Higgs Physics in ep

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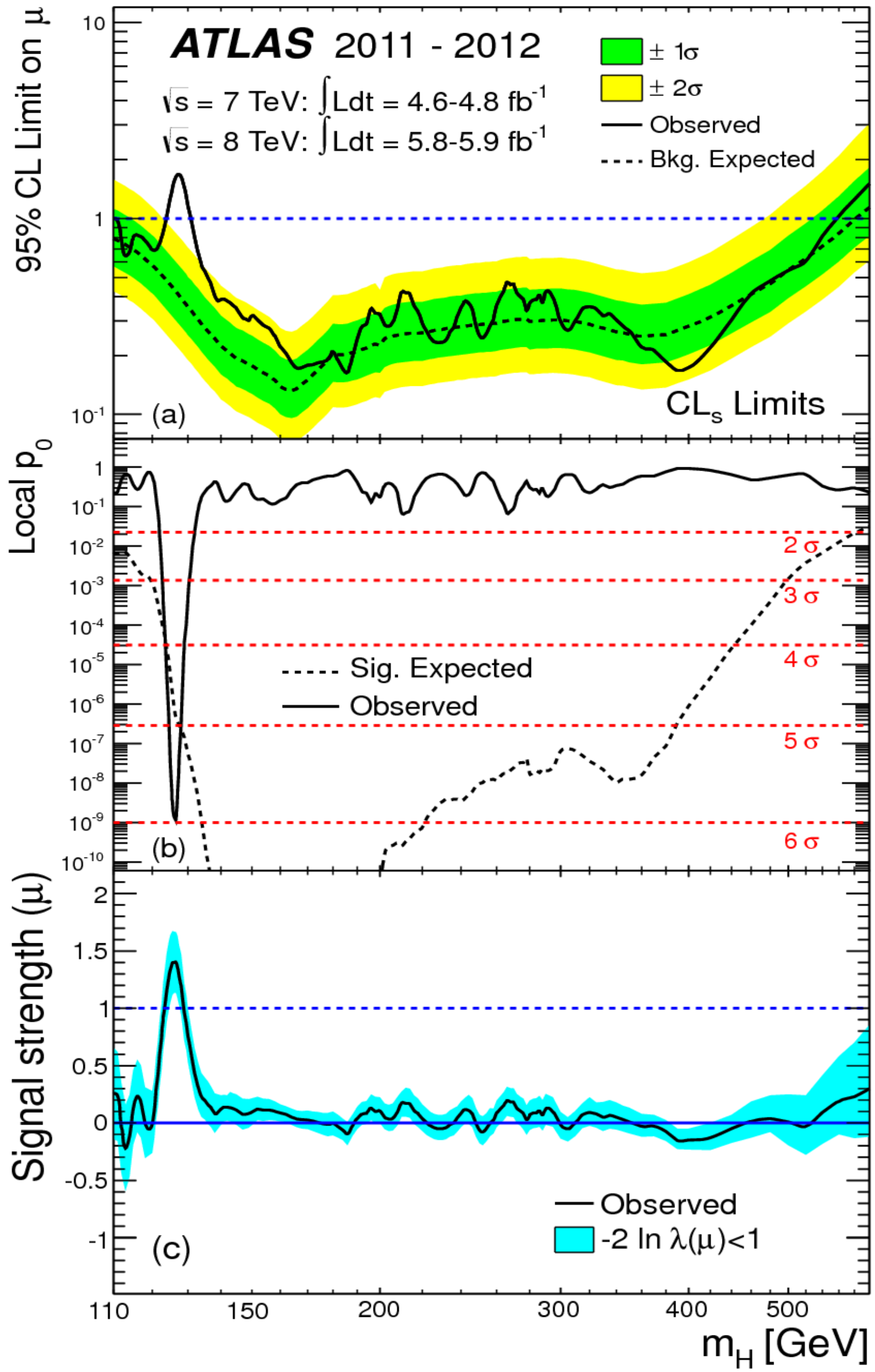
On behalf of the LHeC Study Group

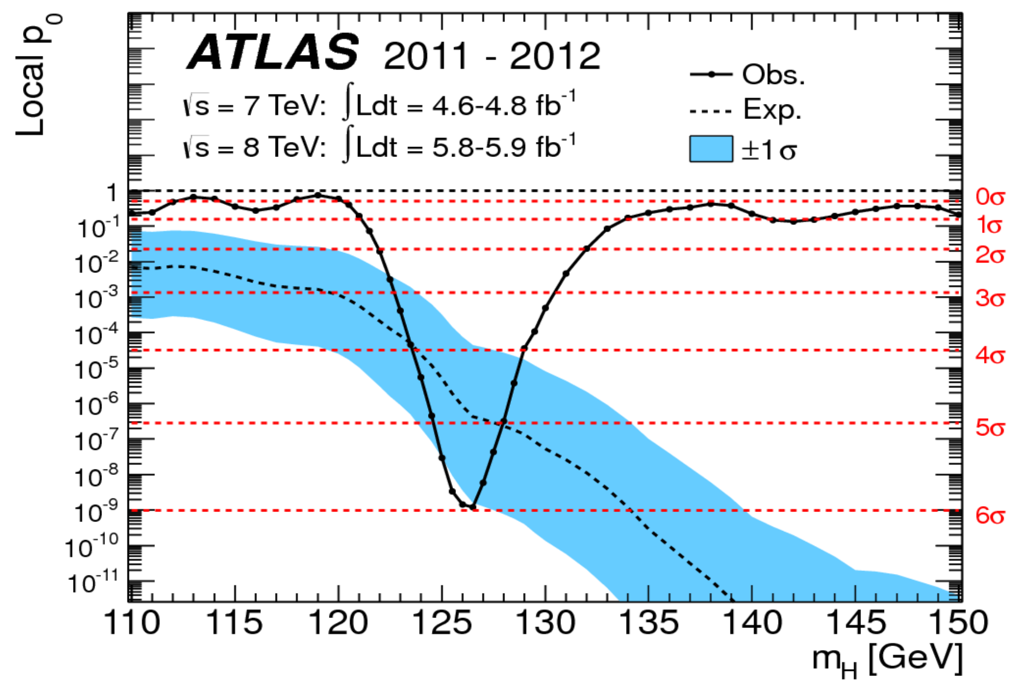
LHeC IAC Meeting, CERN 26/06/14

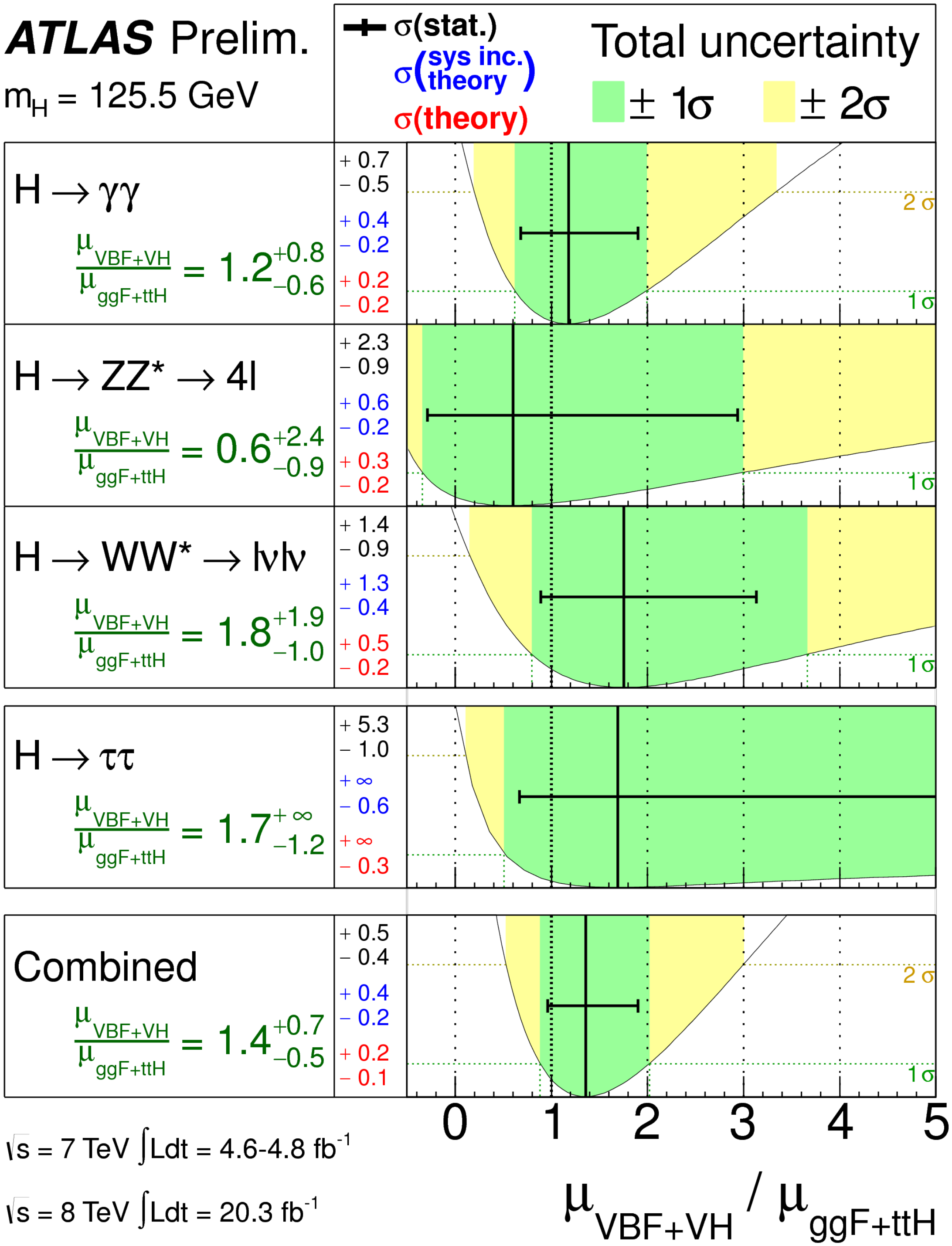


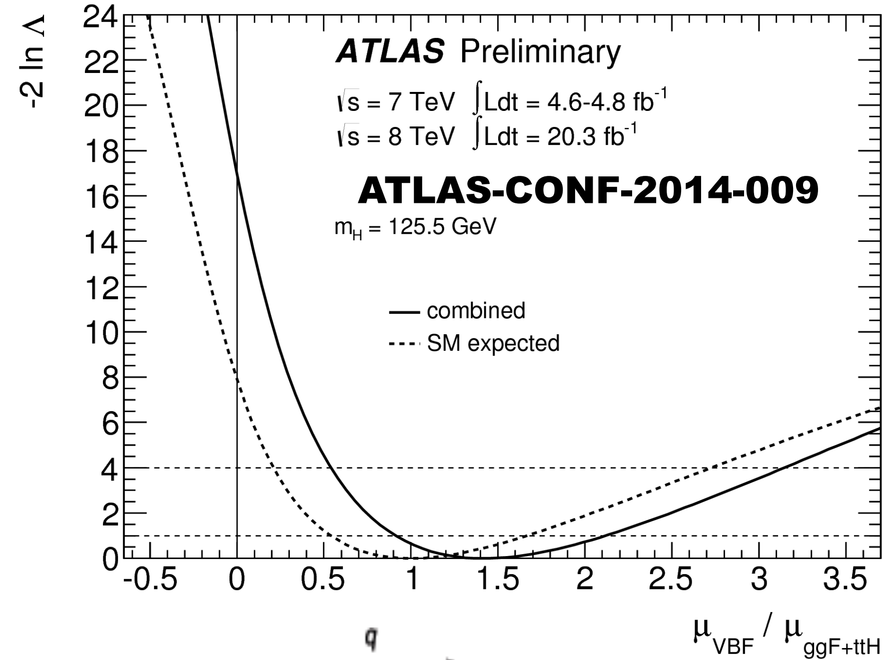
Habemus novum Boson

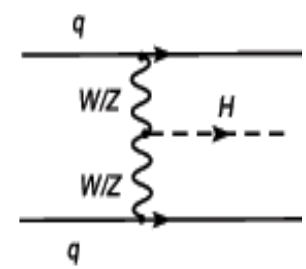
Phys.Lett. B716 (2012) 1-29

On July 4th reported 5σ.
With the addition of WW a 6σ effect is reached and reported in the final paper.







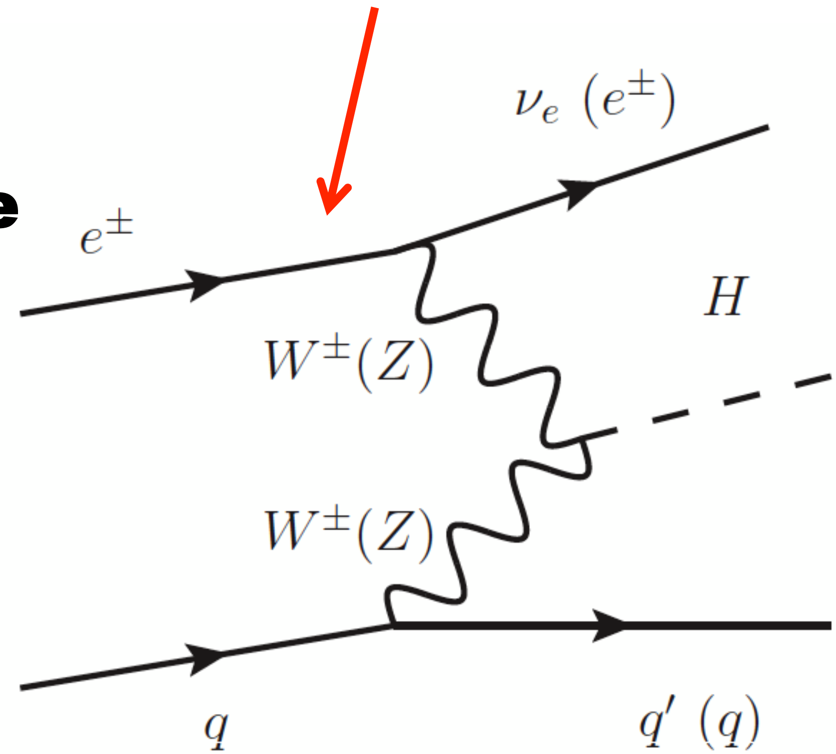


Evidence for VBF and VH production modes given in terms of ratio w.r.t. ggF+ttH modes.

Observe > 4σ evidence.

Higgs at LHeC

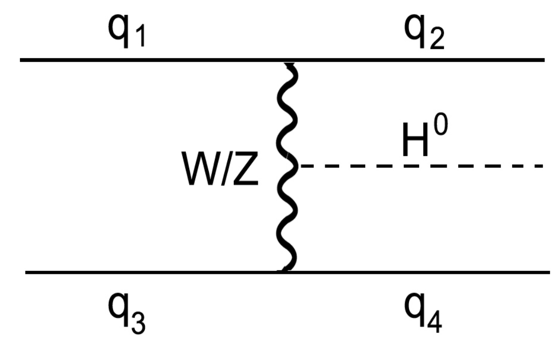
At LHC replace
lepton lines by quark lines



- It is remarkable that VBF diagrams were calculated for lepton nucleon collisions before for pp!
- Consider feasibility for the following point:

$$E_p = 7\ TeV, E_e = 60\ GeV, M_H = 120\ GeV$$

Higgs via VBF
Qualitative remarks



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

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

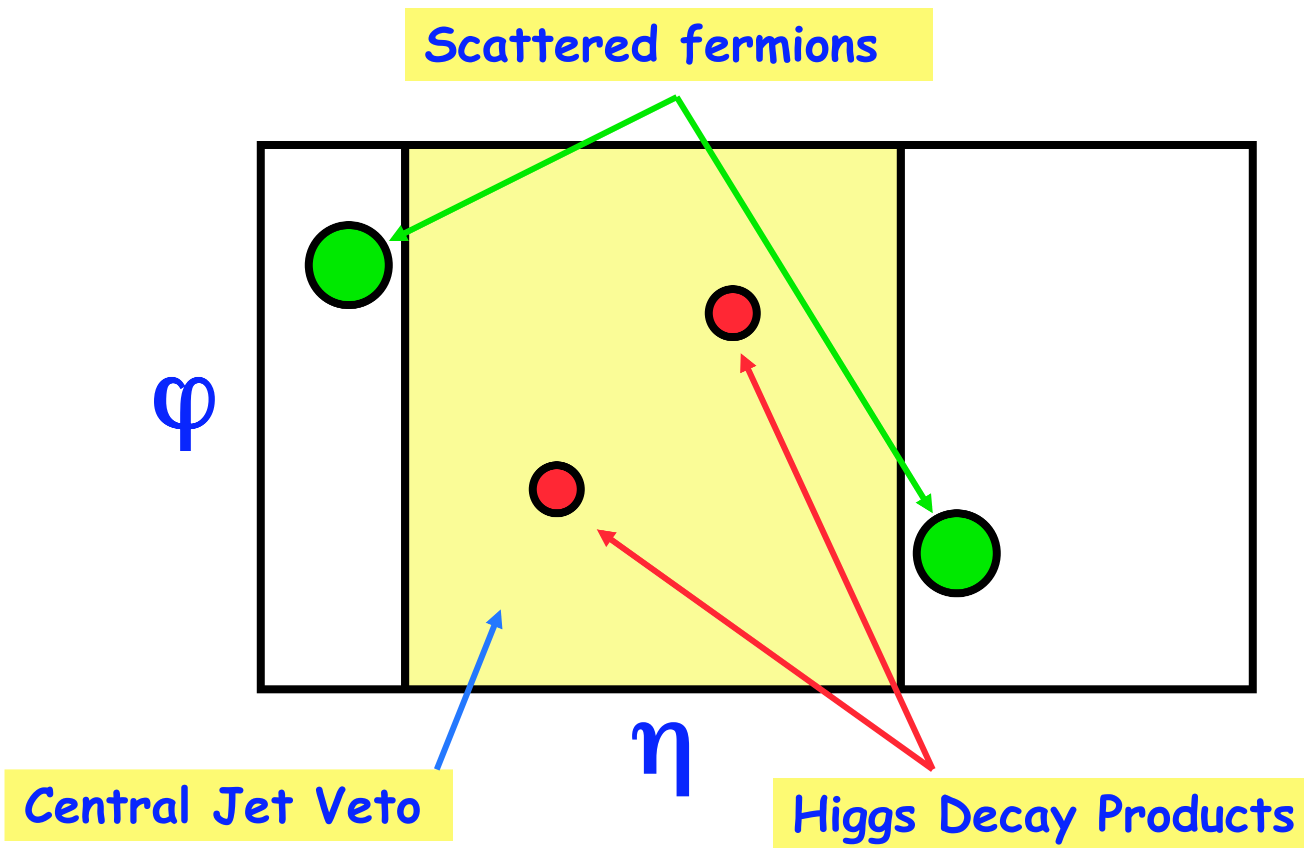
$$P_{V/f}^L(x, p_T^2) = \frac{g_V^2 + g_V^2}{4\pi^2} \frac{1 - x}{x} \frac{(1-x)M_V^2}{(p_T^2 + (1-x)M_V^2)^2}.$$

- **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 in favor of transversely polarized WB at high p_T**

Well-defined prediction of the SM. Kinematics of scattered quarks, very sensitive to new physics

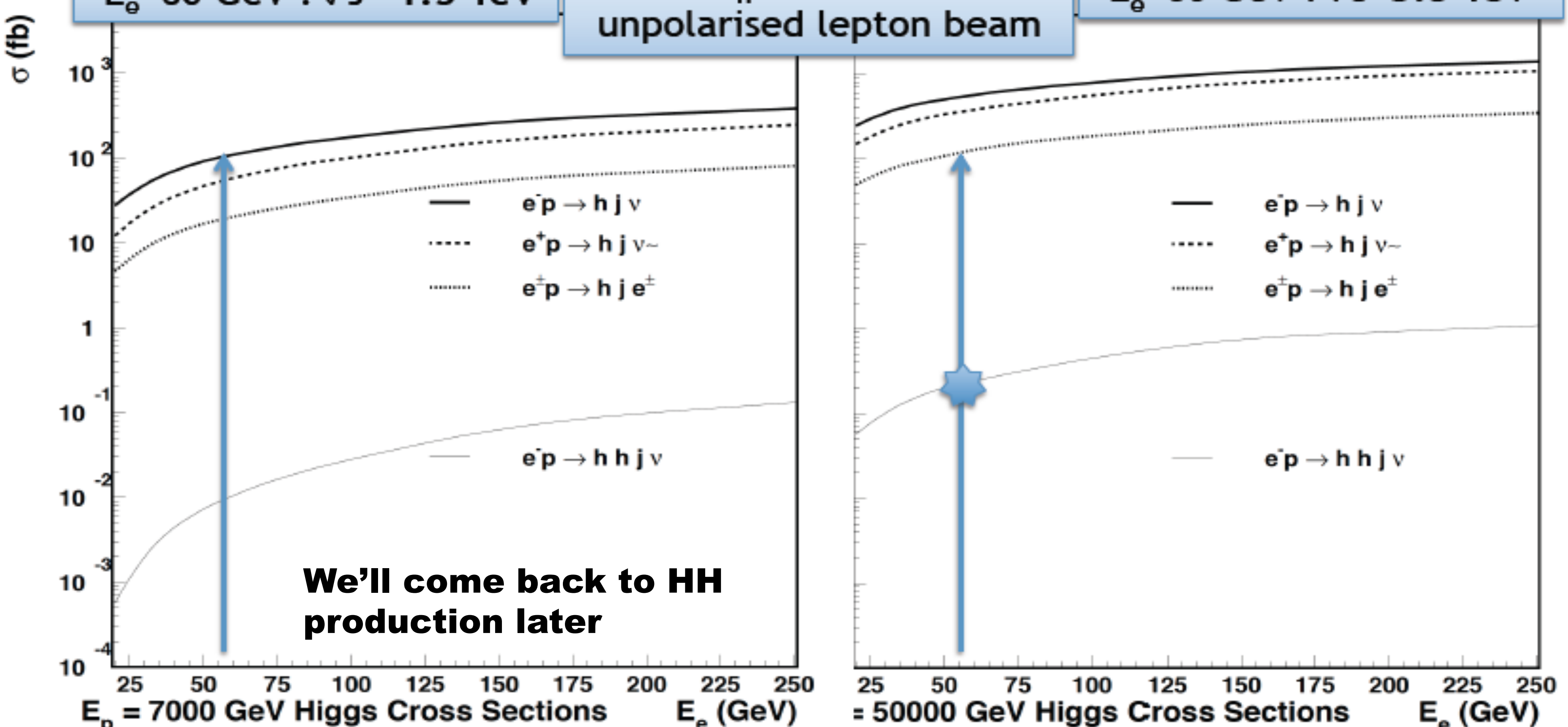


Total Higgs cross sections

E_e=60 GeV : $\sqrt{s}$= 1.3 TeV

M_h=125 GeV
unpolarised lepton beam

E_e=60 GeV : $\sqrt{s}$=3.5 TeV



7 TeV LHC protons

50 TeV FCC protons

and

electrons from a 60 GeV energy recovery LINAC

LHeC, a Higgs Factory

M.Klein

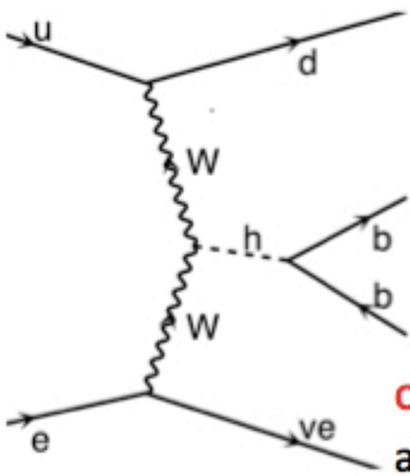
LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350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

MC Samples in Hadron-level study

U.Klein et al.

Signal

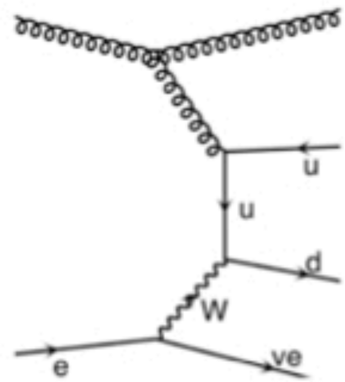
CC: H → $b\bar{b}$ (BR ~ 0.7 at M_H=120GeV)



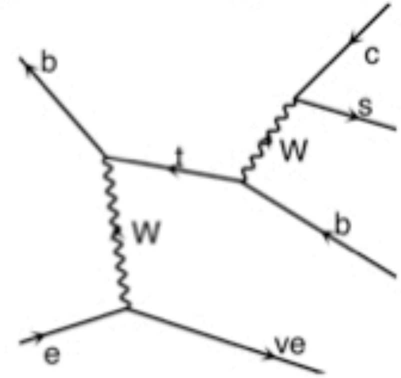
σ~ 0.16 pb
at √s=2.05TeV

Background (examples)

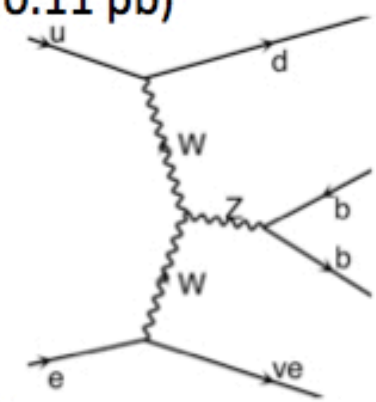
CC: 3 jets (~57 pb)



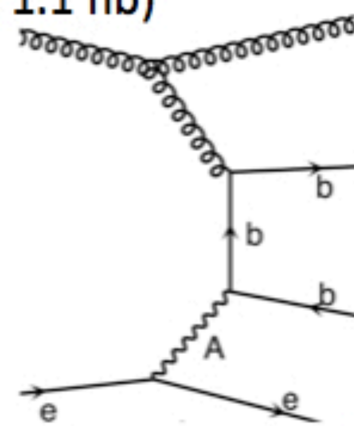
CC: single top production (~4.1 pb)



CC: Z production (~0.11 pb)



NC: b pair production (~1.1 nb)



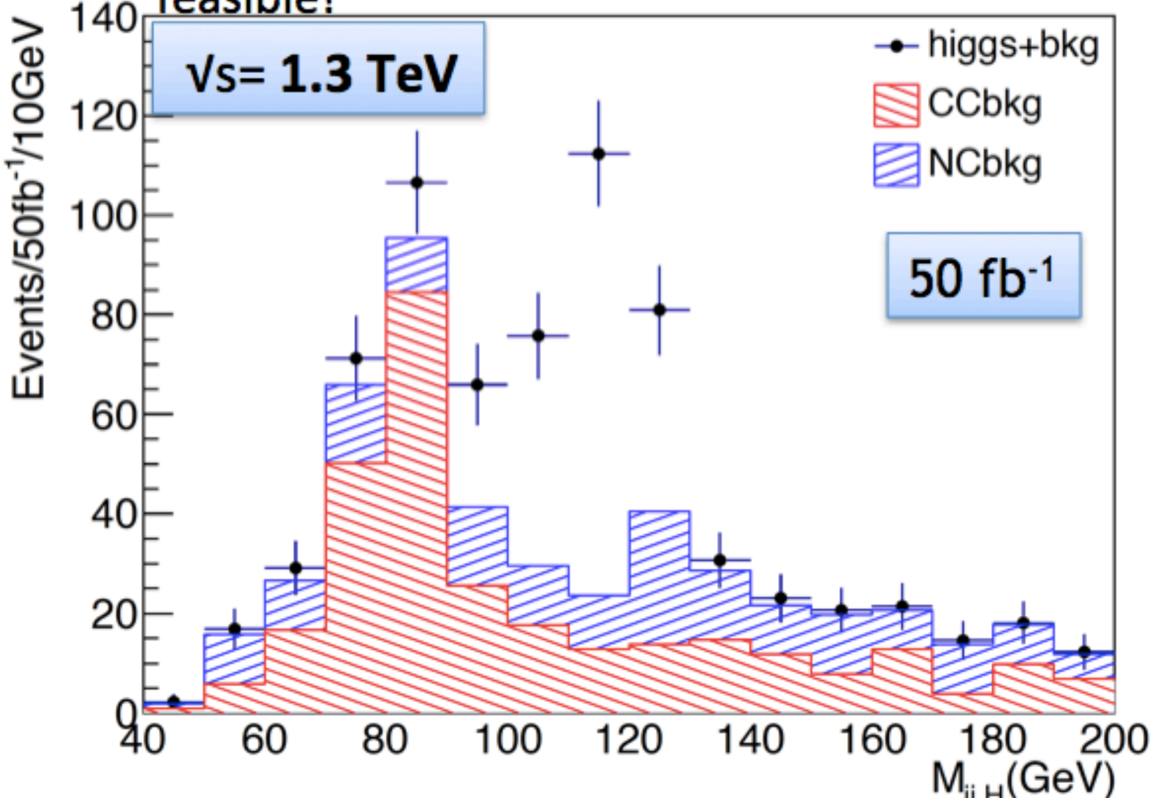
NOTE: Background sample numbers are after pre-selection in generator

H→b$\bar{b}$ results updated

[after Higgs discovery M_H=125 GeV, E_p=7 TeV]

U.Klein

- Case study for electron beam energy of 60 GeV using same analysis strategy
  - luminosity values of 50 fb^{-1} → with high luminosity LHeC 100 fb^{-1}/year would be feasible!



Masahiro Tanaka, BSc thesis, Tokyo Tech 2014

M_H selection [100-130 GeV]	E_e = 60 GeV (50 fb^{-1}, P=0)
H → bb signal	175
S/N	1.9
S/√N	18.1

- Electron energy recovery LINAC with **high electron polarisation of 80% and 10^{34} cm^{-2} s^{-1}** ➔ enhancement by factor 20*1.8 feasible, i.e. around 6300 Higgs candidates for E_e=60 GeV allowing to measure Hbb coupling with ~ **0.5 % - 1%** statistical precision.

	$\sigma(\text{pb})$	Number of samples	$\frac{N}{\sigma}(\text{fb}^{-1})$
CChbb	0.072	0.1M	1390
CCbkg	5.9	0.6M	101.6
NCbkg	28	3M	107.2

CCbkg : p e- > vl j j j /h

NCbkg : p e- > e- j j j /h

CDR analysis is being revisited by Tokyo/ Liverpool

Refining event selection
Work in progress

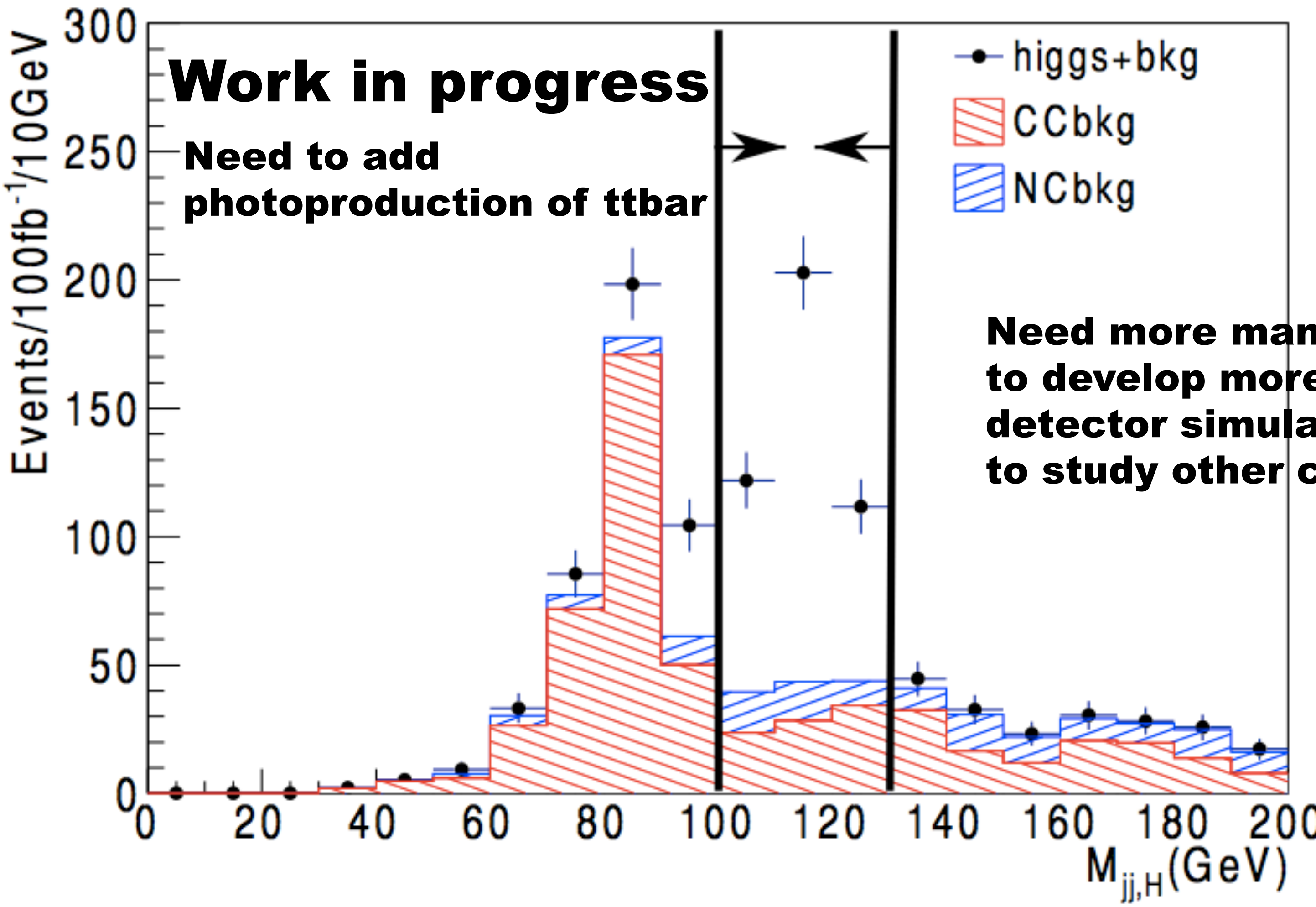
Nbjet	≧2
Njet	≧3
missing ET(GeV)	>20
total ET(GeV)	>100
Nelectron	0
$Q^2(\mathrm{GeV}^2)$	>400
y	<0.9
light jet η	>2
W mass(GeV)	>130
top mass (GeV)	>250
$\Delta\phi$	>0.3

Masahiro Tanaka

- 100 fb^{-1} are assumed

Masahiro Tanaka

Results being cross-checked



Need more man power to develop more realistic detector simulation and to study other channels

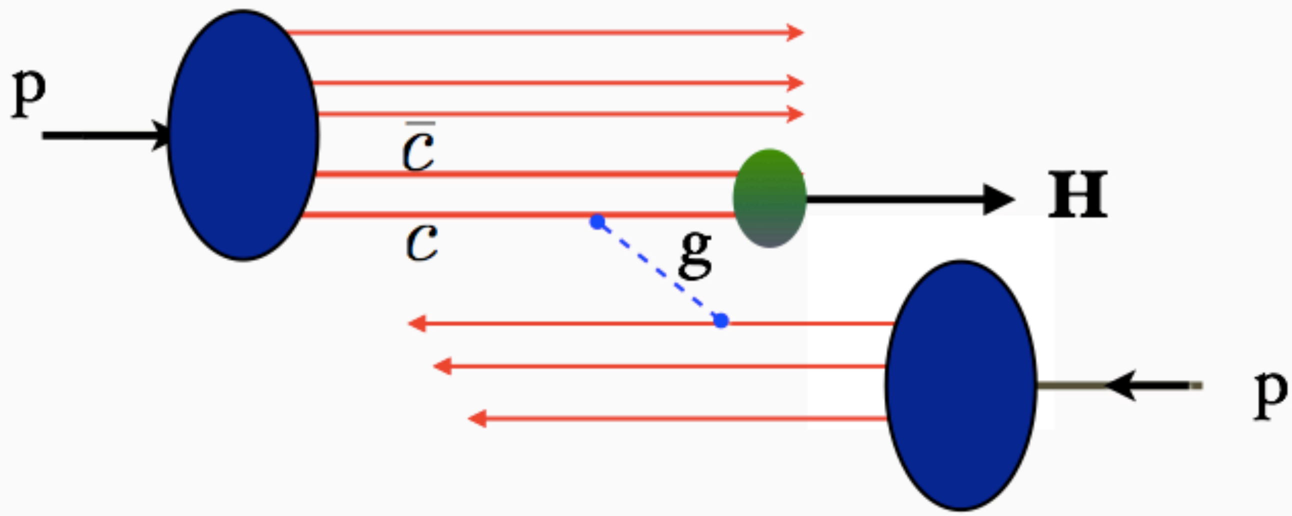
Events in signal region [100,130]GeV

CCHbb	CCbkg	NCbkg
309	86.5	40.1

$$\frac{N_{signal}}{\sqrt{N_{bkg}}} = 27.5$$

Goldhaber, Kopeliovich, Schmidt, sjb

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



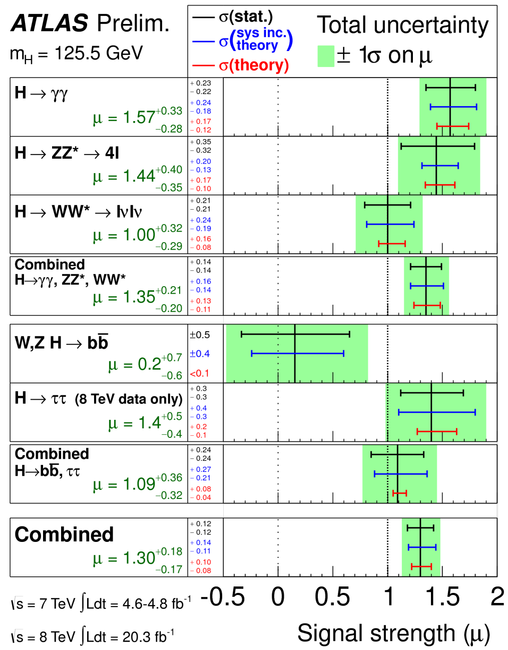
$pp \to HX$

Also: intrinsic strangeness, bottom, top

Higgs can have > 80% of Proton Momentum!

New production mechanism for Higgs

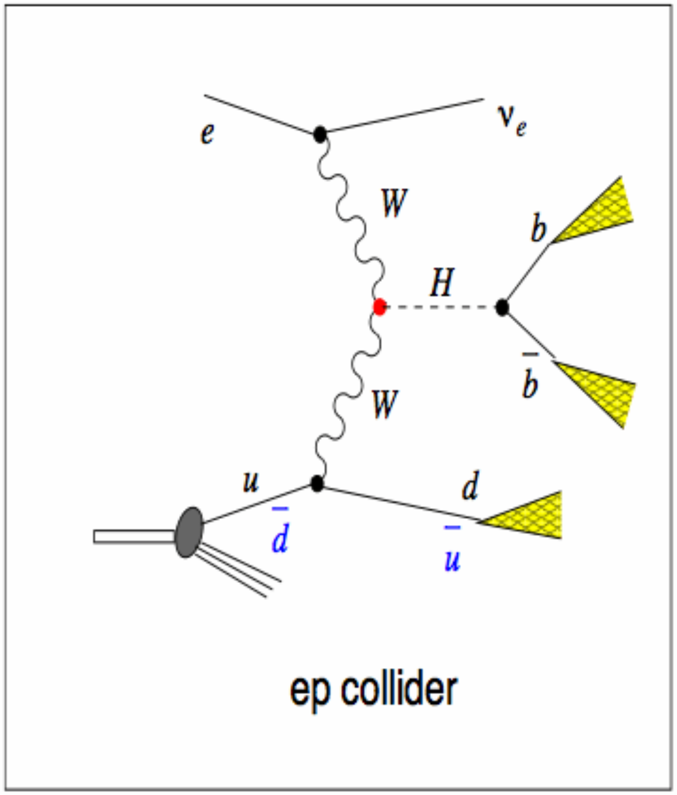
AFTER: Higgs production at threshold!

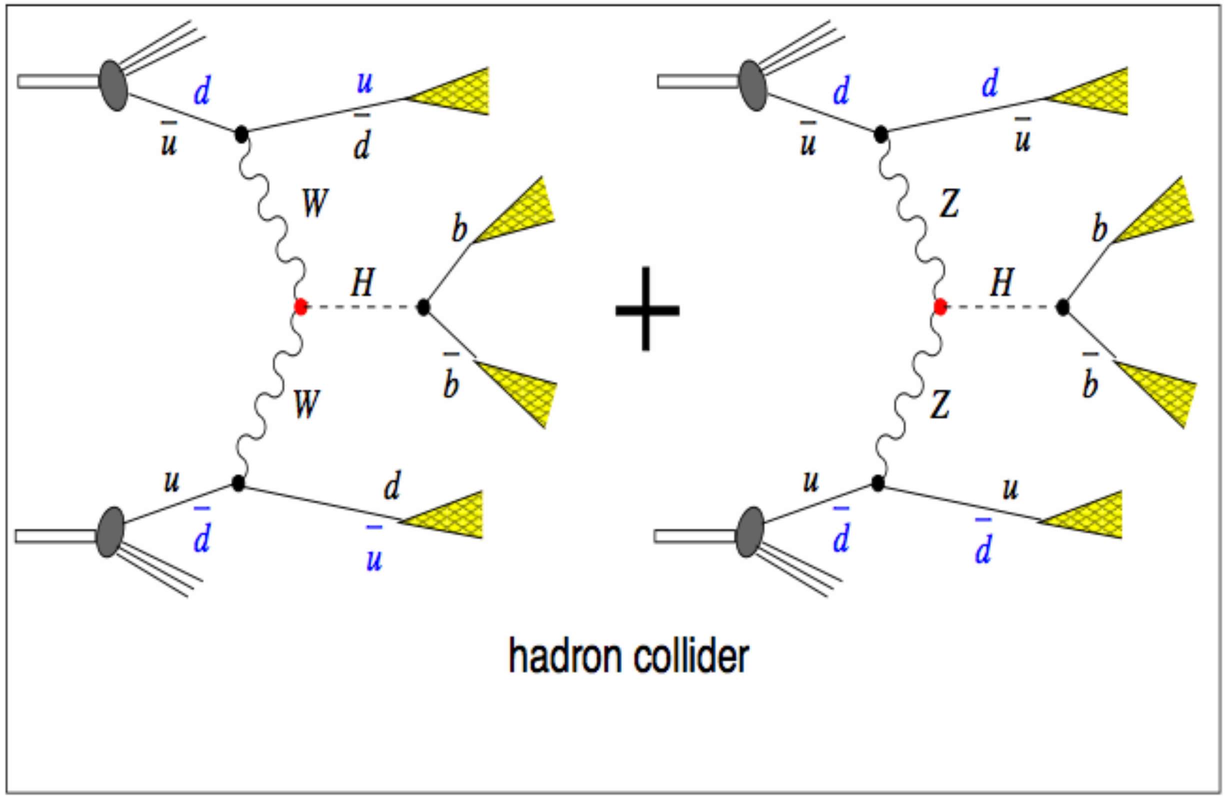


Spin/CP Quantum numbers

At some point the study of the signal strength is not sufficient to understand presence of new physics in Higgs couplings. Scrutiny of kinematics of scattered quarks is a unique window of opportunity to establish admixtures of BSM terms in the HVV coupling

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

CP Structure of HVV Couplings

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)

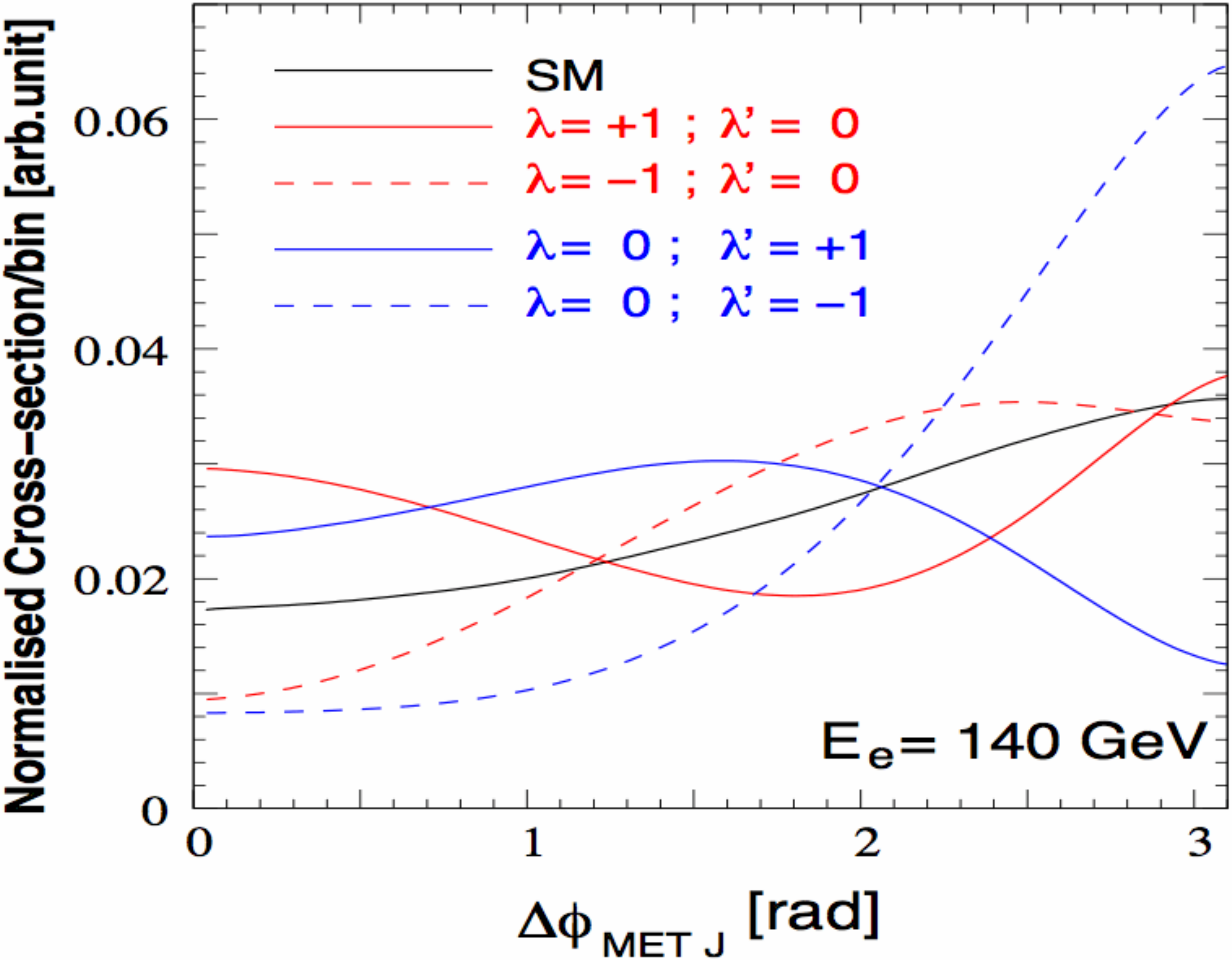
$Hf\bar{f} : -\frac{gm_f}{2M_W}\bar{f}\left(a_f + ib_f\gamma_5\right) fH$

HVV:

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

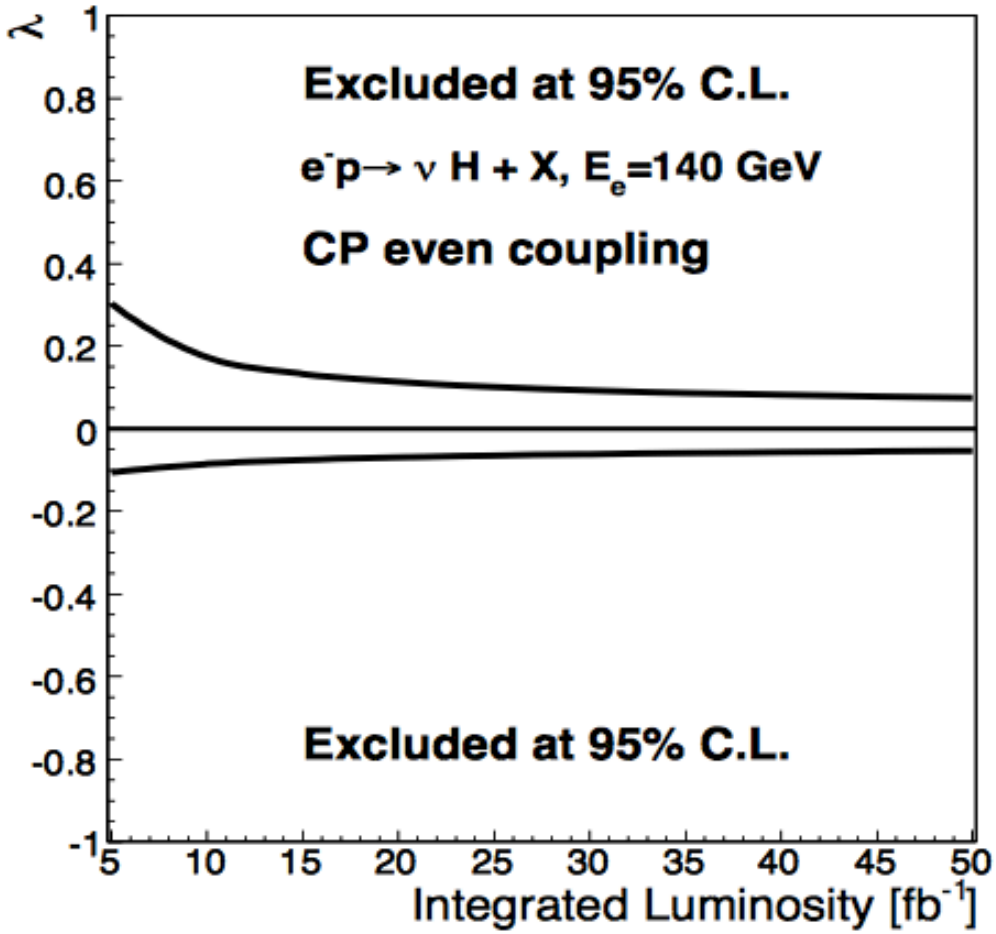
$$\Gamma^{\rm BSM}_{\mu\nu}(p,q) = \frac{g}{M_V}\left[\lambda\left(p\cdot q\, g_{\mu\nu} - p_\nu q_\mu\right) + \lambda'\, \epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

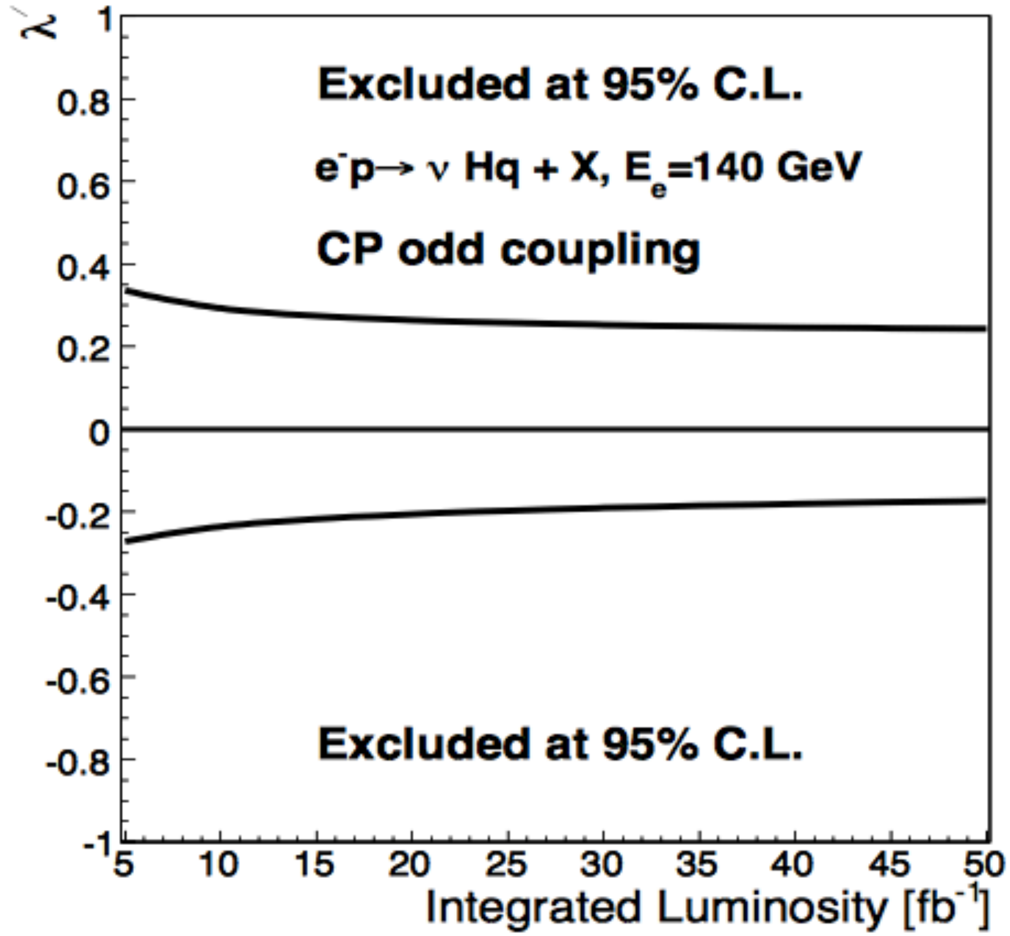
S. Biswal, R. Godbole, B.M. and a S. Raychaudhuri Phys.Rev.Lett. 109 (2012) 261801



SM
λ= +1 ; λ' = 0
λ= −1 ; λ' = 0
λ= 0 ; λ' = +1
λ= 0 ; λ' = −1
E_e= 140 GeV
Normalised Cross−section/bin [arb.unit]
0
0.02
0.04
0.06
0
1
2
3
$\Delta\phi_{MET\ J}$ [rad]

Strong potential to exclude admixture of BSM physics in the HWW coupling





Very conservative systematics assumed

Double Higgs Production with a 50 TeV Proton Beam

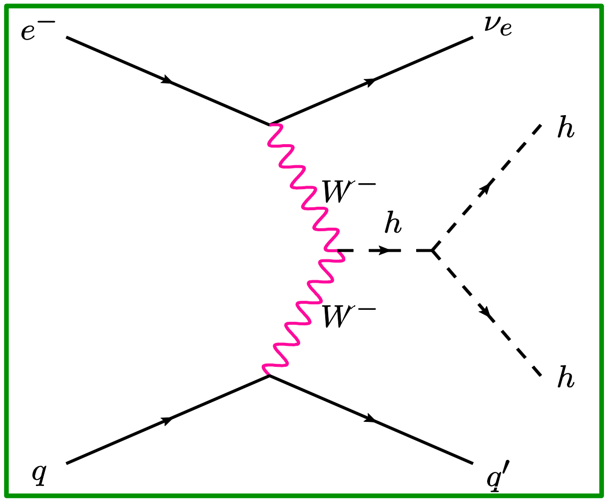
In the light of the FCC kick-off meeting, we are evaluating feasibility of double Higgs production with a 50 TeV beam. Electron-proton collisions offer the advantage of reduced QCD backgrounds and negligible pile-up with the possibility of using the 4b final state.

Feynman rules for the interactions of the scalar boson with gauge bosons, fermions and self-interactions.

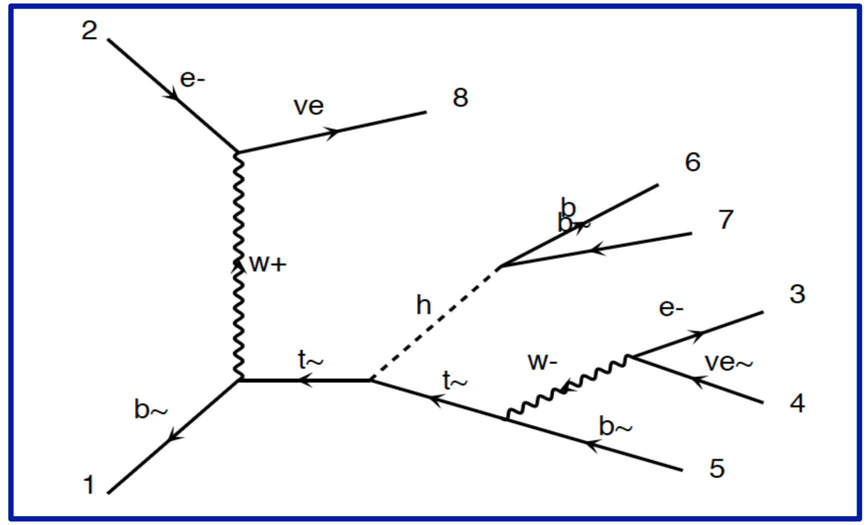
Gauge	Self-interaction	Fermion
$HW^+_\mu W^-_\nu : (-ig_{\mu\nu})2\frac{m_W^2}{\nu}$	$HHH : (i)3\frac{m_H^2}{\nu}$	$H\bar{f}f : (i)\frac{m_f}{\nu}$
$HZ_\mu Z_\nu : (-ig_{\mu\nu})2\frac{m_Z^2}{\nu}$	$HHHH : (i)3\frac{m_H^2}{\nu^2}$	
$HHW^+_\mu W^-_\nu : (-ig_{\mu\nu})2\frac{m_W^2}{\nu^2}$		
$HHZ_\mu Z_\nu : (-ig_{\mu\nu})2\frac{m_Z^2}{\nu^2}$		

Exploring the feasibility of the HHH coupling via double-Higgs boson production

HH and tHt in ep



New Tentative Studies



FCC-he unpolarised Cross section at 3.5 TeV:

Processes	E_e (GeV)	σ(fb)	σ_{eff}(fb)
$e^- p \to \nu_e hhj, h \to b\bar{b}$	60	0.04	0.01
	120	0.10	0.024
	150	0.14	0.034

total : 0.7 fb
fiducial : 0.2 fb
using pt(b,j)>20 GeV
ΔR(j.b)>0.4
η(j) <5
η(b) < 3

Polarisation, max lumi, tuning cuts, bb and WW decays may provide O(10%) precision - tentative

Require time for reliable result (detector, analysis, backgrounds..)

Bruce Mellado, Uta Klein, Masahiro Khuze et a

Cross-sections for CC HH->4b (branching ratios included)
For unpolarized electron beam

Processes	E_e (GeV)	σ(fb)	σ_{eff}(fb)
$e^- p \to \nu_e hhj, h \to b\bar{b}$	60	0.04	0.01
	120	0.10	0.024
	150	0.14	0.034

$p_{T_{j,b}} > 20\ GeV,$

$\not{E}_T > 25\ GeV,$

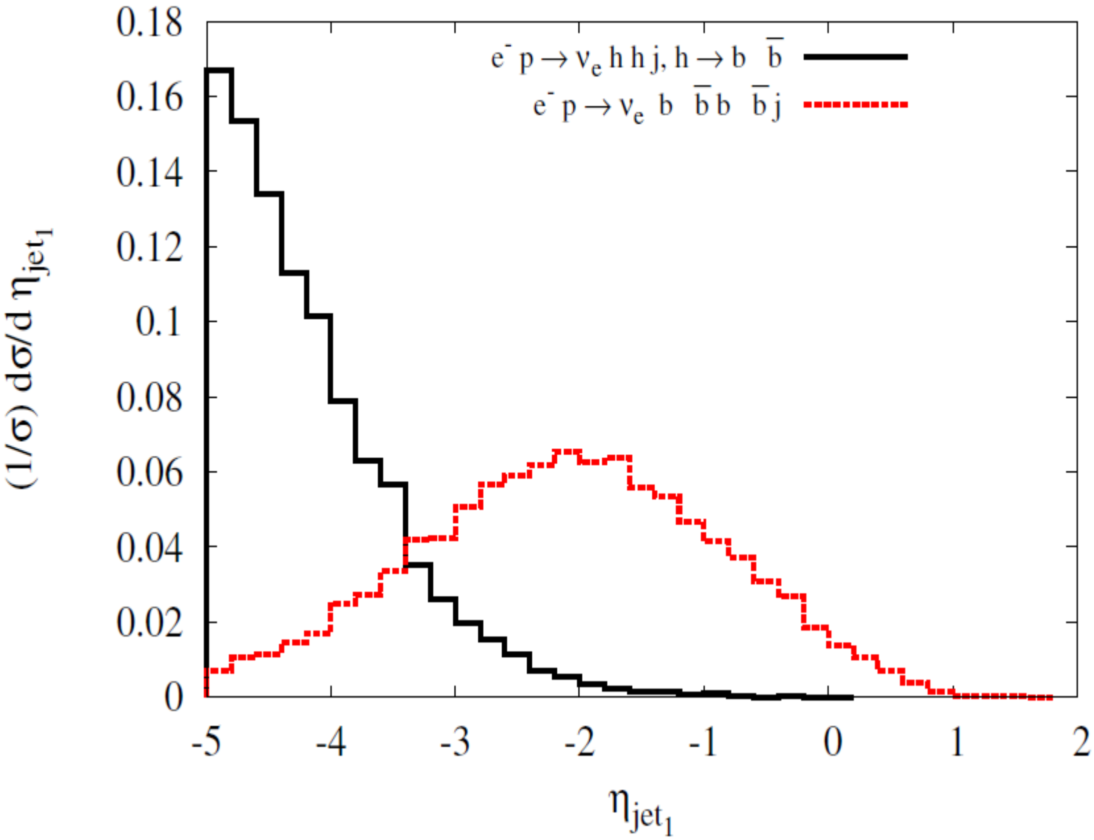
$|\eta_j| < 5,\ \Delta R = 0.4.$

Cross-sections for CC backgrounds in fb for E_e=60,120,150 GeV

Processes	$E_e = 60$ GeV		$E_e = 120$ GeV		$E_e = 150$ GeV	
	σ(fb)	σ_{eff}(fb)	σ(fb)	σ_{eff}(fb)	σ(fb)	σ_{eff}(fb)
$e^- p \to \nu_e b\bar{b}b\bar{b}j$	0.086	0.022	0.14	0.036	0.15	0.038
$e^- p \to \nu_e b\bar{b}c\bar{c}j$	0.12	1.7×10^{-5}	0.36	1.8×10^{-3}	0.44	2.2×10^{-3}
$e^- p \to \nu_e c\bar{c}c\bar{c}j$	0.20	1.0×10^{-6}	0.24	3.4×10^{-5}	0.31	4.3×10^{-5}
$e^- p \to \nu_e b\bar{b}jjj$	26.1	3.9×10^{-3}	54.2	0.008	67.5	0.01
$e^- p \to \nu_e c\bar{c}jjj$	29.6	9.5×10^{-5}	66.9	2.0×10^{-4}	85.4	2.7×10^{-4}
$e^- p \to \nu_e jjjjj$	823.6	4.1×10^{-5}	1986	9.9×10^{-5}	2586	1.3×10^{-4}

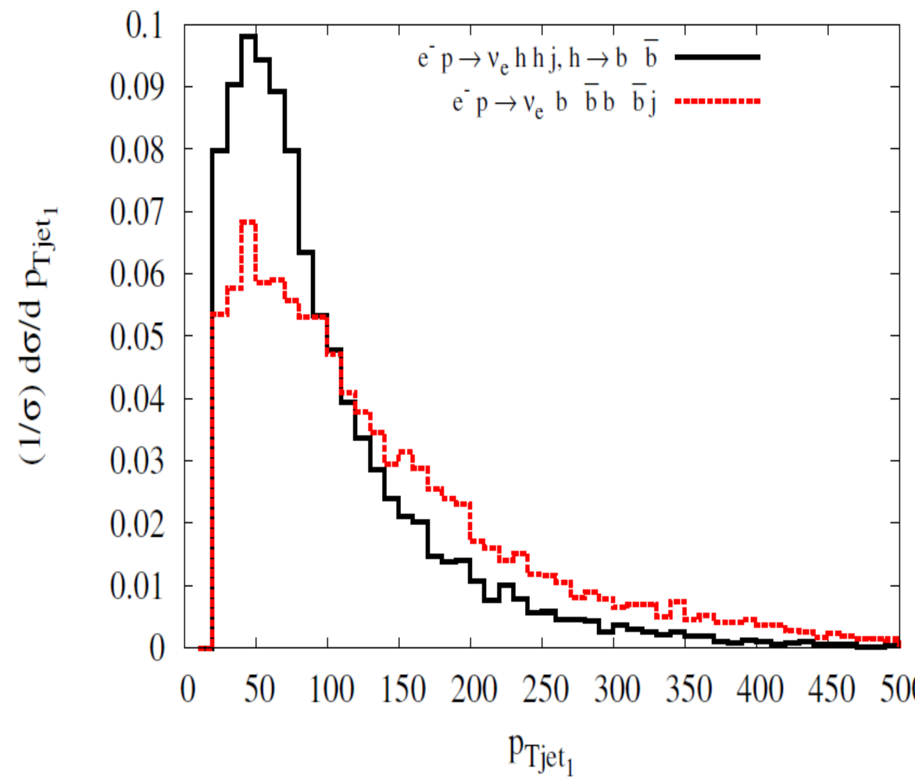
Results promising at parton level, giving comparable signal and background cross-sections even before topological requirements. Looking forward to the particle-level study.

Results assume 70% b-tagging efficiency, 0.1 (0.01) fake rates for c (light) jets



This is a important discriminator to distinguish EW from QCD multi-jet production

Scattered quark is more forward in signal



Lagrangian with generic HHH coupling. Implementing into Feynrules with MG5

M.Kumar, R.Islam

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i C_i \mathcal{O}_i^{(6)} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SILH} \tag{2.5}$$

where

$$\begin{aligned}
\mathcal{L}_{\rm SILH} =& \frac{C_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{C_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{C_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\
& - \left[\frac{C_u}{v^2} y_u (\Phi^\dagger\Phi)\Phi^\dagger \cdot \bar{Q}_L u_R + \frac{C_d}{v^2} y_d (\Phi^\dagger\Phi)\Phi\bar{Q}_L d_R + \frac{C_l}{v^2} y_l (\Phi^\dagger\Phi)\Phi\bar{L}_L l_R + \text{h.c.}\right] \\
& + \frac{igC_W}{m_W^2}[\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi] D^\nu W^k_{\mu\nu} + \frac{ig'C_B}{2m_W^2}[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi] D^\nu B_{\mu\nu} \\
& + \frac{2igC_{HW}}{m_W^2}[(D^\mu\Phi)^\dagger T_{2k}(D^\nu\Phi)]W^k_{\mu\nu} + \frac{ig'C_{HB}}{m_W^2}[(D^\mu\Phi)^\dagger(D^\nu\Phi)]B_{\mu\nu} \\
& + \frac{g'^2 C_\gamma}{m_W^2}(\Phi^\dagger\Phi)B^{\mu\nu}B_{\mu\nu} + \frac{g_S^2 C_g}{m_W^2}(\Phi^\dagger\Phi)G^{a\mu\nu}G^a_{\mu\nu}
\end{aligned} \tag{2.6}$$

In Eq. (2.6), we have used the following notations:

$$\Phi^\dagger \overleftrightarrow{D}^\mu \Phi = \Phi^\dagger(D^\mu\Phi) - (D^\mu\Phi)^\dagger\Phi, \tag{2.7}$$

$$Q_L \cdot \Phi = \epsilon_{ij} Q_L^i \Phi^j, \qquad \Phi^\dagger \cdot \bar{Q}_L = \epsilon^{ij}\Phi_i^\dagger \bar{Q}_{Lj}. \tag{2.8}$$

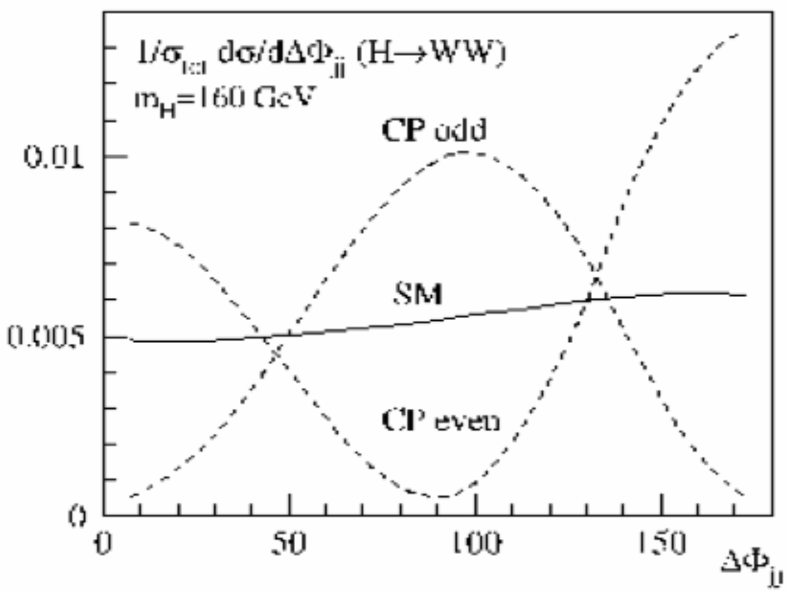
Outlook and Conclusions

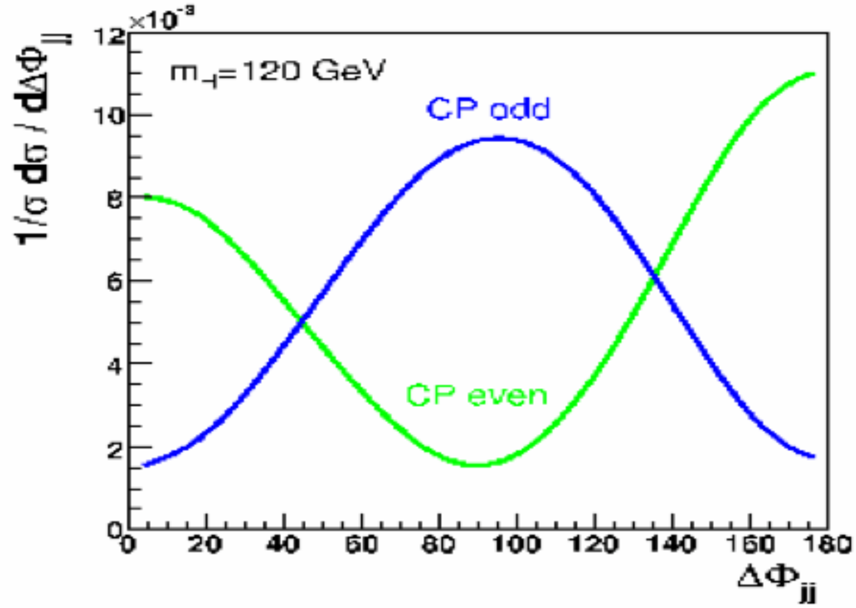
- LHeC displays strong complementarities with the LHC/e^+e^- with regards to Higgs physics
- Forward jet tagging secures the feasibility of the Higgs search in CC and NC in ep collisions
- With the isolation of the $H \to bb$ signal at the LHeC a window of opportunity opens for the exploration of the CP properties of the HWW and HZZ vertexes
  - The latter is a unique feature of the ep collider absent in pp/e^+e^- collisions
- Exploring high lumi scenarios → Higgs factory
- The LHeC removes the PDF/QCD uncertainties for pp: LHeC becomes precision Higgs facility
- Exploring double Higgs production in the contex of FCC. Promissing results at parton level to be evaluated at hadron level

Additional Slides

Study by Zeppenfeld et al:

Study in pp collisions





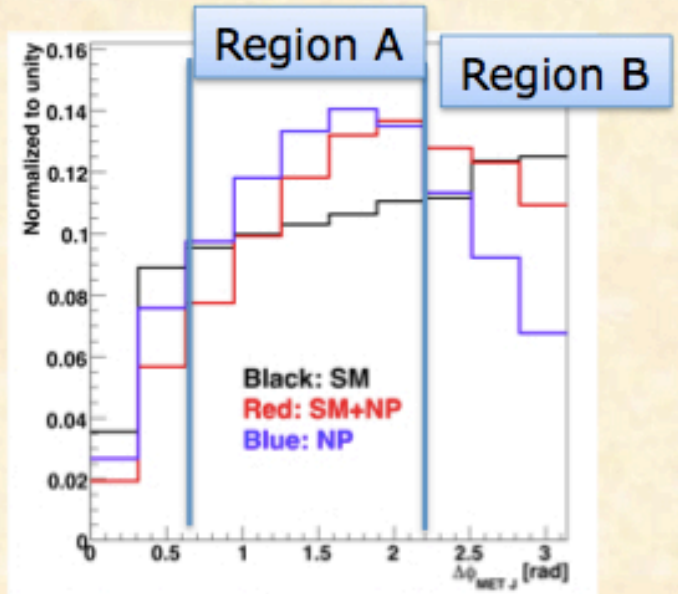
Left plot: VBF, CP even and CP odd refer to the dimension 5 operator.

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

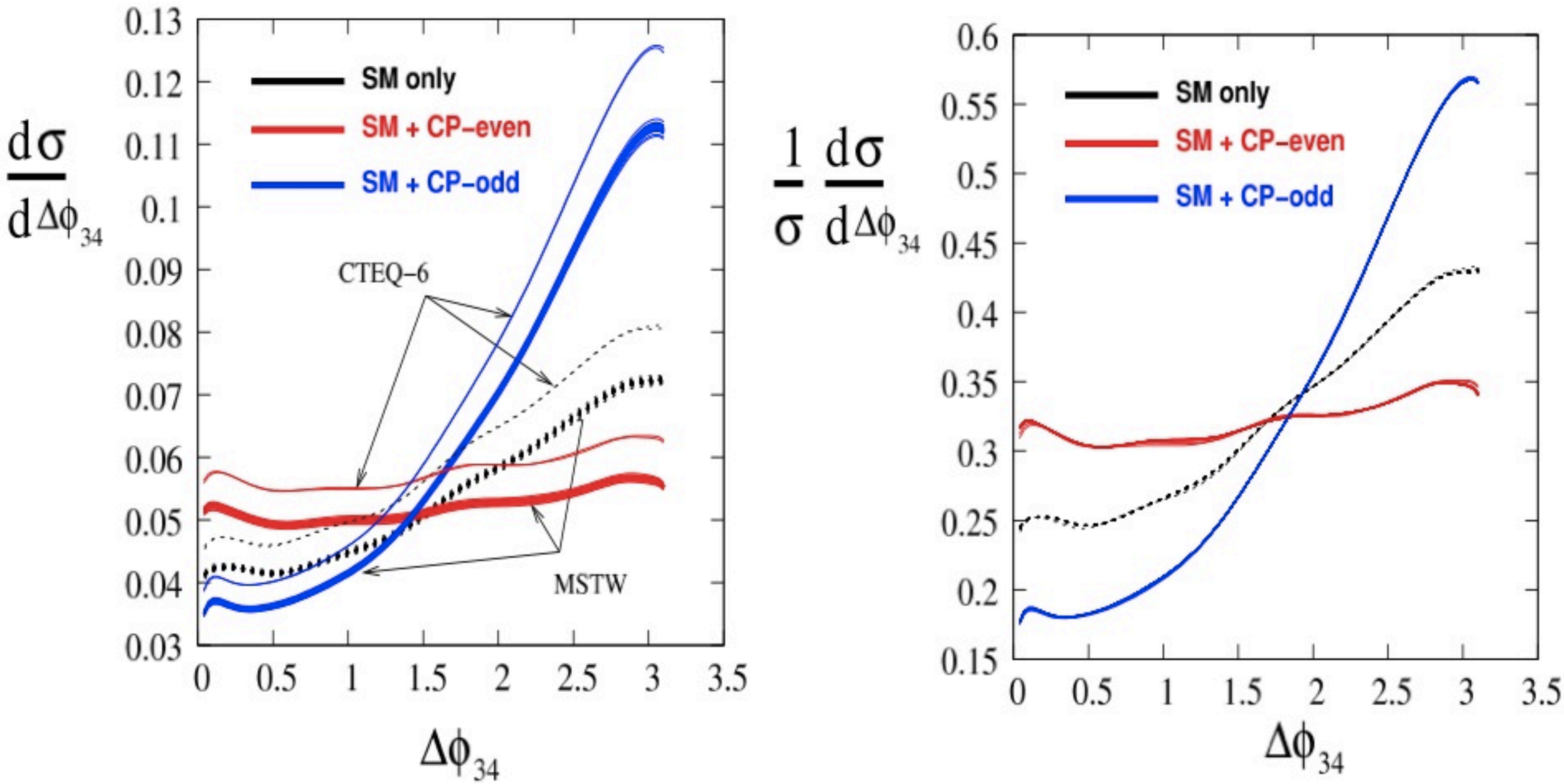
- Measure deviation of the Higgs production with respect to the SM using the absolute rate of events
- The ratio of the number of events in region B to that of region A in the $\Delta\varphi_{MET,J}$ spectrum

CP-odd case

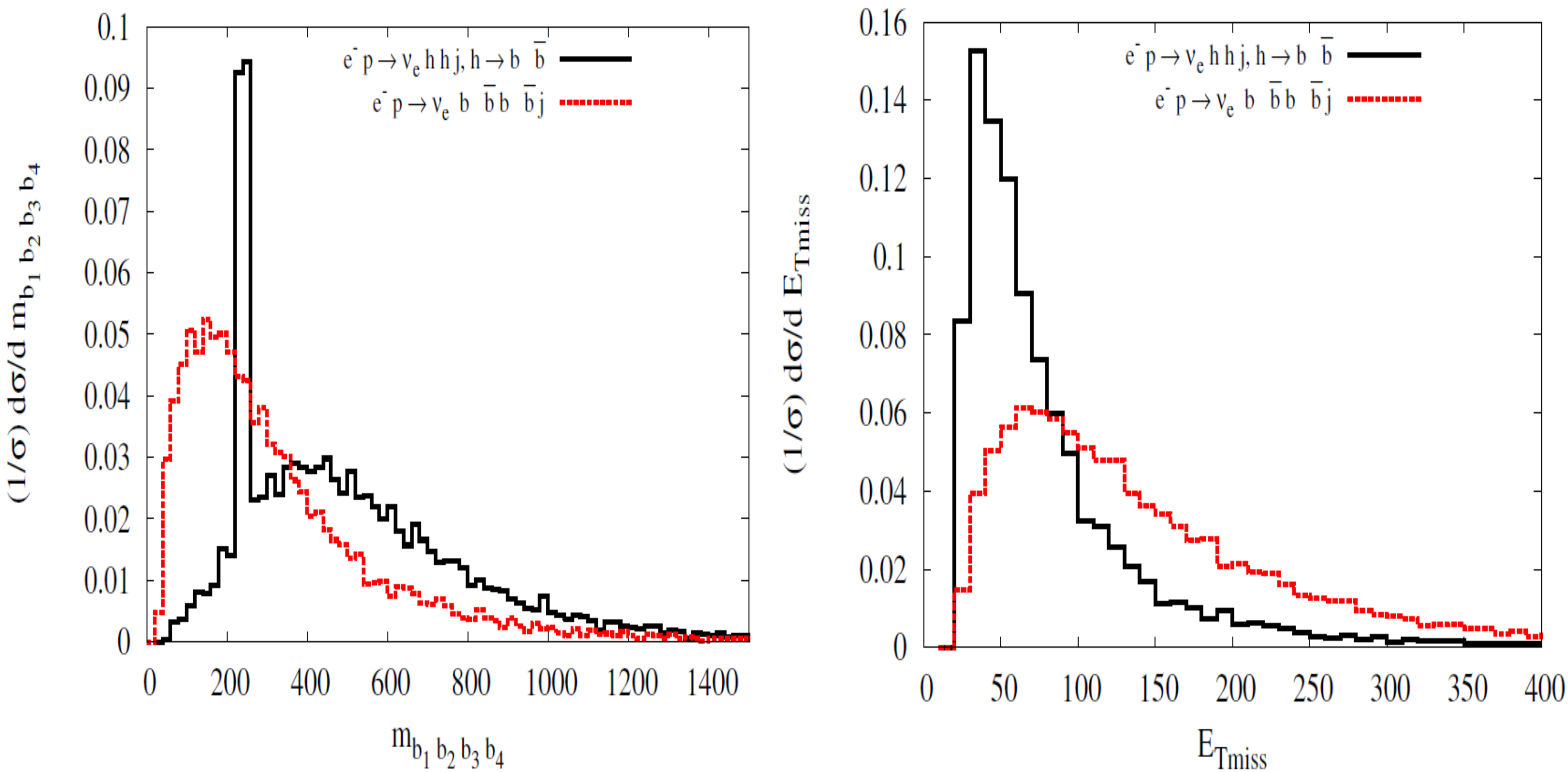


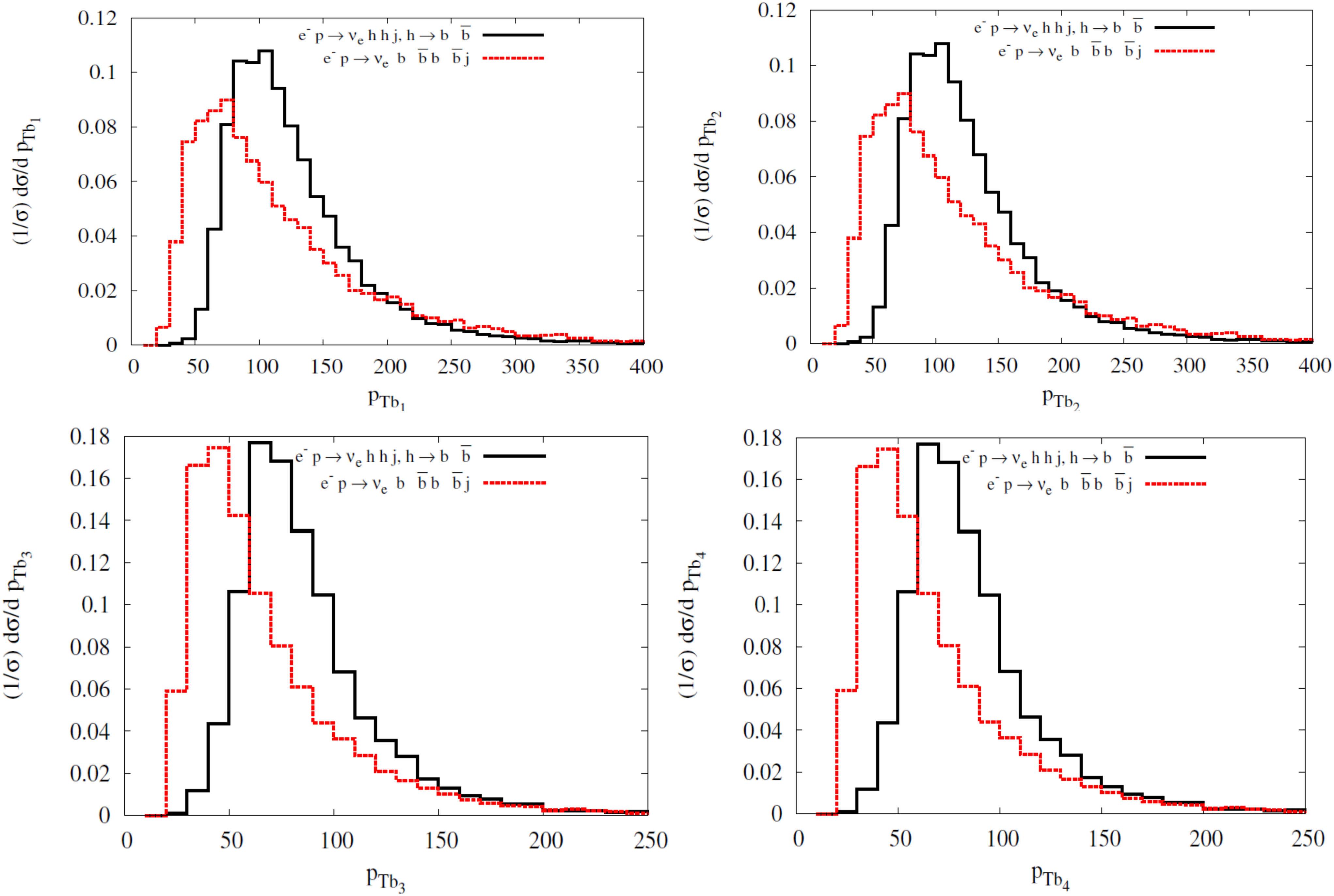
- Assume Gaussian errors and the following systematics:
  - 10% on the background rate
  - 5% on the shape of the $\Delta\varphi_{MET,J}$ in background
  - 5% on the rate of the SM Higgs
  - Evaluating theoretical error on $\Delta\varphi_{MET,J}$ shape

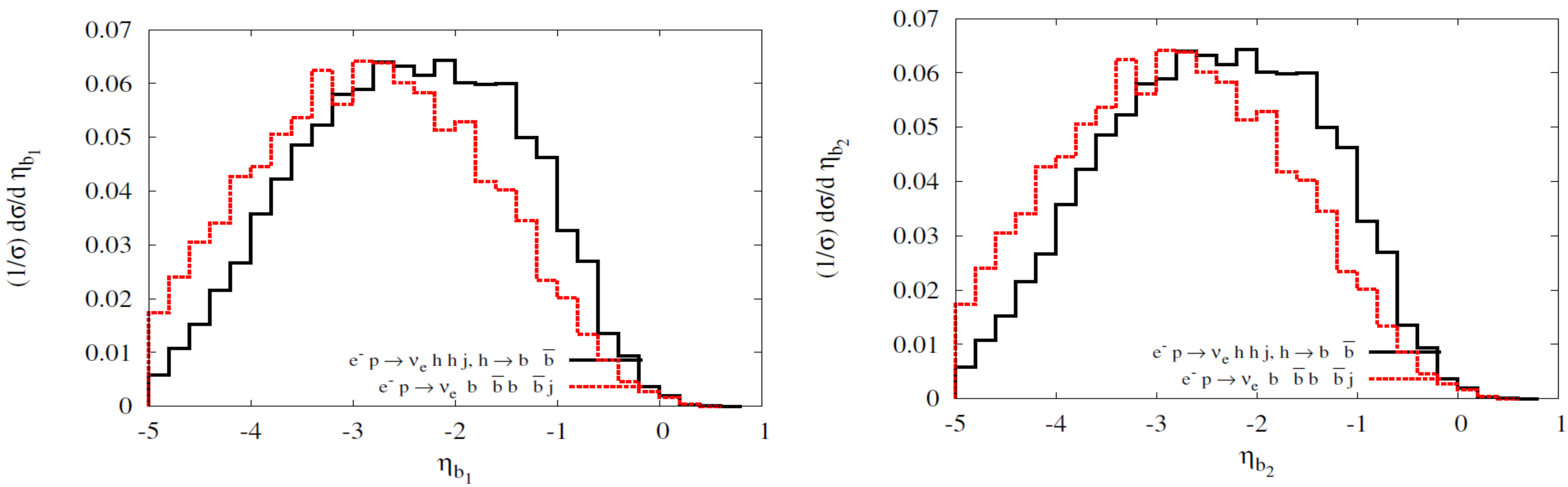
Effect of PDF uncertainties and pdf choice



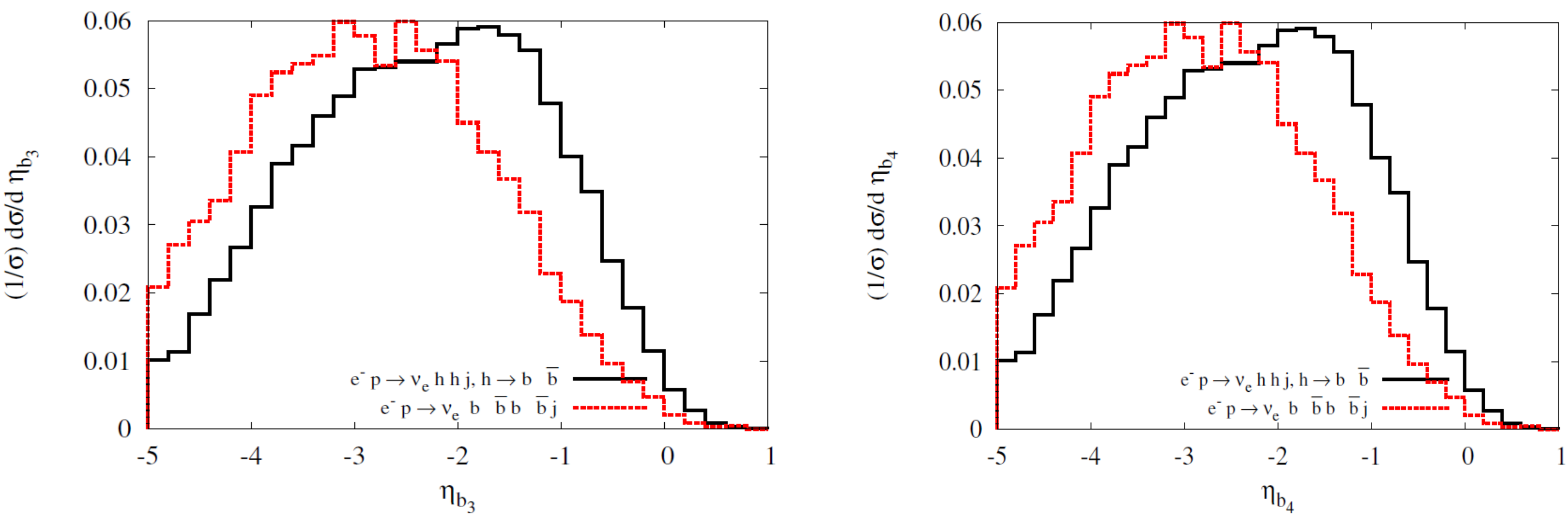
Kinematic Distributions (Ee = 60 GeV)

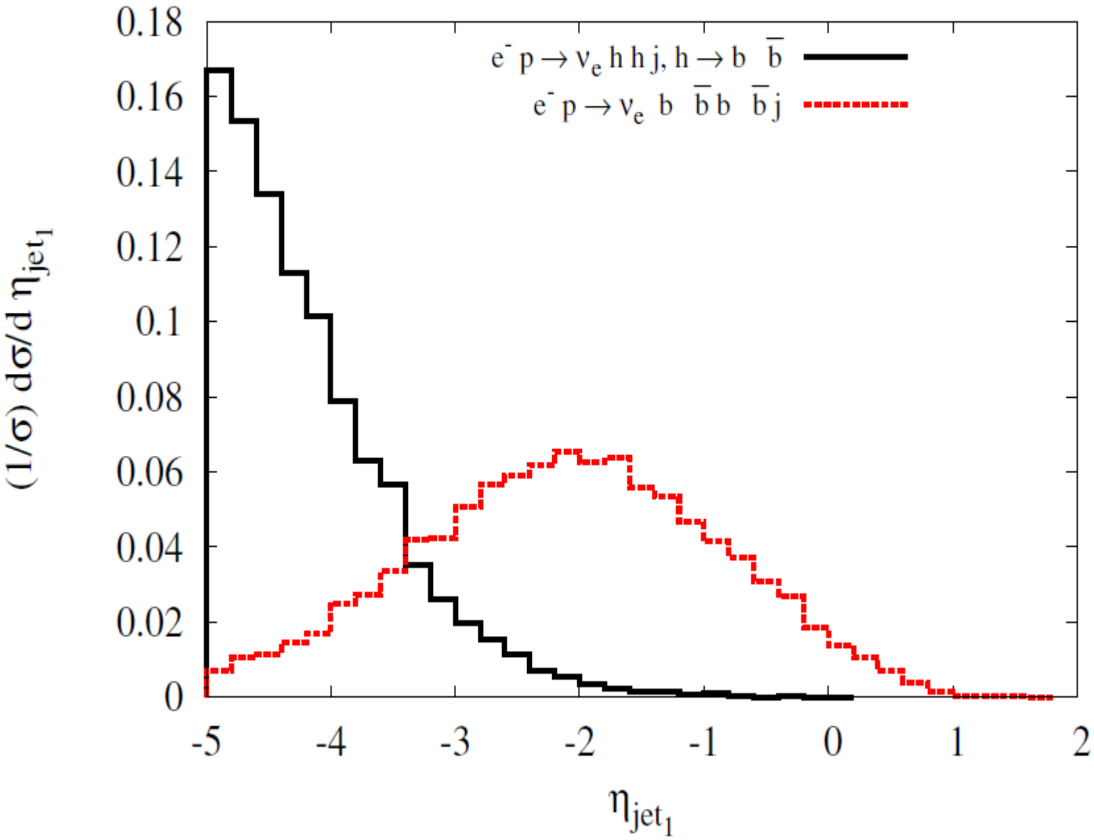



$e^- p \to \nu_e h h j, h \to b \bar{b}$
$e^- p \to \nu_e b \bar{b} b \bar{b} j$
$(1/\sigma)\, d\sigma/d\, p_{Tb_1}$
p_{Tb_1}
$(1/\sigma)\, d\sigma/d\, p_{Tb_2}$
p_{Tb_2}
$(1/\sigma)\, d\sigma/d\, p_{Tb_3}$
p_{Tb_3}
$(1/\sigma)\, d\sigma/d\, p_{Tb_4}$
p_{Tb_4}



Despite large beam energy imbalance, jets are relatively central





This is a important discriminator to distinguish EW from QCD multi-jet production

Scattered quark is more forward in signal