Higgs studies at the LHeC

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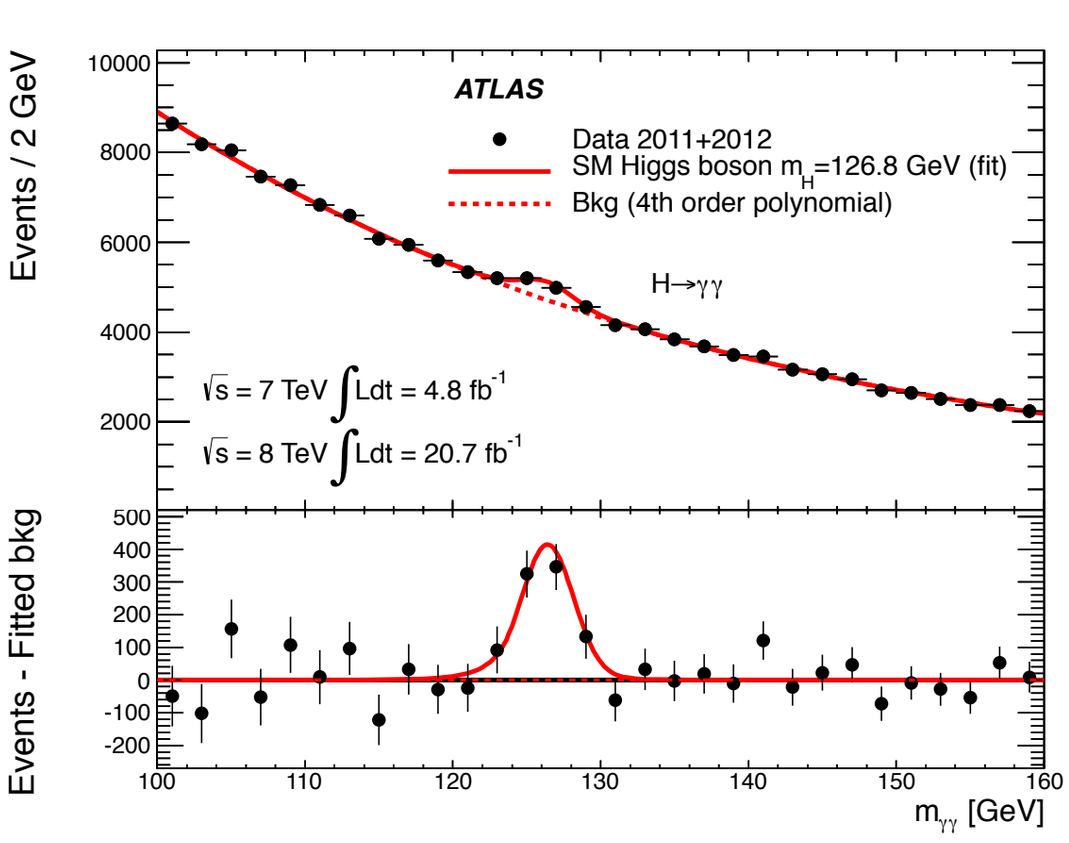
(for the LHeC Collaboration)

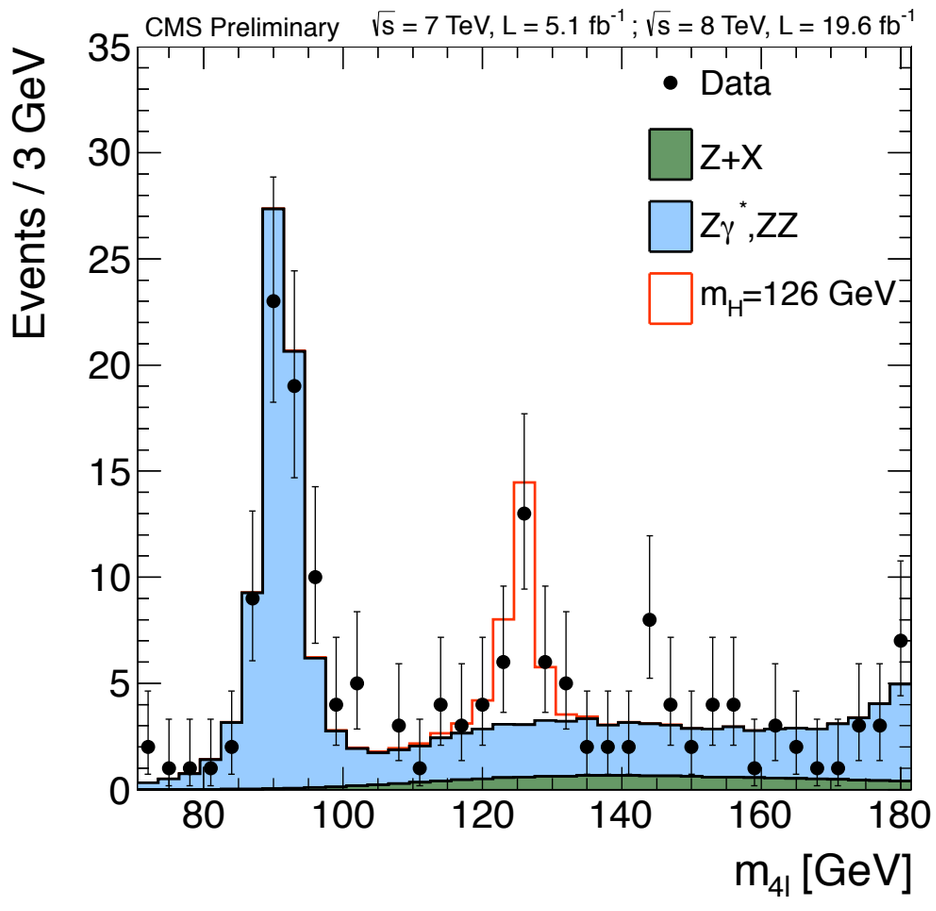
POETIC IV Jyväskylä
5/Sep/2013

A new boson is found

- Full 2011 (7TeV) + 2012 (8TeV) data shown in EPS2013
- ~7 σ significance in single channels



ATLAS H→$\gamma\gamma$

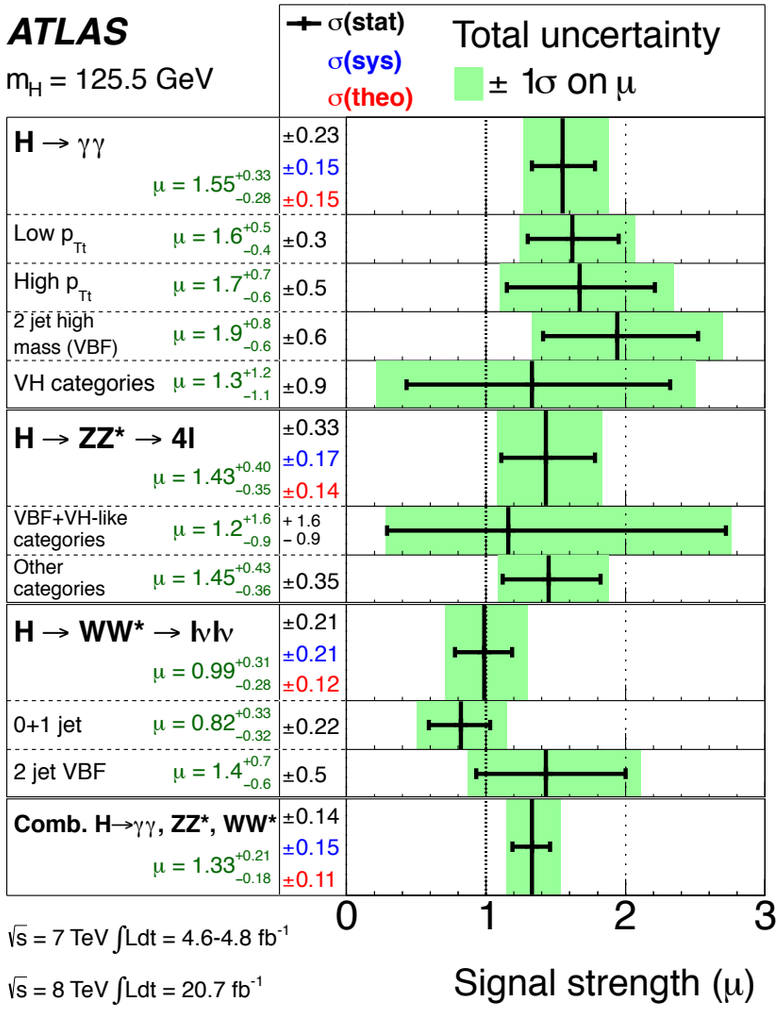


CMS H→ZZ*→4 lepton

Consistent with SM Higgs

Cross section

(divided by σ_{SM})

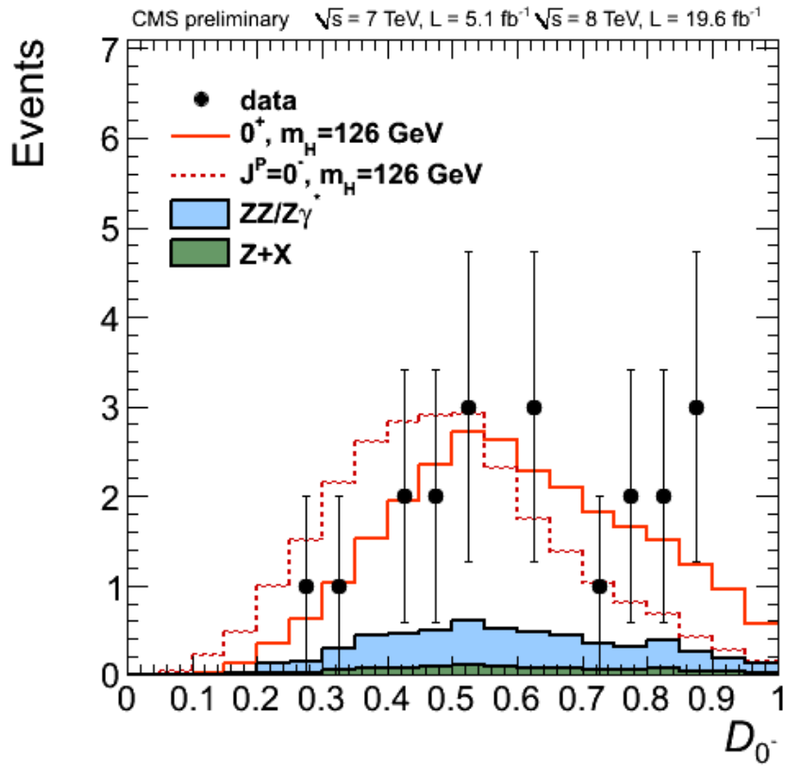


Spin/Parity

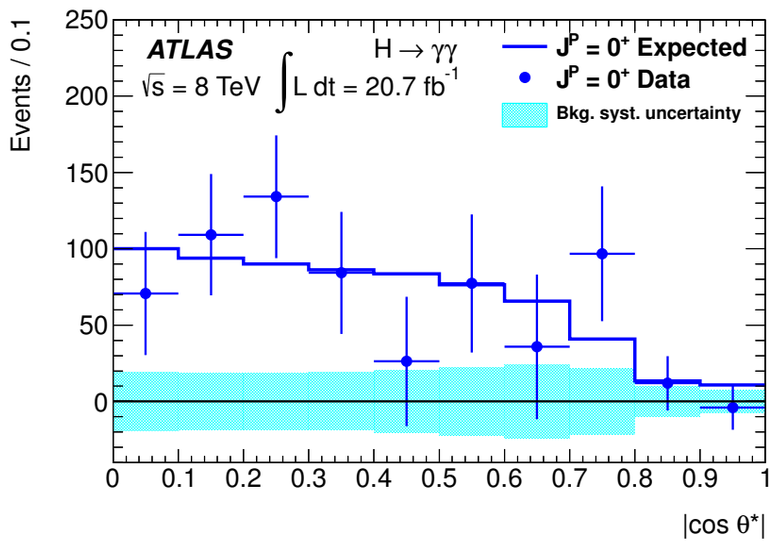
0^+ favored

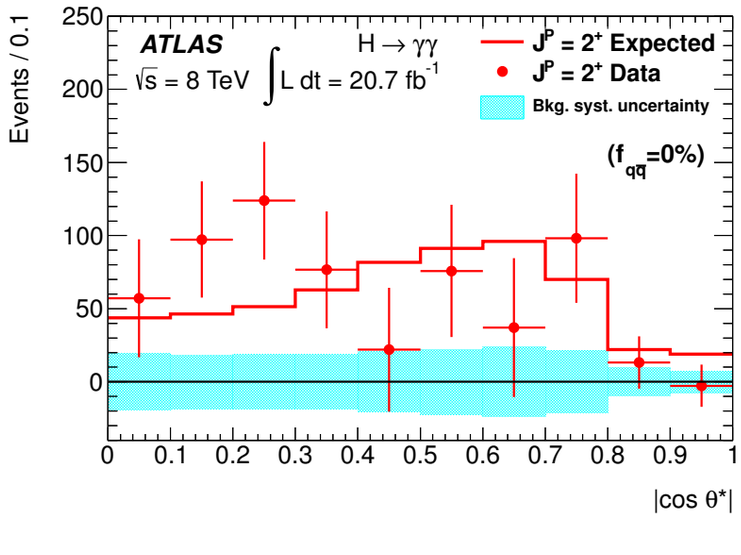
at > ~99% CL

0^+ vs 0^-



0^+ vs 2^+



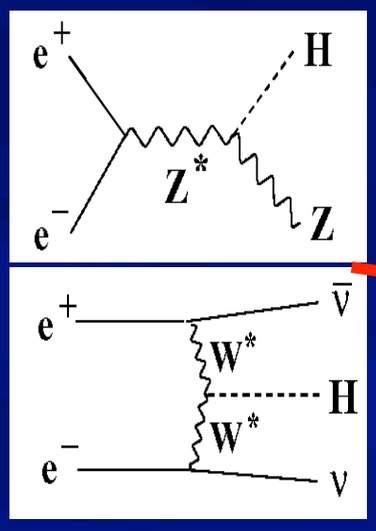


Is this SM or BSM Higgs?

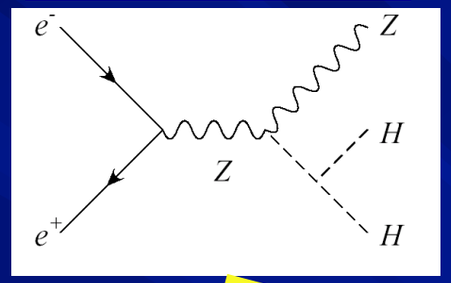
Next important task: measure its coupling to SM particles

Coupling measurements at ILC

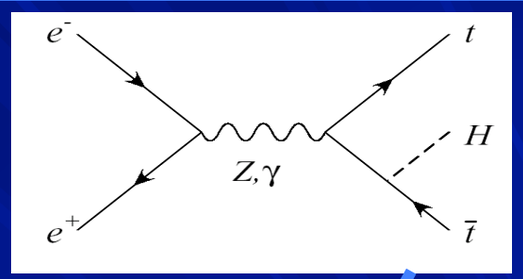
Gauge Coupling



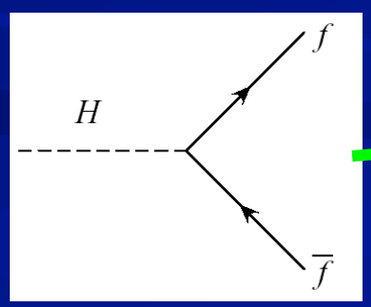
Self-coupling

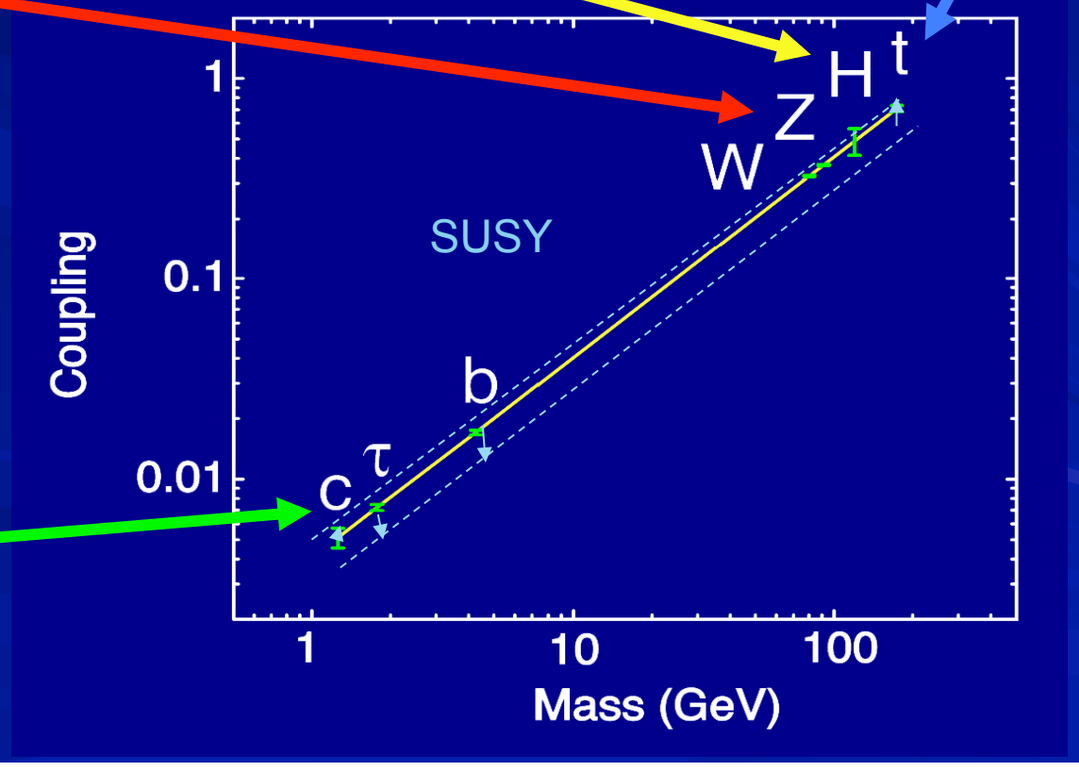


Top Yukawa coupling



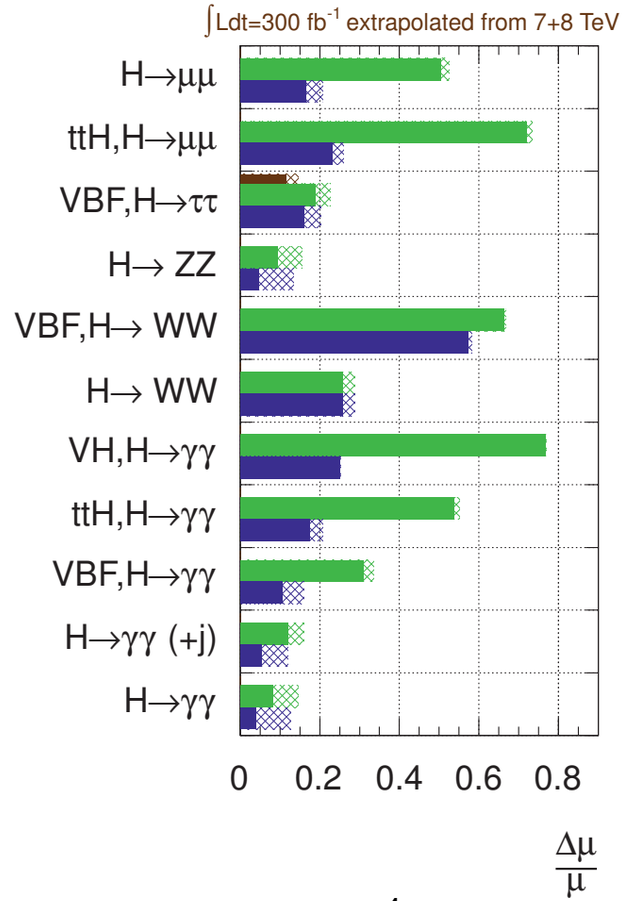
Yukawa coupling



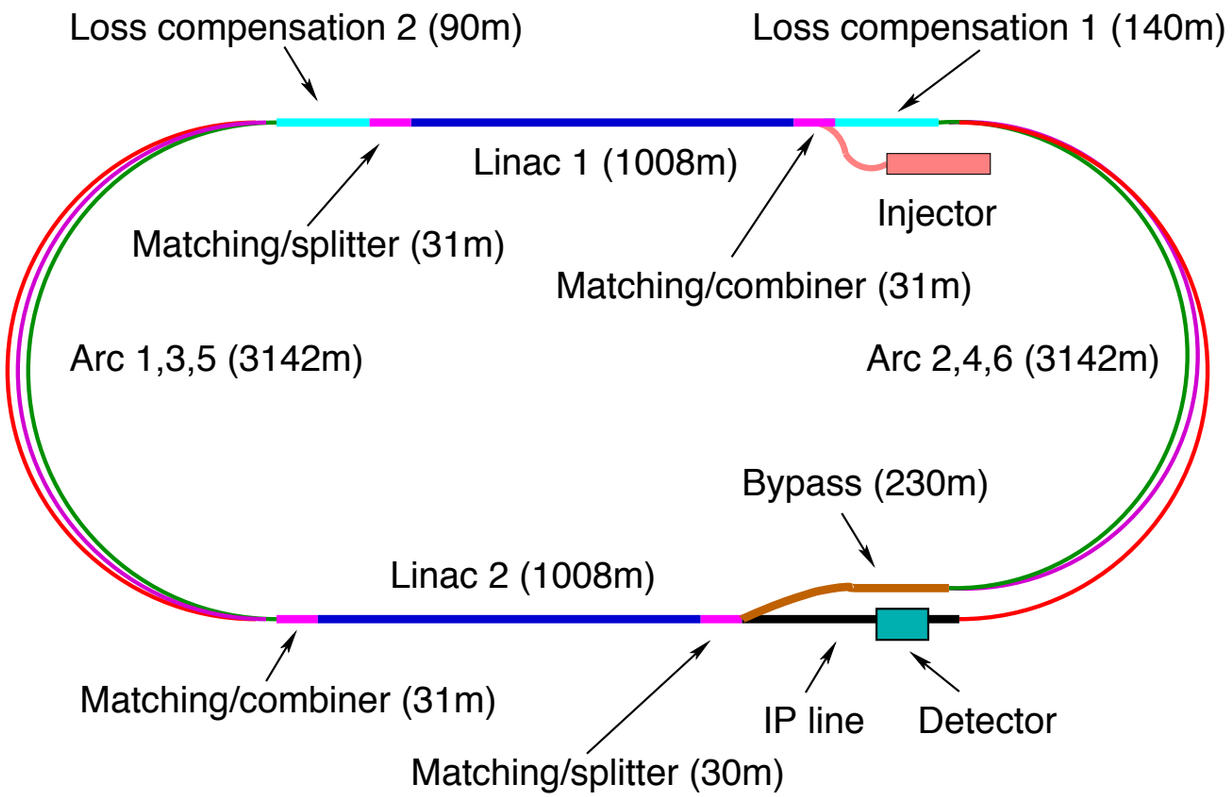


ATLAS-PHYS-PUB-2013-007

HL-LHC prospects for cross section measurements



The LHeC project



60GeV electron beam in racetrack-ERL + 7TeV proton in LHC (and Pb)

√s(ep) = 1.3TeV (4x HERA)

parameter [unit]	LHeC	
species	e^-	p, $^{208}Pb^{82+}$
beam energy (/nucleon) [GeV]	60	7000, 2760
bunch spacing [ns]	25, 100	25, 100
bunch intensity (nucleon) [10^{10}]	0.1 (0.2), 0.4	17 (22), 2.5
beam current [mA]	6.4 (12.8)	860 (1110), 6
rms bunch length [mm]	0.6	75.5
polarization [%]	90	none, none
normalized rms emittance [μm]	50	3.75 (2.0), 1.5
geometric rms emittance [nm]	0.43	0.50 (0.31)
IP beta function $\beta^*_{x,y}$ [m]	0.12 (0.032)	0.1 (0.05)
IP spot size [μm]	7.2 (3.7)	7.2 (3.7)
synchrotron tune Q_s	—	1.9×10^{-3}
hadron beam-beam parameter	0.0001 (0.0002)	
lepton disruption parameter D	6 (30)	
crossing angle	0 (detector-integrated dipole)	
hourglass reduction factor H_{hg}	0.91 (0.67)	
pinch enhancement factor H_D	1.35	
CM energy [TeV]	1300, 810	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1 (10), 0.2	

Baseline design:

L=10^{33} (10 fb^{-1}/y)

High-lumi option:

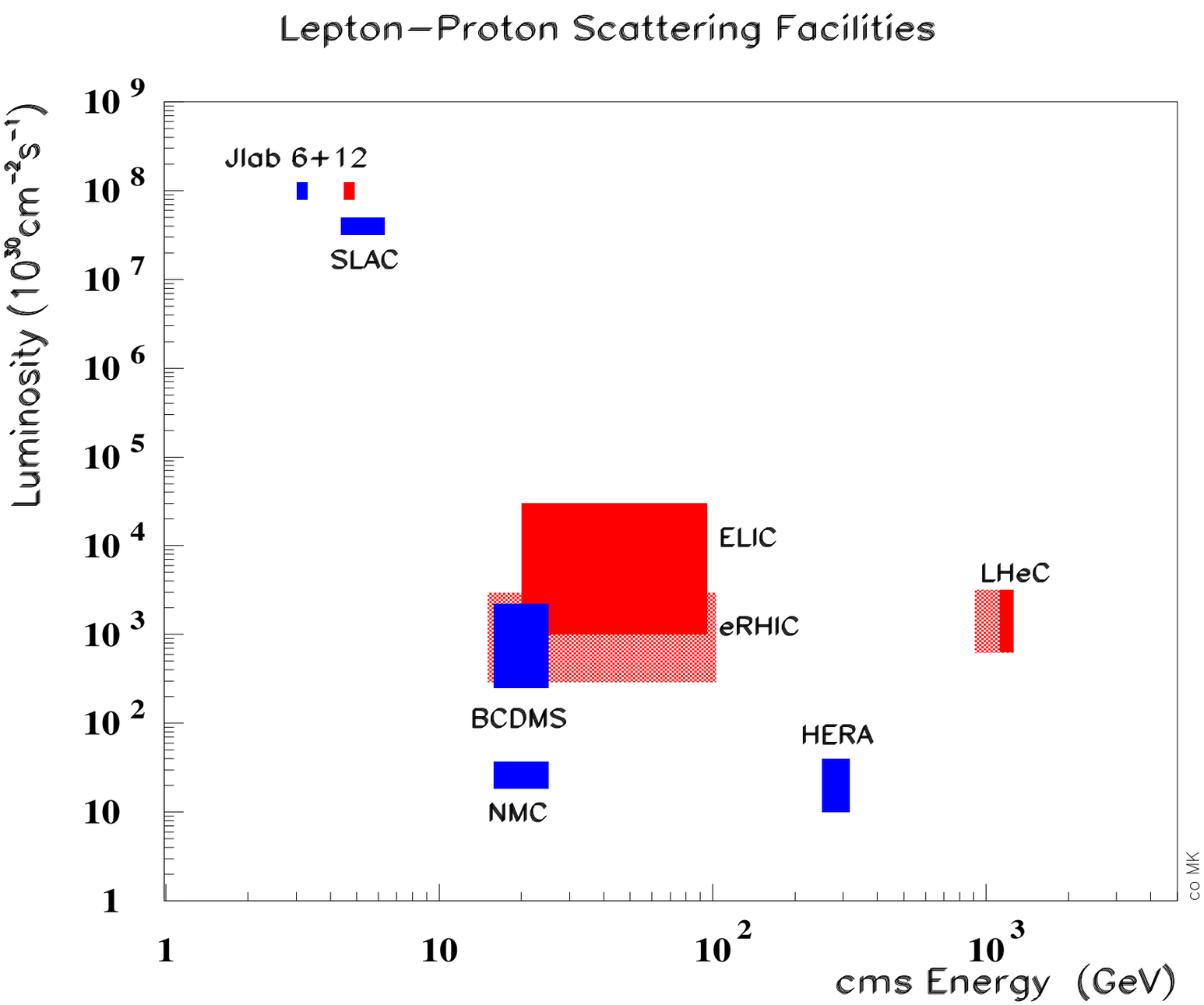
L=10^{34} (100 fb^{-1}/y)

LHeC Study Group, arXiv.1211.5102

O. Brüning and M. Klein, arXiv:1305.2090

The LHeC project

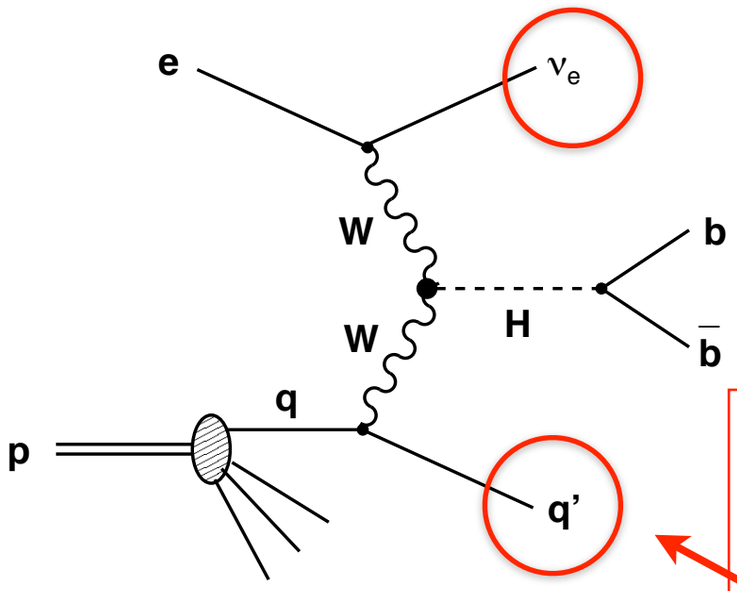
M. Klein, DIS2013



- LHeC is the highest-energy ep facility (also eA)

Higgs production at LHeC

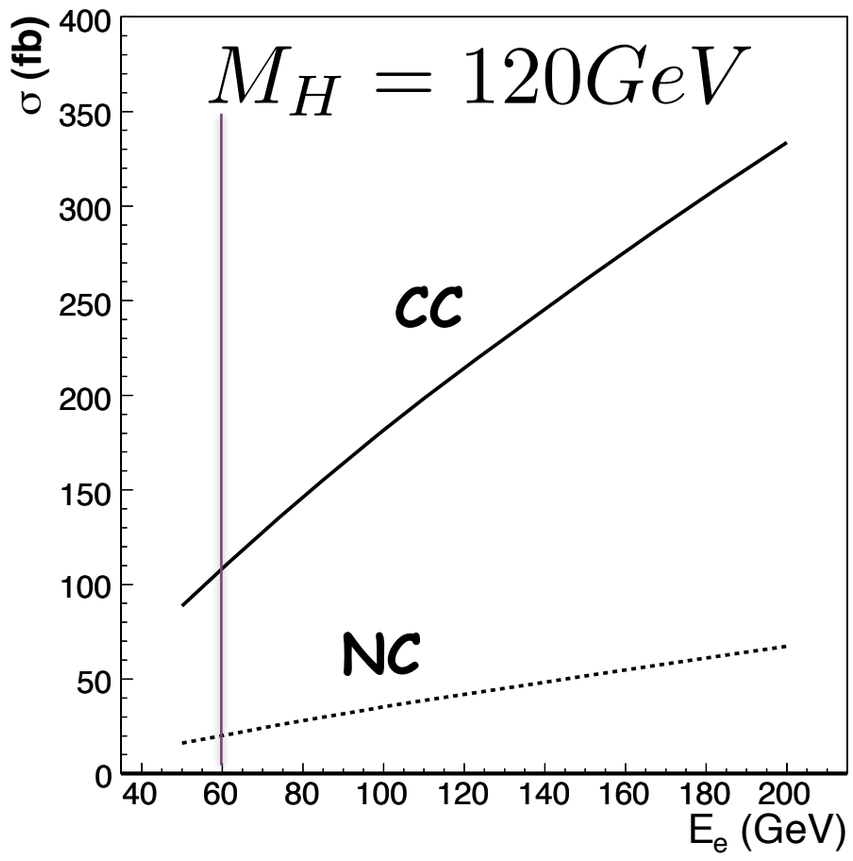
- Mainly via WW fusion in CC process
- NC (ZZ fusion) much smaller



σ~100fb ⟶
for E_e=60GeV

Vector-Boson Fusion
(already established at LHC)
VBF tagging forward jet

B. Mellado



1. Hbb couping measurement (deemed challenging at LHC)

   Tokyo Tech - M. Ishitsuka, K. Kimura (M-thesis), MK

   Liverpool - C. Hengler, U. Klein (for LHeC CDR arXiv:1206.2913)

2. CP property of Higgs (test of anomalous HWW coupling)

   S. Biswal, R. Godbole, B. Mellado, S. Raychaudhuri

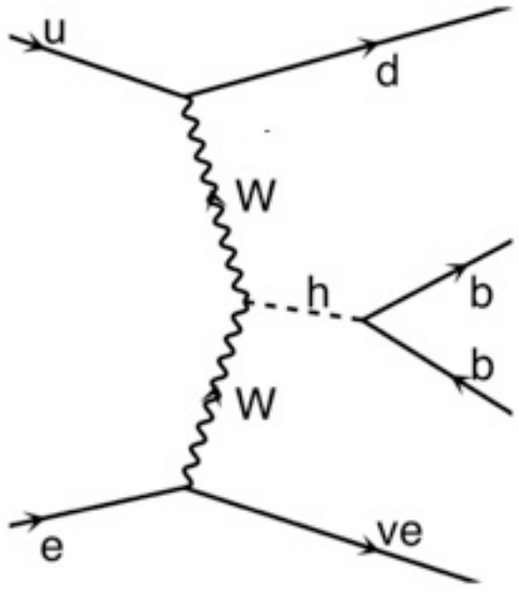
   Phys. Rev. Lett. 109 (2012) 261801

Higgs at LHeC

NOTE: numbers are after pre-selection in generator

Signal

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



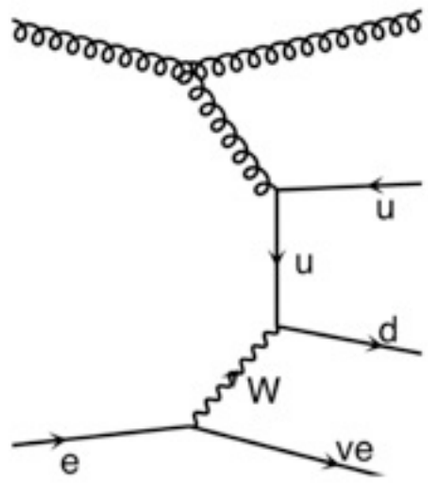
$\sigma \cdot B \sim 0.16$ pb

at $\sqrt{s}$=2.05TeV

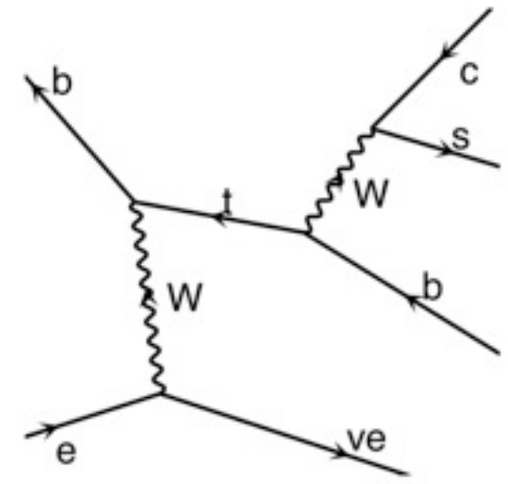
NOTE: The plots shown are from initial study for LHeC CDR (1206.2913), E_e = 150GeV. Results also given for 60GeV (see later).

Background (example)

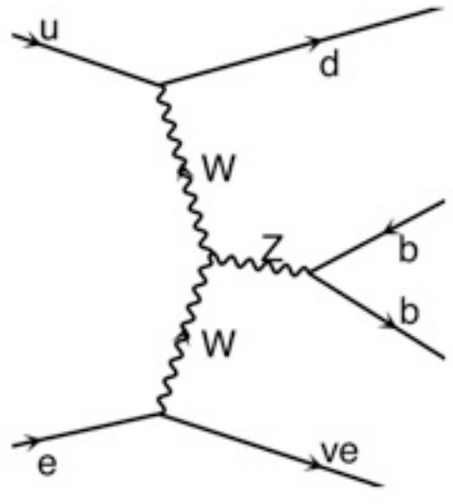
CC: 3 jets (~57pb)



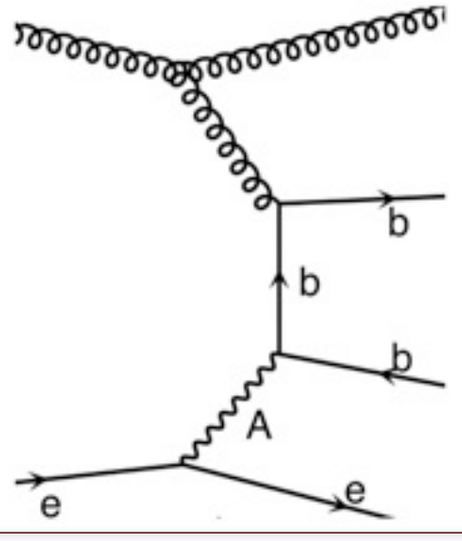
CC: single top production (~4.1pb)



CC: Z production (~0.11pb)



NC: b pair production (~1.1nb)



LHeC in simulation

LHeC CDR arXiv:1206.2913

Event generation
- SM Higgs production
- CC & NC background

by MadGraph/MadEvent

↓

- Fragmentation
- Hadronization

by Pythia (+ mod. for ep)

↓

Fast detector simulation
by PGS

↓

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

✳ Calculate cross-section with tree-level Feynman diagrams

✳ Generate final state of outgoing particles

Input parameters:

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

(+ 60 GeV configuration as comparison)

Generator level cuts

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

LHeC in simulation

Event generation
- SM Higgs production
- CC & NC background

by MadGraph/MadEvent

↓

- Fragmentation
- Hadronization

by Pythia (+ mod. for ep)

↓

Fast detector simulation by PGS

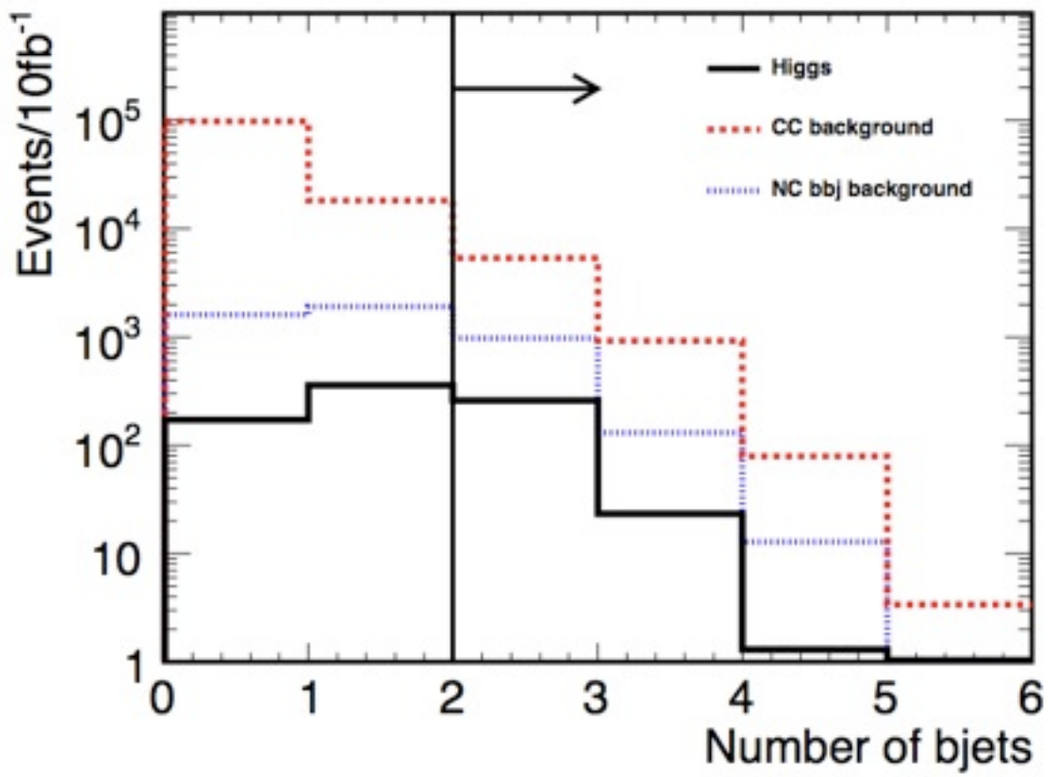
↓

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

- Generic detector with
  - 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 by cone algorithm ($\Delta R=0.7$)
  - b-tag performance
    - Flat efficiency for $|\eta| < 3$
    - Efficiency/mis-ID
      - b-jet: 60%
      - c-jet: 10%
      - Other jets: 1%

Selection of $H \to b\bar{b}$

- NC rejection
  - Exclude electron-tagged events
  - $E_{T,miss} > 20GeV$
  - N_{jet} ($p_T > 20GeV$) ≧ 3
  - $E_{T,total} > 100GeV$
  - $y_{JB} < 0.9$, $Q^2_{JB} > 400GeV$
- b-tag requirement
  - $N_{b\text{-}jet}$ ($p_T > 20GeV$) ≧ 2
- Higgs invariant mass
  - $90 < M_H < 120GeV$
- Single top rejection
  - $M_{jjj,top} > 250GeV$
  - $M_{jj,W} > 130GeV$
- Forward jet tagging
  - $\eta_{jet} > 2$ (lowest η excluding b-tagged jets)



$H \to b\bar{b}$
CC BG
NC BG

b-tag efficiency model

for $|\eta| < 3$

b-jet identification:	$\varepsilon = 60\%$
c-jet mis-ID:	$\varepsilon = 10\%$
Other jet mis-ID:	$\varepsilon = 1\%$

Selection of $H \to b\bar{b}$

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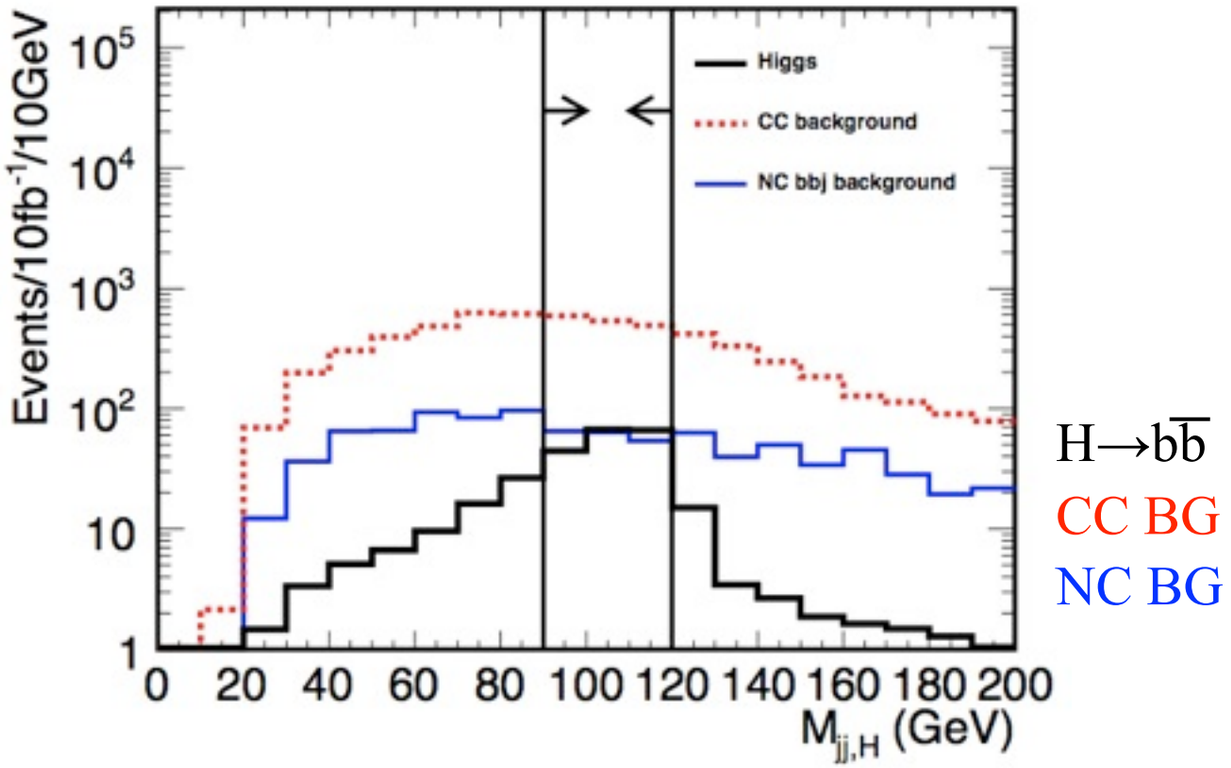
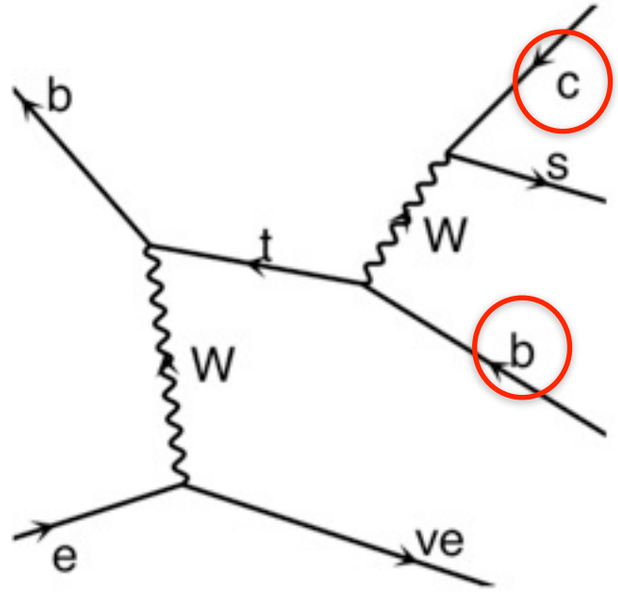


⇒ 44% of remaining BG is single-top…



⇒10% mis-ID

Selection of $H \to b\bar{b}$

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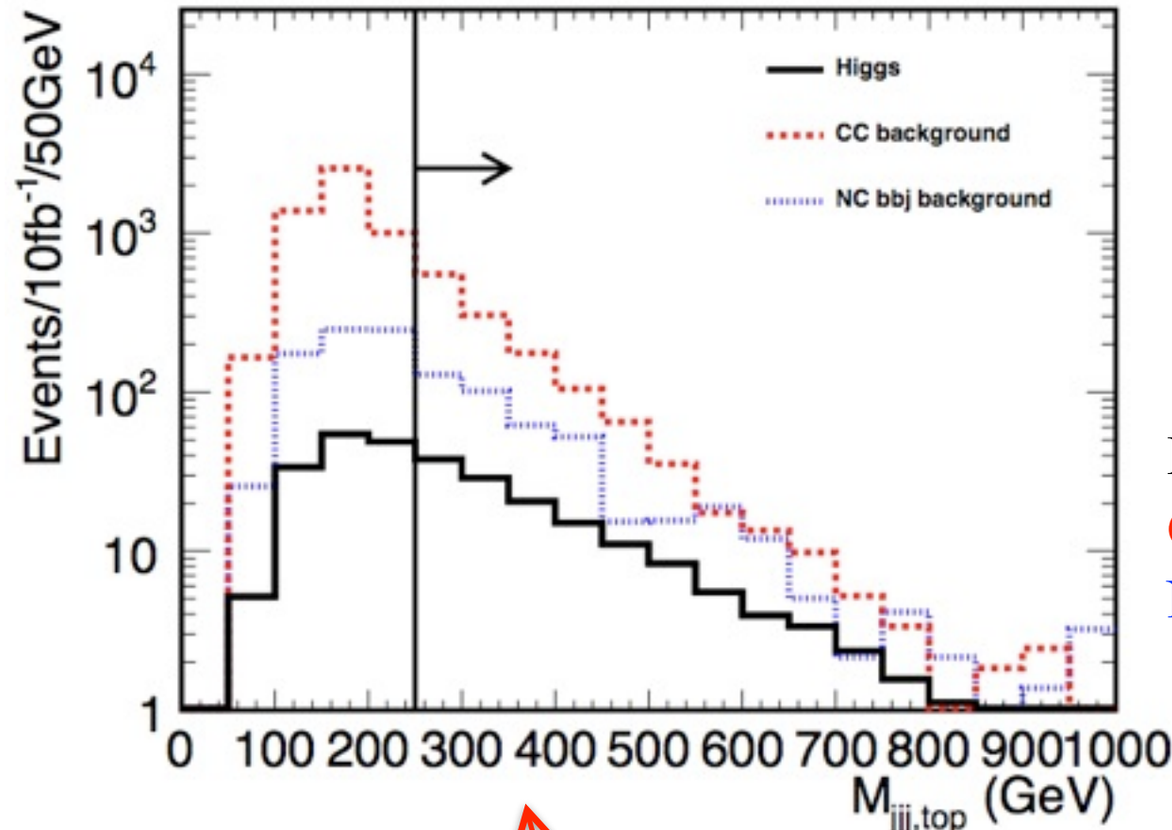
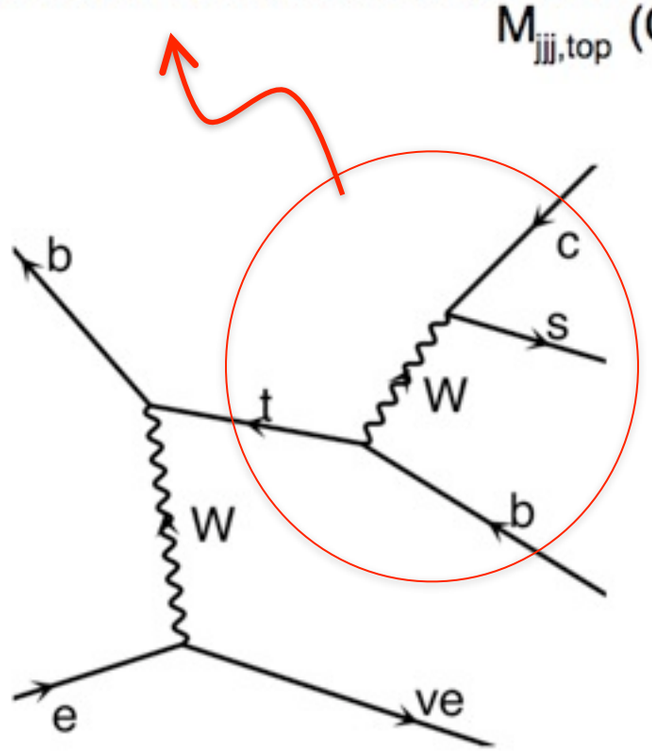


$H \to b\bar{b}$
CC BG
NC BG



Selection of $H \to b\bar{b}$

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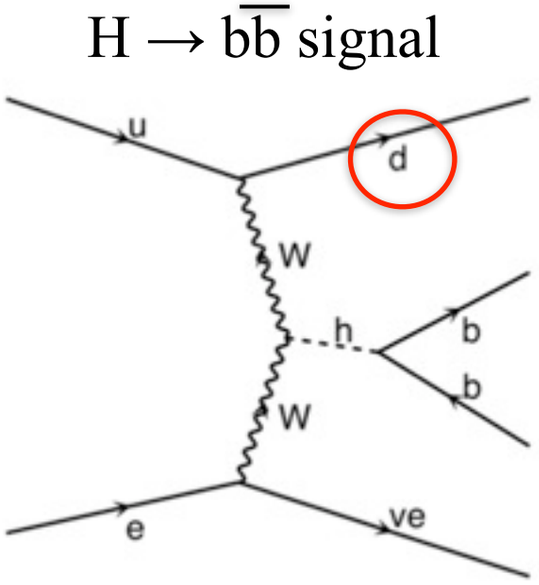
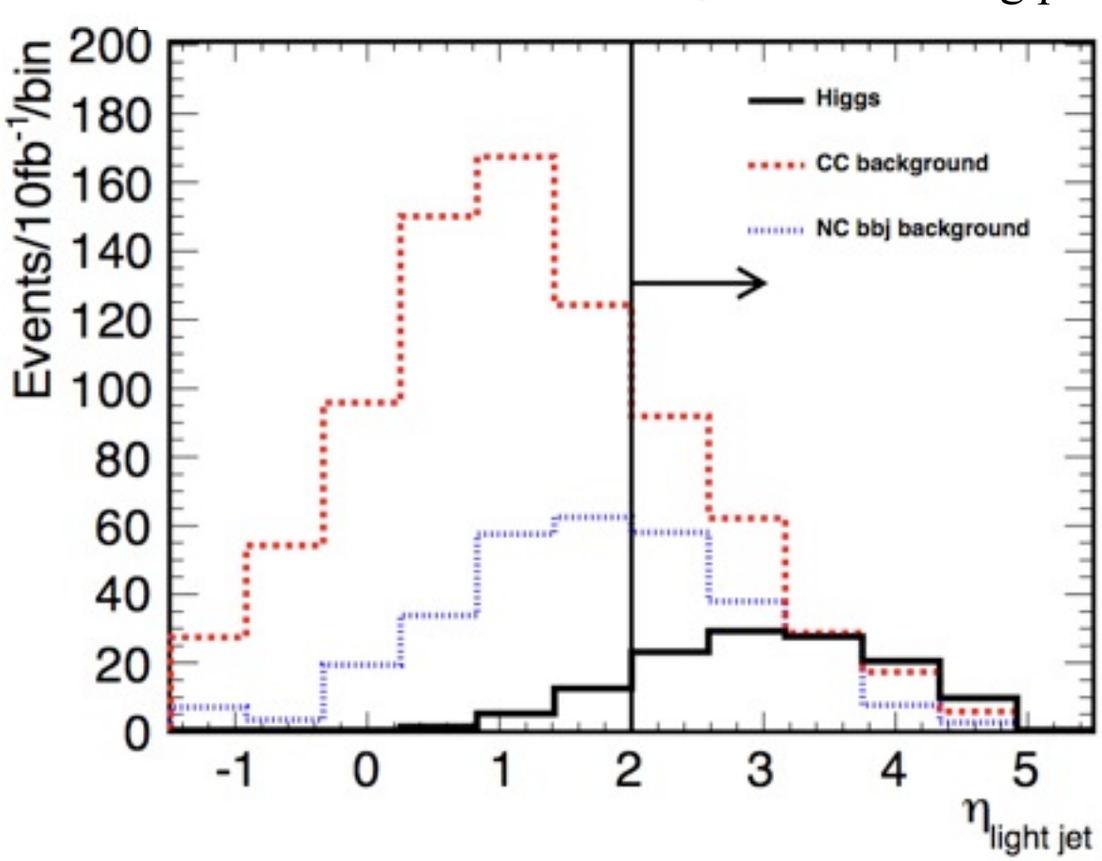


cf.
T. Han, B. Mellado
Phys. Rev. D82 (2010) 016009

Coordinate:
z-axis along proton beam



$H \to b\bar{b}$
CC BG
NC BG

Selection of $H \to b\bar{b}$

- NC rejection
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  - N_{jet} ($p_T > 20GeV$) ≧ 3
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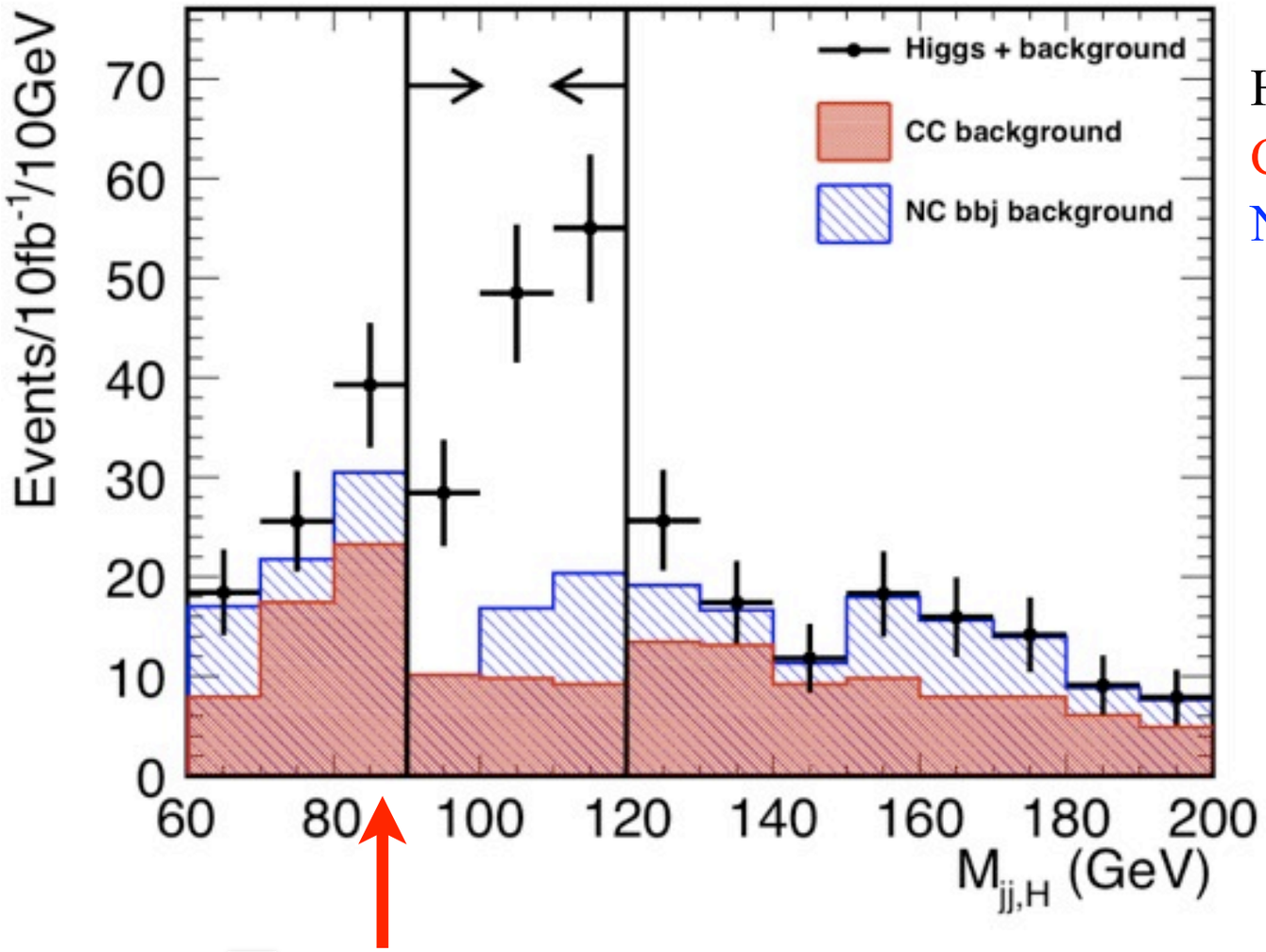
- b-tag requirement
  - $N_{b\text{-}jet}$ ($p_T > 20GeV$) ≧ 2
- Higgs invariant mass
  - $90 < M_H < 120GeV$
- Single top rejection
  - $M_{jjj,top} > 250GeV$
  - $M_{jj,W} > 130GeV$
- Forward jet tagging
  - $\eta_{jet} > 2$ (lowest η excluding b-tagged jets)

Di-jet invariant mass after all selection



$H \to b\bar{b}$

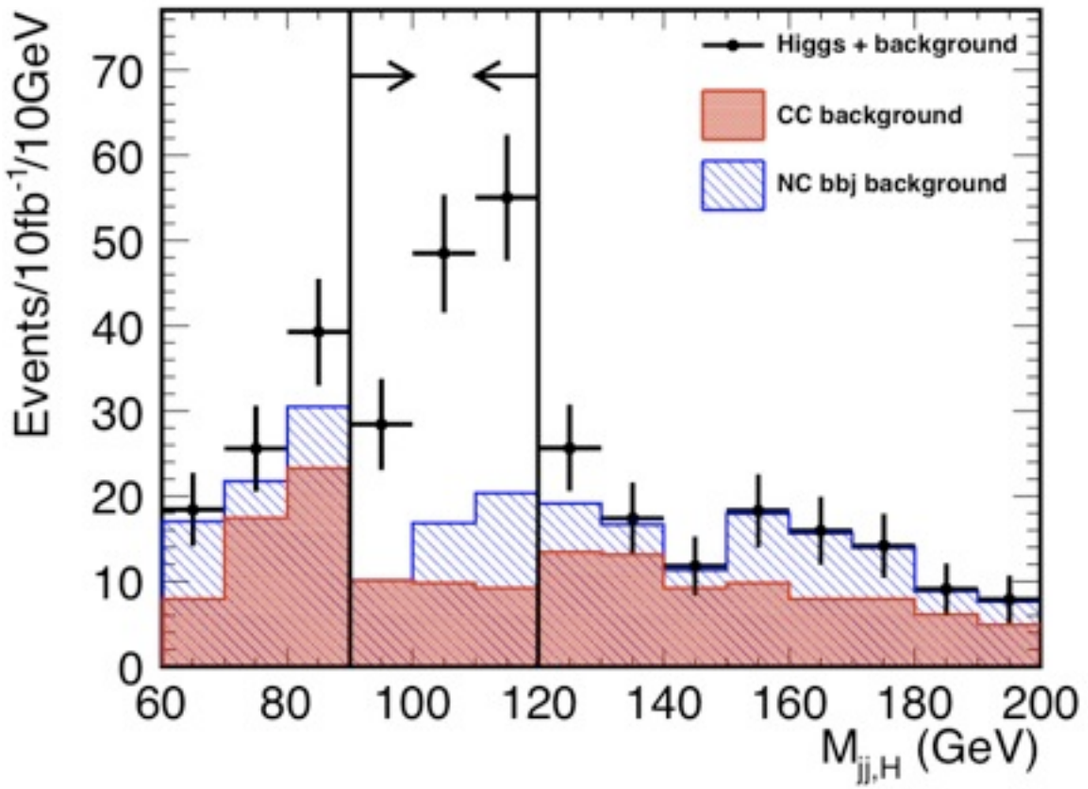
CC BG

NC BG

$Z \to b\bar{b}$ background

CDR Results (for E_e=150GeV)

- Beam energy:
  - Electron beam 150 GeV
  - Proton beam 7 TeV
- SM Higgs mass 120 GeV
- Luminosity 10 fb^{-1}

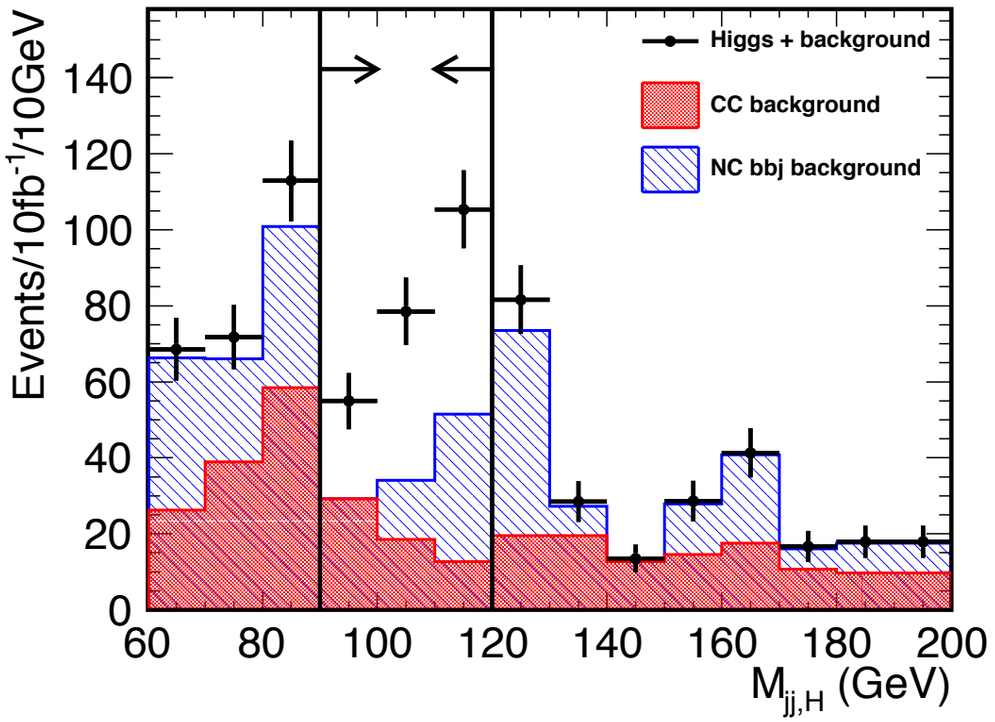


Signal and background cut flow

	H→bb	CC DIS	NC bbj	S/N	S/√N
NC rejection	816	123000	4630	6.38×10^{-3}	2.28
+ b-tag requirement + Higgs invariant mass	178	1620	179	9.92×10^{-2}	4.21
All cuts	84.6	29.1	18.3	1.79	12.3

60GeV case (current baseline)

- Beam energy:
  - Electron beam 150 GeV ⇒ 60 GeV
  - Proton beam 7 TeV
- SM Higgs mass 120 GeV
- Luminosity 10 fb^{-1} ⇒ 100 fb^{-1}
  (1 year in high-lumi option!)



	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

CP property of Higgs

S. Biswal, R. Godbole, B. Mellado, S. Raychaudhuri
Phys. Rev. Lett. 109 (2012) 261801

HVV coupling in SM and Beyond SM

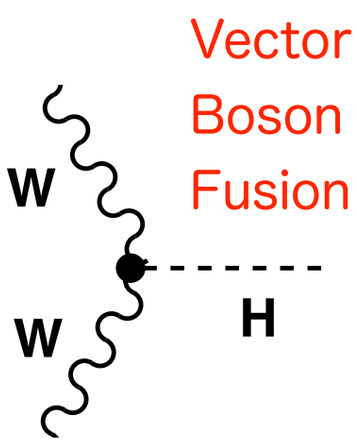
$$\Gamma^{\rm SM}_{\mu\nu} = -gM_V\, g_{\mu\nu}$$

$$\Gamma^{\rm BSM}_{\mu\nu}(p,q) = \frac{g}{M_V}[\lambda(p\cdot q\, g_{\mu\nu} - p_\nu q_\mu) + \lambda'\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma]$$

CP　　$\not{CP}$

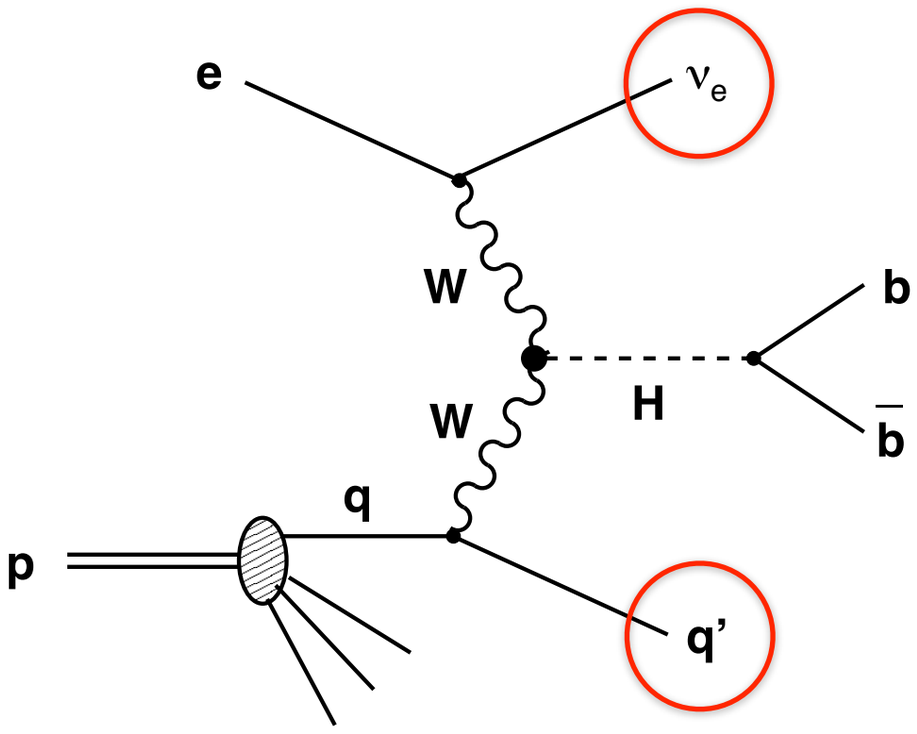
LHeC can probe anomalous HWW couplings independent of other (HZZ, H$\gamma\gamma$) couplings since WW fusion in CC is dominant production.

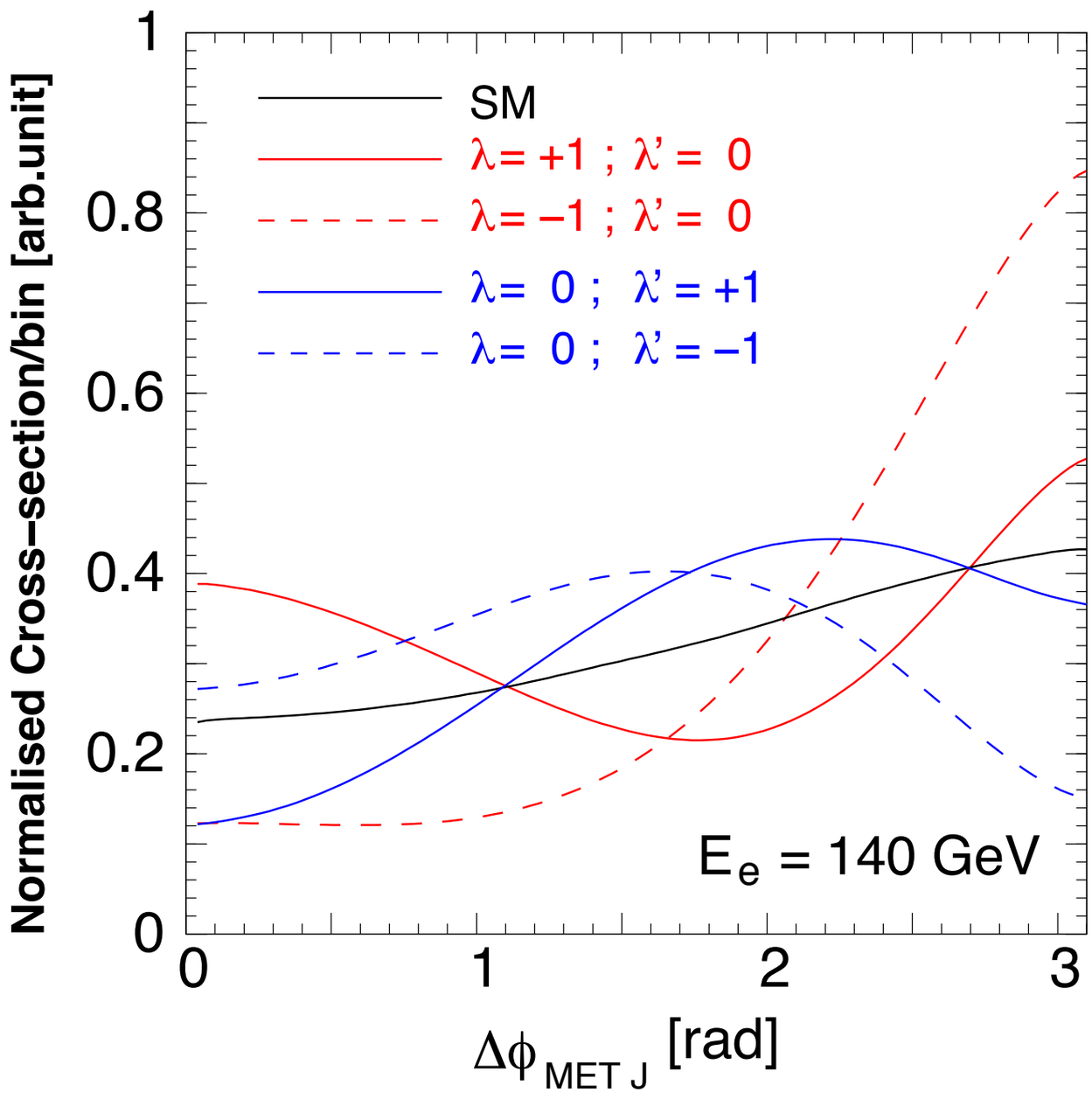
(advantage to LHC, ILC)



Azimuthal correlation

$\Delta\Phi$ between missing E_T and forward CC jet (VBF tagging jet)

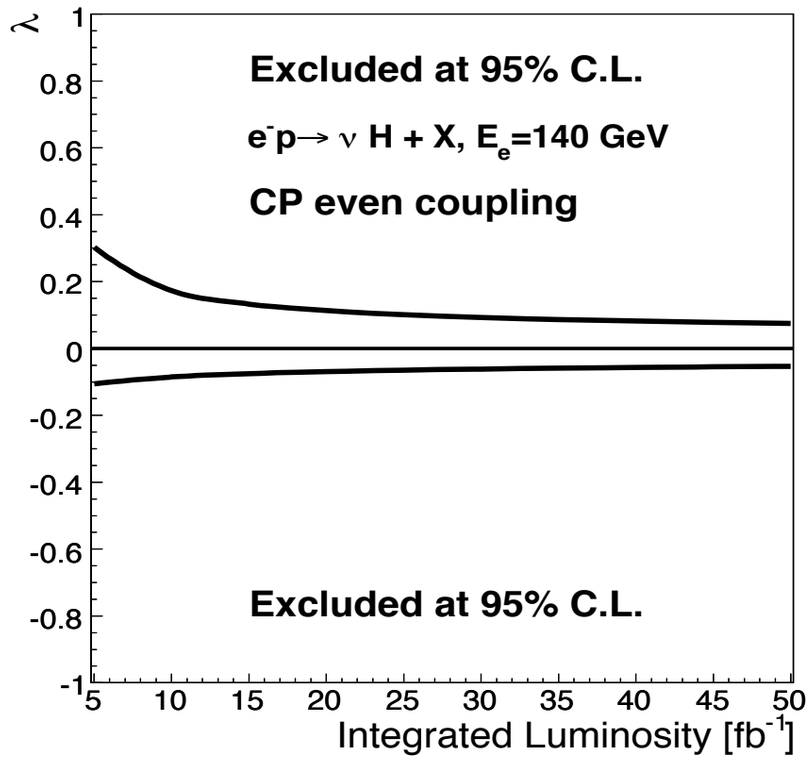


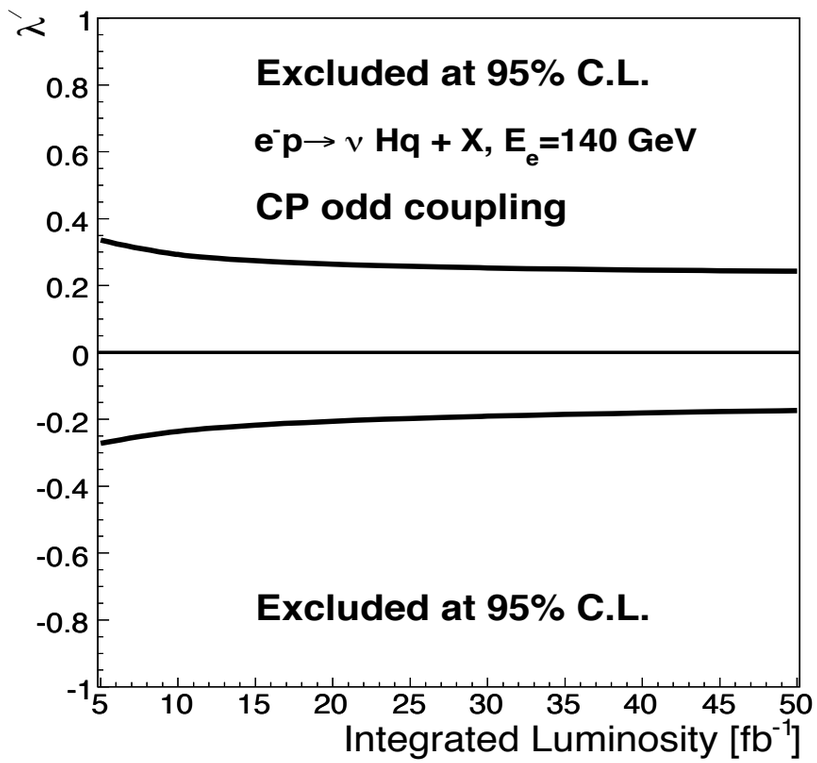


Large modification at $\Delta\Phi \sim 0,\ \pi$

Sensitivity study

- Parton energy smeared with: $\sigma/E = 0.6/\sqrt{E} \oplus 0.03$
- Other selection cuts similar to Hbb study (backup)
- Background taken from Hbb study





- With 10fb-1, possible to test λ (λ') ~ 0.2(0.3)
- Test normalized dist. - insensitive to PDF unc.

High-lumi LHeC - 1000fb^{-1} in 10y

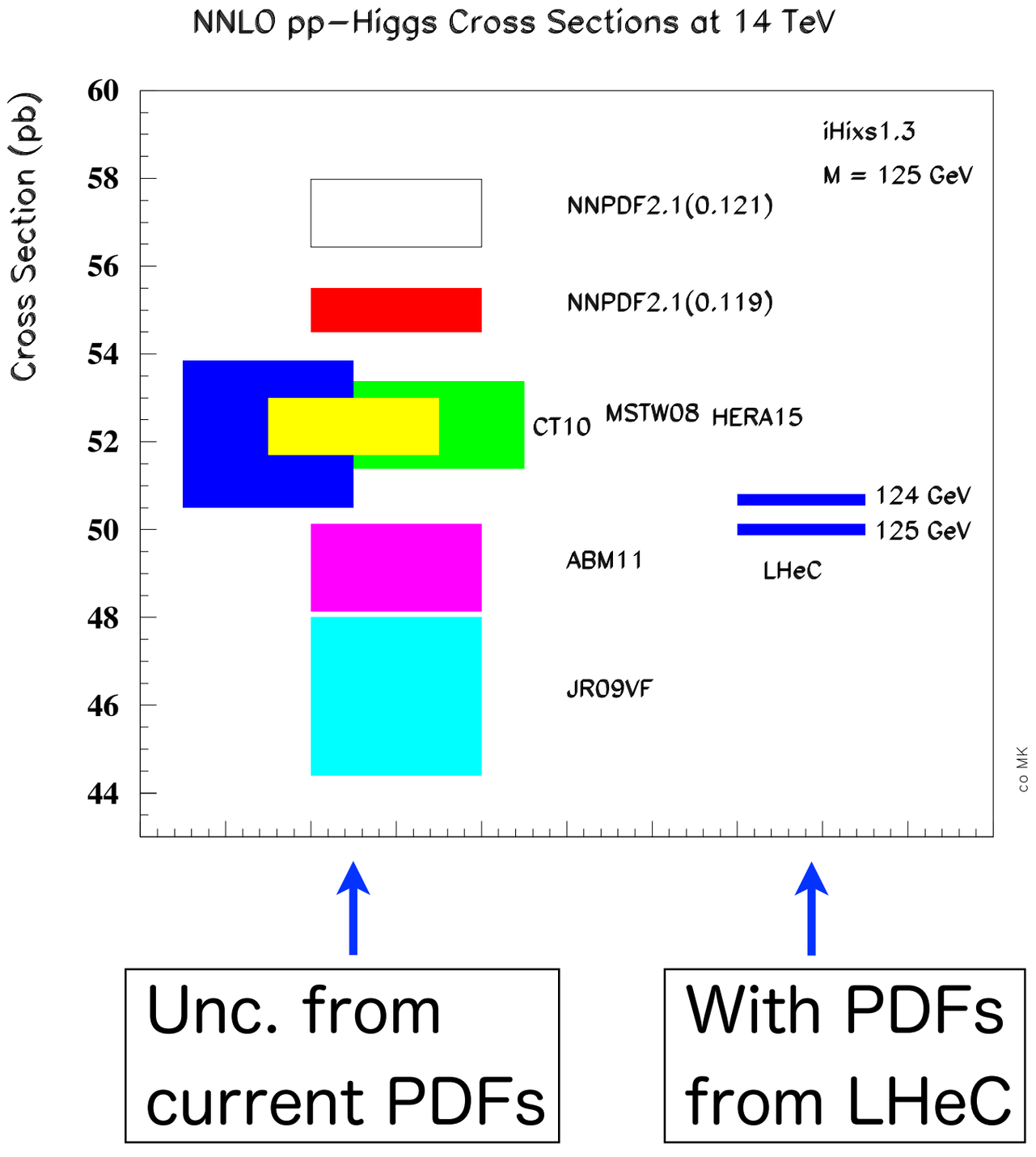
LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	1 600	370
$H \to \mu\mu$	0.00022	50	5	–
$H \to 4l$	0.00013	30	3	–
$H \to 2l2\nu$	0.0106	2 080	250	60
$H \to gg$	0.086	16 850	2 050	500
$H \to WW$	0.215	42 100	5 150	1 250
$H \to ZZ$	0.0264	5 200	600	150
$H \to \gamma\gamma$	0.00228	450	60	15
$H \to Z\gamma$	0.00154	300	40	10

LHeC as Higgs Factory - also other modes (e.g. $\tau\ \tau$) worth studying (complementarity with LHC)

Interplay LHC-LHeC

- Very precise PDF & α_s measurements from LHeC
- Much improved prediction of Higgs xsec at LHC (dominated by ggF)
- ~0.3% uncertainty → sensitivity to mass measurement
- Needs NNNLO developments (Anastasiou, Forte, Grojean, ...)

O. Brüning and M. Klein, arXiv:1305.2090



Summary

- Detailed study of Higgs property (coupling, CP...) is absolutely central in particle physics in the next decade. LHC will of course do it.
- LHeC, with much cleaner experimental conditions (e.g. no pile-up) → LHeC + HL-LHC could be 'the' next Higgs facility.
  - much stronger interplay with LHC than ILC/TLEP because it pins down PDFs and α_s needed at LHC.
  - we have already half of it (LHC): just need an ERL.
  - concrete ideas for 10^{34} option = $1\,ab^{-1}$: quantum leap in statistics.

Summary (2)

- Studies in LHeC CDR: (with limited manpower)
  - Hbb measurement: S:N~1:1 achievable:
    with 1ab^{-1} (10 years in high-lumi mode),
    Hbb coupling precision down to 1%
  - Anomalous HWW: coupling easily testable at ~0.3
- More studies will be pursued.
  - Detailed detector simulation (not PGS), optimization
  - $\tau\ \tau$ decay
  - charm decay (Hcc coupling)
  - Welcome to join in the efforts!

(backup)

Selection cuts for CP study

1203.6285v2

1. It is required that $MET > 25\,\text{GeV}$.

2. Presence of two b-partons with $p_T^b > 30$ GeV and $|\eta_b| < 2.5$. The invariant mass of these b-partons must lie within 10 GeV of the Higgs boson mass.

3. Of the remaining partons, the leading one must have $p_T > 30$ GeV and $1 < \eta < 5$. This will be called the forward tagging parton.

4. We require $\Delta\varphi_{\text{MET}-\text{J}} > 0.2\,\text{rad}$ for all the jets (J).

5. A veto on leptons ($\ell = e, \mu, \tau$) with $p_T^\ell > 10$ GeV and $|\eta_\ell| < 2.5$ is required.

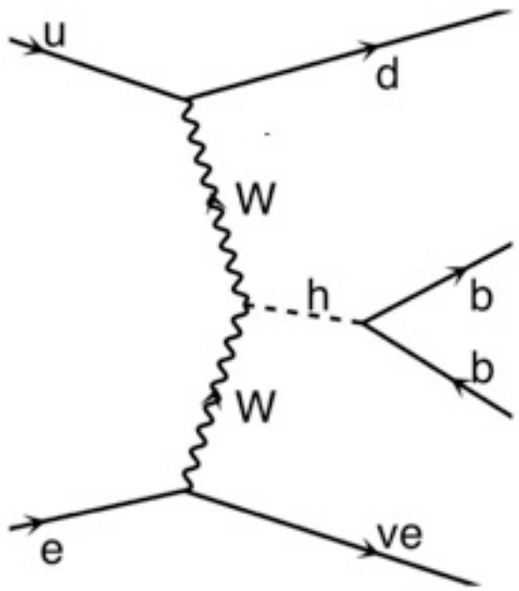
6. The invariant mass of the Higgs boson candidate and the forward tagging jet must be greater than 250 GeV.

7. b-tagging efficiency: $\varepsilon_b = 0.6$ for $|\eta_b| < 2.5$. The mis-tagging factor for c and light quark jets is taken as 0.1 and 0.01 respectively.

Higgs at LHeC

Signal

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

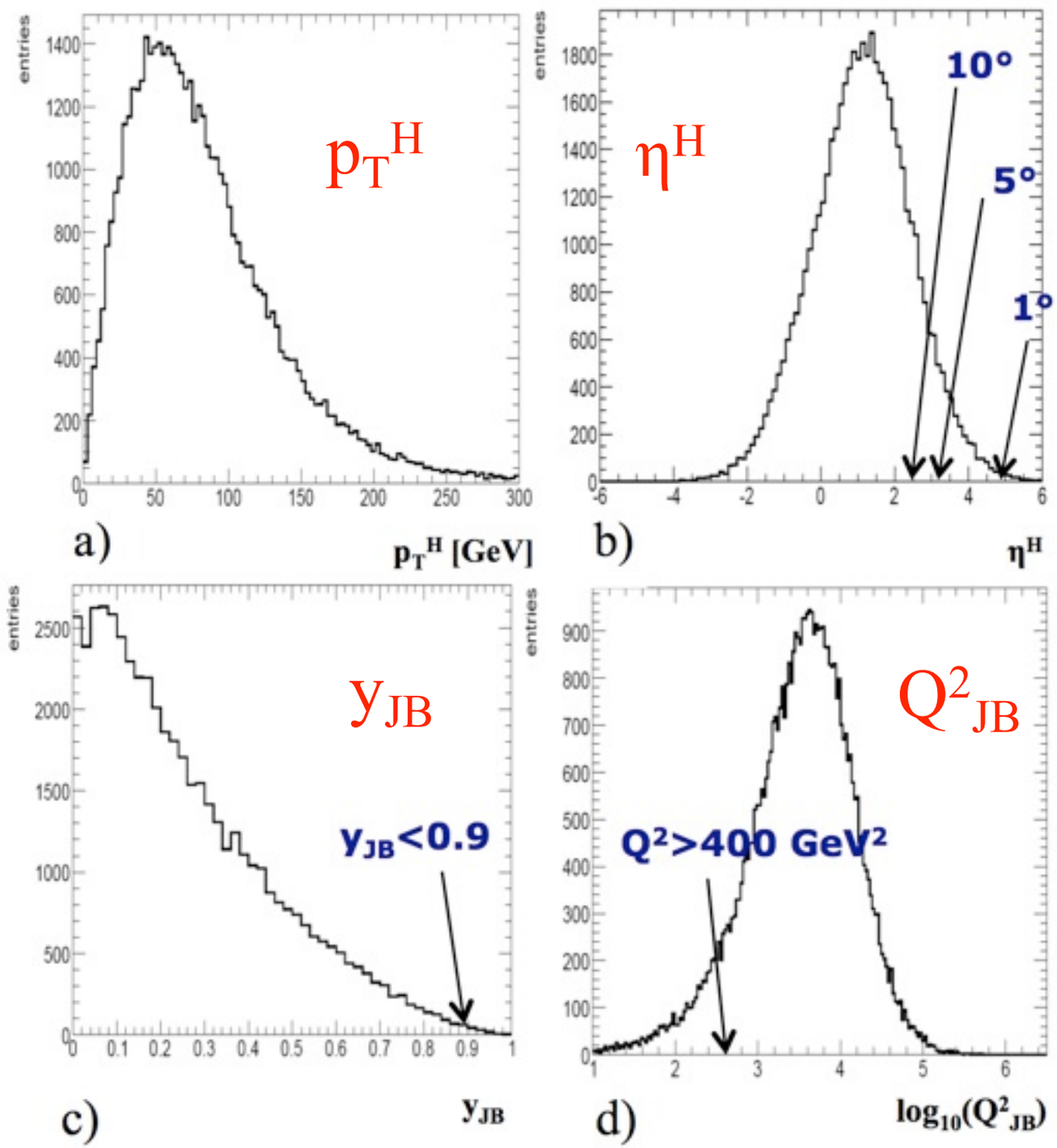


$\sigma \cdot B \sim 0.16$ pb

at $\sqrt{s}$=2.05TeV

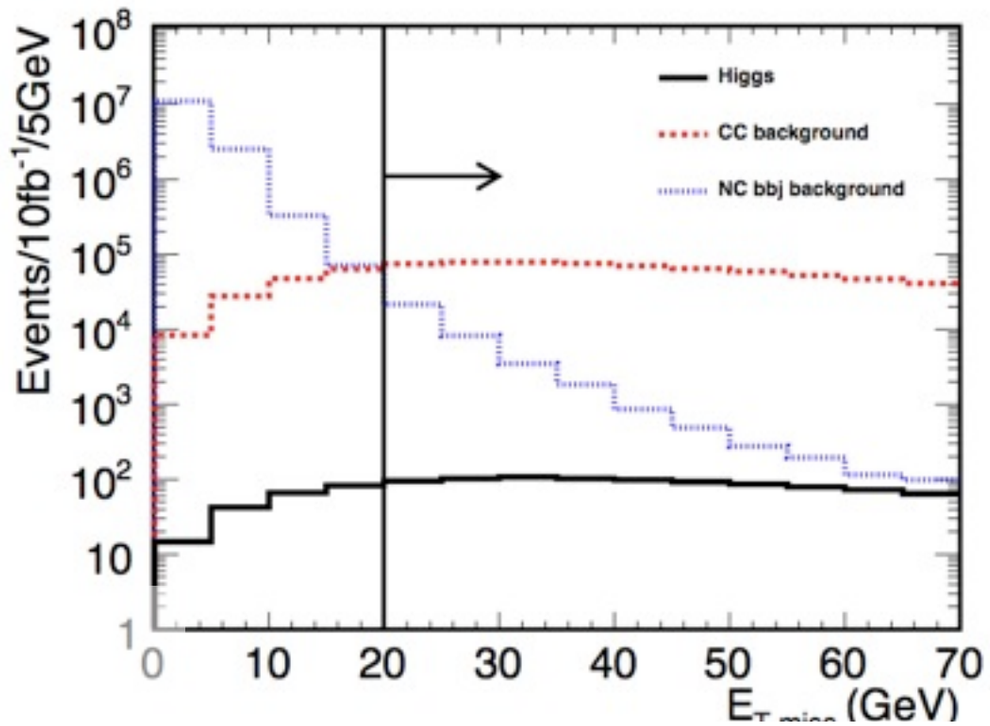
NOTE: The plots shown are from initial study for LHeC CDR (1206.2913) using E_e = 150GeV. Results also given for 60GeV (see later).

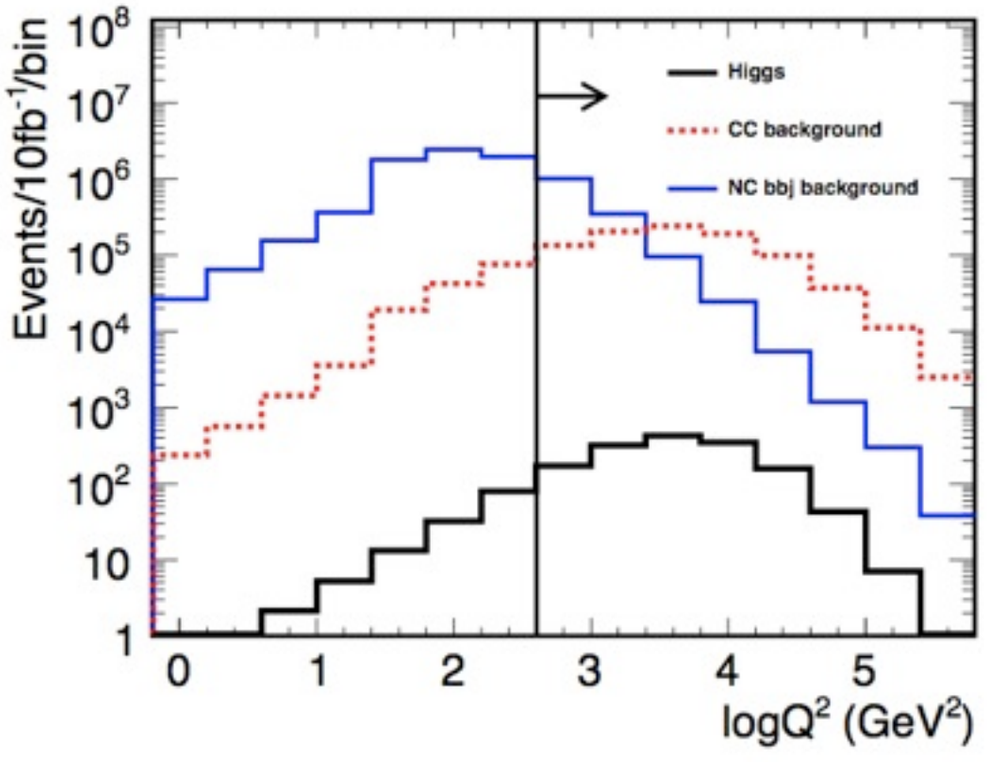
Kinematic distributions of generated Higgs (m_H=120GeV, E_e=150GeV, E_p=7TeV)



Selection of $H \to b\bar{b}$

- NC rejection
  - Exclude electron-tagged events
  - $E_{T,miss} > 20GeV$
  - N_{jet} ($p_T > 20GeV$) ≧ 3
  - $E_{T,total} > 100GeV$
  - $y_{JB} < 0.9$, $Q^2_{JB} > 400GeV$
- b-tag requirement
  - $N_{b\text{-}jet}$ ($p_T > 20GeV$) ≧ 2
- Higgs invariant mass
  - $90 < M_H < 120GeV$
- Single top rejection
  - $M_{jjj,top} > 250GeV$
  - $M_{jj,W} > 130GeV$
- Forward jet tagging
  - $\eta_{jet} > 2$ (lowest η excluding b-tagge





H→bb̄
CC BG
NC BG

Selection of $H \to b\bar{b}$

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  - Exclude electron-tagged events
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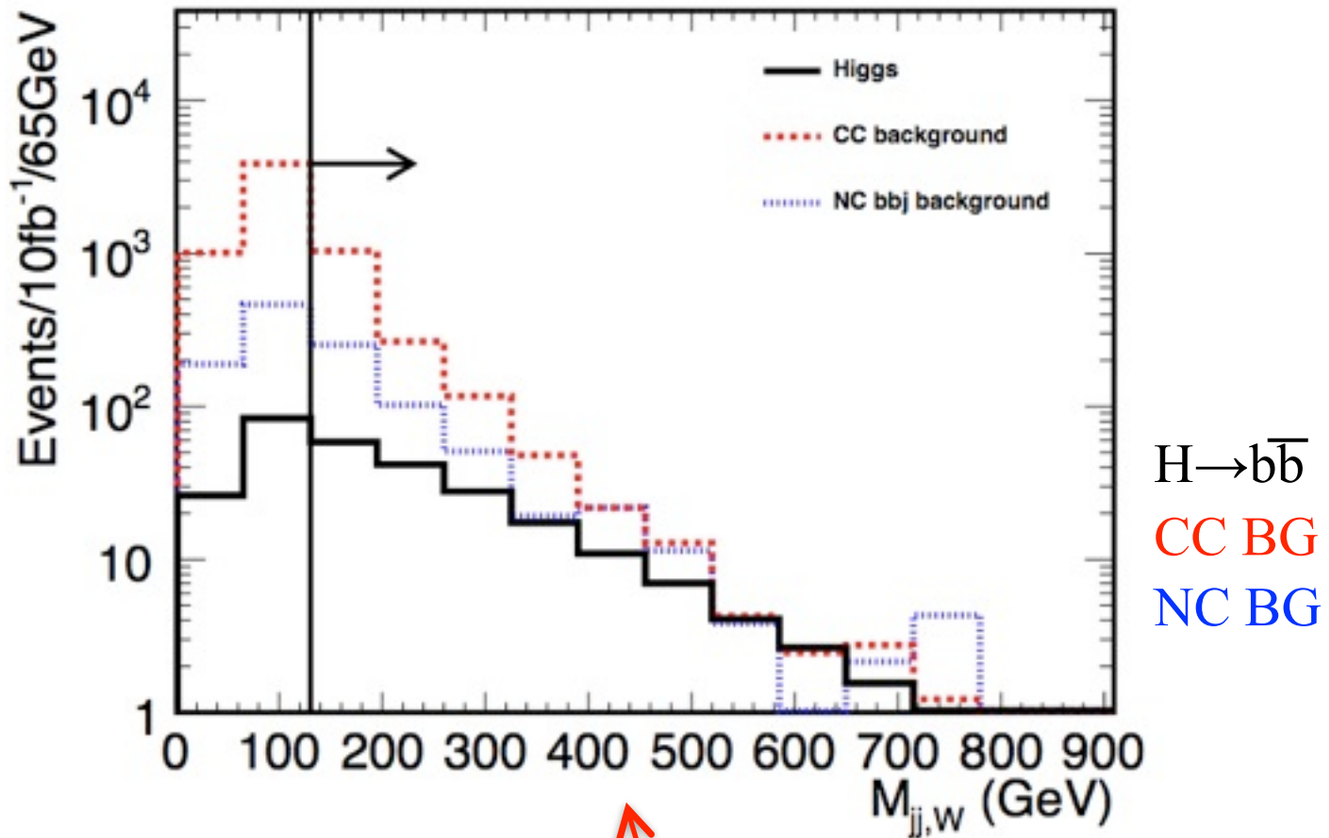

$H \to b\bar{b}$
CC BG
NC BG