Prospects for Higgs Physics at LHeC

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for the LHeC Study Group

UNIVERSITY OF LIVERPOOL

ICHEP 2012, Melbourne, July 7th, 2012

A Large Hadron Electron Collider at CERN

J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001 [arXiv:1206.2913]

LHeC Study Group

CDR : About 200 experimentalists and theorists from 69 institutes

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Further LHeC talks at ICHEP2012:

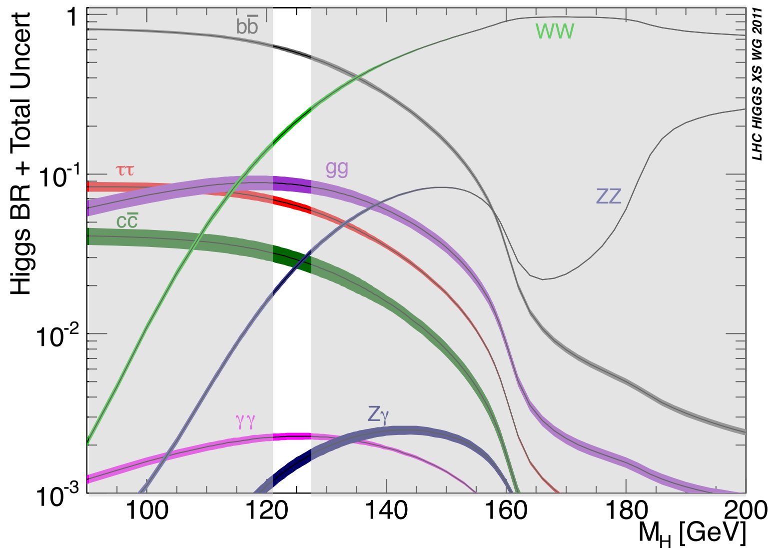
- QCD studies, jets and α_s by Claudia Glasman
- Low-x and eA physics by Paul Newman
- Detector design by Alessandro Polini
- Accelerator overview by Max Klein

http://cern.ch/lhec

Supported by CERN, ECFA, NuPECC

Light SM Higgs production in ep

- Higgs at ~126 GeV : dominant decay to bb

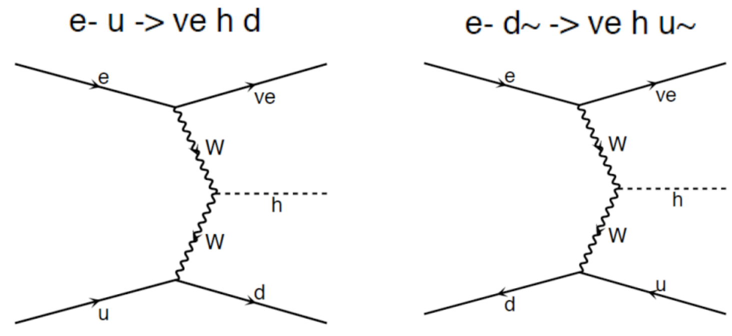


√s=1 – 2 TeV :

- 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)

CC LO SM Higgs Production

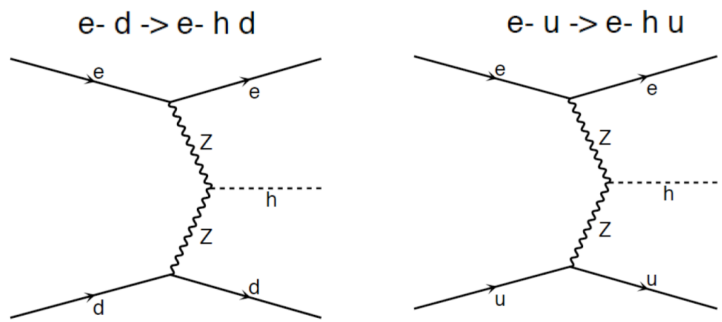
e-p (swap charges for e+p)



around 90-80% | around 10-20%

NC LO SM Higgs Production

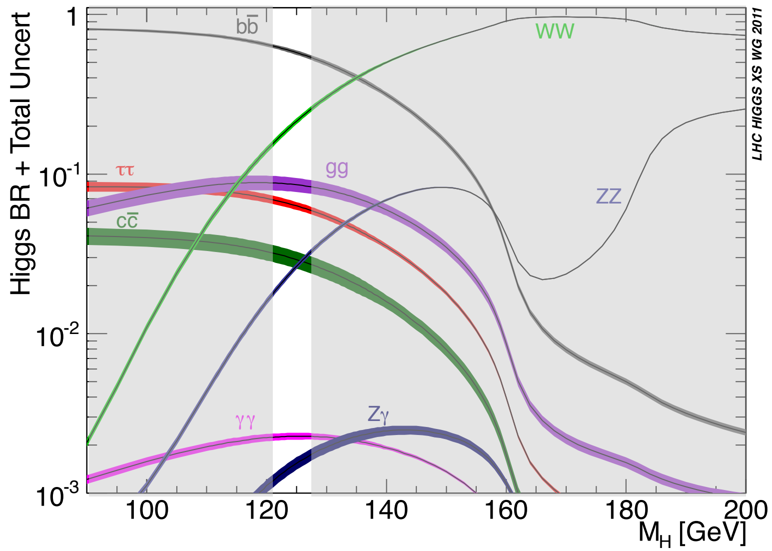
e-p (swap charges for e+p)



around 1/3 | around 1/3

Light SM Higgs production in ep

- Higgs at ~126 GeV : dominant decay to bb



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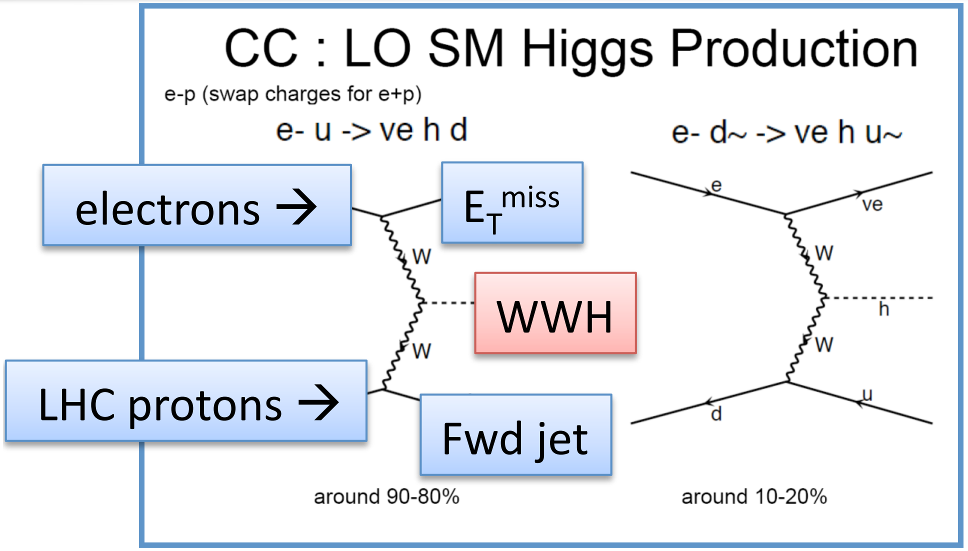
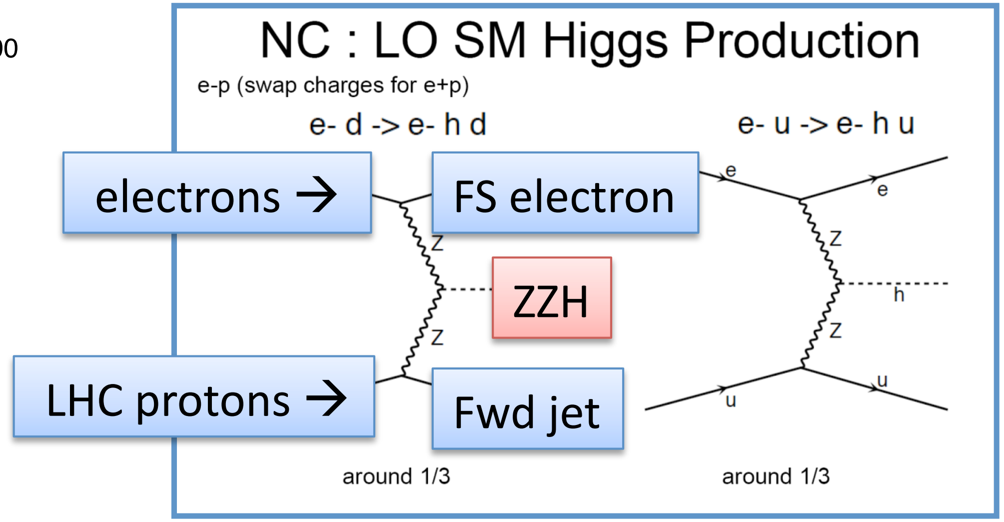




→ In ep, direction of quark (FS) is well defined.

Total SM Higgs cross sections

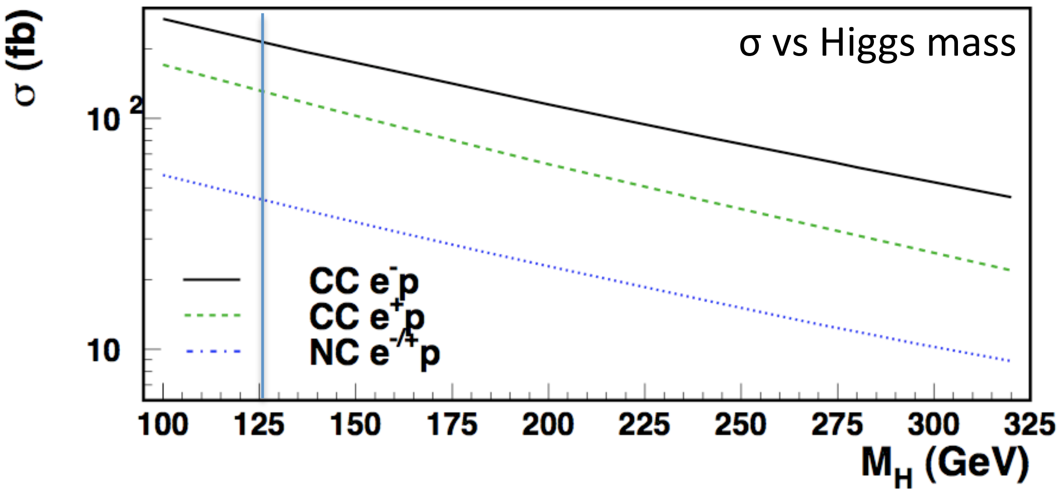
Total CC e^-p Higgs production cross section using design LHC protons of 7 TeV
SM Higgs with M_H = 120 GeV

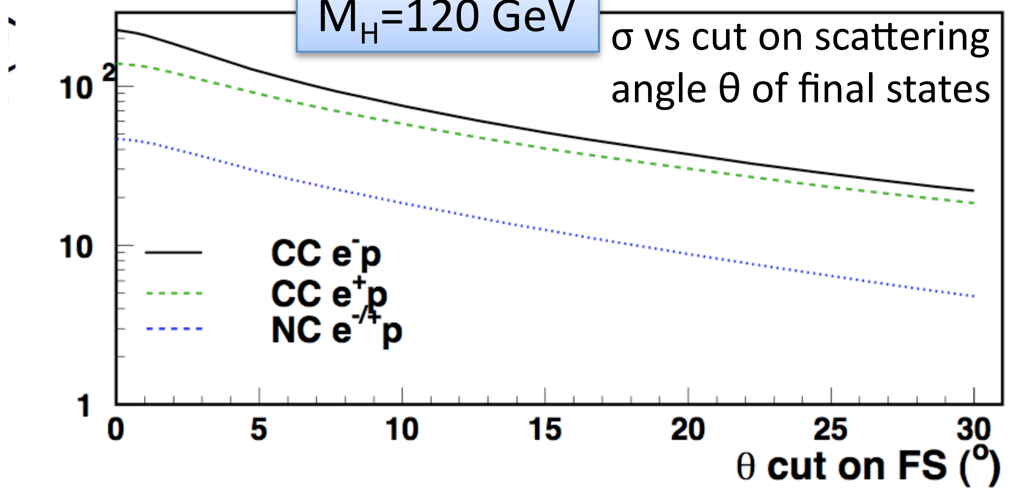
Electron beam energy	50 GeV	100 GeV	150 GeV
cross section [fb]	81	165	239

- **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]

√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 PHYTHIA (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

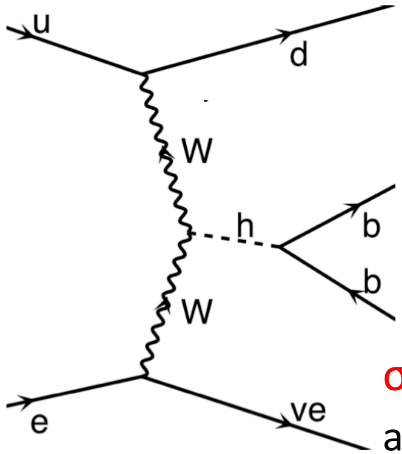
Generator level cuts

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

Generated samples

Signal

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

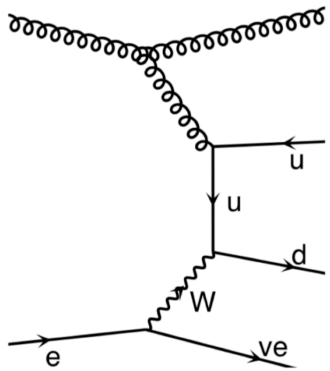


σ~ 0.16 pb
at √s=2.05TeV

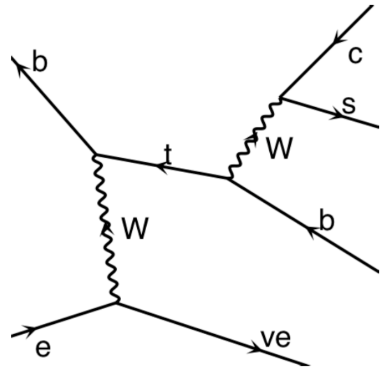
NOTE: Background sample numbers are after pre-selection in generator

Background (examples)

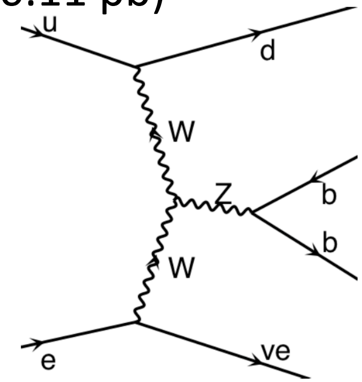
CC: 3 jets (~57 pb)



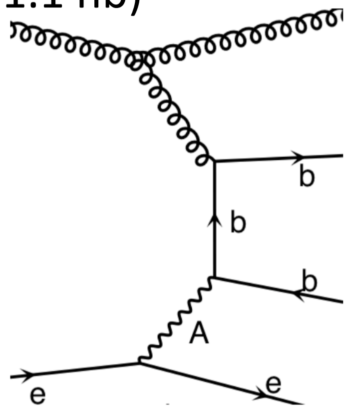
CC: single top production (~4.1 pb)



CC: Z production (~0.11 pb)



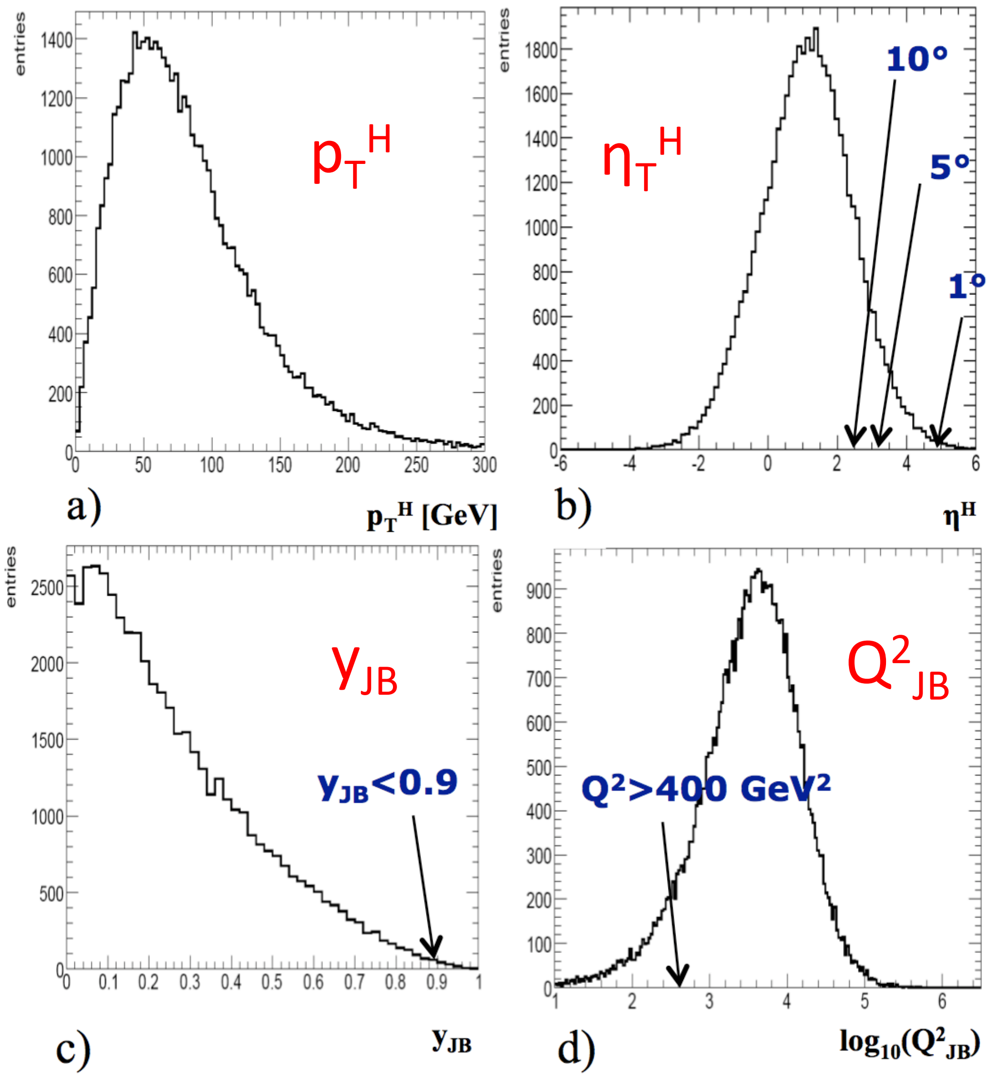
NC: b pair production (~1.1 nb)



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 $H \rightarrow b\bar{b}$

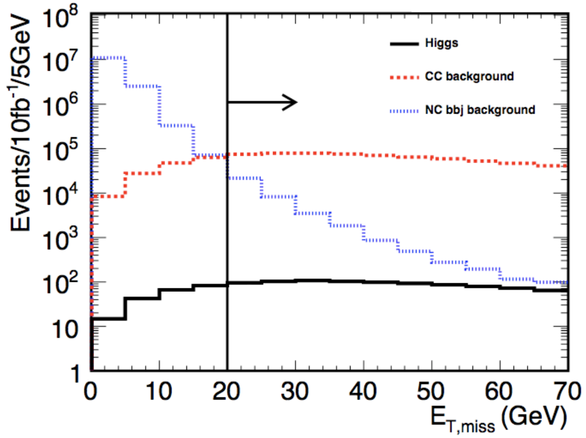
- NC rejection
  - Exclude electron-tagged events
  - $E_{T,miss} > 20$ GeV
  - N_{jet} ($p_T > 20$ GeV) $\geqq 3$
  - $E_{T,total} > 100$ GeV
  - $y_{JB} < 0.9$, $Q^2_{JB} > 400$ GeV^2
- b-tag requirement
  - $N_{b\text{-}jet}$ ($p_T > 20$ GeV) $\geqq 2$
- Higgs invariant mass
  - $90 < M_H < 120$ GeV $\Rightarrow$ 44% of remaining BG is single-top…
- Single top rejection
  - $M_{jjj,top} > 250$ GeV
  - $M_{jj,W} > 130$ GeV

$H \rightarrow b\bar{b}$

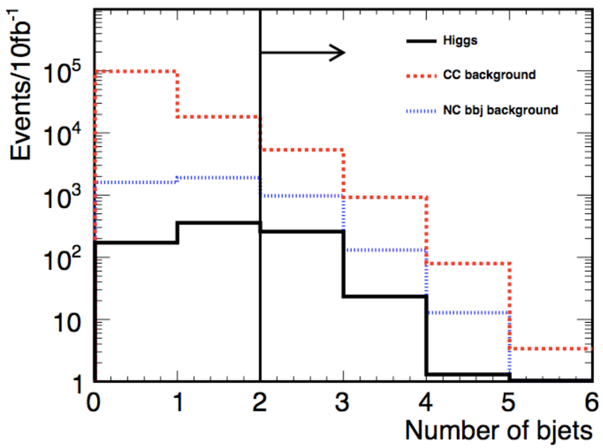
CC BG

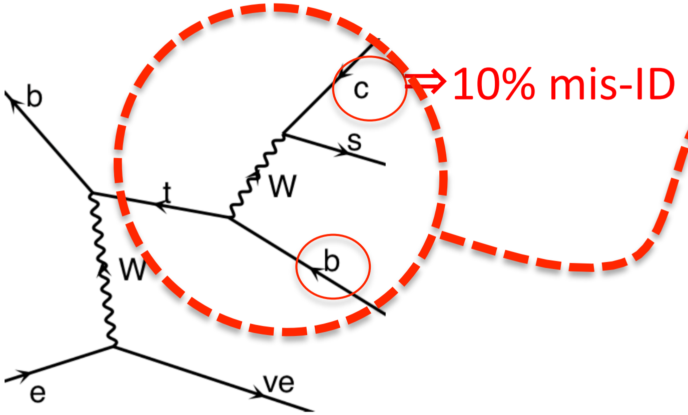
NC BG

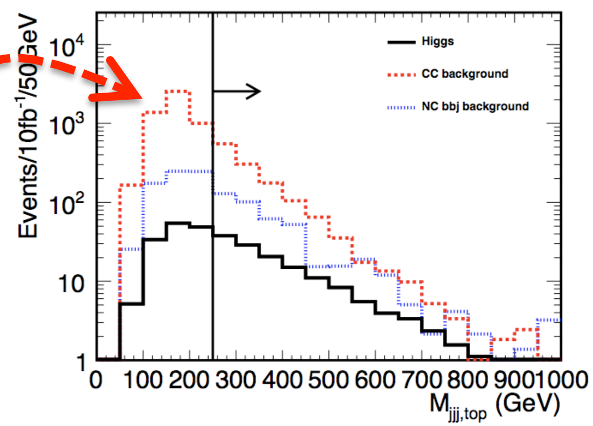
E_T^{miss} cut



b-tag requirement





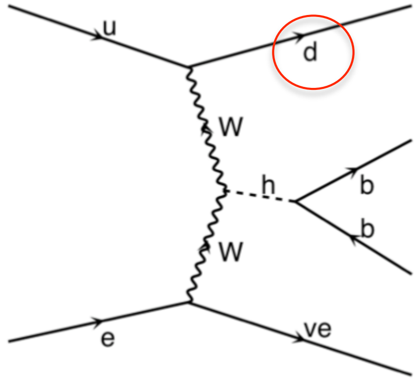


H→b$\bar{b}$ results [M_H=120 GeV, E_p=7 TeV]

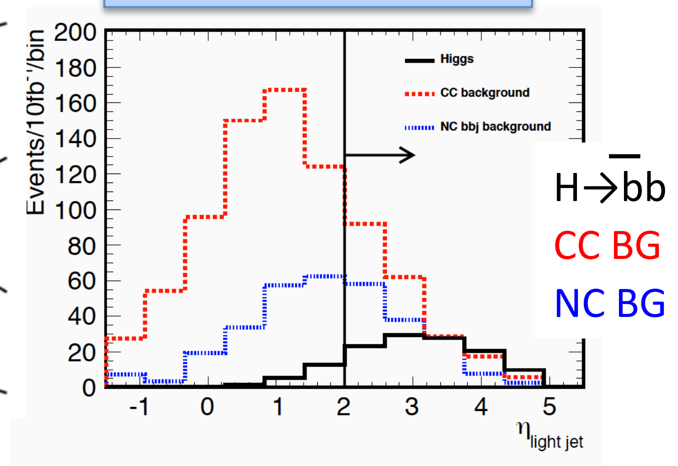
- Forward jet tagging
  - η_{jet} > 2 (lowest η jet excluding b-tagged jets)

Coordinate:
Fwd: +z-axis along proton beam

H → b$\bar{b}$ signal

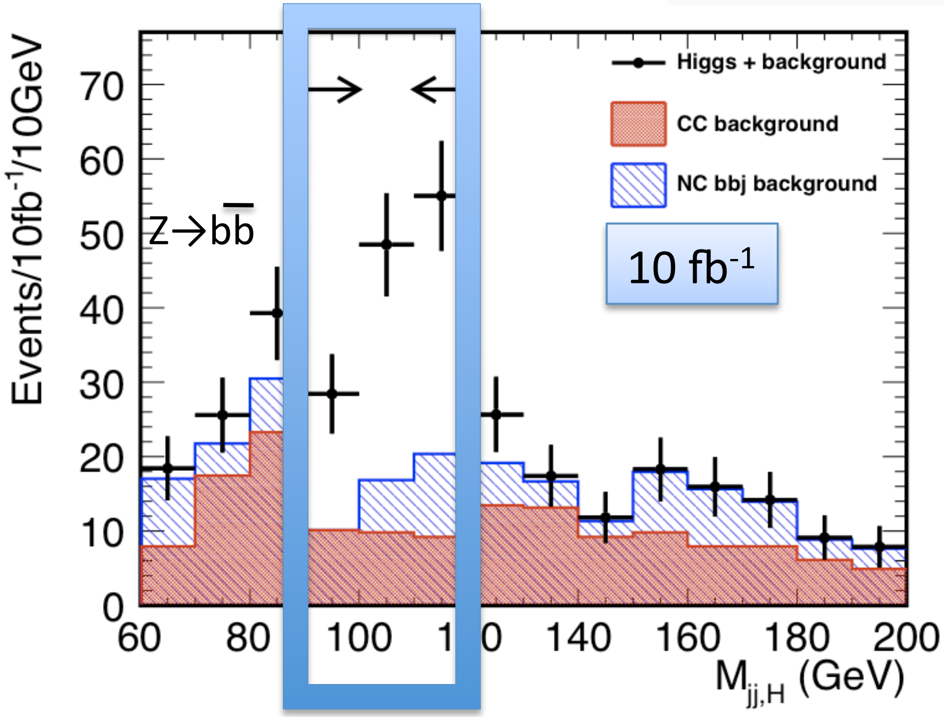


Forward jet η tag



- Higgs invariant mass after all selection

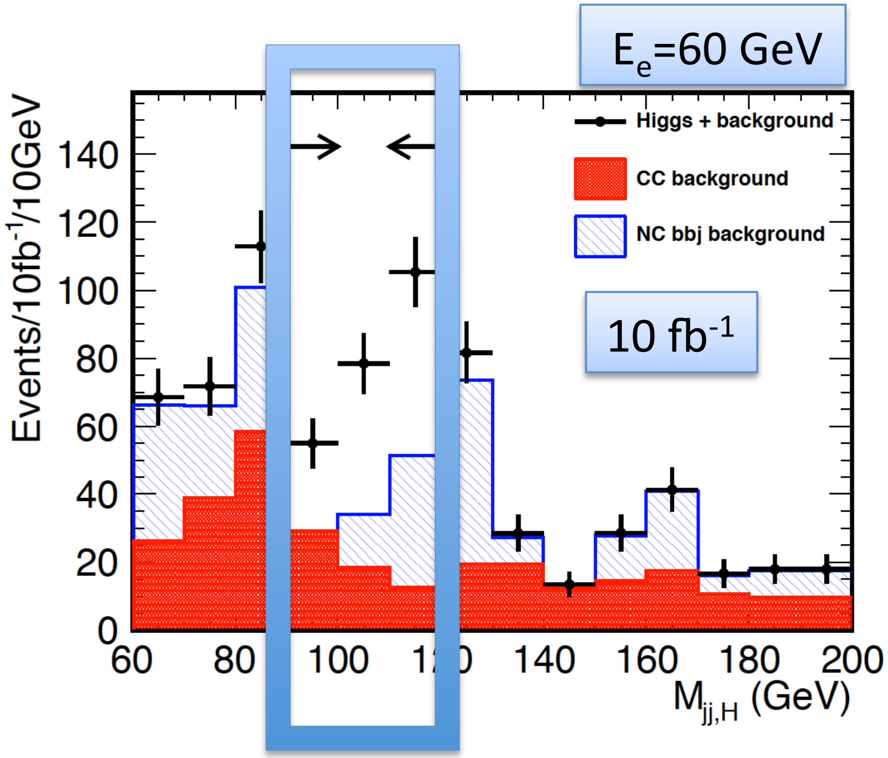
E_e=150 GeV



Clear signal obtained with just cut based analysis already!

H→bb̄ 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.

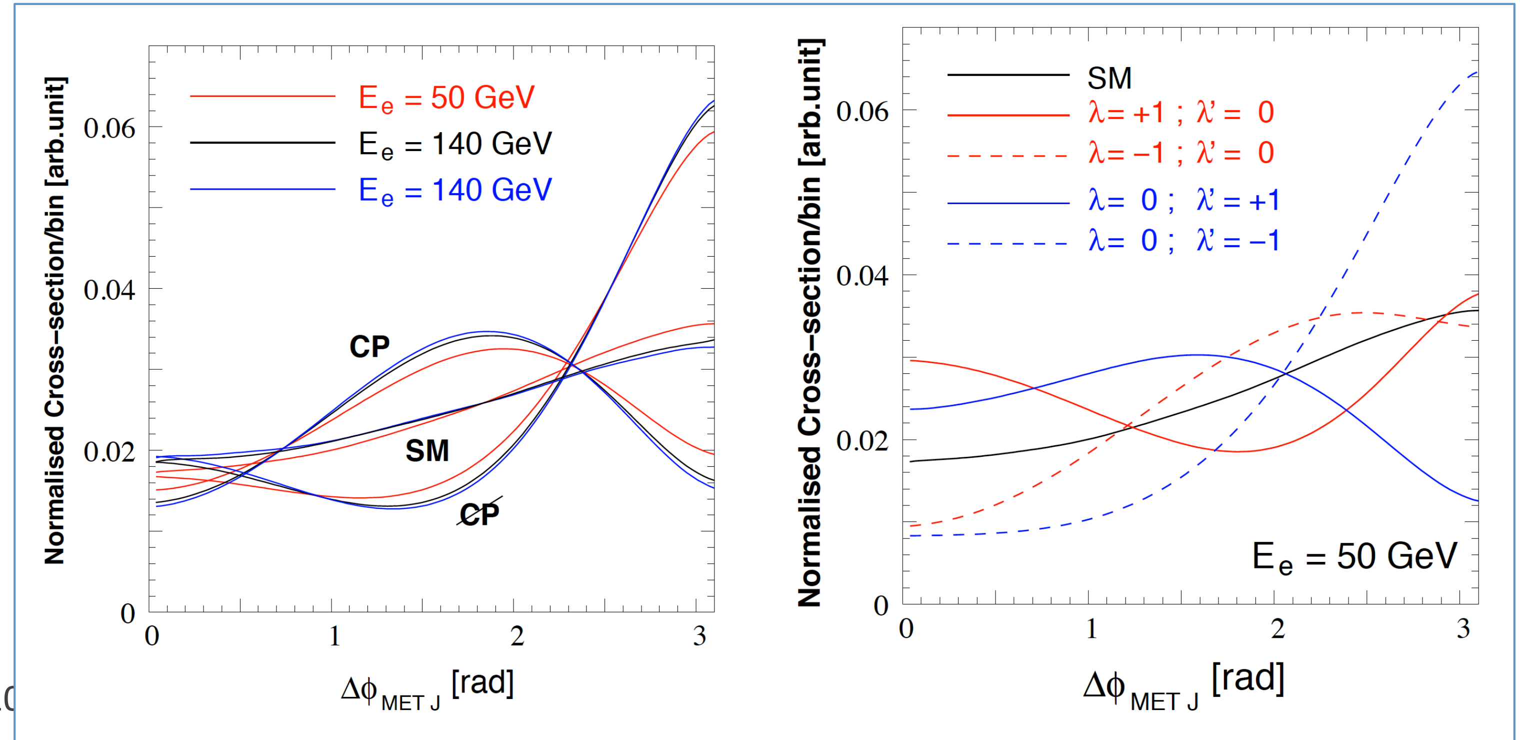
Rohini Godbole

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

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

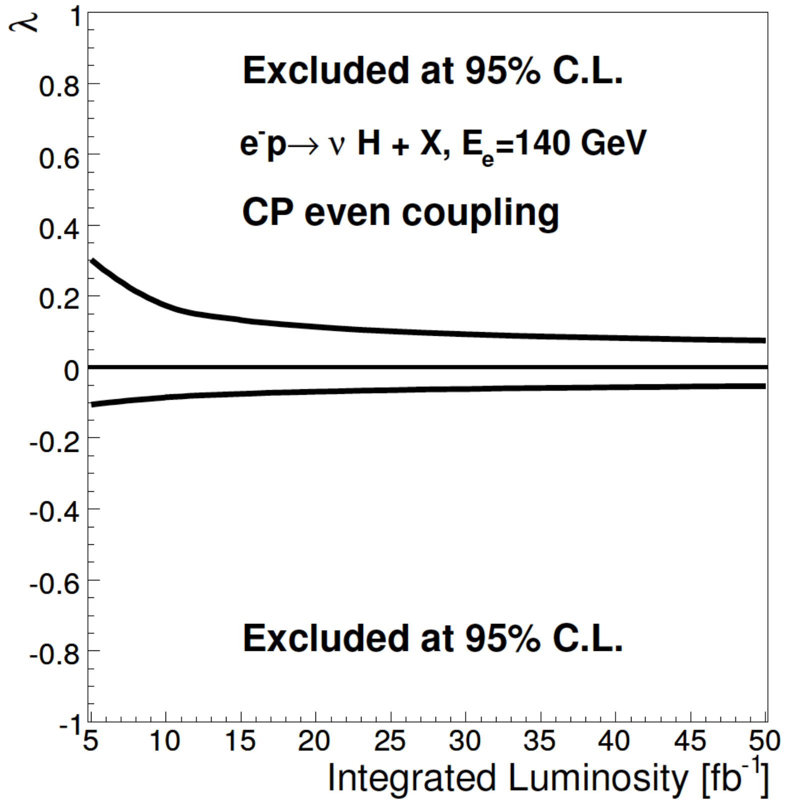
- Study ***shape changes*** in DIS normalised CC Higgs→ bb cross section versus the azimuthal angle between $E_{T,miss}$ and forward jet, $\Delta\phi_{MET,J}$

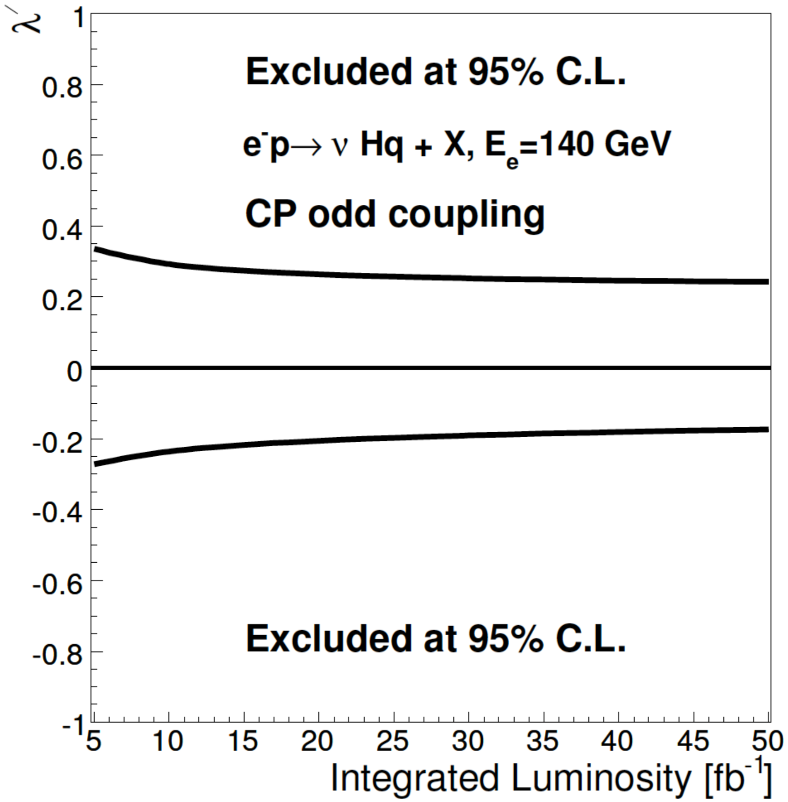


In ep, full Δϕ range can be explored, here not shown yet.

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

Summary

- **LHeC**, in ep(A) collisions synchronous with pp running, could deliver fundamentally new insights on the structure of the proton (and nucleus) with high precision.
- 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. 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.**

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)
0.8	! hadronic calolrimeter resolution * sqrt(E)
0.2	! MET resolution
0.01	! calorimeter cell edge crack fraction
cone	! jet finding algorithm (cone or ktjet)
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

20%→ 5%

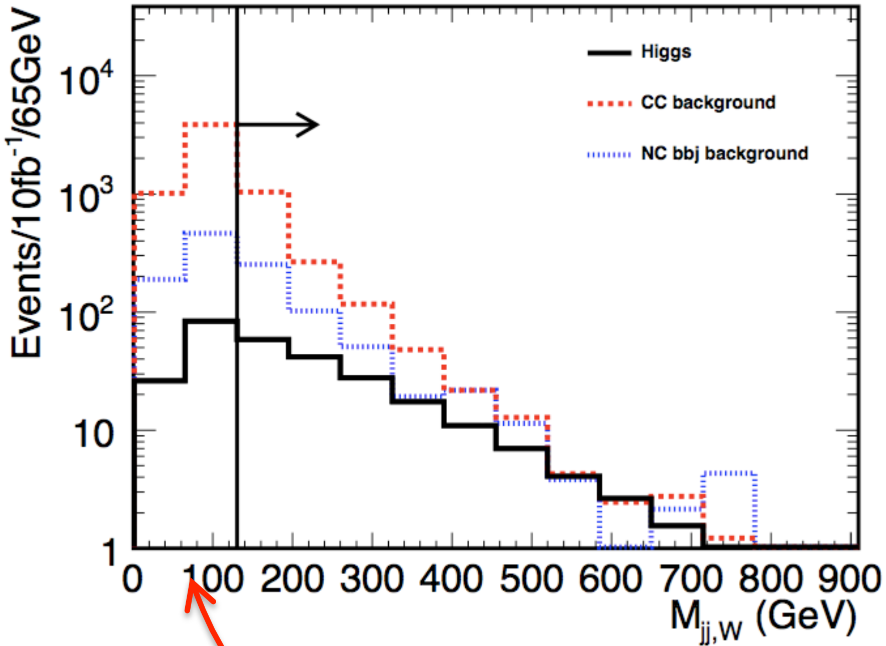
80%→60%

jets: cone<0.7

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

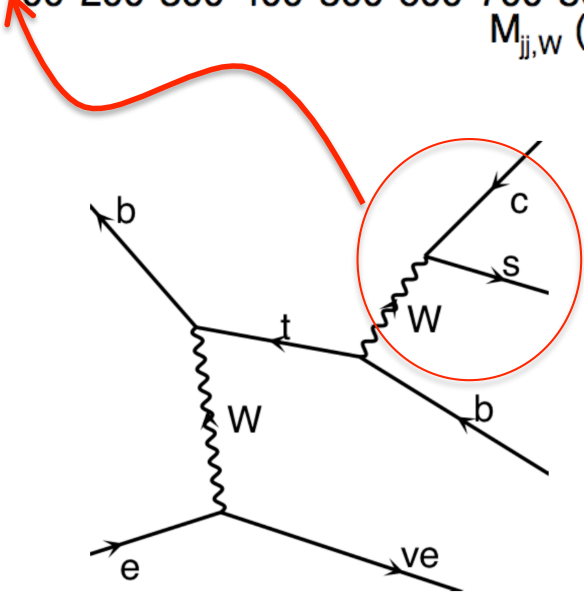
- $M_{jj,W} > 130$ GeV



$H \rightarrow b\bar{b}$

CC BG

NC BG

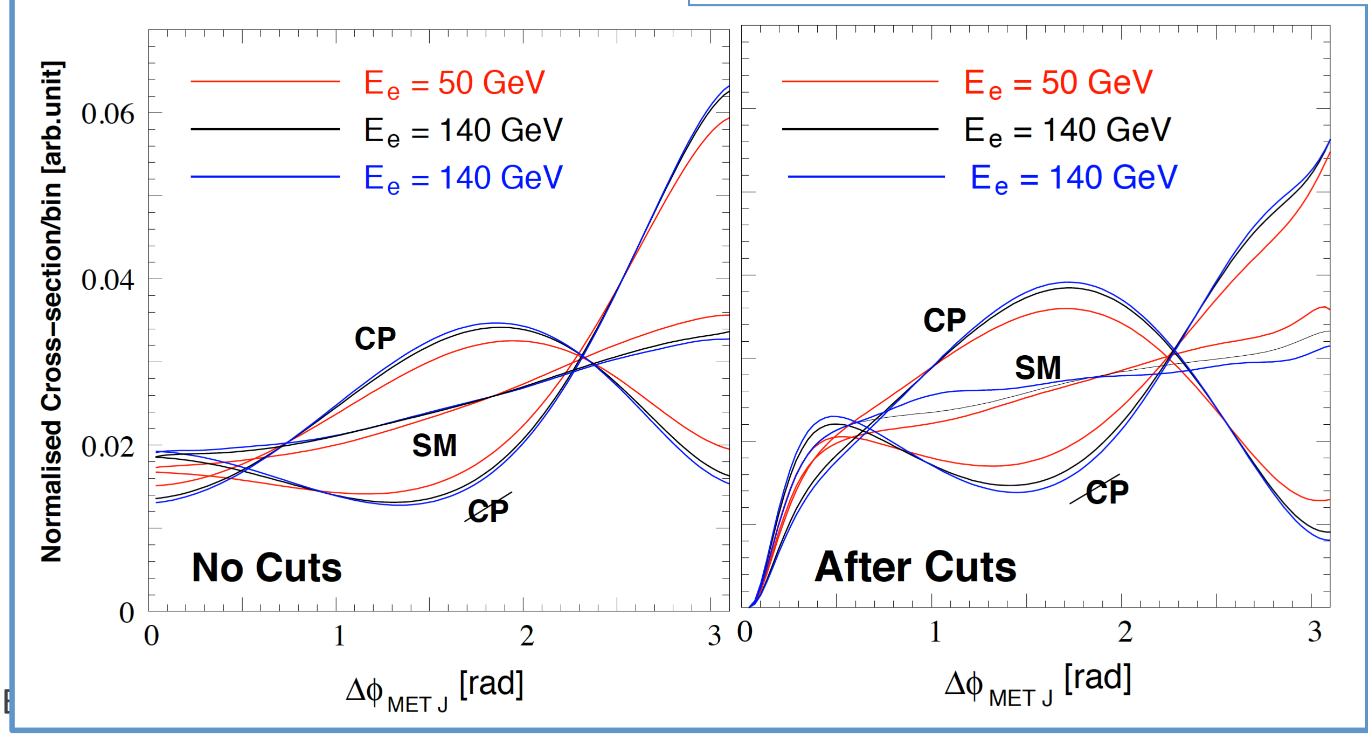


Effect of cuts

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

Cuts

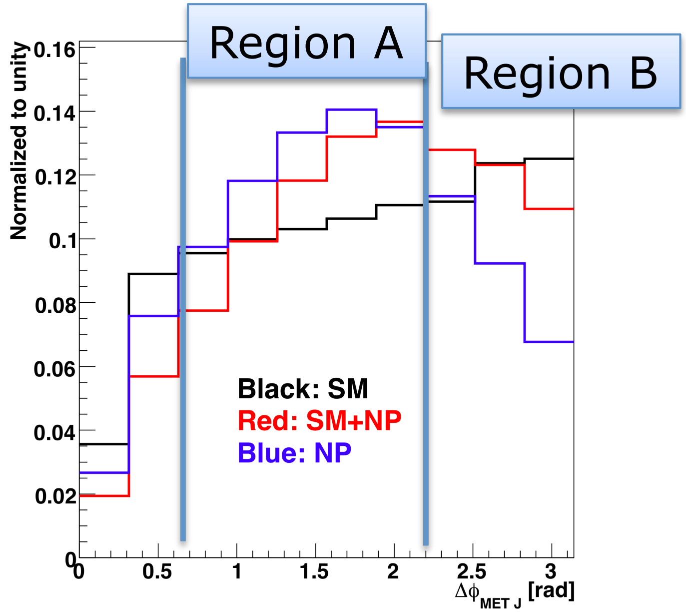
1. All 3 jets have $p_T > 30$ GeV.
2. b-tagged jets must have $|\eta| < 2.5$
3. remaining jet must have $1 < |\eta| < 5$
4. inv. mass of remaining jet and reconstructed Higgs > 250 GeV (at parton level, just the 3-jet invariant mass)
5. MET > 25 GeV
6. $\Delta\phi$ between reconstructed MET and each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