Higgs theory

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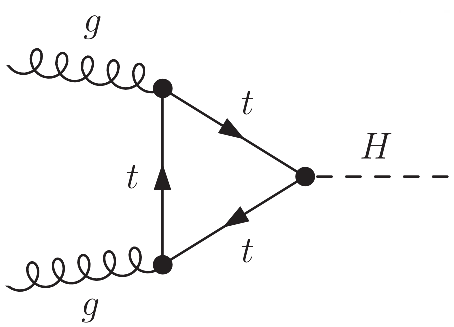
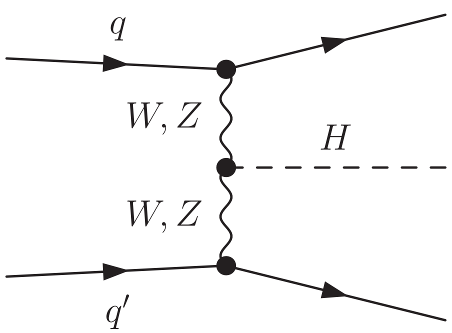
Higgs boson production at the LHC

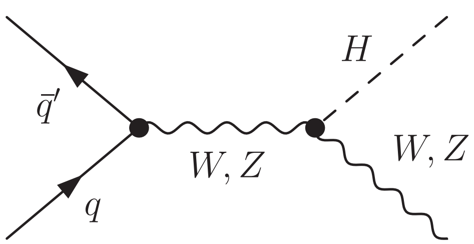
Outline

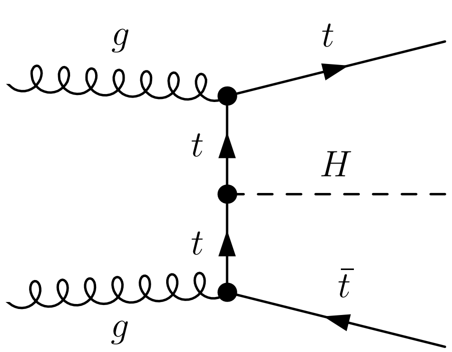
- Overview of production and decay modes
- Gluon fusion and jet vetoes
- Vector boson fusion
- Associate production and boosted Higgs taggers

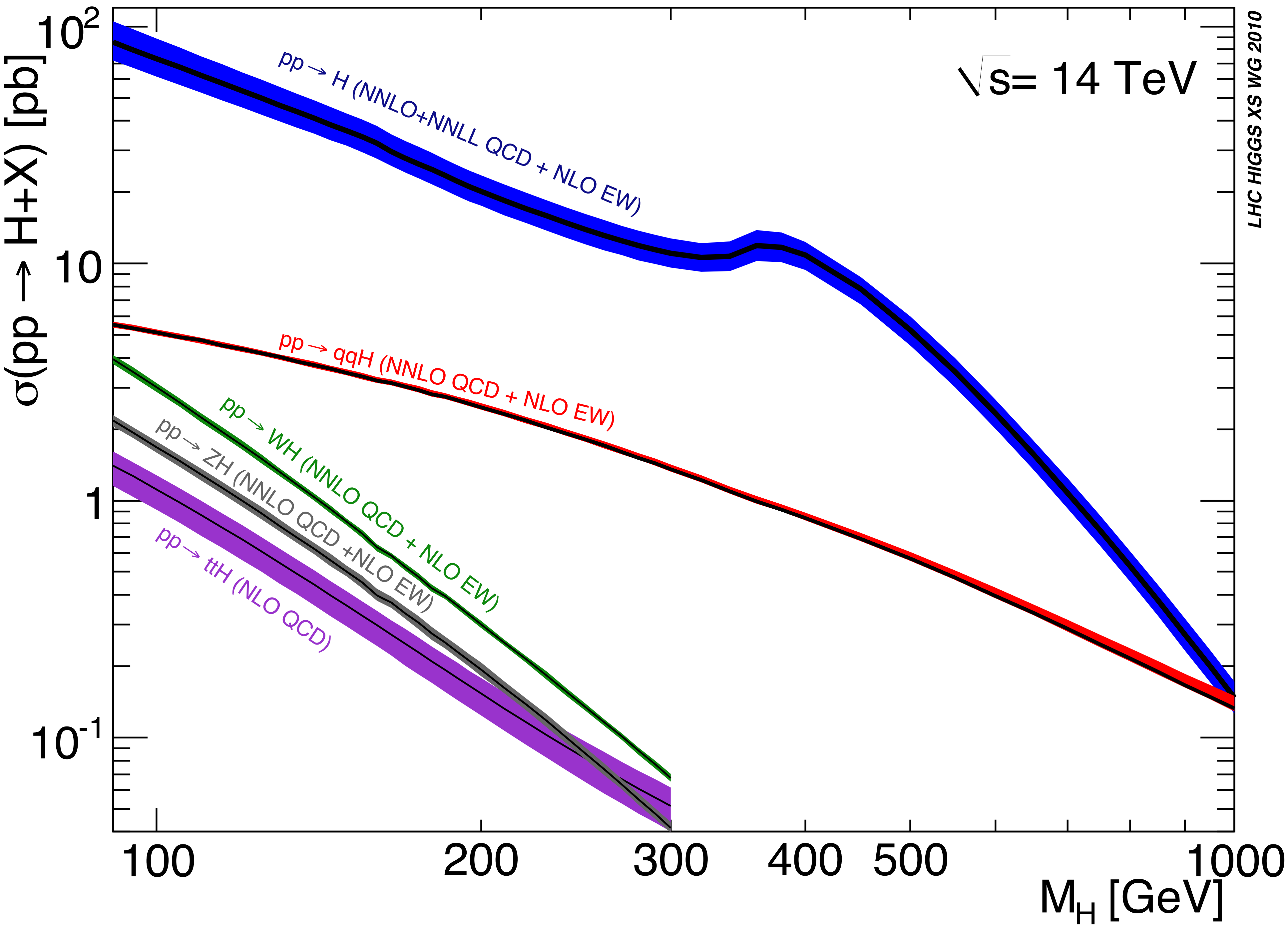
Higgs boson production…



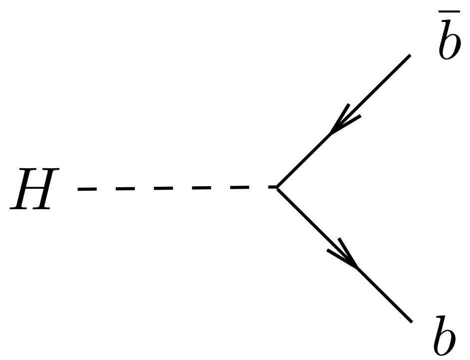




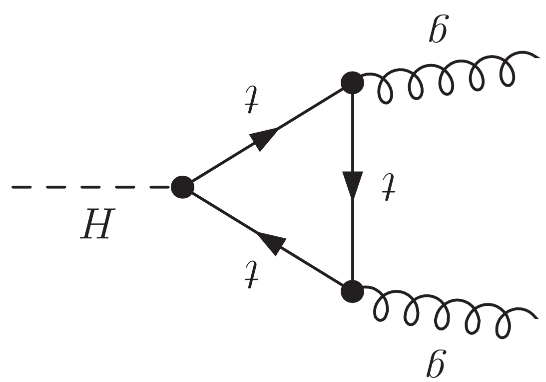




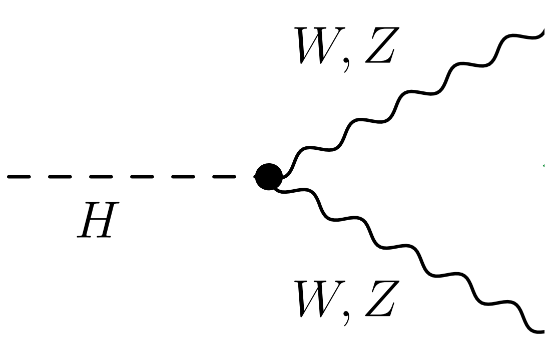
… and decay



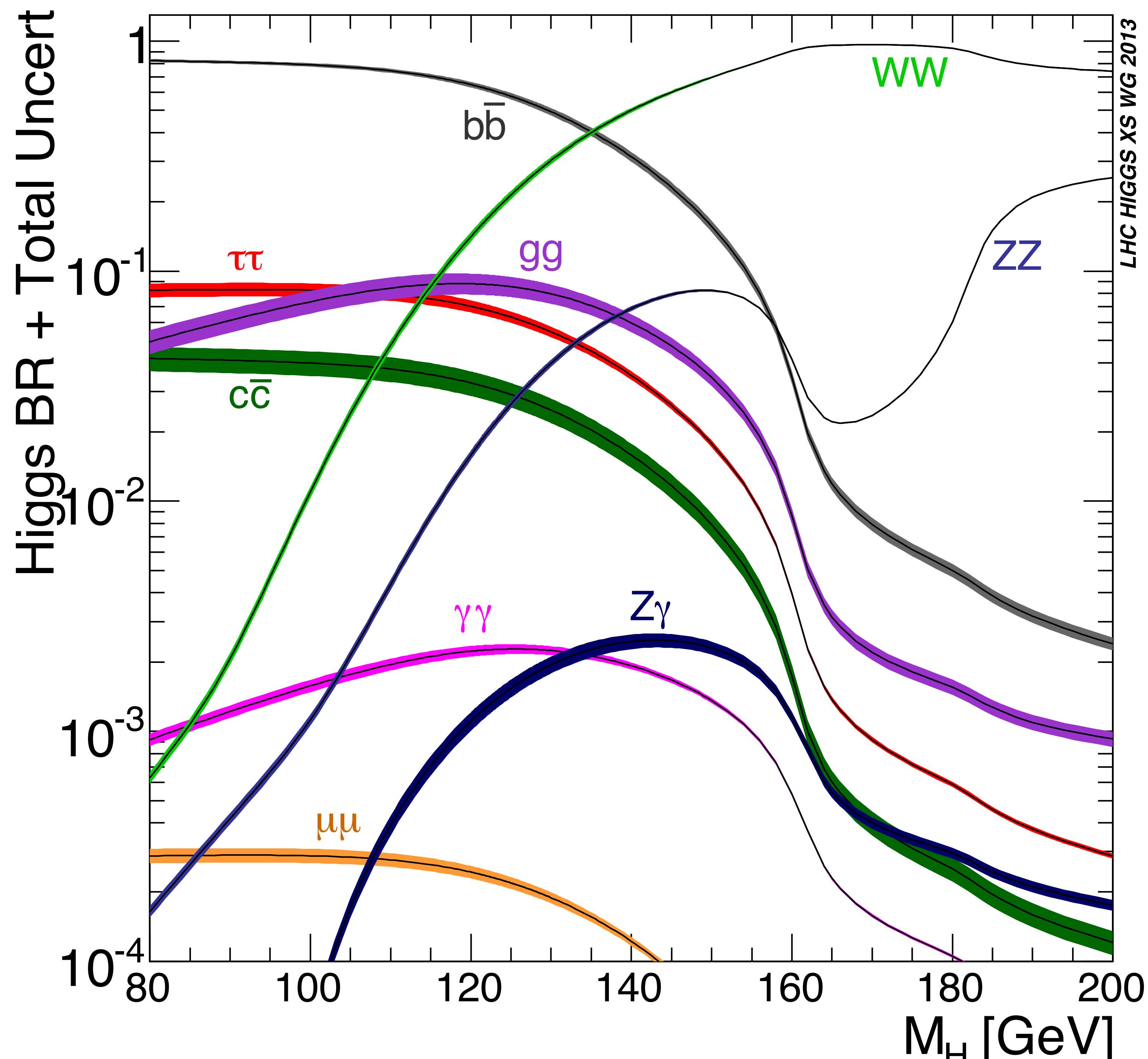
H
$\bar{b}$
b



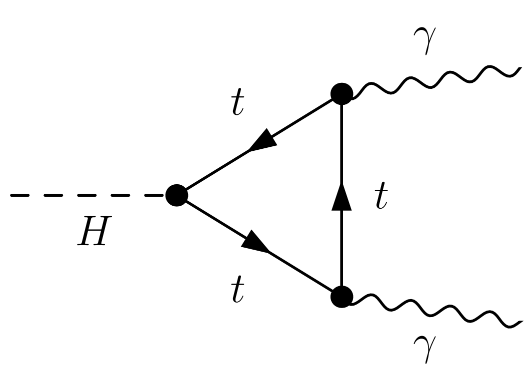
H



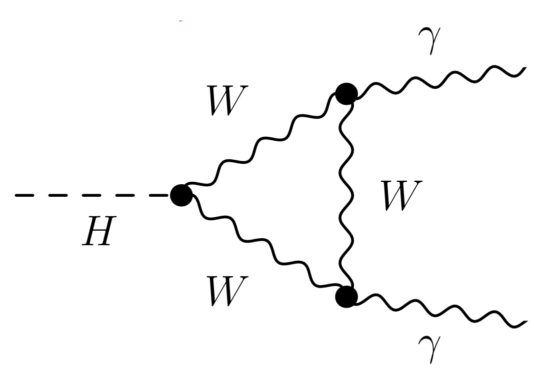
W, Z
H
W, Z



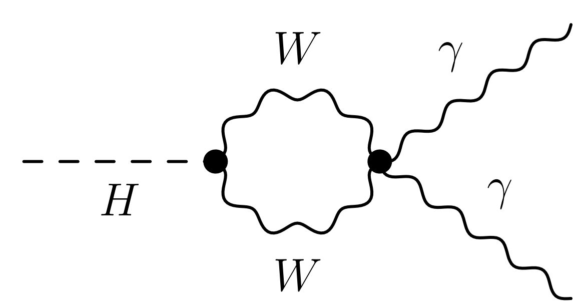
Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]
$b\bar{b}$
WW
ττ
gg
ZZ
$c\bar{c}$
γγ
Zγ
μμ



t
γ
H
t
t
γ



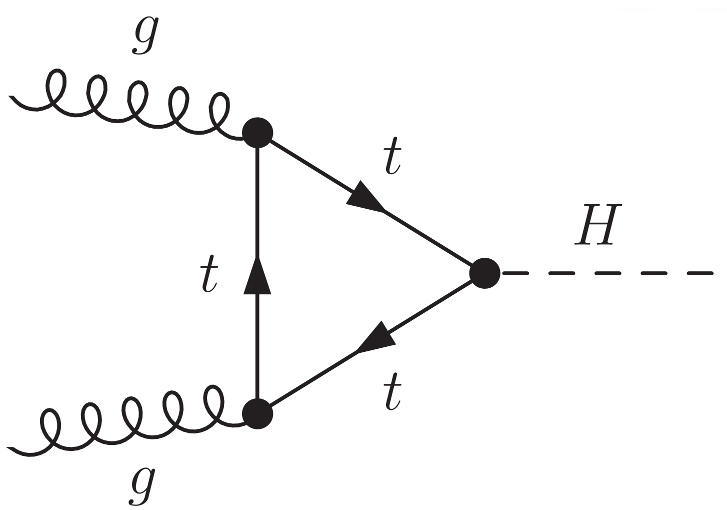
W
γ
H
W
W
γ



W
γ
H
γ
W

Gluon fusion

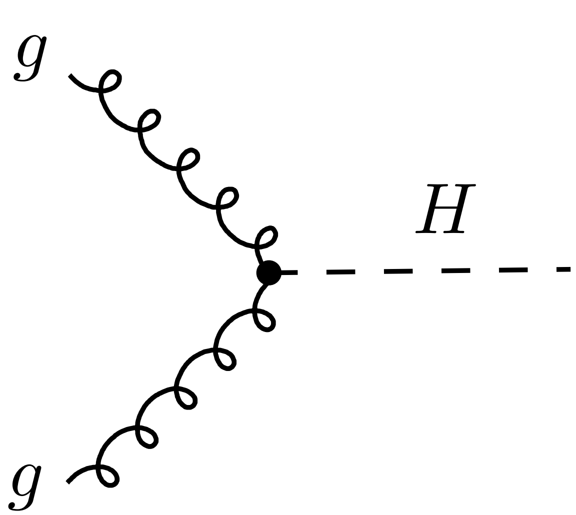
Gluon fusion produces a Higgs through fermion loops



$$\sigma_{gg\to H} = \frac{\alpha_s^2(\mu_R)}{72\pi v^2(N_c^2-1)}\left|\frac{3}{4}F_{1/2}\left(\frac{m_H^2}{4m_t^2}\right)\right|^2 \mathcal{L}_{gg}(\mu_F)$$

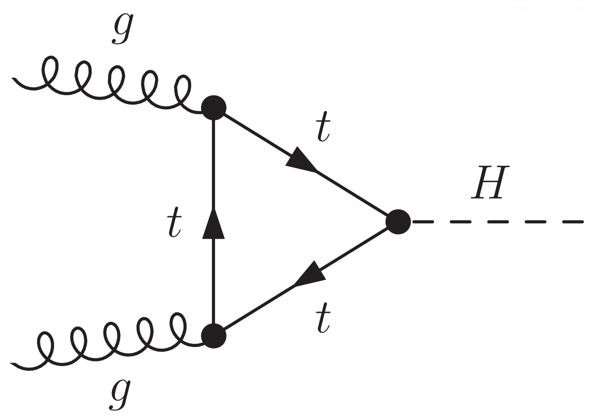
$$\mathcal{L}_{gg}(\mu_F) = \int_0^1 \frac{dx_1}{x_1}\int_0^1 \frac{dx_2}{x_2} f_{g/p}(x_1,\mu_F^2) f_{g/p}(x_2,\mu_F^2)\delta\left(1-\frac{x_1 x_2 s}{m_H^2}\right)$$

For $m_t \gg m_H$ we have $F_{1/2} \to 4/3 \Rightarrow$ effective Hgg Lagrangian



$$\mathcal{L}_{\text{eff}} = -\frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G_a^{\mu\nu} \Phi$$

Total ggH cross section

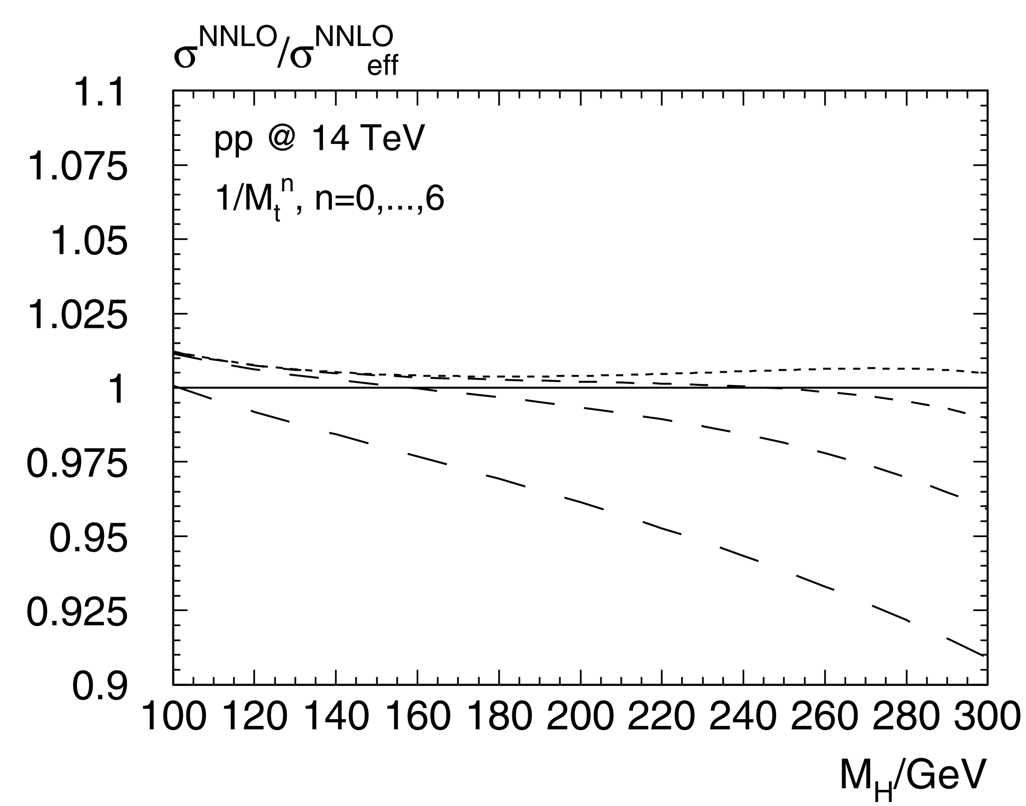


$$\sigma_{gg\to H} \sim \alpha_s^2 \Big(1 + \underbrace{\alpha_s}_{\rm NLO} + \underbrace{\alpha_s^2}_{\rm NNLO} + \dots\Big)\,(1 + \underbrace{\alpha}_{\rm NLO-EW})$$

finite m_t, m_b	NLO	[Spira et al. NPB 453 (1995) 17]
large- m_t	NNNLO	[Anastasiou Duhr Dulat Herzog Mistlberger PRL 114 (2015) 21]
large-m_W	QCD-EW	[Anastasiou Boughezal Petriello JHEP 04 (2009) 003]

The large- m_t approximation is in fact a very good one!

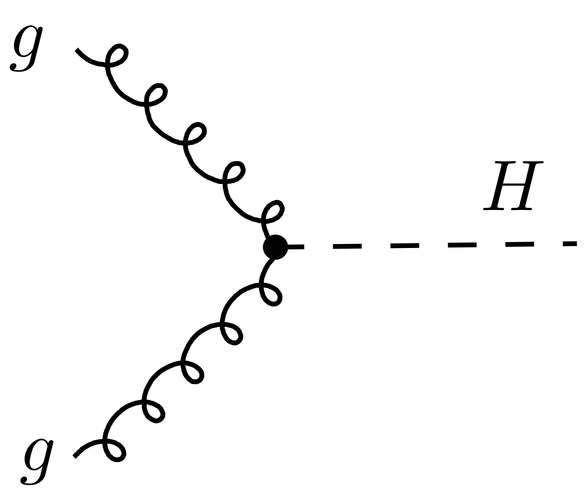
[Harlander Mantler Marzani Ozeren EPJC 66 (2010) 359]



The ggH cross section at NLO

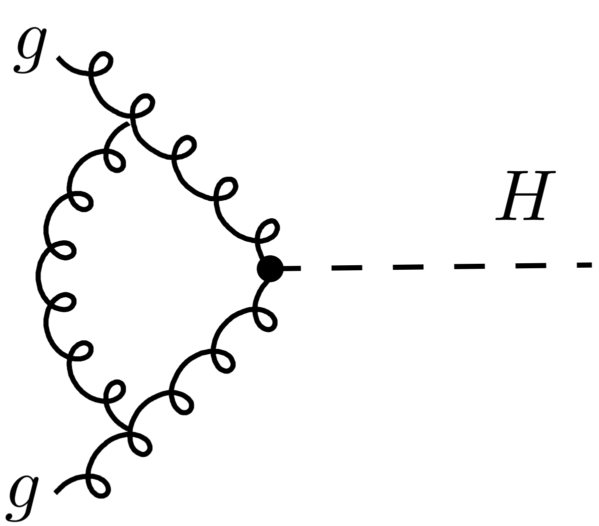
$$\sigma_{gg\to H} = \sum_{ij} \int_0^1 dx_1 \int_0^1 dx_2\, f_{i/p}(x_1,\mu_F^2) f_{j/p}(x_2,\mu_F^2) \hat{\sigma}_{ij\to H}\left(\hat{s}=x_1x_2s, \frac{\mu^2}{m_H^2}, \frac{\mu^2}{\mu_F^2}, \alpha_s(\mu^2)\right)$$

LO partonic cross section



$$\hat{\sigma}^{(0)}_{gg\to H} = \sigma_0\, \delta(1-z) \qquad z = \frac{m_H^2}{\hat{s}}$$

NLO virtual corrections in $D = 4-2\epsilon$ dimensions



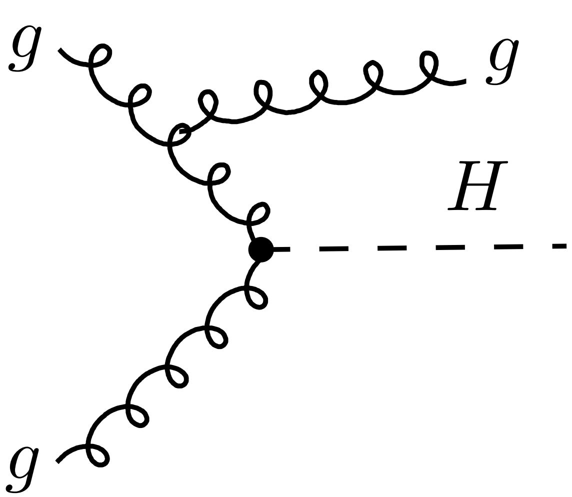
$$\hat{\sigma}^{(1),v}_{gg\to H} = \sigma_0 \frac{\alpha_s}{4\pi} \delta(1-z) \left(\frac{\mu^2}{m_H^2}\right)^{\epsilon} \left(-\frac{2}{\epsilon^2} + \frac{7}{6}\pi^2 + \mathcal{O}(\varepsilon)\right)$$

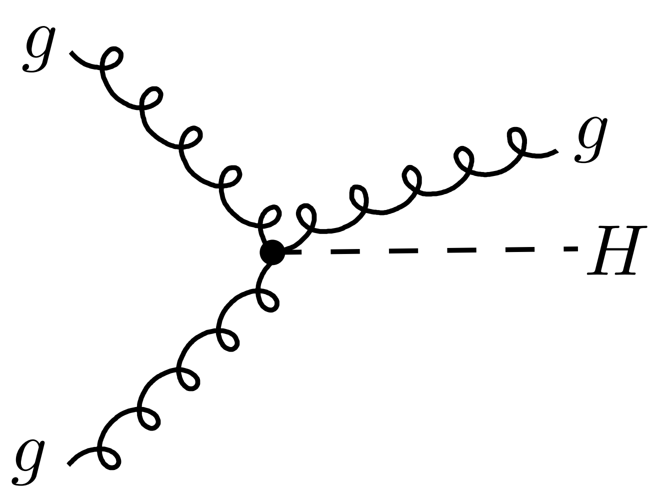
$$\alpha_s^{\rm bare} = \alpha_s^{\rm ren}\left(1 - \frac{\beta_0}{\epsilon}\frac{\alpha_s^{\rm ren}}{4\pi} + \mathcal{O}(\alpha_s^2)\right)$$

The ggH cross section at NLO

$$\sigma_{gg\to H} = \sum_{ij}\int_0^1 dx_1 \int_0^1 dx_2\, f_{i/p}(x_1,\mu_F^2) f_{j/p}(x_2,\mu_F^2)\hat{\sigma}_{ij\to H}\left(\hat{s}=x_1x_2s, \frac{\mu^2}{m_H^2}, \frac{\mu^2}{\mu_F^2}, \alpha_s(\mu^2)\right)$$

Adding NLO real corrections in $D=4-2\epsilon$ dimensions





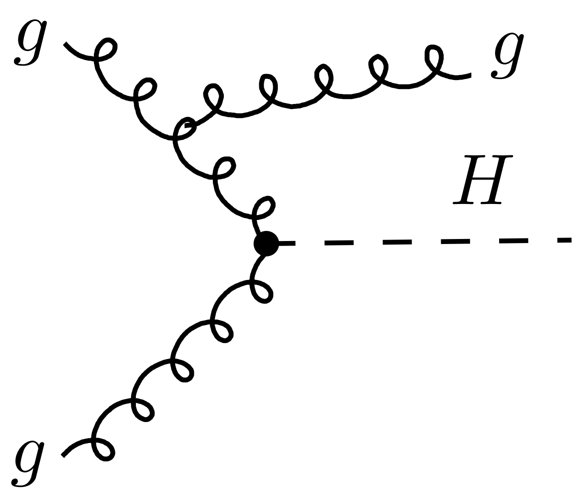
$$\hat{\sigma}^{(1)}_{gg\to H} = \sigma_0 \frac{\alpha_s}{4\pi}\left(\frac{\mu^2}{m_H^2}\right)^{\epsilon} \times$$
$$\times \left[\frac{1}{\epsilon}C_A\left(\frac{8}{1-z}+\frac{8}{z}-8(2-z+z^2)+\frac{22}{3}\delta(1-z)\right)-\frac{1}{\epsilon}n_f\frac{4}{3}\delta(1-z)+\mathcal{O}(1)\right]$$

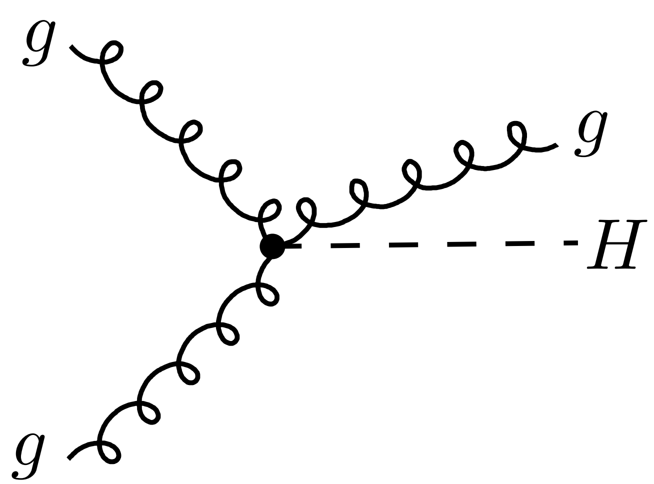
What is the fate of these uncancelled divergences?

The ggH cross section at NLO

$$\sigma_{gg\to H} = \sum_{ij}\int_0^1 dx_1 \int_0^1 dx_2\, f_{i/p}(x_1,\mu_F^2) f_{j/p}(x_2,\mu_F^2)\hat{\sigma}_{ij\to H}\left(\hat{s}=x_1x_2s, \frac{\mu^2}{m_H^2}, \frac{\mu^2}{\mu_F^2}, \alpha_s(\mu^2)\right)$$

Adding NLO real corrections in $D = 4-2\epsilon$ dimensions





$$\hat{\sigma}^{(1)}_{gg\to H} = \sigma_0 \frac{\alpha_s}{4\pi}\left(\frac{\mu^2}{m_H^2}\right)^{\epsilon} \times$$
$$\times\left[\frac{1}{\epsilon}C_A\left(\frac{8}{1-z}+\frac{8}{z}-8(2-z+z^2)+\frac{22}{3}\delta(1-z)\right)-\frac{1}{\epsilon}n_f\frac{4}{3}\delta(1-z)\right.$$
$$+C_A\left(16\frac{\ln(1-z)}{1-z}+\left(\frac{22}{3}+\frac{4}{3}\pi^2\right)\delta(1-z)-16(2-z+z^2)\ln(1-z)\right)$$
$$\left.-8\frac{(1-z+z^2)}{1-z}\ln z-\frac{22}{3}(1-z)^3+\mathcal{O}(\epsilon)\right]$$

The ggH cross section at NLO

$$\sigma_{gg\to H} = \sum_{ij}\int_0^1 dx_1 \int_0^1 dx_2\, f_{i/p}(x_1,\mu_F^2) f_{j/p}(x_2,\mu_F^2)\hat{\sigma}_{ij\to H}\left(\hat{s}=x_1x_2s, \frac{\mu^2}{m_H^2}, \frac{\mu^2}{\mu_F^2}, \alpha_s(\mu^2)\right)$$

Reabsorbe uncancelled collinear divergence in renormalised pdfs

$$\hat{\sigma}^{(1),\mathrm{bare}}_{gg\to H} = \sigma_0\,\frac{\alpha_s}{4\pi}\left(\frac{\mu^2}{m_H^2}\right)^{\epsilon}\left(\frac{2}{\epsilon}P^{(0)}_{gg}(z) + C^{(1)}_{gg}(z) + \mathcal{O}(\epsilon)\right)$$

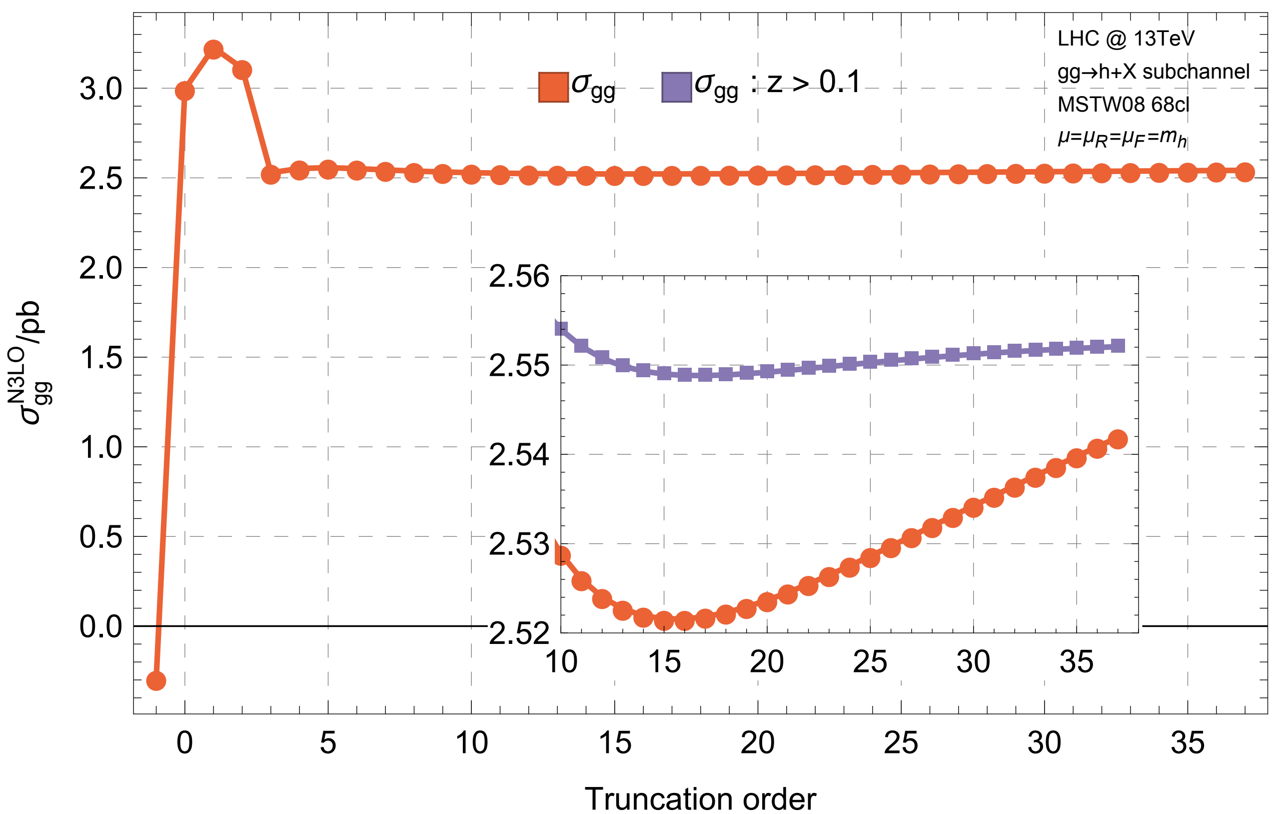
$$f^{\mathrm{ren}}_{g/g}(z,\mu_F^2) = \delta(1-z) - \frac{\alpha_s}{2\pi}\frac{1}{\epsilon}P^{(0)}_{gg}(z)\left(\frac{\mu^2}{\mu_F^2}\right)^{\epsilon}$$

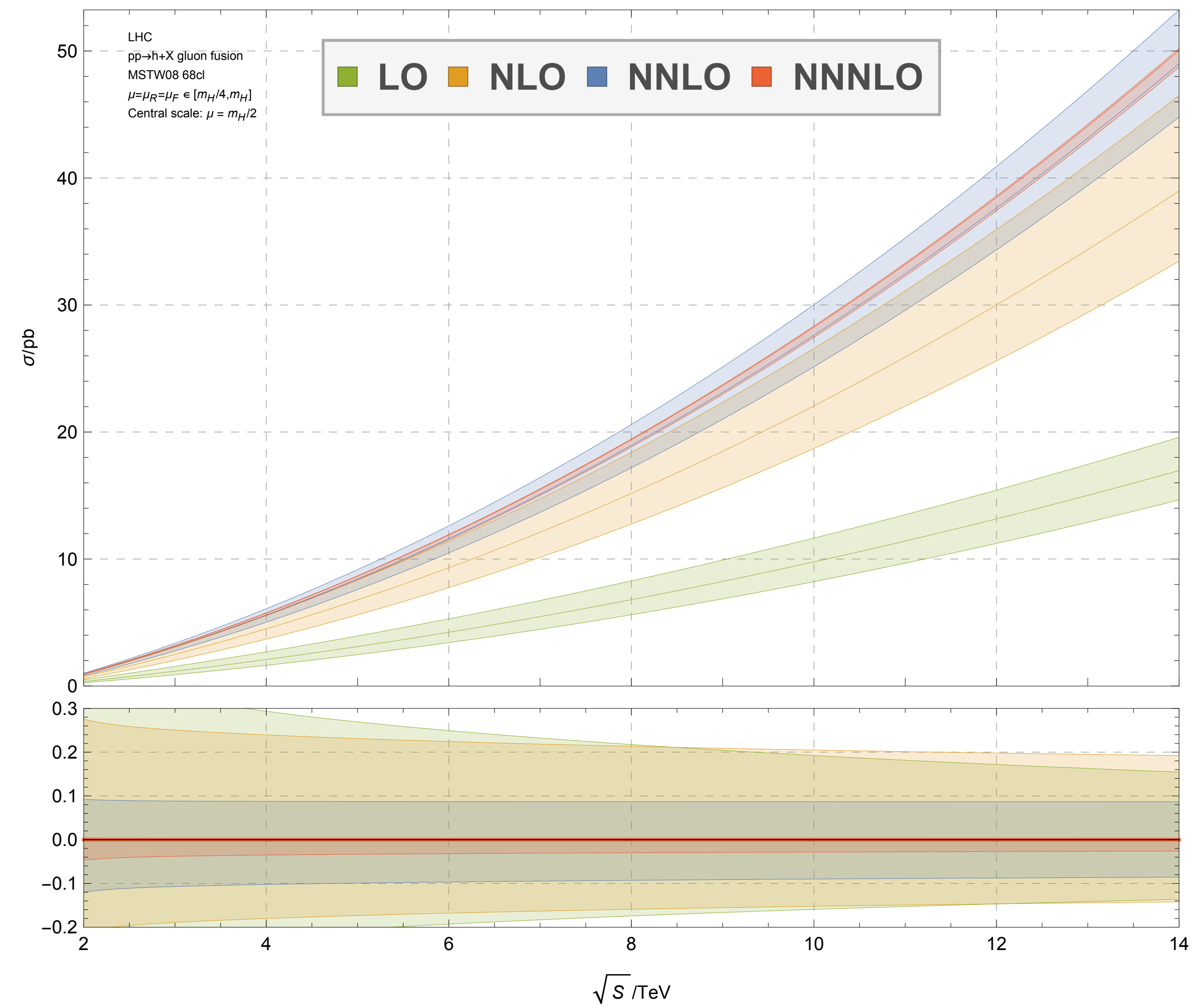
$$\hat{\sigma}^{(1)}_{gg\to H} = \sigma_0\,\left[\delta(1-z) + \frac{\alpha_s}{4\pi}\left(C^{(1)}_{gg}(z) - 2P^{(0)}_{gg}(z)\ln\frac{m_H^2}{\mu_F^2} + \delta(1-z)\ln\frac{\mu^2}{m_H^2}\right)\right]$$

Variation of unphysical scales μ and μ_F is a handle to estimate theoretical uncertainties

Gluon fusion: theoretical uncertainties

Total cross section up to NNNLO via expansion around threshold



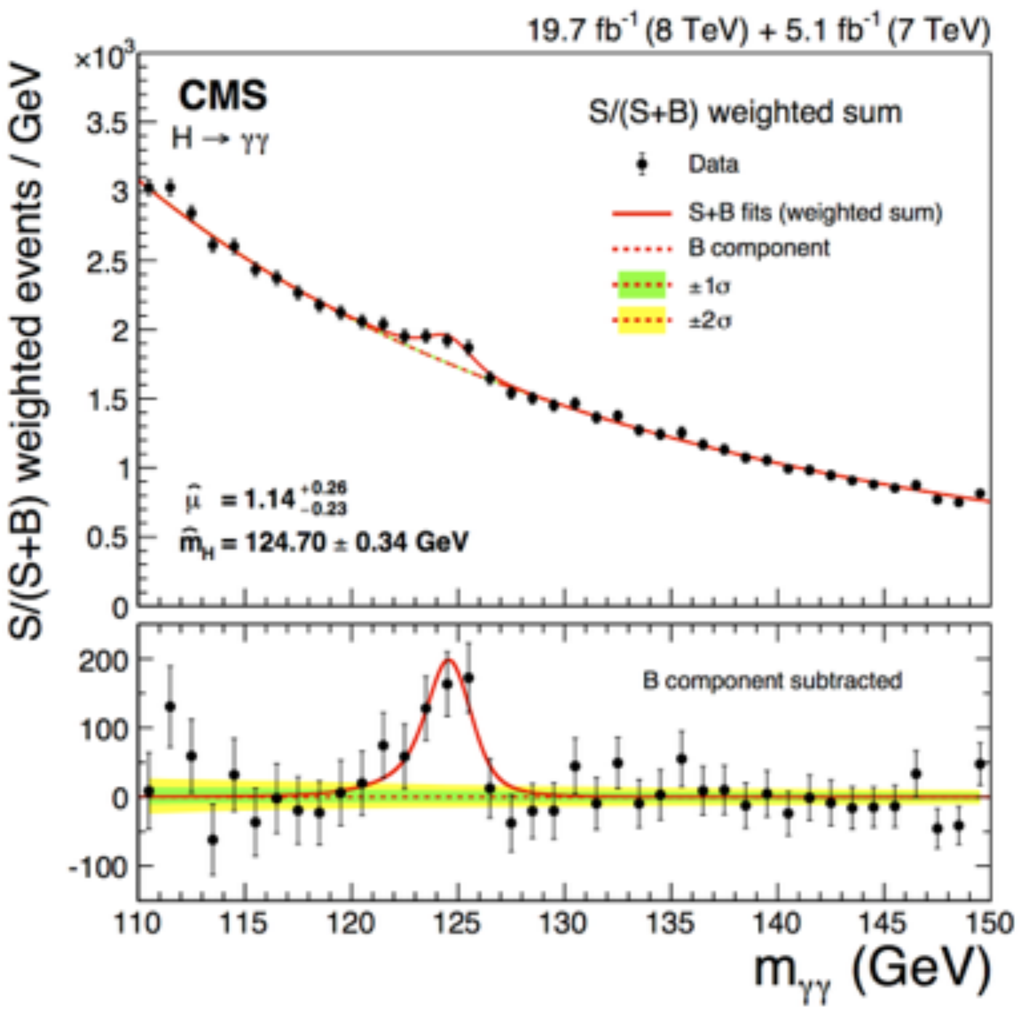


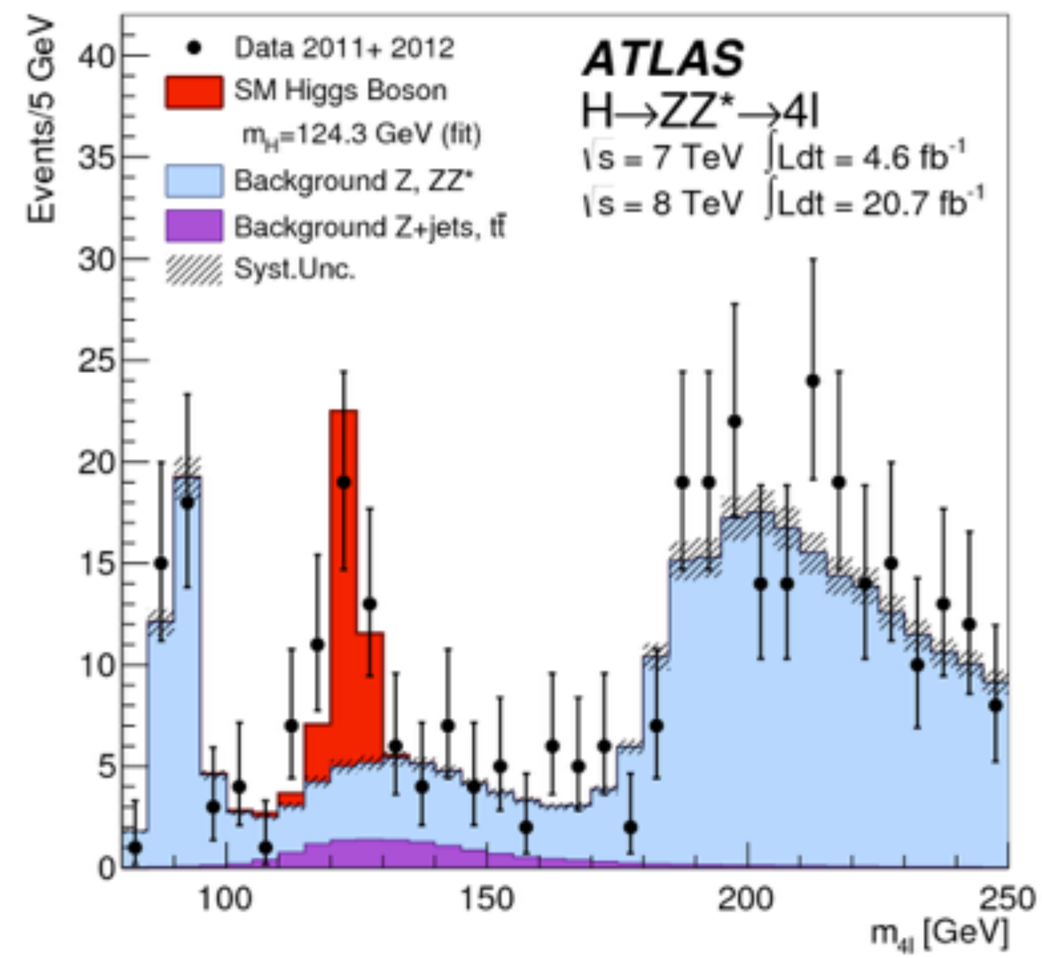
NNLO predictions with different pdf sets

ABM11	ABM12	CT10	MSTW	NN23
39.58 ± 0.77	39.70 ± 0.84	$41.84\,^{+1.30}_{-1.69}$	$42.12\,^{+0.44}_{-0.63}$	43.75 ± 0.41

ggH total cross-section and Higgs discovery

The total Higgs cross section can be used straightaway in $H \to \gamma\gamma$ and $H \to ZZ$





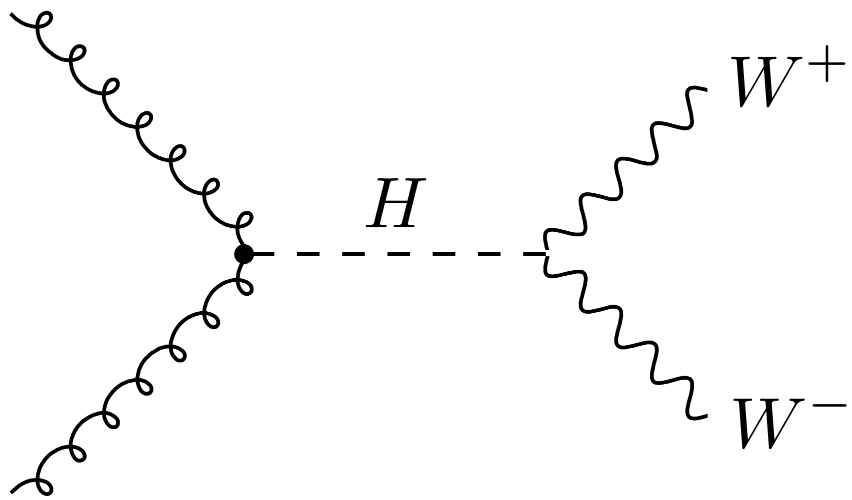
For suitable choices of acceptance cuts, gluon fusion is dominant

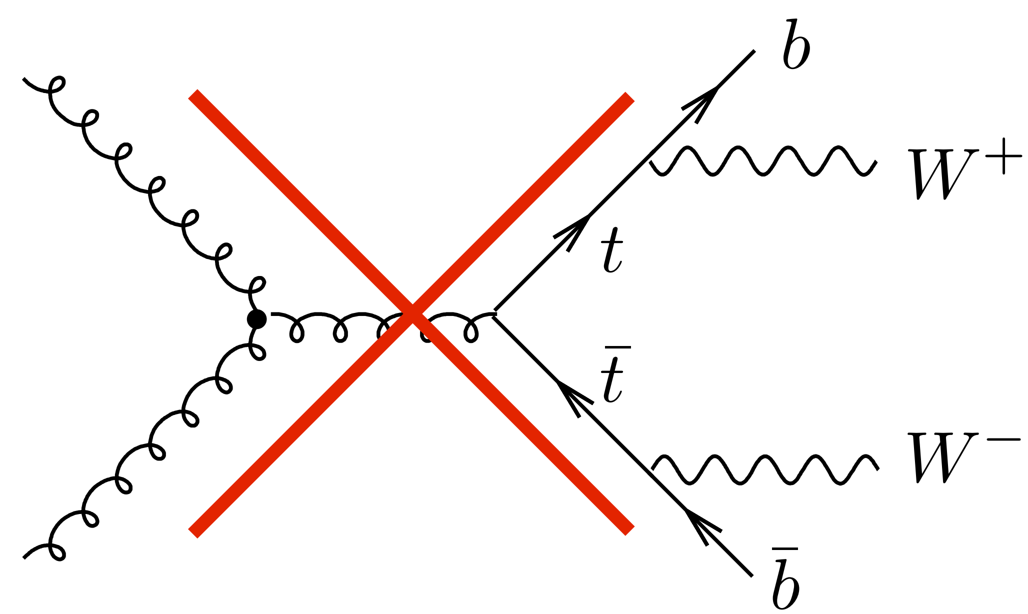
$$n_{\rm obs}^{f} \simeq \mu_f \times [\sigma_{gg\to H} \times {\rm Br}_f] \times A_f \times \epsilon_f \times \mathcal{L} \qquad f = \gamma\gamma, ZZ$$

The acceptance cuts are not extremely sensitive to radiative corrections, so one can safely use the most accurate total cross section

Jet-veto cross sections

If we wish to study $H \to WW$ we need to eliminate a huge background due to top-antitop background



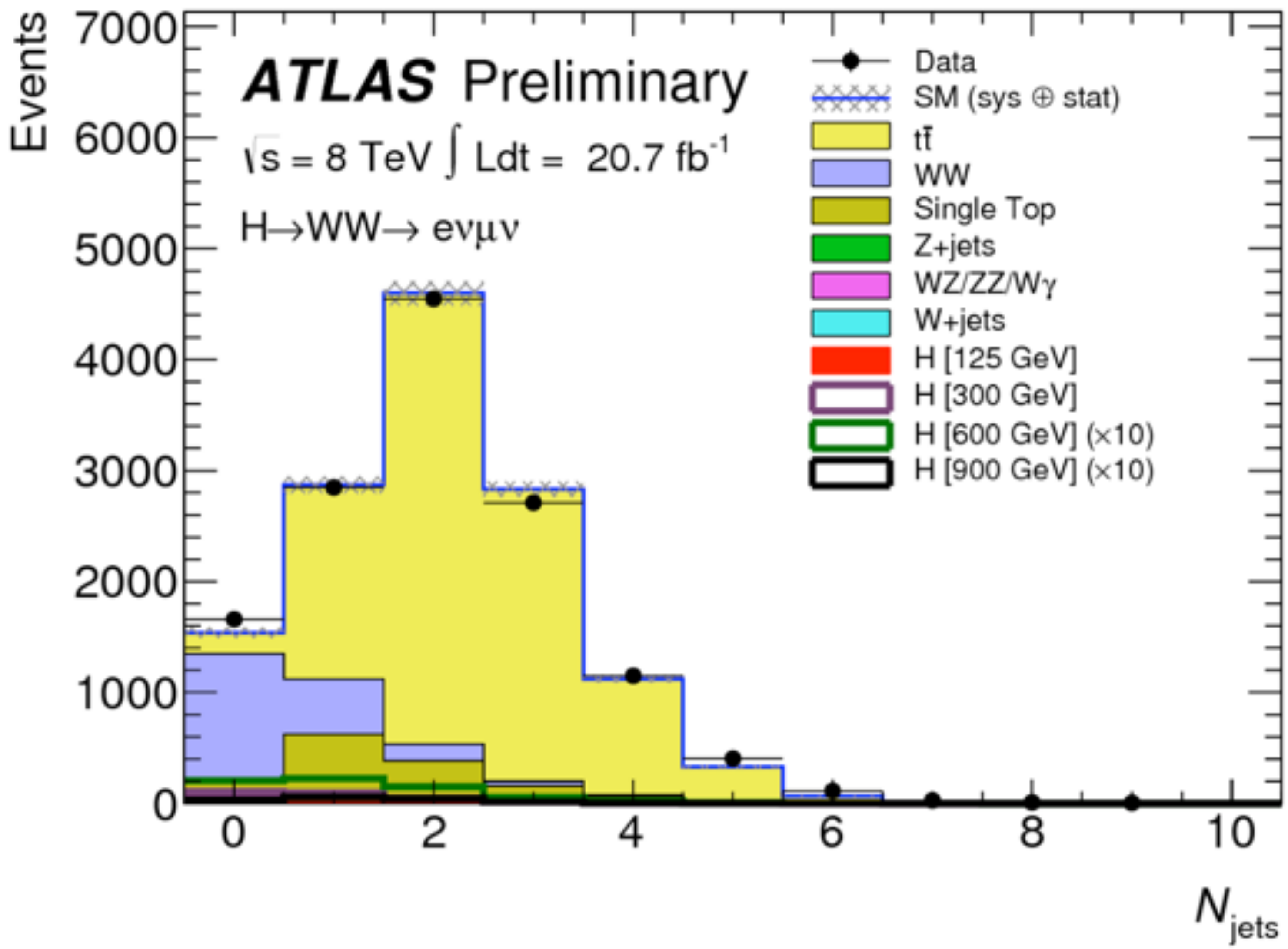


Each top quark produces a b-jet $\Rightarrow$ veto events with jets in the final state

Jet-vetoes are employed in many LHC analyses (e.g. vector-boson cross sections, boosted Higgs searches, etc.)

How to veto jets?

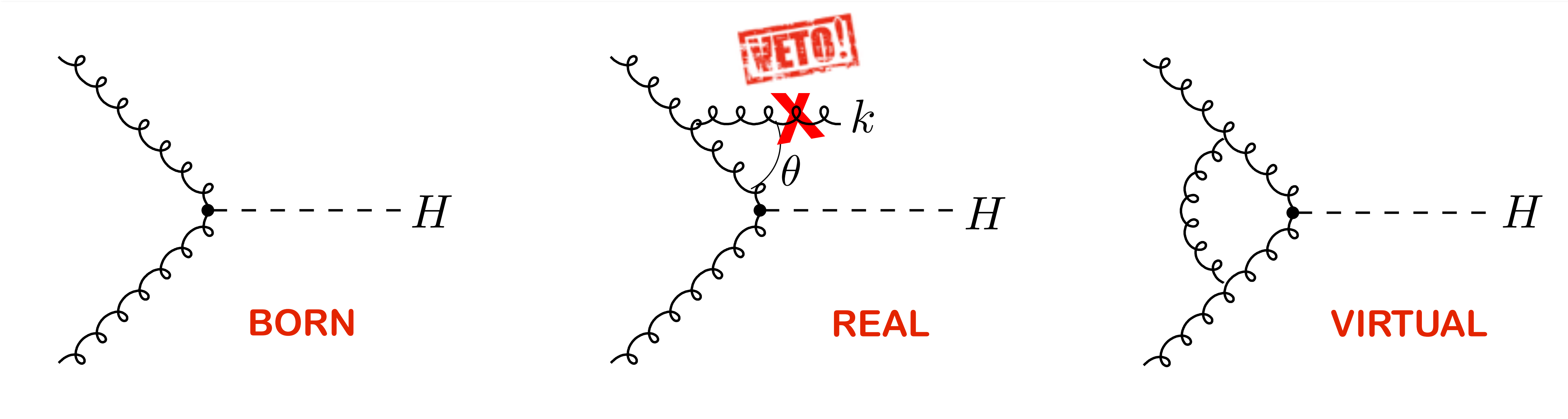
We require that all jets with transverse momentum smaller than $p_{\mathrm{t,veto}}$



This works well: the zero-jet cross section $\sigma_{0-\mathrm{jet}}$ is least contaminated by the huge (yellow) top-antitop background

Problems with jet-veto in QCD

Consider a jet made of a single soft ($E \ll m_H$) and collinear ($\theta \ll 1$) gluon



soft collinear

$$\sigma_0 \left[1 \quad + \quad C_A \frac{\alpha_s}{\pi} \int \frac{dE}{E} \frac{d\theta^2}{\theta^2} \Theta\left(p_{t,\mathrm{veto}} - E\theta\right) \quad - \quad C_A \frac{\alpha_s}{\pi} \int \frac{dE}{E} \frac{d\theta^2}{\theta^2}\right]$$

factorisation of soft radiation

$$\sigma_{0-\mathrm{jet}} = \sigma_0 \left[1 - C_A \frac{\alpha_s}{\pi} \ln^2\left(\frac{m_H}{p_{t,\mathrm{veto}}}\right)\right]$$

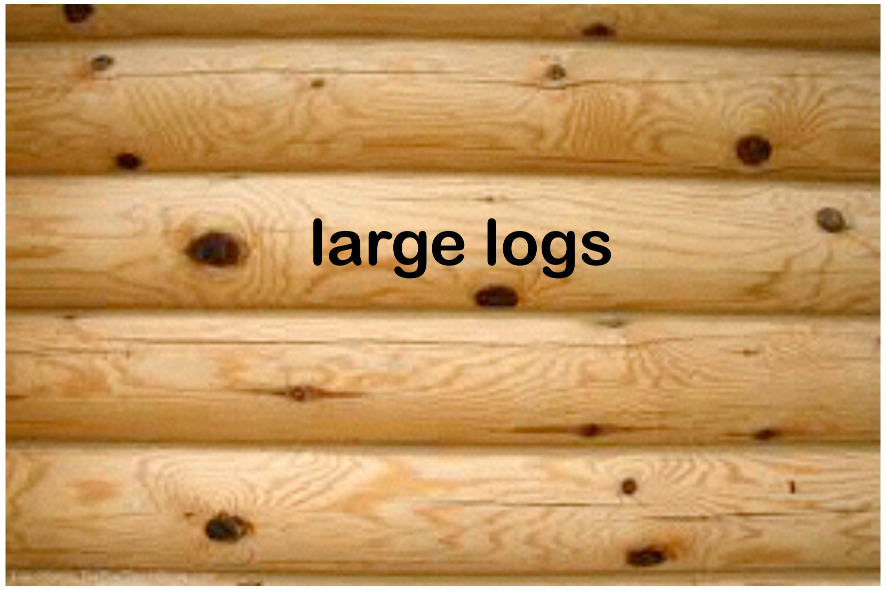
Resummation of large logarithms

The zero-jet cross section contains logarithmic contributions with can become large when $p_{\mathrm{t,veto}} \ll m_H$

$$\sigma_{0-\mathrm{jet}} \simeq \sigma_0 \left(1 - 2C_A \frac{\alpha_s(m_H)}{\pi} \ln^2 \frac{m_H}{p_{\mathrm{t,veto}}} + \ldots \right)$$

LO NLO

breakdown of perturbation theory!



Resummation of large logarithms

Resummation is a reorganisation of the PT series for $\alpha_s \ln(m_H/p_{t,\text{veto}}) \sim 1$

$$\sigma_{0-\text{jet}} \sim \sigma_0 \exp\left[\underbrace{Lg_1(\alpha_s L)}_{\text{LL}} + \underbrace{g_2(\alpha_s L)}_{\text{NLL}} + \underbrace{\alpha_s g_3(\alpha_s L)}_{\text{NNLL}} + \dots\right]$$

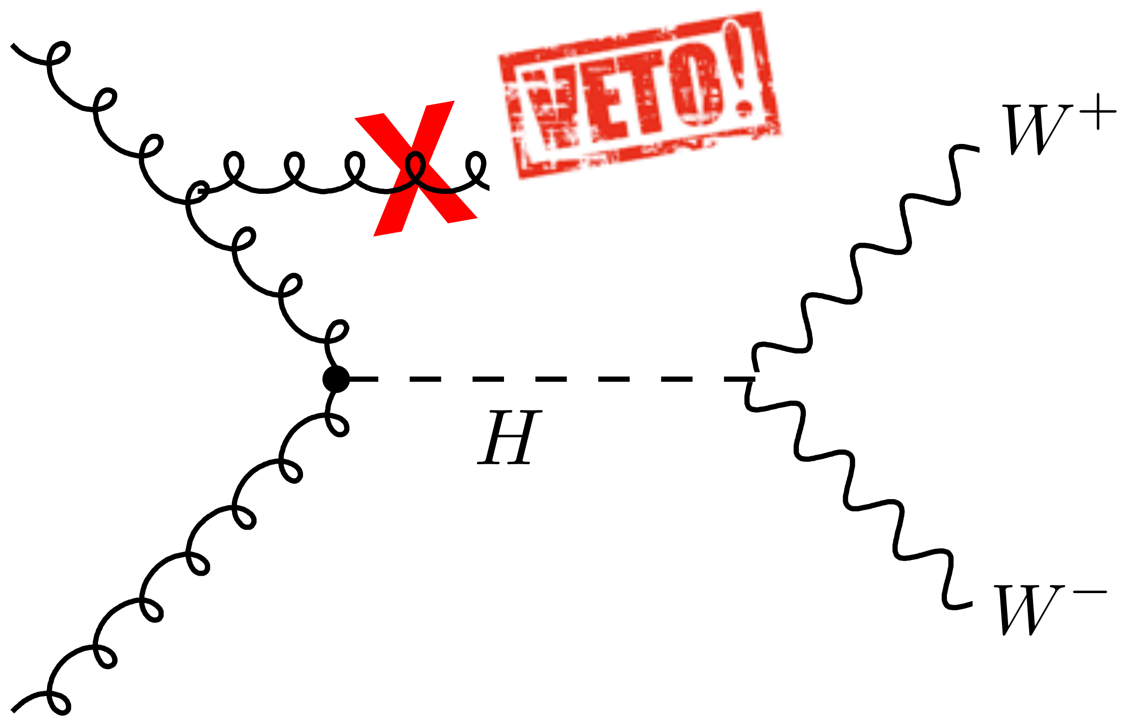
The state-of-the art accuracy for the zero-jet cross section is NNLL

Physical meaning of resummation

Resummed predictions make sense even for $p_{\rm t,veto} \ll m_H$

$$\sigma_{0-\rm jet} \simeq \sigma_0 \left(1 - 2C_A \frac{\alpha_s(m_H)}{\pi} \ln^2 \frac{m_H}{p_{\rm t,veto}} + \dots \right) \to \quad \sigma_0 \, e^{-2C_A \frac{\alpha_s}{\pi} \ln^2 \left(\frac{m_H}{p_{\rm t,veto}}\right)}$$

The resummed zero-jet cross section vanishes for $p_{\rm t,veto} \to 0$

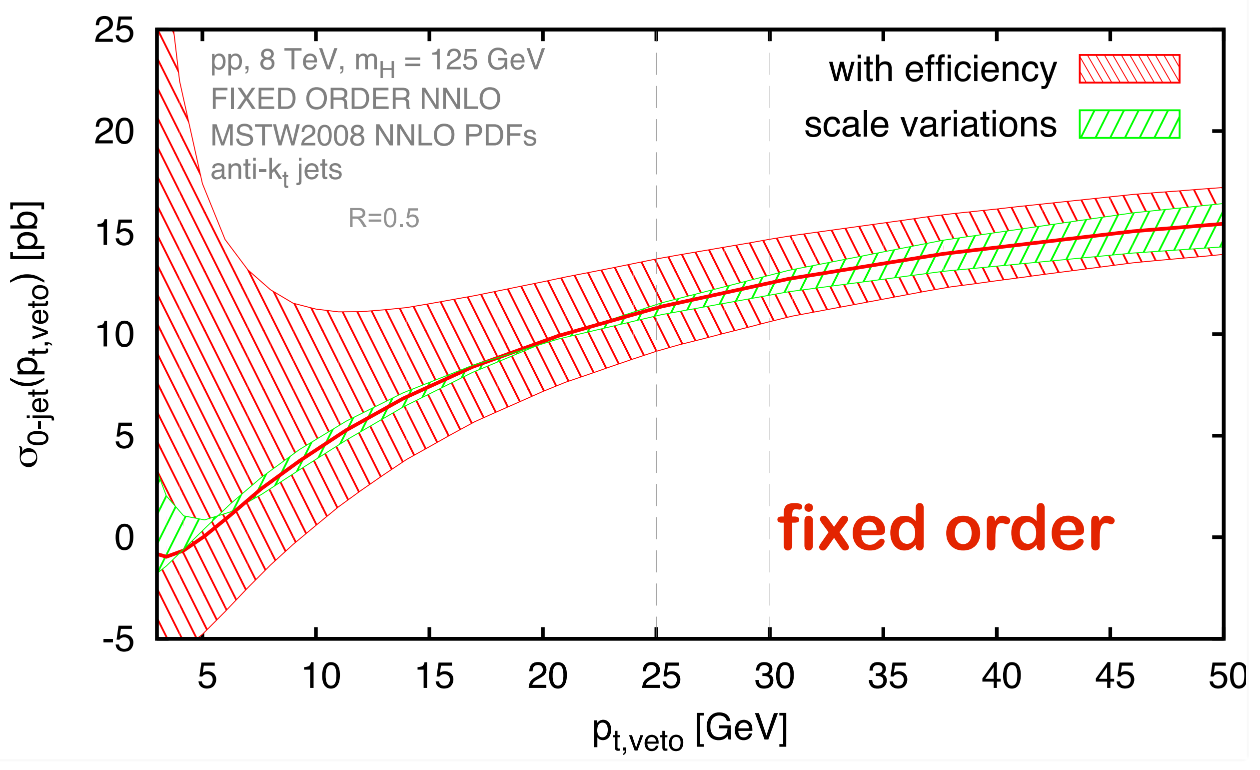


Charged particles always radiate ⇒ the probability of having gluons without accompanying QCD radiation is exactly zero

Benefits of resummation

The zero-jet cross section can be computed at NNLO using exclusive parton-level event generators (FeHiP, HNNLO)

In spite of the high accuracy, different methods to evaluate fixed-order theoretical uncertainties give very different results



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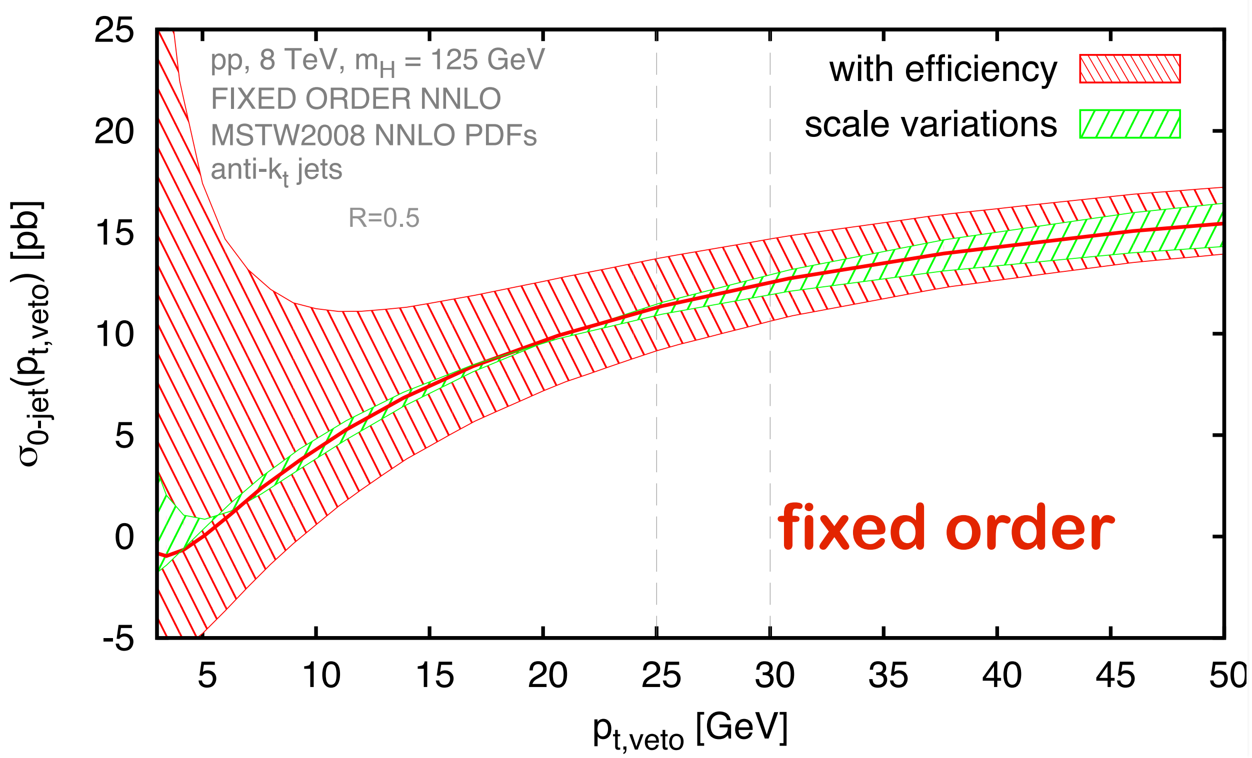
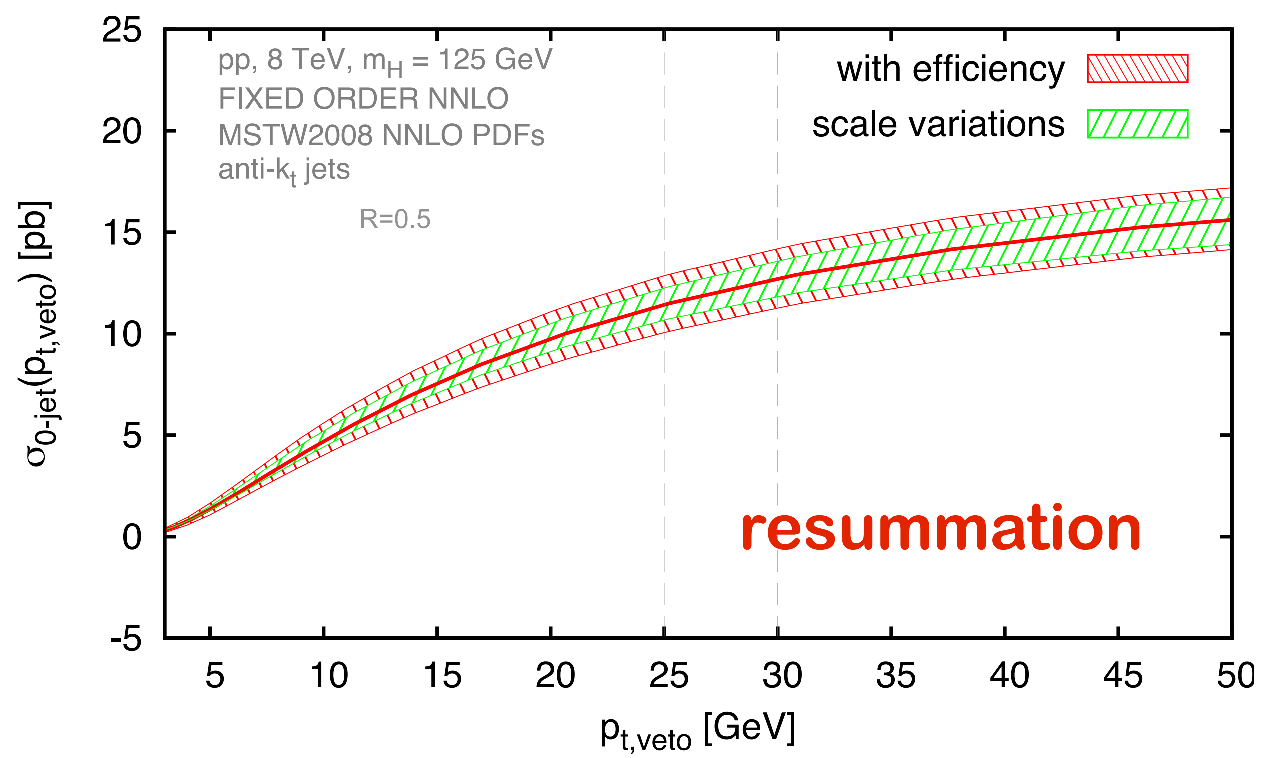


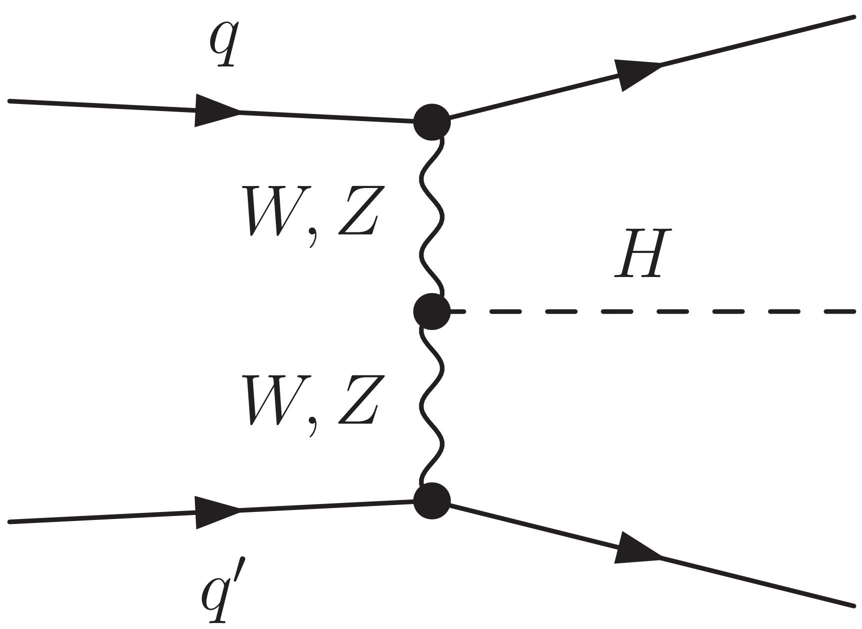


When adding NNLL resummation, theoretical predictions become more stable

Jet-veto cross sections appear in other contexts, including VBF and VH

Vector boson fusion (VBF)

Vector boson fusion directly probes the dynamics of EW symmetry breaking



The exchanged W, Z bosons are mainly in the t-channel $\Rightarrow$ two forward jets

$$M_{jj} > 500\,\mathrm{GeV} \qquad\qquad \Delta\eta_{jj} > 3.6$$

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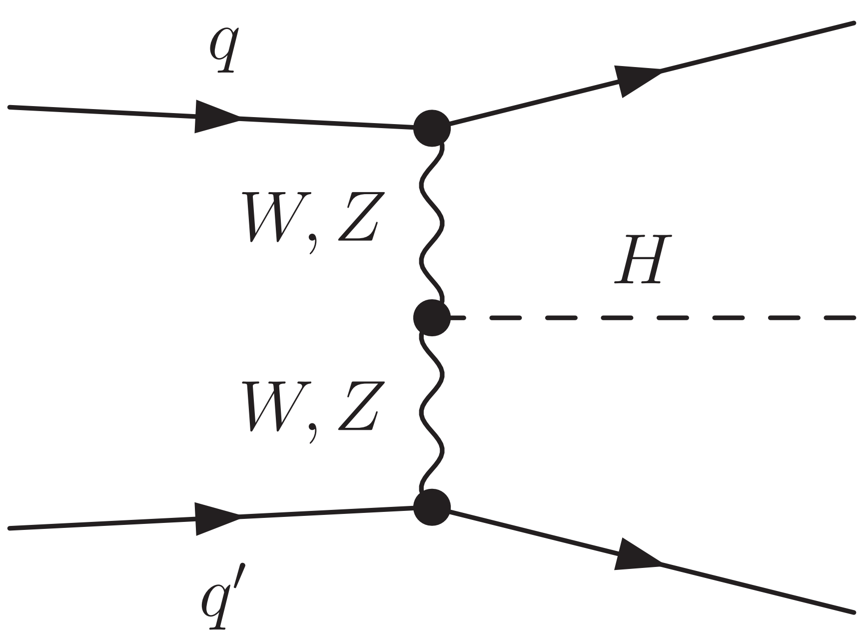
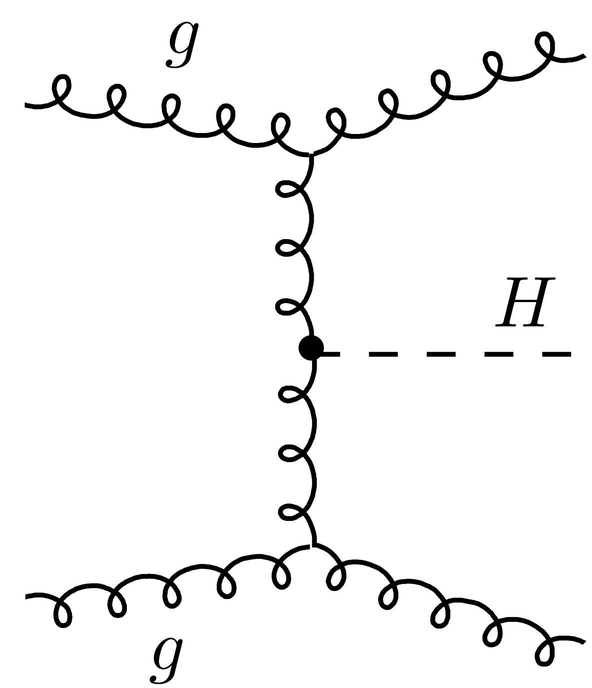
Vector boson fusion directly probes the dynamics of EW symmetry breaking





The exchanged W, Z bosons are mainly in the t-channel $\Rightarrow$ two forward jets

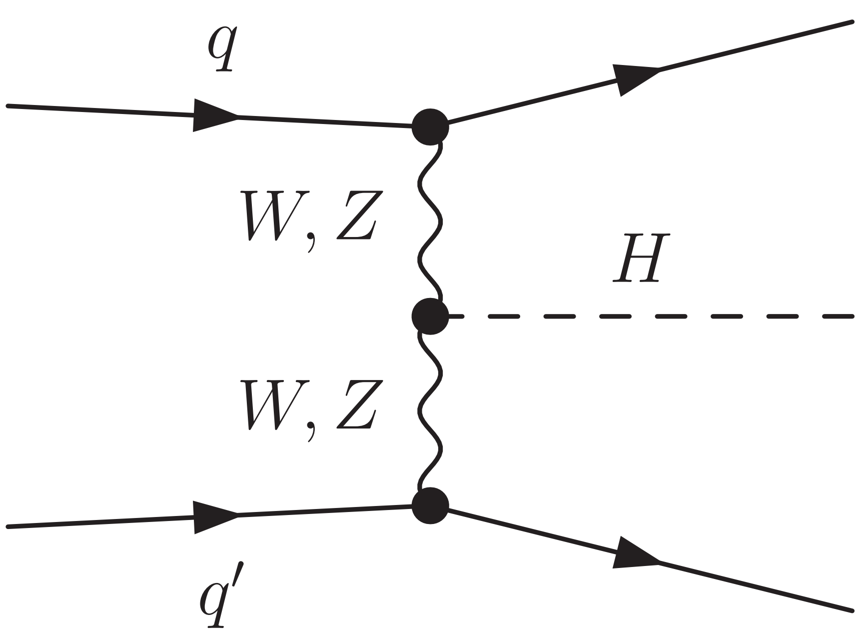
$$M_{jj} > 500\,\mathrm{GeV} \qquad\qquad \Delta\eta_{jj} > 3.6$$

No colour flow between the forward jets $\Rightarrow$ a central jet-veto makes (almost) no harm to VBF, but it does to gluon fusion

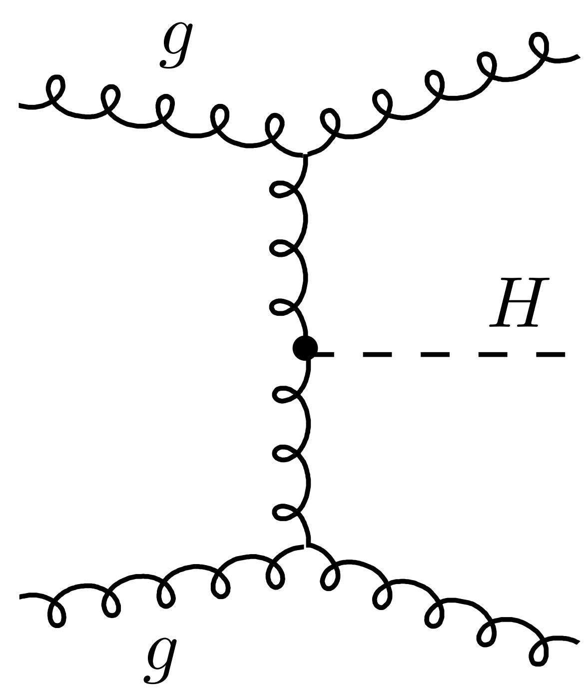
$$p_{T,j_3} < 20\,\mathrm{GeV} \qquad\qquad |\eta_{j_3}| < \eta_{\mathrm{cut}} \simeq 3$$

VBF state of the art

Signal



Background



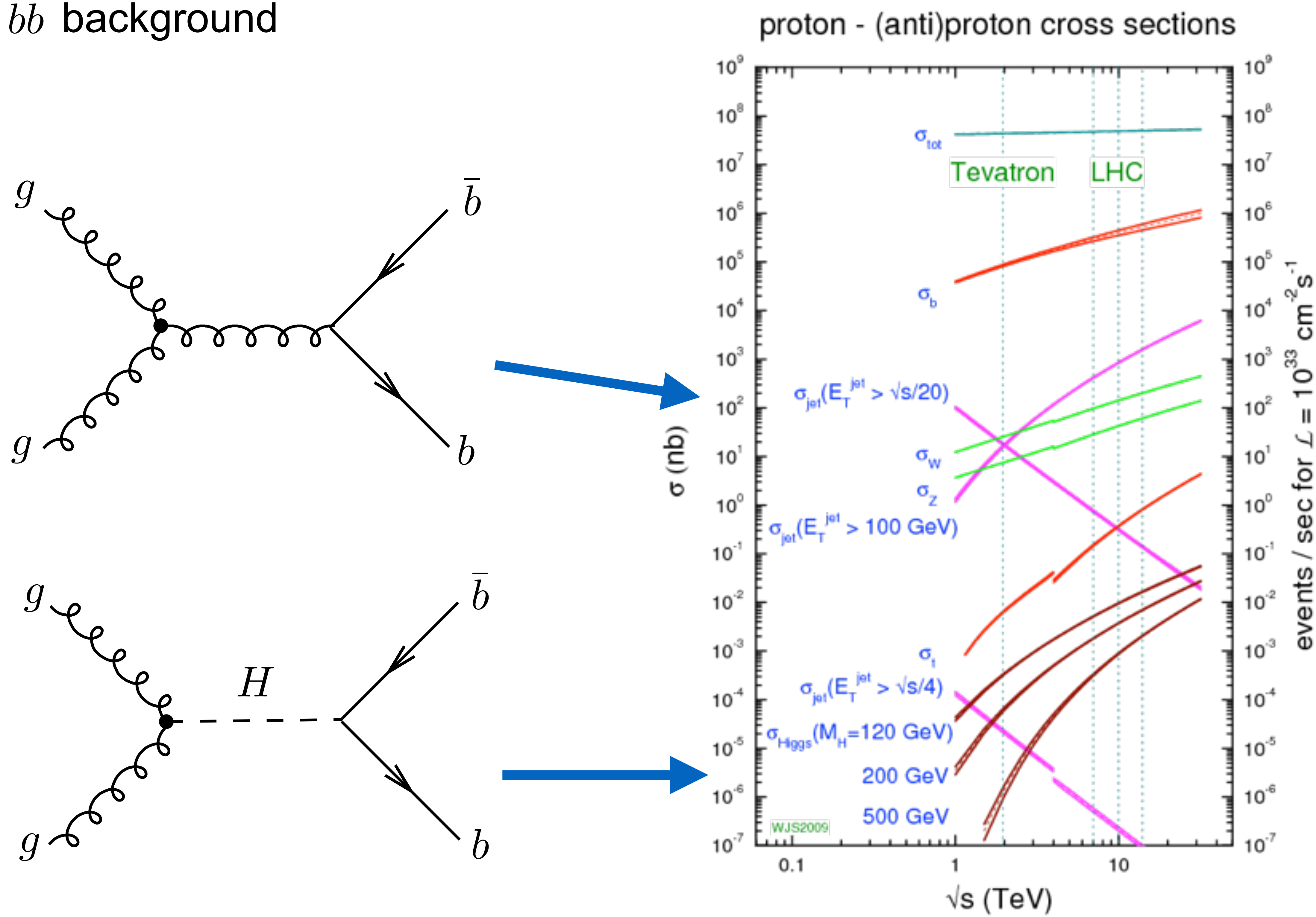
NNLO?	VBF@NNLO, essentially $(DIS)^2$
QCD-EW	HAWK, factorised

H+2jets	NLO, needed for the cross section
H+3jets	NLO, needed for the jet-veto condition

No resummed predictions exists for the jet-veto cross section

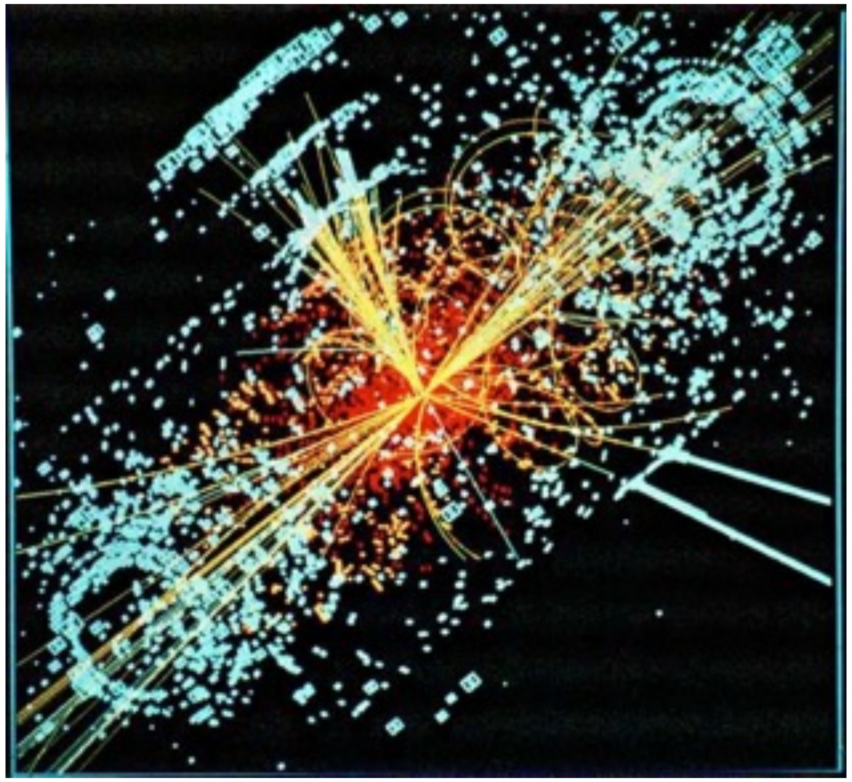
Associate Higgs production: VH

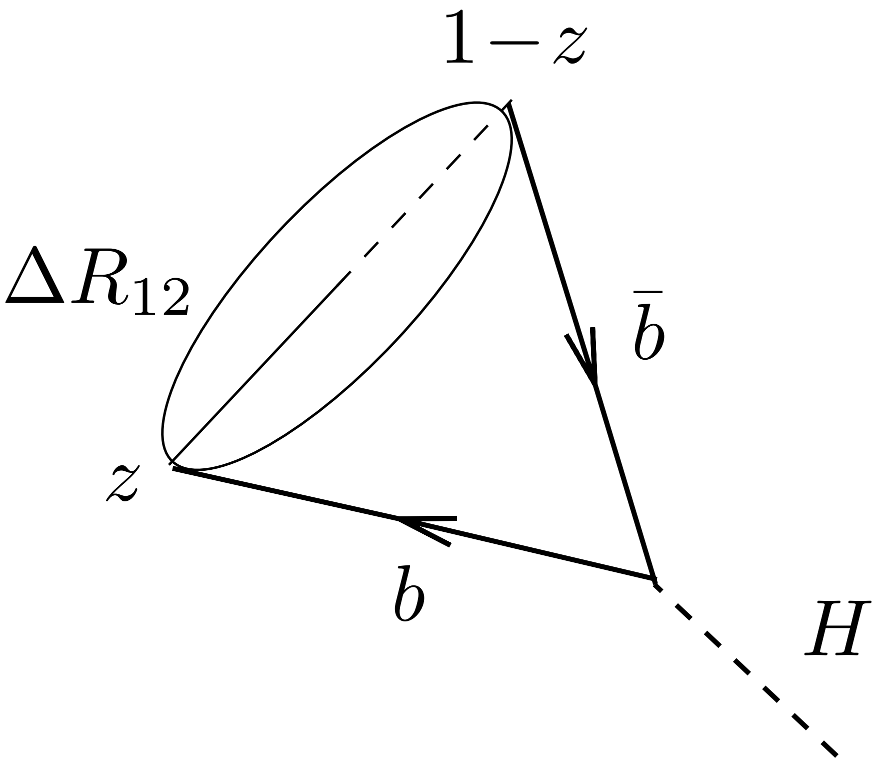
Problem: gluon fusion cannot be used to study $H \to b\bar{b}$, due to overwhelming dijet $b\bar{b}$ background



Associate Higgs production: VH

Solution: let the Higgs recoil against a tagged vector boson to reduce the size of the background





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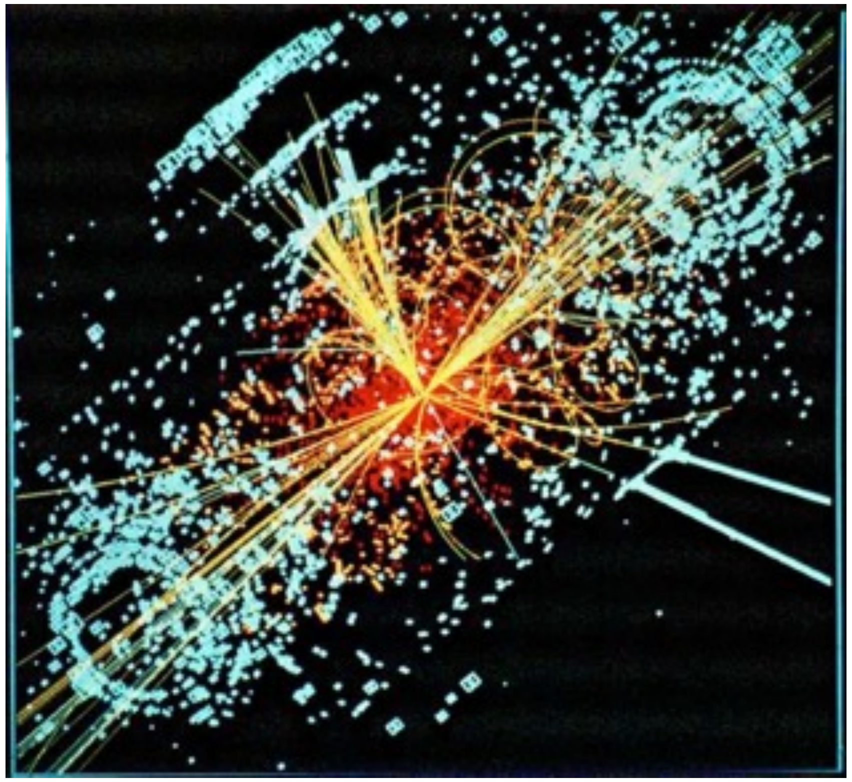
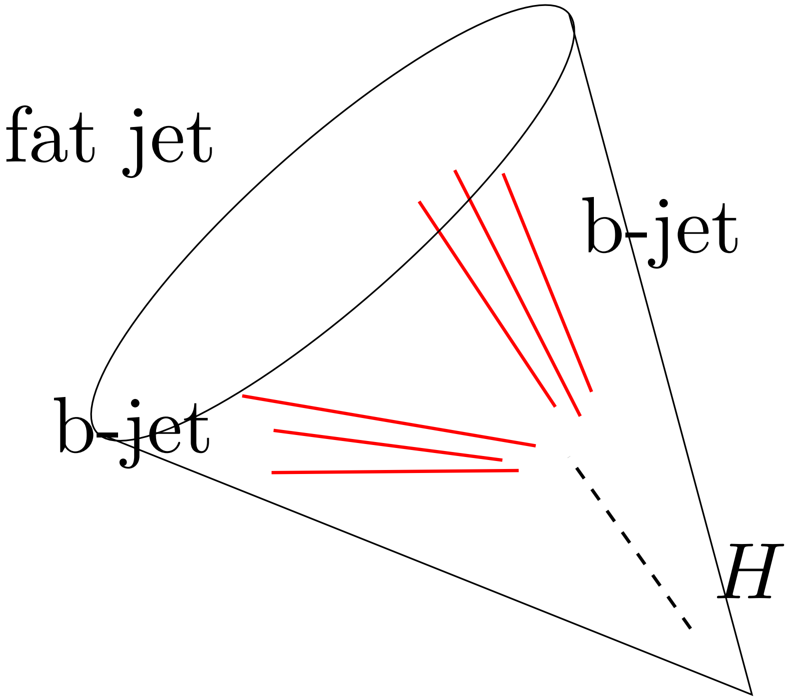




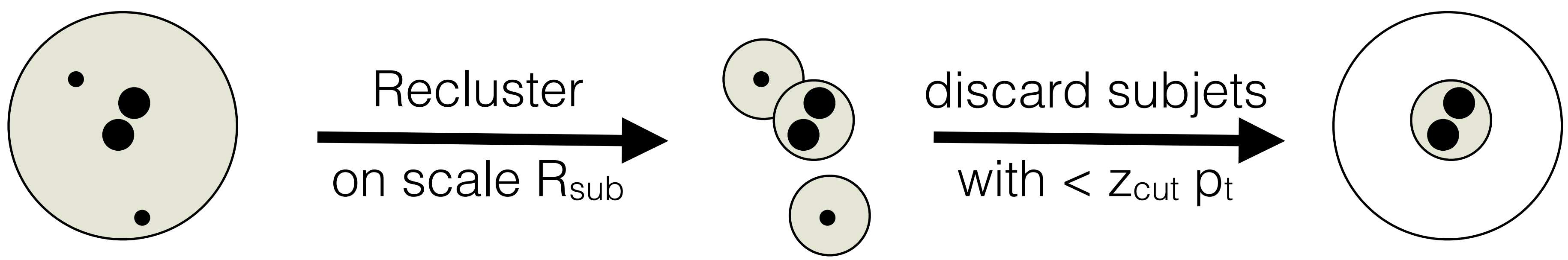
At LHC@13TeV, the Higgs is boosted, so that its decay products tend to fall into the same “fat” jet

$$\Delta R_{12}^2 \simeq \frac{m_H^2}{z(1-z)p_T^2}$$

Tagging boosted objects: cleaning jets

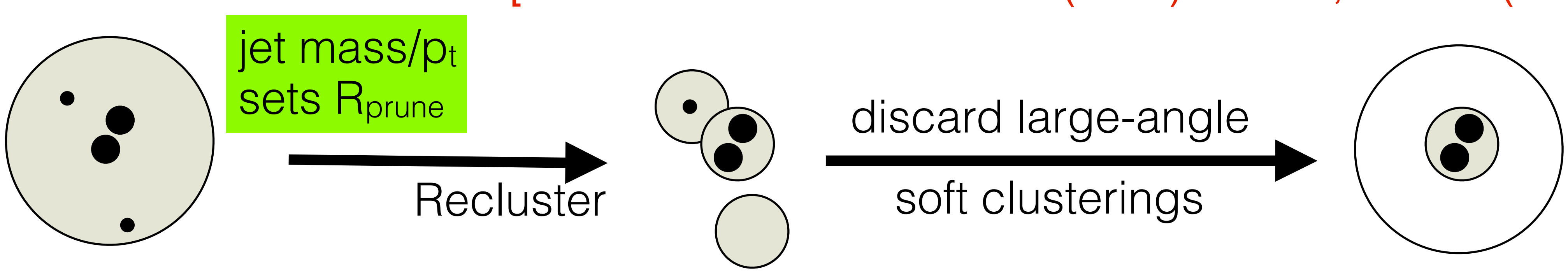
Trimming

[Krohn Thaler Wang JHEP 02 (2010) 084]



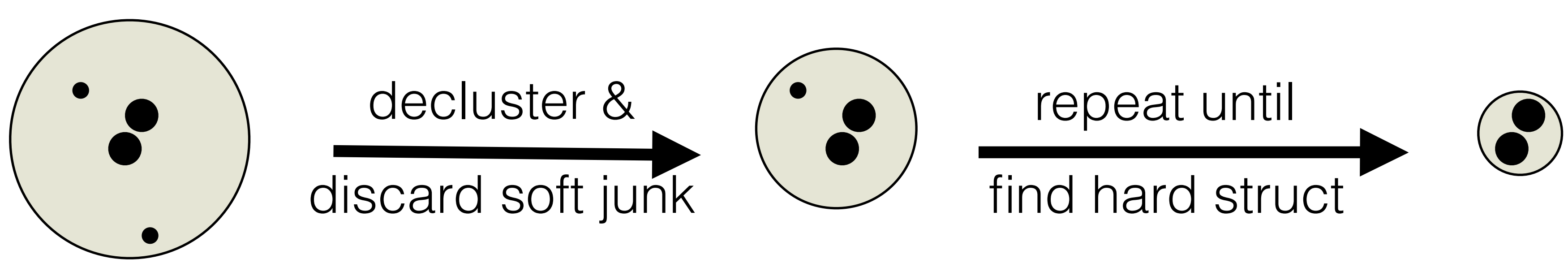
Pruning

[Ellis Vermilion Walsh PRD80 (2009) 051501, PRD81 (2010) 094023]



Mass-drop tagger (MDT)

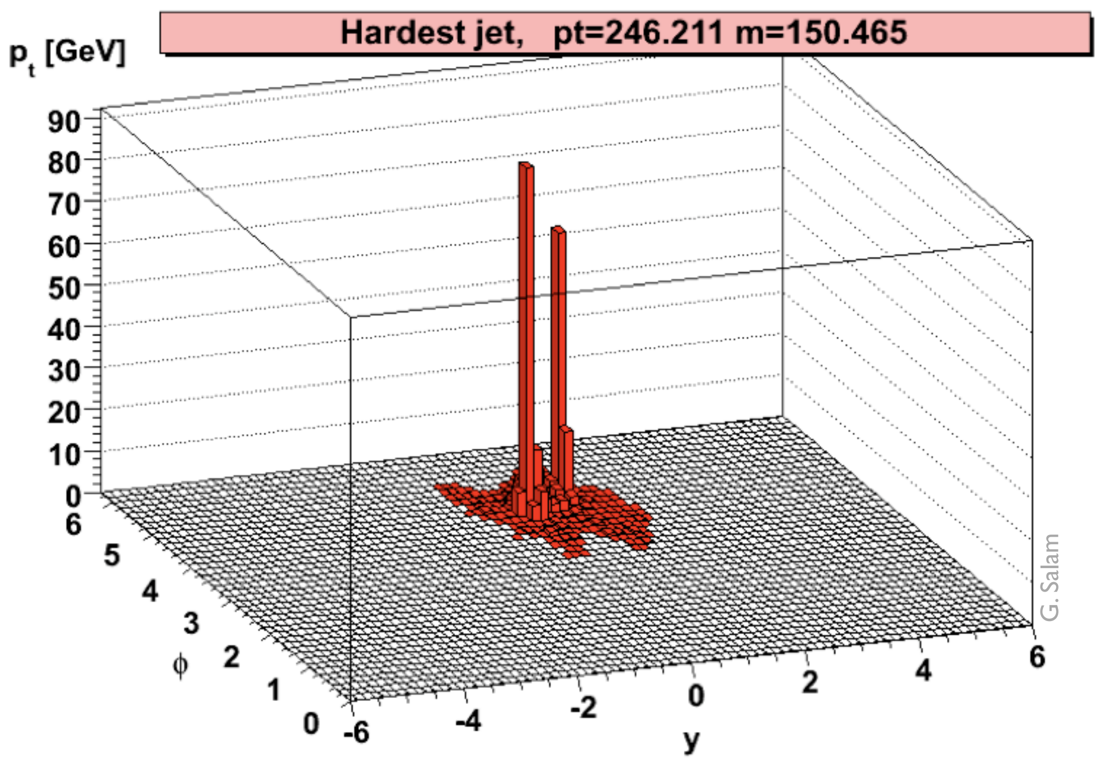
[Butterworth Davison Rubin Salam PRL 100 (2008) 242001]



pictures by G. Salam

Tagging boosted objects: mass drop

The mass-drop tagger, as the name suggests, is also a way to tag a jet arising from a two-pronged decay

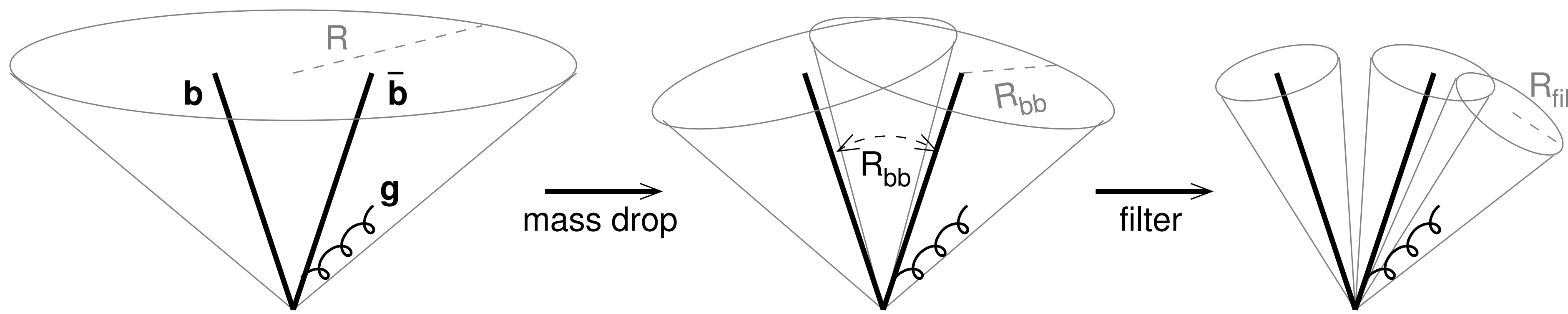


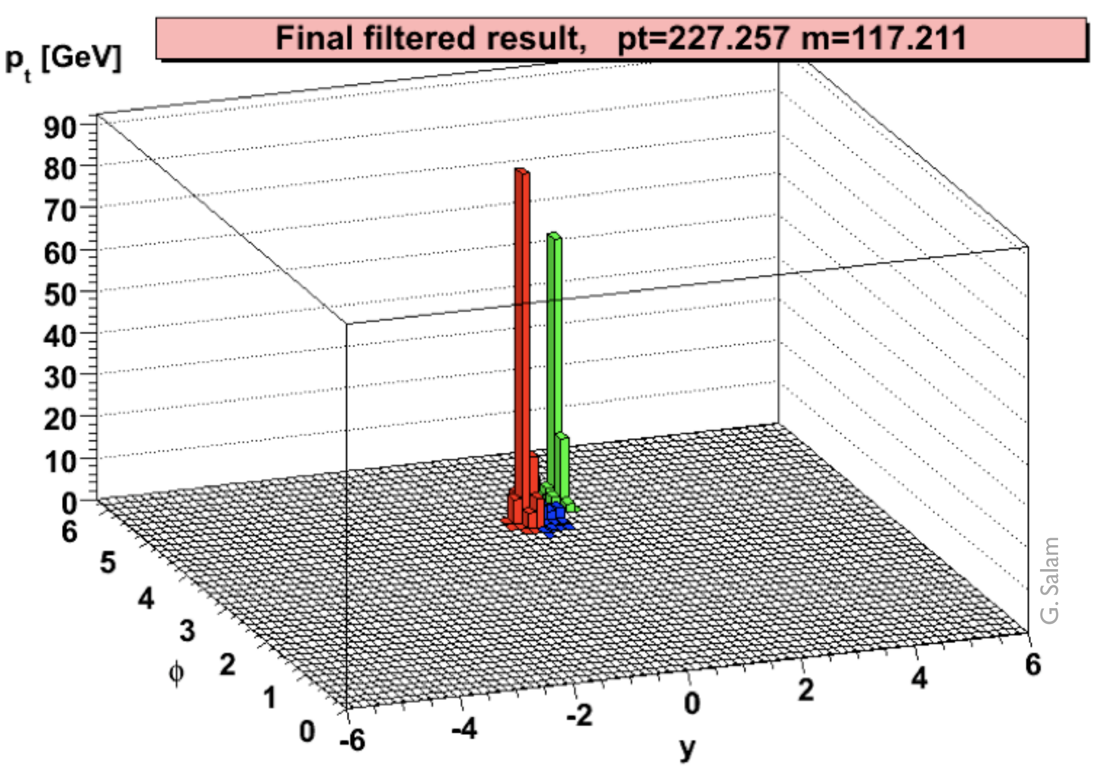
Basic idea: soft "junk" jets do not alter significantly the mass of a jet $\Rightarrow$ undo the clustering until you observe a significant mass drop

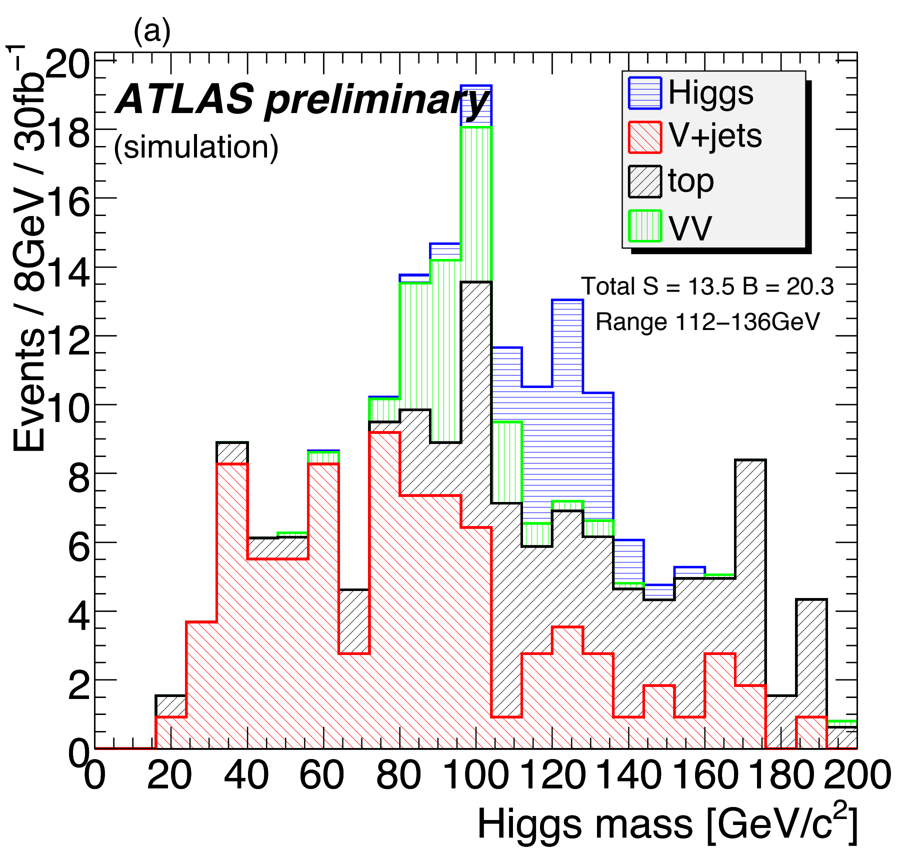
$$\max(m_{j_1}, m_{j_2}) < \mu\, m_j$$

Tagging boosted objects: filtering

Filtering: do not clean too much, try to include also subjets that can arise from soft radiation from the $b\bar{b}$ pair

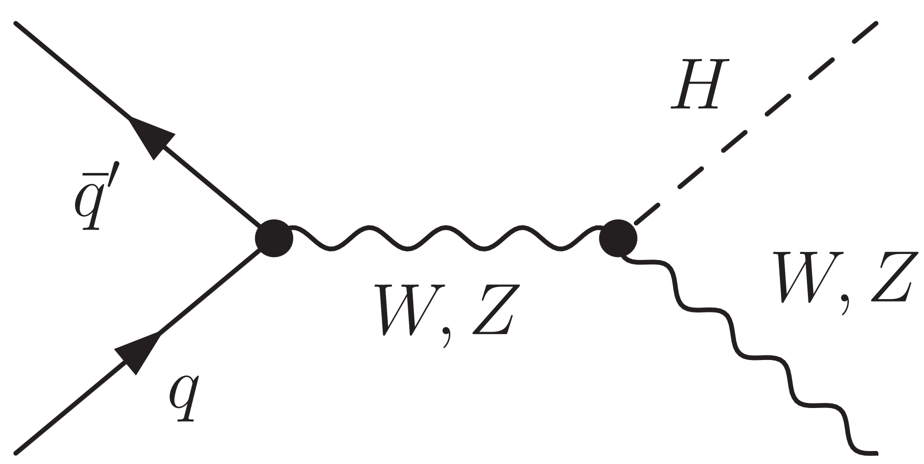




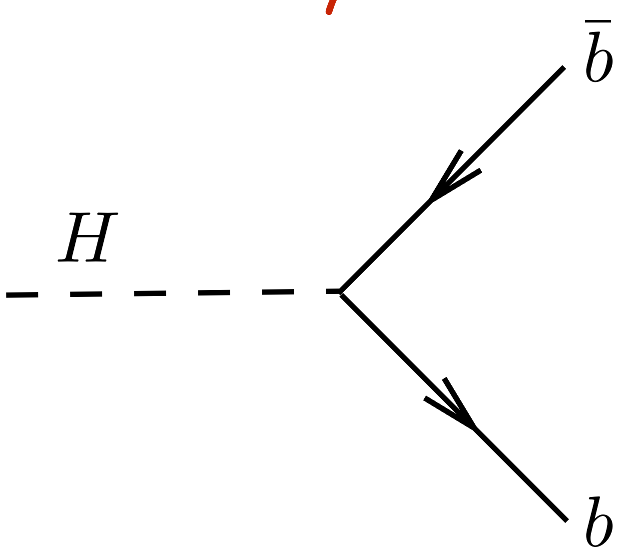


VH calculations: state of the art

Production



Decay



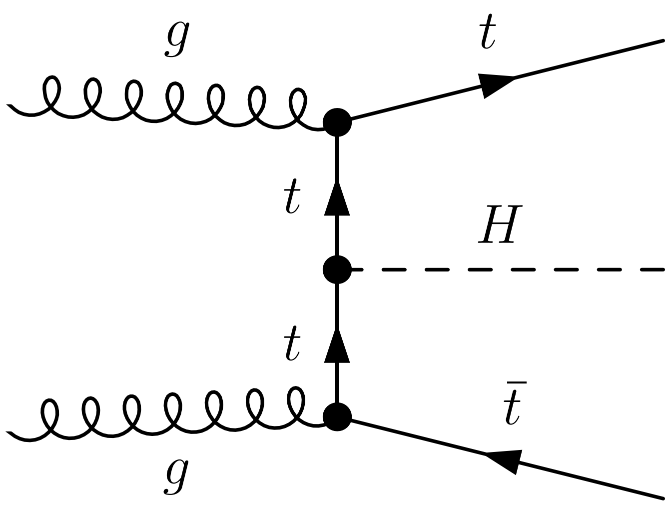
Total cross section	NNLO	VH@NNLO, essentially DY
Fully differential	NNLO	NLO decay only
Jet-veto cross section	NNLL	For HW only

Total rate, massless	NNNLO
Fully differential, massless	NNLO
Fully differential, massive	NLO

Note. Due to complicated phase space cuts involving jets in the final state, it might be very useful to have a code with NNLO production and decay

Associate production: ttH

Higgs production in association with a $t\bar{t}$ pair gives direct access to the top Yukawa coupling



State of the art: NLO calculation for both signal and backgrounds (including $t\bar{t}b\bar{b}$) matched with parton shower to account for higher order QCD radiation effects

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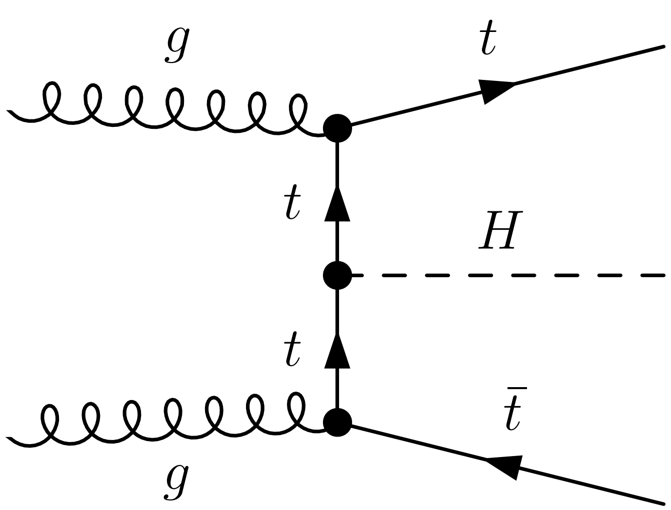
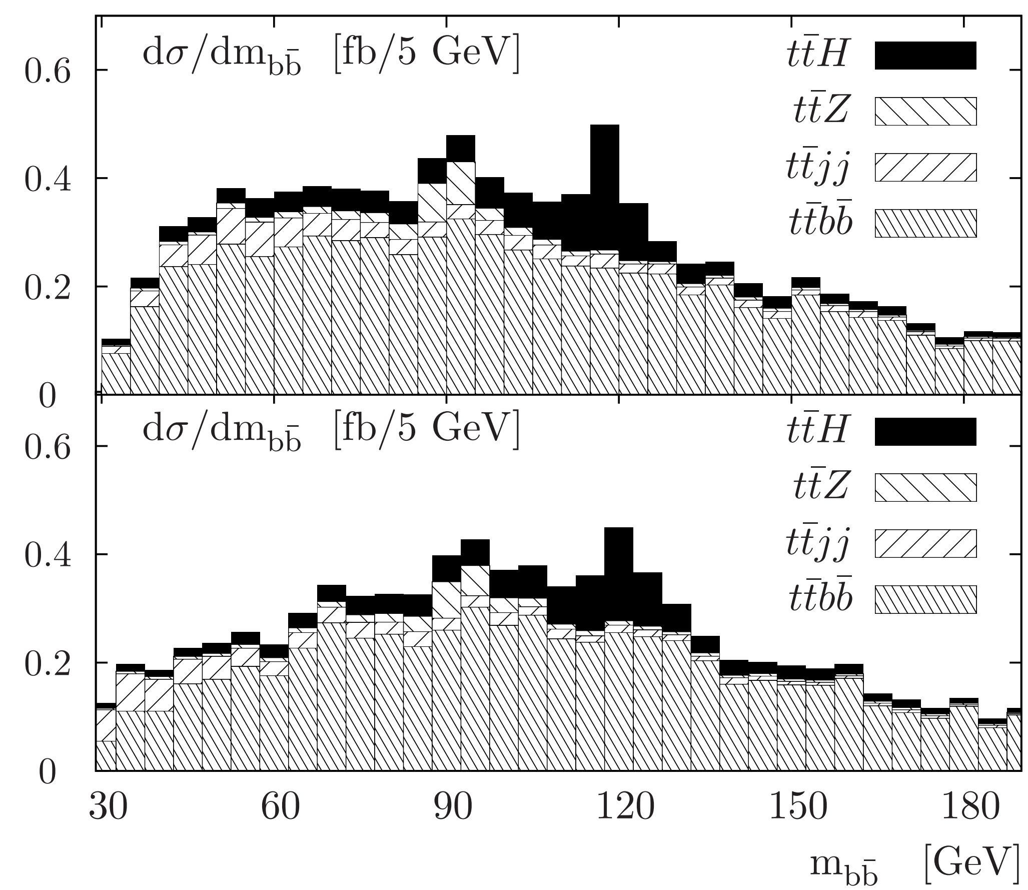


State of the art: NLO calculation for both signal and backgrounds (including $t\bar{t}b\bar{b}$) matched with parton shower to account for higher order QCD radiation effects

Fully hadronic channel ($b\bar{b}b\bar{b}$) very difficult due to combinatorics $\Rightarrow$ exploit boosted object techniques?



Learning outcomes

In this lecture we have learnt

- The basic production mechanisms for Higgs production and the state of the art of QCD and EW calculations
- The gluon fusion cross section suffers from large theoretical uncertainties which require very accurate QCD calculations
- Strategies to devise cuts to separate vector-boson from gluon fusion
- Boosted object techniques to separate signal from background in associate Higgs production