Higgs in ep at the LHeC

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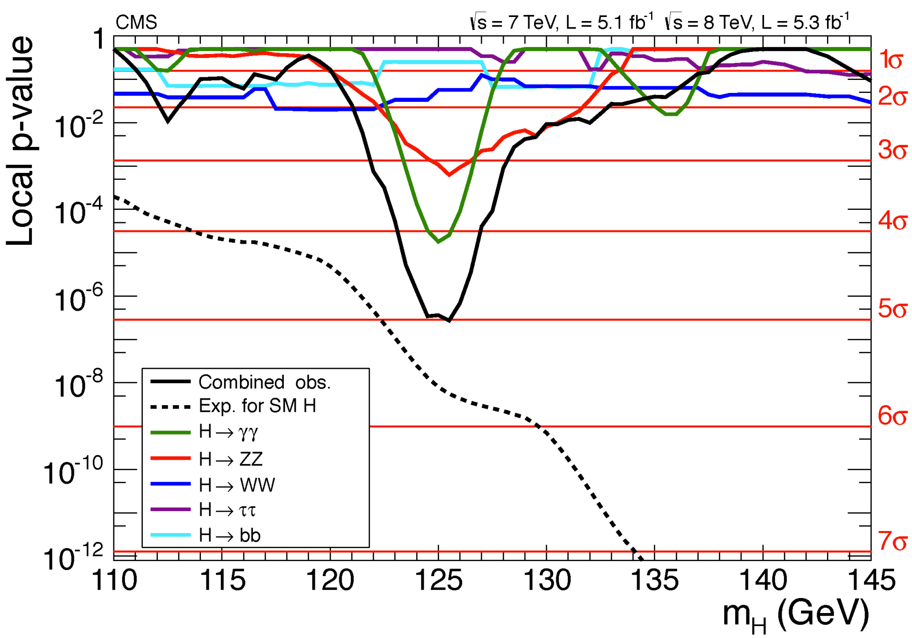
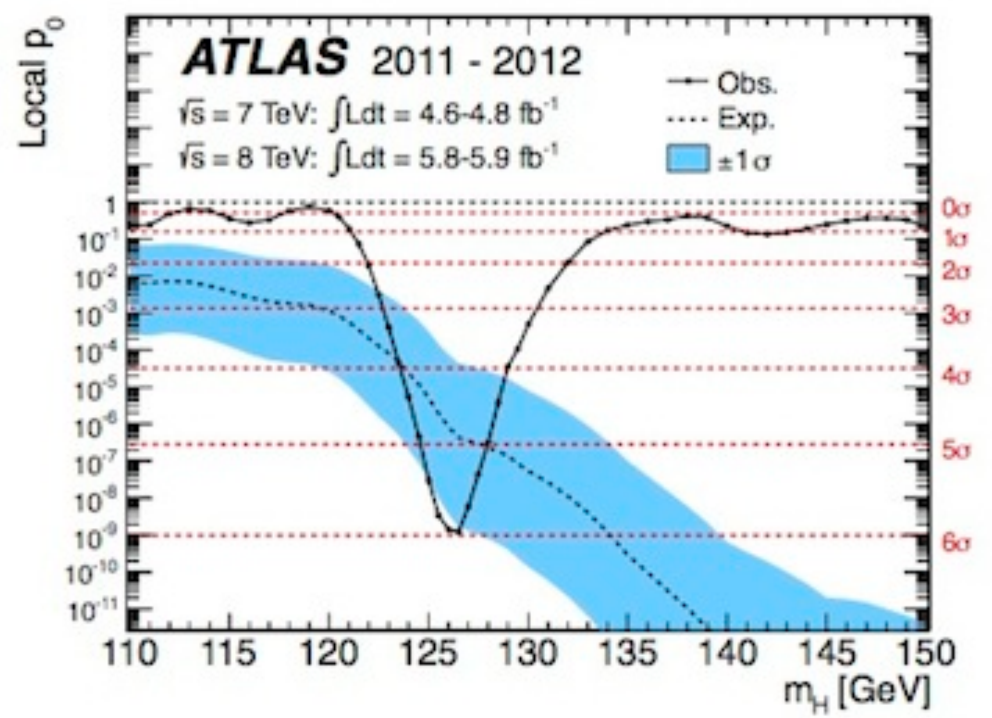
Wits/IFIC
for the LHeC Study Group

LPCC week, CERN, 18/04/13

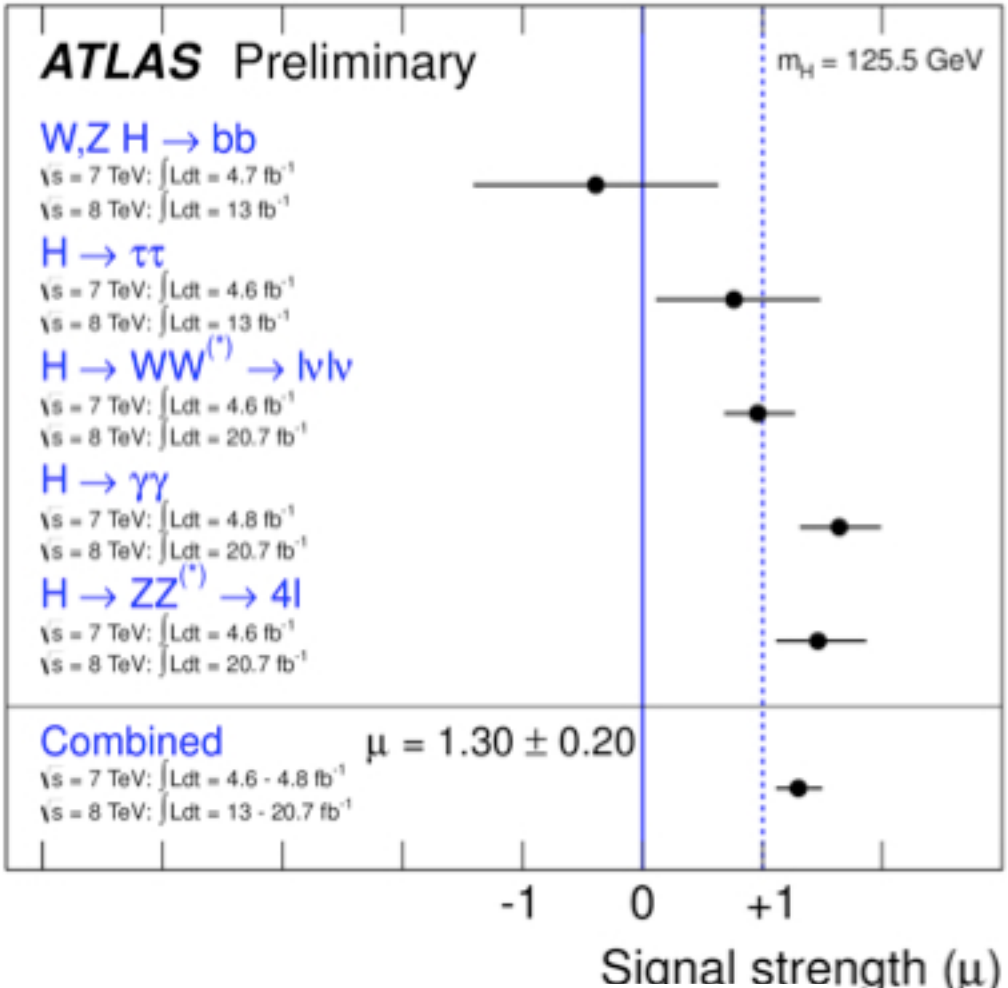
Habemus novum Boson

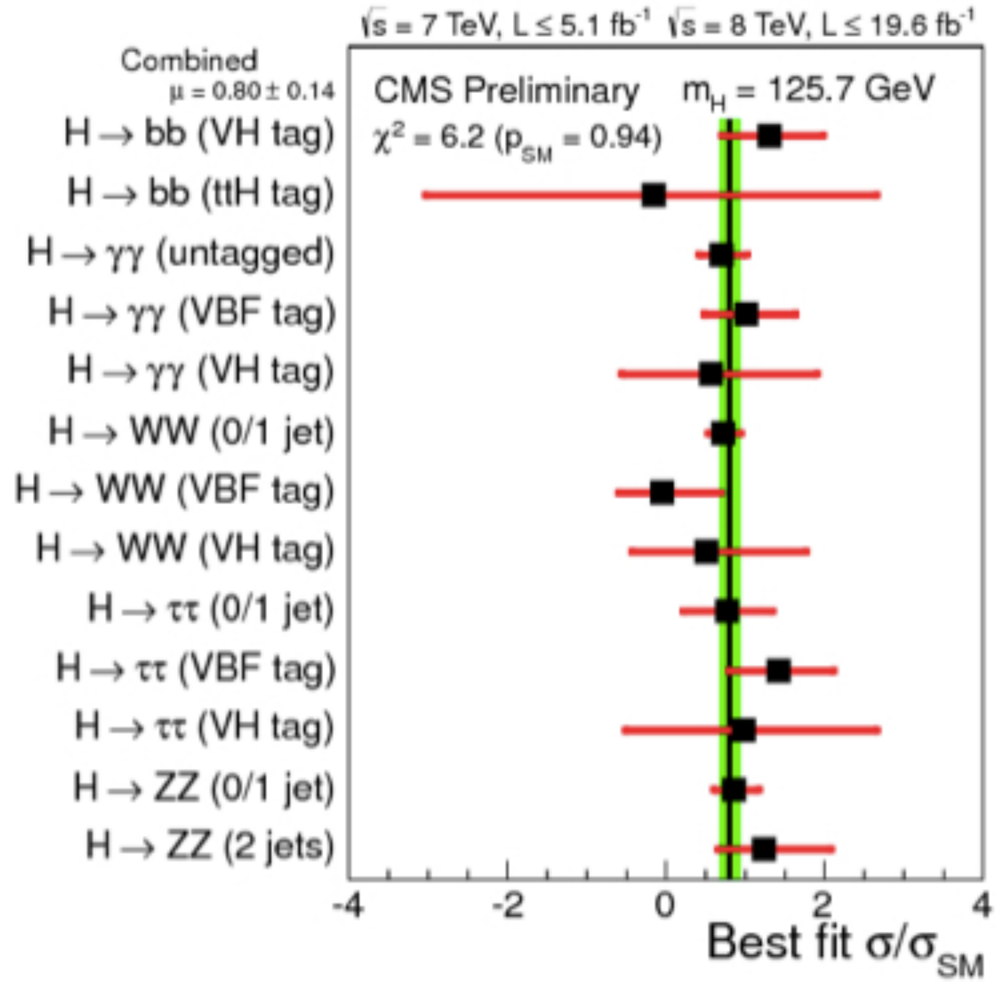
An amazing discovery indeed on its own.
It is also the beginning of a new era for HEP





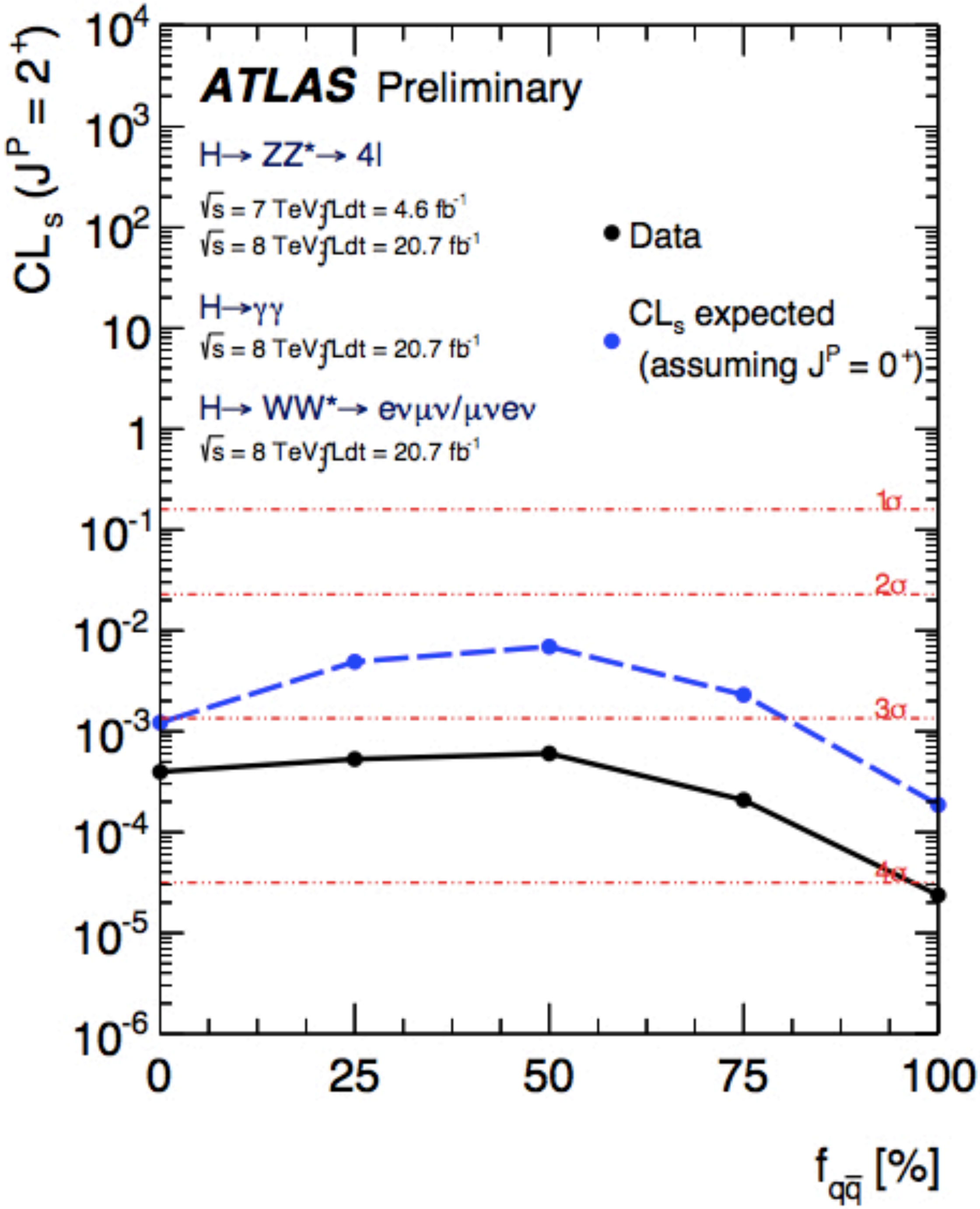
We need to understand to the best of the capabilities of the LHC what boson it is we discovered and whether we see more than one



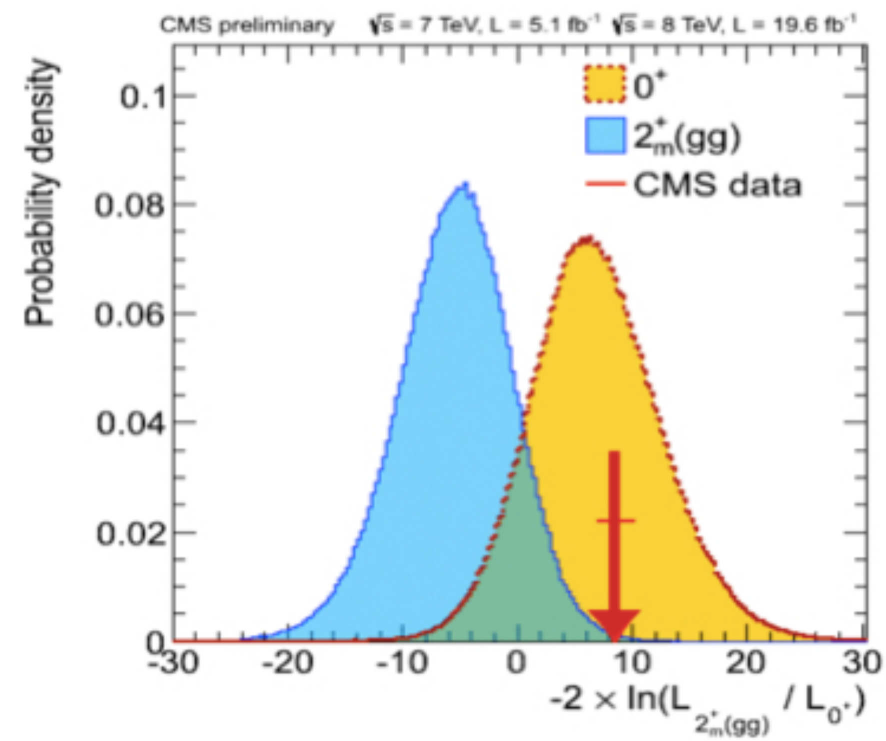


Higgs Boson Decay	μ (m_H=125.5 GeV)
$VH \to Vbb$	−0.4 ± 1.0
$H \to \tau\tau$	0.8 ± 0.7
$H \to WW^{(*)}$	1.0 ± 0.3
$H \to \gamma\gamma$	1.6 ± 0.3
$H \to ZZ^{(*)}$	1.5 ± 0.4
Combined	1.30 ± 0.20

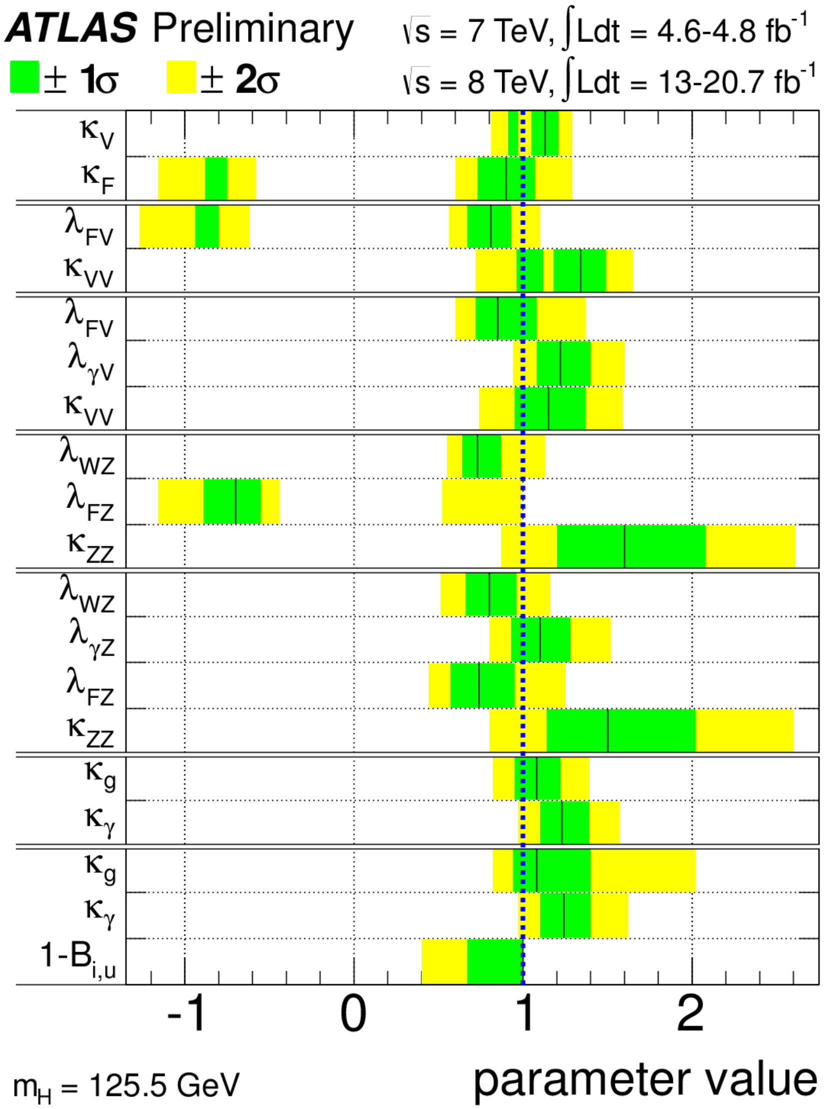
$\mu = 0.80 \pm 0.14$

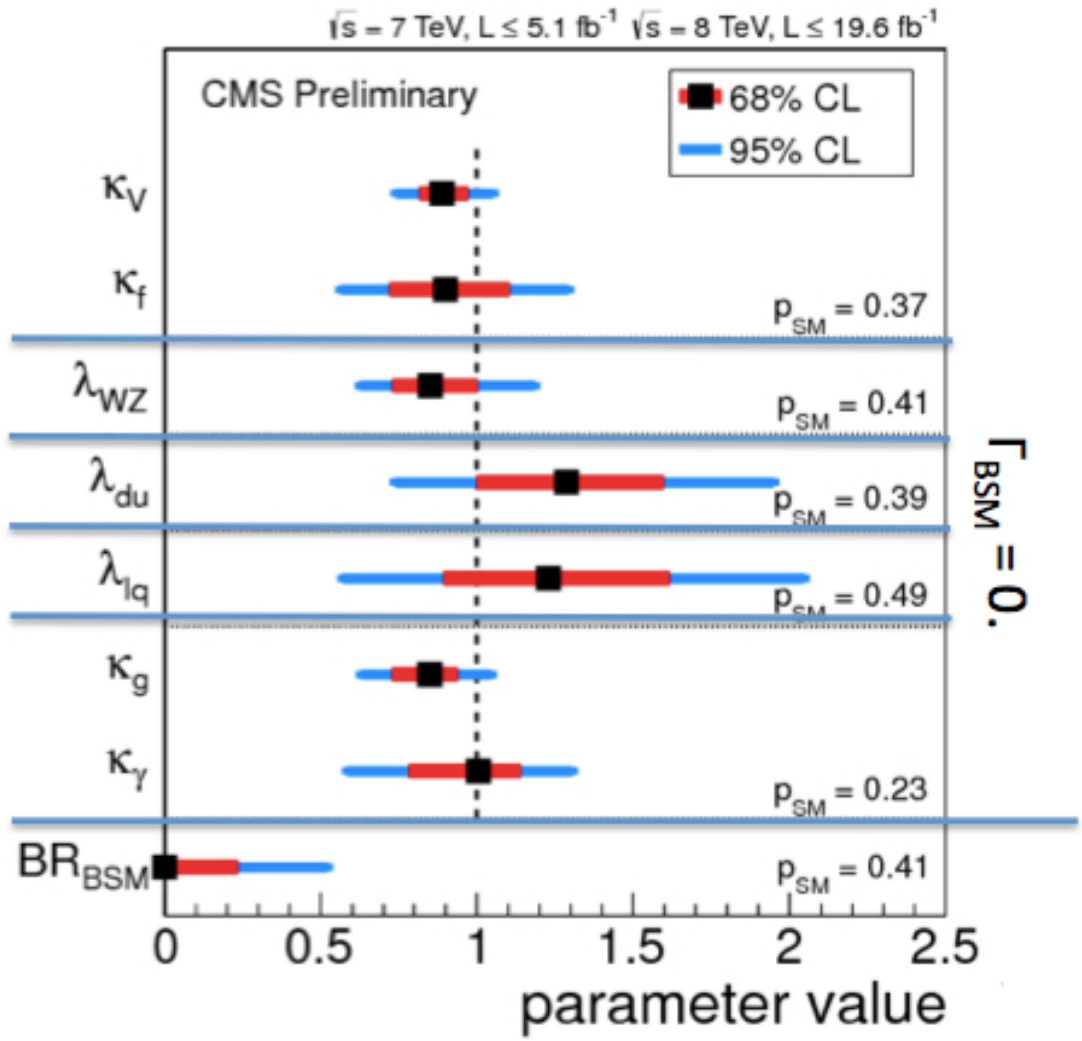


First preliminary combinations of CP-studies by CMS and ATLAS available. Consistent picture: compatibility of data with pure SM 0⁺ hypothesis and incompatibility with other spin-CP hypotheses explored



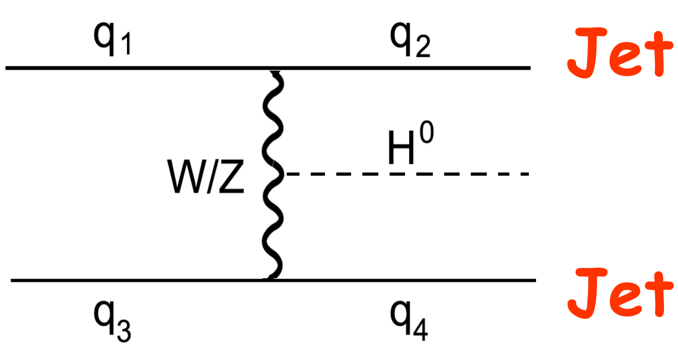
Tests performed so far indicate compatibility with the SM Higgs boson hypothesis





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)**

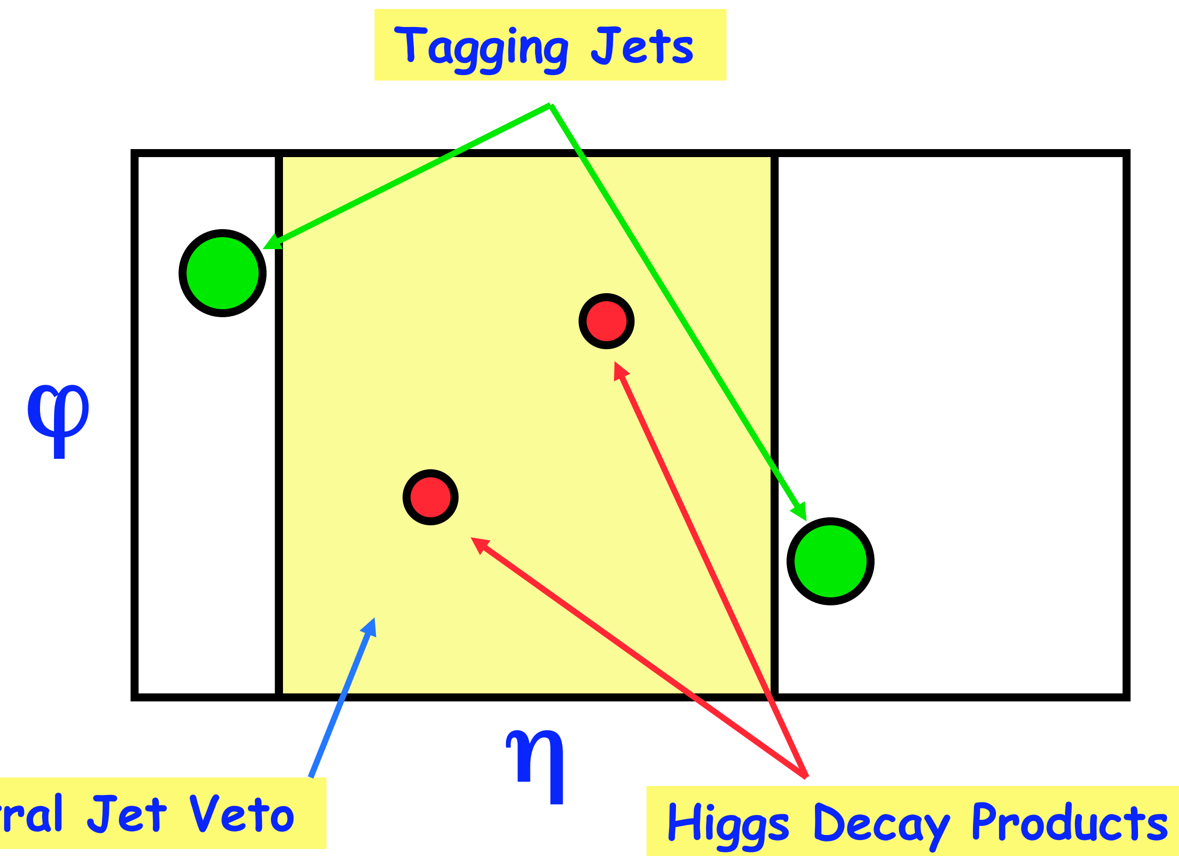


$\eta_{J1} \cdot \eta_{J2} < 0$

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

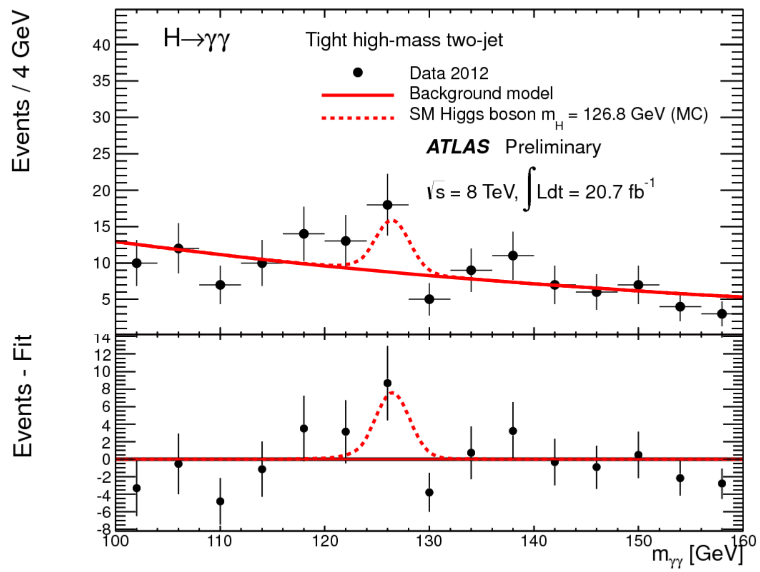
$M_{JJ} > 500 \div 700\mathrm{GeV}$

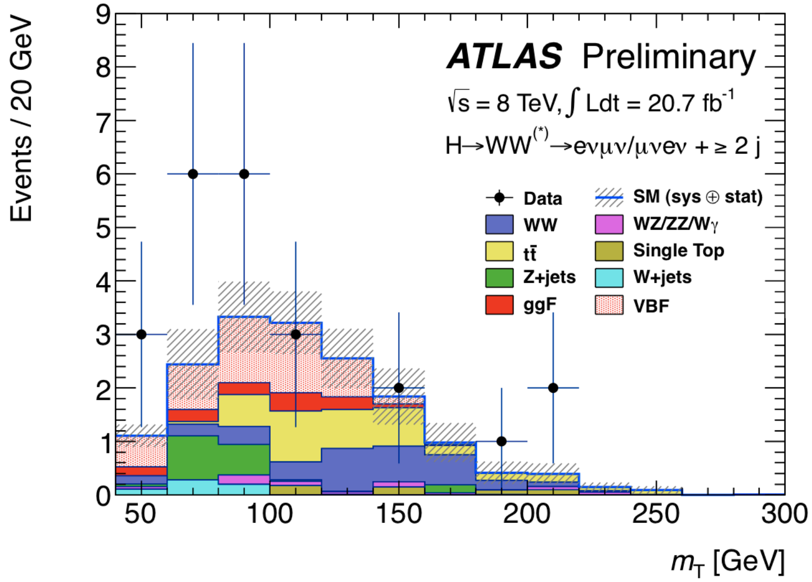
c.j.v.

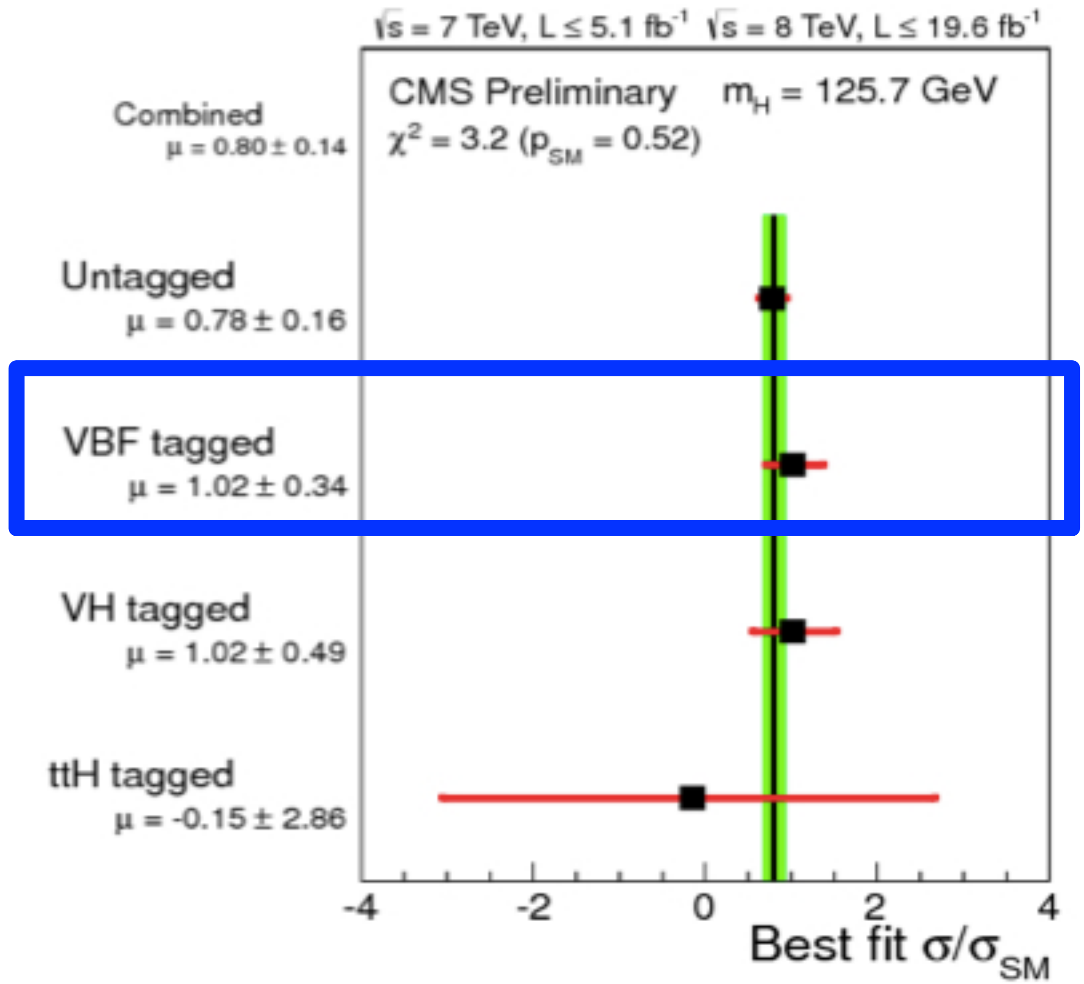


Use of forward jet tagging is not established at the LHC

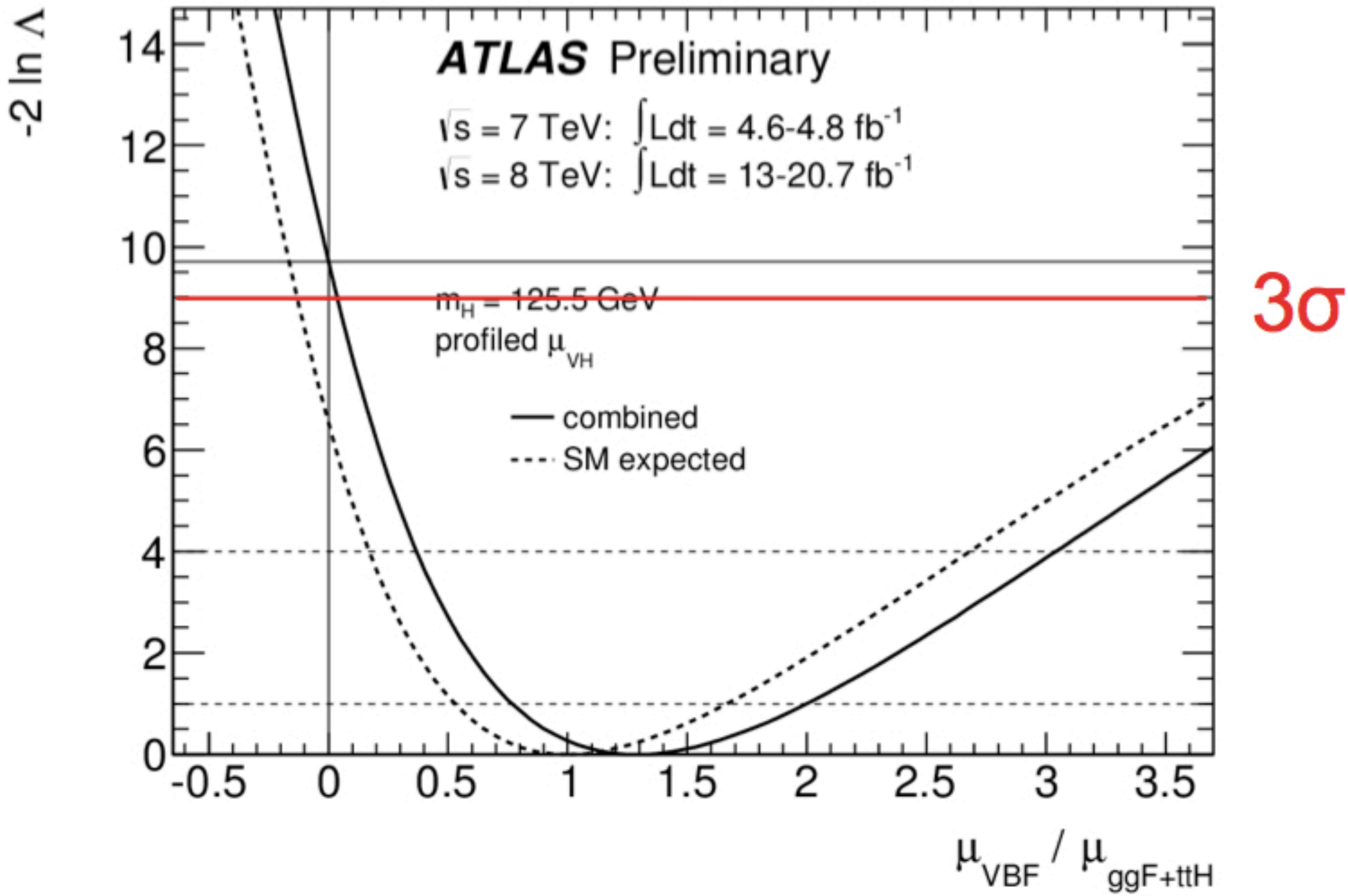
The VBF Signal at the LHC







The VBF Signal at the LHC

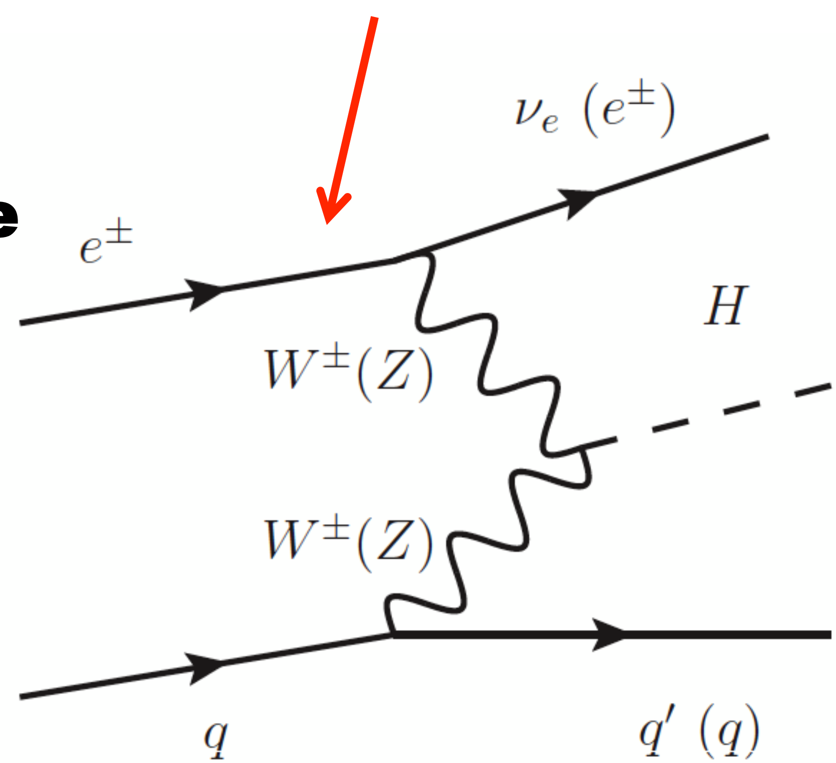


Higgs at LHeC

At LHeC replace
Lepton line by quark line

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

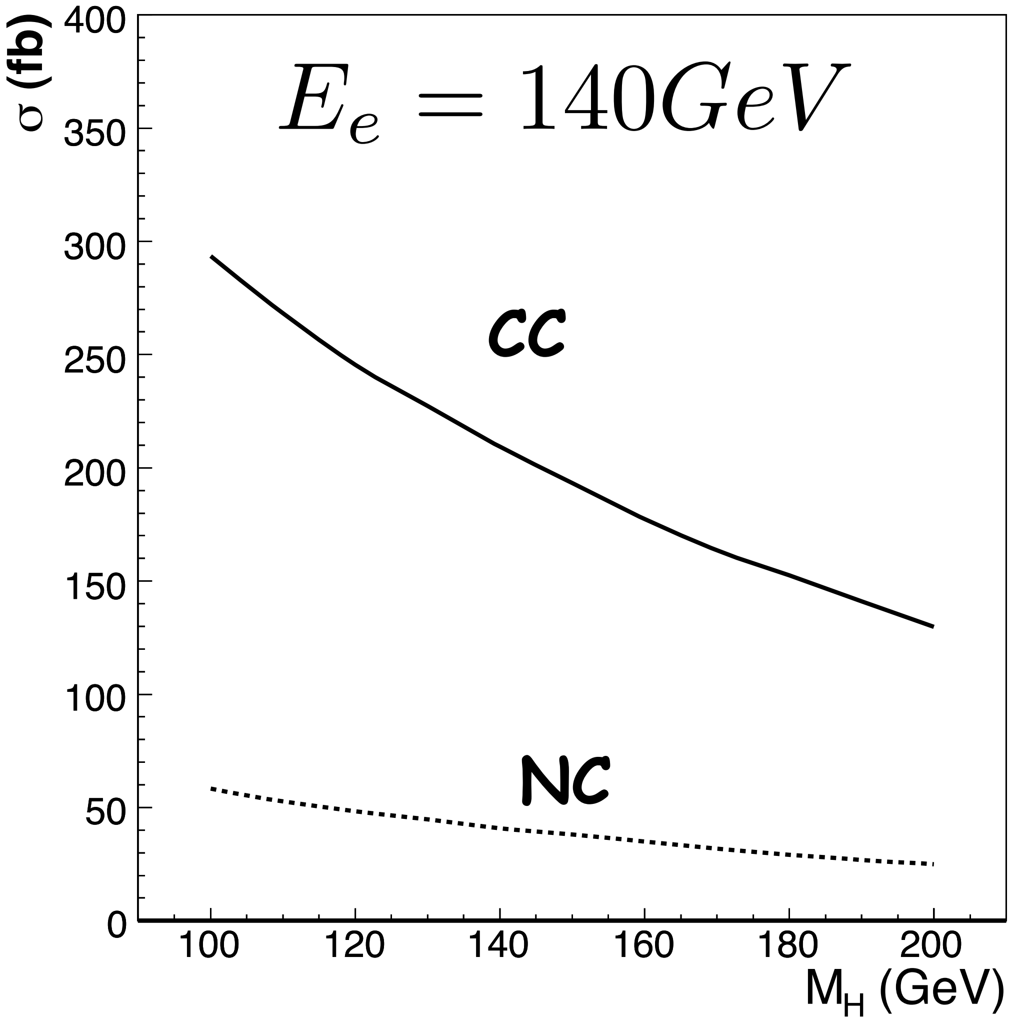
- ❑ **Consider feasibility for the following point:**

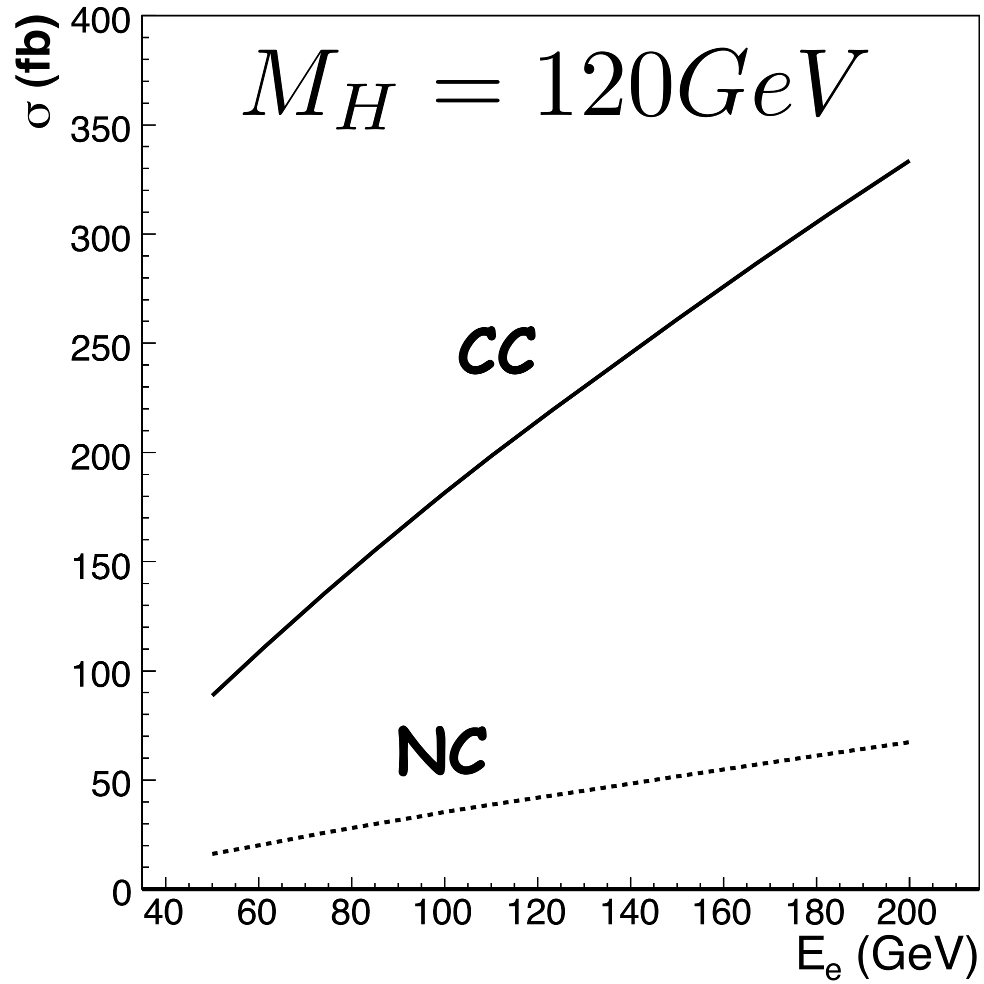


$$E_p = 7\ \ \text{TeV}, \quad E_e = 140\ \ \text{GeV}, \quad M_H = 120\ \ \text{GeV}$$

Cross-Sections

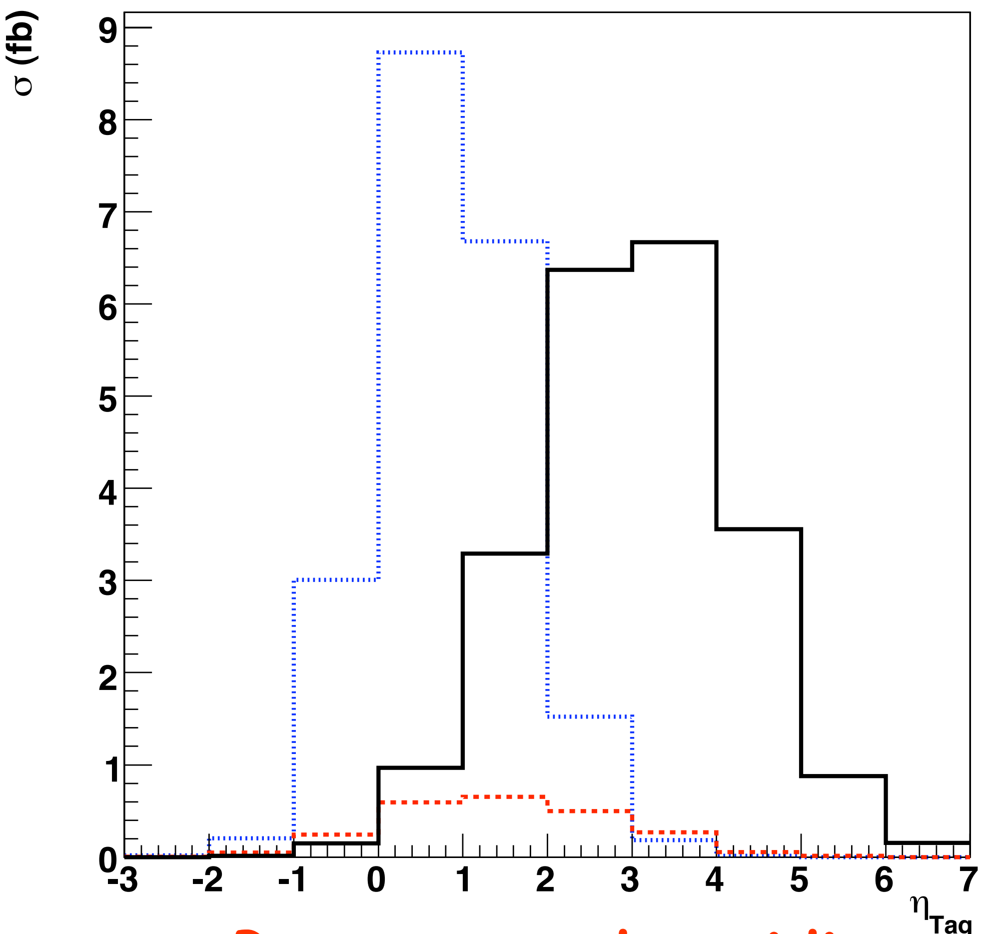
- Used Madgraph and CTEQ6L for e^-p scattering
  - Set scales to M_H. Little scale dependence



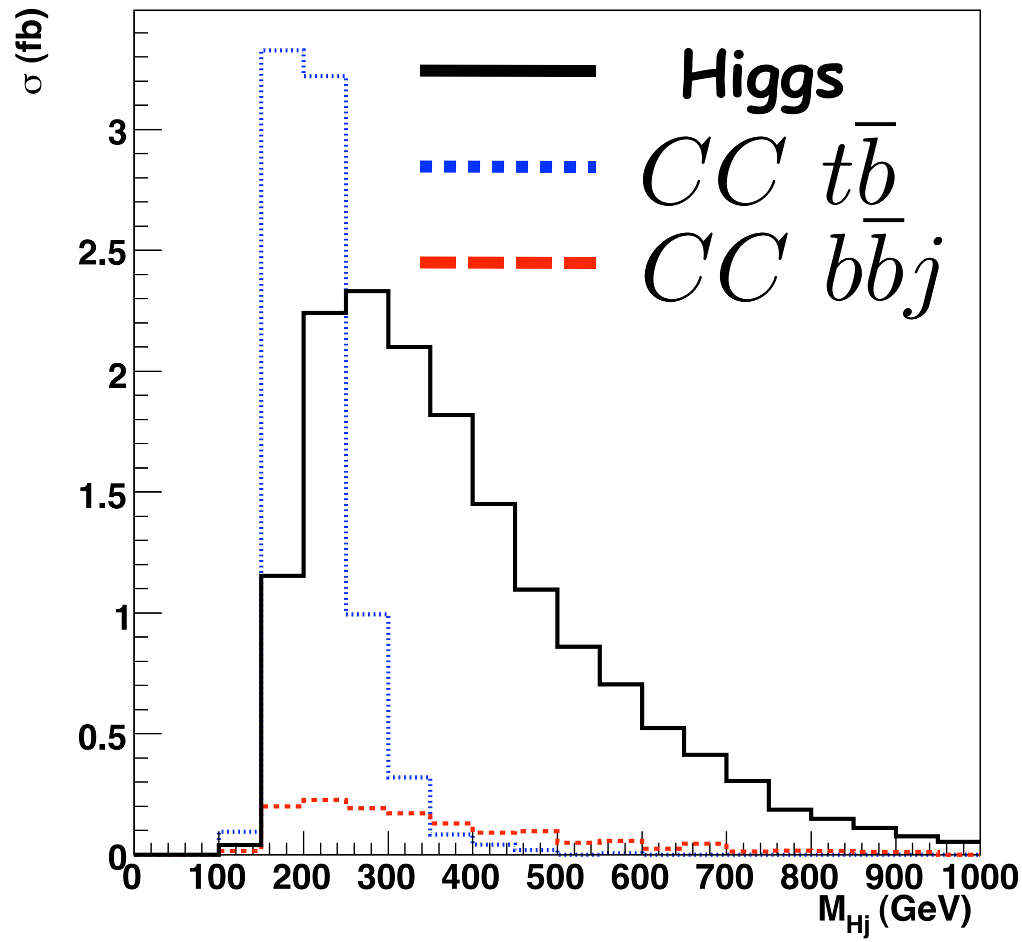


Kinematics in Charge Current Analysis

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



Parton pseudorapidity



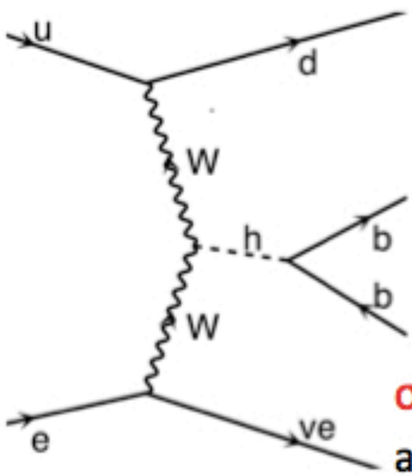
Higgs-Parton Mass

MC Samples in Hadron-level study

U.Klein et al.

Signal

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

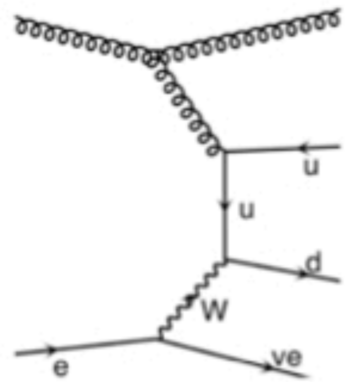


σ~ 0.16 pb
at √s=2.05TeV

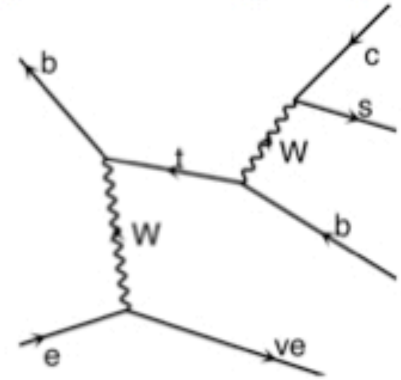
NOTE: Background sample numbers are after pre-selection in generator

Background (examples)

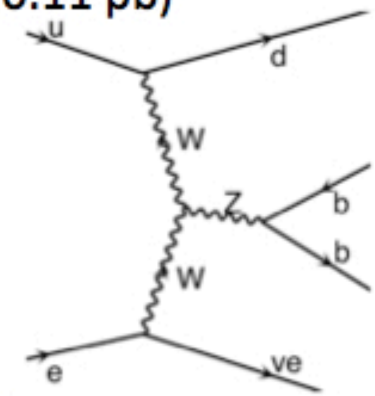
CC: 3 jets (~57 pb)



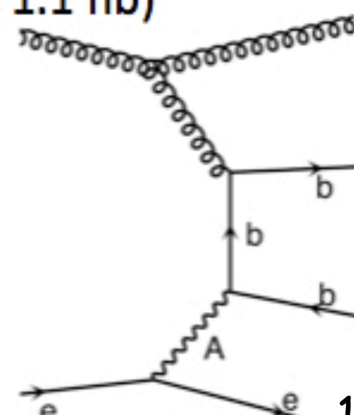
CC: single top production (~4.1 pb)



CC: Z production (~0.11 pb)



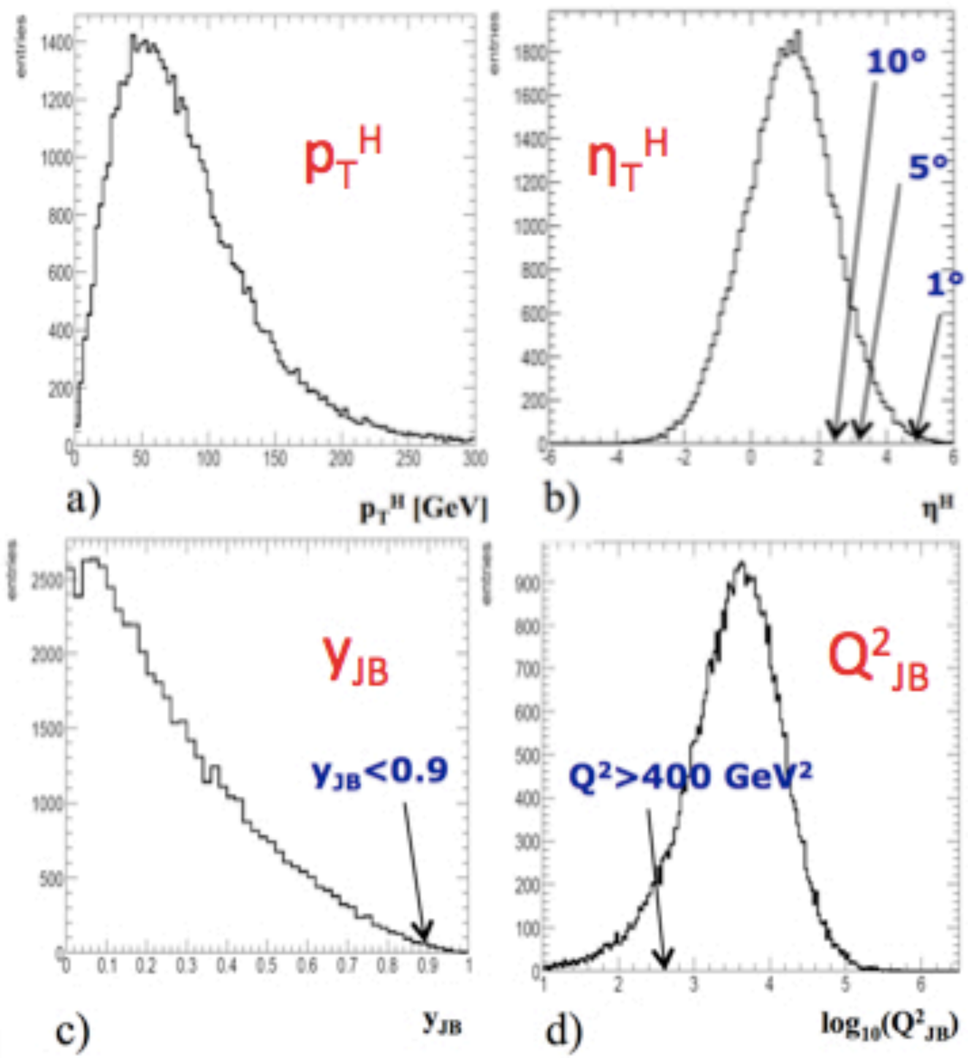
NC: b pair production (~1.1 nb)



Kinematic distributions

[M_H=120 GeV, E_e=150 GeV, E_p=7 TeV]

a-b) Kinematic distributions of generated Higgs
c-d) Reconstructed y_{JB} and Q^2_{JB}



Generated events passed to Pythia and to generic LHC-style detector:

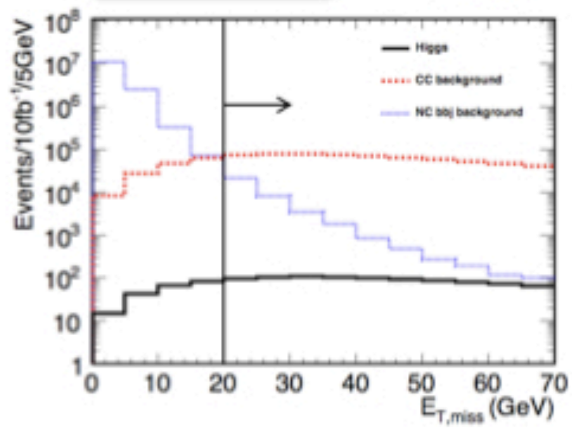
- Coverage:
  - Tracking: $|\eta| < 3$
  - Calorimeter: $|\eta| < 5$
- Calorimeter resolution
  - EM: $1\% \oplus 5\%/\sqrt{E}$
  - Hadron: $60\%/\sqrt{E}$
  - Cell size: $(\Delta\eta, \Delta\phi) = (0.03, 0.03)$
- Jet reconstructed (cone ΔR=0.7)
- b-tag performance
  - Flat efficiency for $|\eta| <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

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

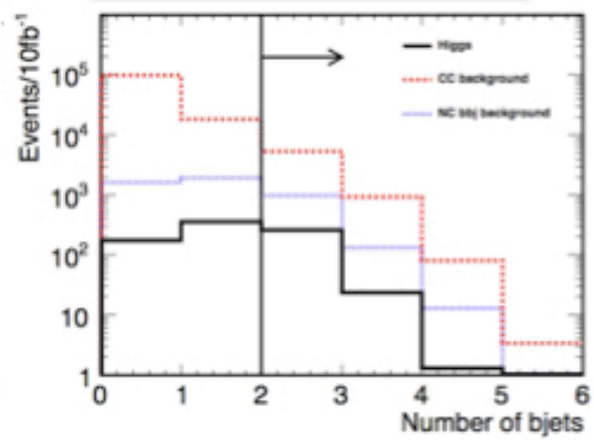
- NC rejection
  - Exclude electron-tagged events
  - $E_{T,miss} > 20$ GeV
  - N_{jet} ($p_T > 20$ GeV) $\geqq 3$
  - $E_{T,total} > 100$ GeV
  - $y_{JB} < 0.9$, $Q^2_{JB} > 400$ GeV^2
- b-tag requirement
  - $N_{b\text{-}jet}$ ($p_T > 20$ GeV) $\geqq 2$
- Higgs invariant mass
  - $90 < M_H < 120$ GeV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

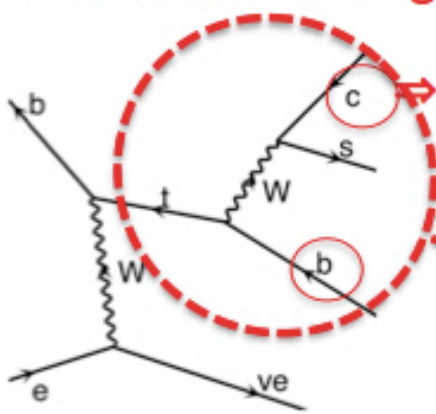
$H \to b\bar{b}$
CC BG
NC BG

E_T^{miss} cut

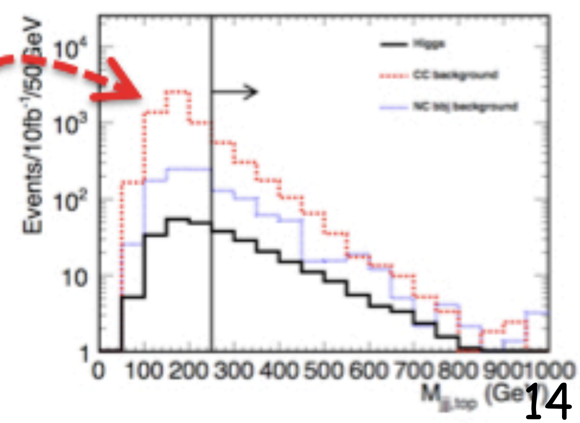


b-tag requirement





⇒10% mis-ID

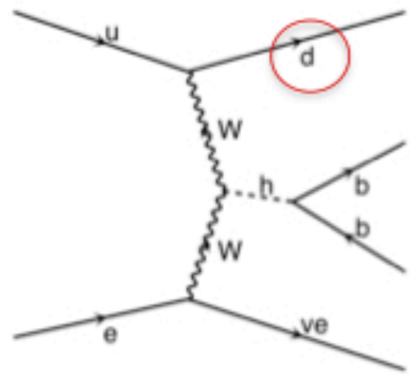


LHeC H→b$\bar{b}$ results [M_H=120 GeV, E_p=7 TeV]

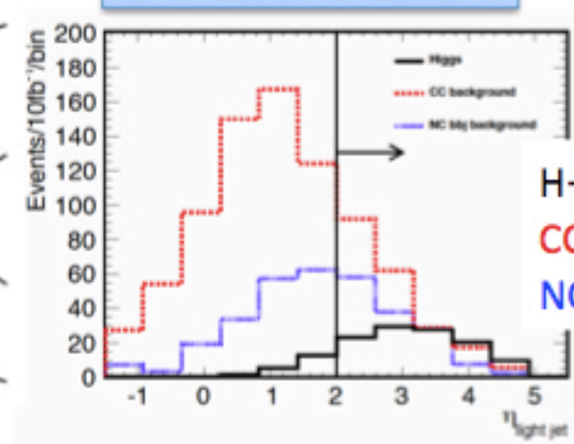
- Forward jet tagging
  - η_{jet} > 2 (lowest η jet excluding b-tagged jets)

  Coordinate:
  Fwd: +z-axis along proton beam

H → b$\bar{b}$ signal

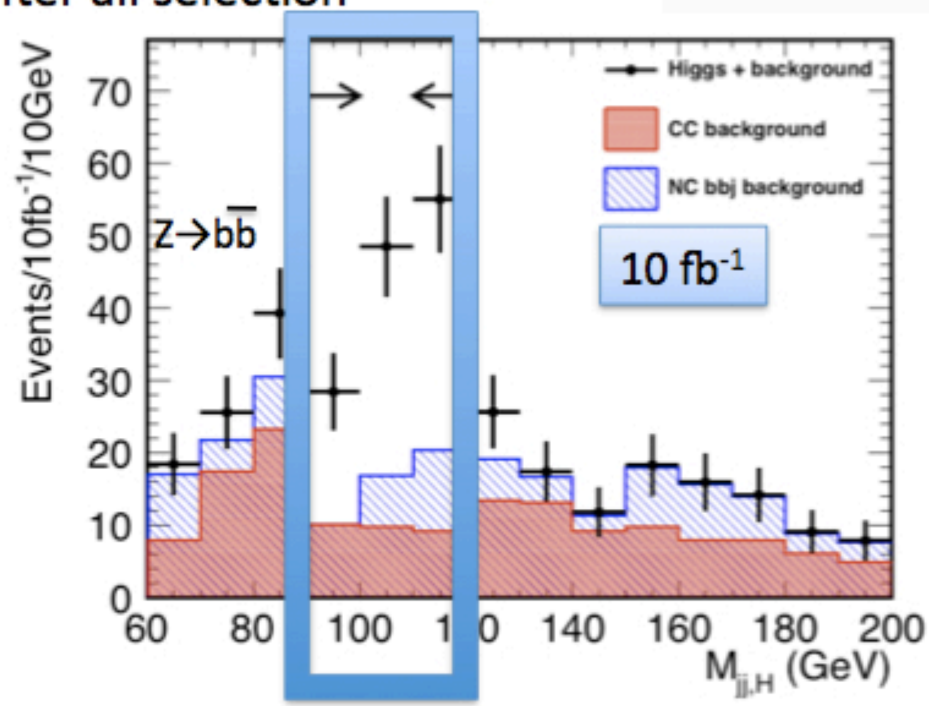


Forward jet η tag



- Higgs invariant mass after all selection

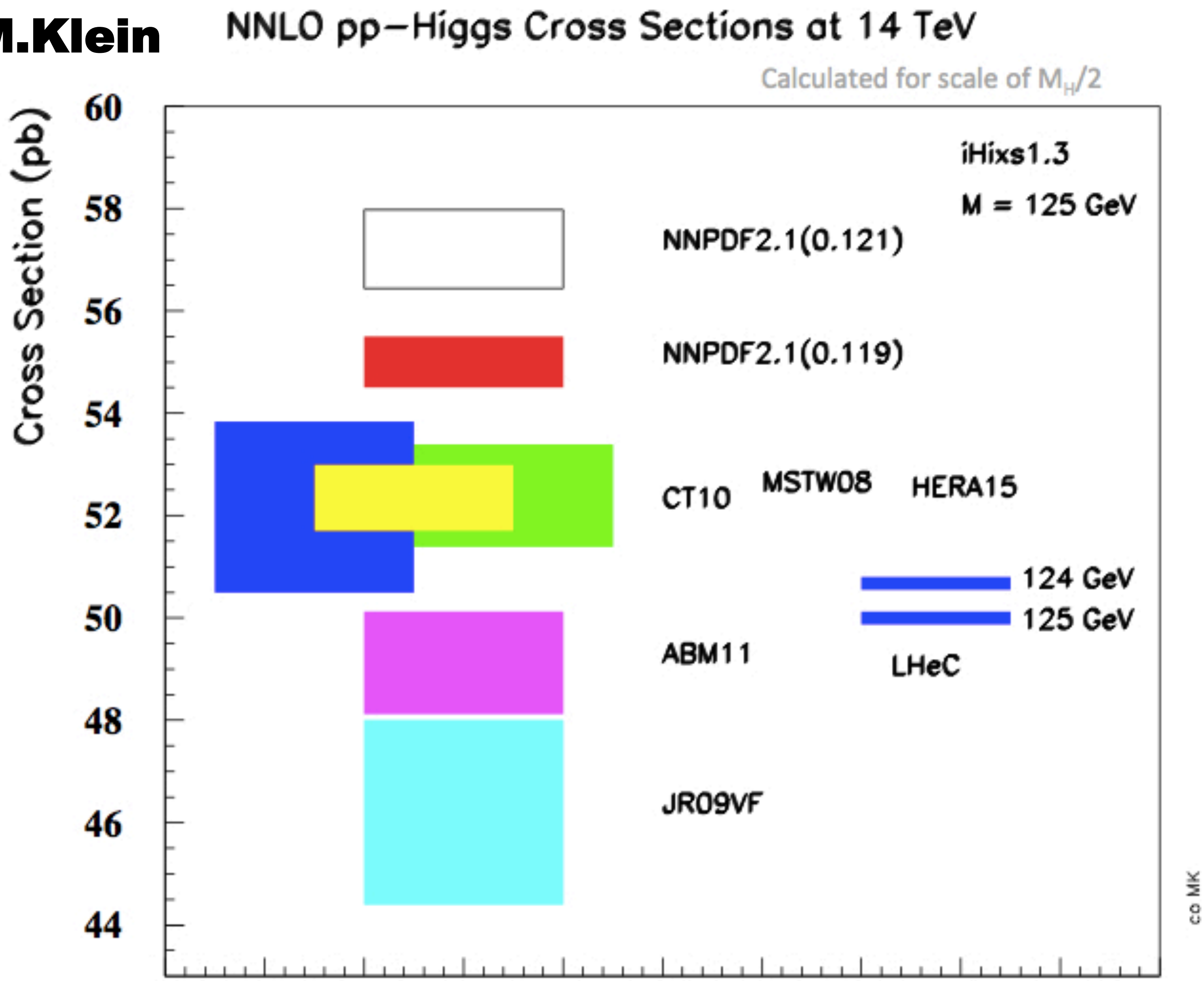
E_e=150 GeV



Expect 500 H->bb events at 60 GeV for 100 fb^{-1} -> 3% cross section measurement

Clear signal obtained with just cut based analysis already!

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

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 $\not{C}\!P$ in a model independent way (most studies so far)

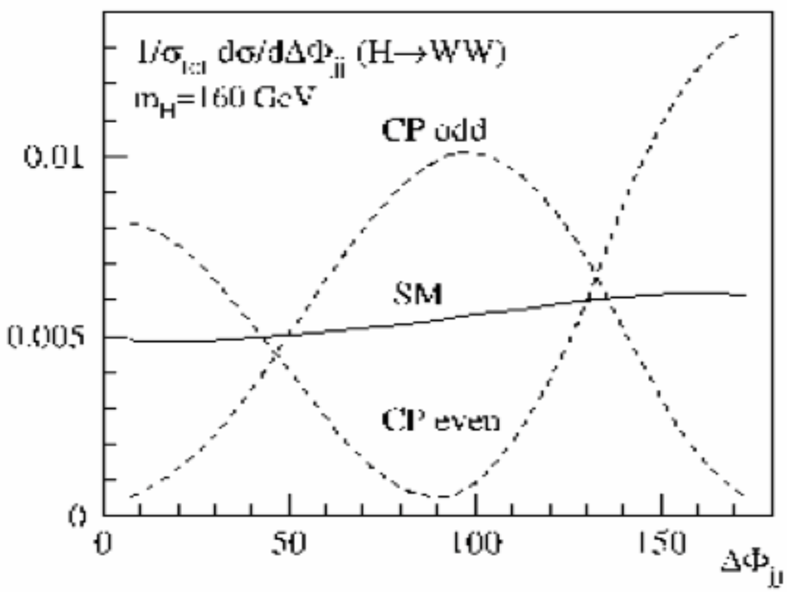
$H f \bar{f} : -\frac{g m_f}{2M_W} \bar{f} \left(a_f + i b_f \gamma_5 \right) f H$

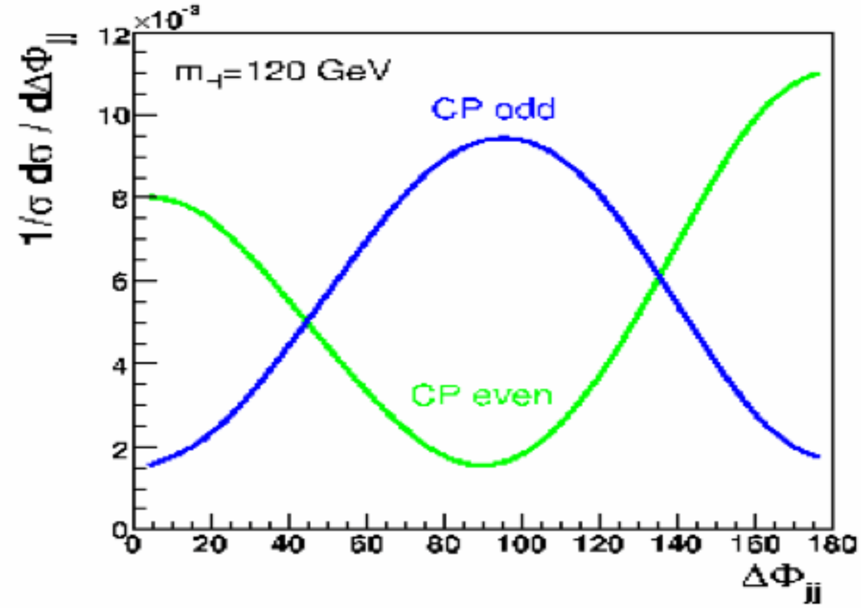
HVV:

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

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

Study by Zeppenfeld et al:

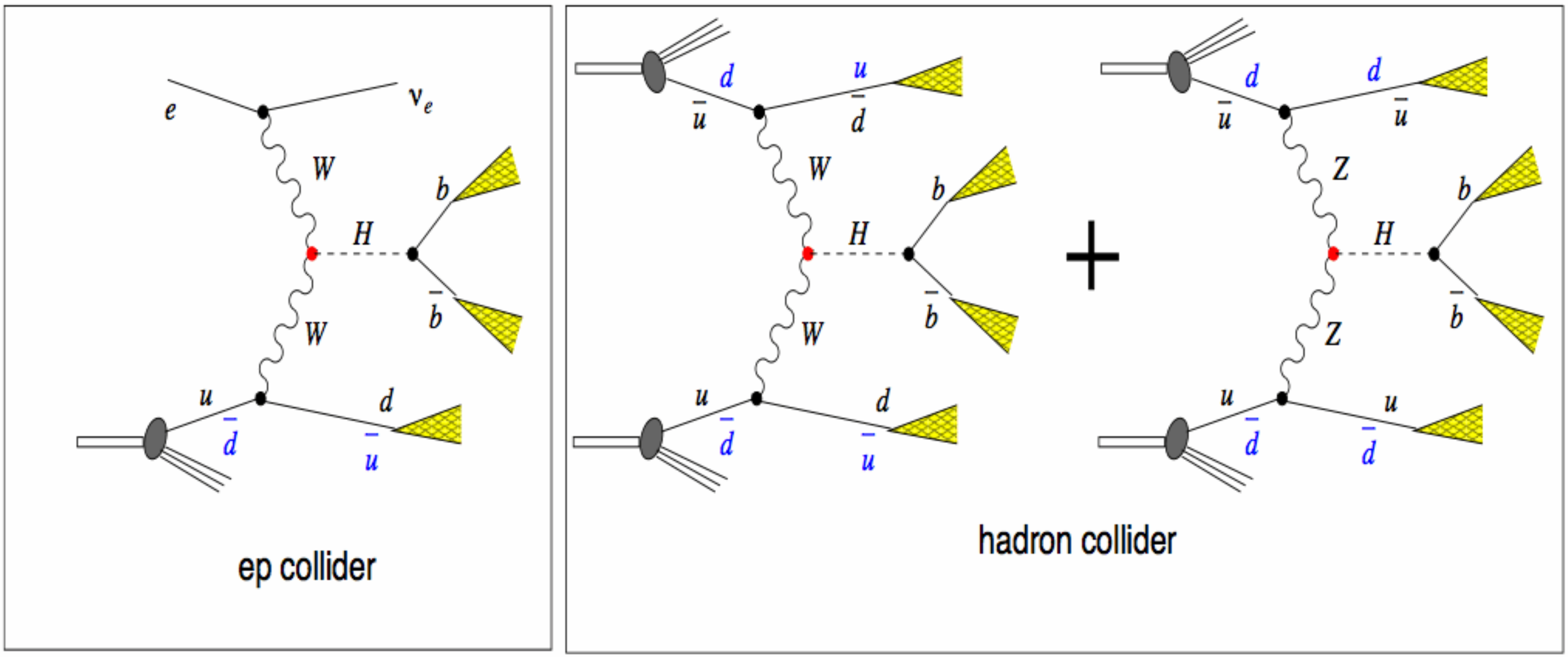




Left plot: VBF, CP even and CP odd refer to the dimension 5 operator.

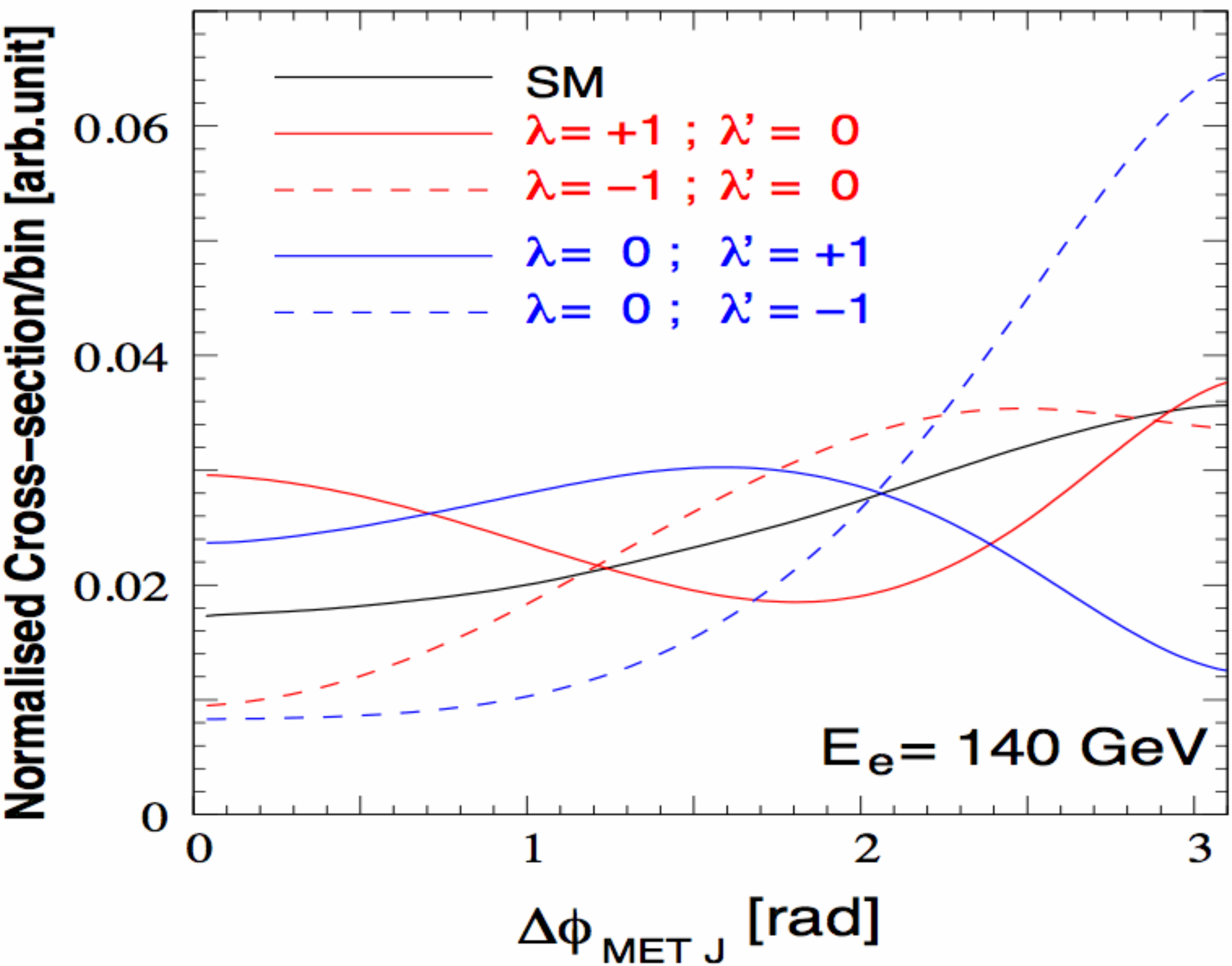
For gluon fusion the angular distribution is decided by the CP property of the $t\bar{t}H$ coupling.

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


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
Δφ MET J [rad]

The behaviour very similar to that seen for pp. So the disribution can look at CP property of the Higgs cleanly.

This behaviour essentially follows from the behaviour of matrix element square.

In LHC studies, the modification in the ϕ distribution (dips and peaks) were used with VBF specific cuts. We see that the structure is there even w/out those cuts.

Further no ambiguity about sign of ϕ.

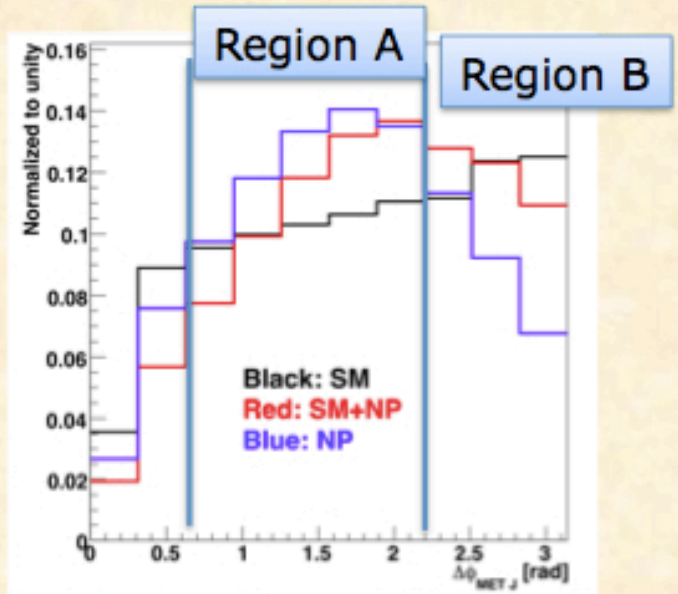
At LHeC the entire range of ϕ is available.

What happens with cuts and reality?

Case Study for M_H=120 GeV

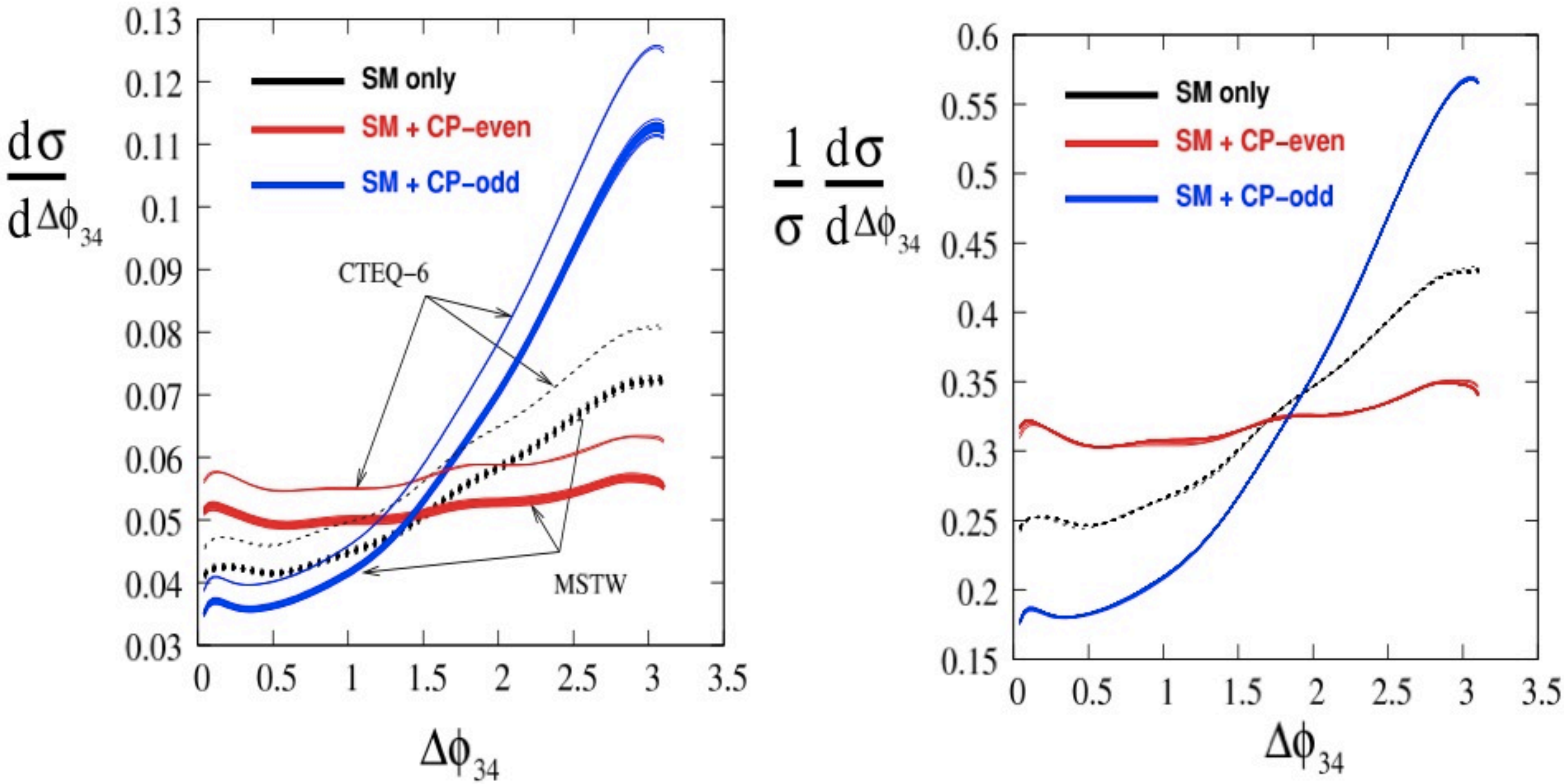
- Measure deviation of the Higgs production with respect to the SM using the absolute rate of events
- The ratio of the number of events in region B to that of region A in the $\Delta\varphi_{MET,J}$ spectrum

CP-odd case



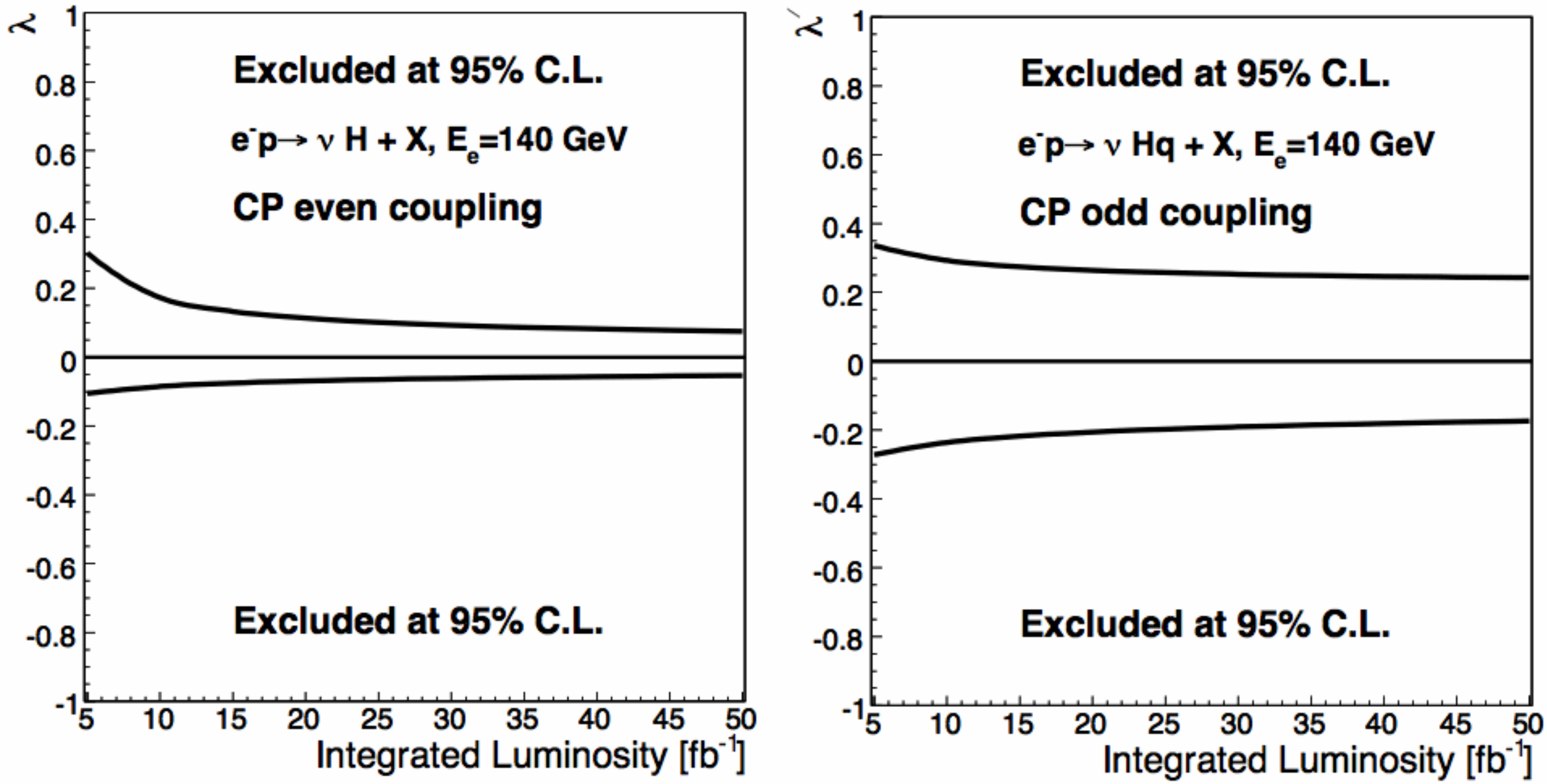
- Assume Gaussian errors and the following systematics:
  - 10% on the background rate
  - 5% on the shape of the $\Delta\varphi_{MET,J}$ in background
  - 5% on the rate of the SM Higgs
  - Evaluating theoretical error on $\Delta\varphi_{MET,J}$ shape

Effect of PDF uncertainties and pdf choice

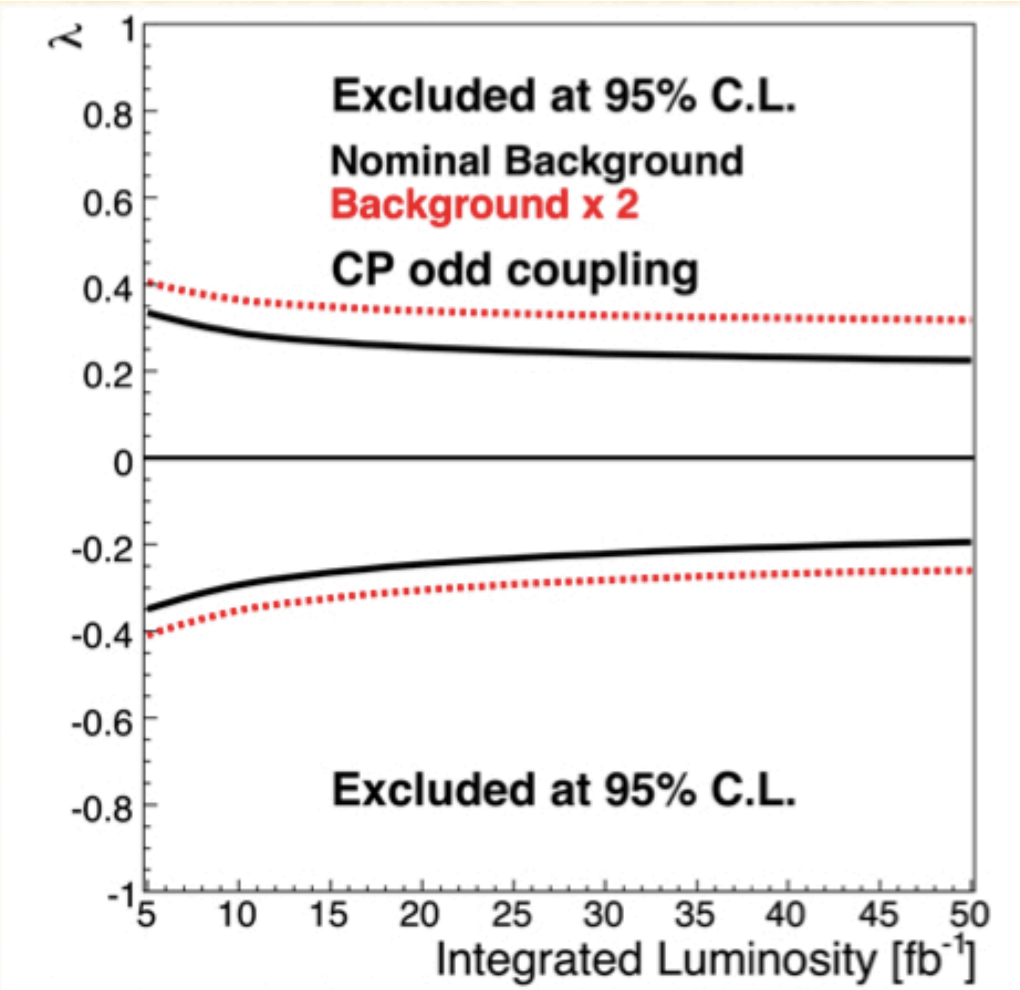


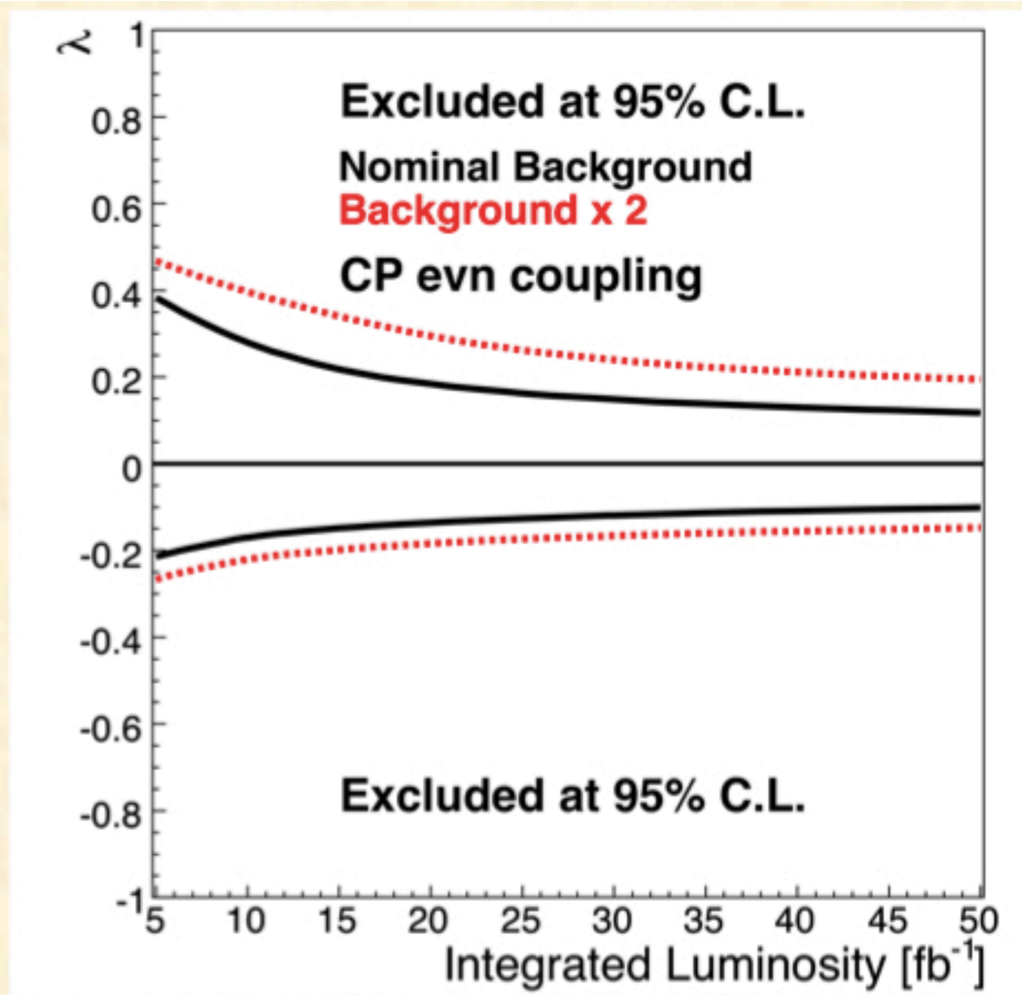
Results on the sensitivity with updated background as per the simulations of U. Klein (DIS 2011)

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



Effect of background normalization on





Considering high luminosity scenarios (contribution to IPAC13)
Aim: to turn the LHeC into a Higgs factory

Exploration of Higgs Boson Properties with the LHeC

Observe the Higgs in decays not accessible by the LHC

Number of events for 100 fb^{-1}. Exploring higher lumi scenarios

Oliver Brüning[1], Rohini Godbole[2], Max Klein[3], Uta Klein[3], Peter Kostka[3,4], Bruce Mellado[5], Frank Zimmermann[1]

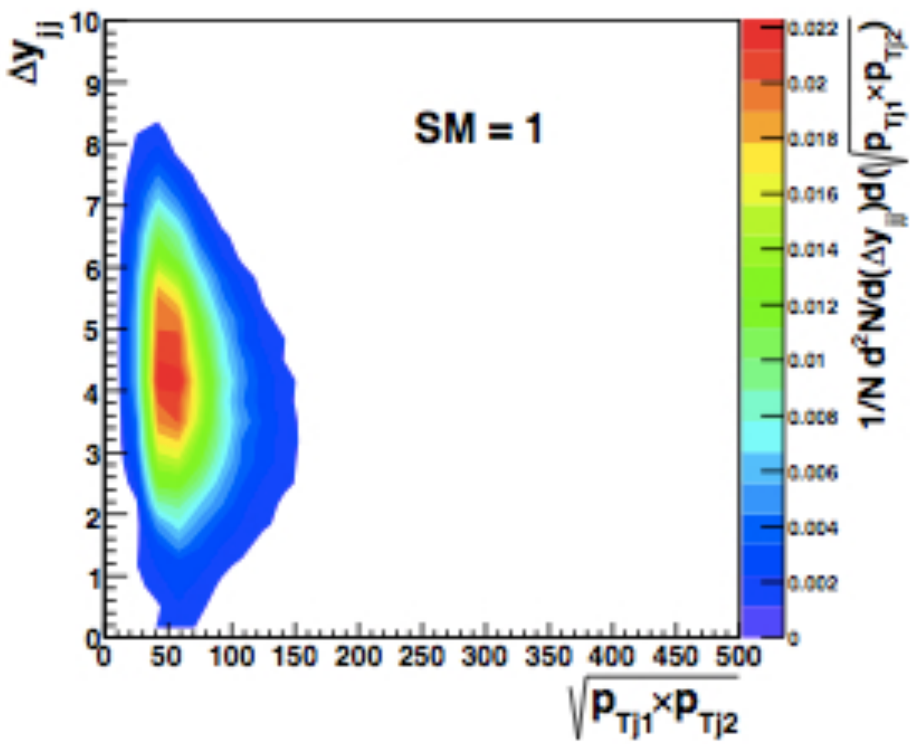
kinematic requirements	CC e^-p	CC e^+p	NC $e^{\pm}p$
cross section	109 fb	58 fb	20 fb
acceptance	0.92	0.94	0.93
H→ $b\bar{b}$	6500	3500	1200
H→ $c\bar{c}$	330	180	60
H→ gg	900	480	160
H→ WW	1400	760	260
H→ ZZ	160	190	30
H→ $\tau\tau$	570	310	100
H→ $\gamma\gamma$	20	12	4

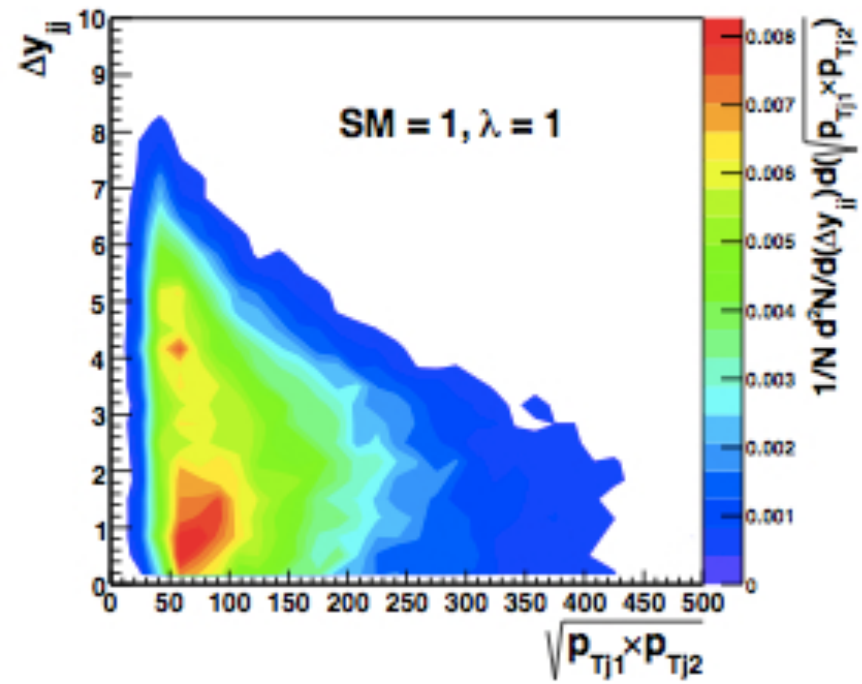
Structure of HVV couplings and jet Kinematics in VBF

C.Englert, D.Goncalves-Netto K.Mawatari and T.Plehn JHEP 1301 (2013) 148

A. Djouadi, R.Godbole, B.M. and K.Mohan, arXiv:1301.4965

New physics in the HVV coupling strongly distort the "VBF" jet kinematics. This also strongly affects the acceptance of the VBF signal





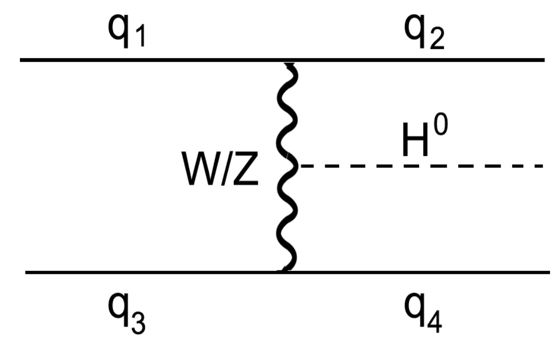
Similar studies are ongoing to assess this effect in ep collisions

Outlook and Conclusions

- A Higgs boson with a mass ~125 GeV has been discovered and evidence for VBF mechanism given
- 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
  - VBF signature established at the LHC
- With the isolation of the $H \rightarrow bb$ 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
  - Separation of HWW and HZZ couplings
  - Excellent signal to background ratio
  - Possibility of tagging H->cc decay
- Exploring high lumi scenarios -> Higgs factory

Extra Slides

Higgs via VBF
Qualitative remarks



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

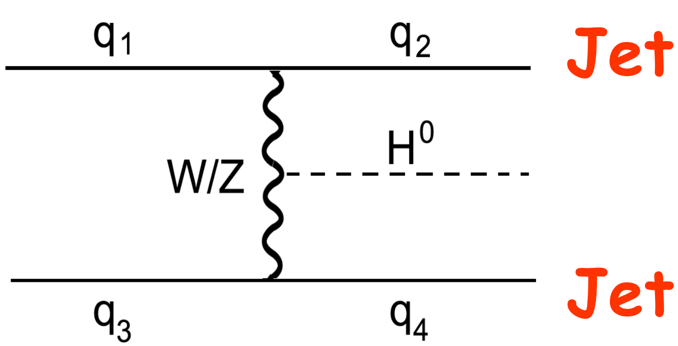
$$P^T_{V/f}(x, p_T^2) = \frac{g_V^2 + g_V^2}{8\pi^2} \frac{1 + (1-x)^2}{x} \frac{p_T^2}{(p_T^2 + (1-x)M_V^2)^2}$$

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

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

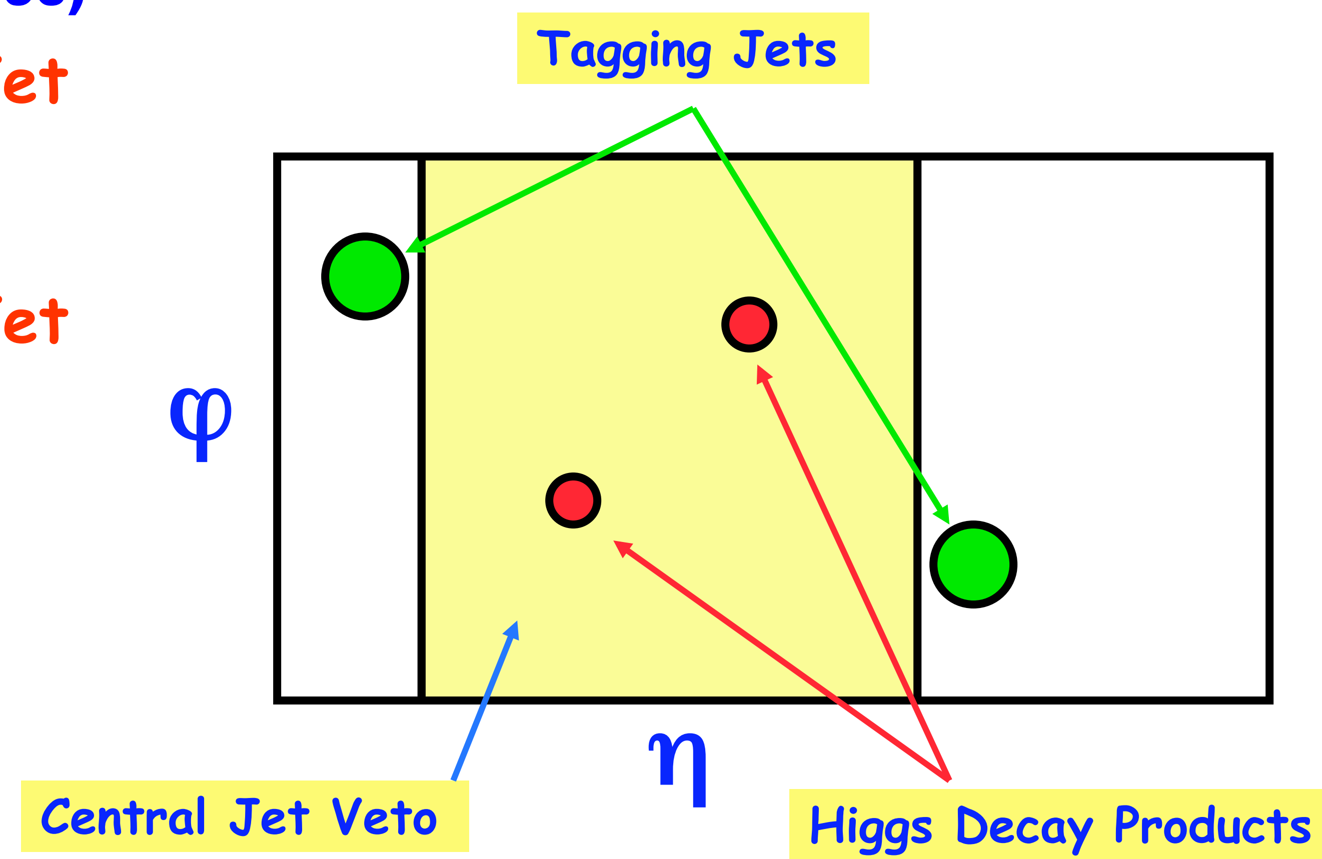


$\eta_{J1} \cdot \eta_{J2} < 0$

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

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

c.j.v.



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

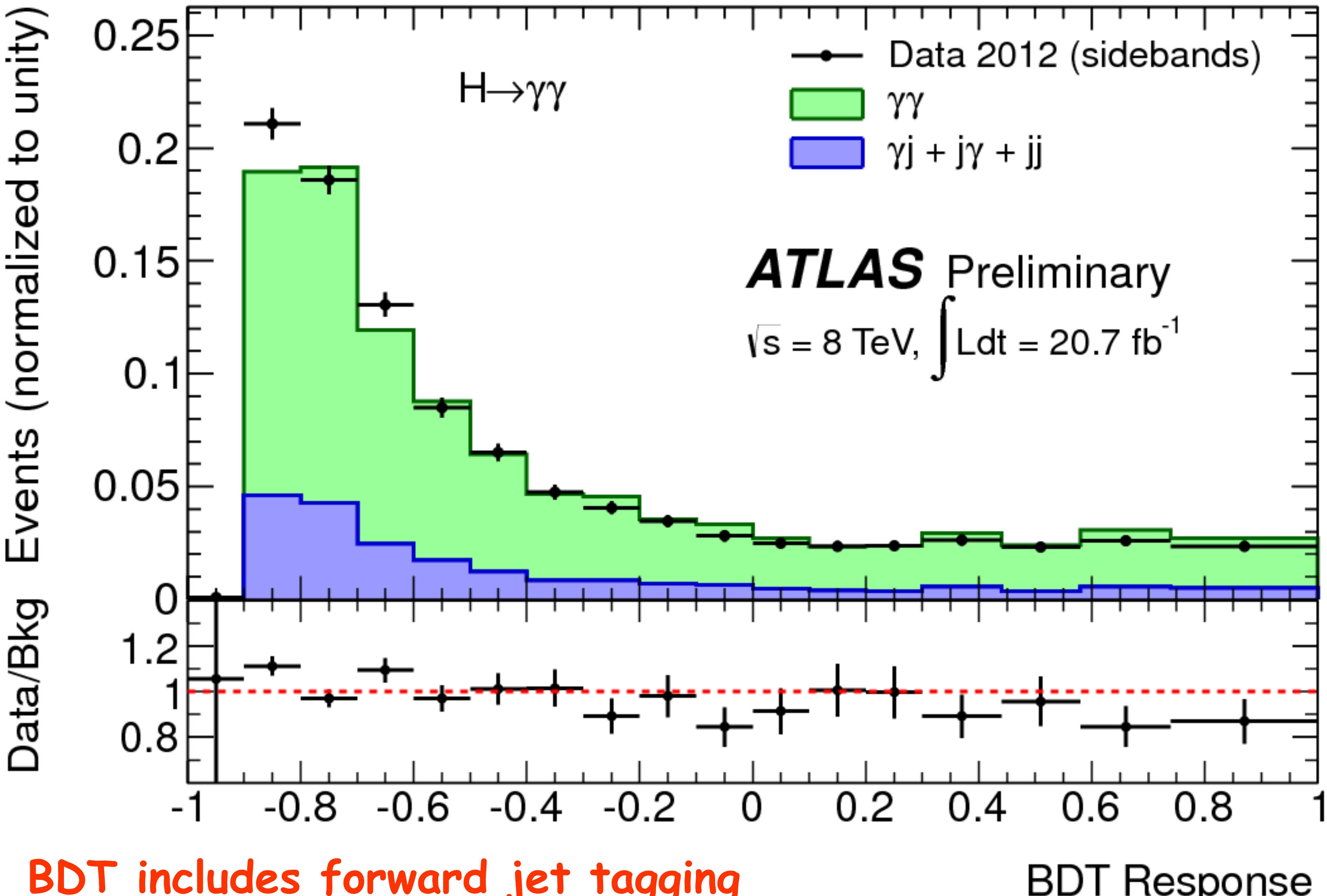
$$P_{T j,b} > 30\,GeV \;\rightarrow\; P_{T j,b} > 20\,GeV$$

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

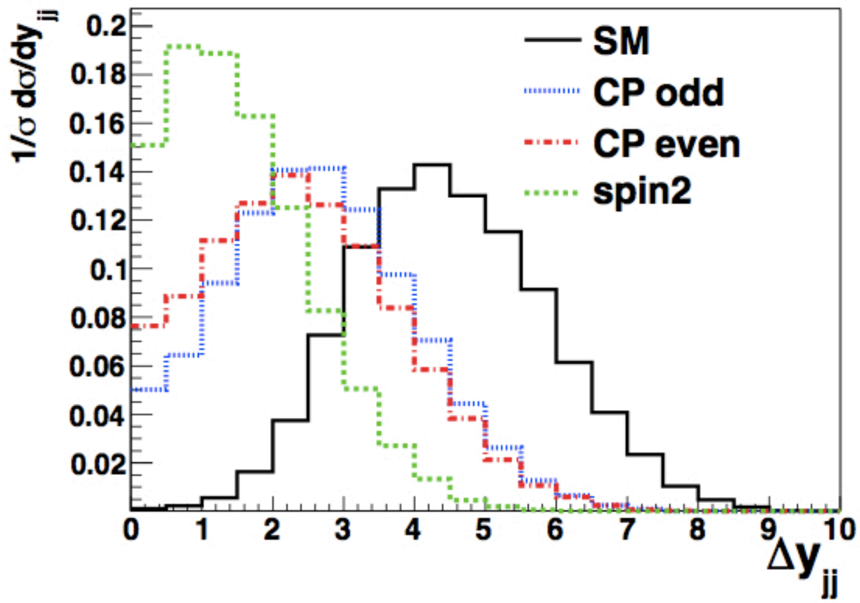
Signal Efficiency for Different E_e

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

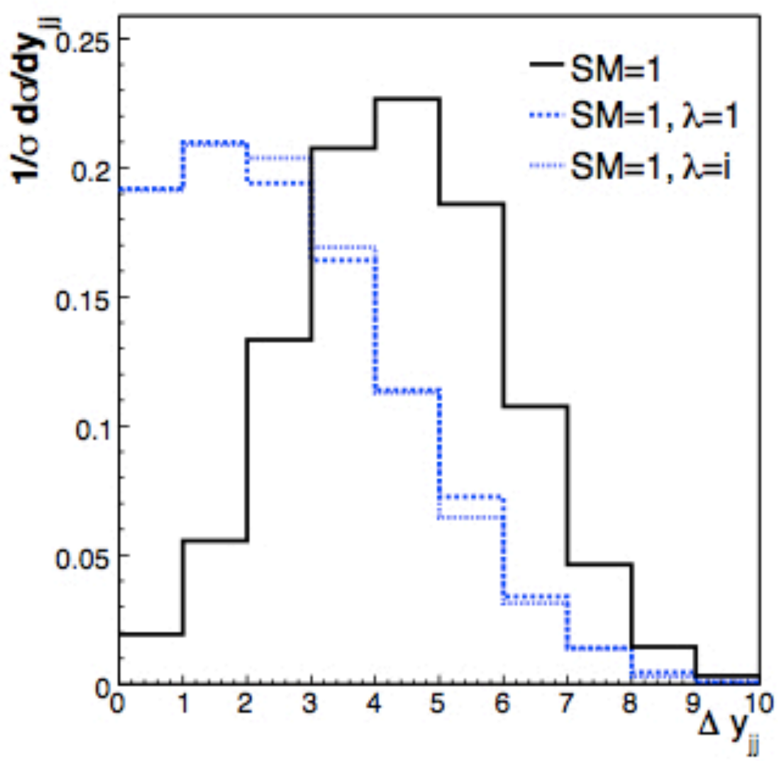
Cut	$E_e = 50$	$E_e = 100$	$E_e = 140$	$E_e = 200$
a	0.129 -	0.157 -	0.166 -	0.171 -
b	0.109 0.84	0.127 0.81	0.132 0.80	0.136 0.80
c	0.076 0.70	0.090 0.71	0.093 0.70	0.095 0.70
d	0.050 0.66	0.067 0.75	0.073 0.79	0.078 0.82



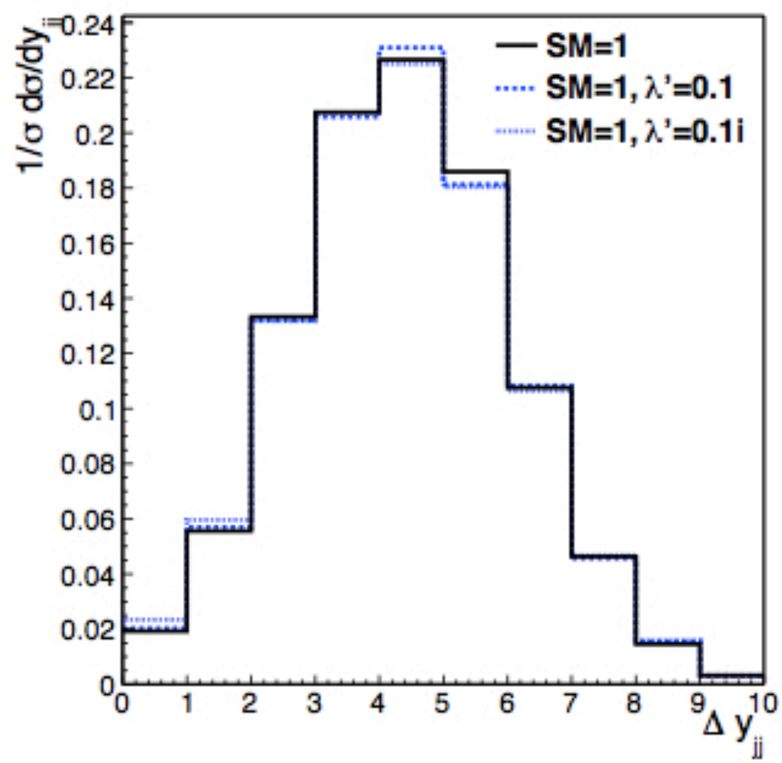
BDT includes forward jet tagging



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