Higgs Boson Searches and the Hbb Coupling at the LHeC

Tao Han and Bruce Mellado

University of Wisconsin-Madison

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Workshop on the LHeC
Electron-proton and electron-ion collisions at the LHC
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Workshop on the LHeC

Divonne, 01-03/09/09

Outline

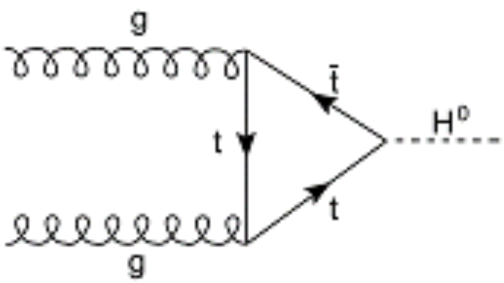
- Introduction
  - Hbb at the LHC
  - Higgs searches using VBF Higgs at the LHC
- Higgs production at the LHeC
  - Cross-sections
  - Quark Kinematics
  - Charge Current Signal
    - Event selection
    - Kinematics and results
  - Neutral Current Signal
- Outlook and Conclusions

Introduction

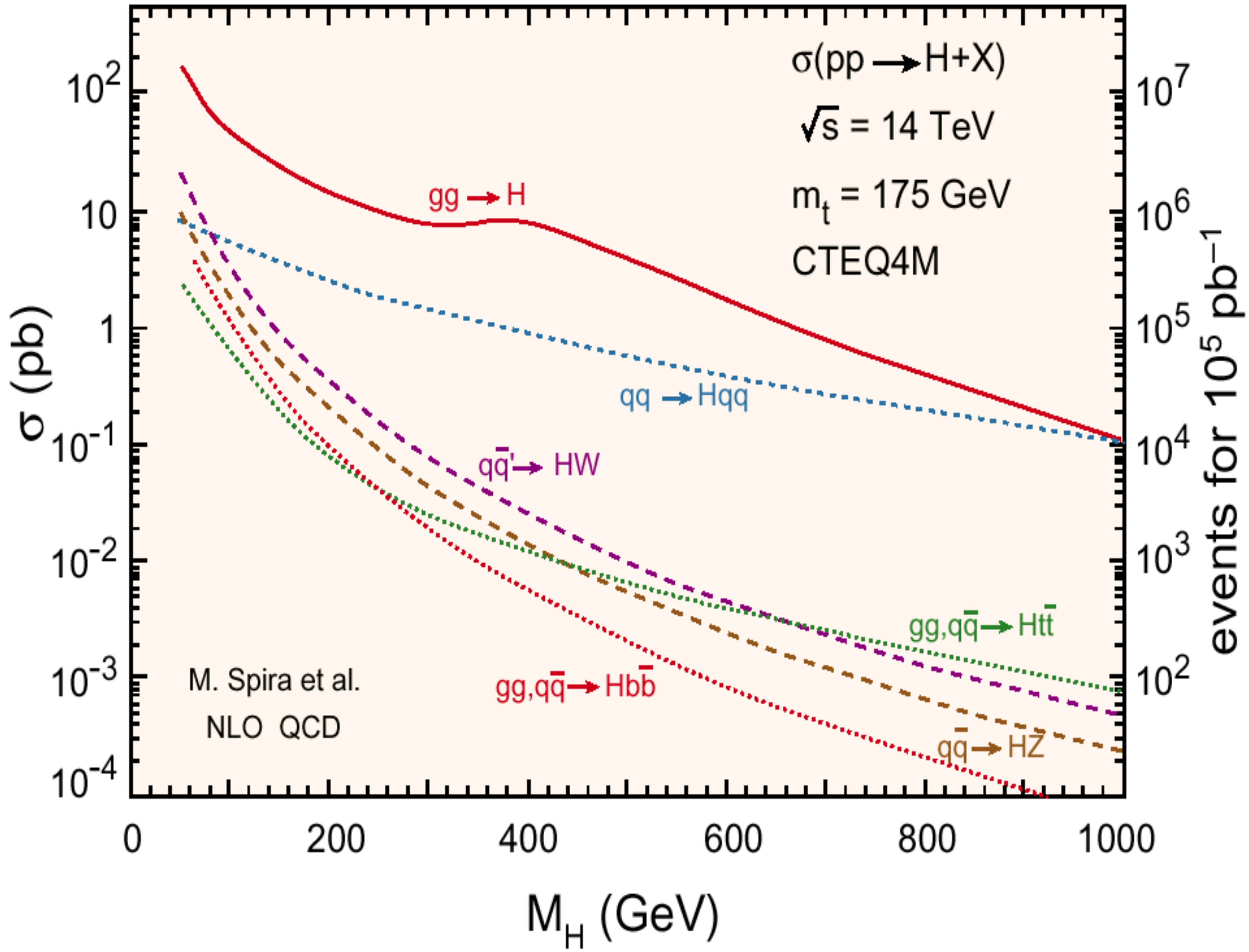
- Extensive feasibility studies indicate observation of the SM Higgs boson at the LHC possible with 1-20 fb^{-1} of integrated luminosity in entire range (M_H=115 GeV-1 TeV)
- Once the Higgs observed emphasis will shift to measuring cross-sections & couplings
- The $gg \rightarrow H$ production indirect test of Htt coupling and $H\tau\tau$ coupling reachable.
- Measurement of Hbb coupling crucial aspect, but challenging at the LHC
  - $ttH(\rightarrow bb)$ and $WH(\rightarrow bb)$ investigated
- Following U. Klein and M. Ishitsuka, we investigate the Higgs production at the LHeC
  - Use forward jet tagging to secure feasibility
    - Similar analysis reported in proceedings of Aachen Workshop 1990 by G.Grindhammer et al

Higgs Production at LHC

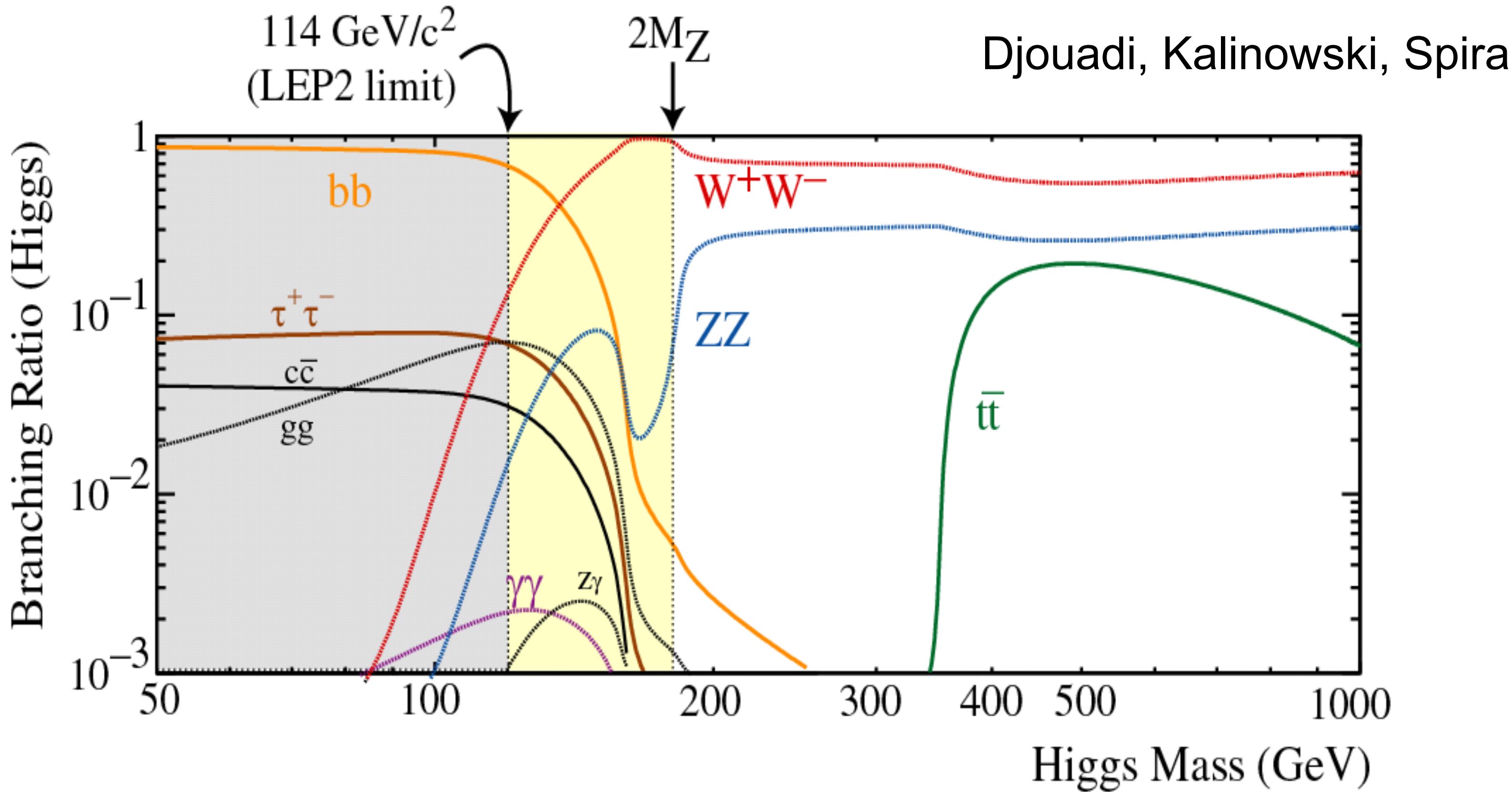
Leading Process (gg fusion)



Sub-leading Process (VBF)



Main Decay Modes



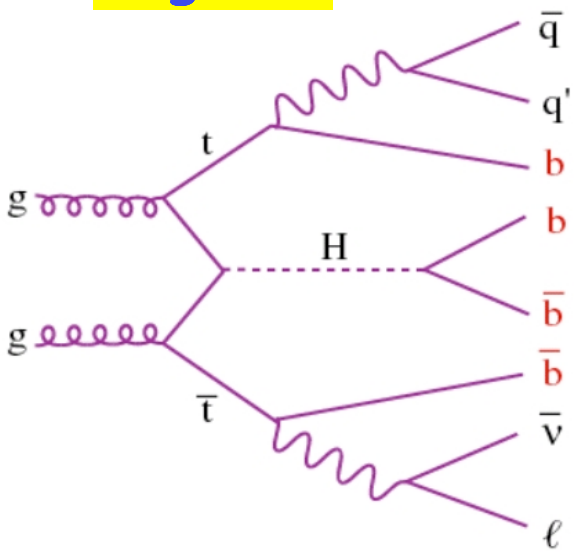
Close to LEP limit:
$H \to \gamma\gamma, \tau\tau, bb$

For M_H>140 GeV:
$H \to WW^{(*)}, ZZ^{(*)}$

H→bb at LHC

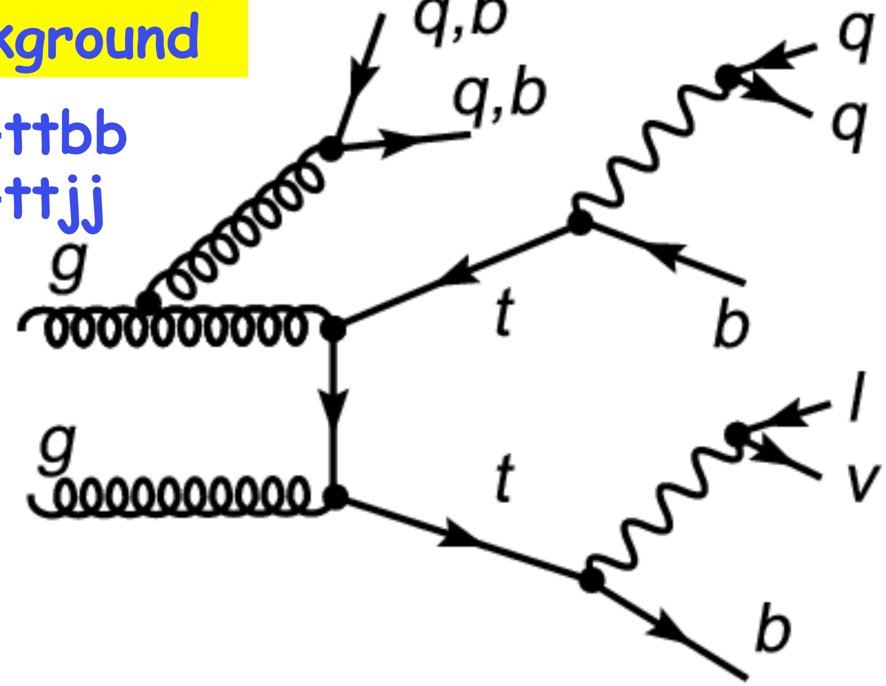
Complex final state: ttH(→bb)→lepton+ν+bbbb+jj

Signal



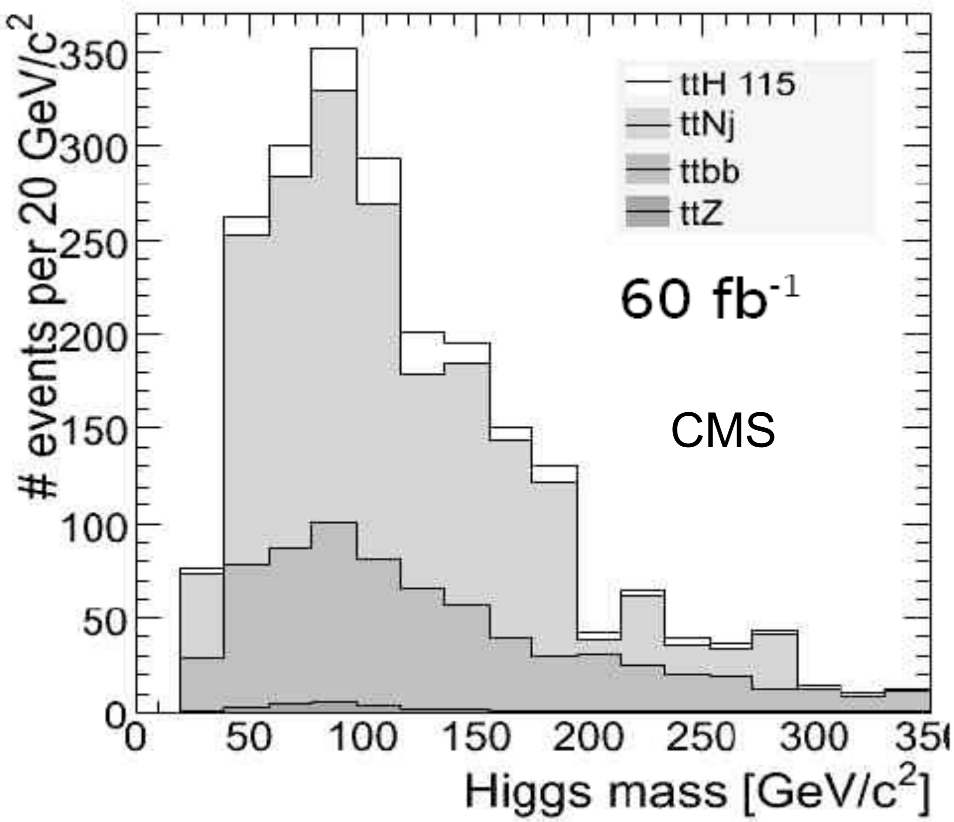
Background

pp→ttbb
pp→ttjj

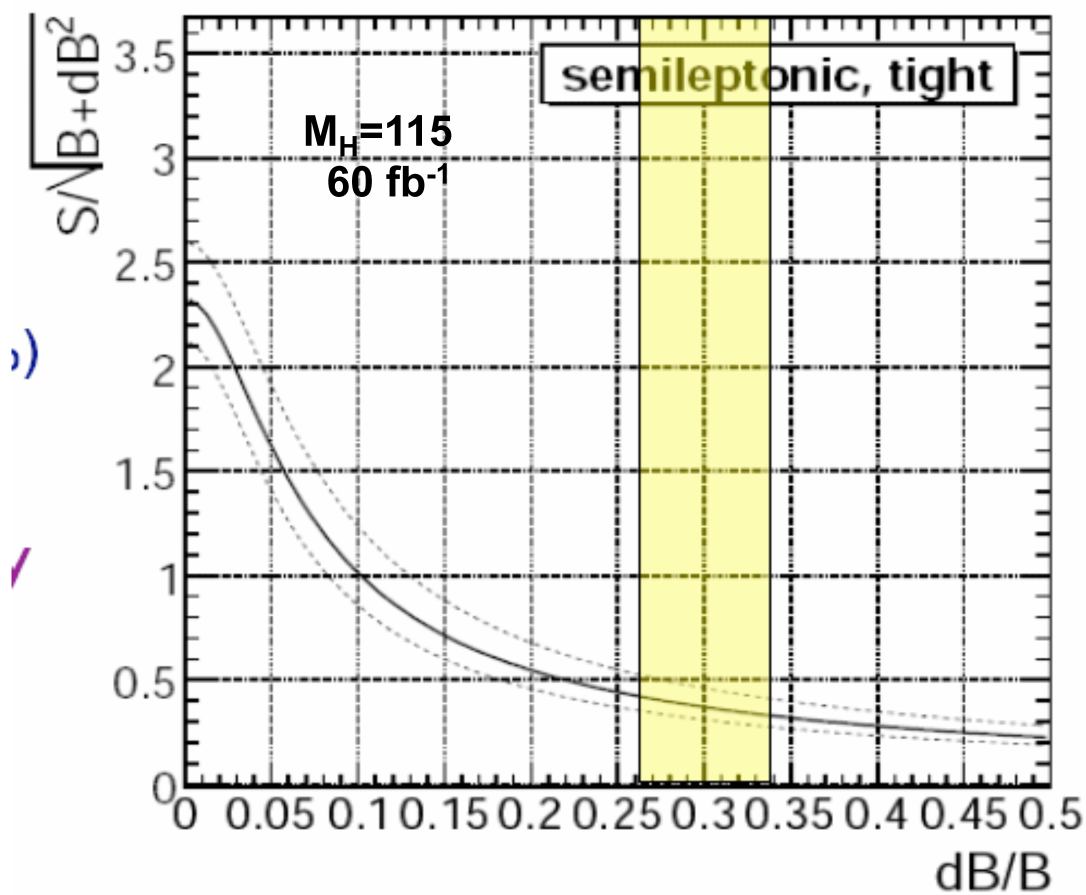


- Analysis very sensitive to b-tagging efficiency (ε_b^4)
  - Parton/Hadron level studies → $\varepsilon_b \geq 60\%$ needed
- Need ~100 times rejection against light jets and ~10 times against charm to suppress ttjj

ttH, H→bb (CMS)

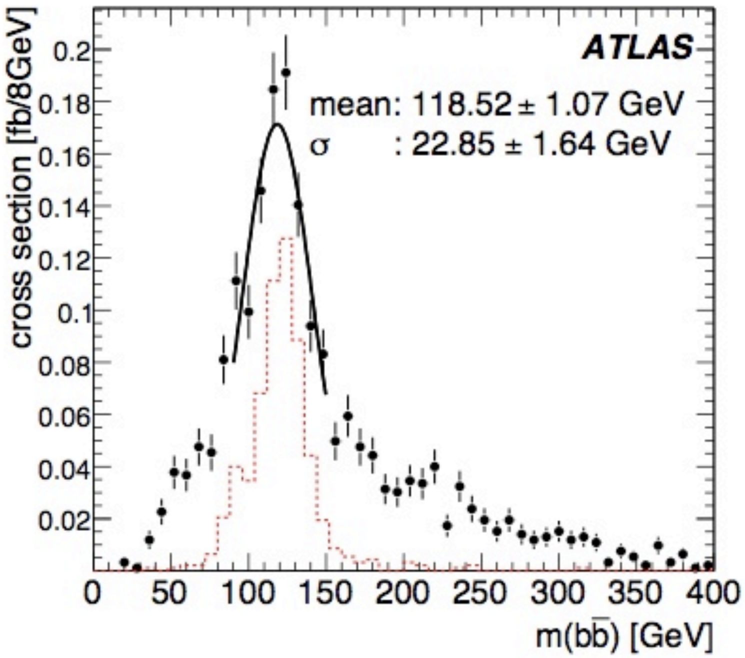


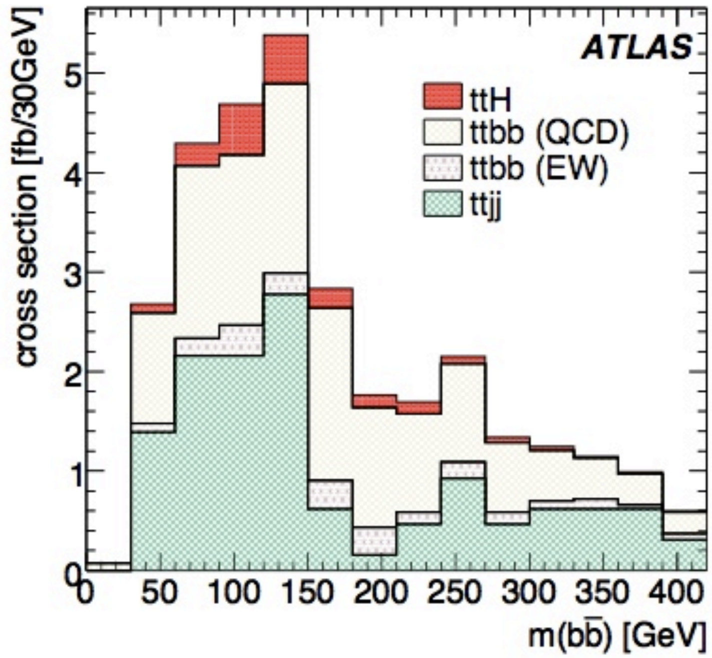
ttH 115
ttNj
ttbb
ttZ
60 fb-1
CMS
events per 20 GeV/c2
Higgs mass [GeV/c2]



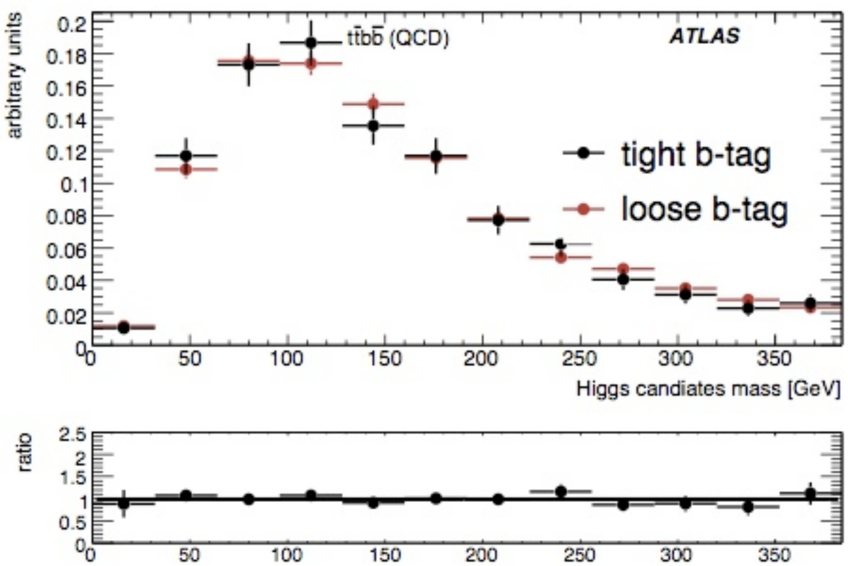
semileptonic, tight
MH=115
60 fb-1
S/√B+dB2
dB/B

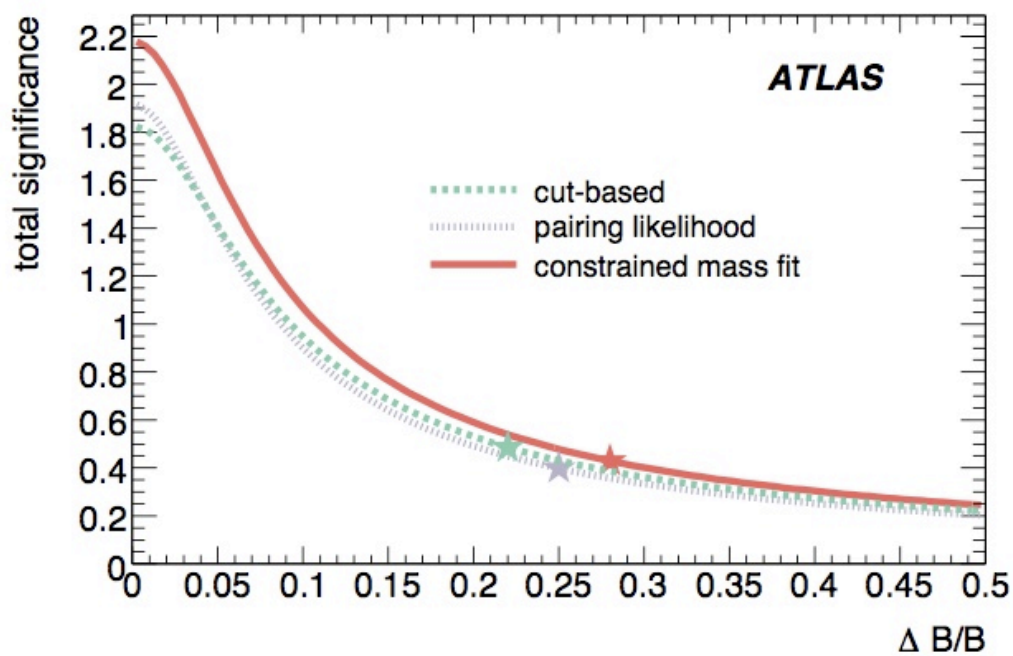
Results of cut analysis





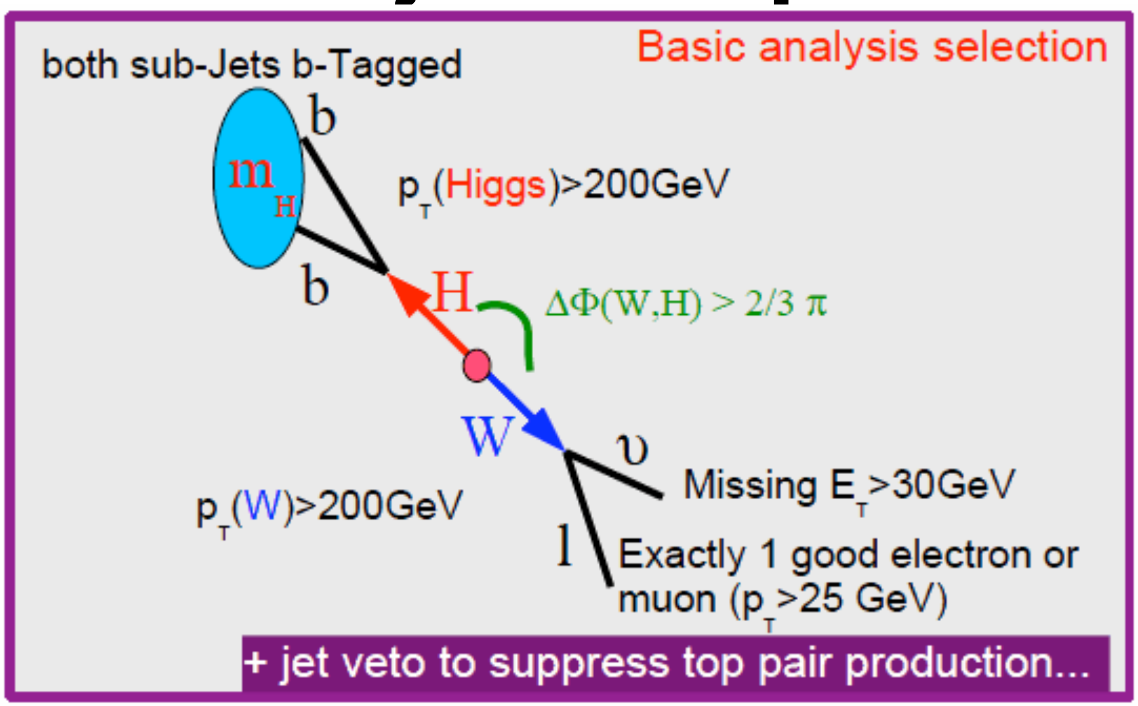
Data-driven extracion of background shape

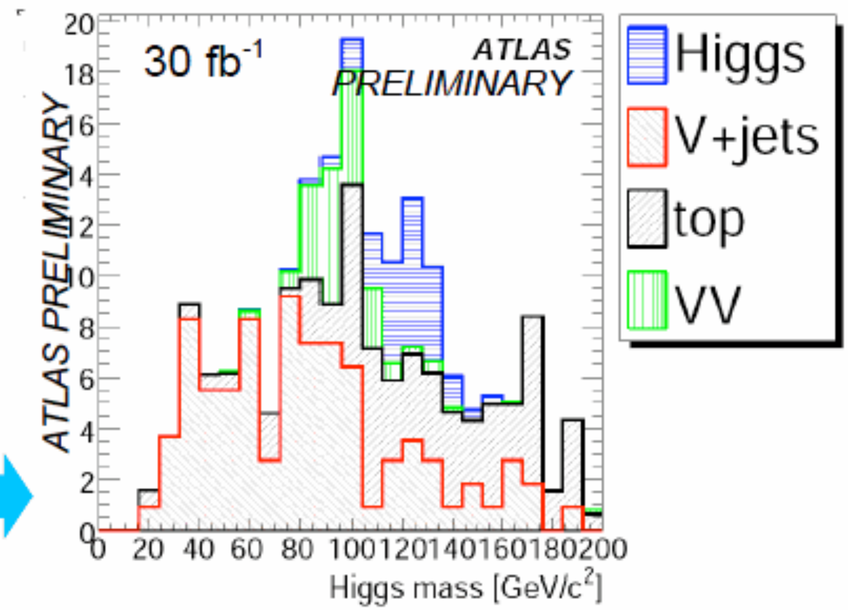




New idea for the LHC WH($\rightarrow$bb) at High P_T

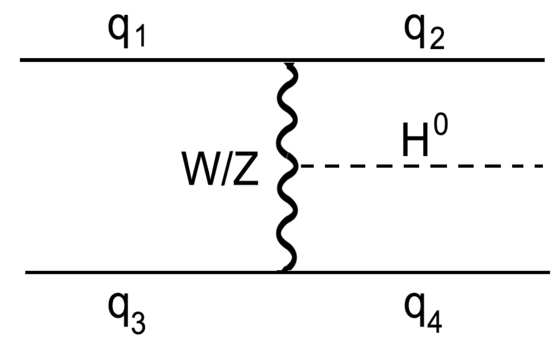
- **Proposed in [J. Butterworth et al, PRL 100:242001,2008] (together with ZH → [llbb,ννbb])**
- **Require both W and bb to have large P_T. The bb pair is very collimated. Use Cambridge-Aachen jet algorithm. Candidates with with a clear splitting into two subjets are kept. 10% mass resolution**





G.Piacquadio

Higgs via VBF
Qualitative remarks



$$\sigma(fa \to f'X) \approx \int dx dp_T^2 P_{V/f}(x, p_T^2)\sigma(Va \to X)$$

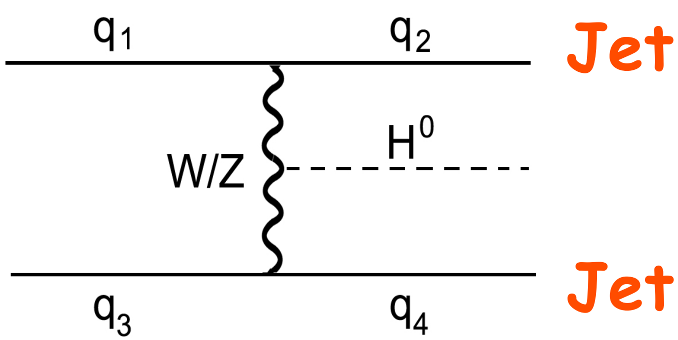
$$P_{V/f}^T(x, p_T^2) = \frac{g_V^2 + g_V^2}{8\pi^2}\frac{1+(1-x)^2}{x}\frac{p_T^2}{(p_T^2 + (1-x)M_V^2)^2}$$

$$P_{V/f}^L(x, p_T^2) = \frac{g_V^2 + g_V^2}{4\pi^2}\frac{1-x}{x}\frac{(1-x)M_V^2}{(p_T^2 + (1-x)M_V^2)^2}.$$

- **Unlike QCD partons that scale like $1/P_T^2$, here P_T~sqrt(1-x)M_W**
- **Due to the 1/x behavior of the Weak boson the outgoing parton energy (1-x)E is large → forward jets**
- **At high P_T** $P_{V/f}^T \sim 1/p_T^2$ and $P_{V/f}^L \sim 1/p_T^4$.
- **Contribution from longitudinally polarized Weak bosons is suppressed (Higgs couples to longitudinally polarized WB)**

SM Higgs + 2jets at the LHC

- **Wisconsin Pheno (D.Zeppenfeld, D.Rainwater, et al.) proposed to search for a Low Mass Higgs in association with two jets with jet veto**
  - **Central jet veto initially suggested in V.Barger, K.Cheung and T.Han in PRD 42 3052 (1990)**

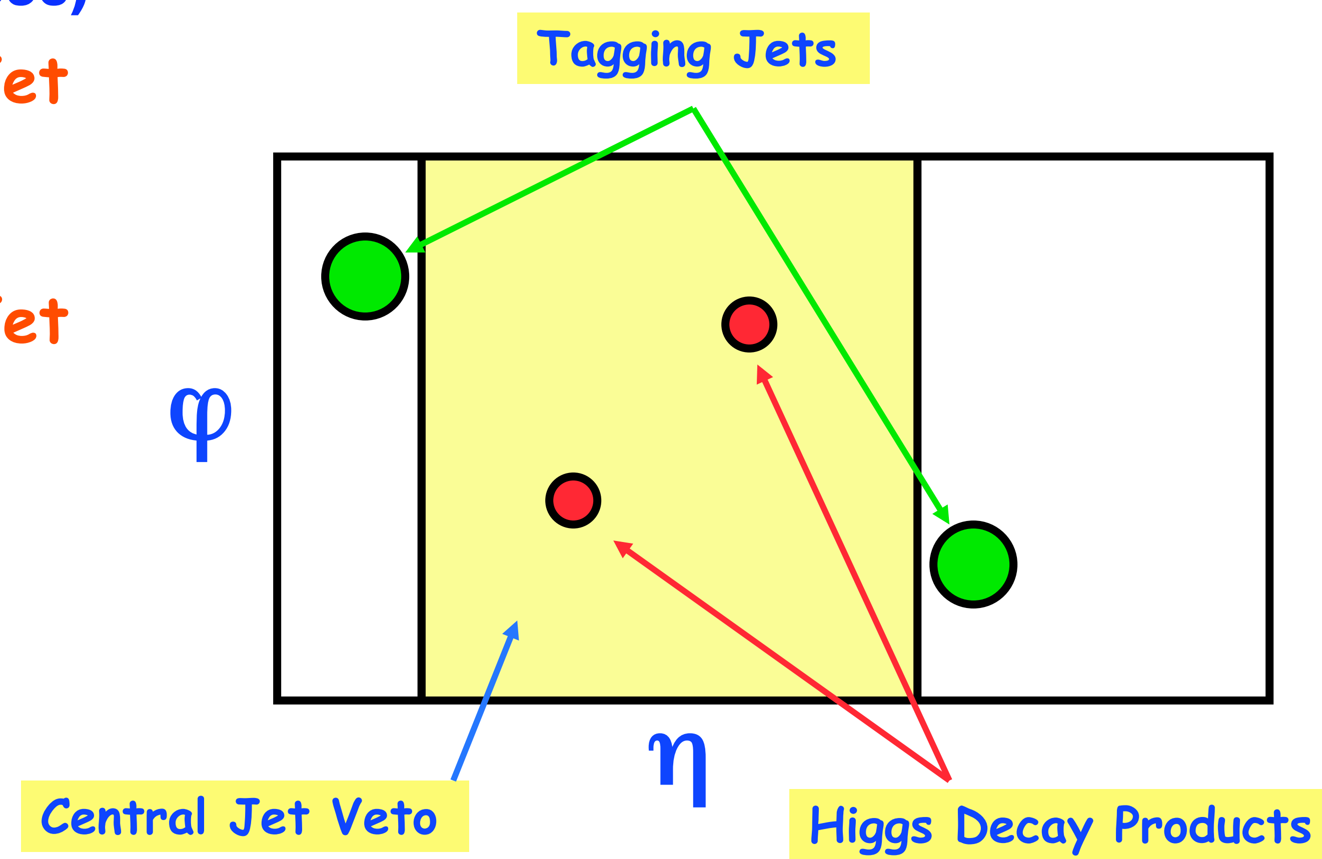


$\eta_{J1} \cdot \eta_{J2} < 0$

$\Delta\eta_{JJ} > 3.5 \div 4$

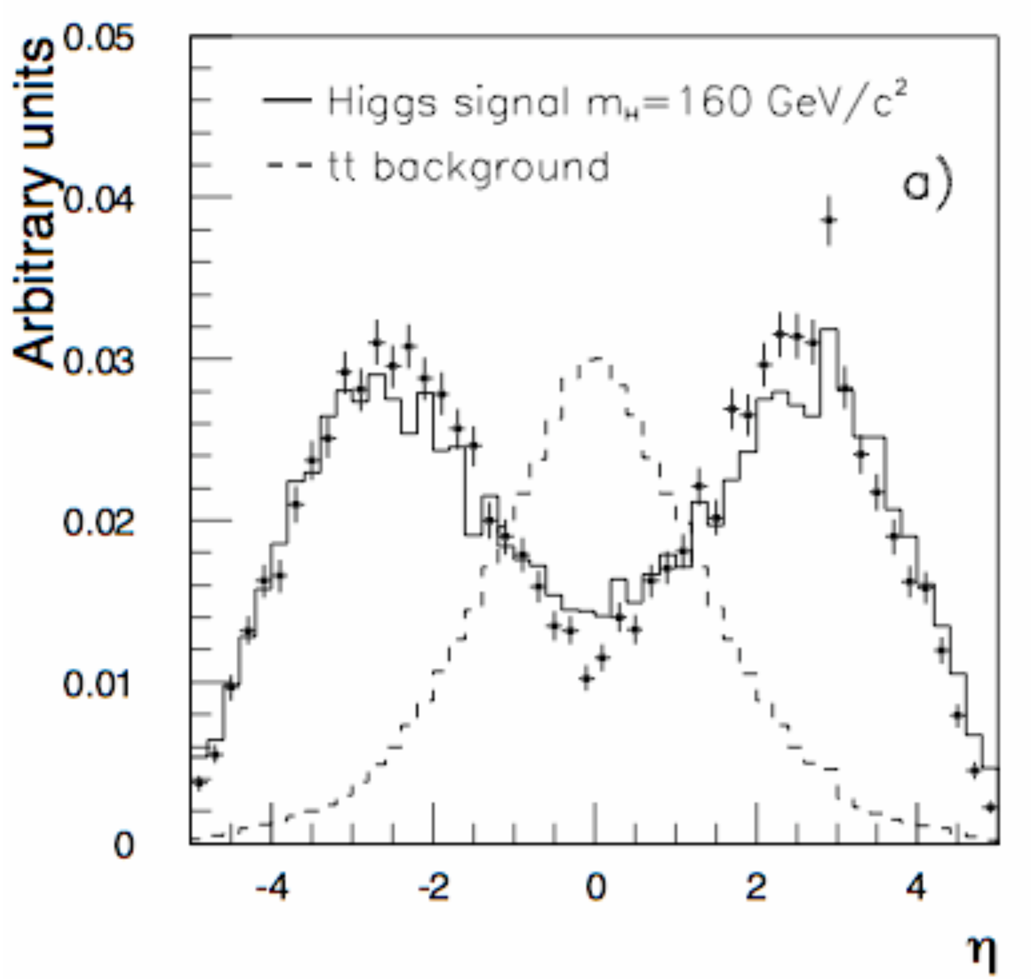
$M_{JJ} > 500 \div 700\text{GeV}$

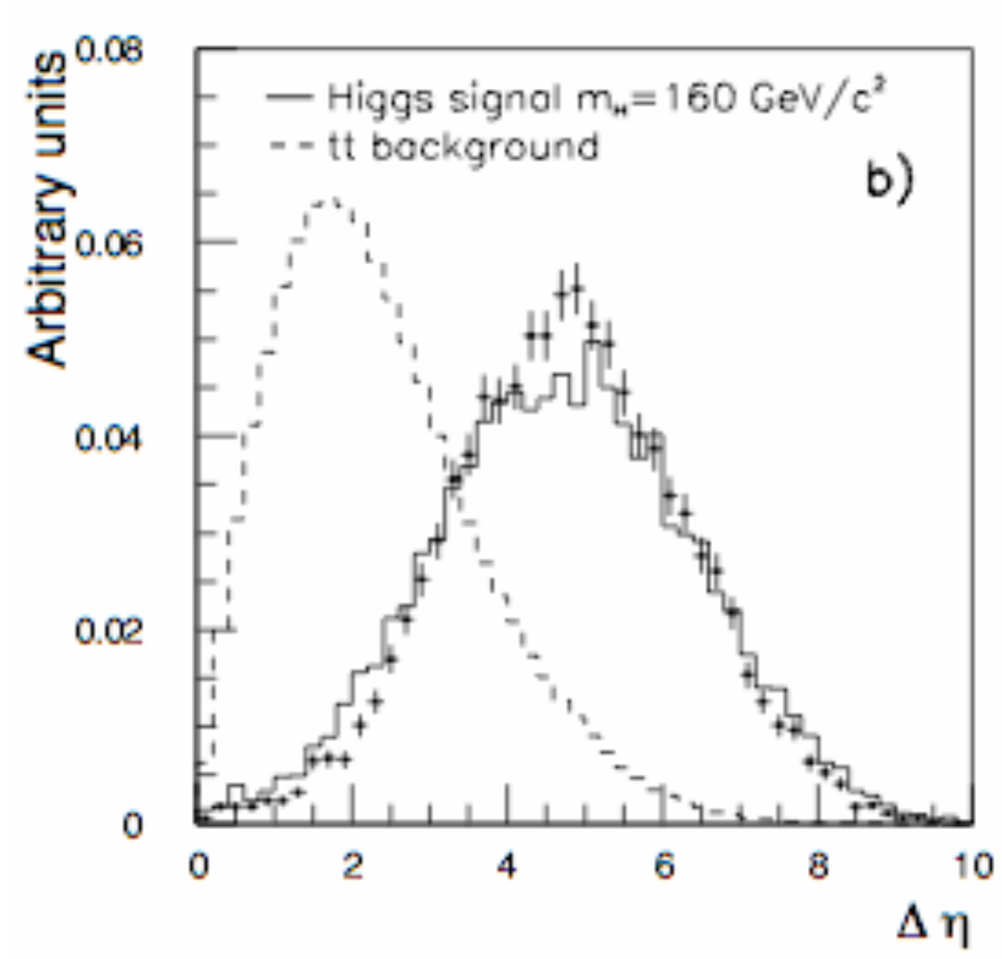
c.j.v.



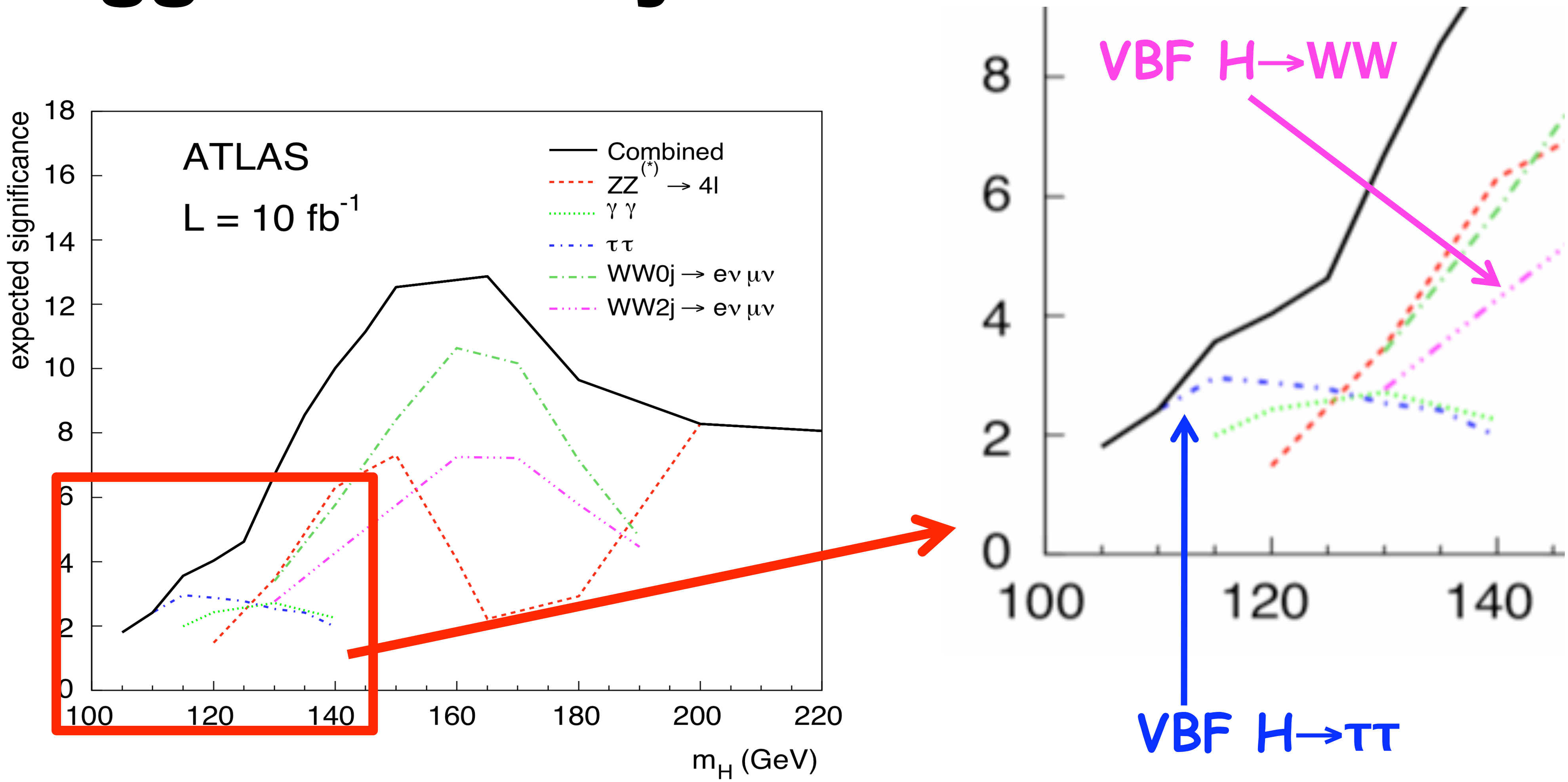
Jets in VBF Higgs

- ATLAS reported results with studies on forward tagging in full simulation in Eur. Phys J. C 32 (2004) s19
  - Histrograms – parton level. Dots - reconstruction





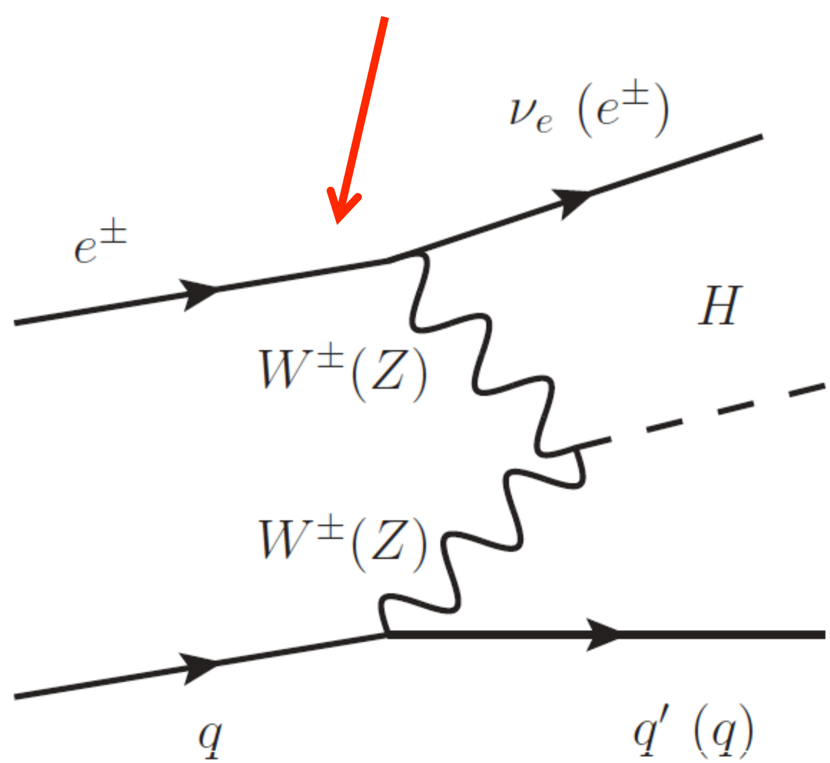
Higgs Discovery Potential with ATLAS



- ❑VBF plays very important role in Higgs discovery
  - ❑CMS and ATLAS prepared for meet the challenges of tagging forward jets

Higgs at LHeC

At LHC replace
Lepton line by quark line

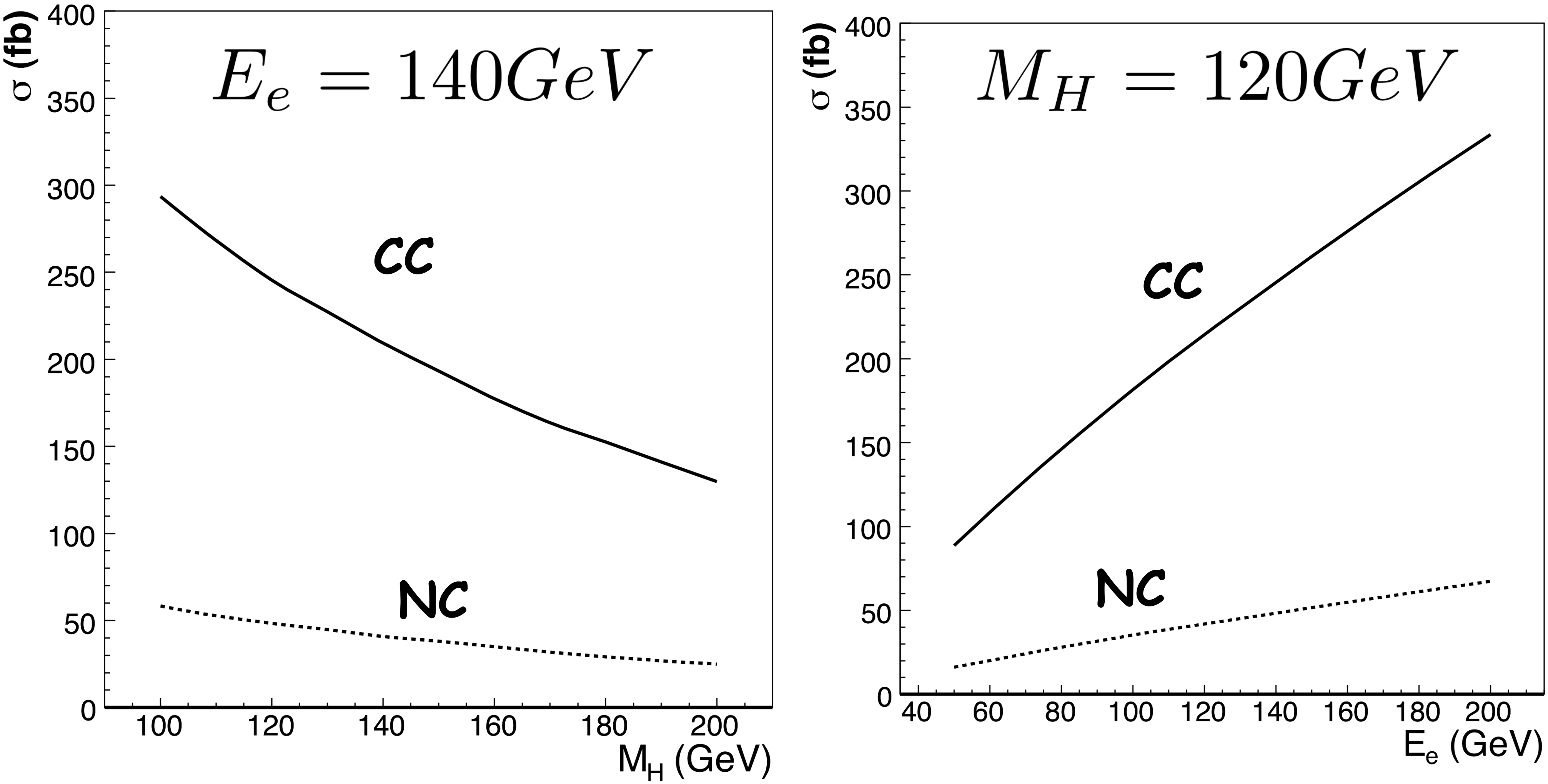


- It is remarkable that VBF diagrams were calculated for lepton nucleon collusions before for pp!
  - T.Han was involved in first calculations and a lot of the phenomenology for pp
- Consider feasibility for the following point:

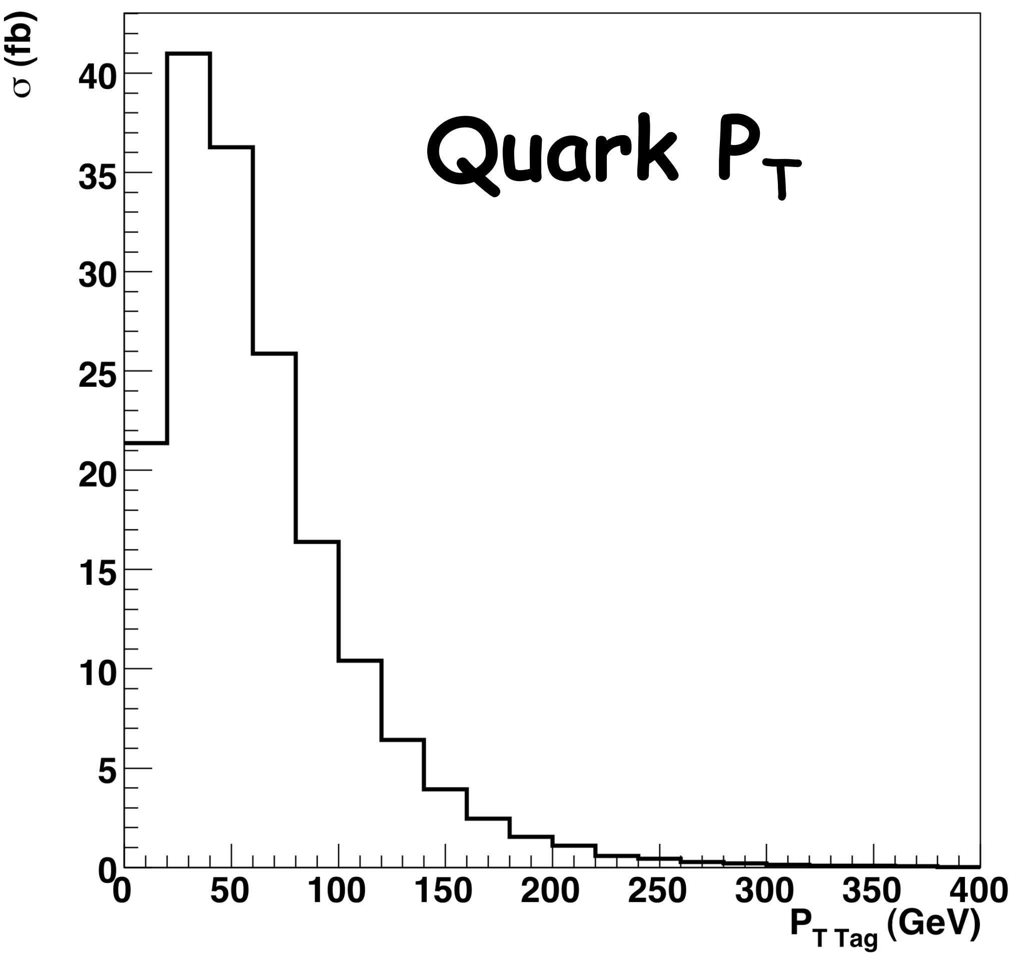
$$E_p = 7 \text{ TeV}, \quad E_e = 140 \text{ GeV}, \quad M_H = 120 \text{ GeV}$$

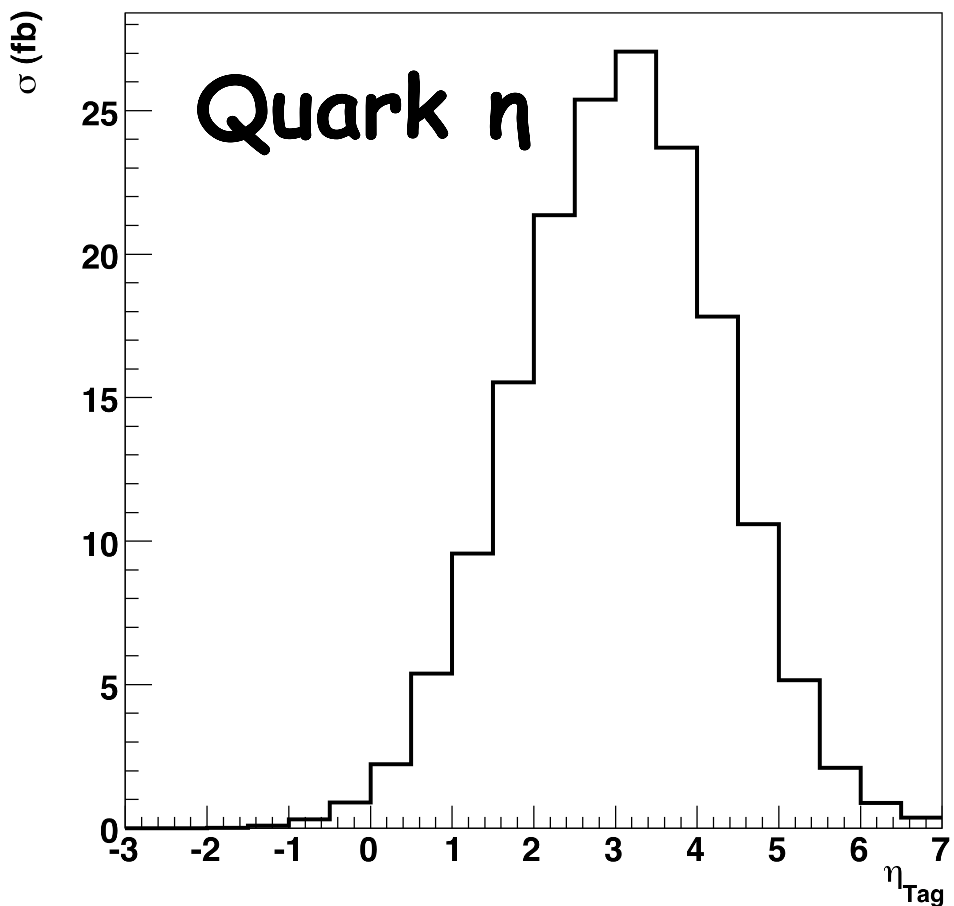
Cross-Sections

- **Used Madgraph and CTEQ6L for e^-p scattering**
  - **Set scales to M_H. Little scale dependence**

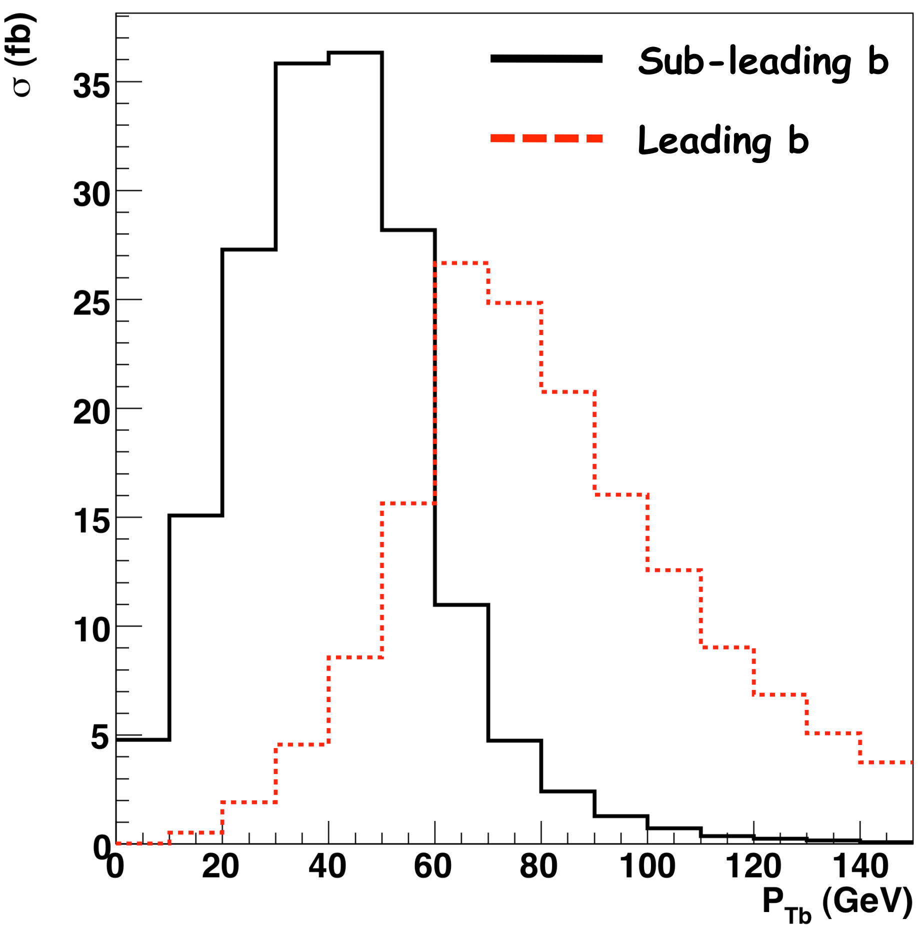


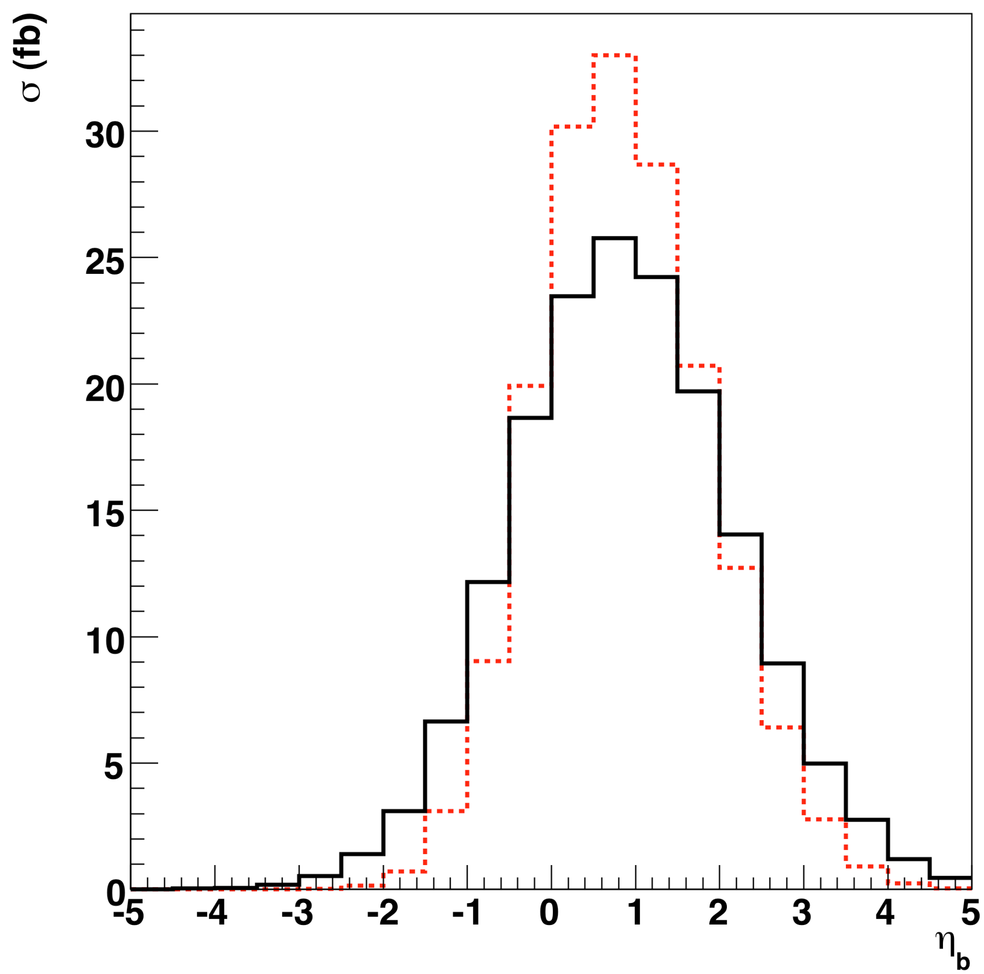
Forward Jet Kinematics





B-quark Kinematics





Charge Current Analysis

- The background processes considered are

$$e^- p \to \nu_e \; qq' \; j + X \quad \left\{ \begin{array}{l} t\bar{b} \\ b\bar{b} \\ jjj \end{array} \right.$$

$$e^- p \to e^- \; qq' \; j + X \quad \left\{ \begin{array}{l} b\bar{b}j \\ t\bar{t} \end{array} \right.$$

- Magraph, CTEQ6L, $P_{Tj} > 15GeV; \; \Delta R_{bb,bj} > 0.4$

(fb)

Cuts	CC			Photo-prod.	
	$t\bar{b}$	$b\bar{b}j$	jjj	$b\bar{b}j$	$t\bar{t}$
Generator level	3800	810	26000	48000	250

Charge Current Analysis
(Event Selection)

a $P_{Tb} > 30\,\mathrm{GeV},\ |\eta_b| < 2.5,\ \mathrm{MET}{>}25\,\mathrm{GeV},$
$\Delta\phi_{jMETmin} > 0.2,\ \mathrm{Lepton\ veto}$

b $|M_{bb} - M_H| < 10\,\mathrm{GeV}$

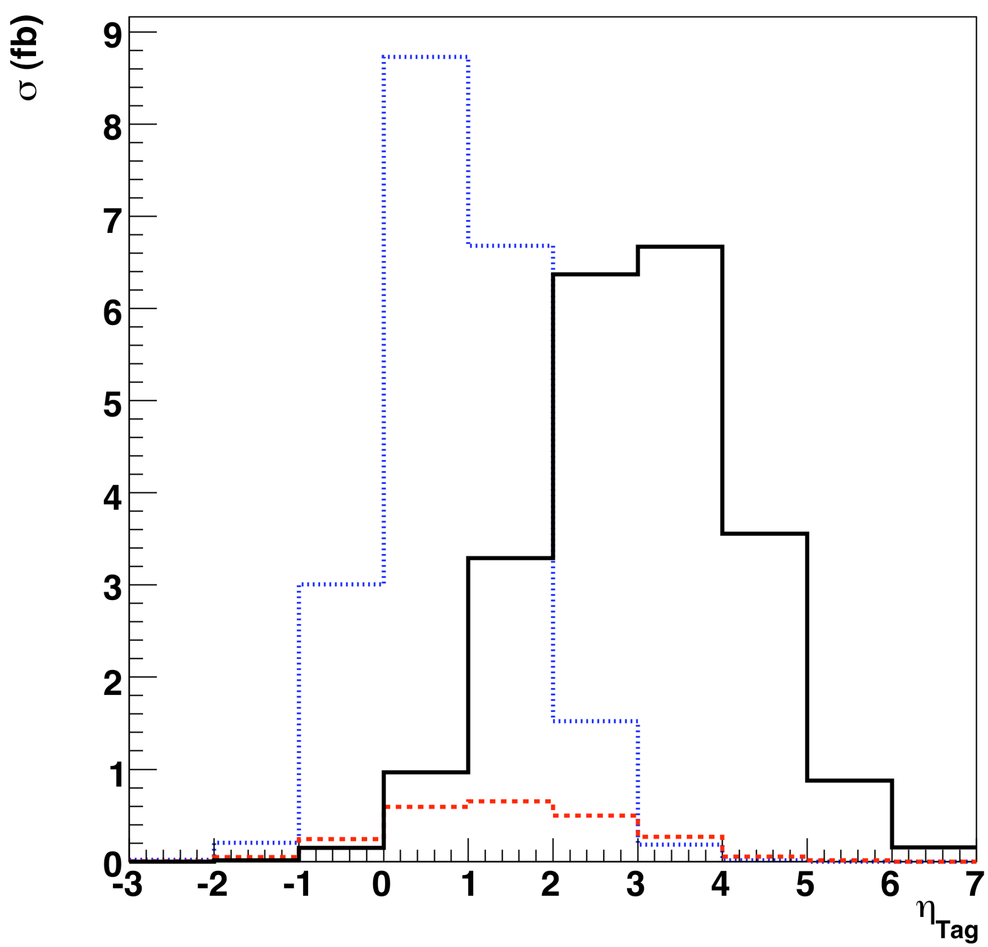
c $P_{Tj} > 30\,\mathrm{GeV\ in}\ 1 < \eta < 5$

d $M_{HJ} > 250\,\mathrm{GeV}$

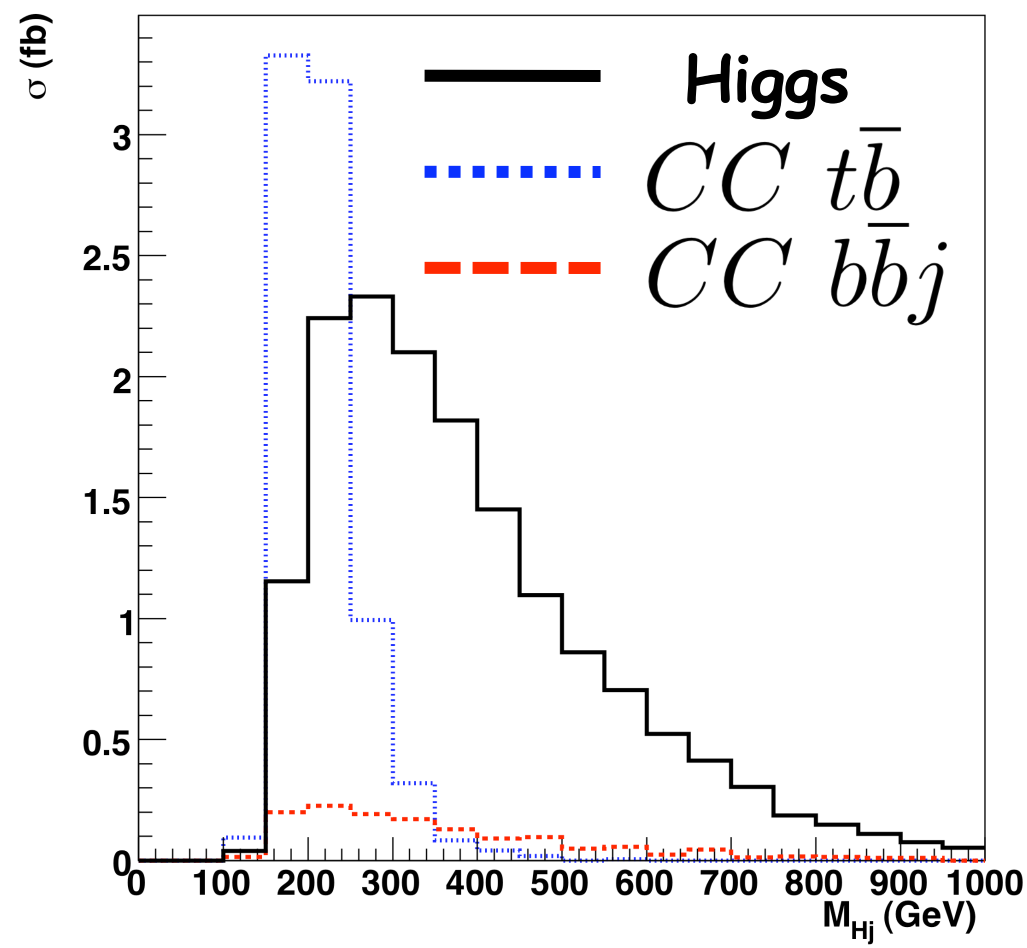
- **Parton level analysis with smearing of parton energy according to** $\frac{\sigma_E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta,\ \alpha = 0.6,\ \beta = 0.03$
- **Assume 60% b-tagging efficiency in |η|<2.5**
  - **Rejections: R_j=100 and R_c=10**

Charge Current Analysis (cont)

After cuts a-b



After cuts a-c



Charge Current Analysis (results)

(fb)

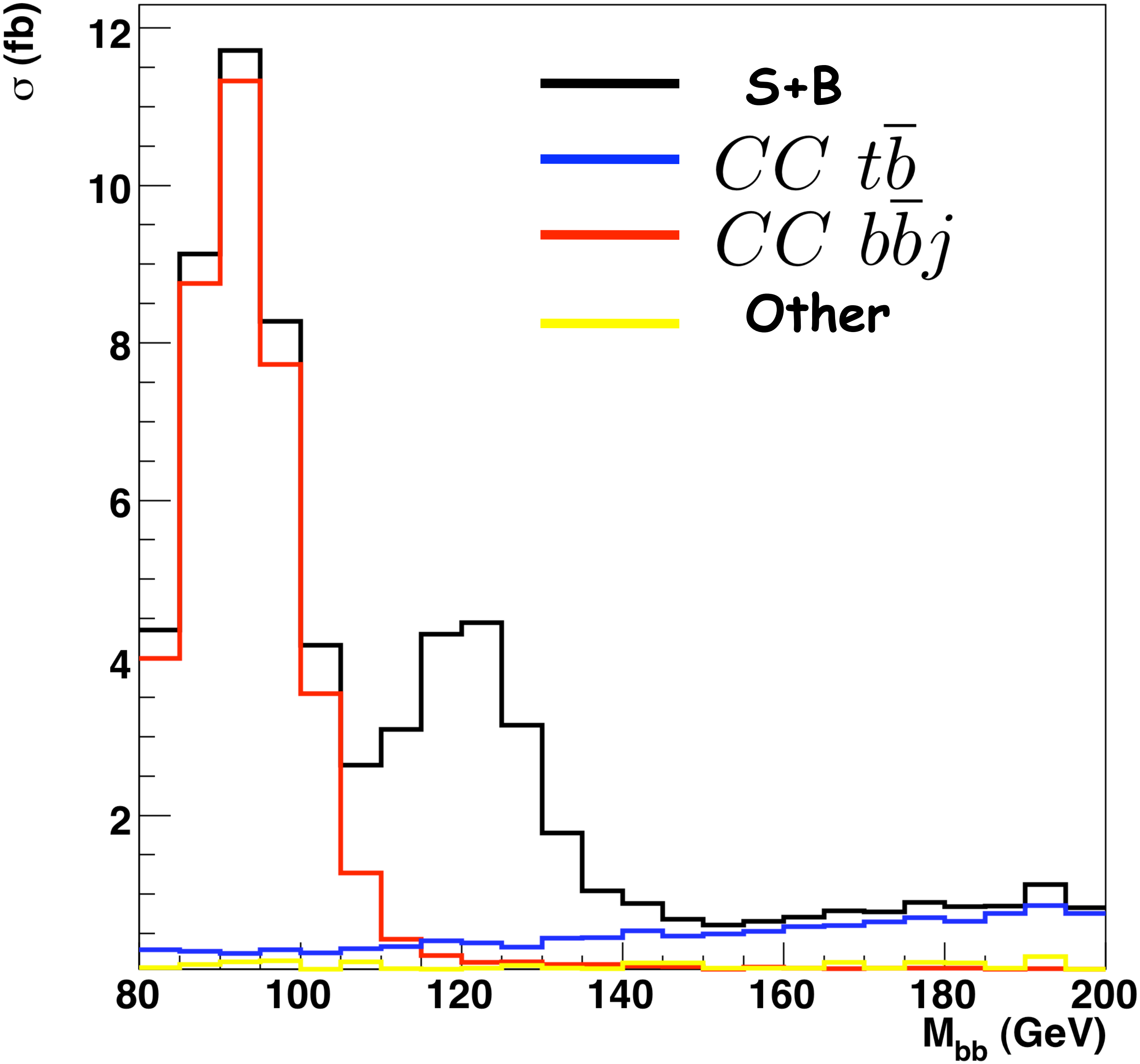
		CC			Photo-prod.		
Cuts	Higgs	$t\bar{b}$	$b\bar{b}j$	jjj	$b\bar{b}j$	$t\bar{t}$	S/B
Generator level	167	3800	810	26000	48000	250	-
a	27.95	152.70	86.25	3.77	6.92	2.29	0.11
b	22.33	20.35	2.37	0.36	0.67	0.27	0.93
c	15.64	8.10	1.36	0.12	0.25	0.14	1.57
d	12.37	1.46	0.92	0.06	0.14	0.04	4.73

Photo-production bbj production from resolved photons not included in this study

Note increase of S/B as forward parton tagging and M_{HJ} cuts are applied

The application of a veto on additional jets with P_{TJ}>30 GeV and |η|<5 reduces top backgrounds by ~40% with a 7% loss of signal efficiency

Charge Current Analysis (results)



Charge Current Analysis (results)

Effect of Jet Energy Resolution

Nominal

Cuts	Higgs	CC $t\bar{b}$	CC $b\bar{b}j$	CC jjj	Photo-prod. $b\bar{b}j$	Photo-prod. $t\bar{t}$	S/B
Generator level	167	3800	810	26000	48000	250	-
a	27.95	152.70	86.25	3.77	6.92	2.29	0.11
b	22.33	20.35	2.37	0.36	0.67	0.27	0.93
c	15.64	8.10	1.36	0.12	0.25	0.14	1.57
d	12.37	1.46	0.92	0.06	0.14	0.04	4.73

$$\frac{\sigma_E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta,\ \alpha = 0.7,\ \beta = 0.05$$

Cuts	Higgs	CC $t\bar{b}$	CC $b\bar{b}j$	CC jjj	Photo-prod. $b\bar{b}j$	Photo-prod. $t\bar{t}$	S/B
a	27.87	153.33	85.46	3.75	33.96	2.28	0.10
b	18.55	20.04	3.51	0.36	4.70	0.27	0.64
c	13.03	7.93	2.24	0.12	1.91	0.14	1.06
d	10.27	1.57	1.64	0.06	1.31	0.03	2.23

Charge Current Analysis (results)

Effect of Range of b-tagging

Nominal

		CC			Photo-prod.		
Cuts	Higgs	$t\bar{b}$	$b\bar{b}j$	jjj	$b\bar{b}j$	$t\bar{t}$	S/B
Generator level	167	3800	810	26000	48000	250	-
a	27.95	152.70	86.25	3.77	6.92	2.29	0.11
b	22.33	20.35	2.37	0.36	0.67	0.27	0.93
c	15.64	8.10	1.36	0.12	0.25	0.14	1.57
d	12.37	1.46	0.92	0.06	0.14	0.04	4.73

$$|\eta_b| < 2.5 \rightarrow |\eta_b| < 3$$

		CC			Photo-prod.		
Cuts	Higgs	$t\bar{b}$	$b\bar{b}j$	jjj	$b\bar{b}j$	$t\bar{t}$	S/B
a	30.23	174.51	94.51	4.15	7.03	2.74	0.11
b	24.41	22.74	2.68	0.39	0.67	0.32	0.91
c	17.08	9.51	1.57	0.13	0.25	0.18	1.47
d	13.15	1.65	1.01	0.05	0.14	0.04	4.55

Charge Current Analysis (results)

Effect of Jet P_T

Nominal

		CC			Photo-prod.		
Cuts	Higgs	$t\bar{b}$	$b\bar{b}j$	jjj	$b\bar{b}j$	$t\bar{t}$	S/B
Generator level	167	3800	810	26000	48000	250	-
a	27.95	152.70	86.25	3.77	6.92	2.29	0.11
b	22.33	20.35	2.37	0.36	0.67	0.27	0.93
c	15.64	8.10	1.36	0.12	0.25	0.14	1.57
d	12.37	1.46	0.92	0.06	0.14	0.04	4.73

$$P_{Tj,b} > 30\,GeV \;\rightarrow\; P_{Tj,b} > 20\,GeV$$

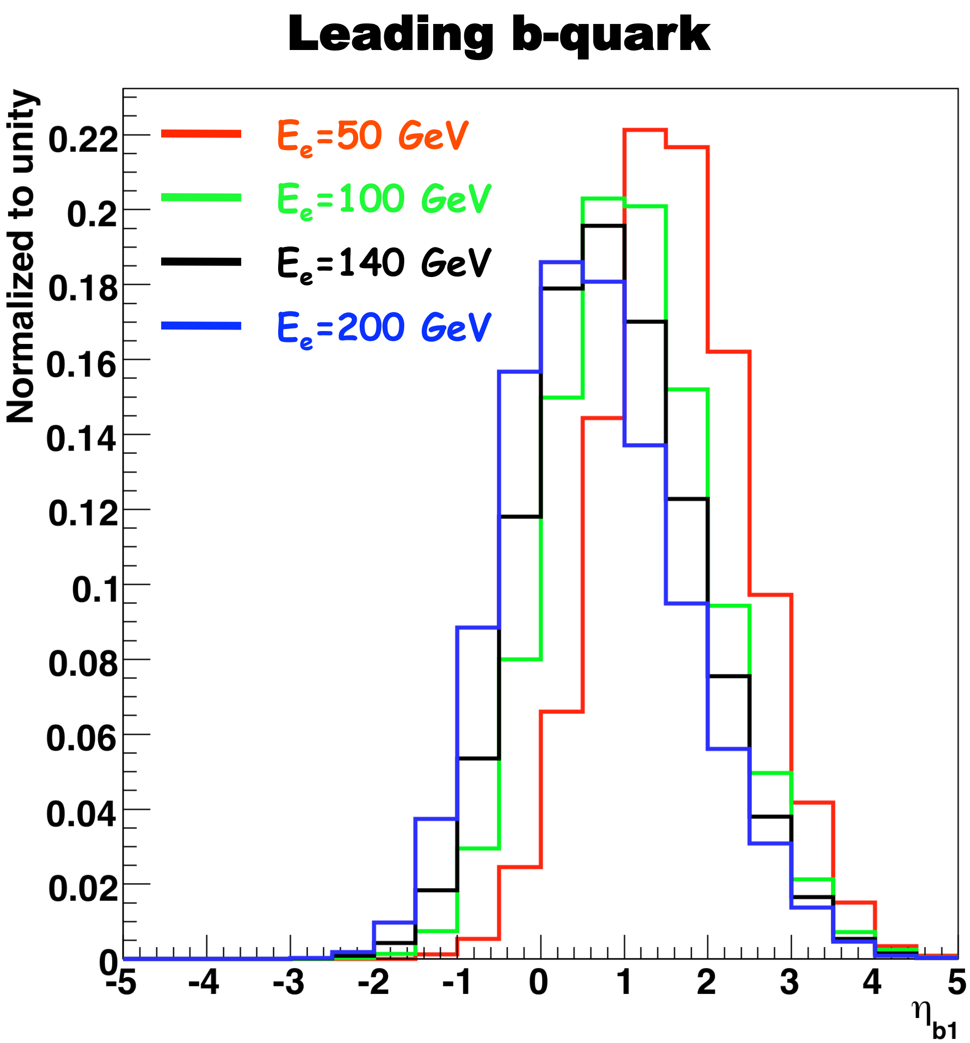
		CC			Photo-prod.		
Cuts	Higgs	$t\bar{b}$	$b\bar{b}j$	jjj	$b\bar{b}j$	$t\bar{t}$	S/B
a	33.48	208.46	134.97	5.85	8.12	2.62	0.09
b	26.52	24.90	2.91	0.47	0.88	0.30	0.90
c	21.47	10.16	1.79	0.26	0.42	0.16	1.68
d	16.24	1.71	1.18	0.10	0.32	0.04	4.84

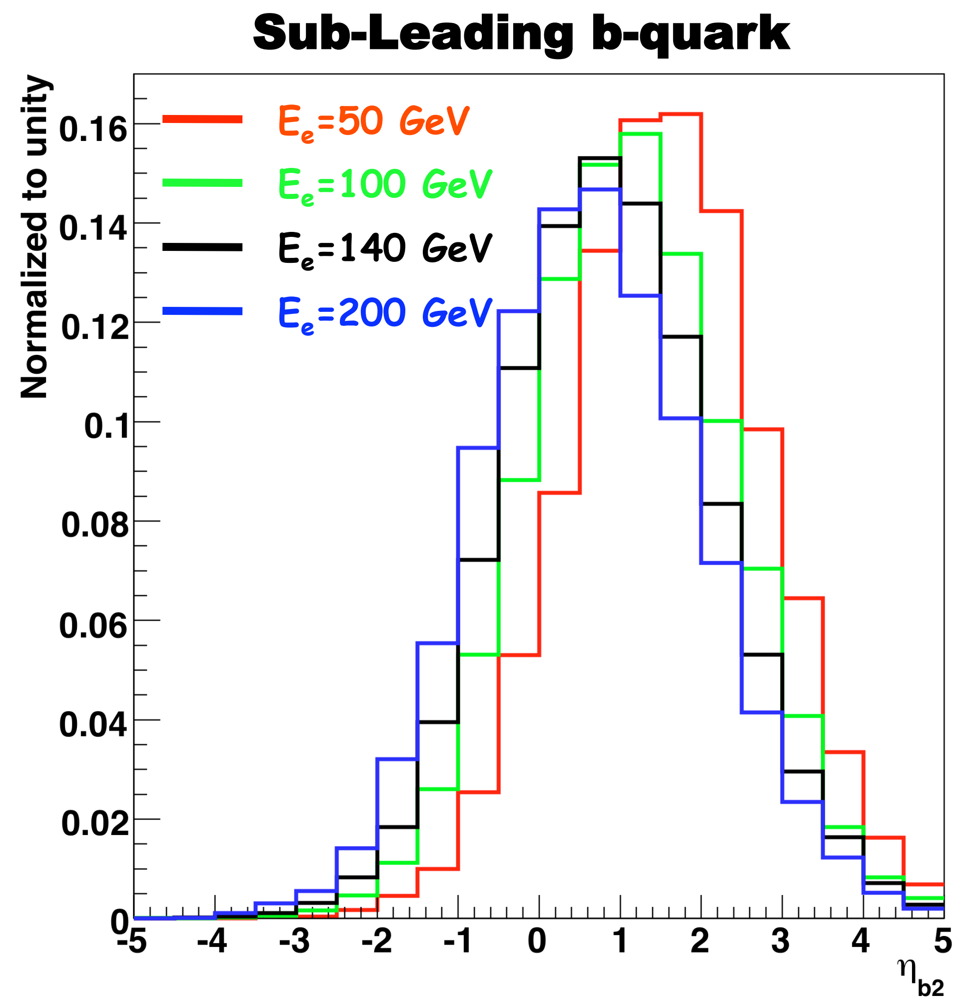
Signal Efficiency for Different E_e

- First row: Cumulative efficiency
- Second row: Efficiency w.r.t. previous cut

Cut	$E_e = 50$	$E_e = 100$	$E_e = 140$	$E_e = 200$
a	0.129 -	0.157 -	0.166 -	0.171 -
b	0.109 0.84	0.127 0.81	0.132 0.80	0.136 0.80
c	0.076 0.70	0.090 0.71	0.093 0.70	0.095 0.70
d	0.050 0.66	0.067 0.75	0.073 0.79	0.078 0.82

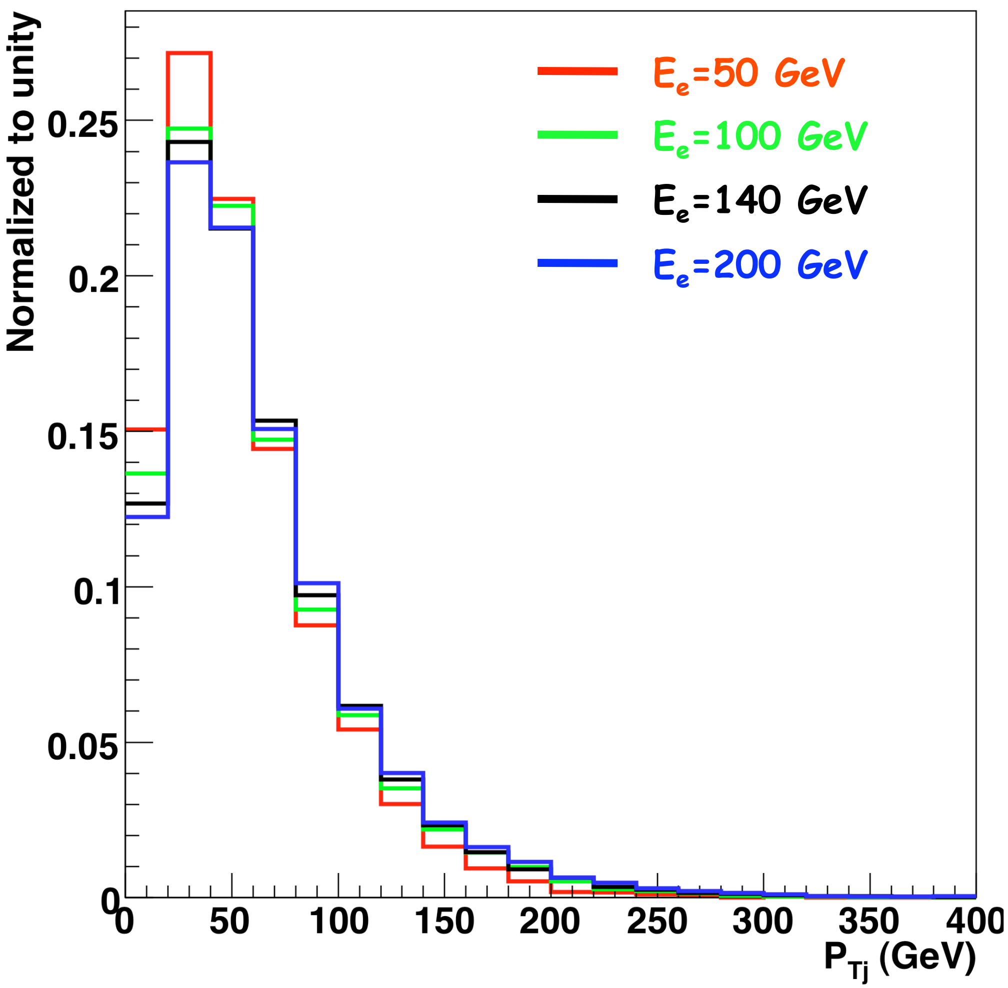
Energy Dependence of b-quark Kinematics

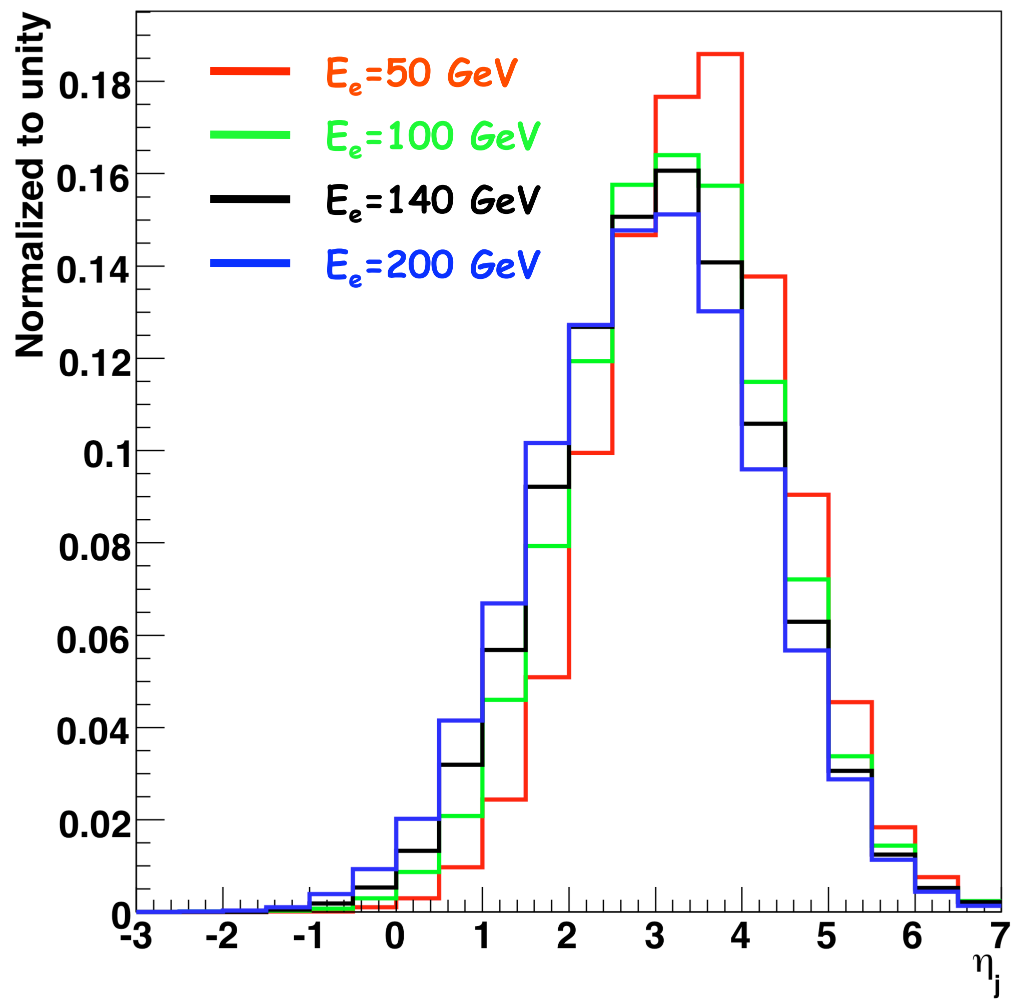




P_T of b-quarks displays little dependence on E_e

Energy Dependence of Forward parton Kinematics





Neutral Current Analysis

- The search for a Higgs boson in NC events is very interesting since it displays a very clean signature due to the presence of a high P_T electron.
- Backgrounds considered:

$$e^- p \rightarrow e^- b\bar{b}j + X \text{ and } e^- p \rightarrow e^- W^{\pm} b\bar{b}j$$

- Applied cuts at the generator level:

$$P_{Tj,b,e} > 30\, GeV,\ \ |\eta_{j,e}| < 5,\ \ |\eta_b| < 2.5, \Delta R_{bb,bj} > 0.4$$

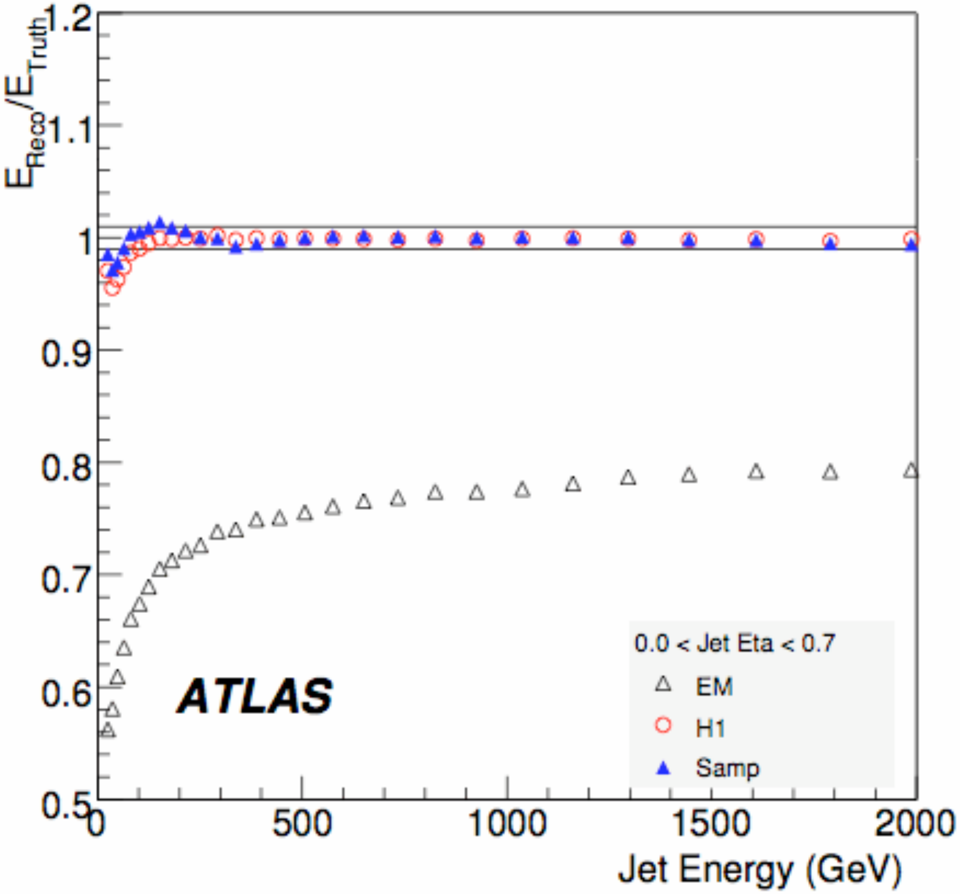
$$|M_{b\bar{b}} - M_H| < 10\, GeV$$

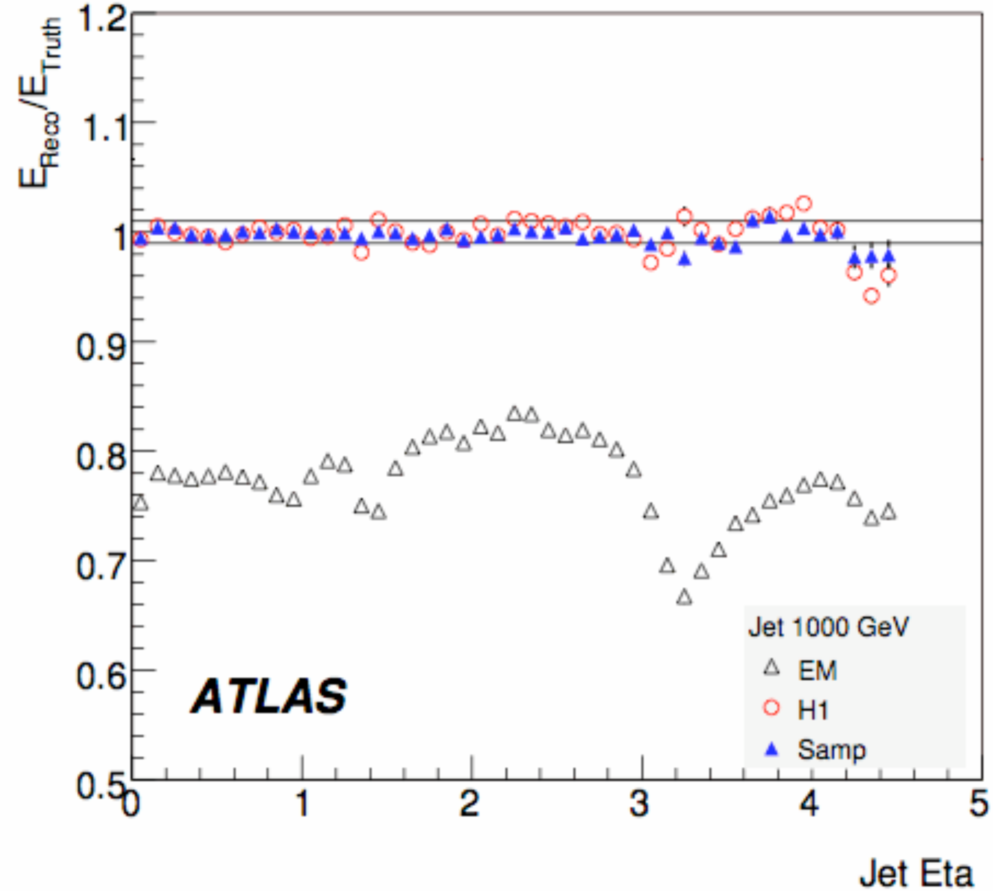
- Signal and background cross-section of 5.7fb and 23.7fb → S/B~0.25
  - Second background process is negligible

Outlook and Conclusions

- The Higgs can be discovered at the LHC. However, measurement of Hbb coupling challenging
- Use of forward jet tagging to isolate the Higgs signal at LHeC very important
  - Forward jet tagging secures feasibility of the Higgs search in CC and NC events
- Excellent hadronic jet resolution and high b-jet tagging efficiency are critical experimental issues
  - Lowering jet P_T thresholds to 20 GeV (parton-level) leads to significant enhancement of signal yield
  - Good control of top background required
- The sensitivity can be improved significantly

Extra Slides

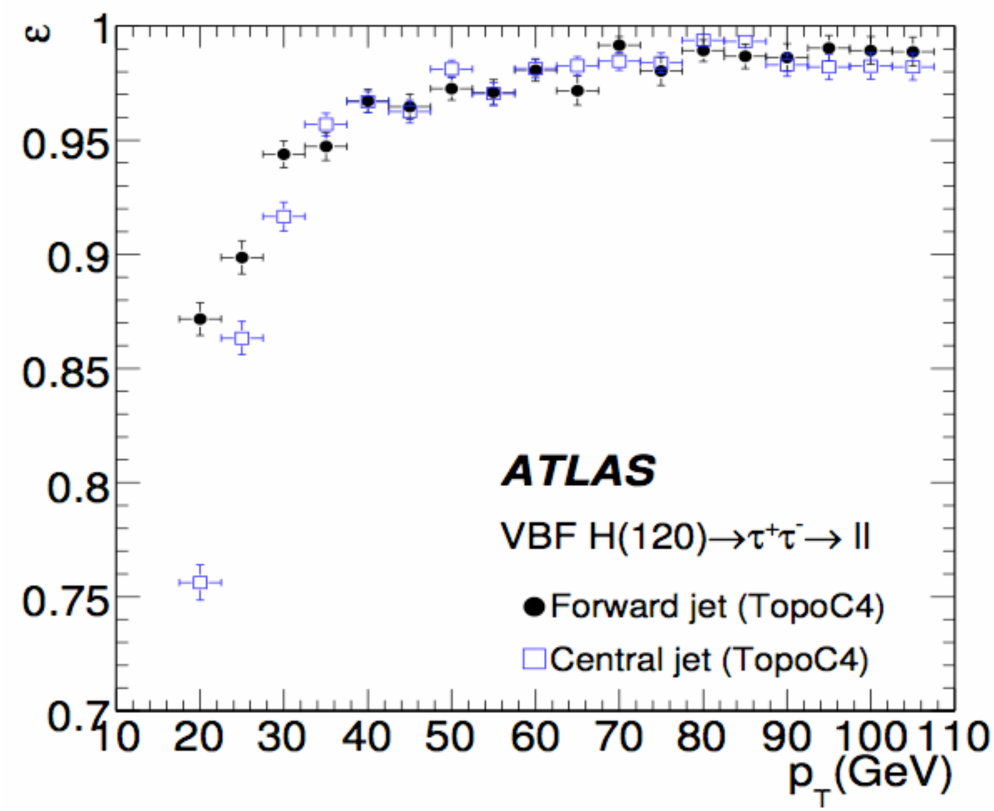


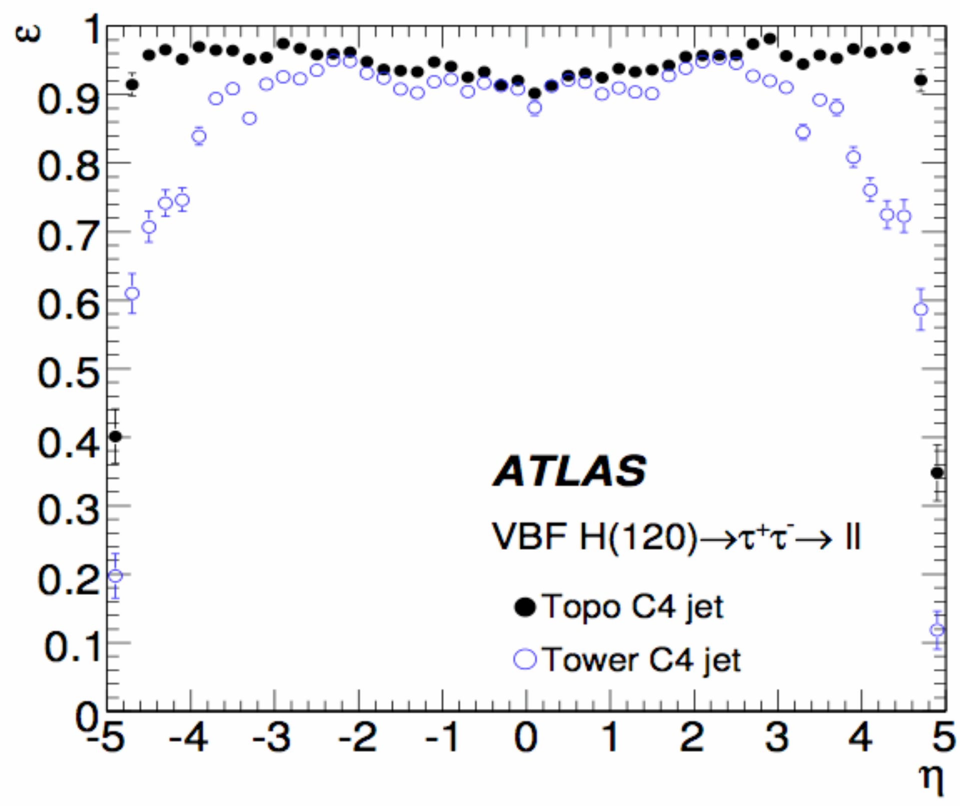


Reconstruction Algorithm	$0 < \eta < 0.5$			$1.5 < \eta < 2.5$		
	a (%)	b (%)	c (GeV)	a (%)	b (%)	c (GeV)
Cone $R_{\rm cone} = 0.7$ Tower	64 ± 4	2.6 ± 0.1	4.9 ± 0.5	103 ± 10	2.6 ± 0.8	8 ± 1
$k_{\rm T} R = 0.6$ Tower	68 ± 5	2.5 ± 0.2	6.3 ± 0.5	110 ± 1	1 ± 1	12.2 ± 2.5
Cone $R_{\rm cone} = 0.7$ Topo	63 ± 4	2.7 ± 0.1	4.2 ± 0.5	107 ± 8	1 ± 1	6.5 ± 1.5
$k_{\rm T} R = 0.6$ Topo	64 ± 5	2.7 ± 0.2	5.4 ± 0.5	112 ± 4	1 ± 1	10.0 ± 1.5

Jets in VBF Higgs

- ATLAS chose to use narrow jets for the VBF analyses. Prefer jets based on topological clusters, as opposed to tower based
  - The latter statement may be reviewed in the future

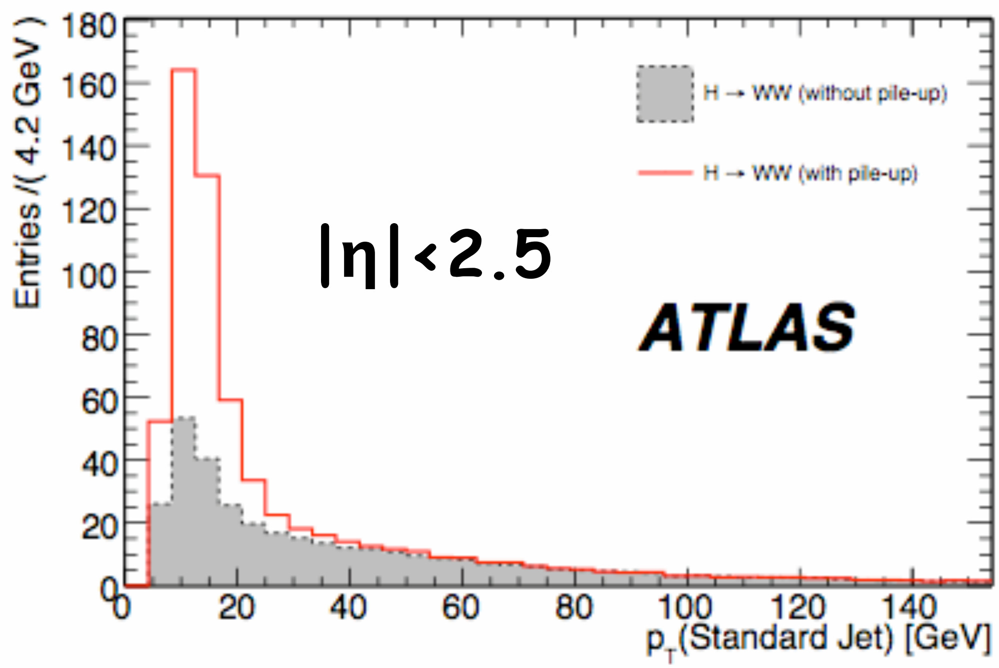


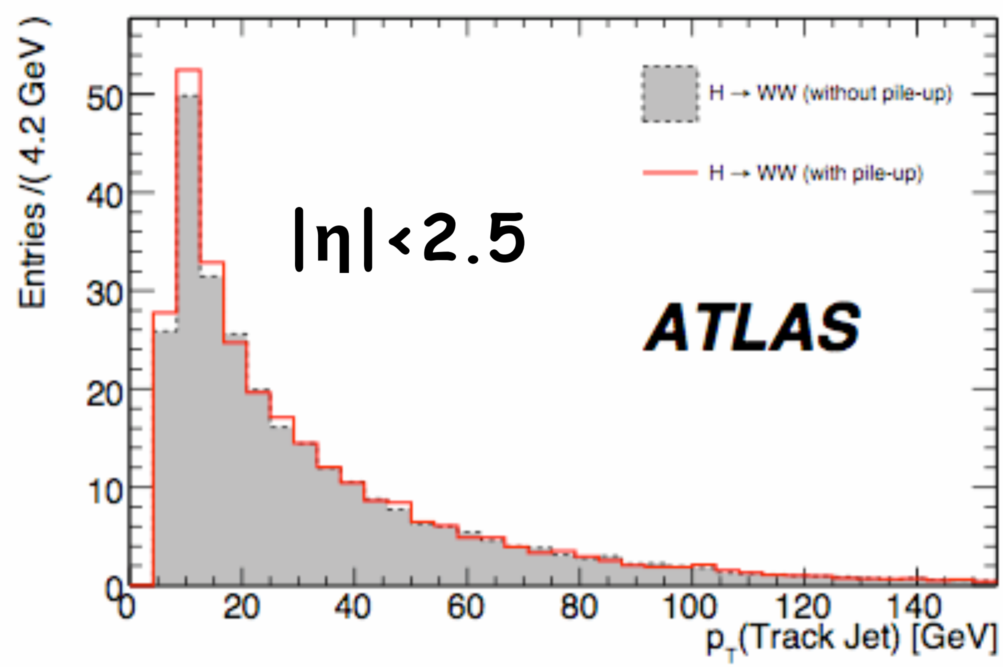


Track-jet for CJ Veto

- Clusterize with a cone algorithm only good quality tracks that point to the Higgs vertex

	$H \to WW$		$t\bar{t}$	
	no pile-up	with pile-up	no pile-up	with pile-up
std jets ($\lvert\eta\rvert < 2.5$)	72.0 ± 1.0	63.0 ± 1.2	28.6 ± 3.4	19.7 ± 3.3
track jets	72.0 ± 1.0	73.5 ± 1.1	28.6 ± 3.4	25.9 ± 3.6
std jets ($\lvert\eta\rvert < 3.2$)	65.4 ± 1.0	57.0 ± 1.2	24.0 ± 3.2	16.3 ± 3.0
combination	65.8 ± 1.0	65.9 ± 1.1	24.0 ± 3.2	23.1 ± 3.5





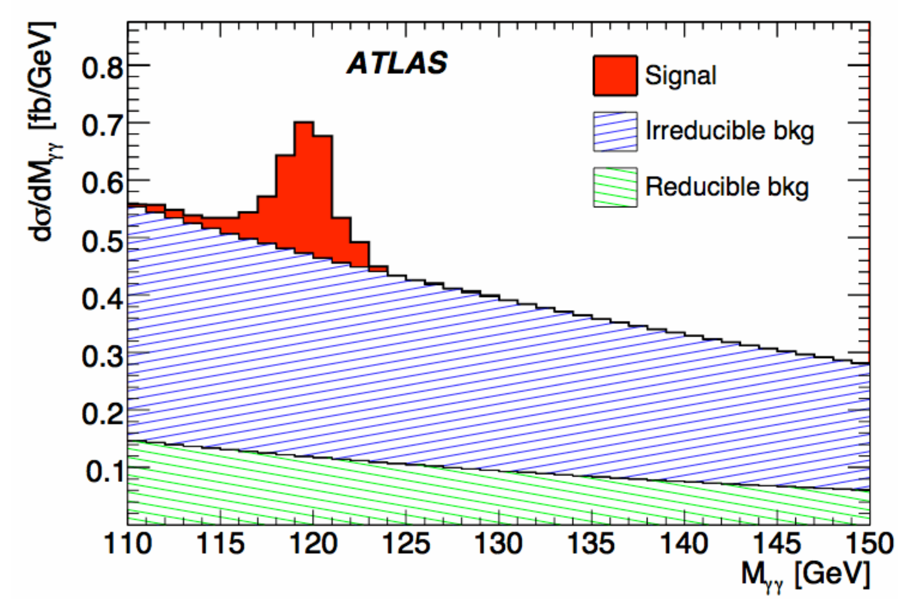
VBF Higgs Efficiency

- ATLAS reported the VBF H efficieny within the context fo the $H\to\gamma\gamma$ analysis
  1. Two quarks with p_T>40GeV and p_T>20GeV ($|\eta|$<5)and in opposite hemispheres
  2. Two reconstructed jets with p_T>40 GeV and p_T>20 GeV ($|\eta|$<5)
  3. Two reconstructed jets are in opposite hemispheres
  4. Jet-parton matching (Delta R<0.4)

Selection	HERWIG (no pileup)	HERWIG (Pileup 10^{33})	PYTHIA (no pileup)
step 1 (quark level)	0.618 ± 0.002	0.613 ± 0.003	0.632 ± 0.002
step 2 (rec level)	0.914 ± 0.002	0.911 ± 0.002	0.943 ± 0.001
step 3 (rec level)	0.801 ± 0.002	0.774 ± 0.003	0.771 ± 0.002
step 4 (matching)	0.757 ± 0.003	0.726 ± 0.003	0.713 ± 0.003

H→γγ + 2 jet in ATLAS

- Sensitivity of individual channels eveluated with simple event counting and a fit-based procedure
  - Include look-else-where effects by leaving mass float



m_H	Inclusive (with K-factors) $\sigma(S,B)$	σ_{1D}^{Fix}	σ_{1D}^{Float}	$H+1$jet (no K-factors) $\sigma(S,B)$	σ_{1D}^{Fix}	σ_{1D}^{Float}	$H+2$jet (no K-factors) $\sigma(S,B)$	σ_{1D}^{Fix}	σ_{1D}^{Float}	Combined $\sigma(S,B)$
120	2.6	2.4	1.5	1.8	1.8	1.3	1.9	2.0	1.1	3.3
130	2.8	2.7	1.8	2.0	2.1	1.6	2.1	2.1	1.2	3.5
140	2.5	2.2	1.3	1.8	1.7	1.2	1.7	2.0	1.0	3.0

Results shown for M_H=120 GeV and 10 fb^{-1}

$H \rightarrow \tau\tau$ Mass Reconstruction

- In order to reconstruct the Z mass need to use the collinear approximation

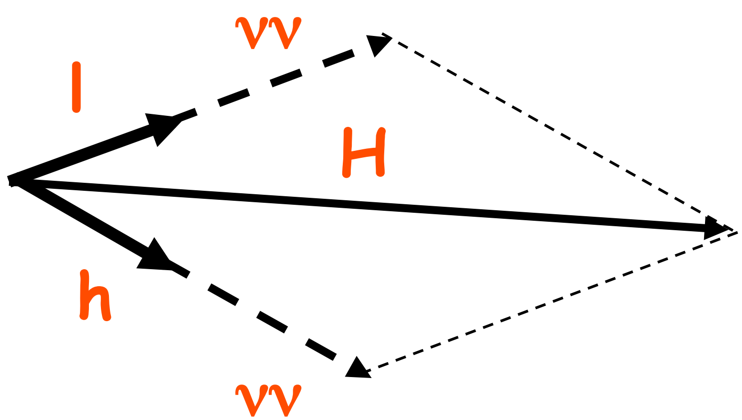
Tau decay products are collinear to tau direction

$$\vec{P}_\tau = \frac{\vec{P}_l}{x_\tau}$$

Fraction of τ momentum carried by visible τ decay

$$M_{\tau\tau} \approx \frac{M_{ll}}{\sqrt{x_{\tau 1} x_{\tau 2}}}$$

$$\vec{P}_{T\tau 1} + \vec{P}_{T\tau 2} = \vec{P}_{Tl 1} + \vec{P}_{Tl 2} + \vec{P}_{Tmiss}$$

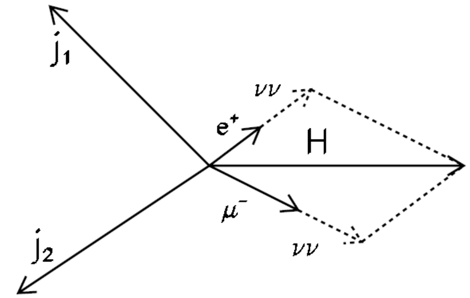


$$x_{\tau_1} = \frac{p_{T_{lep1},x} \cdot p_{T_{lep2},y} - p_{T_{lep1},y} \cdot p_{T_{lep2},x}}{p_{T_{Higgs},x} \cdot p_{T_{lep2},y} - p_{T_{Higgs},y} \cdot p_{T_{lep2},x}}$$

$$x_{\tau_2} = \frac{p_{T_{lep1},x} \cdot p_{T_{lep2},y} - p_{T_{lep1},y} \cdot p_{T_{lep2},x}}{p_{T_{Higgs},y} \cdot p_{T_{lep1},x} - p_{T_{Higgs},x} \cdot p_{T_{lep1},y}}$$

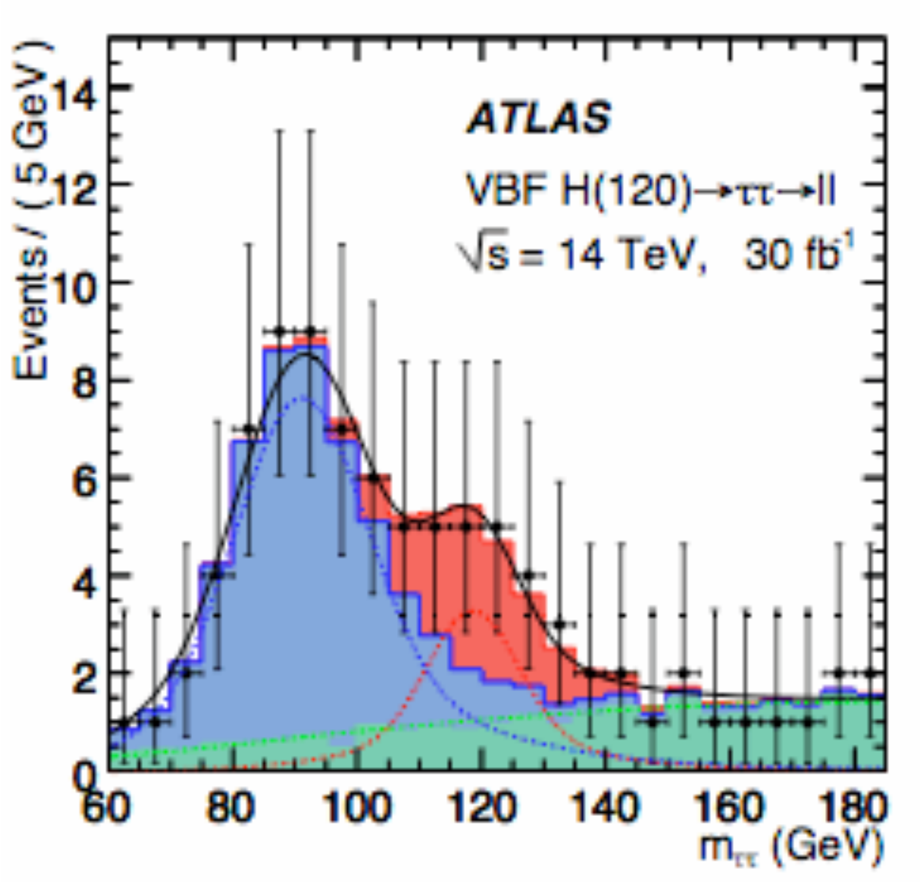
- $x_{\tau 1}$ and $x_{\tau 2}$ can be calculated if the missing E_T is known
- Good missing E_T reconstruction is essential

Low Mass SM H→ττ+jets

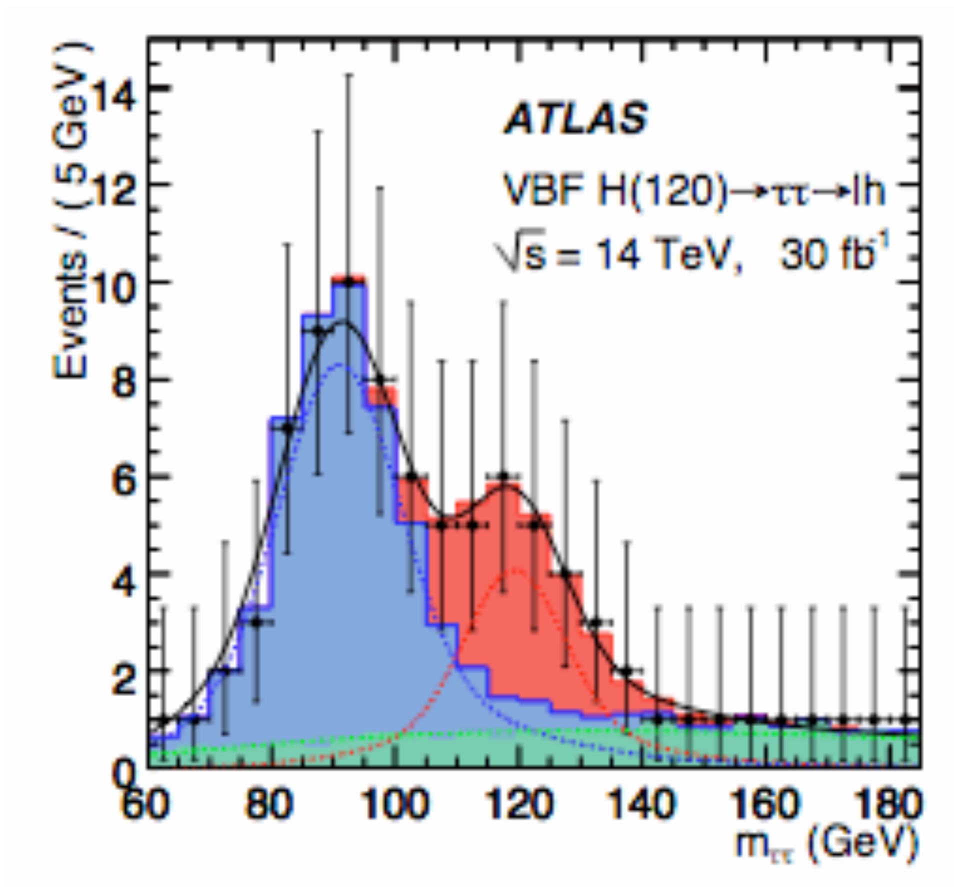


- Reconstruct Higgs mass with collinear approxim

H(→ττ→ll) +≥2jets

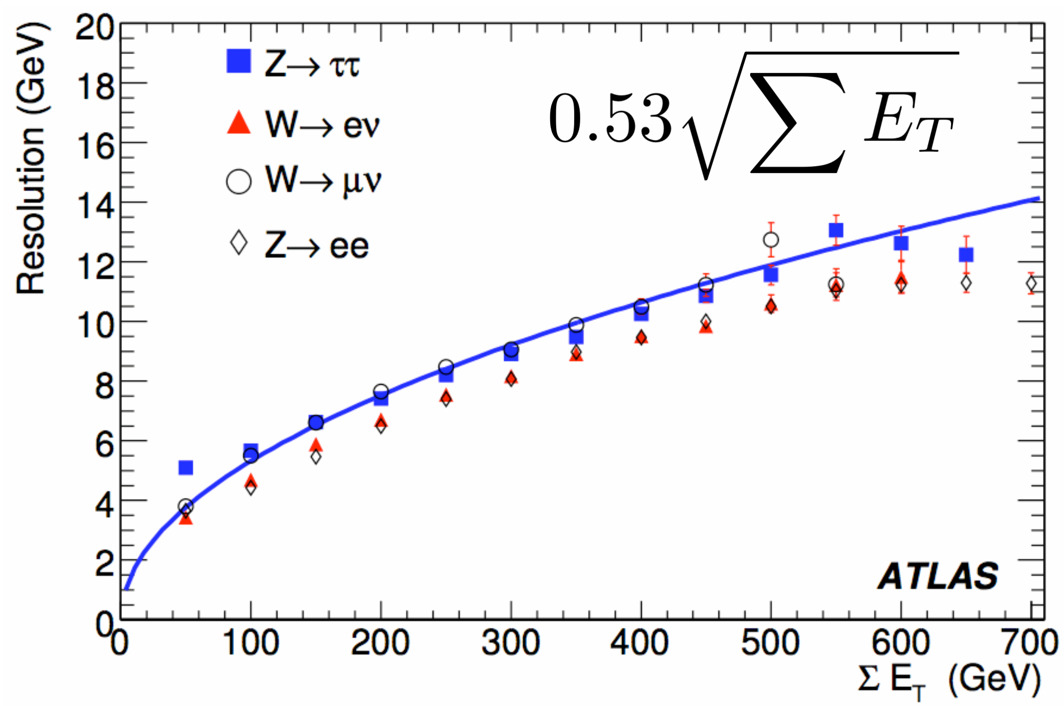


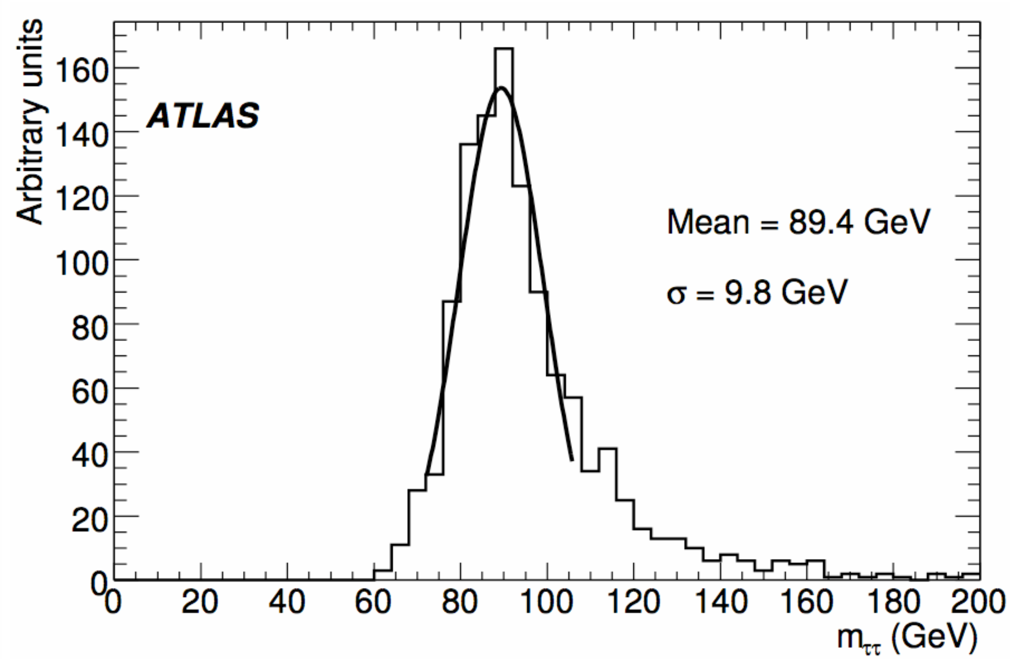
H(→ττ→lh) +≥2jet



MET Reconstruction

- To achieve good MET resolution is crucial in this channel. Requires good understanding of high P_T and low P_T hadronic objects
  - Expect to achieve ~10% resolution in di-tau mass in order to distinguish Higgs signal from Z+jets

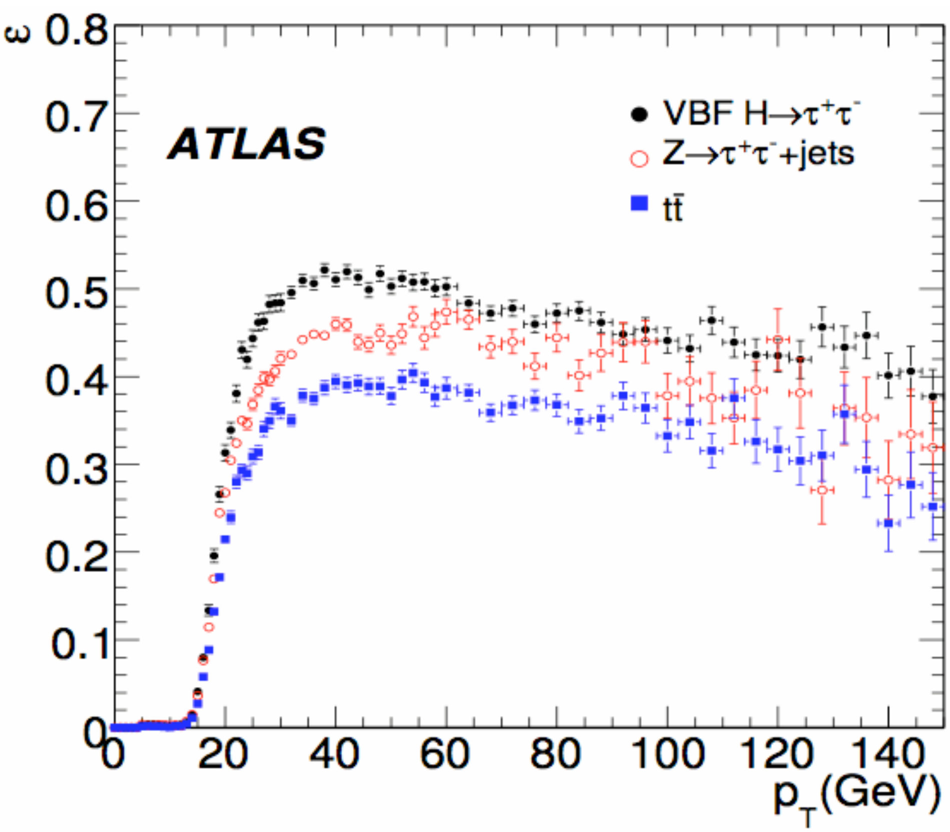


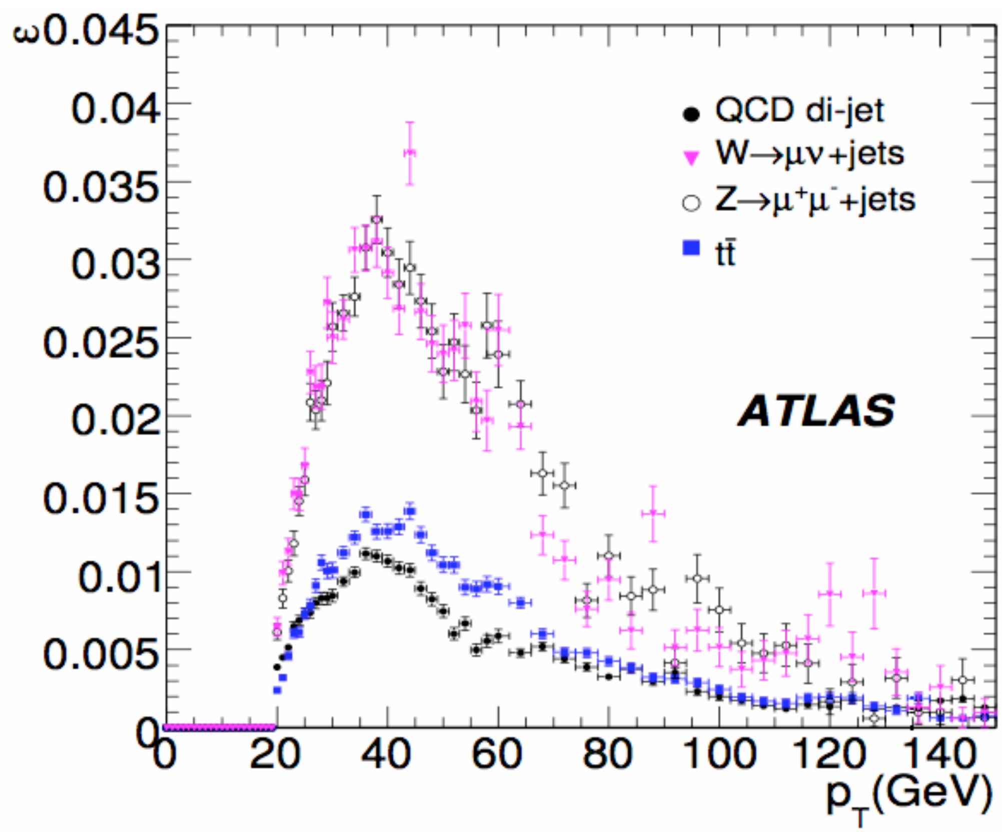


Tau-ID

- In the "Physics book" a calorimeter seeded reconstruction algorithm was used.

Hadronic tau identification
Tau ID: Calorimeter-seeded
$p_T \geq 30$ GeV
Track multiplicity : 1 or 3 tracks
$\lvert charge \rvert = 1$
$Log\ Likelihood\ Ratio \geq 4$
Electron Veto:
minimum TRT $HT/LT \leq 0.2$ if $\lvert\eta_\tau\rvert \leq 1.7$ and $LT \geq 10$
$E_T^{HAD}/p_T \geq 0.002$ in matched electron object

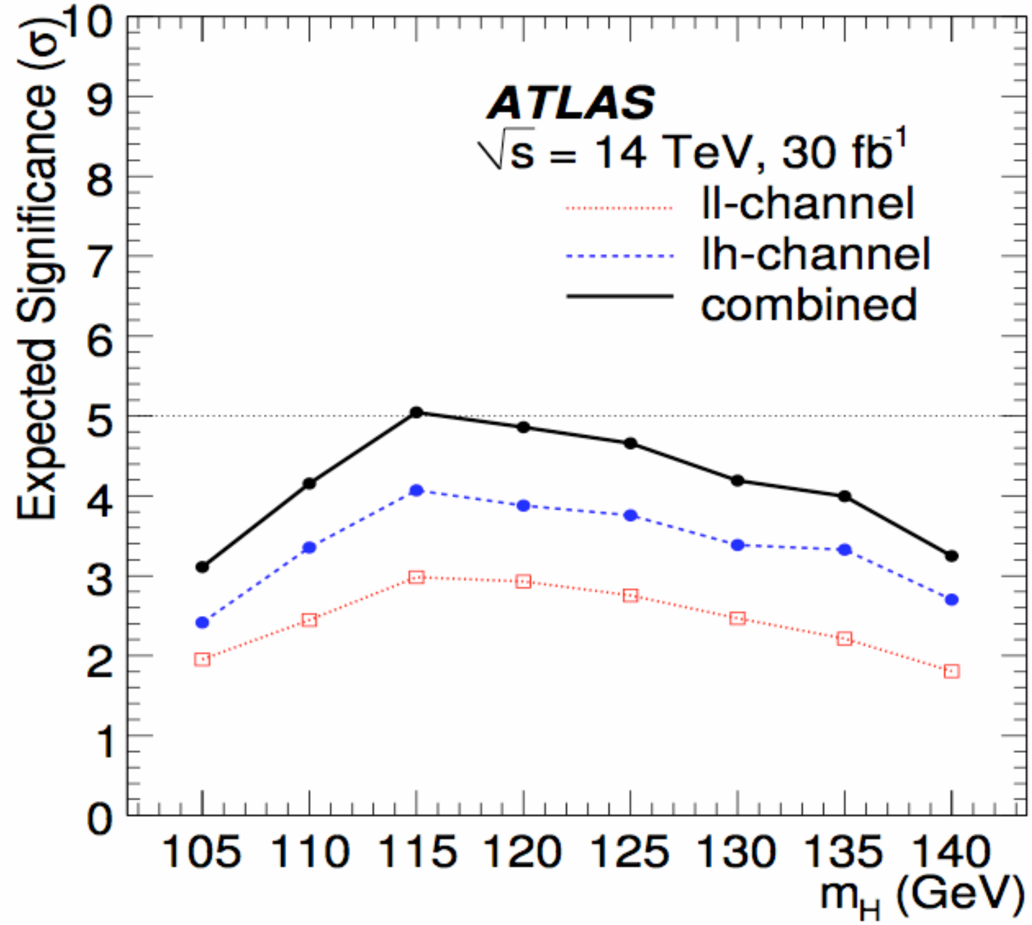




Low Mass SM H→ττ+2jets

Signal significance computation based on a fit to the di-tau mass spectrum . In order to constrain the background rate and shape, we simultaneously fit the signal candidates and the background control sample

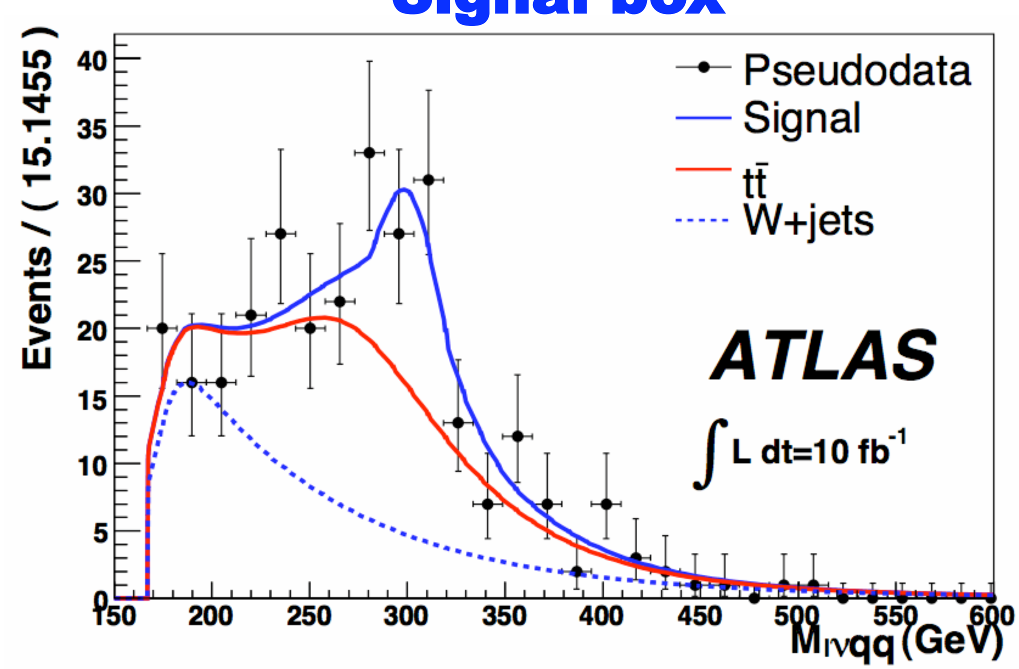
m_H	ll-channel	lh-channel	combined
105	1.95	2.41	3.10
110	2.44	3.35	4.15
115	2.98	4.07	5.04
120	2.92	3.87	4.85
125	2.75	3.75	4.65
130	2.46	3.38	4.18
135	2.21	3.32	3.99
140	1.80	2.70	3.24



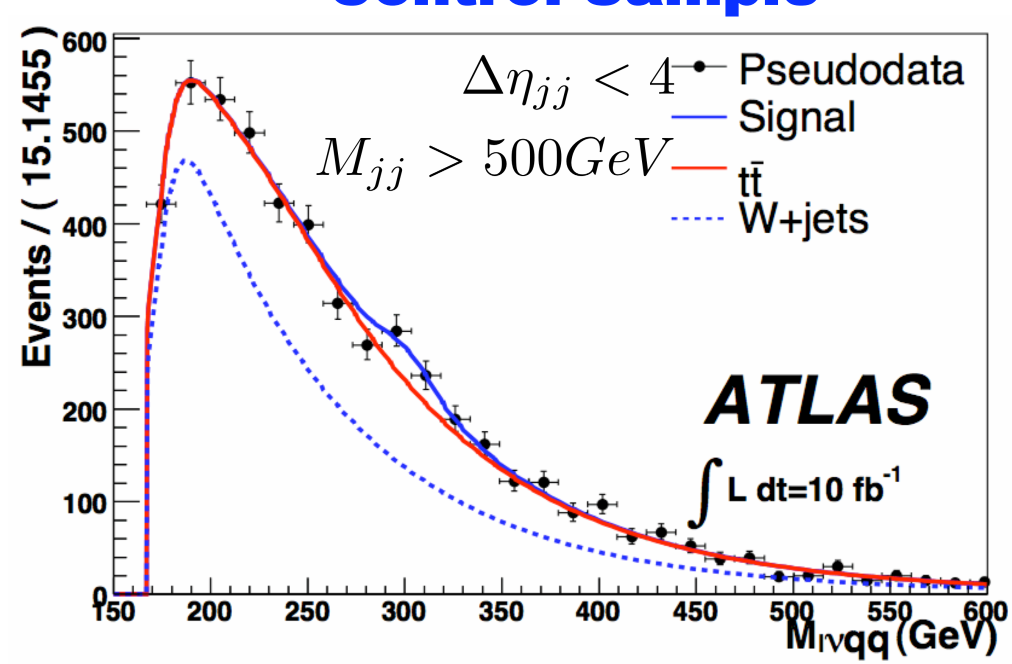
H→WW→lν qq + 2 jet in ATLAS

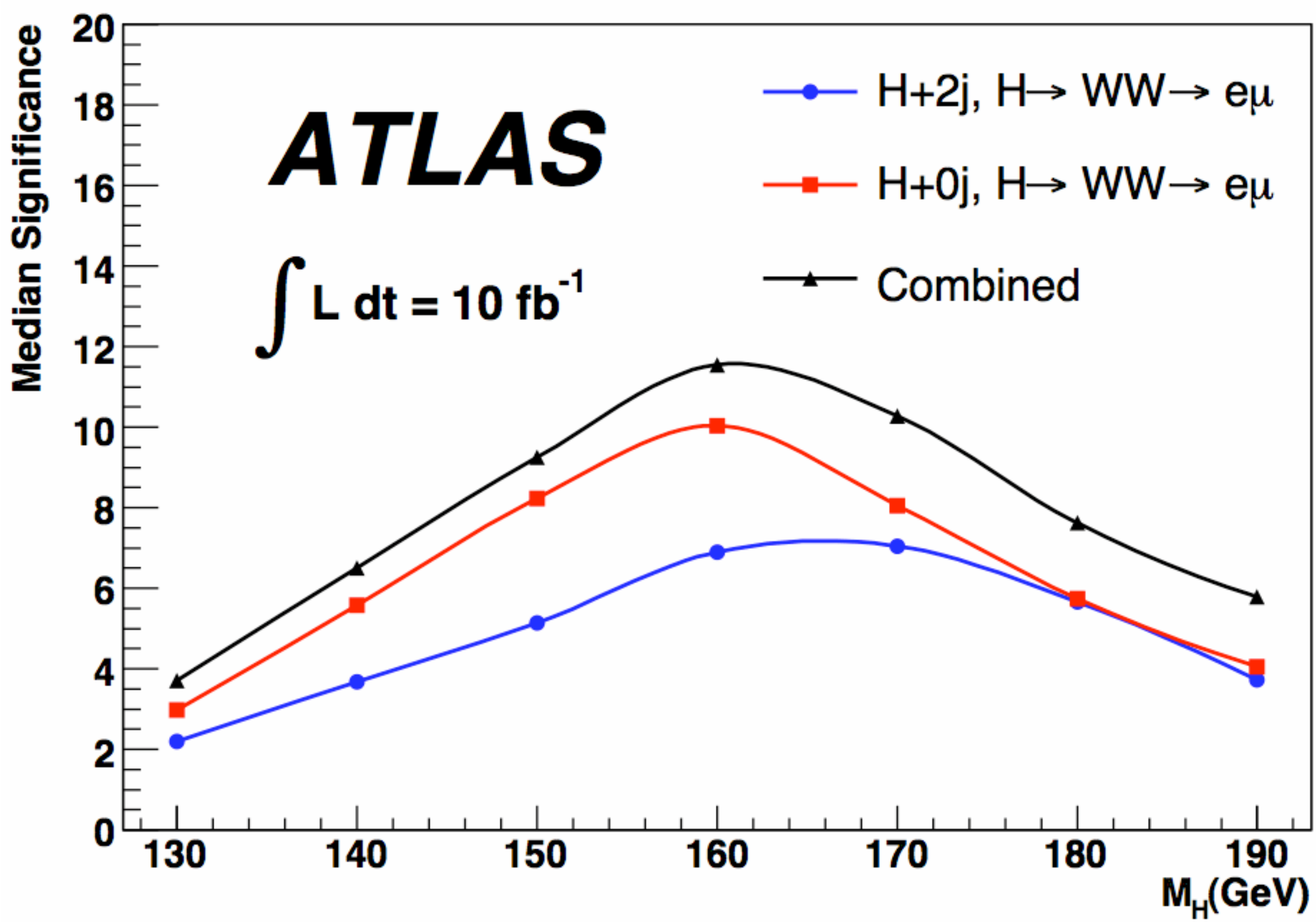
- Very similar approach to the one described for the ll amalysis (see extra slides for cuts & x-sections)
  - Reconstruct mass peak (kinematic fit)
  - Make simultaneous fit in signal box and control region

Signal box



Control Sample

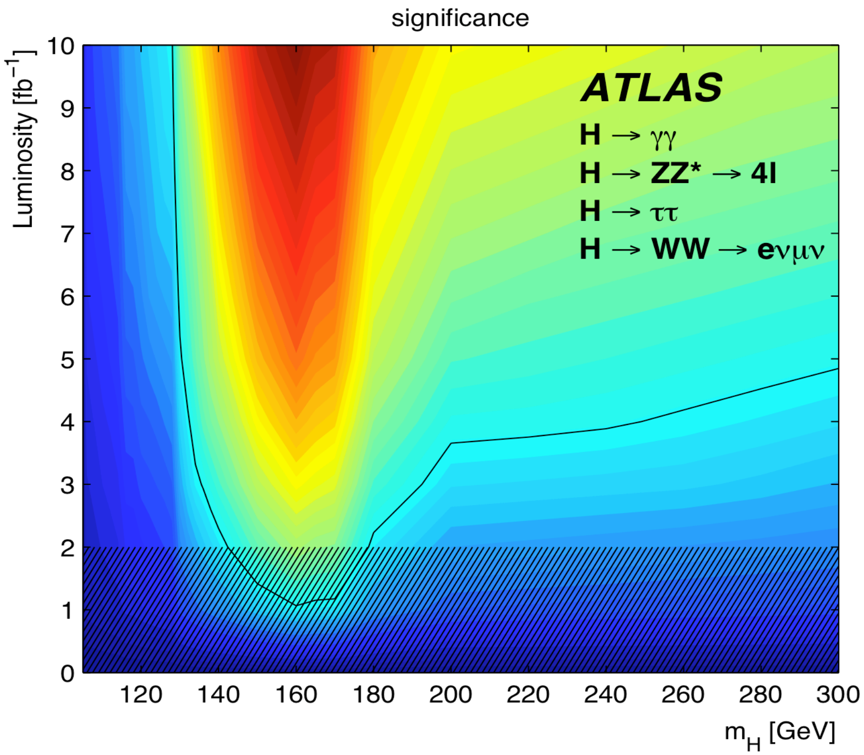


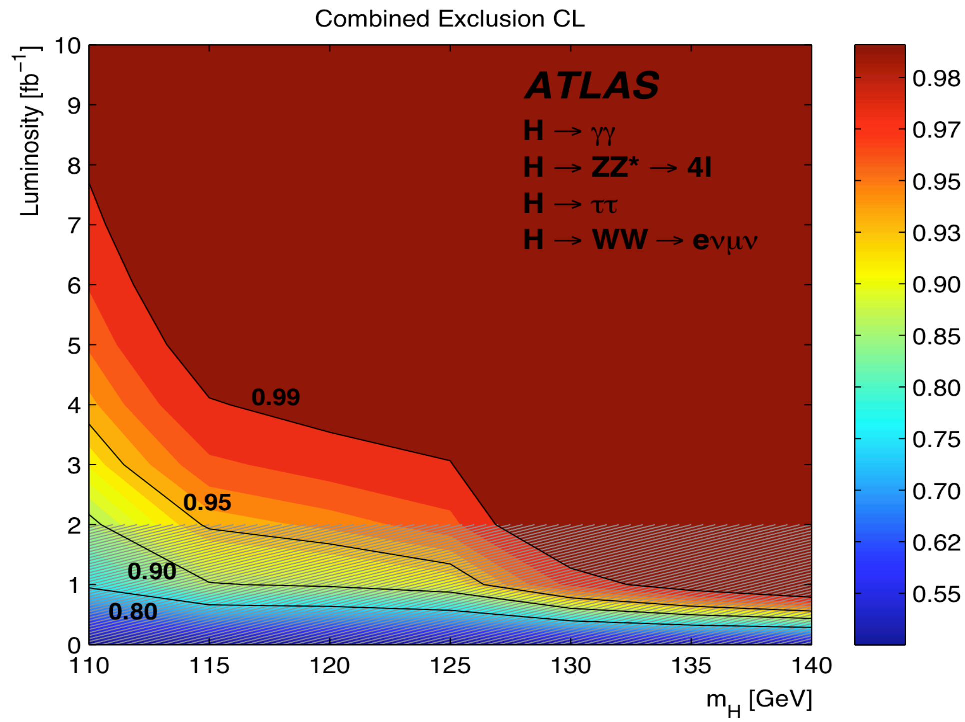


ATLAS
$\int L\, dt = 10\ fb^{-1}$
H+2j, H→ WW→ eμ
H+0j, H→ WW→ eμ
Combined
Median Significance
M_H(GeV)
0
2
4
6
8
10
12
14
16
18
20
130
140
150
160
170
180
190

Overall Sensitivity to SM Higgs

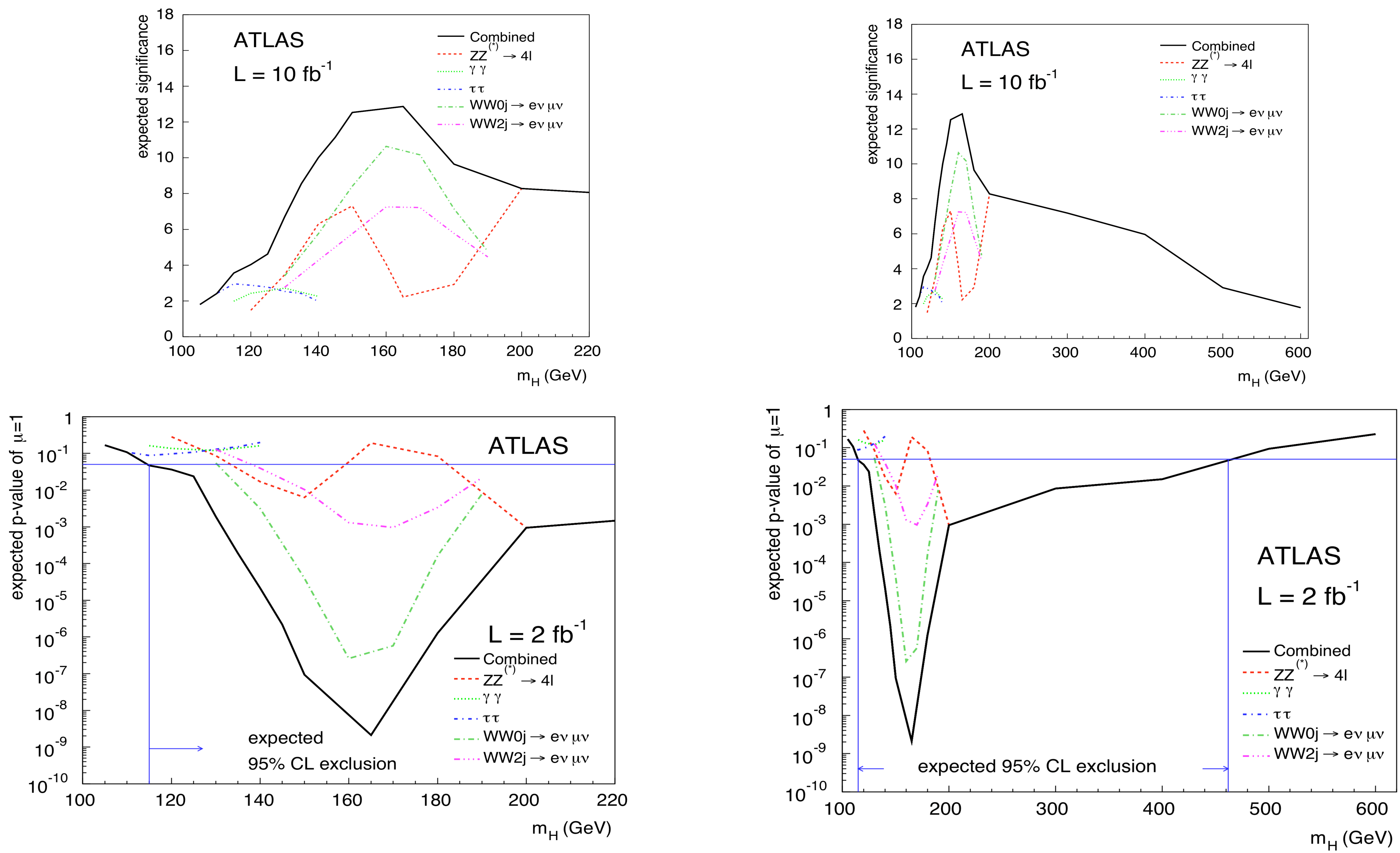
Results obtained for 14 TeV
$H \rightarrow WW^{(*)}, ZZ^{(*)}$ dominate sensitivity for M_H>140 GeV



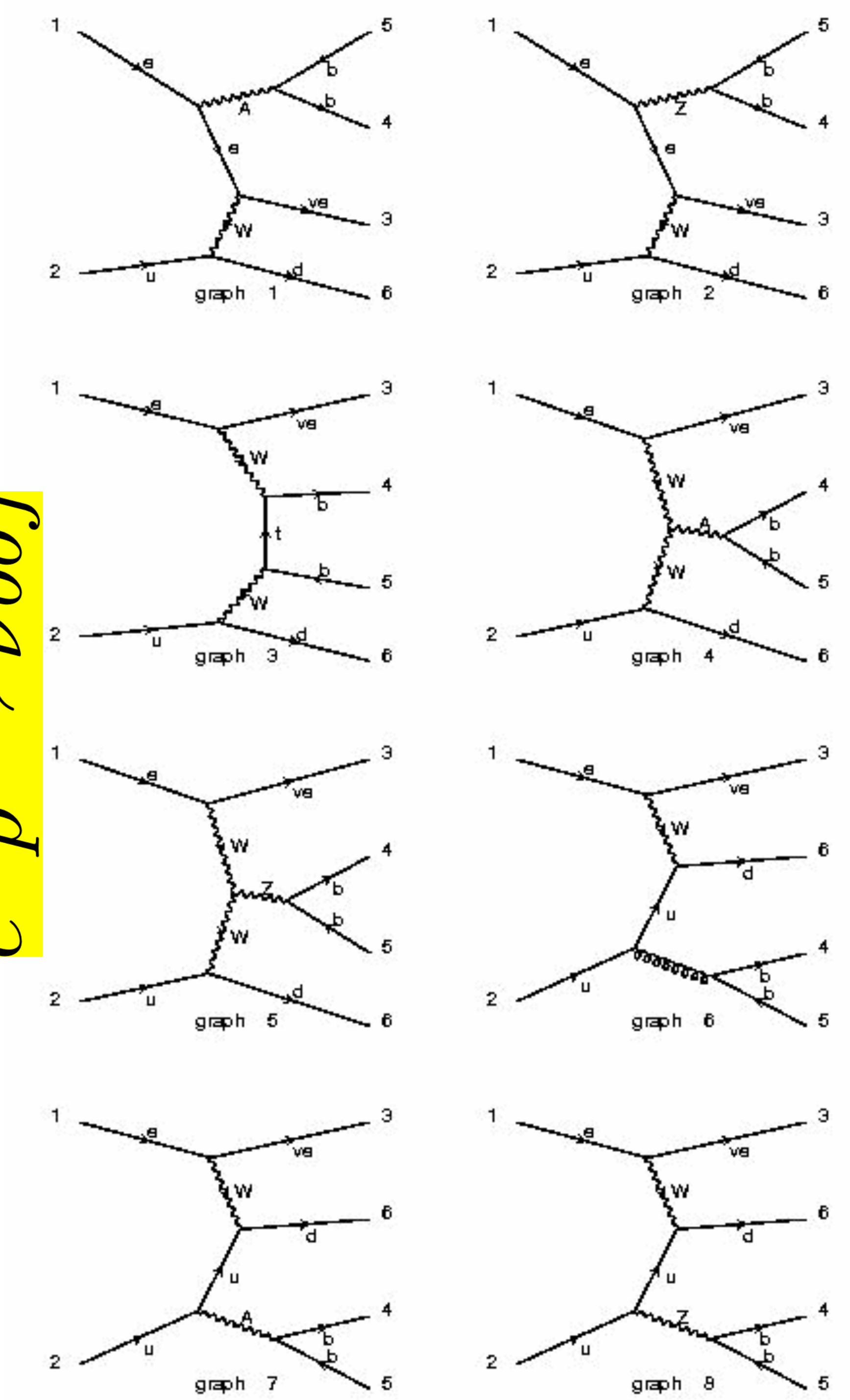


Preliminary studies seem to indicate that ATLAS has the potential to exclude the SM Higgs with M_H around 160 GeV with 10 TeV center of mass energy and 200 pb^{-1} of integrated luminosity

ATLAS Sensitivity to SM Higgs



$e^- p \to \nu b\bar{b}j$



$e^- p \to \nu W^- b\bar{b}$