Top quark Physics at the Electron-Proton colliders

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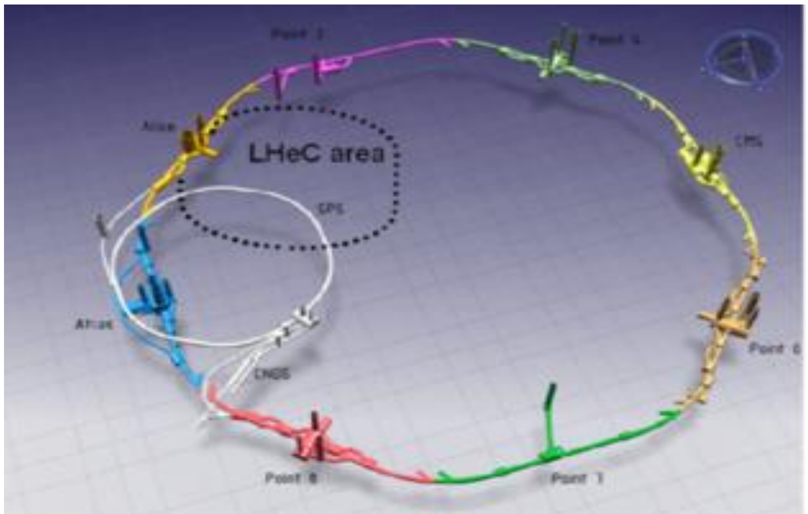
26th International WS on Deep Inelastic Scattering & Related Topics

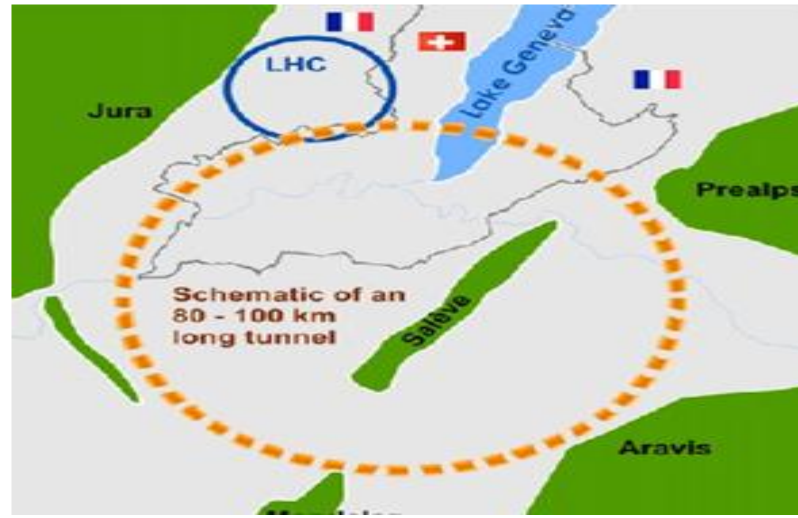
Outline

- ep colliders and top prouction
- selected topics in top sector
- selected progress in top sector
  - FCNC tqH
  - CKM element V_{tx}
- summary

Future projects of ep colliders: LHeC & FCC-eh

Both plan to create new electron facilities





LHeC

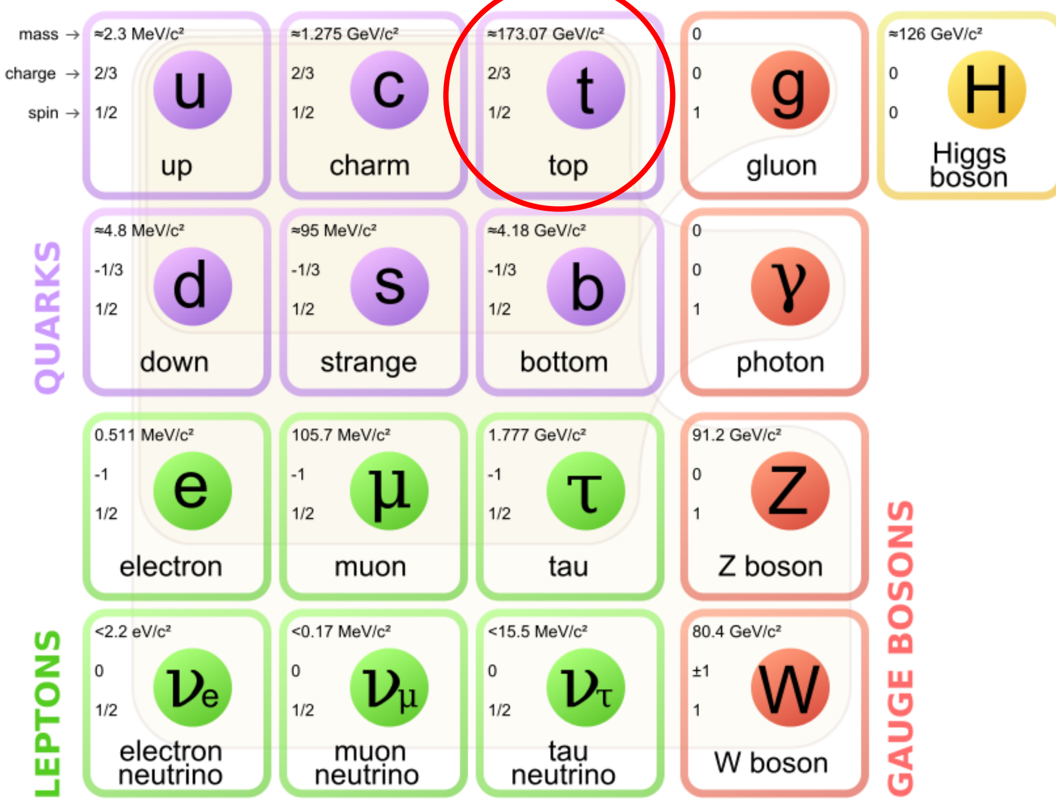
7 TeV proton of LHC and 60 GeV electron ($\sqrt{s}$~1.3 TeV)

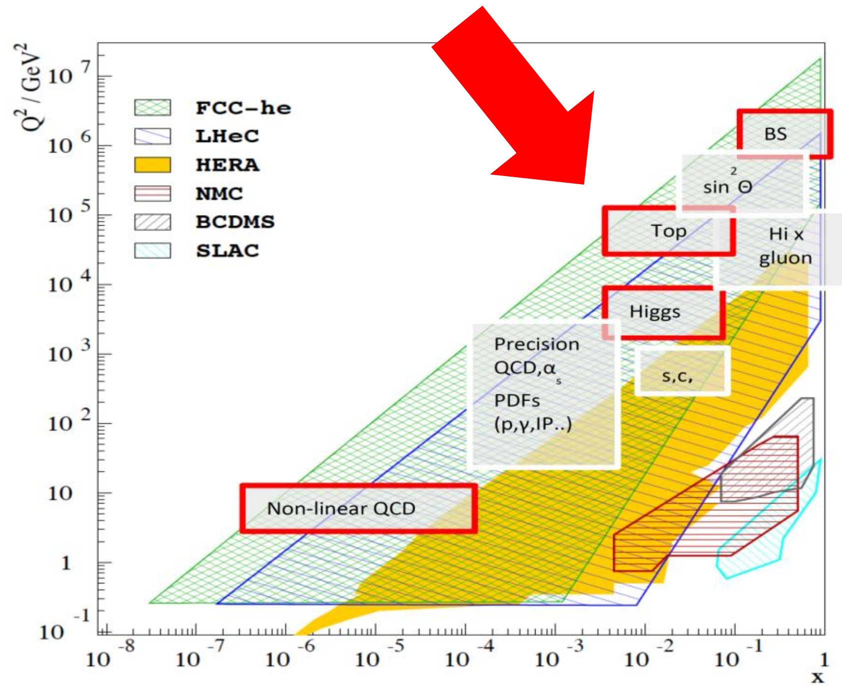
FCC-eh

50 TeV proton of FCC and 60 GeV electron ($\sqrt{s}$~3.5 TeV)

Top quark Physics at ep colliders

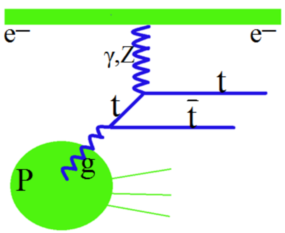
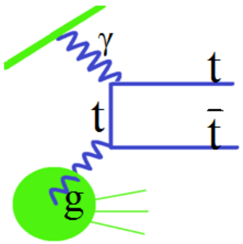
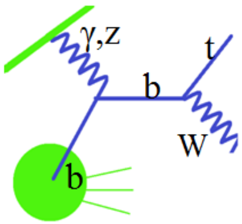
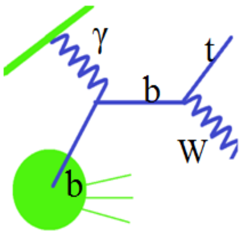
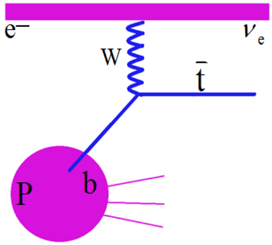
is excepted to be sensitive to BSM physics





Ep collider offers nice prospects to study the top quark, especially to study the EW interactions of the top quarks

Top quark production at the ep colliders

	top pair			single top		
	NC		CC	NC		CC
	DIS	rp	w-exch.	DIS	rp	w-exch.
			–			
30GeV 7TeV	0.003pb	0.009pb		0.003pb	0.013pb	0.74pb
40GeV 7TeV	0.006pb	0.020pb		0.006pb	0.025pb	1.15pb
50GeV 7TeV	0.012pb	0.035pb		0.010pb	0.040pb	1.58pb
60GeV 7TeV	0.017pb	0.053pb		0.014pb	0.056pb	2.02pb
60GeV 50TeV	0.476pb	1.171pb		0.280pb	0.968pb	16.3pb

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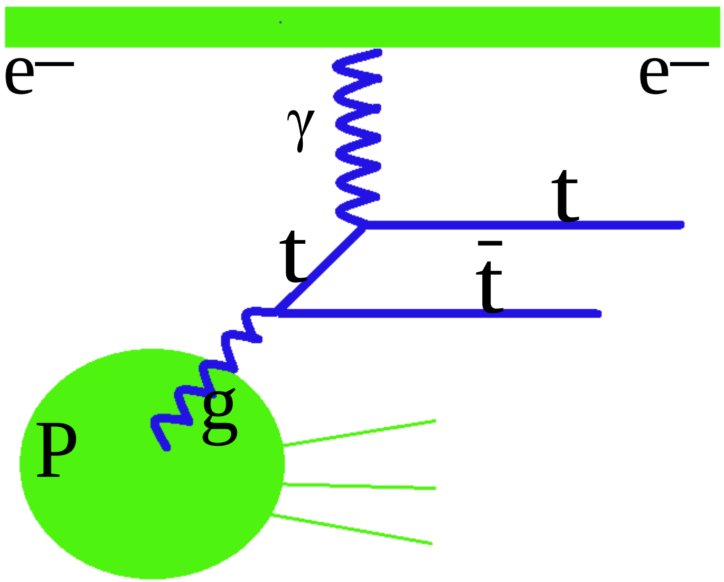
Top Structure Function

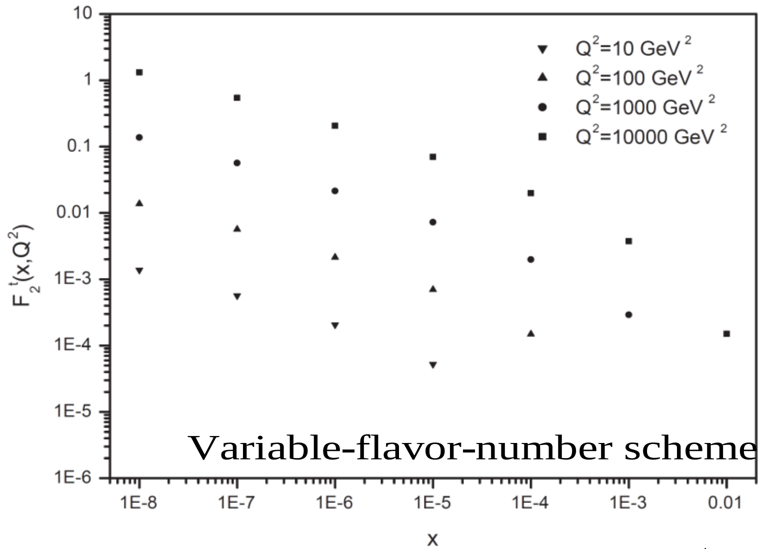
NC

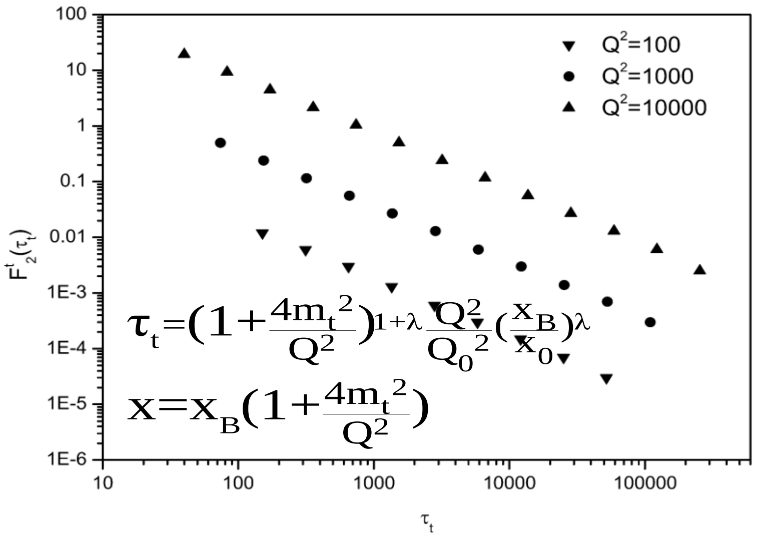


As is know, the DIS ff production is found sensitive to the gluon density in the proton.

Similarly, but using DIS tt production in, for example, photon-gluon fusion mode, it is usefull to

study $F^t_2(x,Q^2)$: the top component of the structure function in the ep projects





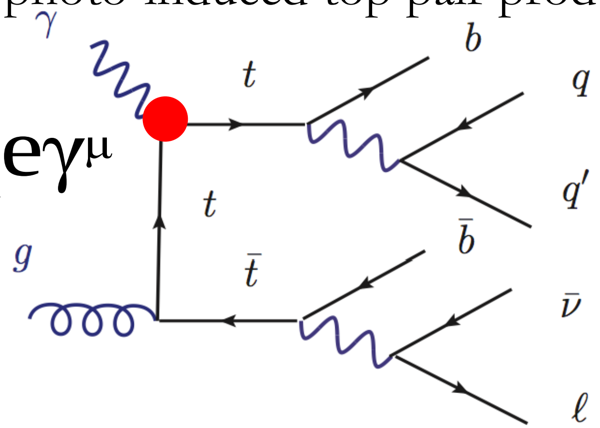
G.R. Boroun Phys.Lett. B744 (2015) 142-145 G.R. Boroun Phys.Lett. B741 (2015) 197-201

$t\bar{t}\gamma$ vertex and top electric charge

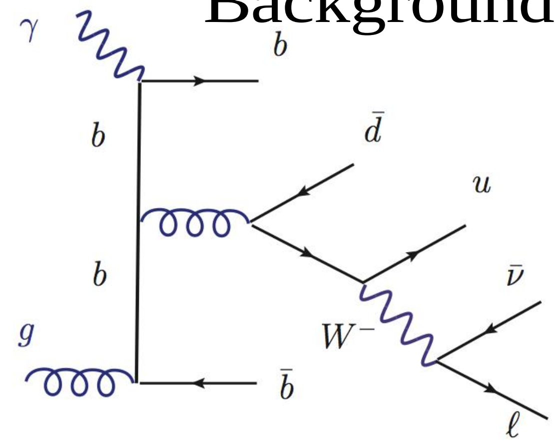
NC

The photo-induced top pair production

$iQ_t e\gamma^\mu$

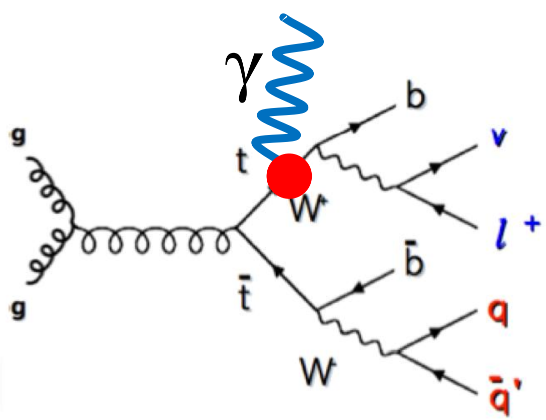


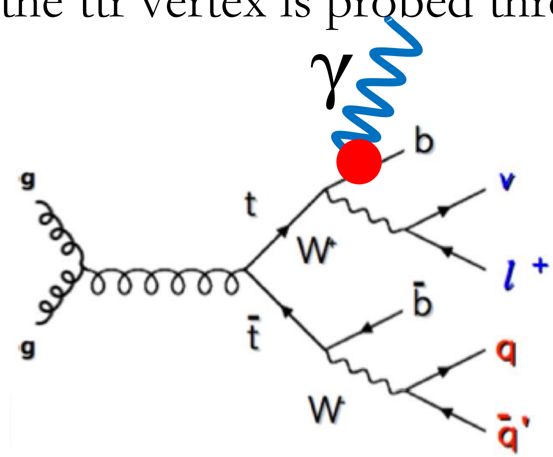
Background



measure top quark electric charge

Different from LHC where the ttr vertex is probed through ttr productions.





The out going photon could come from other charge sources like the top decay products

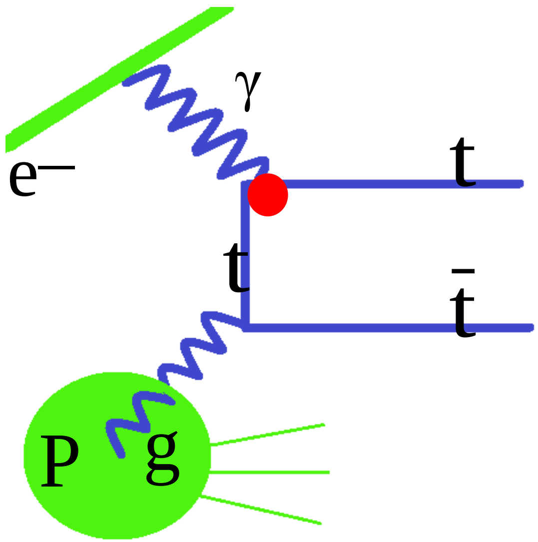
thus make such measurement challenge at the LHC

Anomalous $t\bar{t}\gamma$ couplings

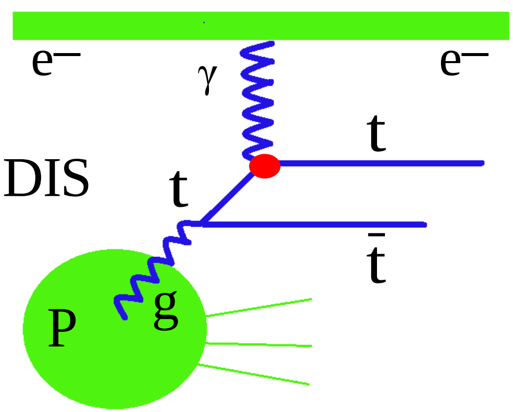
NC

Follow the same idea

$$L_{t\bar{t}\gamma} = e\bar{t}\left(Q_t \gamma^\mu A_\mu + \frac{1}{4m_t}\sigma^{\mu\nu}F_{\mu\nu}(\kappa + i\tilde{\kappa}\gamma_5)\right)t$$

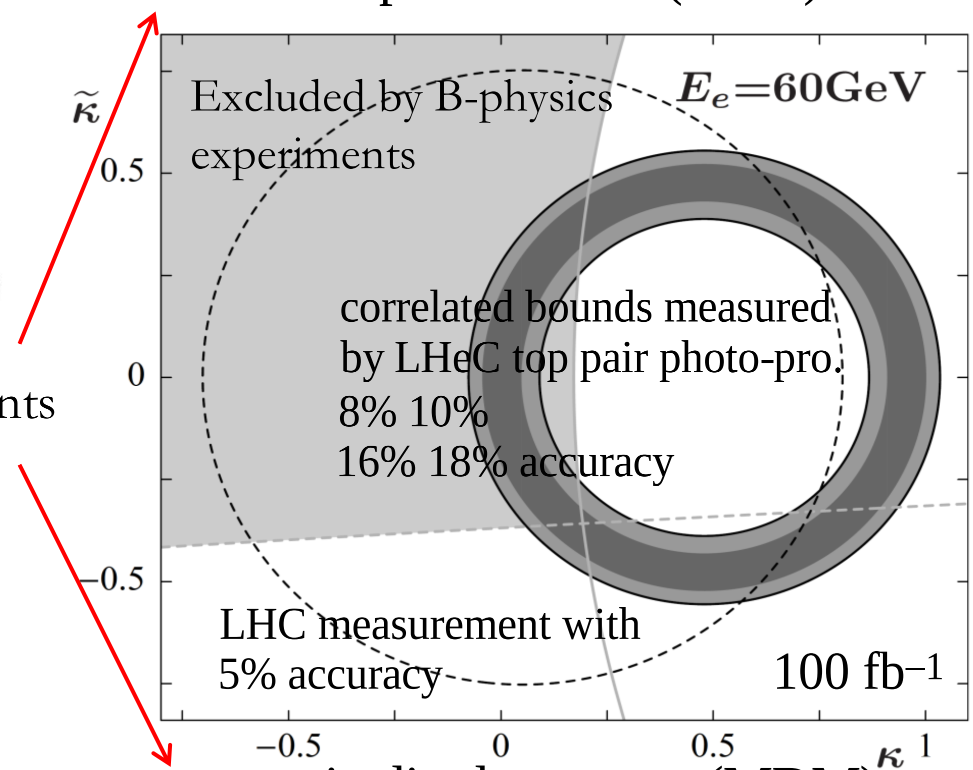


Or



can be used to set constraints

electric dipole moment(EDM): $\tilde{\kappa}$

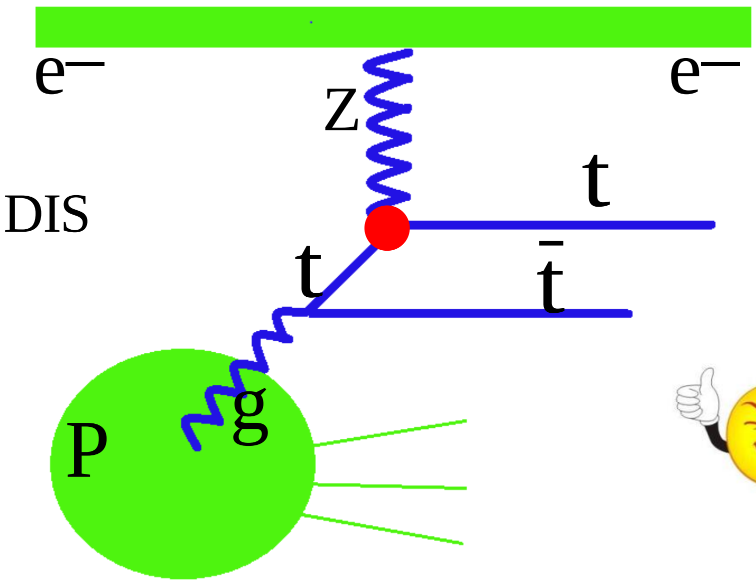


magnetic dipole moment(MDM): κ

A. O. Bouzas and F. Larios, PRD 88, 094007 (2013)

Anomalous $t\bar{t}Z$ couplings

NC



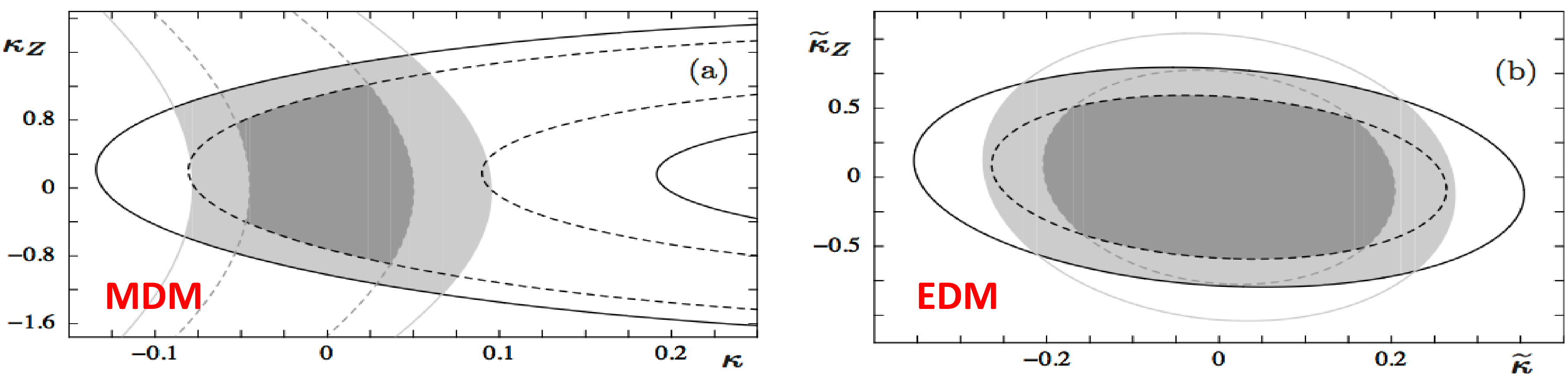
Similarly, but through DIS top pair production from gluon-Z fusion, one can study ⋯

$$L_{t\bar{t}z} = \frac{g}{2c_W}\bar{t}\left(\frac{1}{4m_t}\sigma^{\mu\nu}Z_{\mu\nu}(\kappa_z + i\tilde{\kappa}_z\gamma_5)\right)t$$

Finally, the parapeter bounds can be found:

property	precision
EDM: $\tilde{\kappa}/\tilde{\kappa}_Z$	**0.20-0.28/0.6-0.8**
MDM: κ/κ_Z	**0.05-0.09/0.9-1.3**

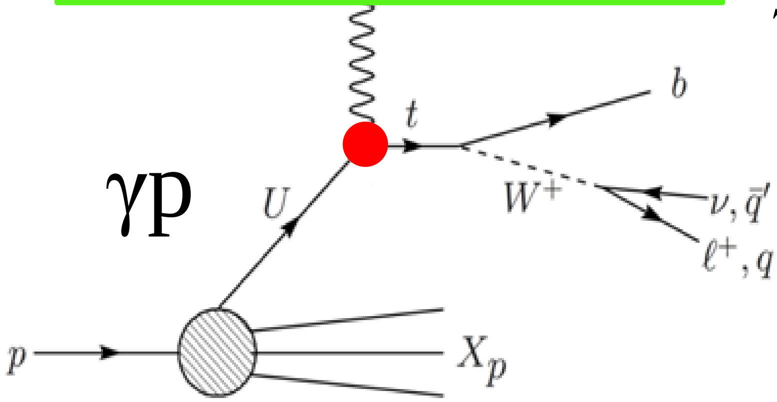
10%-18% accuracy



A. O. Bouzas and F. Larios, PRD 88, 094007 (2013)

Anomalous FCNC tqγ couplings

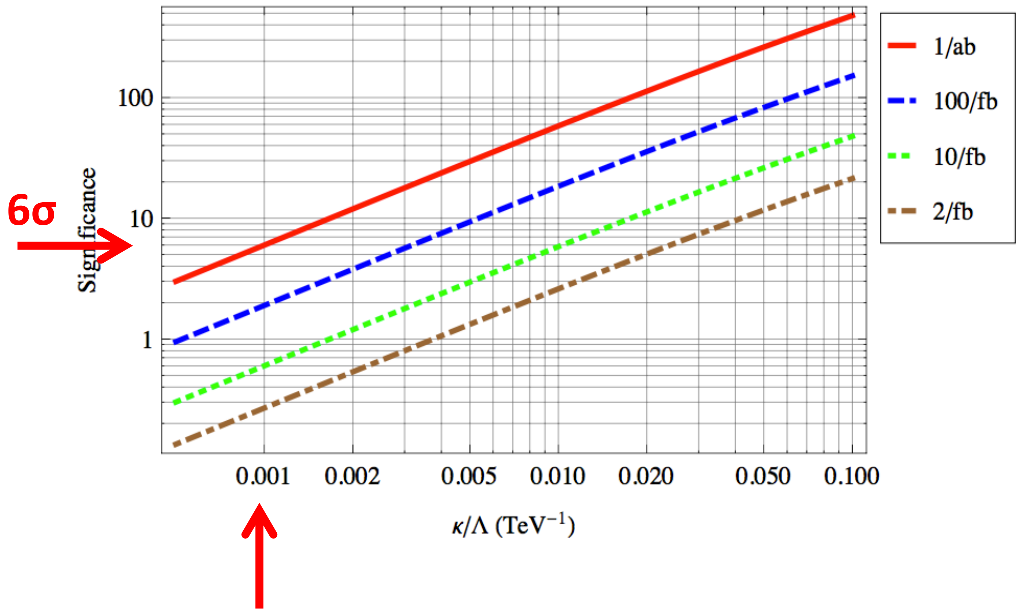
NC



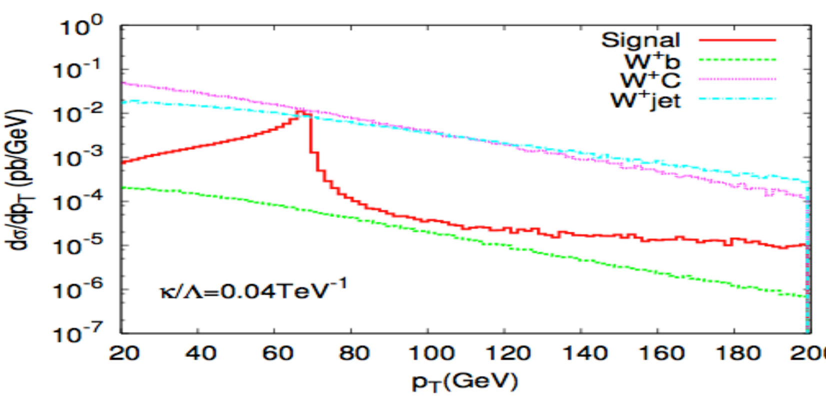
The effective L involving ano. tqr interaction is given:

$$L_{tq\gamma} = -g_e \sum_{q=u,c} Q_q \frac{\kappa_q}{\Lambda} \bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$

It was found that ep based rp collider can provide a nice prospect to probe it:



With 1 ab-1, the tqr coupling can be probed down to order of 10-3 at the LHeC



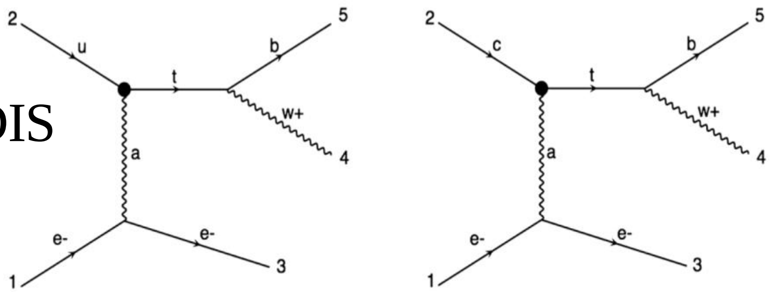
LHeC TDR J.Phys.G39,075001(2012)

AI.T.Cakir, O.Cakir, S.Sultansoy, Phys.Lett.B685:170-173,(2010)

Anomalous FCNC tqγ and tqZ couplings

NC

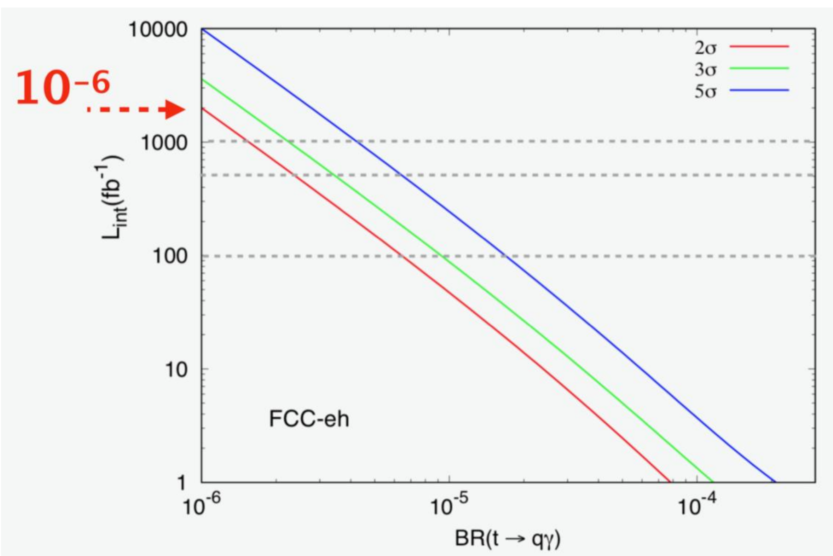
DIS

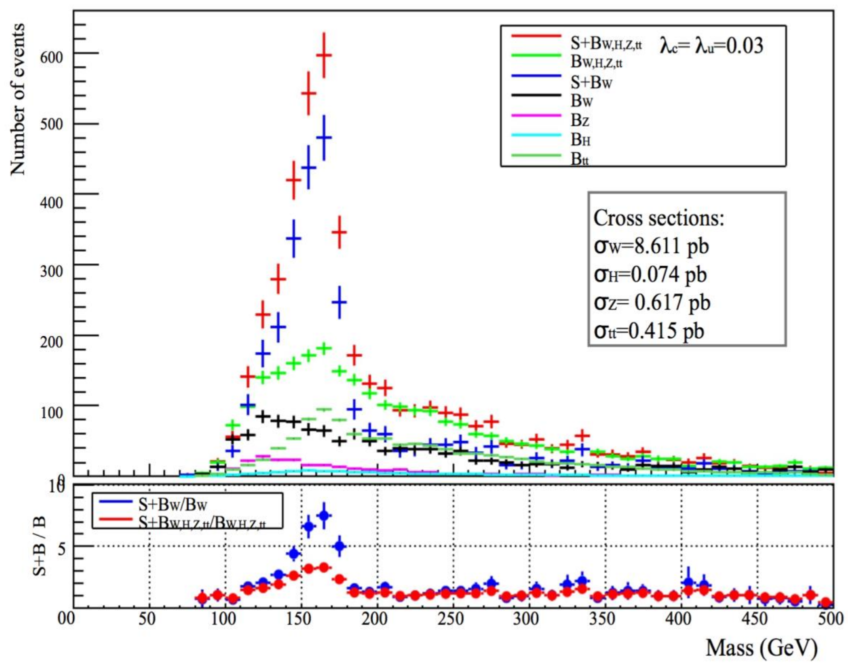


Through the DIS production, one can set constraints to both the tqr and tqZ couplings

Cuts	Definitions
Cut-0	Preselection cuts with number of jets ≥ 3 and one electron with $p_T^e > 20$ GeV
Cut-1	One jet with b-tagging
Cut-2	$p_T^b > 40$ GeV and $p_T^{j_2,j_3} > 30$ GeV,
Cut-3	$-5 < \eta^{b,j_2,j_3} < 0$ and $-2.5 < \eta^e < 2.5$
Cut-4	60 GeV $< M_{\rm inv}^{\rm rec}(j_2, j_3) <$ 90 GeV
Cut-5	130 GeV $< M_{\rm inv}^{\rm rec}(j_b, j_2, j_3) <$ 200 GeV

at the same level at the FCC-eh
after the detector effects are considered.



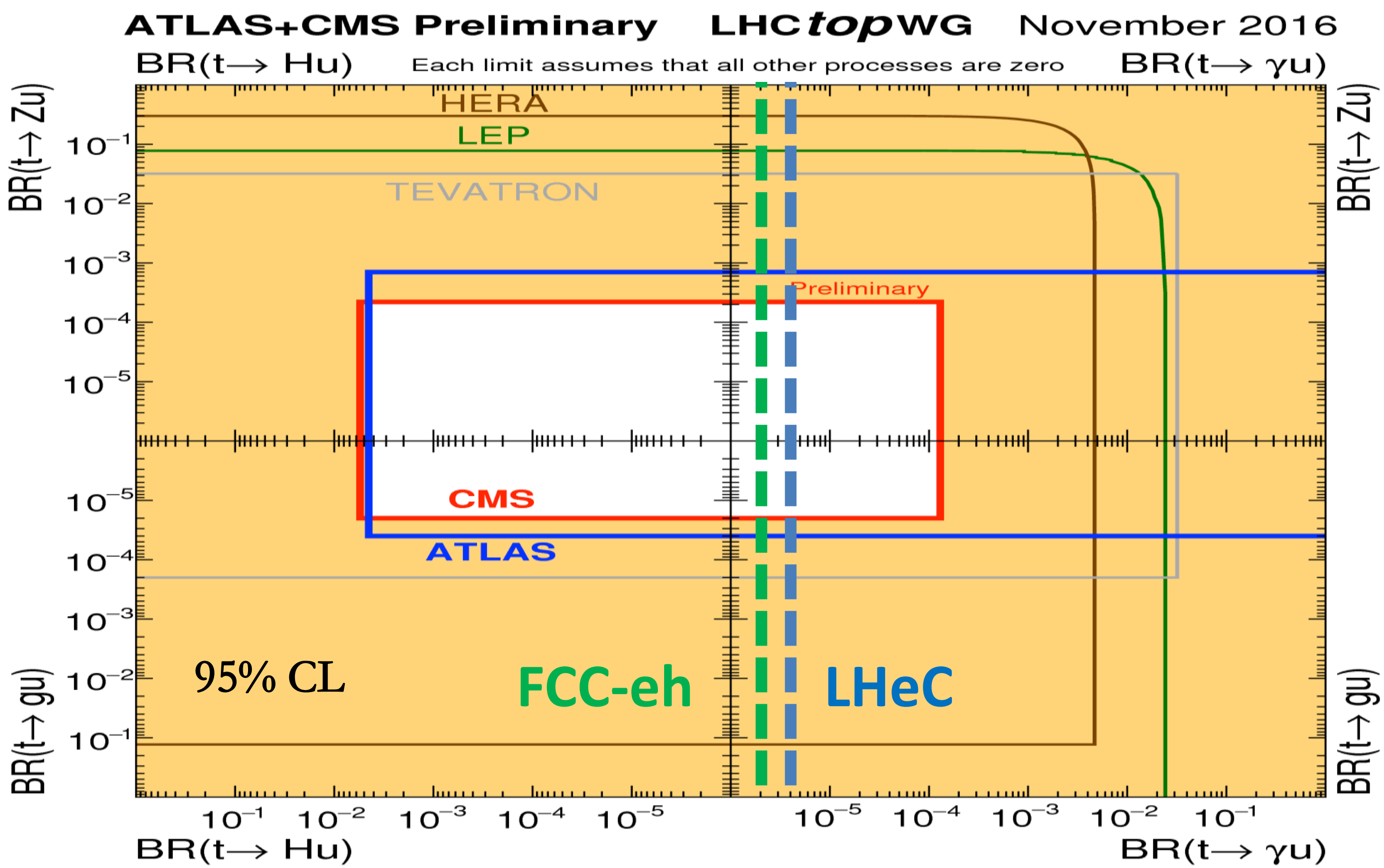


H.Denizli,A.Senol,A.Yilmaz,,I.Turk Cakir,H.Karadeniz,O.Cakir, Phys.Rev.D96:015024,(2017)

Anomalous FCNC tqγ couplings

NC

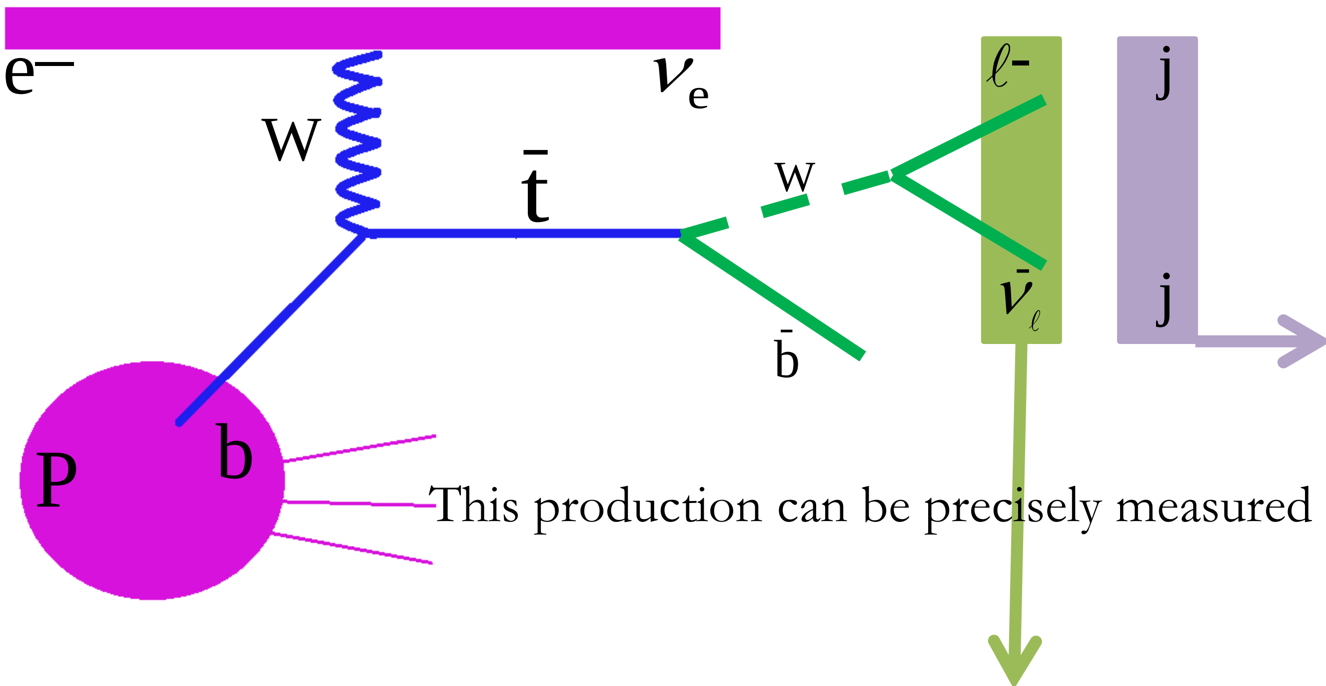
Detector Level study
Ee=60 GeV 2ab-1



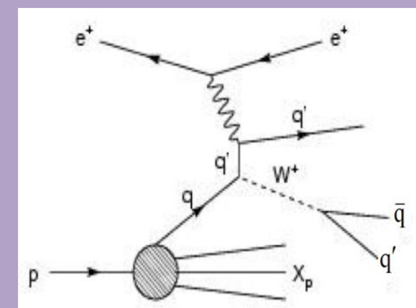
It was found that by performing the detector level study, the branching ratio of t -> qr and t ->qZ can be measured down to order of ~10-6 at the FCC-eh with 2ab-1.

Charged Current Top quark Production

Now let' s see some CC top productions through W-boson exc in both decay modes···

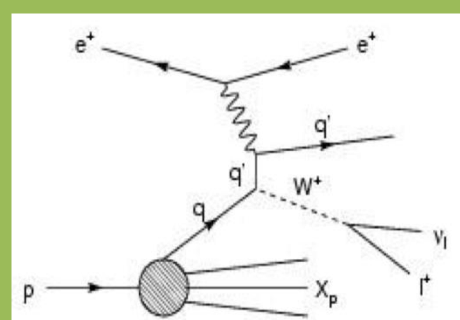


This production can be precisely measured



$\not{E}_T \geq 25\text{GeV}$
$\Delta\Phi_{\not{E},j} \geq 0.4$
$\Delta\Phi_{\not{E},b} \geq 0.4$
$|m_{j_1j_2} - m_W| \leq 22\text{GeV}$
$p^{j,b}_T \geq 20\text{GeV}$
$|\eta^j| \leq 5, |\eta^b| \leq 2.5,$
$\Delta R_{j,b/j} \geq 0.4$

Nt=22000, S/B=1.2

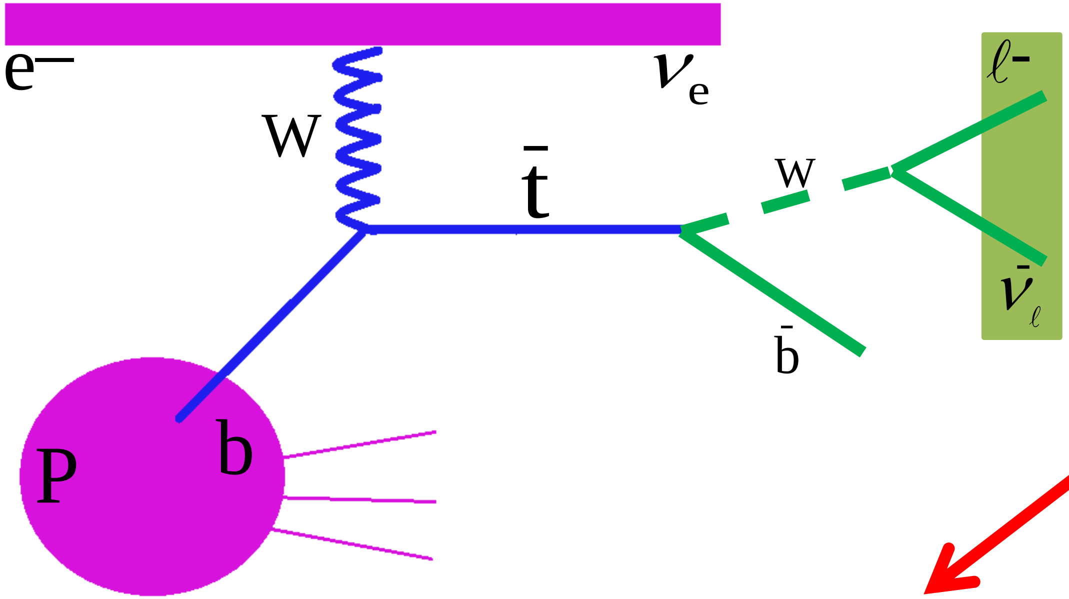


$\not{E}_T \geq 25\text{GeV}$
$\Delta\Phi_{\not{E},j} \geq 0.4$
$\Delta\Phi_{\not{E},b} \geq 0.4$
$\Delta\Phi_{\not{E},\ell} \geq 0.4$
$p^{j,b,\ell}_T \geq 20\text{GeV}$
$|\eta^j| \leq 5, |\eta^{b,\ell}| \leq 2.5,$
$\Delta R_{\ell,b/j} \geq 0.4$

Nt=11000, S/B=11

top quark spin polarisation

CC



Such prediction can be used, for example, to measure the top quark spin polarization.

$$\frac{1}{\Gamma_t}\frac{d\Gamma}{d\cos\theta}=\frac{1}{2}(1+A_{\uparrow\downarrow}\alpha\cos\theta)$$

Here, θ is angle between the charged lepton and the spin quantisation axis in the top rest frame

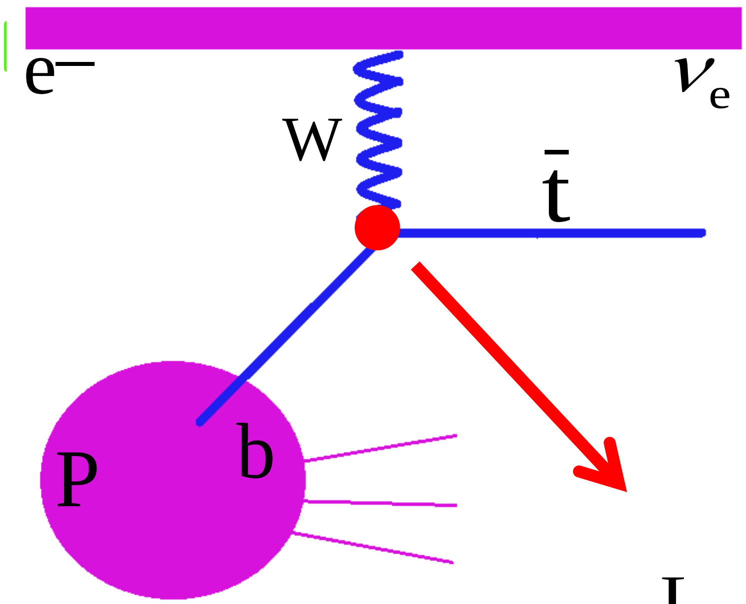
$$A_{\uparrow\downarrow}=\frac{N_{\uparrow}-N_{\downarrow}}{N_{\uparrow}+N_{\downarrow}}$$

spin asymmetry

S.Atag,B.D.Sahin, PRD 69, 034016 (2004)
S.Atag,B.D.Sahin, PRD 70, 037503 (2004)

Anomalous Wtb couplings

CC



The CC single top production is also a good way to test the anomalous tbW couplings.

The Lagrangian is given by this formula

$$L_{Wtb}=\frac{g}{\sqrt{2}}\left[W_{\mu}\bar{t}\gamma^{\mu}(V_{tb}f_V^L P_L+f_V^R P_R)b-\frac{1}{2m_W}W_{\mu\nu}\bar{t}\sigma^{\mu\nu}(f_T^L P_L+f_T^R P_R)b\right]+h.c.$$

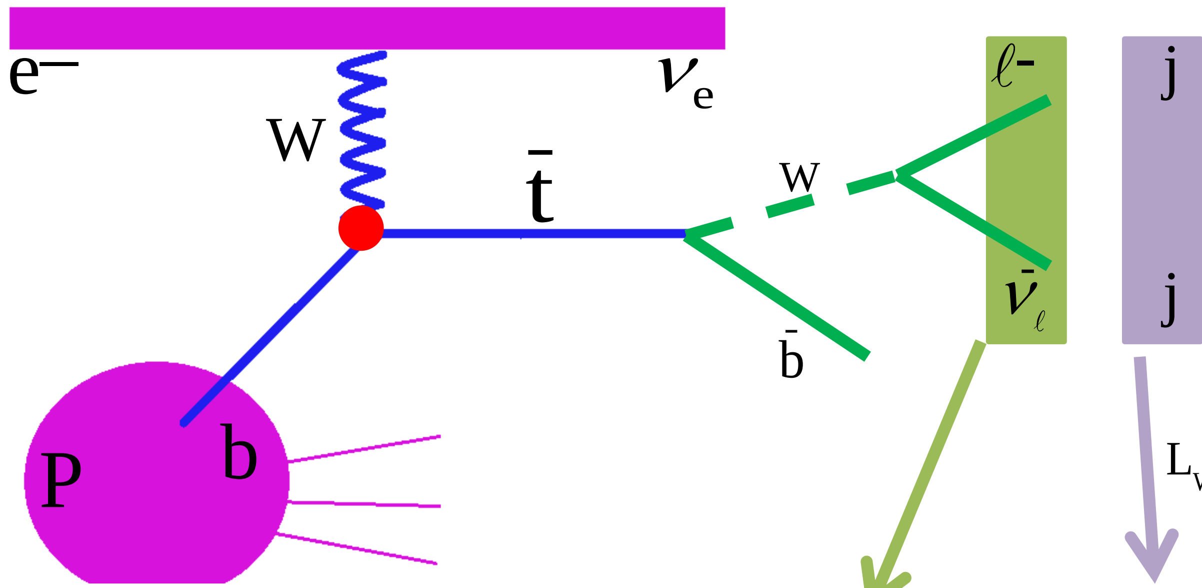
The fact that the left-handed vector current is one to a good approximation, and the vanishing of the other parameters correspond to the SM case as within the SM the tbW vertex is purely left-handed.

$$|V_{tb}|f_V^L\simeq 1, f_V^R, f_T^L, f_T^R=0$$

S. Dutta, A. Goyal, M. Kumar, B. Mellado, Eur. Phys. J. C (2015) 75:577

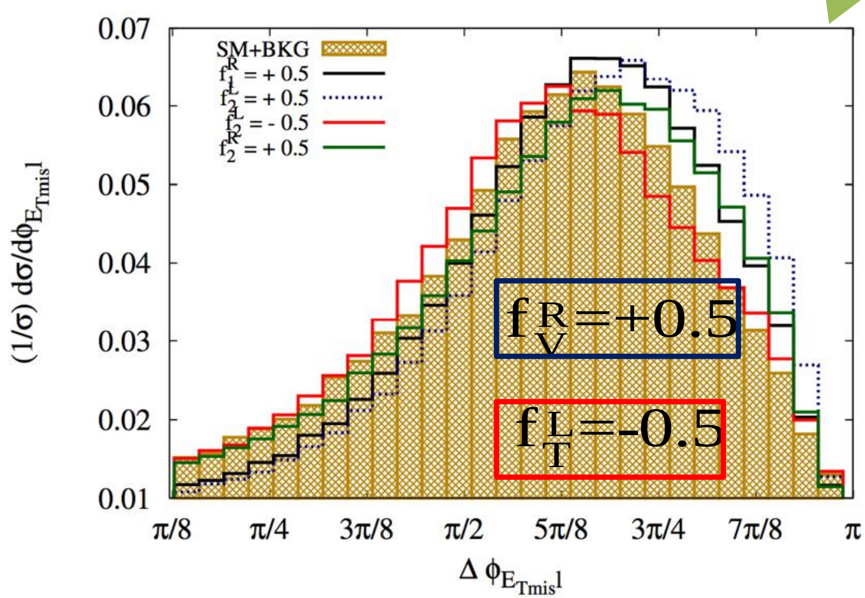
Anomalous Wtb couplings

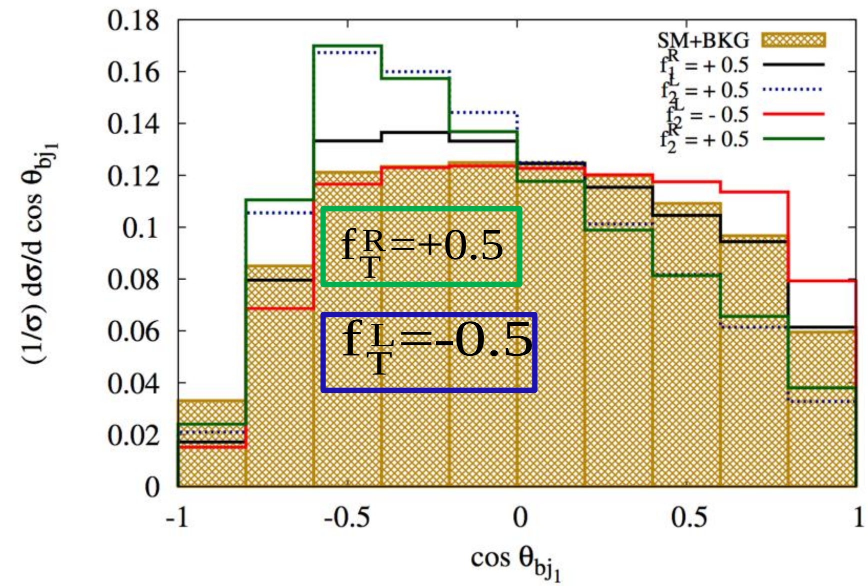
CC



Studies were performed in both the leptonic and hadronic decay modes.

$$L_{Wtb} = \frac{g}{\sqrt{2}}\left[W_\mu \bar{t} \gamma^\mu (V_{tb} f_V^L P_L + f_V^R P_R) b - \frac{1}{2m_W} W_{\mu\nu} \bar{t} \sigma^{\mu\nu} (f_T^L P_L + f_T^R P_R) b \right] + h.c.$$

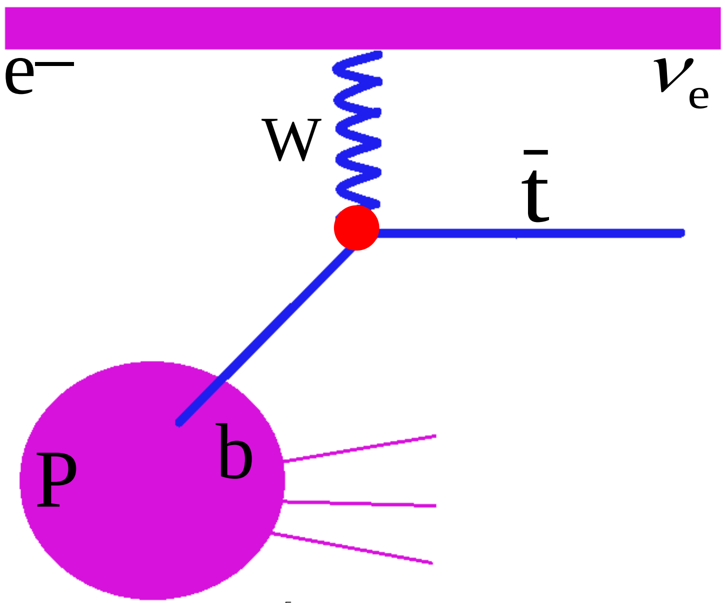




S. Dutta, A. Goyal, M. Kumar, B. Mellado, Eur. Phys. J. C (2015) 75:577

Anomalous Wtb couplings

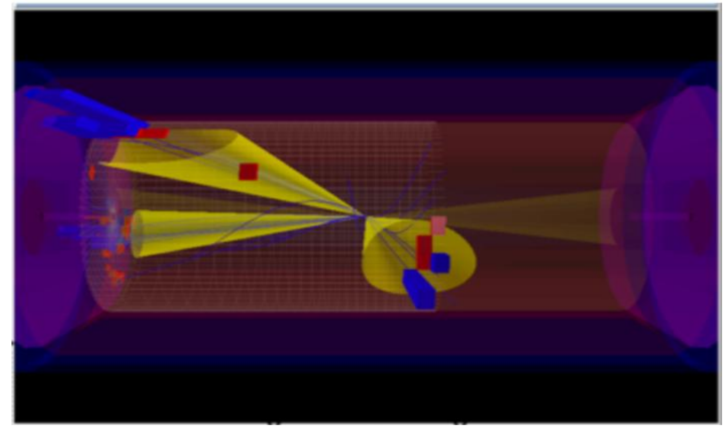
CC

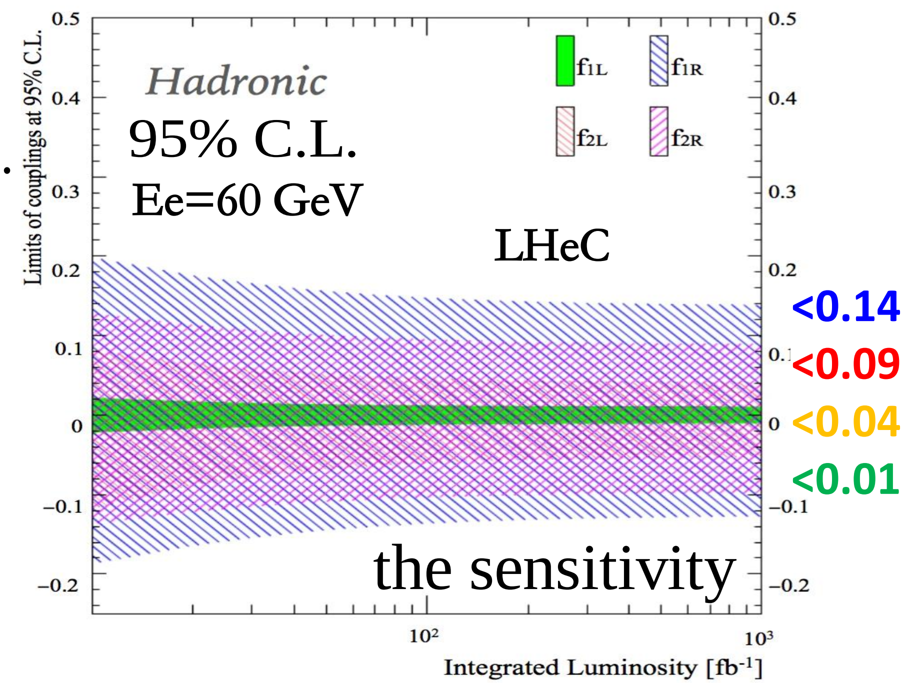


$$L_{Wtb}=\frac{g}{\sqrt{2}}\left[\begin{array}{l} W_\mu \bar{t}\gamma^\mu(V_{tb}f_V^L P_L+f_V^R P_R)b \\ -\frac{1}{2m_W}W_{\mu\nu}\bar{t}\sigma^{\mu\nu}(f_T^L P_L+f_T^R P_R)b \end{array}\right]+h.c.$$

The analysis show that the tbW vertex can be probed at the LHeC, already to a very high accuracy, compare to the existing limits from the LHC.

By including the detector level simulation, the parameter sensitivity are obtained.

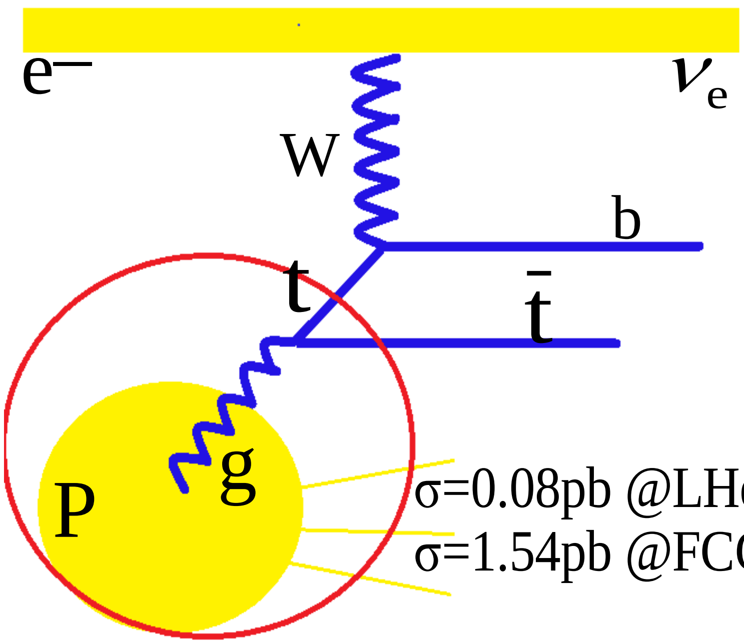




S. Dutta, A. Goyal, M. Kumar, B. Mellado, Eur. Phys. J. C (2015) 75:577

Charged Current Top quark Production

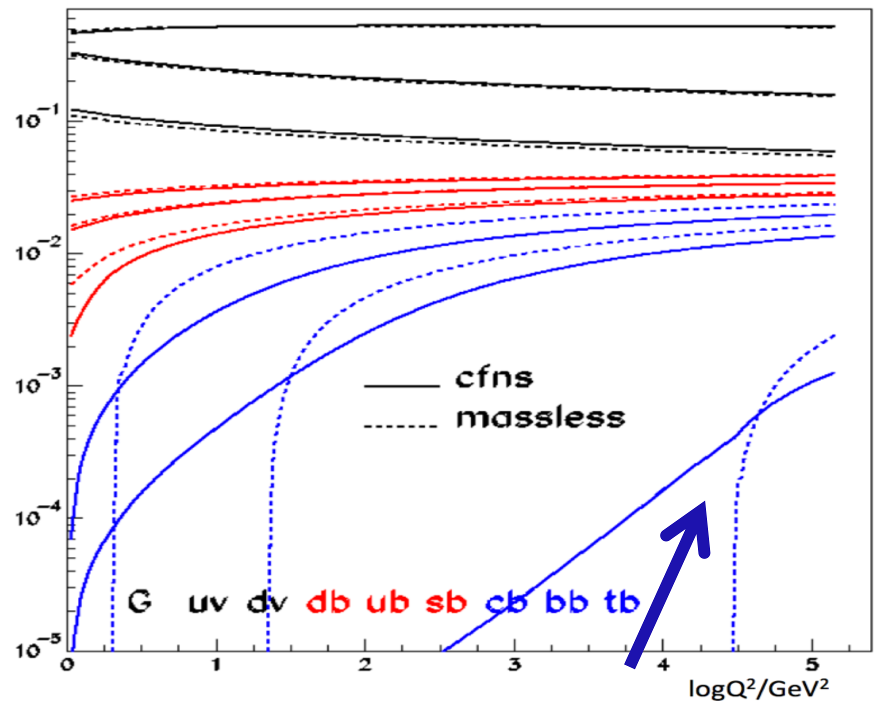
CC



σ=0.08pb @LHeC
σ=1.54pb @FCC-eh

since at very high scale, the top quark may be considered 'light'

Another charged current top production makes it possible to consider quark density for the top.



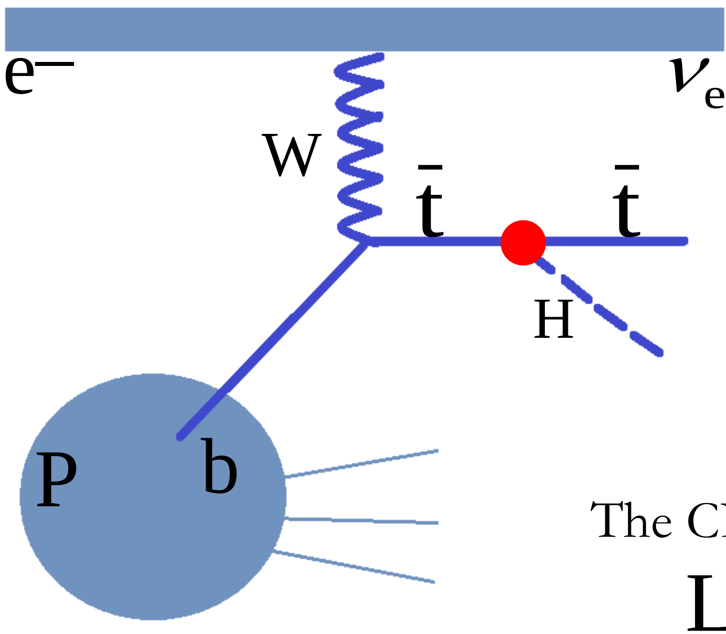
Here a six-flavor-variable-number scheme for top quark can be proposed.

Thus the ep projects offers new field of research for the top quark parton distribution functions.

LHeC TDR J.Phys.G39,075001(2012)

CP nature of top-Higgs couplings

CC



Considering the top and Higgs associated production, we can study the CP nature of the ttH coupling.

The CP-phase dependent lagrangian can be written here:

$$L_{ttH} = -i\frac{m_t}{v}\bar{t}\left[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t\right]tH$$

$\zeta_t=0,\ \kappa=1$ → SM case

$\zeta_t=0$ or $\zeta_t=\pi$ → pure scalar state

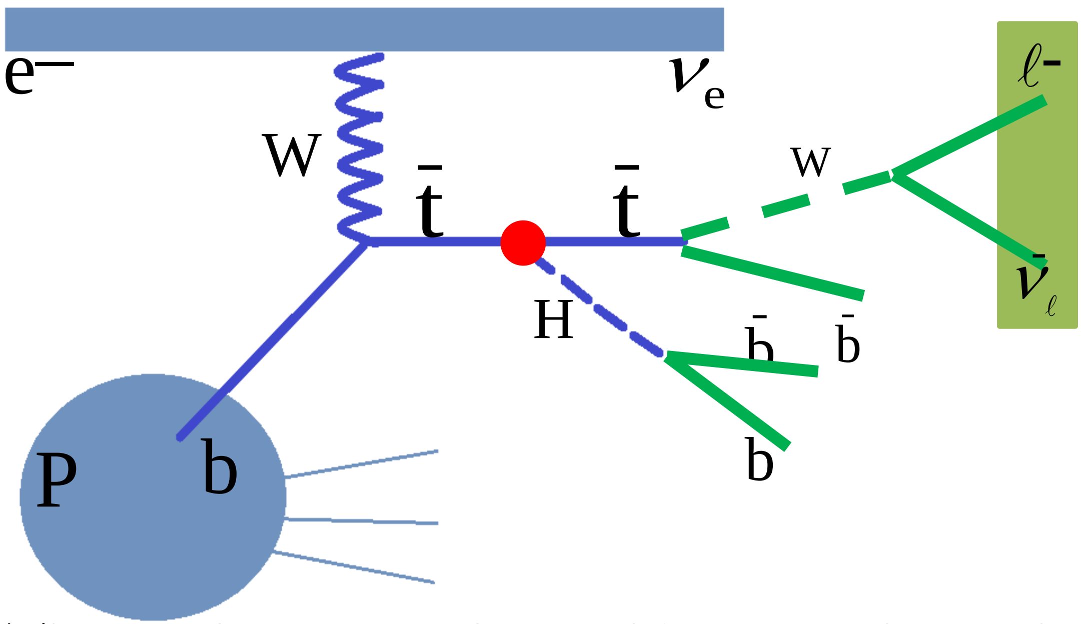
$\zeta_t=\pi/2$ → pure pseudo scalar state

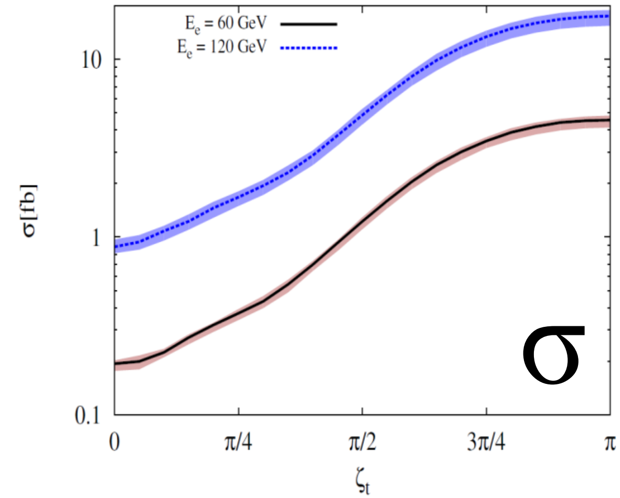
$0<\zeta_t<\pi/2$ or $\pi/2<\zeta_t<\pi$ → mixture CP-states

B. Coleppa, M. Kumar, S. Kumar, B. Mellado, Phys.Lett.B770(2017)335

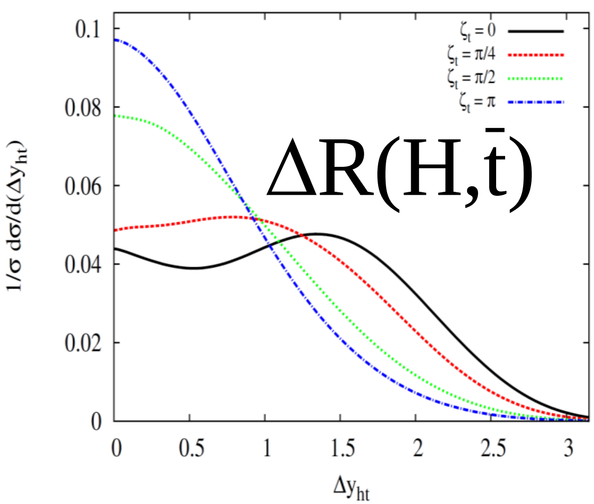
CP nature of top-Higgs couplings

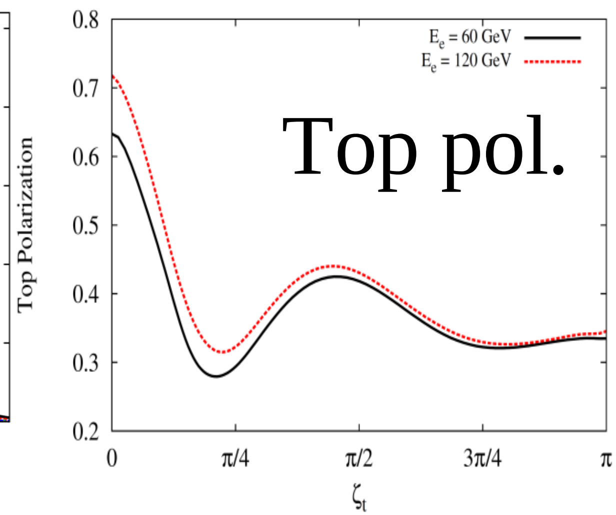
CC

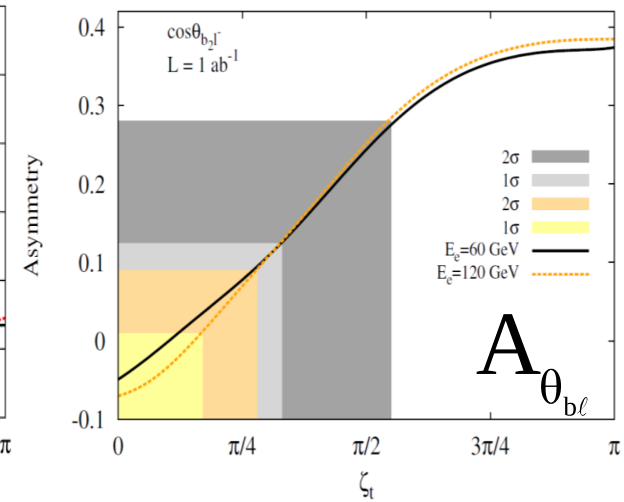




The study was performed by considering h->bb and top leptonic decay.



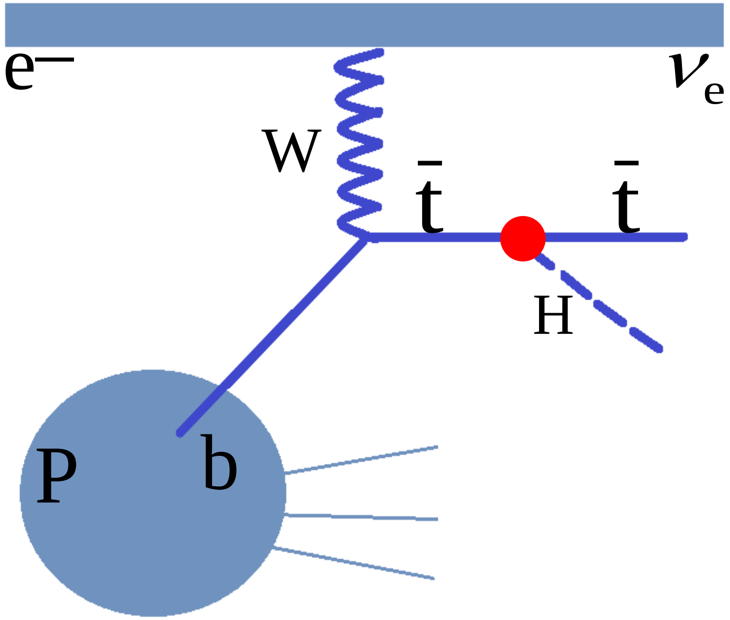


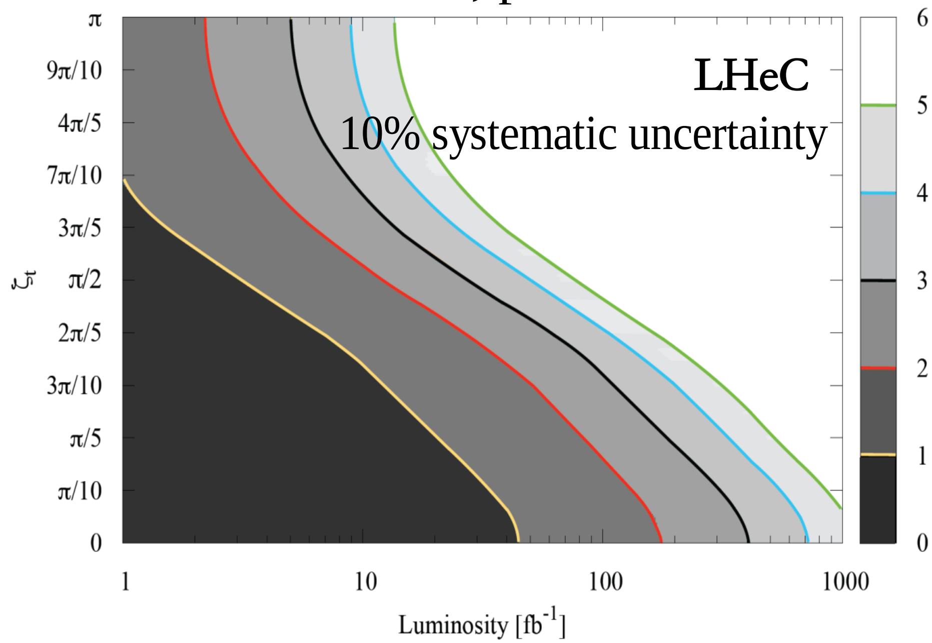


B. Coleppa, M. Kumar, S. Kumar, B. Mellado, Phys.Lett.B770(2017)335

CP nature of top-Higgs couplings

CC





It was found that a non-zero phase can be observed/excluded better than 4 sigma confidence level.

100 fb^{-1}: $\pi/5<\zeta_t<\pi$ (2σ) and $3\pi/10<\zeta_t<\pi$(3σ) Exc.

400 fb^{-1}: $\pi/6<\zeta_t<\pi$ (4σ) and $\pi/4<\zeta_t<\pi$(5σ) Exc.

HL-LHC 3ab^{-1} probe up to $\zeta_t=\pi/6$

The work is preparing to be update at the FCC-eh.

We can conclude that the ep colliders provide a better environment to test the CP nature of the ttH couplings.

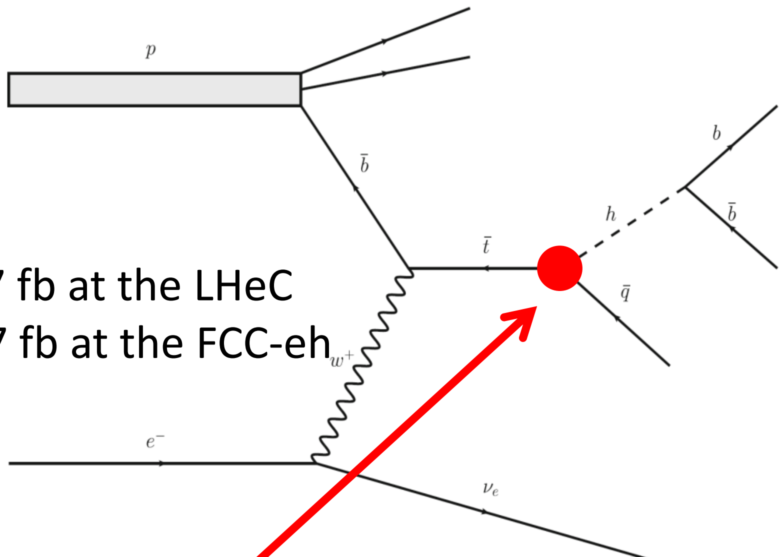
B. Coleppa, M. Kumar, S. Kumar, B. Mellado, Phys.Lett.B770(2017)335

- ep colliders and top prouction
- selected topics in top sector
- selected progress in top sector
  - FCNC tqH
  - CKM element V_{tx}
- summary

CC

Anomalous FCNC tqH couplings

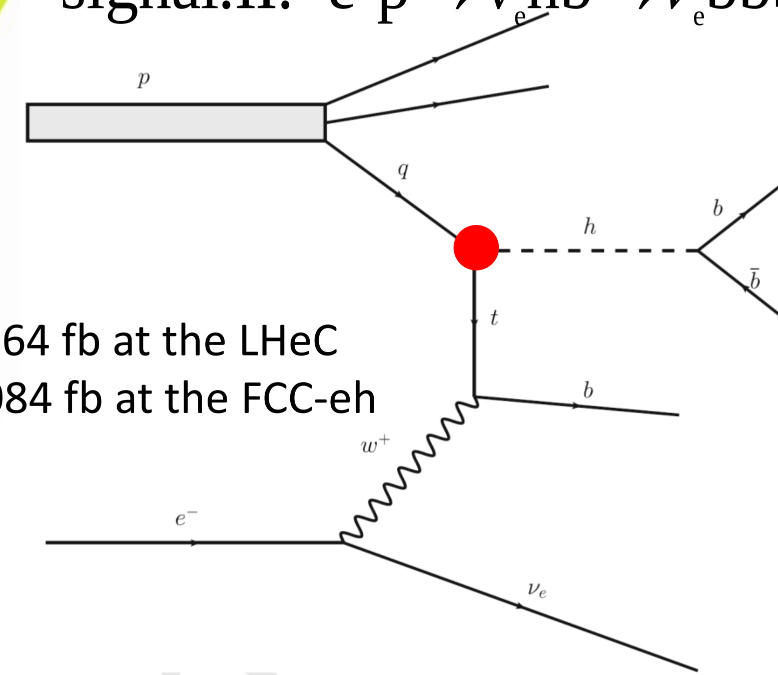
signal.I: $e^- p \to \nu_e \bar{t} \to \nu_e h \bar{q} \to \nu_e b\bar{b}\bar{q}$



7.97 fb at the LHeC

64.27 fb at the FCC-eh

signal.II: $e^- p \to \nu_e h b \to \nu_e b\bar{b} b$



0.64 fb at the LHeC

3.084 fb at the FCC-eh

$$L_{tqH} = \kappa_{tuh}\bar{t}uH + \kappa_{tcH}\bar{t}cH + h.c.$$

$\kappa_{tuh} = 0.1$

$p_T^{k_0} \geq 20\text{GeV}$, $|\eta^{k_0}| < 10$, $k_0 = j, b, \ell$

$\Delta R(k_1, k_2) > 0.01$, $k_1 k_2 = jj, j\ell, jb, bb, b\ell$

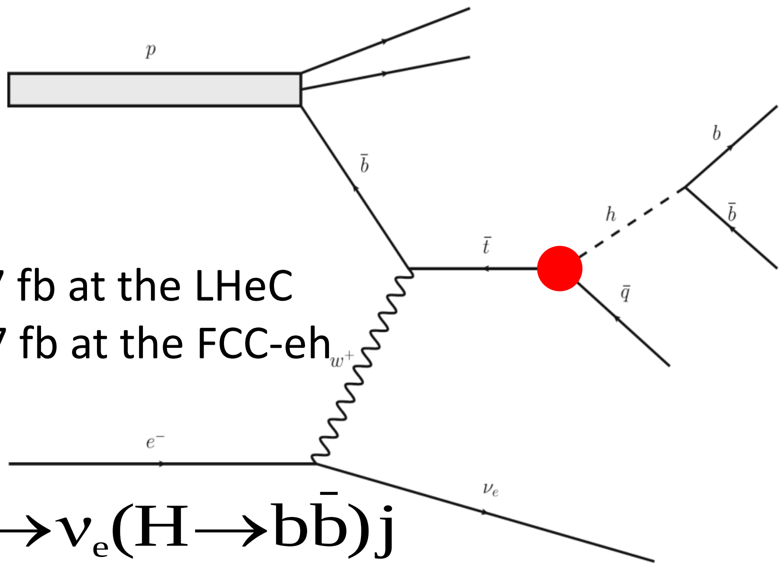
W.Liu, H.Sun, etc, Phys.Rev.D92(2015)7,074015

H.Sun, etc, Eur.Phys.J.C(2018)4,281

Anomalous FCNC tqH couplings

CC

signal.I: $e^- p \to \nu_e \bar{t} \to \nu_e h \bar{q} \to \nu_e b \bar{b} \bar{q}$



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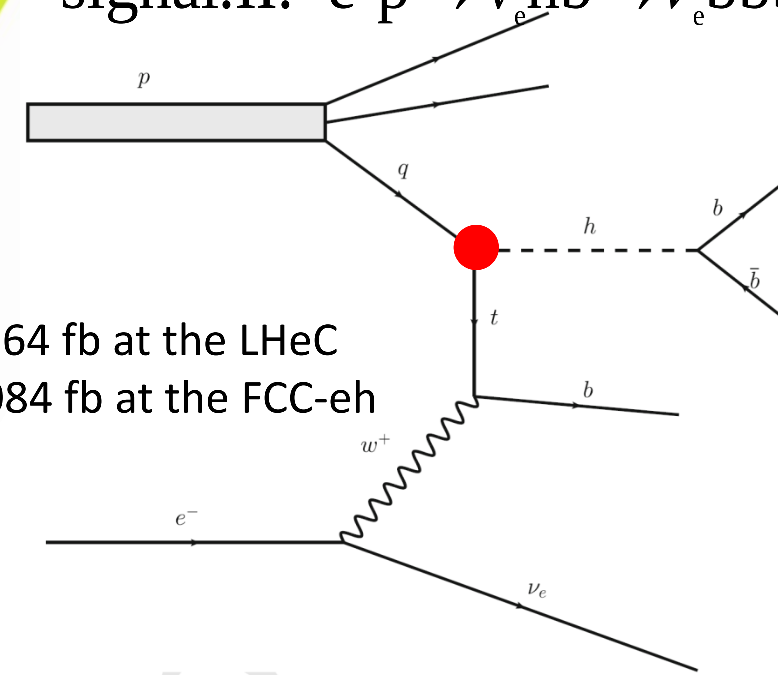


0.64 fb at the LHeC
3.084 fb at the FCC-eh

$e^- p \to \nu_e (H \to b\bar{b}) j$
$e^- p \to \nu_e (Z \to b\bar{b}) j$
$e^- p \to \nu_e (g \to b\bar{b}) j$
$e^- p \to \nu_e jjj$
$e^- p \to \nu_e jjb/\bar{b}$
$e^- p \to \nu_e \bar{t}$
$e^- p \to e^- (g \to b\bar{b}) j$

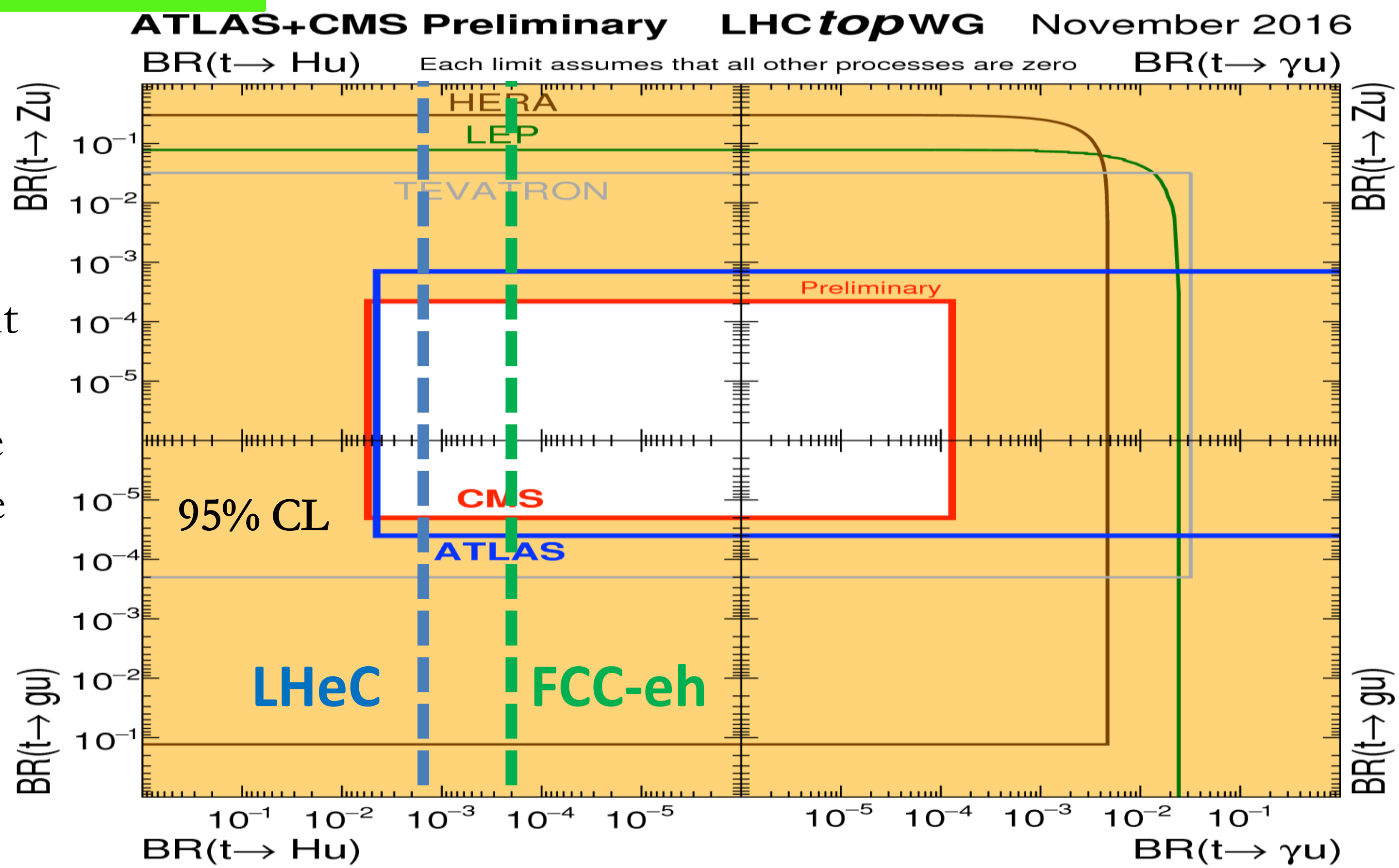
Detector level study

W.Liu, H.Sun, etc, Phys.Rev.D92(2015)7,074015
H.Sun, etc, Eur.Phys.J.C(2018)4,281

Anomalous FCNC tqH couplings

$BR(t \to uh)$
LHeC (1ab-1) $0.15 \times 10{-}2$
FCC-eh (1ab-1) $0.22 \times 10{-}3$

Finally we found that the 2sigma upper limit on the Br of t->hu is order of 10-3 at the LHeC and 10-4 at the FCC-eh.
(all with L = 1ab-1)



Therefore we conclude that the potential to proble the FCNC tqH couplings can be much improved than the LHC experiments and even better than some theorantical sensitivities That obtained at the HL-LHC.

W.Liu, H.Sun, etc, Phys.Rev.D92(2015)7,074015
H.Sun, etc, Eur.Phys.J.C(2018)4,281

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Current progress in V_{td}/V_{ts} measurement

The conventional labeling for the flavor mixing matrix is

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The standard model itself does not predict the elements of V, thus they should be evaluated experimentally.

Currently, the first two rows of V are already being probed with improving precision.

On the other hand, few direct measurement exit on the third row of V

A global CKM fit

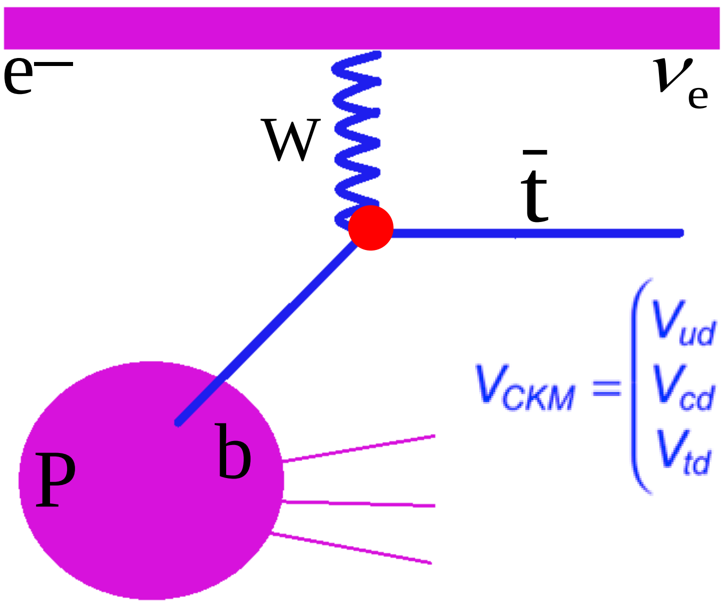
$$|V_{tb}| = 1 - 8.81^{+0.12}_{-0.24} \times 10^{-3}$$

$$|V_{ts}| = 41.08^{+3.0}_{-5.7} \times 10^{-3},$$

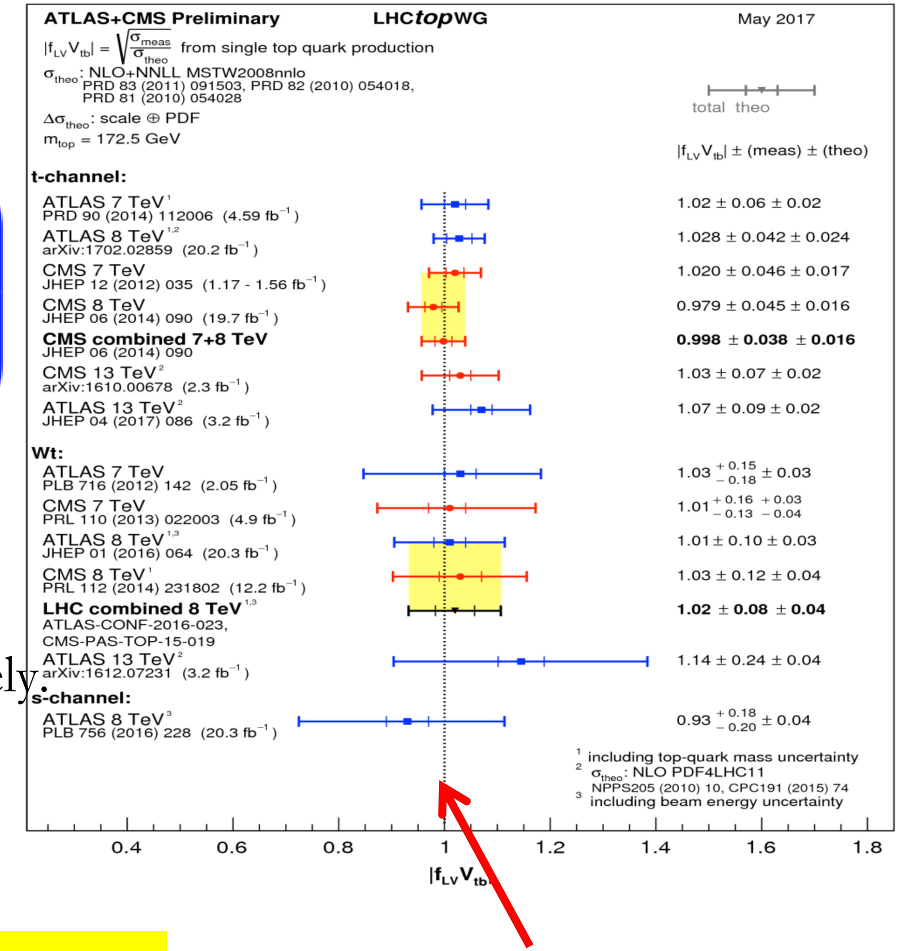
$$|V_{td}| = 8.575^{+0.076}_{-0.098} \times 10^{-3}.$$

V_{tb} measurement

The current way to precisely measure Vtb is in single top productions at the LHC.



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



While at the ep projects, the CC single top production can be used to measure Vtb precisely:

It was found that at the LHeC, with Luminosity of 100 fb-1, the CKM Vtb element can be measured with a precision of 1%.

LHeC, 100 fb-1
1.000 ± 0.01
(expected)

Current progress in V_{td}/V_{ts} measurement

$$V=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The remaining third row Element Vtd and Vts are very small.

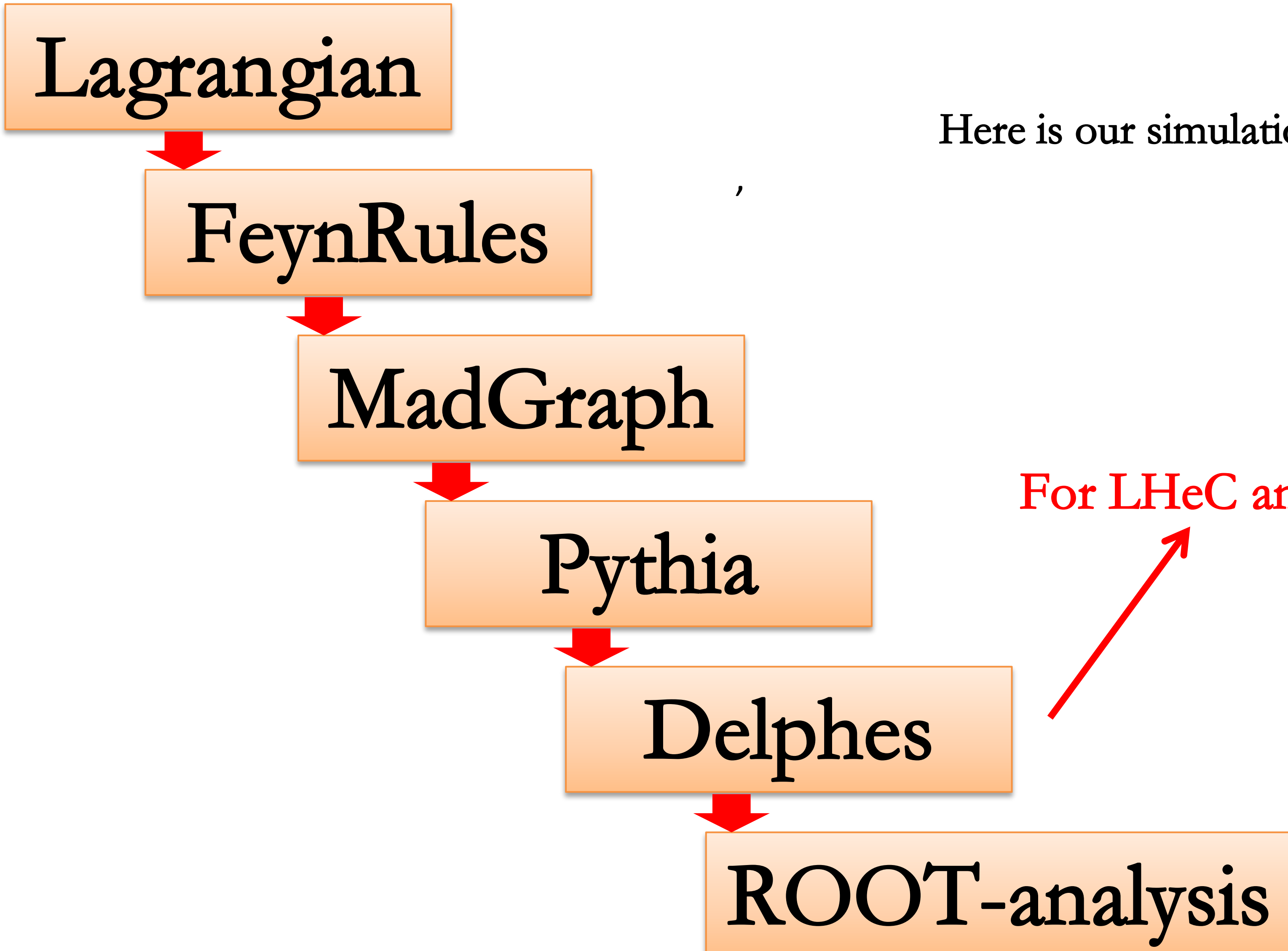
At the LHC, difficult to measure t to d and t to s transitions.

At the ep colliders, the situation is much better:

1. the suppression of the top-pair background
2. the dominant CC single top signal production

We suggest to extract Vtd and Vts elements through single top related production at the ep colliders

Current progress in V_{td}/V_{ts} measurement



Here is our simulation chain.

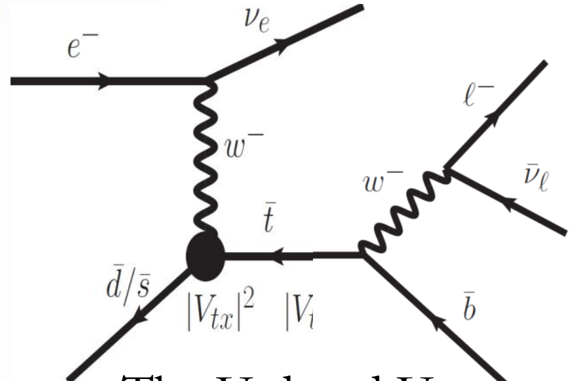
For LHeC and FCC-he

Current progress in V_{td}/V_{ts} measurement

We study the CKM vertex in four channels.

Signal.I:

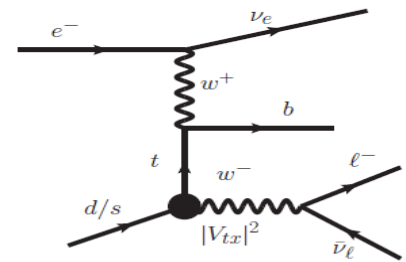
$pe^- \rightarrow \nu_e \bar{t} \rightarrow \nu_e W^- \bar{b} \rightarrow \nu_e \ell^- \bar{\nu}_\ell \bar{b}$



The Vtd and Vts vertex is induced here.

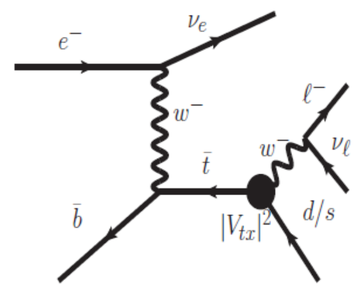
Signal.II:

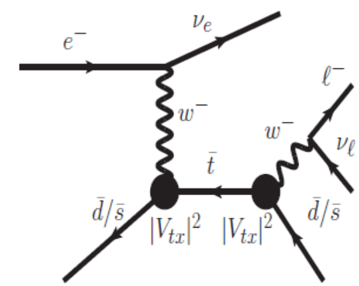
$pe^- \rightarrow \nu_e W^- \bar{b} \rightarrow \nu_e \ell^- \bar{\nu}_\ell \bar{b}$



Signal.III:

$pe^- \rightarrow \nu_e \bar{t} \rightarrow \nu_e W^- j \rightarrow \nu_e \ell^- \bar{\nu}_\ell j$

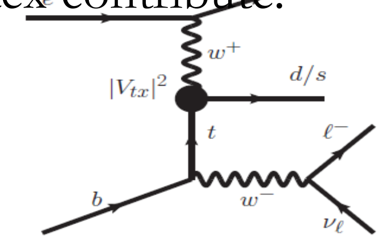


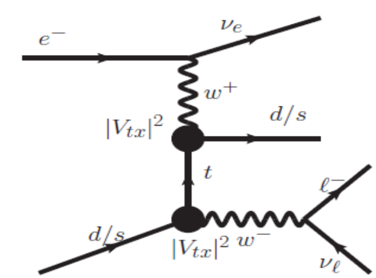


In this case we have two Vtx vertex contribute.

Signal.IV:

$pe^- \rightarrow \nu_e W^- j \rightarrow \nu_e \ell^- \bar{\nu}_\ell j$





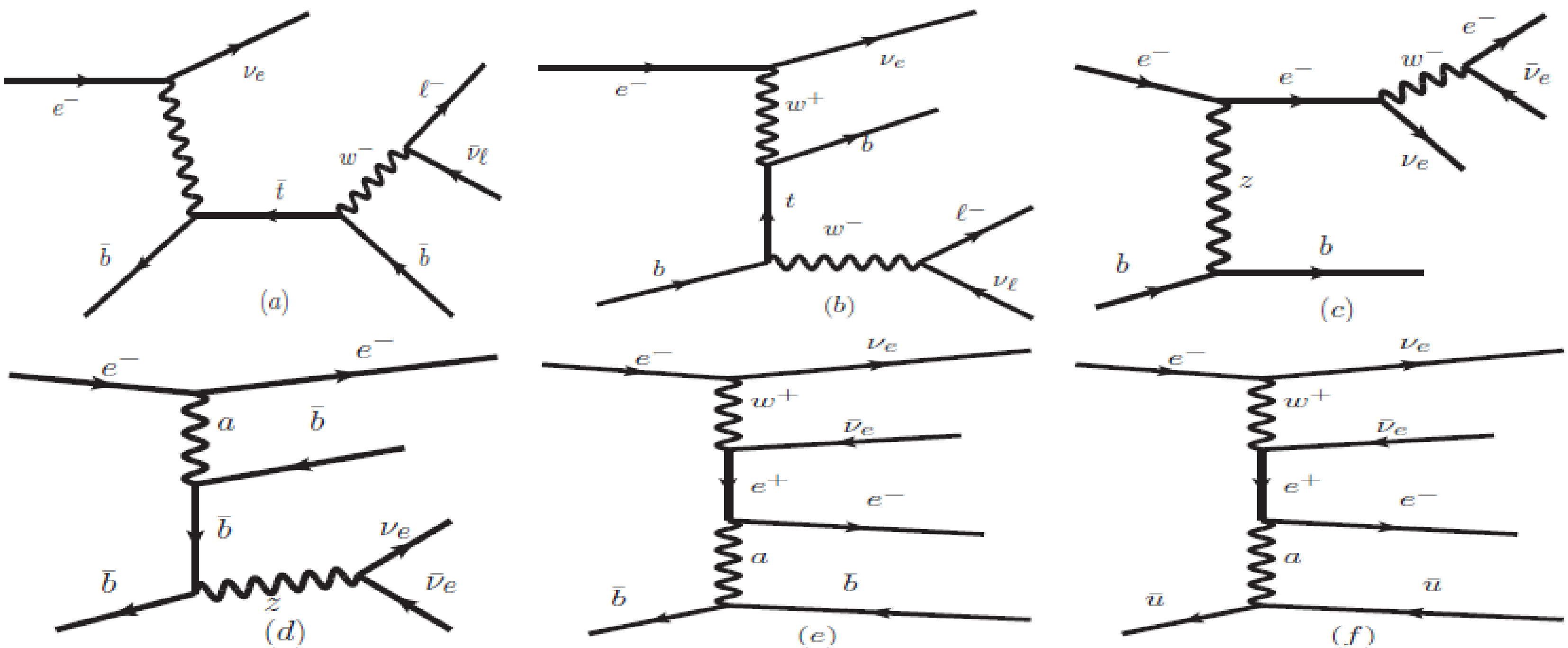
Current progress in V_{td}/V_{ts} measurement

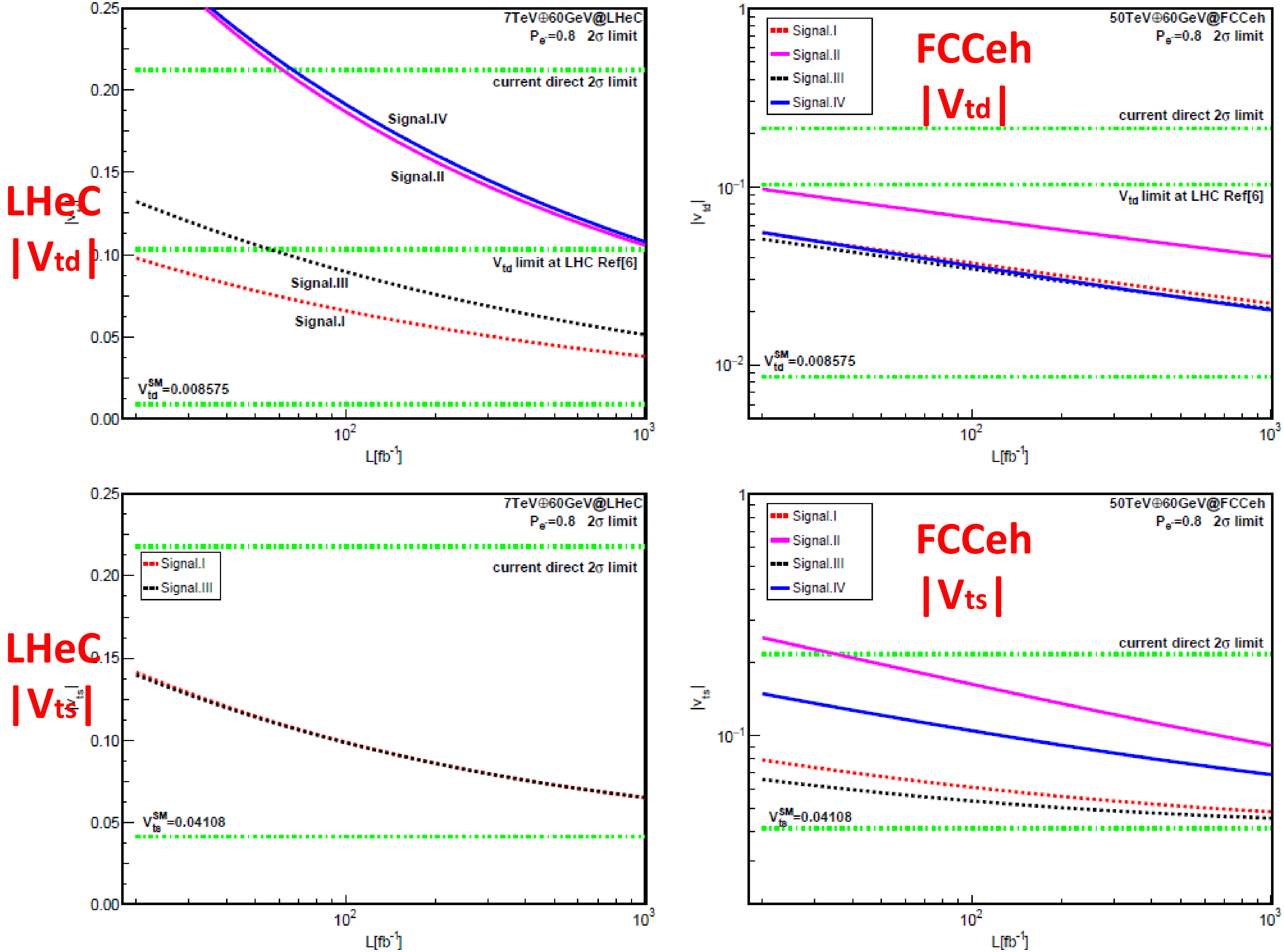
$$B1: pe^- \to \nu_e \bar{t} \to \nu_e W^- \bar{b} \to \nu_e \ell^- \bar{\nu}_\ell \bar{b}$$

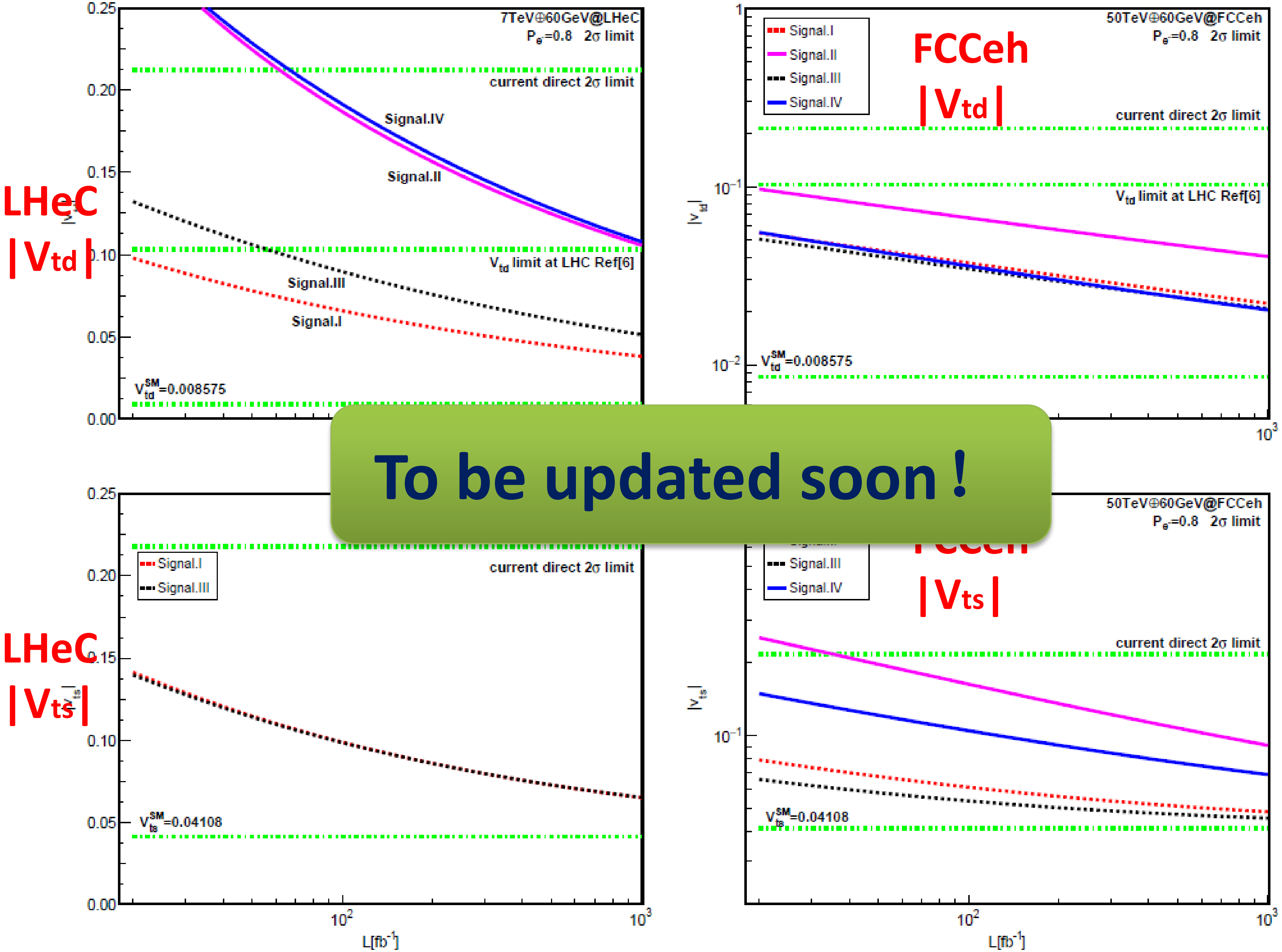
$$B2: pe^- \to \ell^- E_T^{miss} b/\bar{b}$$

See last talk this morning.

$$B3: pe^- \to \ell^- E_T^{miss} j$$




LHeC
|Vtd|
7TeV⊕60GeV@LHeC
Pe=0.8 2σ limit
current direct 2σ limit
Signal.IV
Signal.II
Vtd limit at LHC Ref[6]
Signal.III
Signal.I
V_td^SM=0.008575
L[fb^-1]
FCCeh
|Vtd|
50TeV⊕60GeV@FCCeh
Pe=0.8 2σ limit
Signal.I
Signal.II
Signal.III
Signal.IV
current direct 2σ limit
Vtd limit at LHC Ref[6]
V_td^SM=0.008575
|Vtd|
L[fb^-1]
LHeC
|Vts|
7TeV⊕60GeV@LHeC
Pe=0.8 2σ limit
Signal.I
Signal.III
current direct 2σ limit
V_ts^SM=0.04108
L[fb^-1]
FCCeh
|Vts|
50TeV⊕60GeV@FCCeh
Pe=0.8 2σ limit
Signal.I
Signal.II
Signal.III
Signal.IV
current direct 2σ limit
V_ts^SM=0.04108
|Vts|
L[fb^-1]



To be updated soon !
LHeC
|Vtd|
7TeV⊕60GeV@LHeC
P_e=0.8 2σ limit
current direct 2σ limit
Signal.IV
Signal.II
Signal.III
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Vtd limit at LHC Ref[6]
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P_e=0.8 2σ limit
Signal.III
Signal.IV
current direct 2σ limit
V_ts^SM=0.04108
|Vts|
L[fb^-1]

Summary

1. In this talk we present a short overview of the top physics at the ep collider.
2. Selected topics include, but not limited to:
   ---- top structure funciton
   ---- top PDFs, top spin polarization
   ---- $|V_{tb}|$, $|V_{ts}|$, $|V_{td}|$, electric charge Q_t measurement
   ---- anomalous $tt\gamma$, ttZ, tbW couplings
   ---- FCNC $tq\gamma$, tqZ， tqH couplings
   ---- CP nature of ttH couplings
3. More studies in top sector are welcomed.


Thanks!