Top Quark Physics in ep Scattering

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Deutsches Elektronensynchrotron (DESY)

on behalf of top/BSM LHeC/FCC-he study group

2nd FCC Physics Workshop

18 January 2018

Outline

Introduction
CC Top Production
NC Top Production
BSM Top Production
Conclusions

Outline

Introduction

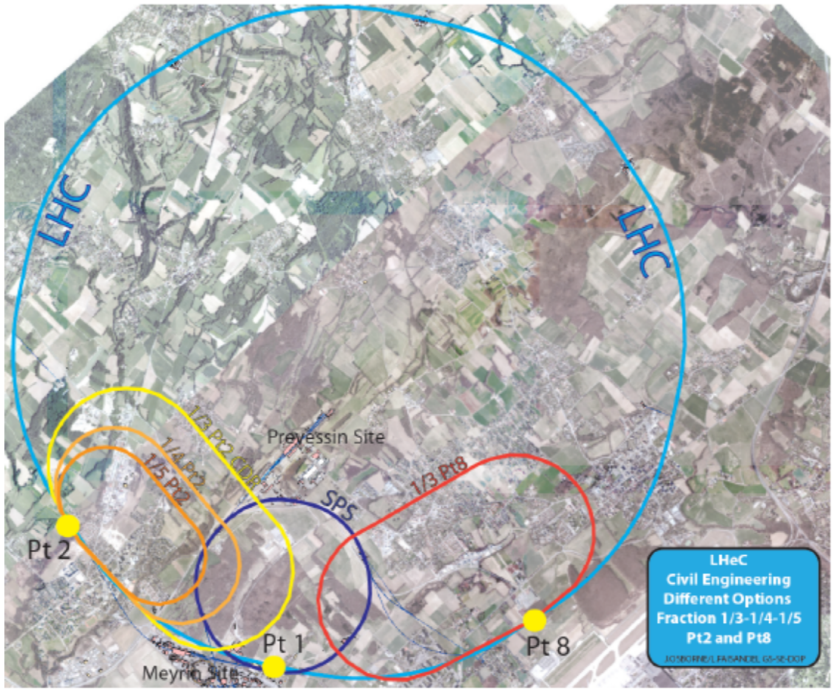
CC Top Production

NC Top Production

BSM Top Production

Conclusions

Linac-Ring Collider, LHeC and FCC-eh



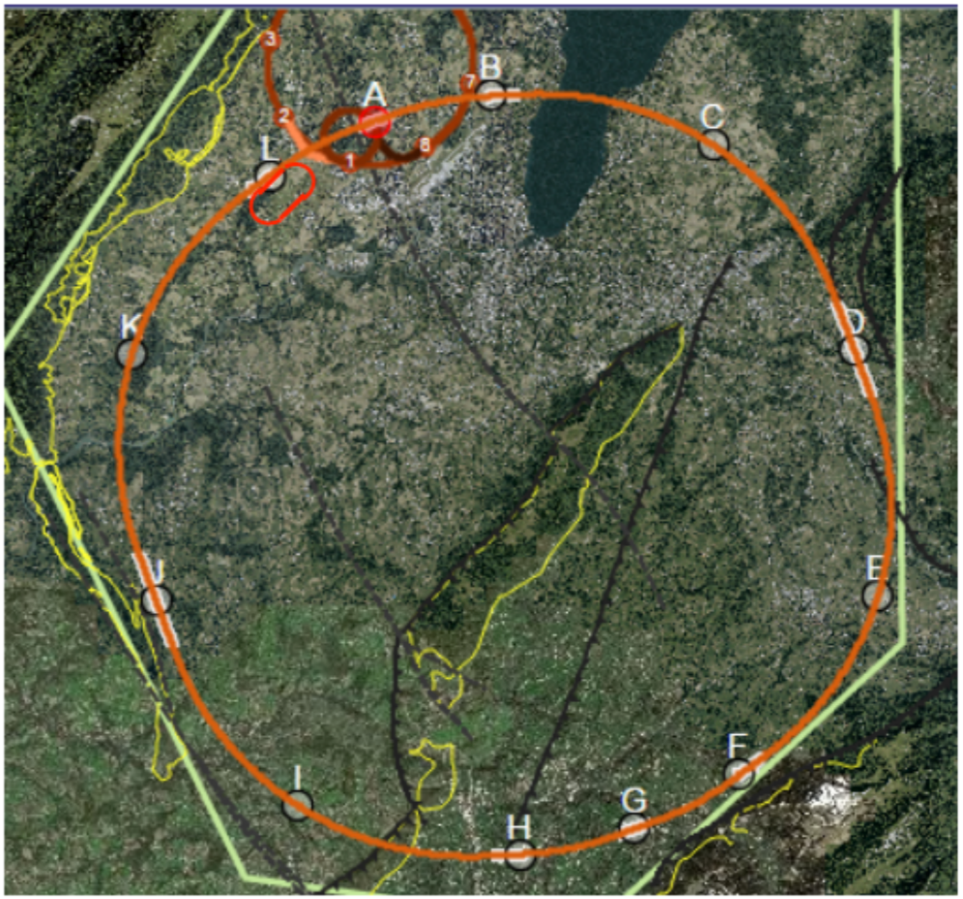
LHeC

Energy Recovering Linac

$e^{\pm}$ beam: 60 GeV

studied here:
L_{int} up to 1 ab^{-1}

FCC-ep

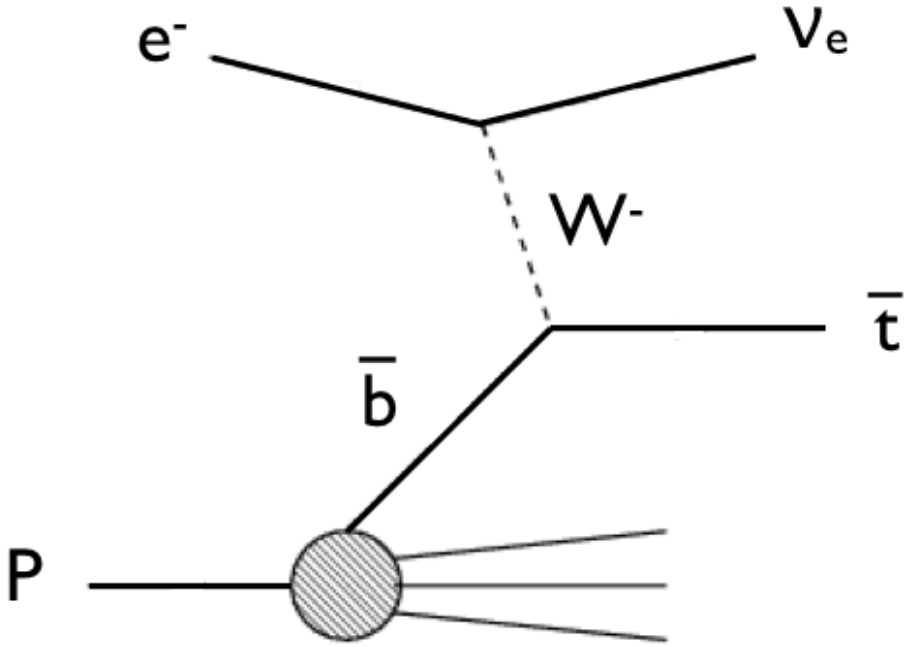


operated synchronously

- **with HL-LHC:**
  p beam: 7 TeV, $\sqrt{s}$=1.3 TeV
- **with HE-LHC:**
  p beam: 13.5 TeV, $\sqrt{s}$=1.8 TeV
- **or later with FCC-hh:**
  p beam: 50 TeV, $\sqrt{s}$=3.5 TeV

SM Top Quark Production

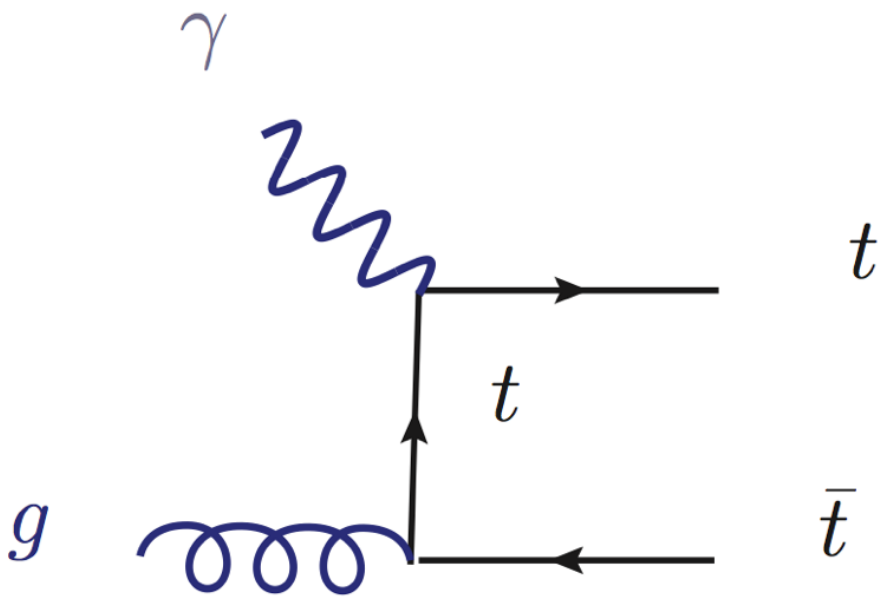
CC DIS top production



σ=1.73pb @ LHeC

σ=15.3pb @ FCC-ep

NC top photoproduction



σ=0.05pb @ LHeC

σ=1.14pb @ FCC-ep

E_e=60 GeV

→ future ep collider is ideal to study EWK interactions of the top quark

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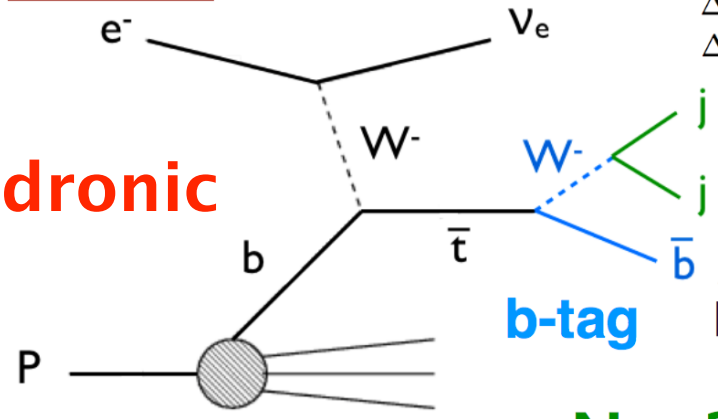
Signal and Backgrounds

LHeC

signal

hadronic



$\not{E}_T \geq 25\,\text{GeV}$

$\Delta\Phi_{\not{E},j} \geq 0.4$

$\Delta\Phi_{\not{E},b} \geq 0.4$

$|m_{j_1 j_2} - m_W| \leq 22\,\text{GeV}$

$p_{T\,j,b} \geq 20\ \text{GeV}$

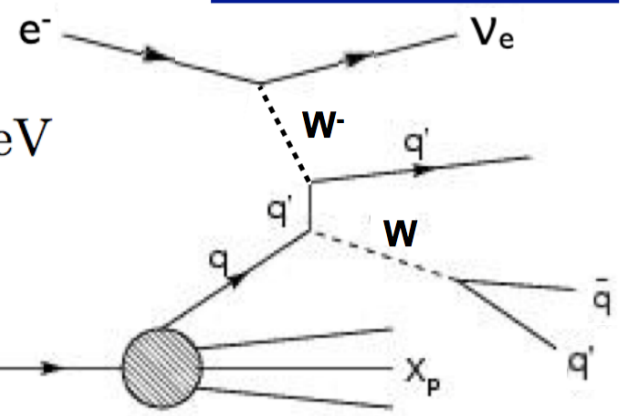
$|\eta_j| \leq 5, |\eta_b| \leq 2.5$

$\Delta R_{j,b/j} \geq 0.4$

b-tag

Dutta, Goyal, Kumar, Mellado, Eur. Phys. J. C75 (2015) no.12, 577

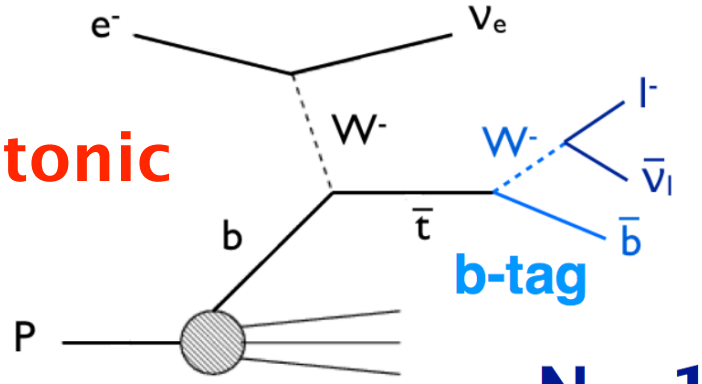
background



N_t=220k, s/b=1.2

e beam: 60 GeV
1000 fb^{-1}

leptonic



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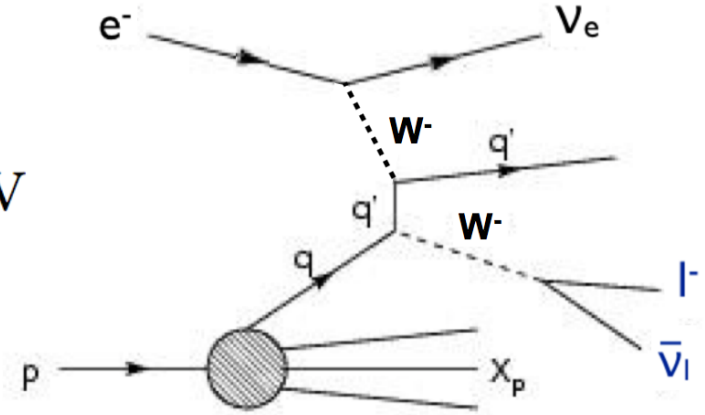


N_t=110k, s/b=11

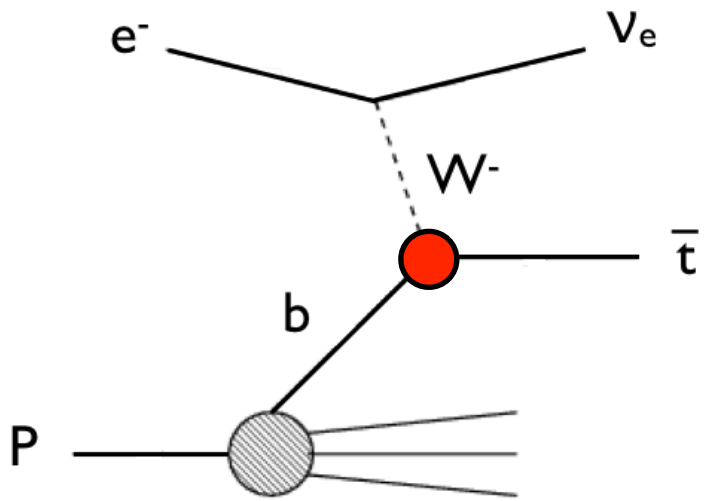
→ **top quark factory (with low backgrounds)**

Limits on Anomalous Wtb Couplings

= 1 in SM

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$

$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$



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

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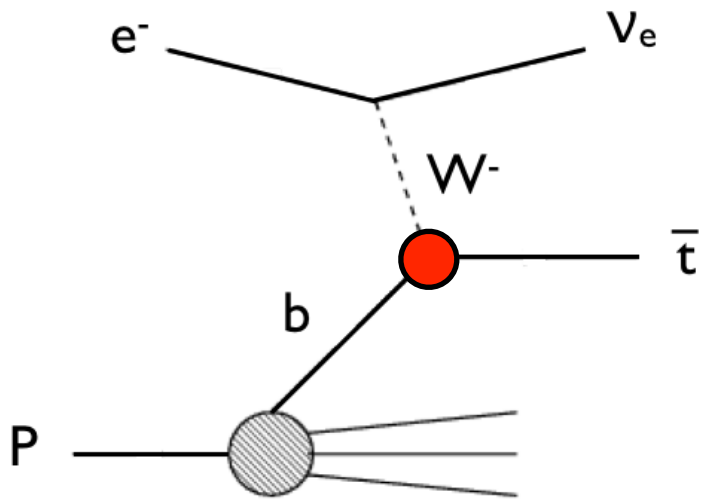

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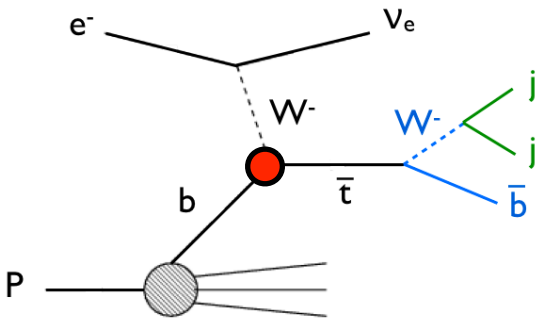
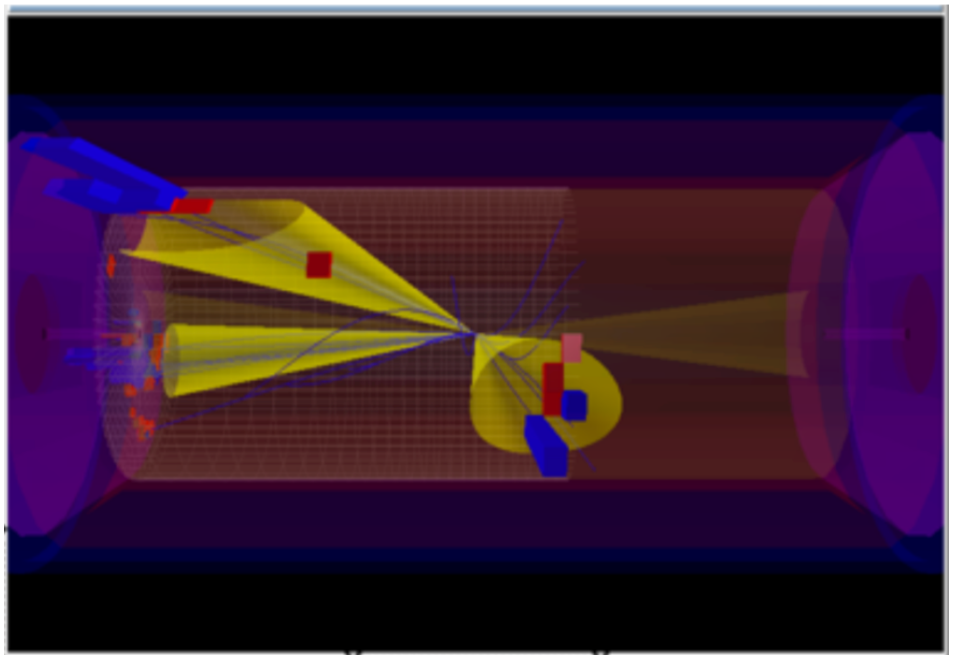
Dutta, Goyal, Kumar, Mellado, Eur. Phys. J. C75 (2015) no.12, 577
Kumar, Ruan, to be publ.



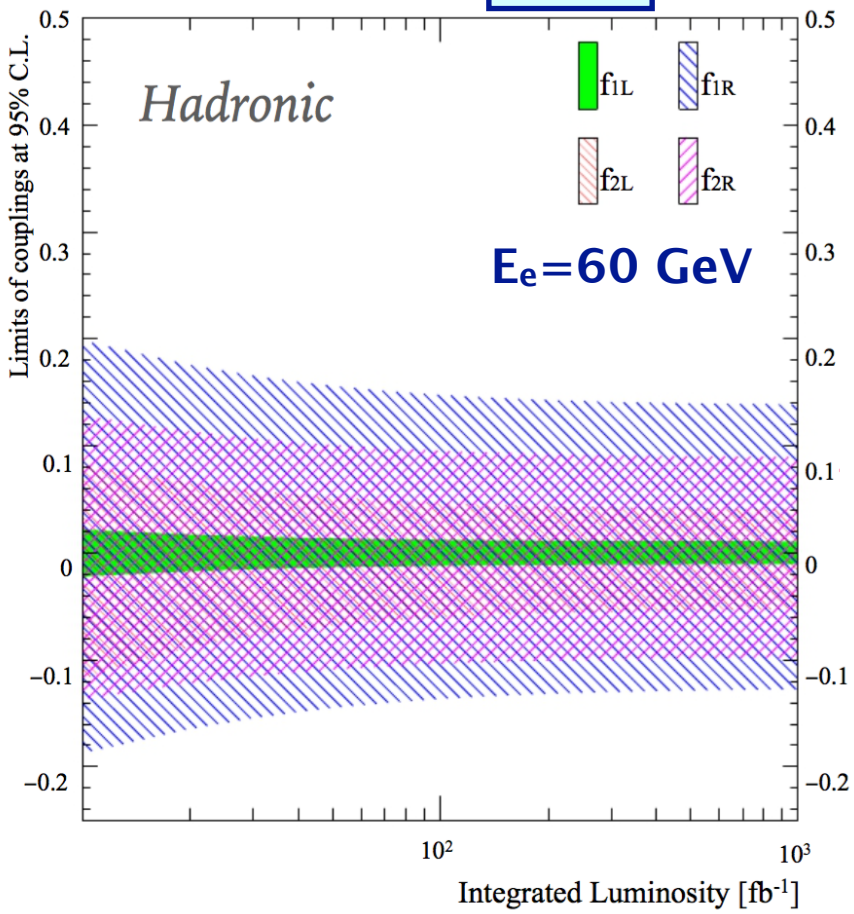
DELPHES



including detector simulation (Delphes)

LHeC

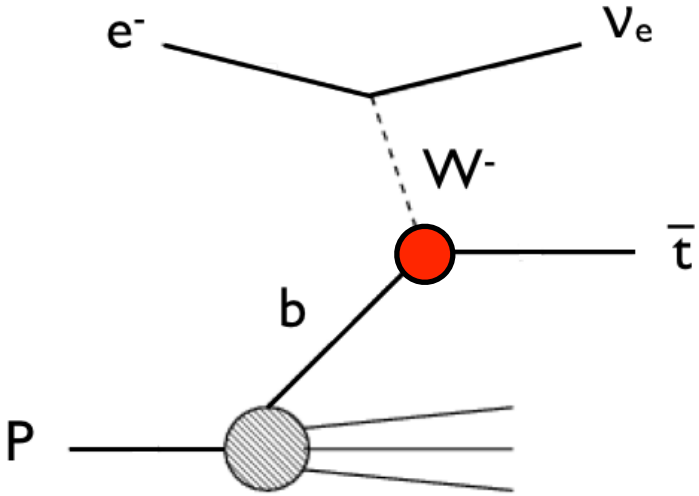
95% C.L.



<0.14
<0.09
<0.04
<0.01

Direct Measurement of $|V_{tb}|$

[1] including top-quark mass uncertainty
[2] σ_{theo}: NLO PDF4LHC11
[3] NPPS205 (2010) 10, CPC191 (2015) 74 including beam energy uncertainty



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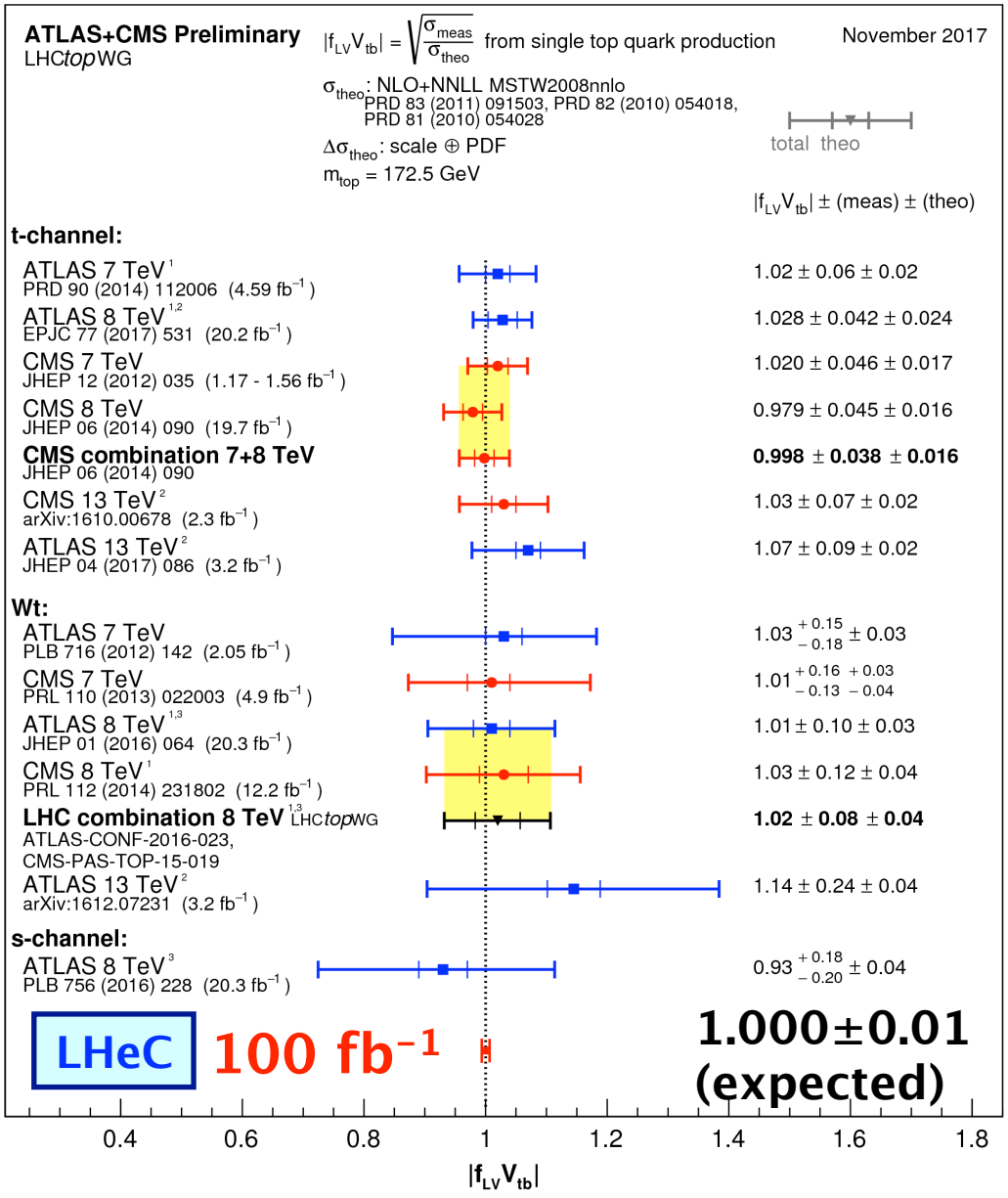
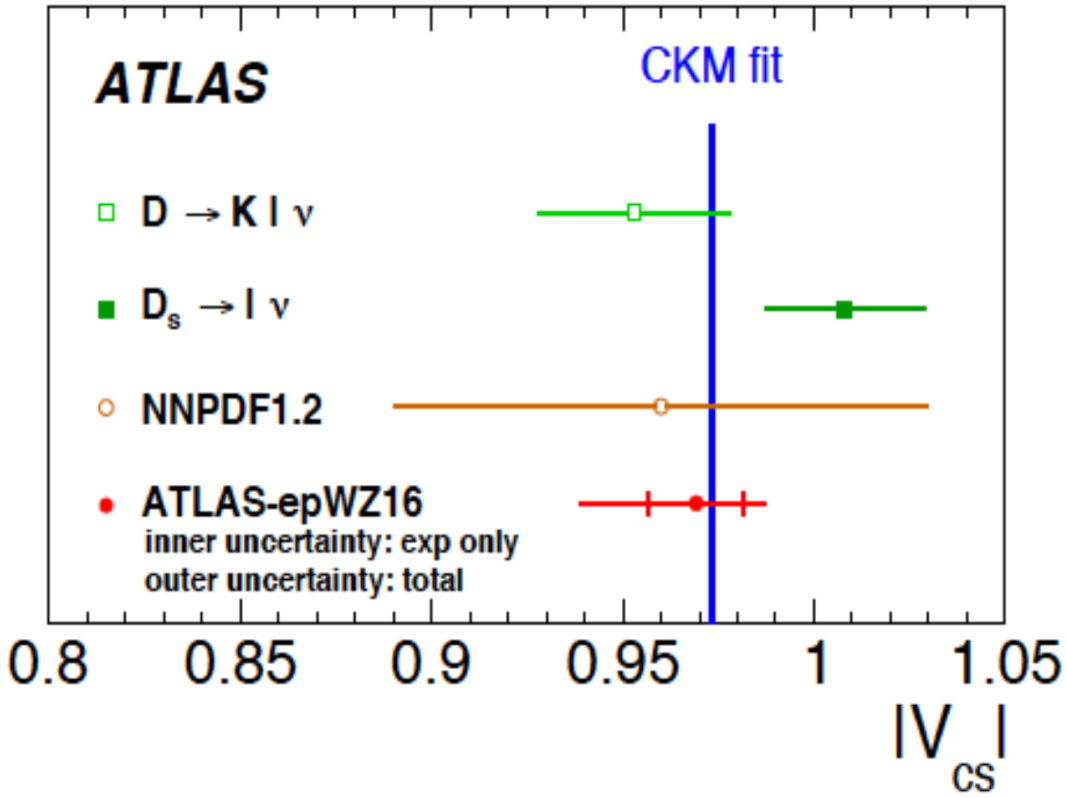


Measurement of $|V_{cs}|$

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



HERA+ATLAS → V_{cs}

Expect LHeC+HL LHC to be 10 x better
from +2-3% to surely 0.5% or below
(work in progress)

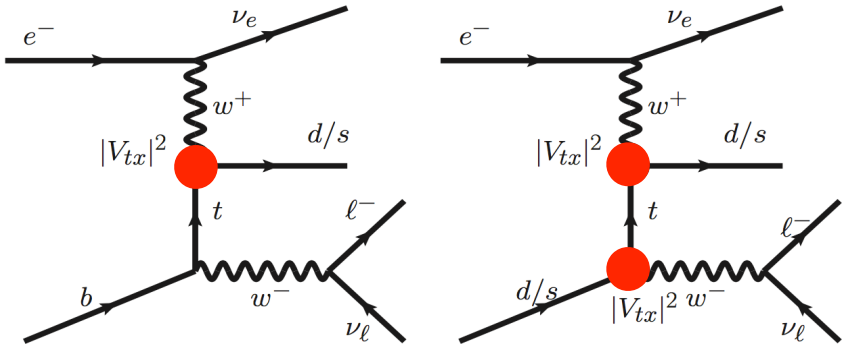
→ **heavy flavour factory**

Measurement of $|V_{td}|$

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

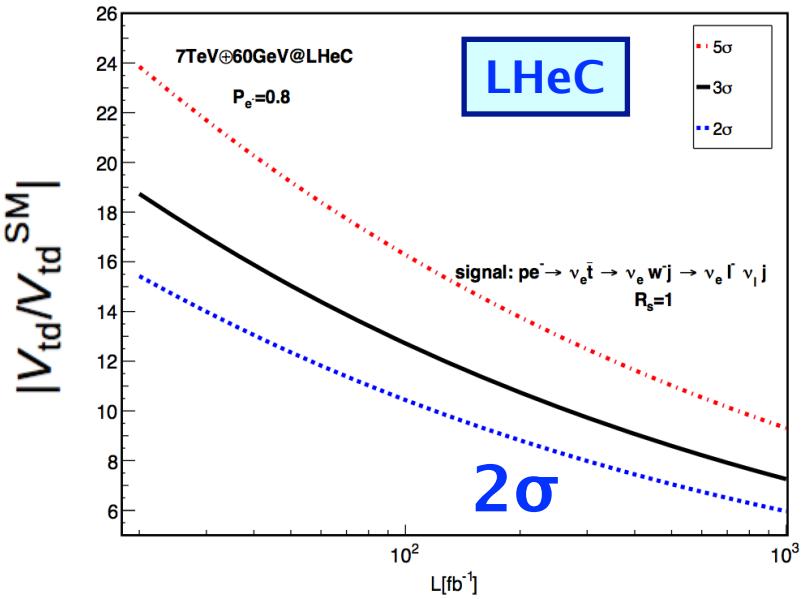
similar

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



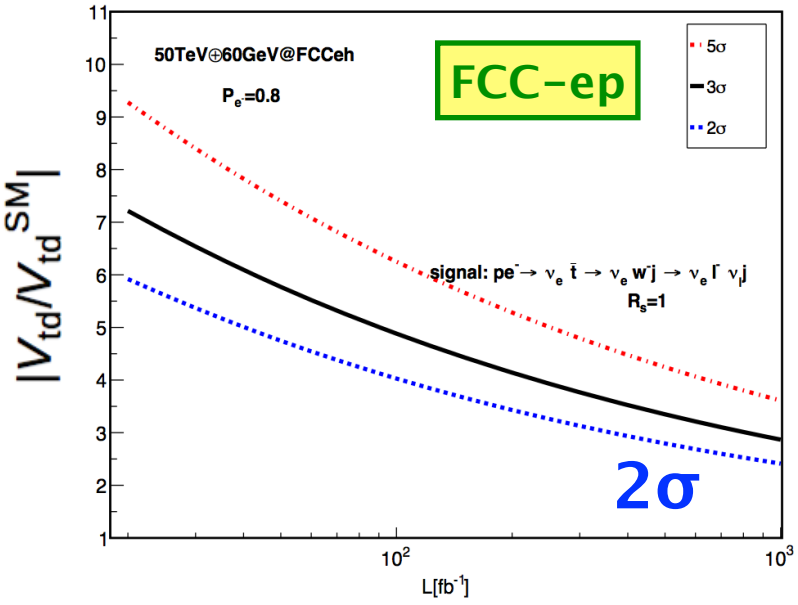
DELPHES

Hao Sun to be publ.



LHC

→ $|V_{td}|<0.05$



→ $|V_{td}|<0.02$ at 2σ C.L.

Measurement of $|V_{td}|$

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

similar

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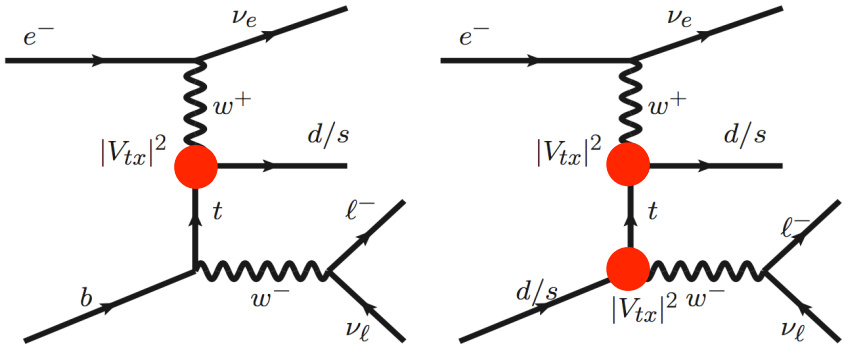
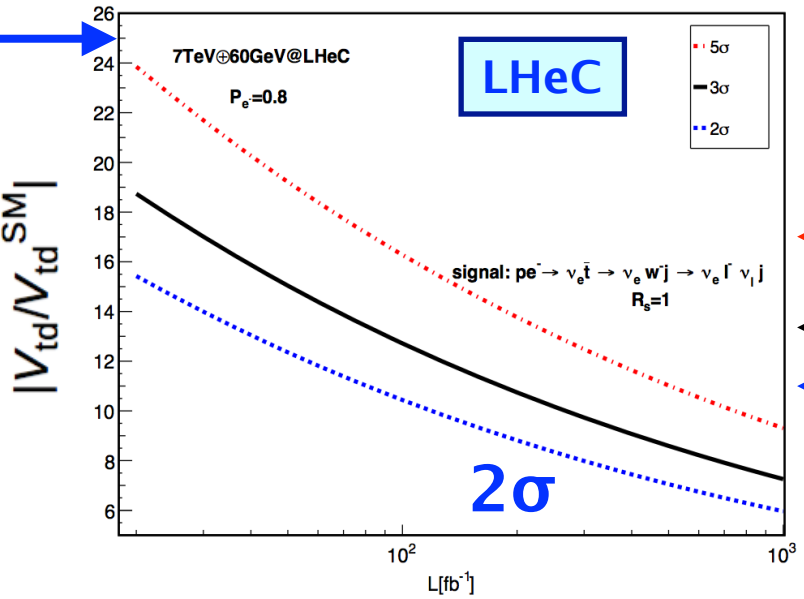


DELPHES

Hao Sun to be publ.

LHC → LHeC



LHC, 3000 fb^{-1}@14TeV

HL-LHC

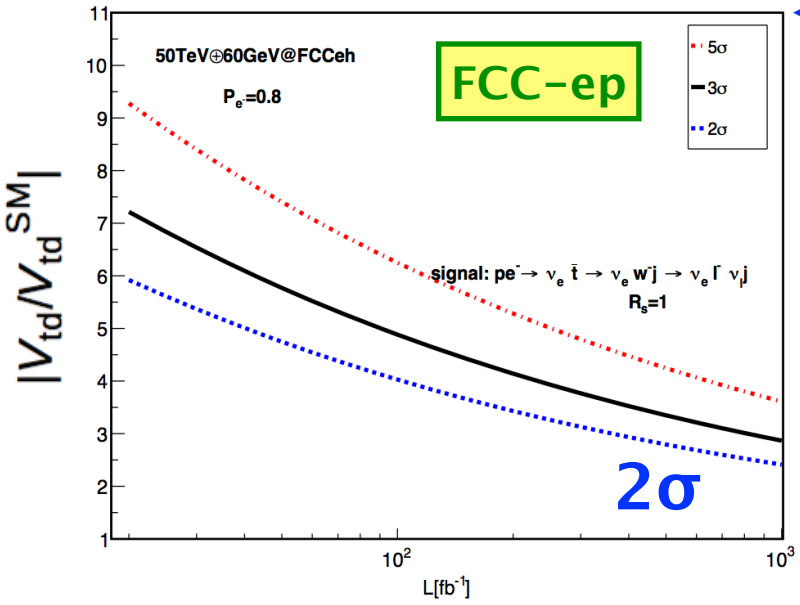
arXiv:1709.07887

5σ

3σ

2σ

→ $|V_{td}|$<0.05

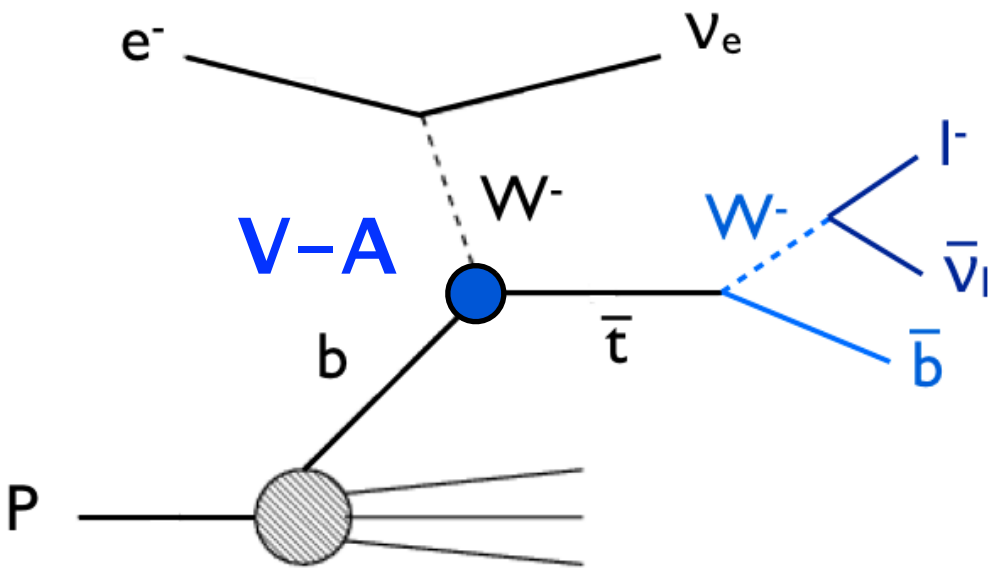


2σ

→ $|V_{td}|$<0.02 at 2σ C.L.

→ extend HL-LHC limits

Top Quark Polarisation



Atag, Sahin,
PRD 73, 074001 (2006)

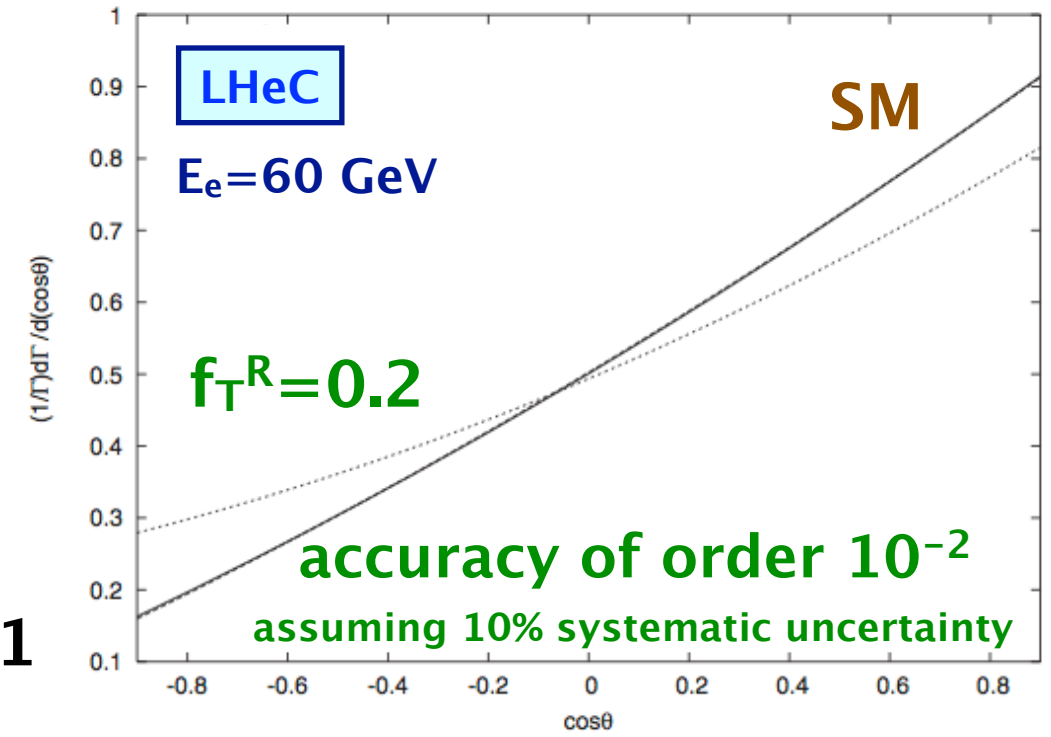
cosθ: angle between charged lepton and spin quantisation axis in top rest frame

$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + A_{\uparrow\downarrow}\alpha\cos\theta) \qquad A_{\uparrow\downarrow} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

using simply e-beam axis: polarisation: P_t = 96%

TESLA+HERAp:

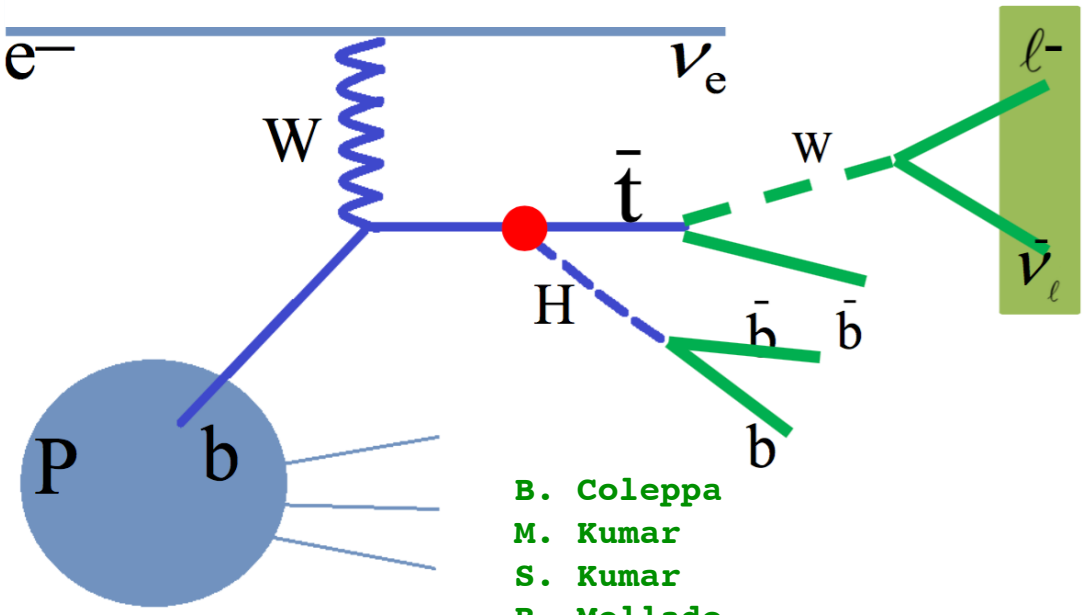
$\sqrt{s}$=1.6 TeV
L_{int}=20 fb^{-1}



CMS 19.7 fb^{-1}: $A_{\uparrow\downarrow}$ = 0.26±0.11

JHEP 04 (2016) 073

CP Nature of Top-Higgs Coupling

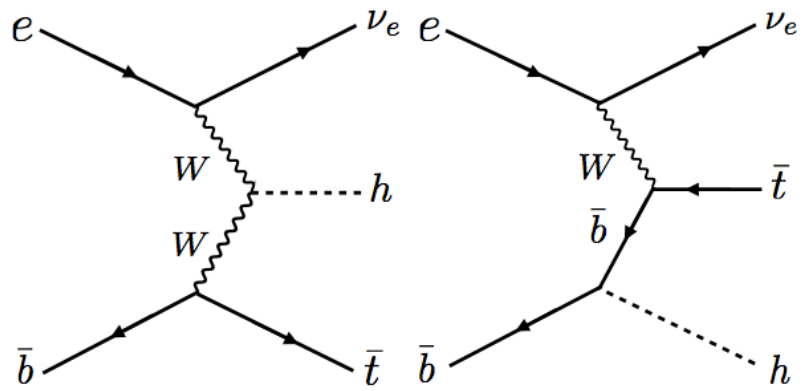


B. Coleppa
M. Kumar
S. Kumar
B. Mellado

parton level

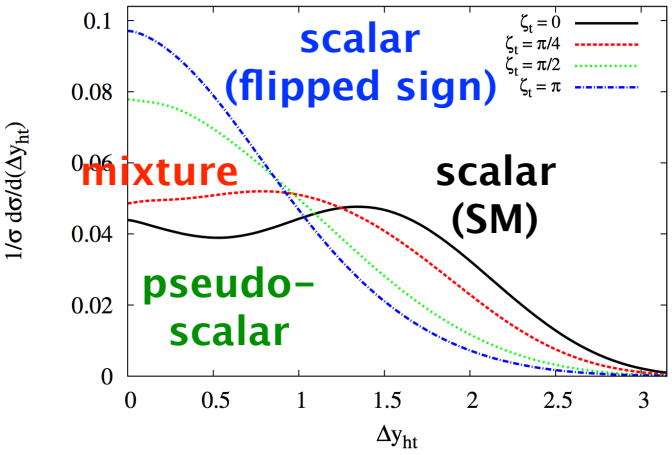
Phys. Lett. B770 (2017) 335

$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]\,t\,h$$

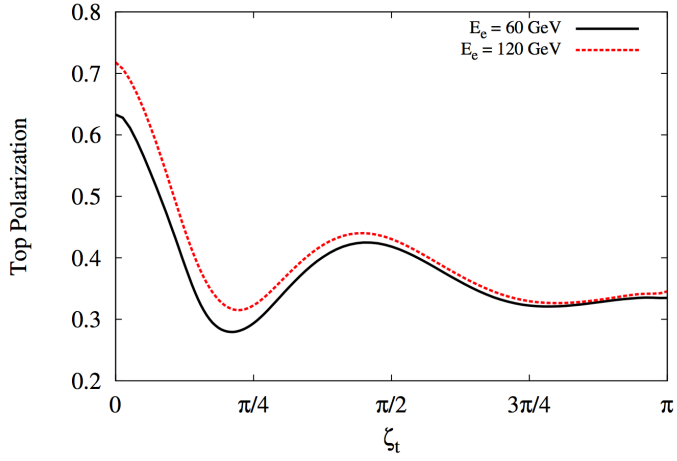


LHeC

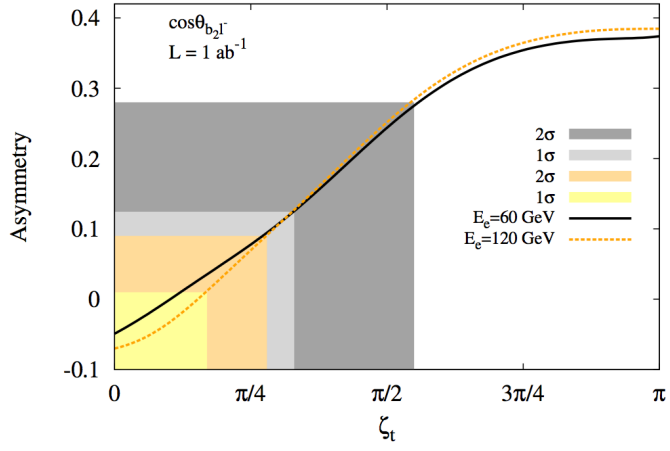
rapidity difference ($H,\bar{t}$)



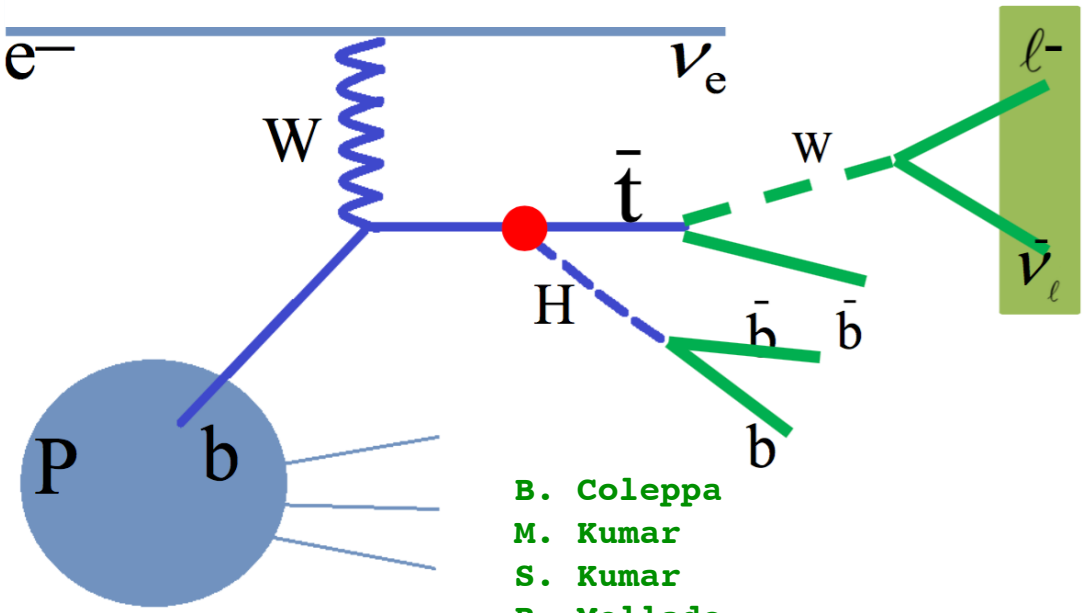
top polarisation



angular asymmetries (b_2,l^-)



CP Nature of Top-Higgs Coupling



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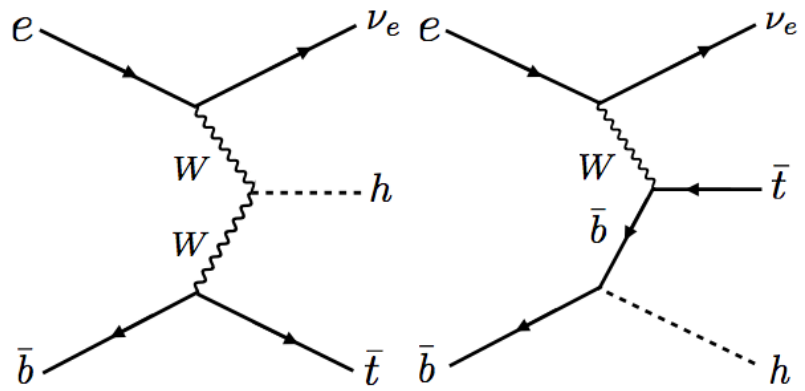
parton level

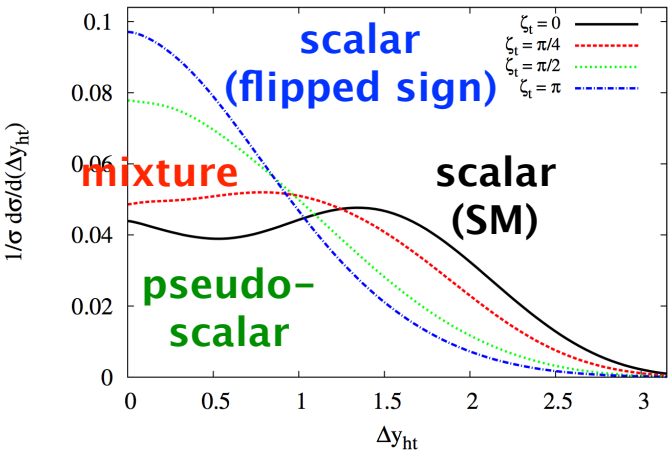
Phys. Lett. B770 (2017) 335

$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]\,t\,h$$

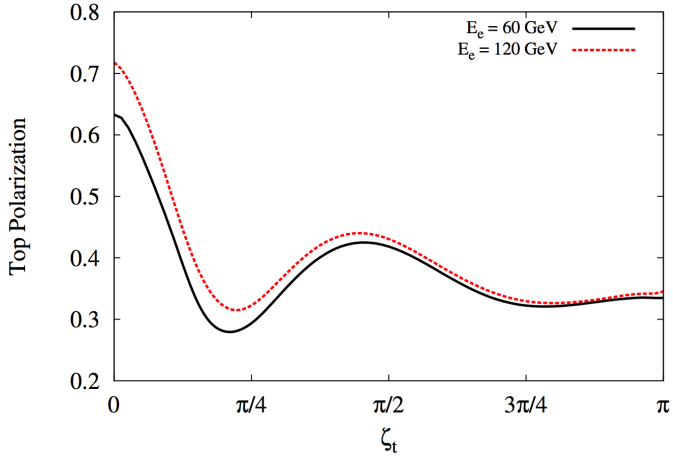


LHeC

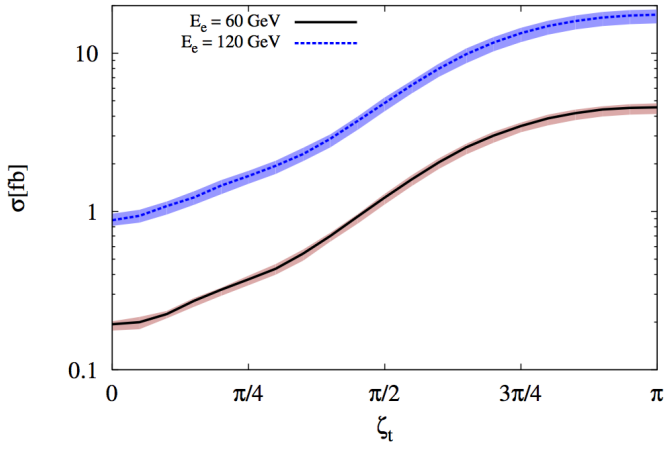
rapidity difference (H,$\bar{t}$)



top polarisation



fiducial incl. cross-section



Exclusion Contours (fiducial cross section)

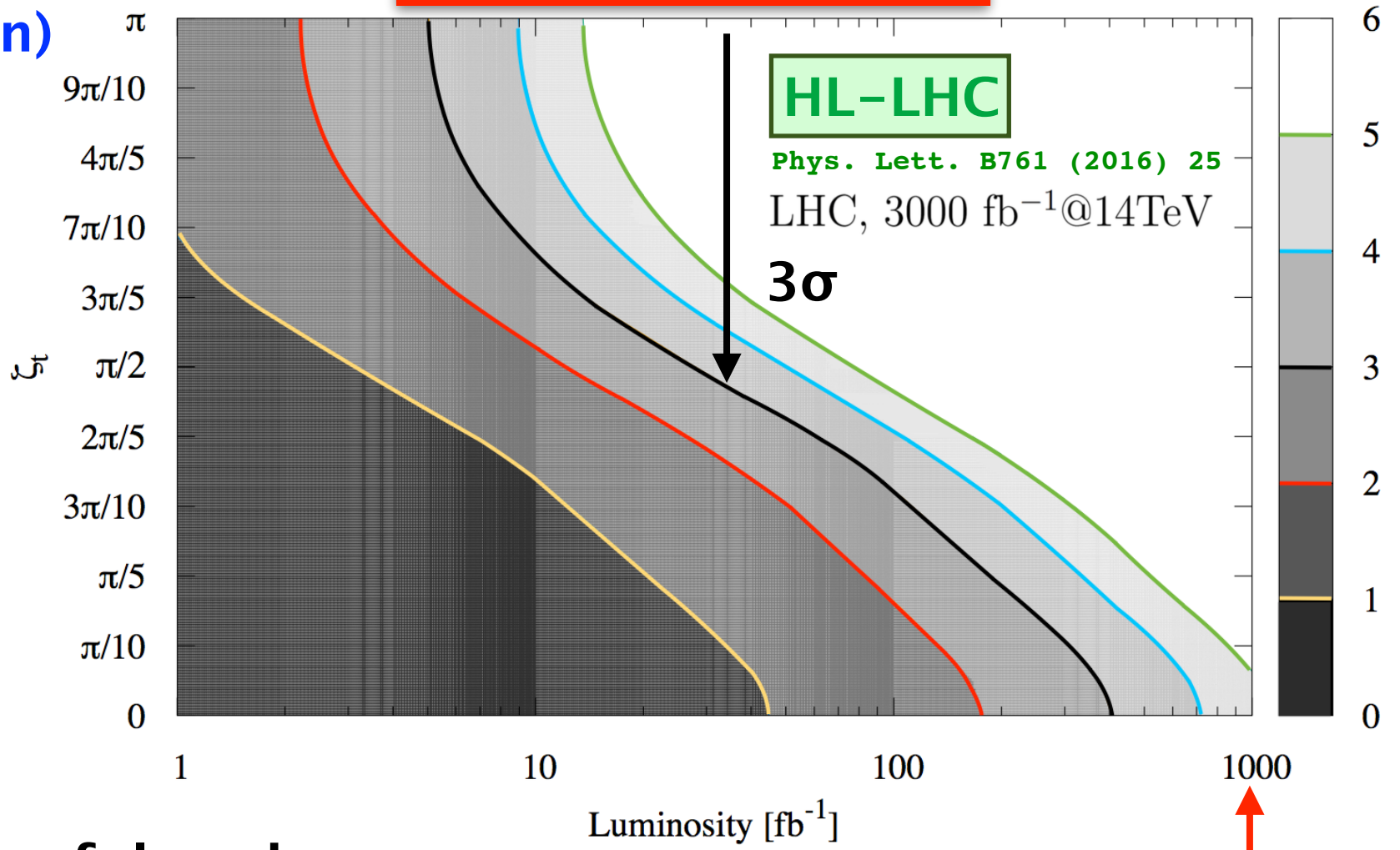
$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]\,t\,h$$

LHeC

CP-even (flipped sign)

CP-odd

CP-even (SM)



→ **powerful probe of ttH coupling**

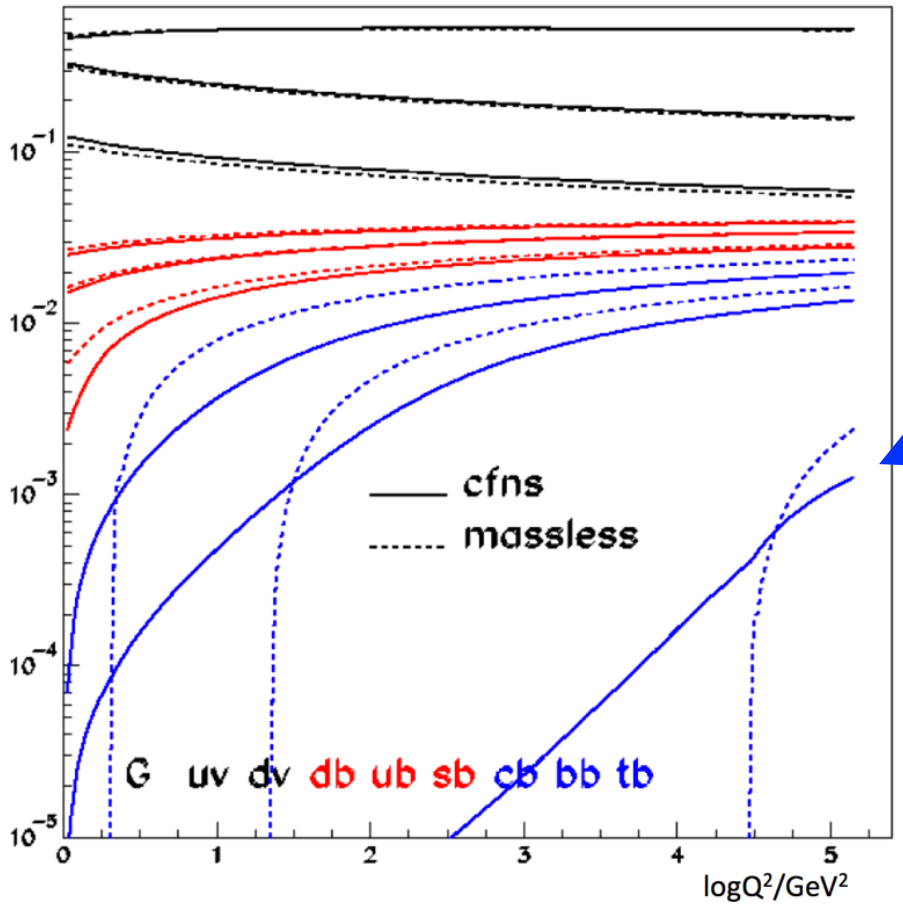
10% uncertainty on background yields

$$\kappa = 1.00 \pm 0.17$$

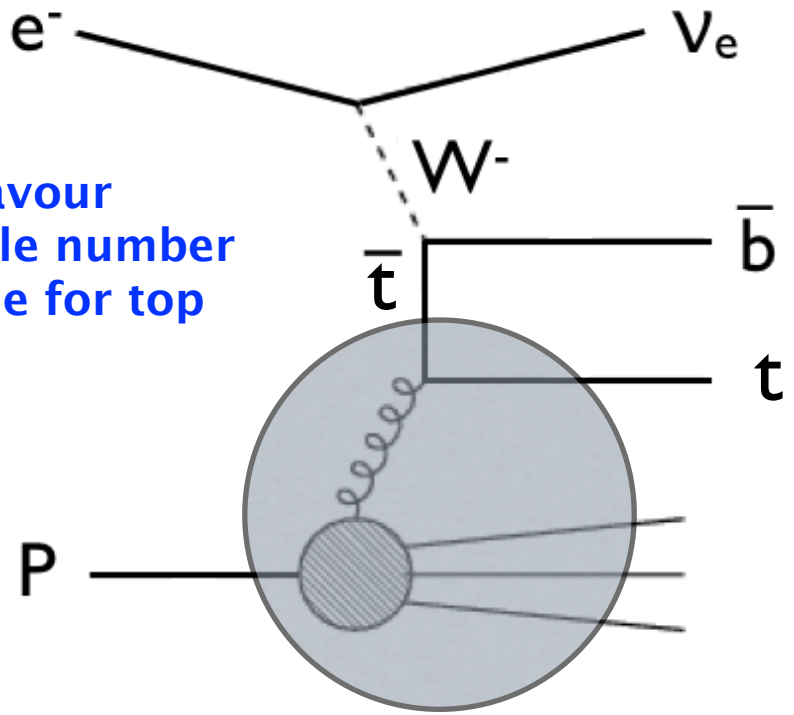
Top Quark Parton Density Function

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

parton momentum fraction



six-flavour variable number scheme for top quark



- in 6 flavour number scheme, top receives at $Q^2 \sim m_t^2$ certain fraction of the proton's momentum
- need to understand what a "top PDF" is in the framework of parton model

→ **LHeC offers new field of research for top quark PDF**

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Introduction

CC Top Production

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BSM Top Production

Conclusions

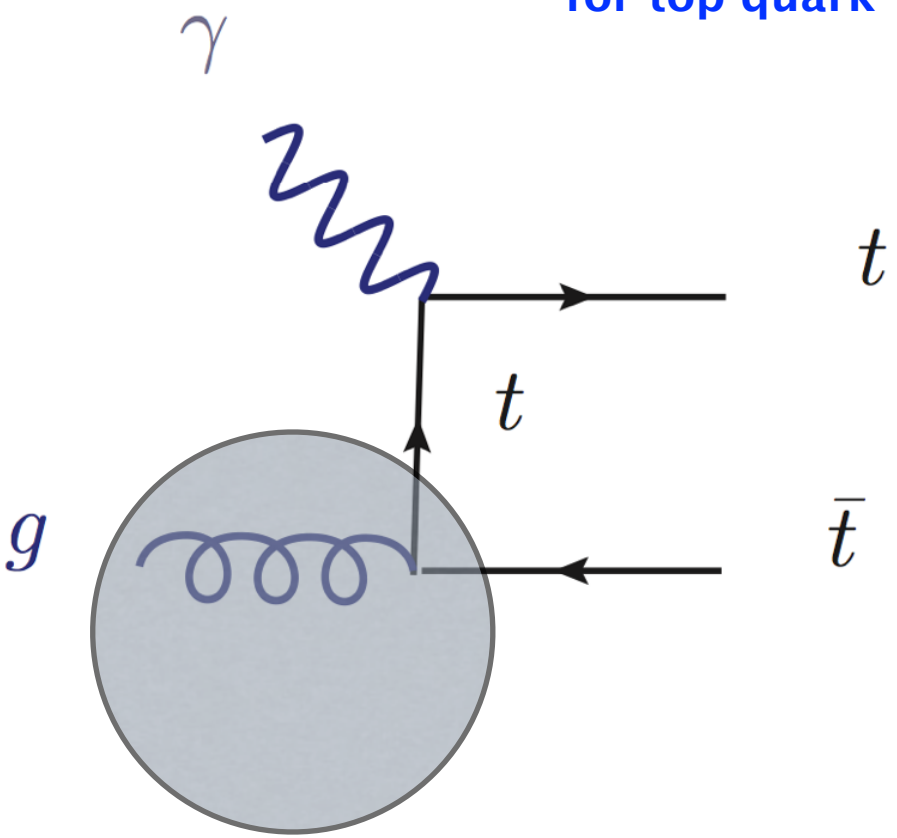
Top Quark Structure Function

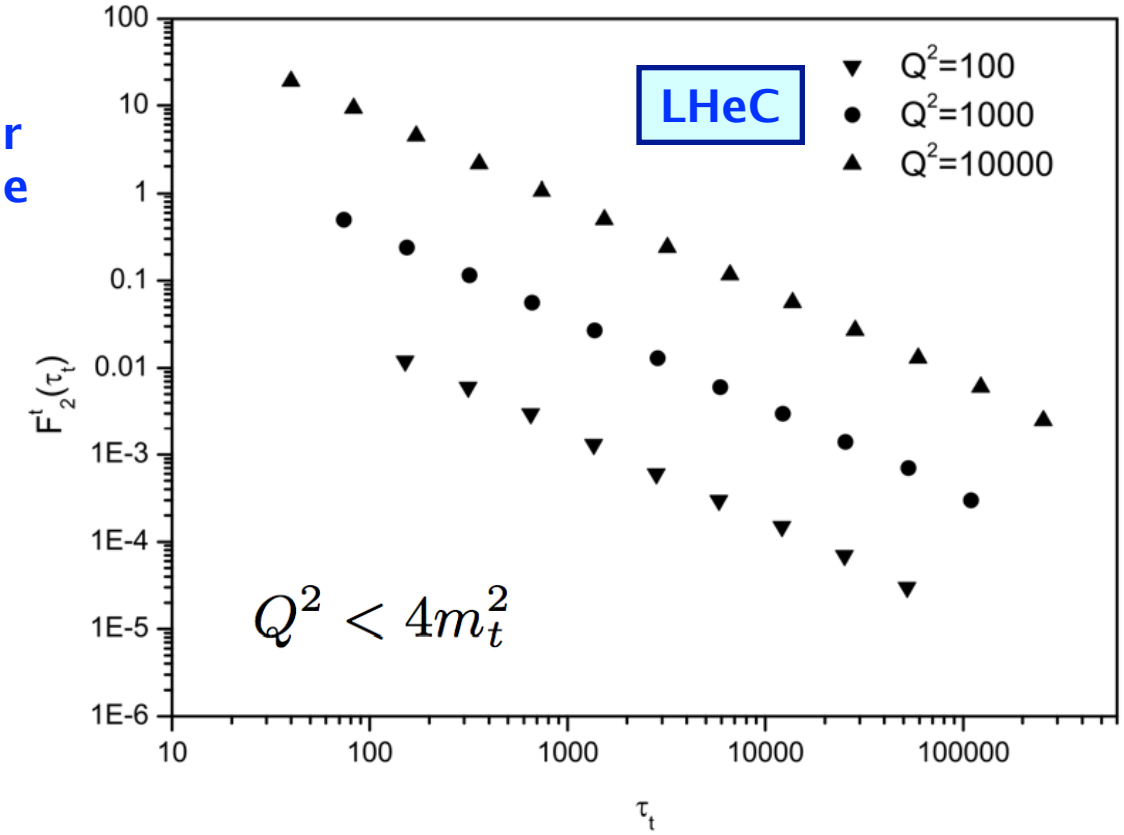
Boroun, Phys. Lett. B744, 142 (2015)

$L_{int}=10\ fb^{-1}$

$E_e=60$ GeV

variable flavour number scheme for top quark





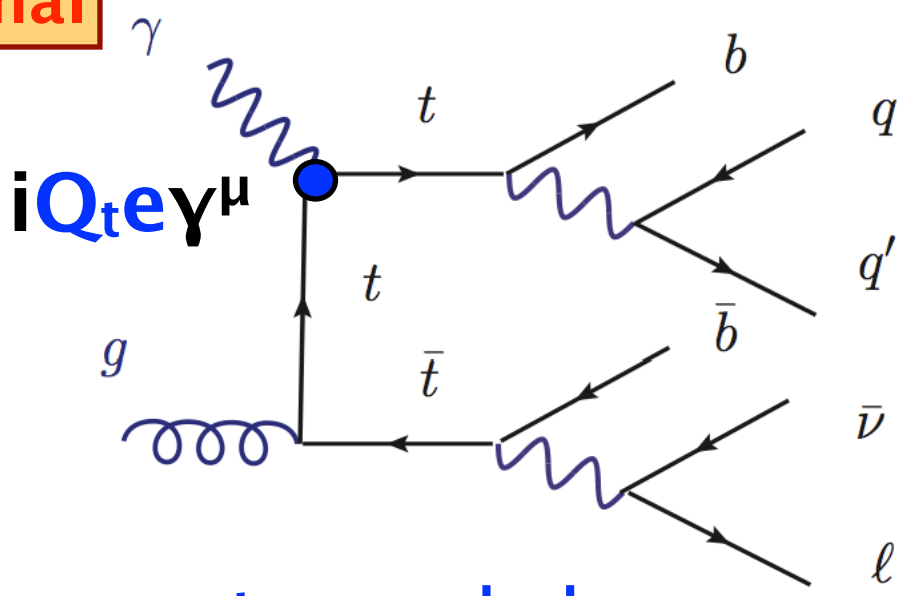
$$\tau_t = (1+\frac{4m_t^2}{Q^2})^{1+\lambda}\frac{Q^2}{Q_0^2}(\frac{x_B}{x_0})^{\lambda}$$

$$x = x_B(1+\frac{4m_t^2}{Q^2})$$

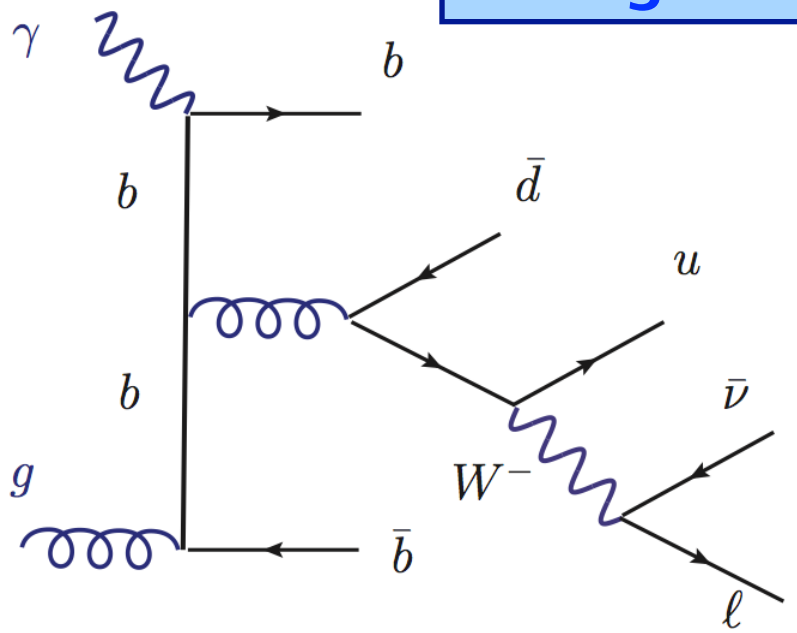
→ **LHeC/FCC-ep opens up a new field of top quark PDFs and to unveil the complete flavour structure of the proton**

Analysis of the $t\bar{t}\gamma$ Vertex

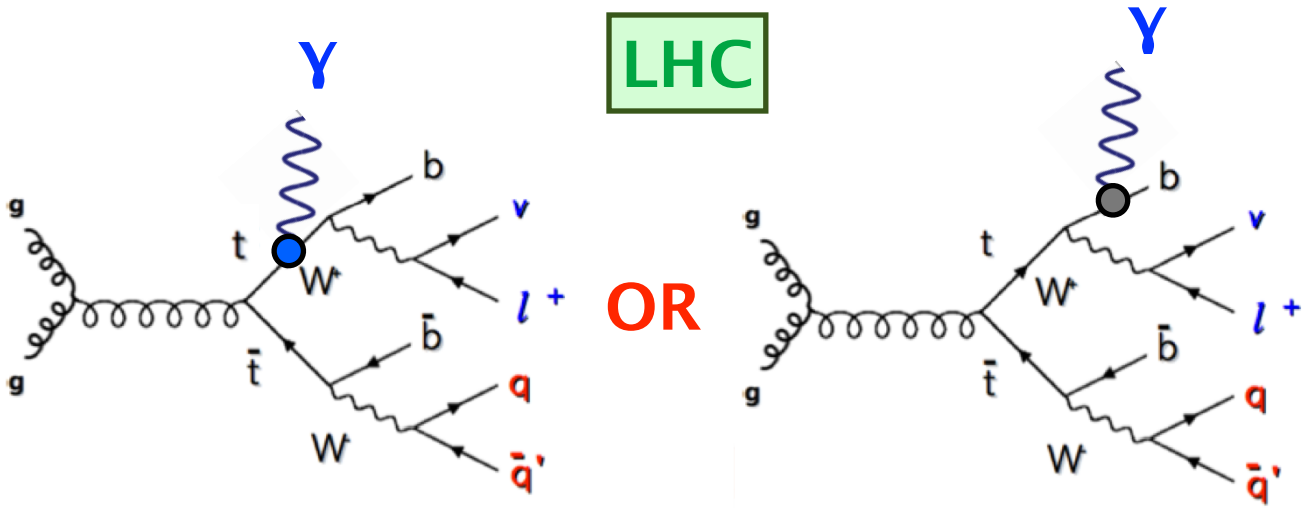
signal



background

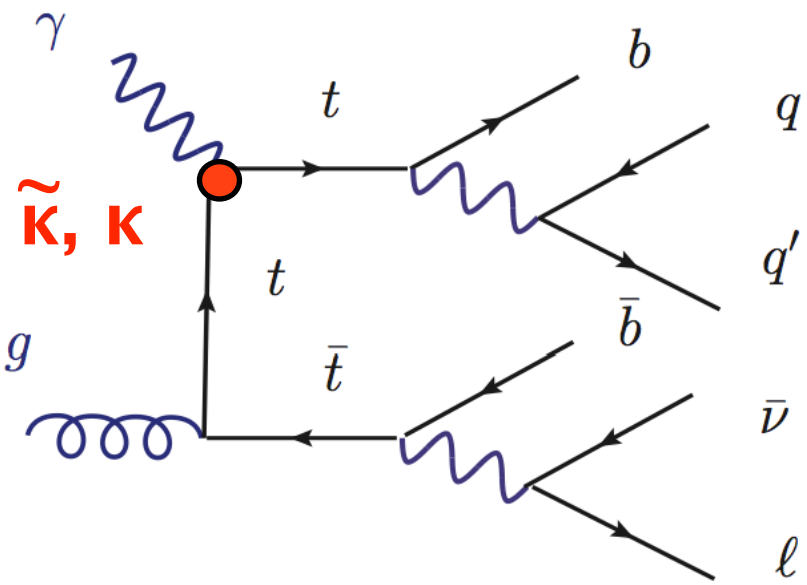


→ measure top quark charge



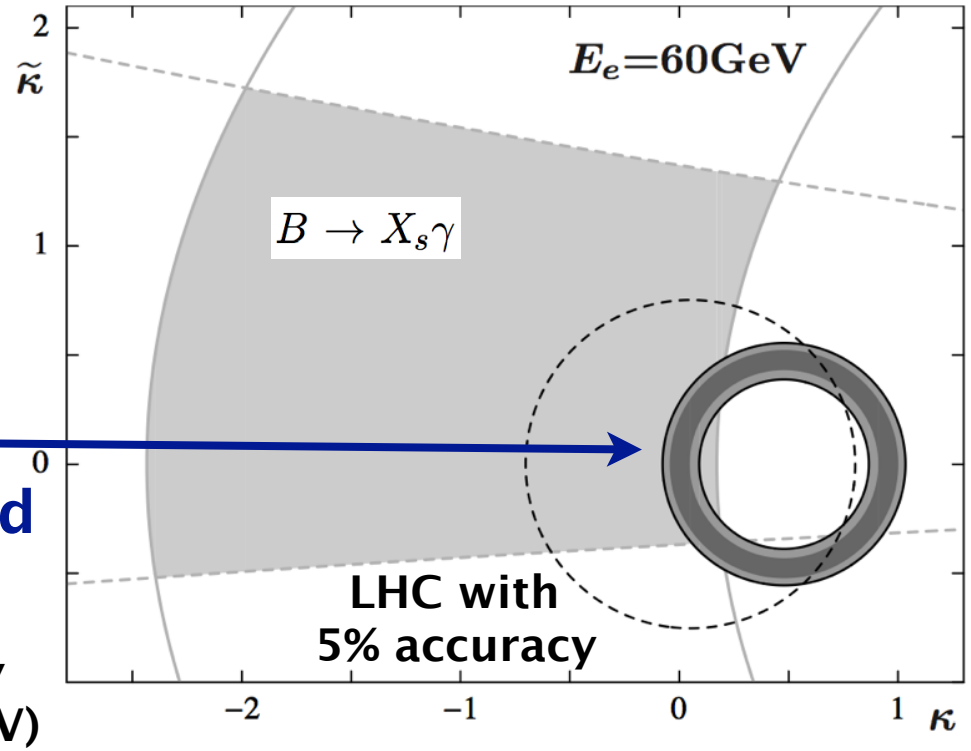
→ not unambiguous at the LHC

Search for Anomalous $t\bar{t}\gamma$ Couplings



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

electric dipole moment: $\tilde{\kappa}$



LHeC

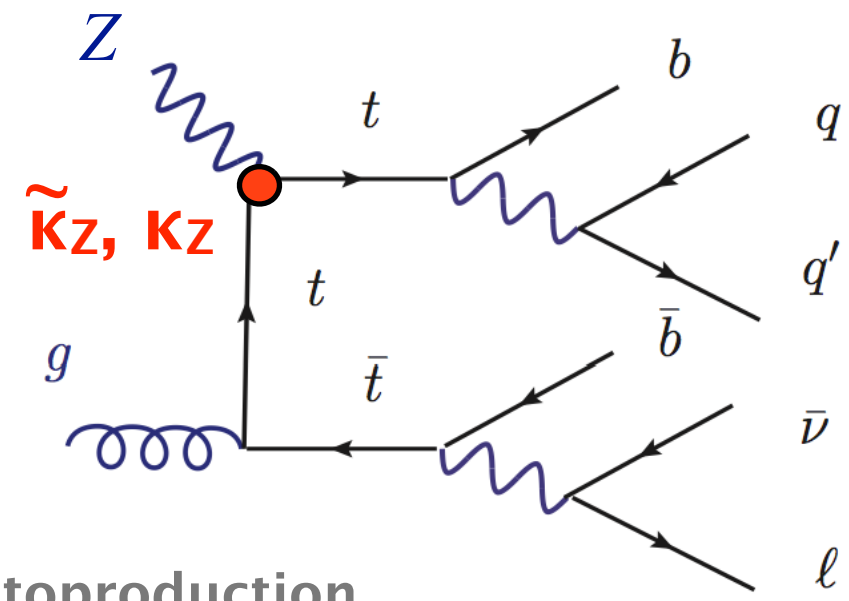
10% and 18% accuracy assumed

27% accuracy
(4.59fb^{-1}, 7 TeV)

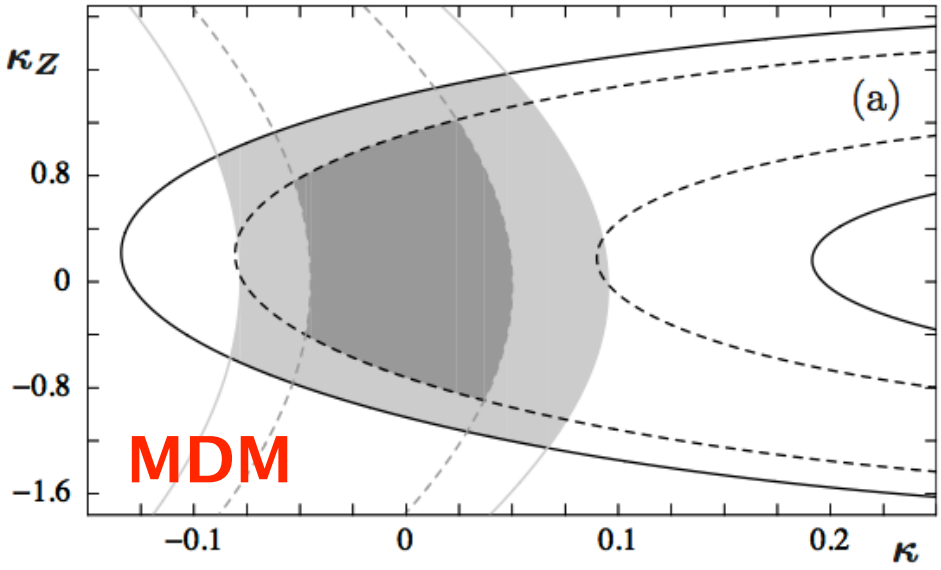
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

magnetic dipole moment: κ

Search for Anomalous $t\bar{t}Z$ Couplings



$t\bar{t}$ photoproduction



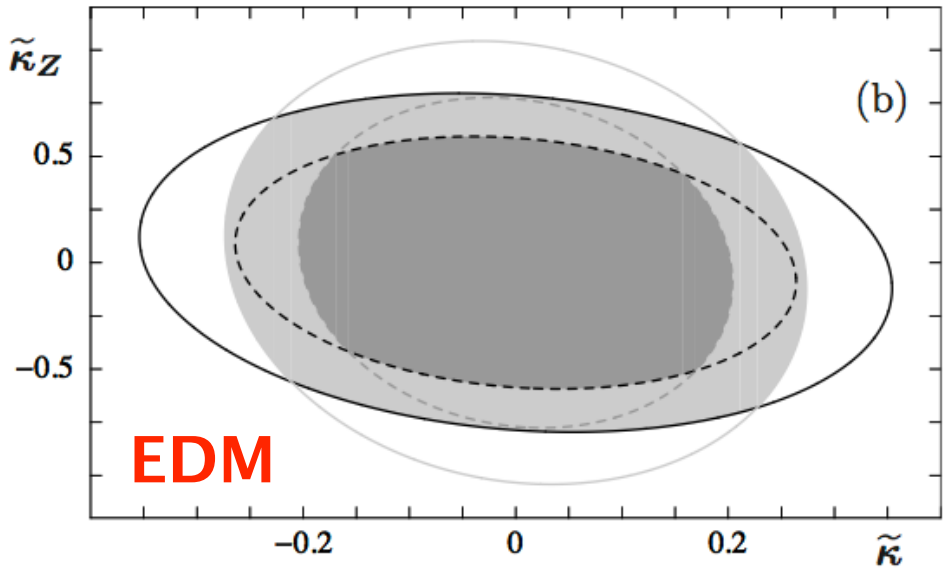
$t\bar{t}$ DIS

Bouzas, Larios,
Physical Review D 88, 094007 (2013)

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

LHeC E_e=60 GeV

10% and 18% accuracy assumed



Outline

Introduction

CC Top Production

NC Top Production

BSM Top Production

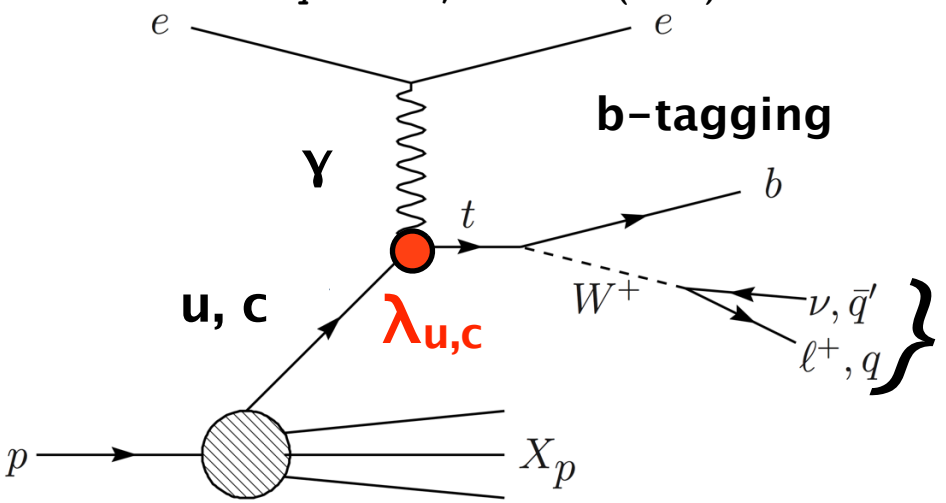
Conclusions

Search for Anomalous FCNC tuγ Coupling

signal

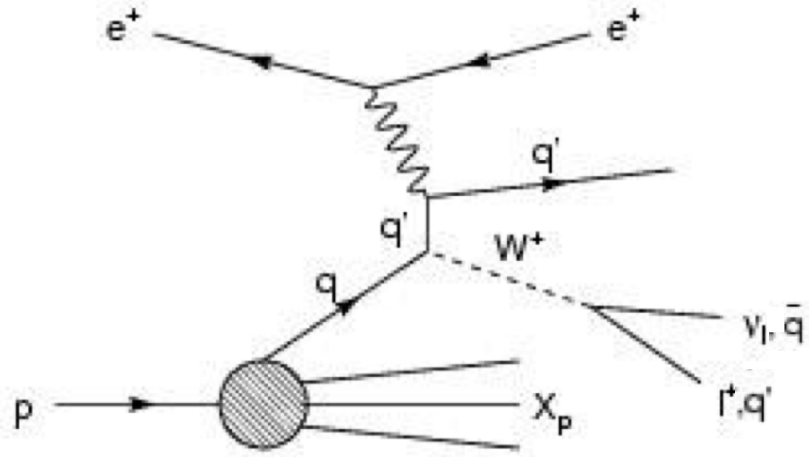
I. Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)

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



50<M_{jj}<100 GeV

background



Search for Anomalous FCNC tuγ Coupling

signal

I. Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)

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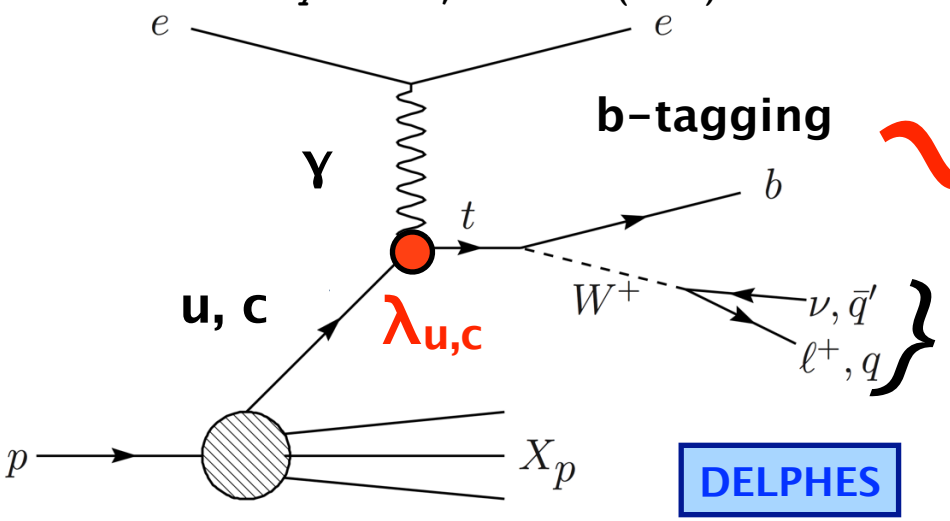
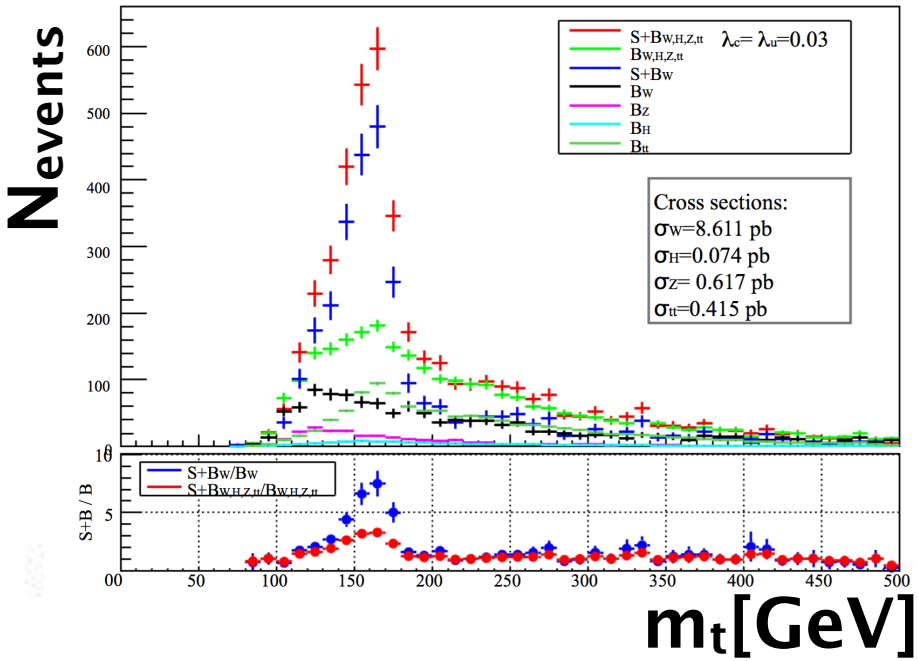


130<M_{Wb}<190 GeV

50<M_{jj}<100 GeV

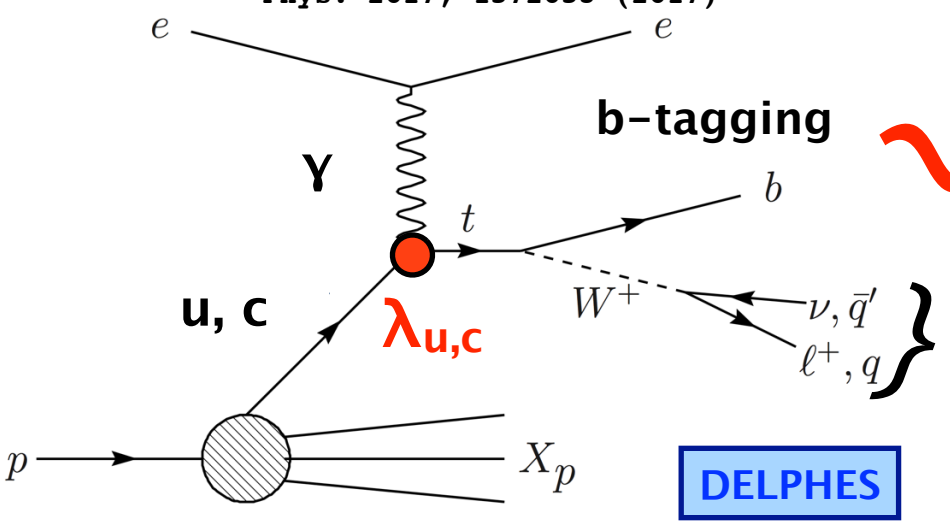
DELPHES



Search for Anomalous FCNC tuγ Coupling

signal

I. Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)



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

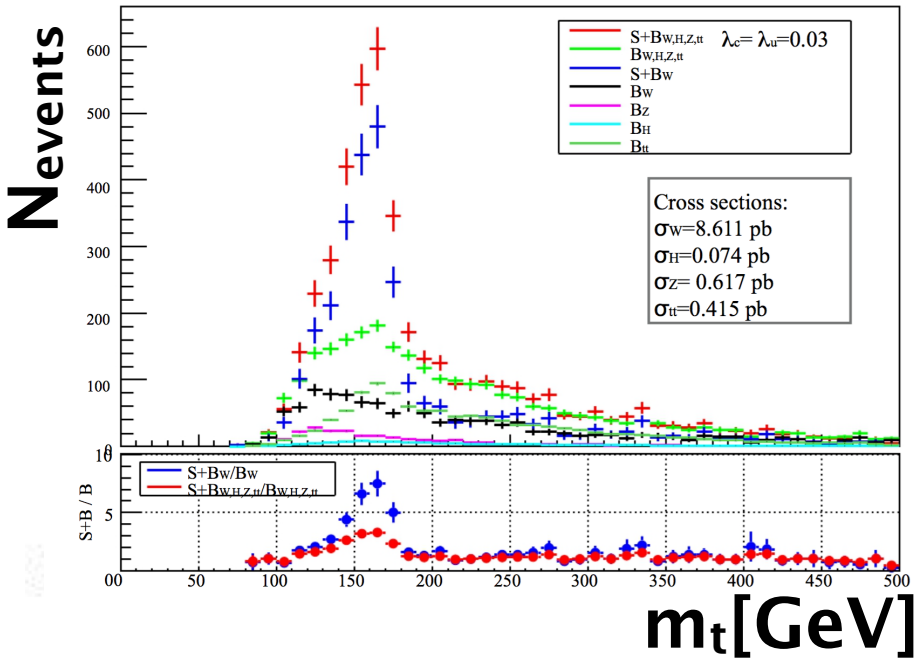
130<M_{Wb}<190 GeV

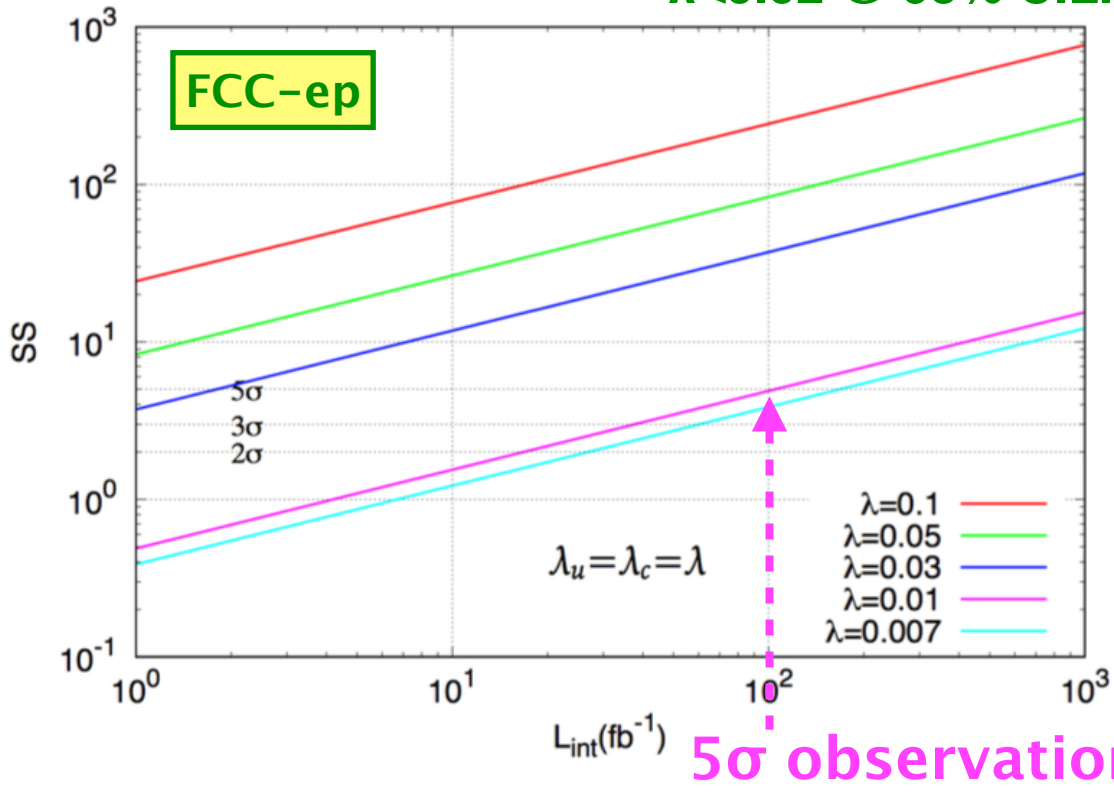
50<M_{jj}<100 GeV

ATLAS: 300 fb^{-1}, √s= 14 TeV: λ<0.022 @ 95% C.L.

ILC: 500 fb^{-1} , √s= 250 GeV: λ<0.02 @ 95% C.L.

DELPHES



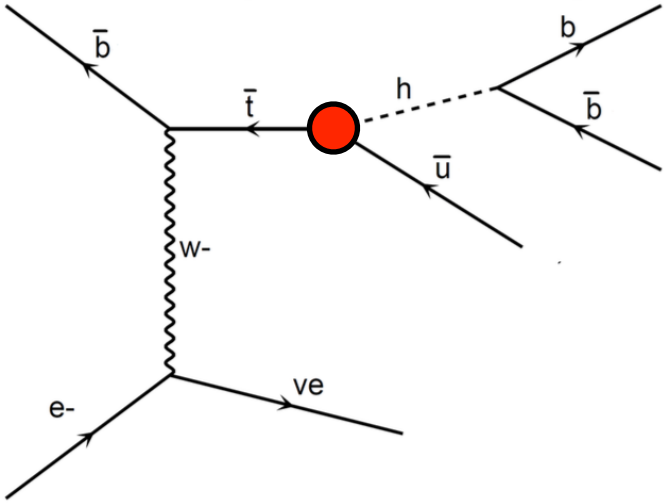


5σ observation

Search for Anomalous FCNC tHu Coupling

signal

Sun, Wang,
arXiv:1602.04670 [hep-ph]



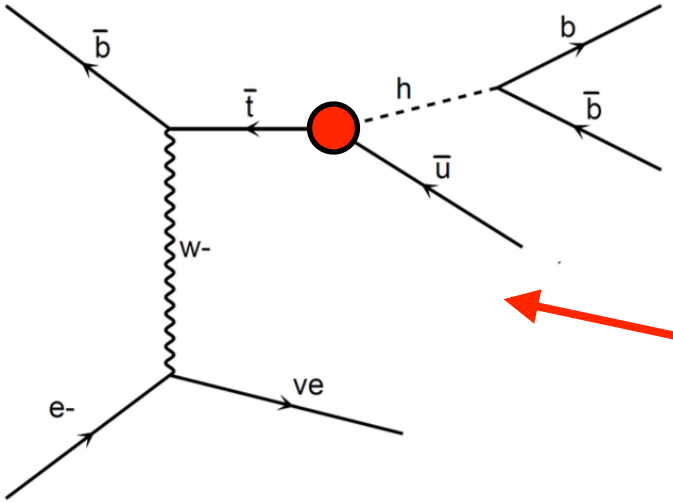
$$e^- p \to \nu_e \bar{t} \to \nu_e h \bar{q} \to \nu_e b \bar{b} \bar{q}, \quad q = u, c$$

$$\mathcal{L} = \kappa_{tuh} \bar{t} u h + \kappa_{tch} \bar{t} c h + h.c.$$

Search for Anomalous FCNC tHu Coupling

signal

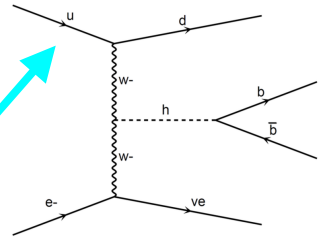
Sun, Wang,
arXiv:1602.04670 [hep-ph]

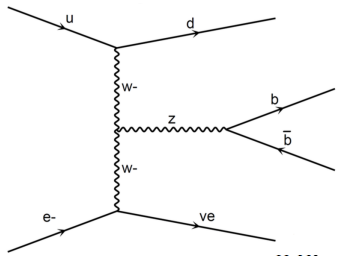


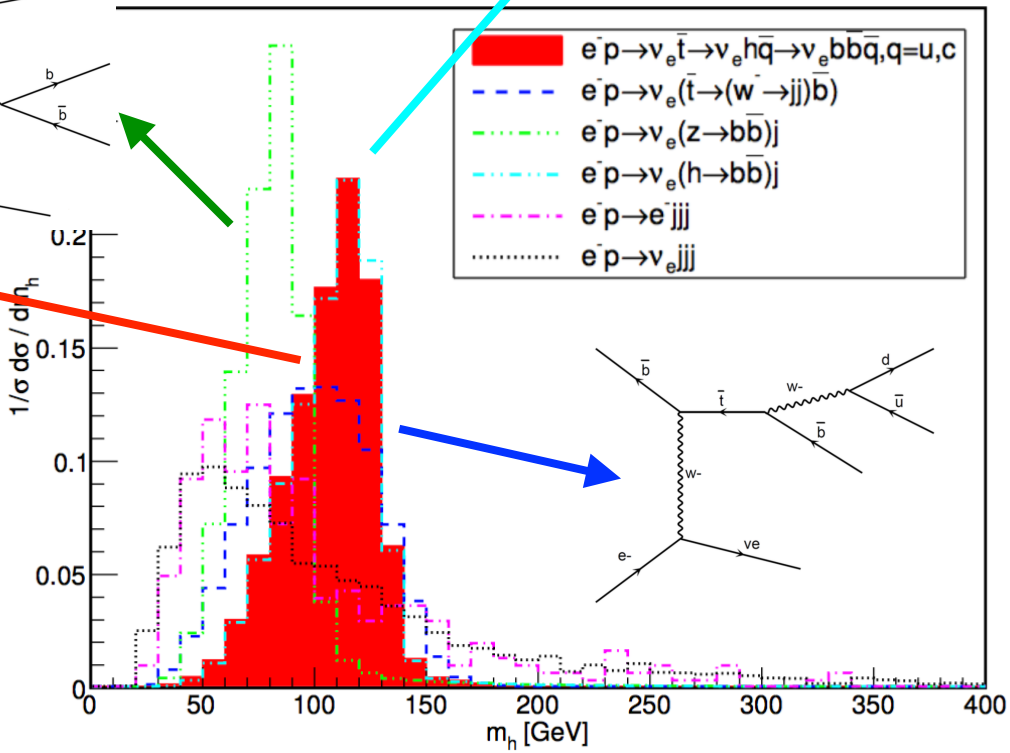
$$e^- p \to \nu_e \bar{t} \to \nu_e h \bar{q} \to \nu_e b \bar{b} \bar{q}, \quad q = u, c$$

$$\mathcal{L} = \kappa_{tuh} \bar{t} u h + \kappa_{tch} \bar{t} c h + \text{h.c.}$$

background



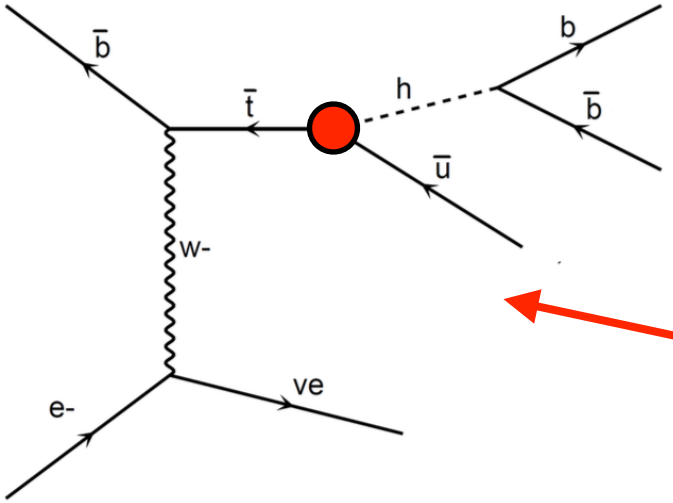




Search for Anomalous FCNC tHu Coupling

signal

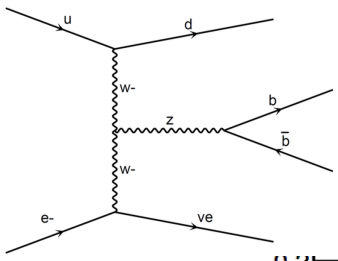
Sun, Wang,
arXiv:1602.04670 [hep-ph]

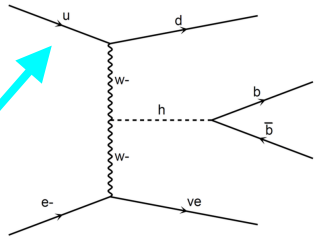


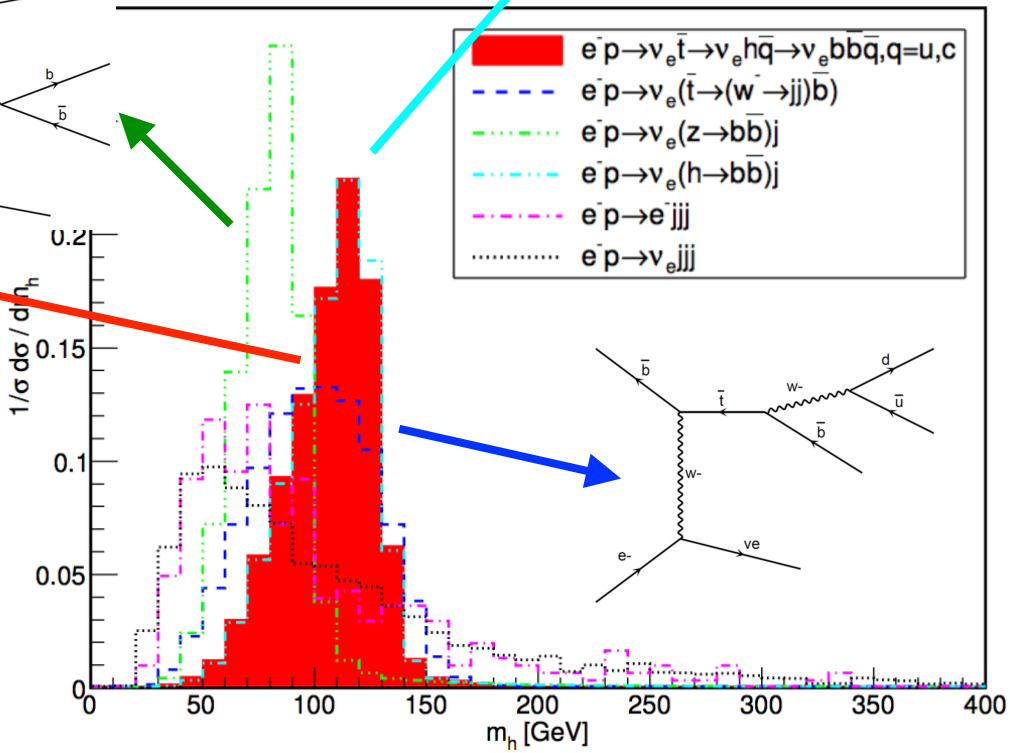
$$e^- p \to \nu_e \bar{t} \to \nu_e h \bar{q} \to \nu_e b \bar{b} \bar{q}, \quad q = u, c$$

$$\mathcal{L} = \kappa_{tuh} \bar{t} u h + \kappa_{tch} \bar{t} c h + h.c.$$

background

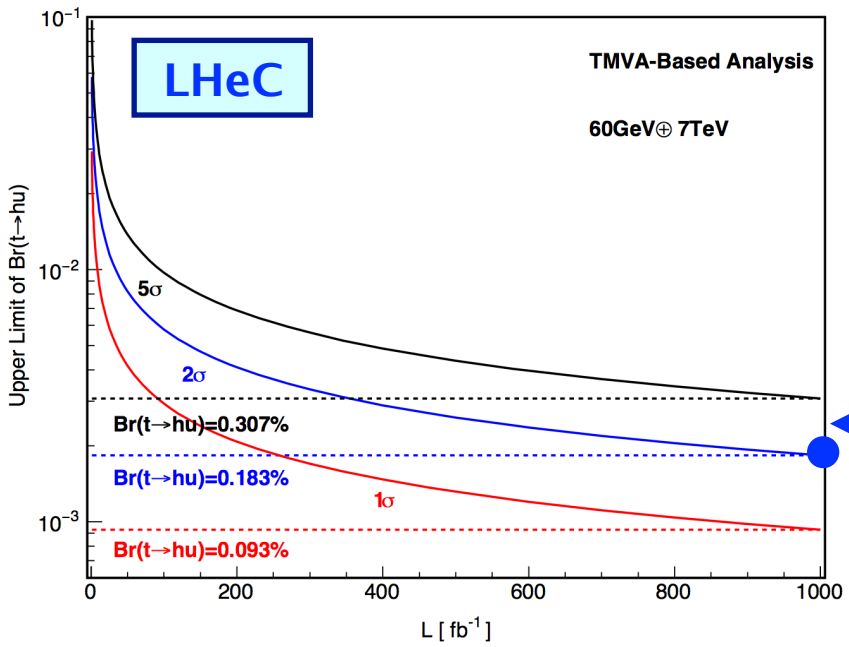






- parametrised assumed resolutions for electrons/photons, muons, jets and unclustered energy using ATLAS values
- b-tag rate of 60%, c-jet fake rate of 10%, light-jet fake rate of 1%
- selections optimized for LHeC and FCC-ep scenarios (s/√(S+B))
- cut-based and MVA-based analyses

Upper Limit on Br(t→uH) in MVA analysis

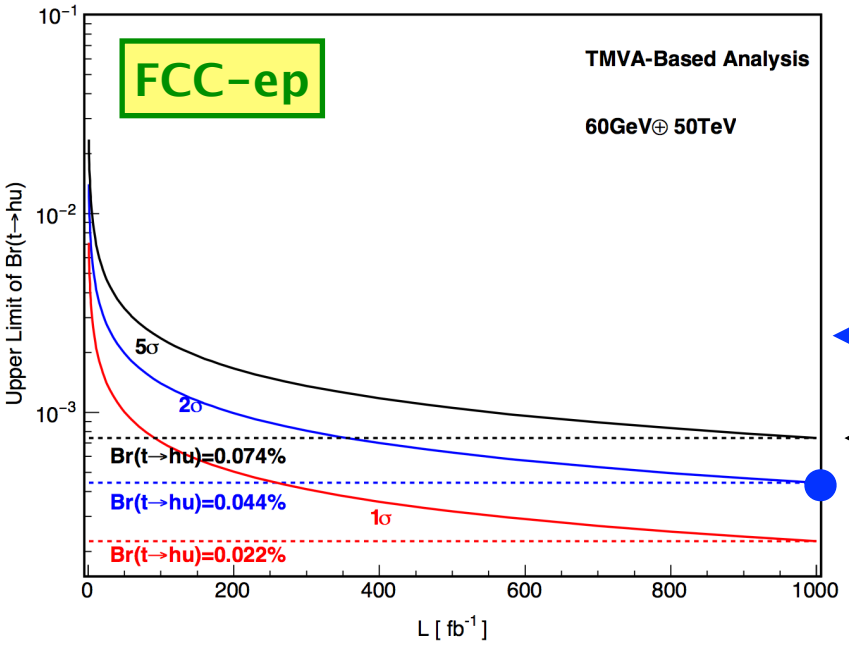


Sun, Wang,
arXiv:1602.04670 [hep-ph]

parametrisation

HL-LHC

LHC, 3000 fb^{-1}@14TeV



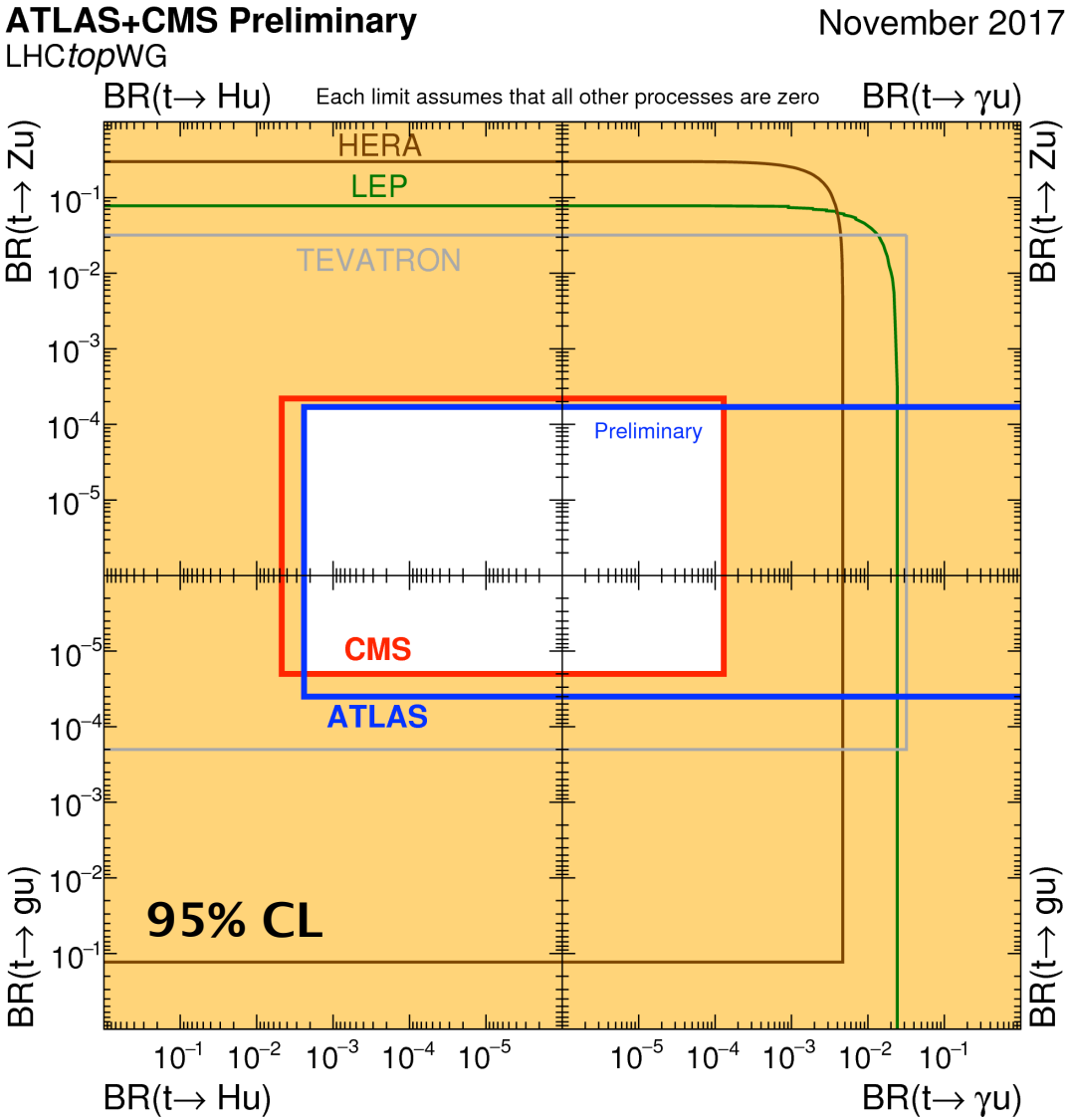
HL-LHC

LHC, 3000 fb^{-1}@14TeV

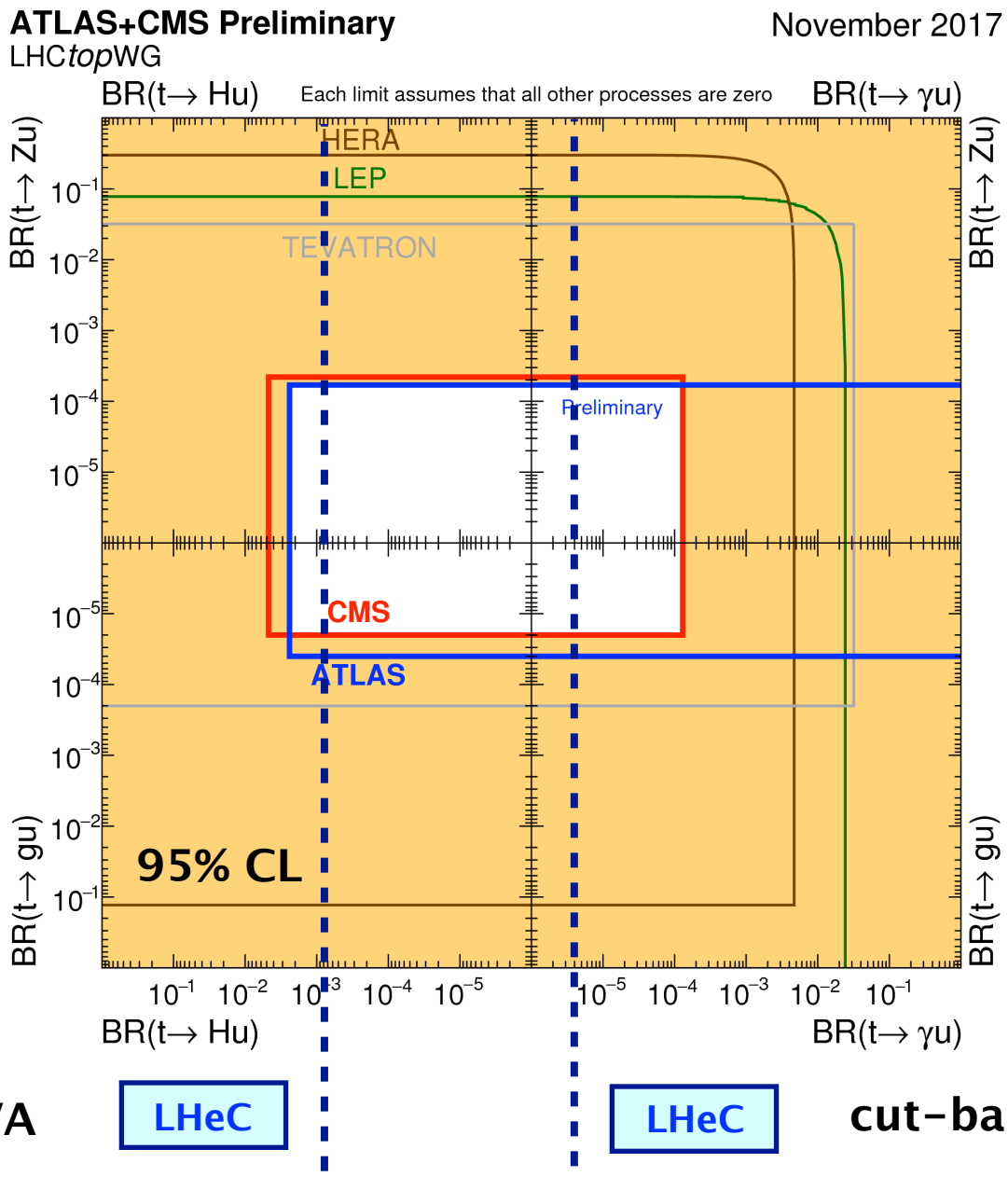
observation

→ improves sensitivity of HL-LHC

FCNC Branching Ratios at Colliders



FCNC Branching Ratios at Colliders

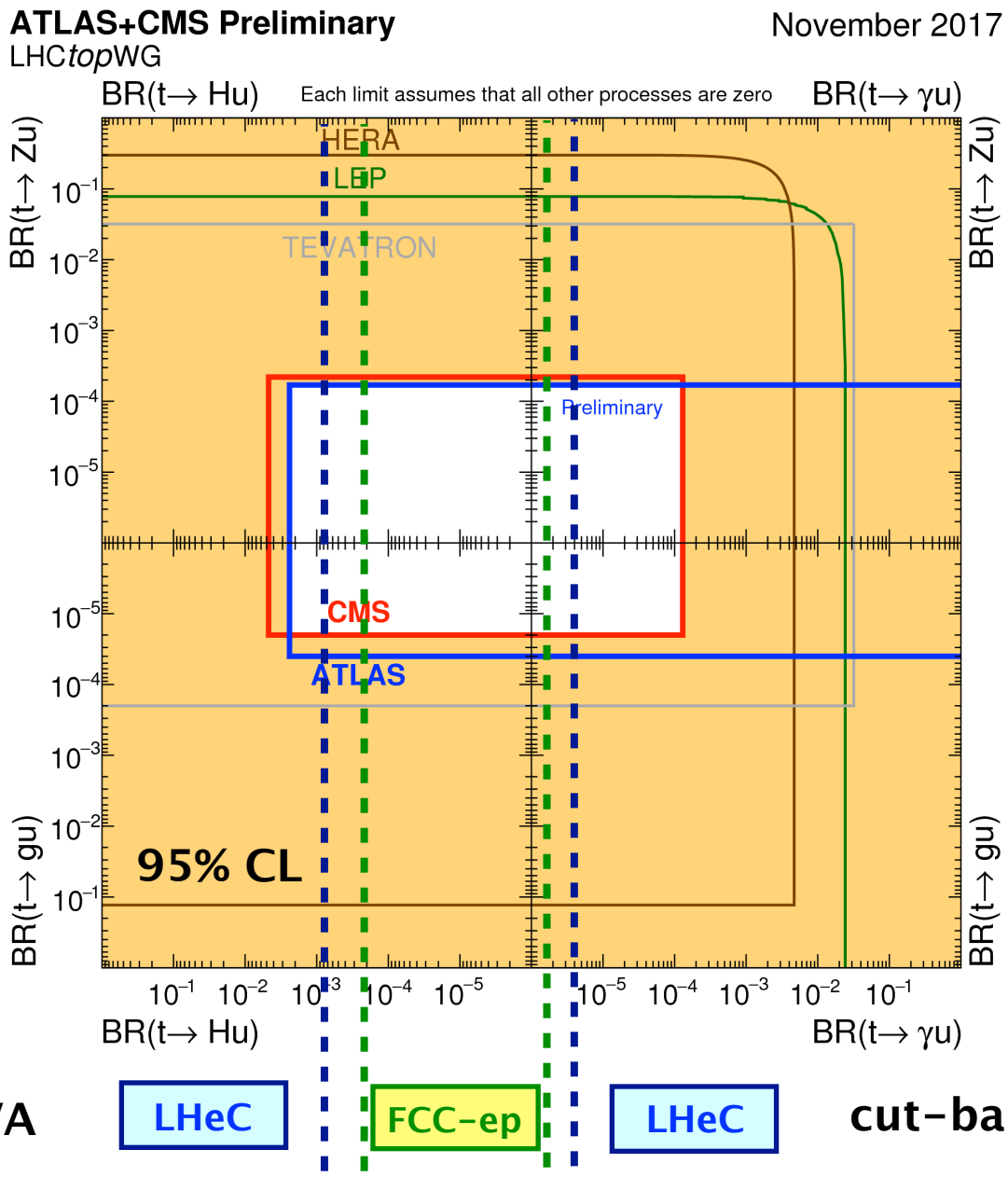


E_e=60 GeV
1000 fb^{-1}

MVA LHeC

LHeC **cut-based**

FCNC Branching Ratios at Colliders



E_e=60 GeV
1000 fb^{-1}

MVA

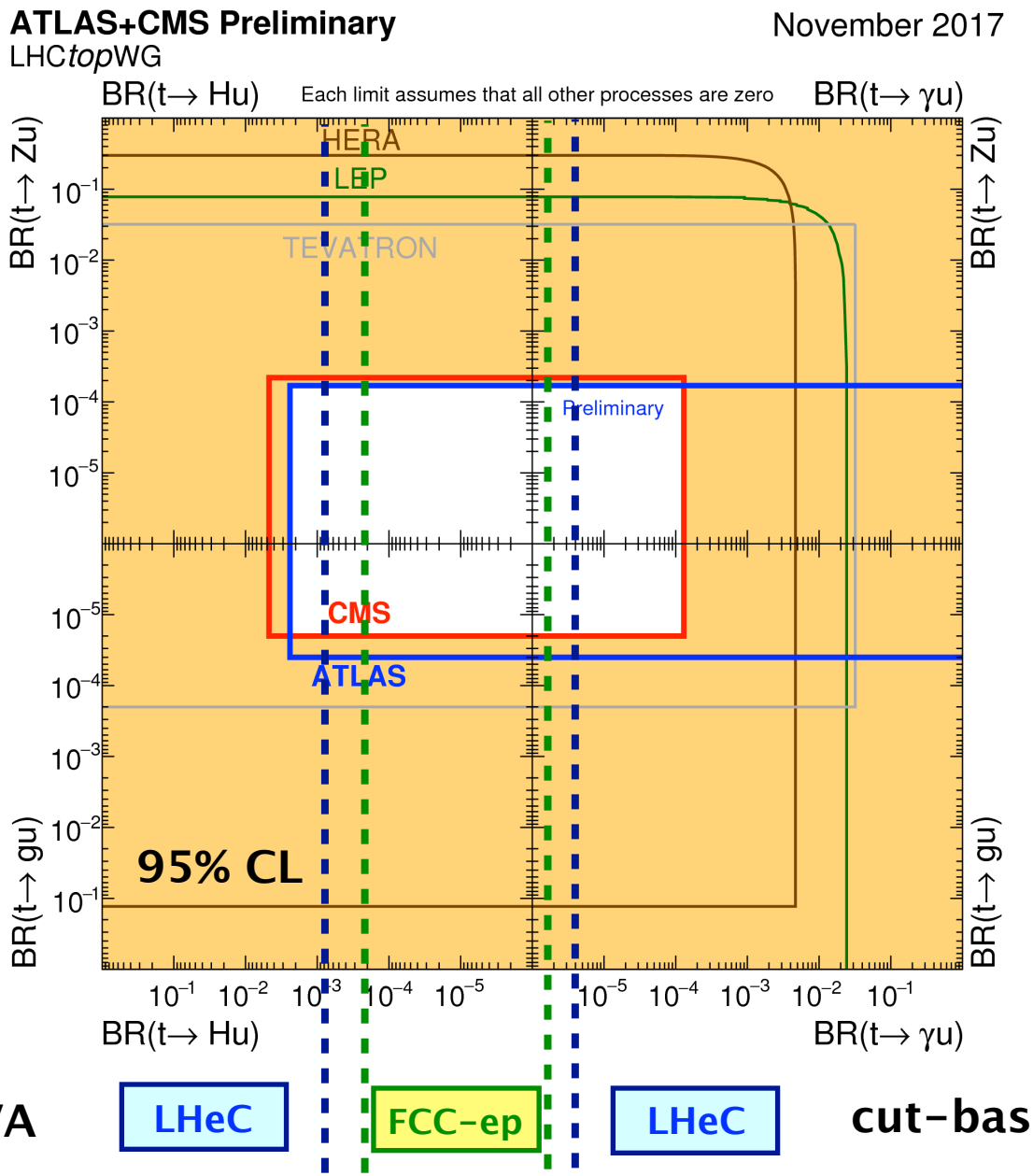
LHeC

FCC-ep

LHeC

cut-based

FCNC Branching Ratios at Colliders



- improve limits on BR(t→γu), BR(t→Hu) considerably

→ test SUSY, little Higgs, technicolor...

E_e=60 GeV
1000 fb^{-1}

MVA

LHeC

FCC-ep

LHeC

cut-based

Outline

Introduction

CC Top Production

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BSM Top Production

Conclusions

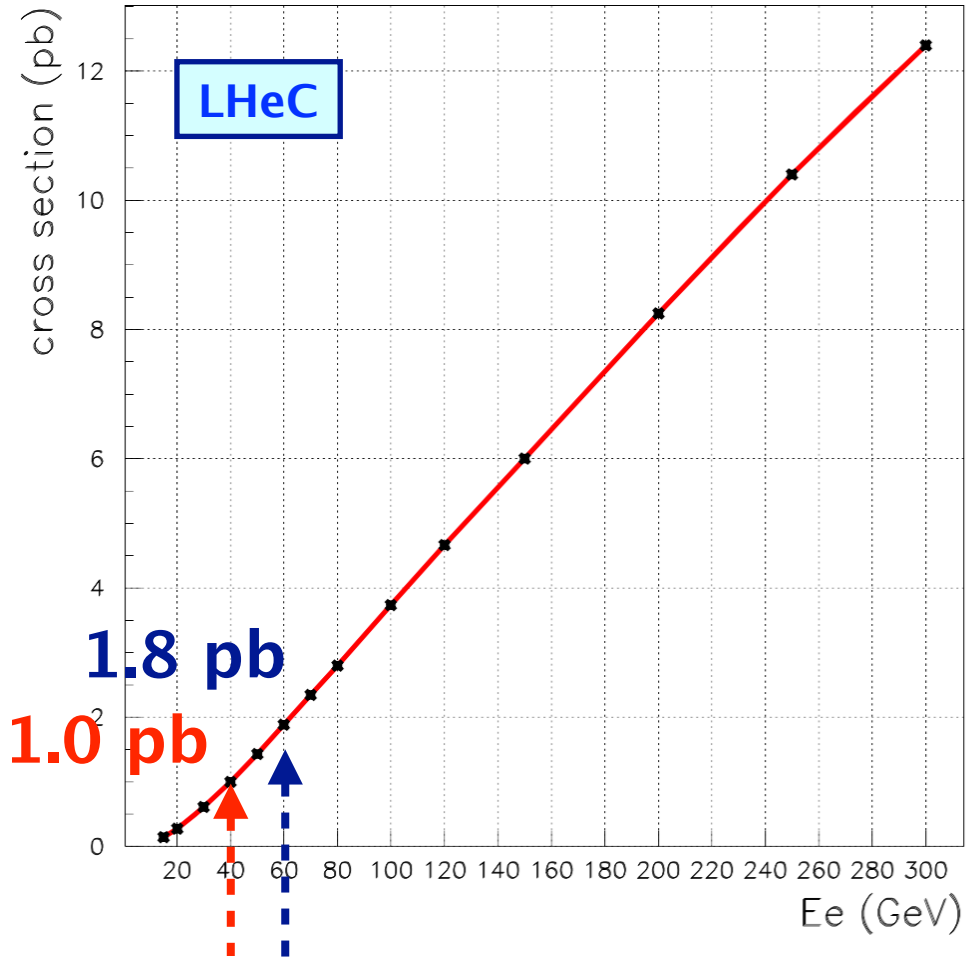
Summary

- future ep collider has a rich analysis programme for top quark physics
- single top quark factory: $|V_{tb}|$ (~1%)
- top quark couplings to electroweak bosons (Wtb, ttγ, ttZ, ttH, …)
- analyse top quark properties with high precision: polarisation, charge, PDFs of tops, …
- many stringent searches for new physics: anomalous couplings, FCNC, CP violation in top-Yukawa, heavy top, SUSY stops…

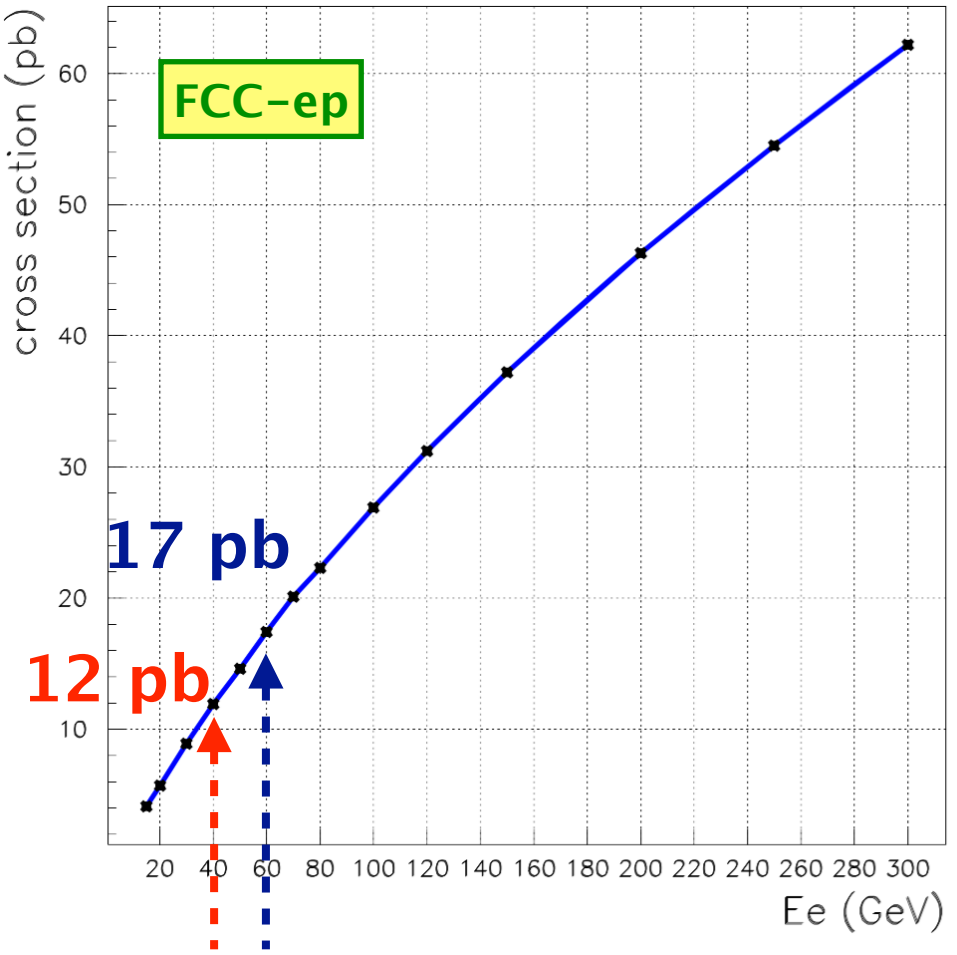
→ further exciting studies/updates to come for

Backup

CC Single Top Quark Cross Section

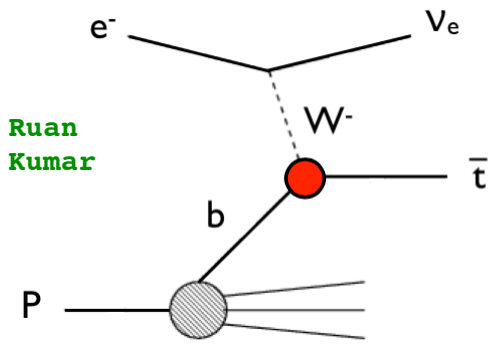


O. Behnke, Madgraph



→ strong rise of cross section with electron beam energy

Status: Top Quark SM+BSM

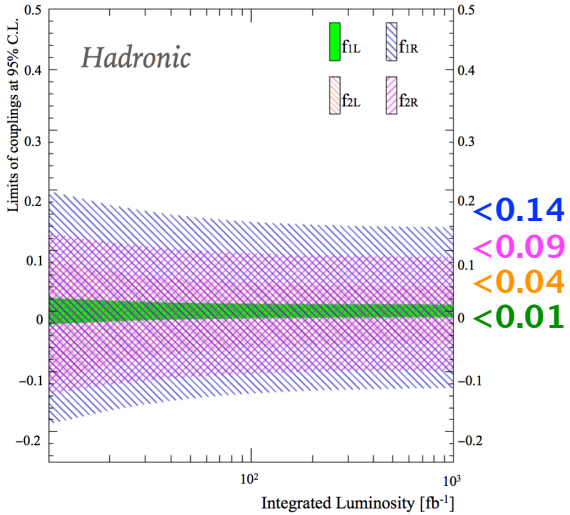


Ruan
Kumar

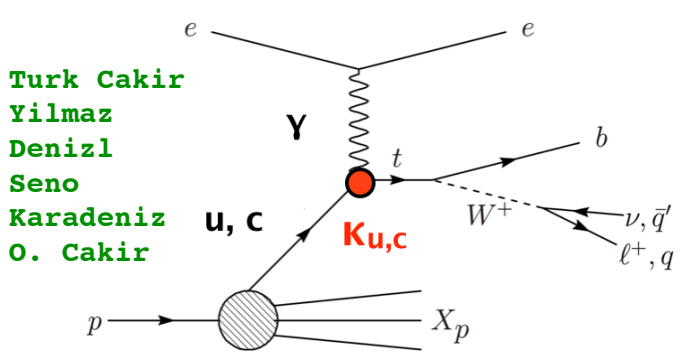
= 1 in SM

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

DELPHES | LHeC+FCC



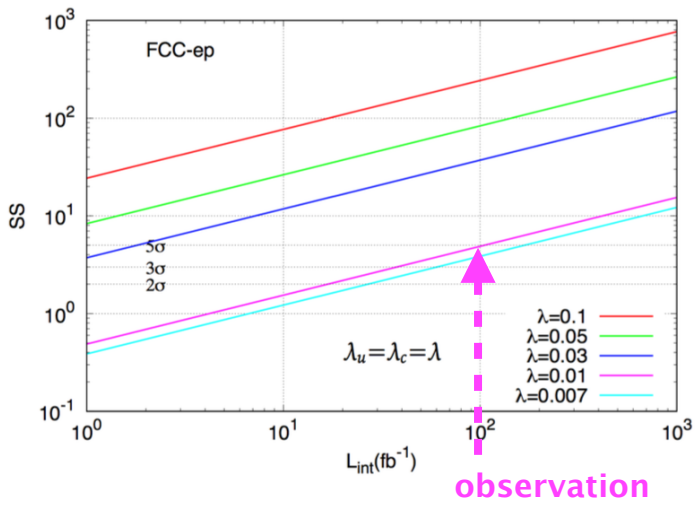
→ to be published
→ ask for SM cross sections



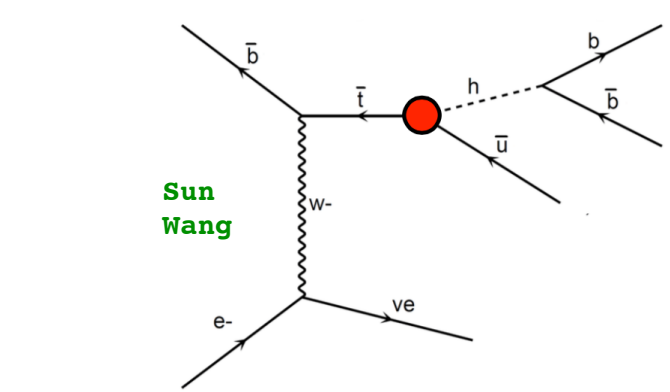
Turk Cakir
Yilmaz
Denizl
Seno
Karadeniz
O. Cakir

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

DELPHES | LHeC+FCC



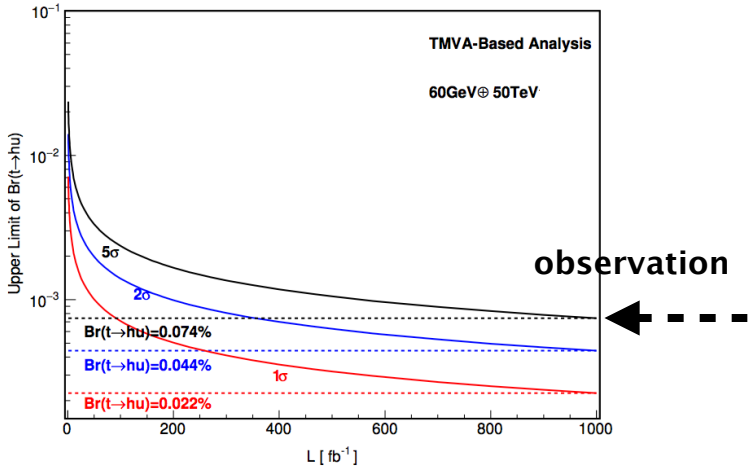
→ published: arXiv:1705.05419
→ ask for BR(t→qγ)



Sun
Wang

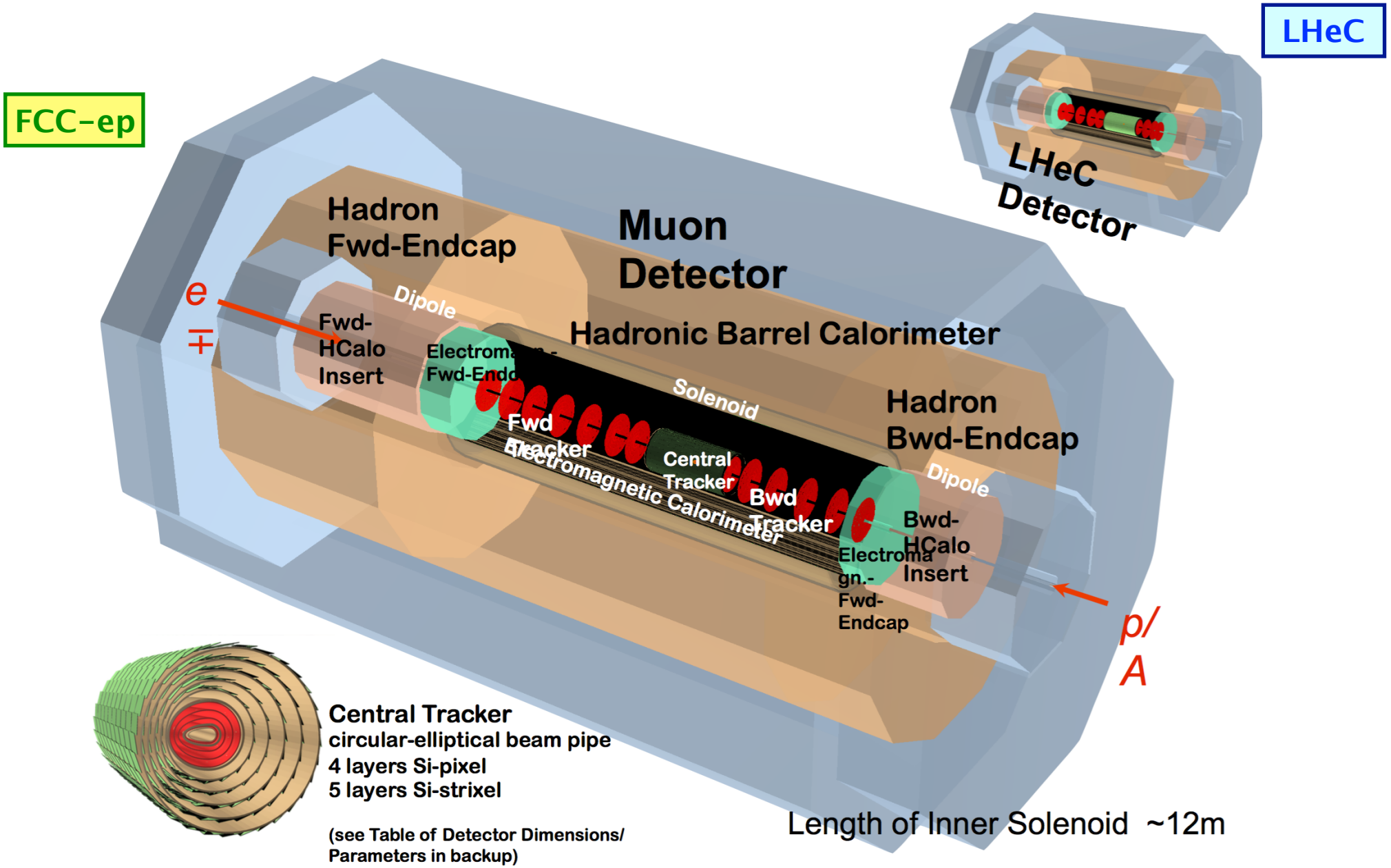
$$\mathcal{L} = \kappa_{tuh}\bar{t}uh + \kappa_{tch}\bar{t}ch + h.c.$$

parametrisation | LHeC+FCC



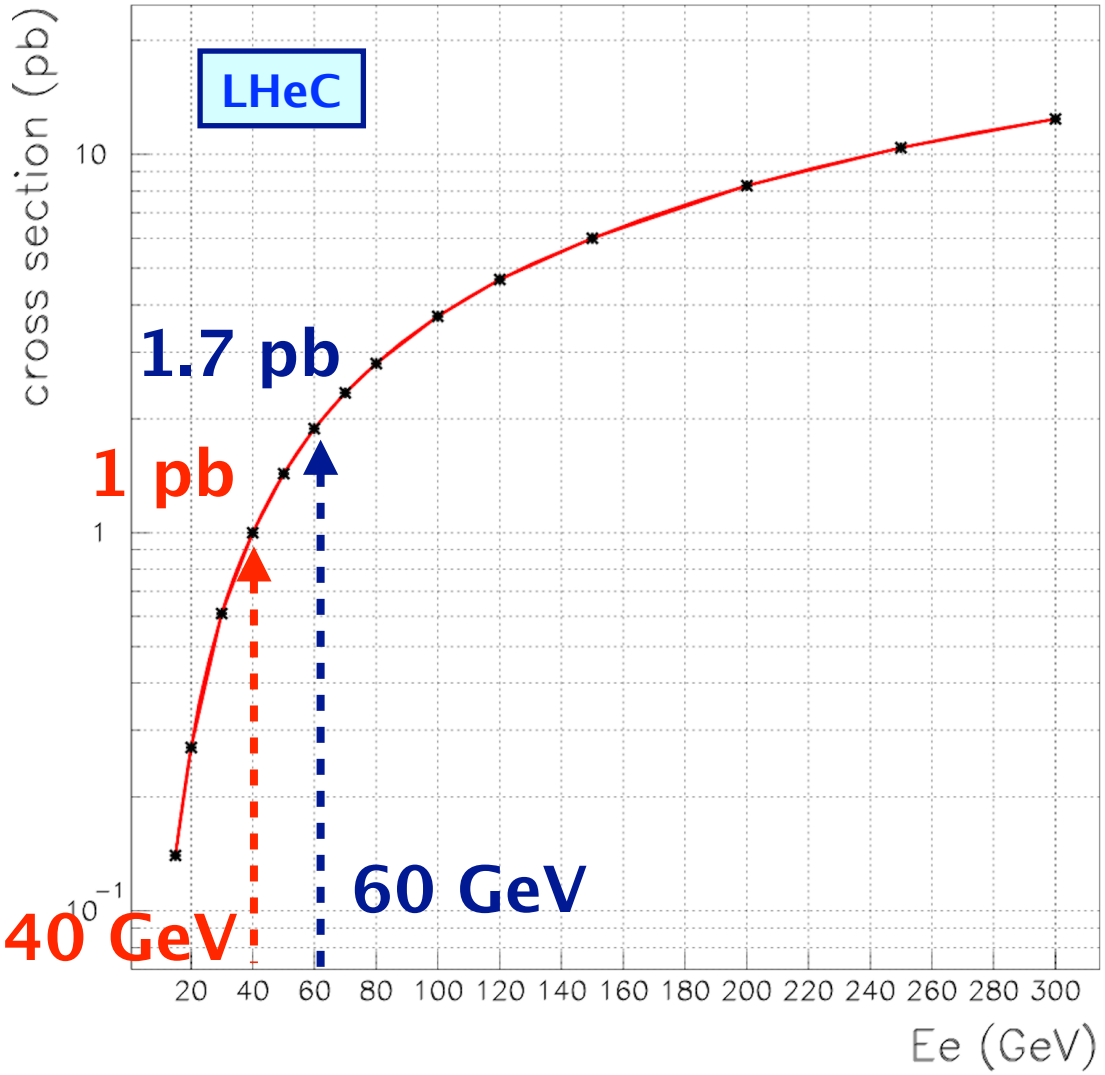
→ published: arXiv:1602.04670

LHeC and FCC-eh Detector Layout



CC Single Top Quark Cross Section

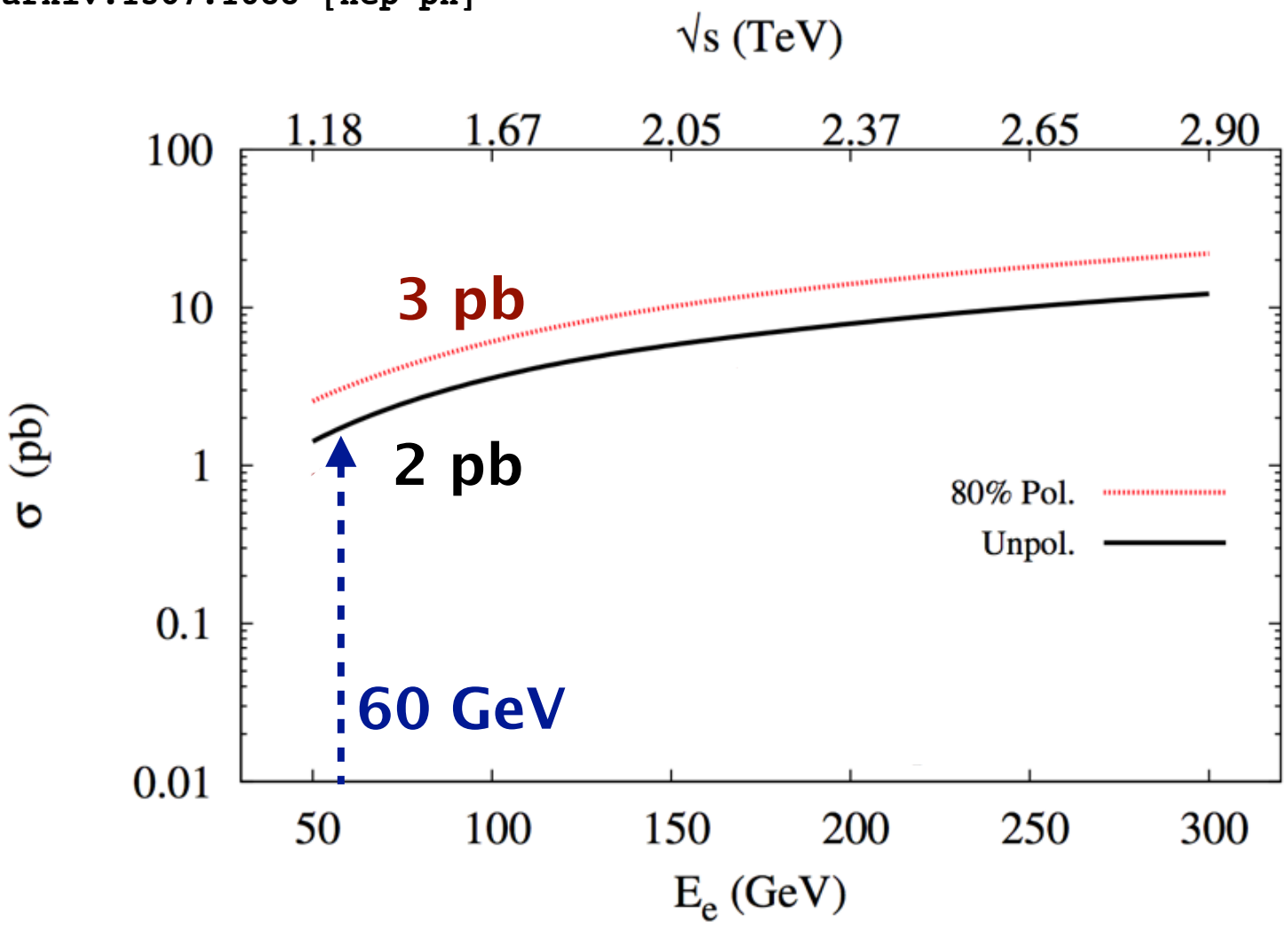
O. Behnke, Madgraph



→ LHeC offers excellent prospects for top quark physics
→ strong rise of cross section with electron beam energy

CC Single Top Quark Cross Section

Dutta, Goyal, Kumar, Mellado,
arXiv:1307.1688 [hep-ph]



100 fb^{-1}:
$2 \cdot 10^5$ events
$3 \cdot 10^5$ events

→ **LHeC offers excellent prospects for top quark physics**

FCC-eh: tracker, calorimeters and steps

Tracker	FST_{pix}	FST_{strix}	CFT_{pix}	CPT_{pix}	CST_{strix}	CBT_{pix}	BST_{strix}	BST_{pix}
#Wheels	7		2	–	–	2	5	
#Rings/Wheel	2_{inner}	3_{outer}	3/4	–	–	3/4	3_{outer}	2_{inner}
#Layers	–	–	–	4	5	–	–	–
$\theta_{min/max}$ [0]	0.5	3.8	3.6	5.1	24/155	176.4	173.1	179.3
$\eta_{max/min}$	5.4	3.4	3.5	±3.1	±1.4	-3.5	-2.8	-5.2
$Si_{pix/strix}$ $[m^2]$	9.7	13.3	2.8	5.4	33.7	2.8	9.7	6.9
Sum-Si $[m^2]$	84.3 double layers taken into account							

Calo	FHC_{SiW}	FEC_{SiW}	$EMC_{SciPb/LAr}$	HAC_{SciFe}	BEC_{SiPb}	BHC_{SiFe}
$\theta_{min/max}$ [0]	0.3	0.4	5.6/173.4	8.6/167	179.4	179.6
$\eta_{max/min}$	6.0	5.6	3.0/-2.7	2.5/-2.2	-5.3	-5.6
Volume $[m^3]$	13.2	3.1	28.8	407	1.98	7.0
Sum-Si $[m^2]$	461					

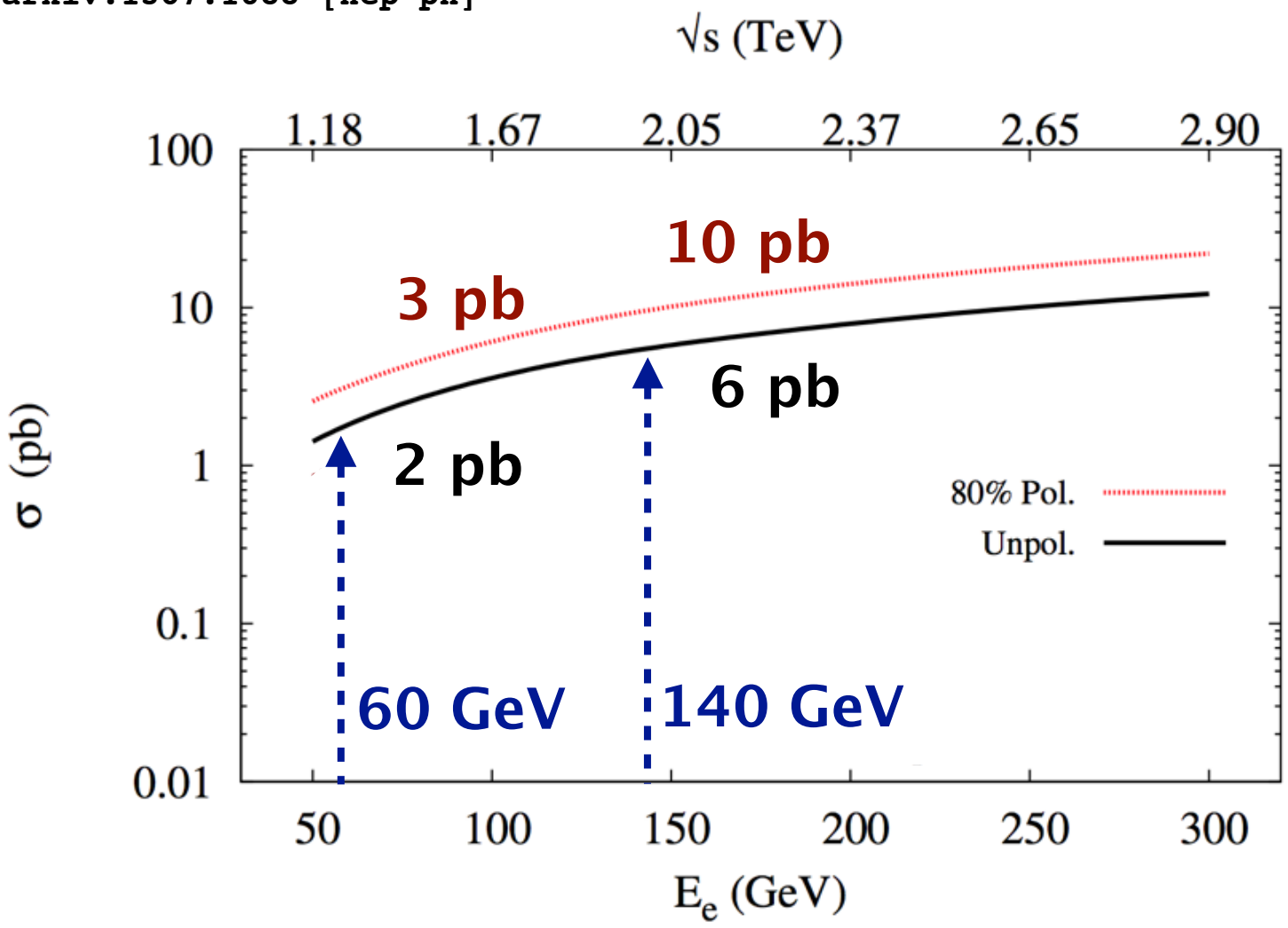
Input to detector design: HERA, ATLAS/CMS+their upgrades, CALICE, LHeC (CDR and update)

At FCC-eh unlike LHeC we think muon momentum measurement is vital (H-μμ)

Next steps: final choice of CDR technology, IR integration, joint eh-hh consideration, software

CC Single Top Quark Cross Section

Dutta, Goyal, Kumar, Mellado,
arXiv:1307.1688 [hep-ph]



100 fb^{-1}:
2–6 · 10^5 events
3–10 · 10^5 events

→ **LHeC offers excellent prospects for top quark physics**

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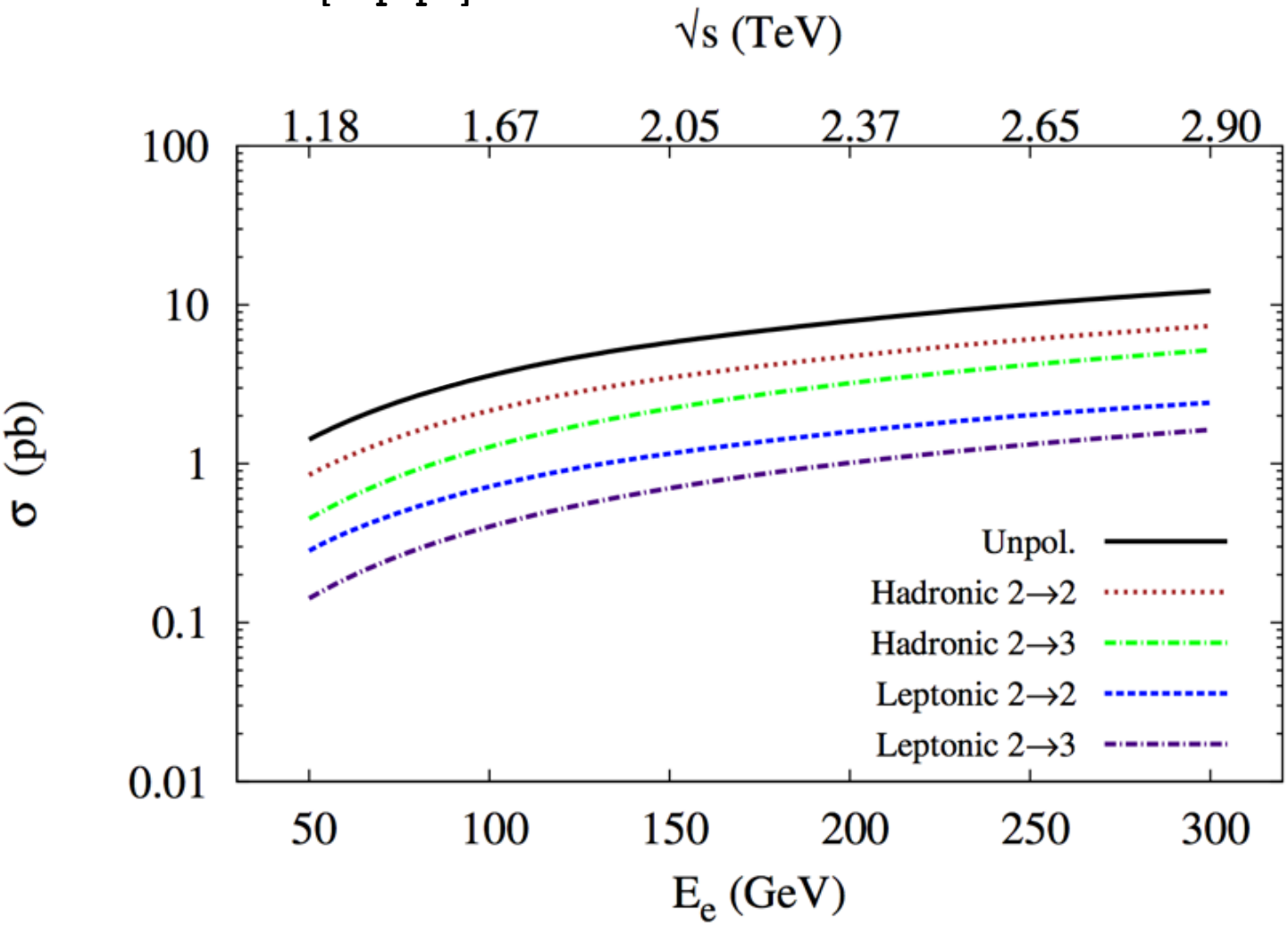
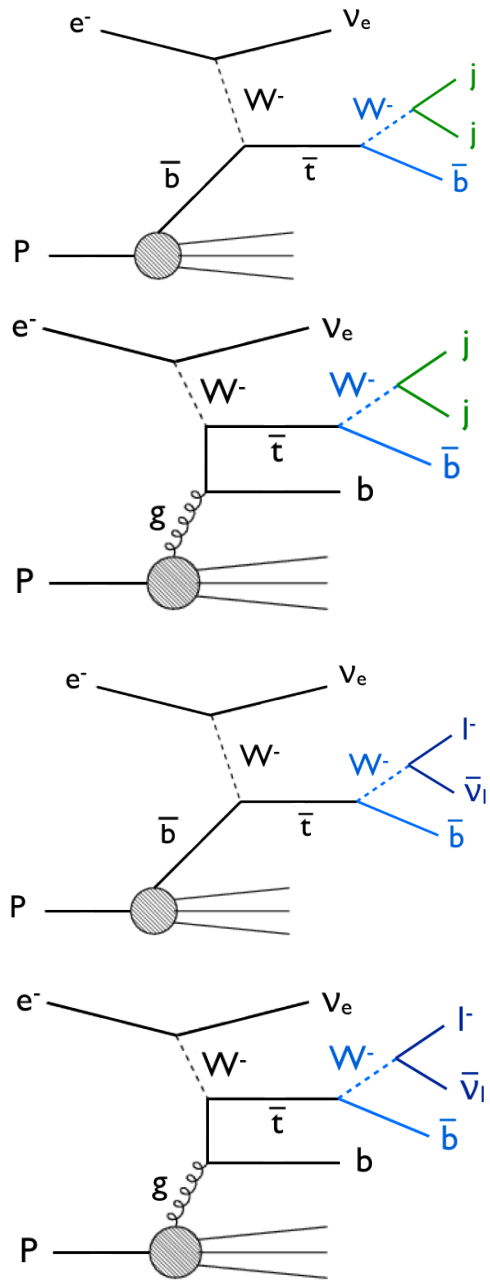




Backgrounds: Hadronic Channel

No.	Background Process	$p_{T\,j,b} \geq 20$ GeV $\lvert\eta_j\rvert \leq 5, \lvert\eta_b\rvert \leq 2.5$ $\Delta R_{j,b/j} \geq 0.4$ $\not{E}_T \geq 25$	$\Delta\Phi_{\not{E},j} \geq 0.4$ $\Delta\Phi_{\not{E},b} \geq 0.4$	$\lvert m_{j_1 j_2} - m_W\rvert \leq 22$ GeV	$\sigma_{\text{eff.}}$
1	$e^- p \to \nu_e W^- \bar{b}$ without anti-top line	7.5×10^{-3}	6.8×10^{-3}	4.5×10^{-3}	2.7×10^{-3}
2	$e^- p \to \nu_e jjj$	4.2×10^{0}	3.6×10^{0}	2.4×10^{0}	7.2×10^{-2}
3	$e^- p \to \nu_e cjj$ & $e^- p \to \nu_e \bar{c} jj$	1.5×10^{0}	1.2×10^{0}	8.6×10^{-1}	8.6×10^{-2}
4	$e^- p \to \nu_e c\bar{c} j$	5.8×10^{-2}	5.0×10^{-2}	3.2×10^{-2}	6.7×10^{-3}
5	$e^- p \to \nu_e b\bar{b} j$	2.5×10^{-2}	2.2×10^{-2}	5.6×10^{-3}	1.3×10^{-3}
6	$e^- p \to \bar{c} \nu_e$ $(\bar{c} \to W^- \bar{s})$	2.5×10^{-2}	2.2×10^{-2}	1.5×10^{-2}	1.5×10^{-4}

Event Selection	$p_{T\,j,b} \geq 20$ GeV $\lvert\eta_j\rvert \leq 5, \lvert\eta_b\rvert \leq 2.5$ $\Delta R_{j,b/j} \geq 0.4$ $\not{E}_T \geq 25$	$\Delta\Phi_{\not{E},j} \geq 0.4$ $\Delta\Phi_{\not{E},b} \geq 0.4$	$\lvert m_{j_1 j_2} - m_W\rvert \leq 22$ GeV	Fiducial Efficiency	$S/\sqrt{S+B}$
SM	3.2×10^4	2.3×10^4	2.2×10^4	66.7 %	–
SM+$\sum_i$ Bkg$_i$	6.5×10^4	5.0×10^4	4.0×10^4	61.5 %	
$\lvert V_{tb}\rvert\, \Delta f_1^L = .5$	7.3×10^4	5.0×10^4	5.0×10^4	68.0 %	1.92
$f_1^R = .5$	4.6×10^4	3.2×10^4	3.2×10^4	69.7 %	1.43
$f_2^L = .5$	4.9×10^4	3.6×10^4	3.6×10^4	73.2 %	1.55
$f_2^L = -.5$	3.4×10^4	2.3×10^4	2.3×10^4	69.6 %	1.40
$f_2^R = .5$	5.7×10^4	4.1×10^4	4.1×10^4	72.3 %	1.69

Backgrounds: Leptonic Channel

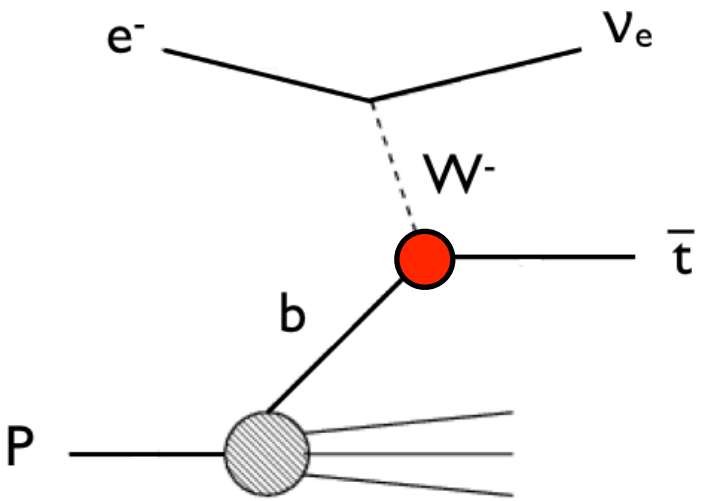
No.	Background Process	$p_{T\,j,b,l} \geq 20$ GeV, $\Delta R_{j,b/j} \geq 0.4$, $\not{E}_T \geq 25$ $\lvert\eta_j\rvert \geq 5$, $\lvert\eta_{b,l}\rvert \geq 2.5$	$\Delta\Phi_{\not{E},j} \geq 0.4$ $\Delta\Phi_{\not{E},b} \geq 0.4$ $\Delta\Phi_{\not{E},l} \geq 0.4$	$\sigma_{\text{eff.}}$
1	$e^- p \to l^- \bar{\nu}_l \nu_e j$	1.5×10^{-1}	1.4×10^{-1}	1.4×10^{-3}
2	$e^- p \to l^- \bar{\nu}_l \nu_e c$ & $e^- p \to l^- \bar{\nu}_l \nu_e \bar{c}$	6.6×10^{-3}	6.1×10^{-3}	6.1×10^{-4}
3	$e^- p \to l^- \bar{\nu}_l \nu_e b$ & $e^- p \to l^- \bar{\nu}_l \nu_e \bar{b}$ Without top line	3.6×10^{-3}	3.2×10^{-3}	1.9×10^{-3}
4	$e^- p \to e^- l^- \bar{\nu}_l c$	1.5×10^{-2}	6.9×10^{-3}	6.9×10^{-4}
5	$e^- p \to e^- l^- \bar{\nu}_l j$	1.2×10^{-1}	5.5×10^{-2}	5.5×10^{-4}

Event Selection	$p_{T\,j,b} \geq 20$ GeV $\lvert\eta_j\rvert \leq 5, \lvert\eta_b\rvert \leq 2.5$ $\Delta R_{j,b/j} \geq 0.4$ $\not{E}_T \geq 25$	$\Delta\Phi_{\not{E},j} \geq 0.4$ $\Delta\Phi_{\not{E},b} \geq 0.4$ $\Delta\Phi_{\not{E},l} \geq 0.4$	Fiducial Efficiency	$S/\sqrt{S+B}$
SM	1.2×10^4	1.1×10^4	92.0 %	–
SM+$\sum_i$ Bkg$_i$	1.3×10^4	1.2×10^4	92.0 %	–
$\lvert V_{tb}\rvert\, \Delta f_1^L = .5$	4.5×10^4	2.5×10^4	92.6 %	1.55
$f_1^R = .5$	2.8×10^4	1.6×10^4	94.1 %	1.23
$f_2^L = .5$	3.1×10^4	1.7×10^4	89.5 %	1.27
$f_2^L = -.5$	1.8×10^4	1.0×10^4	90.9 %	0.95
$f_2^R = .5$	3.6×10^4	2.0×10^4	90.9 %	1.38

Direct Measurement of $|V_{tb}|$

Dutta, Goyal, Kumar, Mellado,
arXiv:1307.1688 [hep-ph]

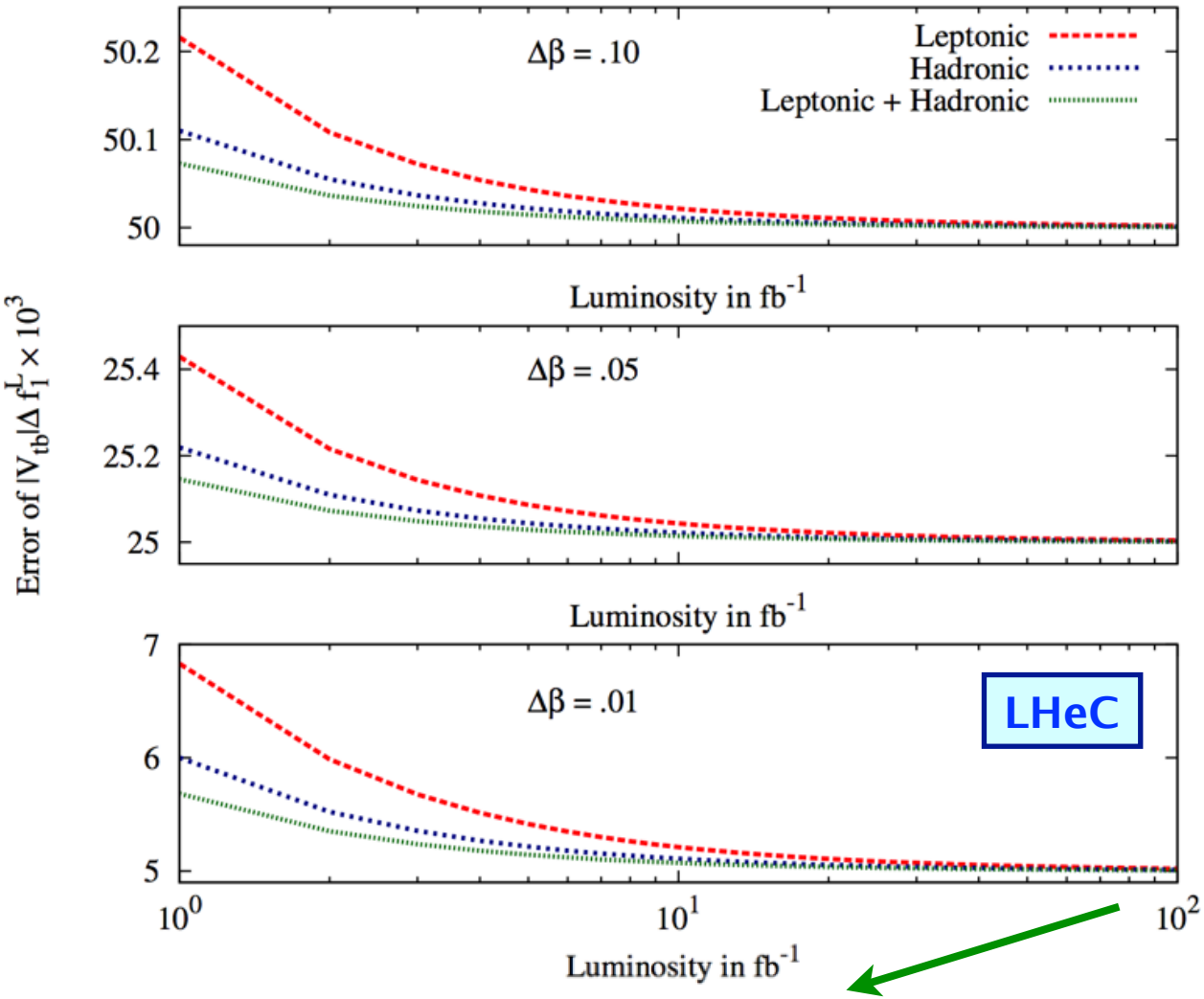
E_e=60 GeV



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

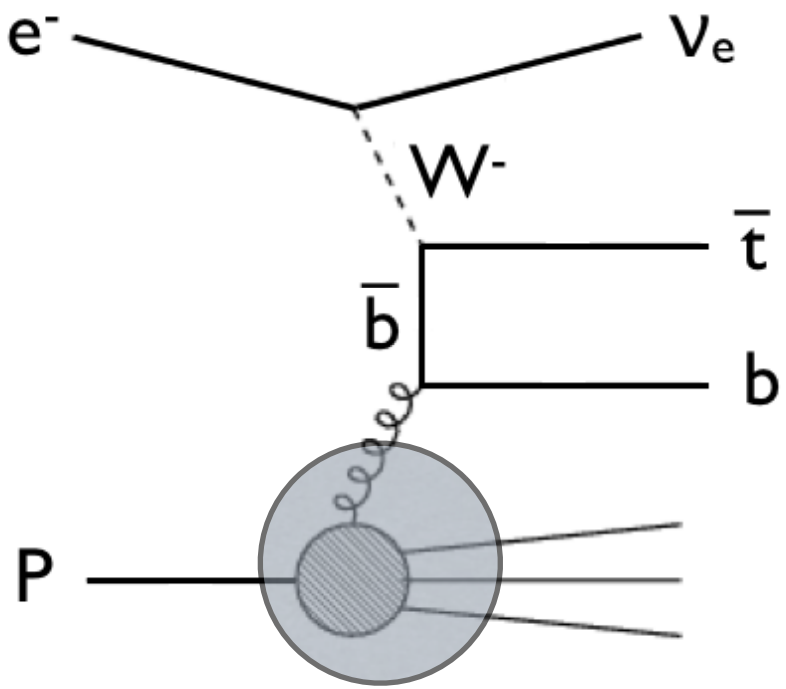
$\Delta|V_{tb}| \cdot 1000$

Δβ: luminosity uncertainty



100 fb^{-1}: $\Delta|V_{tb}|$=0.005

Gluon Parton Density Function



→ **measure gluon density at high x**

Search for Anomalous Wtb Couplings

= 1 in SM

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$

$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

Search for Anomalous Wtb Couplings

= 1 in SM

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$

$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

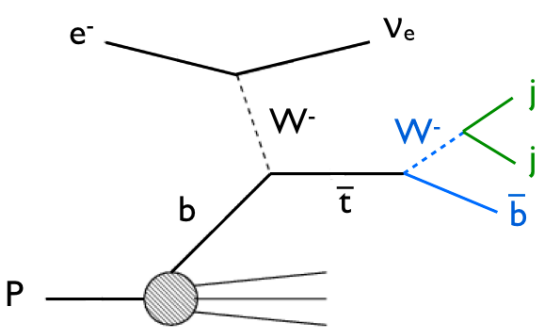
Search for Anomalous Wtb Couplings

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$

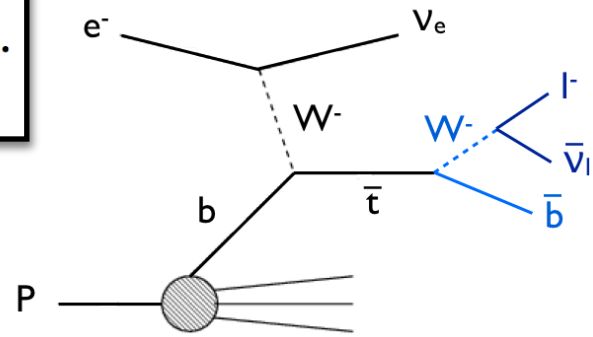
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

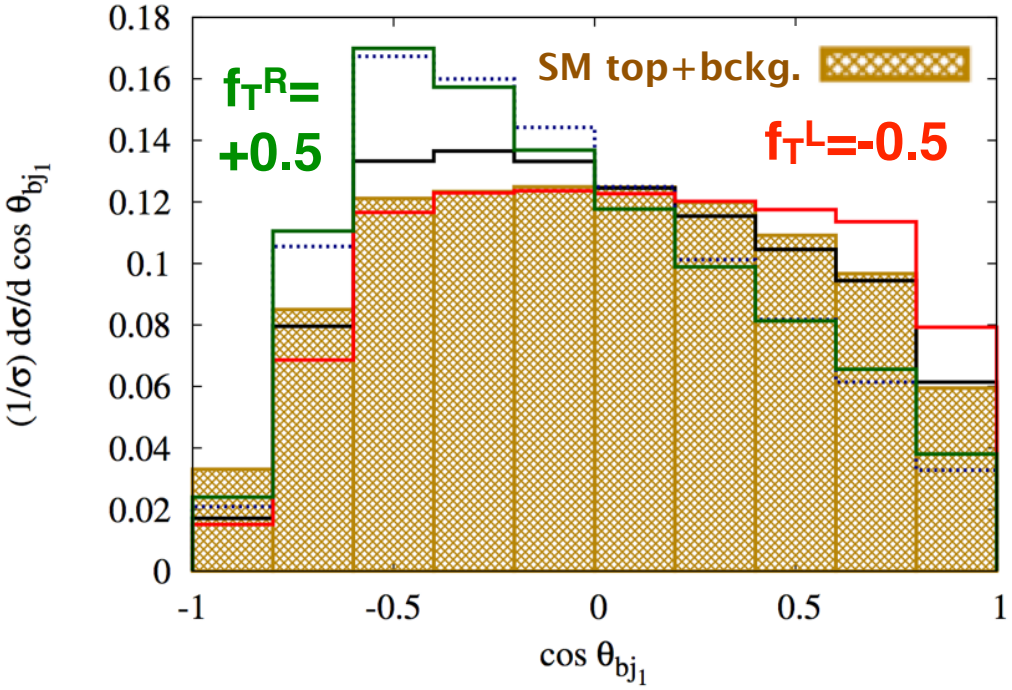
= 1 in SM

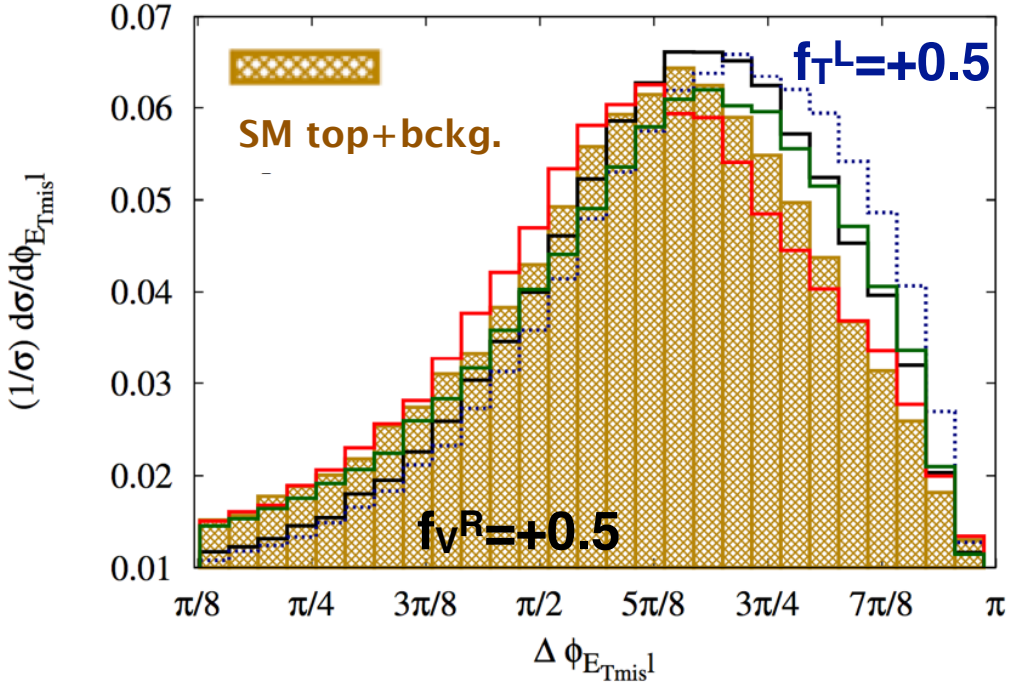
Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688



$L_{int} = 100\ fb^{-1}$



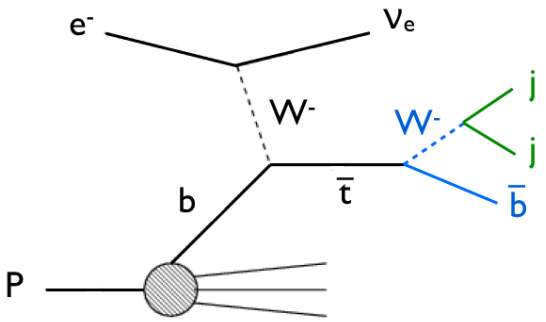




+ other variables sensitive on W helicity

Search for Anomalous Wtb Couplings

= 1 in SM



$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$

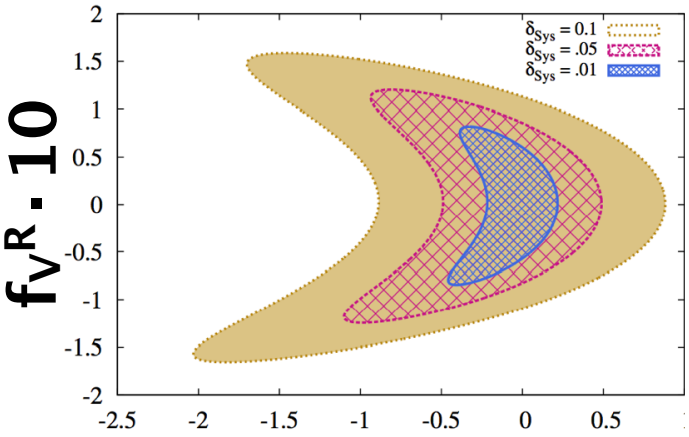
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688

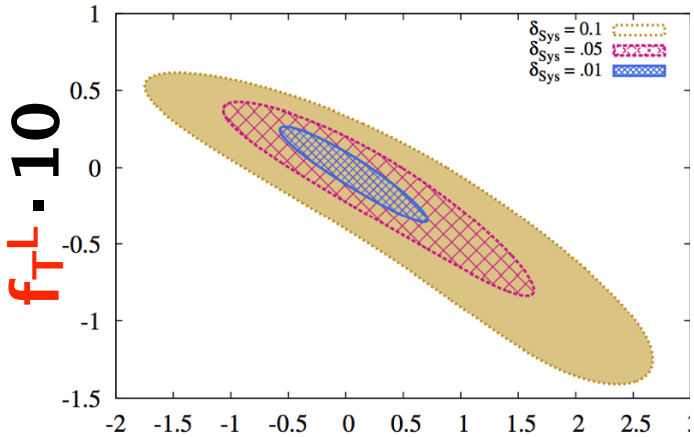
68% C.L.

property	precision
f_V^L	0.001–0.01
f_V^R, f_T^L, f_T^R	0.01–0.1

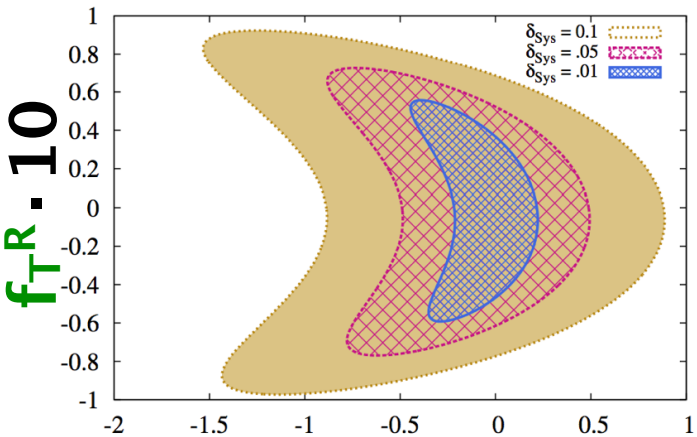
syst. error



syst. error



syst. error



Search for Anomalous Wtb Couplings

= 1 in SM

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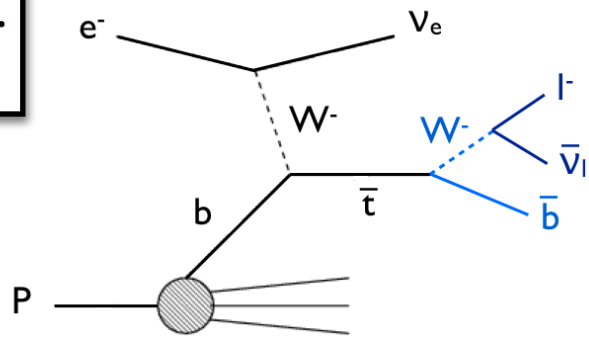
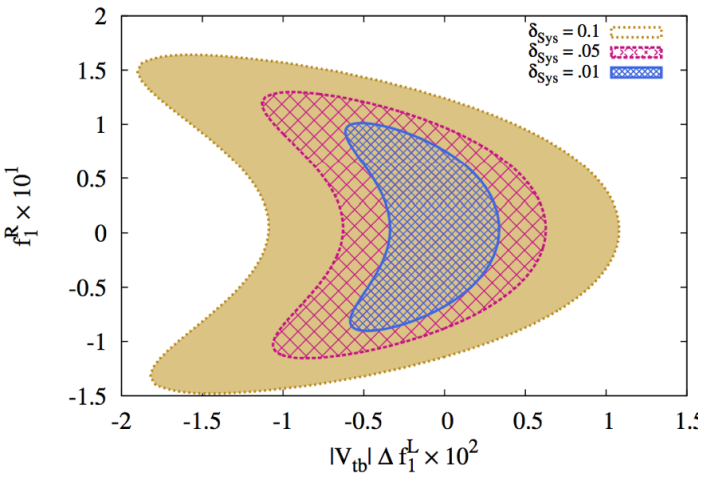
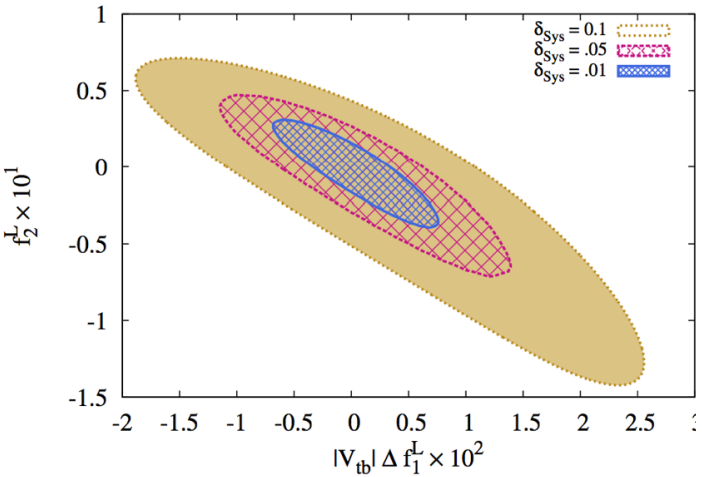
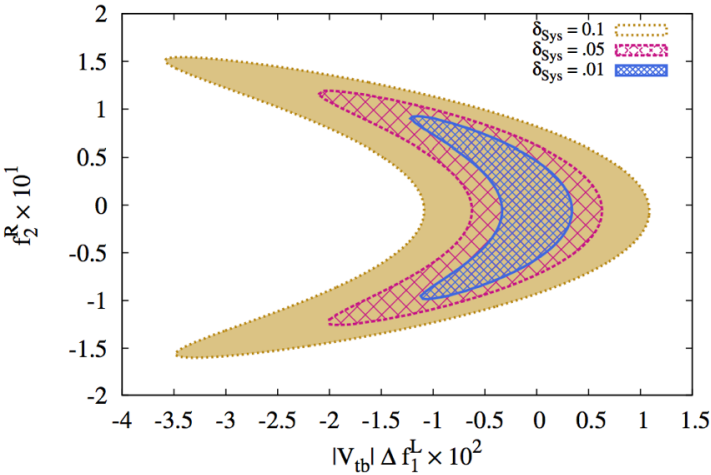
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

68% C.L.









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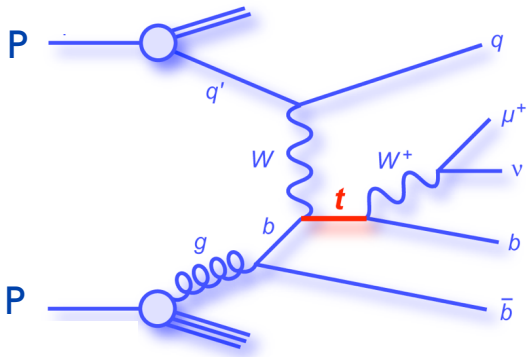
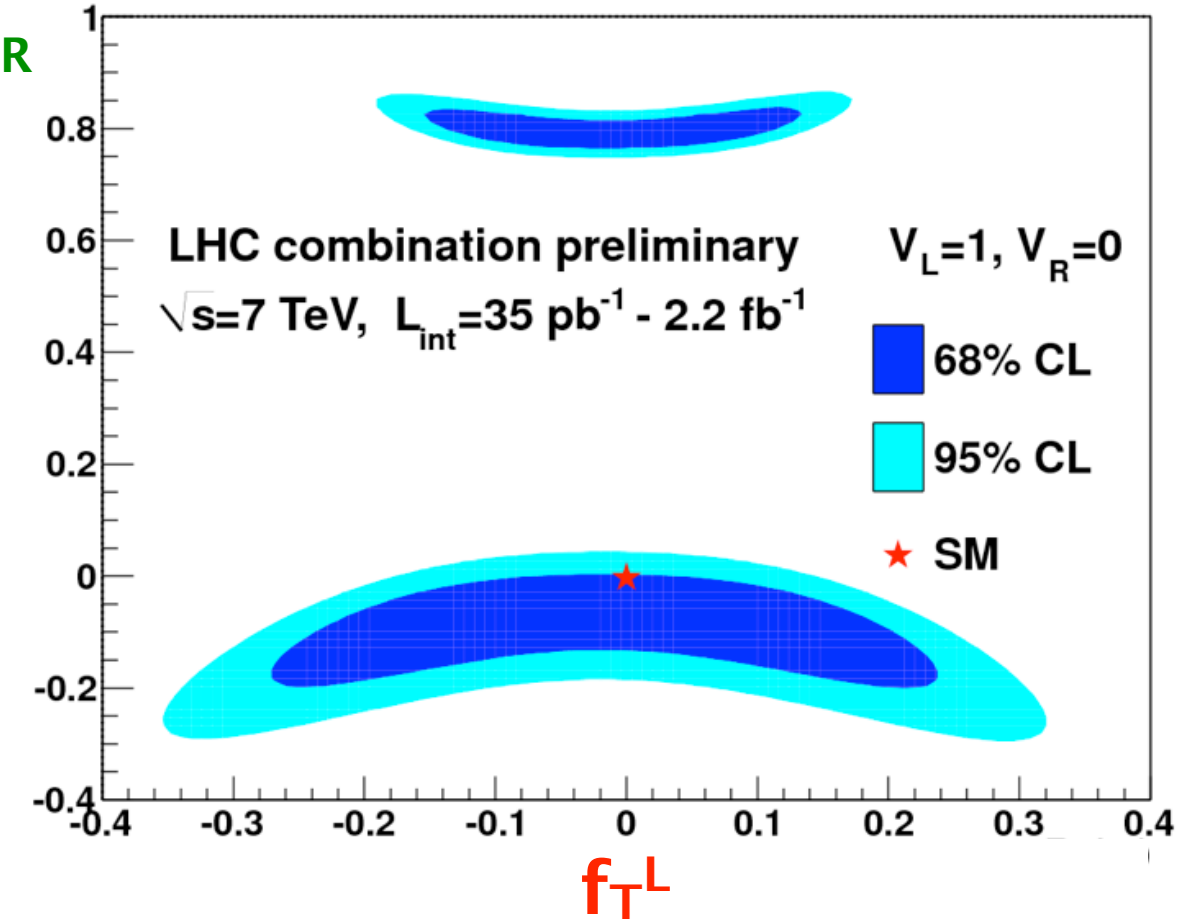
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$



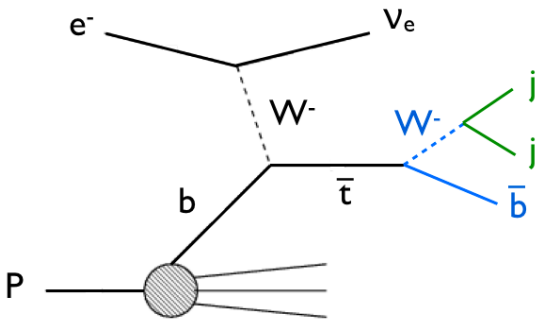


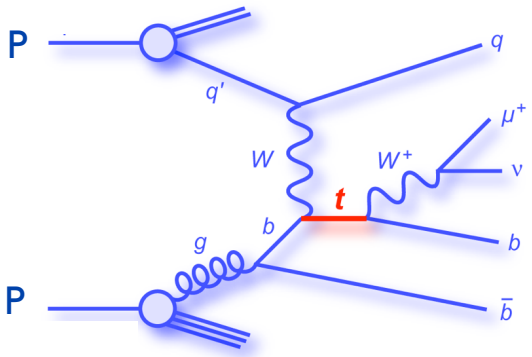
Search for Anomalous Wtb Couplings

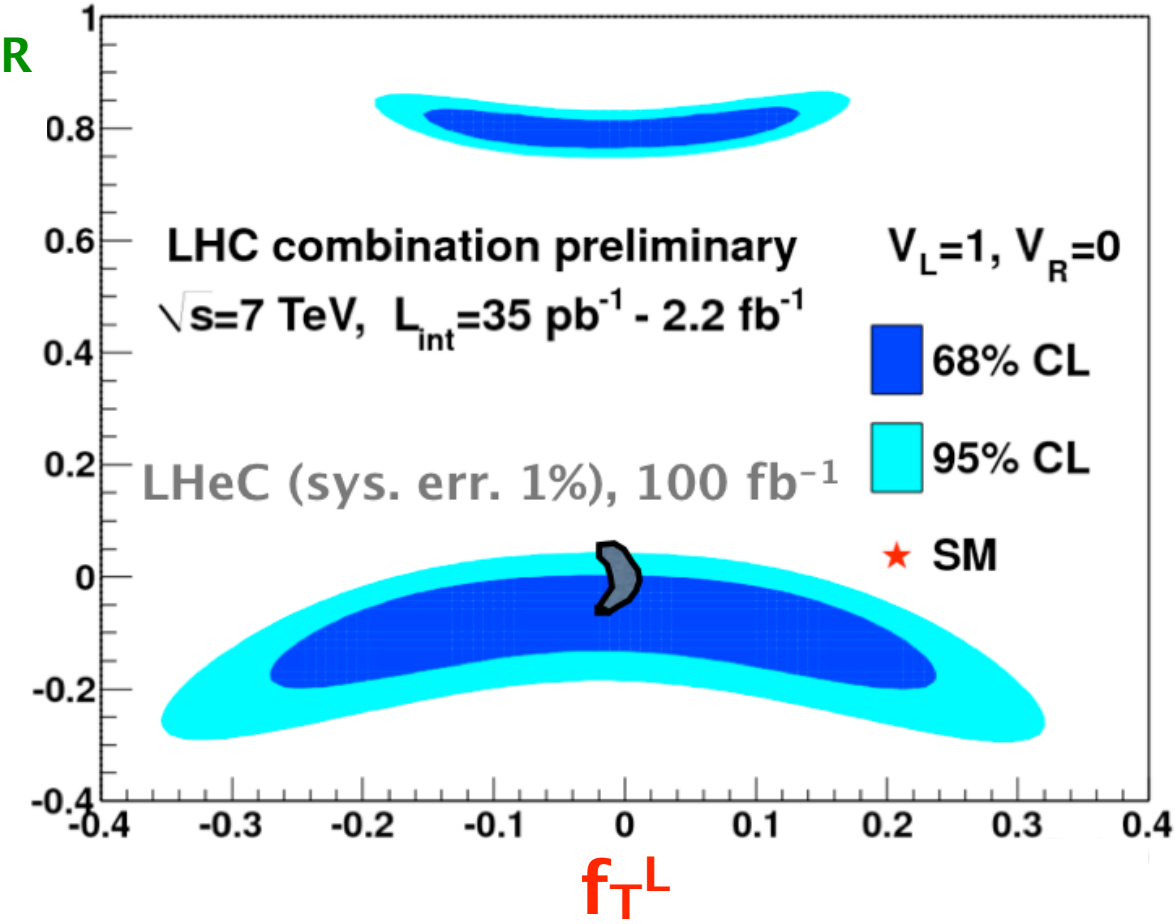
= 1 in SM

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$

$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$





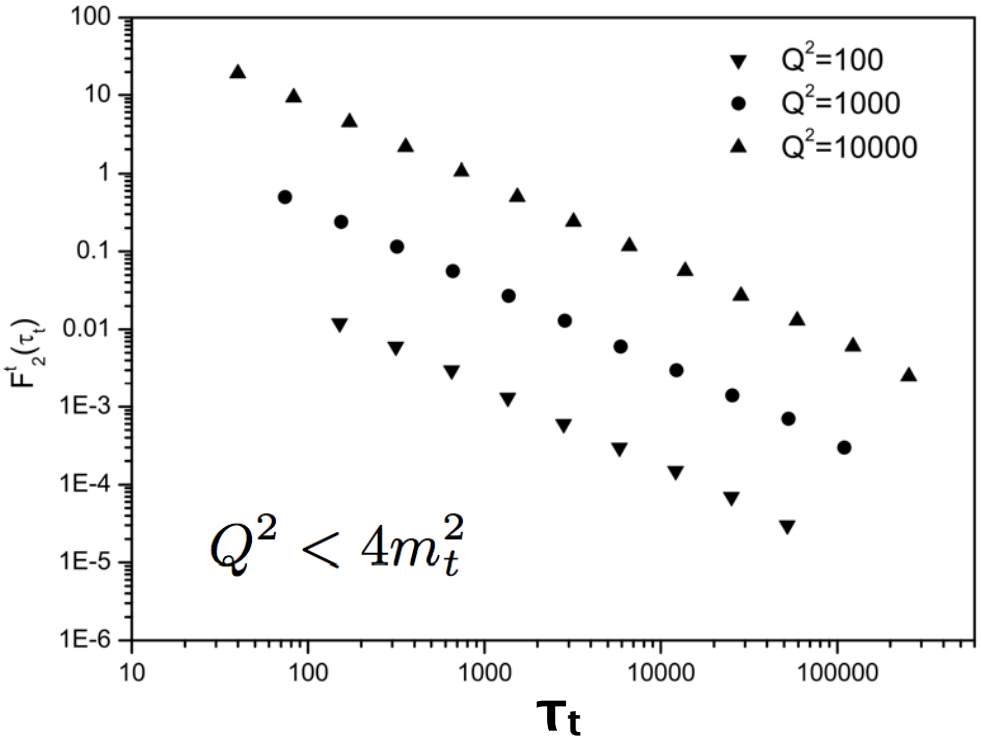


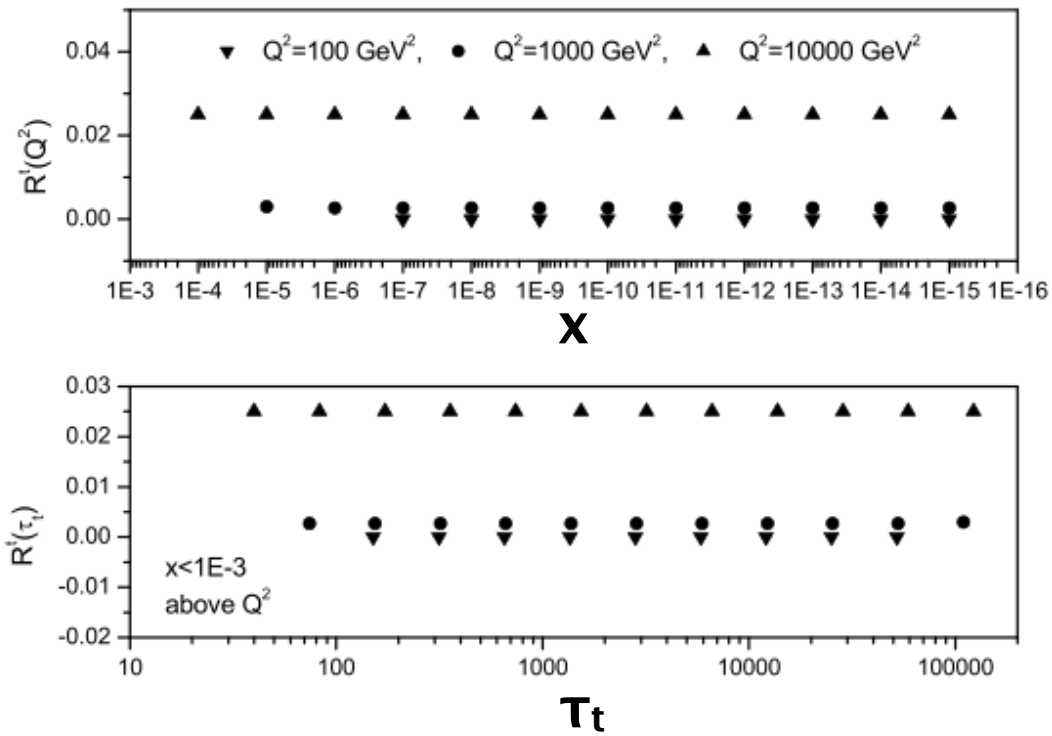
Top Quark Structure Function

Boroun, Phys. Lett. B744, 142 (2015)

$$\tilde{\sigma}^{t\bar{t}}(\tau_t) \rightarrow F_2^t(\tau_t)[1 - R^t(\tau_t)]$$

variable flavour number scheme for top quark



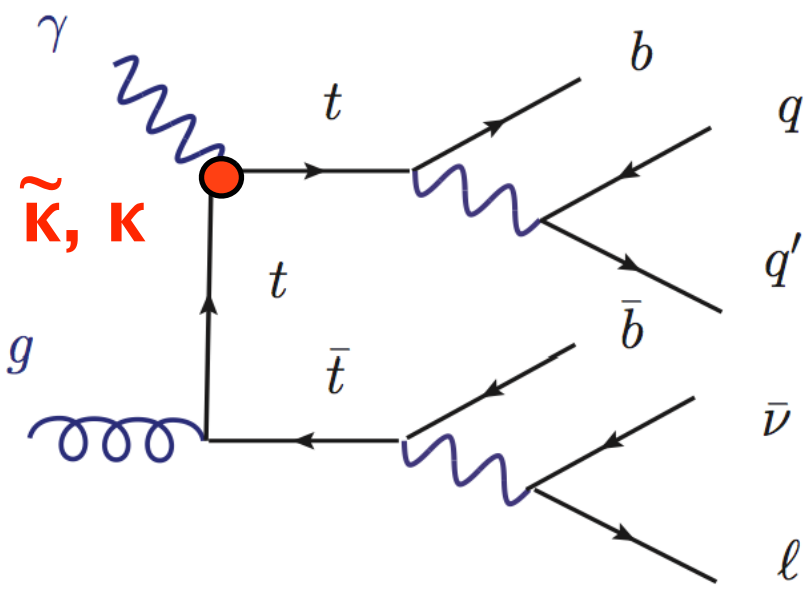


→ approximately: $1/\tau_t$

→ independent of x and τ_t

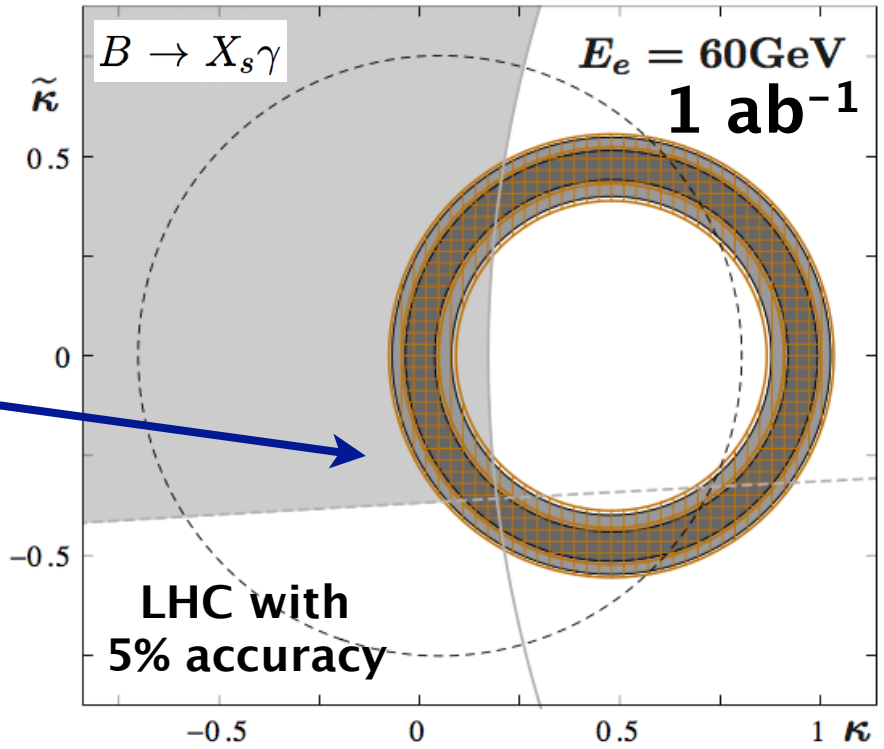
→ longitudinal top structure function component could be good to probe top quark density in proton at $Q^2 \simeq 4m_t^2$

Search for Anomalous $t\bar{t}\gamma$ Couplings



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

electric dipole moment: $\tilde{\kappa}$



magnetic dipole moment: κ

LHeC

8% and 16% accuracy
10% 18%
→ systematically limited

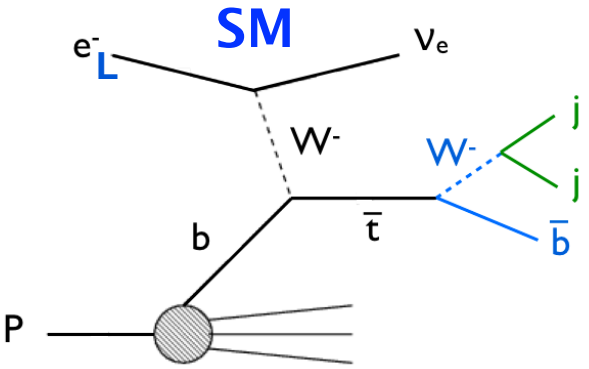
27% accuracy
(4.59fb^{-1}, 7 TeV)

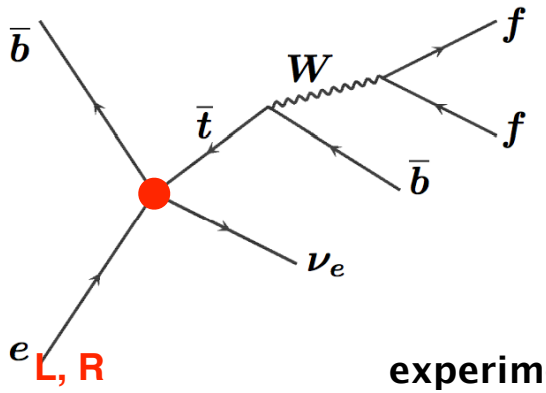
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

Top Quark Dimension 6 Operators

$$\Lambda^2 \mathcal{L}_{4f} = C_1(\bar{\nu}_L \gamma^\mu t_L \bar{b}_L \gamma_\mu e_L + h.c.) + [C_2 \bar{\nu}_L e_R \bar{b}_R t_L + C_3 \bar{b}_L e_R \bar{\nu}_L t_R + C_4 \bar{\nu}_L e_R \bar{b}_L t_R + h.c.]$$

Λ=1TeV





property	precision
C_1	0.50–0.85
C_2^r	2.2–5.0
C_3^r	1.4–2.9
C_4^r	2.2–4.9

Sarmiento-Alvarado, Bouzas, Larios, arXiv:1412.6679

experimental error

68% C.L.

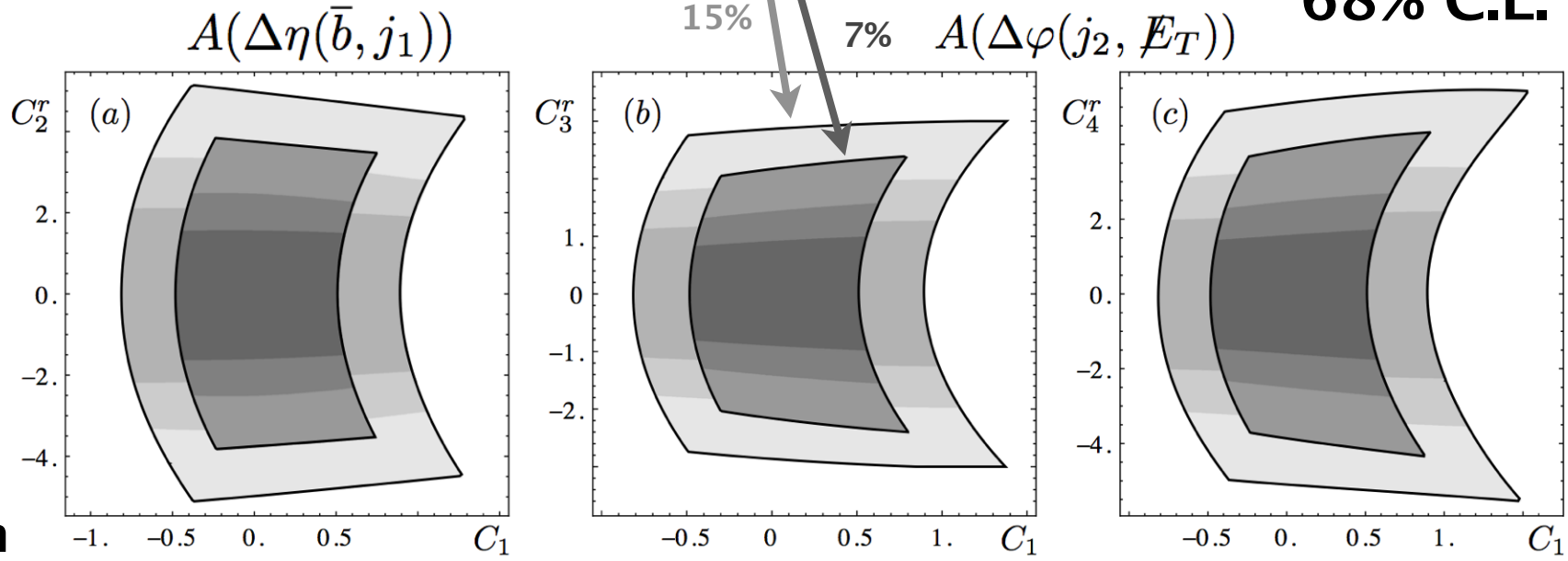
15%

7%

$\mathcal{P}_e = 0$

$\mathcal{P}_e = 0.4$

$\mathcal{P}_e = 0.7$



cross section

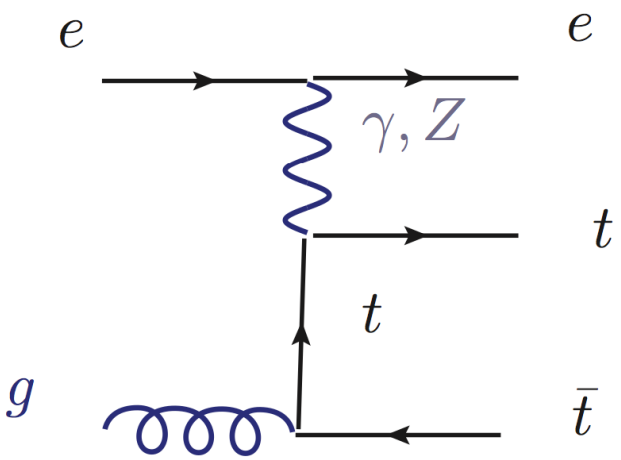
NC Top Quark Production

Bouzas, Larios,
Physical Review D 88, 094007 (2013)

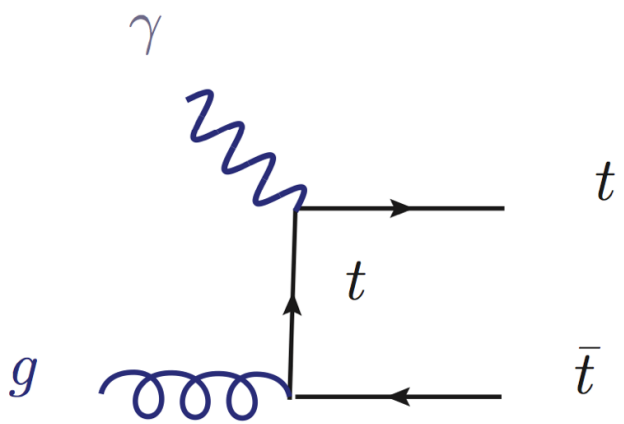
top pair production

single top production

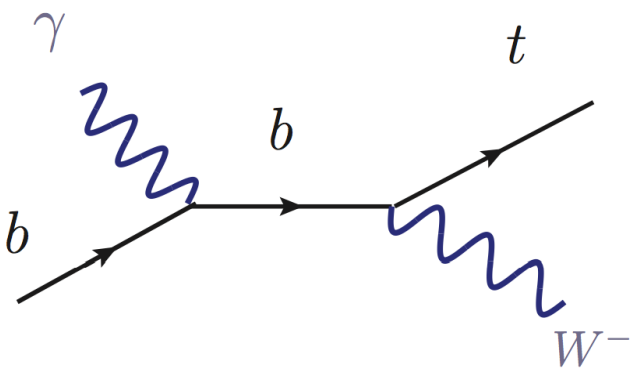
DIS



photoproduction



photoproduction



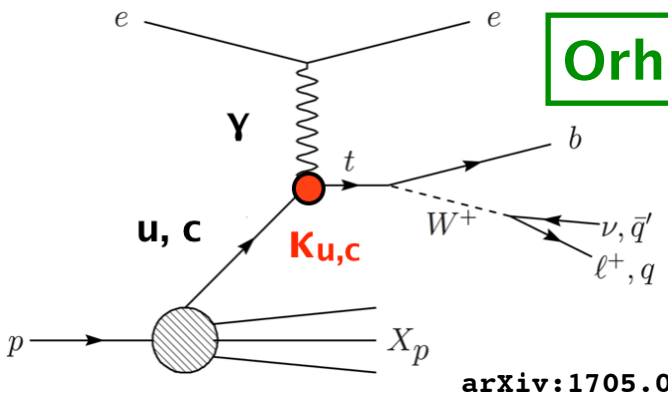
e-beam 60 GeV, 1000 fb^{-1}:

0.023 pb	0.70 pb	0.031 pb
$N_{t\bar{t}}$=23,000	$N_{t\bar{t}}$=700,000	N_t=31,000

FCNC tuγ and tuH Couplings

T. Cakir
Yilmaz
Denizl
Seno
Karadeniz
O. Cakir

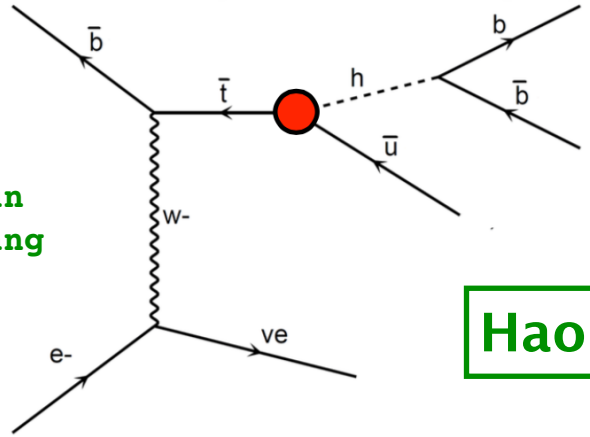
Orhan Cakir



arXiv:1705.05419

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

Sun
Wang

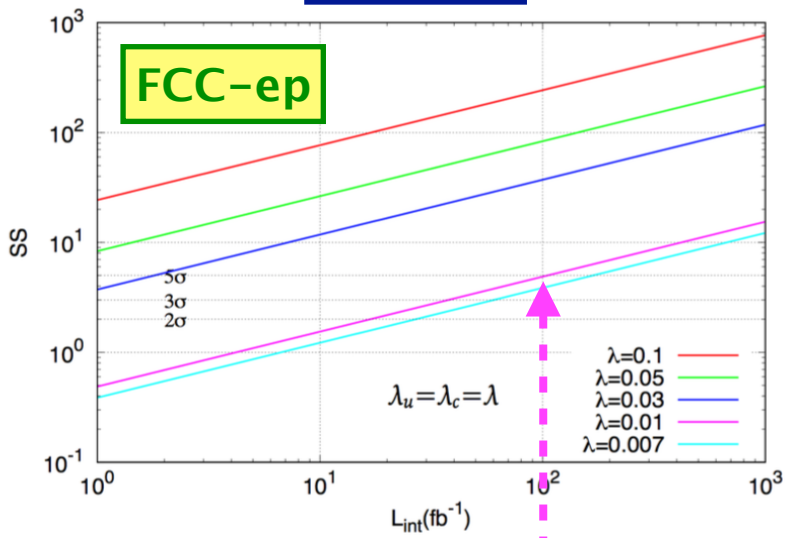


Hao Sun

$$\mathcal{L} = \kappa_{tuh}\bar{t}uh + \kappa_{tch}\bar{t}ch + \text{h.c.}$$

DELPHES

FCC-ep

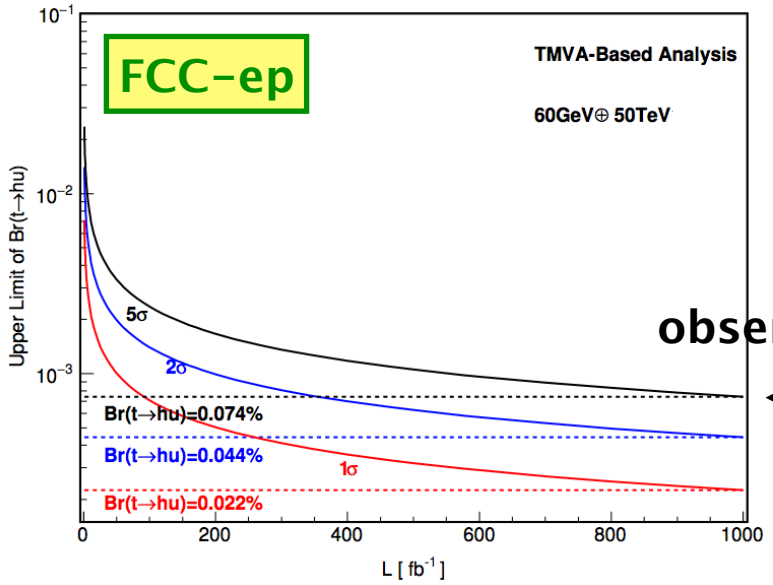


observation

Ee=60 GeV

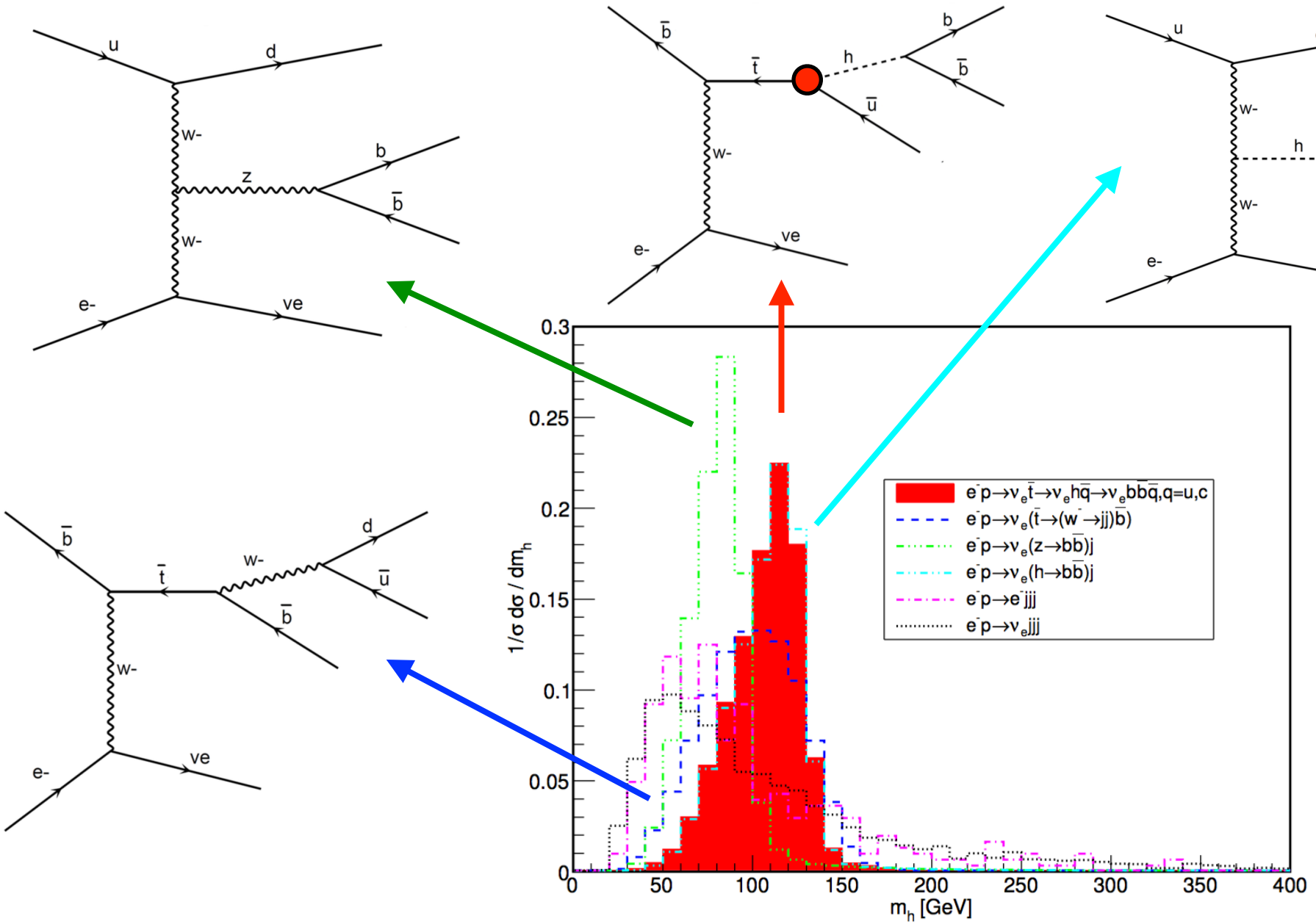
parametrisation

FCC-ep

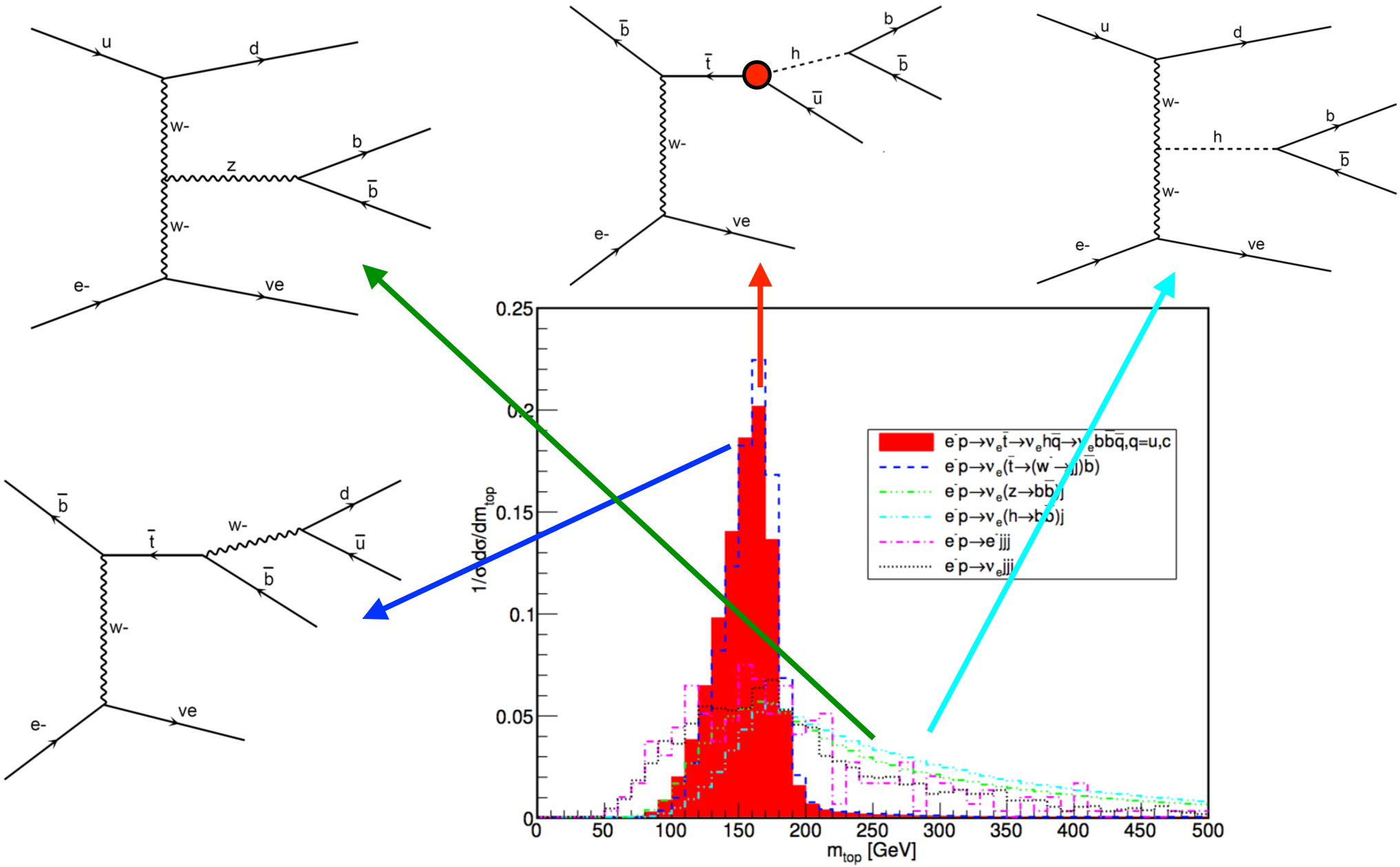


observation

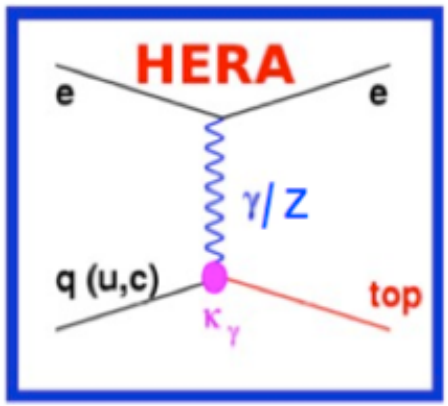
Reconstructed Higgs mass

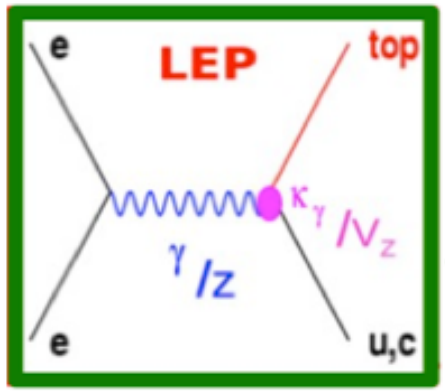


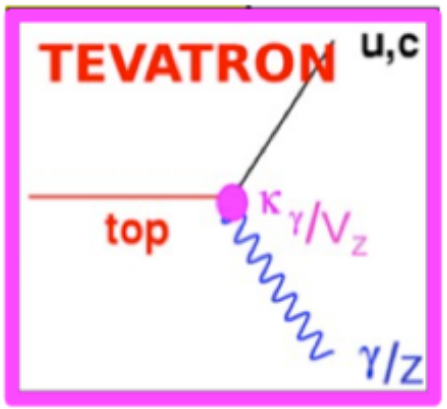
Reconstructed top quark mass

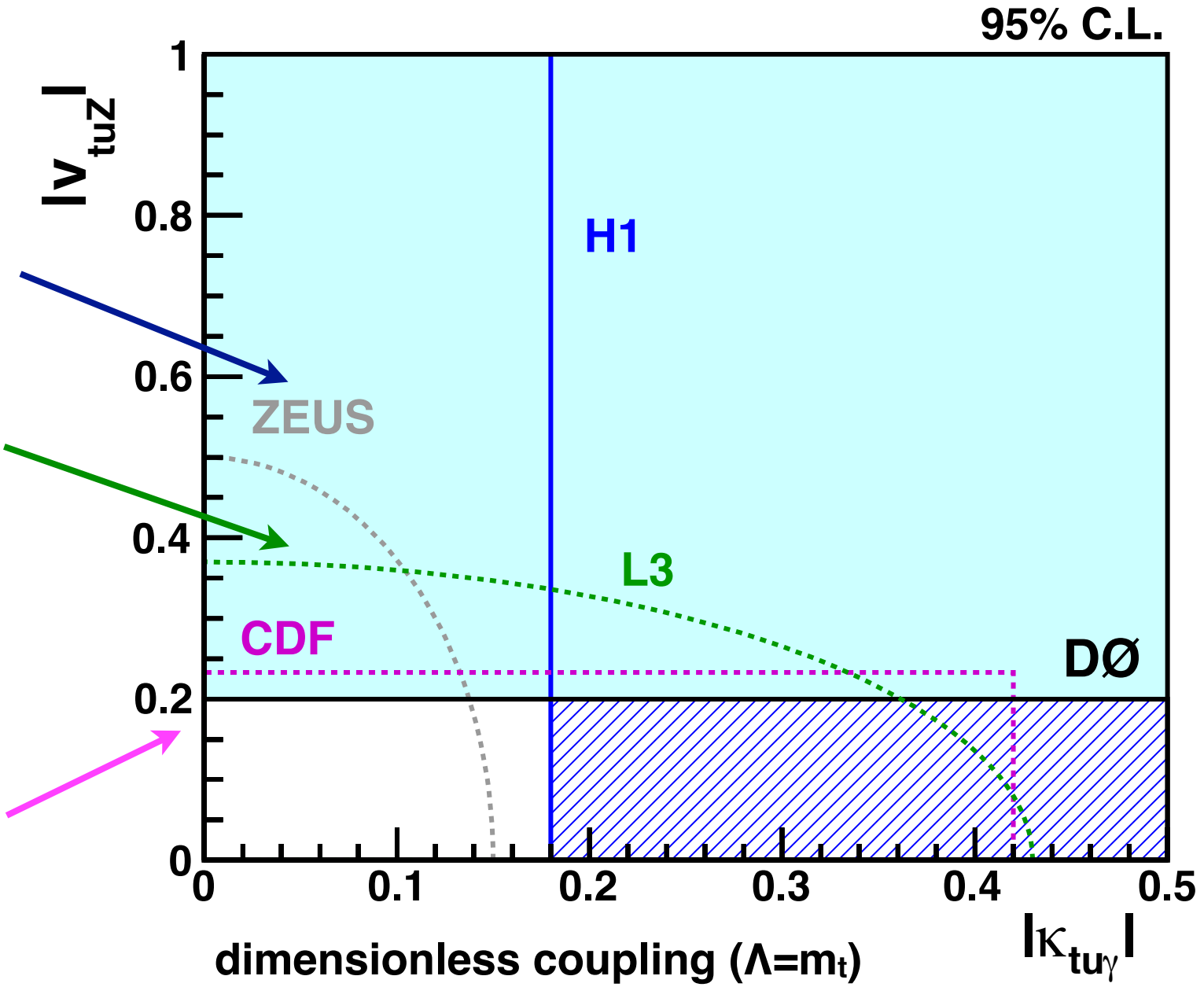


FCNC Top Couplings at Colliders



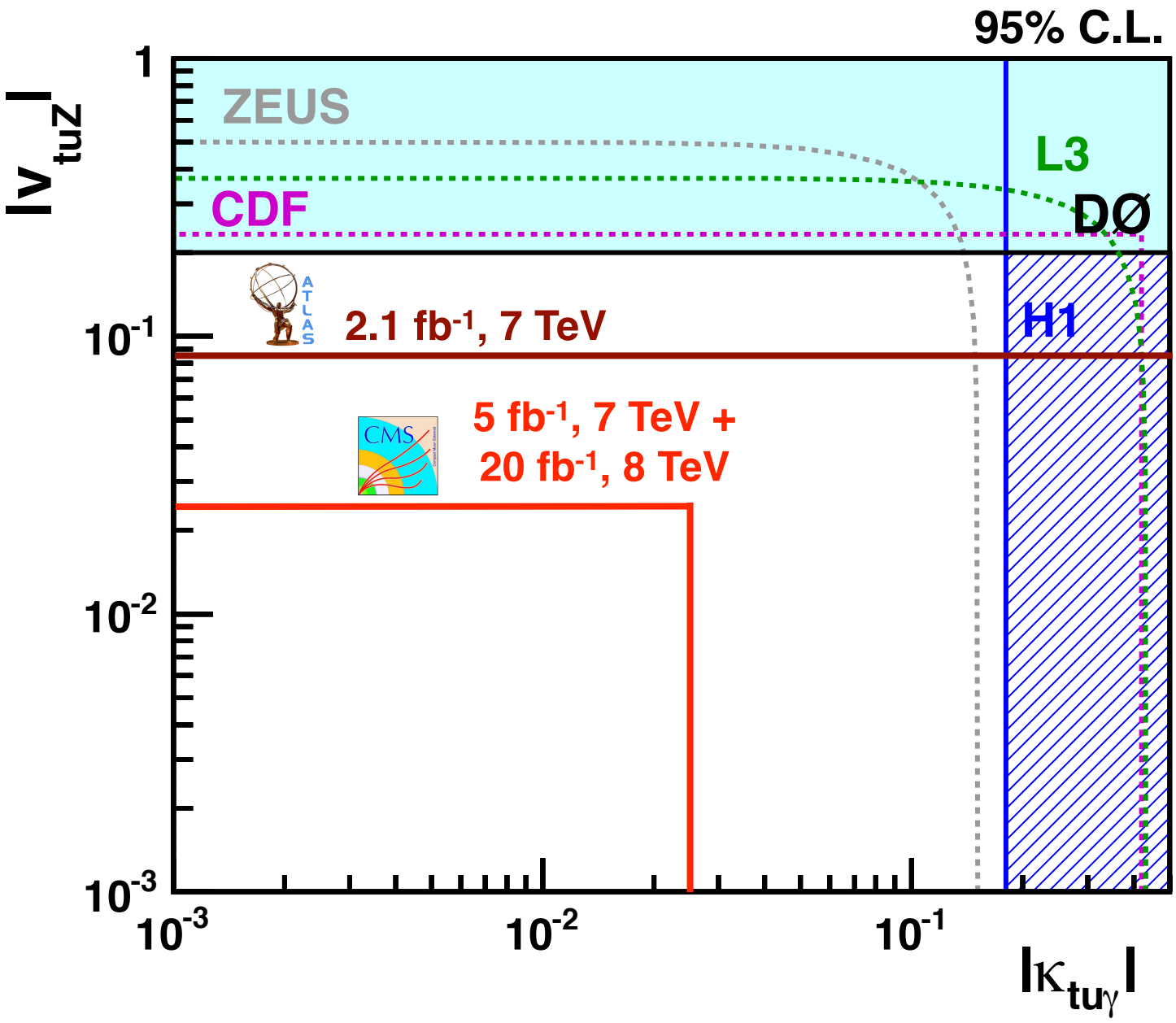


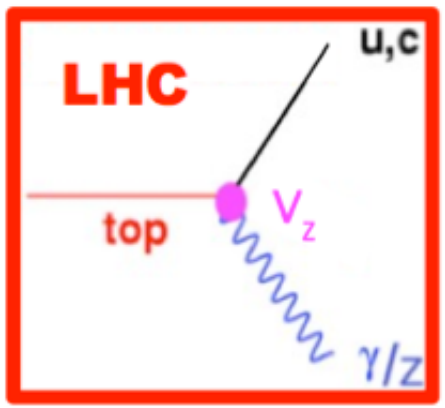




FCNC Top Couplings at Colliders

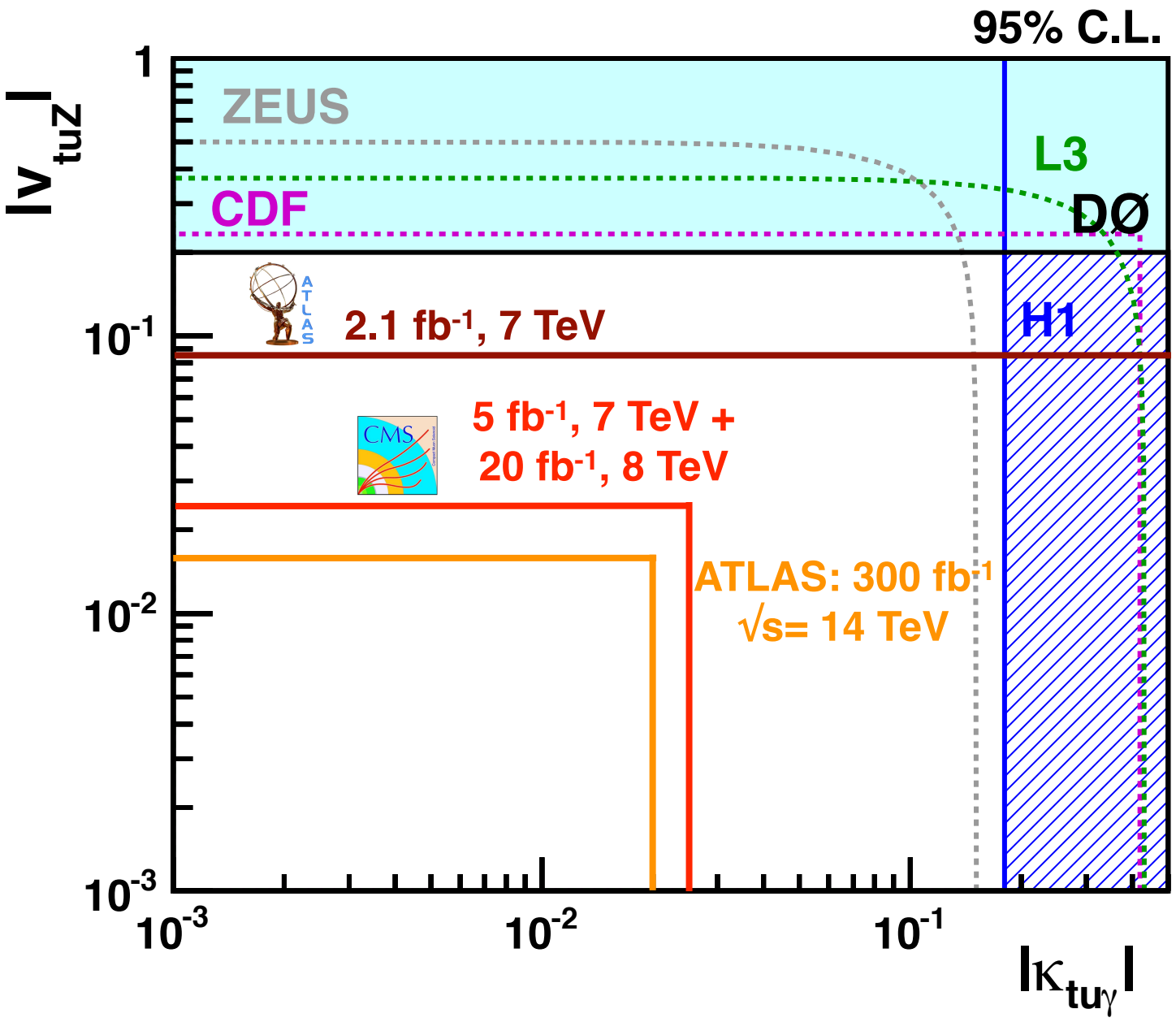
Top Quark Working Group Collaboration, arXiv:1311.2028 [hep-ph]

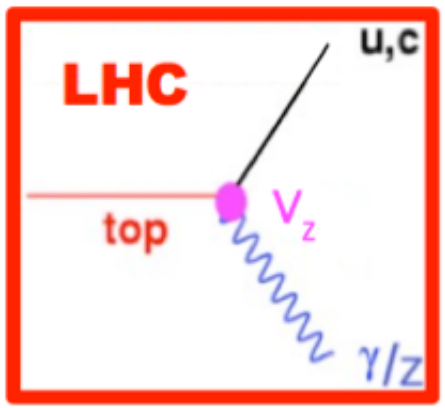




FCNC Top Couplings at Colliders

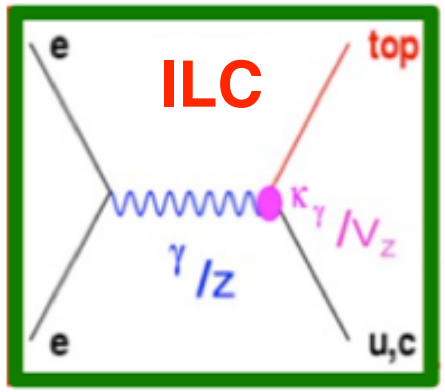
Top Quark Working Group Collaboration, arXiv:1311.2028 [hep-ph]

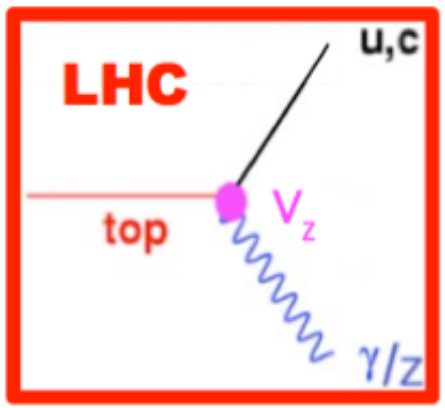


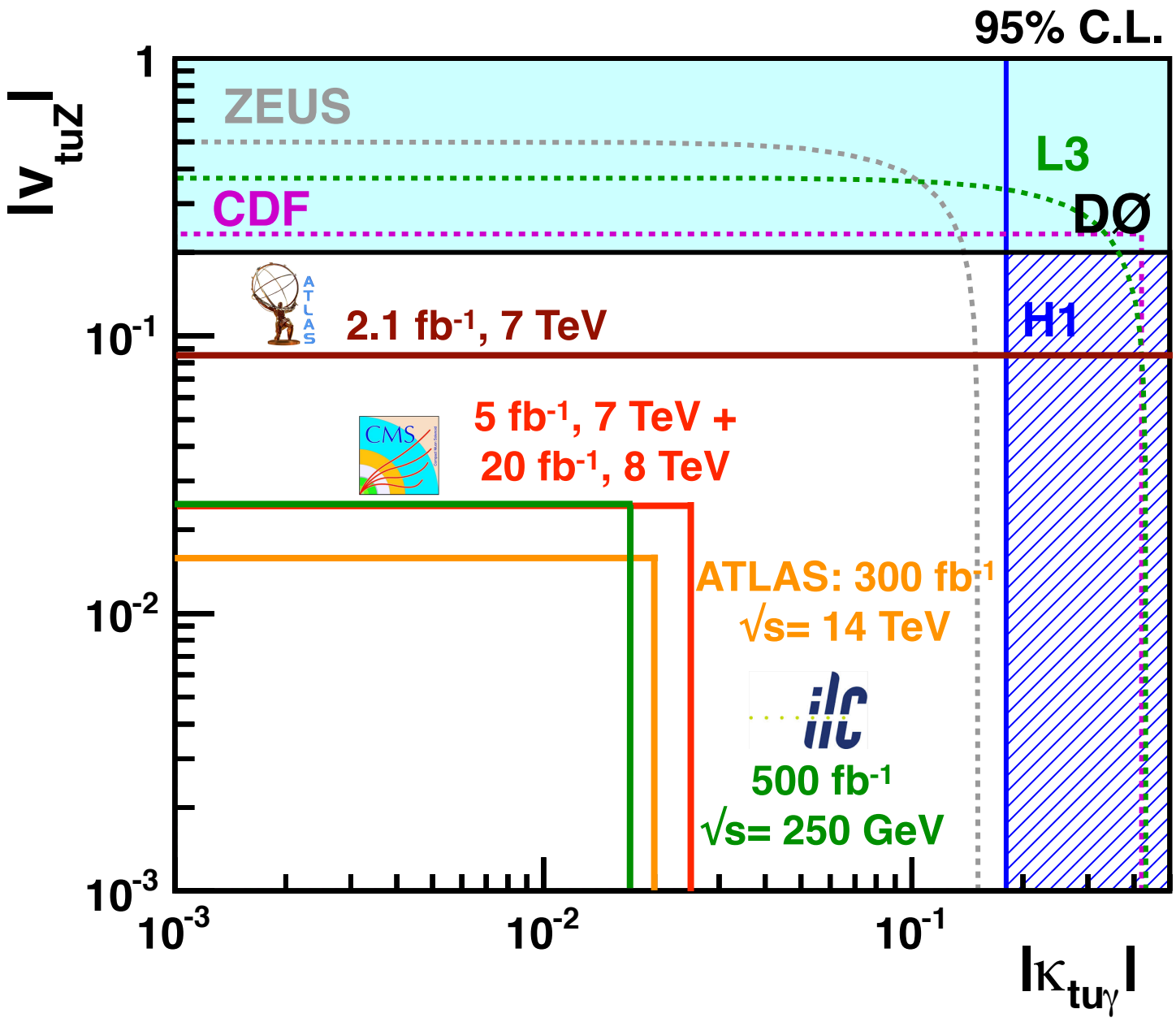


FCNC Top Couplings at Colliders

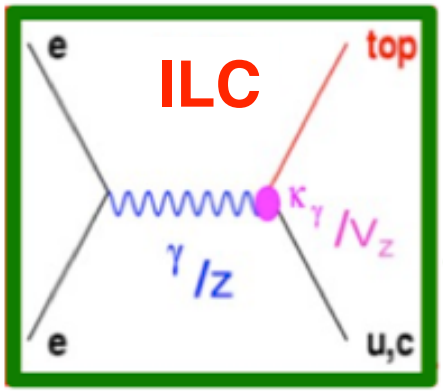
Top Quark Working Group Collaboration, arXiv:1311.2028 [hep-ph]

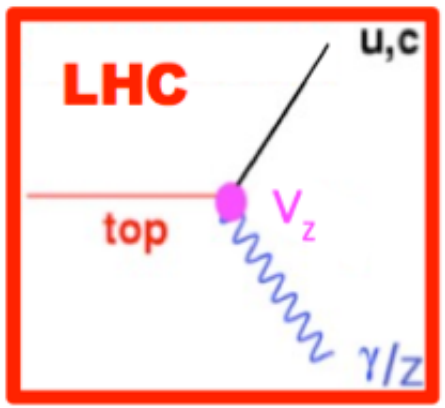


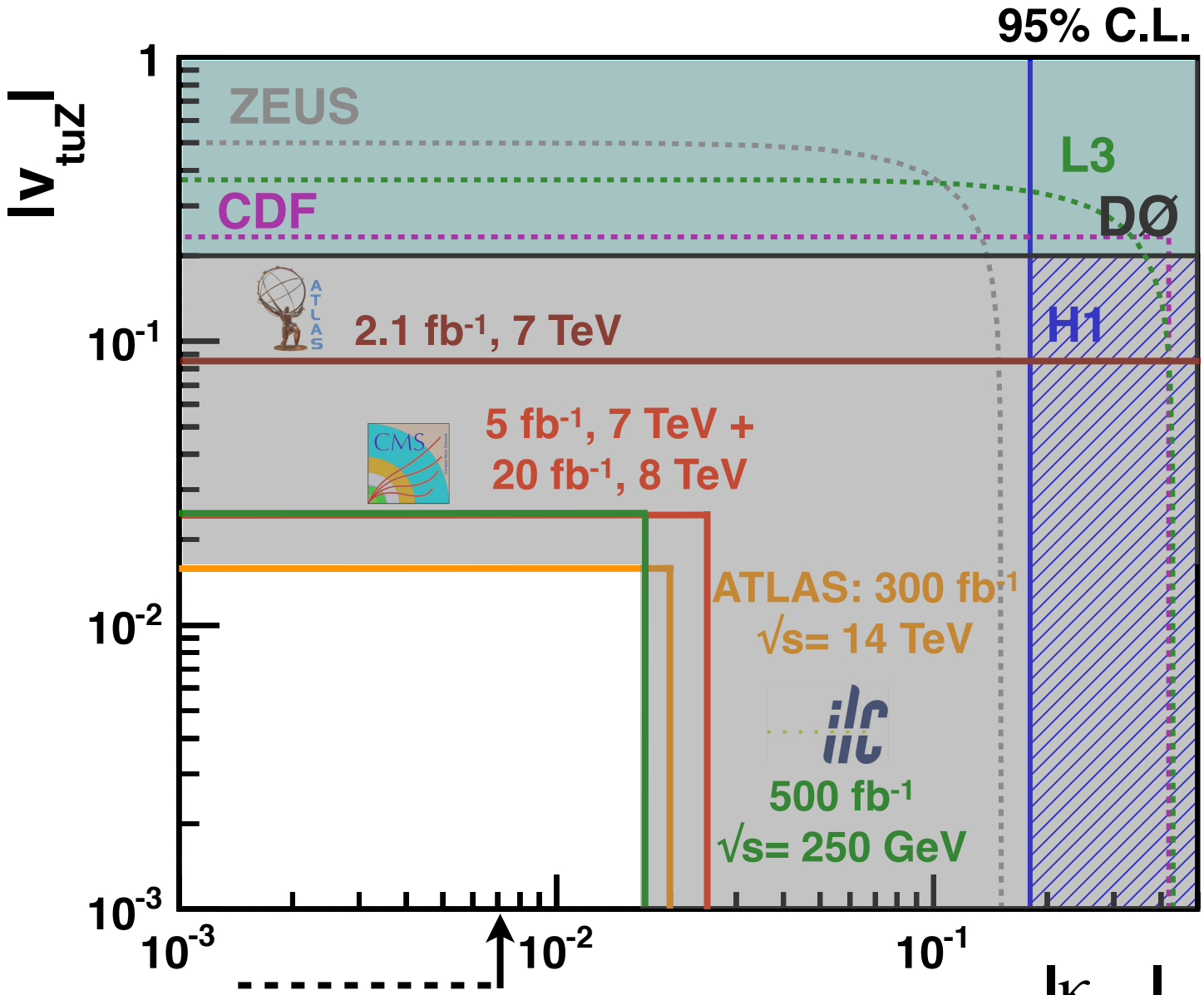




FCNC Top Couplings at Colliders

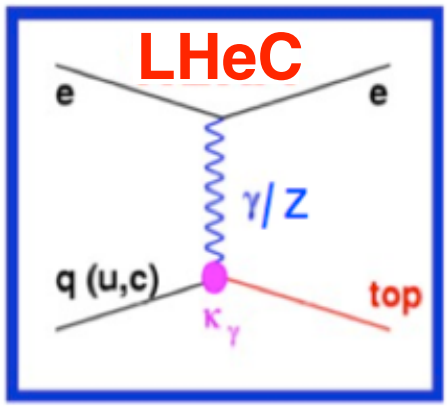


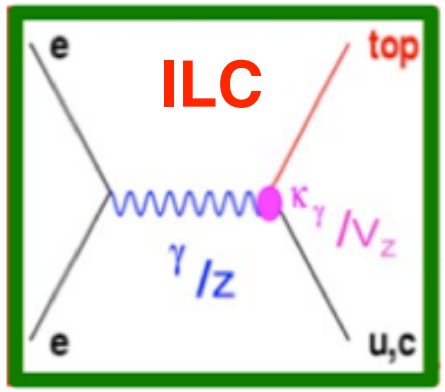


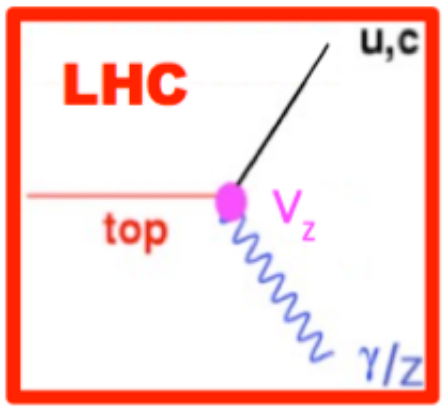


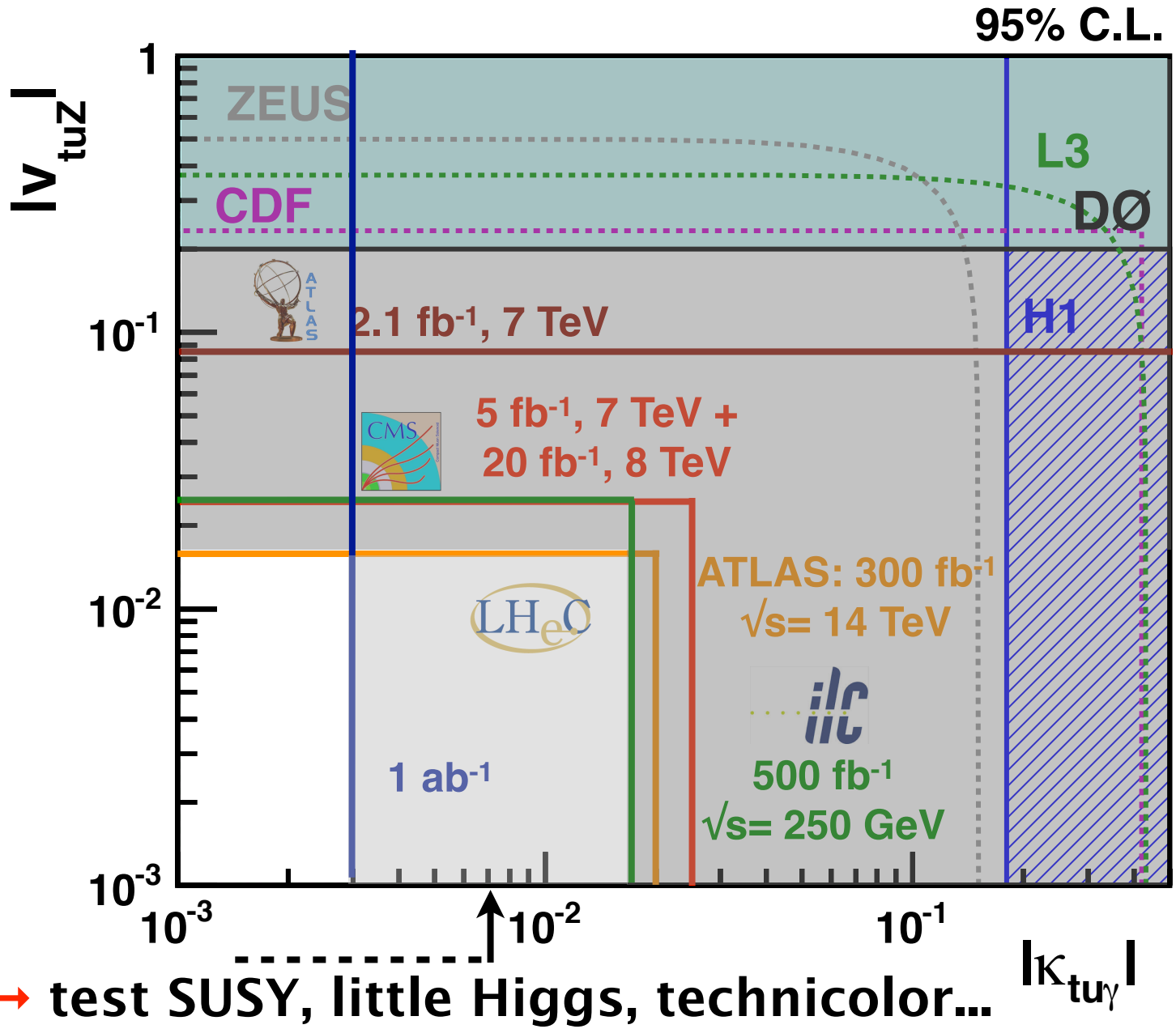
→ test SUSY, little Higgs, technicolor...

FCNC Top Couplings at Colliders



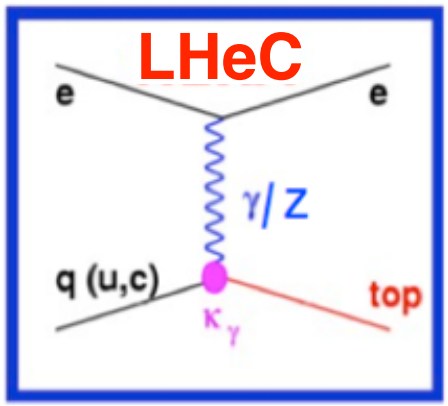


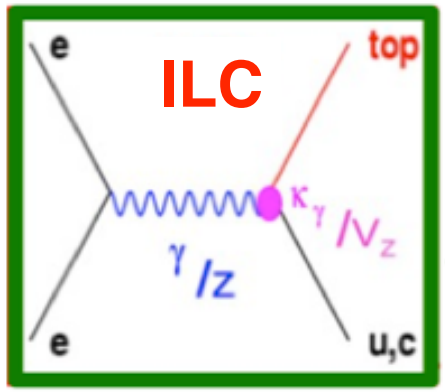


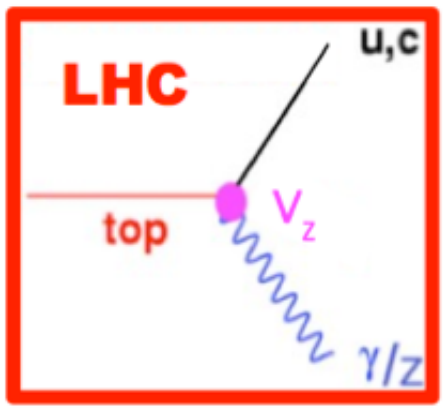


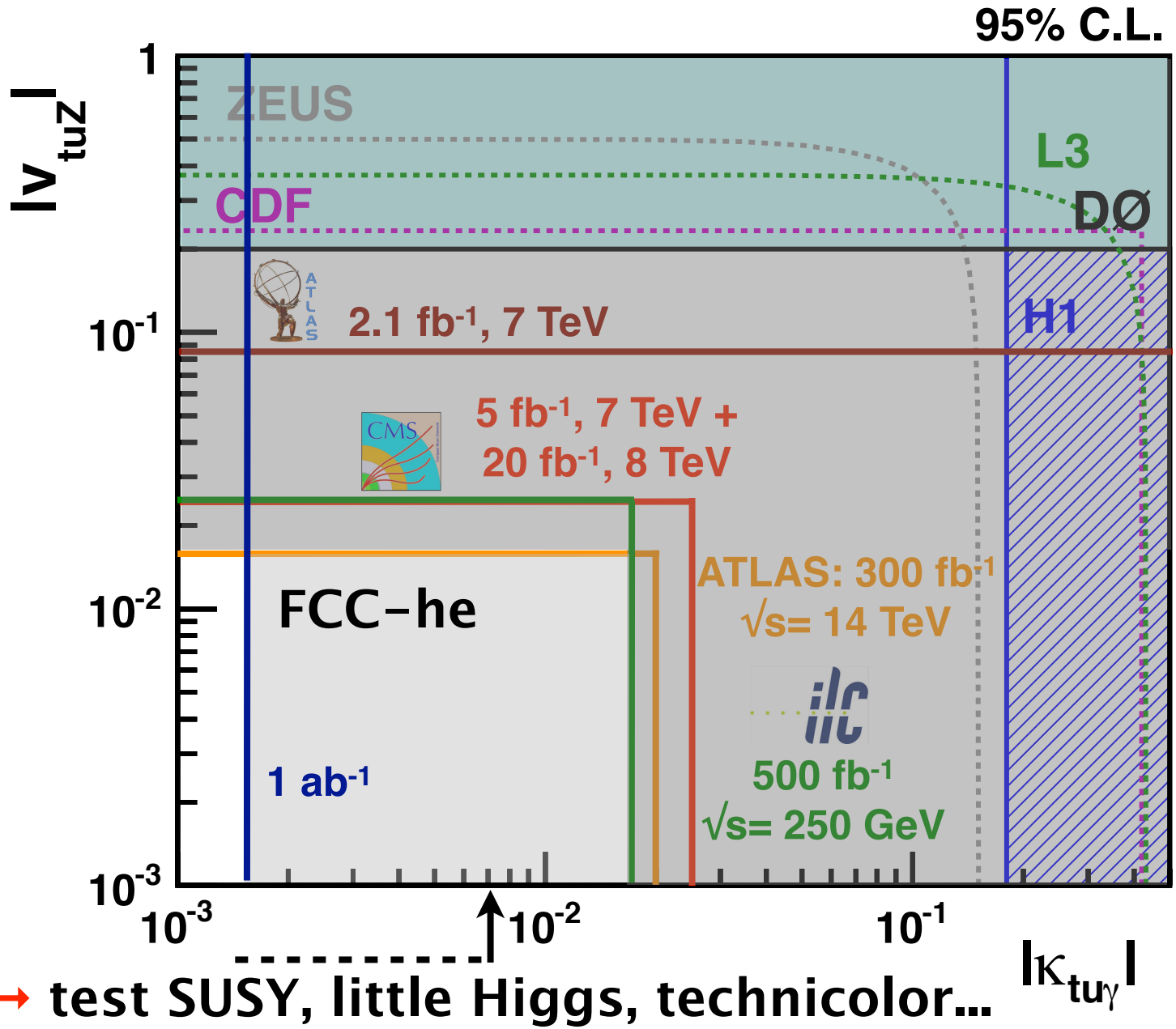
→ test SUSY, little Higgs, technicolor...

FCNC Top Couplings at Colliders







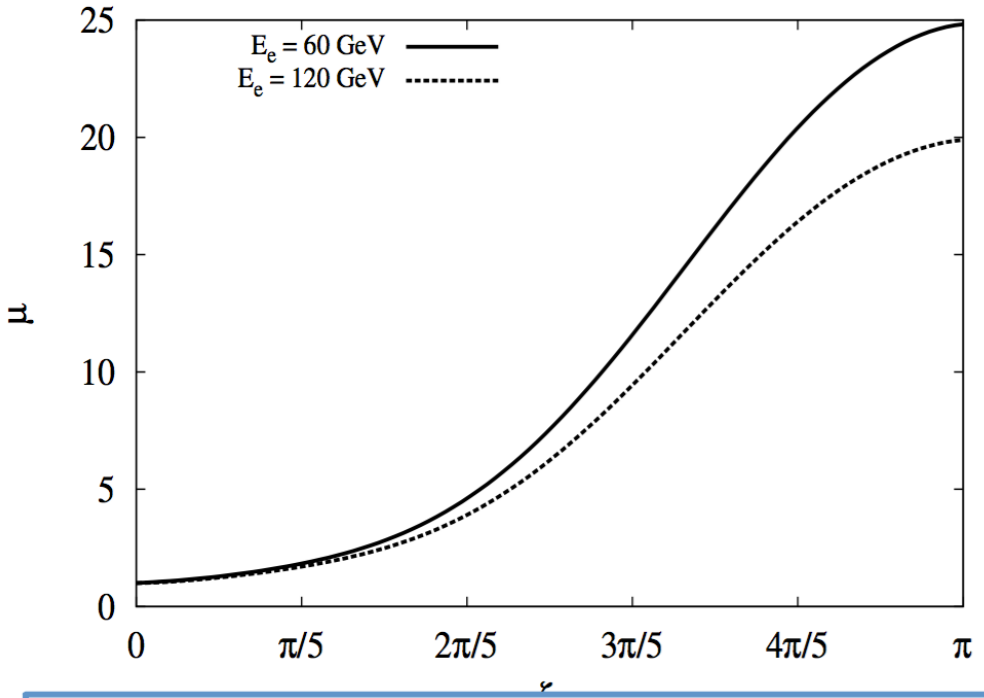


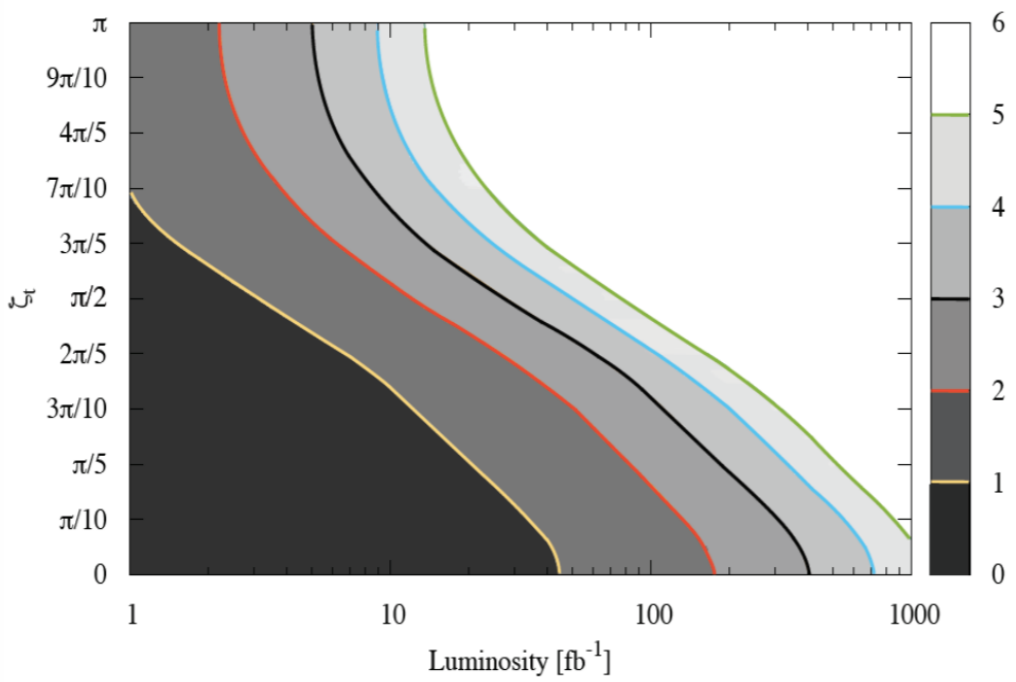
→ test SUSY, little Higgs, technicolor...

Observation/Exclusion Contours

LHeC

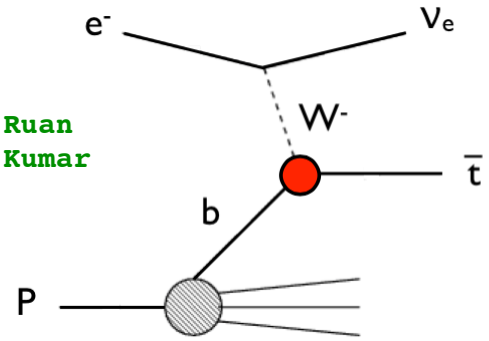
$\zeta_t=0$ or $\zeta_t=\pi$ → pure scalar state
$\zeta_t=\pi/2$ → pure pseudo scalar state
$0<\zeta_t<\pi/2$ or $\pi/2<\zeta_t<\pi$ → mixture CP-states
$\zeta_t=0$, $\kappa=1$ → SM case





Observe/Exclude non-zero phase to better than 4σ ➔ With Zero Phase: Measure coupling with 17% accuracy ➔ work ongoing on FCC-eh prospects

Top Quark SM+BSM

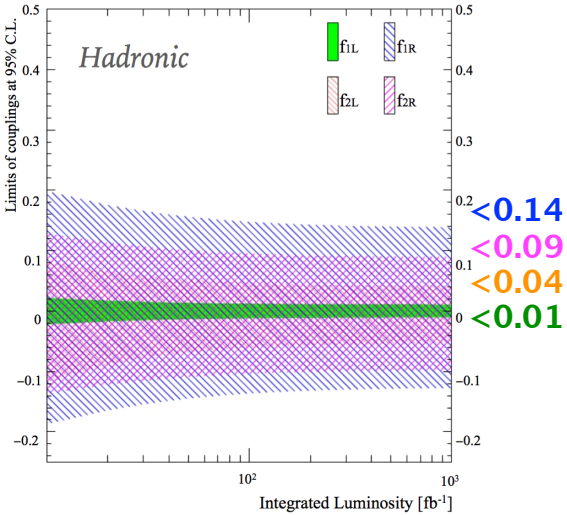


Ruan Kumar

= 1 in SM

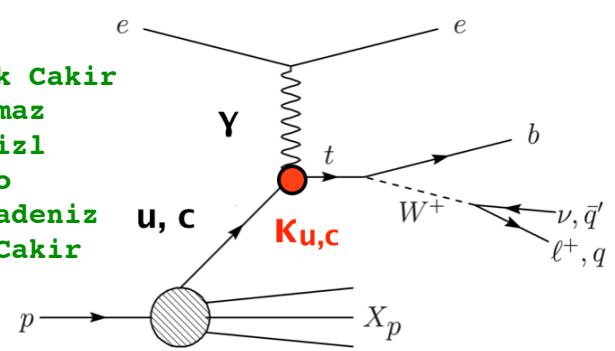
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

DELPHES **LHeC+FCC**



→ to be published

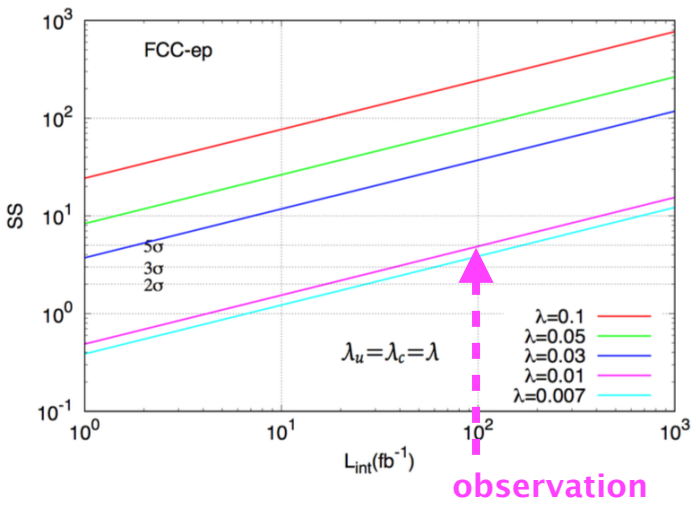
→ ask for SM cross sections



Turk Cakir
Yilmaz Denizl
Seno Karadeniz
O. Cakir

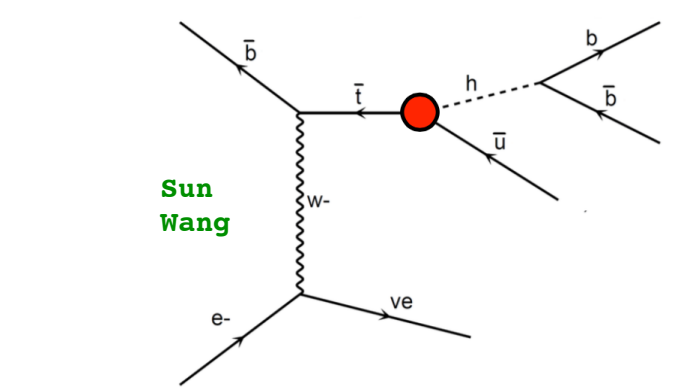
$$L = -g_e \sum_{q=u,c} Q_q \frac{\kappa_q}{\Lambda}\bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$

DELPHES **LHeC+FCC**



→ published: arXiv:1705.05419

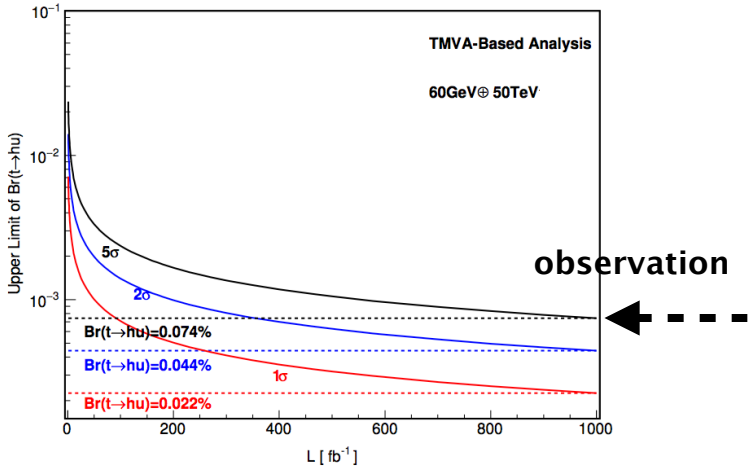
→ ask for BR(t→qγ)



Sun Wang

$$\mathcal{L} = \kappa_{tuh}\bar{t}uh + \kappa_{tch}\bar{t}ch + h.c.$$

parametrisation **LHeC+FCC**



→ published: arXiv:1602.04670

Signal and Backgrounds

LHeC

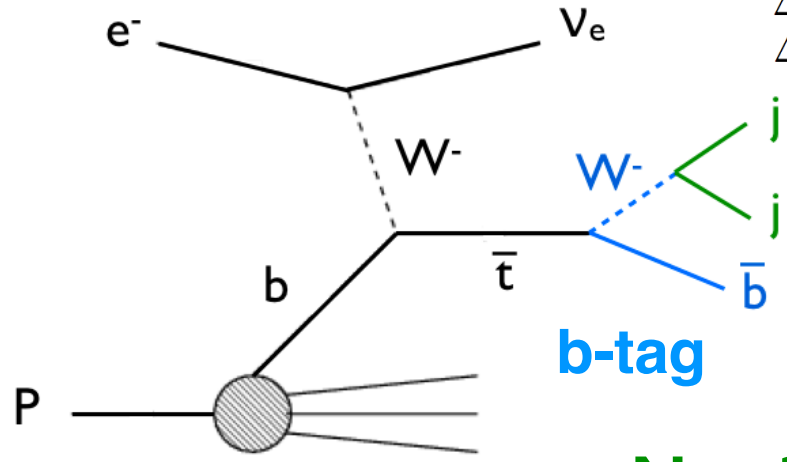
signal

Dutta, Goyal, Kumar, Mellado, Eur. Phys. J. C75 (2015) no.12, 577

$\not{E}_T \geq 25\,\text{GeV}$

$\Delta\Phi_{\not{E},j} \geq 0.4$

$\Delta\Phi_{\not{E},b} \geq 0.4$



$|m_{j_1 j_2} - m_W| \leq 22\,\text{GeV}$

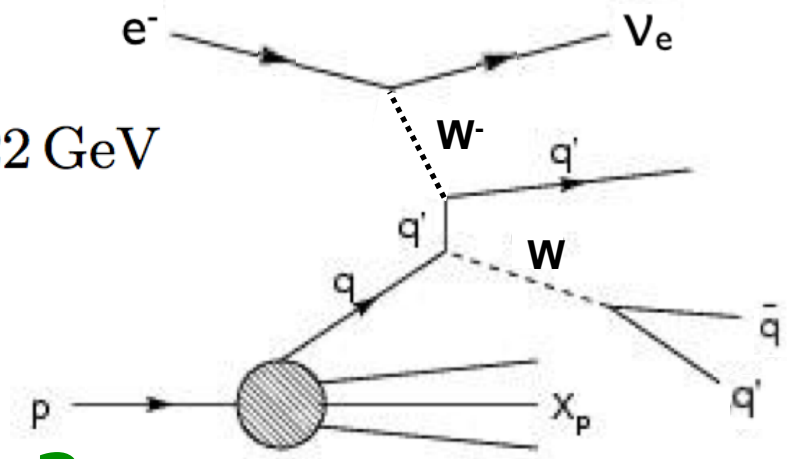
b-tag

$p_{T\,j,b} \geq 20\ \text{GeV}$

$|\eta_j| \leq 5, |\eta_b| \leq 2.5$

$\Delta R_{j,b/j} \geq 0.4$

background



N_t=220k, s/b=1.2

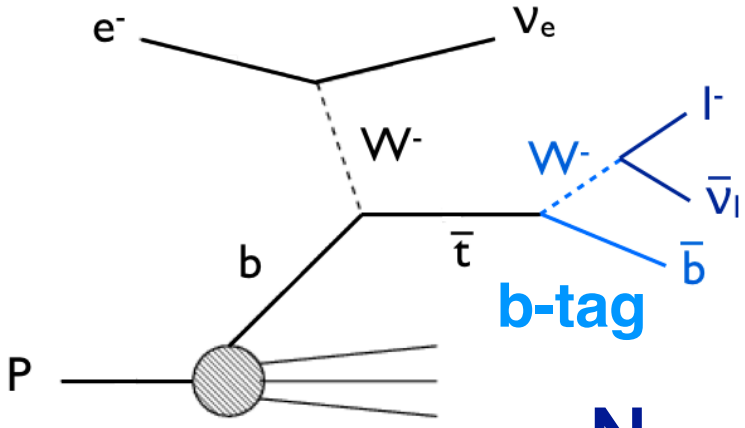
e beam: 60 GeV
1000 fb^{-1}

$\not{E}_T \geq 25\,\text{GeV}$

$\Delta\Phi_{\not{E},j} \geq 0.4$

$\Delta\Phi_{\not{E},b} \geq 0.4$

$\Delta\Phi_{\not{E},l} \geq 0.4$

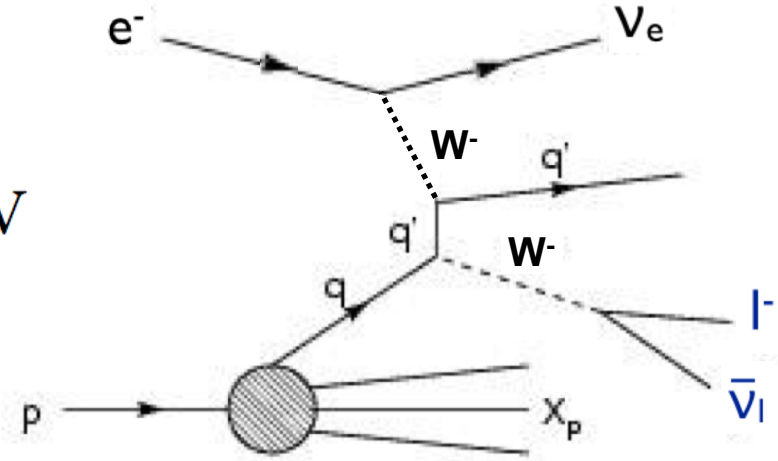


b-tag

$p_{T\,j,b,l} \geq 20\ \text{GeV}$

$|\eta_j| \leq 5,\ |\eta_{b,l}| \leq 2.5$

$\Delta R_{j,b/j} \geq 0.4$



N_t=110k, s/b=11