New Physics at Large Scales at an LHeC

- **Motivation**
- **Leptoquarks**
- **Single Top**
- **Higgs**
- **Outlook**

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DIS09, Future Facilities, April 28, 2009

Motivation

Strong theoretical arguments that our Standard Model picture of electroweak symmetry breaking is incomplete.

→ numerous extensions of SM at electroweak scale proposed;

→ at least some of the new particles and interactions predicted by such extended theories are *expected* to be discovered and studied at the LHC.

Ultimate goal of experiments is to determine the correct theory of physics at the TeV scale.

Likely Model Features …

- **Physics at TeV scale is weakly coupled, and there is a *light Higgs* as motivated by precision electroweak data.**

- **A number of new states are present at the TeV scale. New particles can be paired up with known SM states, with states in the same pair carrying identical gauge charges.**

- **New states carry a parity quantum number distinct from their SM counterparts, implying that the lightest new particle is stable.**

- **The lightest new particle is weakly interacting as suggested by cosmological constraints on stable particles.**

Models and LHC Signatures

Some of best known models are, e.g.

- **Minimal Supersymmetric Standard Model (MSSM)**
- **Models with universal extra dimensions**
- **Little Higgs Models with T-parity**

Those new physics production do have LHC signatures which are dominated by the coloured states which are *pair produced* and then decay down to lightest new particles and SM states.

→ **Most interesting final states involve jets associated with large missing transverse energy and possibly leptons and/or photons.**

→ **A discrimination of the models needs detailed studies of the new objects, e.g. spin, couplings ...**

→ **This may be a quite complicated task and may require more colliders/experiments ...**

What is the Potential of an LHeC?

- **LHC results will guide our design of new facilities dedicated to the study of such new objects, see e.g. CERN-Theory Institute (Feb 2009).**
- **A large hadron-electron collider, although mainly build to study proton structure and new QCD phenomena with great precision may add value compared to LHC alone.**
- **Goal towards a CDR: Thorough study of the new physics potential at c.m.s. energies in the range of 1 - 2 TeV in e+/e- p collisions with luminosities around 100 – 10 fb^{-1} and lepton beam polarisation.**
- **Results need to be compared with capabilities of LHC and an LC…**
- **Here, first studies of the 'obvious'. All work in progress.**

New Physics at an LHeC

Wide range of basic physics:

- **Leptoquark production and decay**
- **Squarks and gluinos**
- **composite electrons**
- **Lepton-flavour violation**
- **ZZ, WZ, WW elastic and inelastic collisons …**

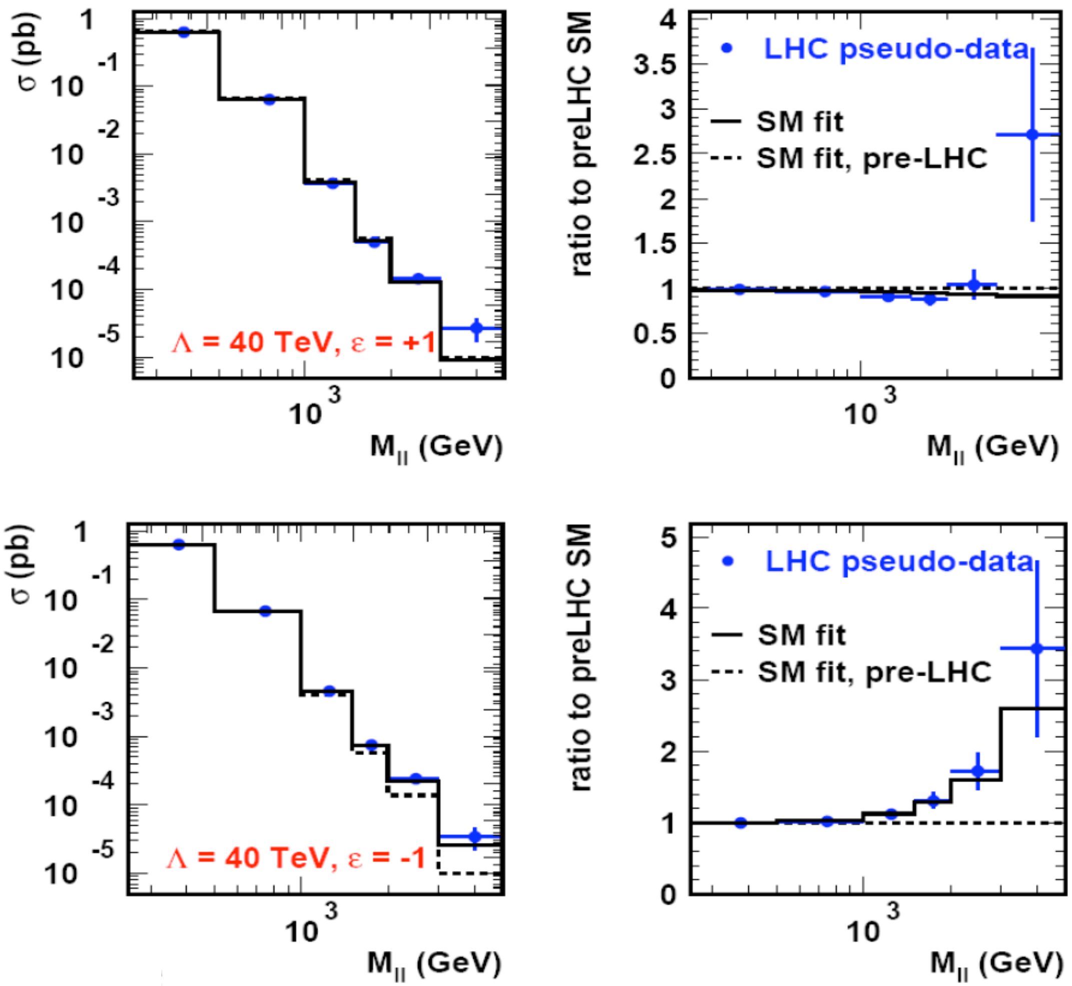
Following a discovery at LHC, LHeC may provide additional information to constrain underlying theory, e.g.:

- **electron-quark resonances**
- **structure of an eeqq interaction**
- **study of new leptons (sleptons, excited e*/ν*)**
- **SM light Higgs couplings**
- **new Z′ boson couplings** [T.Rizzo, PRD77(2008)115016]

A better knowledge of PDFs at LHC kinematics may be needed to establish new physics effects found at LHC.

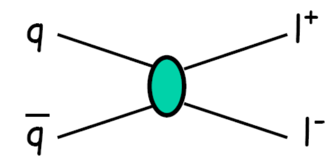
E. Perez, Divonne08

PDFs and 'faked' New Physics?



High Mass Drell-Yan at the LHC

Drell-Yan with M_{ll} ~ TeV involves quarks and antiquarks with x_{Bj} ~ 0.1



Generic approach for new physics in DY final states : contact interactions

$$\mathcal{L}_{CI} = \sum_{i,j=L,R} \varepsilon_{ij}^{eq} \frac{4\pi}{\Lambda^2} (\bar{e}_i \gamma^\mu e_i)(\bar{q}_j \gamma_\mu q_j)$$

Even if NP scenario looks quite different from SM (including stat. and known PDF uncertainties)
→ **NP effects can easily be accommodated with a new DGLAP fit**

→ **but PDFs from LHeC data could disentangle between NP models**
→ **and may help to identify IS/FS effects present in pp**

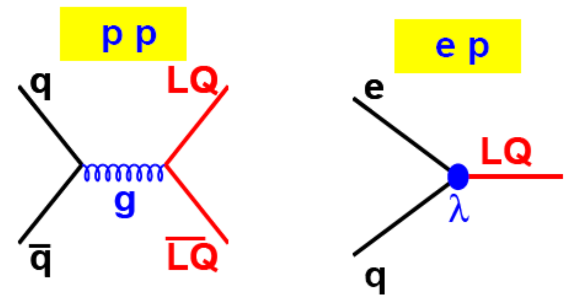
A.F. Zarnecki, DIS08
E. Perez, Divonne08

Leptoquarks

LQ appear in many SM extensions
Buchmueller-Rueckl-Wyler Model:

- 7 scalar and 7 vector colour triplet bosons .
- Carry both L and B & frac. e.m. charge.
- Also squarks in R-parity violating SUSY.
- Either left or right-handed couplings.
- Only family diagonal couplings (avoid FCNC).

Model	Fermion number F	Charge Q	$BR(LQ \to e^{\pm}q)$ β	LQ-e-q Coupling	Channel	
$S_\circ$	2	$-1/3$	$\frac{1+r}{2+r}$	λ_L	eu	νd
				λ_R	eu	
$\tilde{S}_\circ$	2	$-4/3$	1	λ_R	ed	
$S_{1/2}$	0	$-5/3$	1	λ_L	$e\bar{u}$	
				λ_R	$e\bar{u}$	
		$-2/3$	$\frac{1}{1+r}$	λ_L		$\nu\bar{u}$
				λ_R	$e\bar{d}$	
$\tilde{S}_{1/2}$	0	$-2/3$	1	λ_L	$e\bar{d}$	
		$+1/3$	0	λ_L		$\nu\bar{d}$
S_1	2	$-4/3$	1	$\sqrt{2}\lambda_L$	ed	
		$-1/3$	$1/2$	λ_L	eu	νd
		$+2/3$	0	$\sqrt{2}\lambda_L$		νu
$V_\circ$	0	$-2/3$	$\frac{1+r}{2+r}$	λ_L	$e\bar{d}$	$\nu\bar{u}$
				λ_R	$e\bar{d}$	
$\tilde{V}_\circ$	0	$-5/3$	1	λ_R	$e\bar{u}$	



λ (unknown) coupling l-q-LQ

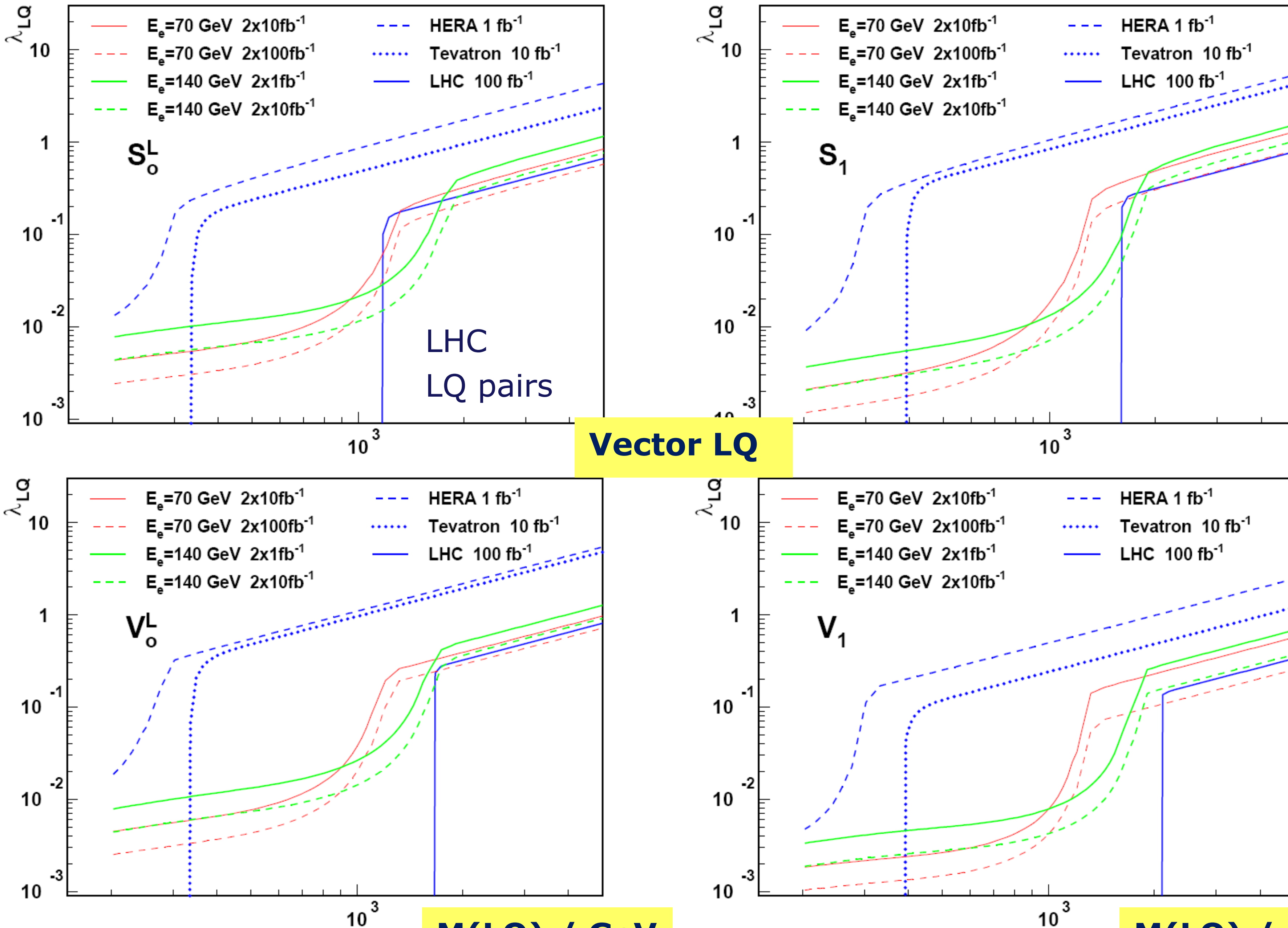
LQ decays into lq or νq:
(assuming narrow LQ)

ep : resonant peak, angular distribution
pp : high-ET lljj events

LHC may discover eq resonances with a mass up to 1.5-2 TeV via pair production.

A.F. Zarnecki, DIS08

Scalar LQ



Expected limits only.

M(LQ) / GeV

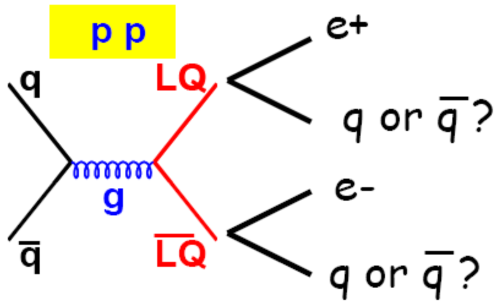
M(LQ) / GeV

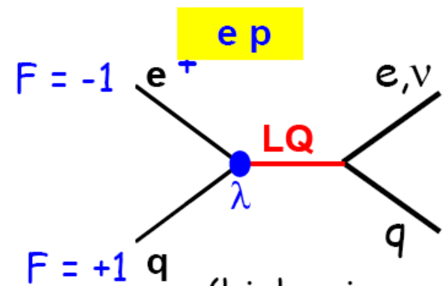
Leptoquark Properties?

pp, pair production

ep, resonant production

- Fermion number



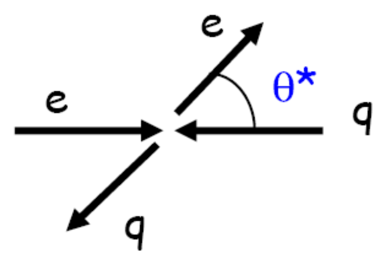


F=0 LQs : $\sigma(e^+)$ higher
F=2 LQs : $\sigma(e^-)$ higher

(high x i.e. mostly q in initial state)

- Scalar or Vector

$q\bar{q} \to g \to LQ\,\overline{LQ}$:
angular distributions depend on the structure of g-LQ-LQ. If coupling similar to γWW, vector LQs would be produced unpolarised…



cos(θ*) distribution gives the LQ spin.

- Chiral couplings

?

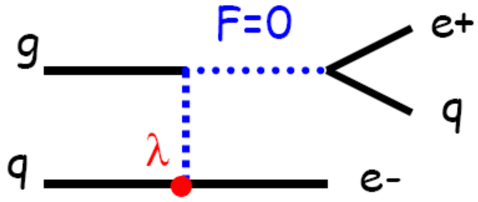
Play with lepton beam polarisation.

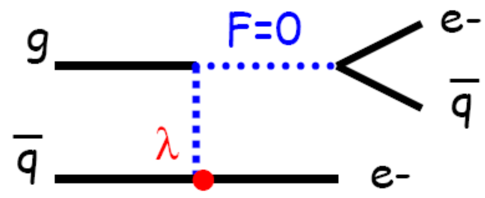
Single LQ production looks better suited for LQ property studies, also possible in pp, but with much lower cross section…

(*) E. Perez, JINST1(2006)P10001

Leptoquark Fermion Number?

In pp: look at signal separately when resonance is formed by (e^+ + jet) and (e^- + jet) :





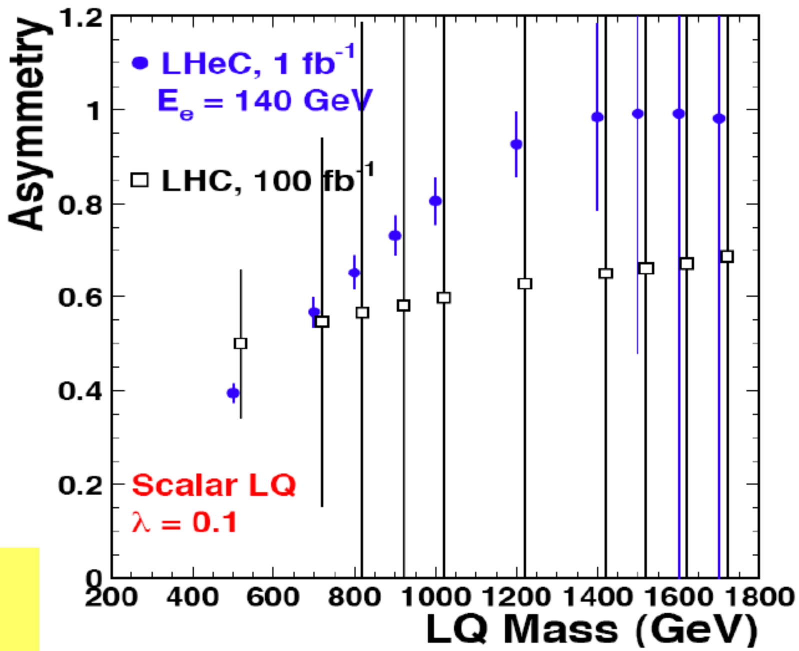
$\sigma(e^+_{out}) > \sigma(e^-_{out})$
for F=0

Sign of the asymmetry gives F, but could be statistically limited at LHC. (*)

Easier in ep ! Just look at the signal with incident e+ and incident e-, build the asymmetry between $\sigma(e^+_{in})$ and $\sigma(e^-_{in})$.

If LHC observes a LQ-like resonance, M < 1 - 1.5 TeV, with indications (single prod) that λ not too small, LHeC would solve the possibly remaining ambiguities.

Interesting and promising interplay between single LQ studies at LHC versus potential LHeC.



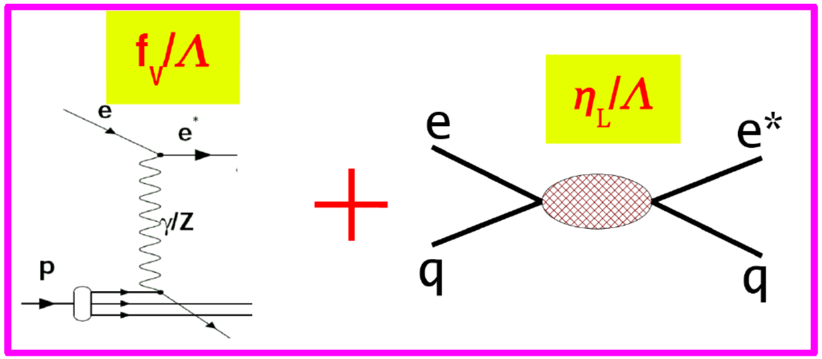
e.g. LHC single LQ study:
T. Papadopoulou, Divonne08

Excited Leptons

If found, direct proof of compositeness of fermions at composite scale Λ

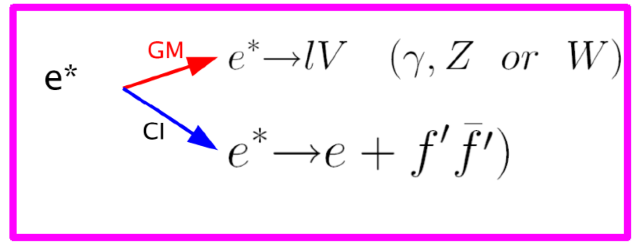
Searched for at LEP, HERA, Tevatron, …

➘ For production:



GM **CI**

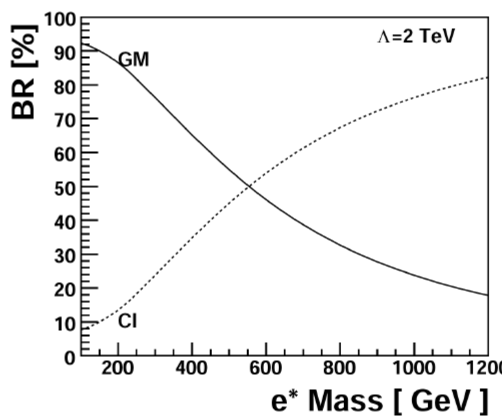
➘ For decay:

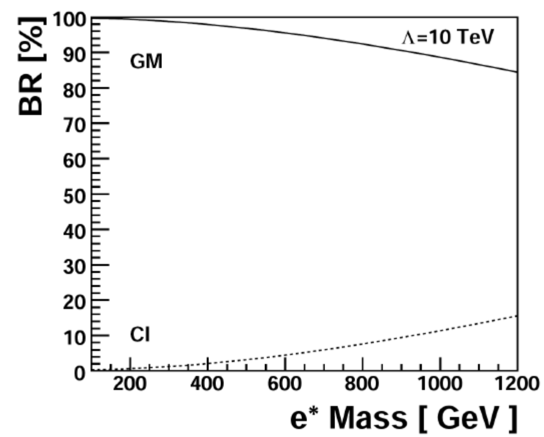


Branching ratio of GM and CI depends on e* mass and Λ

→ for large Λ,

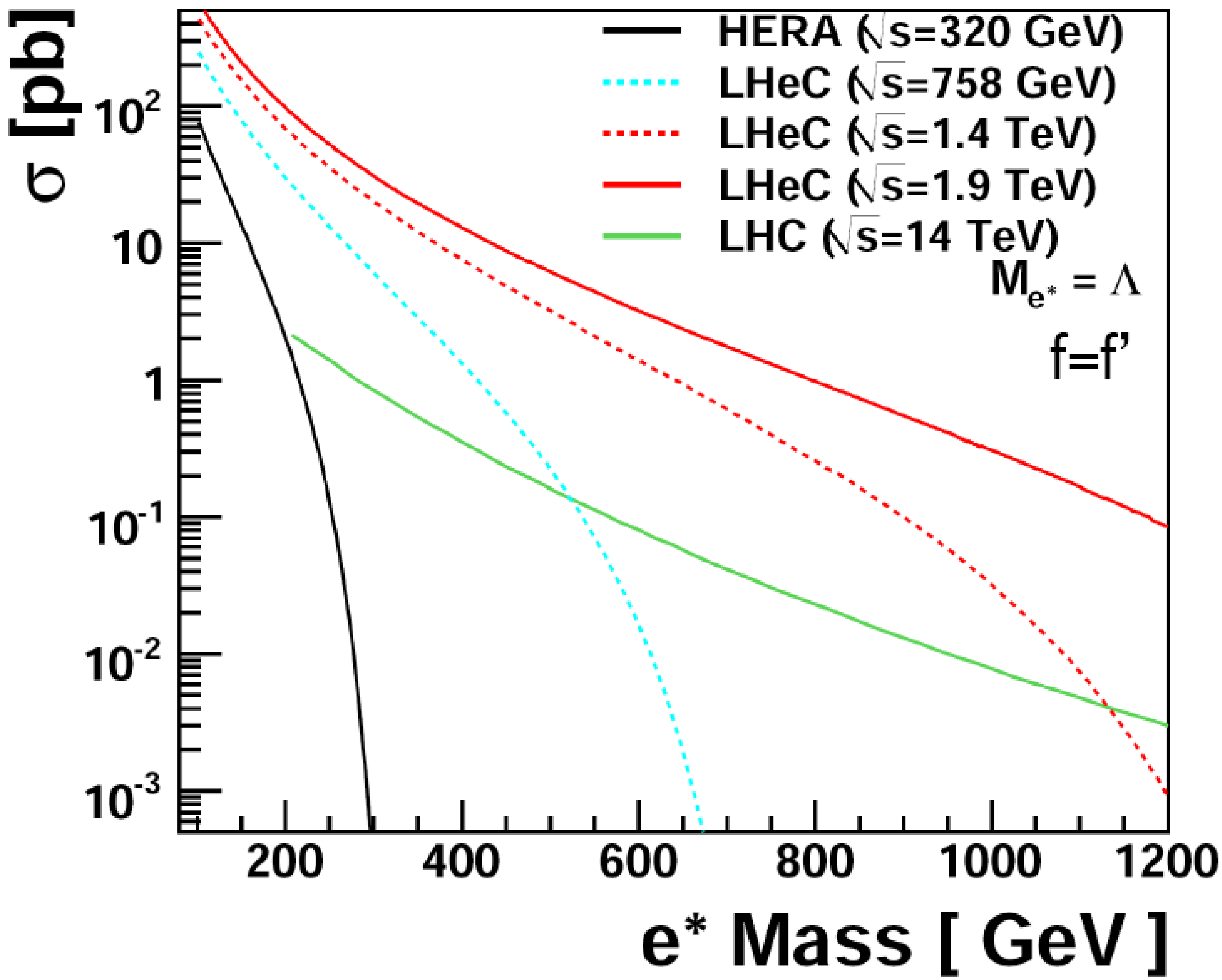
e* decays via CI negligible





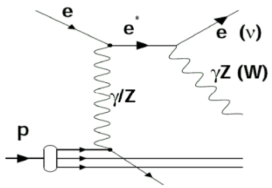
Single e Total Cross Section*

GM only & assuming M* = Λ (f,f′ electroweak gauge couplings)

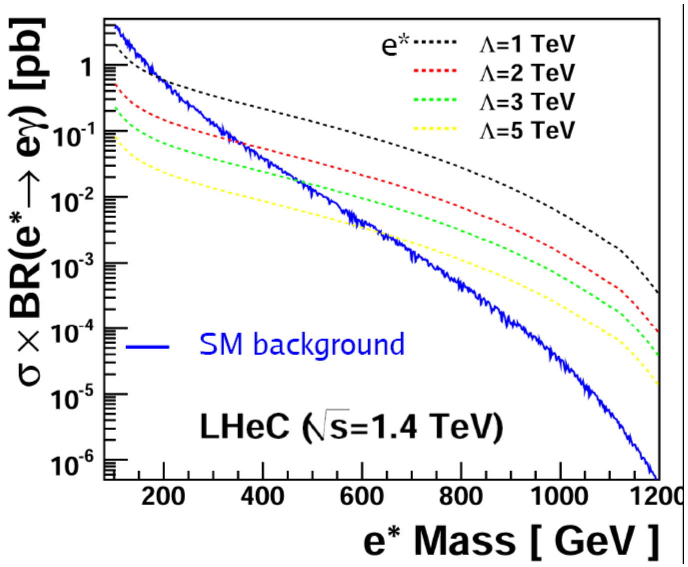


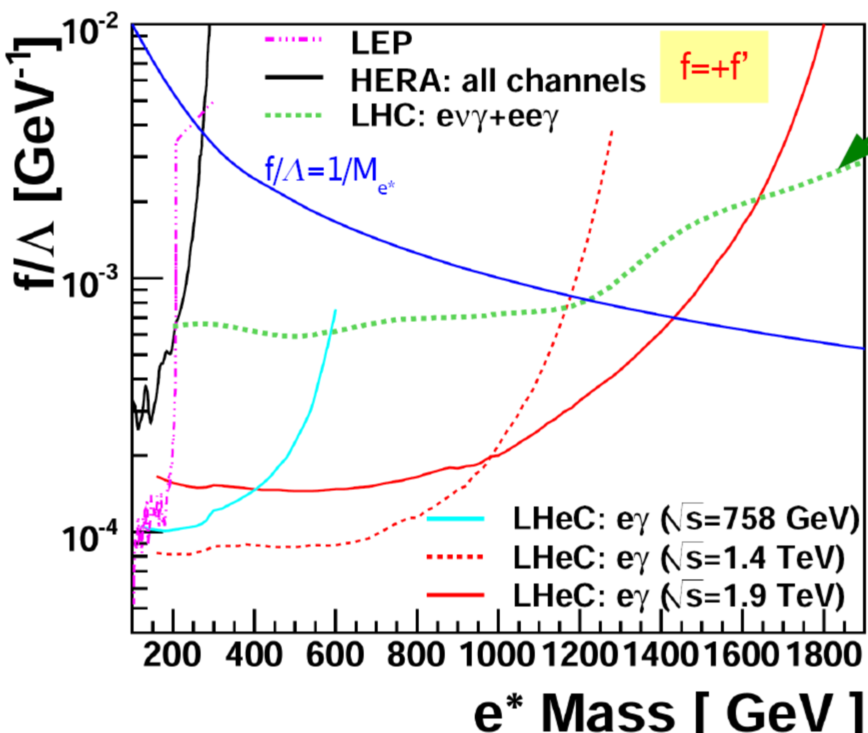
Search for e* → eγ

T. Trinh & E. Sauvan,
Divonne08



LHeC preliminary analysis
including SM NC and Compton background
If LHC discovers pair produced e*:
At LHeC, sensitive to much smaller f/Λ couplings
Determination of quantum numbers
would be possible at LHeC (a la LQ).
Branching fractions (M*>300 GeV):
νW ~60%, eγ ~30%, eZ ~10%



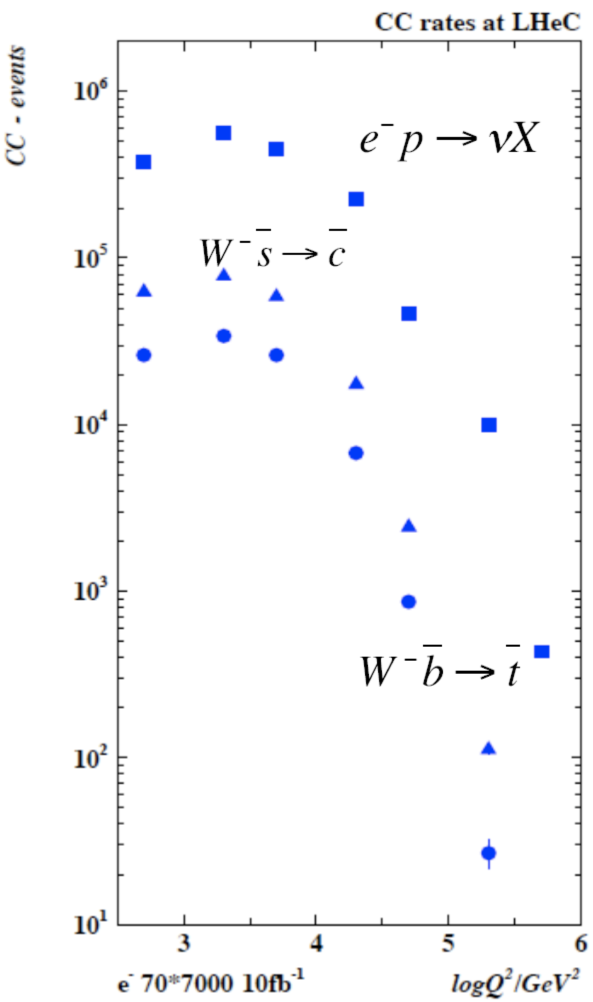


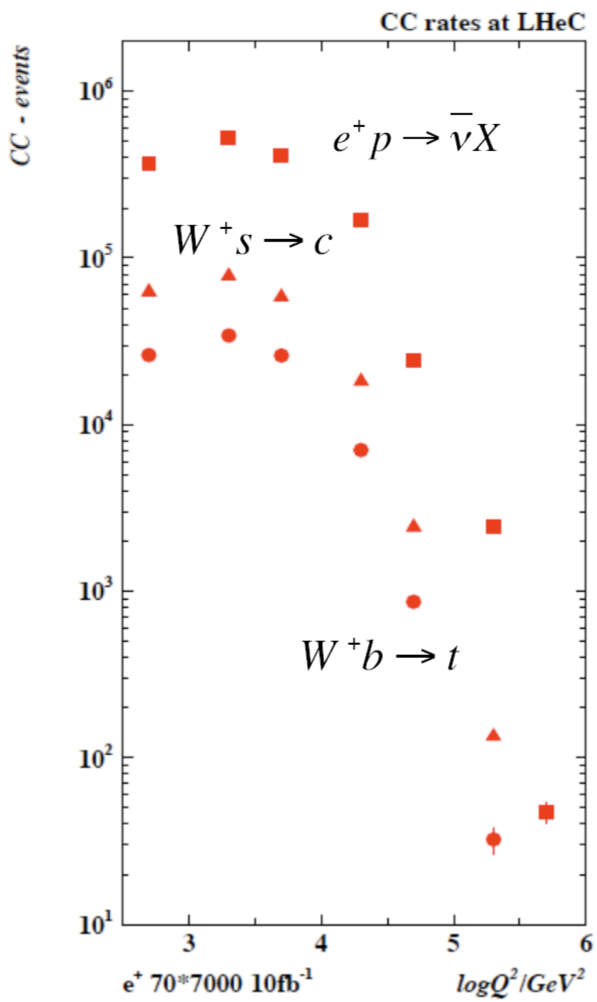
**LHeC sensitivity,
with L=10 fb^{-1} for Ee=70/20 GeV
with L=1 fb^{-1} for Ee=140 GeV**

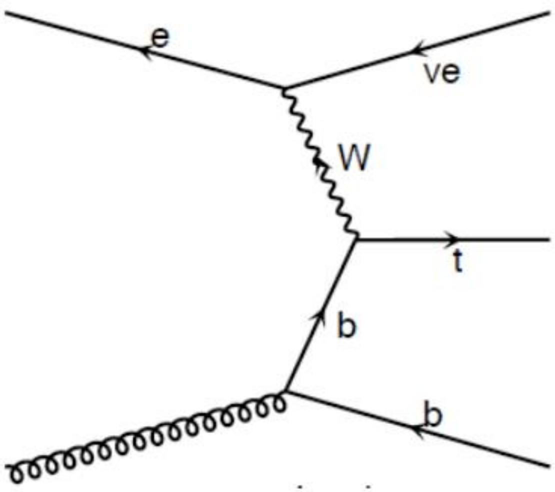
At LHeC, discovery potential for higher e* masses.

SM Single Top and Topbar

SM σ CC (simple LO calculation) ***O*(10pb)**







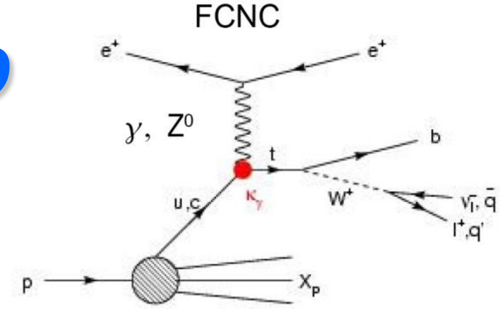
LHeC potential to explore t properties:

A single top factory via e+p.

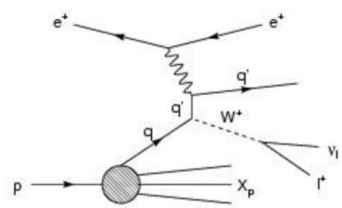
A single topbar factory via e-p.

Anomalous Top Production

G. Brandt, Divonne08

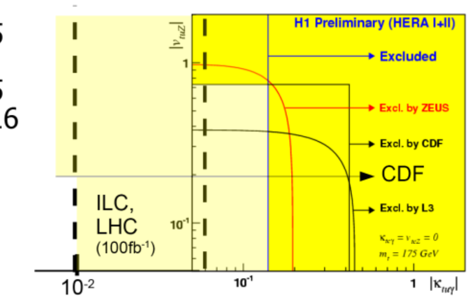


LHeC preliminary analysis
for e+p (70x7000 GeV^2) using eff. FCNC Lagrangian & conventions a la HERA including single W background simulated with Pythia and EPVEC (~31pb)



Summary of Limits on $\kappa_{tu\gamma}$

Experiment	$\kappa_{tu\gamma}$	Br($t\rightarrow u\gamma$)	
L3	0.43	4.1e-2	measured
CDF	0.41	3.2e-2	
ZEUS	0.17	5.9e-3	
H1	0.14	3.8e-3	
ATLAS	0.059	6.8e-4	
γP@LHC	0.029	1.6e-4	
ILC (TESLA)	0.011	2.2e-5	
LHC (100fb^{-1})	0.007	1.2e-5	
SM	-	3.7e-16	



Use $\kappa_{tu\gamma}=0.01$ to estimate what happens at LHeC

LHeC first estimates:

$$N = \underbrace{c_{\gamma} \cdot \kappa_{tu\gamma}^{2}}_{\sigma} \cdot L \cdot Br \cdot \varepsilon$$

Option	Ee [GeV]	Ep [GeV]	Int. Lumi [fb]	$\sigma(\kappa_{tu\gamma}=0.01)$ [pb]	N_{obs}	
LHeC (RR)	70	7000	100	0.0152 31.4 2	760 94000 10000	FCNC top SM W SM top
LHeC (LR)	140	7000	10	0.0207 pb	103	

- **At LHeC, very difficult to help FCNC top prod. at a first look.**
- **Large SM W,t samples open potential to study (σ, couplings, polarisations, ...)**

Light SM Higgs

E. Perez, M. Kuze,
U. Klein, B. Kniehl, Divonne08
M. Ishitsuka, U. Klein, LHeC@DIS09

If a light SM Higgs at LHC discovered, 100< mH < 150 GeV, it will be challenging to measure e.g. H->bbar coupling at LHC, although H→ bbar branching fractions are 90 – 10 %.

if so, we aim for a confirmation at LHeC

→ **production cross section for a 120 GeV Higgs@LHeC is sizeable: good qualitative agreement of cross section calculations by E. Perez (CompHep), B. Kniehl (private code) and U. Klein (MadGraph)**

→ **Hbb coupling may be measured in cleaner ep environment, but this requires detailed background studies of add. to CC dijets sources like**

σ for 150 GeV, Etjet>5 GeV, MadGraph:

NC W+ and W- production (~ 6 pb each)
CC W- production (~9 pb)
CC Z production (~ 1 pb)
CC top production (~4-6 pb)

Also important dijets in DIS & photoproduction.

ep

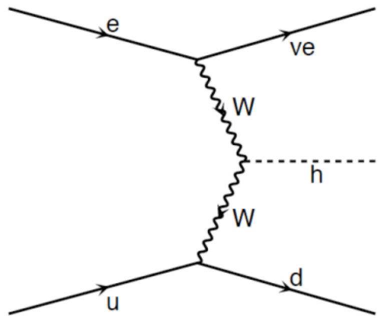
U. Klein, Divonne08 using MadGraph

CC : LO SM Higgs Production

~ 200 fb

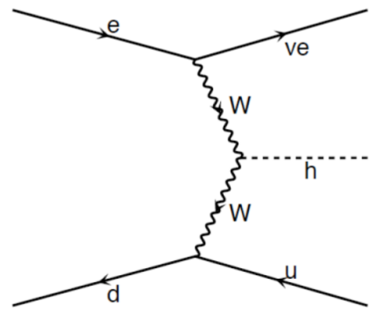
e-p (swap charges for e+p)

e- u -> ve h d



around 90-80%

e- d~ -> ve h u~



around 10-20%

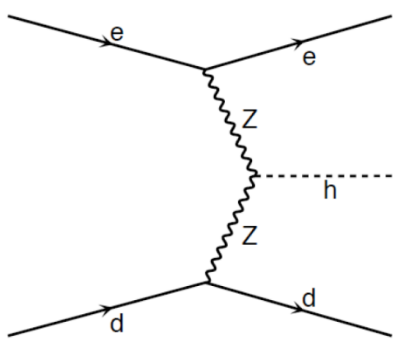
NC : LO SM Higgs Production

~ 50 fb

(Z heavier than W and couplings to fermions smaller)

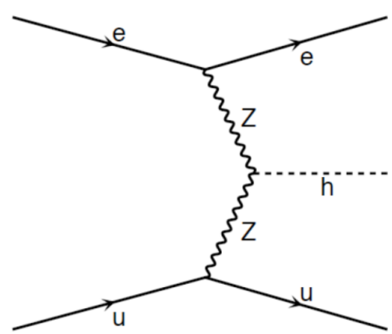
e-p (swap charges for e+p)

e- d -> e- h d



around 1/3

e- u -> e- h u



around 1/3

U. Klein,
LHeC@DIS09

CC e-p Higgs Cross Sections (fb) versus Electron Beam Energy

Ep = 7000 GeV, MadGraph, 100 k events

	100 GeV	120 GeV	160 GeV	200 GeV	240 GeV	280 GeV
50 GeV	102.4	80.6	50.3	31.6	19.9	12.5
100 GeV	201.3	165.3	113.2	78.6	55.2	39.1
150 GeV	286.3	239.5	170.4	123.3	90.5	67.1

Comparison for Ee=140 GeV and mh=115 GeV
CompHEP : 256.2 fb (M. Ishitsuka)
Madgraph : 235.7 +- 0.12 fb

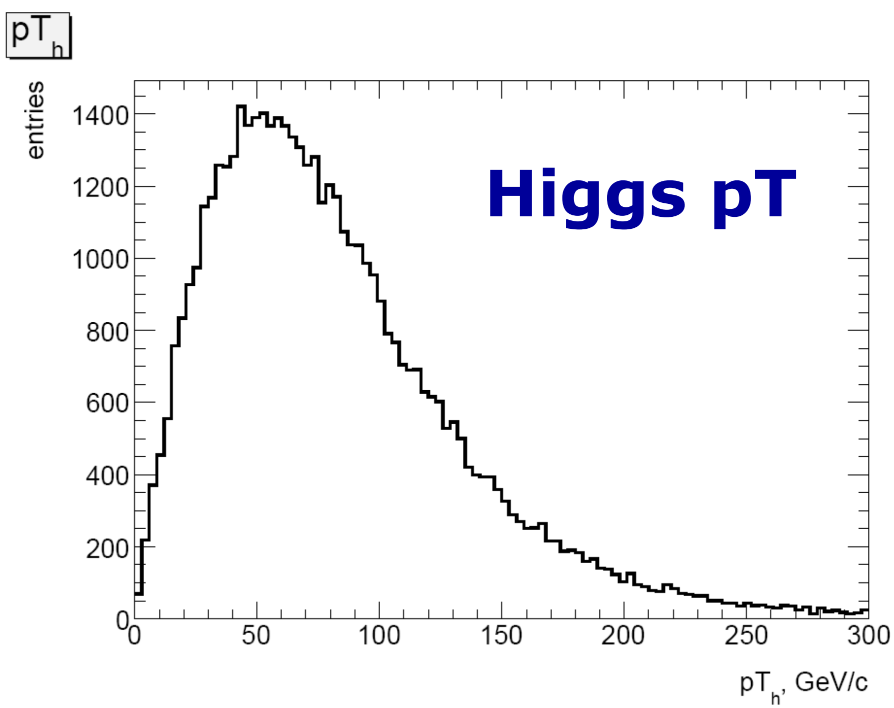
Prel. Results for e-p CC Higgs

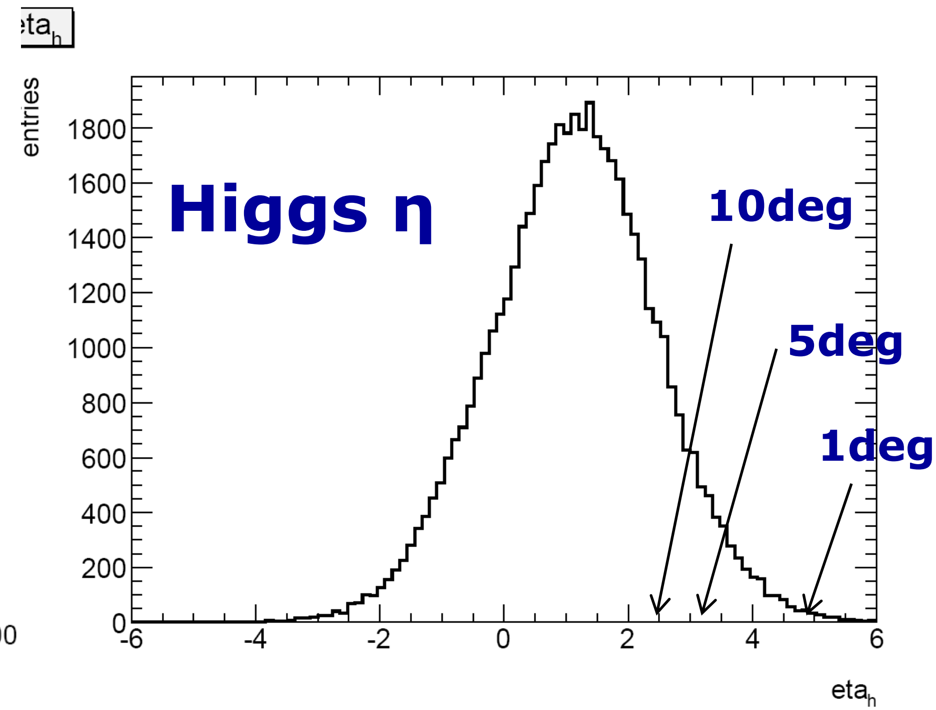
M. Ishitsuka,
U. Klein,
LHeC@DIS09

Two independent analyses studied effect of CC dijet background:

- mh=115 GeV, 140x7000 GeV^2, CompHEP+Pythia for signal, Djangoh+Ariadne for background, no detector effects
- mh=120 GeV, 150x7000 GeV^2, NEW for DIS: MadGraph/MadEvent for signal and background (Pythia and simple, generic LHC detector/PGS)

Higgs decay via Pythia





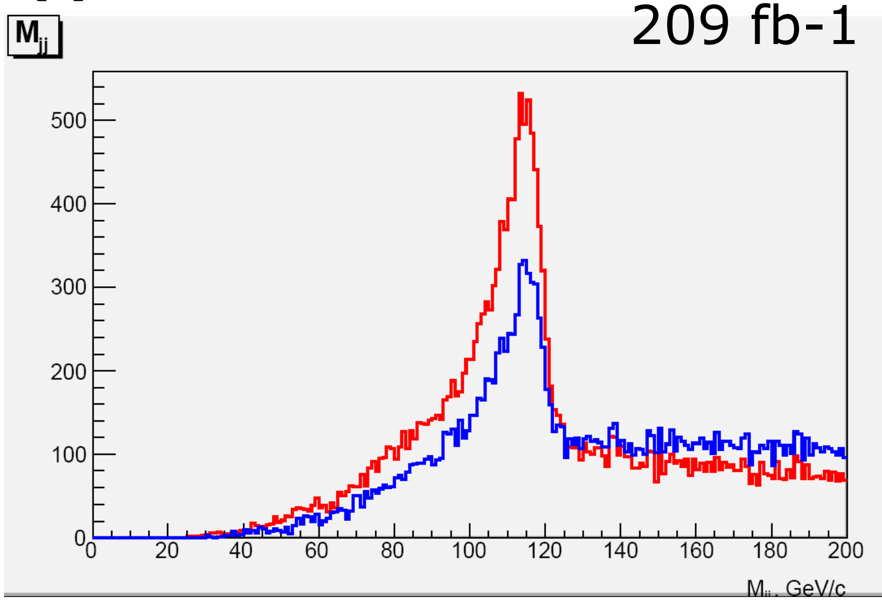
Higgs rapidity in central to forward region

M. Ishitsuka, U. Klein,
LHeC@DIS09

Invariant Dijet Mass

Q^2>400 GeV^2, yJB<0.9, Et_jet>20 GeV, Etmiss>20 GeV, jet_angle>1 °(CAL), NO b-tagging (!)

209 fb-1



RED : 2 jets with lowest rapidity

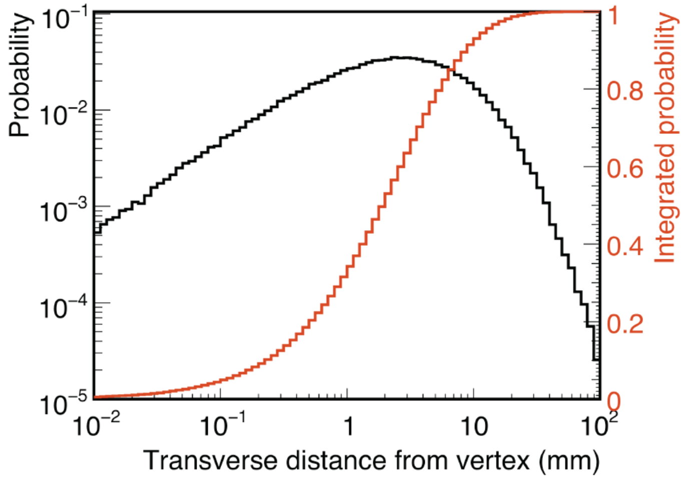
& Et_total>100 GeV

BLUE : 2 jets with highest pT

→ analysis strategy under development

still, first looks yielded consistent results of S/√B = 3 → b-tagging is crucial

Transverse distance of B decay point from generation vertex



b-tagging by flight length:

- cγτ~5 μm for 50 GeV B-mesons
- more than 95% efficiency of b-tag with 100 μm vertex reconstruction performance in the transverse direction

→looks very promising

Outlook

- **First look on obvious signatures like leptoquarks, excited leptons, SM single top and W rates and SM Higgs production are promising.**
- **Development of tools for detailed signal and background studies including detector design considerations (use here synergy to HERA, LHC and LC tools) are under way, e.g. use of Madgraph/Pythia/PGS now possible.**
- **Study full LHeC model discrimination potential for CDR, e.g. WWγ, WWZ, Hbb, … couplings.**

BackUps

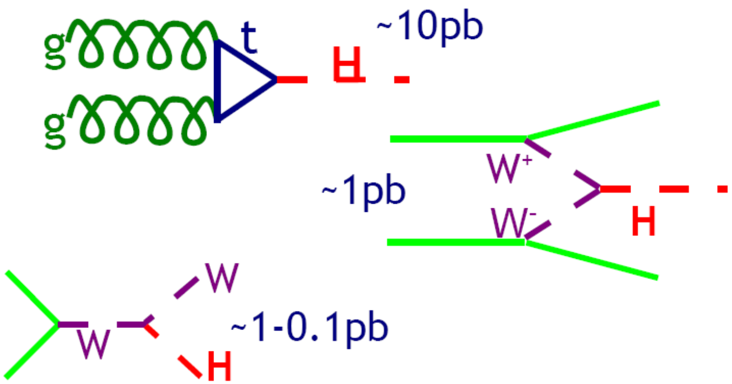
Leptoquarks

Aachen notation

Model	Fermion number F	Charge Q	$BR(LQ \rightarrow e^{\pm}q)$ β	Coupling		Squark type
$S_{\circ}^{L}$	2	$-1/3$	1/2	$e_L u$	νd	$\tilde{d}_R$
$S_{\circ}^{R}$	2	$-1/3$	1	$e_R u$		
$\tilde{S}_{\circ}$	2	$-4/3$	1	$e_R d$		
$S_{1/2}^{L}$	0	$-5/3$	1	$e_L \bar{u}$		
		$-2/3$	0		$\nu \bar{u}$	
$S_{1/2}^{R}$	0	$-5/3$	1	$e_R \bar{u}$		
		$-2/3$	1	$e_R \bar{d}$		
$\tilde{S}_{1/2}$	0	$-2/3$	1	$e_L \bar{d}$		$\bar{\tilde{u}}_L$
		$+1/3$	0		$\nu \bar{d}$	$\bar{\tilde{d}}_L$
S_1	2	$-4/3$	1	$e_L d$		
		$-1/3$	1/2	$e_L u$	νd	
		$+2/3$	0		νu	
$V_{\circ}^{L}$	0	$-2/3$	1/2	$e_L \bar{d}$	$\nu \bar{u}$	
$V_{\circ}^{R}$	0	$-2/3$	1	$e_R \bar{d}$		
$\tilde{V}_{\circ}$	0	$-5/3$	1	$e_R \bar{u}$		
$V_{1/2}^{L}$	2	$-4/3$	1	$e_L d$		
		$-1/3$	0		νd	
$V_{1/2}^{R}$	2	$-4/3$	1	$e_R d$		
		$-1/3$	1	$e_R u$		
$\tilde{V}_{1/2}$	2	$-1/3$	1	$e_L u$		
		$+2/3$	0		νu	
V_1	0	$-5/3$	1	$e_L \bar{u}$		
		$-2/3$	1/2	$e_L \bar{d}$	$\nu \bar{u}$	
		$+1/3$	0		$\nu \bar{d}$	

SM Higgs Production Examples

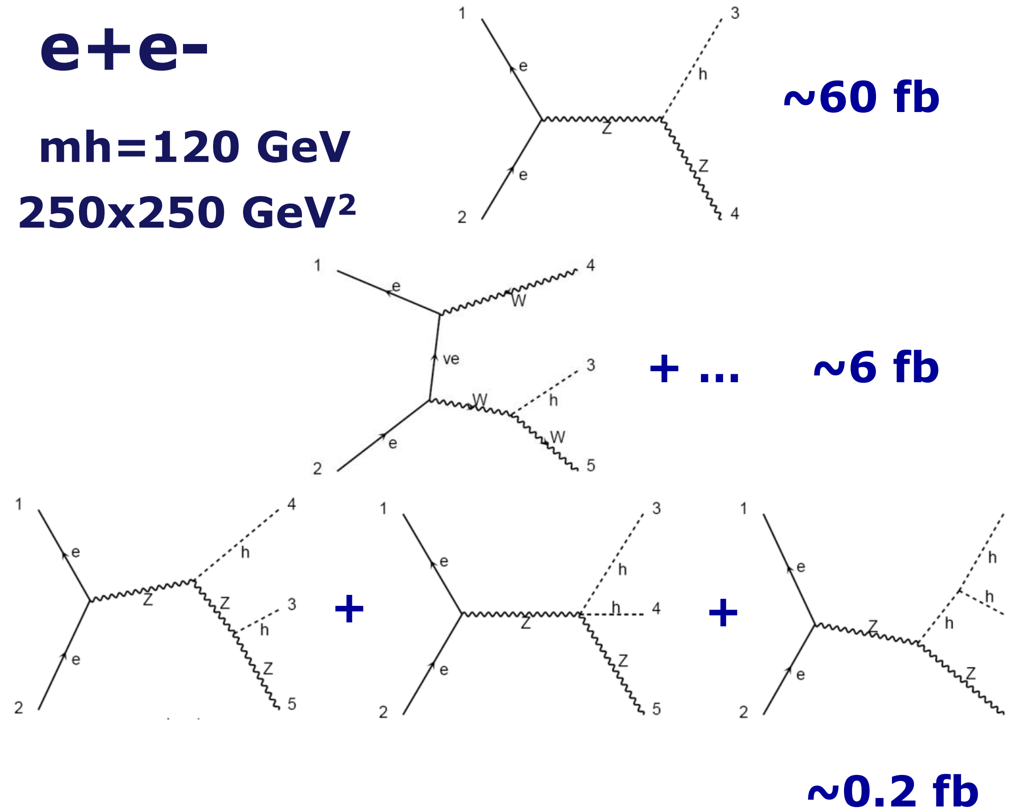
pp



e+e-

mh=120 GeV

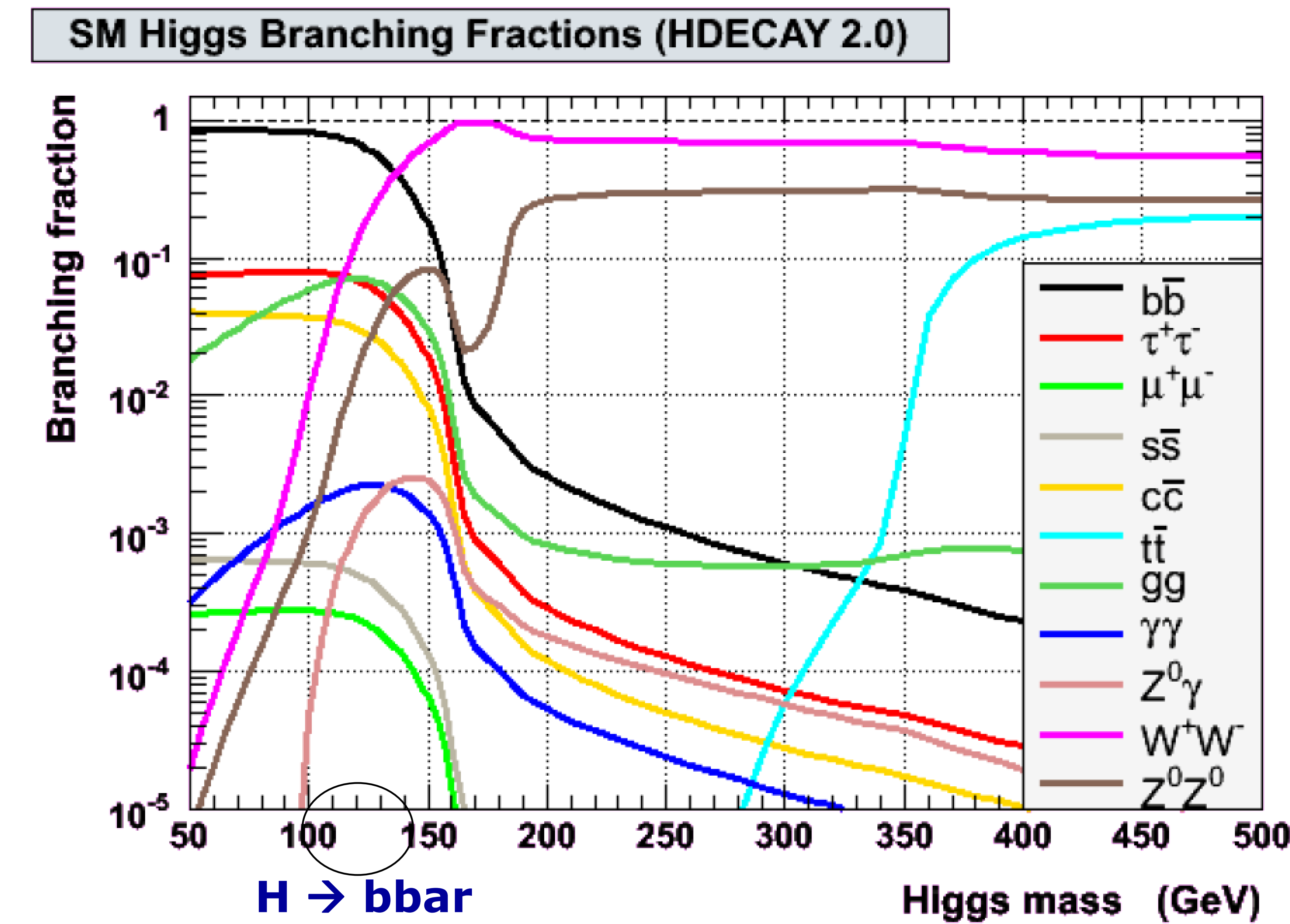
250x250 GeV^2



Decay depends strongly on m_h

- **low masses : bbar, but also γγ, τ+τ-**
- **high masses : WW, ZZ … ttbar**

Variety of search topologies with different S/B

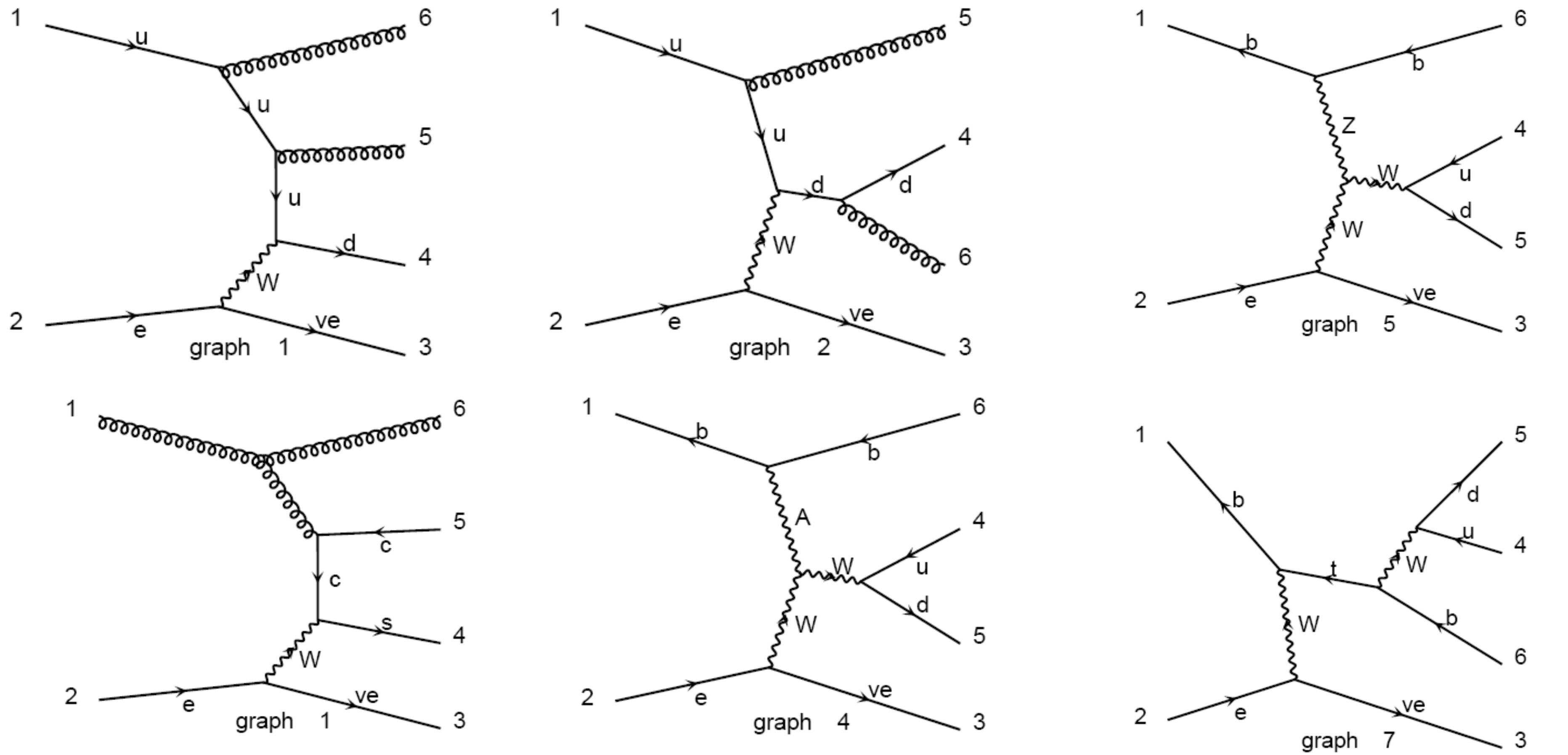

SM Higgs Branching Fractions (HDECAY 2.0)
Branching fraction
1
10-1
10-2
10-3
10-4
10-5
50
100
150
200
250
300
350
400
450
500
Higgs mass (GeV)
bb̄
τ+τ-
μ+μ-
ss̄
cc̄
tt̄
gg
γγ
Z0γ
W+W-
Z0Z0
H → bbar

Background

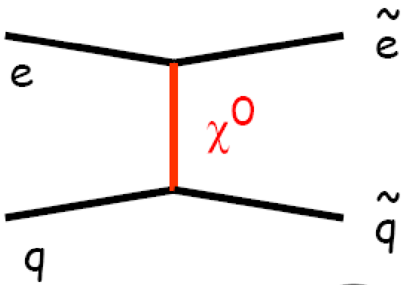
20 k CC dijet events, E_jet>5 GeV, theta_jet>0.5 deg, Mjj>30 GeV

58.8 pb

MadGraph generated 542 diagrams including higgs…, e.g.



Cross section for selectron + squark production at LHeC



O. Buchmueller et al, '08 E. Perez

tan β = 10, M_2 = 380 GeV, μ = -500 GeV