Top Physics at the LHeC and FCC-eh

Christian Schwanenberger
DESY
for the LHeC/FCC-eh Study Group

Electrons for the LHC: Workshop

Chavannes de Bogis, Suisse
24 October 2019

Outline

Introduction

CC Top Production

NC Top Production

BSM Top Production

Conclusions

Outline

Introduction

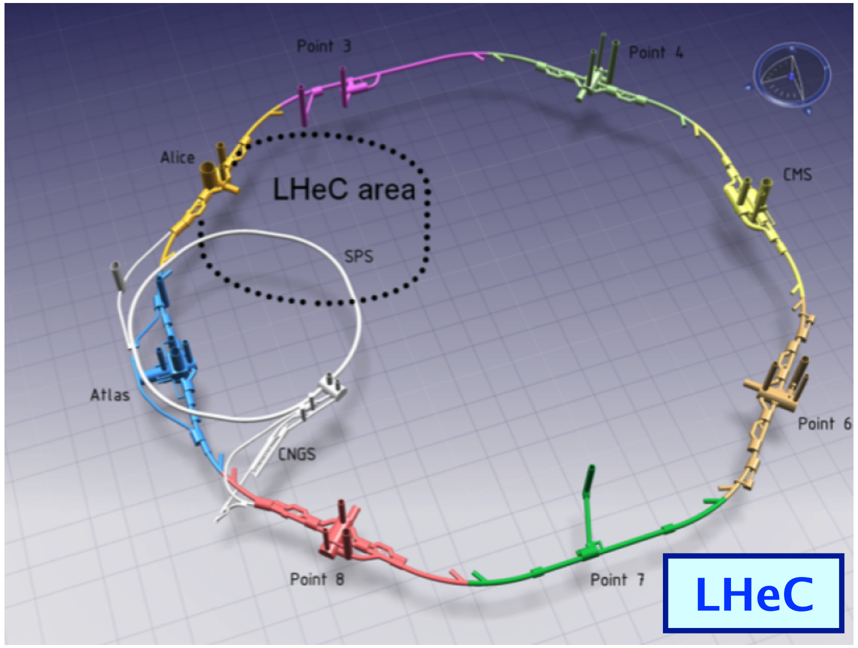
CC Top Production

NC Top Production

BSM Top Production

Conclusions

Linac-Ring Collider, LHeC and FCC-eh



operated synchronously

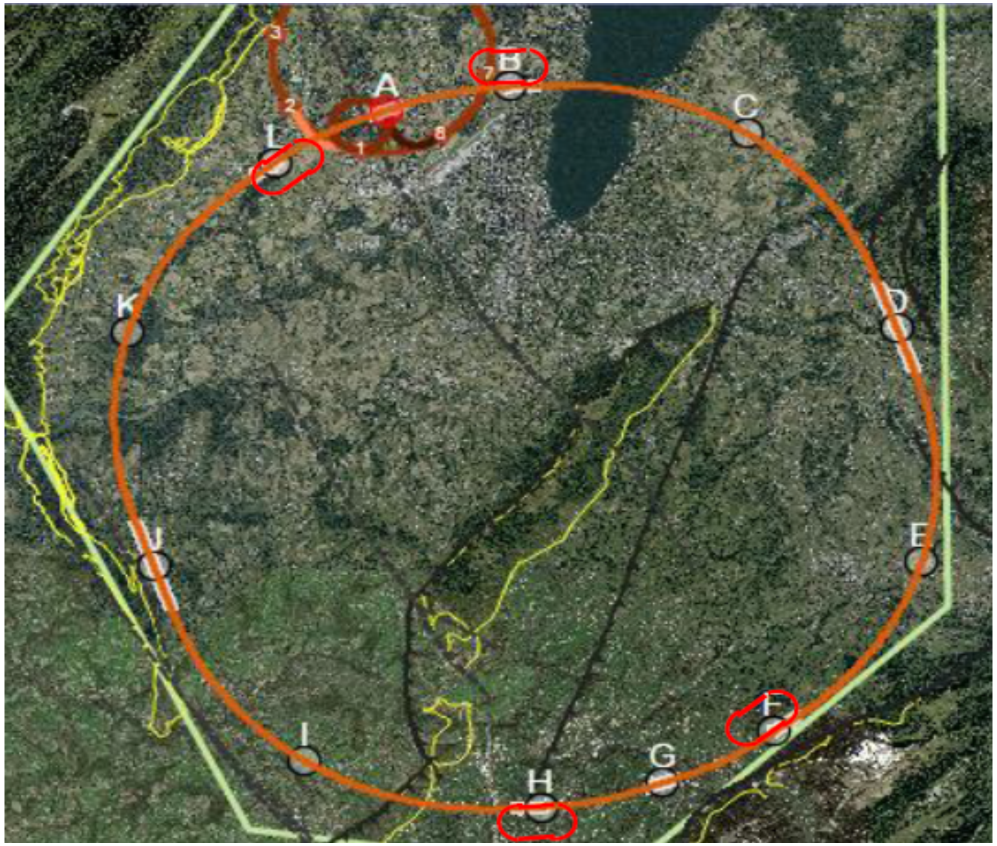
- with HL-LHC:
  p beam: 7 TeV, √s=1.3 TeV
- with HE-LHC:
  p beam: 13.5 TeV, √s=1.8 TeV
- or later with LE-FCC-hh:
  p beam: 19 TeV, √s=2.1 TeV
- or later with FCC-hh:
  p beam: 50 TeV, √s=3.5 TeV

Energy Recovering Linac

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

L_{int} = 1-3 ab^{-1} (1k-3k HERA!)

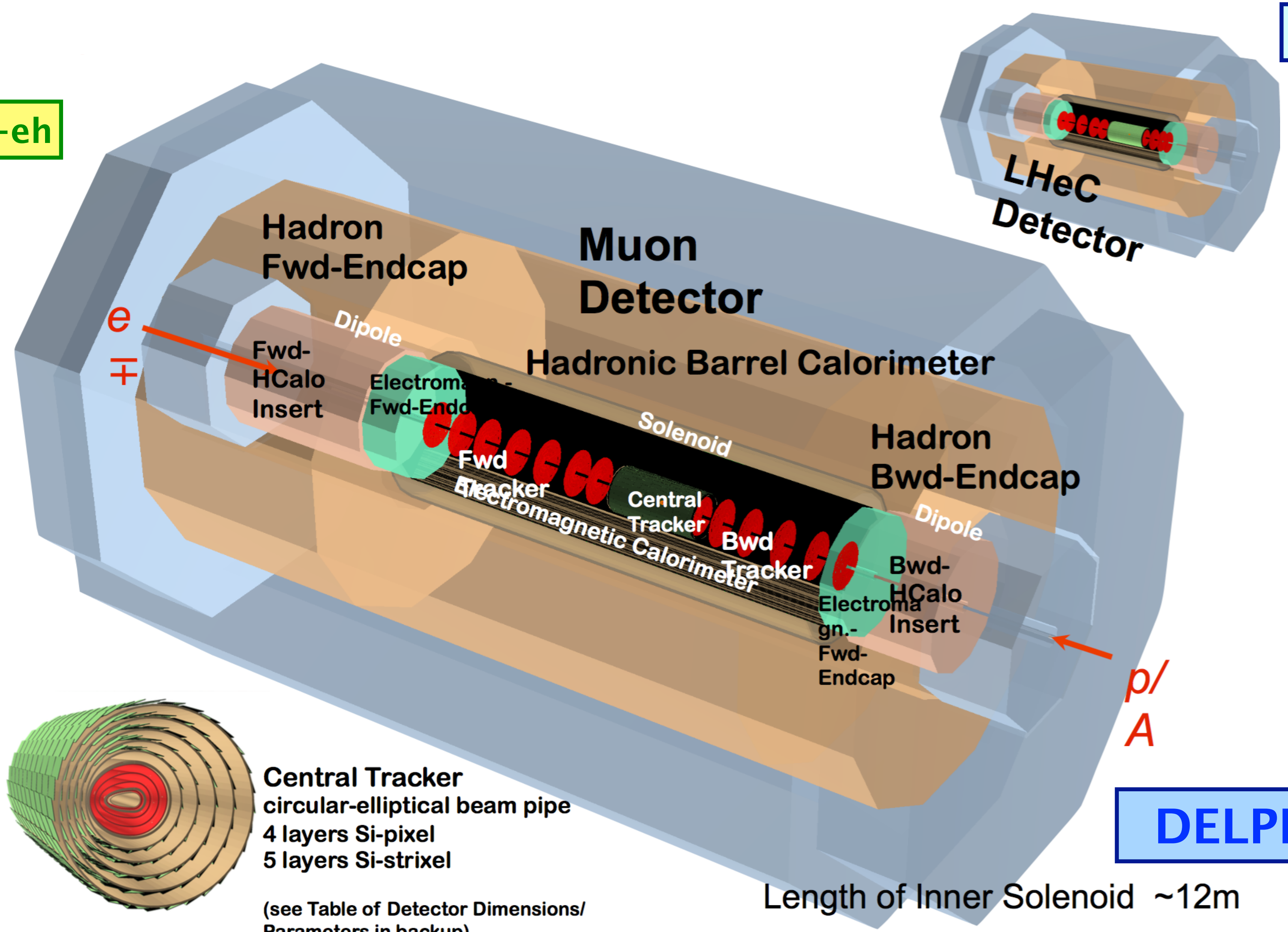
FCC-eh



LHeC and FCC-eh Detector Layout

FCC-eh

LHeC



Central Tracker
circular-elliptical beam pipe
4 layers Si-pixel
5 layers Si-strixel

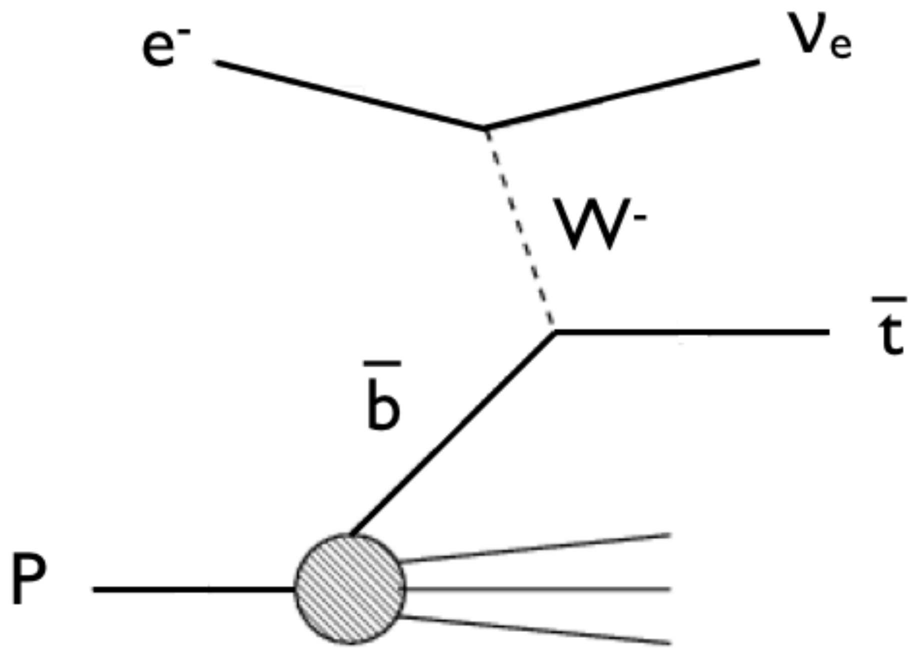
(see Table of Detector Dimensions/
Parameters in backup)

DELPHES

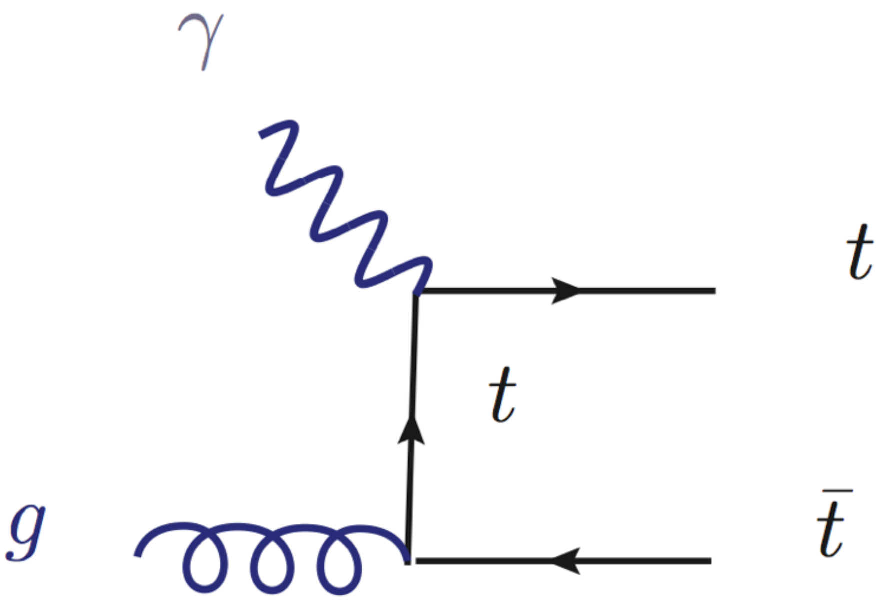
Length of Inner Solenoid ~12m

SM Top Quark Production

CC DIS top production



NC top photoproduction



σ=1.89pb @ LHeC

σ=4.46pb @ HE-LHC

σ=15.3pb @ FCC-eh

E_e=60 GeV

σ=0.05pb @ LHeC

σ=0.??pb @ HE-LHC

σ=1.14pb @ FCC-eh

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

Outline

Introduction

CC Top Production

NC Top Production

BSM Top Production

Conclusions

Signal and Backgrounds

LHeC

signal

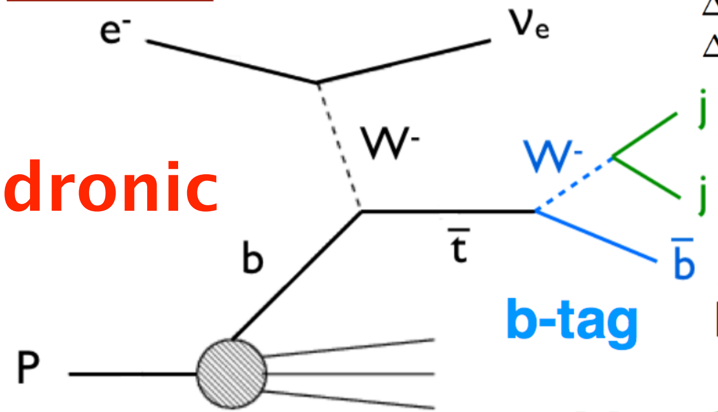
background

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

hadronic

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

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

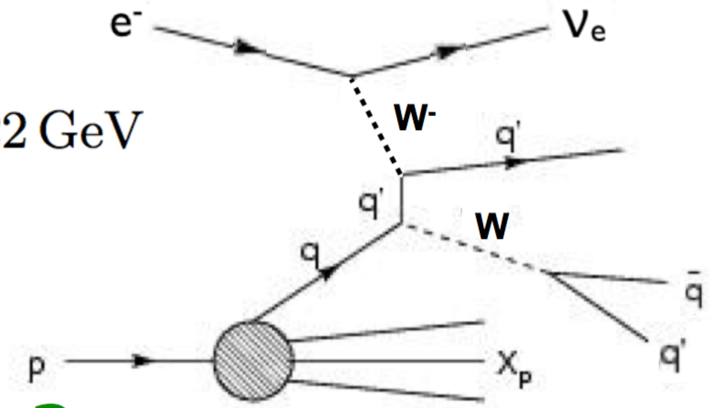


$|m_{j_1 j_2} - m_W| \leq 22$ GeV

${p_T}_{j,b} \geq 20$ GeV

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

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



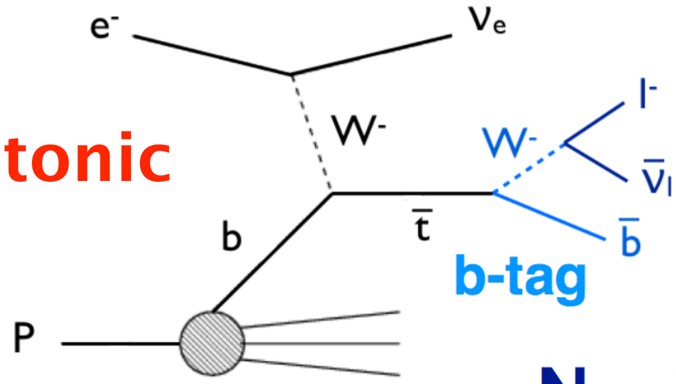
N_t=220k, s/b=1.2

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

leptonic

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

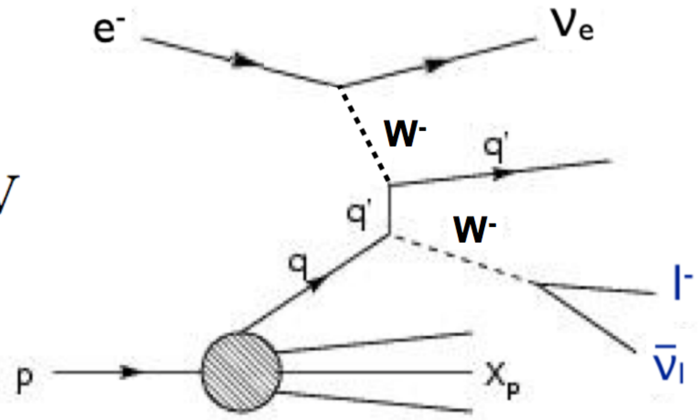
$\Delta\Phi_{\not{E},j} \geq 0.4$
$\Delta\Phi_{\not{E},b} \geq 0.4$
$\Delta\Phi_{\not{E},l} \geq 0.4$



${p_T}_{j,b,l} \geq 20$ GeV

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

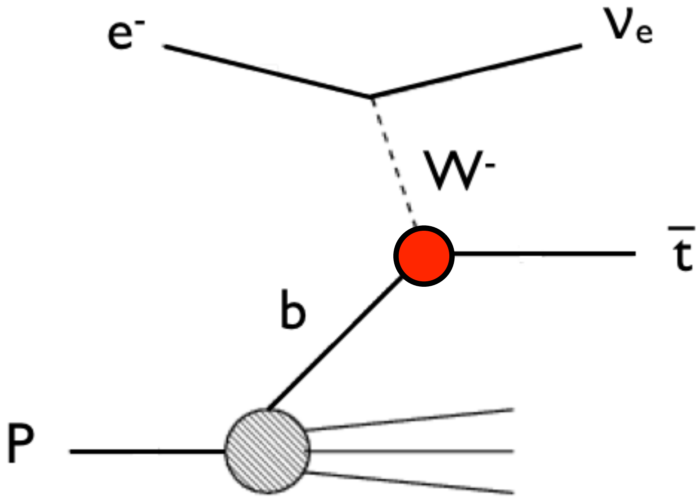
$\Delta R_{j,b/j} \geq 0.4$



N_t=110k, s/b=11

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

Direct Measurement of $|V_{tb}|$

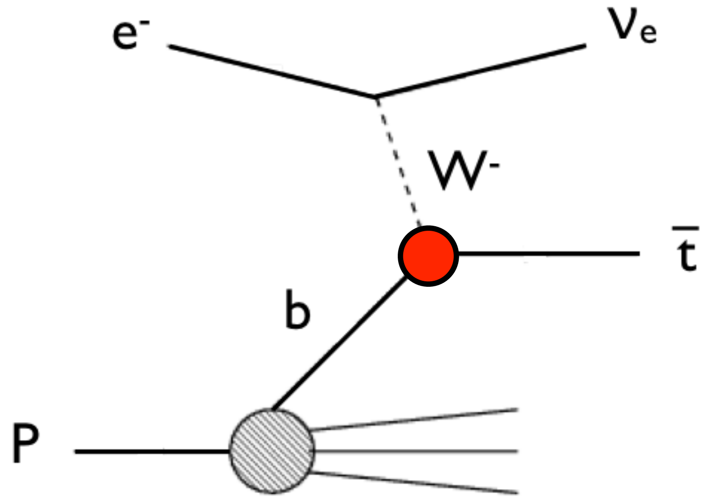


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Limits on Anomalous Wtb Couplings

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

= 1 in SM

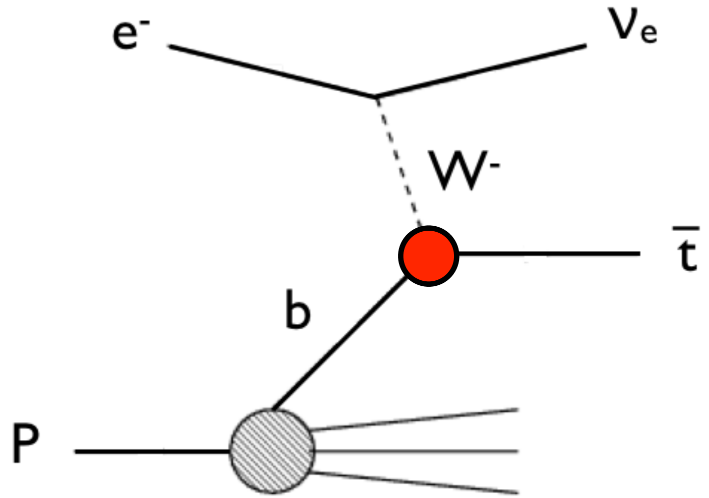


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Limits on 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

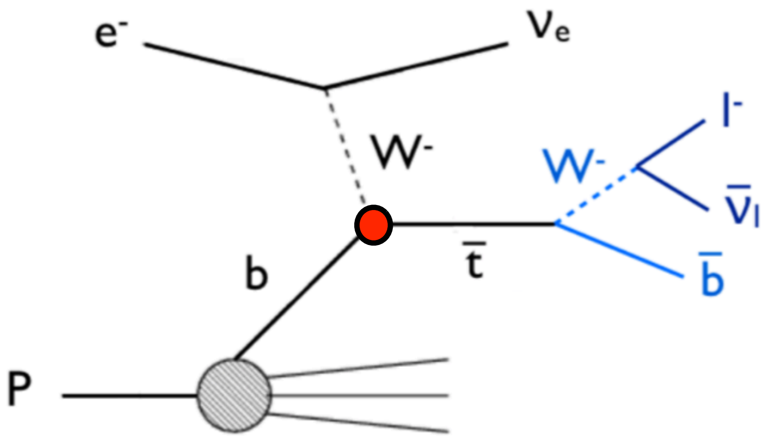


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

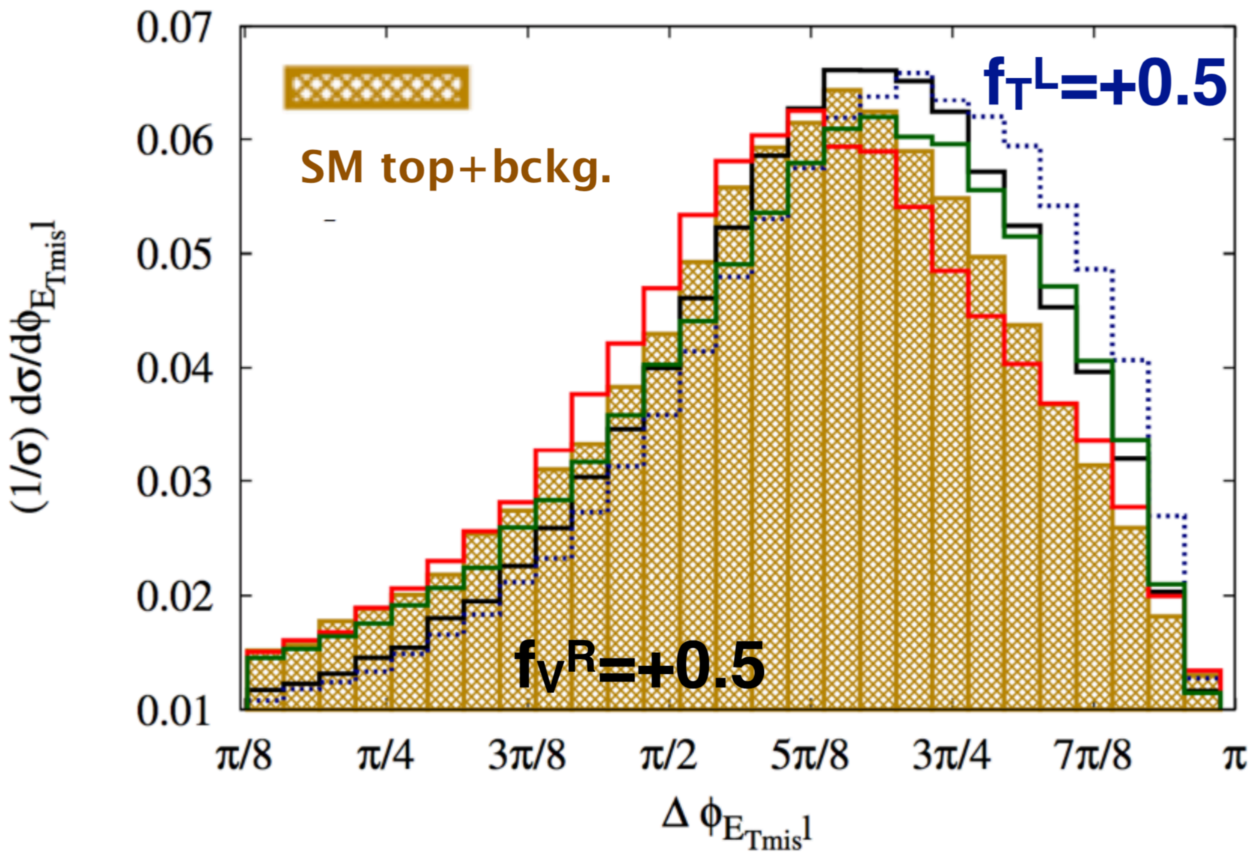
Limits on Anomalous Wtb Couplings

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

= 1 in SM



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



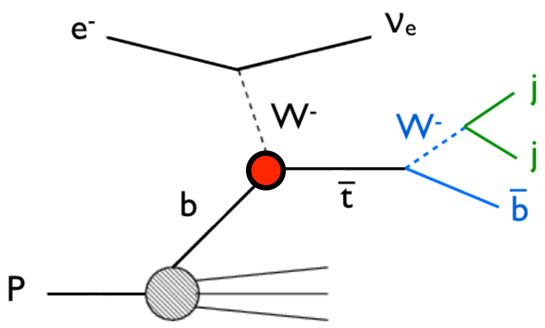
+ other variables sensitive on W helicity

Limits on Anomalous Wtb Couplings

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

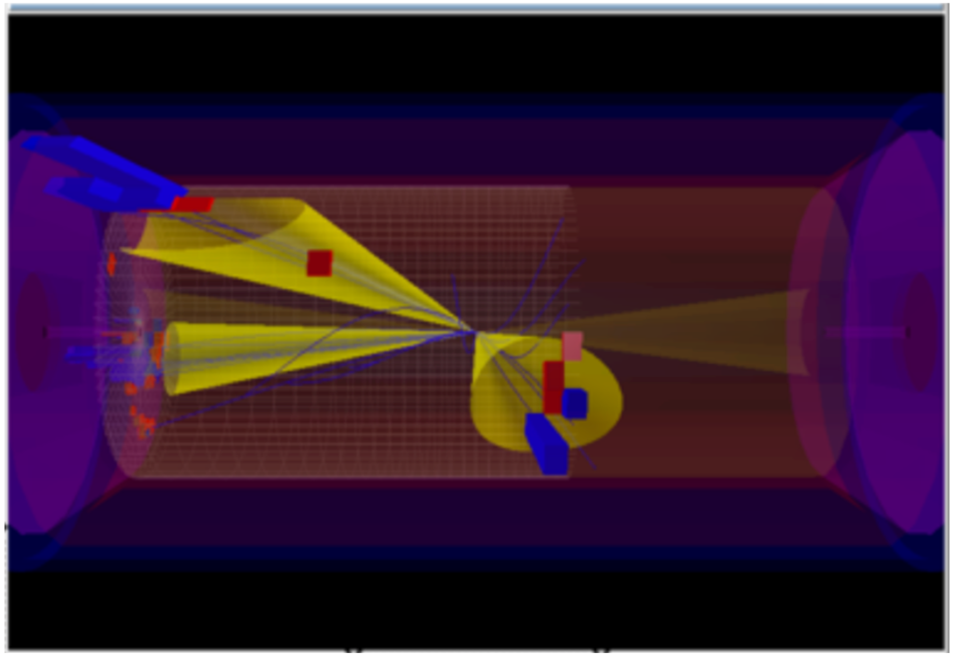
Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688
Kumar, Ruan, to be publ.

= 1 in SM



95% C.L.

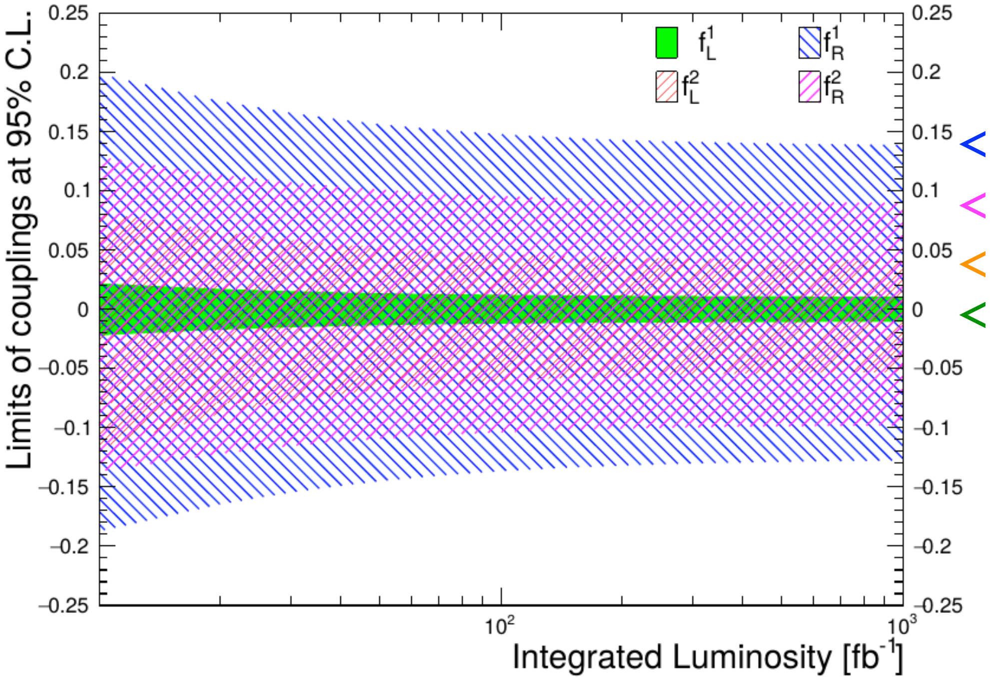
DELPHES



including detector simulation (Delphes)

LHeC

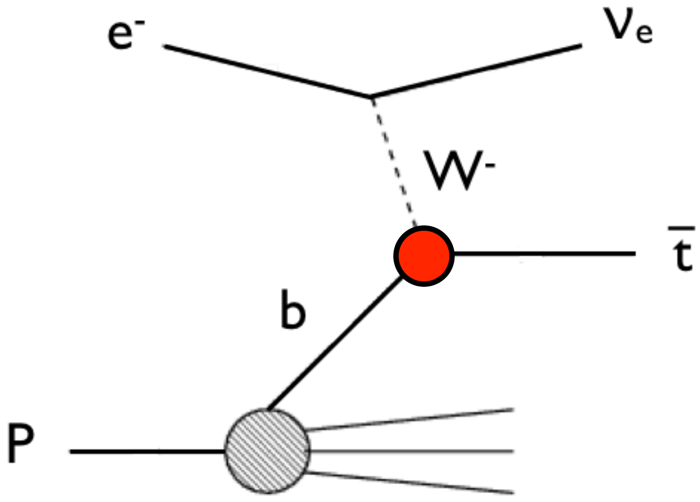
hadronic channel:



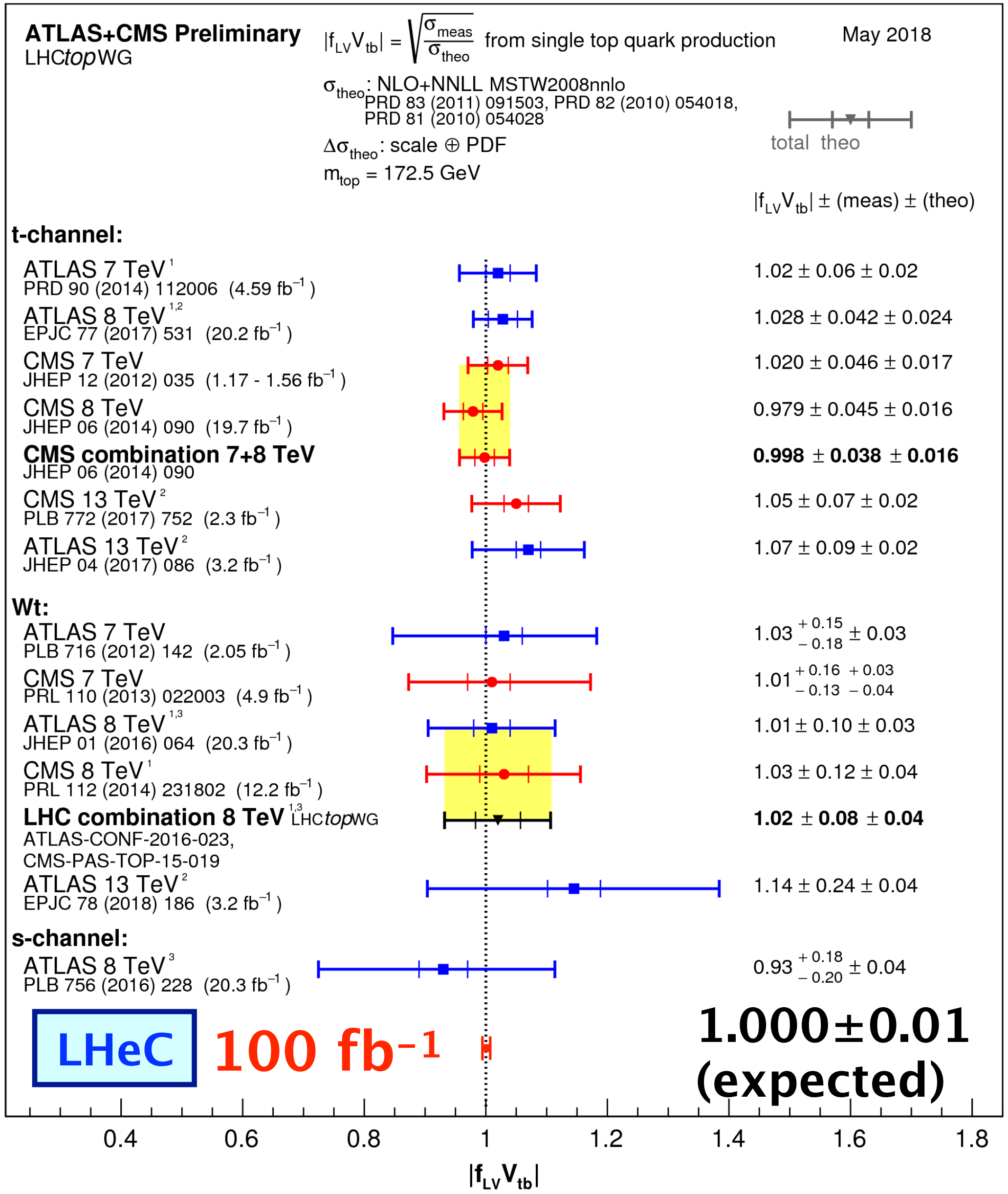
<0.14
<0.09
<0.04
<0.01

Direct Measurement of $|V_{tb}|$

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



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



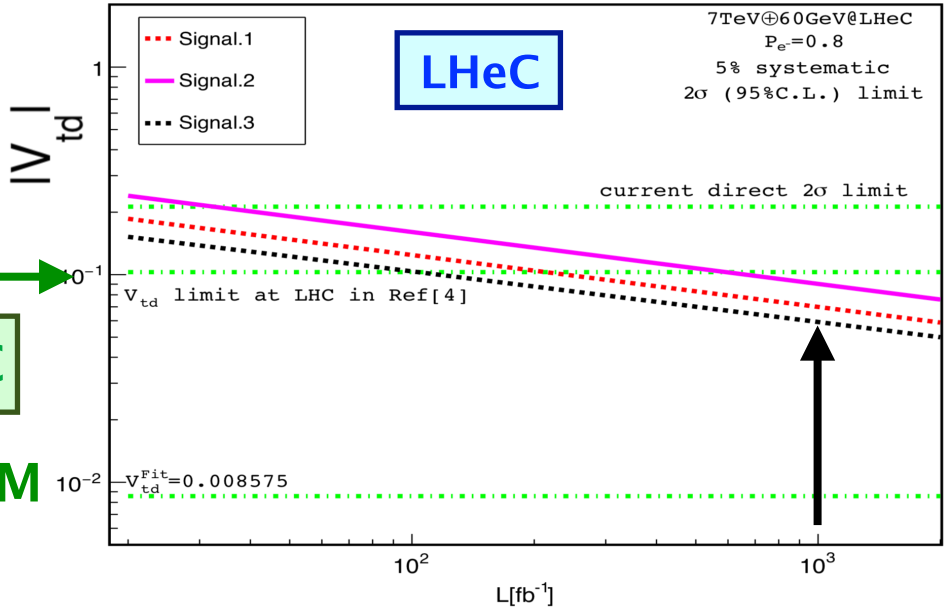
Measurement of $|V_{td}|$

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

arXiv:1709.07887

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

HL-LHC

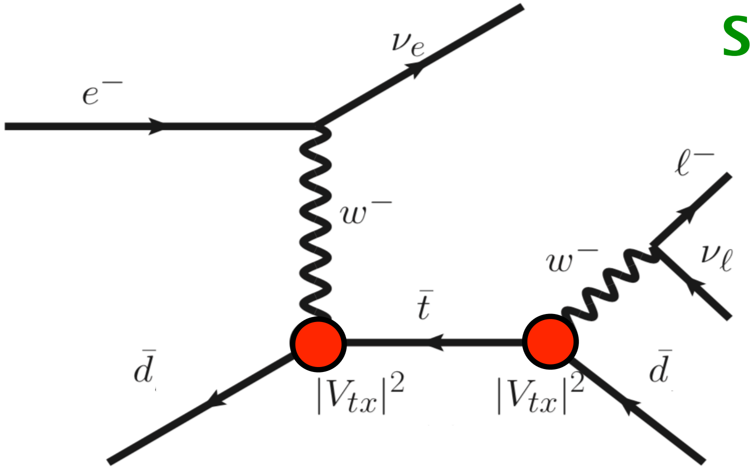


2σ

LHC

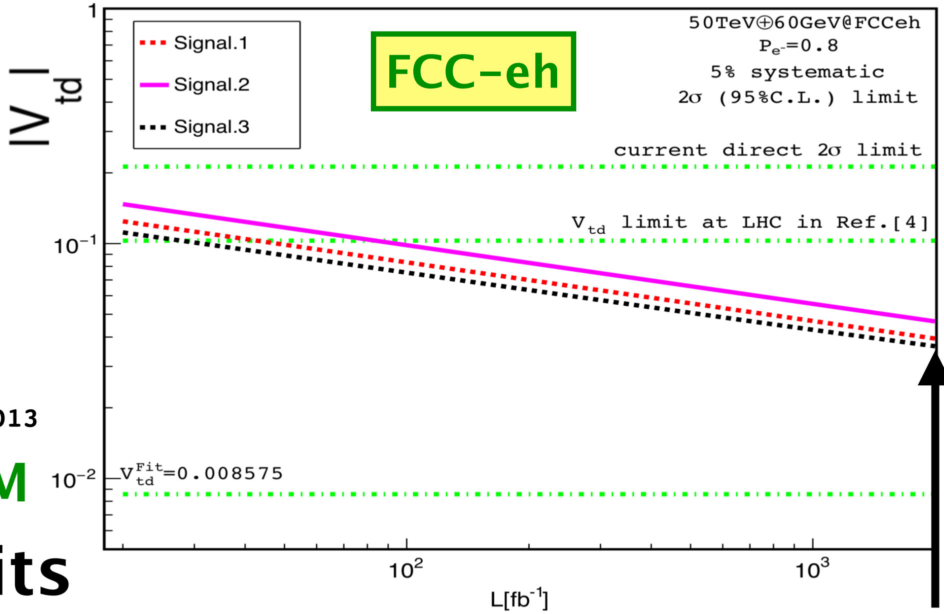
→ $|V_{td}|<0.06$

SM



DELPHES

arXiv:1501.05013



LHC

HL-LHC

→ $|V_{td}|<0.037$

SM

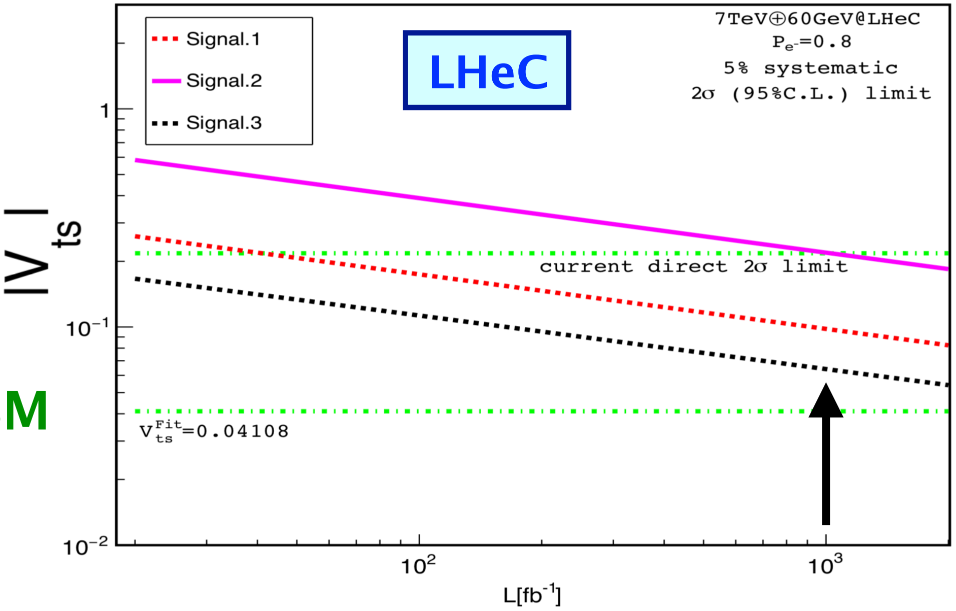
H. Sun PoS DIS 2018, 167 (2018)

→ **extend HL-LHC limits**

Measurement of $|V_{ts}|$

2σ

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

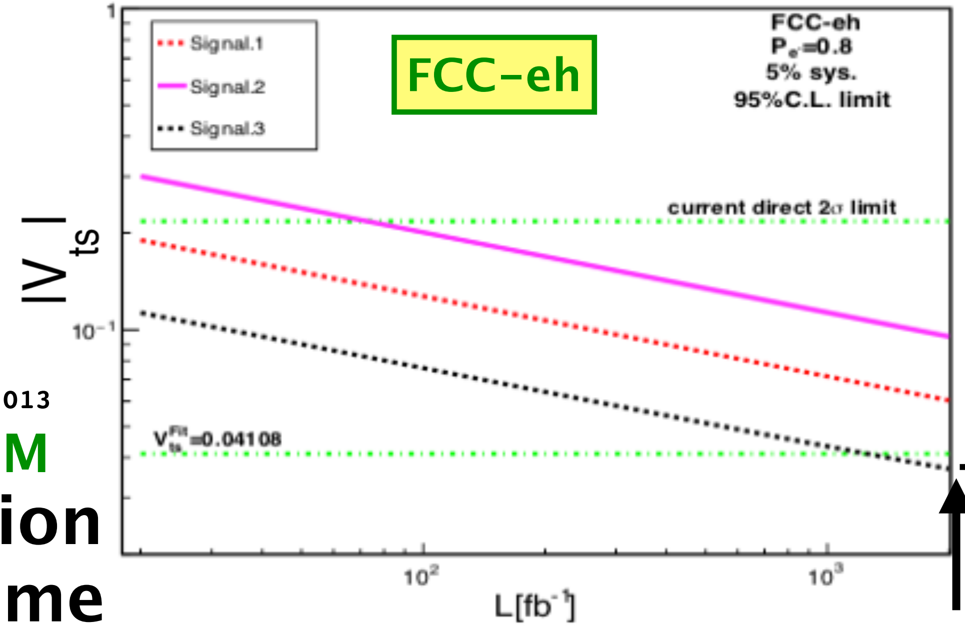


LHC

→ $|V_{ts}|<0.06$

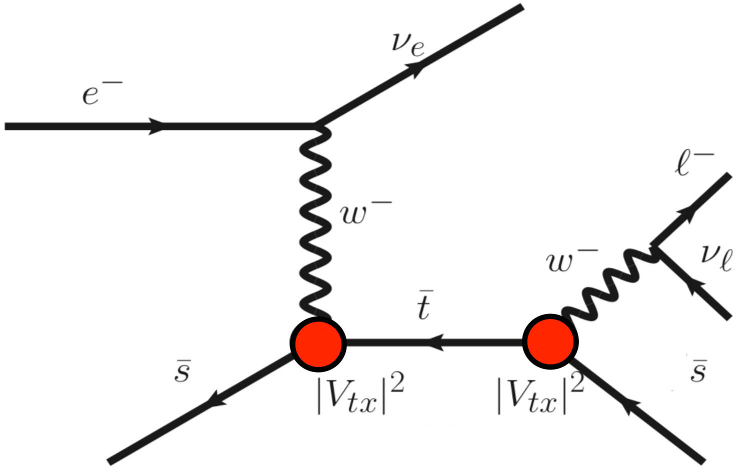
SM

FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)



LHC

→ $|V_{ts}|<0.037$



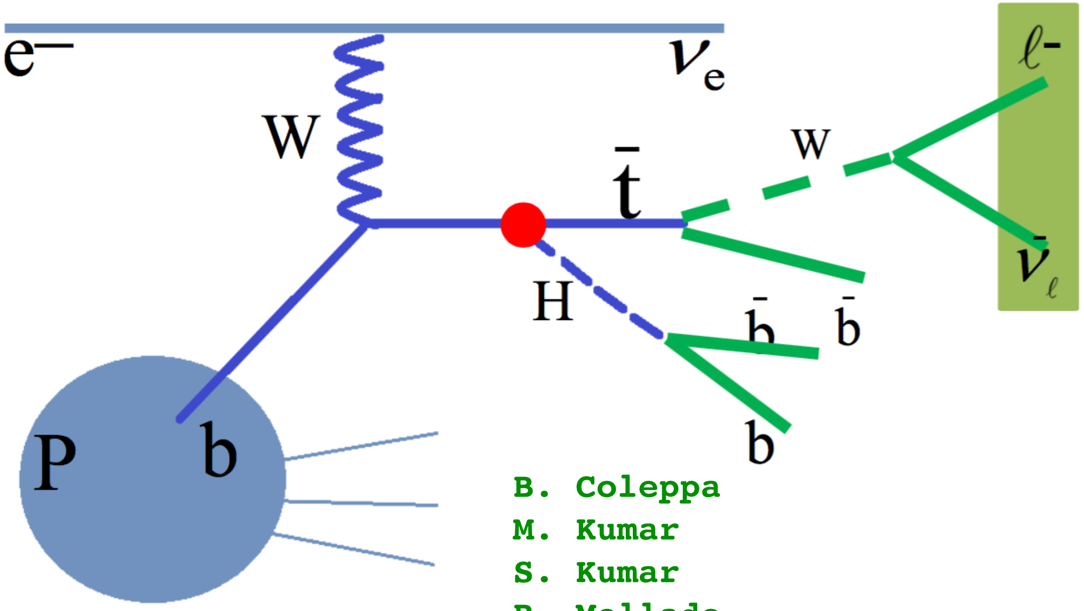
DELPHES

arXiv:1501.05013

H. Sun PoS DIS 2018, 167 (2018) **SM**

→ **probing SM prediction directly for the first time**

CP Nature of Top-Higgs Coupling

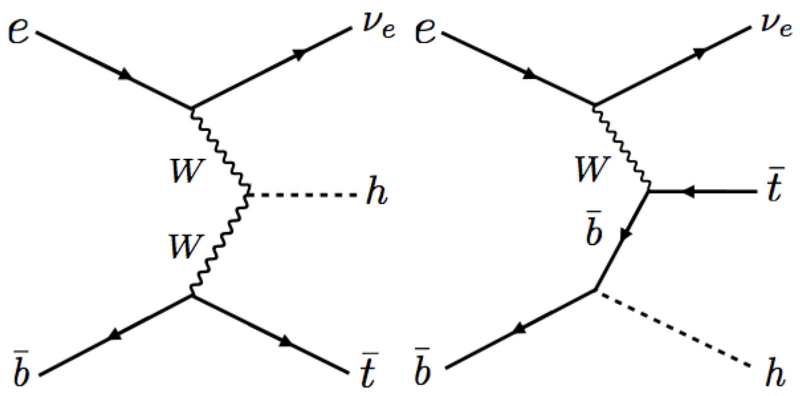


B. Coleppa
M. Kumar
S. Kumar
B. Mellado

parton level

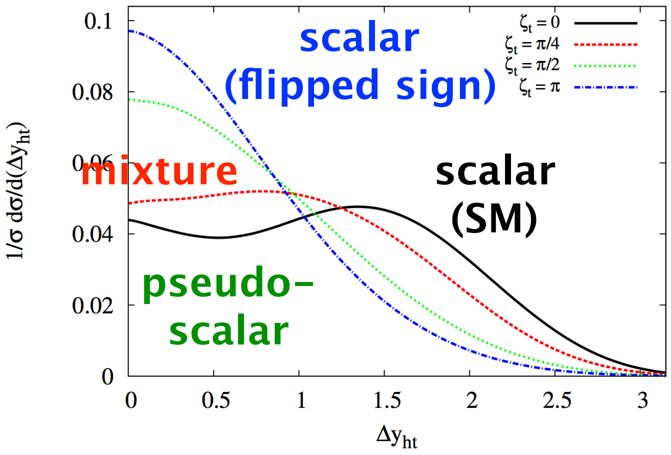
Phys. Lett. B770 (2017) 335

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

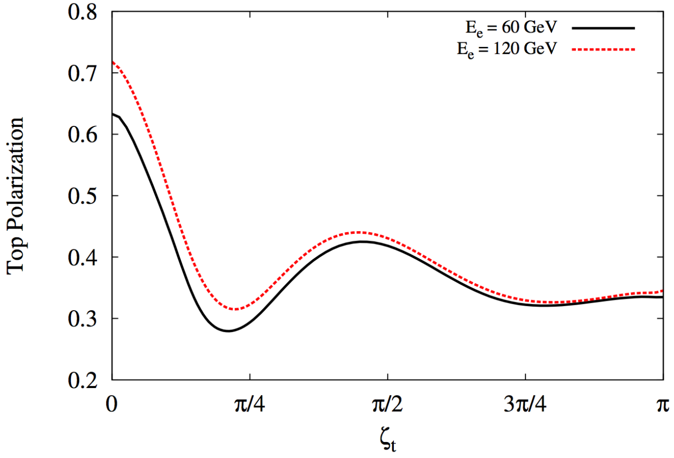


LHeC

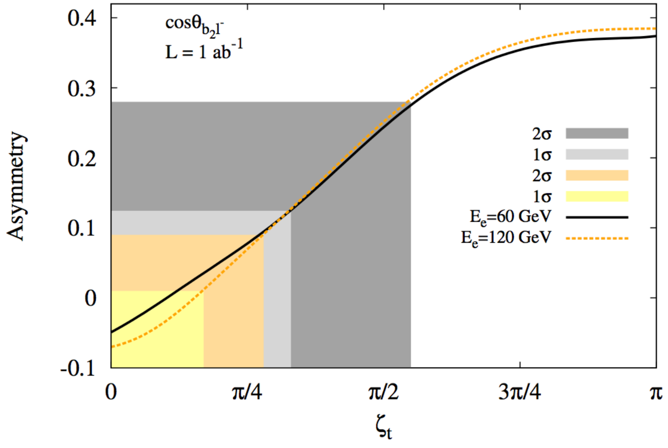
rapidity difference (H,$\bar{t}$)



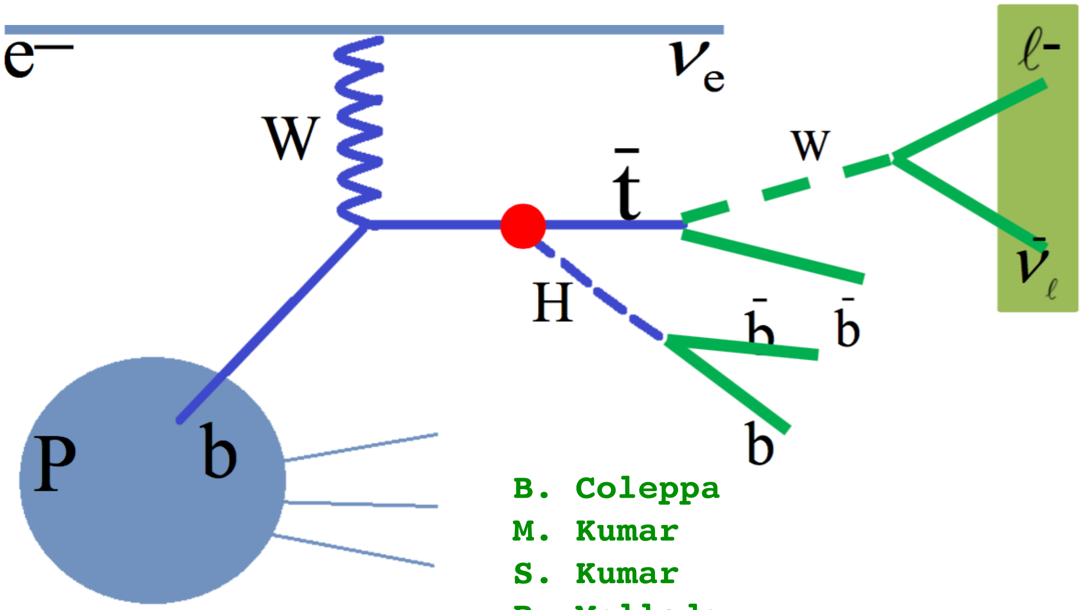
top polarisation



angular asymmetries (b₂,l⁻)



CP Nature of Top-Higgs Coupling

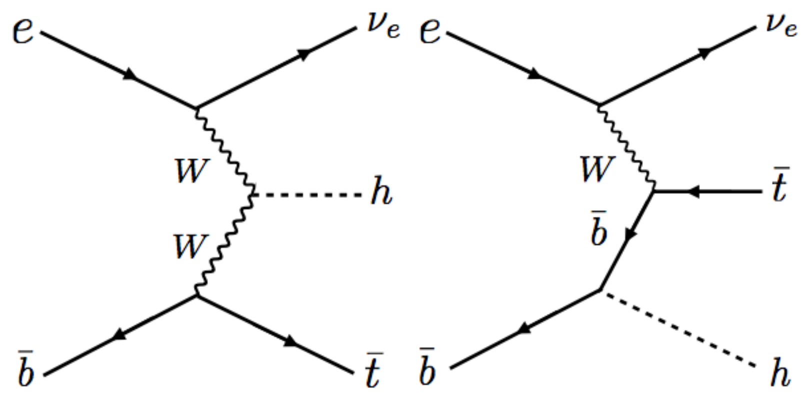


B. Coleppa
M. Kumar
S. Kumar
B. Mellado

parton level

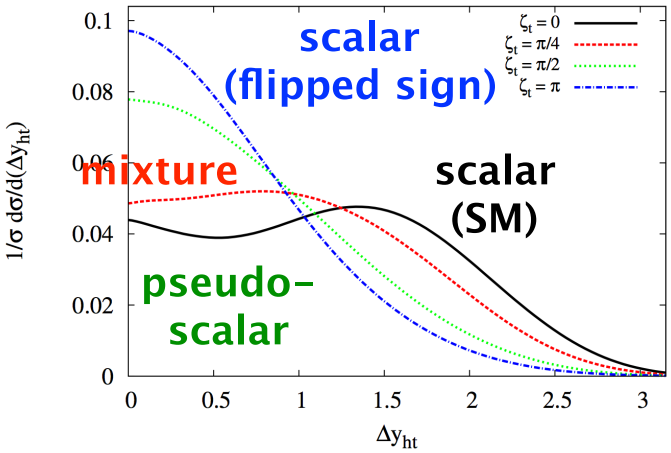
Phys. Lett. B770 (2017) 335

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

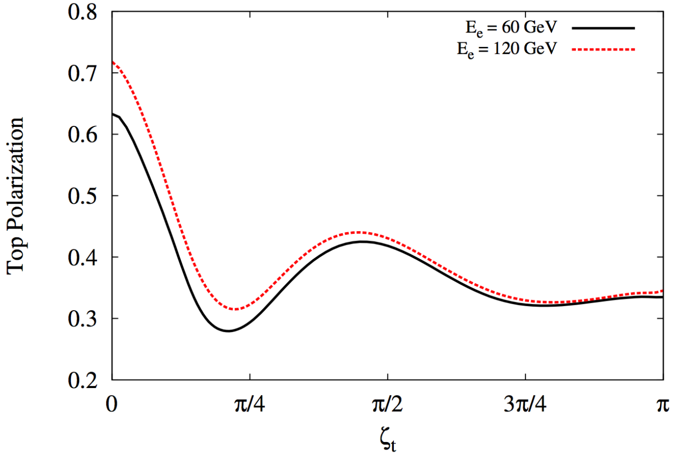


LHeC

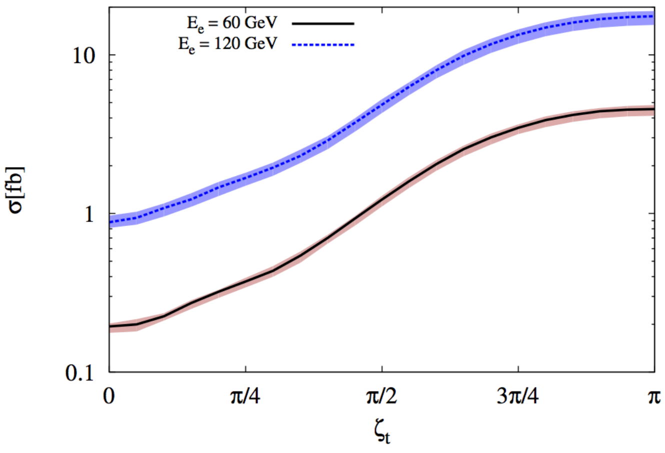
rapidity difference (H,t̄)



top polarisation



fiducial incl. cross-section



Exclusion Contours (fiducial cross section)

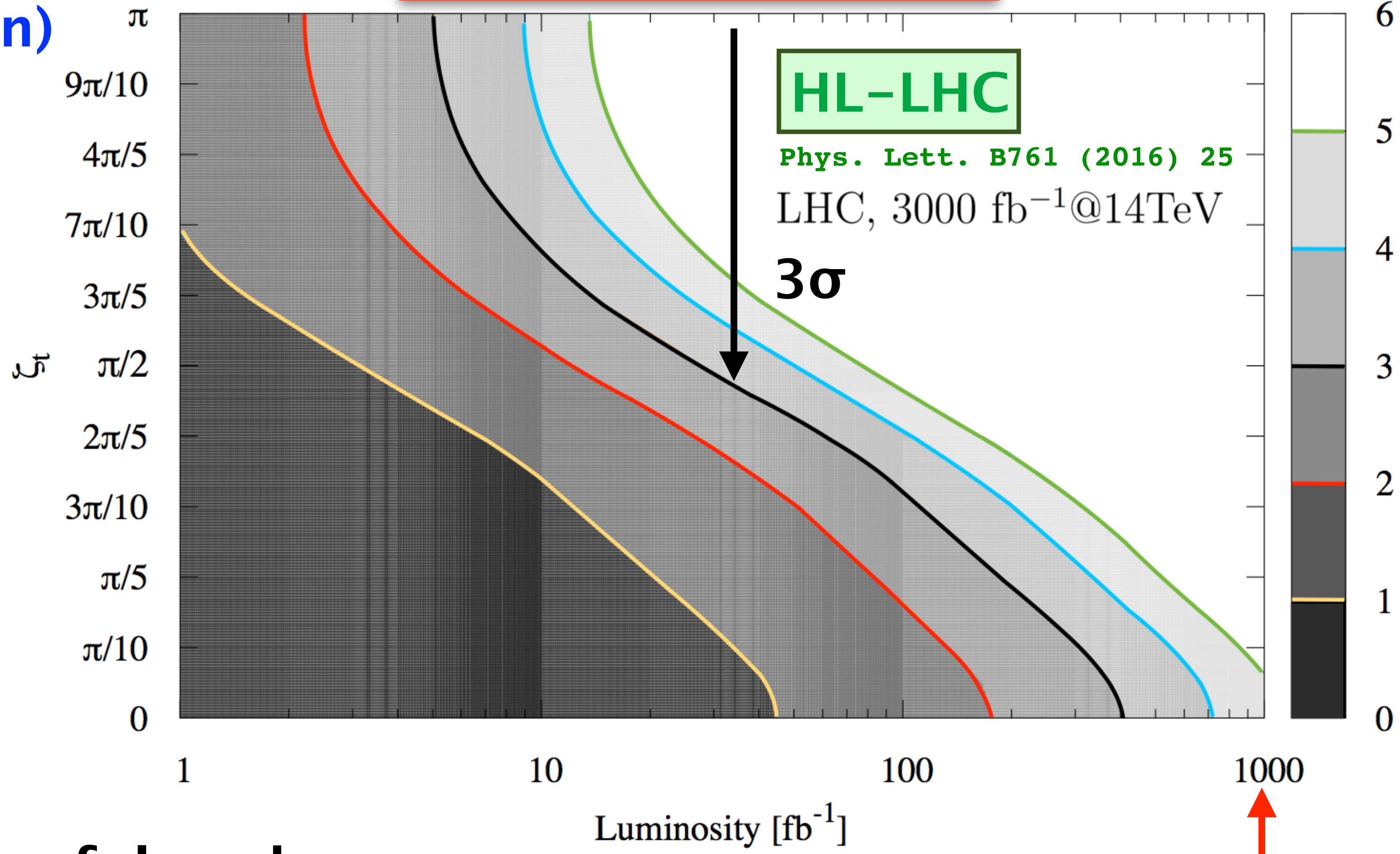
$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa \cos\zeta_t + i\gamma_5 \sin\zeta_t]t\,h$$

LHeC

CP−even (flipped sign)

CP−odd

CP−even (SM)



HL−LHC

Phys. Lett. B761 (2016) 25

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

3σ

→ **powerful probe of ttH coupling**

10% uncertainty on background yields

$\kappa = 1.00 \pm 0.17$

Outline

Introduction

CC Top Production

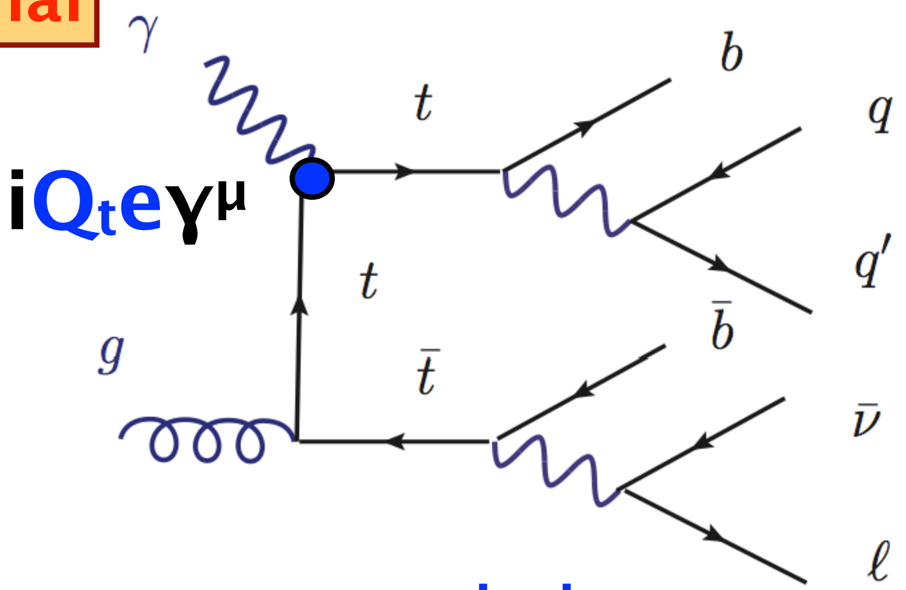
NC Top Production

BSM Top Production

Conclusions

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

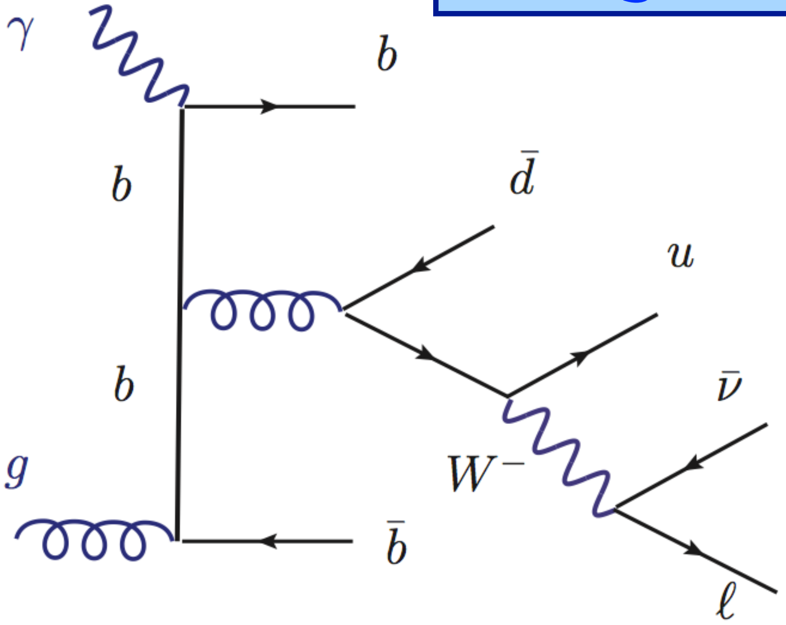
signal



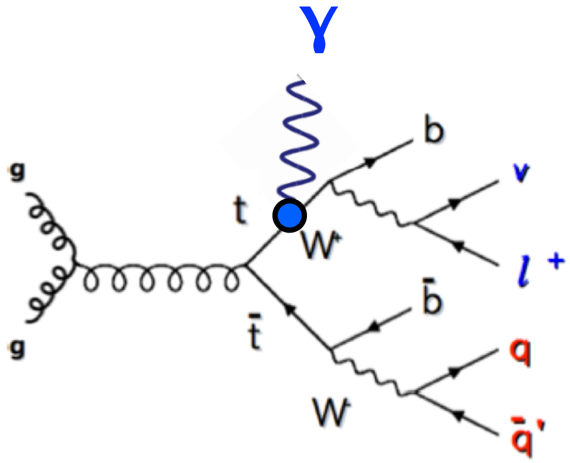
$iQ_te\gamma^\mu$

→ measure **top quark charge**

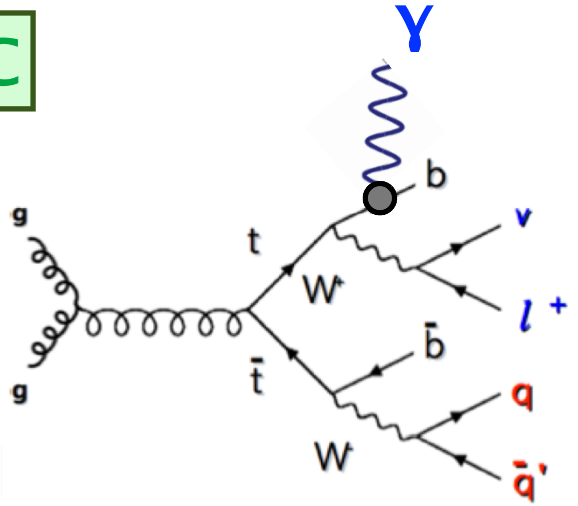
background



LHC



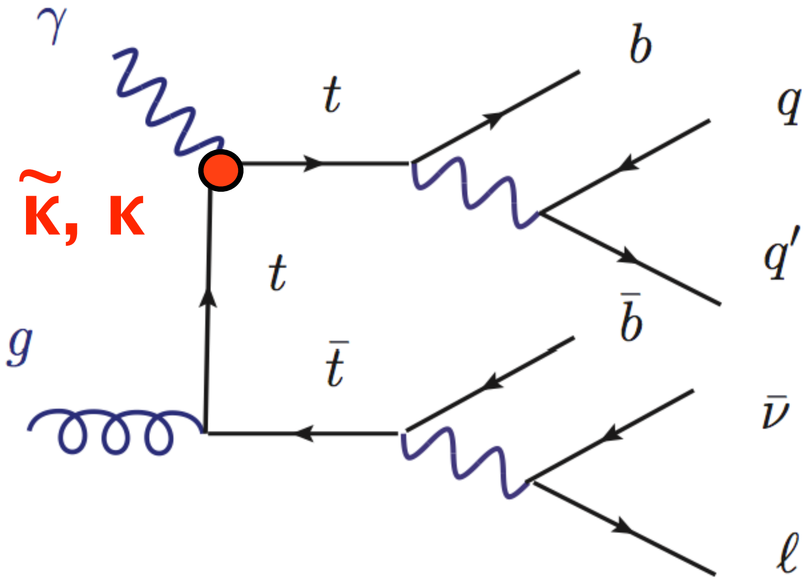
OR



?

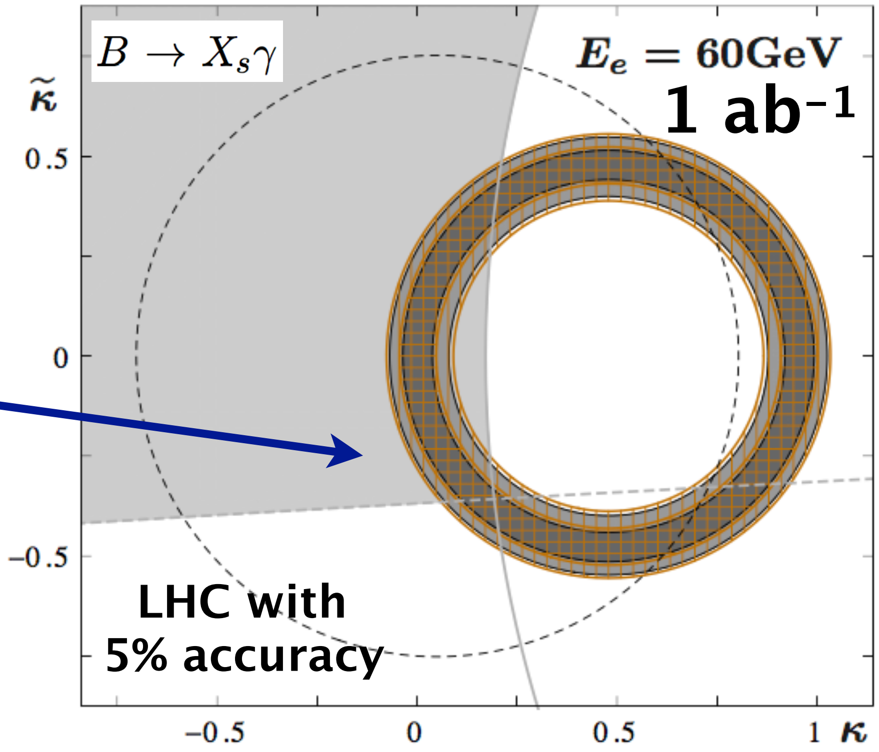
→ difficult at the LHC

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: $\tilde{\kappa}$



magnetic dipole moment: κ

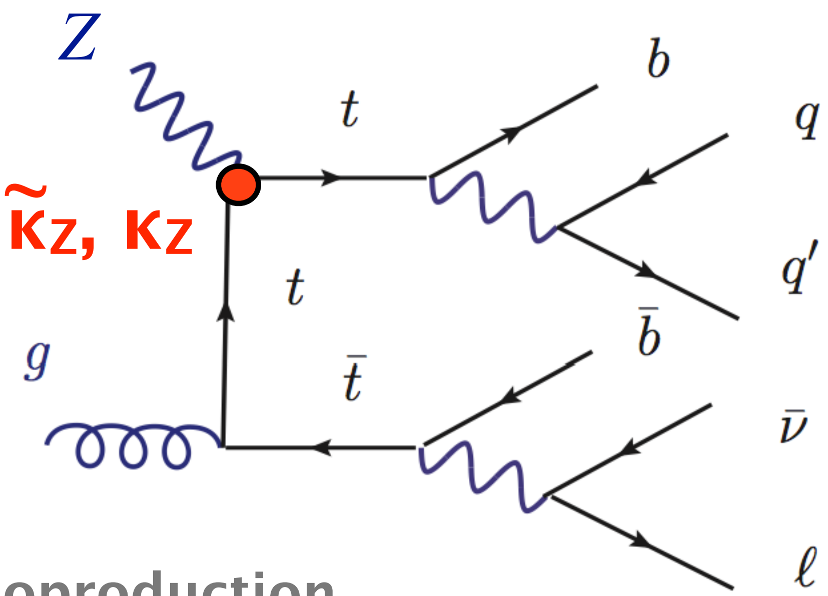
LHeC

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

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

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

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



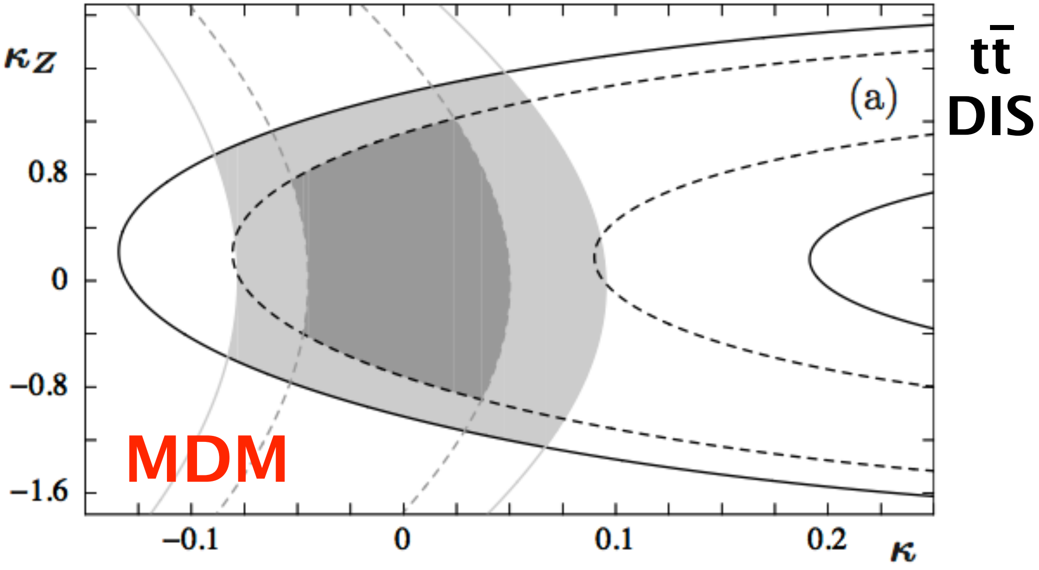
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

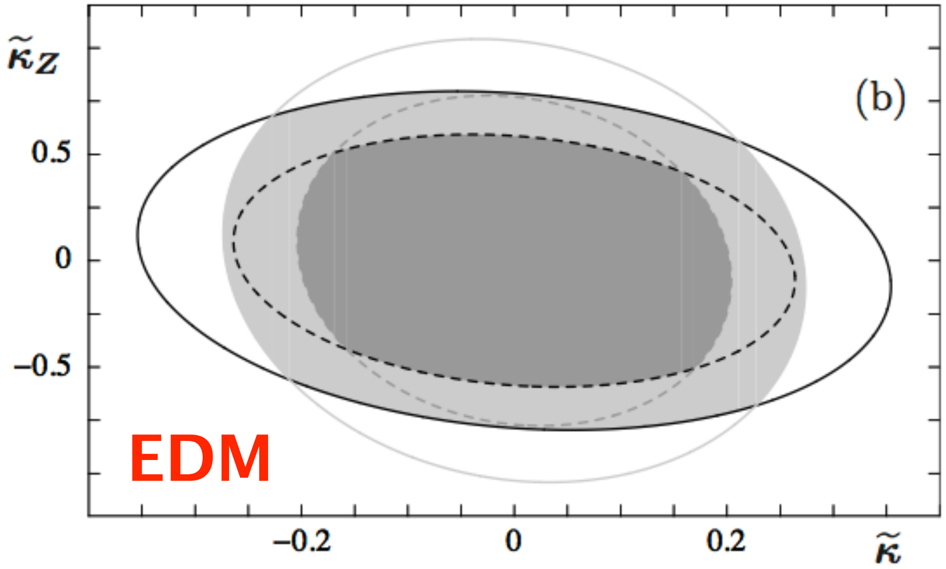
property	precision
EDM: $\tilde{\kappa}$ / $\tilde{\kappa}_Z$	0.20–0.28/0.6–0.8
MDM: κ / κ_Z	0.05–0.09/0.9–1.3

LHeC

10% and 18% accuracy

$t\bar{t}$ photoproduction





Outline

Introduction

CC Top Production

NC Top Production

BSM Top Production

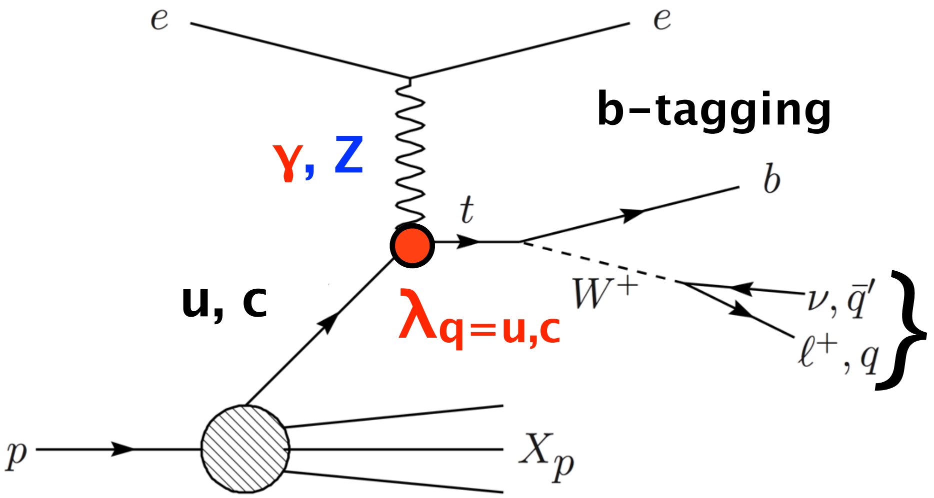
Conclusions

Search for Anomalous FCNC tuγ, tuZ Couplings

signal

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

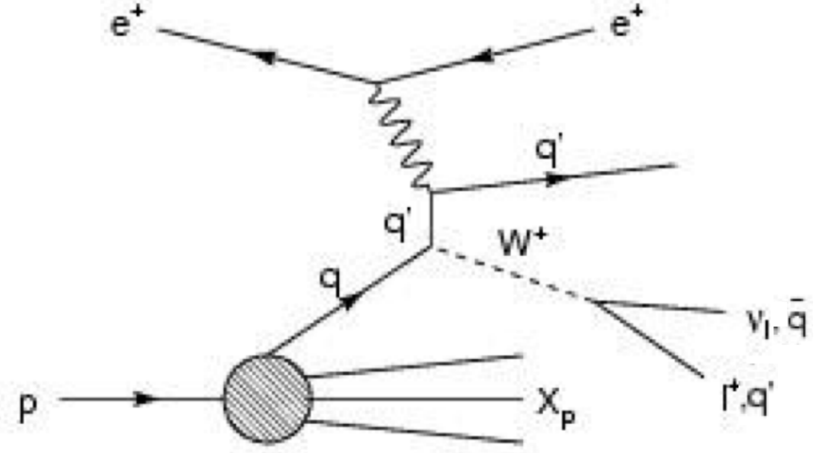
$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda_q}{\Lambda} \bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5) q A_{\mu\nu} + h.c.$$



b-tagging

$50 < M_{jj} < 100$ GeV

background

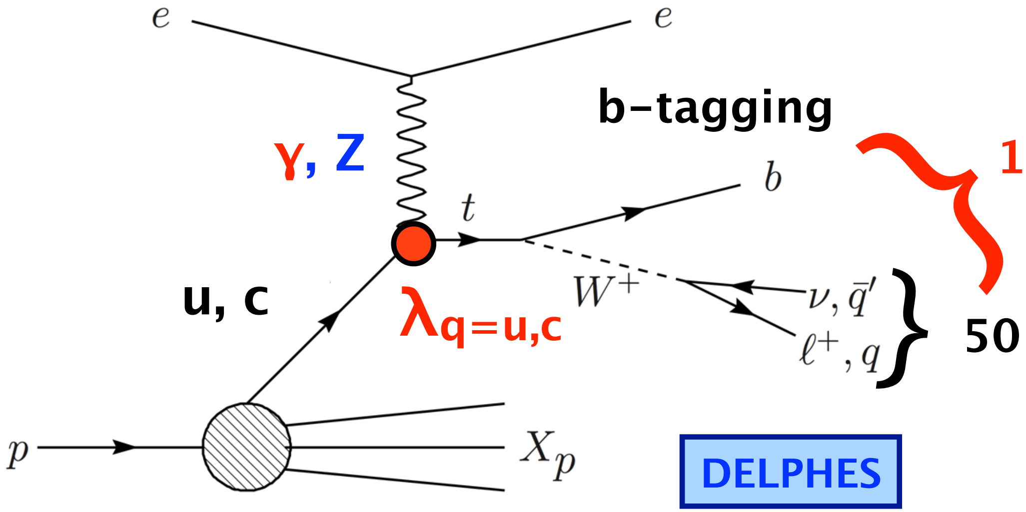


Search for Anomalous FCNC tuγ Coupling

signal

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

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

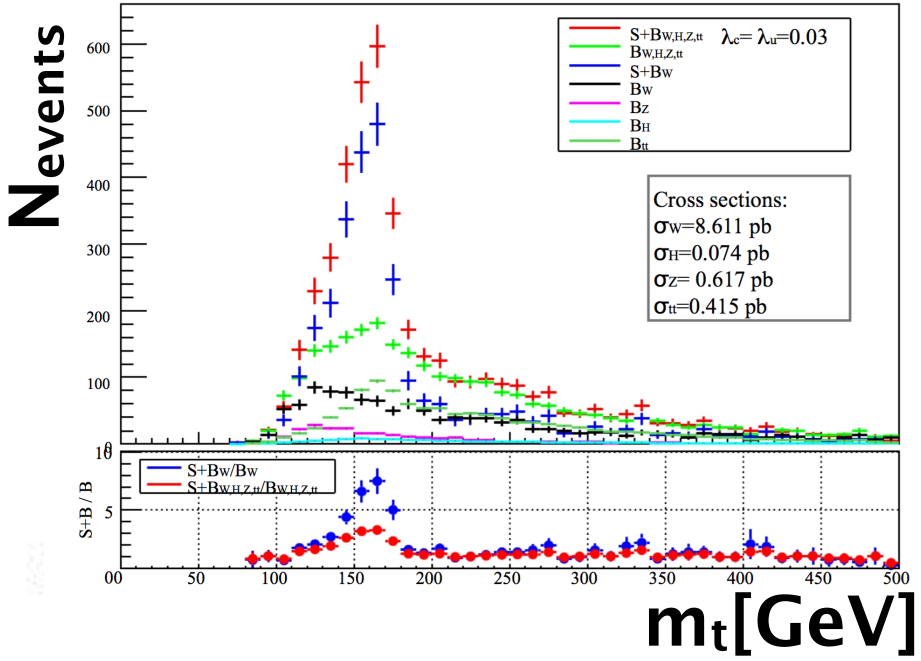


b-tagging

130<M_{Wb}<190 GeV

50<M_{jj}<100 GeV

DELPHES

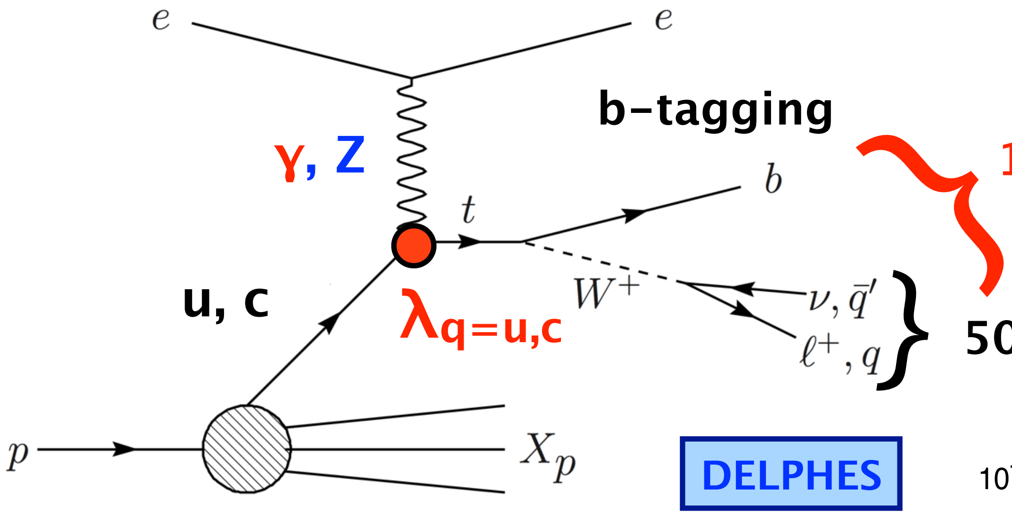


Search for Anomalous FCNC tuγ Coupling

signal

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

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



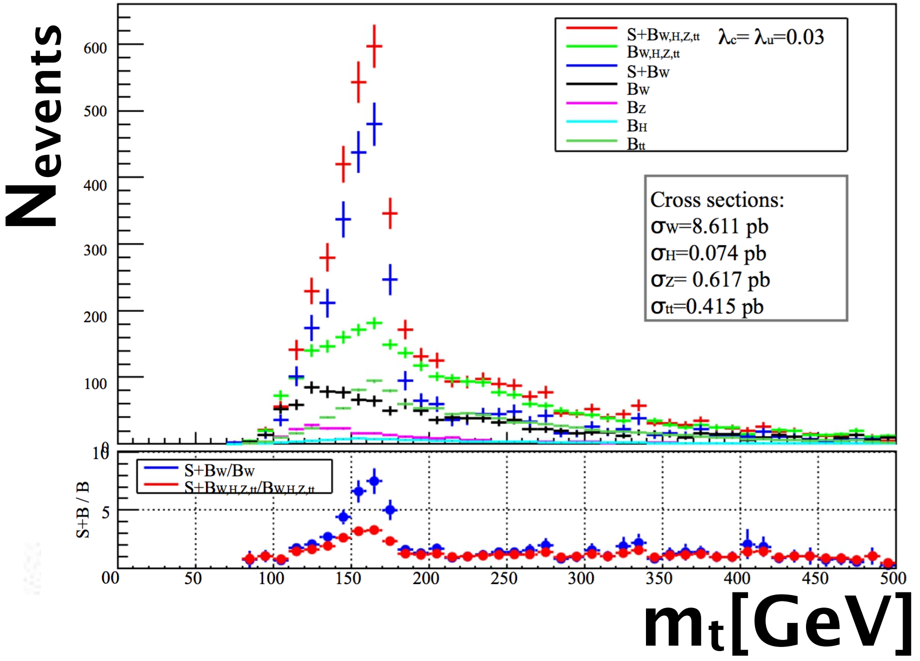
b-tagging

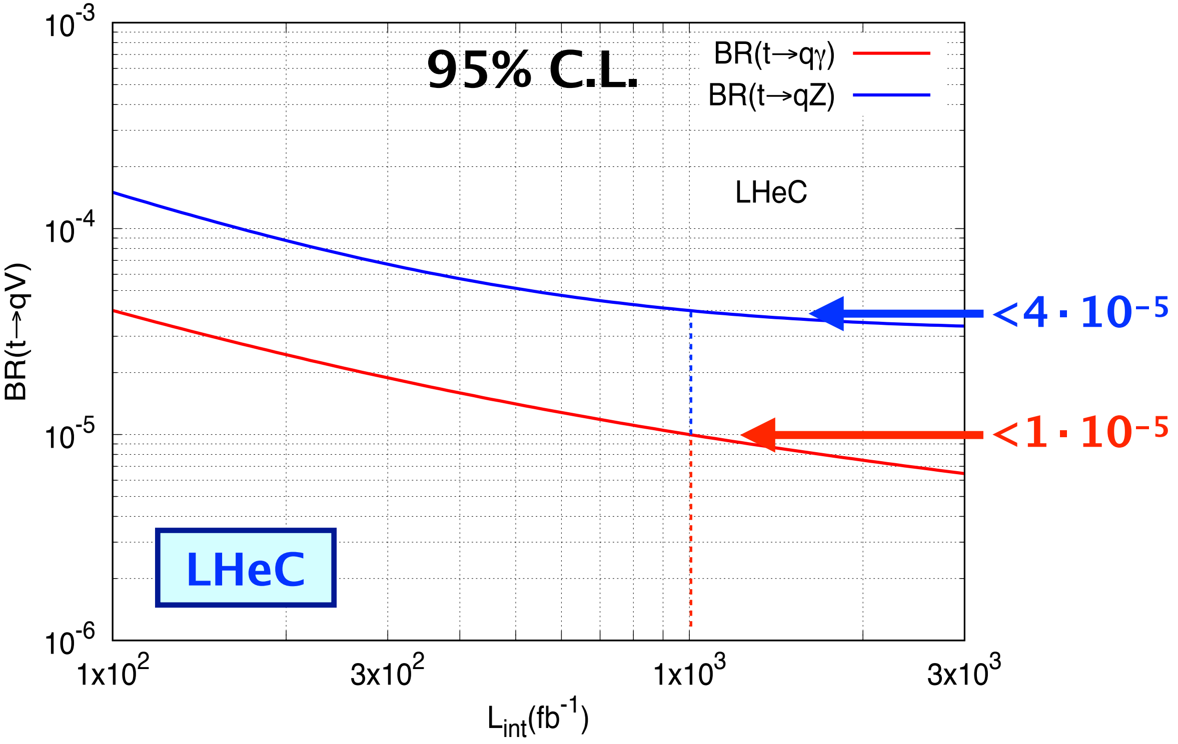
$130 < M_{Wb} < 190$ GeV

$50 < M_{jj} < 100$ GeV

→ **test exotic models leading to FCNC**

DELPHES



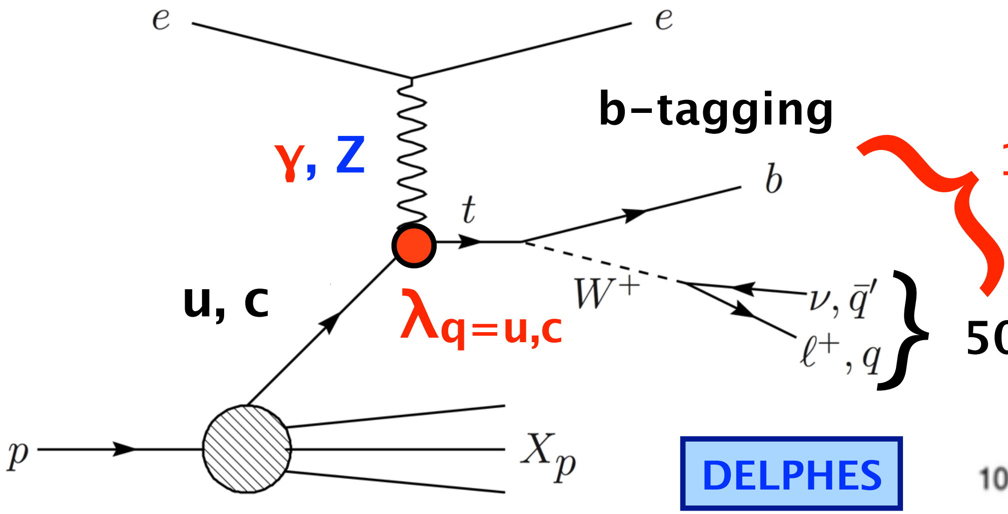


Search for Anomalous FCNC tuy Coupling

signal

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

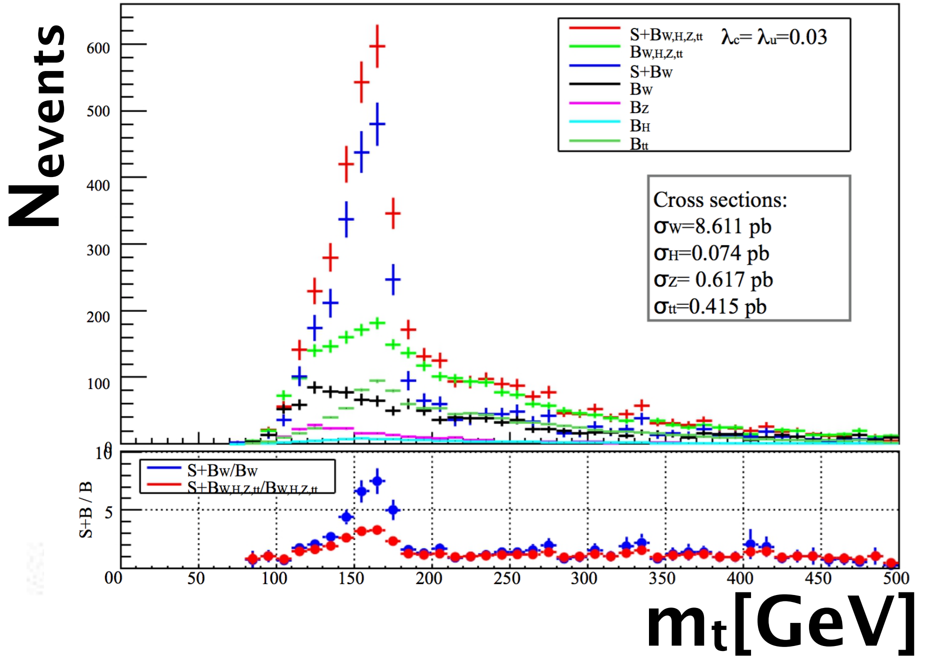
$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda_q}{\Lambda} \bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$



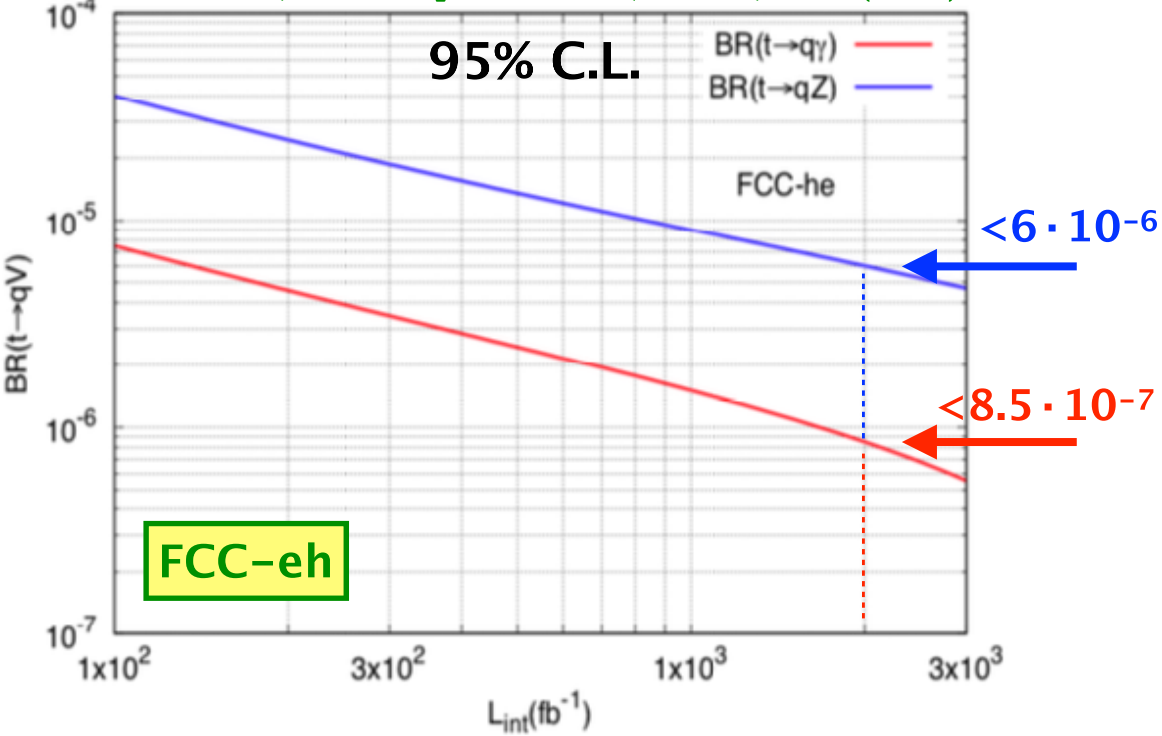
$130 < M_{Wb} < 190$ GeV

$50 < M_{jj} < 100$ GeV

→ **test exotic models leading to FCNC**



FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)

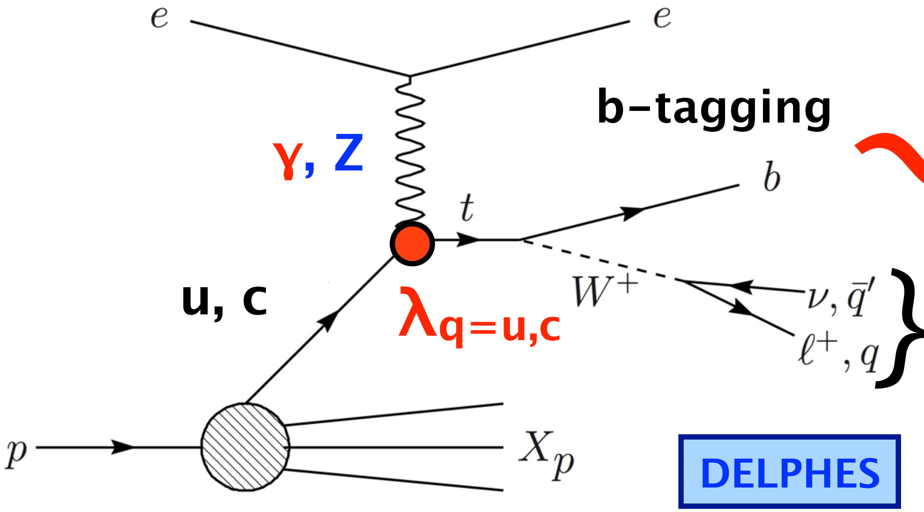


Search for Anomalous FCNC tuγ Coupling

signal

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

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

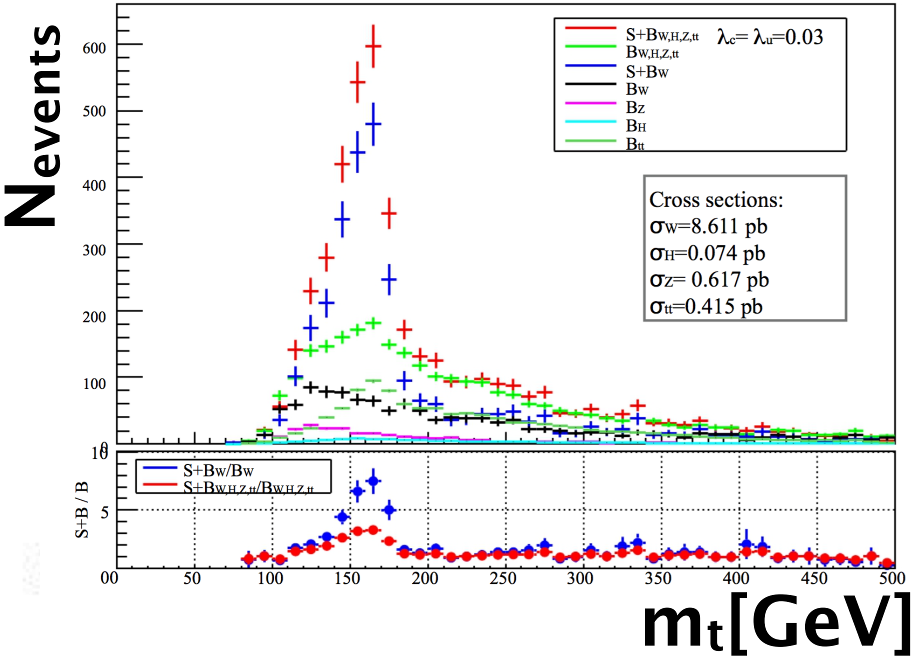


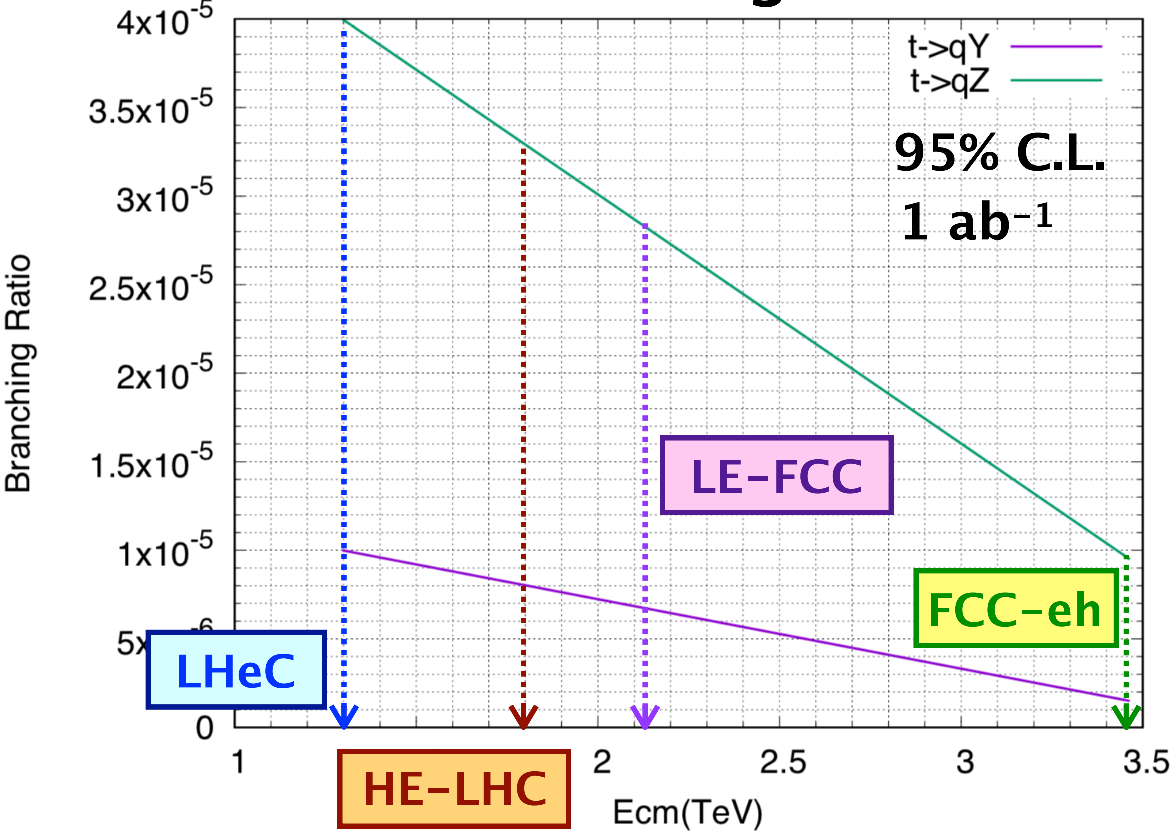
130<M_{Wb}<190 GeV

50<M_{jj}<100 GeV

→ **test exotic models leading to FCNC**

DELPHES

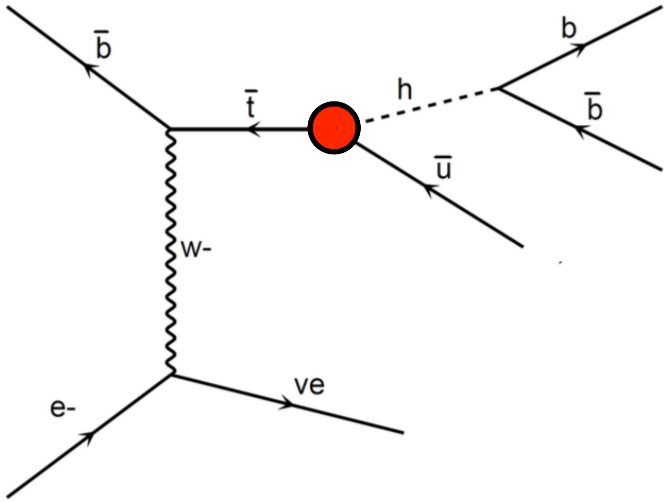




Search for Anomalous FCNC tHu Coupling

signal

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



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

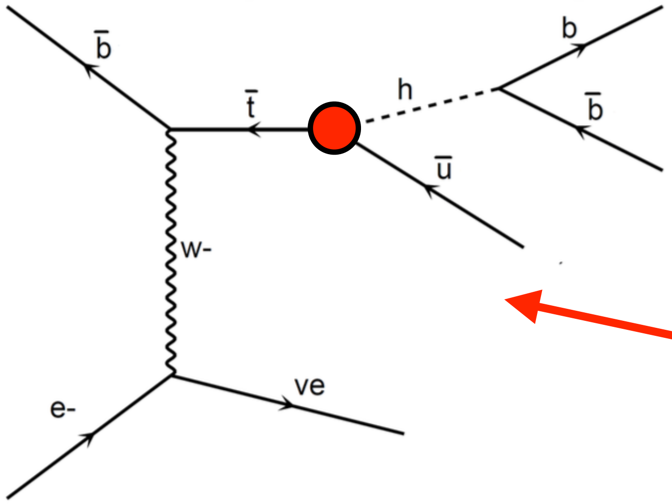
$$\boxed{\mathcal{L} = \kappa_{tuh} \bar{t} u h + \kappa_{tch} \bar{t} c h + h.c.}$$

Search for Anomalous FCNC tHu Coupling

signal

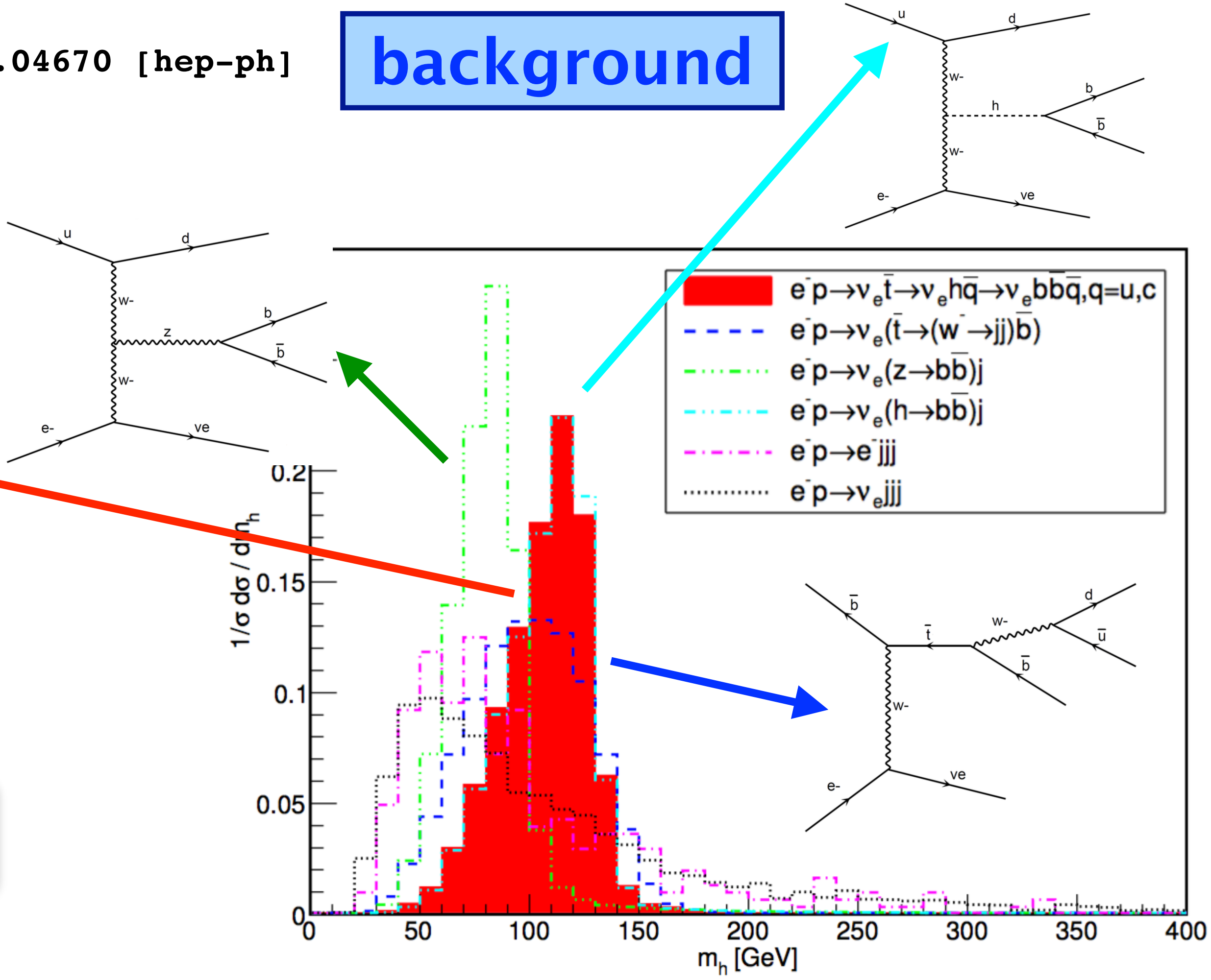
Sun, Wang,
arXiv:1602.04670 [hep-ph]

background



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

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

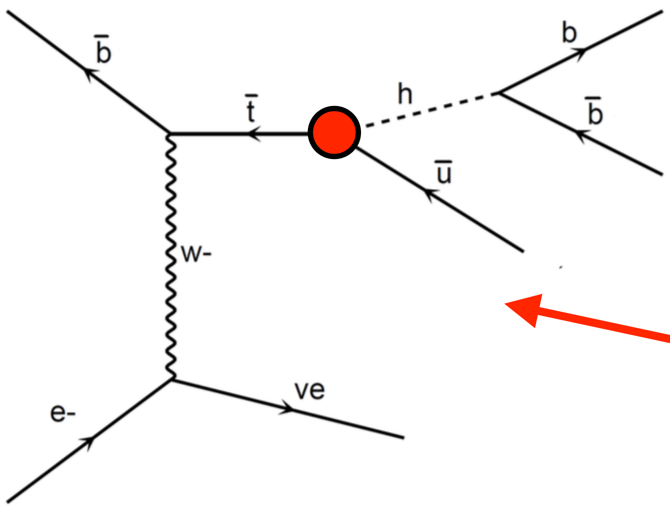


Search for Anomalous FCNC tHu Coupling

signal

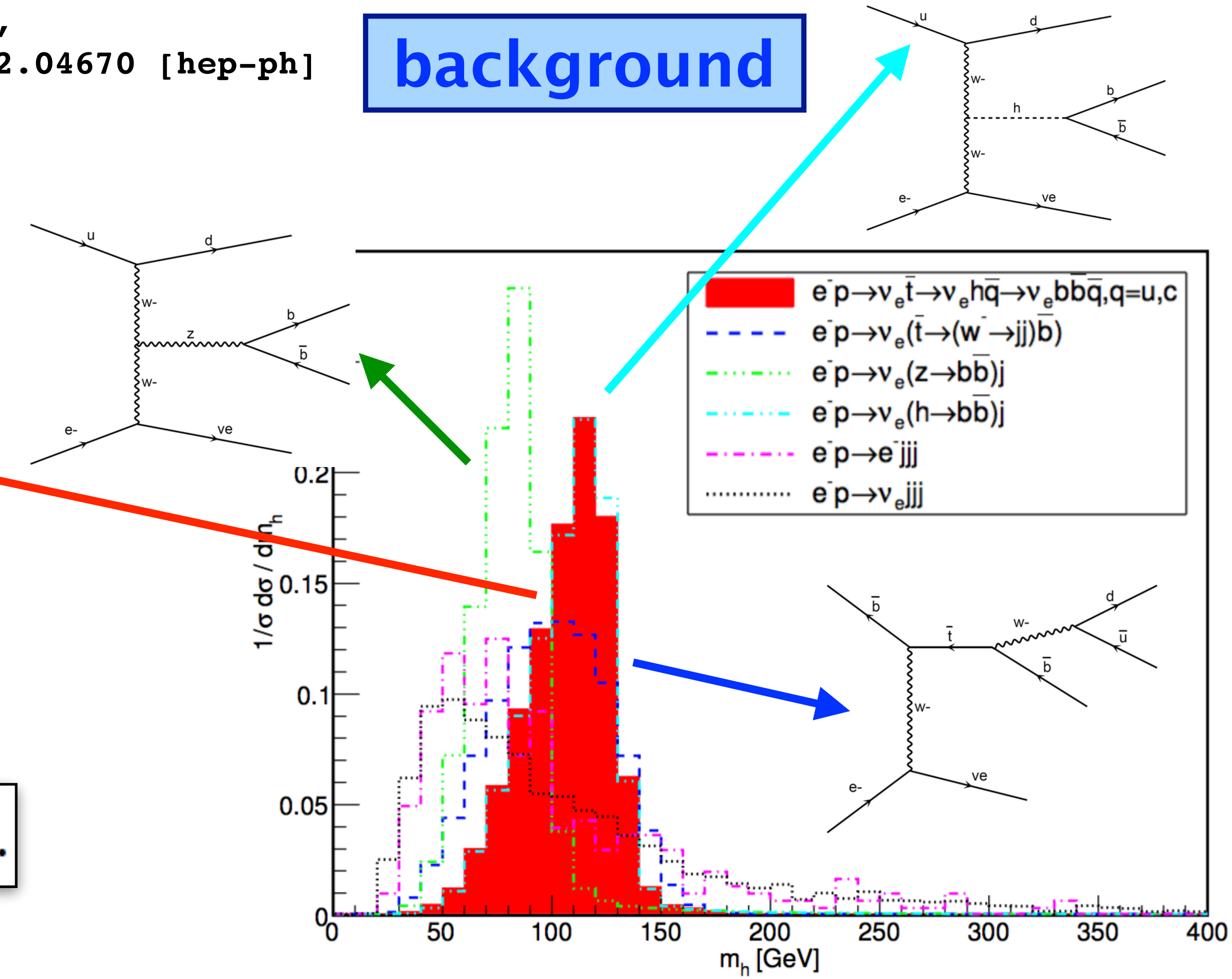
Sun, Wang, arXiv:1602.04670 [hep-ph]

background



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

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

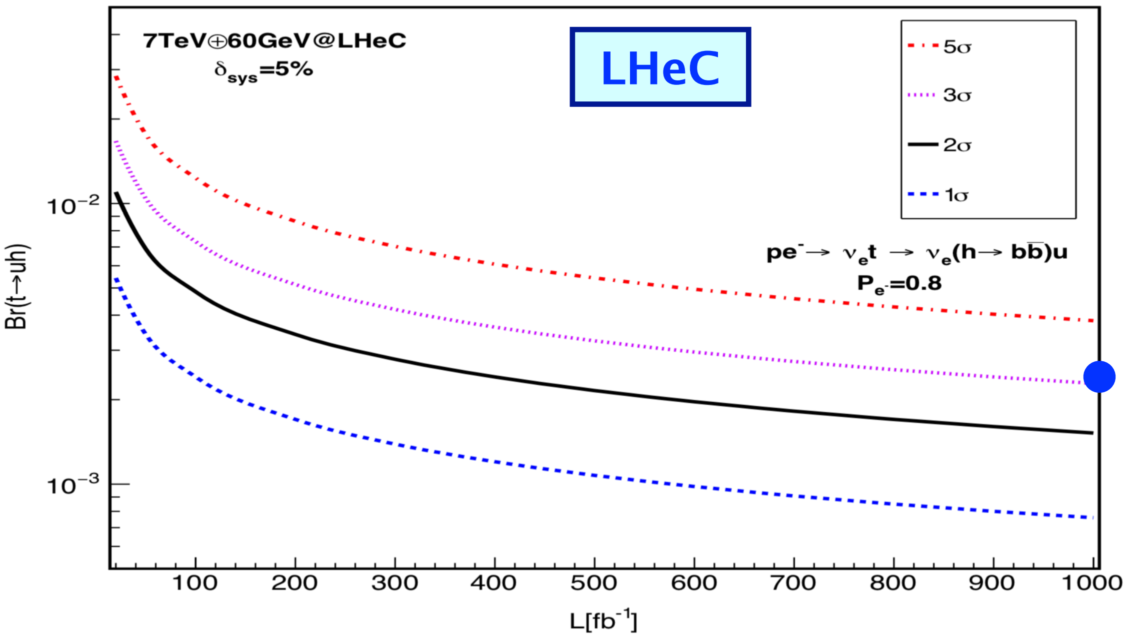


- parametrised assumed resolutions for electrons/photons, muons, jets and unclustered energy using ATLAS values
- b-tag rate of 60%, c-jet fake rate of 10%, light-jet fake rate of 1%
- selections optimized for LHeC and FCC-ep scenarios (s/√(S+B))
- cut-based and MVA-based analyses

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

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

parametrisation



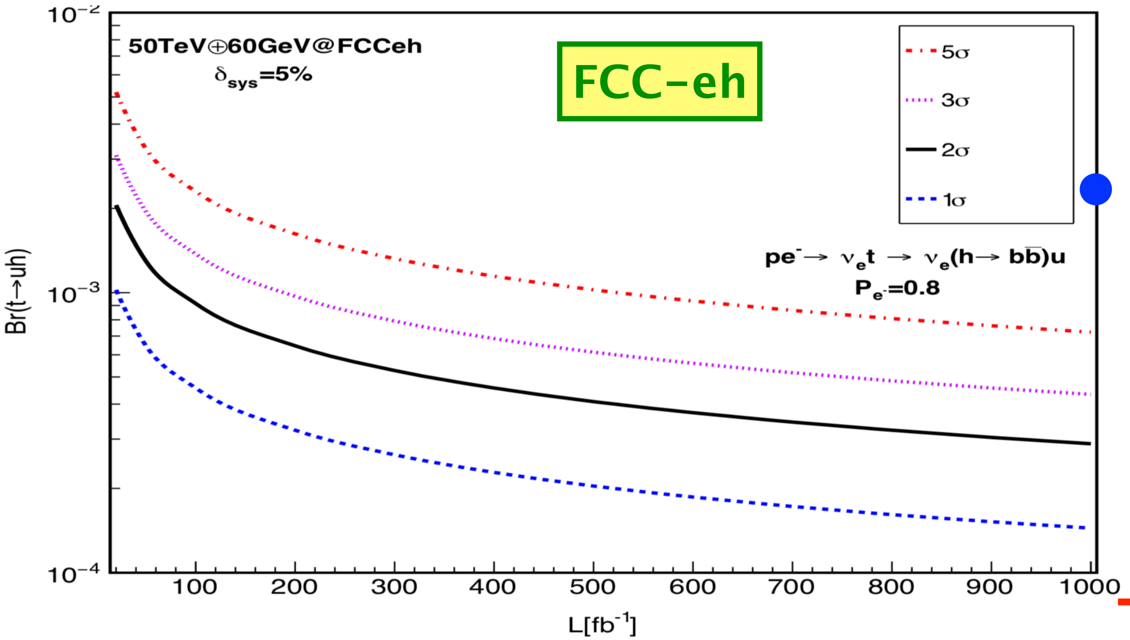
HL-LHC

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

<0.0015

2σ

(1ab^{-1})



HL-LHC

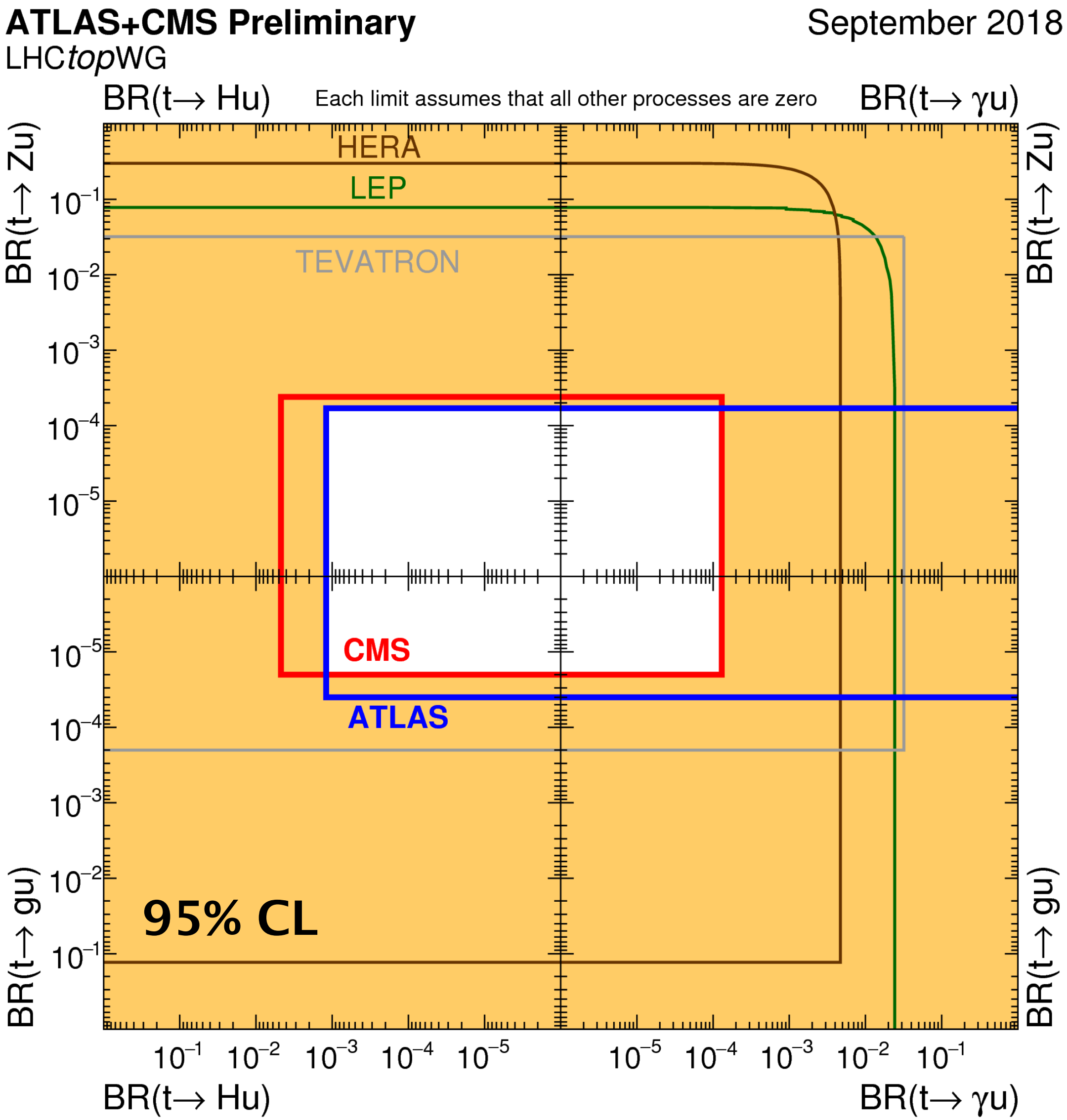
LHC, 3000 fb^{-1}@14TeV

2σ

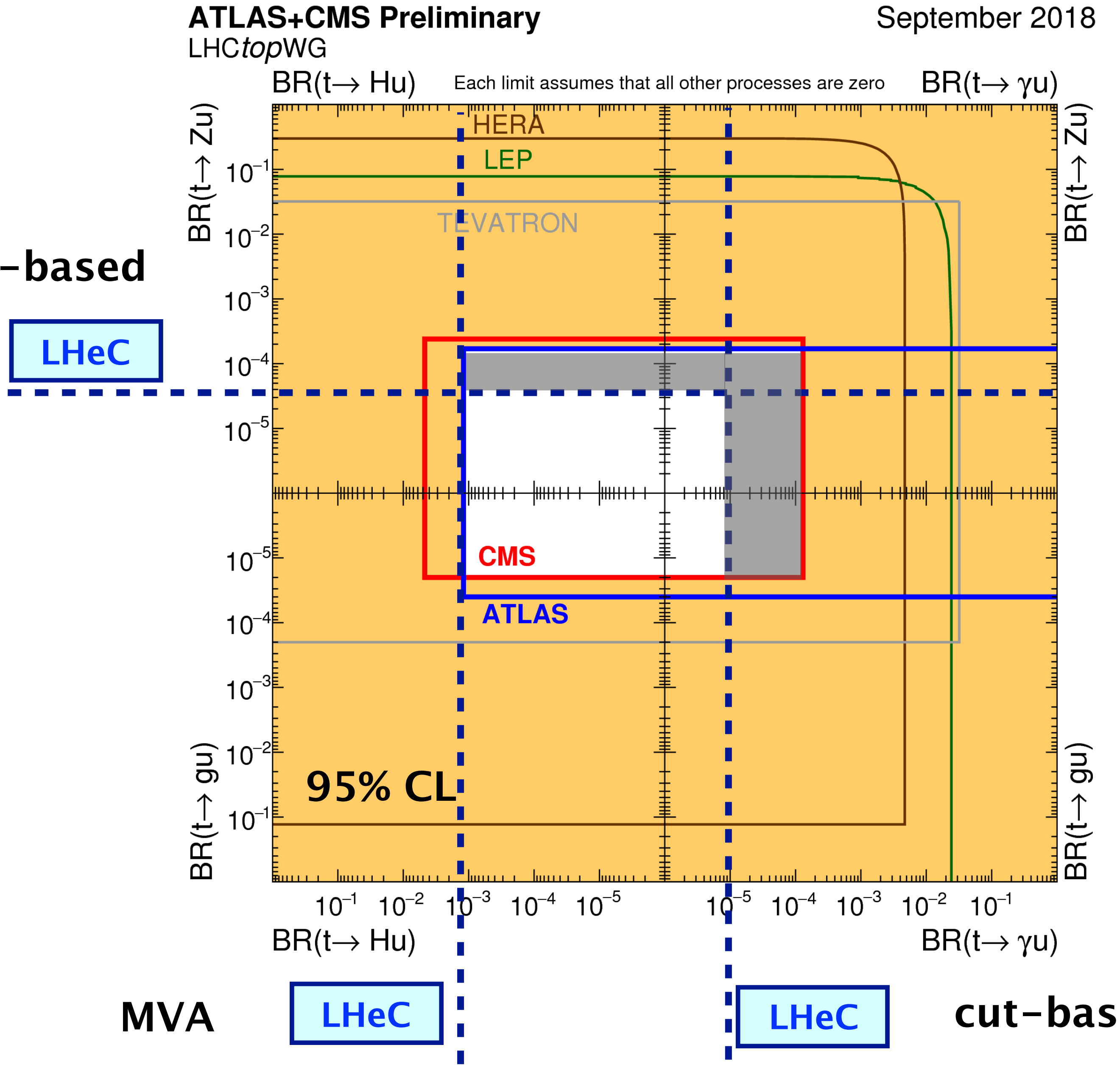
<0.0002 **(2ab^{-1})**

→ **improves HL-LHC sensitivity**

FCNC Branching Ratios at Colliders



FCNC Branching Ratios at Colliders



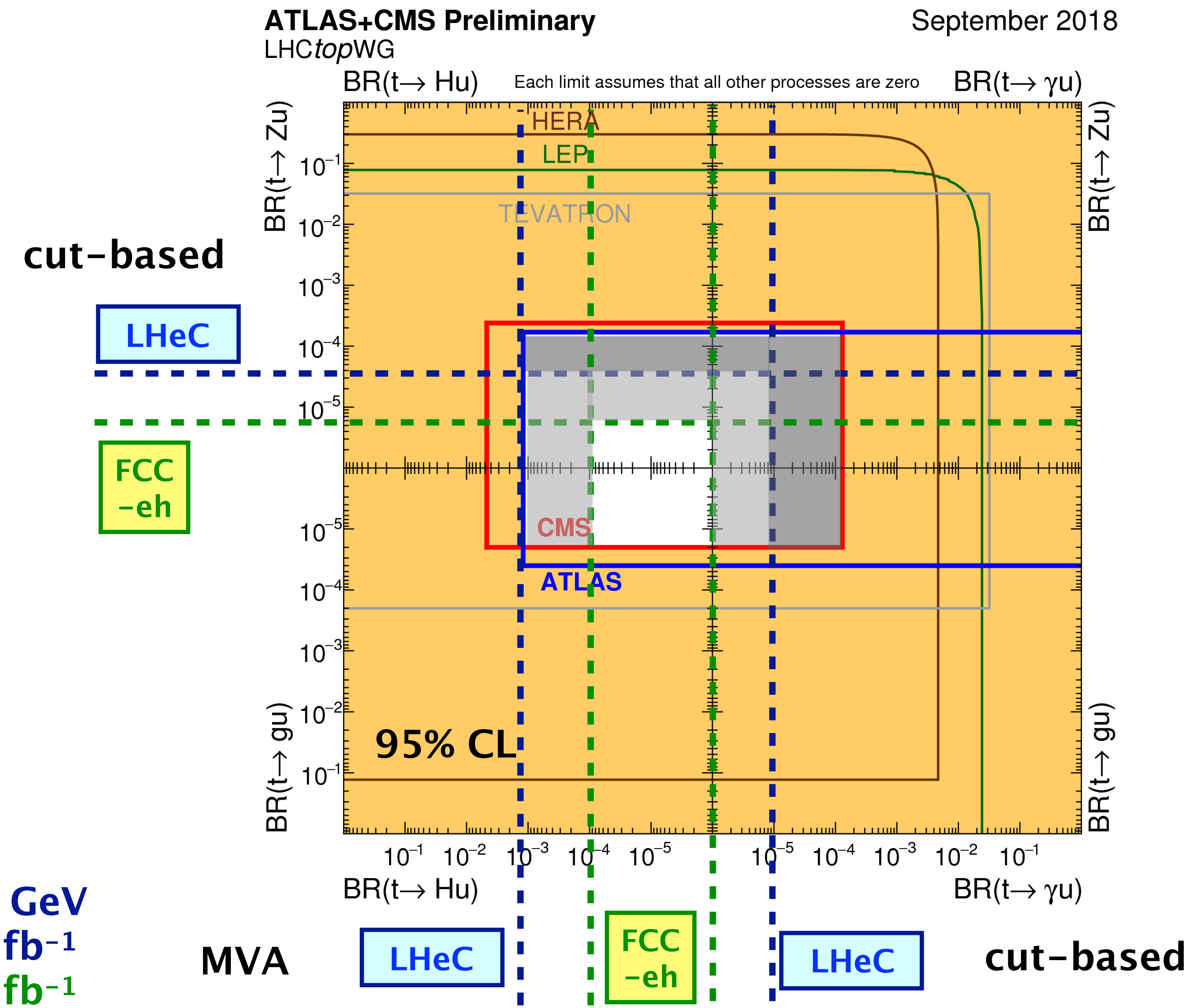
cut−based

LHeC

E_e=60 GeV
1000 fb^{-1}

MVA **LHeC** **LHeC** **cut−based**

FCNC Branching Ratios at Colliders

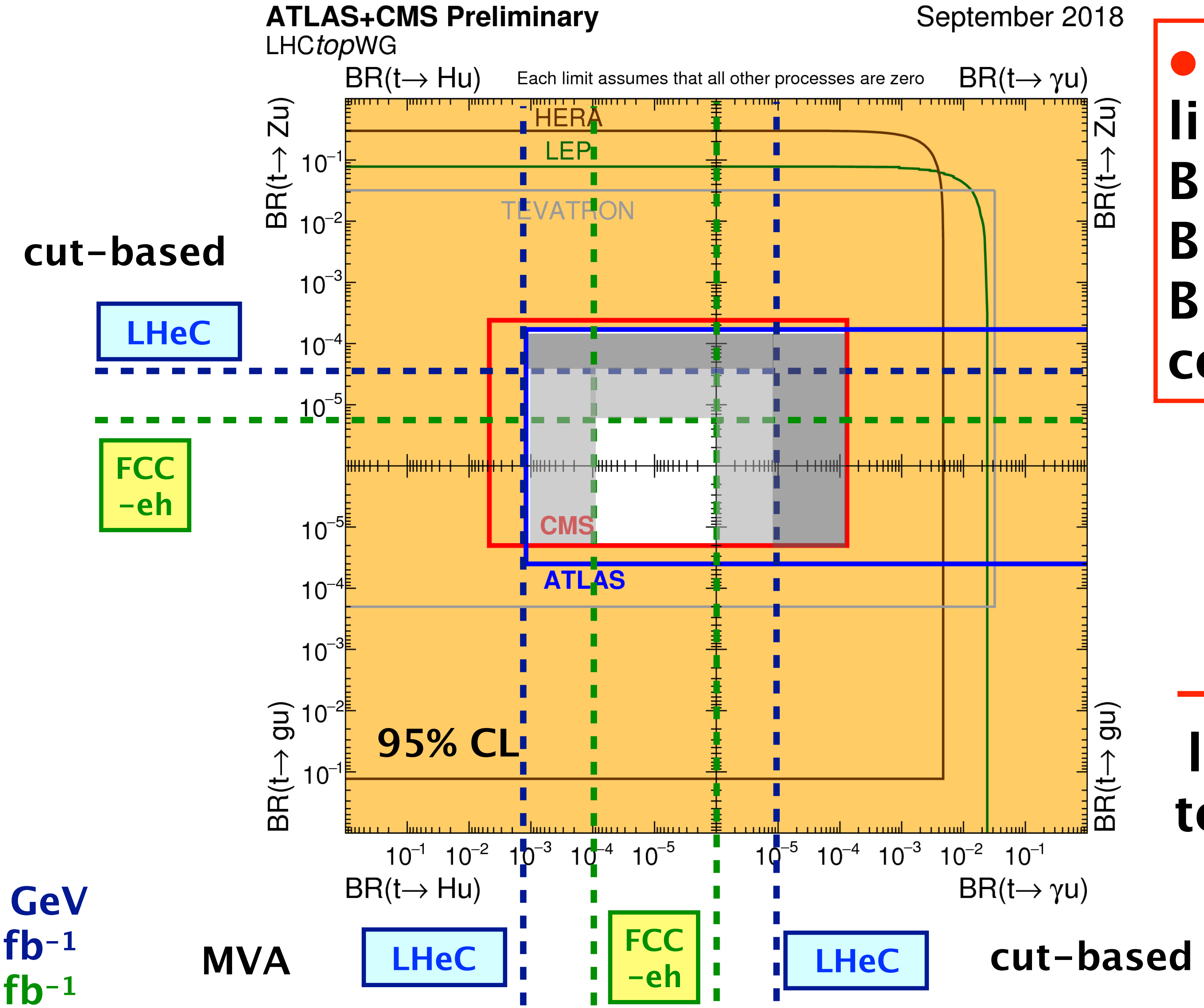


E_e=60 GeV

1000 fb^{-1}

2000 fb^{-1}

FCNC Branching Ratios at Colliders



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

→ test SUSY, little Higgs, technicolor...

E_e=60 GeV
1000 fb^{-1}
2000 fb^{-1}

Outline

Introduction

CC Top Production

NC Top Production

BSM Top Production

Conclusions

Summary

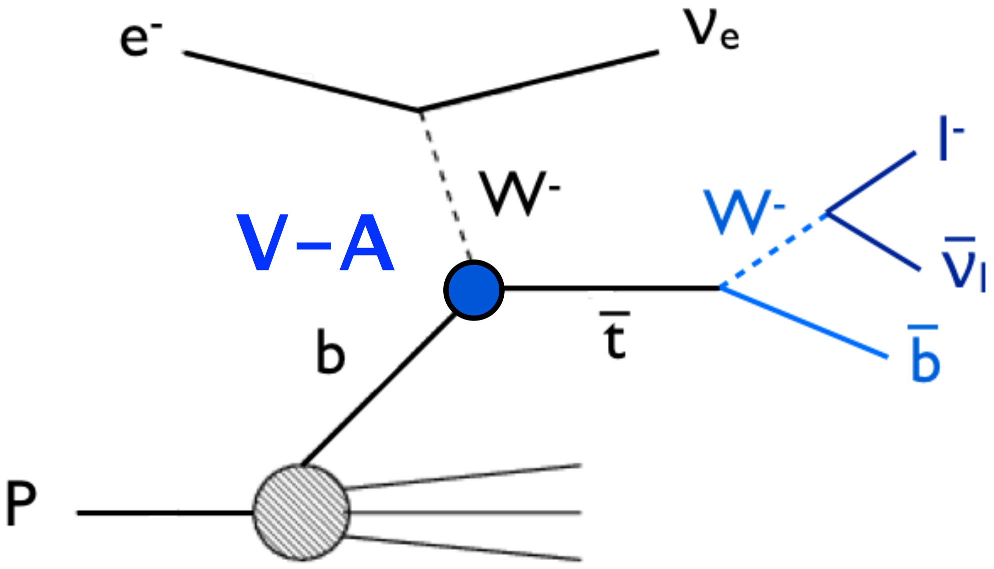
- future ep collider has a rich analysis programme, in particular for electroweak interactions of top quark
- single top quark factory: $|V_{tb}|$ (~1%)
- top quark couplings to bosons (Wtb, ttγ, ttZ, tH, FCNC)
- analyse top quark properties with high precision: polarisation, charge, PDFs of tops, ...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

→ DIS is competitive and complementary in performing high precision measurements of top properties

→ large sensitivities to discover new physics!

Backup

Top Quark Polarisation



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

TESLA+HERAp:

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

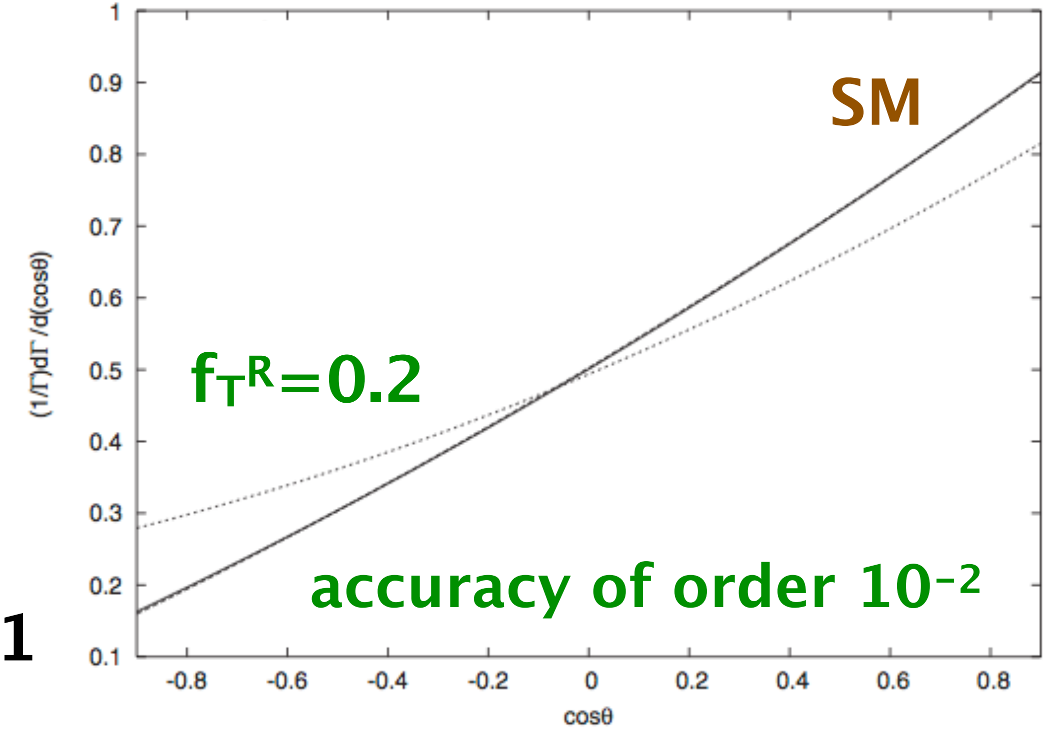
19.7 fb^{-1}: $A_{\uparrow\downarrow} = 0.26 \pm 0.11$

JHEP 04 (2016) 073

Atag, Sahin,
PRD 73, 074001 (2006)

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

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



SM

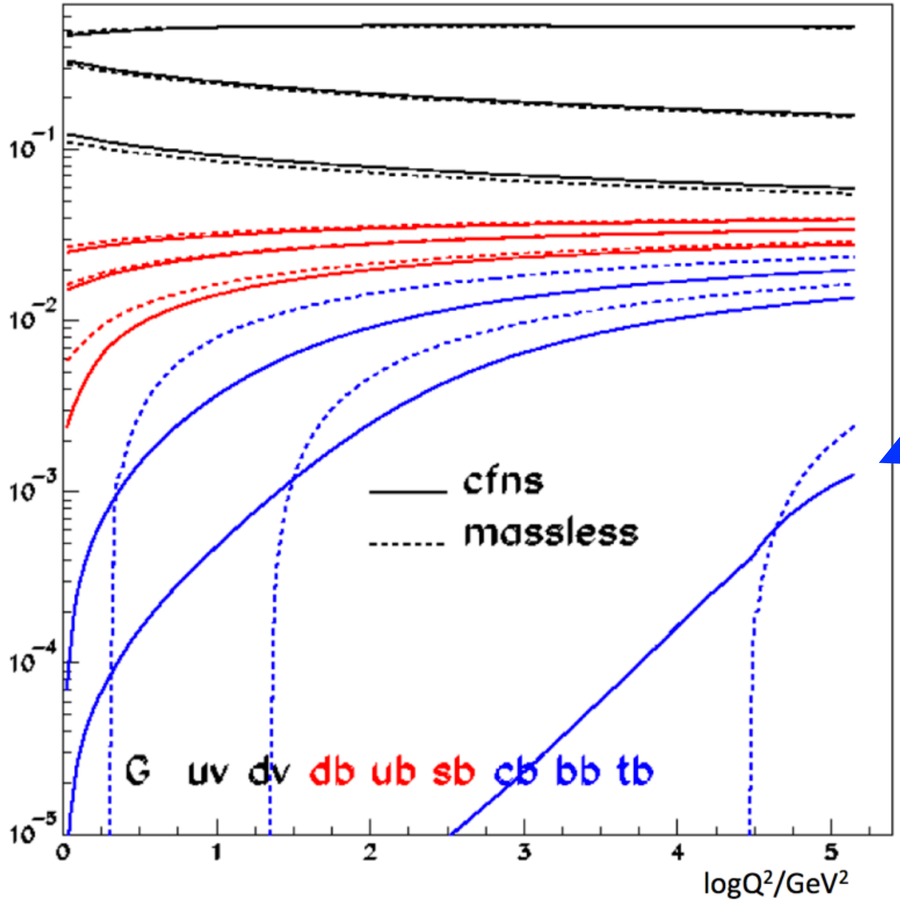
f_T^R=0.2

accuracy of order 10^{-2}

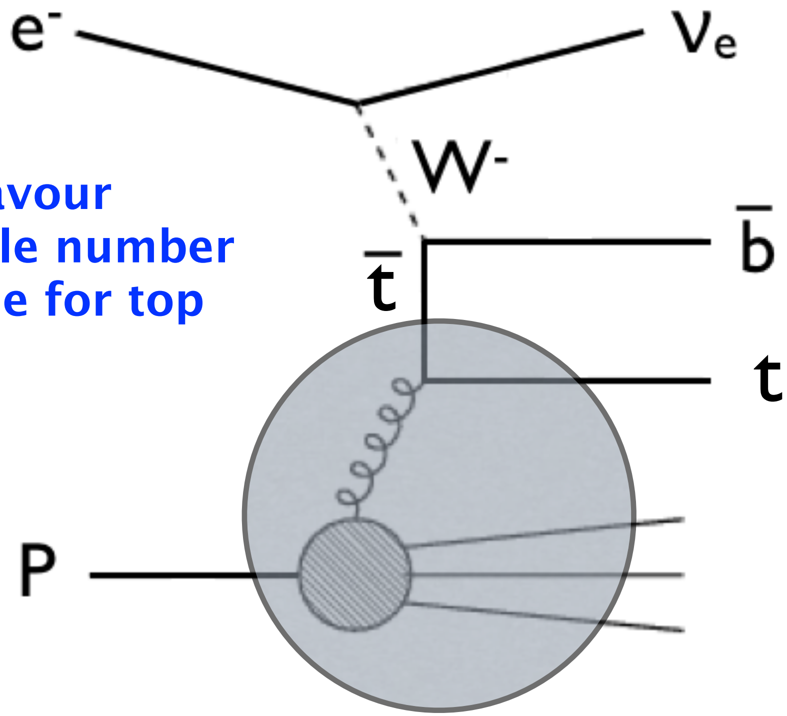
Top Quark Parton Density Function

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

parton momentum fraction



six-flavour variable number scheme for top quark



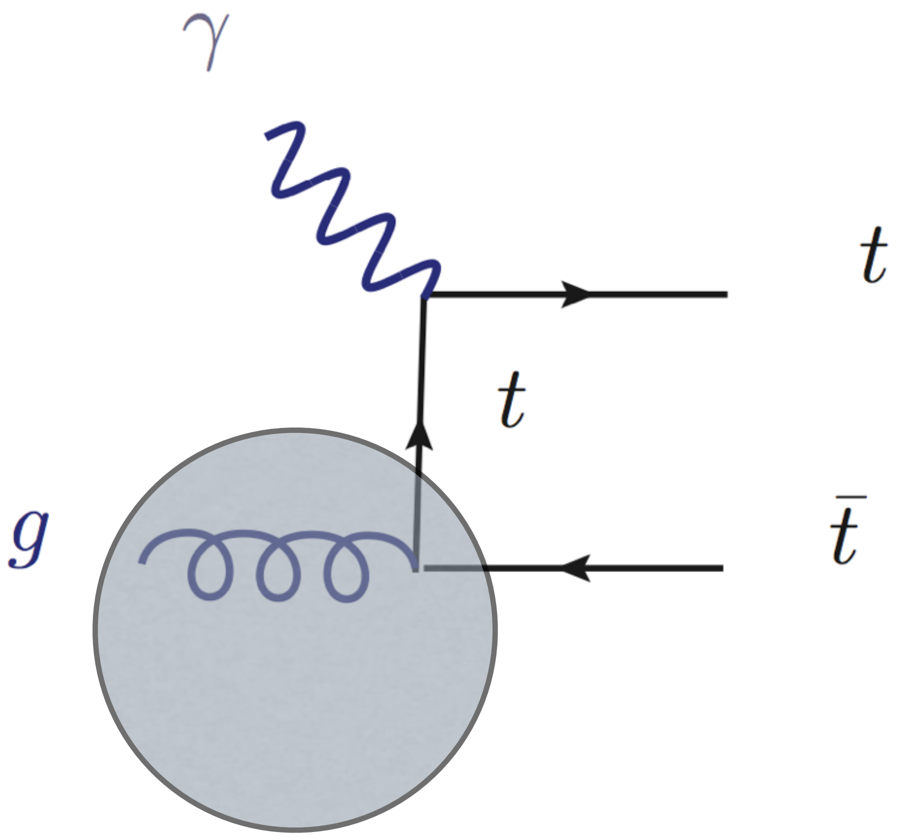
→ LHeC offers new field of research for top quark PDF

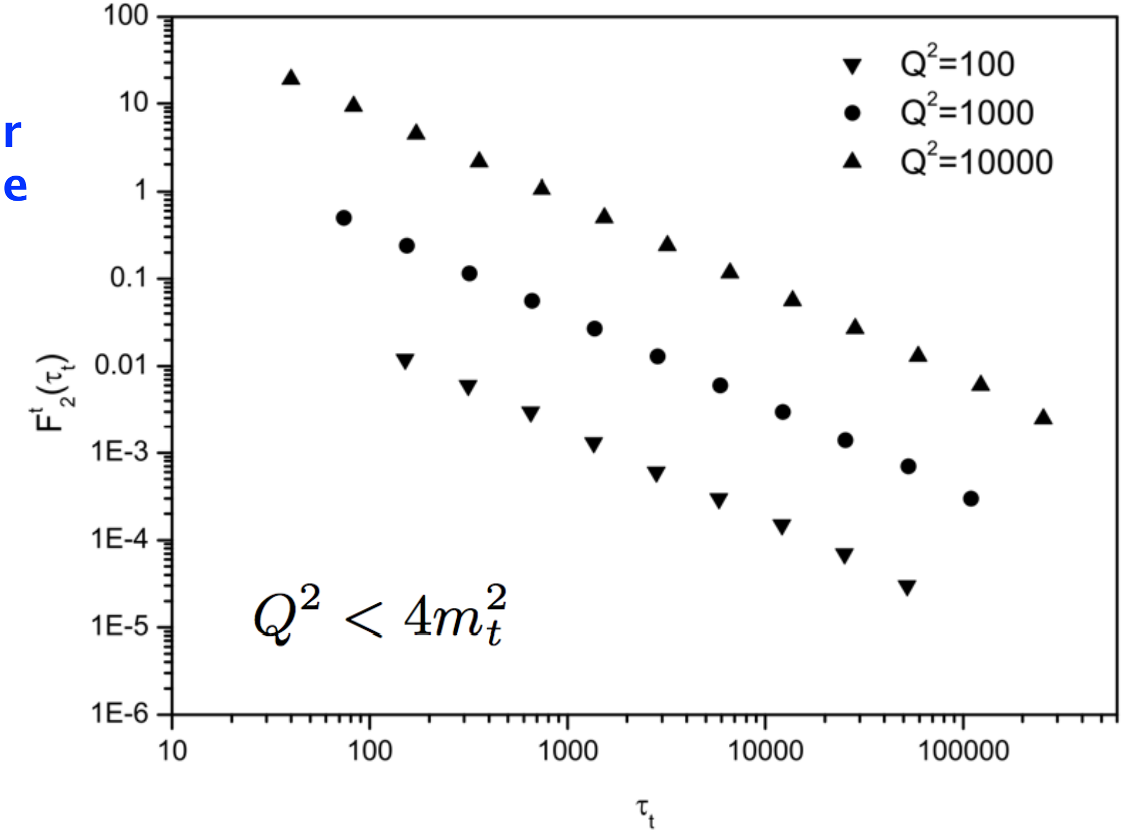
Top Quark Structure Function

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

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

variable flavour number scheme for top quark





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

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

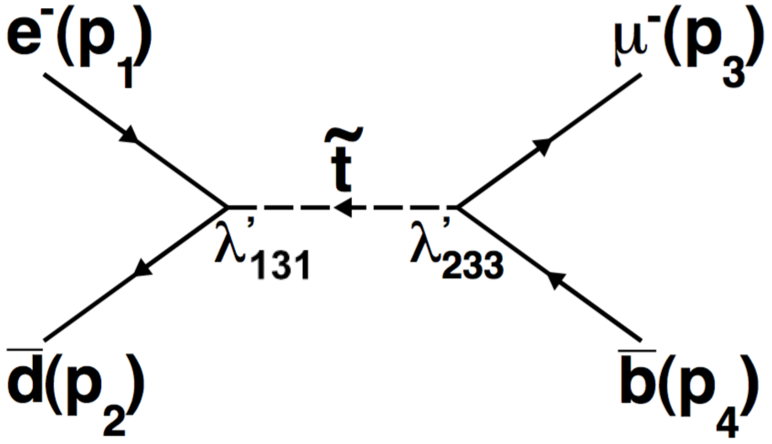
→ LHeC opens up a new field of top quark PDFs

Searches for RPV SUSY and stops

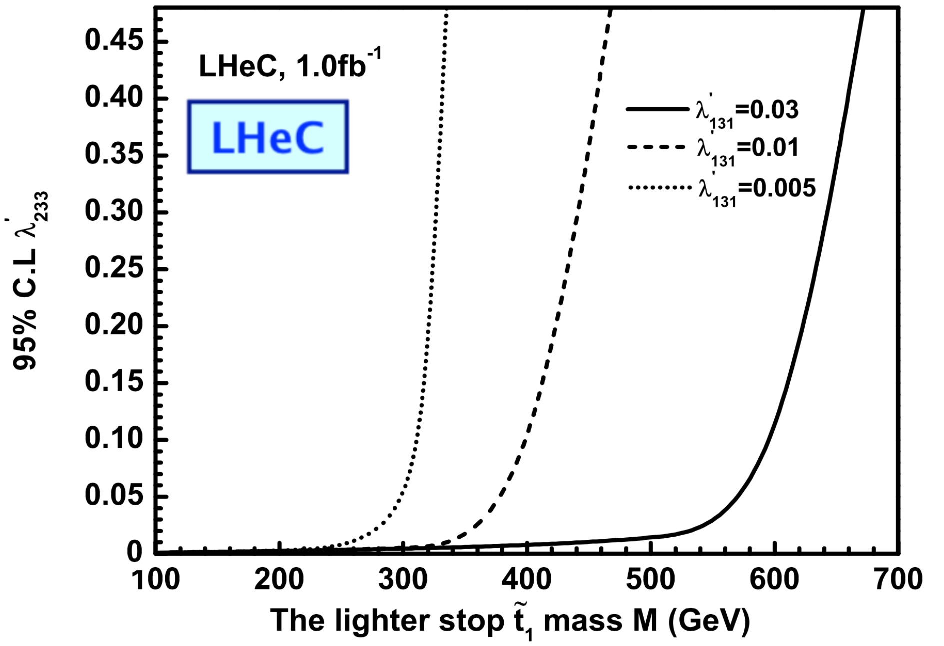
$$W_{\not R p} = \overbrace{\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{H}_u}^{L\text{-number violating terms}} + \underbrace{\lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k}_{B\text{-number violating terms}}$$

bilinear terms

ΔL =1, 9 λ couplings, 27 λ’ couplings



similar to leptoquark searches
with generation mixing

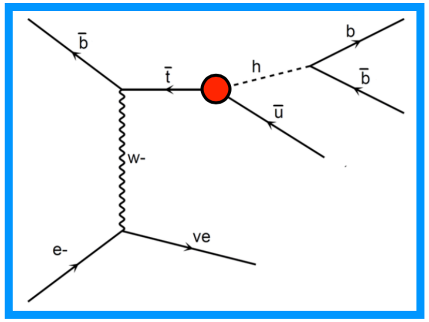


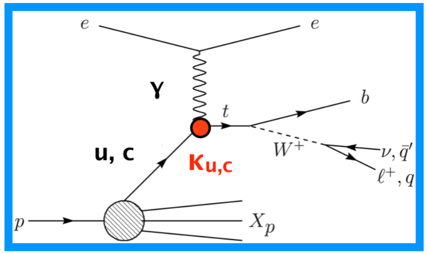
→ very promising with high luminosity

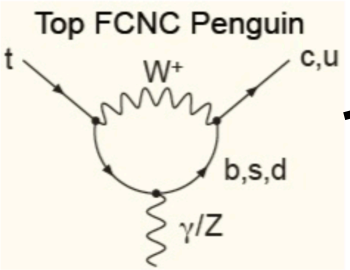
→ RPV can be probed at unprecedented levels

FCNC Top Quark Couplings

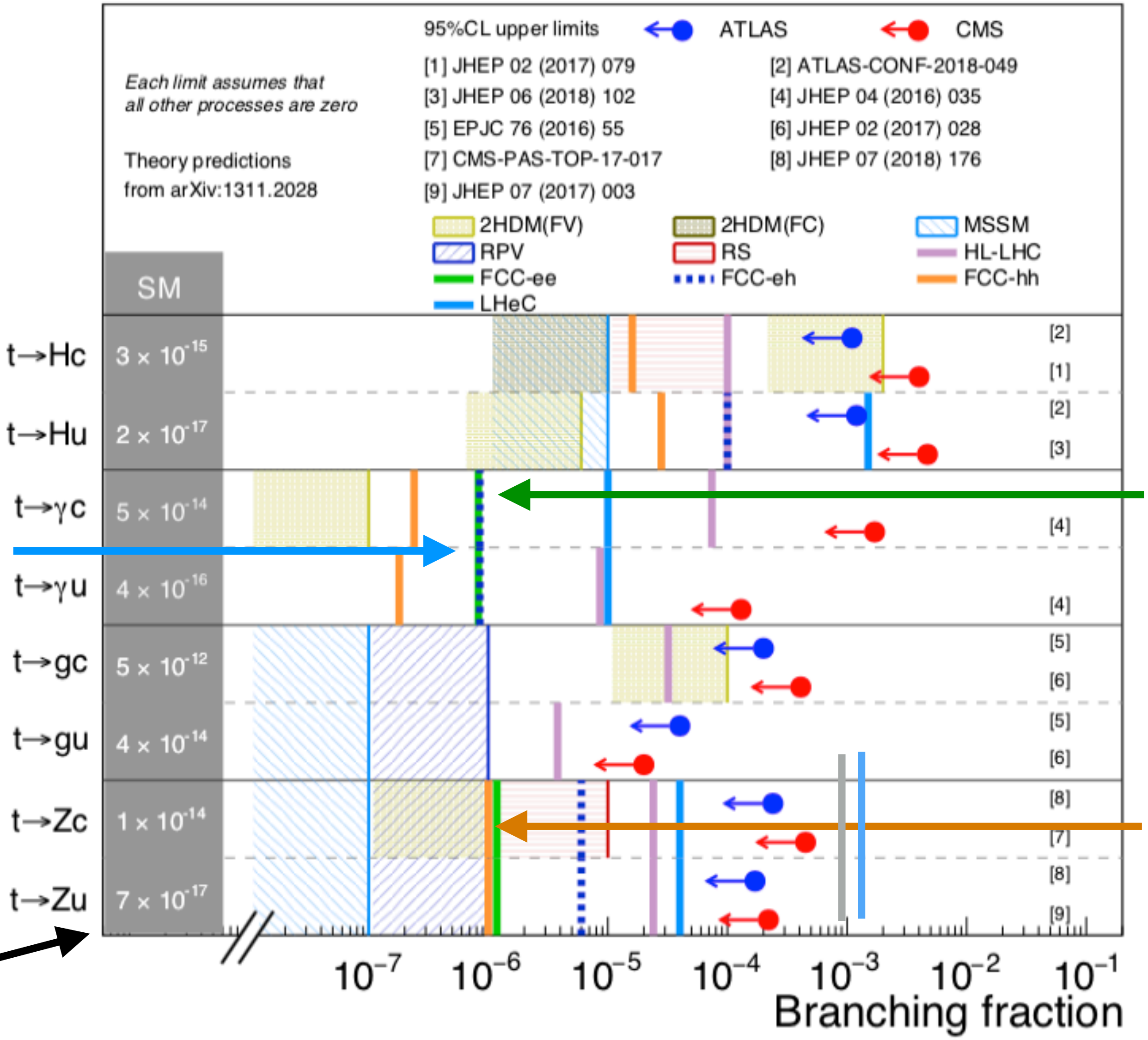
LHeC **FCC-ep**



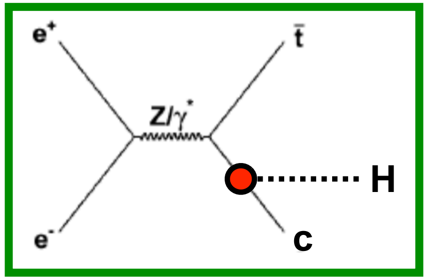


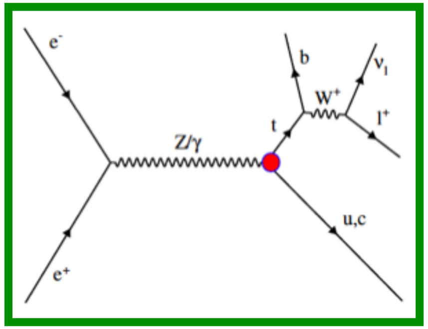


FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)



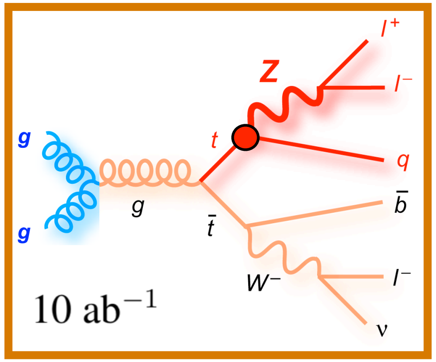
→ **complementarity of colliders**





CLIC **FCC-ee**

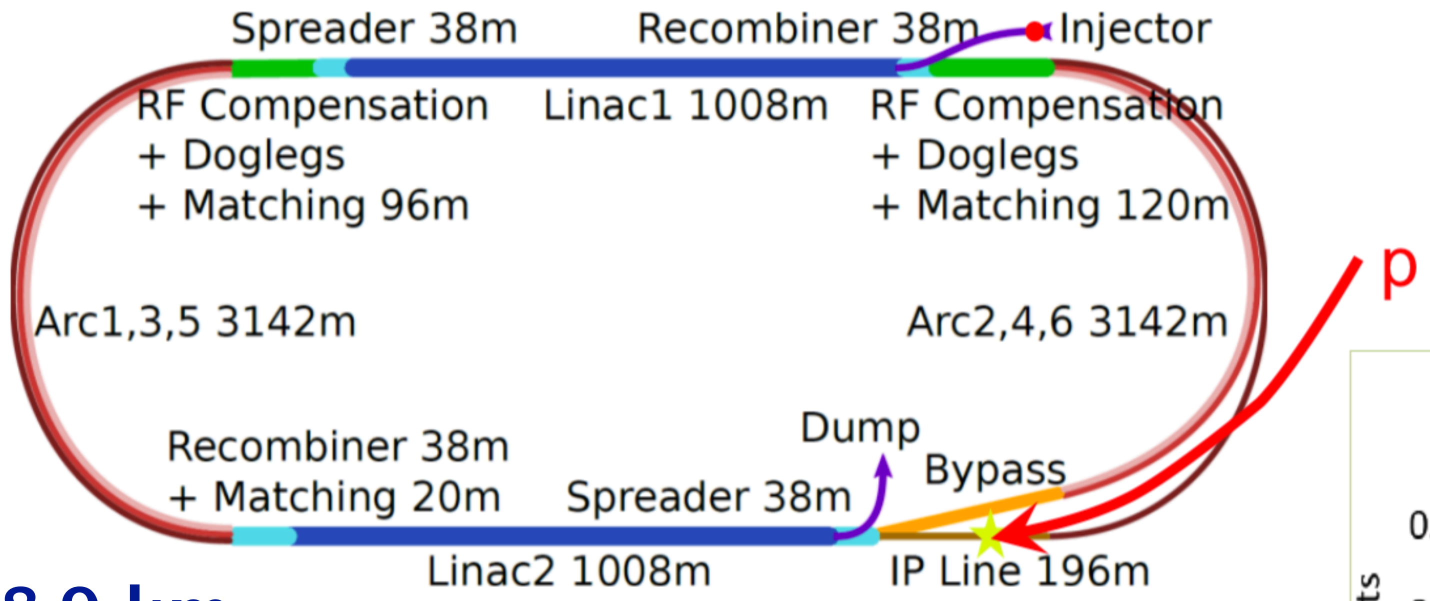
FCC-pp



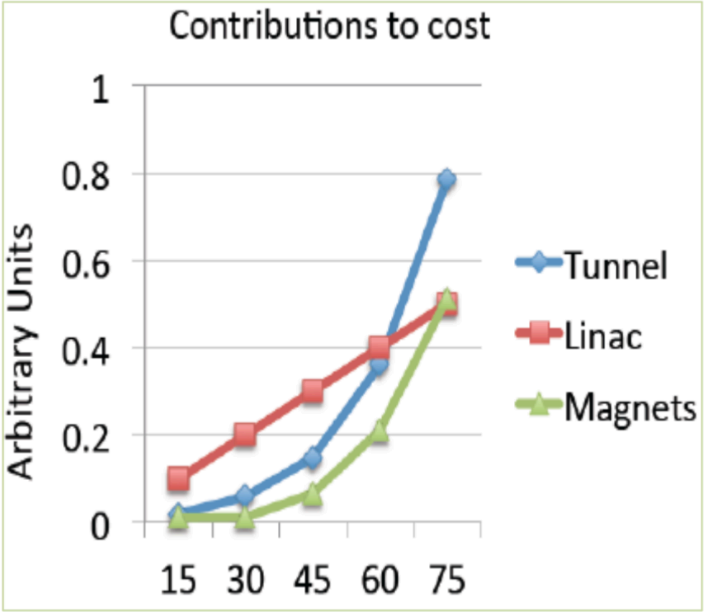
Energy Recovering Linac

Energy Recovering Linac (ERL):

E_e=60 GeV



8.9 km



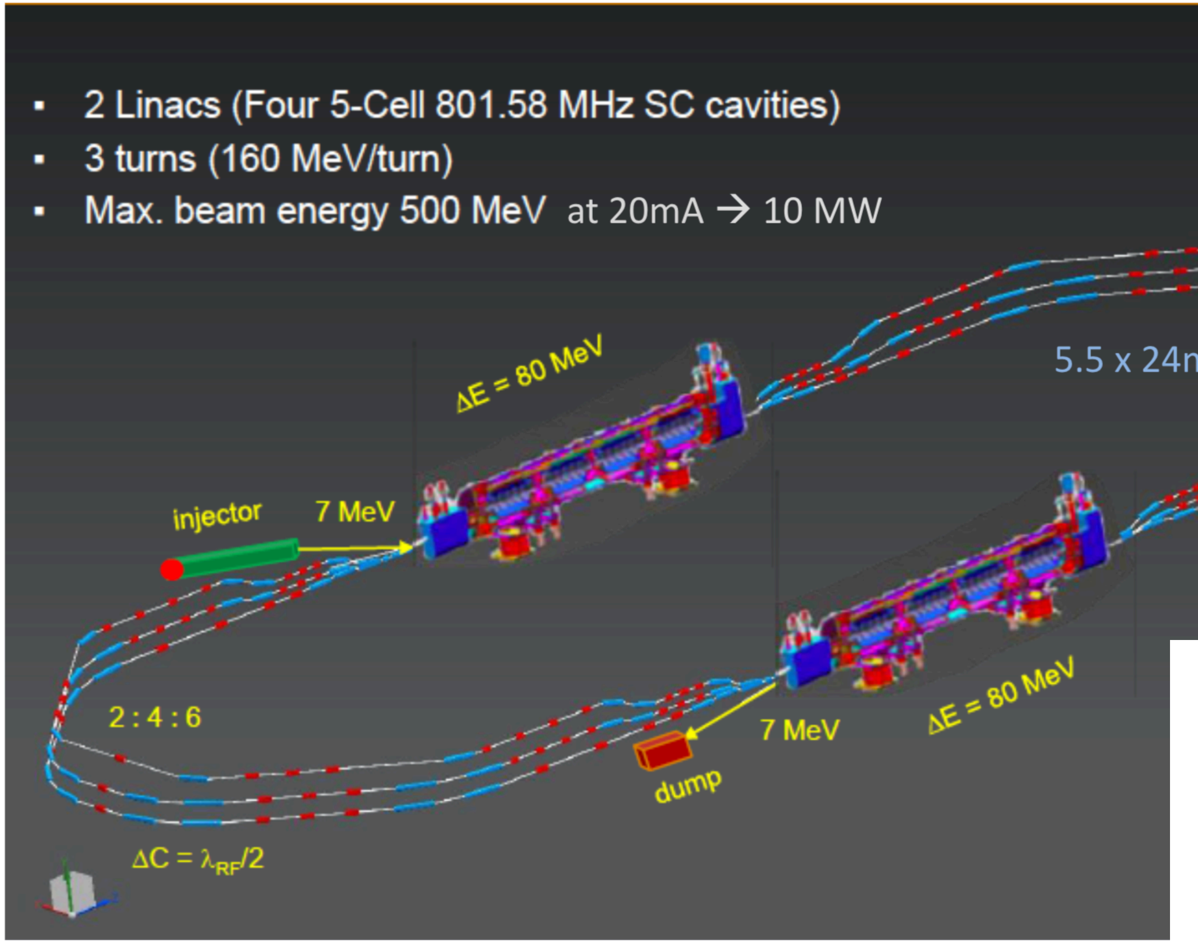
M. Klein, F. Zimmermann

Initial, tentative, rough scaling estimate of basic cost (tunnel, linac (XFEL), magnets

- power limit: 100 MW
- luminosity: 10^{34} cm^{-2} s^{-1}
- factor of 15/120 (LHeC/FCC-eh) extension of Q^2, 1/x reach

Powerful ERL for Experiments (PERLE)

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV at 20mA → 10 MW



cf Walid Kaabi at Amsterdam FCC

CERN
cnrs IN2P3 Les deux infinis
Jefferson Lab
Science & Technology Facilities Council
Budker Institute of Nuclear Physics
UNIVERSITY OF LIVERPOOL

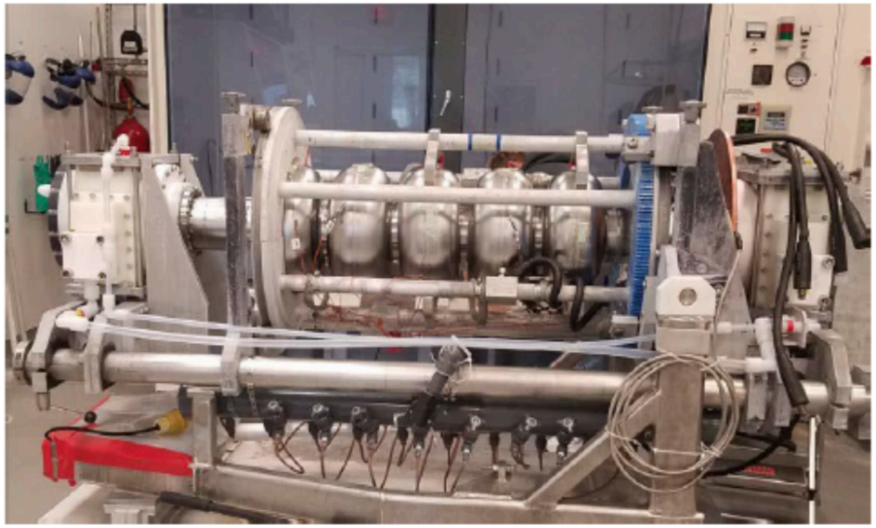
→ **ERL demonstrator**
→ **O(10 MeV) physics**

in Orsay

- **BINP**
- **CERN**
- **Daresbury/Liverpool**
- **Jlab**
- **Orsay**

→ **CDR 1705.08783 [J. Phys G]**
→ **TDR in 2019**

First 802 MHz cavity successfully built (Jlab)



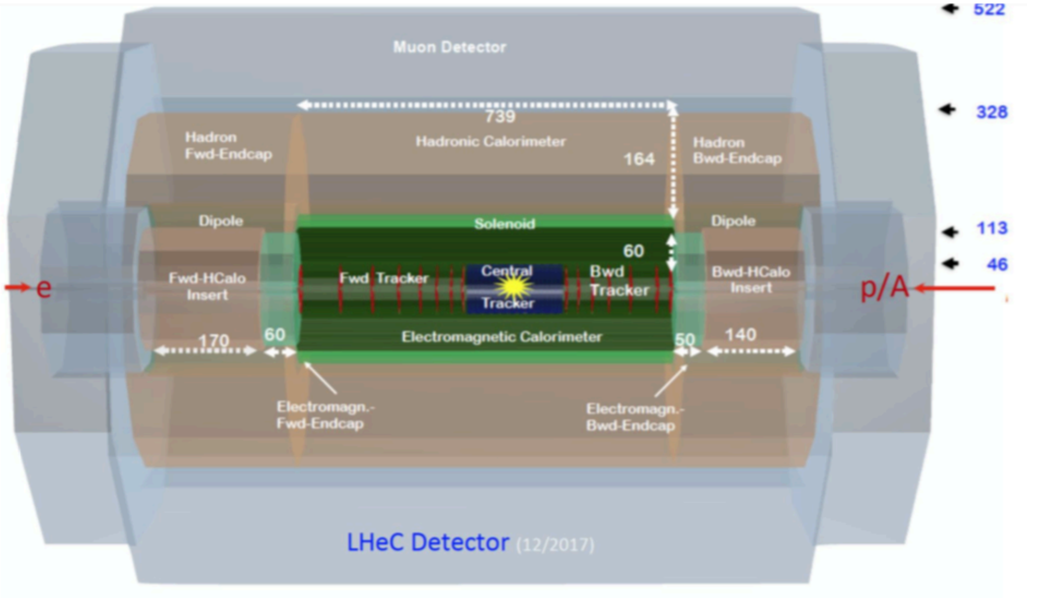
LHeC Detector Layout

- Cross section with MadGraph5
  - tree-level Feynman diagrams using p_T of scattered quark as scale for ep processes
  - Fragmentation & hadronisation uses ep-customised Pythia.

- DELPHES Fast Detector Simulation
  - ‘Standard’ GPD LHC-detectors
    - Optimising vertex resolution a la ATLAS IBL of ~ 5 μm
    - ATLAS b-tagging efficiencies
    - Using state-of-the art hadronic and el.mag. Resolutions
  - Considering displaced vertices and impact parameter distributions

Slide: M. Schott

[arXiv:1802.04317]

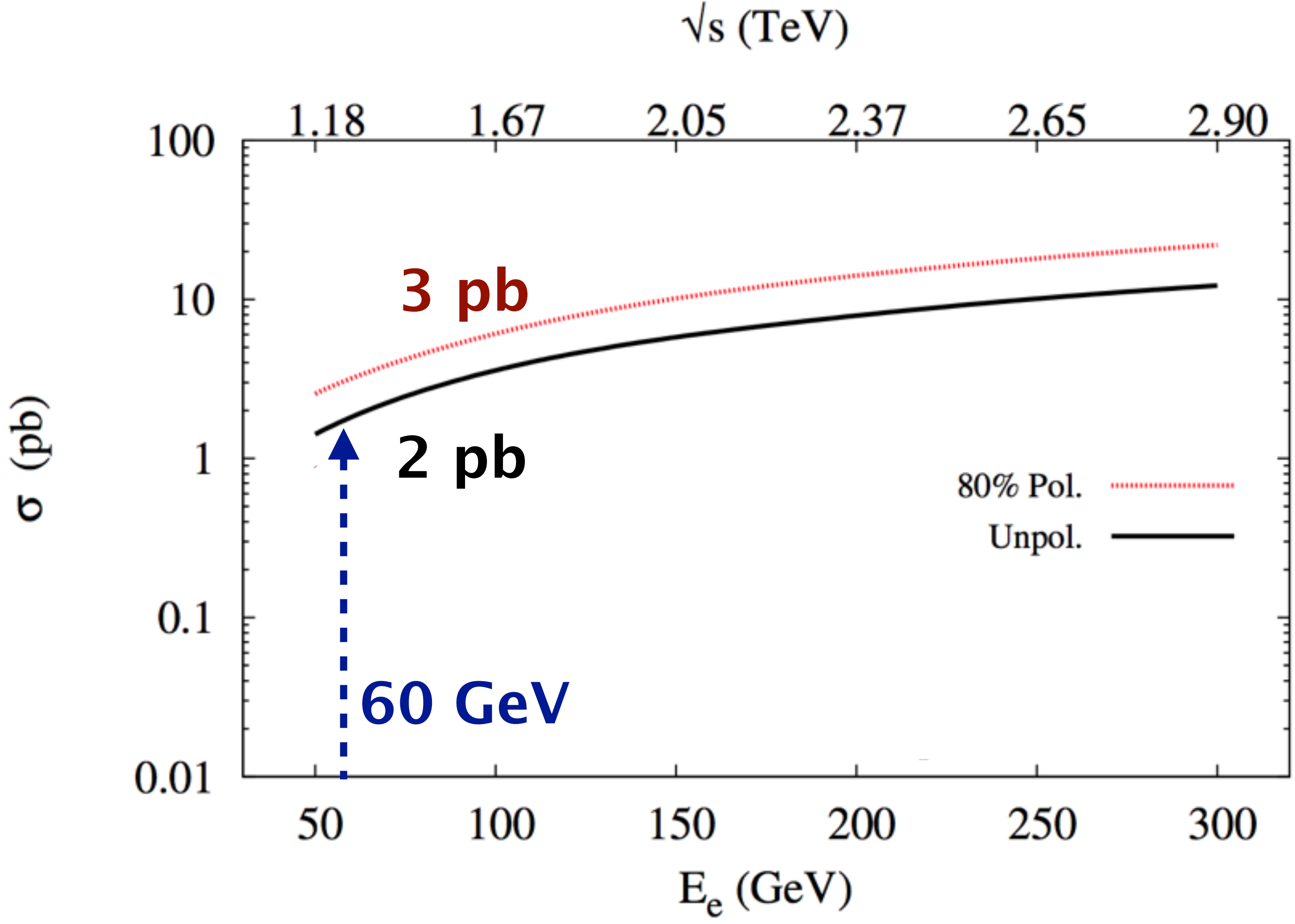


Length x Diameter: LHeC (13.3 x 9 m^2) HE-LHC (15.6 x 10.4) FCCeh (19 x 12)
ATLAS (45 x 25) CMS (21 x 15): [LHeC < CMS, FCC-eh ~ CMS size]

Object	Acceptance
Electrons	$\|\eta\|<4.7$
Muons	$\|\eta\|<4.7$
Jets	$\|\eta\|<5$
b-tagging	$\|\eta\|<3.5$

CC Single Top Quark Cross Section

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



100 fb^{-1}:

$2 \cdot 10^5$ events

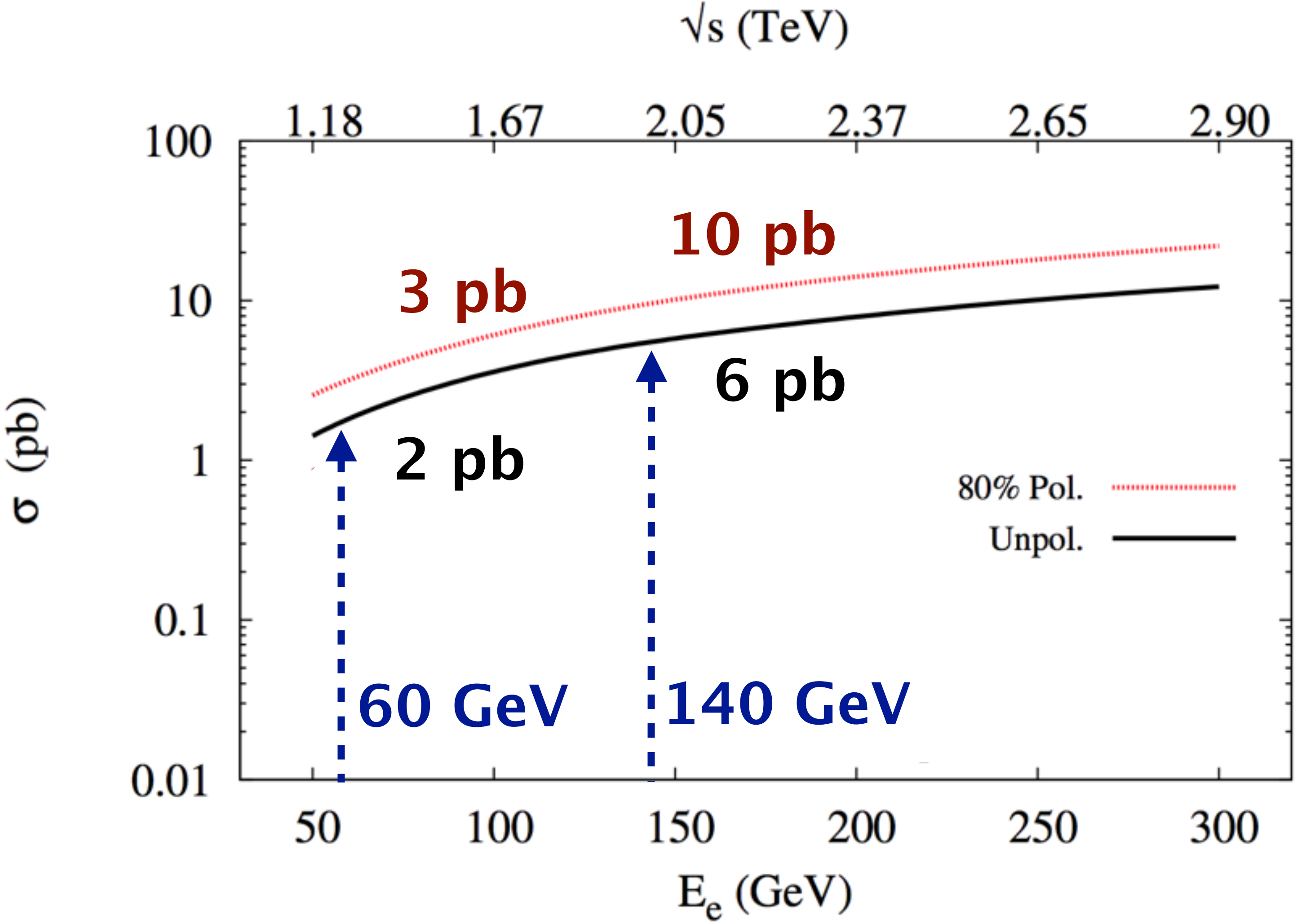
$3 \cdot 10^5$ events

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

CC Single Top Quark Cross Section

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

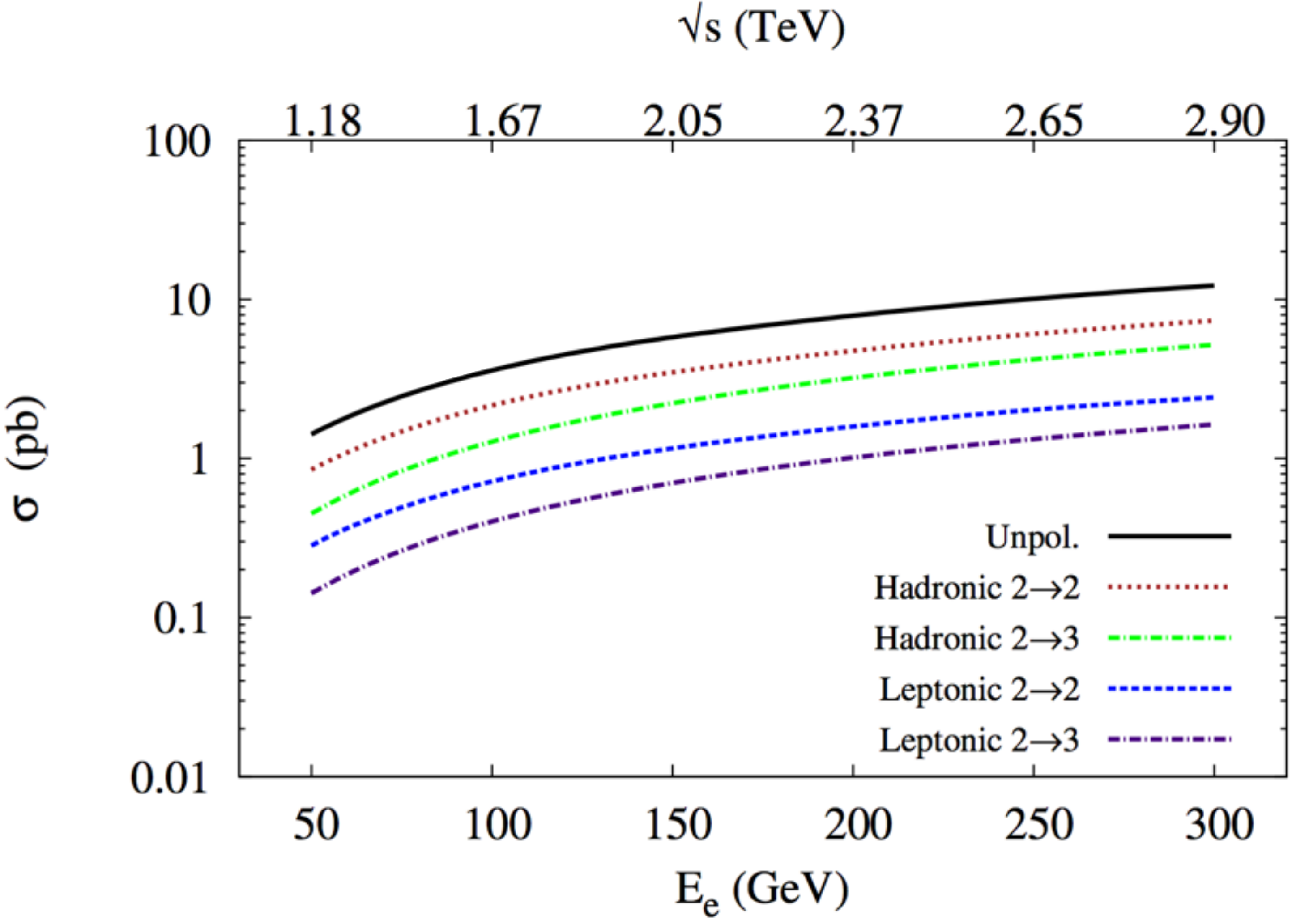
$100\ \text{fb}^{-1}$:
$2-6 \cdot 10^5$ events
$3-10 \cdot 10^5$ events

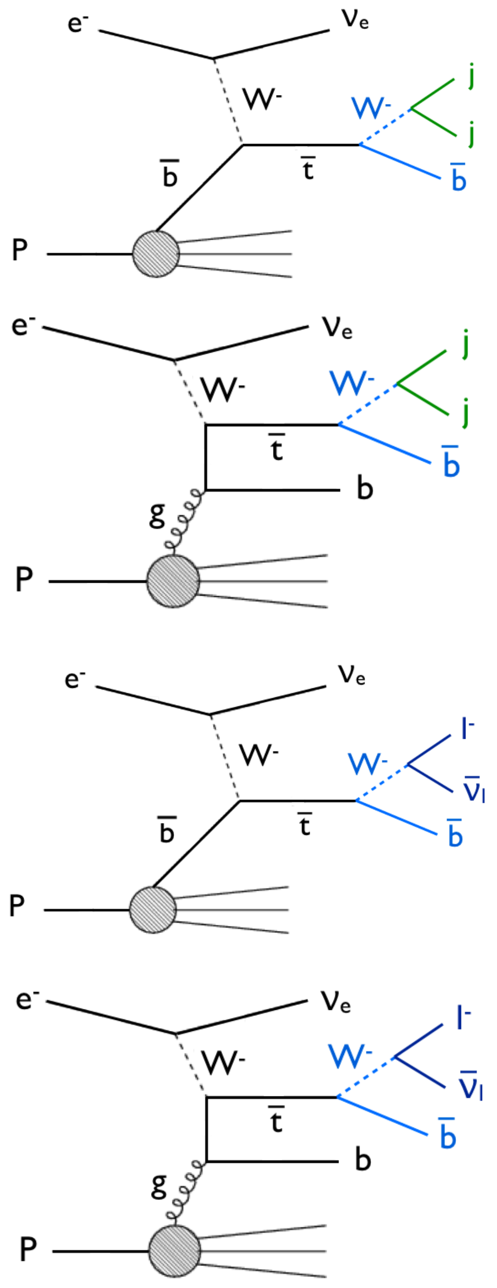


→ **LHeC offers excellent prospects for top quark physics**

CC Single Top Quark Cross Section

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



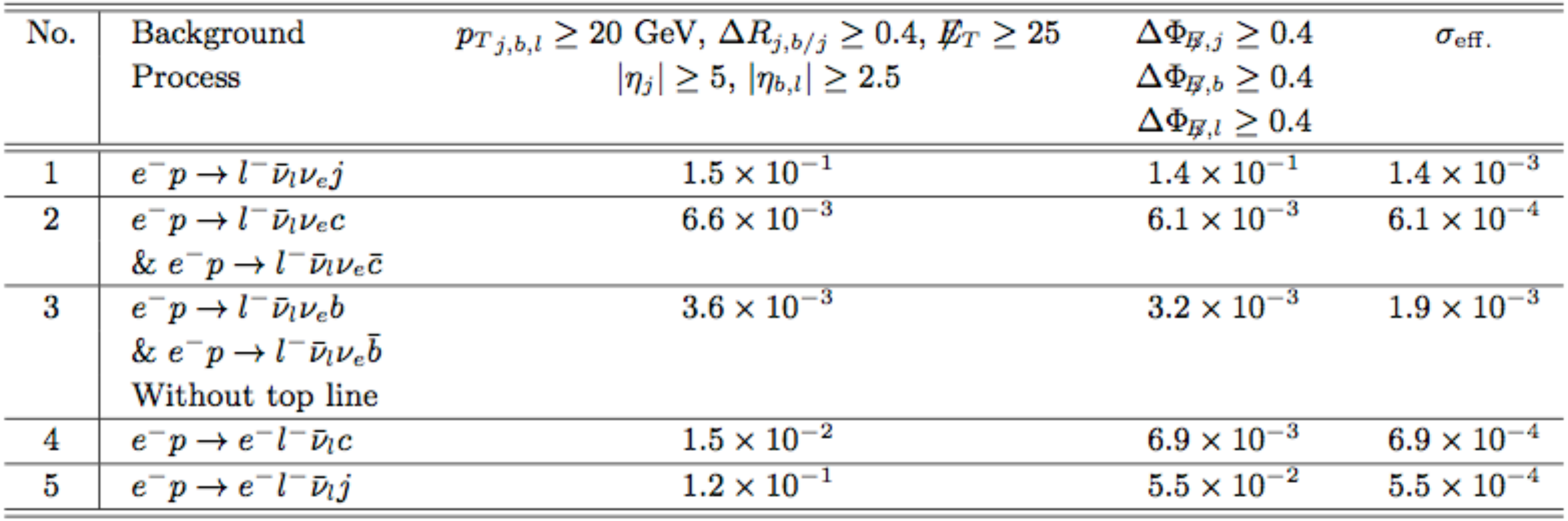


Backgrounds: Hadronic Channel

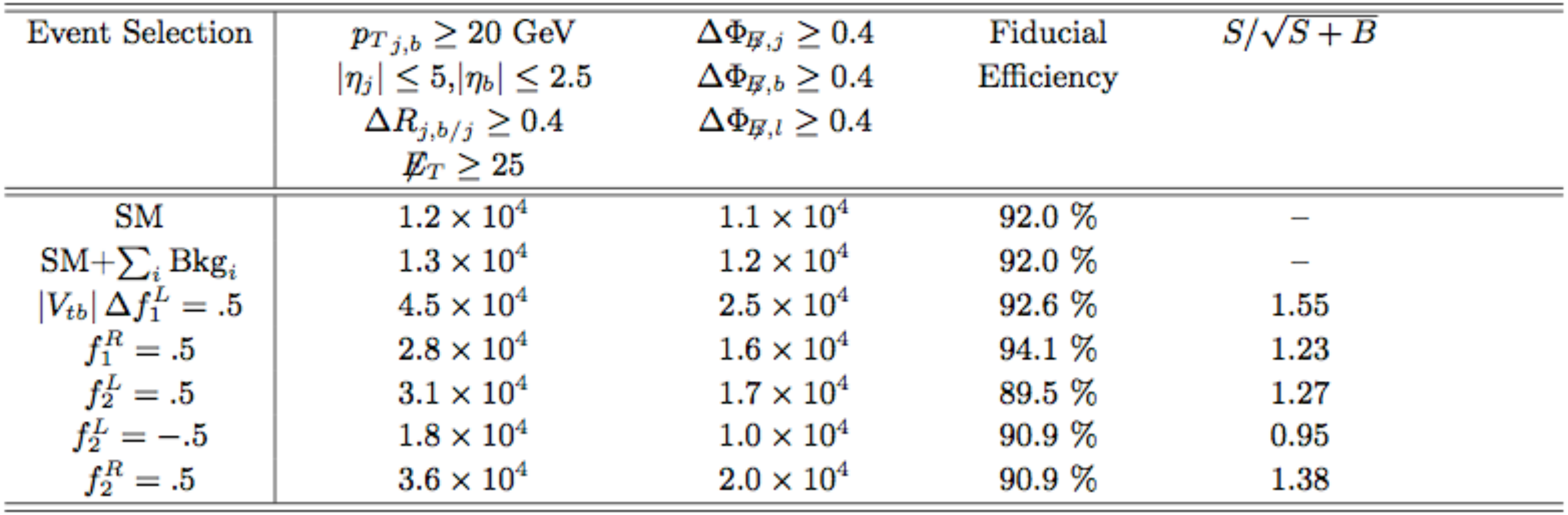
No.	Background Process	$p_{T\,j,b} \geq 20$ GeV $\lvert\eta_j\rvert \leq 5, \lvert\eta_b\rvert \leq 2.5$ $\Delta R_{j,b/j} \geq 0.4$ $\not{E}_T \geq 25$	$\Delta\Phi_{\not{E},j} \geq 0.4$ $\Delta\Phi_{\not{E},b} \geq 0.4$	$\lvert m_{j_1 j_2} - m_W\rvert \leq 22$ GeV	$\sigma_{\mathrm{eff.}}$
1	$e^- p \to \nu_e W^- \bar{b}$ 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

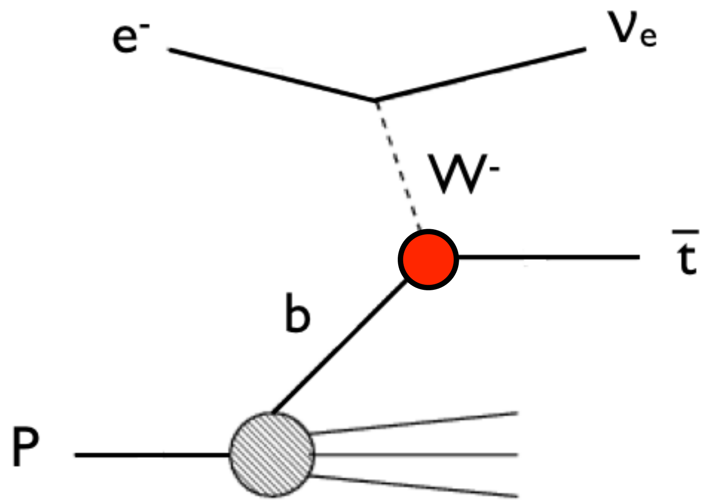


No.	Background Process	$p_{T\,j,b,l} \geq 20$ GeV, $\Delta R_{j,b/j} \geq 0.4$, $\not{E}_T \geq 25$ $\lvert\eta_j\rvert \geq 5$, $\lvert\eta_{b,l}\rvert \geq 2.5$	$\Delta\Phi_{\not{E},j} \geq 0.4$ $\Delta\Phi_{\not{E},b} \geq 0.4$ $\Delta\Phi_{\not{E},l} \geq 0.4$	$\sigma_{\text{eff}}.$
1	$e^- p \to l^- \bar{\nu}_l \nu_e j$	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

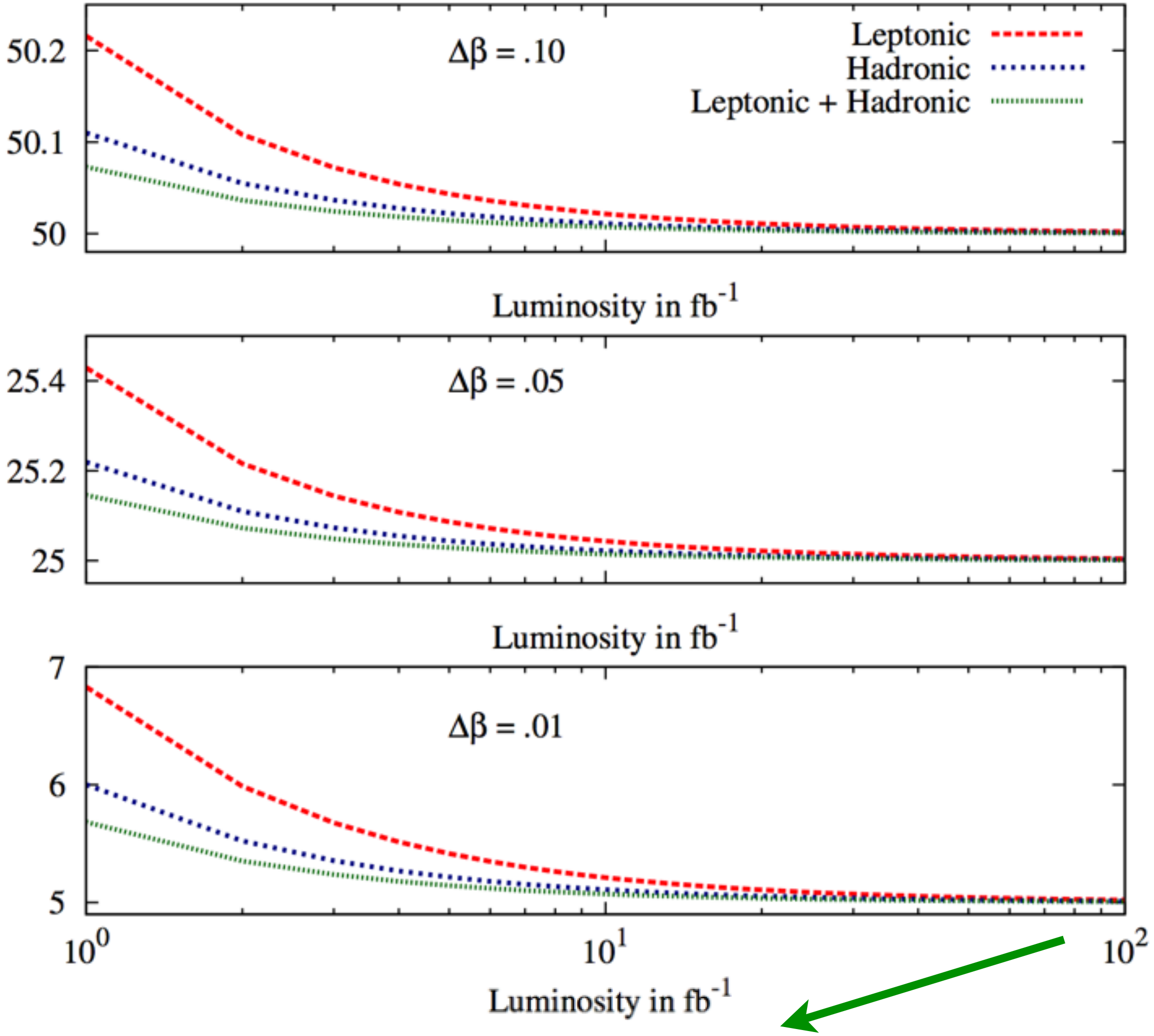
Direct Measurement of $|V_{tb}|$



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

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

$\Delta\beta$: luminosity uncertainty



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

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

Search for Anomalous Wtb Couplings

= 1 in SM

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

Search for Anomalous Wtb Couplings

= 1 in SM

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

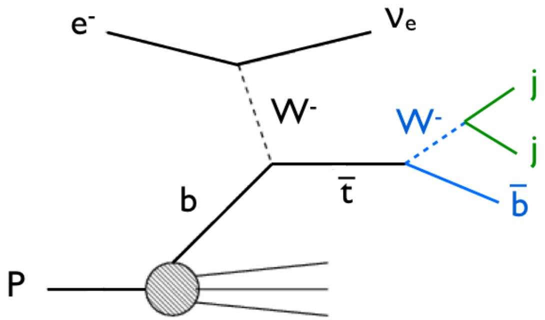
Search for Anomalous Wtb Couplings

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

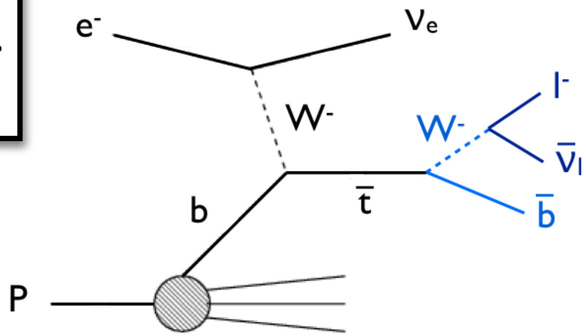
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

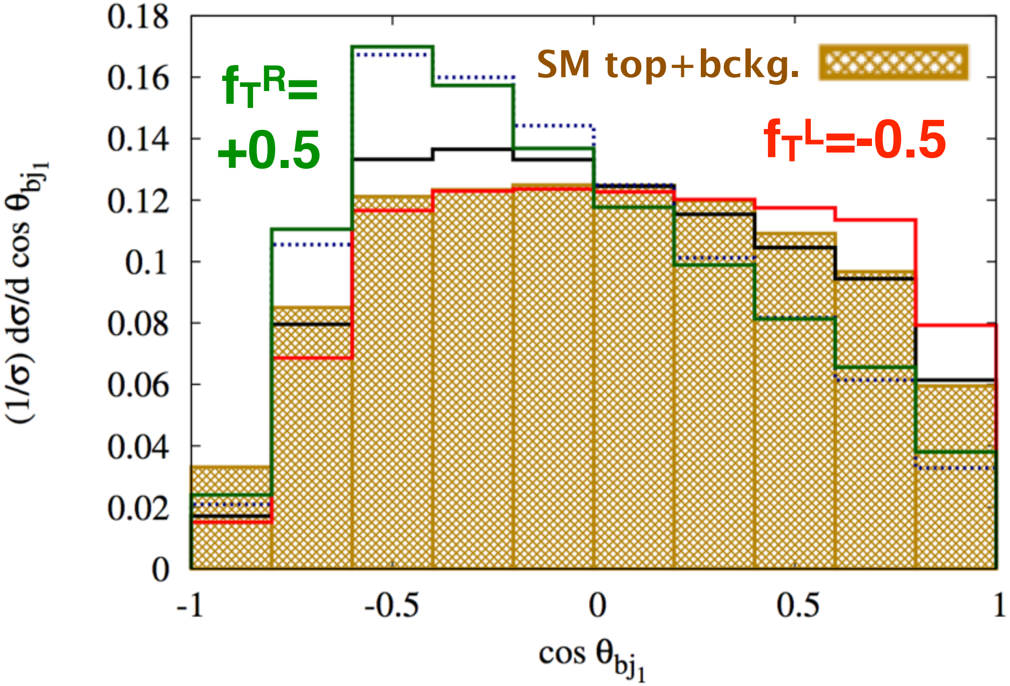
= 1 in SM

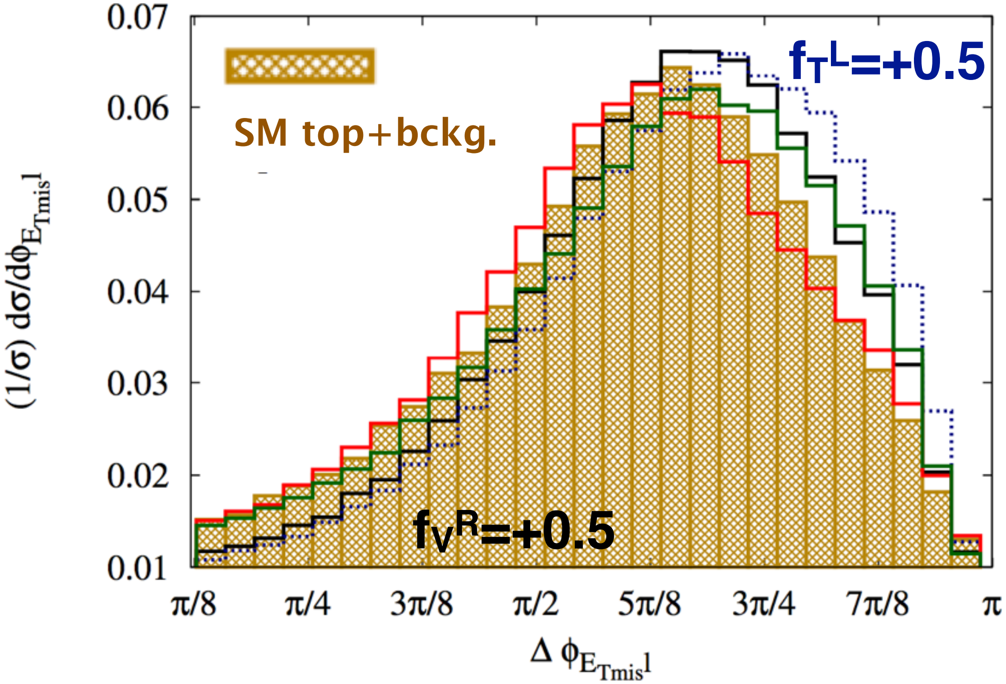
Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688



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







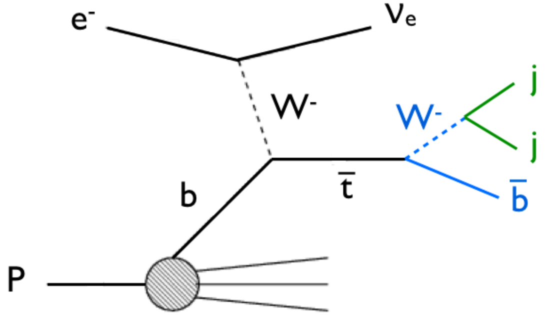
+ other variables sensitive on W helicity

Search for Anomalous Wtb Couplings

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

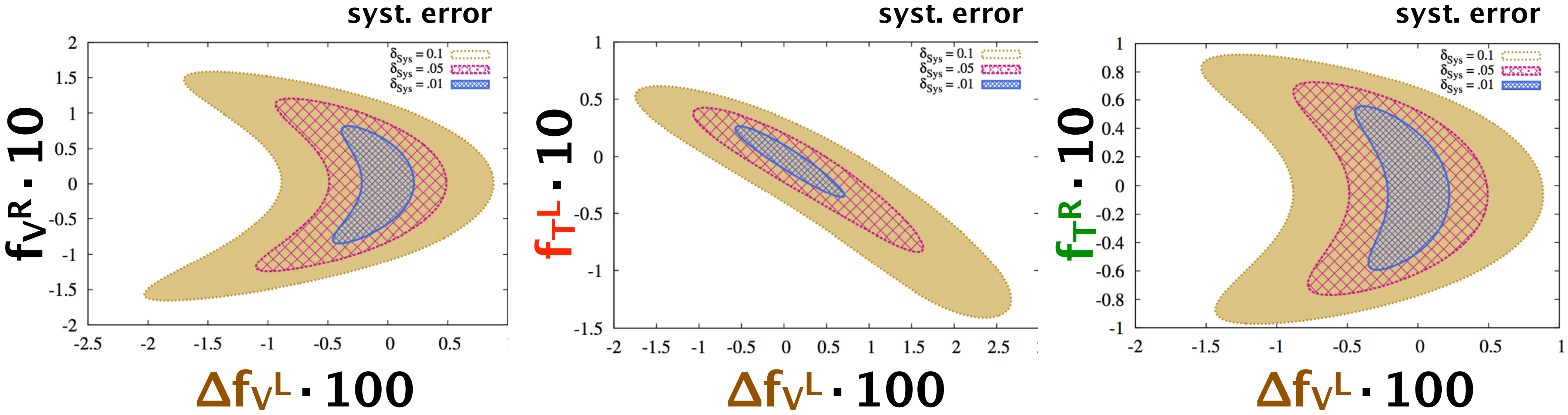
= 1 in SM

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688



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

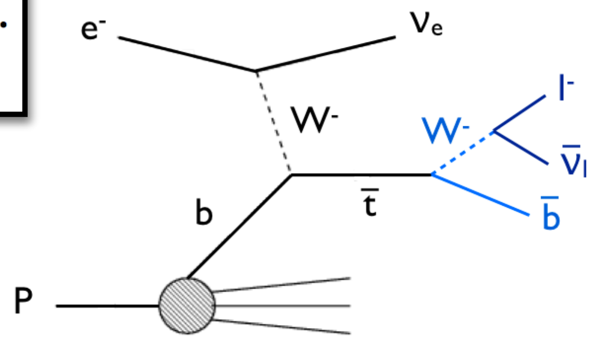


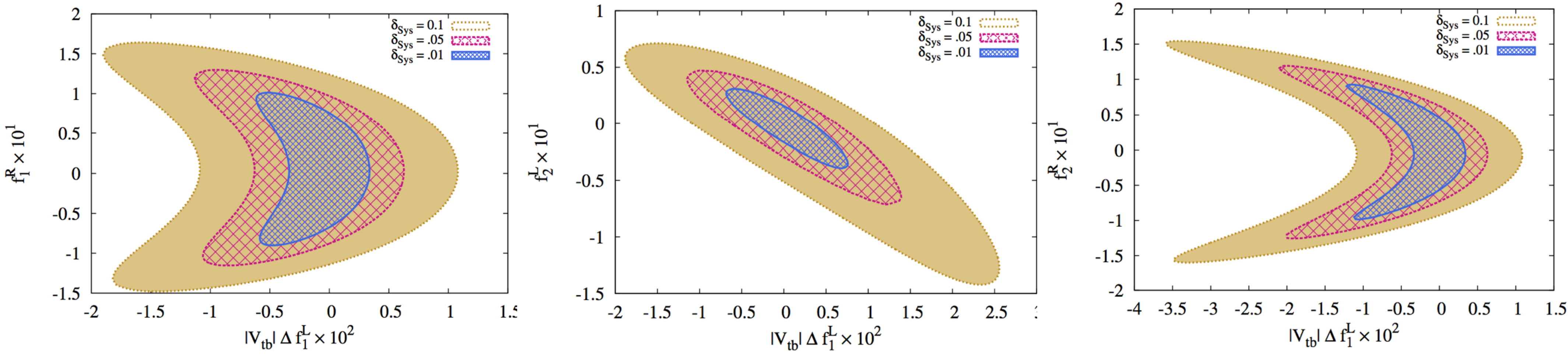
Search for Anomalous Wtb Couplings

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

= 1 in SM

68% C.L.

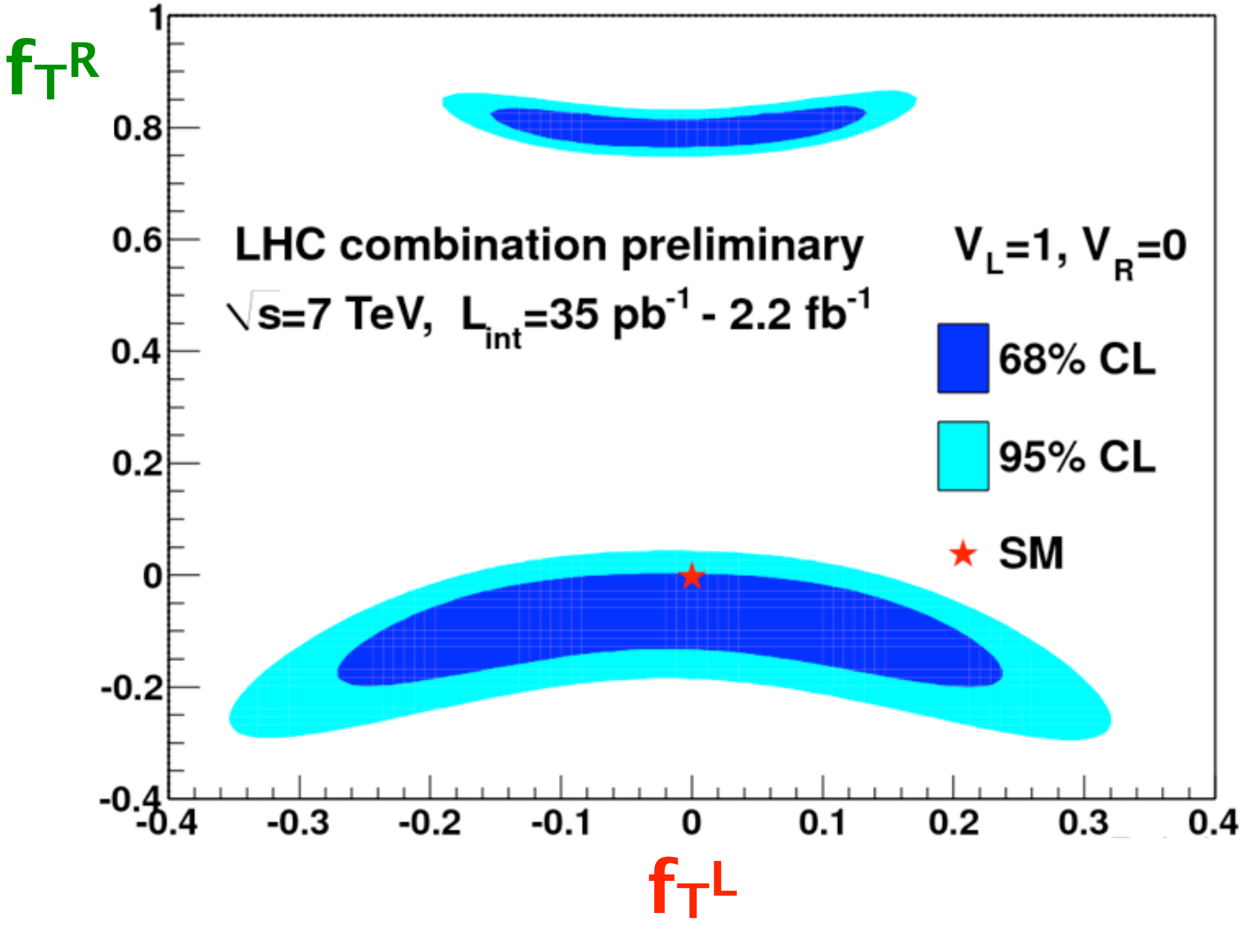


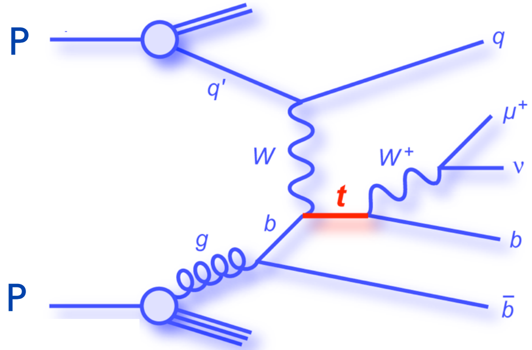


Search for Anomalous Wtb Couplings

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

= 1 in SM

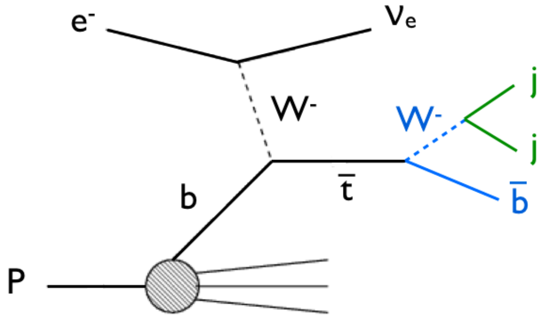


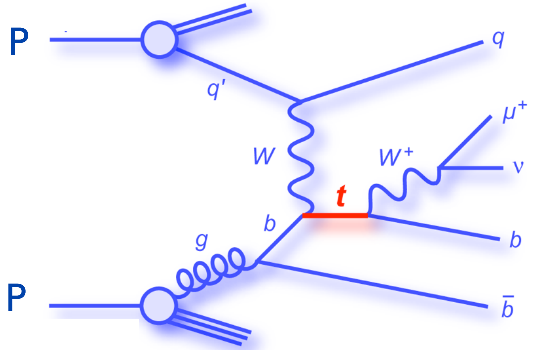


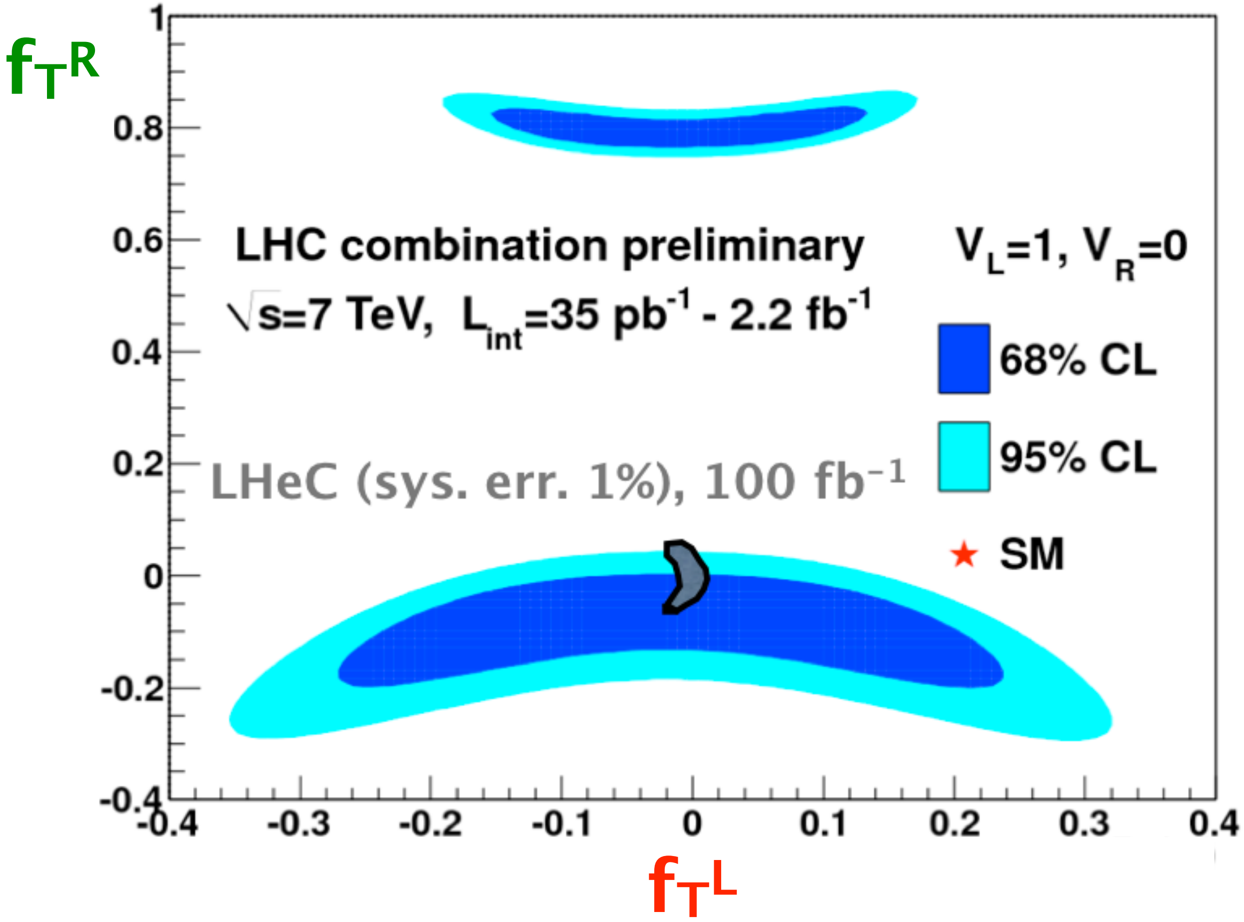
Search for Anomalous Wtb Couplings

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

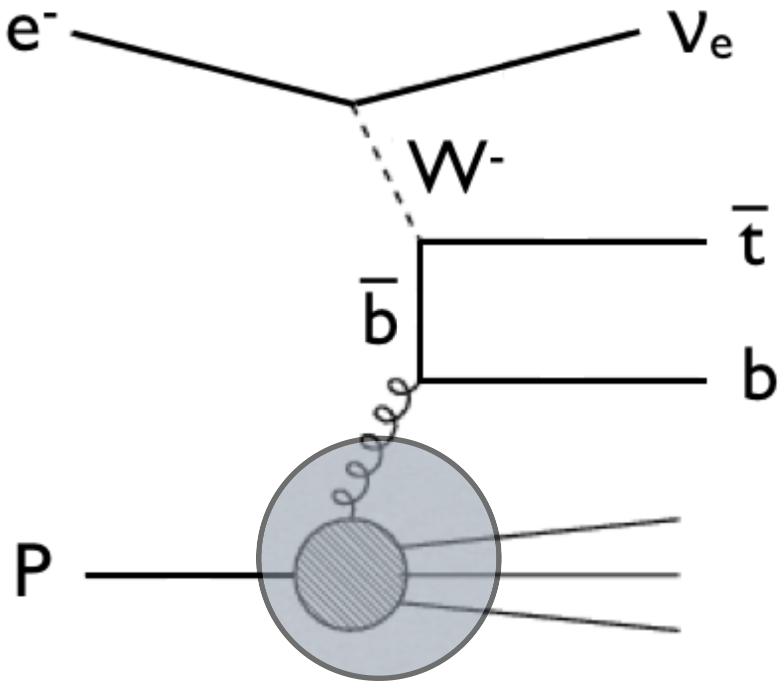
= 1 in SM







Gluon Parton Density Function



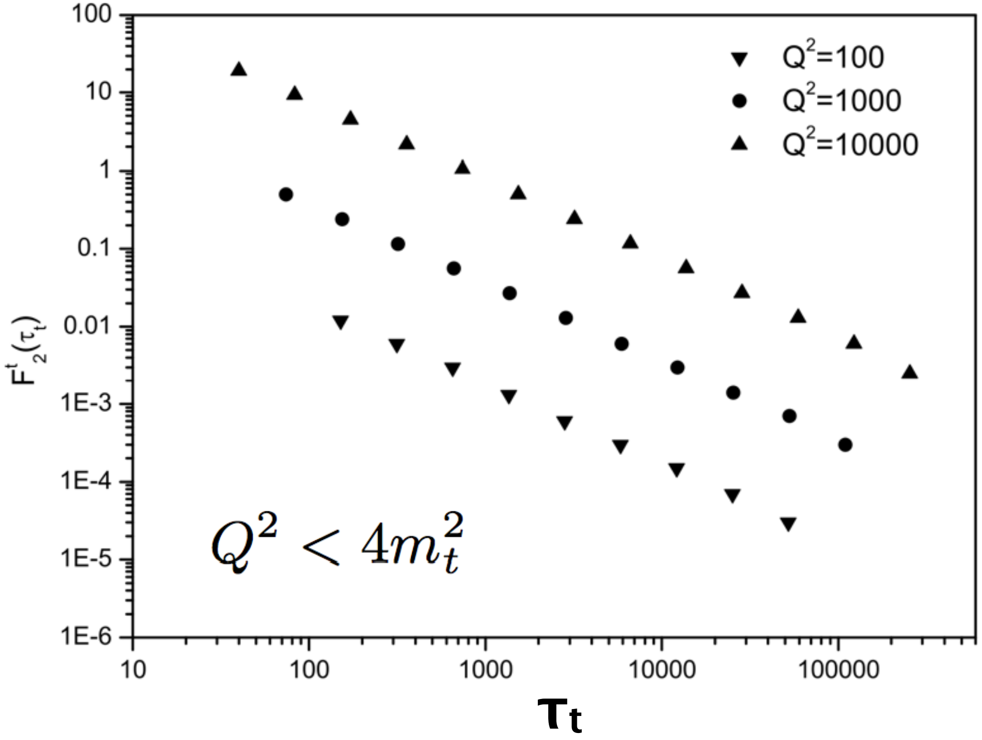
→ **measure gluon density at high x**

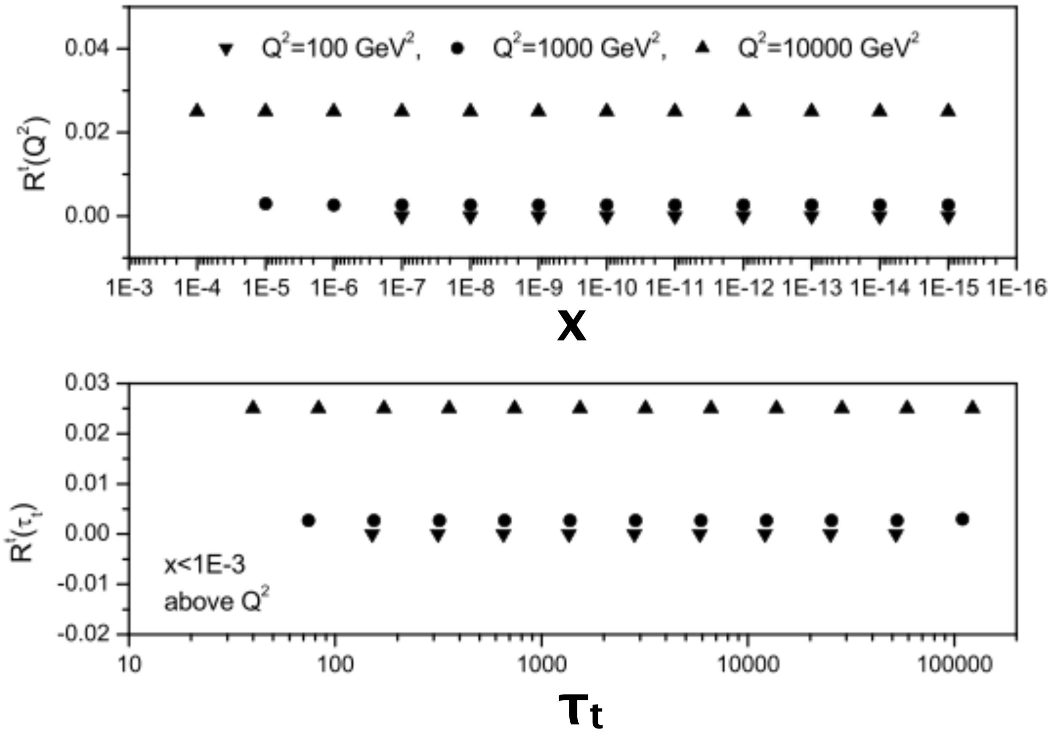
Top Quark Structure Function

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 $Q^2 \simeq 4m_t^2$

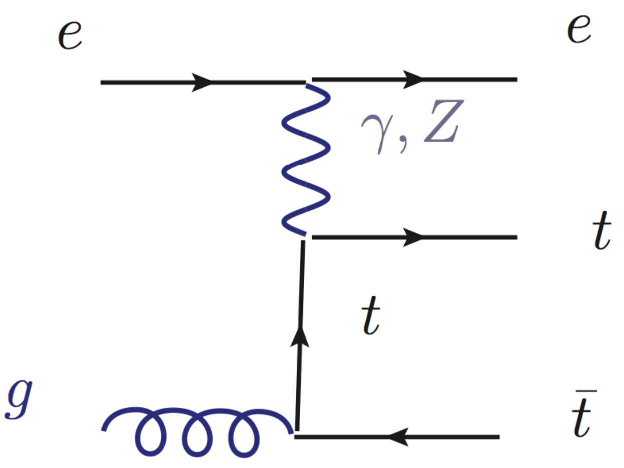
NC Top Quark Production

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

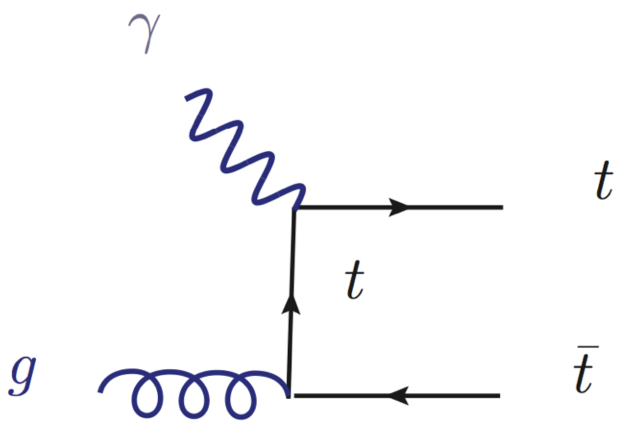
top pair production

single top production

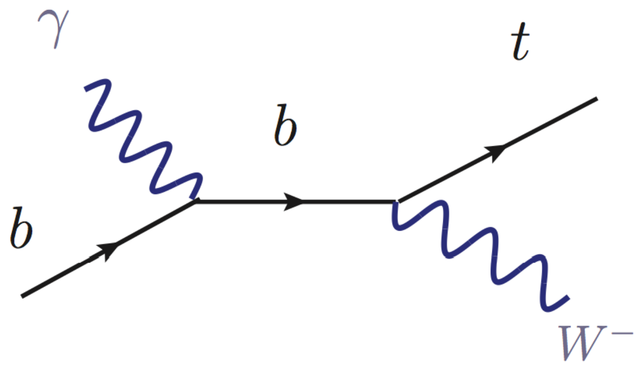
DIS



photoproduction



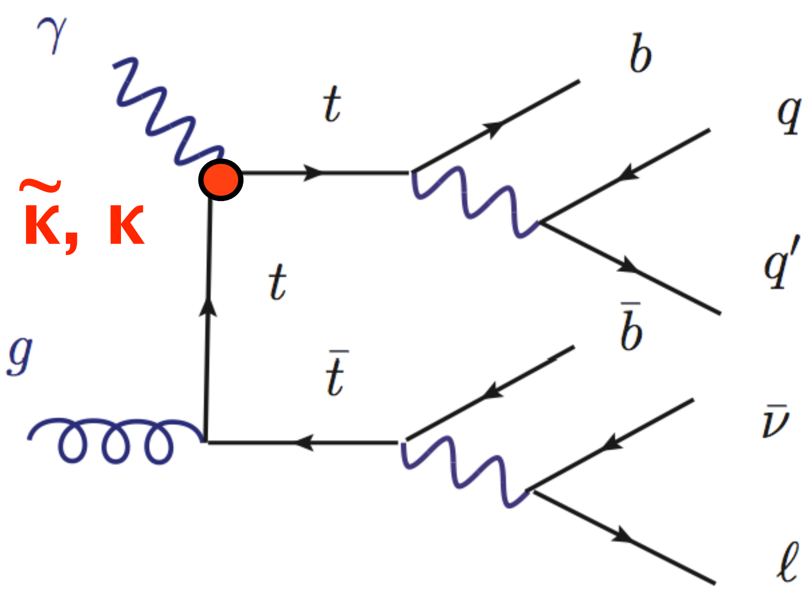
photoproduction



e-beam 60 GeV, 100 fb^{-1}:

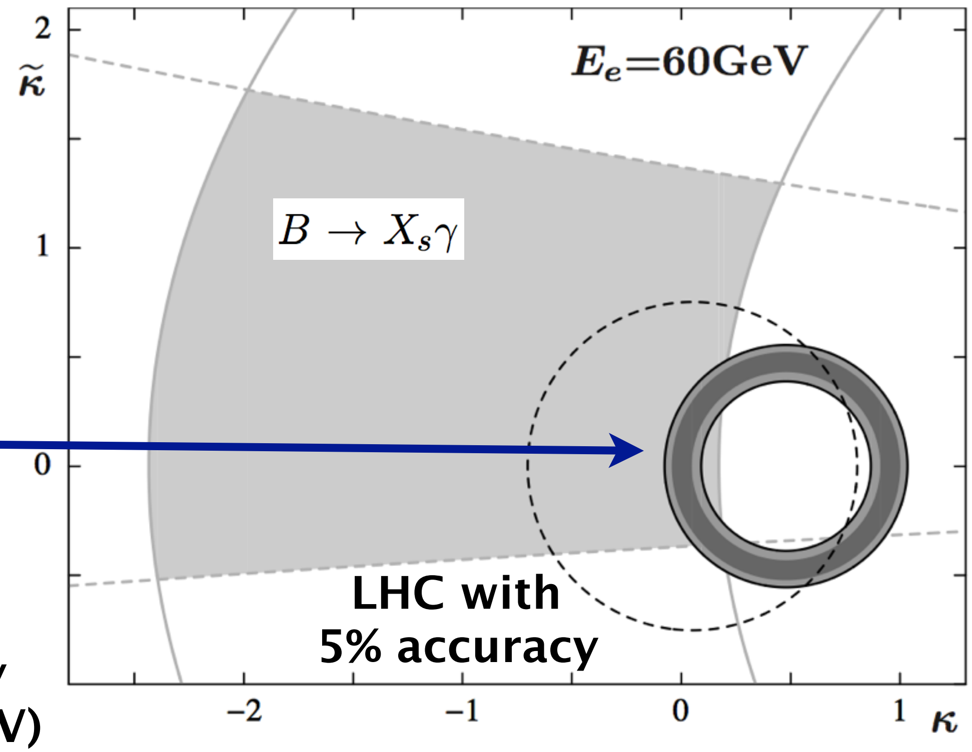
0.023 pb	**0.70 pb**	**0.031 pb**
$N_{t\bar{t}}$=2,300	**$N_{t\bar{t}}$=70,000**	**N_{t}=3,100**

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

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

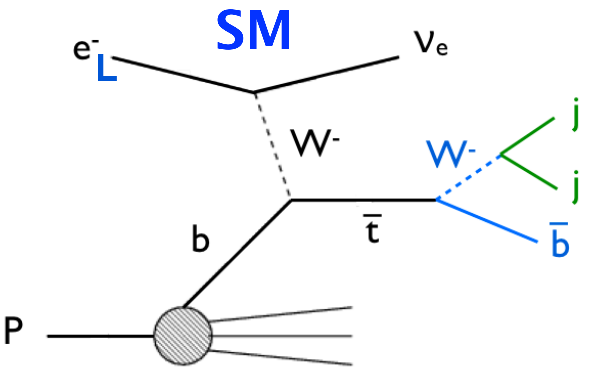
magnetic dipole moment: κ

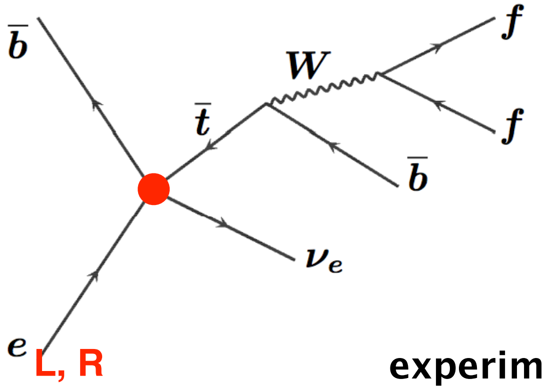
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

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

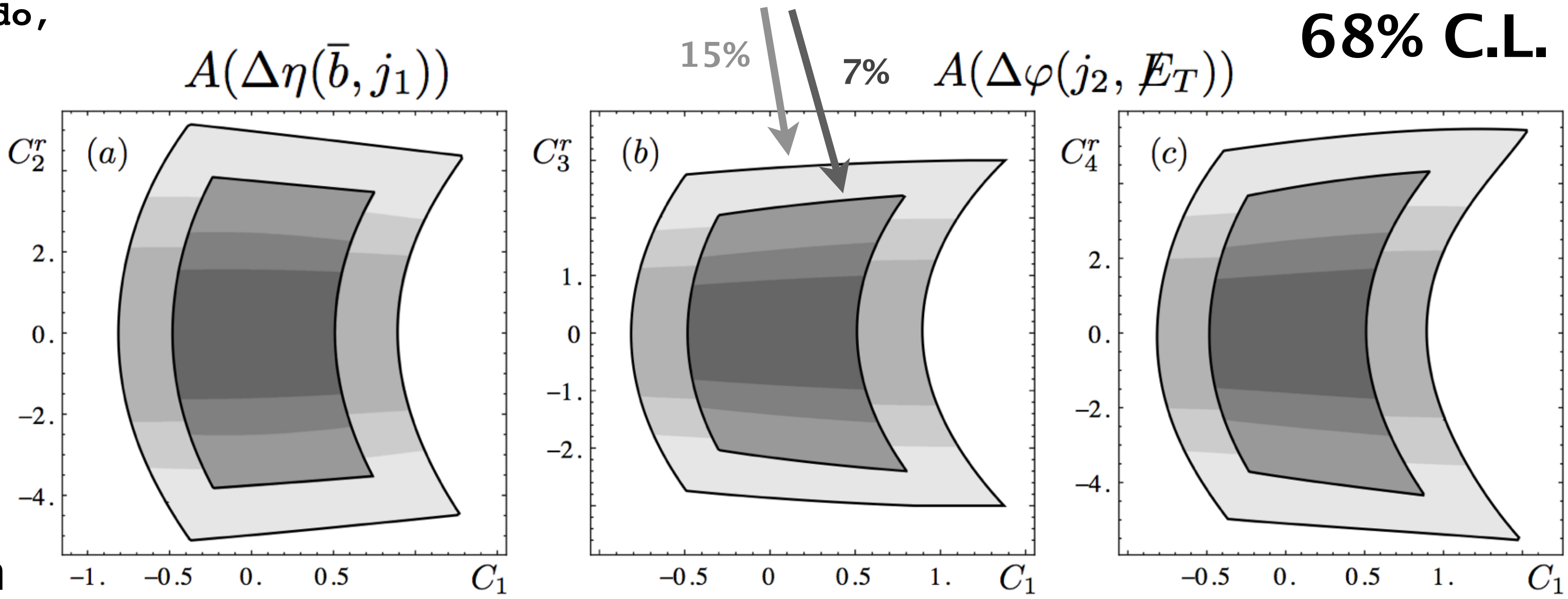




property	precision
C_1	0.50–0.85
C_2^r	2.2–5.0
C_3^r	1.4–2.9
C_4^r	2.2–4.9

Sarmiento-Alvarado, Bouzas, Larios, arXiv:1412.6679

experimental error



68% C.L.

$\mathcal{P}_e = 0$

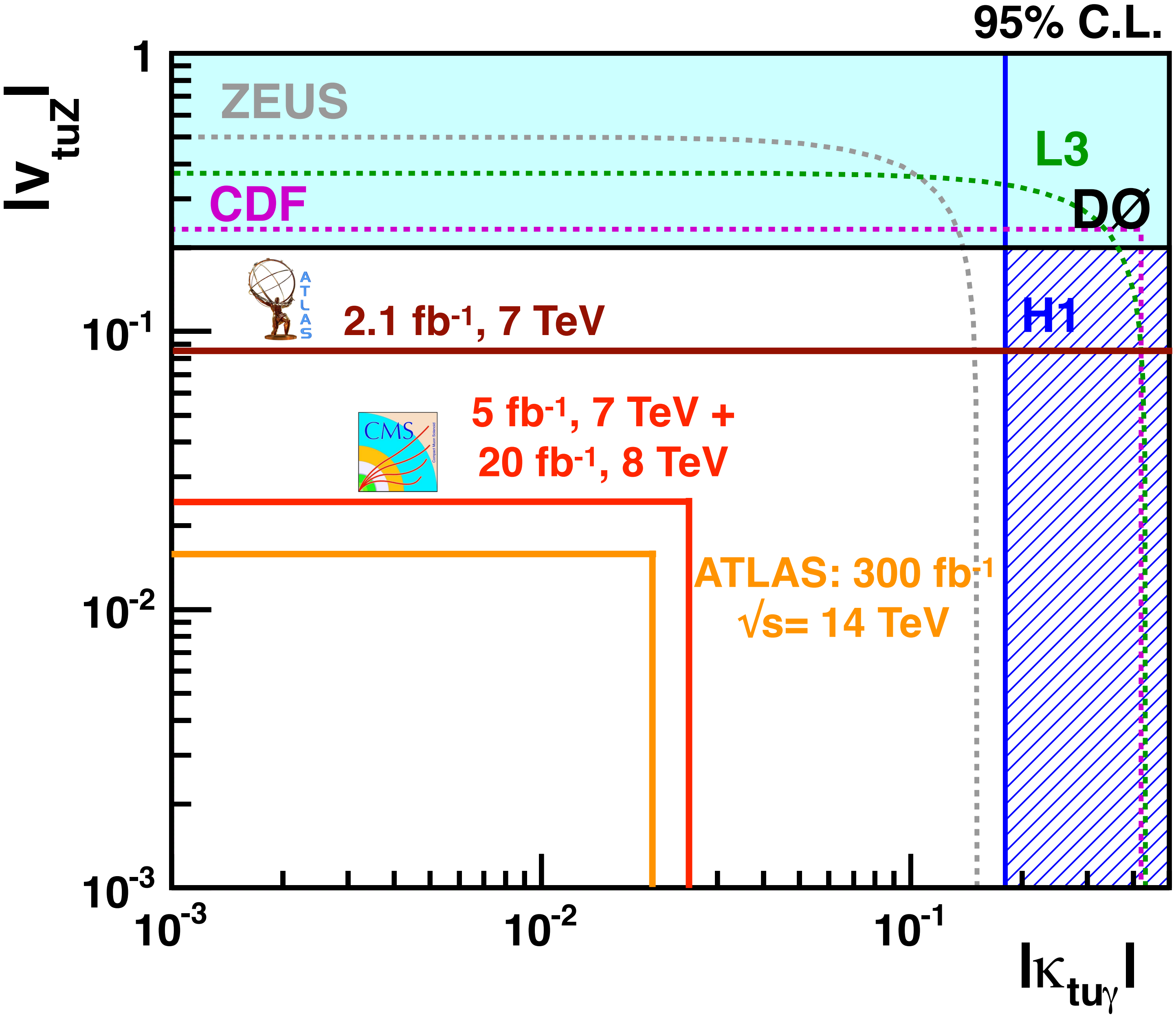
$\mathcal{P}_e = 0.4$

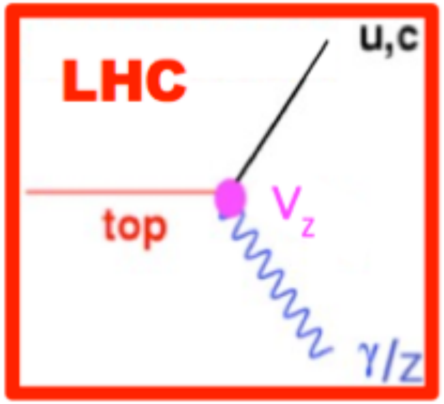
$\mathcal{P}_e = 0.7$

cross section

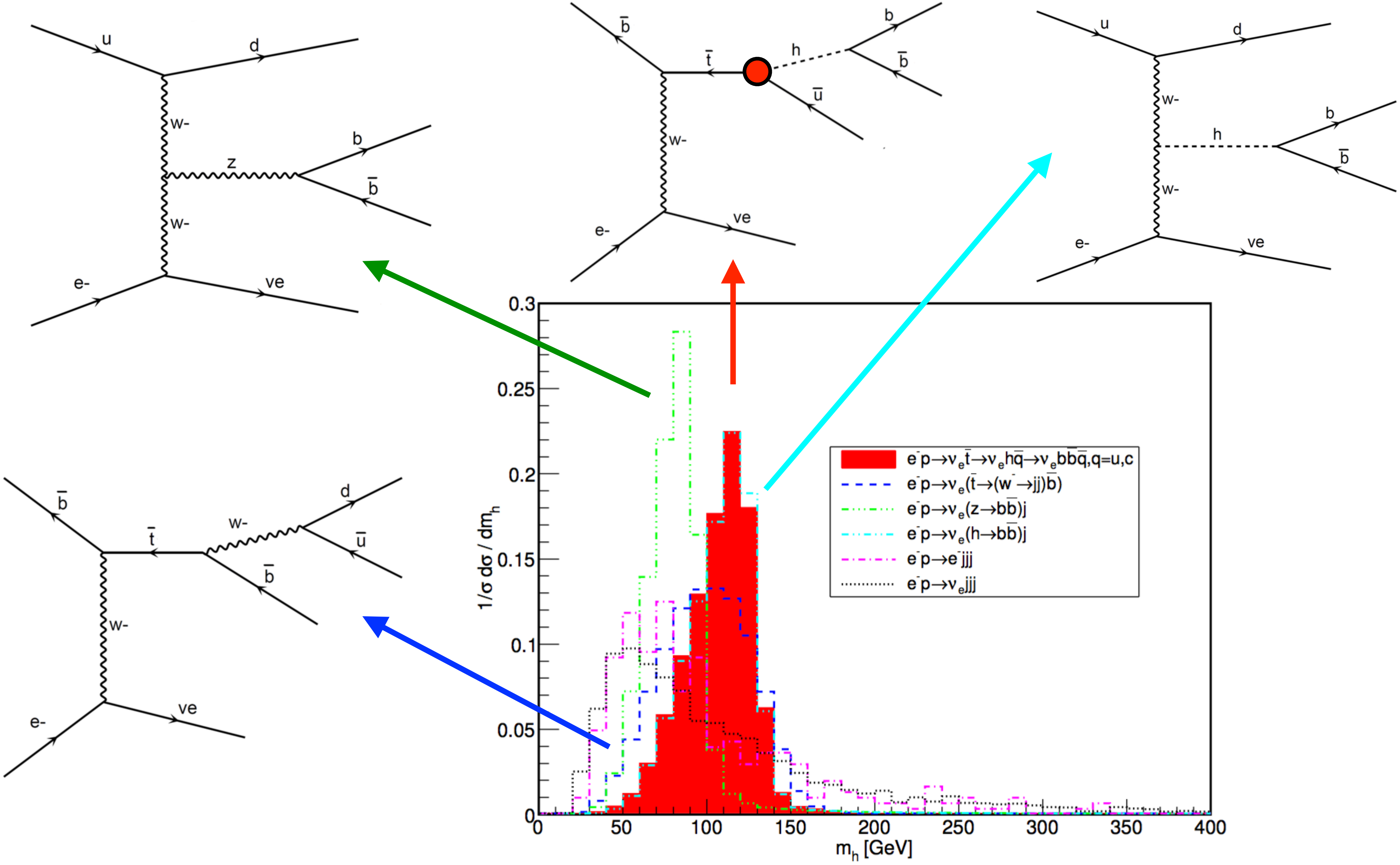
FCNC Top Couplings at Colliders

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





Reconstructed Higgs mass



Reconstructed top quark mass