Double Higgs Production at the FCC-he

M.Kumar, X.Ruan, A.Cornell, R.Islam, M.Klein, U.Klein and B.Mellado

LHeC Workshop, Chavannes-de-Bogis, 26/06/15

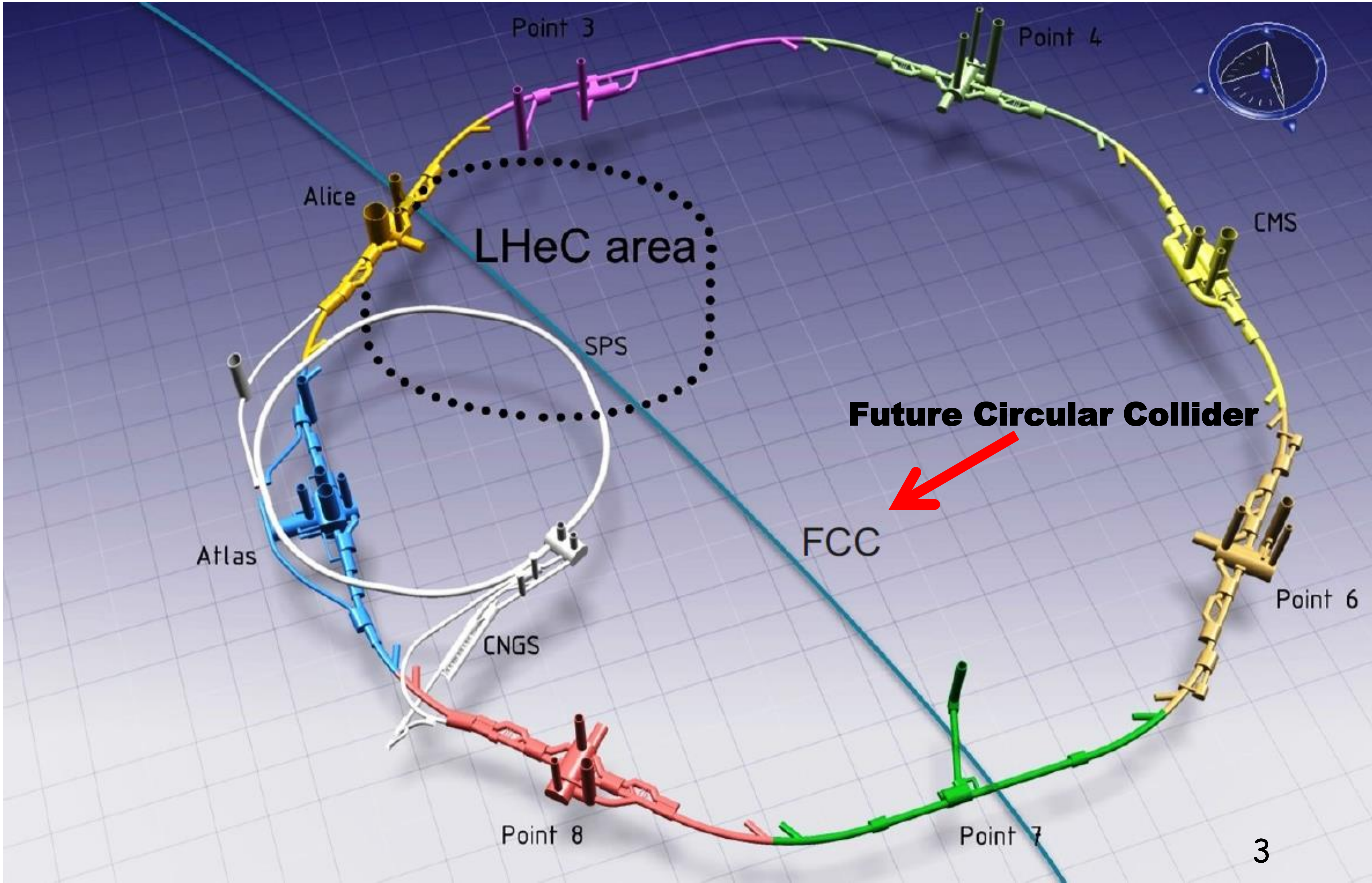
M.Klein

LHeC, a Higgs Facility

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

Demonstrated ability to identify the Higgs boson. No Underlying event, pile up and excellent S/B

What about the FCC-he option?

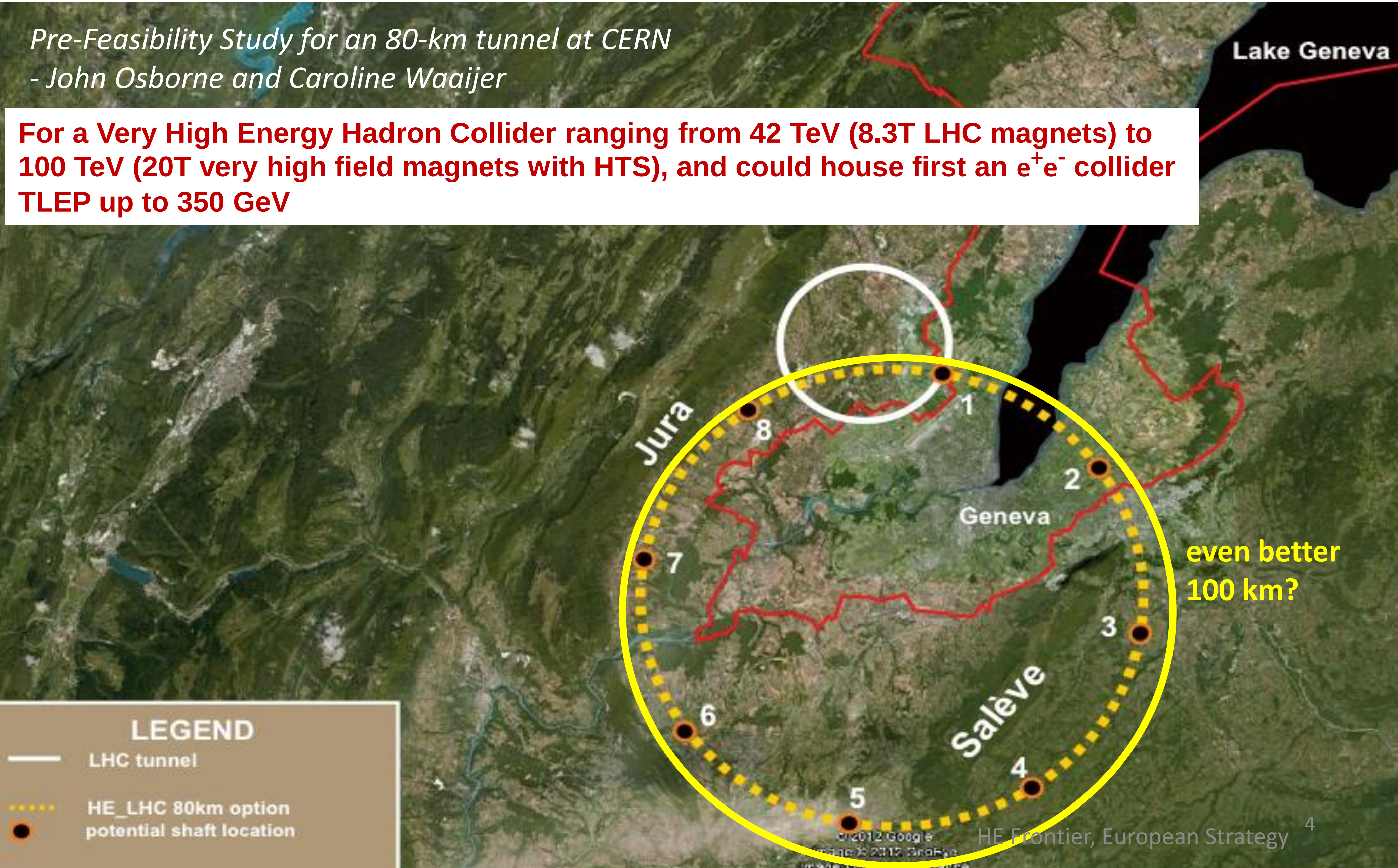

Point 3
Point 4
Alice
LHeC area
CMS
SPS
Future Circular Collider
FCC
Atlas
Point 6
CNGS
Point 8
Point 7

Lake-side option kept for further studies

P. Jenni

Pre-Feasibility Study for an 80-km tunnel at CERN
- John Osborne and Caroline Waaijer

For a Very High Energy Hadron Collider ranging from 42 TeV (8.3T LHC magnets) to 100 TeV (20T very high field magnets with HTS), and could house first an e^+e^- collider TLEP up to 350 GeV



collider parameters	FCC ERL	FCC-ee ring		protons
species	$e^-(e^+?)$	$e^\pm$	$e^\pm$	p
beam energy [GeV]	60	60	120	50000
bunches/beam	-	10600	1360	10600
bunch intensity [10^{11}]	0.05	0.94	0.46	1.0
beam current [mA]	25.6	480	30	500
rms bunch length [cm]	0.02	0.15	0.12	8
rms emittance [nm]	0.17	1.9 (x)	0.94 (x)	0.04 [0.02 y]
$\beta^*_{x,y}$ [mm]	94	8, 4	17, 8.5	400 [200 y]
$\sigma^*_{x,y}$ [μ m]	4.0	4.0, 2.0		equal
beam-b. parameter ξ	$(D = 2)$	0.13	0.13	0.022 (0.0002)
hourglass reduction	0.92 $(H_D = 1.35)$	0.21	0.39	
CM energy [TeV]	3.5	3.5	4.9	
luminosity [10^{34} cm^{-2}s^{-1}]	1.0	6.2	0.7	

F. Zimmermann, ICHEP2014

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

HWW coupling well probed at LHeC. However, physics in hh production can also be due to HHWW, which is not constrained.

$$\mathcal{L}^{(3)}_{hhh} = \frac{m_h^2}{2v}(1 - g^{(1)}_{hhh})h^3 + \frac{1}{2} g^{(2)}_{hhh} h\partial_\mu h \partial^\mu h,$$

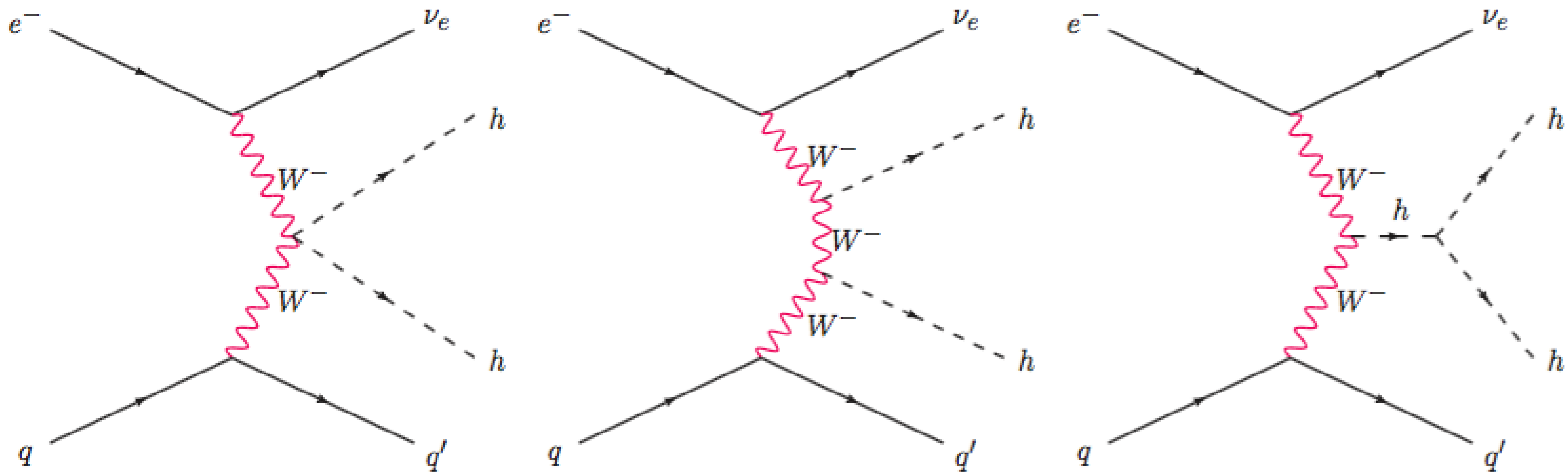
$$\mathcal{L}^{(3)}_{hWW} = -\frac{g}{2m_W} g^{(1)}_{hWW} W^{\mu\nu} W^\dagger_{\mu\nu} h - \frac{g}{m_W}\left[g^{(2)}_{hWW} W^\nu \partial^\mu W^\dagger_{\mu\nu} h + \text{h.c.}\right]$$
$$- \frac{g}{2m_W}\tilde{g}_{hWW} W^{\mu\nu}\tilde{W}^\dagger_{\mu\nu} h,$$

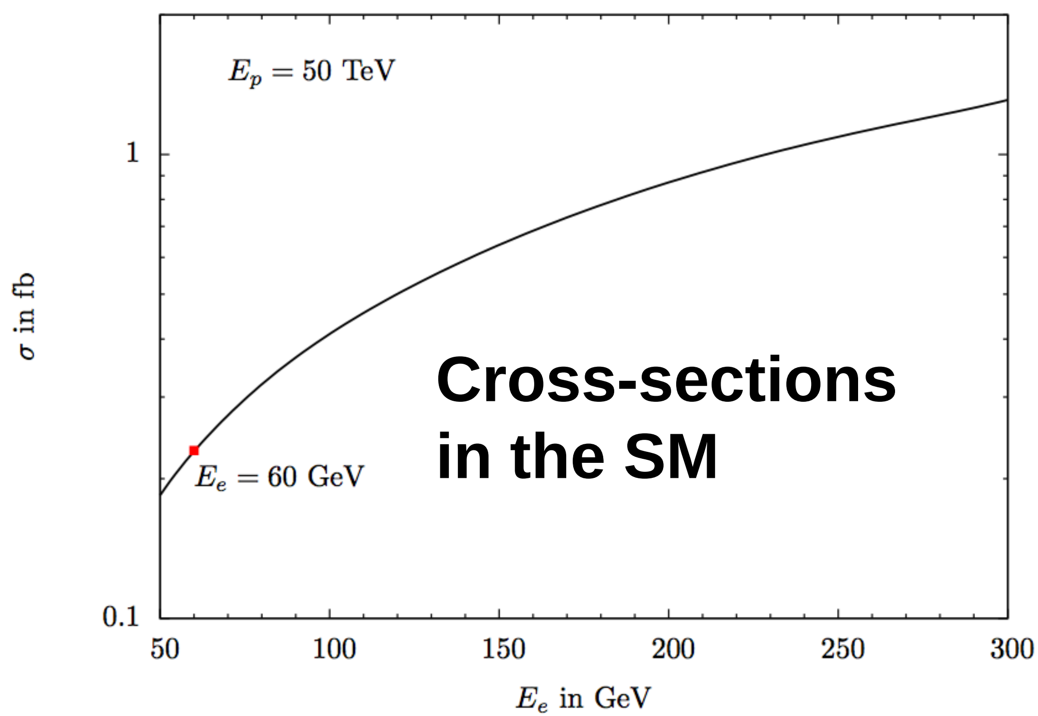
$$\mathcal{L}^{(4)}_{hhWW} = -\frac{g^2}{4m_W^2} g^{(1)}_{hhWW} W^{\mu\nu} W^\dagger_{\mu\nu} h^2 - \frac{g^2}{2m_W^2}\left[g^{(2)}_{hhWW} W^\nu \partial^\mu W^\dagger_{\mu\nu} h^2 + \text{h.c.}\right]$$
$$- \frac{g^2}{4m_W^2}\tilde{g}_{hhWW} W^{\mu\nu}\tilde{W}^\dagger_{\mu\nu} h^2.$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}^{(3)}_{hhh} + \mathcal{L}^{(3)}_{hWW} + \mathcal{L}^{(4)}_{hhWW}$$

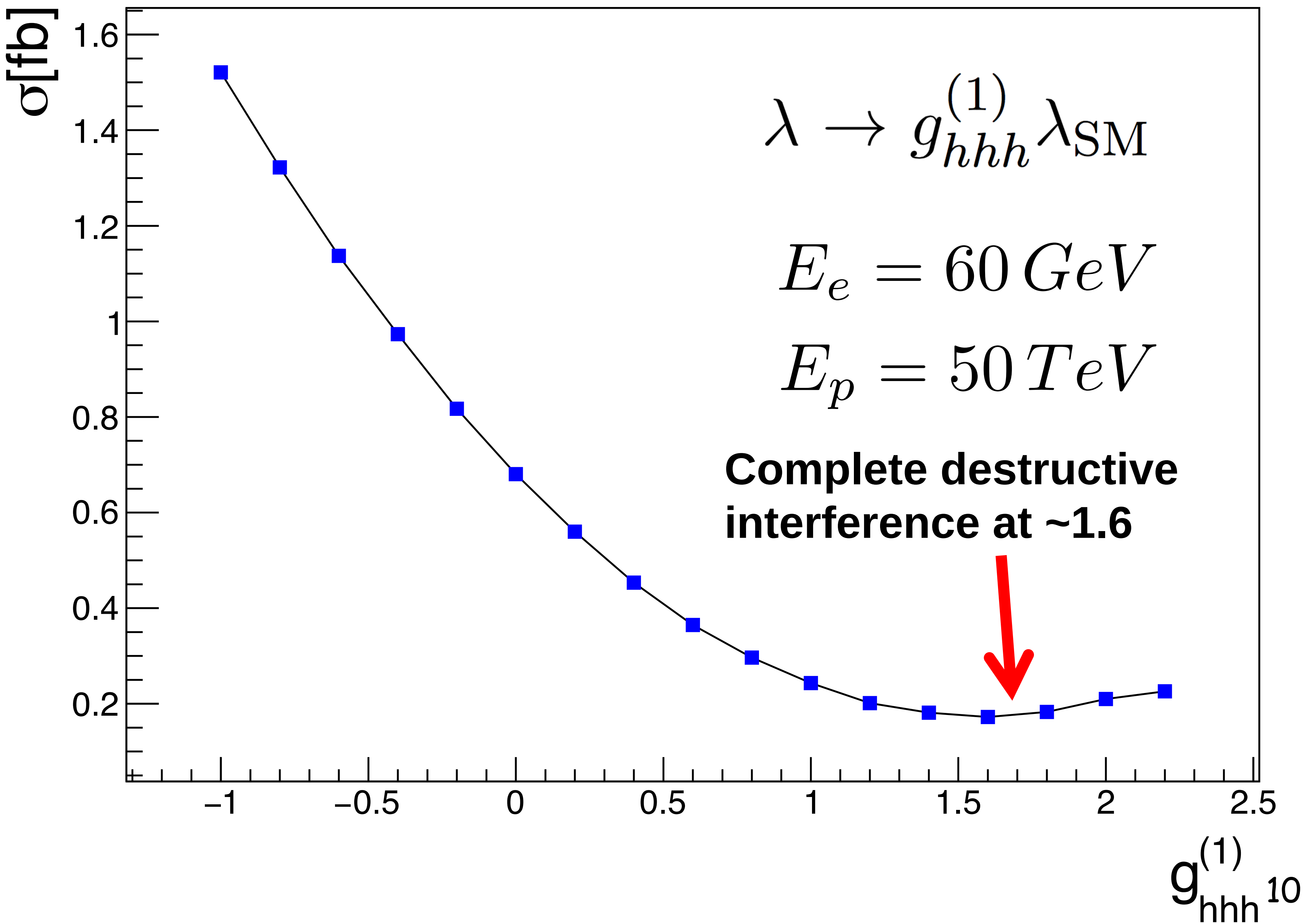
Effective vertices. Note the dependence on momenta in non-SM vertices. This induces significant impact on scattering kinematics.

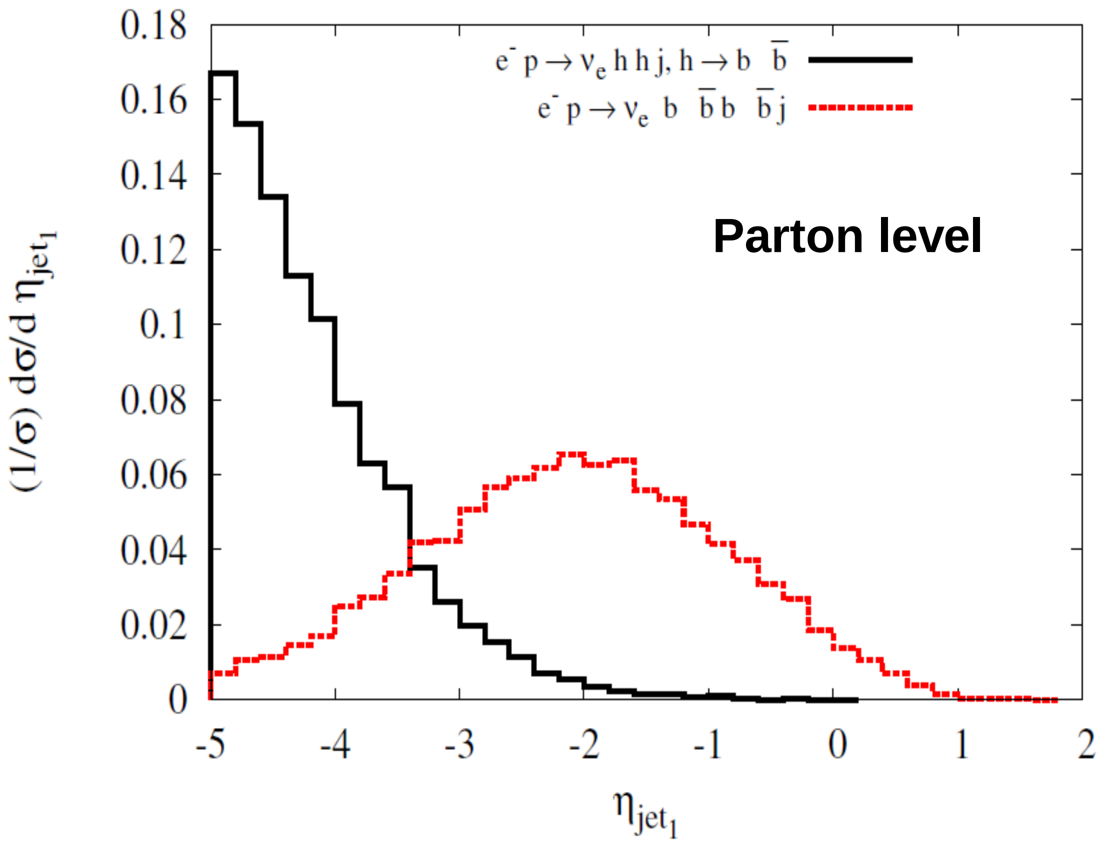
$$
\begin{aligned}
\mathrm{i}\Gamma_{hhh} =& -6\mathrm{i}v\lambda g^{(1)}_{hhh} - \mathrm{i}g^{(2)}_{hhh}(p_1\cdot p_2 + p_2\cdot p_3 + p_3\cdot p_1),\\
\mathrm{i}\Gamma_{hW^-W^+} =& \mathrm{i}\left[\left\{\frac{g^2}{2}v + \frac{g}{m_W}g^{(1)}_{hWW}p_2\cdot p_3 + \frac{g}{m_W}g^{(2)}_{hWW}(p_2^2+p_3^2)\right\}\eta^{\mu_2\mu_3}\right.\\
&-\frac{g}{m_W}g^{(1)}_{hWW}p_2^{\mu_3}p_3^{\mu_2} - \frac{g}{m_W}g^{(2)}_{hWW}(p_2^{\mu_2}p_2^{\mu_3}+p_3^{\mu_2}p_3^{\mu_3})\\
&\left.-\mathrm{i}\frac{g}{m_W}\tilde{g}_{hWW}\epsilon_{\mu_2\mu_3\mu\nu}p_2^{\mu}p_3^{\nu}\right],\\
\mathrm{i}\Gamma_{hhW^-W^+} =& \mathrm{i}\left[\left\{\frac{g^2}{2} + \frac{g^2}{m_W^2}g^{(1)}_{hhWW}p_3\cdot p_4 + \frac{g^2}{m_W^2}g^{(2)}_{hhWW}(p_3^2+p_4^2)\right\}\eta^{\mu_3\mu_4}\right.\\
&-\frac{g^2}{m_W^2}g^{(1)}_{hhWW}p_3^{\mu_4}p_4^{\mu_3} - \frac{g^2}{m_W^2}g^{(2)}_{hhWW}(p_3^{\mu_3}p_3^{\mu_4}+p_4^{\mu_3}p_4^{\mu_4})\\
&\left.-\mathrm{i}\frac{g^2}{m_W^2}\tilde{g}_{hhWW}\epsilon_{\mu_3\mu_4\mu\nu}p_3^{\mu}p_4^{\nu}\right].
\end{aligned}
$$





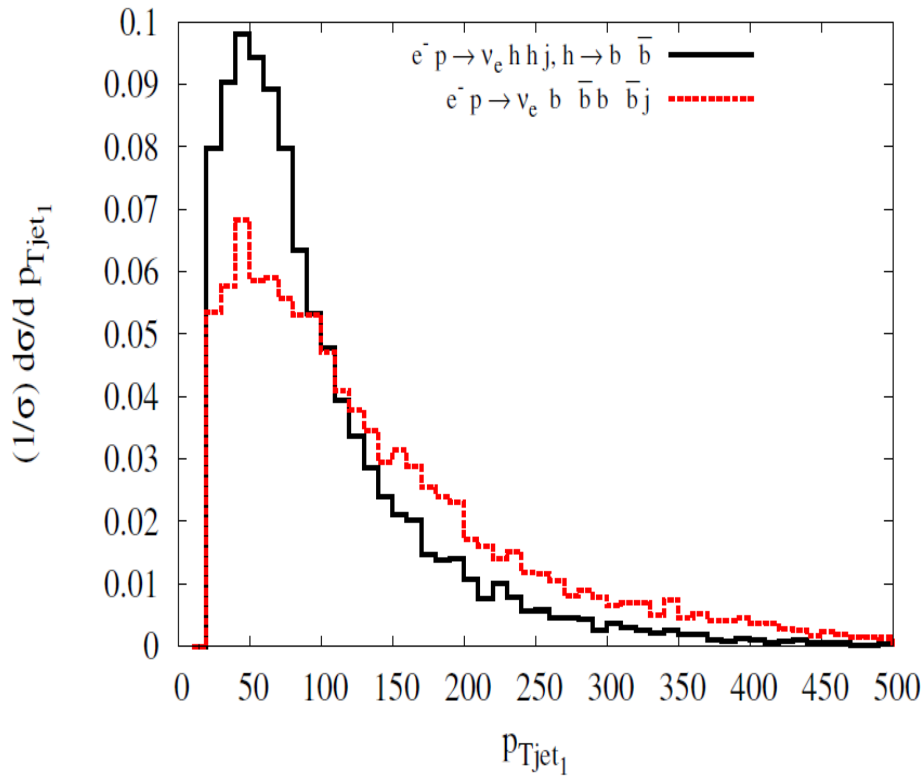
Considering highly asymmetric collisions


σ[fb]
$\lambda \to g^{(1)}_{hhh}\lambda_{\rm SM}$
$E_e = 60\,GeV$
$E_p = 50\,TeV$
Complete destructive interference at ~1.6
$g^{(1)}_{hhh}$ 10
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
−1
−0.5
0
0.5
1
1.5
2
2.5



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

Scattered quark is more forward in signal



This is an important characteristic of SM production in VBF that is, in turn, sensitive to coupling structures. Strong advantage of the LHeC

Background classification

(Charm and light partons also considered)

- CC processes:

$$pe^- \to \begin{cases} b\bar{b}b\bar{b}j\nu_e; \\ b\bar{b}jjj\nu_e; \\ zzj\nu_e, z \to b\bar{b}; \\ t\bar{t}j\nu_e, \text{(hadronic/semi-leptonic)}; \end{cases}$$

- NC processes:

$$pe^- \to \begin{cases} b\bar{b}b\bar{b}je^-; \\ b\bar{b}jjje^-; \\ zzje^-, z \to b\bar{b}; \\ t\bar{t}je^-, \text{(hadronic/semi-leptonic)}; \end{cases}$$

Particularly dangerous background

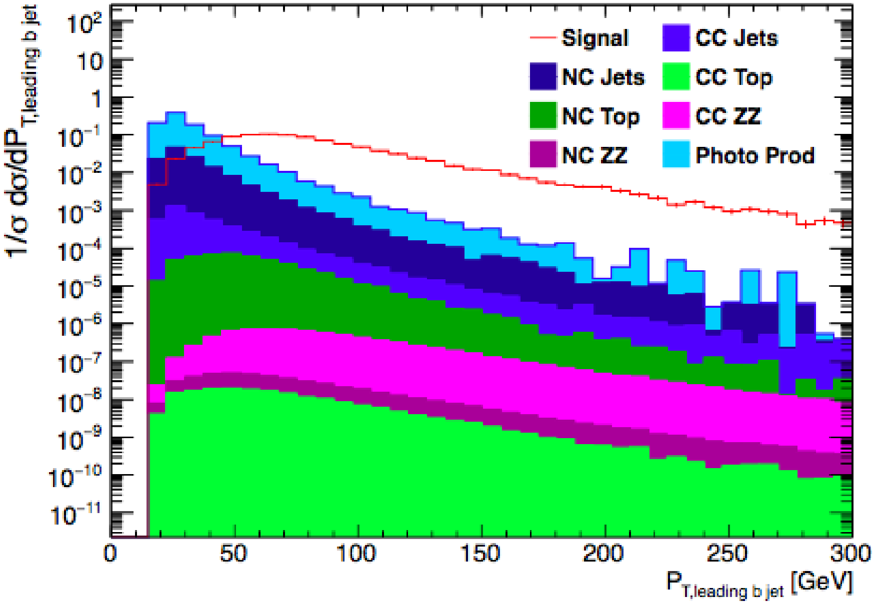
- PHOTO-production:

$$p\gamma \to \begin{cases} b\bar{b}b\bar{b}j; \\ b\bar{b}jjj; \\ zzj, z \to b\bar{b}; \\ t\bar{t}j, \text{(hadronic/semi-leptonic)}. \end{cases}$$

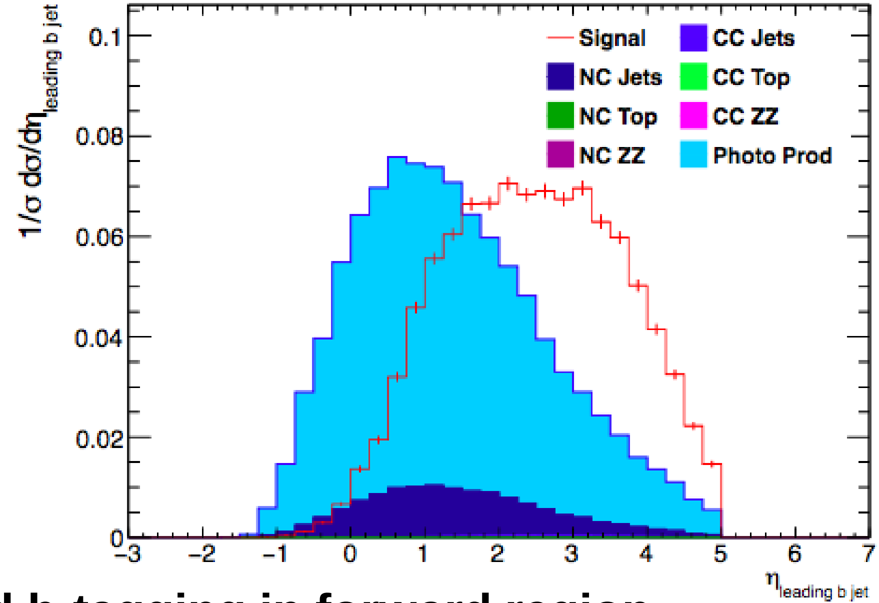
Tree-level cross-sections with Madgraph. Generation requires p_T>10 GeV for partons and MET, ΔR_{jj}>0.4, ΔR_{ll}>0.2.

Process	CC (fb)	NC (fb)	PHOTO (fb)
Signal:	2.40×10^{-1}	3.95×10^{-2}	3.30×10^{-6}
$b\bar{b}b\bar{b}j$:	8.20×10^{-1}	$3.60 \times 10^{+3}$	$2.85 \times 10^{+3}$
$b\bar{b}jjj$:	$6.50 \times 10^{+3}$	$2.50 \times 10^{+4}$	$1.94 \times 10^{+6}$
$zzj(z \to b\bar{b})$:	7.40×10^{-1}	1.65×10^{-2}	1.73×10^{-2}
$t\bar{t}j$ (hadronic):	3.30×10^{-1}	$1.40 \times 10^{+2}$	$3.27 \times 10^{+2}$
$t\bar{t}j$ (semi-leptonic):	1.22×10^{-1}	$4.90 \times 10^{+1}$	$1.05 \times 10^{+2}$

Use Pythia + Delphes



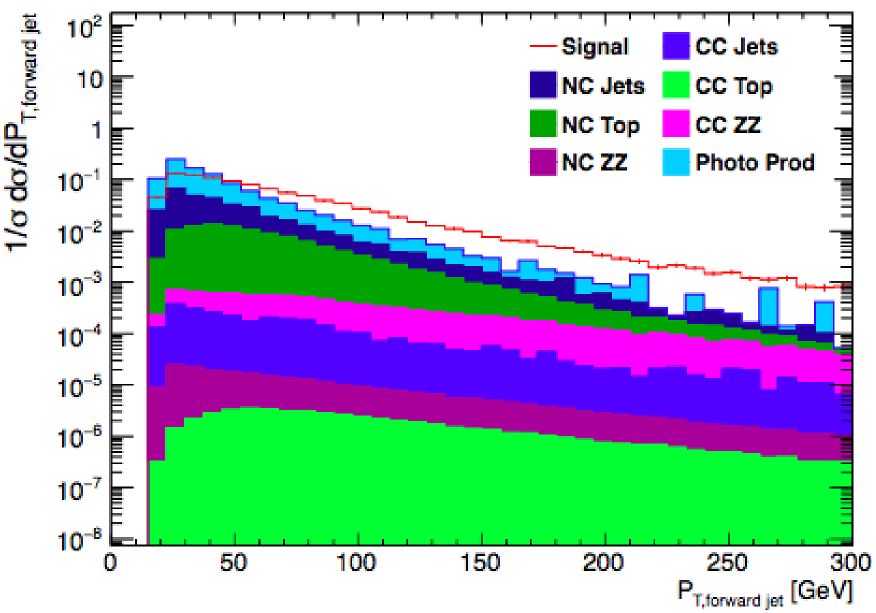
(a)

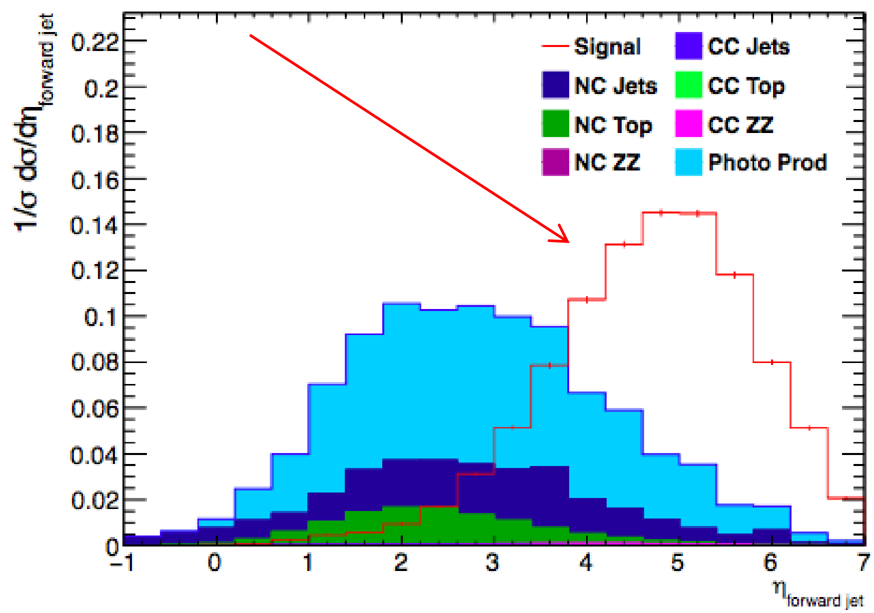


Need b-tagging in forward region

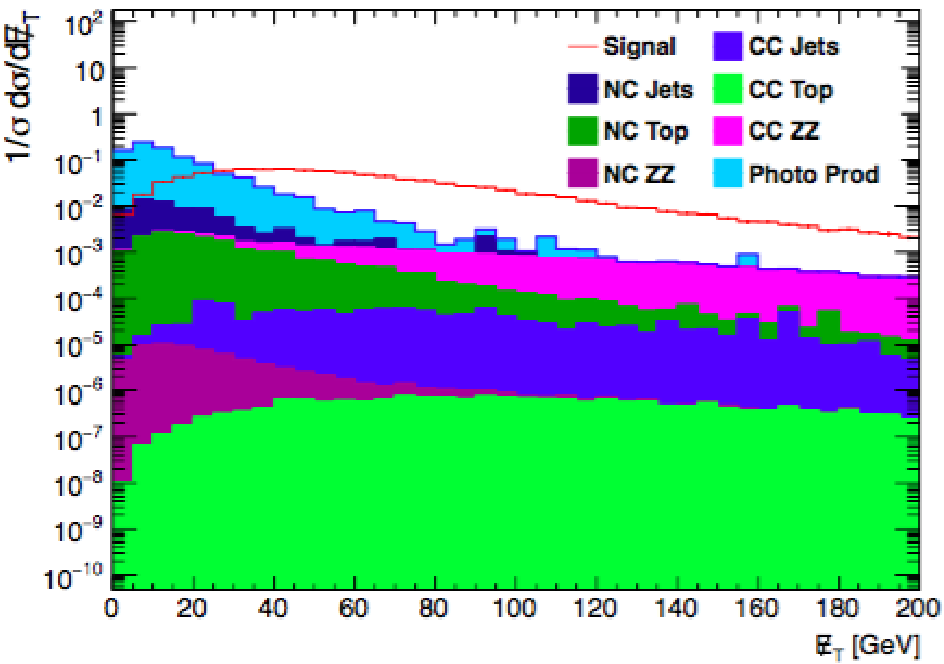
(b)

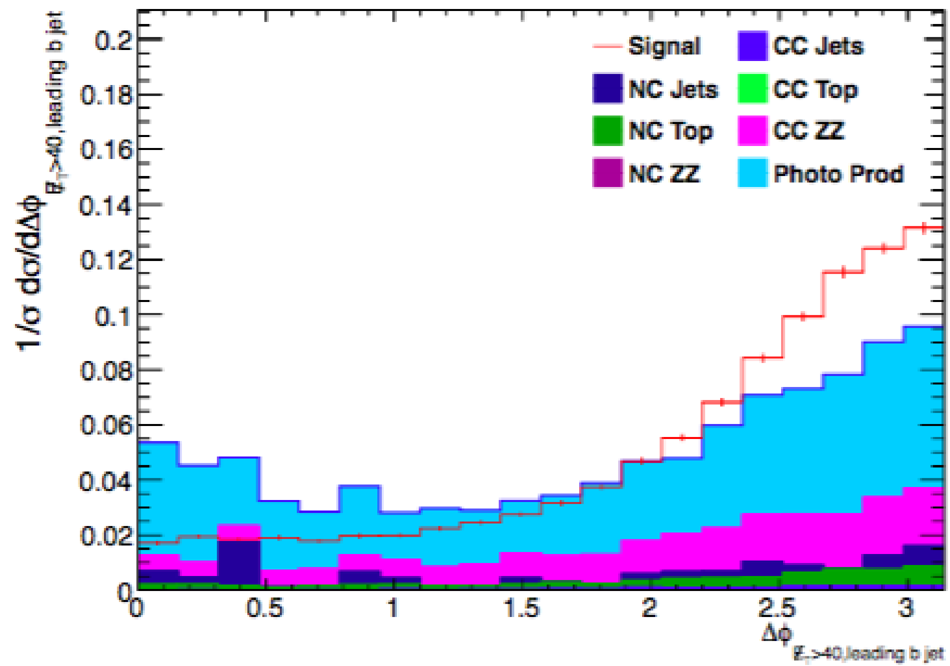
Note how forward the scattered quark is



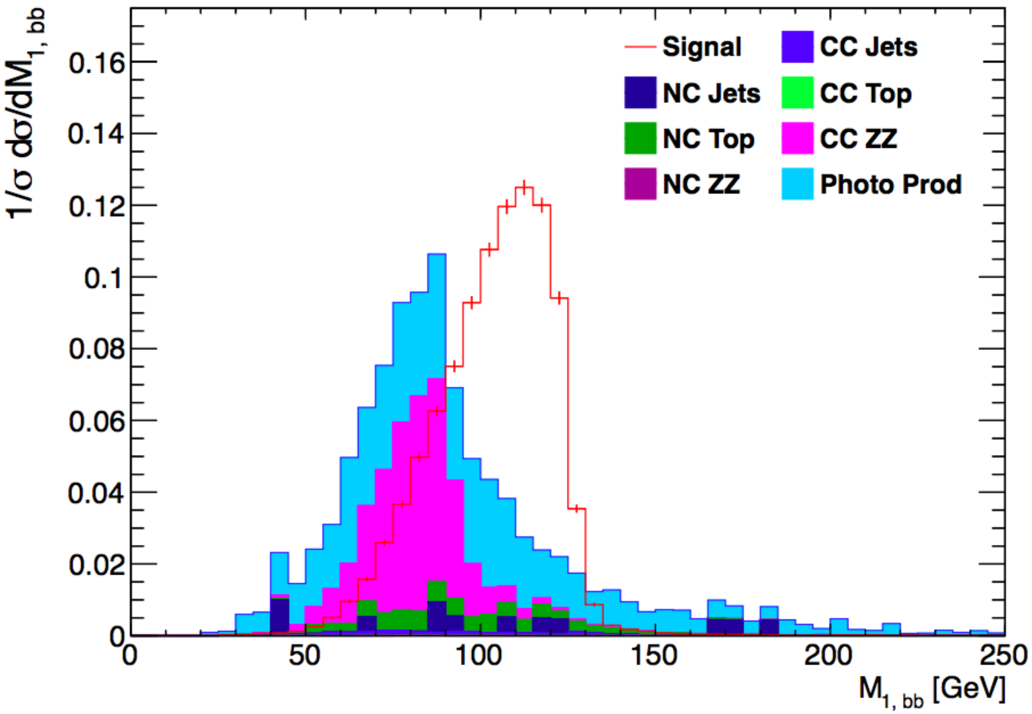


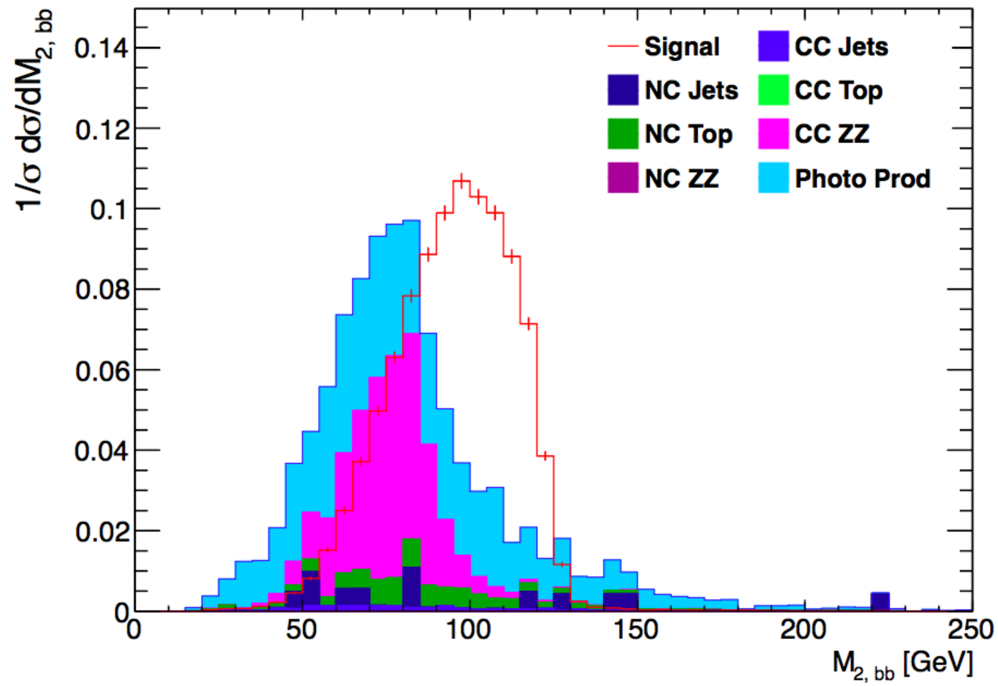
The reconstruction of Missing E_T is critical to the suppression of the photo-production background. Lack of pile-up in ep collisions is critical to search feasibility.





B-jet invariant mass distributions are used to further suppress background. Mass windows are defined following optimization procedure





Final event selection

Require 4-btags. Forward jet is leading non-b-jet. Leading b-jet pair contains leading b-jet.

$$p_{Tb}, p_{Tj} > 20\,GeV$$

$$|\eta_j| < 7, |\eta_b| < 5, \Delta R > 0.7$$

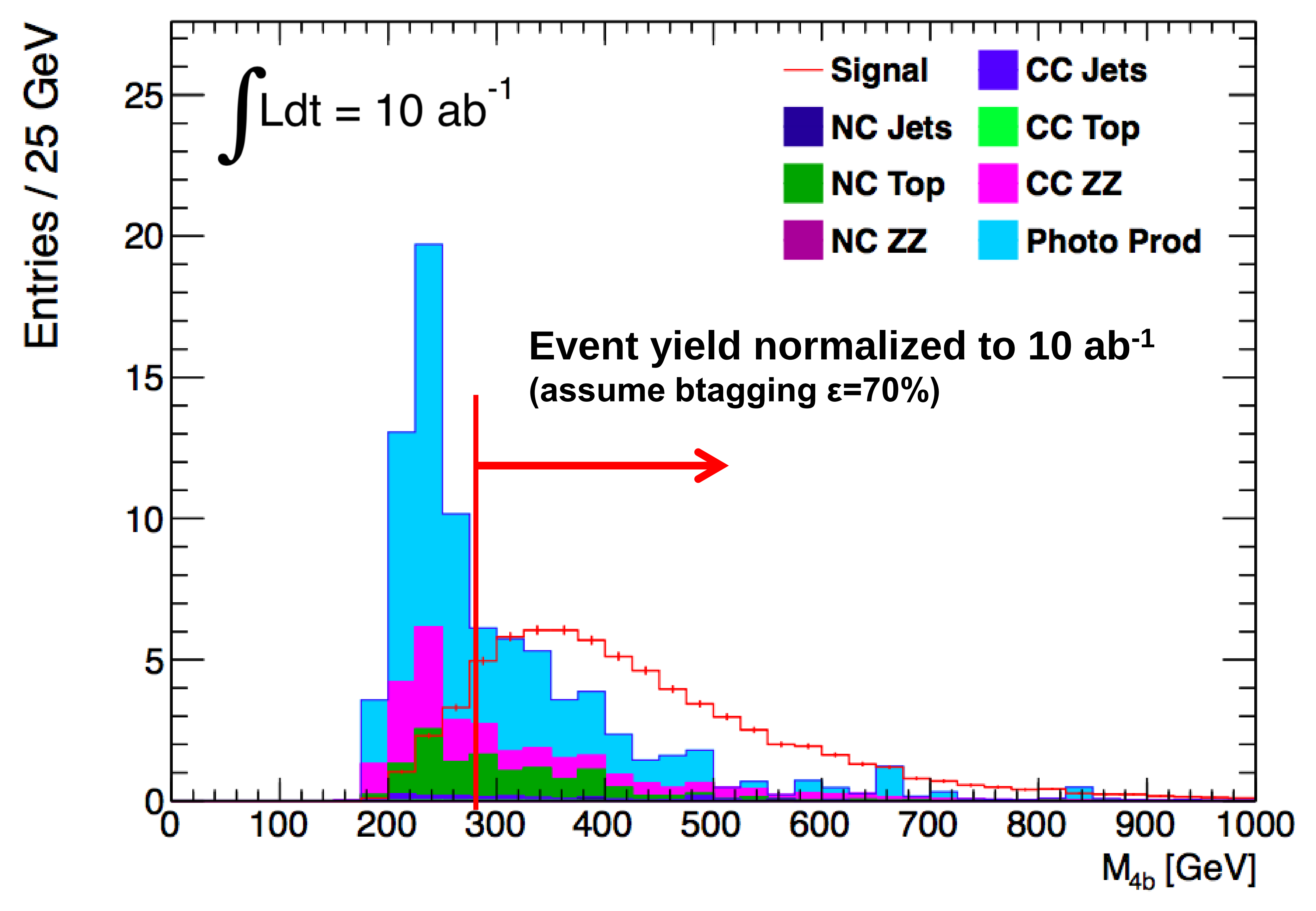
$$p_T^{e^-} < 10 GeV$$

$$\eta_{Tag} > 4$$

$$MET > 40\,GeV, \Delta\Phi_{MET,b_1}, \Delta\Phi_{MET,b_2} > 0.4$$

$$90 < M_1 < 125\,GeV, 75 < M_2 < 125\,GeV$$

$$M_{4b} > 280\,GeV$$

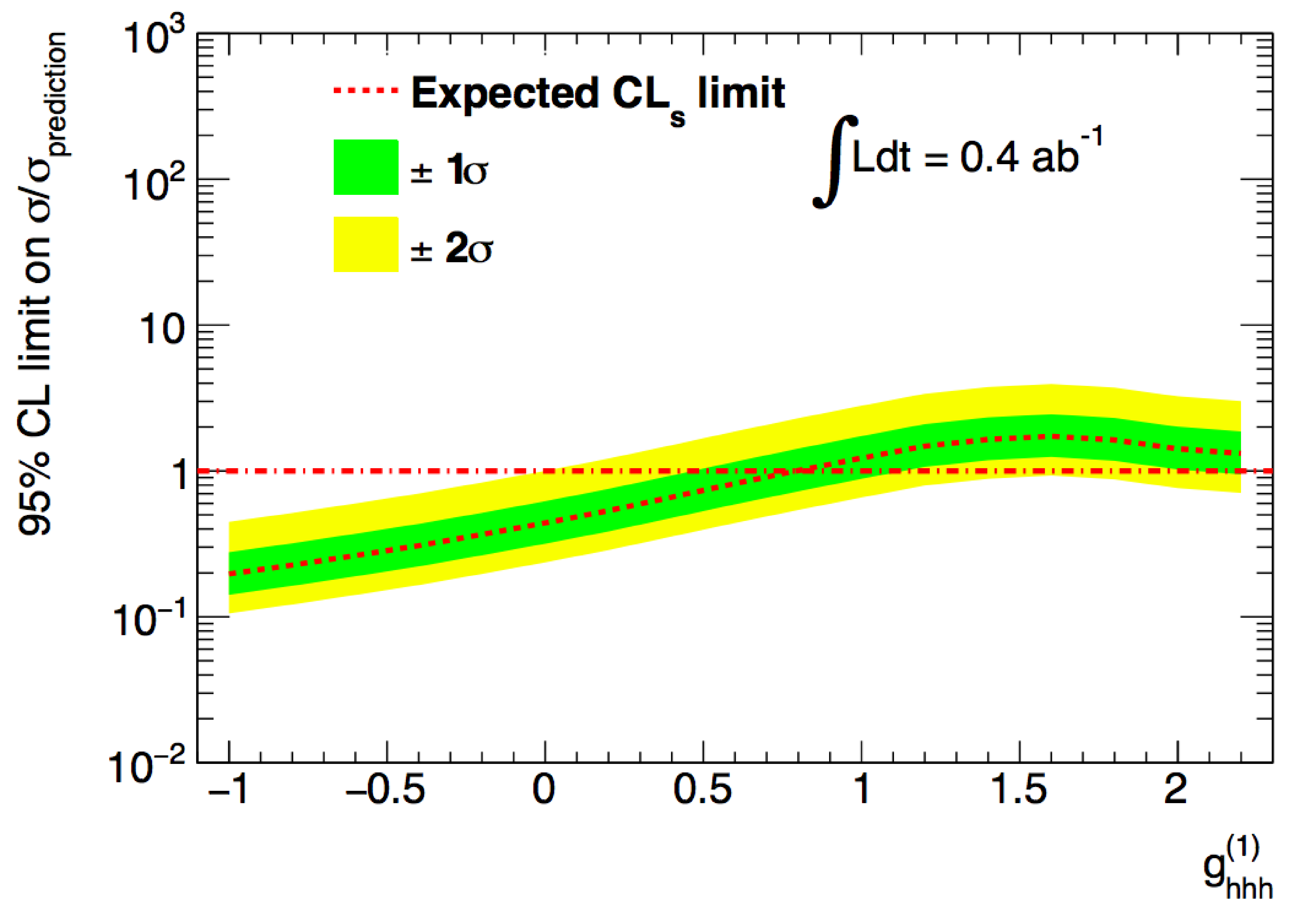


Entries / 25 GeV
$\int Ldt = 10\ ab^{-1}$
Signal
CC Jets
NC Jets
CC Top
NC Top
CC ZZ
NC ZZ
Photo Prod
Event yield normalized to 10 ab^{-1}
(assume btagging ε=70%)
0
5
10
15
20
25
0
100
200
300
400
500
600
700
800
900
1000
M_{4b} [GeV]

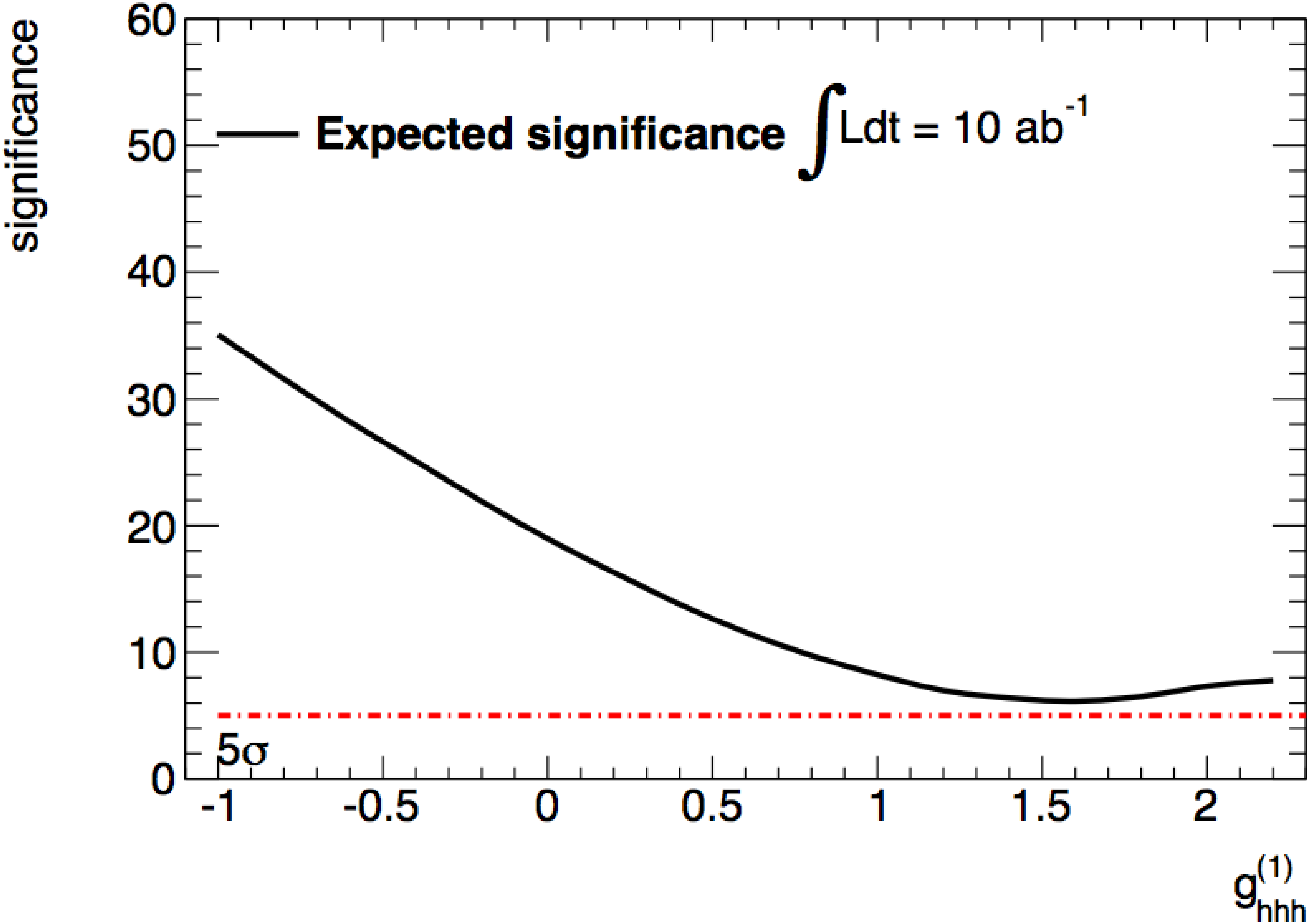
Samples	Signal	CC Jets	NC Jets	CC Top	NC Top
Initial	$2.36\times10^3\pm4.82$	$6.45\times10^6\pm9.3\times10^3$	$2.5\times10^8\pm4.26\times10^5$	$4.49\times10^3\pm5.03$	$7.4\times10^6\pm6.86\times10^3$
4 b and 1 light jets	299 ± 1.16	293 ± 7.56	$2.23\times10^4\pm678$	5.72 ± 0.023	$9.87\times10^3\pm31.1$
Electron rejection	299 ± 1.16	293 ± 7.56	$6.84\times10^3\pm385$	5.66 ± 0.0229	$6.43\times10^3\pm28$
Forward jet	224 ± 1.01	22.9 ± 1.39	864 ± 65.1	0.399 ± 0.00537	307 ± 5.8
$\not{E}_T$	149 ± 0.823	18.7 ± 0.981	93.9 ± 26.7	0.372 ± 0.00524	85.4 ± 2.86
$\not{E}_T-\phi$ rejection	128 ± 0.76	16.8 ± 0.957	45.3 ± 14	0.326 ± 0.00493	63.6 ± 2.48
M_1M_2	71 ± 0.568	1.49 ± 0.216	0.151 ± 0.0866	0.06 ± 0.00212	11.1 ± 1.08
M_{4b}	63.4 ± 0.536	0.849 ± 0.191	0.151 ± 0.0866	0.0346 ± 0.00141	5.4 ± 0.776

Samples	CC ZZ	NC ZZ	Photo Prod	Total background	Significance
Initial	$7.36\times10^3\pm10.6$	338 ± 0.426	$2.1\times10^9\pm3.43\times10^6$	$2.36\times10^9\pm3.5\times10^6$	0.049
4 b and 1 light jets	678 ± 2.19	21.7 ± 0.0707	$7.36\times10^4\pm4.21\times10^3$	$1.07\times10^5\pm4.3\times10^3$	0.92
Electron rejection	678 ± 2.19	14 ± 0.0614	$6.23\times10^4\pm1.29\times10^3$	$7.65\times10^4\pm1.4\times10^3$	1.1
Forward jet	380 ± 1.64	1.04 ± 0.014	$1.43\times10^4\pm297$	$1.59\times10^4\pm3\times10^2$	1.8
$\not{E}_T$	342 ± 1.55	0.18 ± 0.00575	980 ± 21.9	$1.52\times10^3\pm35$	3.8
$\not{E}_T-\phi$ rejection	287 ± 1.42	0.1 ± 0.00427	440 ± 10.4	853 ± 18	4.3
M_1M_2	16.8 ± 0.344	0.00613 ± 0.00117	54.4 ± 1.21	84.00 ± 1.68	6.9
M_{4b}	7.43 ± 0.229	0.00239 ± 0.000661	21.9 ± 0.63	35.78 ± 1.05	8.7

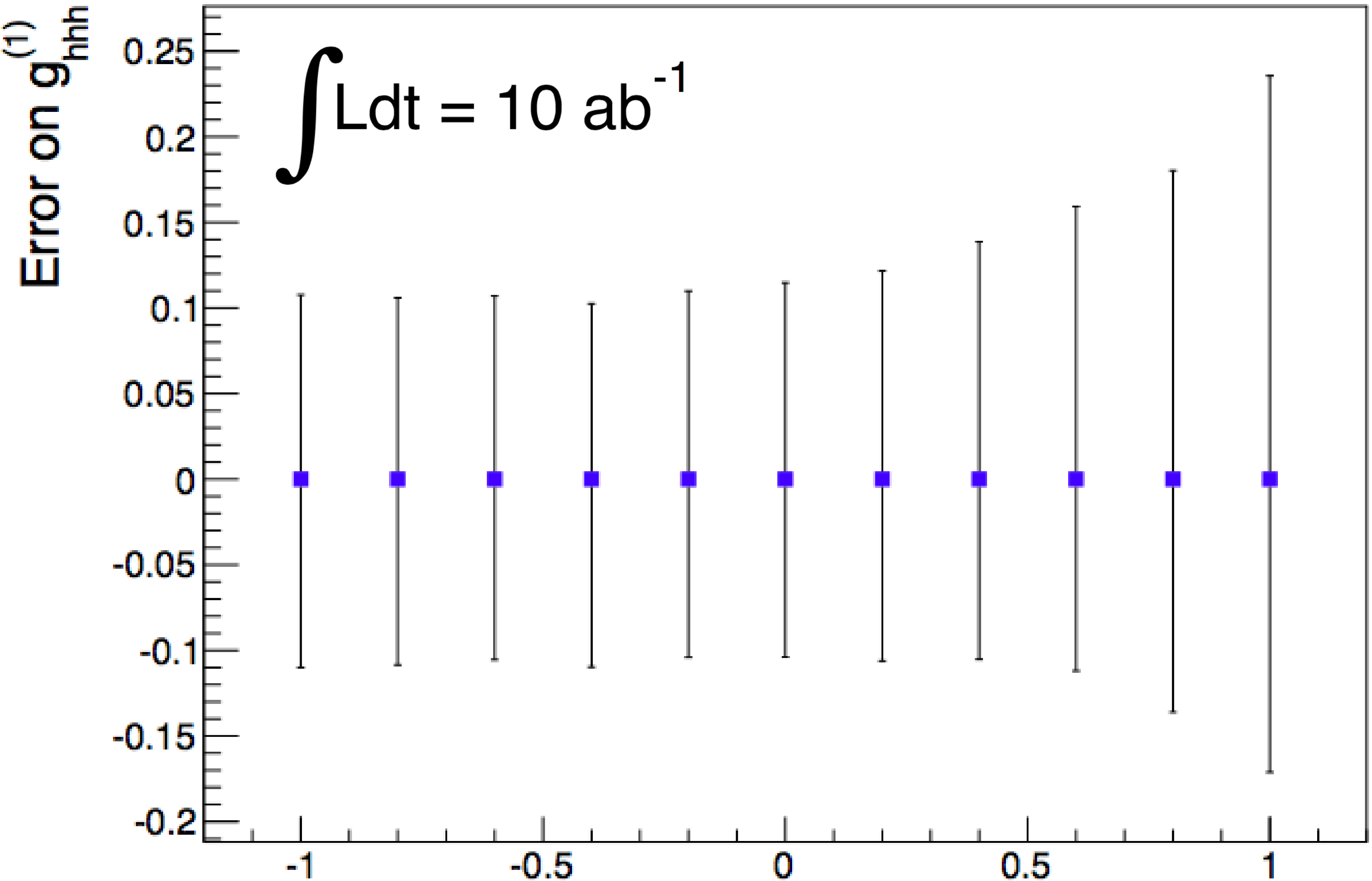
Table 6: Number of events after optimisation, and weighted with luminosity $\mathcal{L}=10\,\mathrm{ab}^{-1}$. The abbreviations CC(NC)Jet and CC(NC)Top accounts for the weighted sum of CC(NC) backgrounds 1, 2 and 4, 5 as given in Table 4. NCPhotoProd refer to weighted sums of all PHOTO-production.



95% CL limit on σ/σ_prediction
Expected CL_s limit
± 1σ
± 2σ
∫Ldt = 0.4 ab^-1
10^3
10^2
10
1
10^-1
10^-2
-1
-0.5
0
0.5
1
1.5
2
g_hhh^(1)

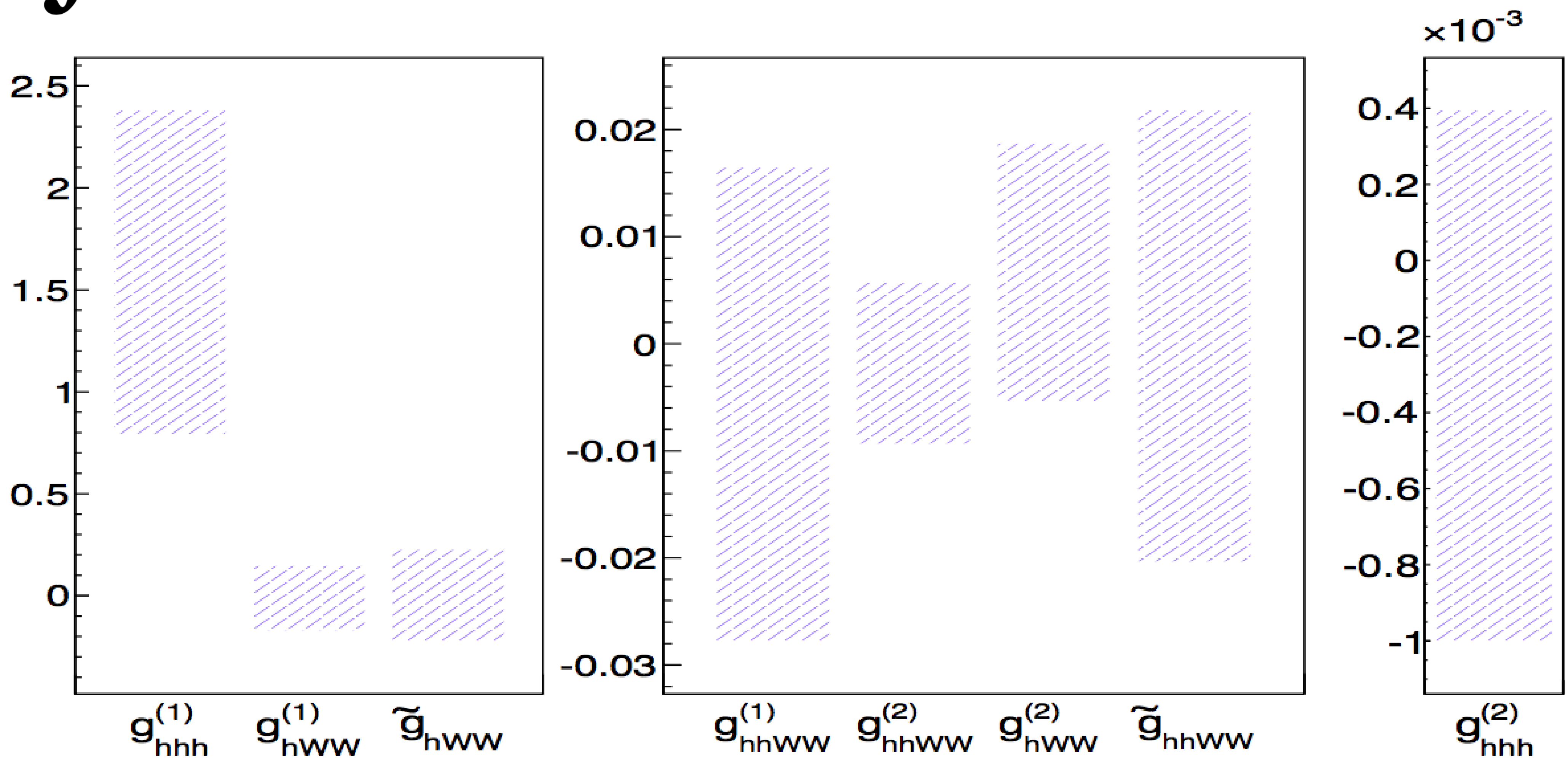


significance
Expected significance $\int Ldt = 10\ ab^{-1}$
5σ
$g^{(1)}_{hhh}$
0
10
20
30
40
50
60
-1
-0.5
0
0.5
1
1.5
2



Error determination of λ, 20% for SM

$\int L dt = 0.4\ ab^{-1}$



95% CL limits on different couplings

Outlook and Conclusions

- First look at search for double Higgs boson production at high-energy collisions ep collisions
  - E_e=60 GeV, E_p=50 TeV. Highly assymetric collisions. Requires very forward jet tagging and b-tagging
  - May achieve S/B>1
  - May reach more than 5σ effect with 20% measurement of λ for 10 ab^{-1}
  - ep offers possibility of exploring structure of hhh, hhWW couplings
    - Sensitivity to non-SM couplings explored
- Promising results, to be validated with full simulation studies