Top Quark Physics at FCC

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Deutsches Elektronensynchrotron (DESY)

FCC Week Amsterdam

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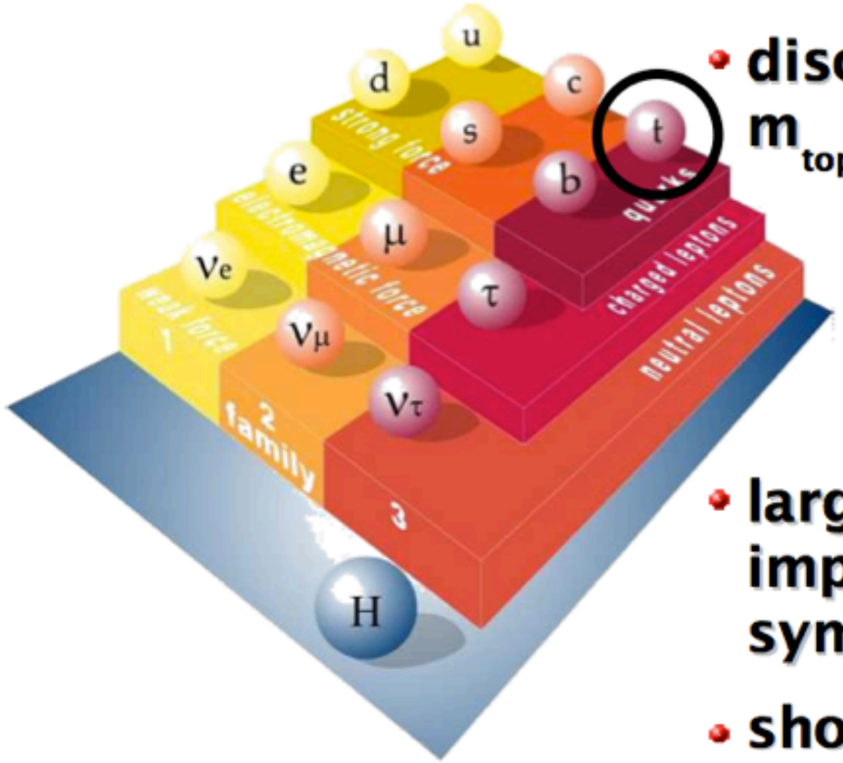
Special thanks to: P. Azzi, P. Janot, M. Klein, M. Mangano

The Top Quark



- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold nucleus
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}\text{s} \ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe "naked" quark

Is the top quark the particle as predicted by the SM?

FCC-ee, FCC-eh and FCC-hh

Energy Recovering Linac

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

operated synchronously

- with HL-LHC:
  p beam: 7 TeV, √s=1.3 TeV
- or later with FCC-hh:
  p beam: 50 TeV, √s=3.5 TeV

LHeC

FCC-ep

0.1-2 ab^{-1}

FCC-pp

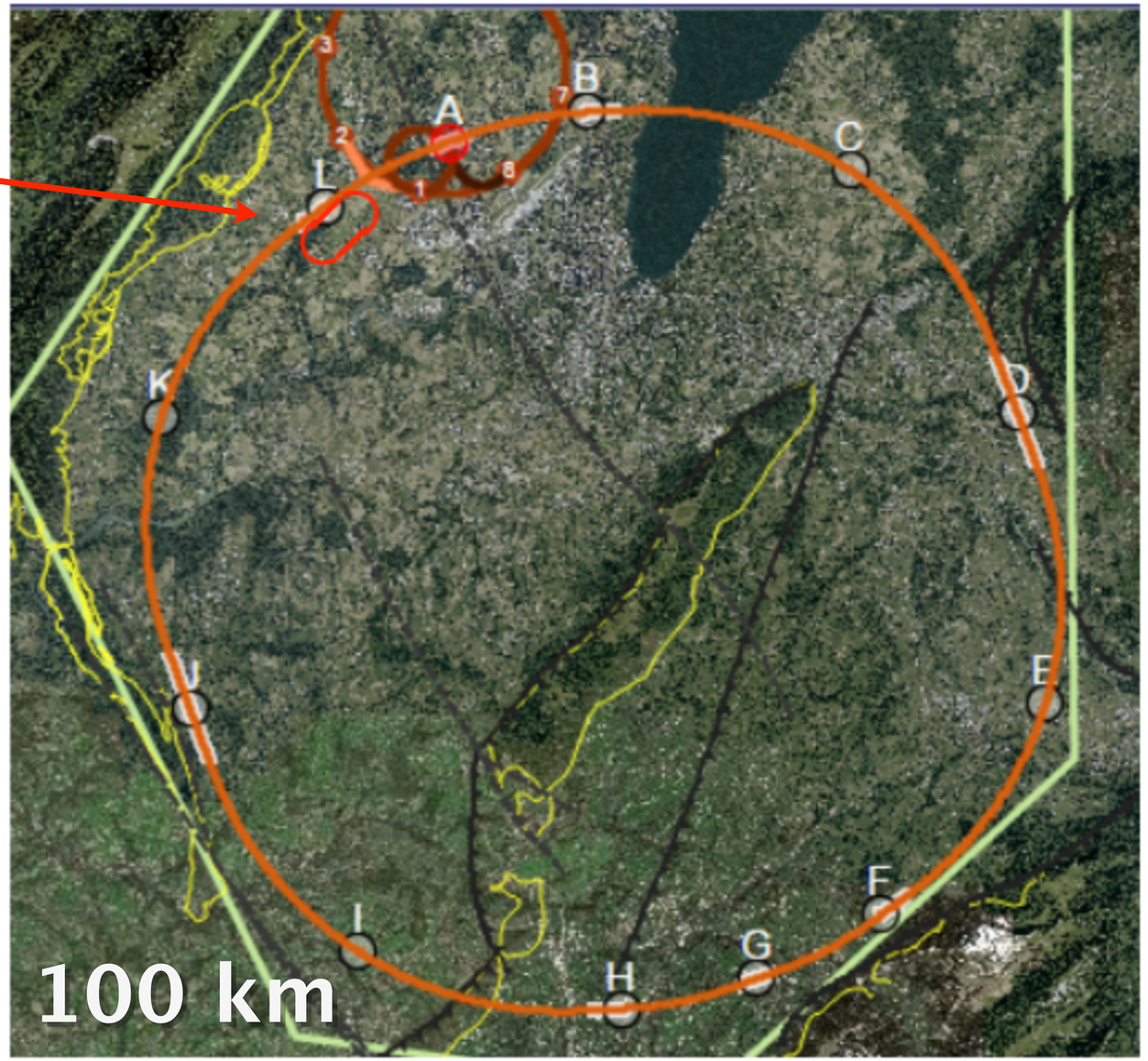
√s=100 TeV

10 ab^{-1}

FCC-ee

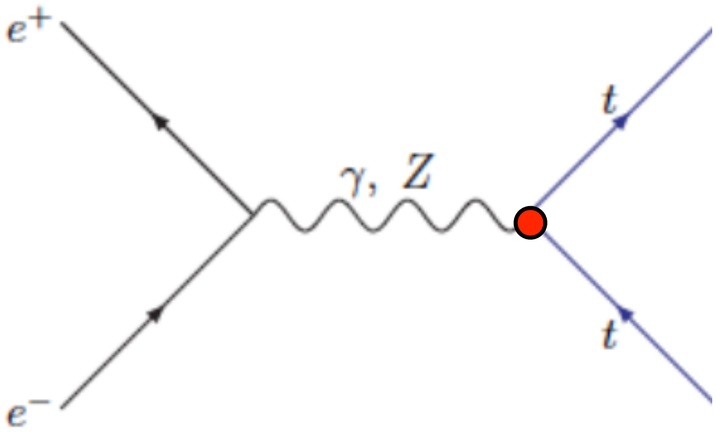
√s varying

0.2-10 ab^{-1}

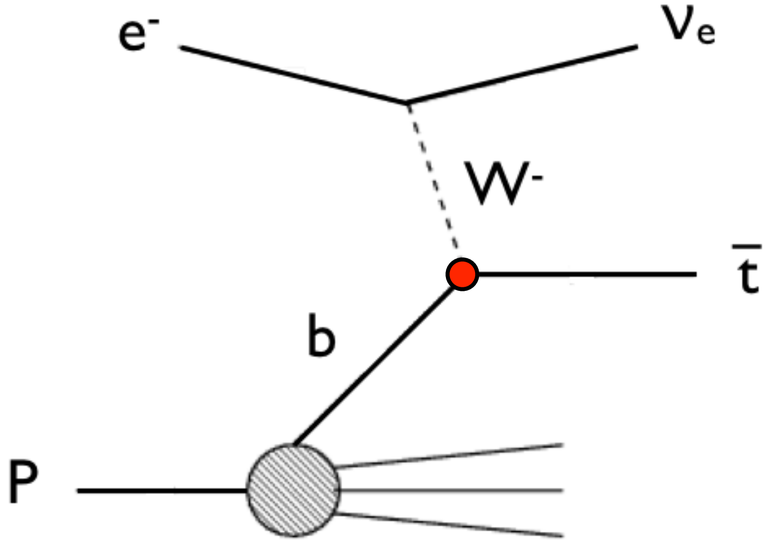


Top Quark Production at FCC-ee, FCC-eh and FCC-hh

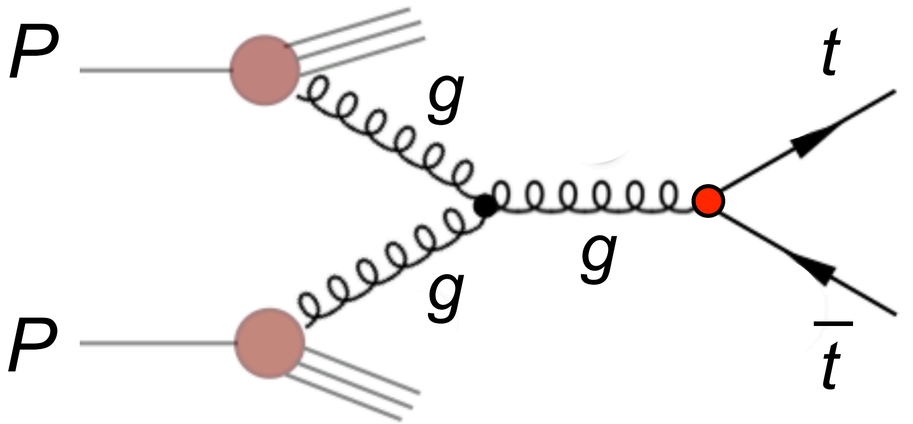
FCC-ee



FCC-ep

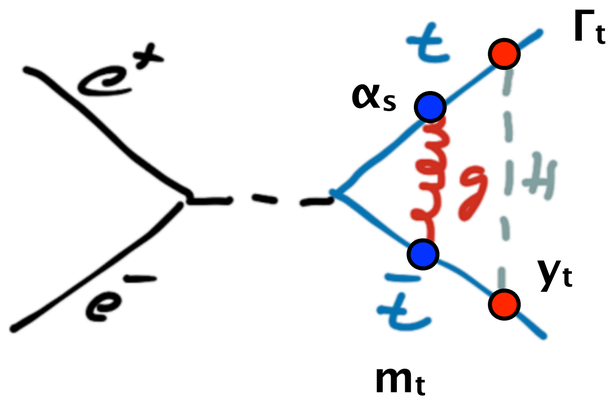


FCC-pp

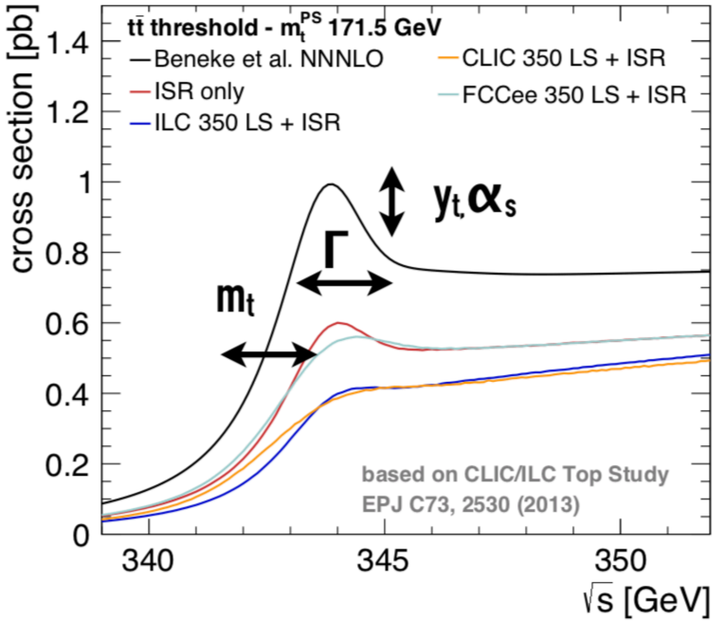


→ **precision measurements of top quark properties**
→ **complementary information**

Top Quark Measurements at Threshold



m_t

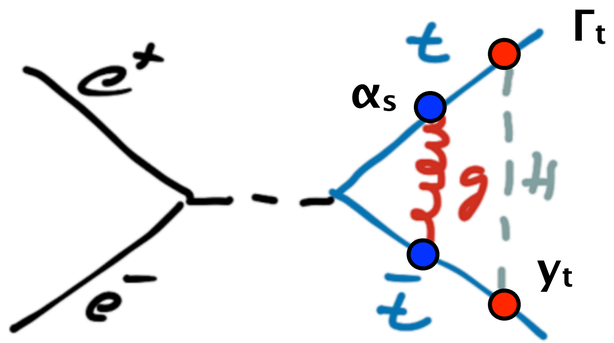


→ **properly defined 1S mass!**

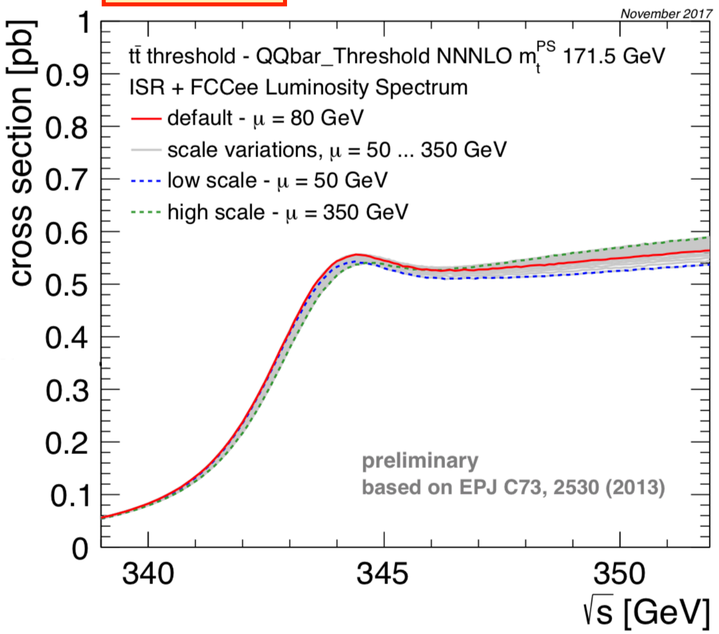
see talk by Patrizia Azzi

Top Quark Measurements at Threshold

F. Simon



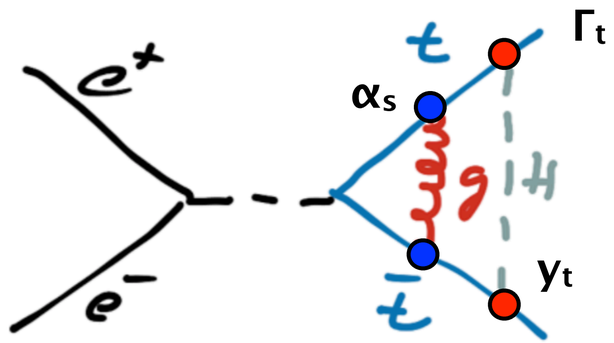
FCC-ee



→ **mass only: 8.8 MeV** (stat), **5.4 MeV** (α_s [2 x 10^{-4}]), **44 MeV** (theo)

full simulation

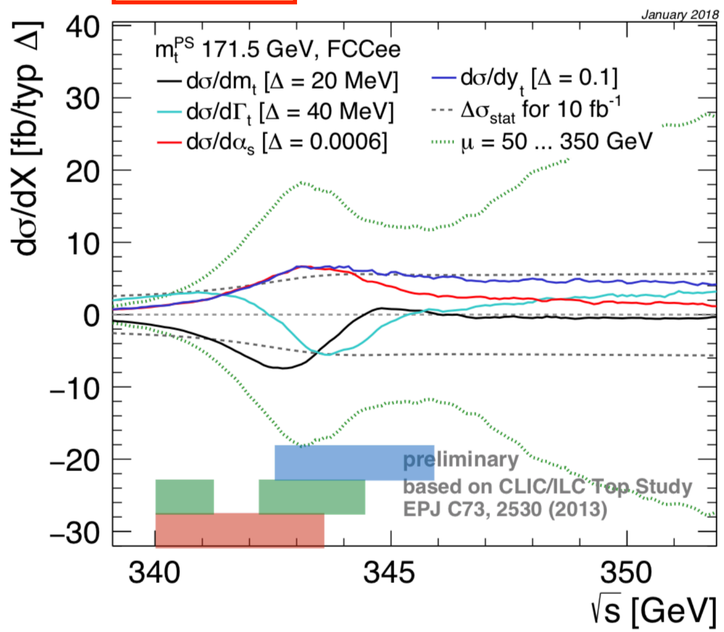
Top Quark Measurements at Threshold



FCC-ee

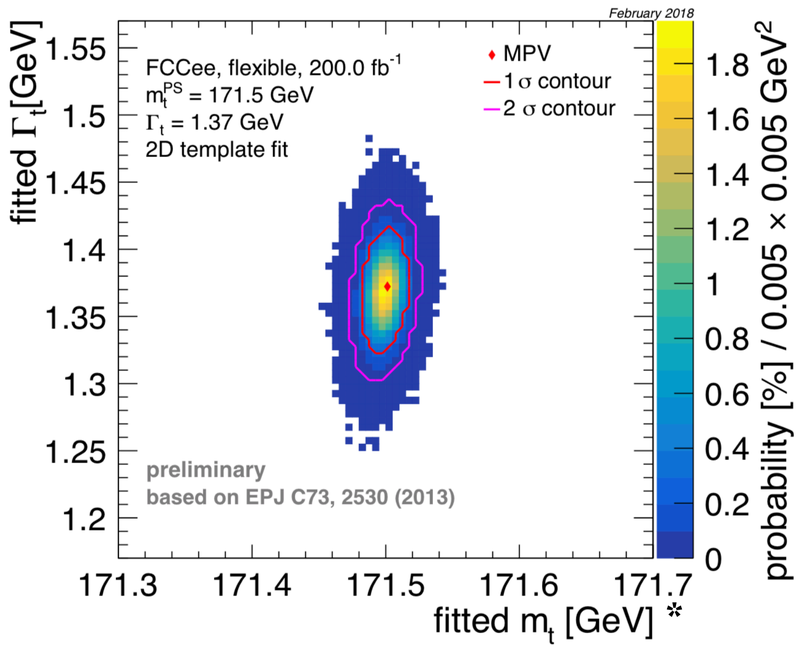
sensitivity to:

- mass
- width
- Yukawa



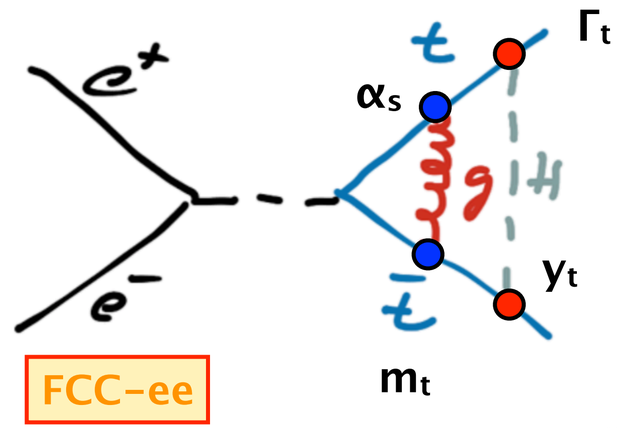
→ **threshold scan under investigation**

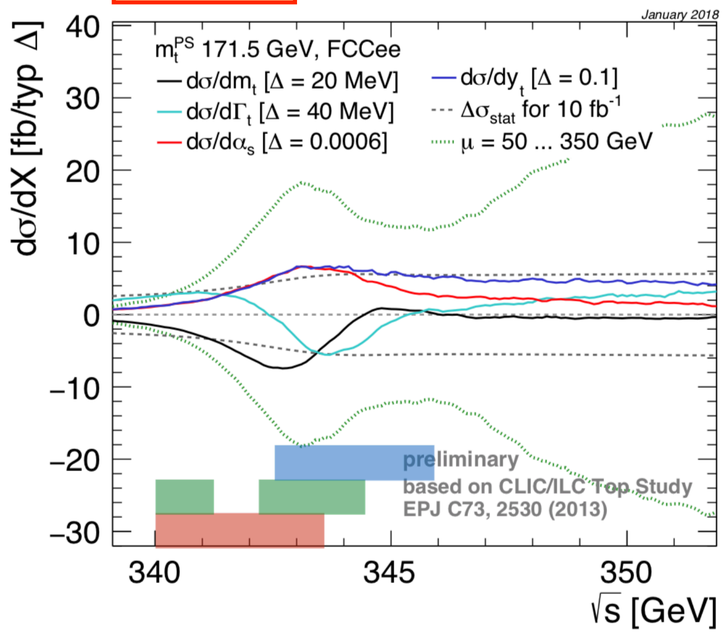
Top Quark Measurements at Threshold

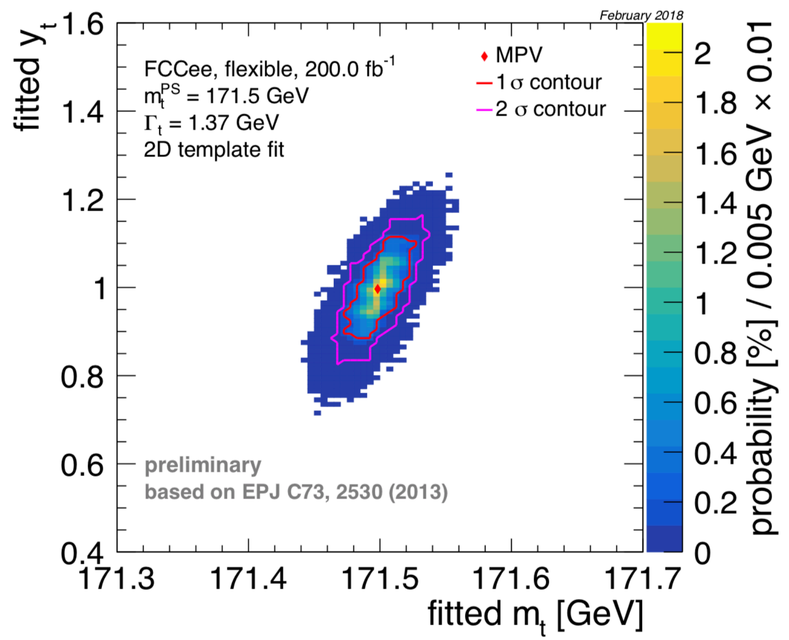


Extension of 1σ contour:
mass: +16.6 MeV, -18.8 MeV
width: +45 MeV, -50 MeV
Theory uncertainty (symm.):
mass: 45 MeV; width: 36 MeV

sensitivity to:
- mass
- width
- Yukawa







Extension of 1σ contour:
mass: +29 MeV, - 26 MeV
y_t: +0.12, -0.11
Theory uncertainty (symm.):
mass: 36 MeV; y_t: 0.11
α_s parametric uncertainty (0.0002)
mass: 3 MeV; y_t: 0.02

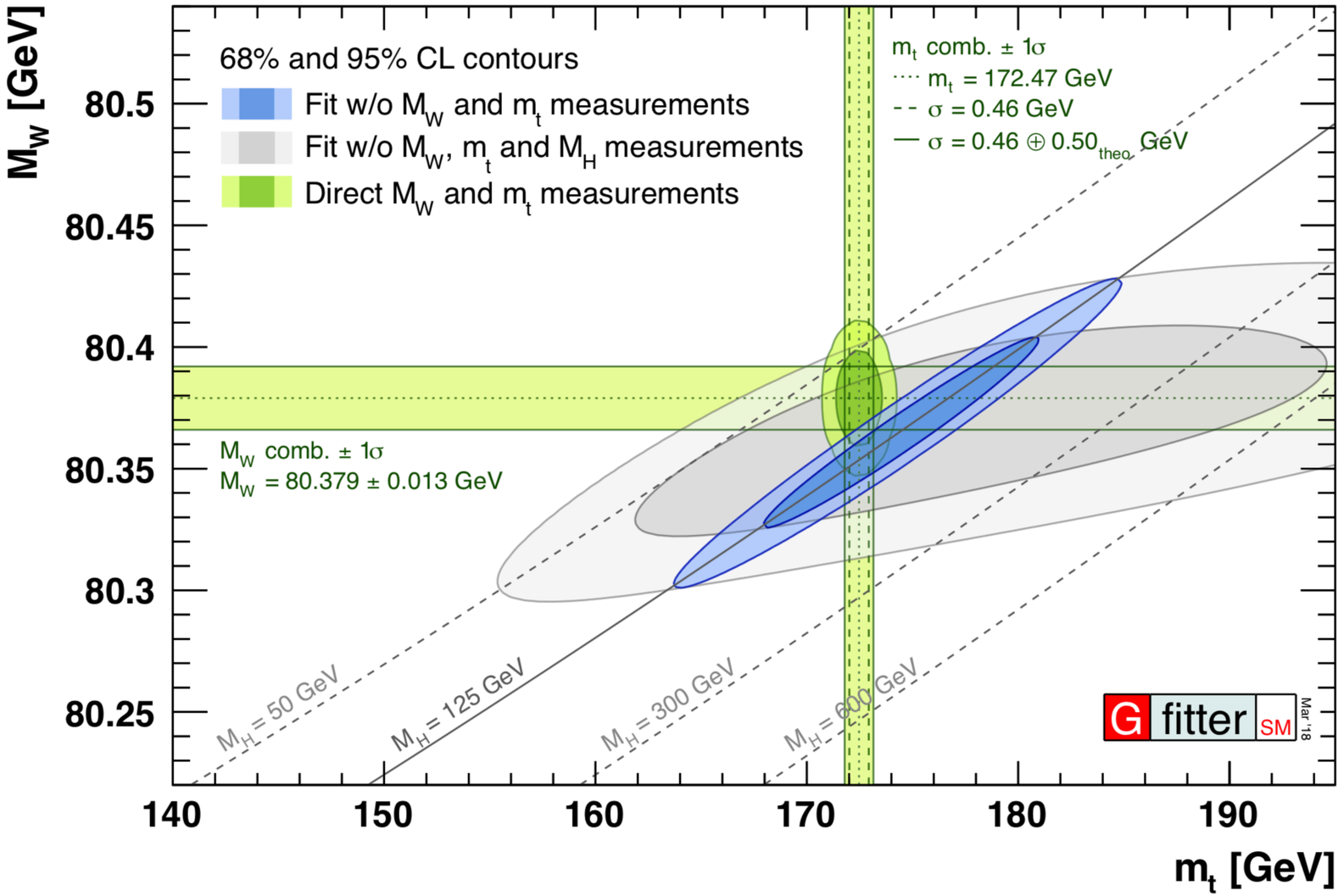
* m_t^{PS}=171.5 GeV ≙ m_t^{pole}=173.3 GeV (WA)

→ **threshold scan under investigation**

full simulation

Electroweak Constraints for top vs. W mass

[Gfitter, 1803.01853]



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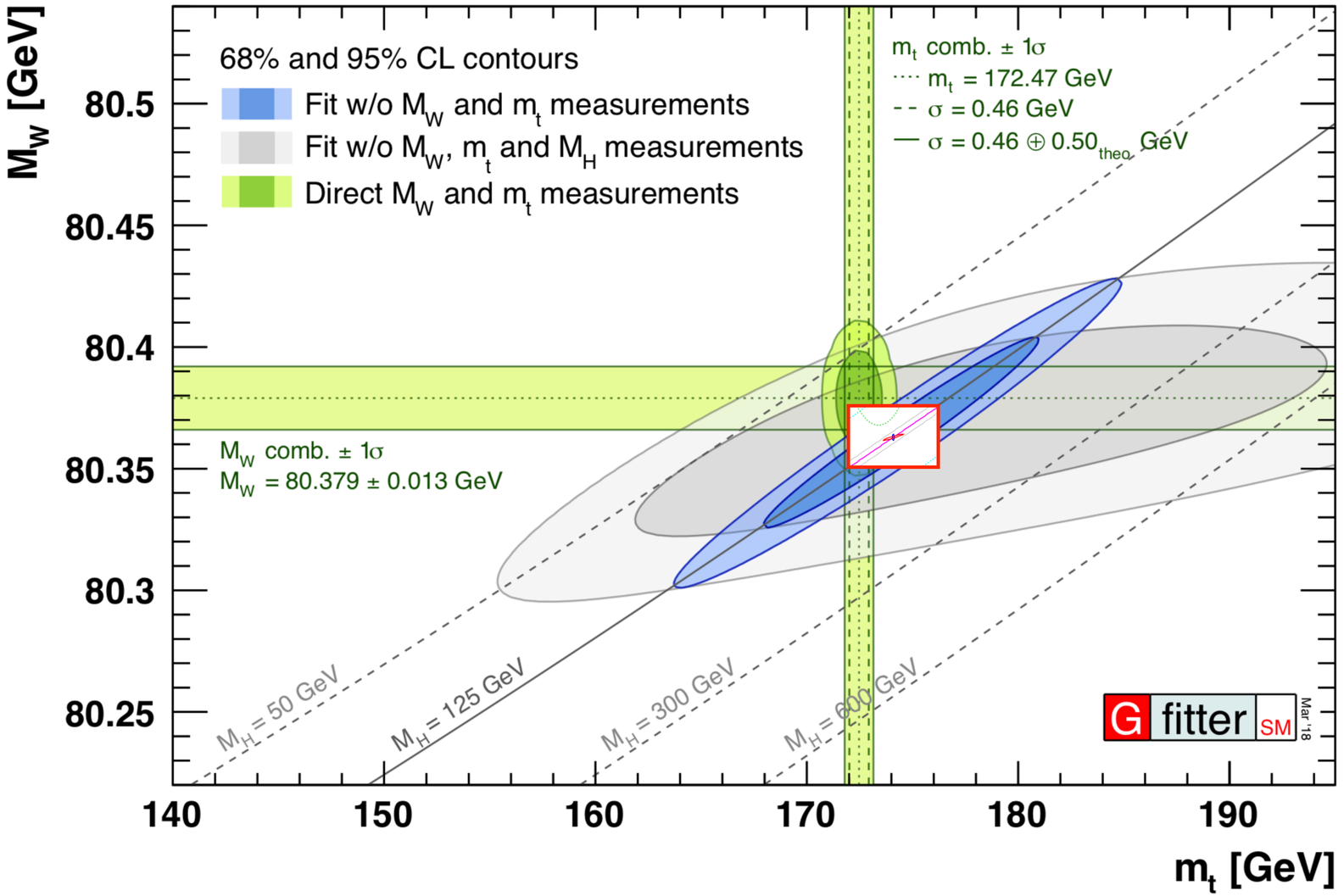
P. Janot



FCC-ee

Electroweak Constraints for top mass vs. W mass

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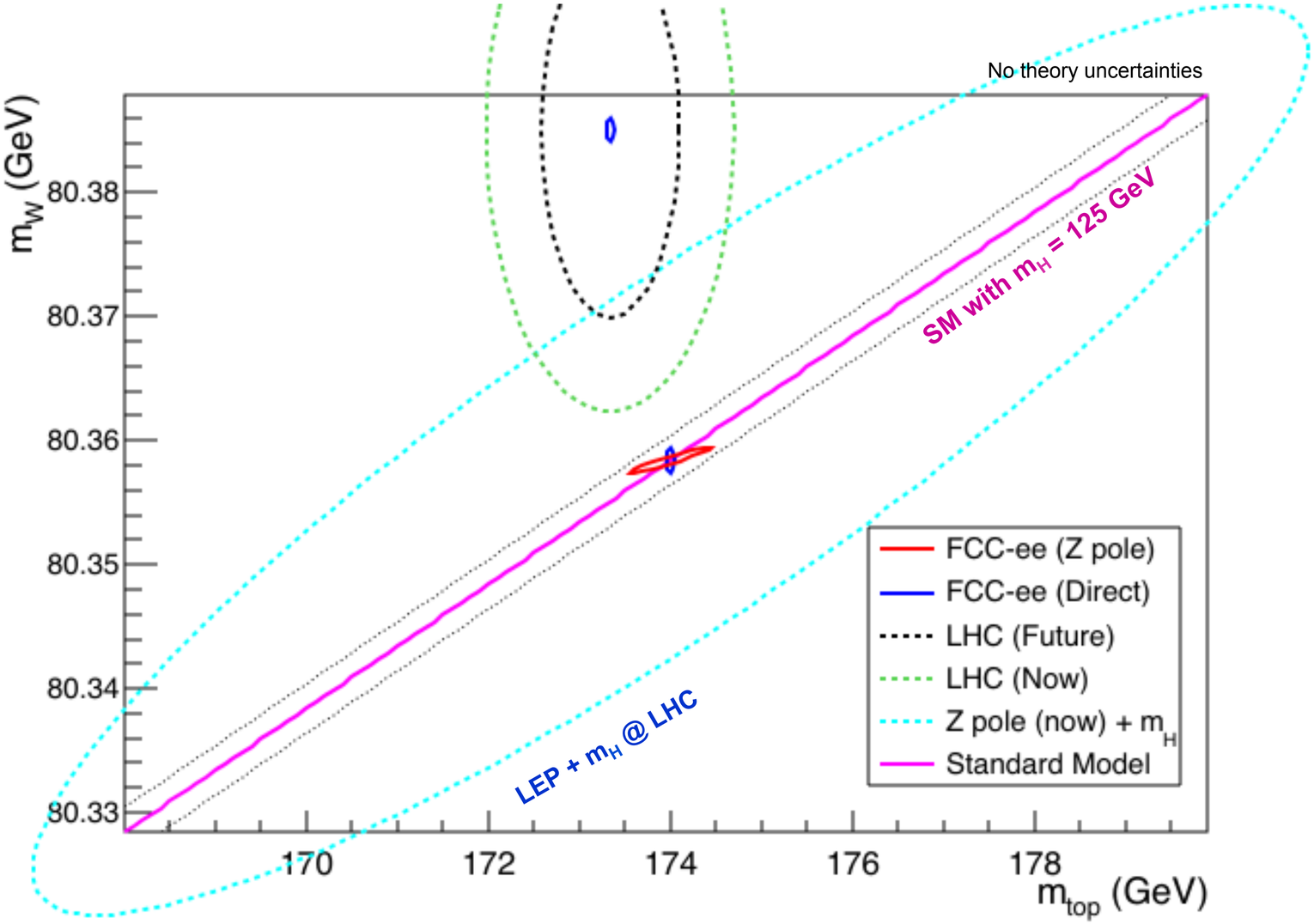
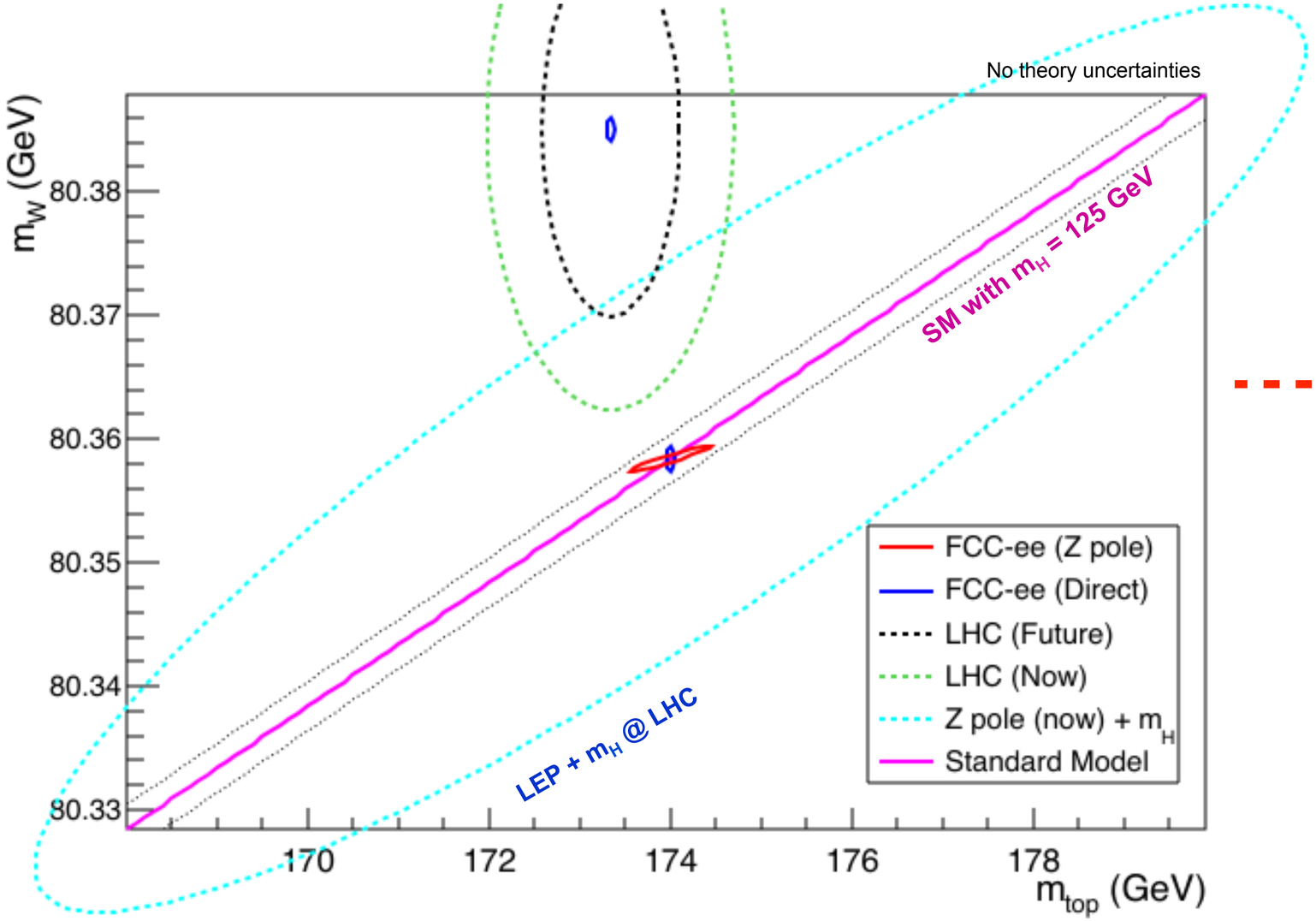


→ very high precision in testing self-consistency of SM

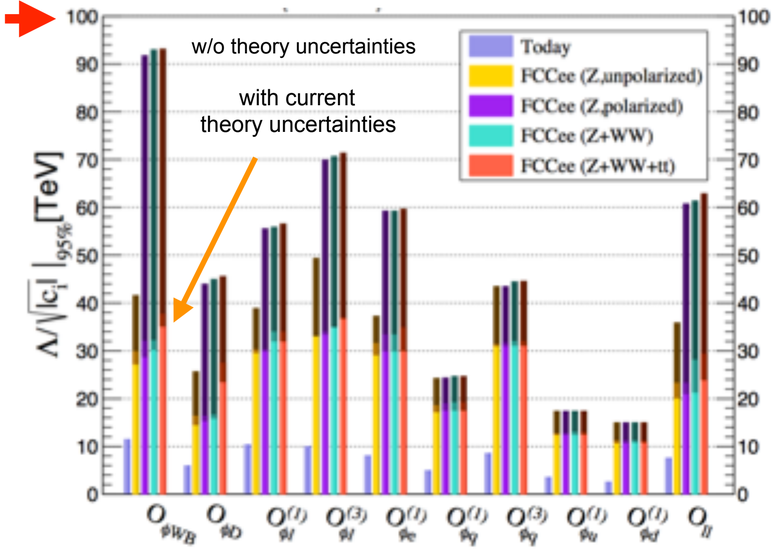
FCC-ee

Electroweak Constraints for top mass vs. W mass



$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

Sensitivity for new phenomena scale extended up to 100 TeV!



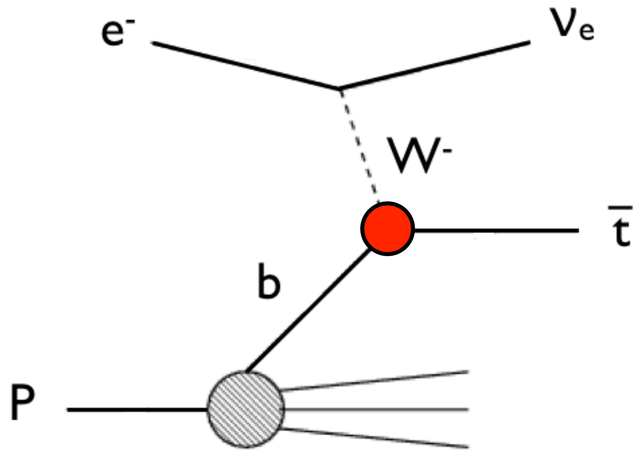
J. De Blas

FCC-ee

→ **very high precision in testing self-consistency of SM**

Direct Measurement of $|V_{tb}|$

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



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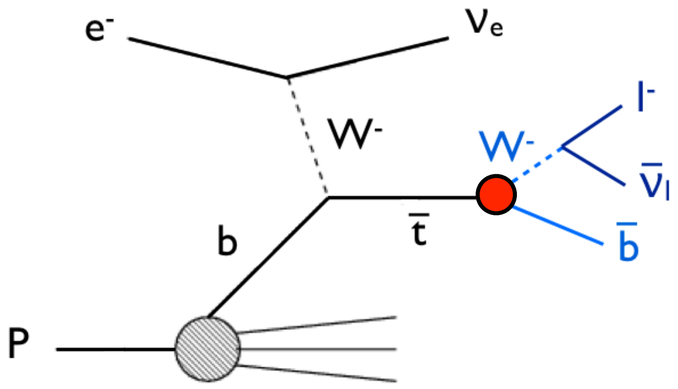
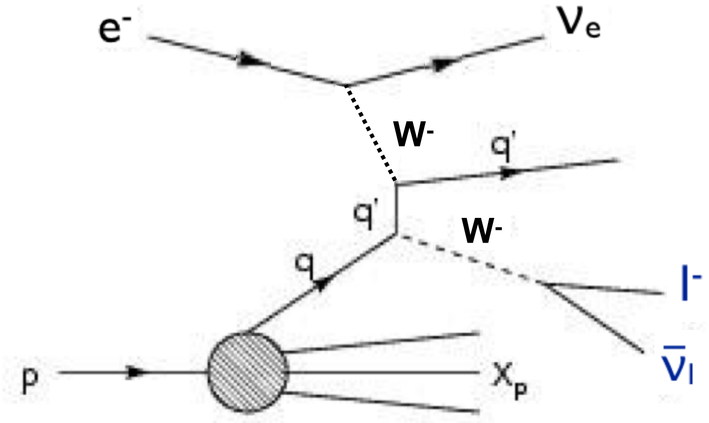


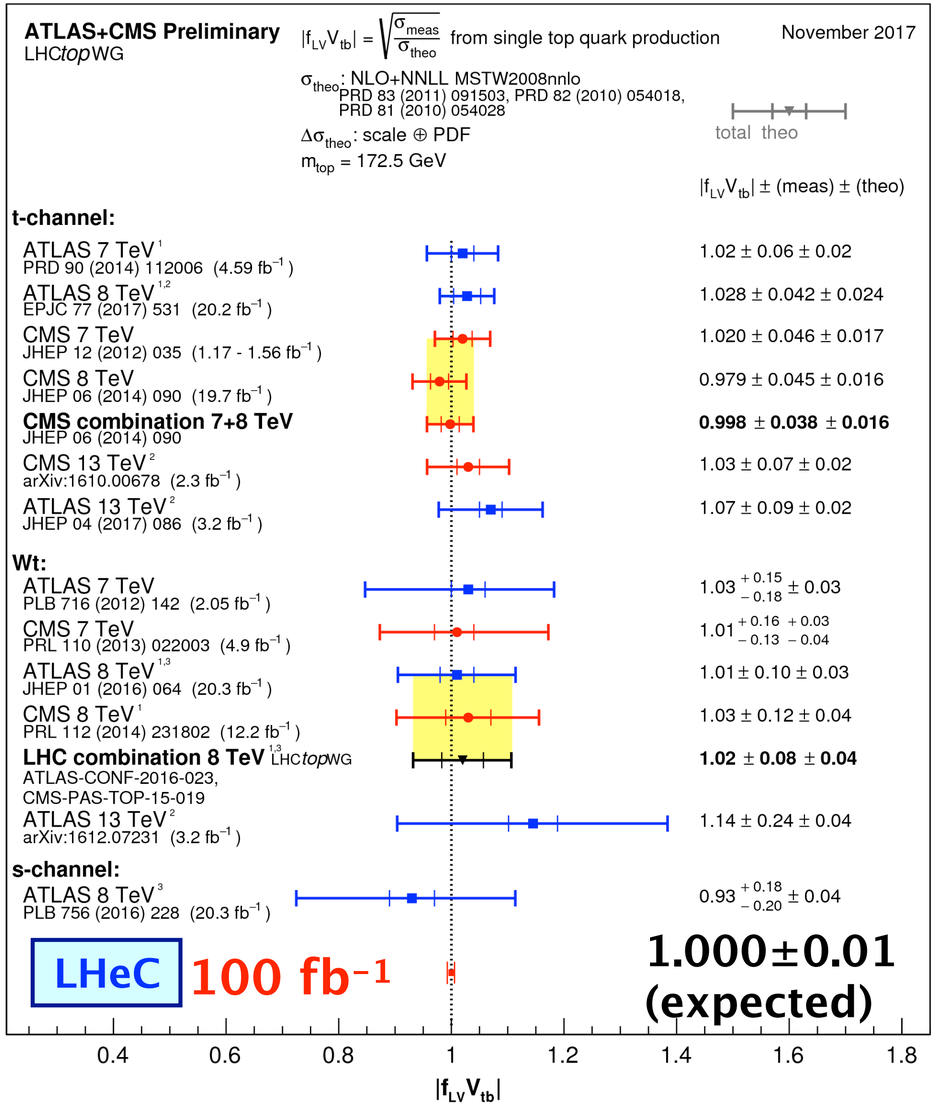
signal



background

s/b=11

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

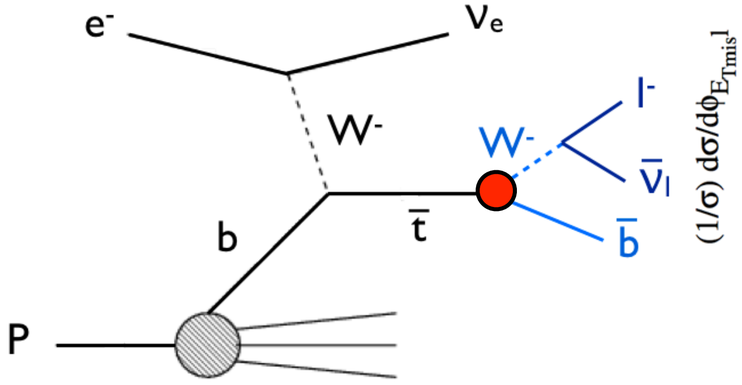


Search for Anomalous Wtb Couplings

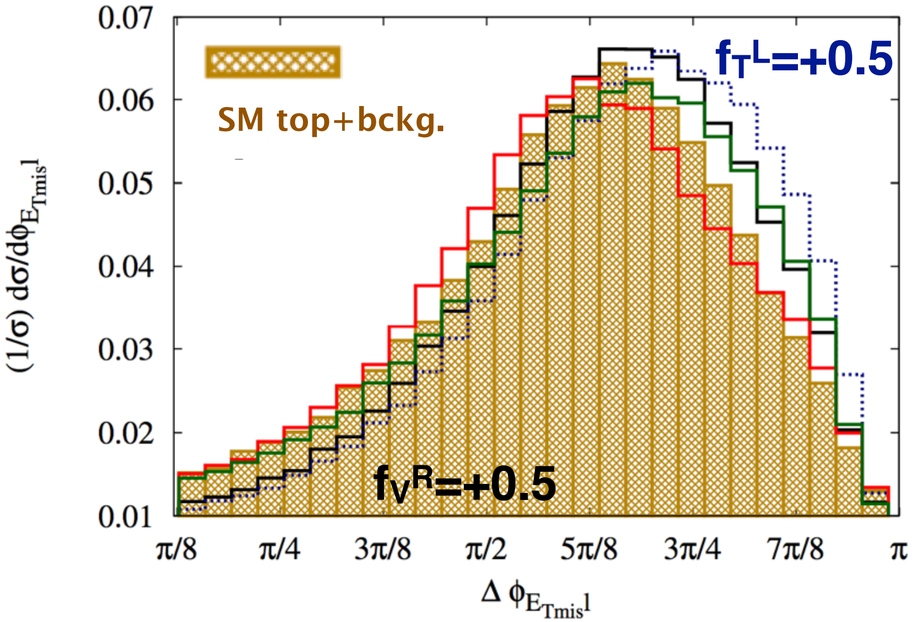
= 1 in SM

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

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



signal



+ other variables sensitive on W helicity

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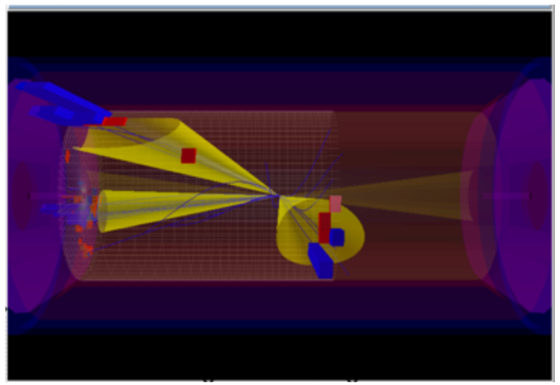
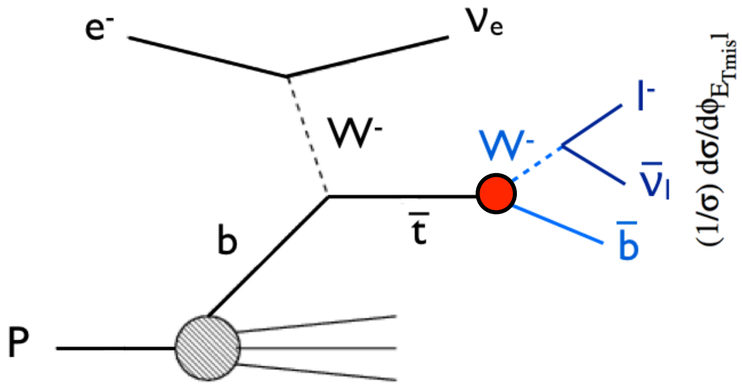
DELPHES



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



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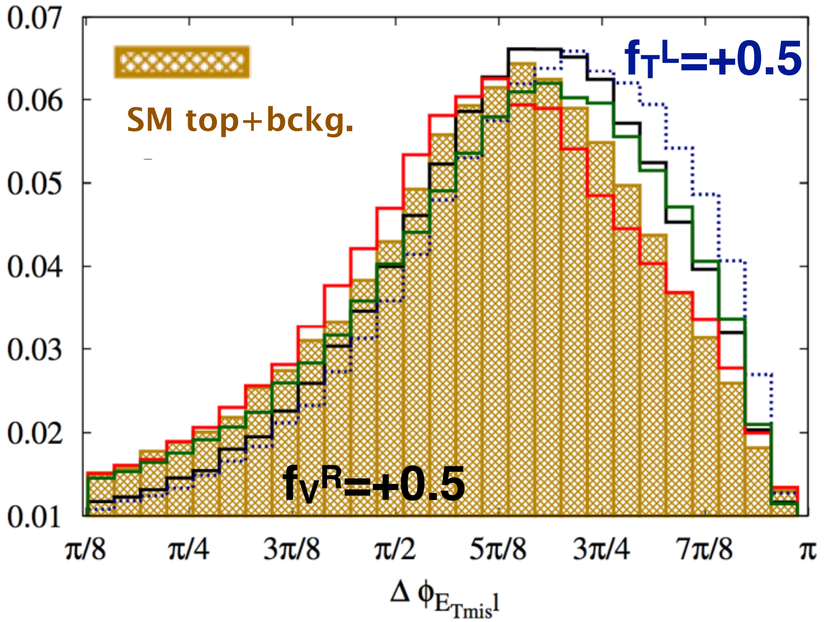
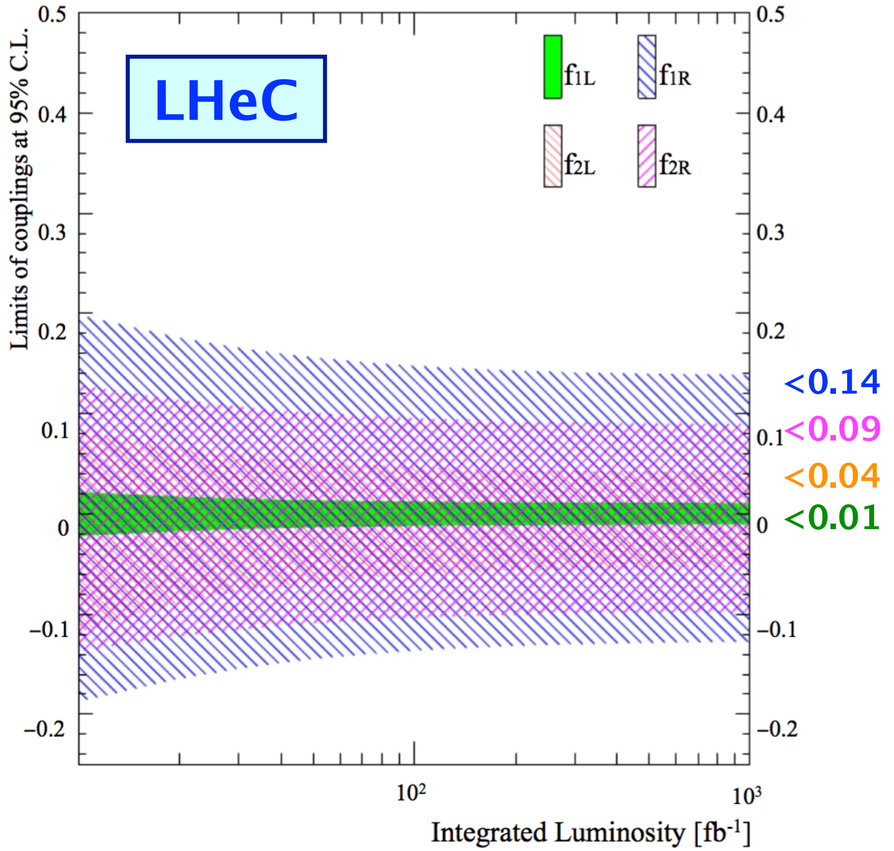
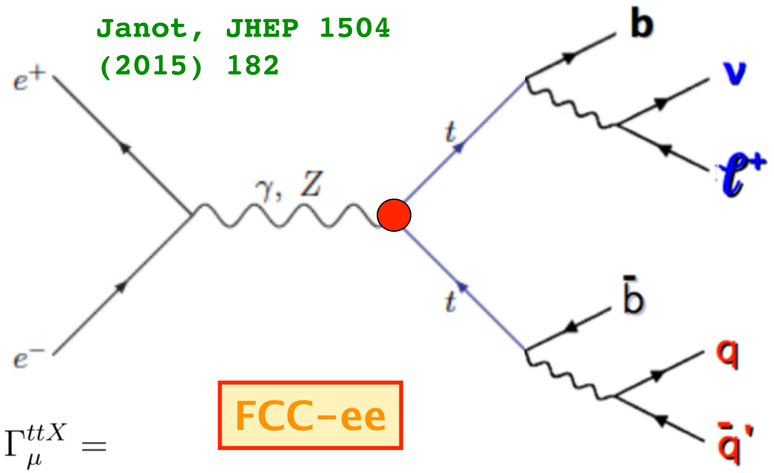




+ other variables sensitive on W helicity

$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments

Janot, JHEP 1504 (2015) 182



FCC-ee

$$\Gamma_{\mu}^{ttX} = -ie\left\{\gamma_{\mu}\left(F_{1V}^{X}+\gamma_{5}F_{1A}^{X}\right)+\frac{\sigma_{\mu\nu}}{2m_{\mathrm{t}}}(p_{t}+p_{\bar{t}})^{\nu}\left(iF_{2V}^{X}+\gamma_{5}F_{2A}^{X}\right)\right\}$$

$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments

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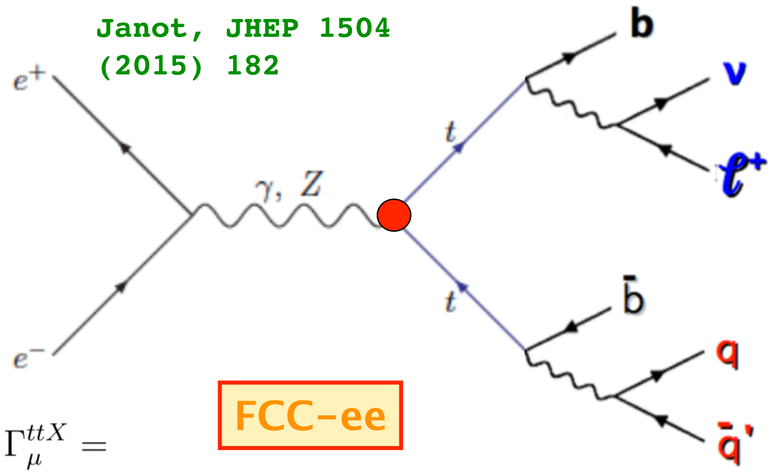

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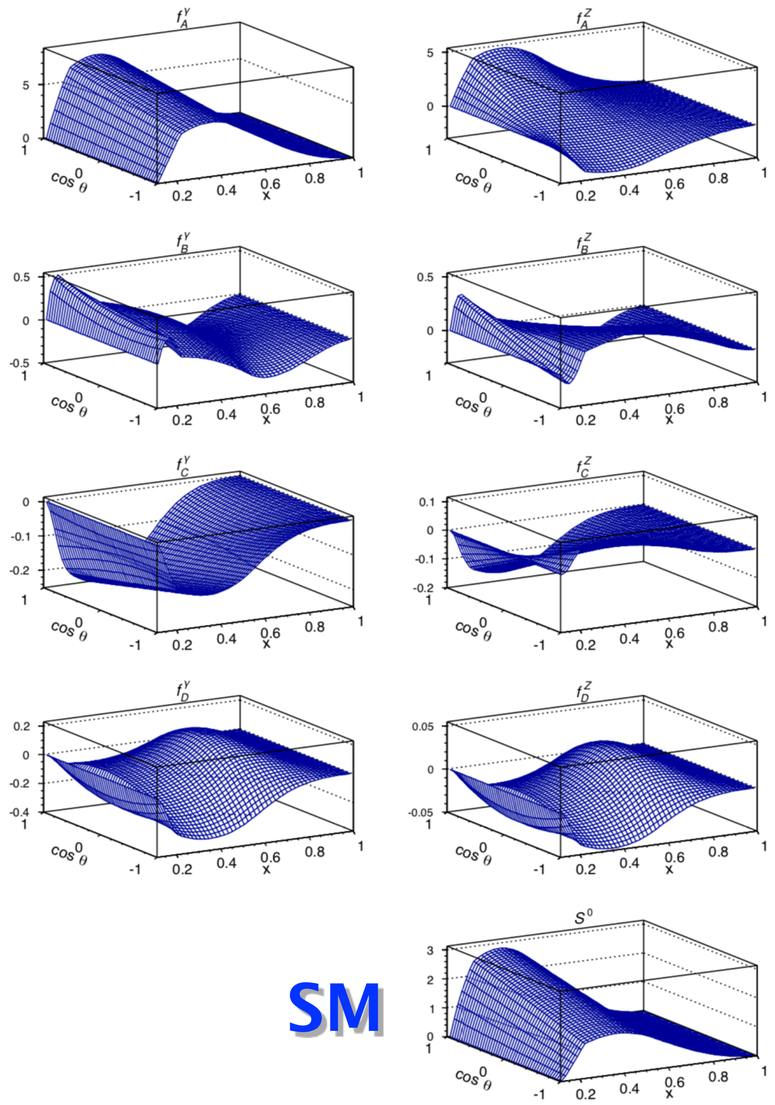


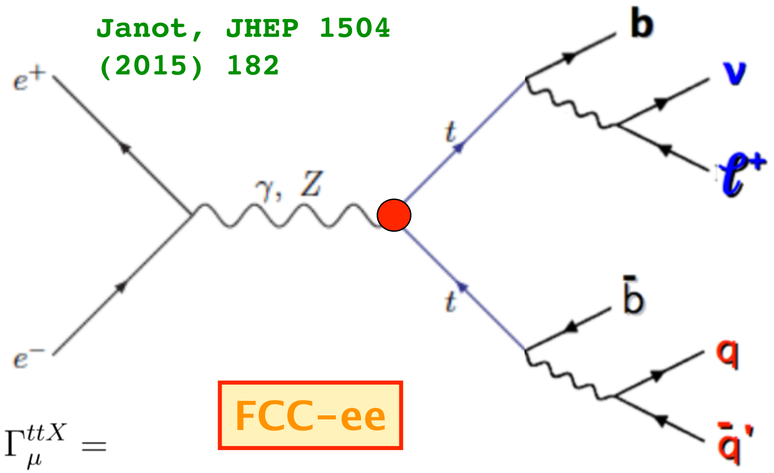
SM

- use lepton energy and angular distributions in top decay to distinguish ttγ and ttZ
- use optimal observable analysis (confirmed by full simulation analysis)

→ no beam polarisation needed, use top polarisation instead

$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments

Janot, JHEP 1504 (2015) 182



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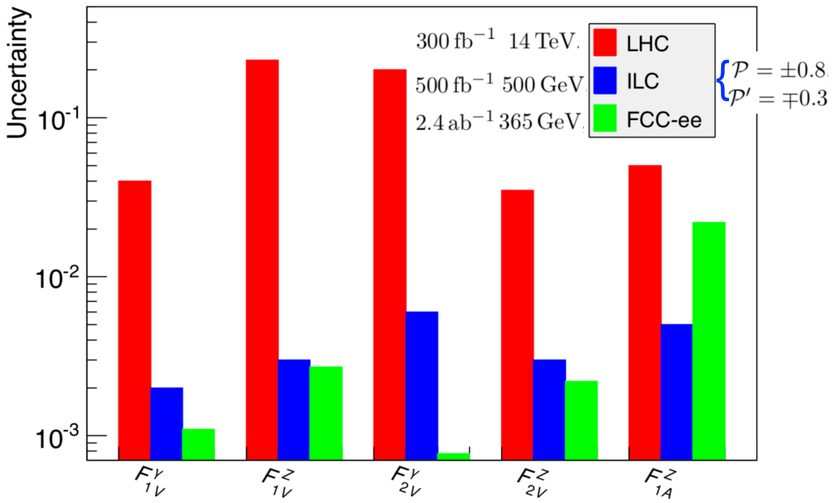
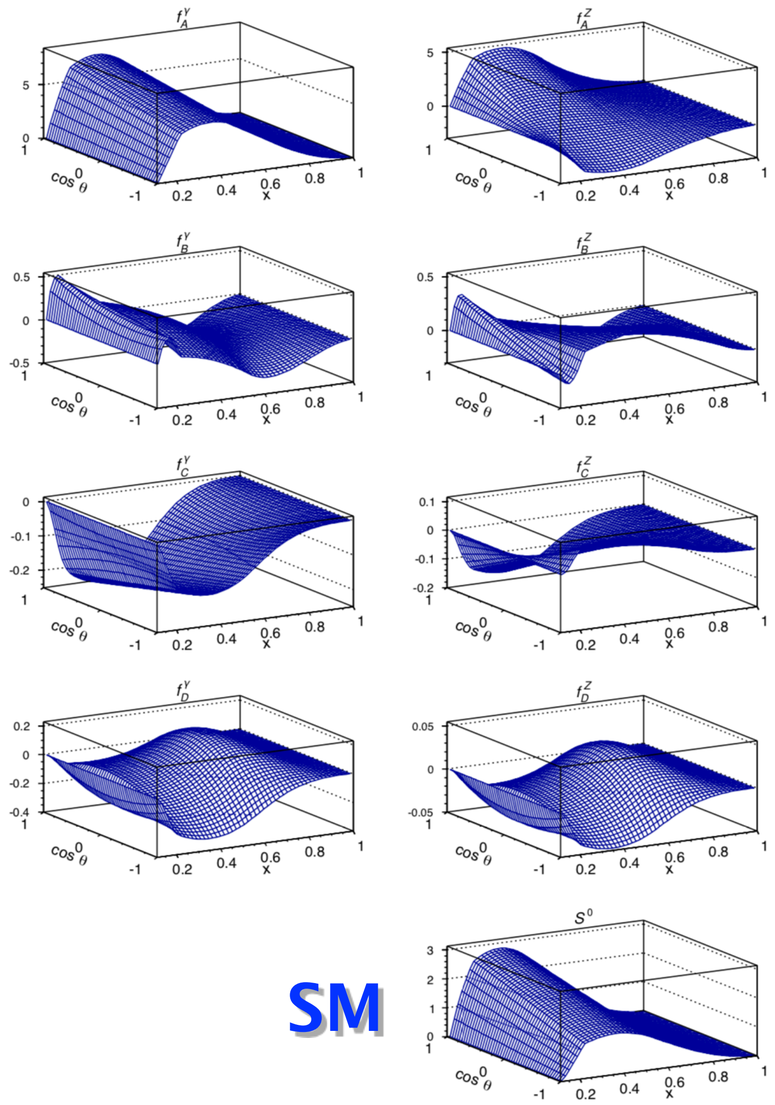


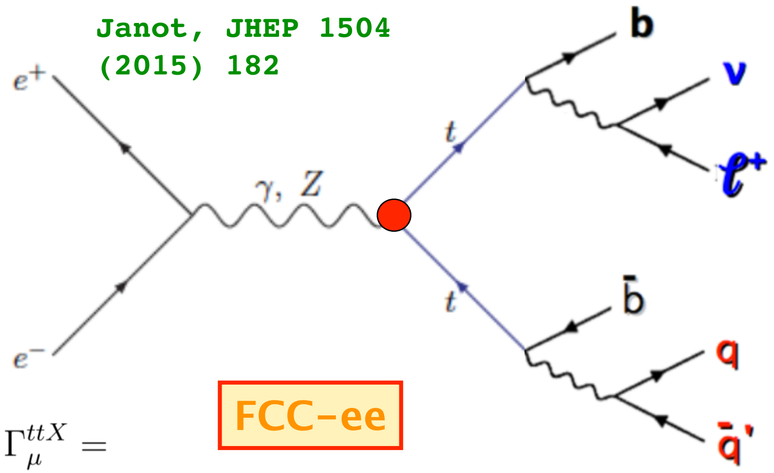
→ expected precision of order 10^{-2} to 10^{-3}



SM

$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments

Janot, JHEP 1504 (2015) 182



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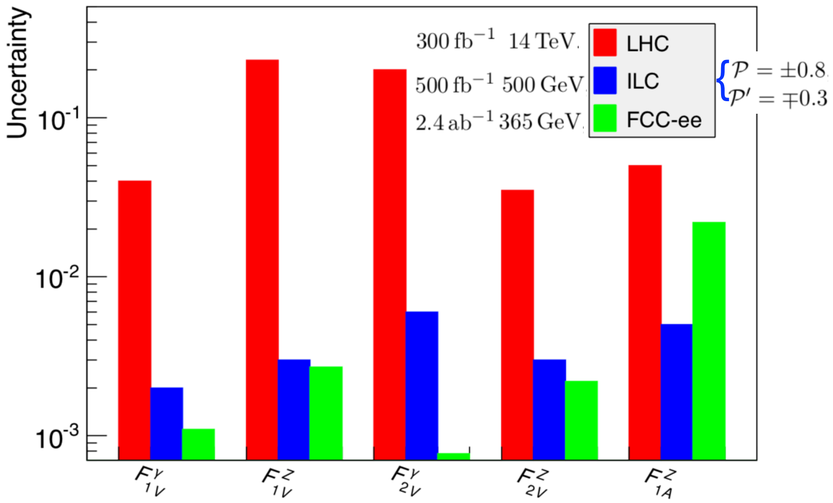

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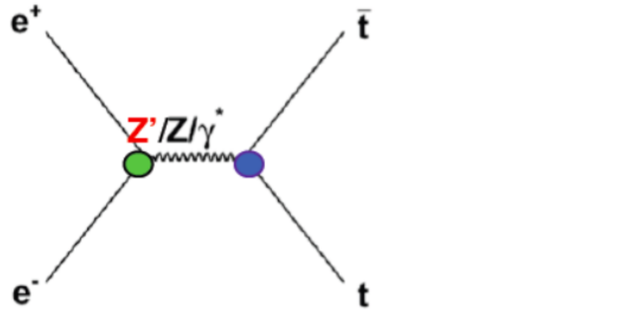
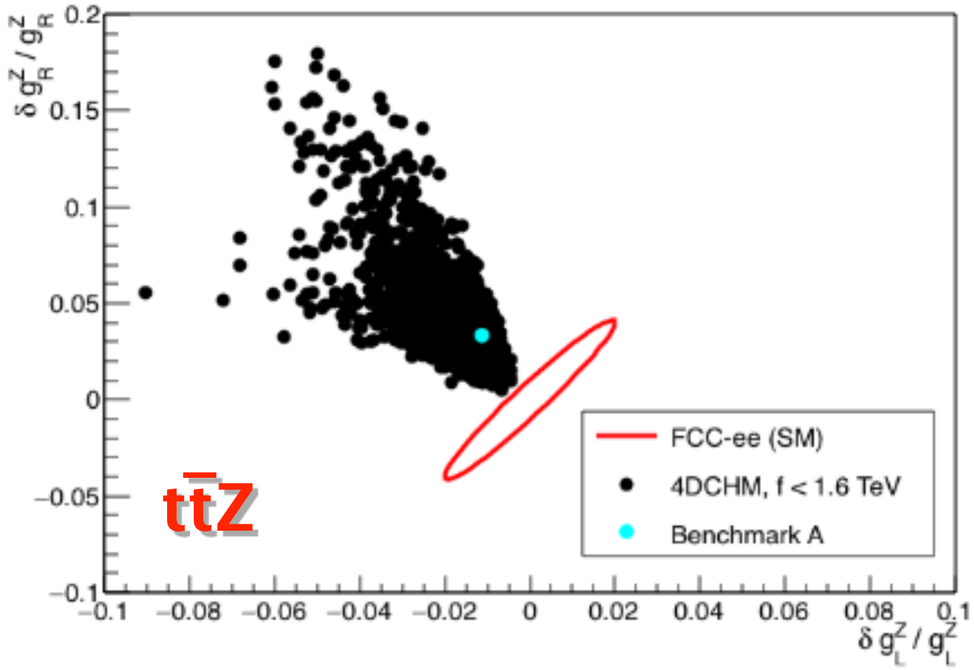
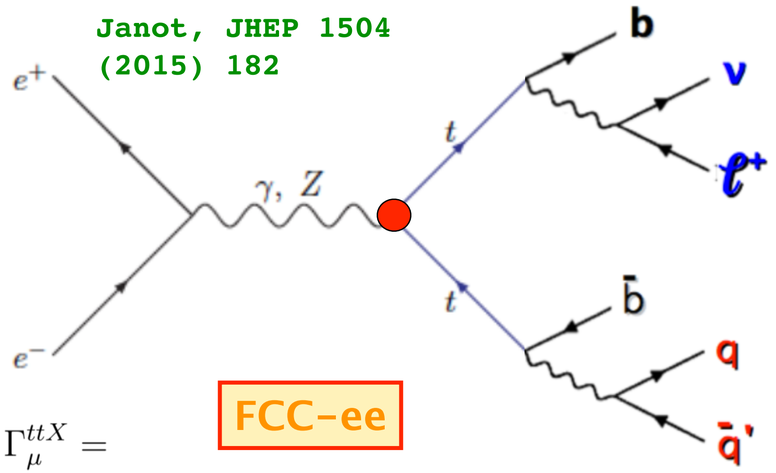




→ exclude composite Higgs models up to $m_{Z'} \sim 3$ TeV

$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments

Janot, JHEP 1504 (2015) 182



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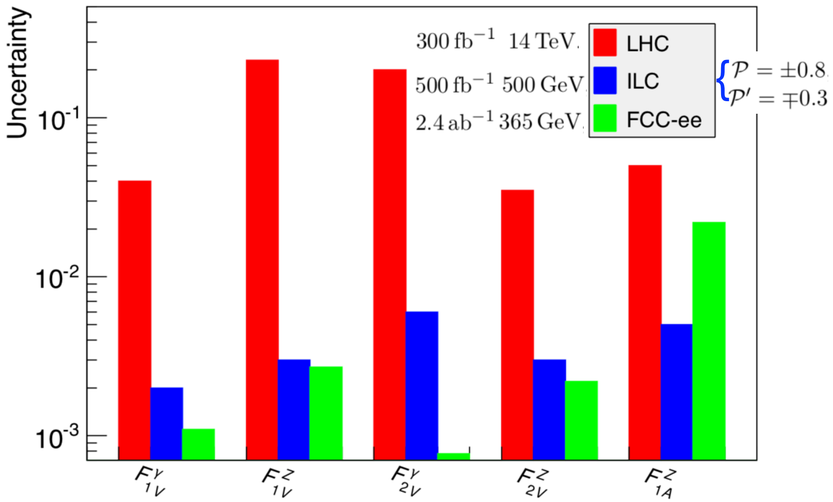

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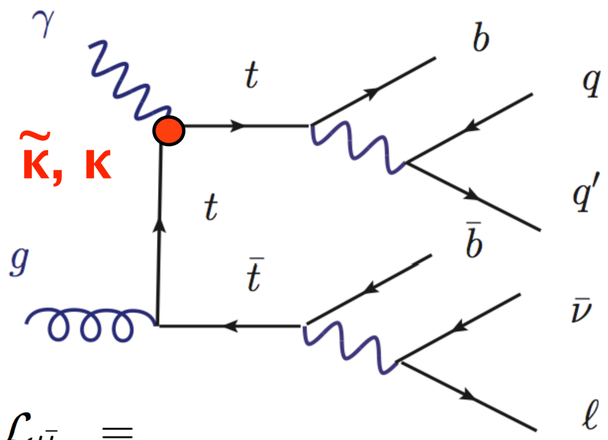
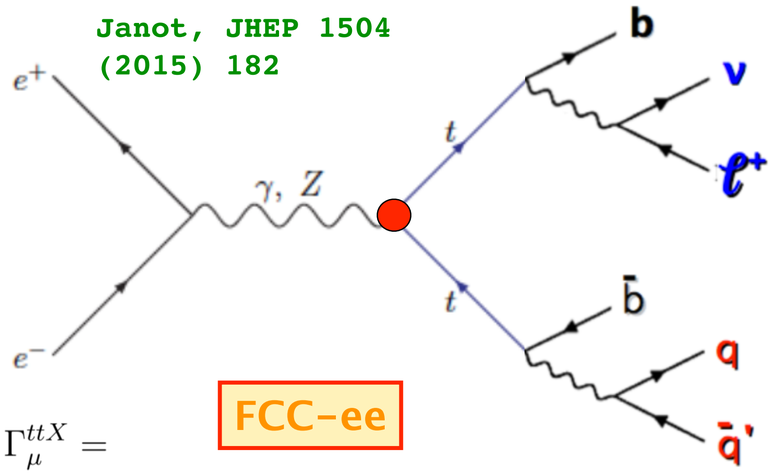


$$\mathcal{L}_{t\bar{t}\gamma} = e\bar{t}\left(Q_t\gamma^\mu A_\mu + \frac{1}{4m_t}\sigma^{\mu\nu}F_{\mu\nu}(\kappa + i\tilde{\kappa}\gamma_5)\right)t$$

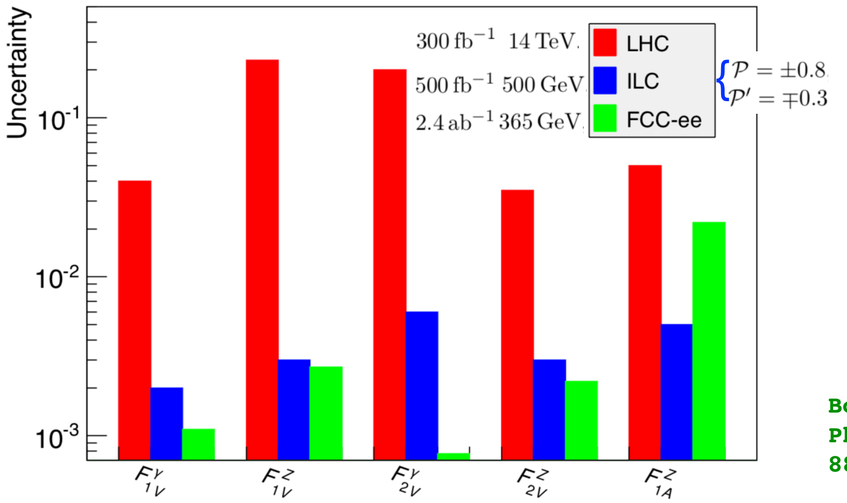
$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments

Janot, JHEP 1504 (2015) 182



FCC-ee

$$\Gamma_\mu^{ttX} = -ie\left\{\gamma_\mu\left(F_{1V}^X + \gamma_5 F_{1A}^X\right) + \frac{\sigma_{\mu\nu}}{2m_t}(p_t + p_{\bar{t}})^\nu\left(iF_{2V}^X + \gamma_5 F_{2A}^X\right)\right\}$$



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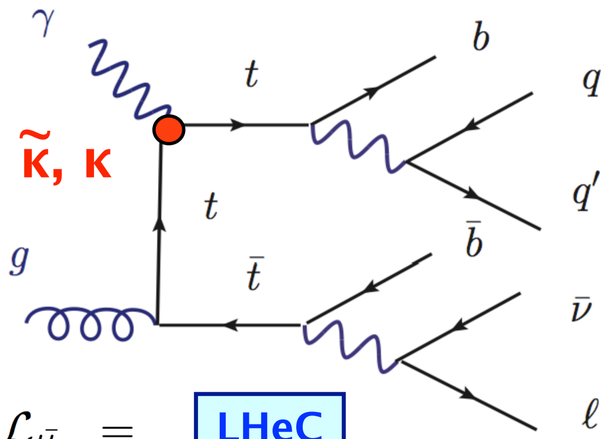

LHeC

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

10% 18% accuracy (syst. limited)

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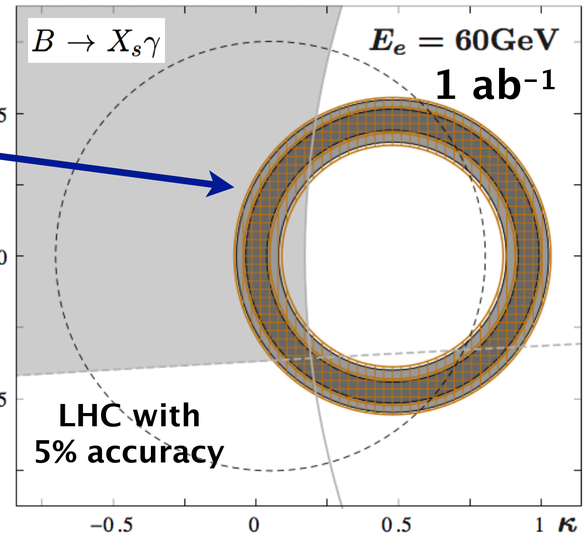

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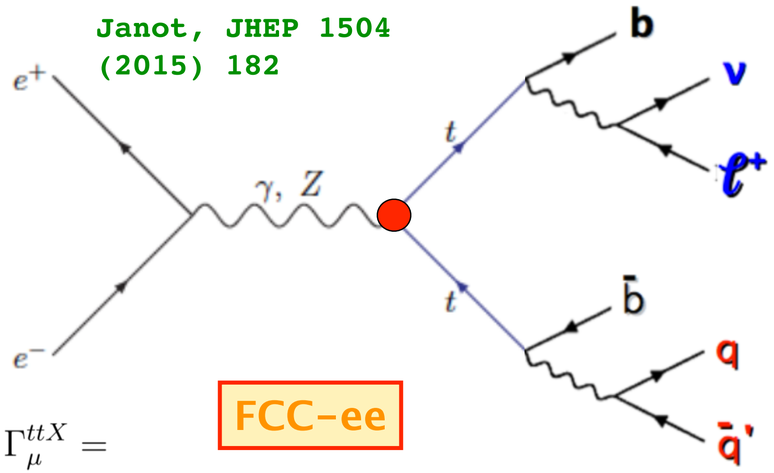
$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments

Janot, JHEP 1504 (2015) 182



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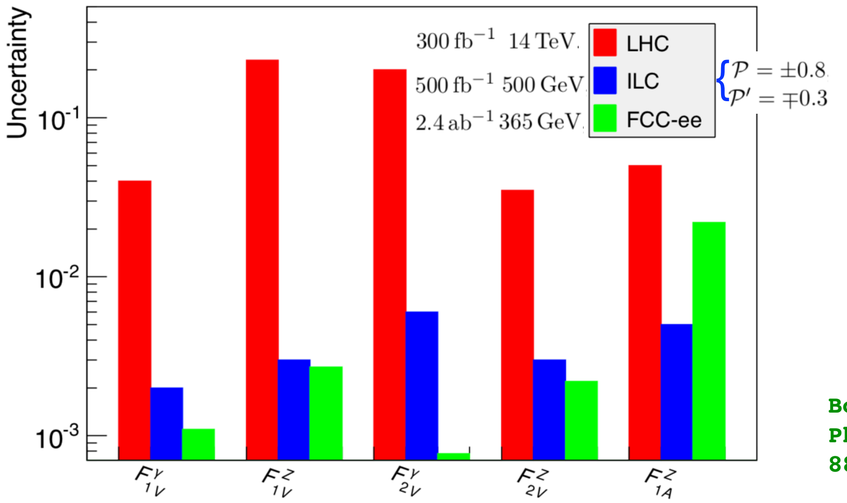

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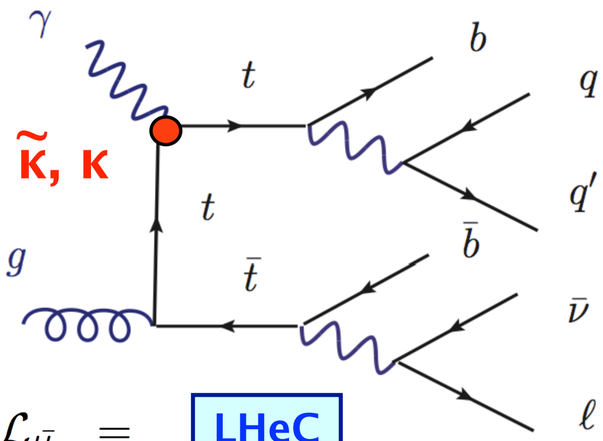

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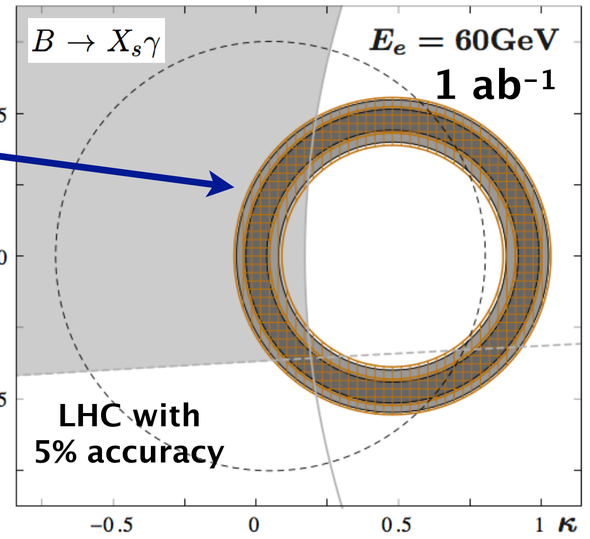

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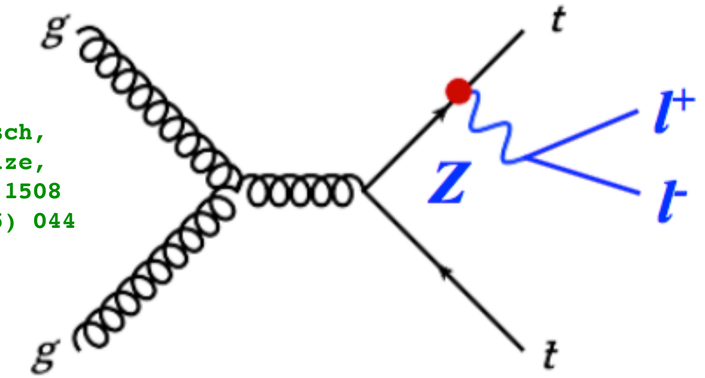
Röntsch, Schulze, JHEP 1508 (2015) 044



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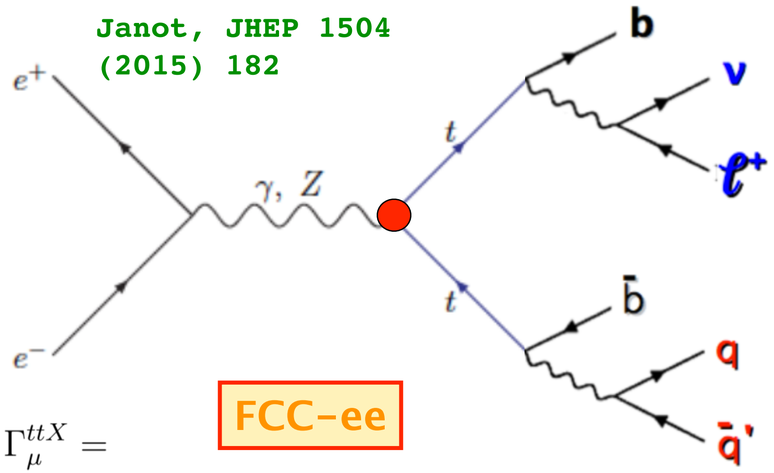
investigate angular correlations of Z leptons

$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments

Janot, JHEP 1504 (2015) 182



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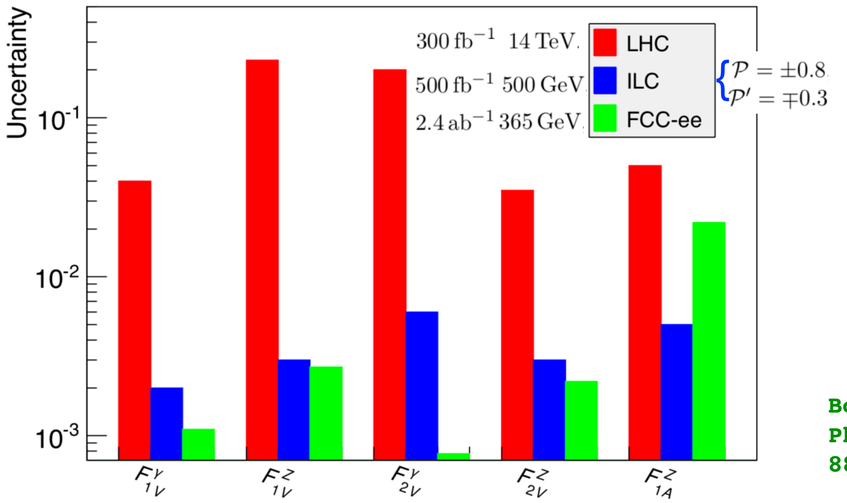

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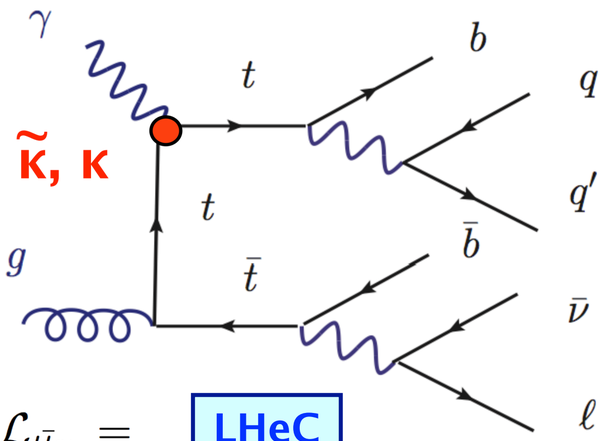

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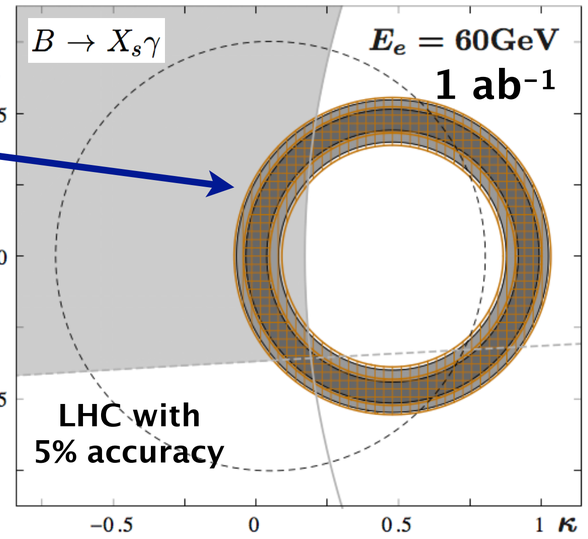

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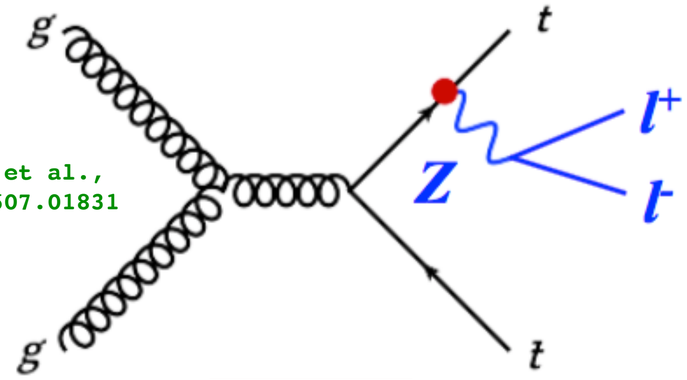

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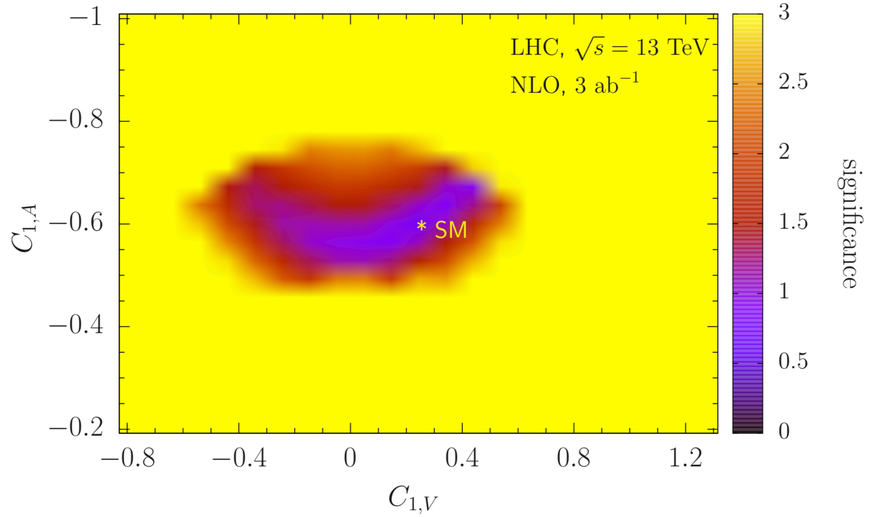

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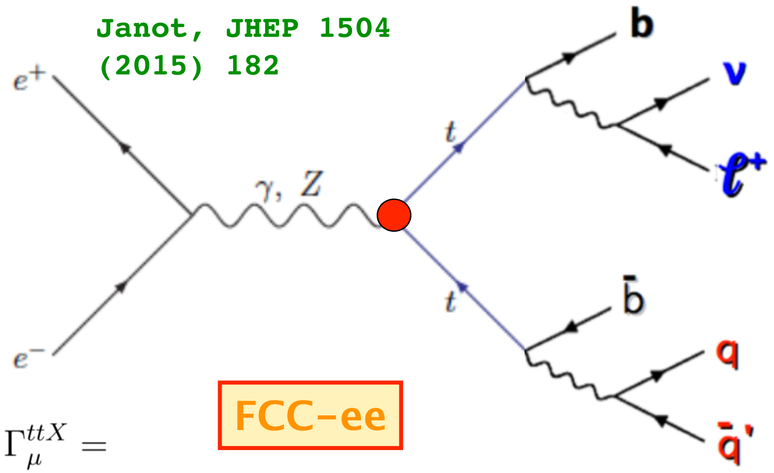

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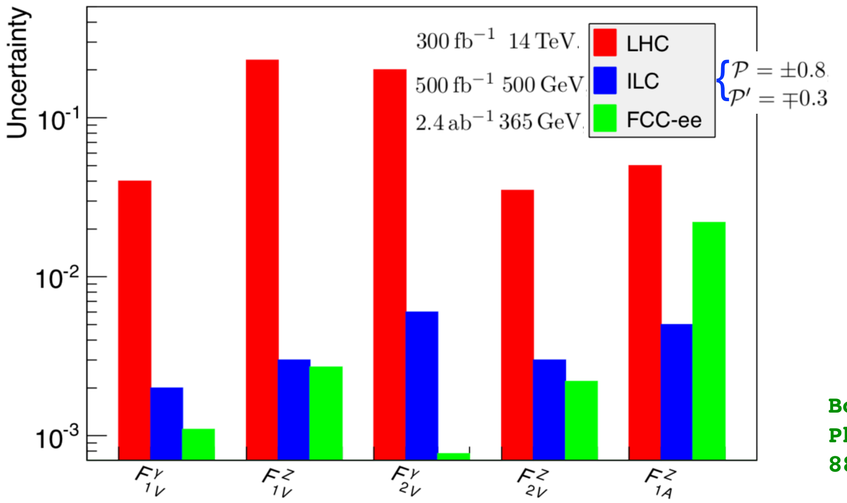

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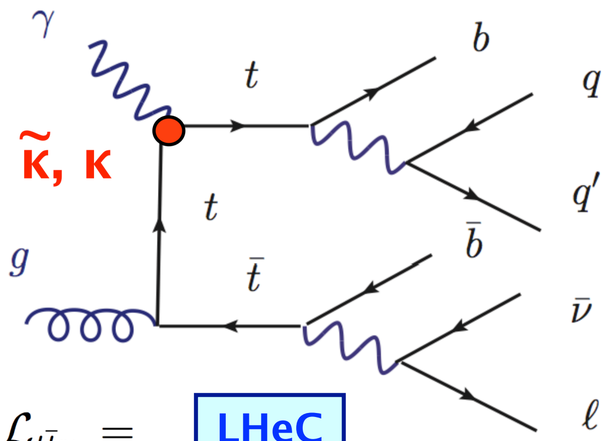

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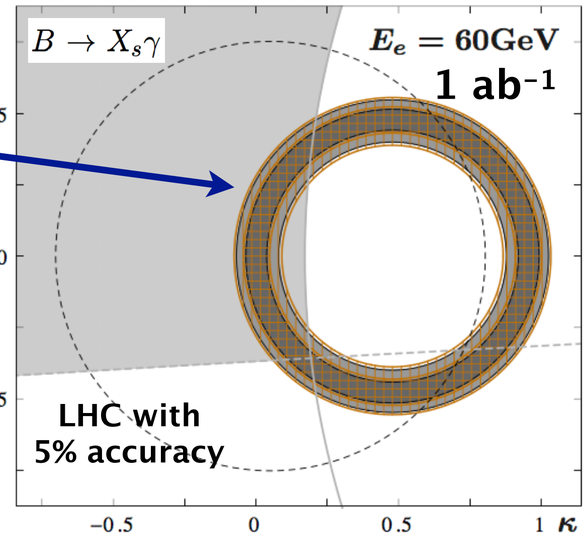

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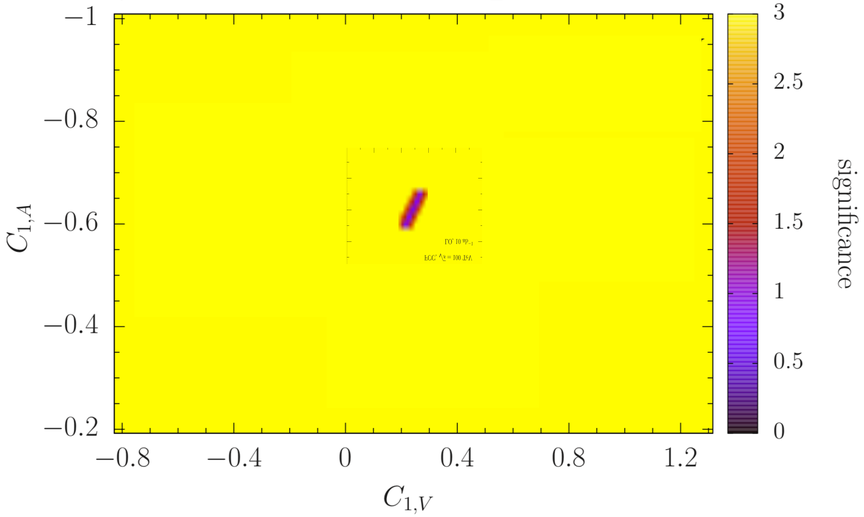
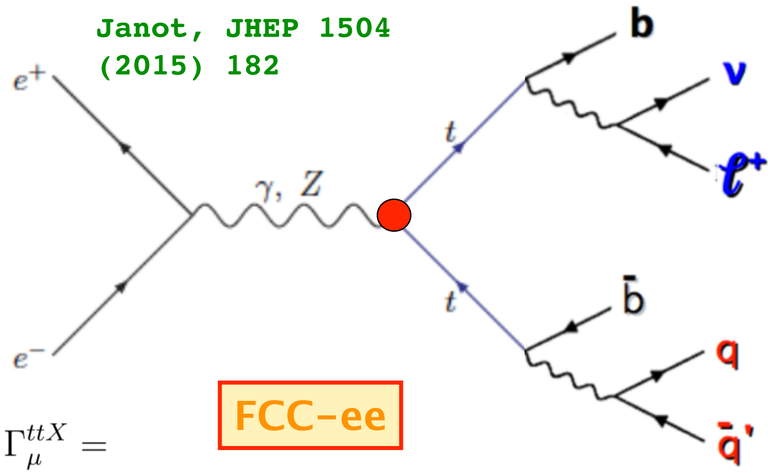


$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments

Janot, JHEP 1504 (2015) 182



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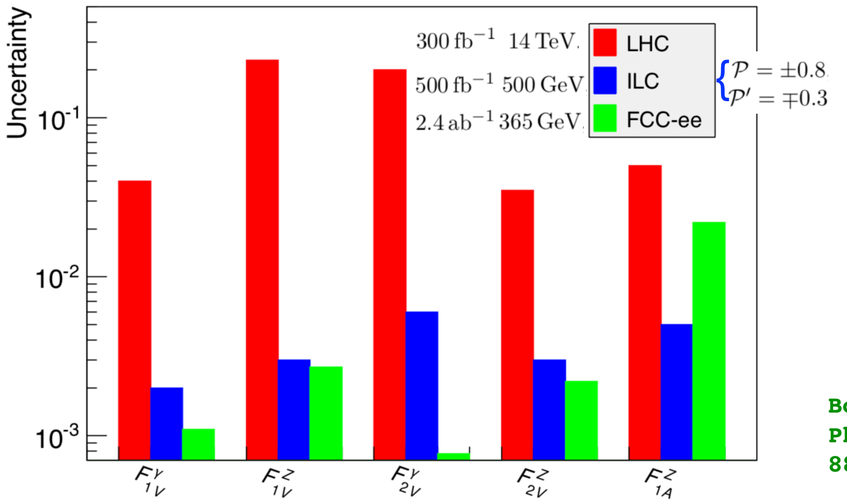

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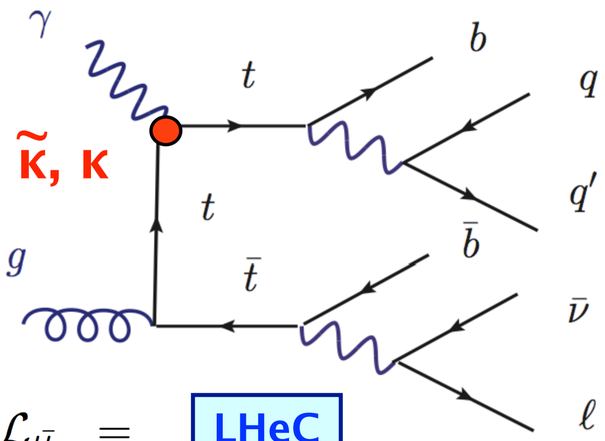

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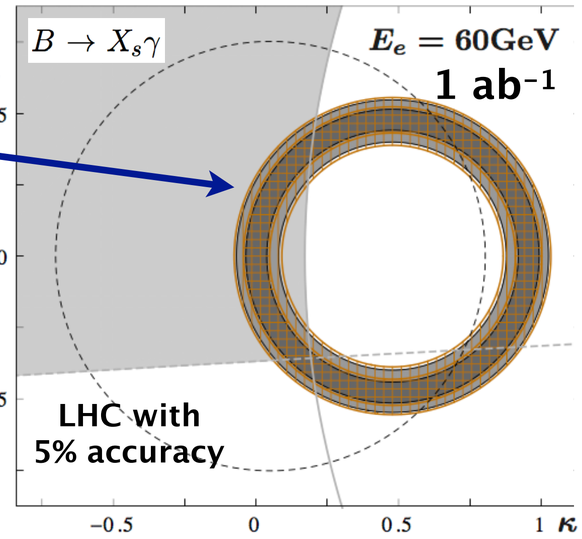

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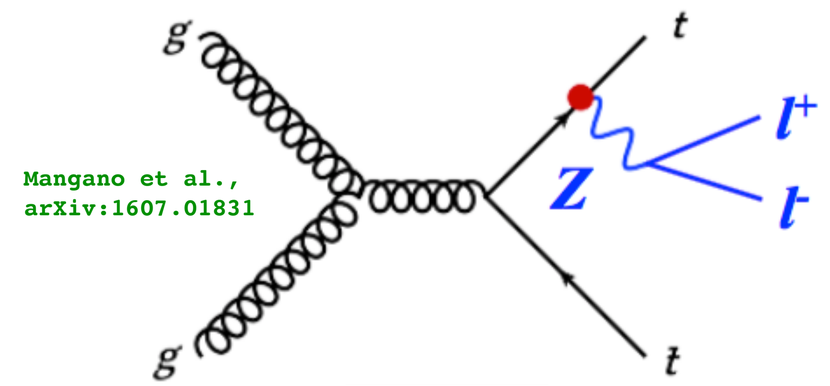

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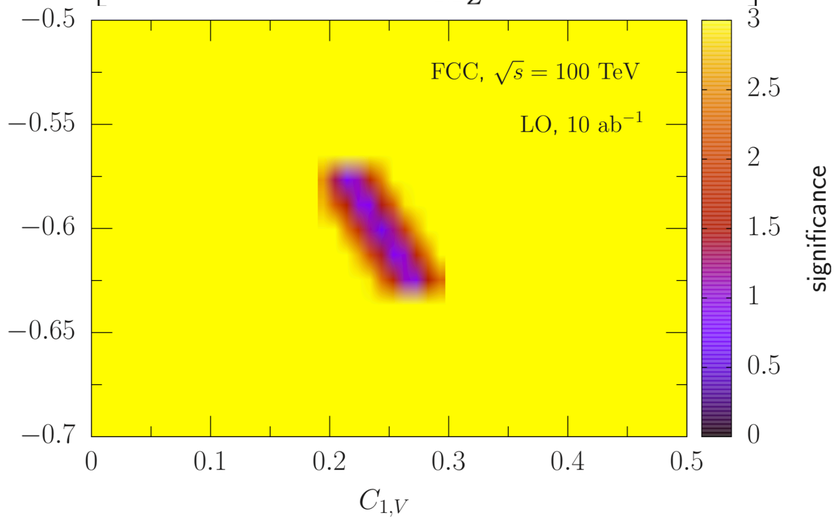

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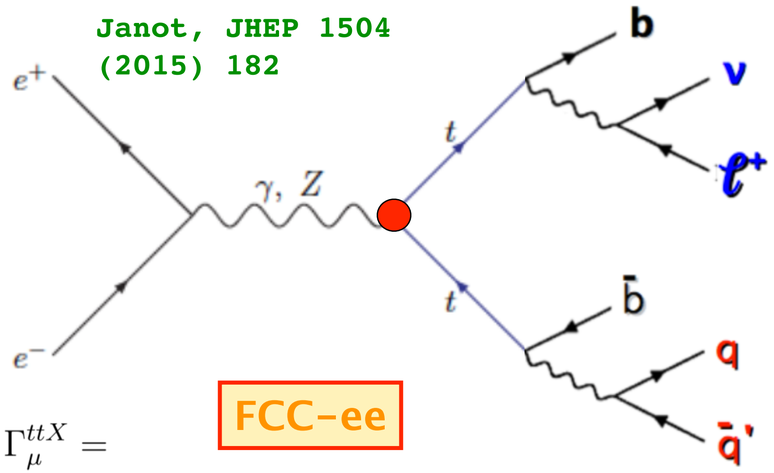

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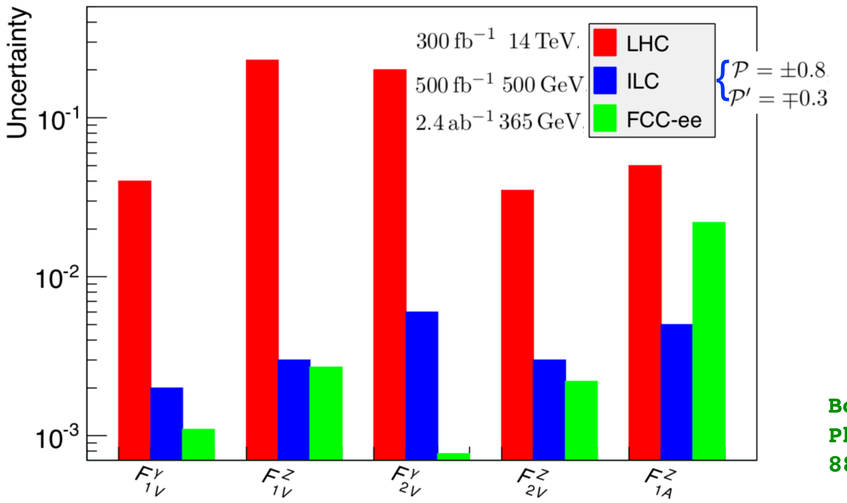

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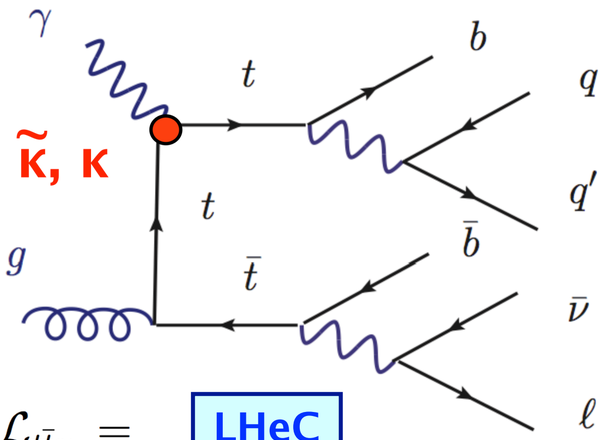

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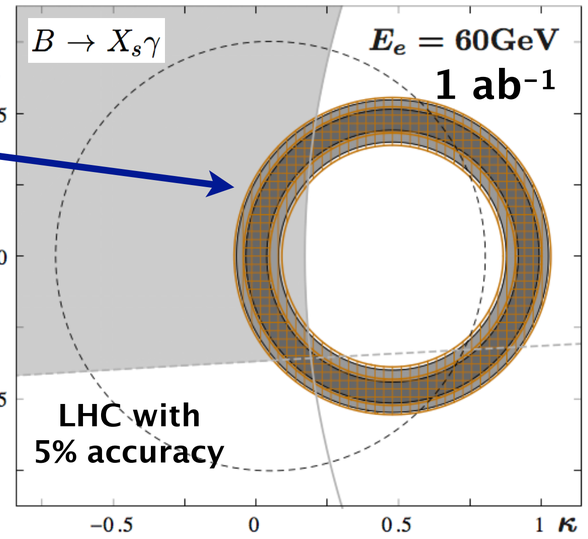

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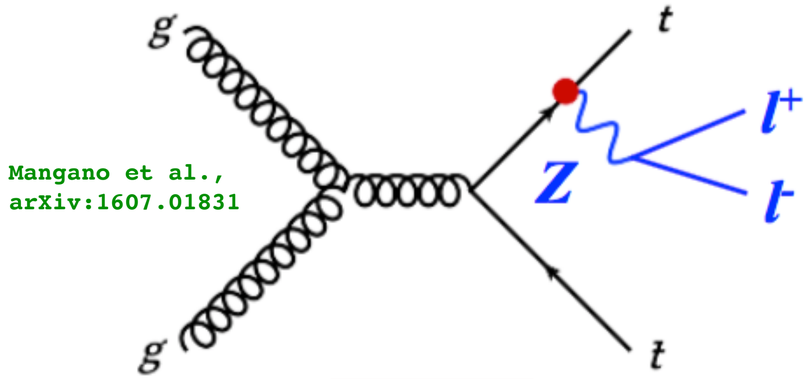

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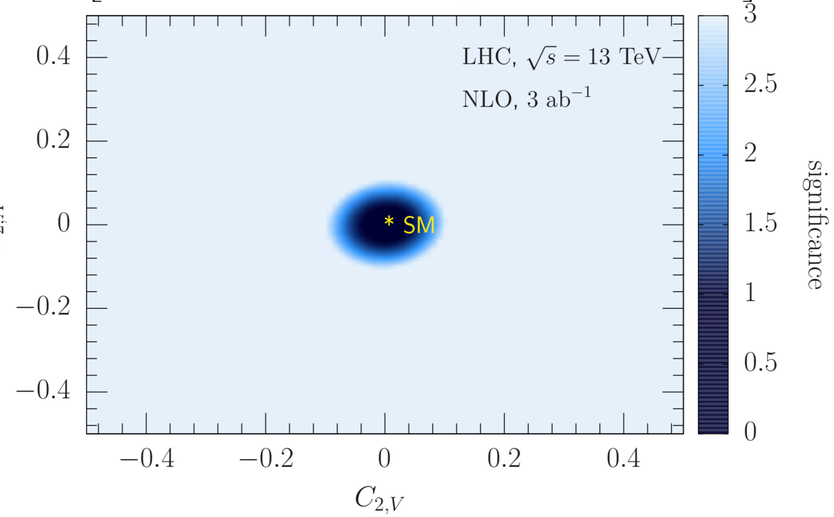

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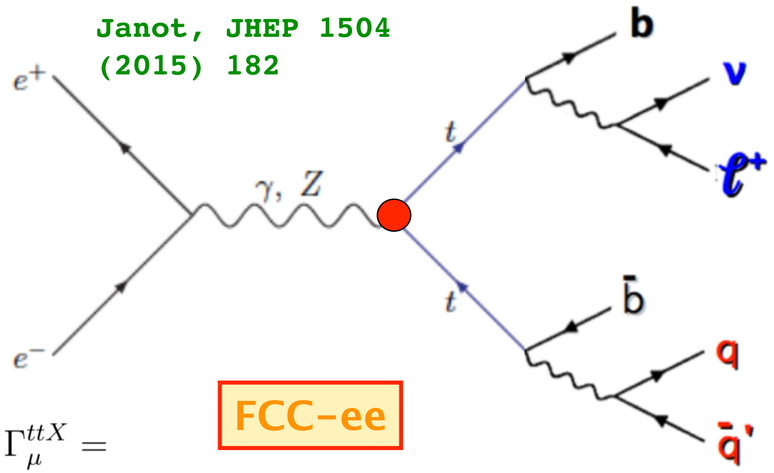

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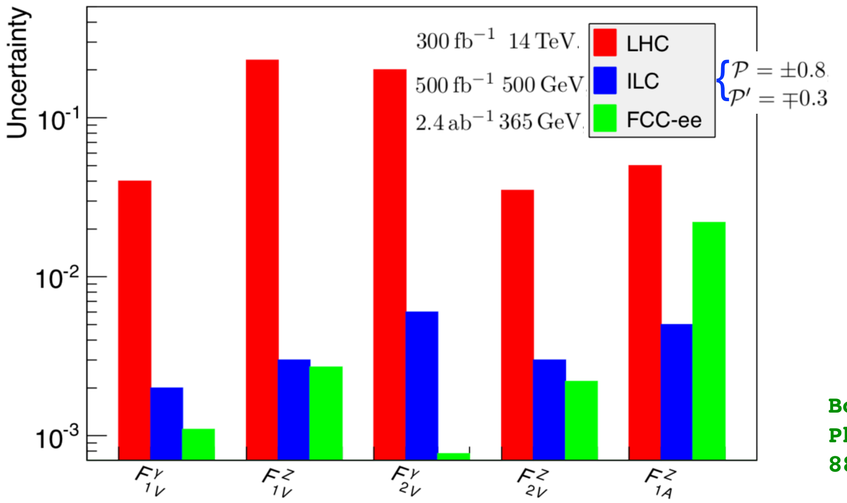

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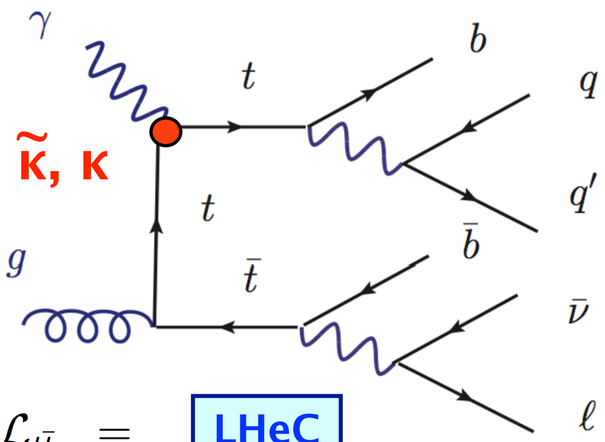

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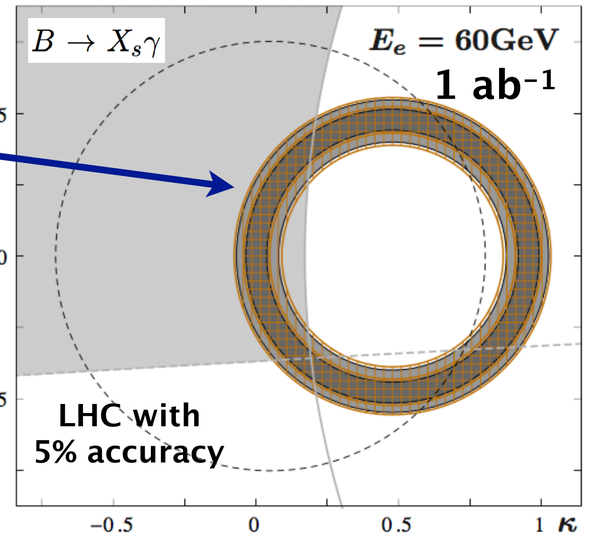

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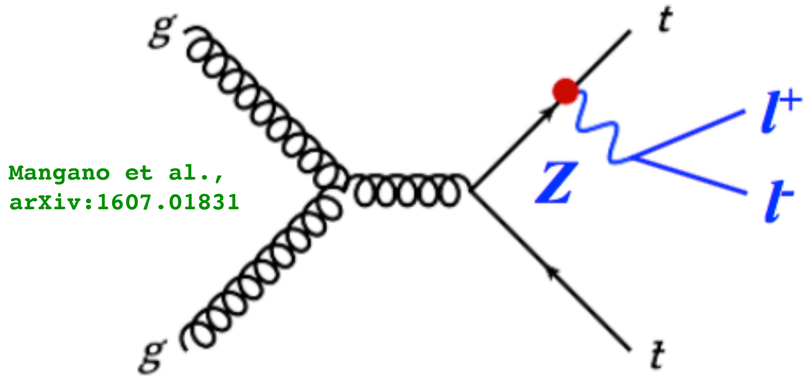

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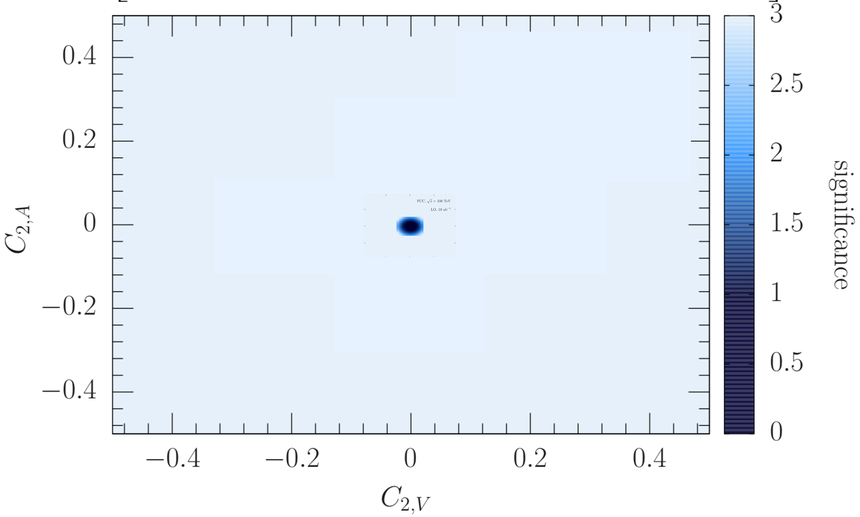

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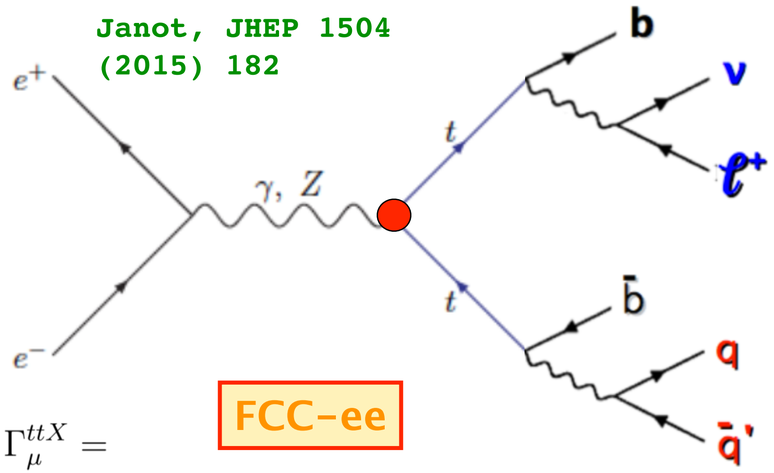

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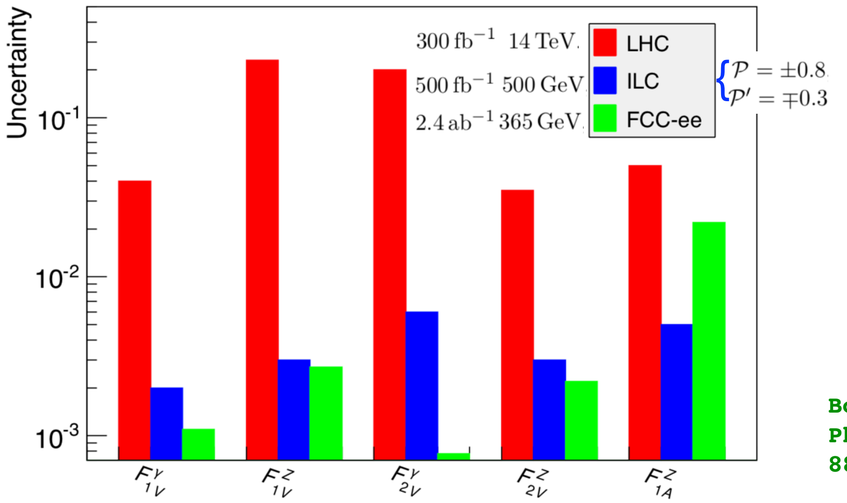
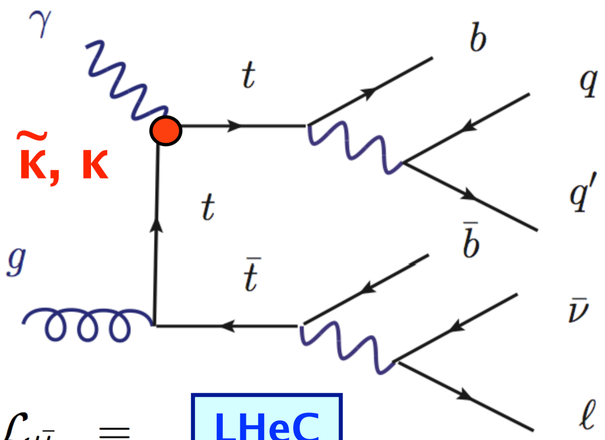


→ expected precision of order 10^{-2} to 10^{-3}

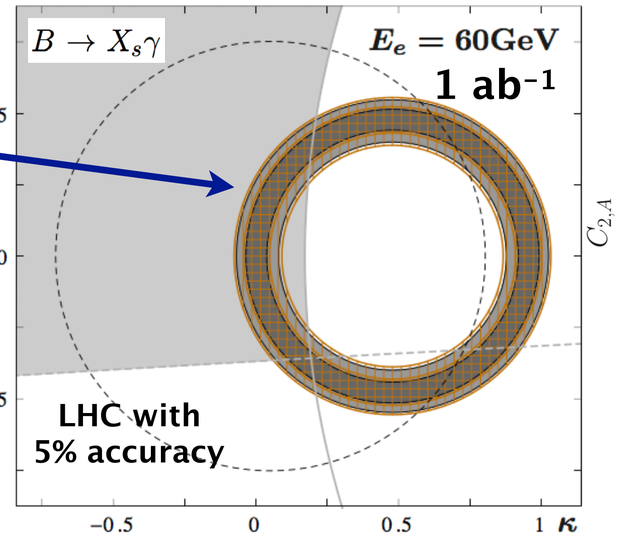


LHeC

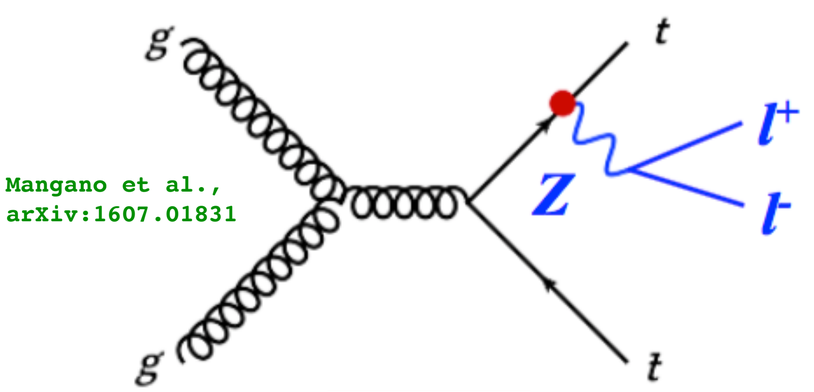
$$\mathcal{L}_{t\bar{t}\gamma} = e\bar{t}\left(Q_t\gamma^\mu A_\mu + \frac{1}{4m_t}\sigma^{\mu\nu}F_{\mu\nu}(\kappa + i\tilde{\kappa}\gamma_5)\right)t$$

10% 18% accuracy (syst. limited)

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



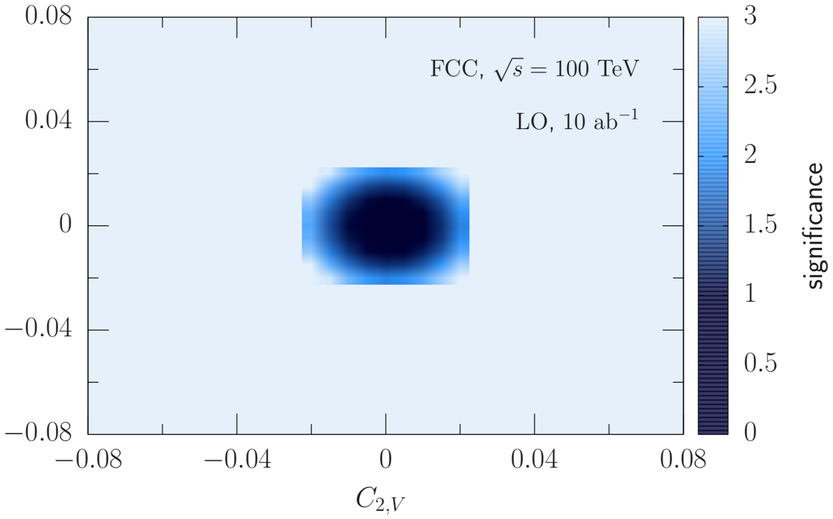
→ expected precision of order 10^{-1} to 10^{-2}



Mangano et al., arXiv:1607.01831

FCC-pp

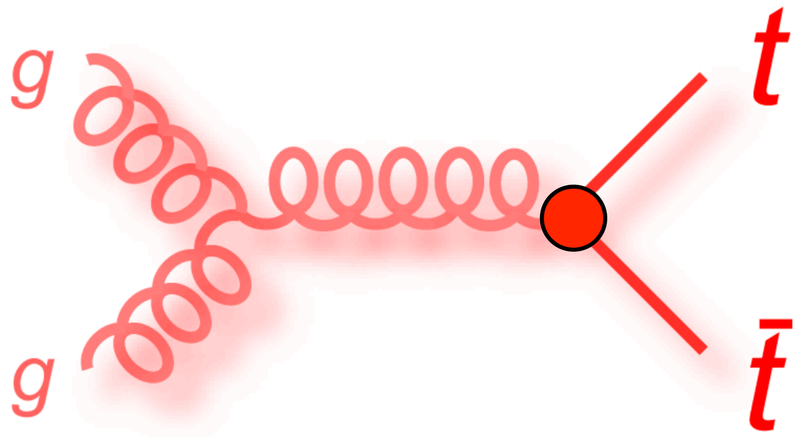
$$\mathcal{L}_{t\bar{t}Z} = e\bar{\psi}_t\left[\gamma^\mu\left(C_{1,V} + \gamma_5 C_{1,A}\right) + \frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(C_{2,V} + i\gamma_5 C_{2,A}\right)\right]\psi_t Z_\mu$$



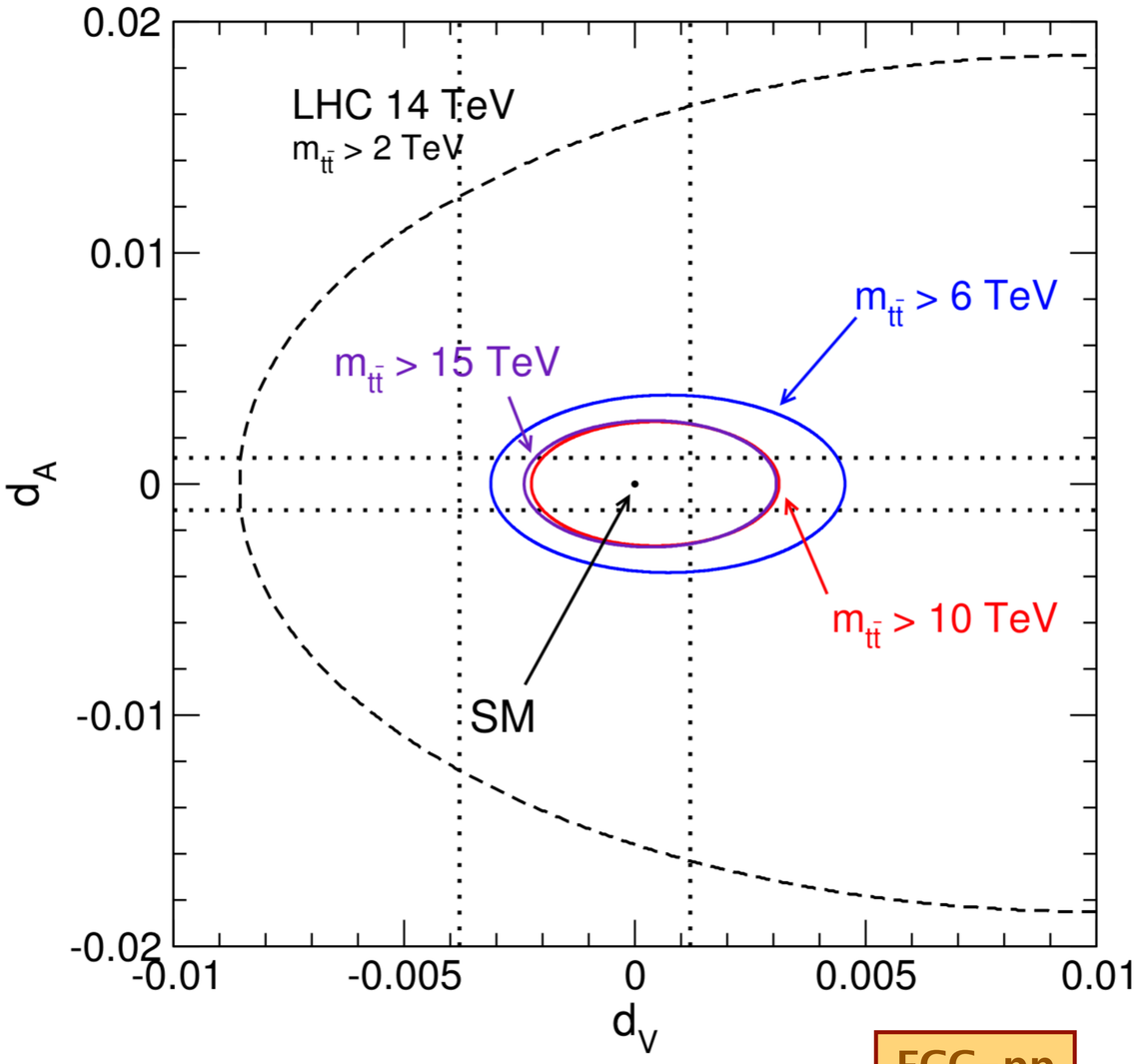
→ expected precision of order 10^{-2}

Chromoelectric and Chromomagnetic Dipole Moments

$$\mathcal{L} = \mathcal{L}_{\mathrm{QCD}} + \frac{g_s}{m_t}\,\bar{t}\sigma^{\mu\nu}(d_V + \mathrm{i}\,d_A\gamma_5)\frac{\lambda_a}{2}\,t\,G^a_{\mu\nu}$$



Mangano et al., arXiv:1607.01831

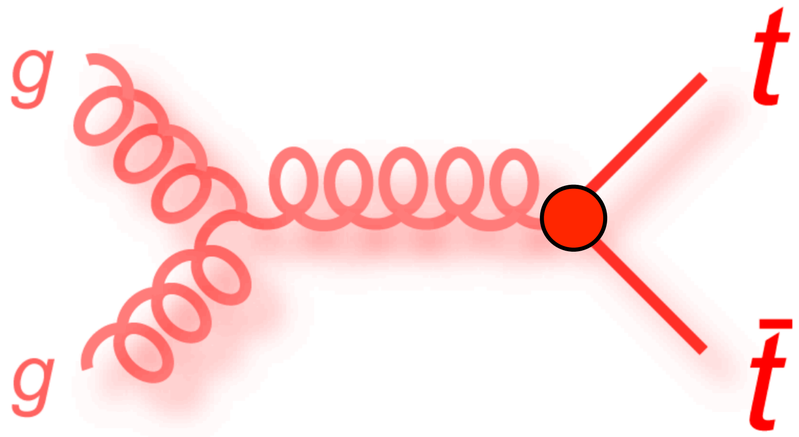


FCC-pp

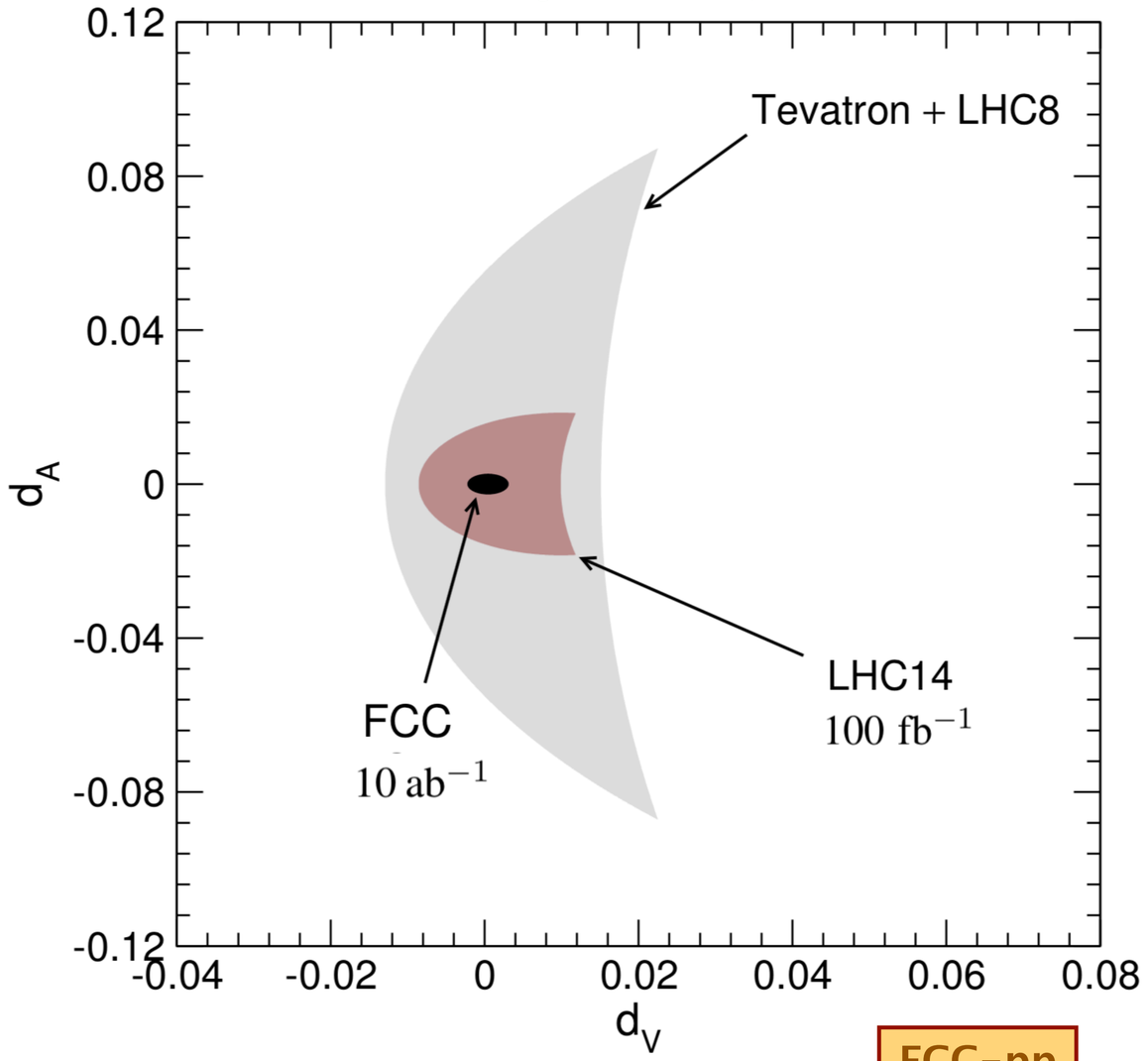
→ **expected precision of order 10^{-2}**

Chromoelectric and Chromomagnetic Dipole Moments

$$\mathcal{L} = \mathcal{L}_{\mathrm{QCD}} + \frac{g_s}{m_t}\,\bar{t}\sigma^{\mu\nu}(d_V + \mathrm{i}\,d_A\gamma_5)\frac{\lambda_a}{2}\,t\,G^a_{\mu\nu}$$



Mangano et al., arXiv:1607.01831



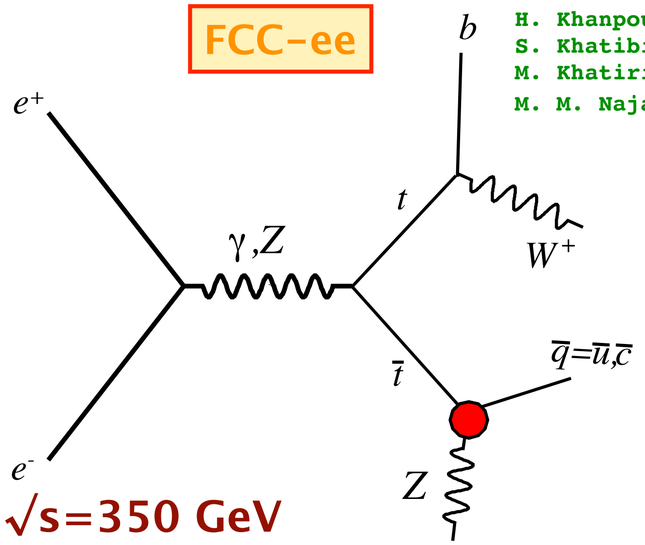
FCC-pp

→ **expected precision of order 10^{-2}**

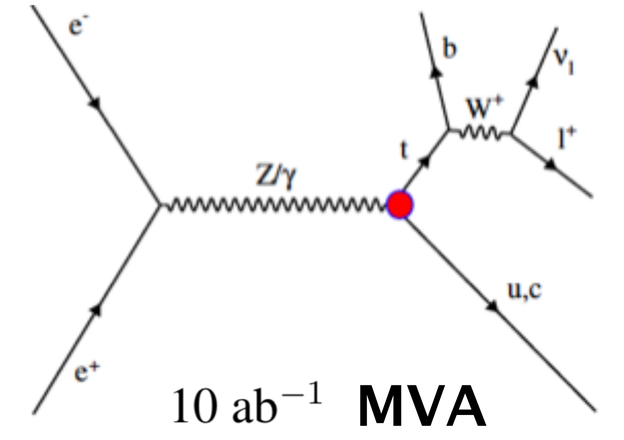
Flavor Changing Neutral Current Couplings

FCC-ee

H. Khanpou
S. Khatibi
M. Khatiri
M. M. Najafabadi



√s=350 GeV



√s=240 GeV and √s=350 GeV

Br(t→qγ), Br(t→qZ)<O(10^{-6}–10^{-5})

Flavor Changing Neutral Current Couplings

FCC-ee

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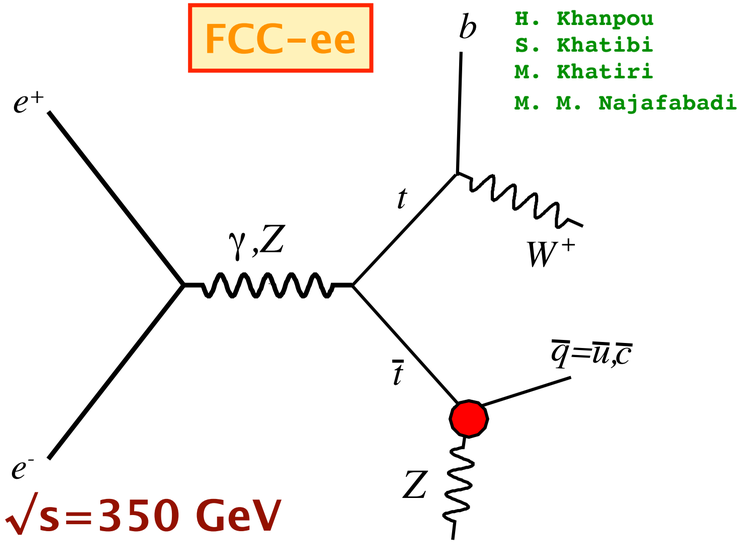
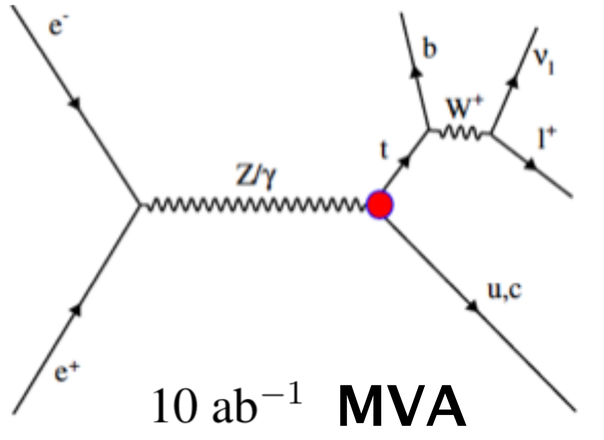


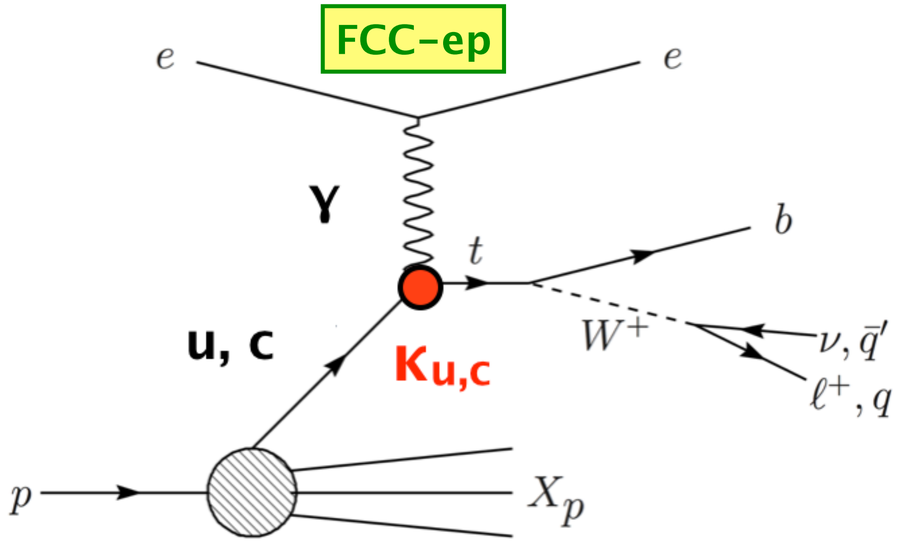
√s=350 GeV



$10\ \text{ab}^{-1}$ **MVA**

√s=240 GeV and √s=350 GeV

FCC-ep



Br(t→qγ), Br(t→qZ)<O(10⁻⁶–10⁻⁵)

Flavor Changing Neutral Current Couplings

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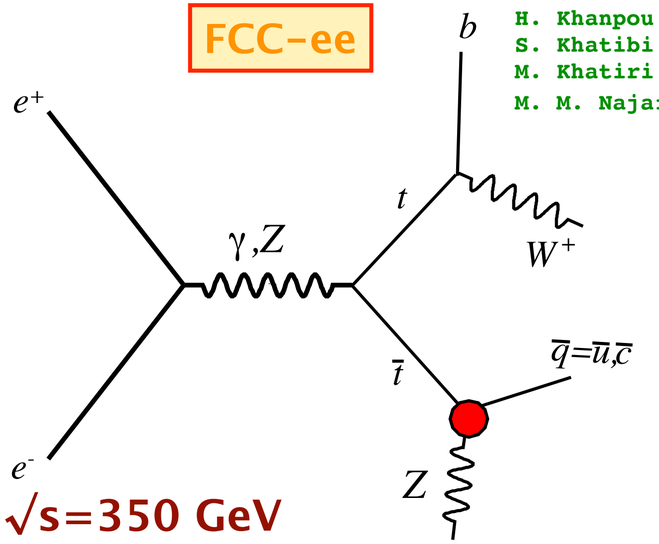
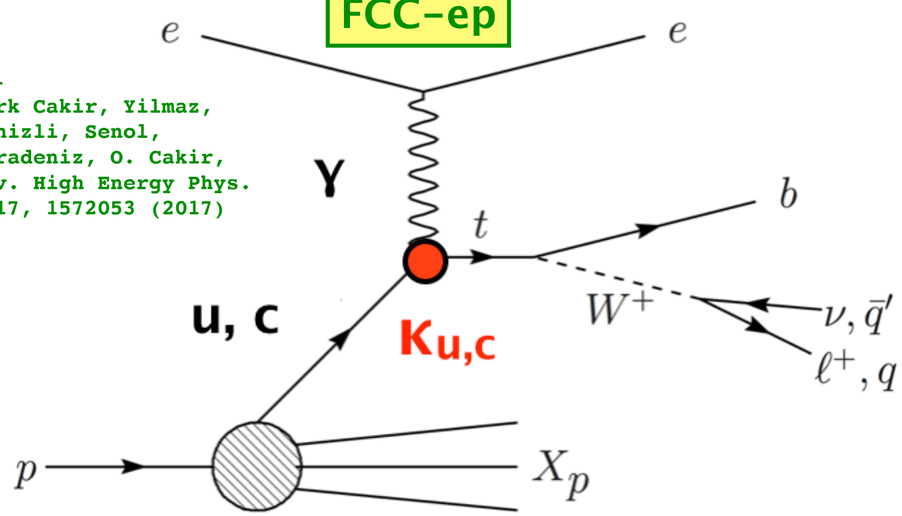
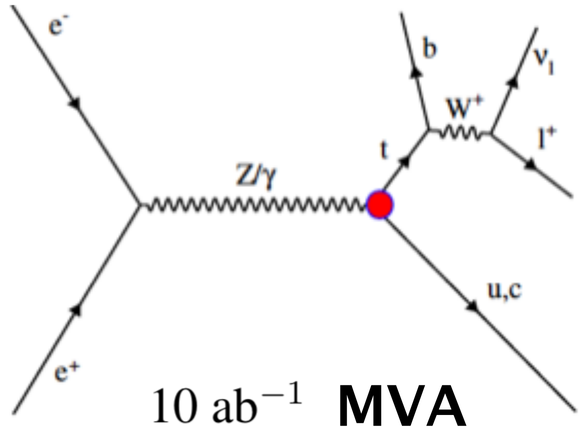


$\sqrt{s}$=350 GeV

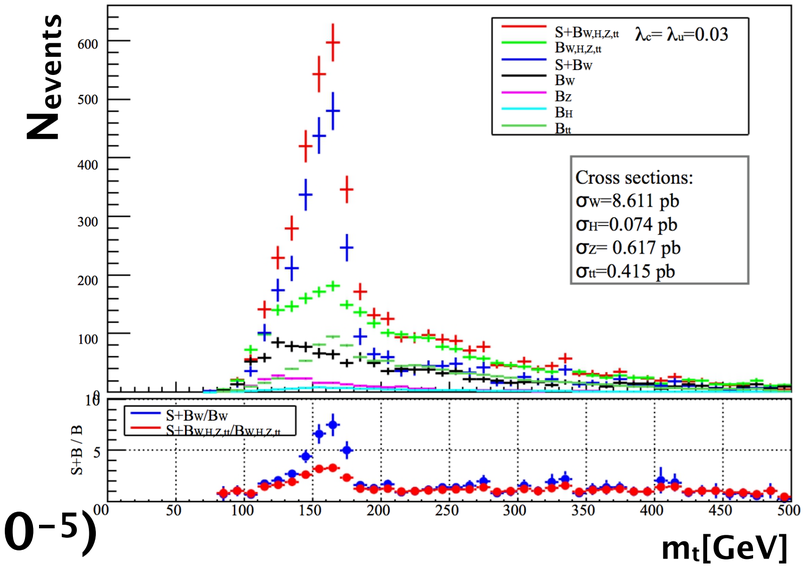
FCC-ep

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





$\sqrt{s}$=240 GeV and $\sqrt{s}$=350 GeV



Br(t→qγ), Br(t→qZ)<O(10^{-6}–10^{-5})

Flavor Changing Neutral Current Couplings

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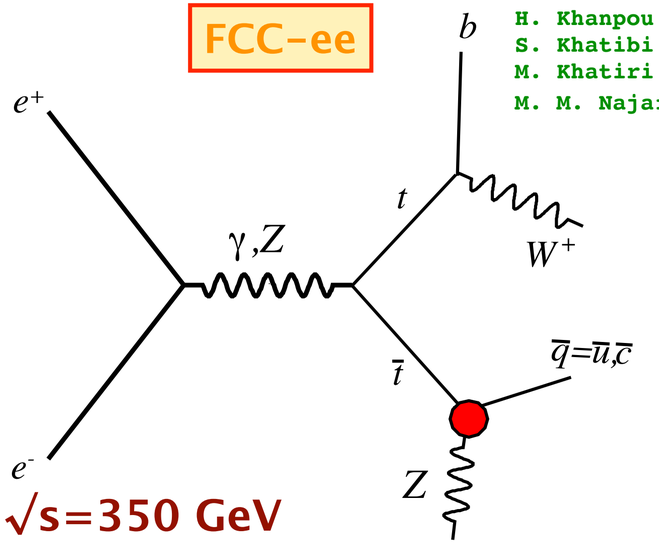
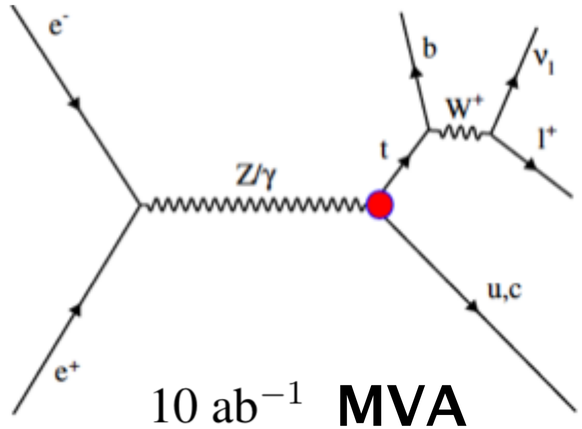


√s=350 GeV

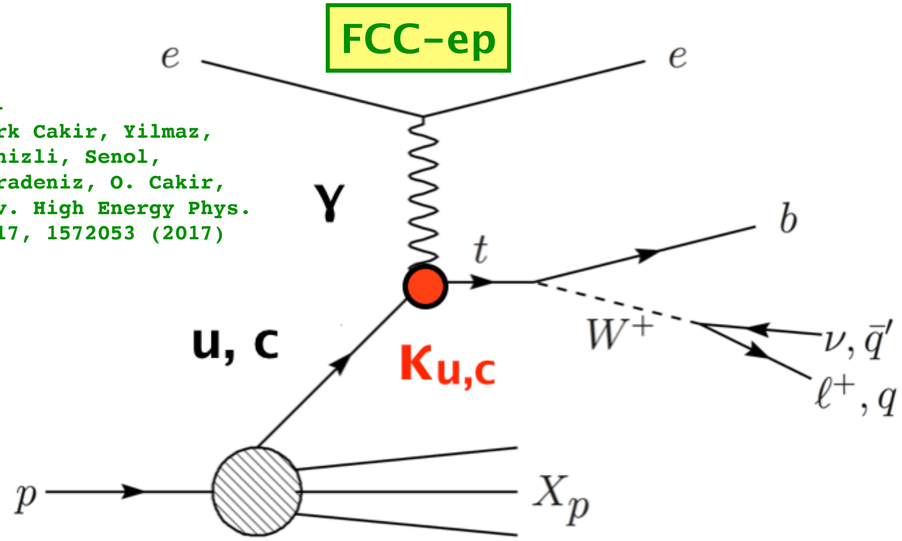


$10\ ab^{-1}$ **MVA**

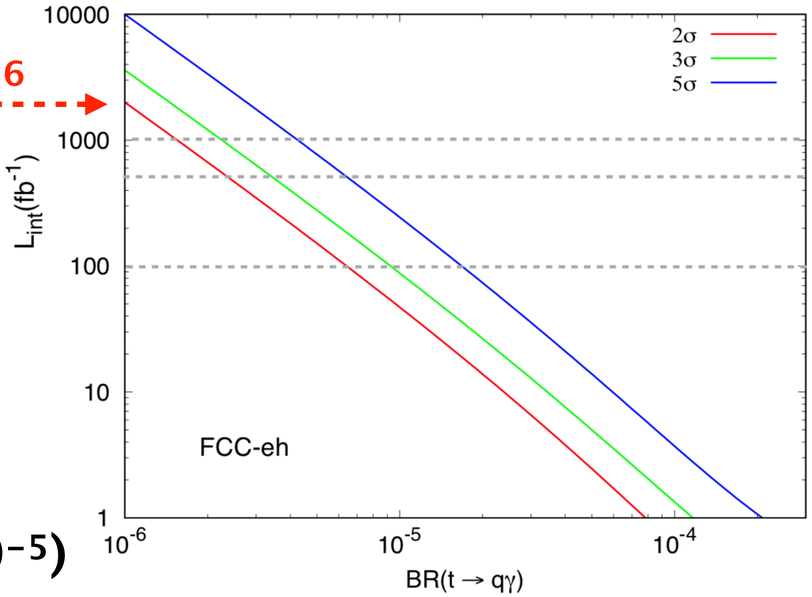
√s=240 GeV and √s=350 GeV

FCC-ep

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



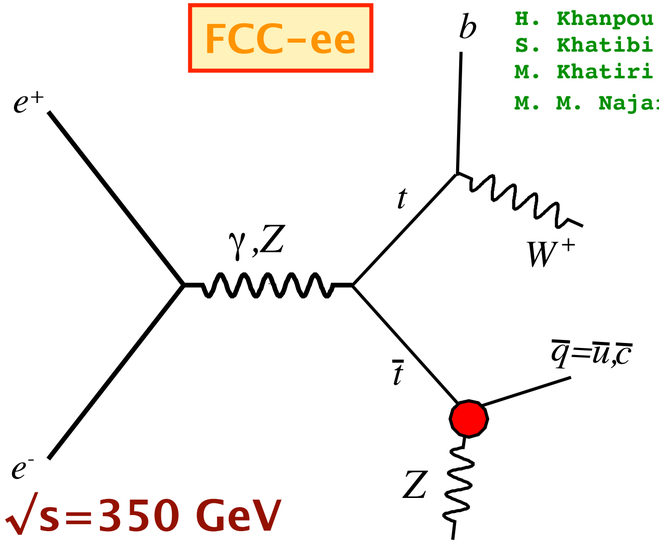
10⁻⁶



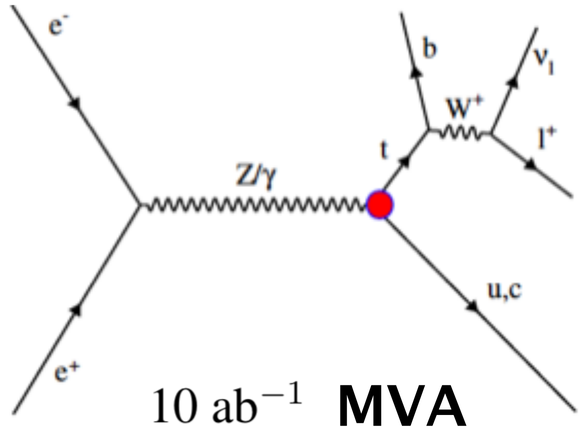
Br(t→qγ), Br(t→qZ)<O(10⁻⁶–10⁻⁵)

Flavor Changing Neutral Current Couplings

FCC-ee



√s=350 GeV



10 ab^{-1} **MVA**

√s=240 GeV and √s=350 GeV

Br(t→qγ), Br(t→qZ)<O(10⁻⁶–10⁻⁵)

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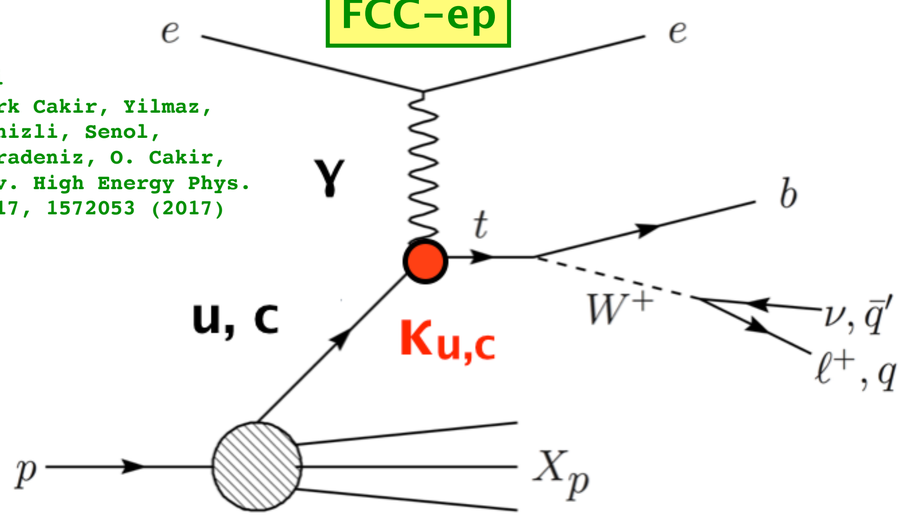
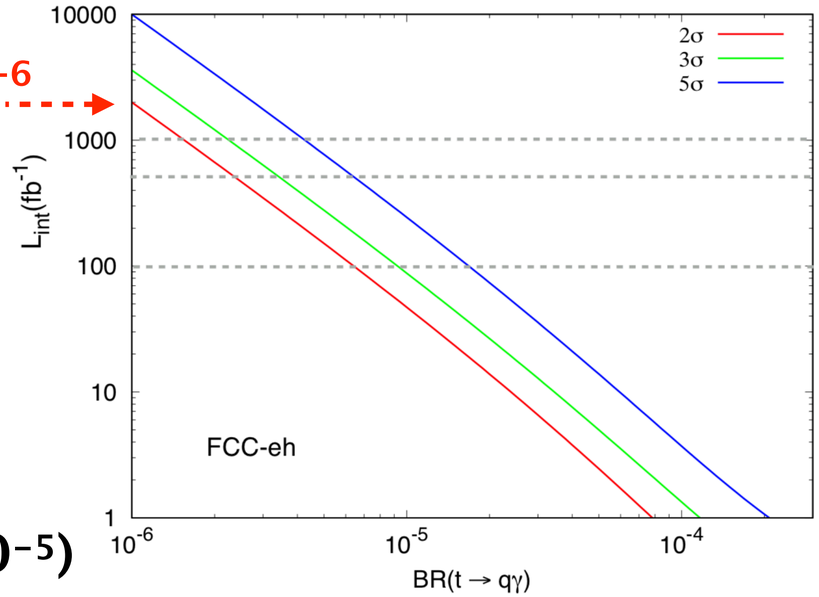
Turk Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)

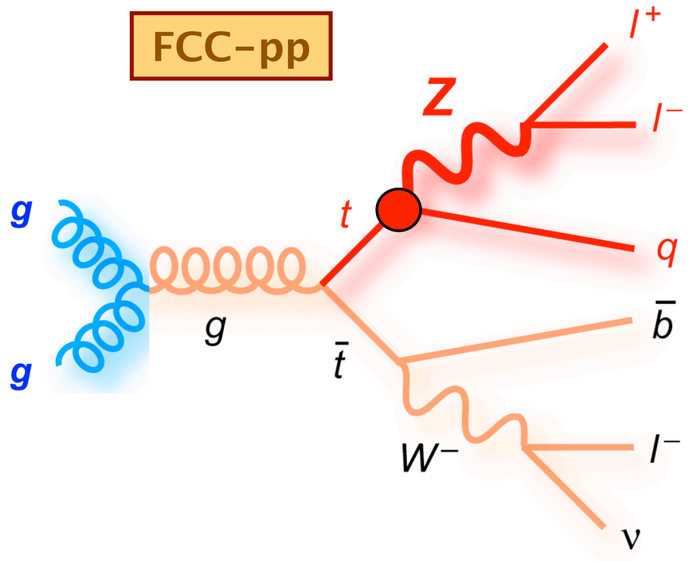
FCC-ep



10⁻⁶



FCC-pp



Br(t→qZ)<10⁻⁷

(rescaling of the LHC expectations)

10 ab^{-1}

Flavor Changing Neutral Current Couplings

FCC-ee

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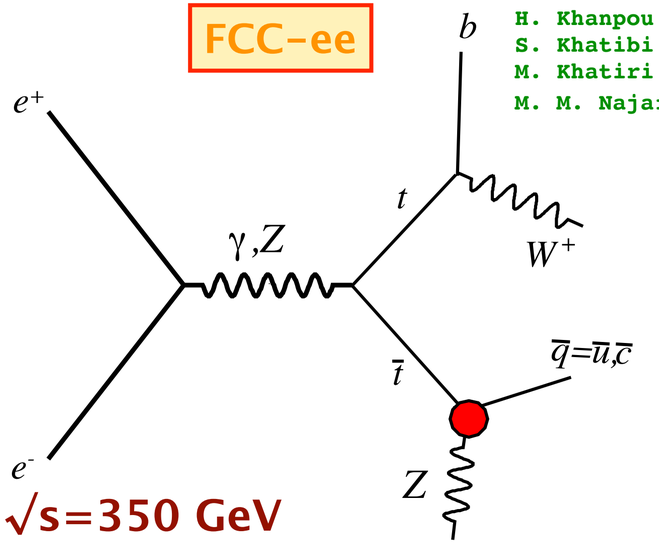
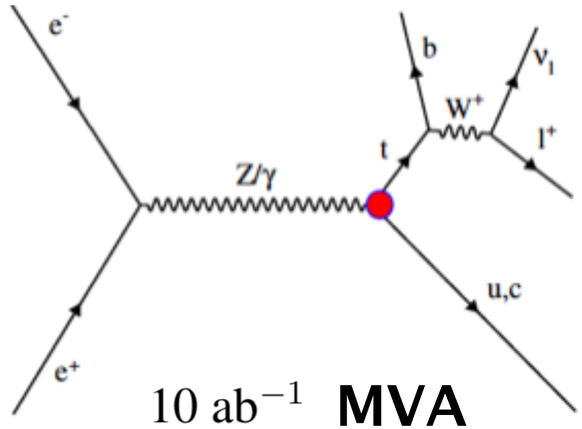


√s=350 GeV



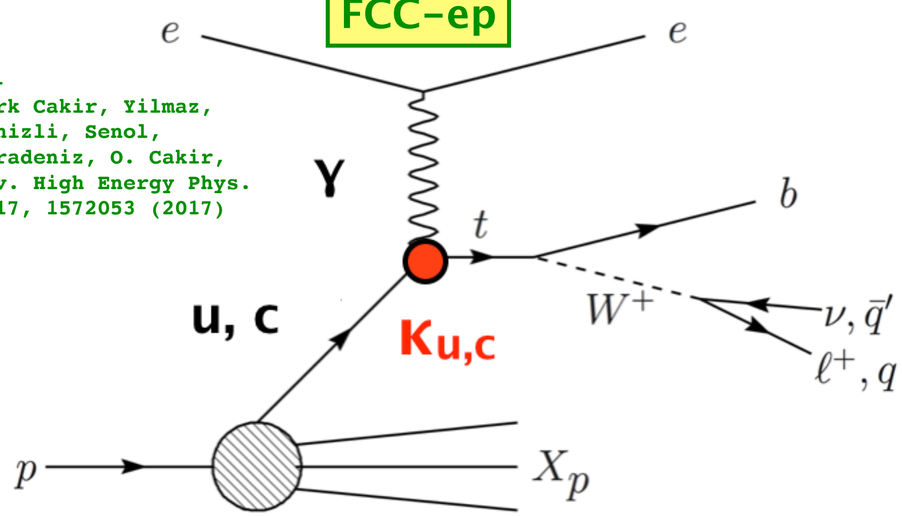
$10\ ab^{-1}$ **MVA**

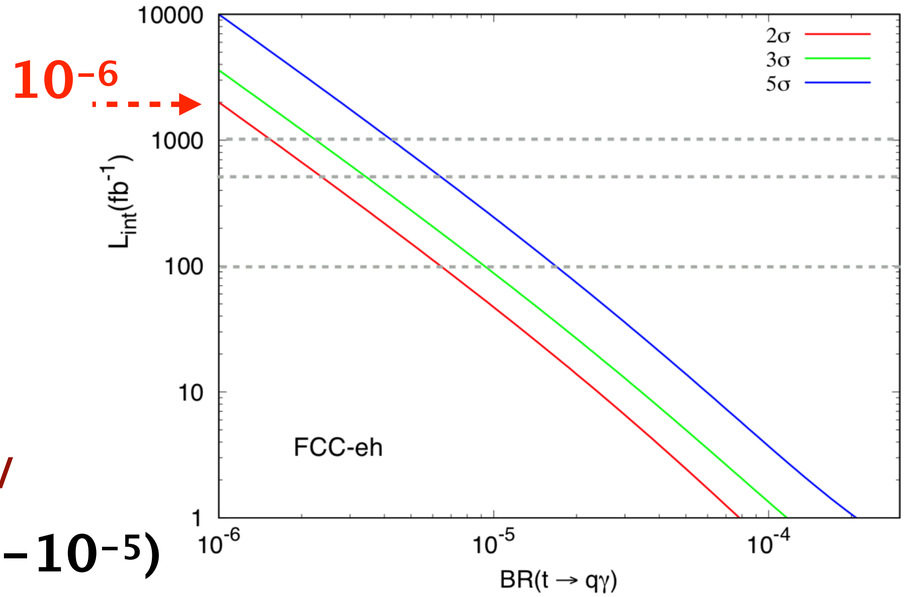
√s=240 GeV and √s=350 GeV

Br(t→qγ), Br(t→qZ)<O(10^{-6}–10^{-5})

FCC-ep

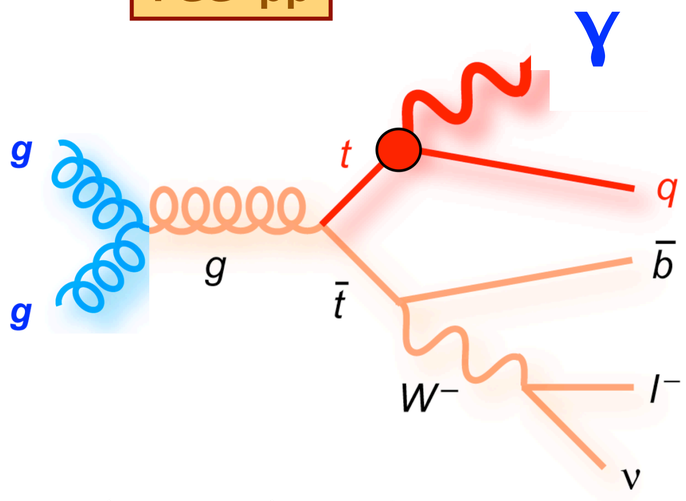
Turk Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)





10^{-6}

FCC-pp



Br(t→qγ)<10^{-7}

(rescaling of the LHC expectations)

$10\ ab^{-1}$

Flavor Changing Neutral Current Couplings

FCC-ee

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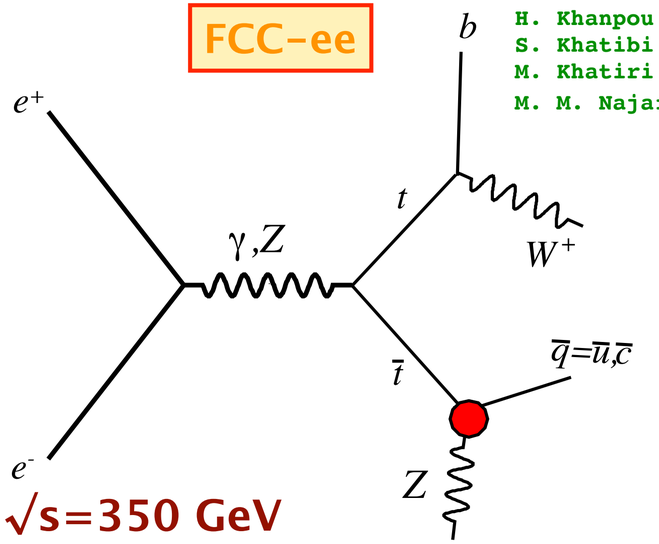
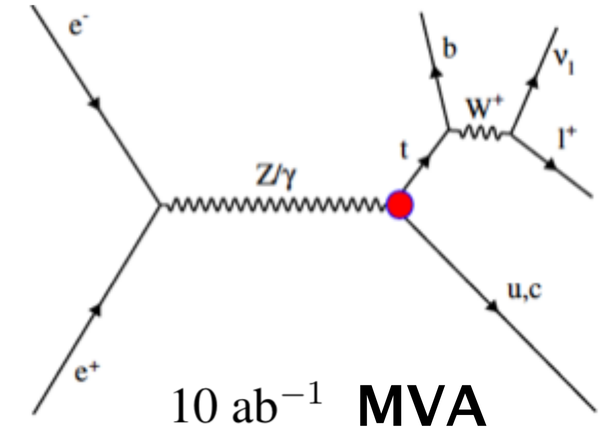


$\sqrt{s}$=350 GeV

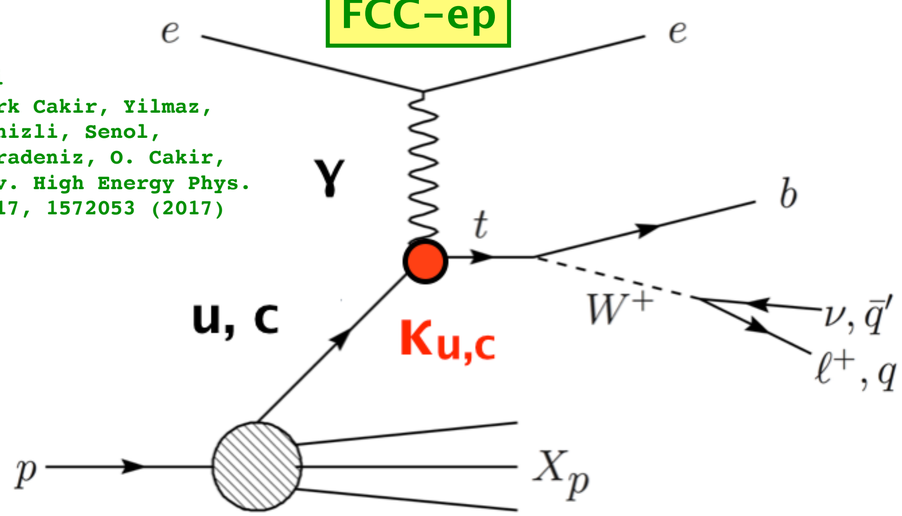


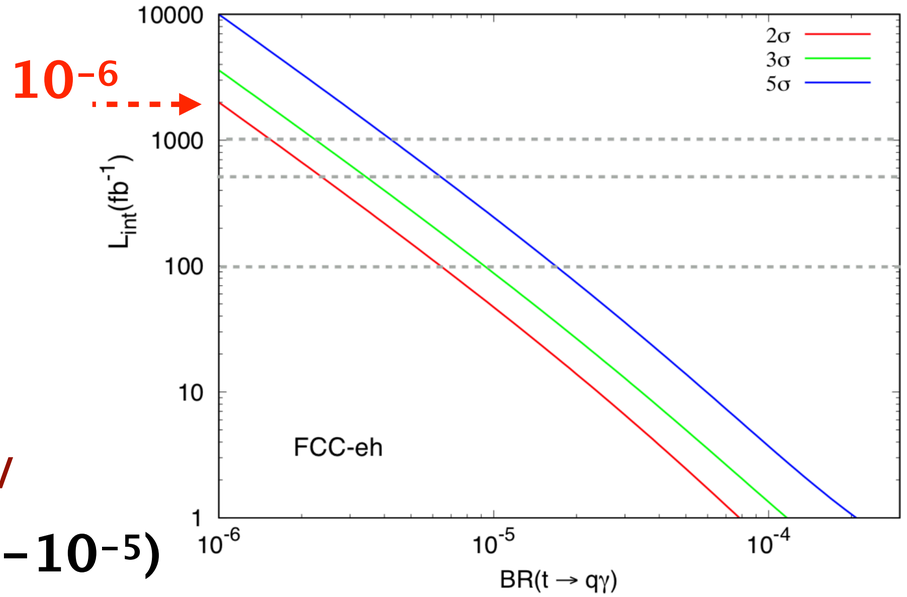
10 ab^{-1} **MVA**

$\sqrt{s}$=240 GeV and $\sqrt{s}$=350 GeV

FCC-ep

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

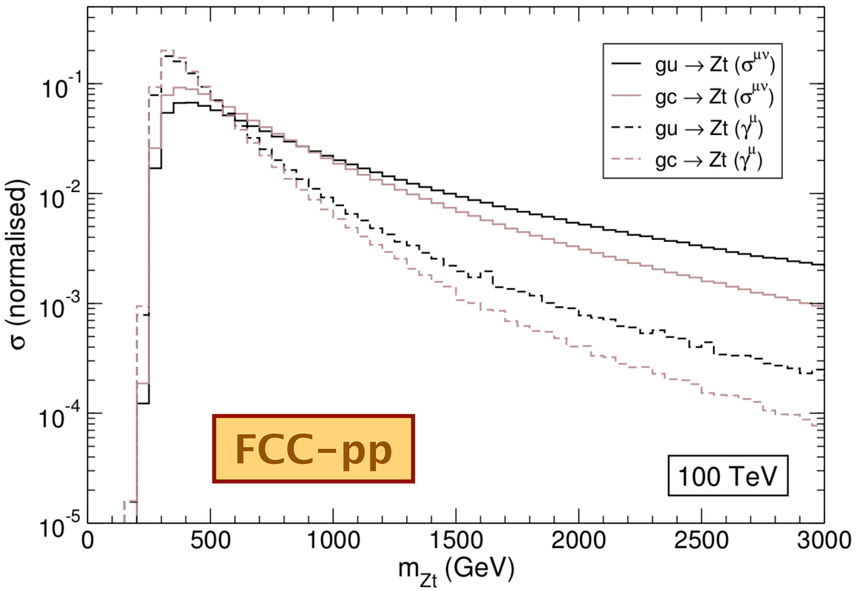


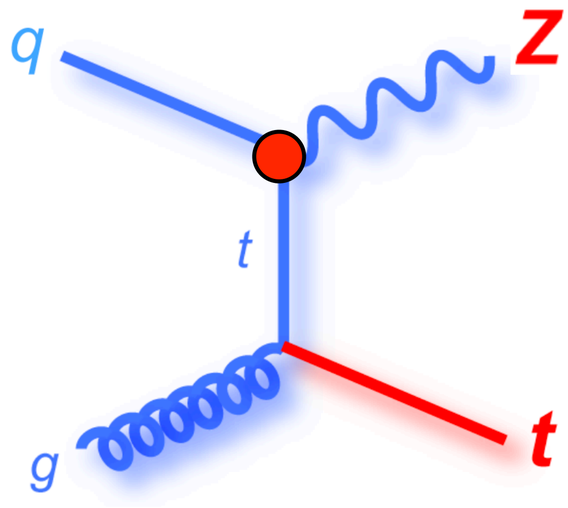


10^{-6}

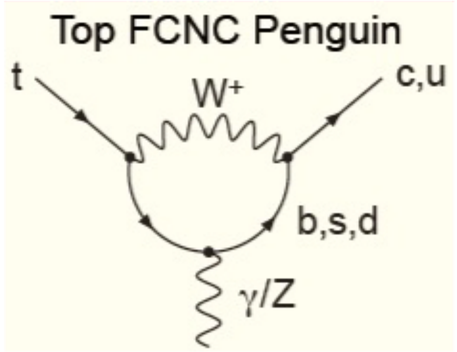
Br(t→qγ), Br(t→qZ)<O(10^{-6}–10^{-5})

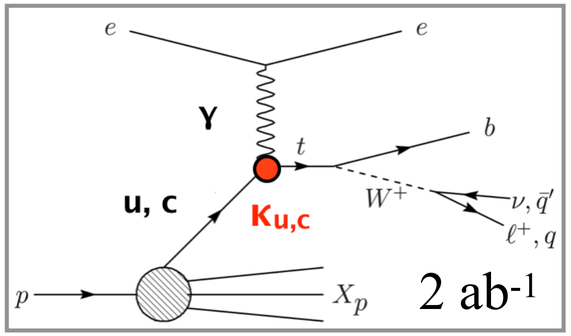
Mangano et al., arXiv:1607.01831





FCNC Branching Ratios at Colliders

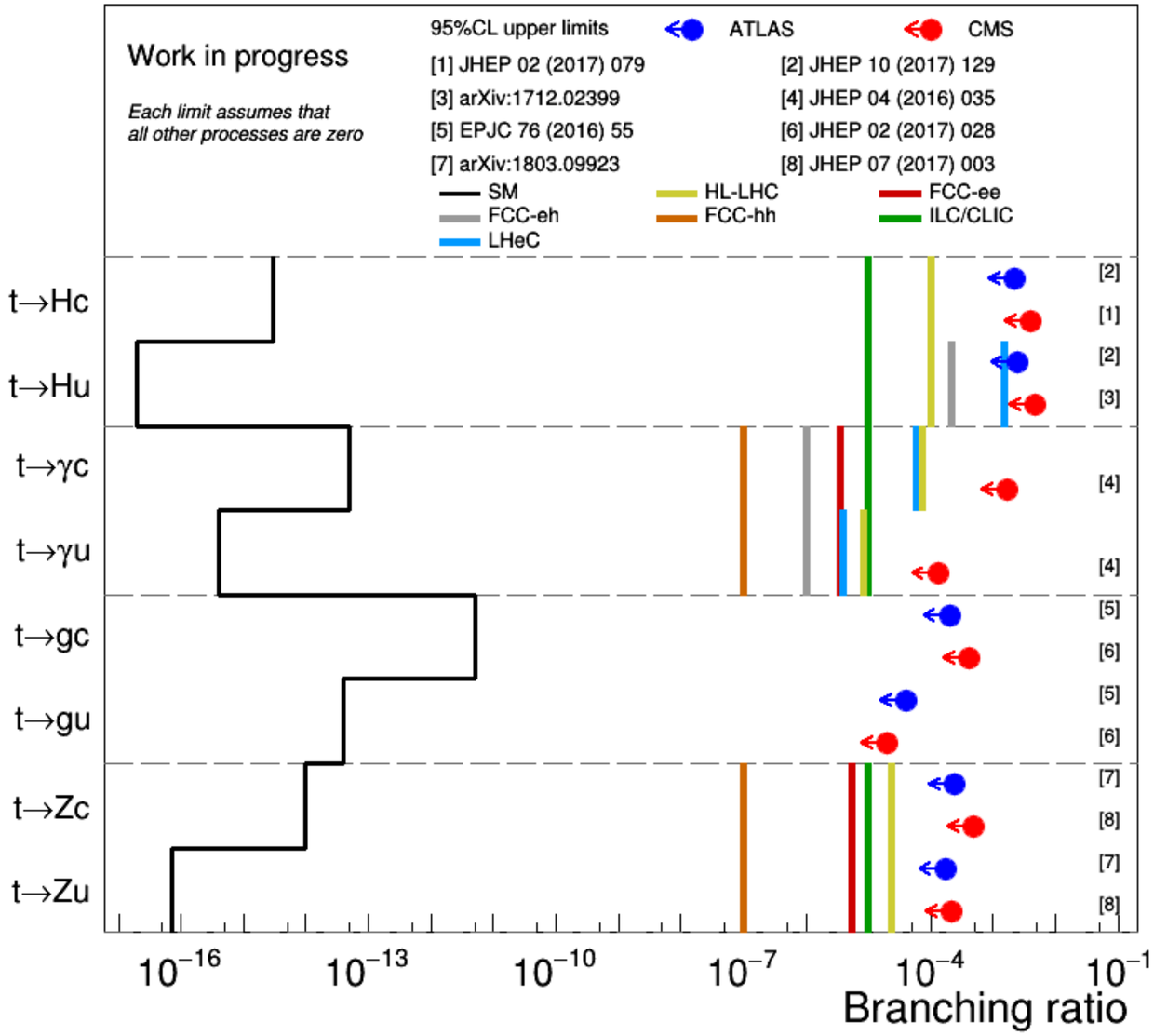




FCC-ep

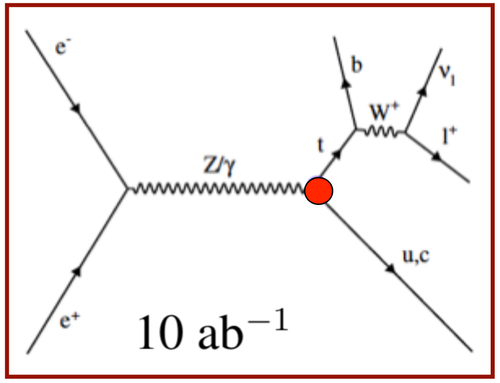
see talk O. Cakir

→ test SUSY, little Higgs, technicolor...

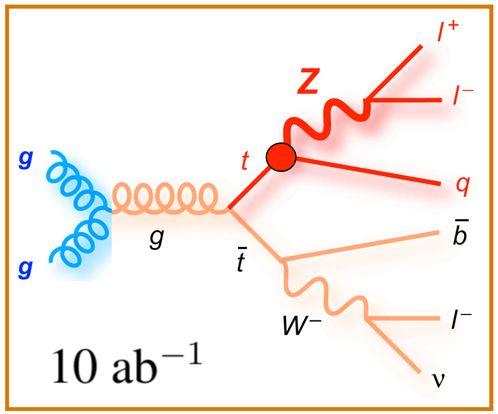


K. Skovpen

FCC-ee



FCC-pp

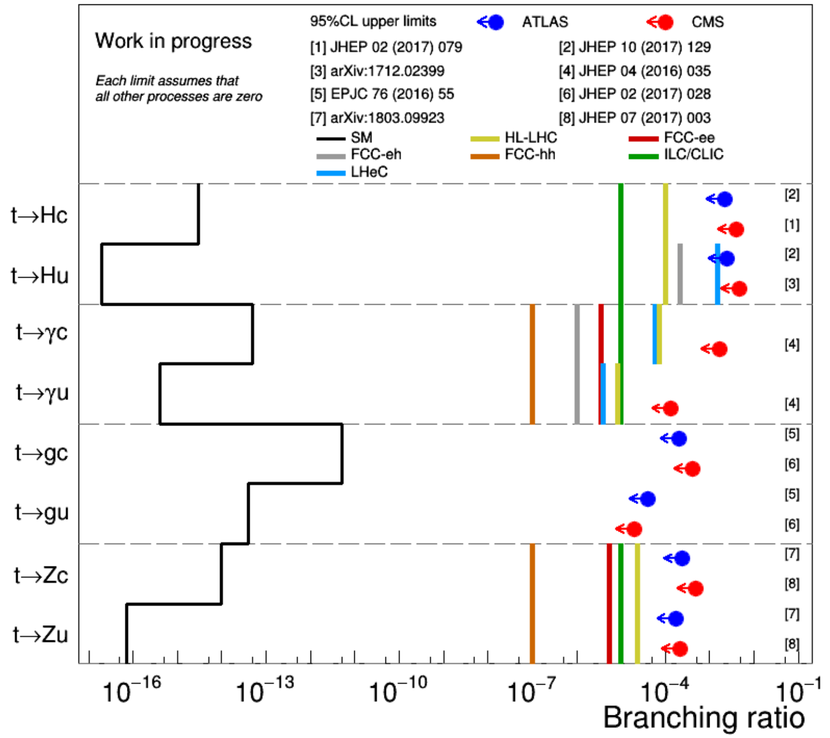


Summary

- **future ee, ep, pp colliders have a rich analysis programme for top quark physics**
- **analyse top quark properties with high precision:**
  mass, width, polarisation, charge, asymmetry, PDFs of tops, …
- **top quark couplings:**
  (Wtb, ttγ, ttZ, ttg, ttH, …)
- **many stringent searches for new physics:**
  anomalous couplings, FCNC, composite Higgs, …
- **complementarity of different colliders**

→ more exciting studies exist

→ more exciting studies to come

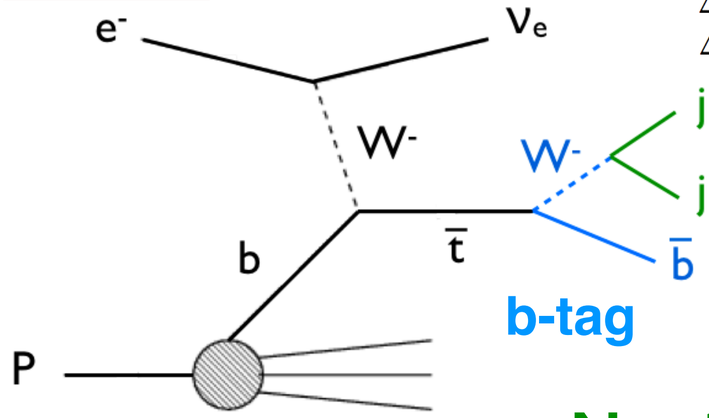


Backup

Signal and Backgrounds

LHeC

signal



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

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

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

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

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

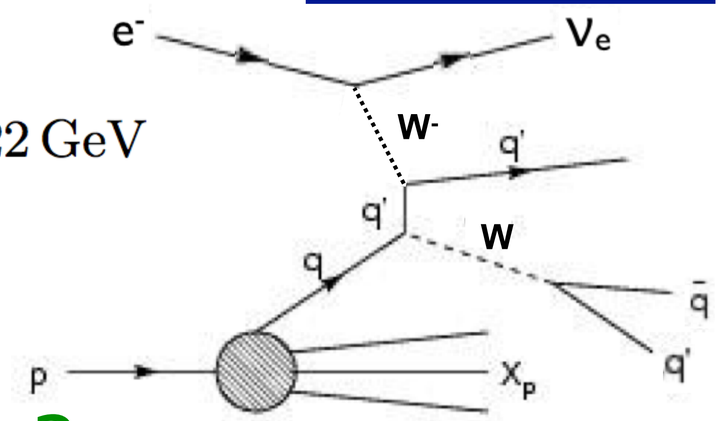
$|\eta_j| \leq 5, |\eta_b| \leq 2.5$

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

b-tag

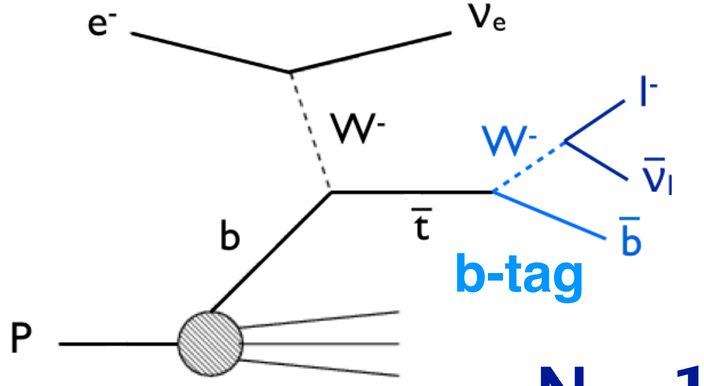
Dutta, Goyal, Kumar, Mellado, Eur. Phys. J. C75 (2015) no.12, 577

background



N_t=220k, s/b=1.2

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



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

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

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

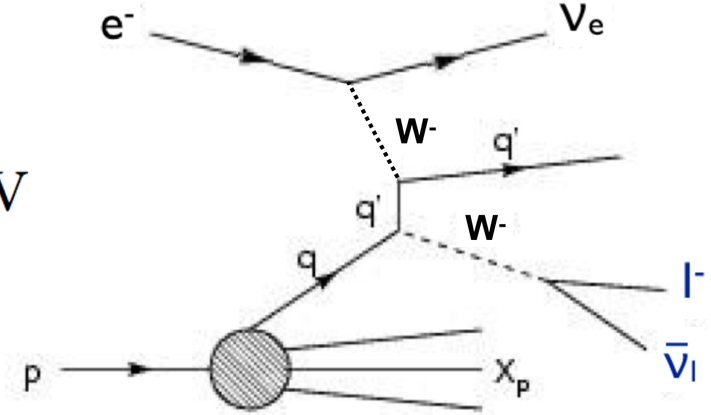
$\Delta\Phi_{\not{E},l} \geq 0.4$

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

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

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

b-tag



N_t=110k, s/b=11

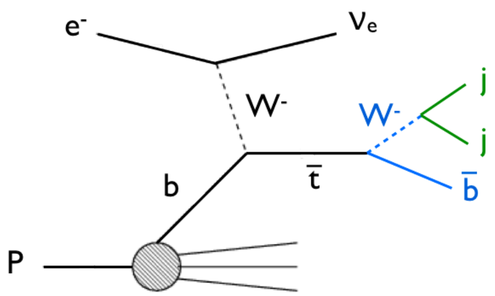
Search for Anomalous Wtb Couplings

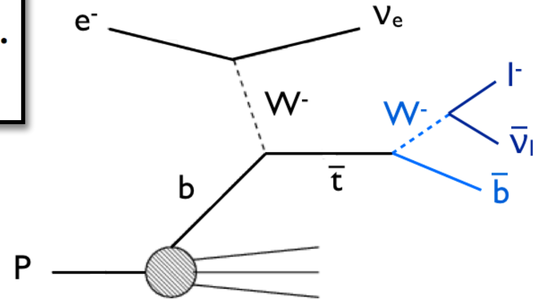
= 1 in SM

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

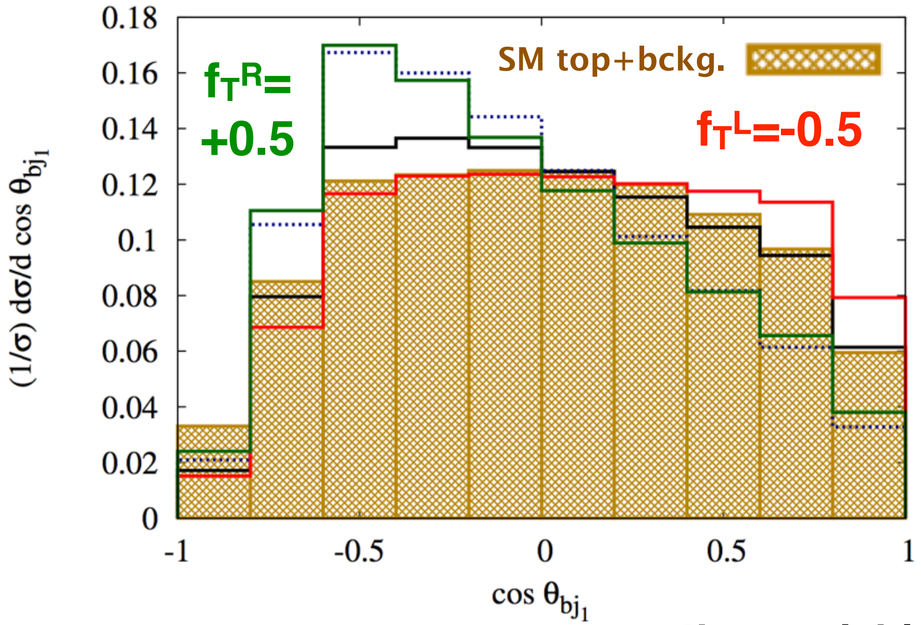
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

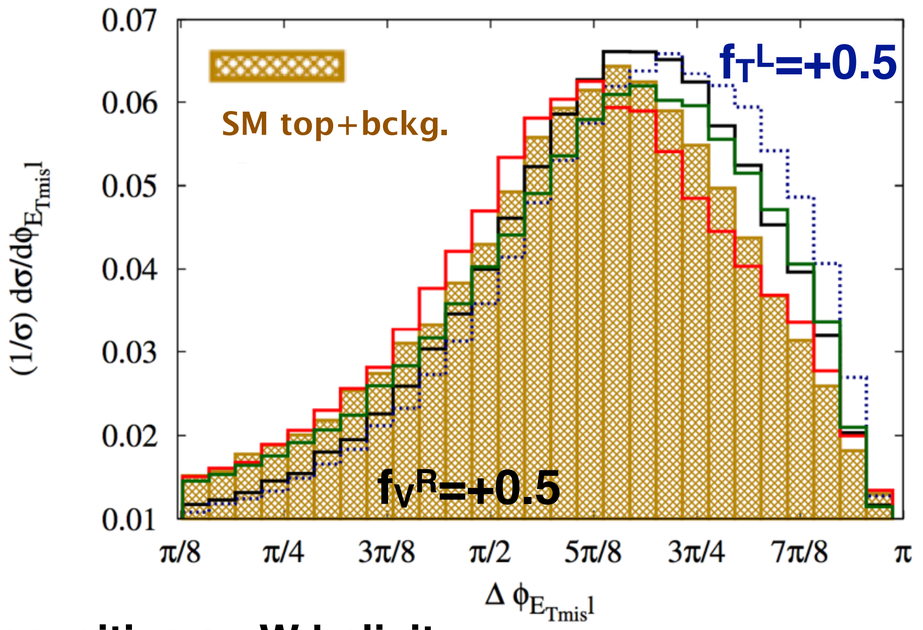
Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688





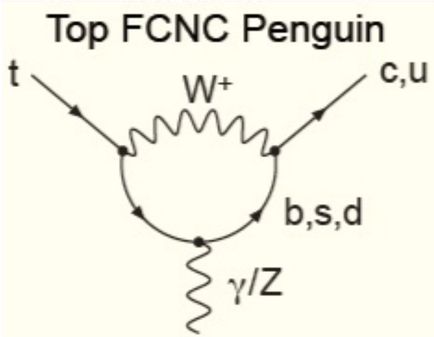
$L_{int} = 100\ fb^{-1}$

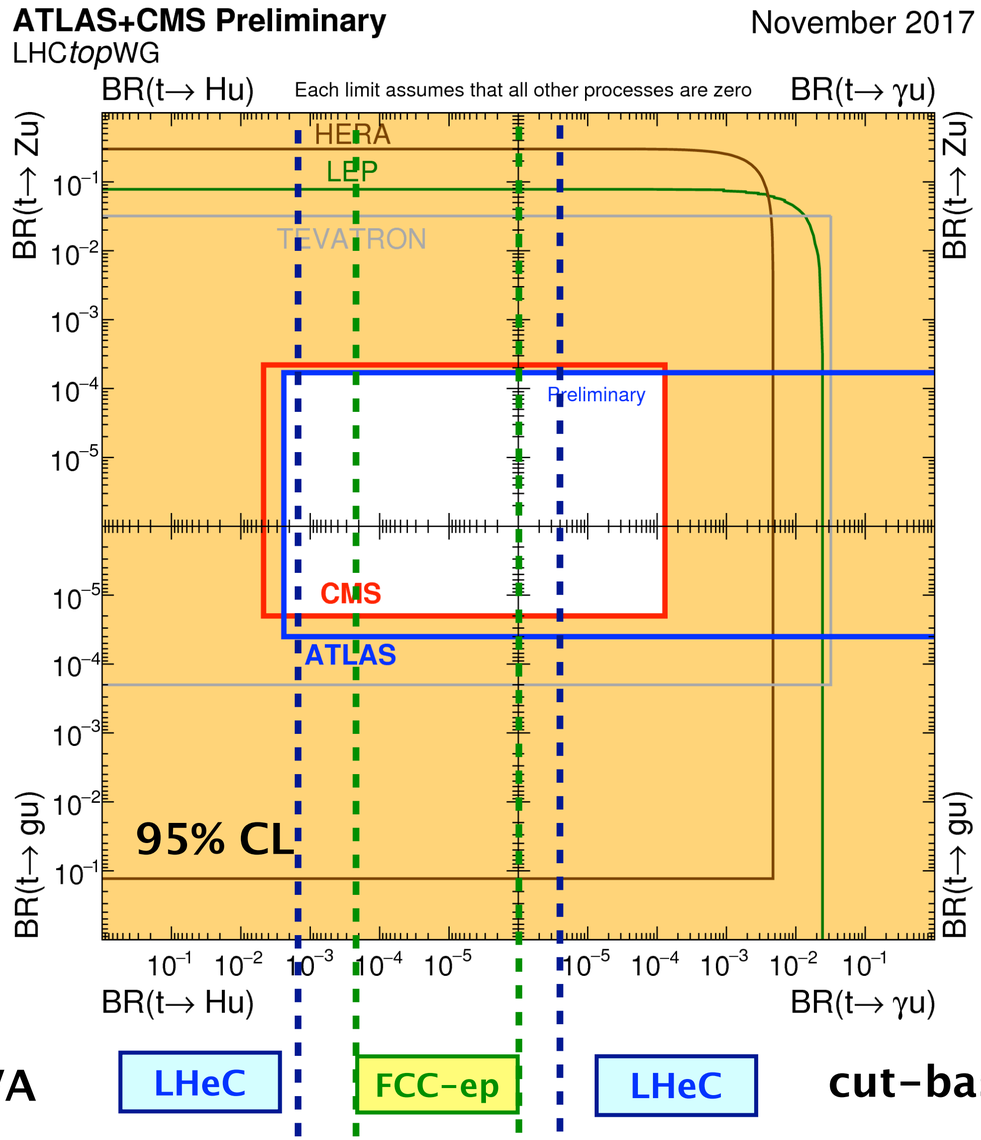




+ other variables sensitive on W helicity

FCNC Branching Ratios at Colliders





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

→ test SUSY, little Higgs, technicolor...

E_e=60 GeV
1000 fb^{-1}

MVA

LHeC

FCC-ep

LHeC

cut-based

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

J-A Aguilar-Saavedra, Fuks, etal, arXiv:1412.6654

$$\mathcal{L}_{\rm tg} = -g_s \bar{t}\gamma^\mu \frac{\lambda_a}{2} t\, G^a_\mu + \frac{g_s}{m_t}\bar{t}\sigma^{\mu\nu}(d_V + i d_A \gamma_5)\frac{\lambda_a}{2} t\, G^a_{\mu\nu}$$

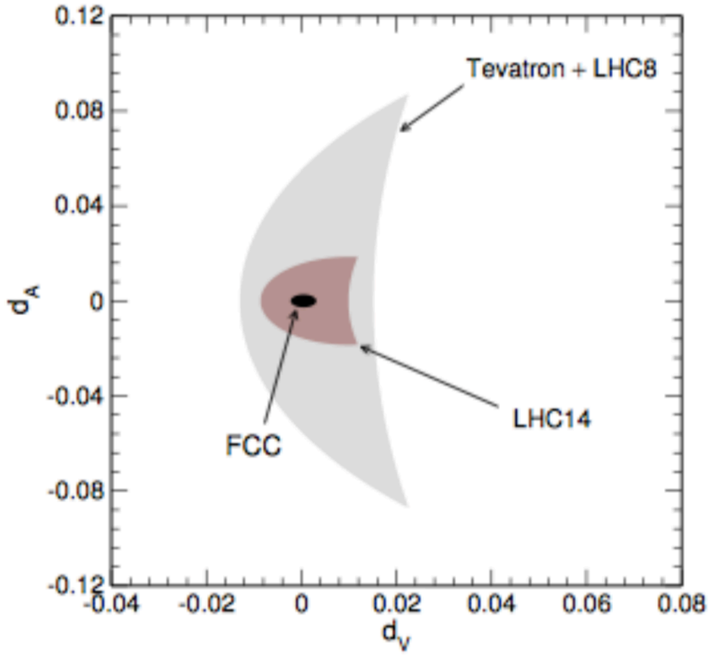
$$O^{33}_{uG\phi} = (\bar{q}_{L3}\lambda_a \sigma^{\mu\nu} t_R)\tilde{\phi}\, G^a_{\mu\nu} \quad \Rightarrow \quad d_V = \frac{\sqrt{2} v m_t}{g_s \Lambda^2}\,\mathrm{Re}\, C^{33}_{uG\phi}\,, \quad d_A = \frac{\sqrt{2} v m_t}{g_s \Lambda^2}\,\mathrm{Im}\, C^{33}_{uG\phi}$$

At 100 TeV, constraints from event rate at M_{tt} > 10 TeV:

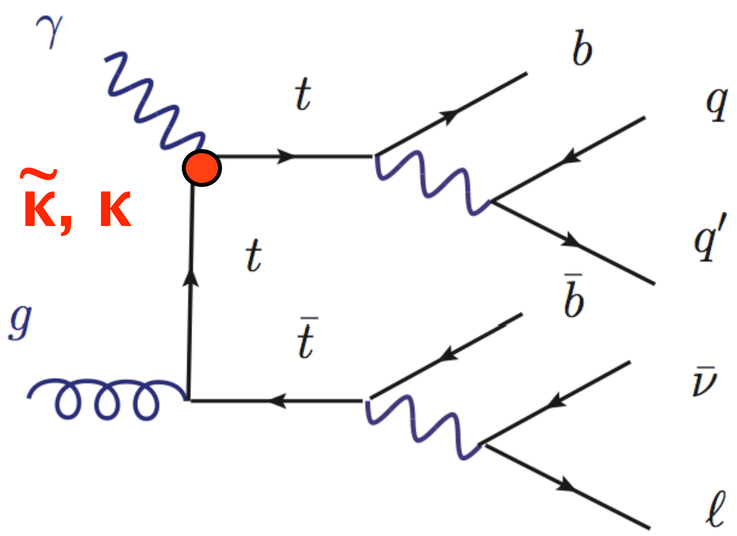
$-0.0022 \leq d_V \leq 0.0031$

$|d_A| \leq 0.0026$

$\Rightarrow \Lambda \gtrsim 17$ TeV



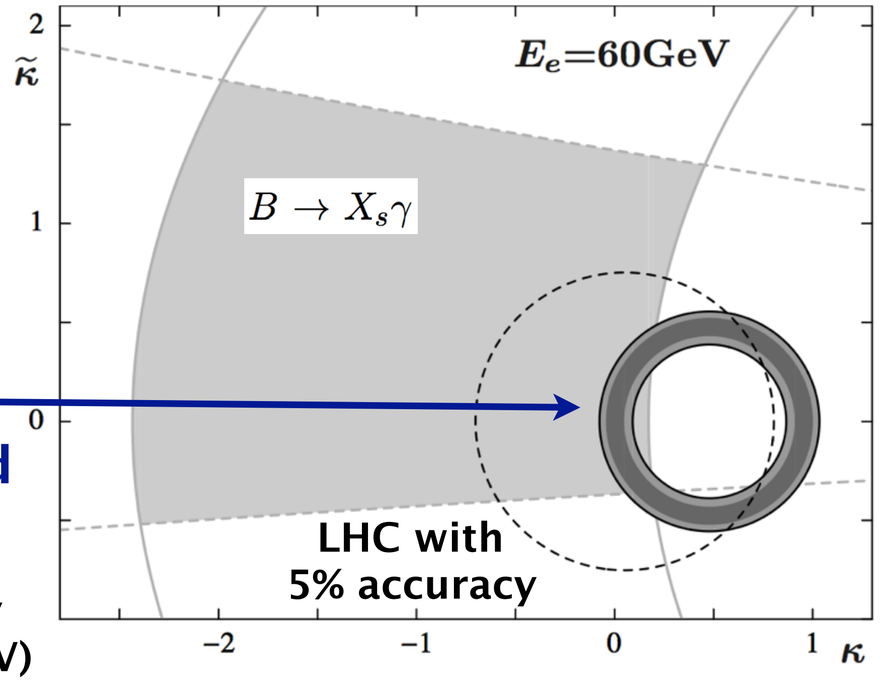
Search for Anomalous $t\bar{t}\gamma$ Couplings



$\tilde{\kappa}$, κ

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

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



magnetic dipole moment: κ

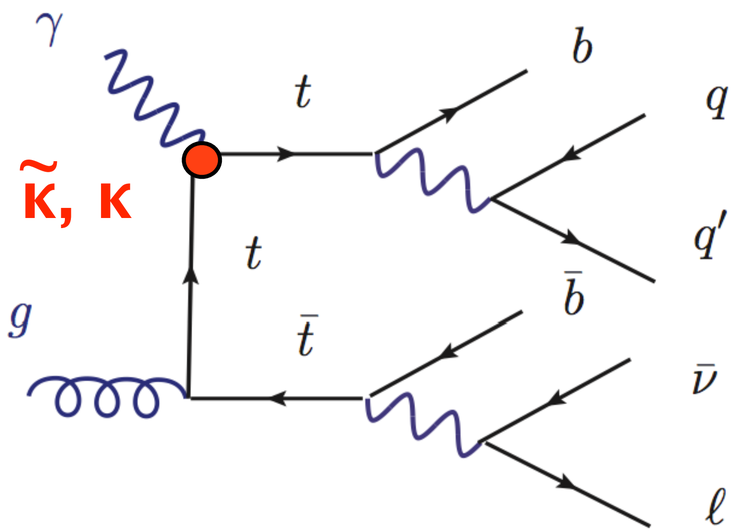
LHeC

10% and 18% accuracy assumed

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

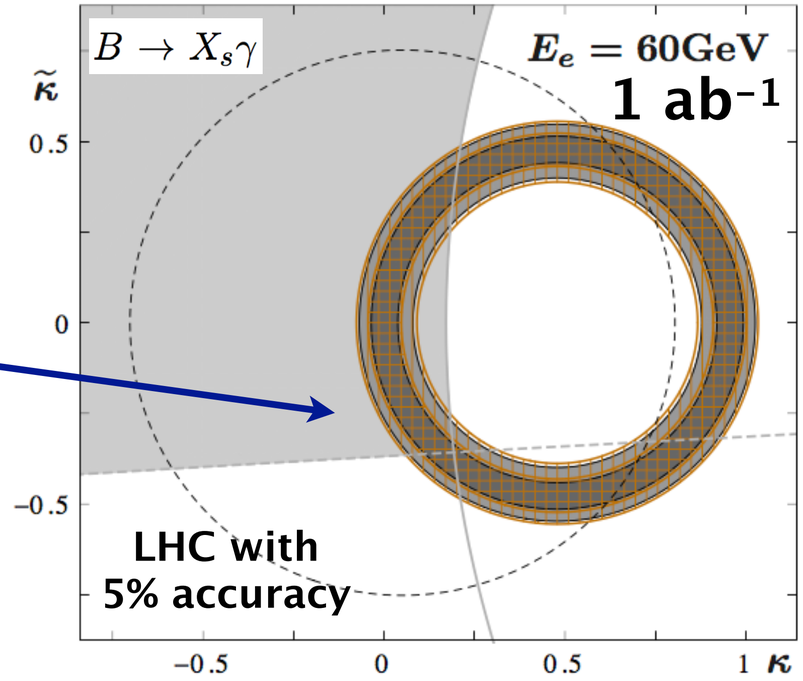
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

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



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

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



magnetic dipole moment: κ

LHeC

8% and 16% accuracy

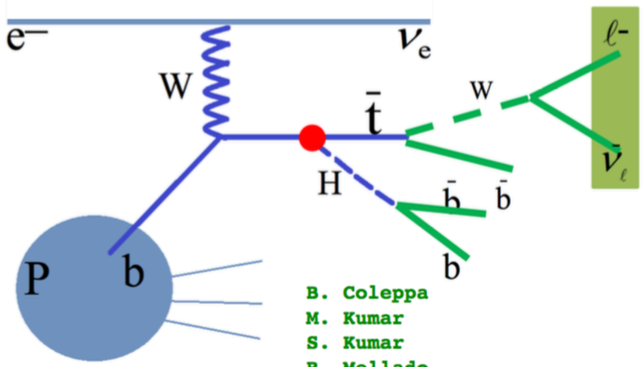
10% 18%

→ systematically limited

ATLAS 27% accuracy (4.59fb⁻¹, 7 TeV)

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

CP Nature of Top-Higgs Coupling

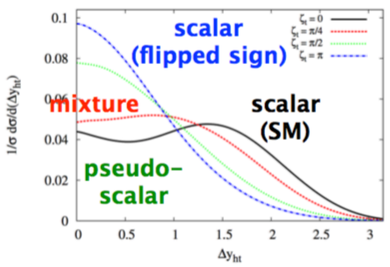


B. Coleppa
M. Kumar
S. Kumar
B. Mellado

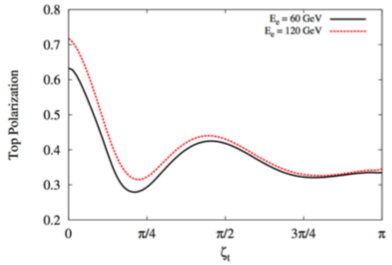
parton level

Phys. Lett. B770 (2017) 335

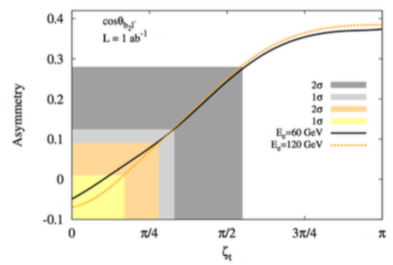
rapidity difference (H,$\bar{t}$)



top polarisation



angular asymmetries (b_2,l^-)



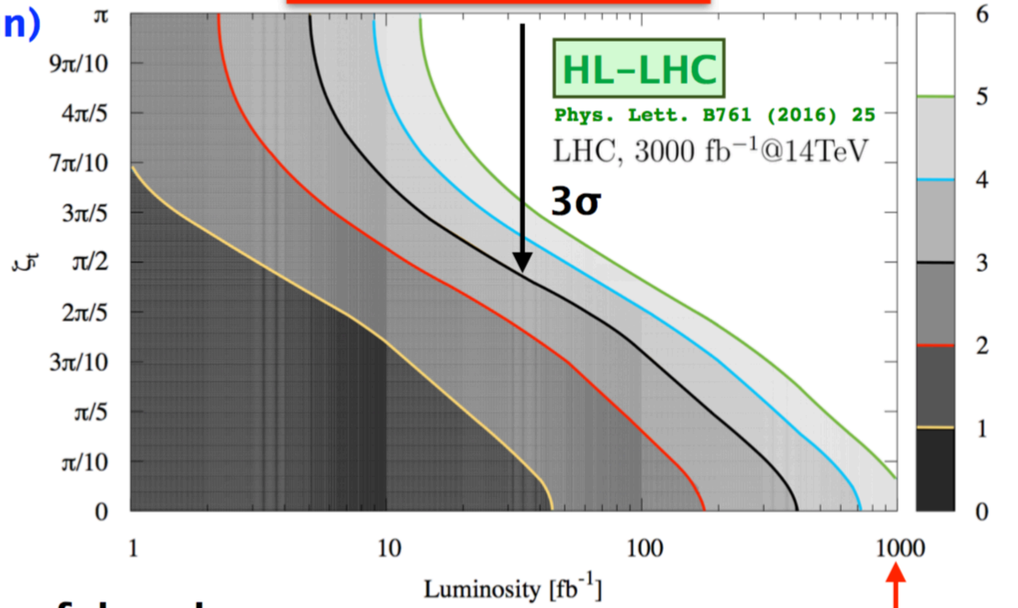
CP-even (flipped sign)

CP-odd

CP-even (SM)

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

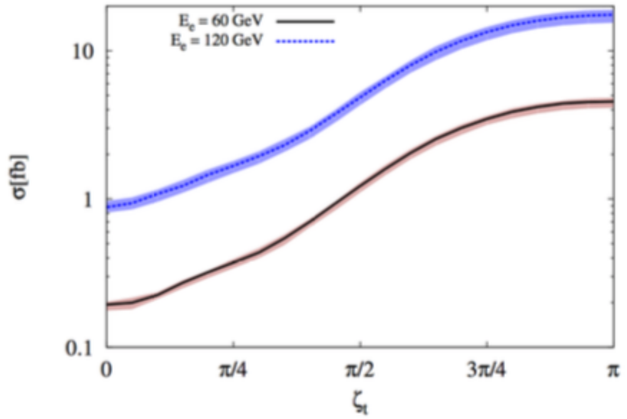
LHeC



10% uncertainty on background yields

$\kappa = 1.00 \pm 0.17$

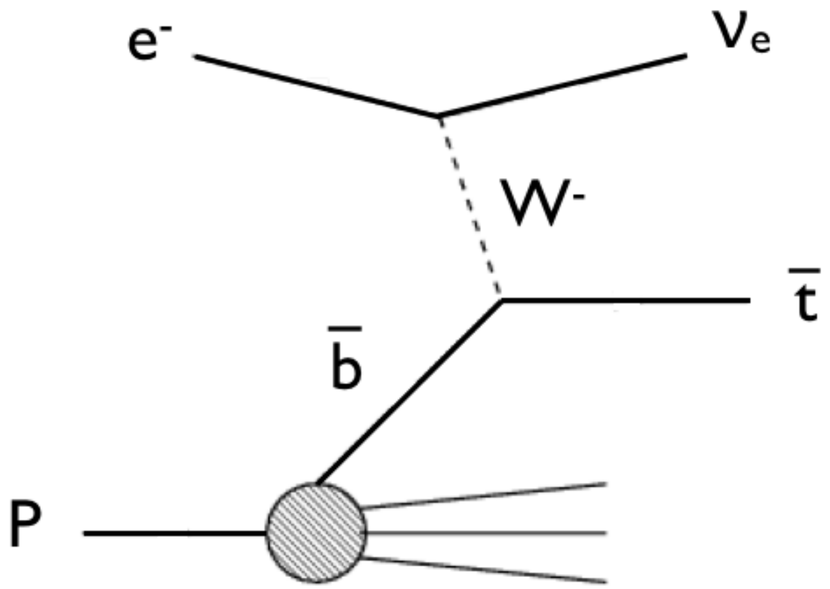
fiducial incl. cross-section



→ **powerful probe of ttH coupling**

SM Top Quark Production

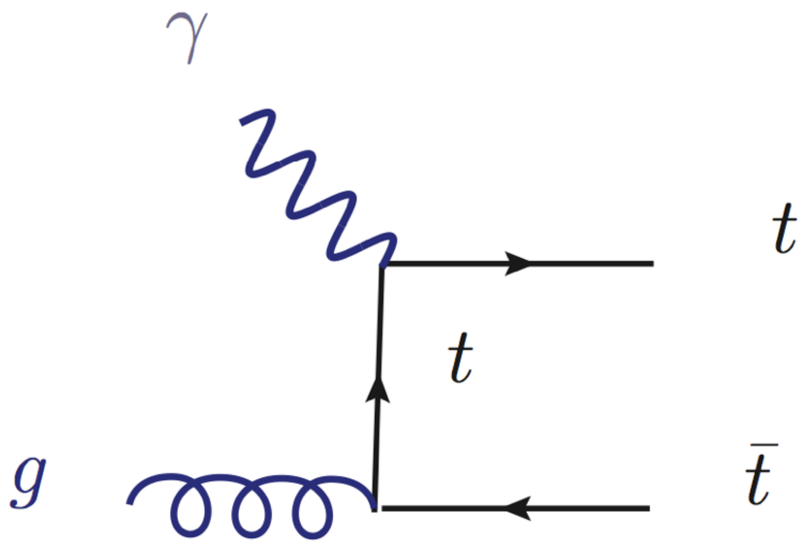
CC DIS top production



σ=1.73pb @ LHeC

σ=15.3pb @ FCC-ep

NC top photoproduction



σ=0.05pb @ LHeC

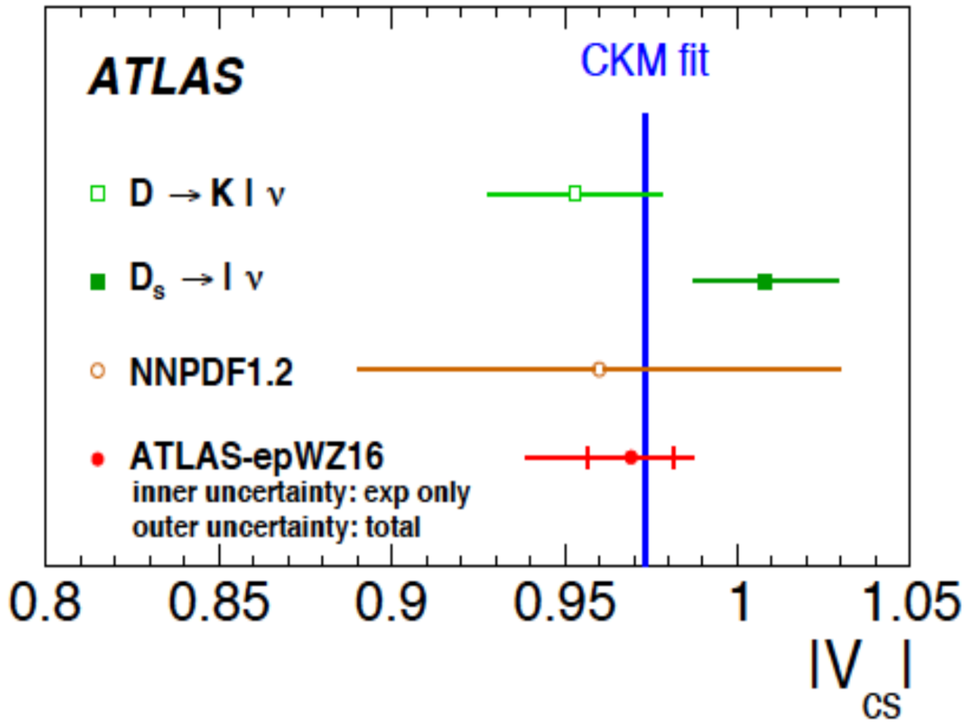
σ=1.14pb @ FCC-ep

E_e=60 GeV

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

Measurement of $|V_{cs}|$

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



HERA+ATLAS → V_{cs}

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

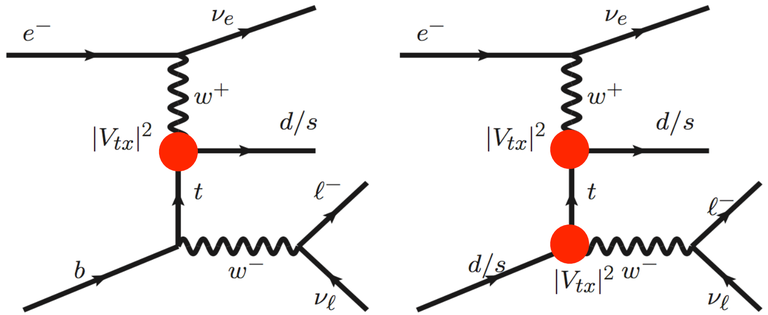
→ **heavy flavour factory**

Measurement of $|V_{td}|$

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

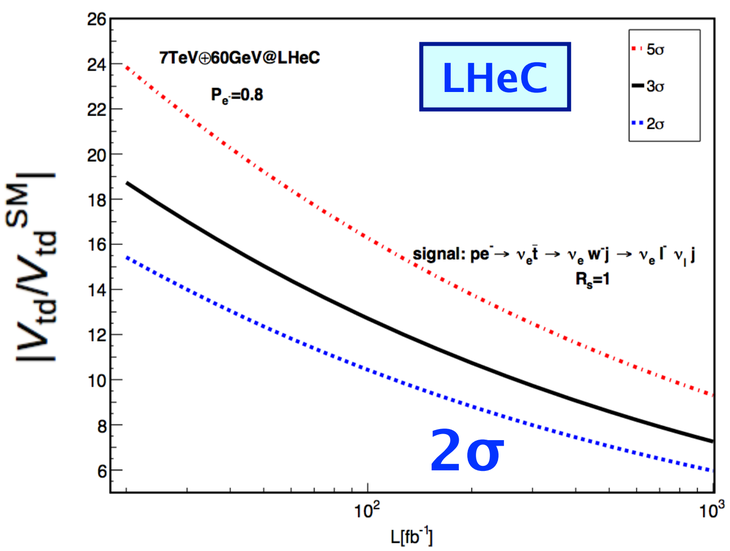
similar

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



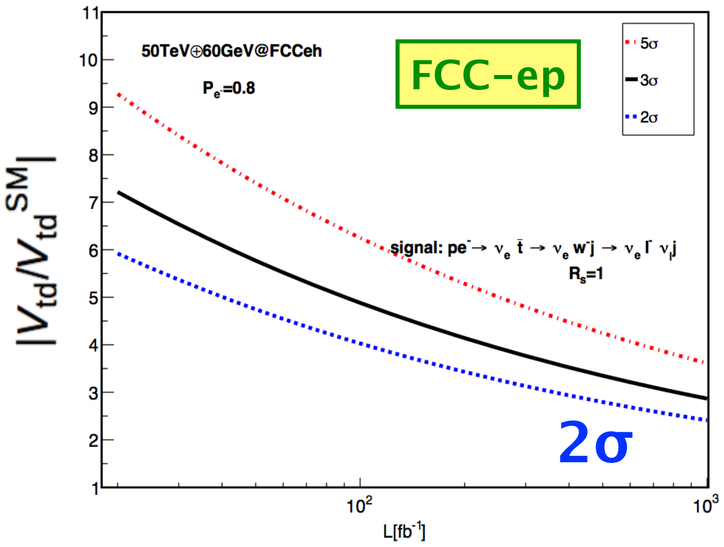
DELPHES

Hao Sun to be publ.



LHC

→ $|V_{td}|<0.05$



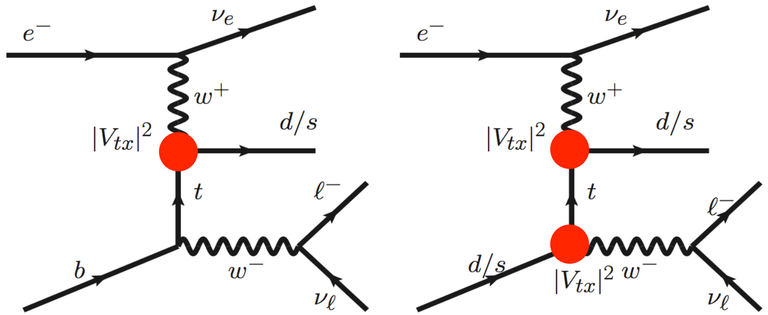
→ $|V_{td}|<0.02$ at 2σ C.L.

Measurement of $|V_{td}|$

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

similar

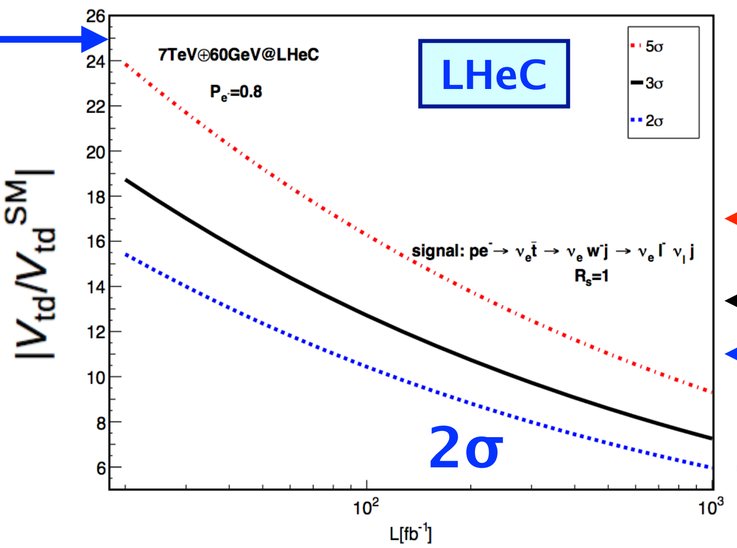
$$|V_{td}^{\mathrm{SM}}| = 8.575^{+0.076}_{-0.098} \times 10^{-3}$$



DELPHES

Hao Sun to be publ.

LHC



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

HL-LHC

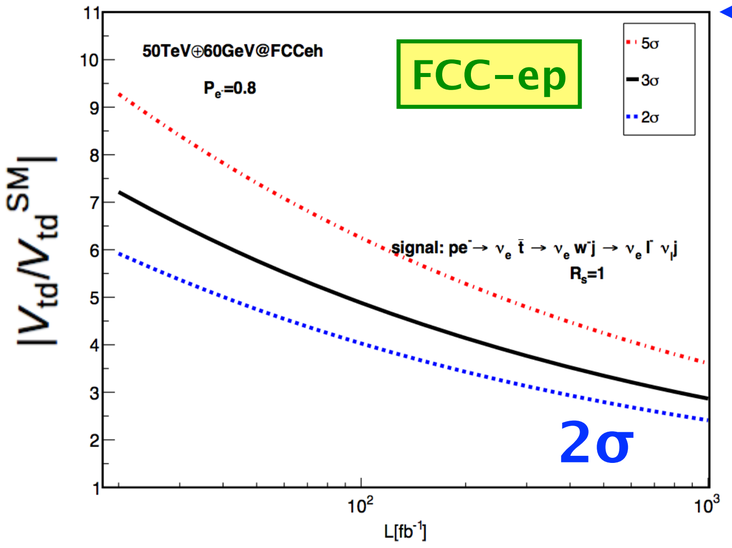
arXiv:1709.07887

5σ

3σ

2σ

→ $|V_{td}|$<0.05

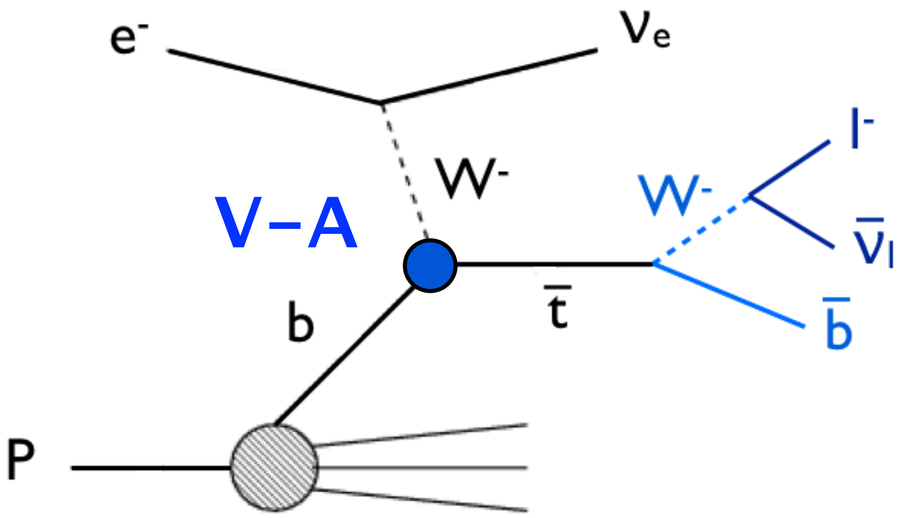


2σ

→ $|V_{td}|$<0.02 at 2σ C.L.

→ extend HL-LHC limits

Top Quark Polarisation



Atag, Sahin,
PRD 73, 074001 (2006)

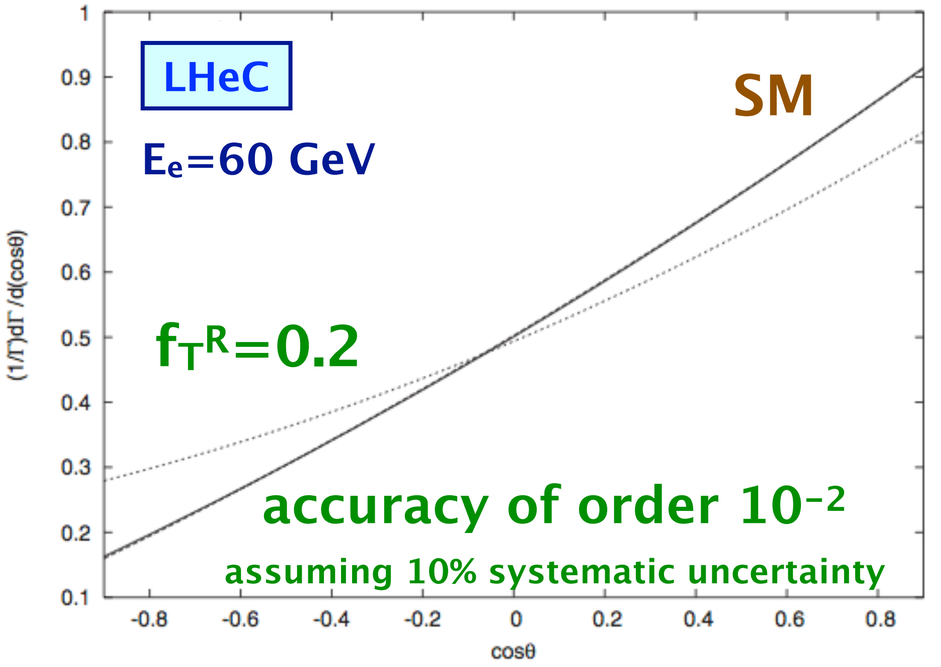
cosθ: angle between charged lepton and spin quantisation axis in top rest frame

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

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

TESLA+HERAp:

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



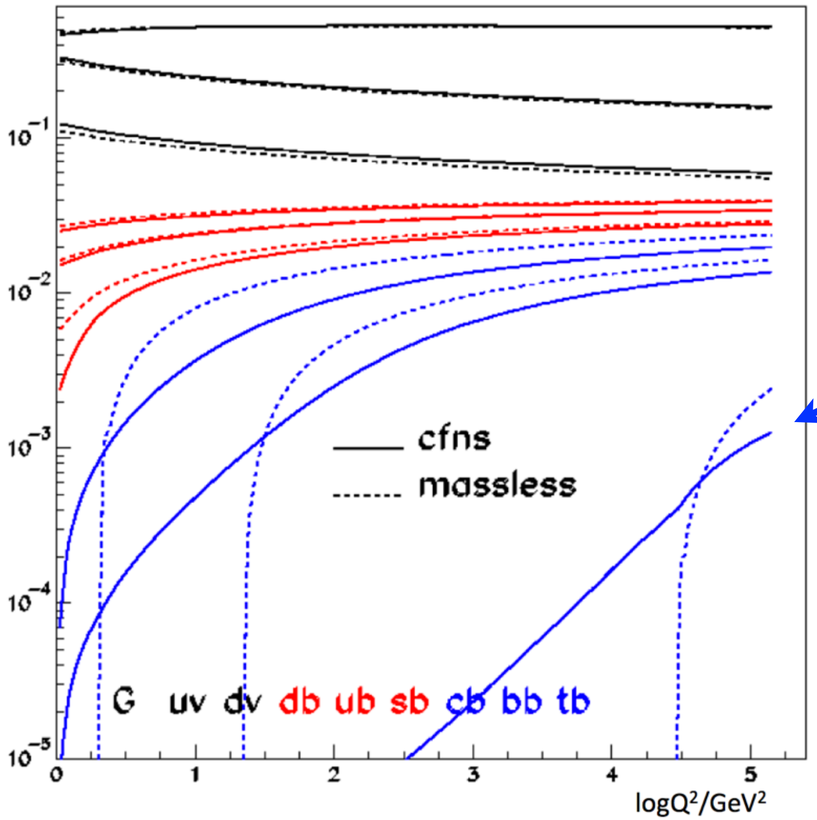
19.7 fb^{-1}: $A_{\uparrow\downarrow}$ = 0.26±0.11

JHEP 04 (2016) 073

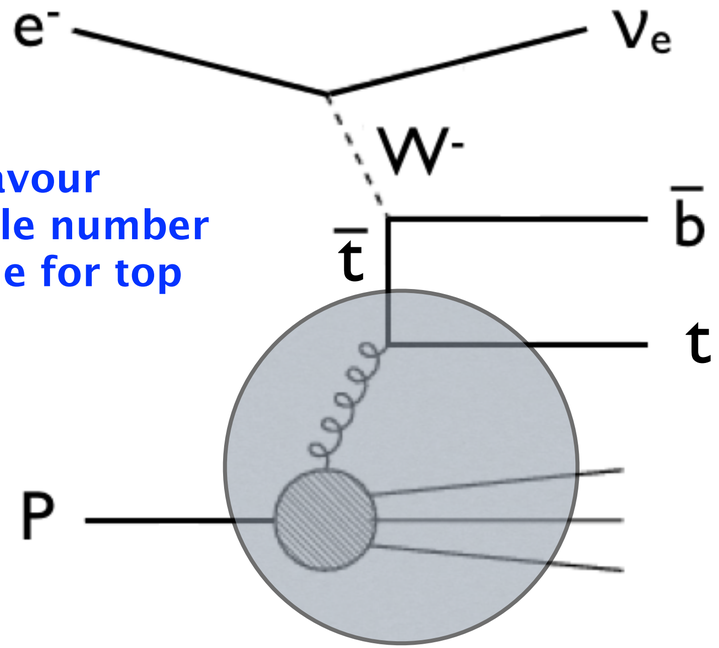
Top Quark Parton Density Function

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

parton momentum fraction



six-flavour variable number scheme for top quark



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

→ LHeC offers new field of research for top quark PDF

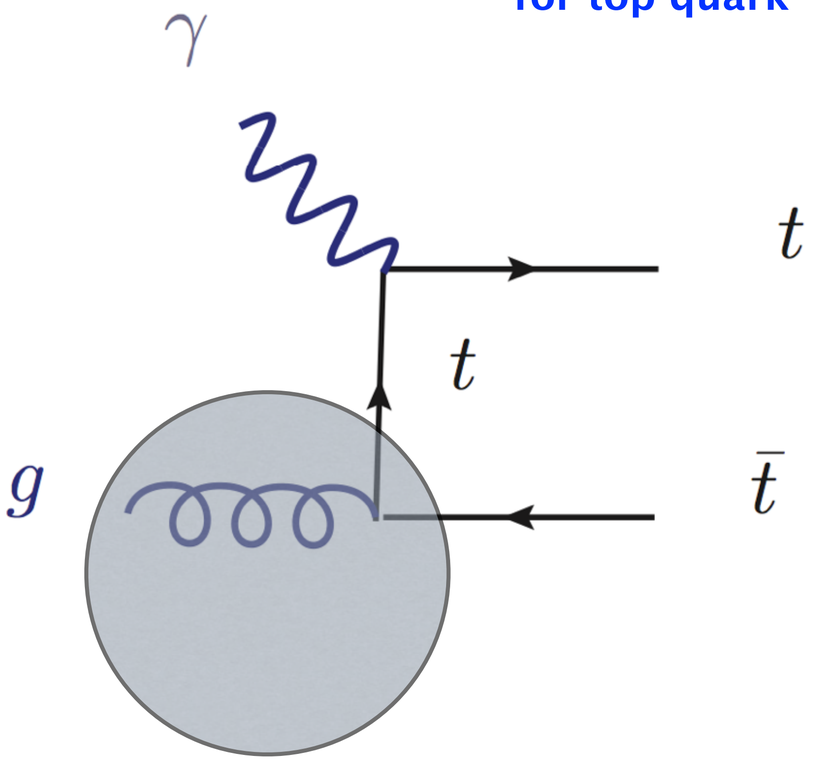
Top Quark Structure Function

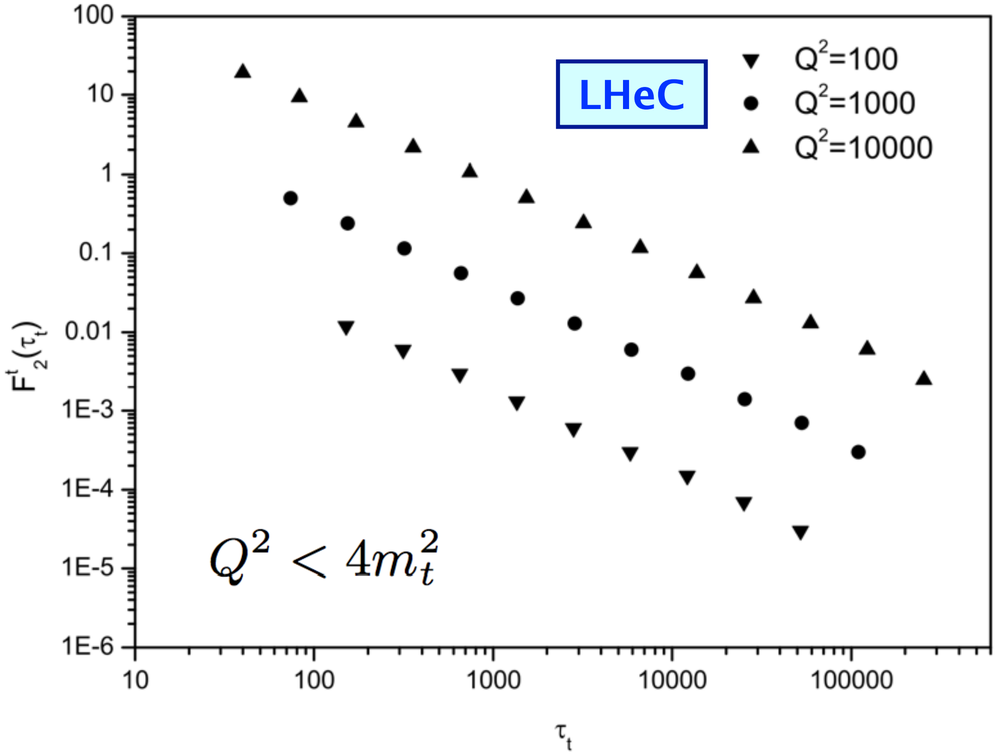
Boroun, Phys. Lett. B744, 142 (2015)

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

E_e=60 GeV

variable flavour number scheme for top quark





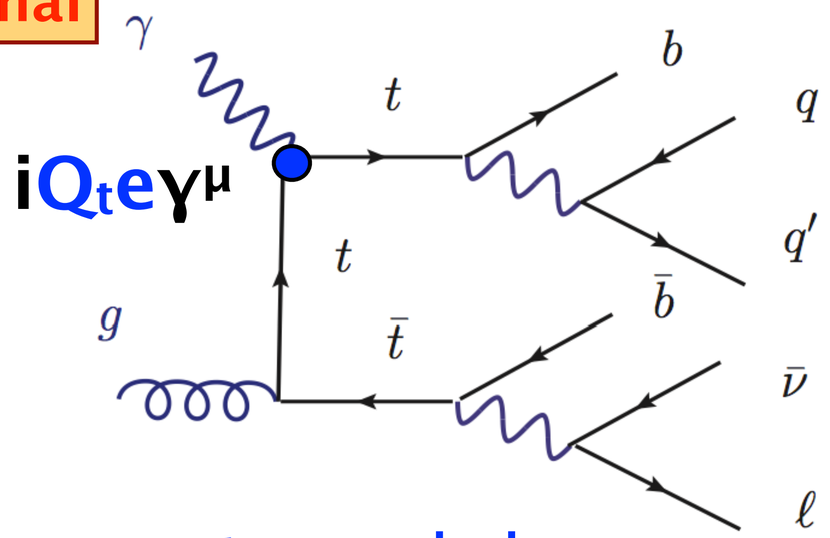
$$\tau_t = (1+\frac{4m_t^2}{Q^2})^{1+\lambda}\frac{Q^2}{Q_0^2}(\frac{x_B}{x_0})^{\lambda}$$

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

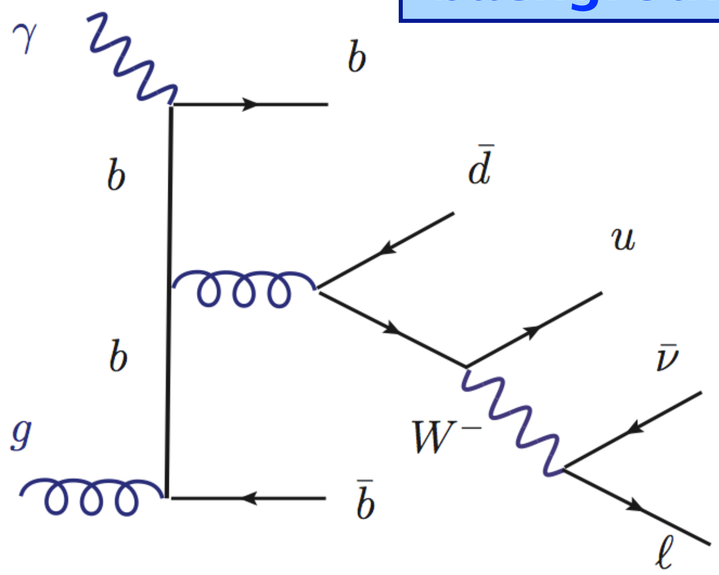
→ **LHeC/FCC-ep opens up a new field of top quark PDFs and to unveil the complete flavour structure of the proton**

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

signal

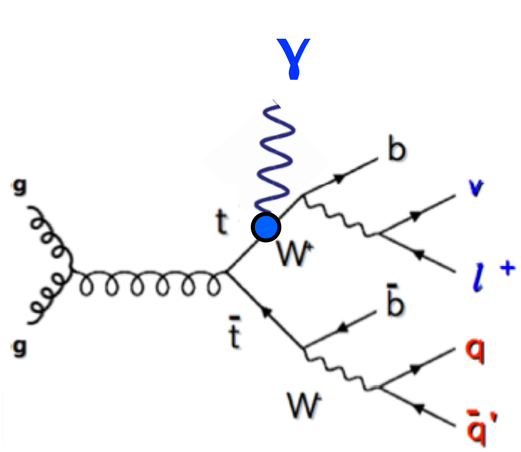


background

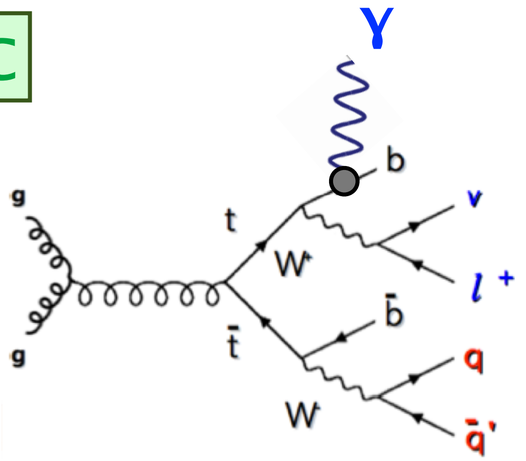


→ measure top quark charge

LHC



OR



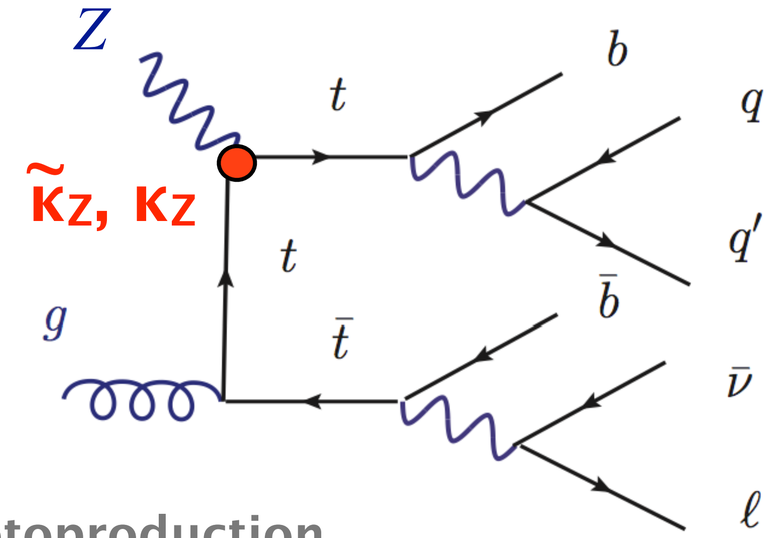
?

→ not unambiguous at the LHC

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

$\tilde{\kappa} = 2m_t d_t$

$\kappa = 2m_t \mu_t$



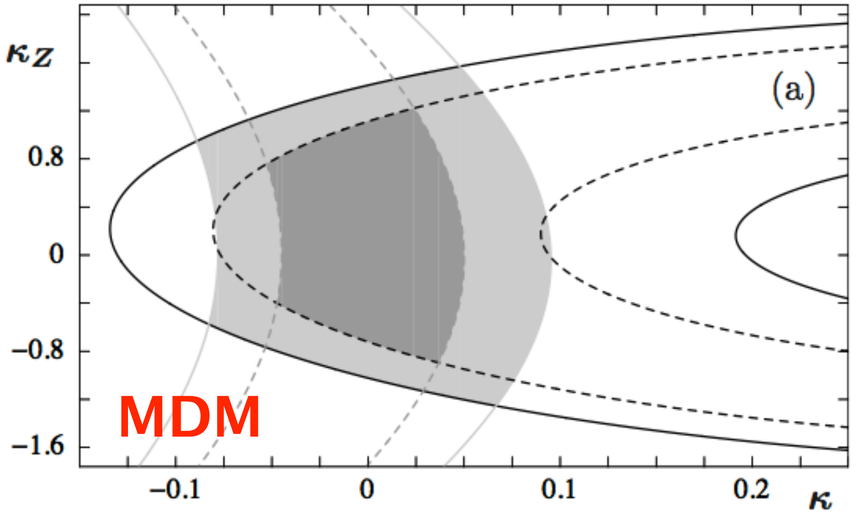
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

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

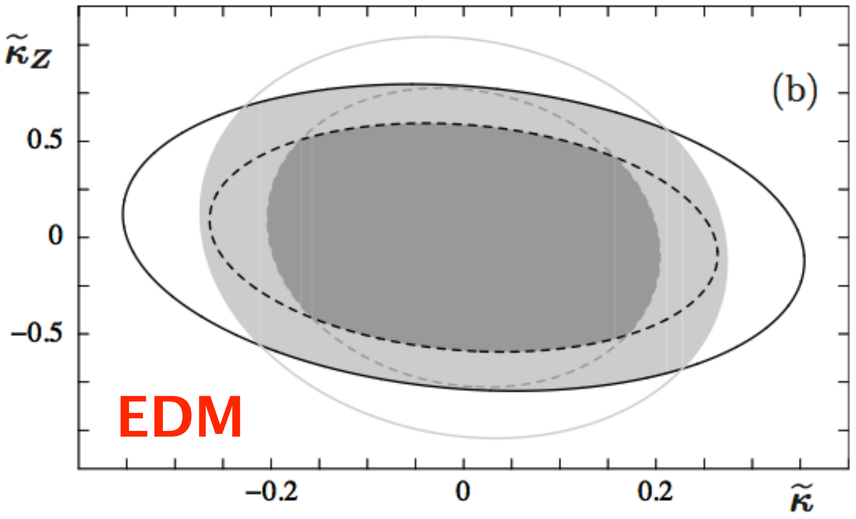
LHeC E_e=60 GeV

$t\bar{t}$ photoproduction

10% and 18% accuracy assumed



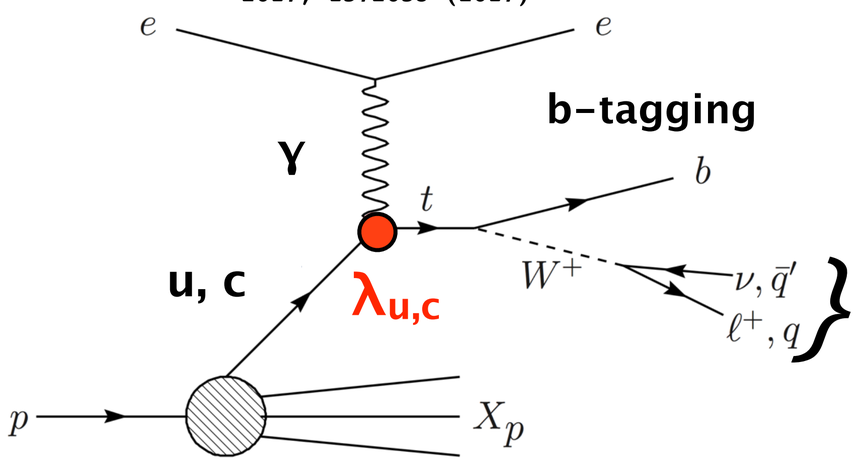
$t\bar{t}$ DIS



Search for Anomalous FCNC tuγ Coupling

signal

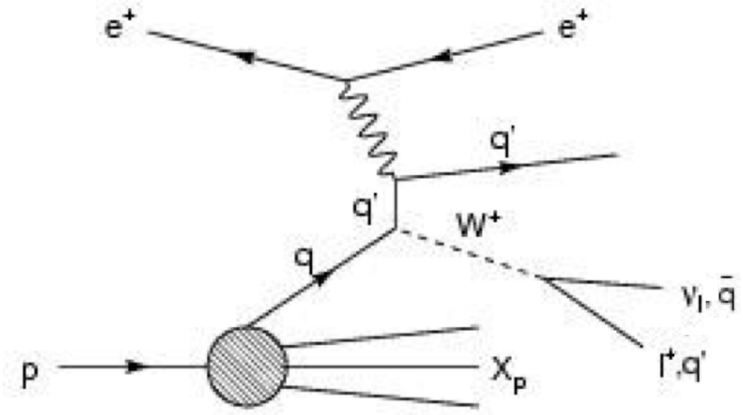
I. Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)



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

50<Mjj<100 GeV

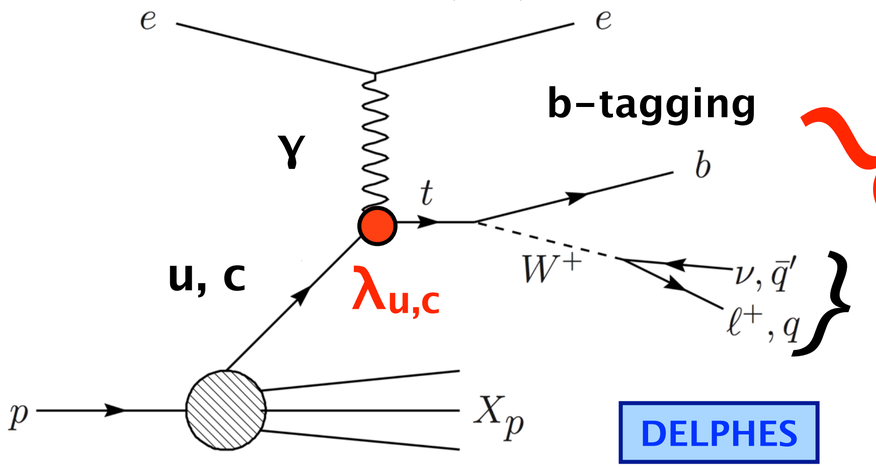
background



Search for Anomalous FCNC tuγ Coupling

signal

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



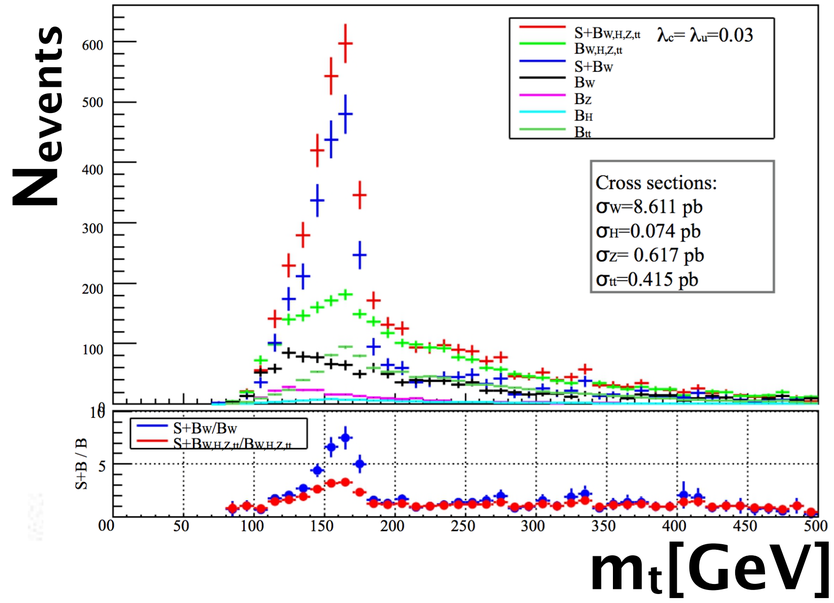
$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda_q}{\Lambda} \bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$

b-tagging

130<M_{Wb}<190 GeV

50<M_{jj}<100 GeV

DELPHES



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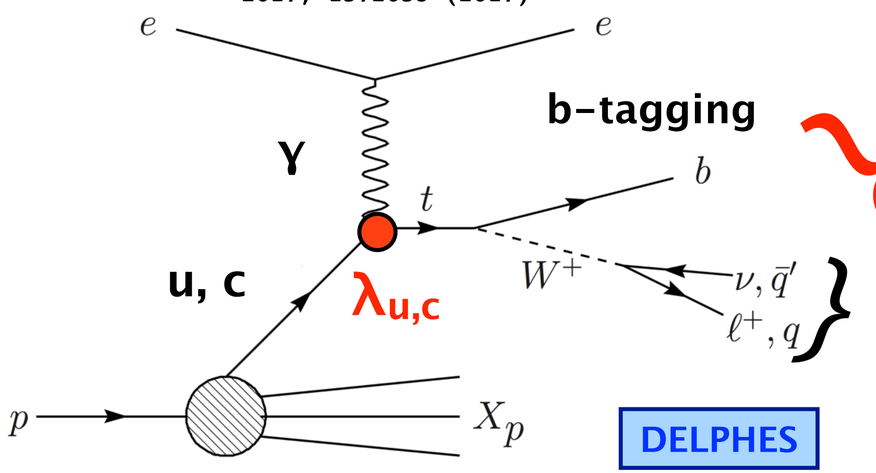


$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda_q}{\Lambda} \bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$

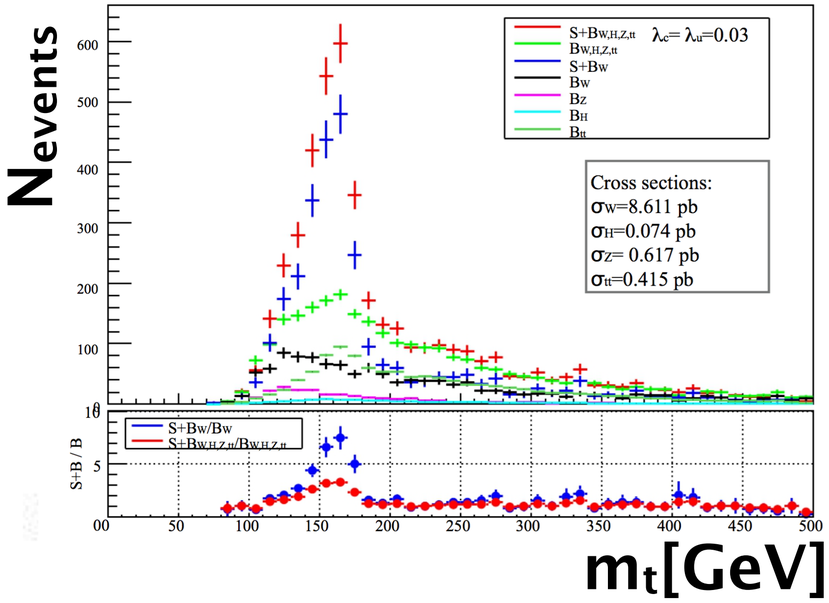
130<M_{Wb}<190 GeV

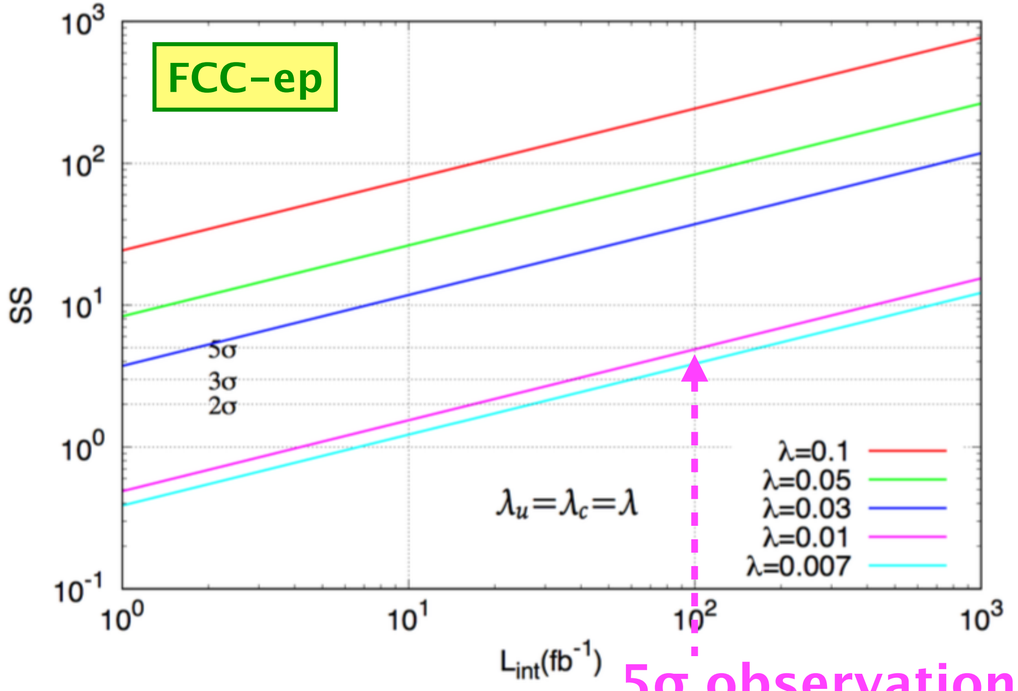
50<M_{jj}<100 GeV

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

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

DELPHES





5σ observation

LHeC and FCC-eh Detector Layout