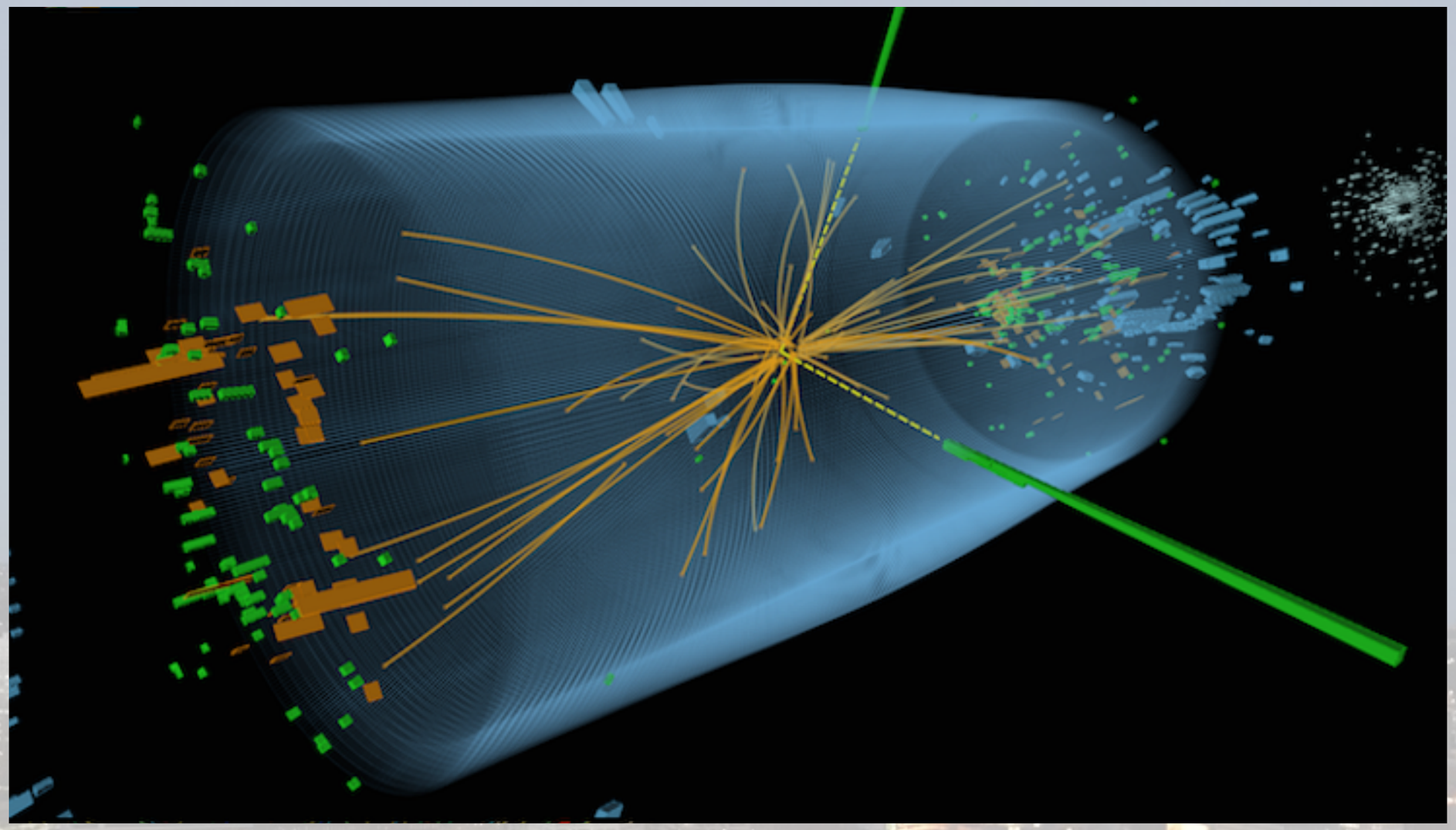


Higgs Decay to Light Jets

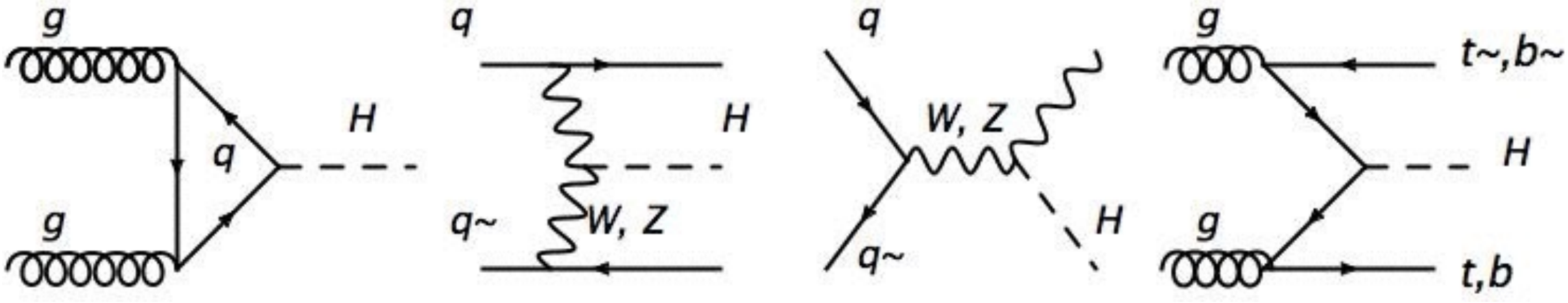
Zhuoni Qian (May 8th, 2017)

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou. Phys. Rev. D 95, no. 5, 053003 (2017)

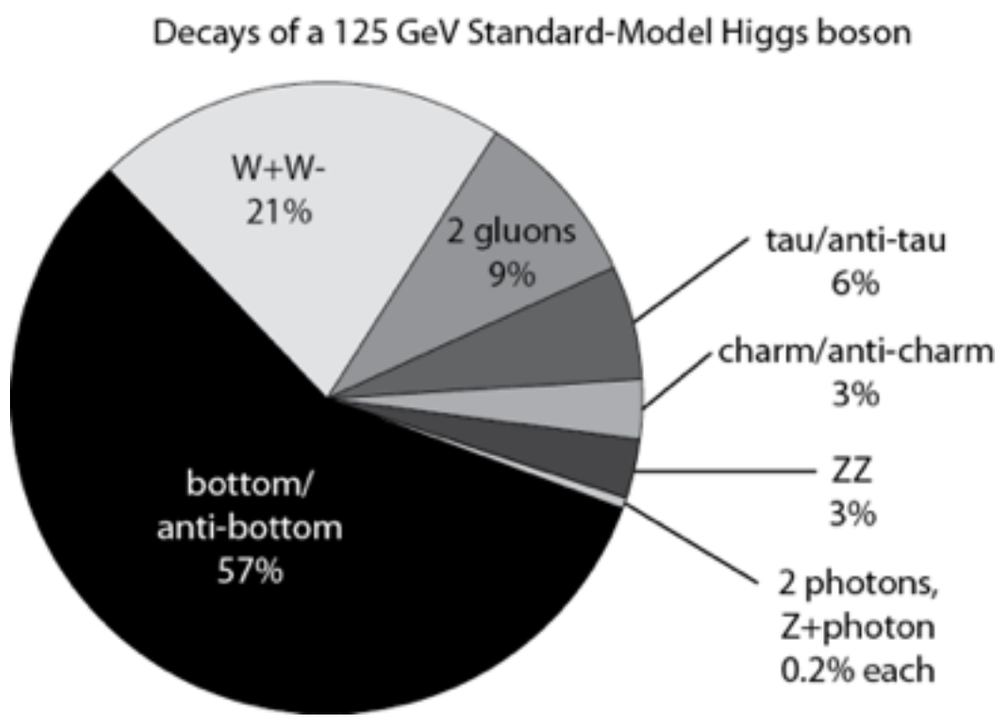
Contents

- Current Status
- Signal & Background
- Kinematics
- Results
- Improvements

Higgs Production
Hadron Collider (LHC)

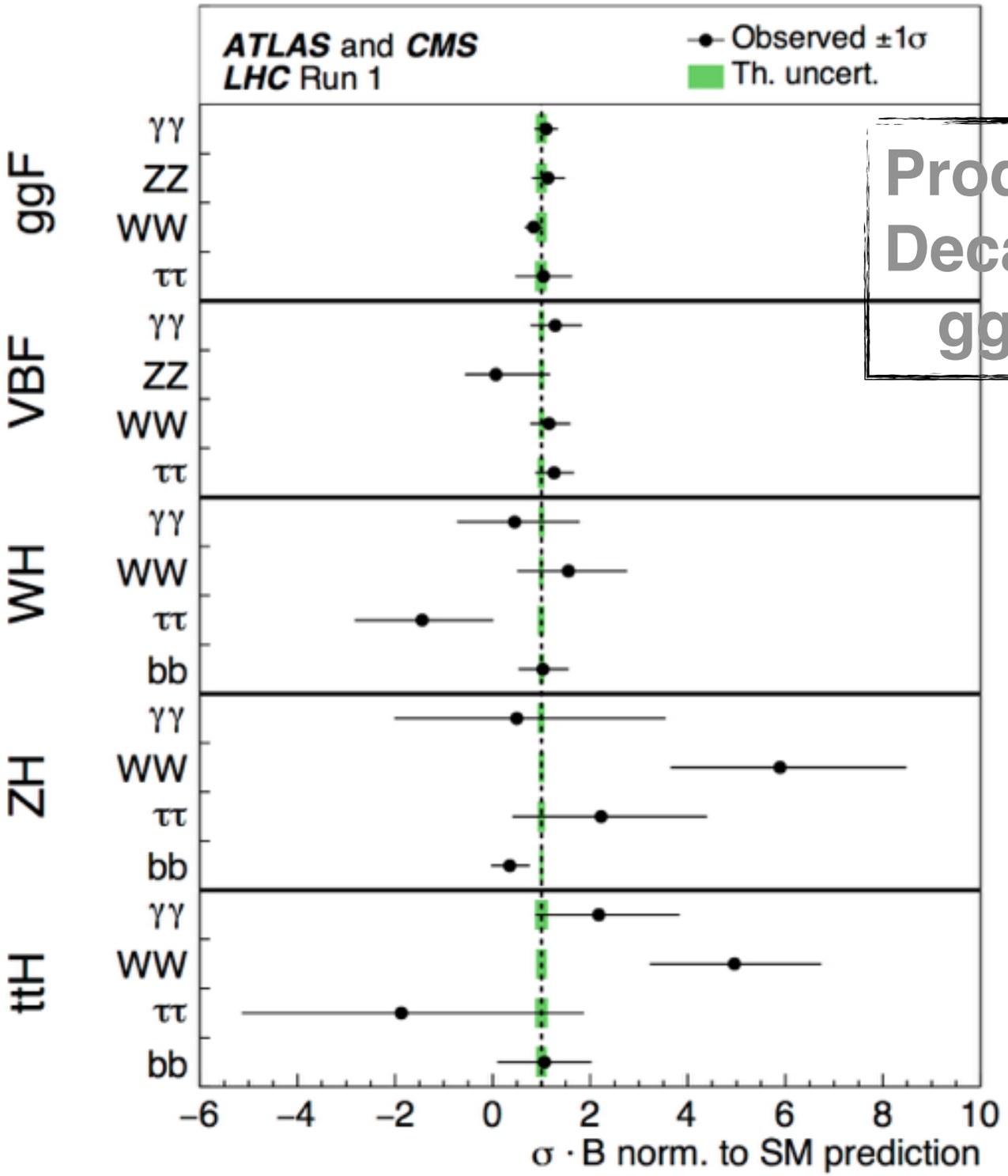


ggF VBF V(W,Z)H ttH



Current Status

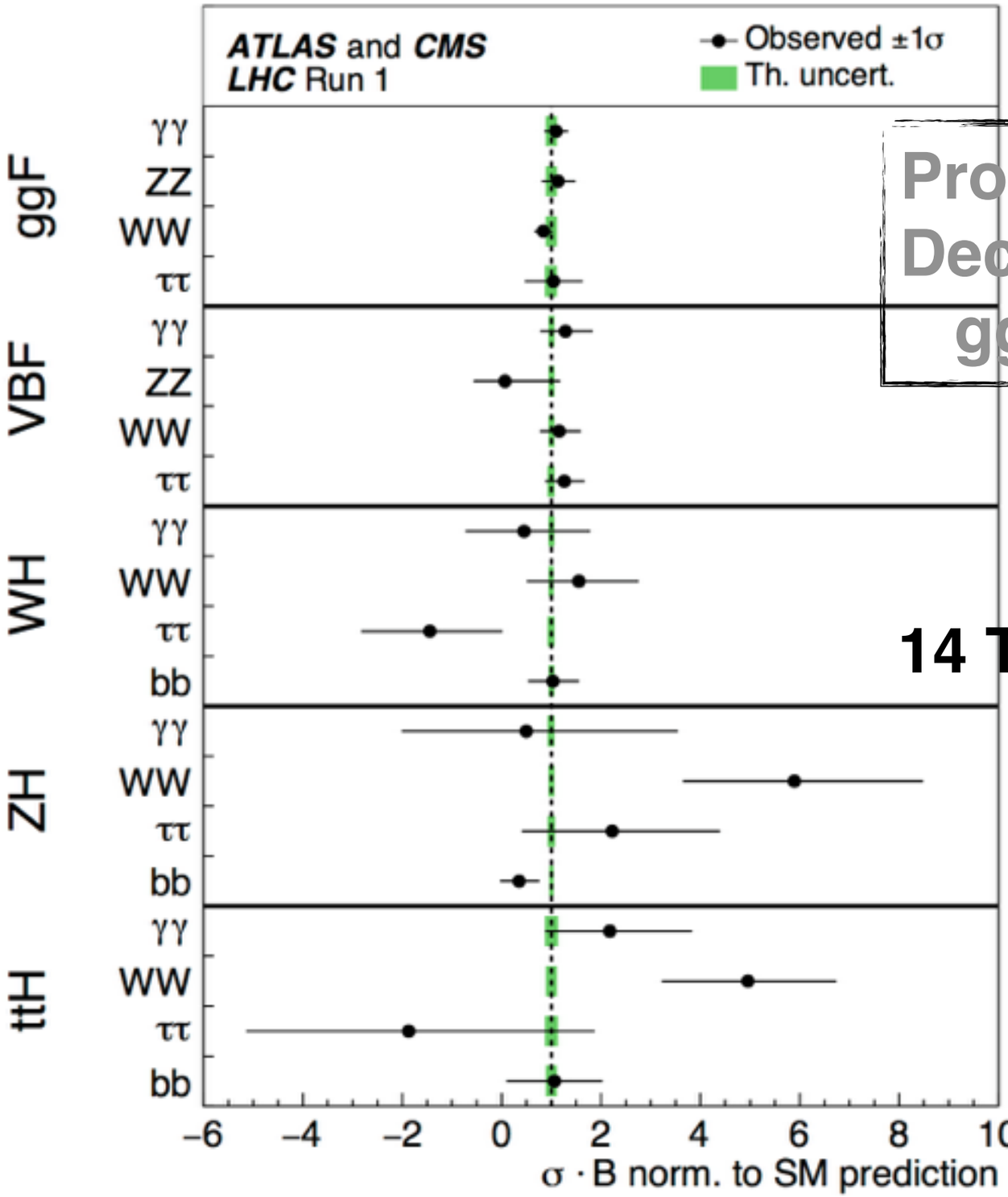
ATLAS+CMS combined analysis 7&8 TeV (2015):



Production: **ggF, VBF,** WH, ZH, ttH
Decay: **ZZ, γγ, WW, ττ,** μμ, Zγ, bb, gg, cc, ss, uu, dd, ee

Current Status

ATLAS+CMS combined analysis 7&8 TeV (2015):

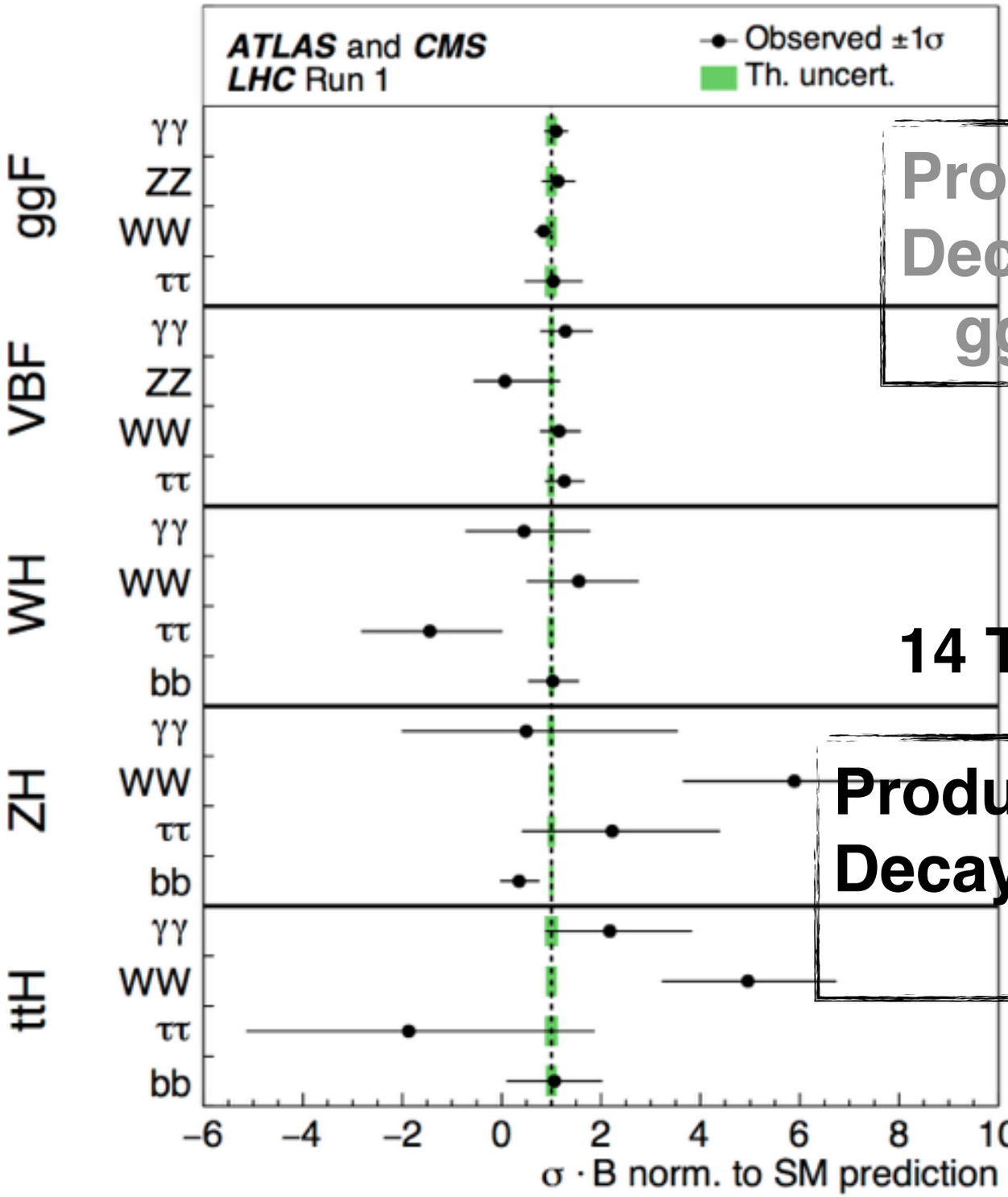


Production: ggF, VBF, WH, ZH, ttH
Decay: ZZ, γγ, WW, ττ, μμ, Zγ, bb, gg, cc, ss, uu, dd, ee

14 TeV LHC, HL-LHC(300, 3000 fb^{-1}):

Current Status

ATLAS+CMS combined analysis 7&8 TeV (2015):



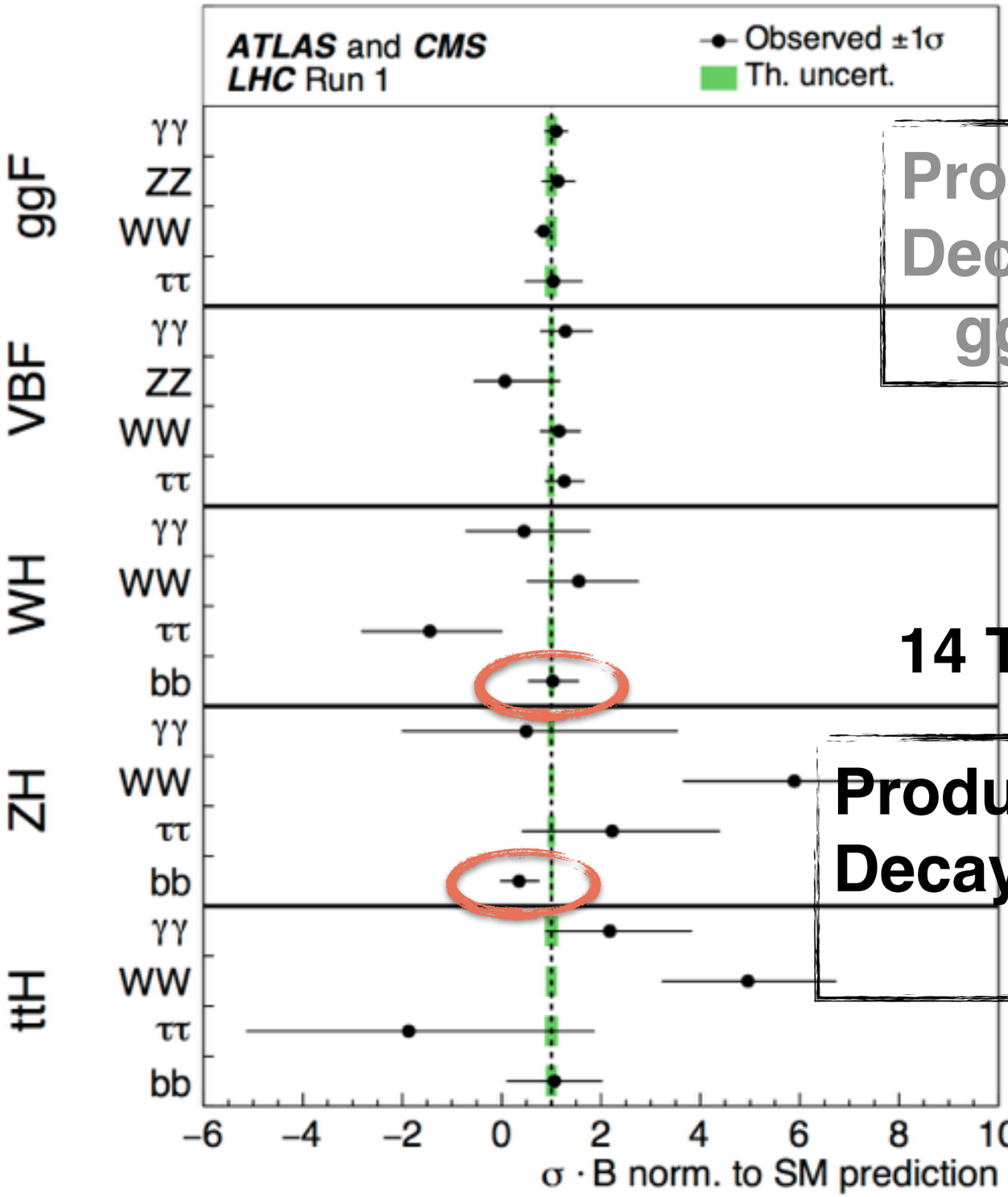
Production: ggF, VBF, WH, ZH, ttH
Decay: ZZ, γγ, WW, ττ, μμ, Zγ, bb, gg, cc, ss, uu, dd, ee

14 TeV LHC, HL-LHC(300, 3000 fb^{-1}):

Production: ggF, VBF, WH, ZH, ttH
Decay: ZZ, γγ, WW, ττ, bb, μμ, Zγ (4), gg, cc, ss, uu, dd, ee

Current Status

ATLAS+CMS combined analysis 7&8 TeV (2015):



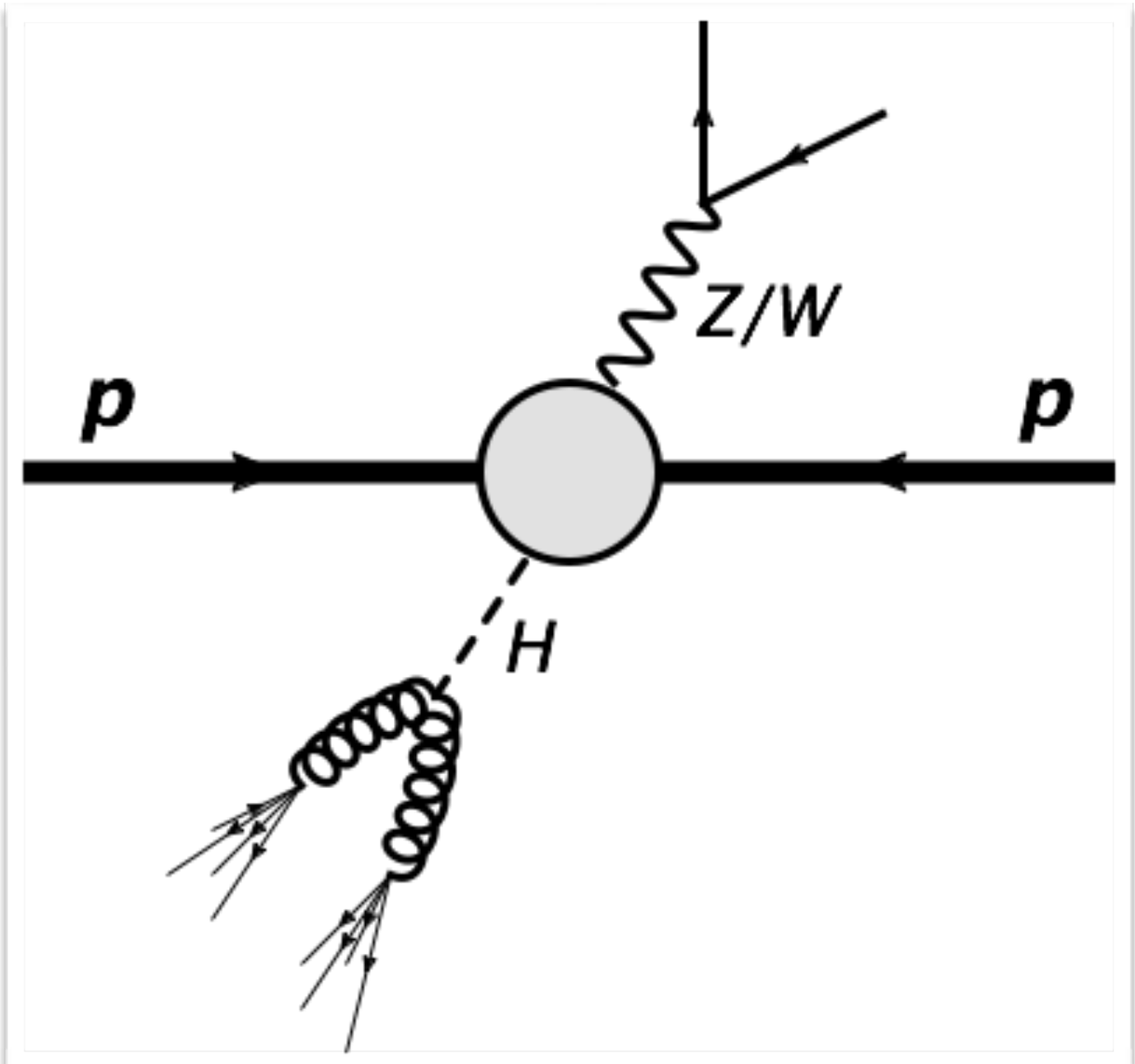
Production: ggF, VBF, WH, ZH, ttH
Decay: ZZ, γγ, WW, ττ, μμ, Zγ, bb, gg, cc, ss, uu, dd, ee

14 TeV LHC, HL-LHC(300, 3000 fb^{-1}):

Production: ggF, VBF, WH, ZH, ttH
Decay: ZZ, γγ, WW, ττ, bb, μμ, Zγ (4), gg, cc, ss, uu, dd, ee

Higgs Decay to Light Jets

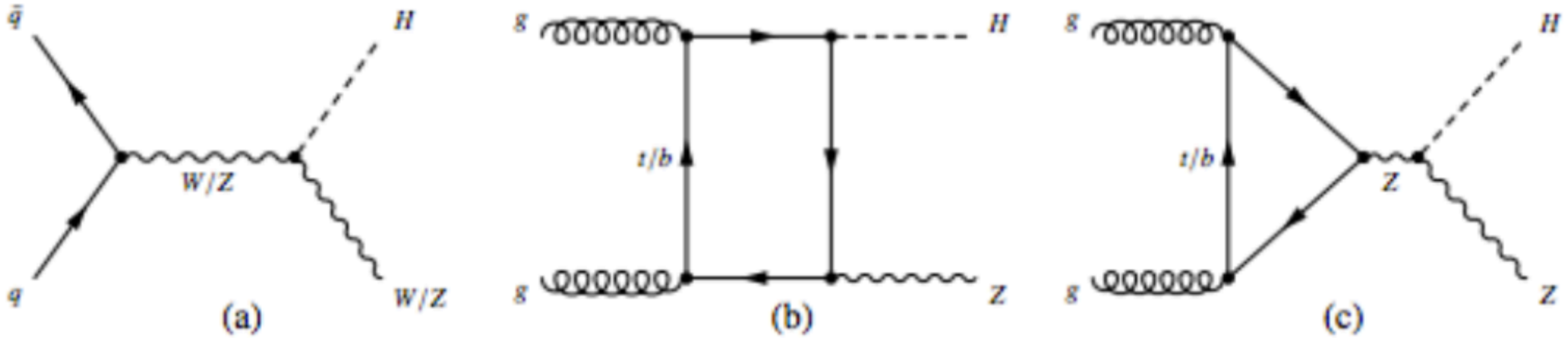
Signal Process



Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

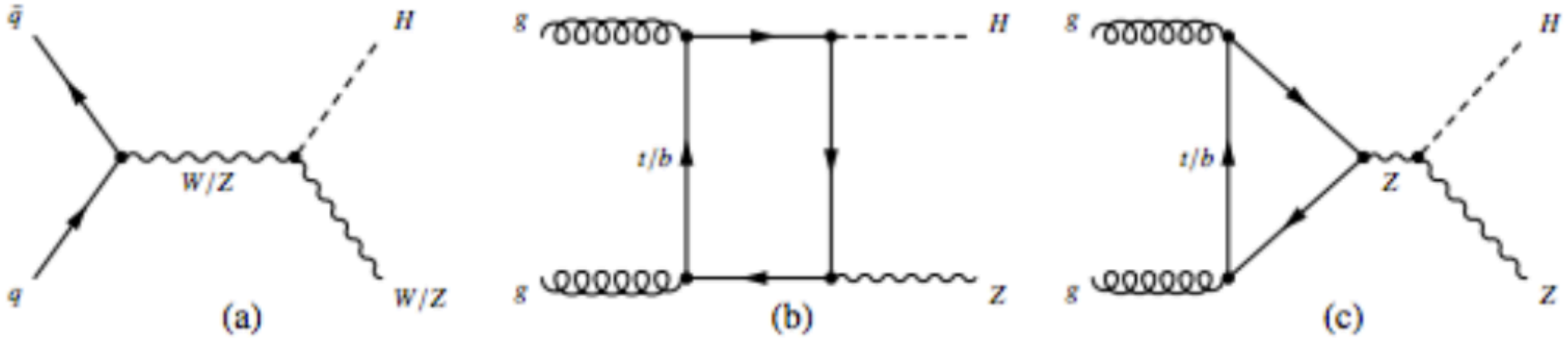
Signal Process

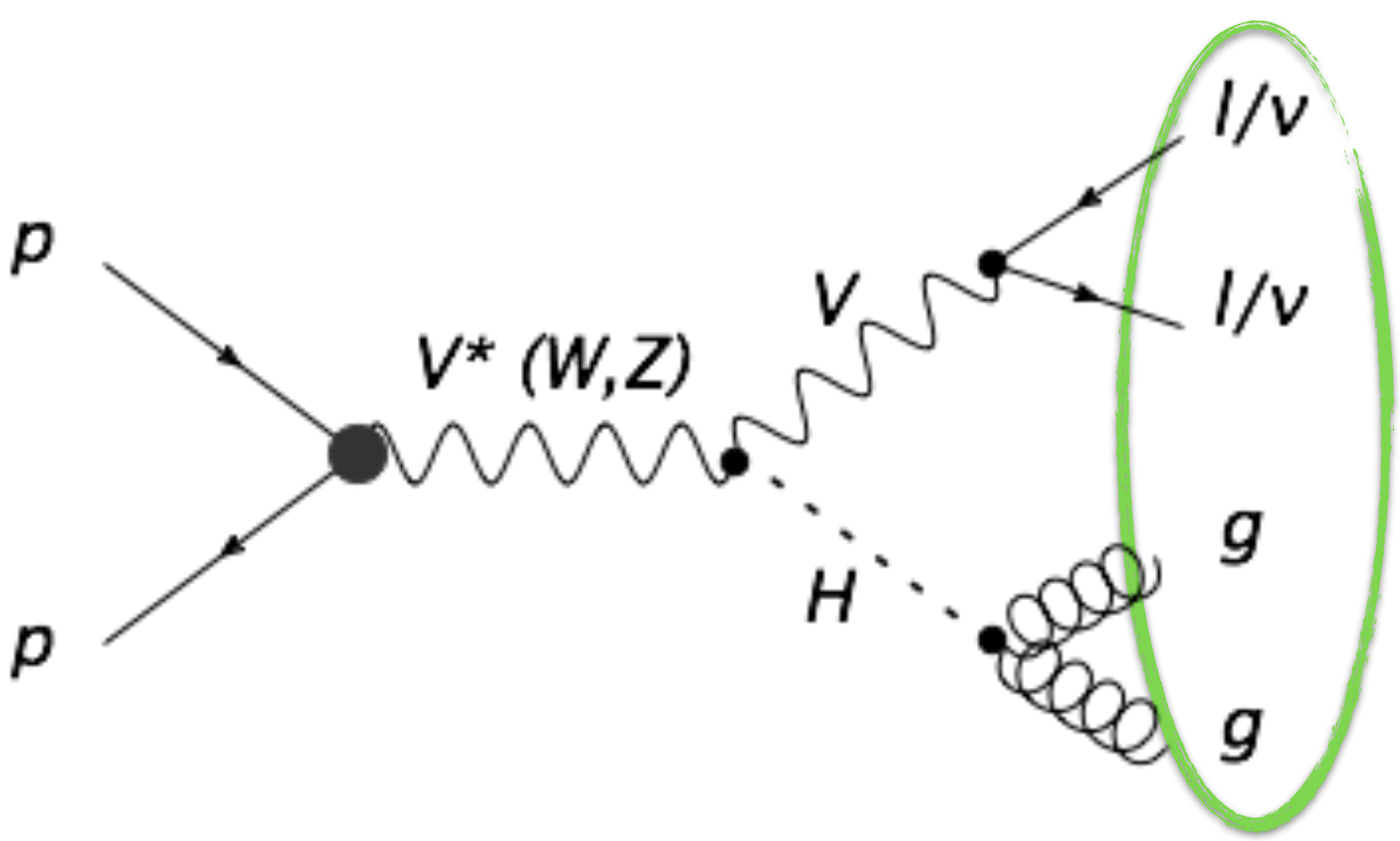


Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Signal Process

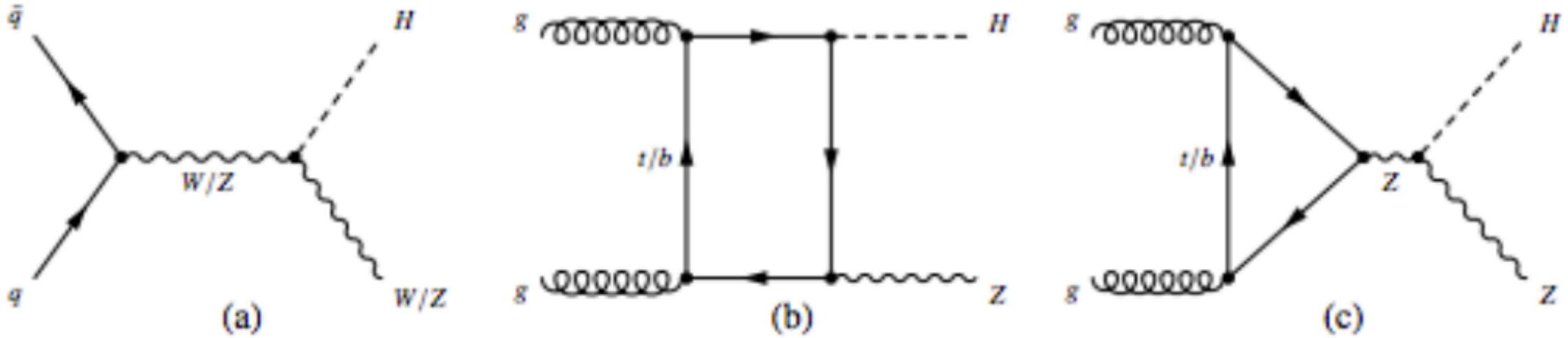


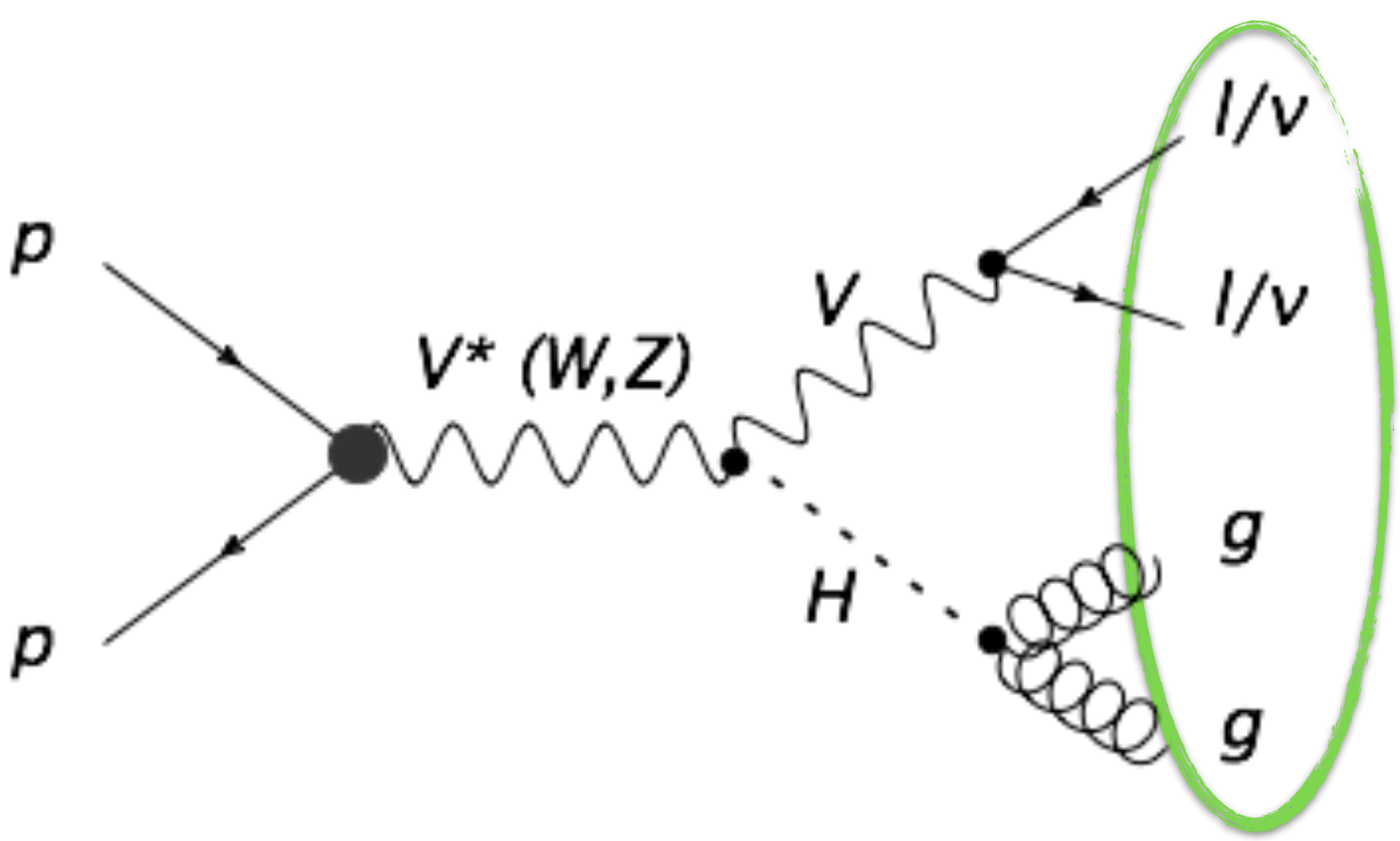


Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Signal Process





<u>3 Channels:</u>

2 leptons, 2 jets

1 lepton + MET, 2 jets

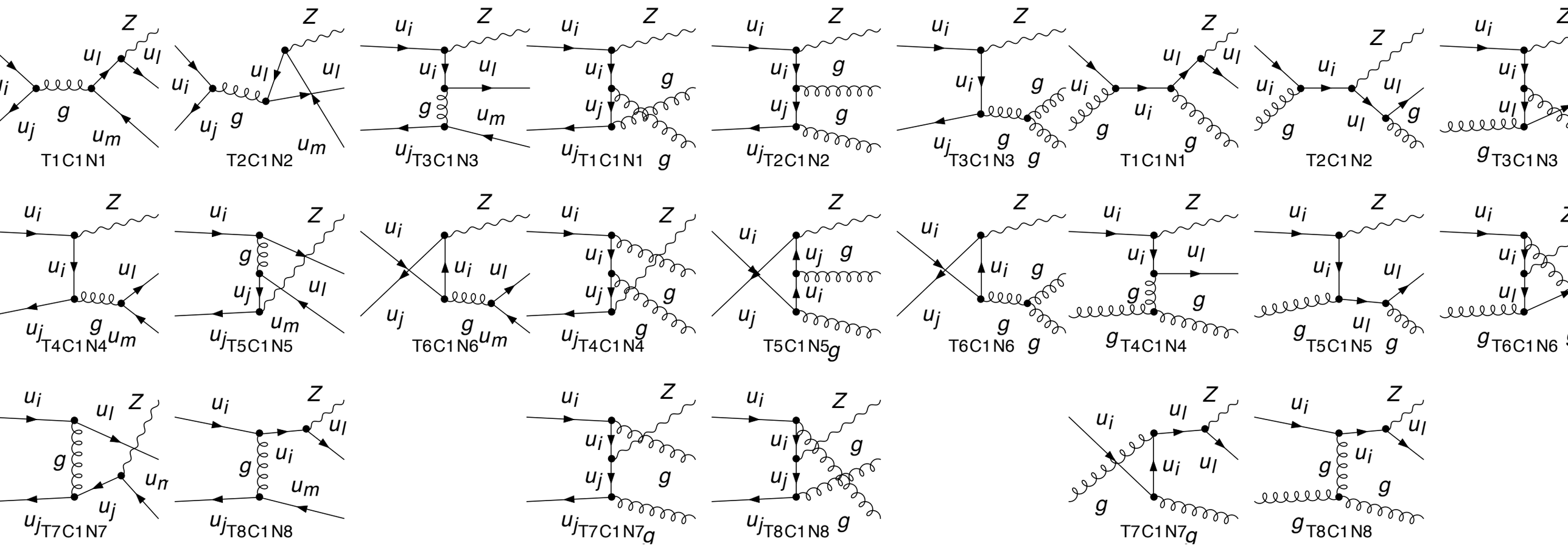
MET, 2 jets

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Background Process

$u_i \; u_j \to Z \; u_l \; u_m$ $u_i \; u_j \to Z \; g \; g$ $u_i \; g \to Z \; u_l \; g$



Irreducible QCD Background: $Z/W + jj, \quad j = q, g$

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Background Process

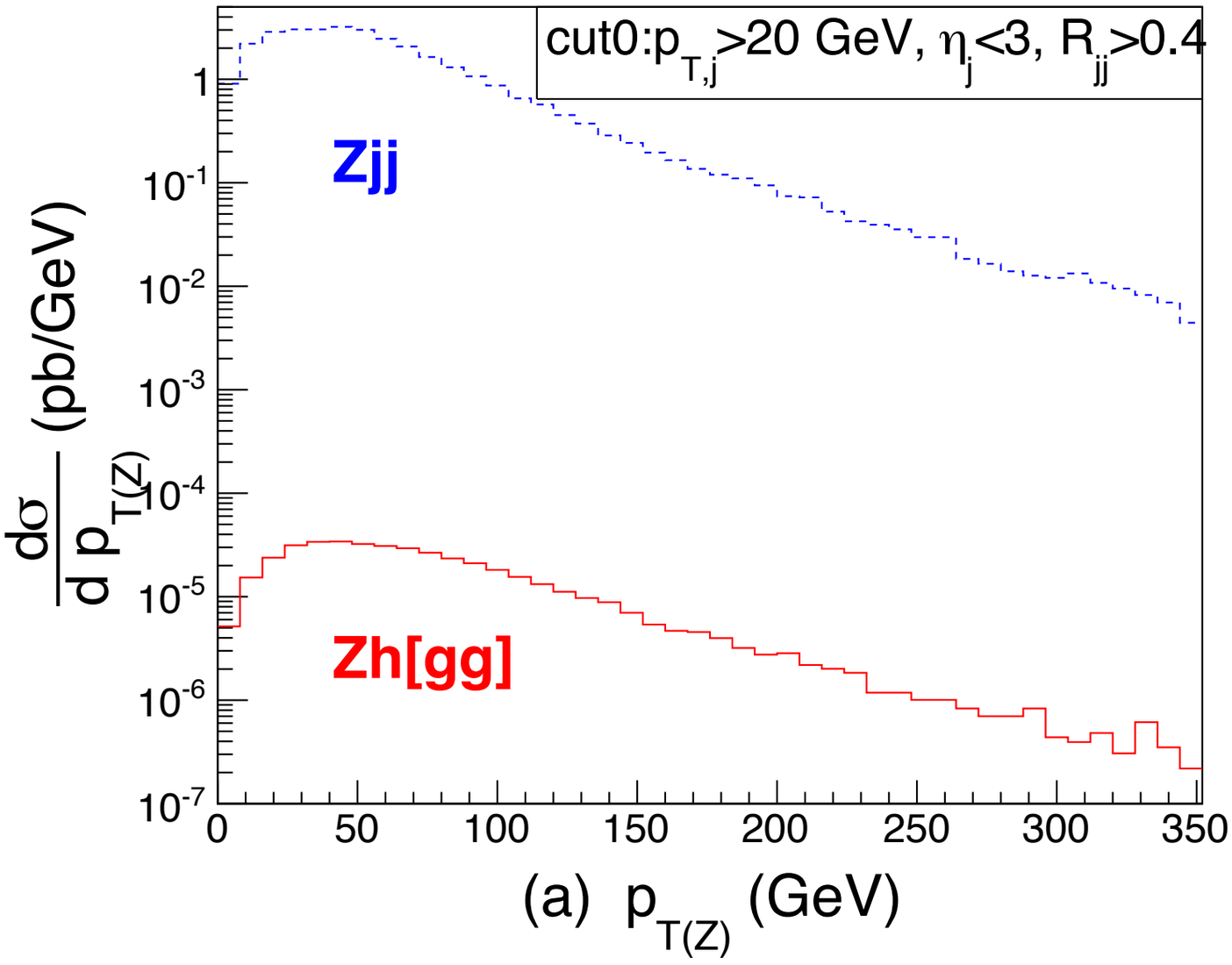
σ (fb)	cuts Eq. (2.3)
$q\bar{q} \to Zh \to \ell^+\ell^-\ gg$	3.5
$gg \to Zh \to \ell^+\ell^-\ gg$	0.71
$q\bar{q} \to Zjj \to \ell^+\ell^-\ jj$	2.5×10^5
$q\bar{q} \to Wh \to \ell\nu\ gg$	20
$q\bar{q} \to Wjj \to \ell\nu\ jj$	2.5×10^6
$pp \to t\bar{t} \to \ell\nu jjb\bar{b}$	1.1×10^5
$q\bar{q} \to Zh \to \nu\nu\ gg$	11
$gg \to Zh \to \nu\nu\ gg$	2.1
$q\bar{q} \to Zjj \to \nu\nu\ jj$	7.4×10^5

$$\textbf{cut0}: \quad \mathbf{p_{T(j)} > 20\mathrm{GeV}}, \quad \mathbf{|\eta_j| < 3}, \quad \mathbf{R_{jj} > 0.4} \qquad \textbf{(2.3)}$$

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

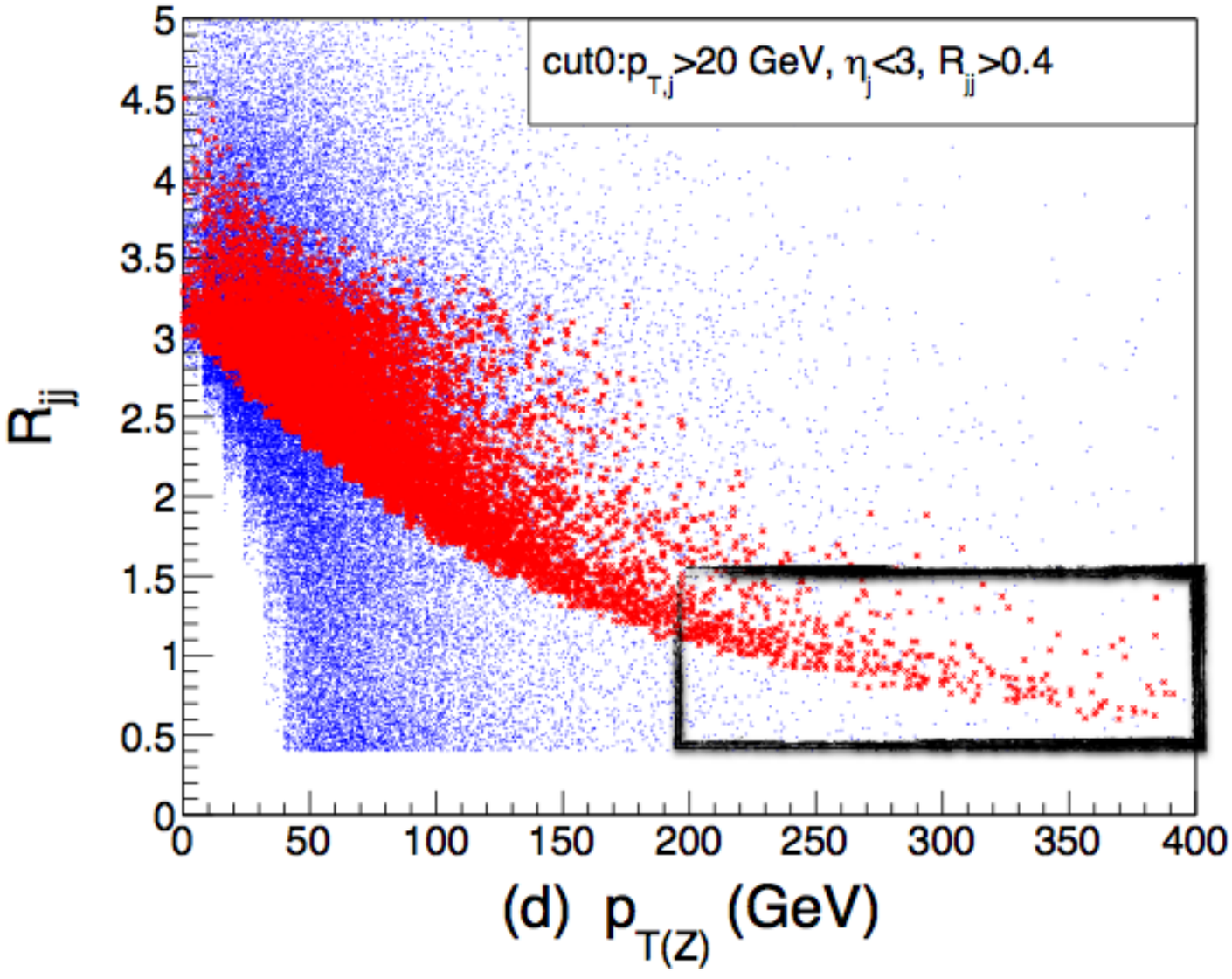
Kinematics



Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Kinematics



$$R_{jj} \approx \frac{1}{\sqrt{z(1-z)}} \frac{m_h}{p_{T(h)}},$$

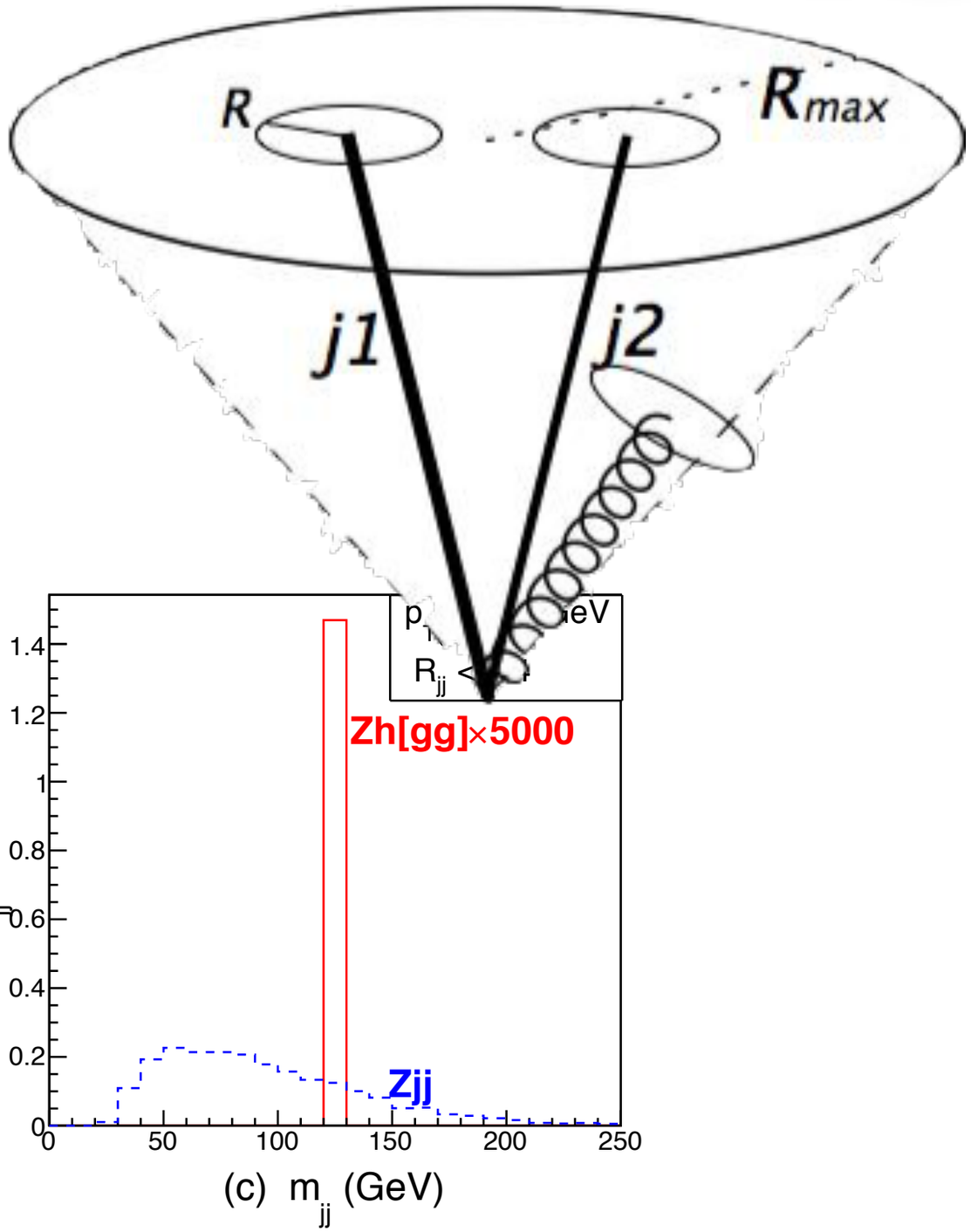
$$p_{T(j,\ell)} > 30\text{GeV}, \quad |\eta_{j,\ell}| < 2.5$$

$$p_{T(\ell\ell,\ell\nu,\nu\nu)} > 200\text{GeV}, \quad R_{jj} < 1.4$$

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Kinematics

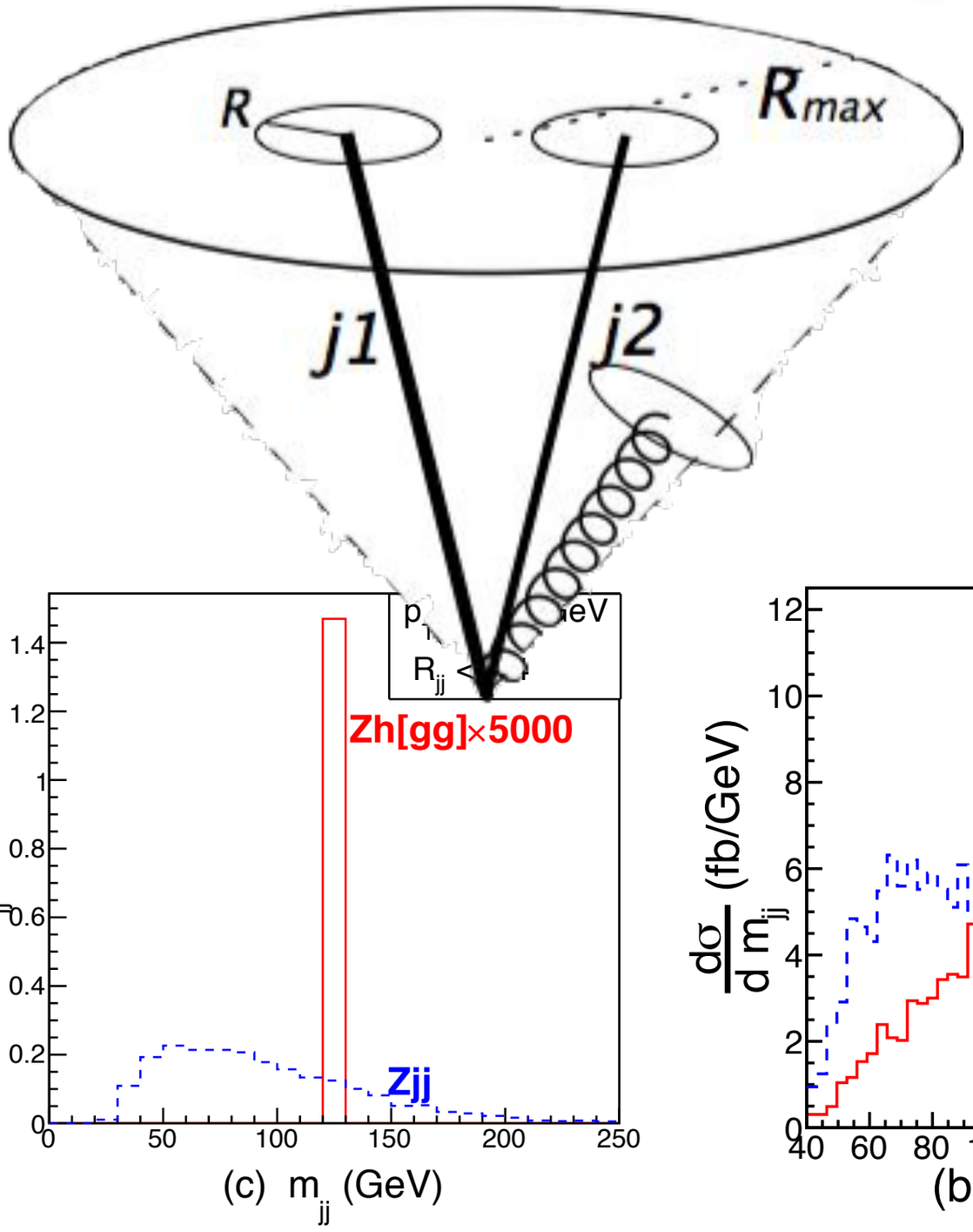


Two Leading jets
& additional jets within R<1.4

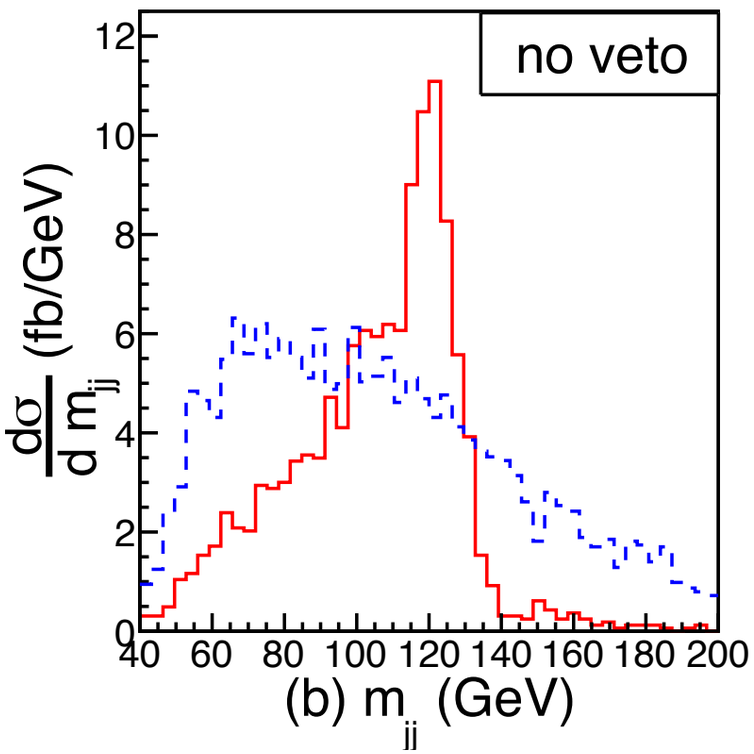
Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

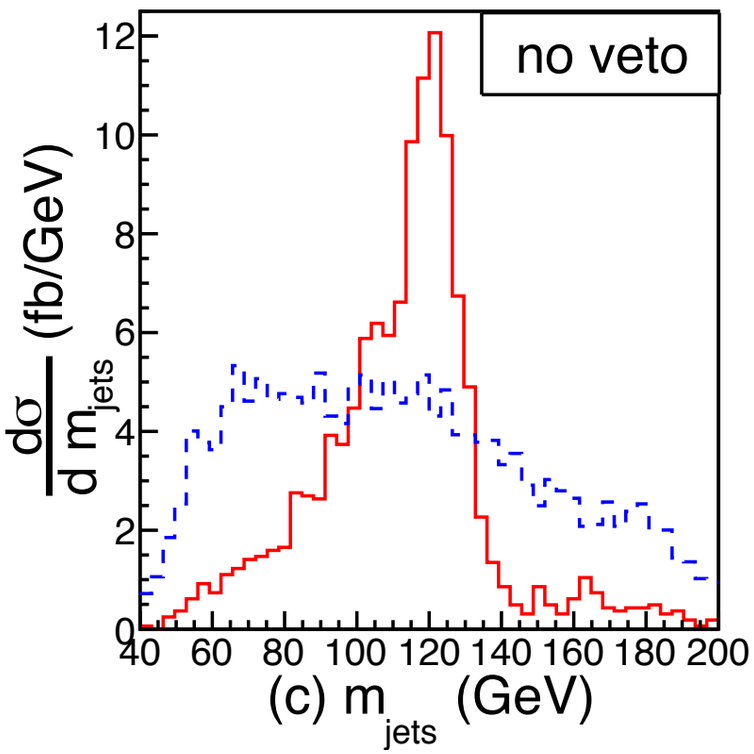
Higgs Decay to Light Jets

Kinematics



Two Leading jets
& additional jets within R<1.4

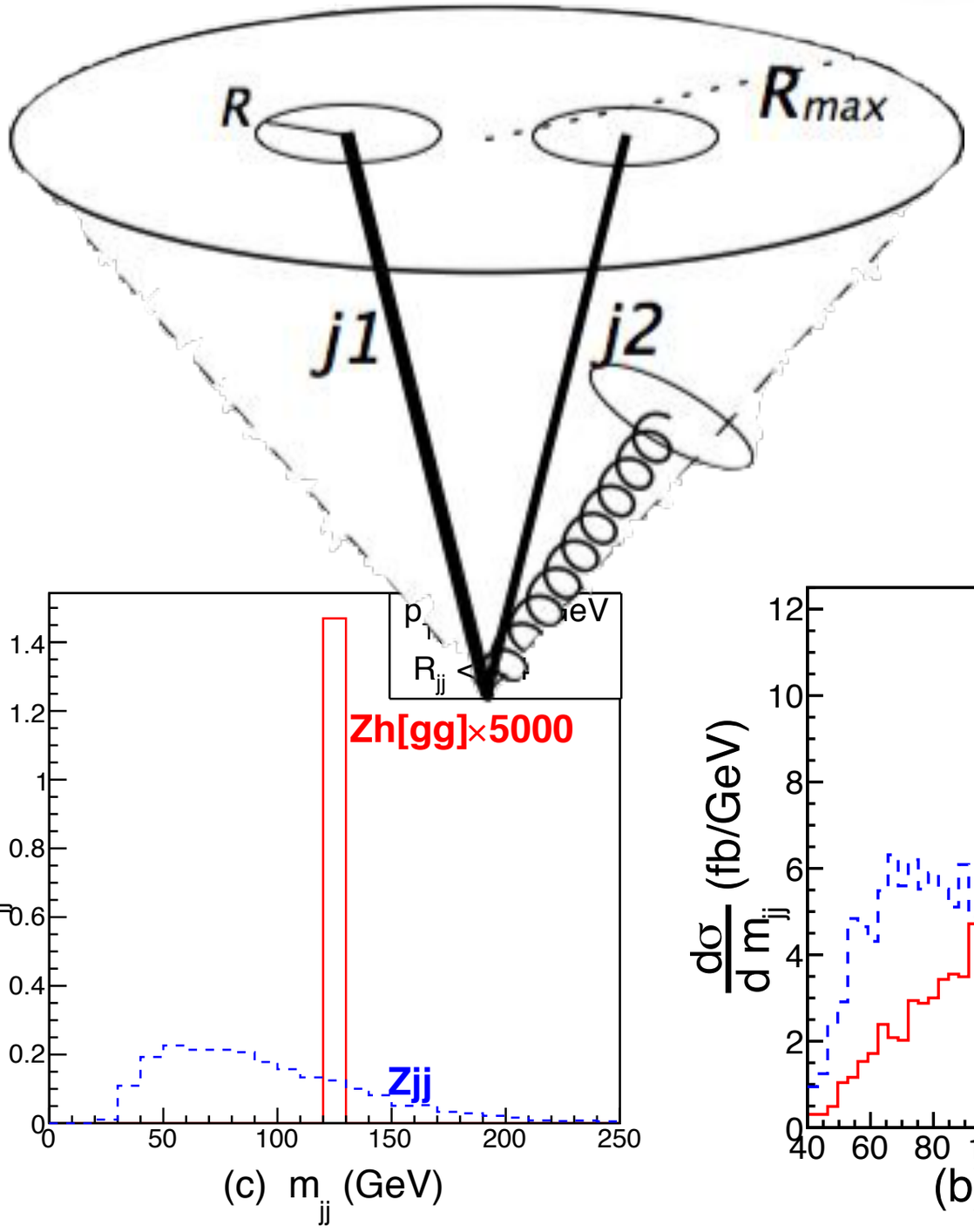




Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

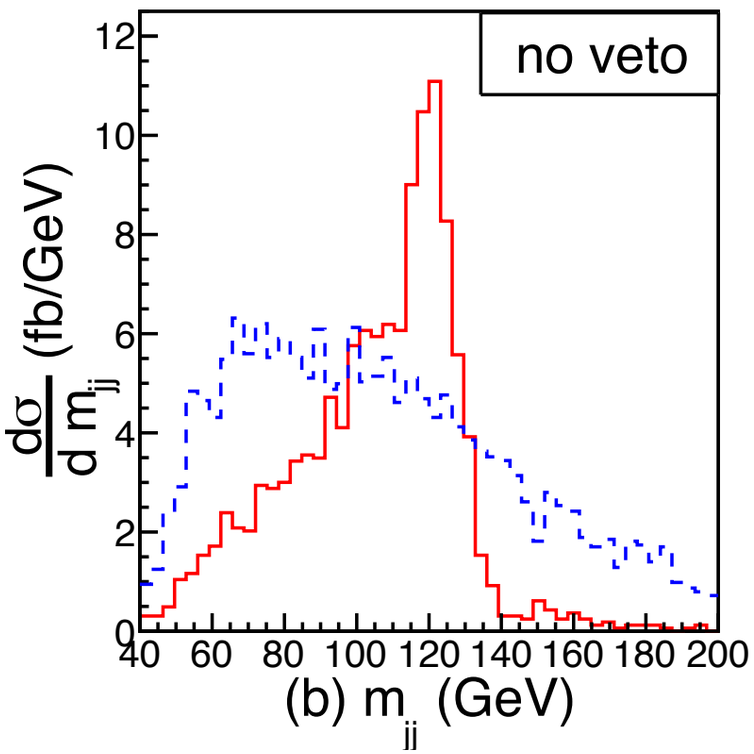
Higgs Decay to Light Jets

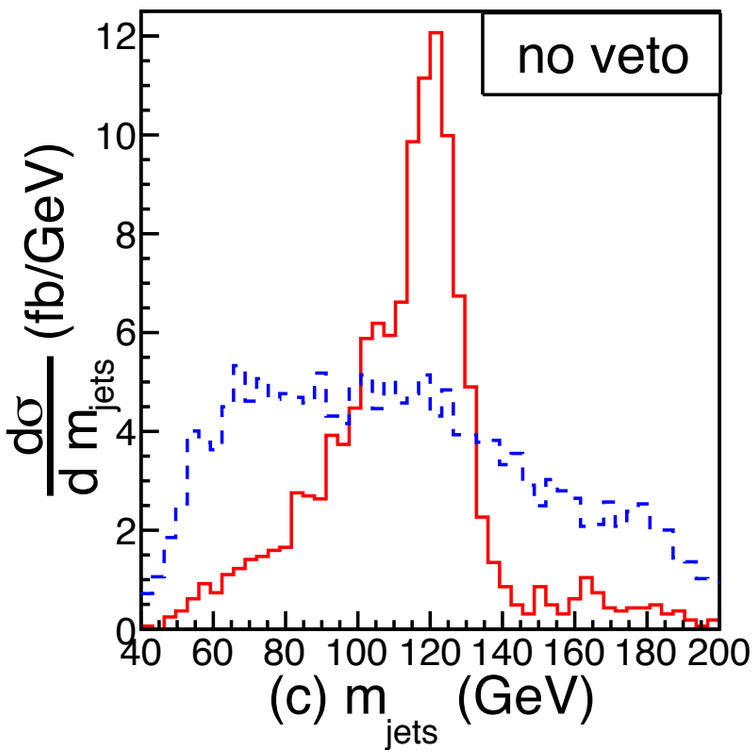
Kinematics



Two Leading jets
& additional jets within R<1.4

$95 < m_H < 145$ (GeV)





Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Results

σ (fb)	$\ell^+\ell^- + jj$	$\ell^\pm + \not{E}_T + jj$	$\not{E}_T + jj$	combined
Vh signal	7.0×10^{-2}	4.1×10^{-1}	3.6×10^{-1}	
Vjj background	2.4×10^{2}	2.5×10^{3}	1.6×10^{3}	

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Results

σ (fb)	$\ell^+\ell^- + jj$	$\ell^\pm + \not{E}_T + jj$	$\not{E}_T + jj$	combined
Vh signal	7.0×10^{-2}	4.1×10^{-1}	3.6×10^{-1}	
Vjj background	2.4×10^{2}	2.5×10^{3}	1.6×10^{3}	

B/S ~ 10^3-10^4

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Results

σ (fb)	$\ell^+\ell^- + jj$	$\ell^\pm + \not{E}_T + jj$	$\not{E}_T + jj$	combined
Vh signal	7.0×10^{-2}	4.1×10^{-1}	3.6×10^{-1}	
Vjj background	2.4×10^{2}	2.5×10^{3}	1.6×10^{3}	

B/S ~ 10^3-10^4

Sideband Fitting:

{ Fitting Functions
Fitting Ranges

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

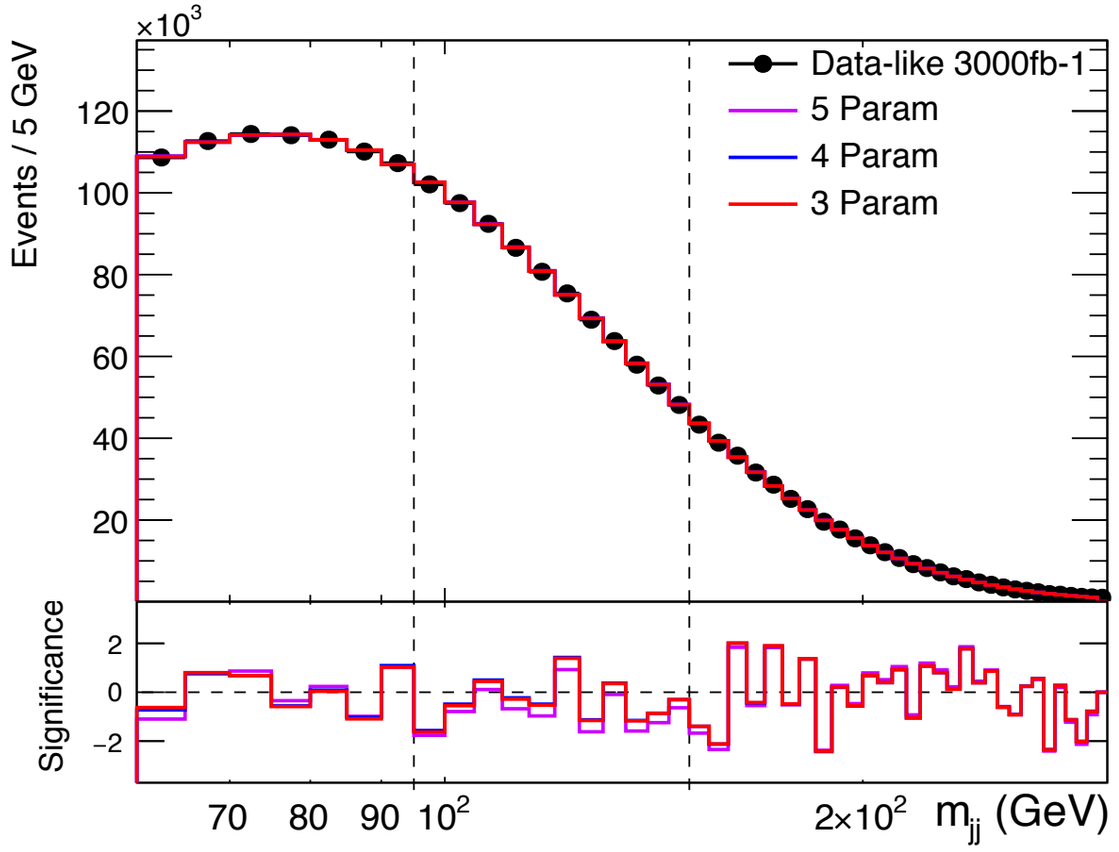
Results

σ (fb)	$\ell^+\ell^- + jj$	$\ell^\pm + \not{E}_T + jj$	$\not{E}_T + jj$	combined
Vh signal	7.0×10^{-2}	4.1×10^{-1}	3.6×10^{-1}	
Vjj background	2.4×10^{2}	2.5×10^{3}	1.6×10^{3}	

B/S ~ 10^3-10^4

Sideband Fitting:

{ Fitting Functions
{ Fitting Ranges



Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Results

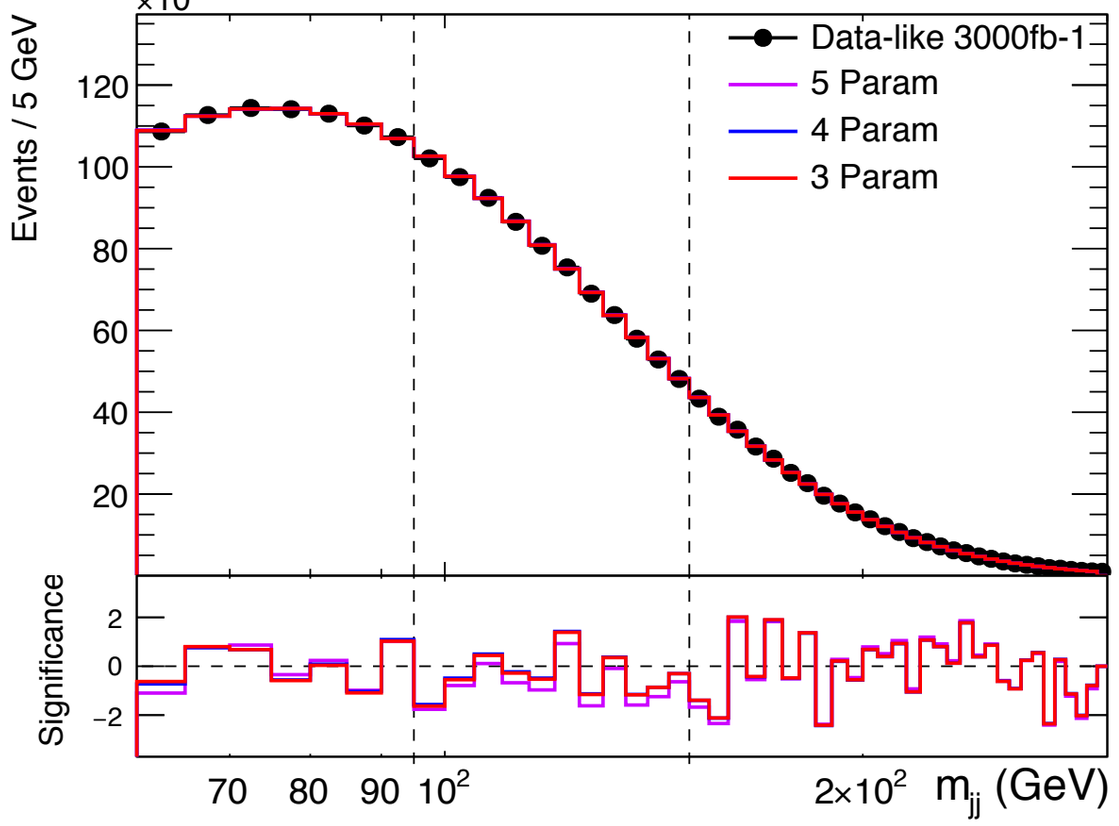
σ (fb)	$\ell^+\ell^- + jj$	$\ell^\pm + \not{E}_T + jj$	$\not{E}_T + jj$	combined
Vh signal	7.0×10^{-2}	4.1×10^{-1}	3.6×10^{-1}	
Vjj background	2.4×10^{2}	2.5×10^{3}	1.6×10^{3}	

B/S ~ 10^3-10^4

Sideband Fitting:

{ Fitting Functions
Fitting Ranges

$$\epsilon_B \sim 10^{-3}$$



Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Results

$$N = \sigma \times 3000\text{fb}^{-1}$$

σ (fb)	$\ell^+\ell^- + jj$	$\ell^\pm + \not{E}_T + jj$	$\not{E}_T + jj$	combined
Vh signal	7.0×10^{-2}	4.1×10^{-1}	3.6×10^{-1}	
Vjj background	2.4×10^{2}	2.5×10^{3}	1.6×10^{3}	
$\mathcal{S}$	0.25	0.61	0.49	0.82
$\mathcal{S}_{\text{sys}}$	0.09	0.17	0.17	0.26

$$\mathcal{S} = \frac{N_{\text{sig}}}{\sqrt{N_{\text{bkg}}}} \qquad \mathcal{S}_{\text{sys}} = \frac{N_{\text{sig}}}{\epsilon_B \times N_{\text{bkg}}}$$

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Results

$$N = \sigma \times 3000\text{fb}^{-1}$$

σ (fb)	$\ell^+\ell^- + jj$	$\ell^\pm + \not{E}_T + jj$	$\not{E}_T + jj$	combined
Vh signal	7.0×10^{-2}	4.1×10^{-1}	3.6×10^{-1}	
Vjj background	2.4×10^{2}	2.5×10^{3}	1.6×10^{3}	
$\mathcal{S}$	0.25	0.61	0.49	0.82
$\mathcal{S}_{\text{sys}}$	0.09	0.17	0.17	0.26

$$\mathcal{S} = \frac{N_{\text{sig}}}{\sqrt{N_{\text{bkg}}}} \qquad \mathcal{S}_{\text{sys}} = \frac{N_{\text{sig}}}{\epsilon_B \times N_{\text{bkg}}}$$

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

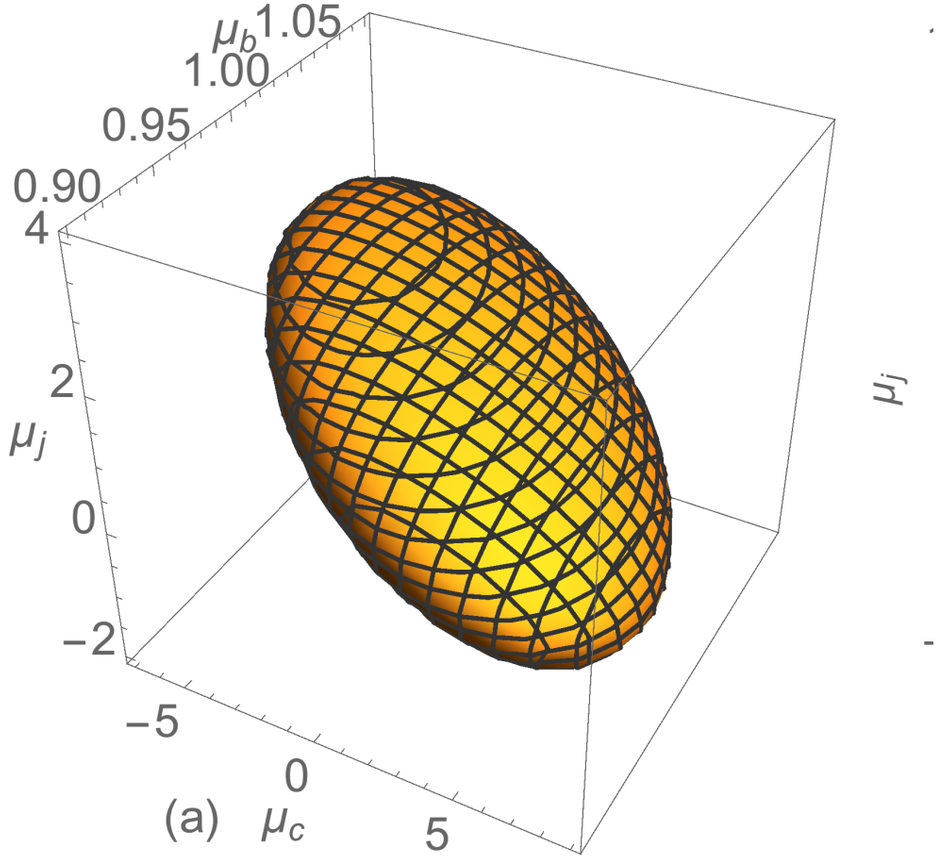
Higgs Decay to Light Jets

Results

$$\mathcal{S}^2 > \sum_a \chi_a^2 = \sum \frac{(x_a - \overline{x}_a)^2}{\sigma_a^2}$$

$$= \sum_a \frac{(\sum_i \epsilon_{ai}^2 \mathrm{BR}_i N_{\mathrm{sig}}^{prod} - \sum_i \epsilon_{ai}^2 \mathrm{BR}_i^{\mathrm{SM}} N_{\mathrm{sig}}^{prod})^2}{(\sqrt{N_{\mathrm{bkg}}})^2}$$

$$= \sum_a \frac{(\sum_i e_{ai}\ \mu_i - 1)^2}{(1/\mathcal{S}_a)^2}$$



Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

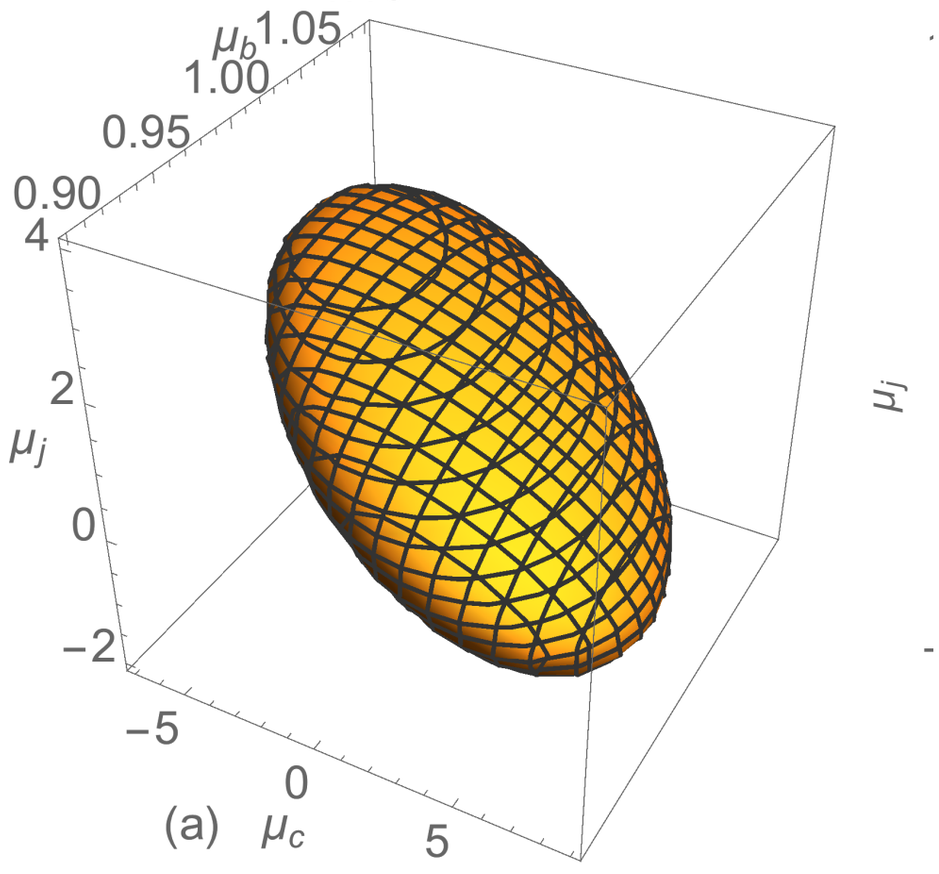
Higgs Decay to Light Jets

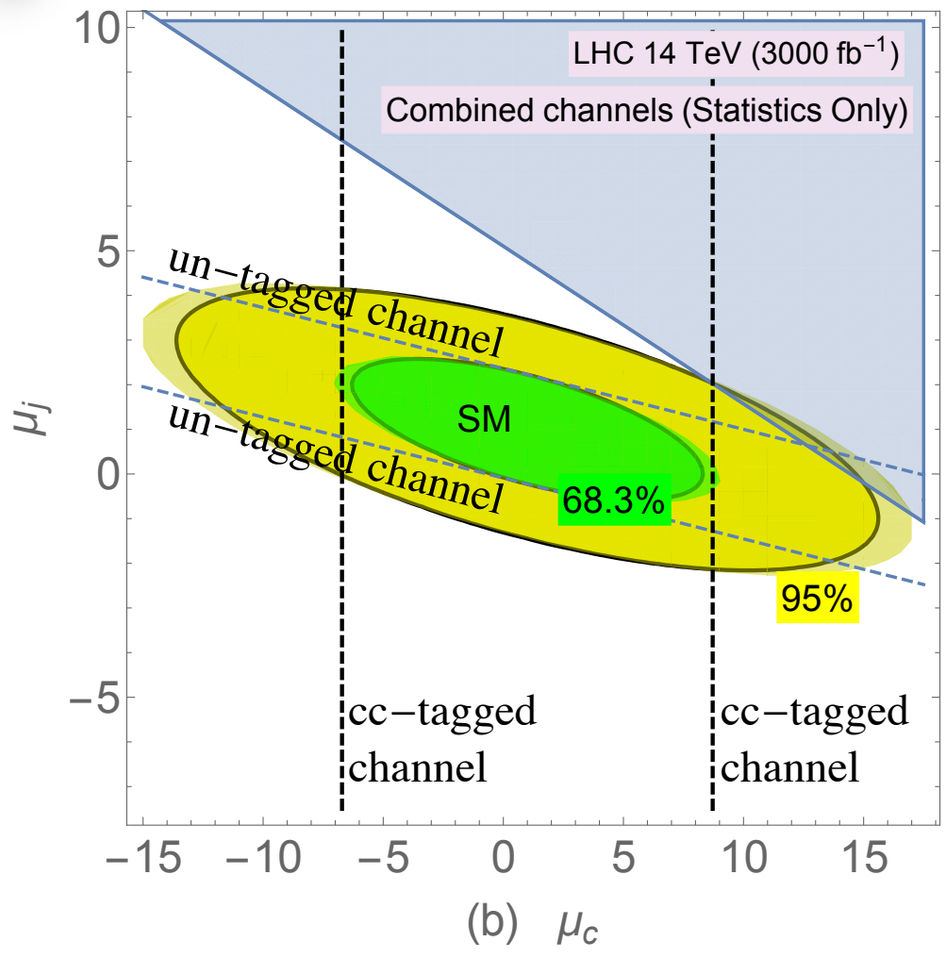
Results

$$\mathcal{S}^2 > \sum_a \chi_a^2 = \sum \frac{(x_a - \overline{x}_a)^2}{\sigma_a^2}$$

$$= \sum_a \frac{(\sum_i \epsilon_{ai}^2 \mathrm{BR}_i N_{\mathrm{sig}}^{prod} - \sum_i \epsilon_{ai}^2 \mathrm{BR}_i^{\mathrm{SM}} N_{\mathrm{sig}}^{prod})^2}{(\sqrt{N_{\mathrm{bkg}}})^2}$$

$$= \sum_a \frac{(\sum_i e_{ai}\ \mu_i - 1)^2}{(1/\mathcal{S}_a)^2}$$





Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

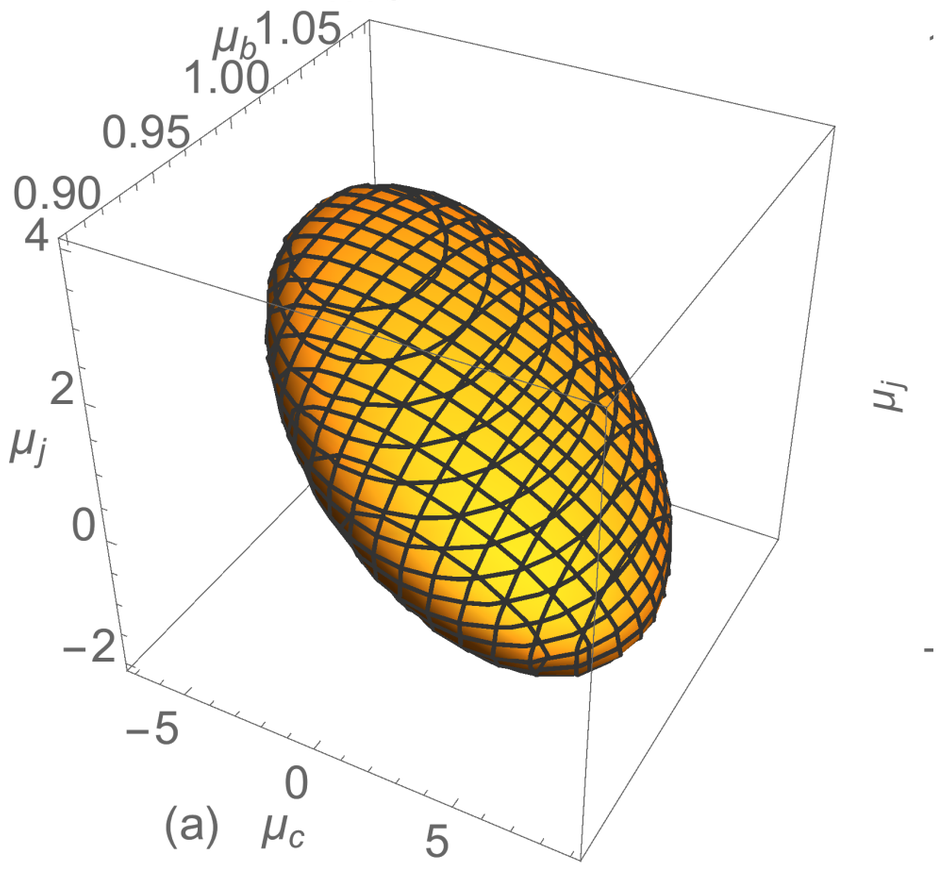
Higgs Decay to Light Jets

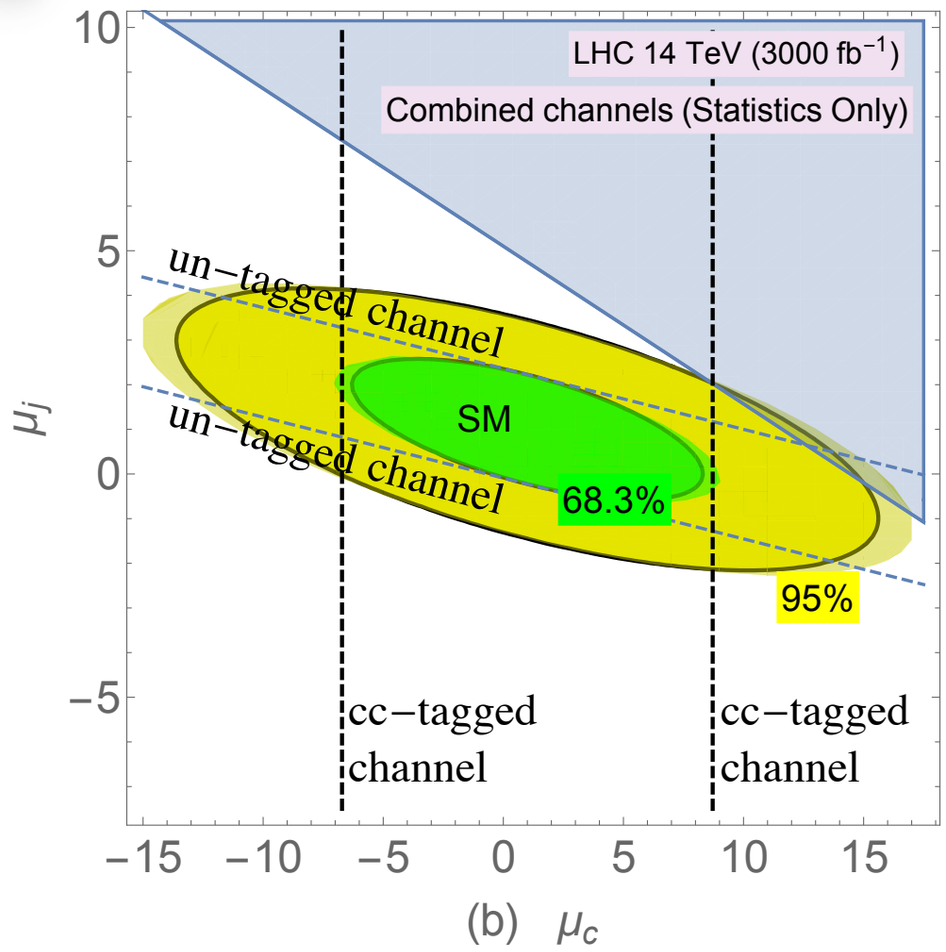
Results

$$\mathcal{S}^2 > \sum_a \chi_a^2 = \sum \frac{(x_a - \overline{x}_a)^2}{\sigma_a^2}$$

$$= \sum_a \frac{(\sum_i \epsilon_{ai}^2 \mathrm{BR}_i N_{\mathrm{sig}}^{prod} - \sum_i \epsilon_{ai}^2 \mathrm{BR}_i^{\mathrm{SM}} N_{\mathrm{sig}}^{prod})^2}{(\sqrt{N_{\mathrm{bkg}}})^2}$$

$$= \sum_a \frac{(\sum_i e_{ai}\ \mu_i - 1)^2}{(1/\mathcal{S}_a)^2}$$





$$\mu(h \to jj) \leq 4(9)$$

$$\mu(h \to c\bar{c}) \leq 15$$

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

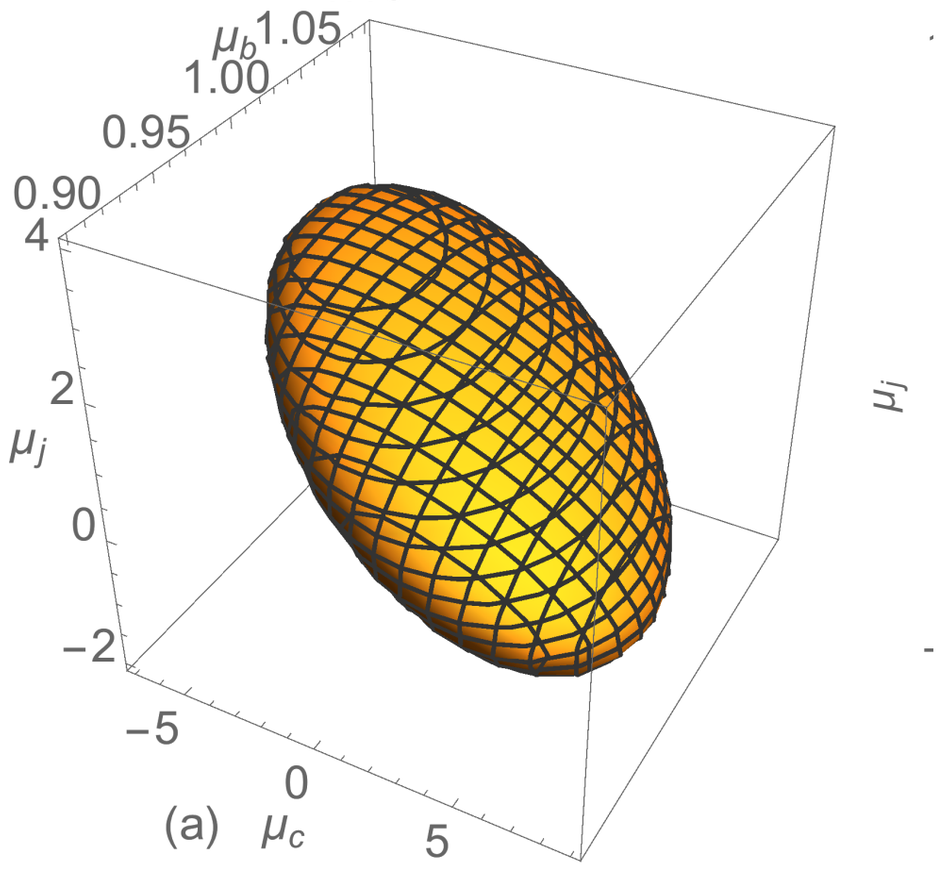
Higgs Decay to Light Jets

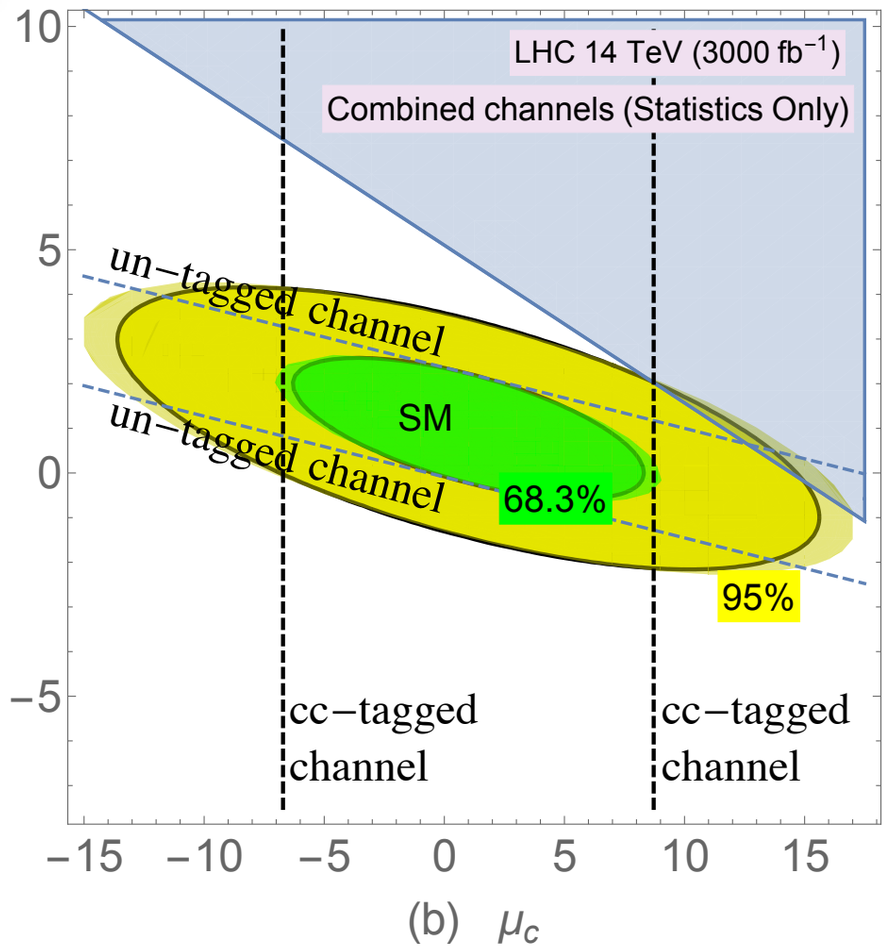
Results

$$\mathcal{S}^2 > \sum_a \chi_a^2 = \sum \frac{(x_a - \overline{x}_a)^2}{\sigma_a^2}$$

$$= \sum_a \frac{(\sum_i \epsilon_{ai}^2 \mathrm{BR}_i N_{\mathrm{sig}}^{prod} - \sum_i \epsilon_{ai}^2 \mathrm{BR}_i^{\mathrm{SM}} N_{\mathrm{sig}}^{prod})^2}{(\sqrt{N_{\mathrm{bkg}}})^2}$$

$$= \sum_a \frac{(\sum_i e_{ai}\ \mu_i - 1)^2}{(1/\mathcal{S}_a)^2}$$





$$\mu(h \to jj) \leq 4(9)$$

$$\mu(h \to c\bar{c}) \leq 15$$

$$\sigma \propto y_q^2, \quad y_c \lesssim 4 y_c^{SM}$$

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Results

$$\mu(h \to jj) \leq 4$$

$$\sigma(h \to gg) \leq 4\sigma(h \to gg)^{SM} \Rightarrow \sigma(h \to uu, dd, ss) \leq 3\sigma(h \to gg)^{SM}$$

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Light Jets

Results

$$\mu(h \to jj) \leq 4$$

$$\sigma(h \to gg) \leq 4\sigma(h \to gg)^{SM} \Rightarrow \sigma(h \to uu, dd, ss) \leq 3\sigma(h \to gg)^{SM}$$

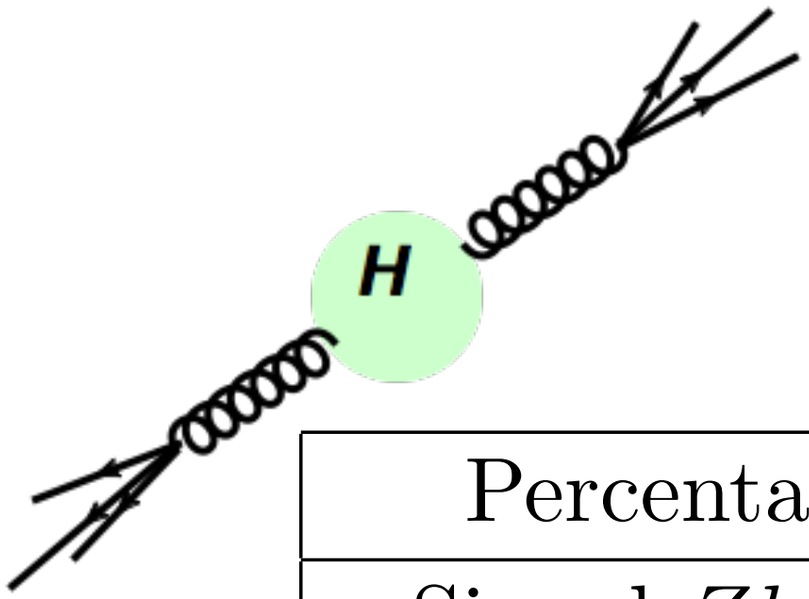
TABLE X. Extrapolated upper bounds at 95% CL on the light-quark Yukawa couplings $\bar{\kappa}_q = y_q/y_b^{\rm SM}(\kappa_q = y_q/y_q^{\rm SM})$ for $q = u,\ d,\ s$.

$\mathcal{L}(\mathrm{fb}^{-1})$	$\bar{\kappa}_u(\kappa_u)$	$\bar{\kappa}_d(\kappa_d)$	$\bar{\kappa}_s(\kappa_s)$
300 (untagged $j'j'$)	1.2 (2600)	1.2 (1200)	1.2 (61)
3000 (untagged $j'j'$)	0.65 (1500)	0.65 (680)	0.65 (34)

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)

Higgs Decay to Gluon Pair

Improvements



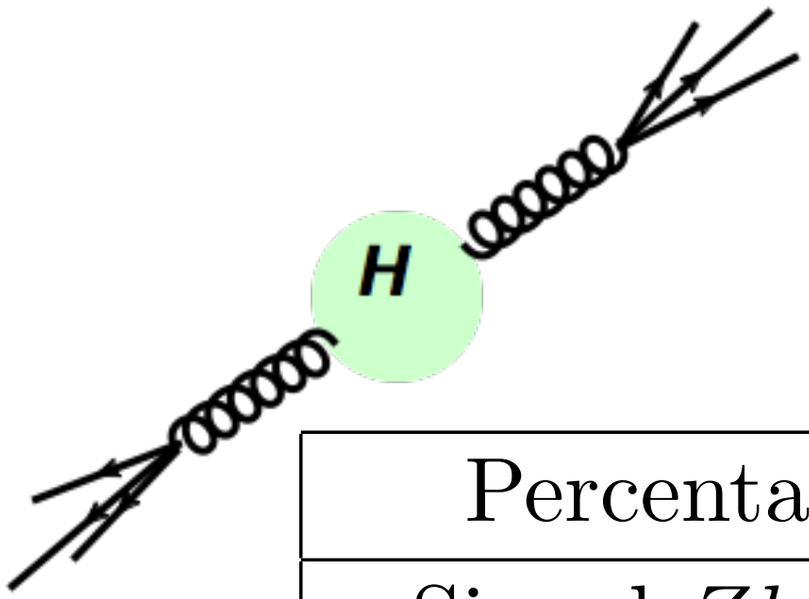
H-> gg Decay

Percentage	qq	qg	gg
Signal $Zh[gg]$	0	0	100%
Background Zjj	9%	77%	14%

(LO QCD)

Higgs Decay to Gluon Pair

Improvements



H-> gg Decay

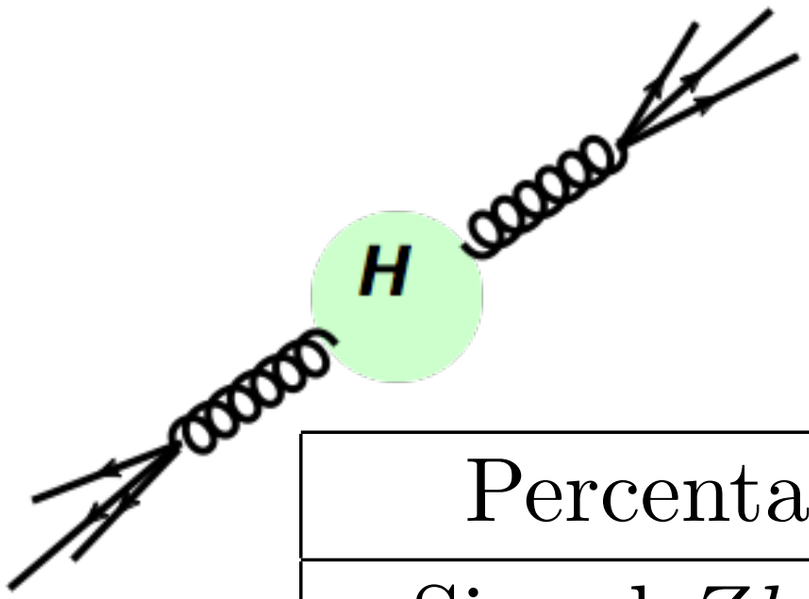
Percentage	qq	qg	gg
Signal $Zh[gg]$	0	0	100%
Background Zjj	9%	77%	14%

(LO QCD)

Quark/Gluon Tagging

Higgs Decay to Gluon Pair

Improvements



H-> gg Decay

Percentage	qq	qg	gg
Signal $Zh[gg]$	0	0	100%
Background Zjj	9%	77%	14%

(LO QCD)

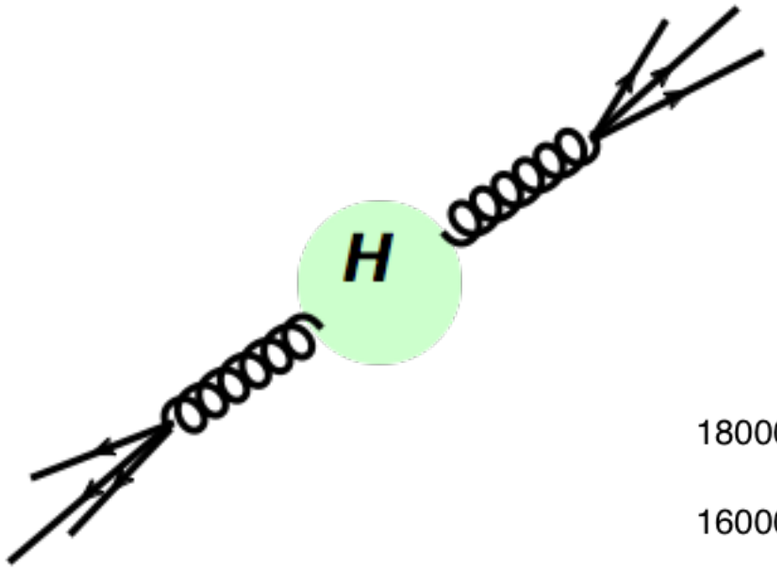
Quark/Gluon Tagging

Additional Jet Kinematics: $A_{jj} = \frac{|p_T(j_1) - p_T(j_2)|}{p_T(j_1) + p_T(j_2)}$

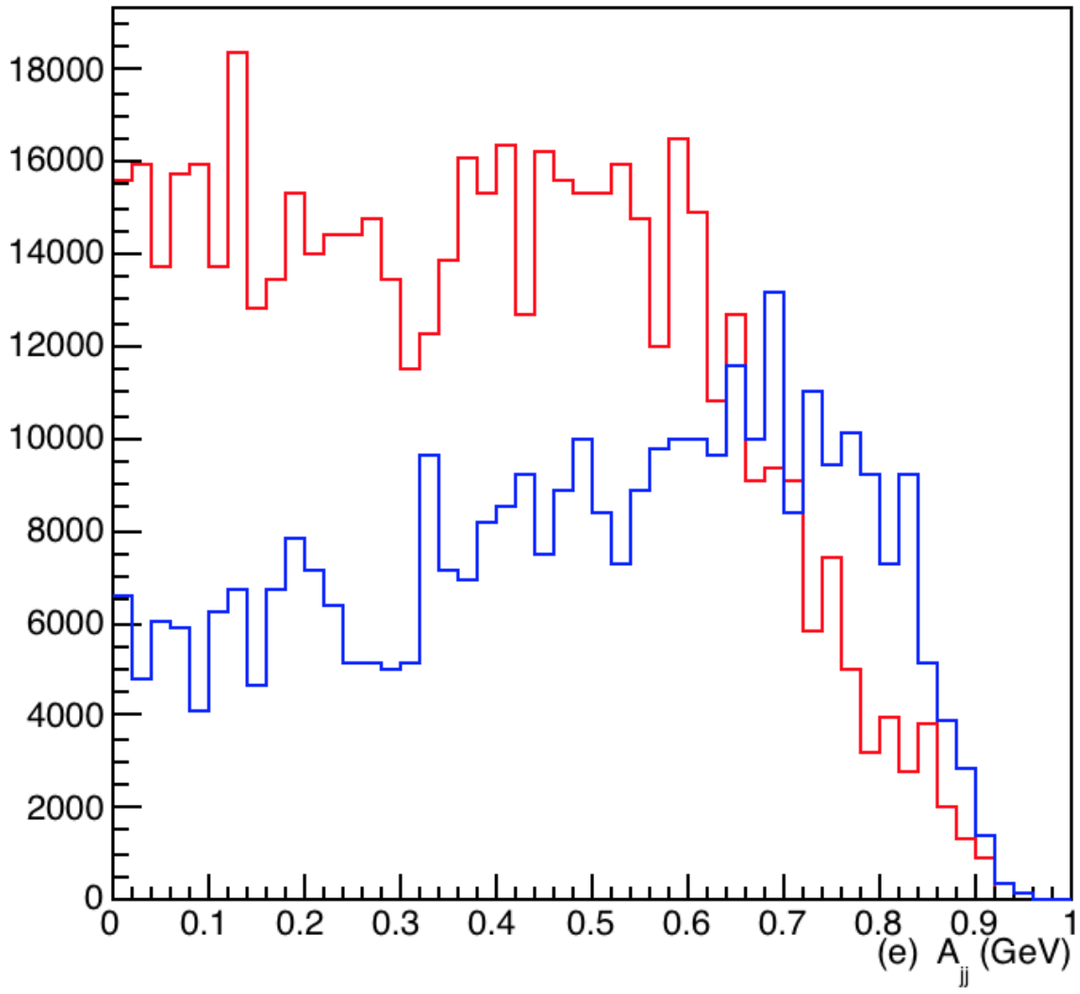
The End

Higgs Decay to Gluon Pair

Improvements



$$A_{jj} = \frac{|p_T(j_1) - p_T(j_2)|}{p_T(j_1) + p_T(j_2)}$$



ZH[gg]

Zjj

Current Status

2017 Moriond (https://home.cern/cern-people/updates/2017/04/wealth-precise-new-results-moriond)

- **H> μμ, Higgs Mass, ttH**

Current Status

2017 Moriond (https://home.cern/cern-people/updates/2017/04/wealth-precise-new-results-moriond)

13 TeV LHC (40 fb^{-1}):

- **H> μμ, Higgs Mass, ttH**

Current Status

2017 Moriond (https://home.cern/cern-people/updates/2017/04/wealth-precise-new-results-moriond)

13 TeV LHC (40 fb^{-1}):

- **H> μμ, Higgs Mass, ttH**
- **Differential cross section**