Prospects for Higgs Physics at LHeC

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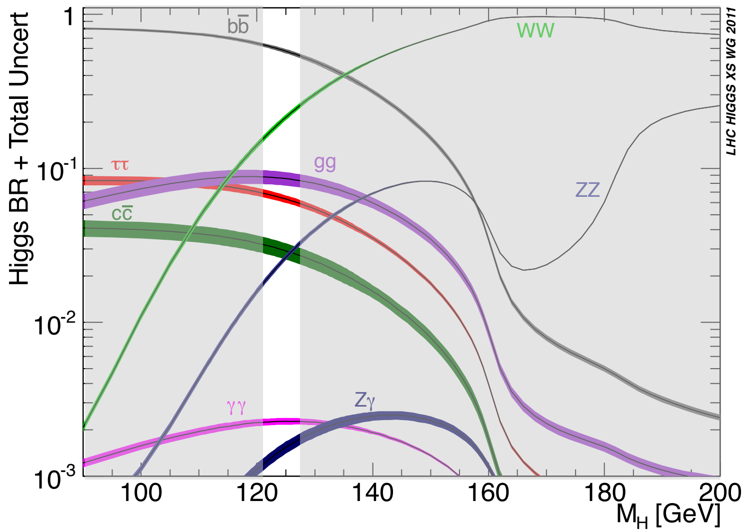
UNIVERSITY OF LIVERPOOL

Uk LHeC Meeting, Liverpool, May 8th, 2013

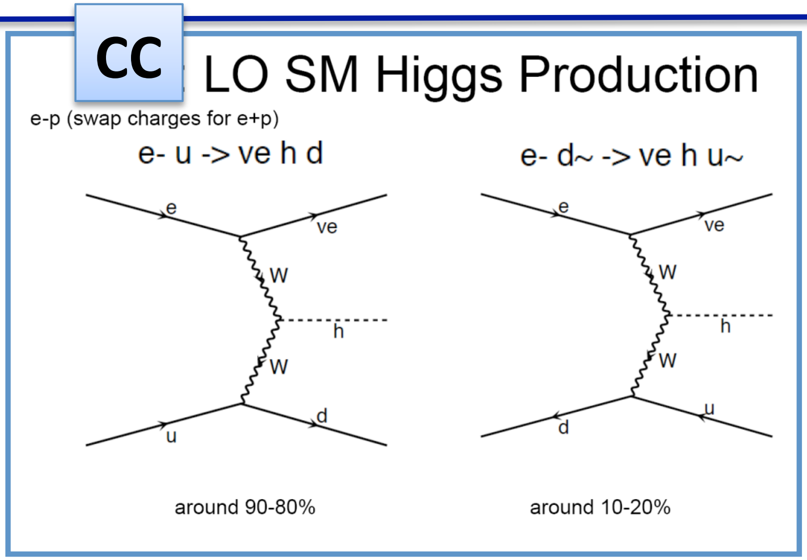
Light SM Higgs production in ep

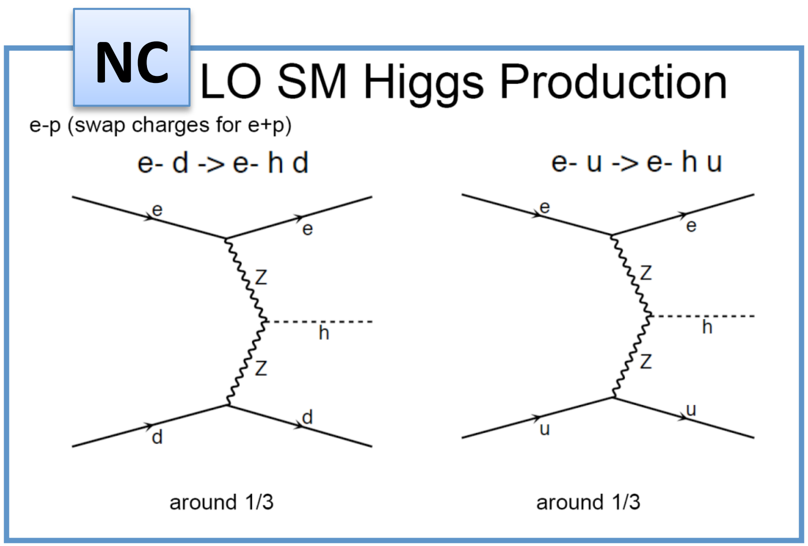
- Higgs at ~125 GeV : dominant decay to bb (58%)



√s=1 – 2 TeV :

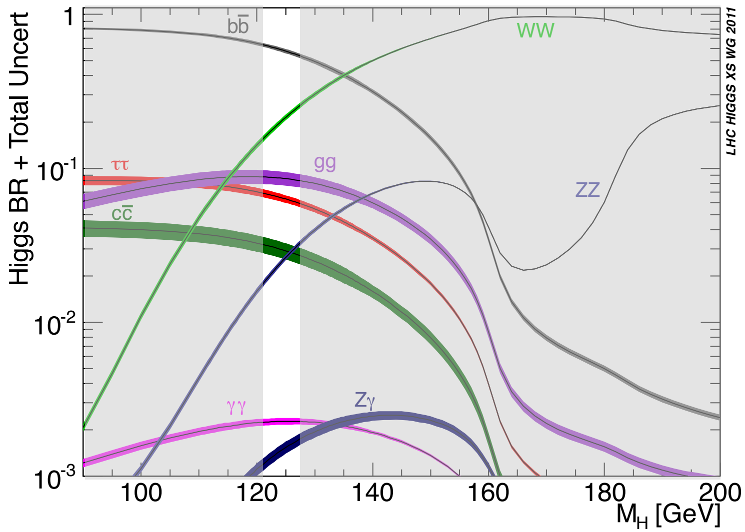
- LHeC : up to 100 times HERA luminosity! (no pile-up)
- CC: σ~ 200 fb (@HERA ~0.5 fb)
- NC: σ~ 50 fb (Z heavier than W and couplings to fermions smaller)





Light SM Higgs production in ep

- Higgs at ~126 GeV : dominant decay to bb



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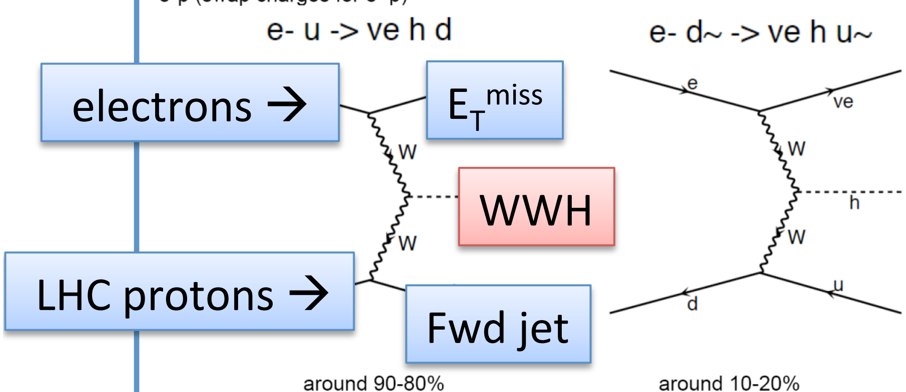
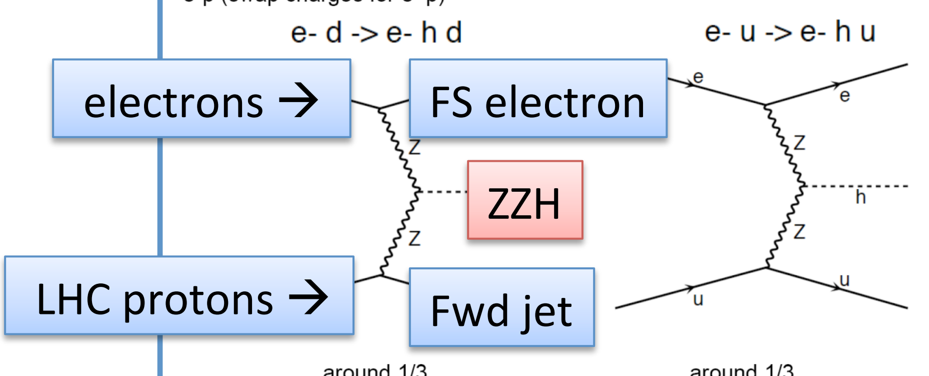
CC : LO SM Higgs Production



NC : LO SM Higgs Production



→ In ep, direction of quark (FS) is well defined.

LHeC Total SM Higgs cross sections

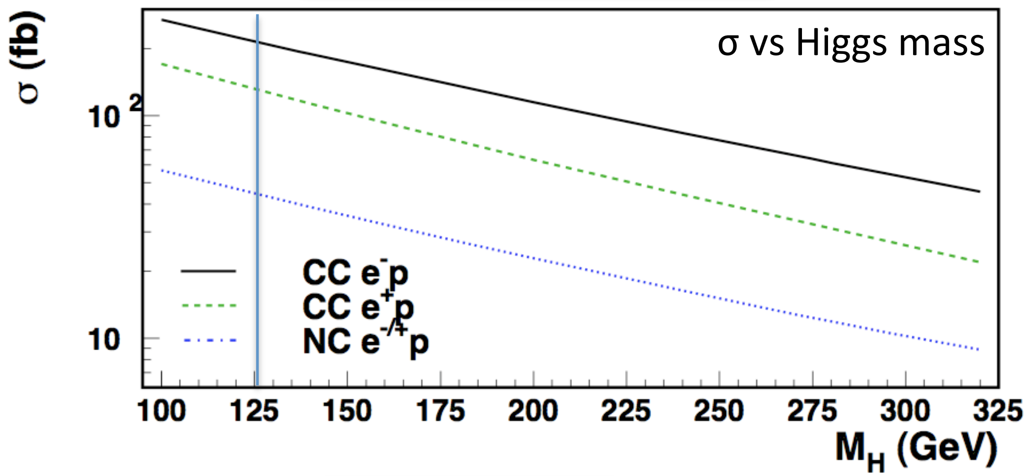
Total CC e^-p Higgs production cross section using design LHC protons of 7 TeV
SM Higgs with M_H = 120 GeV

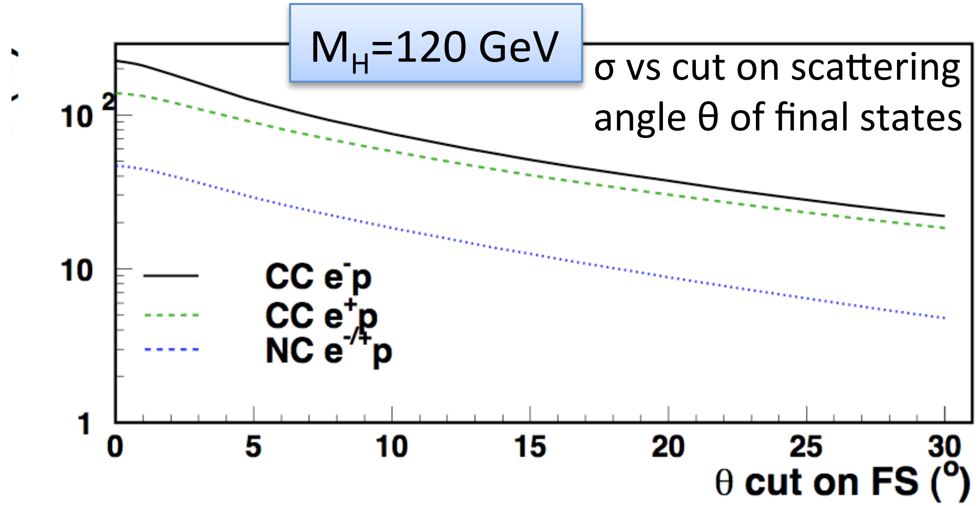
Electron beam energy	50 GeV	100 GeV	150 GeV
cross section [fb]	81	165	239

•**Scale dependencies of the LO calculations are in the range of 5-10%.**
• **QCD and QED corrections are moderate but sensitive to experimental cuts.**
• **NLO QCD corrections are small, but shape distortions of kinematic distributions up to 20%. QED corrections up to -5%.**

[J. Blumlein, G.J. van Oldenborgh , R. Ruckl, Nucl.Phys.B395:35-59,1993]
[B.Jager, arXiv:1001.3789]

$\sqrt{s}$ = 1.98 TeV
E_e=140 GeV, E_p=7 TeV





Analysis framework

Event generation

- SM Higgs production
- CC & NC background

by MadGraph/MadEvent

↓

- Fragmentation
- Hadronization

by PYTHIA (modified for ep)

↓

Fast detector simulation

by PGS (LHC-style detector)

↓

$H \rightarrow b\bar{b}$ selection

- Calculate cross section with tree-level Feynman diagrams (PDF CTEQ6L1)
- Generate final state of outgoing particles

Input parameters for initial studies (CC e^-p):

- 150 GeV electron beam

  [60 GeV configuration as comparison]

- 7 TeV proton beam
- 120 GeV SM Higgs boson mass

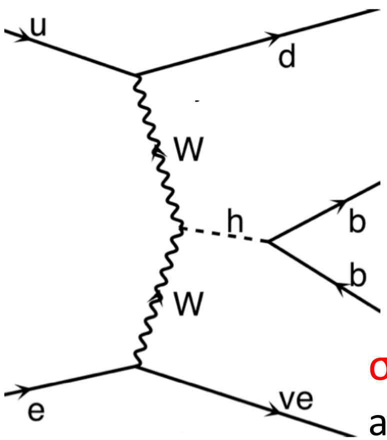
Generator level cuts

- $p_T > 5$ GeV (for partons besides b)
- $|\eta| < 5.0$
- For NC: Number of b quarks $\geqq 2$

Generated samples

Signal

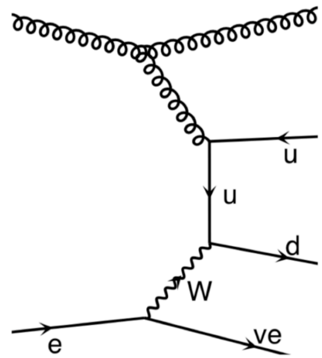
CC: H → $b\bar{b}$ (BR ~ 0.7 at M_H=120GeV)



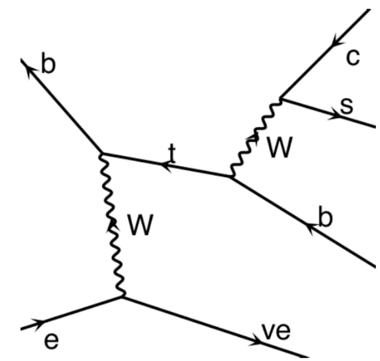
σ~ 0.16 pb
at √s=2.05TeV

Background (examples)

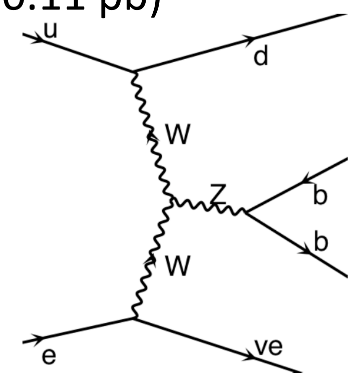
CC: 3 jets (~57 pb)



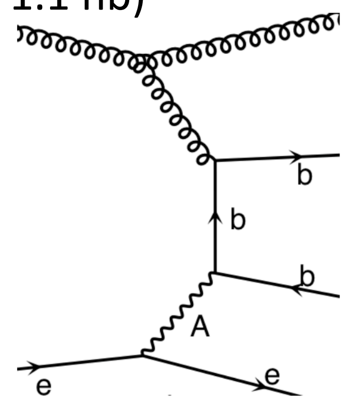
CC: single top production (~4.1 pb)



CC: Z production (~0.11 pb)



NC: b pair production (~1.1 nb)

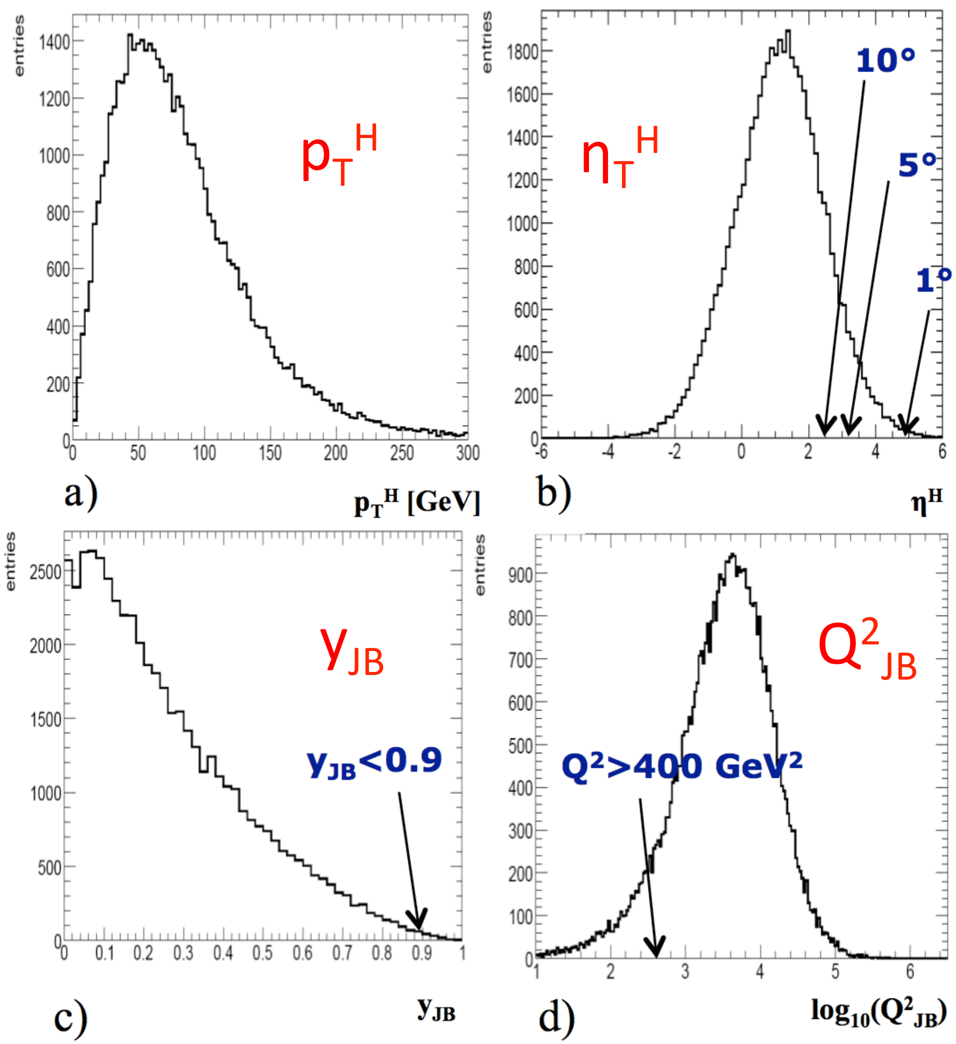


NOTE: Background sample numbers are after pre-selection in generator

Kinematic distributions

[M_H=120 GeV, E_e=150 GeV, E_p=7 TeV]

a-b) Kinematic distributions of generated Higgs
c-d) Reconstructed y_{JB} and Q^2_{JB}



Generated events passed to Pythia and to generic LHC-style detector:

- Coverage:
  - Tracking: $|\eta| < 3$
  - Calorimeter: $|\eta| < 5$
- Calorimeter resolution
  - EM: $1\% \oplus 5\%/\sqrt{E}$
  - Hadron: $60\%/\sqrt{E}$
  - Cell size: $(\Delta\eta,\Delta\phi) = (0.03, 0.03)$
- Jet reconstructed (cone ΔR=0.7)
- b-tag performance
  - Flat efficiency for $|\eta| < 3$
  - Efficiency/mis-ID
    - b-jet: 60%
    - c-jet: 10%
    - Other jets: 1%

Selection of H→b$\bar{b}$

- NC rejection
  - Exclude electron-tagged events
  - $E_{T,miss} > 20$ GeV
  - N_{jet} ($p_T > 20$ GeV) $\geqq 3$
  - $E_{T,total} > 100$ GeV
  - $y_{JB} < 0.9$, $Q^2_{JB} > 400$ GeV^2
- b-tag requirement
  - $N_{b\text{-}jet}$ ($p_T > 20$ GeV) $\geqq 2$
- Higgs invariant mass
  - $90 < M_H < 120$ GeV

⇒ 44% of remaining BG is single-top…

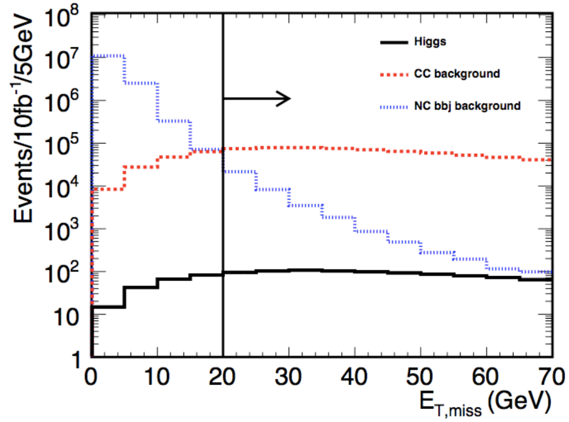
- Single top rejection
  - $M_{jjj,top} > 250$ GeV
  - $M_{jj,W} > 130$ GeV

H→b$\bar{b}$

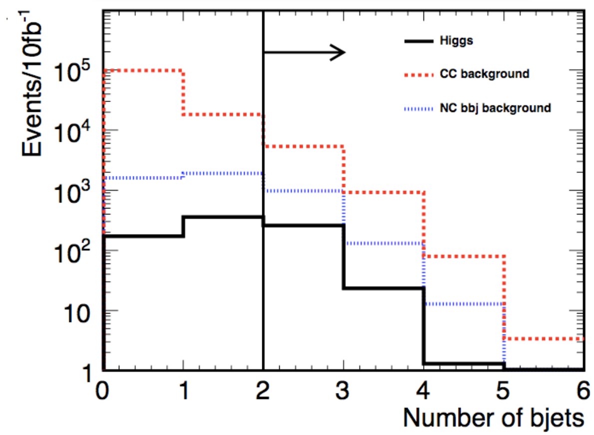
CC BG

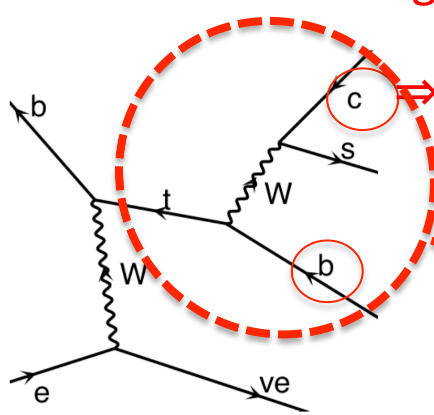
NC BG

E_T^{miss} cut

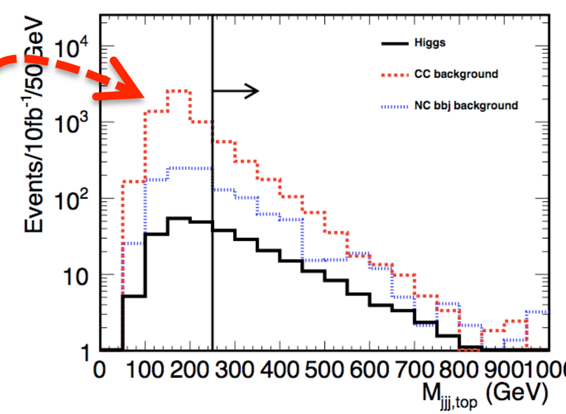


b-tag requirement





⇒10% mis-ID

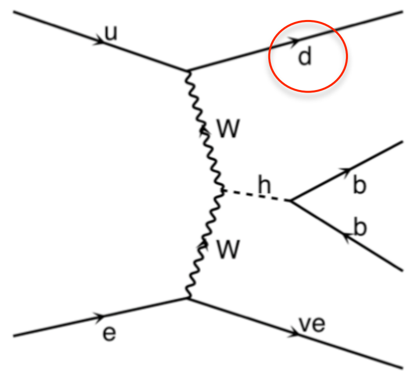


$H \rightarrow b\bar{b}$ results [M_H=120 GeV, E_p=7 TeV]

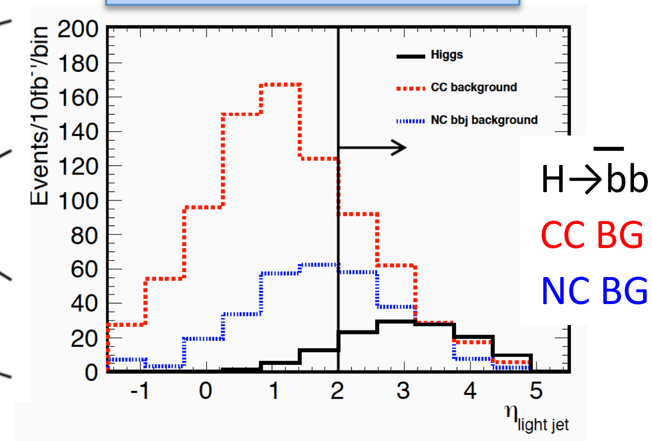
- Forward jet tagging
  - $\eta_{jet} > 2$ (lowest η jet excluding b-tagged jets)

Coordinate:
Fwd: +z-axis along proton beam

$H \rightarrow b\bar{b}$ signal

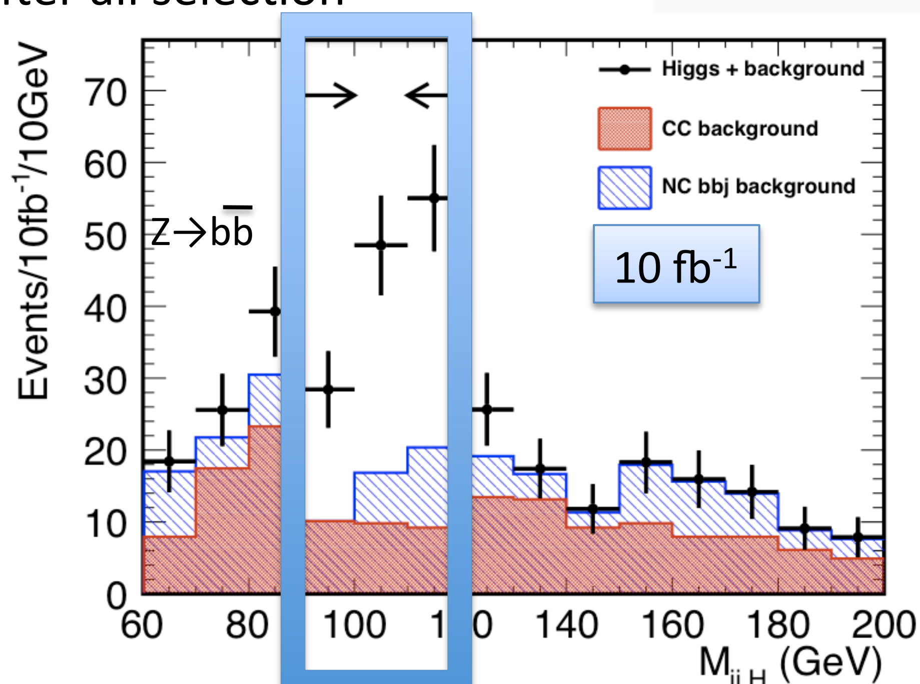


Forward jet η tag



- Higgs invariant mass after all selection

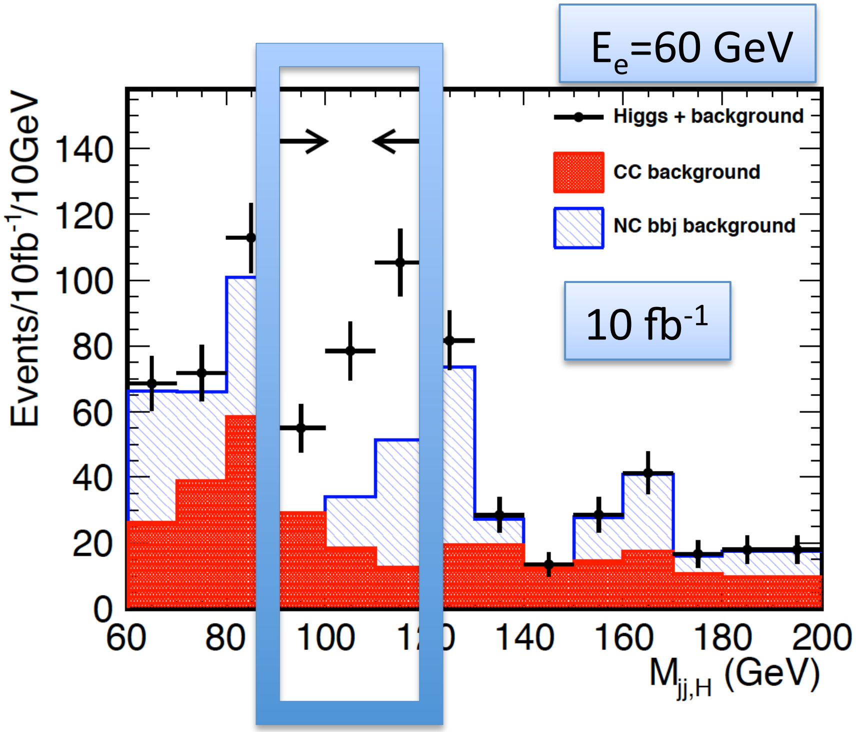
E_e=150 GeV



Clear signal obtained with just cut based analysis already!

H→$b\bar{b}$ results [M_H=120 GeV, E_p=7 TeV]

- Case study for electron beam energy of 60 GeV using same analysis strategy
  - luminosity values of 100 fb^{-1} (10 fb^{-1}/year) are feasible



	E_e = 150 GeV (10 fb^{-1})	E_e = 60 GeV (100 fb^{-1})
H → bb signal	84.6	248
S/N	1.79*	1.05
S/√N	12.3	16.1

*Note: A parton-level study delivered S/N of 4.7.

- Linac with high electron polarisation of about 90% ➔ enhancement by factor 1.9 feasible, i.e. around 500 Higgs candidates for E_e=60 GeV allowing to measure Hbb coupling with 4 % statistical precision.

- Conservative estimate of S/N ➔ more detailed study using OWN detector required.

CP Nature of a SM Higgs and BSM

- In SM, the only fundamental neutral scalar is a $J^{PC} = 0^{++}$.

- Various extensions of the SM can have several Higgs bosons with different CP properties : e.g. MSSM has two CP-even and one CP-odd states.

- Therefore, should a neutral spin-0 particle be detected, a study of its CP-properties would be essential to establish it as *the* SM Higgs boson.

- To study the effects beyond SM, we need to establish the CP eigenvalues for the Higgs states if CP is conserved, and measure the mixing between CP-even and CP-odd states if it is not.

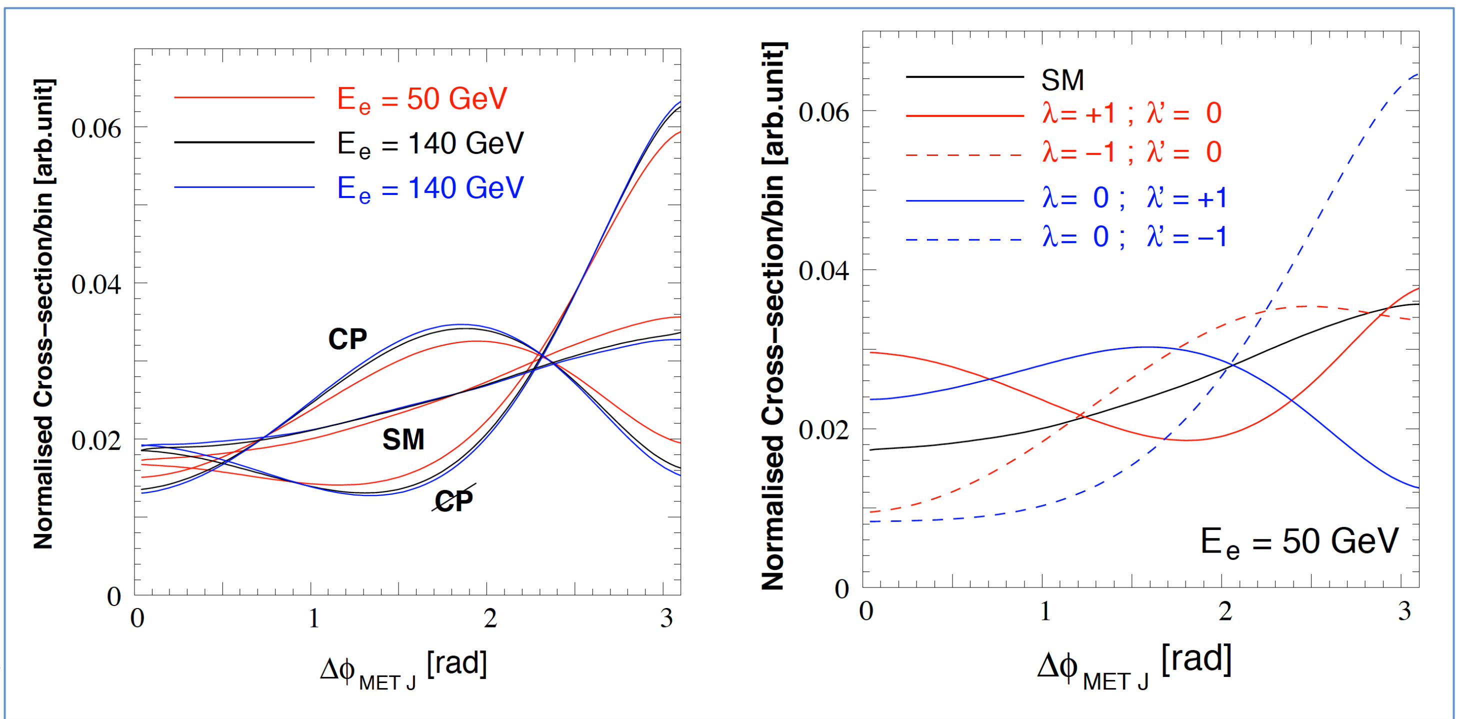
Rohini Godbole

Measure CP properties of Higgs

- Higgs couplings with a pair of gauge bosons (WW/ZZ) and a pair of heavy fermions (t/b/τ) are largest.
- Higgs@LHeC allows uniquely to access HWW vertex → explore the CP properties of HVV couplings: BSM will modify CP-even (λ) and CP-odd (λ') states differently

$$\Gamma^{\mu\nu}_{(\mathrm{SM})}(p,q) = g M_W \, g^{\mu\nu} \quad \rightarrow \quad \Gamma^{(\mathrm{BSM})}_{\mu\nu}(p,q) = \frac{-g}{M_W}\left[\lambda\,(p.q\, g_{\mu\nu} - p_\nu q_\mu) + i\,\lambda'\,\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

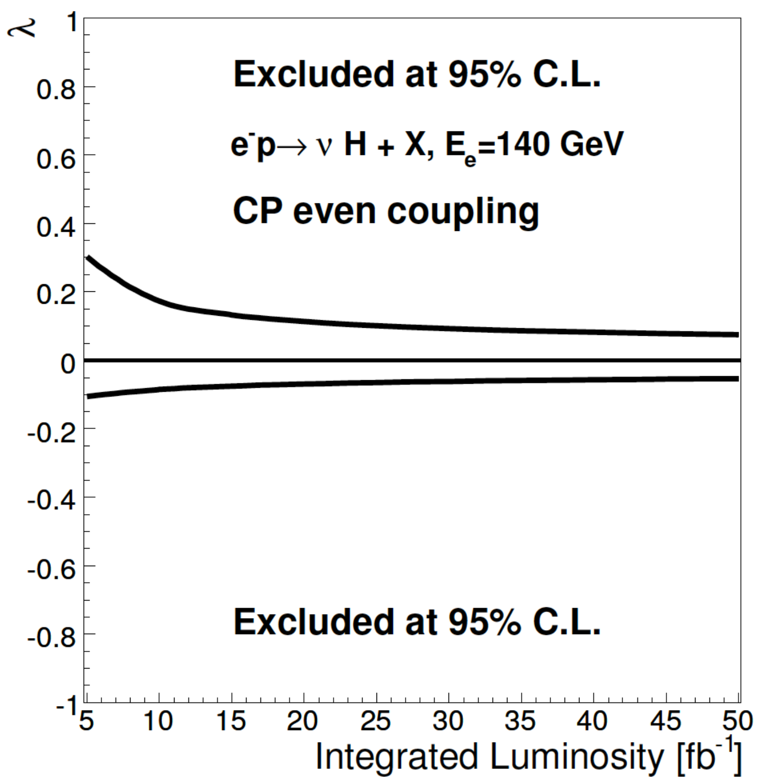
- Study ***shape changes*** in DIS normalised CC Higgs→ bb cross section versus the azimuthal angle between $E_{T,miss}$ and forward jet, $\Delta\phi_{MET,J}$

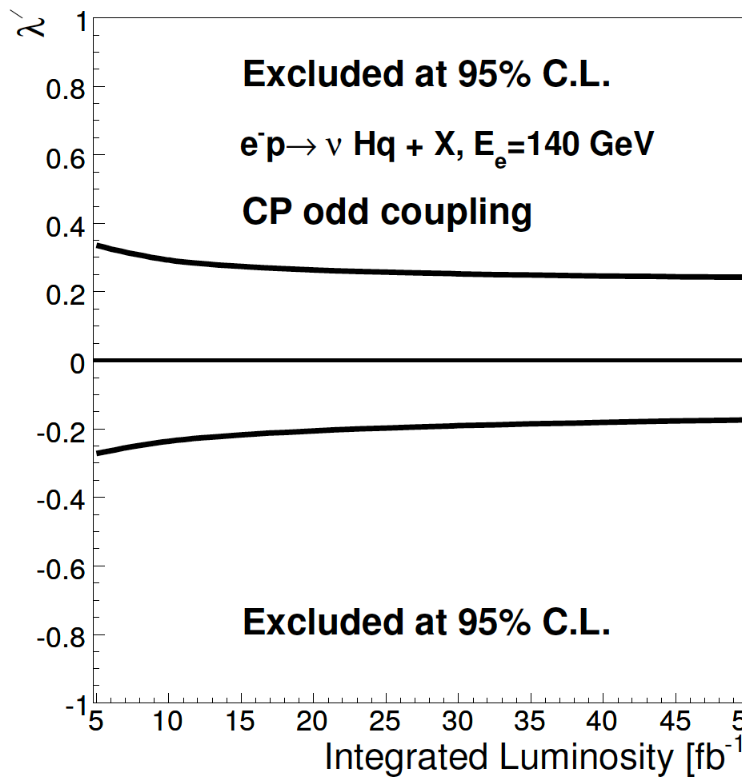


In ep, full Δφ range can be explored, here not shown yet.

Higgs CP couplings

- Limits on effective coupling strengths of CP-even and CP-odd couplings are correlated.
- At LHeC, with 5-10 fb^{-1}, $|\lambda|$ values up to 0.2 to 0.4 can be uniquely probed for both the CP-even and CP-odd states of a light SM Higgs for electron beam energies in the range of 50 to 150 GeV.

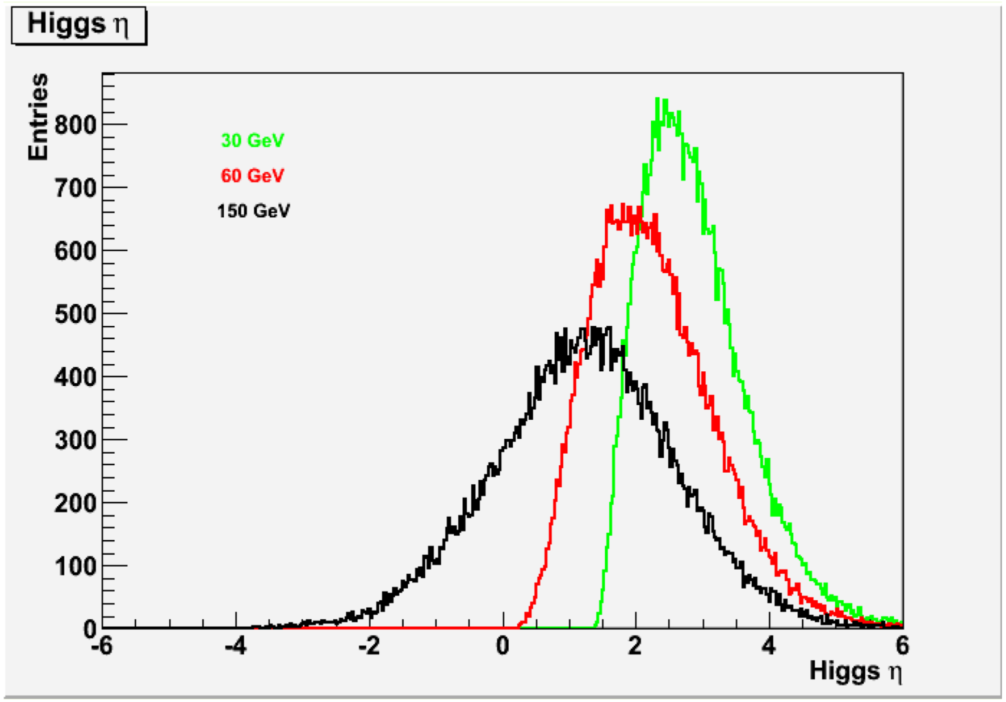


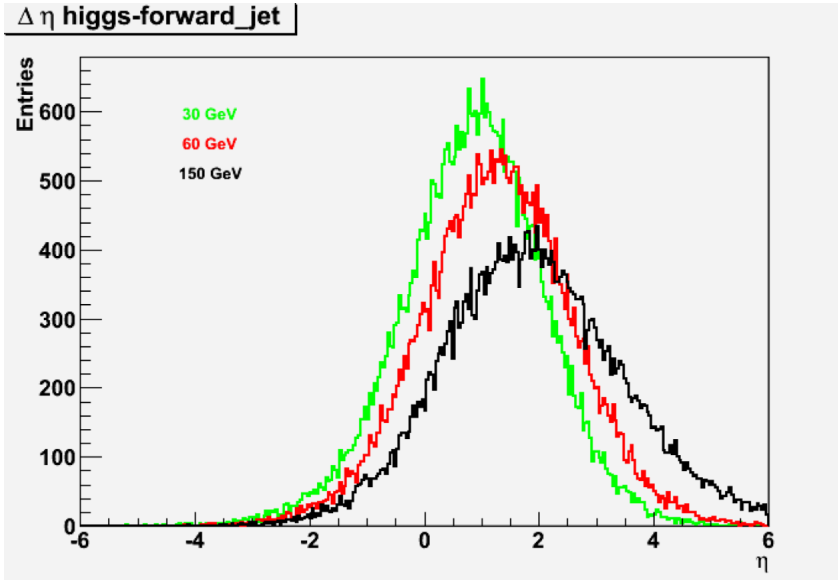


M_H=120 GeV

Higgs acceptance vs E-beam energy

- Master thesis by Sergio Mandelli, Liverpool 2013 : M_H=125 GeV





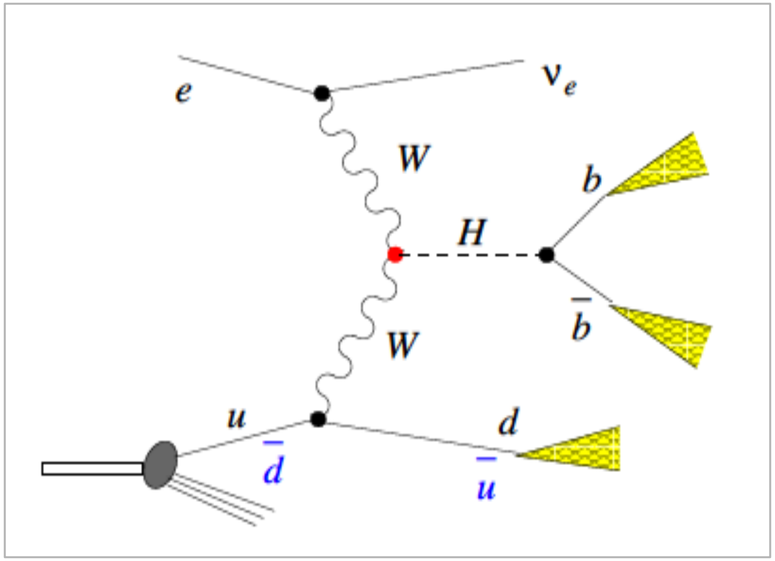
E_e =30 η_{rms} = 2.878
E_e =60 η_{rms} = 2.259
E_e =150 η_{rms} = 1.361

➔ lowering of electron beam energy (more cost efficient) will challenge more detector design: separation is getting worse between higgs and forward jet and higgs is more forward

… as a Higgs "Factory"

→ empoying fully polarised electrons: 200 fb cross section in CC e⁻p:

→ **L= 1 ab^{-1}**: 2 10^{5} Higgs events : Clean final state, no pile-up, low QCD bgd, WWH and ZZH



LHeC Higgs	CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation	-0.8	0	0
Luminosity [ab^{-1}]	1	1	0.1
Cross Section [fb]	196	20	58
Acceptance	0.92	0.93	0.94
Decay Channel	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	117 500	12 000	3500
$H \to c\bar{c}$	5 900	600	180
$H \to gg$	16 200	1 600	480
$H \to WW$	25 200	2 600	760
$H \to ZZ$	2 880	1900	560
$H \to \tau^+\tau^-$	10 260	1 000	310
$H \to \gamma\gamma$	360	40	12

Ultimate e and p beams, 10 years of operation

Table 1: Cross sections and rates of Higgs production in ep scattering with the LHeC. The cross sections are obtained with MADGRAPH5 (v1.5.4) using the p_T of the scattered quark as scale, CTEQ6L1 partons and $M_H = 125\,\text{GeV}$. The acceptance is obtained with kinematic cuts on final state particles ($|\eta_{jet}| < 5$, $|\eta_{e,\gamma}| < 4.7$, $p_{T,jet} > 1\,\text{GeV}$, $E_{jet} > 15\,\text{GeV}$, $E'_e > 10\,\text{GeV}$, $E_\gamma > 5\,\text{GeV}$) but excludes the tagging probabilities for b, c, τ and further g, W, Z reconstruction efficiencies. In an initial study (CDR) the $b\bar{b}$ final state is reconstructed with an efficiency of about 5 %. This leads to $\simeq$ 5000 events in this channel, at an S/N of 1.

ILC: 10^{34} cm^{-2}s^{-1}, 280fb, 15000 cavities, H width - LHeC: 10^{34} 200fb 960 cavities, no width

Summary

- At LHeC, a light Higgs boson and its CP eigenstates could be uniquely accessed via WW and ZZ fusion - complementary to LHC experiments.
- Sensitivity to H → bb is estimated by an initial simulation study: LHeC has the potential to measure H → bb coupling to ~4% accuracy with 60 GeV electron beam (conservative estimate). Other production and decay channels have to be explored still using dedicated LHeC detector simulation, instead of the PGS used so far.
- With the isolation of the H→bb signal at the LHeC, a window of opportunity opens for the exploration of the CP properties of the HVV vertex: LHeC offers a number of advantages
  - Clear separation of HWW and HZZ couplings
  - Very good signal to background ratio
  - Identification of backward forward directions (and full azimuthal coverage)
- Detector design is crucial for an efficient H→ bbar signal selection and CC/NC multi-jet background rejection. **Prospects have just started to be explored, and high luminosities (~1000 fb-1) opens totally new potential**
- **Briliant opportunities for very nice BSc and Master thesis, and ~10% PostDoc work**

Additional material

Total CC e^-p cross sections [fb]

- SM Higgs cross section predictions [fb] for various electron beam energies

	100 GeV	120 GeV	160 GeV	200 GeV	240 GeV	280 GeV
E=50 GeV	102.4	80.6	50.3	31.6	19.9	12.5
E=100 GeV	201.3	165.3	113.2	78.6	55.2	39.1
E=150 GeV	286.3	239.5	170.4	123.3	90.5	67.1

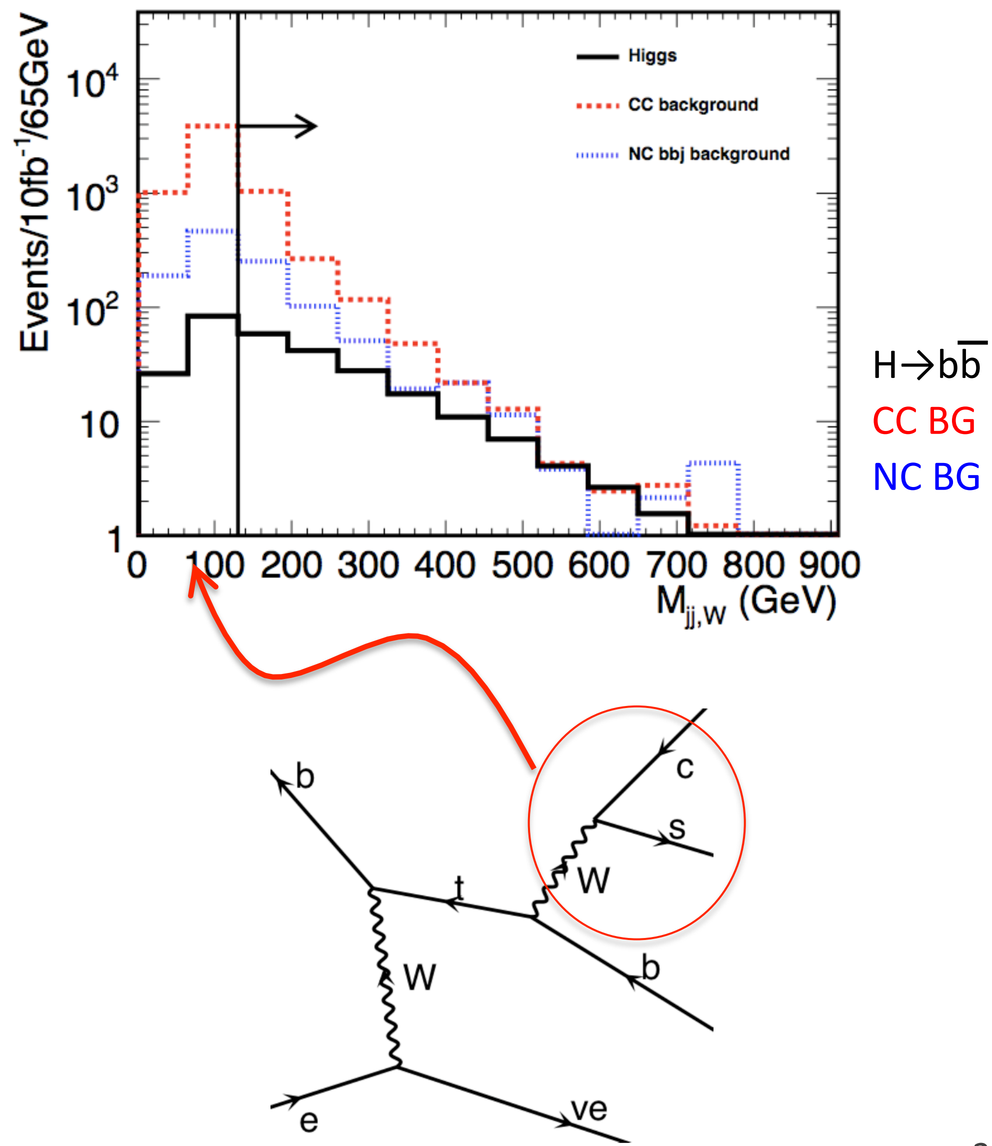
'Detector'

LHC	! parameter set name	
320	! eta cells in calorimeter	
200	! phi cells in calorimeter	
0.0314159	! eta width of calorimeter cells |eta| < 5	
0.0314159	! phi width of calorimeter cells	
0.01	! electromagnetic calorimeter resolution const	
0.2	! electromagnetic calorimeter resolution * sqrt(E)	20% → 5%
0.8	! hadronic calolrimeter resolution * sqrt(E)	80% → 60%
0.2	! MET resolution	
0.01	! calorimeter cell edge crack fraction	
cone	! jet finding algorithm (cone or ktjet)	jets: cone<0.7
5.0	! calorimeter trigger cluster finding seed threshold (GeV)	
1.0	! calorimeter trigger cluster finding shoulder threshold (GeV)	
0.5	! calorimeter kt cluster finder cone size (delta R)	
2.0	! outer radius of tracker (m)	
4.0	! magnetic field (T)	
0.000013	! sagitta resolution (m)	
0.98	! track finding efficiency	
1.00	! minimum track pt (GeV/c)	
3.0	! tracking eta coverage	
3.0	! e/gamma eta coverage	
2.4	! muon eta coverage	
2.0	! tau eta coverage	

Disclaimer :
PGS of LHC detector
+ flat b-tagging
in the full tracking range of
$|\eta|<3.0$
b: 60%, c: 10%, udsg: 1%
CAL coverage until $|\eta|<5.0$

Anti-top selection

- $M_{jj,W} > 130$ GeV

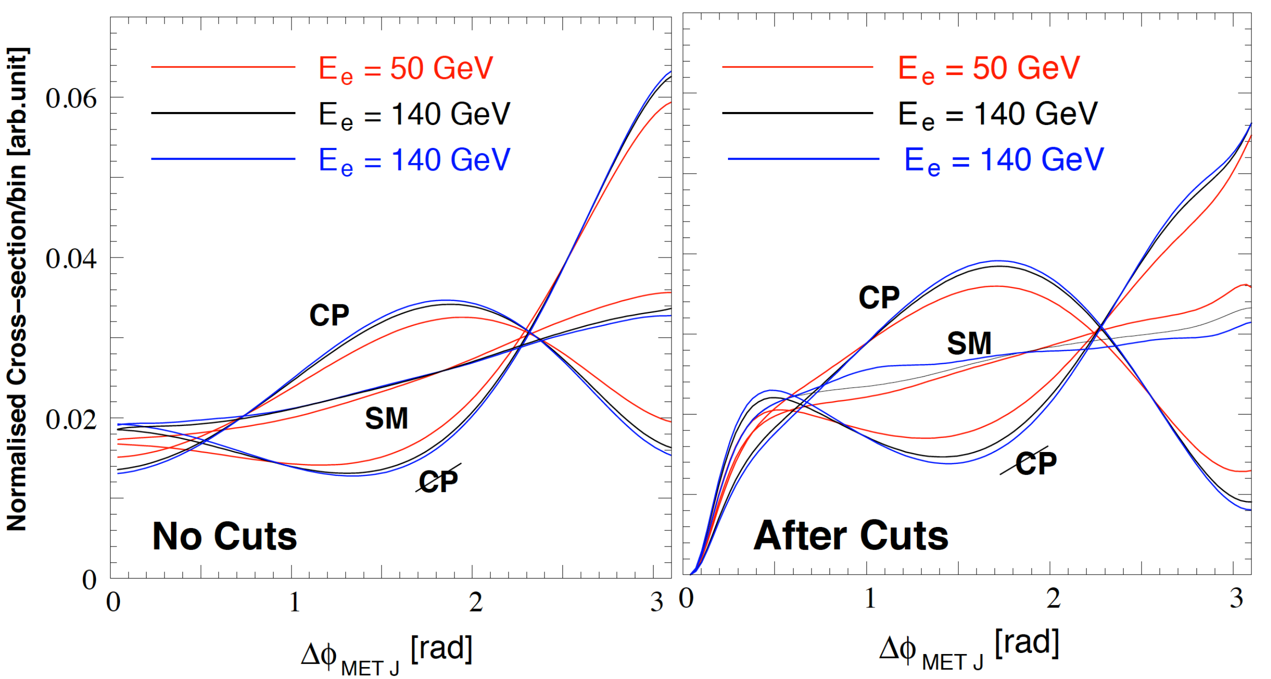


Effect of cuts

Experimental cuts will not change the basic picture of the $\Delta\varphi_{MET,J}$ dependence of normalised DIS CC Higgs cross section

Cuts

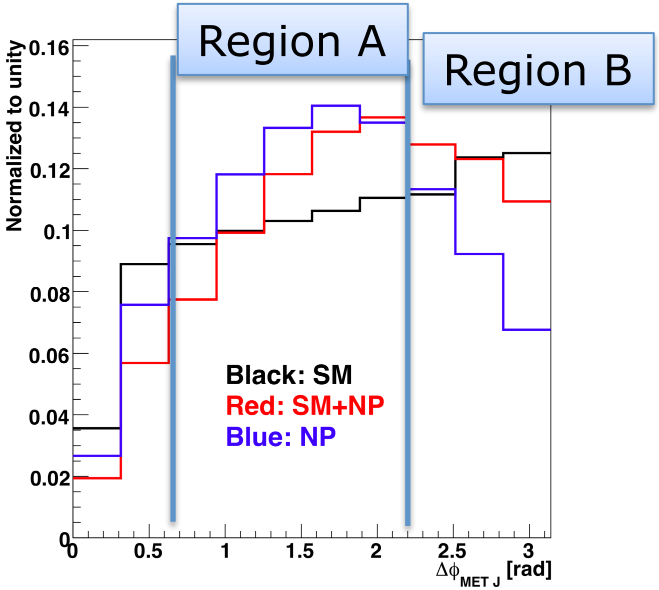
1. All 3 jets have $p_T > 30$ GeV.
2. b-tagged jets must have $|\eta| < 2.5$
3. remaining jet must have $1 < |\eta| < 5$
4. inv. mass of remaining jet and reconstructed Higgs > 250 GeV (at parton level, just the 3-jet invariant mass)
5. MET > 25 GeV
6. $\Delta\phi$ between reconstructed MET and each jets > 0.2.



Case Study for M_H=120 GeV

- Measure deviation of the Higgs production with respect to the SM using the absolute rate of events
- The ratio of the number of events in region B to that of region A in the $\Delta\phi_{MET,J}$ spectrum

CP-odd case



- Assume Gaussian errors and the following systematics:

  - 10% on the background rate
  - 5% on the shape of the $\Delta\phi_{MET,J}$ in background
  - 5% on the rate of the SM Higgs
  - Evaluating theoretical error on $\Delta\phi_{MET,J}$ shape