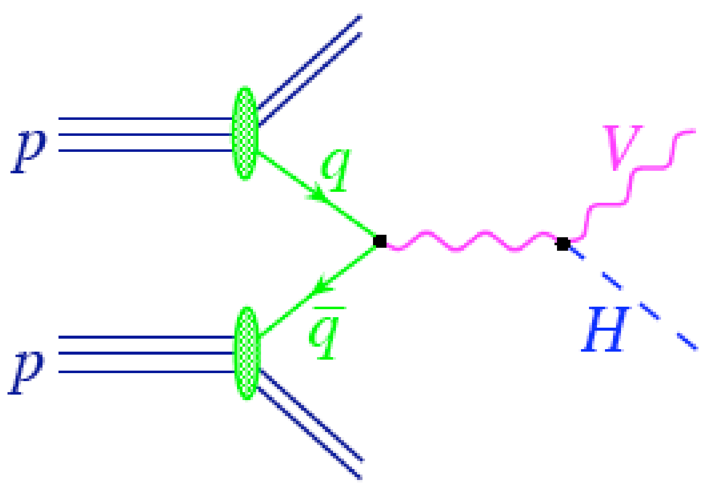
Higgs production at hadron colliders



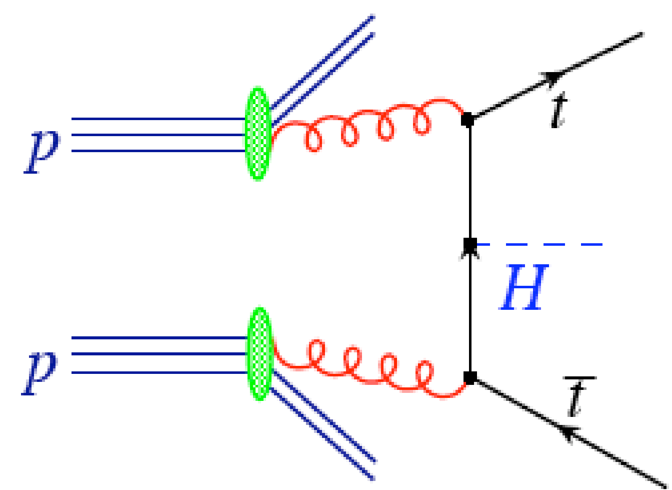
Gluon fusion



Weak-Boson Fusion

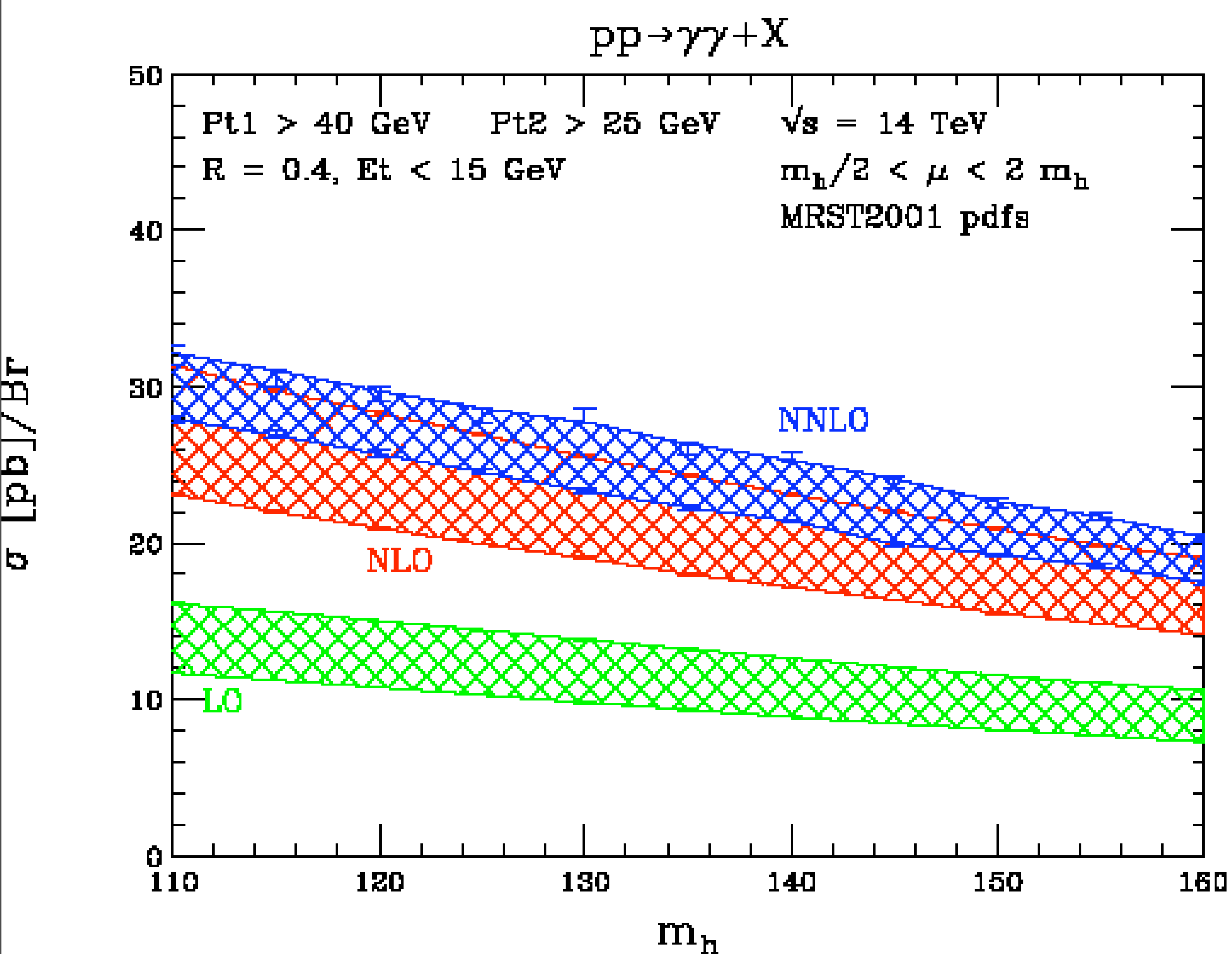


Higgs Strahlung



$t\bar{t}H$

gg→H



Dominant production mechanism at hadron colliders.
The story of the most accurate prediction in QCD:

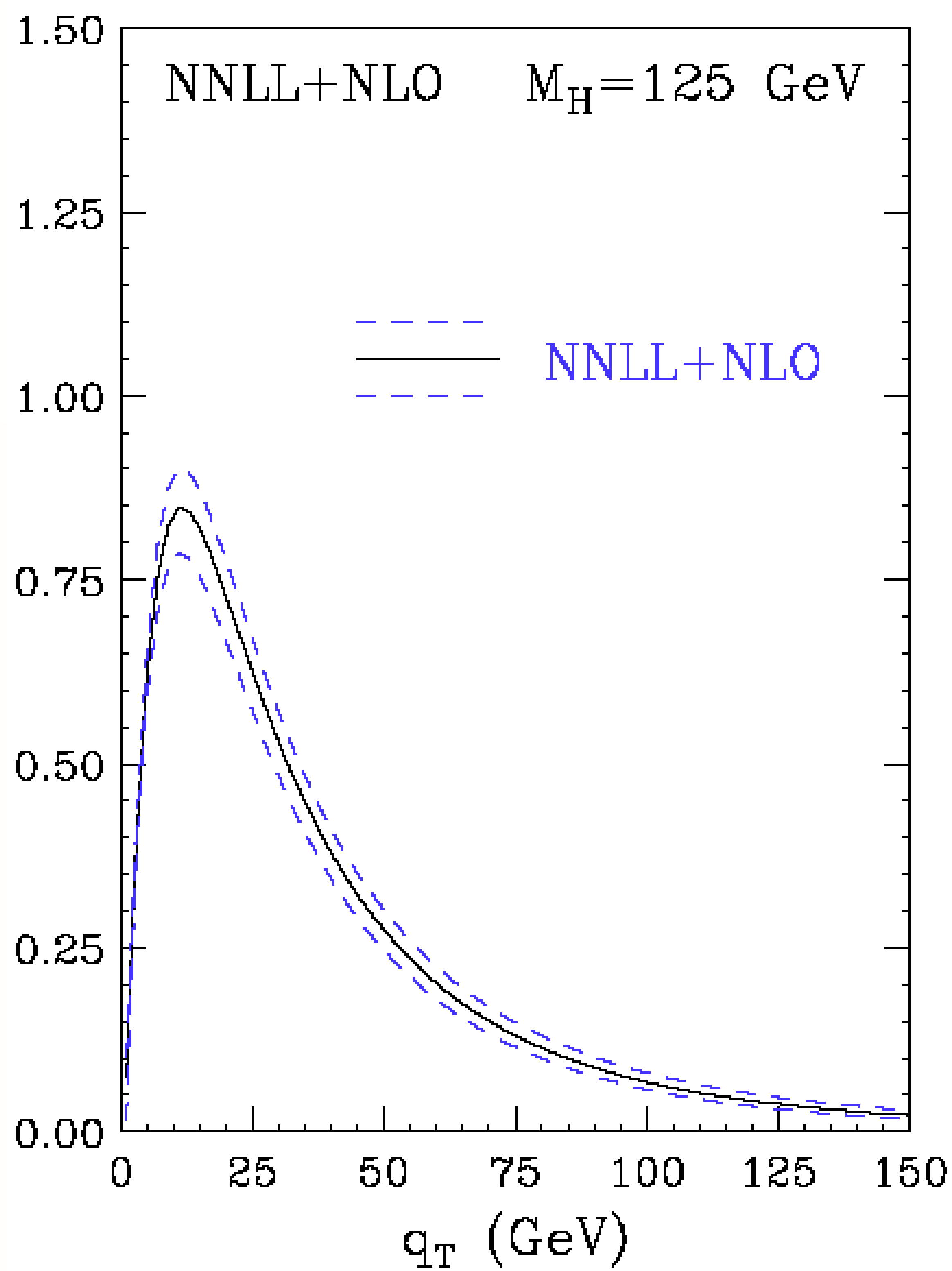
QCD corrections:
[Daswon.1991] [Djouadi, Graudenz, Spira, Zerwas. 1991]
[Kramer, Laenen, Spira.1998] [Catani, De Florian, Grazzini.2001]
[Harlander, Kilgore.2001,2002] [Anastasiou, Melnikov.2002]
[Ravindran,Smith, Van Neerven. 2003]
[Catani, De Florian, Grazzini, Nason.2003]

Two-loop EW corrections:
[Djouadi, Gambino, Kniehl. 1998]
[Aglietti, Bonciani, Degrassi, Vicini. 2004]
[Degrassi, FM. 2004]
[Actis, Passarino, Sturm, Uccirati, 2008]

PDF evolution at NNLO (“Guinness of QCD”):
[Moch, Vogt, Vermaseren, 2004]

Best QCD predictions at present:
> Fully exclusive (PS interfaced) prediction
at NLO+NLL in MC@NLO, POWHEG and SHERPA
> Fully exclusive prediction at NNLO (HNNLO and
> Resummed pt distribution at NLO+NNLL

$gg \to H$



Dominant production mechanism at hadron colliders.
The story of the most accurate prediction in QCD:

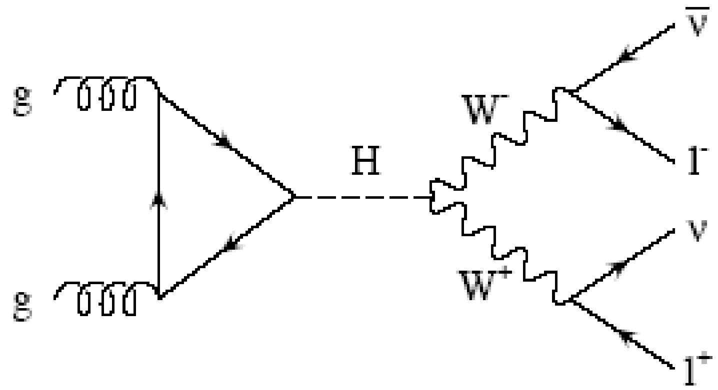
QCD corrections:
[Daswon.1991] [Djouadi, Graudenz, Spira, Zerwas. 1991]
[Kramer, Laenen, Spira.1998] [Catani, De Florian, Grazzini.2001]
[Harlander, Kilgore.2001,2002] [Anastasiou, Melnikov.2002]
[Ravindran,Smith,Van Neerven. 2003]
[Catani, De Florian, Grazzini, Nason.2003]

Two-loop EW corrections:
[Djouadi, Gambino, Kniehl. 1998]
[Aglietti, Bonciani, Degrassi,Vicini. 2004]
[Degrassi, FM. 2004]
[Actis, Passarino, Sturm, Uccirati, 2008]

PDF evolution at NNLO ("Guinness of QCD"):
[Moch,Vogt,Vermaseren, 2004]

Best QCD predictions at present:
> Fully exclusive (PS interfaced) prediction
at NLO+NLL in MC@NLO, POWHEG and SHERPA
> Fully exclusive prediction at NNLO (HNNLO and
> Resummed pt distribution at NLO+NNLL

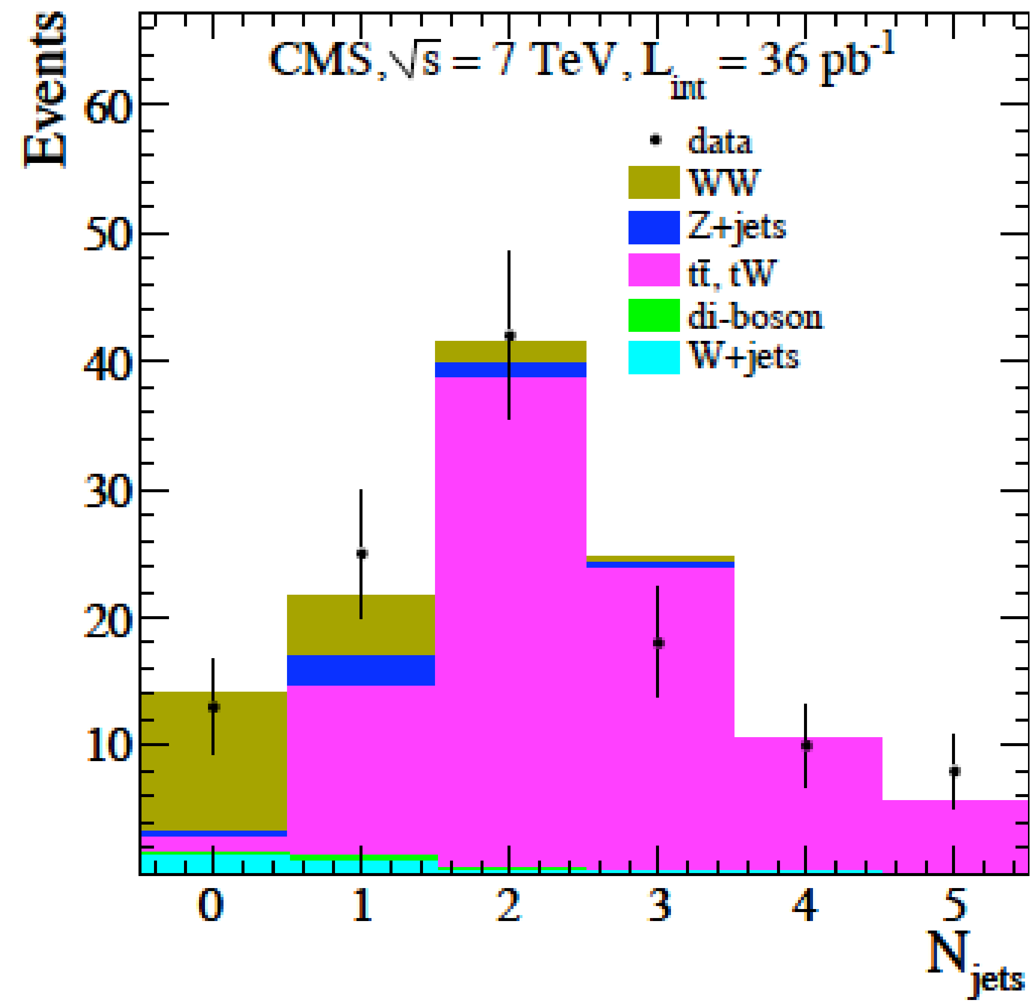
Search for the Higgs in $H \rightarrow W^+ W^-$



$$\text{Amp}(H \to \ell\ell\nu\nu) \propto (\ell^+ \cdot \bar{\nu})\,(\ell^- \cdot \nu)$$

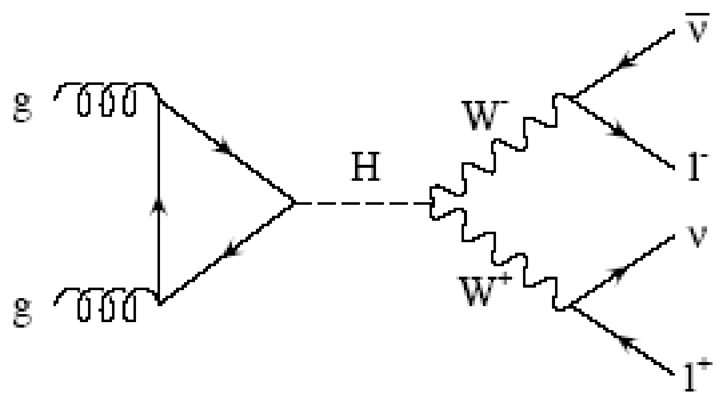
The amplitude is maximal when the leptons go in the same direction (Angular momentum conservation).

No other jets at LO!



We can curb the ttbar background by imposing a jet veto!
But additional uncertainties come in!

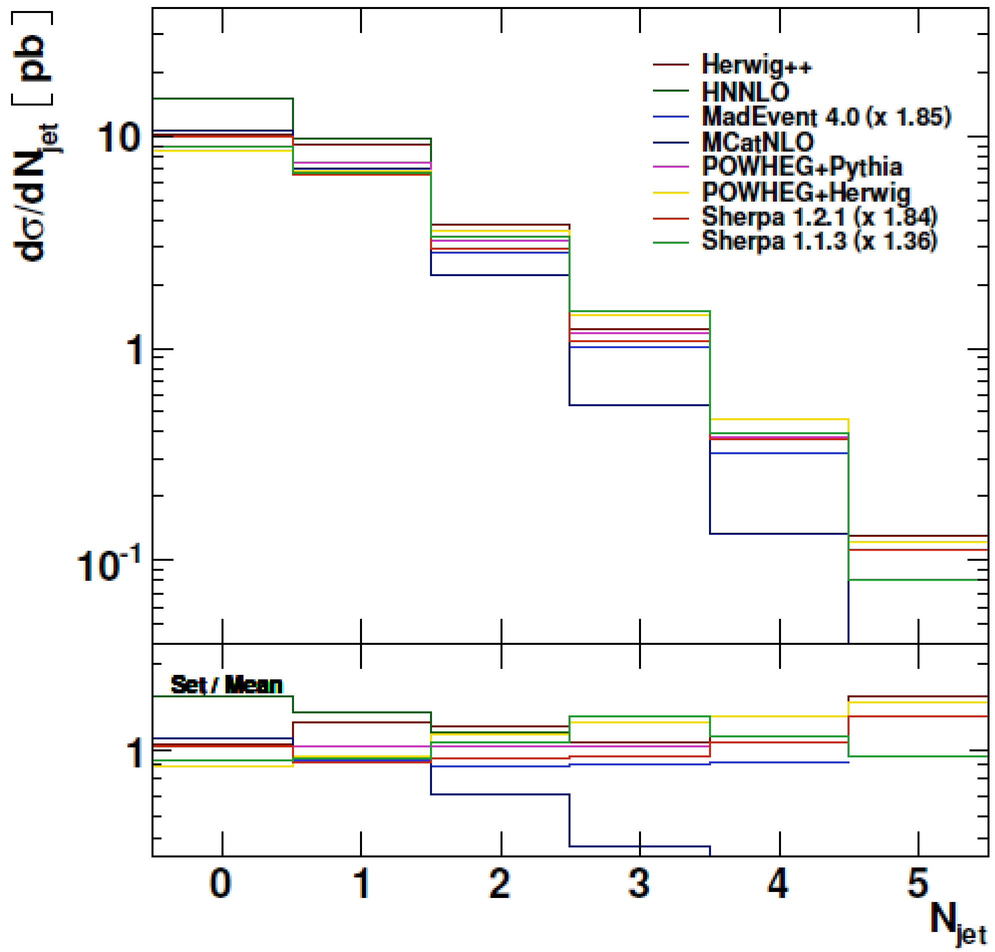
Search for the Higgs in H→W⁺W⁻



$$\mathrm{Amp}(H \to \ell\ell\nu\nu) \propto (\ell^+ \cdot \bar{\nu})\,(\ell^- \cdot \nu)$$

The amplitude is maximal when the leptons go in the same direction (Angular momentum conservation).

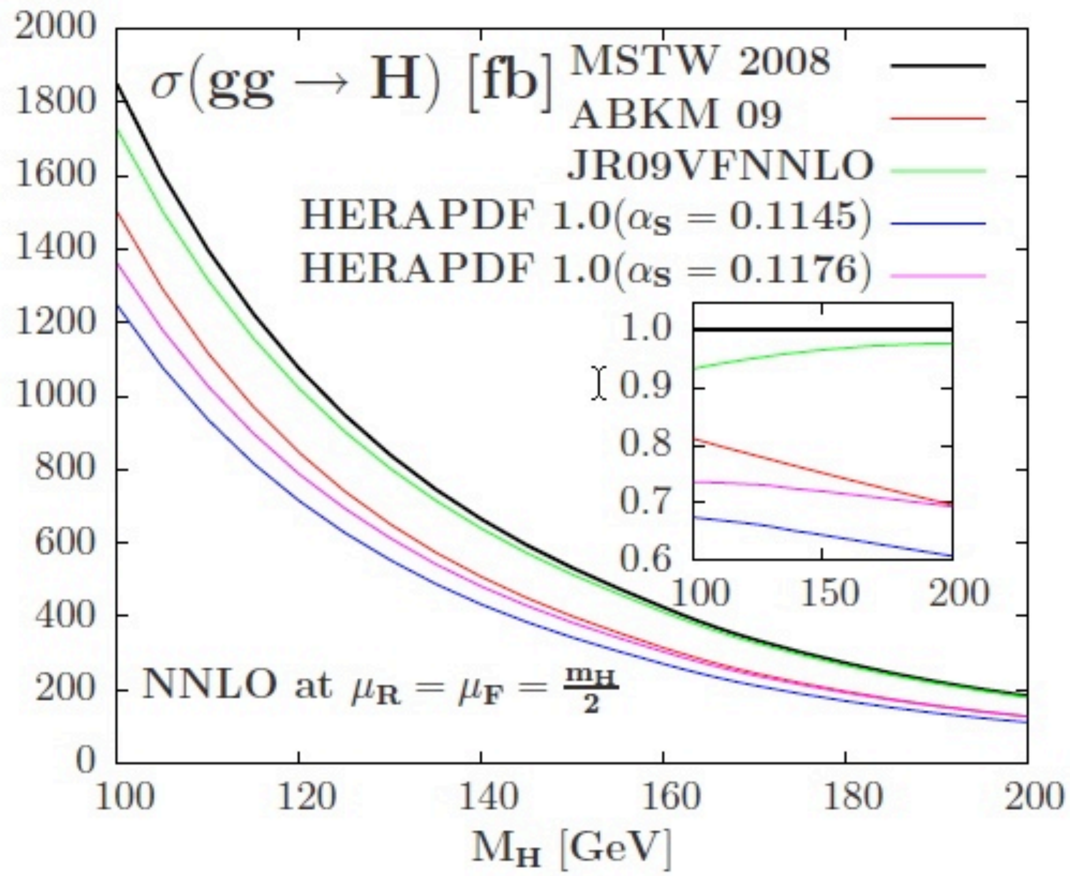
No other jets at LO!

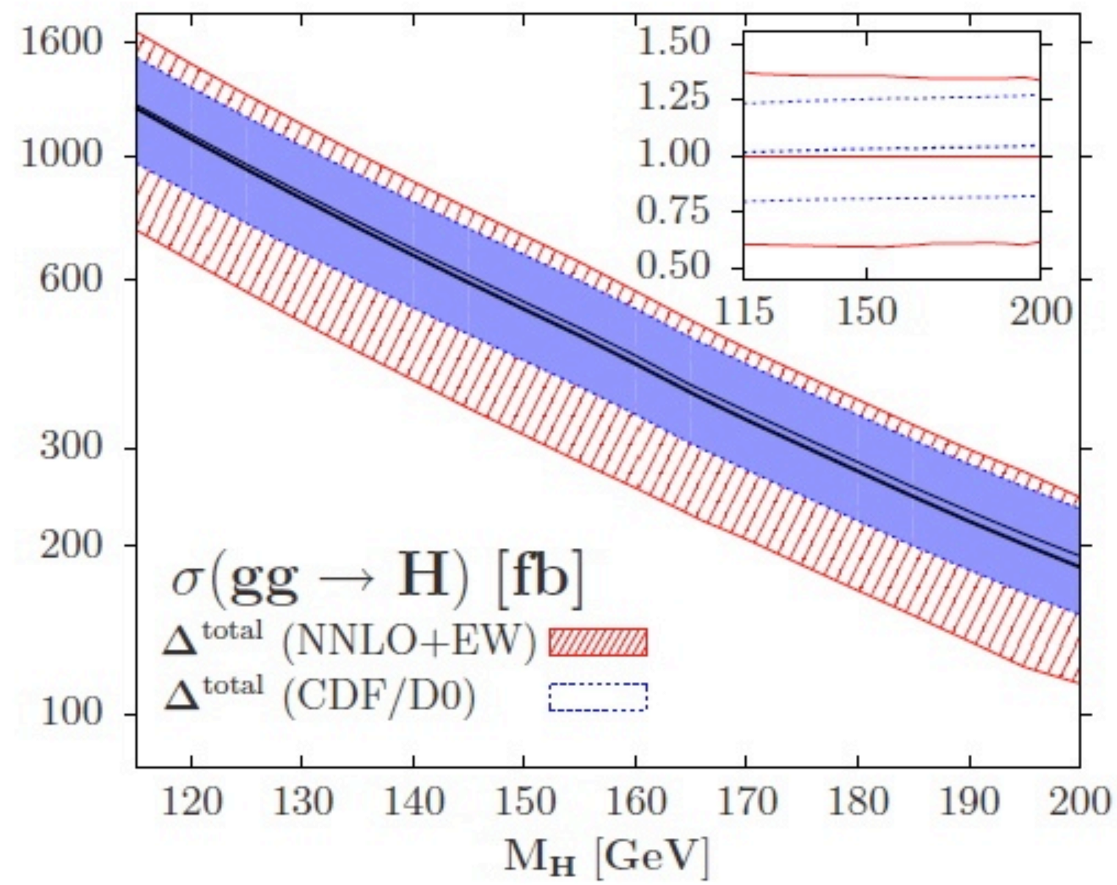


We can curb the ttbar background by imposing a jet veto!
But additional uncertainties come in!

The Higgs exclusion : discussion

[Baglio, Djouadi, et al., 2010]

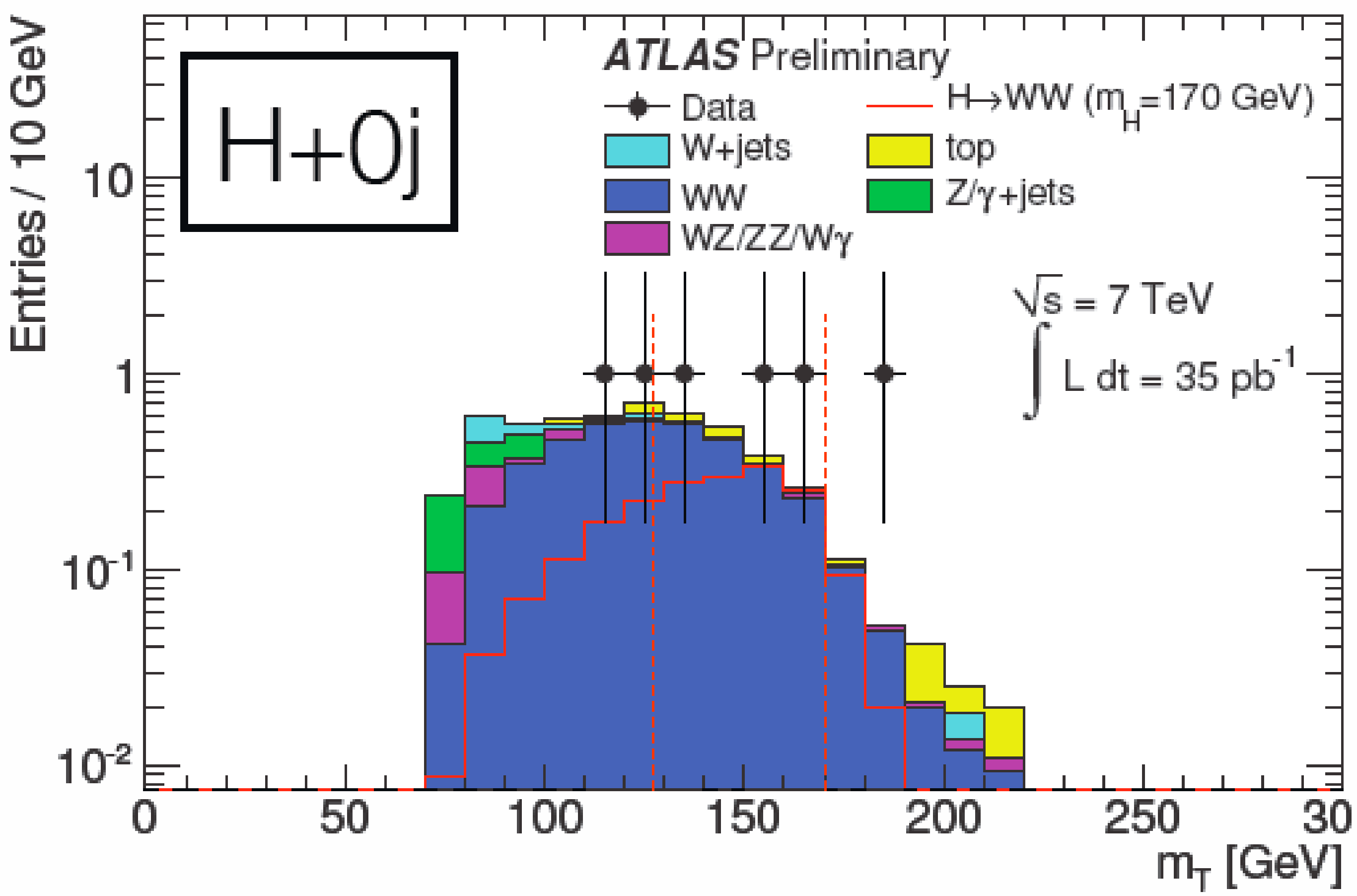




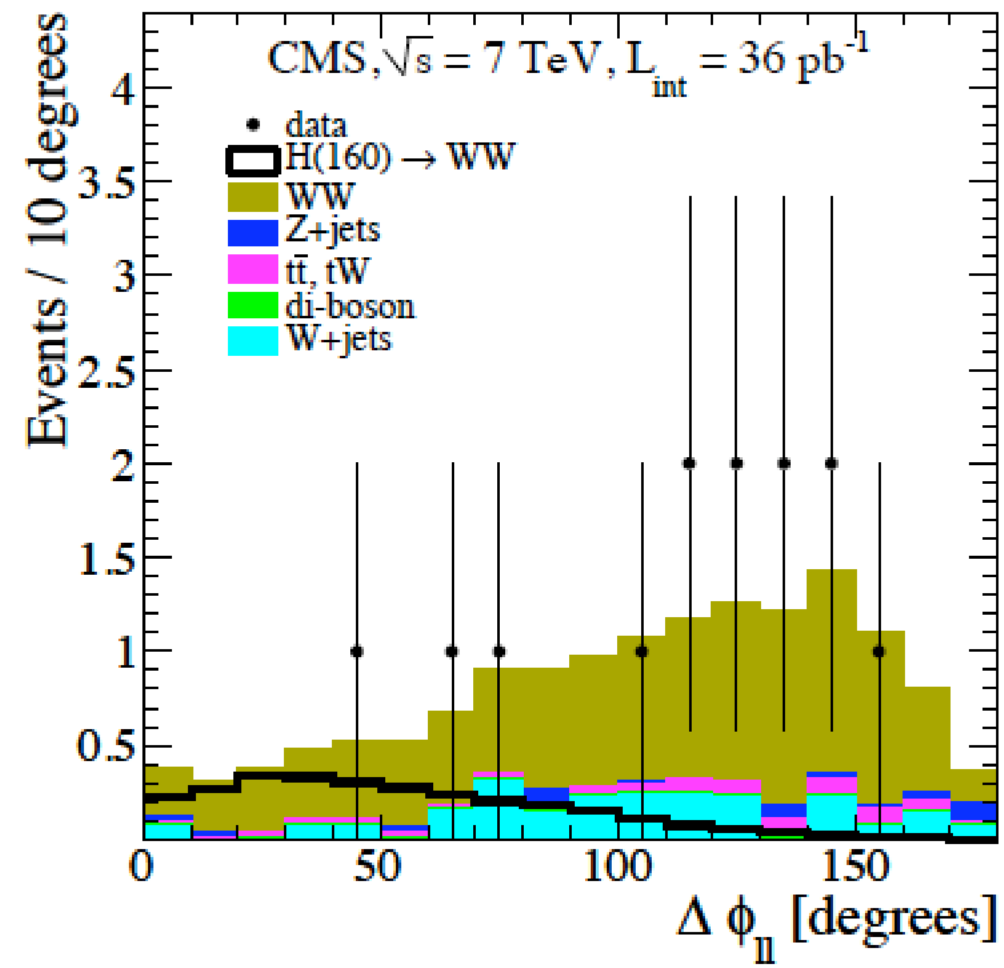
1. Scale uncertainty ⇒ from 10 to 20%
2. PDF uncertainties ⇒from 10 to 40%
3. EFT uncertainties ⇒ 5%

Uncertainties underestimated at Tevatron?

Search for the Higgs in $H \to W^+ W^-$

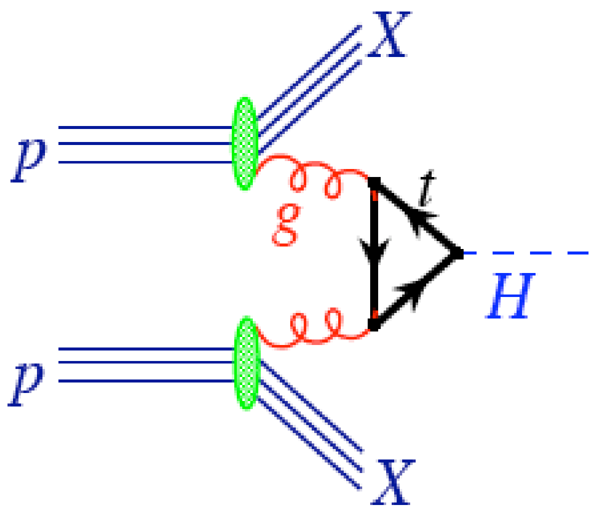


$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$

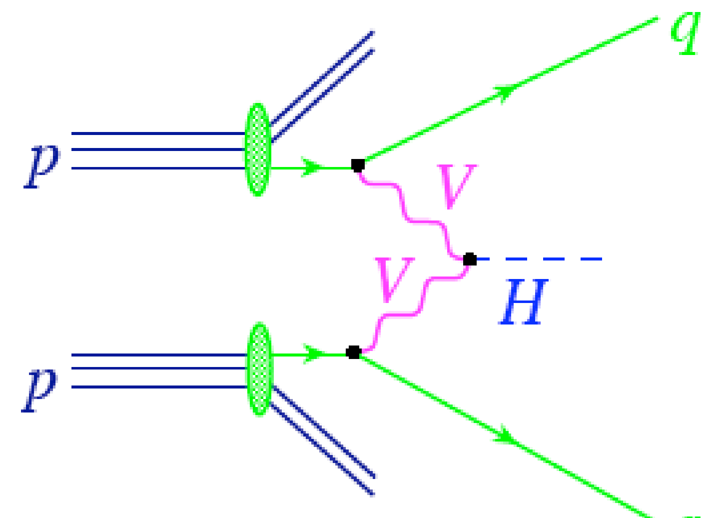


First results already from ATLAS and CMS!!!

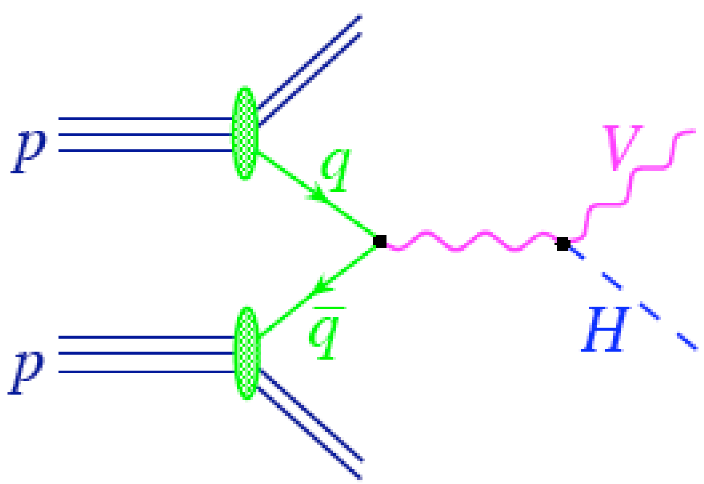
Higgs production at hadron colliders



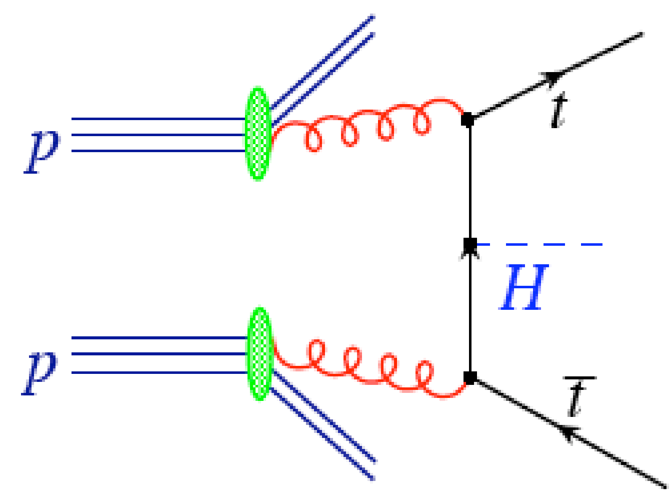
Gluon fusion



Weak-Boson Fusion

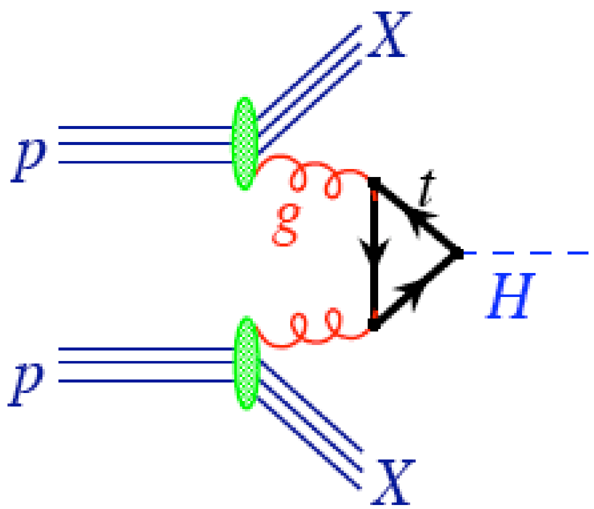


Higgs Strahlung

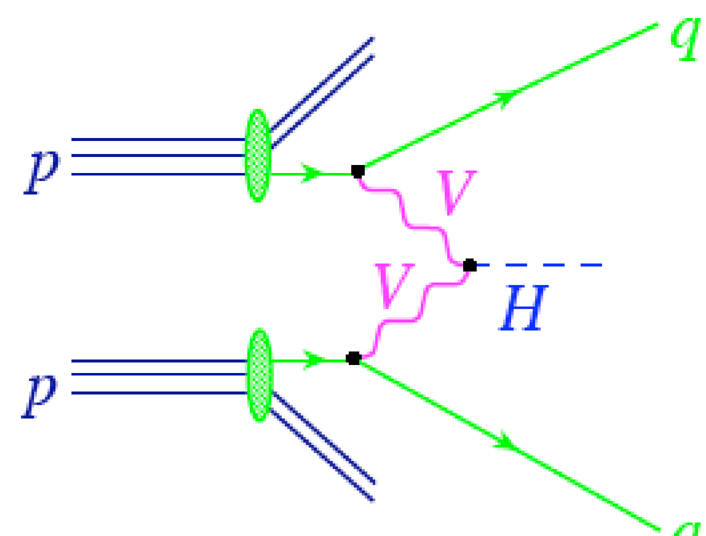


$t\bar{t}H$

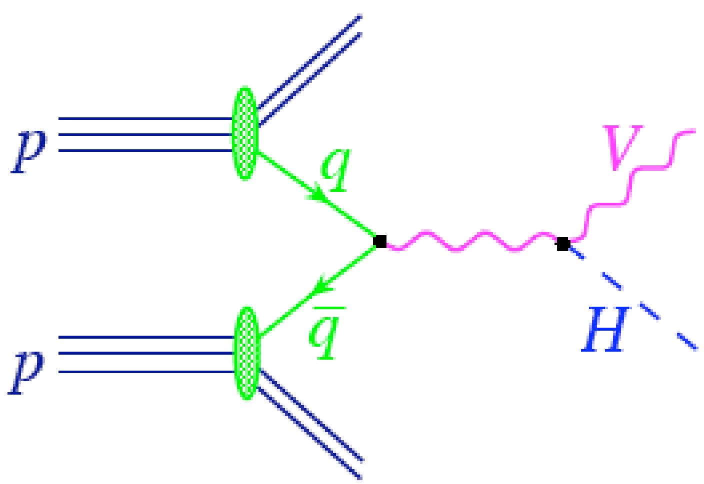
Higgs production at hadron colliders



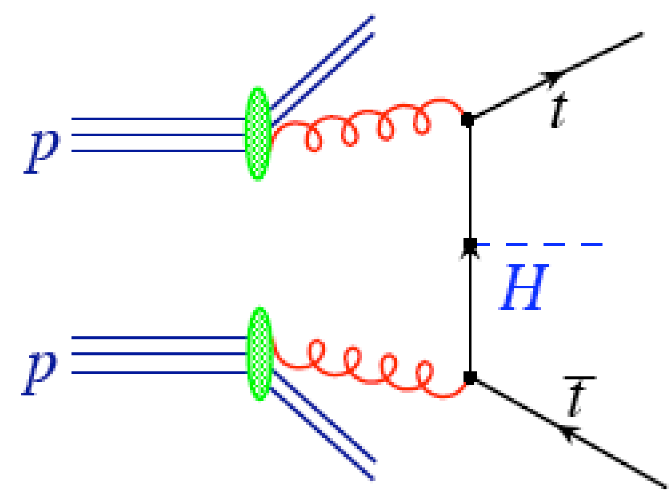
Gluon fusion



Weak-Boson Fusion



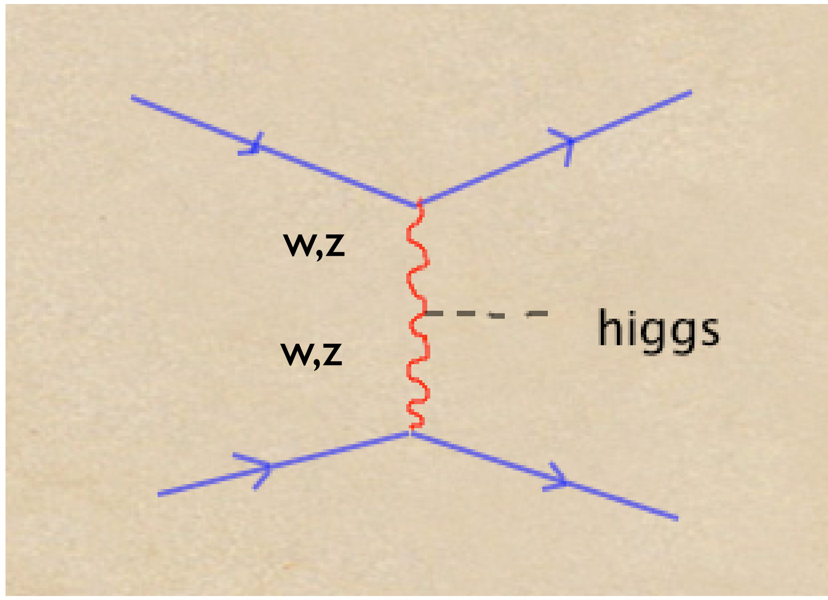
Higgs Strahlung



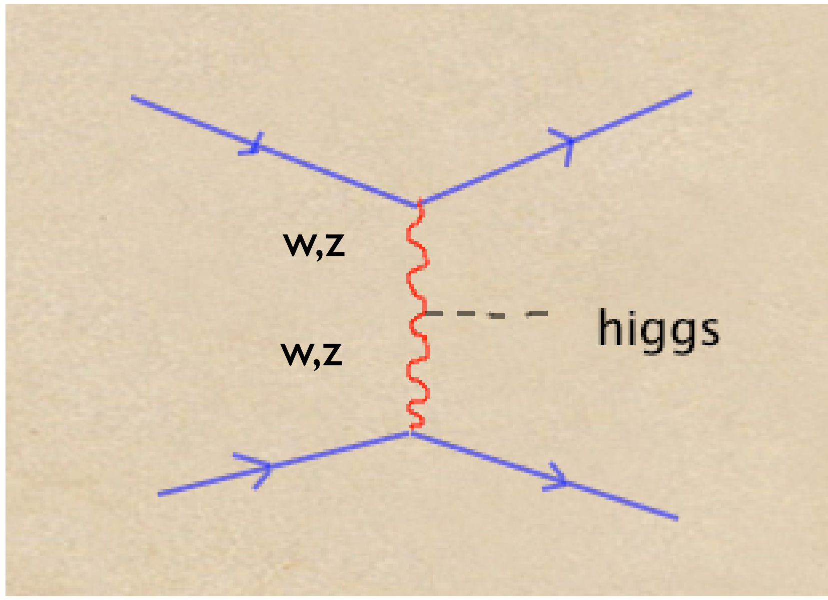
$t\bar{t}H$

VBF

VBF

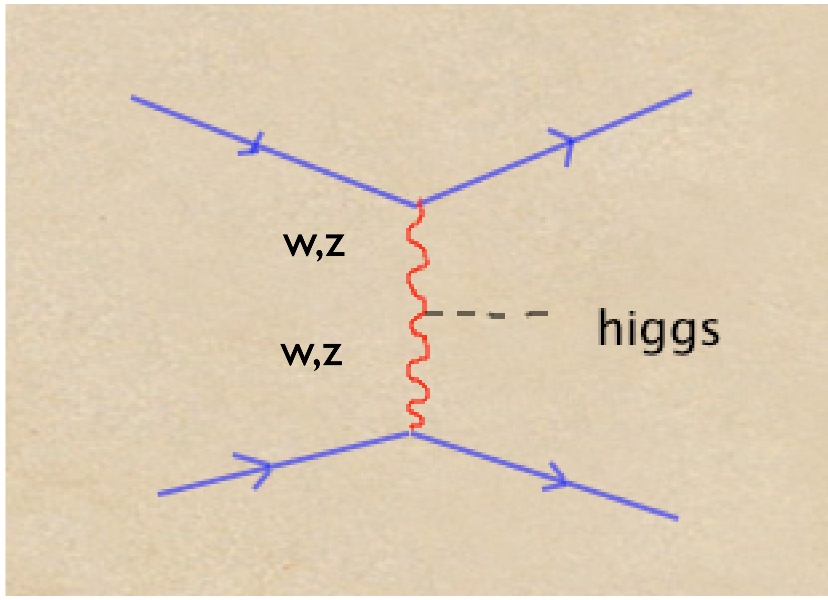


VBF



Facts:

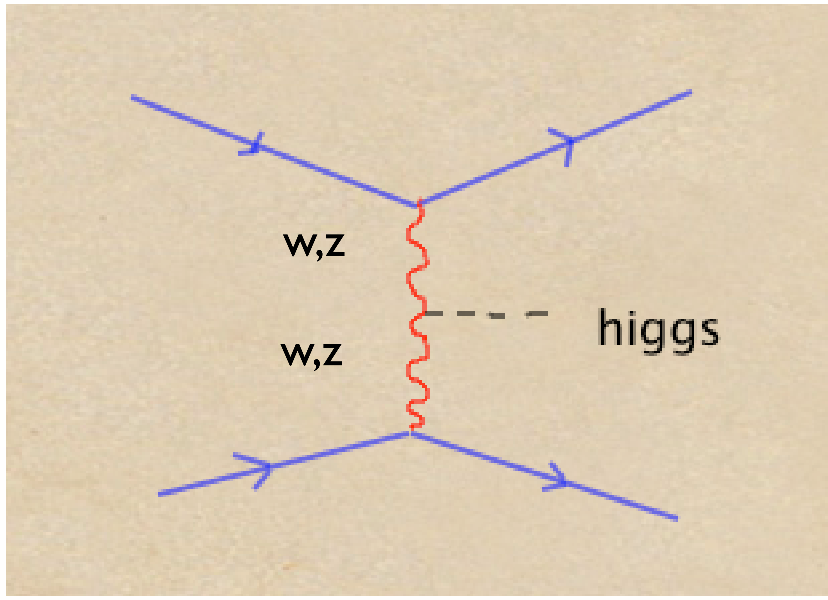
VBF



Facts:

1. Important channel for light Higgs both for discovery and measurement

VBF

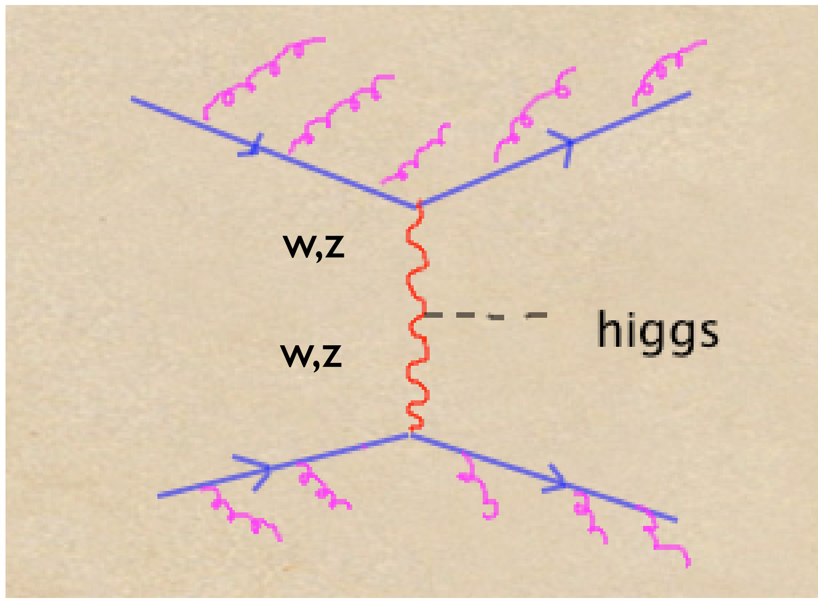


Facts:

1. Important channel for light Higgs both for discovery and measurement

2. Color singlet exchange in the t-channel

VBF

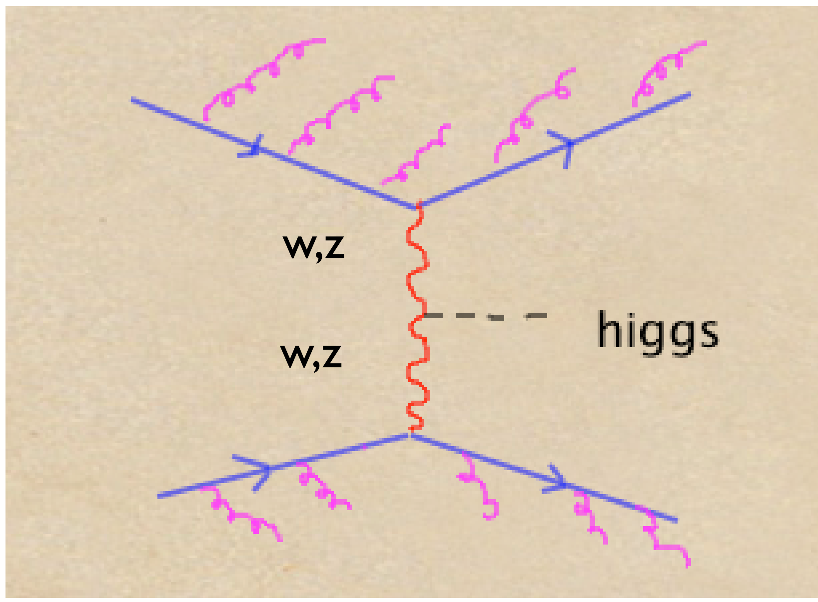


Facts:

1. Important channel for light Higgs both for discovery and measurement

2. Color singlet exchange in the t-channel

VBF



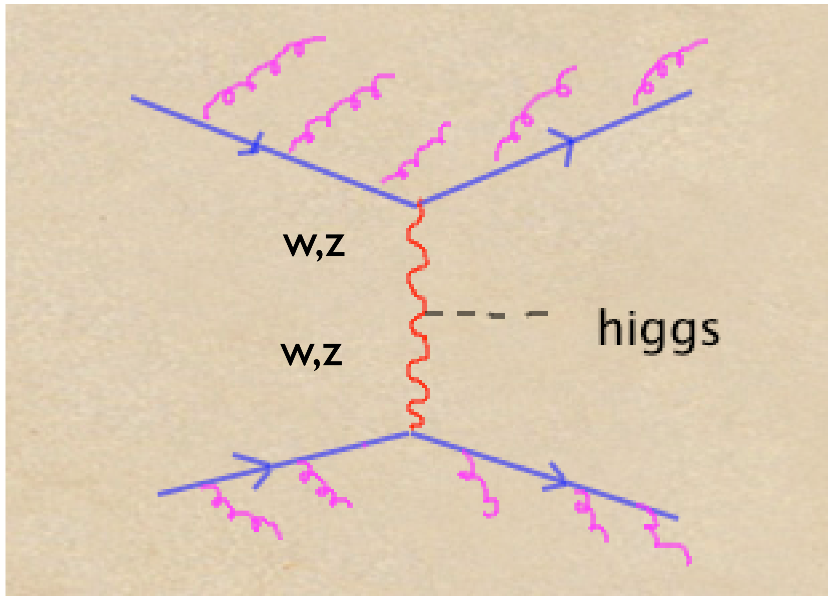
Facts:

1. Important channel for light Higgs both for discovery and measurement

2. Color singlet exchange in the t-channel

3. Characteristic signature: forward-backward jets + RAPIDITY GAP

VBF

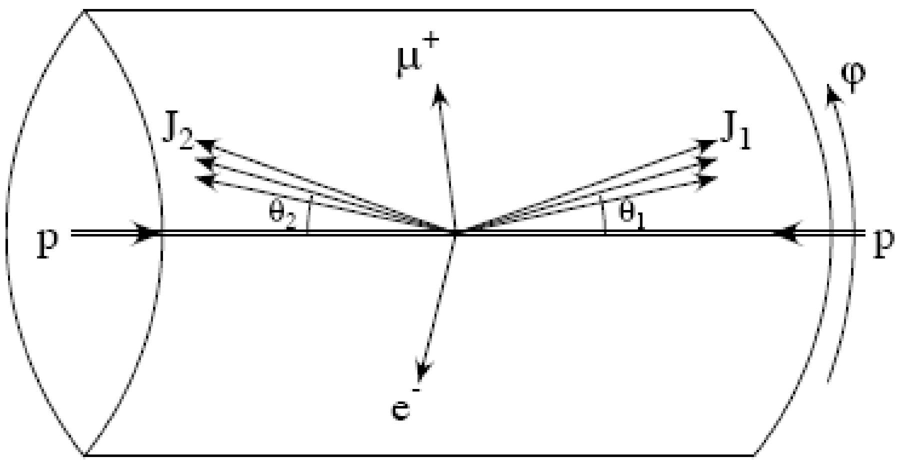


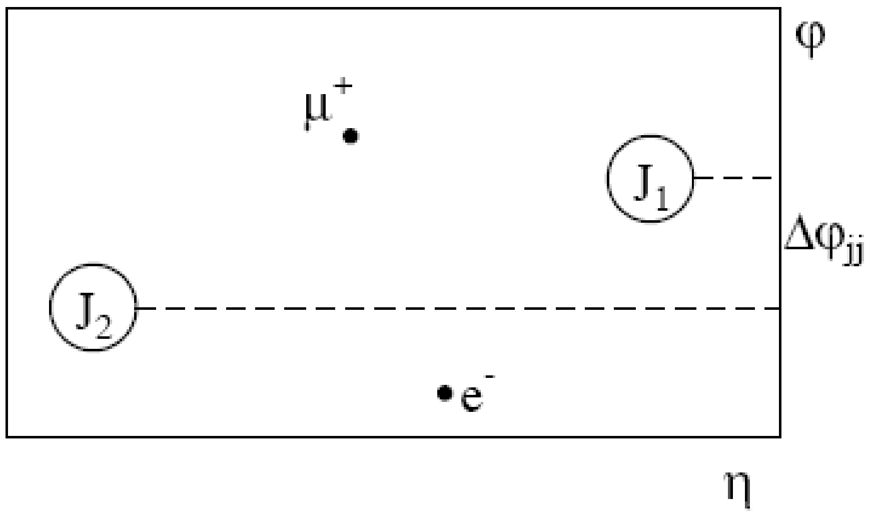
Facts:

1. Important channel for light Higgs both for discovery and measurement

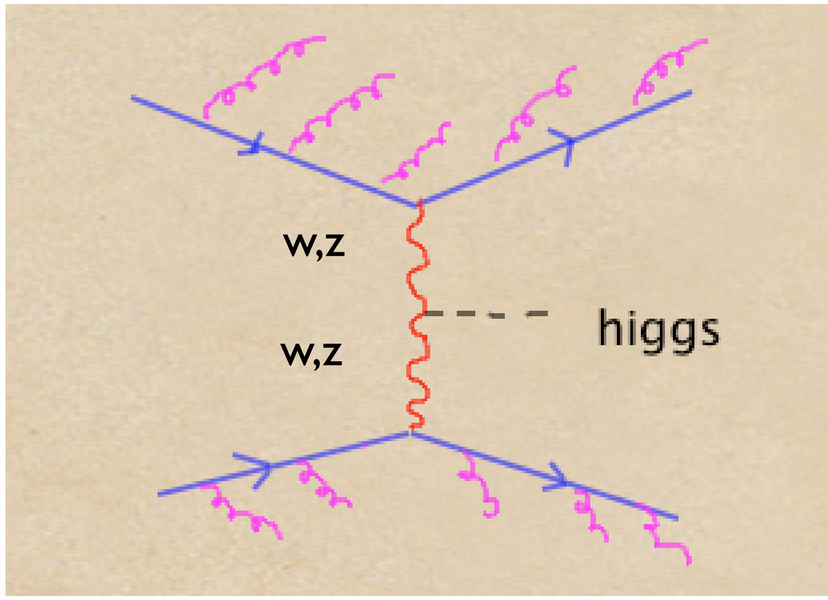
2. Color singlet exchange in the t-channel

3. Characteristic signature: forward-backward jets + RAPIDITY GAP





VBF



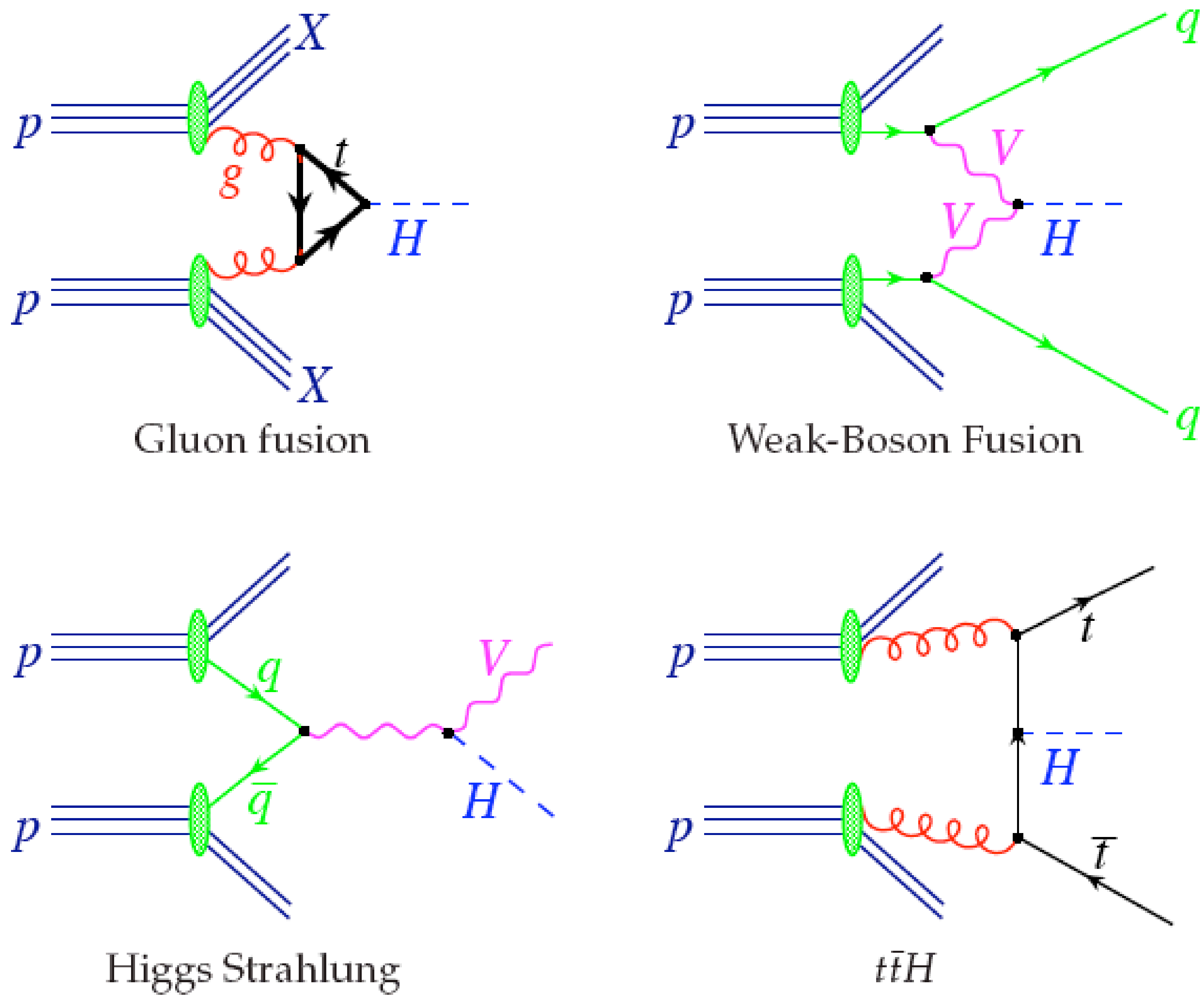
Facts:

1. Important channel for light Higgs
both for discovery and measurement

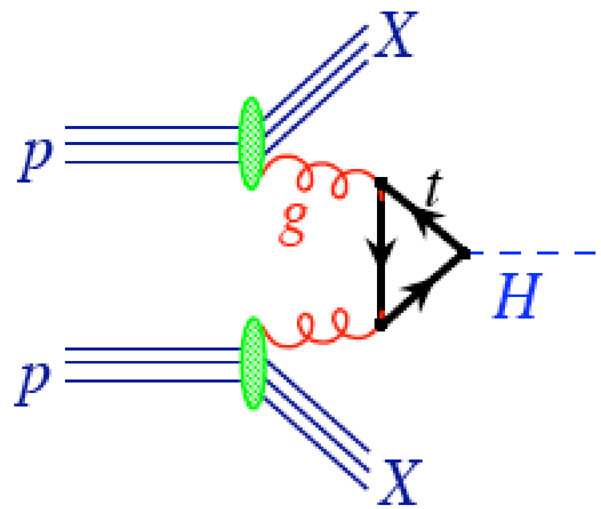
2. Color singlet exchange in the t-channel

3. Characteristic signature:
forward-backward jets + RAPIDITY GAP

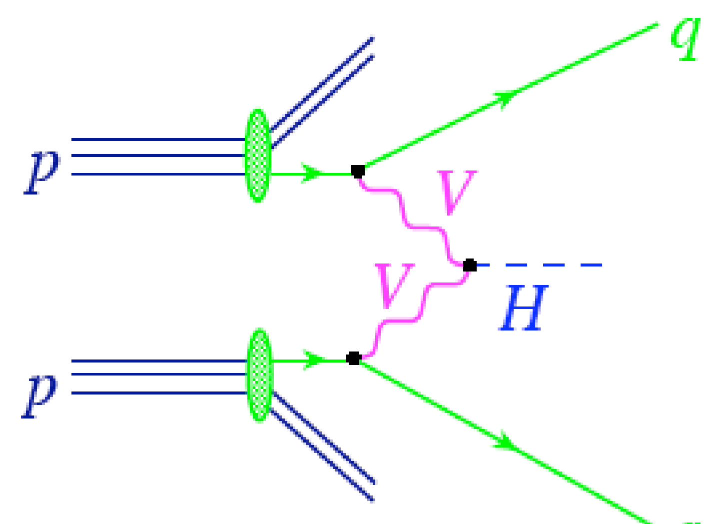
Higgs production at hadron colliders



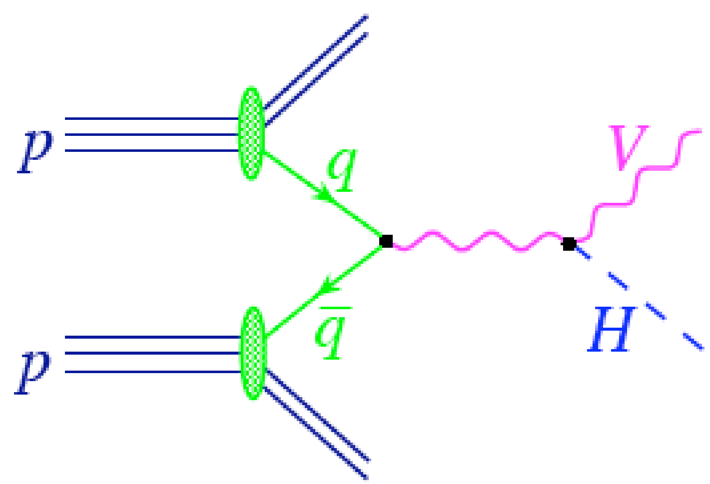
Higgs production at hadron colliders



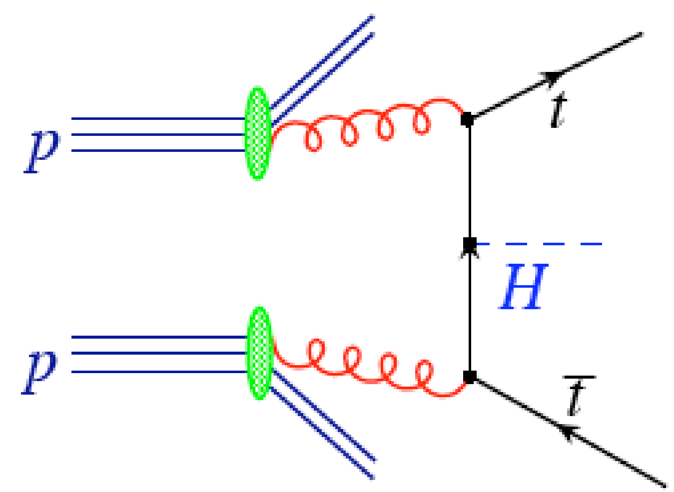
Gluon fusion



Weak-Boson Fusion

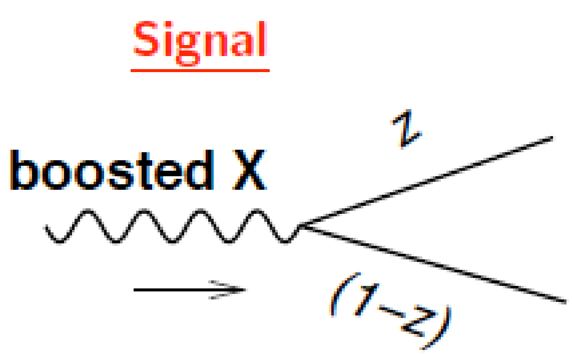


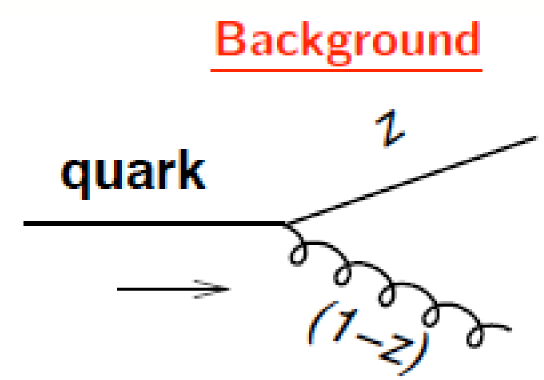
Higgs Strahlung



$t\bar{t}H$

Boosted Higgs





$P(z) \propto 1$

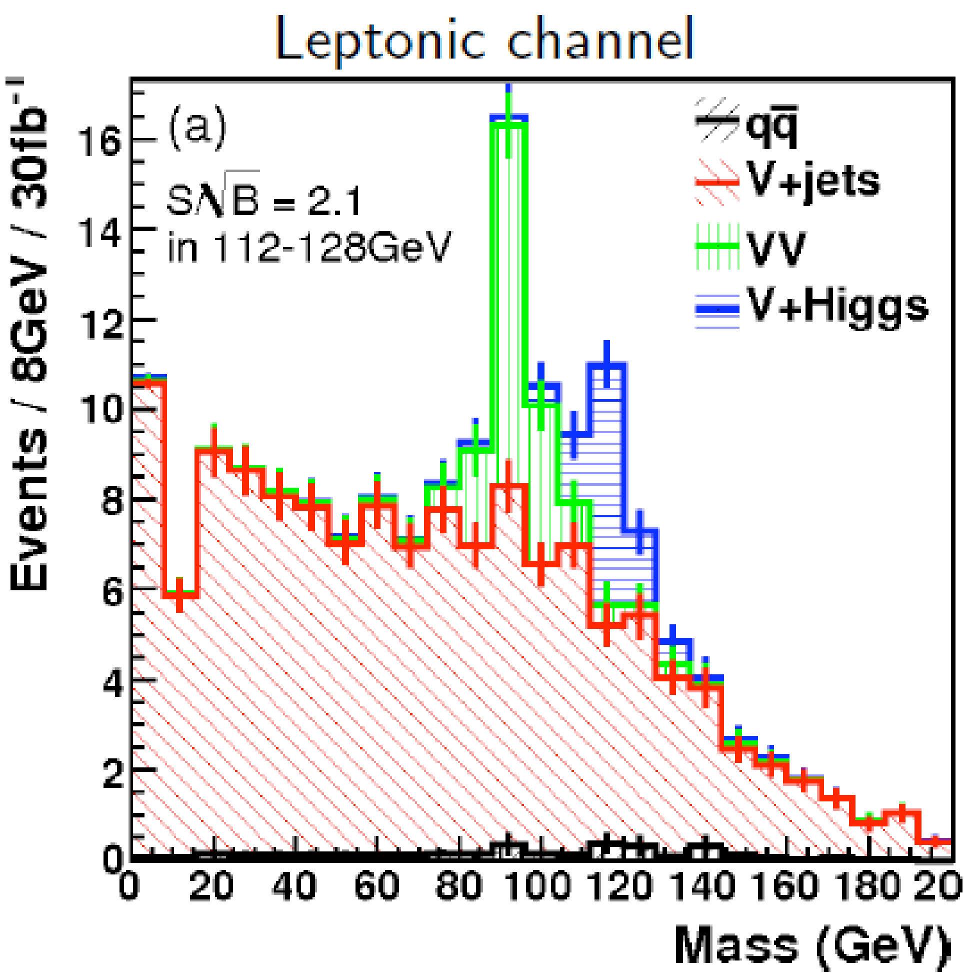
$P(z) \propto \frac{1+z^2}{1-z}$

1. Heavy-object decays share energy symmetrically, QCD background events with same mass share energy asymmetrically.

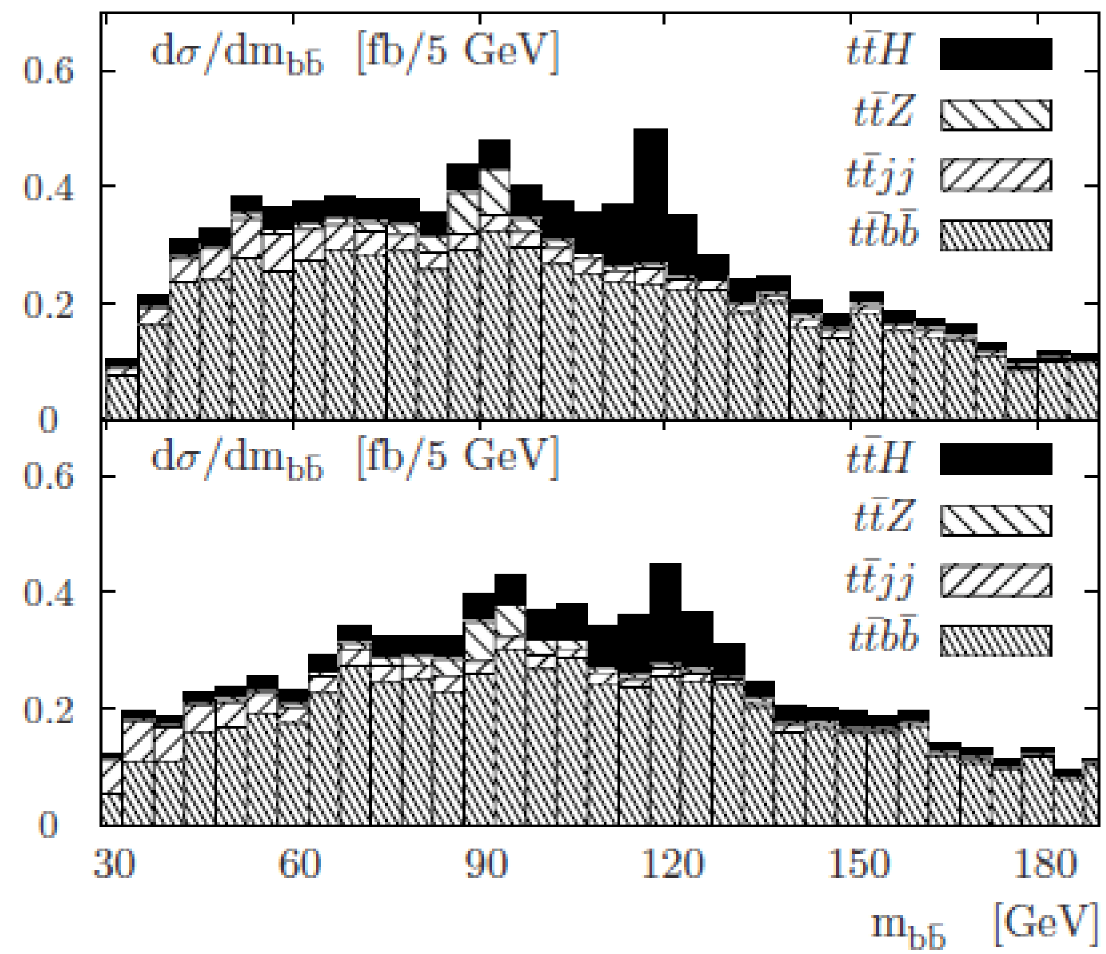
2. QCD radiation from a colour-neutral heavy-object decay is limited by angular ordering.

3. QCD radiation from Higgs decay products is point-like, noise (UE, pileup) is diffuse.

Boosted Higgs



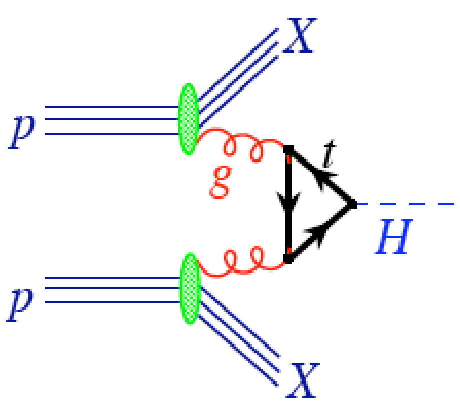
[Butterworth, Davison, Salam, Rubin, 2008]



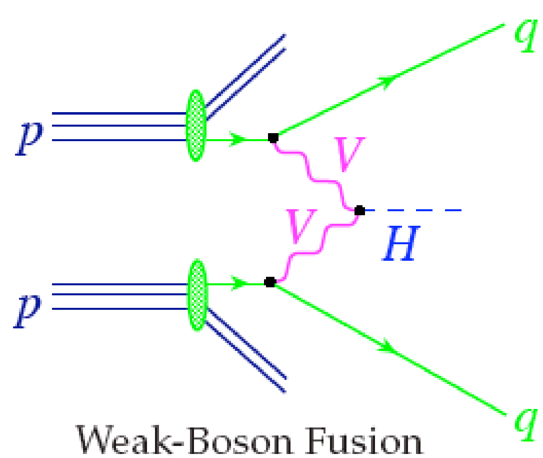
[Plehn, Salam, Spannowsky, 2010]

Promising with enough luminosity for both VH and ttH

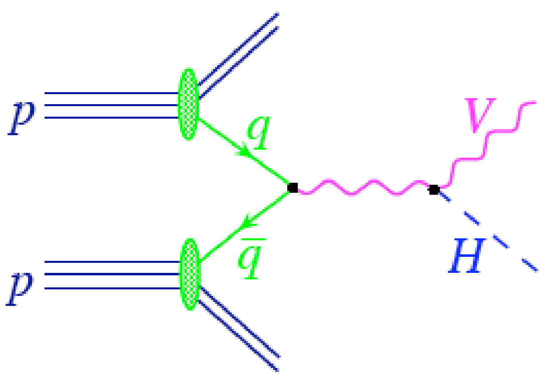
The Higgs channel game



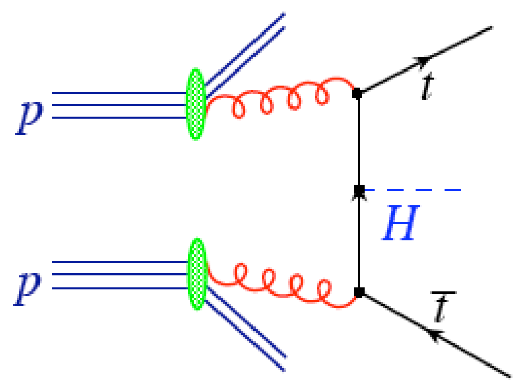
Gluon fusion



Weak-Boson Fusion

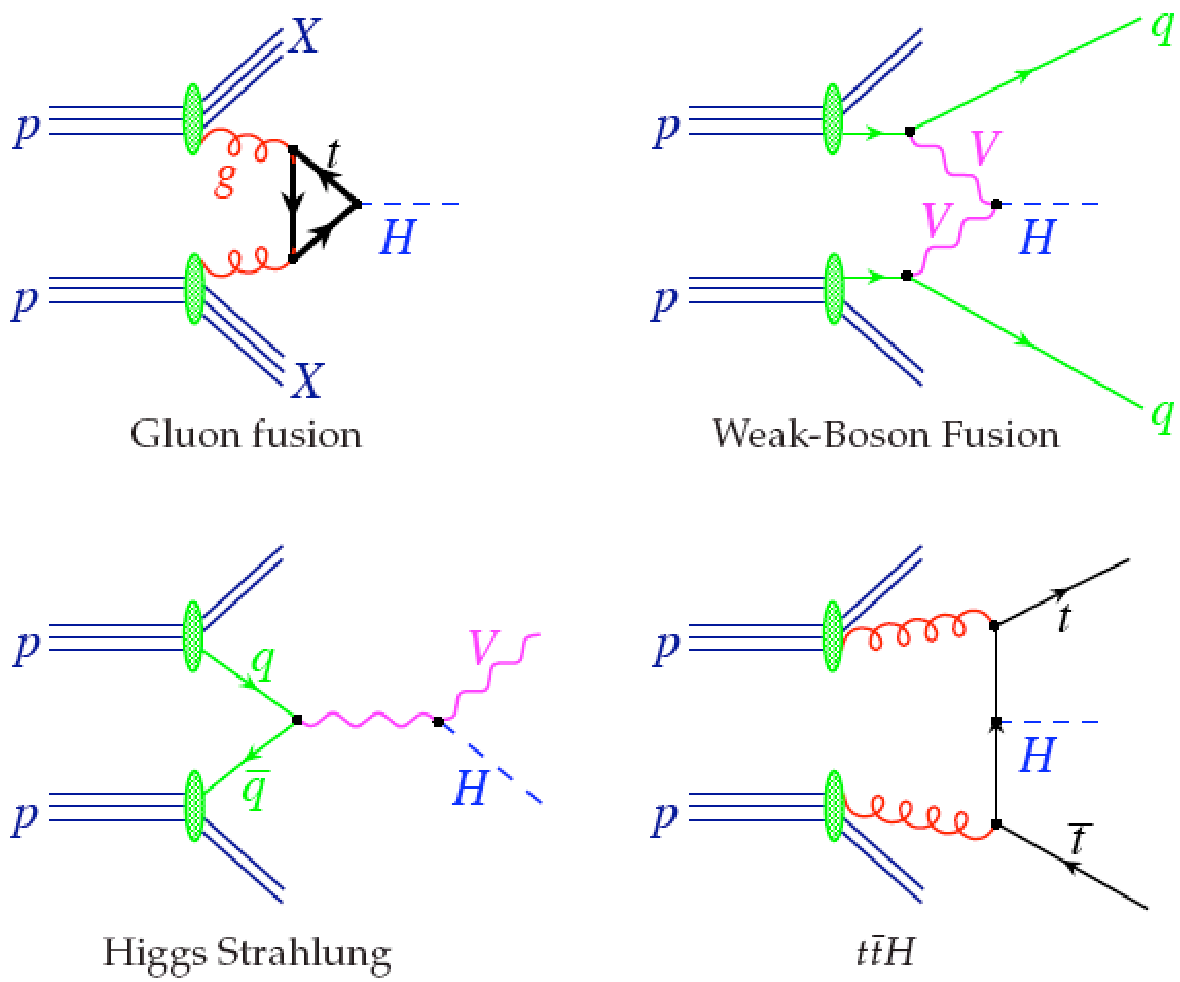


Higgs Strahlung



$t\bar{t}H$

The Higgs channel game



Bottom line:

QCD radiation plays a

key role

in ALL Higgs searches

at the LHC !