Higgs Physics at the LHeC

LHeC, a Higgs Factory

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On behalf of the LHeC Study Group

EU-Italy-Russia@Dubna Round Table, 04/03/14

ISSN 0954-3899

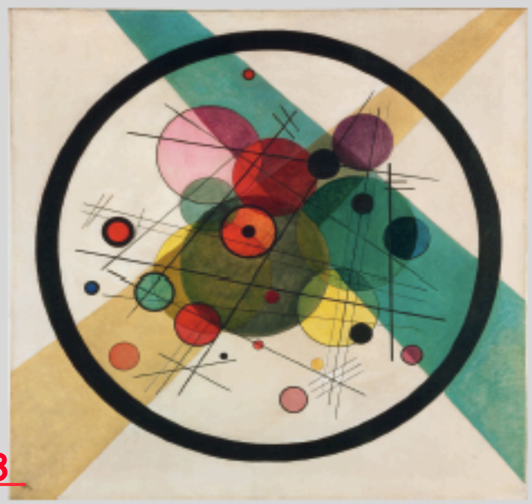
Journal of Physics G
Nuclear and Particle Physics

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

Journal of Physics G Nuclear and Particle Physics Vol 39, No7 075001 July 2012

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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

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

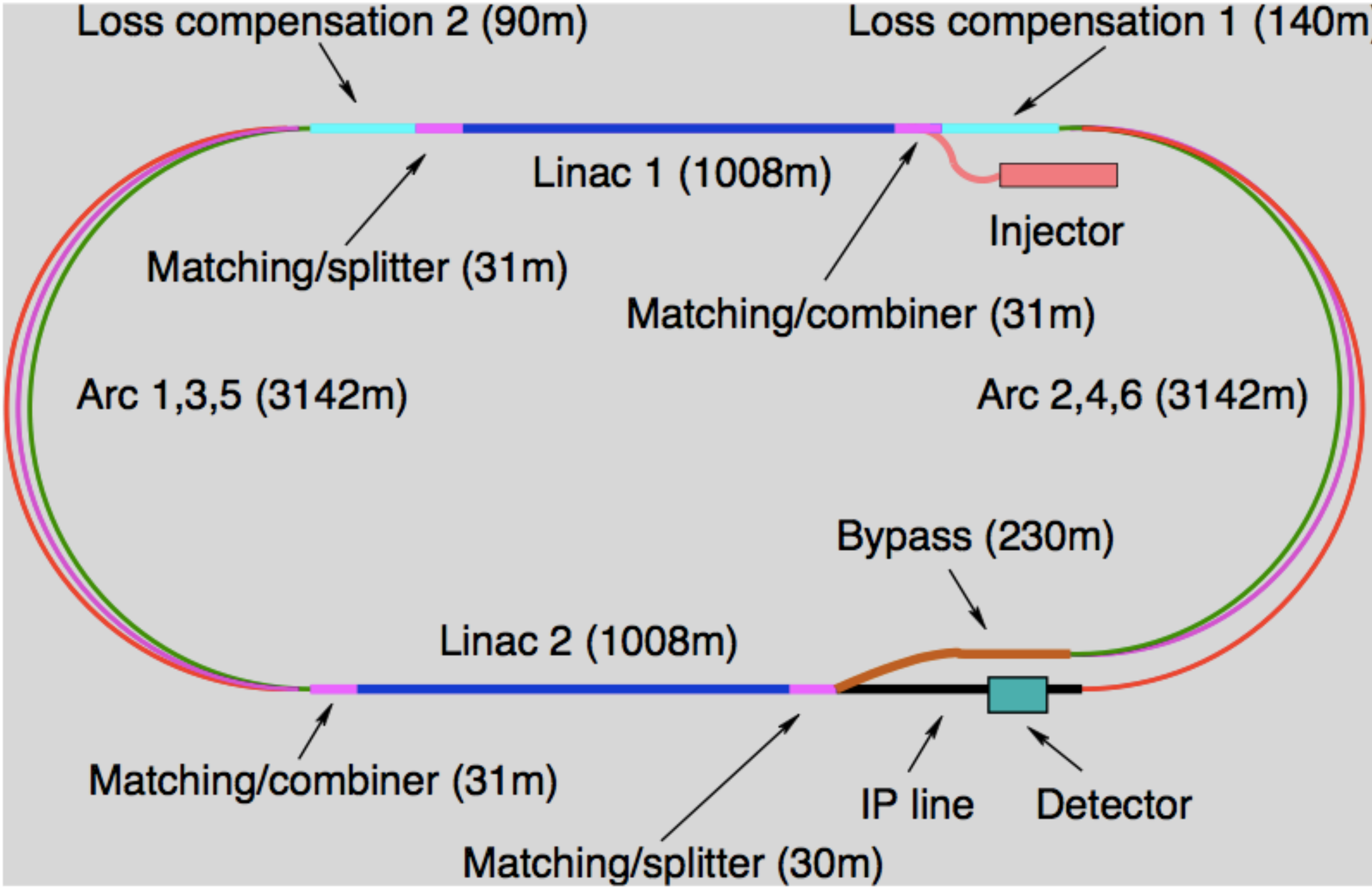
QCD Discoveries	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$
Higgs	WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate
Substructure	electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H?
New and BSM Physics	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…

CDR: Physics, Accelerator, Detector

M.Klein



JPhysG:39(2012)075001, arXiv:1206.2913 http://cern.ch/lhec

CDR: default design. 60 GeV. $L=10^{33}cm^{-2}s^{-1}$, P< 100 MW → ERL, synchronous ep/pp

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

(parameters in parenthesis) Turn the LHeC into a Higgs factory

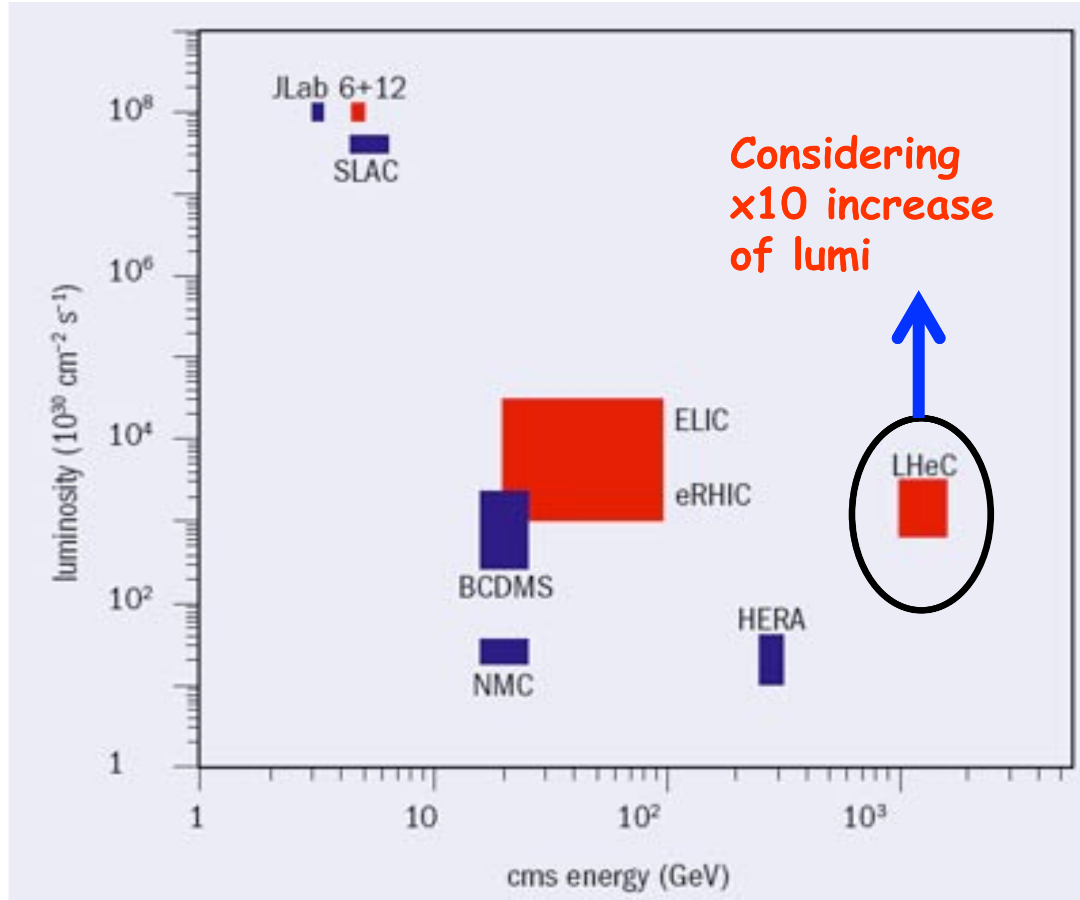
parameter [unit]	LHeC	
species	e^-	p, $^{208}\mathrm{Pb}^{82+}$
beam energy (/nucleon) [GeV]	60	7000, 2760
bunch spacing [ns]	25, 100	25, 100
bunch intensity (nucleon) [10^{10}]	0.1 (0.2), 0.4	17 (22), 2.5
beam current [mA]	6.4 (12.8)	860 (1110), 6
rms bunch length [mm]	0.6	75.5
polarization [%]	90	none, 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

Some LHeC Context

The LHeC is not the first proposal for TeV scale DIS, but it is the first with the potential for significantly higher luminosity than HERA …



DESY 06-006
Cockcroft-06-05

Deep Inelastic Electron-Nucleon Scattering at the LHC*

J. B. Dainton[1], M. Klein[2], P. Newman[3], E. Perez[4], F. Willeke[2]

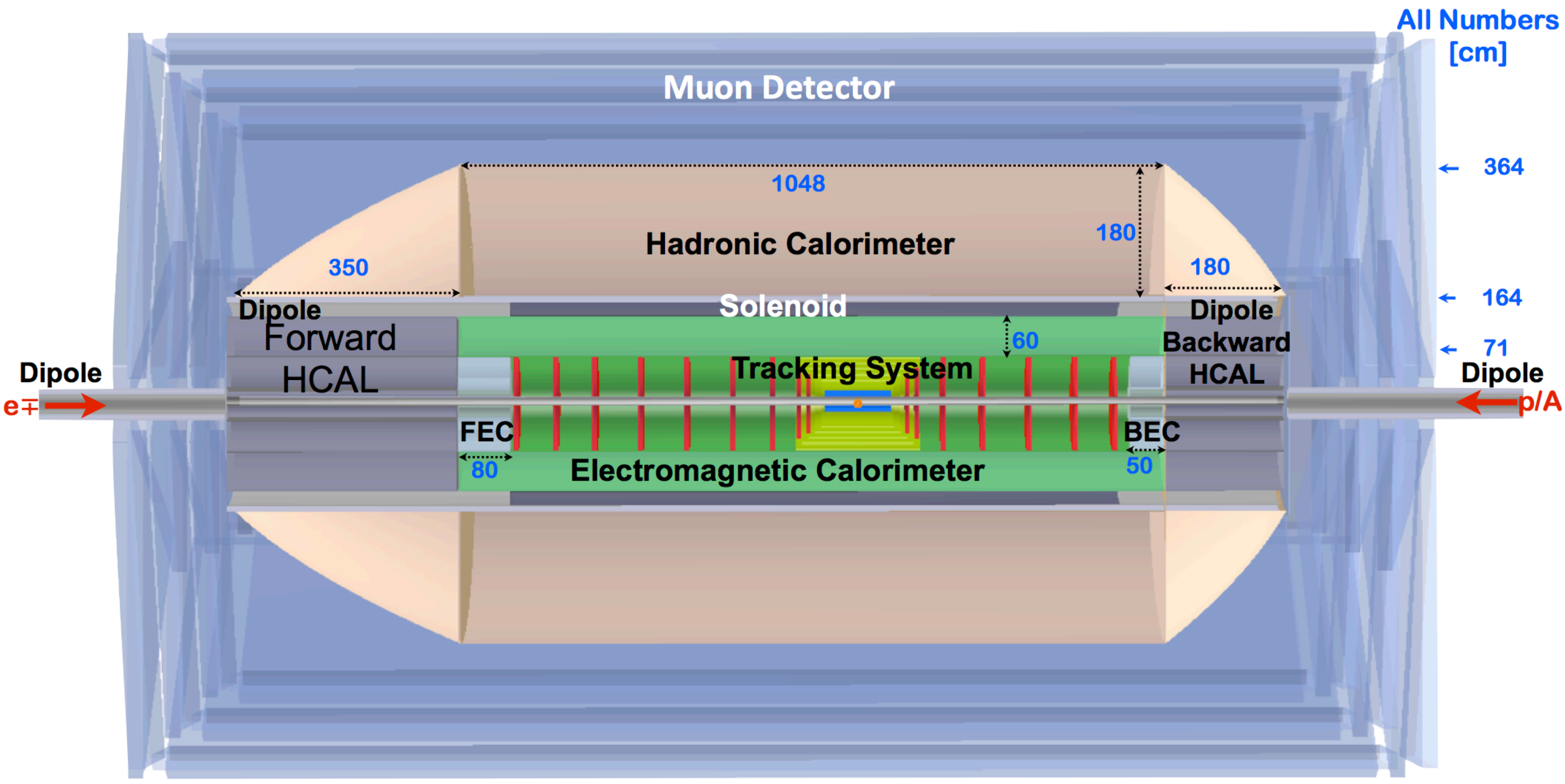
[1] Cockcroft Institute of Accelerator Science and Technology, Daresbury International Science Park, UK
[2] DESY, Hamburg and Zeuthen, Germany
[3] School of Physics and Astronomy, University of Birmingham, UK
[4] CE Saclay, DSM/DAPNIA/Spp, Gif-sur-Yvette, France

… achievable with a new electron accelerator at the LHC …

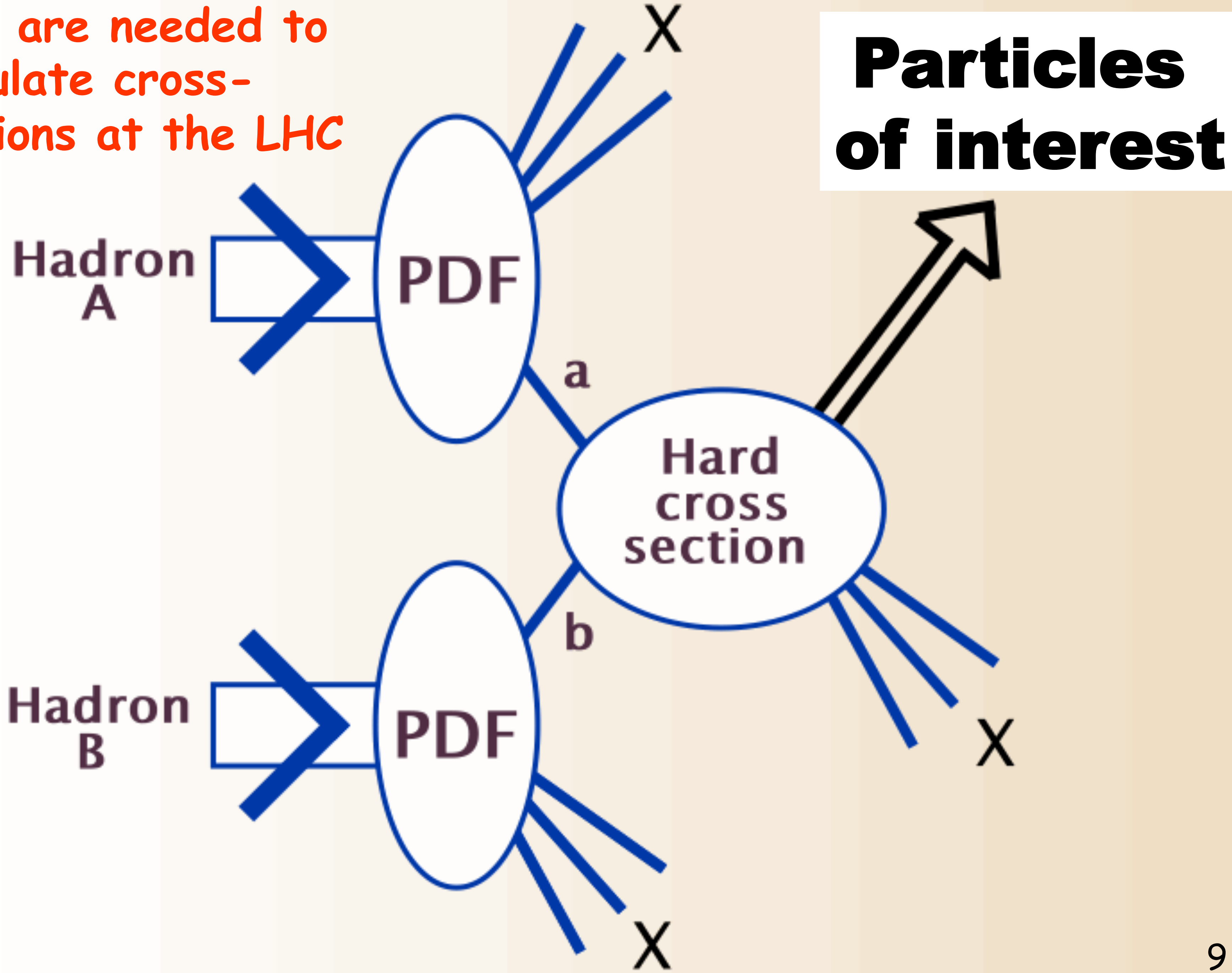
[JINST 1 (2006) P10001]

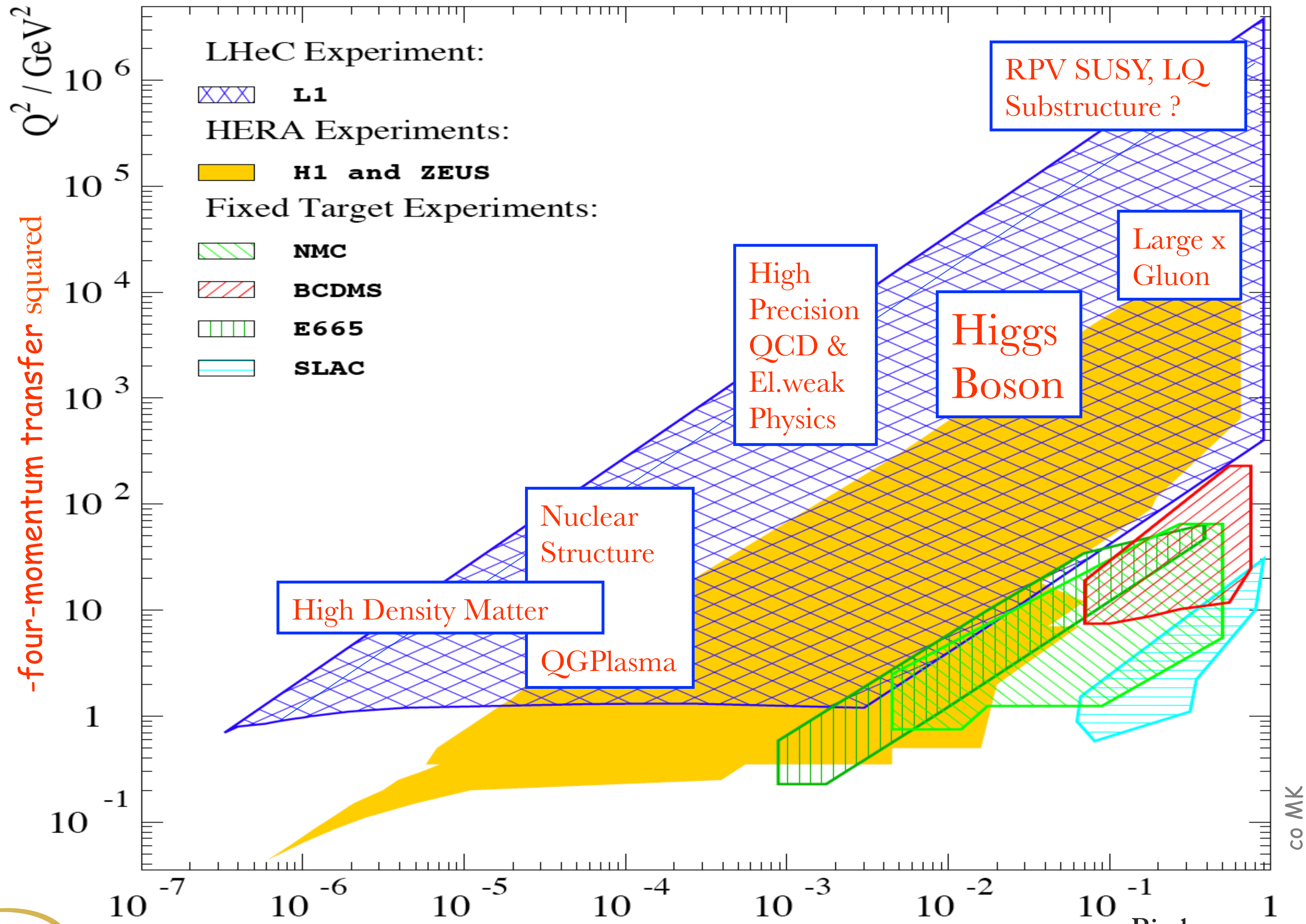
The LHeC Detector

P. Kostka



Pdfs are needed to calculate cross-sections at the LHC

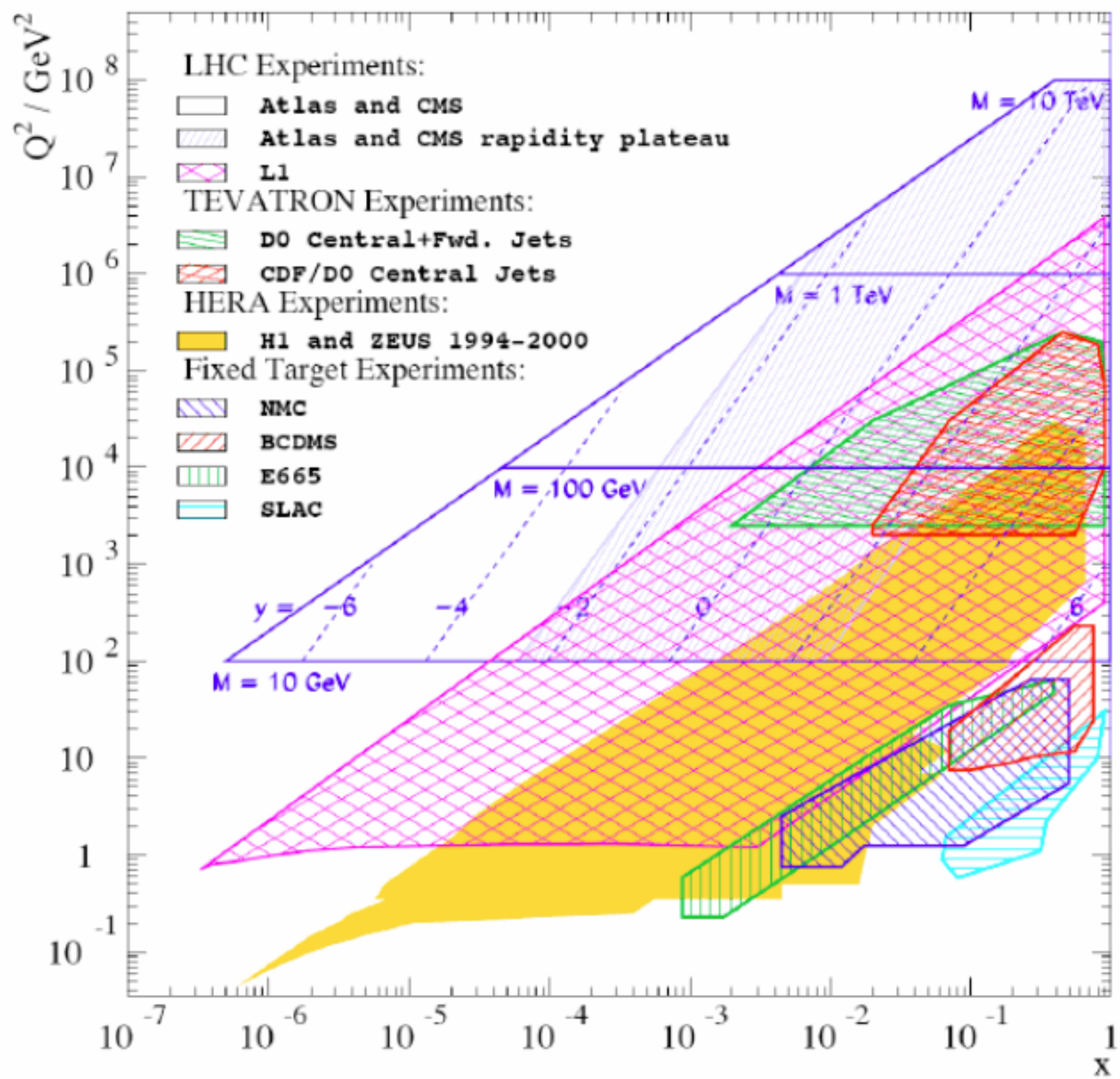




LHeC Experiment:
L1
HERA Experiments:
H1 and ZEUS
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
RPV SUSY, LQ
Substructure ?
Large x
Gluon
High
Precision
QCD &
El.weak
Physics
Higgs
Boson
Nuclear
Structure
High Density Matter
QGPlasma
Q^2 / GeV^2
-four-momentum transfer squared
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1
Bjorken x
10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6
co MK
LHeC

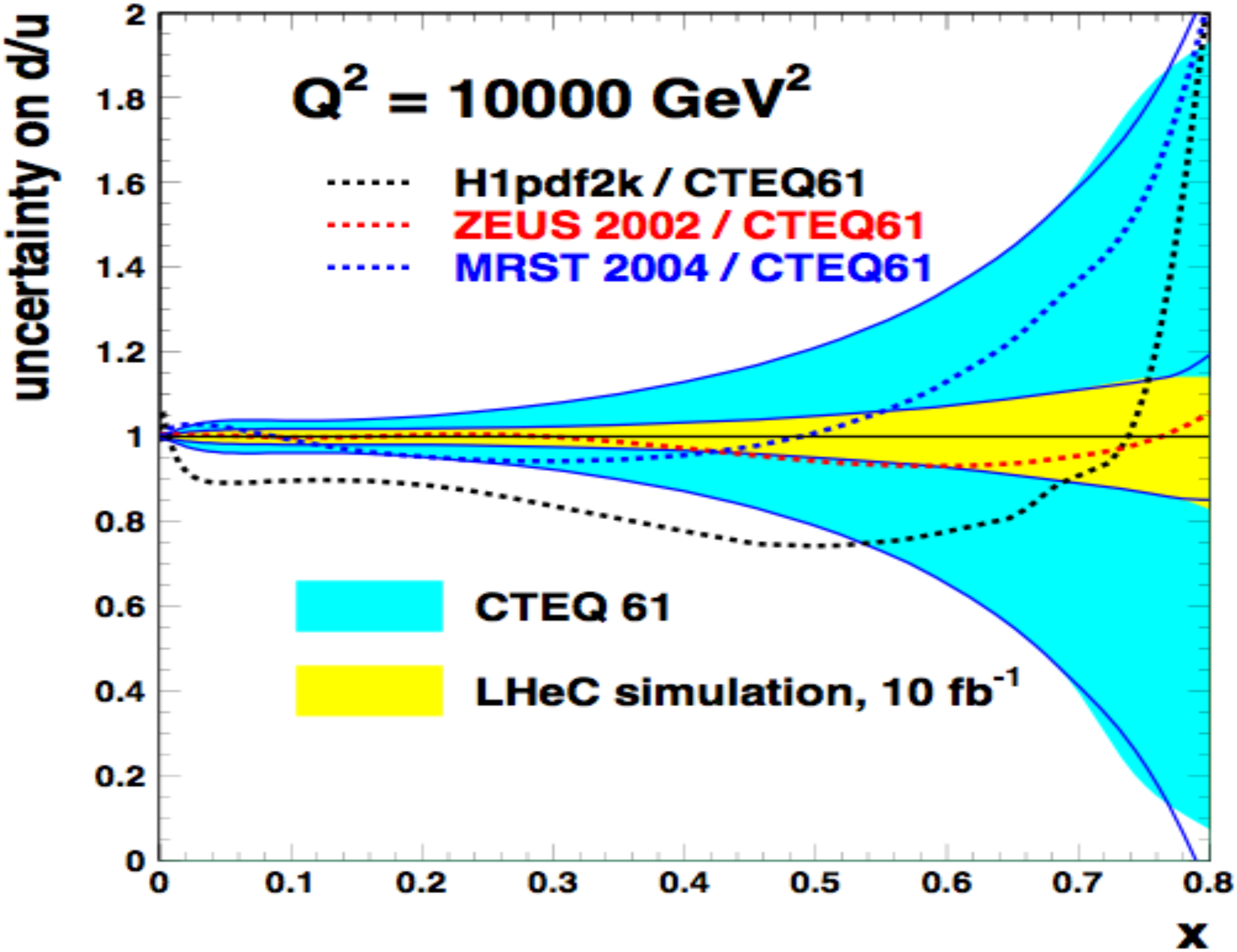
LHeC Kinematics and the LHC

Extension of parton density measurements at the LHeC very important for upgraded LHC



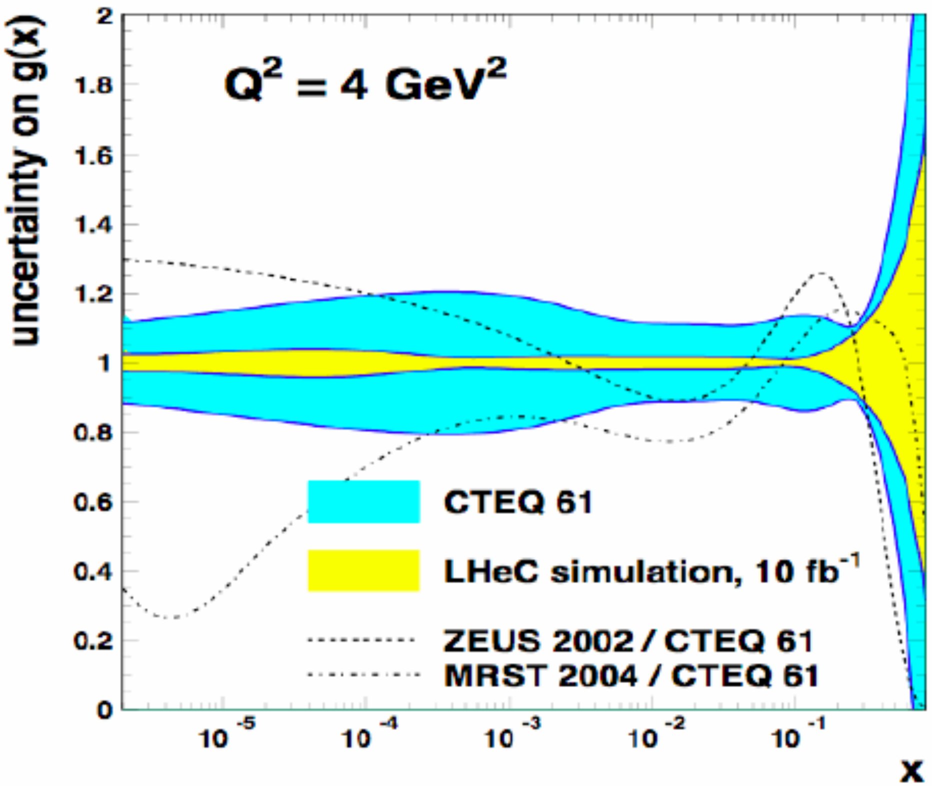
Luminosity

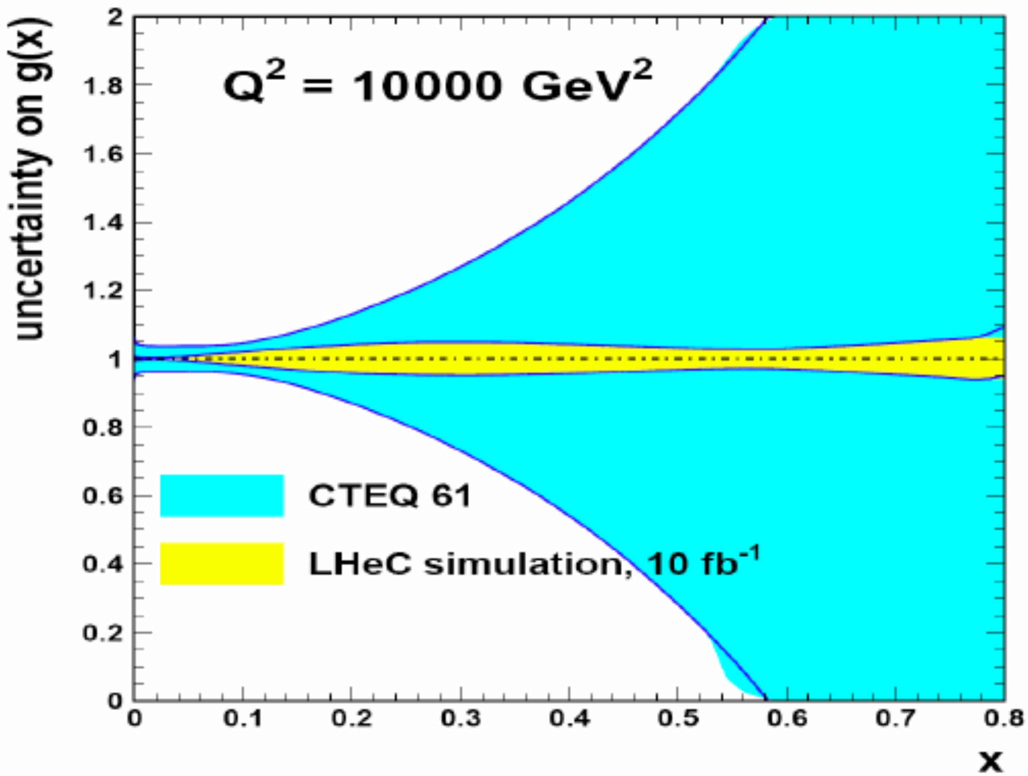
d/u at large x



Lead motivation for a LHeC: pdfs at high x for discovery physics

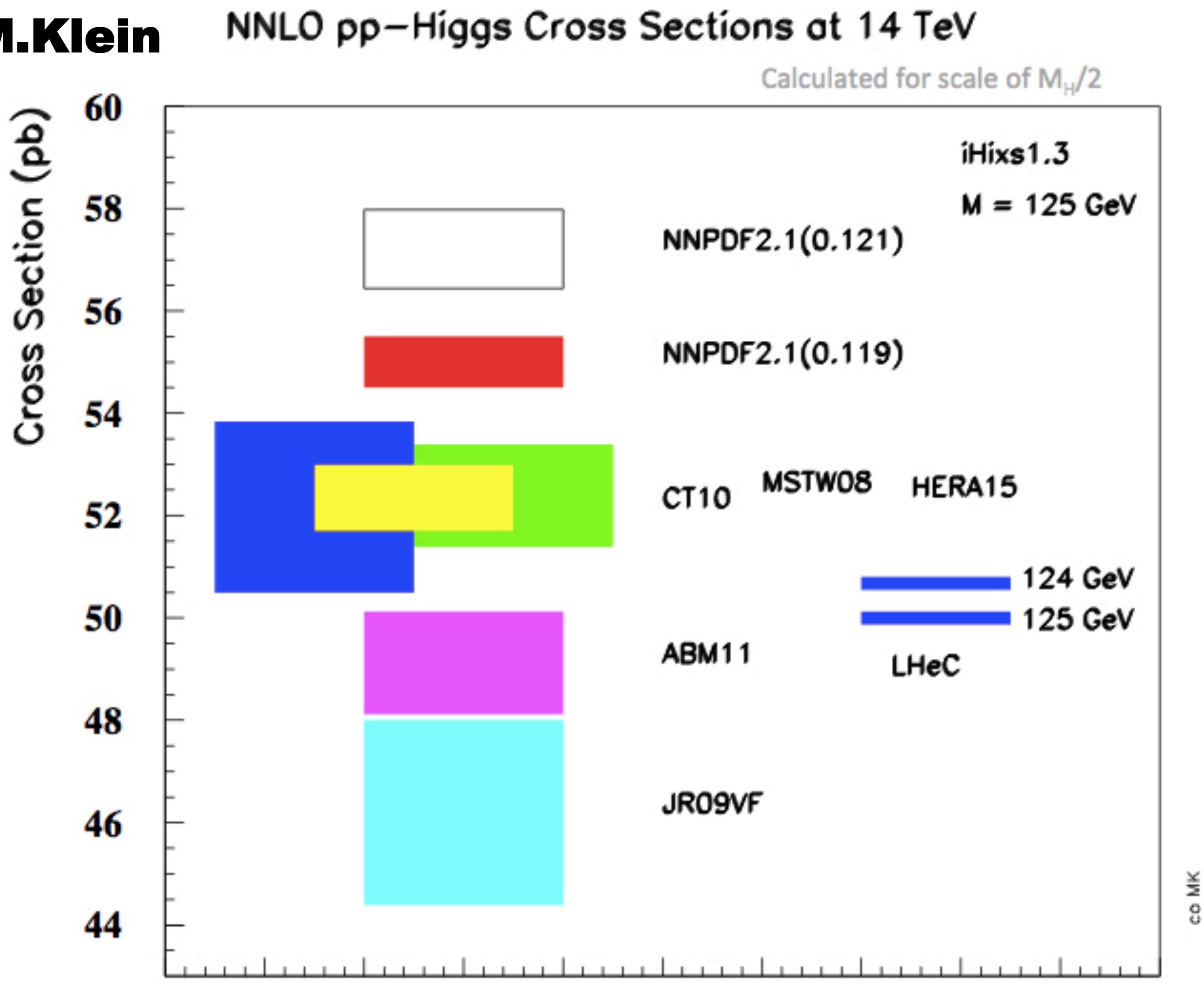
Gluon Density Distribution





Spectacular increase in the precision of gluon density function at high x. This is important for discovery physics at the LHC

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^3LO

HQ treatment important

PRECISION σ(H)

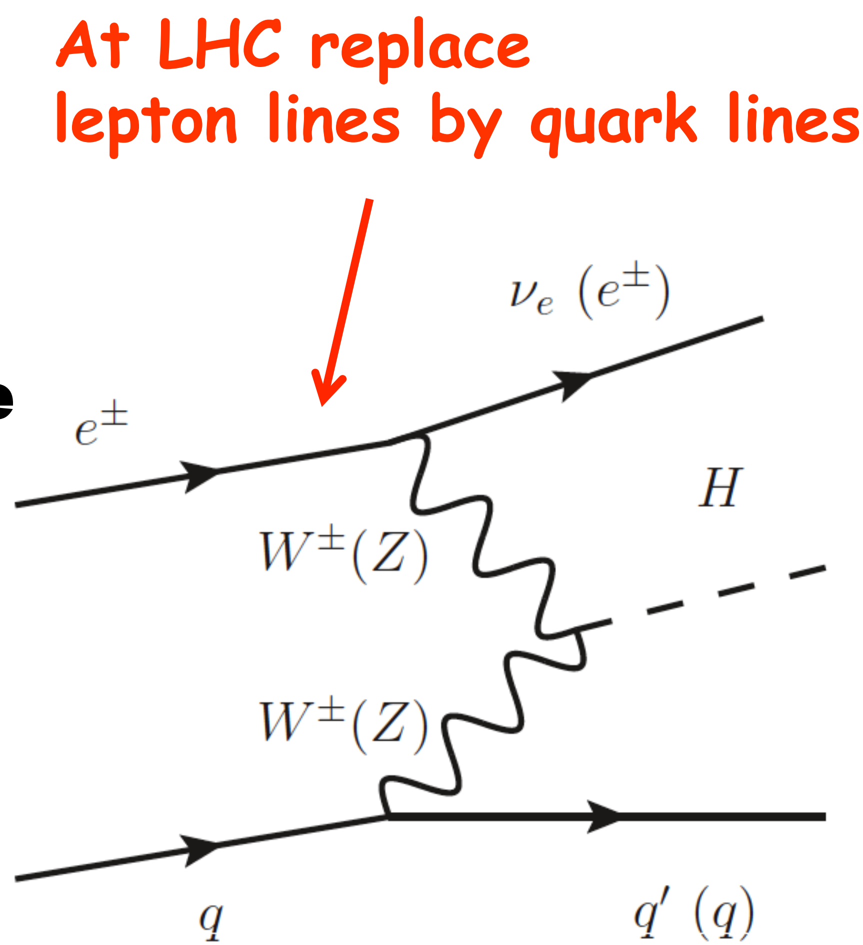
Higgs production (gg) at the LHC is $\propto \alpha_s^2(M_H^2) xG(x, M_H^2) \otimes xG(x, M_H^2)$

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

Higgs at LHeC

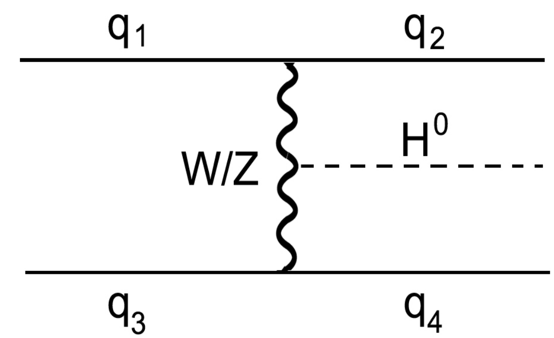
- It is remarkable that VBF diagrams were calculated for lepton nucleon collisions before for pp!

- Consider feasibility for the following point:



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

Higgs via VBF
Qualitative remarks



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

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

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

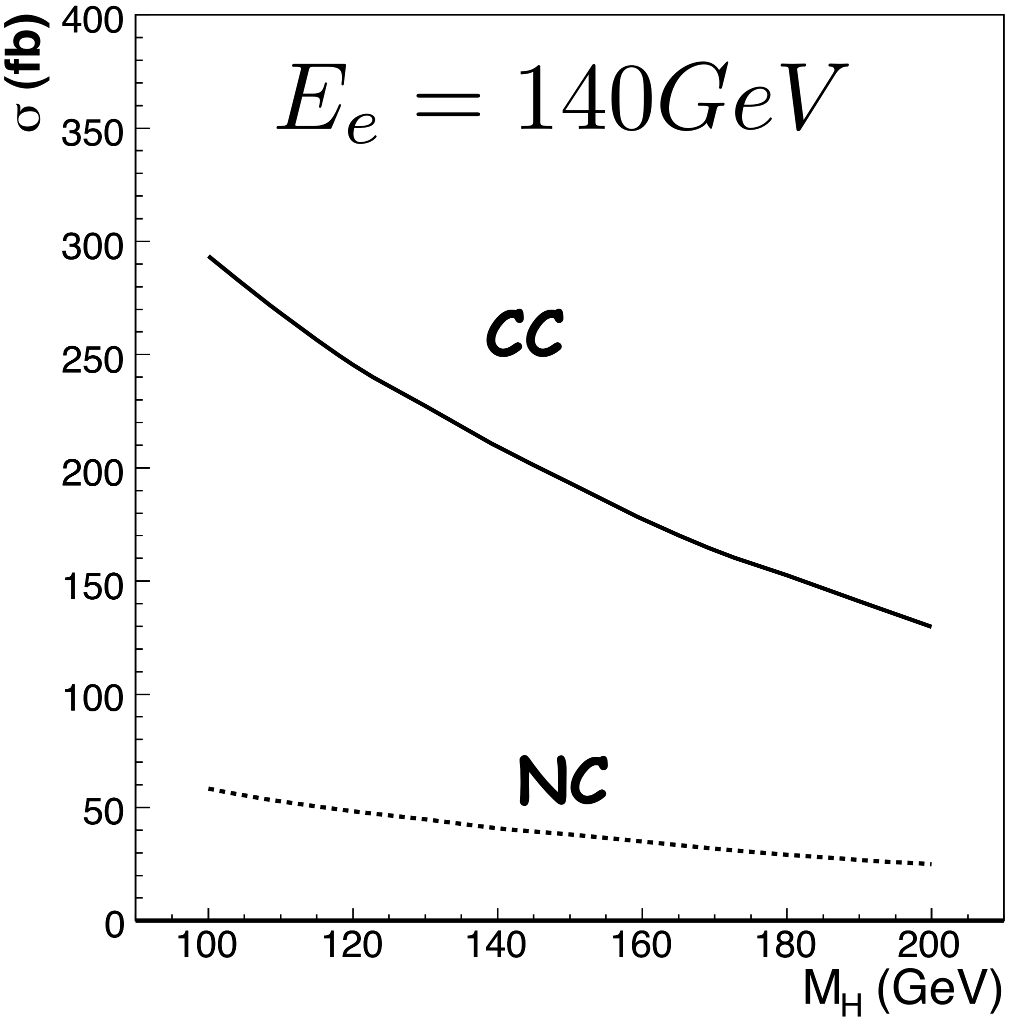
- **Unlike QCD partons that scale like $1/P_T^2$, here $P_T \sim$ sqrt(1-x)M_W**

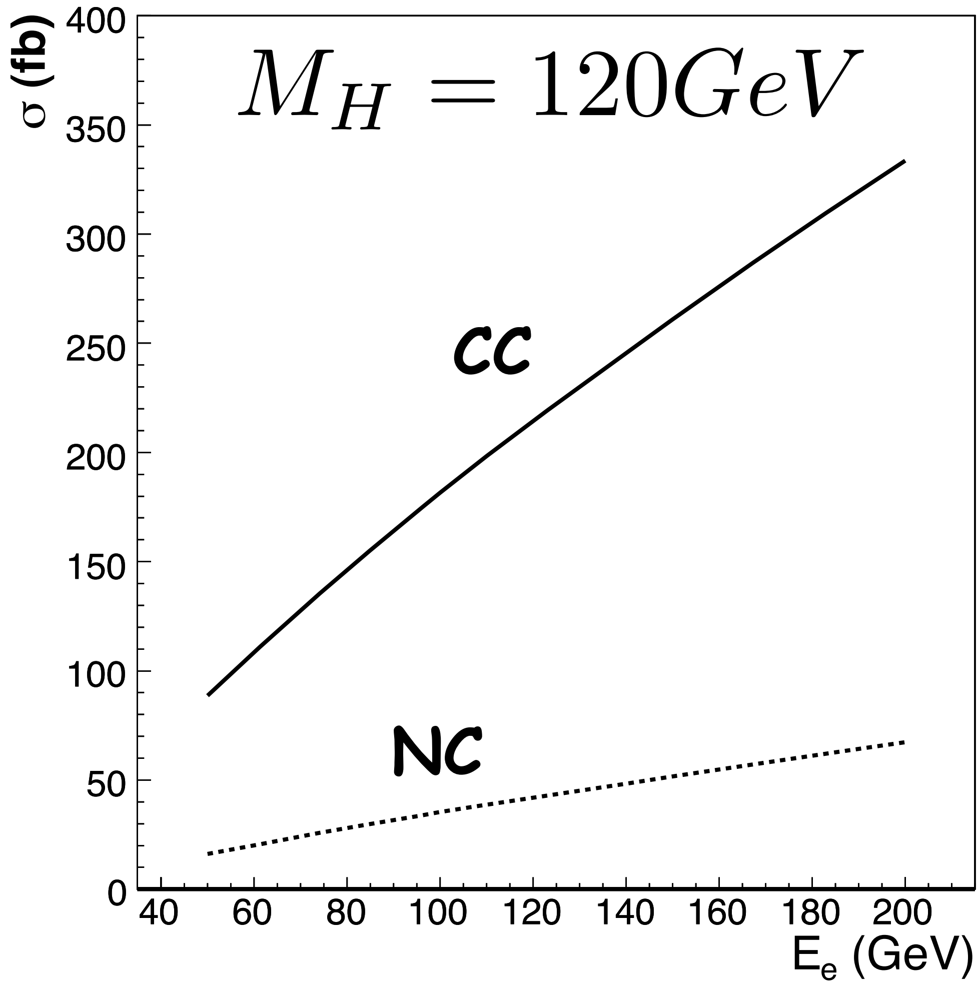
- **Due to the 1/x behavior of the Weak boson the outgoing parton energy (1-x)E is large → forward jets**
- **At high P_T** $P^T_{V/f} \sim 1/p_T^2$ and $P^L_{V/f} \sim 1/p_T^4$.

- **Contribution from longitudinally polarized Weak Bosons is suppressed in favor of transversely polarized WB at high p_T**

Cross-Sections

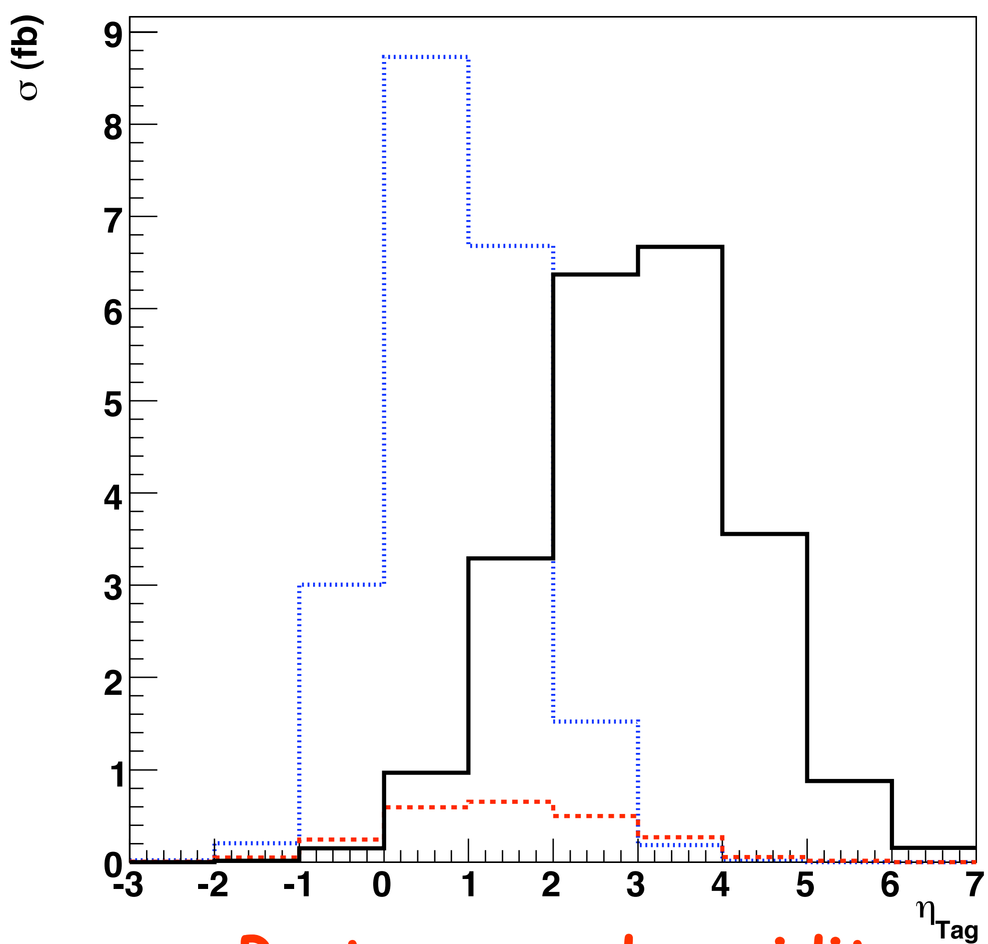
- Used Madgraph and CTEQ6L for $e^- p$ scattering
  - Set scales to M_H. Little scale dependence



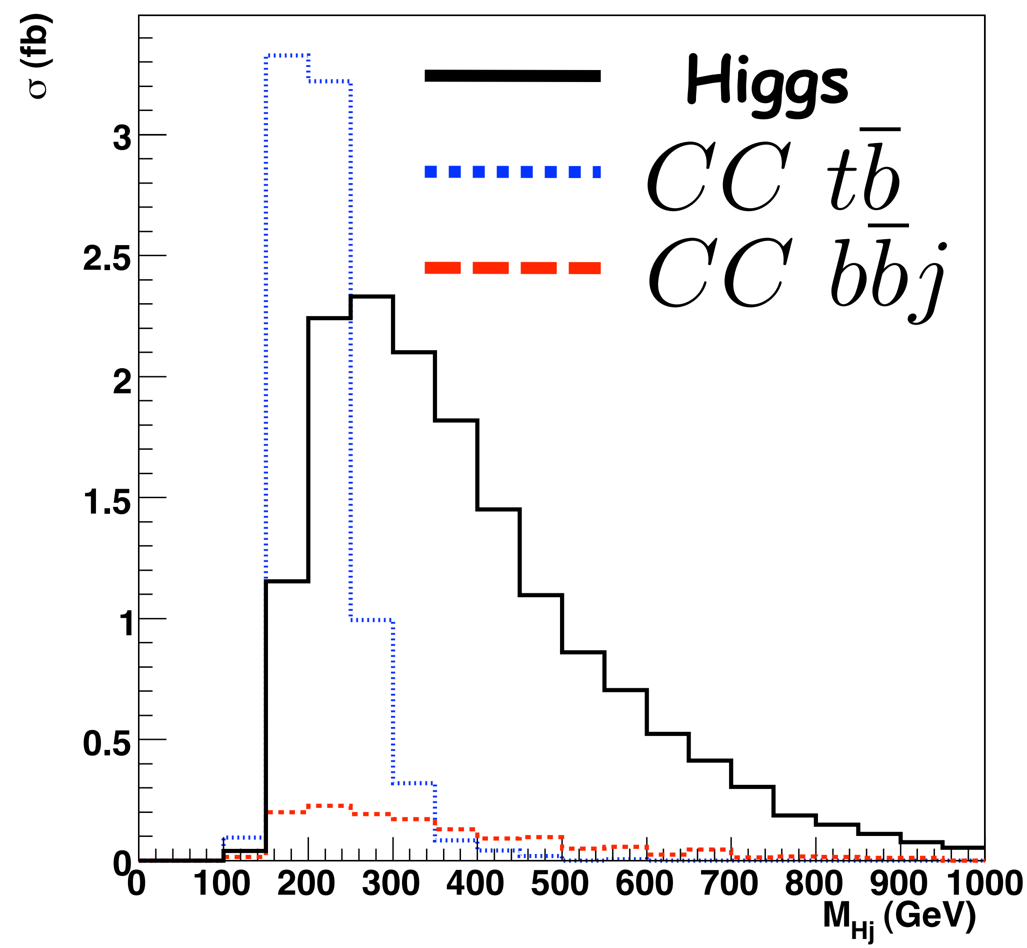


Charge Current Analysis

T.Han & BM Phys.Rev.D82:016009,2010.



Parton pseudorapidity



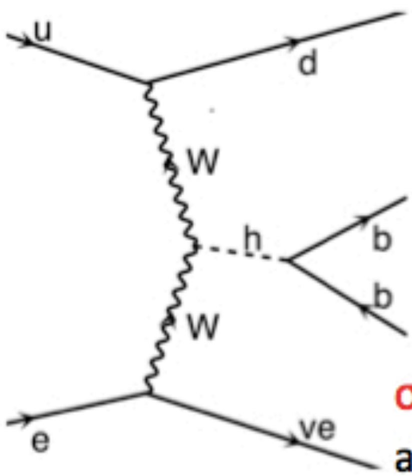
Higgs-Parton Mass

MC Samples in Hadron-level study

U.Klein et al.

Signal

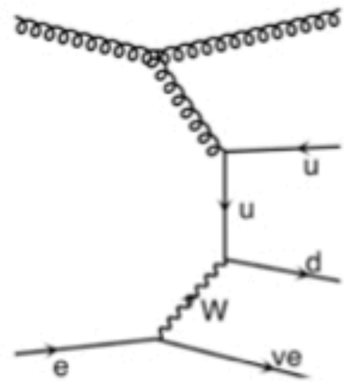
CC: $H \rightarrow b\bar{b}$ (BR ~ 0.7 at M_H=120GeV)



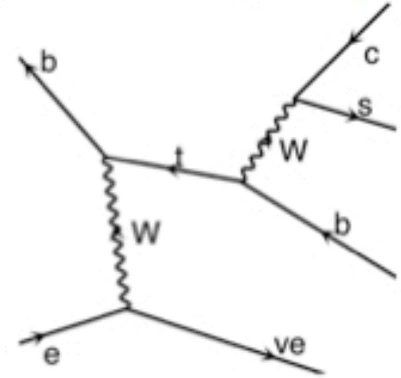
σ~ 0.16 pb
at √s=2.05TeV

Background (examples)

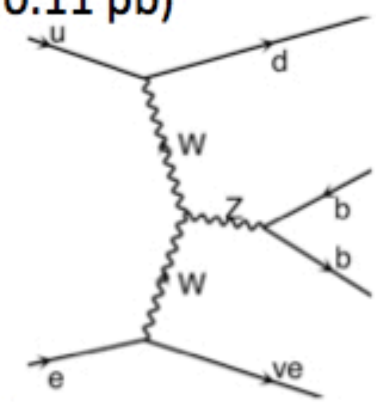
CC: 3 jets (~57 pb)



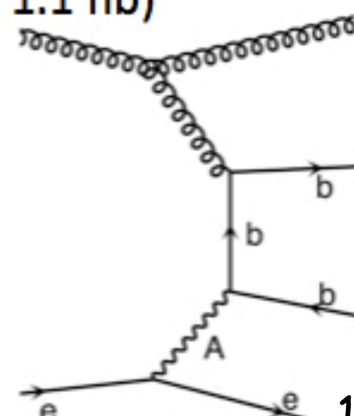
CC: single top production (~4.1 pb)



CC: Z production (~0.11 pb)



NC: b pair production (~1.1 nb)



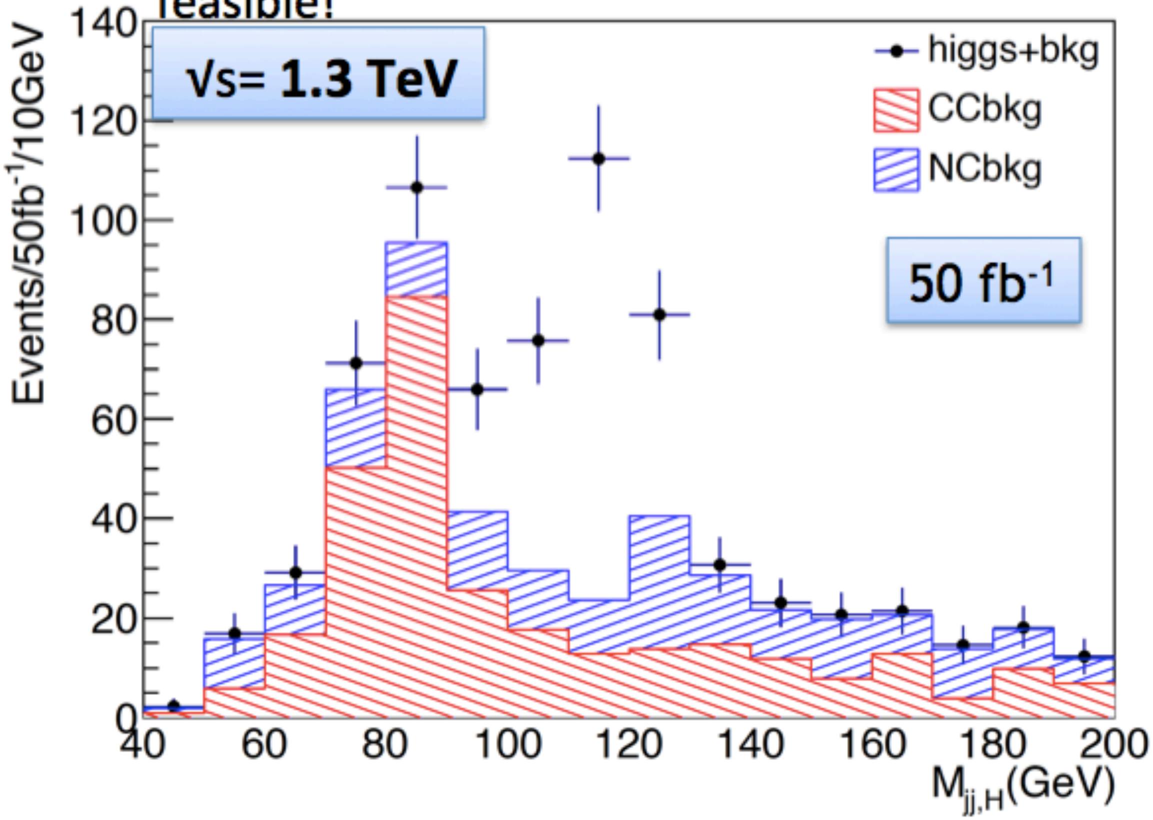
NOTE: Background sample numbers are after pre-selection in generator

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

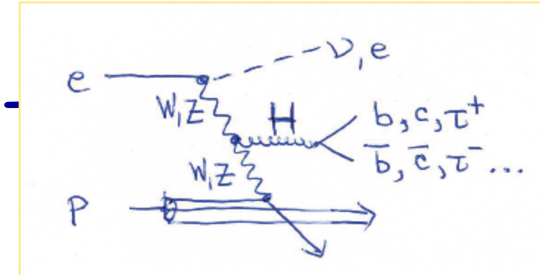


Masahiro Tanaka, BSc thesis, Tokyo Tech 2014

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.

From Higgs facility (LHeC) to Higgs ‘factory’ (FCC-



Higgs in $e^- p$		CC - LHeC	NC - LHeC	CC - FHeC
Polarisation		-0.8	-0.8	-0.8
Luminosity [ab^{-1}]		1	1	5
Cross Section [fb]		196	25	850
Decay	BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \rightarrow b\bar{b}$	0.577	113 100	13 900	2 450 000
$H \rightarrow c\bar{c}$	0.029	5 700	700	123 000
$H \rightarrow \tau^+\tau^-$	0.063	12 350	1 600	270 000
$H \rightarrow \mu\mu$	0.00022	50	5	1 000
$H \rightarrow 4l$	0.00013	30	3	550
$H \rightarrow 2l2\nu$	0.0106	2 080	250	45 000
$H \rightarrow gg$	0.086	16 850	2 050	365 000
$H \rightarrow WW$	0.215	42 100	5 150	915 000
$H \rightarrow ZZ$	0.0264	5 200	600	110 000
$H \rightarrow \gamma\gamma$	0.00228	450	60	10 000
$H \rightarrow Z\gamma$	0.00154	300	40	6 500

Cross section
1pb ep→ νHX

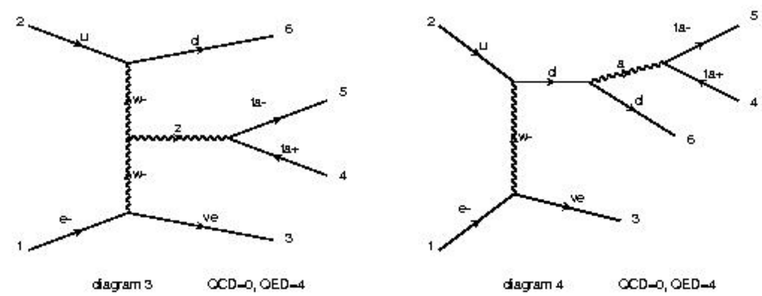
Luminosity
> 10^{34} crucial
for H → HH
0.5 fb
and rare decays

First sets of
Parameters for
LR and RR

M.Klein

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

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)

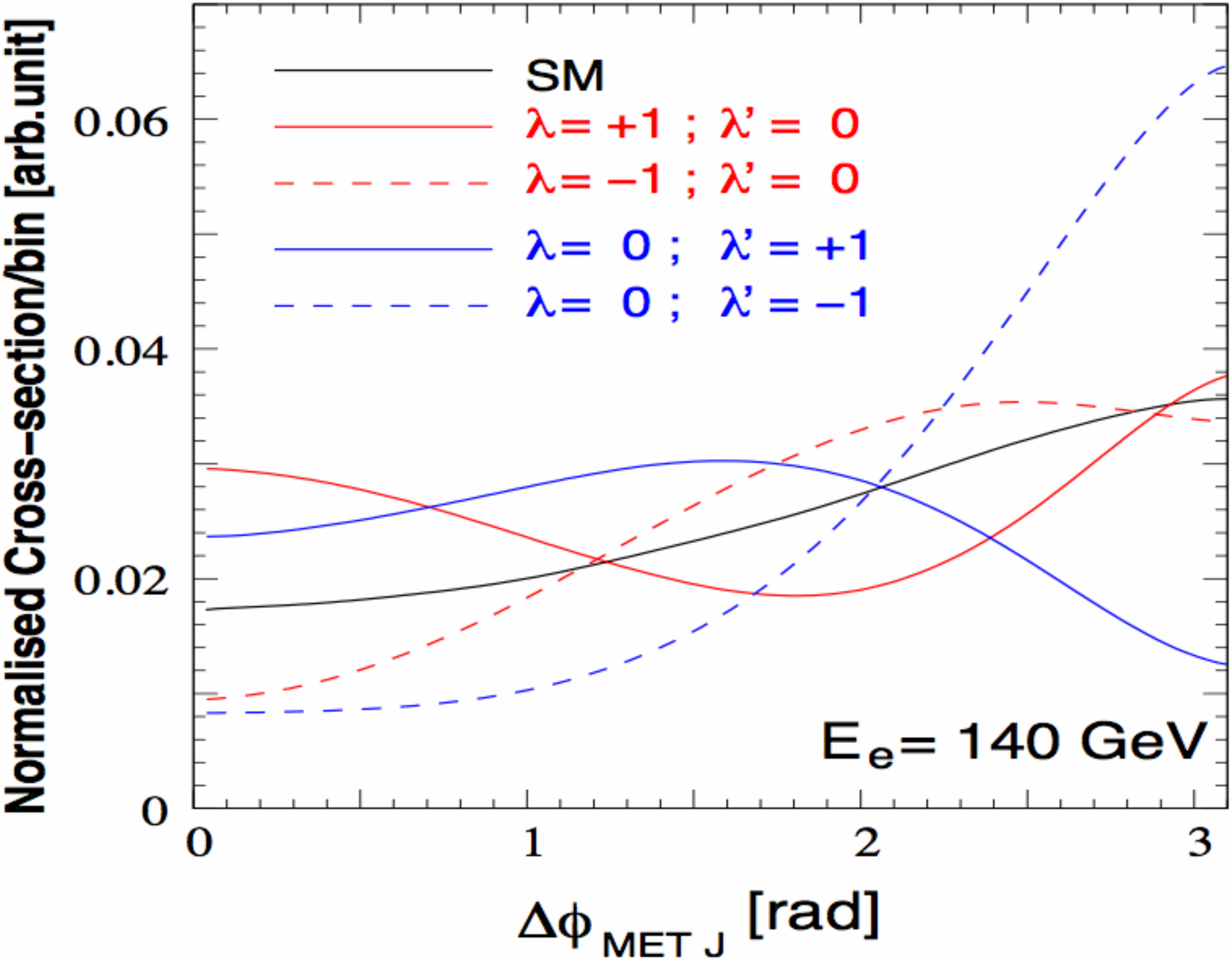
$Hf\bar{f} : -\frac{gm_f}{2M_W}\bar{f}\left(a_f + ib_f\gamma_5\right) fH$

HVV:

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

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

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

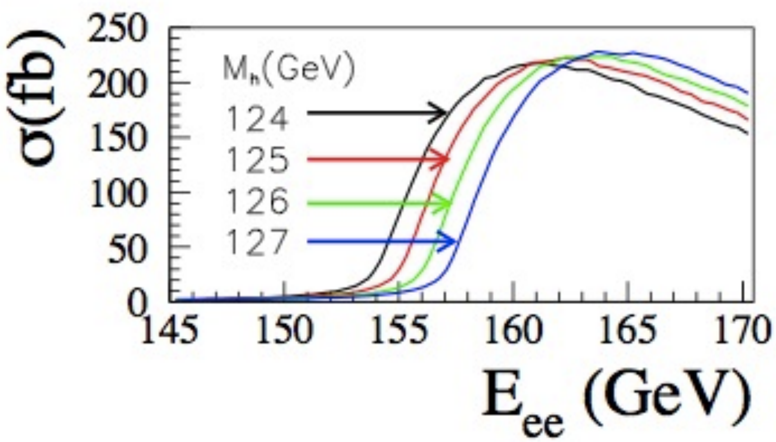


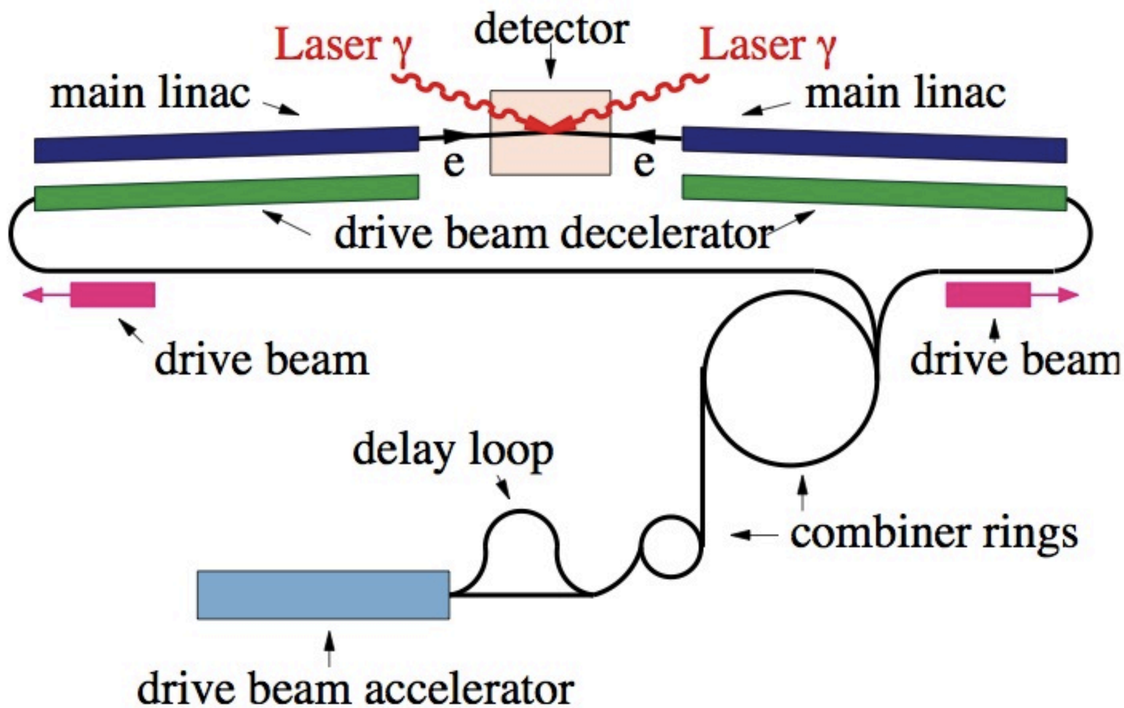
SM
λ= +1 ; λ' = 0
λ= −1 ; λ' = 0
λ= 0 ; λ' = +1
λ= 0 ; λ' = −1
E_e= 140 GeV
Normalised Cross−section/bin [arb.unit]
0.06
0.04
0.02
0
0
1
2
3
$\Delta\phi_{MET\ J}$ [rad]

SAPPHiRE: a Small $\gamma\gamma$ Higgs Factory

A photon-photon collider can be associated to LHeC effort

S. A. Bogacz[1], J. Ellis[2,3], L. Lusito[4], D. Schulte[3], T. Takahashi[5], M. Velasco[4], M. Zanetti[6] and F. Zimmermann[3]





Strong potential to measure CP mixing and violation thanks to control over photon polarization

decay mode	raw events/year	S/B	ϵ_{sel}	$\mathcal{BR}$	$\Delta\Gamma_{\gamma\gamma}\mathcal{BR}/\Gamma_{\gamma\gamma}\mathcal{BR}$
$b\bar{b}$	11540	4.5	0.30	57.7%	2%
W^+W^-	4300	1.3	0.29	21.5%	5%
$\gamma\gamma$	45	—	0.70	0.23%	8%

Double Higgs Production with a 50 TeV Proton Beam

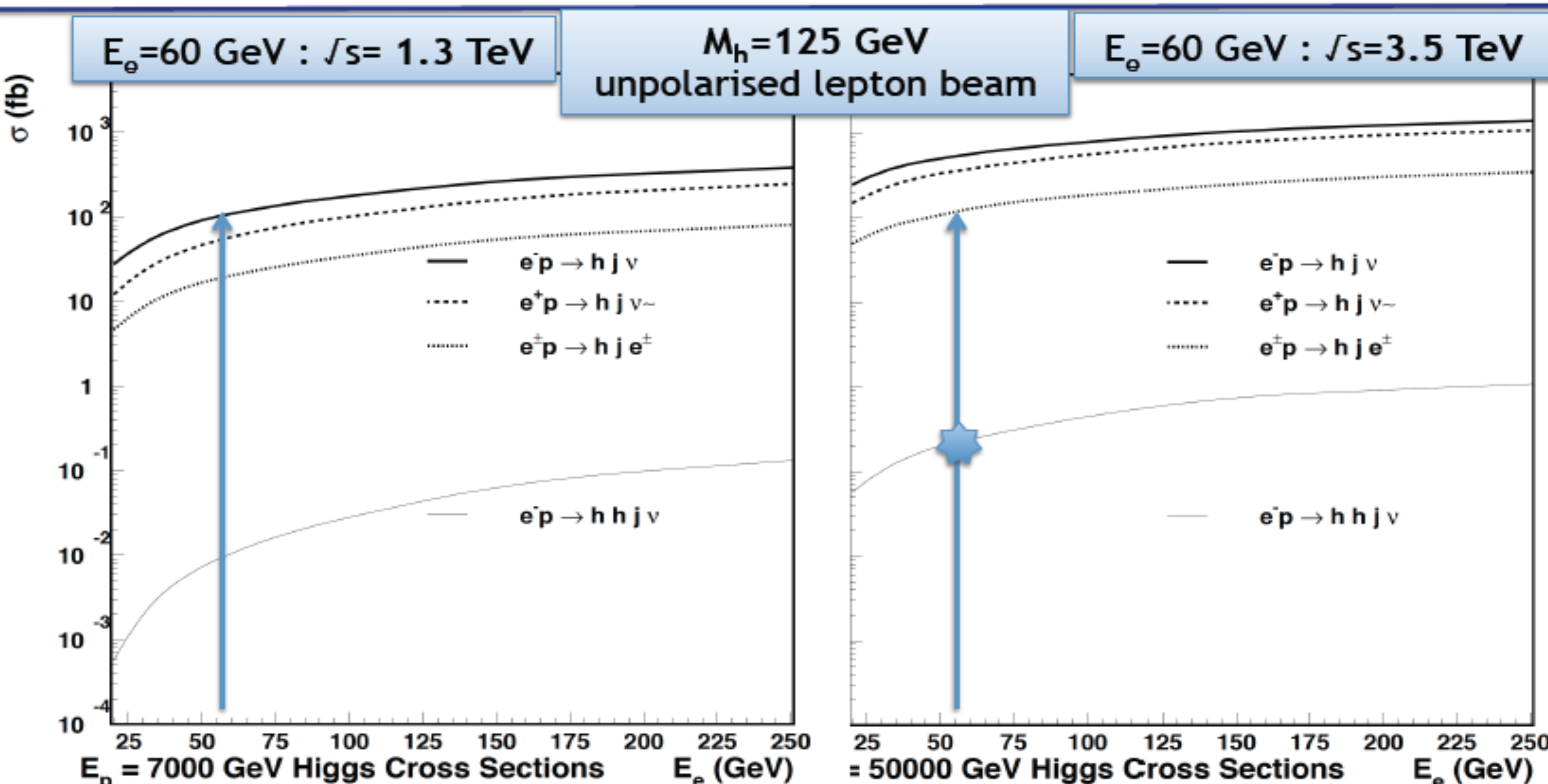
In the light of the FCC kick-off meeting, we are evaluating feasibility of double Higgs production with a 50 TeV beam. Electron-proton collisions offer the advantage of reduced QCD backgrounds and negligible pile-up with the possibility of using the 4b final state.

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

Total Higgs cross sections



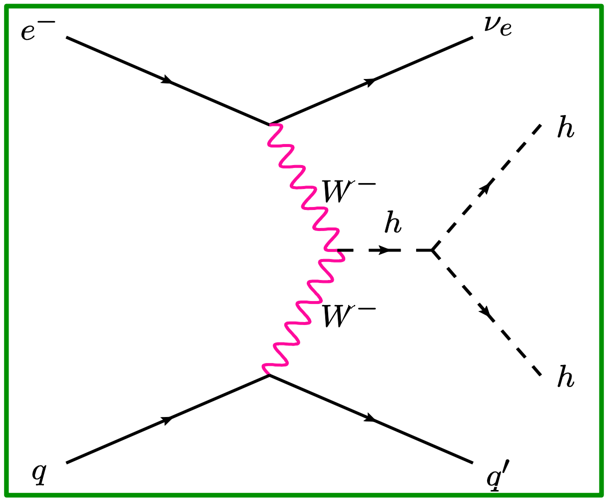
7 TeV LHC protons

50 TeV FCC protons

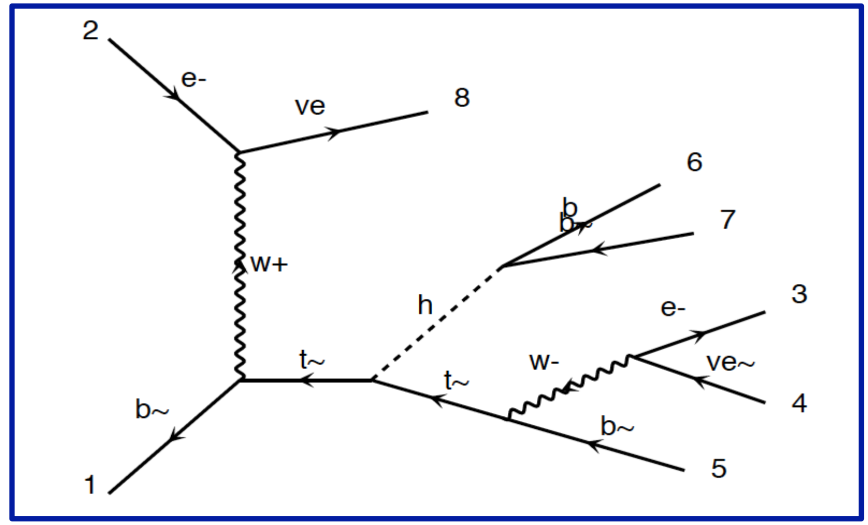
and

electrons from a 60 GeV energy recovery LINAC

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

Further Path Determined with IAC Mandate

M.Klein

Guido Altarelli (Rome) *)
Sergio Bertolucci (CERN)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – **Chair**
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)

The IAC was invited in 12/13 by the DG with the following

Mandate 2014-2017

Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:

Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.

Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

*) IAC Composition End of January 2014 + Oliver Brüning Max Klein ex officio

Coordination Group for Future DIS at CERN

M.Klein

LCG (2014-2017) *)

Nestor Armesto
Oliver Brüning
Stefano Forte
Andrea Gaddi
Bruce Mellado
Max Klein
Peter Kostka
Daniel Schulte
Frank Zimmermann

Directors (ex-officio)
Sergio Bertolucci, Frederick Bordry

The coordination group was invited end of December 2013 by the CERN directorate with the following mandate (2014-2017)

The group has the task to coordinate the study of the scientific potential and possible technical realisation of an ep/eA collider and the associated detectors at CERN, with the LHC and the FCC, over the next four years. It also should coordinate the design of an ERL test facility at CERN as part of the preparations for a larger energy electron accelerator employing ERL techniques.

The group will cooperate with CERN and an International Advisory Committee, chaired by the emeritus DG of CERN, Professor Herwig Schopper, who also advises the CERN directorate. The Coordination Group is asked to represent the ep/eA collider development towards CERN, its committees and the international community. The currently tentative composition is listed *left*. CERN has asked Max Klein to chair and Oliver Brüning to co-chair this activity

*) LCG Composition early January 14

Outlook and Conclusions

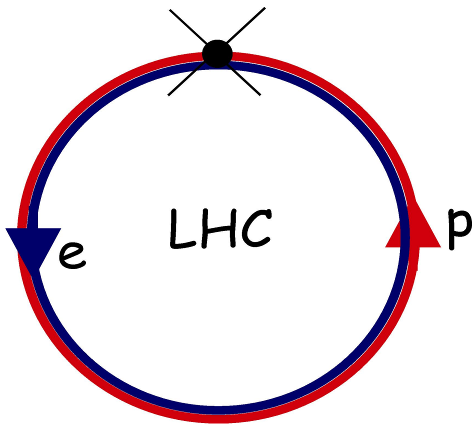
- LHeC displays strong complementarities with the LHC/e^+e^- with regards to Higgs physics
- Forward jet tagging secures the feasibility of the Higgs search in CC and NC in ep collisions
- With the isolation of the H→bb signal at the LHeC a window of opportunity opens for the exploration of the CP properties 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
- IAC and Coordination group with new mandate

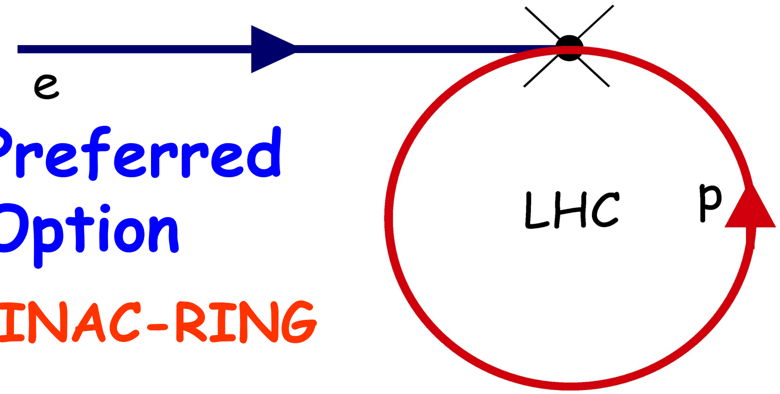
Extra Slides

How Could ep be Done using LHC?

... <u>whilst allowing simultaneous ep and pp running</u> ...

RING-RING





Preferred Option

LINAC-RING

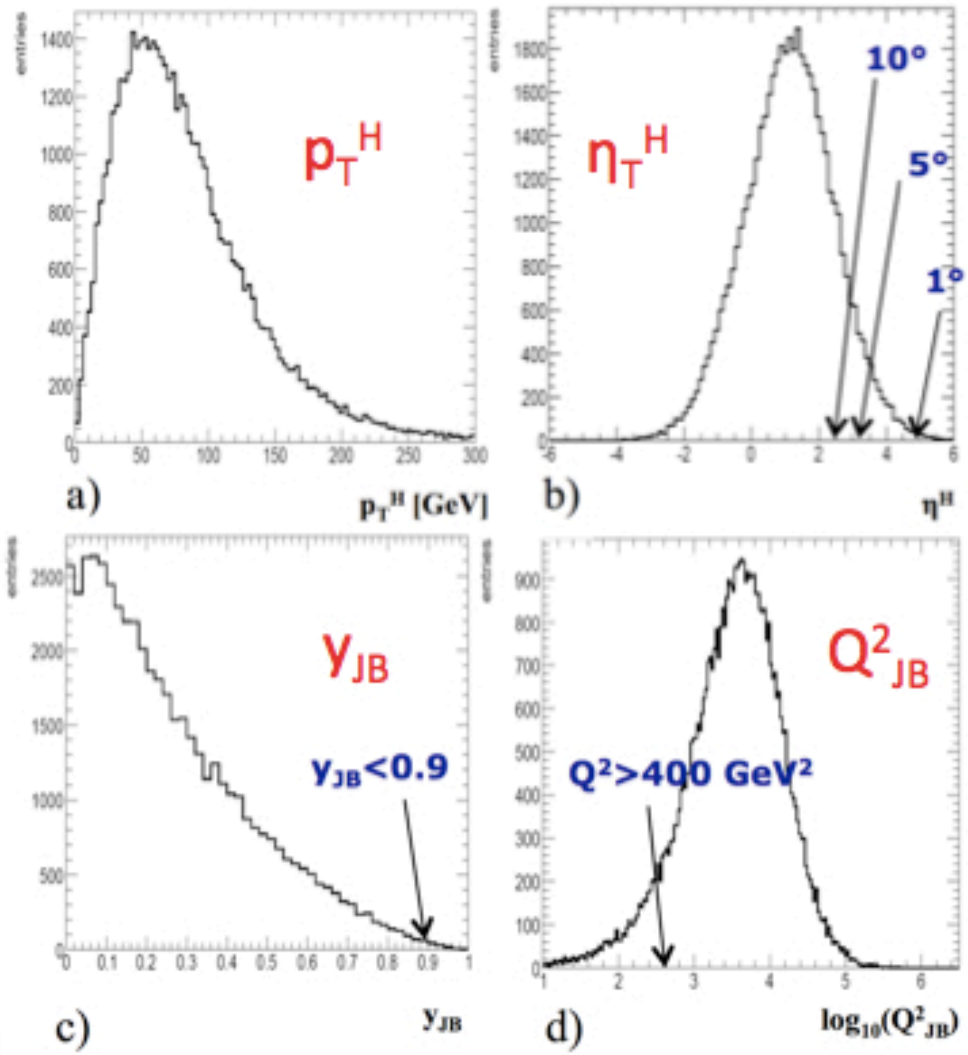
- First considered (as LEPxLHC) in 1984 ECFA workshop
- Main advantage: high peak lumi obtainable (~2.10^{33} cm^{-2} s^{-1})
- Main difficulties: building round existing LHC, e beam energy (60GeV?) and lifetime limited by synchrotron radiation

- Previously considered as `QCD explorer' (also THERA)
- Main advantages: low interference with LHC, high E_e (→ 150 GeV?) and lepton polarisation
- Somewhat lower luminosity at reasonable power, no previous experience exists

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:

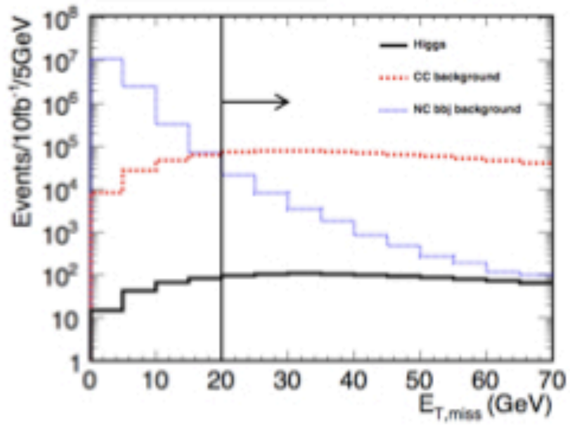
- Coverage:
  - Tracking: $|\eta| < 3$
  - Calorimeter: $|\eta| < 5$
- Calorimeter resolution
  - EM: 1% ⊕ 5%/√E
  - Hadron: 60%/√E
  - Cell size: $(\Delta\eta, \Delta\phi) = (0.03, 0.03)$
- Jet reconstructed (cone ΔR=0.7)
- b-tag performance
  - Flat efficiency for $|\eta| < 3$
  - Efficiency/mis-ID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

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

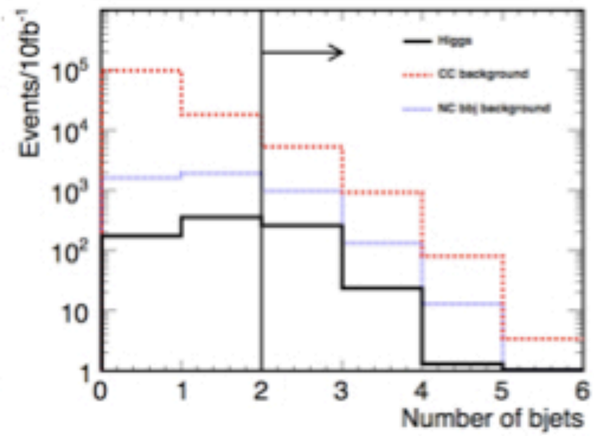
- NC rejection
  - Exclude electron-tagged events
  - $E_{T,miss} > 20$ GeV
  - N_{jet} ($p_T > 20$ GeV) $\geqq 3$
  - $E_{T,total} > 100$ GeV
  - $y_{JB} < 0.9$, $Q^2_{JB} > 400$ GeV^2
- b-tag requirement
  - $N_{b\text{-}jet}$ ($p_T > 20$ GeV) $\geqq 2$
- Higgs invariant mass
  - $90 < M_H < 120$ GeV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

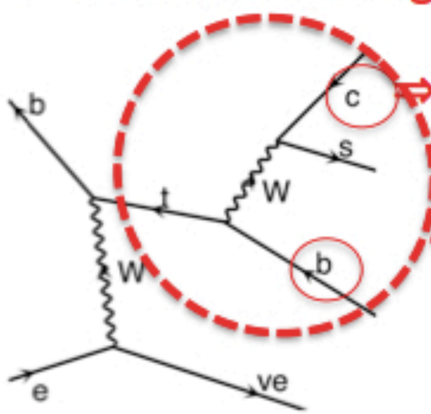
$H \rightarrow b\bar{b}$
CC BG
NC BG

E_T^{miss} cut

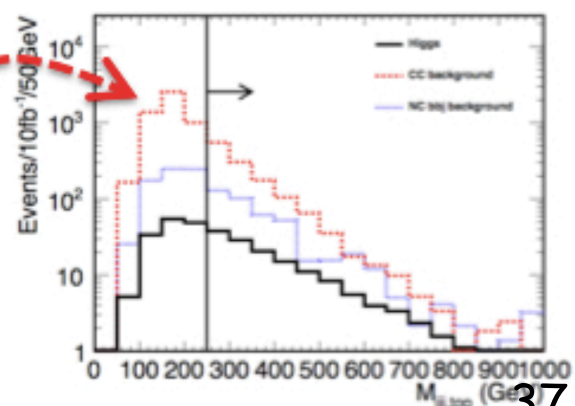


b-tag requirement





⇒10% mis-ID

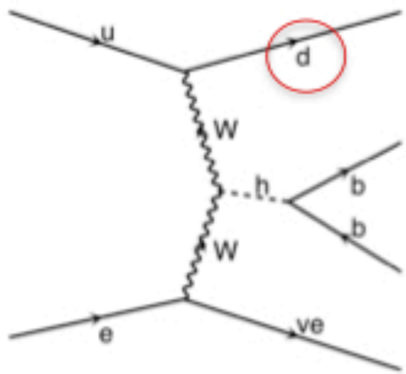


LHeC $H \to b\bar{b}$ results [M_H=120 GeV, E_p=7 TeV]

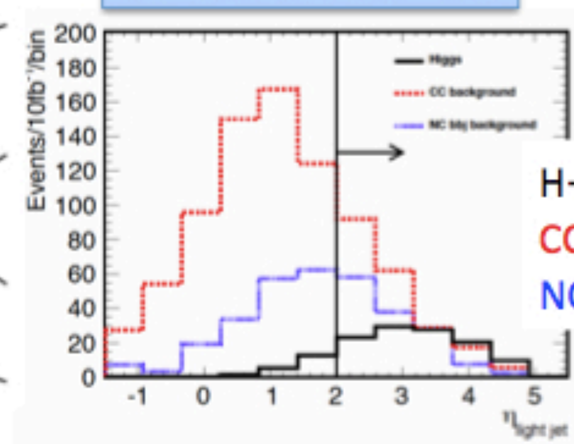
- Forward jet tagging
  - $\eta_{jet} > 2$ (lowest η jet excluding b-tagged jets)

Coordinate:
Fwd: +z-axis along proton beam

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



Forward jet η tag

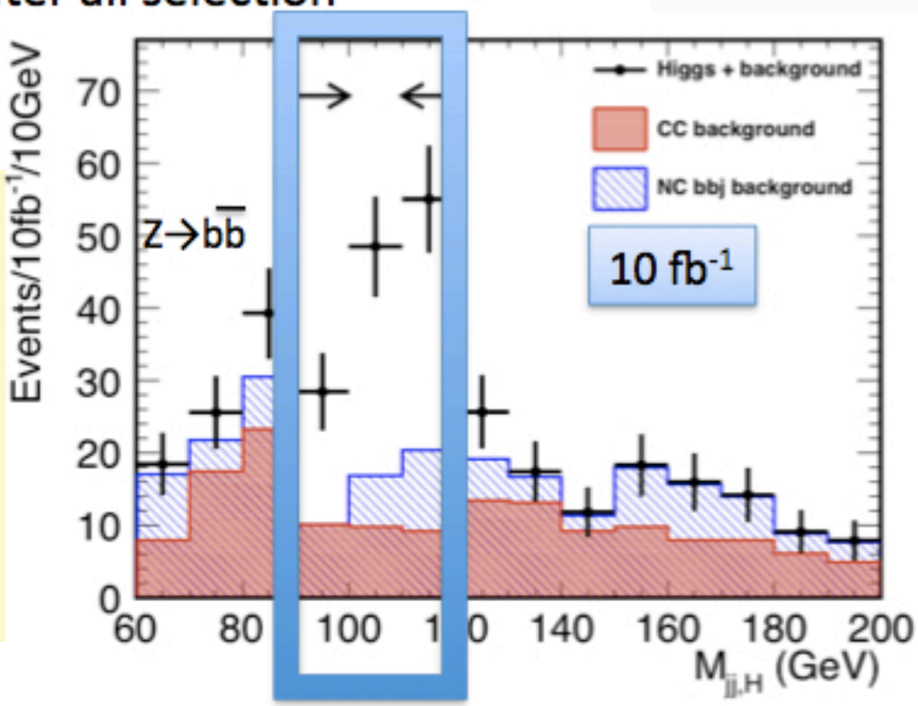


- Higgs invariant mass after all selection

E_e=150 GeV

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

→LHeC is high precision Higgs facility

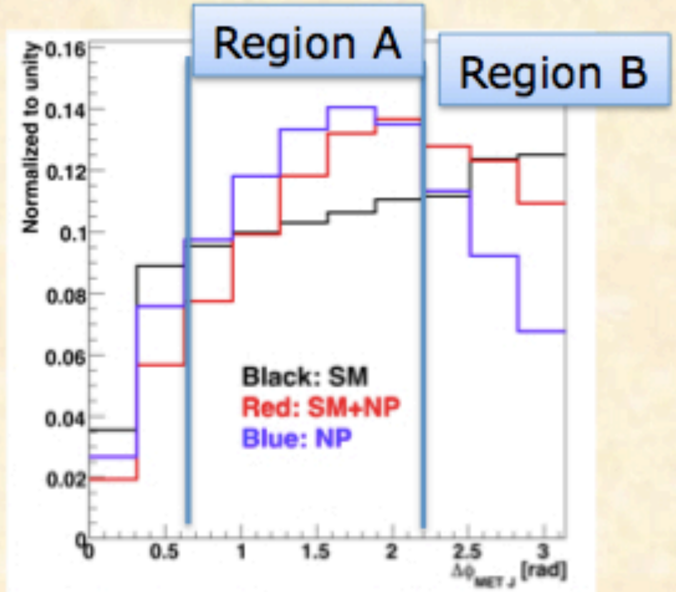


Clear signal obtained with just cut based analysis already!

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

Charge Current Analysis (results)

Effect of Jet Energy Resolution

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

Effect of Range of b-tagging

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

$$|\eta_b| < 2.5 \ \rightarrow \ |\eta_b| < 3$$

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	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

Charge Current Analysis (results)

Effect of Jet P_T

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

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

		CC			Photo-prod.		
Cuts	Higgs	$t\bar{b}$	$b\bar{b}j$	jjj	$b\bar{b}j$	$t\bar{t}$	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

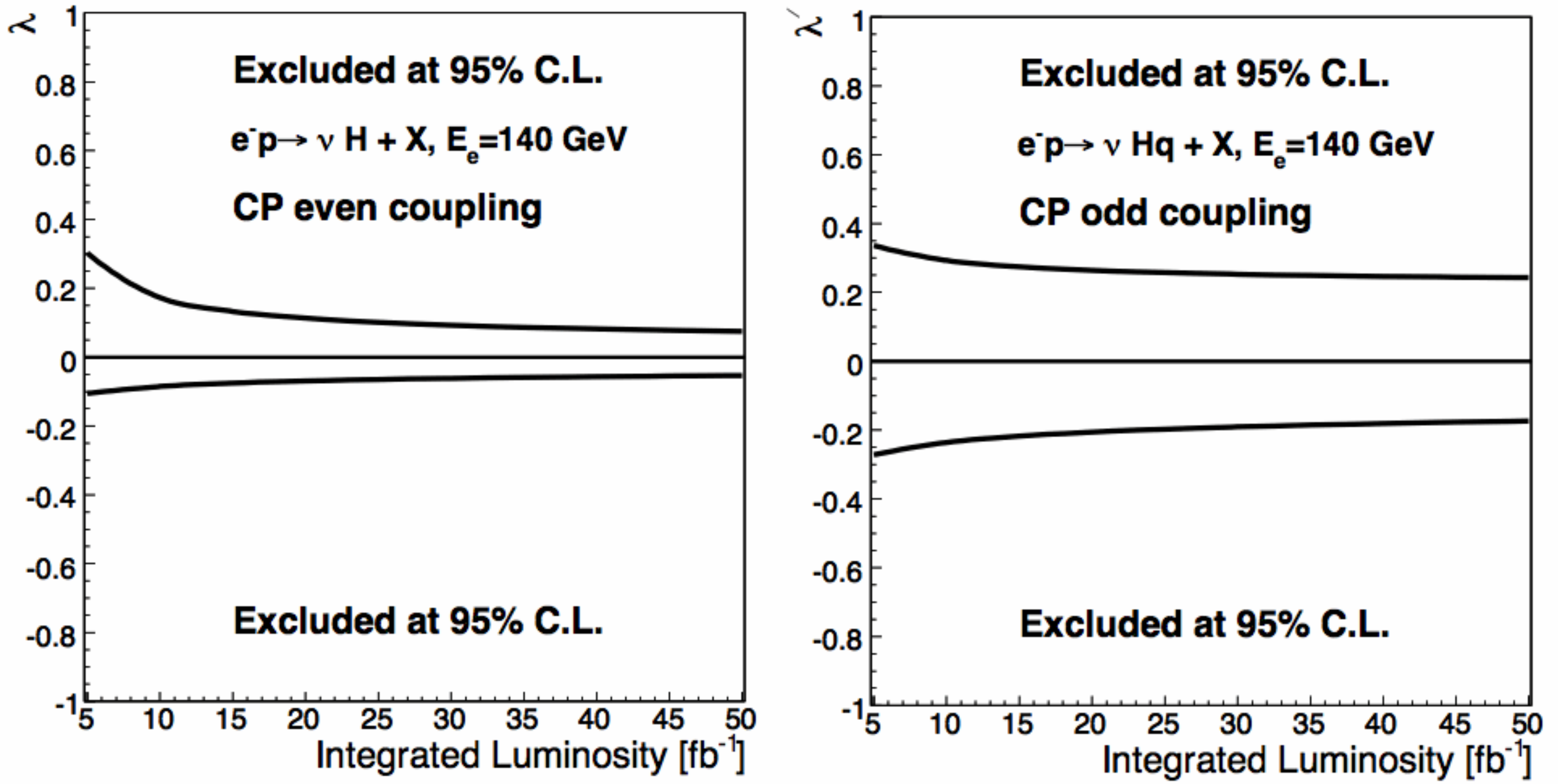
Signal Efficiency for Different E_e

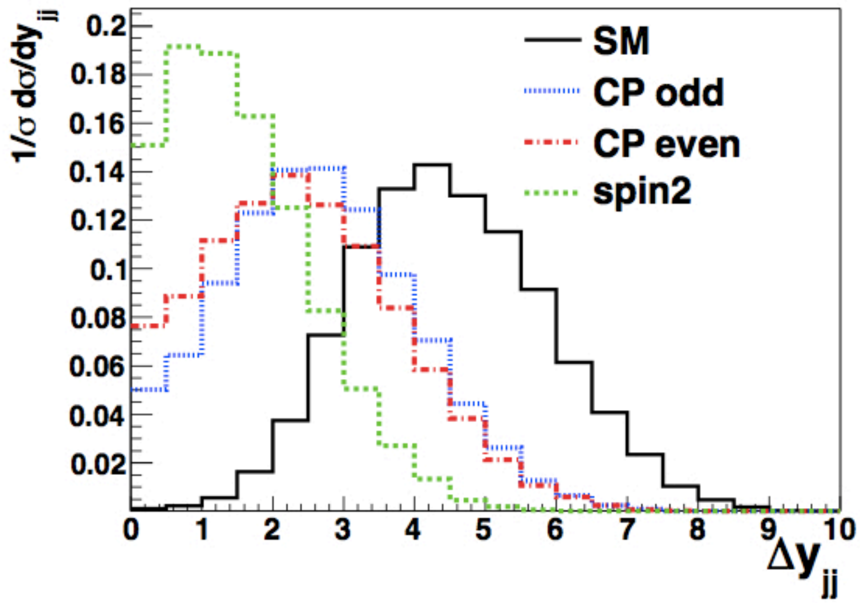
- First row: Cumulative efficiency
- Second row: Efficiency w.r.t. previous cut

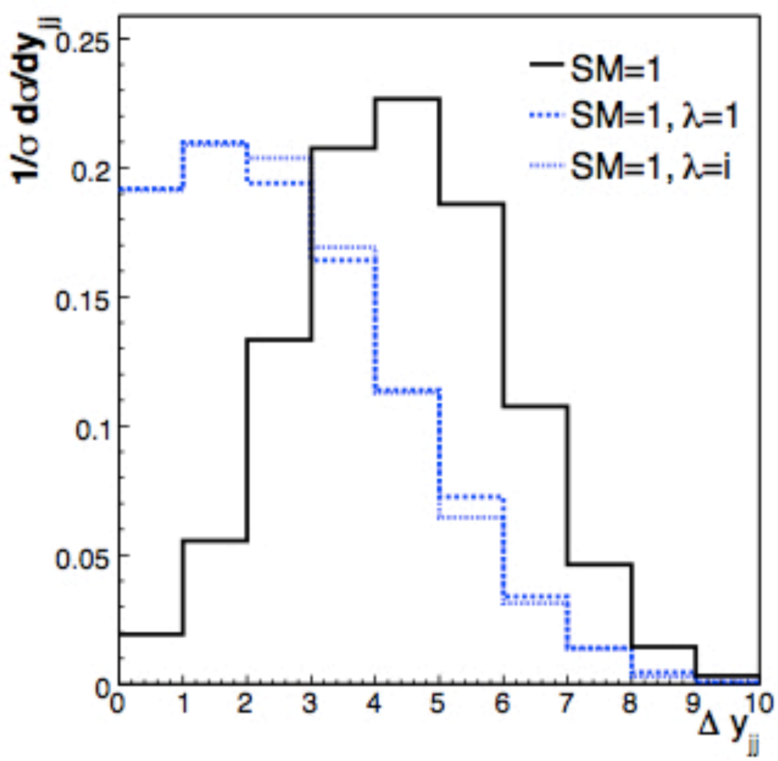
Cut	$E_e = 50$	$E_e = 100$	$E_e = 140$	$E_e = 200$
a	0.129 -	0.157 -	0.166 -	0.171 -
b	0.109 0.84	0.127 0.81	0.132 0.80	0.136 0.80
c	0.076 0.70	0.090 0.71	0.093 0.70	0.095 0.70
d	0.050 0.66	0.067 0.75	0.073 0.79	0.078 0.82

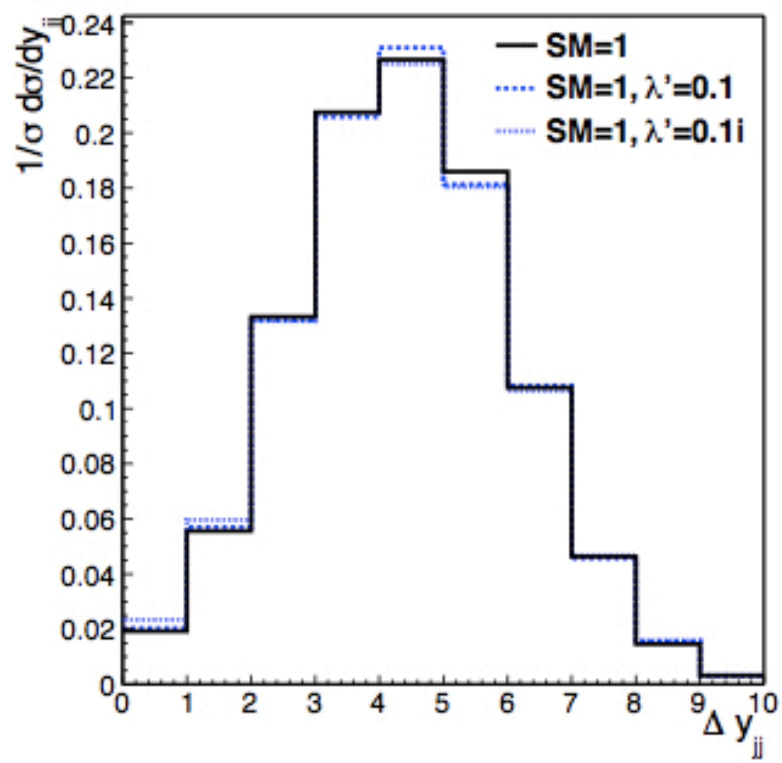
Results on the sensitivity with updated background as per the simulations of U. Klein (DIS 2011)

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

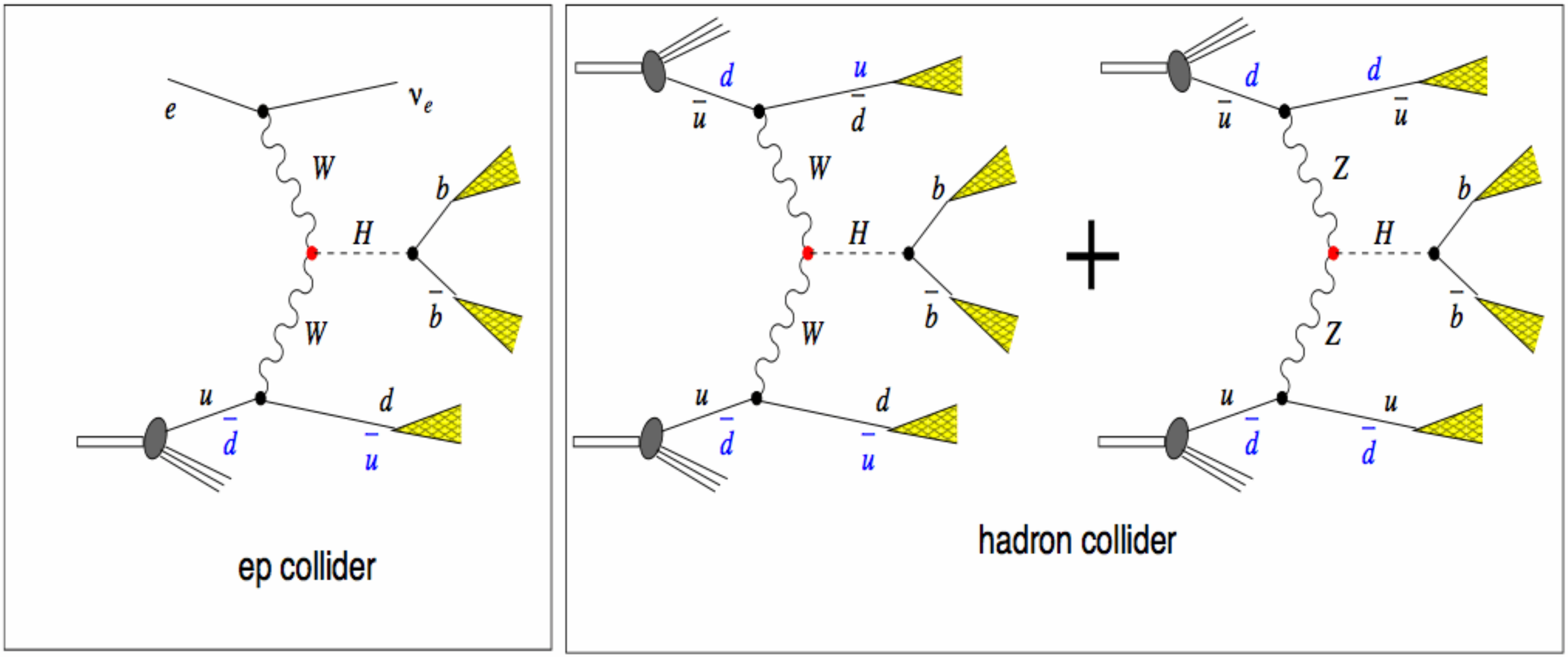



SM
CP odd
CP even
spin2
1/σ dσ/dy_jj
Δy_jj


SM=1
SM=1, λ=1
SM=1, λ=i
1/σ dσ/dy_jj
Δ y_jj


SM=1
SM=1, λ'=0.1
SM=1, λ'=0.1i
1/σ dσ/dy_jj
Δ y_jj

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

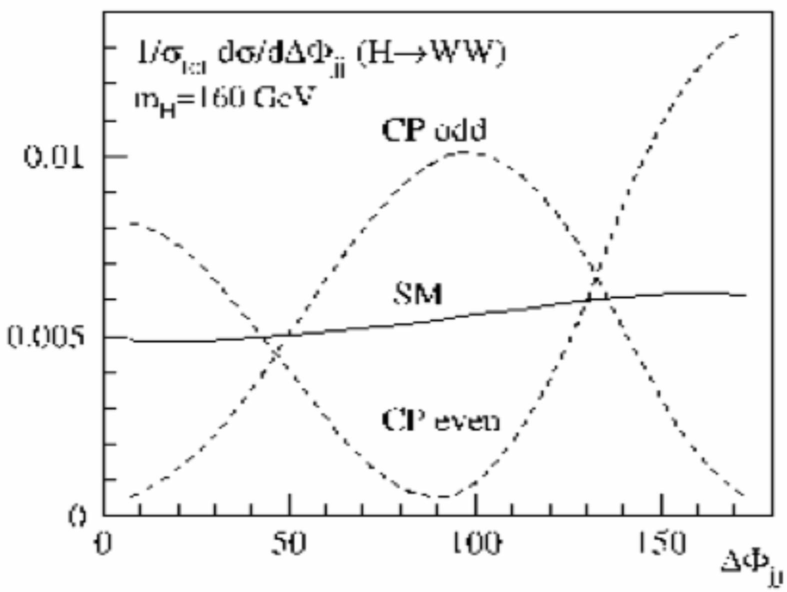


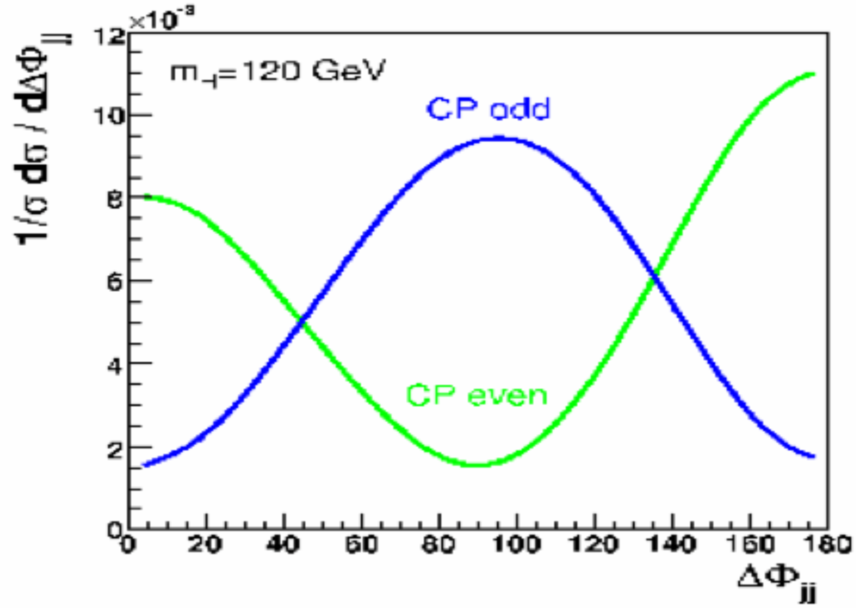
ep **process uniquely addresses the HWW vertex.**

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

Study by Zeppenfeld et al:

Study in pp collisions





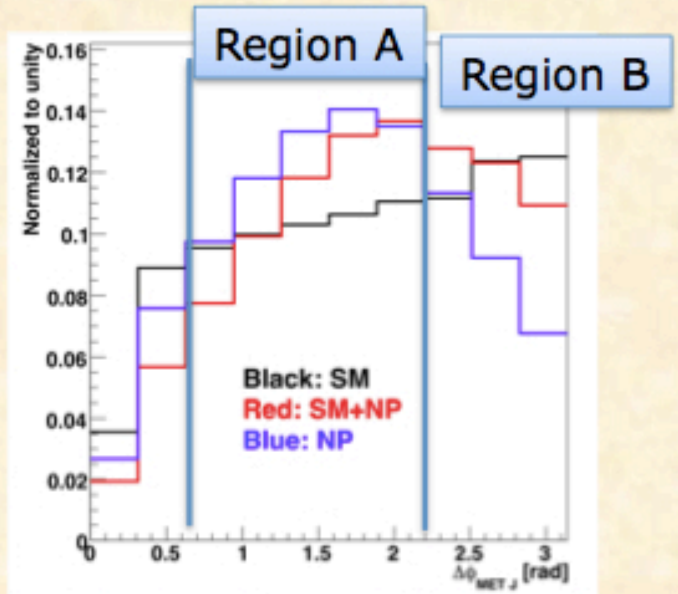
Left plot: VBF, CP even and CP odd refer to the dimension 5 operator.

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

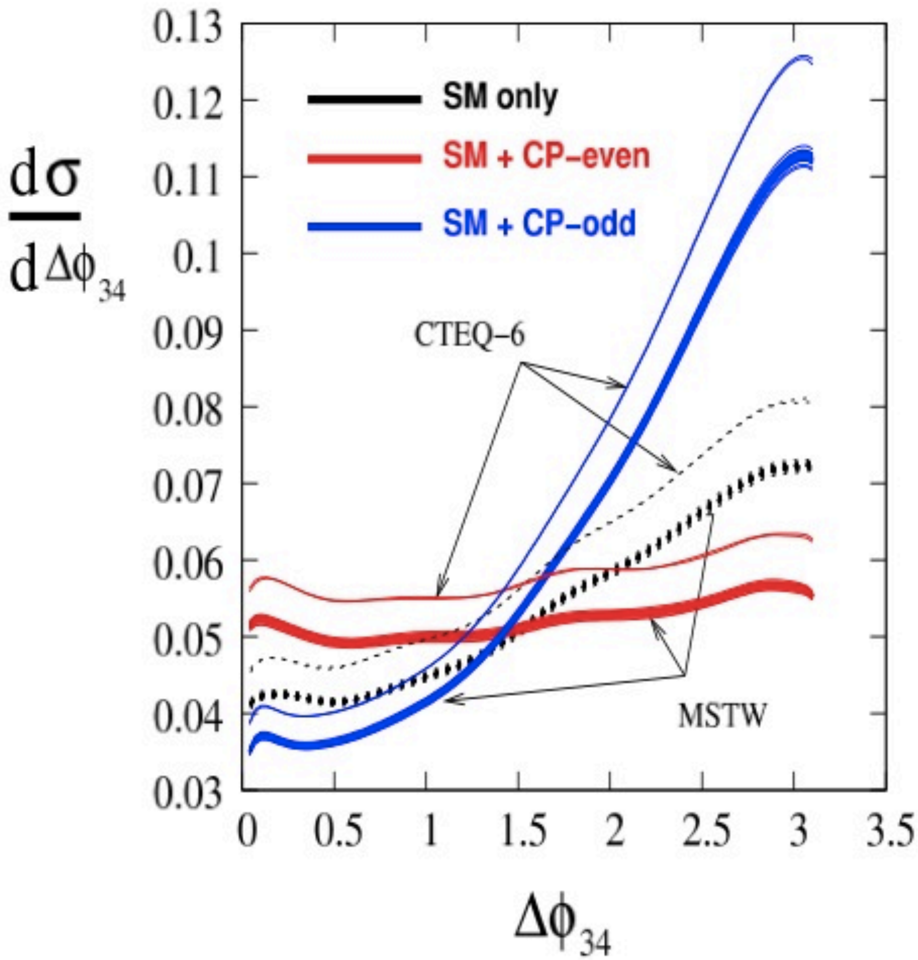
- Measure deviation of the Higgs production with respect to the SM using the absolute rate of events
- The ratio of the number of events in region B to that of region A in the $\Delta\varphi_{MET,J}$ spectrum

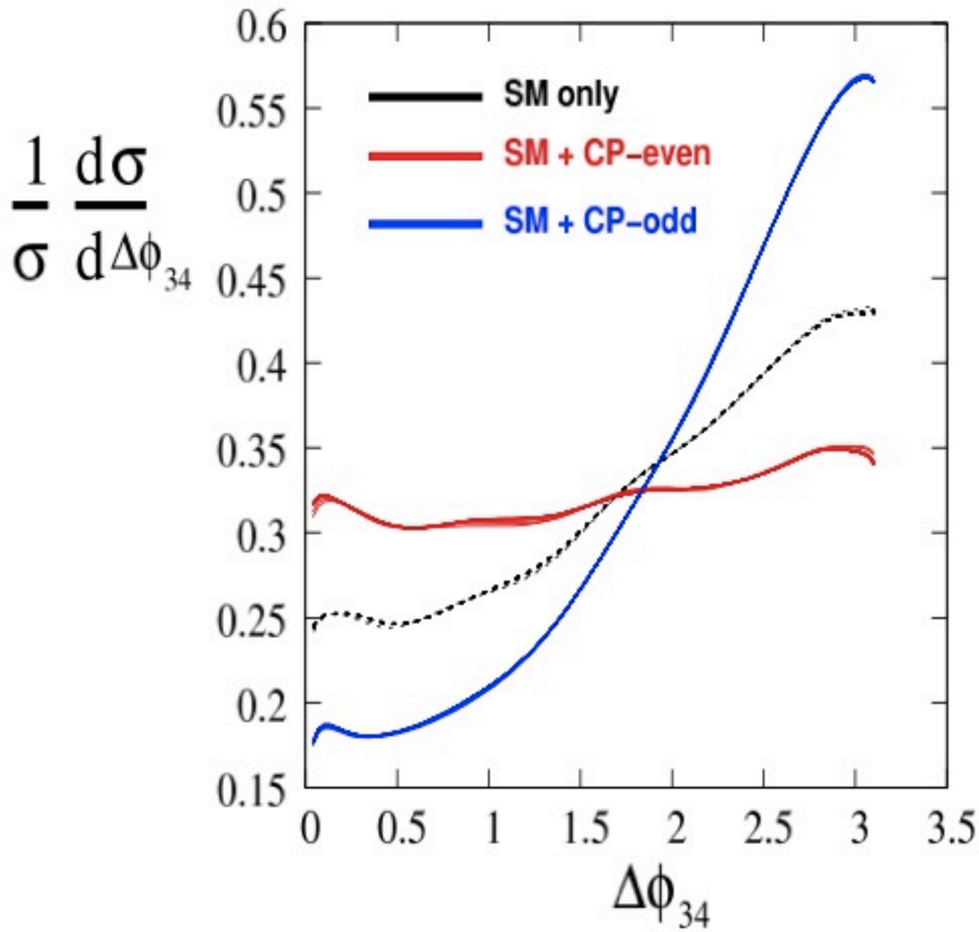
CP-odd case



- 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

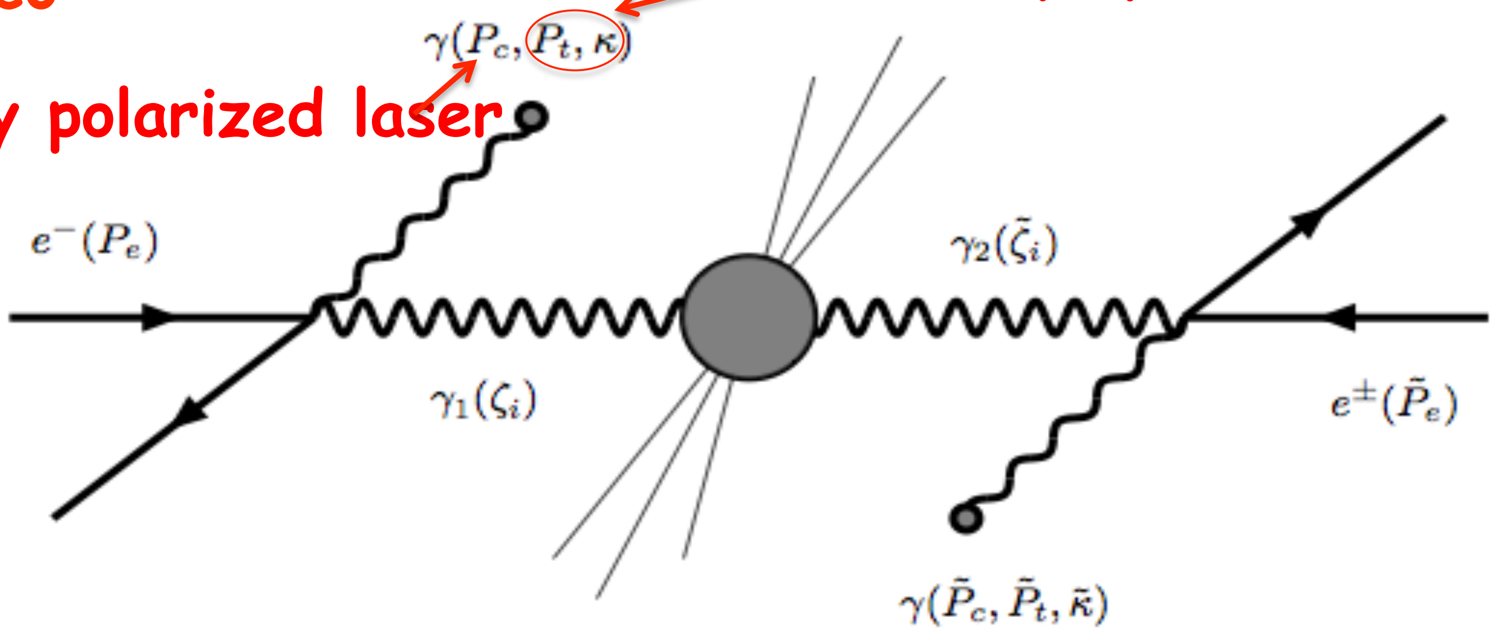




$\gamma\gamma$ Ideal To Measure CP Mixing and Violation

The LHC will tell us the SPIN and Parity of the Higgs.
Higgs factories should go beyond...

M.Velasco



ζ_2 is the degree of circular polarization

(ζ_3, ζ_1) are the degrees of linear polarization

ζ_2 is the degree of circular polarization

(ζ_3, ζ_1) are the degrees of linear polarization

M.Velasco

Only with $\gamma\gamma C$

In s-channel production of Higgs:

$$\overline{|\mathcal{M}^{H_i}|^2} = \overline{|\mathcal{M}^{H_i}|_0^2} \left\{ [1 + \zeta_2\tilde{\zeta}_2] + \mathcal{A}_1 \left[\zeta_2 + \tilde{\zeta}_2\right] + \mathcal{A}_2 \left[\zeta_1\tilde{\zeta}_3 + \zeta_3\tilde{\zeta}_1\right] - \mathcal{A}_3 \left[\zeta_1\tilde{\zeta}_1 - \zeta_3\tilde{\zeta}_3\right] \right\}$$

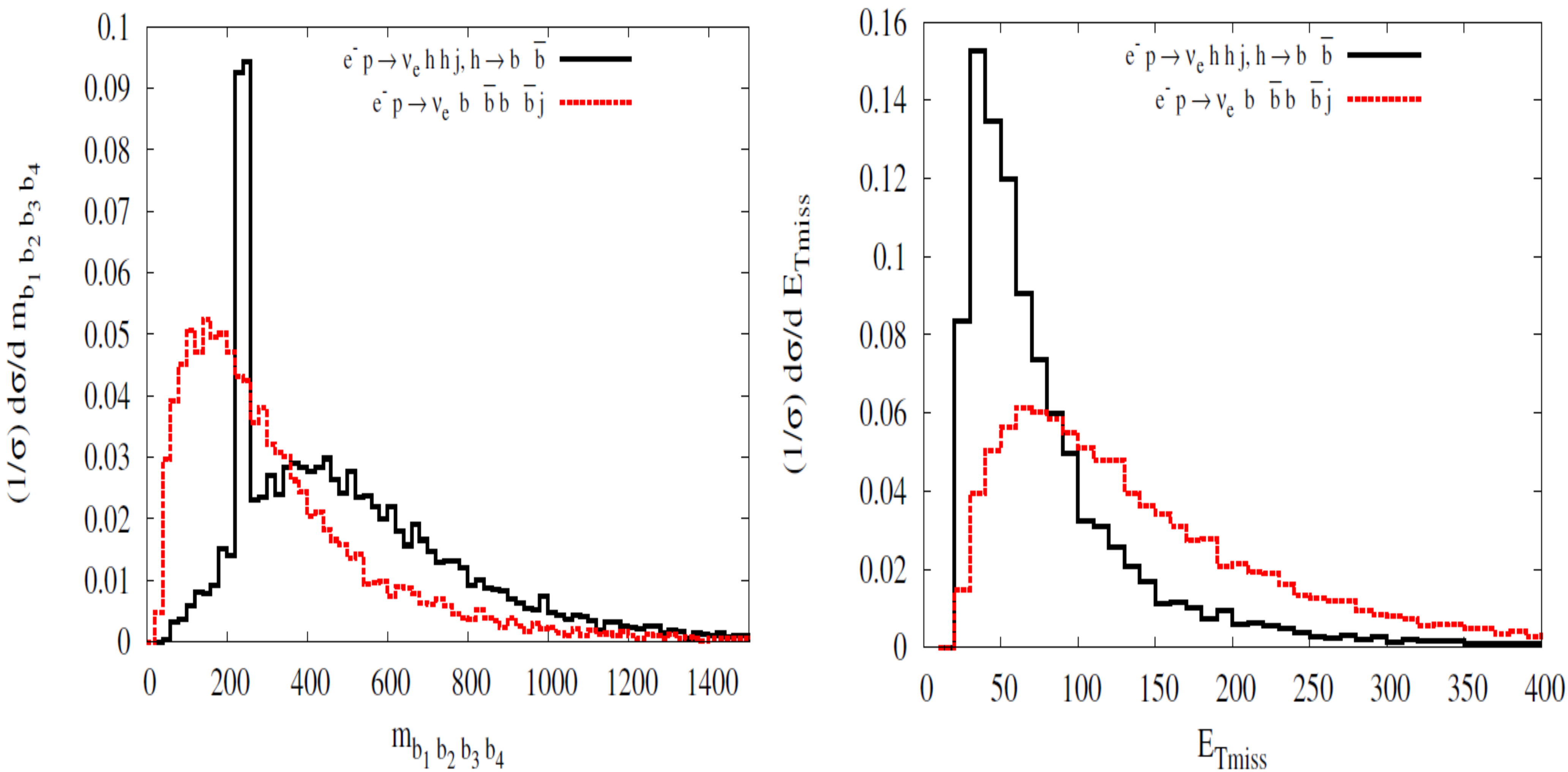
== 0 if CP is conserved

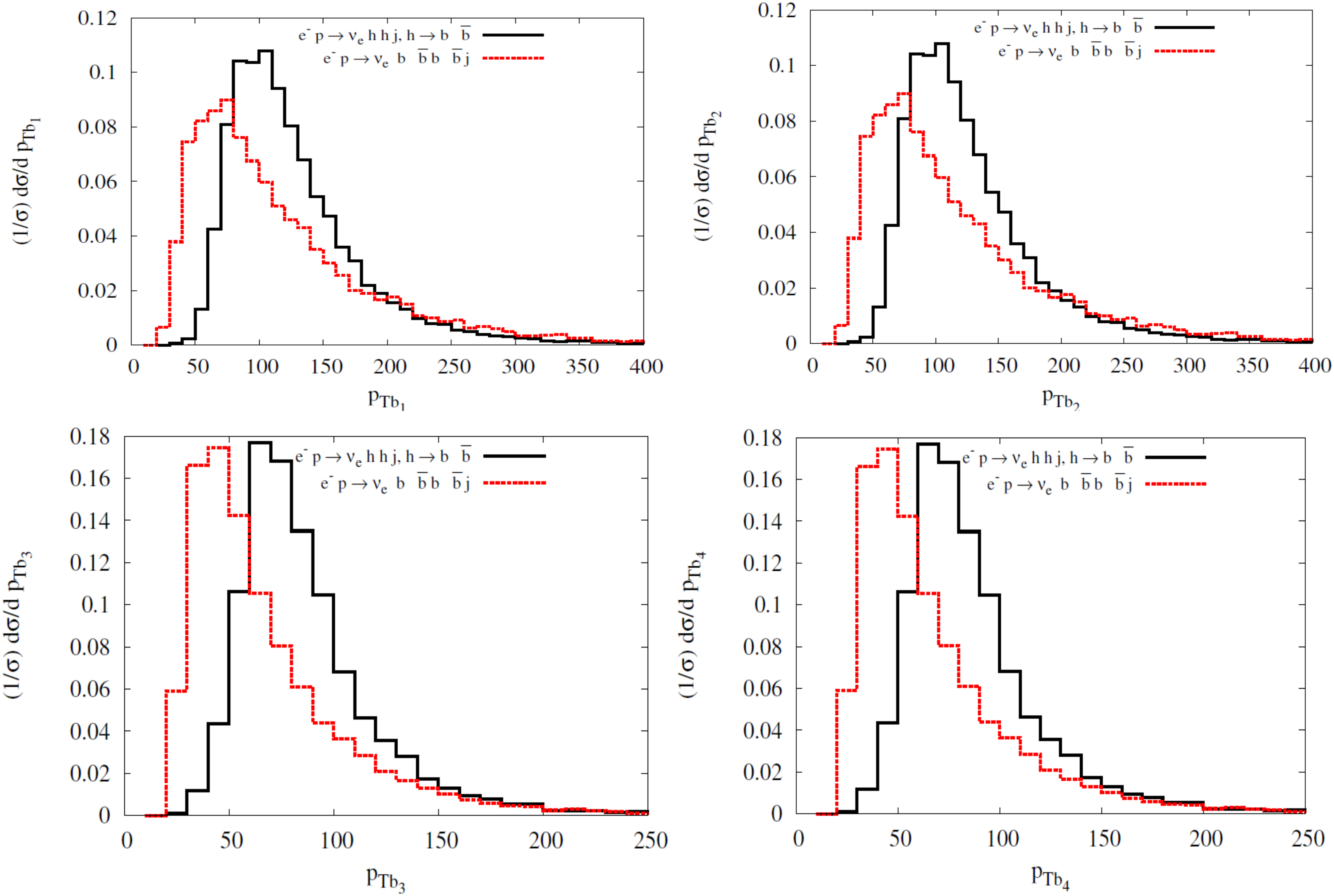
== +1 (-1) for CP is conserved forA CP-Even (CP-Odd) Higgs

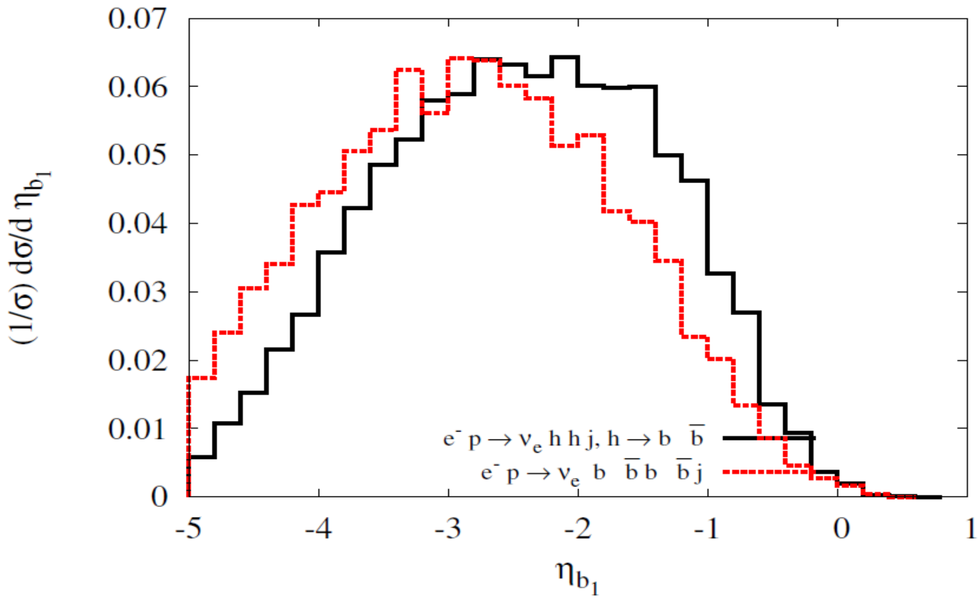
- If $\mathcal{A}_1 \neq 0$, $\mathcal{A}_2 \neq 0$ and/or $|\mathcal{A}_3| < 1$, the Higgs is a mixture of CP-Even and CP-Odd states
- Possible to search for CP violation in gg→ H → fermions without having to measure their polarizatio
- In bb, a ≤1% asymmetry can be measure with 100 fb^{-1} that is, in 1/2 years

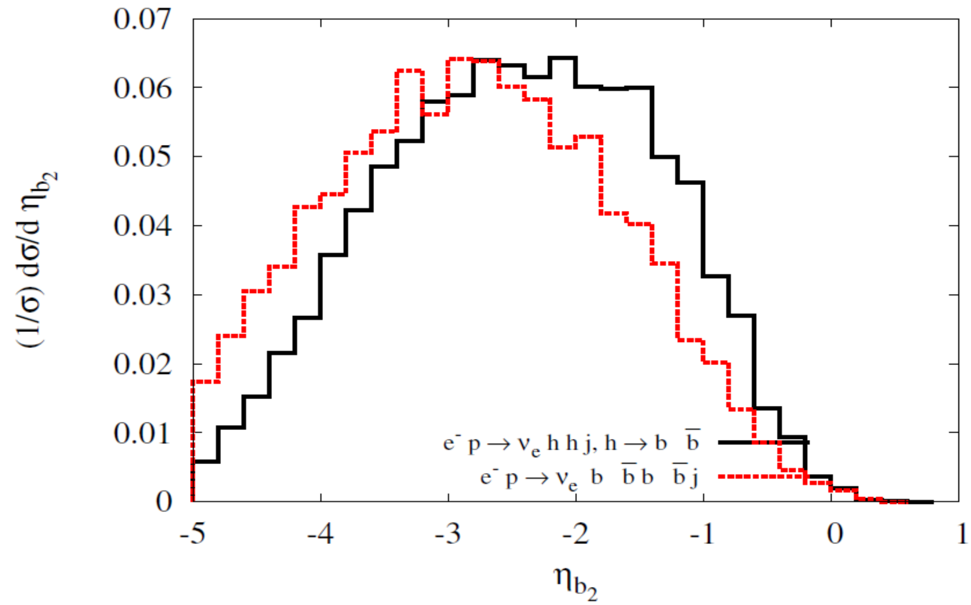
arXiv:0705.1089v2

Kinematic Distributions (Ee = 60 GeV)

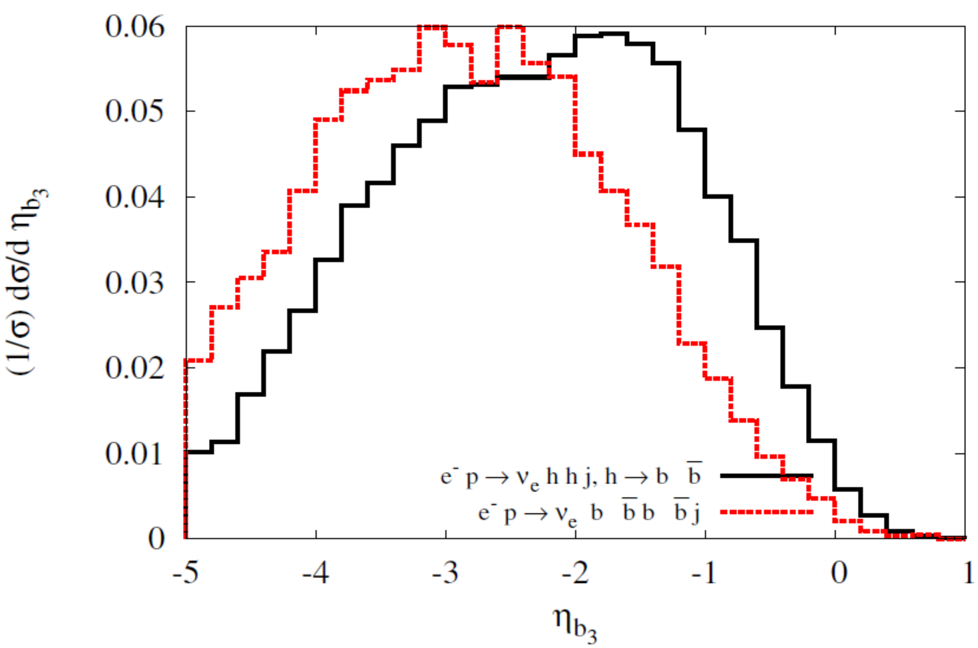


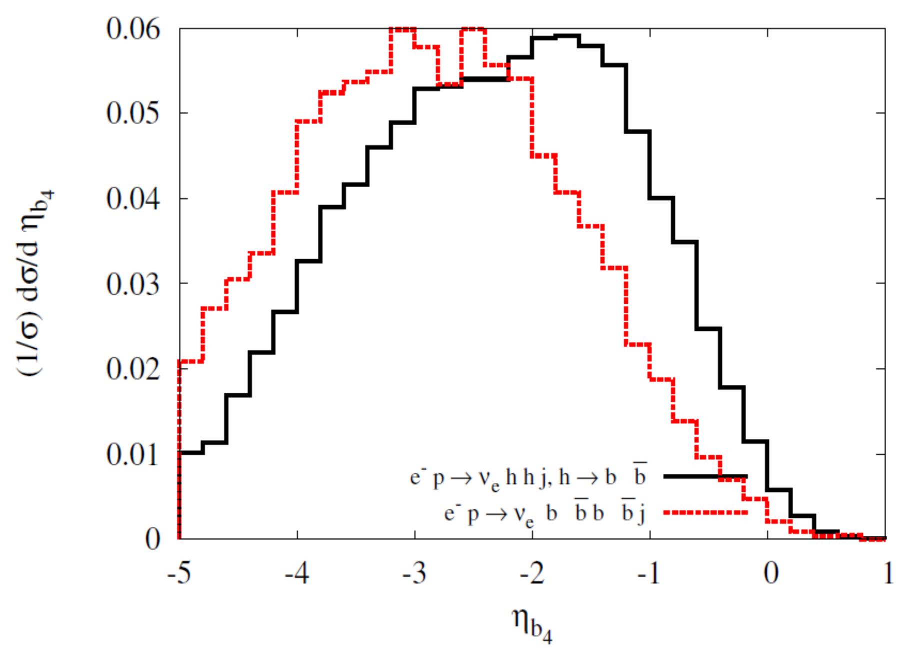

$e^- p \to \nu_e h h j, h \to b \bar{b}$
$e^- p \to \nu_e b \bar{b} b \bar{b} j$
$(1/\sigma)\, d\sigma/d\, p_{Tb_1}$
p_{Tb_1}
$(1/\sigma)\, d\sigma/d\, p_{Tb_2}$
p_{Tb_2}
$(1/\sigma)\, d\sigma/d\, p_{Tb_3}$
p_{Tb_3}
$(1/\sigma)\, d\sigma/d\, p_{Tb_4}$
p_{Tb_4}

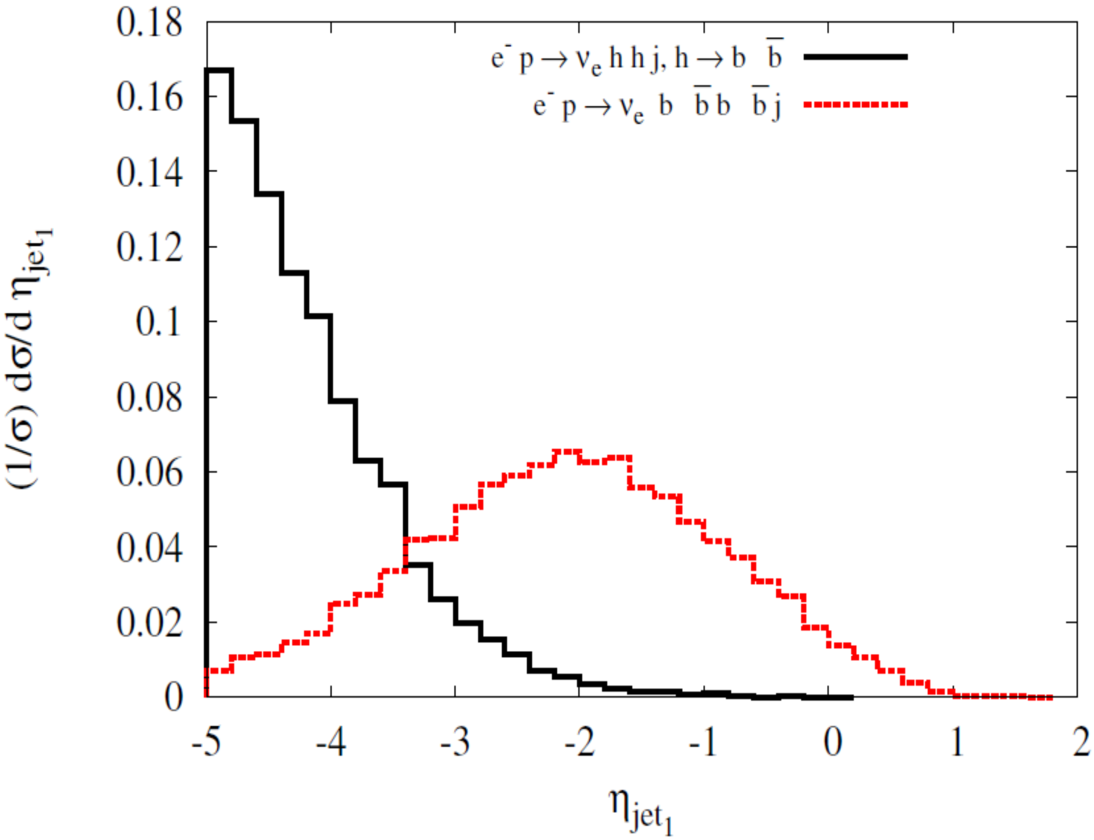




Despite large beam energy imbalance, jets are relatively central







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

Scattered quark is more forward in signal