

Top and EWK Physics at the LHeC and FCC-eh



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DESY



for the LHeC/FCC-eh Study Group

EPS-HEP 2019
Ghent, Belgium
12 July 2017



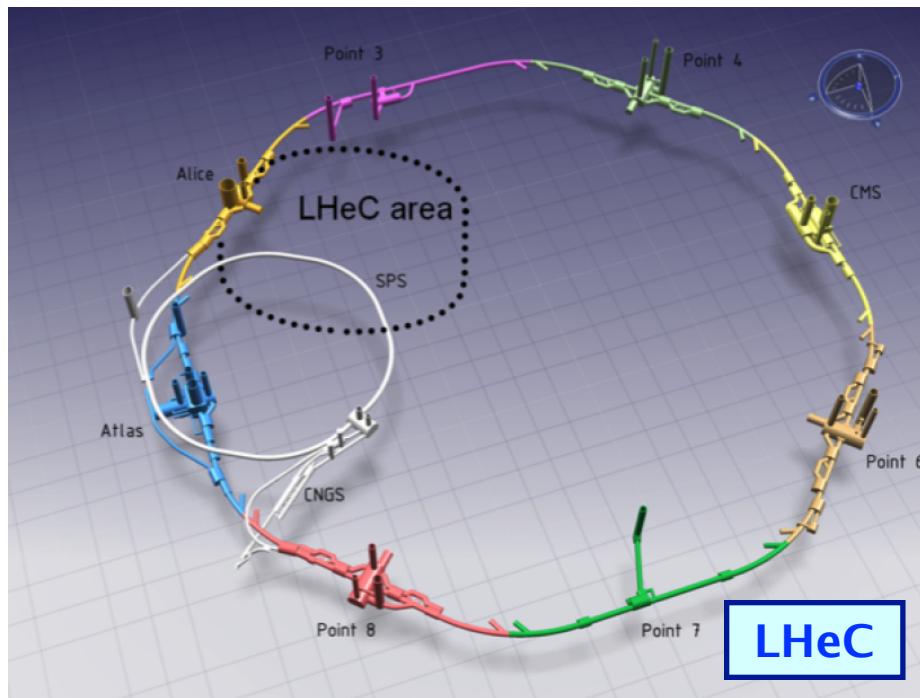
Outline

**Introduction
Electroweak Physics
Top Quark Physics
Conclusions**

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Linac-Ring Collider, LHeC and FCC-eh



operated synchronously

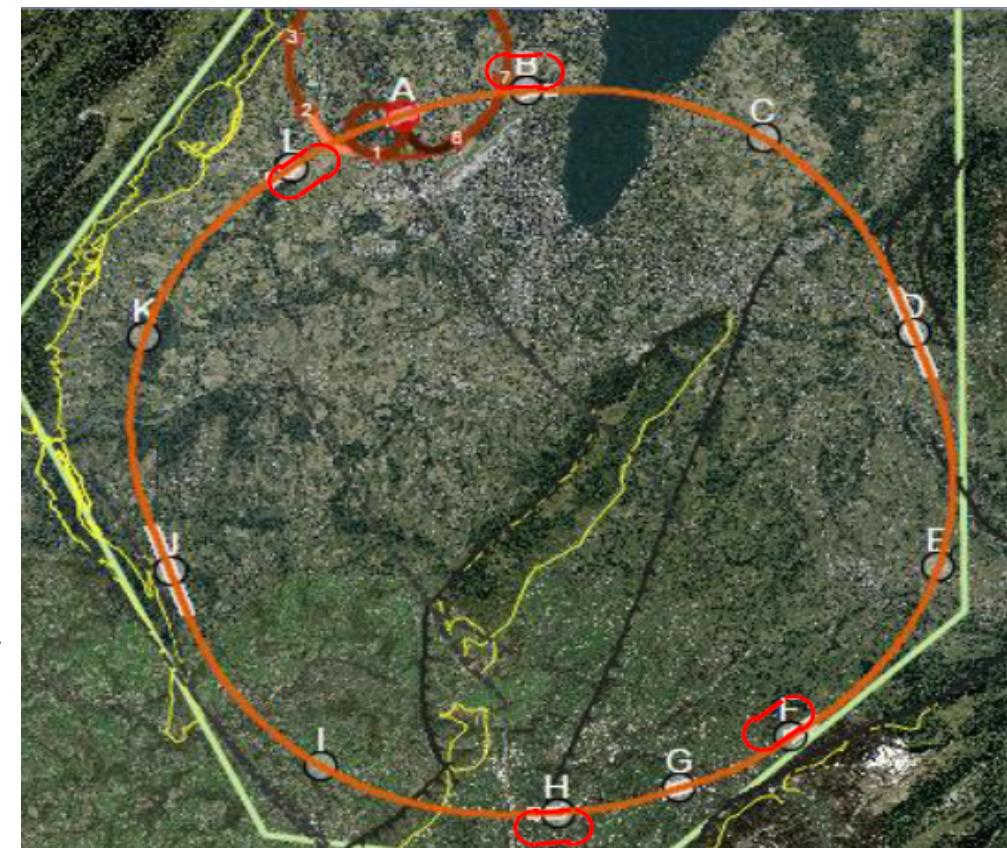
- with **HL-LHC**:
p beam: 7 TeV, $\sqrt{s}=1.3$ TeV
- with **HE-LHC**:
p beam: 13.5 TeV, $\sqrt{s}=1.8$ TeV
- or later with **FCC-eh**:
p beam: 50 TeV, $\sqrt{s}=3.5$ TeV

Energy Recovering Linac

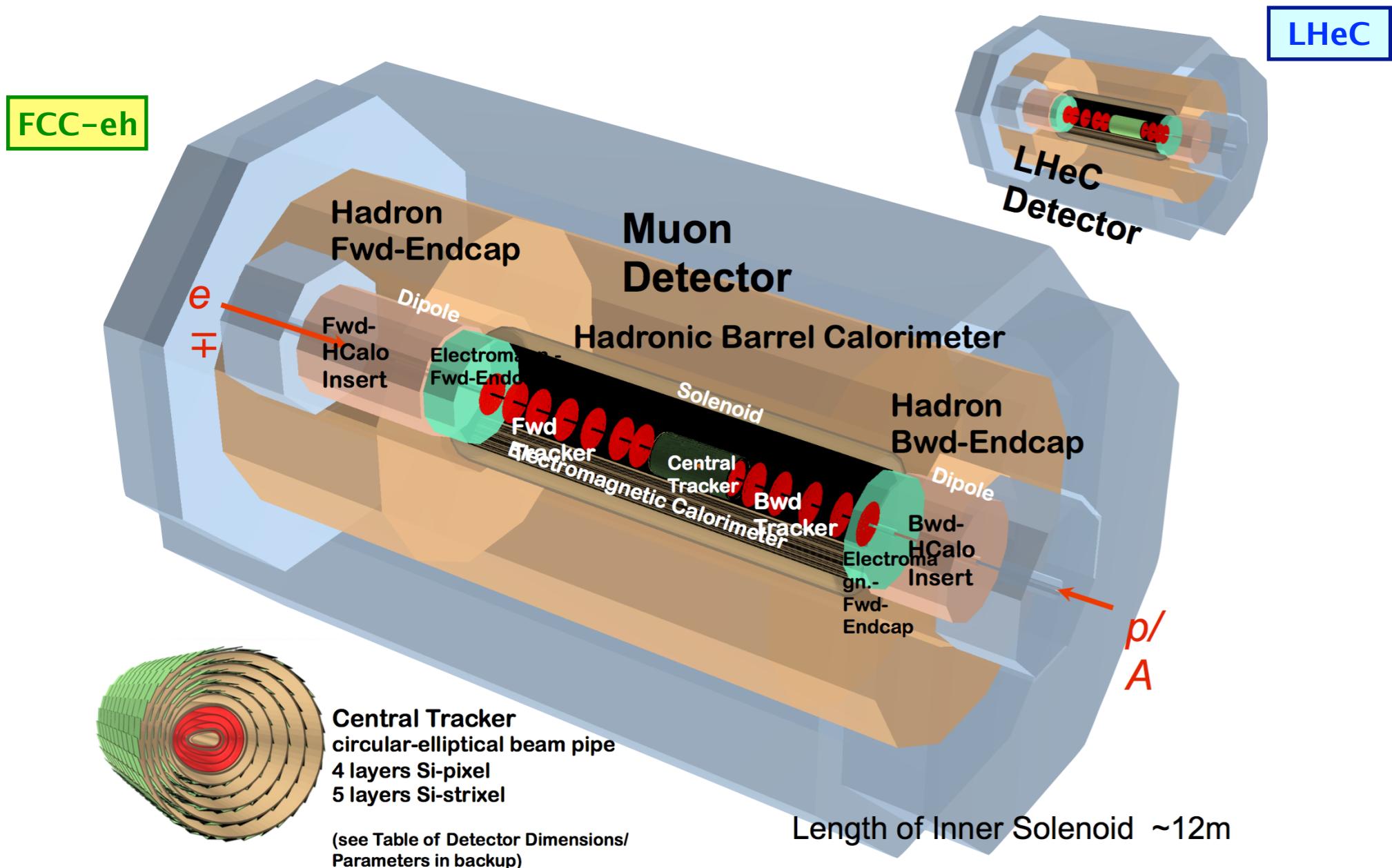
e \pm beam: 60 GeV

L_{int} = 1–3 ab⁻¹ (1k–3k HERA!)

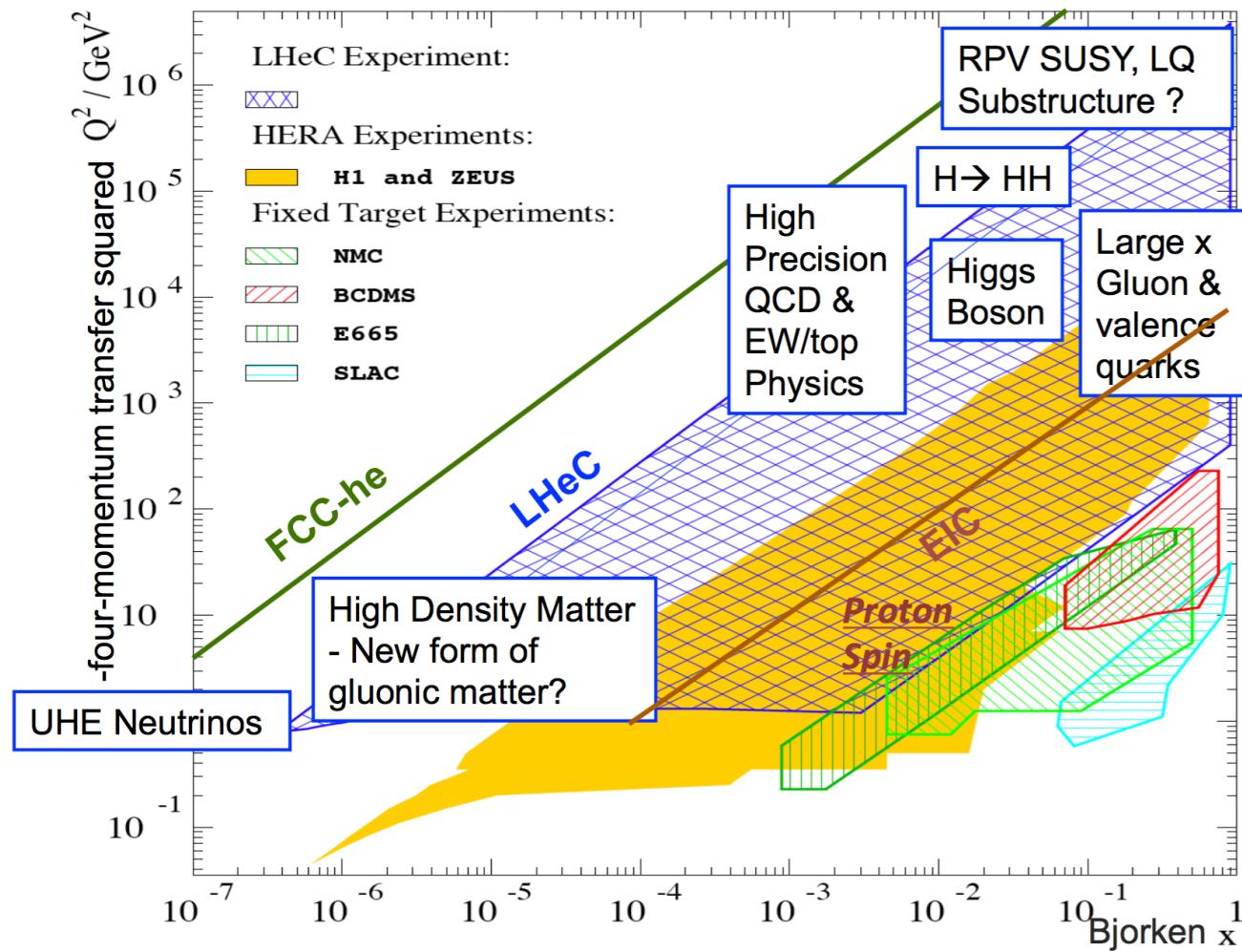
FCC-eh



LHeC and FCC-eh Detector Layout



High energy frontier eh physics



EW symmetry breaking:

- precision EW measurements
- top quark factory: study EW interactions with top quarks
- search for new physics

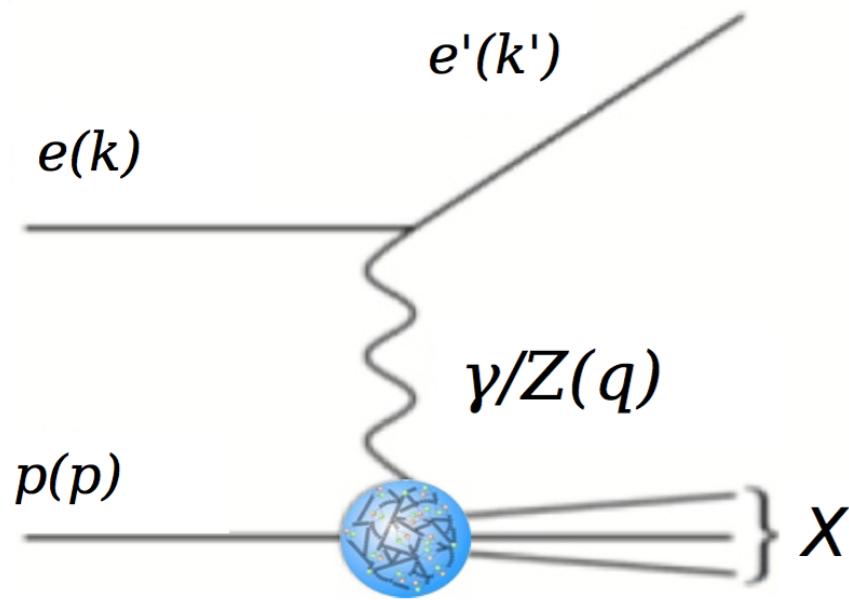
→ ep collider excellent to explore EW theory

Outline

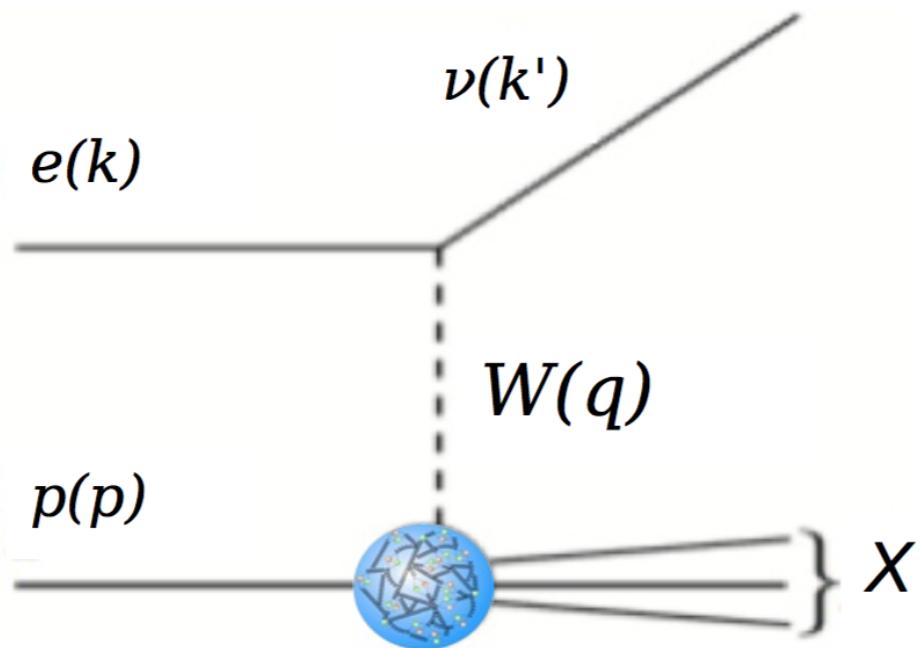
**Introduction
Electroweak Physics
Top Quark Physics
Conclusions**

Deep Inelastic Scattering

Neutral Current (NC)



Charged Current (CC)



→ LHeC/FCC-eh are **unique facilities for testing EW theory:** NC+CC, two e-beam charge and polarisation states, p or isoscalar targets

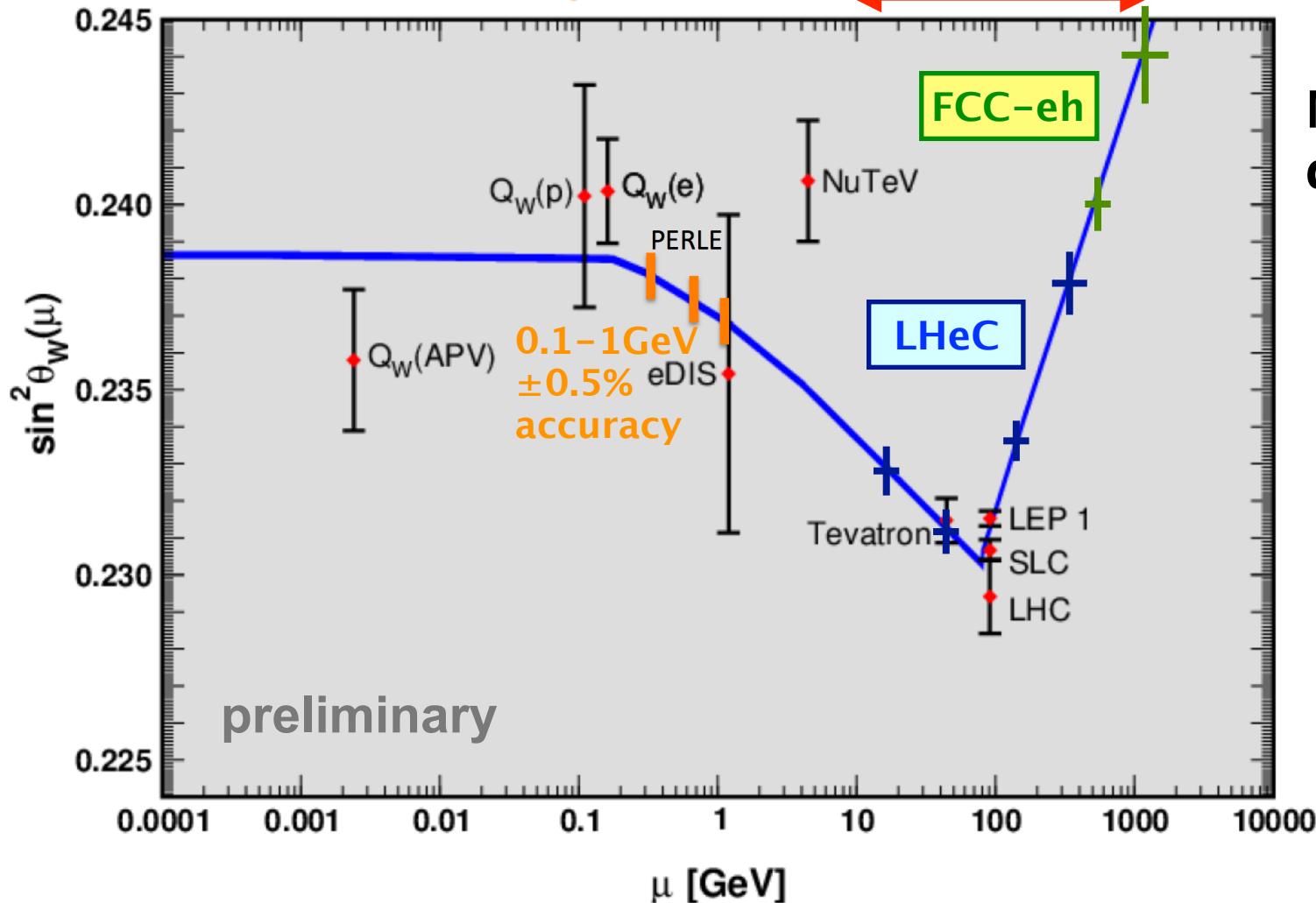
Scale Dependence of $\sin^2\theta_W$

PERLE CDR, Arduini et al, to be published
ICFA BeamNewsletter 68 (January 2016)



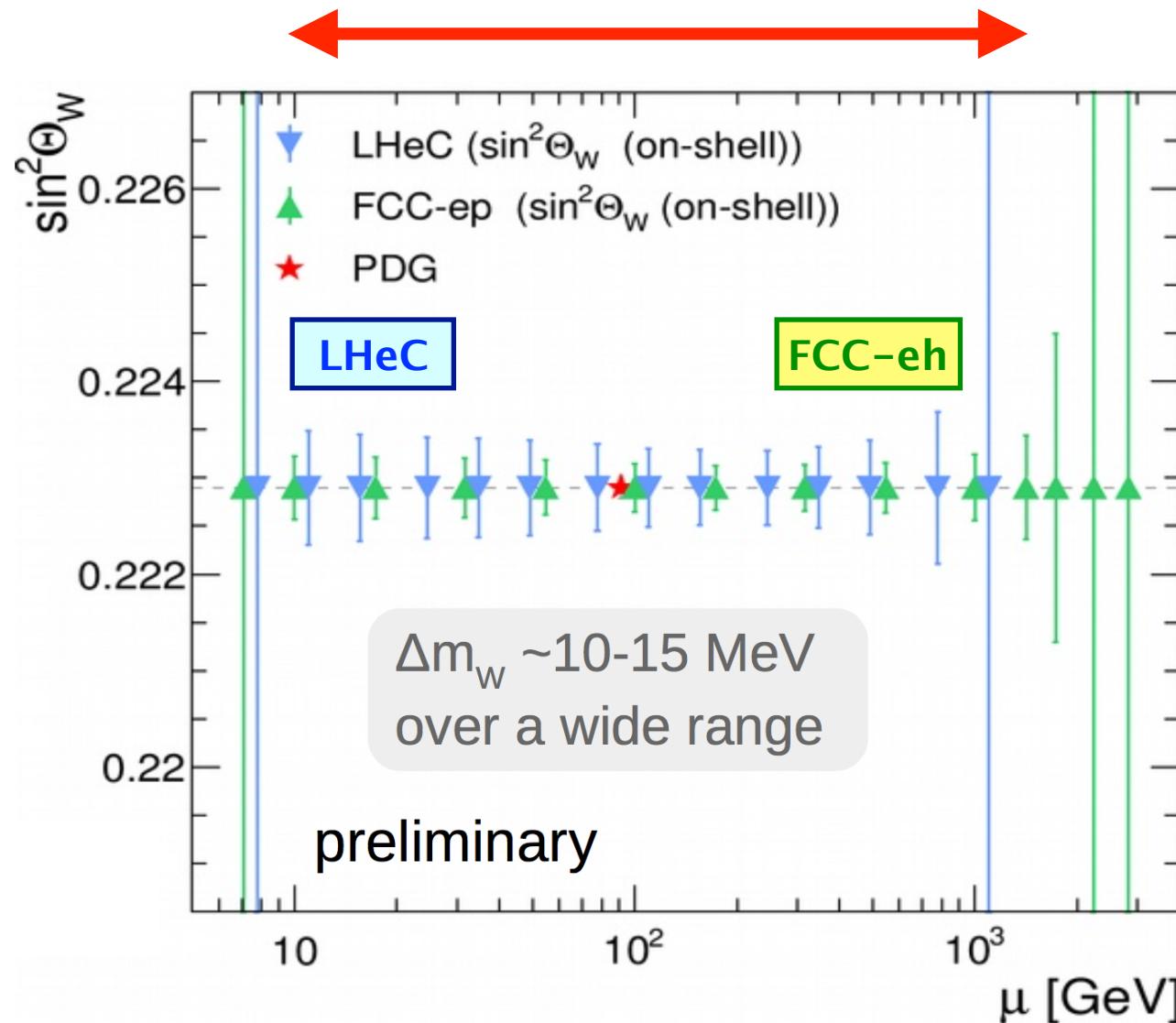
LHeC CDR,
J.Phys. G39,
075001 (2012)

MSbar definition



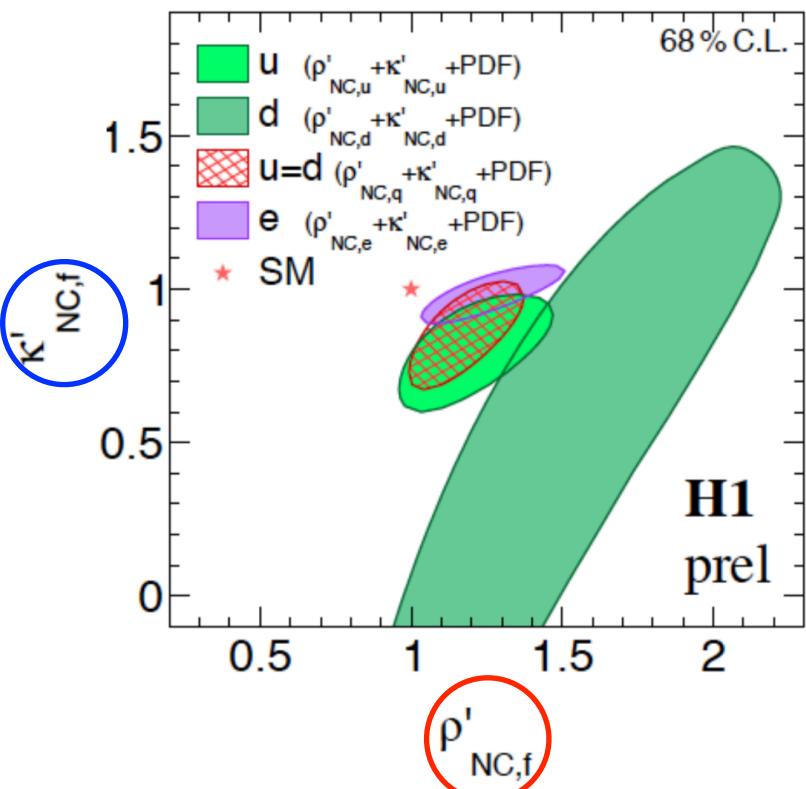
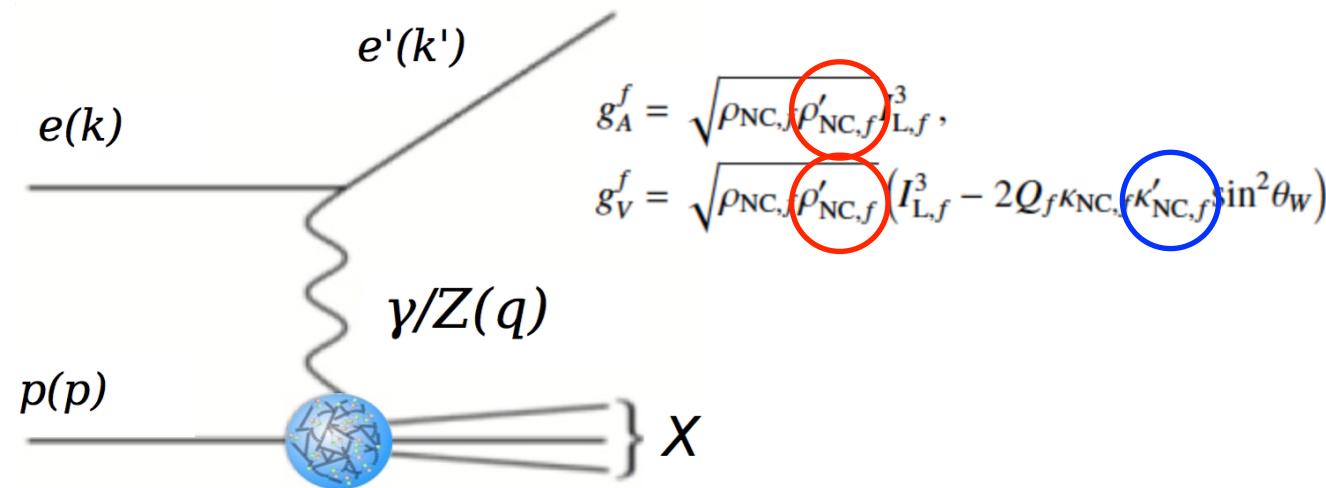
→ probe large range of scale dependence

Scale Dependence of $\sin^2\theta_W$

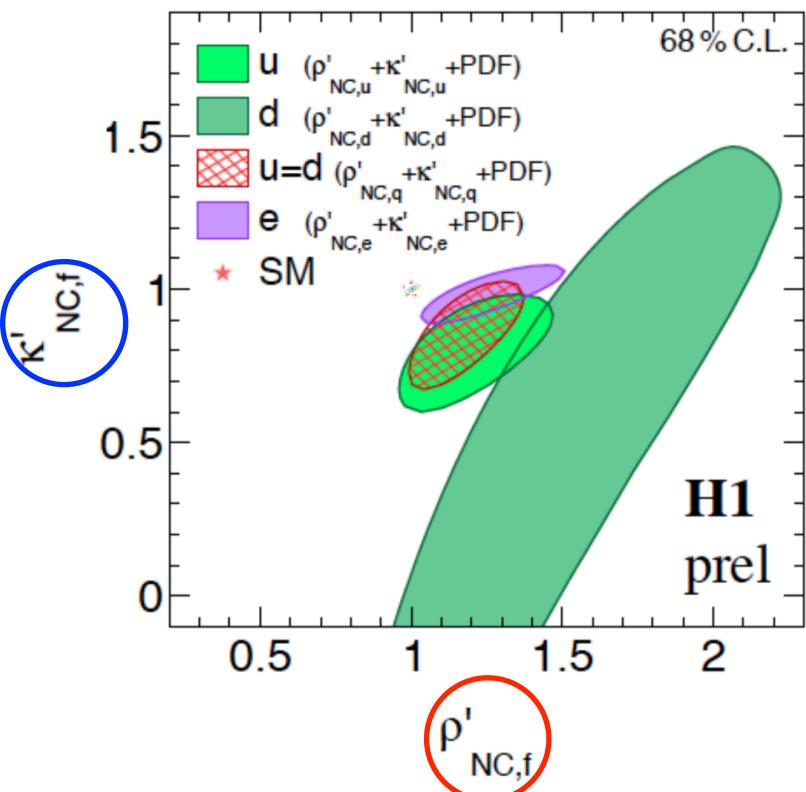
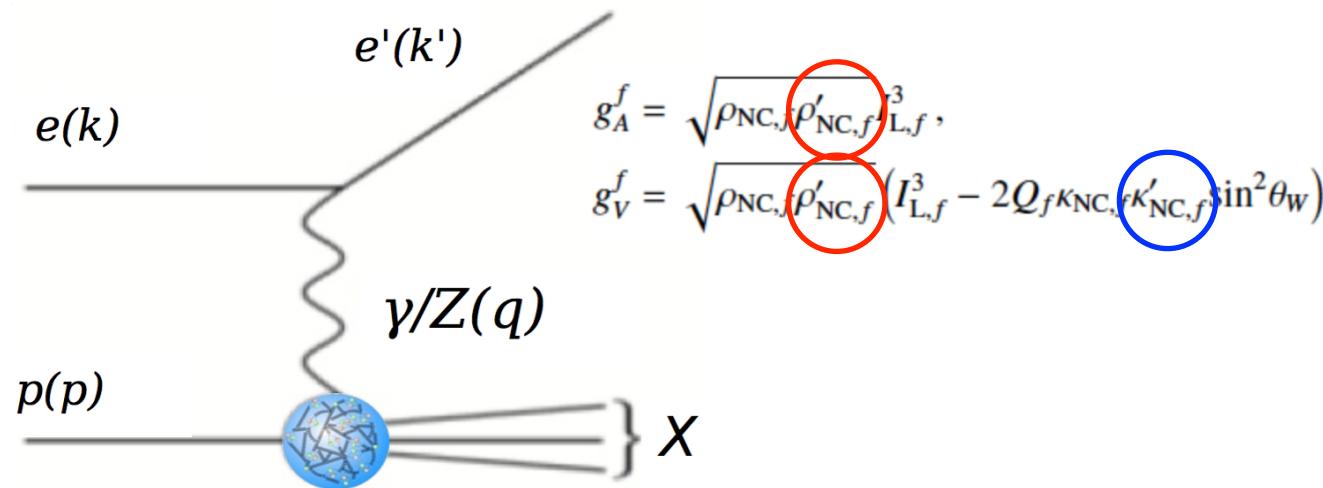


→ probe large range of scale dependence

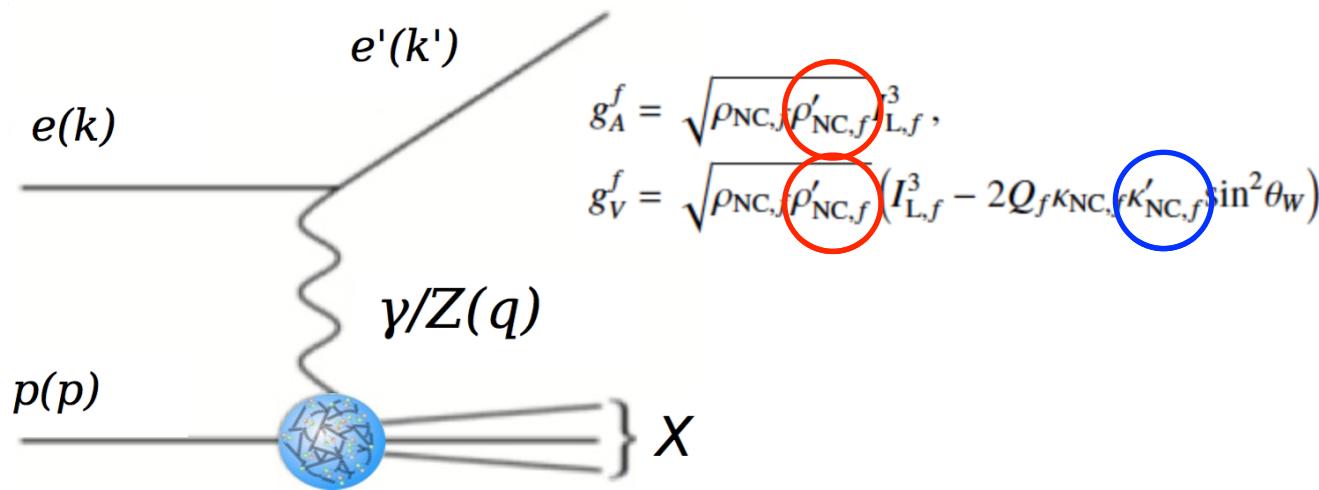
Electroweak Fermion Couplings



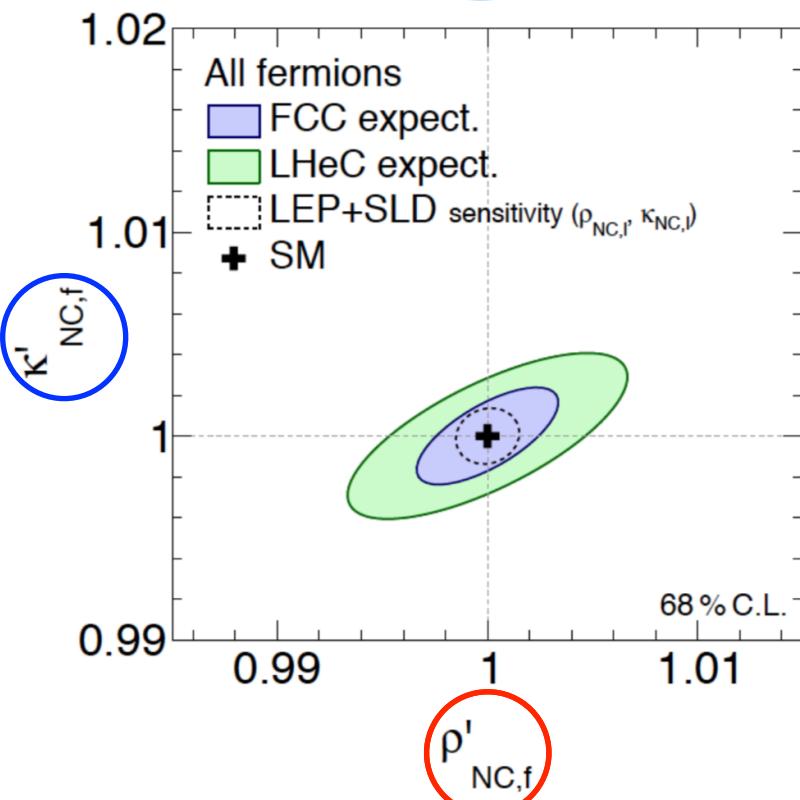
Electroweak Fermion Couplings



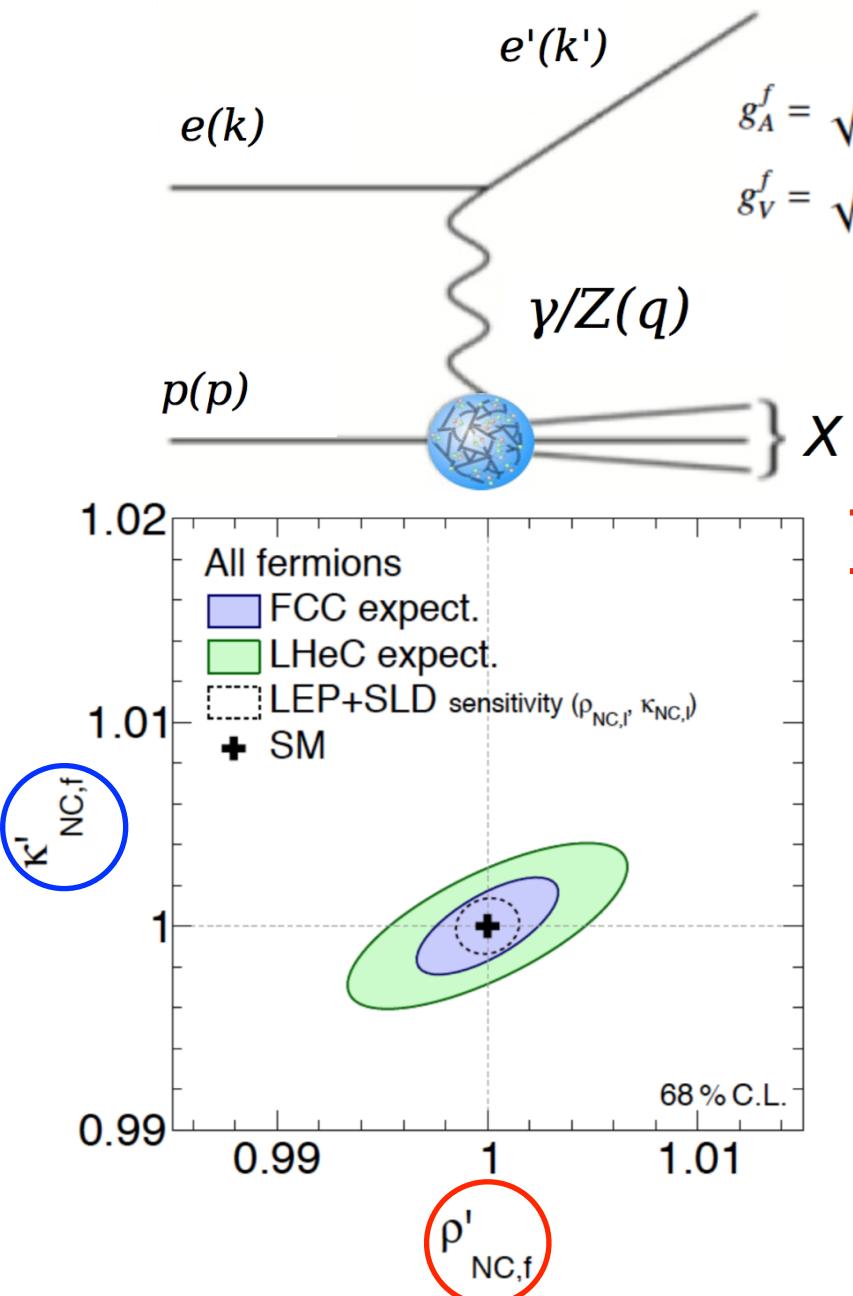
Electroweak Fermion Couplings



\rightarrow precision < 1%



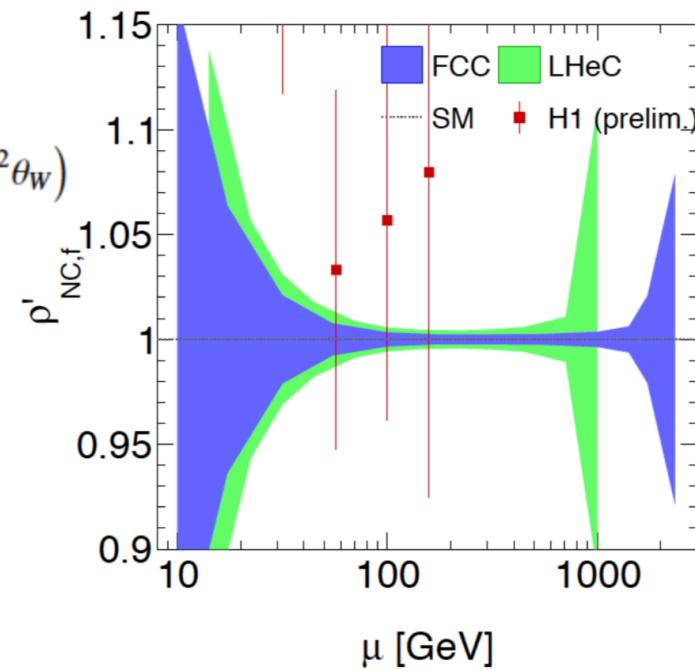
Electroweak Fermion Couplings



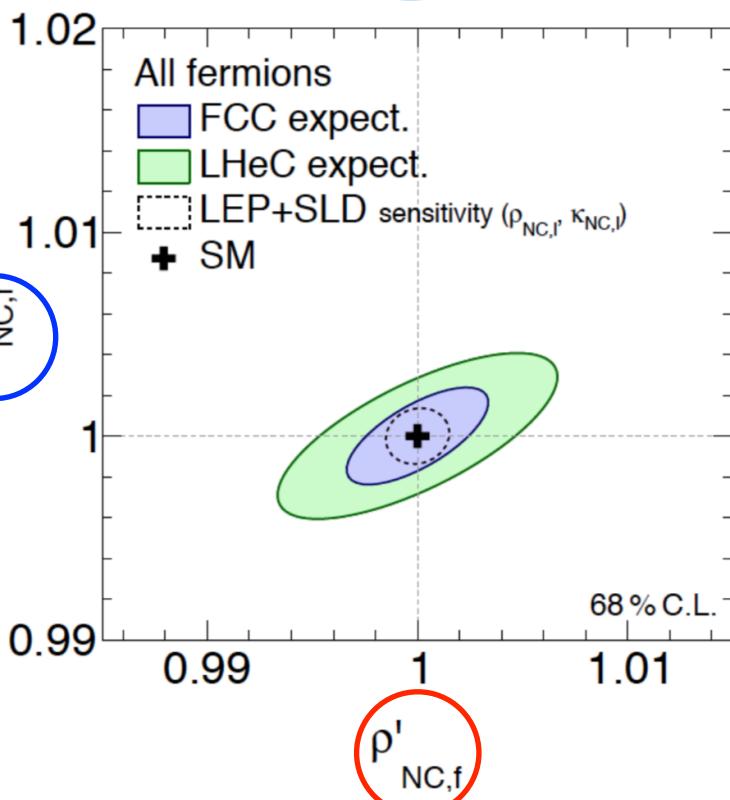
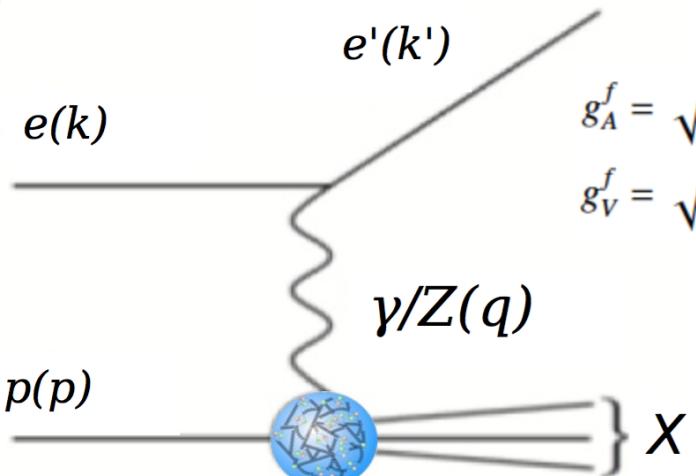
$$g_A^f = \sqrt{\rho_{NC,f} \rho'_{NC,f}} I_{L,f}^3,$$

$$g_V^f = \sqrt{\rho_{NC,f} \rho'_{NC,f}} (I_{L,f}^3 - 2Q_f \kappa_{NC,f} \kappa'_{NC,f} \sin^2 \theta_W)$$

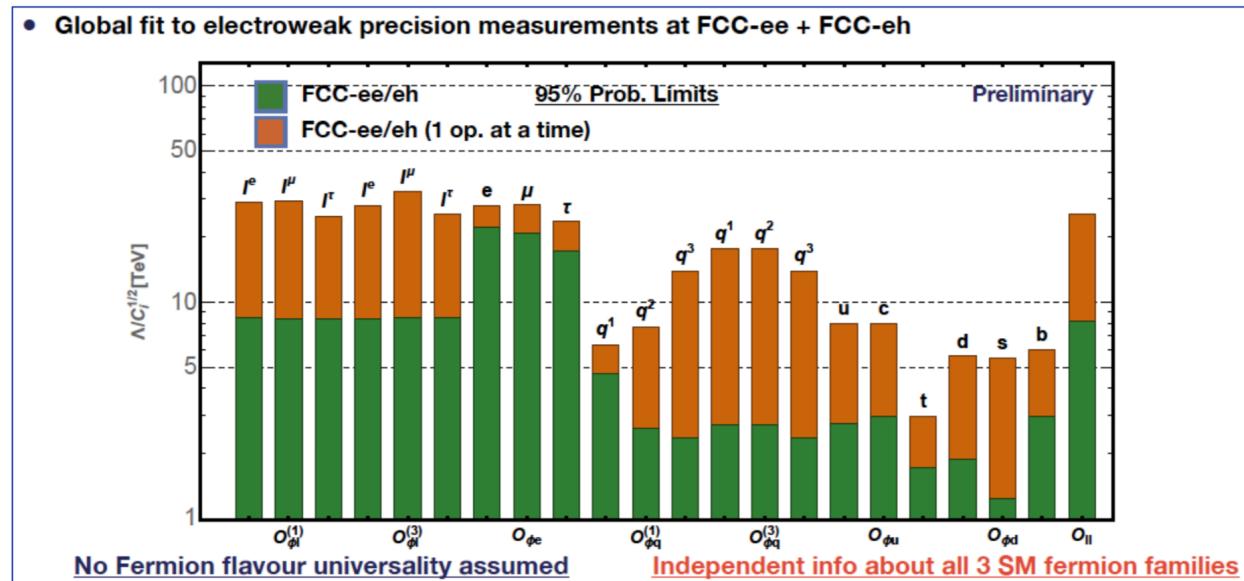
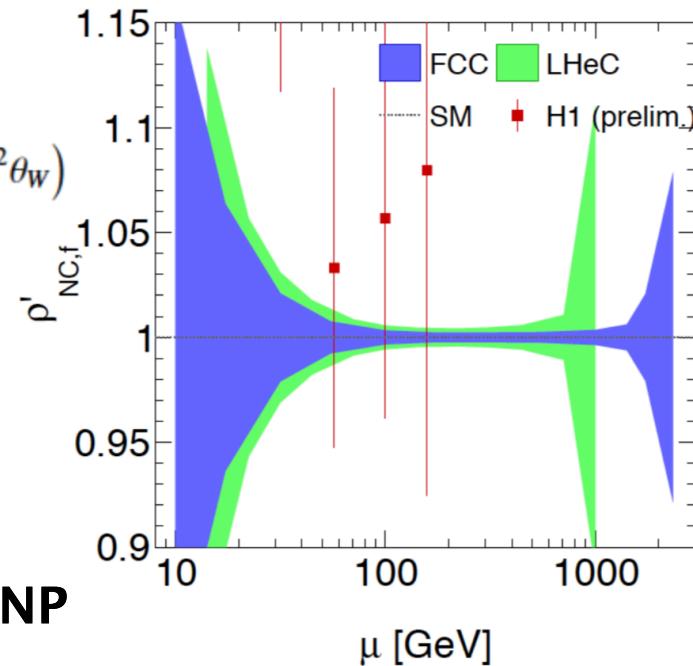
→ precision < 1%
→ scale dependence



Electroweak Fermion Couplings

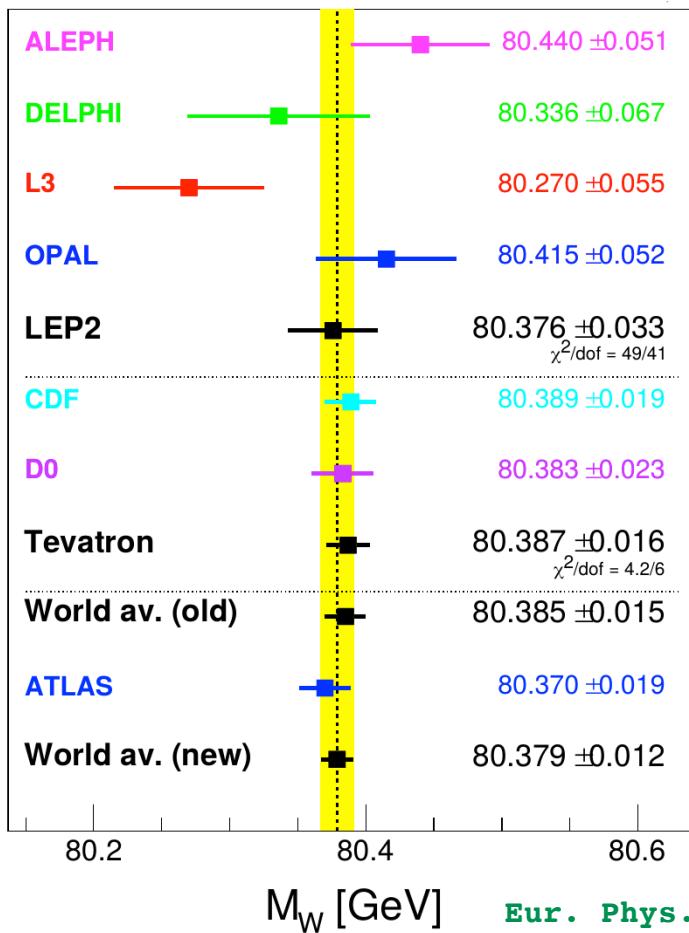


- precision < 1%
- scale dependence
- high sensitivity to NP

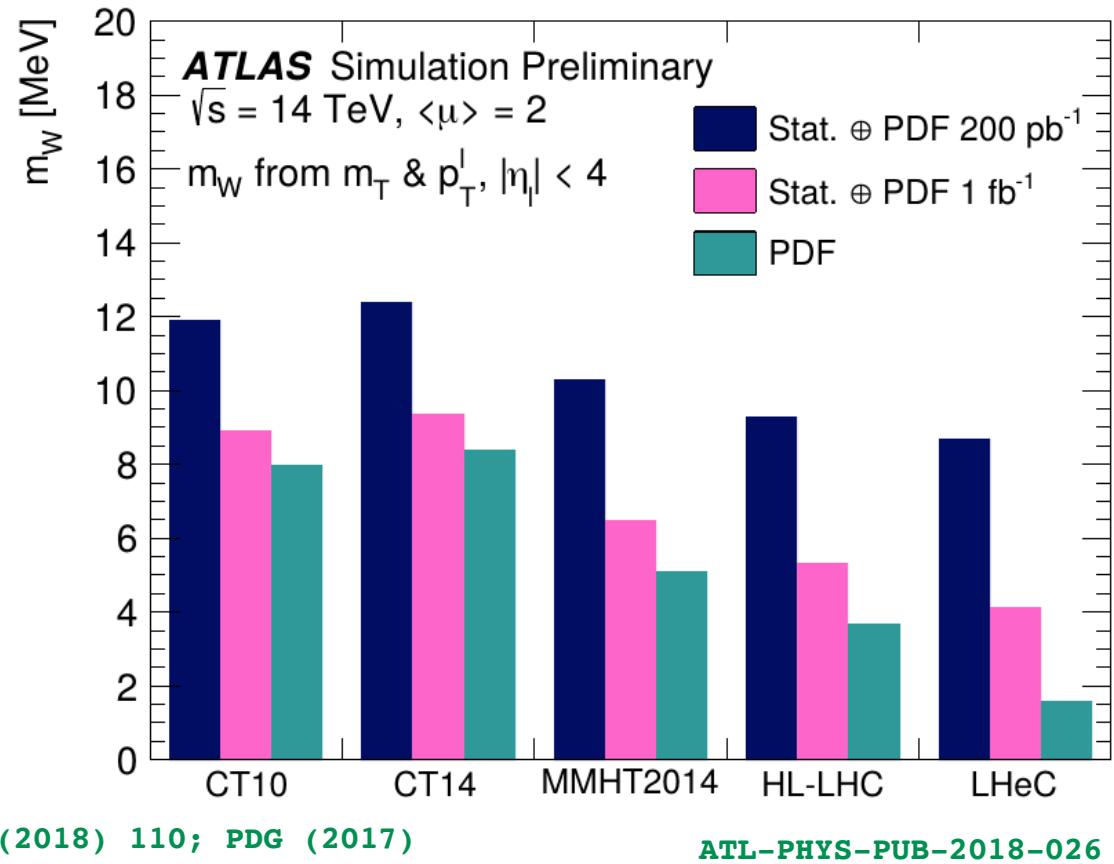


W mass measurements at HL-LHC

- @LHC: precision limited by PDFs ($\Delta m_W^{\text{PDF}} \sim 9.2 \text{ MeV}$)



- @HL-LHC: major reduction of PDF uncertainty with LHeC PDFs ($\Delta m_W^{\text{PDF}} \sim 2 \text{ MeV}$)



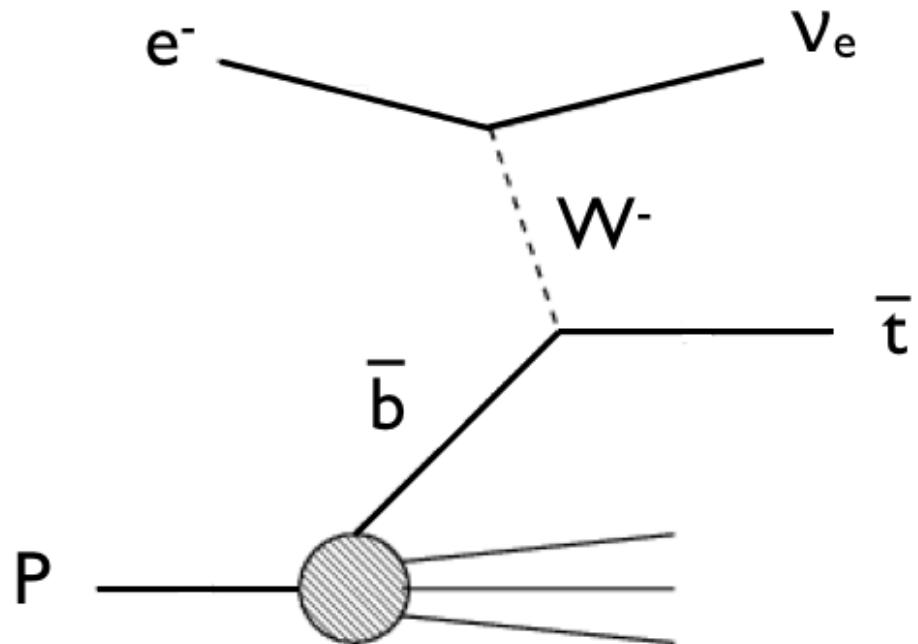
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
$m_T-p_T^l, W^\pm, e-\mu$	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Outline

Introduction Electroweak Physics Top Quark Physics Conclusions

SM Top Quark Production

CC DIS top production



$\sigma = 1.89 \text{ pb} @$

LHeC

$\sigma = 4.46 \text{ pb} @$

HE-LHC

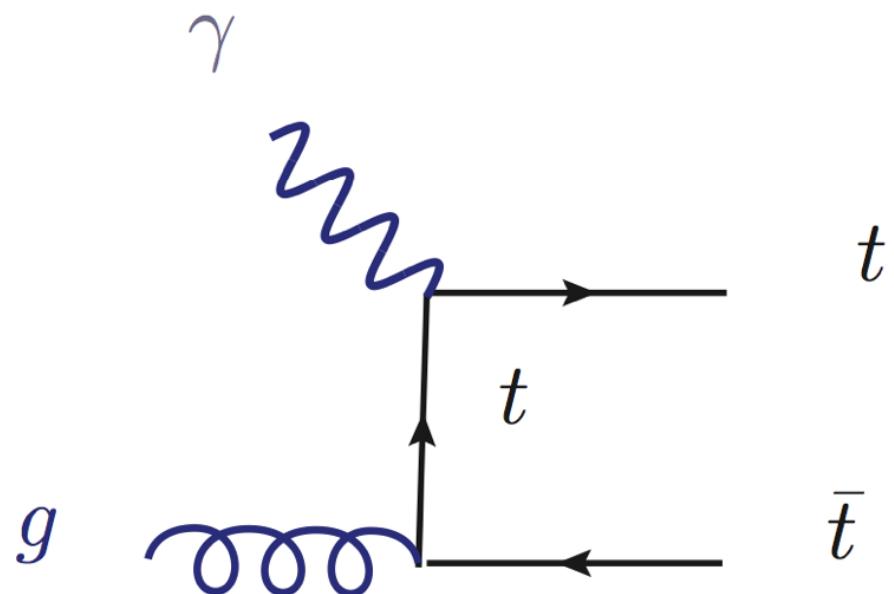
$\sigma = 15.3 \text{ pb} @$

FCC-eh

$E_e = 60 \text{ GeV}$

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

NC top photoproduction



$\sigma = 0.05 \text{ pb} @$

LHeC

$\sigma = 0.?? \text{ pb} @$

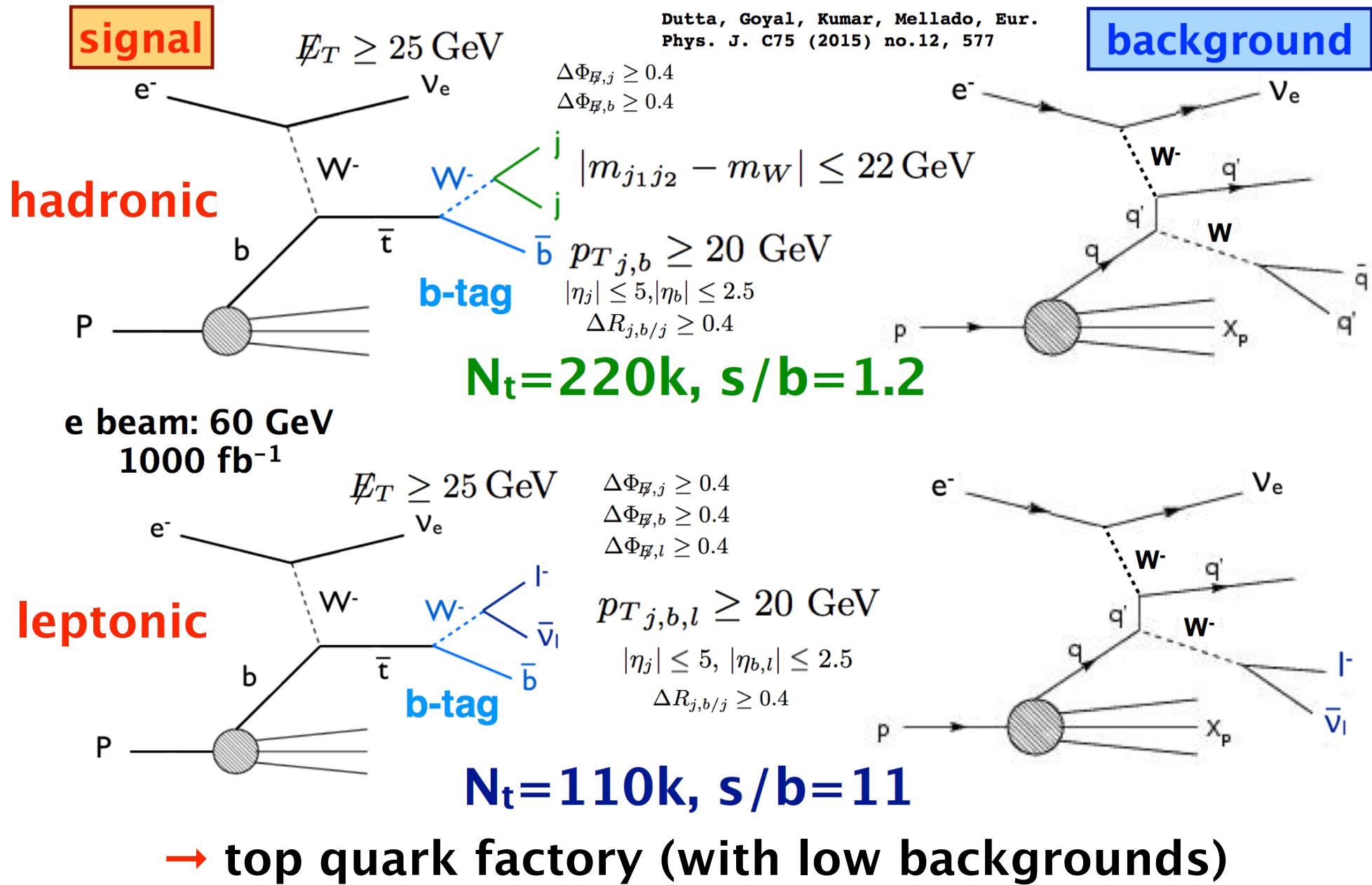
HE-LHC

$\sigma = 1.14 \text{ pb} @$

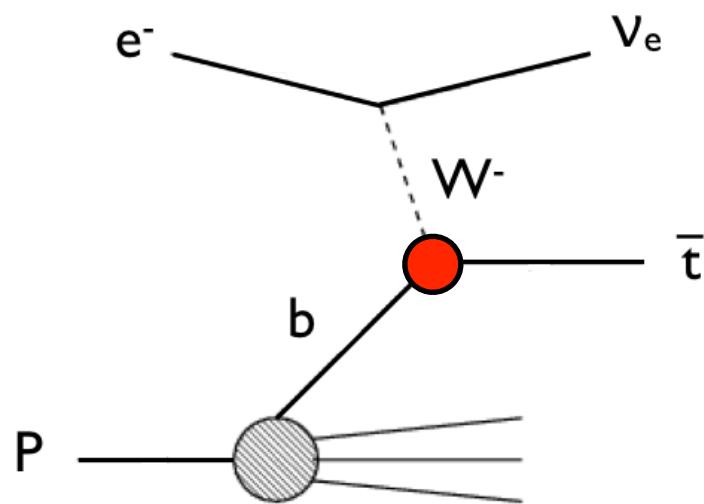
FCC-eh

Signal and Backgrounds

LHeC



Direct Measurement of $|V_{tb}|$

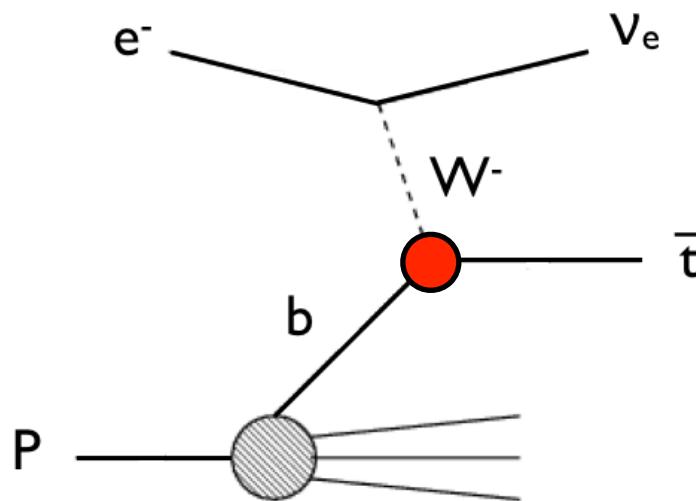


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Limits on Anomalous Wtb Couplings

= 1 in SM

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



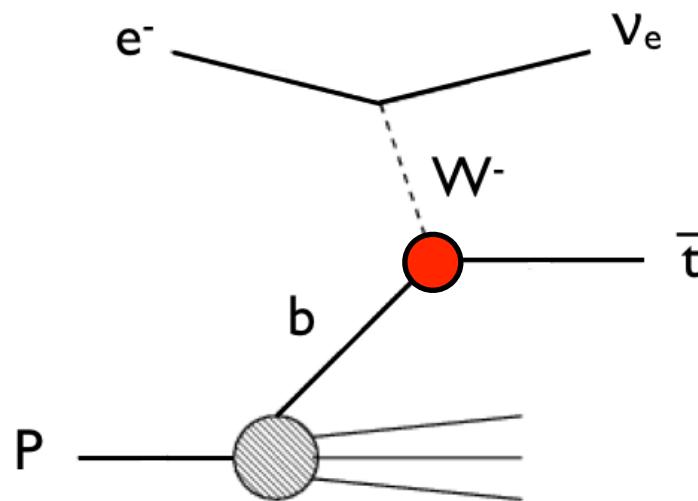
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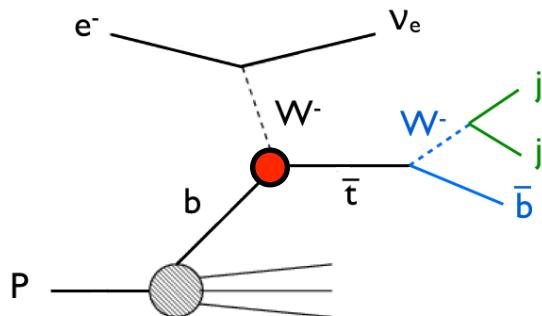
$$-\frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (f_T^L P_L + f_T^R P_R) t W_\mu^- + h.c.$$



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

Limits on Anomalous Wtb Couplings

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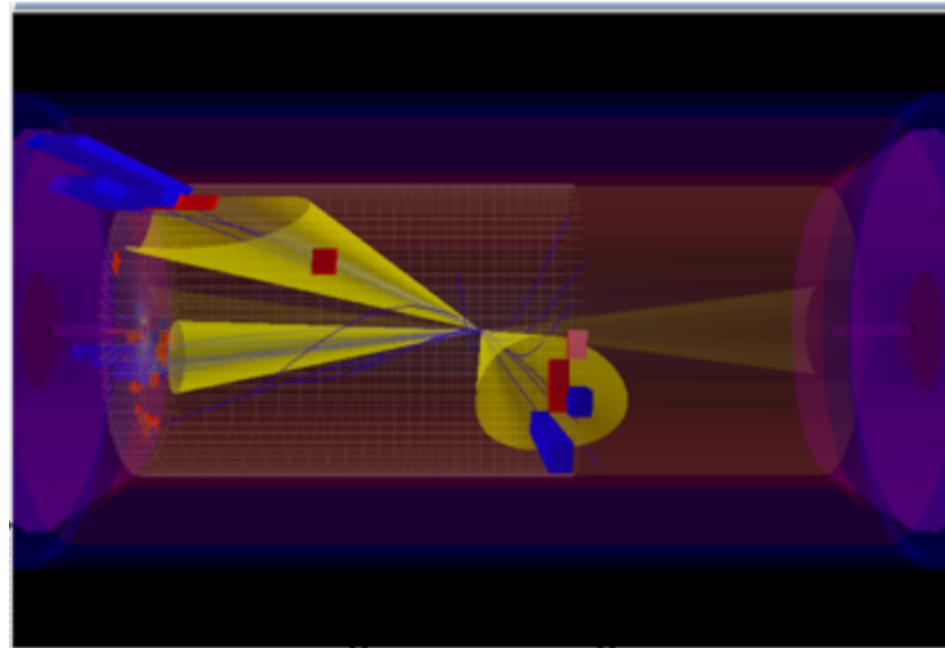
$$-\frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (f_T^L P_L + f_T^R P_R) t W_\mu^- + h.c.$$

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

95% C.L.

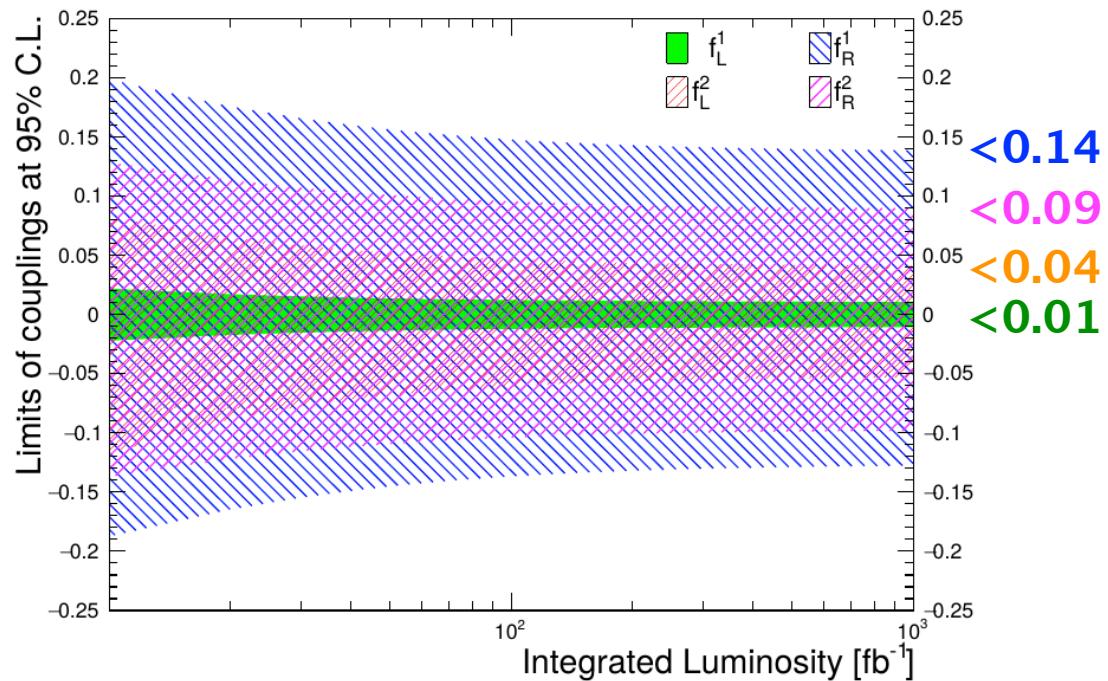
DELPHES

LHeC

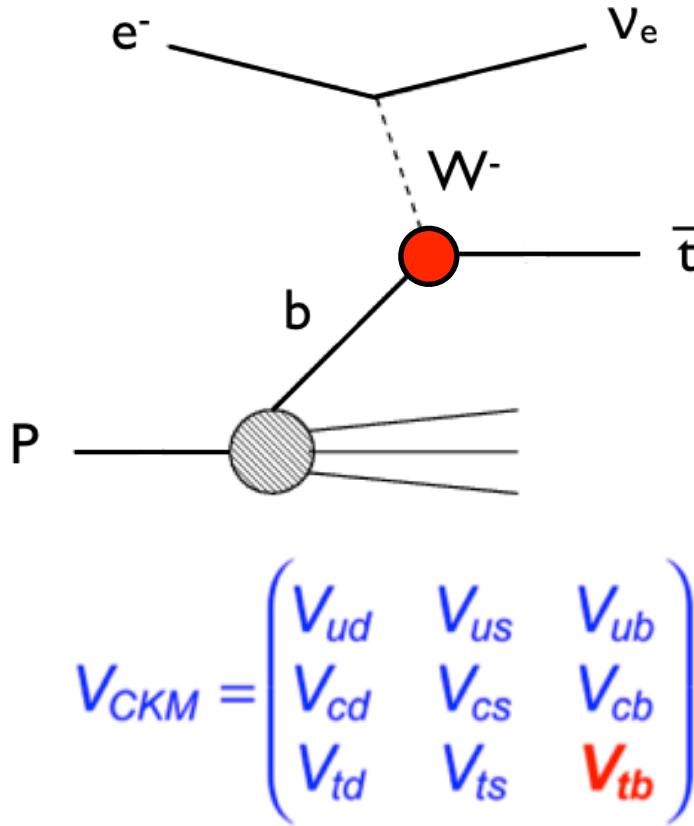


including detector simulation (Delphes)

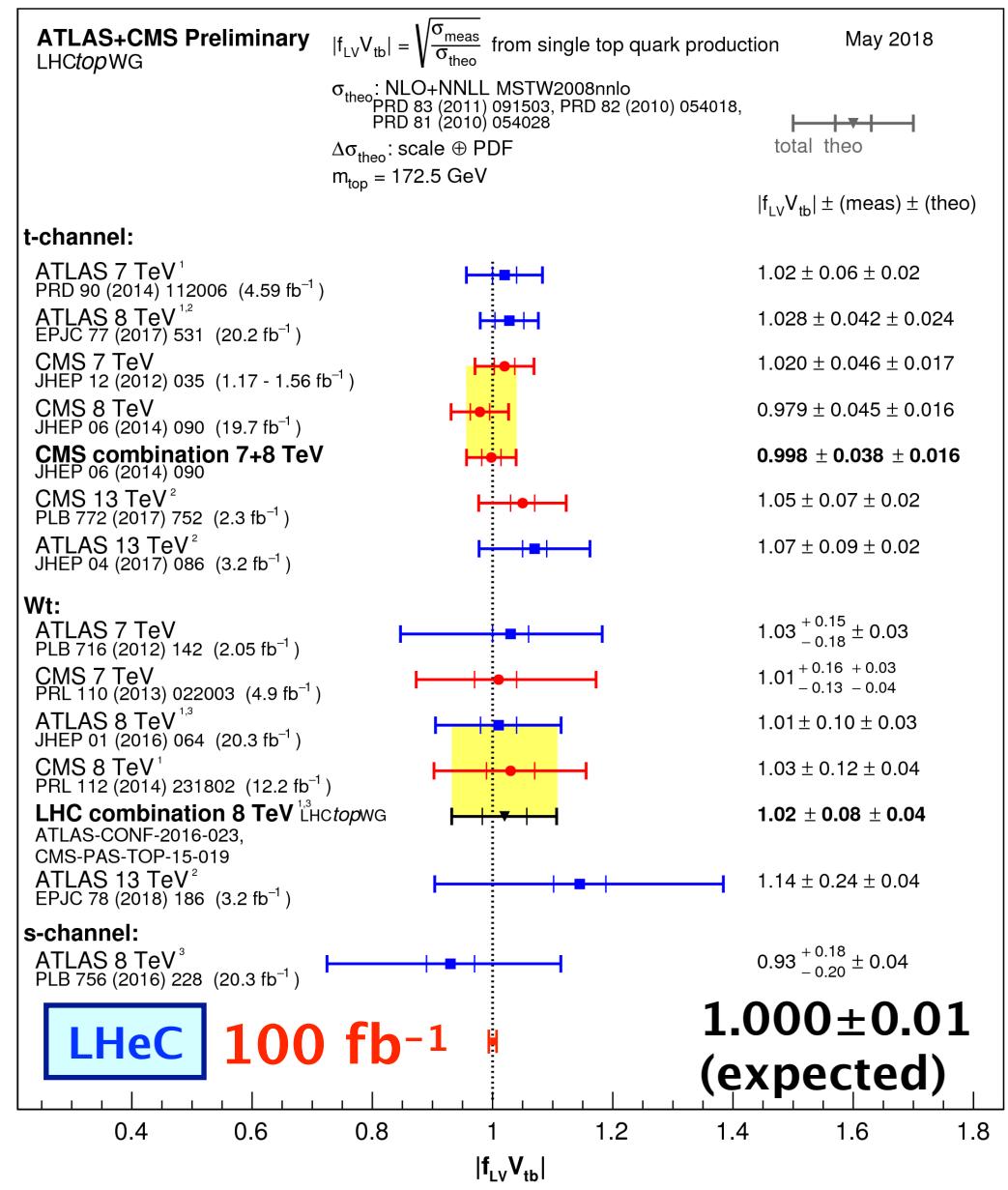
hadronic channel:



Direct Measurement of $|V_{tb}|$

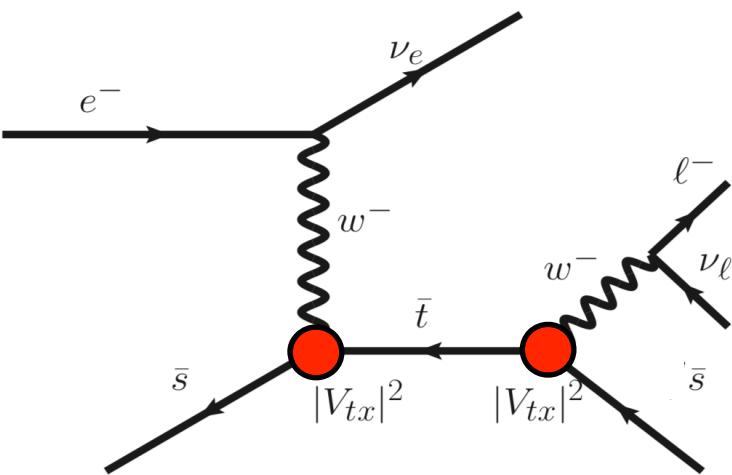


- ¹ including top-quark mass uncertainty
² σ_{theo} : NLO PDF4LHC11
³ NPPS205 (2010) 10, CPC191 (2015) 74
⁴ including beam energy uncertainty



Measurement of $|V_{ts}|$

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



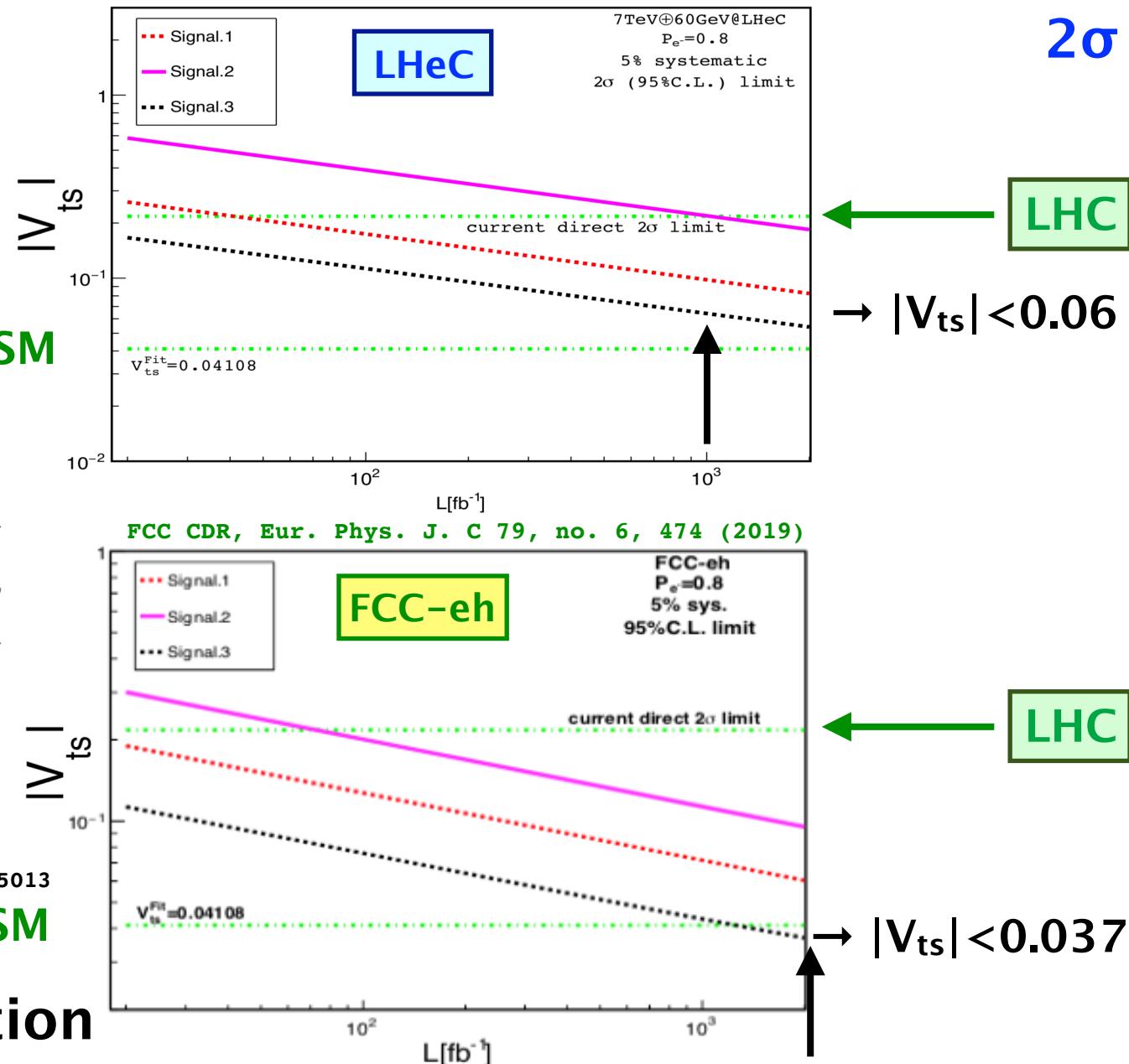
DELPHES

arXiv:1501.05013

SM

H. Sun PoS DIS 2018, 167 (2018)

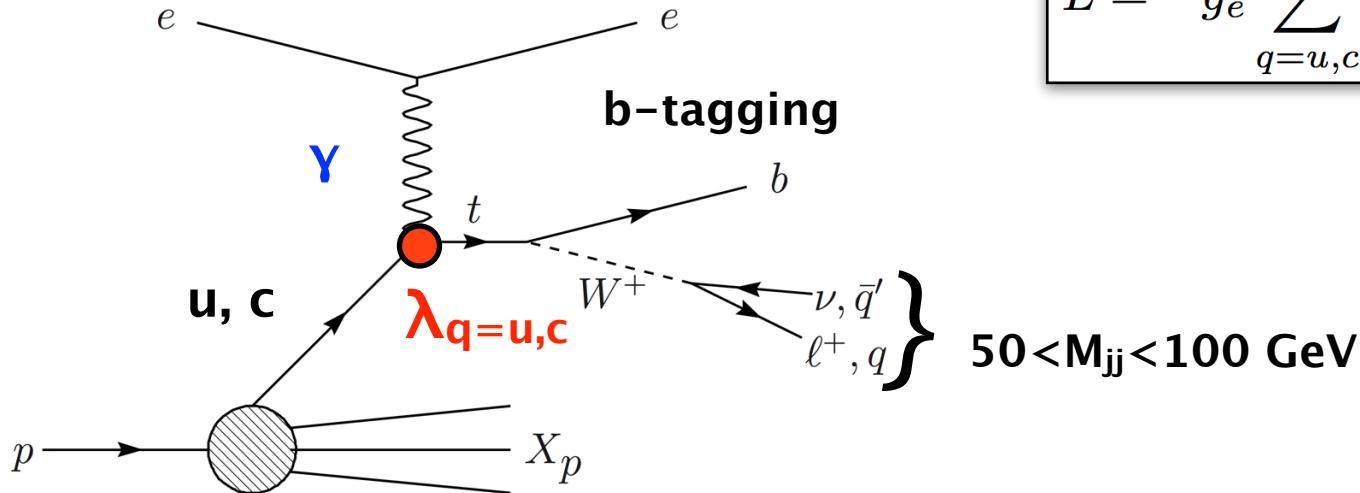
→ probing SM prediction



Search for Anomalous FCNC tuy Coupling

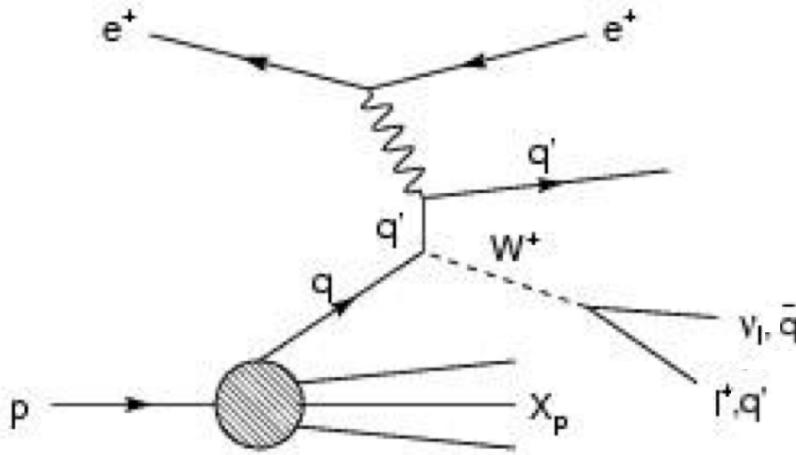
signal

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



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

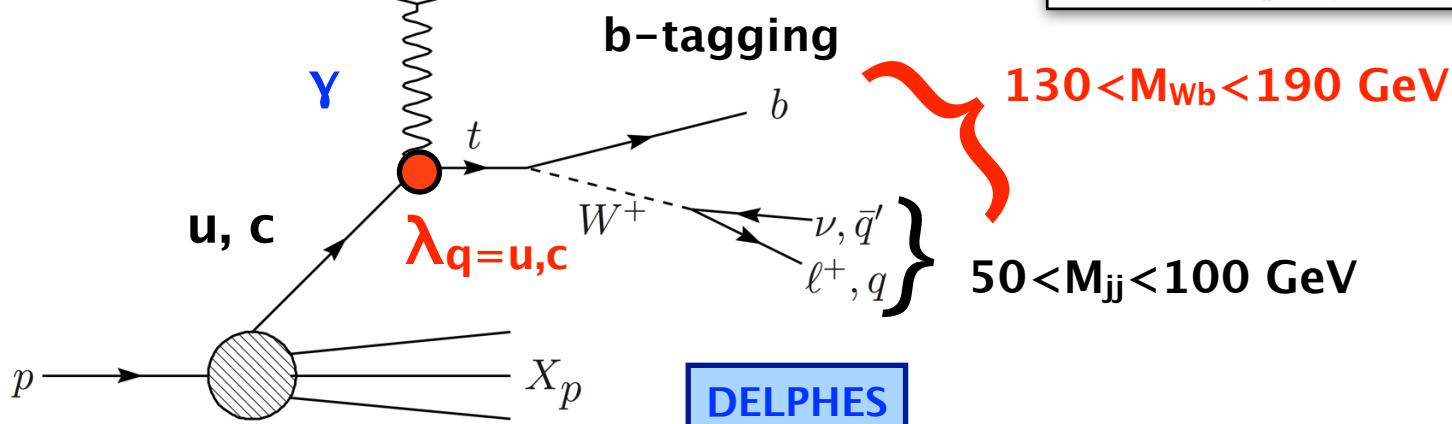
background



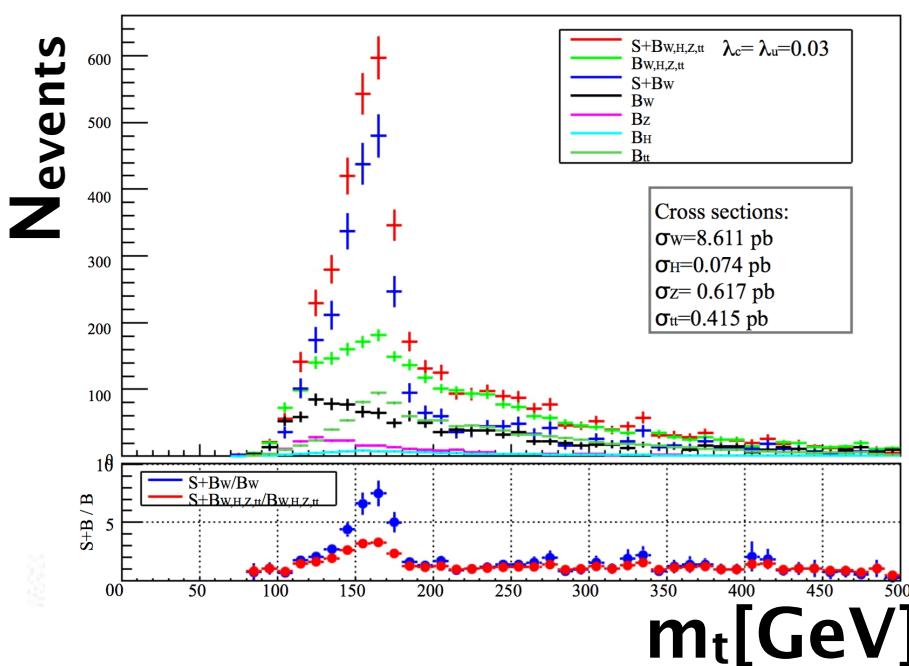
Search for Anomalous FCNC tuy Coupling

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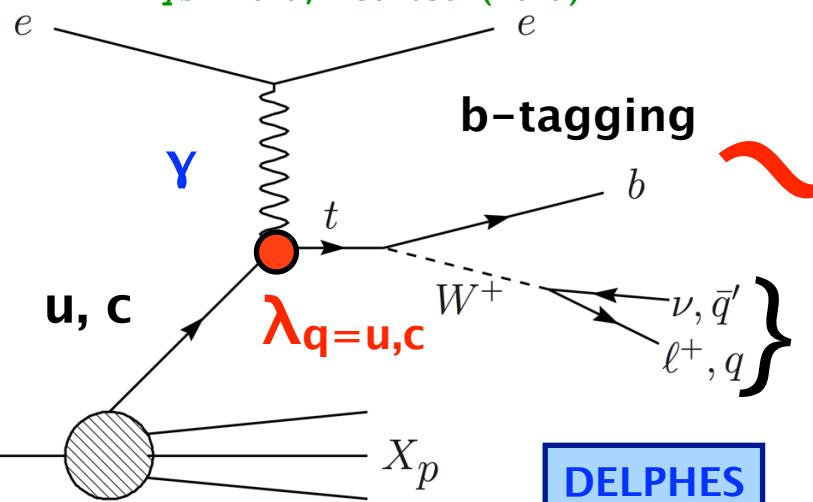
$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda^q}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_q + h_q \gamma_5) q A_{\mu\nu} + h.c.$$



Search for Anomalous FCNC tuy Coupling

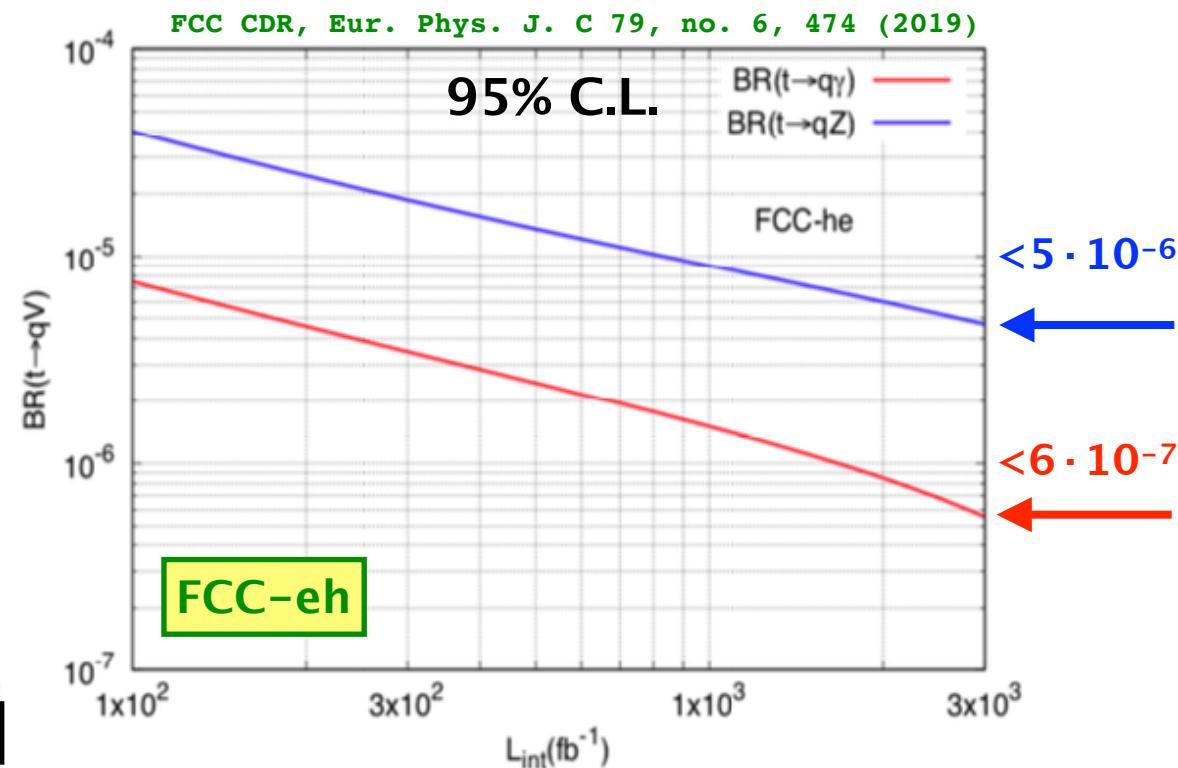
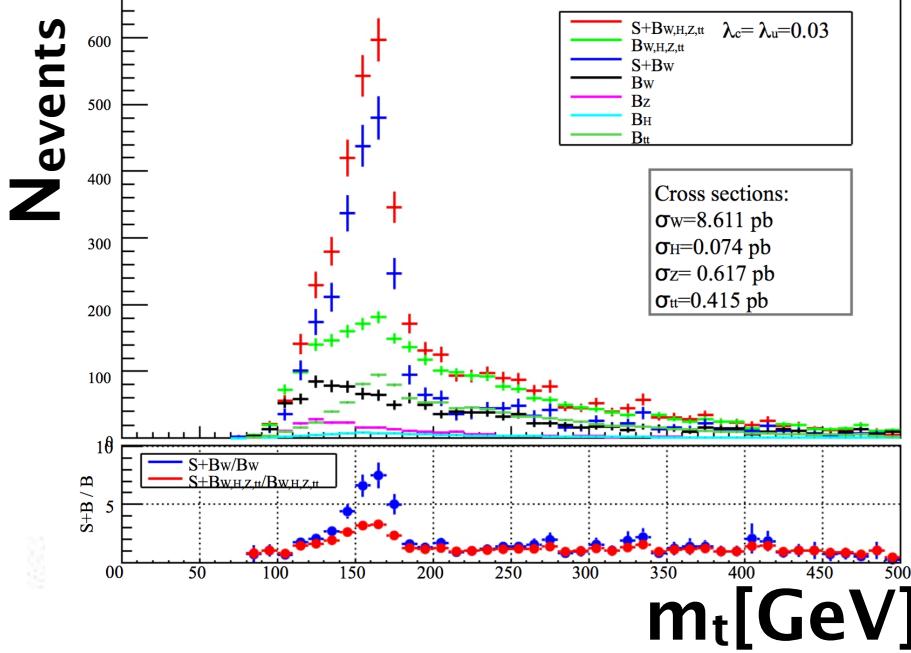
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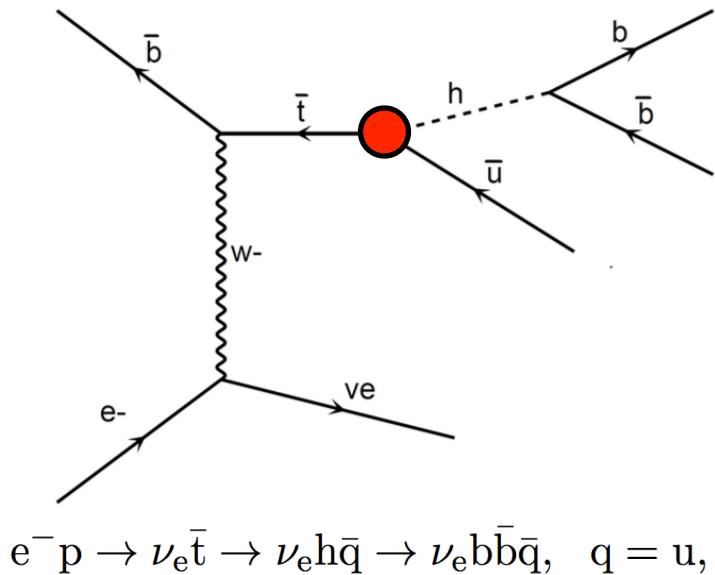
→ test exotic models leading to FCNC



Search for Anomalous FCNC tHu Coupling

signal

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

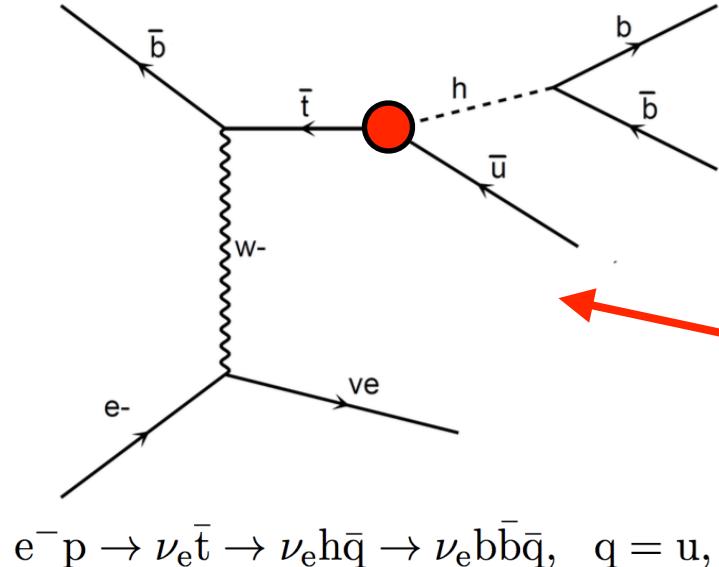


$$\mathcal{L} = \kappa_{tuh} \bar{t} u h + \kappa_{tch} \bar{t} c h + \text{h.c.}$$

Search for Anomalous FCNC tHu Coupling

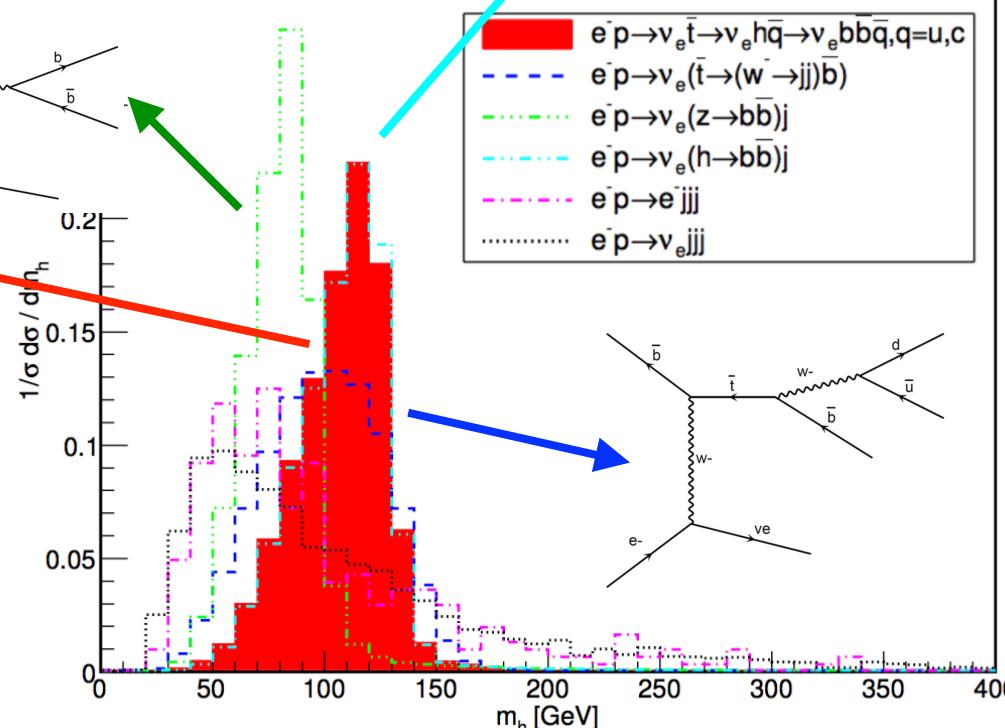
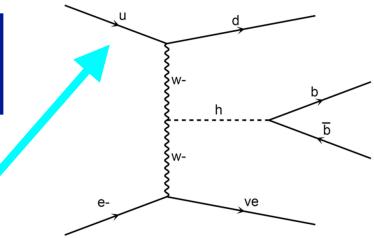
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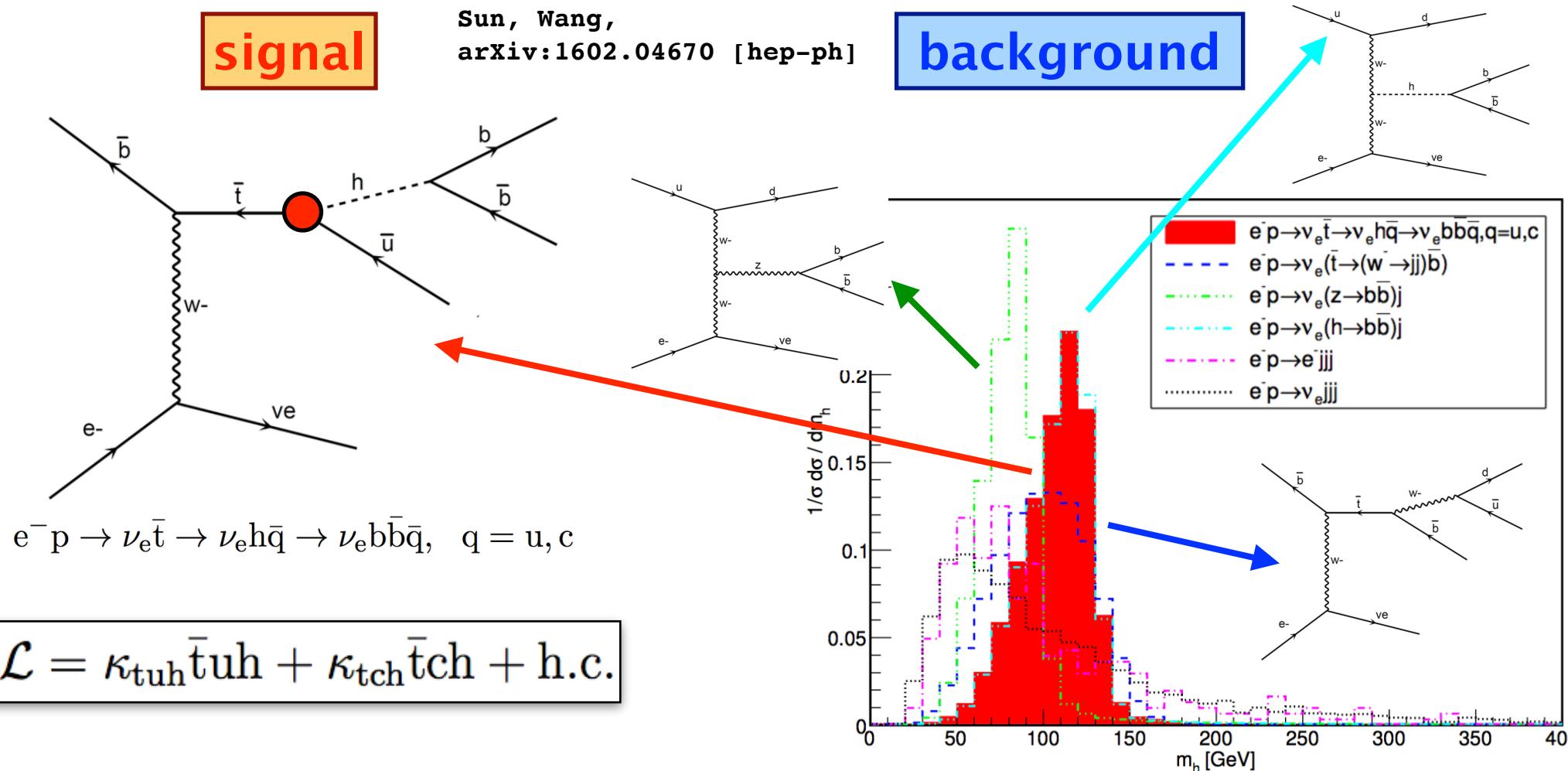


$$\mathcal{L} = \kappa_{tuh} \bar{t} u h + \kappa_{tch} \bar{t} c h + \text{h.c.}$$

background



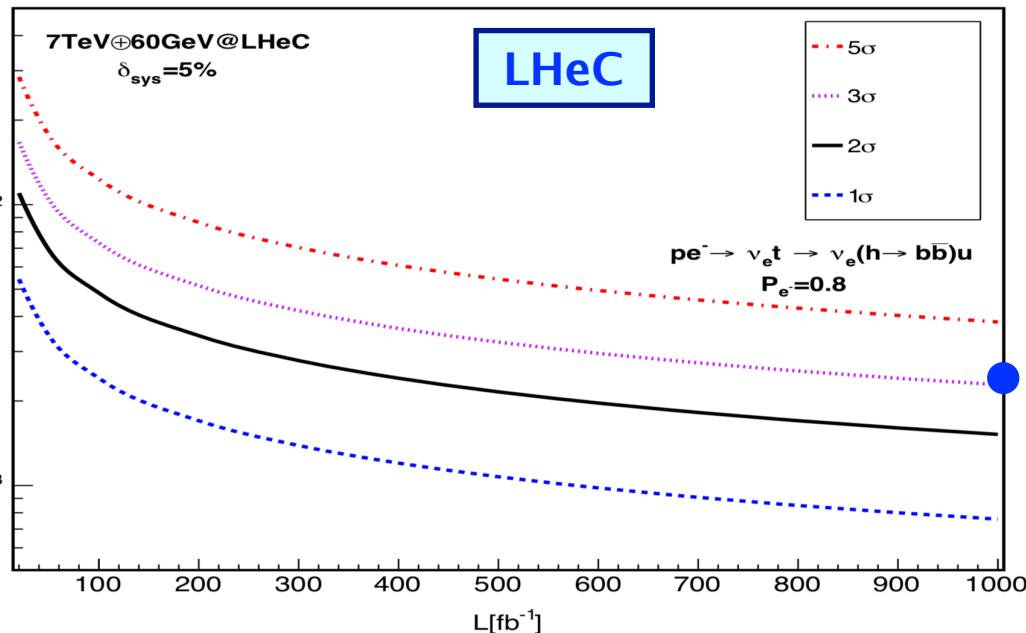
Search for Anomalous FCNC tHu Coupling



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

- 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 ($s/\sqrt{(S+B)}$)
- cut-based and MVA-based analyses

Upper Limit on $\text{Br}(t \rightarrow uH)$ in MVA analysis



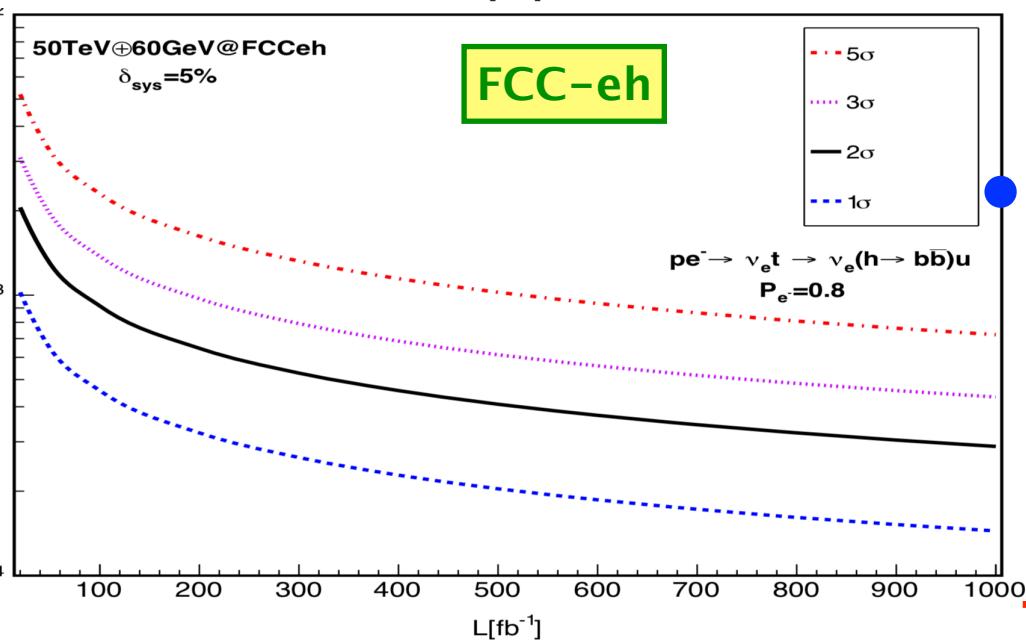
Sun, Wang,
arXiv:1602.04670 [hep-ph]

parametrisation

HL-LHC

LHC, 3000 fb^{-1} @14TeV
<0.0015
(1ab $^{-1}$)

2 σ

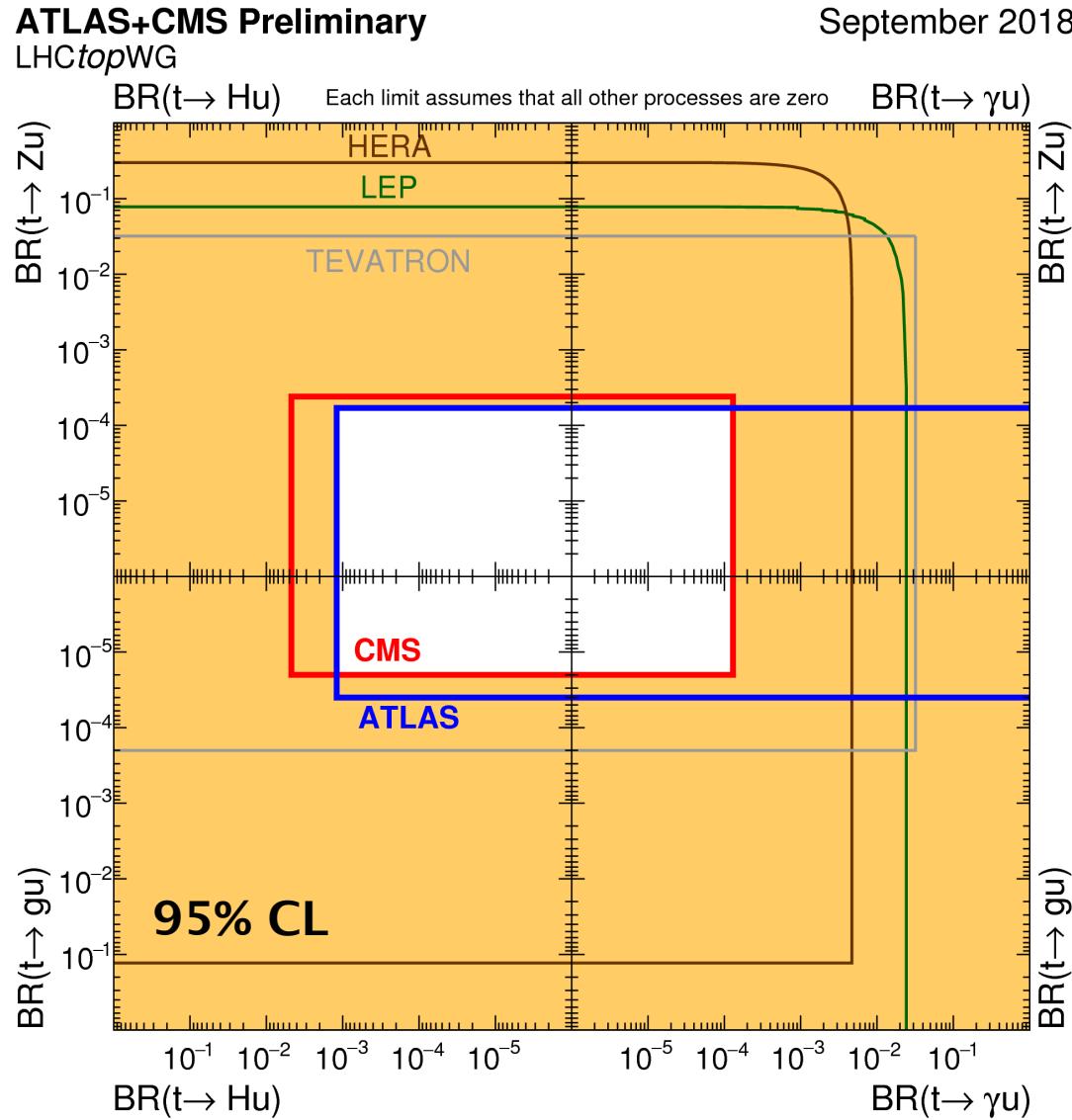


HL-LHC
LHC, 3000 fb^{-1} @14TeV

2 σ
<0.0002 (2ab $^{-1}$)

improves HL-LHC sensitivity

FCNC Branching Ratios at Colliders



FCNC Branching Ratios at Colliders

cut-based

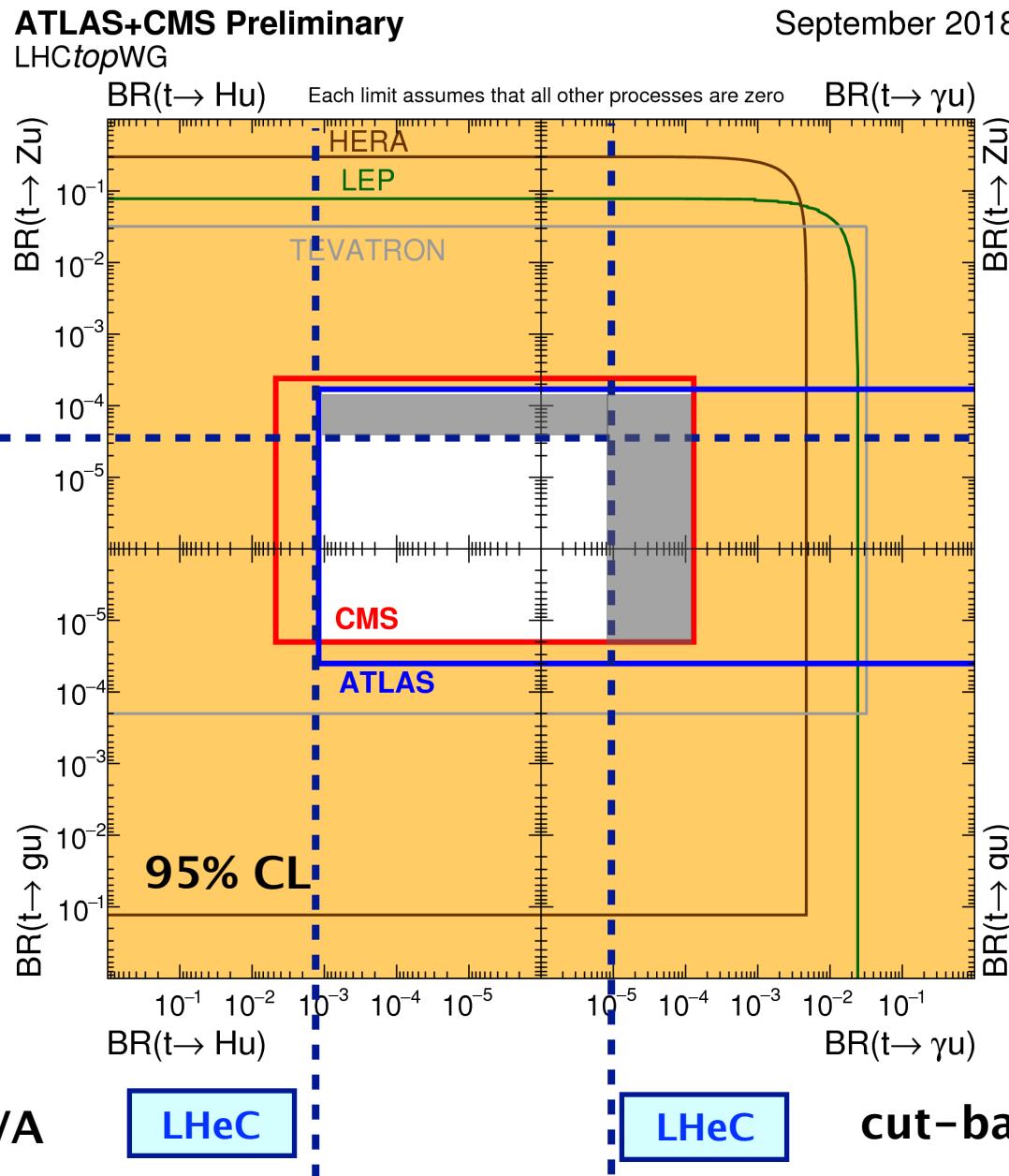
LHeC

$E_e = 60 \text{ GeV}$
 1000 fb^{-1}

MVA

LHeC

cut-based

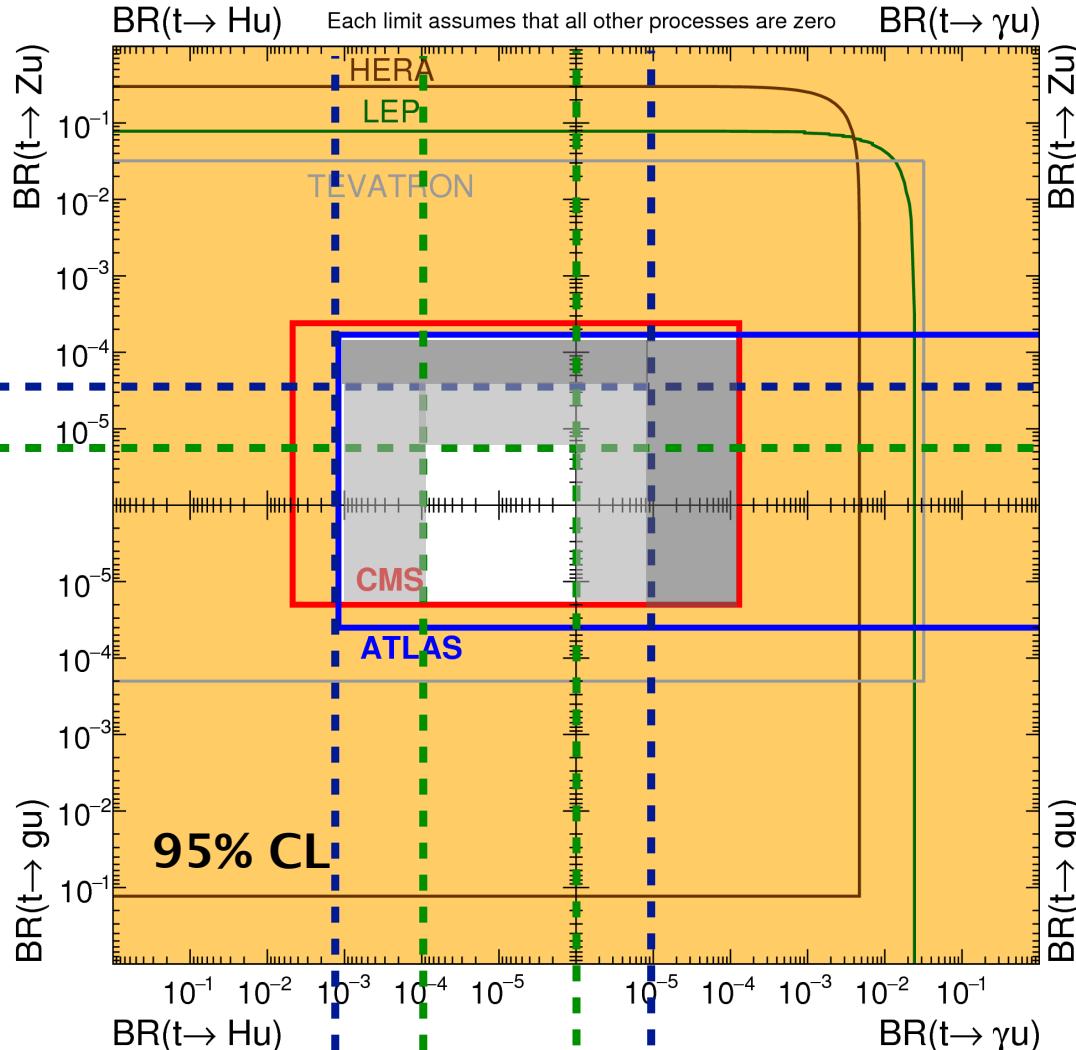


FCNC Branching Ratios at Colliders

ATLAS+CMS Preliminary

September 2018

LHCtopWG



MVA

LHeC

FCC-ep

LHeC

cut-based

FCNC Branching Ratios at Colliders

cut-based



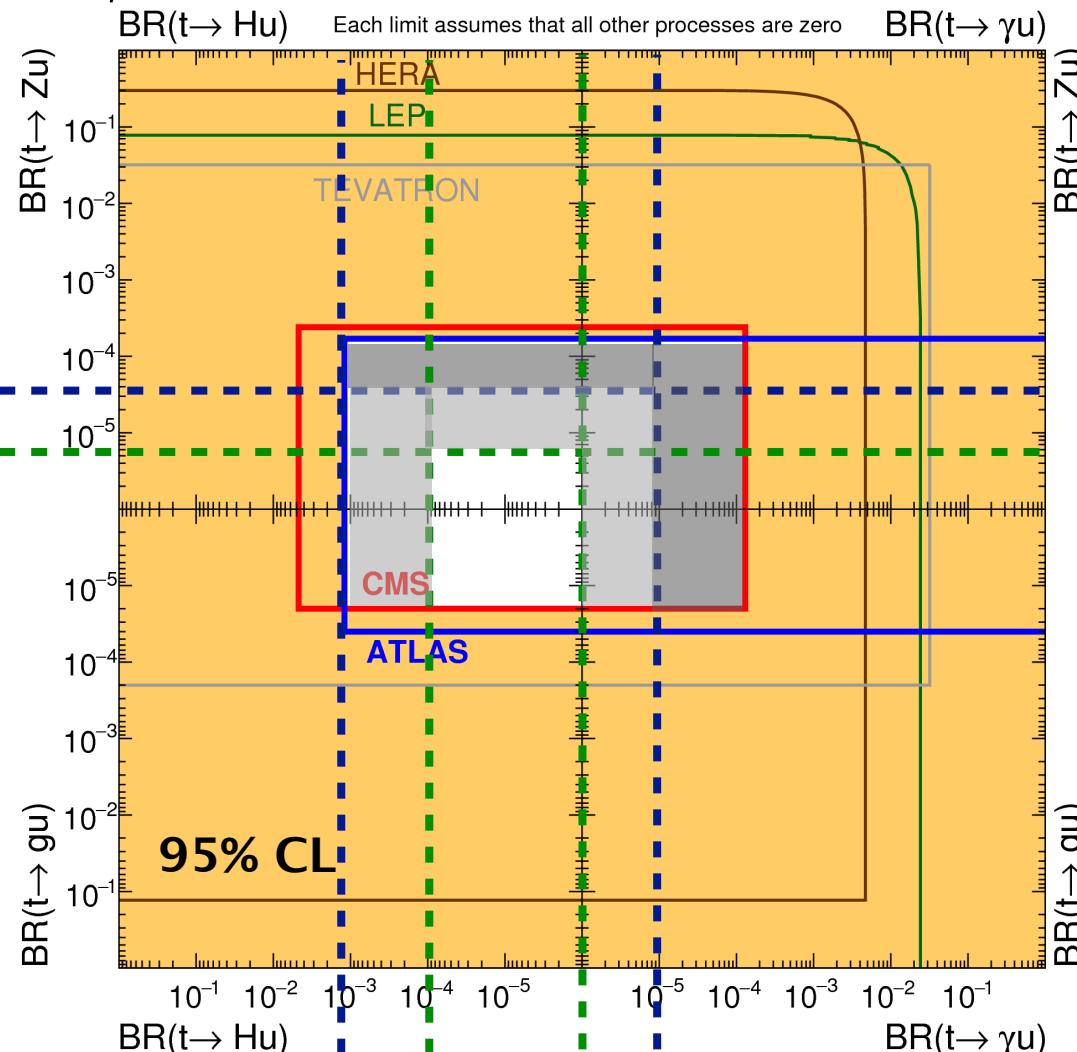
$E_e = 60 \text{ GeV}$
 1000 fb^{-1}
 2000 fb^{-1}

MVA

ATLAS+CMS Preliminary

LHCtopWG

September 2018



- **improve limits on $\text{BR}(t \rightarrow \gamma u)$, $\text{BR}(t \rightarrow \text{Zu})$, $\text{BR}(t \rightarrow \text{Hu})$ considerably**

→ test SUSY,
little Higgs,
technicolor...

cut-based



cut-based

Outline

Introduction Electroweak Physics Top Quark Physics **Conclusions**

Summary

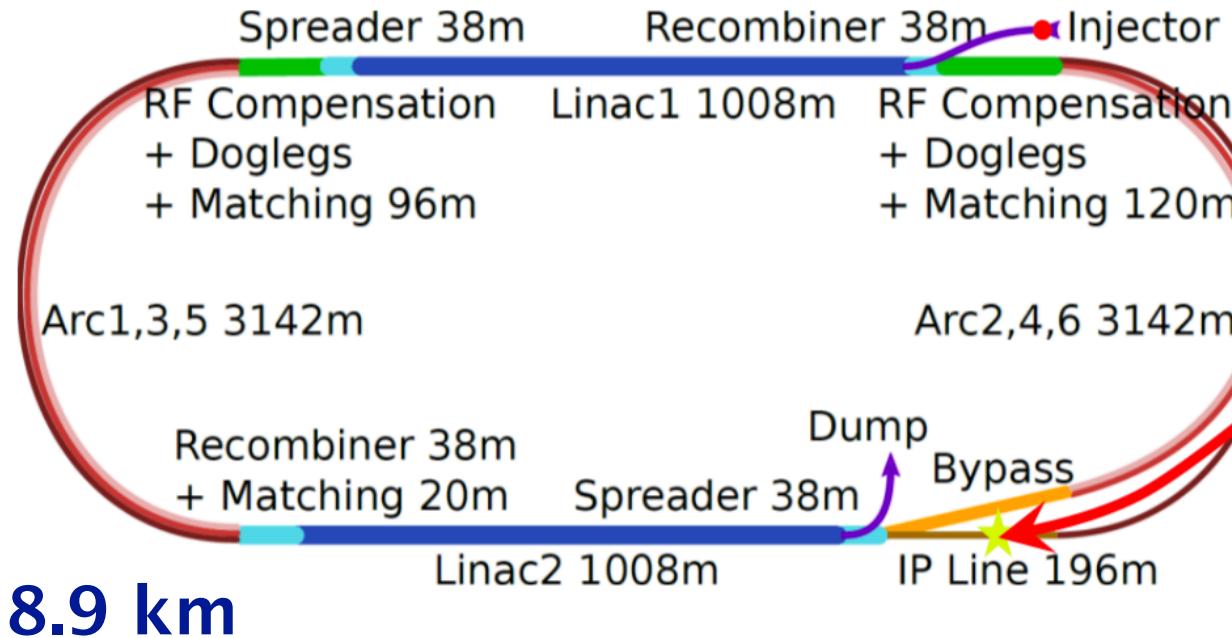
- future ep collider has a rich analysis programme for electroweak interactions of light and heavy quarks
 - high precision EW measurements: $\sin^2\theta_W$, light quark couplings to bosons (v_u, a_u, v_d, a_d), W mass and Z mass, ...
 - single top quark factory: $|V_{tb}|$ ($\sim 1\%$)
 - top quark couplings to bosons ($|V_{tb}|$, W_{tb} , $t\bar{t}\gamma$, $t\bar{t}Z$, 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 $t\bar{t}H$, heavy top, SUSY stops...
- DIS is **competitive** and **complementary** in performing **high precision** measurements of particle properties
- **large sensitivities to discover new physics!**

Backup

Energy Recovering Linac

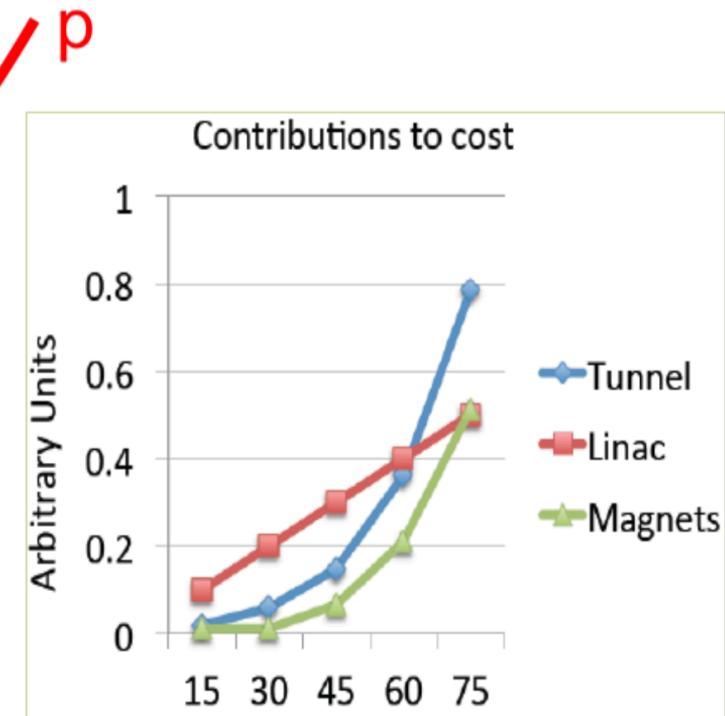
Energy Recovering Linac (ERL):

$E_e = 60 \text{ GeV}$



- power limit: 100 MW
- luminosity: $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- factor of 15/120 (LHeC/FCC-eh)

extension of Q^2 , $1/x$ reach

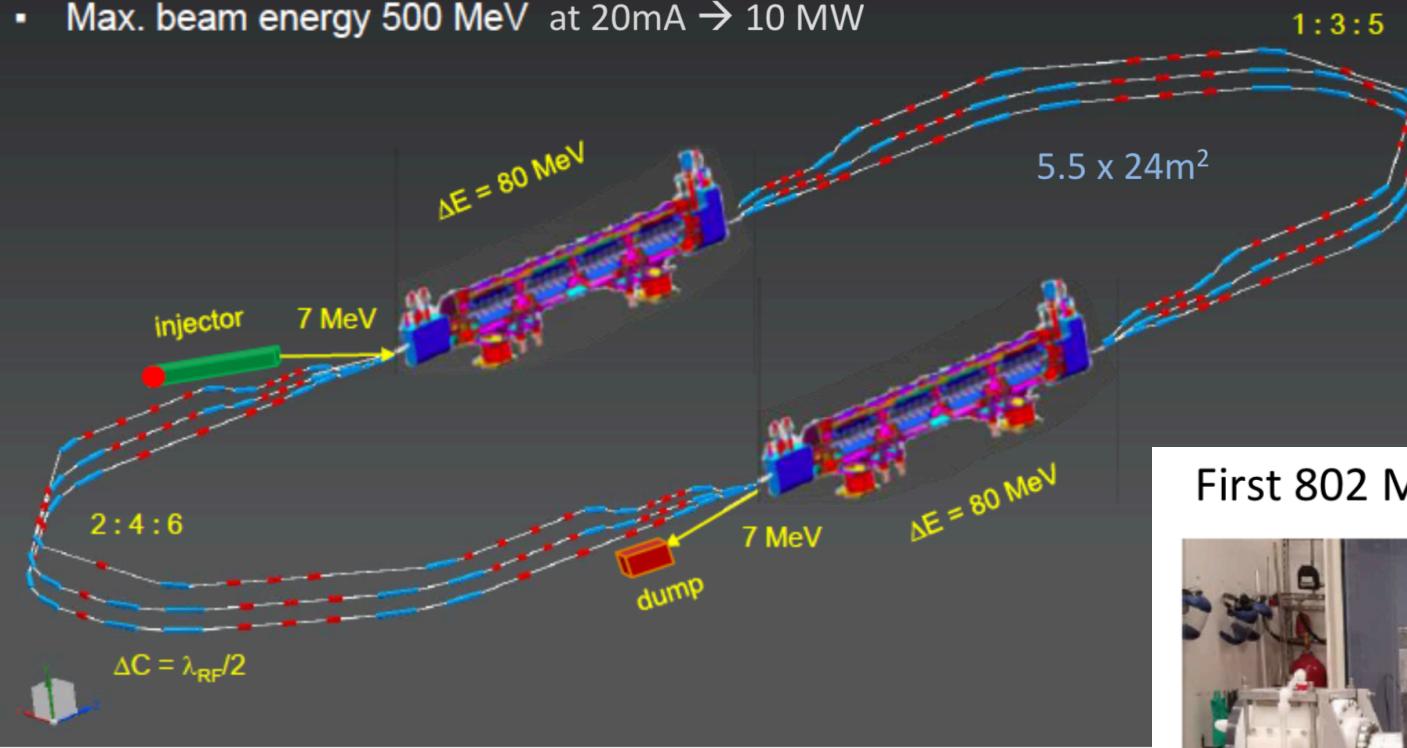


M. Klein, F. Zimmermann

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

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 \rightarrow 10 MW



cf Walid Kaabi at Amsterdam FCC



→ ERL demonstrator
→ O(10 MeV) physics

in Orsay

- BINP
 - CERN
 - Daresbury/Liverpool
 - Jlab
 - Orsay
- CDR 1705.08783
[J. Phys G]
→ TDR in 2019

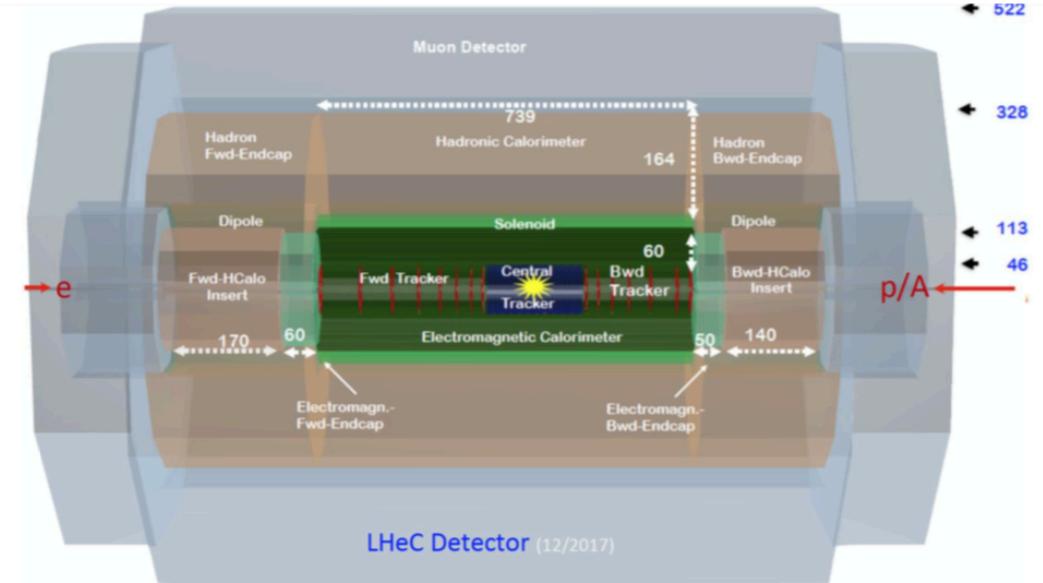
First 802 MHz cavity successfully built (Jlab)



LHeC Detector Layout

[arXiv:1802.04317]

- 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 $\sim 5 \mu\text{m}$
 - ATLAS b-tagging efficiencies
 - Using state-of-the art hadronic and el.mag. Resolutions
 - Considering displaced vertices and impact parameter distributions



Length x Diameter: LHeC (13.3 x 9 m²) 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$

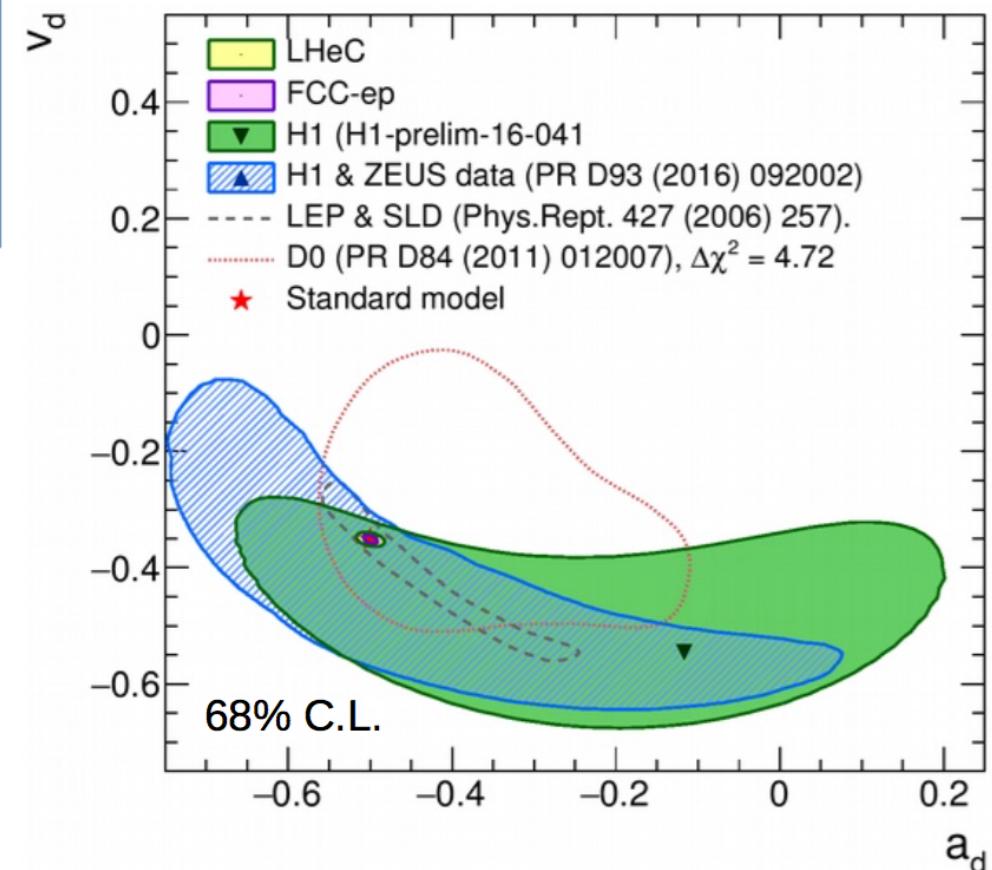
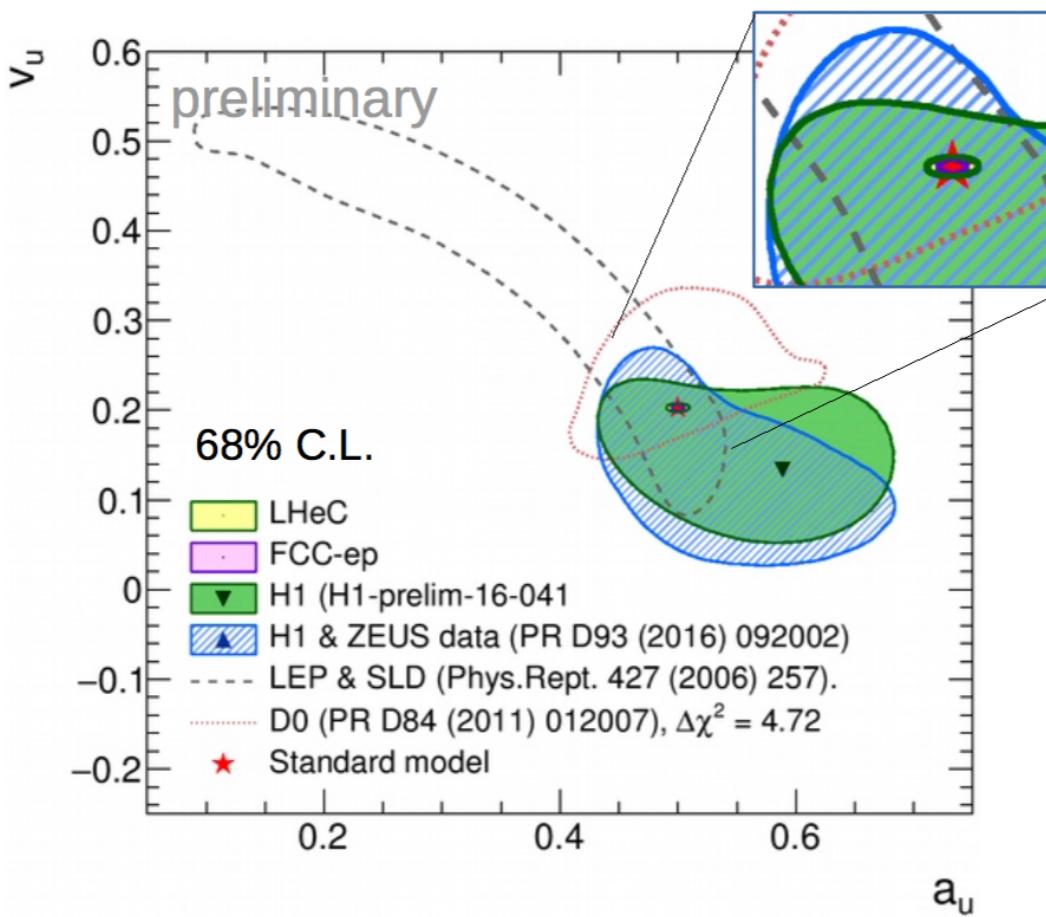
Slide: M. Schott

Vector and Axial Vector NC Couplings

LHeC

- simultaneous extraction with PDFs

FCC-ep

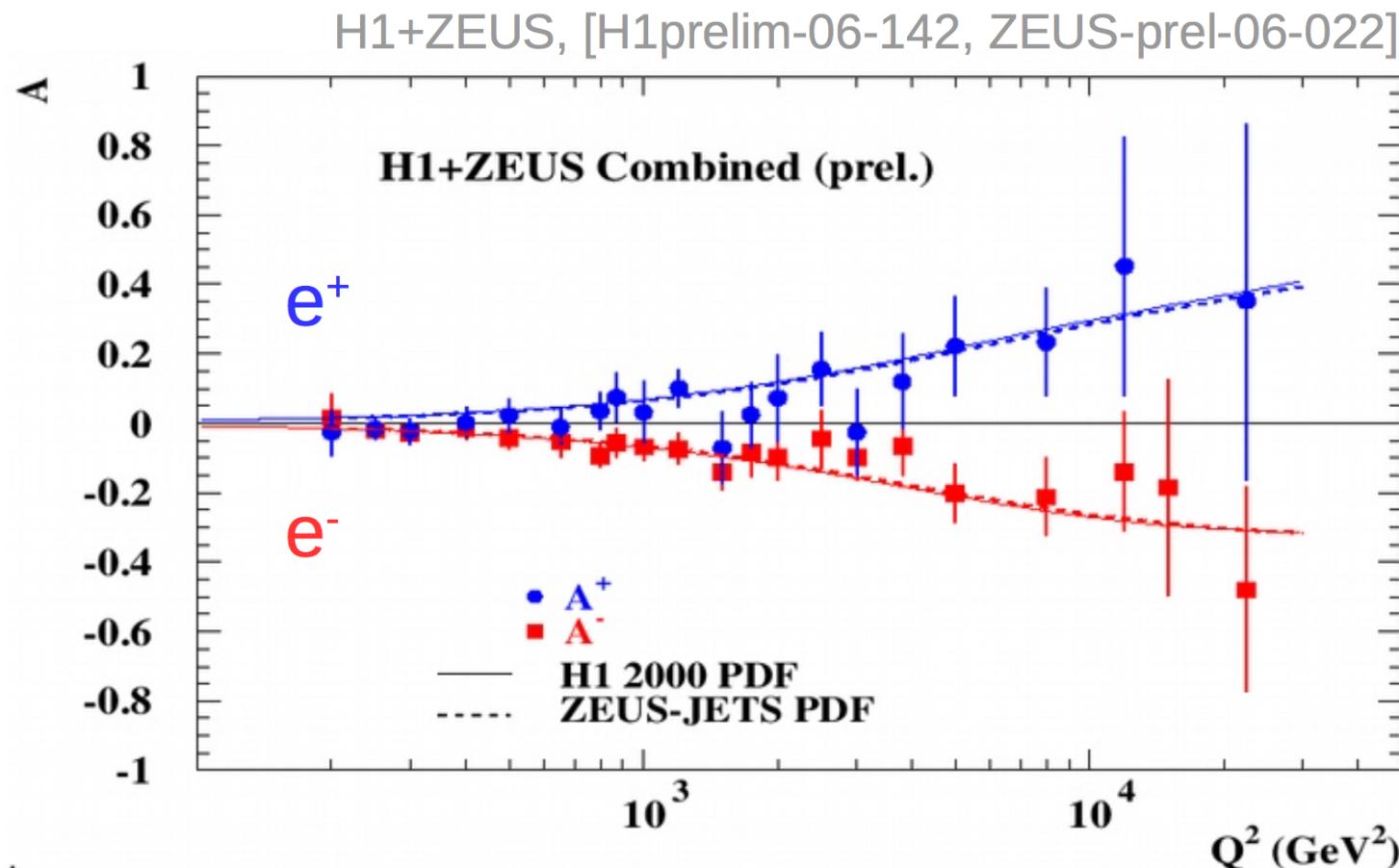


- high precision measurement of light quark couplings
- test new physics: Z' boson, R-parity violating SUSY, leptoquarks

Asymmetry Measurements

$$A^\pm = \frac{2}{P_L^\pm - P_R^\pm} \cdot \frac{\sigma^\pm(P_L^\pm) - \sigma^\pm(P_R^\pm)}{\sigma^\pm(P_L^\pm) + \sigma^\pm(P_R^\pm)}$$

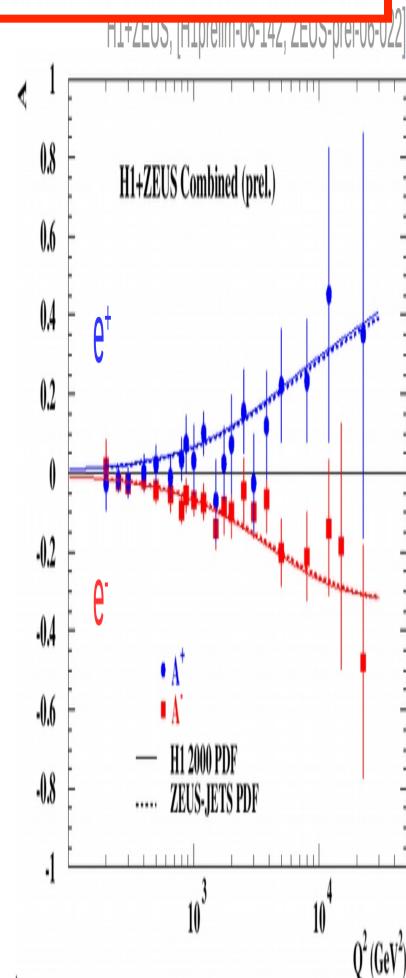
- study P-violation in NC-EW interactions



Asymmetry Measurements

$$A^\pm = \frac{2}{P_L^\pm - P_R^\pm} \cdot \frac{\sigma^\pm(P_L^\pm) - \sigma^\pm(P_R^\pm)}{\sigma^\pm(P_L^\pm) + \sigma^\pm(P_R^\pm)}$$

- study P-violation in NC EWK interactions

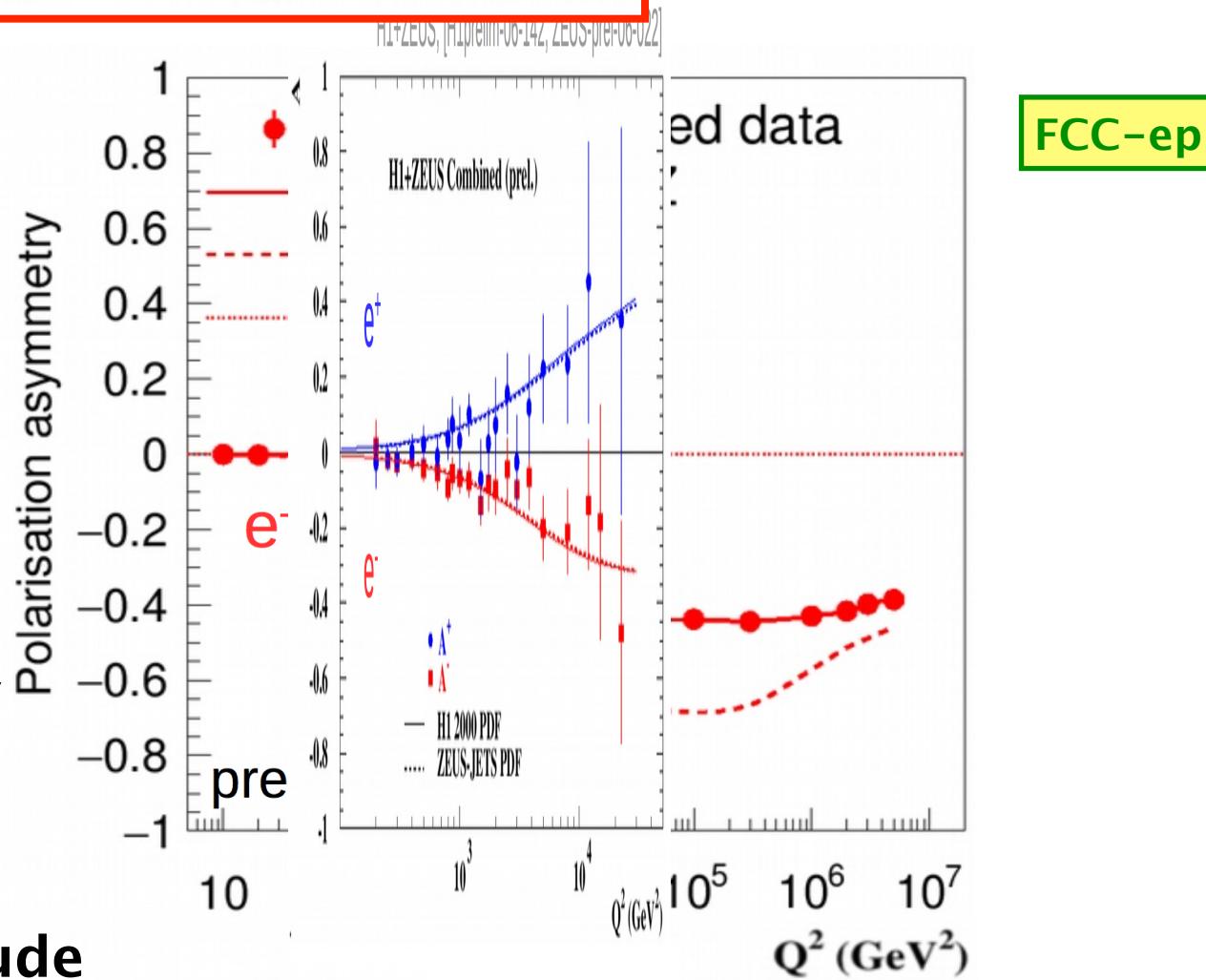


Asymmetry Measurements

$$A^\pm = \frac{2}{P_L^\pm - P_R^\pm} \cdot \frac{\sigma^\pm(P_L^\pm) - \sigma^\pm(P_R^\pm)}{\sigma^\pm(P_L^\pm) + \sigma^\pm(P_R^\pm)}$$

- study P-violation in NC EWK interactions

- 11 times higher center-of-mass energy
- 100–1000 times higher luminosity
- 2–3 times higher polarisation
- extend by 2–3 orders of magnitude

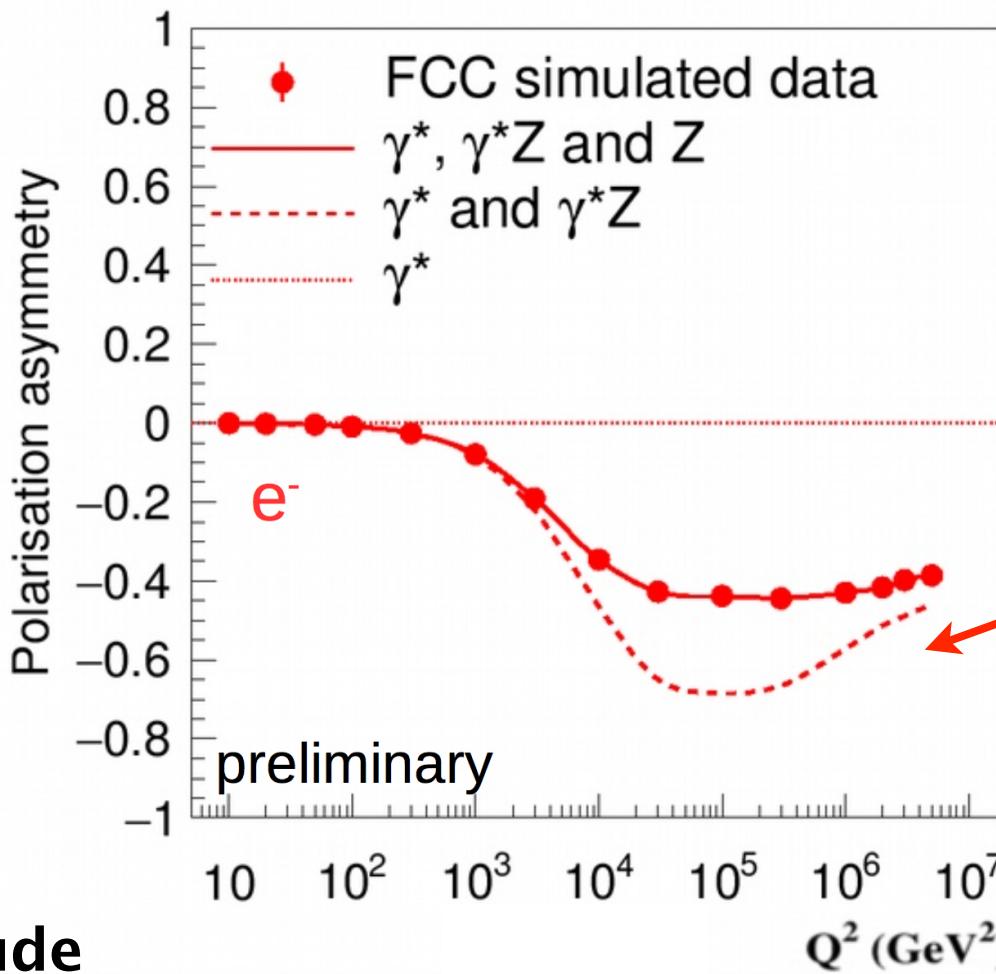


FCC-ep

Asymmetry Measurements

$$A^\pm = \frac{2}{P_L^\pm - P_R^\pm} \cdot \frac{\sigma^\pm(P_L^\pm) - \sigma^\pm(P_R^\pm)}{\sigma^\pm(P_L^\pm) + \sigma^\pm(P_R^\pm)}$$

- study P-violation in NC EWK interactions



FCC-ep

pure Z exchange becomes important

- 11 times higher center-of-mass energy
- 100–1000 times higher luminosity
- 2–3 times higher polarisation
- extend by 2–3 orders of magnitude

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	—	—	—
$\theta_{min/max}$ [°]	0.5	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}		
$\theta_{min/max}$ [°]	0.3	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					

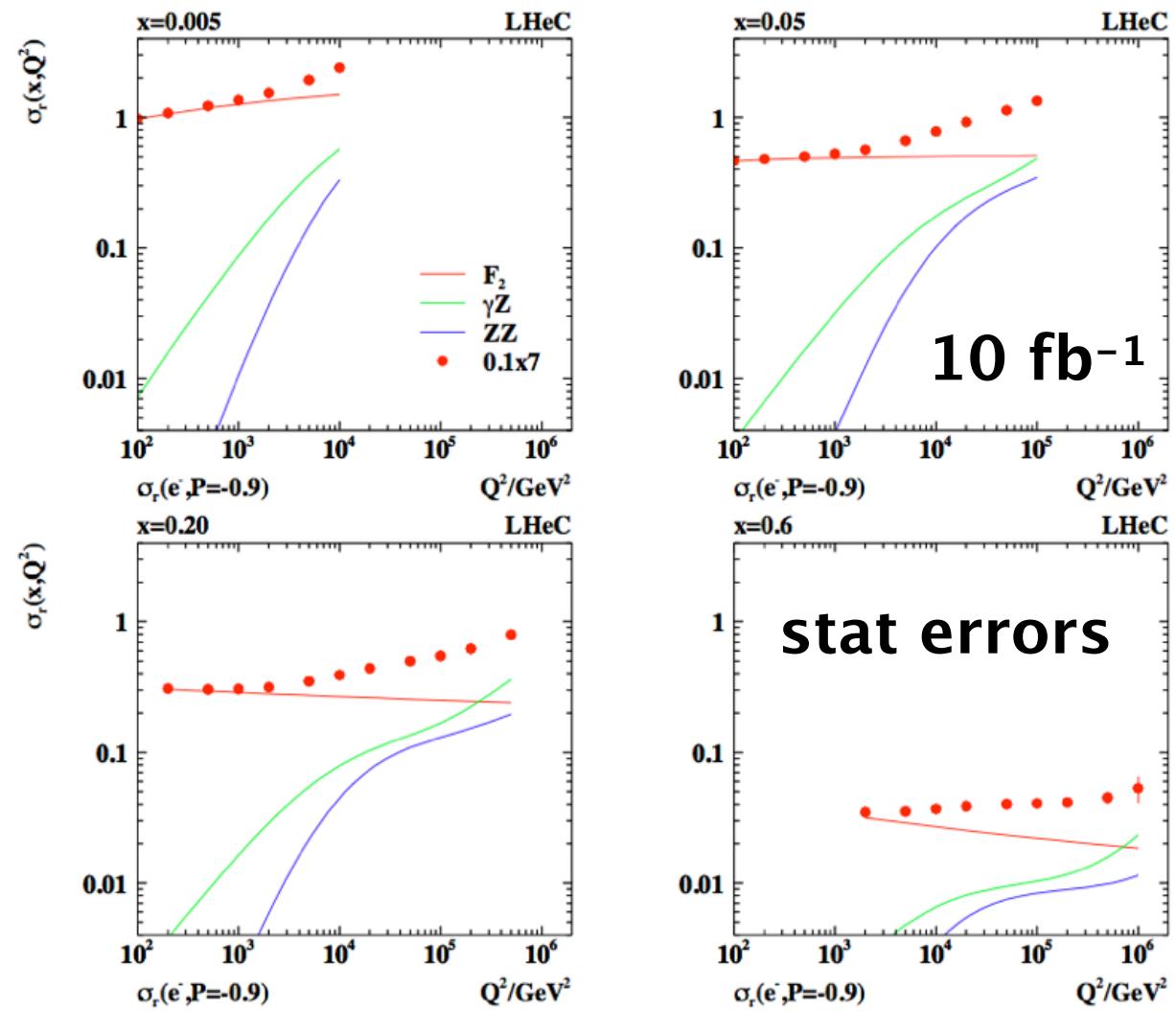
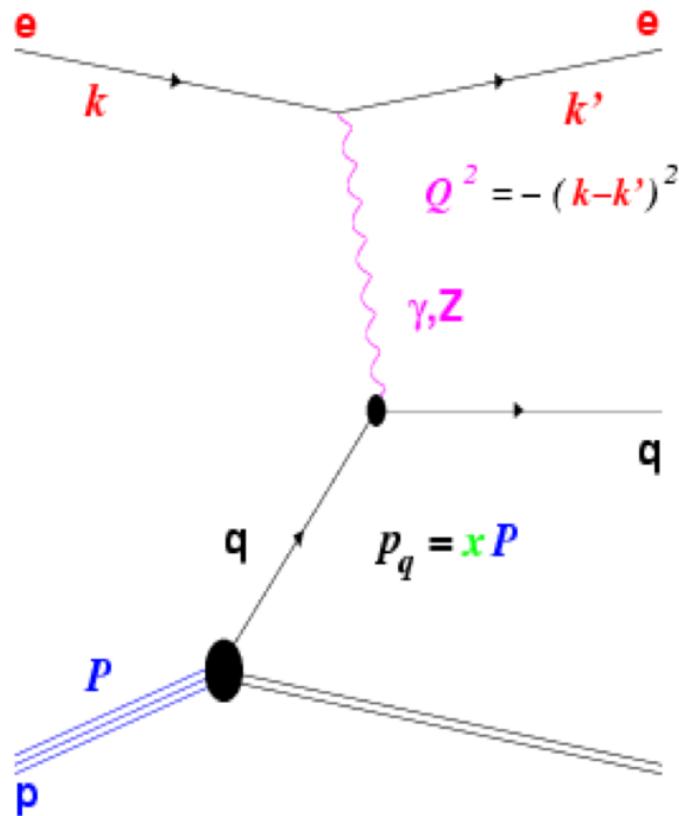
Input to detector design: HERA, ATLAS/CMS+their upgrades, CALICE, LHeC (CDR and update)

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

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

NC Cross Section Measurement

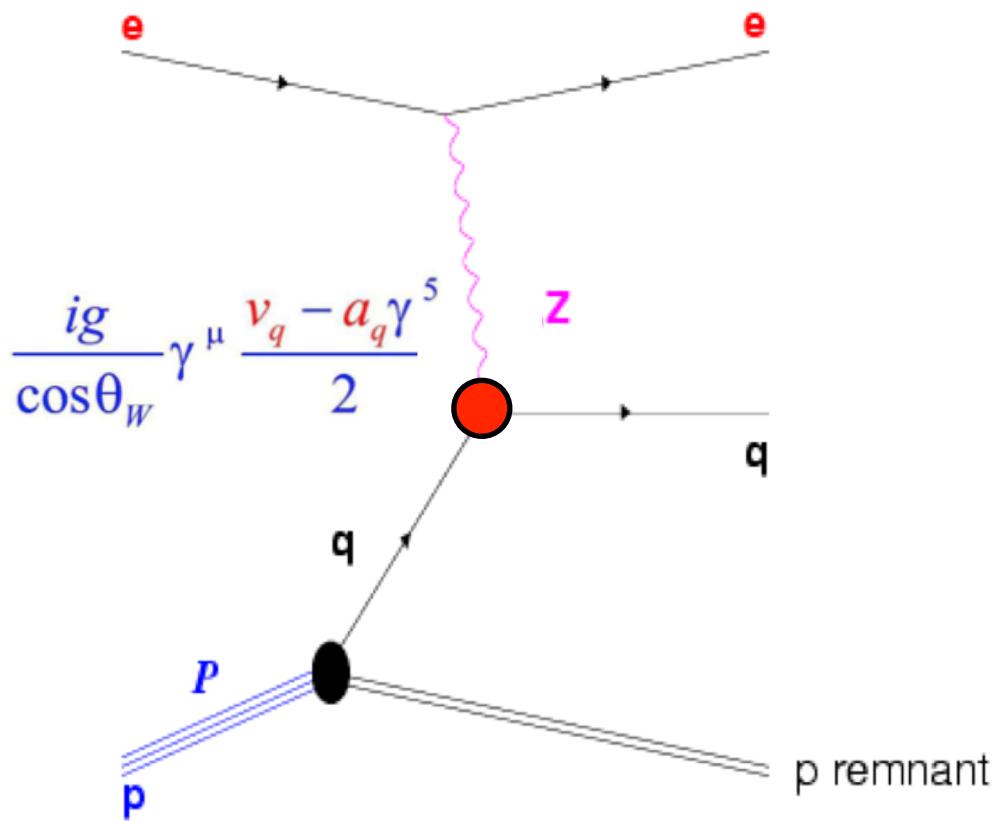
Neutral Current (NC)



→ high precision in large range of Bjørken x and Q^2

Quark Couplings to the Z boson

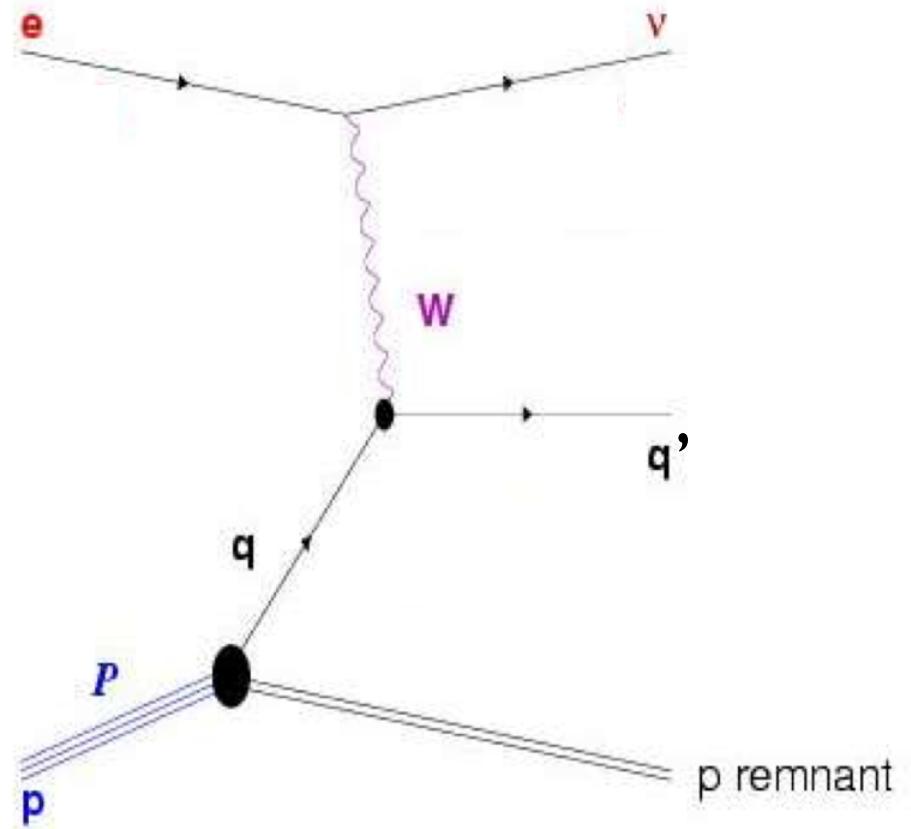
Neutral Current (NC)



$$a_q = I_3^L \quad \text{Axial coupling, } I^3 = +1/2 \text{ for u, } -1/2 \text{ for d}$$

$$v_q = I_3^L - 2e_q \sin^2 \theta_W \quad \text{Vector coupling}$$

Charged Current (CC)



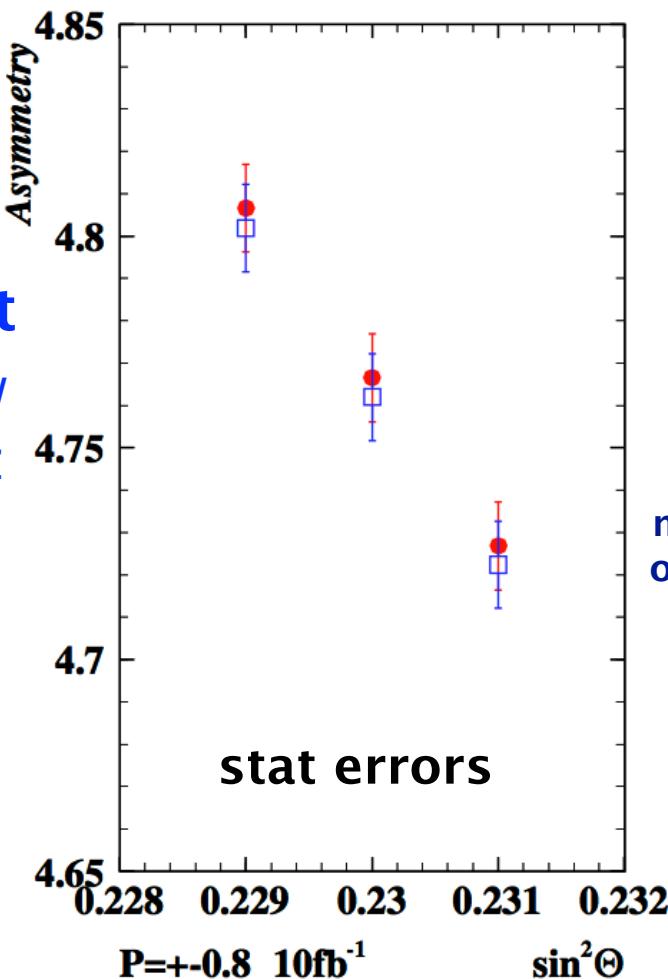
**fit to simulated NC and CC data to extract
a_u, a_d, v_u, v_d and PDFs simultaneously**

Asymmetry Measurements

$$A^\pm = \frac{\sigma_{NC}^\pm(P_R) - \sigma_{NC}^\pm(P_L)}{\sigma_{NC}^\pm(P_R) + \sigma_{NC}^\pm(P_L)}$$

$$R^\pm = \frac{\sigma_{NC}^\pm}{\sigma_{CC}^\pm}$$

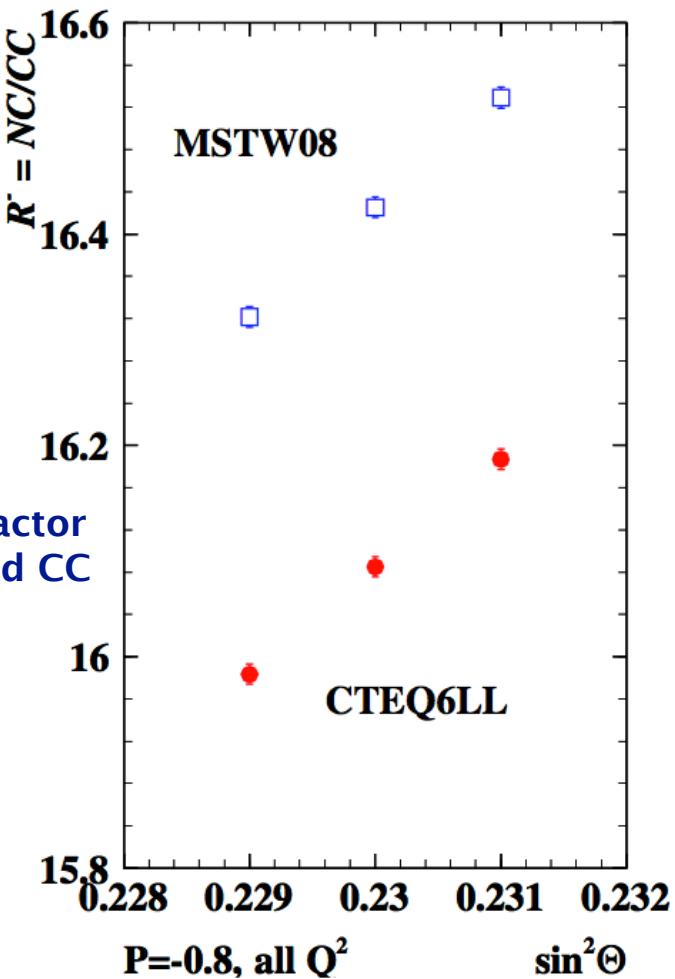
A-
extract
 $\sin^2\theta_W$
(α , m_Z
fixed)



10 fb⁻¹
e beam:
60 GeV

mean x differs by factor
of 6 between NC and CC

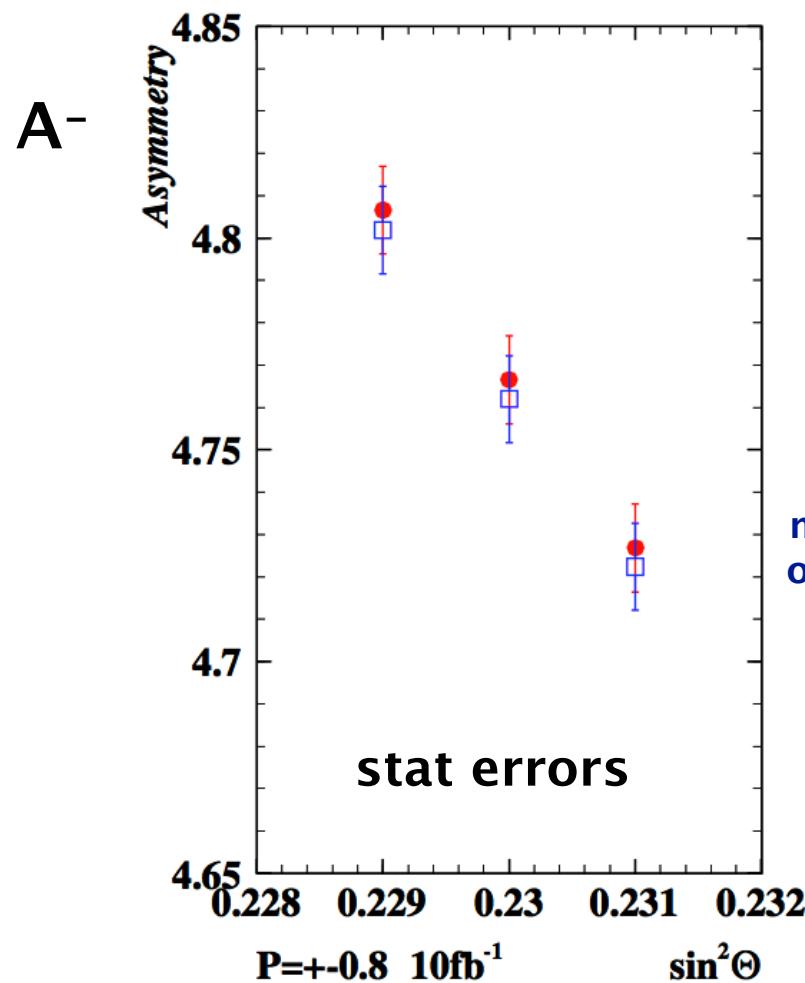
DESY



Asymmetry Measurements

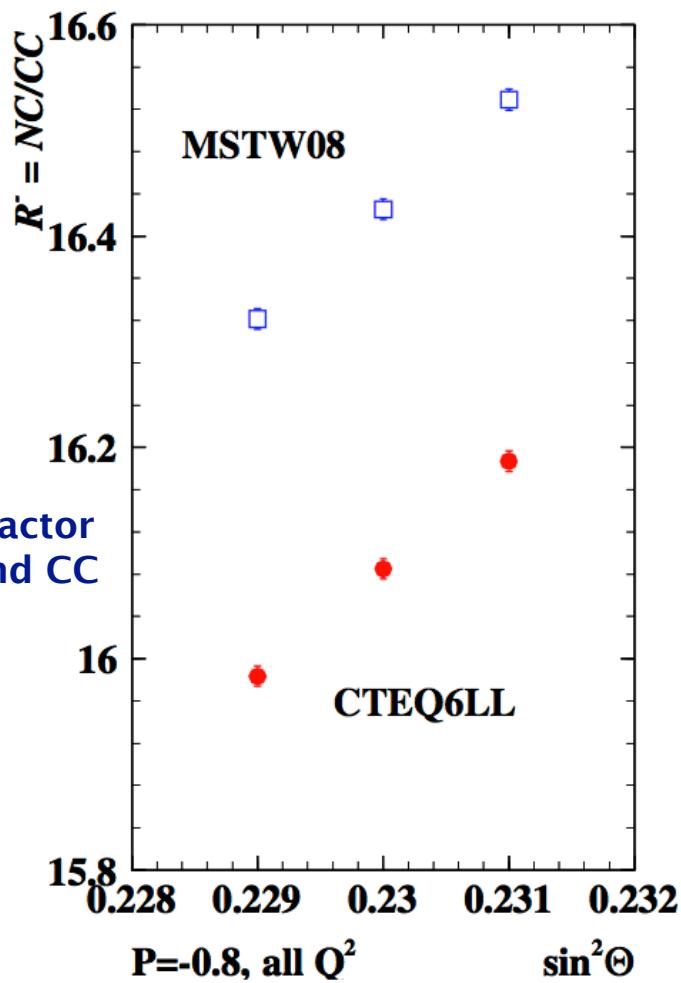
$$A^\pm = \frac{\sigma_{NC}^\pm(P_R) - \sigma_{NC}^\pm(P_L)}{\sigma_{NC}^\pm(P_R) + \sigma_{NC}^\pm(P_L)}$$

$$R^\pm = \frac{\sigma_{NC}^\pm}{\sigma_{CC}^\pm}$$



10 fb⁻¹
e beam:
60 GeV

mean x differs by factor
of 6 between NC and CC

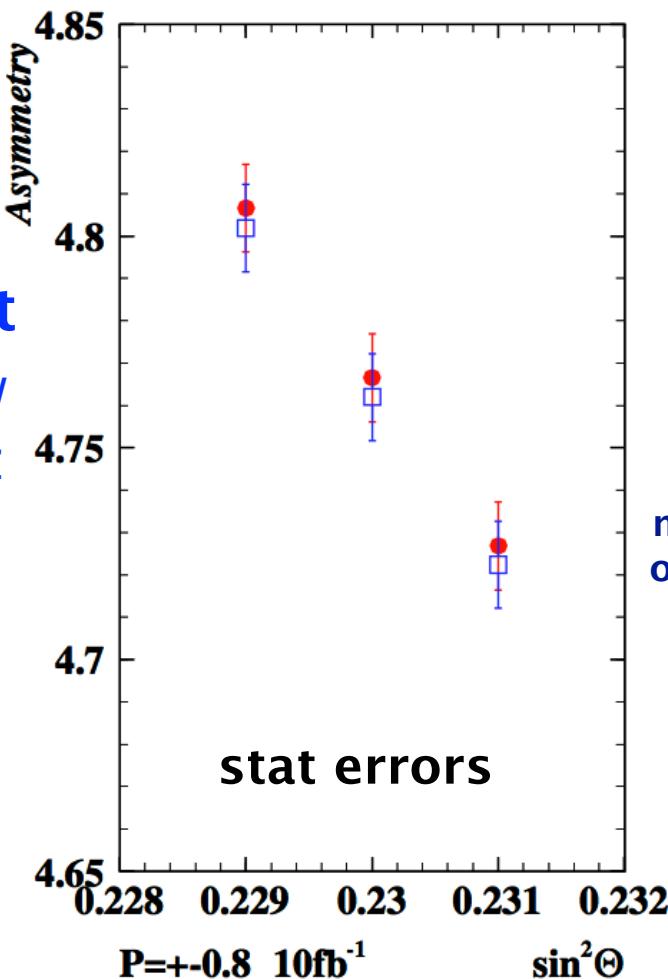


Asymmetry Measurements

$$A^\pm = \frac{\sigma_{NC}^\pm(P_R) - \sigma_{NC}^\pm(P_L)}{\sigma_{NC}^\pm(P_R) + \sigma_{NC}^\pm(P_L)}$$

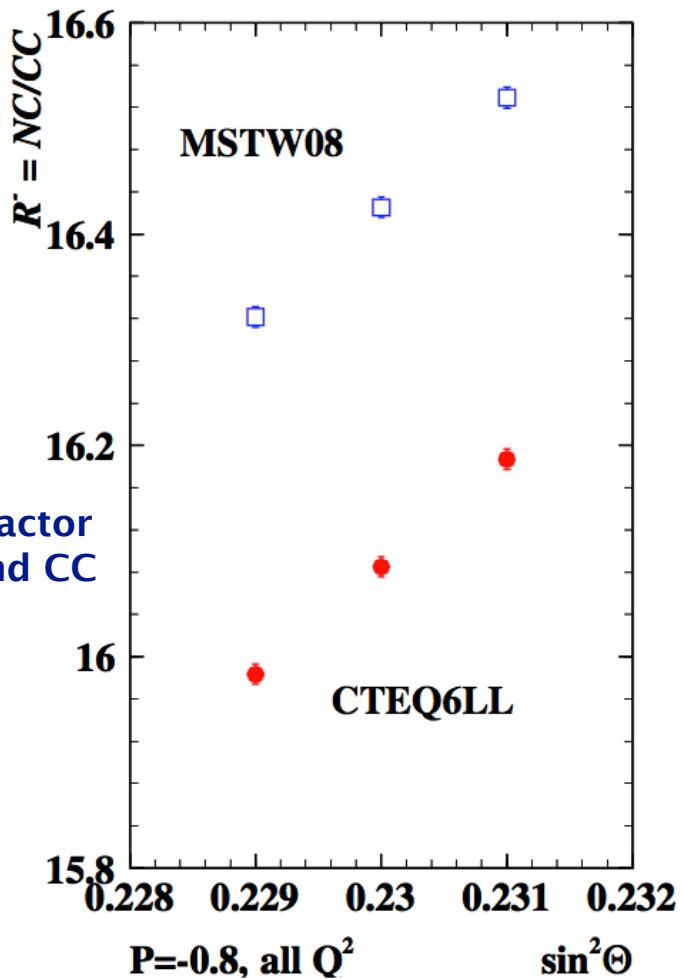
$$R^\pm = \frac{\sigma_{NC}^\pm}{\sigma_{CC}^\pm}$$

A-
extract
 $\sin^2\theta_W$
(α , m_Z
fixed)



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

mean x differs by factor
of 6 between NC and CC

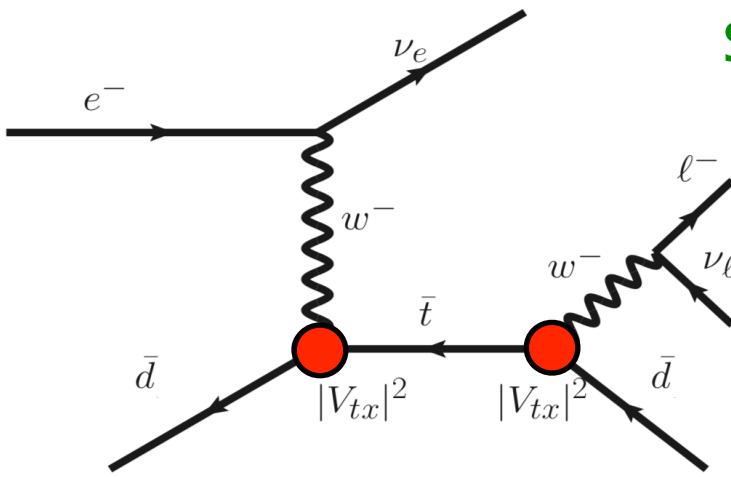


Measurement of $|V_{td}|$

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

arXiv:1709.07887
LHC, 3000 fb^{-1} @ 14 TeV

HL-LHC

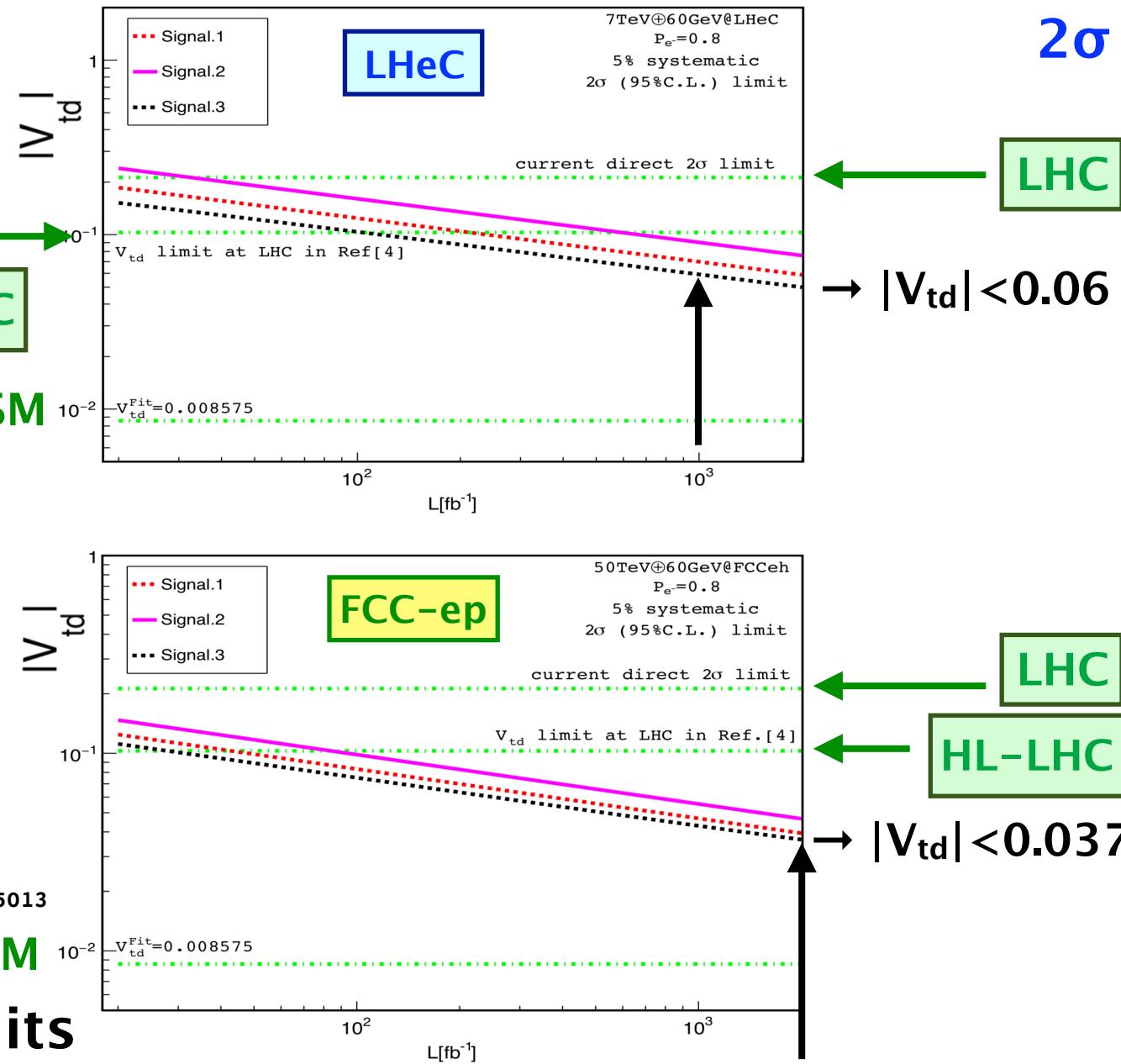


DELPHES

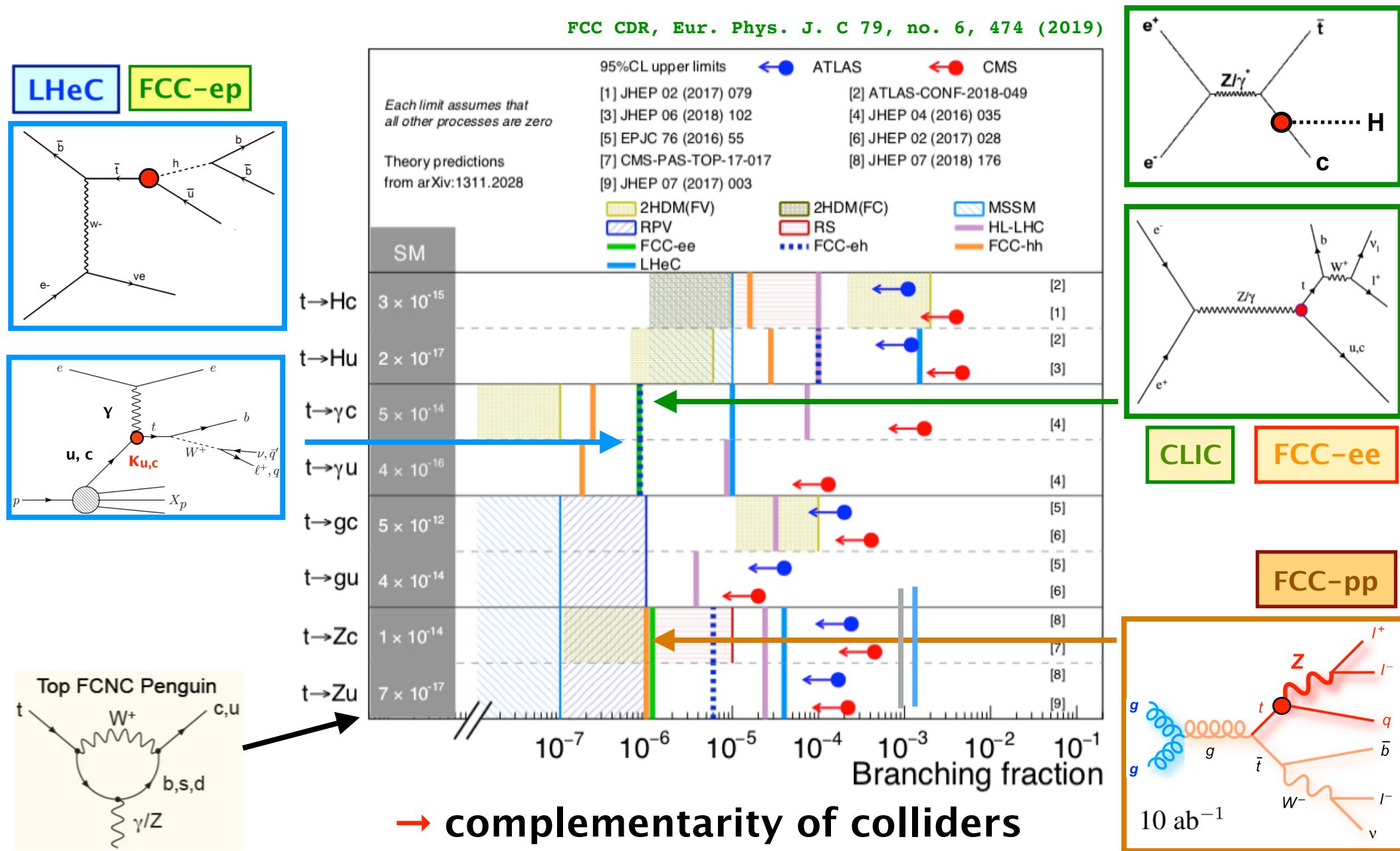
arXiv:1501.05013

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

→ extend HL-LHC limits



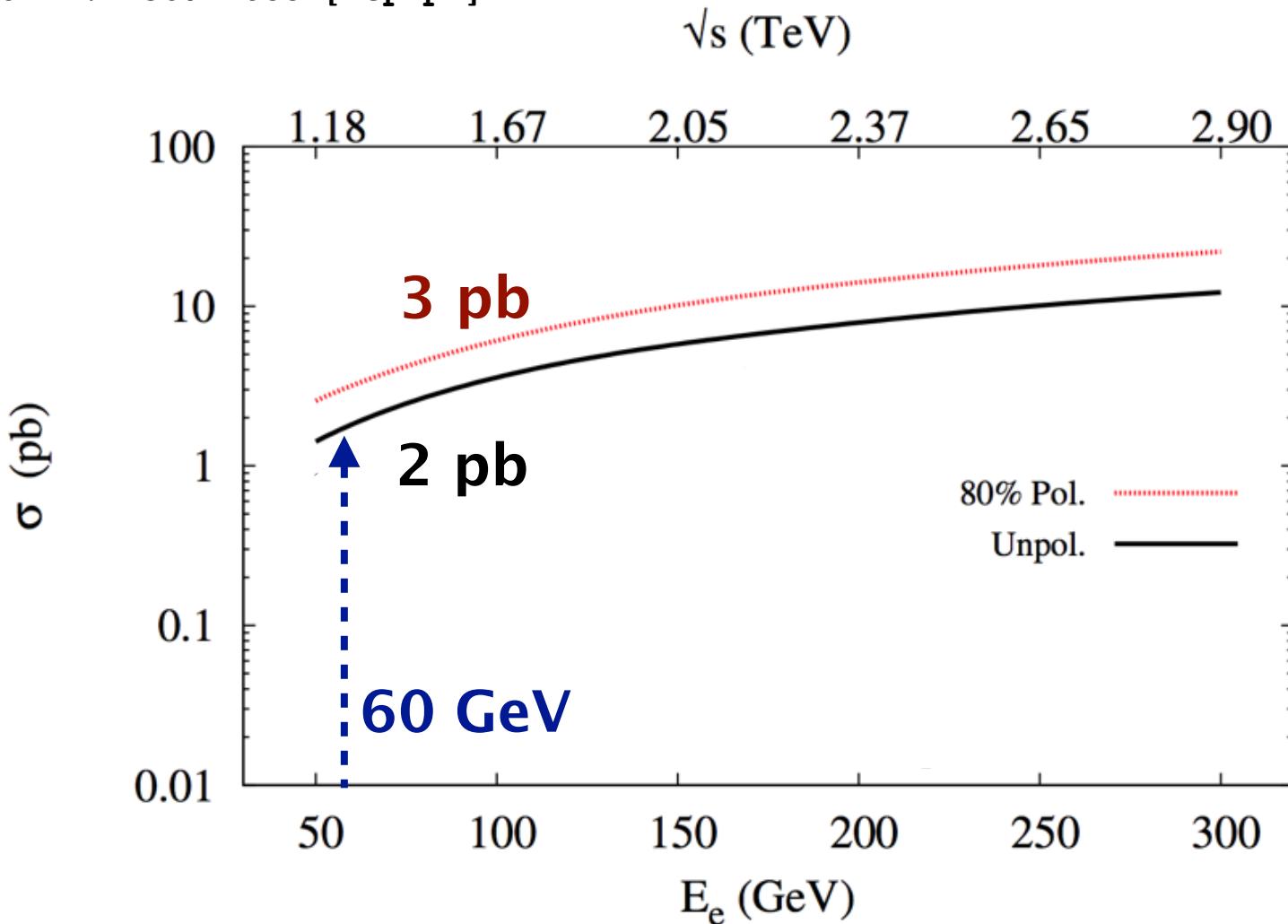
FCNC Top Quark Couplings



CC Single Top Quark Cross Section

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

100 fb⁻¹:
2 · 10⁵ events
3 · 10⁵ events

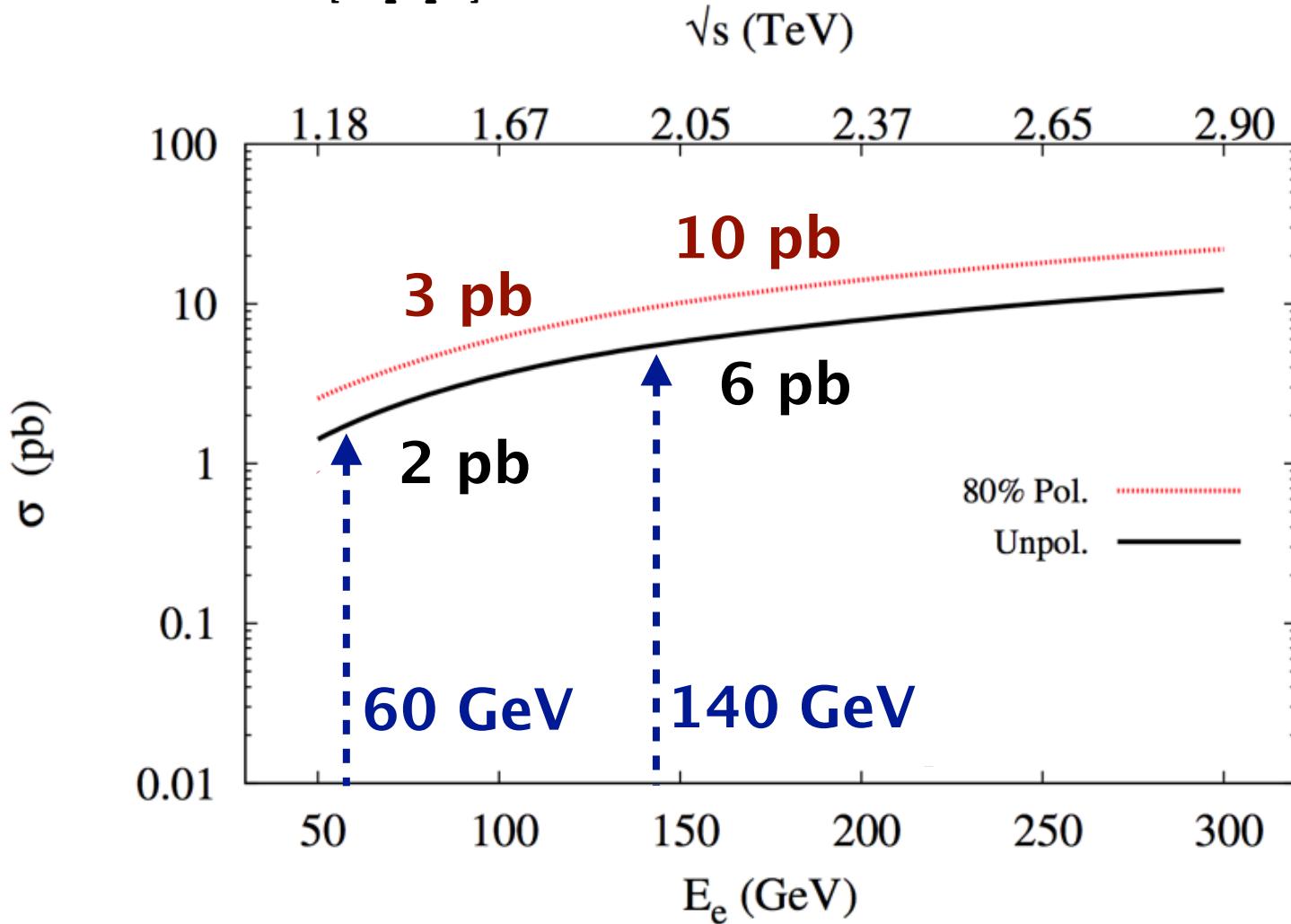


→ LHeC offers excellent prospects for top quark physics

CC Single Top Quark Cross Section

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

100 fb⁻¹:
2-6 · 10⁵ events
3-10 · 10⁵ events

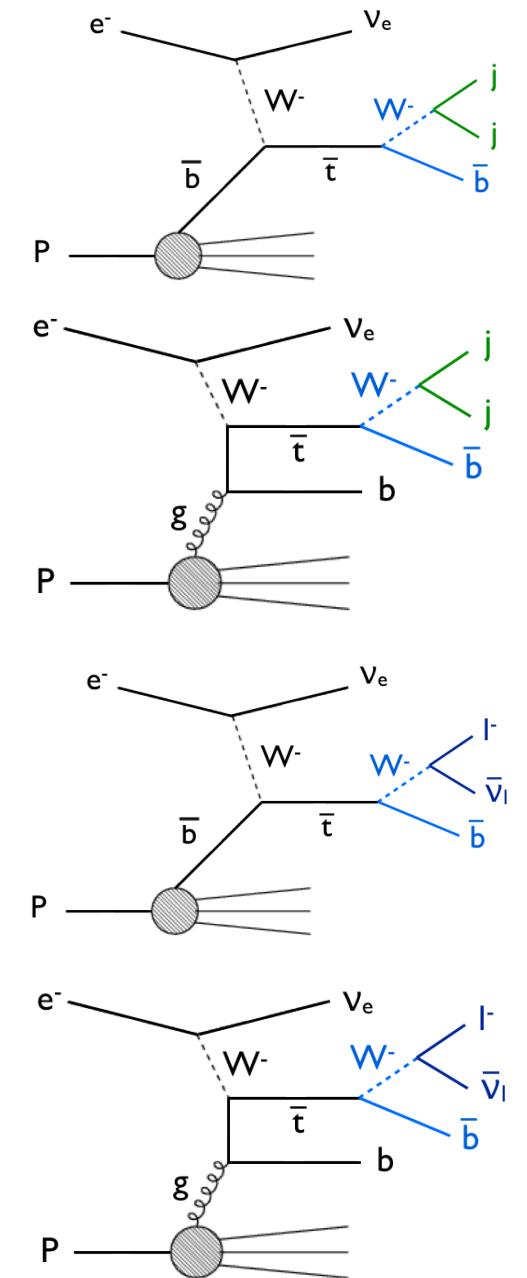
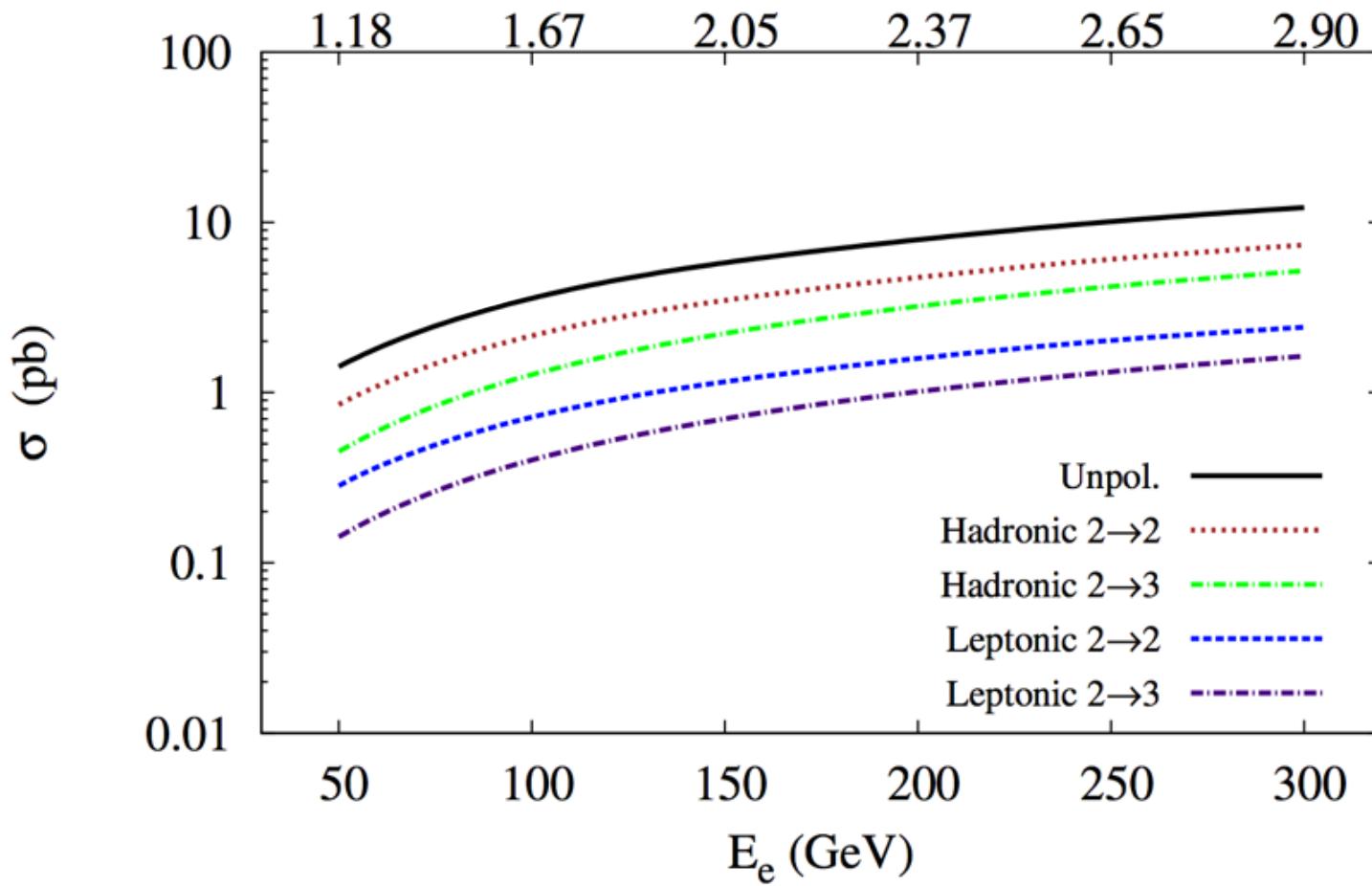


→ LHeC offers excellent prospects for top quark physics

CC Single Top Quark Cross Section

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

\sqrt{s} (TeV)



Backgrounds: Hadronic Channel

No.	Background Process	$p_{T,j,b} \geq 20 \text{ GeV}$ $ \eta_j \leq 5, \eta_b \leq 2.5$ $\Delta R_{j,b/j} \geq 0.4$ $\cancel{E}_T \geq 25$	$\Delta\Phi_{B,j} \geq 0.4$	$ \mathbf{m}_{j_1 j_2} - m_W \leq 22 \text{ GeV}$	$\sigma_{\text{eff.}}$
1	$e^- p \rightarrow \nu_e W^- \bar{b}$ without anti-top line	7.5×10^{-3}	6.8×10^{-3}	4.5×10^{-3}	2.7×10^{-3}
2	$e^- p \rightarrow \nu_e jjj$	4.2×10^0	3.6×10^0	2.4×10^0	7.2×10^{-2}
3	$e^- p \rightarrow \nu_e cjj$ & $e^- p \rightarrow \nu_e \bar{c}jj$	1.5×10^0	1.2×10^0	8.6×10^{-1}	8.6×10^{-2}
4	$e^- p \rightarrow \nu_e c\bar{c}j$	5.8×10^{-2}	5.0×10^{-2}	3.2×10^{-2}	6.7×10^{-3}
5	$e^- p \rightarrow \nu_e b\bar{b}j$	2.5×10^{-2}	2.2×10^{-2}	5.6×10^{-3}	1.3×10^{-3}
6	$e^- p \rightarrow \bar{c}\nu_e$ ($\bar{c} \rightarrow W^- \bar{s}$)	2.5×10^{-2}	2.2×10^{-2}	1.5×10^{-2}	1.5×10^{-4}

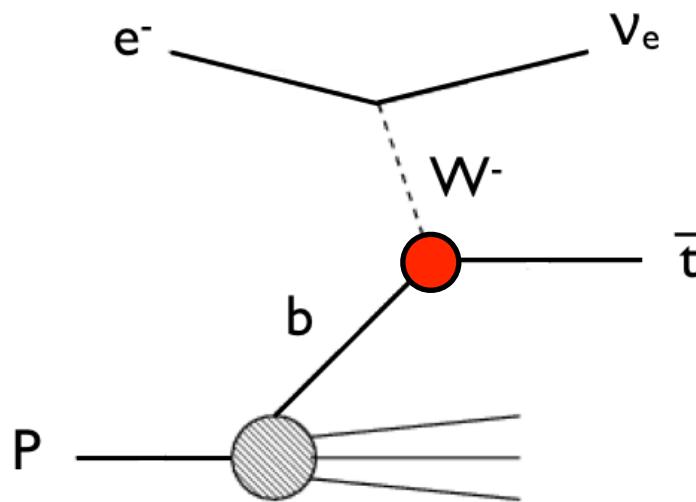
Event Selection	$p_{T,j,b} \geq 20 \text{ GeV}$ $ \eta_j \leq 5, \eta_b \leq 2.5$ $\Delta R_{j,b/j} \geq 0.4$ $\cancel{E}_T \geq 25$	$\Delta\Phi_{B,j} \geq 0.4$	$ \mathbf{m}_{j_1 j_2} - m_W \leq 22 \text{ GeV}$	Fiducial Efficiency	$S/\sqrt{S+B}$
SM	3.2×10^4	2.3×10^4	2.2×10^4	66.7 %	-
$SM + \sum_i \text{Bkg}_i$	6.5×10^4	5.0×10^4	4.0×10^4	61.5 %	
$ V_{tb} \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	$p_{T,j,b,l} \geq 20 \text{ GeV}$, $\Delta R_{j,b/j} \geq 0.4$, $\cancel{E}_T \geq 25$ $ \eta_j \geq 5$, $ \eta_{b,l} \geq 2.5$	$\Delta\Phi_{\cancel{E},j} \geq 0.4$ $\Delta\Phi_{\cancel{E},b} \geq 0.4$ $\Delta\Phi_{\cancel{E},l} \geq 0.4$	$\sigma_{\text{eff.}}$
1	$e^- p \rightarrow l^- \bar{\nu}_l \nu_e j$	1.5×10^{-1}	1.4×10^{-1}	1.4×10^{-3}
2	$e^- p \rightarrow l^- \bar{\nu}_l \nu_e c$ & $e^- p \rightarrow l^- \bar{\nu}_l \nu_e \bar{c}$	6.6×10^{-3}		6.1×10^{-3}
3	$e^- p \rightarrow l^- \bar{\nu}_l \nu_e b$ & $e^- p \rightarrow l^- \bar{\nu}_l \nu_e \bar{b}$ Without top line	3.6×10^{-3}		3.2×10^{-3}
4	$e^- p \rightarrow e^- l^- \bar{\nu}_l c$	1.5×10^{-2}		6.9×10^{-3}
5	$e^- p \rightarrow e^- l^- \bar{\nu}_l j$	1.2×10^{-1}		5.5×10^{-2}
				5.5×10^{-4}

Event Selection	$p_{T,j,b} \geq 20 \text{ GeV}$ $ \eta_j \leq 5, \eta_b \leq 2.5$ $\Delta R_{j,b/j} \geq 0.4$ $\cancel{E}_T \geq 25$	$\Delta\Phi_{\cancel{E},j} \geq 0.4$ $\Delta\Phi_{\cancel{E},b} \geq 0.4$ $\Delta\Phi_{\cancel{E},l} \geq 0.4$	Fiducial Efficiency	$S/\sqrt{S+B}$
SM	1.2×10^4	1.1×10^4	92.0 %	—
$\text{SM} + \sum_i \text{Bkg}_i$	1.3×10^4	1.2×10^4	92.0 %	—
$ V_{tb} \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 $|V_{tb}|$

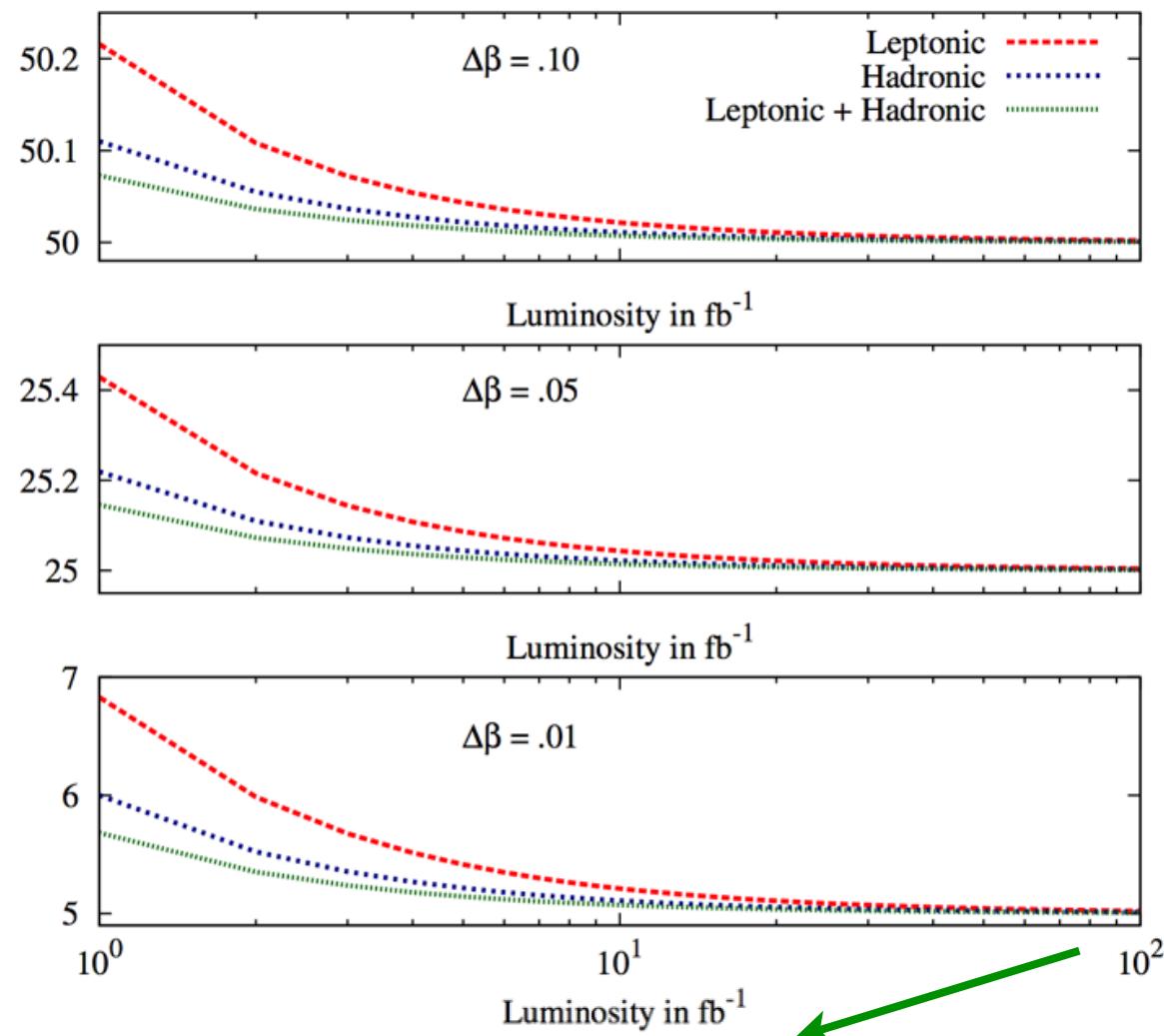


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

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

$\Delta\beta$: luminosity uncertainty



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

Search for Anomalous Wtb Couplings

= 1 in SM

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

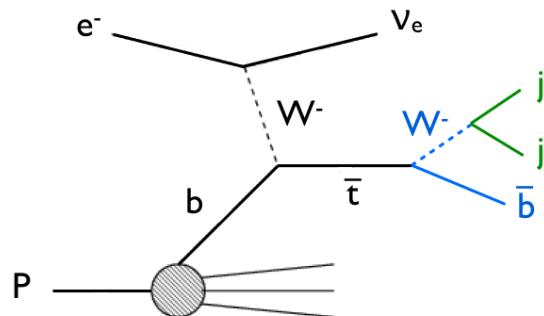
Search for Anomalous Wtb Couplings

= 1 in SM

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

Search for Anomalous Wtb Couplings

= 1 in SM

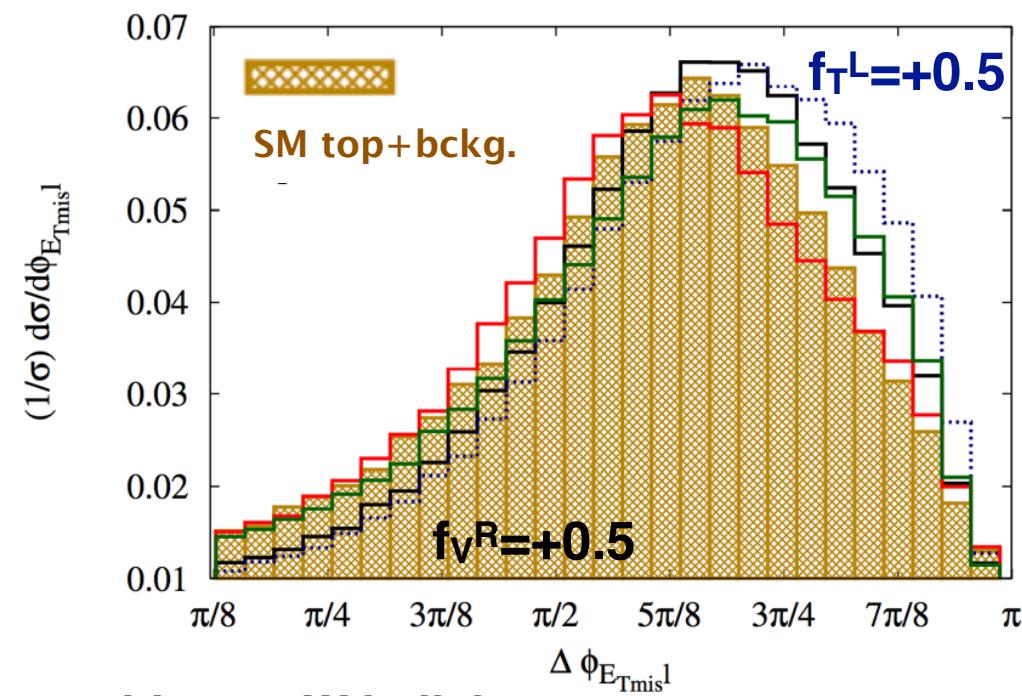
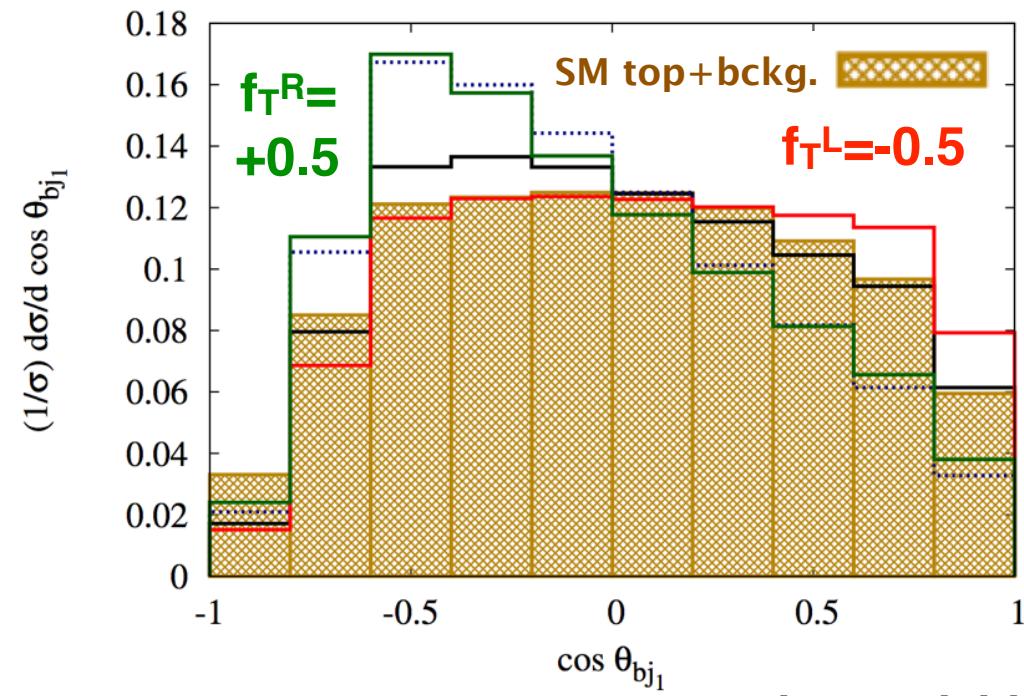
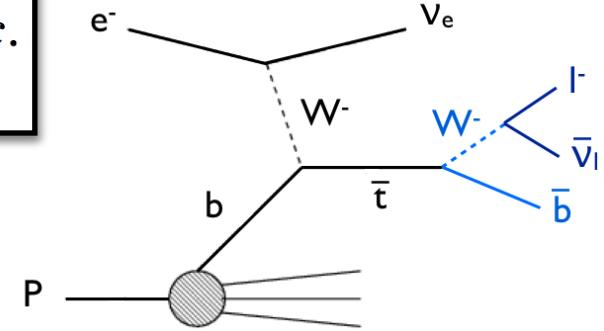


$$L = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} \left(f_V^L P_L + f_V^R P_R \right) t W_\mu^-$$

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

Dutta, Goyal, Kumar,
Mellado, arXiv:1307.1688

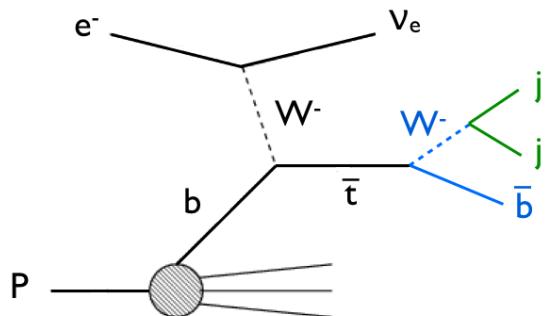
$L_{int}=100 \text{ fb}^{-1}$



+ other variables sensitive on W helicity

Search for Anomalous Wtb Couplings

= 1 in SM



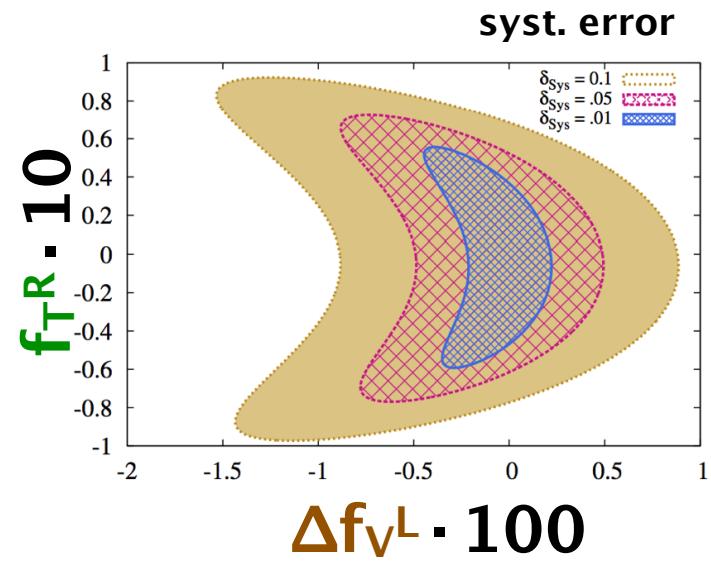
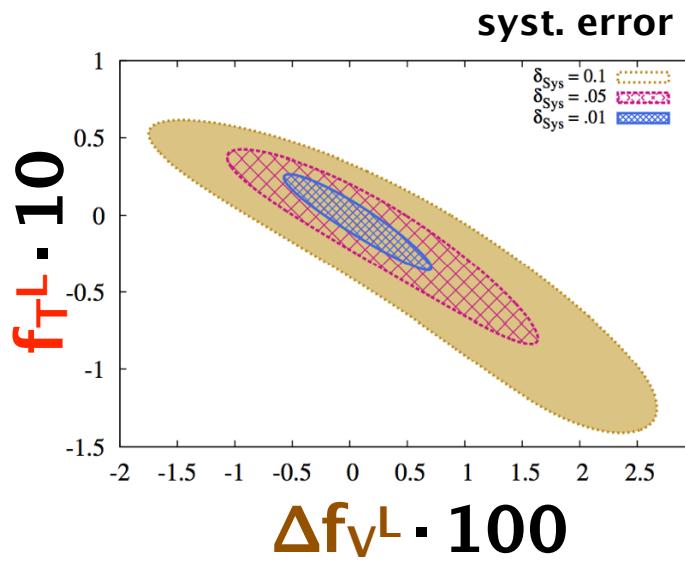
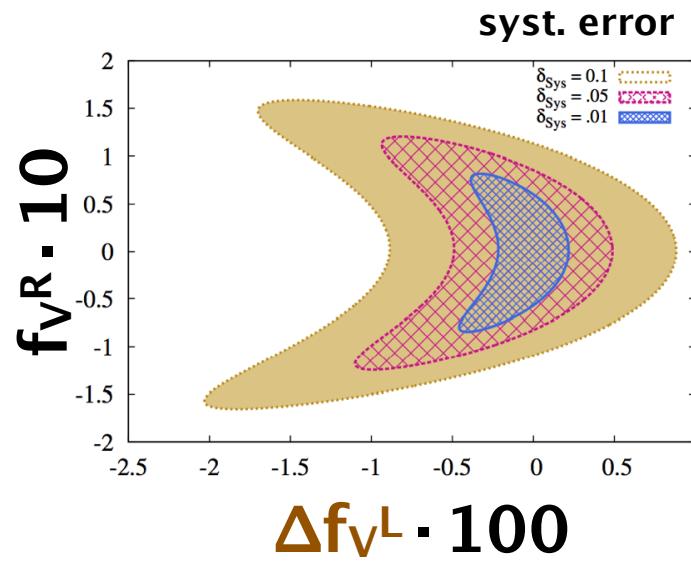
$$L = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_V^L P_L + f_V^R P_R) t W_\mu^-$$

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

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



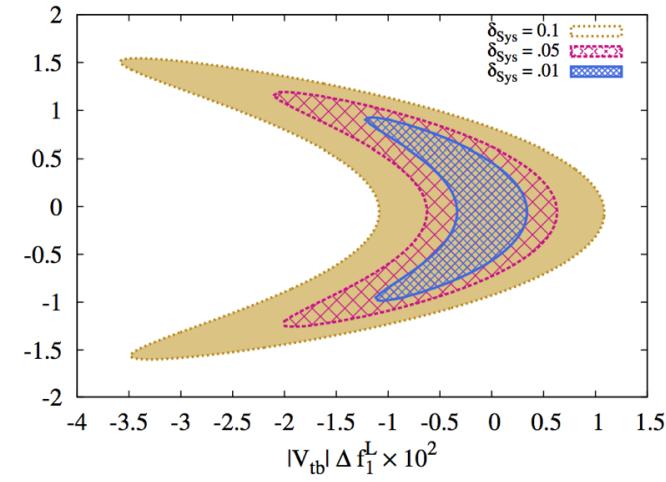
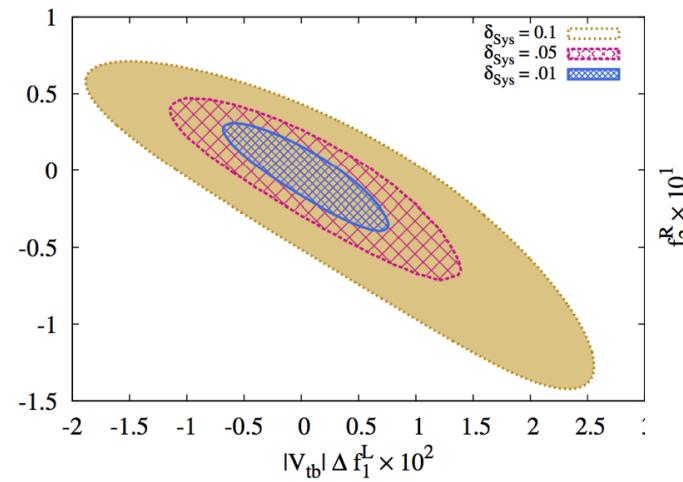
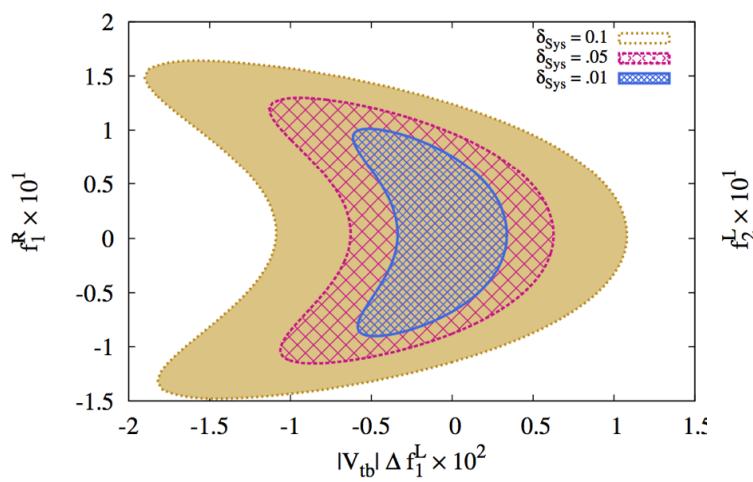
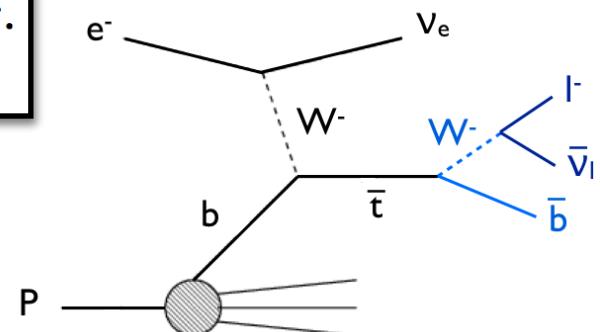
Search for Anomalous Wtb Couplings

= 1 in SM

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

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

68% C.L.

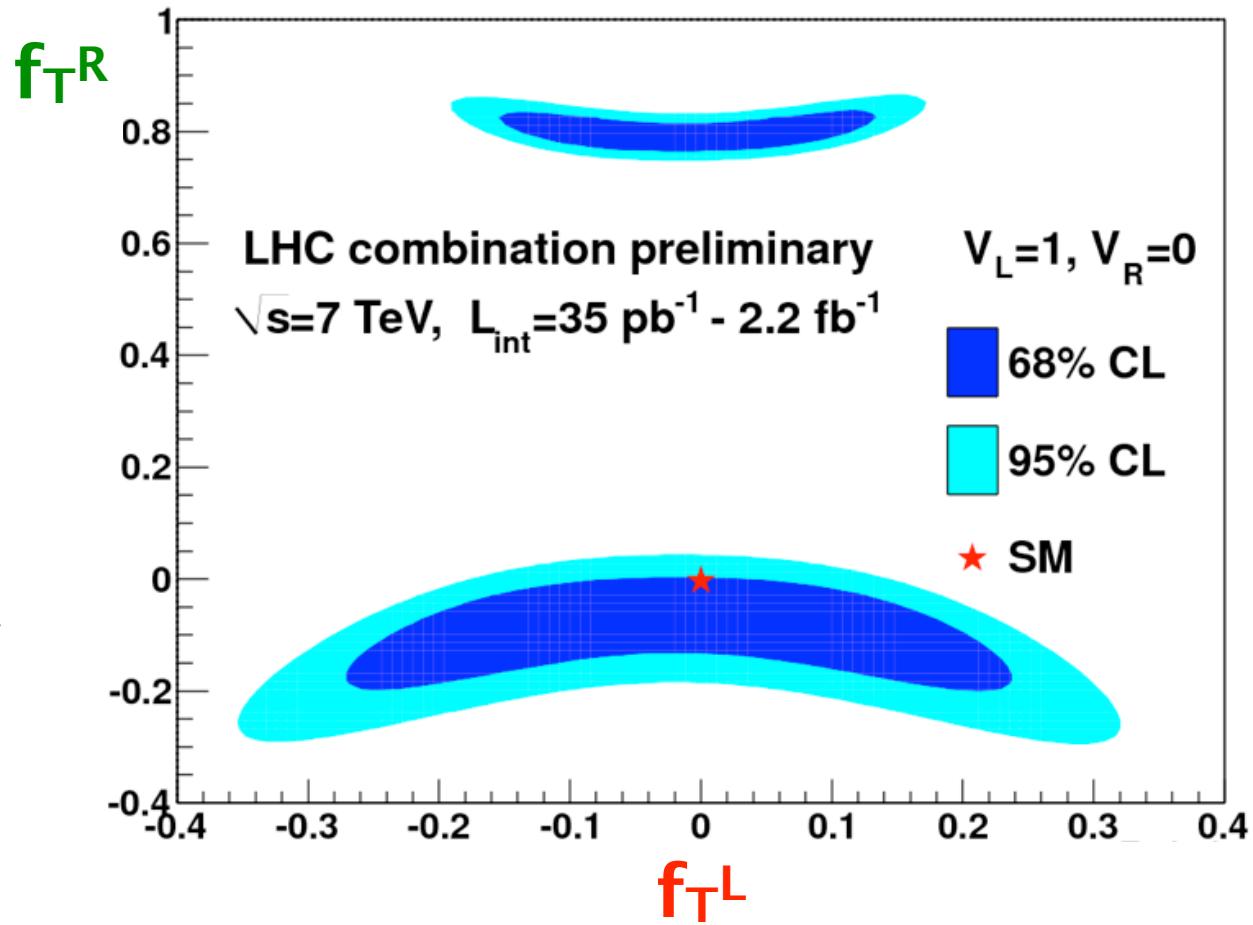
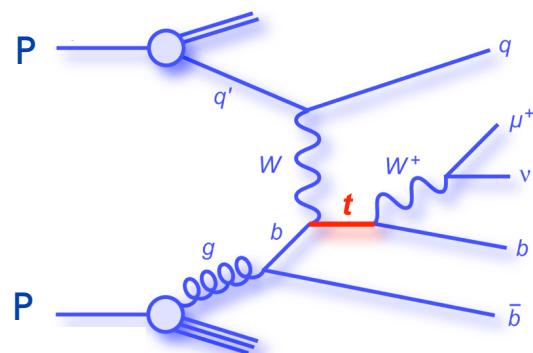


Search for Anomalous Wtb Couplings

= 1 in SM

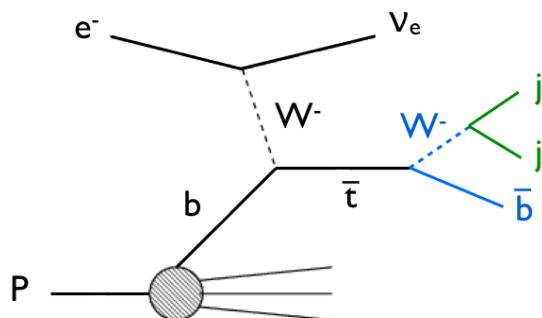
$$L = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} \left(f_V^L P_L + f_V^R P_R \right) t W_\mu^-$$

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



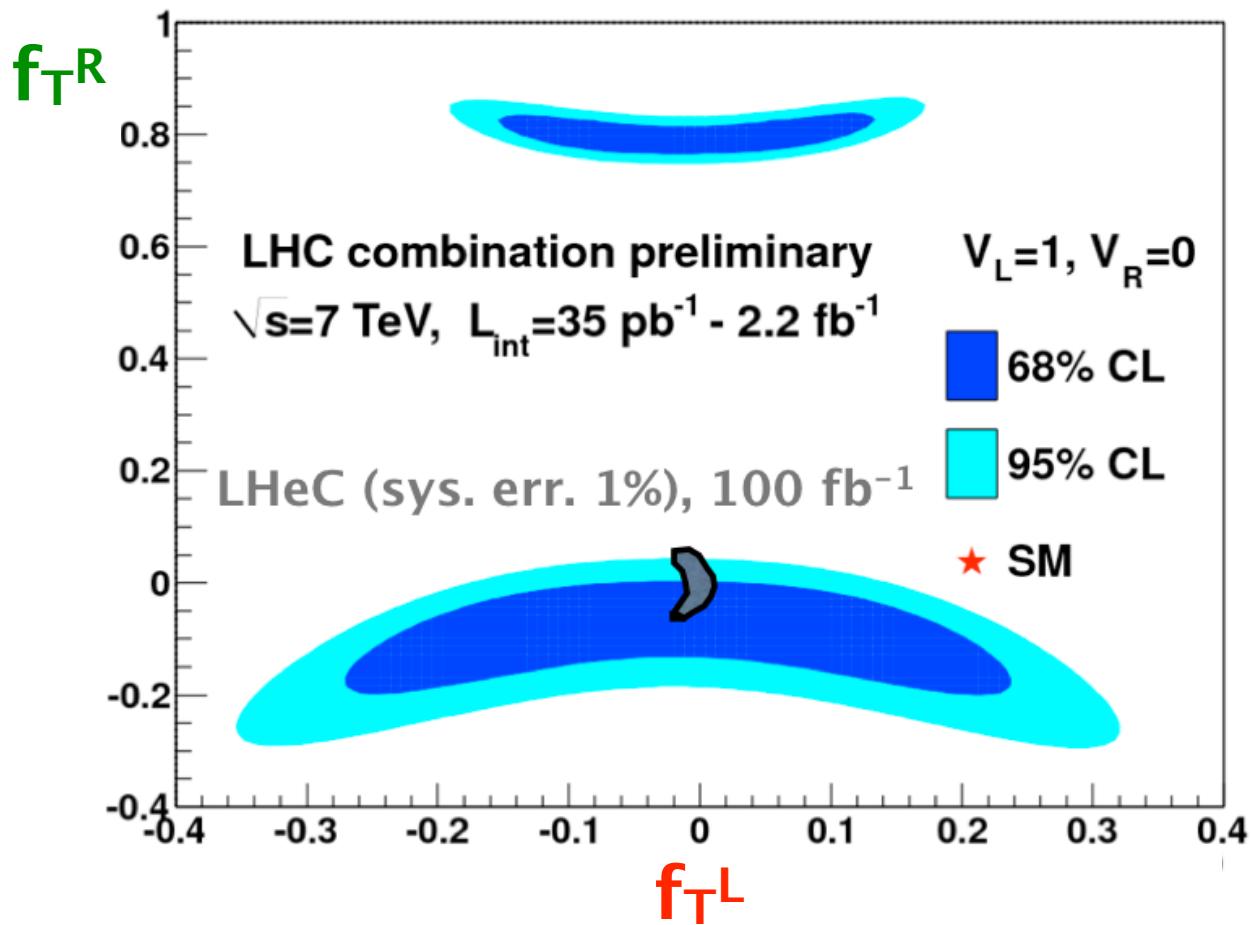
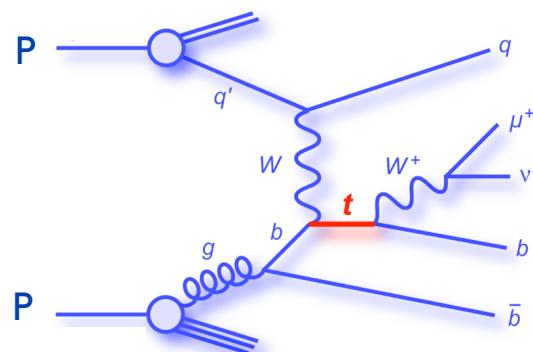
Search for Anomalous Wtb Couplings

= 1 in SM

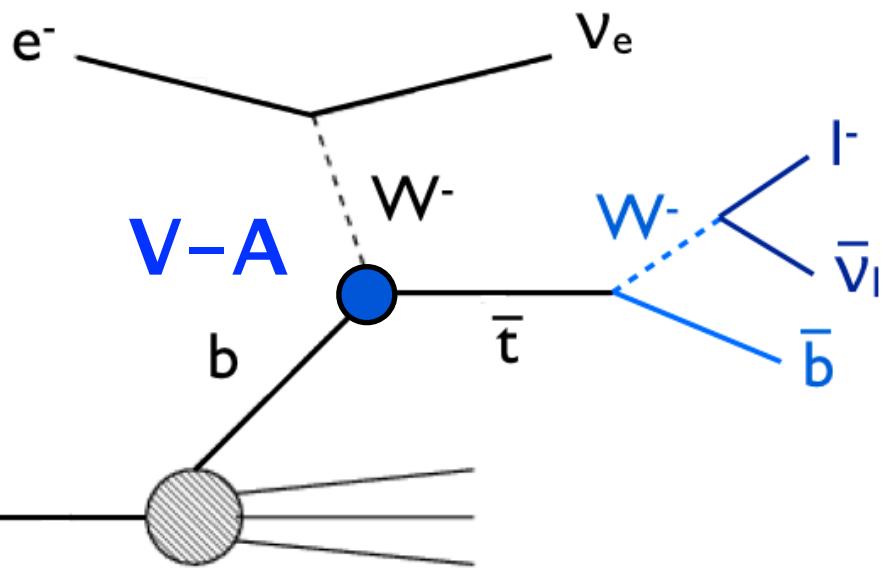


$$L = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} \left(f_V^L P_L + f_V^R P_R \right) t W_\mu^-$$

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



Top Quark Polarisation



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

TESLA+HERAp:

$\sqrt{s}=1.6 \text{ TeV}$

$L_{\text{int}}=20 \text{ fb}^{-1}$



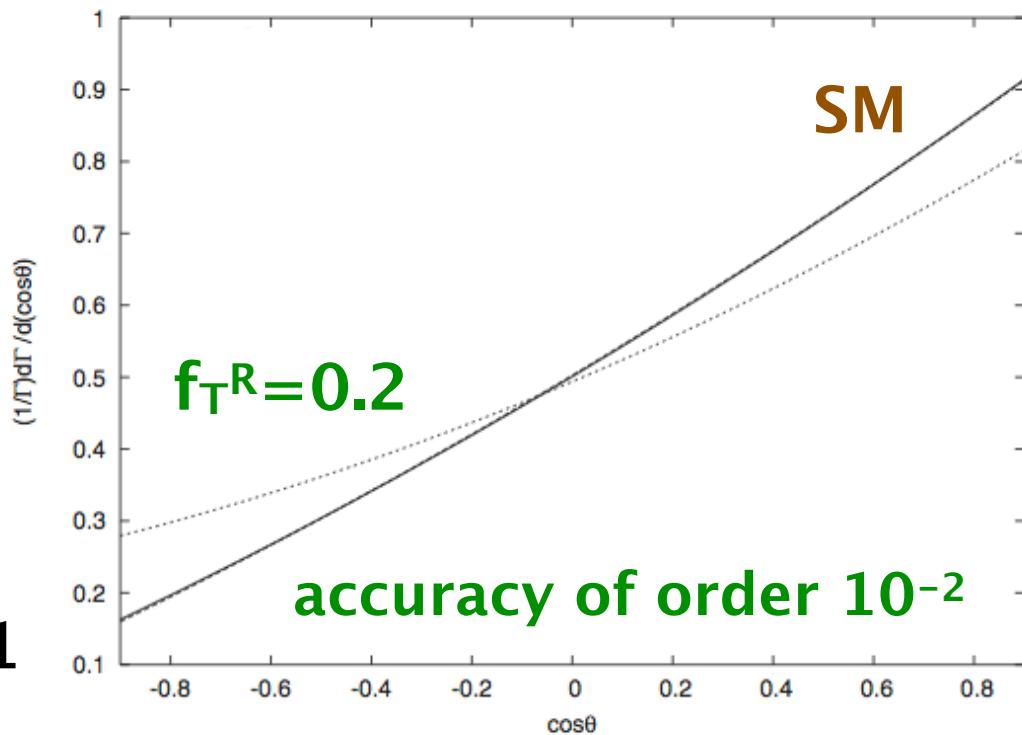
19.7 fb^{-1} : $A_{\uparrow\downarrow} = 0.26 \pm 0.11$

JHEP 04 (2016) 073

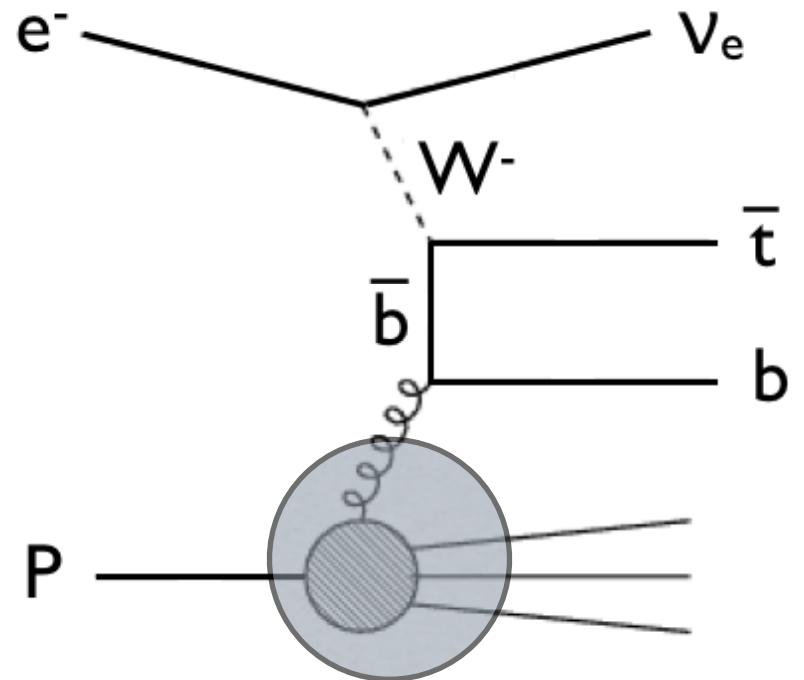
Atag, Sahin,
PRD 73, 074001 (2006)

$\cos\theta$: angle between charged lepton and spin quantisation axis in top rest frame

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



Gluon Parton Density Function



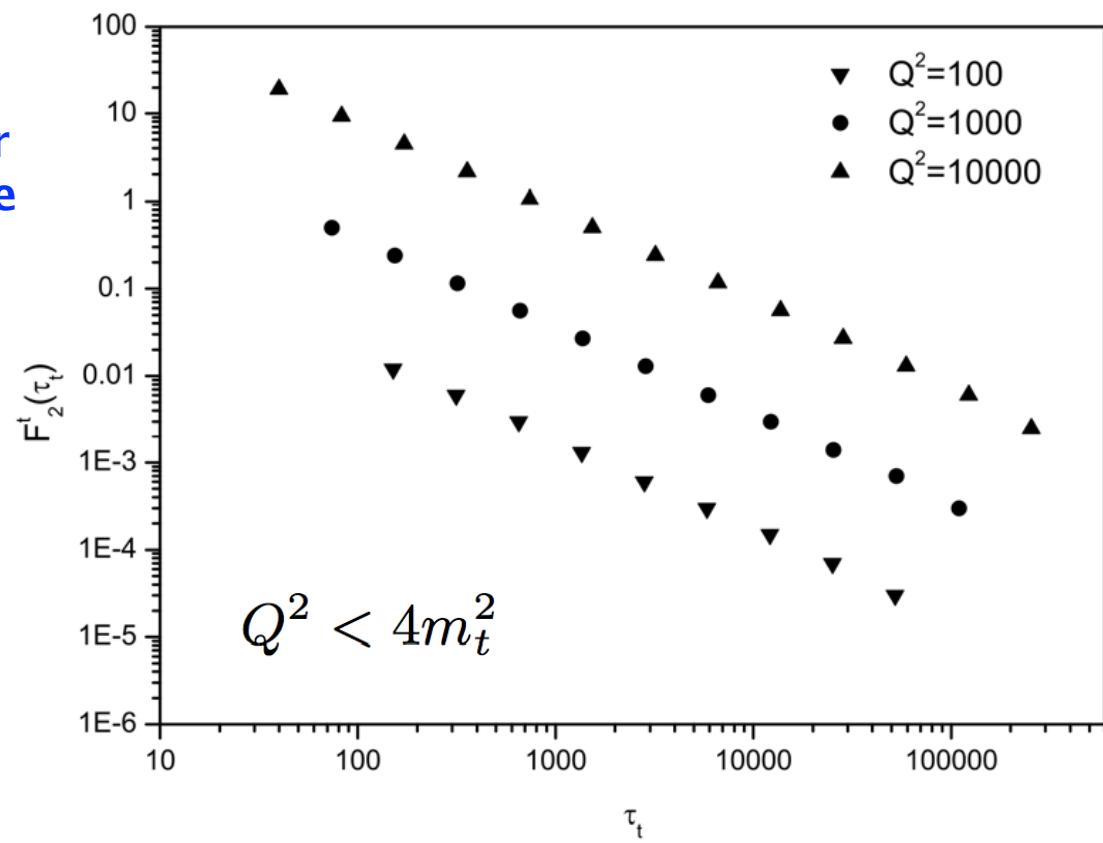
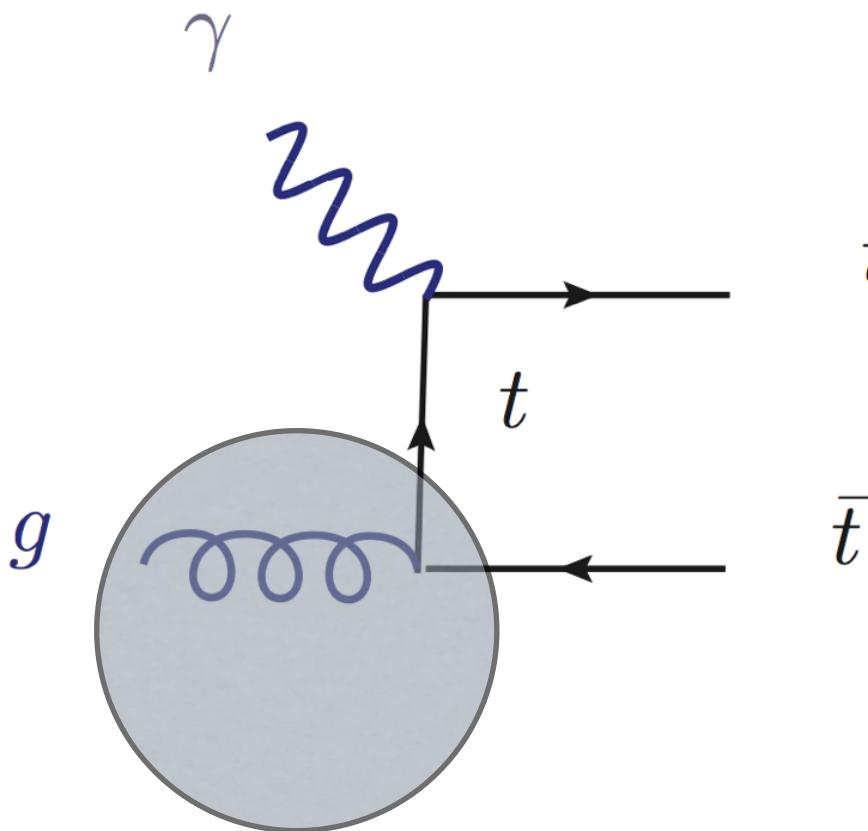
→ measure gluon density at high x

Top Quark Structure Function

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

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

variable flavour
number scheme
for top quark



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

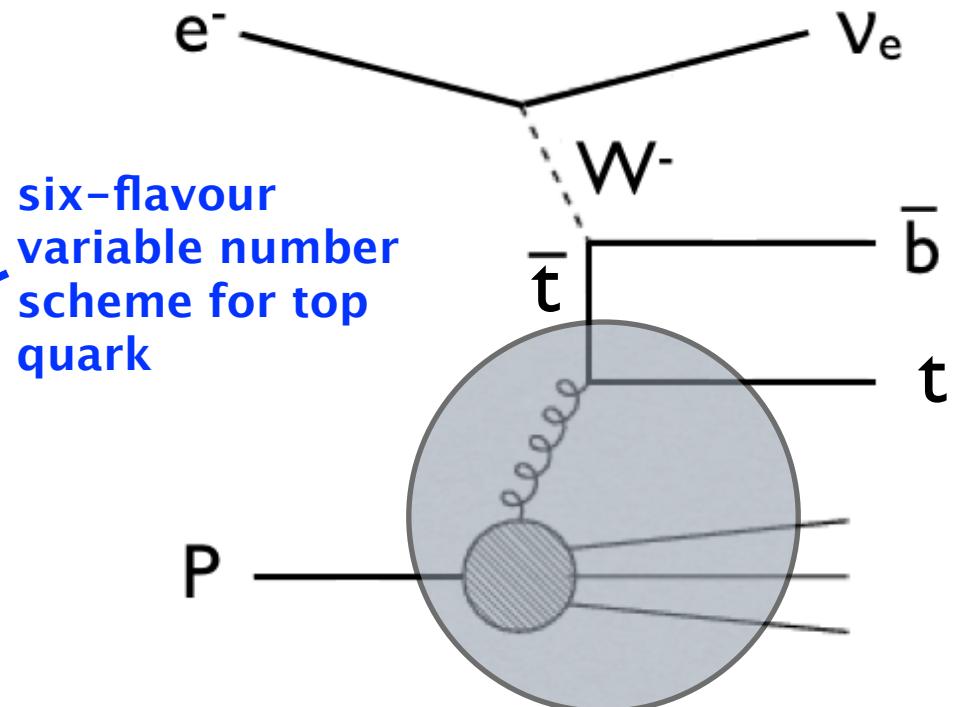
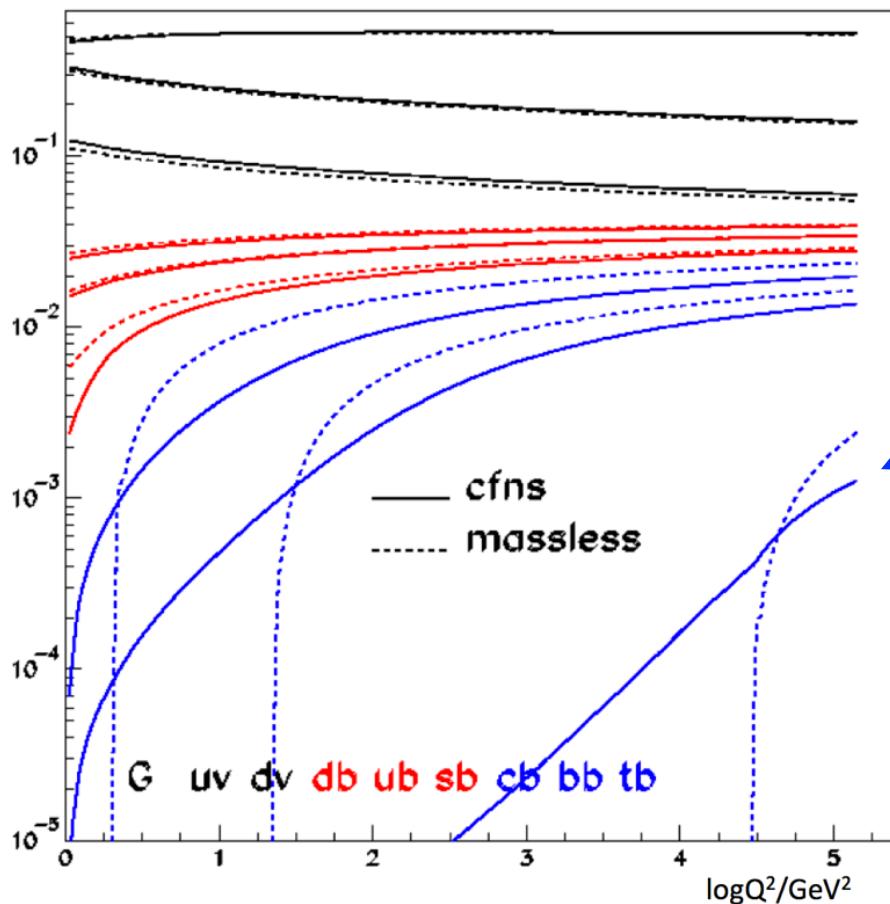
$$x = x_B \left(1 + \frac{4m_t^2}{Q^2}\right)$$

→ LHeC opens up a new field of top quark PDFs

Top Quark Parton Density Function

parton momentum fraction

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



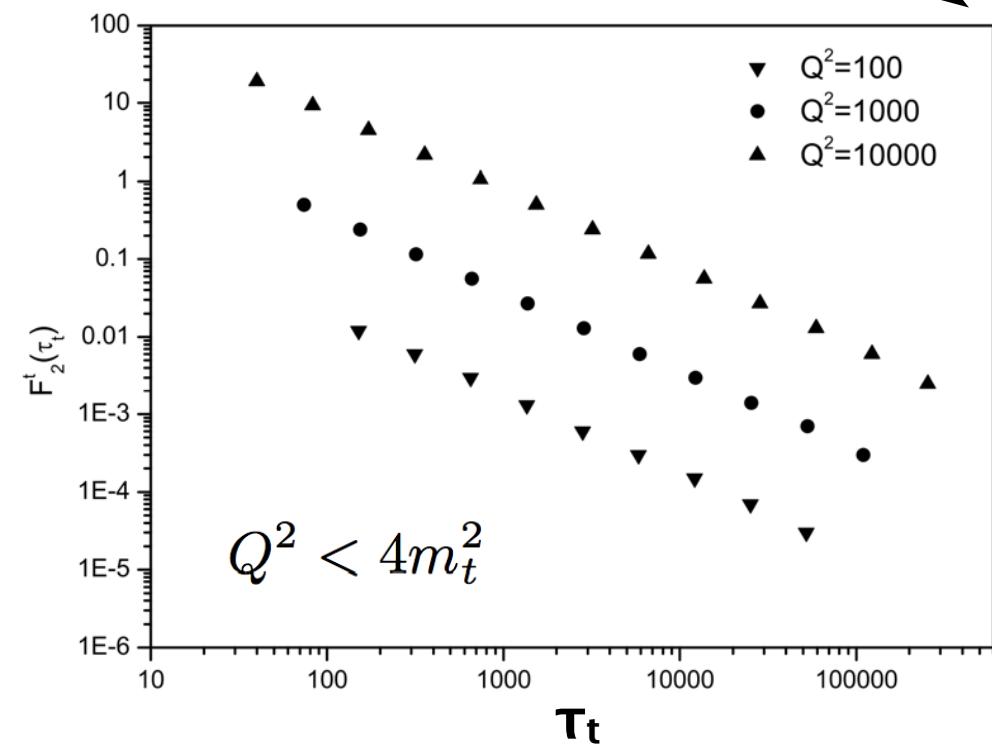
→ LHeC offers new field of research for top quark PDF

Top Quark Structure Function

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

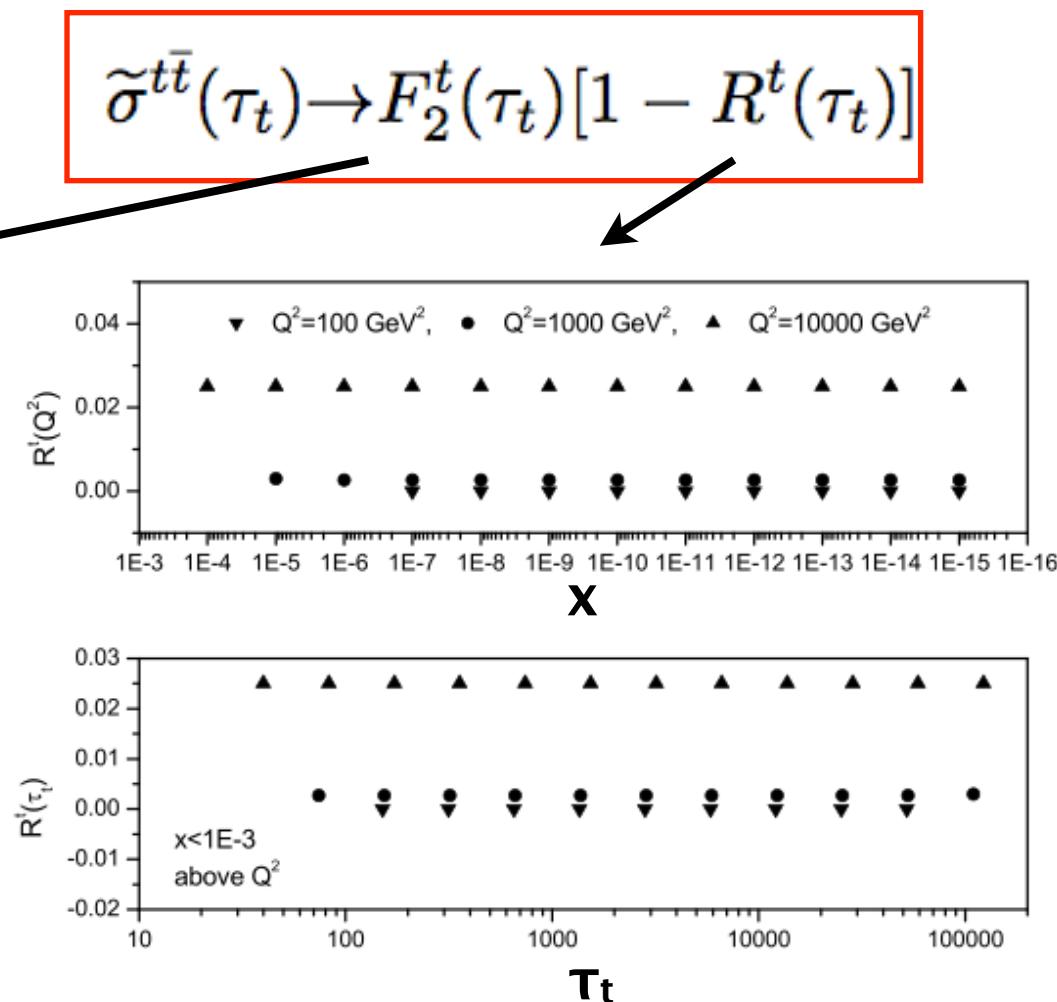
variable flavour
number scheme
for top quark

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



→ approximately: $1/\tau_t$

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



→ independent of x and τ_t

NC Top Quark Production

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

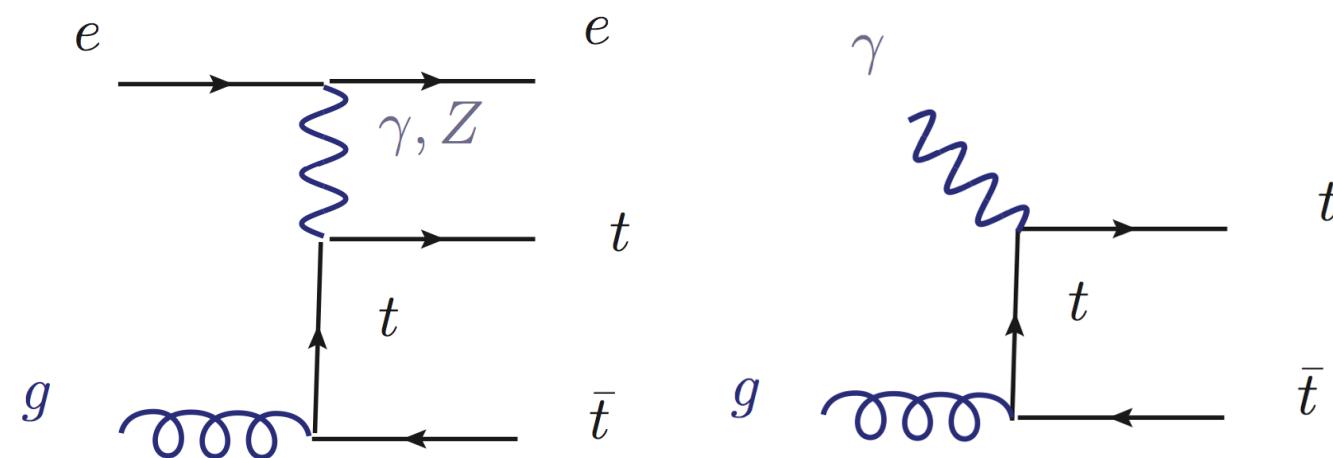
top pair production

single top production

DIS

photoproduction

photoproduction



e-beam 60 GeV, 100 fb⁻¹:

0.023 pb

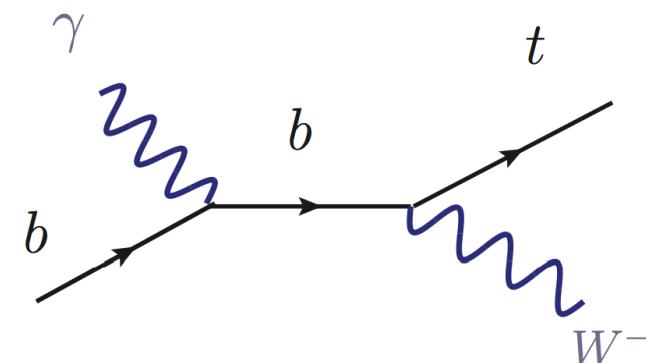
$N_{t\bar{t}}=2,300$

0.70 pb

$N_{t\bar{t}}=70,000$

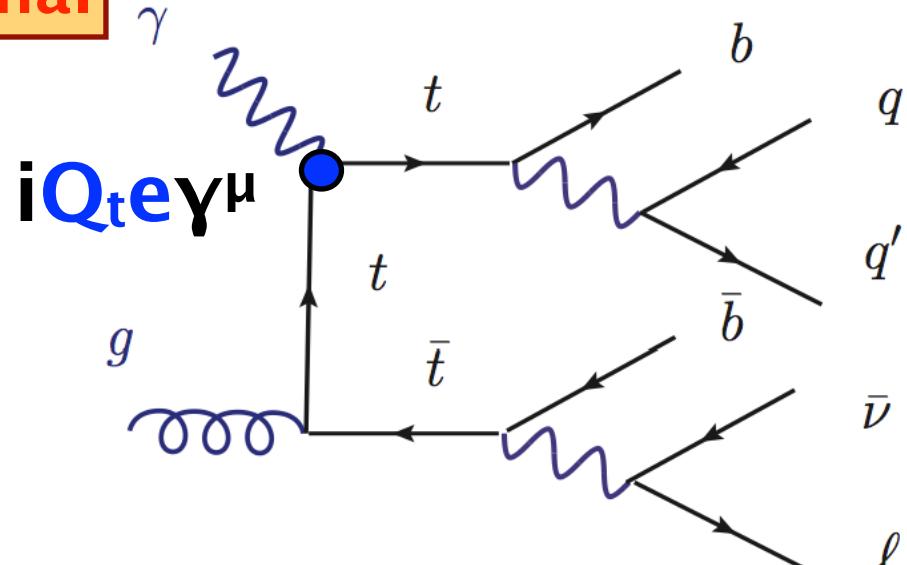
0.031 pb

$N_t=3,100$



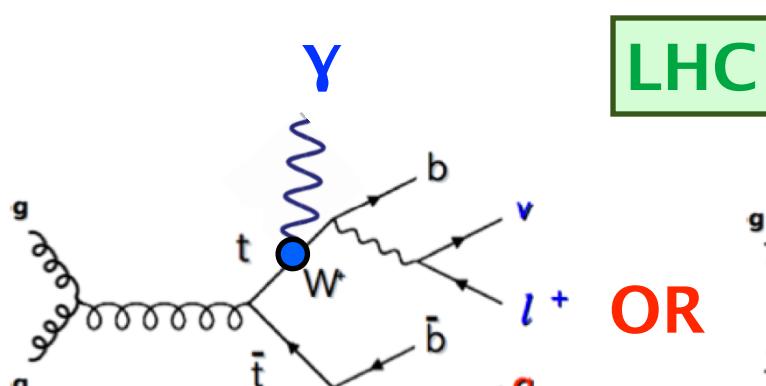
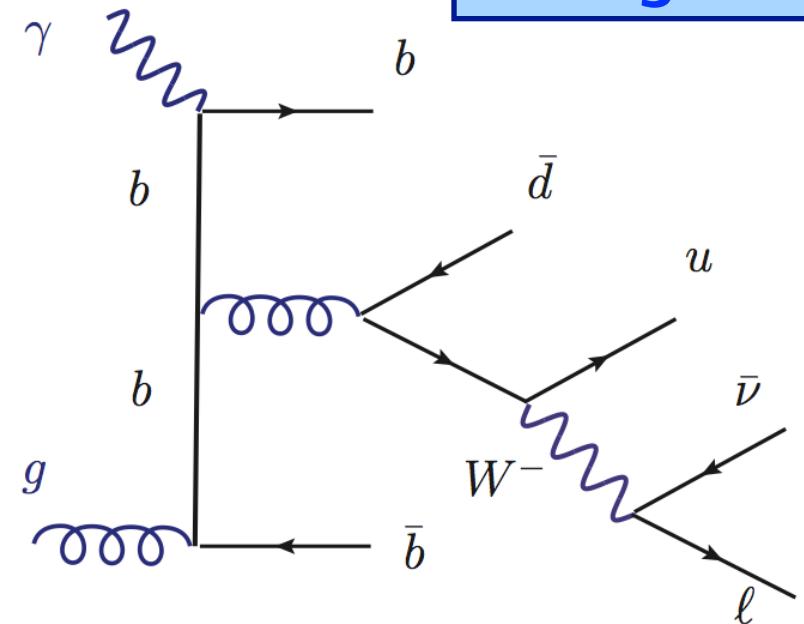
Analysis of the $t\bar{t}\gamma$ Vertex

signal



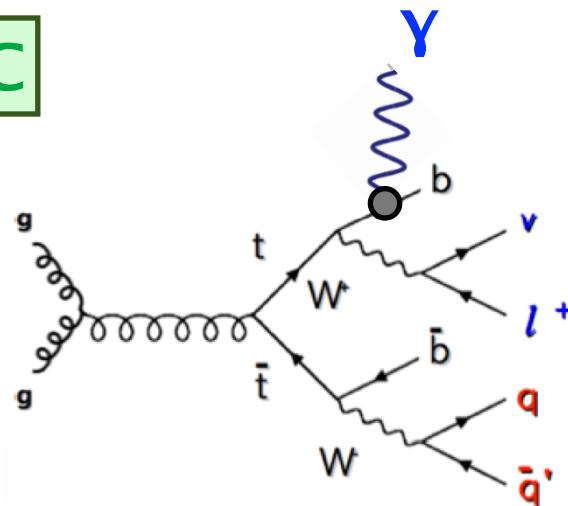
→ measure top quark charge

background



LHC

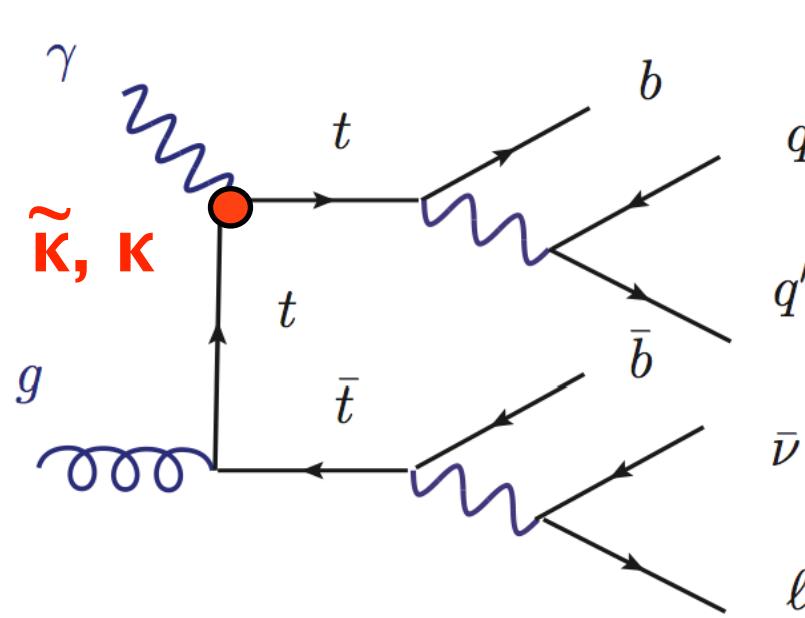
OR



?

→ difficult at the LHC

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



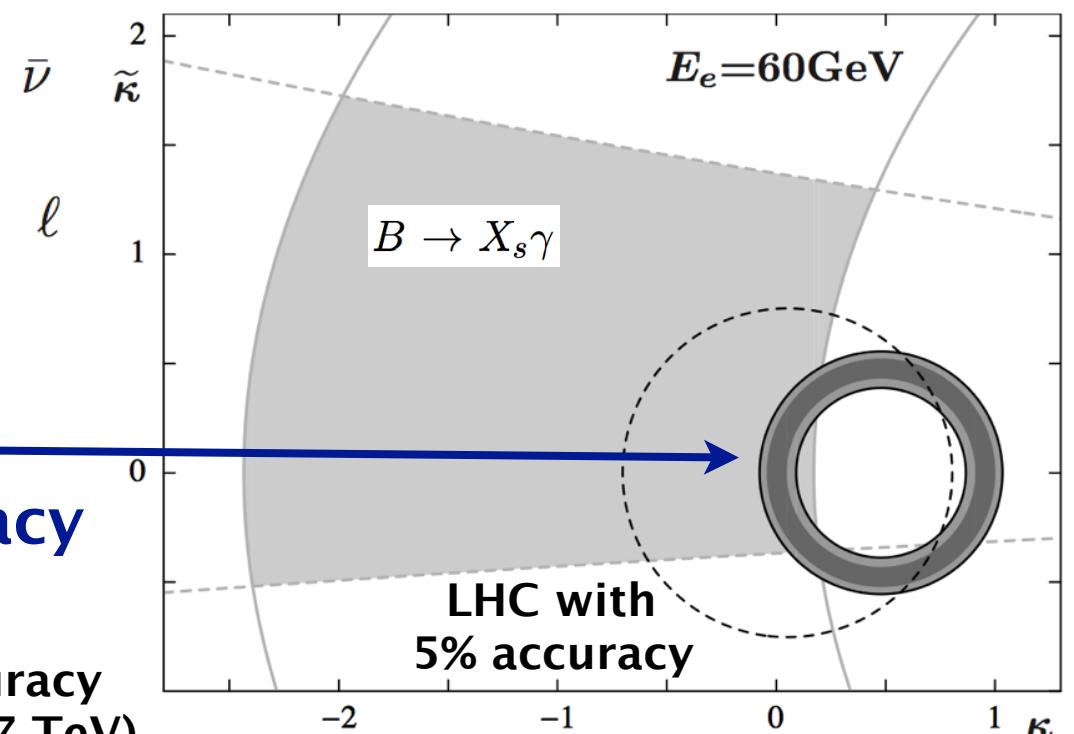
$$\mathcal{L}_{t\bar{t}\gamma} = e\bar{t} \left(Q_t \gamma^\mu A_\mu + \frac{1}{4m_t} \sigma^{\mu\nu} F_{\mu\nu} (\kappa + i\tilde{\kappa}\gamma_5) \right) t$$

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

LHeC:
10% and 18% accuracy



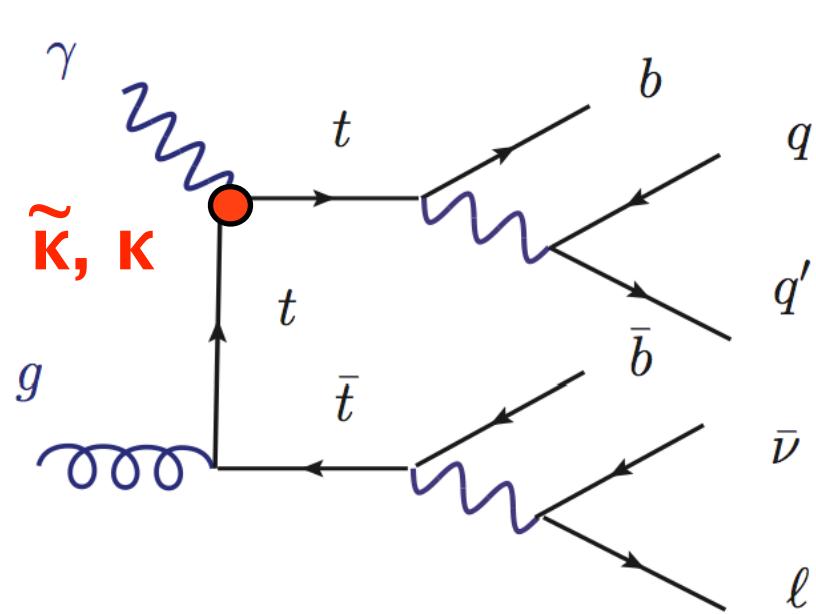
27% accuracy
(4.59fb^{-1} , 7 TeV)



magnetic dipole moment: κ

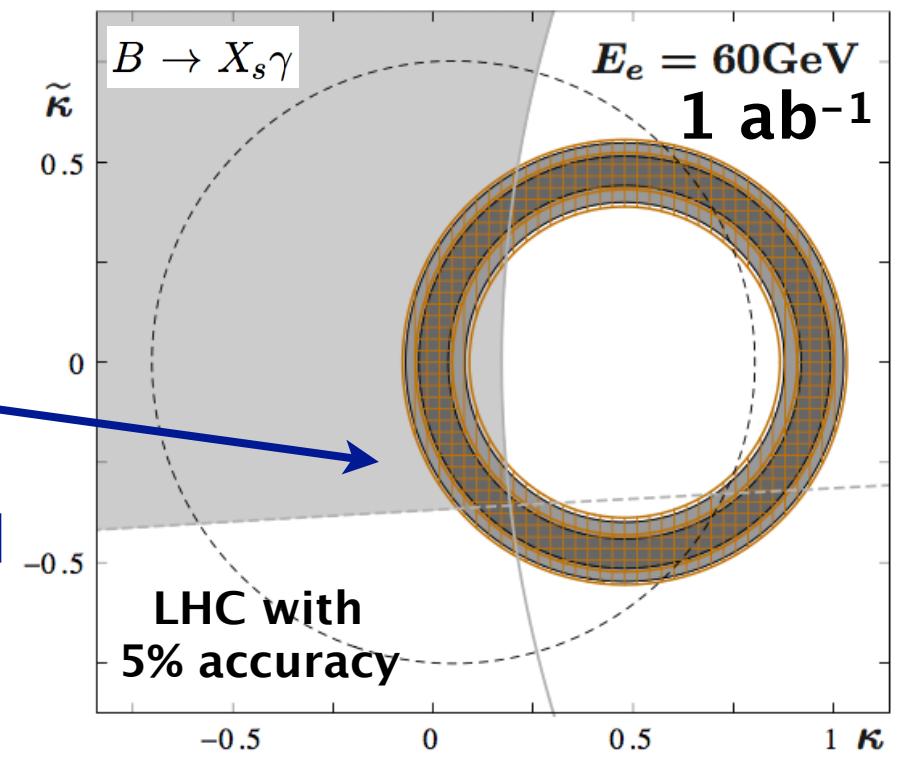
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

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



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

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



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



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

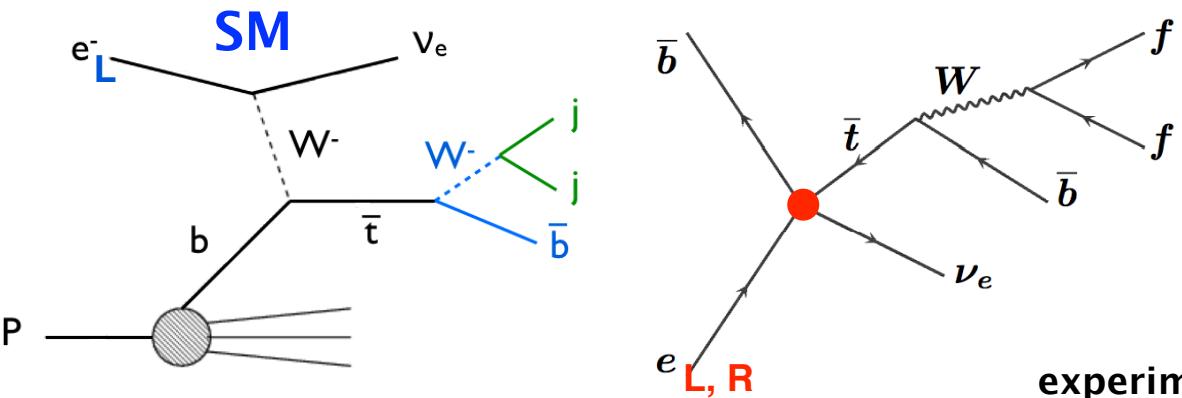
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

magnetic dipole moment: κ

Top Quark Dimension 6 Operators

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

$\Lambda=1\text{TeV}$



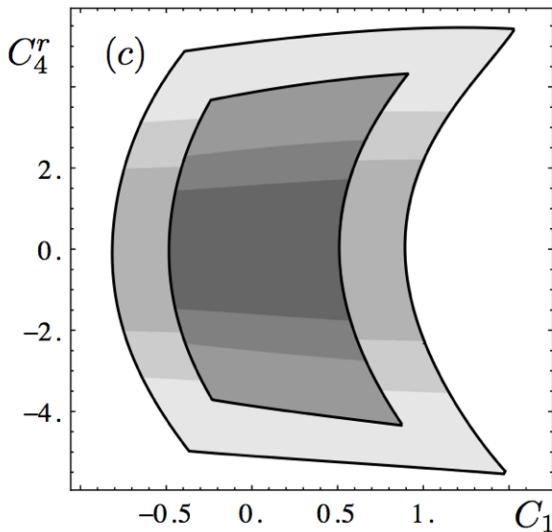
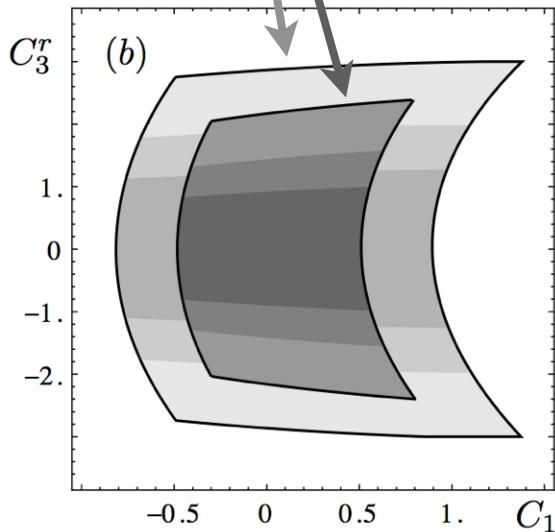
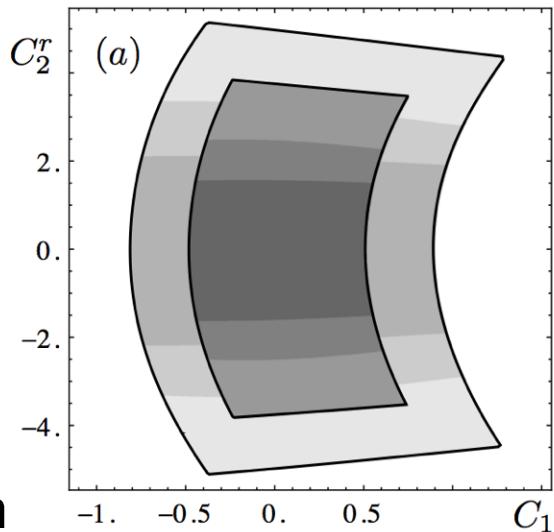
Sarmiento-Alvarado,
Bouzas, Larios,
arXiv:1412.6679

$$\mathcal{P}_e = 0$$

$$\mathcal{P}_e = 0.4$$

$$\mathcal{P}_e = 0.7$$

cross section

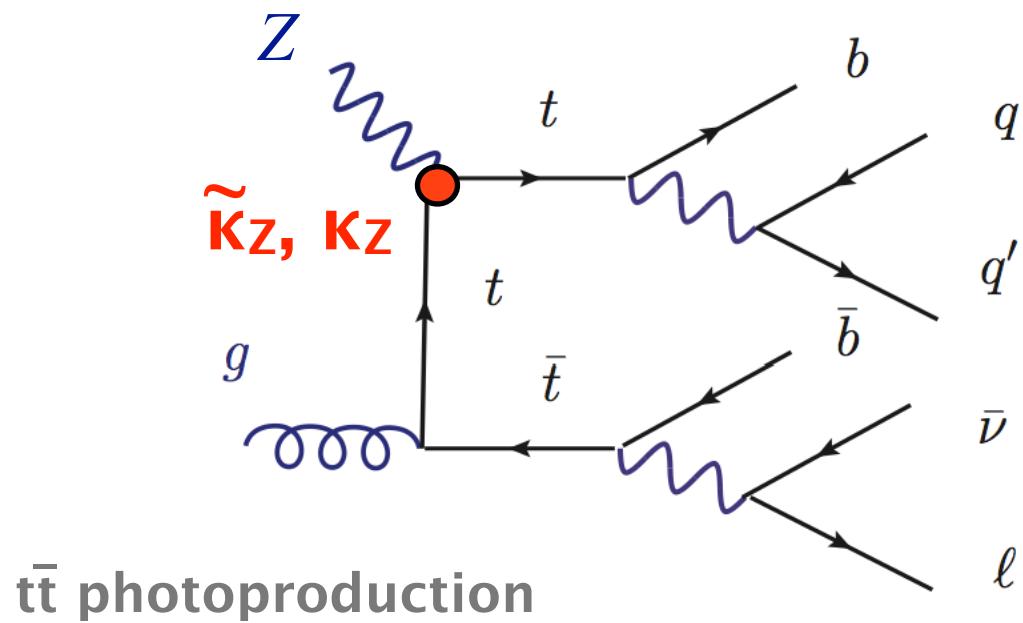


experimental error

68% C.L.

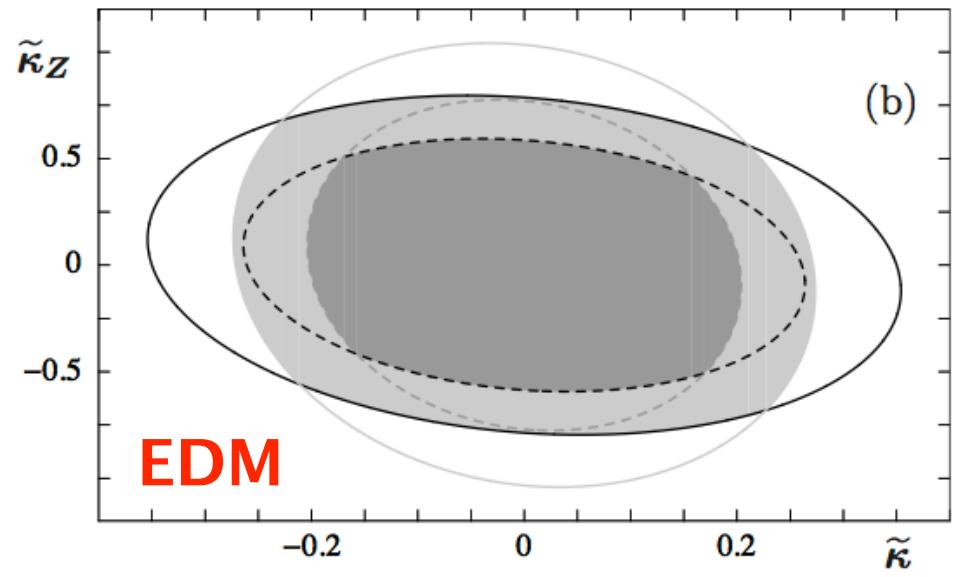
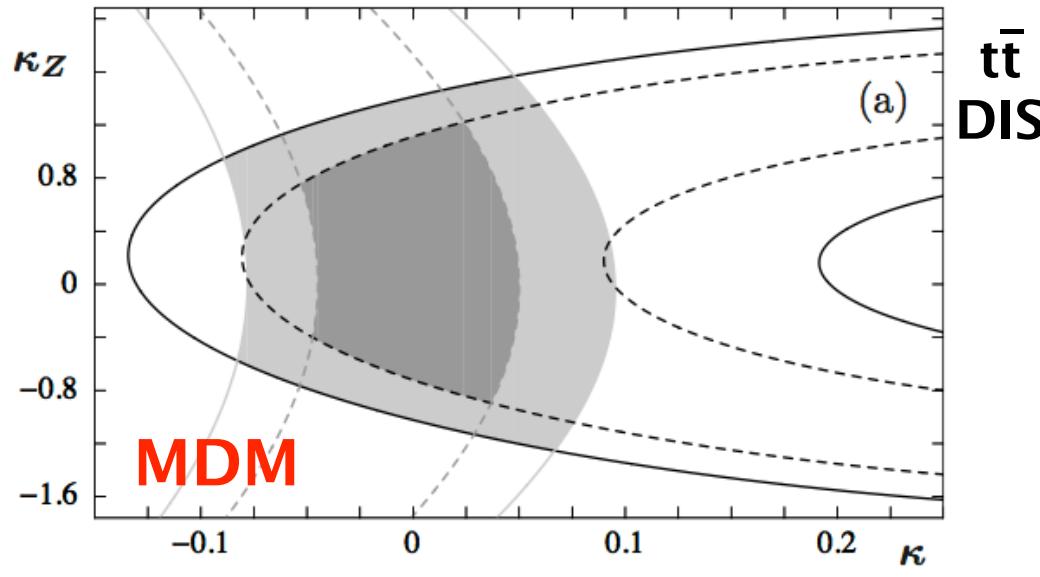
property	precision
C_1	0.50–0.85
C_2^r	2.2–5.0
C_3^r	1.4–2.9
C_4^r	2.2–4.9

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



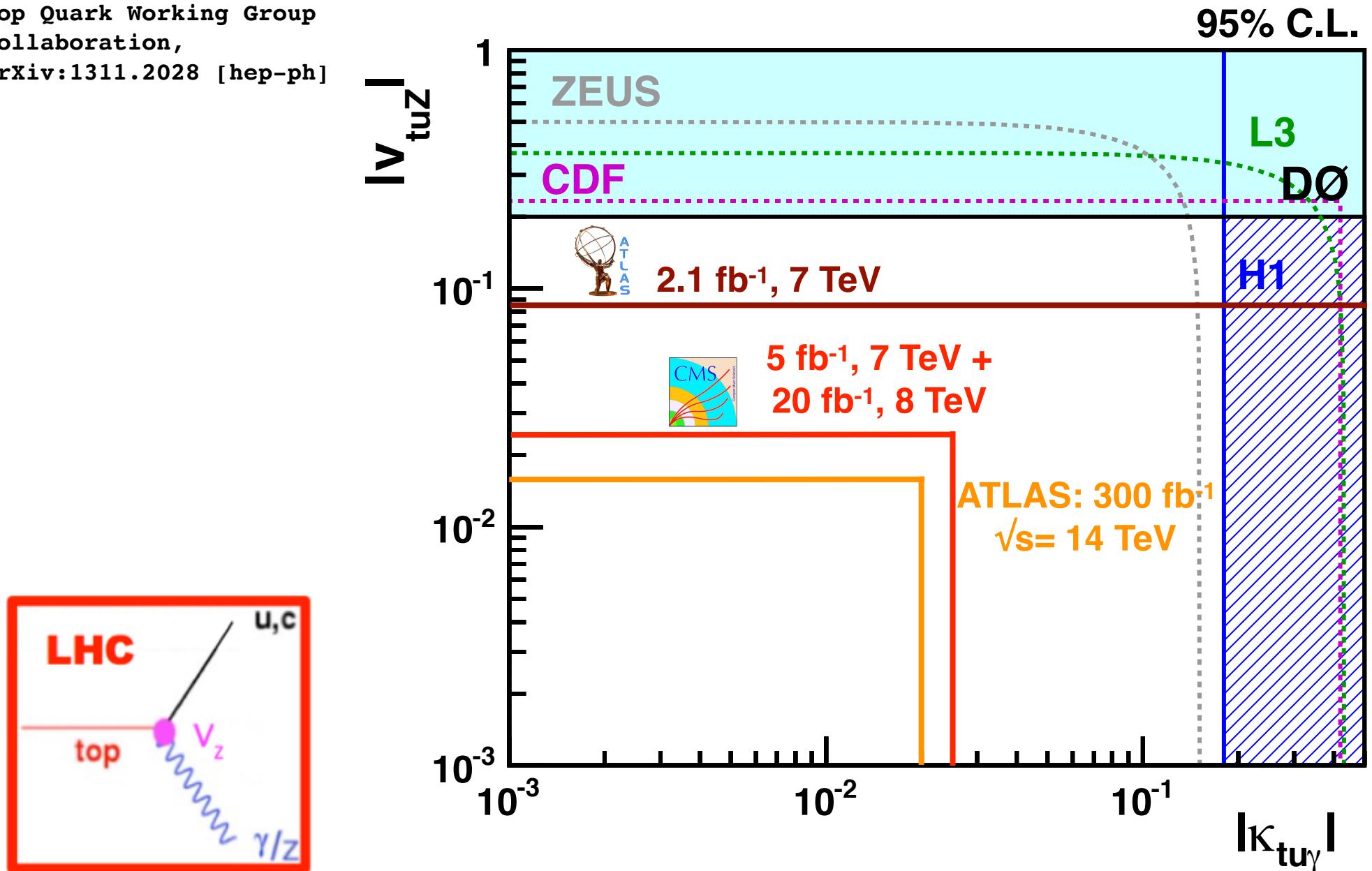
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

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

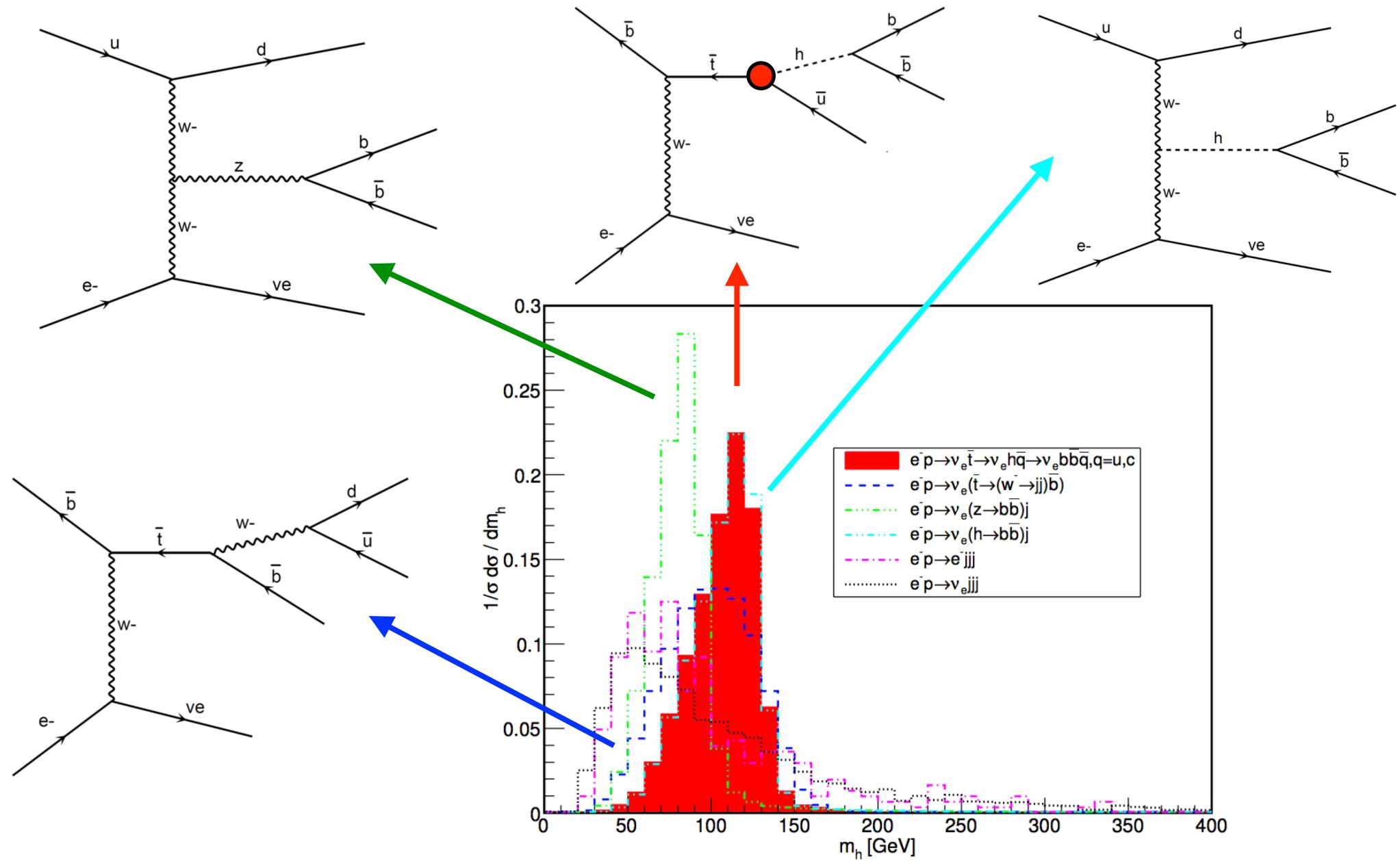


FCNC Top Couplings at Colliders

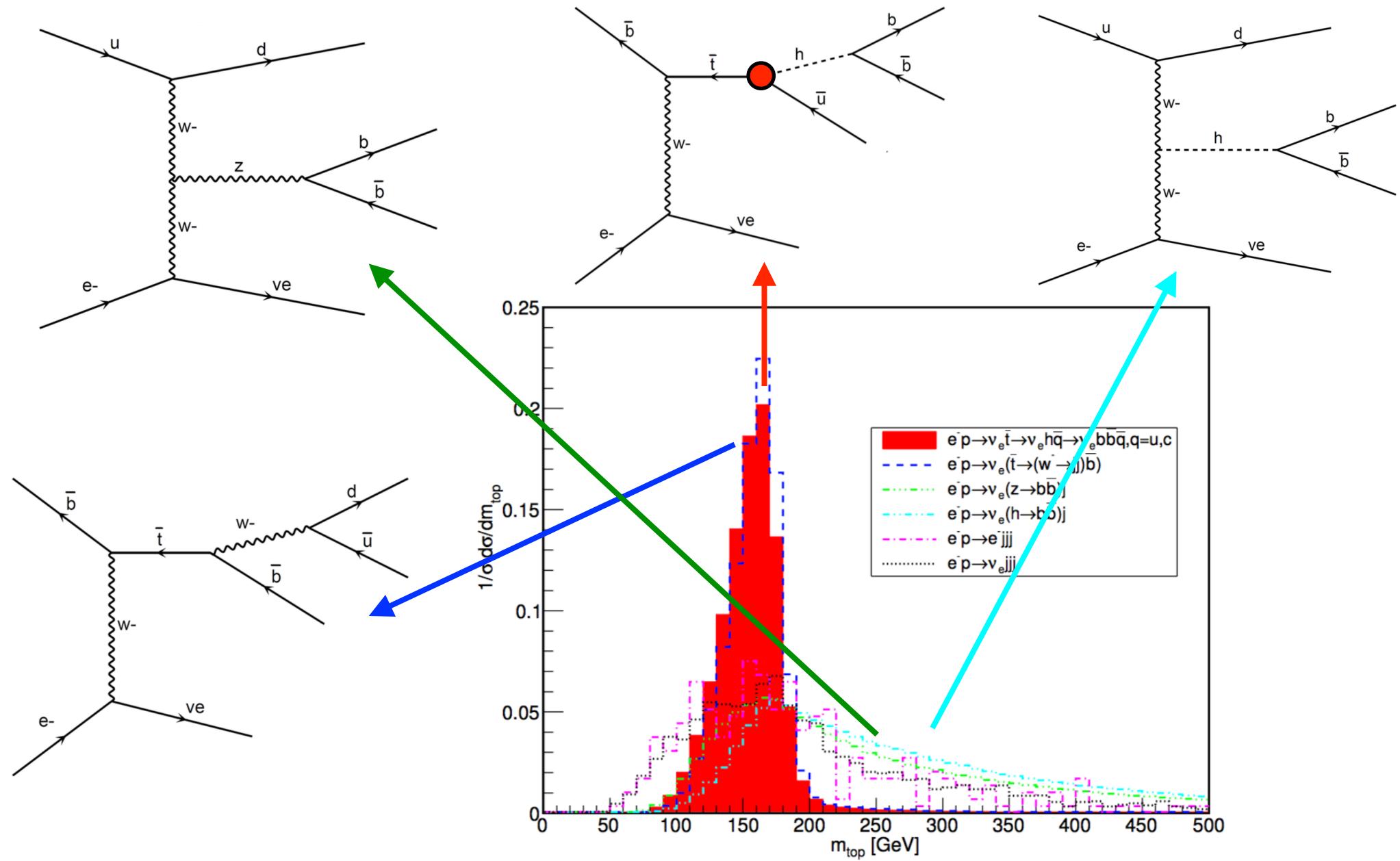
Top Quark Working Group
Collaboration,
arXiv:1311.2028 [hep-ph]



Reconstructed Higgs mass



Reconstructed top quark mass



Searches for RPV SUSY and stops

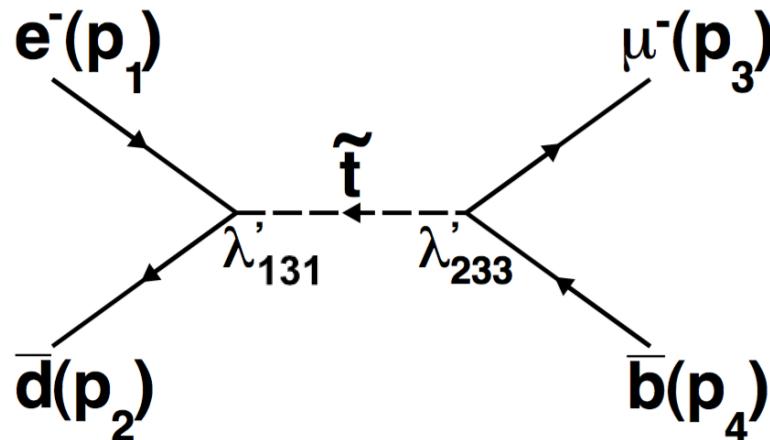
$$W_{Rp} = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^C + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k^C + \epsilon_i \hat{L}_i \hat{H}_u + \lambda''_{ijk} \hat{U}_i^C \hat{D}_j^C \hat{D}_k^C$$

L-number violating terms

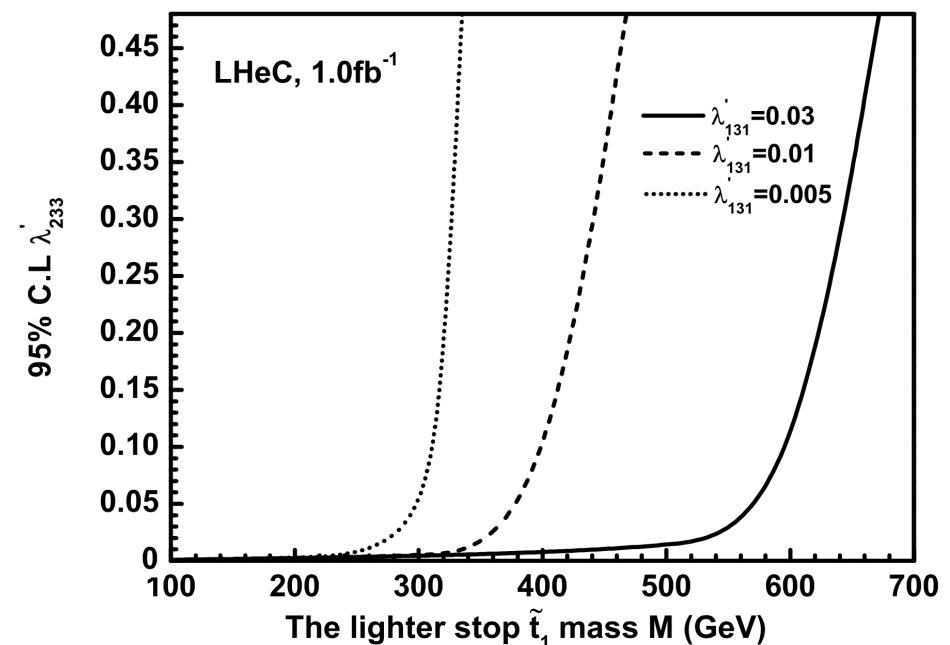
bilinear terms

B-number violating terms

$\Delta L = 1, 9 \lambda$ couplings, $27 \lambda'$ couplings



similar to leptoquark searches
with generation mixing



→ very promising with high luminosity

→ RPV can be probed at unprecedented levels