Top Quark Physics and Anomalous Couplings

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Deutsches Elektronensynchrotron (DESY)

LHeC Workshop

CERN/Chavannes-de-Bogis

25 June 2015

Outline

Introduction
Charged Current
Neutral Current
Summary

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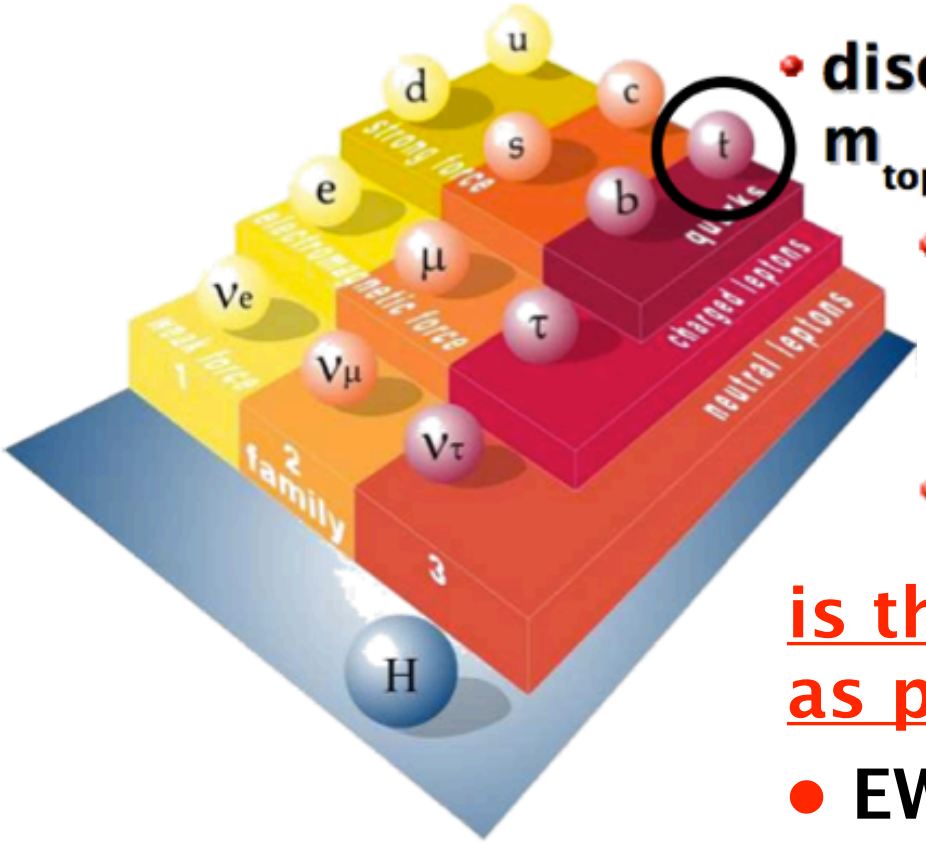
Charged Current

Neutral Current

Summary

The Top Quark



- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom
  - large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
  - large contribution to Higgs mass

is the top quark the particle as predicted in the SM?

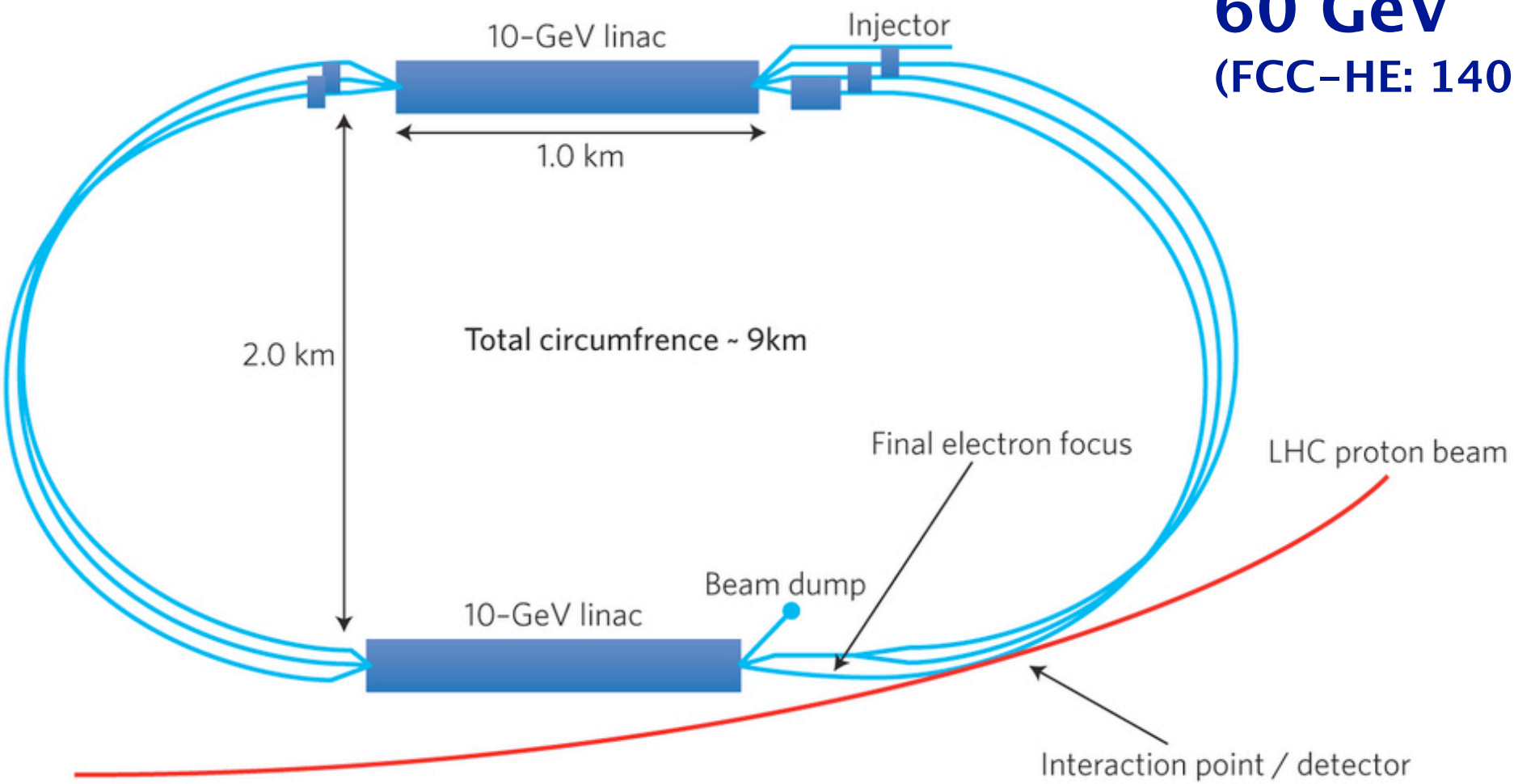
- EWK interactions of top quarks
- top quark properties
- search for new physics

→ ep collider excellent to explore the top quark

LHeC, Linac-Ring Collider

Energy Recovering Linac

$e^{\pm}$ beam:
60 GeV
(FCC-HE: 140 GeV)



$L_{int} \leq 1$ ab^{-1}

p beam: 7 TeV

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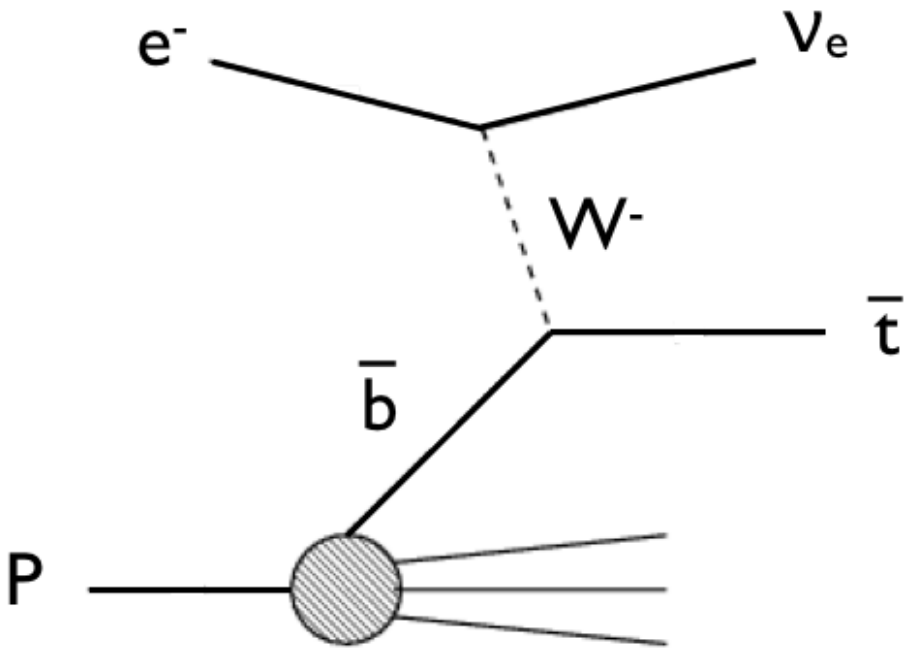
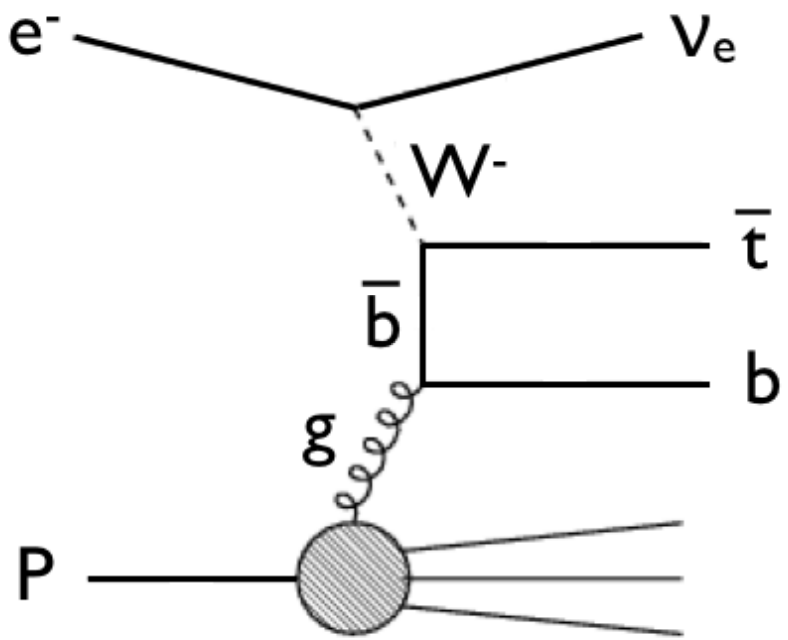
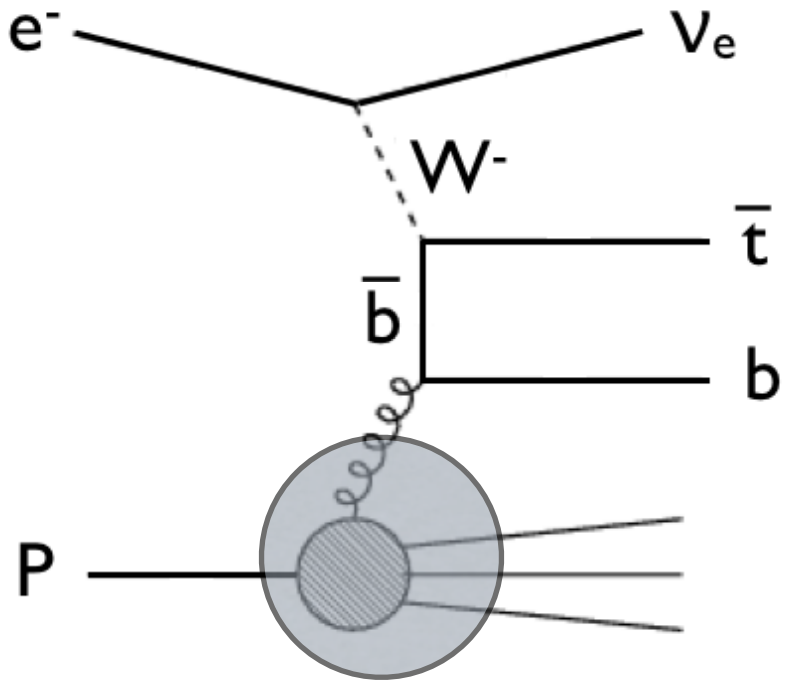
CC Single Top Quark Production





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

Gluon Parton Density Function

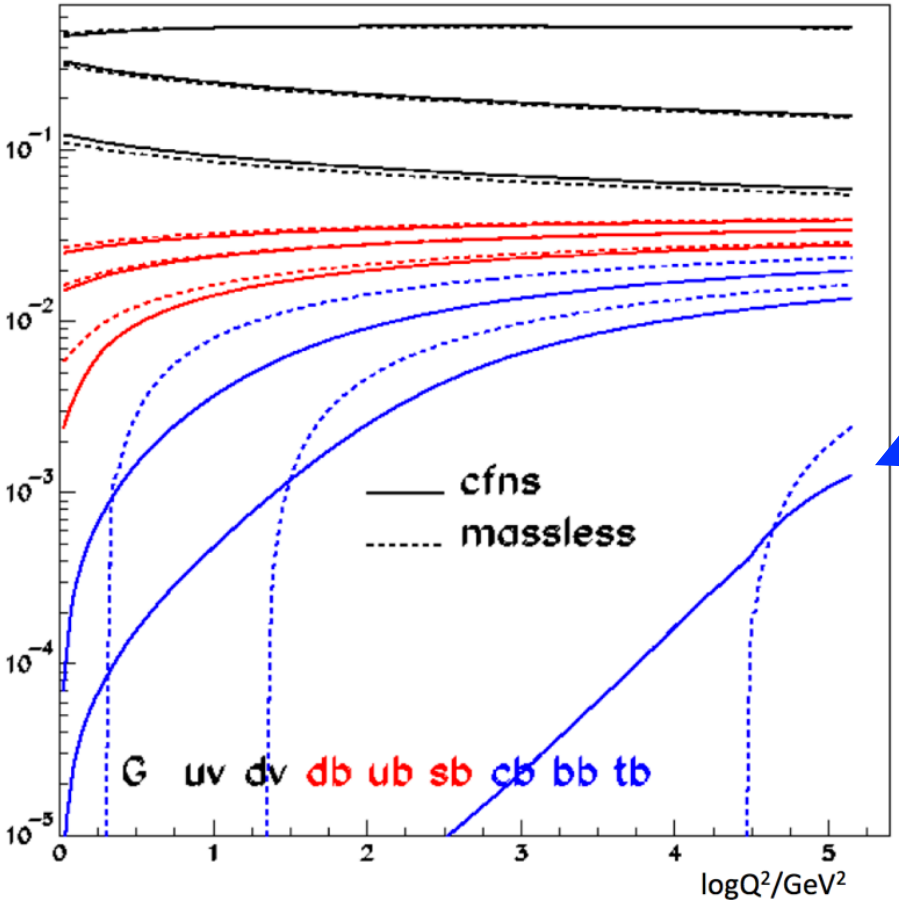


→ **measure gluon density at high x**

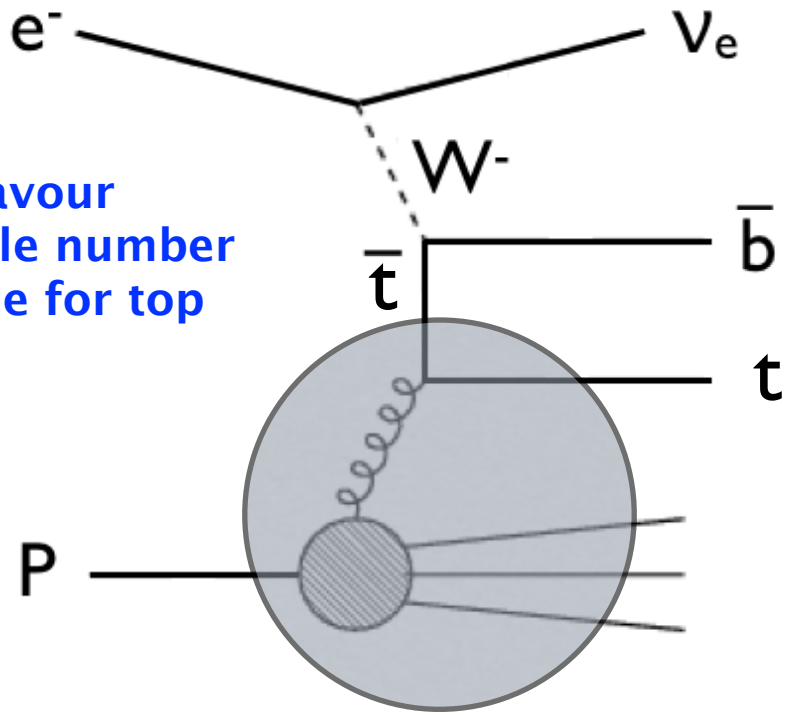
Top Quark Parton Density Function

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

parton momentum fraction



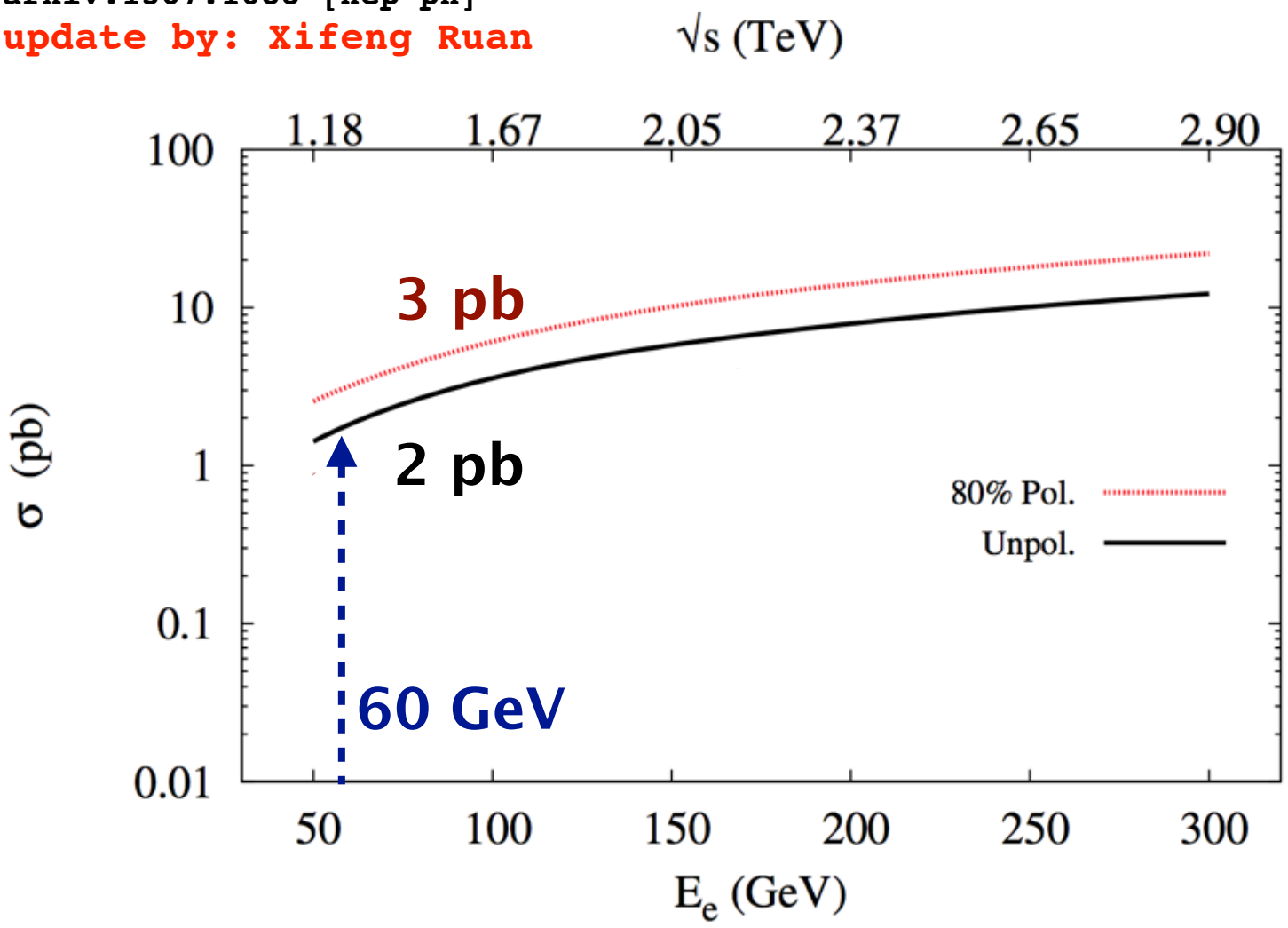
six-flavour variable number scheme for top quark



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

CC Single Top Quark Cross Section

Dutta, Goyal, Kumar, Mellado,
arXiv:1307.1688 [hep-ph]
update by: Xifeng Ruan

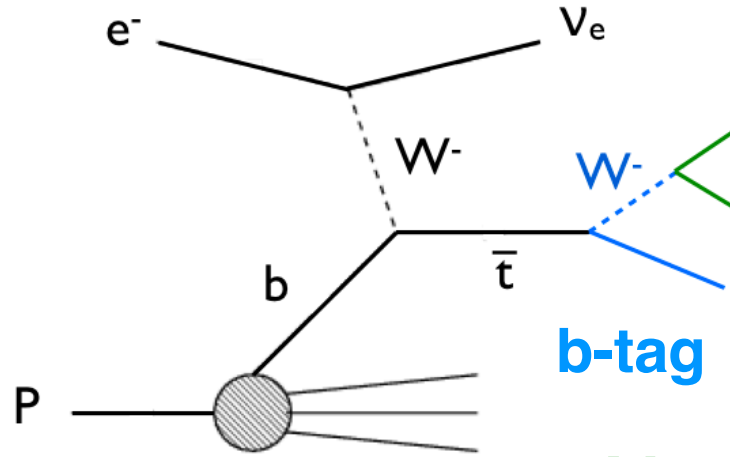


100 fb^{-1}:
2 · 10^5 events
3 · 10^5 events

→ LHeC offers excellent prospects for top quark physics

Signal and Backgrounds

signal



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

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

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

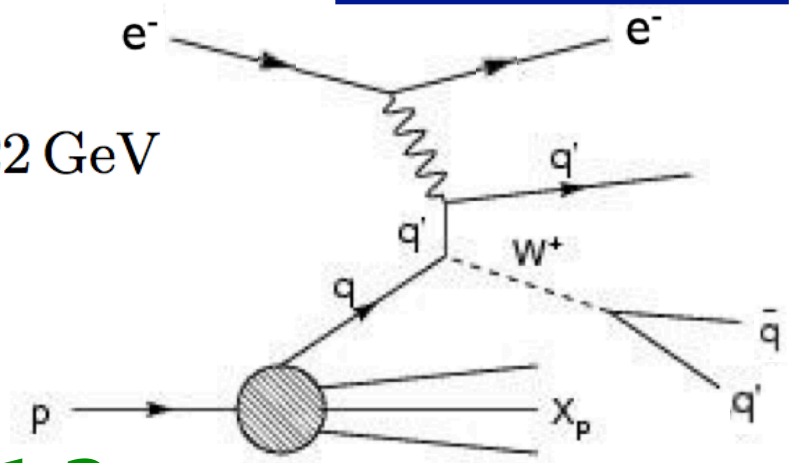
$p_{T\,j,b} \geq 20\ \text{GeV}$

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

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

b-tag

background



N_t=22000, s/b=1.2

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

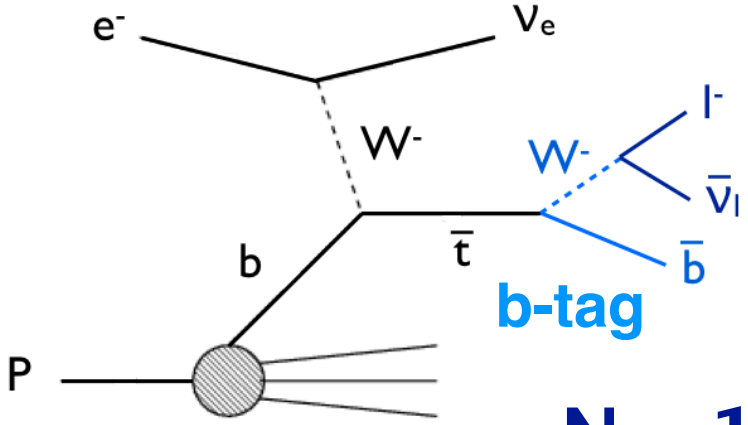
$\not{E}_T \geq 25\,\text{GeV}$

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

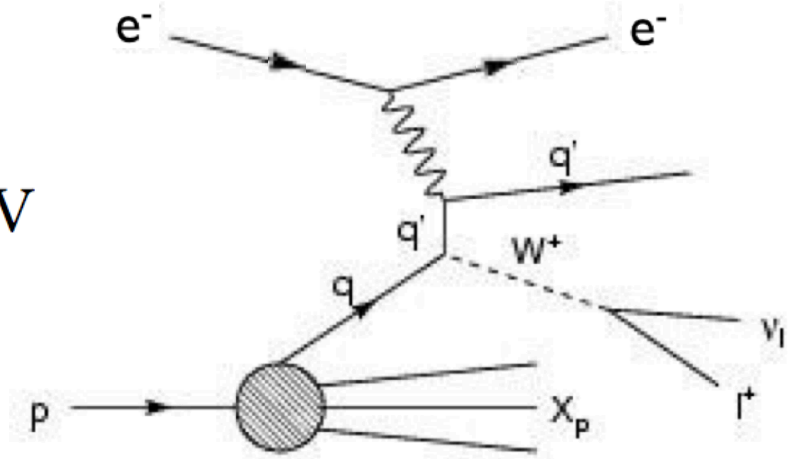
$p_{T\,j,b,l} \geq 20\ \text{GeV}$

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

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

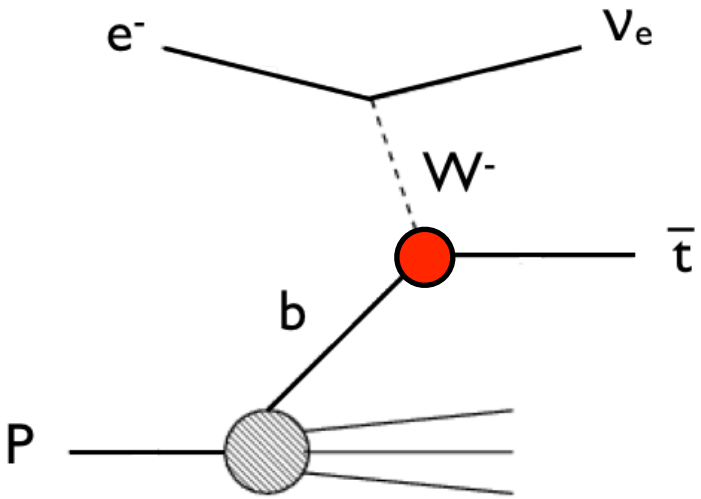


b-tag



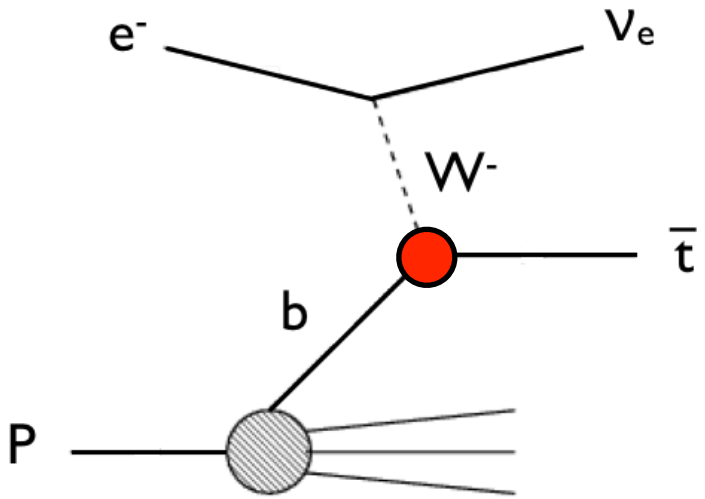
N_t=11000, s/b=11

Direct Measurement of $|V_{tb}|$



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

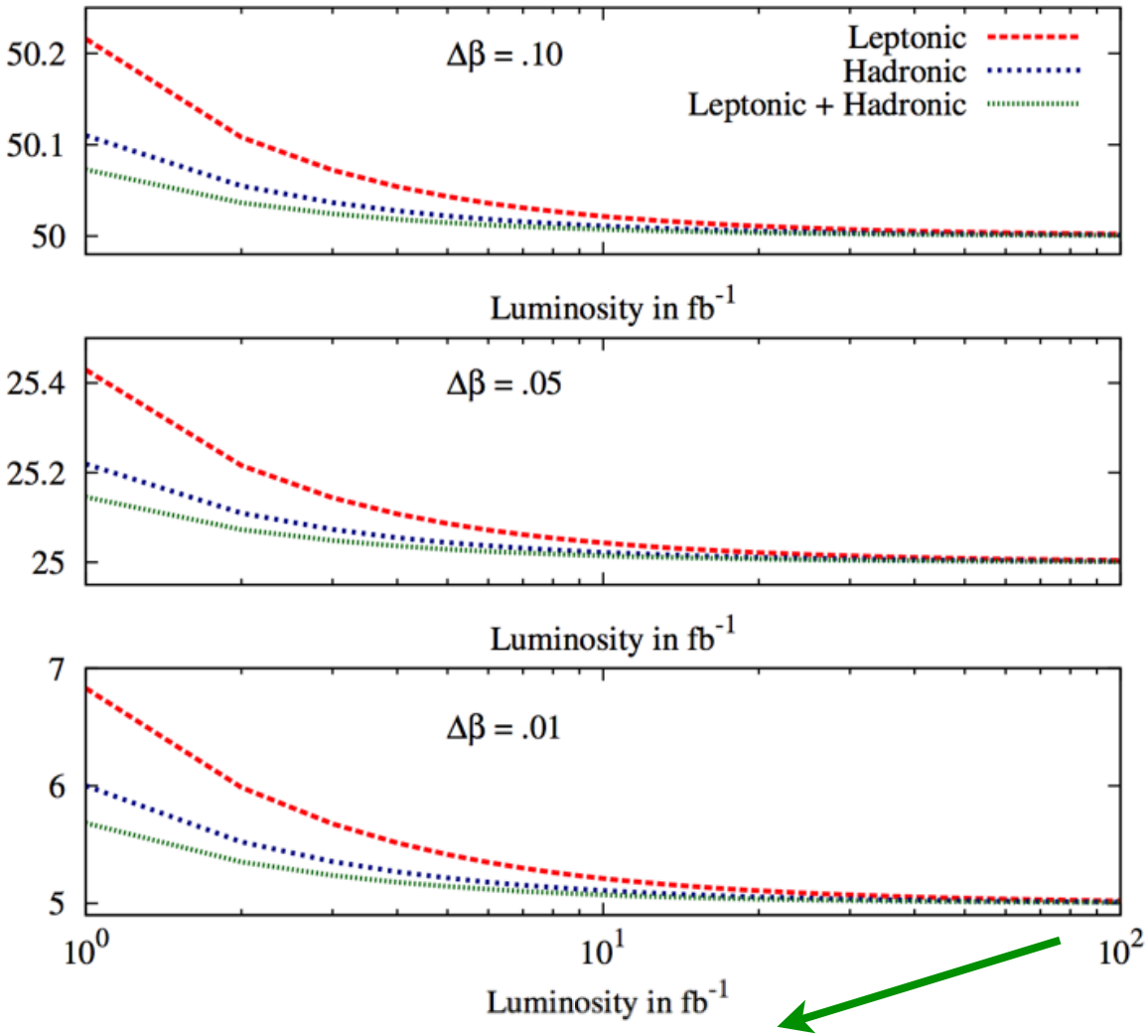
Direct Measurement of $|V_{tb}|$



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

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

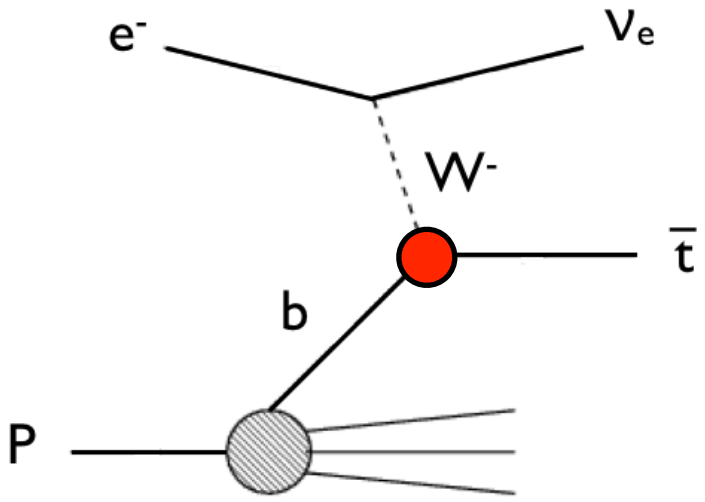
$\Delta\beta$: luminosity uncertainty



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

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

Direct Measurement of $|V_{tb}|$



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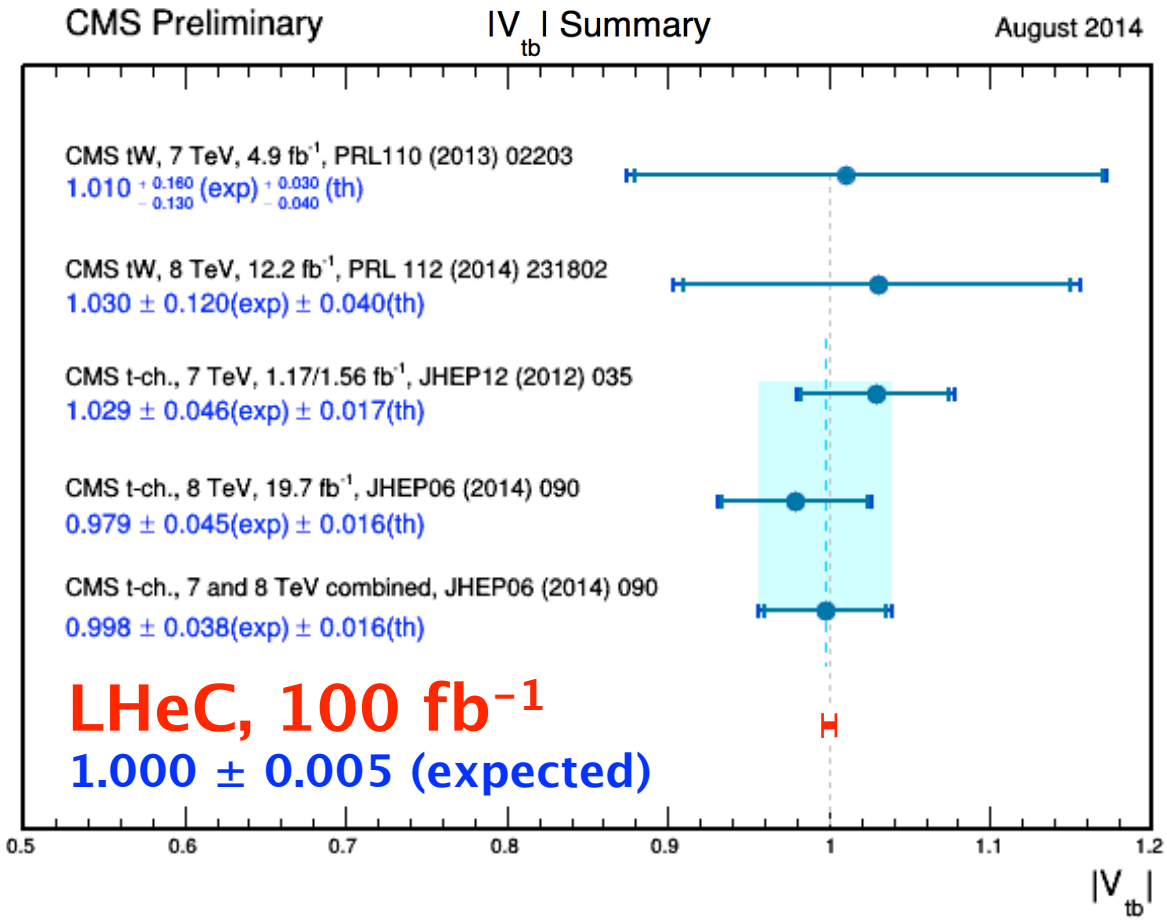

→ **high precision measurement**

Search for Anomalous Wtb Couplings

= 1 in SM

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

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

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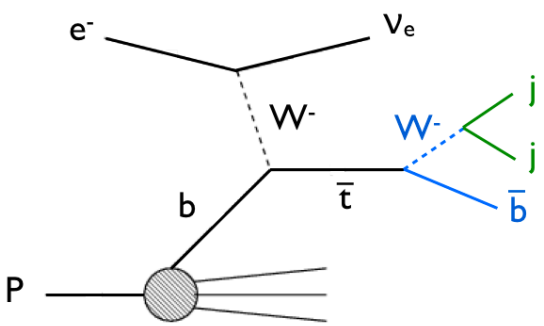
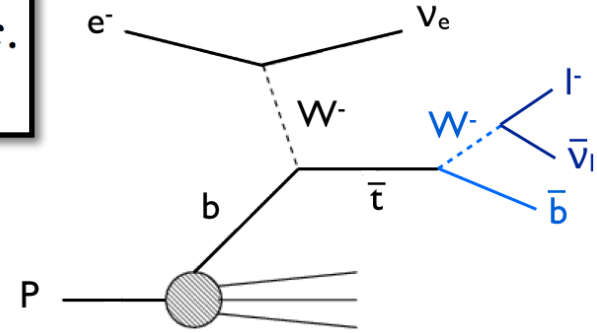
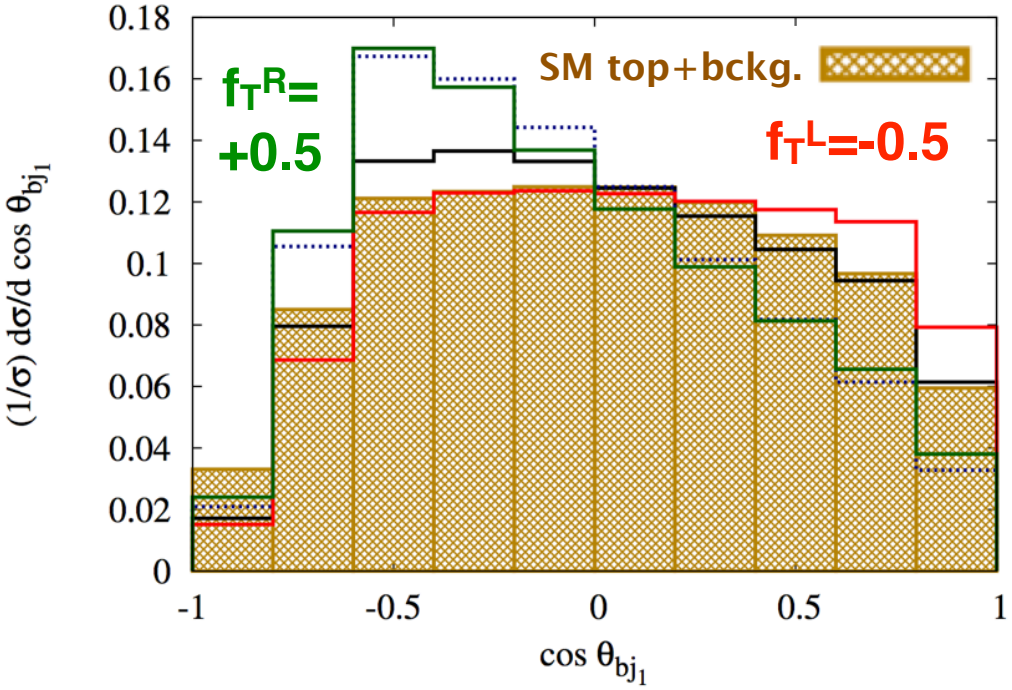
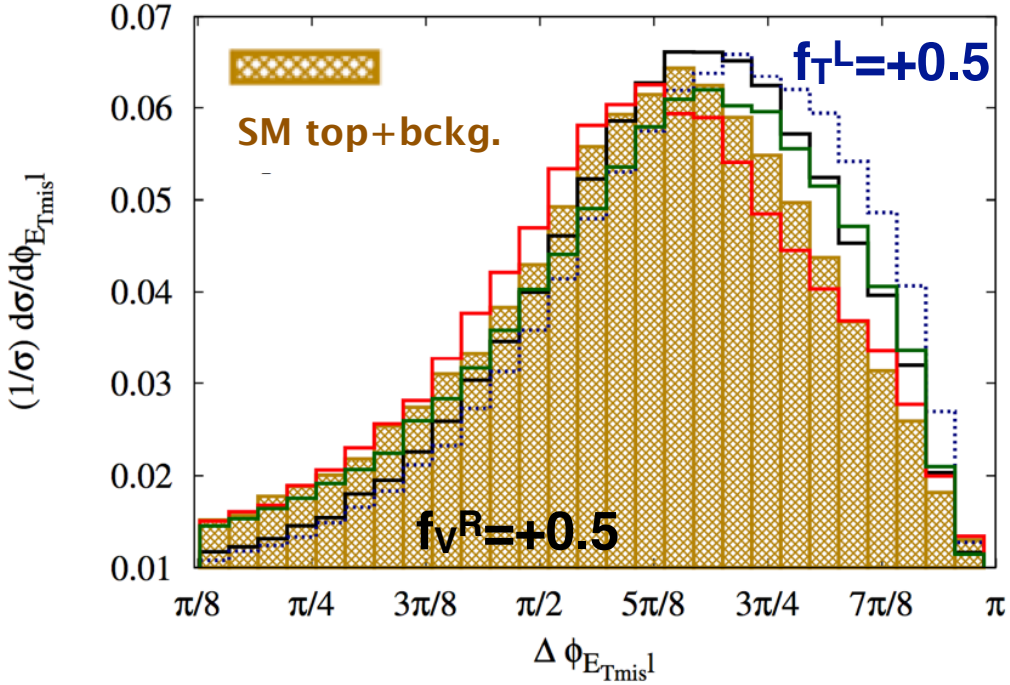
Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688
update by: Xifeng Ruan





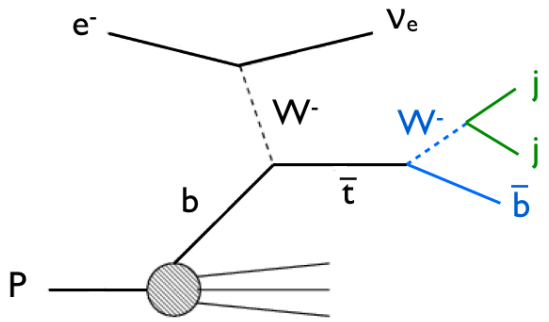




+ other variables sensitive on W helicity

Search for Anomalous Wtb Couplings

= 1 in SM



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

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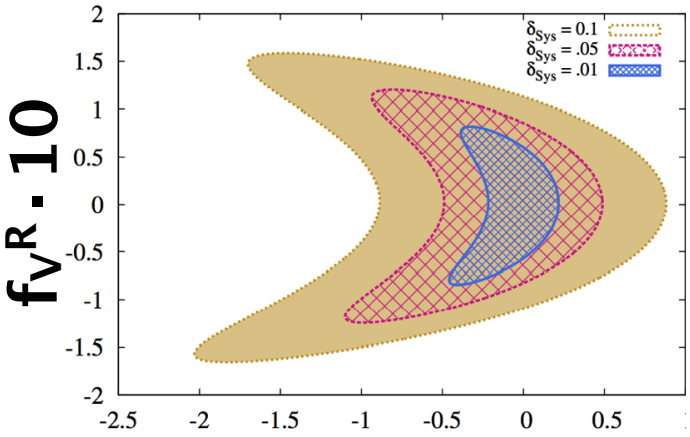
Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688

update by: Xifeng Ruan

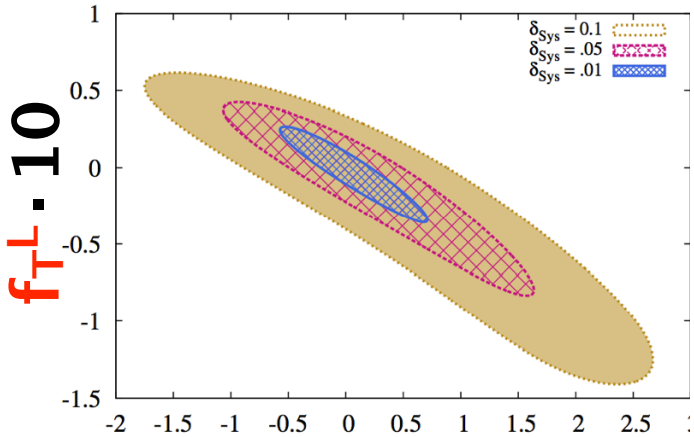
68% C.L.

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

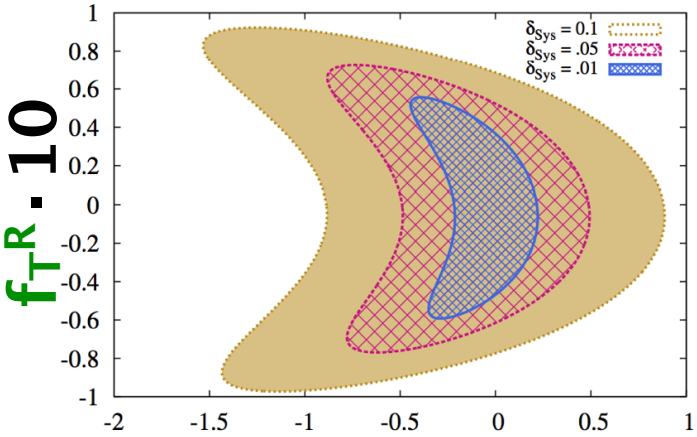
syst. error



syst. error



syst. error



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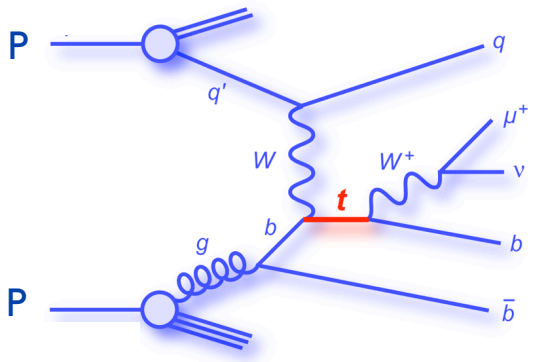

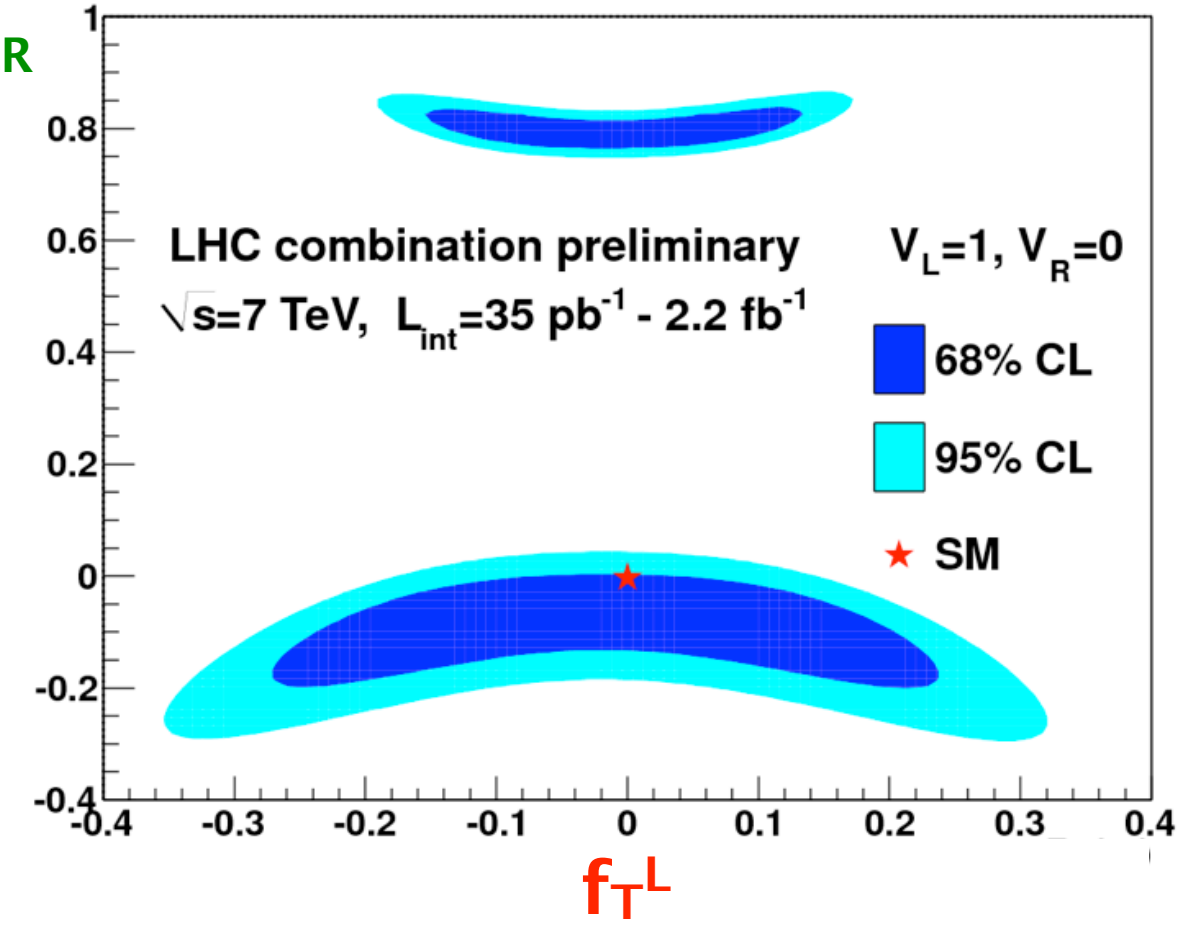

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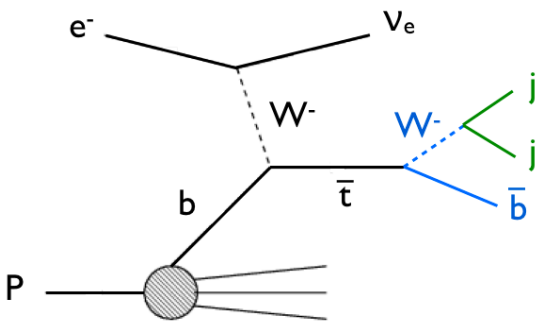
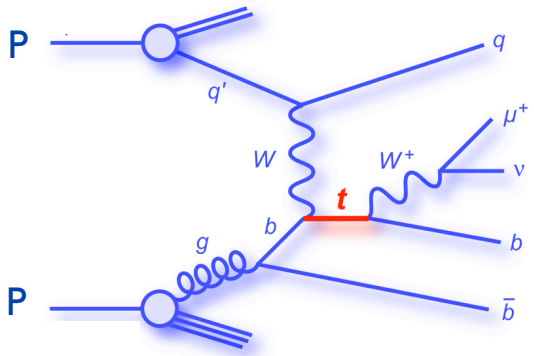
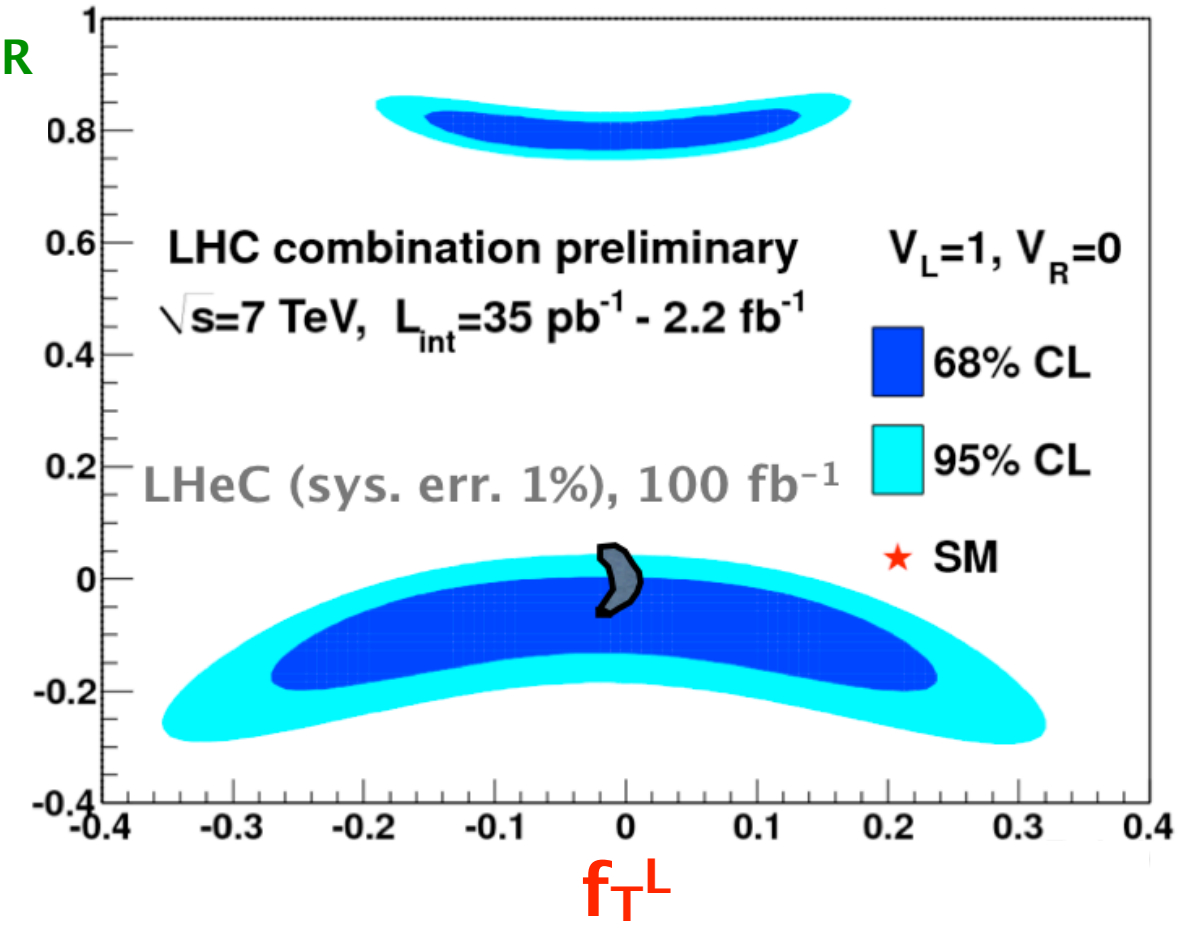
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$



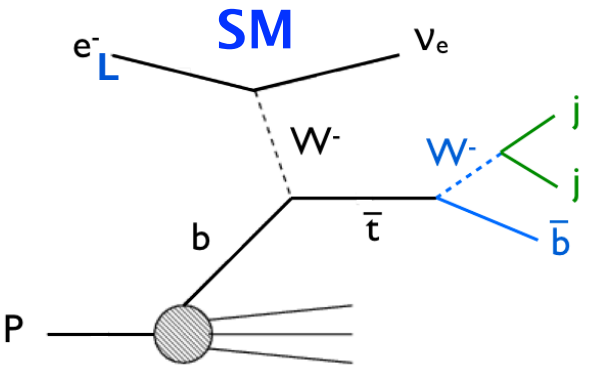


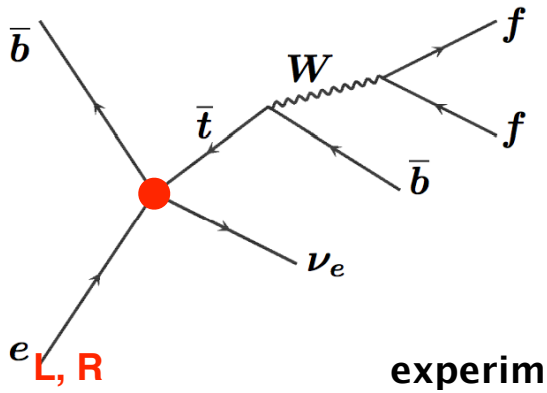


Top Quark Dimension 6 Operators

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

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

$\mathcal{P}_e = 0$

$\mathcal{P}_e = 0.4$

$\mathcal{P}_e = 0.7$

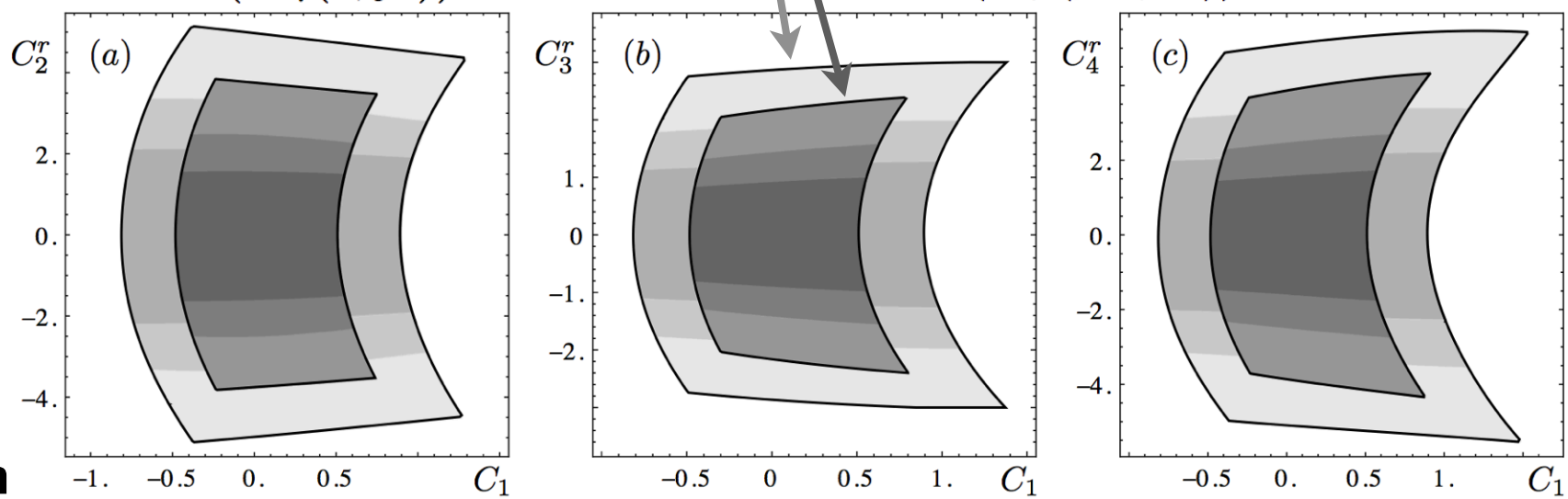
cross section

experimental error

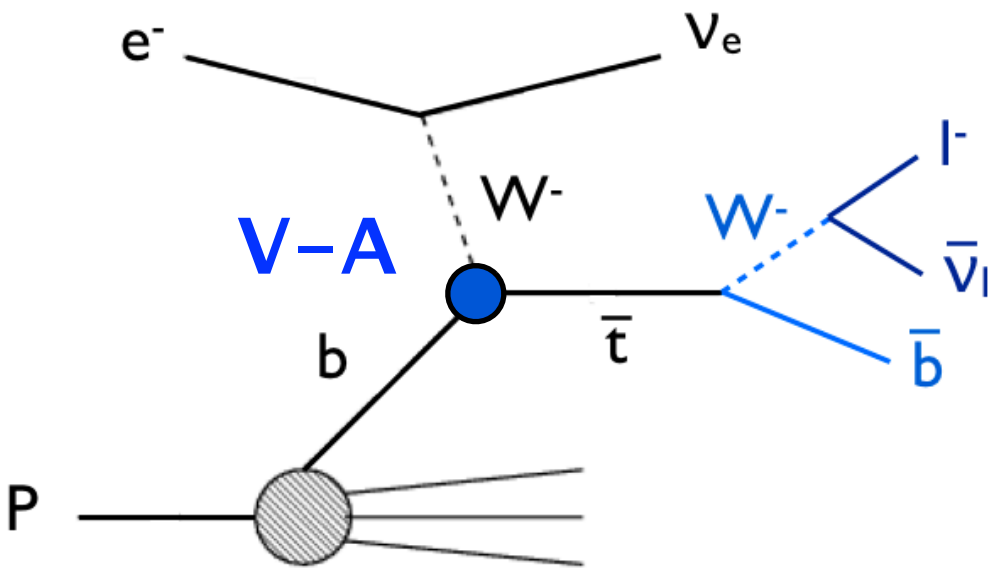
15% 7%

68% C.L.

$A(\Delta\eta(\bar{b}, j_1))$ $A(\Delta\varphi(j_2, \not{E}_T))$



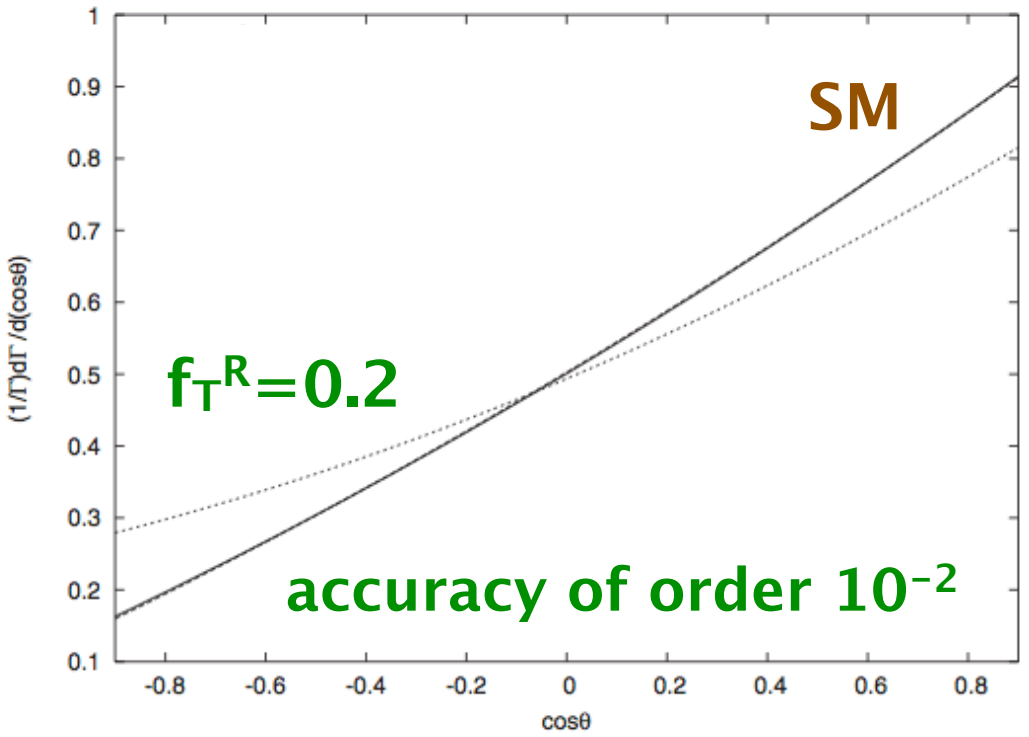
Top Quark Polarisation



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:

√s=1.6 TeV
L_{int}=20 fb^{-1}

20 fb^{-1}: P_t = 0.82±0.34

CMS-PAS-TOP-13-001

Outline

Introduction
Charged Current
Neutral Current
Summary

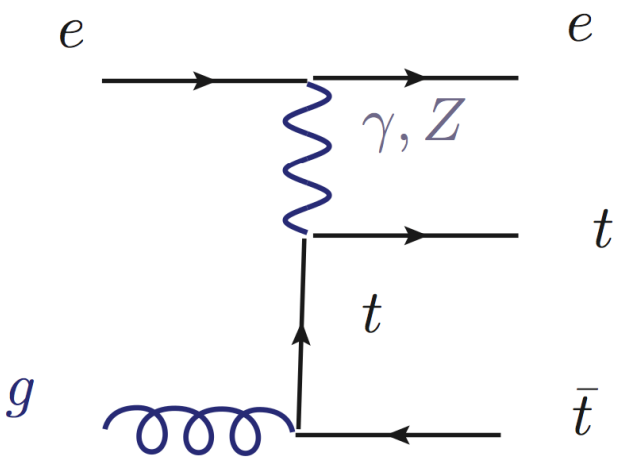
NC Top Quark Production

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

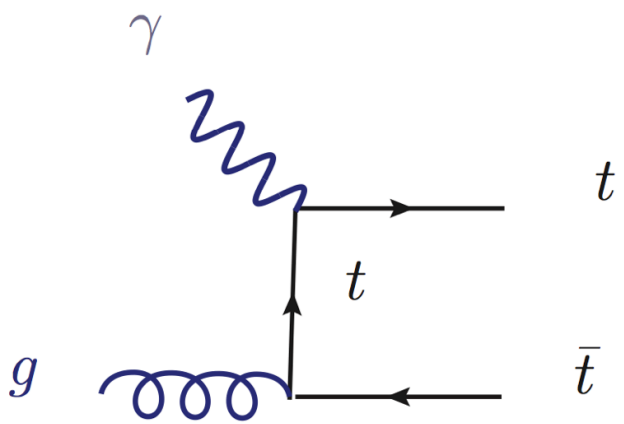
top pair production

single top production

DIS



photoproduction



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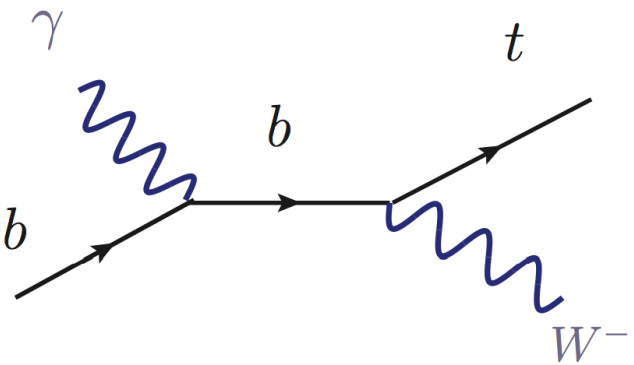


e-beam 60 GeV, 100 fb^{-1}:

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

Top Quark Structure Function

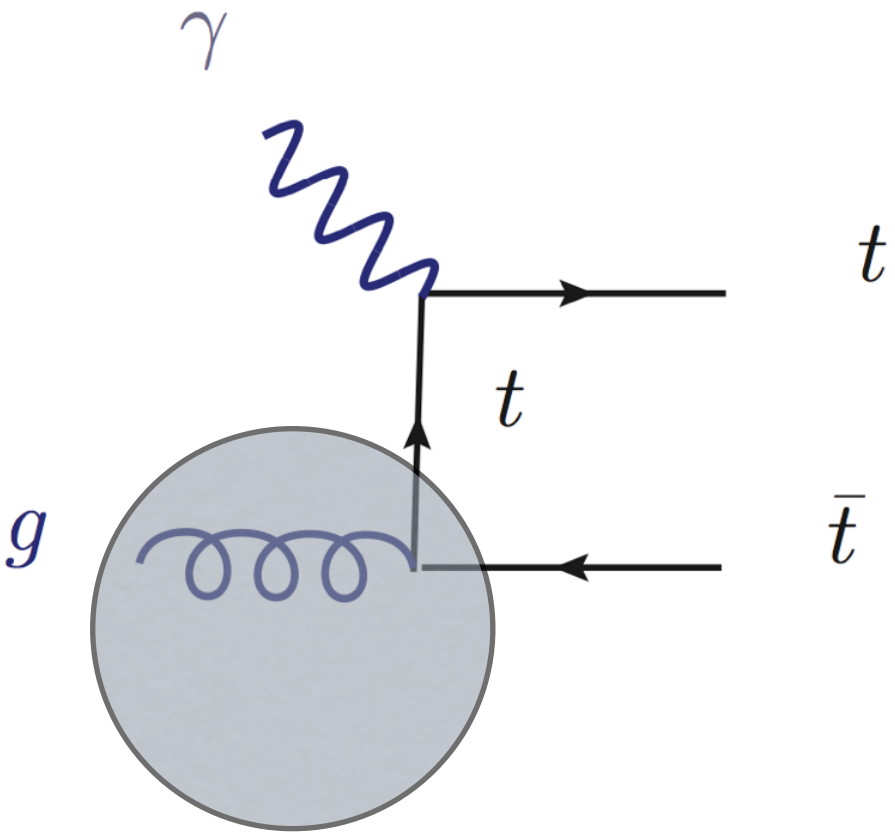
Boroun, Phys. Lett. B744, 142 (2015)

variable flavour number scheme for top quark

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

low and moderate $Q^2 \simeq m_t^2$

$$R^t(x, Q^2) = \frac{F_L^t(x, Q^2)}{F_2^t(x, Q^2)}$$



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

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

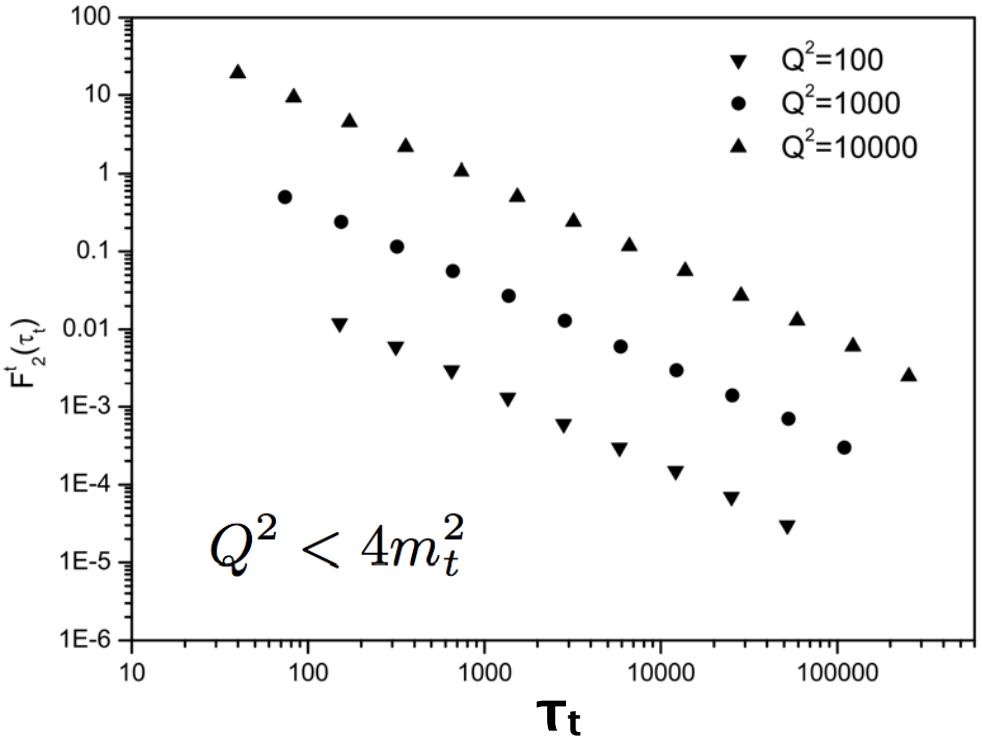
→ **predicted top structure function at LHeC**

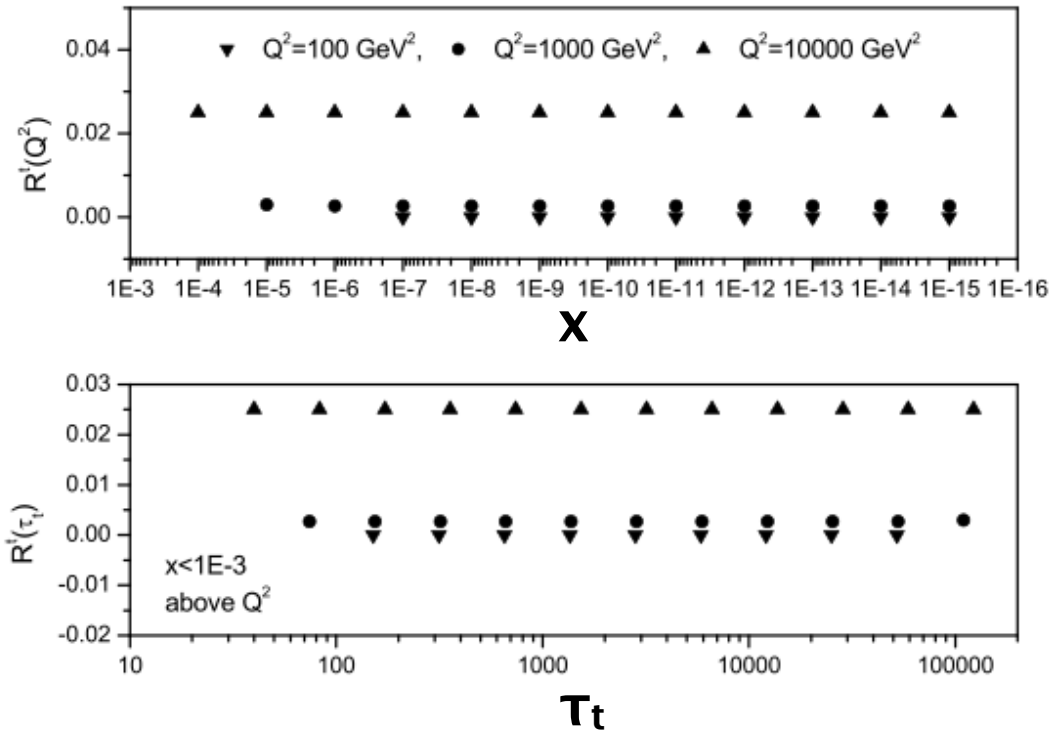
Top Quark Structure Function

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





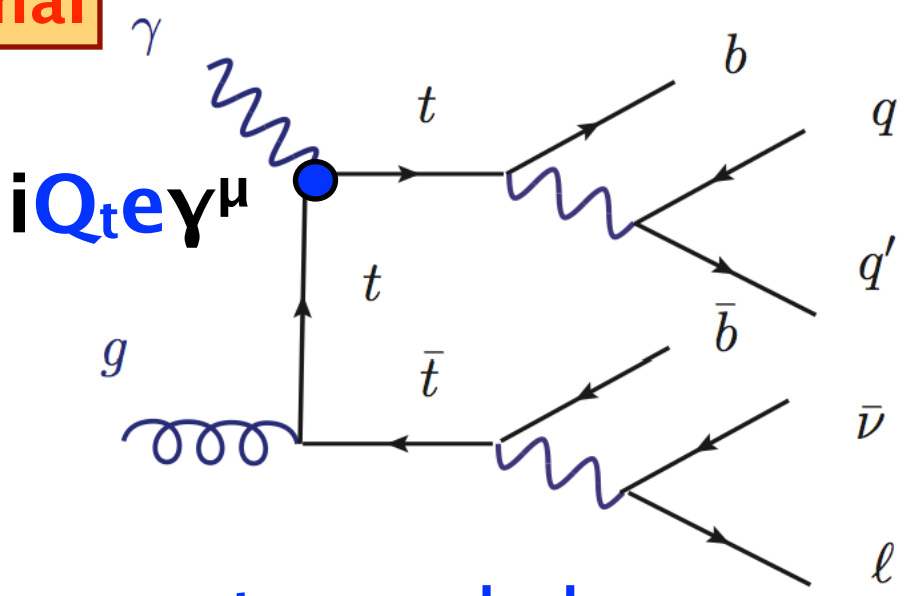
→ approximately: $1/\tau_t$

→ independent of x and τ_t

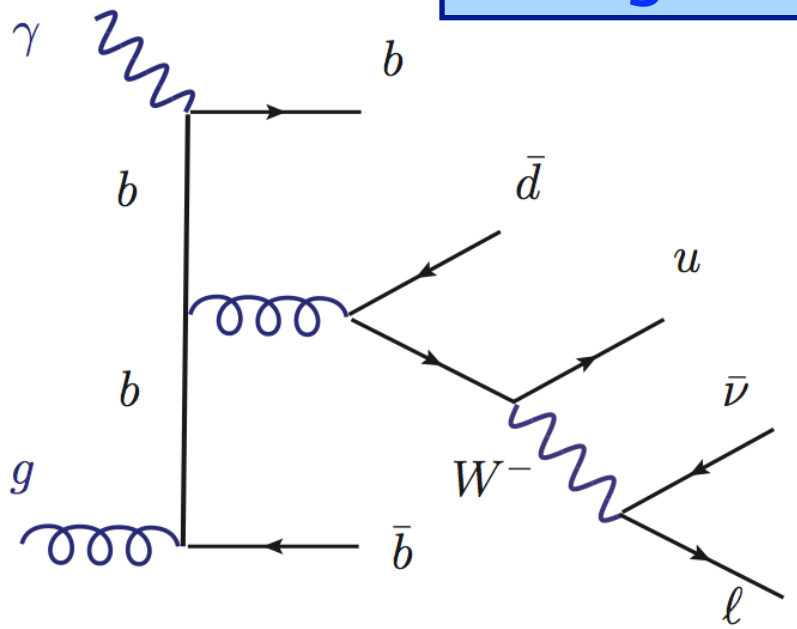
→ longitudinal top structure function component could be good to probe top quark density in proton at $Q^2 \simeq 4m_t^2$

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

signal

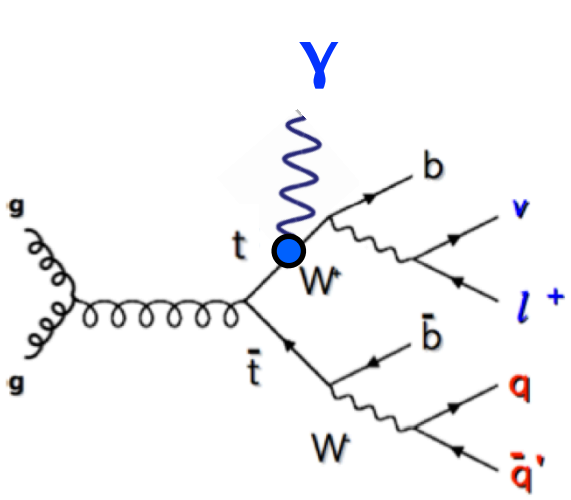


background

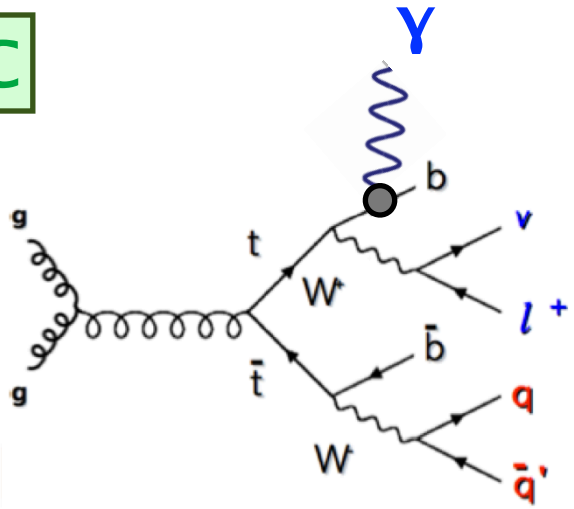


→ measure top quark charge

LHC



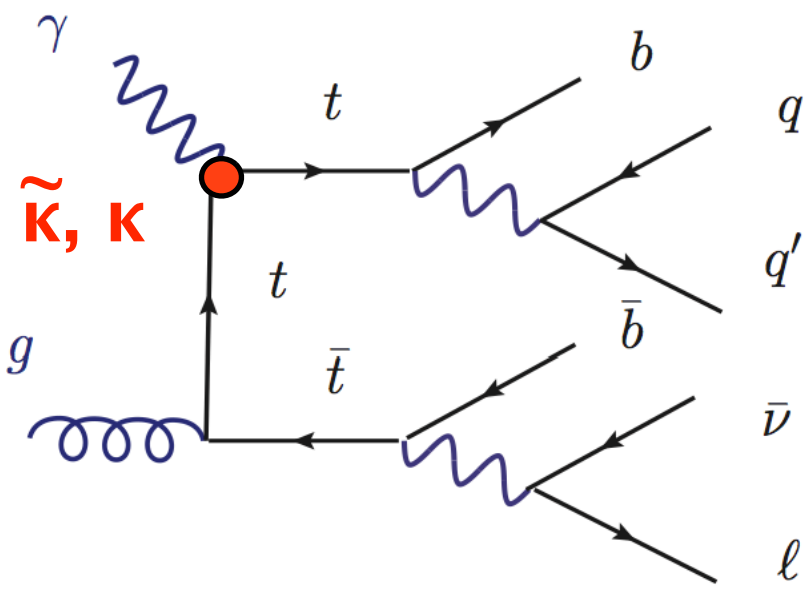
OR



?

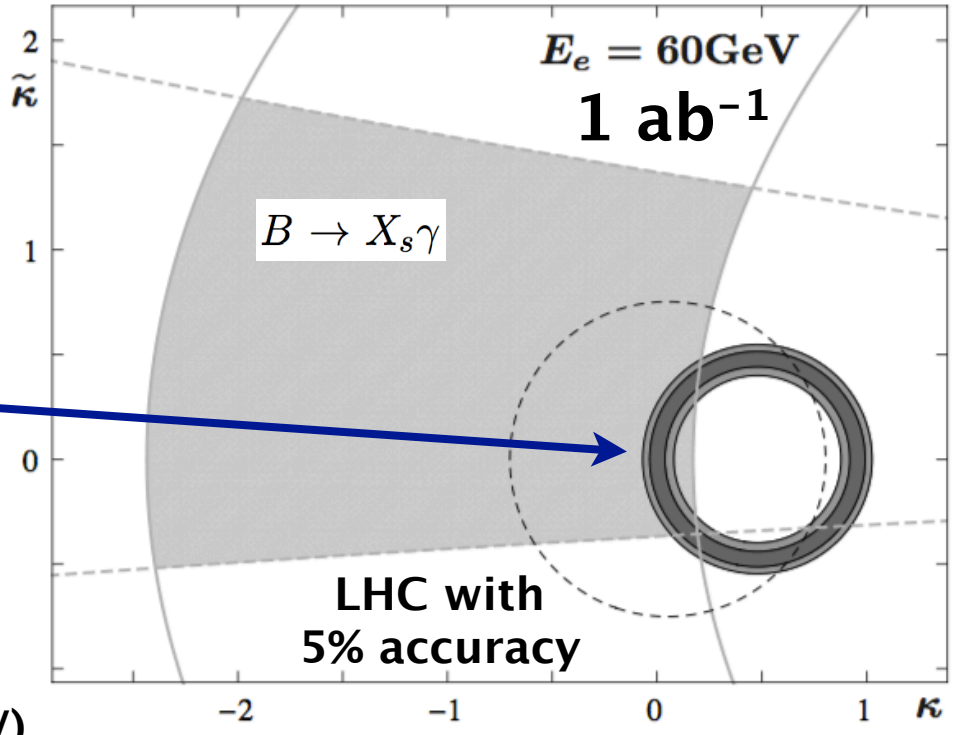
→ difficult at the LHC

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: $\tilde{\kappa}$



NEW

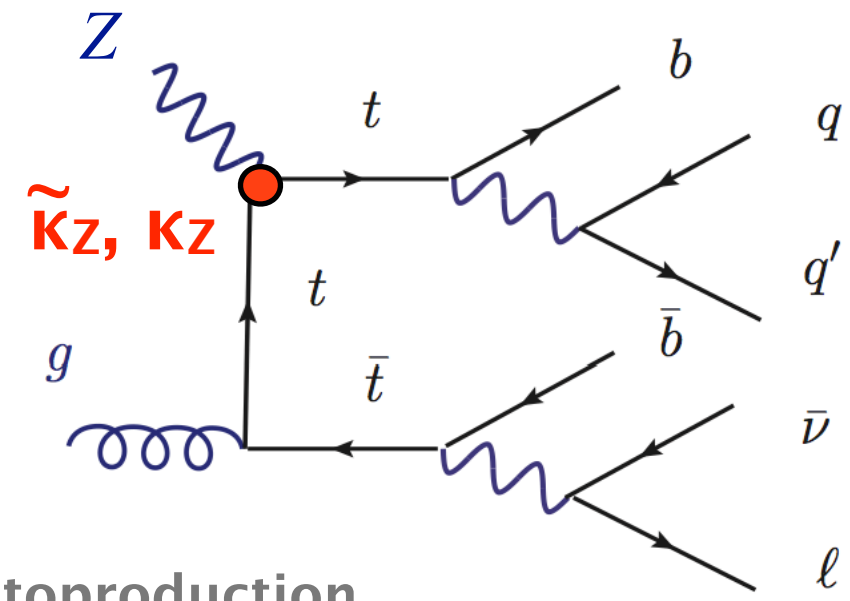
LHeC:
8% and 16% accuracy

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

magnetic dipole moment: κ

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

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



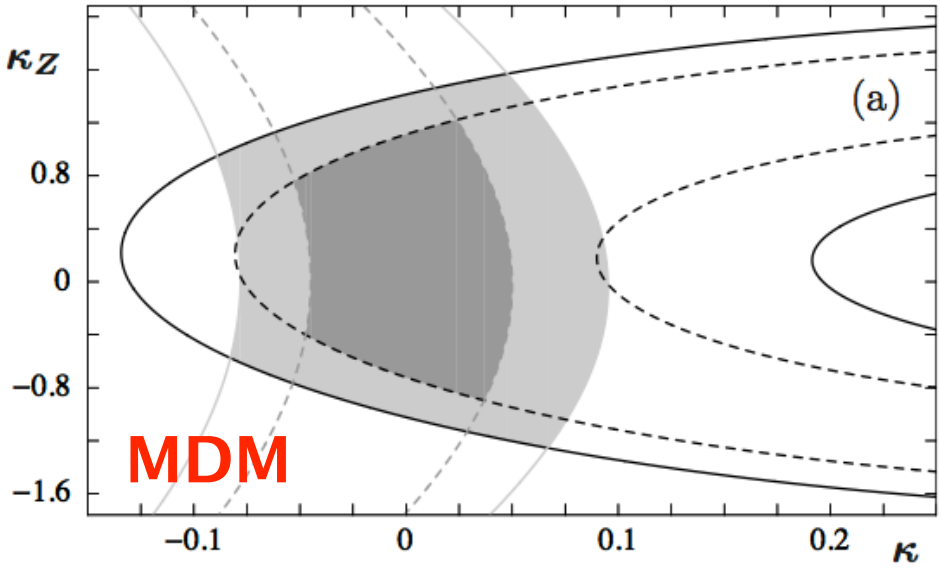
$t\bar{t}$ photoproduction

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

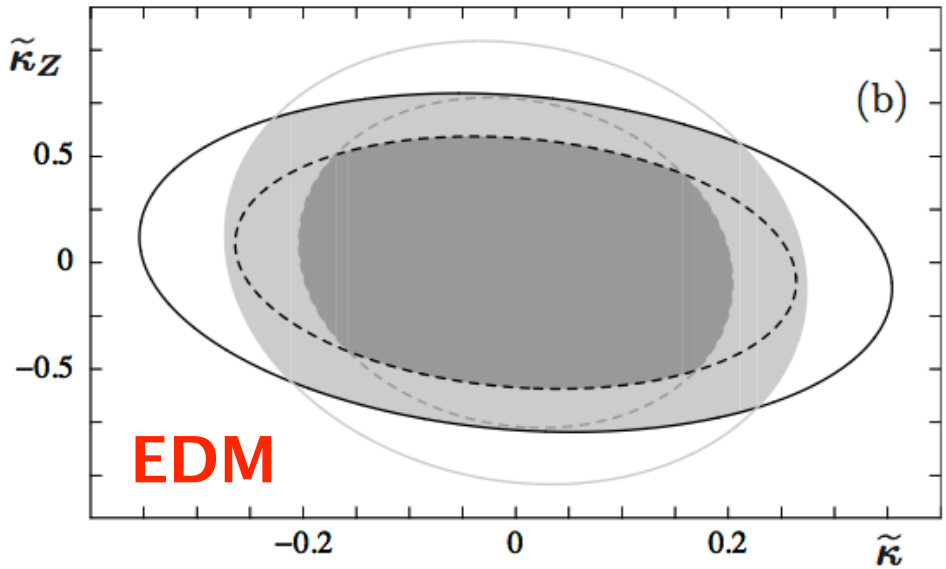
property	precision
EDM: $\tilde{\kappa}$ / $\tilde{\kappa}_Z$	0.20–0.28/0.6–0.8
MDM: κ / κ_Z	0.05–0.09/0.9–1.3

100 fb^{-1}

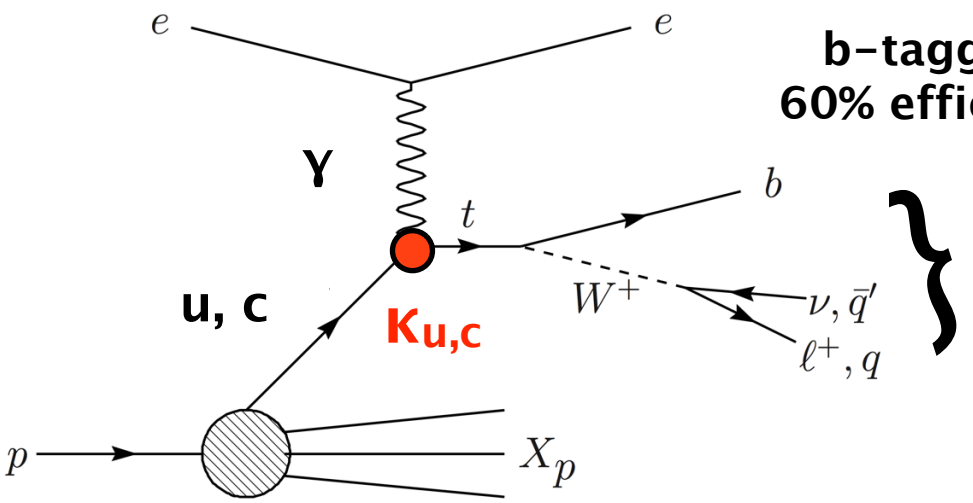
LHeC:
10% and 18% accuracy



$t\bar{t}$ DIS

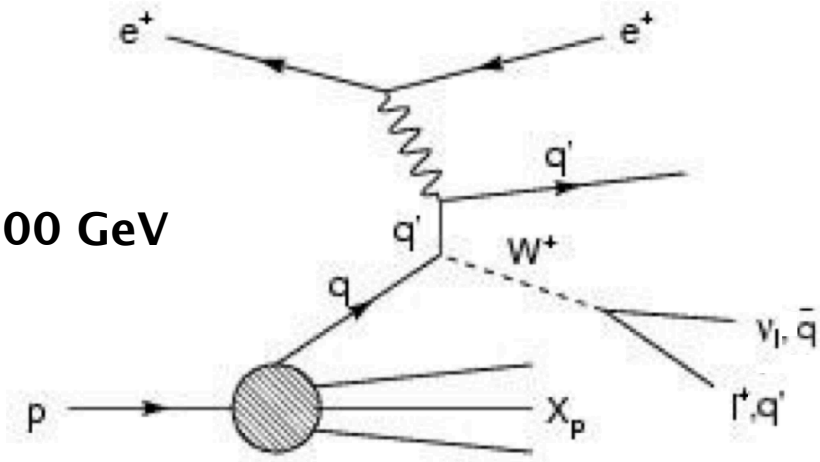


Single Top Quark Production: FCNC



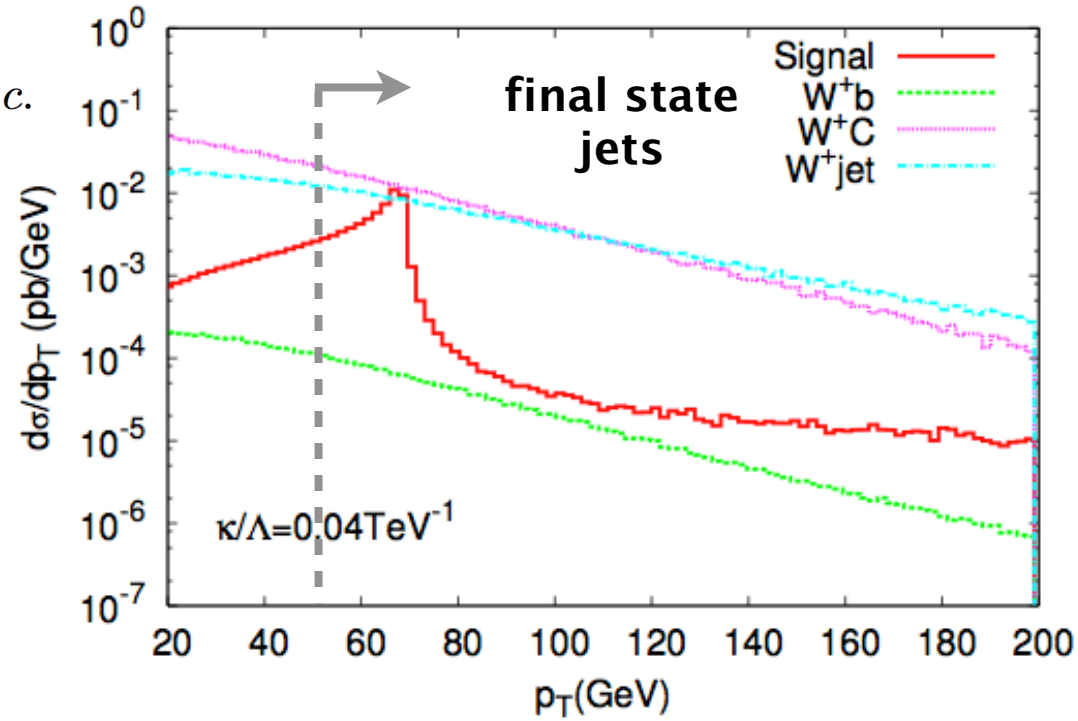
b-tagging:
60% efficiency

150<M_{Wb}<200 GeV



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

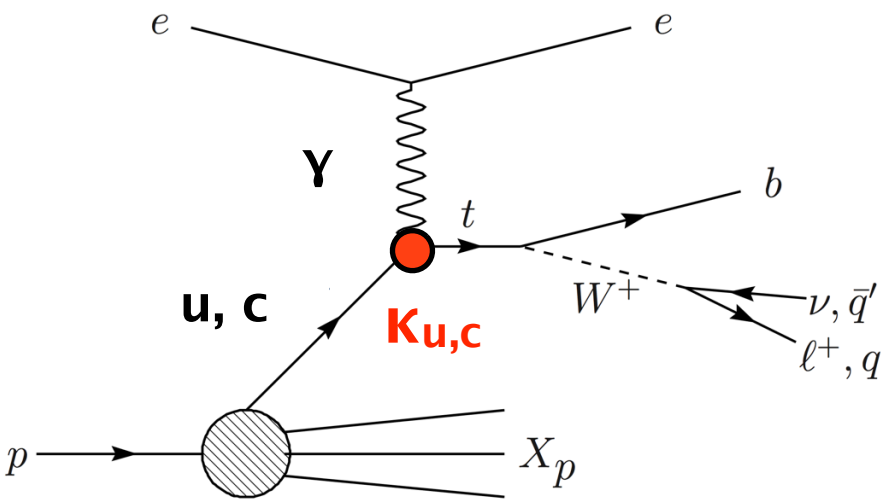
LHeC TDR,
J.Phys. G39,
075001 (2012)



γp collider:

e-beam 70 GeV
γ: 80% of e-energy
L_{int}=10 fb^{-1}

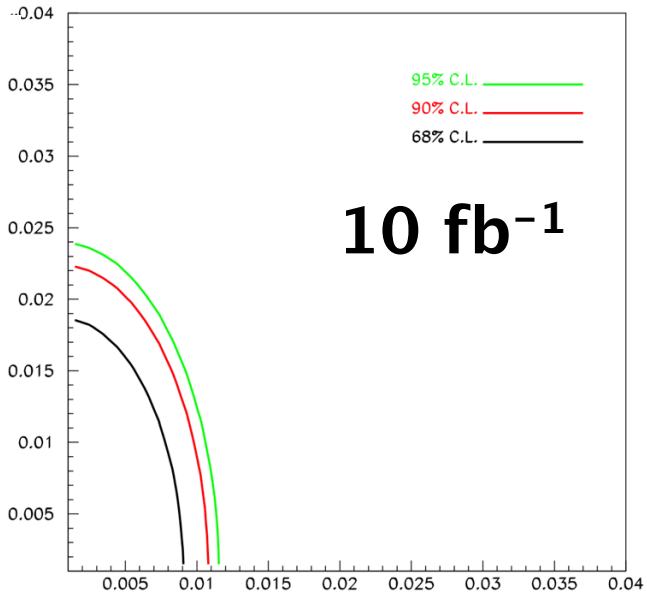
Single Top Quark Production: NC



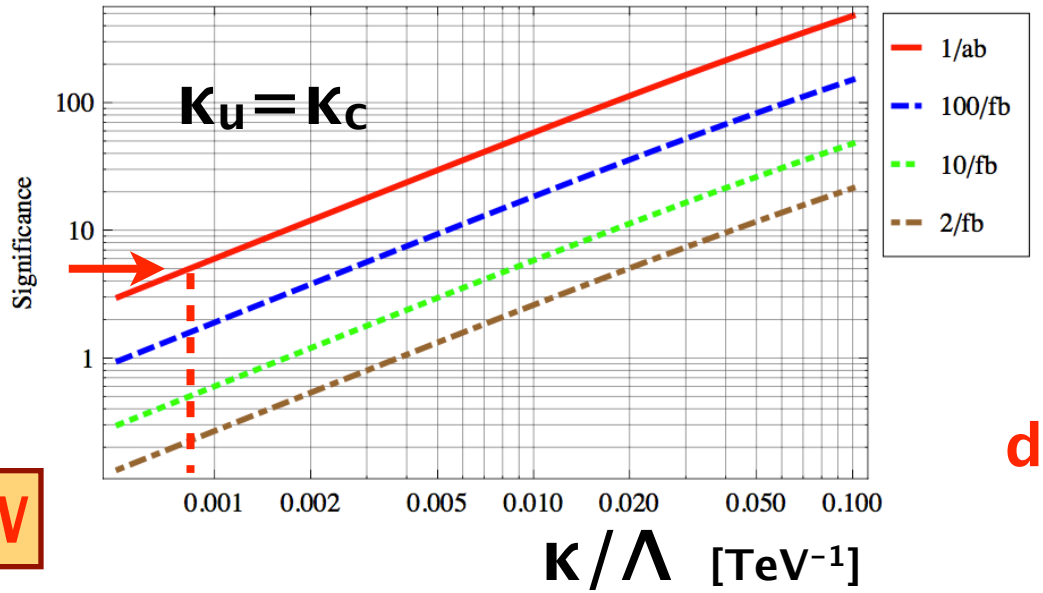
$$L = -g_e \sum_{q=u,c} Q_q \frac{\kappa_q}{\Lambda} \bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$

κ_c/Λ [TeV^{-1}]

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



κ_u/Λ [TeV^{-1}]

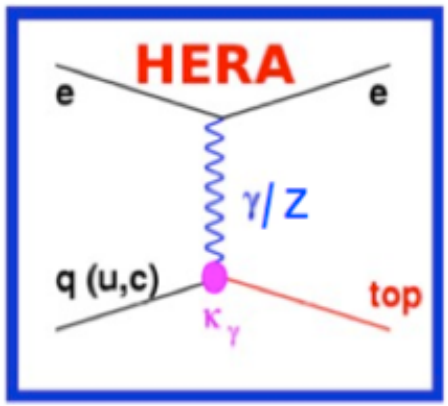


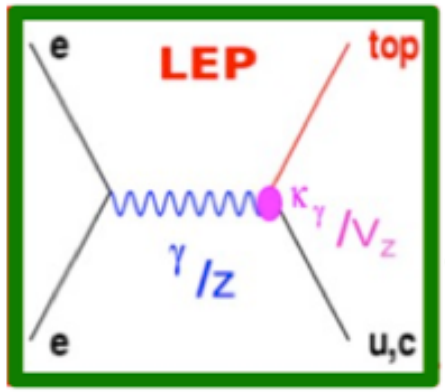
5σ

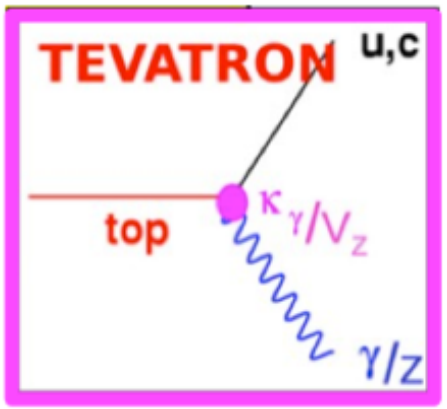
NEW

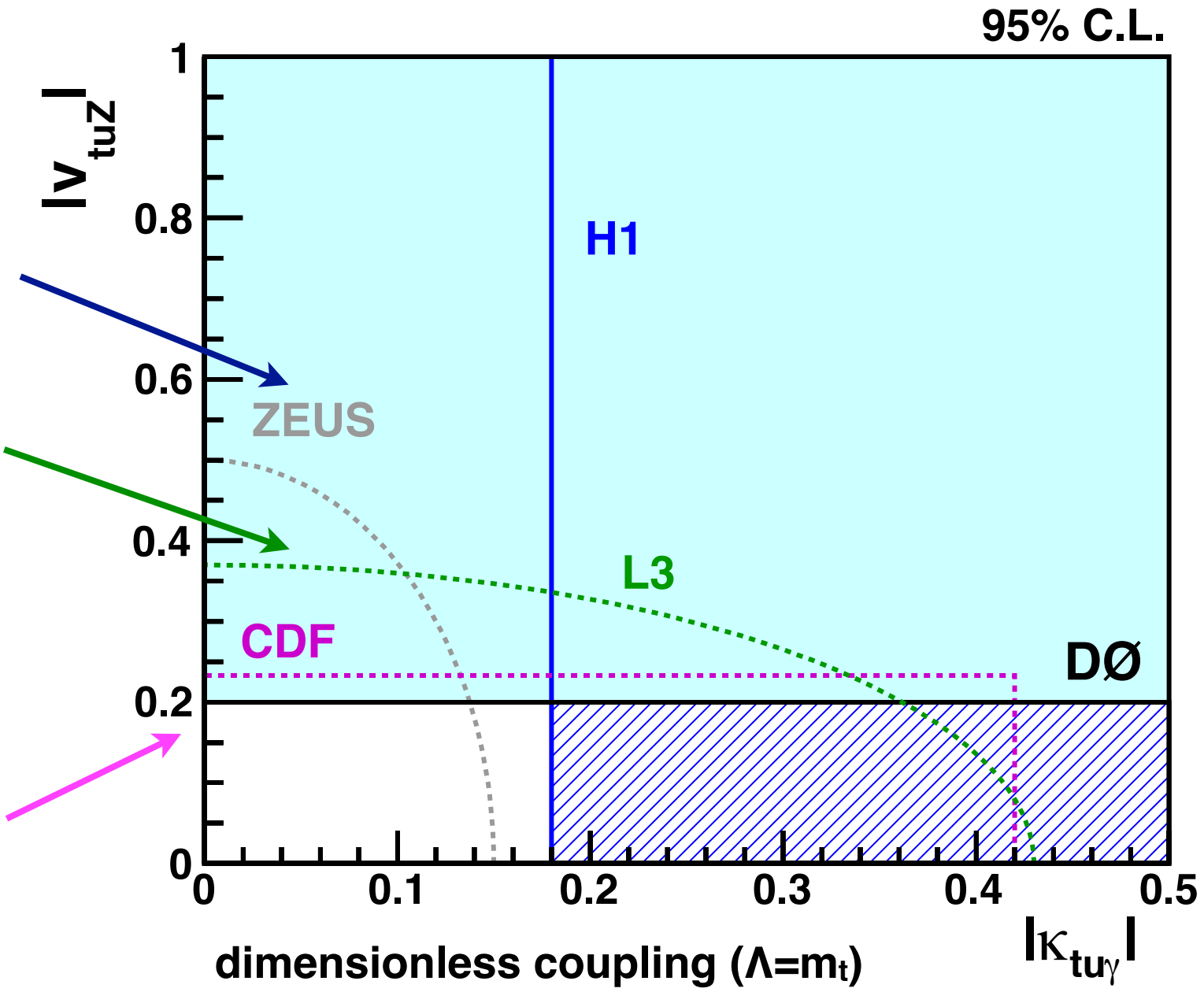
1 ab^{-1}: discovery for order 10^{-3}

FCNC Top Couplings at Colliders

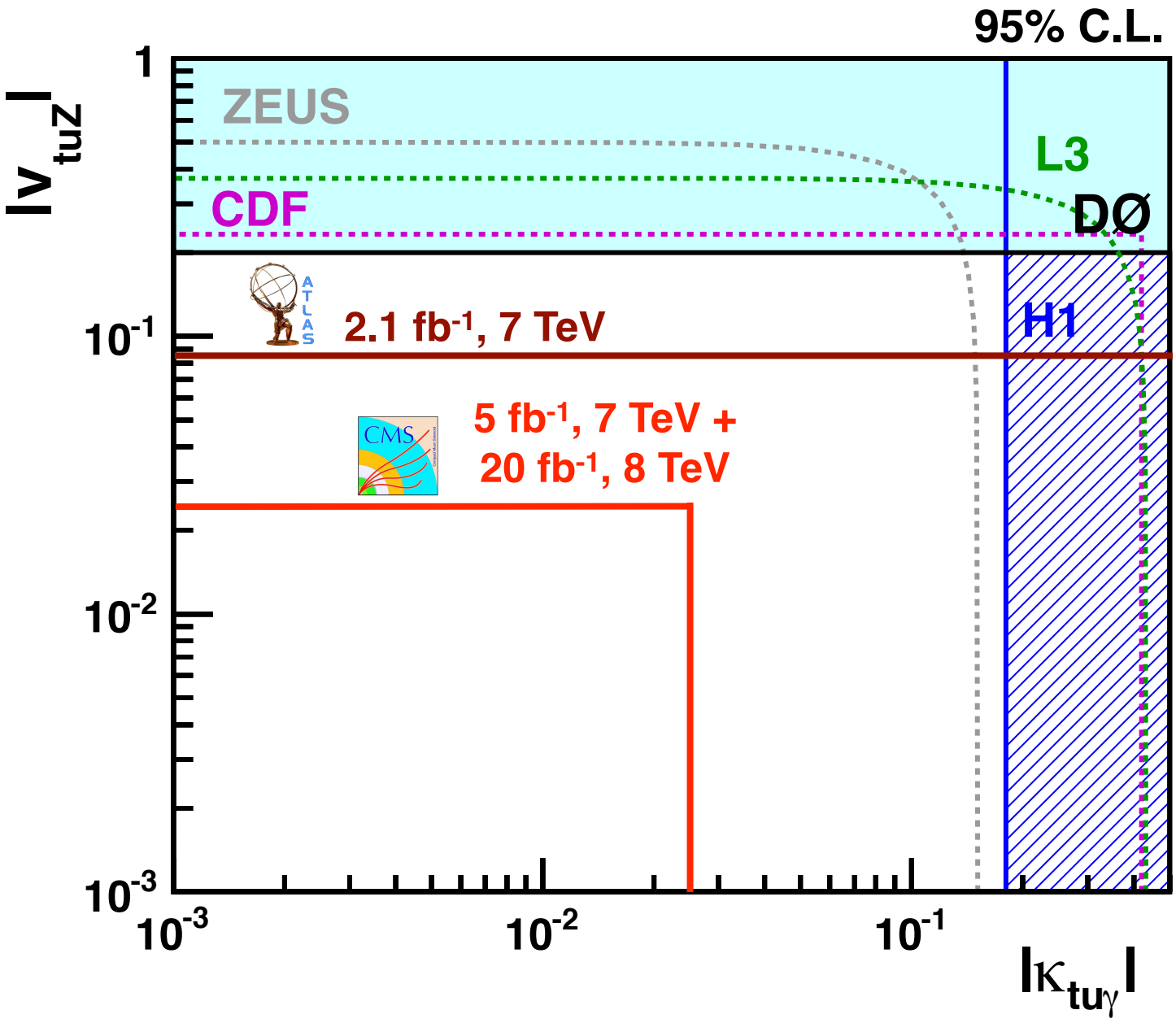


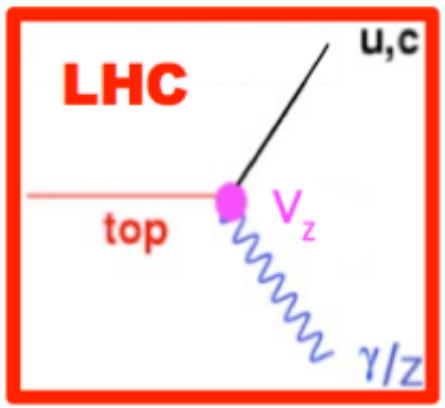






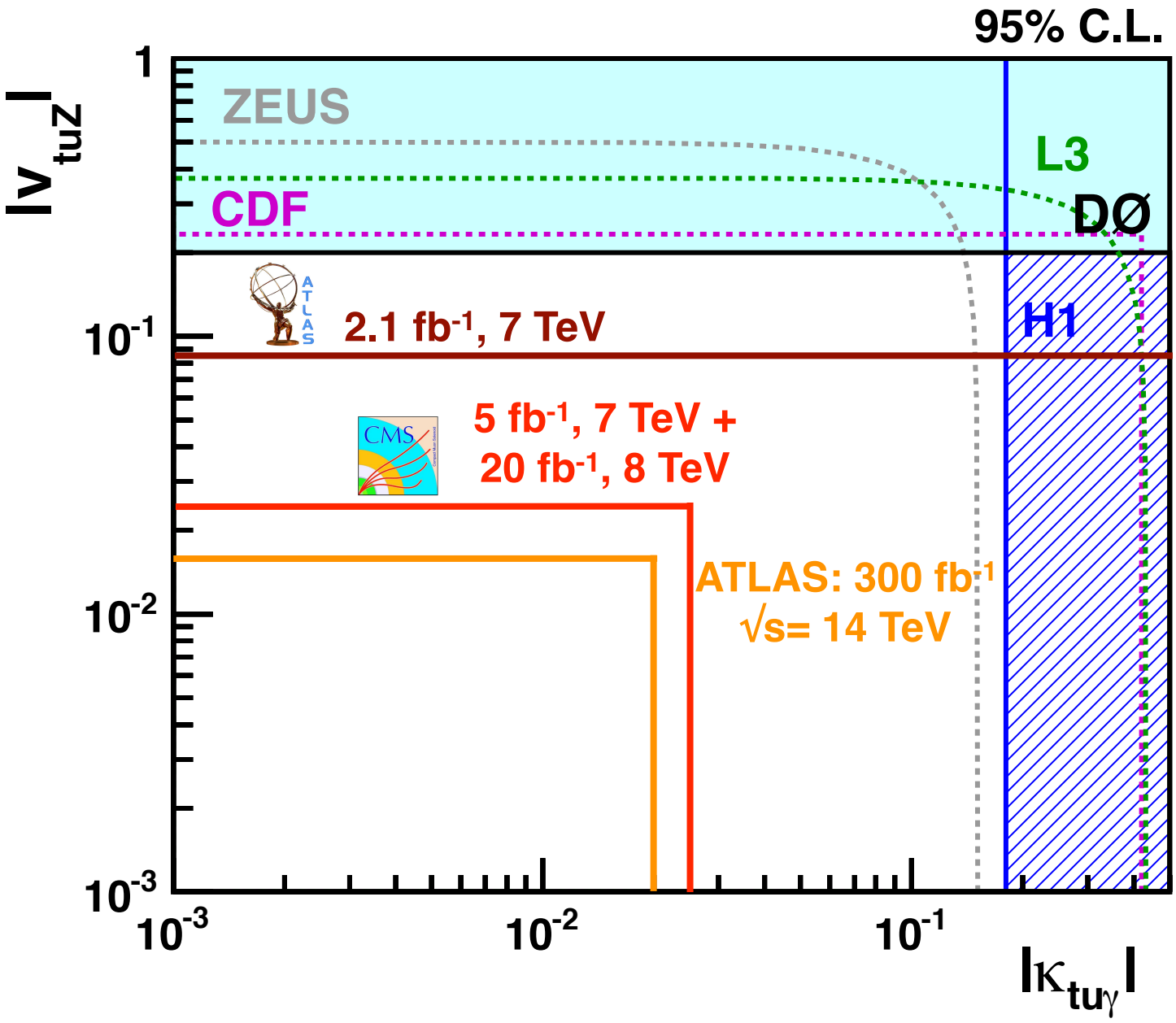
FCNC Top Couplings at Colliders

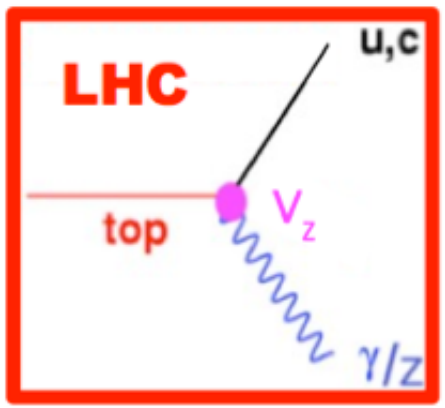




FCNC Top Couplings at Colliders

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





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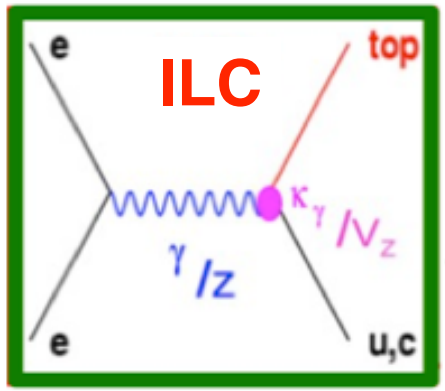

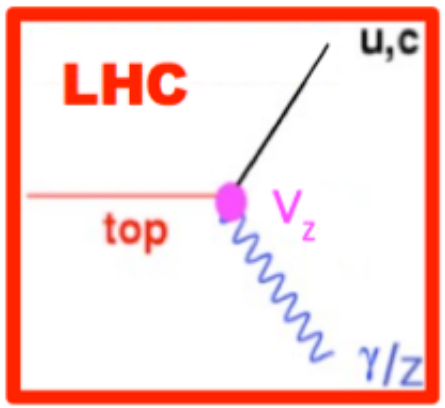

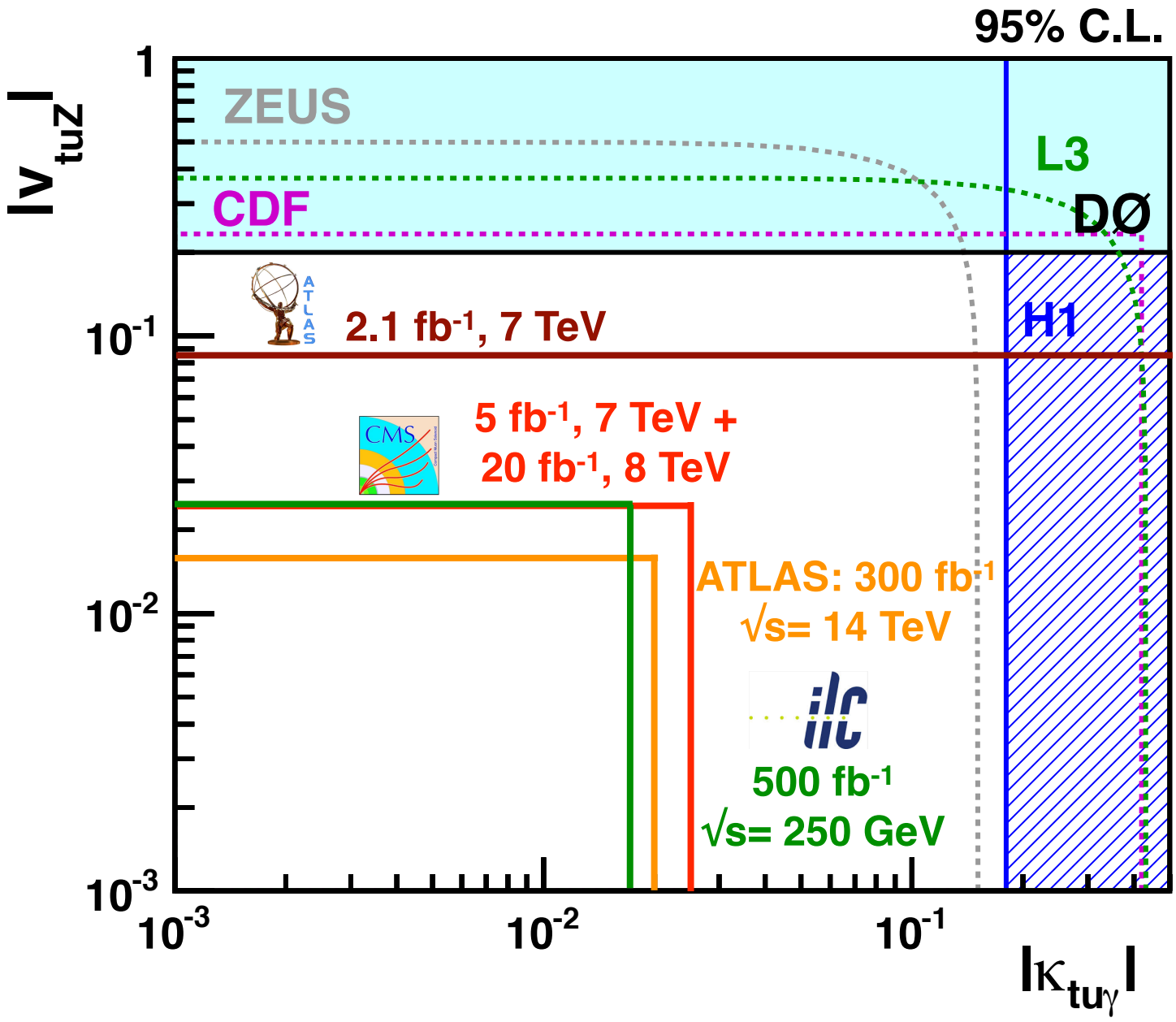

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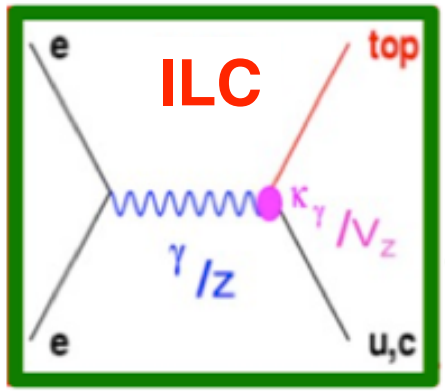
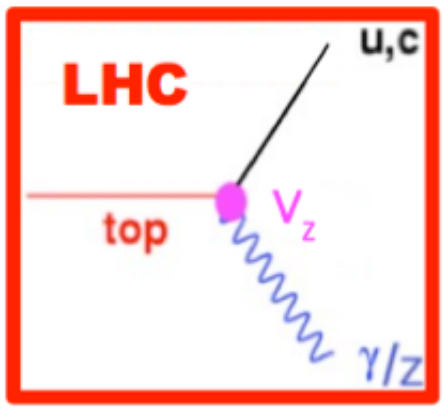
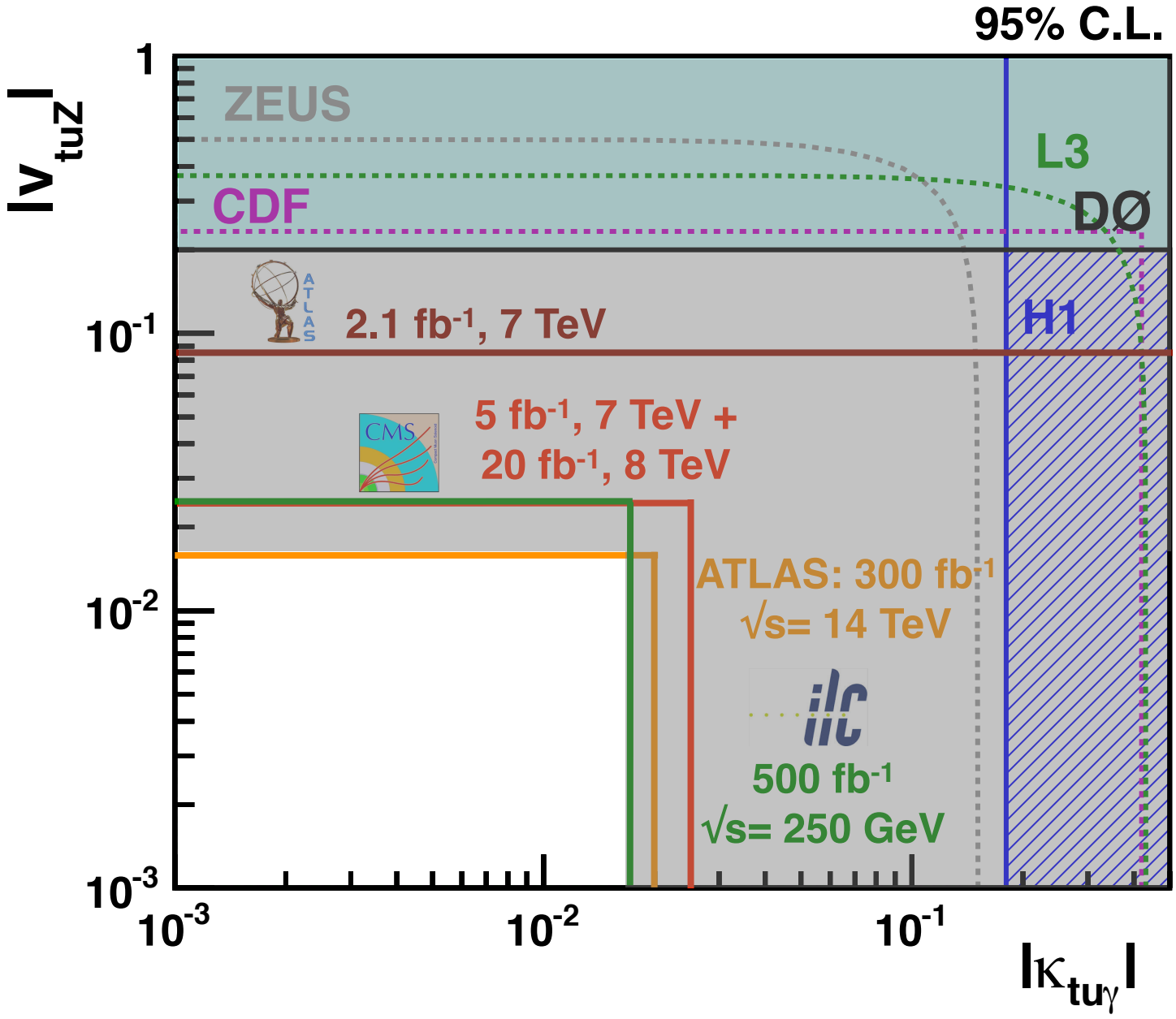
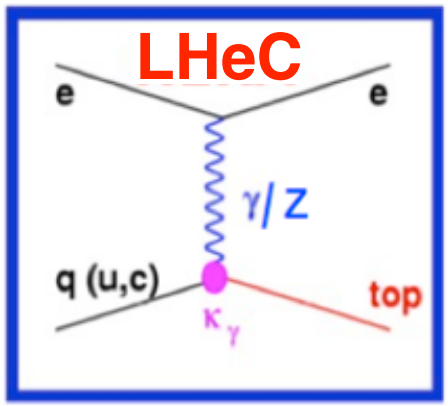
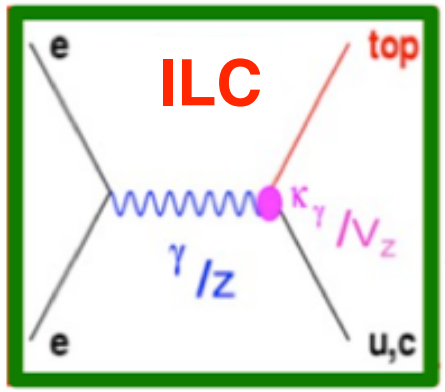


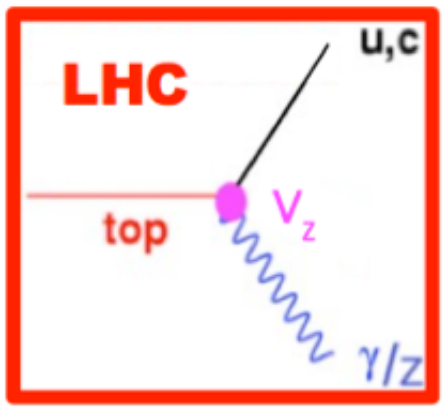


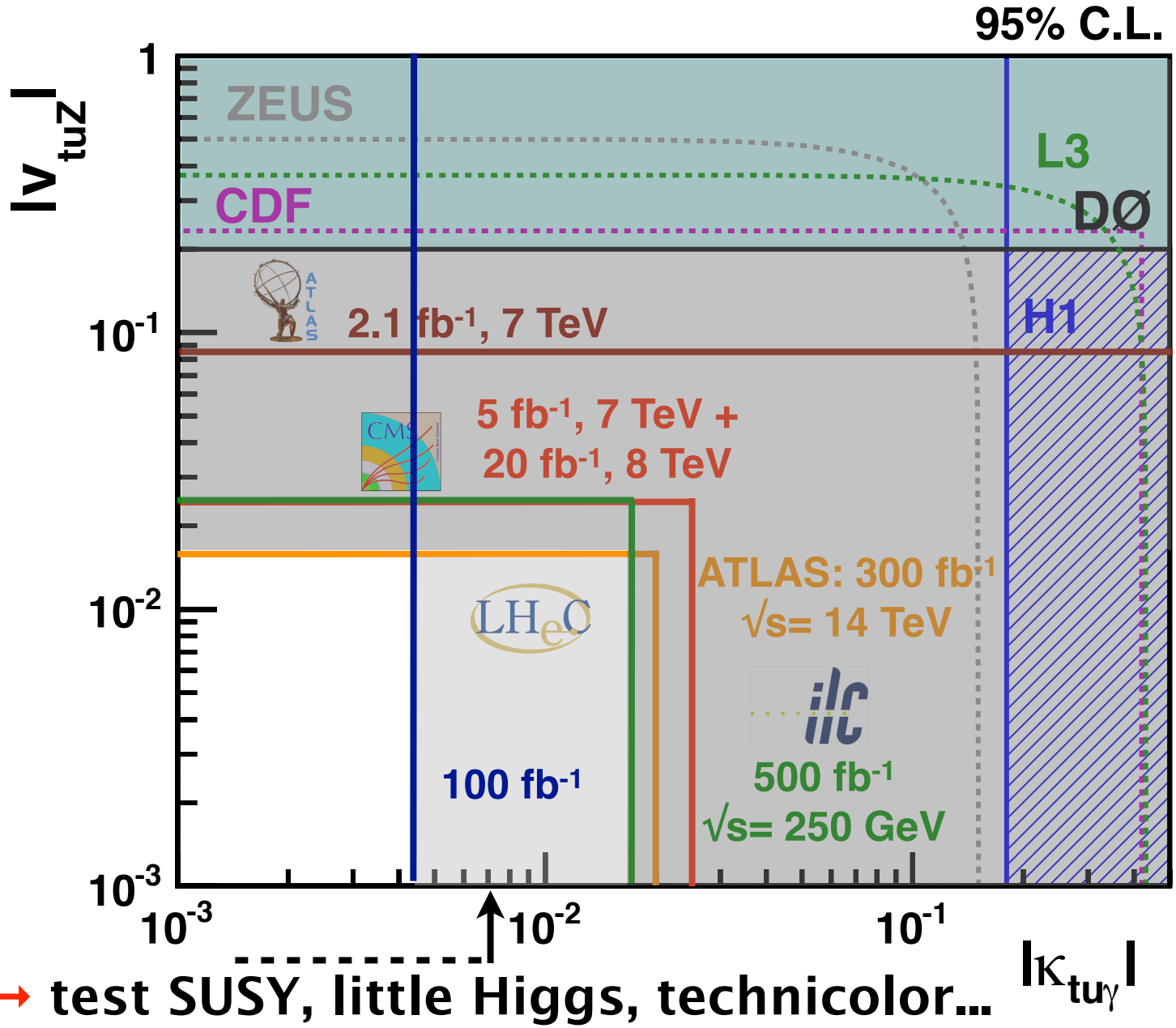


FCNC Top Couplings at Colliders



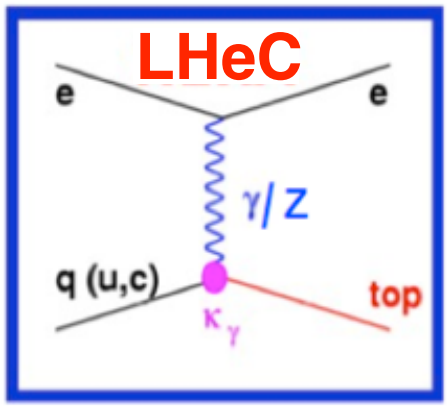


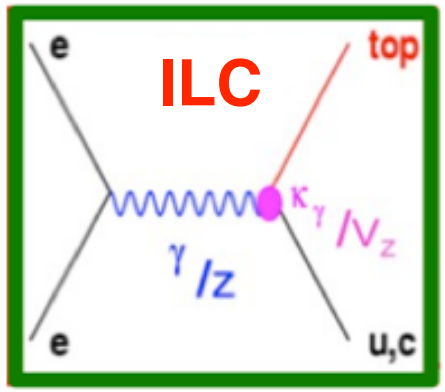


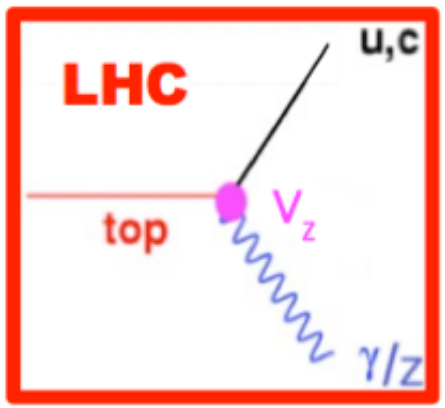


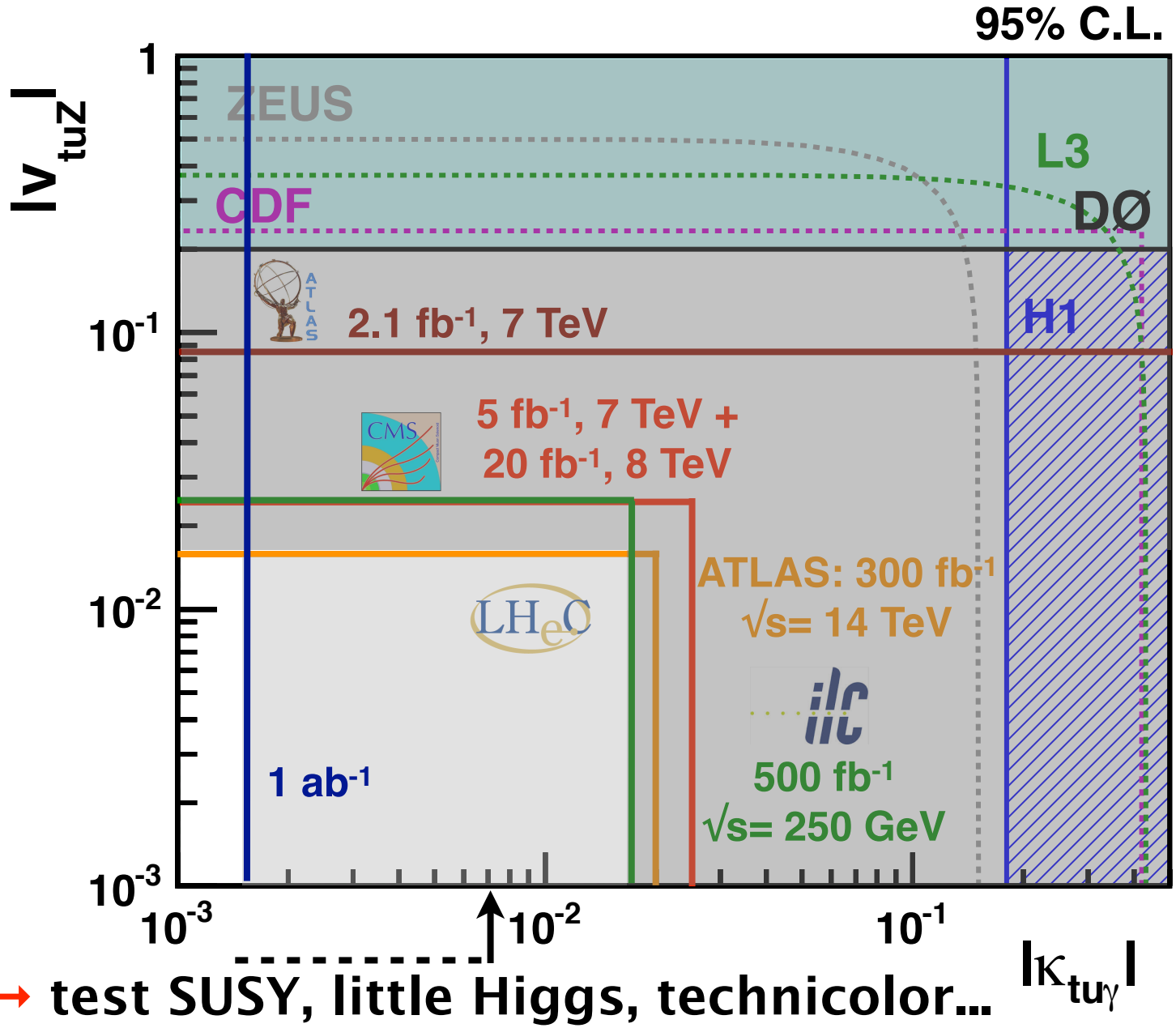
→ test SUSY, little Higgs, technicolor...

FCNC Top Couplings at Colliders









Outline

Introduction
Charged Current
Neutral Current
Summary

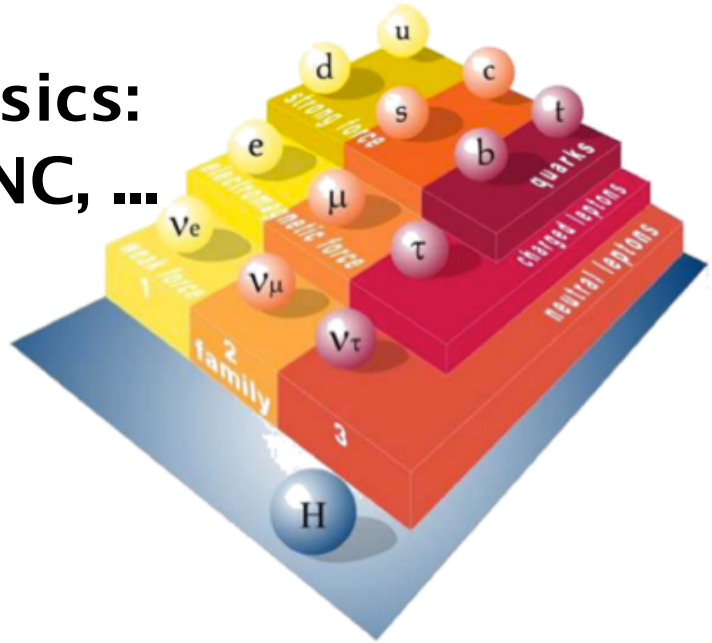
Summary of Top Quark Properties

property	E_e (GeV)	L_{int} (fb^{-1})	SM value	precision
t: CC unpol.	60	100	2 pb	N_t=200,000
t: CC 80% pol.	60	100	3 pb	N_t=300,000
t: NC photoprod.	60	100	0.031 pb	N_t=3,100
$t\bar{t}$: NC DIS	60	100	0.023 pb	N_{tt}=2,300
$t\bar{t}$: NC photoprod.	60	100	0.70 pb	N_{tt}=70,000
top PDF	60	10		measurable
$\|V_{tb}\|$	60	100	1	0.005
f_V^L	60	100	1	0.001–0.01
f_V^R, f_T^L, f_T^R	60	100	0	0.01–0.1
C_1	60	100	0	0.50–0.85
C_2^r, C_3^r, C_4^r	60	100	0	1.4–5.0
polarisation P_t	$\sqrt{s}$=1.6 TeV	20	0.96	O(10%)
f_T^L, f_T^R from pol.	$\sqrt{s}$=1.6 TeV	20	0	0.01–0.09
EDM: $\tilde{\kappa}$ / $\tilde{\kappa}_Z$	60	100	0 / 0	0.20–0.28/0.6–0.8
MDM: κ / κ_Z	60	100	0 / 0	0.05–0.09/0.9–1.3
FCNC: $\kappa_u = \kappa_c$	70 (γp)	1000	0	0.0014

Conclusions

- **future ep collider has a rich analysis programme for top quarks**

- **study top at ep collider for the first time**
- **high precision measurements top quark couplings to EWK gauge bosons (mainly $|V_{tb}|$, ttγ, ttZ)**
- **analyse top quark properties: polarisation, charge, PDFs of tops, ...**
- **many stringent searches for new physics: anomalous couplings, EDM, MDM, FCNC, ...**

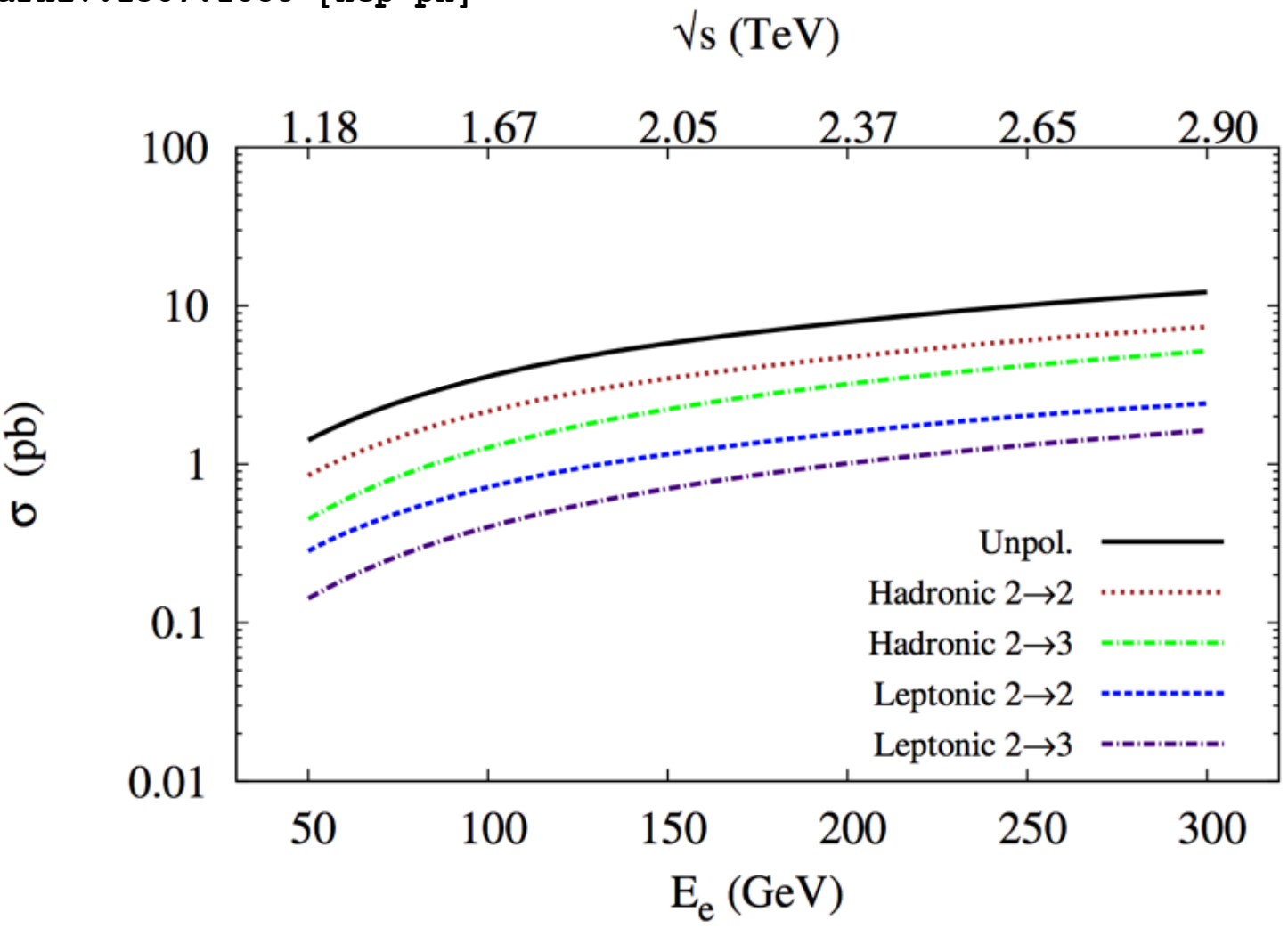


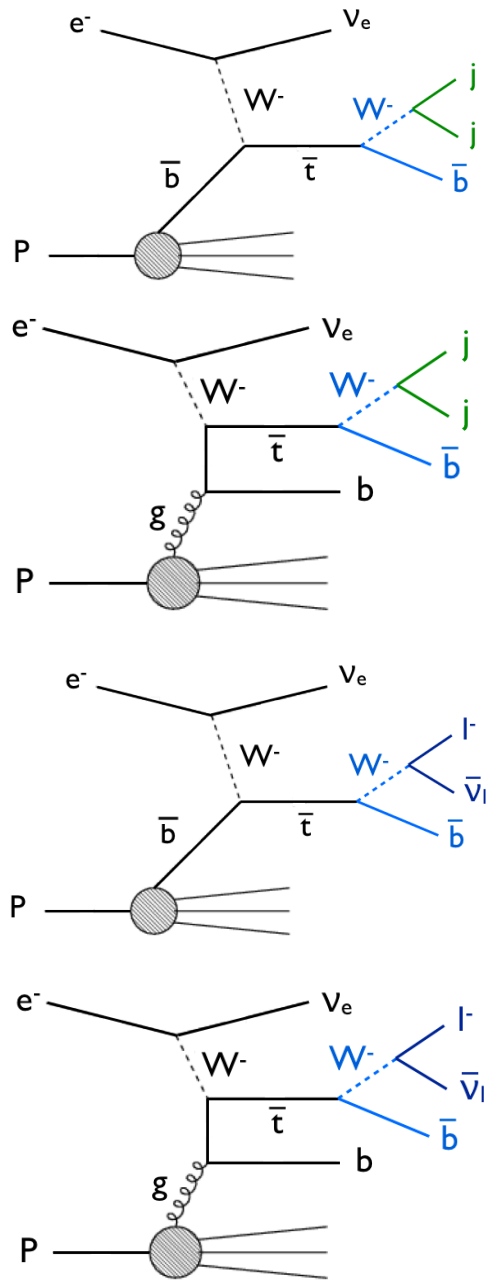
→ important studies to test if top quark is as predicted in the SM or if it is connected to new physics

Backup

CC Single Top Quark Cross Section

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





CC Single Top Quark Cross Section

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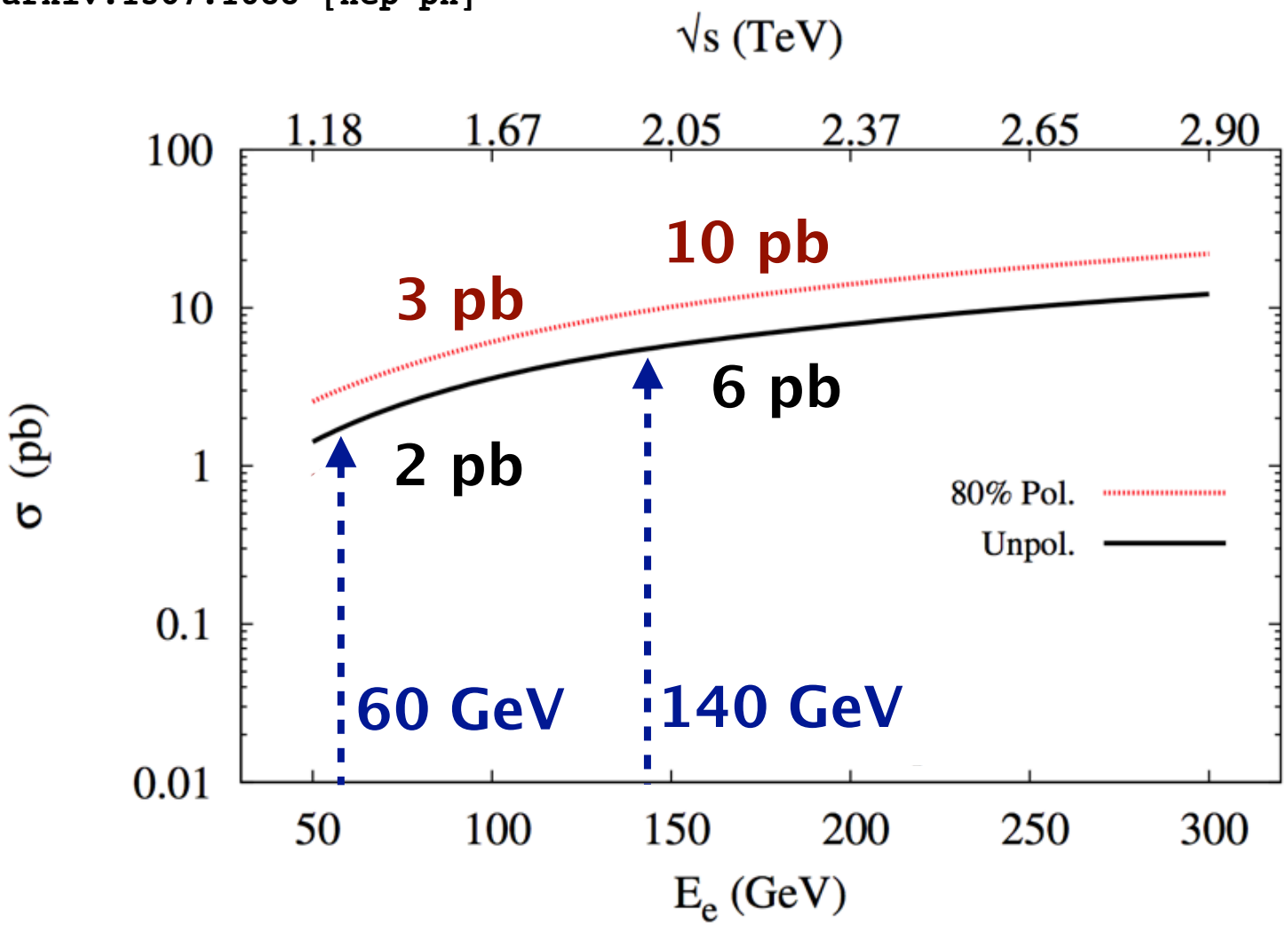


100 fb^{-1}:
2–6 · 10^5 events
3–10 · 10^5 events

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

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

Search for Anomalous Wtb Couplings

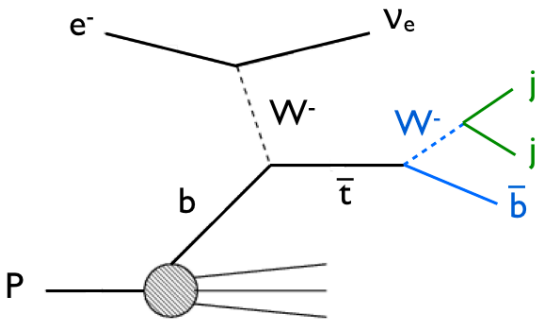
= 1 in SM

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

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

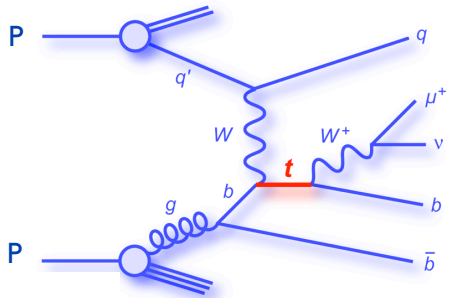
Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688

68% C.L.

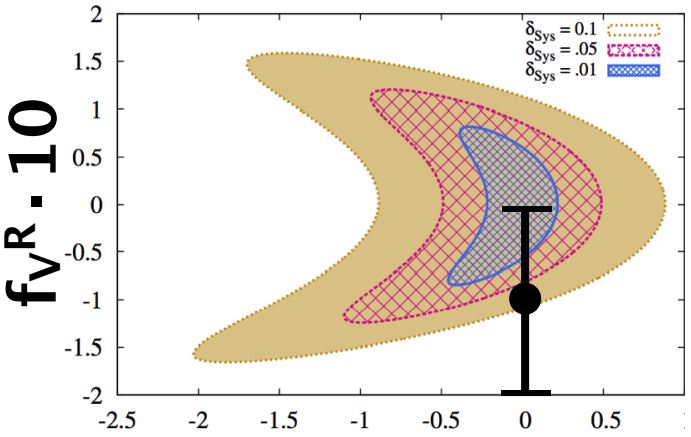


LHC combination preliminary

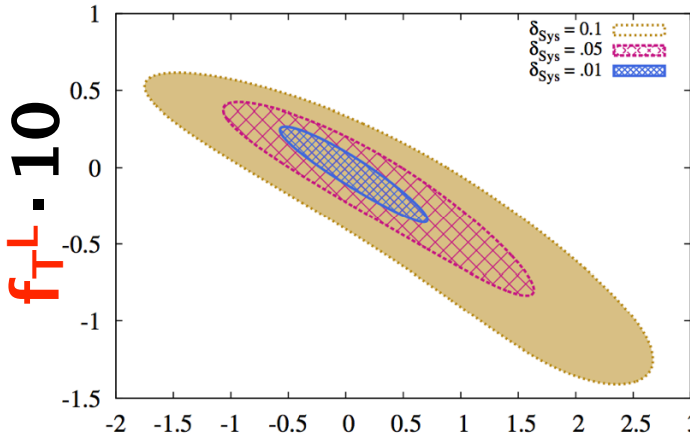
$\sqrt{s}$=7 TeV, L_{int}=35 pb^{-1} - 2.2 fb^{-1}



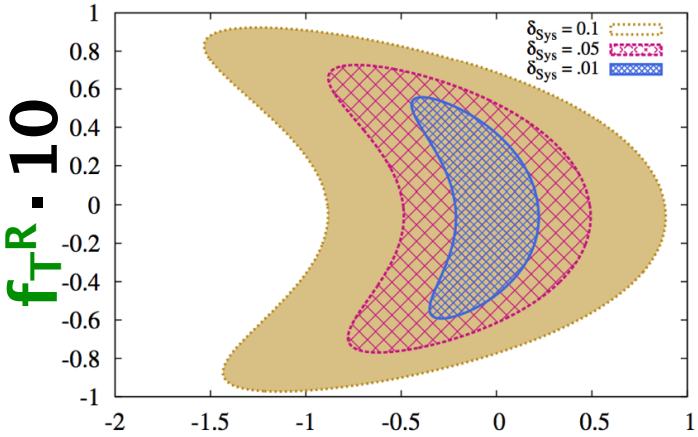
syst. error



syst. error



syst. error



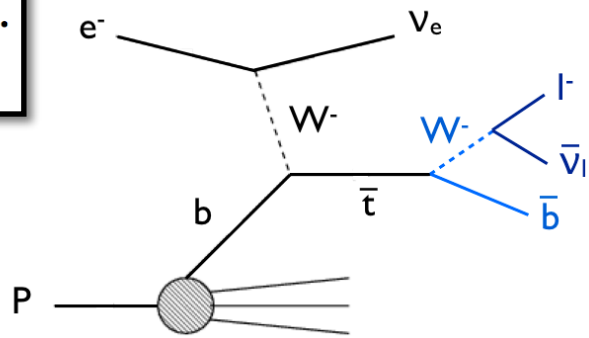
Search for Anomalous Wtb Couplings

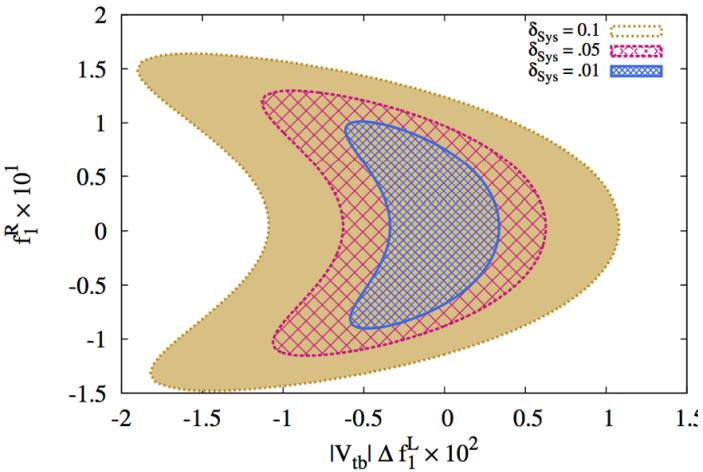
= 1 in SM

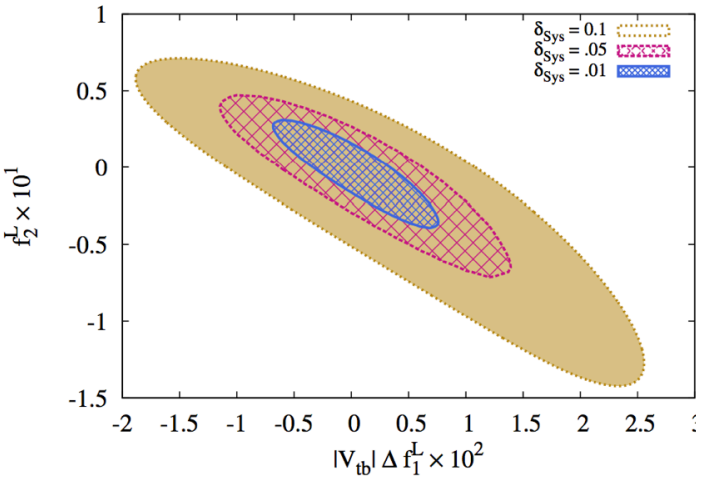
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$

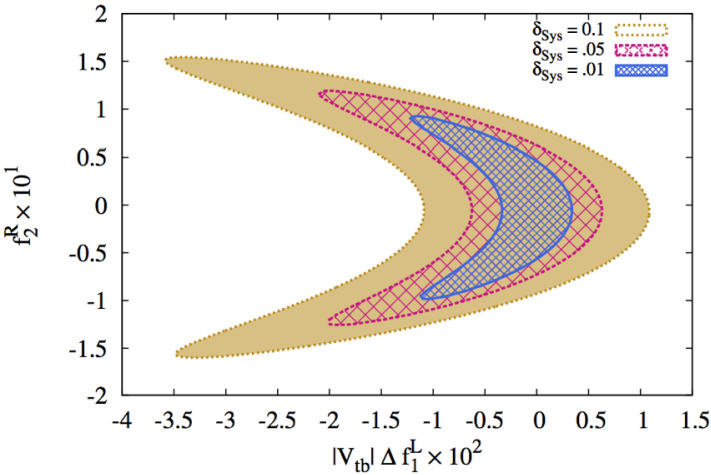
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

68% C.L.









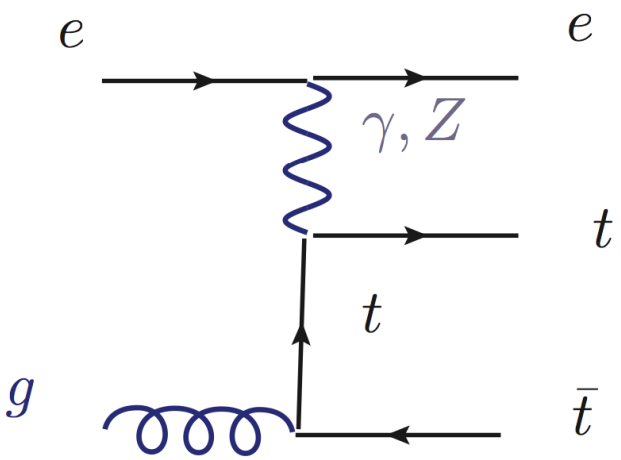
NC Top Quark Production

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

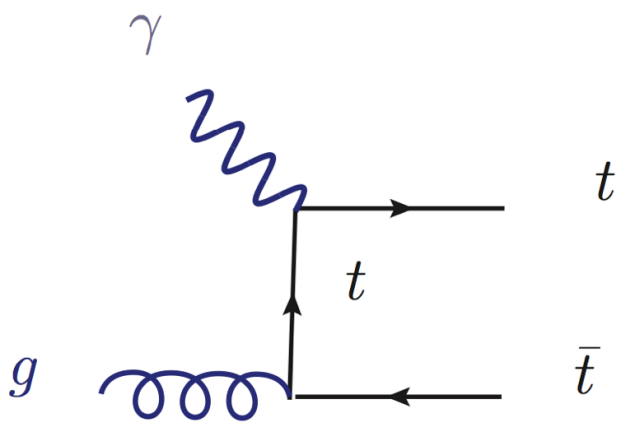
top pair production

single top production

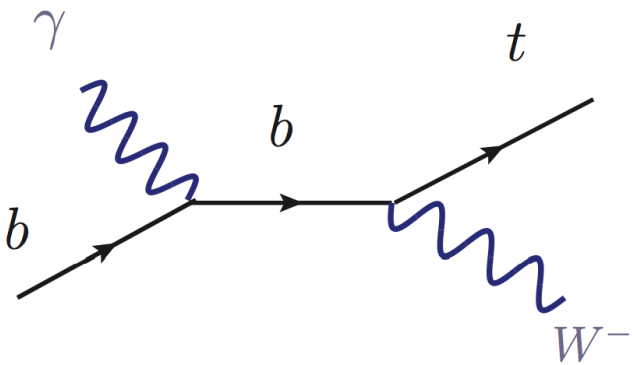
DIS



photoproduction



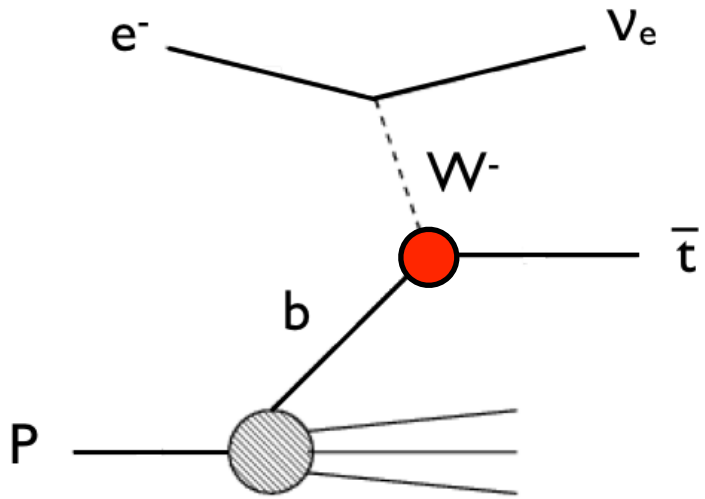
photoproduction



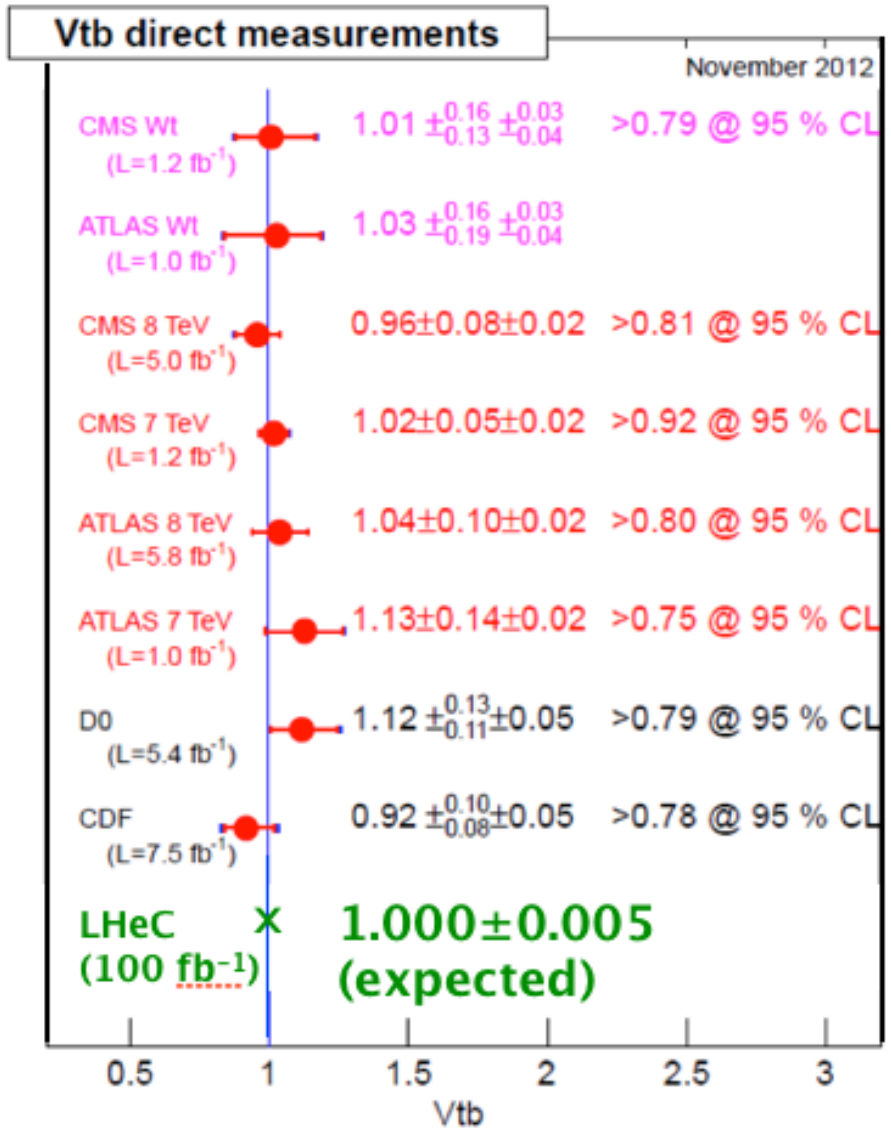
e-beam 140 GeV, 100 fb^{-1}:

0.12 pb	3.2 pb	0.143 pb
$N_{t\bar{t}}$=12,000	$N_{t\bar{t}}$=320,000	N_t=14,300

Direct Measurement of $|V_{tb}|$

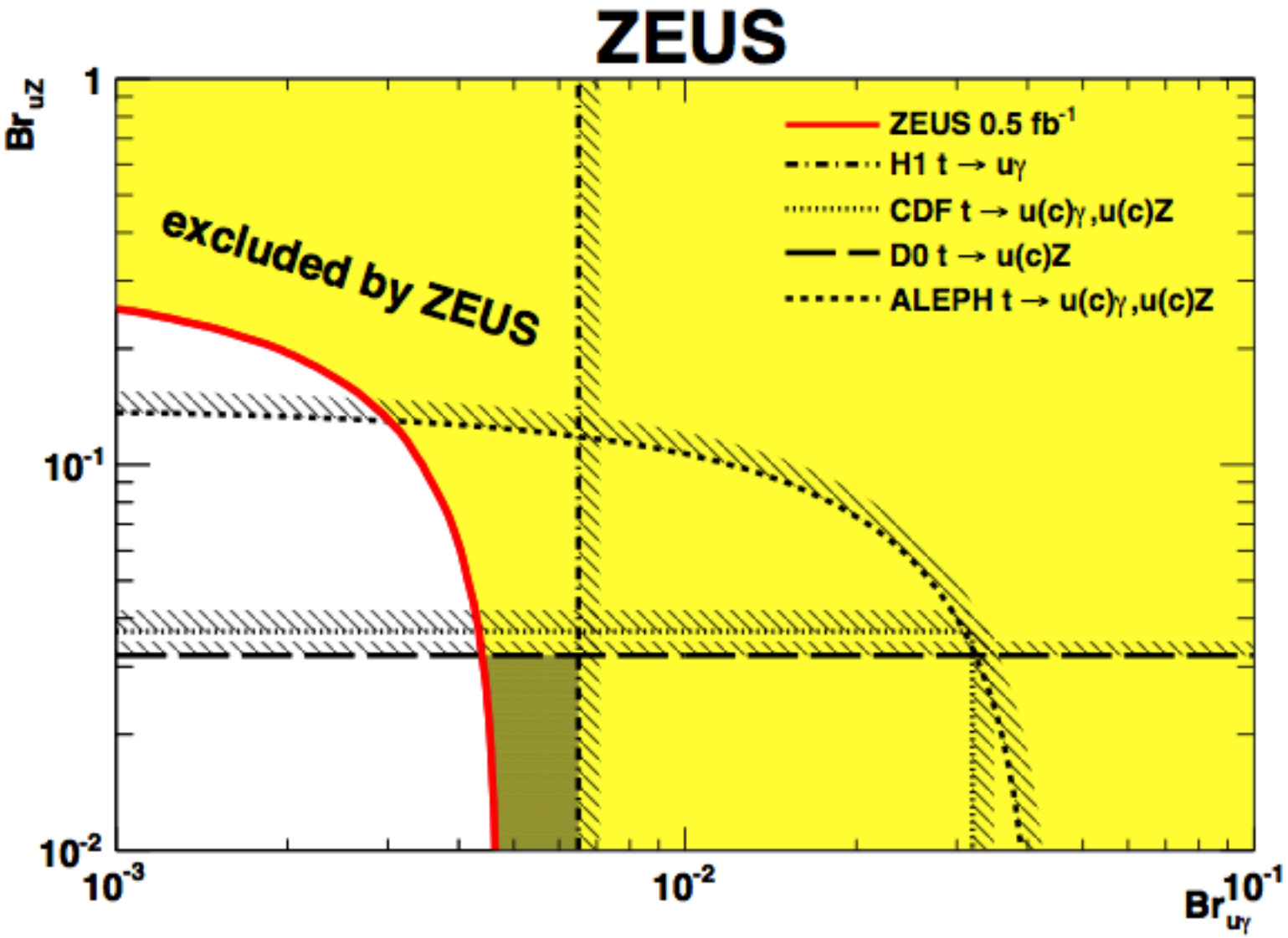


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \mathbf{V_{tb}} \end{pmatrix}$$



→ **high precision measurement**

Search for FCNC in Top Quark Decays



Search for FCNC in Top Quark Decays