Higgs in ep at the LHeC

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for the LHeC Study Group

Snowmass meeting, Seattle, 07/02/13

Journal of Physics G Nuclear and Particle Physics   Vol 39, No 7   075001   July 2012

ISSN 0954-3899

Journal of Physics G

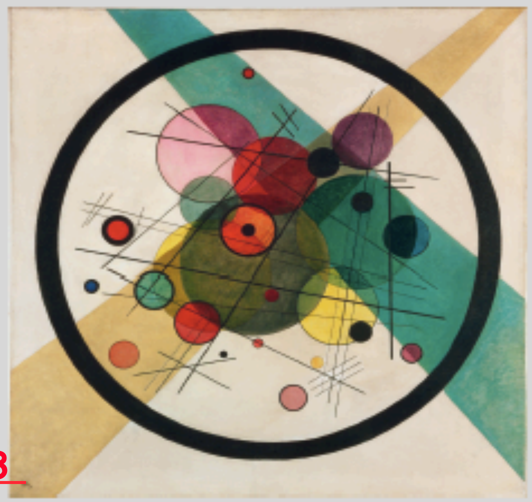
Nuclear and Particle Physics

Volume 39   Number 7   July 2012   Article 075001

A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group



arXiv:1206.2913

iopscience.org/jphysg

IOP Publishing

arXiv:1211.4831 and 5102

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Published 600 pages conceptual design report (CDR) written by 150 authors from 60 Institutes. Reviewed by ECFA, NuPECC (long range plan), Referees invited by CERN. Published June 2012.

http://cern.ch/lhec

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Present LHeC Study group and CDR authors

About 200 Experimentalists and Theorists from 76 Institutes

Supported by
CERN, ECFA, NuPECC

LHeC Physics Programme

CDR, arXiv:1211.4831 and 5102
http://cern.ch/lhec

QCD Discoveries	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$
Higgs	WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate
Substructure	electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H?
New and BSM Physics	leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s
Top Quark	top PDF, $xt = x\overline{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c
Precision DIS	$\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure	Proton, Deuteron, Neutron, Ions, Photon
Quark Distributions	valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \overline{s}$?, charm, beauty, top
QCD	N^{3}LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing
Heavy Ions	initial QGP, nPDFs, hadronization inside media, black limit, saturation
Modified Partons	PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

Ultra high precision (detector, e-h redundancy) - new insight
Maximum luminosity and much extended range - rare, new effects
Deep relation to (HL-) LHC (precision+range) - complementarity

Strong coupling 0.1%; Full unfolding of PDFs; Gluon: low x: saturation?, high x: HL LHC searches…

After the Higgs discovery: LHeC $10^{33 \rightarrow 34}$ Luminosity

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	

Table 1: LHeC ep and eA collider parameters. The numbers give the default CDR values, with optimum values for maximum ep luminosity in parentheses and values for the ePb configuration separated by a comma.

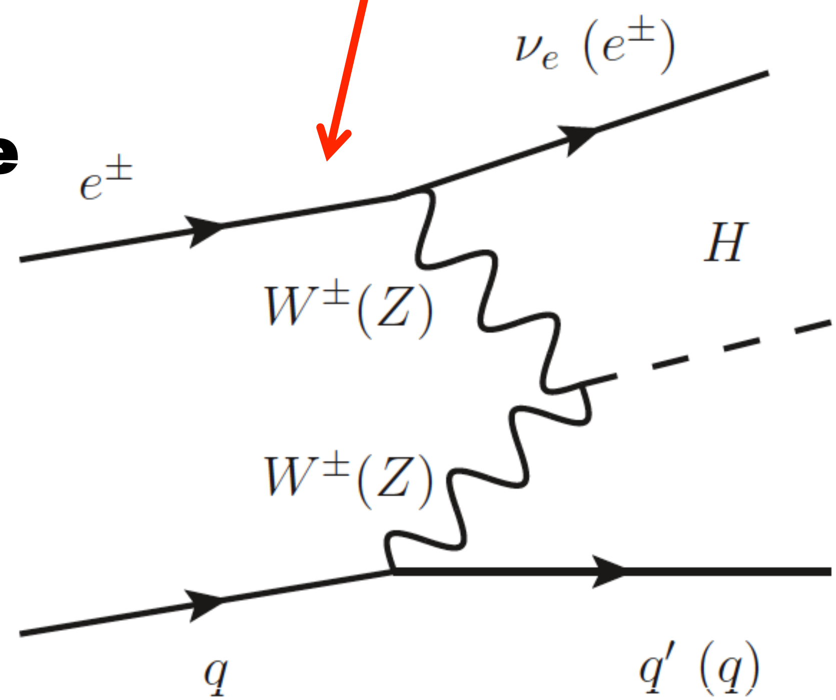
LHeC Collaboration arXiv:1211:5102, see also O.Bruening and M.Klein arXiv:1305.2090

Higgs at LHeC

At LHC replace
lepton lines by quark lines
but dominantly gg → H

- It is remarkable that VBF diagrams were calculated for lepton nucleon collisions before for pp!

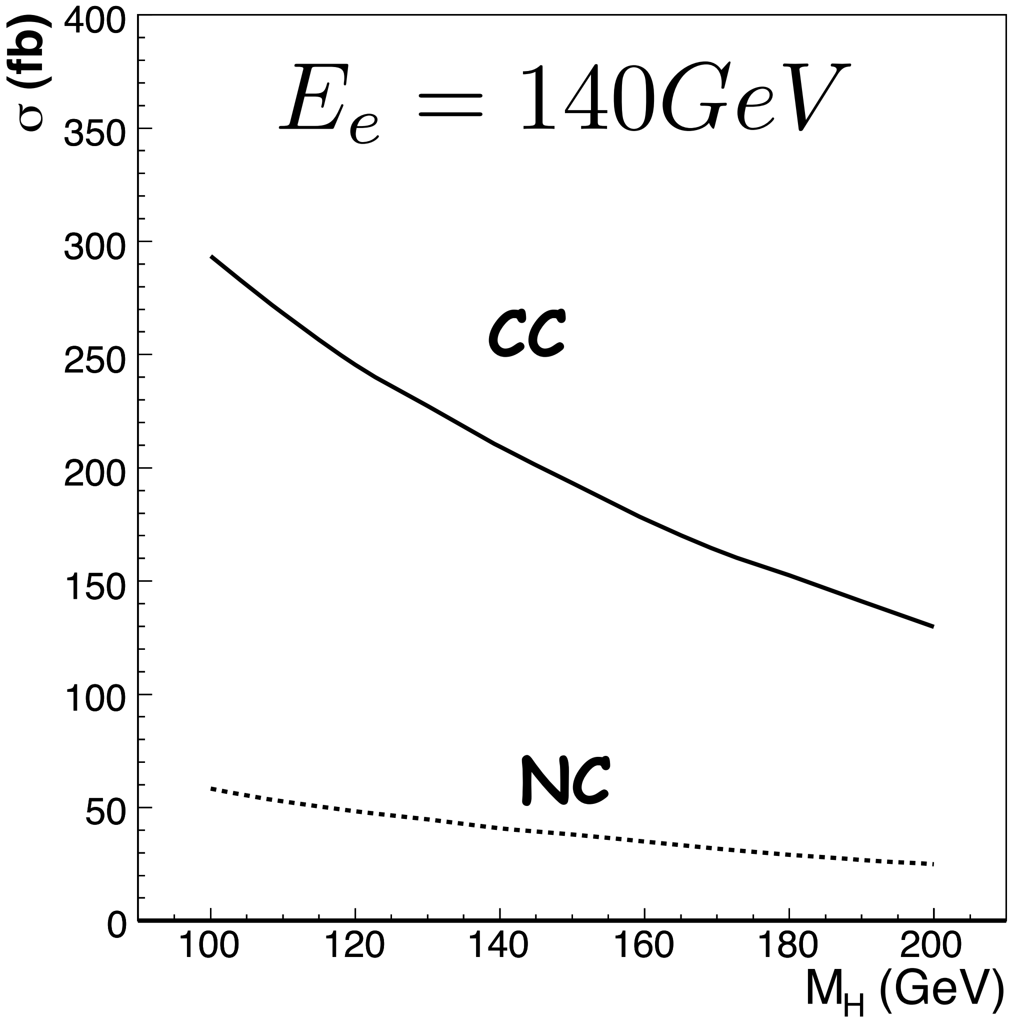
- Consider feasibility for the following point:

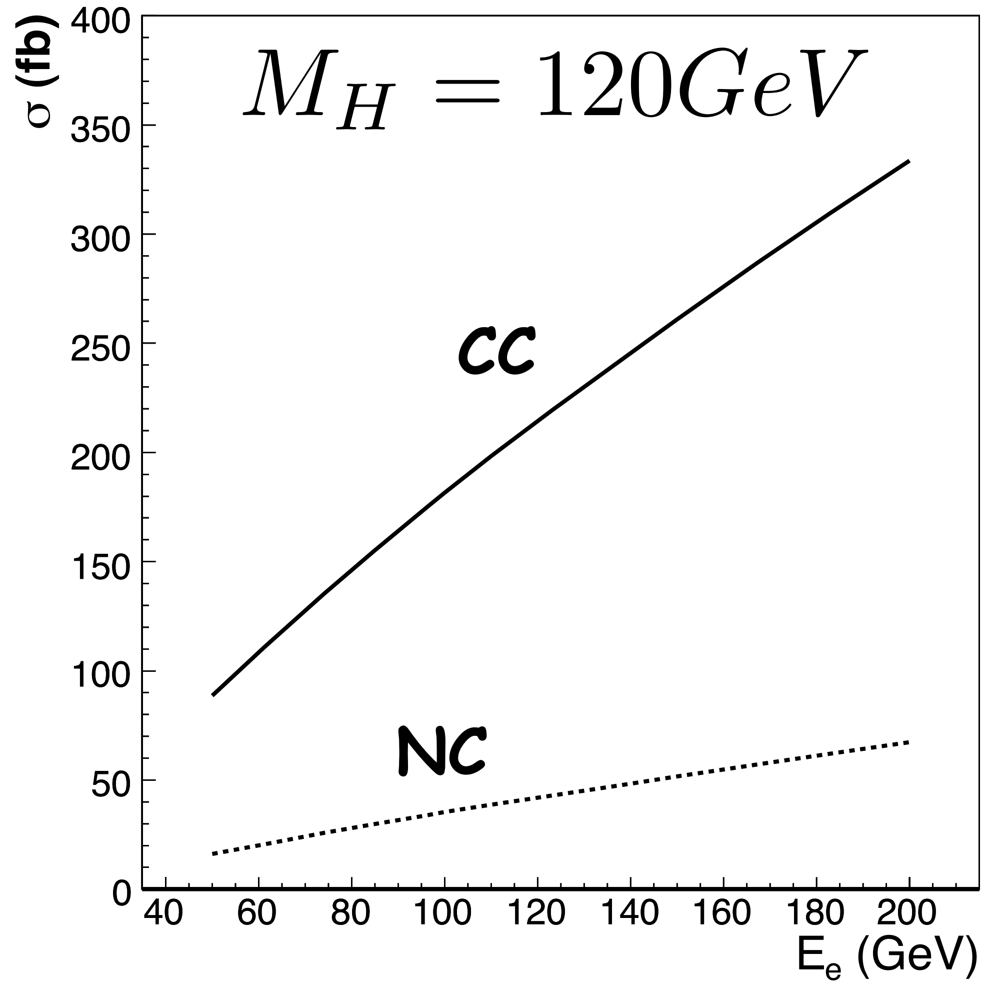


$$E_p = 7\ \text{TeV}, \quad E_e = 140\ \text{GeV}, \quad M_H = 120\ \text{GeV}$$

Cross-Sections

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



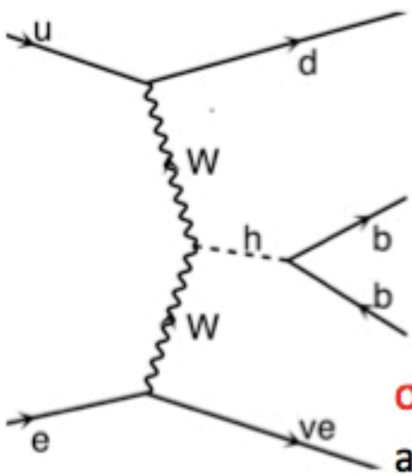


MC Samples in Hadron-level study

U.Klein et al.

Signal

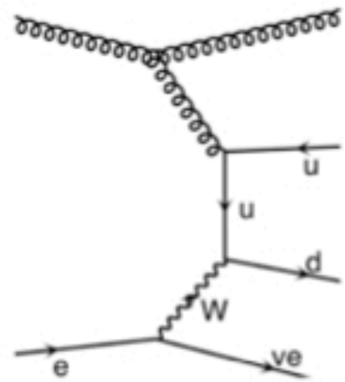
CC: $H \to b\bar{b}$ (BR ~ 0.7 at M_H=120GeV)



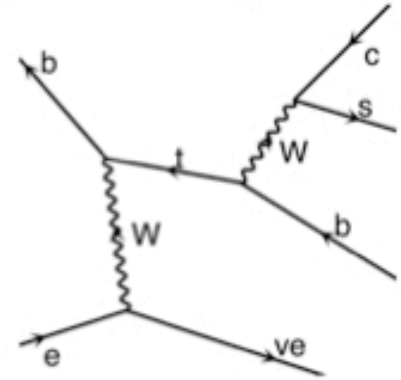
σ~ 0.16 pb
at √s=2.05TeV

Background (examples)

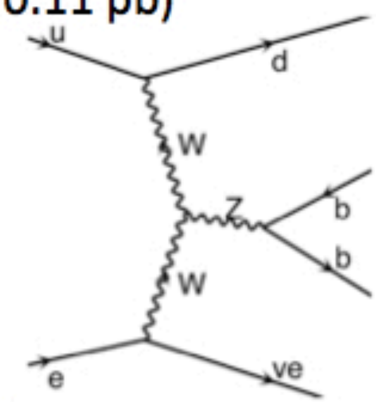
CC: 3 jets (~57 pb)



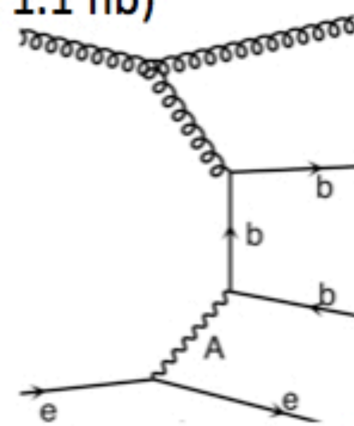
CC: single top production (~4.1 pb)



CC: Z production (~0.11 pb)



NC: b pair production (~1.1 nb)

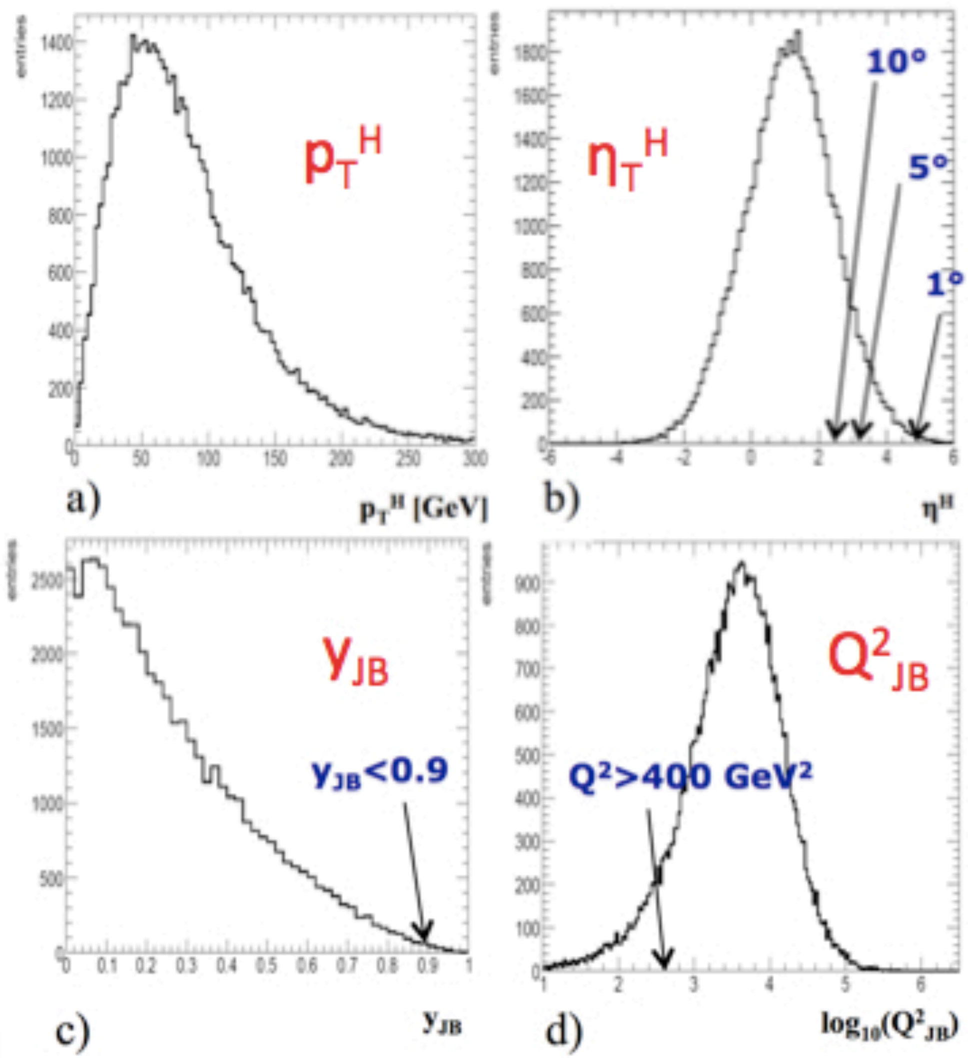


NOTE: Background sample numbers are after pre-selection in generator

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:

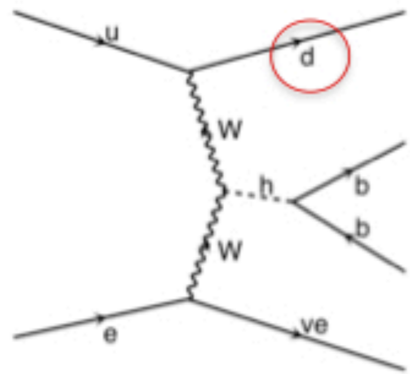
- Coverage:
  - Tracking: $|\eta| < 3$
  - Calorimeter: $|\eta| < 5$
- Calorimeter resolution
  - EM: $1\% \oplus 5\%/\sqrt{E}$
  - Hadron: $60\%/\sqrt{E}$
  - Cell size: $(\Delta\eta,\Delta\phi) = (0.03, 0.03)$
- Jet reconstructed (cone ΔR=0.7)
- b-tag performance
  - Flat efficiency for $|\eta| < 3$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

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

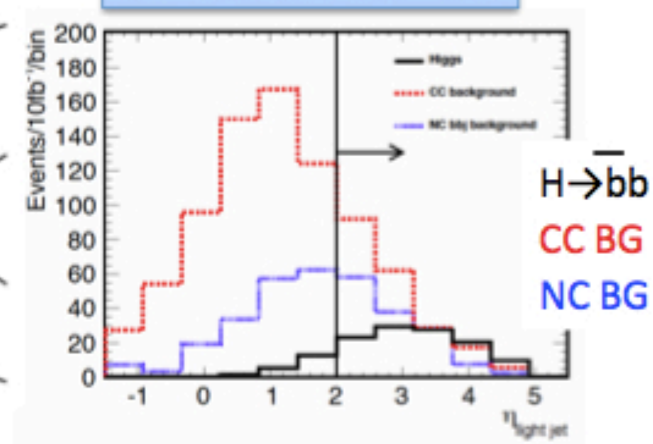
- Forward jet tagging
  - $\eta_{jet} > 2$ (lowest η jet excluding b-tagged jets)

Coordinate:
Fwd: +z-axis along proton beam

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



Forward jet η tag

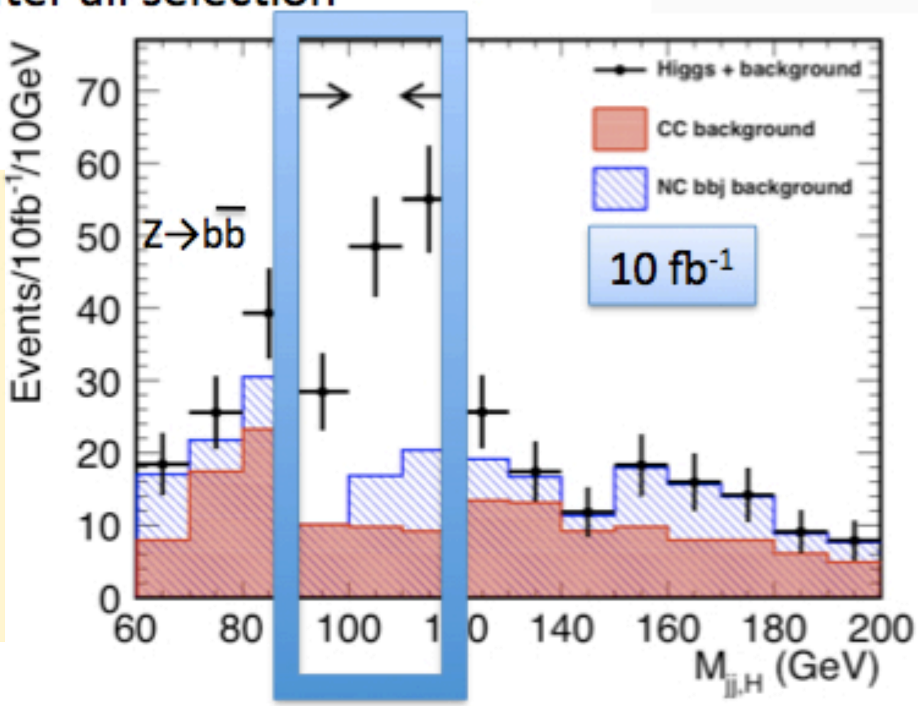


- Higgs invariant mass after all selection

E_e=150 GeV

Expect 5000 H → bb events at 60 GeV for $1ab^{-1}$ → 0.7% coupling measurement at S/B ~1.

→LHeC is high precision Higgs facility



Clear signal obtained with just cut based analysis already!

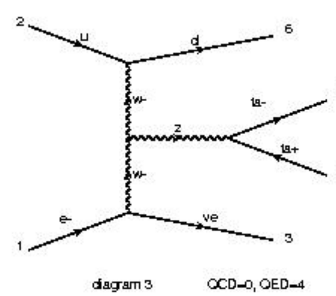
LHeC Higgs Rates

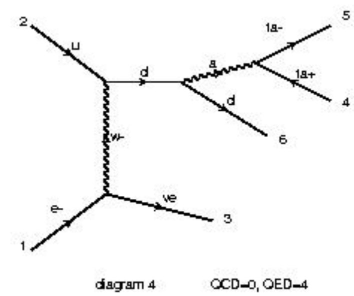
LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	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

Precision measurements on fermions [ττ under study], WW, gg?

Status of di-tau Feasibility

- **Looks like the following combinations will work**
  - **mu+ tau_had**
  - **mu- tau_had**
  - **tau_had tau_had**
  - **e+ mu-**
  - **mu+mu- (?)**





- **The main background will come from di-tau production. This is a good start.**
- **Next step is to look into the prospects of fakes, although if these channels are possible at the LHC, they have to be possible at the LHeC.**
- **Need to look into NC production of taus**

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

Higgs Couplings with pair of gauge bosons (ZZ/WW) and the pair of heavy fermions (t/τ) are largest. Study $\not{C}\not{P}$ in a model independent way (most studies so far)

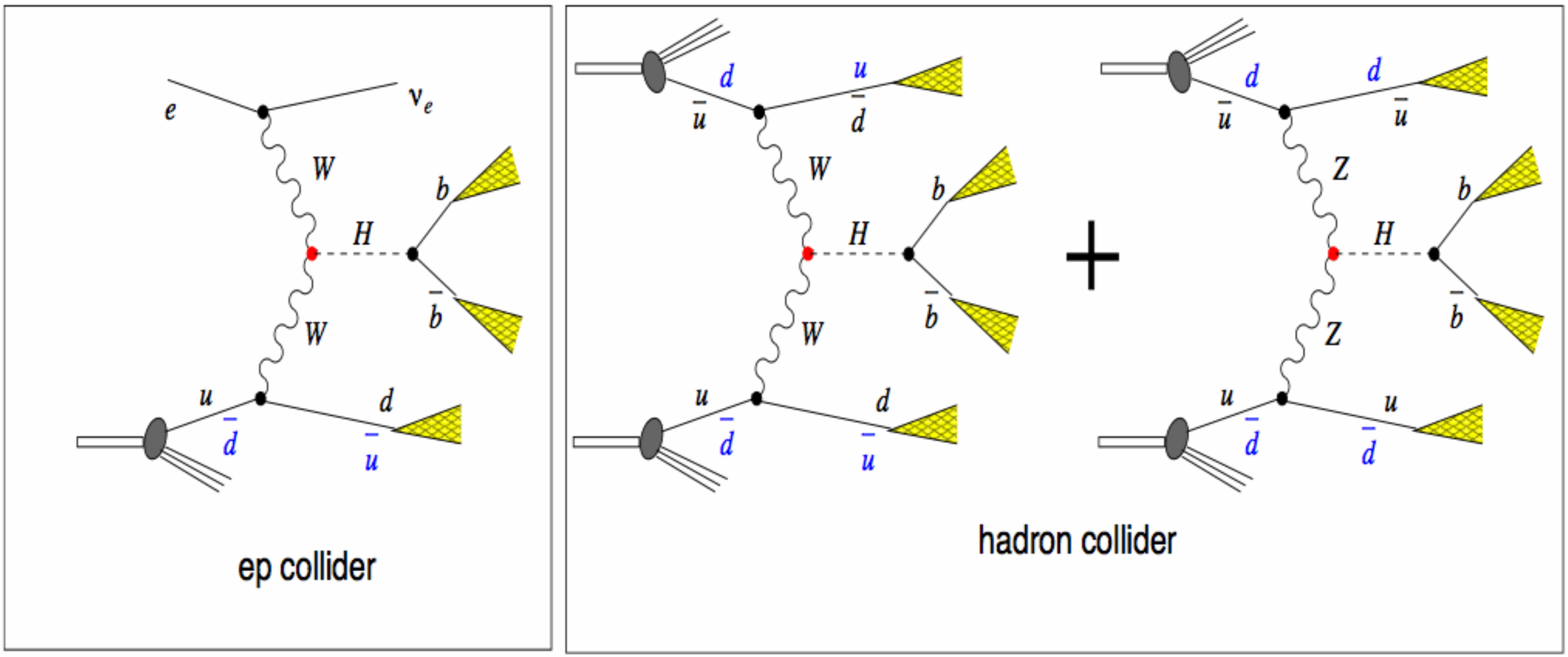
$Hf\bar{f} : -\frac{g m_f}{2M_W}\bar{f}\left(a_f + i b_f \gamma_5\right) f H$

HVV:

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

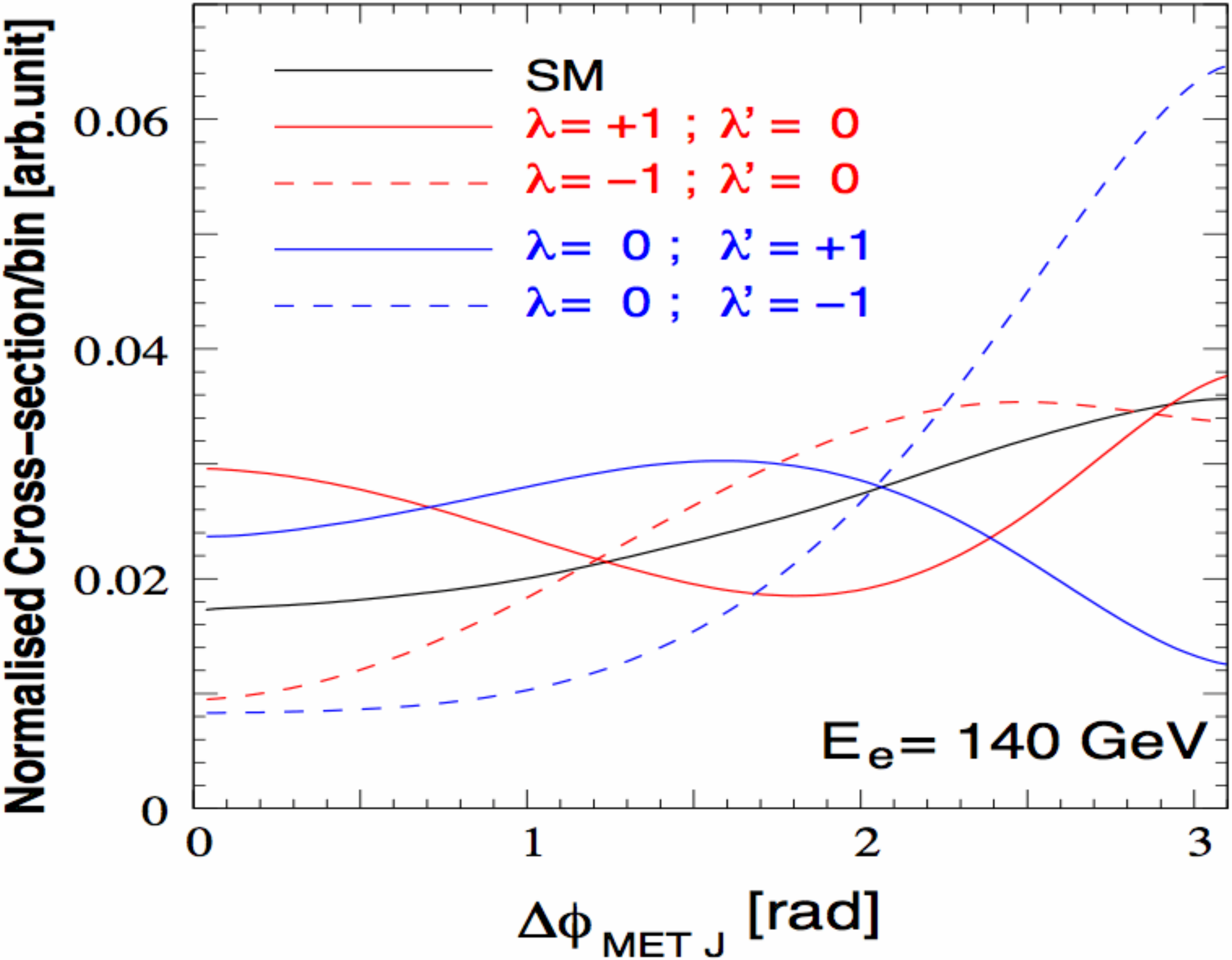
$$\Gamma^{\rm BSM}_{\mu\nu}(p,q) = \frac{g}{M_V}\left[\lambda\left(p\cdot q\, g_{\mu\nu} - p_\nu q_\mu\right) + \lambda' \, \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma\right]$$

higgs + 2jets: VBF (LHC), higgs + jet + missing E_T (LHeC)



ep **process uniquely addresses the** HWW **vertex.**

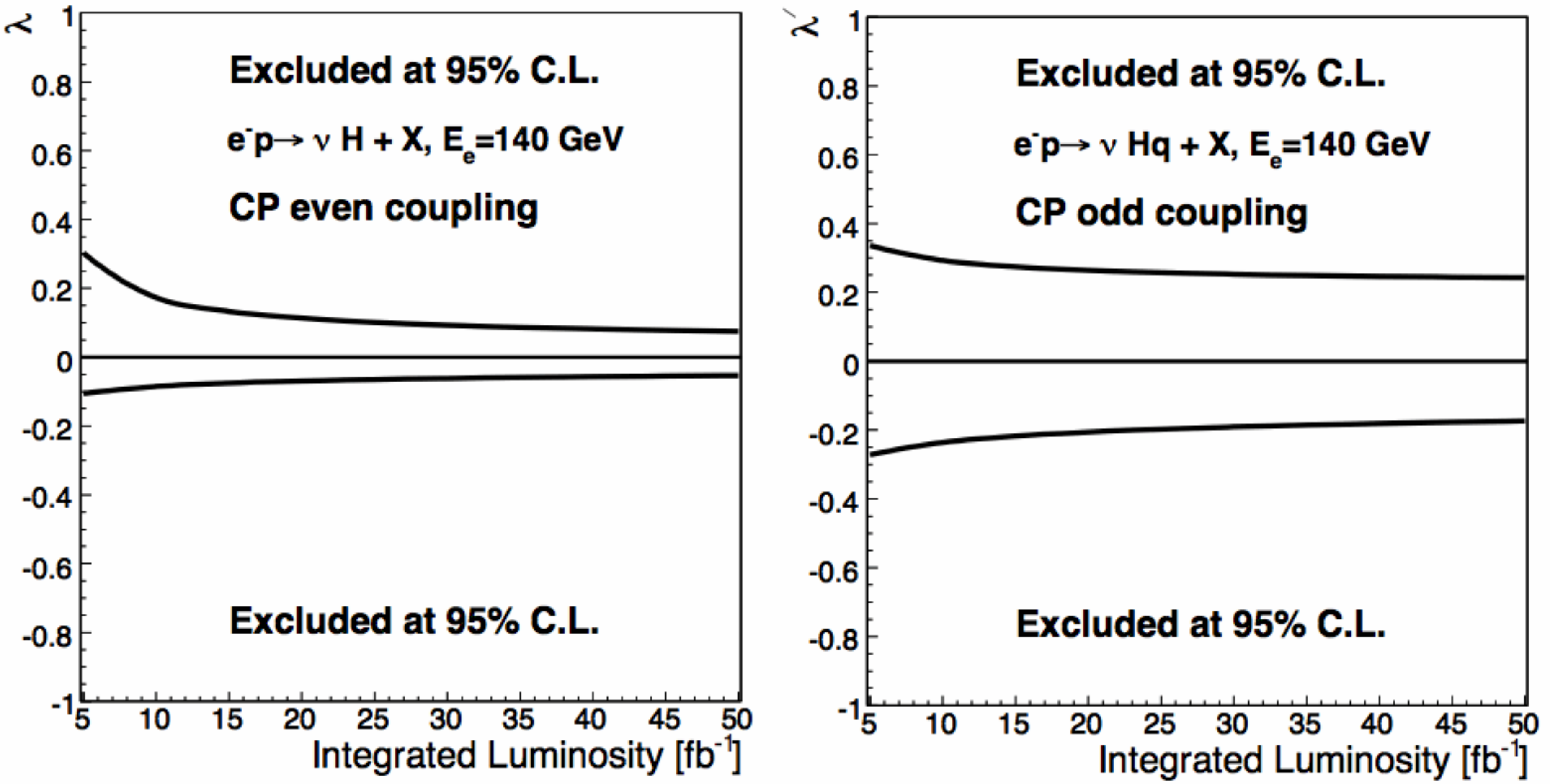
Need to investigate physics beyond the SM within the 0^+ hypothesis with high precision



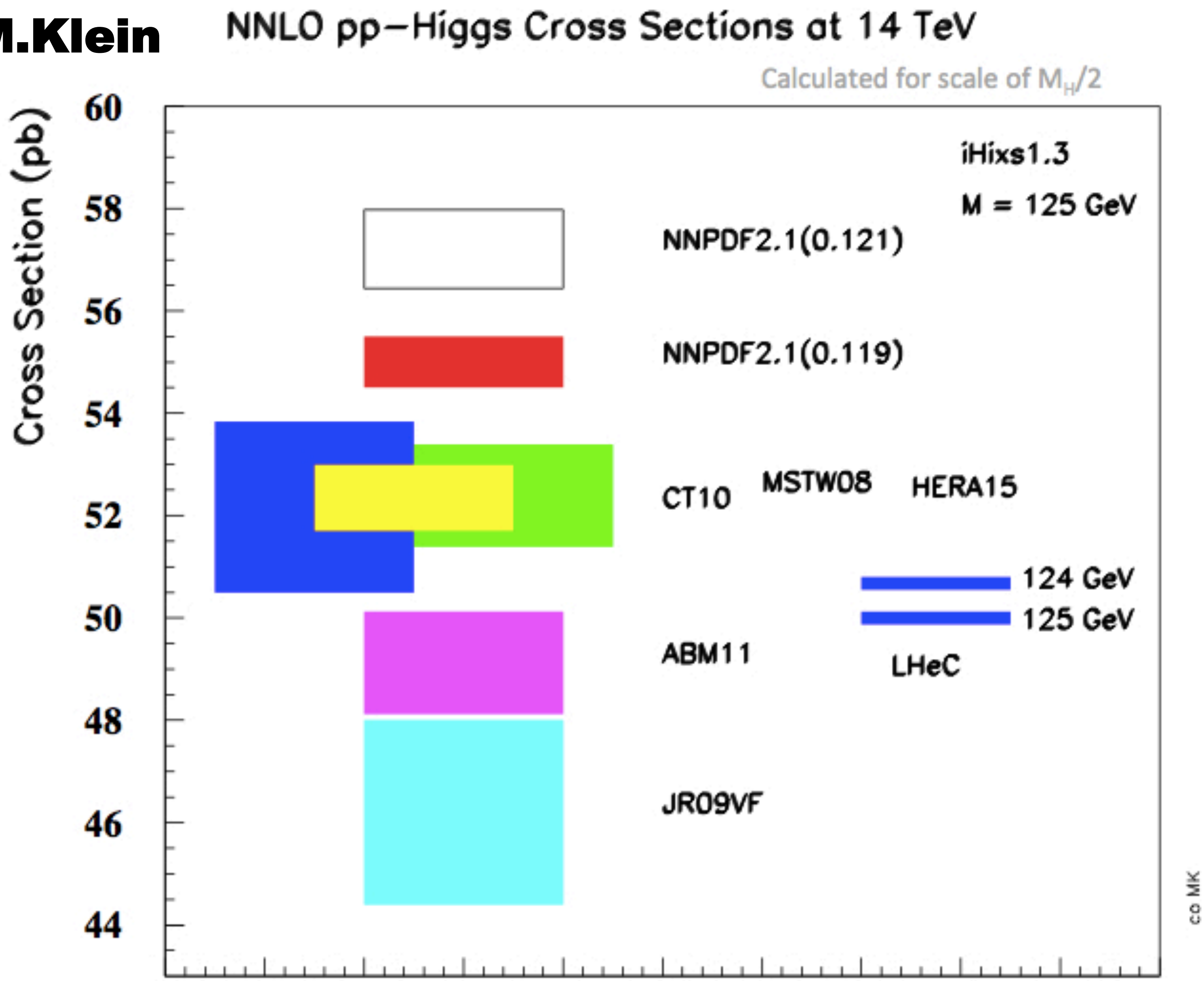
Normalised Cross-section/bin [arb.unit]
0.06
0.04
0.02
0
SM
λ= +1 ; λ' = 0
λ= −1 ; λ' = 0
λ= 0 ; λ' = +1
λ= 0 ; λ' = −1
E_e= 140 GeV
0
1
2
3
Δφ MET J [rad]

Results on the sensitivity with updated background as per the simulations of U. Klein (DIS 2011)

URL: http://www.ep.ph.bham.ac.uk/exp/LHeC/talks/DIS11.Klein2.pdf



M.Klein



Exp uncertainty of LHeC Higgs cross section is 0.25% (sys+sta), using LHeC only.

Leads to mass sensitivity..

Strong coupling underlying parameter (0.005 – 10%). LHeC: 0.0002

Needs N^{3}LO

HQ treatment important

PRECISION σ(H)

Higgs production (gg) at the LHC is $\propto \alpha_s^2(M_H^2) xG(x, M_H^2) \otimes xG(x, M_H^2)$

Bandurin (ICHEP12) Higgs physics at the LHC is limited by the PDF knowledge

Projects in Progress

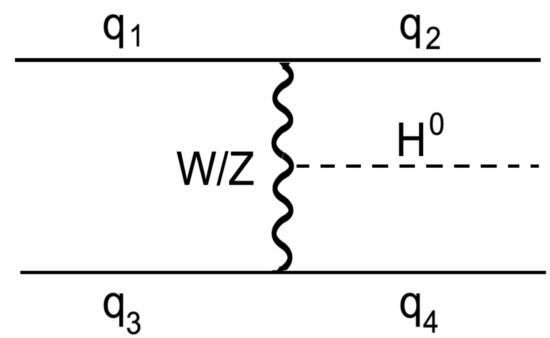
- Understanding of the impact tensor structure of the HVV coupling on the acceptance of forward jet tagging. This is a follow up of recent studies in pp collisions
- Feasibility of tautau channel.
- Aiming at combined LHC/LHeC Yukawa coupling determination
- Revisiting single-top studies
    - Negligible background from double-top production as opposed to the LHC. Backgrounds from single W production are suppressed with b-tagging
    - Preprint to appear within a week

Outlook and Conclusions

- LHeC displays strong complementarities with the LHC with regards to Higgs physics
- Forward jet tagging secures the feasibility of the Higgs search in CC and NC in ep collisions
- 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 HWW and HZZ vertexes
- The LHeC offers a number of advantages
  - Unique separation of HWW and HZZ couplings
  - Excellent signal to background ratio (no pile-up!)
  - Possibility of tagging H → cc decay
- Exploring high lumi scenarios → Higgs „factory"
- The LHeC removes the PDF/QCD uncertainties for pp: LHC becomes precision Higgs facility

Extra Slides

Higgs via VBF
Qualitative remarks



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

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

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

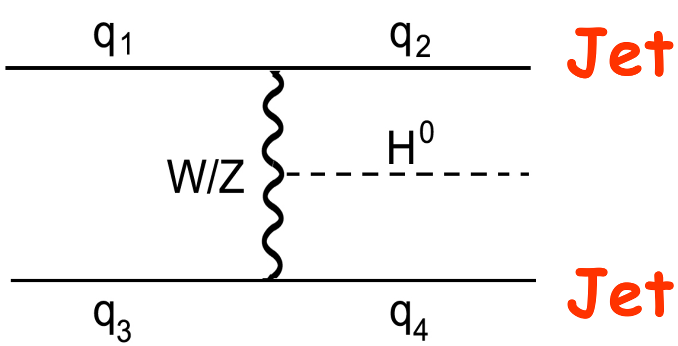
- **Unlike QCD partons that scale like $1/P_T^2$, here $P_T \sim sqrt(1-x)M_W$**

- **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)**

Low mass SM Higgs + 2jets

- 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)

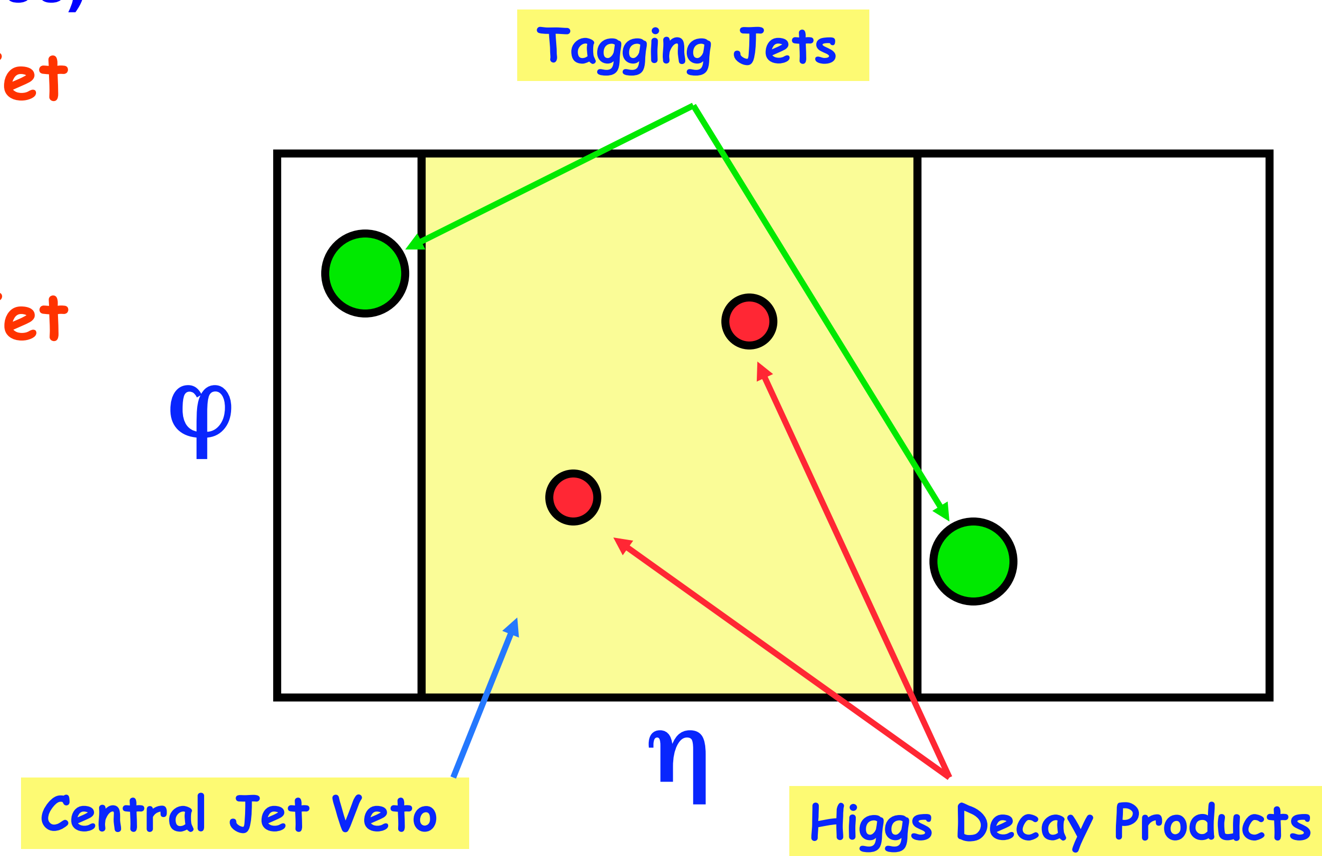


$\eta_{J1}\cdot\eta_{J2}<0$

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

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

c.j.v.



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

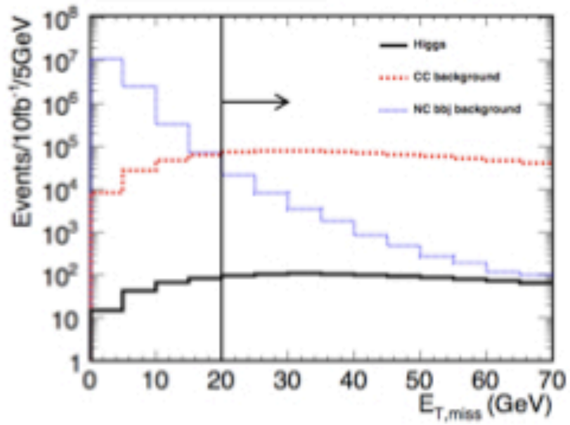
- NC rejection
  - Exclude electron-tagged events
  - $E_{T,miss} > 20$ GeV
  - N_{jet} ($p_T > 20$ GeV) $\geqq 3$
  - $E_{T,total} > 100$ GeV
  - $y_{JB} < 0.9$, $Q^2_{JB} > 400$ GeV^2
- b-tag requirement
  - $N_{b\text{-}jet}$ ($p_T > 20$ GeV) $\geqq 2$
- Higgs invariant mass
  - $90 < M_H < 120$ GeV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

$H \to b\bar{b}$

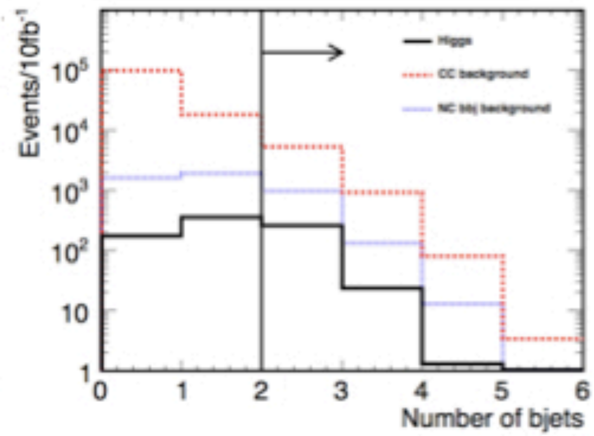
CC BG

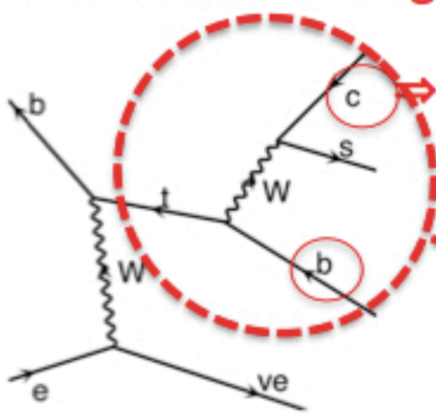
NC BG

E_T^{miss} cut

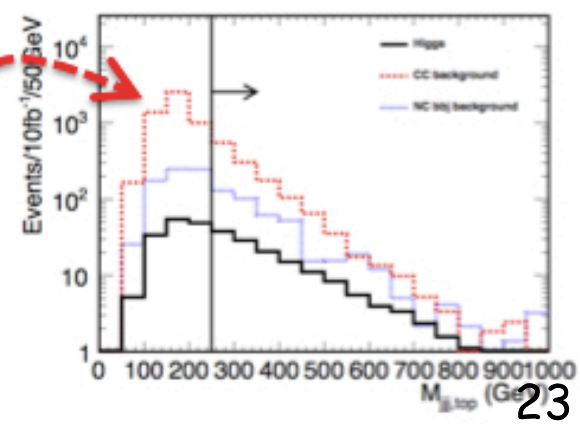


b-tag requirement

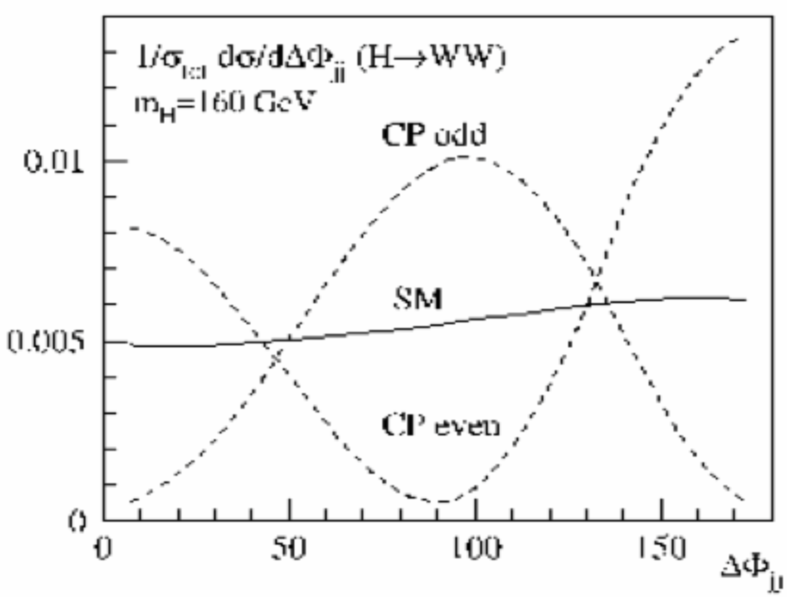


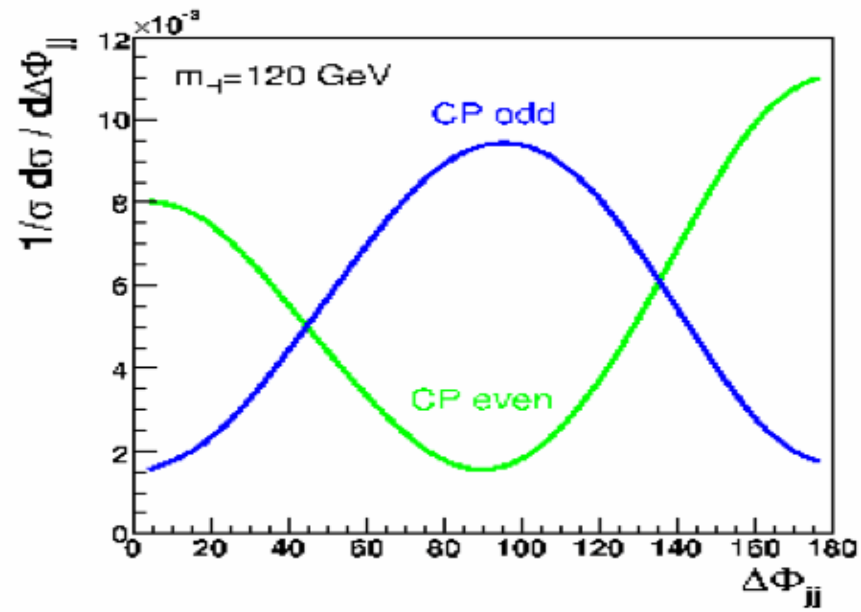


⇒10% mis-ID



Study by Zeppenfeld et al:





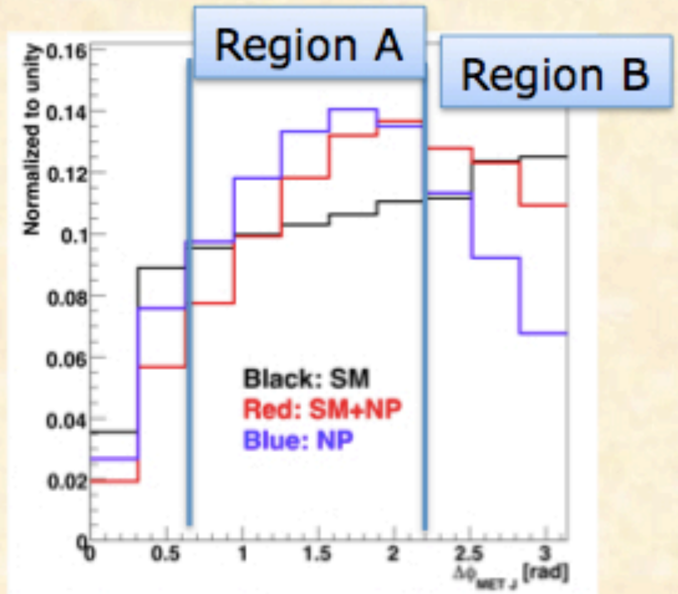
Left plot: VBF, CP even and CP odd refer to the dimension 5 operator.

For gluon fusion the angular distribution is decided by the CP property of the $t\bar{t}H$ coupling.

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 $\Delta\varphi_{MET,J}$ spectrum

CP-odd case



- Assume Gaussian errors and the following systematics:
  - 10% on the background rate
  - 5% on the shape of the $\Delta\varphi_{MET,J}$ in background
  - 5% on the rate of the SM Higgs
  - Evaluating theoretical error on $\Delta\varphi_{MET,J}$ shape

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

Effect of Jet Energy Resolution

Charge Current Analysis (results)

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

Effect of Jet P_T

Charge Current Analysis (results)

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

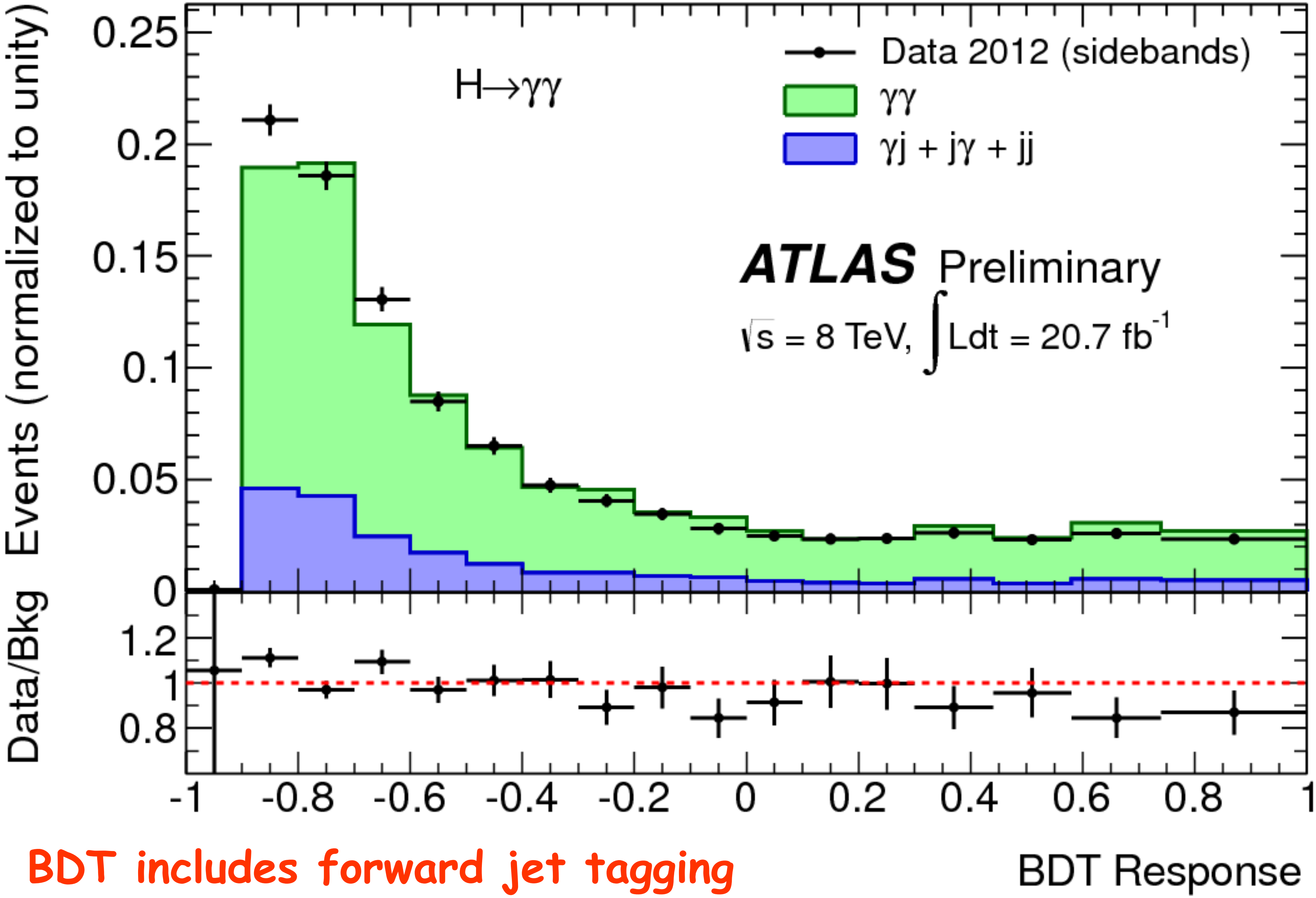
$$P_{Tj,b} > 30\,GeV \;\rightarrow\; P_{Tj,b} > 20\,GeV$$

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	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

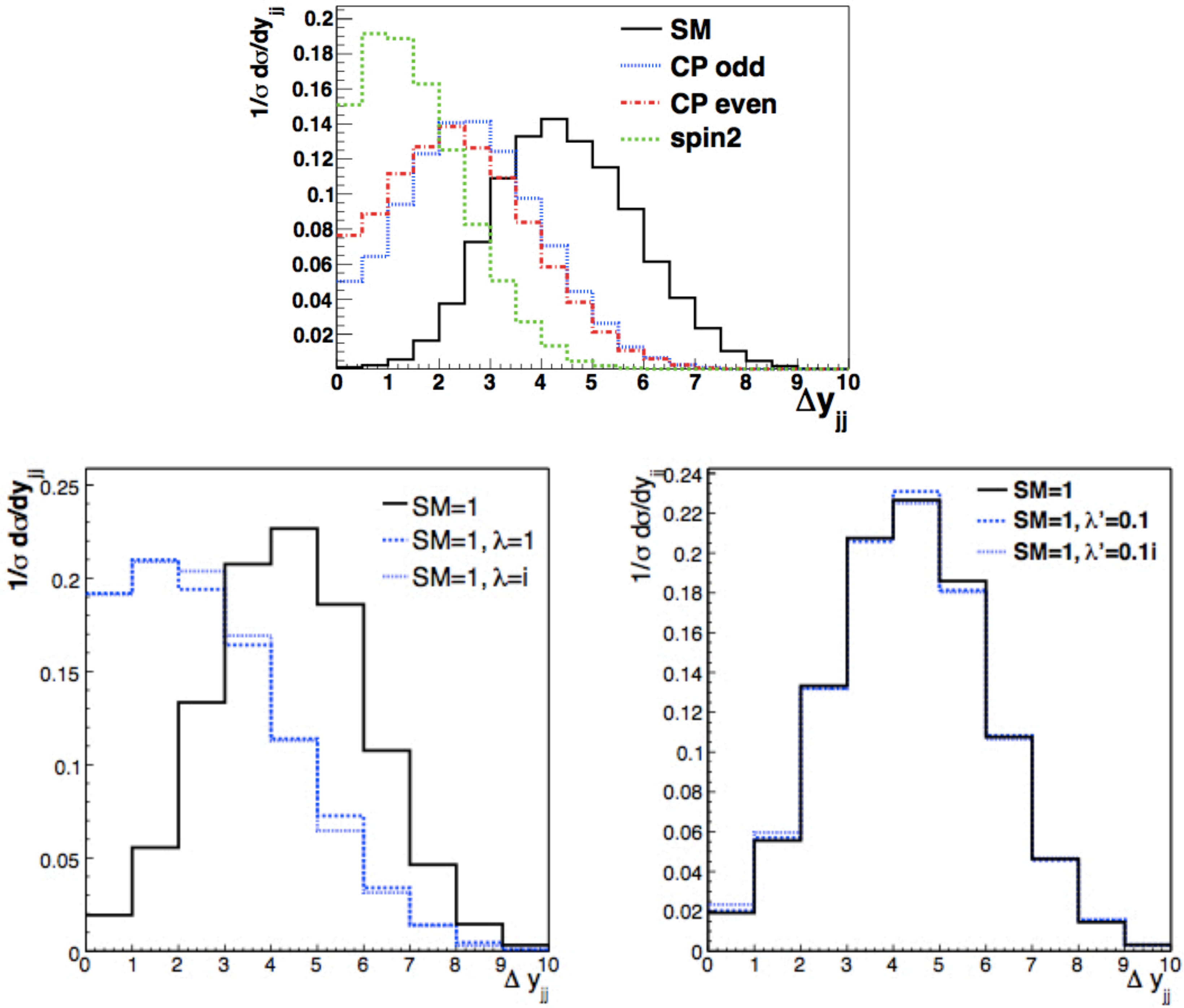
Signal Efficiency for Different E_e

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

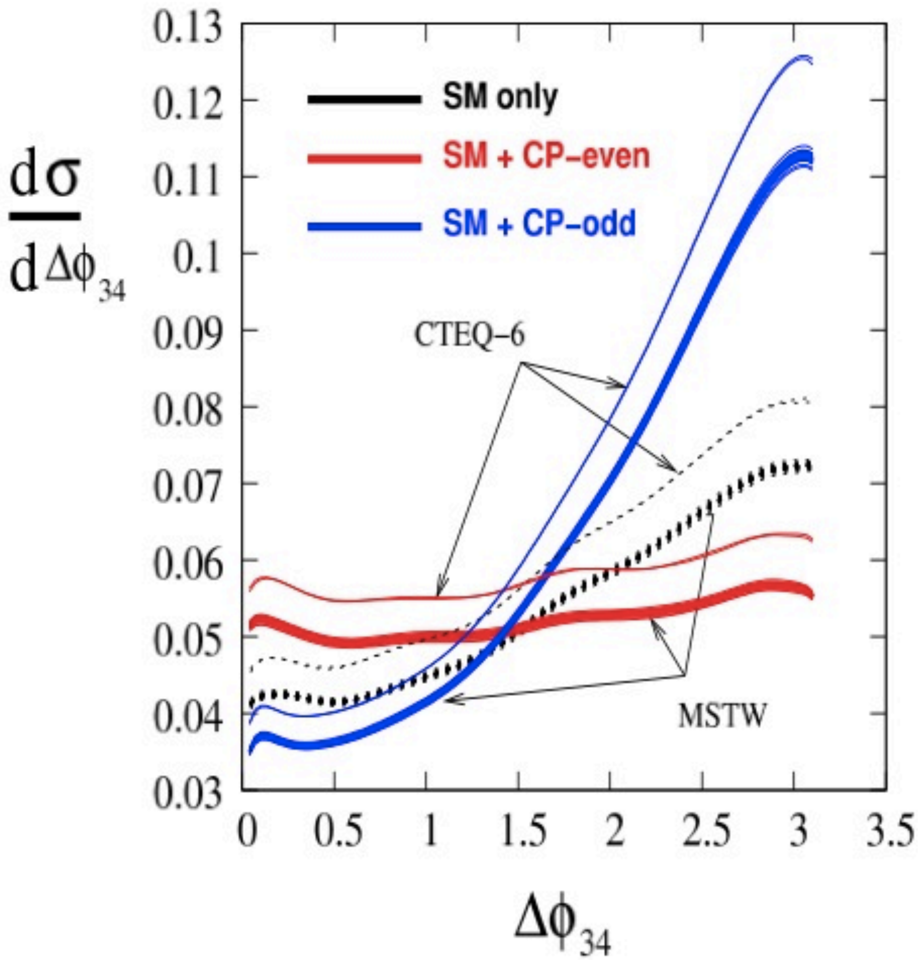
Cut	$E_e = 50$	$E_e = 100$	$E_e = 140$	$E_e = 200$
a	0.129 -	0.157 -	0.166 -	0.171 -
b	0.109 0.84	0.127 0.81	0.132 0.80	0.136 0.80
c	0.076 0.70	0.090 0.71	0.093 0.70	0.095 0.70
d	0.050 0.66	0.067 0.75	0.073 0.79	0.078 0.82

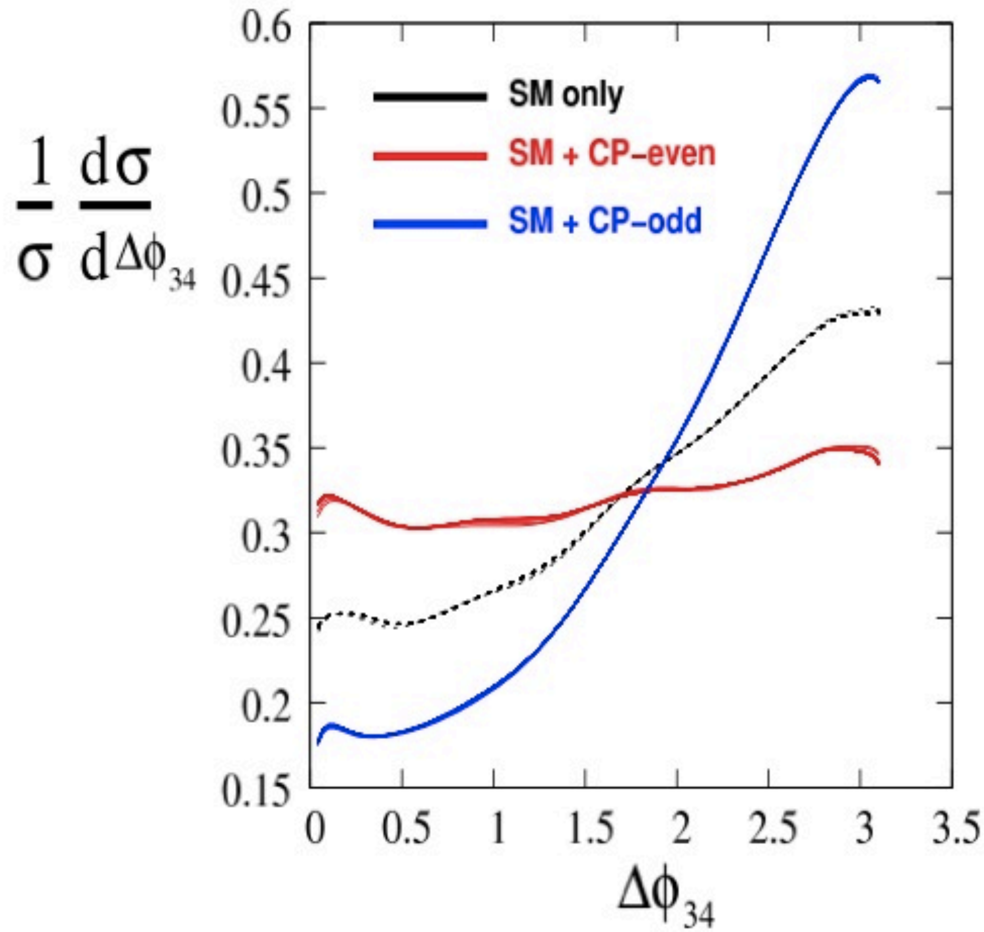


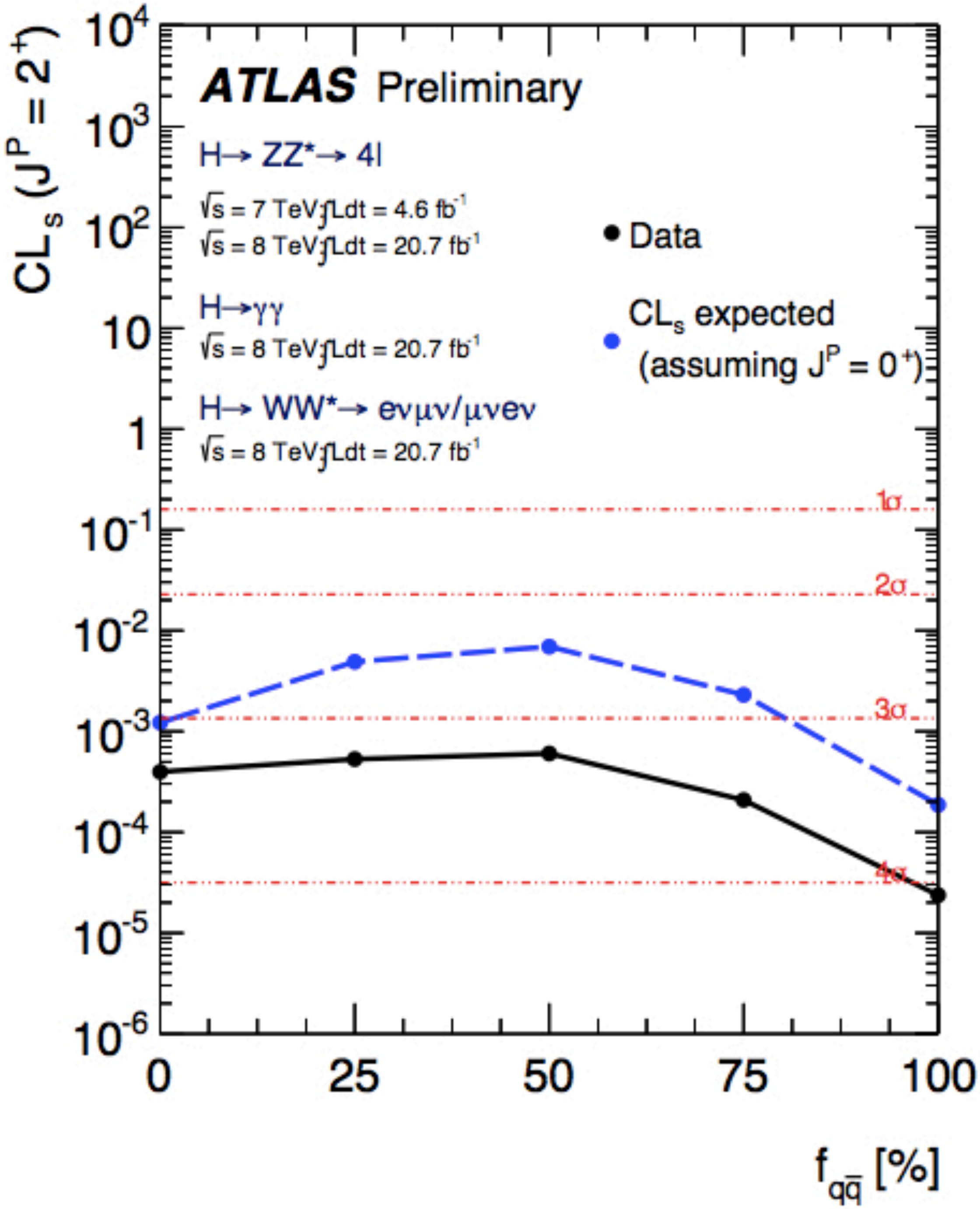
BDT includes forward jet tagging


1/σ dσ/dy_jj
SM
CP odd
CP even
spin2
Δy_jj
1/σ dσ/dy_jj
SM=1
SM=1, λ=1
SM=1, λ=i
Δ y_jj
1/σ dσ/dy_jj
SM=1
SM=1, λ'=0.1
SM=1, λ'=0.1i
Δ y_jj

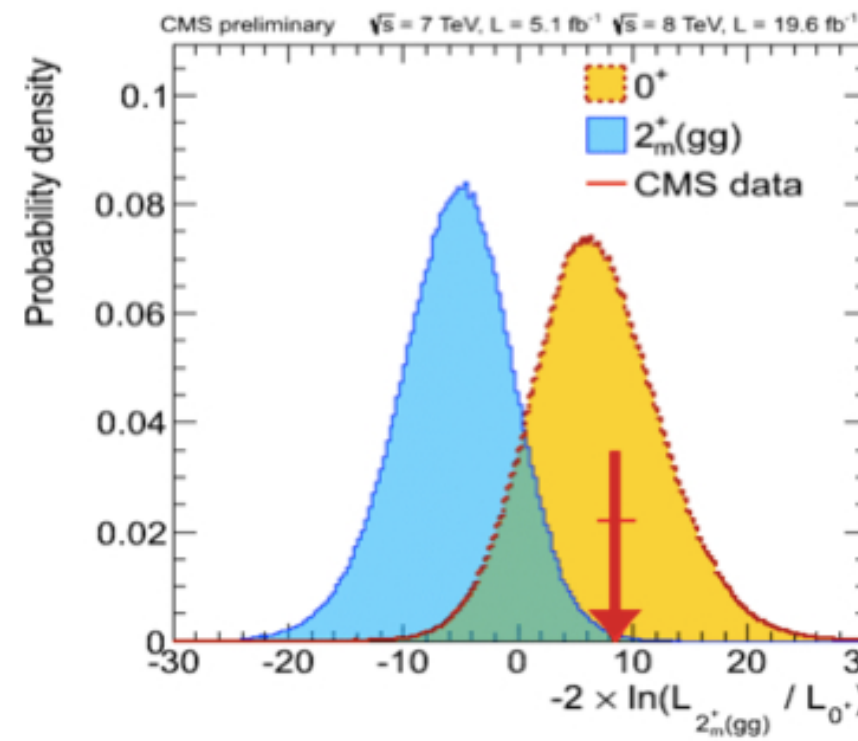
Effect of PDF uncertainties and pdf choice



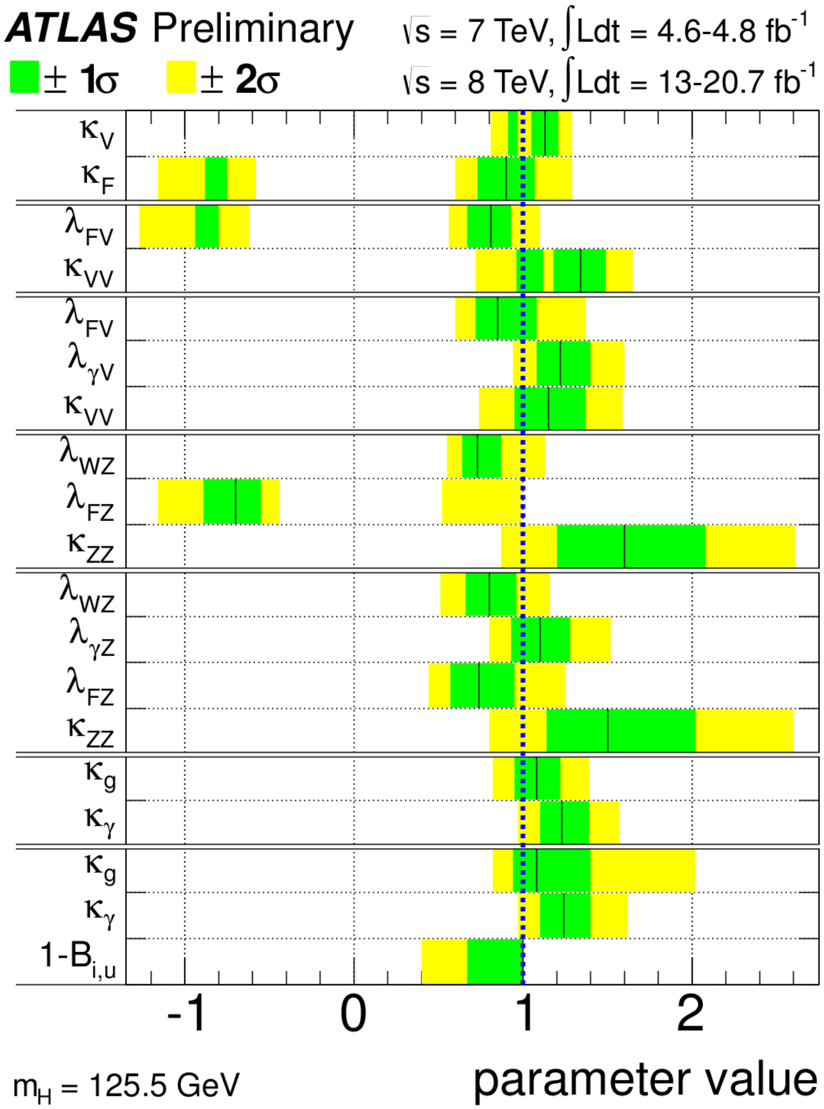


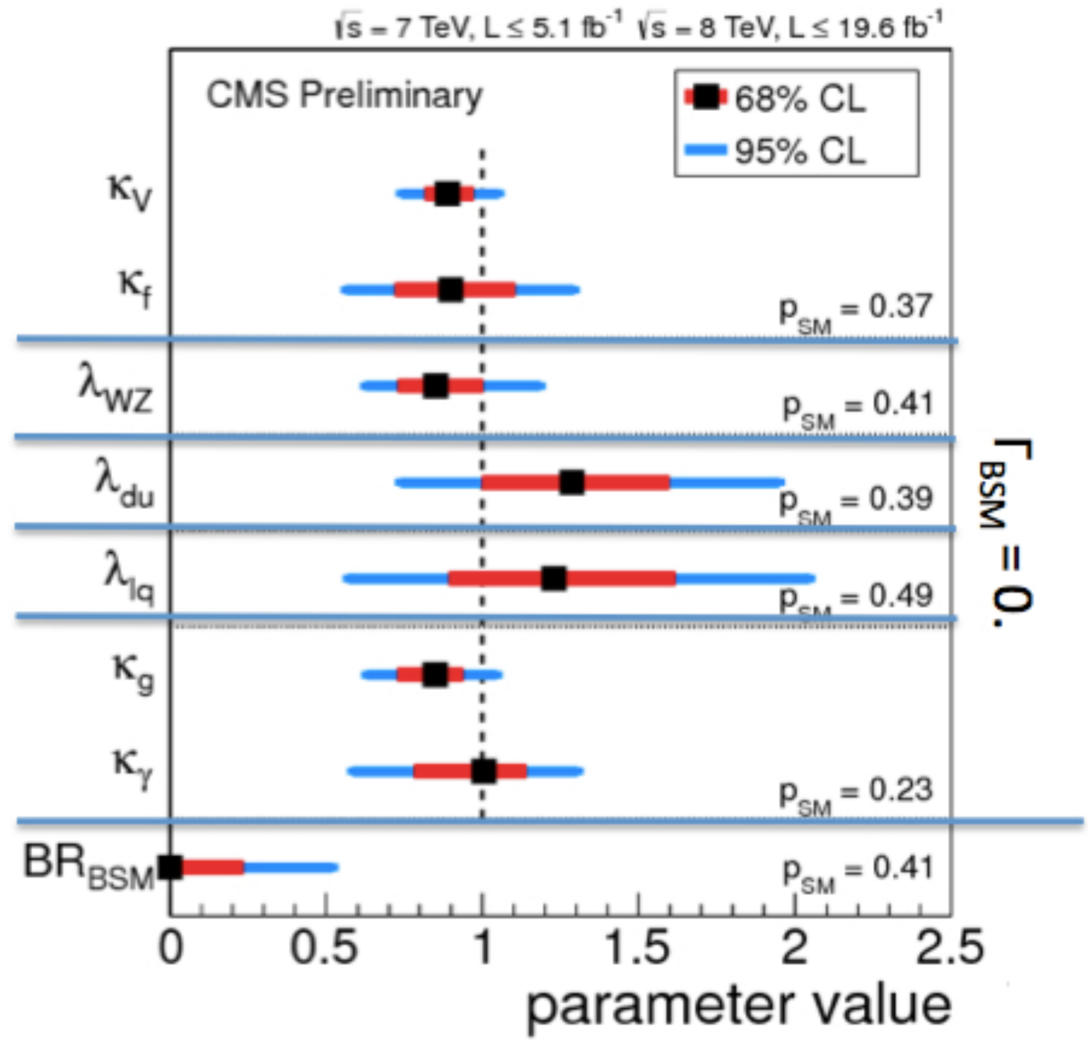


First preliminary combinations of CP-studies by CMS and ATLAS available. Consistent picture: compatibility of data with pure SM 0^+ hypothesis and incompatibility with other spin-CP hypotheses explored



Tests performed so far indicate compatibility with the SM Higgs boson hypothesis





Effect of background normalization on