



Outlook: Precision Higgs Physics

Robert Harlander

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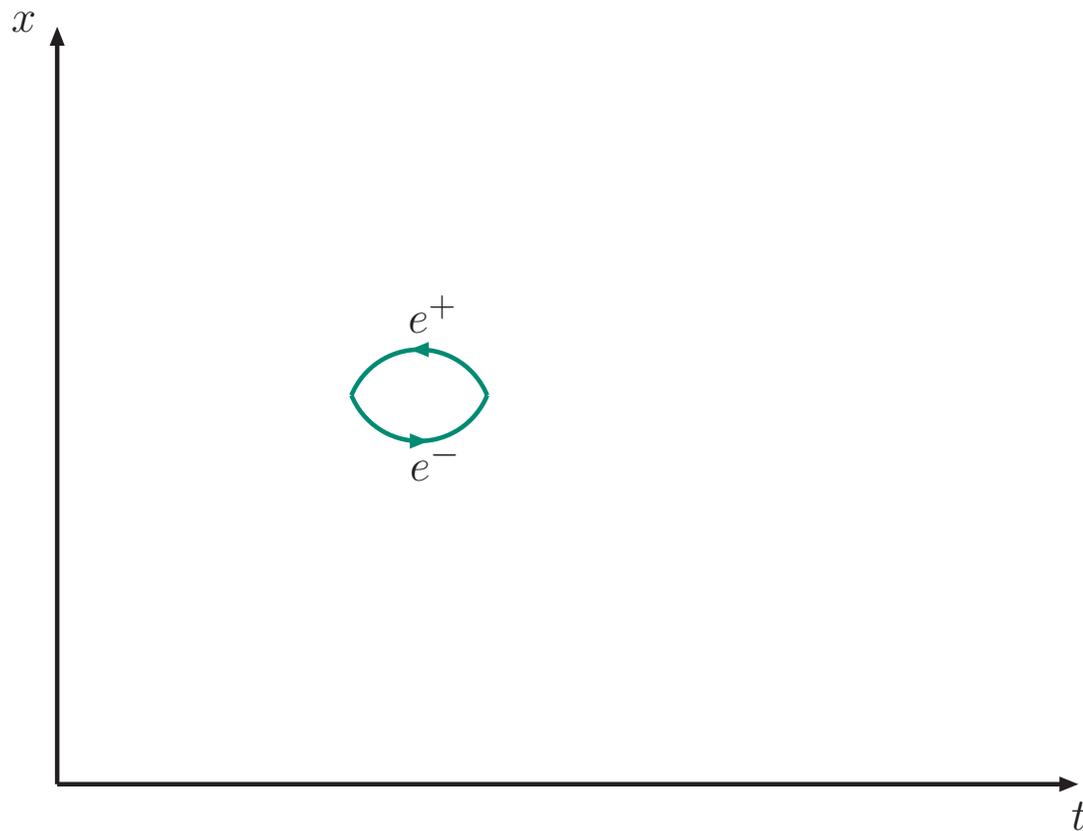
Workshop on Higgs Boson Phenomenology

Zürich, Jan 7–9, 2009

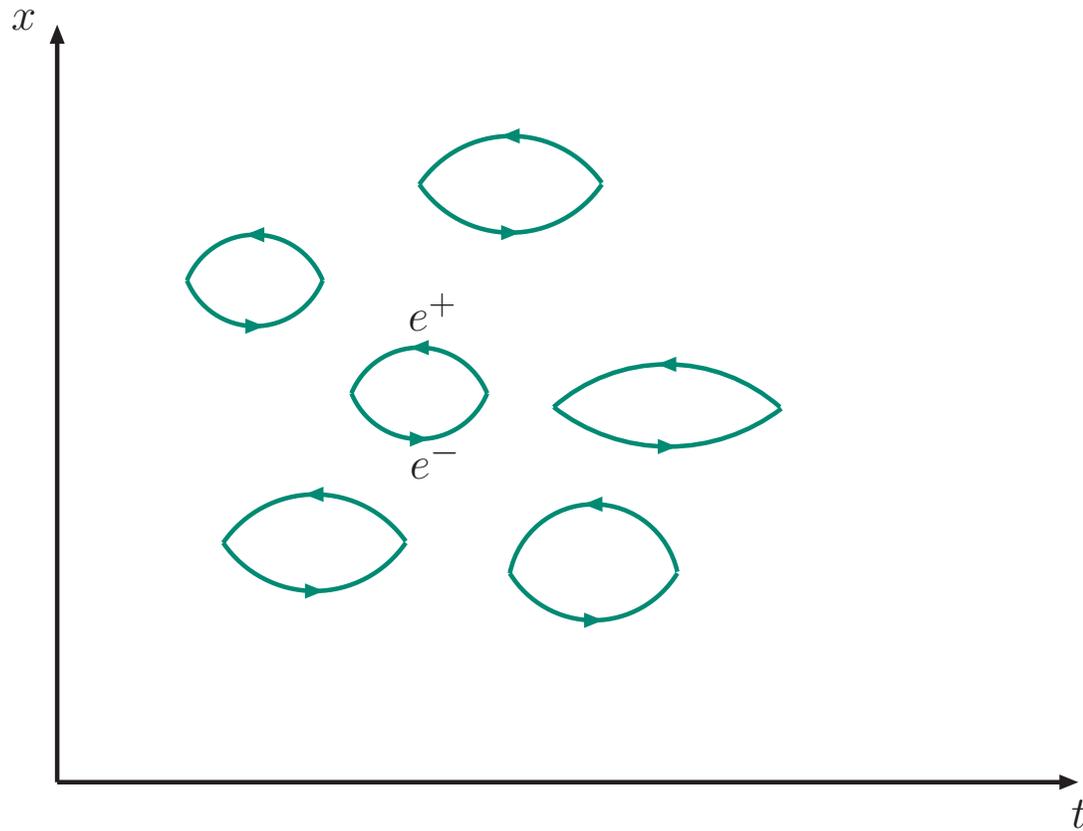
Vacuum



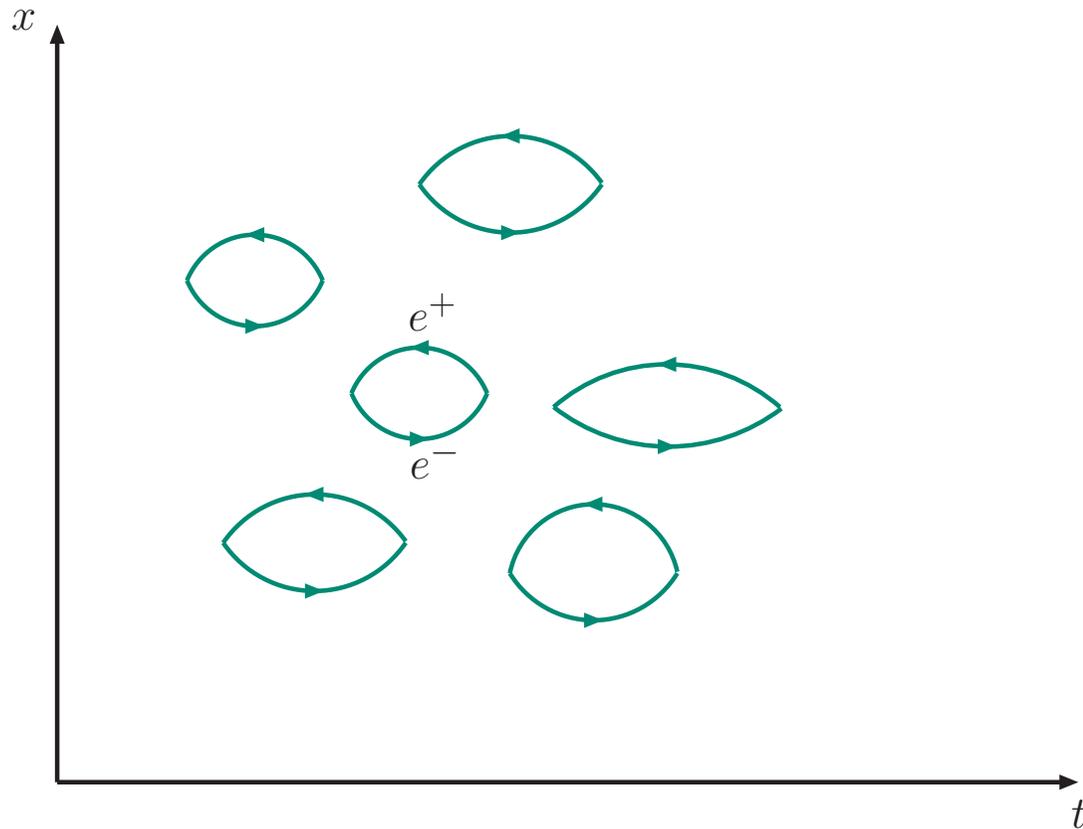
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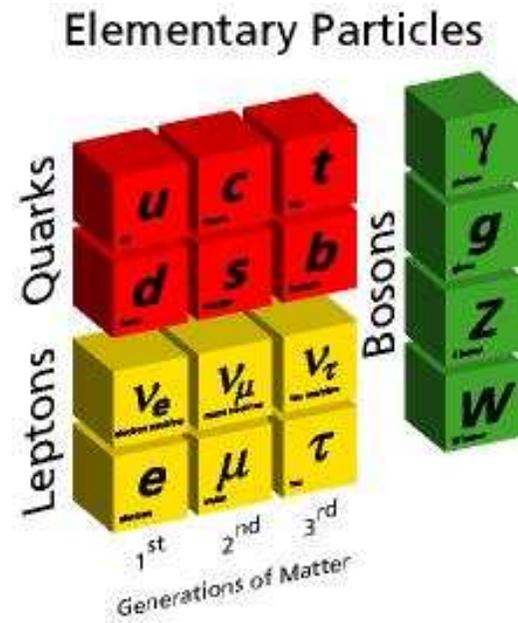
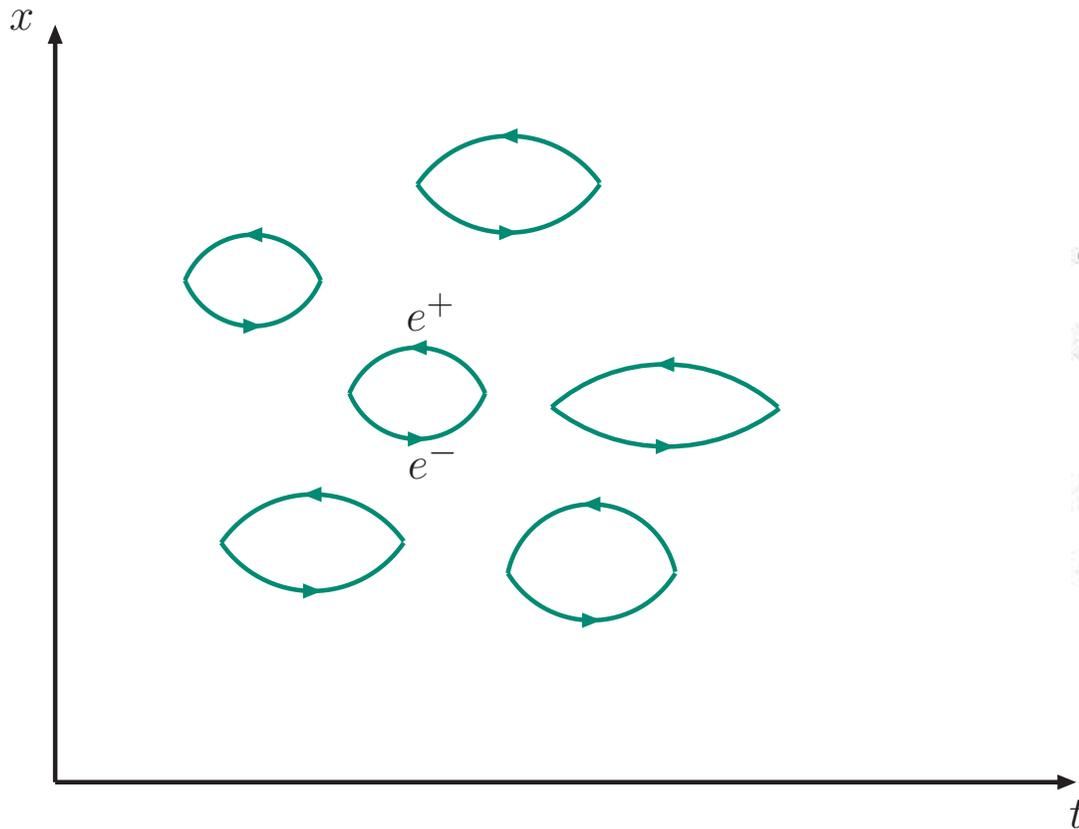
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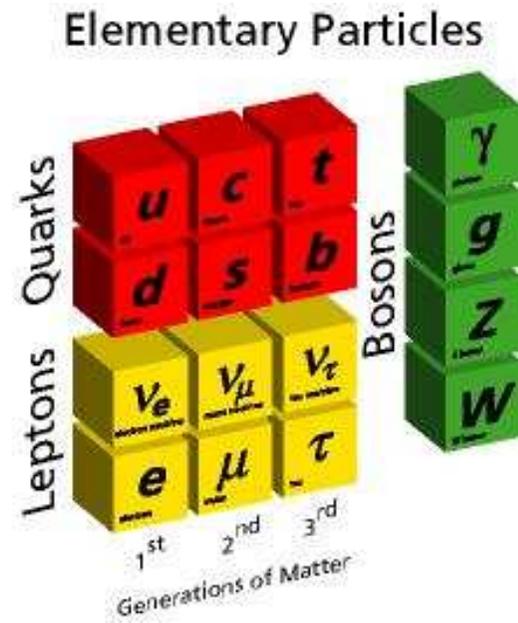
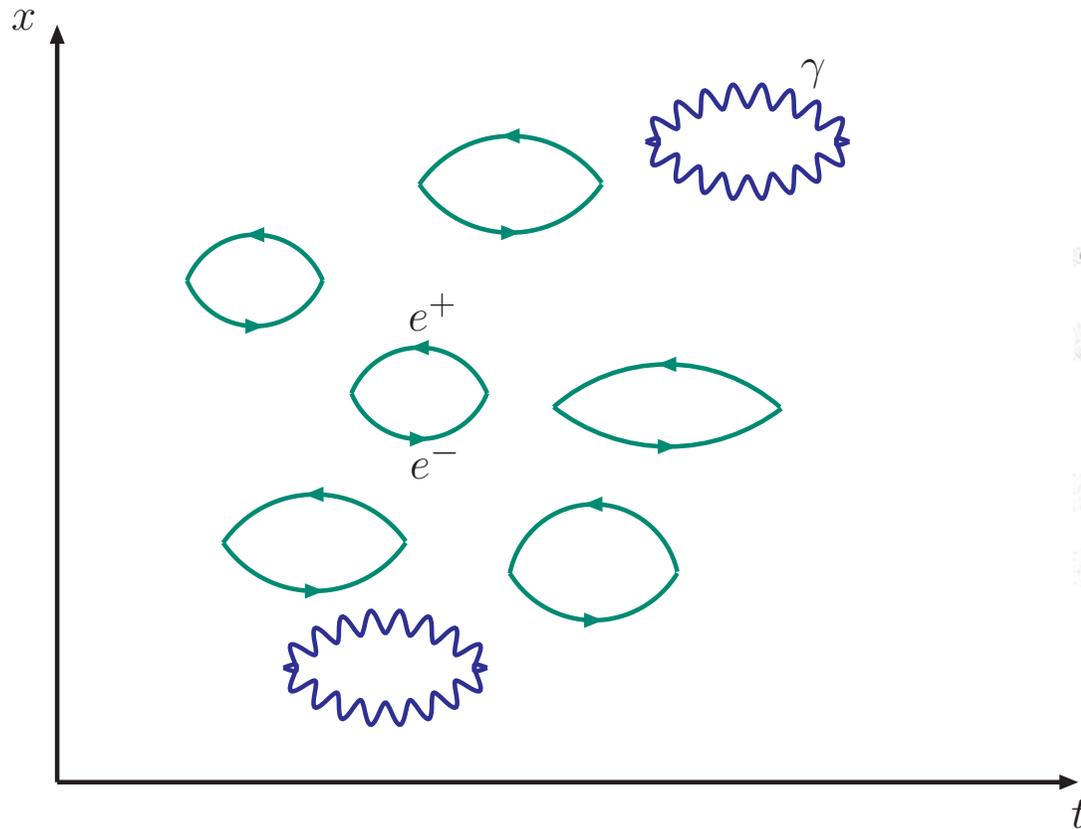
Vacuum fluctuations



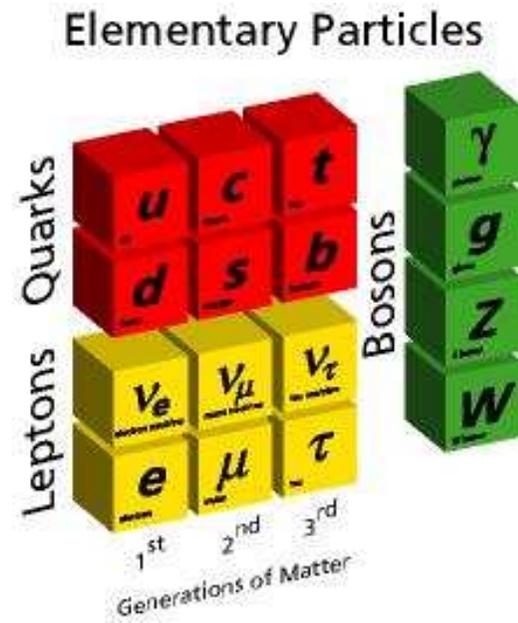
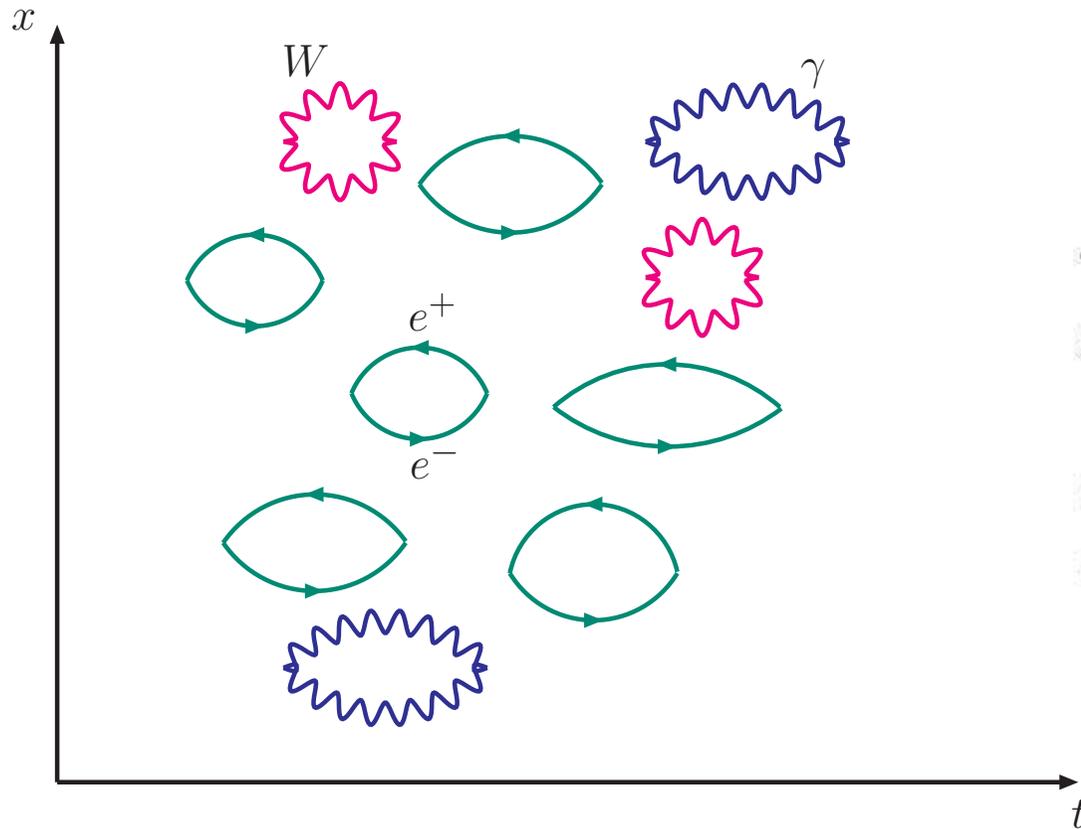
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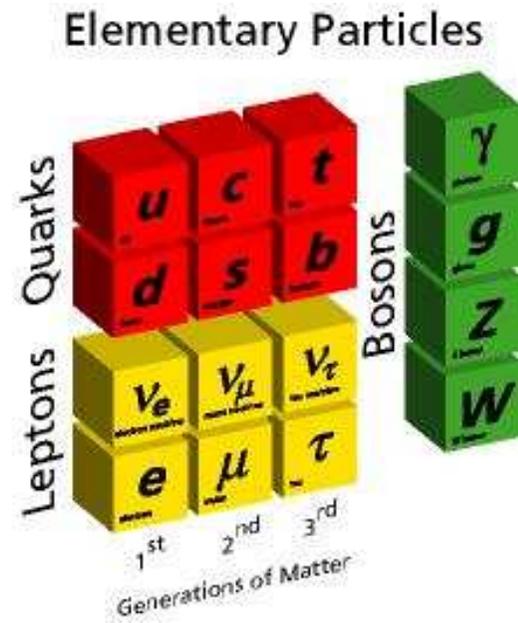
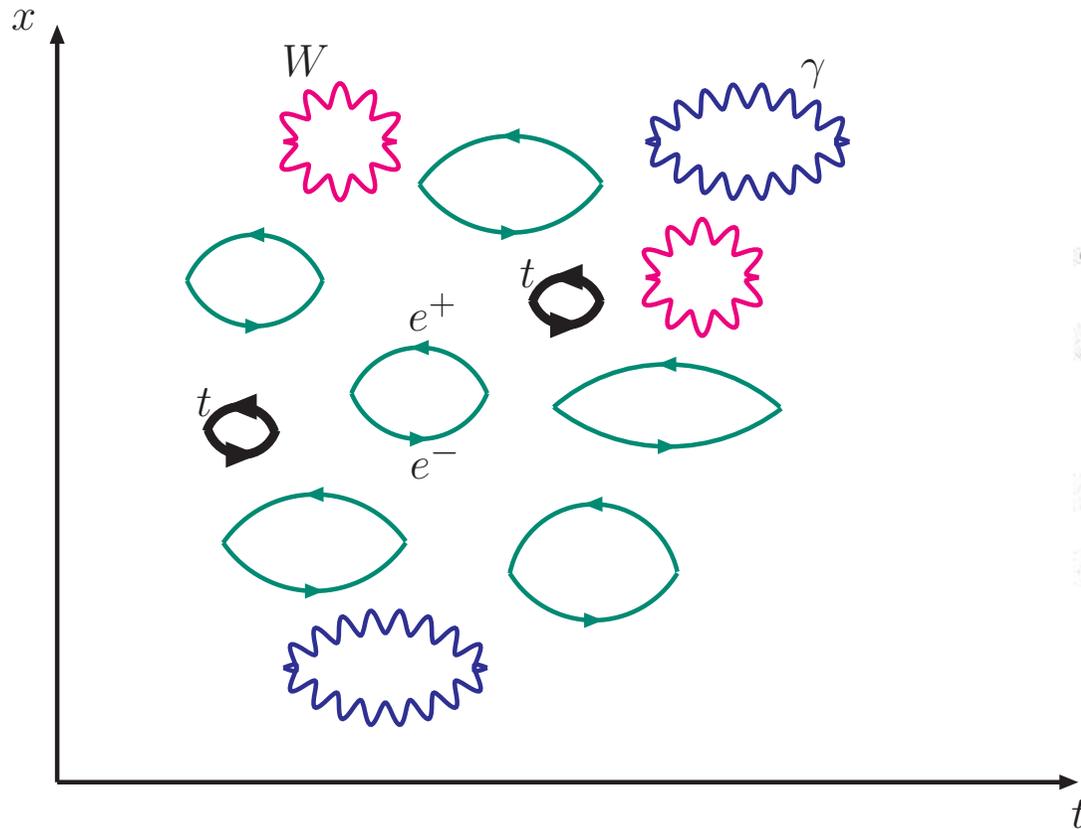
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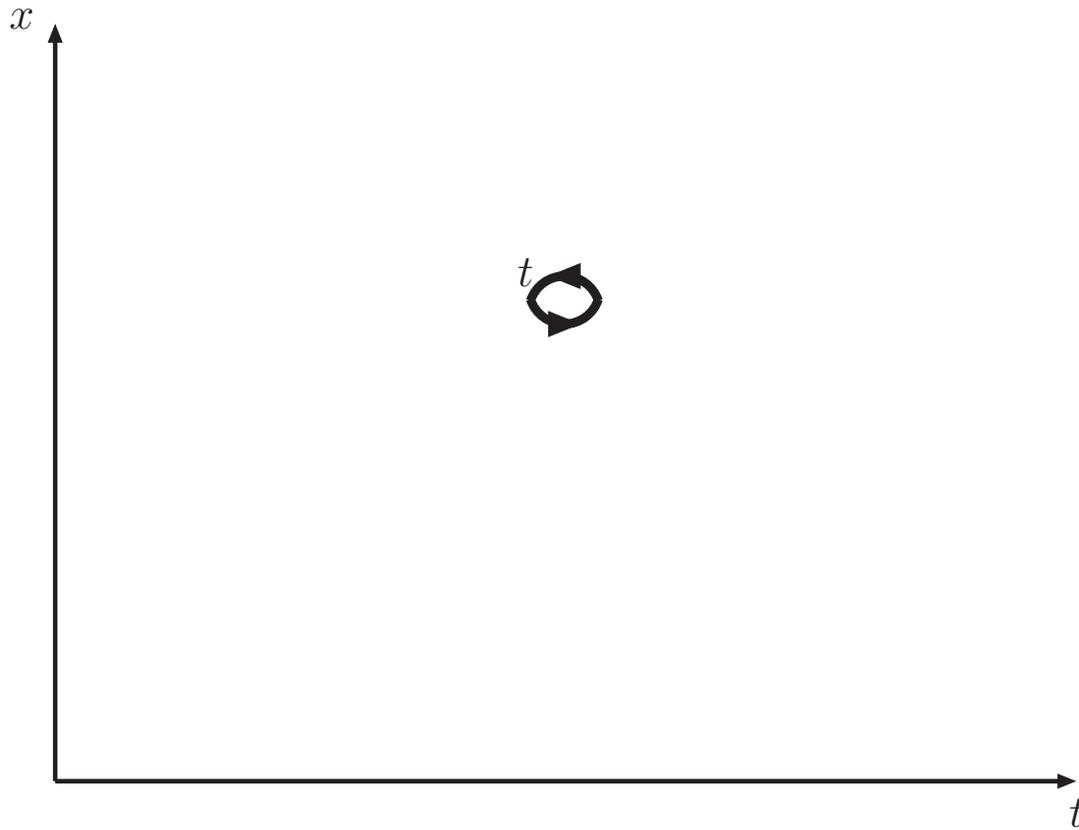
Vacuum fluctuations



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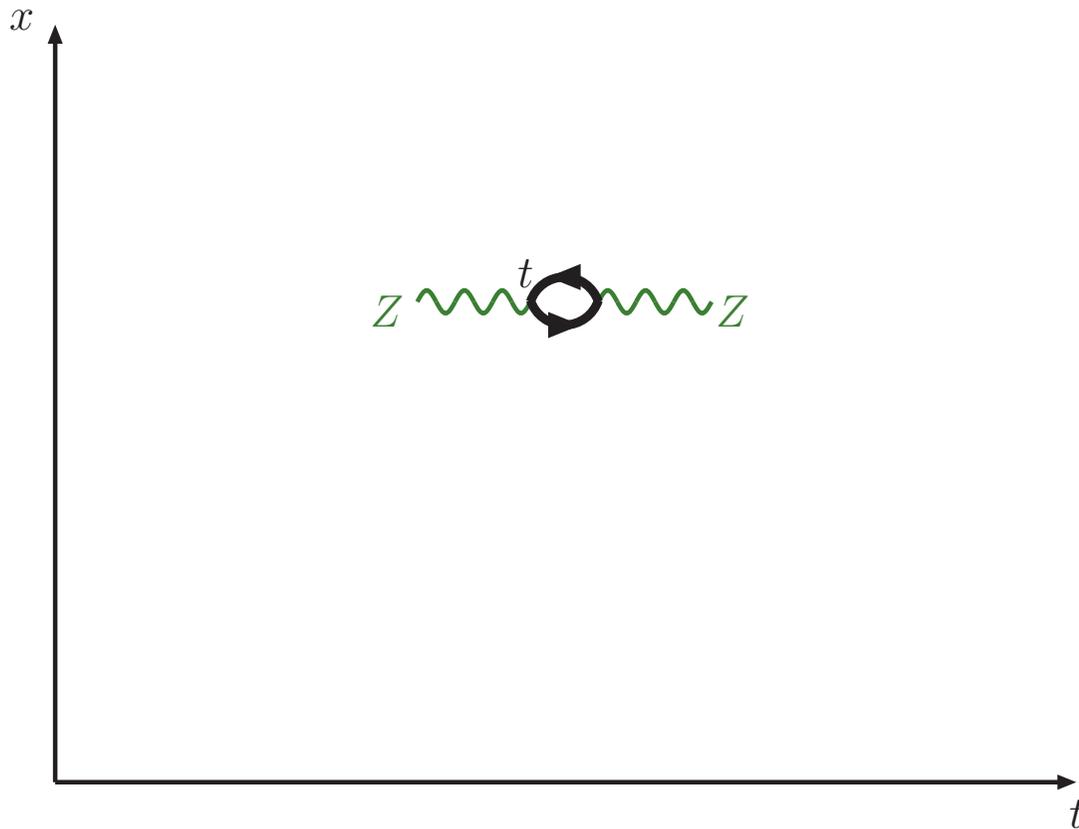


ρ parameter



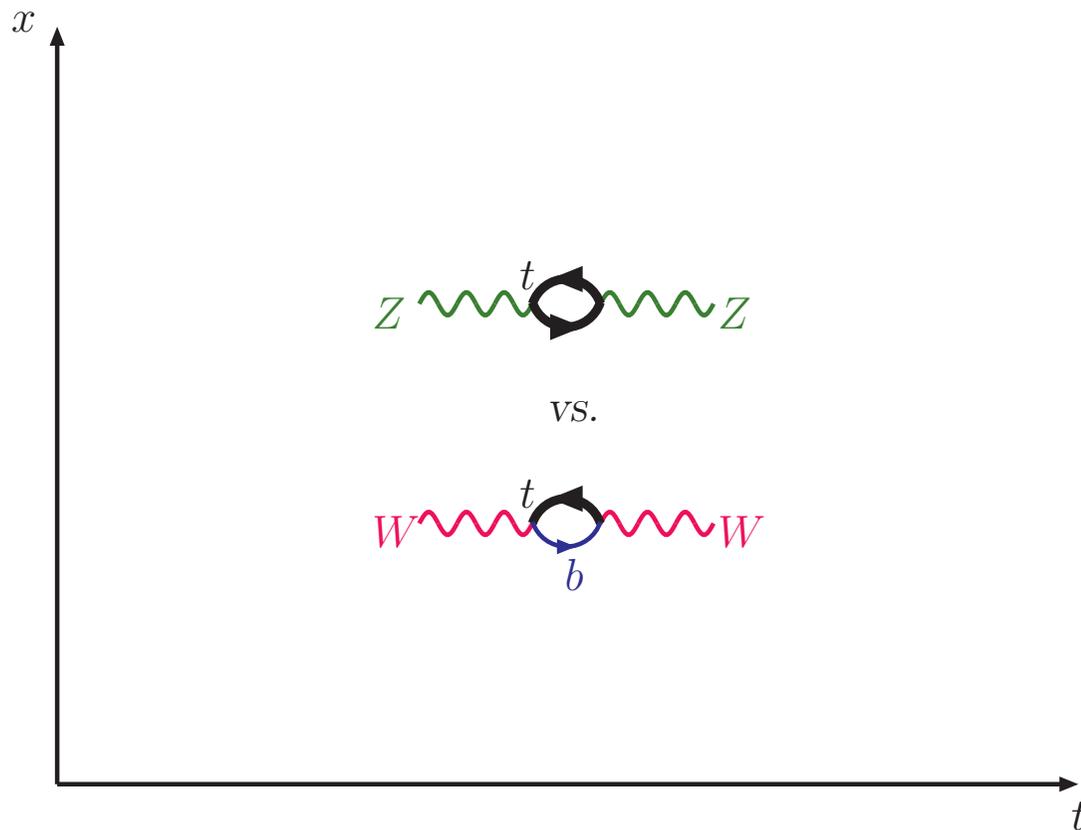
$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2} = \frac{g'^2}{g^2 + g'^2}$$

ρ parameter



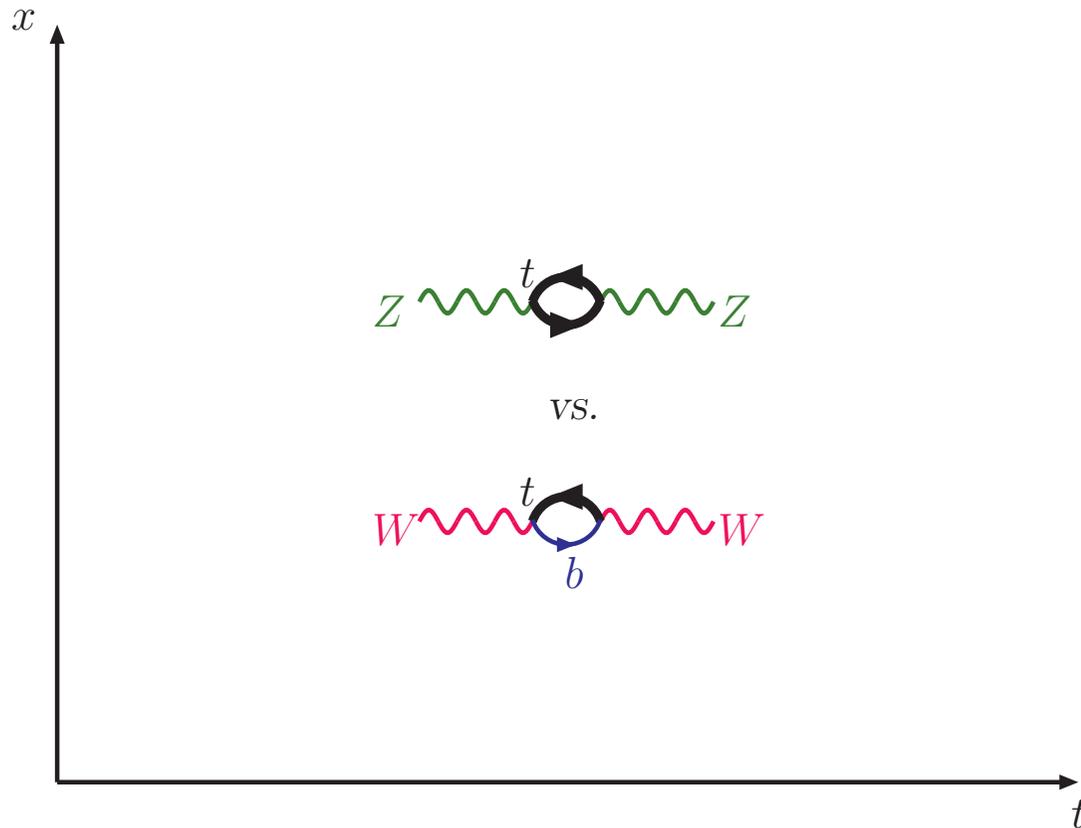
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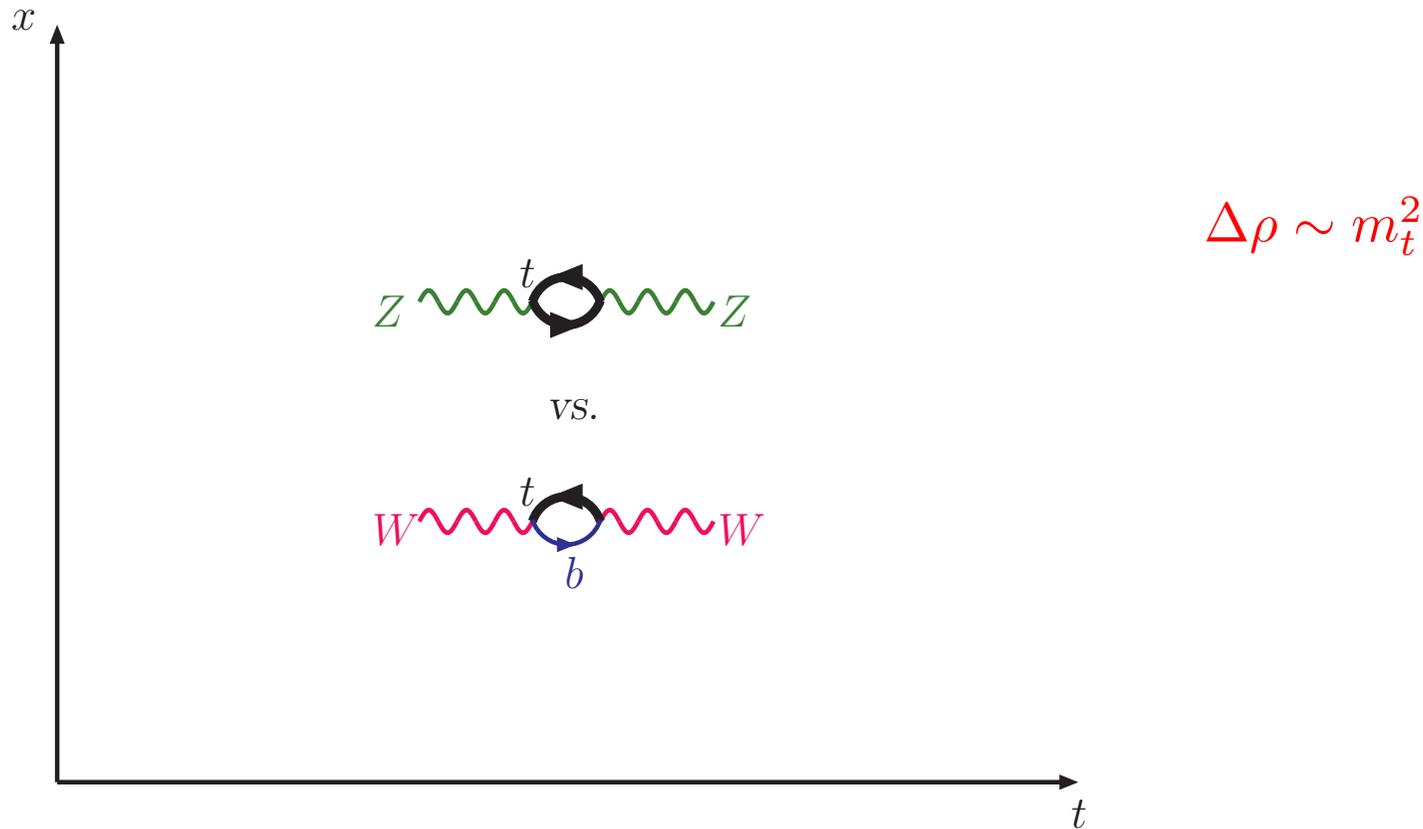
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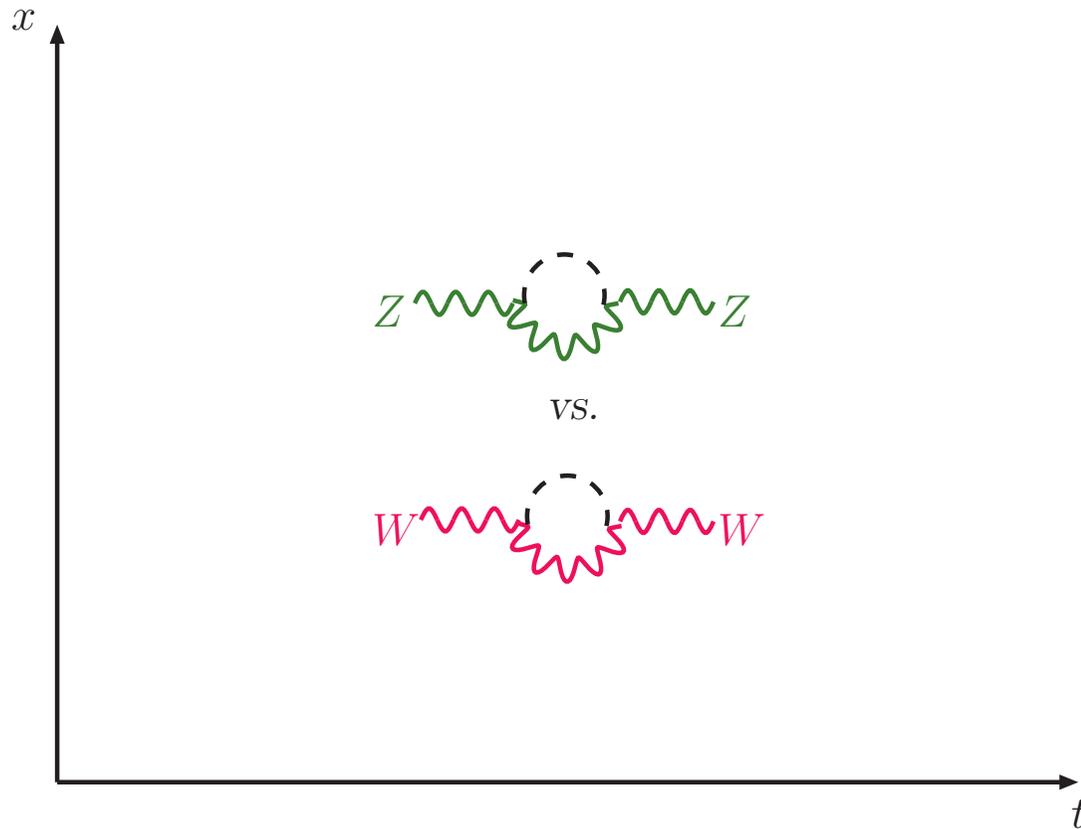
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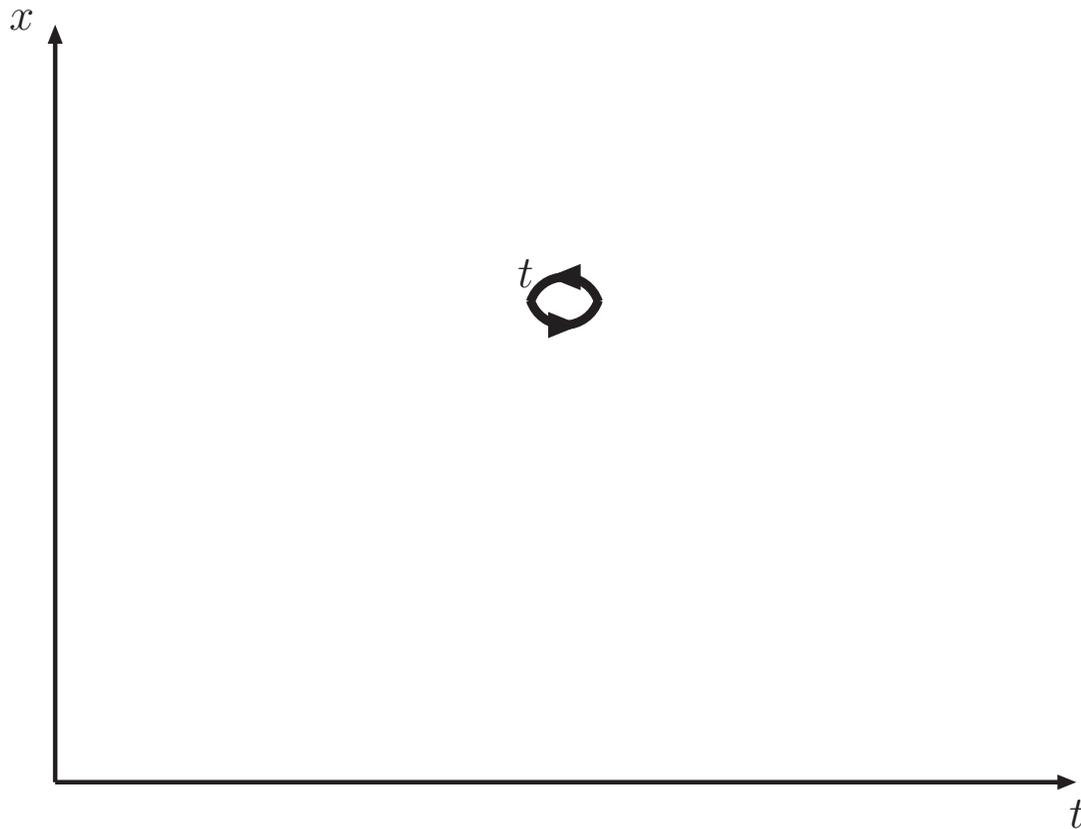


$$\Delta\rho \sim m_t^2$$

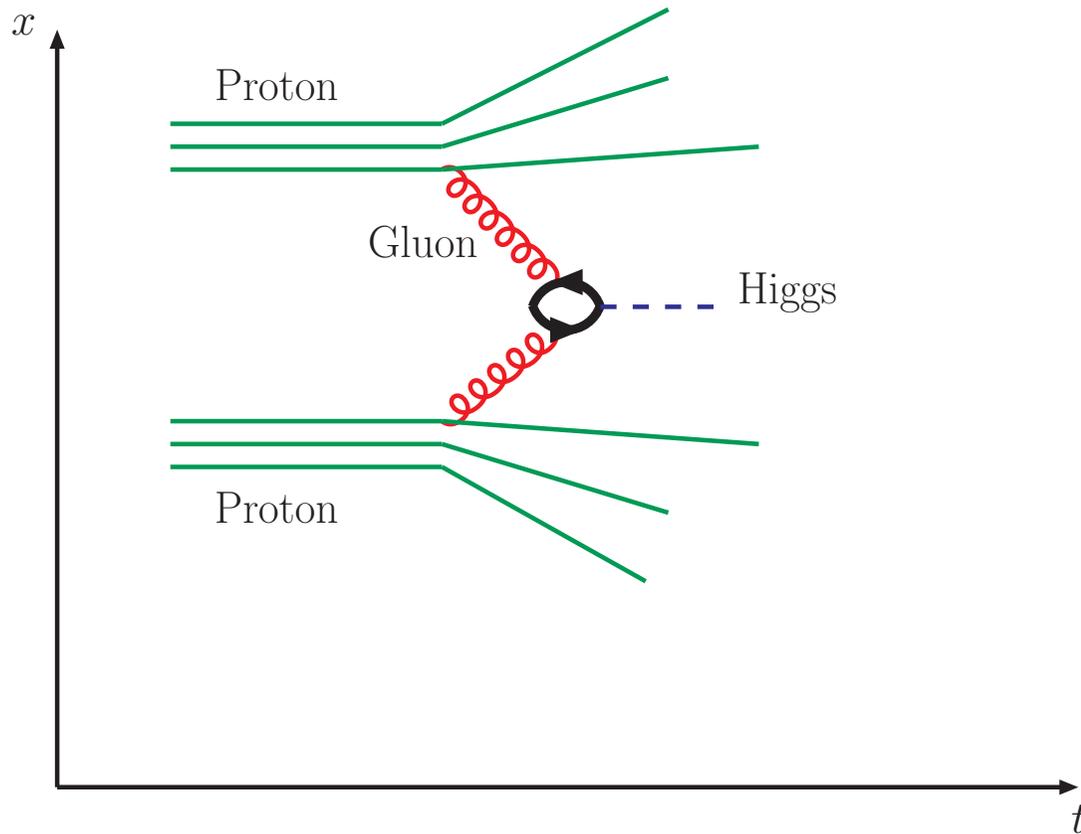
$$\Delta\rho \sim \ln M_H^2$$

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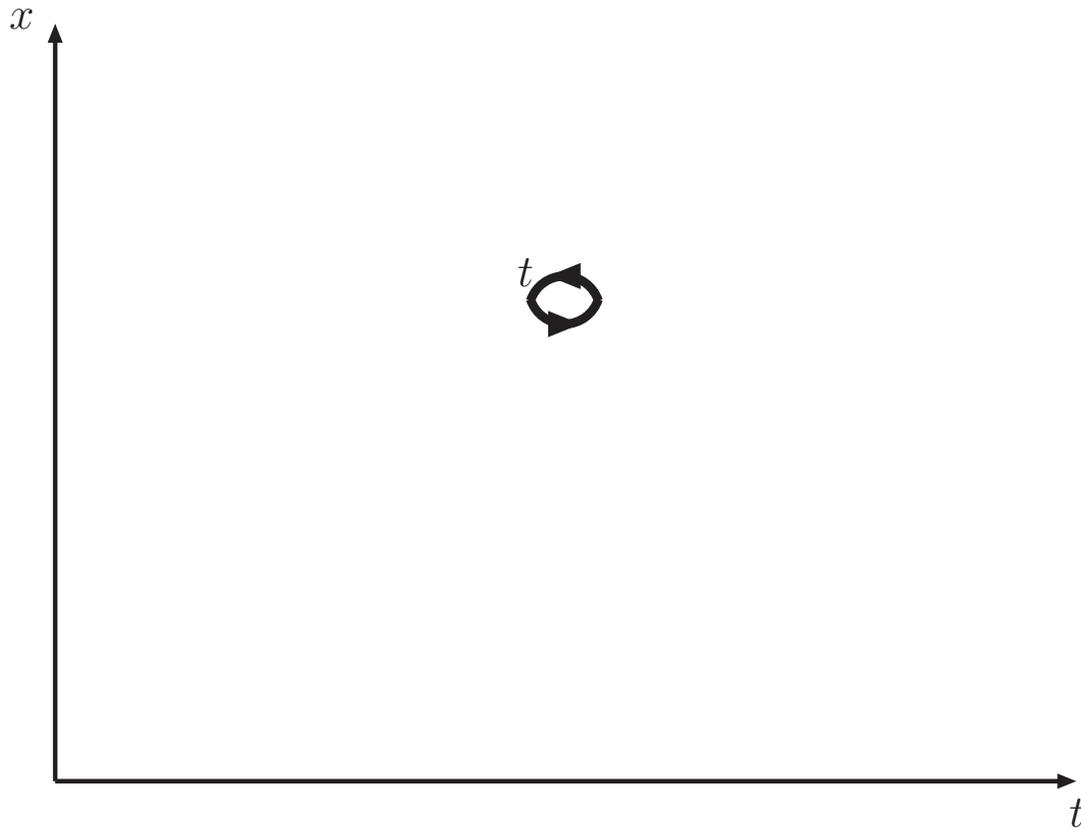
Higgs production



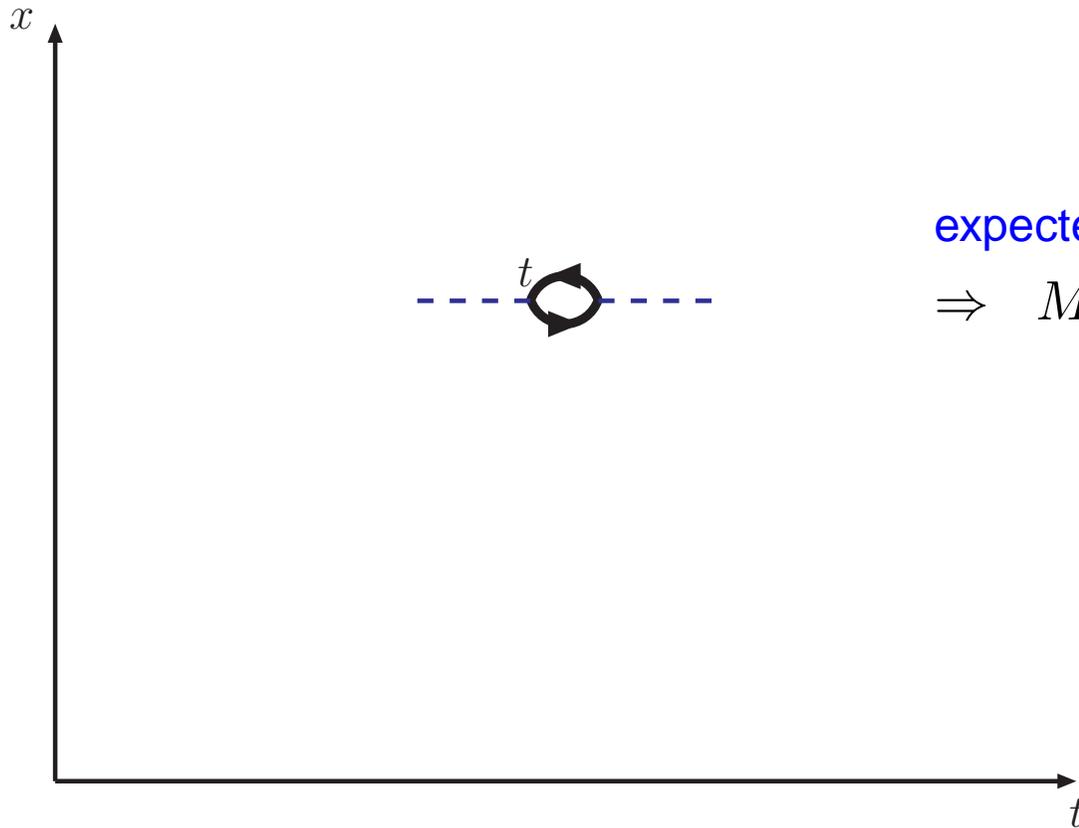
Higgs production



Example: Higgs mass

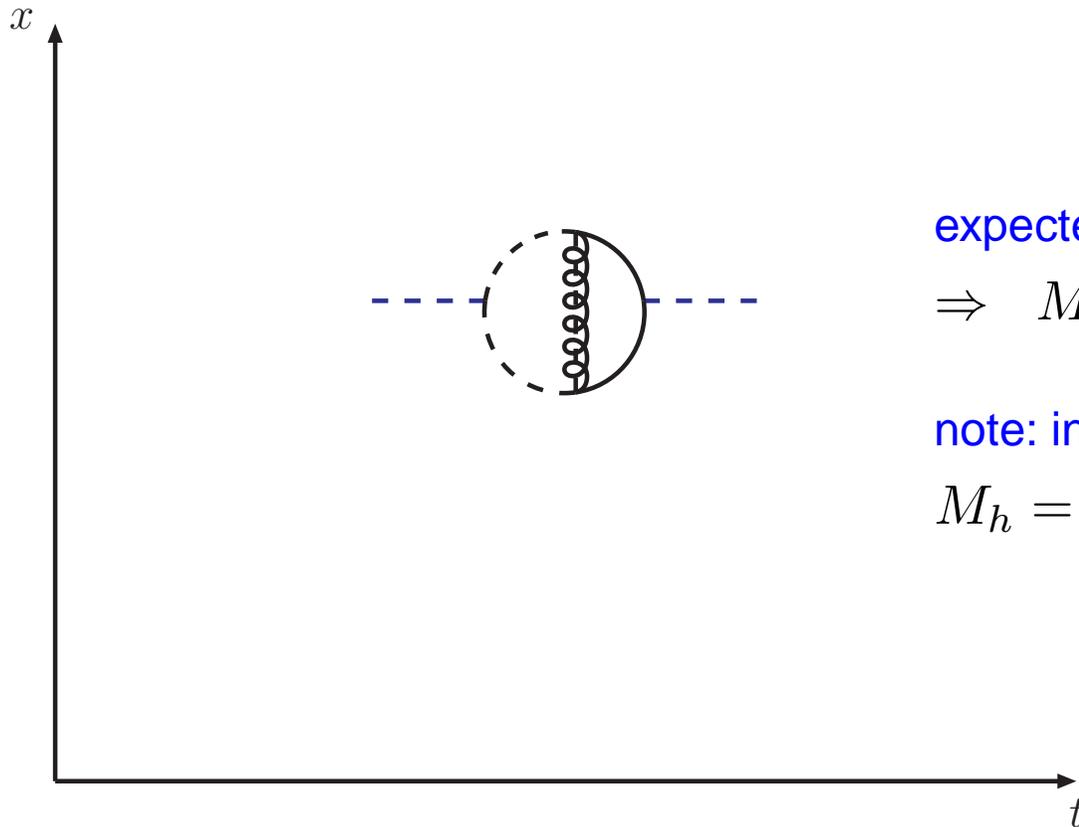


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expected: $\Delta M_h^{\text{exp}} \sim \mathcal{O}(0.1\%)$
 $\Rightarrow M_h$ will be **precision quantity**

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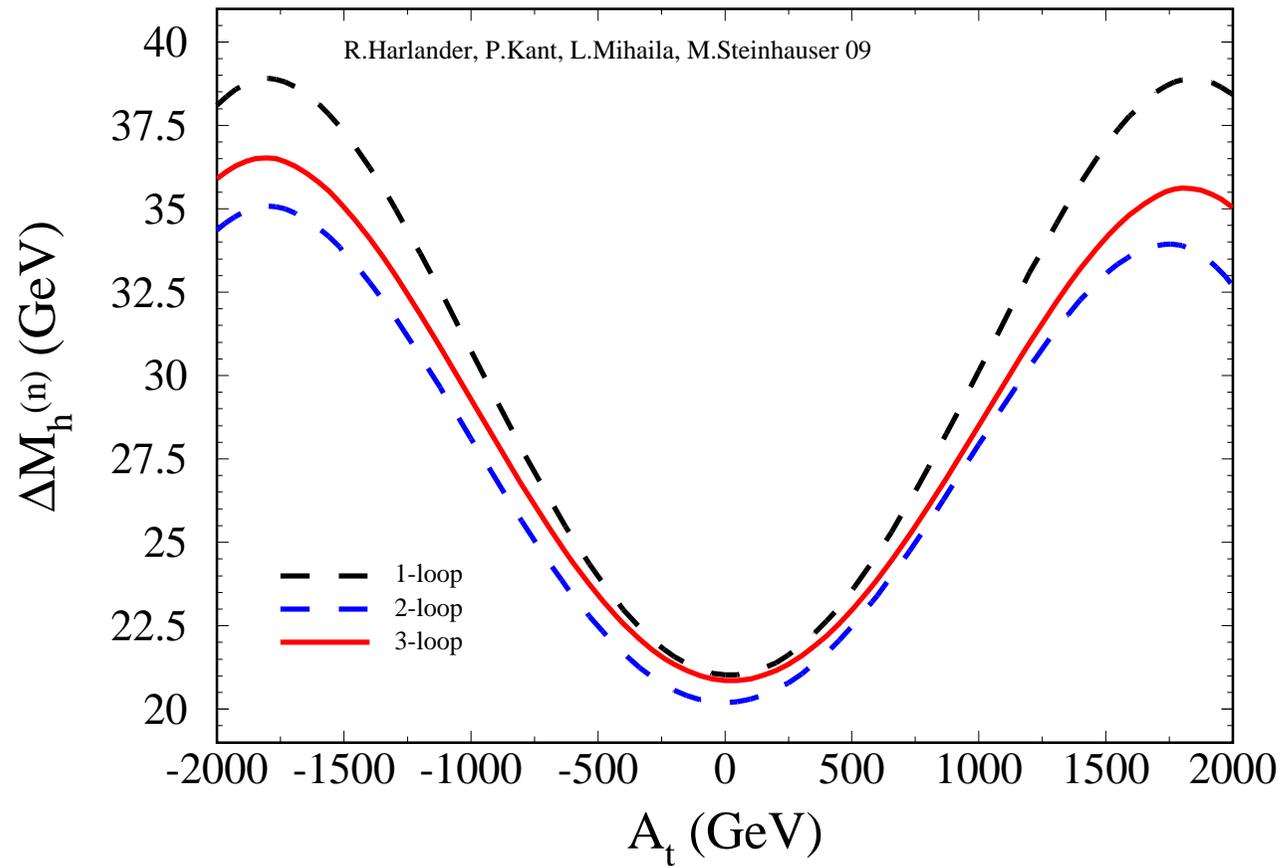
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note: in SUSY

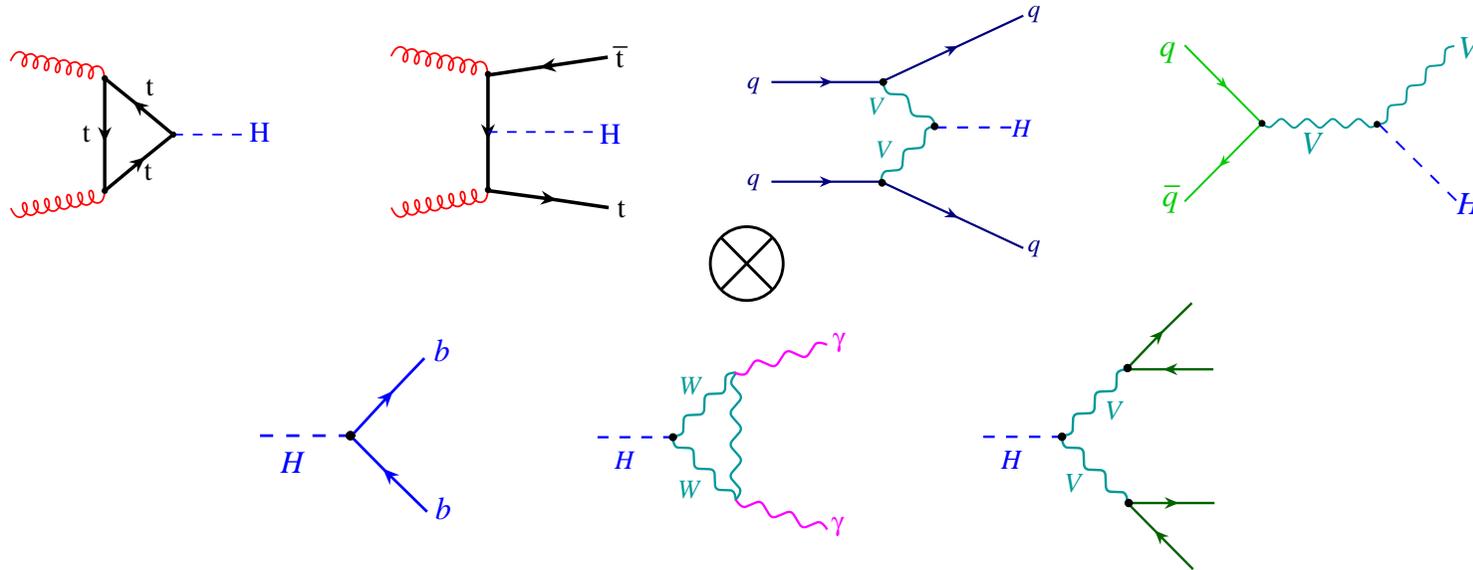
$$M_h = M_h(M_A, \tan \beta, \dots)$$

Example: Higgs mass

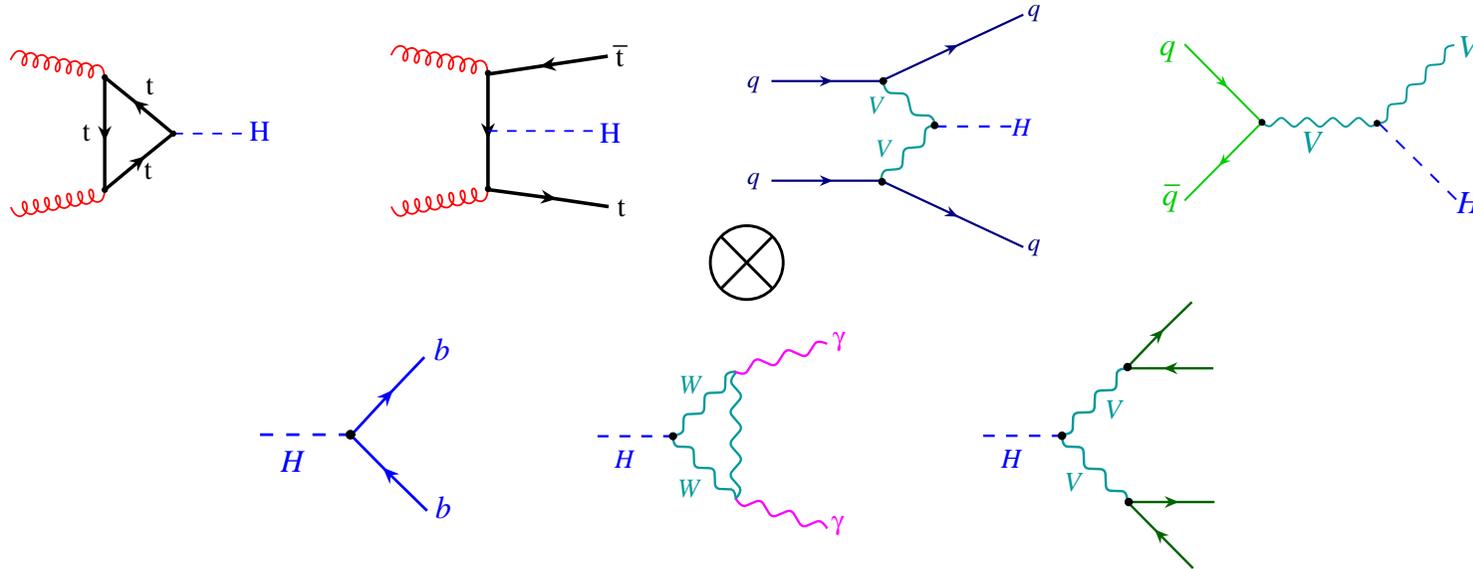


cf. talk by L. Mihaila

Higgs couplings



Higgs couplings



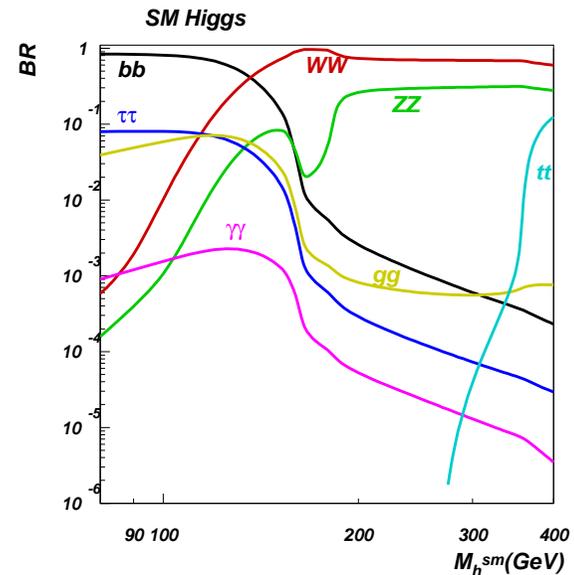
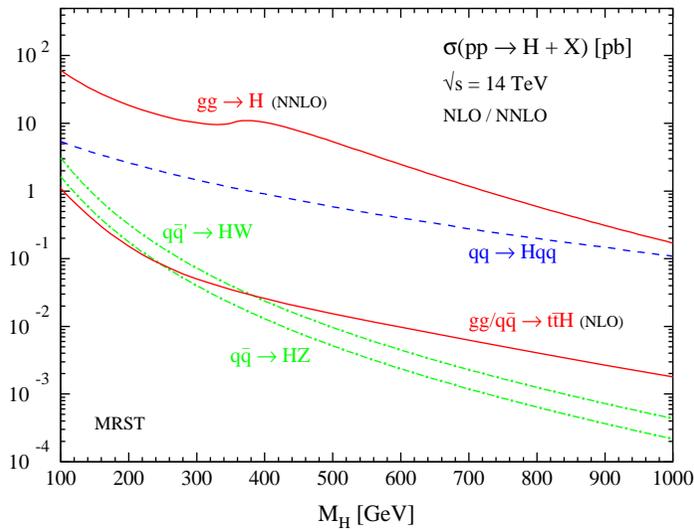
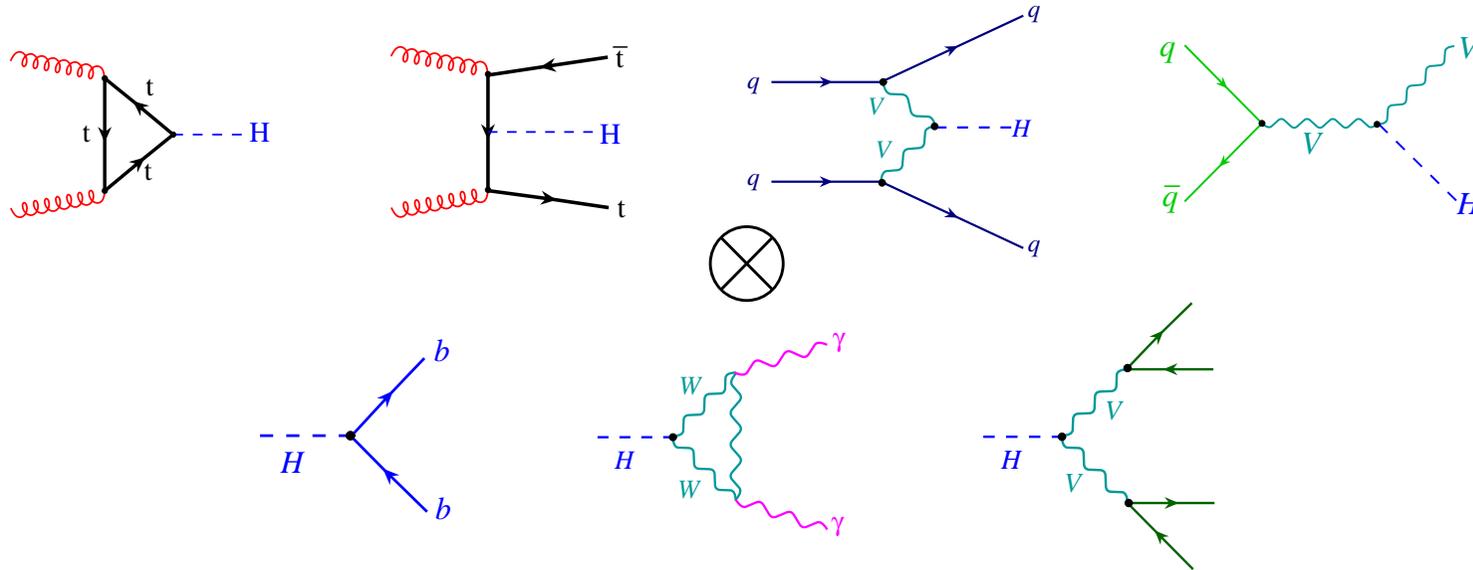
$$\Rightarrow \frac{\Gamma_g \Gamma_\gamma}{\Gamma}, \quad \frac{\Gamma_g \Gamma_V}{\Gamma}, \quad \frac{\Gamma_V \Gamma_V}{\Gamma}, \quad \frac{\Gamma_V \Gamma_\tau}{\Gamma}, \quad \text{etc.}$$

$$\Rightarrow \frac{\Gamma_V}{\Gamma} (\Gamma_g + \Gamma_V + \Gamma_\tau + \dots) = \Gamma_V$$

$$\Rightarrow \Gamma_\gamma, \Gamma_g, \text{ etc.} \quad [\text{Zeppenfeld et al.}, [\text{Dührssen et al.}]]$$

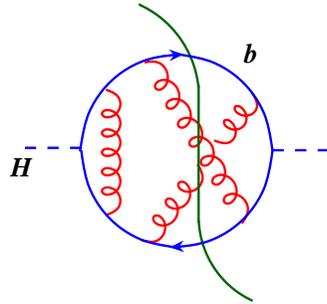
cf. talks by T. Plehn and K. Jakobs

$pp \rightarrow H$ at 14 GeV



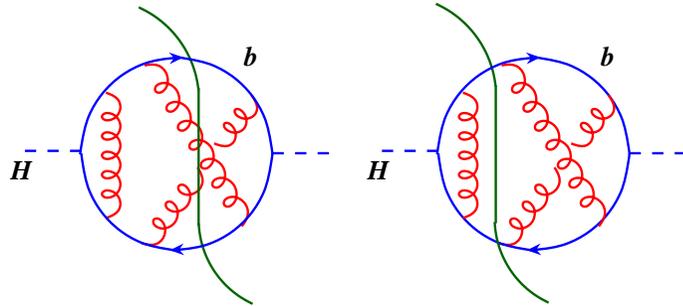
Decays

- theory predictions usually simpler due to **optical theorem**:



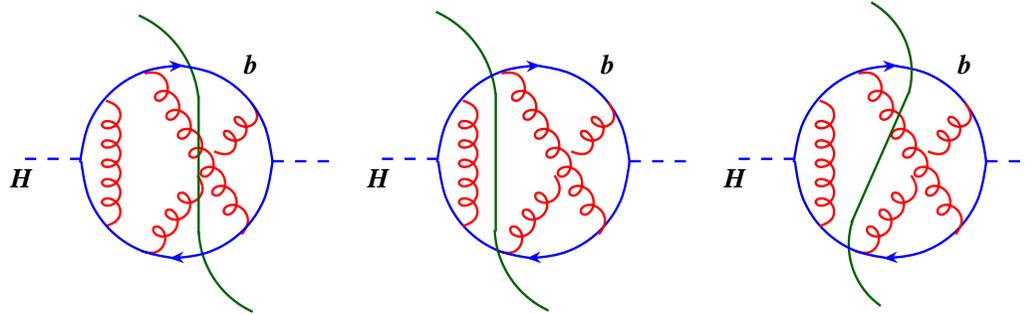
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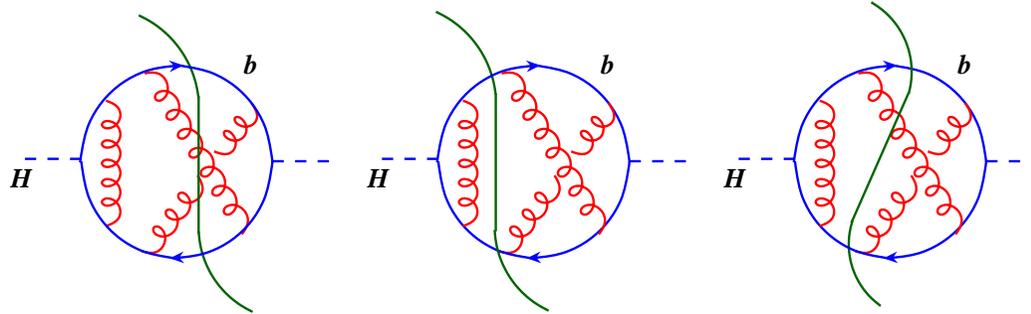
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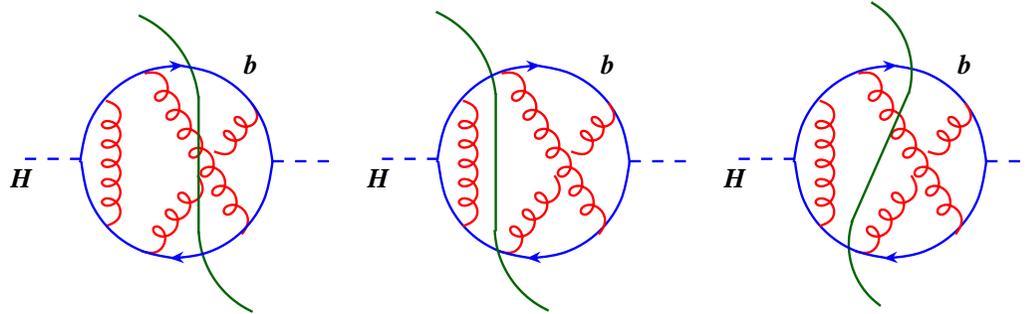


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- $H \rightarrow q\bar{q}$: through $\mathcal{O}(\alpha_s^3)$
[Chetyrkin, Steinhauser, Kwiatkowski], [Larin, v.Ritbergen, Vermaseren]
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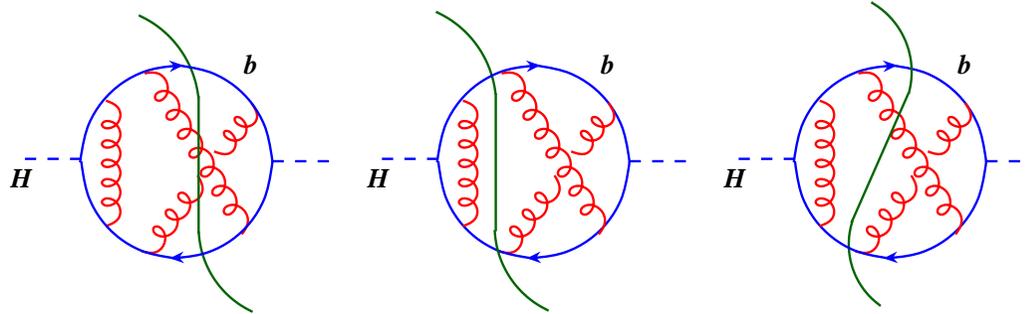


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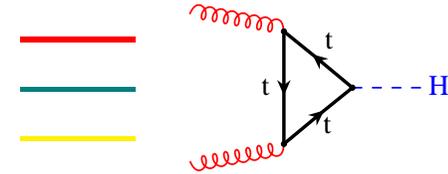
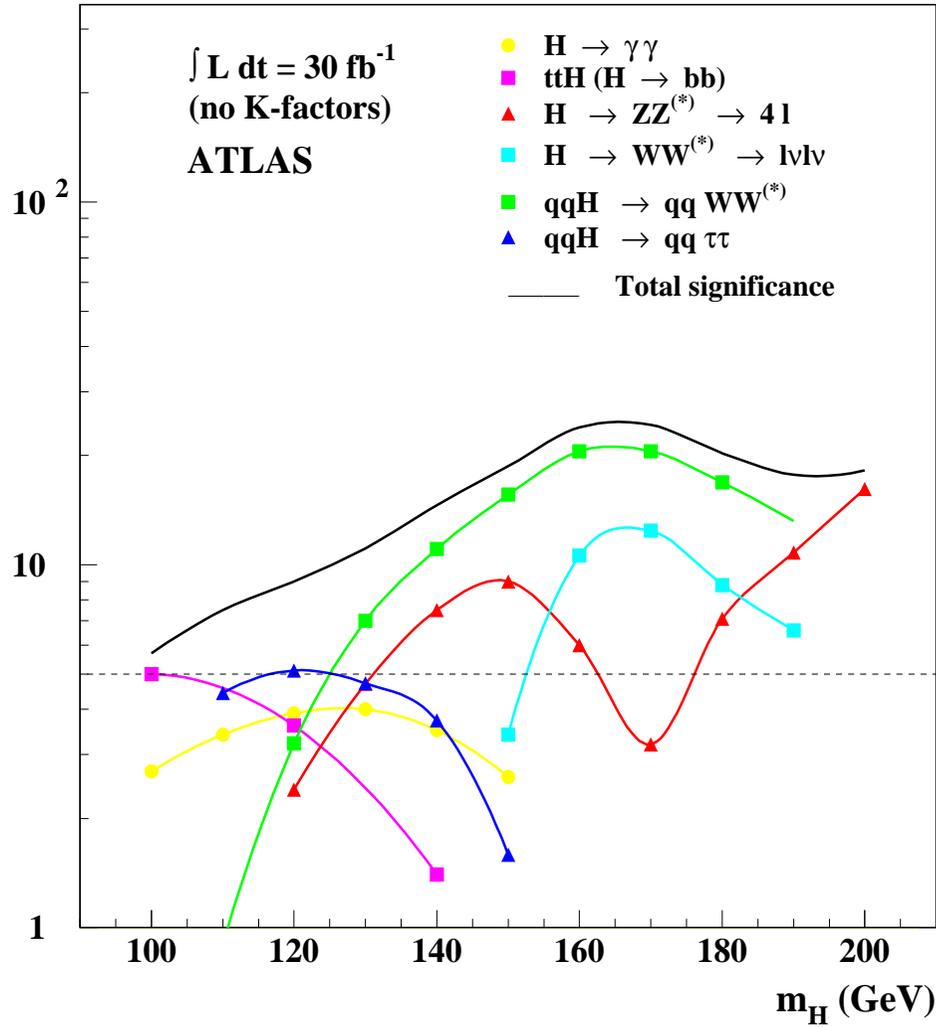


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- $H \rightarrow 4f$: NLO QCD+EW [Bredenstein, Denner, Dittmaier, Weber '07]

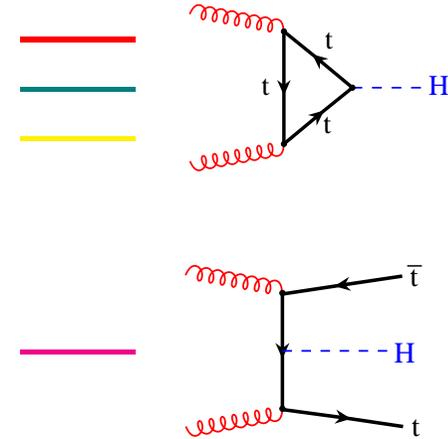
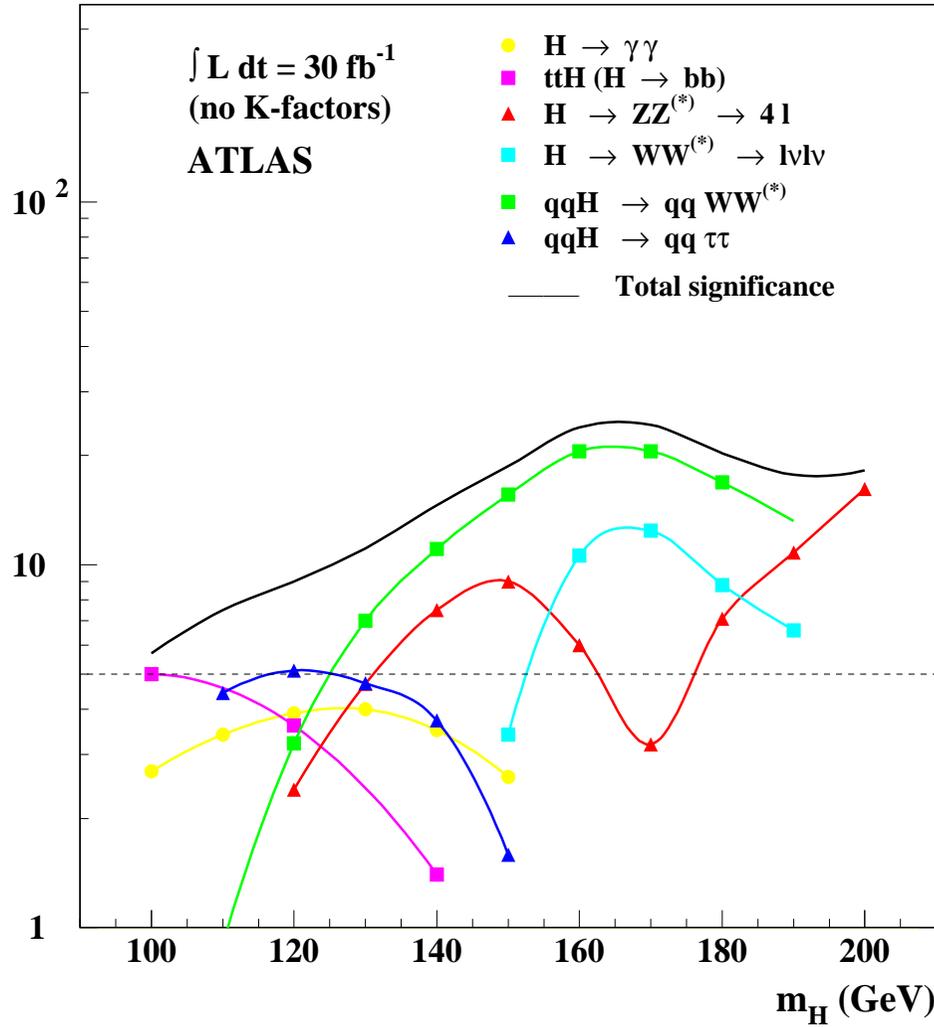
Discovery Potential

Signal significance



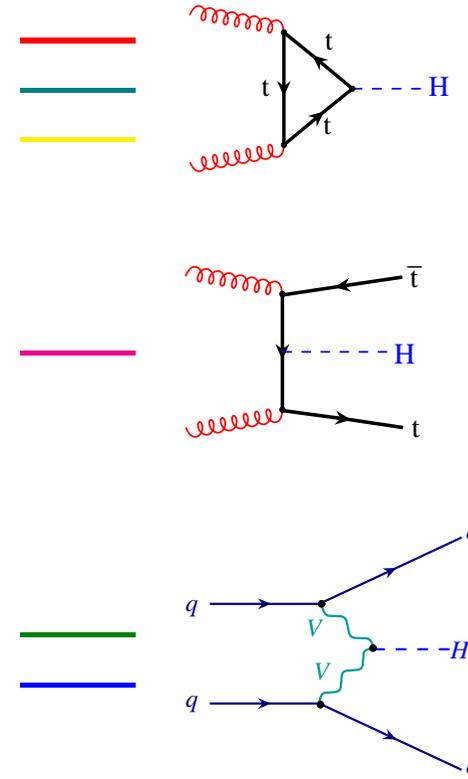
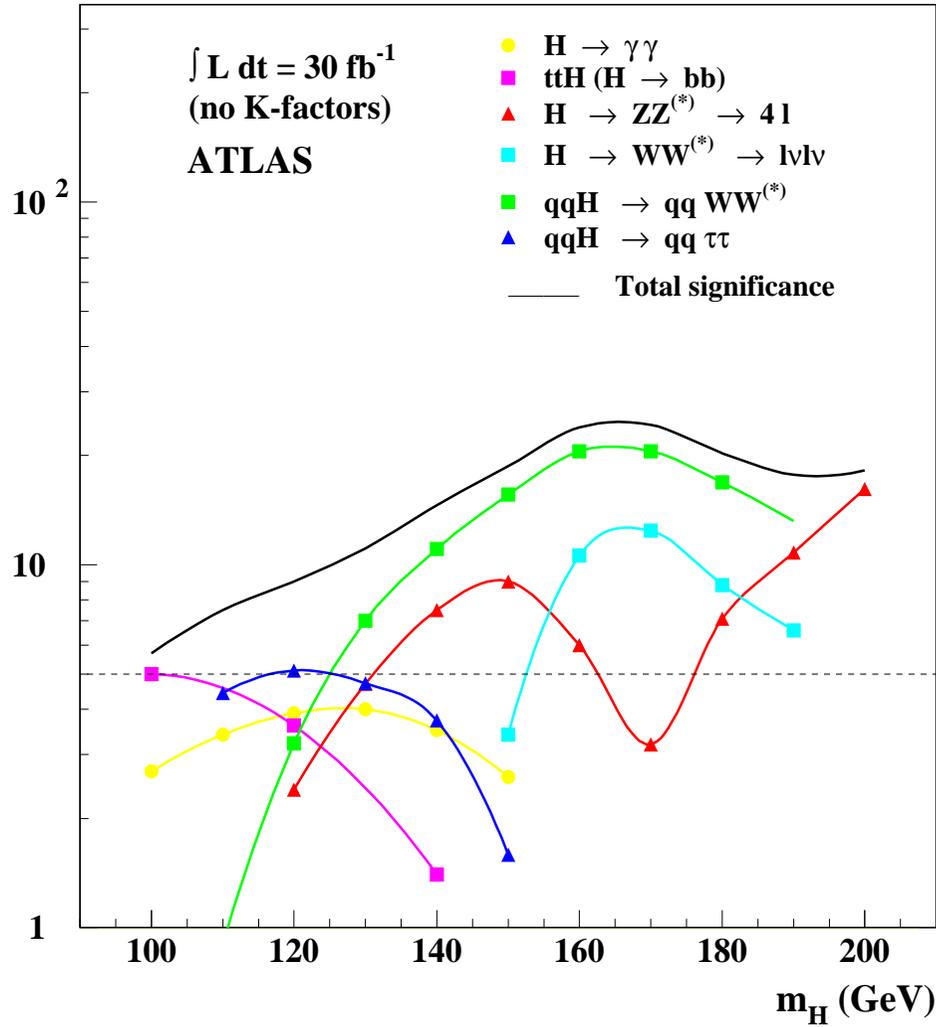
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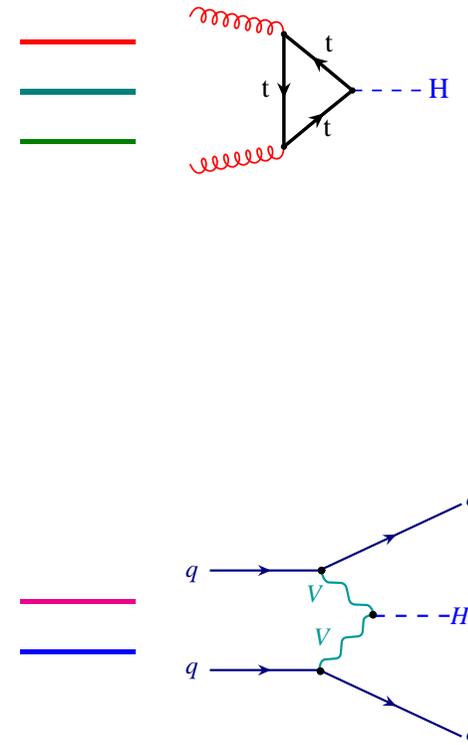
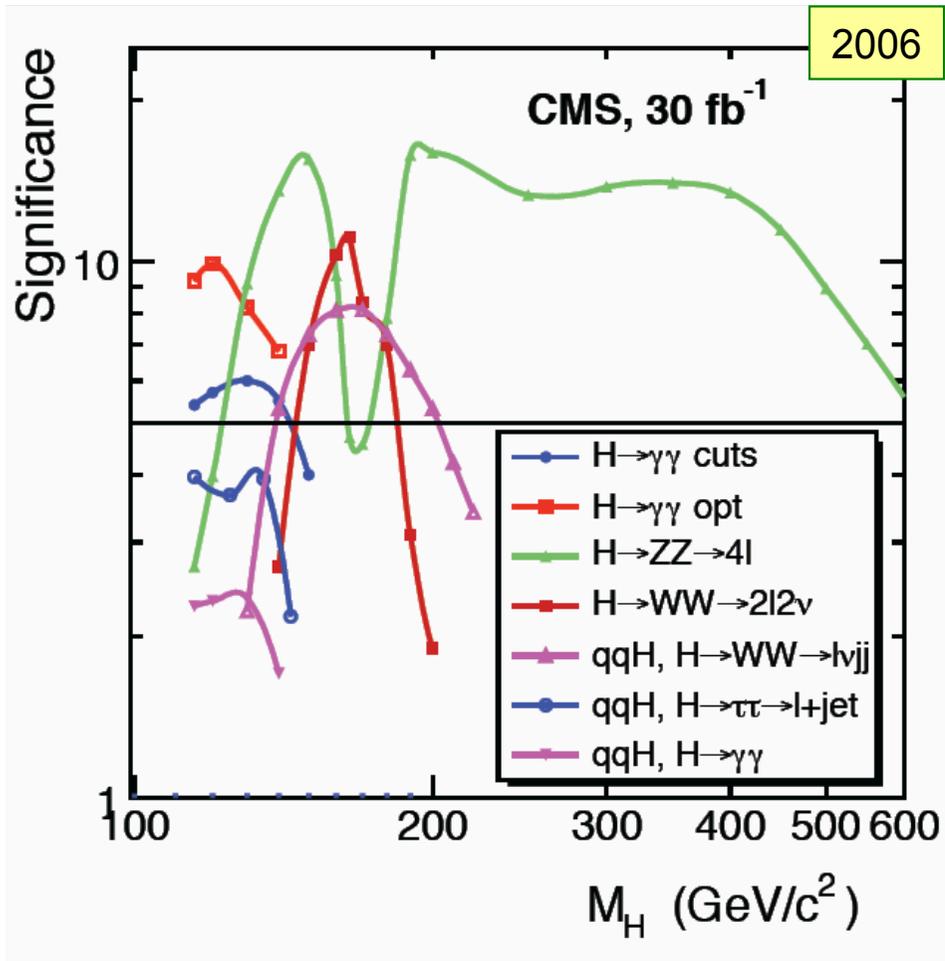


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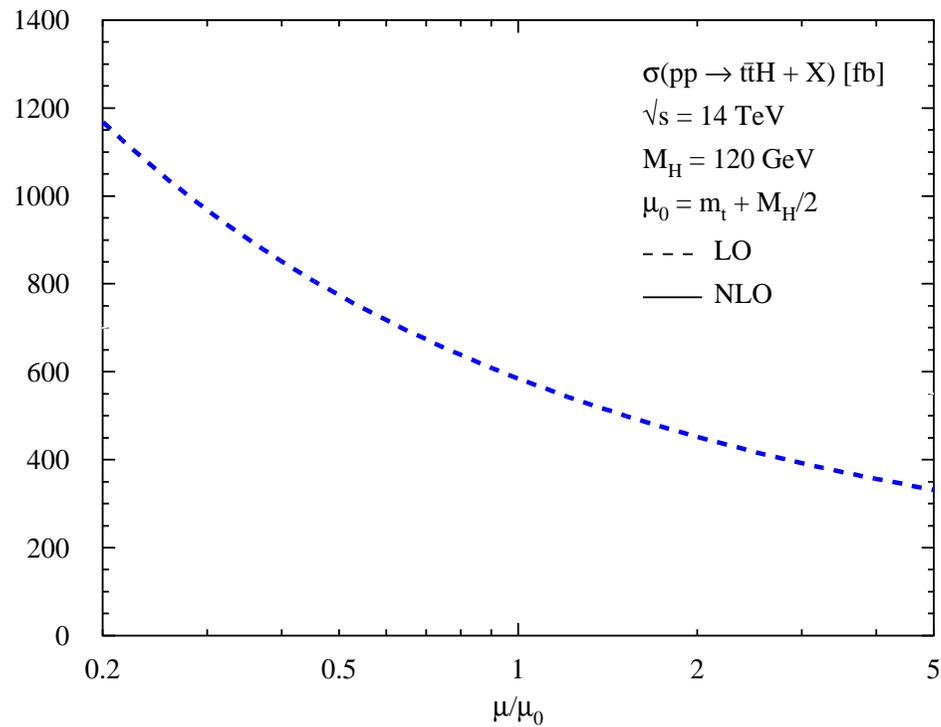
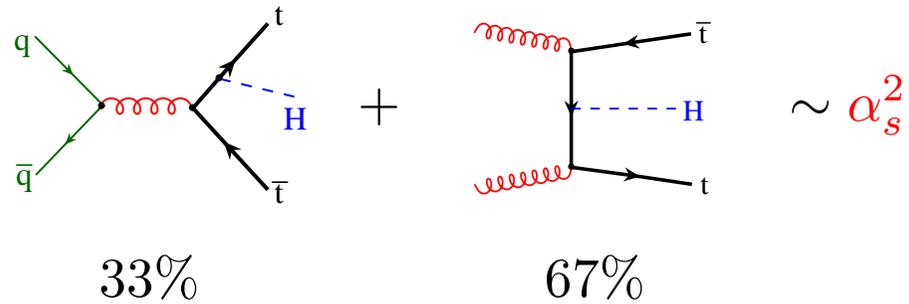
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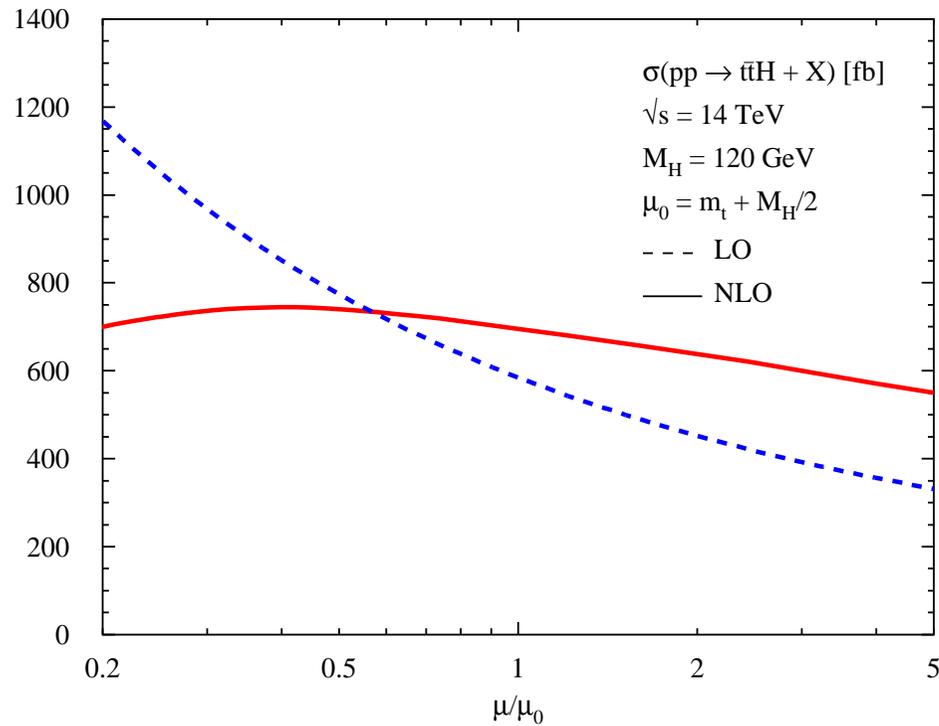
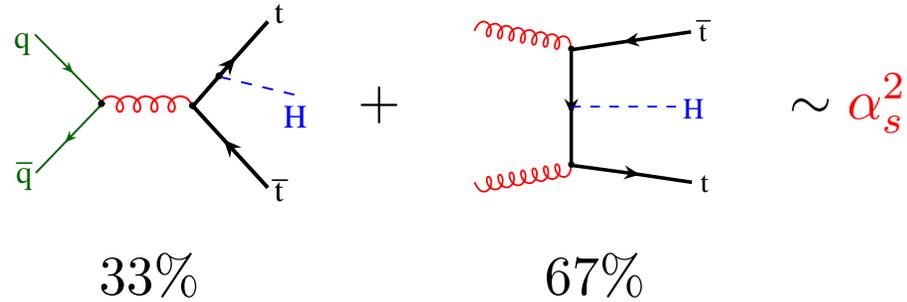
Discovery Potential



$\bar{t}tH$ at NLO



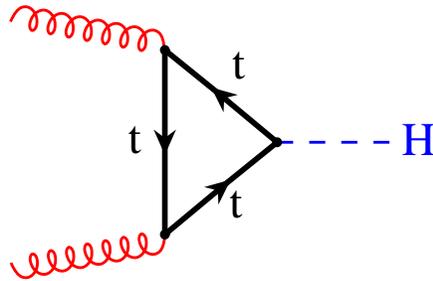
$\bar{t}tH$ at NLO



[Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01]

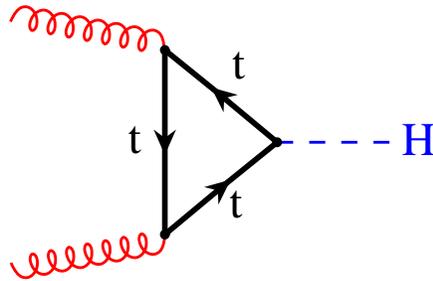
[Dawson, Reina, Wackerroth, Orr, Jackson '01-'03]

Gluon Fusion



- dominant production mode
- sensitive to heavy particle spectrum

Gluon Fusion

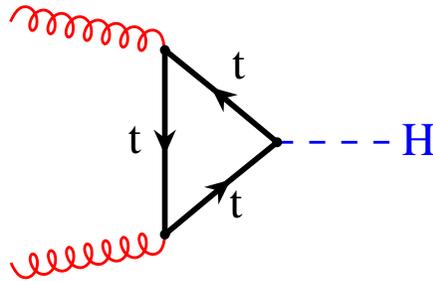


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but

- $H \rightarrow b\bar{b}$ decay mode not usable for discovery
- LO is 1-loop \rightarrow radiative corrections difficult
- depends on Yukawa coupling

Gluon Fusion



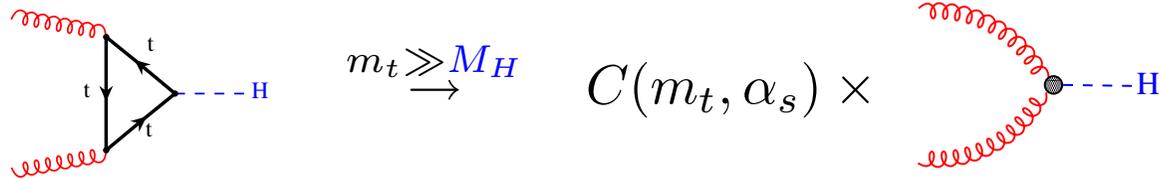
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- LO is 1-loop \rightarrow radiative corrections difficult — really?
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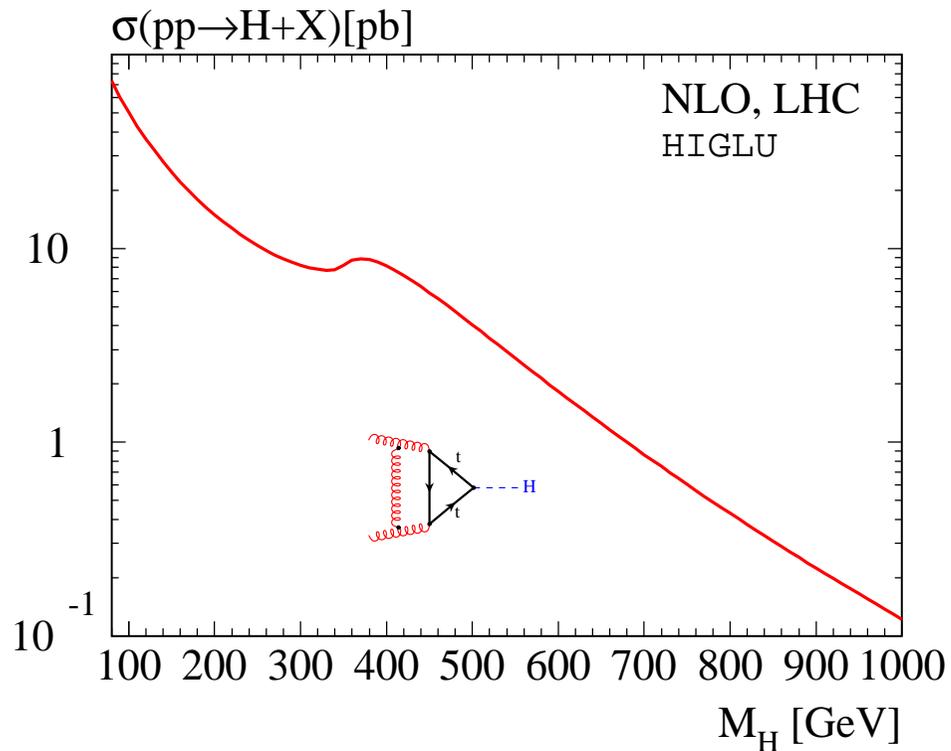
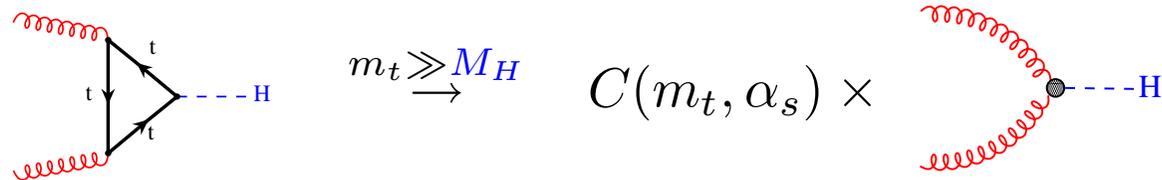
Gluon fusion

effective theory for $m_t \gg M_H$:



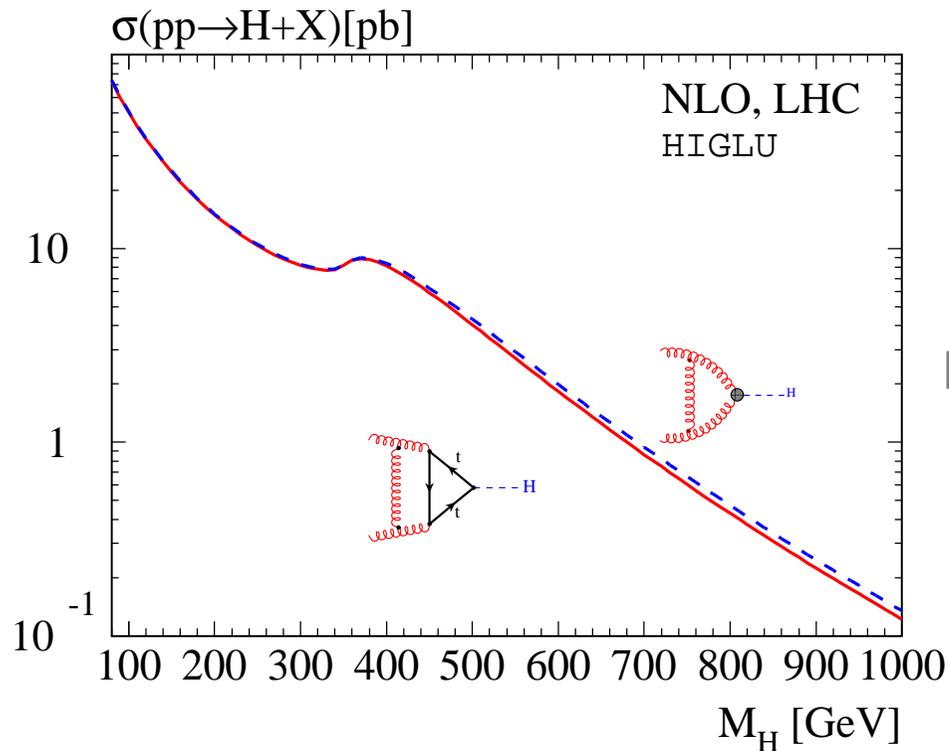
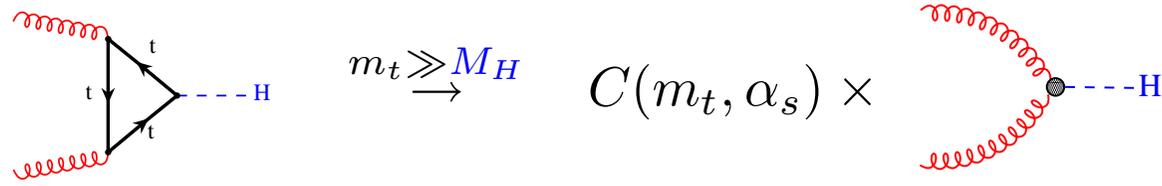
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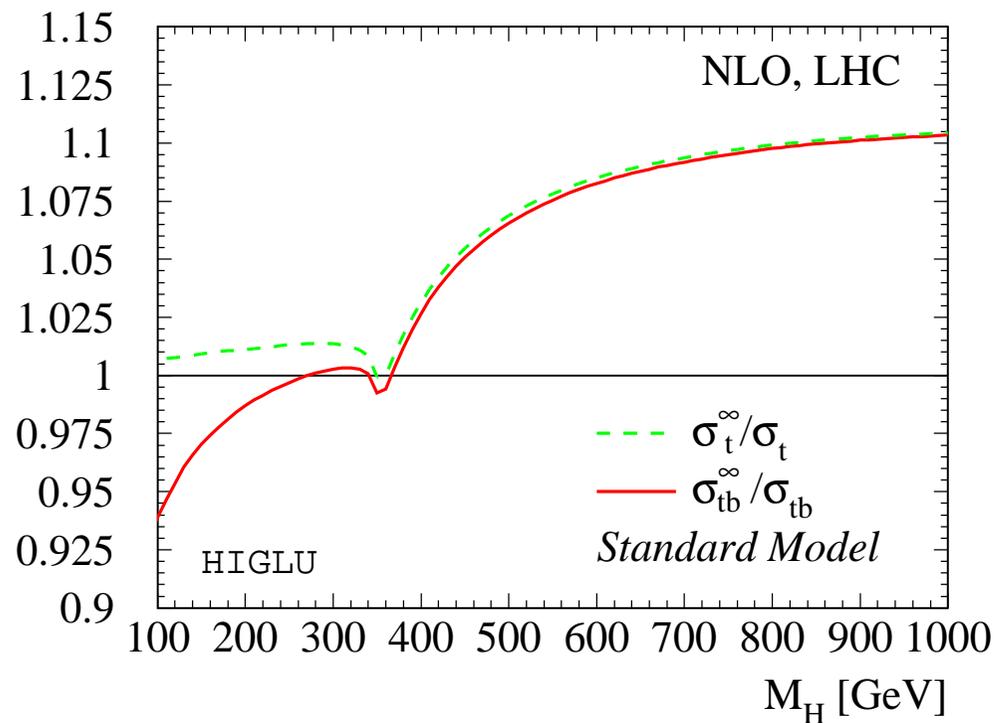
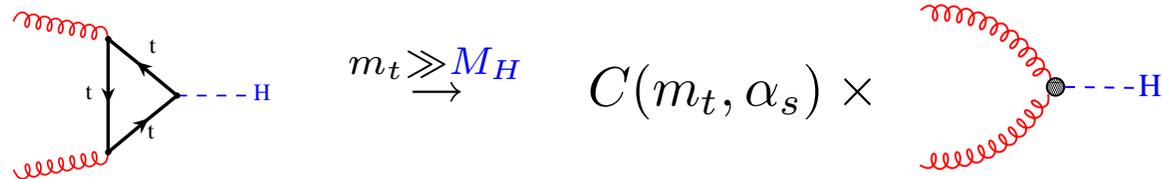
effective theory for $m_t \gg M_H$:



[Krämer, Laenen, Spira '96]

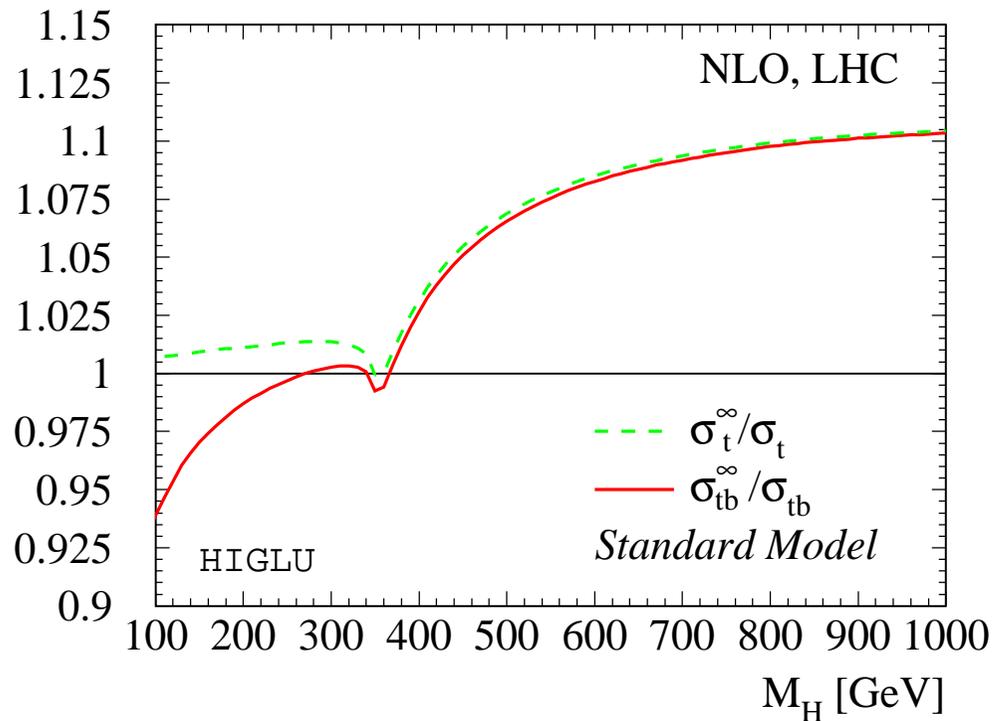
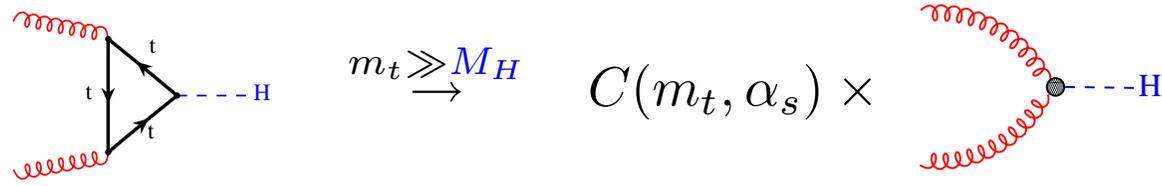
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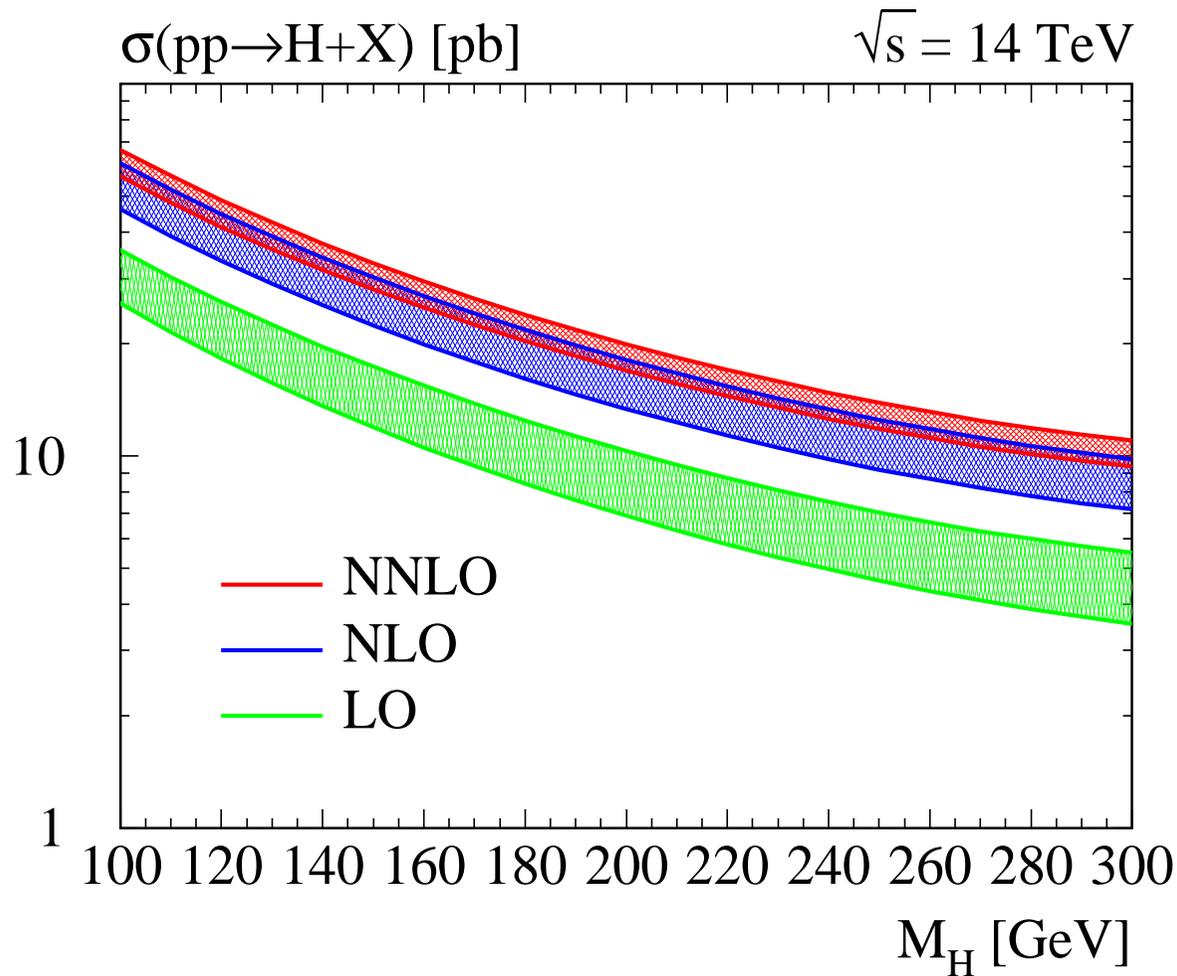
Gluon fusion

effective theory for $m_t \gg M_H$:



Reason? Still debated!

Gluon fusion at NNLO

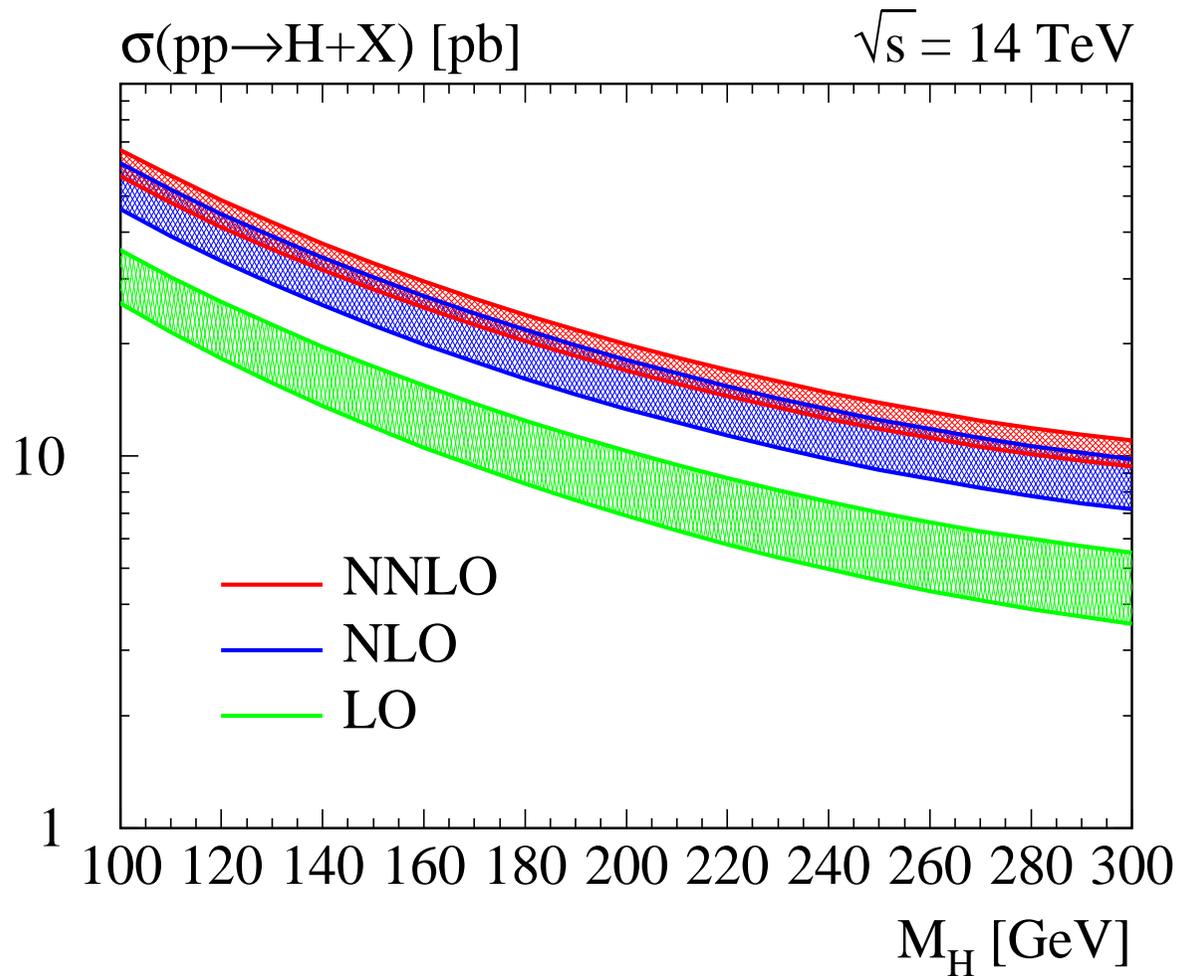


[R.H., Kilgore '02]
[Anastasiou, Melnikov '02]
[Ravindran, Smith, Neerven '03]

[Spira, Djouadi, Graudenz,
Zerwas '91/'93]

[Dawson '91]

Gluon fusion at NNLO



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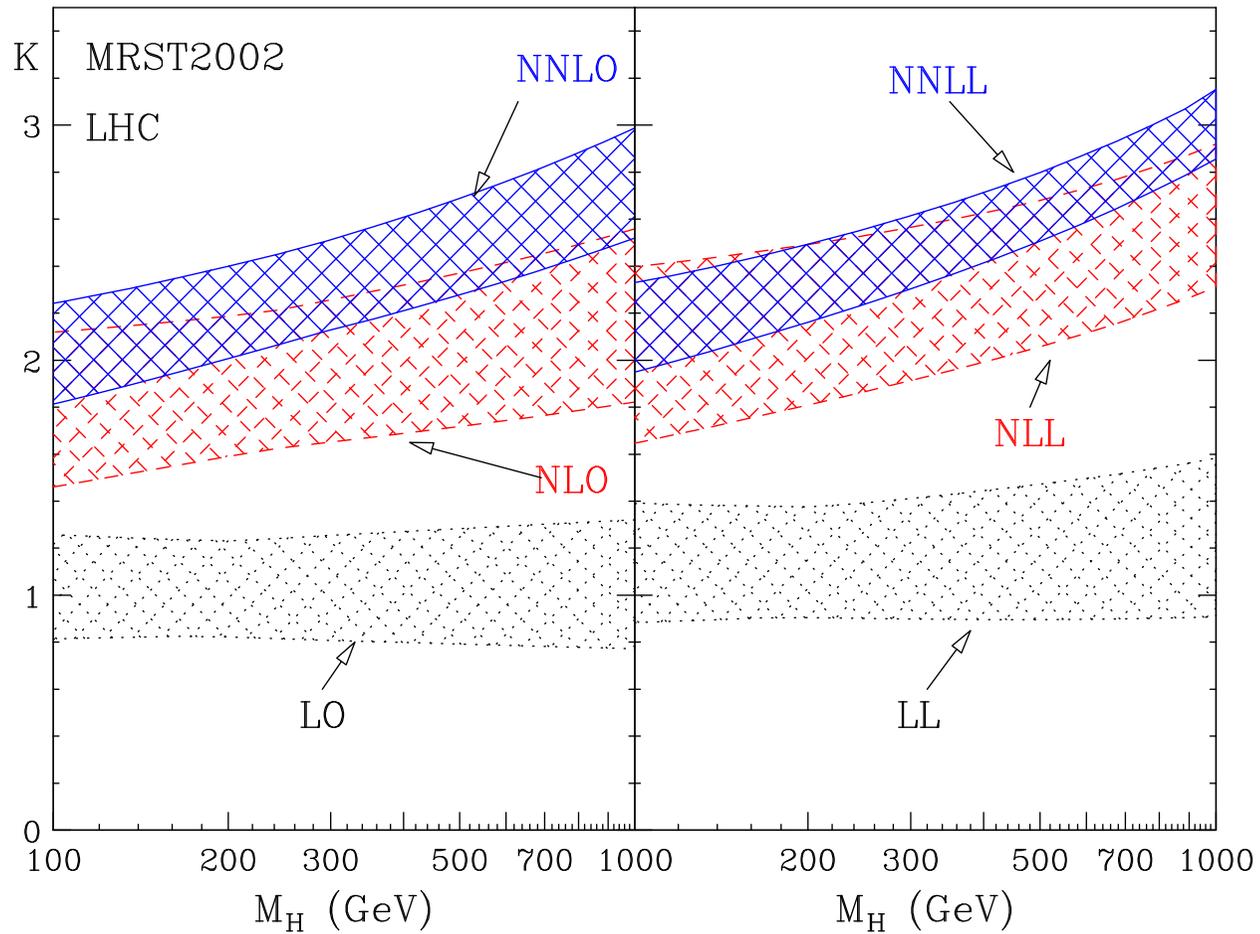
[Spira, Djouadi, Graudenz,
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[Dawson '91]

Why so large?

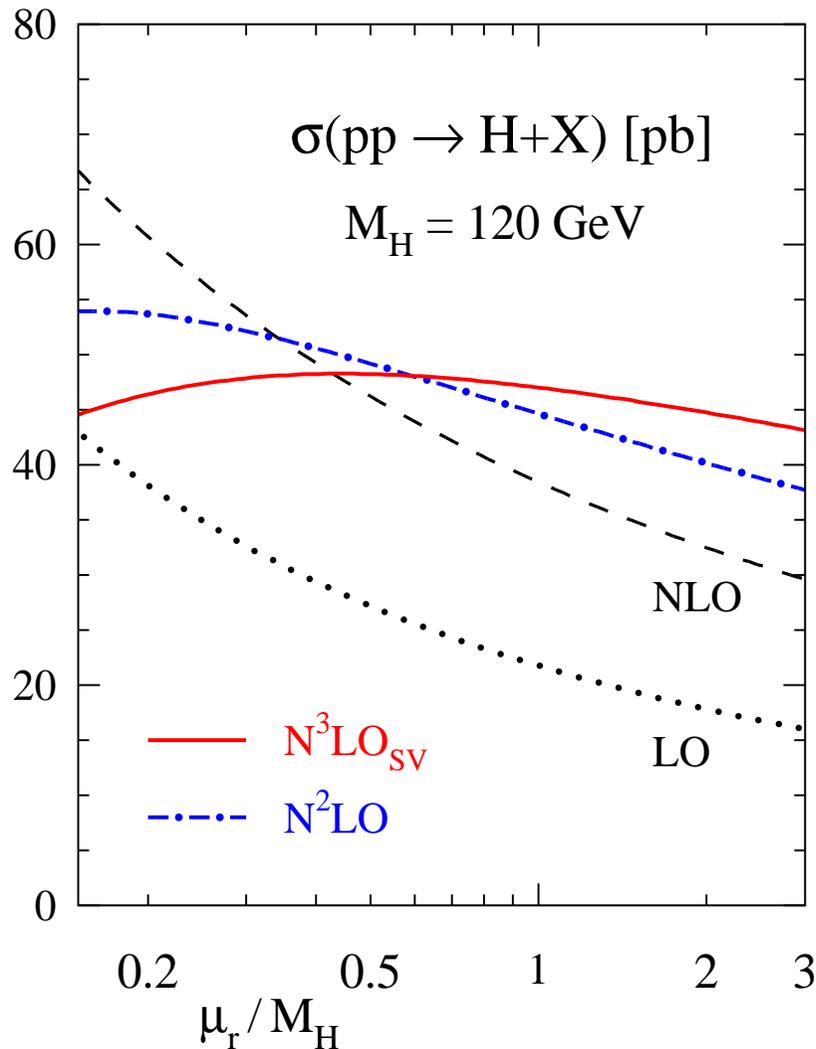
Gluon fusion – beyond NNLO

- soft resummation $\hat{s} \rightarrow M_H^2$ [Catani, Grazzini, de Florian, Nason '03]



Gluon fusion – beyond NNLO

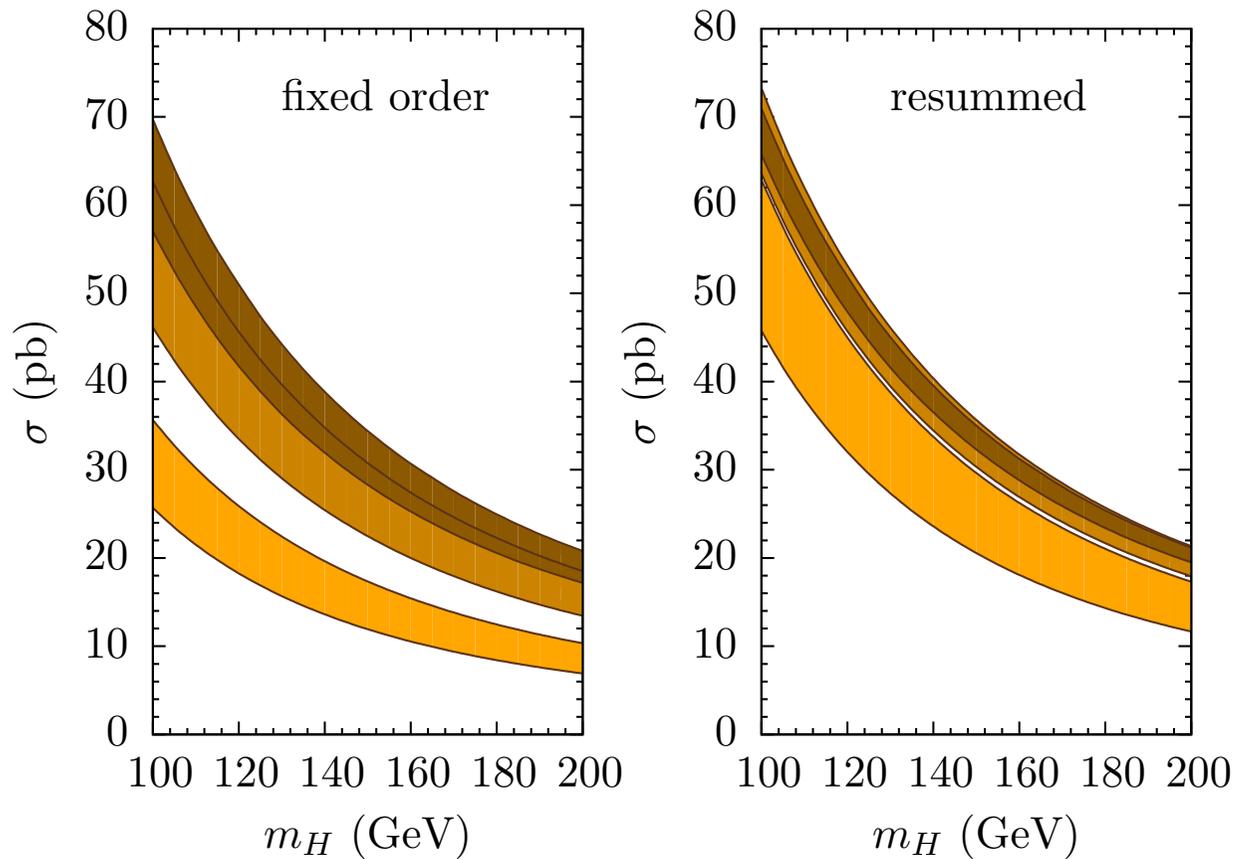
● N³LO soft



[Moch, Vogt '05]
[Laenen, Magnea '05]
[Ravindran '05]
[Kidonakis '05]
[Idilbi, Ju, Yuan '06]

Latest developments

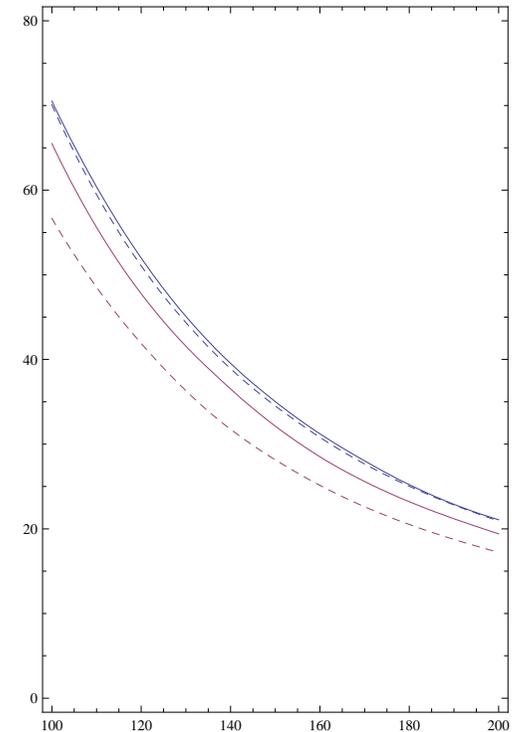
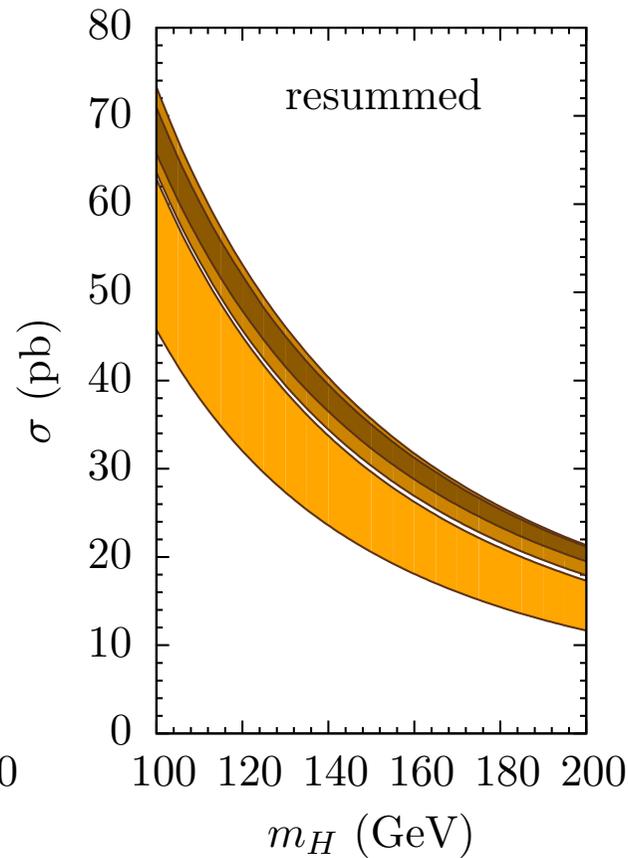
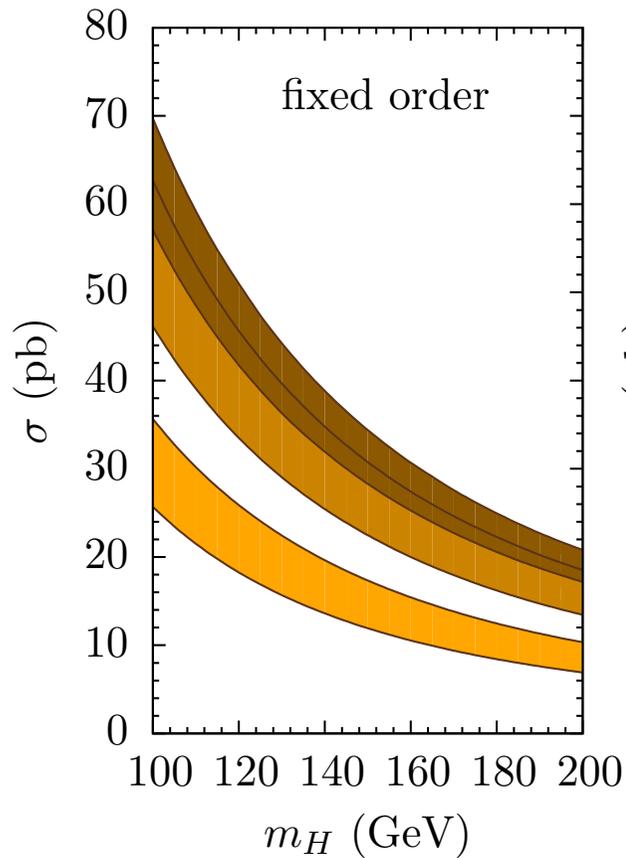
Resumming $(C_A \pi \alpha_s)^n$ from $\ln(-q^2) = \ln q^2 - i\pi$



[Ahrens, Becher, Neubert, Yang 08]

Latest developments

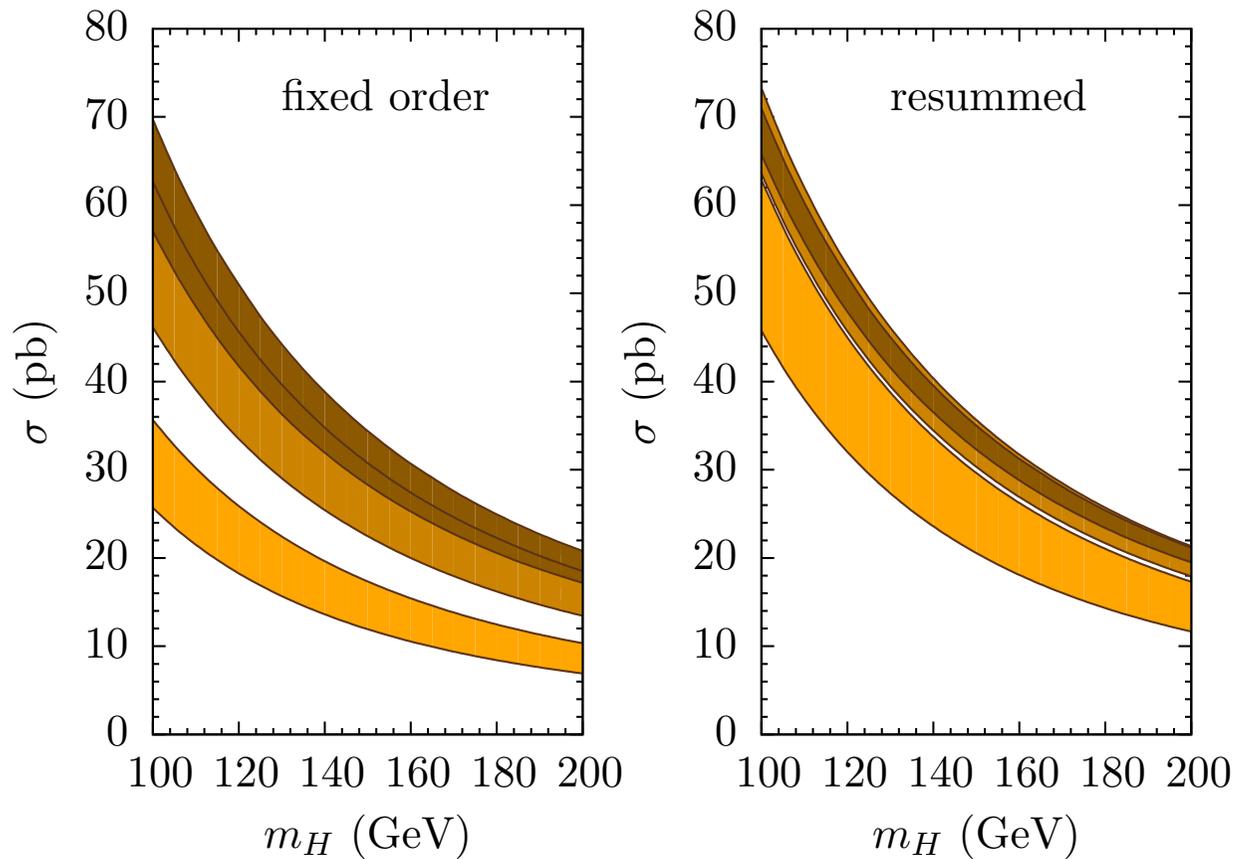
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[Ahrens, Becher, Neubert, Yang 08]

Latest developments

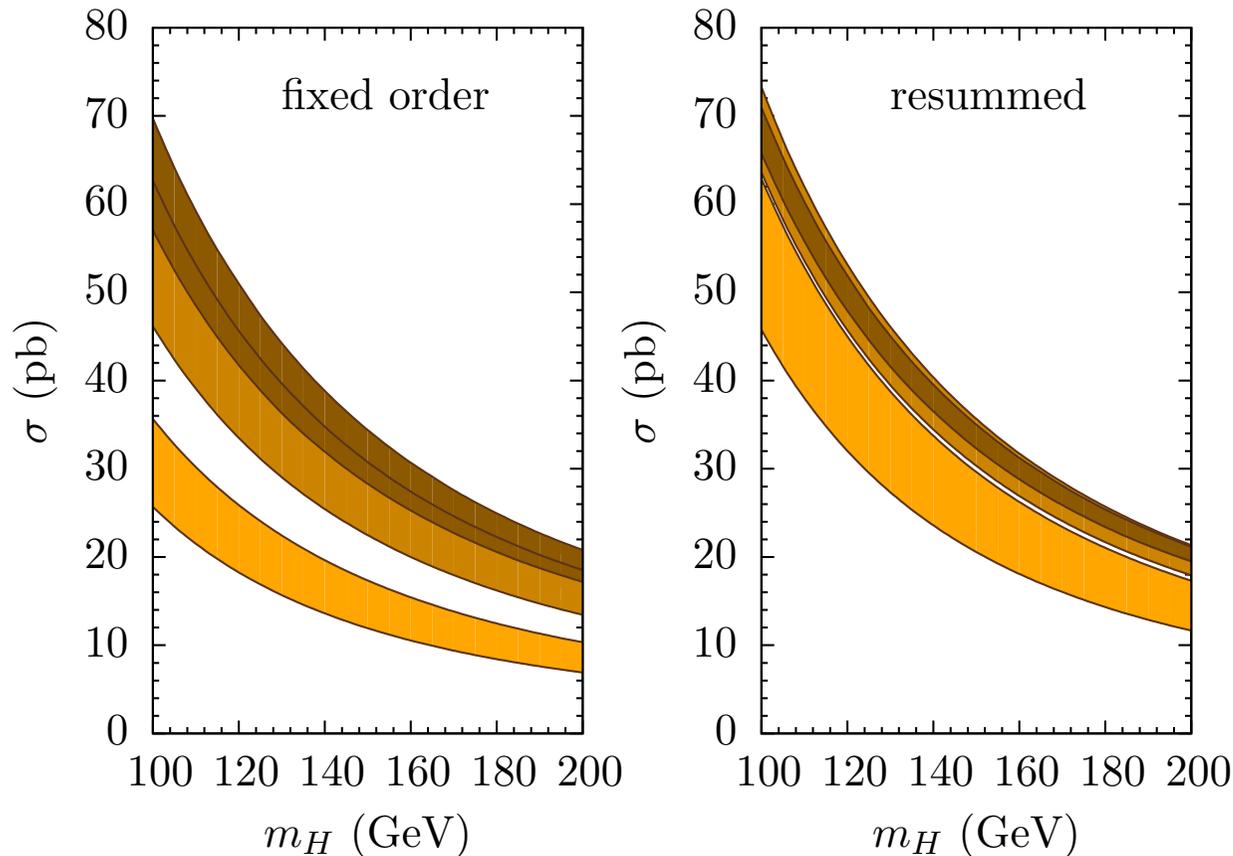
Resumming $(C_A \pi \alpha_s)^n$ from $\ln(-q^2) = \ln q^2 - i\pi$



Message: π^2 is large

Latest developments

Resumming $(C_A \pi \alpha_s)^n$ from $\ln(-q^2) = \ln q^2 - i\pi$



Message: π^2 is large but some π^2 's are larger than others!

Gluon fusion

- QCD corrections
 - under good control, **but**
 - final word on **origin** of large corrections (probably) not spoken
 - better understanding more important than full N^3LO

Gluon fusion

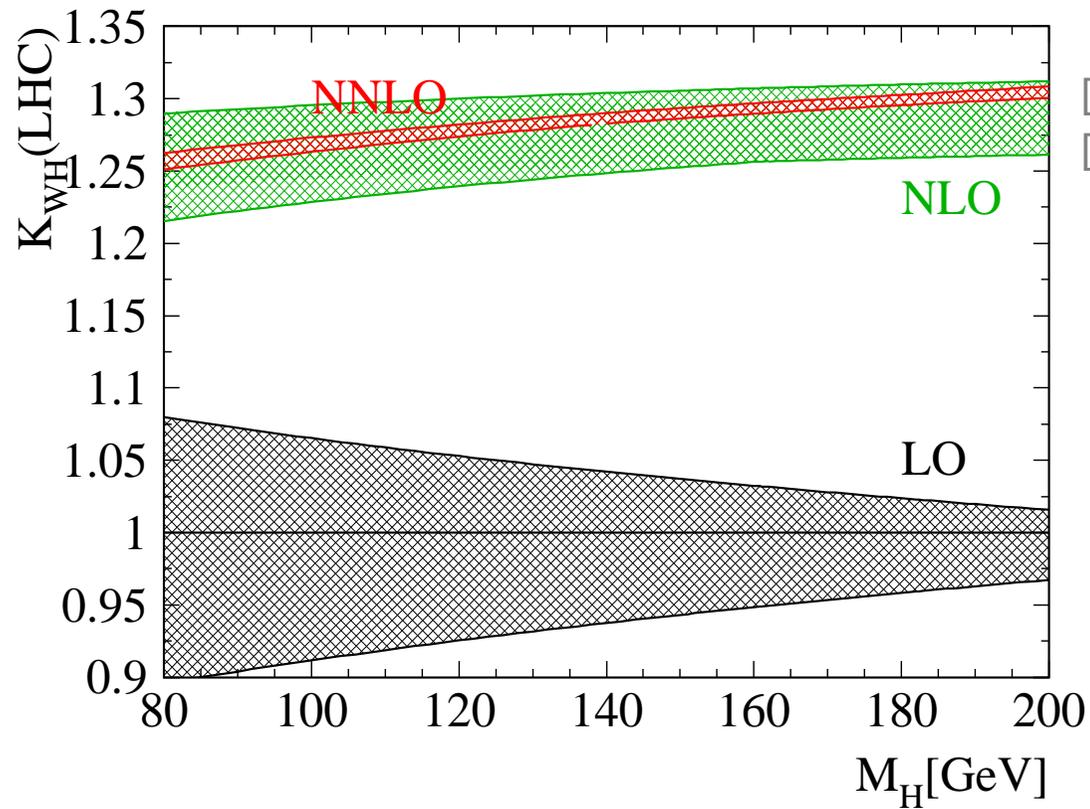
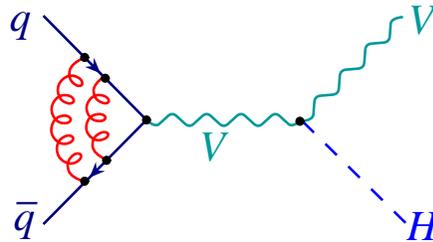
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- can be large at LHC due to “Sudakov” $\ln^2(\hat{s}/M_W^2)$
- in fact:
 - Higgs-Strahlung [Ciccolini, Dittmaier, Krämer '03]

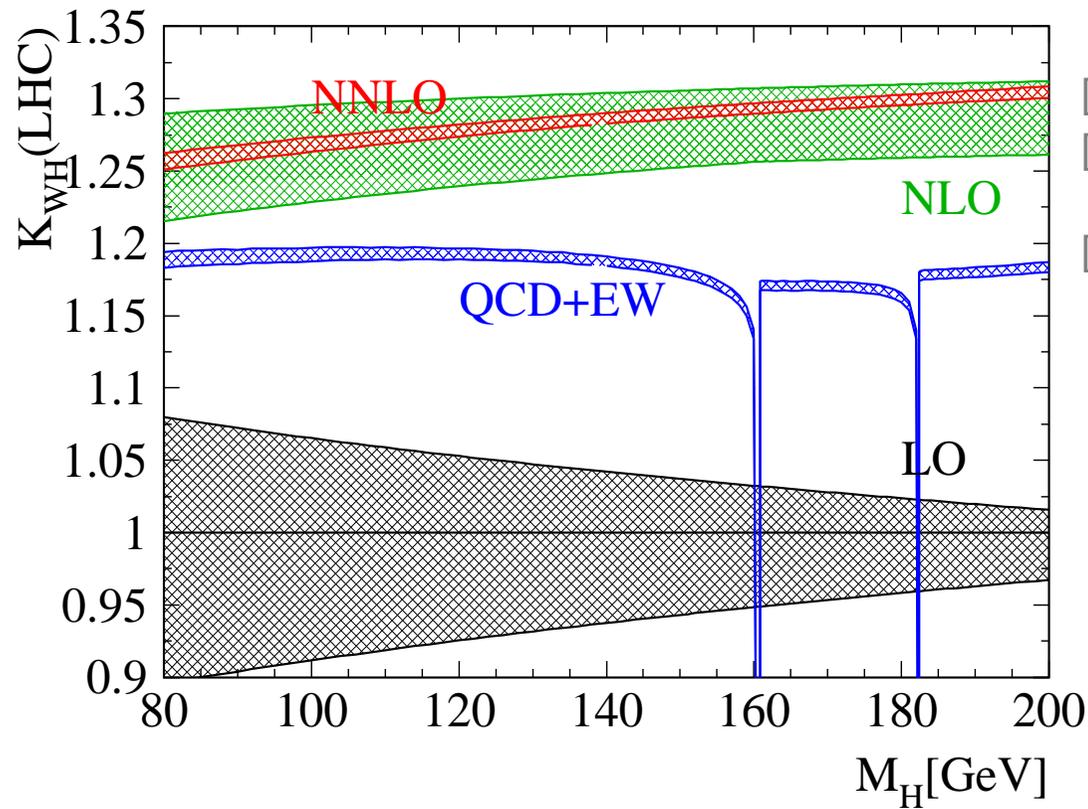
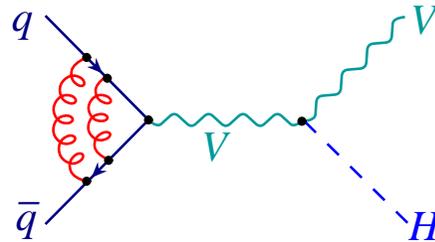
Higgs Strahlung



[Brein, Djouadi, R.H. '03]

[Han, Willenbrock '90]

Higgs Strahlung



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Gluon fusion

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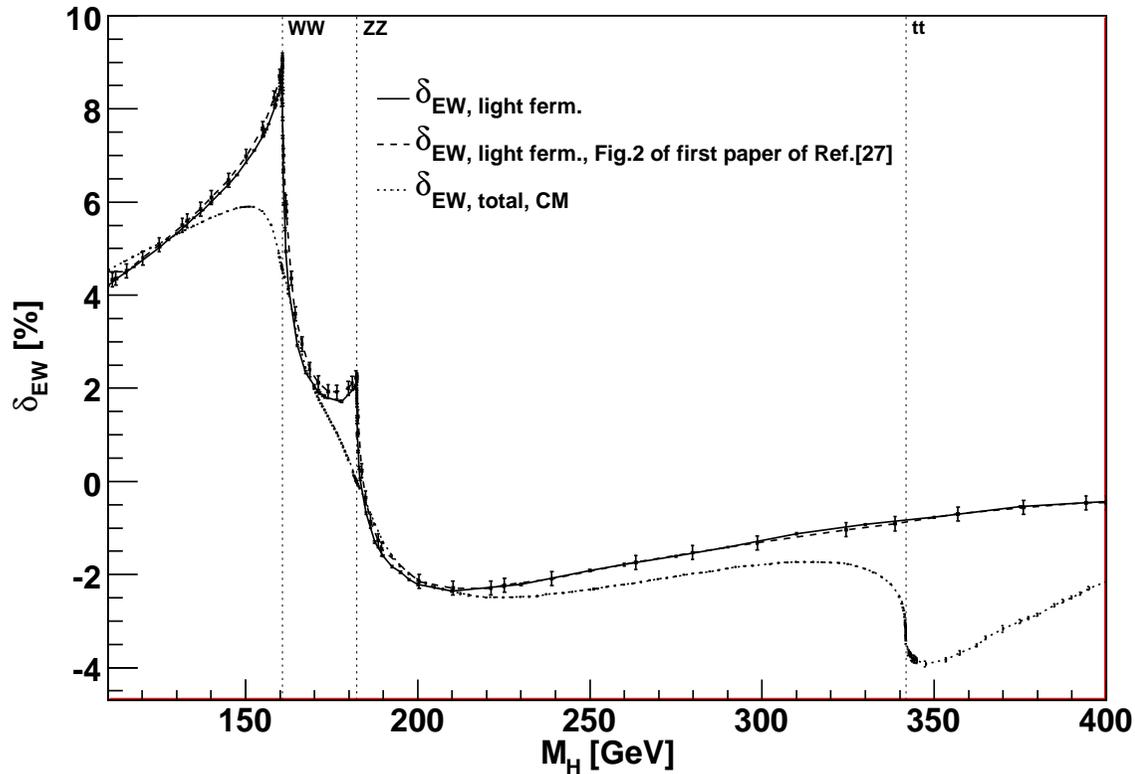
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Gluon fusion

● electro-weak corrections:



[Actis, Passarino, Sturm, Uccirati '08]

partial:

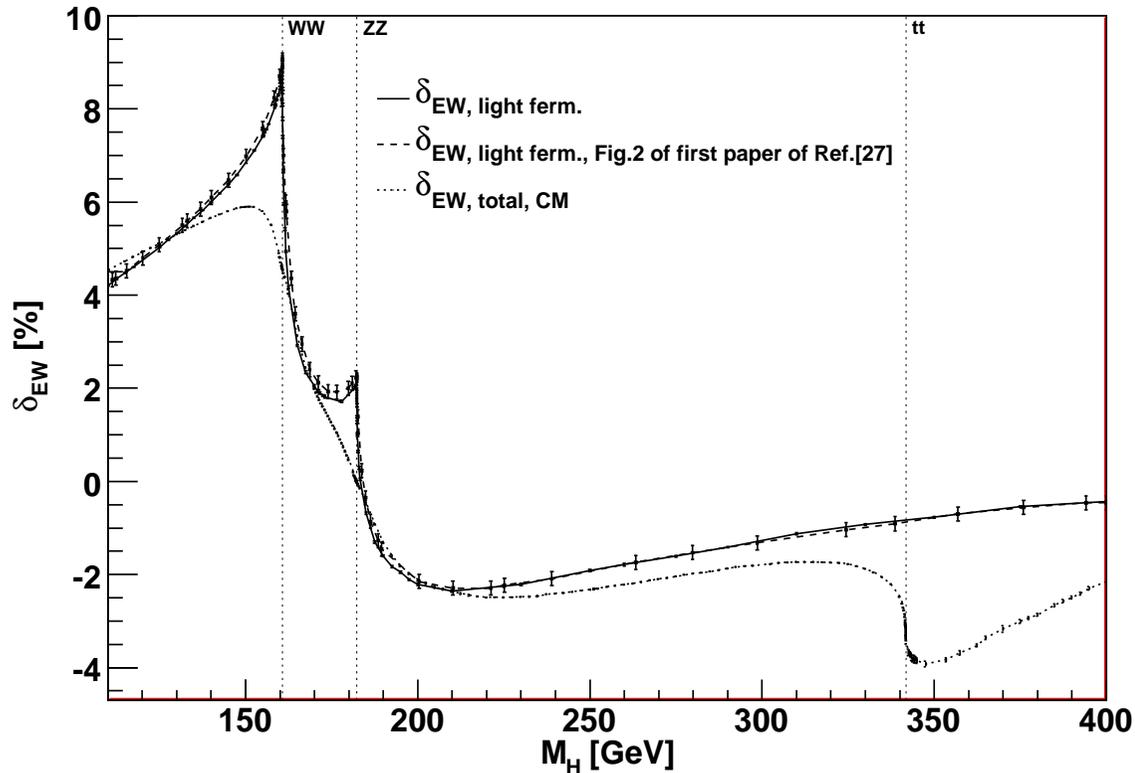
[Aglietti, Bonciani, Degrassi, Vicini '04]

[Degrassi, Maltoni '04]

[Djouadi, Gambino '94]

Gluon fusion

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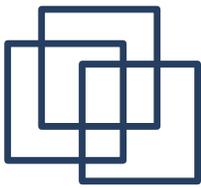
[Aglietti, Bonciani, Degrassi, Vicini '04]

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[Djouadi, Gambino '94]

● mixed EW/QCD? (remember LEP?)

→ do they factorize?



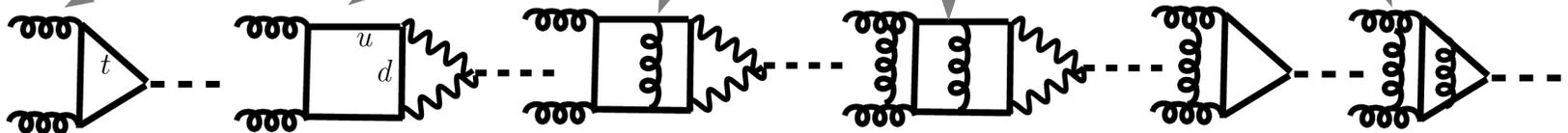
An effective theory with $M_H < M_W$

Checking Complete Factorization assumption requires $O(\alpha\alpha_s)$ and $O(\alpha\alpha_s^2)$

- Calculate leading term of $O(\alpha\alpha_s)$ for $M_H < M_W$
- Estimate the effect of $O(\alpha\alpha_s^2)$

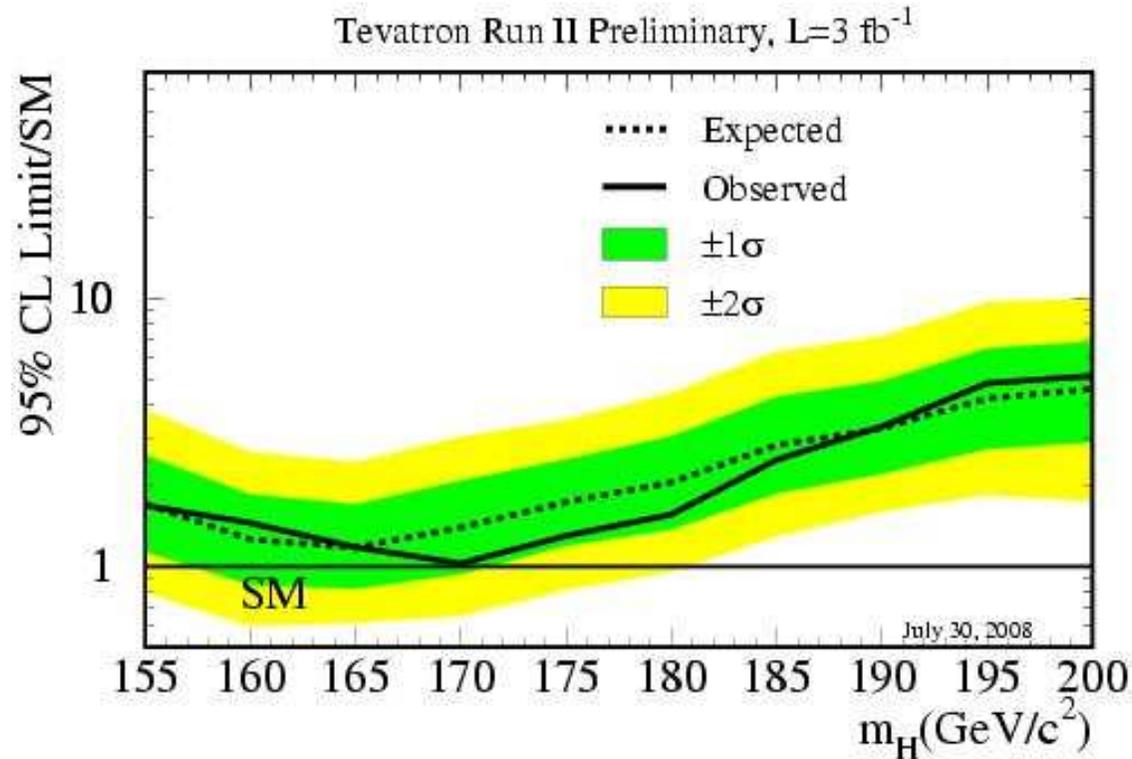
$$L_{eff} = -\alpha_s \frac{C_1}{4V} H G_{\mu\nu}^a G^{a\mu\nu}$$

$$C_1 = -\frac{1}{3\pi} \left\{ 1 + \lambda_{EW} \left[1 + a_s C_{1w} + a_s^2 C_{2w} \right] + a_s C_{1q} + a_s^2 C_{2q} \right\}$$



Putting things together...

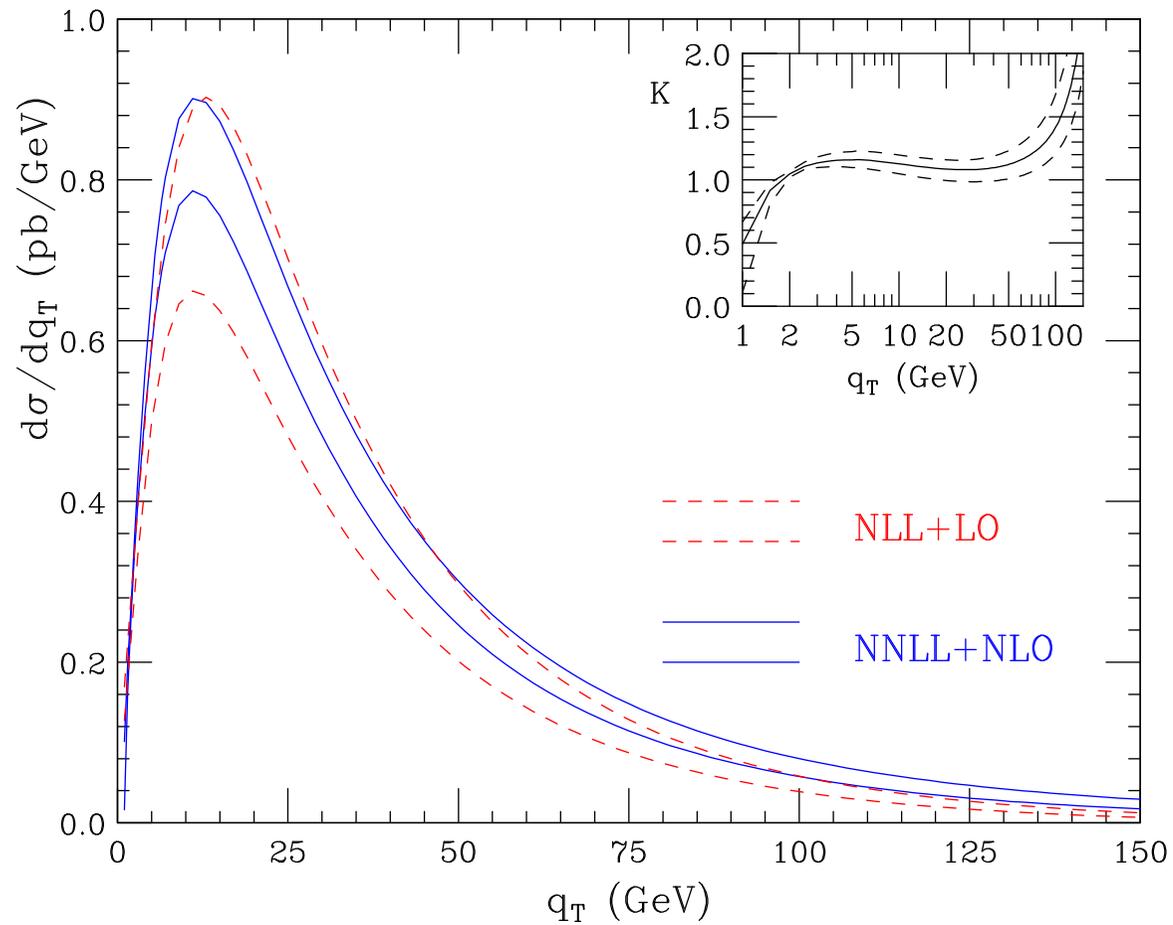
⇒ 7-10% higher cross section that used by Tevatron



but:

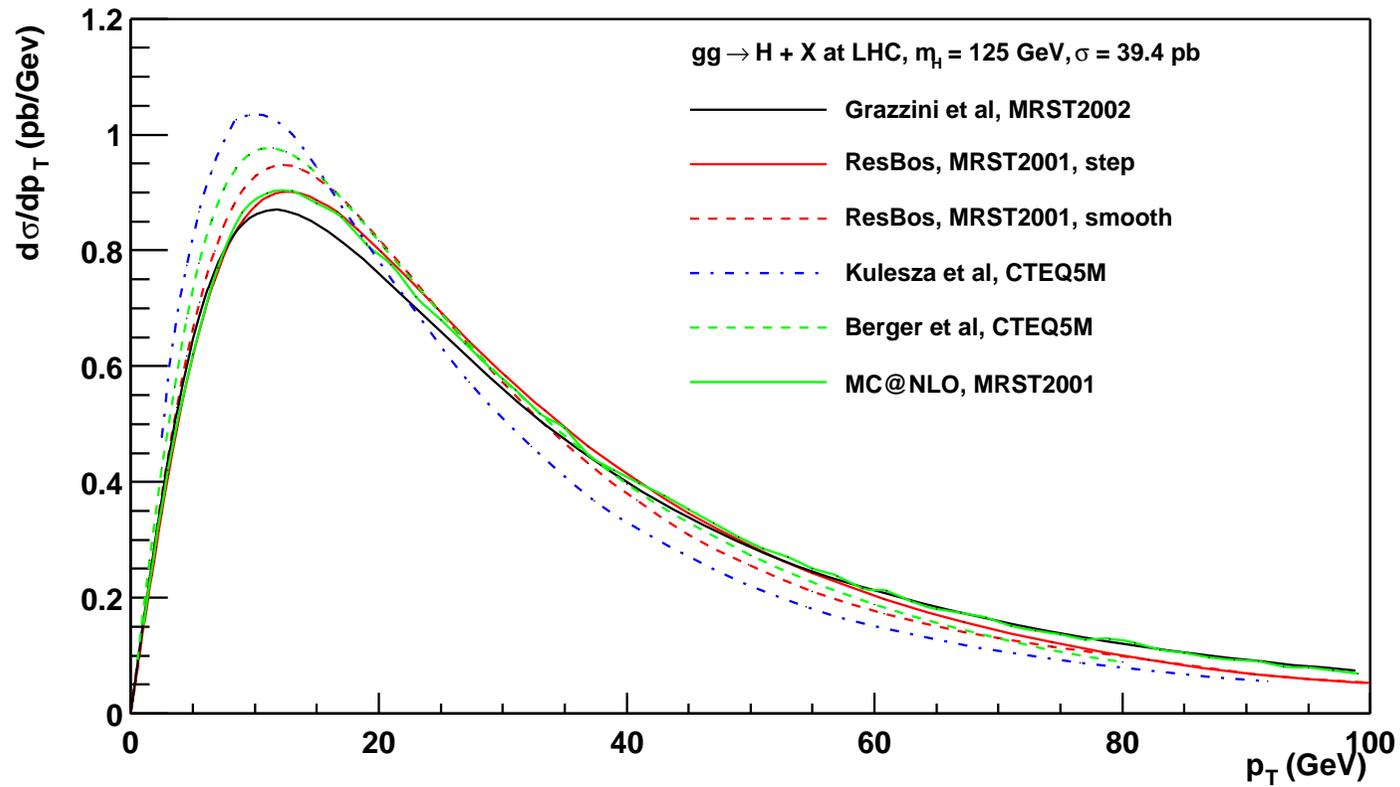
- “ π^2 -resummation” not included
- MRST 2006 → MSTW 2008

Distributions



[Bozzi, Catani, de Florian, Grazzini '05]

Distributions

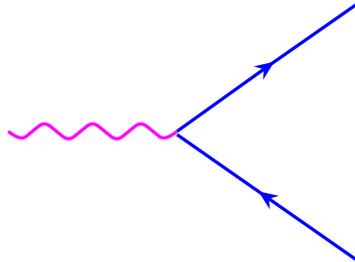


from [hep-ph/0403052]

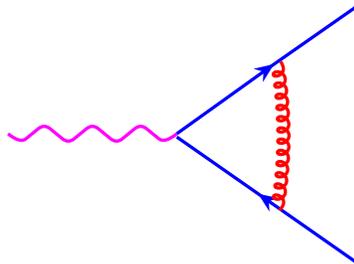
Higher orders with Cuts

Consider $Z \rightarrow 2$ jets: **inclusive**

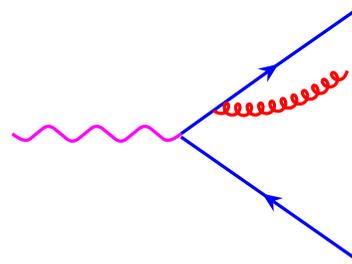
LO:



NLO:



+ \int



$$\frac{A}{\epsilon} + B$$

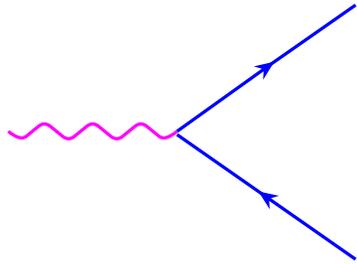
$$- \frac{A}{\epsilon} + C$$

$$= B + C$$

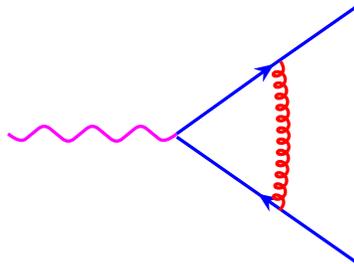
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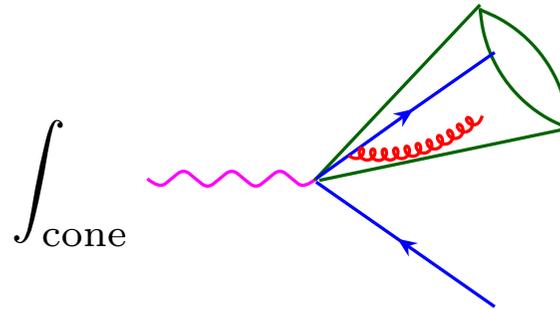
LO:



NLO:



+

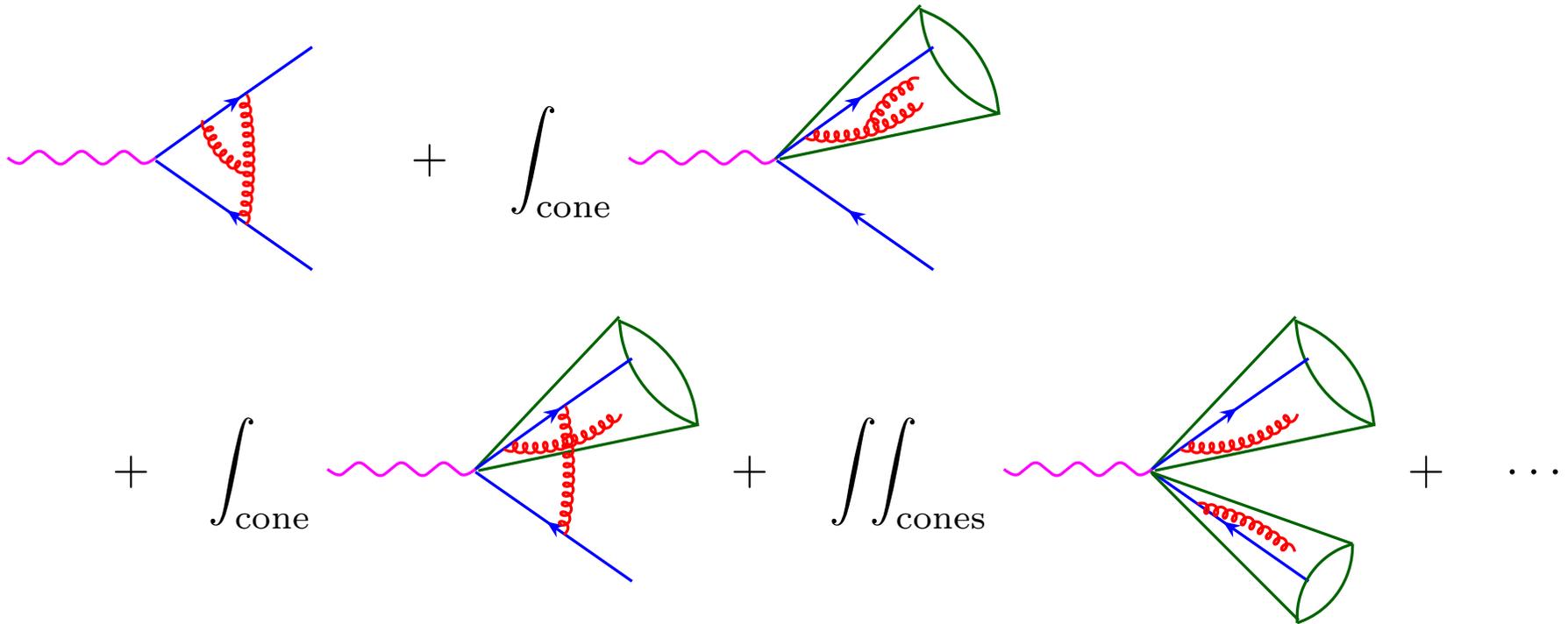


$$\frac{A}{\epsilon} + B$$

$$-\frac{A}{\epsilon} + C_{\text{cut}}$$

$$= B + C_{\text{cut}}$$

Exclusive at NNLO



[Anastasiou, Melnikov, Petriello], [Gehrmann, G.-de Ridder, Glover],
[Grazzini, Frixione], [Kilgore], [Kosower], [Somogyi, Trocsanyi, Del Duca], [Weinzierl]

Exclusive at NNLO

● $e^+e^- \rightarrow 2 \text{ jets}$

[Anastasiou, Melnikov, Petriello '04]

using sector decomposition [Binoth, Heinrich]

● $e^+e^- \rightarrow 3 \text{ jets}$

[Gehrmann-De Ridder, Gehrmann, Glover, Heinrich '08]

[Weinzierl '08]

using antenna subtraction [Gehrmann-De Ridder, Gehrmann, Glover]

● $q\bar{q} \rightarrow V$

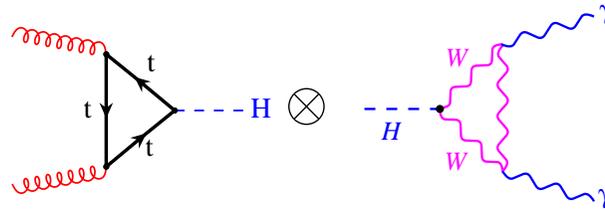
[Melnikov, Petriello '06]

● $gg \rightarrow H$

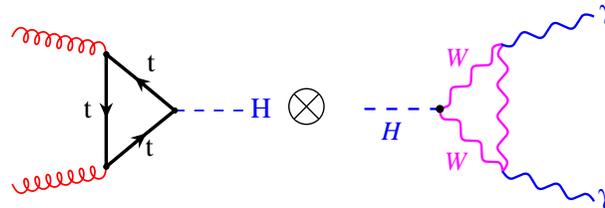
FEHIP: [Anastasiou, Melnikov, Petriello '04]

HNNLO: [Catani, Grazzini '07] subtraction method

NNLO with cuts



NNLO with cuts



m_h	$\sigma_{\text{NNLO}}^{\text{cut}} / \sigma_{\text{NNLO}}^{\text{inc}}$	$K_{\text{cut}}^{(2)} / K_{\text{inc}}^{(2)}$
110	0.590	0.981
115	0.597	0.968
120	0.603	0.953
125	0.627	0.970
130	0.656	1.00
135	0.652	0.98

[Anastasiou, Melnikov, Petriello '05]

NNLO with cuts

$$gg \rightarrow H \rightarrow WW \rightarrow l^+ \nu l^- \bar{\nu}$$

[Stöckli]

$\sigma(\text{fb})$	LO	NLO	NNLO
$\mu = \frac{M_h}{2}$	21.002 ± 0.021	22.47 ± 0.11	18.45 ± 0.54
$\mu = M_h$	17.413 ± 0.017	21.07 ± 0.11	18.75 ± 0.37
$\mu = 2M_h$	14.529 ± 0.014	19.50 ± 0.10	19.01 ± 0.27

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- $\sigma^{\text{NNLO}} < \sigma^{\text{NLO}}$!
- **Questions:**
 - can one understand the size of the radiative corrections (with cuts)?
 - are the cuts sensitive to heavy top limit?
 - effect of “ π^2 -resummation” ?

Including soft radiation

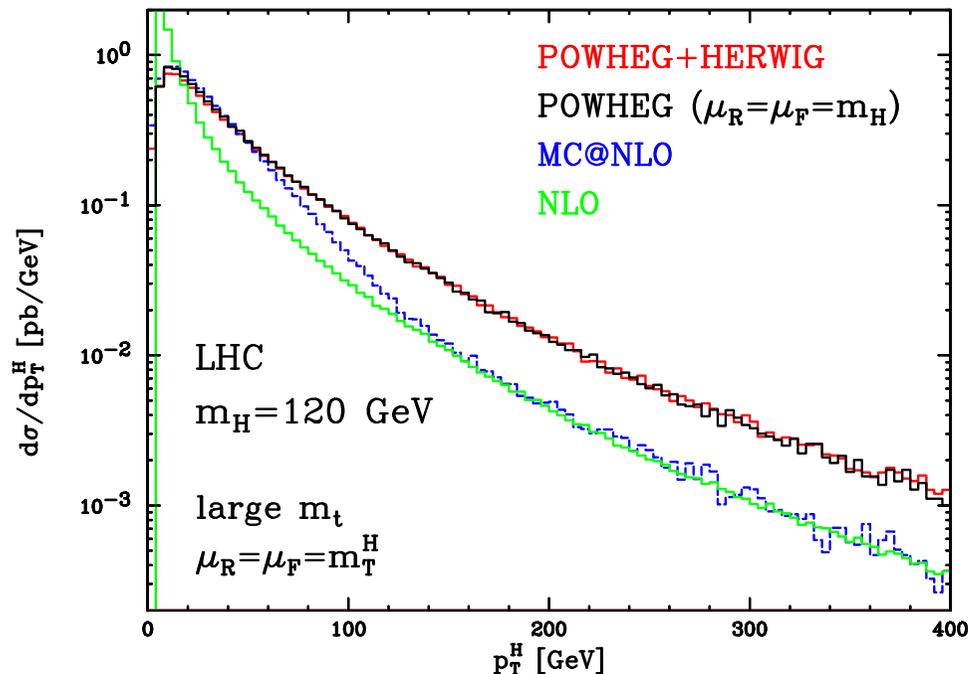
- match NLO calculation with parton shower
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- two successful approaches so far:
 - MC@NLO [Frixione, Nason, Webber '03]
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[Alioli, Nason, Oleari, Re '08]

Including soft radiation

● approximate solutions:

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• ME \oplus PS

CKKW [Catani, Kuhn, Krauss, Webber] \rightarrow SHERPA [Gleisberg et al.]

AlpGen [Mangano]

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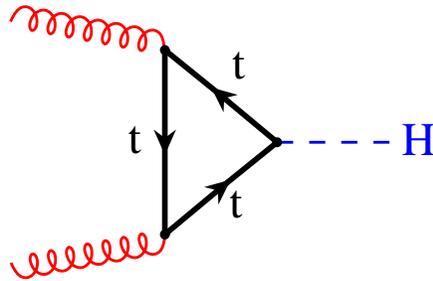
AlpGen [Mangano]

● differential re-weighting of LO MC

e.g. reweight Pythia by FEHIP

[Davatz *et al.* '04,'06]

Gluon Fusion

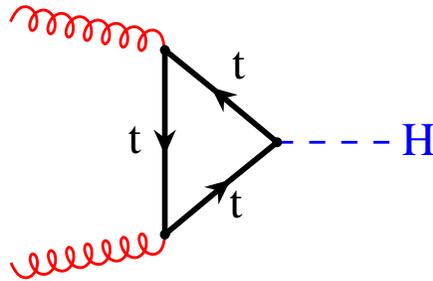


- dominant production mode
- sensitive to heavy particle spectrum

but

- $H \rightarrow b\bar{b}$ decay mode not usable for discovery
- LO is 1-loop \rightarrow radiative corrections difficult
- depends on Yukawa coupling

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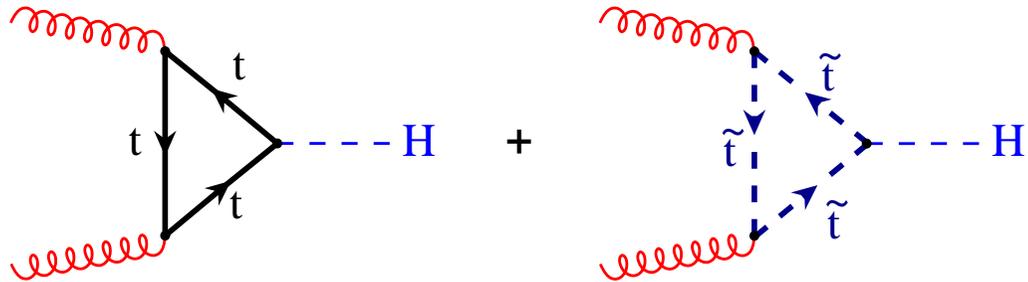


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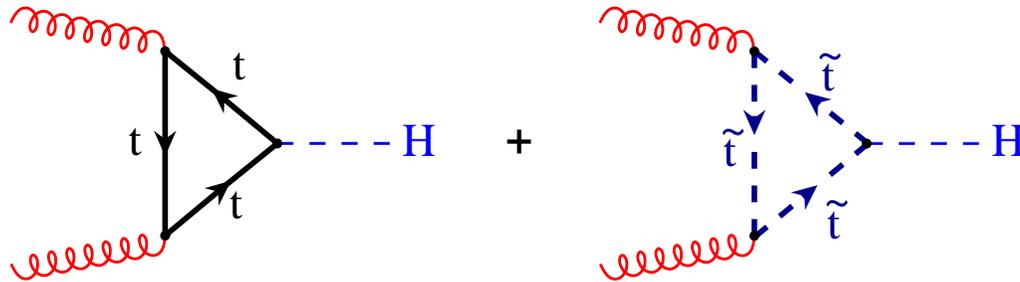
Gluon fusion in SUSY



may interfere destructively!

[Djouadi '98], [Carena *et al.* '99]

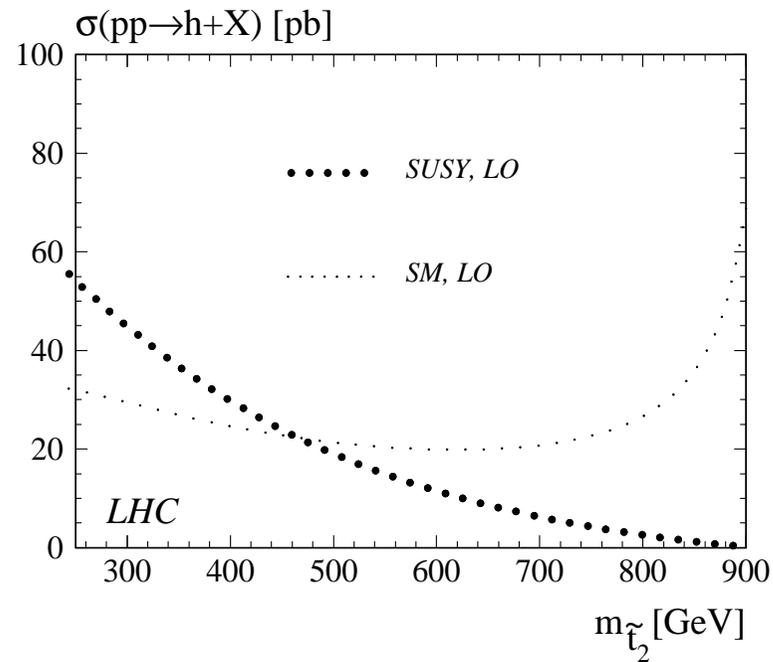
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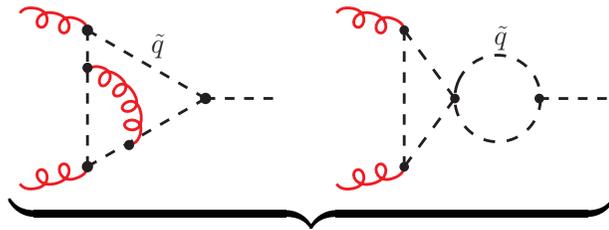
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[Djouadi '98], [Carena *et al.* '99]

$$\begin{aligned}
 m_{\tilde{t}_1} &= 200 \text{ GeV} \\
 m_{\tilde{g}} &= 1 \text{ TeV} \\
 \tan \beta &= 10, \quad \alpha = 0, \\
 \theta_t &= \frac{\pi}{4}
 \end{aligned}$$



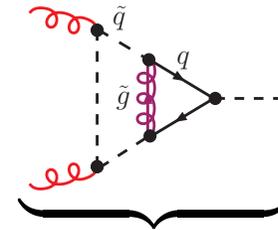
Radiative corrections



[Aglietti, Bonciani, Degrassi, Vicini '06]

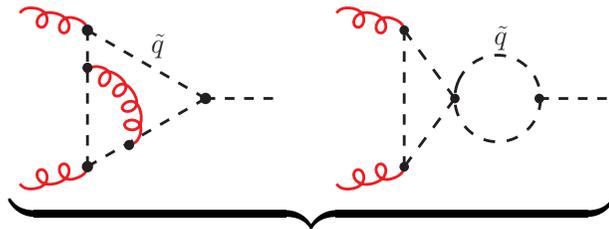
[Anastasiou, Beerli, Bucherer, Daleo, Kunstz '06]

[Mühlleitner, Spira '07]



[Anastasiou, Beerli, Daleo '08]

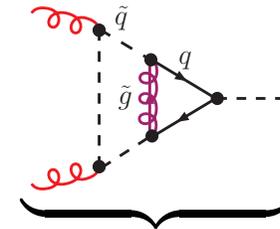
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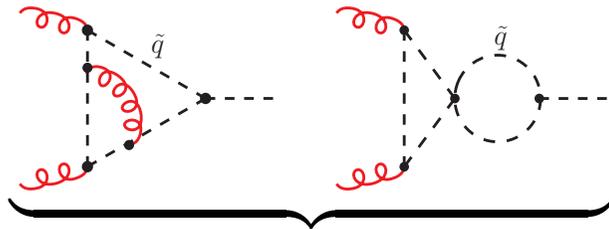
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- limit $M_{\tilde{g}}, M_{\tilde{t}} \gg m_t$ and small $\tan \beta$
 [R.H., Steinhauser '04], [Degrassi, Slavich '08]

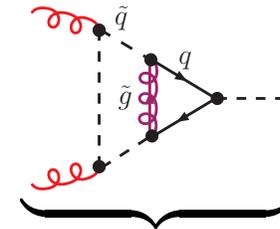
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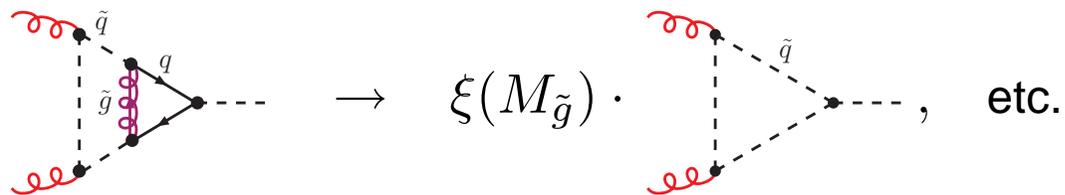


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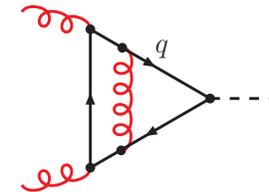
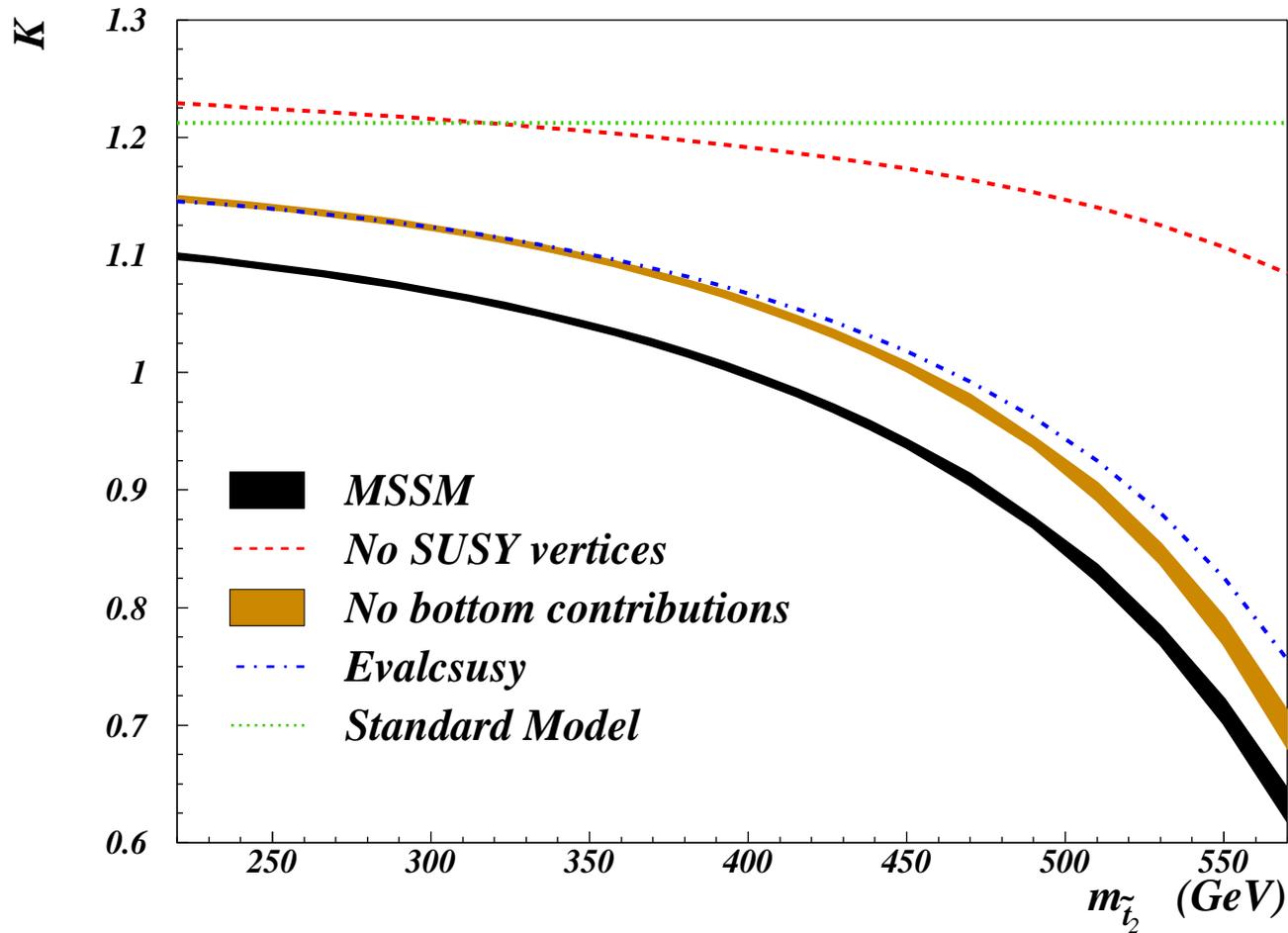
[R.H., Steinhauser '04], [Degrassi, Slavich '08]

- limit $M_{\tilde{g}} \gg M_{\tilde{t}}, m_t, M_H$:



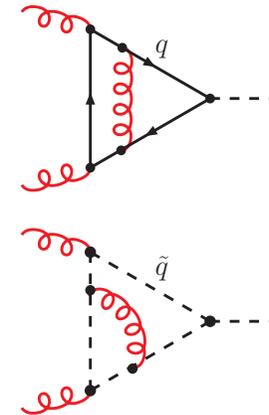
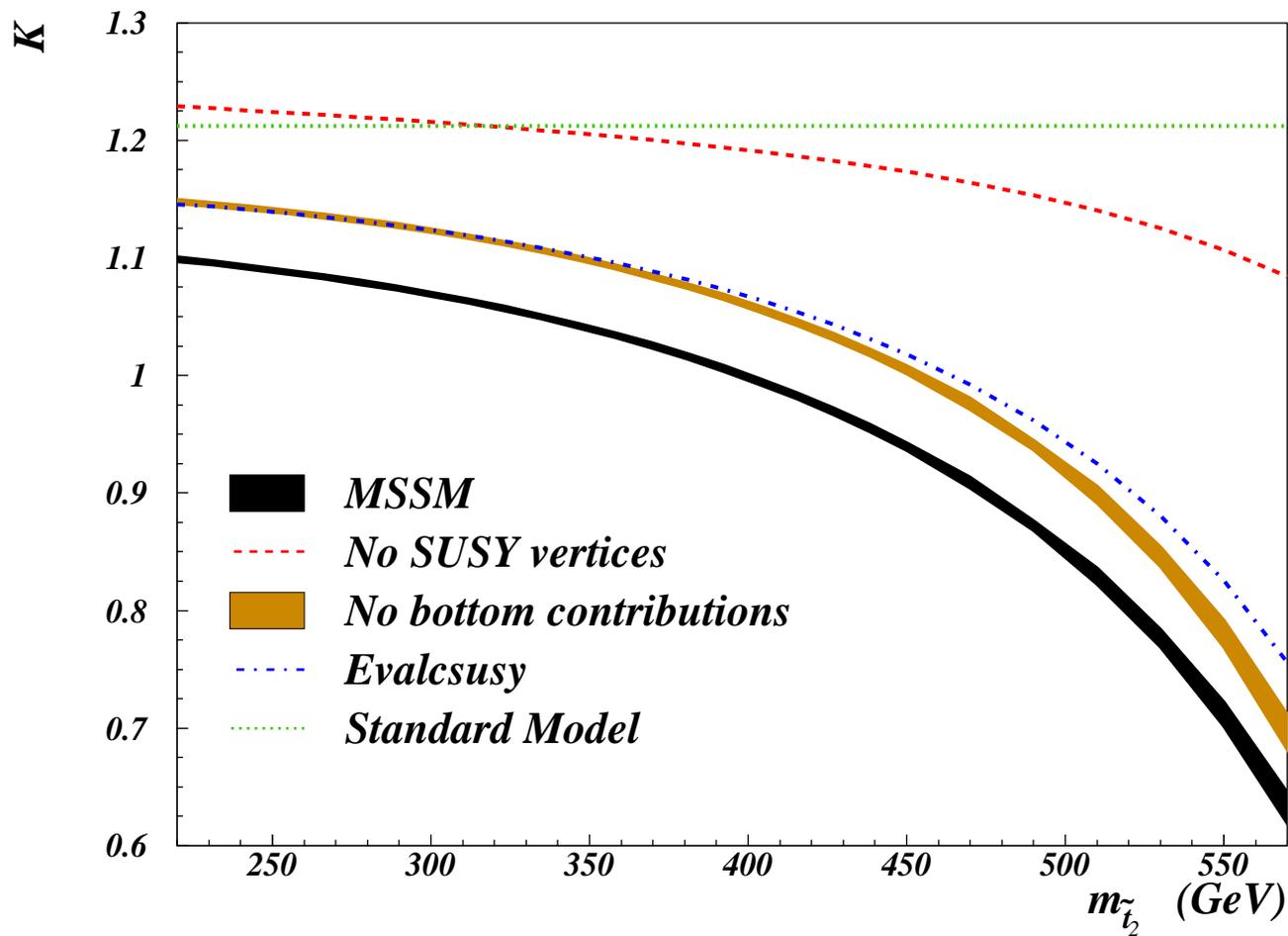
[Mühlleitner, Rzehak, Spira '08]

Numerical Impact



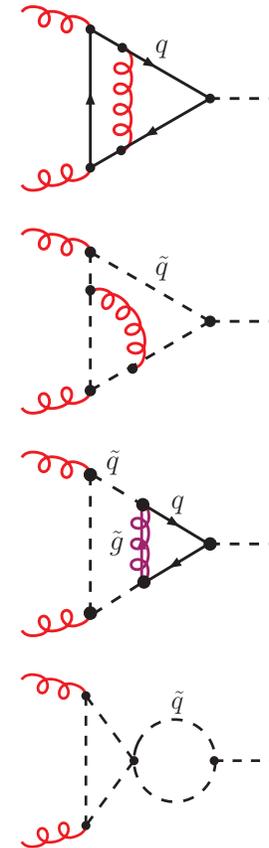
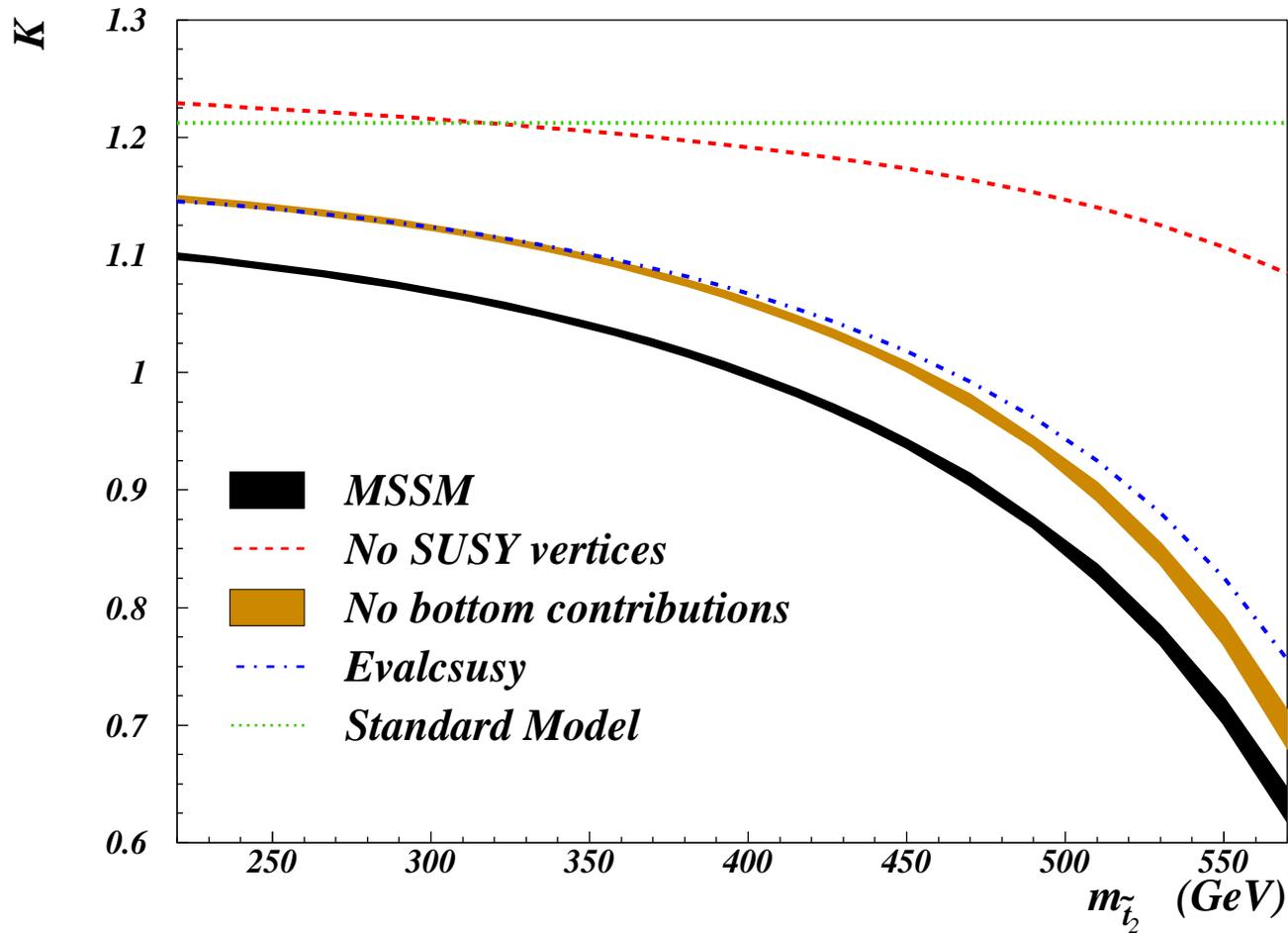
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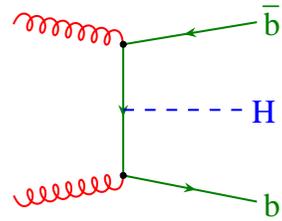
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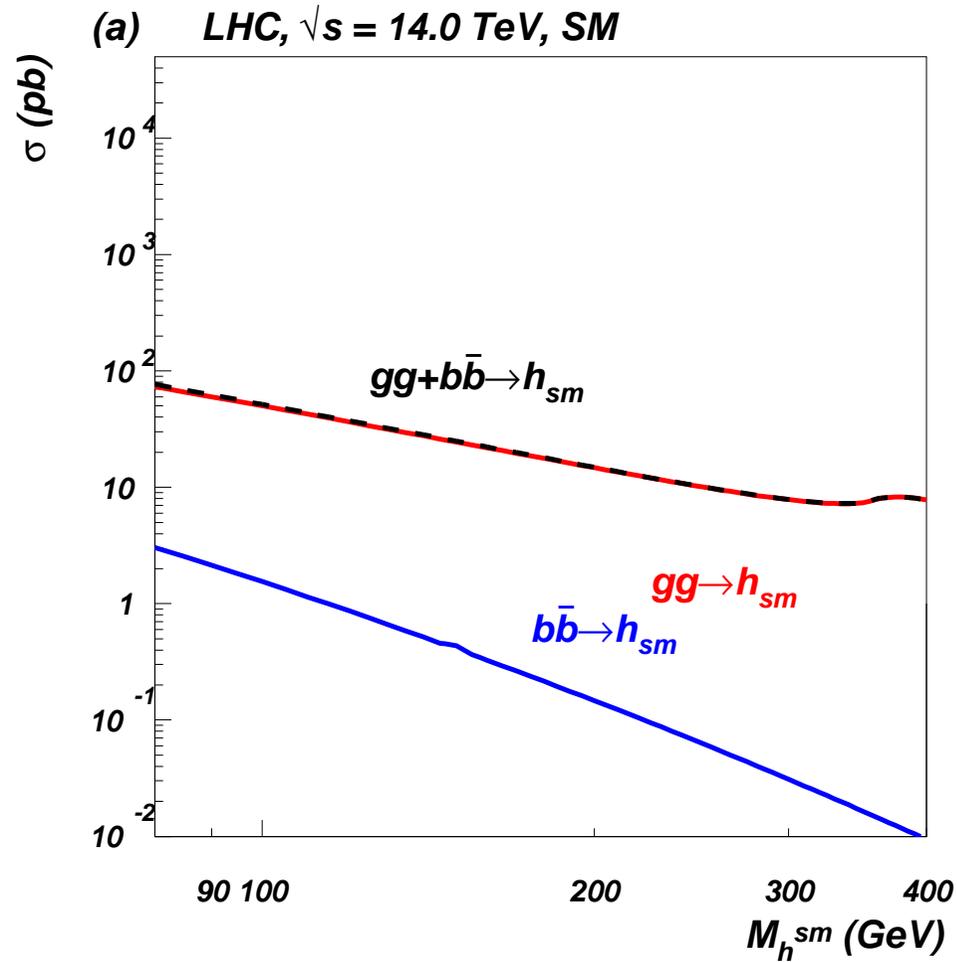


[Anastasiou, Daleo '08]

$H/A + b\bar{b}$

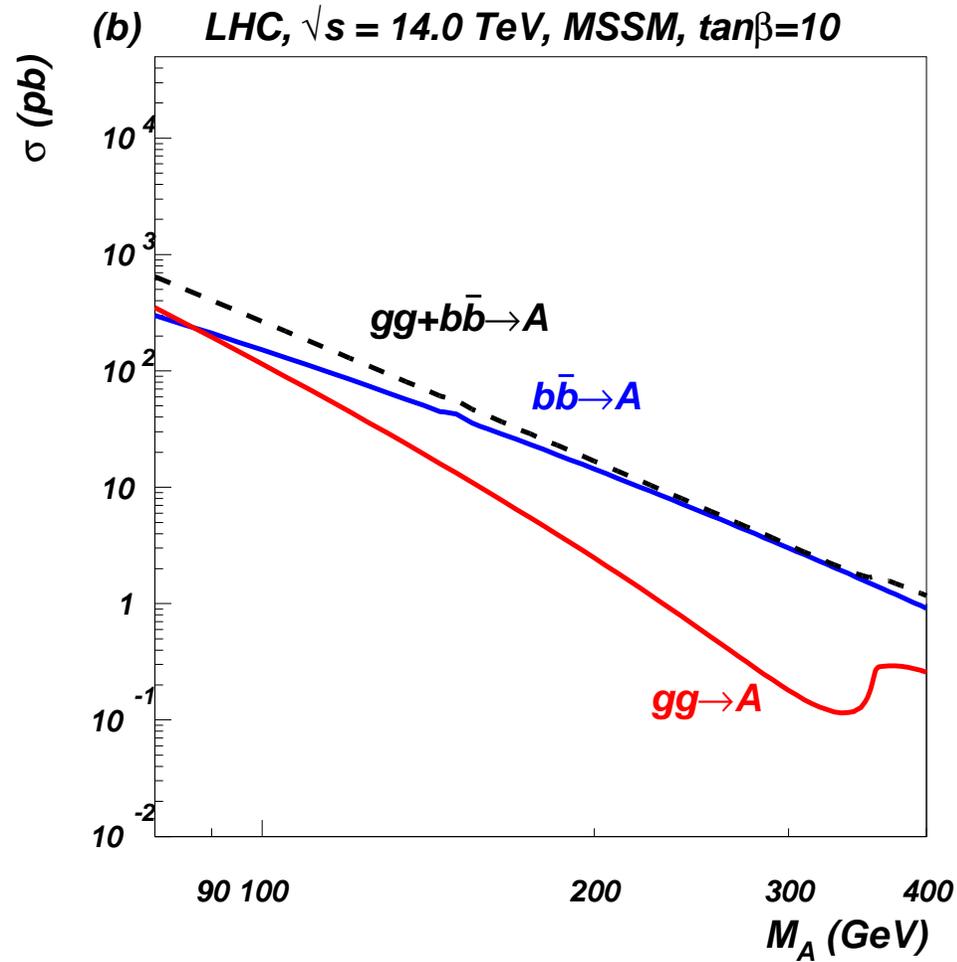


Numerical relevance



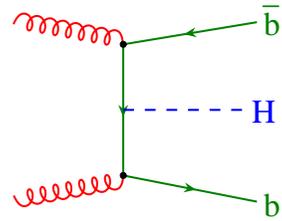
from [Belyaev et al., '05]

Numerical relevance

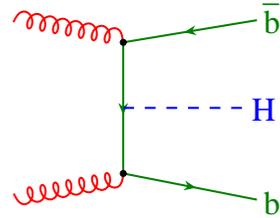


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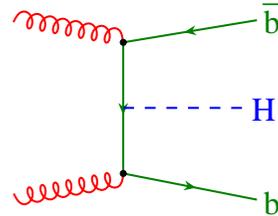


$H/A + b\bar{b}$



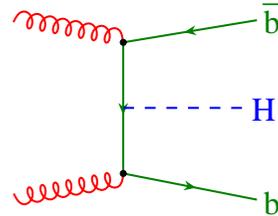
● collinear logarithms: $\sim \alpha_s \ln(m_b/M_H) \sim \alpha_s \ln(5/200)$

$H/A + b\bar{b}$



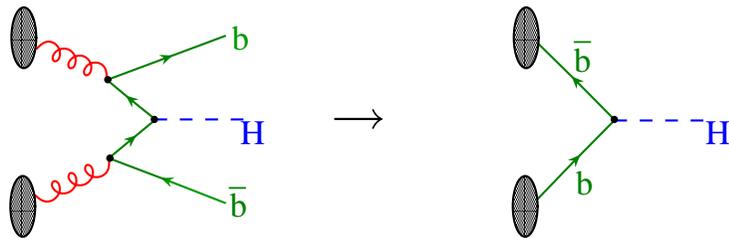
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→ cf. talk by M. Krämer on $b\bar{t}H^+$ production

$H/A + b\bar{b}$

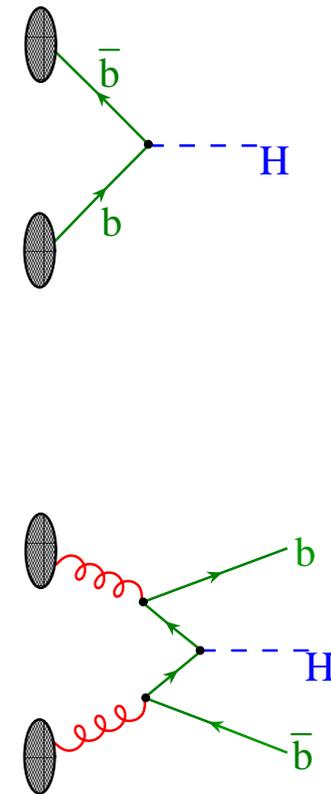
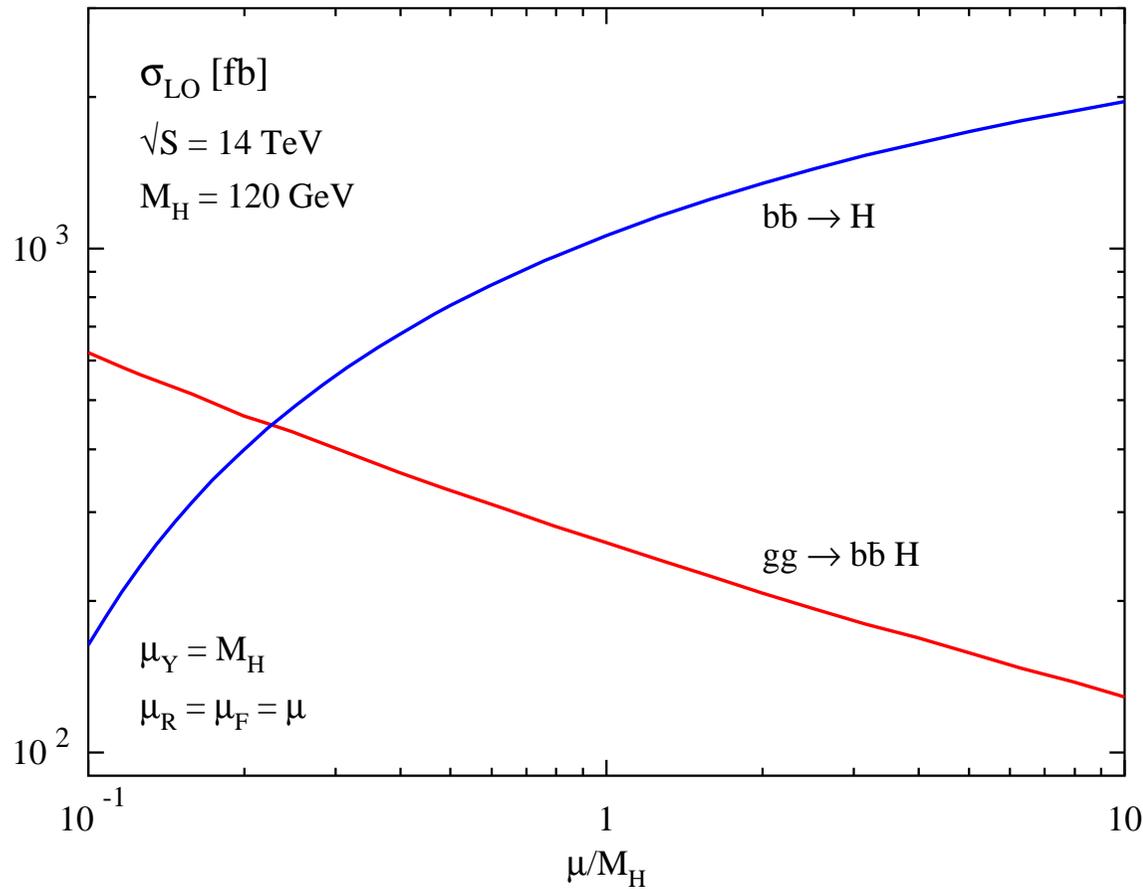


- collinear logarithms: $\sim \alpha_s \ln(m_b/M_H) \sim \alpha_s \ln(5/200)$
→ cf. talk by M. Krämer on $b\bar{t}H^+$ production

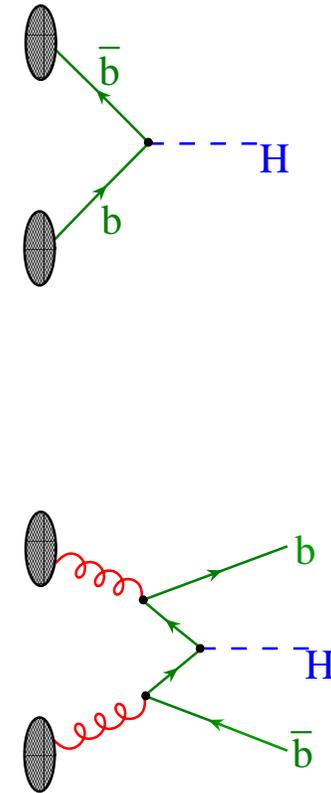
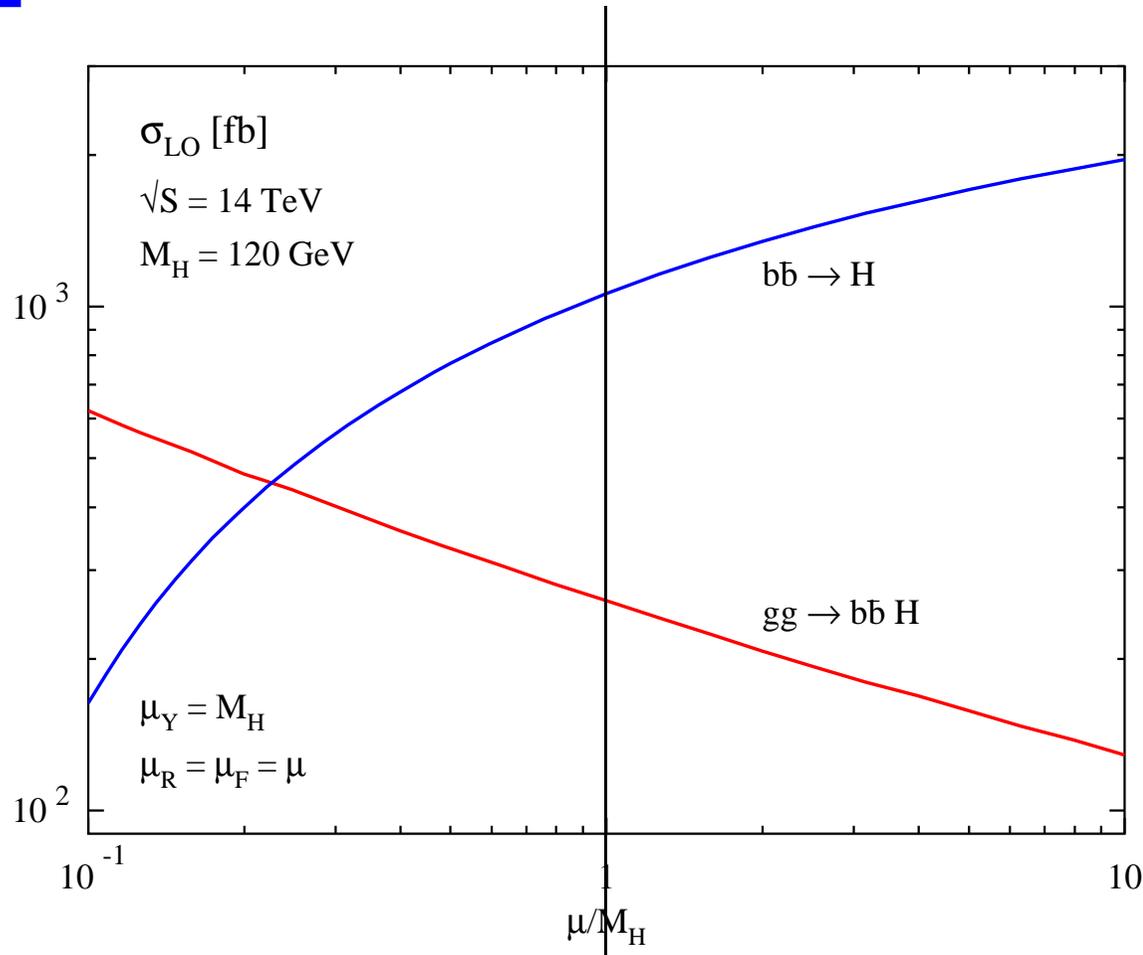
- resummation: **bottom quarks as partons**



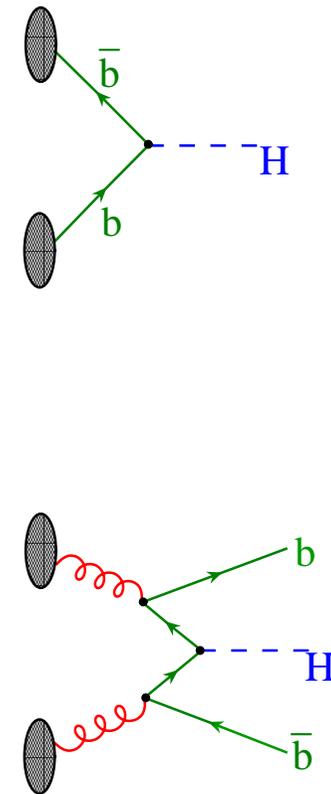
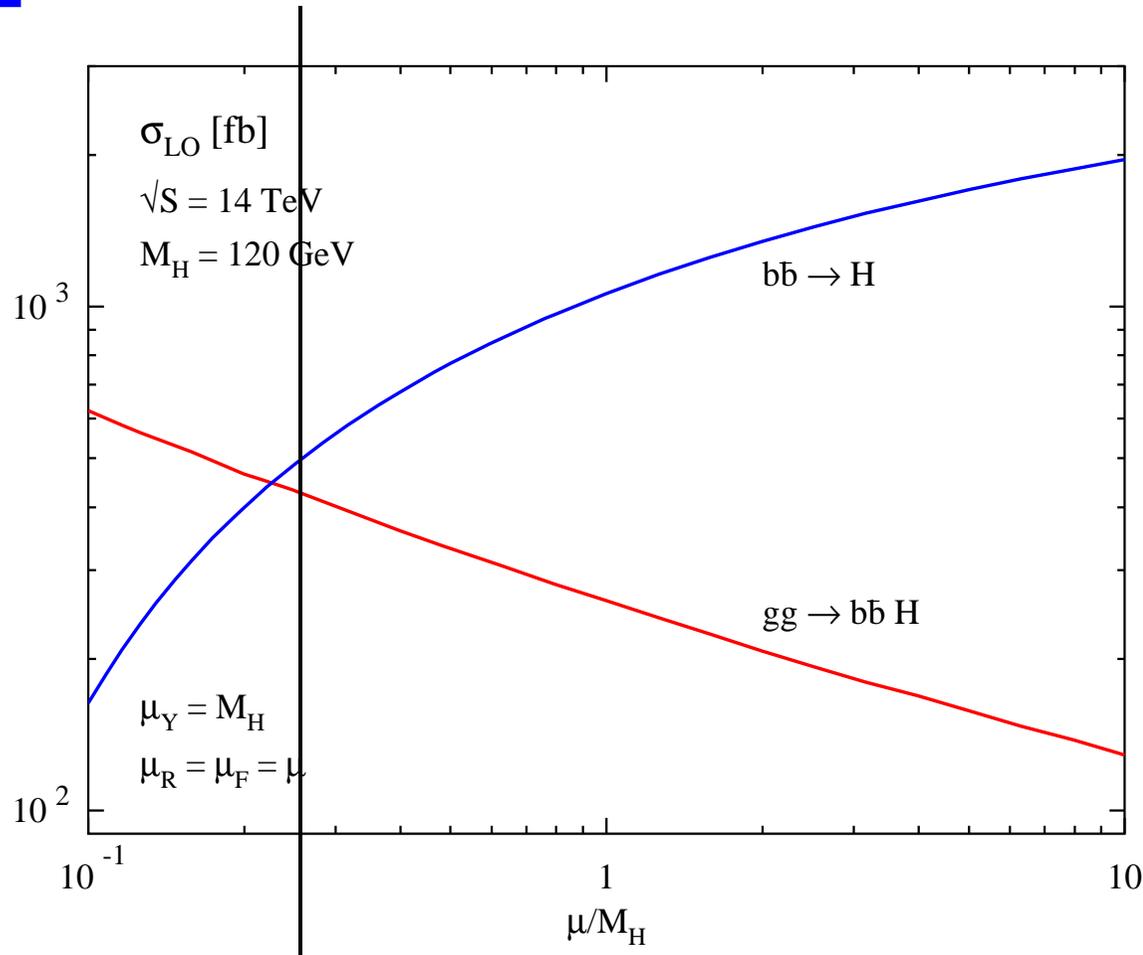
4-FNS vs. 5-FNS



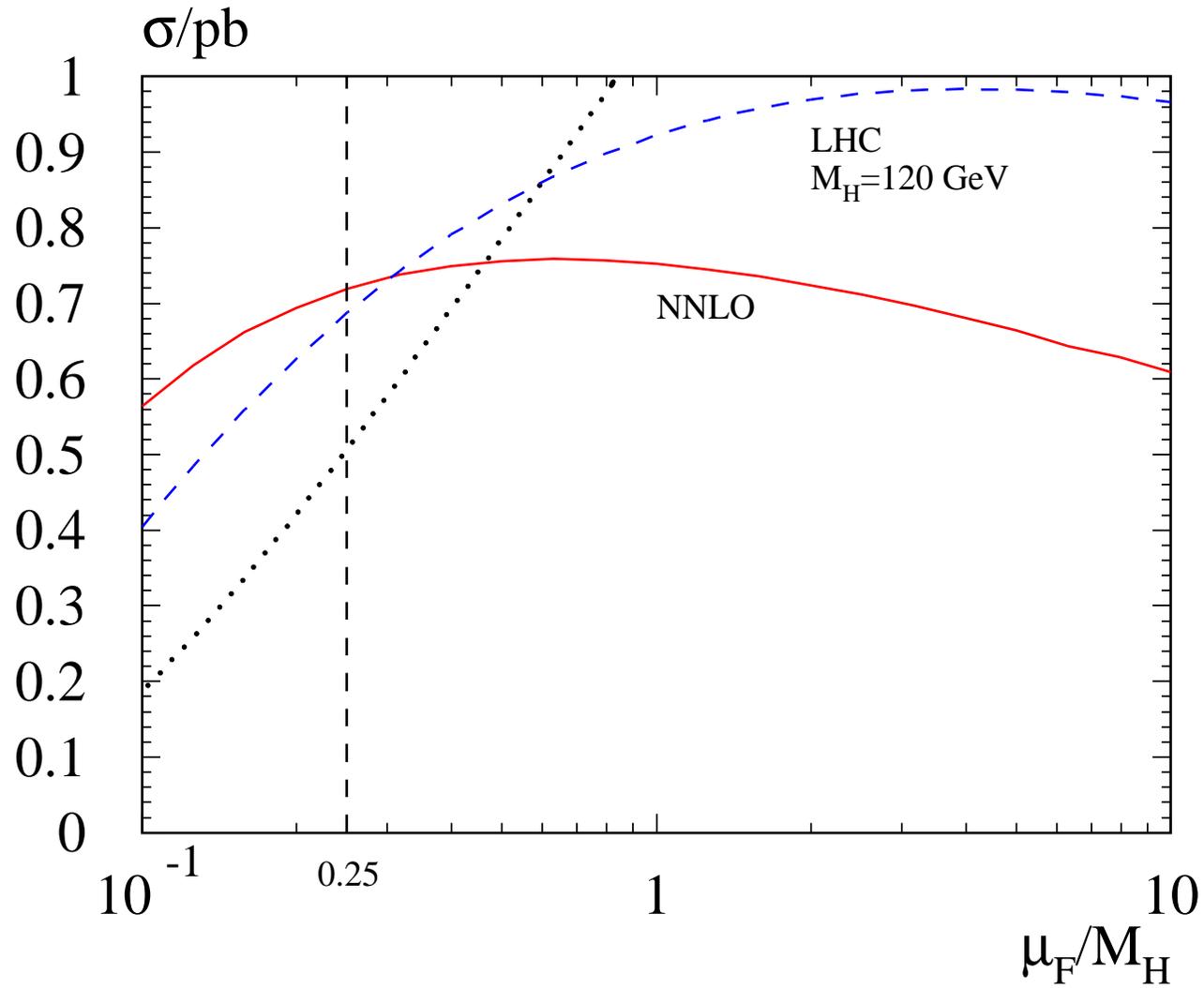
4-FNS vs. 5-FNS



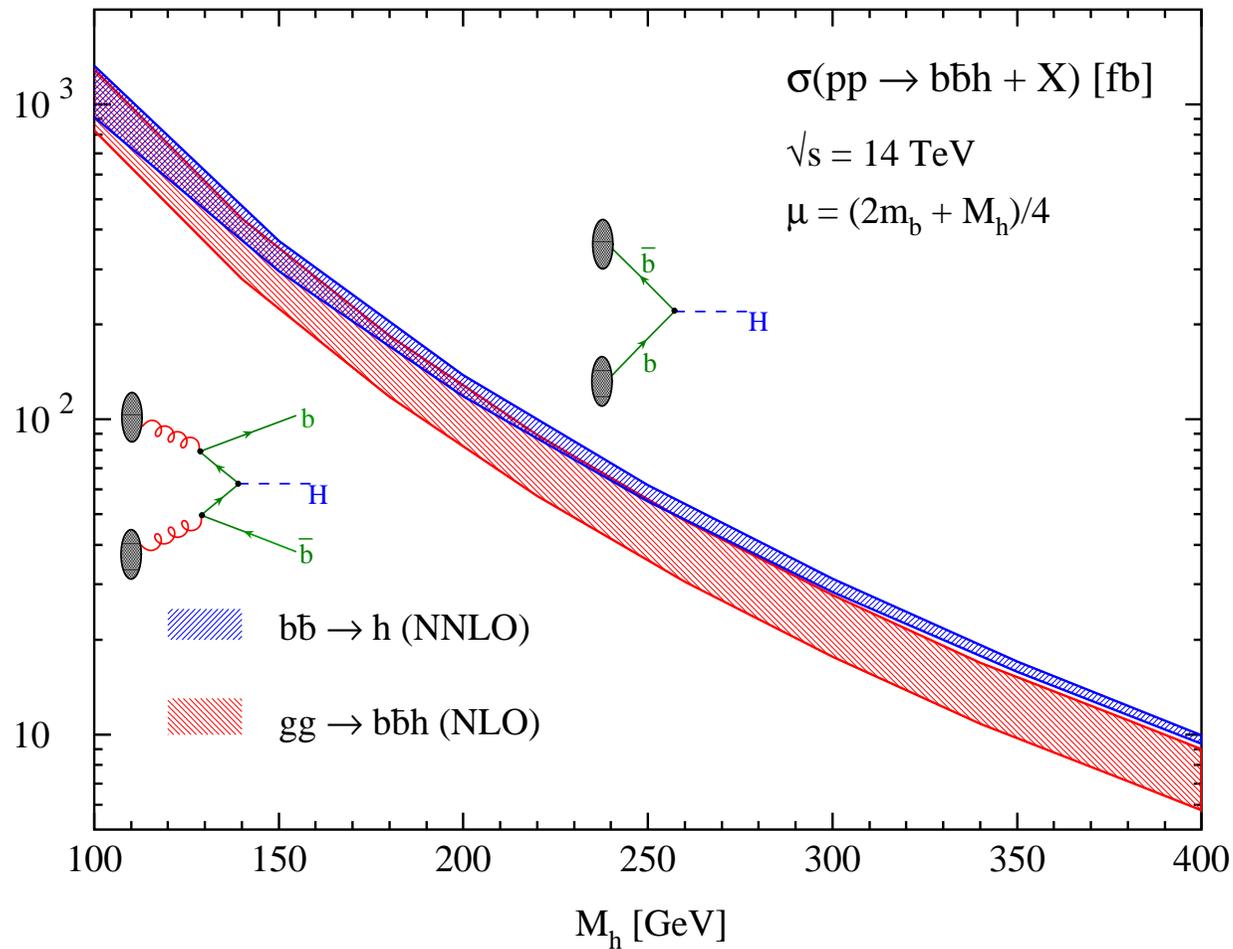
4-FNS vs. 5-FNS



5-FNS at NNLO



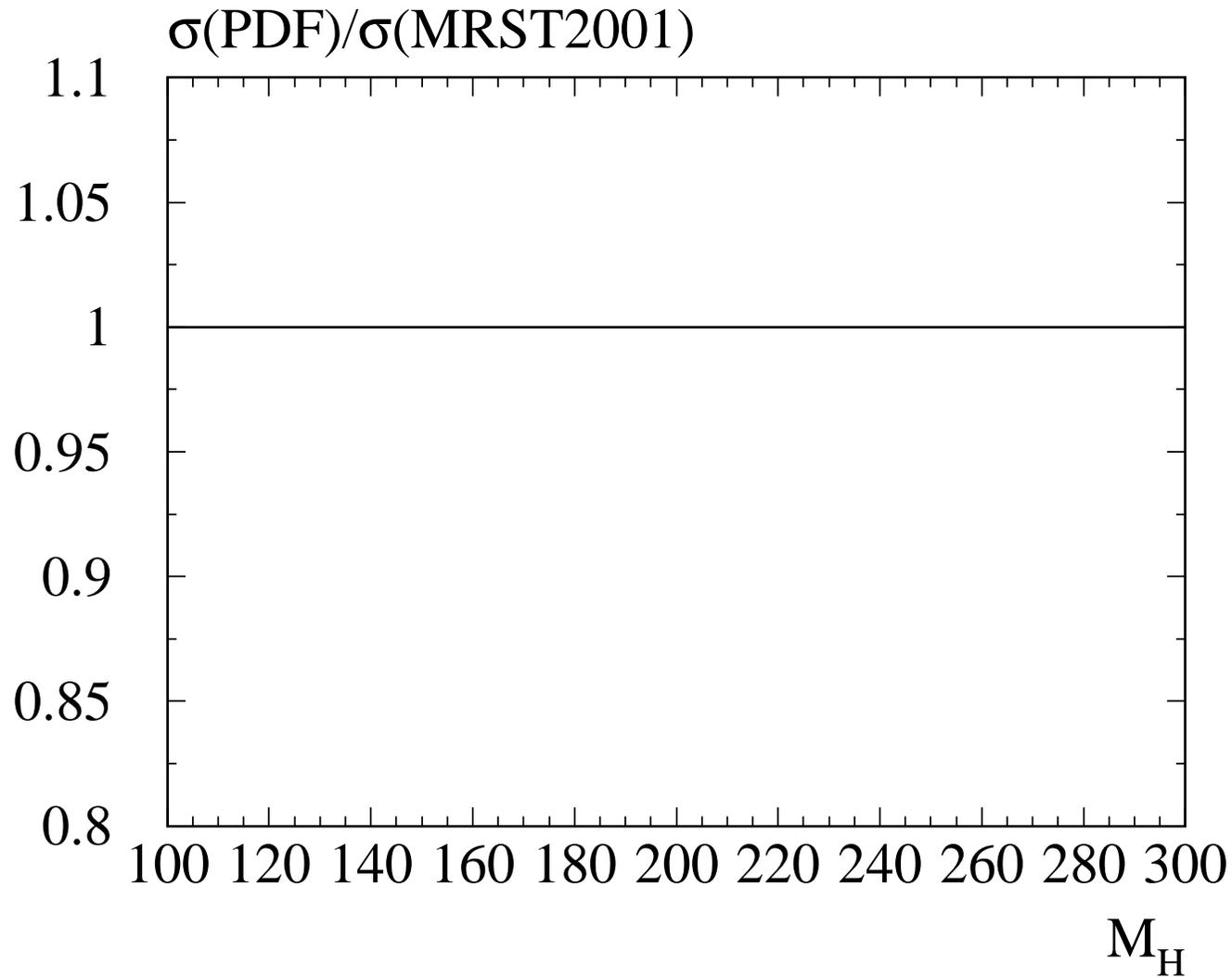
$pp \rightarrow H + b\bar{b}$



meanwhile also electro-weak corrections available

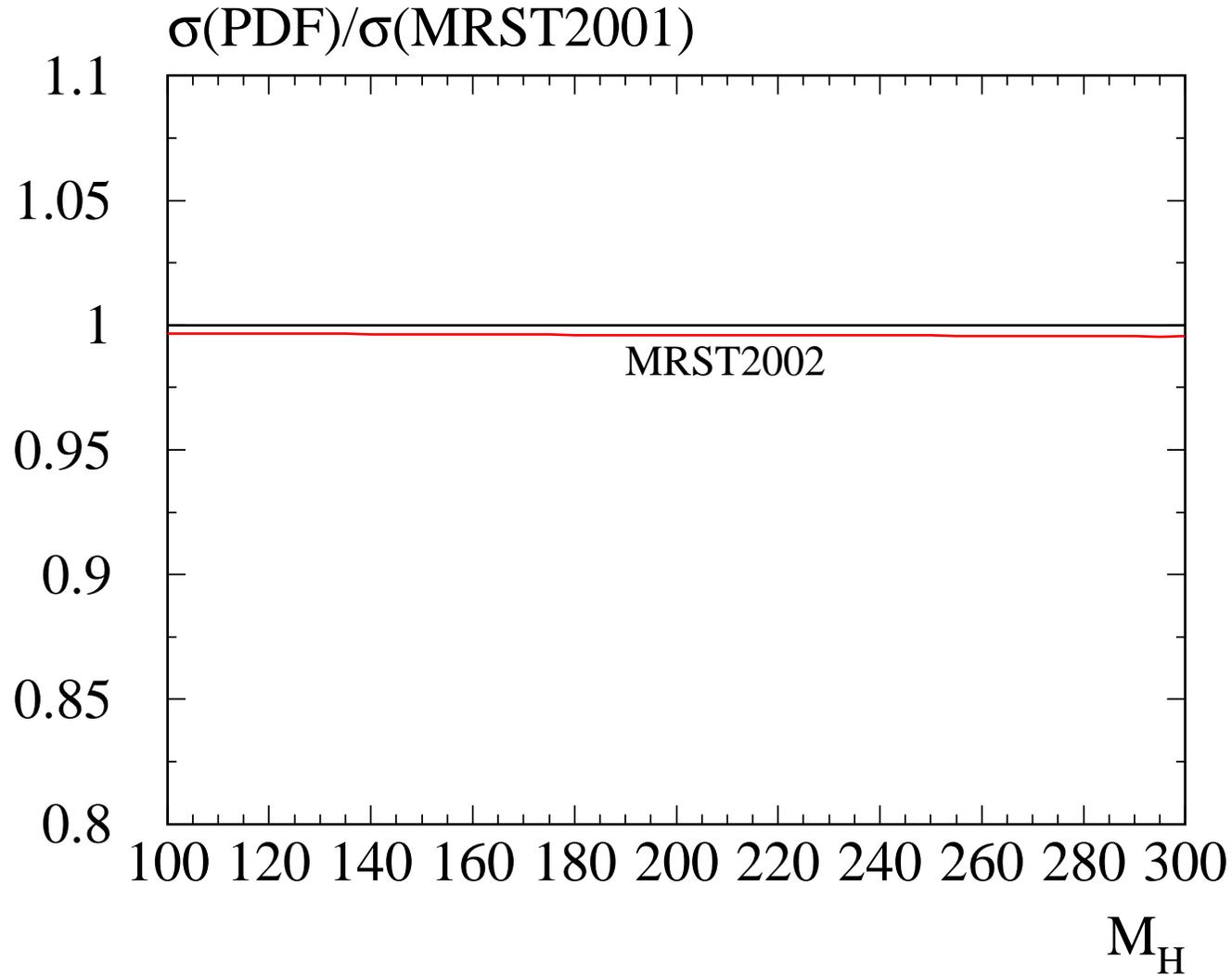
[Dittmaier, Krämer, Mück, Schlüter '06]

“True” b -PDF uncertainty?



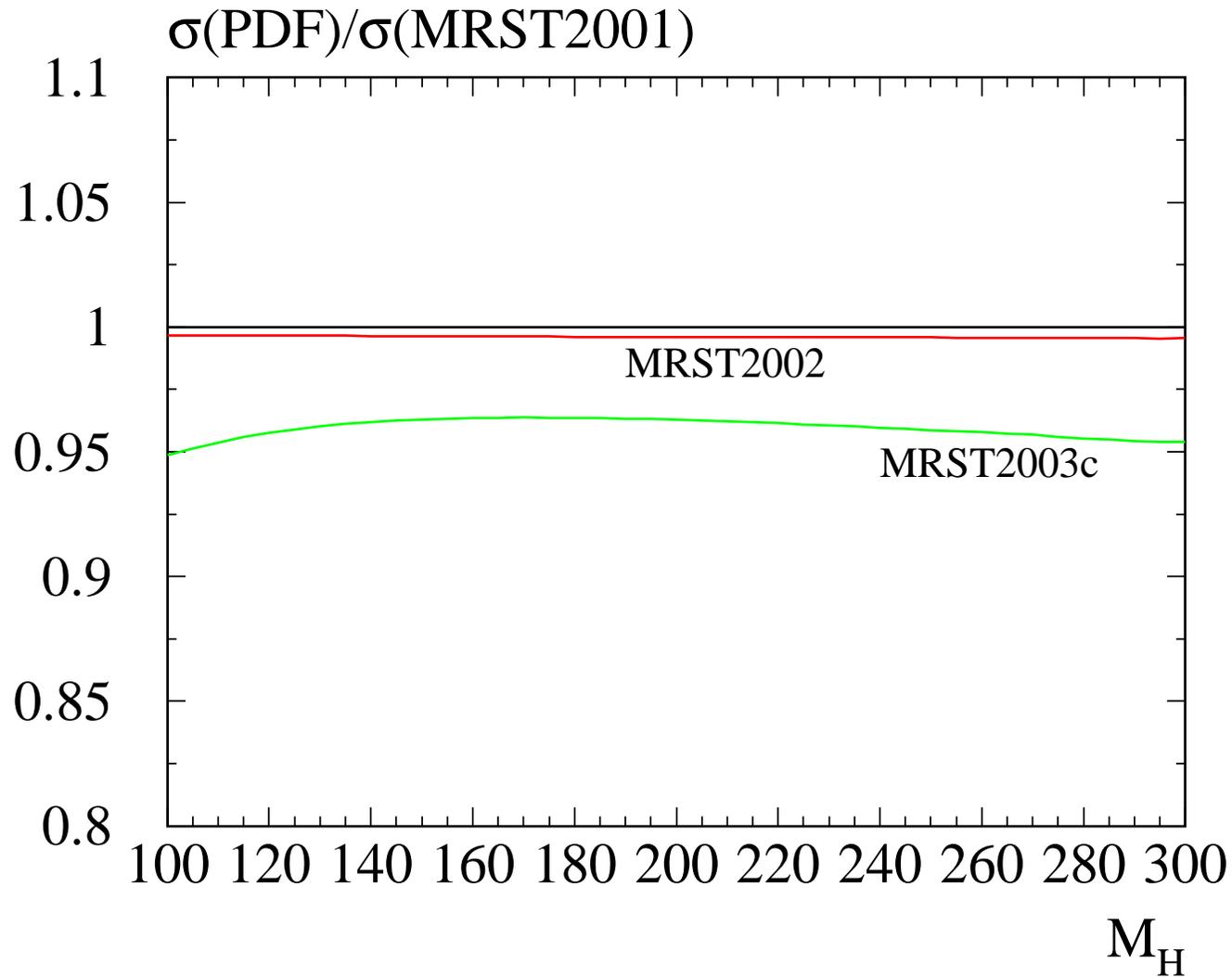
possible test: $Z/W + b\bar{b}$? [cf. also talk by L. Reina]

“True“ b -PDF uncertainty?



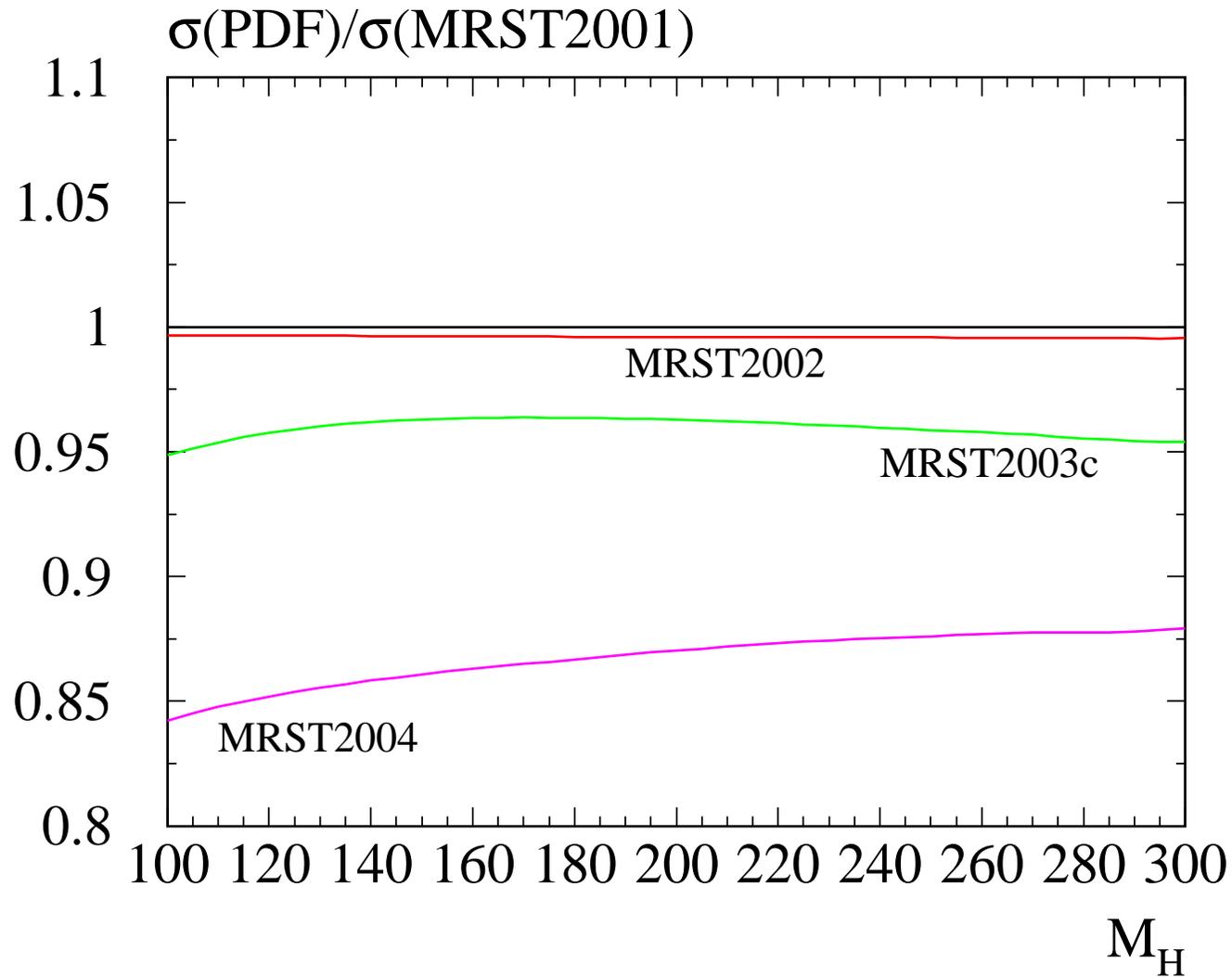
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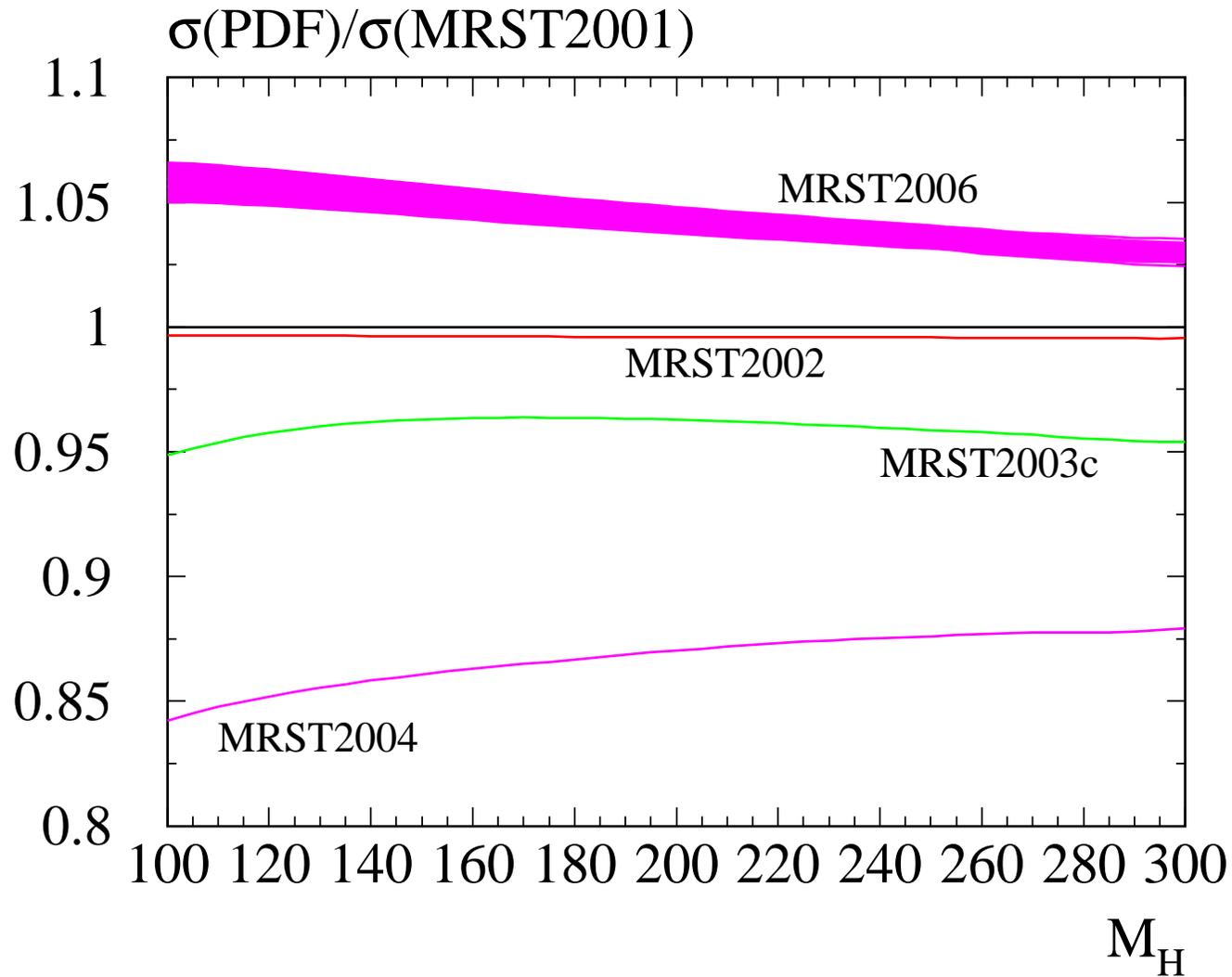
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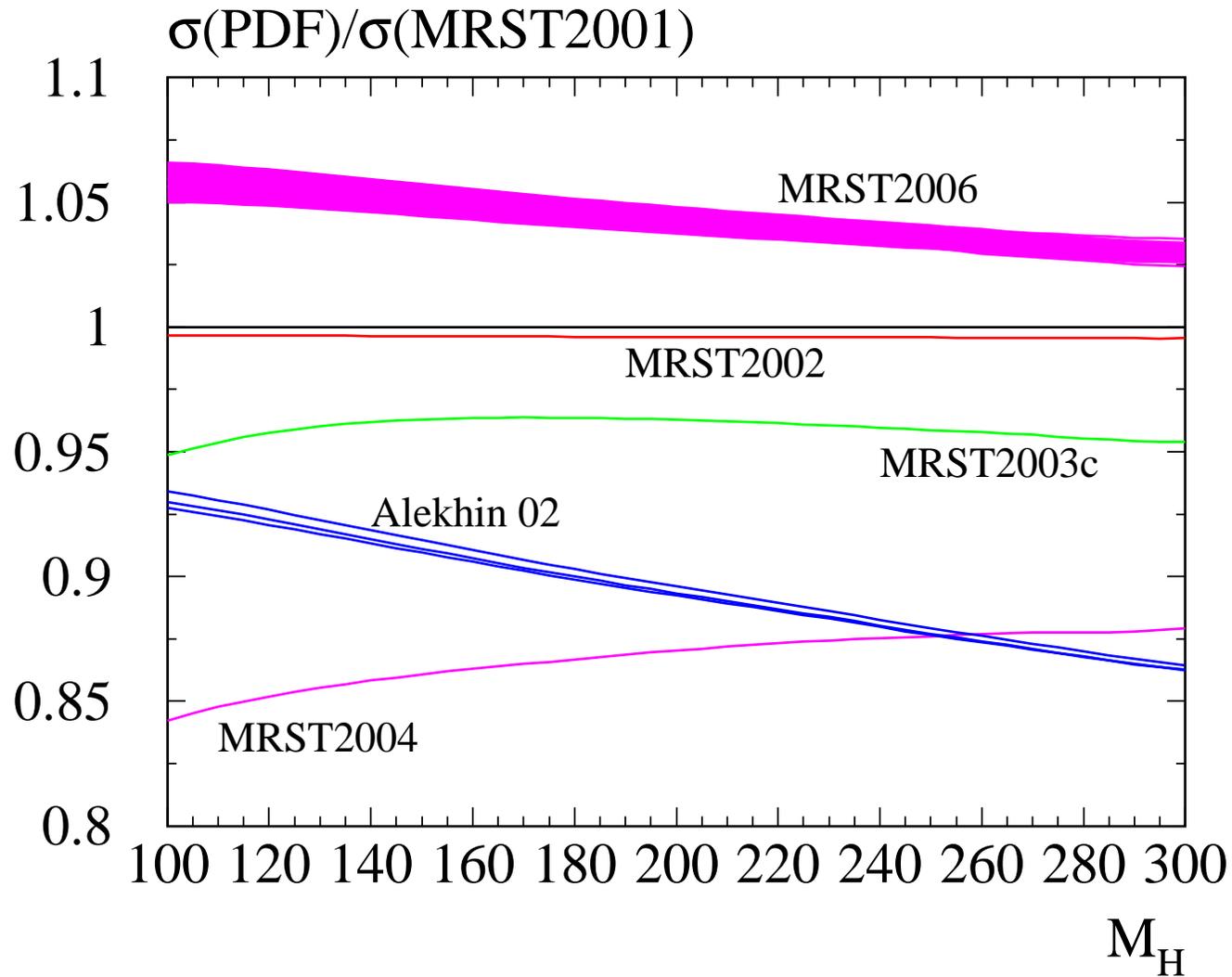
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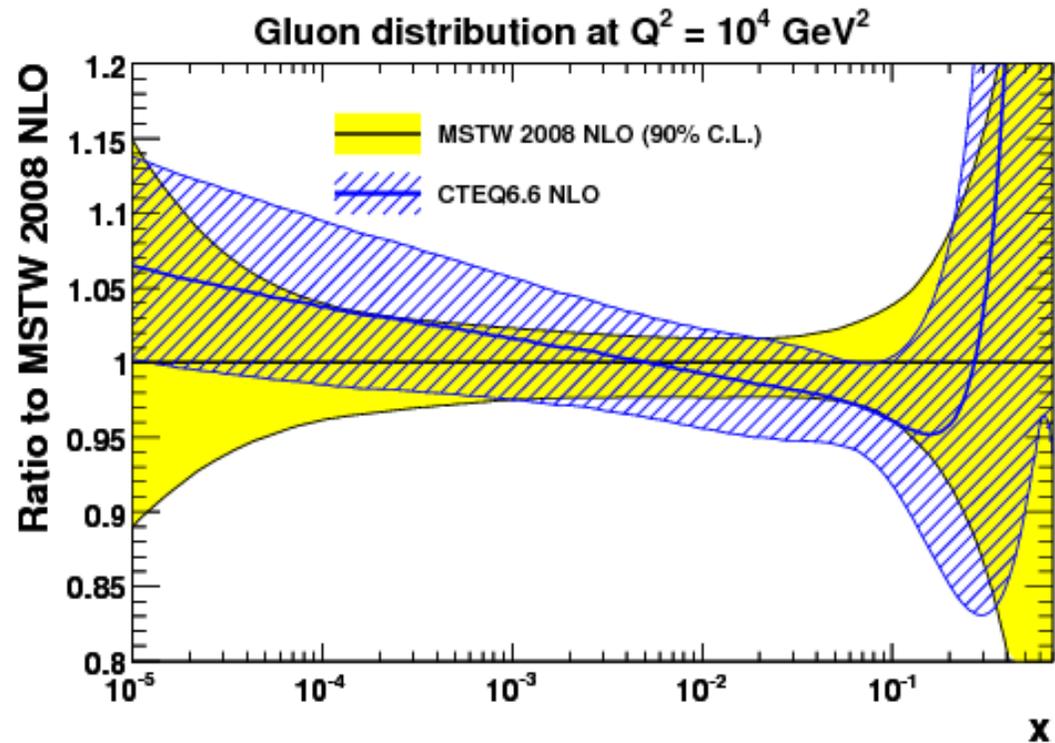
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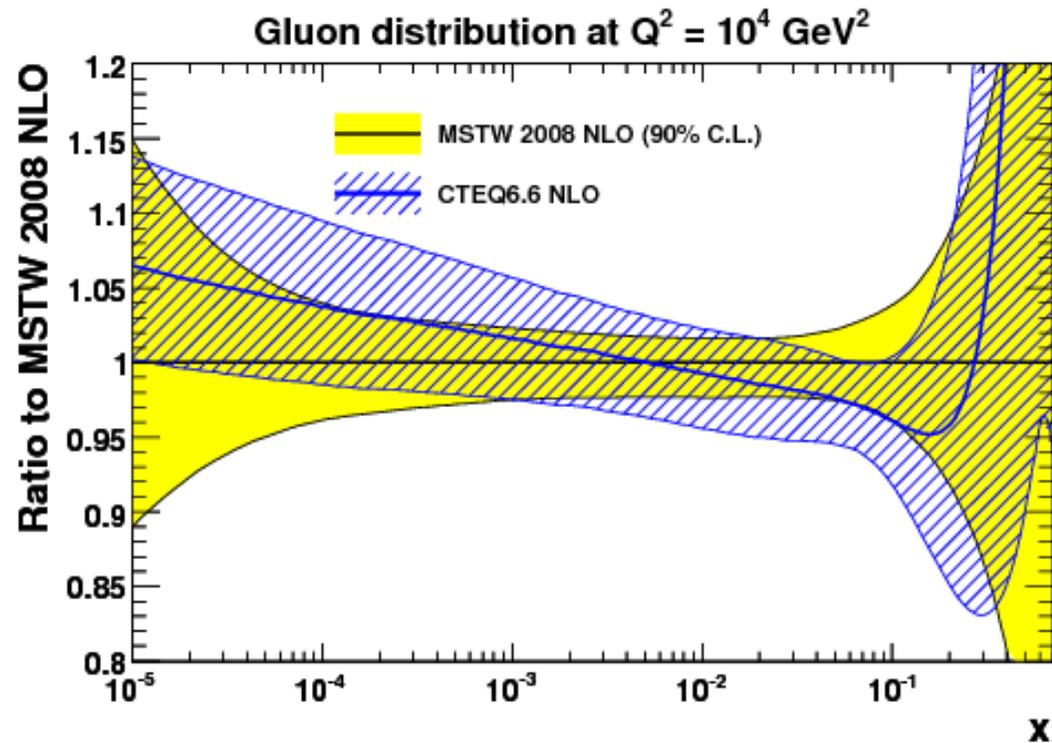
Talking about pdfs...

- MSTW 2008 [cf. talk by J. Stirling]



Talking about pdfs...

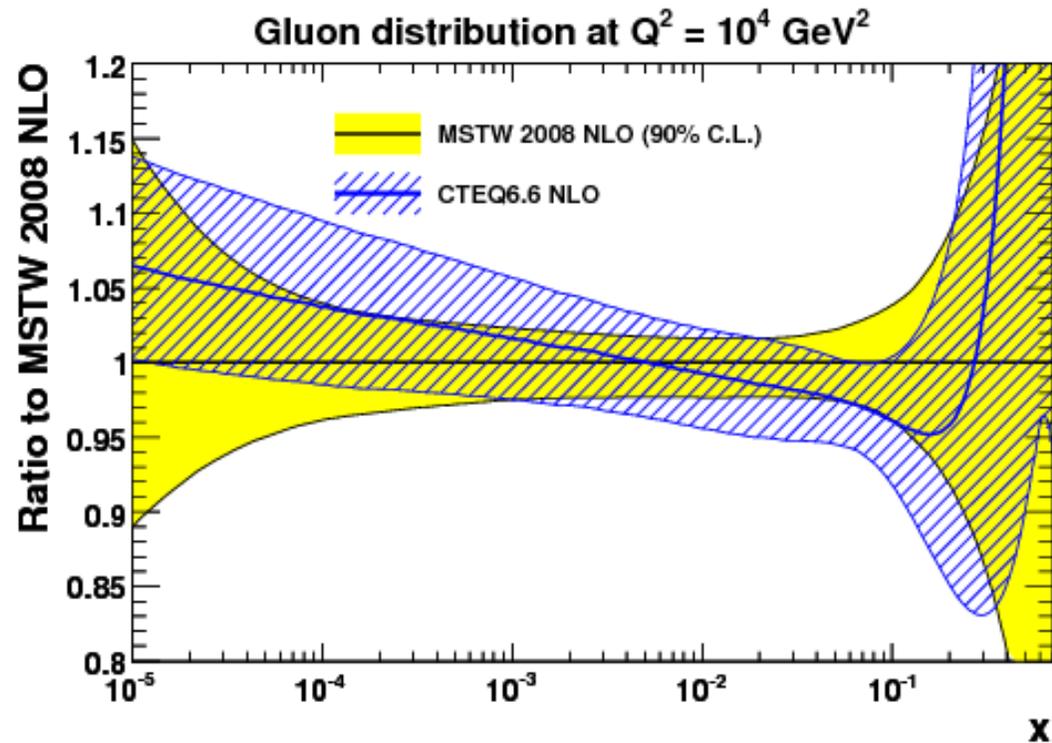
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- how reliable are the errors?

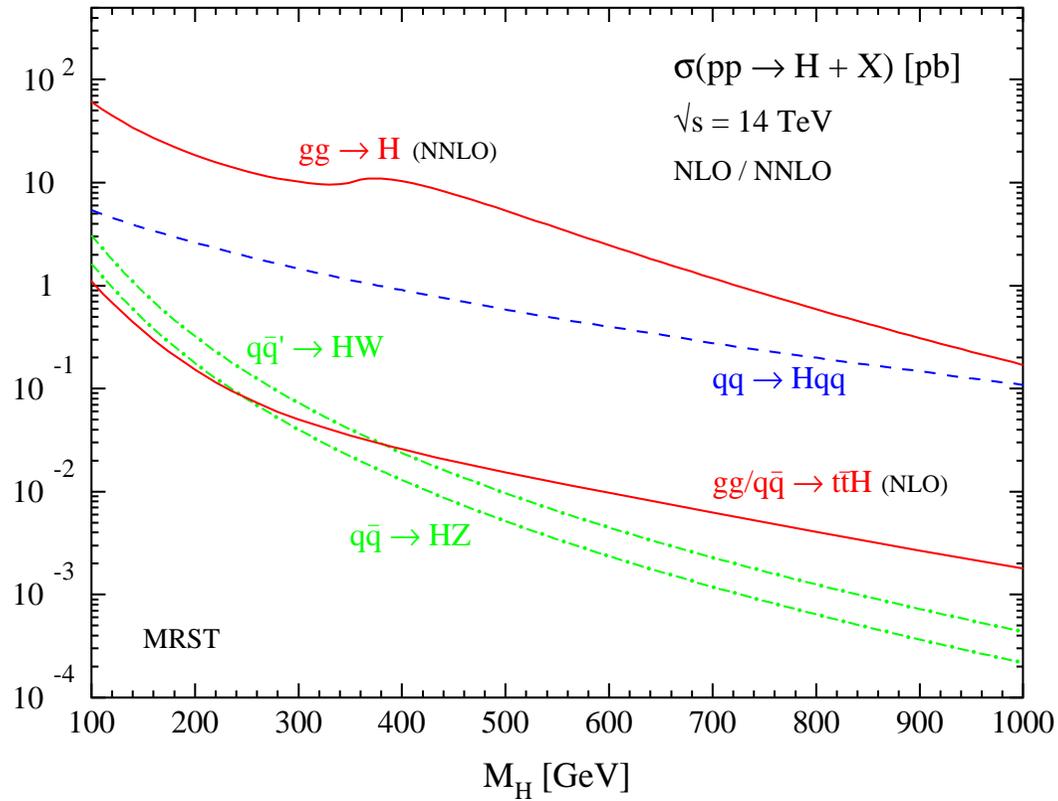
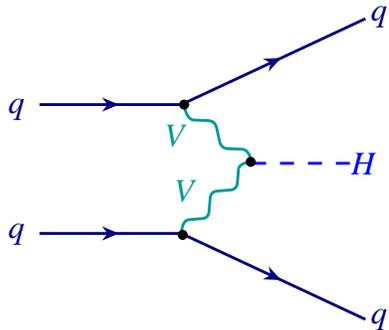
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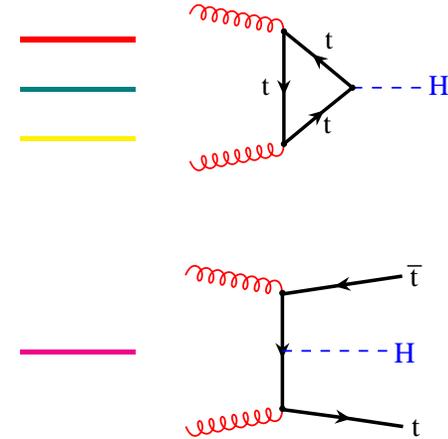
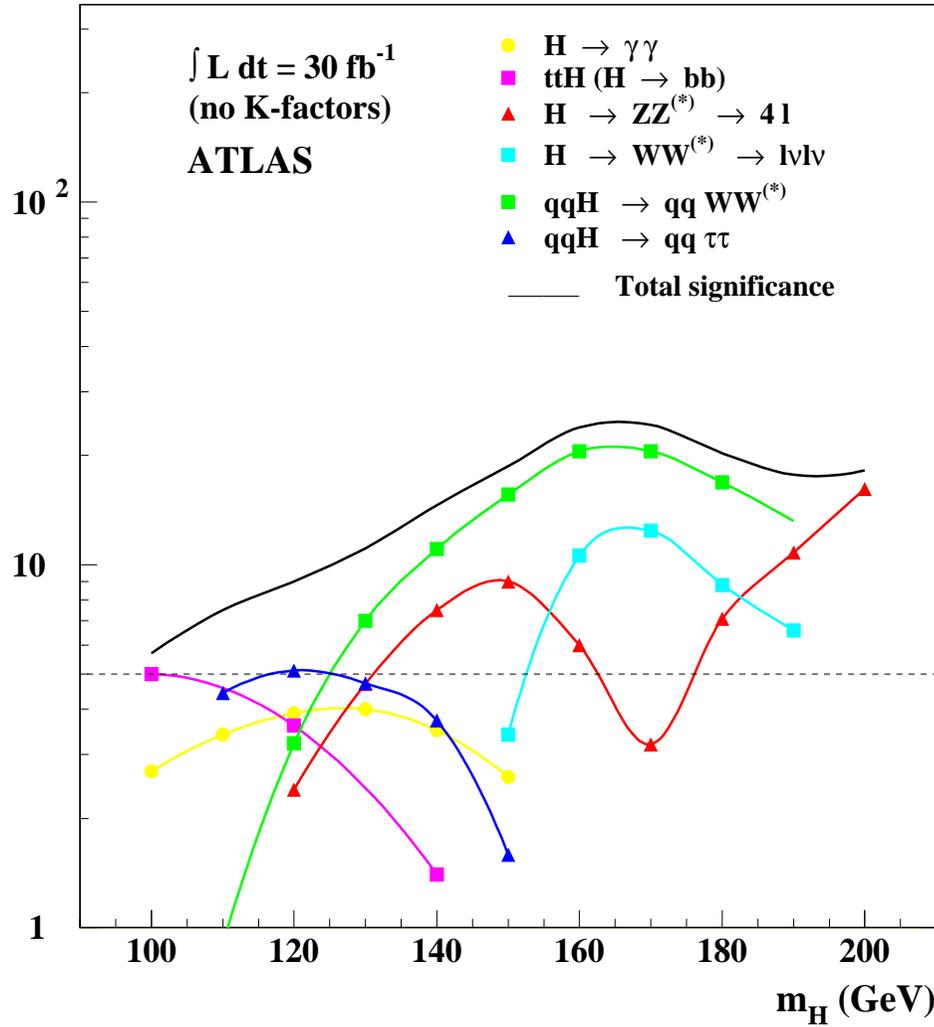
- how reliable are the errors?
- wait for LHC data?

Weak Boson Fusion



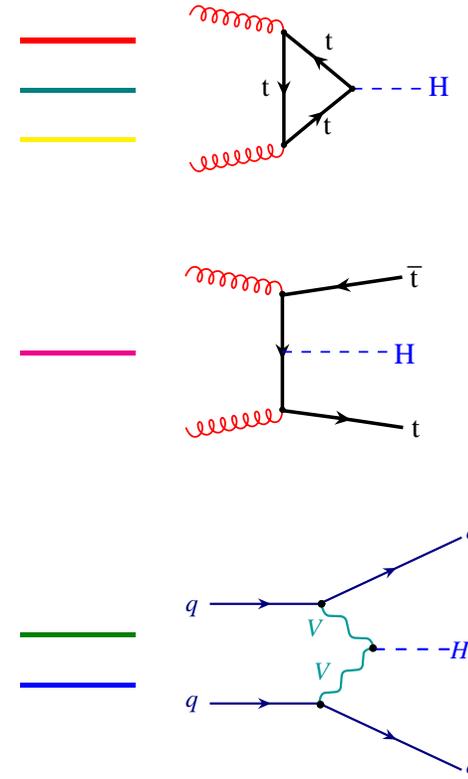
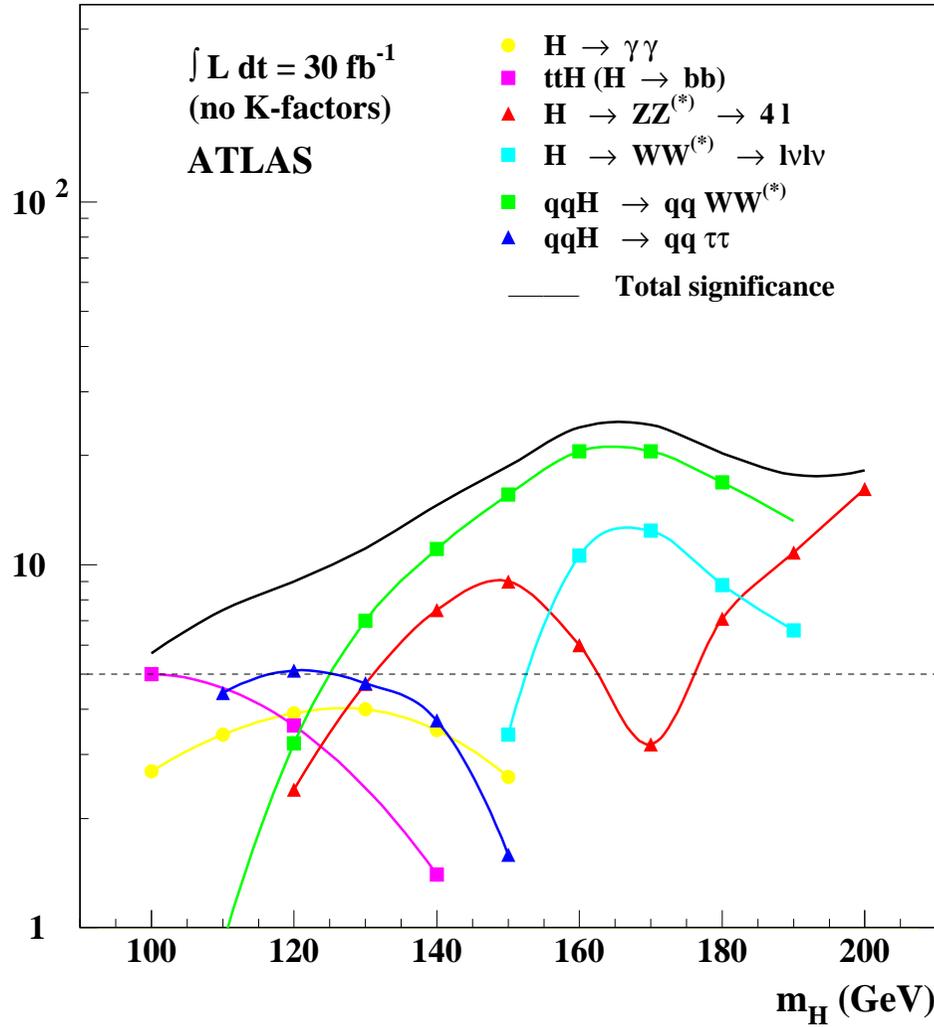
Discovery Potential

Signal significance

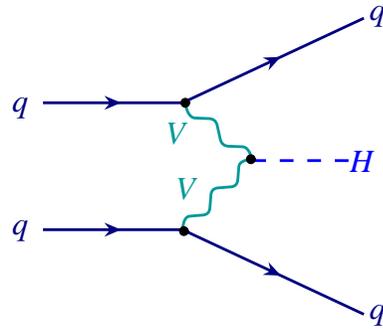


Discovery Potential

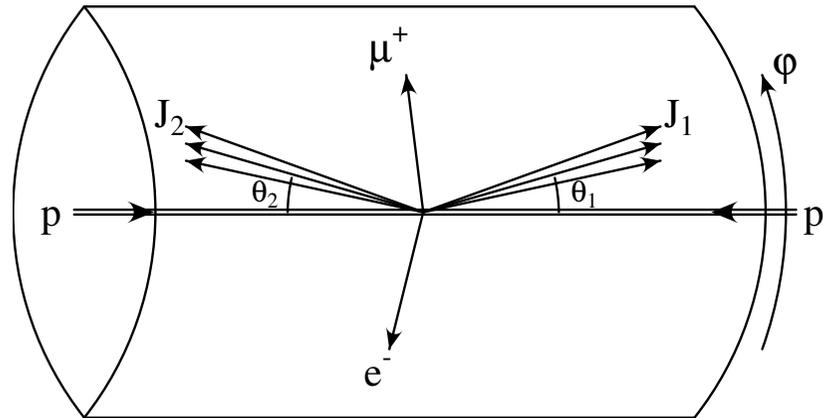
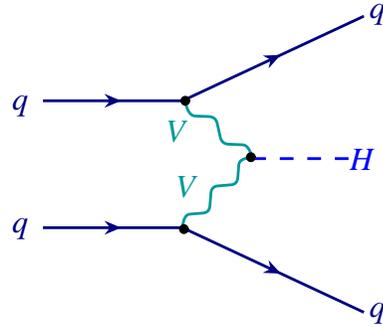
Signal significance



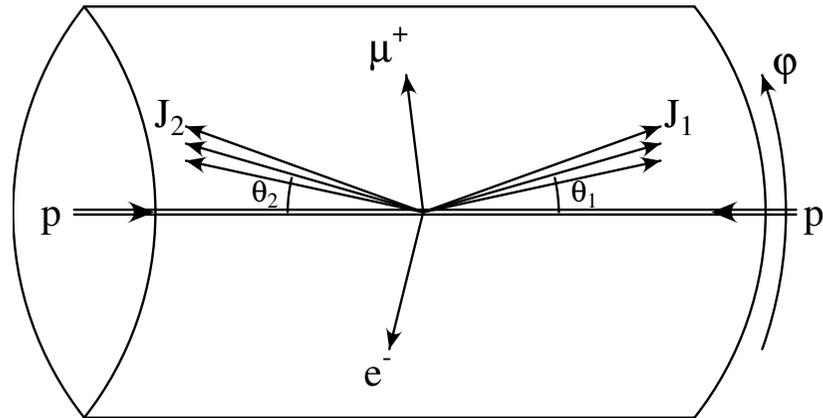
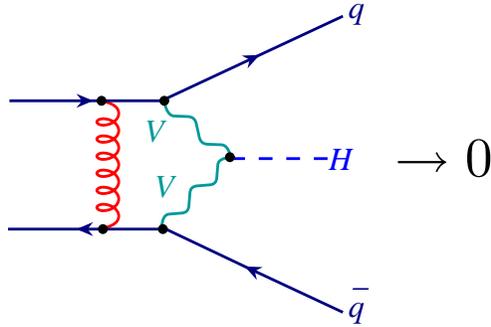
WBF Signature



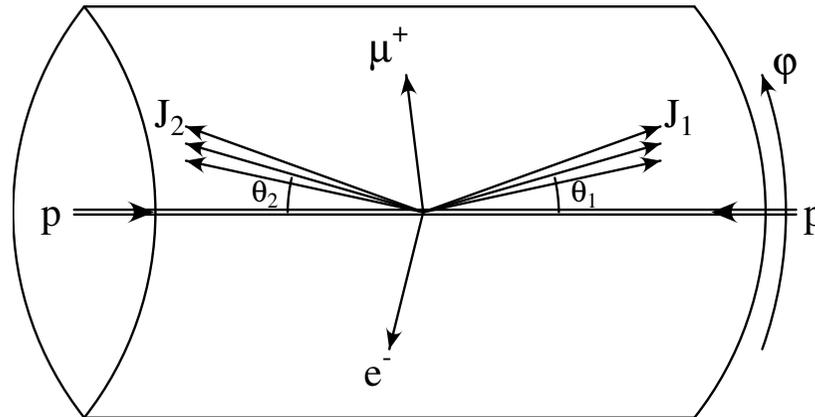
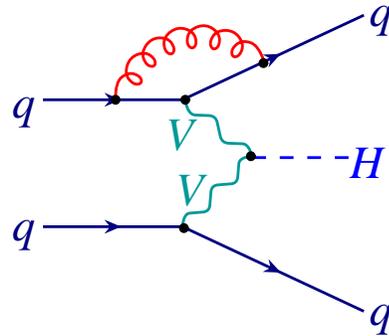
WBF Signature



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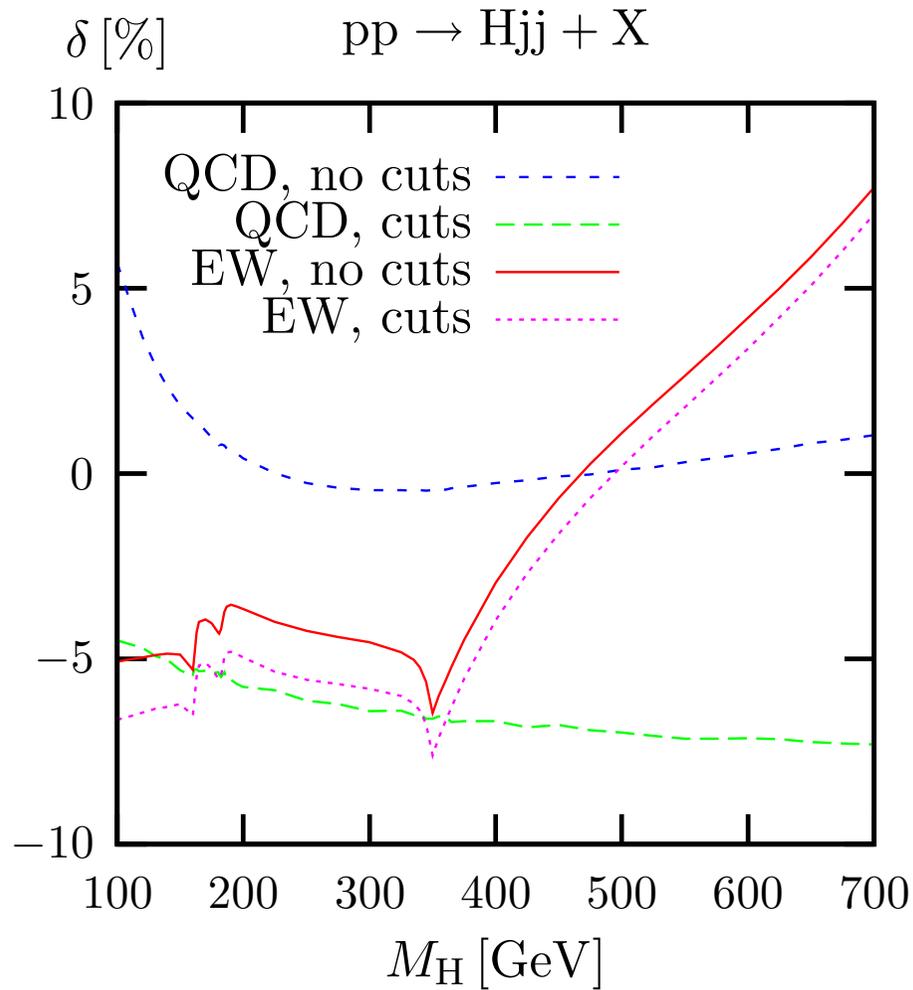


WBF Signature



NLO QCD: [Figy, Oleari, Zeppenfeld '03] + EW: [Ciccolini, Denner, Dittmaier '08]

WBF: QCD+EW corrections

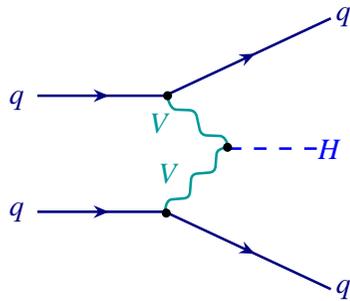


[Ciccolini, Denner, Dittmaier '08]

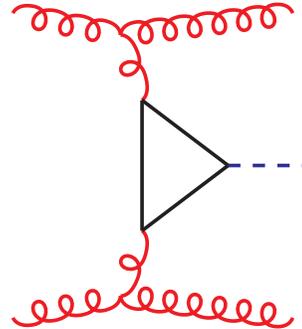
WBF: other corrections

- mixed QCD/EW [Bredenstein, Hagiwara, Jäger '08]
- gluon fusion/WBF interference [Andersen, Binoth, Heinrich, Smillie '07]
- gluon induced WBF [R.H., Vollinga, Weber '08]

Weak Boson Fusion

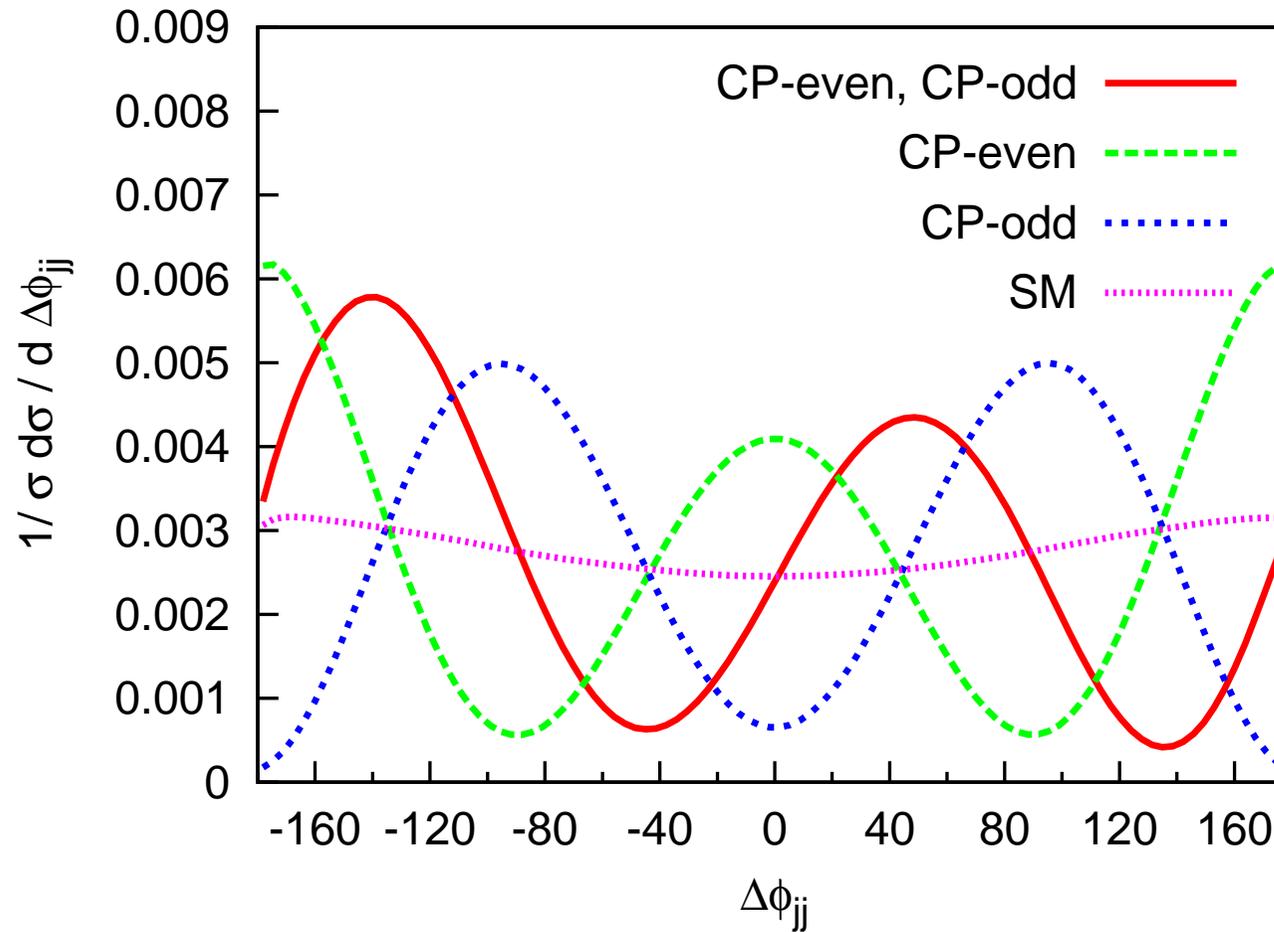


VS.



- $gg \rightarrow H + 2 \text{ jets}$: [Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld '01]
- NLO for $m_t \rightarrow \infty$: [Campbell, Ellis, Zanderighi '06]
- $gg \rightarrow H + n \text{ jets}$: [Andersen, Del Duca, White '08]
- appropriate cuts allow distinction

Measure CP



cf. talk by D. Zeppenfeld

General theory progress

- 1-loop multileg

- “classical” approach

[Passarino, Veltman '79], [Davydychev '91],
[Giele, Glover '04], [Ellis, Giele, Zanderighi '05], [Denner, Dittmaier '05],
[v. Hameren, Vollinga, Weinzierl '05], [Binoth *et al.* '08]

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● generalized unitarity

[Bern, Dixon, Dunbar, Kosower '94],
[Britto, Cachazo, Feng '05], [Berger, Bern, Dixon, Forde, Kosower '06],
[Ossola, Papadopoulos, Pittau '08], [Giele, Kunszt, Melnikov '08],
[Giele, Zanderighi '08], [Ellis, Giele, Kunszt, Melnikov, Zanderighi '08]

Background processes: Les Houches '05 wishlist

Reaction	background for	existing calculations
$pp \rightarrow VVj$	$t\bar{t}H$, new physics	WWj : Dittmaier, Kallweit, Uwer '07 WWj : Campbell, R.K.Ellis, Zanderighi '07 WWj : Binoth, Guillet, Karg, Kauer, Sanguinetti (in progress)
$pp \rightarrow t\bar{t}b\bar{b}$	$t\bar{t}H$	this talk
$pp \rightarrow t\bar{t}jj$	$t\bar{t}H$	—
$pp \rightarrow VVb\bar{b}$	VBF $\rightarrow H \rightarrow VV$, $t\bar{t}$, NP	—
$pp \rightarrow VVjj$	VBF $\rightarrow H \rightarrow VV$	VBF: Jäger, Oleari, Zeppenfeld '06 + Bozzi '07
$pp \rightarrow Vjjj$	new physics	amplitudes: Berger et al. '08, R.K.Ellis et al. '08
$pp \rightarrow VVV$	SUSY trilepton signal	ZZZ : Lazopoulos, Melnikov, Petriello '07 WWZ : Hankele, Zeppenfeld '07 VVV : Binoth, Ossola, Papadopoulos, Pittau '08

- NLO for $2 \rightarrow 3$ processes established
- very few calculations for $2 \rightarrow 4$, no complete calculation for pp process

$$e^+e^+ \rightarrow 4f \text{ (EW)} \quad \text{Denner et al. '05}, \quad e^+e^+ \rightarrow HH\nu\bar{\nu} \text{ (EW)} \quad \text{Boudjema et al. '05}$$

$$\gamma\gamma \rightarrow t\bar{t}b\bar{b} \text{ (QCD)} \quad \text{Lei et al. '07}, \quad u\bar{u} \rightarrow s\bar{s}b\bar{b} \text{ (QCD)} \quad \text{Binoth et al. '08}$$

Open questions

- perturbative calculations become more and more precise – beware of the non-perturbative factors:
 - take pdf variations serious
 - underlying event models? → VBF central jet veto!
- to what extent do we need (N)NLO MC's?
- can we put CKKW, MLM on a more solid ground?

Some thoughts

- $SU(3) \times SU(2) \times U(1)$ tested with very high precision
- symmetry breaking mechanism?
- so: how seriously do we expect a SM Higgs? After all:
 - minimality?
 - we know there is more than the SM!
 - naturalness (there are no elementary scalars!)
 - ...
- however:
 - QFT works
 - QCD works

so most of the tools developed will work in *any* theory

Handwritten notes consisting of several lines of vertical bars and symbols, possibly representing a data set or a specific notation system.

△	i	-	┌	○	I	△	>	△	8	└	△
F	∅	B	E	5	8	F	2	F	D	6	3
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6	C	7	9	D	2	E	4	9	3	E	6

s △ ⊥

Handwritten notes consisting of several lines of vertical bars and symbols, similar to the top section.

