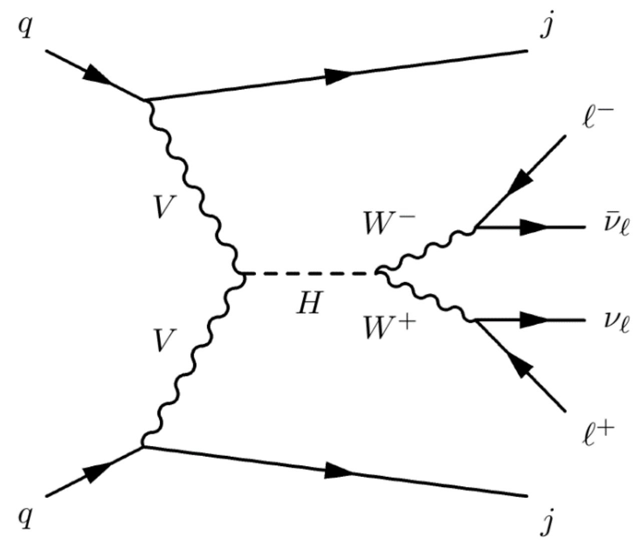


Polarised W bosons in Vector Boson Fusion $H \to WW^* \to e\nu\mu\nu$ at the LHC

Kees Ligtenberg

Nikhef, 11 April 2016

Outline

- What are polarised W bosons?
- Why are they interesting?
- How can they be studied at the LHC?
- What are the properties the signal process?
- How is it calculated?
- How can the signal be separated from the background?
- Conclusions

W bosons acquire third polarisation through Higgs mechanism

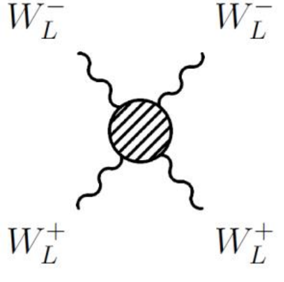
- W bosons are the mediators of the weak force and have 3 polarisations
- Masses and longitudinal polarisations are added by Higgs mechanism
- Higgs doublet ϕ: 4 degrees of freedom

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ v + h + i\phi_4 \end{pmatrix} \to \phi' = U\phi = \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

- 3 Degrees of freedom are recast as longitudinal polarisations

$$\epsilon_L^\mu = \frac{1}{m}(q_z, 0, 0, E) \xrightarrow{E \gg m} \epsilon_L^\mu = \frac{q^\mu}{m},$$

- Extra polarisation of gauge boson causes divergence in scattering

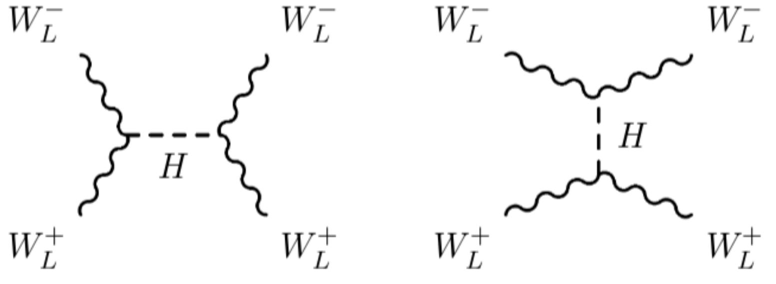


O(s) divergence in W boson scattering

- After summing the 4 point vertex and γ/Z exchange, an $O(s)$ divergence remains

$$i\mathcal{M}_{Higgsless} = -i\frac{g^2}{4m_W^2}u$$

- The $O(s)$ divergence is cancelled by the Higgs exchange diagrams

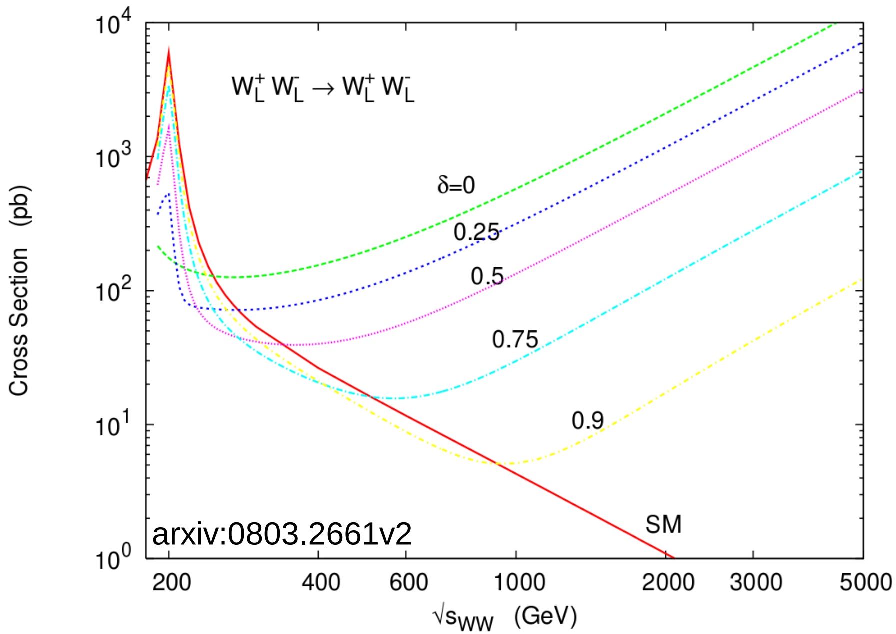


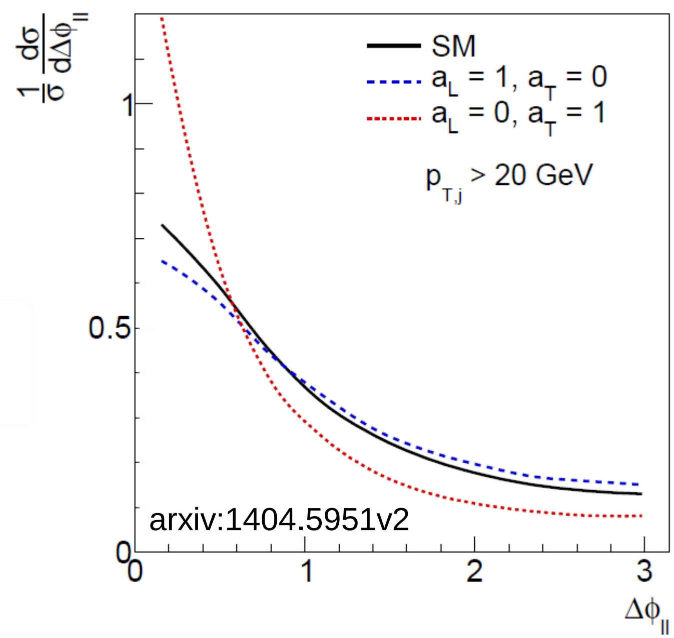
$$i\mathcal{M}_{Higgs} = -i\frac{g^2}{4m_W^2}\left(\frac{(s-2m_W^2)^2}{s-m_h^2} + \frac{(t-2m_W^2)^2}{t-m_h^2}\right)$$

- Cancelling is only exact if all couplings are precisely SM values

Why are polarised W bosons interesting?

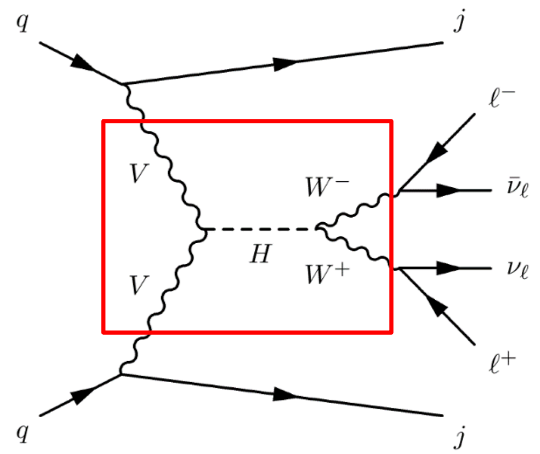
- If coupling different $g_{HWW} = \sqrt{\delta}\, g_{SM}$, the divergence still exists

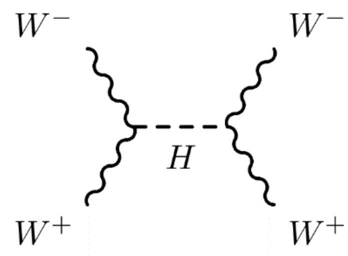




- Lepton opening angle and other distributions are sensitive to different transverse and longitudinal couplings

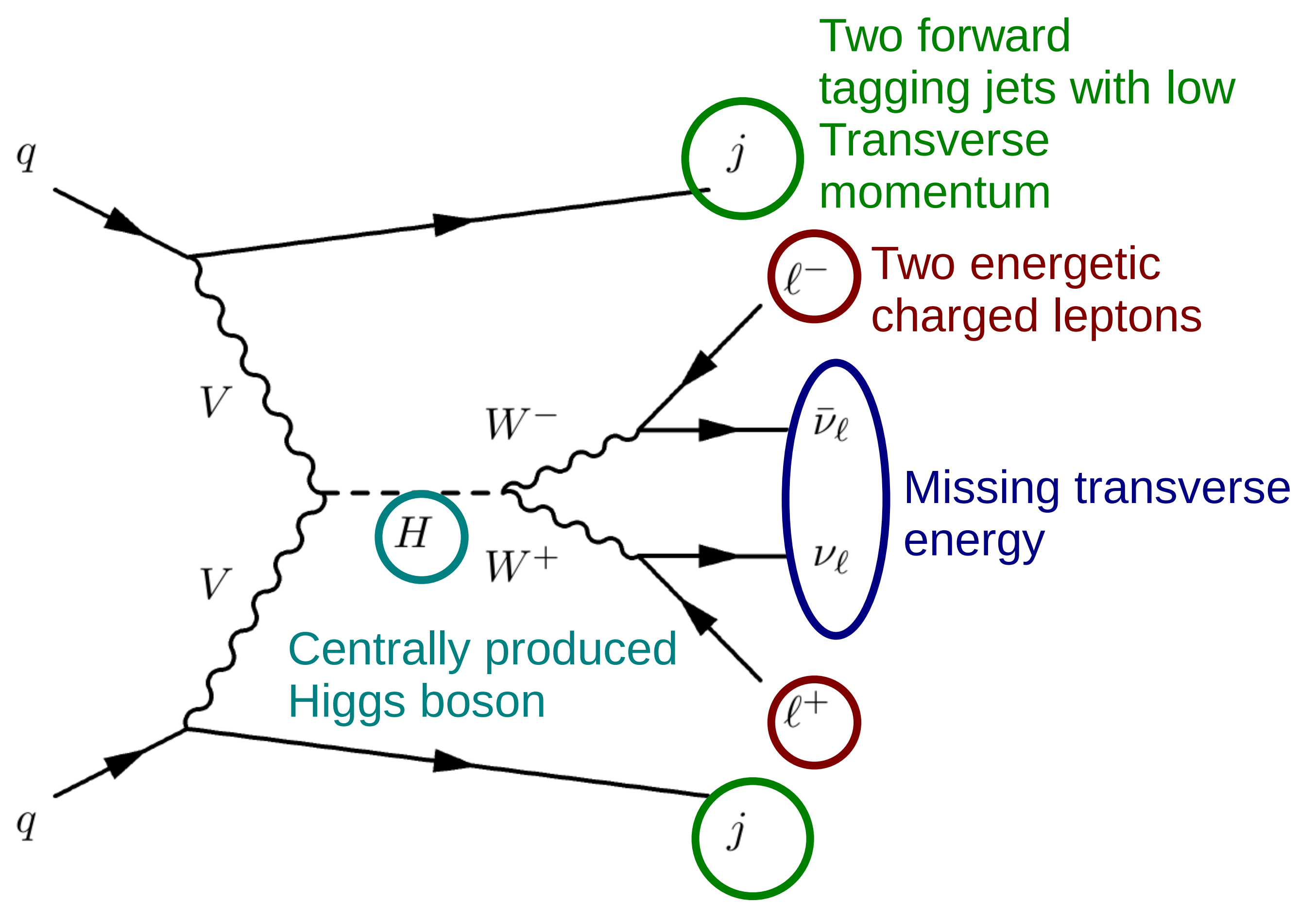
W boson fusion at a hadron collider





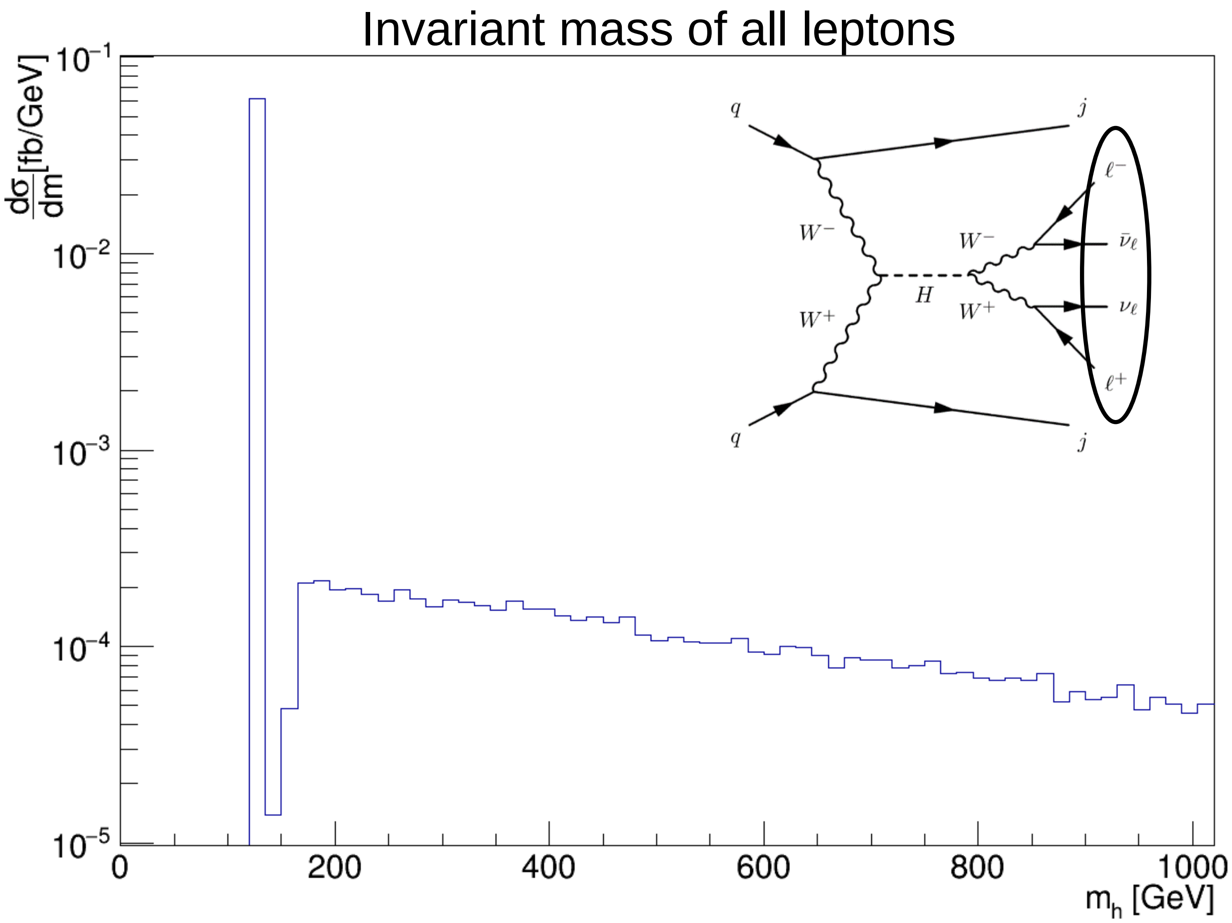
- Two W bosons radiated from incoming quarks
- Fuse to Higgs boson
- Higgs decays to leptons: $H \rightarrow WW^* \rightarrow e\nu\mu\nu$
- Rare process: cross section of a few fb

Properties of vector boson fusion $H \rightarrow WW^* \rightarrow e\nu\mu\nu$



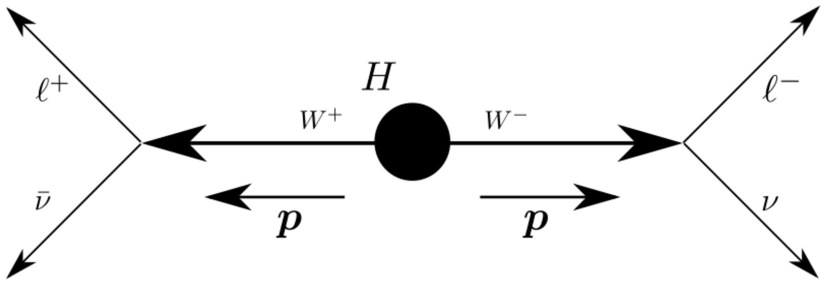
- **Higgs resonance** and **small charged lepton angle** are discussed on the next slides

Most of the signal is at the Higgs mass

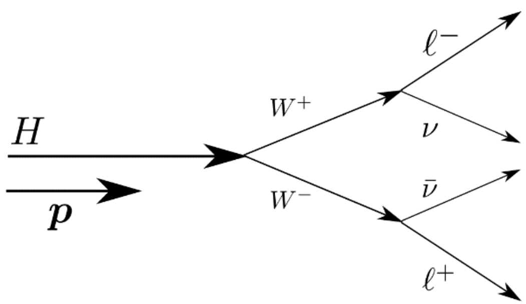


- Cross section around Higgs mass resonance of 125 GeV is orders of magnitude larger than at other invariant masses

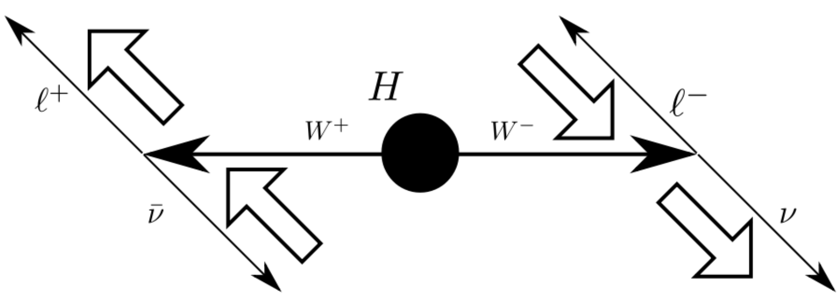
Angle between charged leptons



W boson momentum makes the two charged leptons more anti-parallel

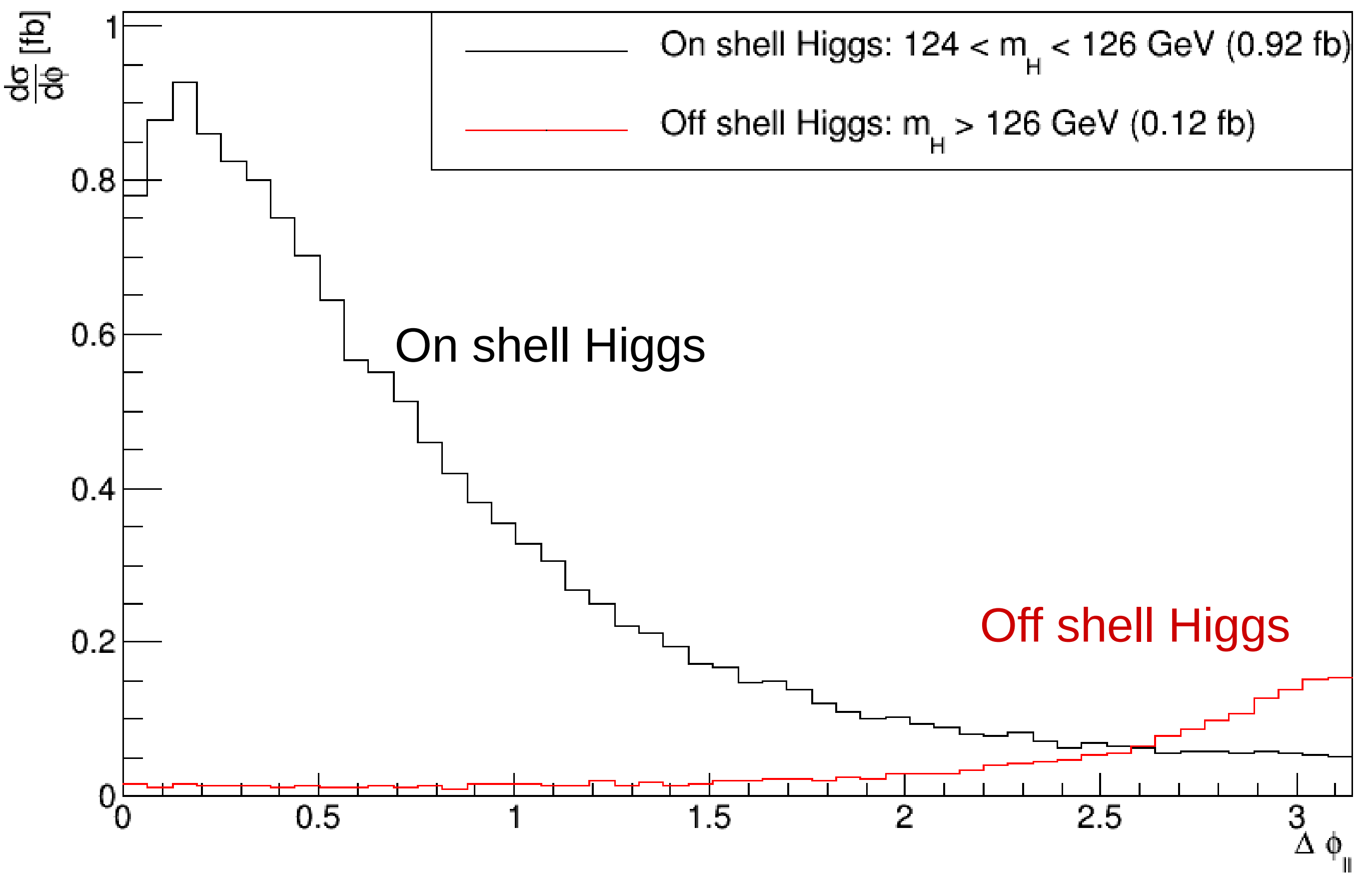


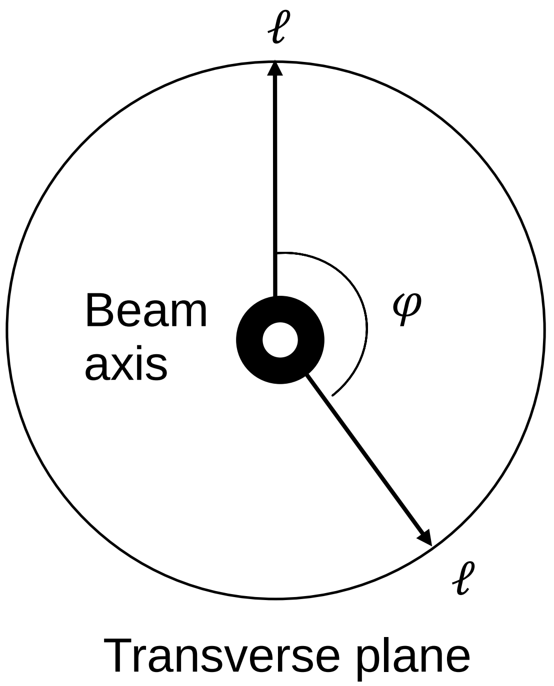
Higgs boson momentum makes the two charged leptons more parallel



The spins of the particles make the two charged leptons more parallel

Angle between two charged leptons is small





- Azimuthal angle ϕ between two charged leptons is small, so the aligning effects are stronger

Investigation using simulated events

- Distributions are calculated using Madgraph5_MC@NLO
- Using preselection cuts from ATLAS High Luminosity-LHC prospect at 14 TeV
- Focus on two differently flavoured leptons: $e^+$and μ^-
- Only leading order (LO)

Input Parameter	Value
E_{beam1}	6.5 TeV
E_{beam2}	6.5 TeV
m_H	125 GeV
Γ_H	4.4 MeV
Parton dristibution function	CTEQ6L1
Madgraph model	sm

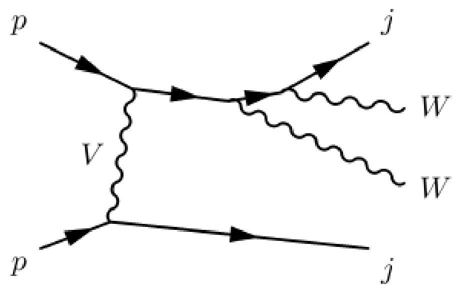
Minimal cuts
$\lvert\eta_j\rvert < 5.5$
$\lvert\eta_l\rvert < 2.5$
$\Delta R_{jj} > 0.4$
$\Delta R_{\ell j} > 0.3$
$\Delta R_{e\mu} > 0.1$
jet $p_T > 20$ GeV
lepton $p_T > 10$ GeV

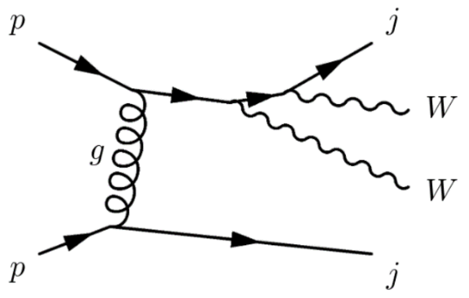
Preselection cut
minimal cuts
leading lepton $p_T > 25$ GeV
subleading lepton $p_T > 15$ GeV
leading jet $p_T > 45$ GeV
subleading jet $p_T > 45$ GeV
$p_T^{miss} > 20$ GeV
$m_{ll} > 10$ GeV
opposite jets $\eta_{j1} \cdot \eta_{j2} < 0$

W boson fusion in experimental data

- The signal vector boson fusion occurs at the LHC
- However, experimental data contains signal process and other processes, backgrounds
- Most of the important backgrounds are calculated

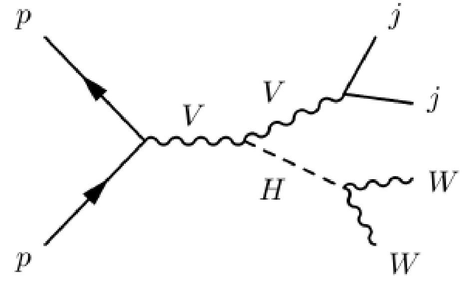
Non resonant backgrounds



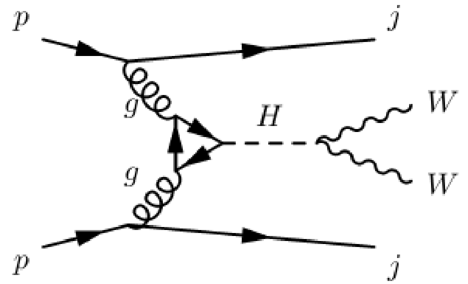


- Production of 2 W bosons under gluon or vector boson exchange
- Same final state
- No Higgs resonance, less energetic jets, larger lepton angle

Other Higgs production channels

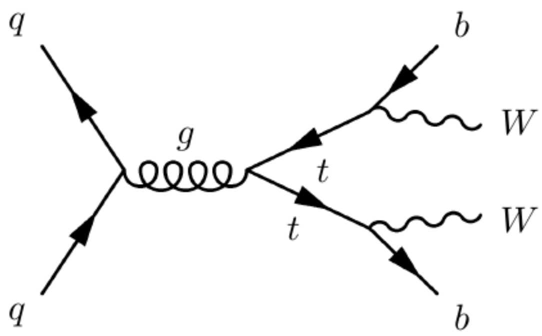


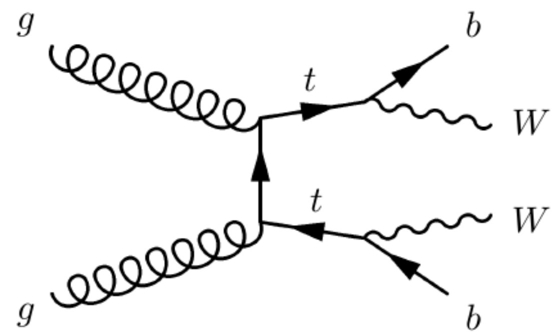
- Associated production has low jet mass



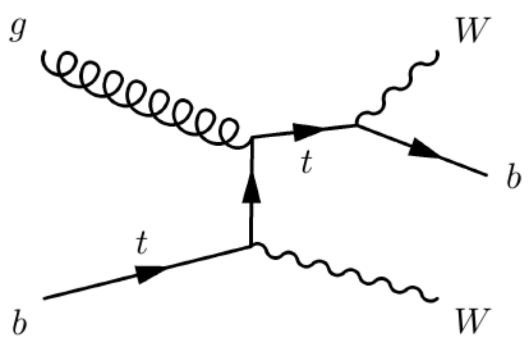
- gluon-gluon Fusion (ggF) approximated with Higgs effective field theory
- Often higher jet multiplicity than signal

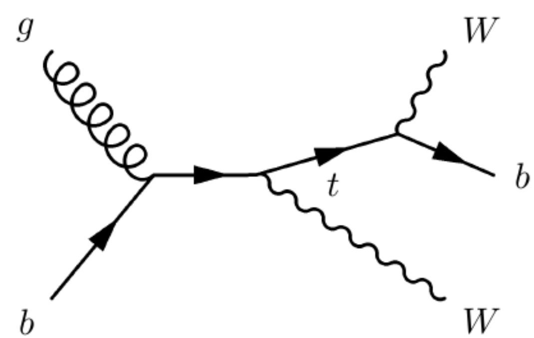
Top backgrounds





- $t\bar{t}$ is the largest background



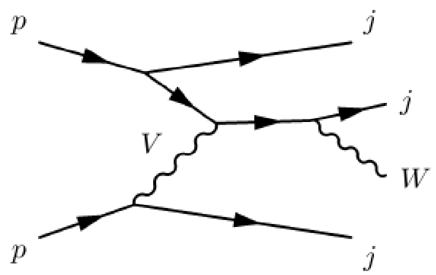


- Single top has a single jet at LO, additional jets from showering
- b tagging reduces background, which is work in progress

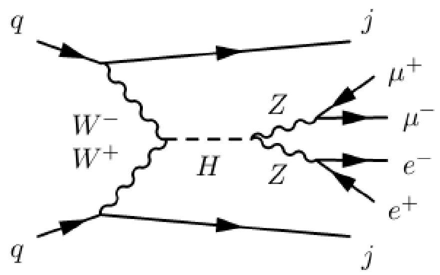
Other excluded backgrounds

- Not included because related to detector response

Misidentified leptons

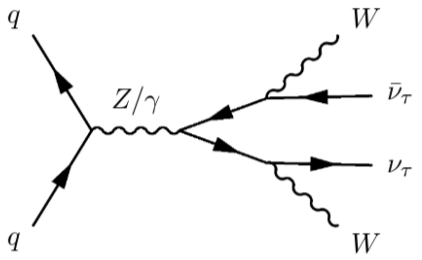


Other di-boson backgrounds



- Not included because involving 2 NLO jets

$\tau\tau$ Drell-Yan

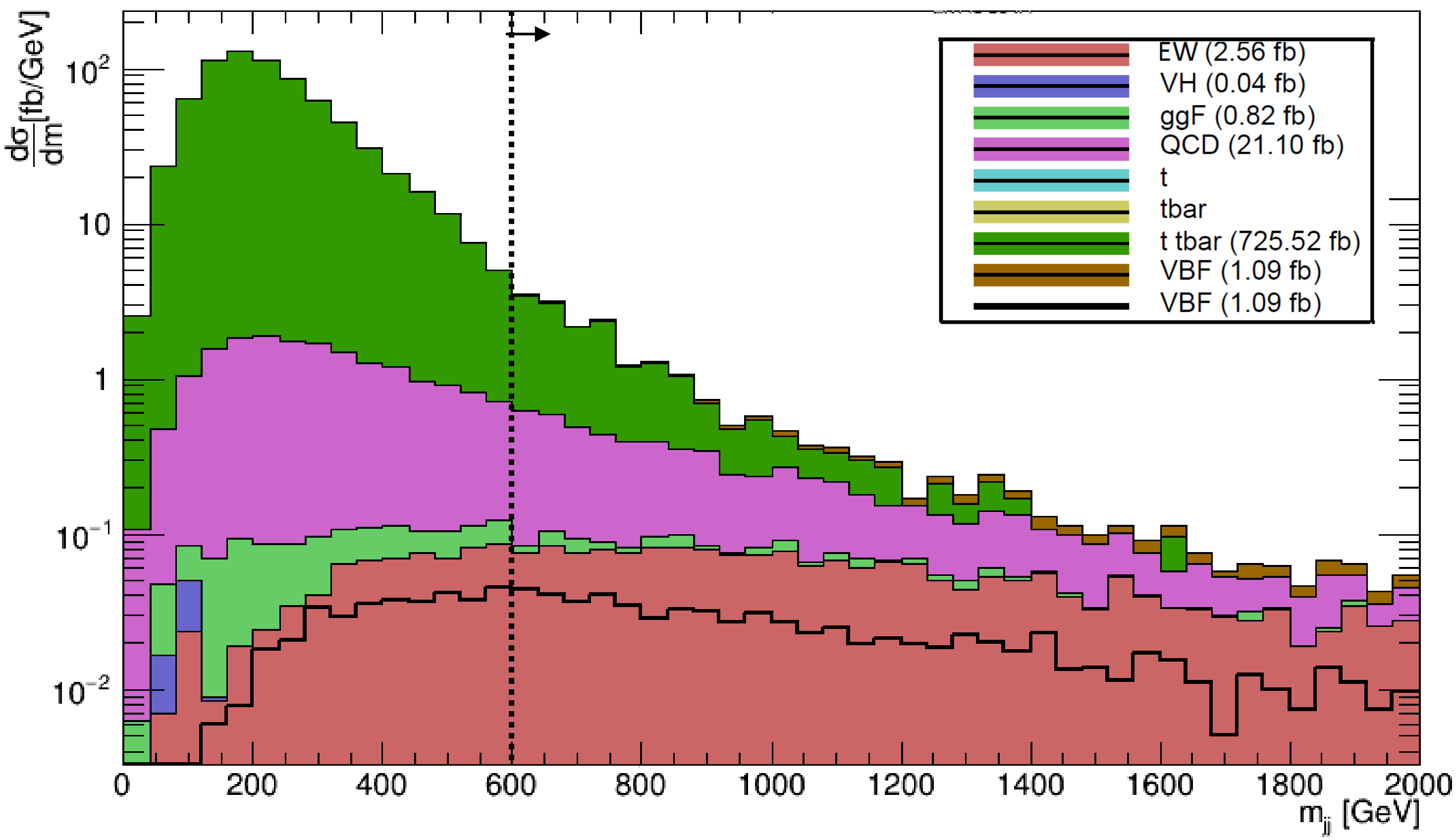


Separate signal from backgrounds using cuts

- Separate signal events from backgrounds events using a series of selection criteria, cuts
- Sequentially apply cuts, i.e. only use remaining events to chose next cut
- Cuts on the next slides are selected to optimise signal separation from included backgrounds at parton level

- First at parton level
- Then after showering and hadronisation, which is work in progress

Cut on $m_{jj} > 600$ GeV



- Cut on invariant mass of the two jets m_{jj} because signal features two energetic jets

Add transverse mass cut

- Combined mass of all leptons cannot be reconstructed because neutrino's are not detectable at the LHC
- Transverse mass can be calculated using missing transverse momentum instead of neutrino momentum

$$m_T^2 = (E_T^{\text{missing}} + E_T^{\text{charged leptons}})^2 - (\boldsymbol{p}_T^{\text{charged leptons}} + \boldsymbol{p}_T^{\text{missing}})^2$$

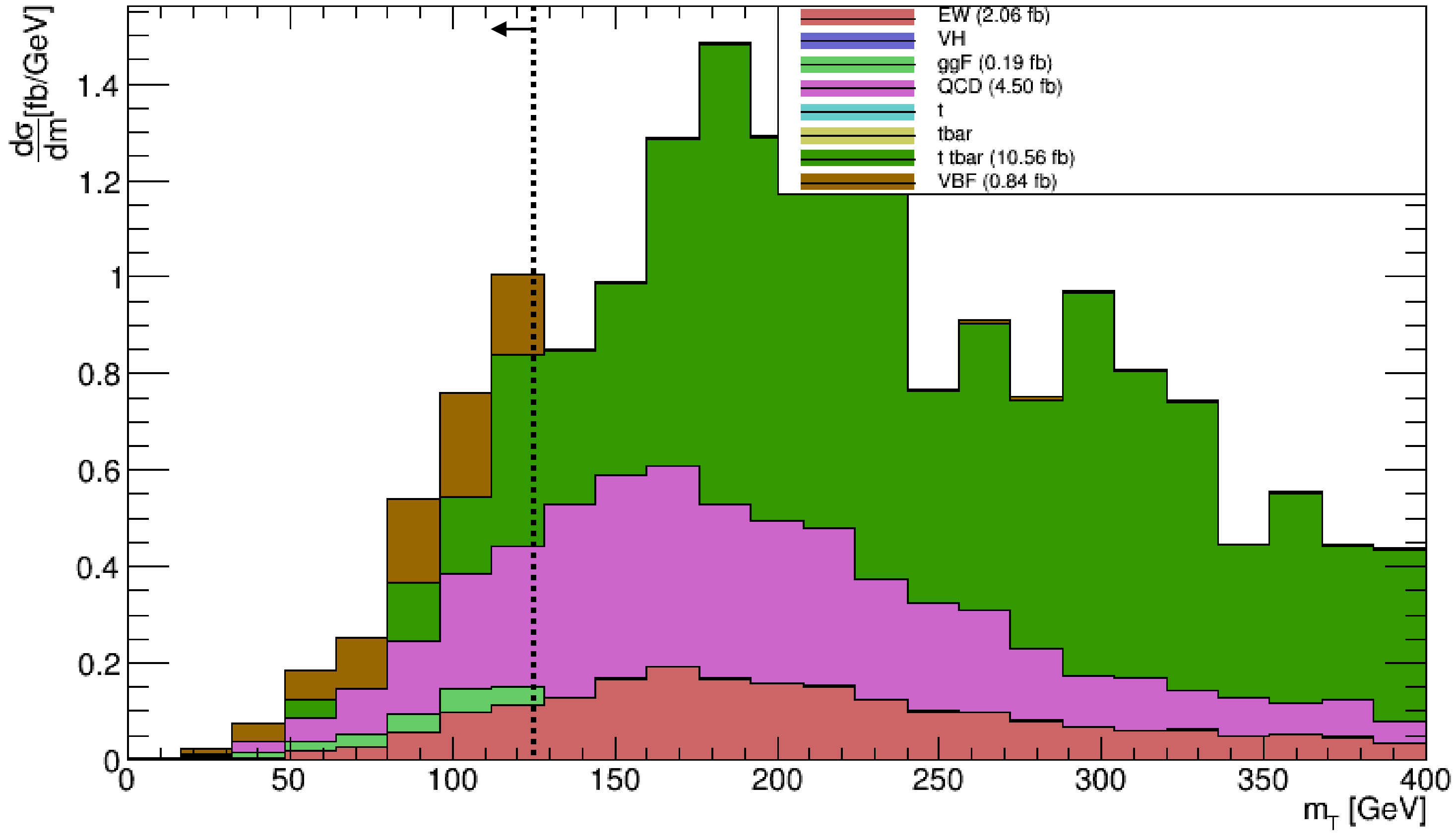
- And assume

$$(E_T^{\text{missing}})^2 = (\boldsymbol{p}_T^{\text{missing}})^2$$

- Transverse mass is smaller than true combined mass

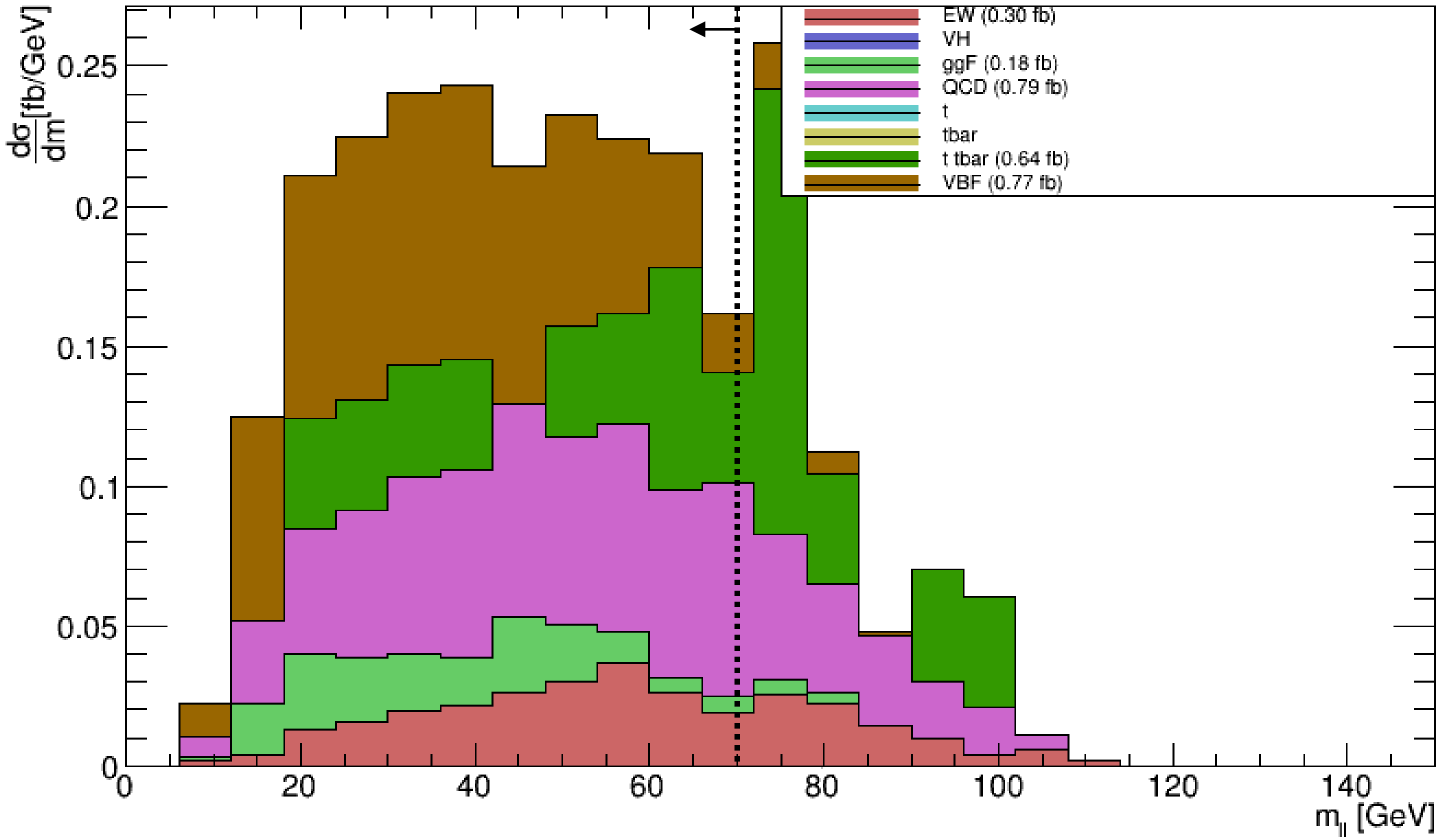
$$m_T \leq m_{\text{leptons}}$$

Add transverse mass cut $m_T < 130$ GeV



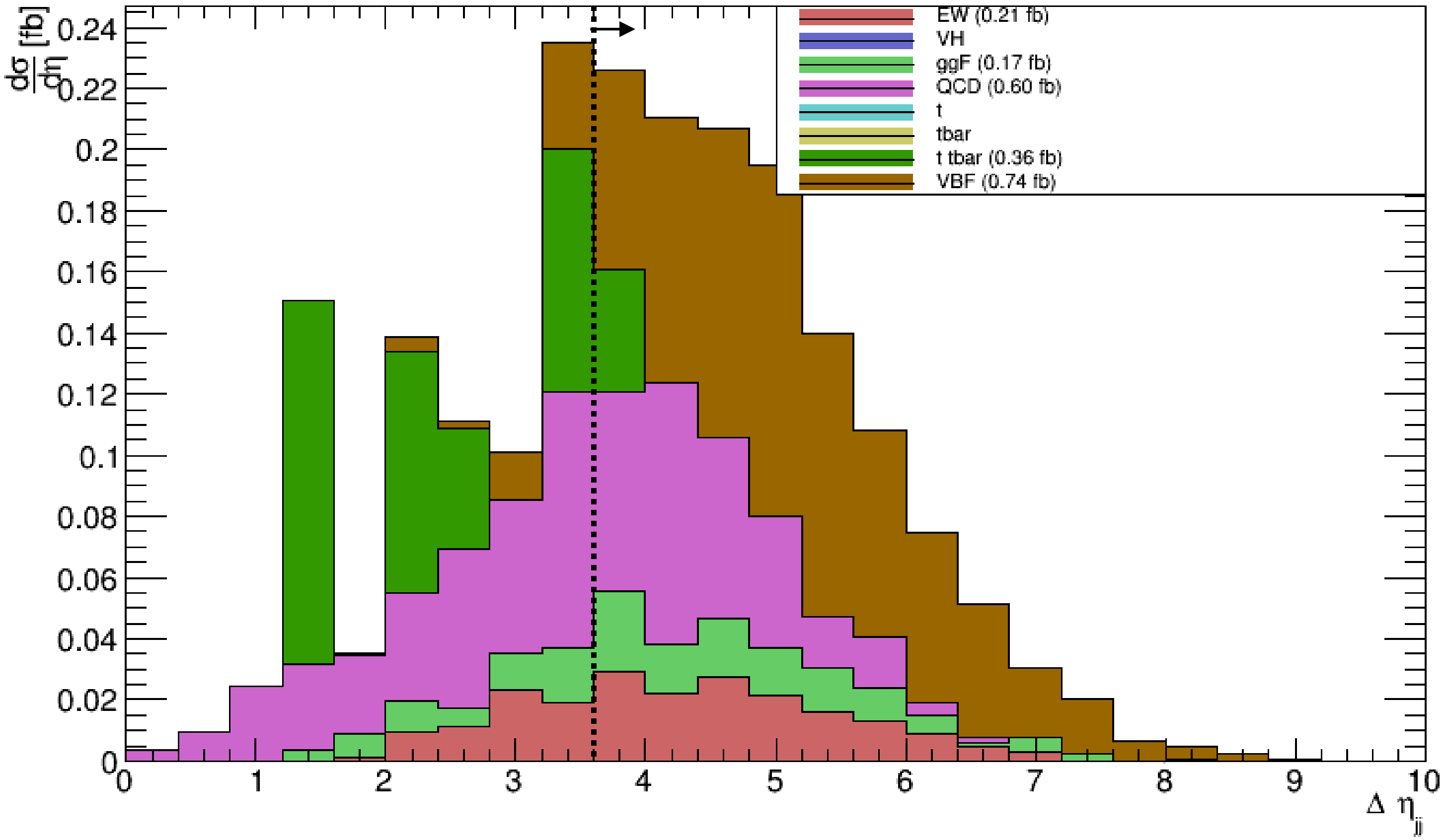
Cuts selects the Higgs resonance

Add cut $m_{ll} < 70$ GeV



Signal has small lepton angle and thus small lepton mass

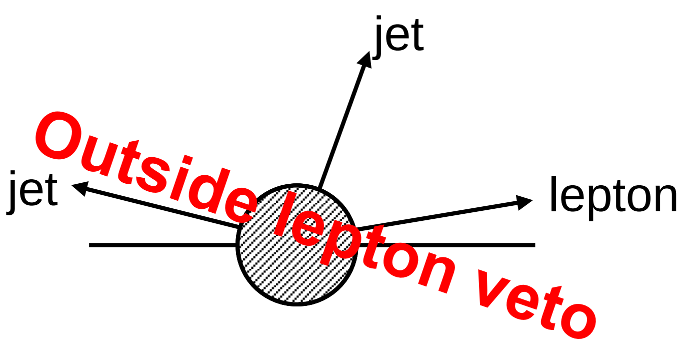
Add $\Delta\eta_{jj} > 3.6$ Cut

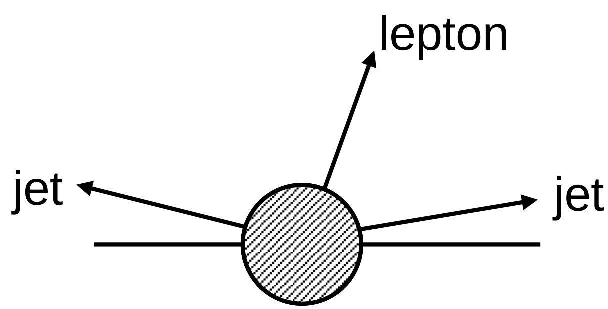


- Cut on psuedorapidity η difference of two jets
- The signal jets are highly forward

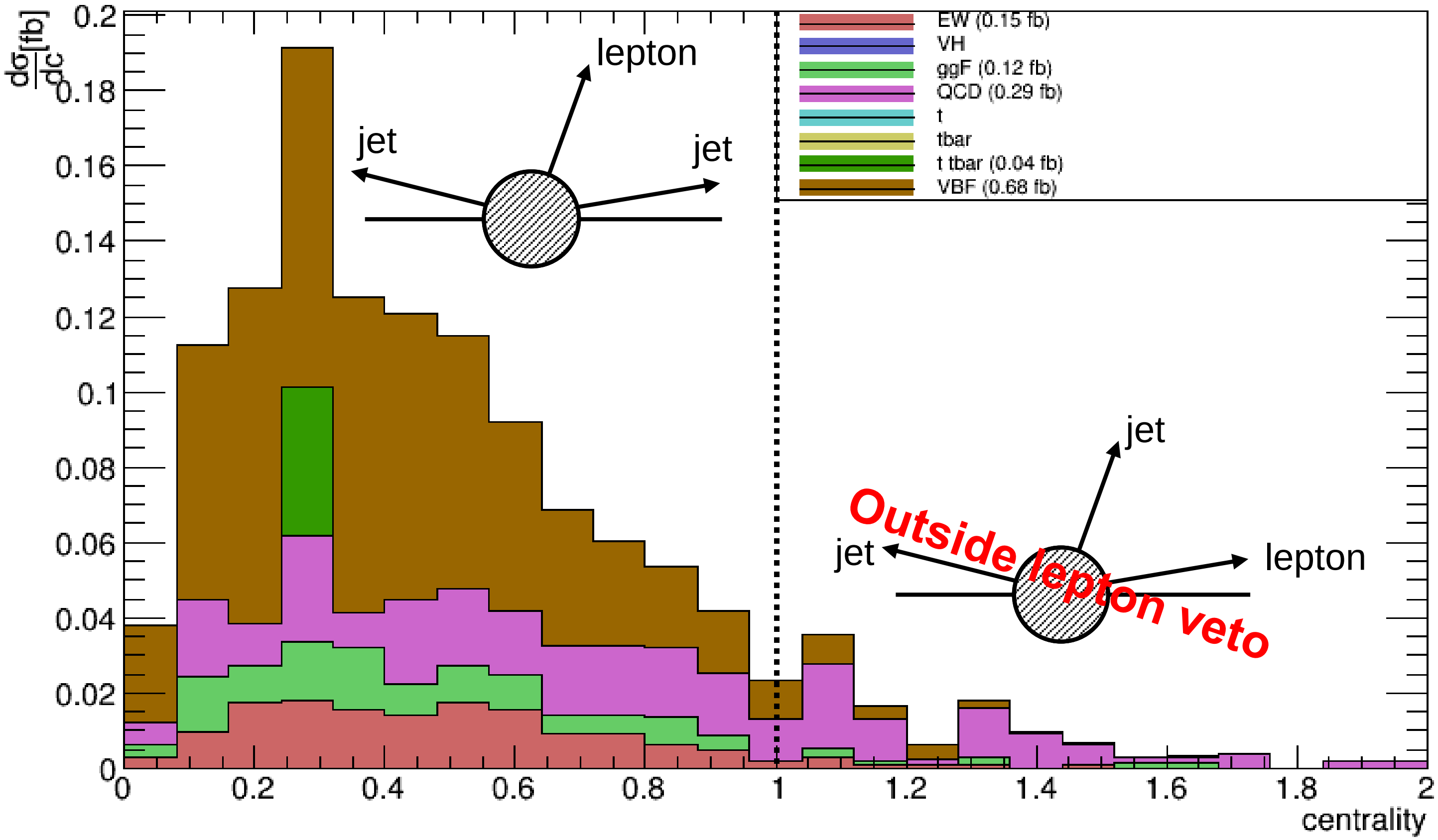
Add outside lepton veto

- Lepton rapidity must be between two jets
  $\eta_{jet\ 1} < \eta_{lepton} < \eta_{jet\ 2}$





Add outside lepton veto



Lepton rapidity must be between two jets $\eta_{j1} < \eta_\ell < \eta_{j2}$

Overview of selection

- Signal can be separated from background at parton level
- The number of events at 300 fb^{-1} gives rise to optimism for a possible measurement of the polarised couplings

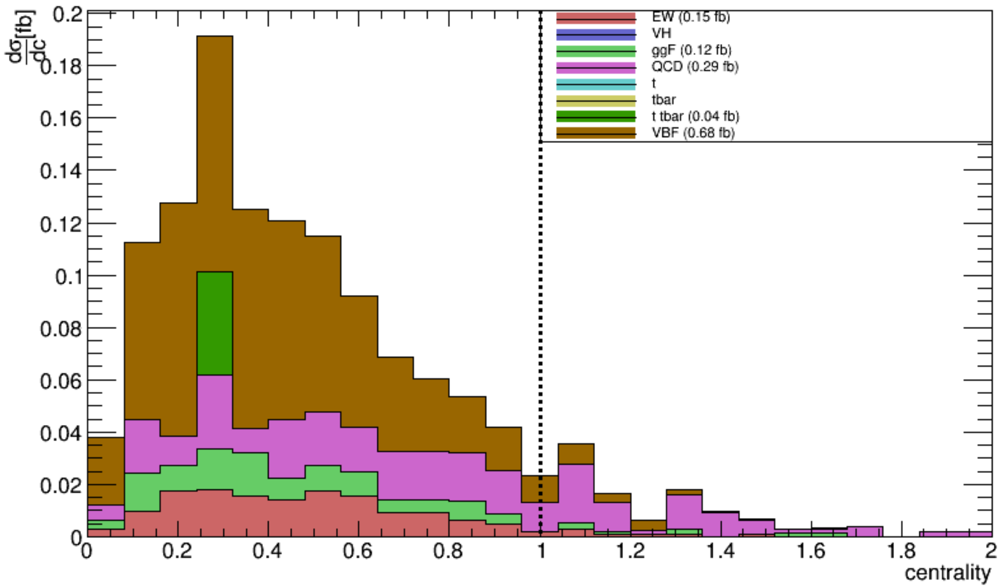
Cutflow at parton level (fb)

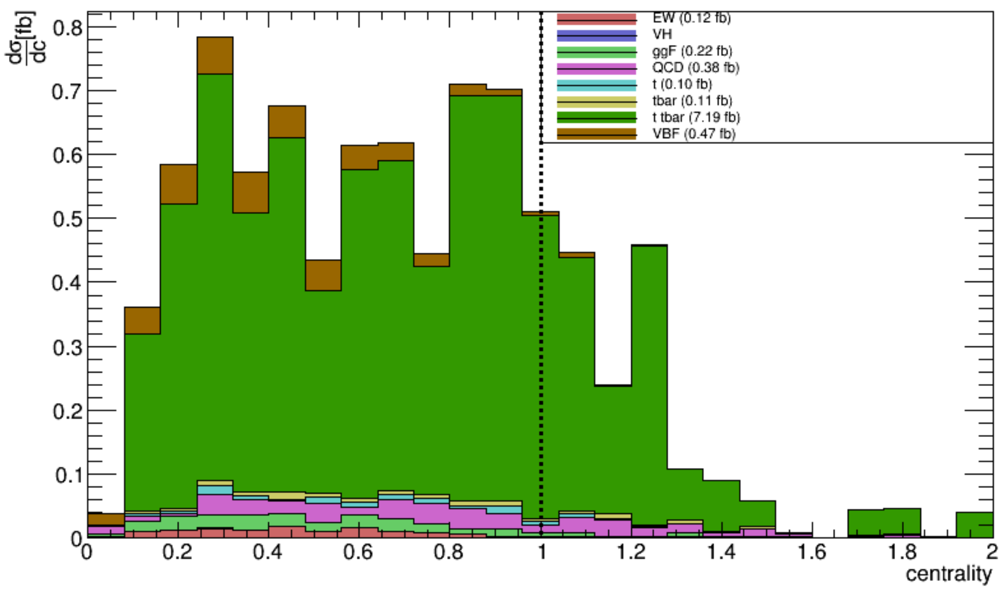
Cut	VBF	QCD	EW	ggF	VH	t tbar	$S/\sqrt{S+B}$	S/B
Preselection	1.25	19.97	3.06	0.84	0.04	725.52	0.04	0.00
$m_{jj} > 600$	0.90	4.66	2.39	0.20	0.00	13.10	0.17	0.03
$m_T < 125$	0.77	0.65	0.30	0.18	0.00	0.64	0.43	0.33
$m_{ll} < 70$	0.74	0.53	0.21	0.17	0.00	0.36	0.47	0.42
$\Delta\eta_{jj} > 3.6$	0.68	0.22	0.15	0.12	0.00	0.04	0.56	0.85
OLV	0.66	0.18	0.14	0.11	0.00	0.04	0.58	1.01
events at 300 $fb^{-}1$	198	54	42	33	0	12	10.05	1.01

Selection after showering and hadronisation is work in progress

Initial and final state radiation, and hadronisation make signal separation harder

With the same selection, there is considerably more background left after showering and hadronisation, for example at the outside lepton veto:





To do is change cuts and add a b-jet veto

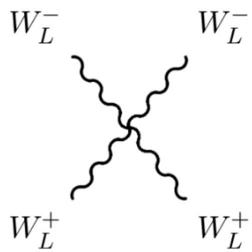
Conclusions

- Vector boson fusion can test W boson polarisation couplings
- The signal has distinctive properties, that make it possible to separate the backgrounds
- The projected number of events for 300 fb^{-1} at parton level is promising
- Selection after showering and hadronisation is coming along

Thank you for your attention

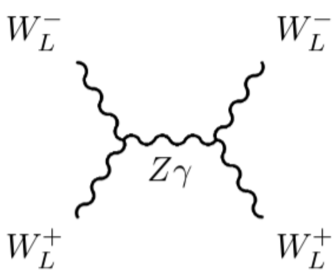
O(s²) divergence in W boson scattering

- Longitudinal polarised W boson scattering has an $O(s^2)$ divergence in the matrix element of the four point vertex

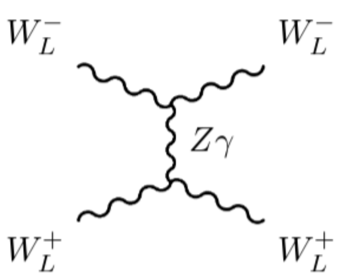


$$i\mathcal{M}_4 = i\frac{g^2}{4m_W^4}\left(s^2 + 4st + t^2 - 4m_W^2(s+t) - \frac{8m_W^2}{s}ut\right)$$

- The $O(s^2)$ divergence is cancelled by the γ/Z exchange



$$i\mathcal{M}_s^{Z\gamma} = -i\frac{g^2}{4m_W^4}\left(s(t-u) - 3m_W^2(t-u)\right)$$



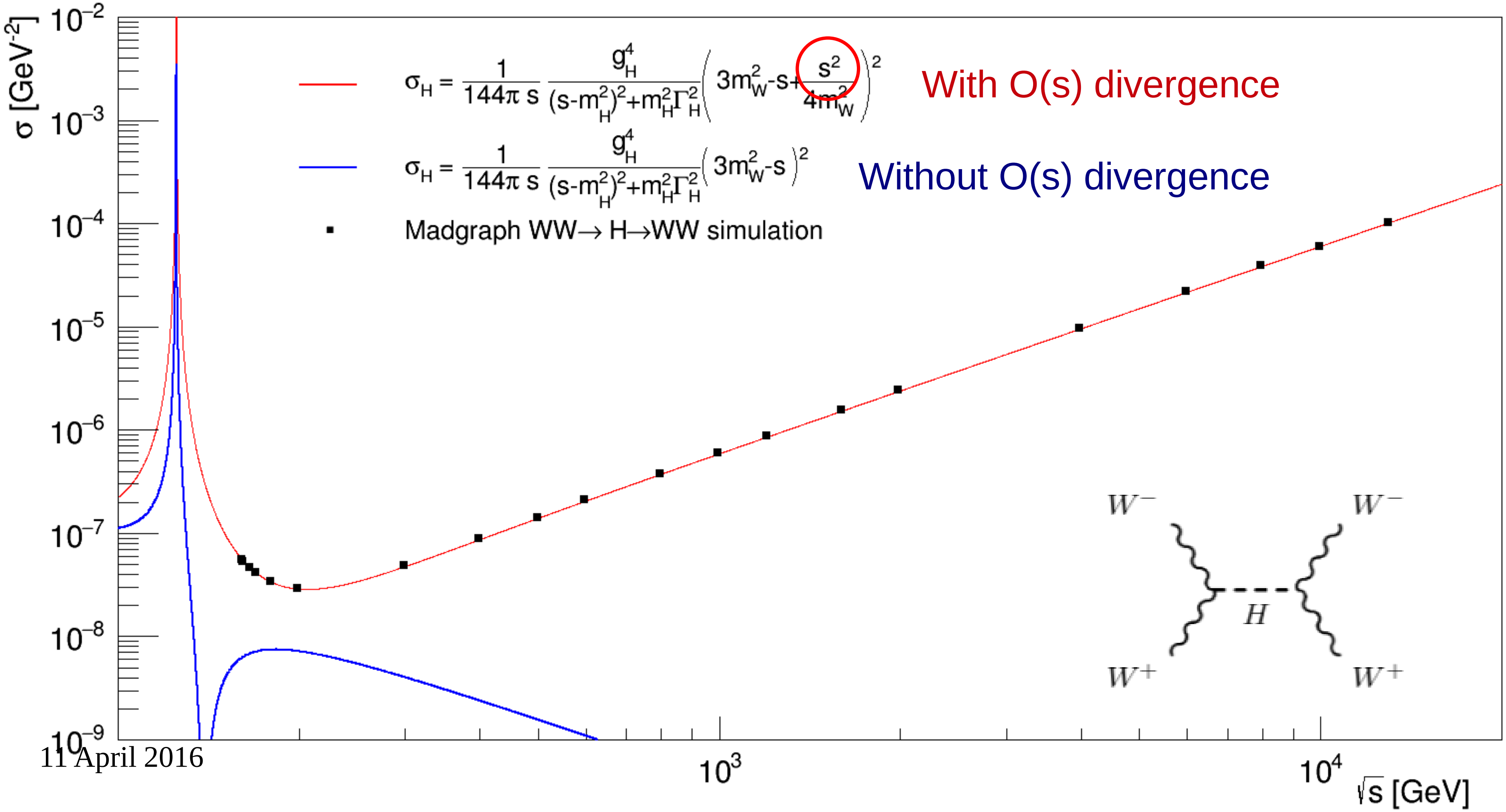
$$i\mathcal{M}_t^{Z\gamma} = -i\frac{g^2}{4m_W^4}\left((s-u)t - 3m_W^2(s-u) + \frac{8m_W^2}{s}u^2\right)$$

Centrality

$$\text{Centrality}_{\eta_3} = \frac{|2\eta_3 - \eta_1 - \eta_2|}{|\eta_1 - \eta_2|}.$$

Divergence of cross section

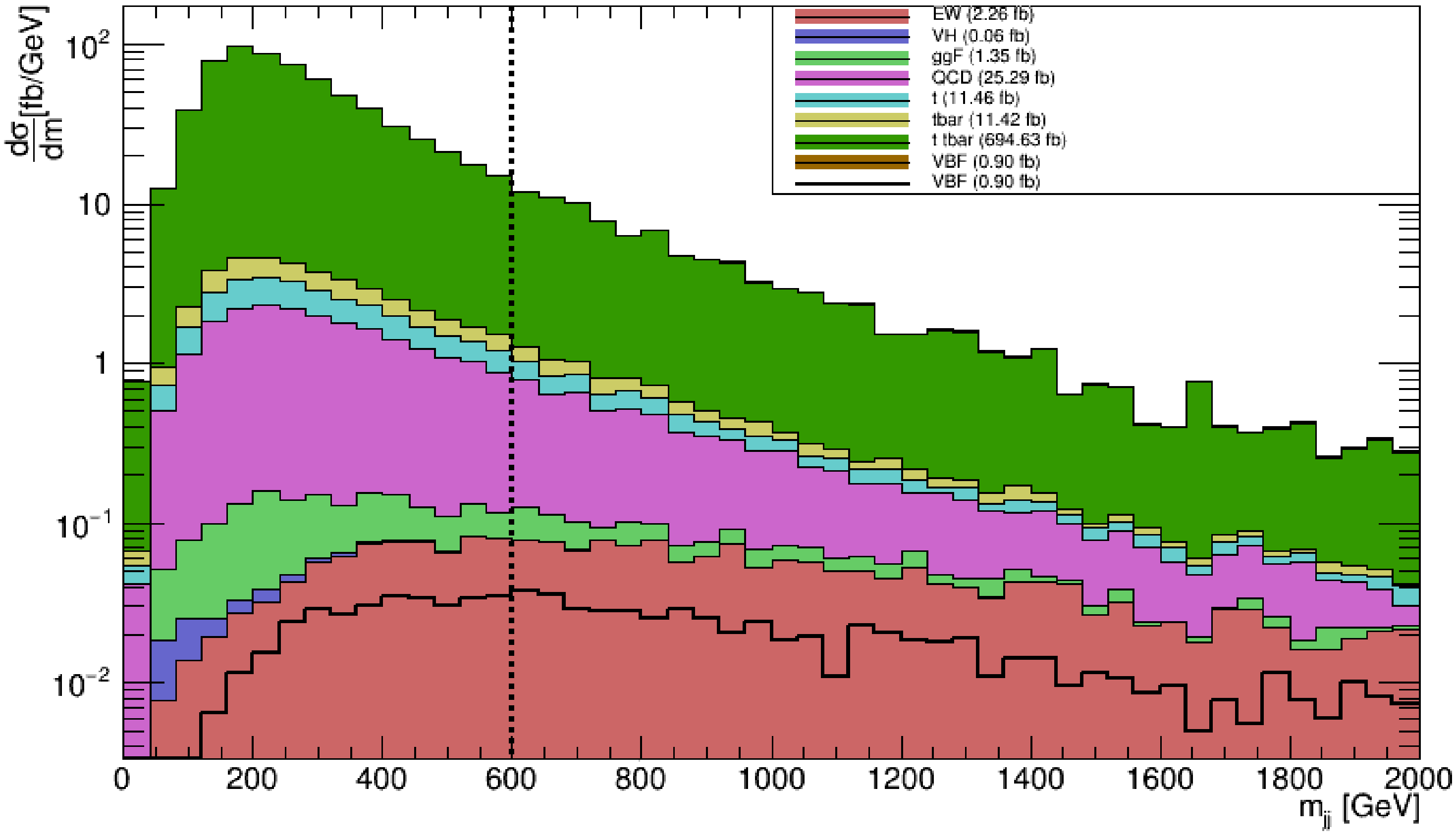
WW->H->WW scattering:



Complete cutflow

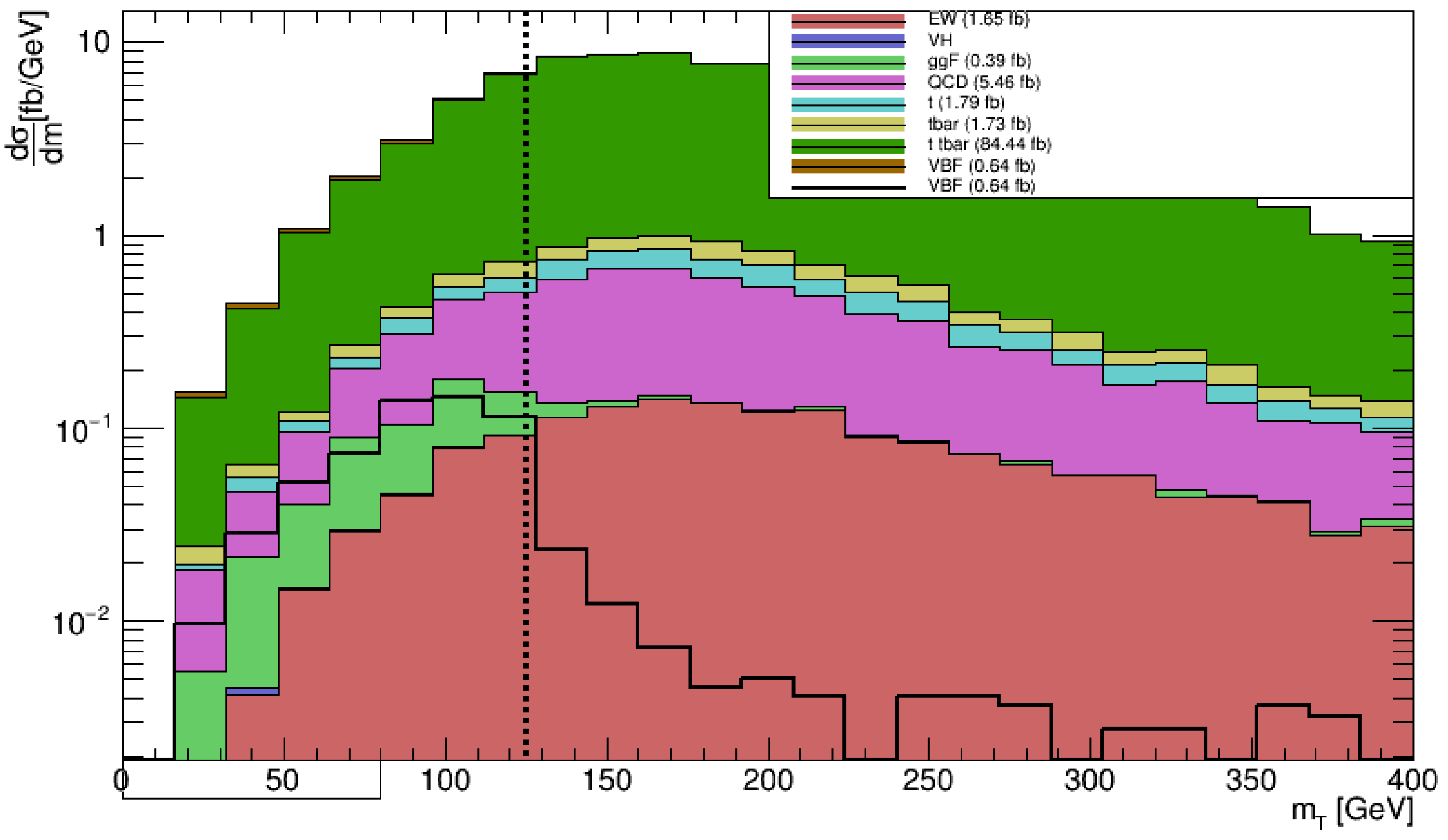
Cut	VBF	QCD	t	tbar	QED	ggF	VH	t tbar	$S/\sqrt{S+B}$	S/B
					Parton Level					
Preselection	1.25	19.97	13.64	13.13	3.06	0.84	0.04	725.52	0.04	0.00
$m_{jj} > 600$	0.90	4.66	3.64	3.46	2.39	0.20	0.00	13.10	0.17	0.03
$m_T < 125$	0.77	0.65	0.33	0.27	0.30	0.18	0.00	0.64	0.43	0.33
$m_{ll} < 70$	0.74	0.53	0.29	0.20	0.21	0.17	0.00	0.36	0.47	0.42
$\Delta\eta_{jj} > 3.6$	0.68	0.22	0.19	0.09	0.15	0.12	0.00	0.04	0.56	0.85
OLV	0.66	0.18	0.13	0.04	0.14	0.11	0.00	0.04	0.58	1.01
					After showering and hadronization					
Preselection	1.01	25.37	19.02	19.31	2.61	1.39	0.07	714.24	0.04	0.00
$m_{jj} > 600$	0.69	5.64	4.76	4.67	1.90	0.42	0.00	87.02	0.07	0.01
$m_T < 125$	0.55	0.96	0.52	0.40	0.24	0.33	0.00	13.74	0.13	0.03
$m_{ll} < 70$	0.53	0.72	0.38	0.33	0.18	0.32	0.00	10.52	0.15	0.04
$\Delta\eta_{jj} > 3.6$	0.48	0.37	0.25	0.16	0.12	0.23	0.00	6.79	0.16	0.06
OLV	0.46	0.28	0.20	0.13	0.12	0.20	0.00	5.16	0.18	0.08
CJV ($p_T > 20$)	0.28	0.04	0.04	0.04	0.06	0.04	0.00	0.40	0.29	0.44

Cut on $m_{jj} > 600$ GeV



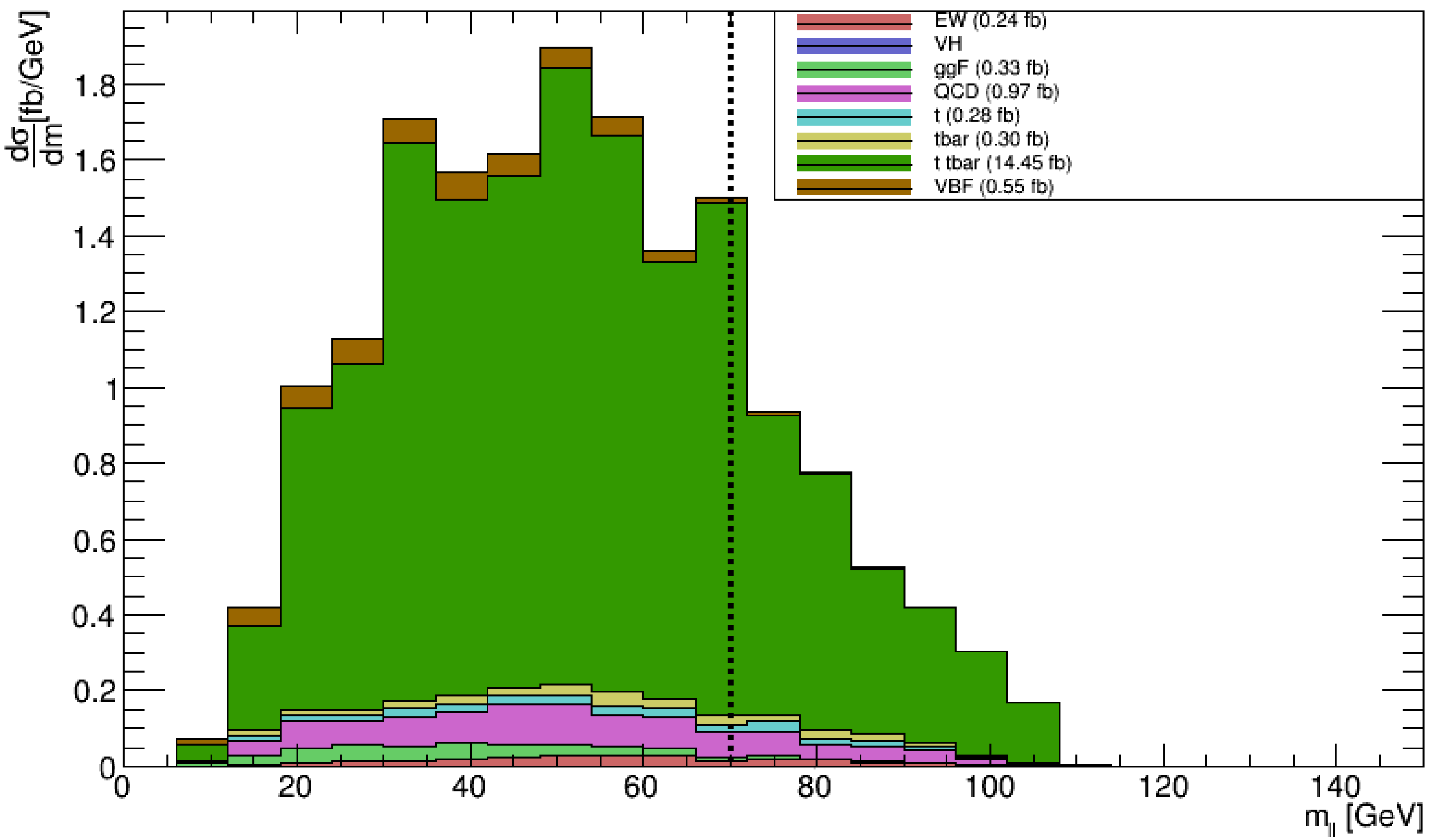
- Cut on invariant mass of the two jets m_{jj} because signal features two energetic jets

Add transverse mass cut $m_T < 130$ GeV



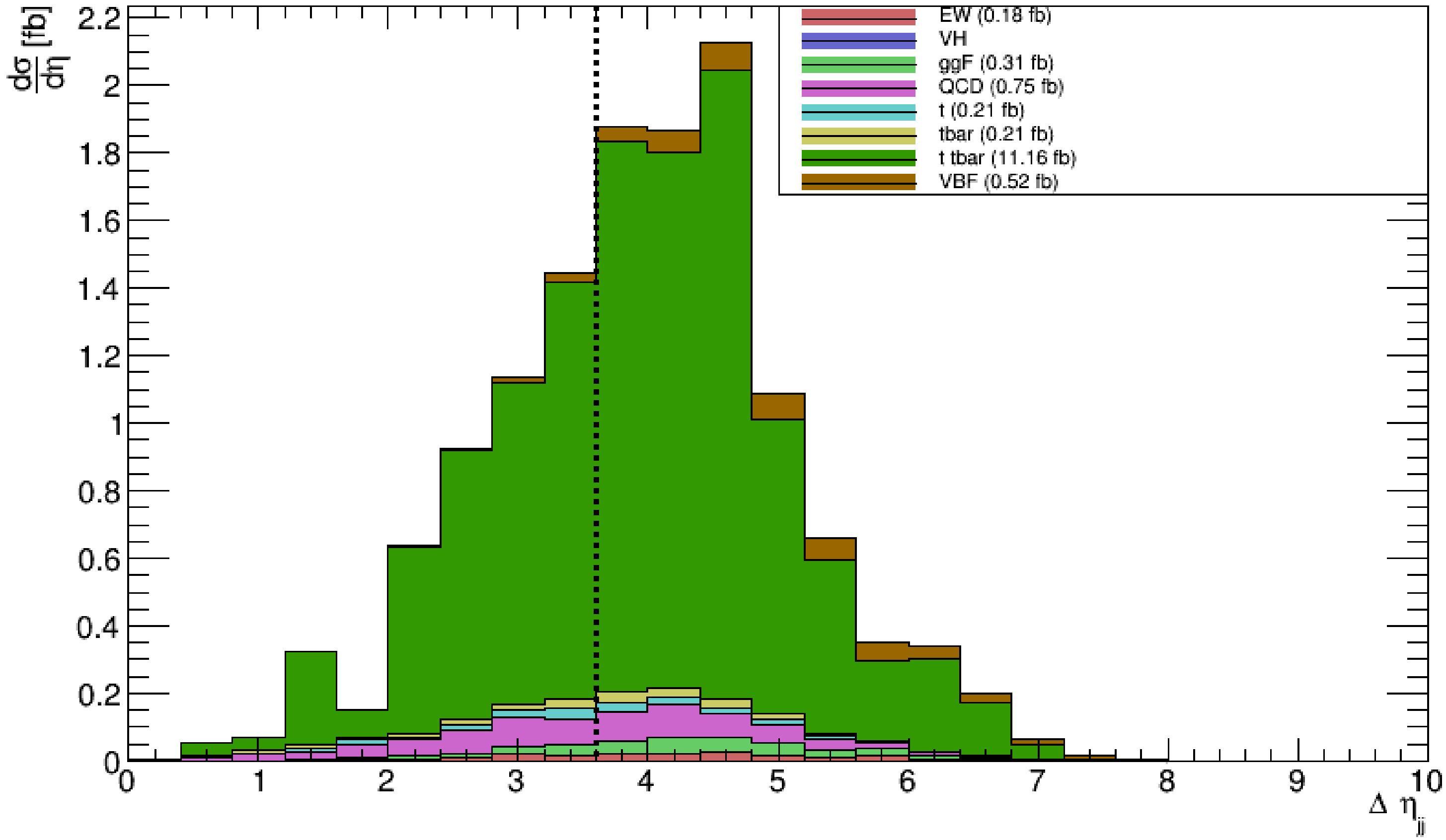
Cuts selects the Higgs resonance

Add cut $m_{ll} < 70$ GeV



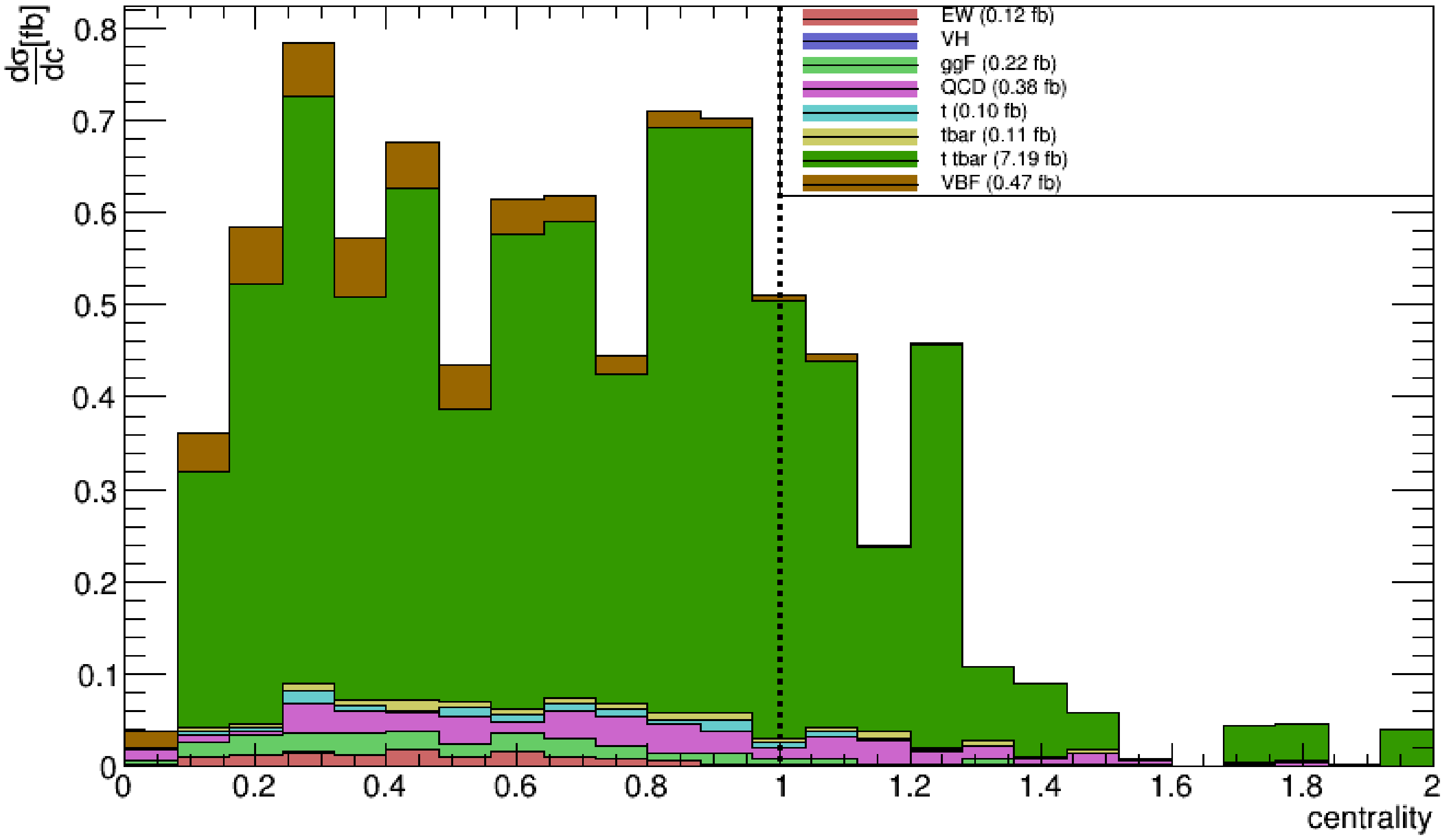
Signal has small lepton angle and thus small lepton mass

Add $\Delta\eta_{jj} > 3.6$ Cut



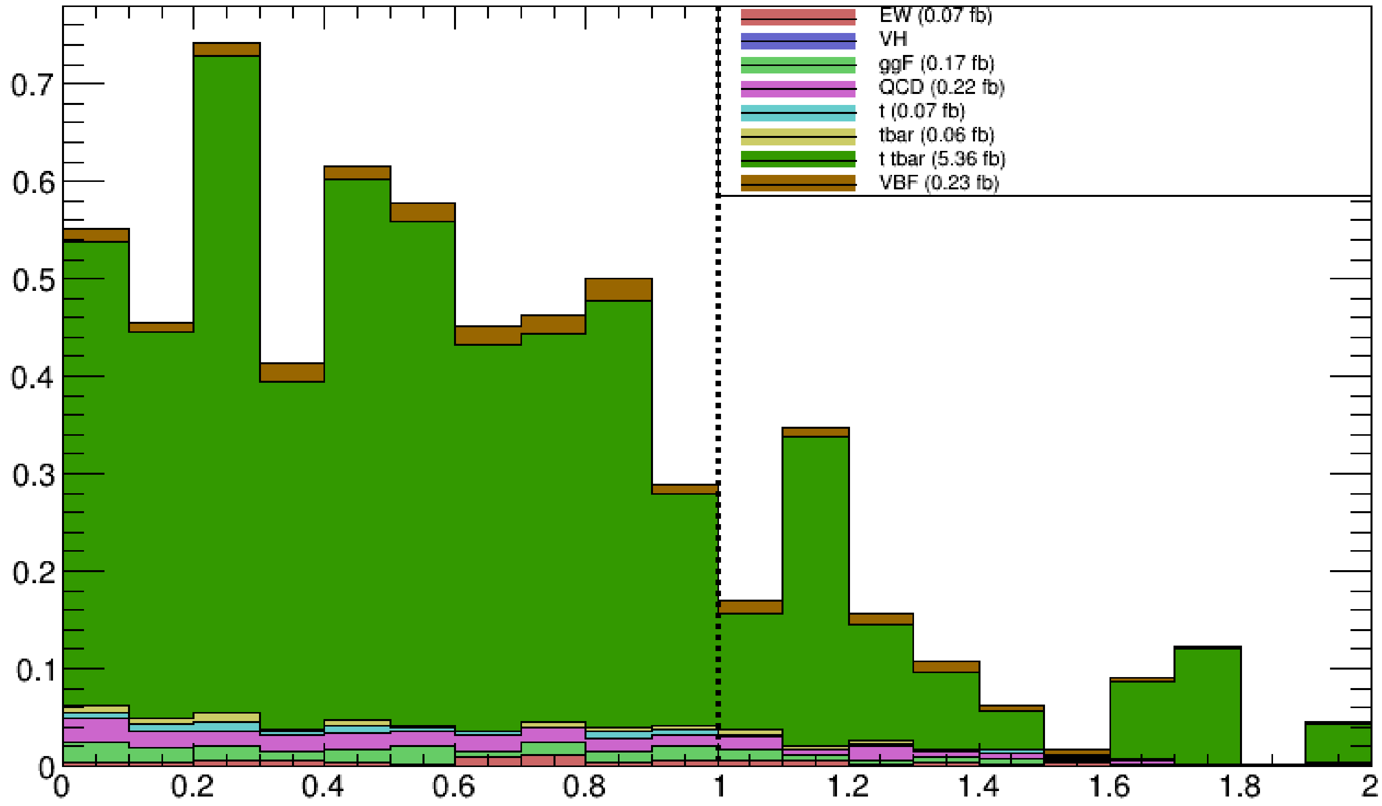
- Cut on η difference of two jets
- The signal jets are highly forward

Add outside lepton veto

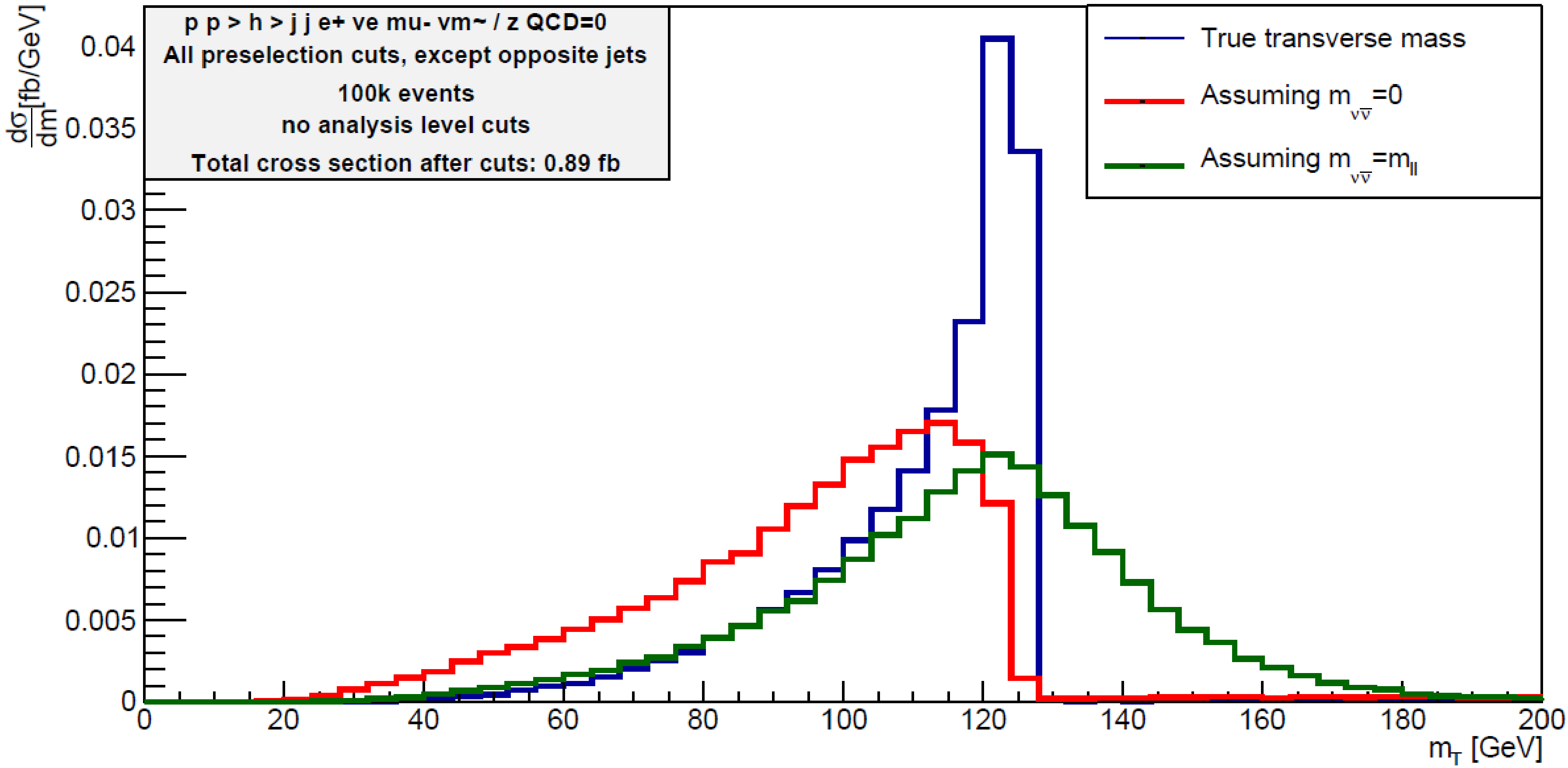


Lepton rapidity must be between two jets $\eta_{j1} < \eta_{\ell} < \eta_{j2}$

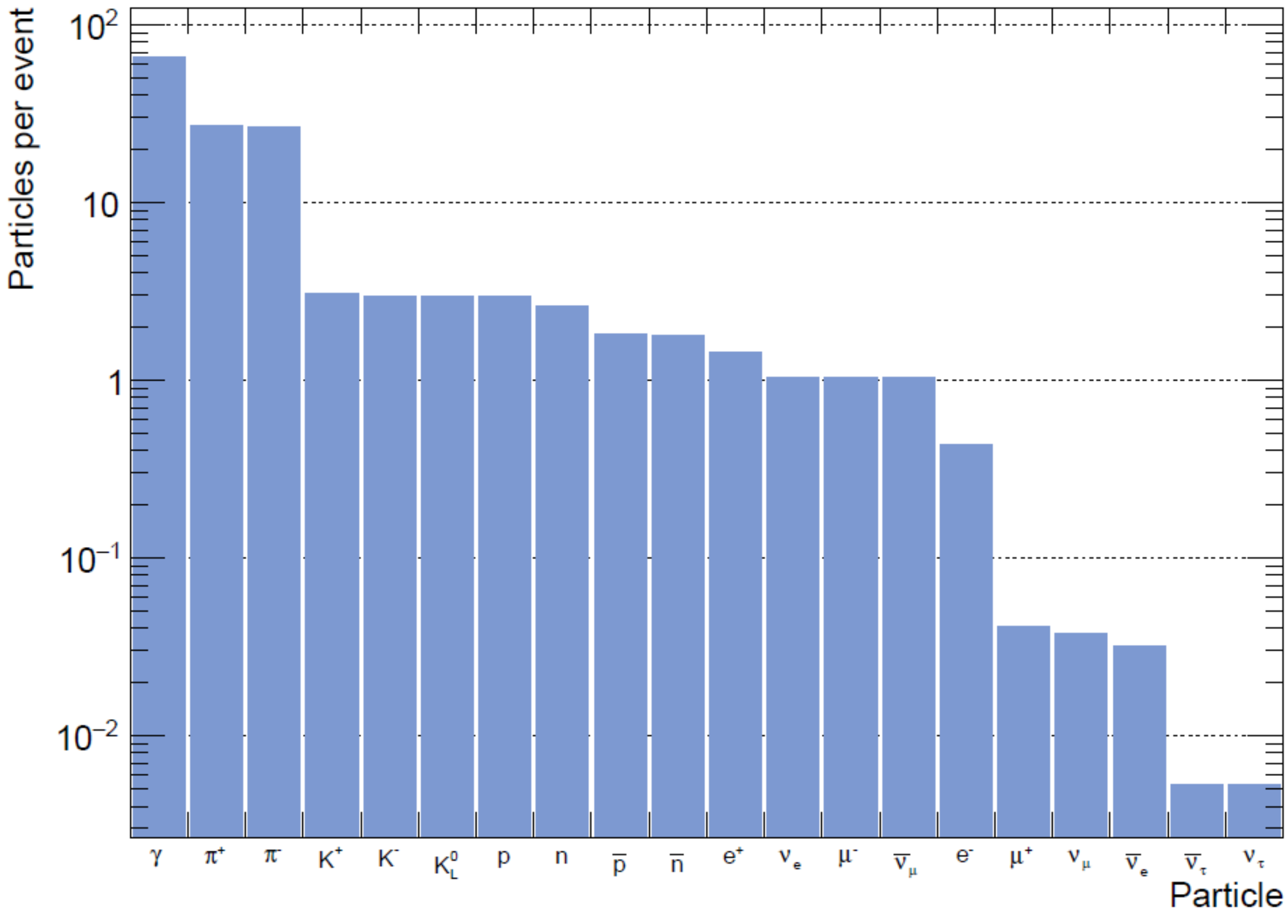
Central jet veto



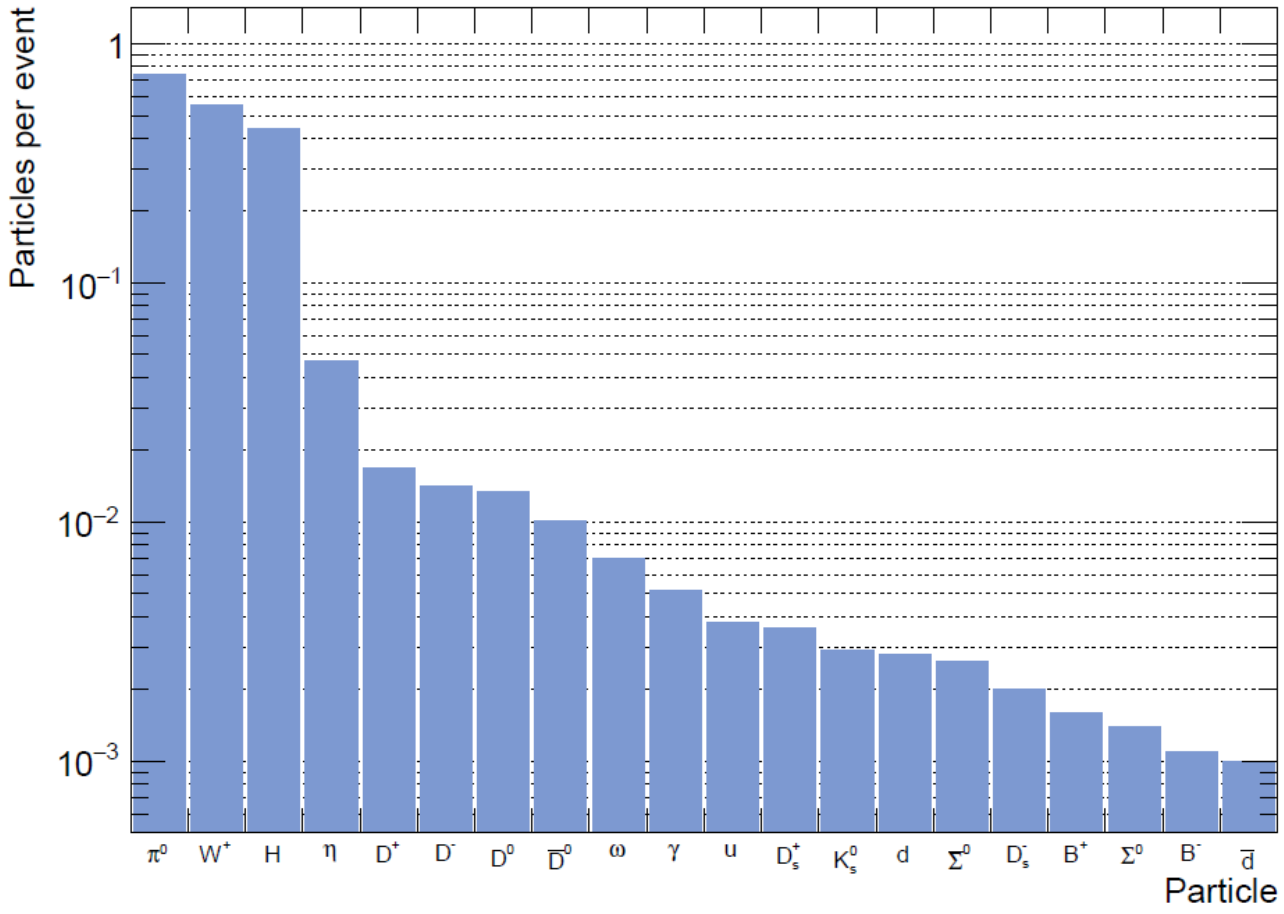
Transverse mass



Final state particles



Electron and positron mothers



	BJP article	Nika Valencic (8 TeV)	Nika Valencic (HL-LHC)
Preselection			
Jet count n_j	$= 2$	≥ 2	≥ 2
Jet p_T	> 25 GeV	> 25 GeV ($\|\eta\| < 2.4$) > 30 GeV ($2.5 < \|\eta\| < 4.5$)	> 45 GeV
Leading lepton p_T	> 20 GeV	> 22 GeV	> 25 GeV
Subleading lepton p_T	> 10 GeV	> 10 GeV	> 15 GeV
Missing E_T	> 20 GeV	no cut	$p_T^{\text{miss,jet-corr}} > 20$ (ee/$\mu\mu$?)
Lepton mass m_{ll}	no cut	> 10 GeV	> 10 GeV
Jet Vertex Fraction (JVF)	no cut	> 0.5	> 0.1 ($p_T < 50$ GeV) > 0.5 ($50 < p_T < 80$ GeV)
opposing jets $\eta_1 \cdot \eta_2 < 0$	cut	no cut?	cut
Background rejection			
Tau $m_{\tau\tau} < m_Z - 25$	no cut	cut	cut or similar cut
b-jets n_b	n/a	=0	=0
Summed p_T^{sum}	no cut	< 15 GeV	< 20
VBF topology			
Jet mass m_{jj}	> 500 GeV	> 600 GeV	> 1250 GeV
Jet rapidity difference $\Delta\eta_{jj}$	> 4.2	> 3.6	no, but $\|\eta_j\| > 2.0$
Central jet veto (CJV)	n/a	cut	cut($p_T > 30$ GeV)
Outside lepton veto (OLV)	no cut	cut	cut
$H \to WW^* \to l^+\nu l^-\bar{\nu}$ topology			
Lepton mass m_{ll}	no cut	< 50 GeV	< 60 GeV
Lepton azimuthal angle$\Delta\phi_{ll}$	no cut	< 1.8	< 1.8
Transverse mass	$50 < m_T < 130$ GeV	$m_T < 130$ GeV	$m_T < 1.07 m_H$

After showering and hadronisation

- Initial state radiation, final state radiation and hadronisation
- PYTHIA 8.2
- Clustered using anti-k_T clustering with $R = 0.4$ and $p_T > 10$ GeV
- Tagging jets selected by p_T
- Charged leptons selected by p_T and isolation from jets