Top Quark and Flavor Physics at Future Colliders

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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

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GROSSE HERAUSFORDERUNGEN

FH DESY Future Collider Day
11 November 2024

Special thanks: P. Azzi, G. Hiller, J. List, M. Mangano, M. Vos, X. Zuo, K. Skovpen

FCC-ee, FCC-eh and FCC-hh

Energy Recovering Linac

e$^{\pm}$ beam: 50-60 GeV

operated synchronously

- with HL-LHC
- or later with FCC-hh:

bridge project

- fast track to optimal SRF performance of a Higgs factory & cost/risk reduction for SRF@FCC-ee
- re-use of modules
- use as injector

LHeC

$\sqrt{s}$=1.2-1.3 TeV

0.25-1 ab^{-1}

FCC-ep

$\sqrt{s}$=3.5 TeV

2 ab^{-1}

FCC-ee

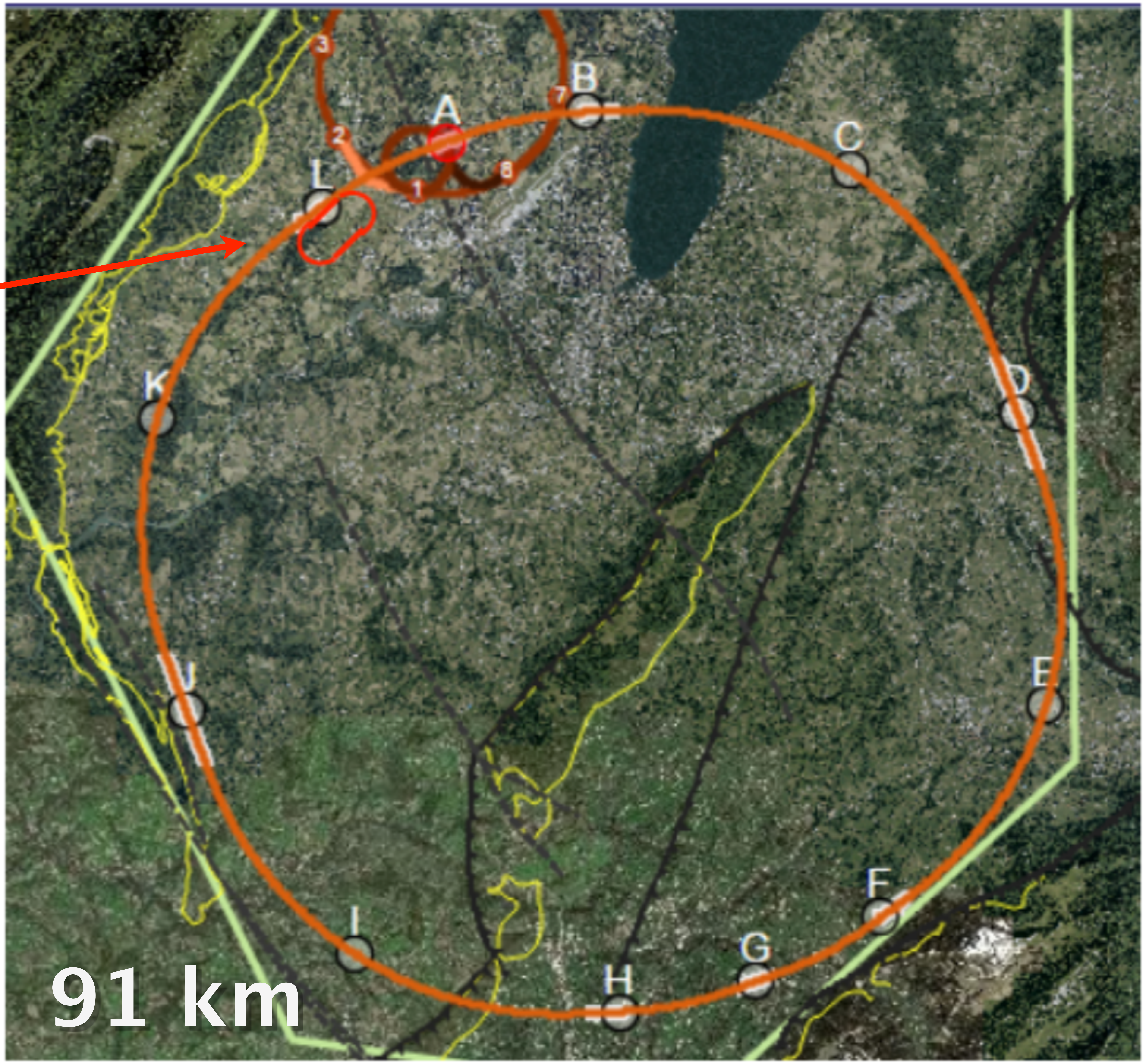
$\sqrt{s}$=90-365 GeV

3-200 ab^{-1} each

CepC

$\sqrt{s}$=90-240 GeV

35.6-16 ab^{-1} each

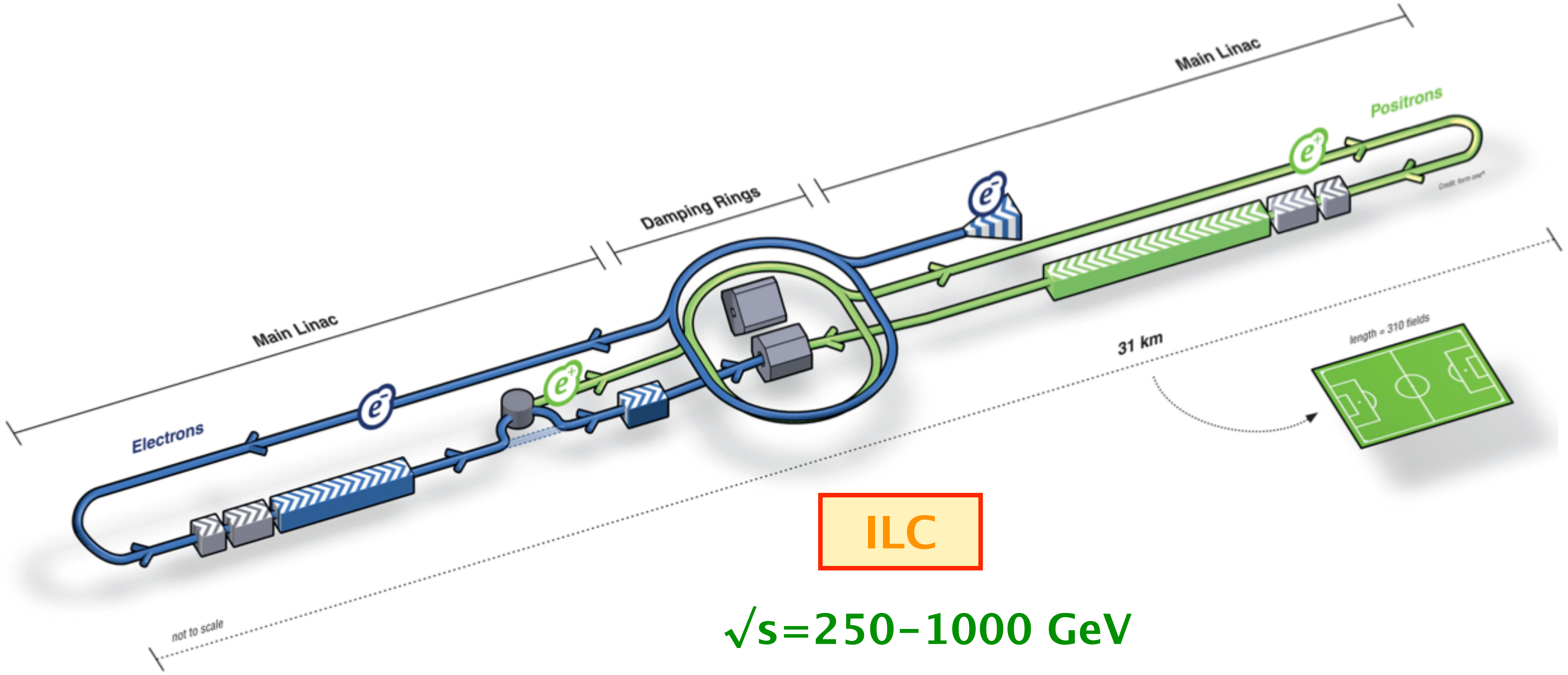


FCC-pp

$\sqrt{s}$=100 TeV

20-30 ab^{-1}

Linear Colliders

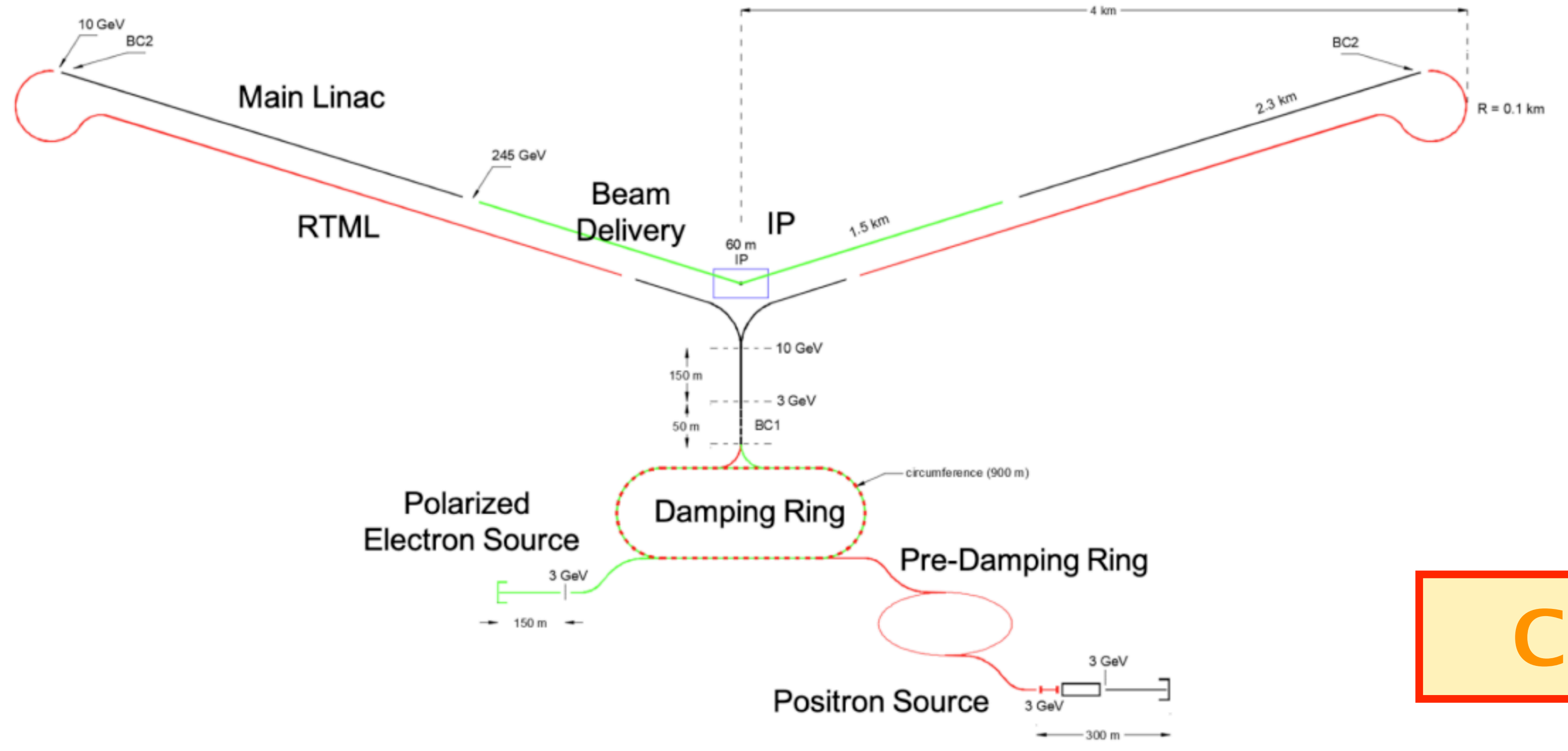


ILC

$\sqrt{s}$=250–1000 GeV

2-5.4 ab^{-1} each

C³ - 8 km footprint for 250/550 GeV

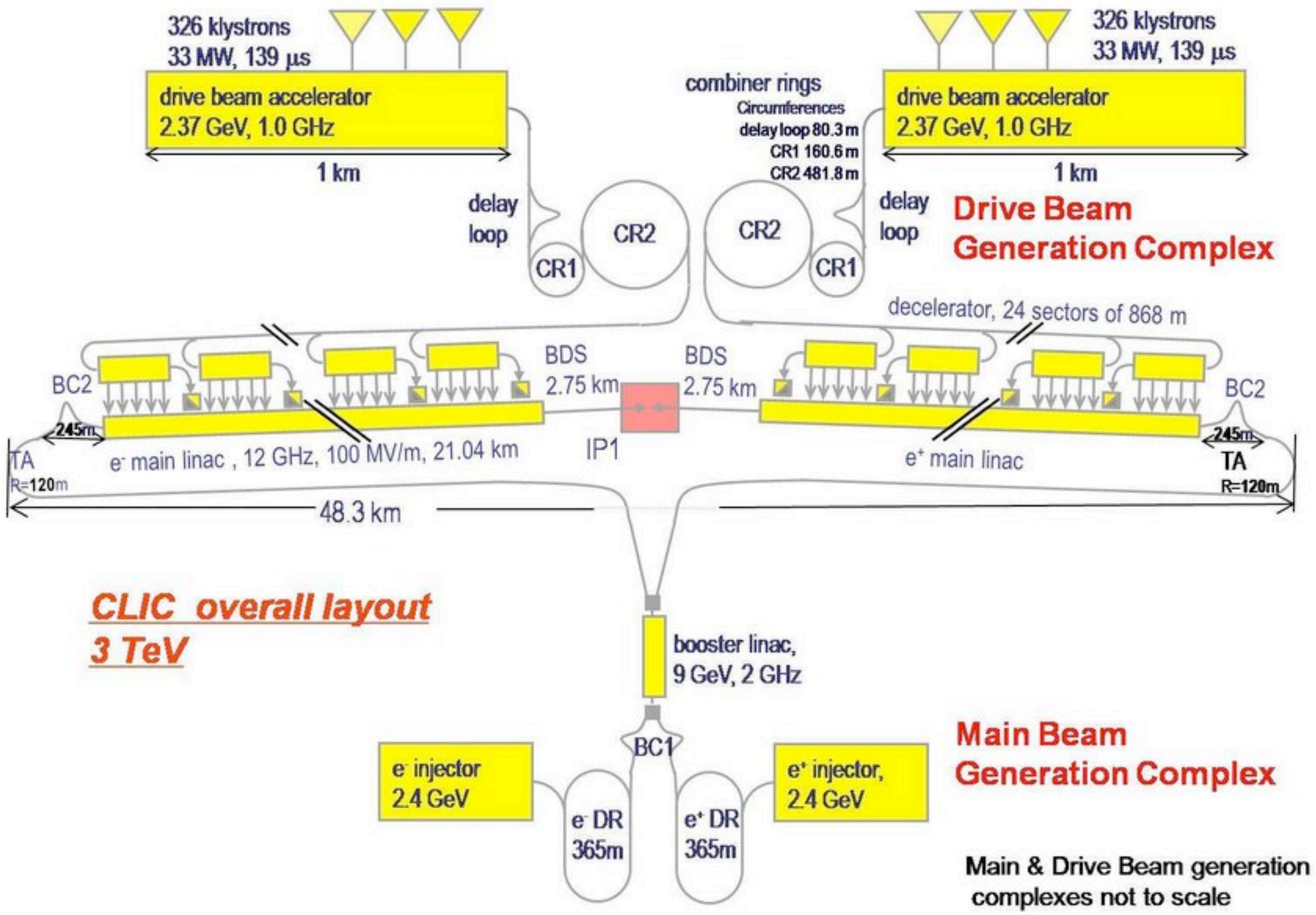


C³

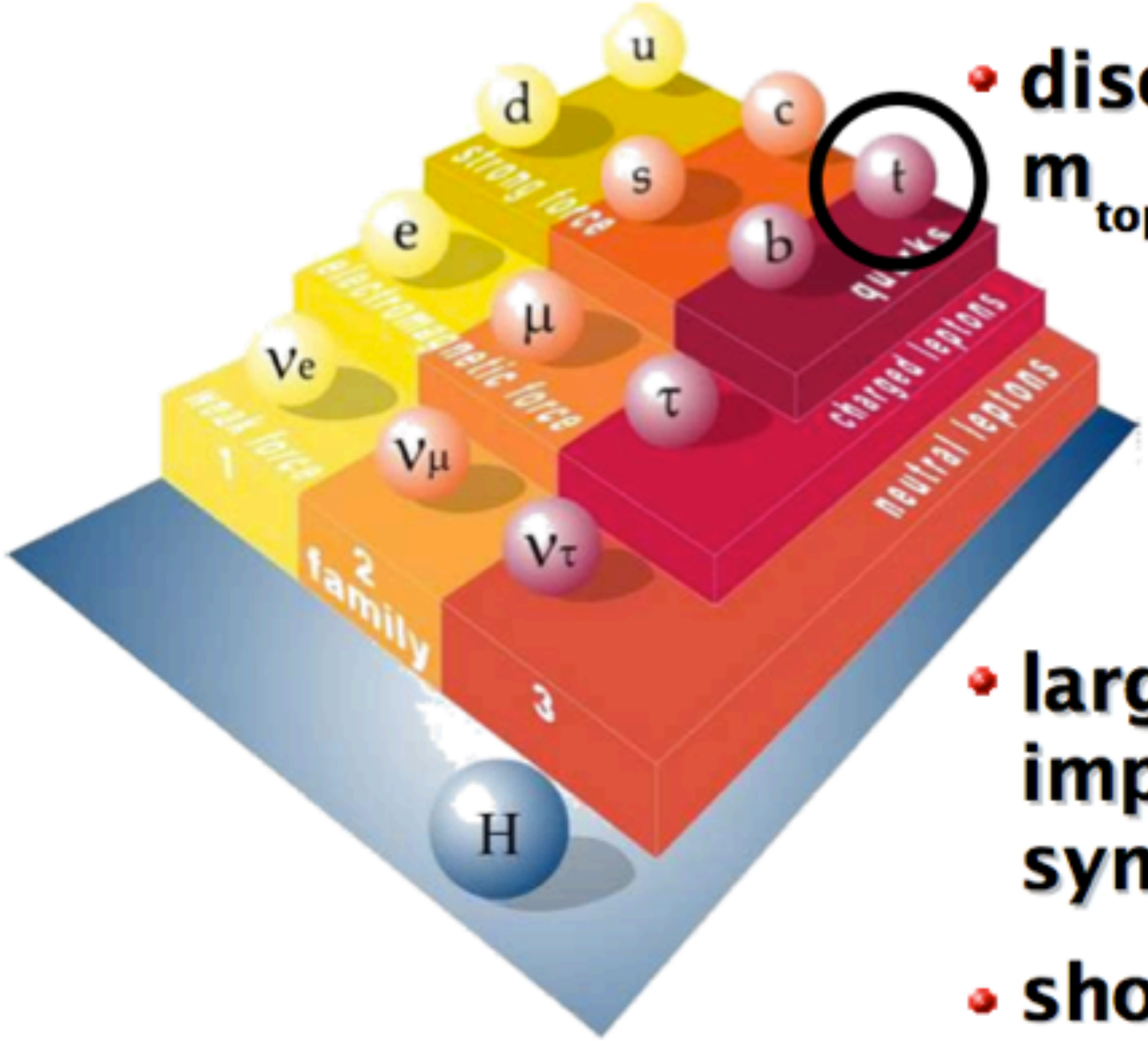
CLIC

$\sqrt{s}$=380–3000 GeV

1.5-5 ab^{-1} each



The Top Quark



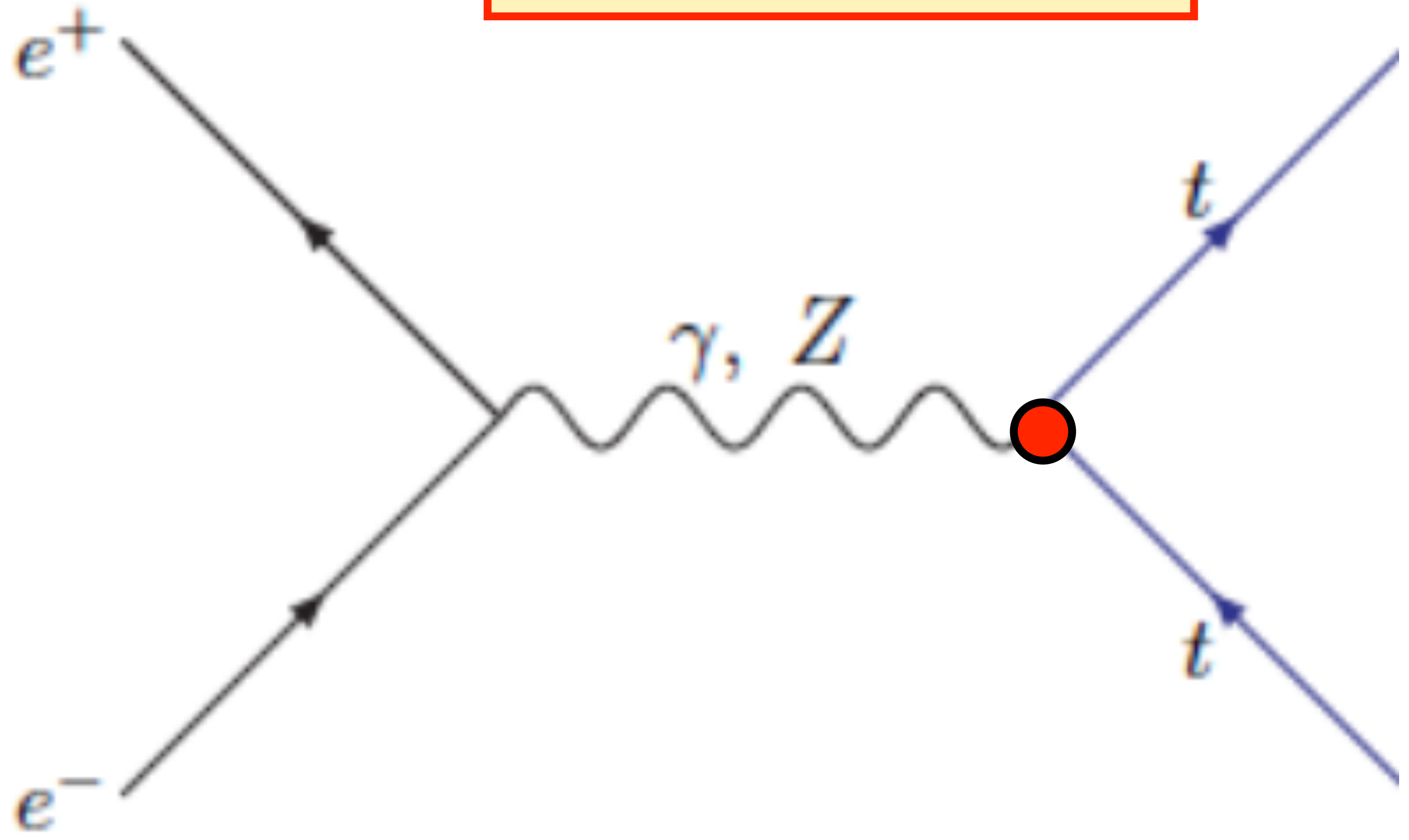
- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold nucleus
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}\mathrm{s} \ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe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

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

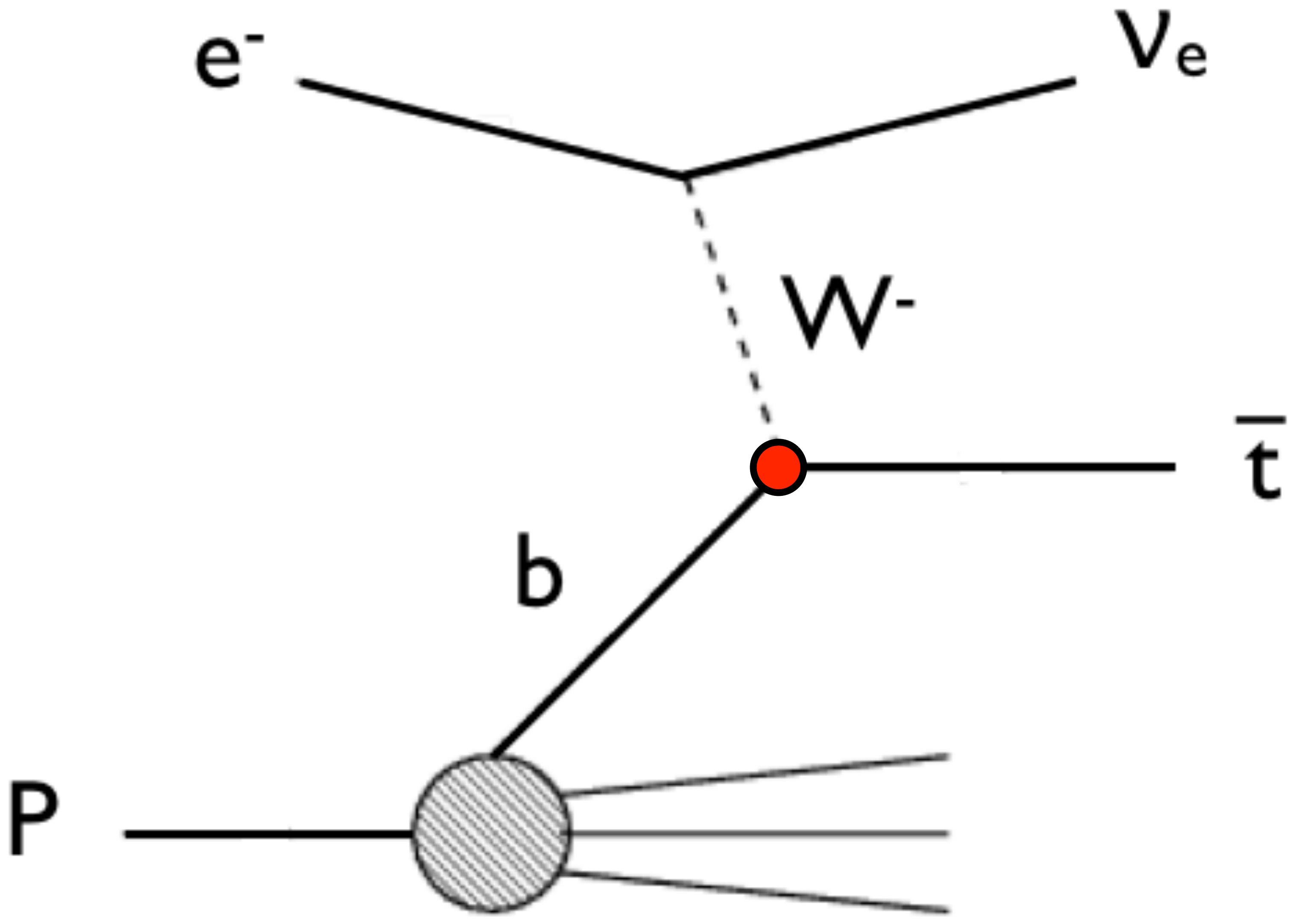
Top Quark Production at FCC-ee, FCC-eh and FCC-hh

FCC-ee **ILC**

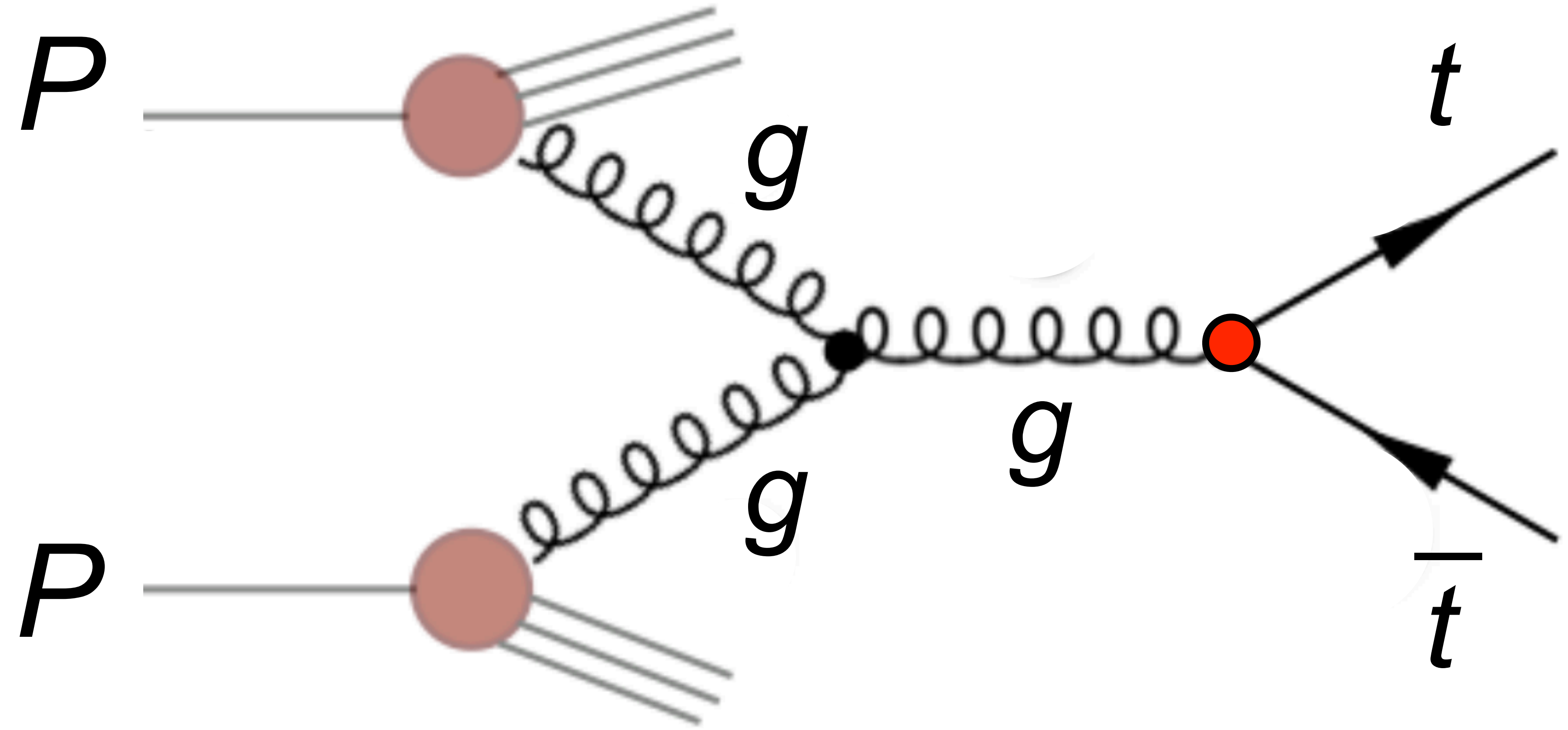
CLIC



FCC-ep



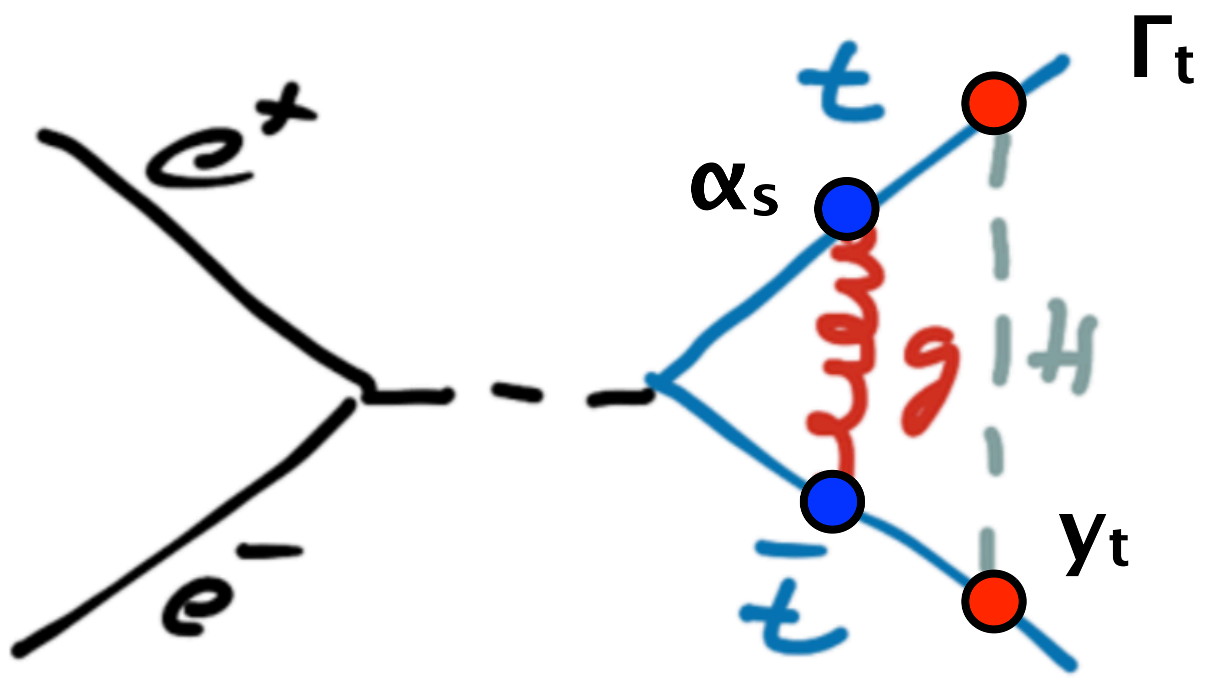
FCC-pp



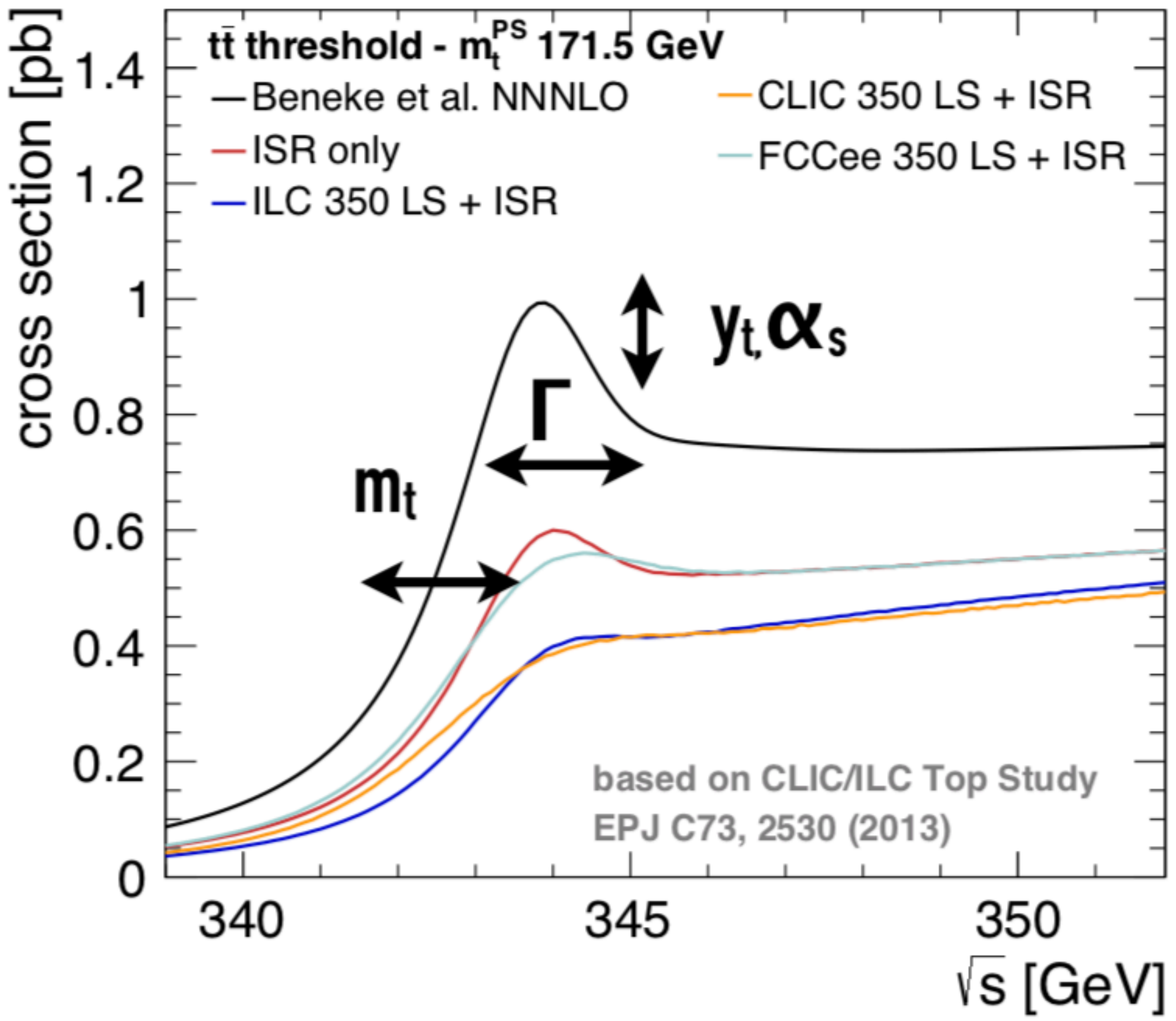
→ **precision measurements of top quark properties**

→ **complementary information**

Top Quark Measurements at Threshold

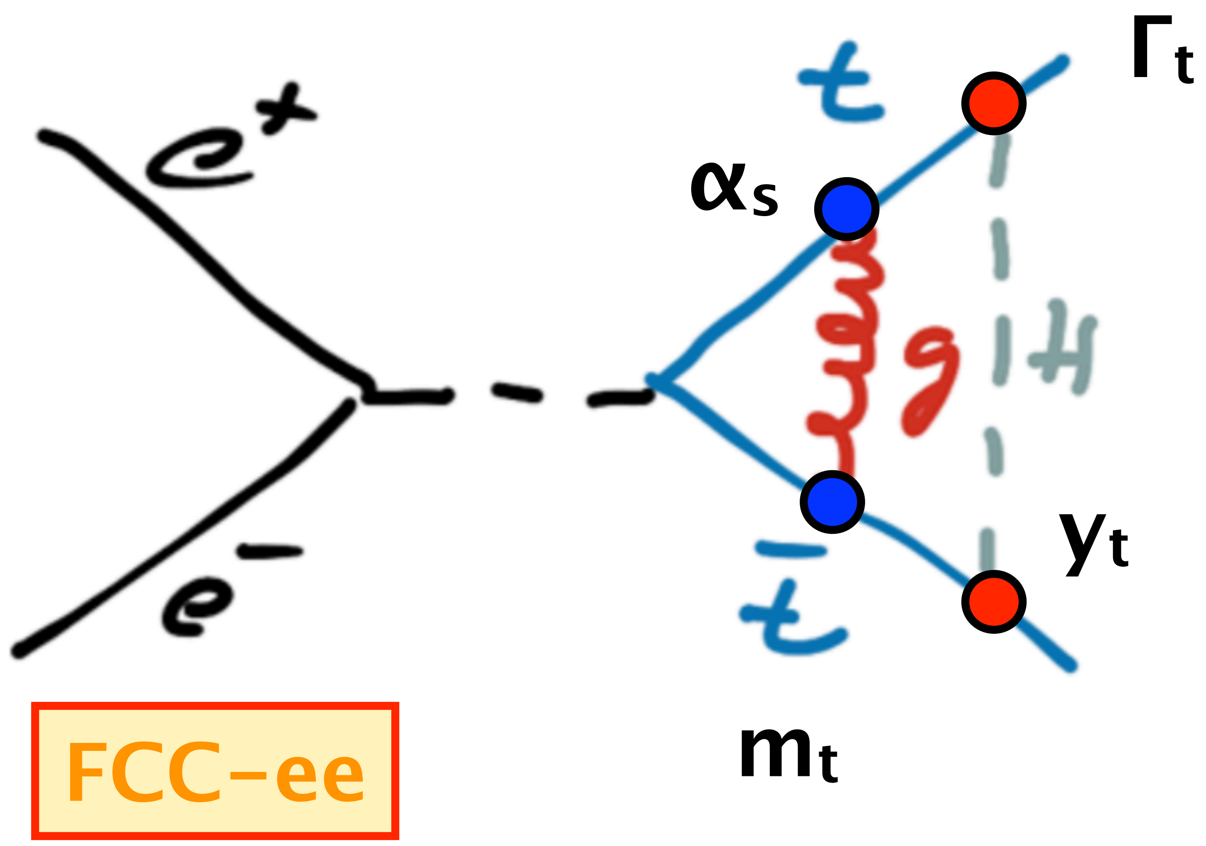


ILC

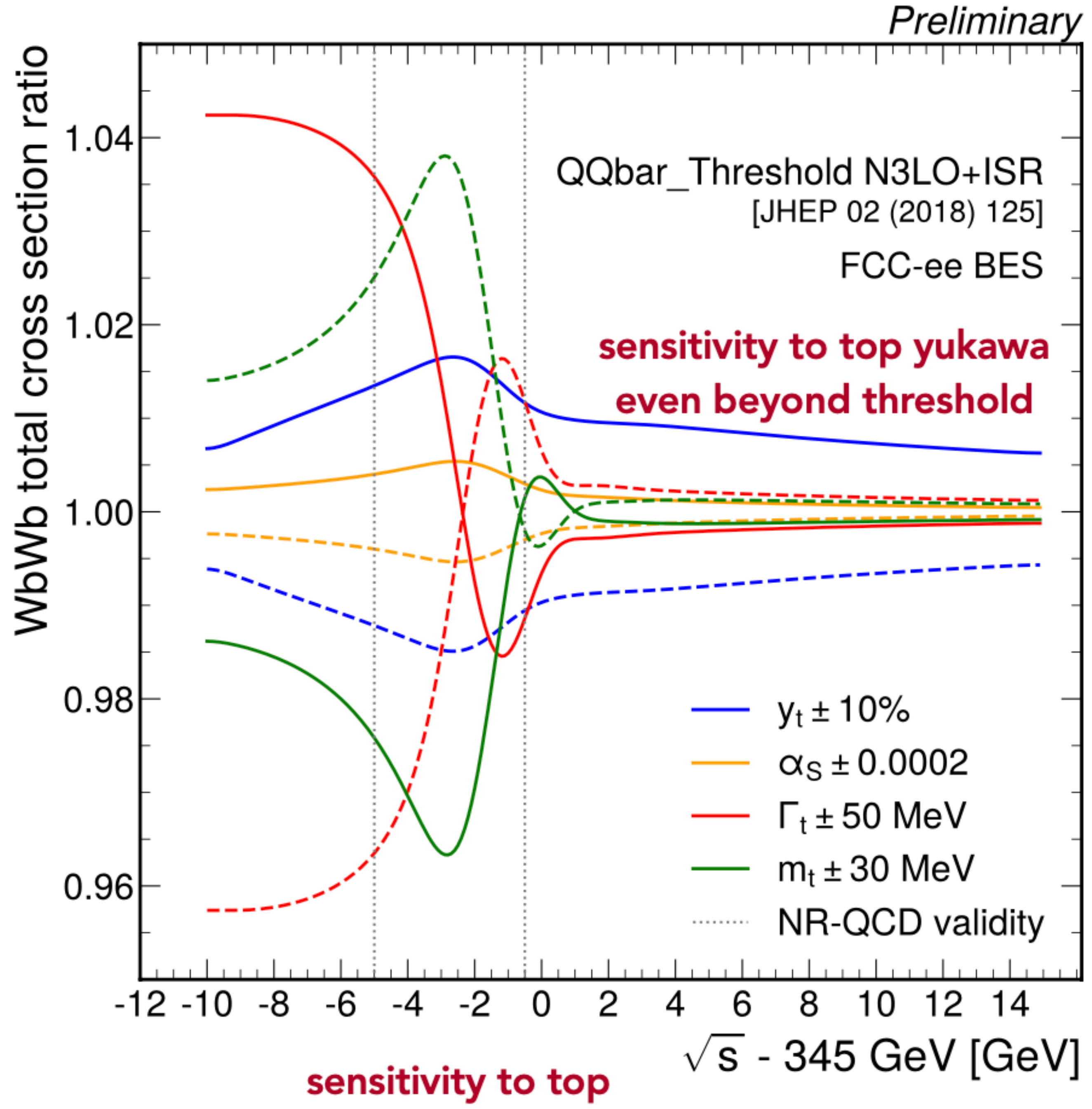


→ **properly defined 1S mass!**

Top Quark Measurements at Threshold



FCC-ee



sensitivity to top yukawa even beyond threshold

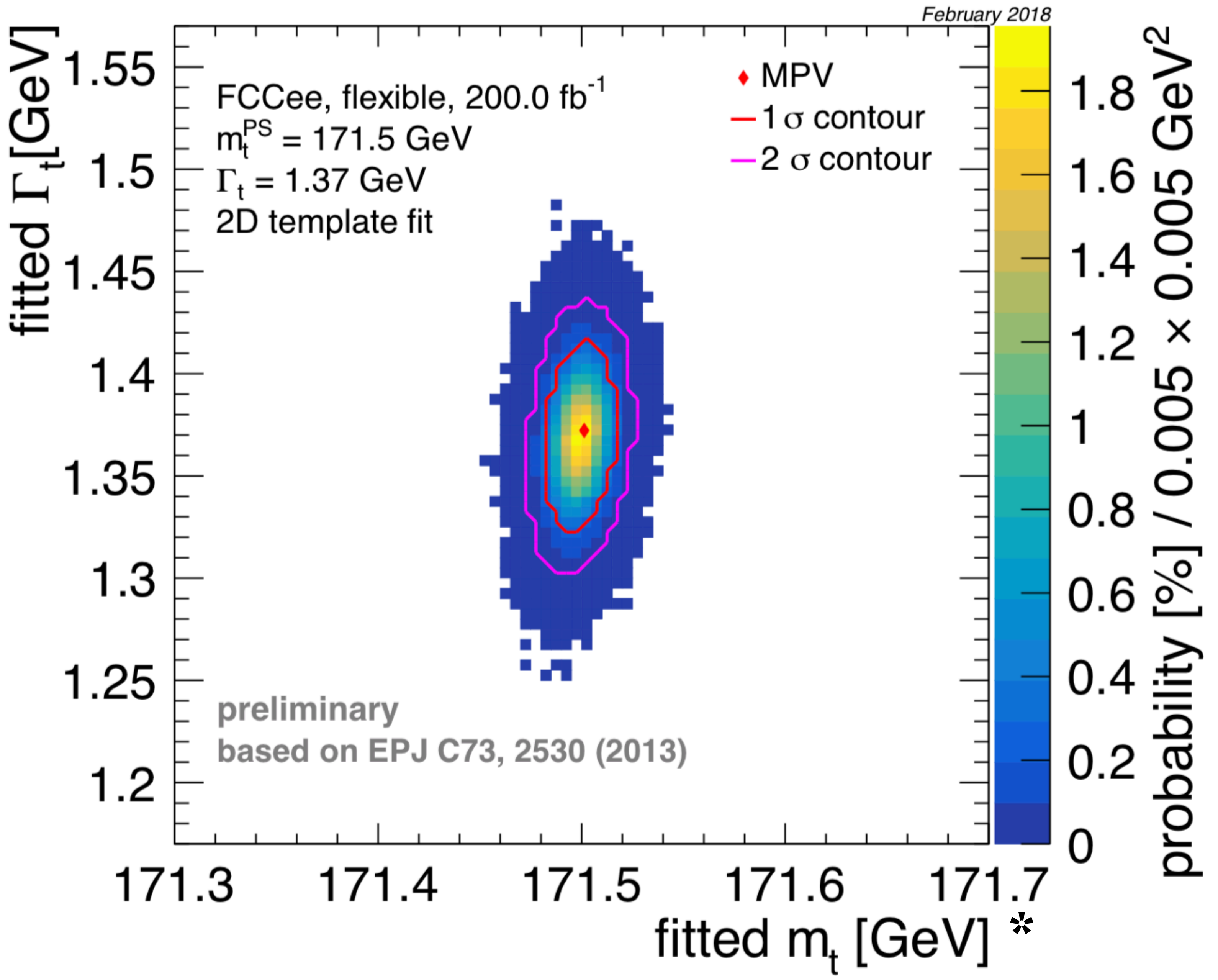
sensitivity to top mass and width

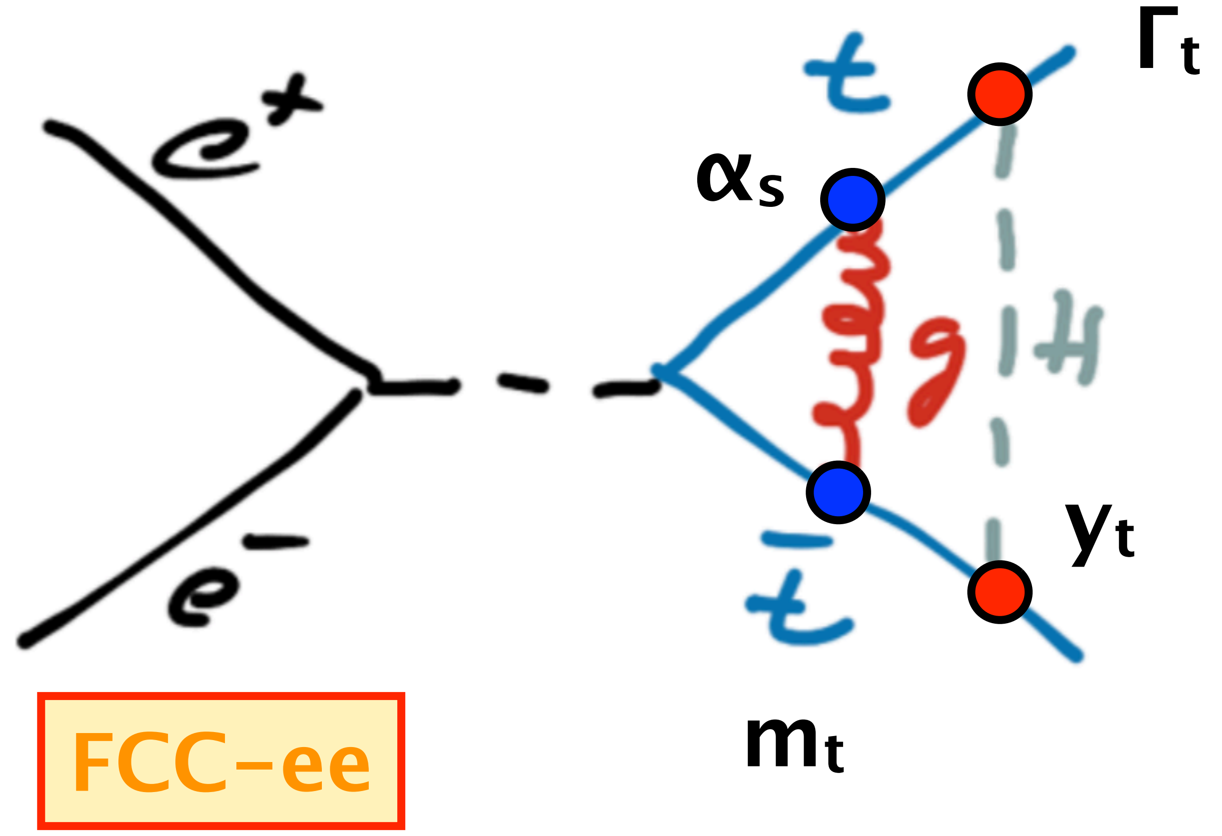
→ threshold scan

toponium and quantum effects (such as quantum entanglement)

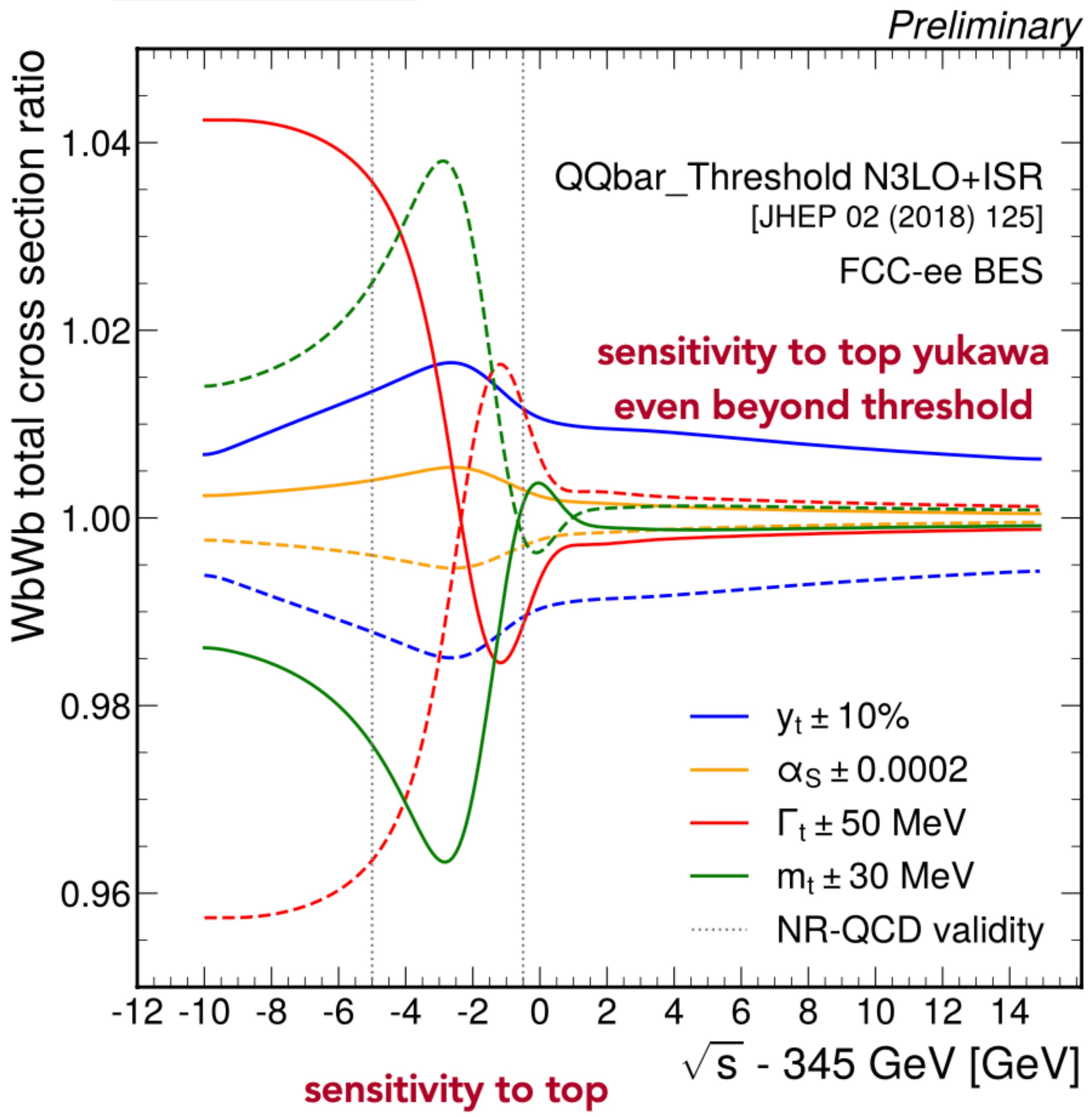
arXiv:2404.08049

Top Quark Measurements at Threshold



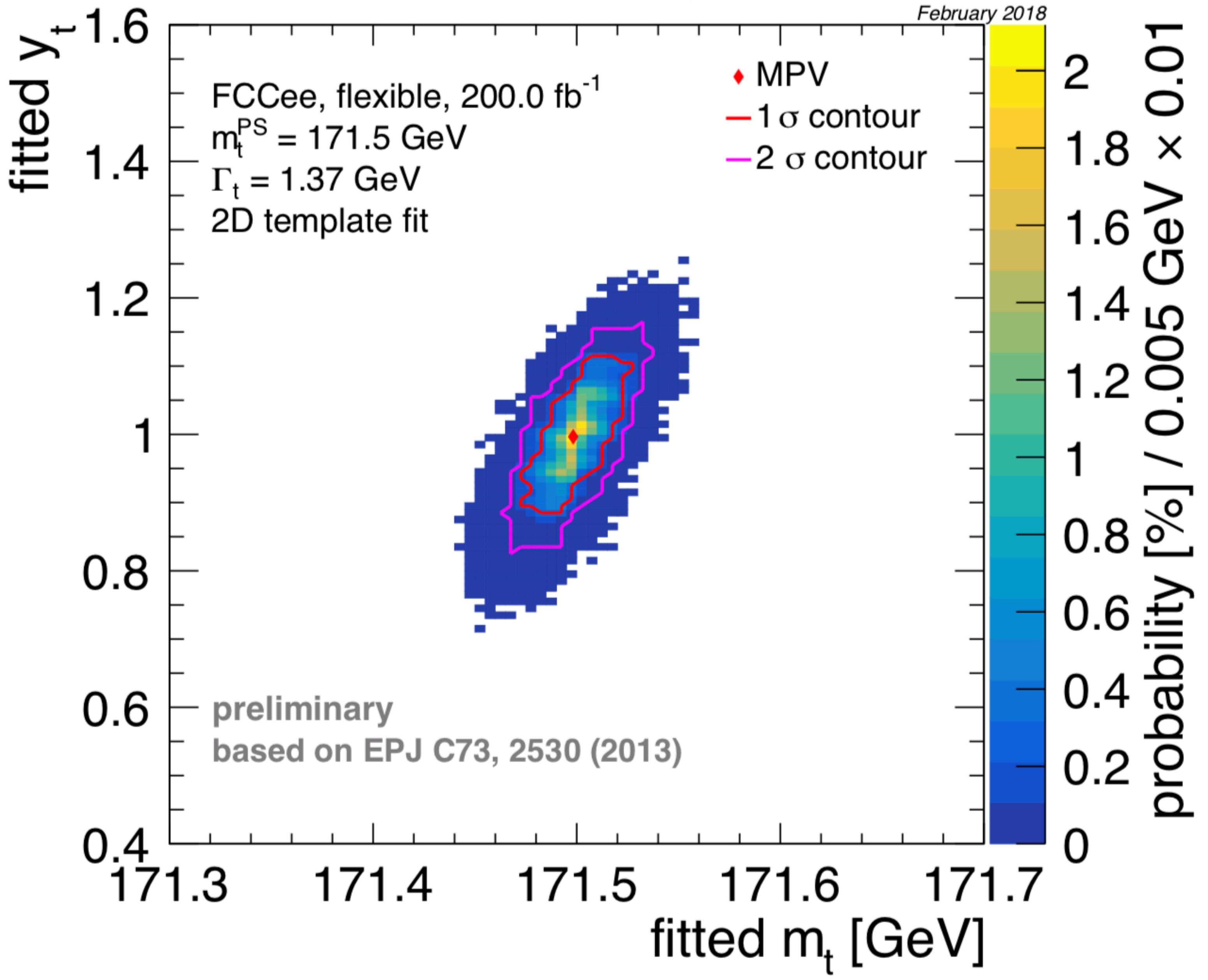


FCC-ee



sensitivity to top mass and width

EPJC 79 (2019) 474



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

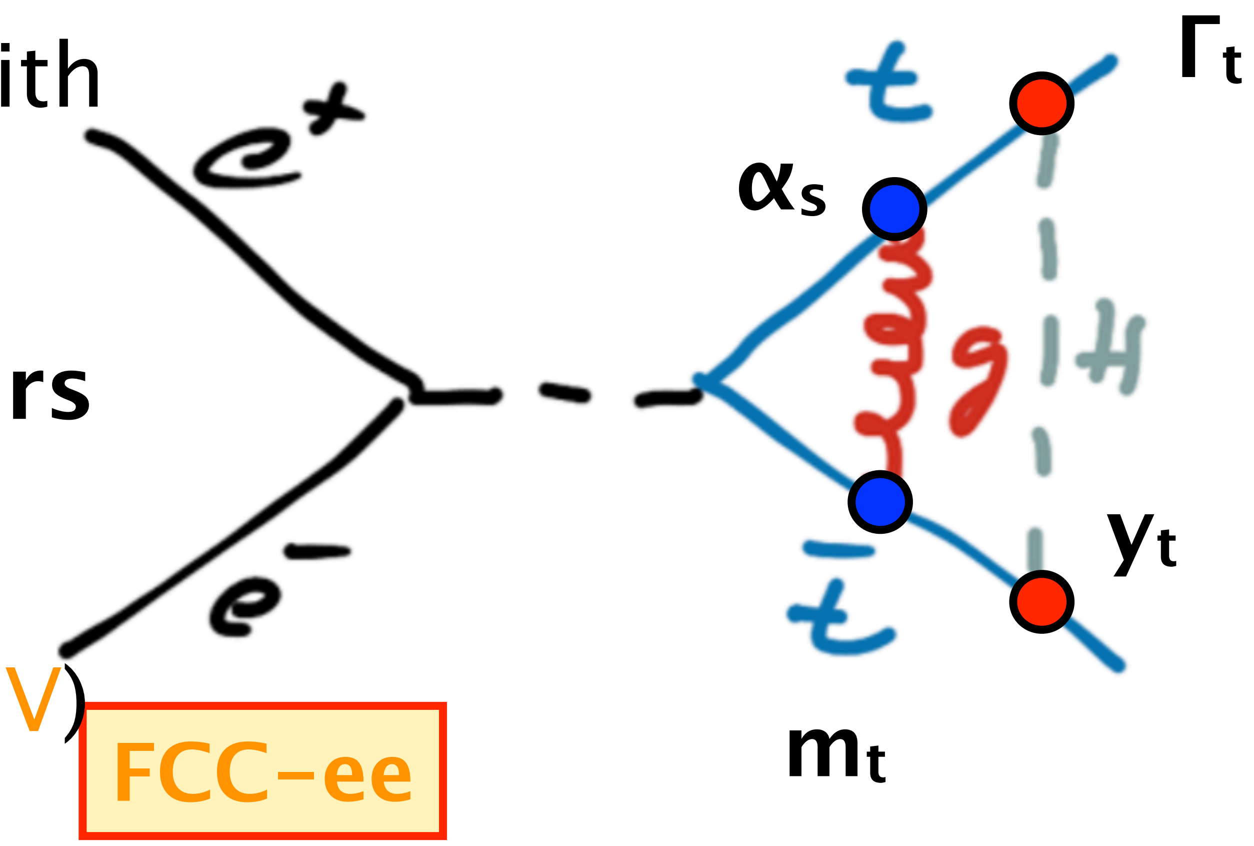
Extension of 1σ contour:
mass: +29 MeV, - 26 MeV
y_t: +0.12, -0.11
Theory uncertainty (symm.):
mass: 36 MeV; y_t: 0.11
α_s parametric uncertainty (0.0002)
mass: 3 MeV; y_t: 0.02

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

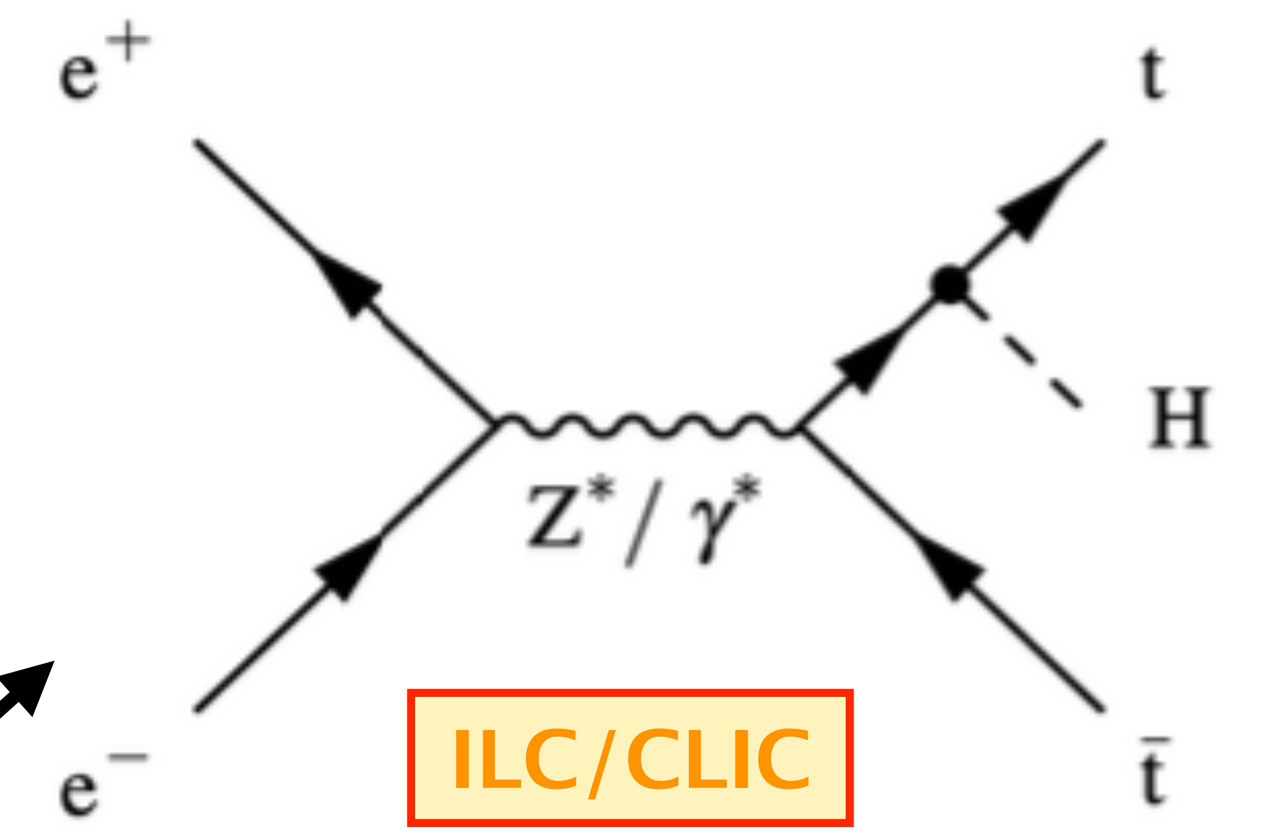
→ **threshold scan**

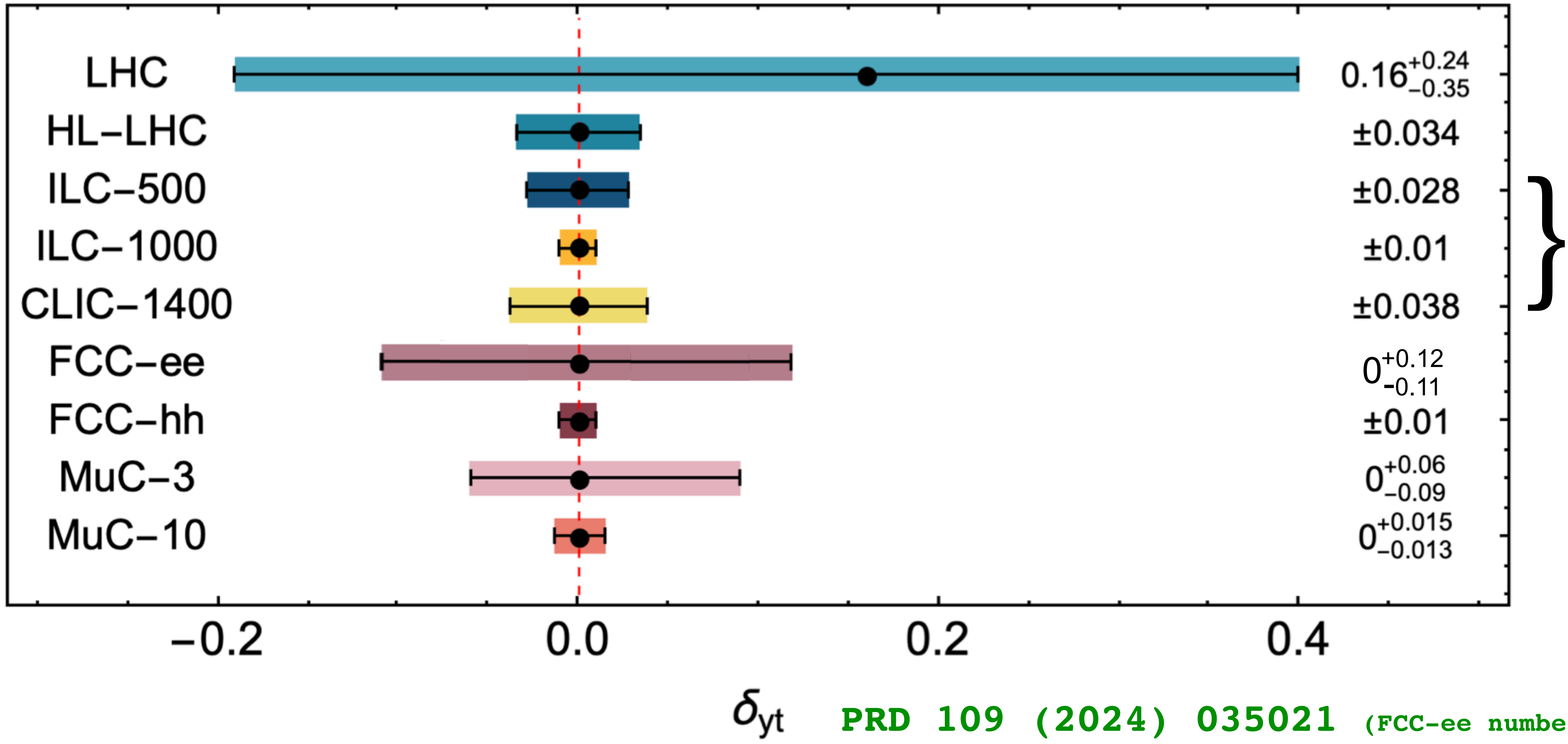
Top Quark Yukawa Coupling

- Indirect probe of at FCC-ee at threshold with ≈10% uncertainty – but involves additional assumptions and uncertainties
- High energy reach of **linear lepton colliders** (> 500 GeV) provides direct access
- Possible to reach ≈3-4% precision at ILC/CLIC (improvement by factor 2.5 at 550 GeV)
- expected uncertainty of ≈ 1.5% at **MuC**



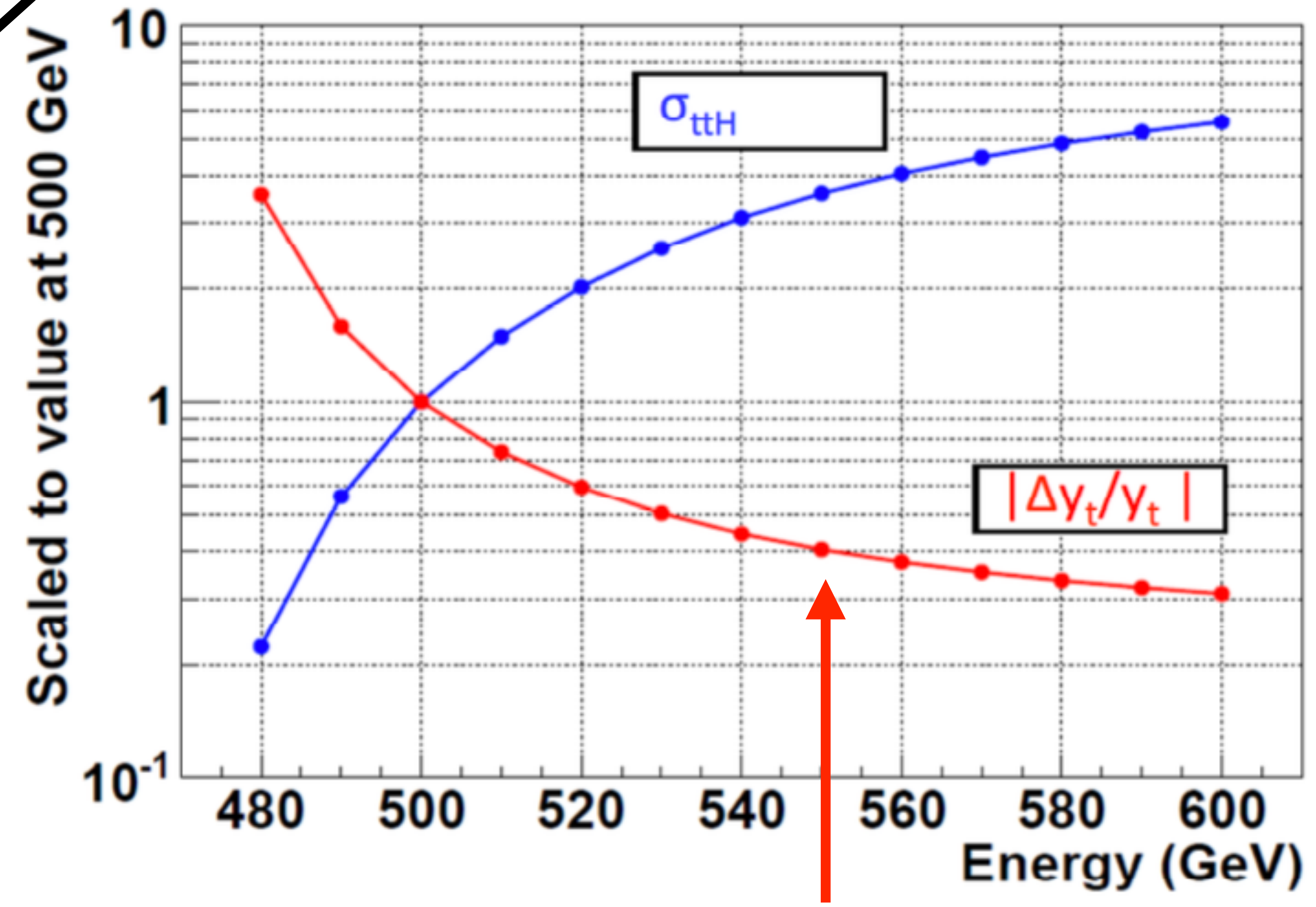
ILC-NOTE-2015-068





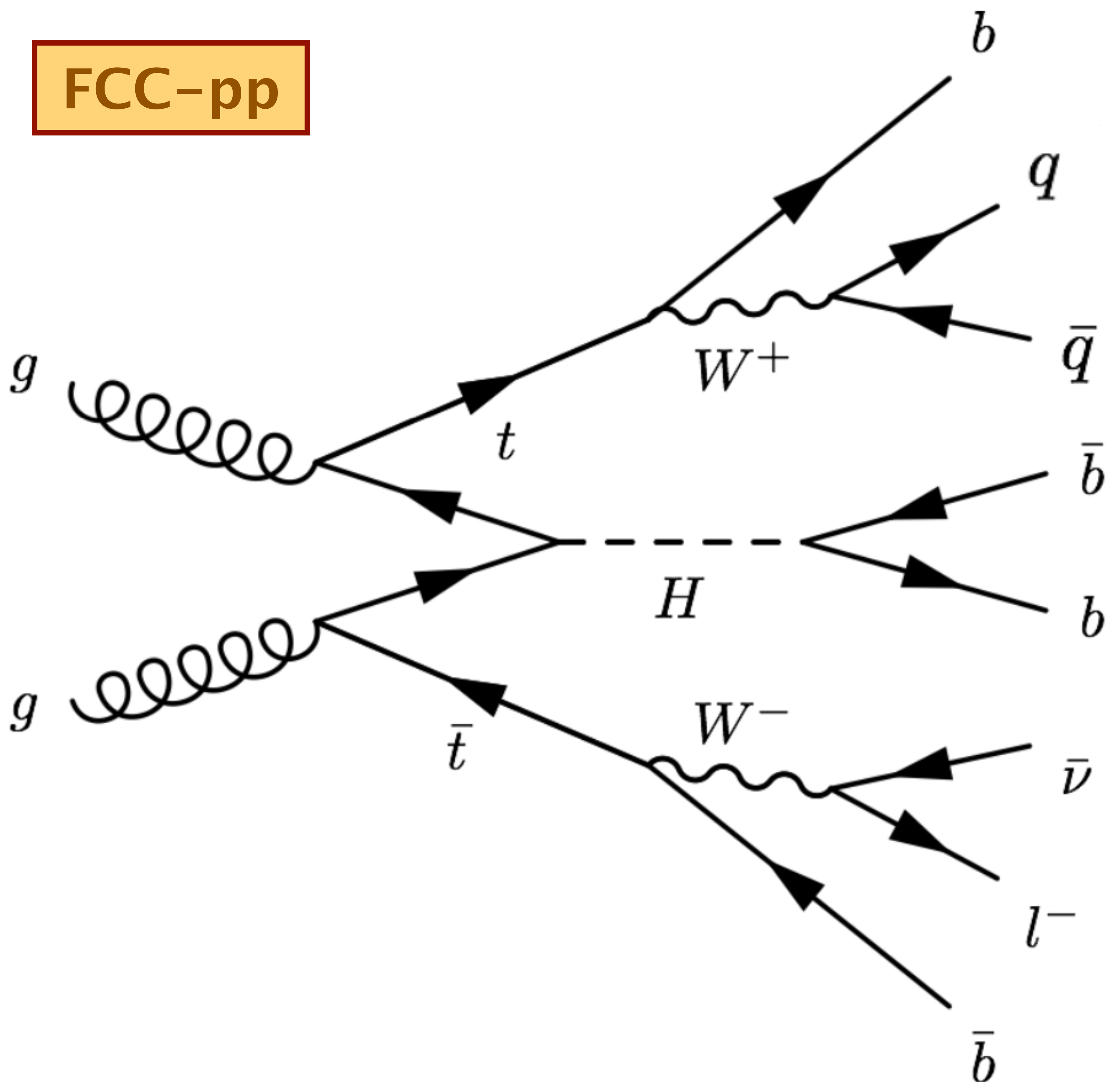
PRD 109 (2024) 035021 (FCC-ee number adapted)

- higher energy is also essential for CP analysis of the ttH vertex



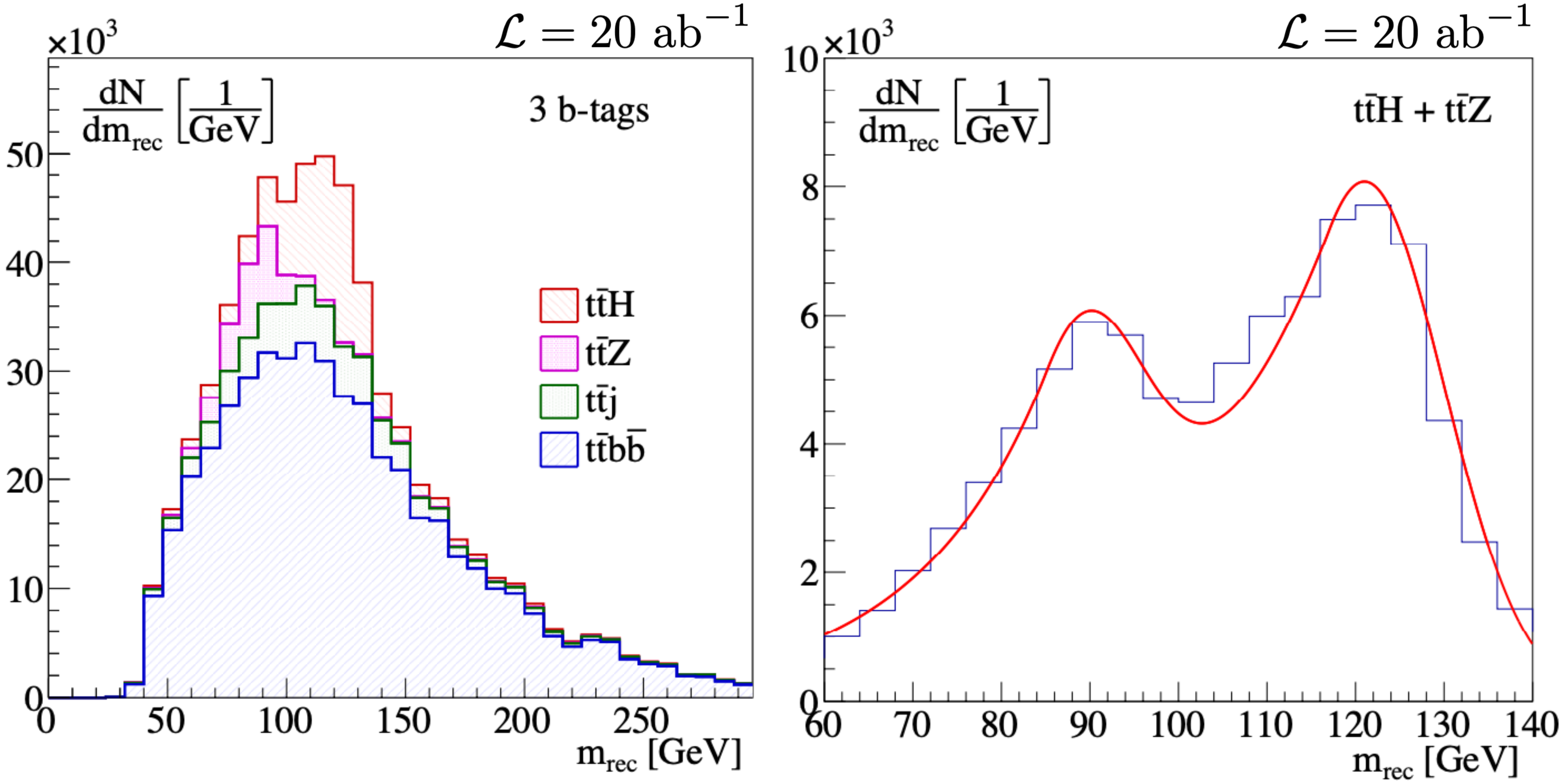
Top Quark Yukawa Coupling

FCC-pp



- fat jet
- fat jet
- lepton

reconstructed m_{bb}



reduce systematic and theoretical uncertainties

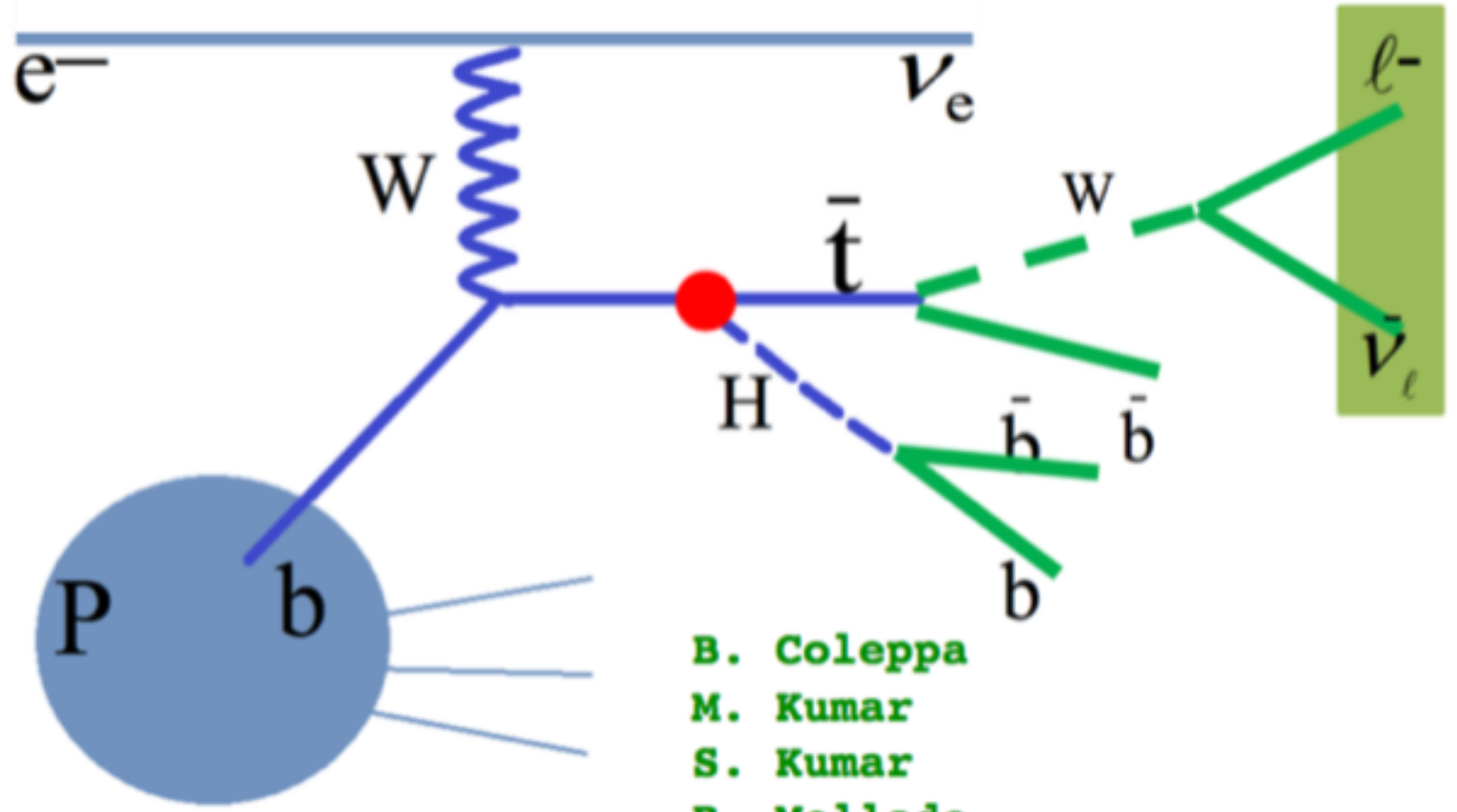
- from side bands
- from ttH/ttZ ratios

→ expected uncertainty of 1%

continuum background subtraction

(one order of magnitude better than LHC, but resolutions are crucial to understand here)

Top Quark Yukawa Coupling and CP Nature

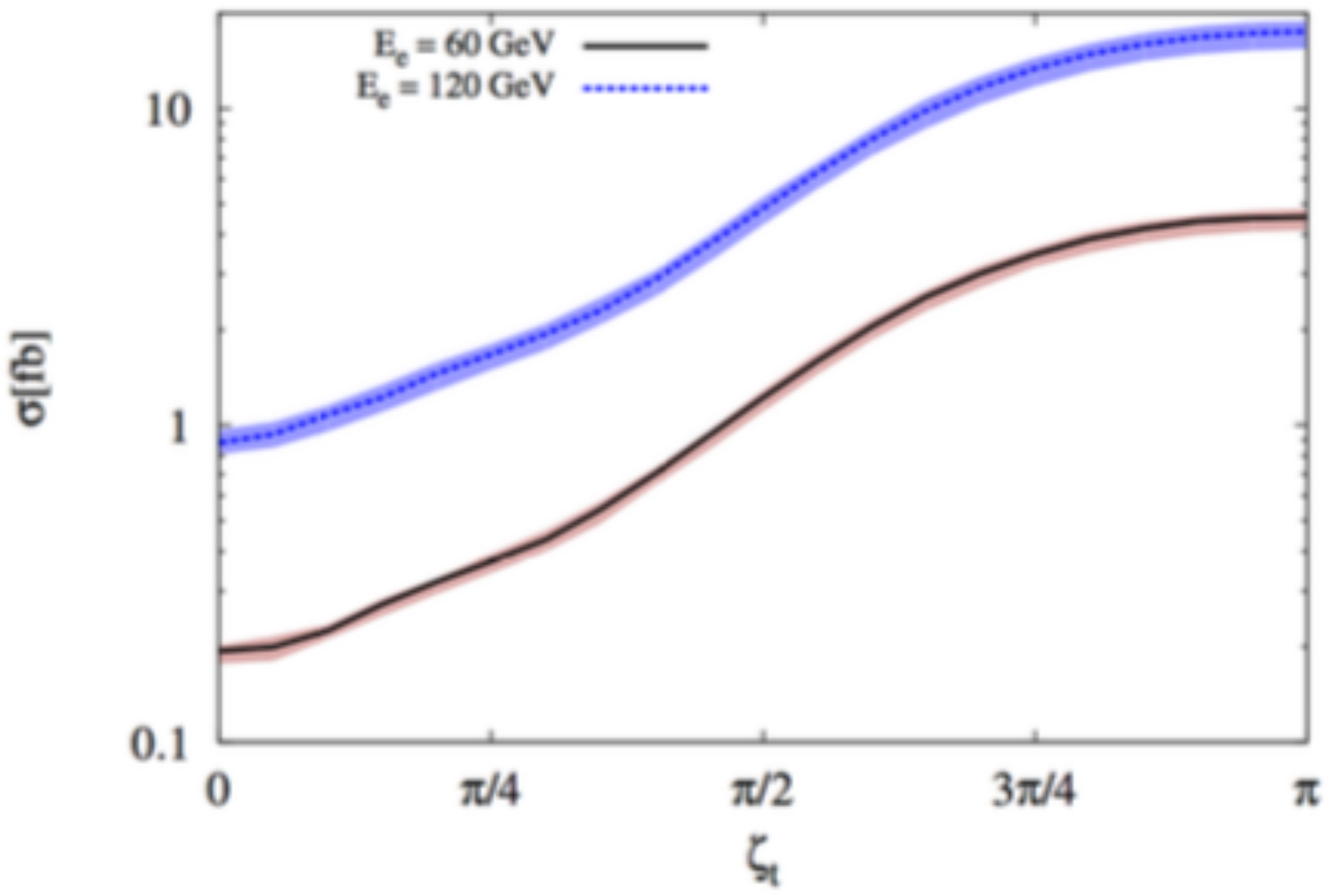


B. Coleppa
M. Kumar
S. Kumar
B. Mellado

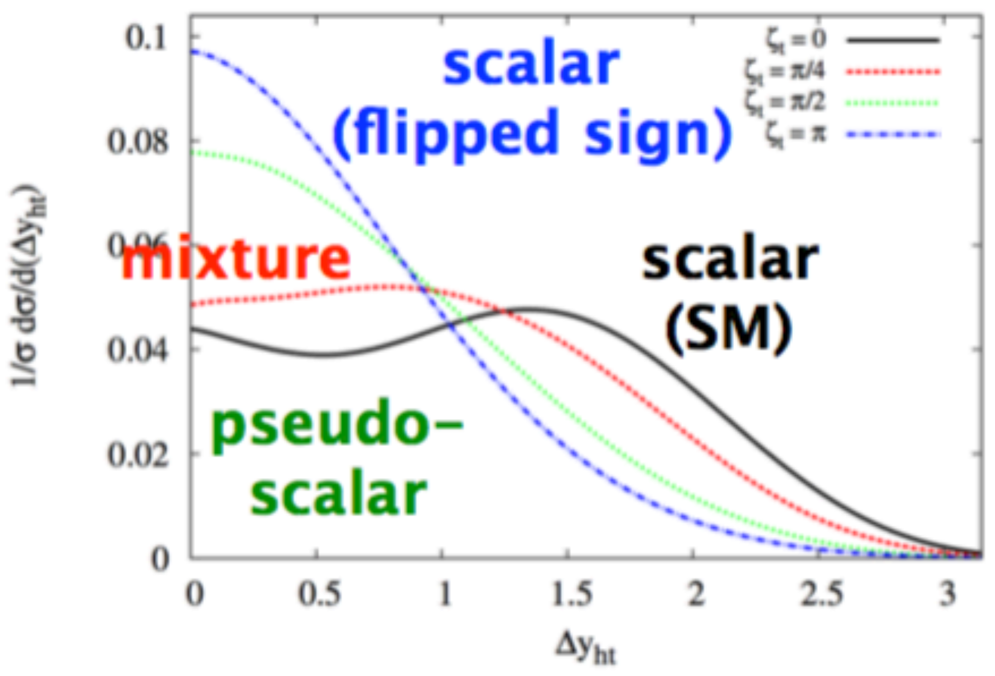
parton level

Phys. Lett. B770 (2017) 335

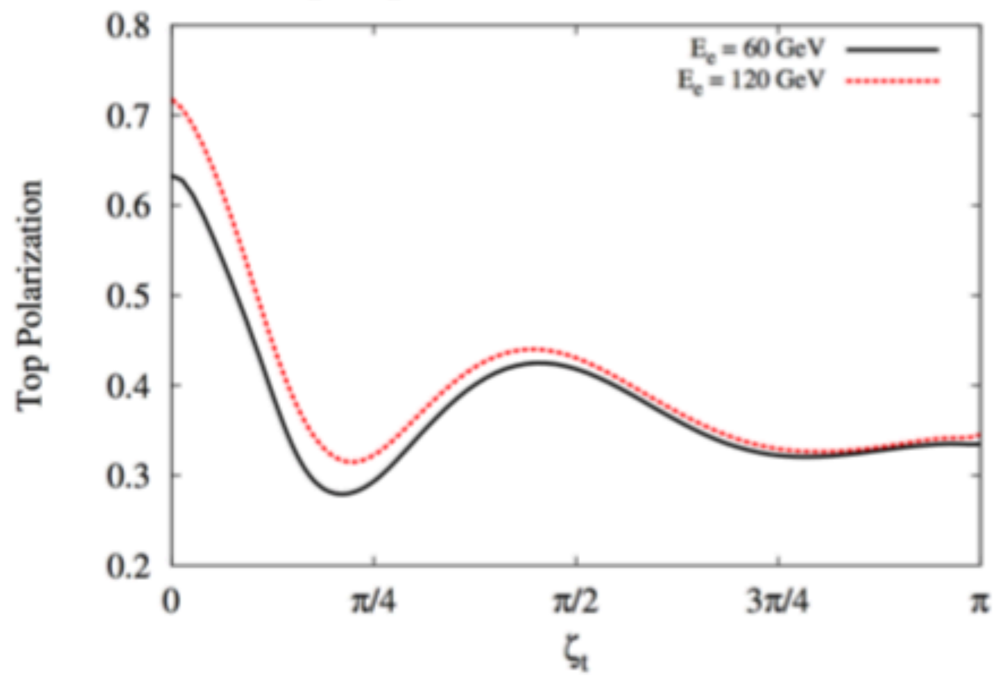
fiducial incl. cross-section



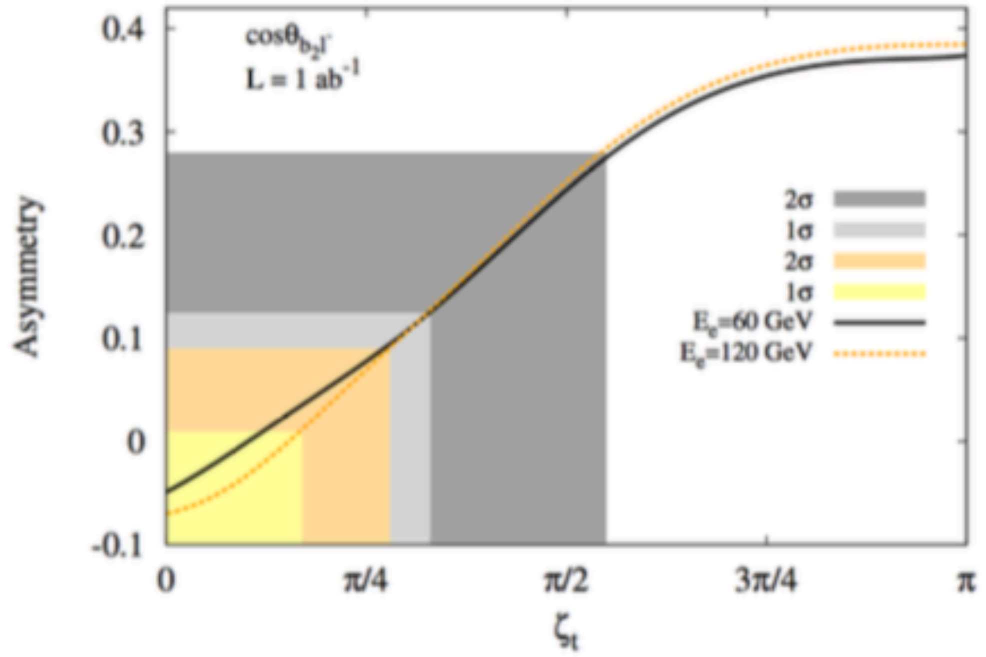
rapidity difference (H,t̄)



top polarisation

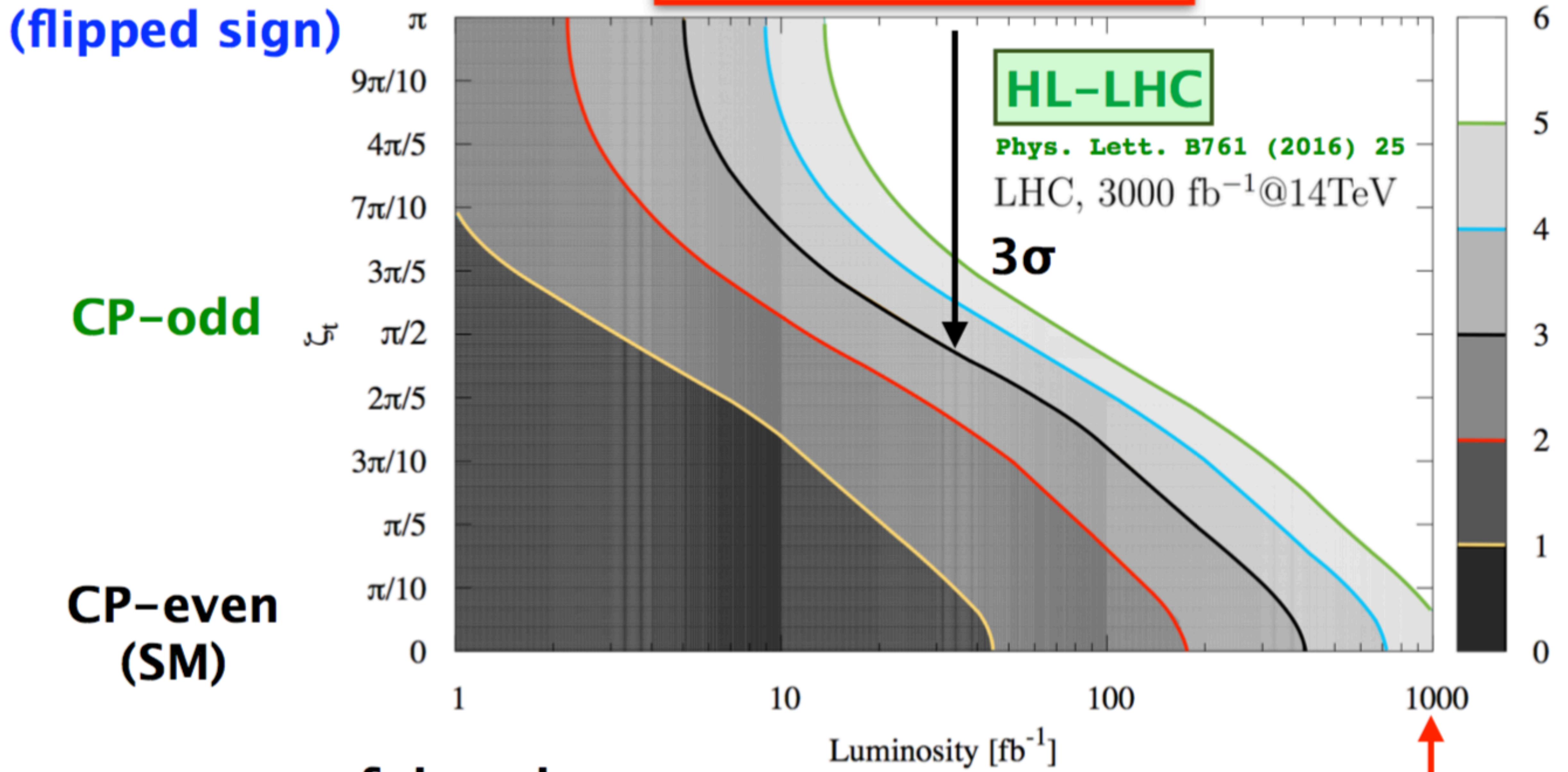


angular asymmetries (b_2,l⁻)



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

LHeC



- LC: analysis of CP nature profits from direct production at high energies

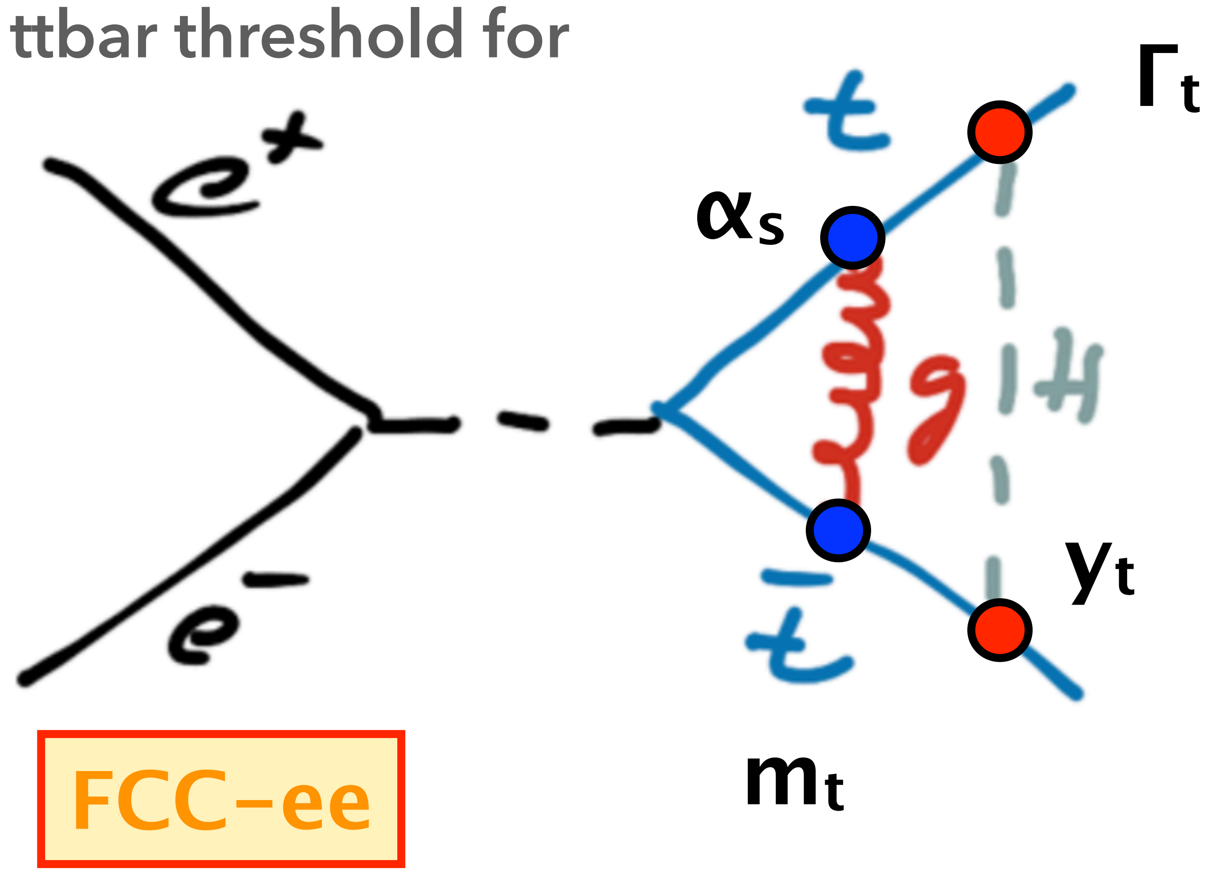
→ **powerful probe of ttH coupling**

10% uncertainty on background yields

$\kappa = 1.00 \pm 0.17$

New $t\bar{t}$ Threshold Fit Strategy

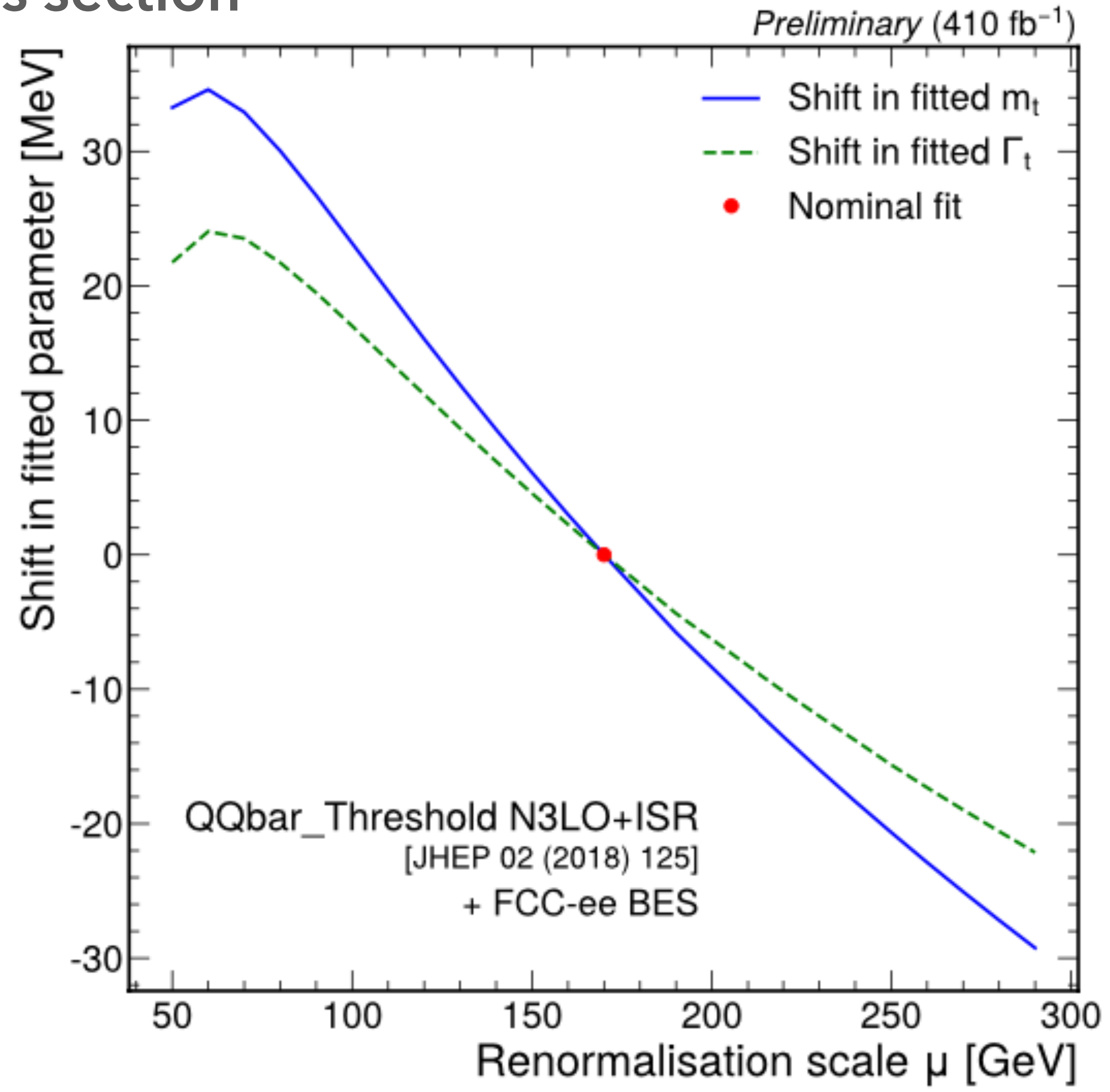
- Performed a study of WW and WbWb production around the ttbar threshold for different values of center-of-mass energy points



- Targeted events in semi-hadronic and hadronic categories
- High lepton acceptance at all center-of-mass energy points (after a minimal cut on momentum) and 100% for jets (no event selection)
- BDT classifier used for signal and background discrimination

FCC−ee

- Performed a simultaneous binned maximum likelihood fit to b-tagged jet distributions in the signal and background control regions to extract cross section
- WW background well under control (per-mille level impact on WbWb cross section)
- Simultaneous fit of N3LO theory prediction to measured cross section
- 8 MeV (stat.) uncertainty in top mass
- 11 MeV (stat.) uncertainty in top width
- Measurement of mass and width limited by QCD scale variations
- Effect of theory uncertainties on top Yukawa to be studied



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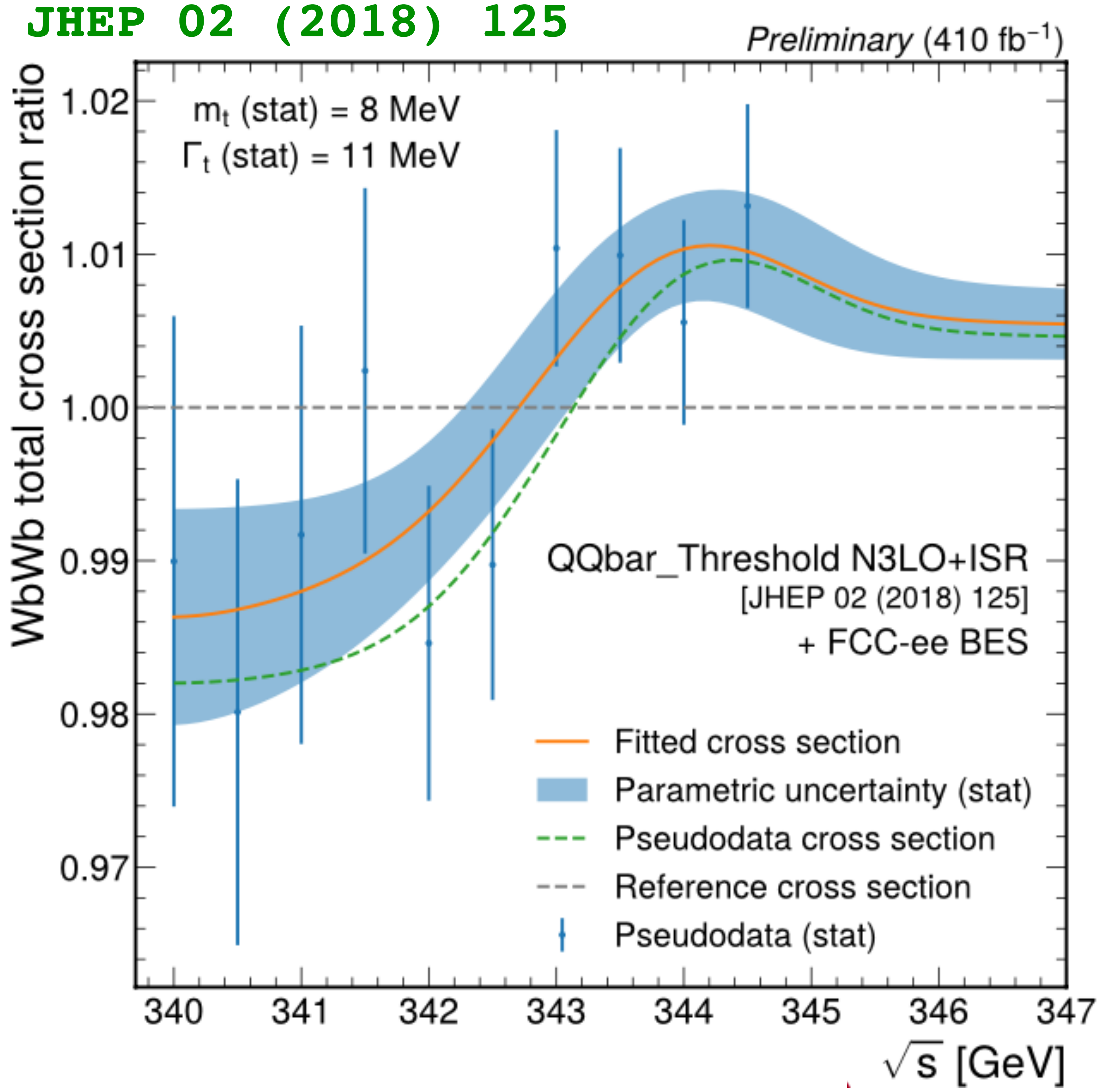
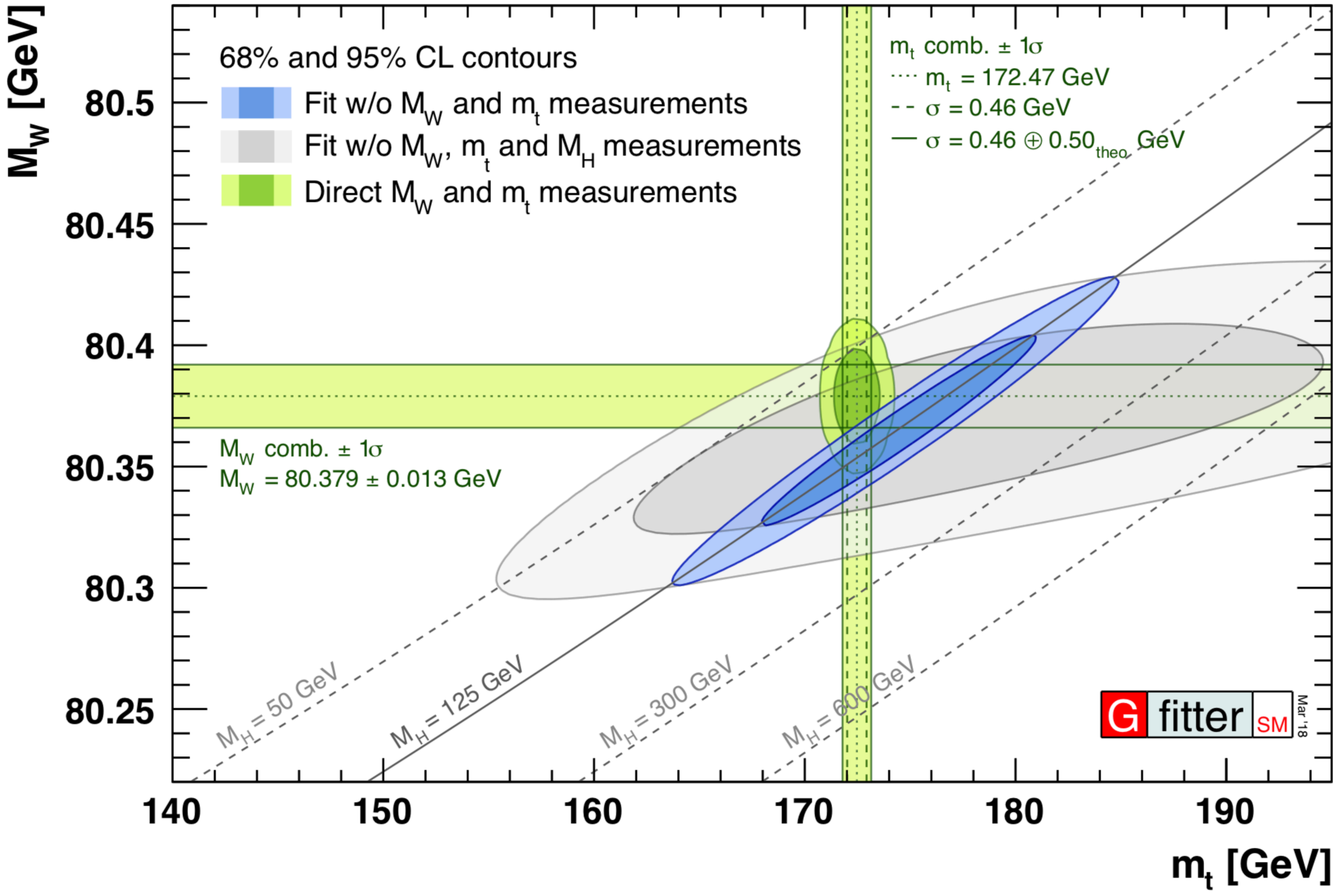


considering 10 scan points (stat only!)

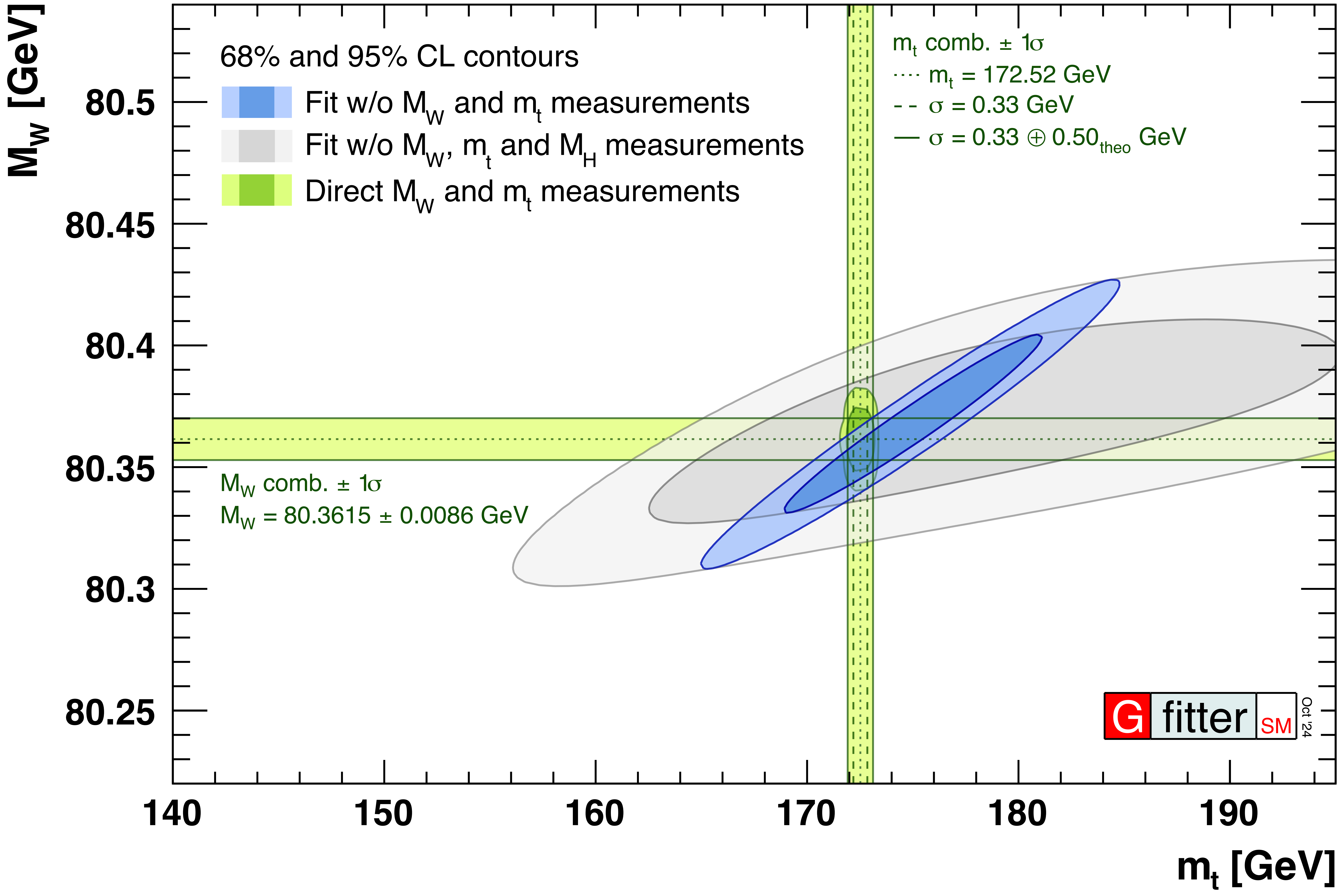
- Additional high-statistic point (2.65/ab) at 365 GeV allows to measure top Yukawa coupling to 1.7% statistical uncertainty (assuming only Yukawa corrections to Ztt vertex)

Electroweak Constraints for top vs. W mass

[Gfitter, 1803.01853]

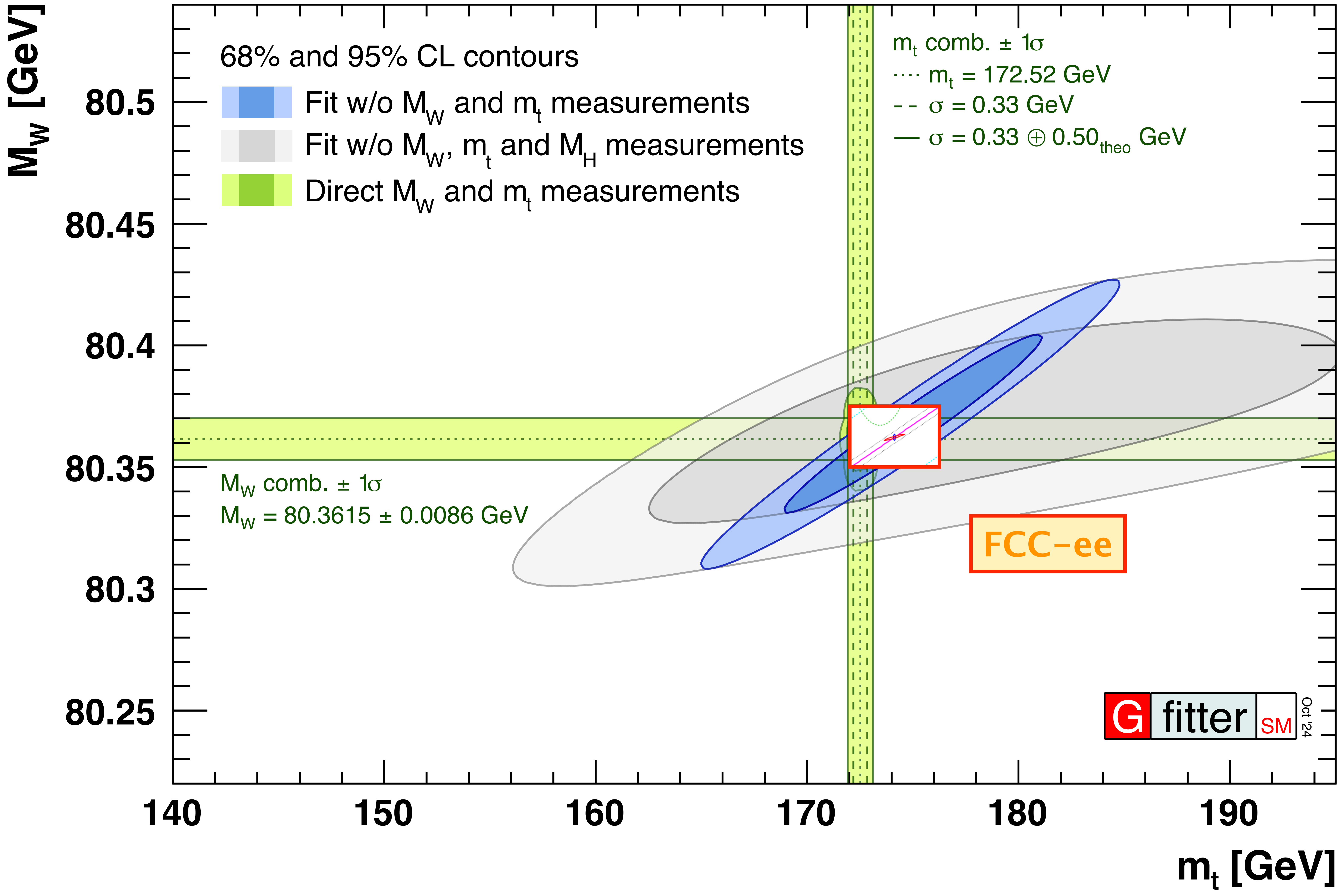


Electroweak Constraints for top vs. W mass



Gfitter group, Oct 24

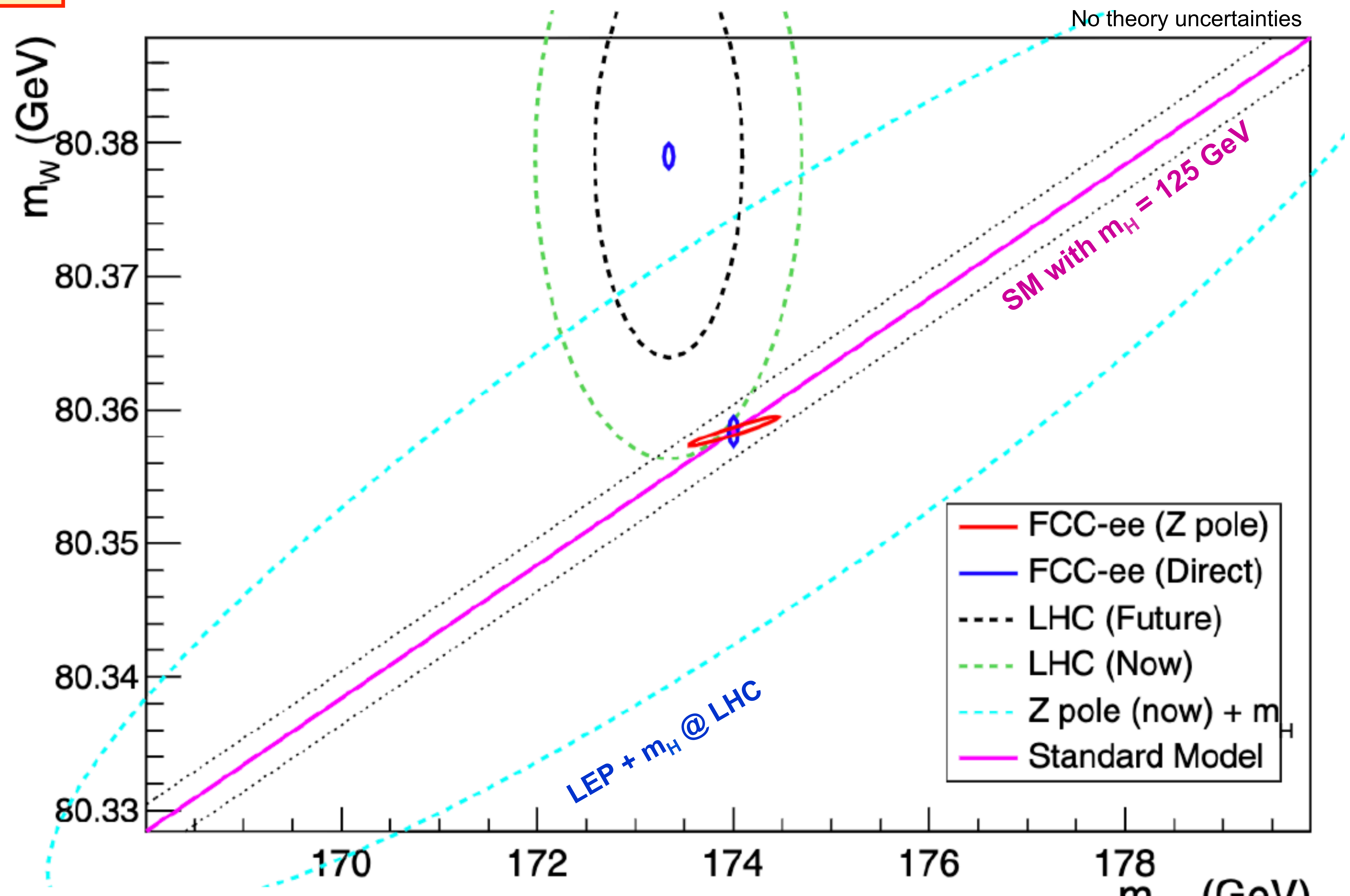
Electroweak Constraints for top vs. W mass



Gfitter group, Oct 24

Electroweak Constraints for top mass vs. W mass

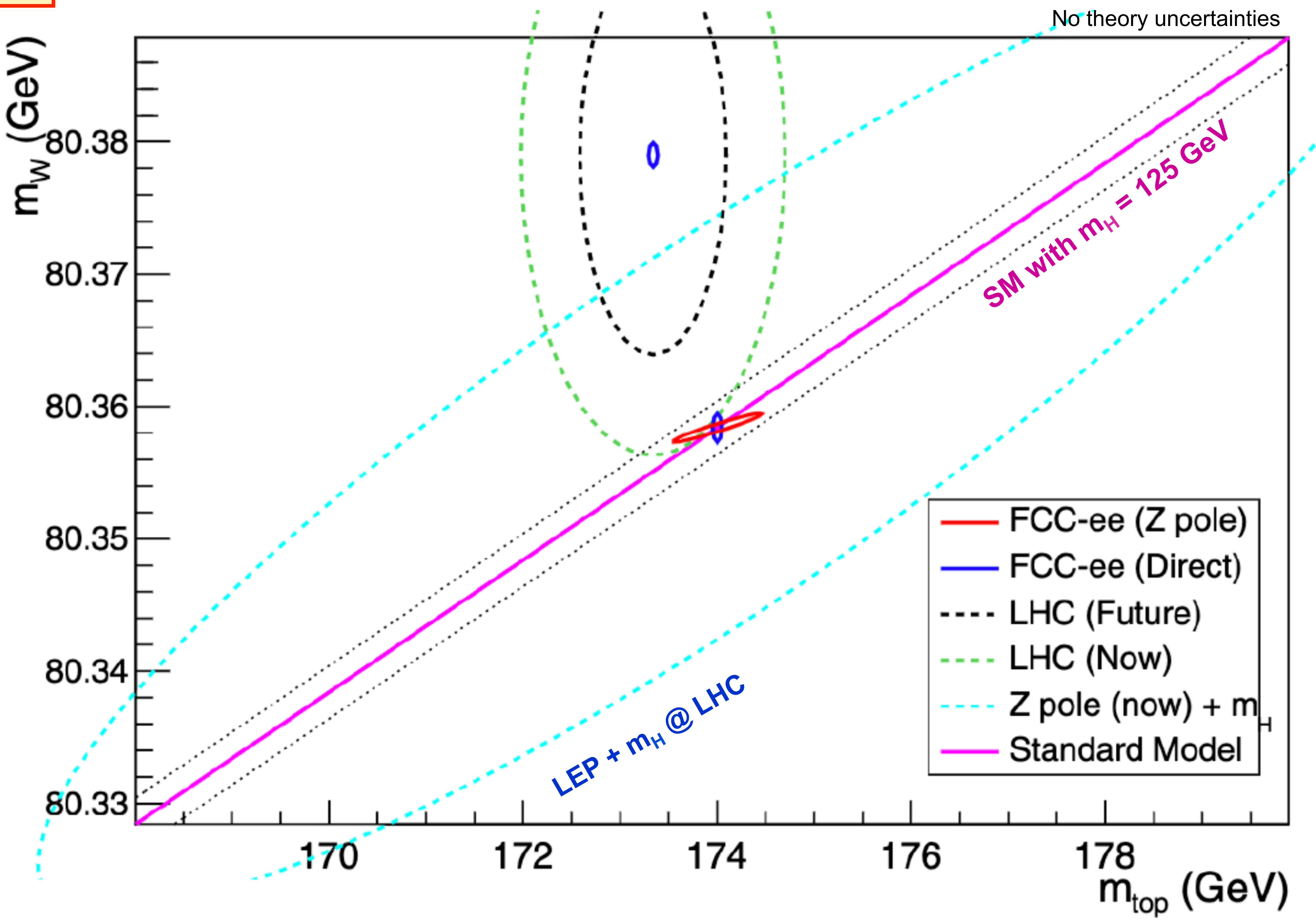
FCC-ee

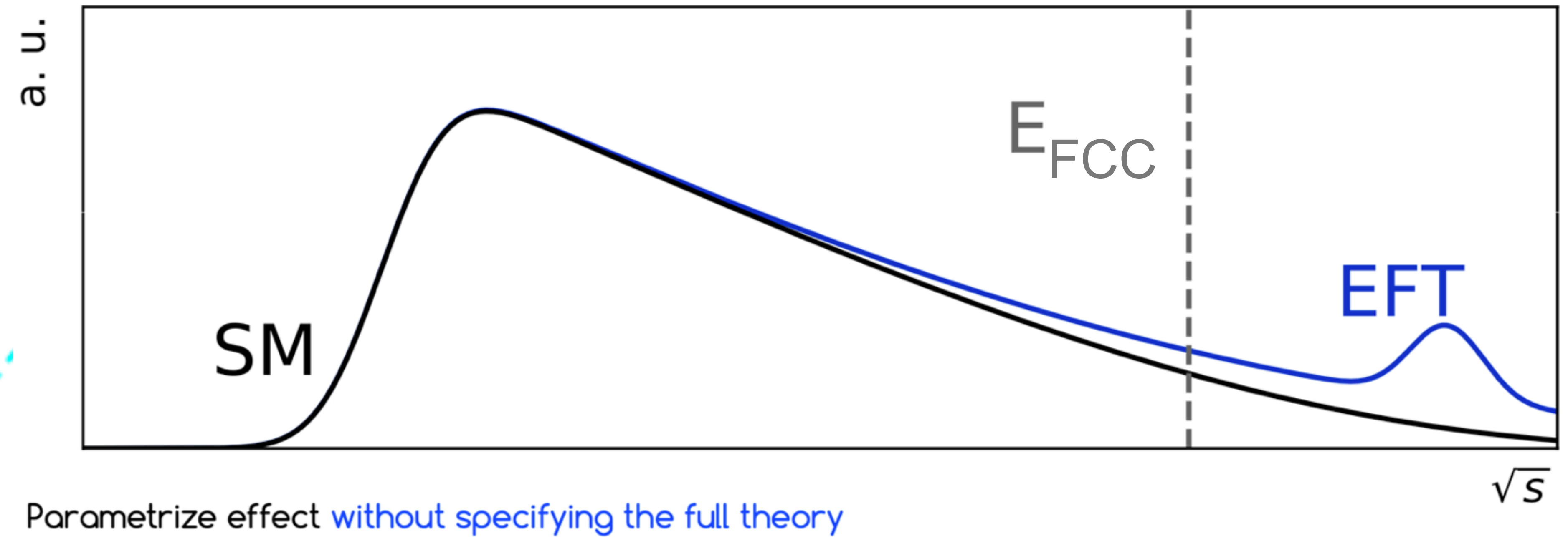


→ **very high precision in testing self-consistency of SM**

Electroweak Constraints for top mass vs. W mass

FCC-ee

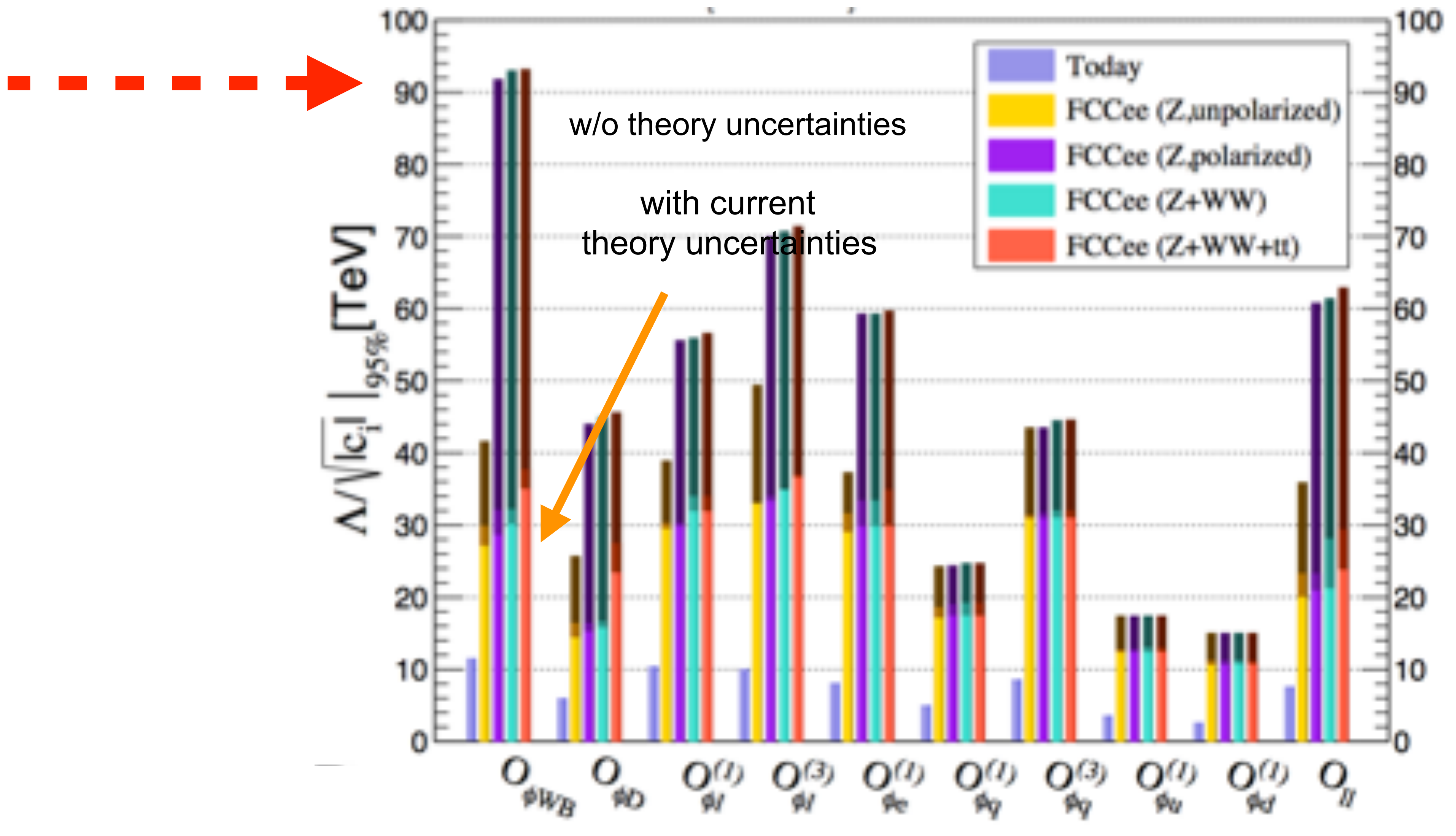




Parametrize effect without specifying the full theory

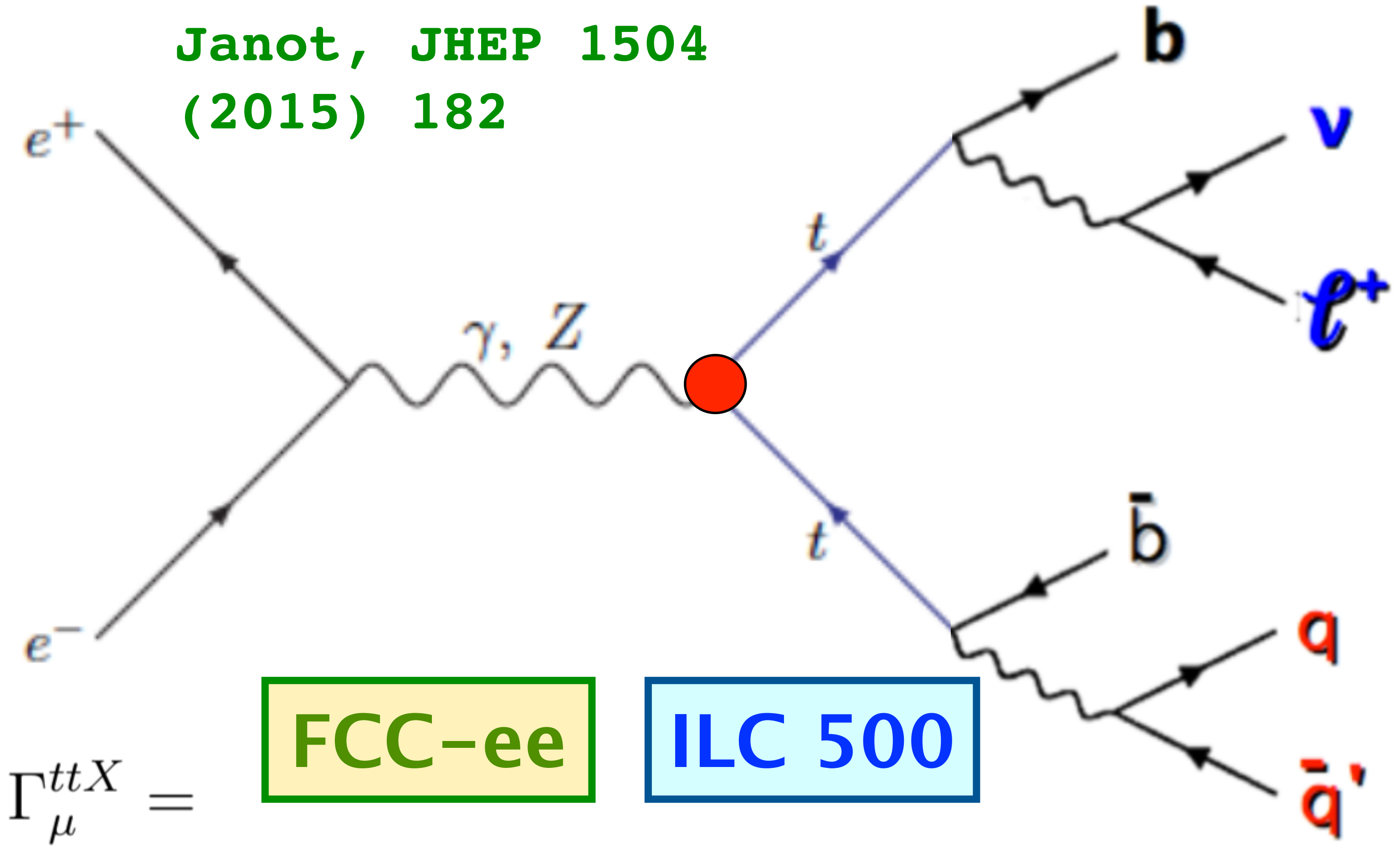
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Sensitivity for new phenomena scale extended up to 10-100 TeV!



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

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



Janot, JHEP 1504 (2015) 182

FCC-ee

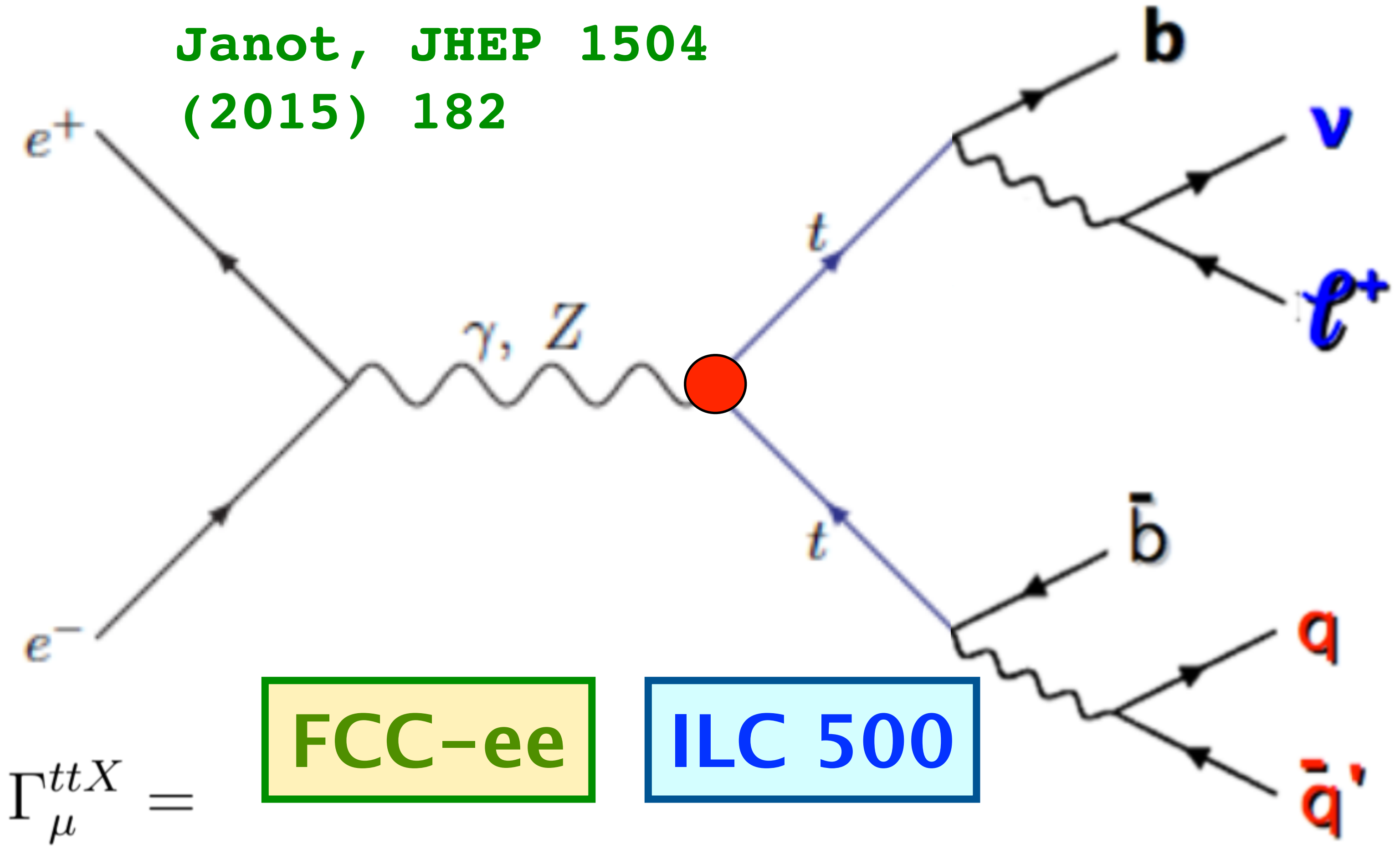
ILC 500

$$\Gamma_{\mu}^{ttX} =$$

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

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

Janot, JHEP 1504 (2015) 182

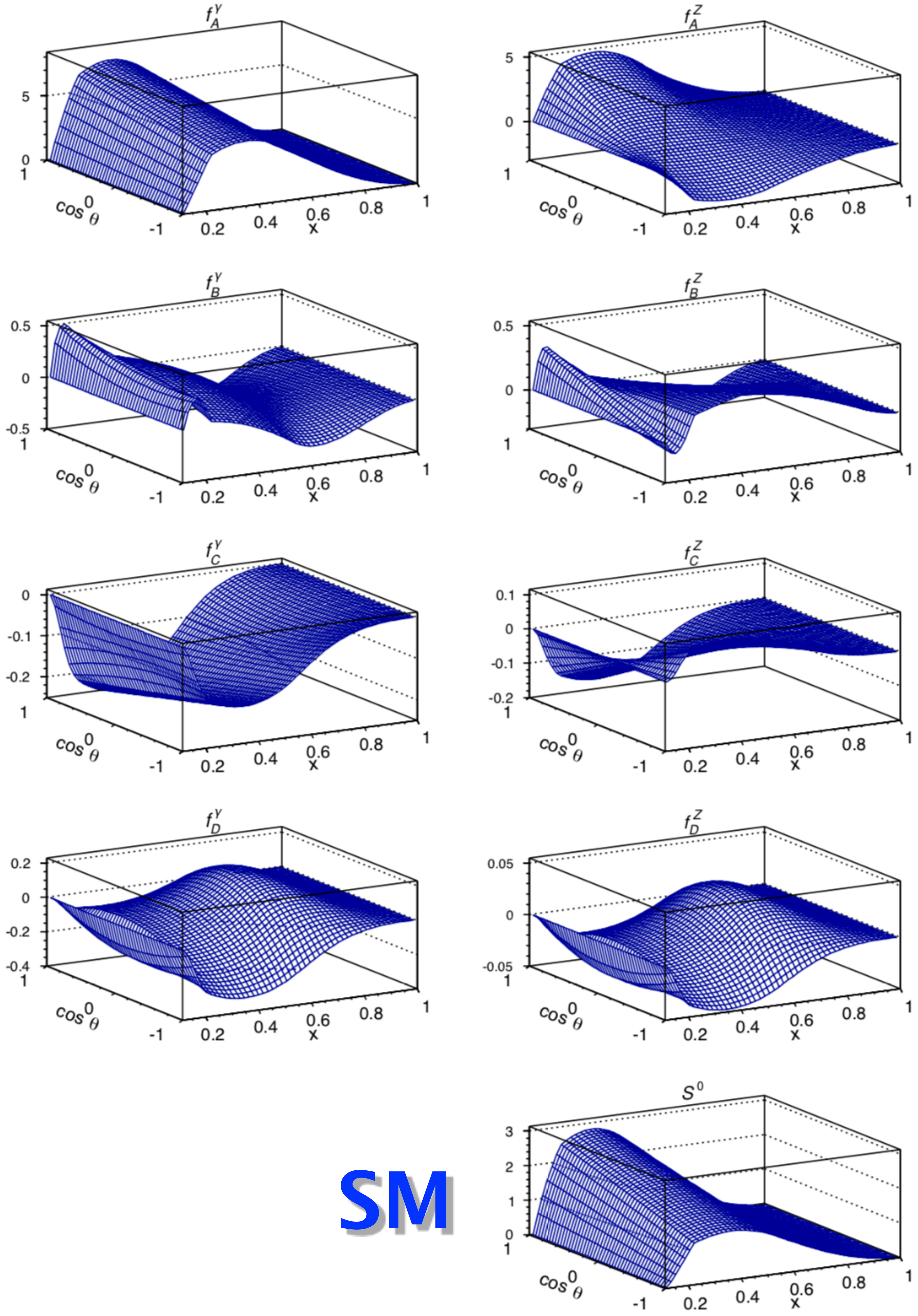


FCC-ee **ILC 500**

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

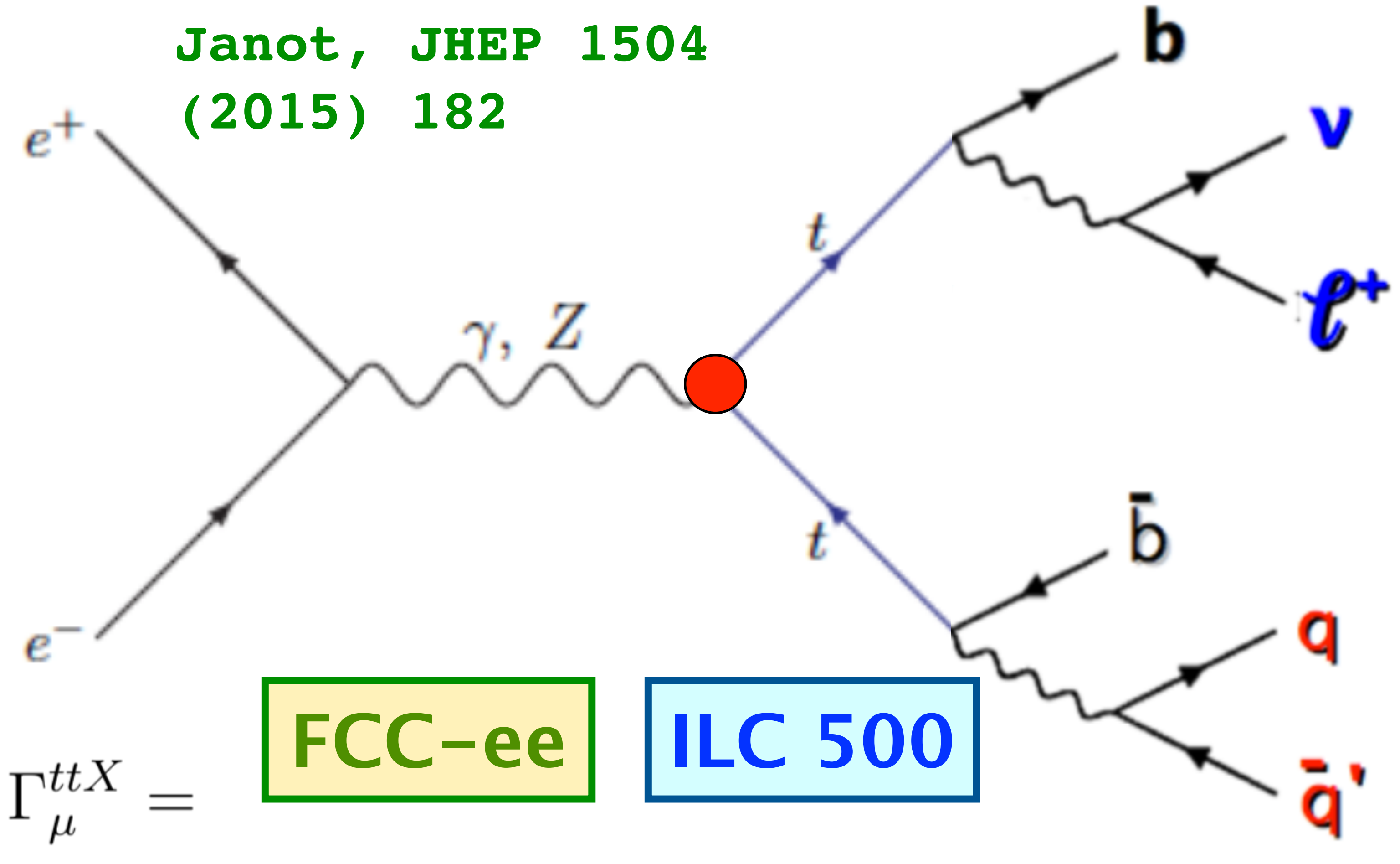
- use lepton energy and angular distributions in top decay to distinguish ttγ and ttZ
- use optimal observable analysis (confirmed by full simulation analysis)

→ no beam polarisation needed, use top polarisation instead



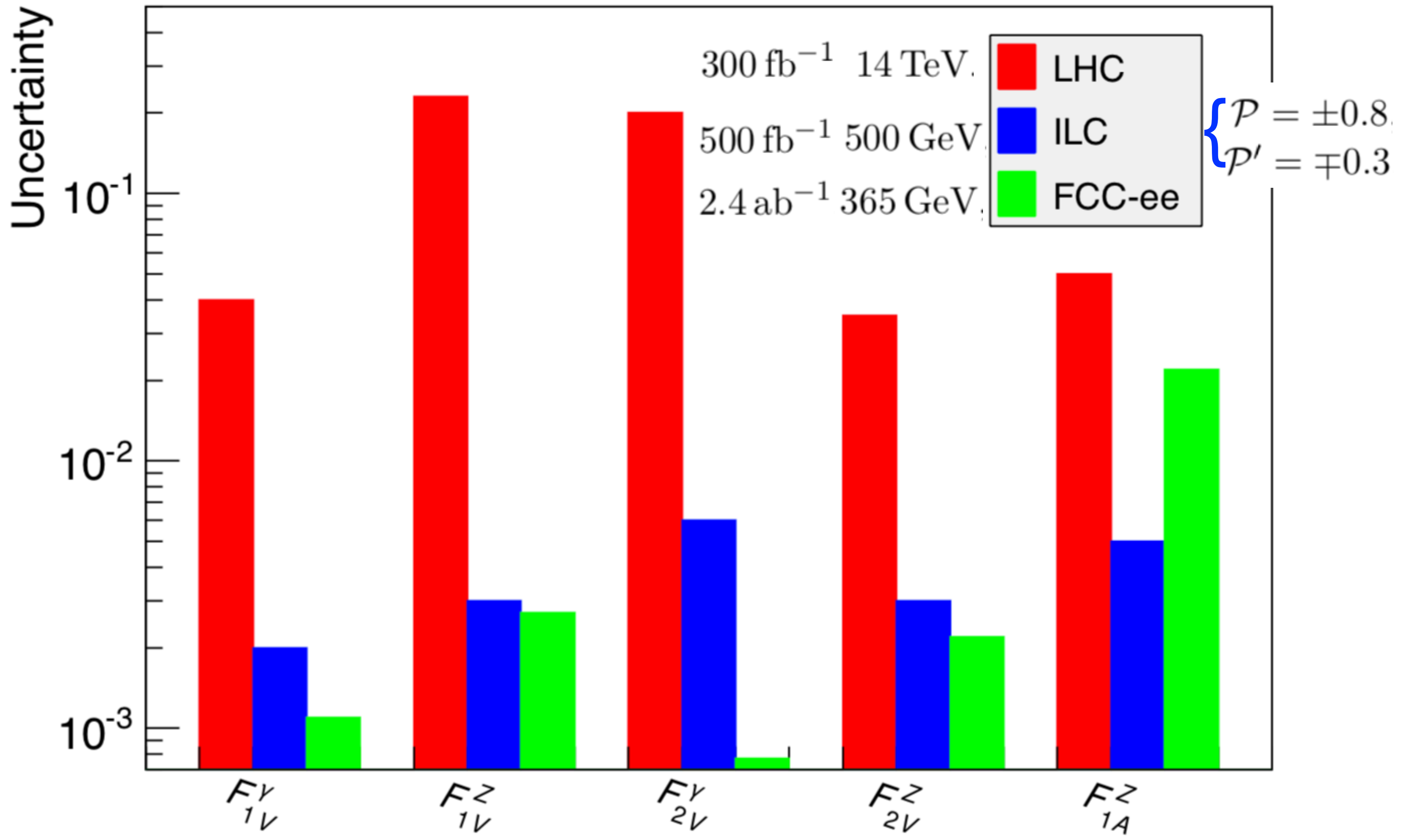
t$\bar{t}$Z and t$\bar{t}$γ Vertex and Dipole Moments

Janot, JHEP 1504 (2015) 182



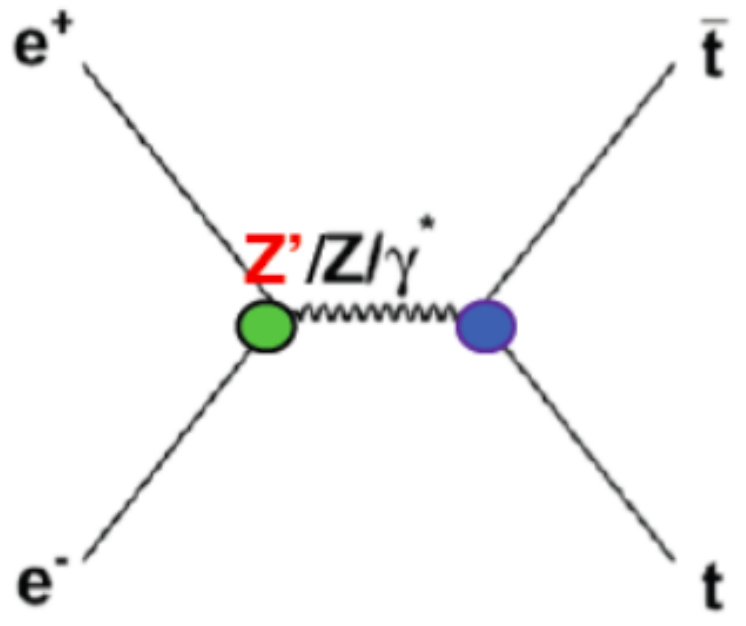
FCC-ee **ILC 500**

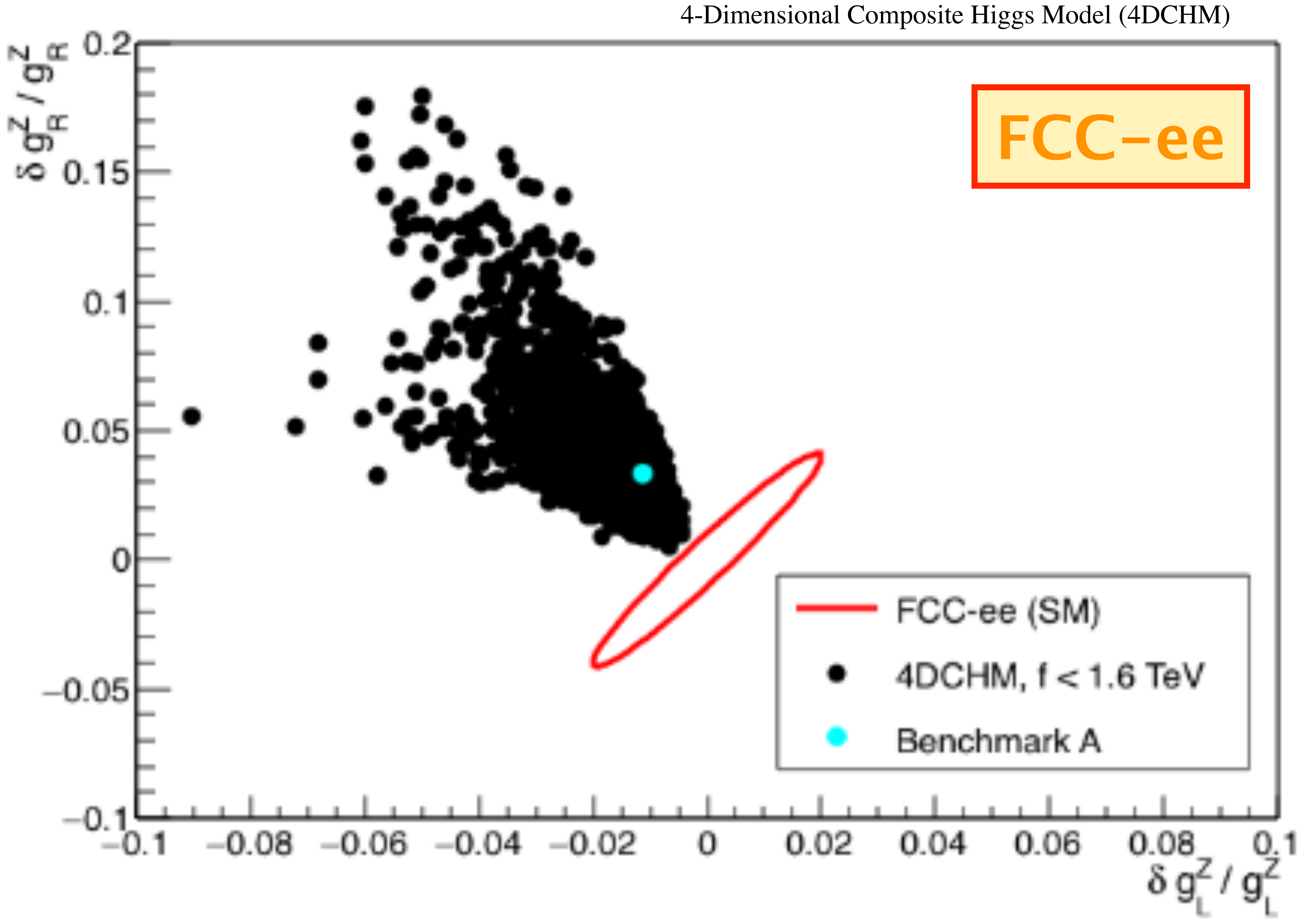
$$\Gamma_\mu^{ttX} = -ie\left\{\gamma_\mu\left(F_{1V}^X+\gamma_5F_{1A}^X\right)+\frac{\sigma_{\mu\nu}}{2m_t}(p_t+p_{\bar{t}})^\nu\left(iF_{2V}^X+\gamma_5F_{2A}^X\right)\right\}$$



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

t$\bar{t}$Z

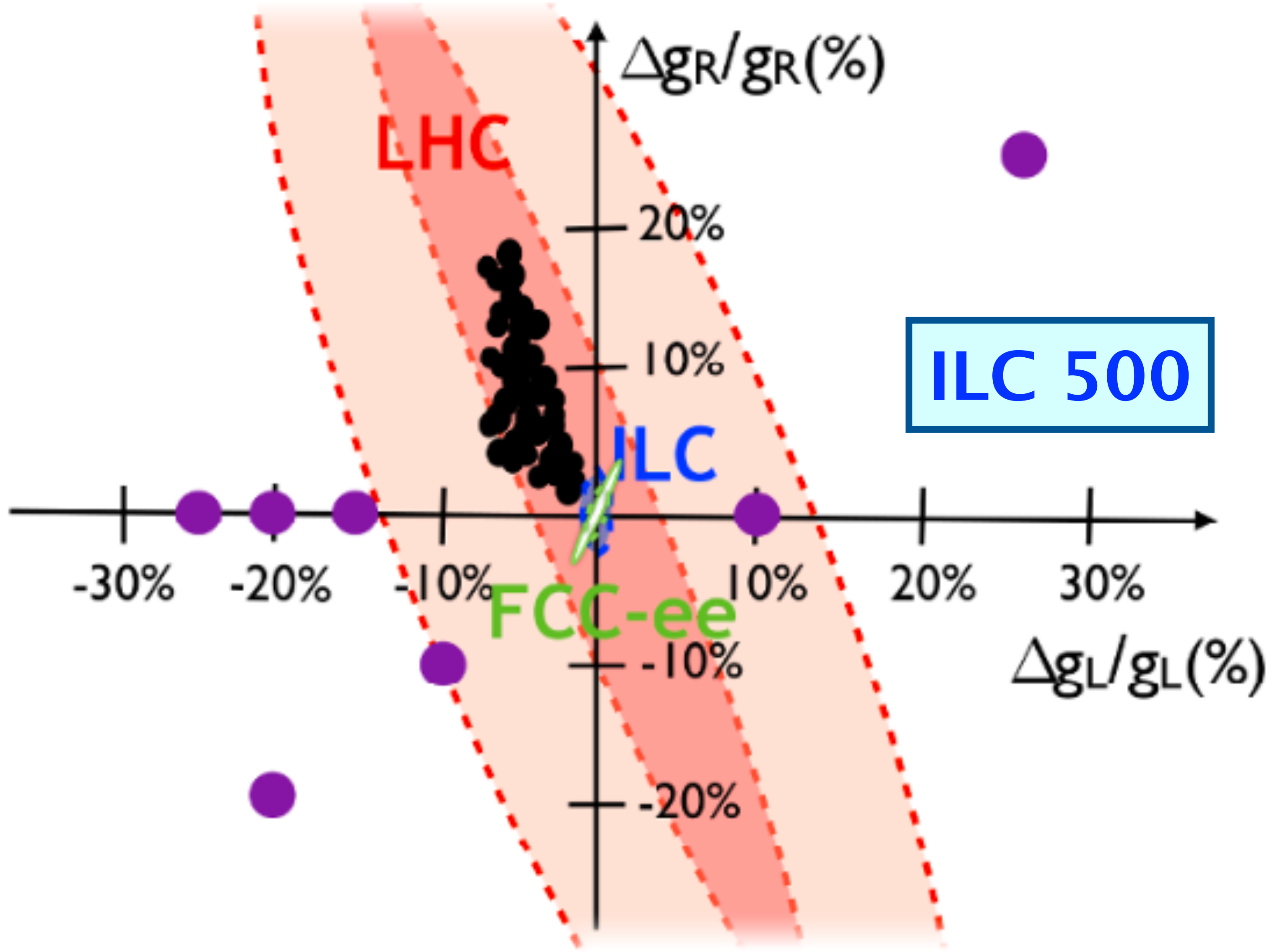




→ **exclude composite Higgs models up to m$_{Z'}$~3 TeV**

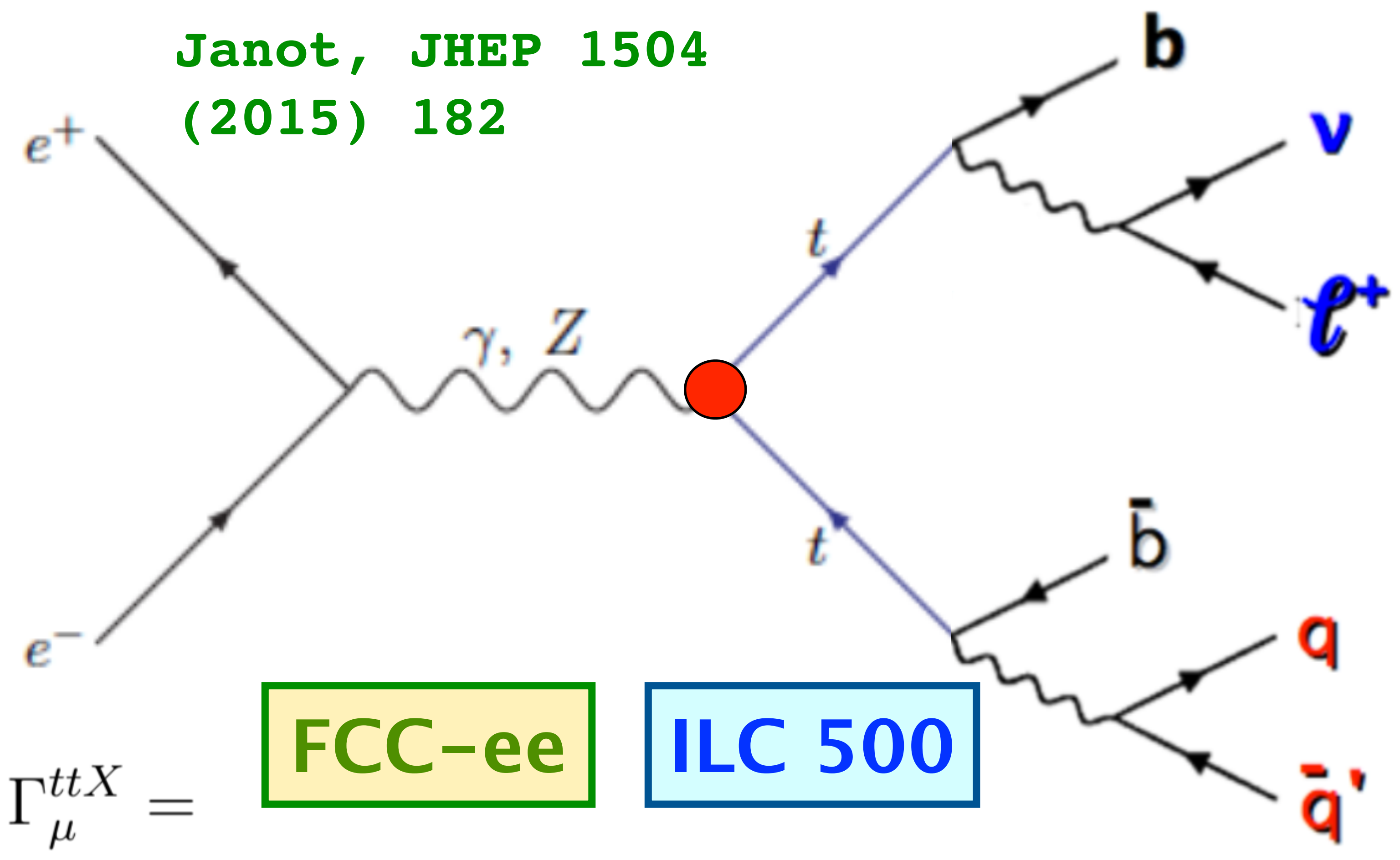
FCC-ee: study angular and energy distribution of leptons (b-quarks))

$\boxed{Zt_Lt_L \text{ and } Zt_Rt_R \text{ couplings}}$



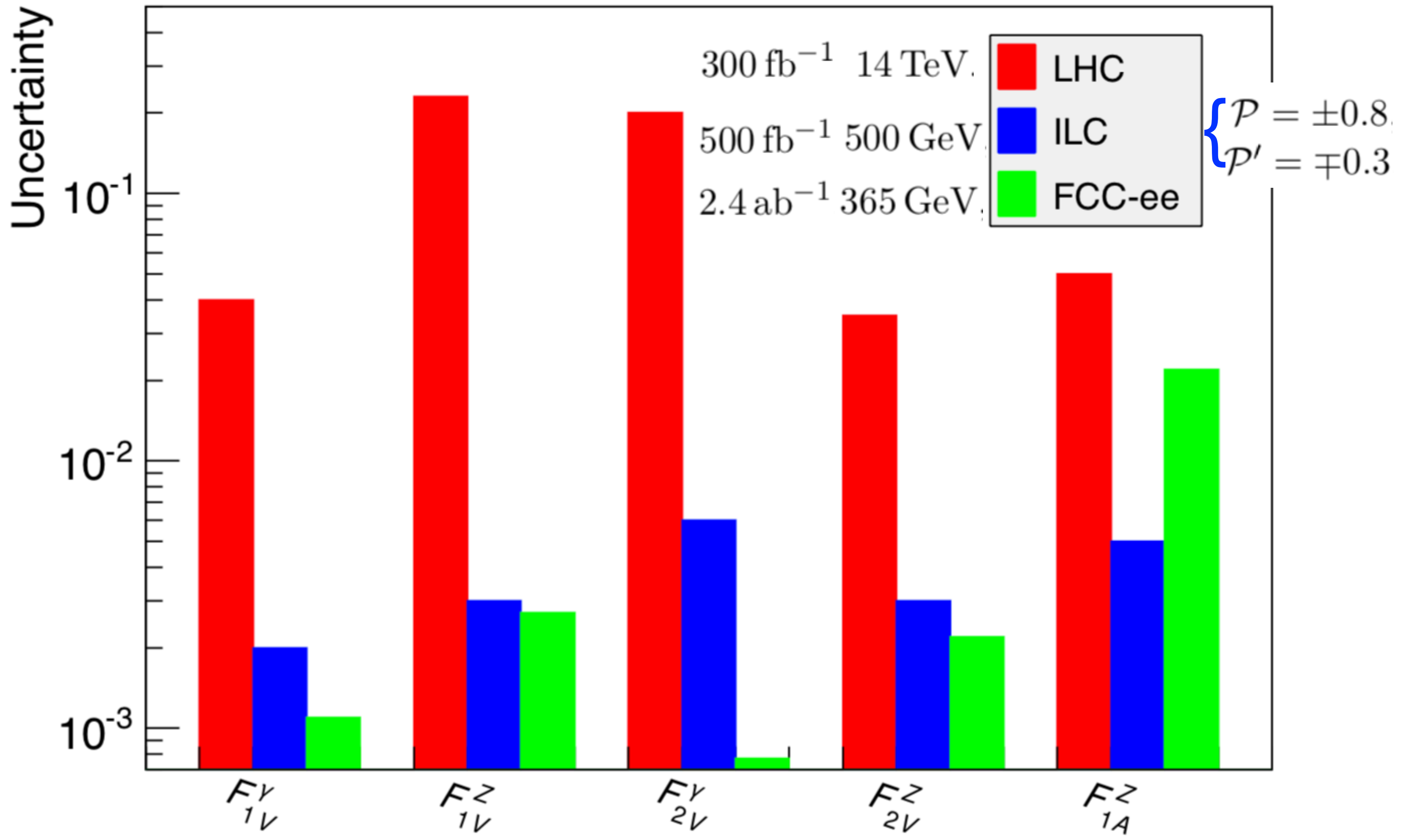
$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments

Janot, JHEP 1504 (2015) 182

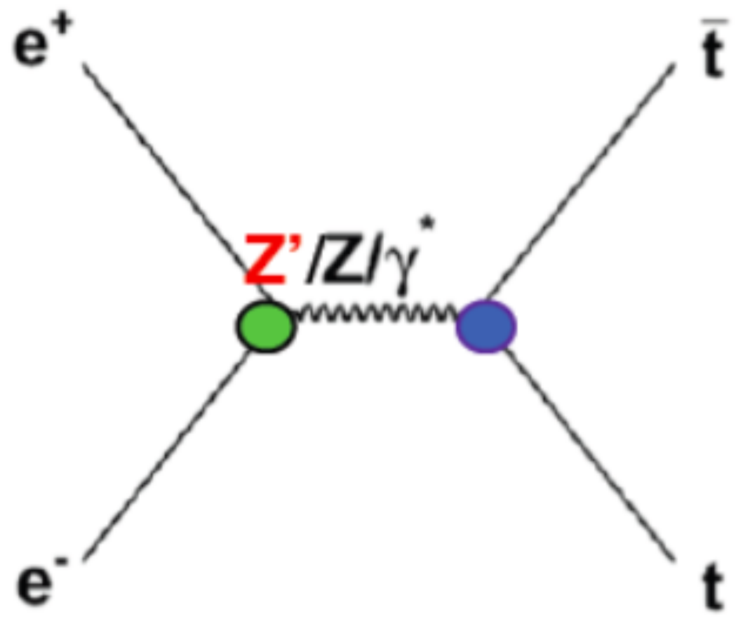


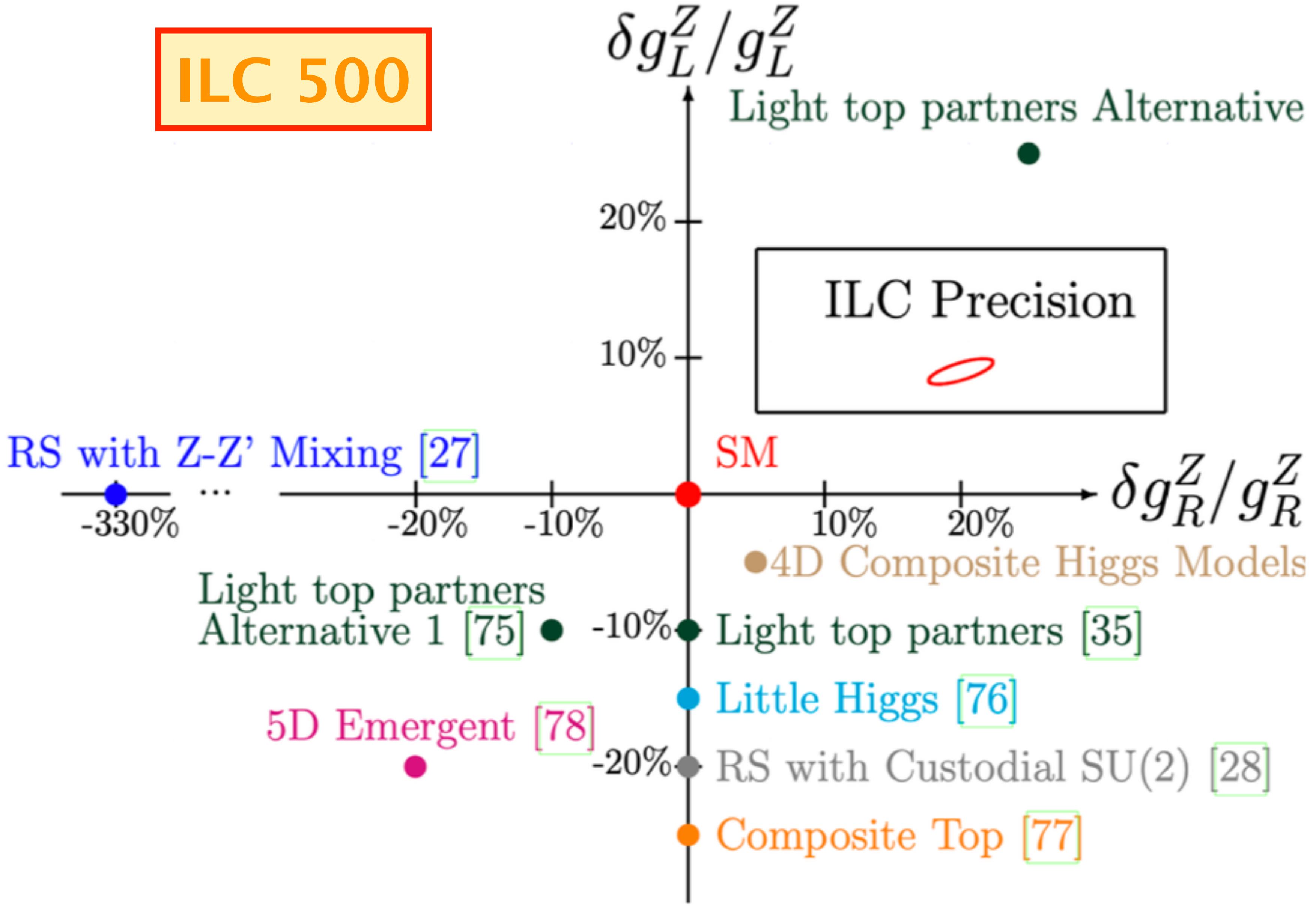
FCC-ee **ILC 500**

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

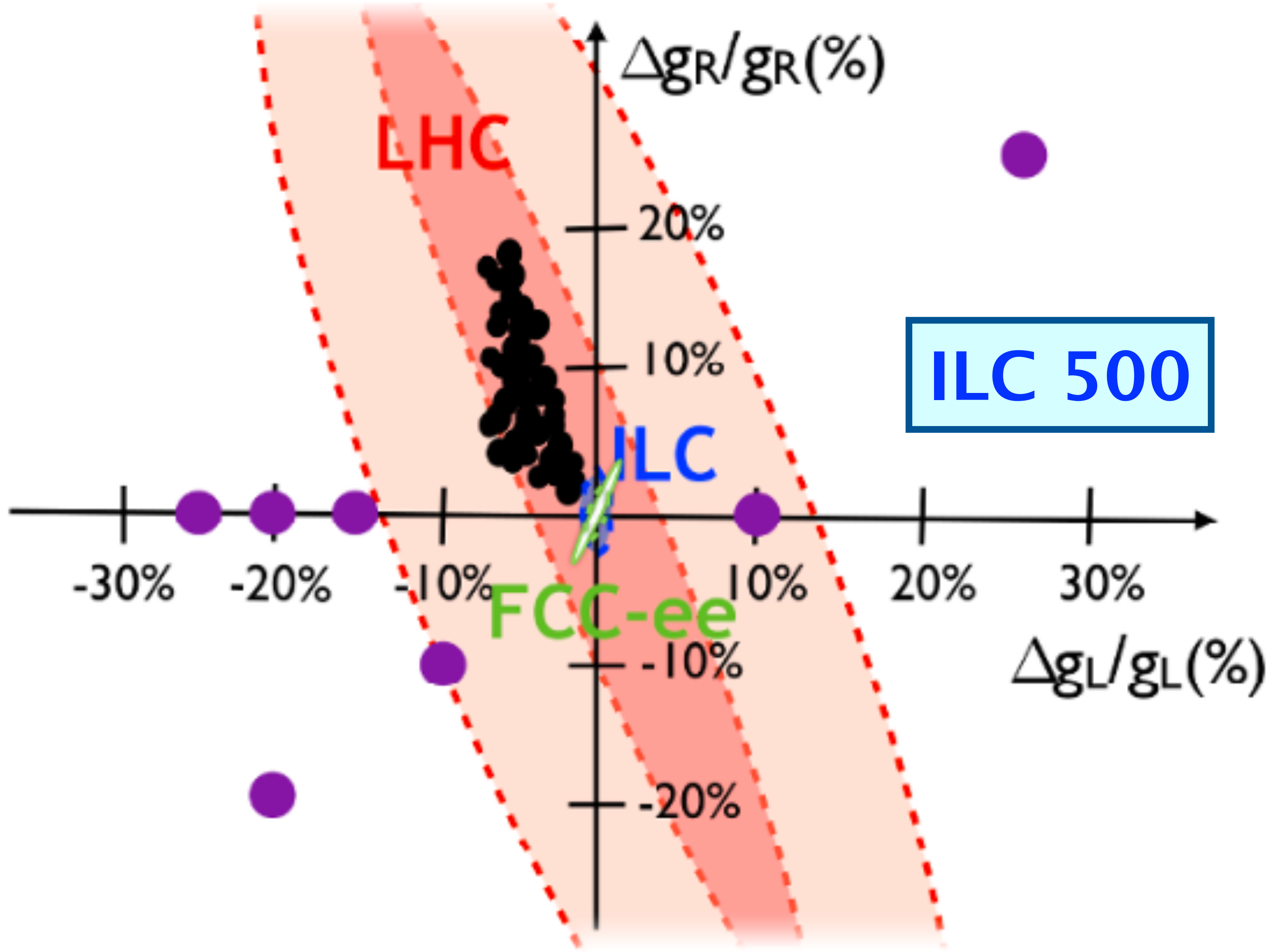


→ **expected precision of order 10^{-2} to 10^{-3}**

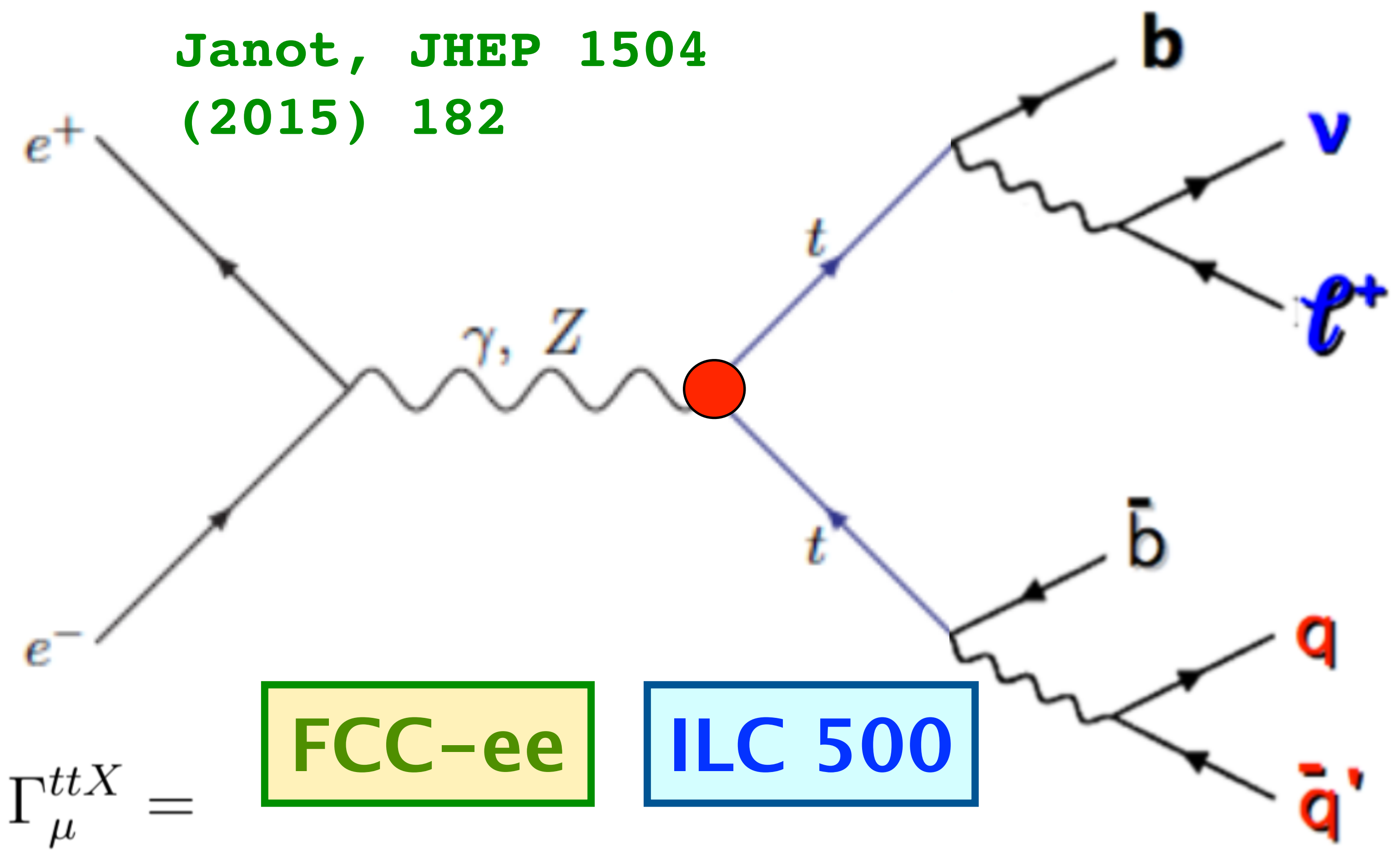




Zt_Lt_L and Zt_Rt_R couplings



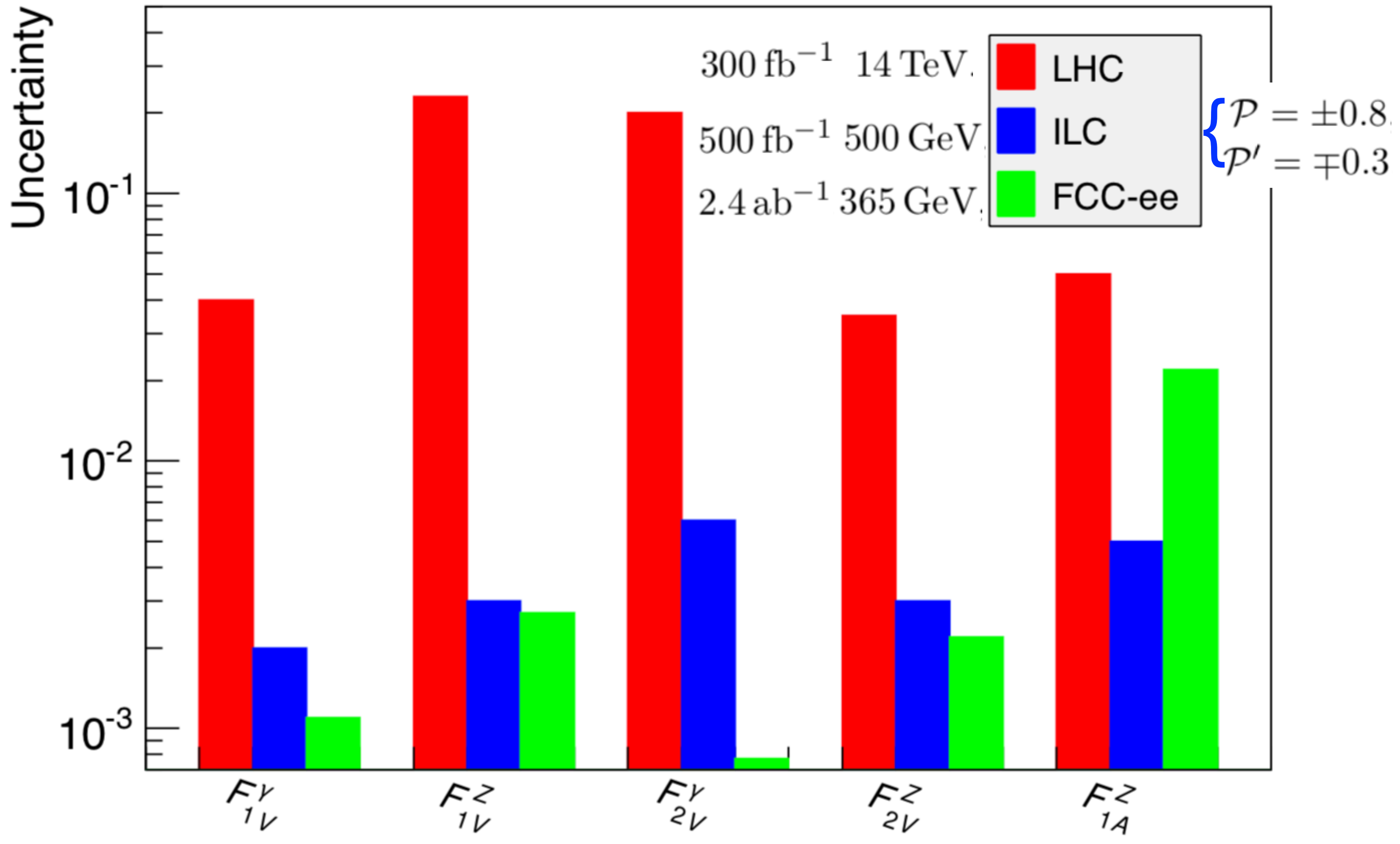
$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments



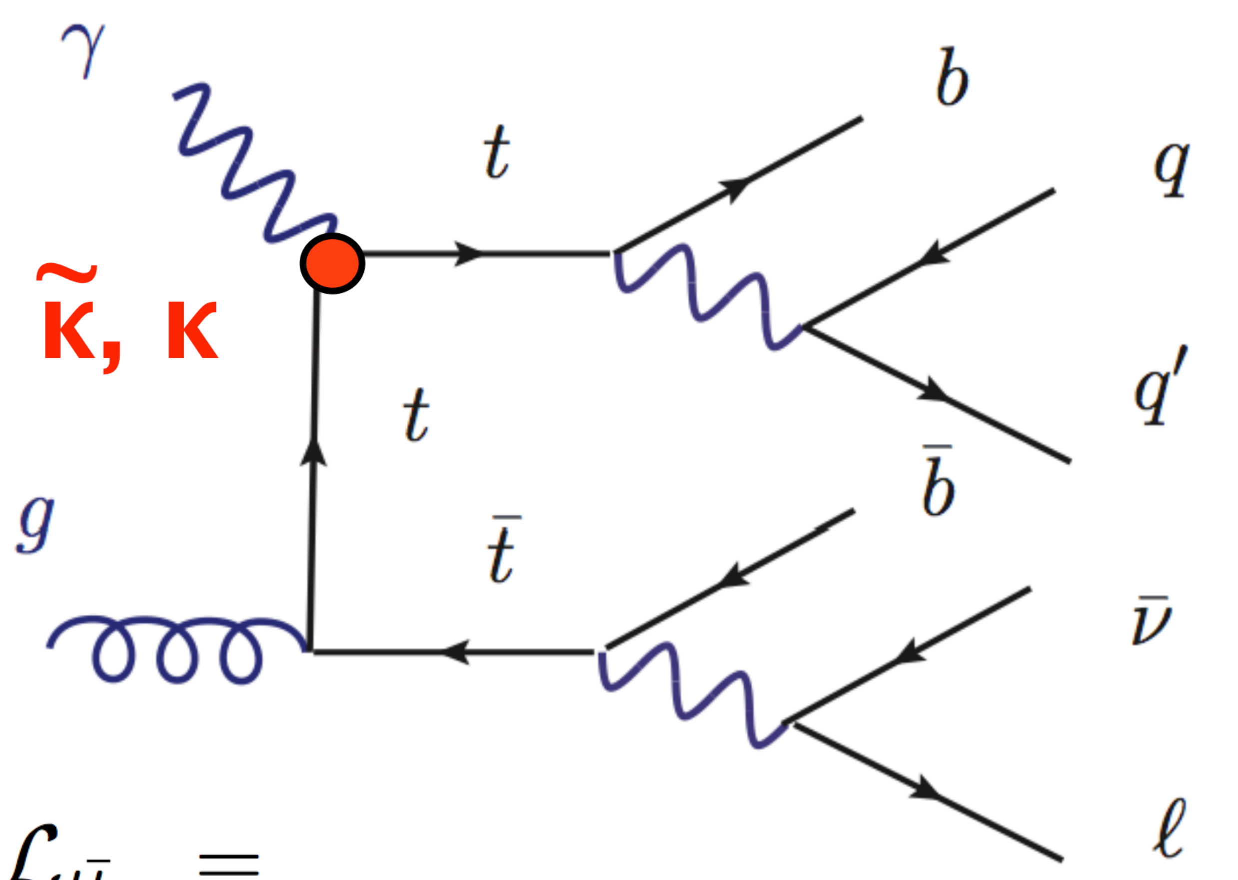
Janot, JHEP 1504 (2015) 182

FCC-ee **ILC 500**

$$\Gamma_\mu^{ttX} = -ie\left\{\gamma_\mu\left(F_{1V}^X+\gamma_5F_{1A}^X\right)+\frac{\sigma_{\mu\nu}}{2m_\mathrm{t}}(p_t+p_{\bar{t}})^\nu\left(iF_{2V}^X+\gamma_5F_{2A}^X\right)\right\}$$



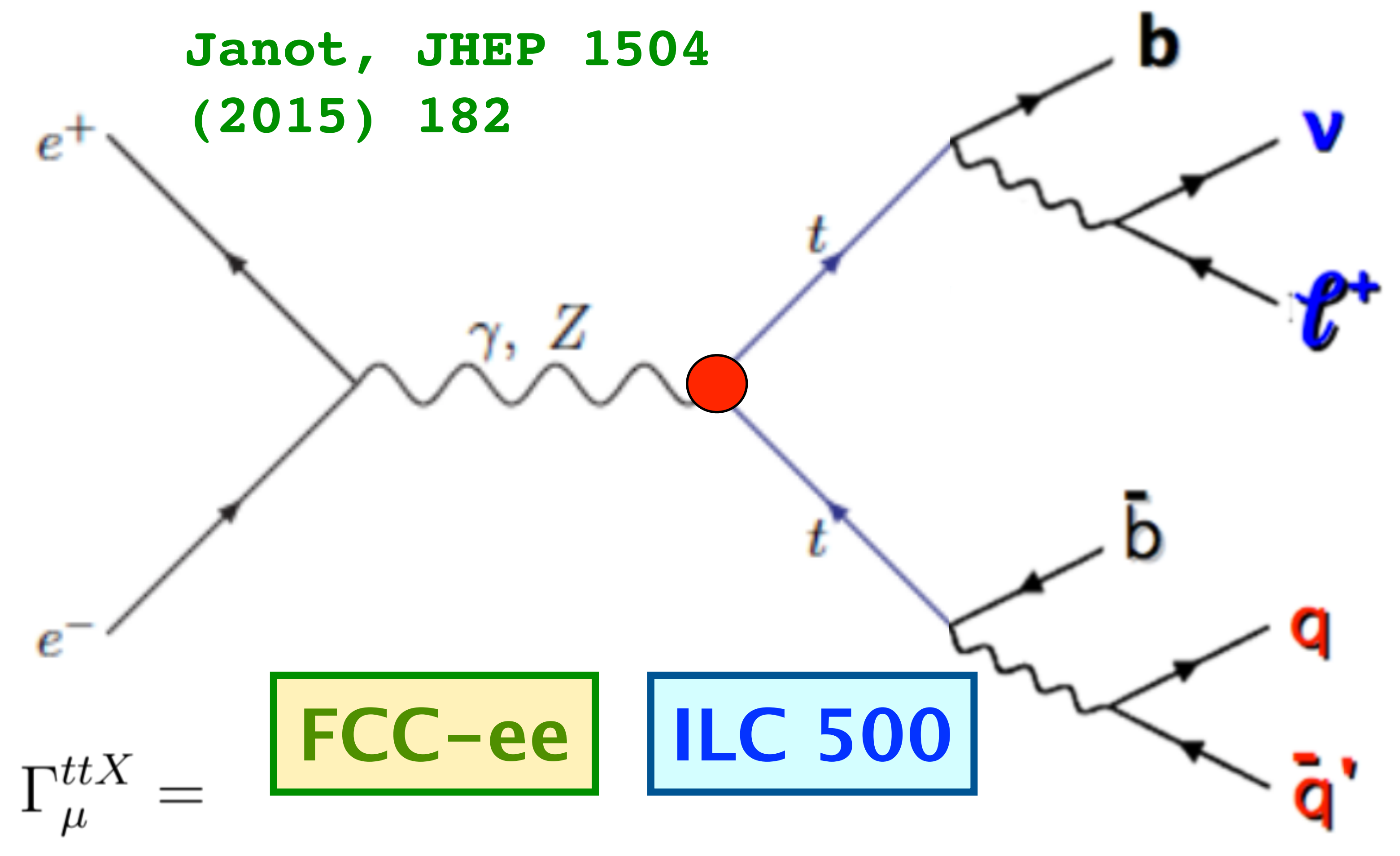
→ **expected precision of order 10^{-2} to 10^{-3}**



$\tilde{\kappa}$, κ

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

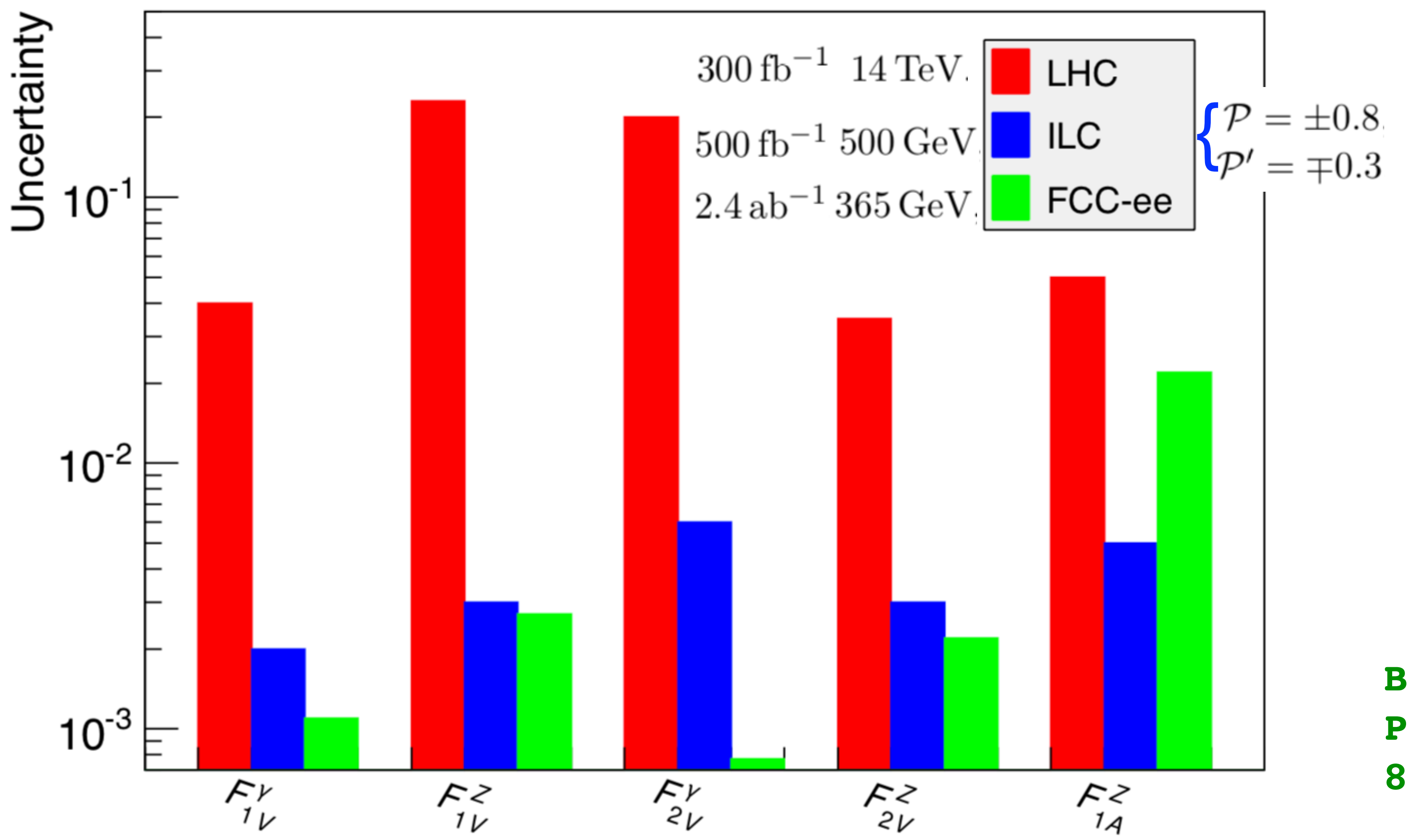
$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments



Janot, JHEP 1504 (2015) 182

FCC-ee **ILC 500**

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



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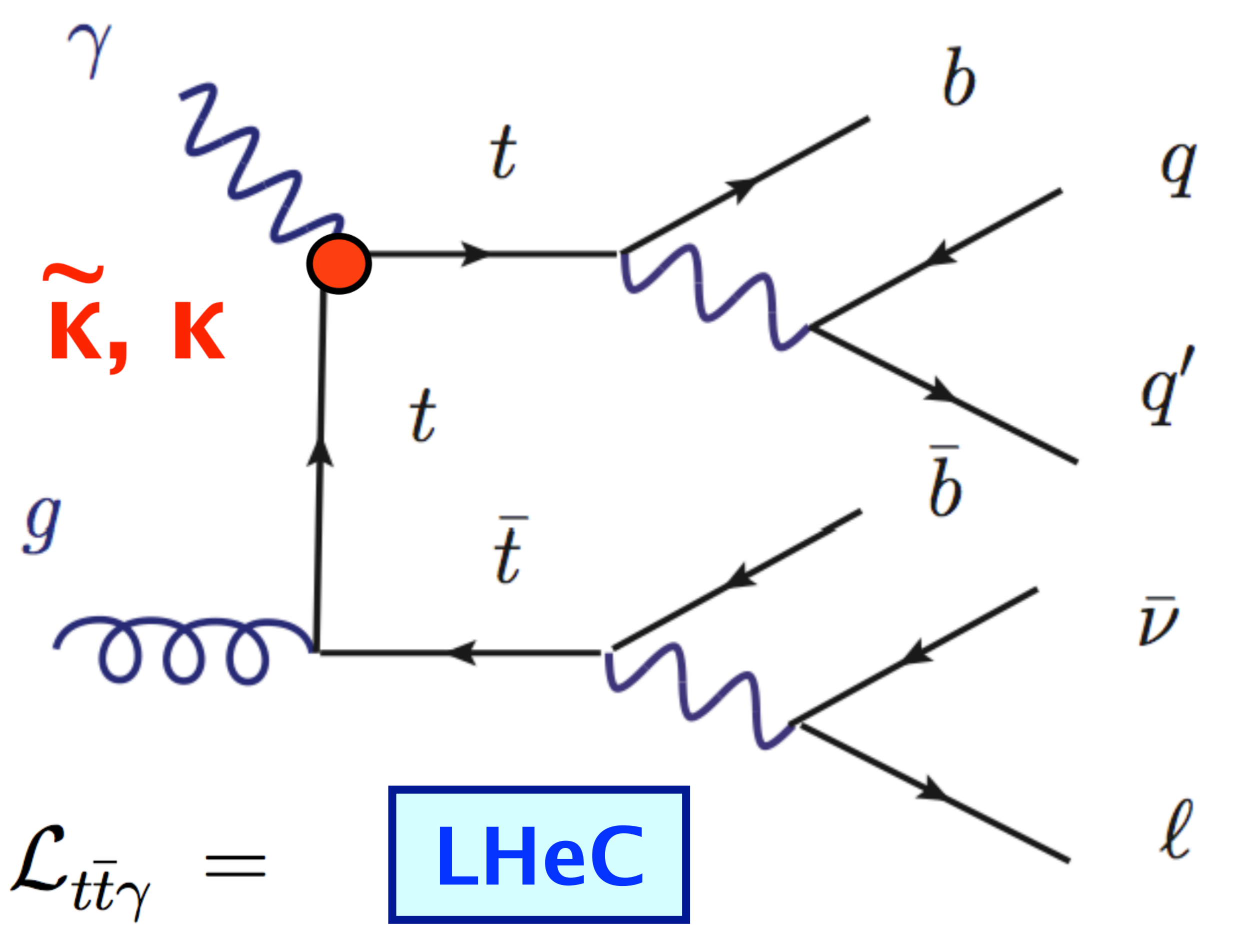
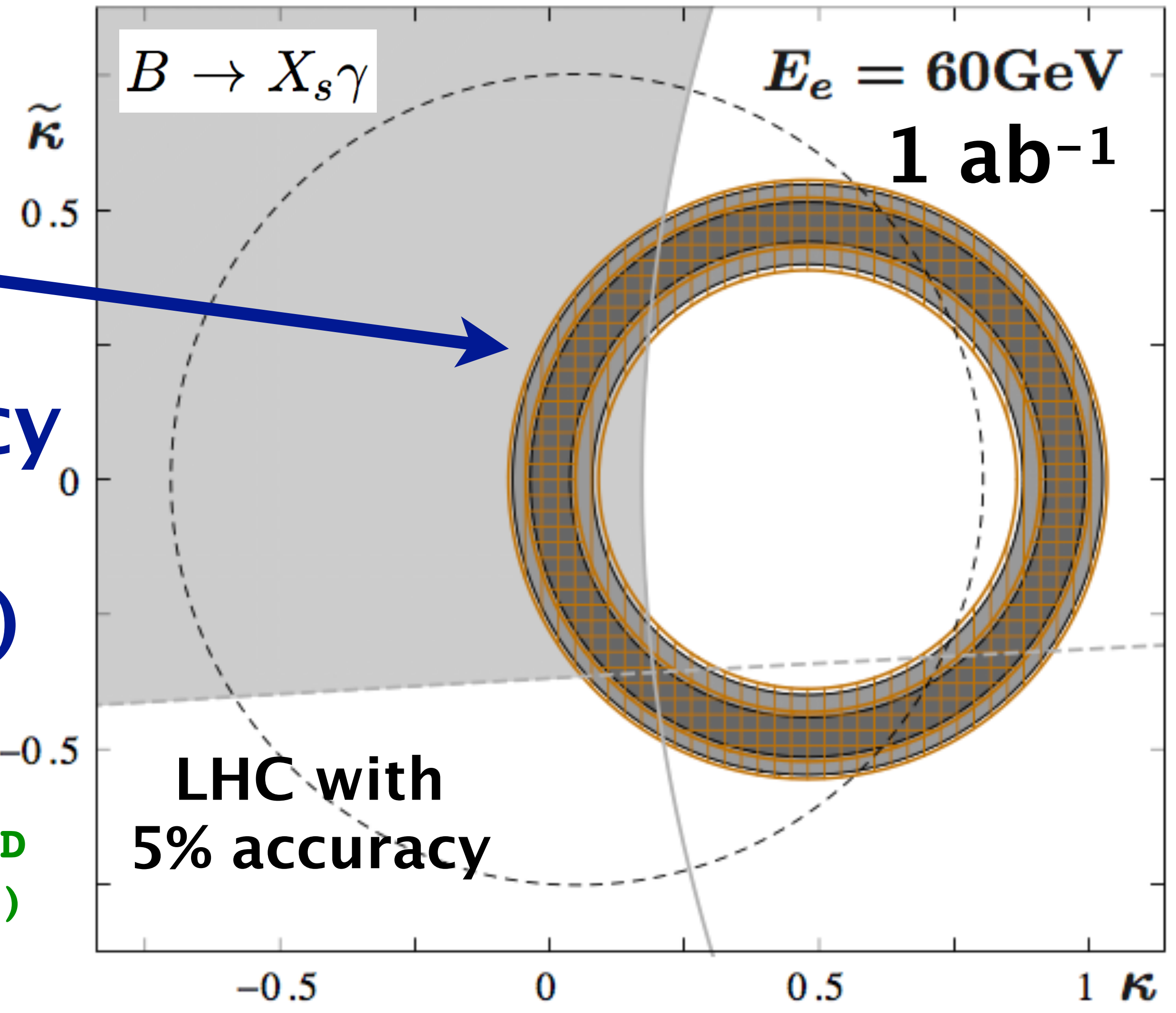


LHeC

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

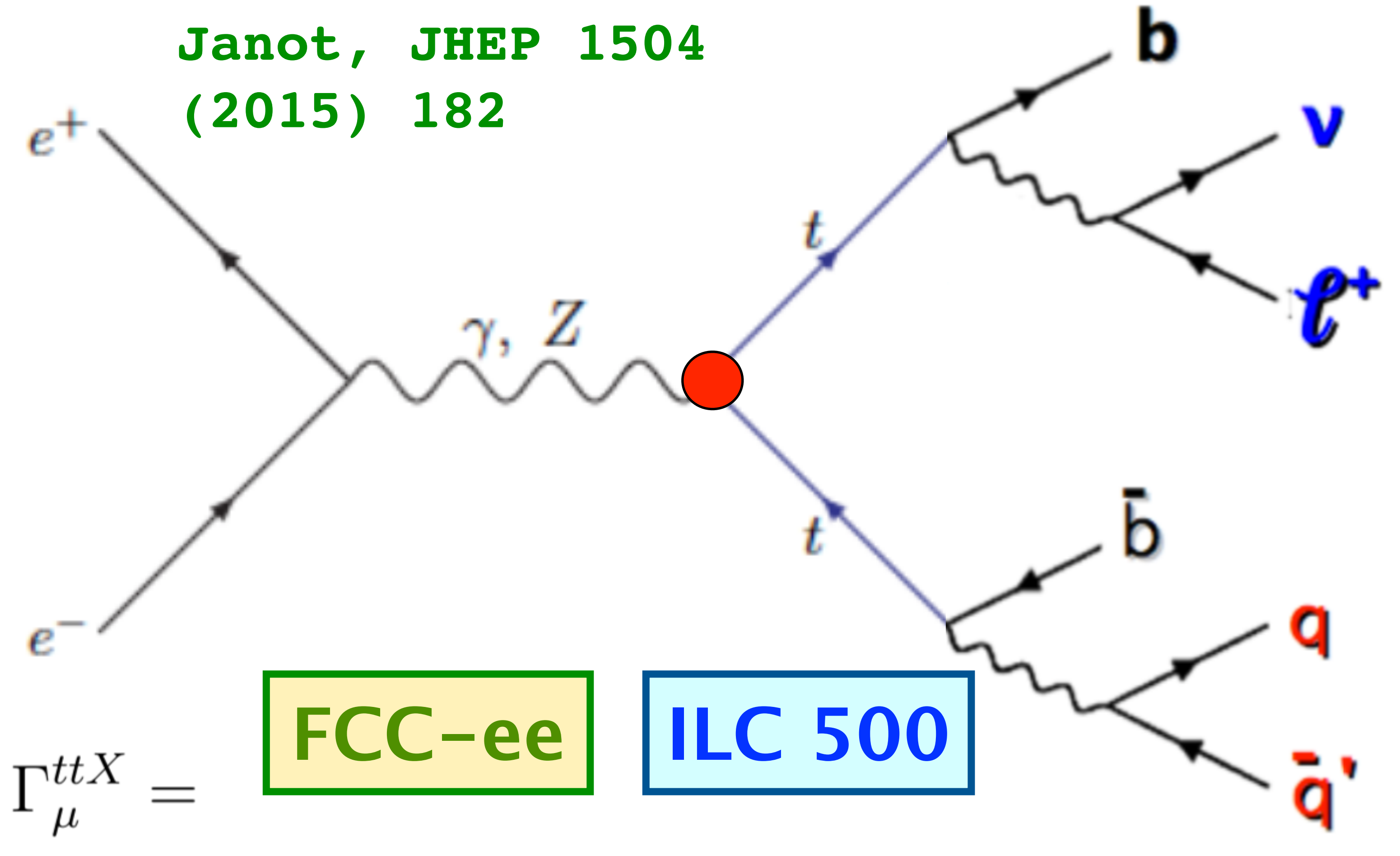
10%
18%
accuracy (syst. limited)

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



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

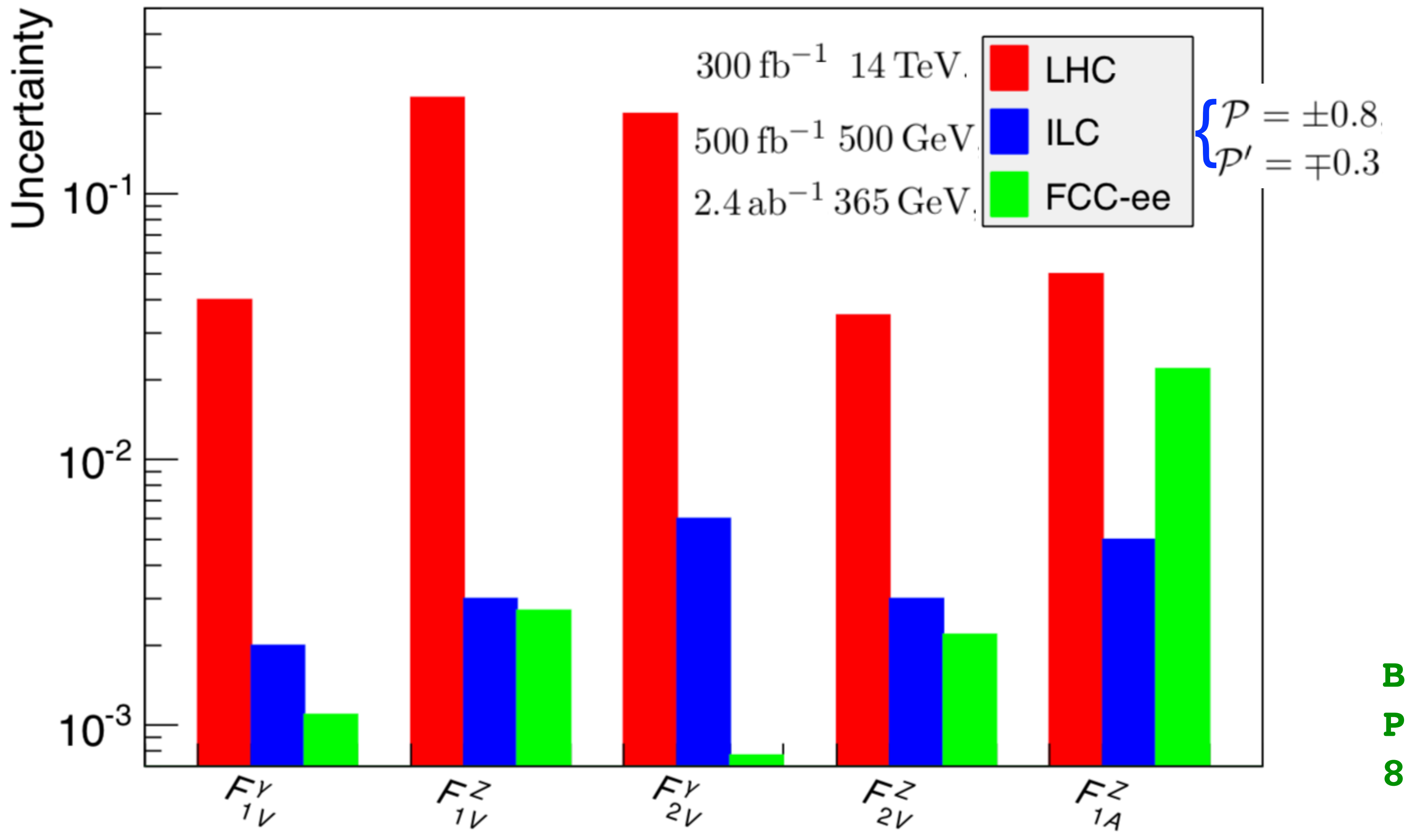
$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments



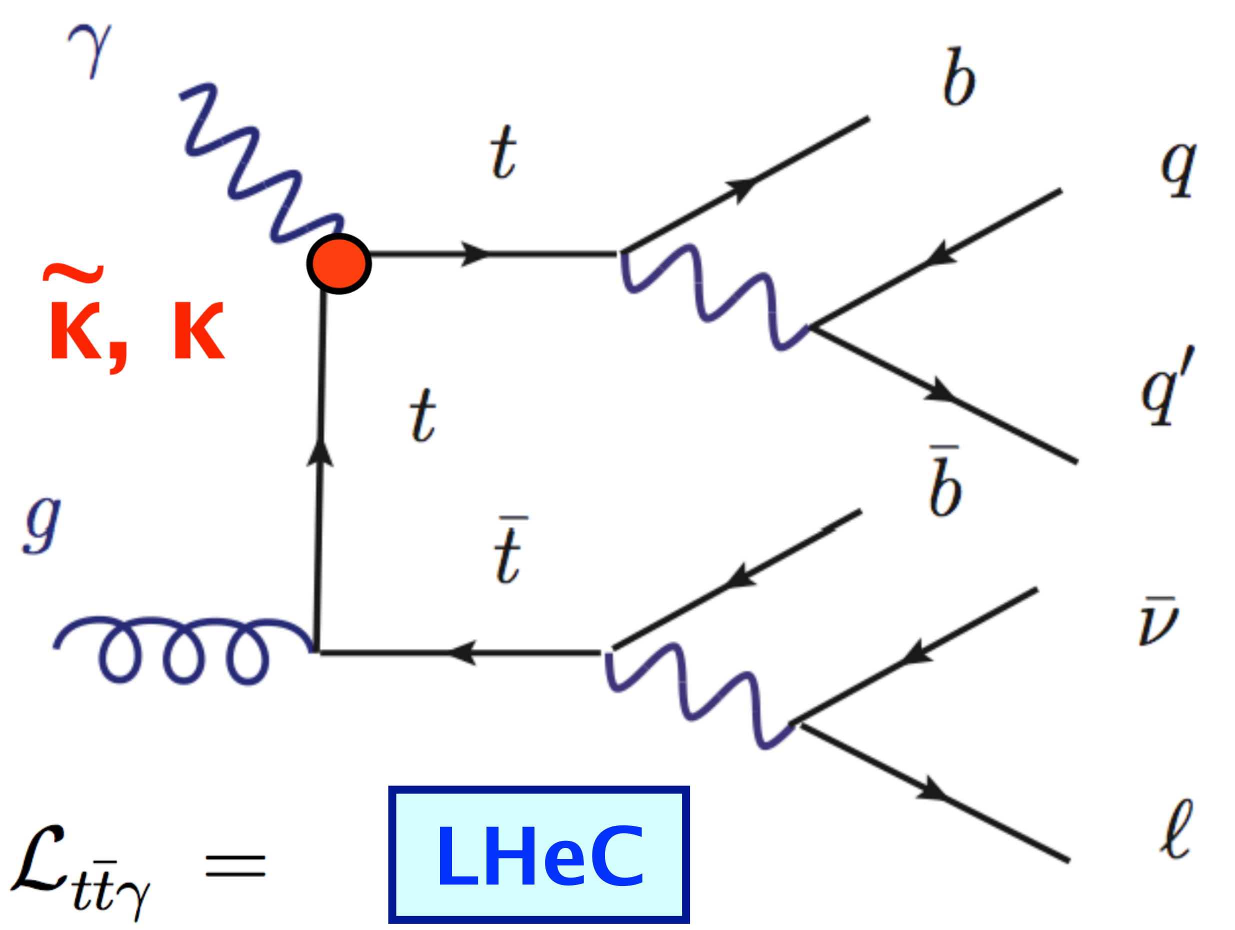
Janot, JHEP 1504 (2015) 182

FCC-ee **ILC 500**

$$\Gamma_\mu^{ttX} = -ie\left\{\gamma_\mu\left(F_{1V}^X+\gamma_5F_{1A}^X\right)+\frac{\sigma_{\mu\nu}}{2m_t}(p_t+p_{\bar t})^\nu\left(iF_{2V}^X+\gamma_5F_{2A}^X\right)\right\}$$



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



LHeC

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

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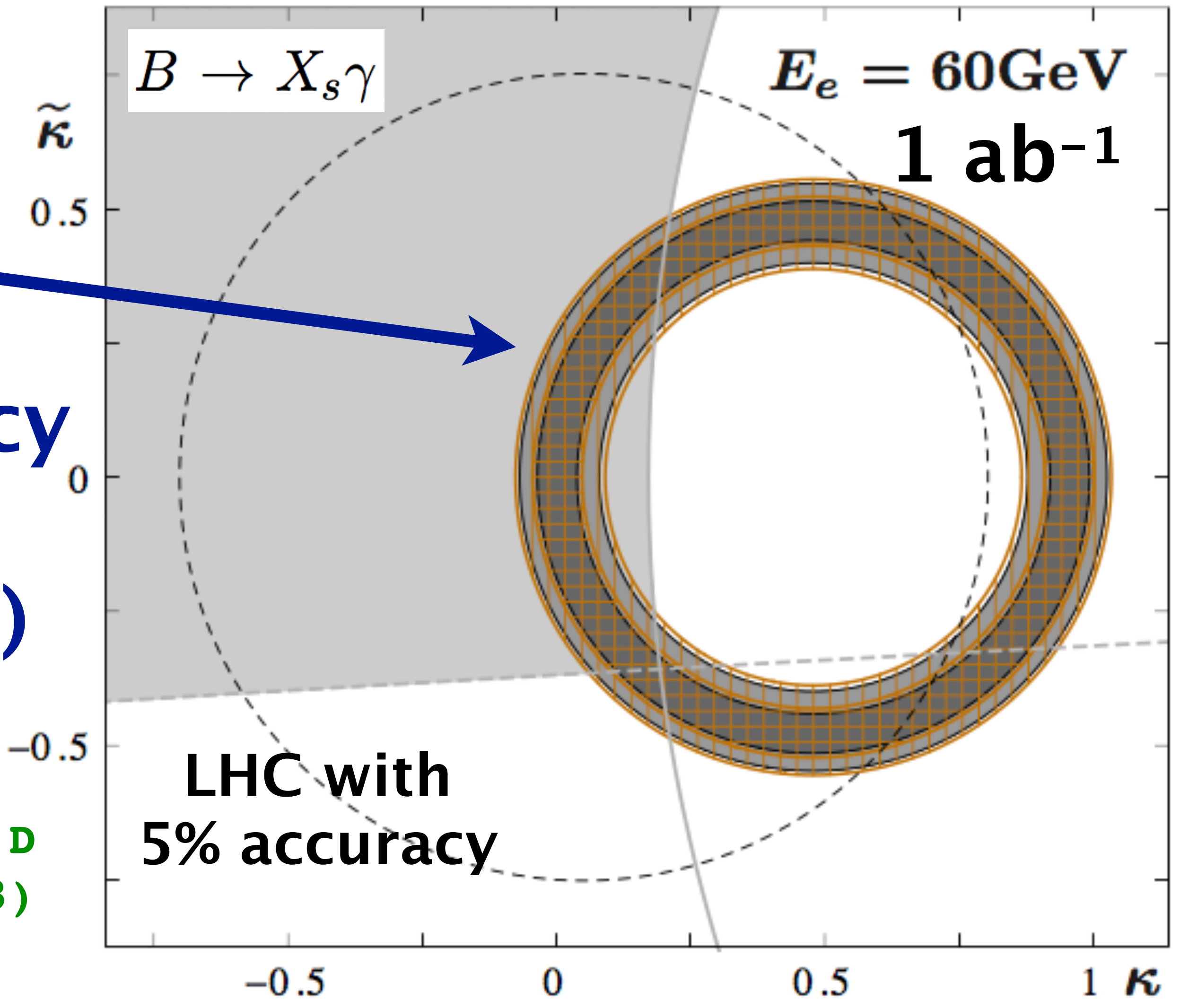

Bouzas, Larios, Physical Review D 88, 094007 (2013)

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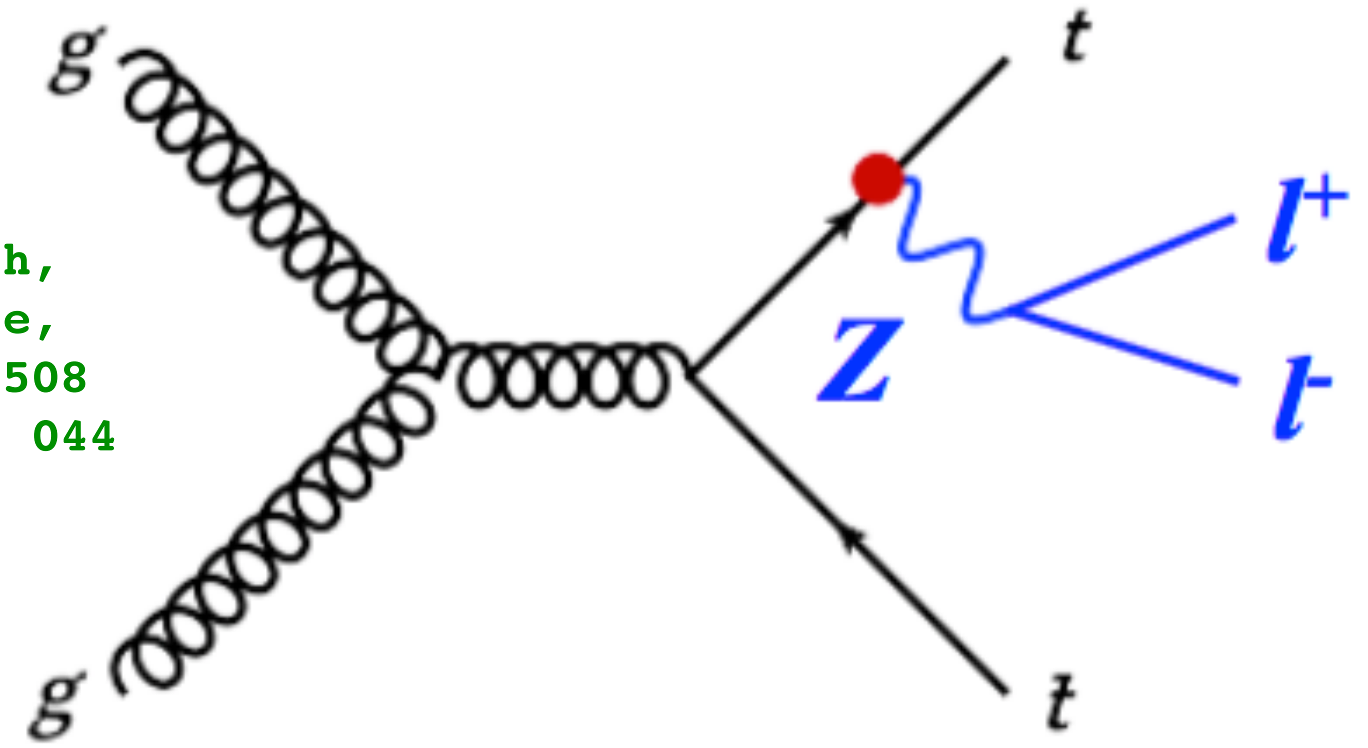

Röntsch, Schulze, JHEP 1508 (2015) 044

FCC-pp

$$\mathcal{L}_{t\bar tZ} = e\bar\psi_t\left[\gamma^\mu(C_{1,V}+\gamma_5C_{1,A})+\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}(C_{2,V}+i\gamma_5C_{2,A})\right]\psi_tZ_\mu$$

investigate angular correlations of Z leptons

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

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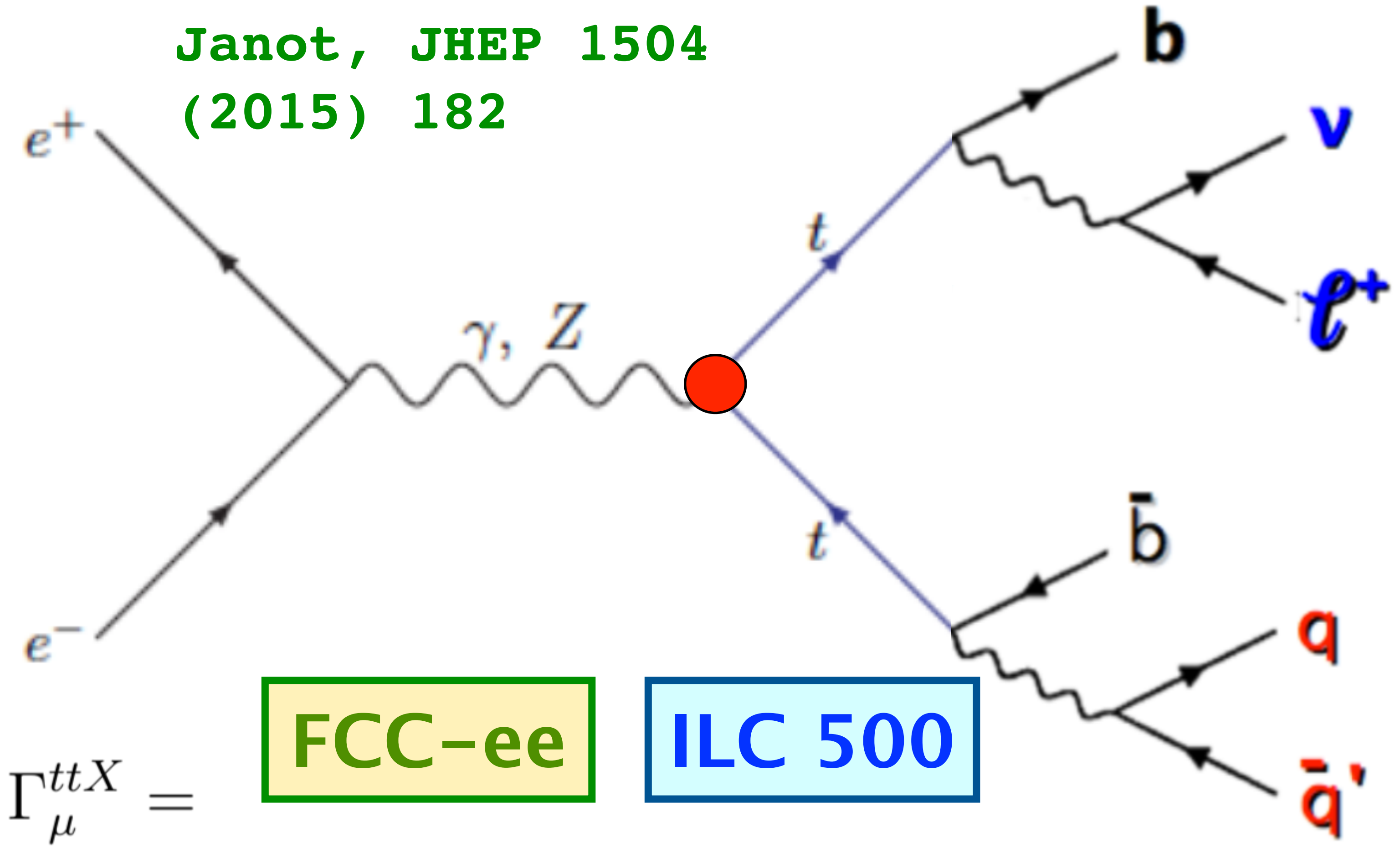

FCC-ee **ILC 500**

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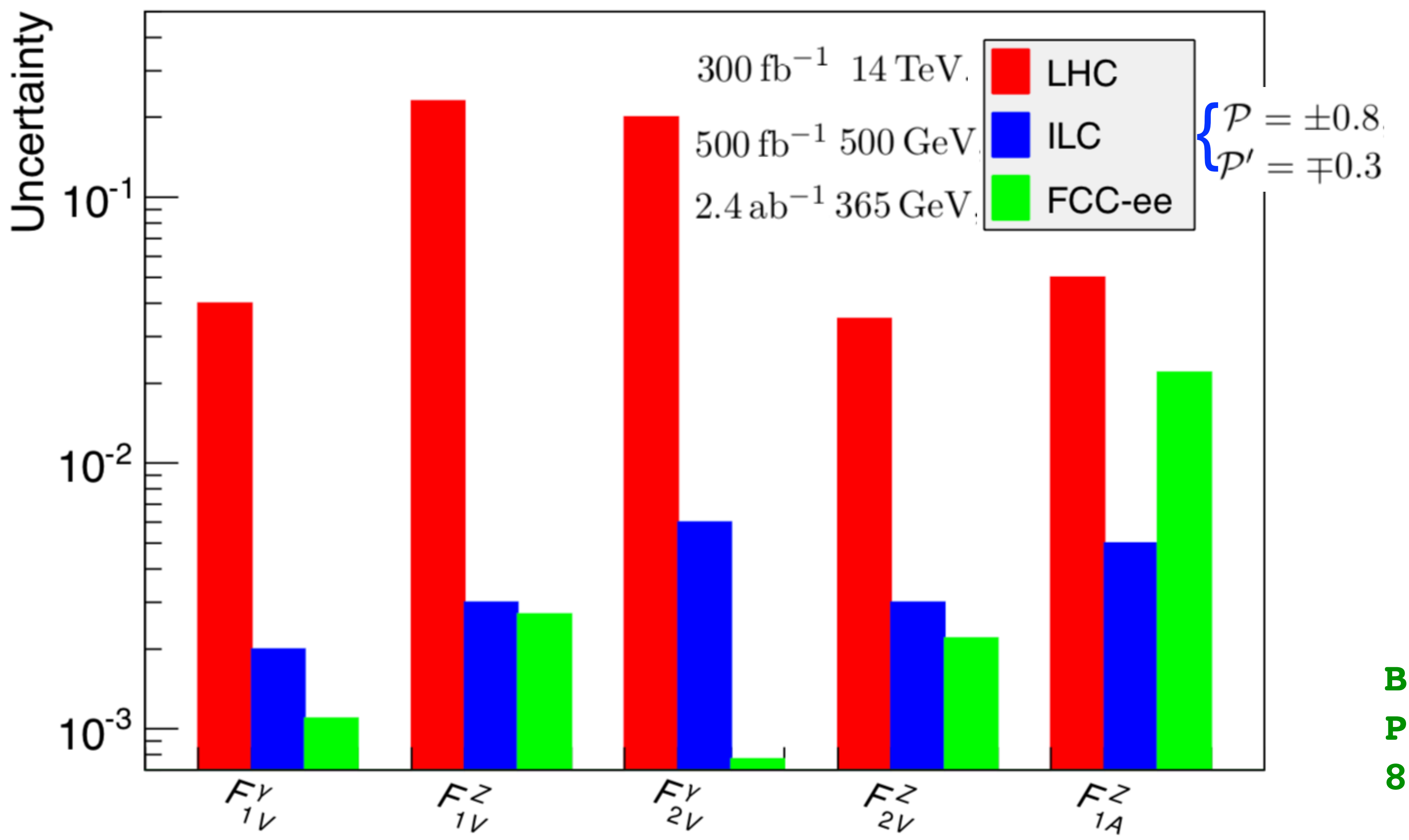

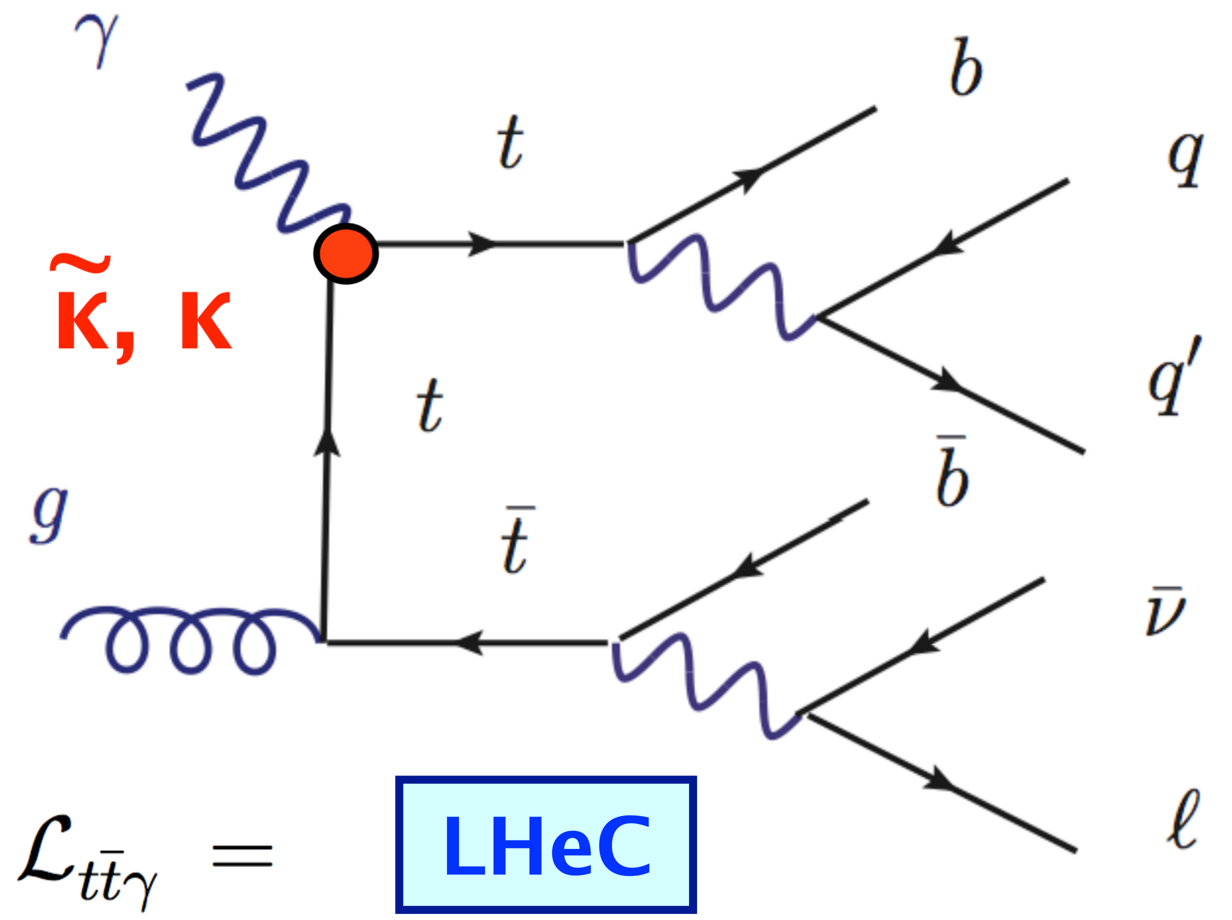

κ̃, κ

LHeC

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

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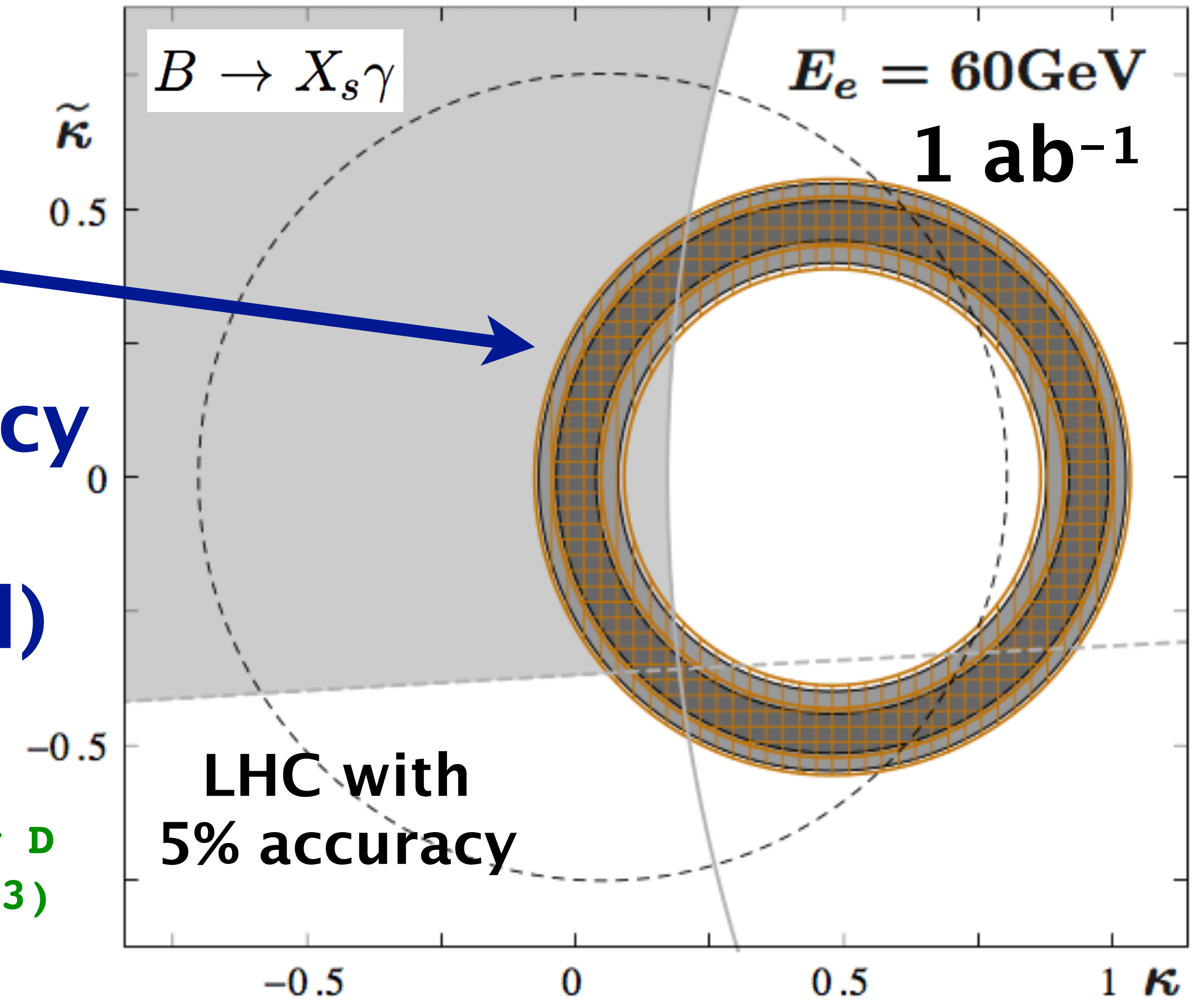
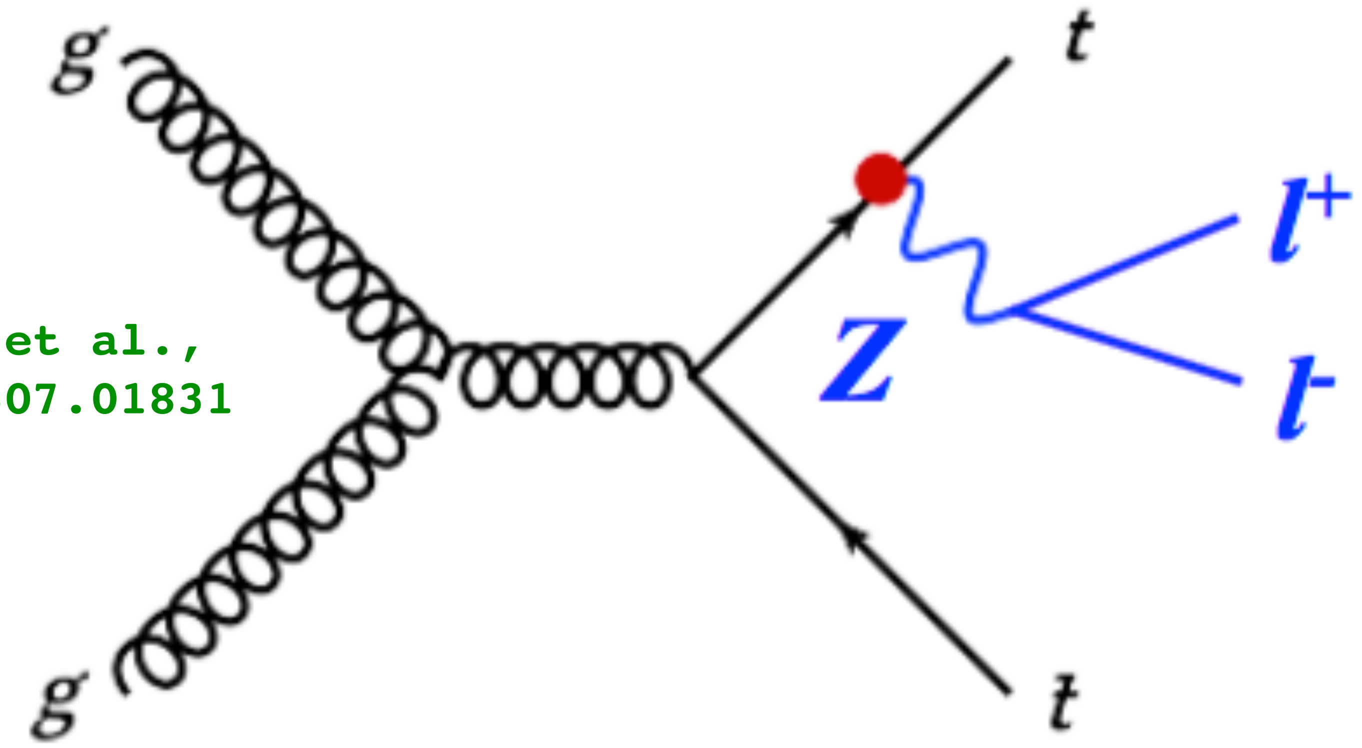
18%
accuracy (syst. limited)



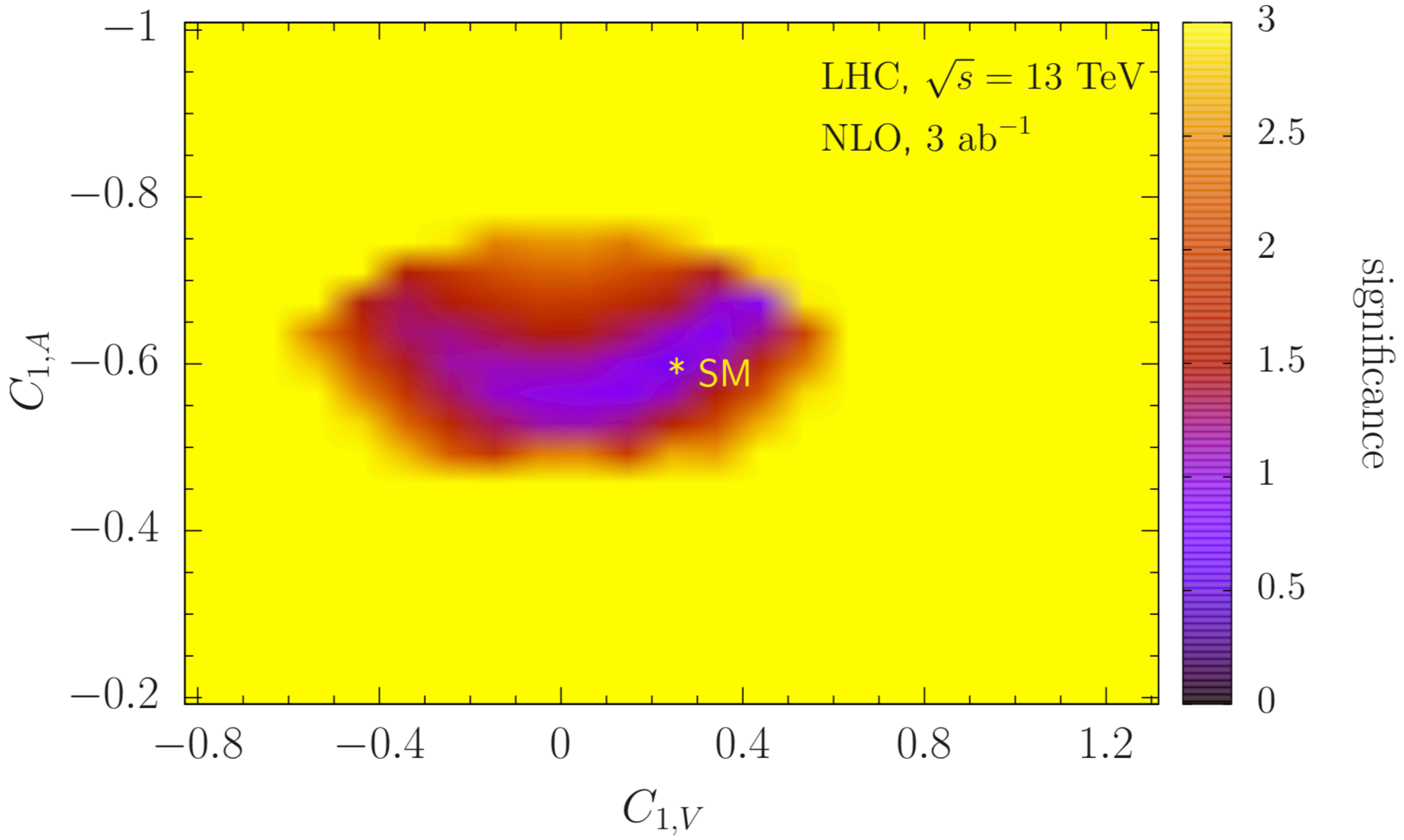
Bouzas, Larios, Physical Review D 88, 094007 (2013)

Mangano et al., arXiv:1607.01831



FCC-pp

$$\mathcal{L}_{t\bar{t}Z} = e\bar{\psi}_t\left[\gamma^\mu\left(C_{1,V}+\gamma_5C_{1,A}\right)+\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(C_{2,V}+i\gamma_5C_{2,A}\right)\right]\psi_tZ_\mu$$

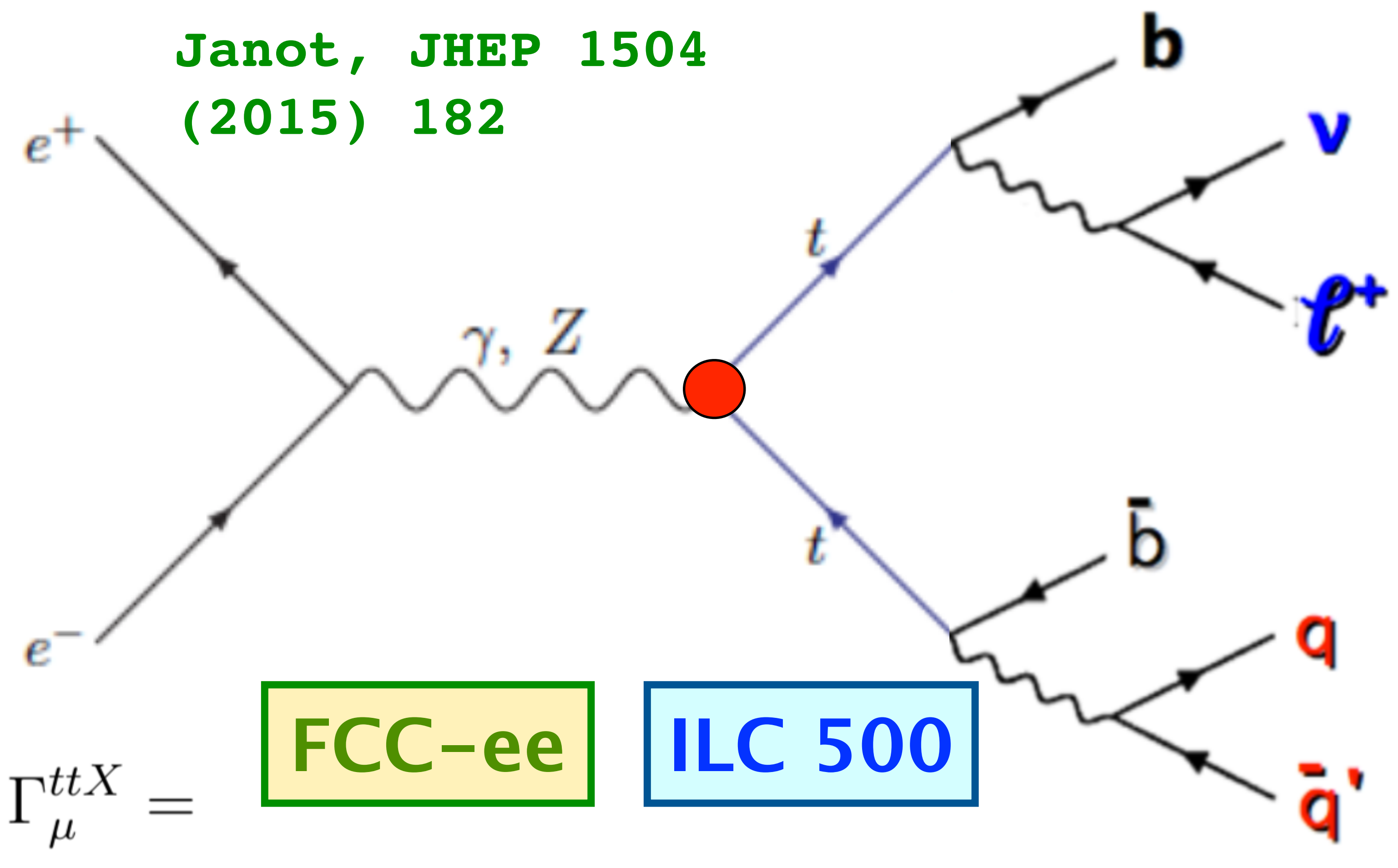


→ **expected precision of order 10^{-2} to 10^{-3}**

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

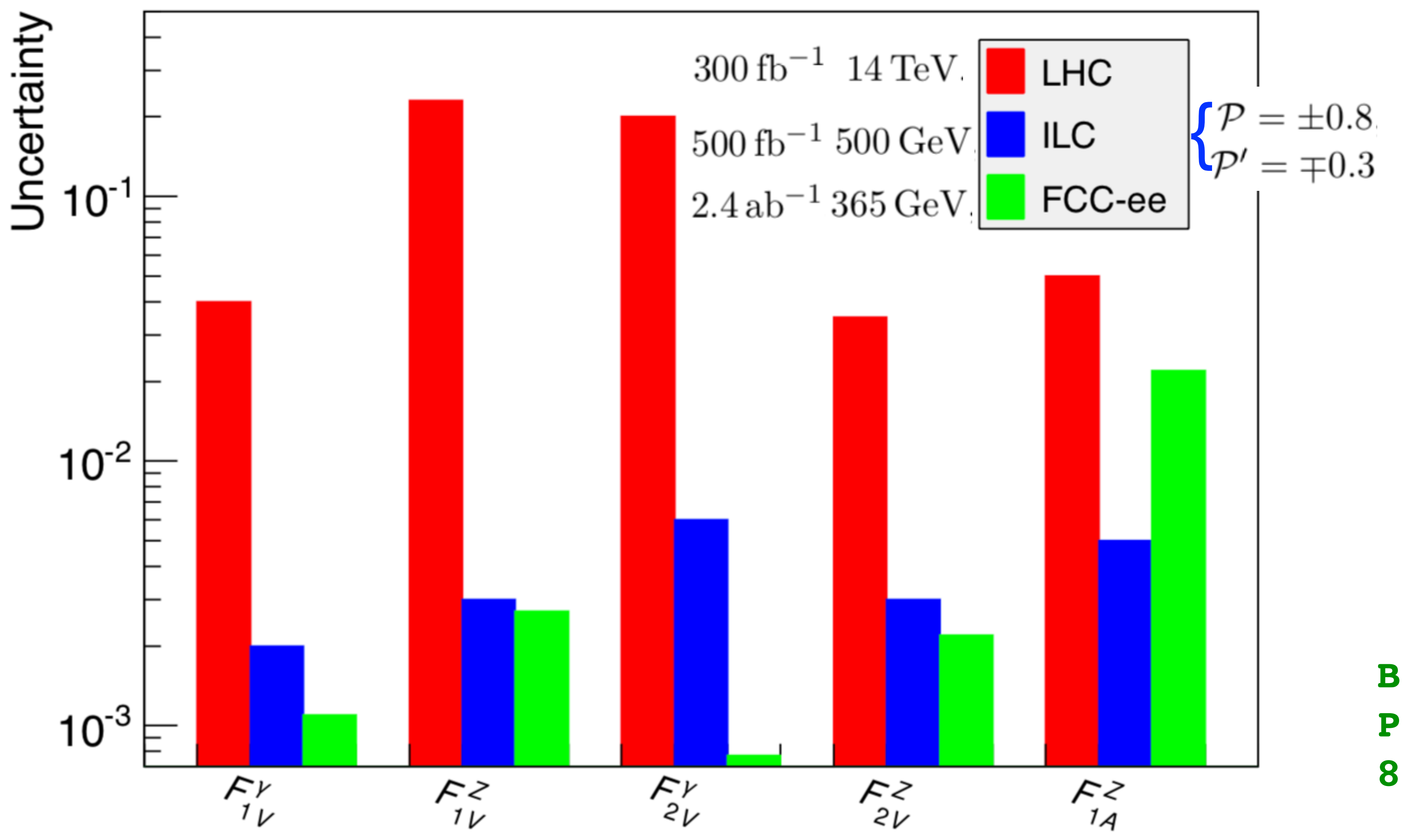
$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments

Janot, JHEP 1504 (2015) 182

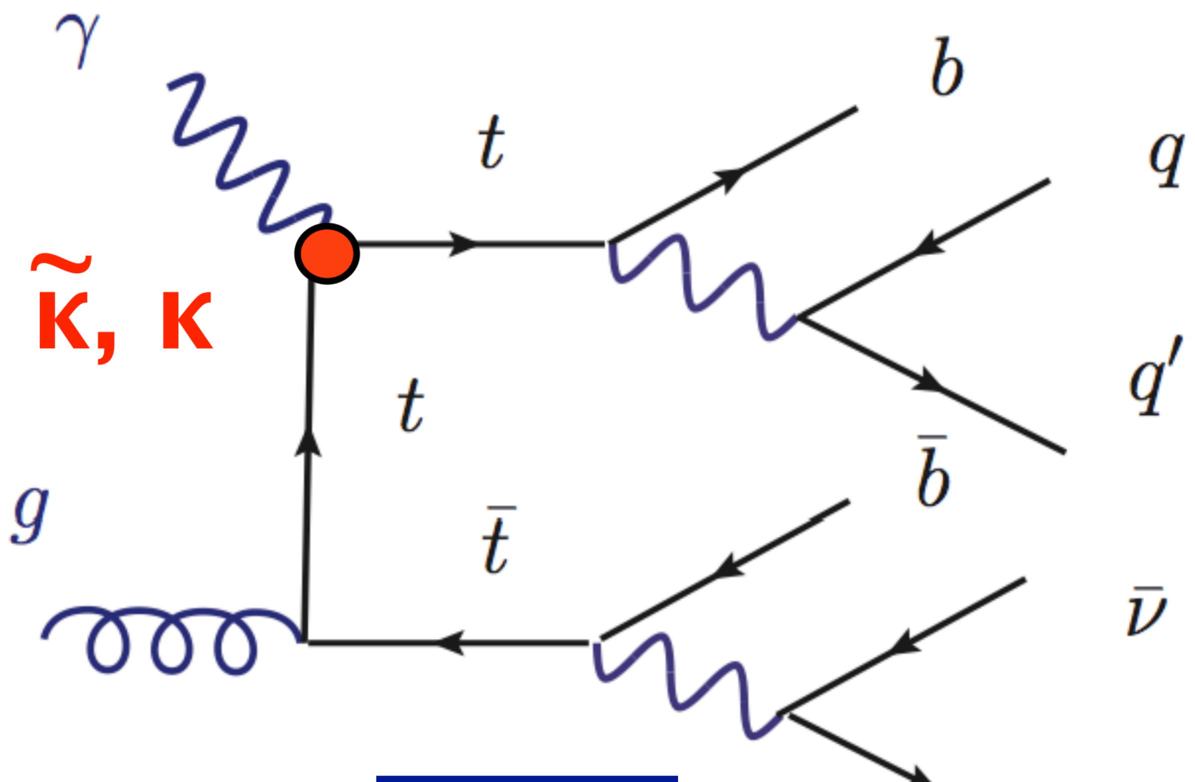


FCC-ee **ILC 500**

$$\Gamma^{ttX}_\mu = -ie\left\{\gamma_\mu\left(F^X_{1V}+\gamma_5F^X_{1A}\right)+\frac{\sigma_{\mu\nu}}{2m_t}(p_t+p_{\bar{t}})^\nu\left(iF^X_{2V}+\gamma_5F^X_{2A}\right)\right\}$$



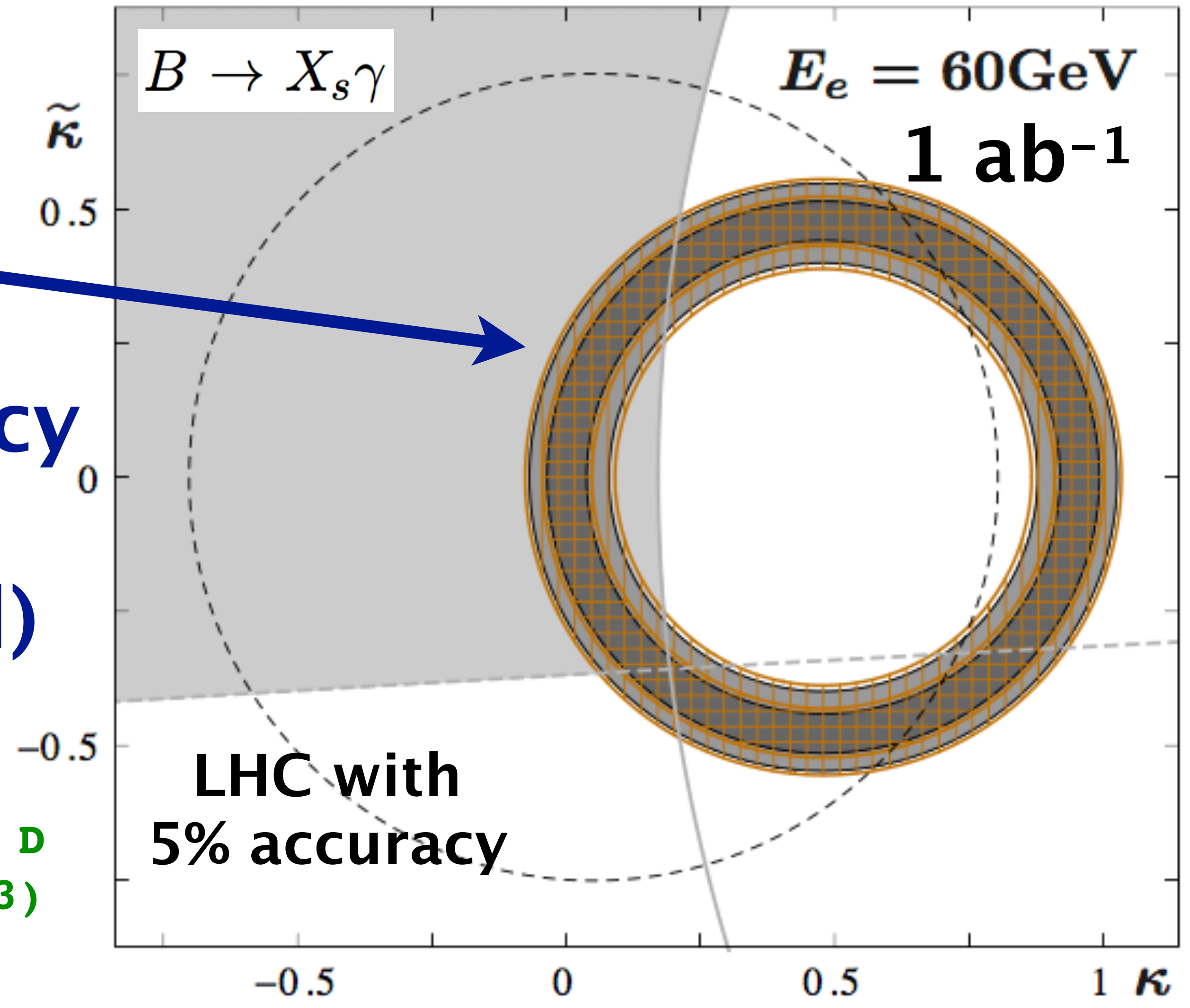
→ expected precision of order 10⁻² to 10⁻³



LHeC

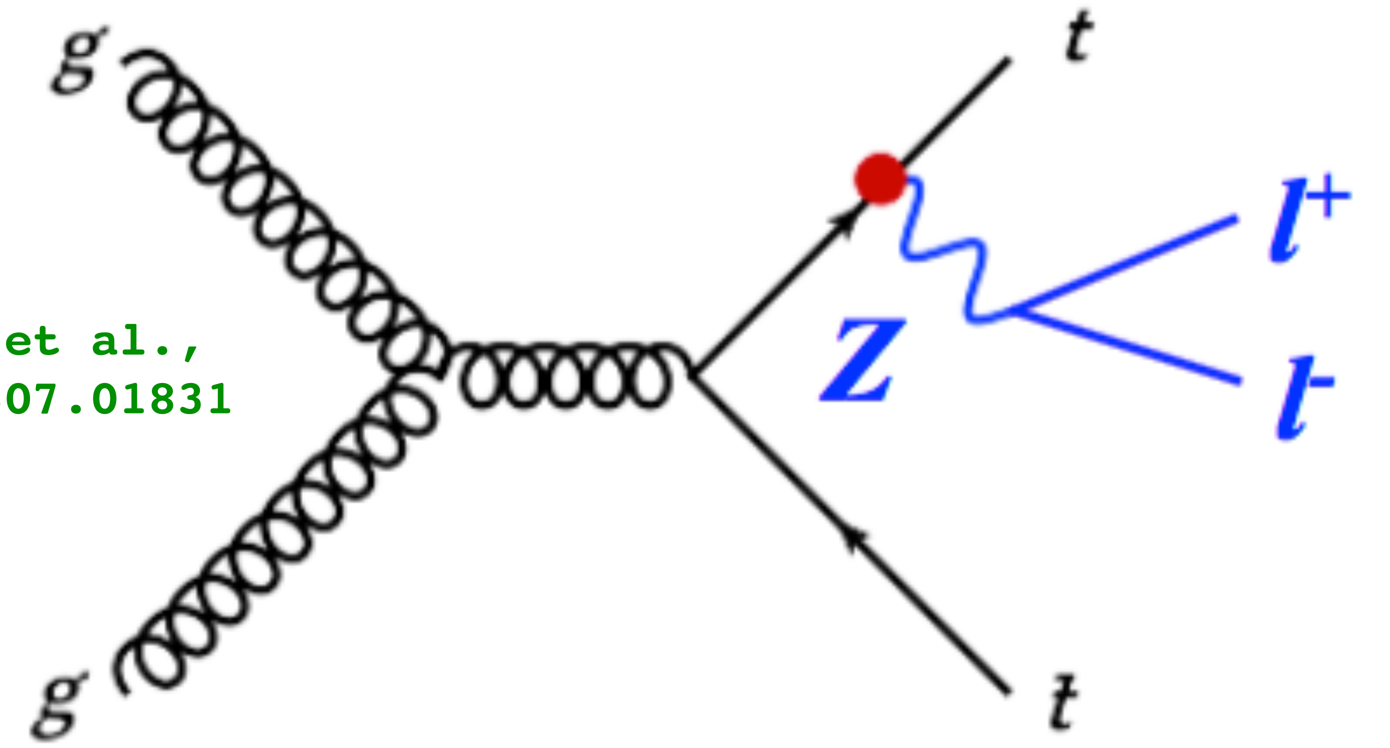
$$\mathcal{L}_{t\bar{t}\gamma} = e\bar{t}\left(Q_t\gamma^\mu A_\mu+\frac{1}{4m_t}\sigma^{\mu\nu}F_{\mu\nu}(\kappa+i\tilde{\kappa}\gamma_5)\right)t$$

10%
18%
accuracy
(syst.
limited)



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

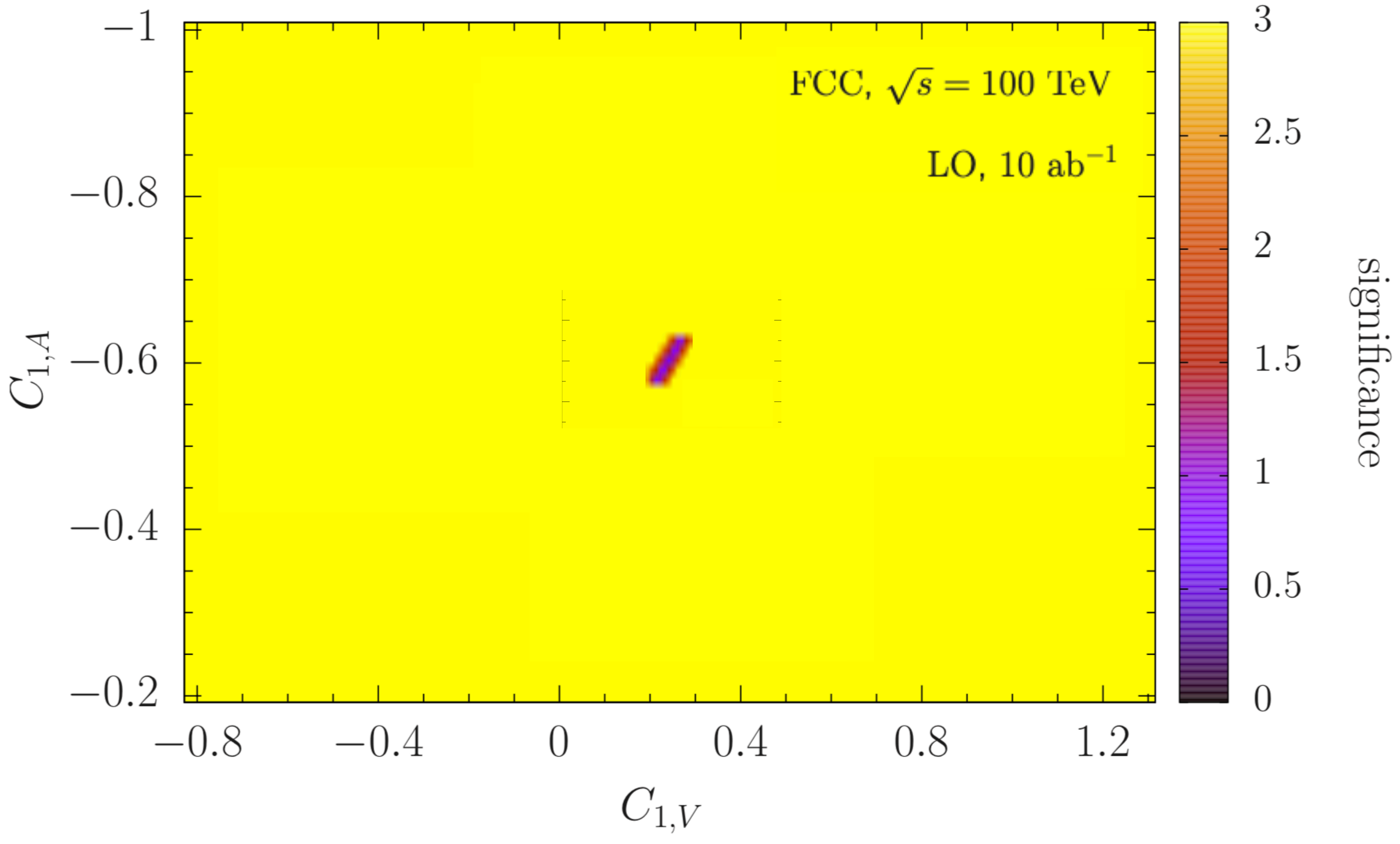
→ expected precision of order 10⁻¹ to 10⁻²



Mangano et al., arXiv:1607.01831

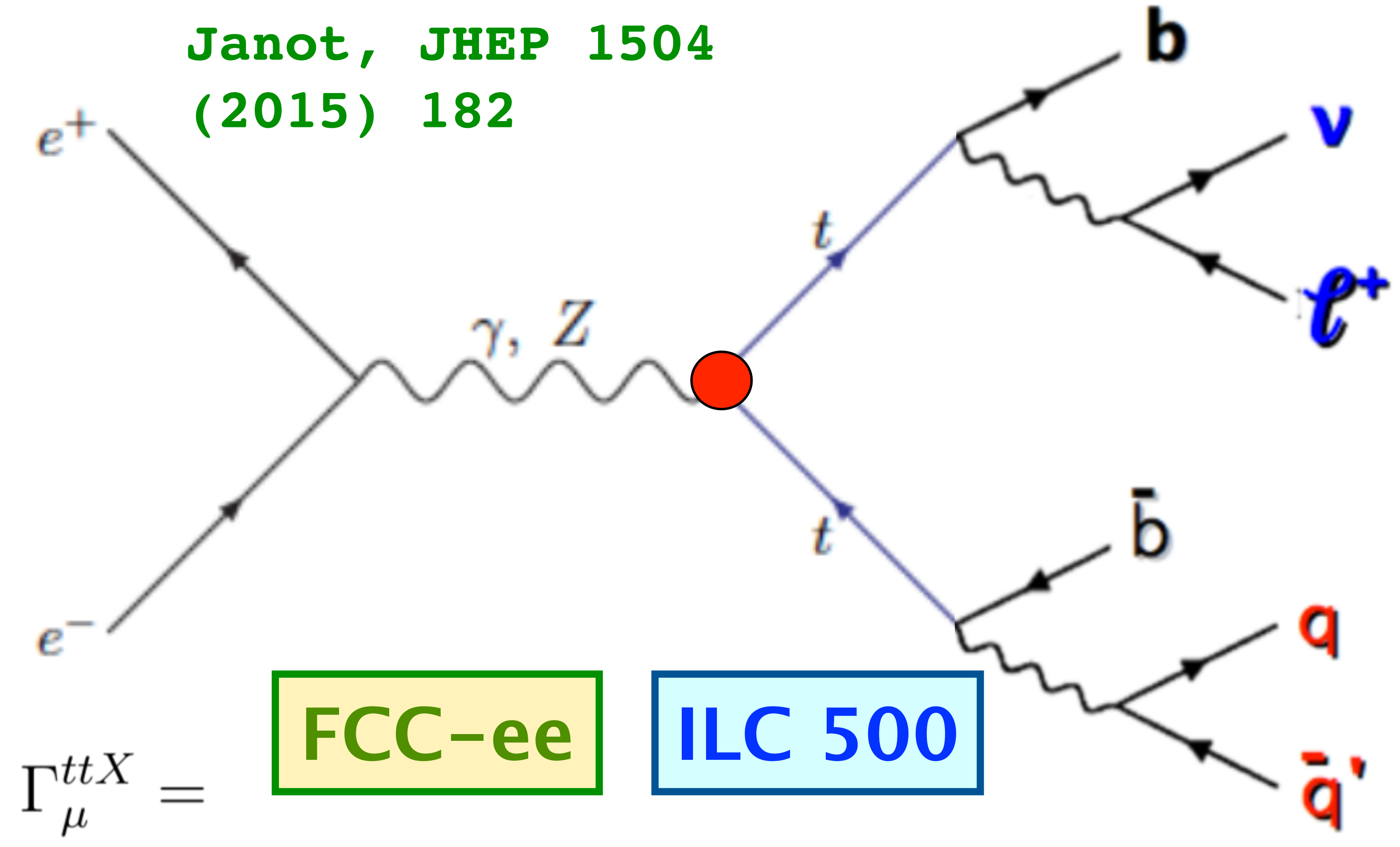
FCC-pp

$$\mathcal{L}_{t\bar{t}Z} = e\bar{\psi}_t\left[\gamma^\mu\left(C_{1,V}+\gamma_5C_{1,A}\right)+\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(C_{2,V}+i\gamma_5C_{2,A}\right)\right]\psi_tZ_\mu$$



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

Janot, JHEP 1504 (2015) 182



FCC-ee **ILC 500**

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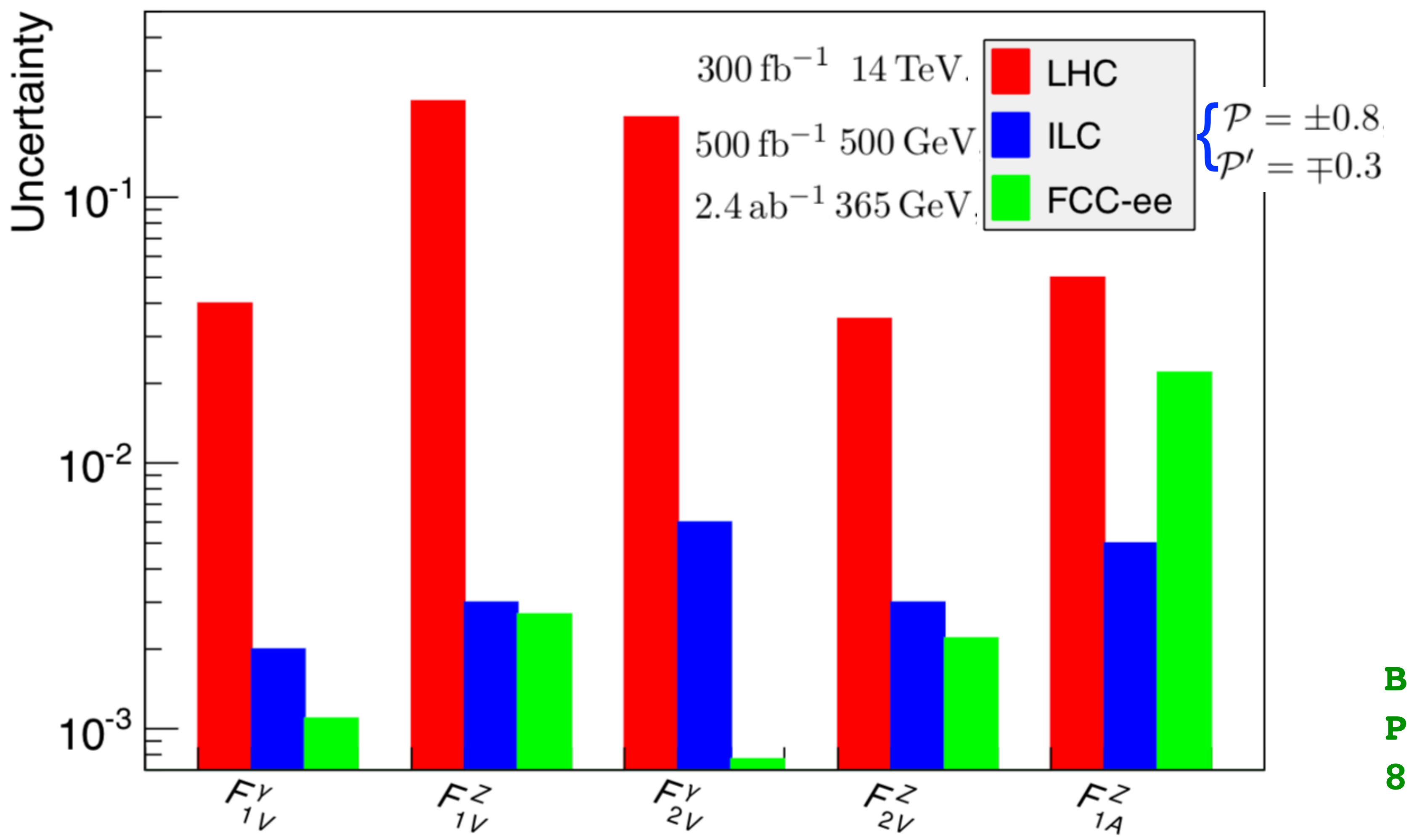
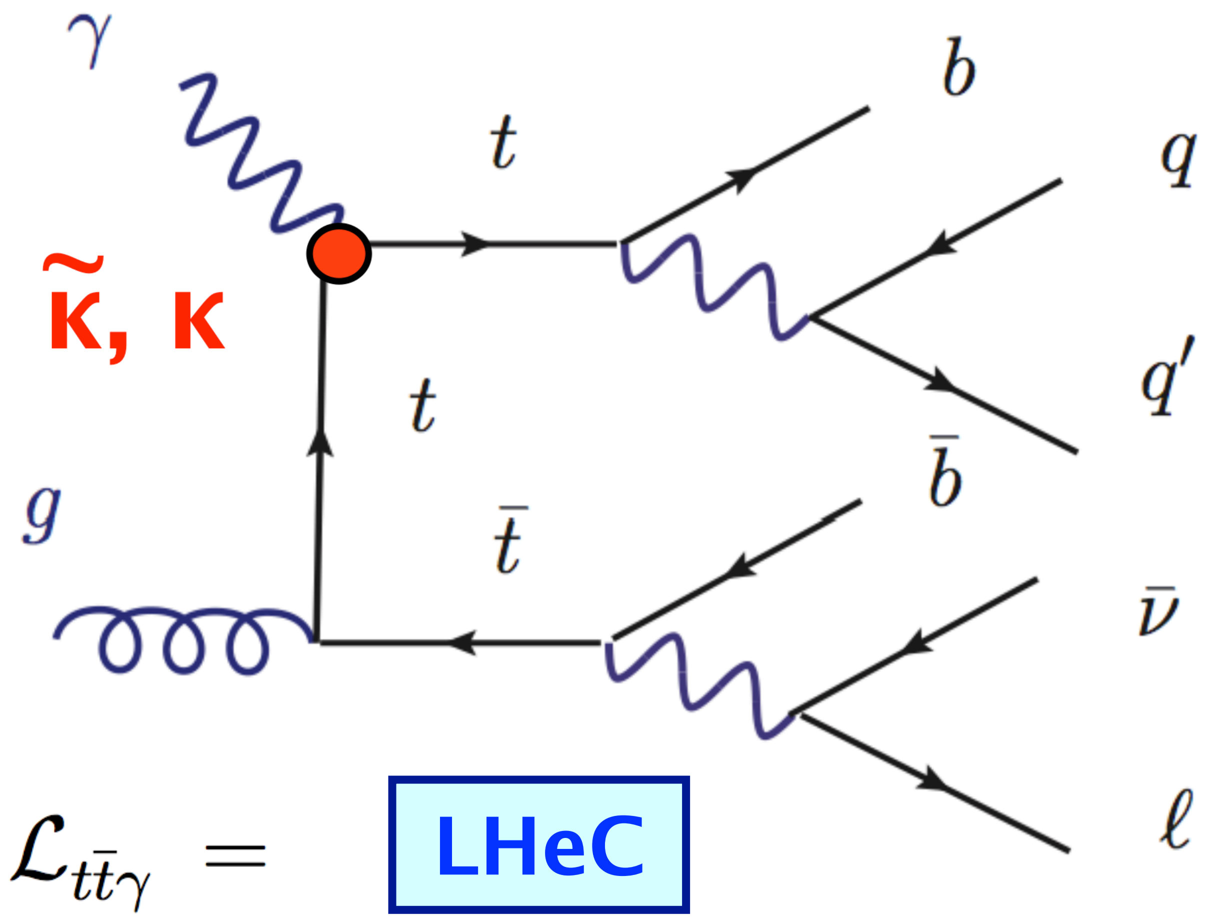


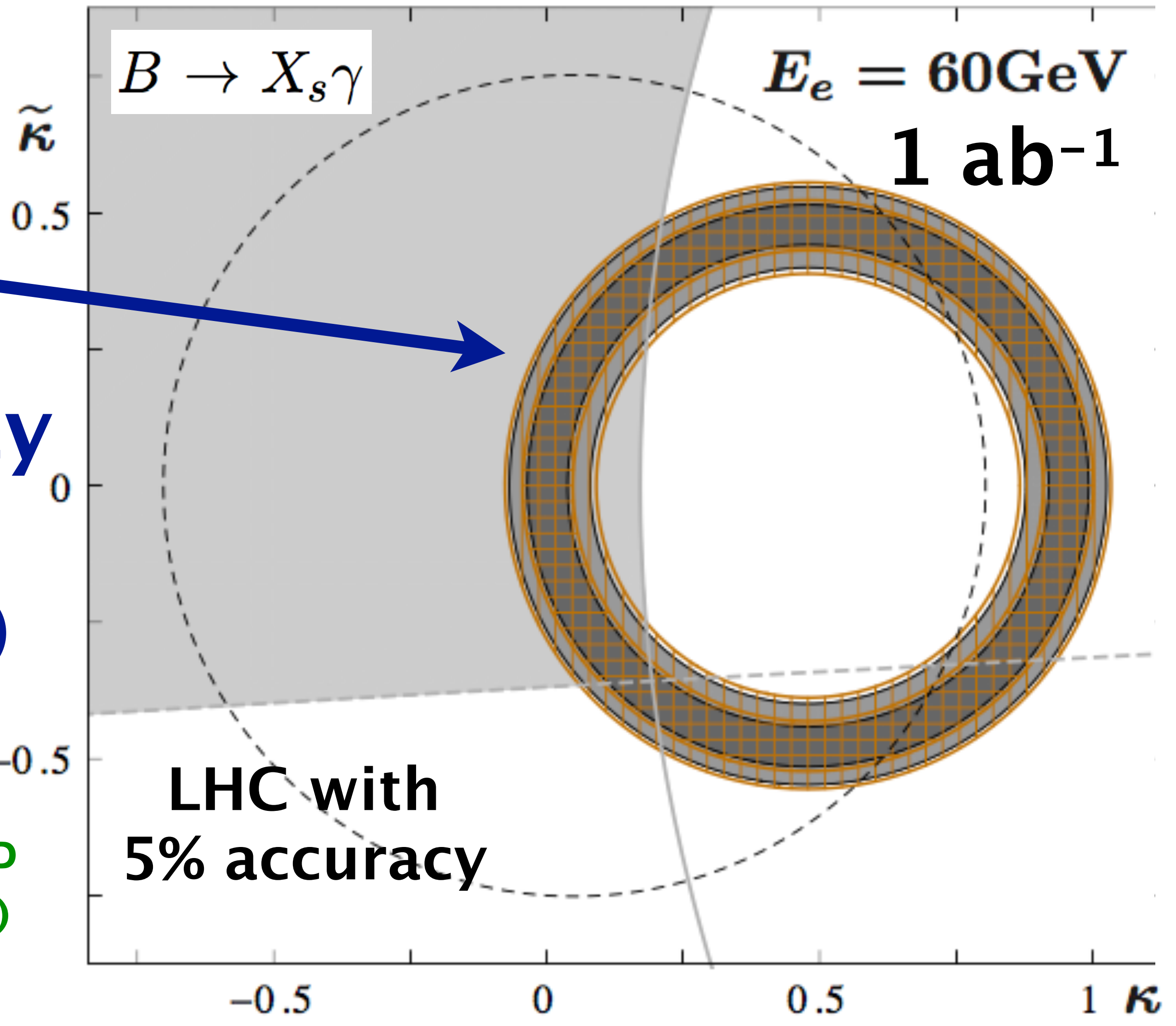
→ expected precision of order 10^{-2} to 10^{-3}



LHeC

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

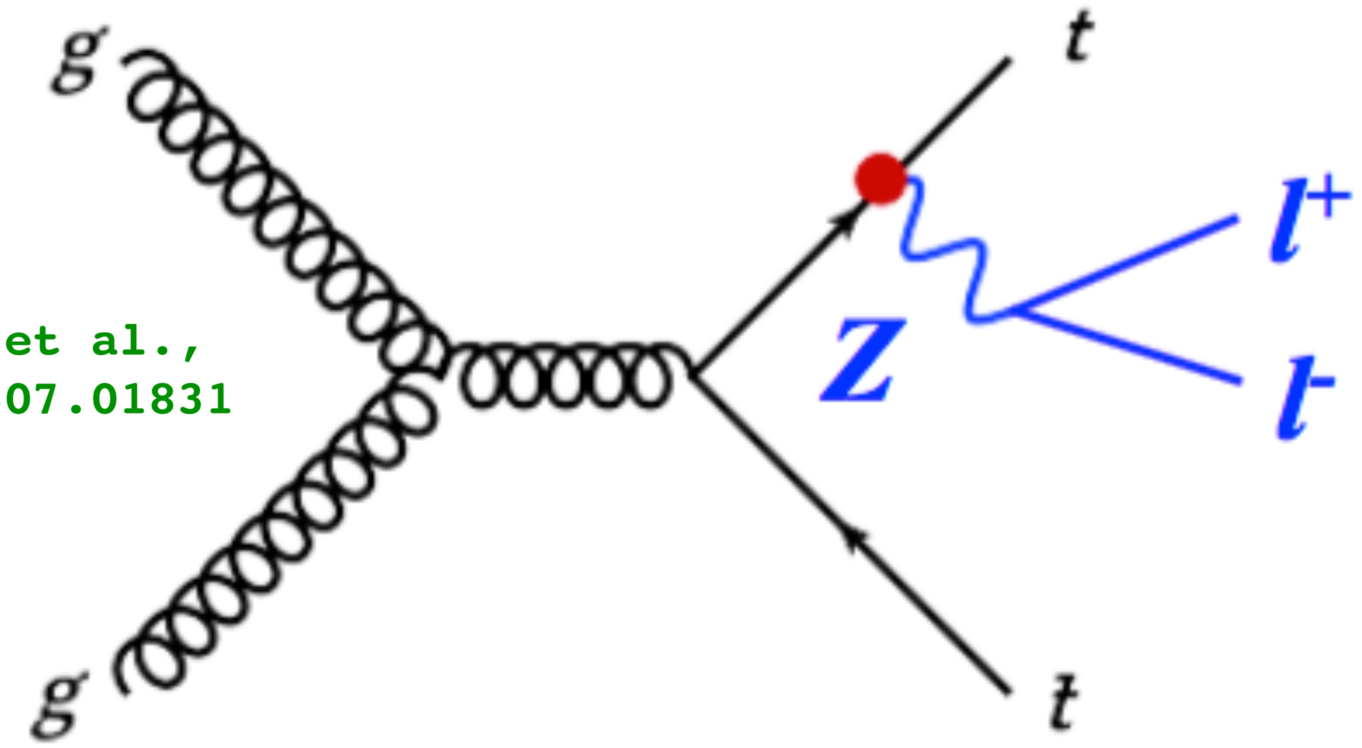
10%
18%
accuracy (syst. limited)



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

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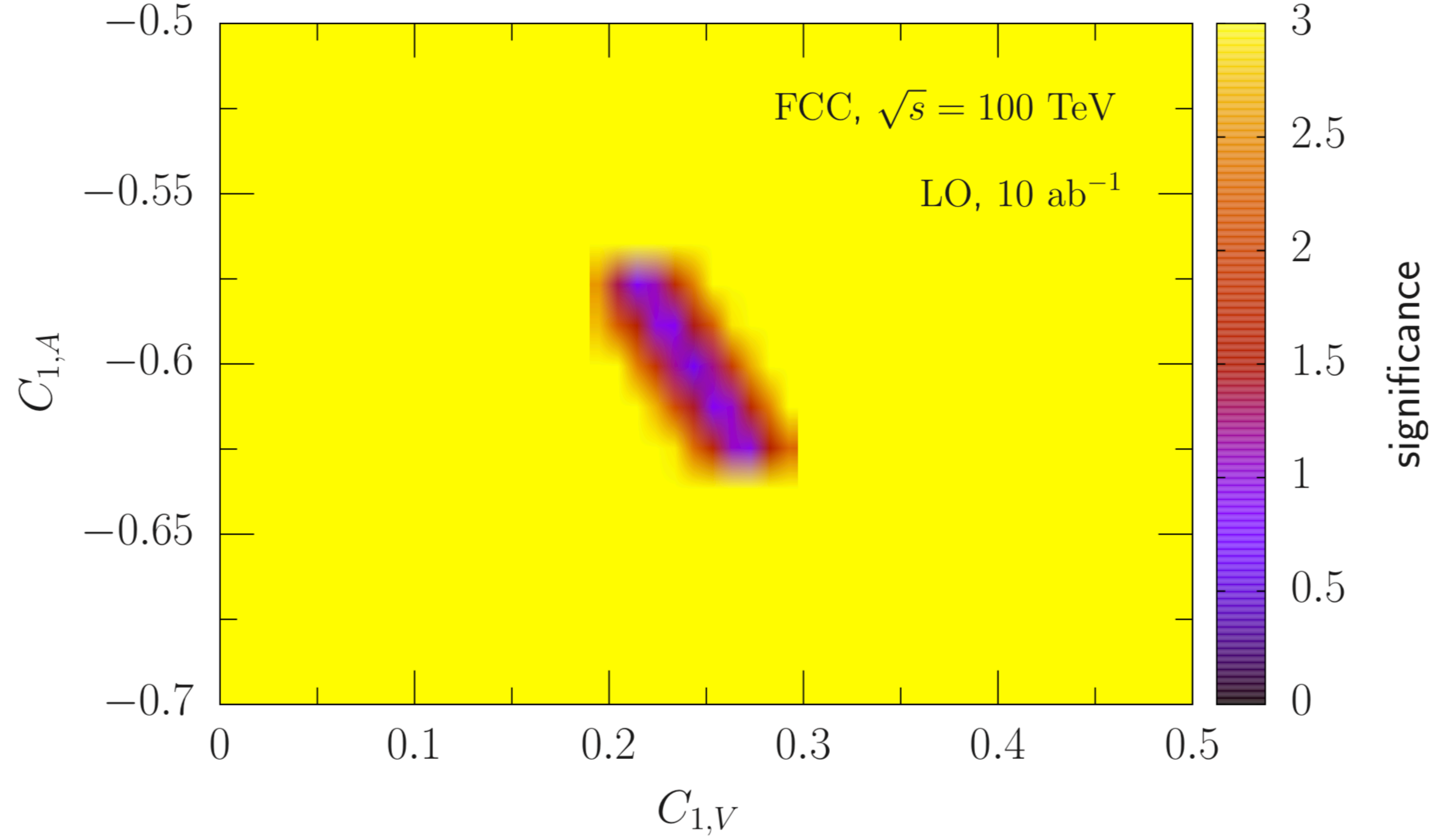

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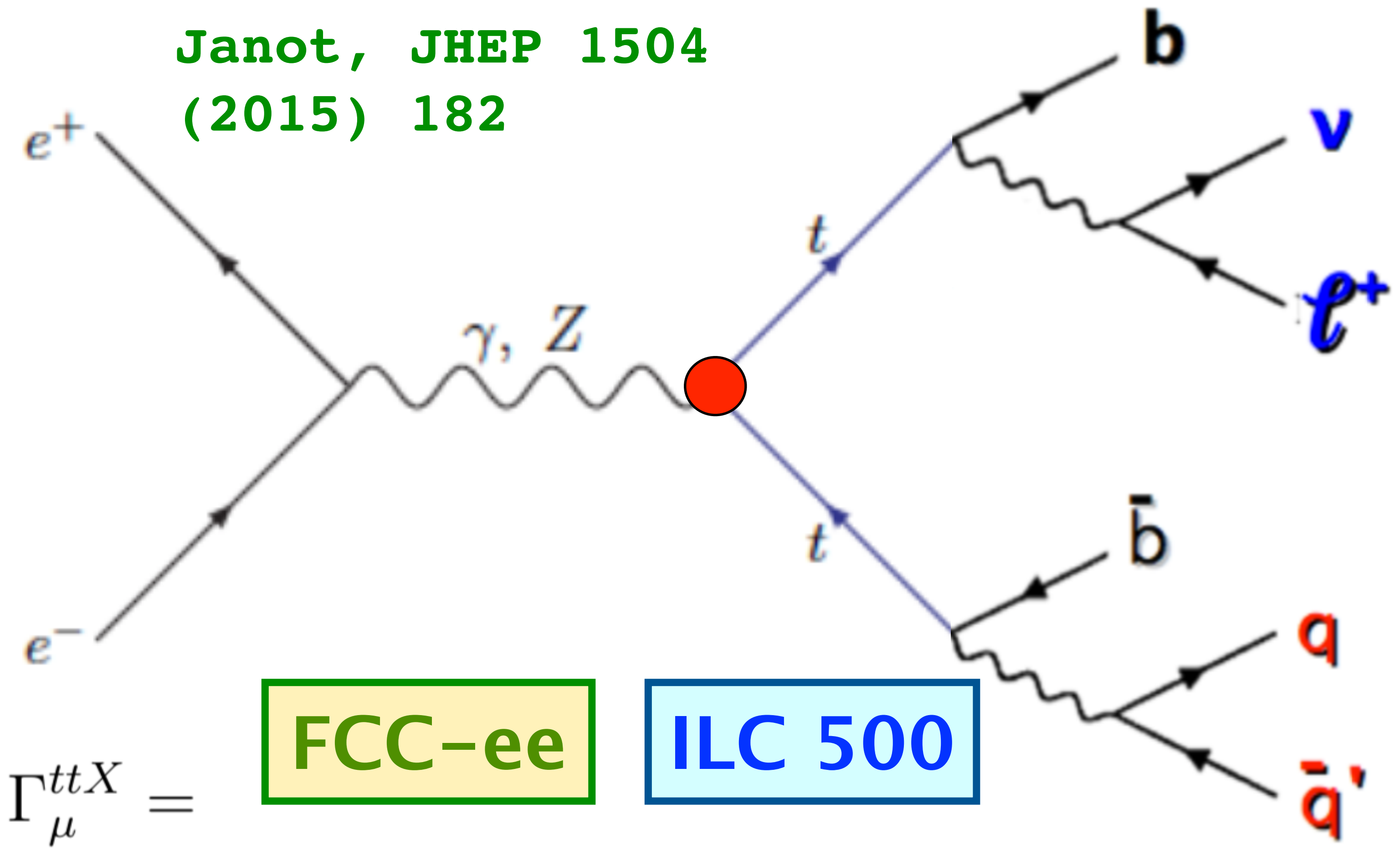
$t\bar tZ$ and $t\bar t\gamma$ Vertex and Dipole Moments

Janot, JHEP 1504 (2015) 182



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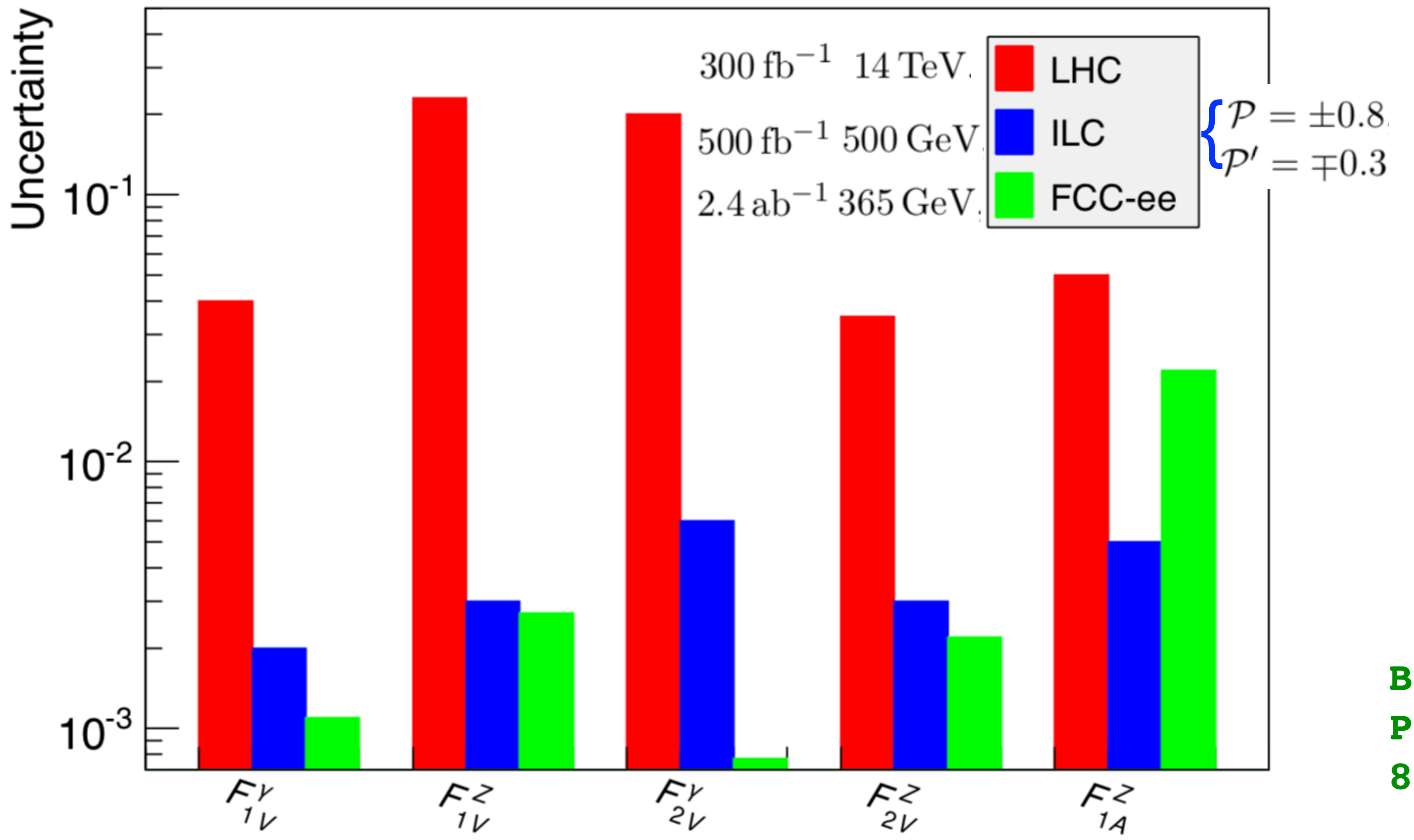
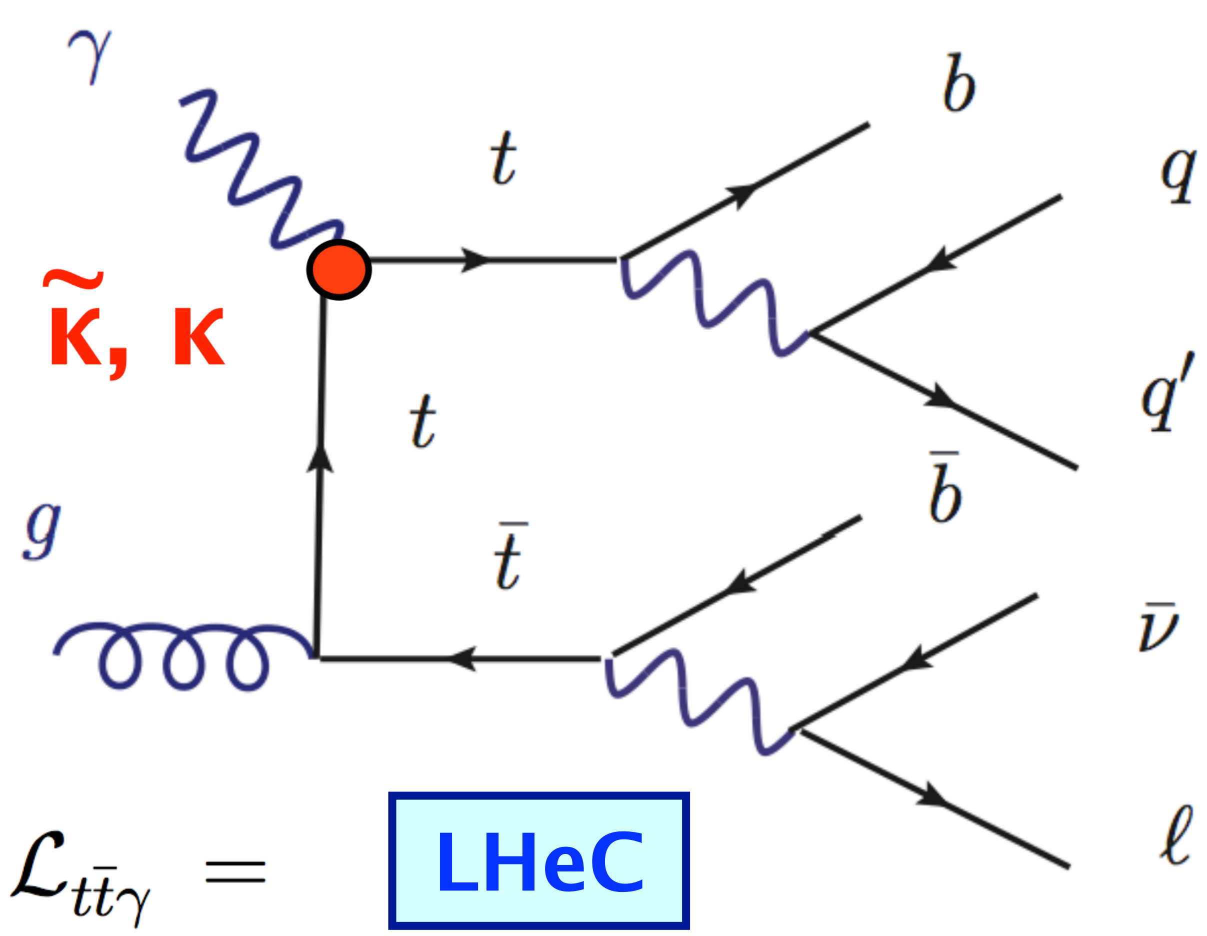


→ expected precision of order 10^{-2} to 10^{-3}



κ̃, κ

LHeC

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

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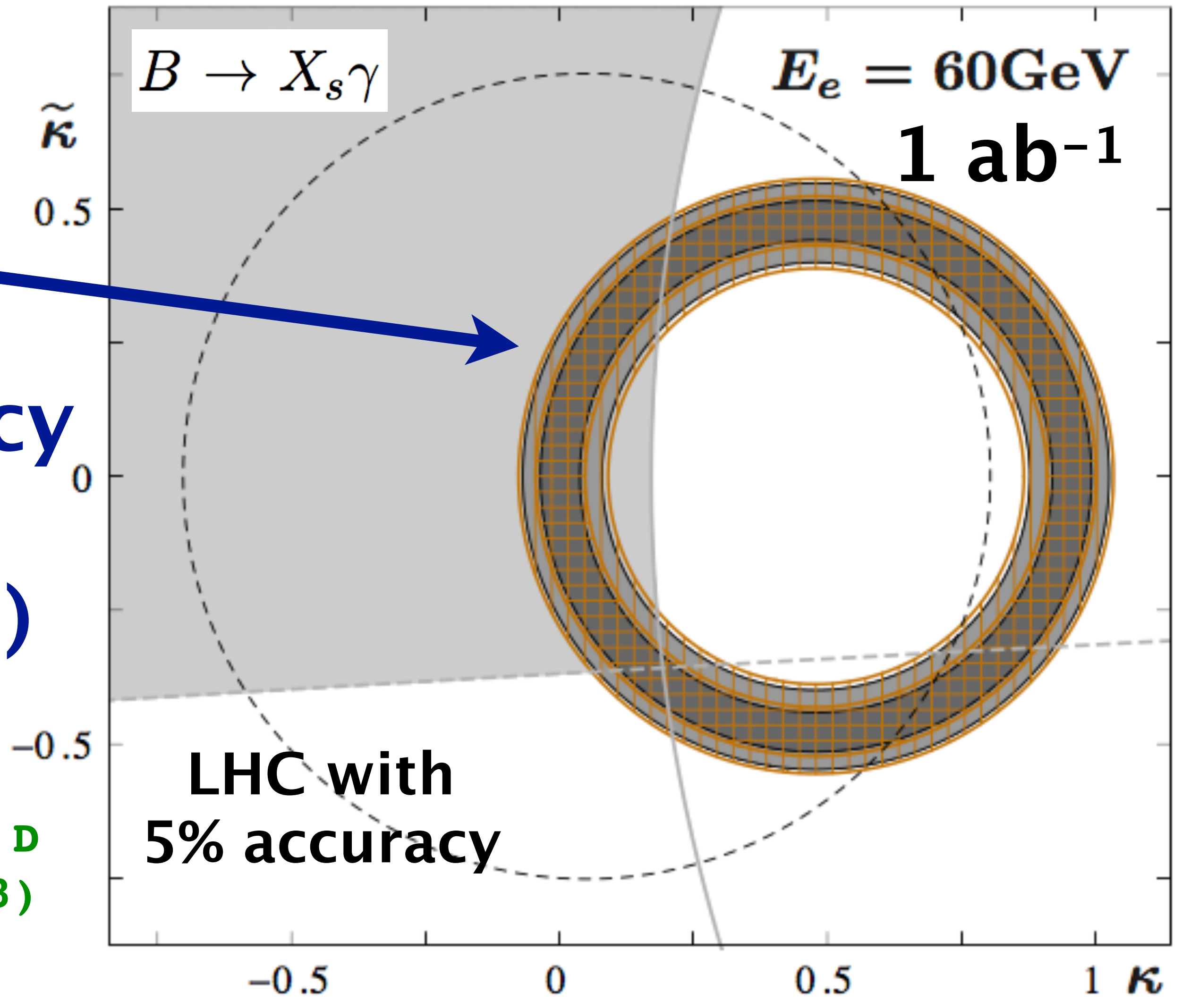
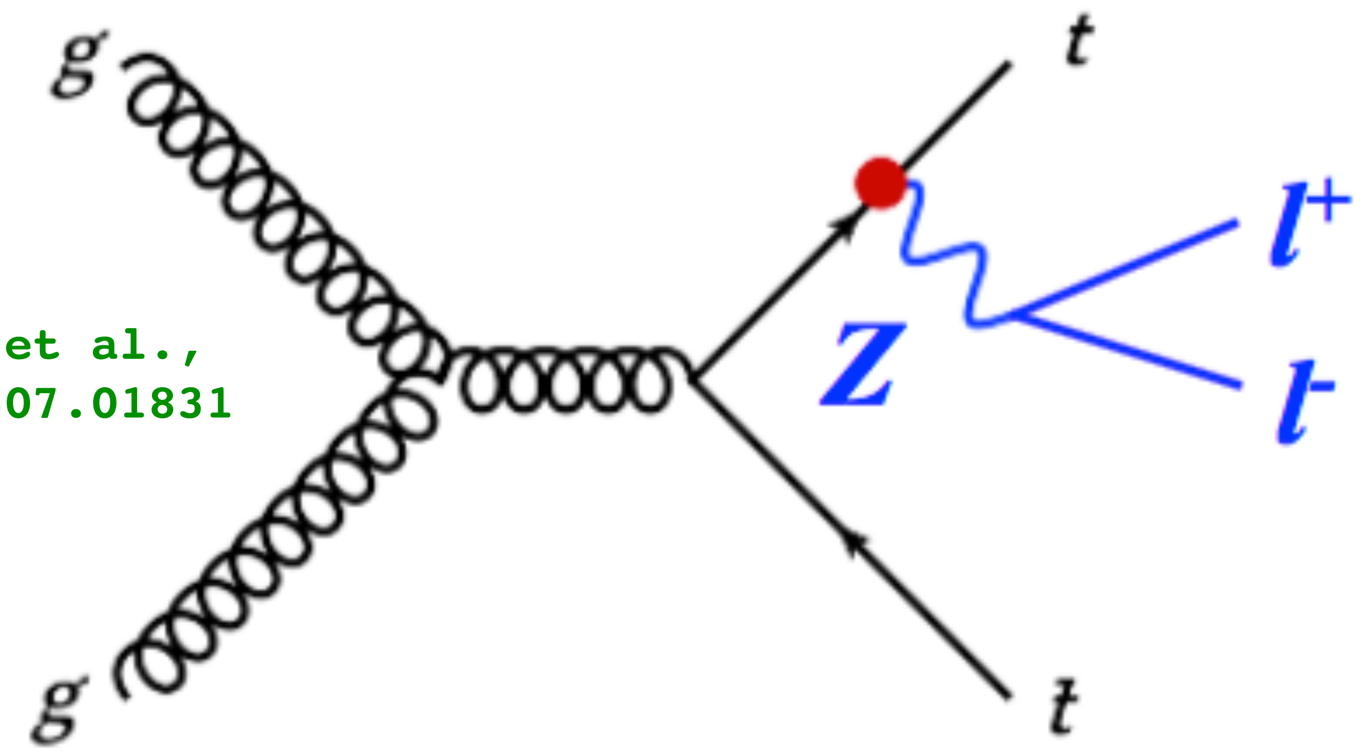


Bouzas, Larios, Physical Review D 88, 094007 (2013)

Mangano et al., arXiv:1607.01831



FCC-pp

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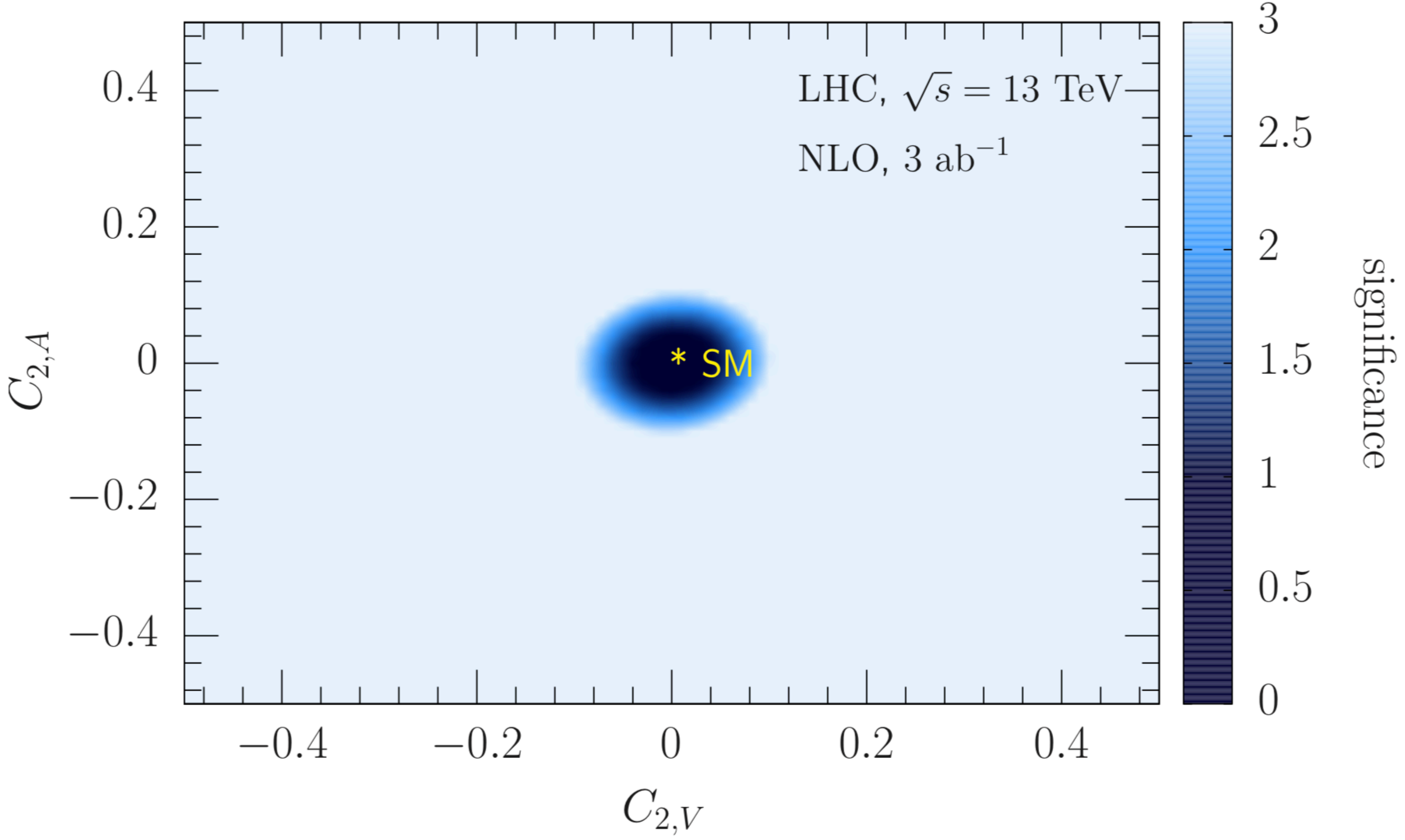

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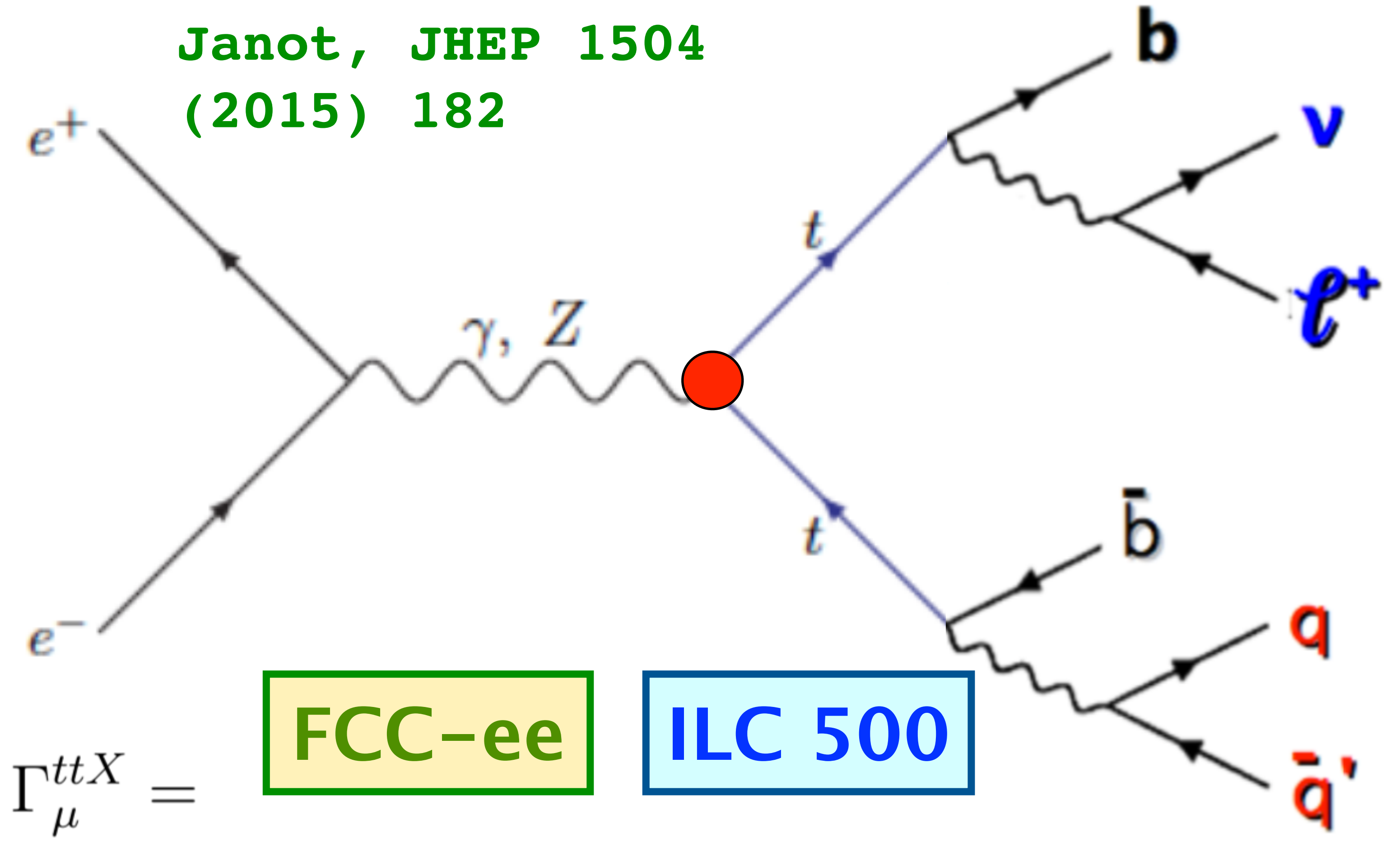

Janot, JHEP 1504 (2015) 182

FCC-ee **ILC 500**

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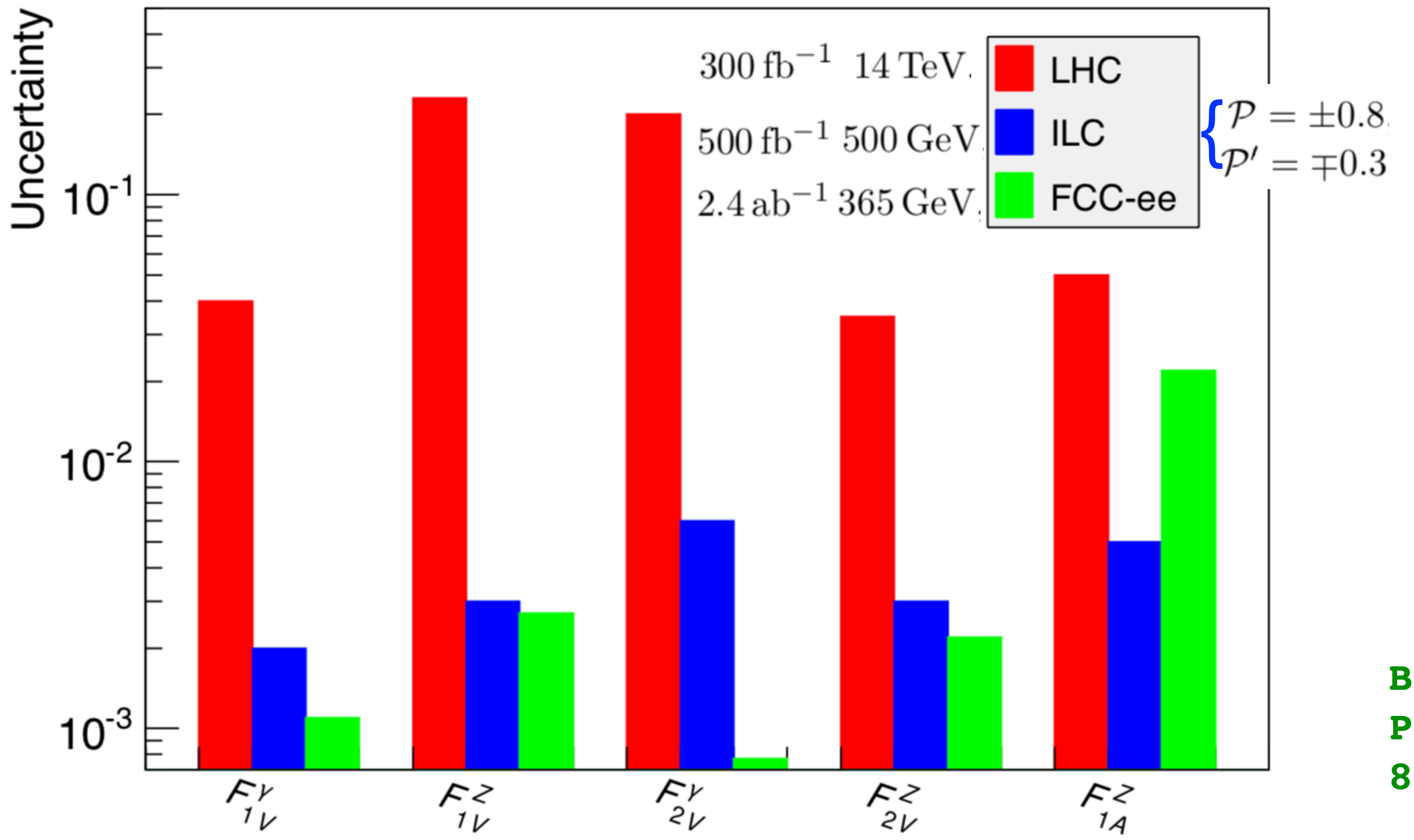

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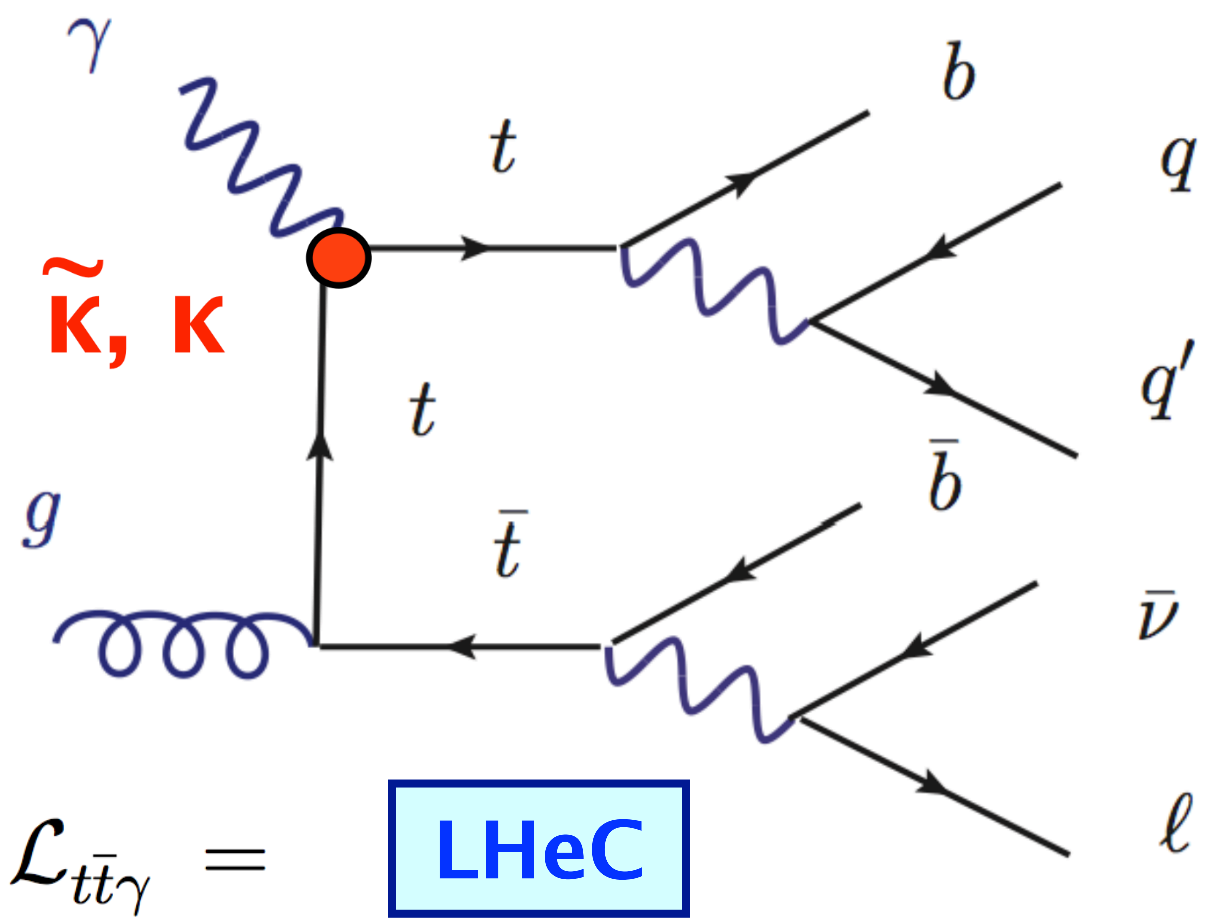

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LHeC

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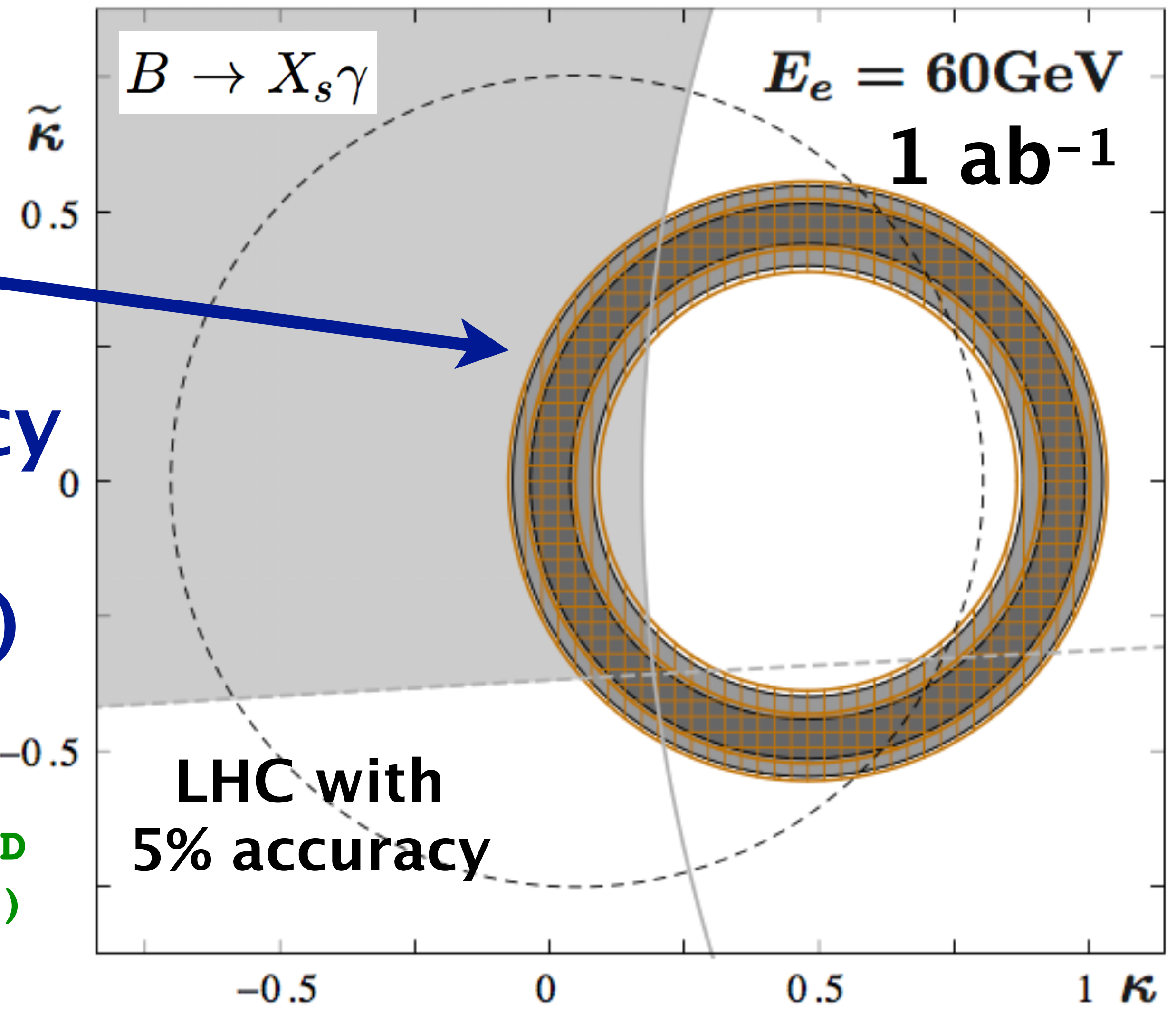

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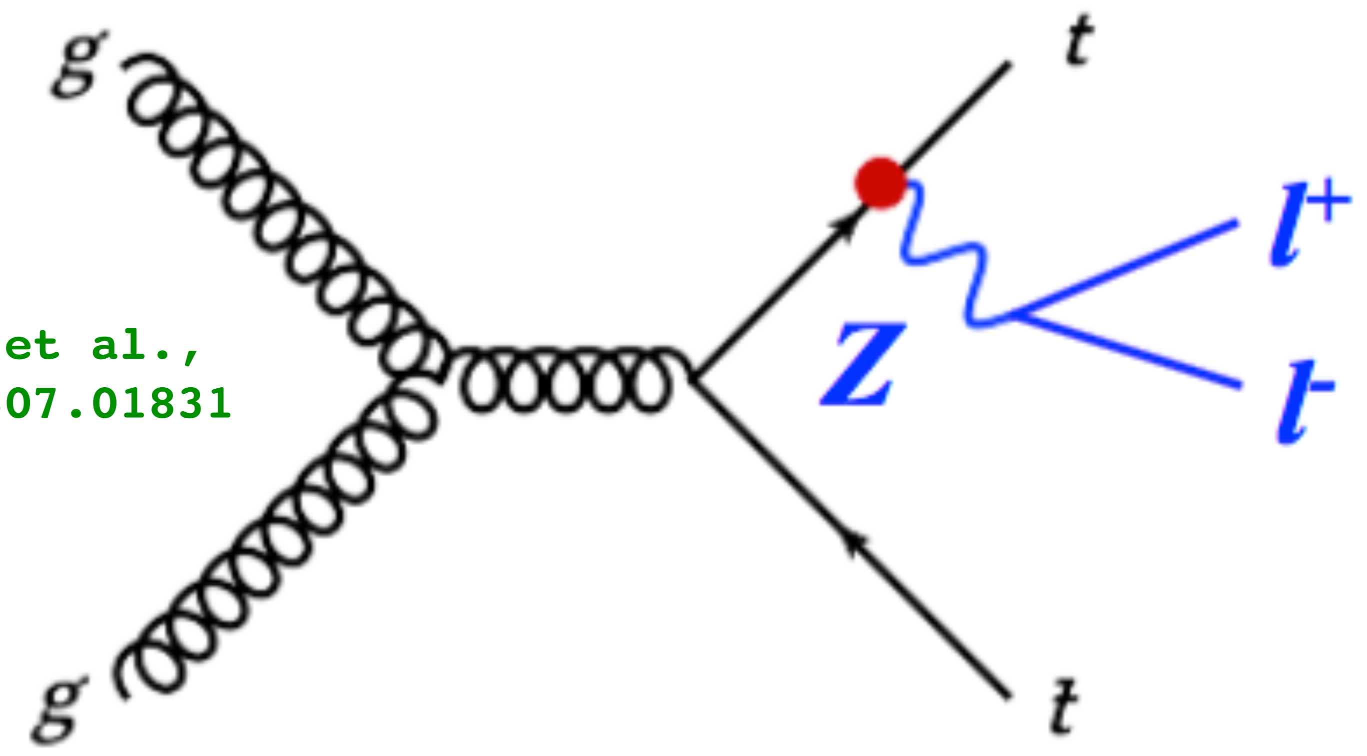
Mangano et al., arXiv:1607.01831



FCC-pp

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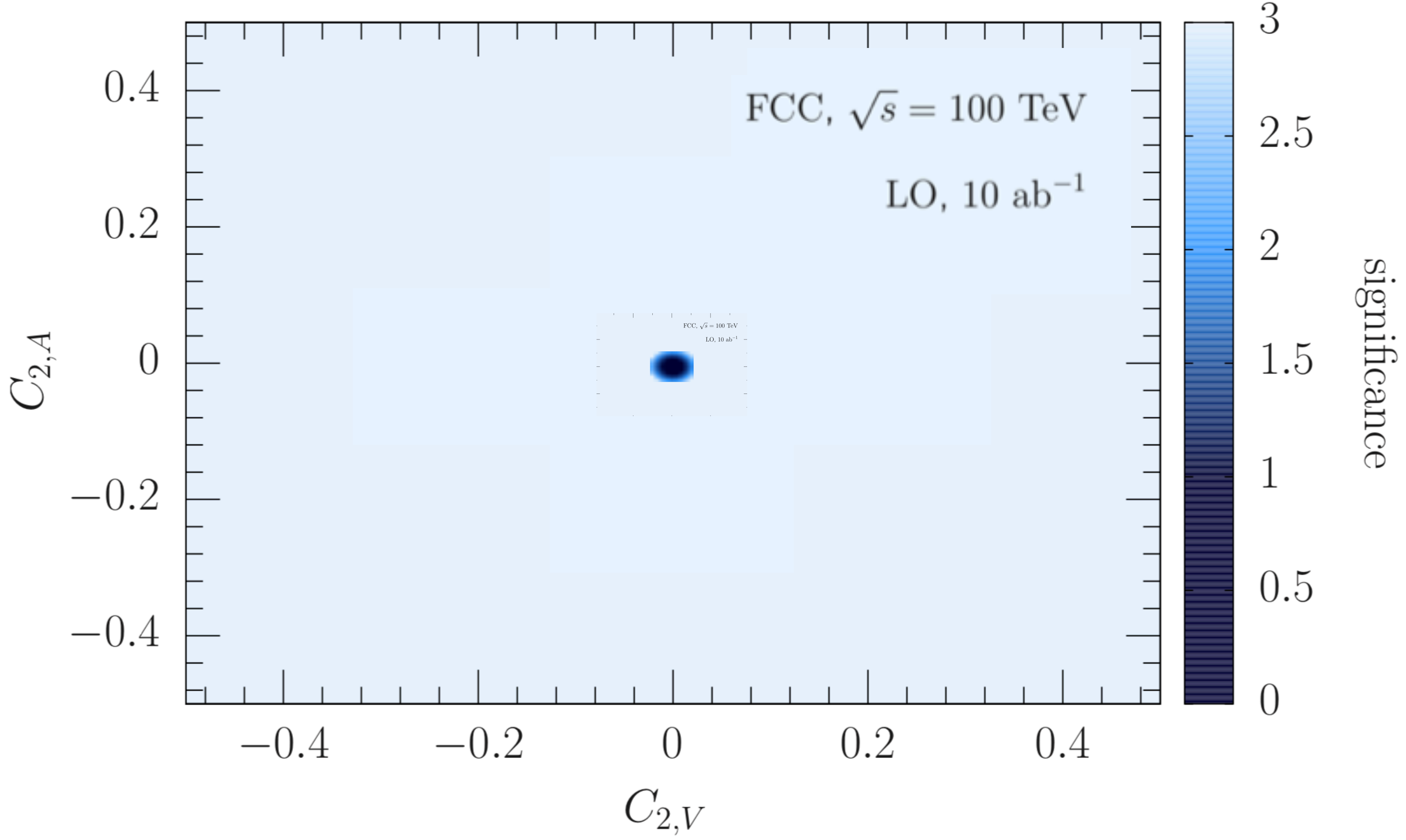
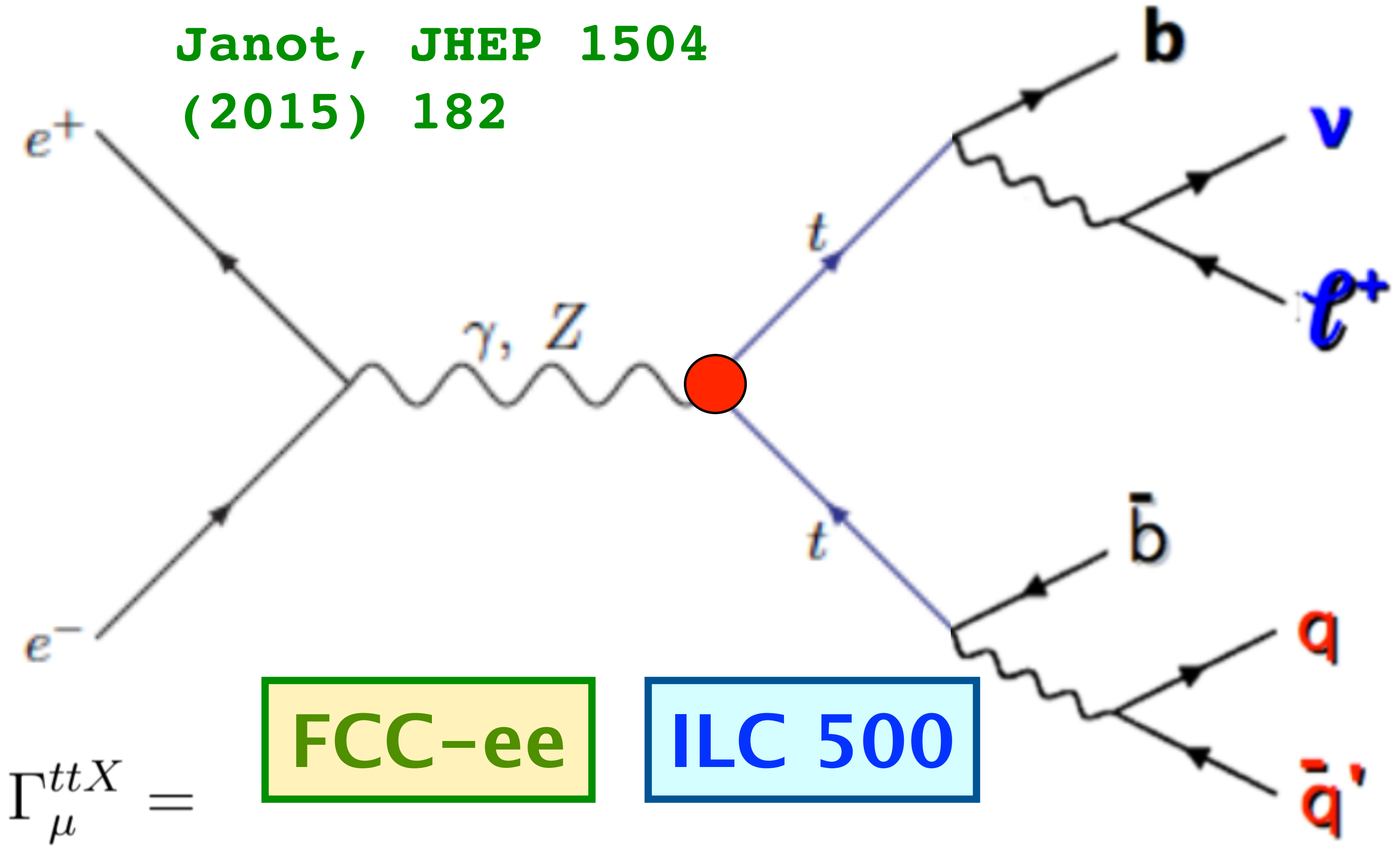


$t\bar{t}Z$ and $t\bar{t}\gamma$ Vertex and Dipole Moments



Janot, JHEP 1504 (2015) 182

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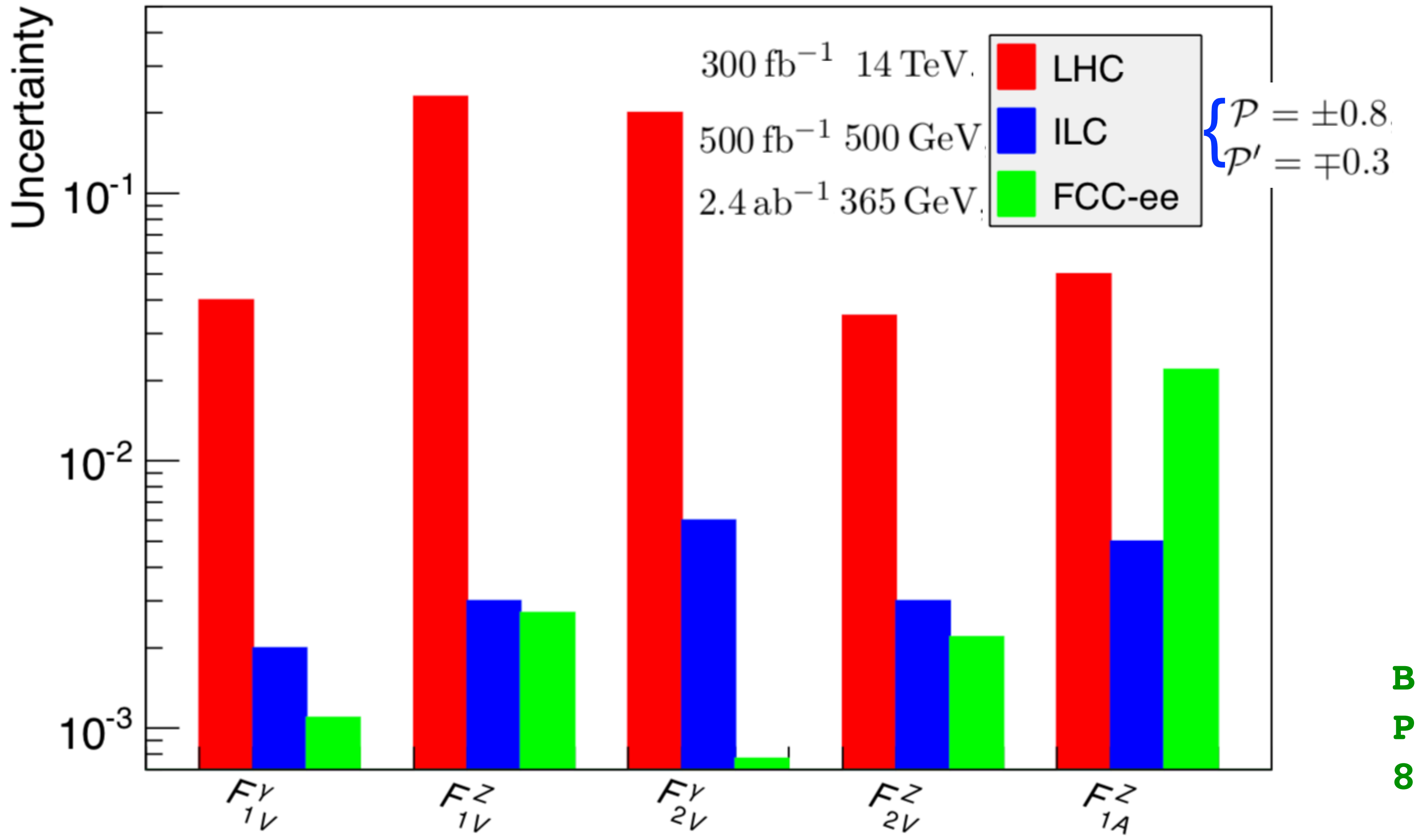
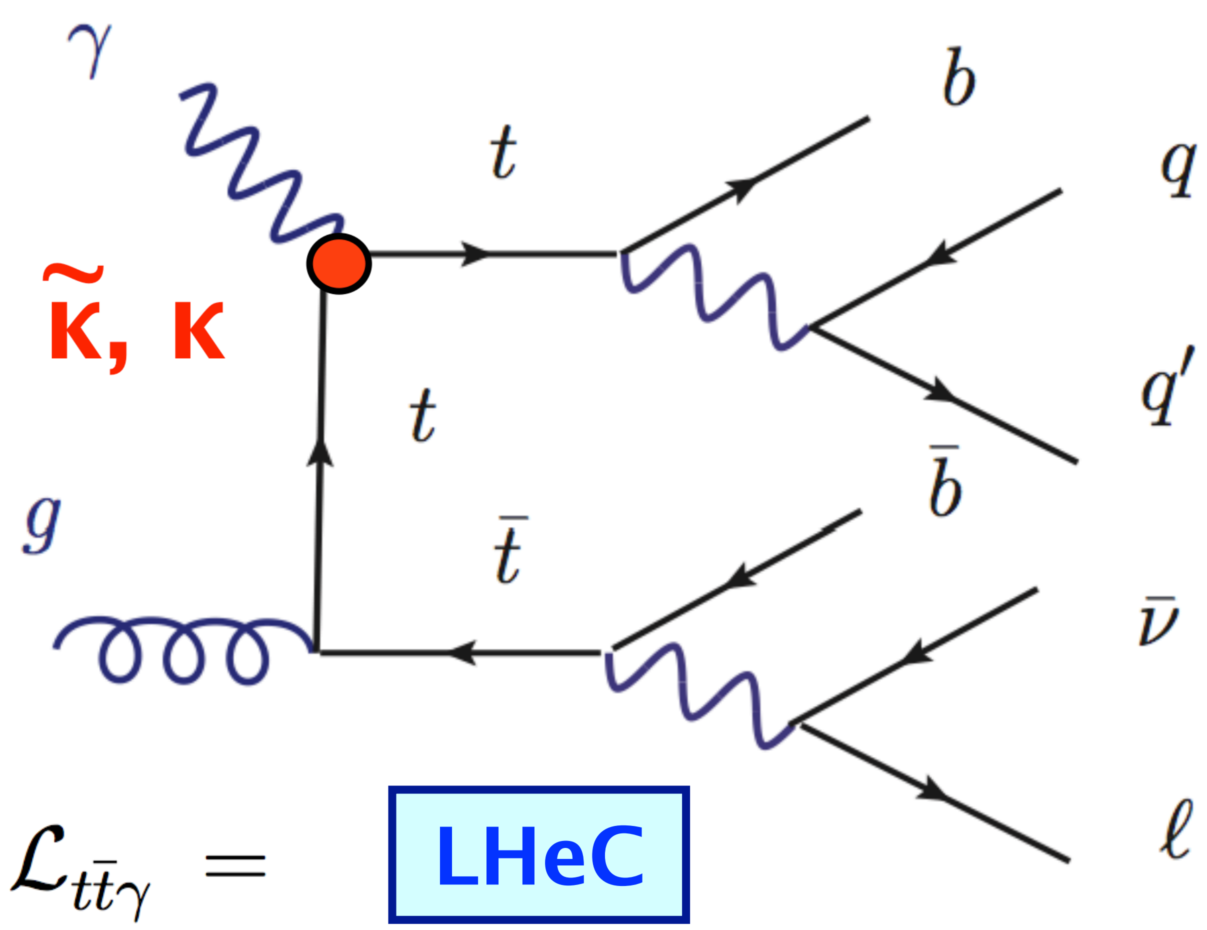


→ **expected precision of order 10^{-2} to 10^{-3}**



κ̃, κ

LHeC

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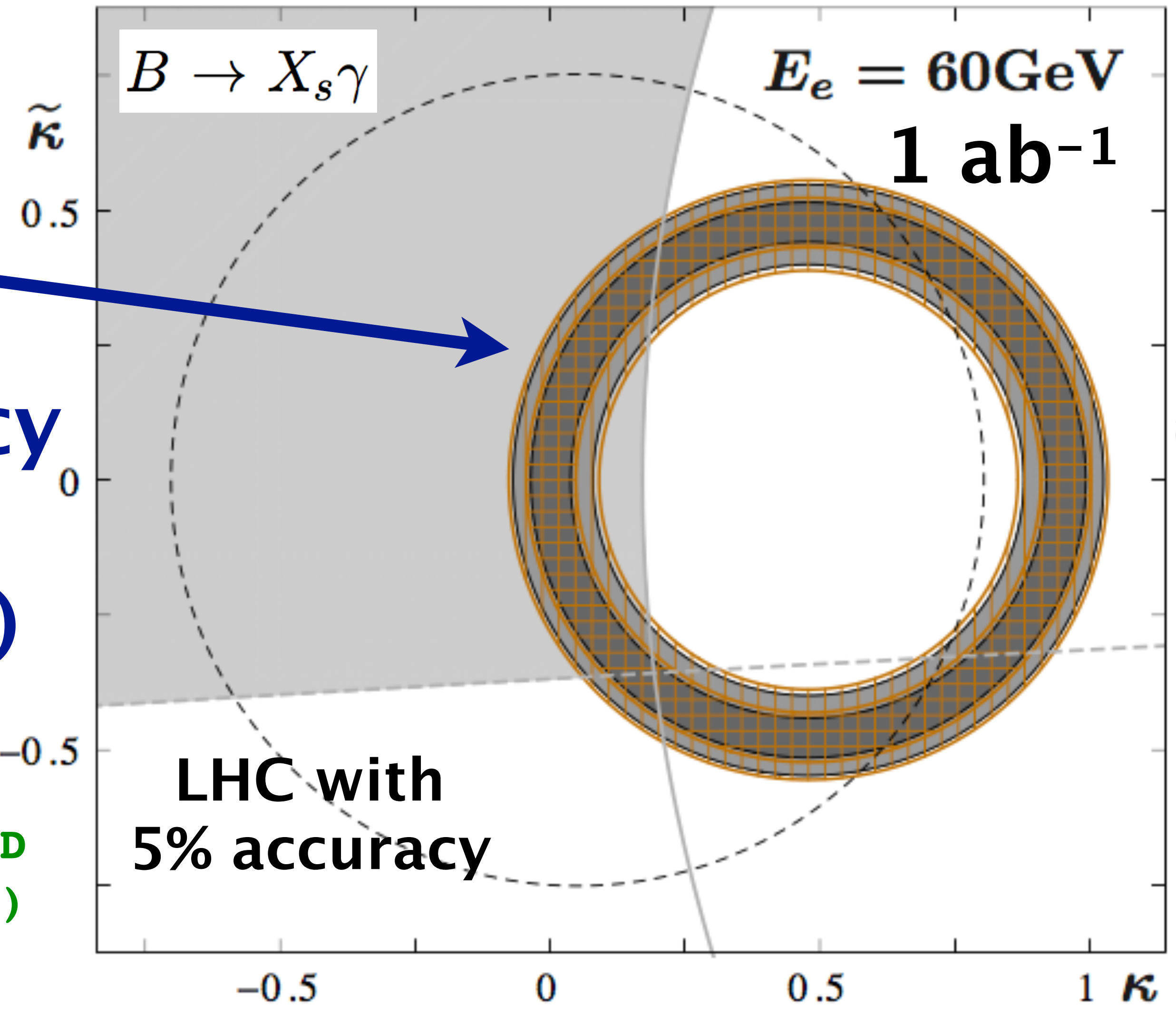
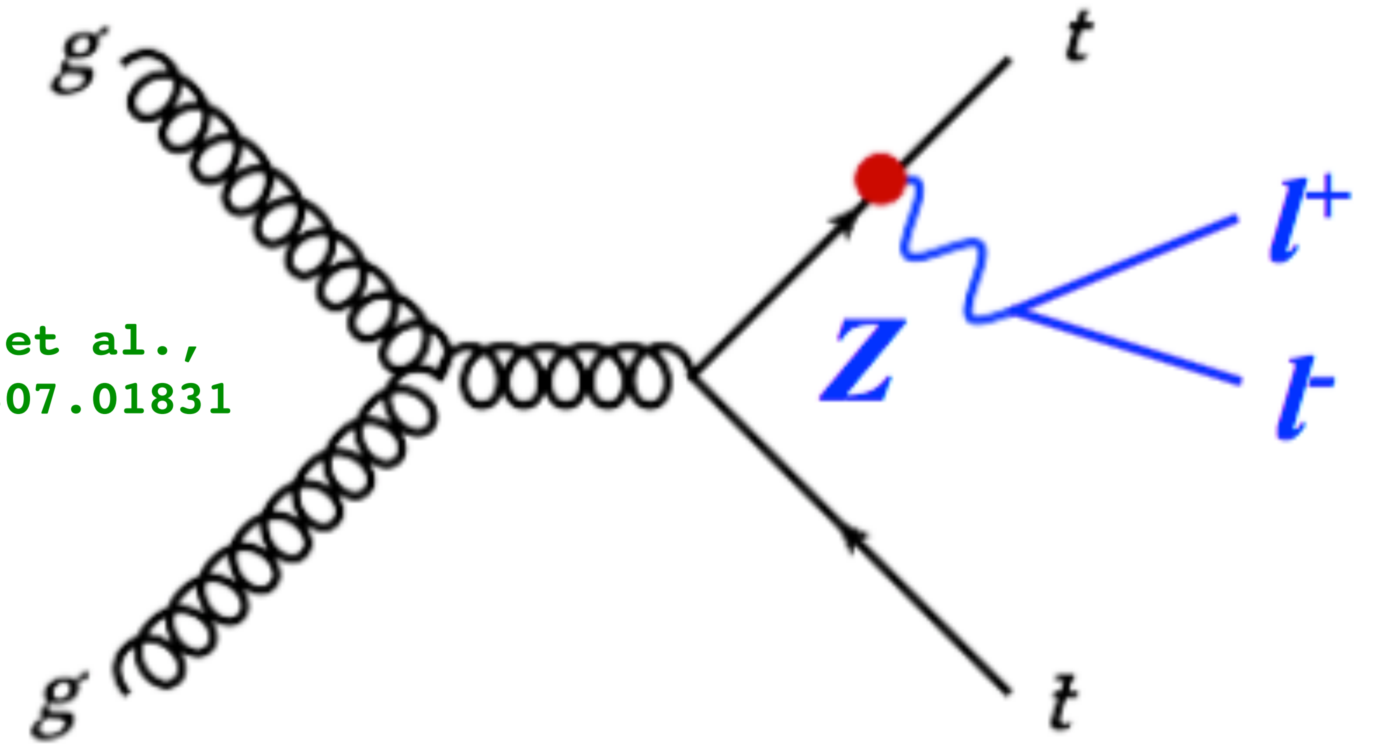


Bouzas, Larios, Physical Review D 88, 094007 (2013)

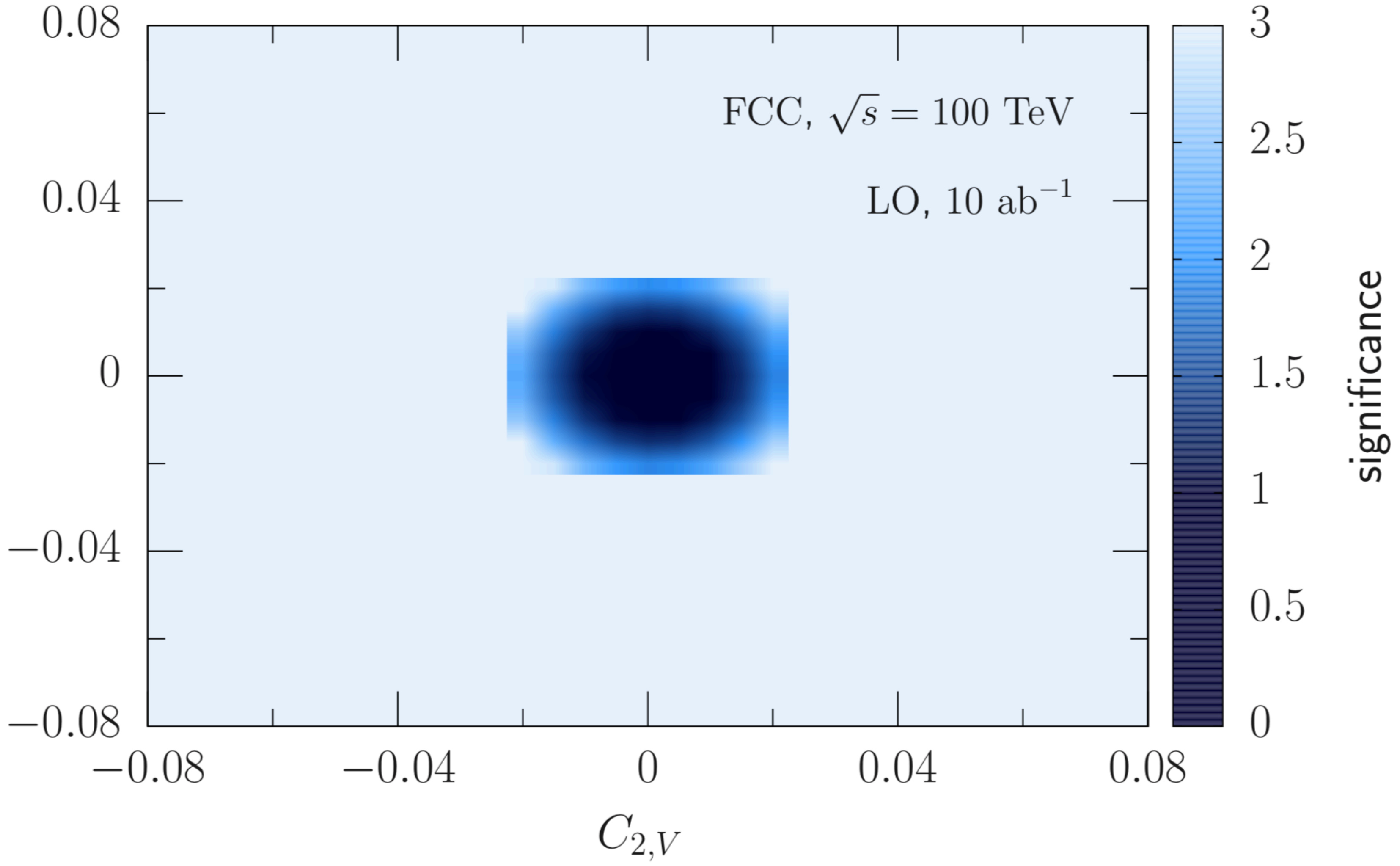
→ **expected precision of order 10^{-1} to 10^{-2}**

Mangano et al., arXiv:1607.01831



FCC-pp

$$\mathcal{L}_{t\bar{t}Z} = e\bar{\psi}_t\left[\gamma^\mu(C_{1,V}+\gamma_5C_{1,A})+\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}(C_{2,V}+i\gamma_5C_{2,A})\right]\psi_tZ_\mu$$

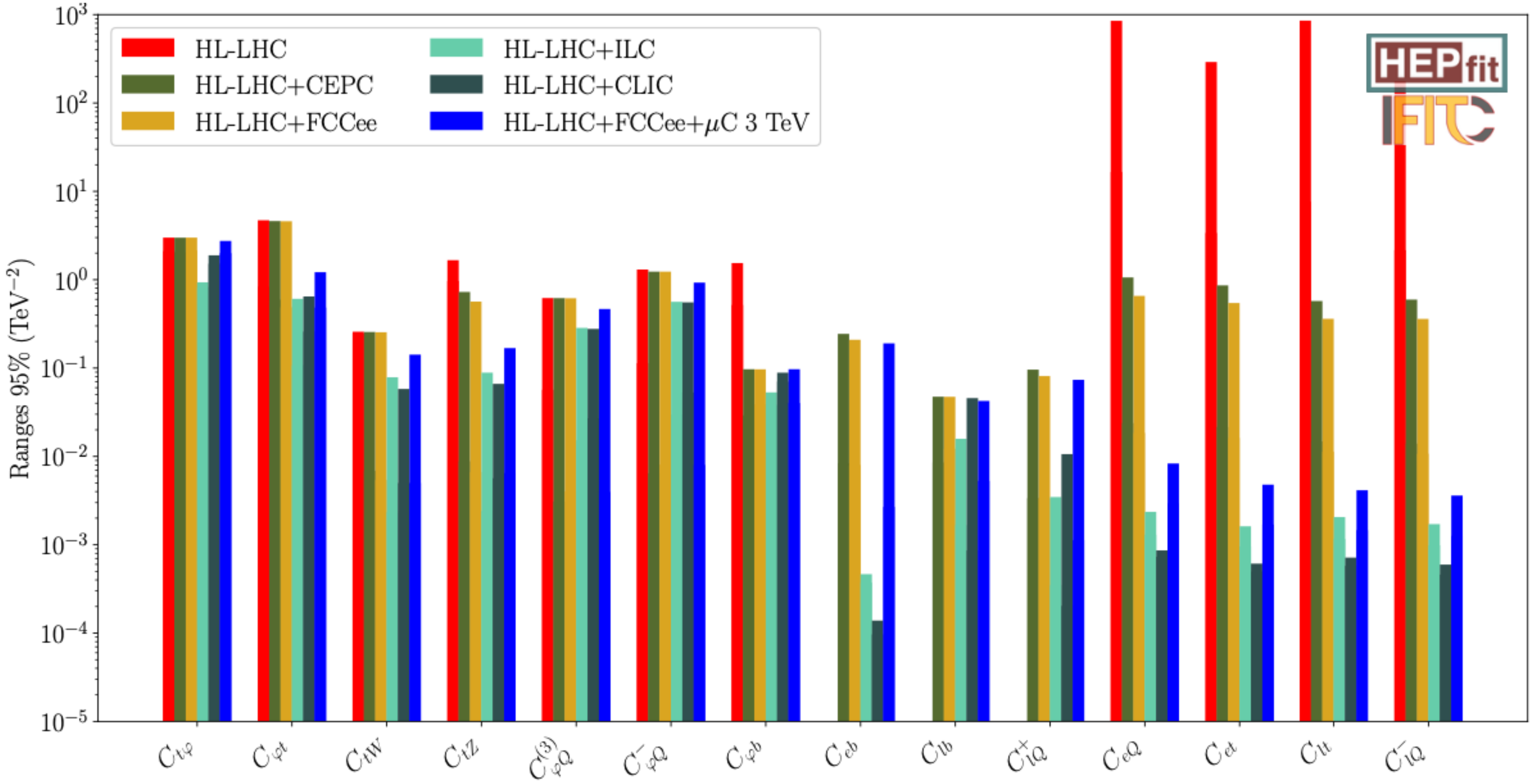


→ **expected precision of order 10^{-2}**

Global Search for EFT Couplings in Top Production and Decay

arXiv:2205.02140 [hep-ph]

FCC-ee **ILC** **CLIC**



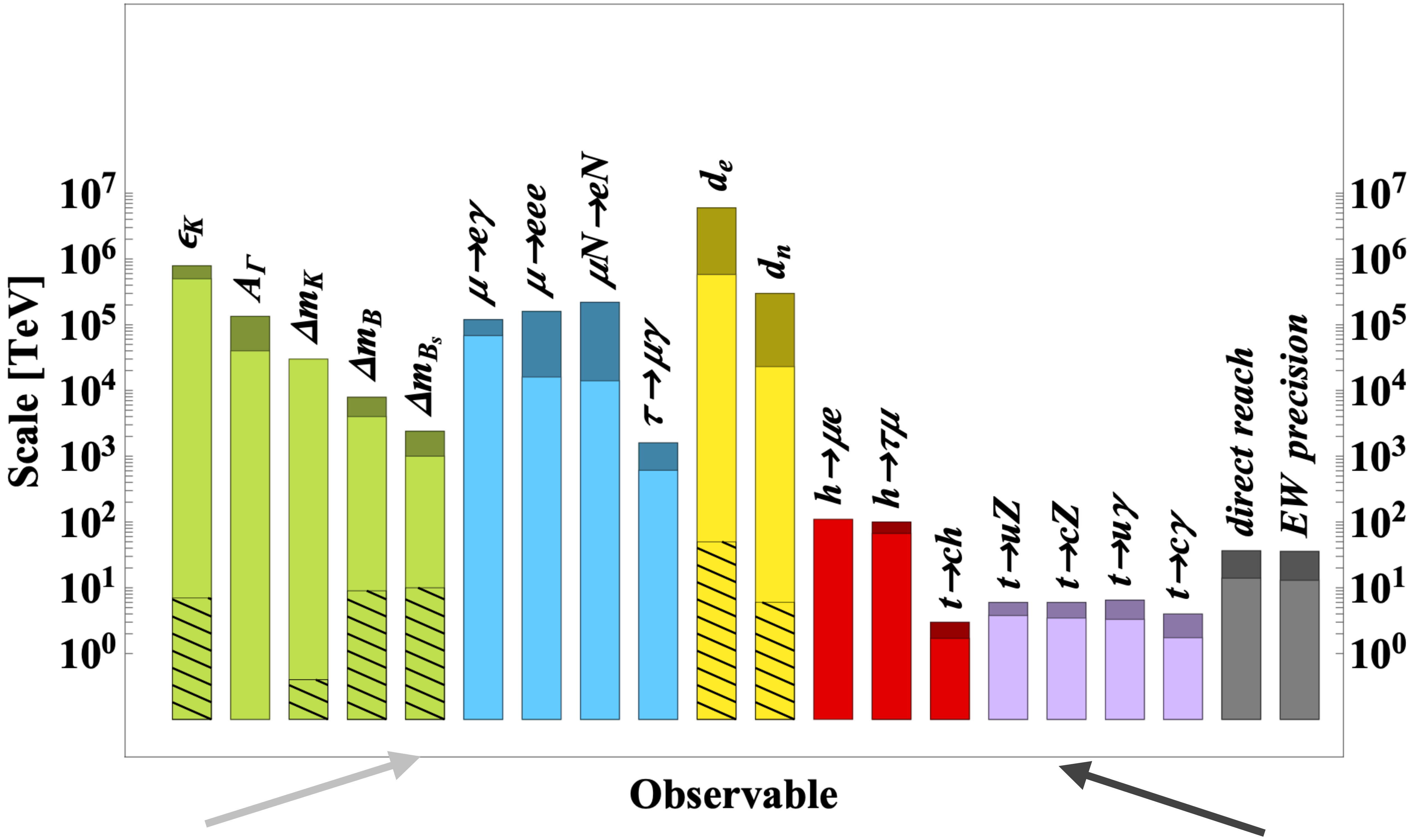
- Significant improvement for two-fermion electroweak operators at **FCC-ee**
- Vast improvements for various two-fermion operators at higher energies at **ILC/CLIC**
- **crucial input for ee→ZH at NLO** (needs accuracy of highest energy operation+polarisation!)

Flavor Physics: Big Questions and Great Reach

1. **origin of matter** (matter-antimatter asymmetry, CP violation, needs New Physics)
2. **origin of flavor** (patterns, hierarchies, needs New Physics)
3. **origin of mass** (is the Higgs responsible for quark and lepton masses, Yukawa propto mass? New Physics search. → Higgs talk

The specificities of the SM flavor sector with its suppressions and systematics (GIM, CKM, approx symmetries e.g. LFC) implies sensitivity and invites dedicated tests.

4. **Where does the SM fail and is New Physics flavorful?** SMEFT, and model, rare decays, searches, null tests
5. **nature of dark matter** (probing for invisibles/dark sector w. rare



present data

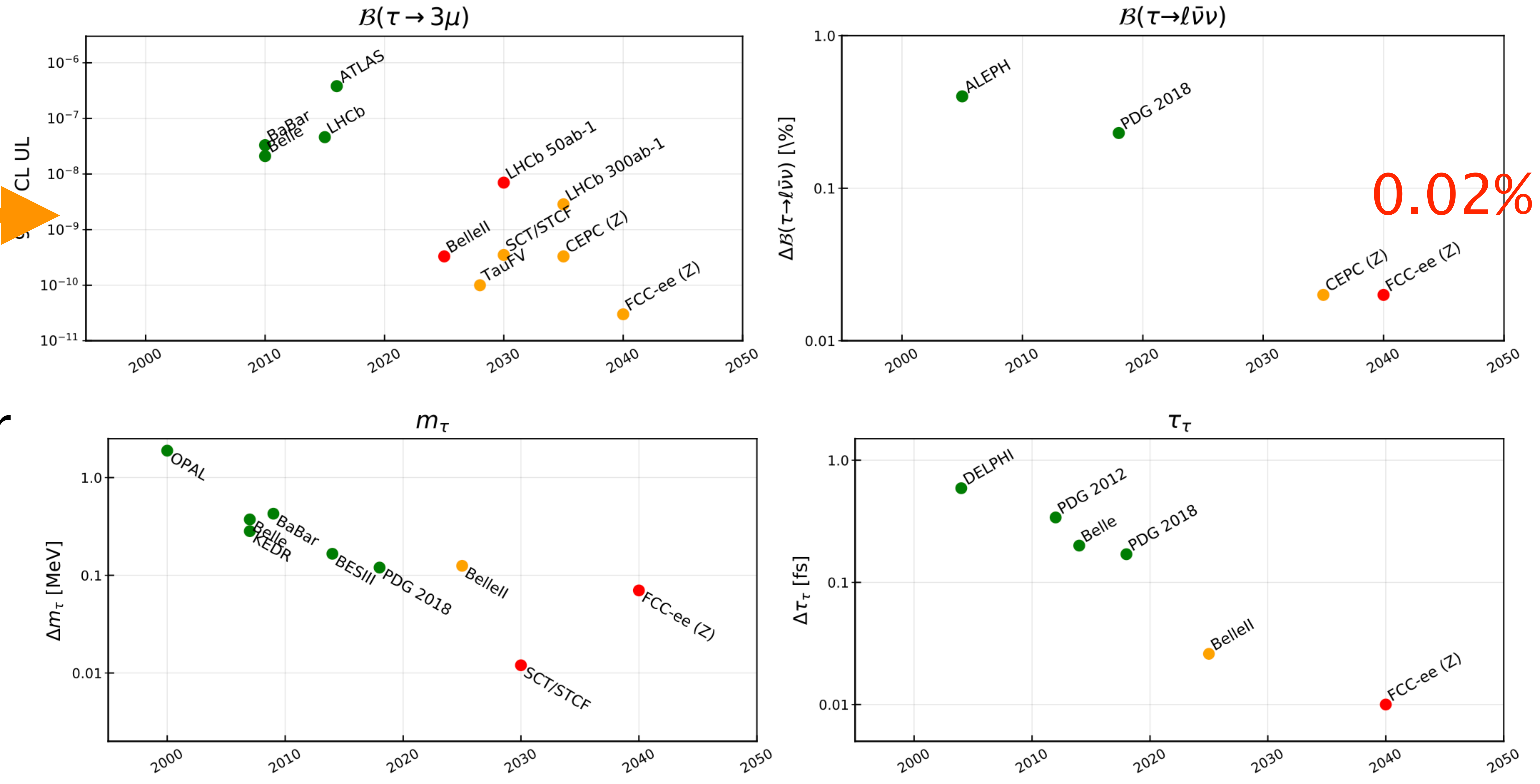
mid–term prospects

Flavor Physics: Topics at Future Colliders

- Z–flavor factory: Giga–Z@LC: 10^9 Z's with polarized beams, Tera–Z ≥ 10^{12} Z's needed to improve flavor–physics precision tests, e.g. $B_{s,d} \to \tau^+\tau^-$ and $B \to K^{(*)}\tau^+\tau^-$ decays
- lepton universality can be performed at a Z–factory: 1.7×10^{11} $\tau^+\tau^-$ pairs (precision level 10^{-5} with Tera–Z samples, statistics is important, longitudinal polarisation not so much) and ~10^{12} $Z \to b\bar{b}$ and $Z \to c\bar{c}$ decays ($B(Z \to \bar{b}b) = 0.15$, $B(Z \to c\bar{c}) = 0.12$)

FCC–ee **CepC**

- charm: e.g. charm–Yukawa coupling
- τ lepton universality and presision τ measurements as EW precision studies, at Z–pole best conditions
- Flavor violating Z couplings
- Flavor violating Higgs decays: one or two orders of magnitude improvements e.g. for h→τμ
- top couplings and FCNC decays



Flavor changing charged current Wtb couplings

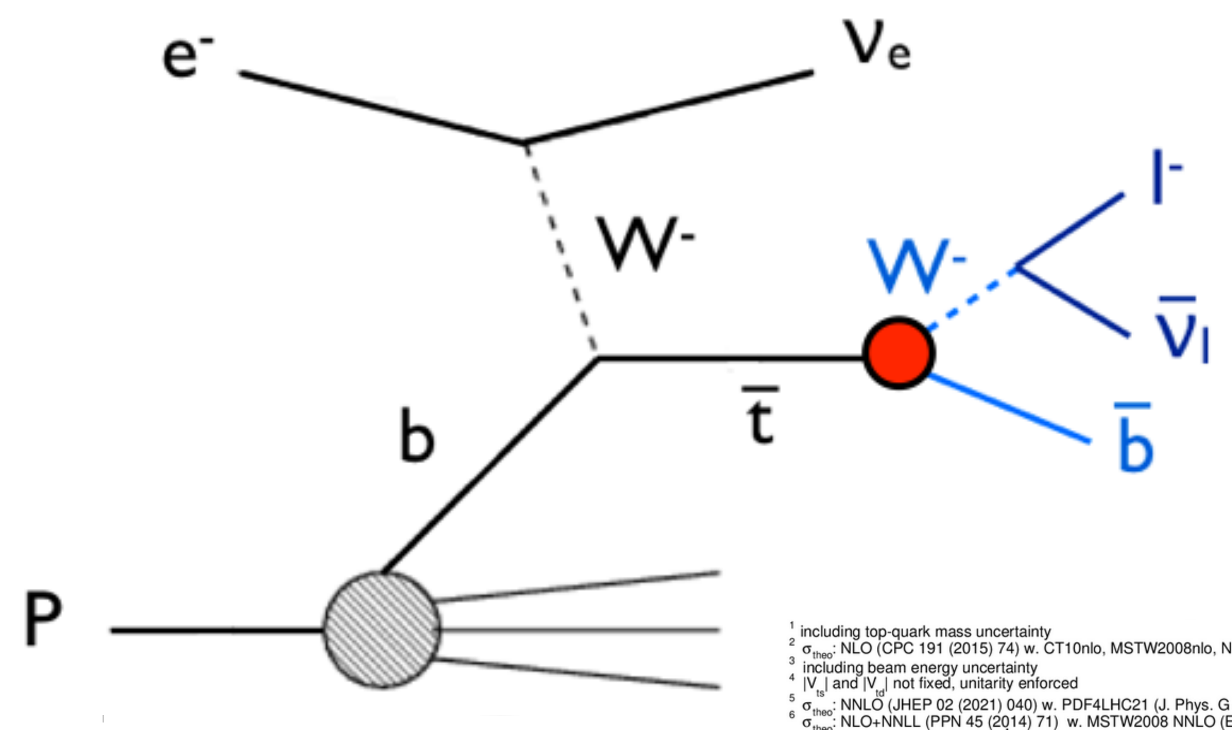
= 1 in SM

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

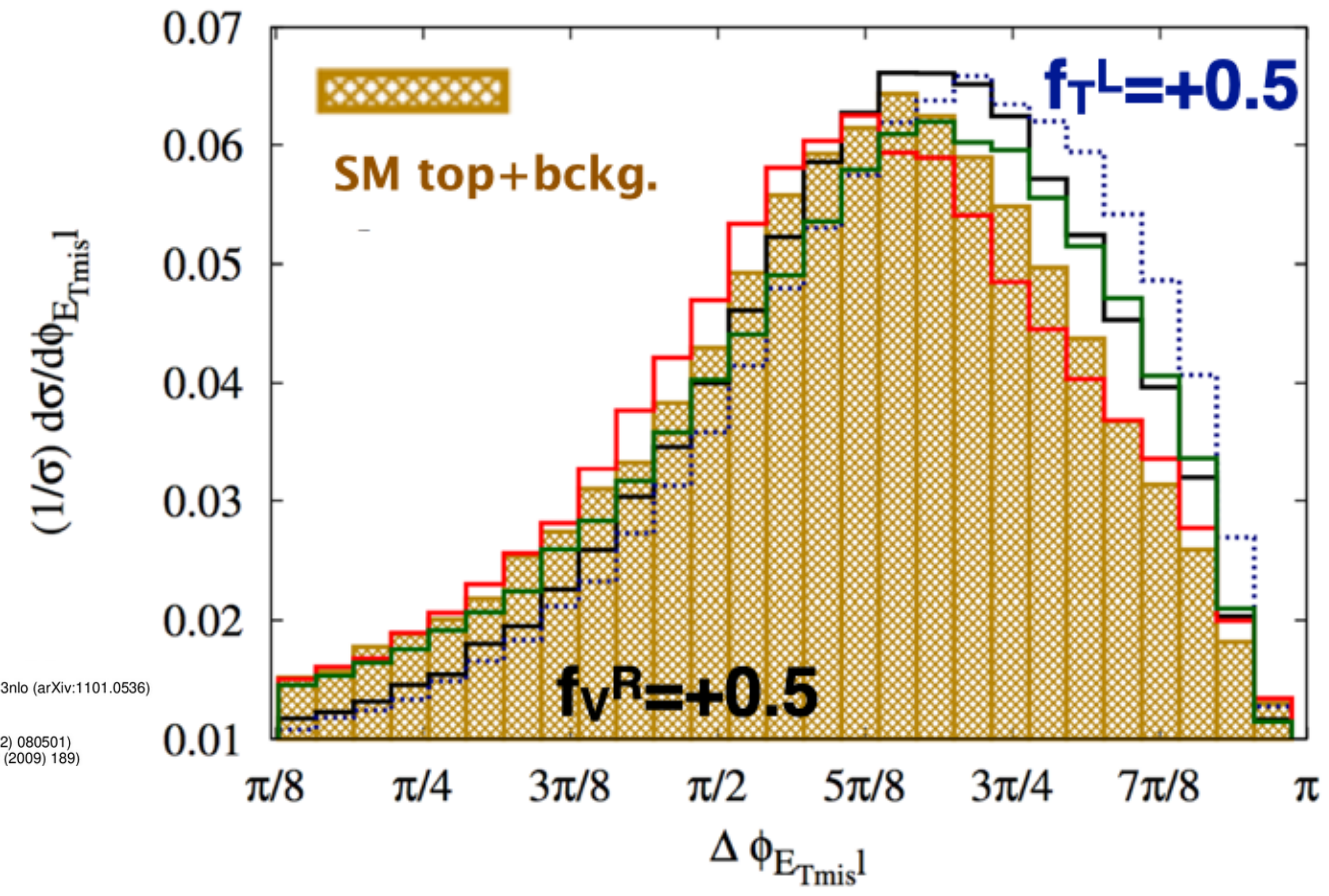
Dutta, Goyal, Kumar, Mellado,
arXiv:1307.1688
Kumar, Ruan, to be publ.

LHeC

CC DIS top production



[1] including top-quark mass uncertainty
[2] σ_{theo}: NLO (CPC 191 (2015) 74) w. CT10nlo, MSTW2008nlo, NNPDF2.3nlo (arXiv:1101.0536)
[3] including beam energy uncertainty
[4] $|V_{ts}|$ and $|V_{td}|$ not fixed, unitarity enforced
[5] σ_{theo}: NNLO (JHEP 02 (2021) 040) w. PDF4LHC21 (J. Phys. G 49 (2022) 080501)
[6] σ_{theo}: NLO+NNLL (PPN 45 (2014) 71) w. MSTW2008 NNLO (EPJC 63 (2009) 189)



+ other variables sensitive on W helicity

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

Expected measurements of Wtb couplings

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

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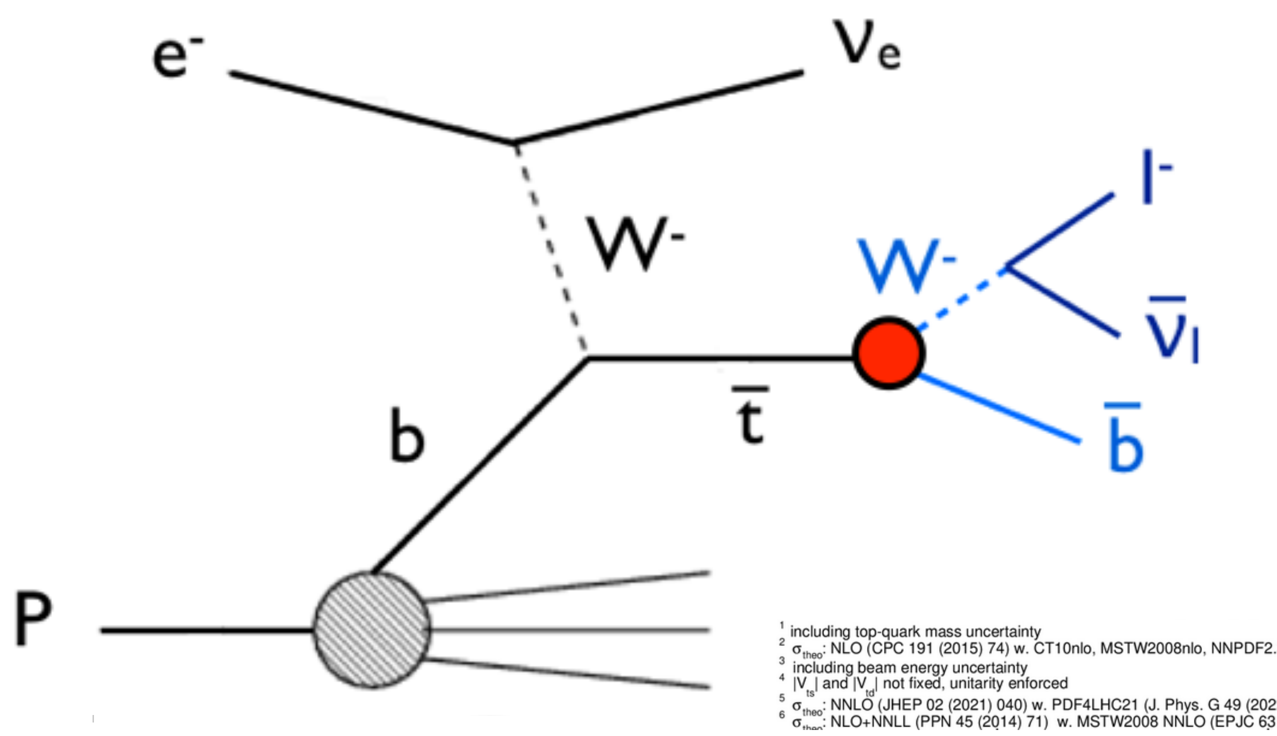
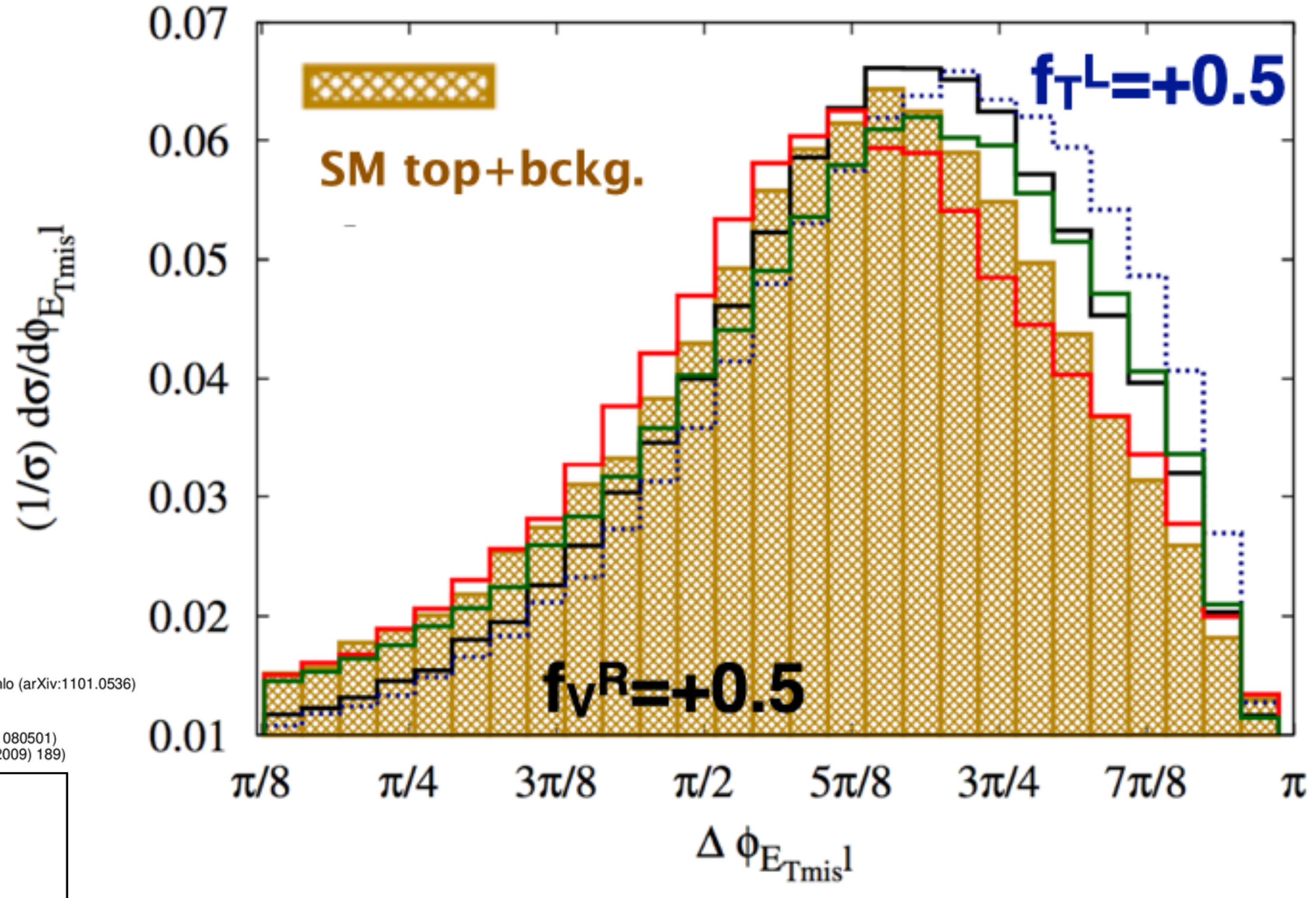


LHeC



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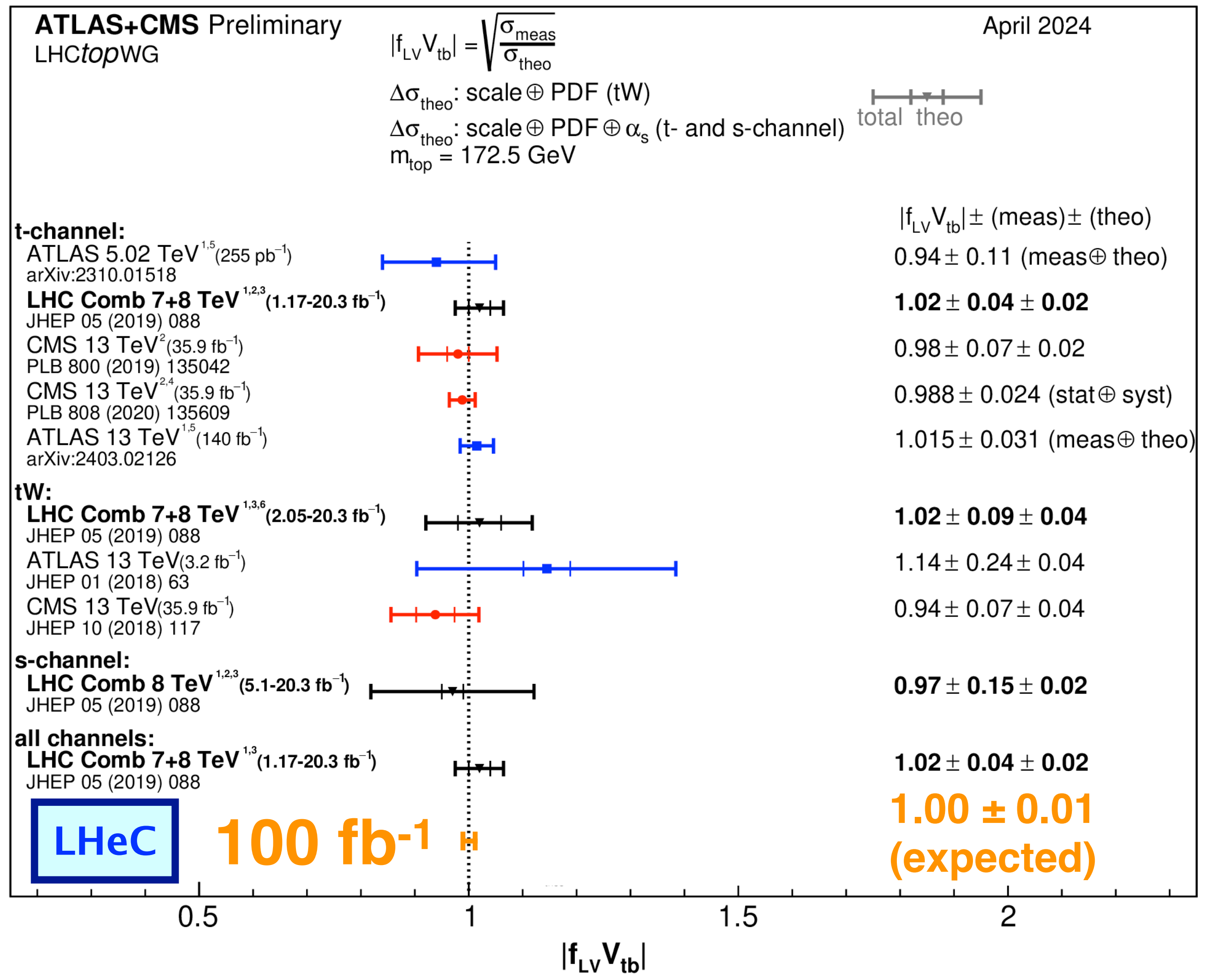
Unprecedented precision < 1%



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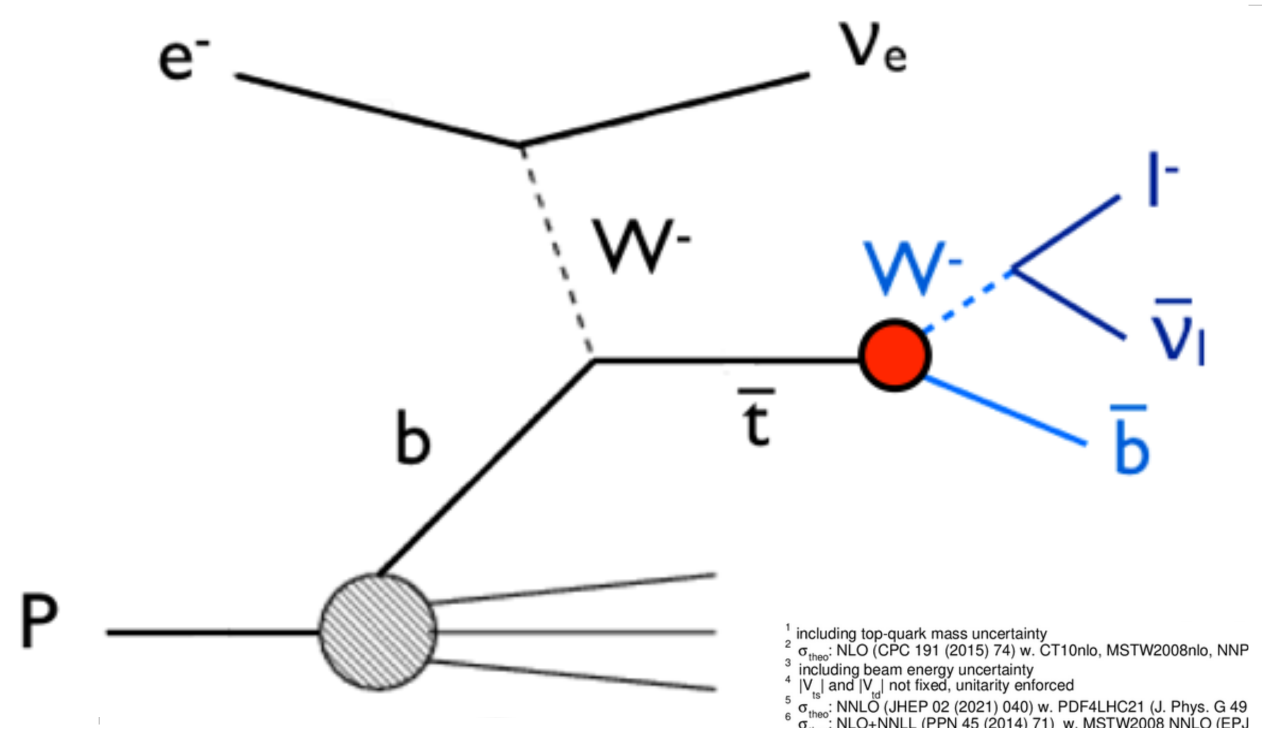

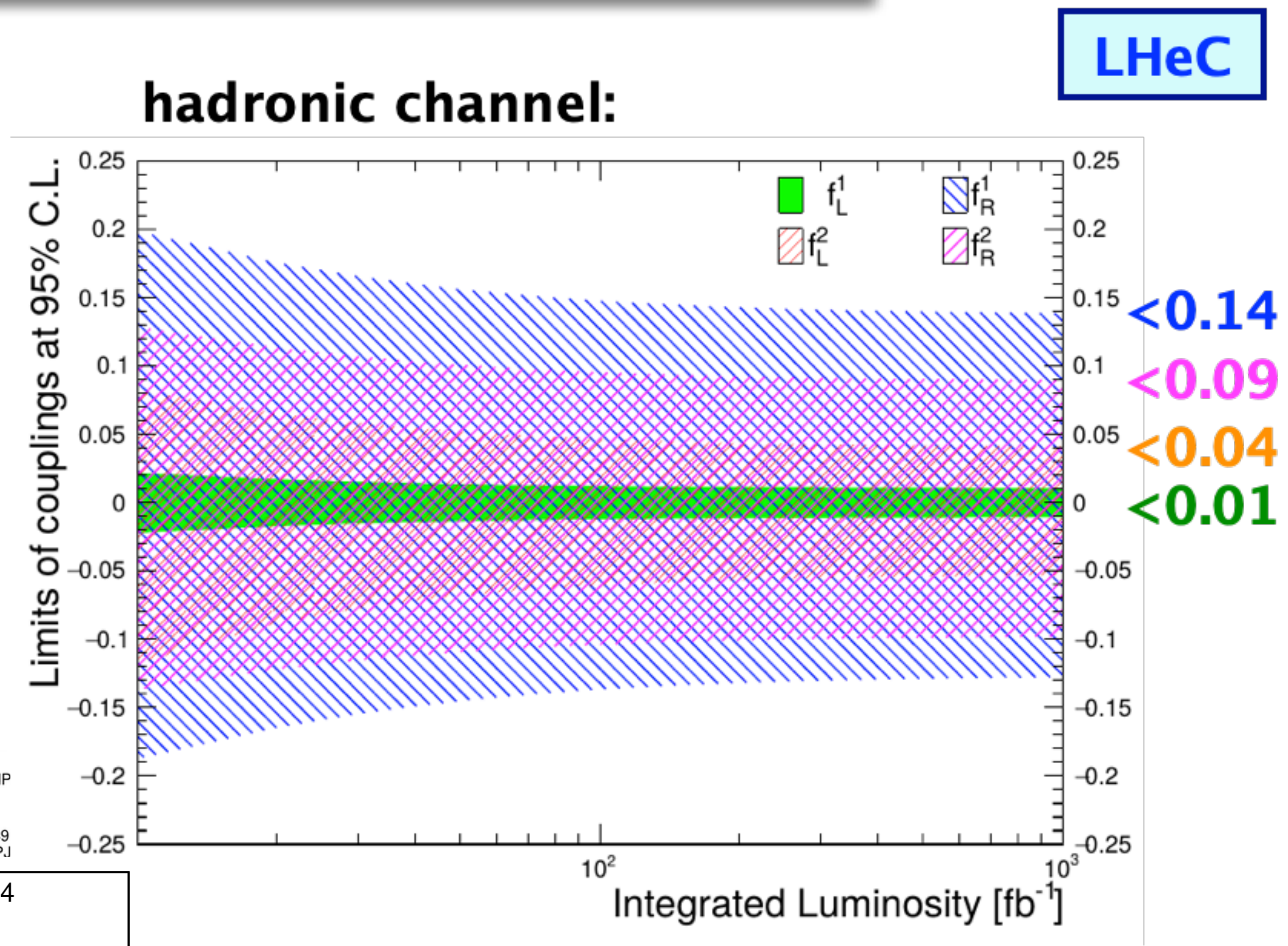

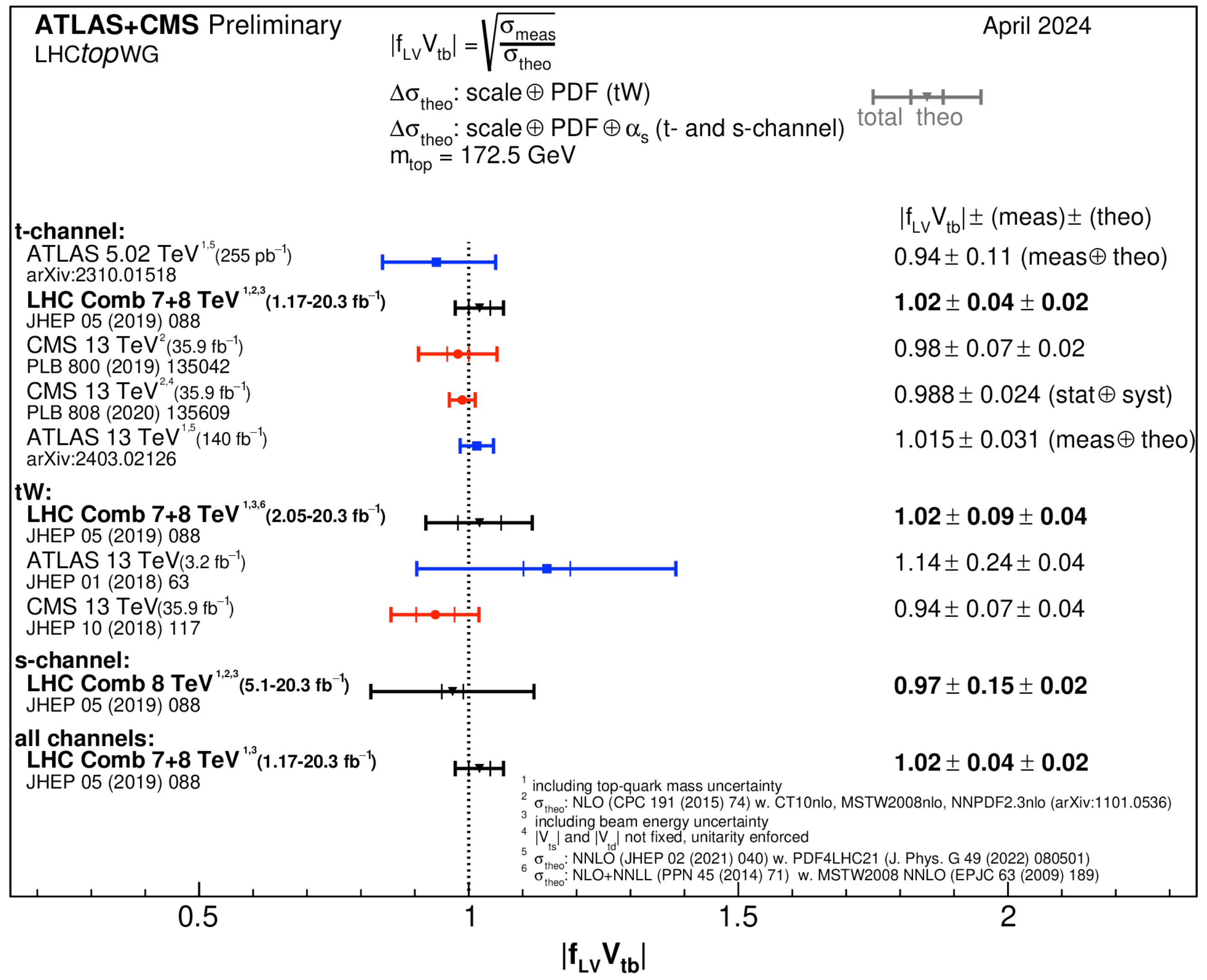

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Unprecedented precision < 1%

Expected measurements of Wtq couplings

= 1 in SM

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

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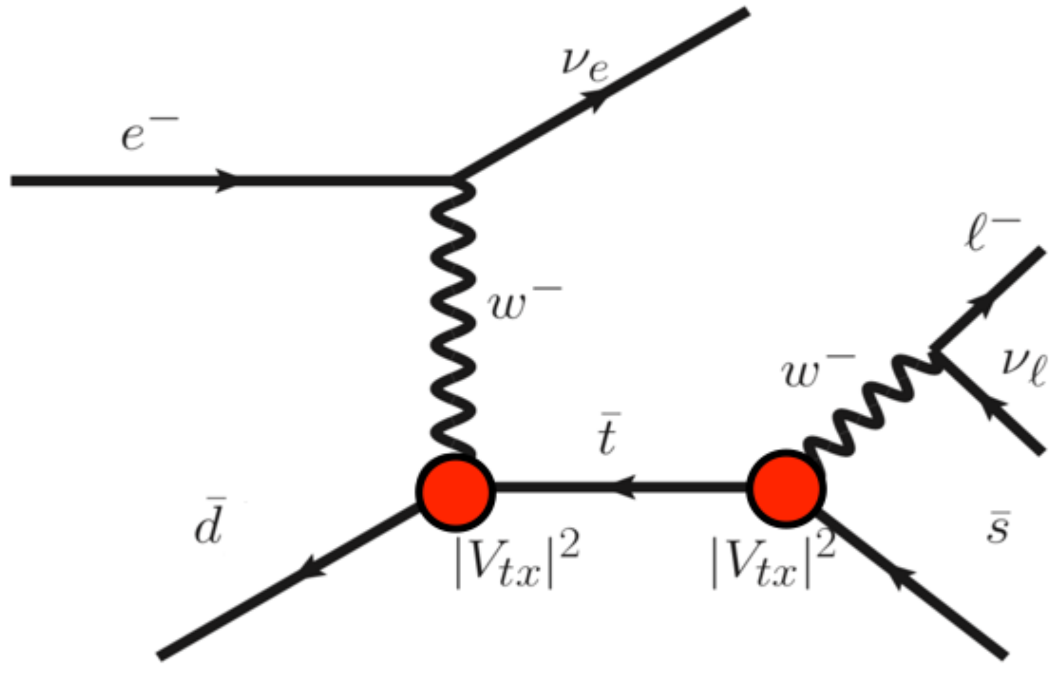
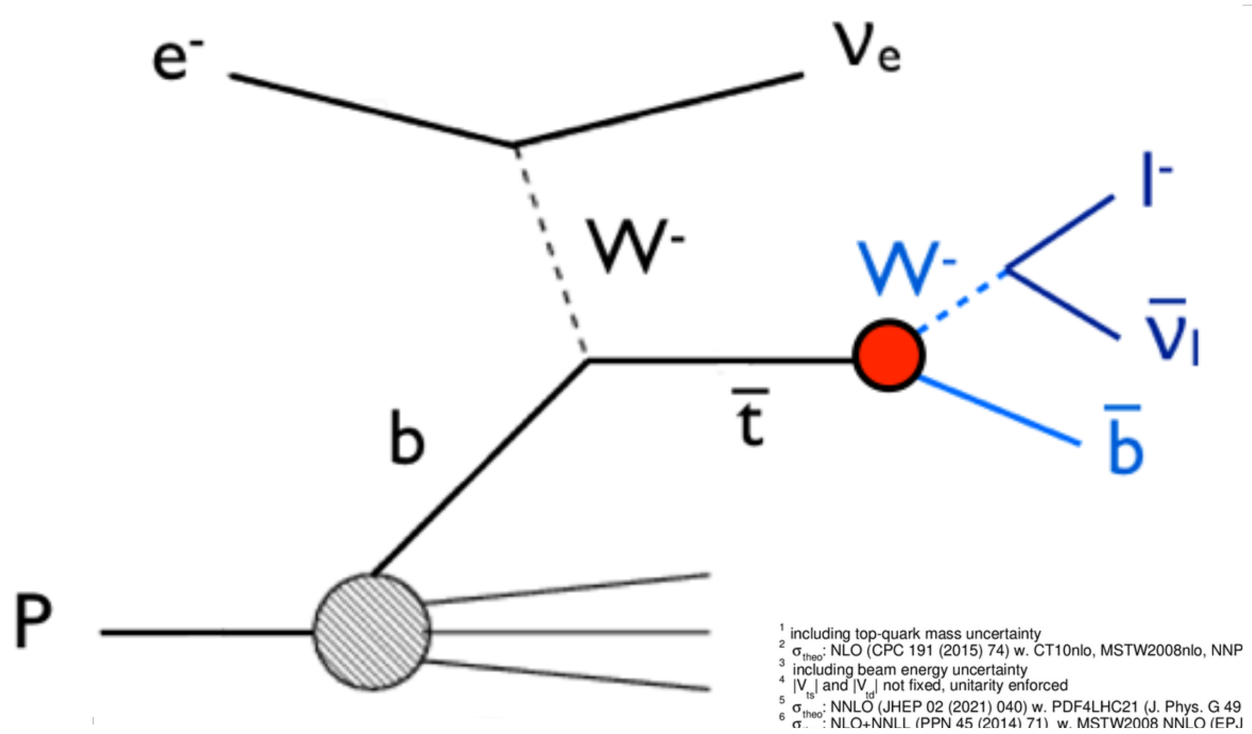
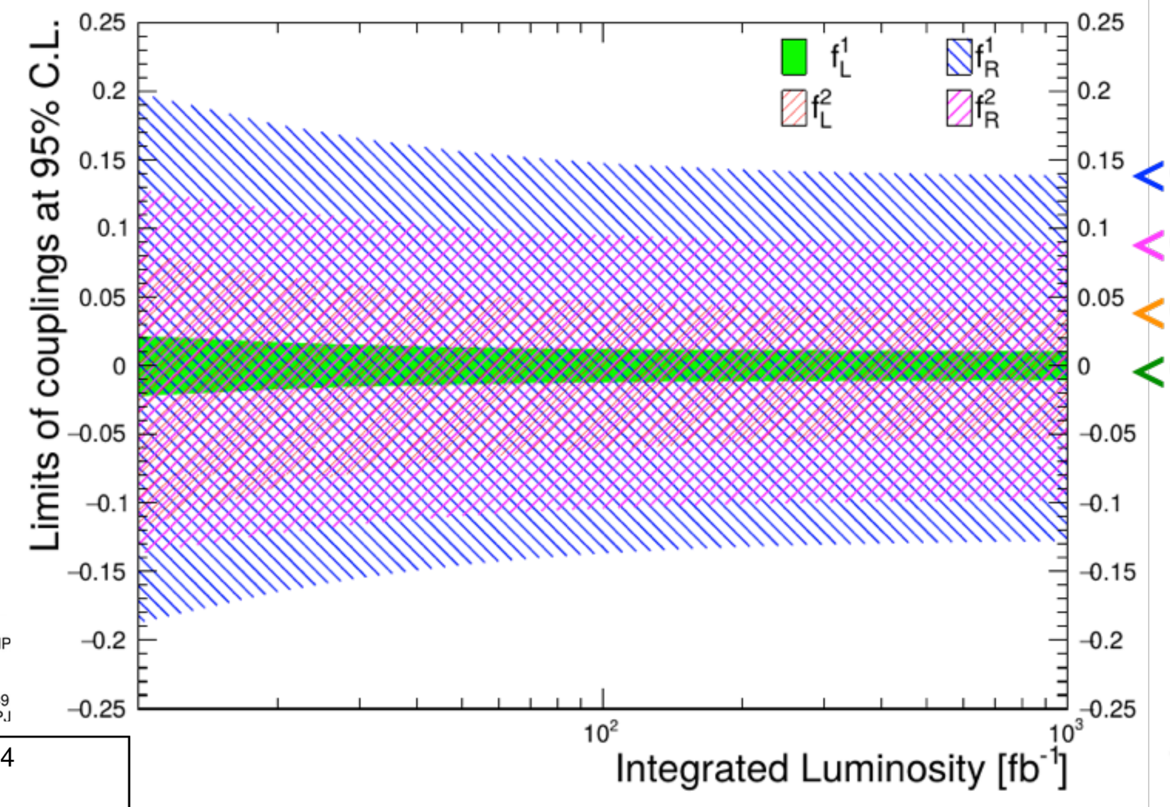


CC DIS top production

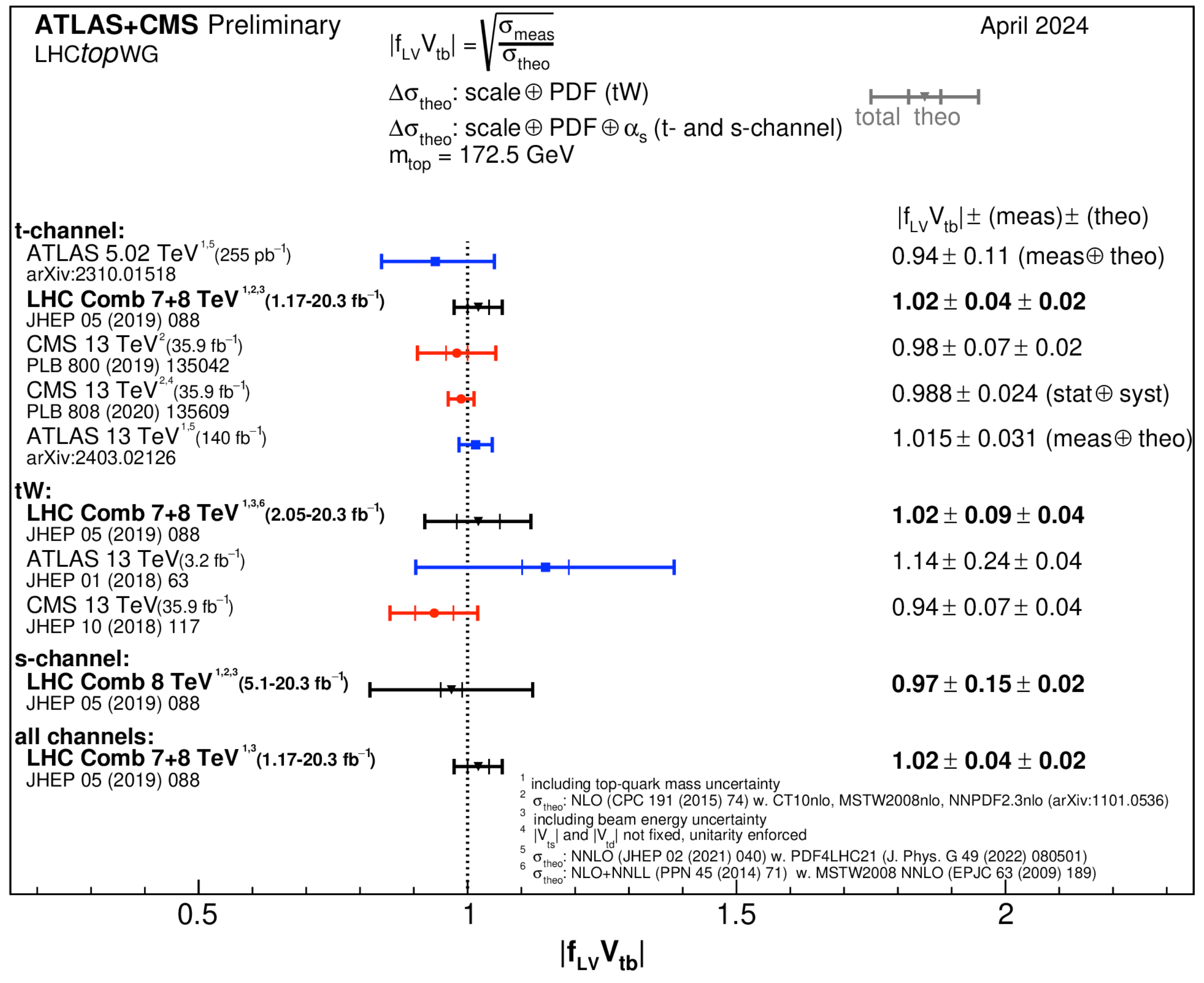


hadronic channel:

LHeC



<0.14
<0.09
<0.04
<0.01



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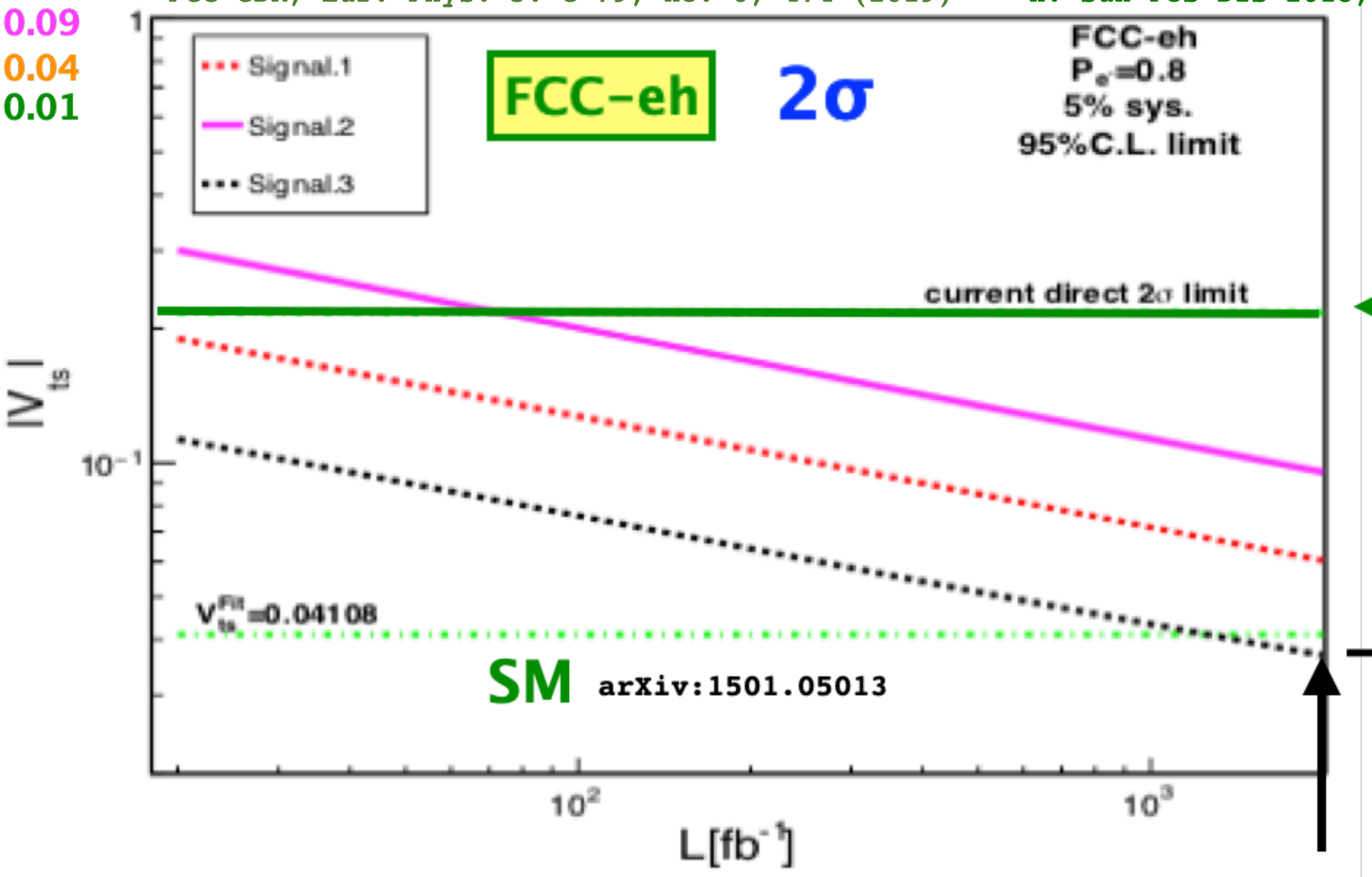
Unprecedented precision < 1%

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

H. Sun PoS DIS 2018, 167 (2018)

FCC-eh **2σ**



arXiv:1501.05013

arXiv:1709.07887

LHC

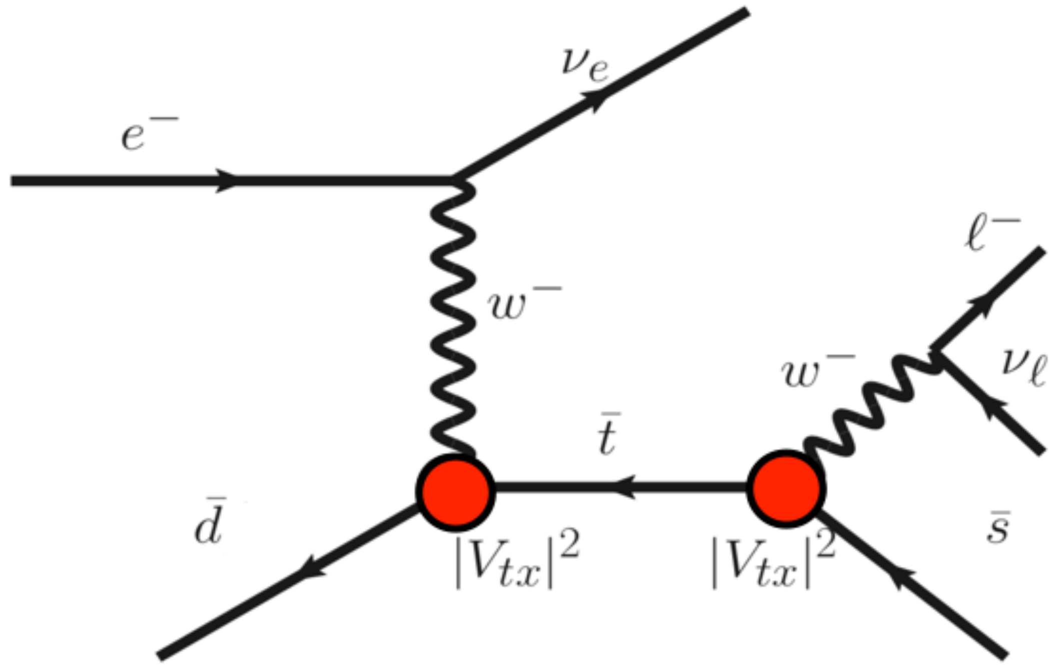
→ $|V_{ts}|<0.037$

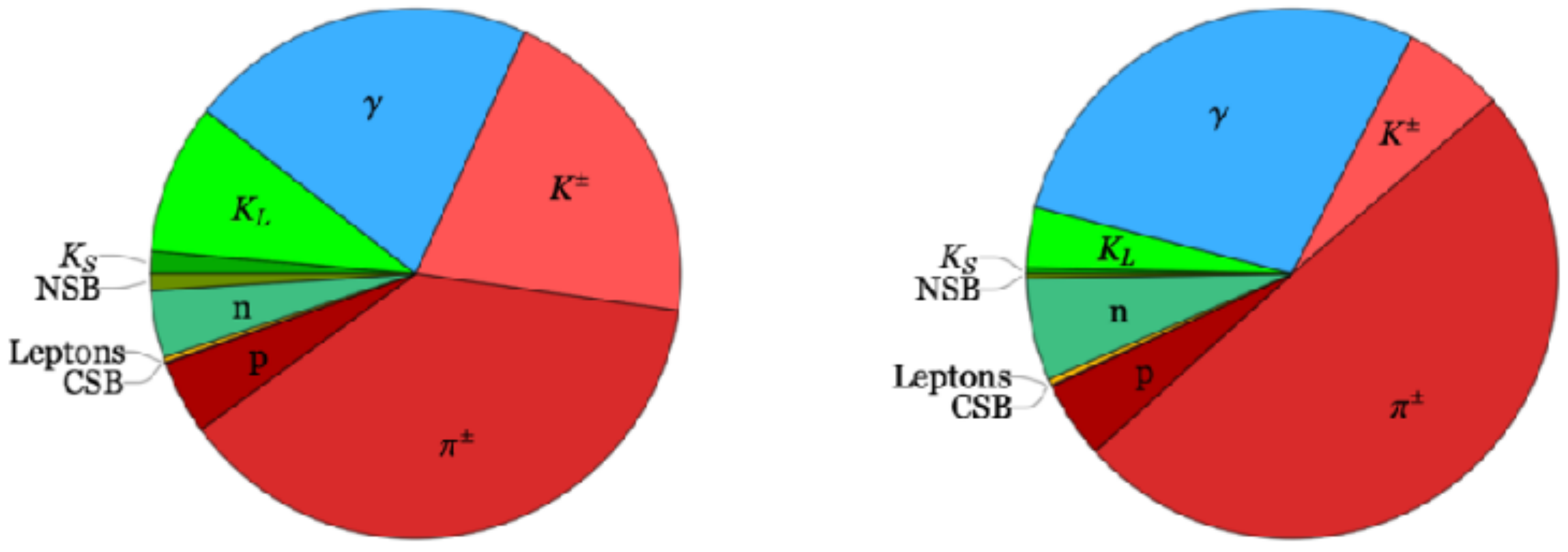
Probing SM prediction directly for the first time

Expected measurements of Wts couplings

strange tagging

arXiv:2003.09517 [hep-ph]





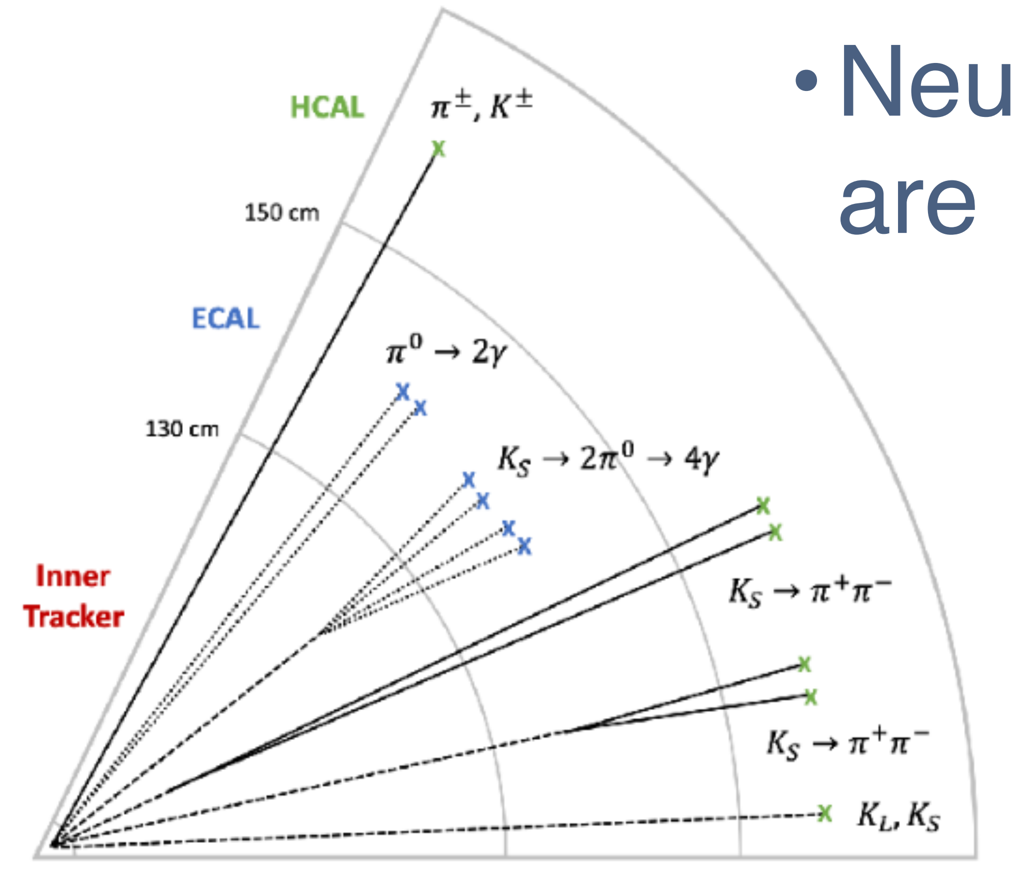
Momentum fraction

Strange $p_T = 45\,\mathrm{GeV}$ Down $p_T = 45\,\mathrm{GeV}$

FCC-ee

- Higher fraction of momentum carried by **kaons**

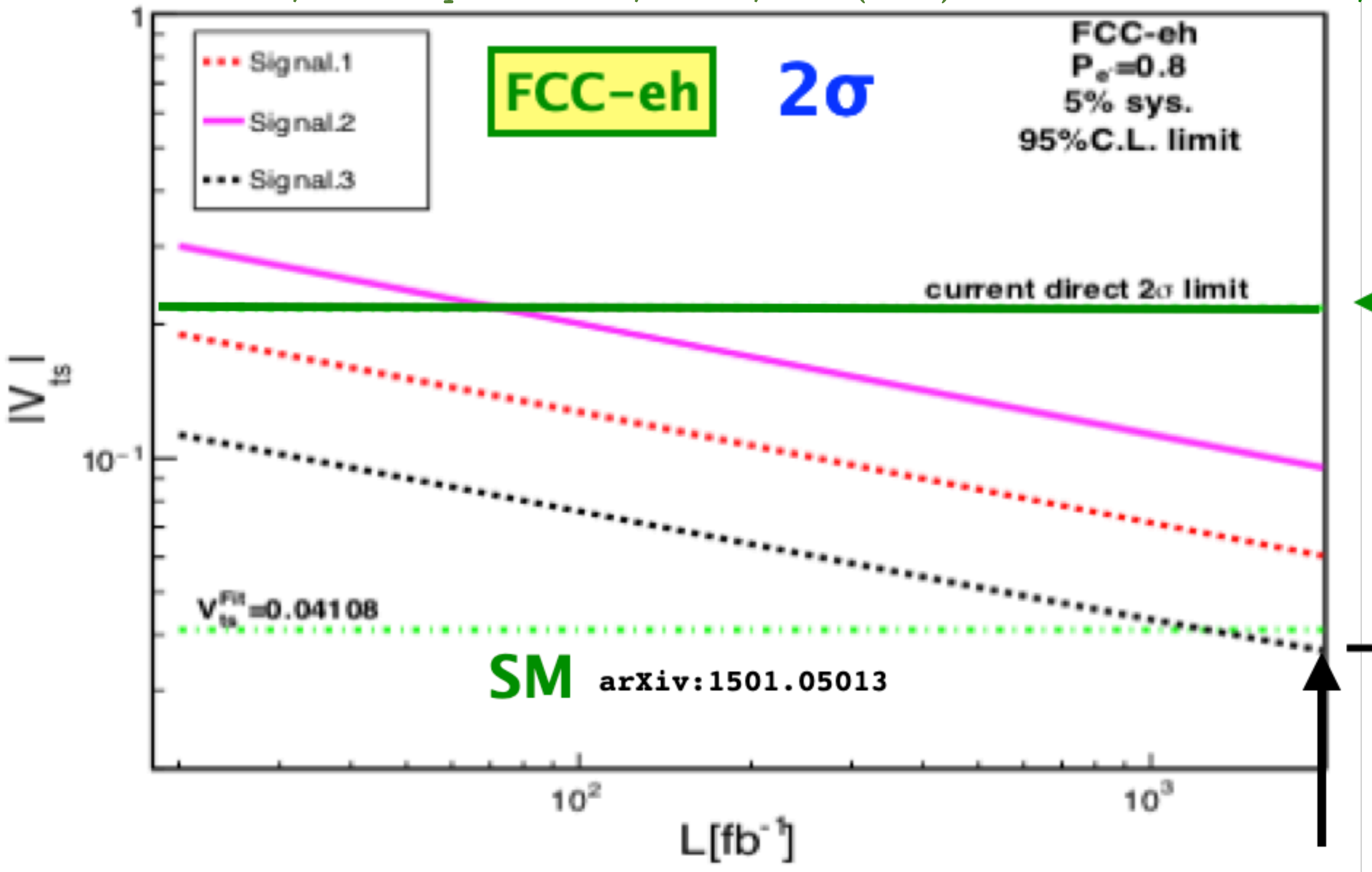
Not to scale



s-baryons Λ, Σ, Ξ have $c\tau \approx 1 - 10$ cm

- Neutral kaons and s-baryons are long-lived
- As $B(t \to Ws) \propto |V_{ts}|^2$ expect $\sigma(|V_{ts}|) \sim 10\%$
- more work to be done on pheno impacs

FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019) H. Sun PoS DIS 2018, 167 (2018)



arXiv:1709.07887

LHC

→ $|V_{ts}|<0.037$

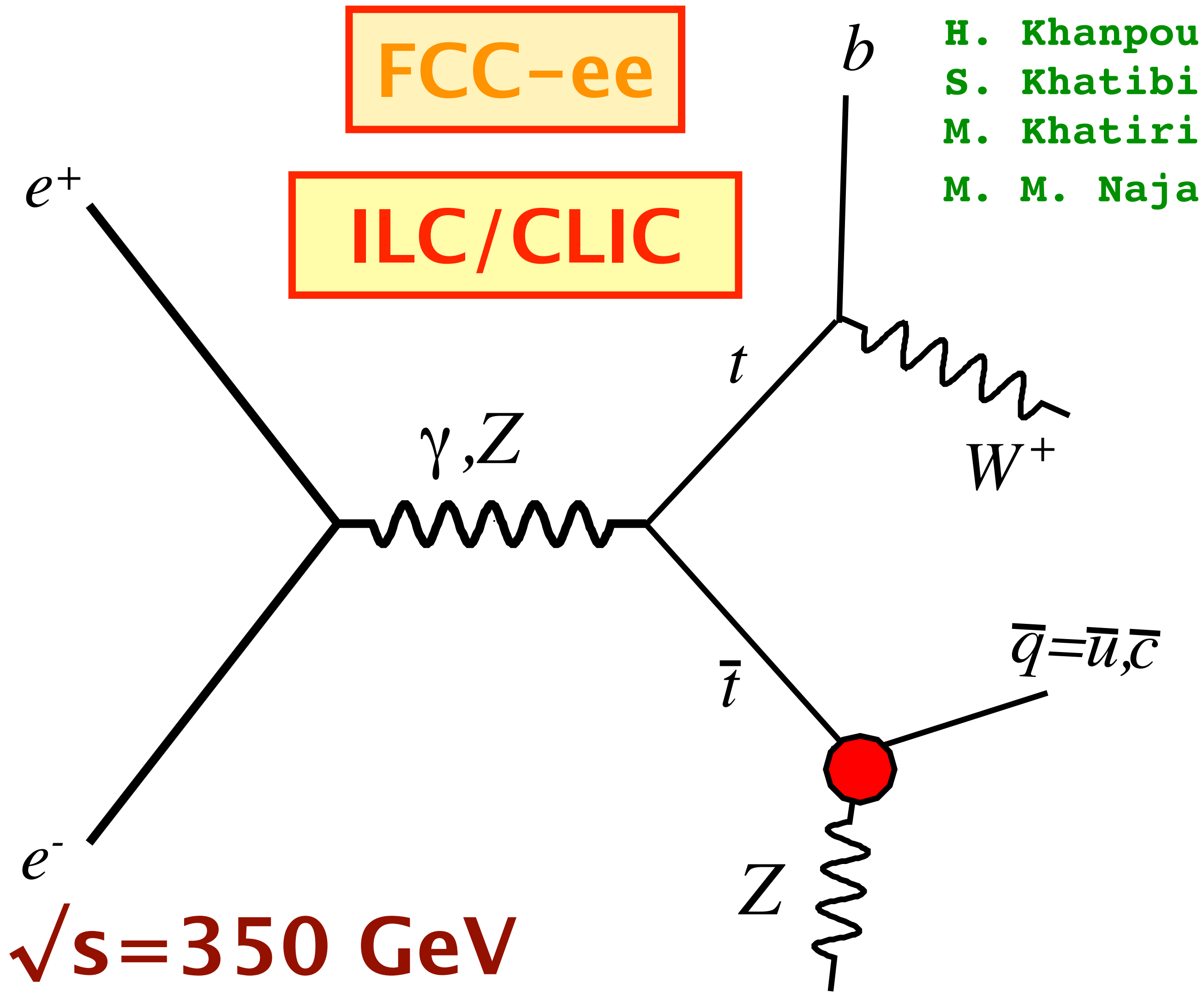
Probing SM prediction directly for the first time

Flavor Changing Neutral Current Couplings

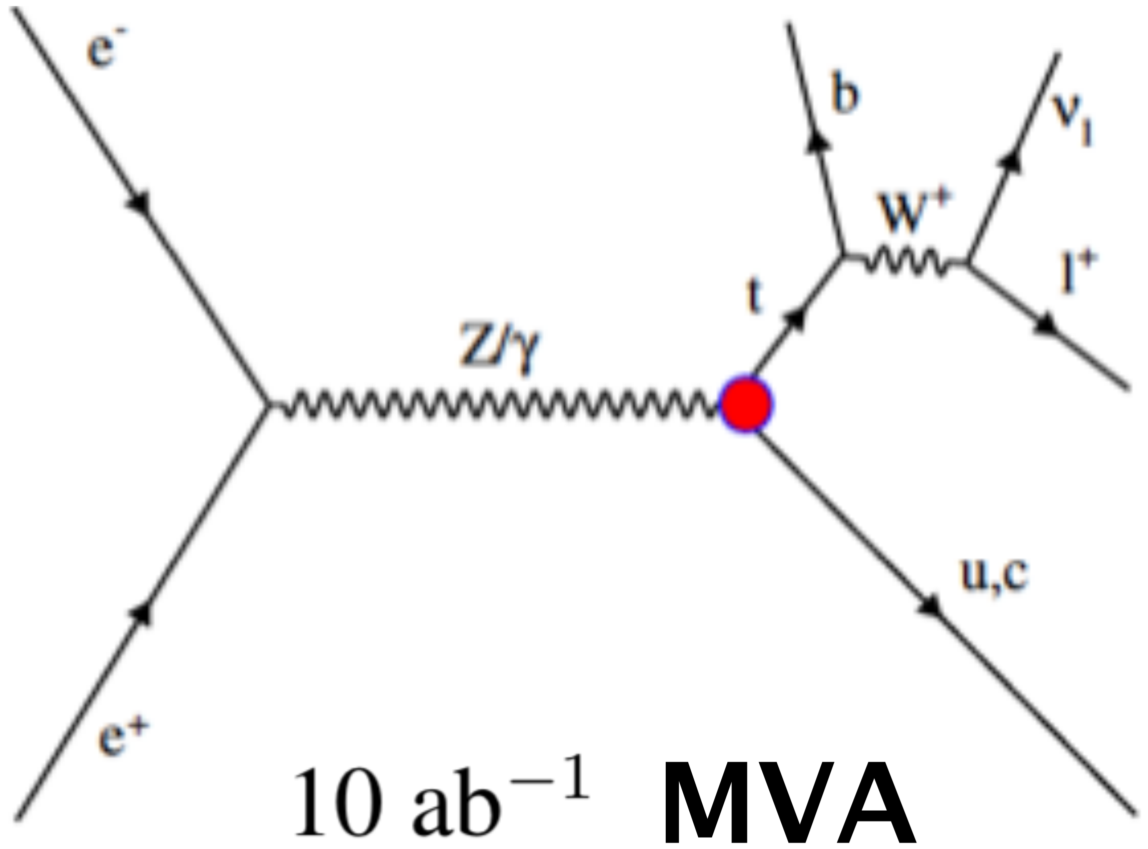
FCC-ee

ILC/CLIC

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



$\sqrt{s}=350$ GeV



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

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

$Br(t\to q\gamma)$, $Br(t\to qZ) < O(10^{-6}-10^{-5})$

Flavor Changing Neutral Current Couplings

FCC-ee

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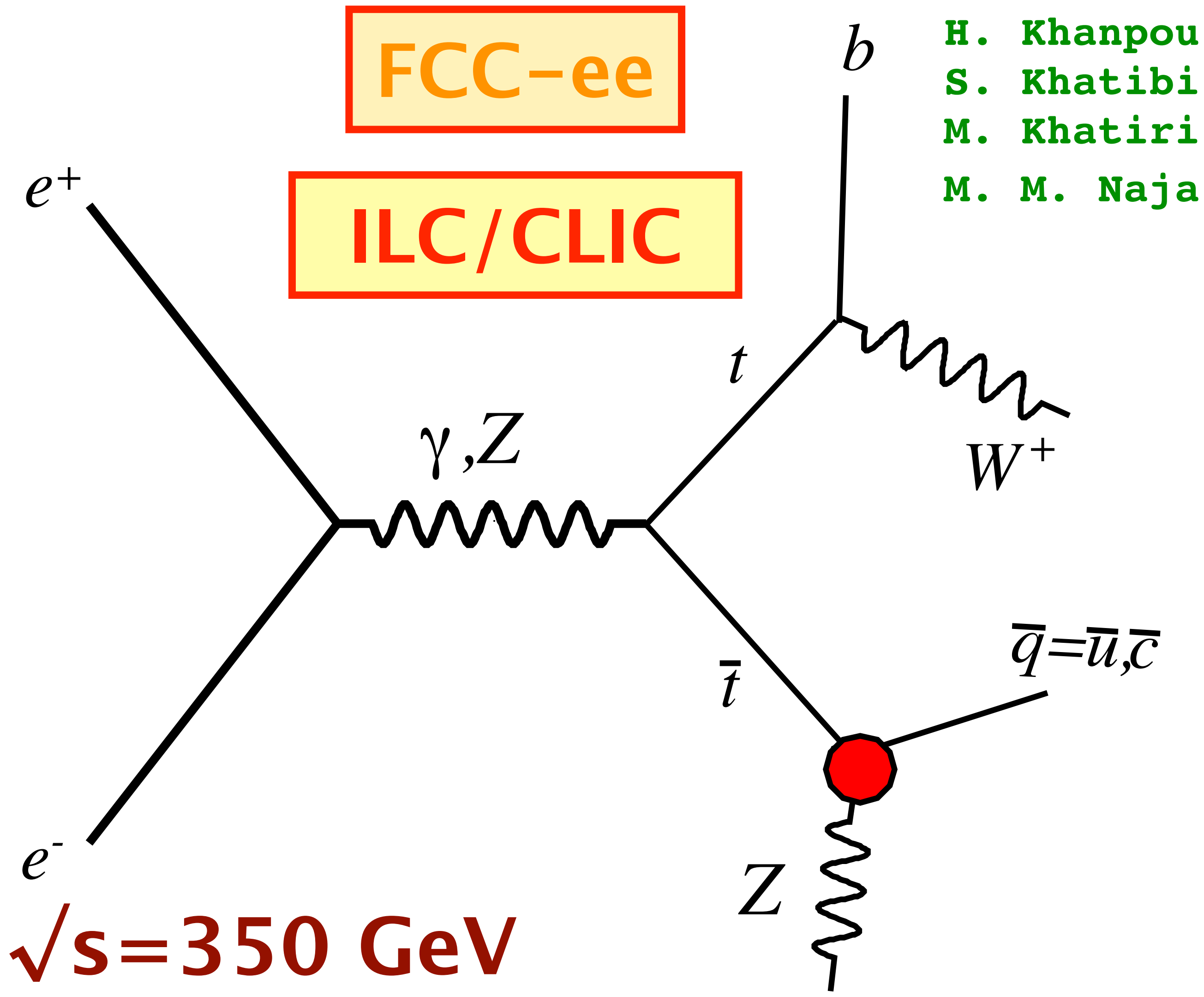

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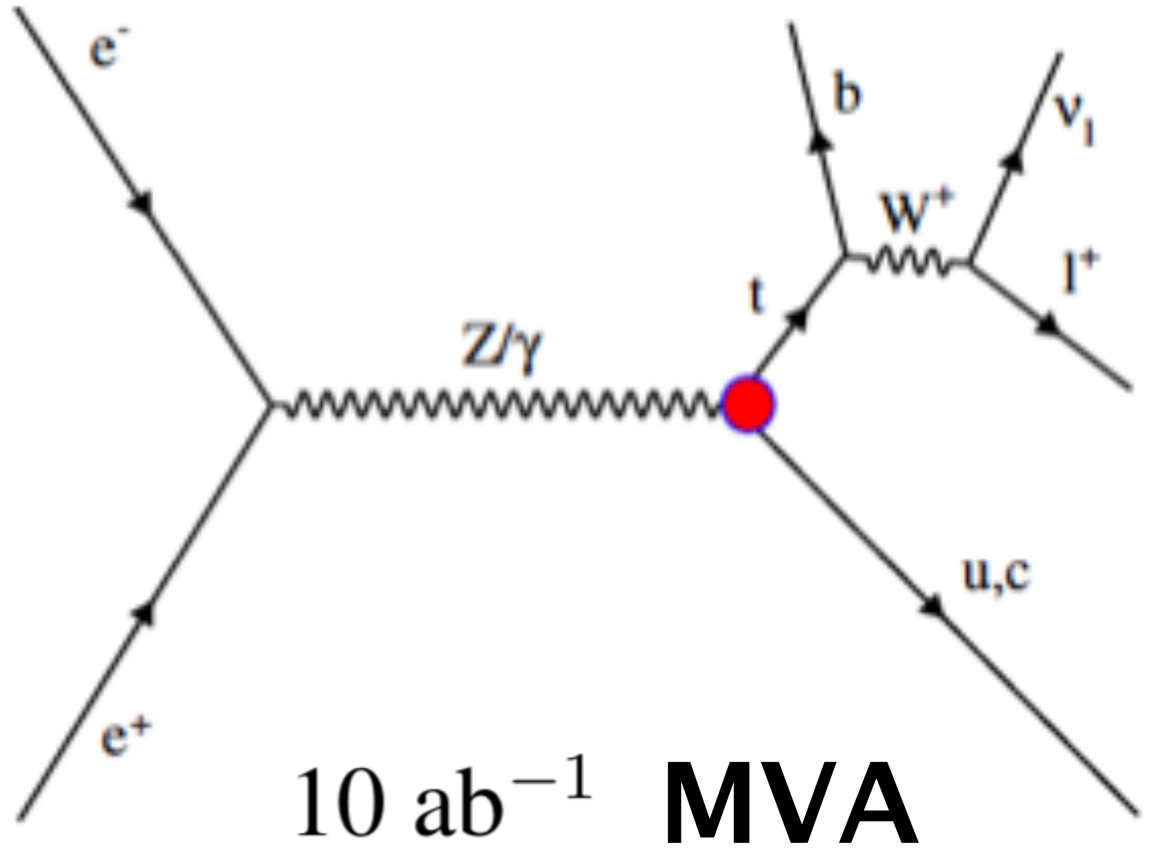
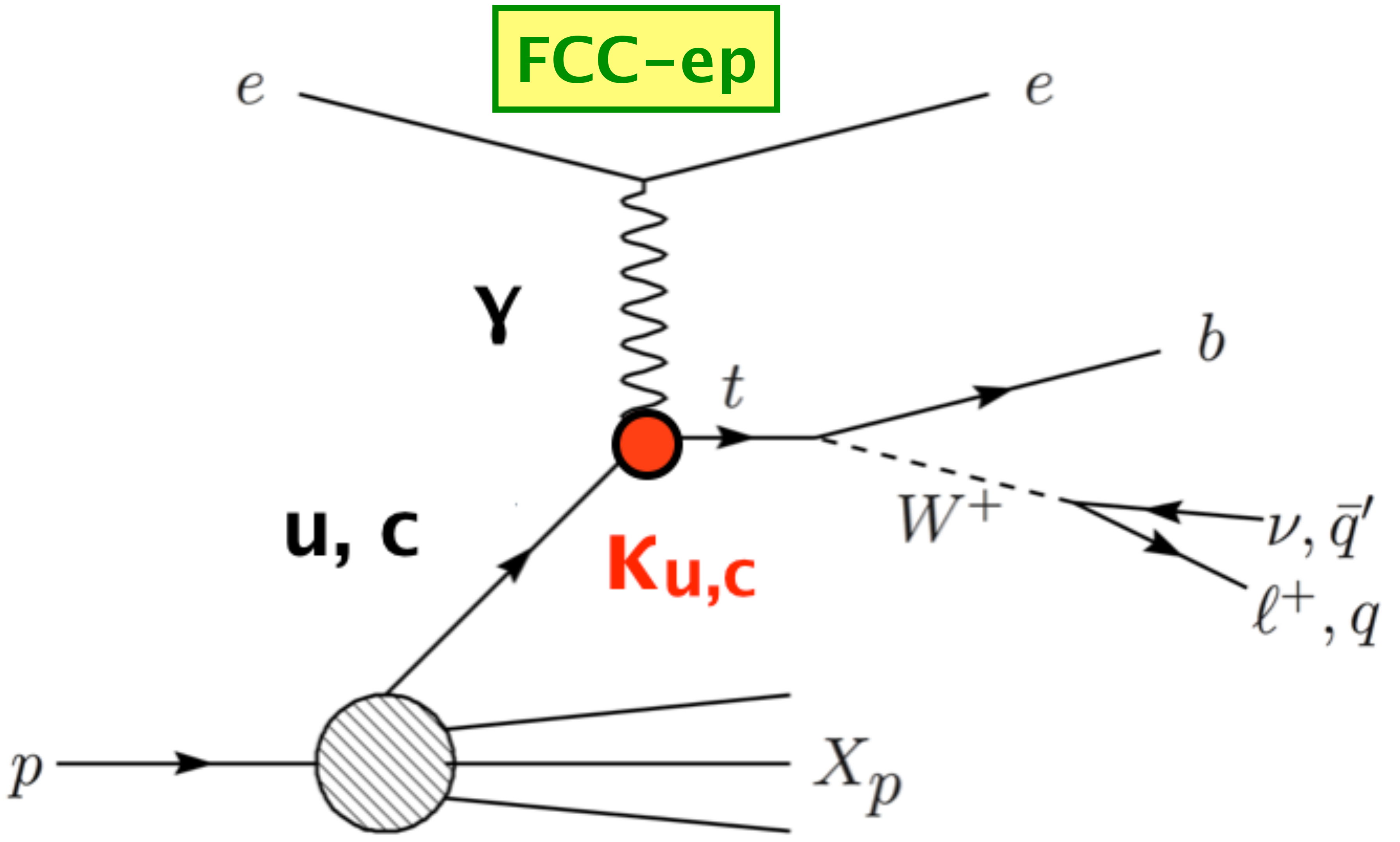


$10\ \mathrm{ab}^{-1}$ **MVA**

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

FCC-ep

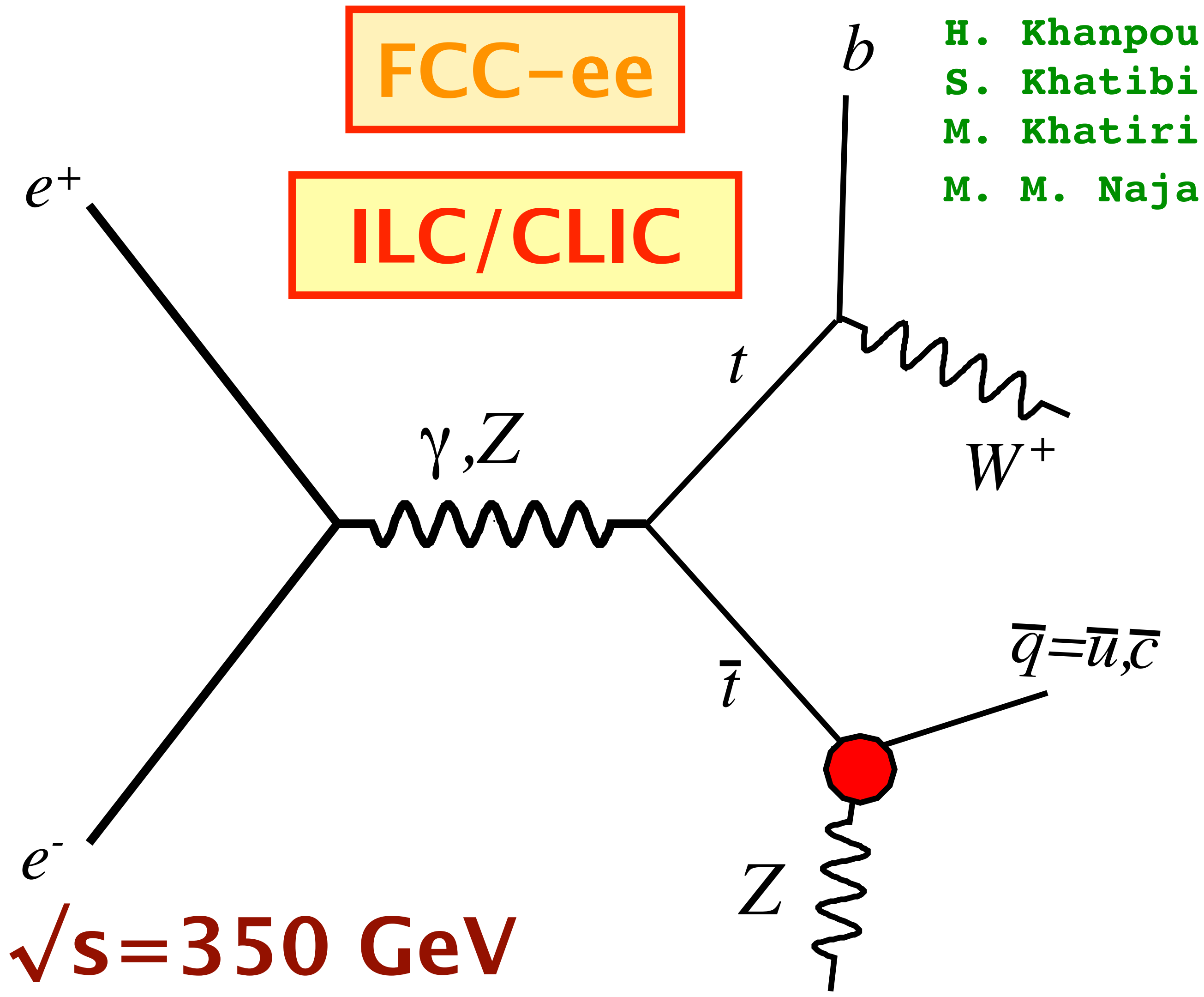


Br(t→qγ), Br(t→qZ)<O(10^{-6}–10^{-5})

Flavor Changing Neutral Current Couplings

FCC-ee

ILC/CLIC



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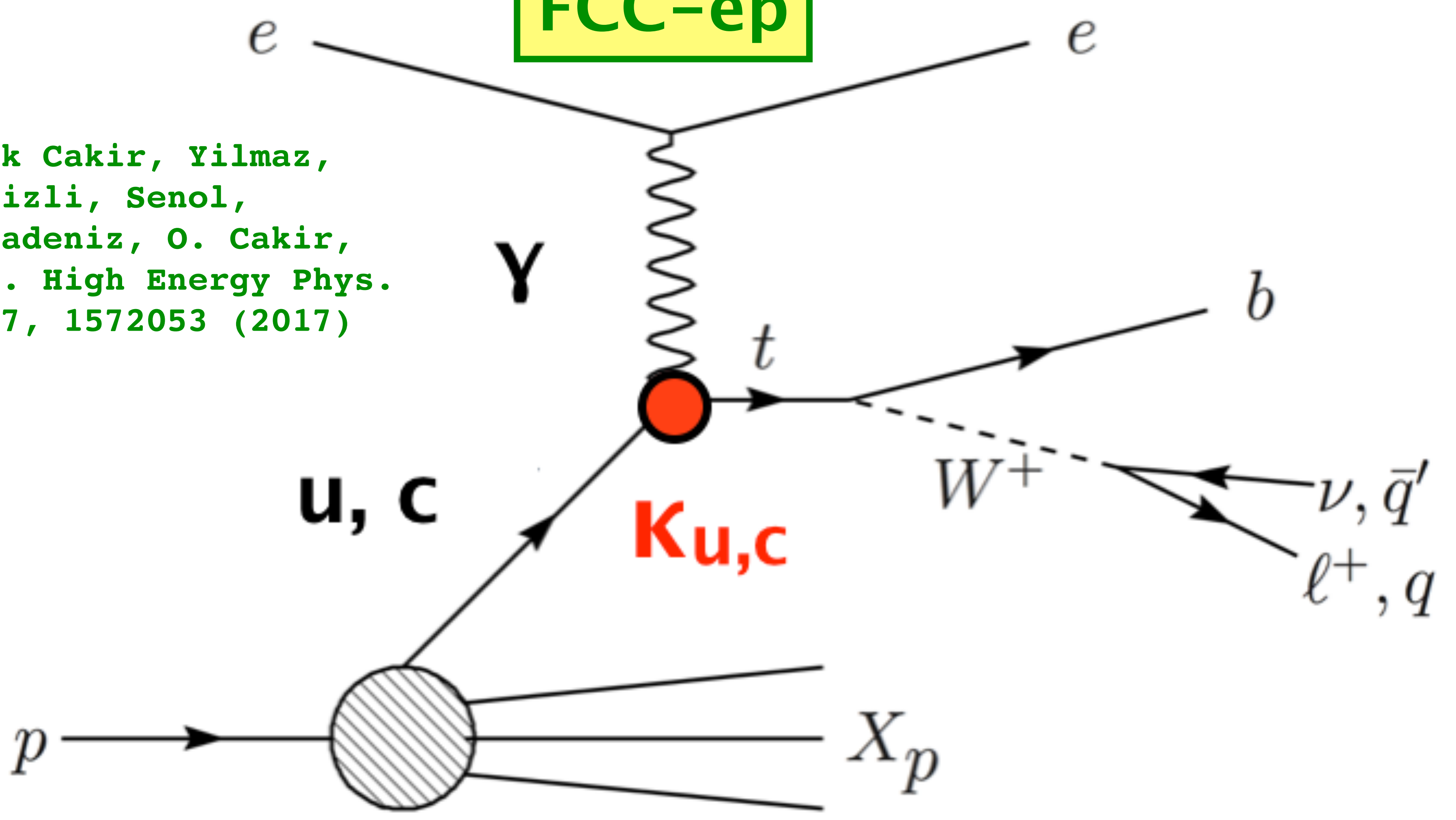
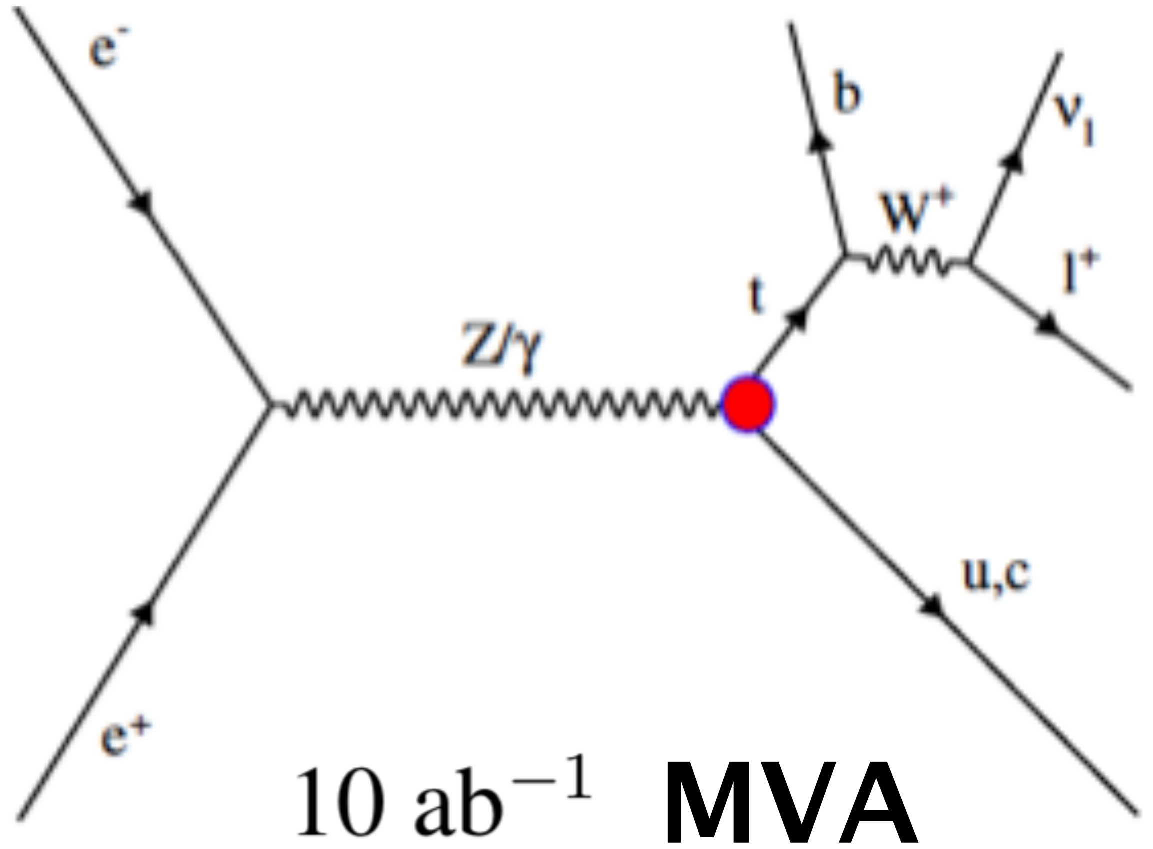
Turk Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)

FCC-ep



$\sqrt{s}$=350 GeV



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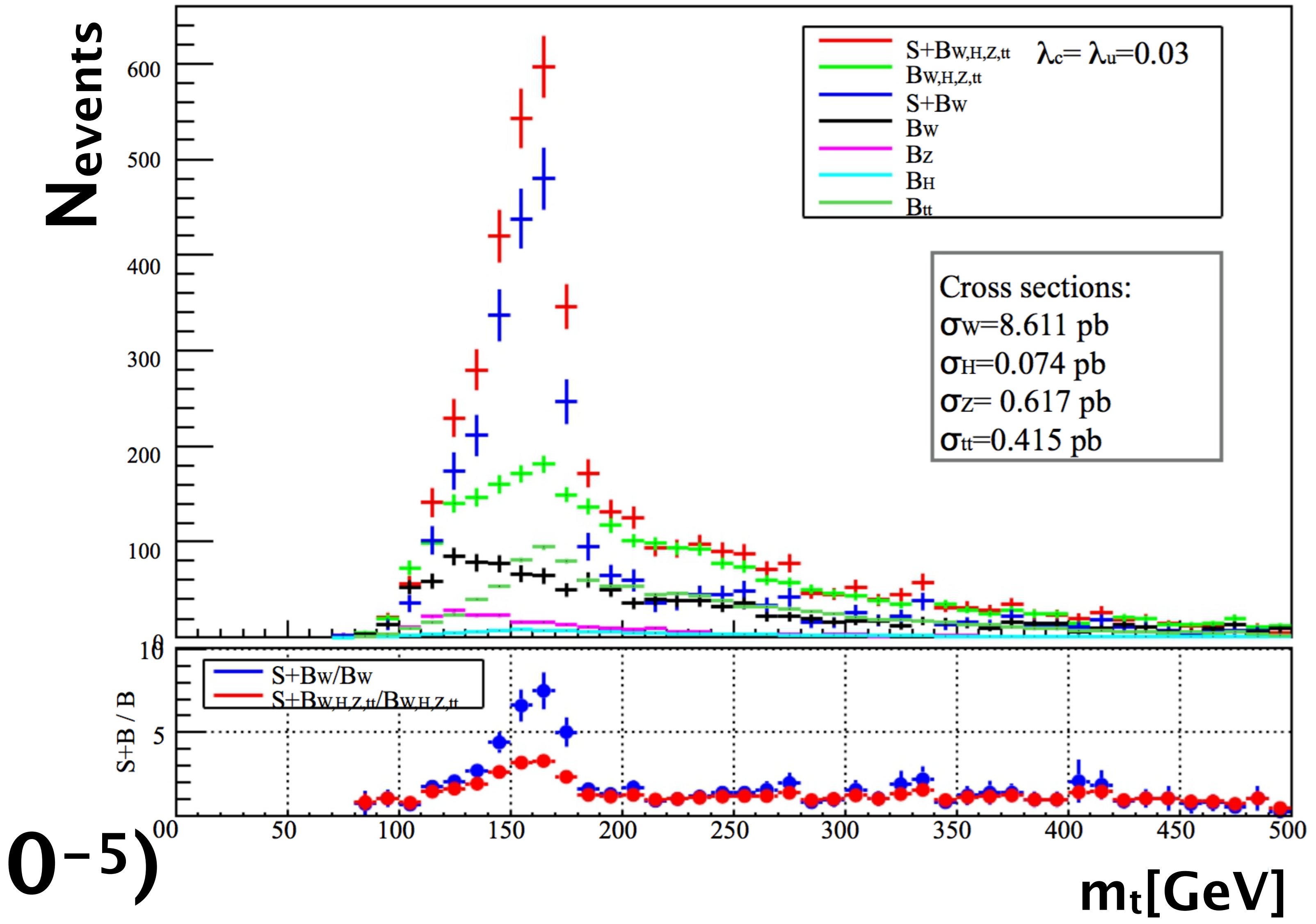
$\sqrt{s}$=240 GeV and $\sqrt{s}$=350 GeV

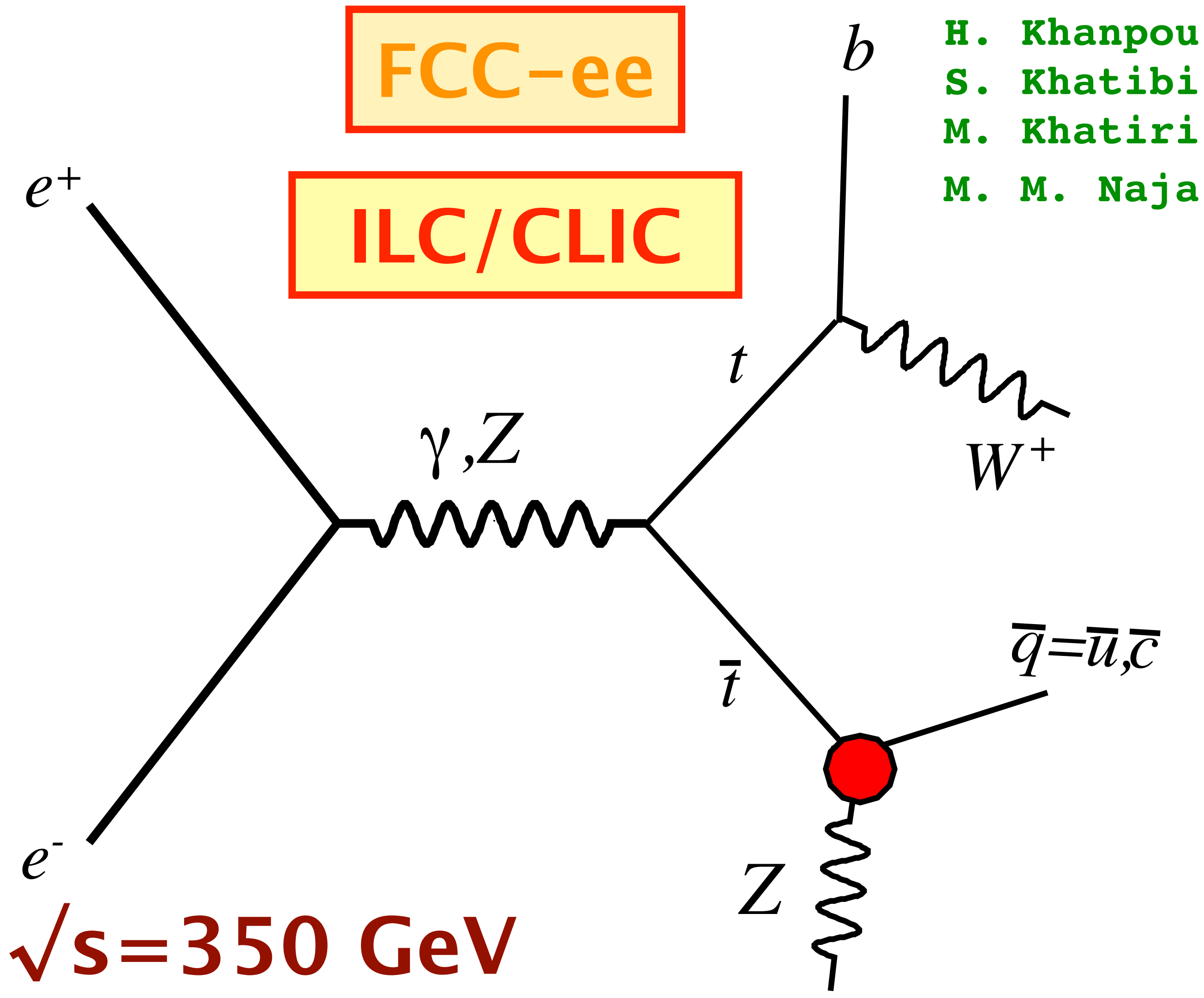


Br(t→qγ), Br(t→qZ)<O(10^{-6}–10^{-5})

Flavor Changing Neutral Current Couplings

FCC-ee

ILC/CLIC



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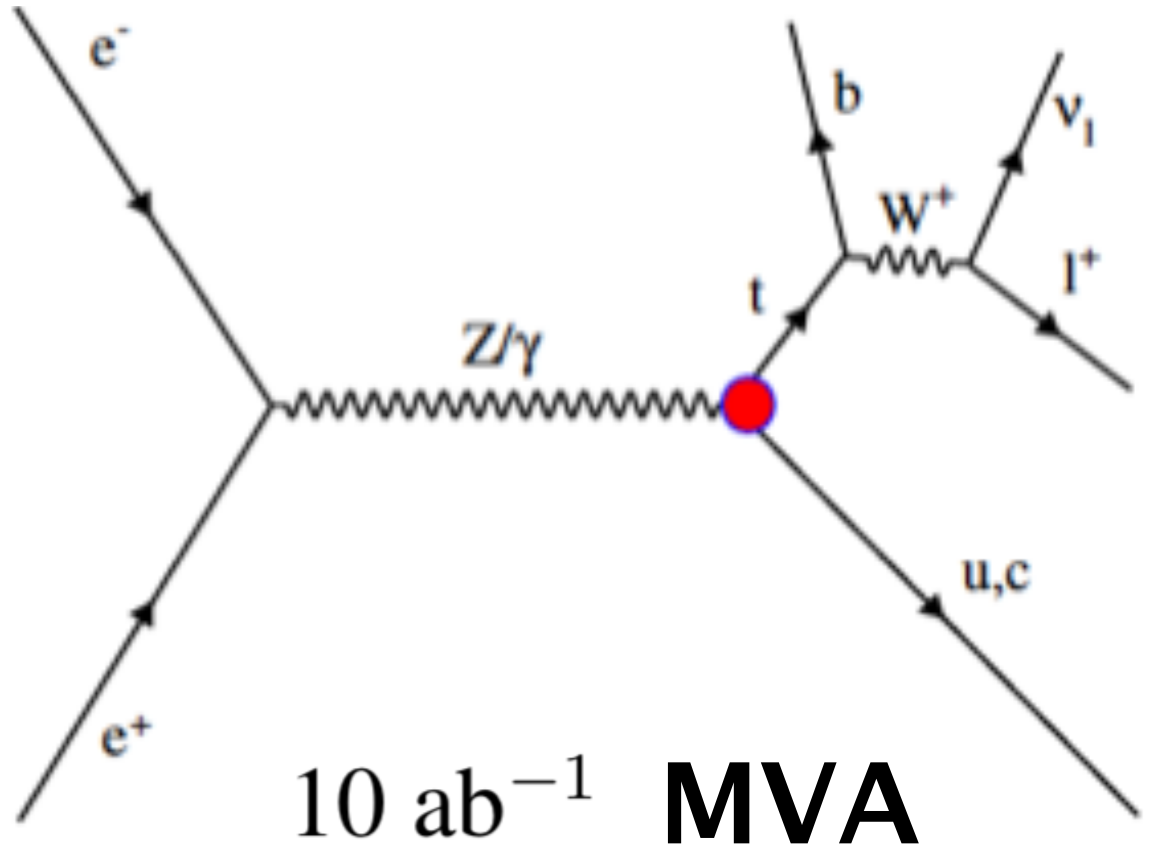
$\sqrt{s}$=350 GeV



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FCC-ep

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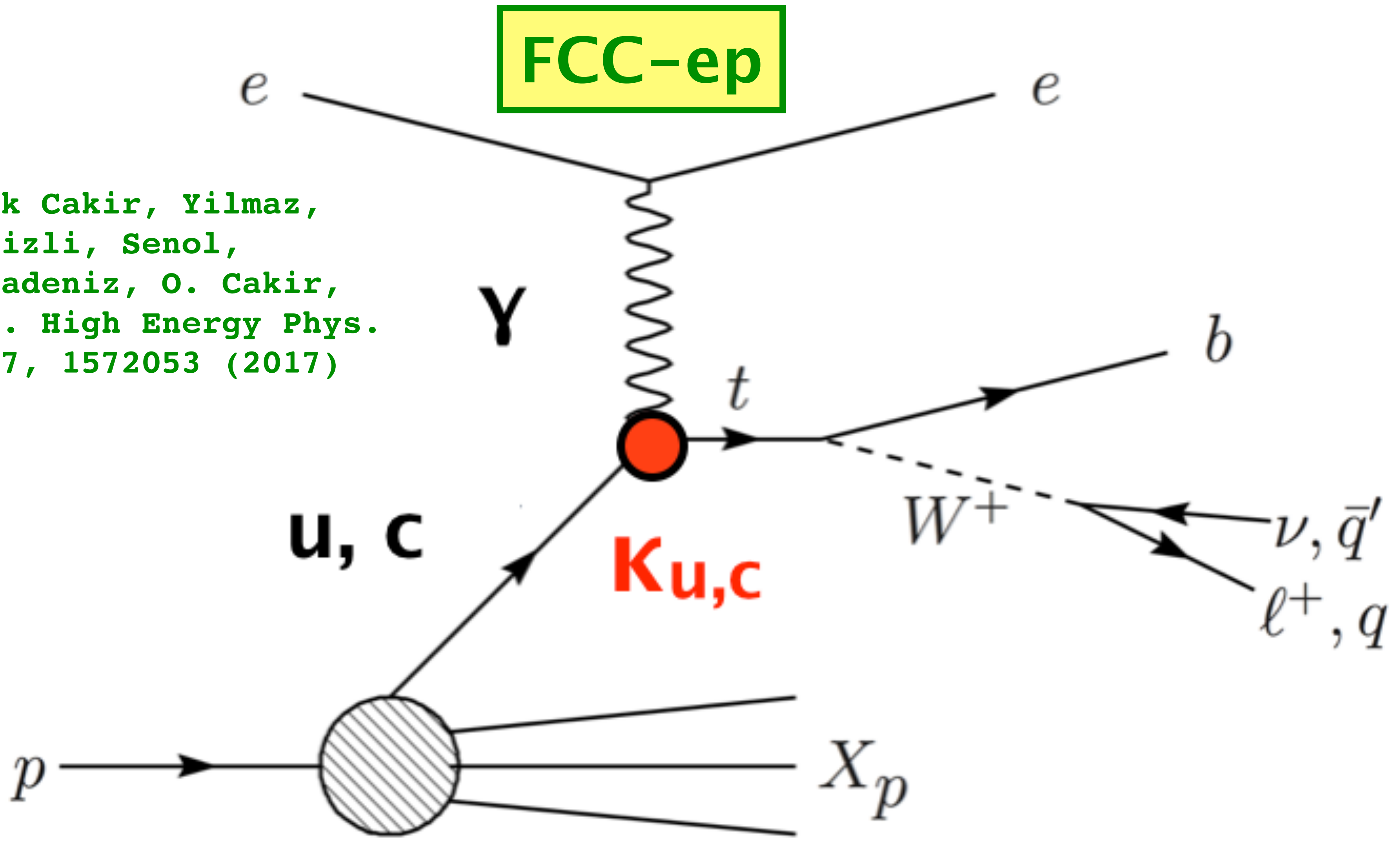
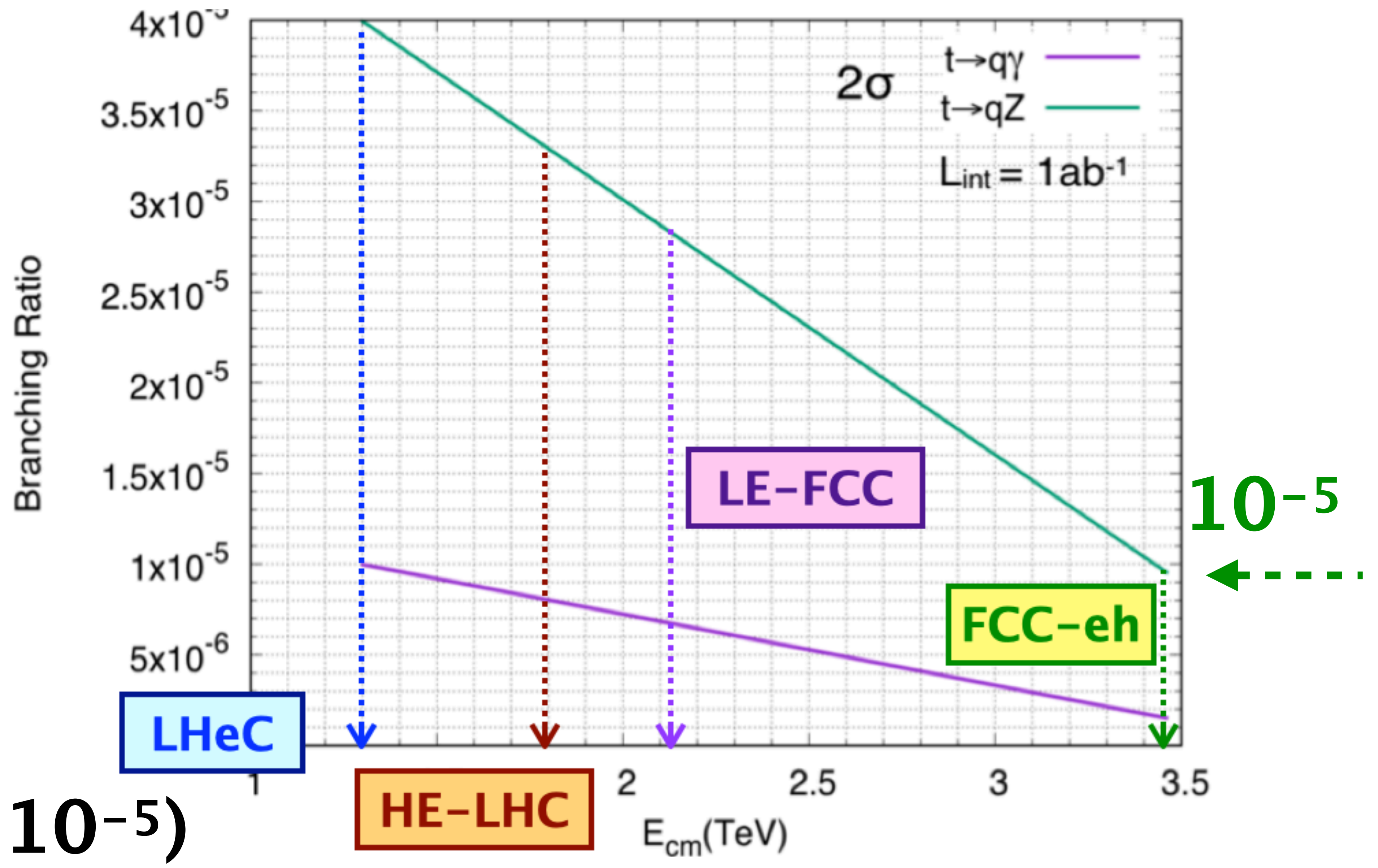




LE-FCC

FCC-eh

LHeC

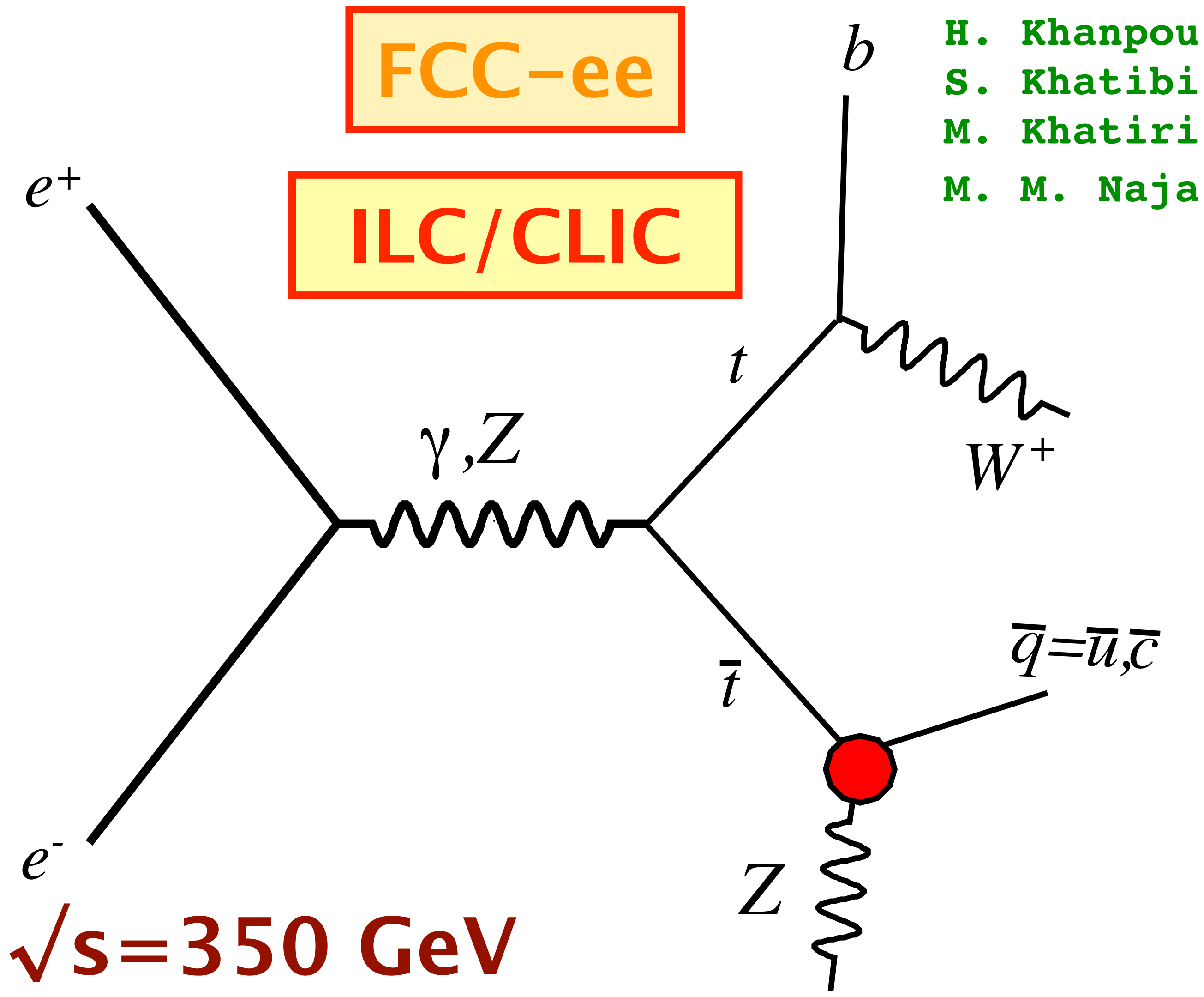
HE-LHC

10^{-5}

Flavor Changing Neutral Current Couplings

FCC-ee

ILC/CLIC



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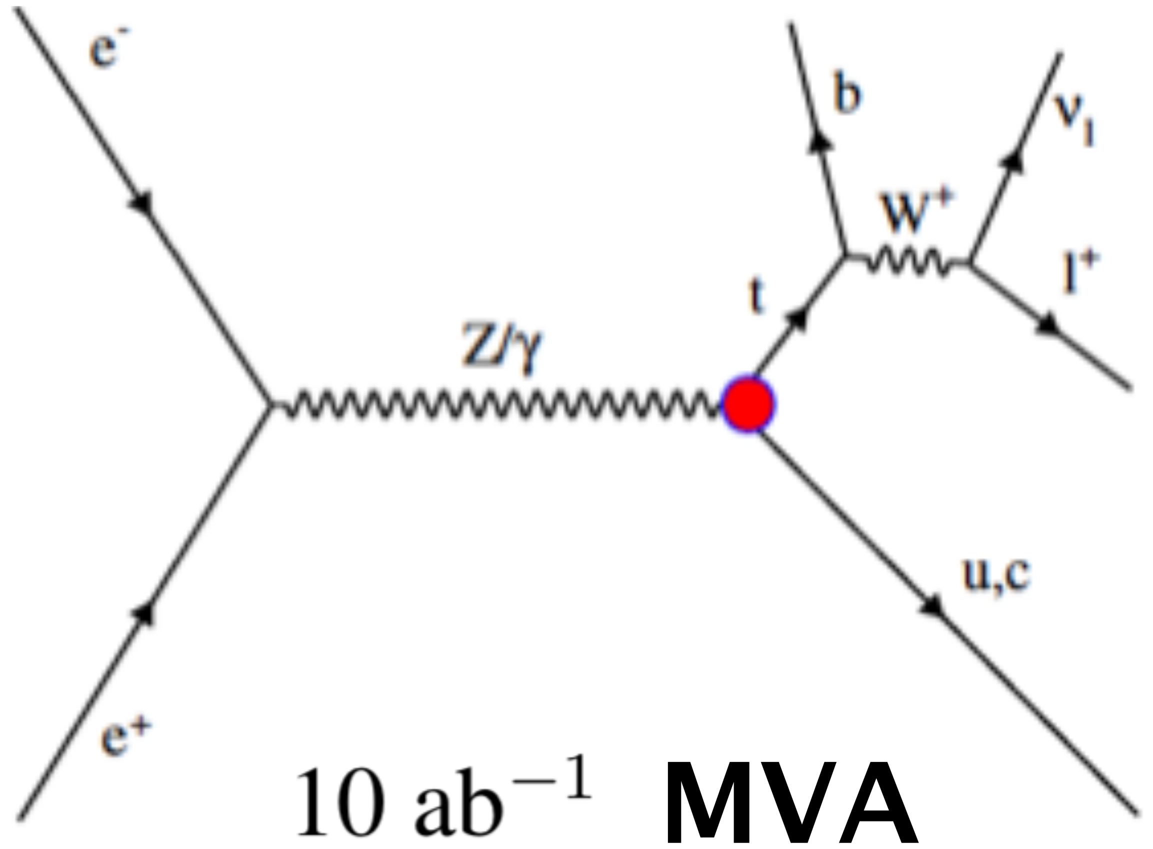
$\sqrt{s}$=350 GeV

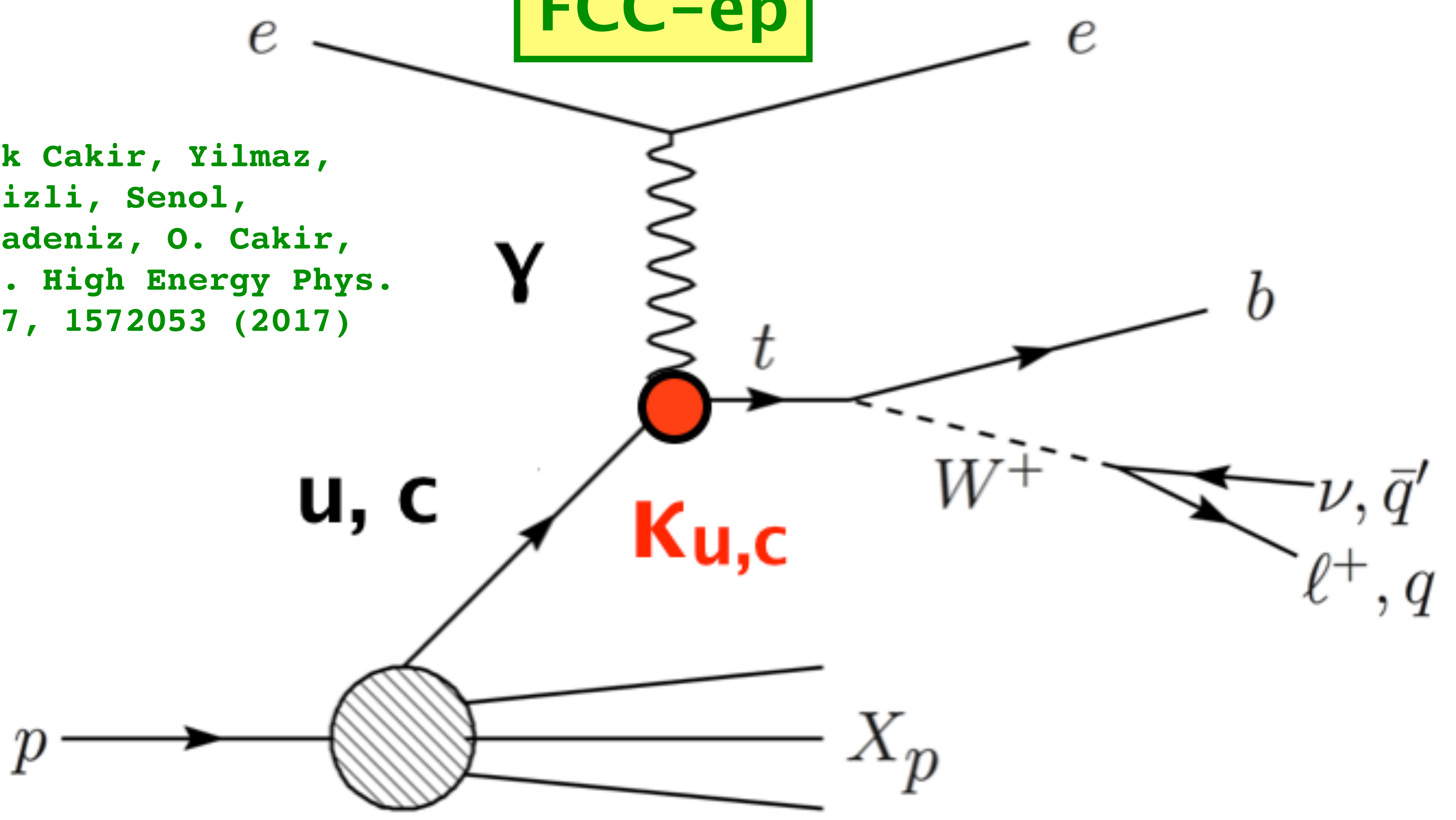


$10\ \mathrm{ab}^{-1}$ **MVA**

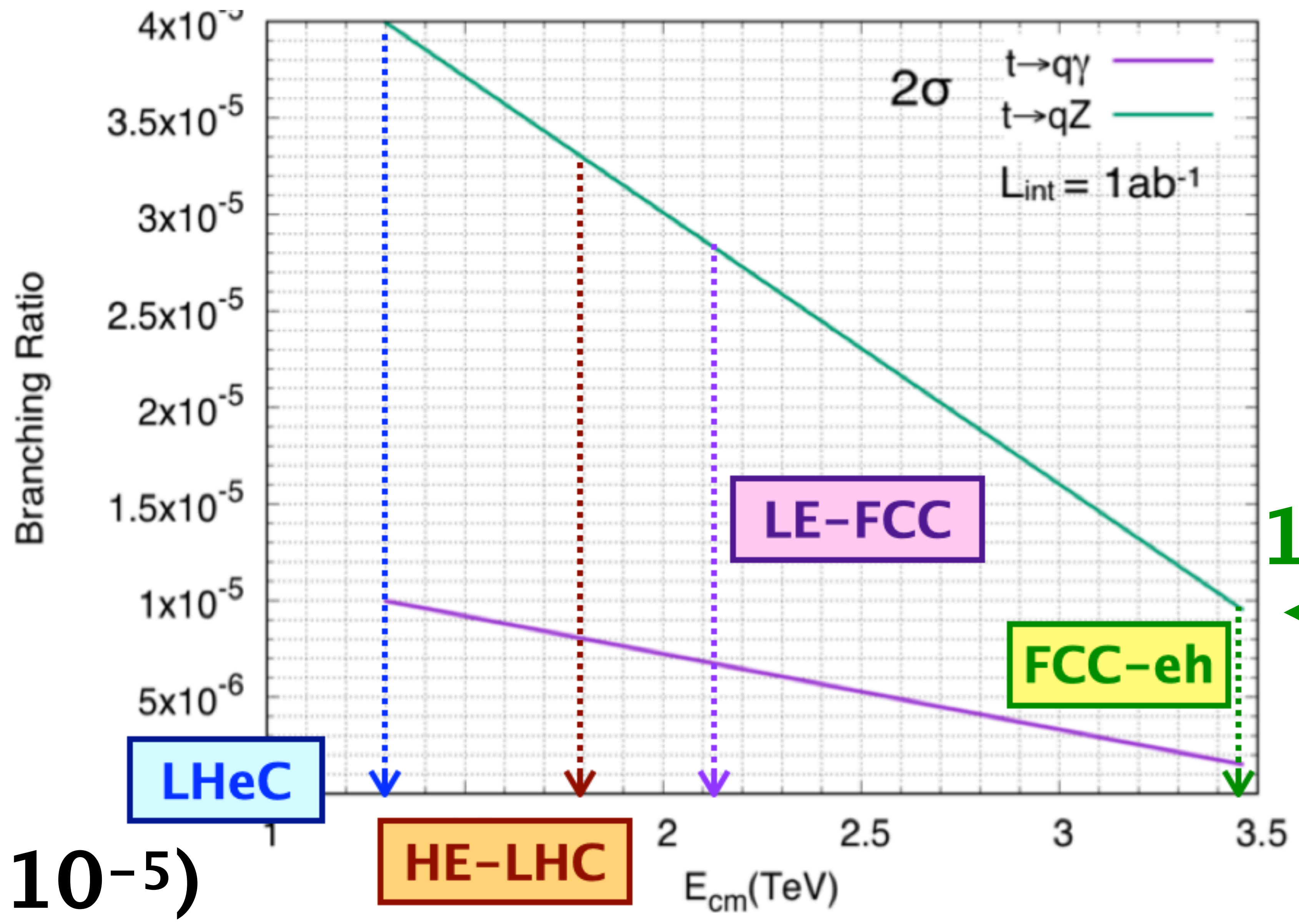
$\sqrt{s}$=240 GeV and $\sqrt{s}$=350 GeV

Br(t→qγ), Br(t→qZ)<O(10^{-6}–10^{-5})

FCC-ep

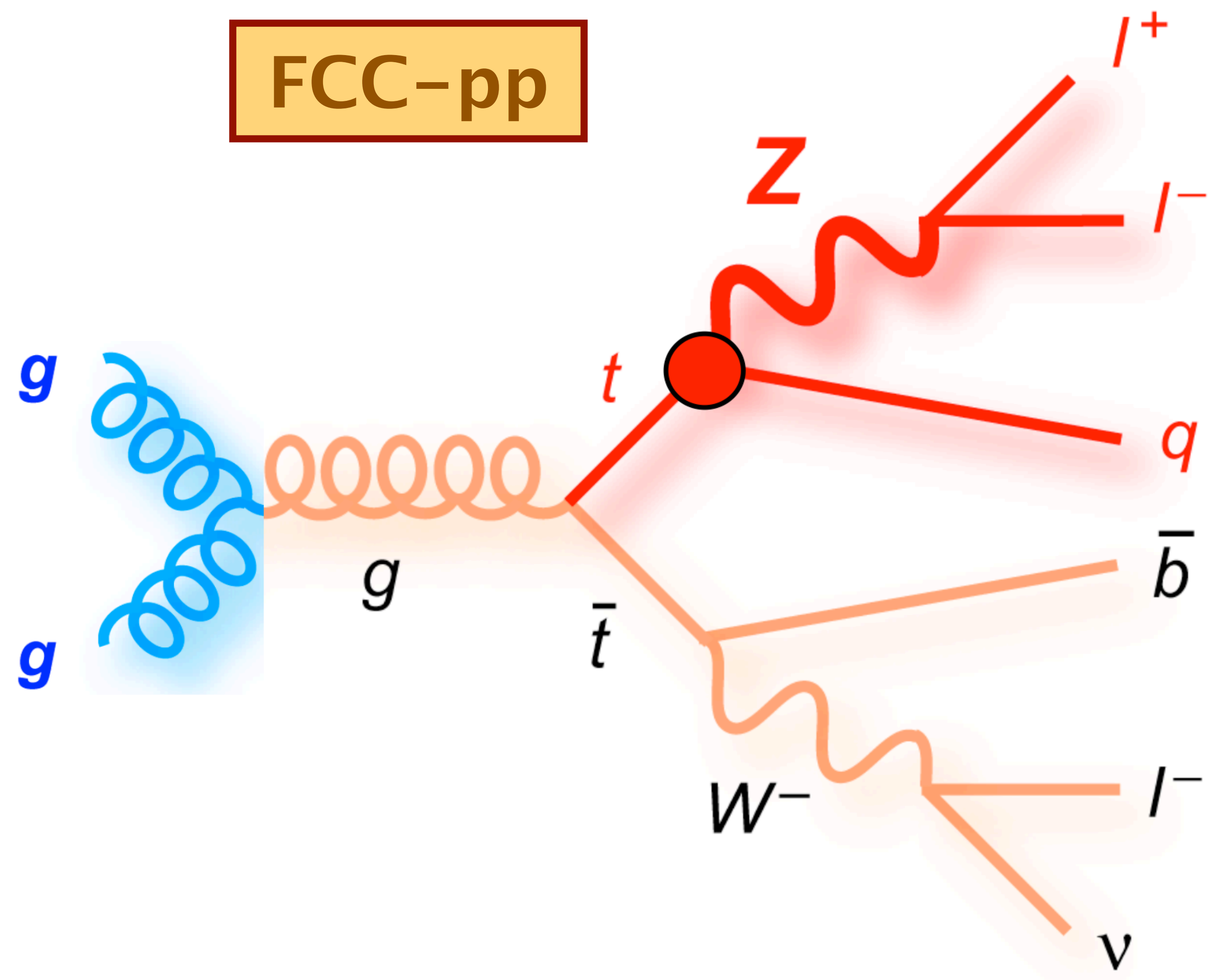


Turk Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)



10^{-5}

FCC-pp



Br(t→qZ)<10^{-7}

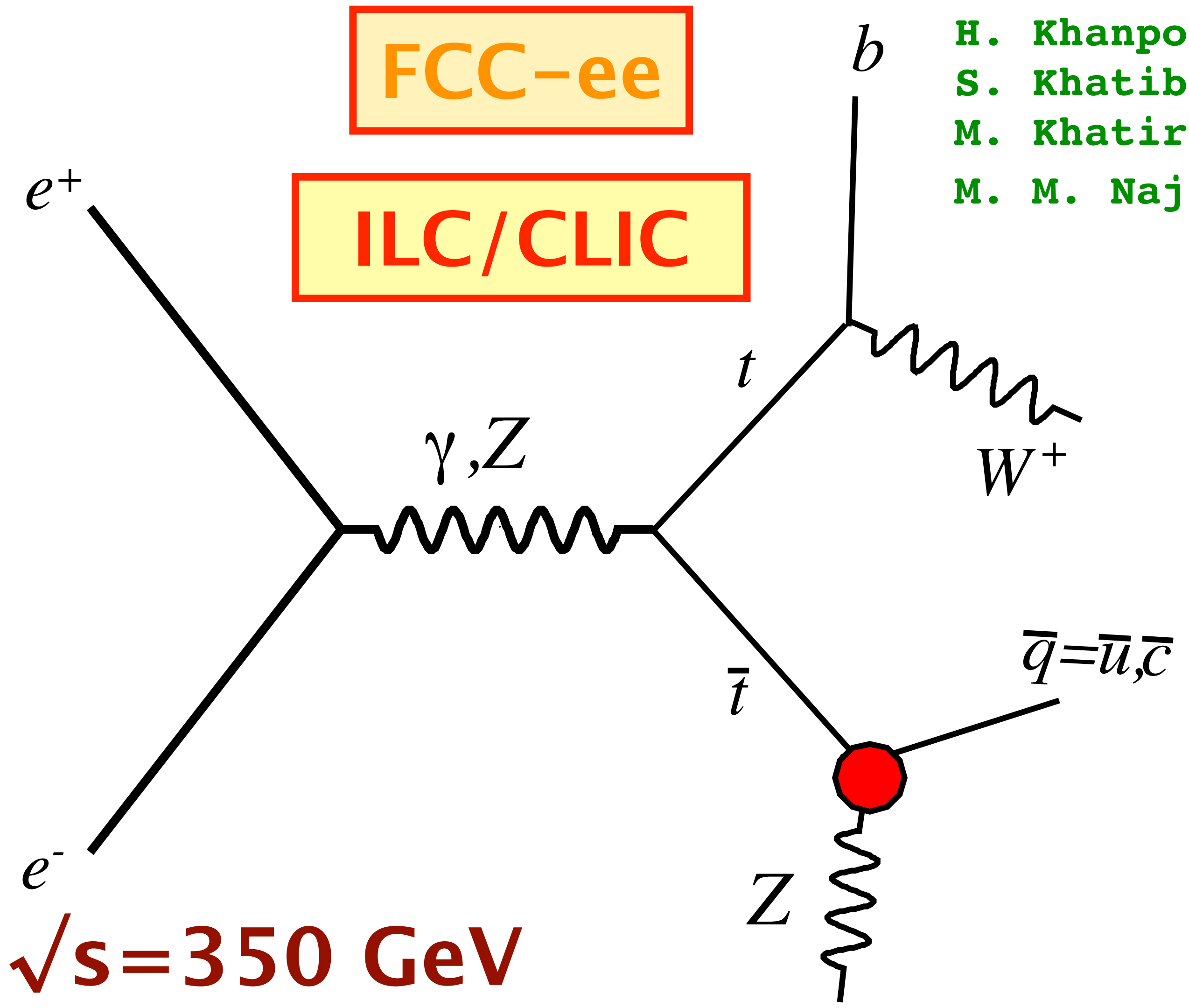
(rescaling of the LHC expectations)

$10\ \mathrm{ab}^{-1}$

Flavor Changing Neutral Current Couplings

FCC-ee

ILC/CLIC



$\sqrt{s}$=350 GeV

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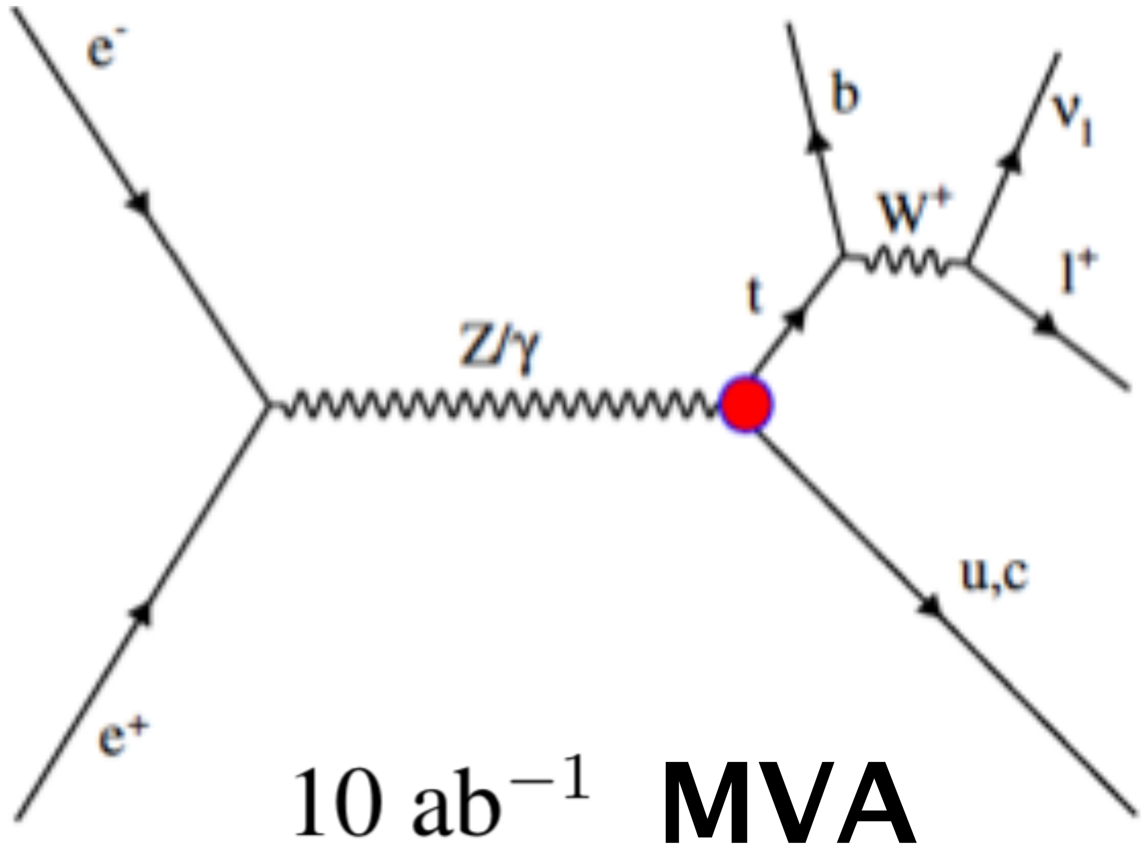

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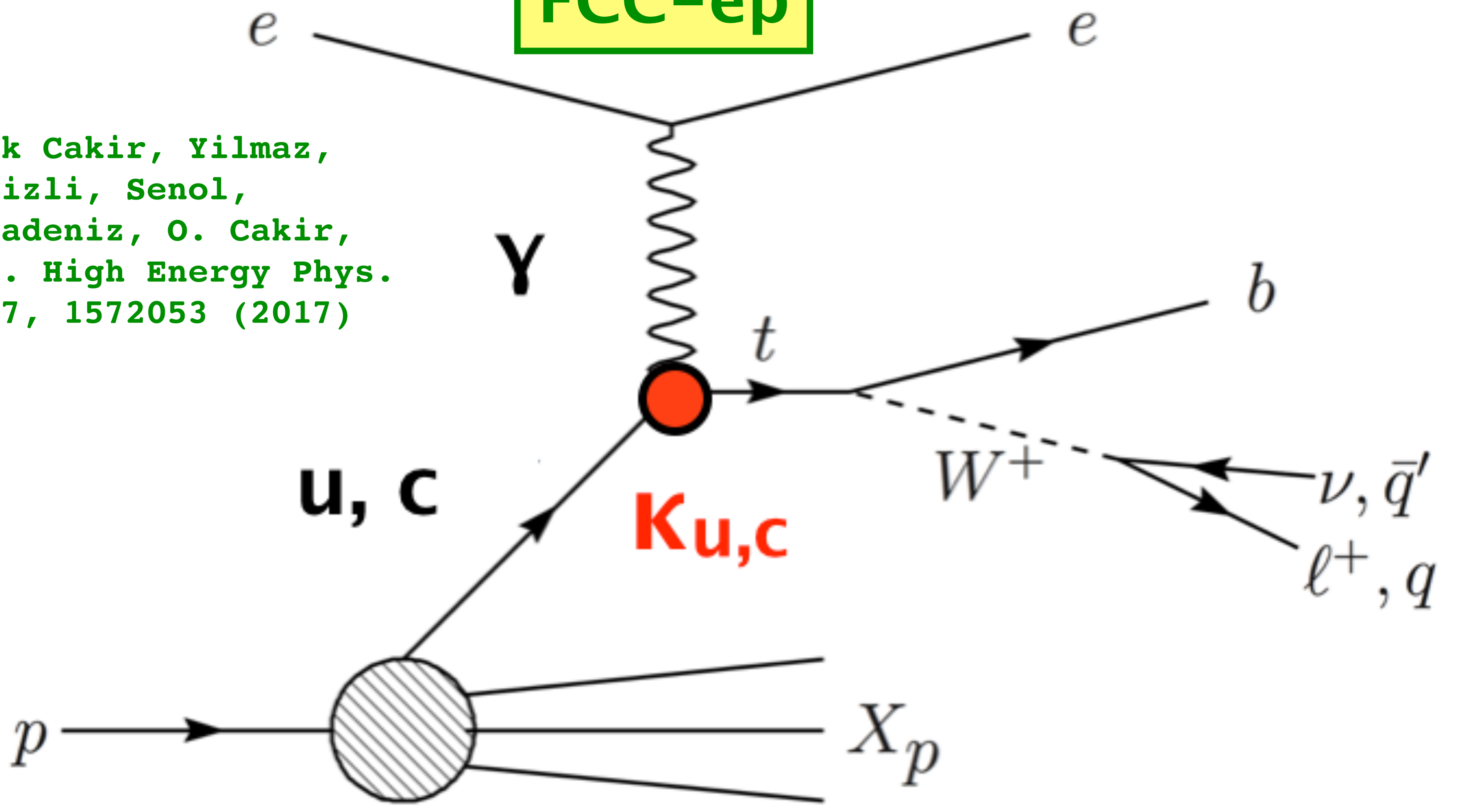
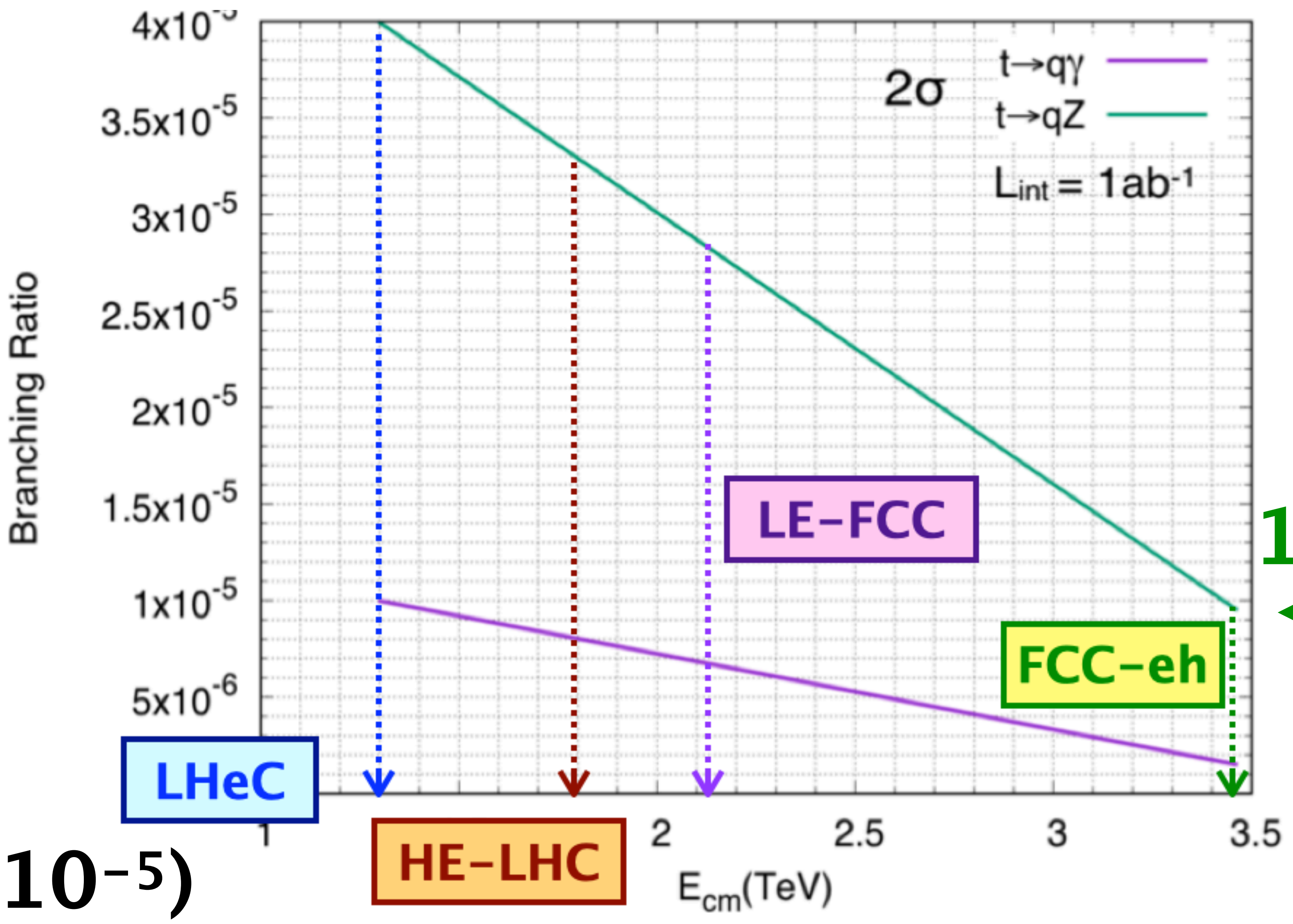
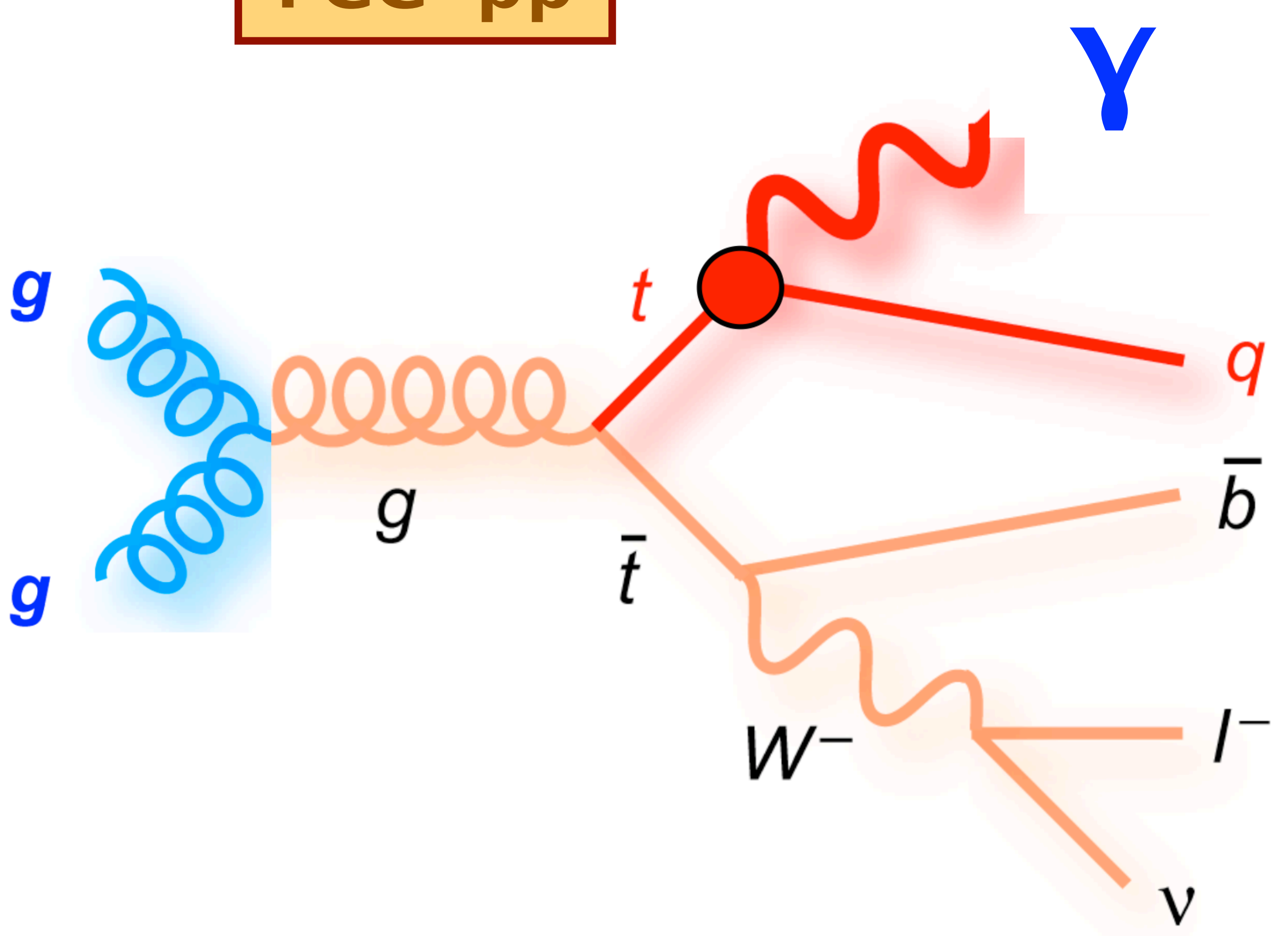
2017, 1572053 (2017)





10^{-5}

FCC-pp



Br(t→qγ)<10^{-7}

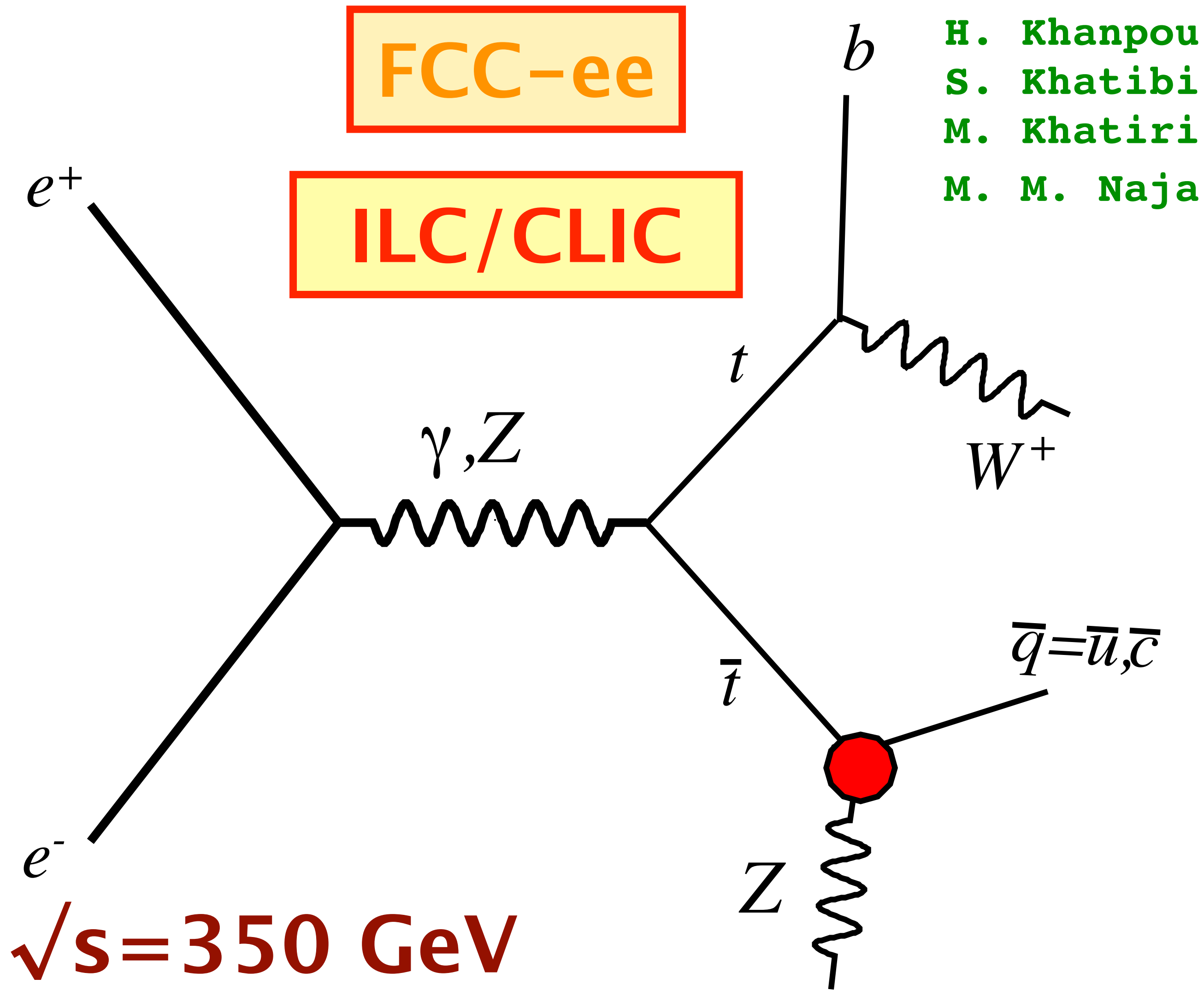
(rescaling of the LHC expectations)

$10\ \mathrm{ab}^{-1}$

Flavor Changing Neutral Current Couplings

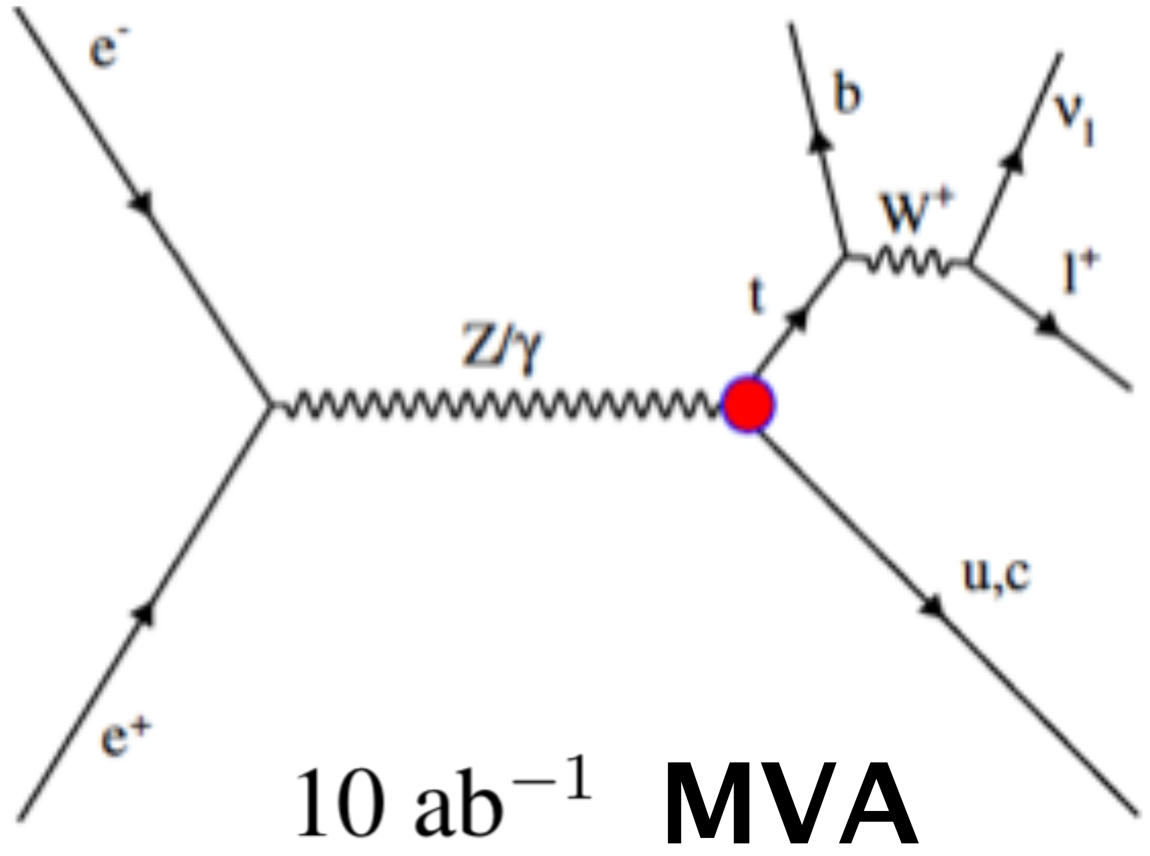
FCC-ee

ILC/CLIC



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

$\sqrt{s}$=350 GeV



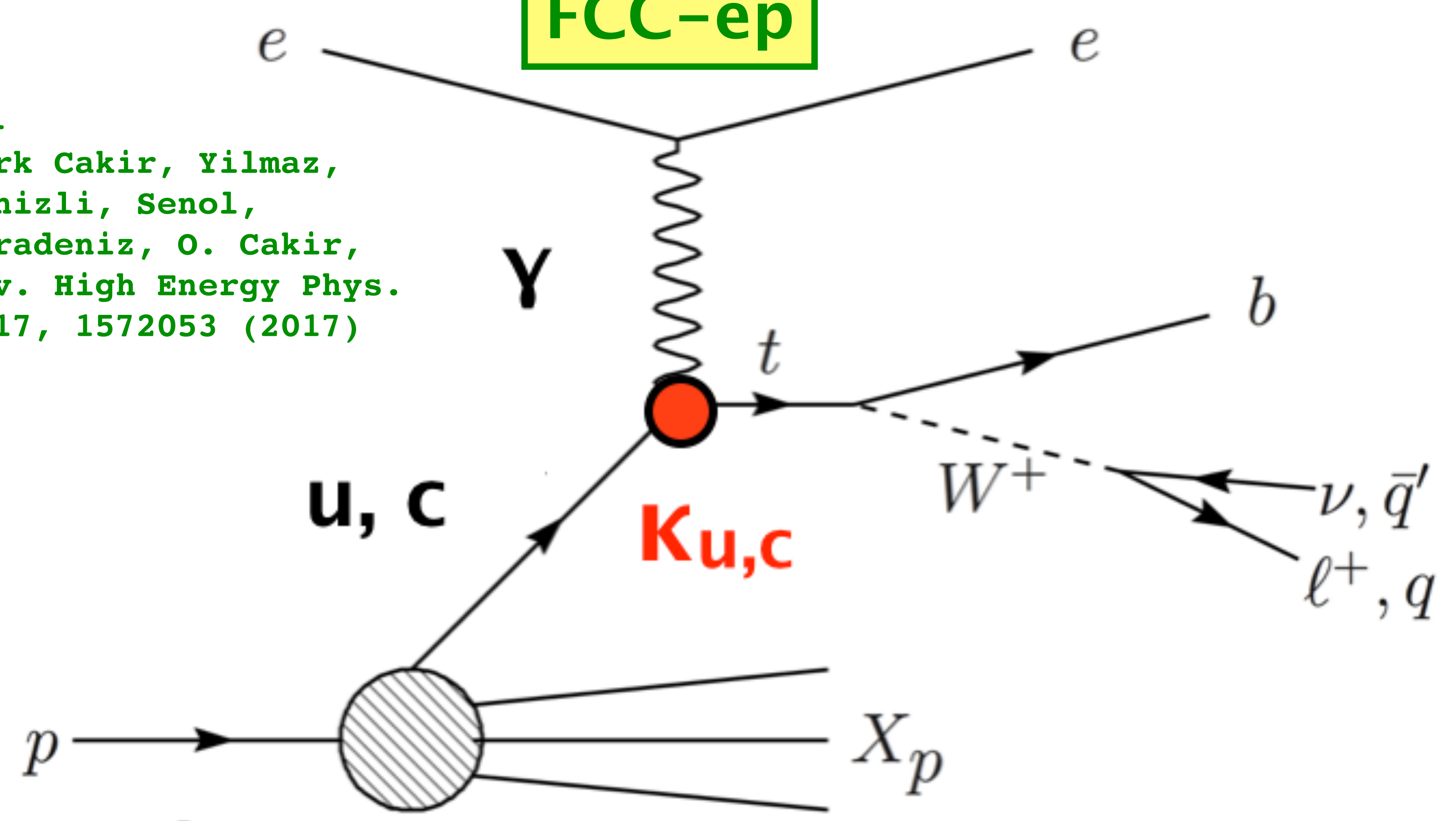
$10\ \mathrm{ab}^{-1}$ **MVA**

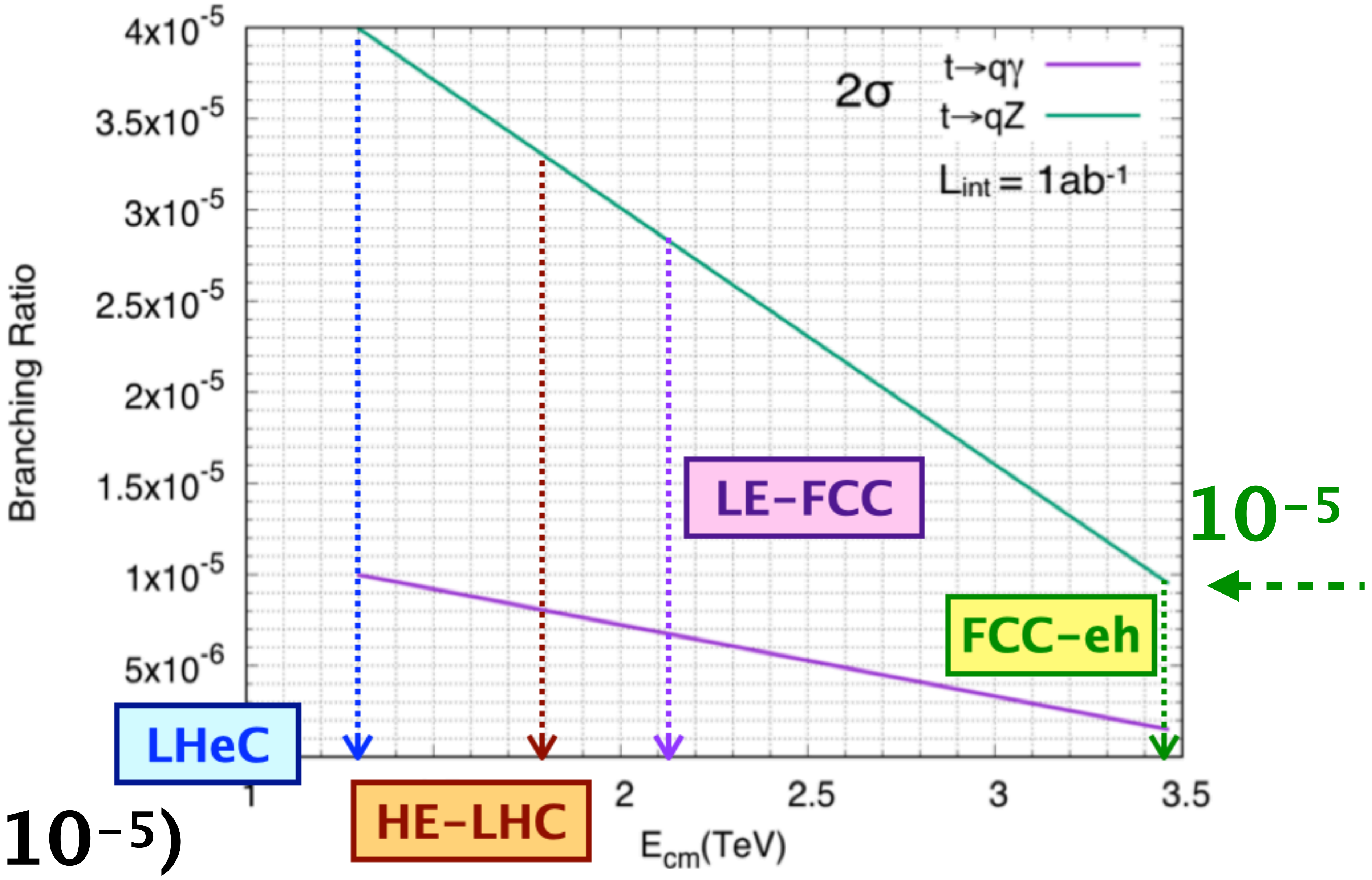
$\sqrt{s}$=240 GeV and $\sqrt{s}$=350 GeV

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)





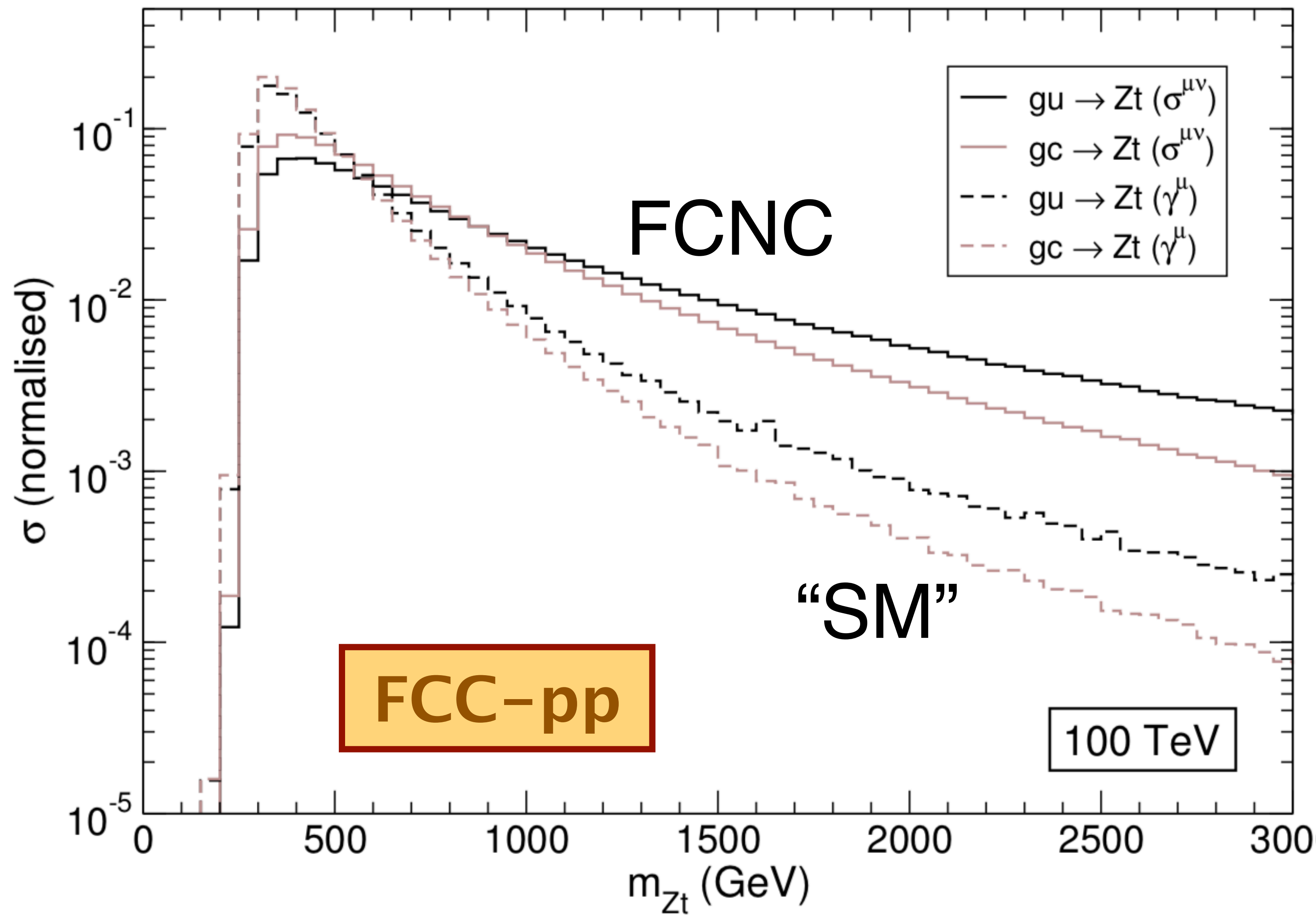
LHeC

HE-LHC

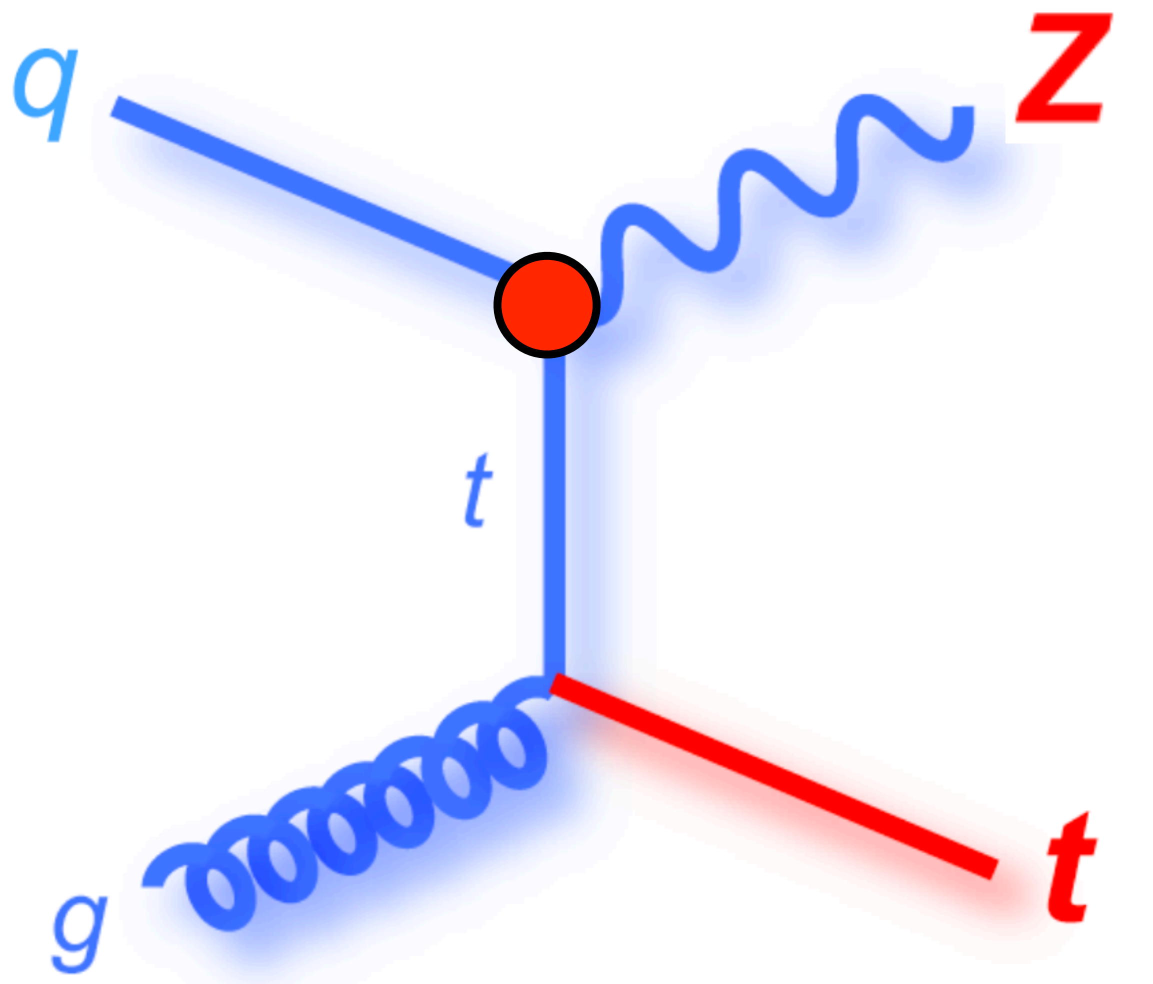
LE-FCC

FCC-eh

Mangano et al., arXiv:1607.01831

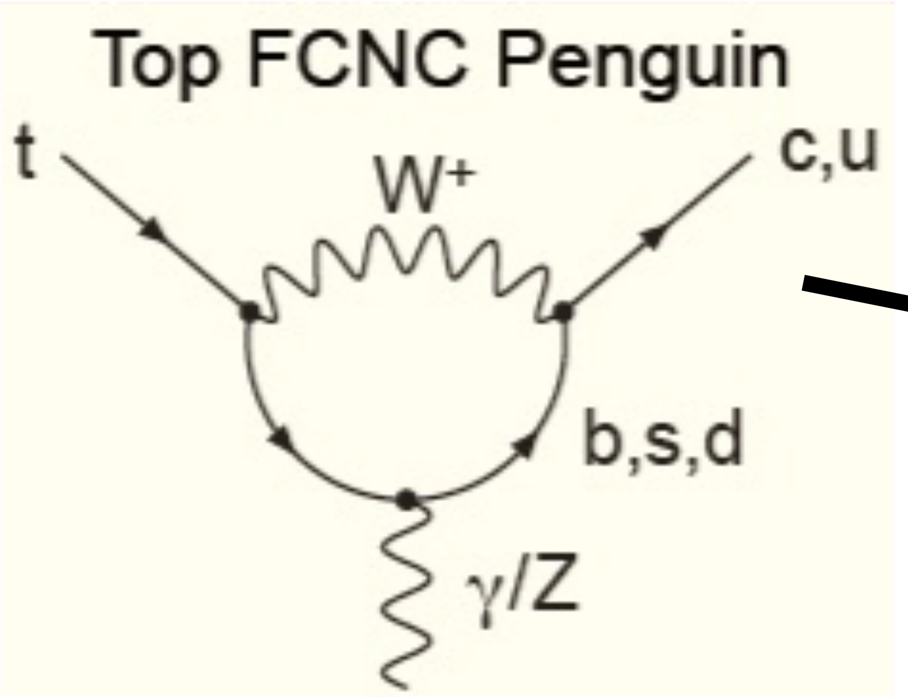


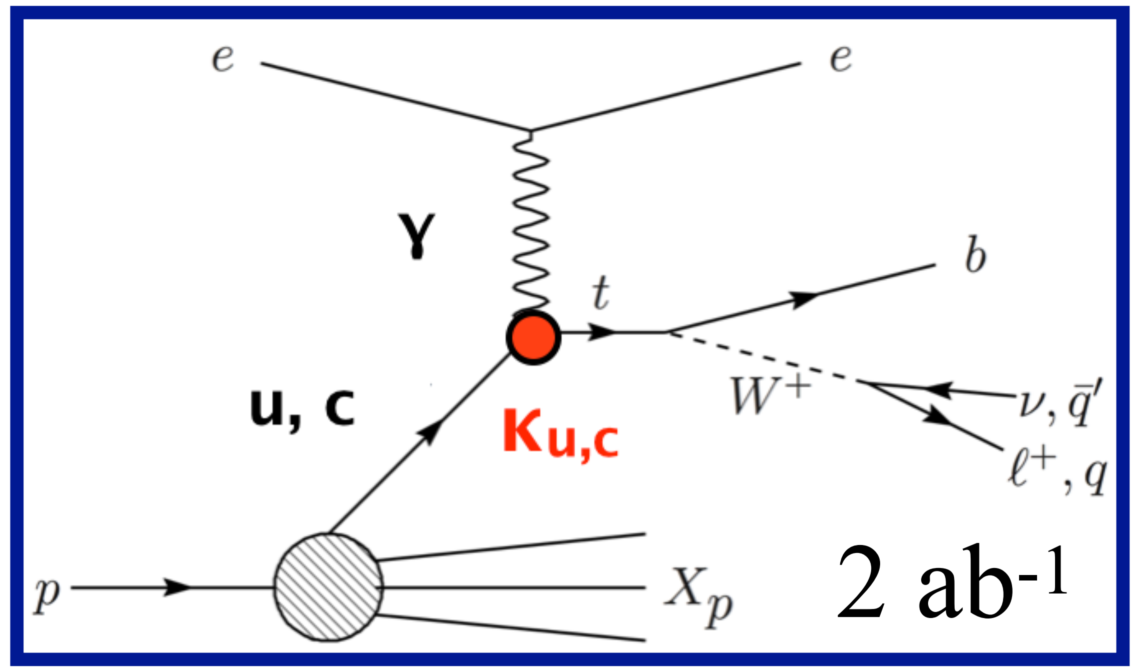
FCC-pp



FCNC Branching Ratios at Colliders

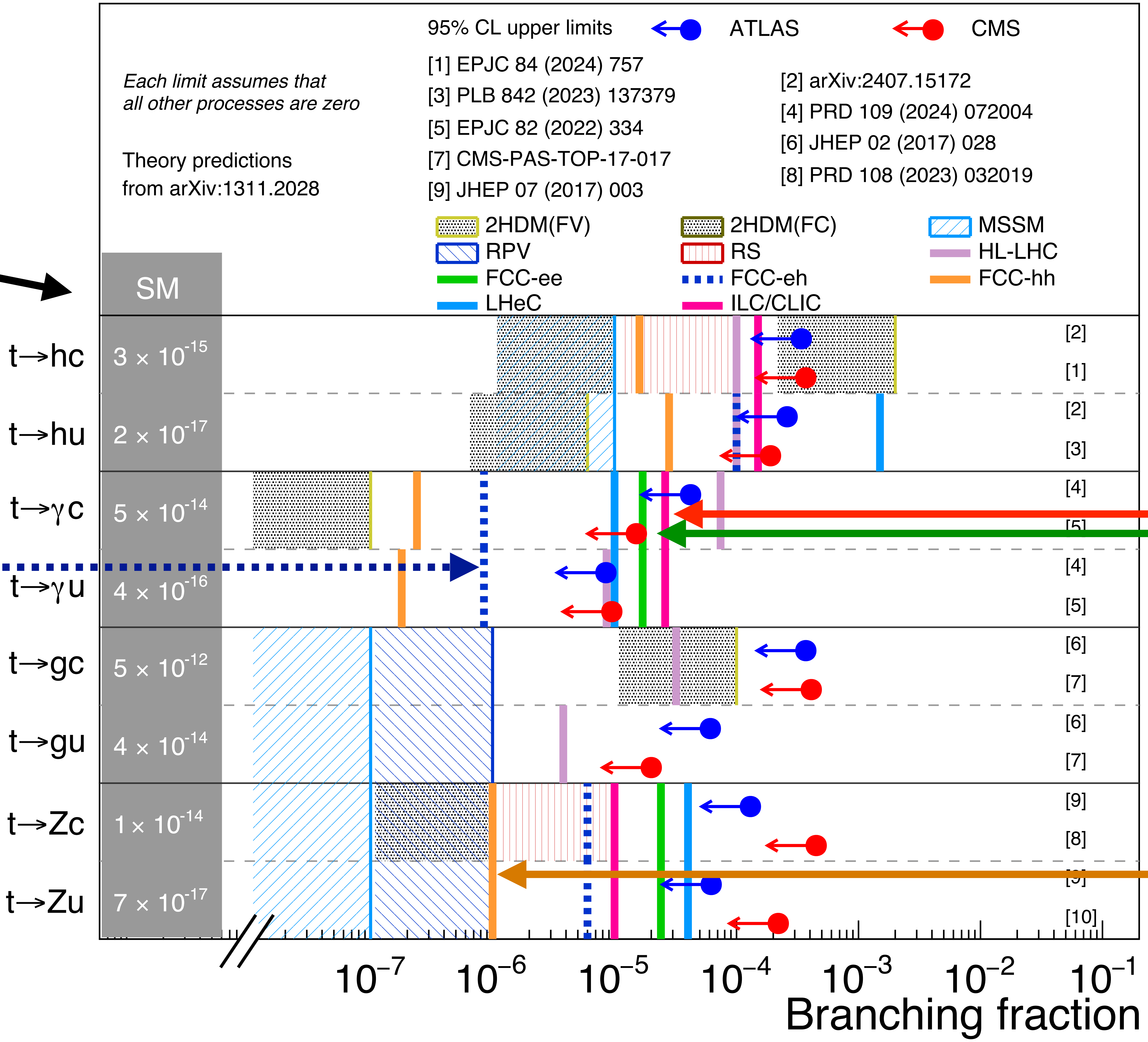
FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019), updated by K. Skovpen, 10/2024



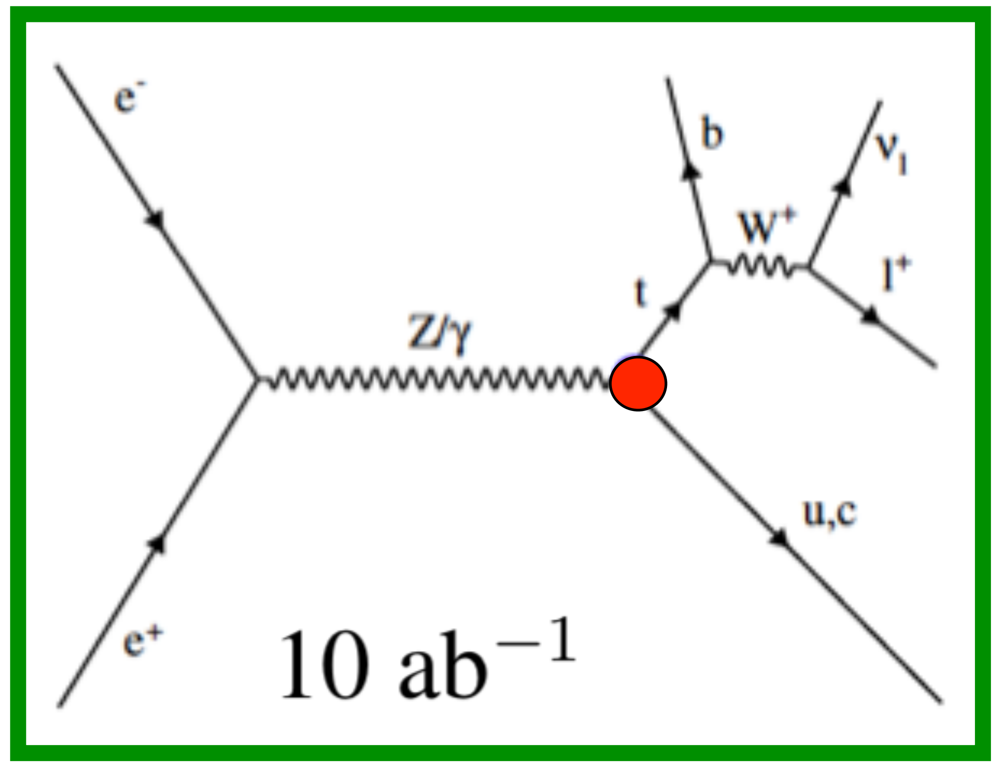


FCC-eh

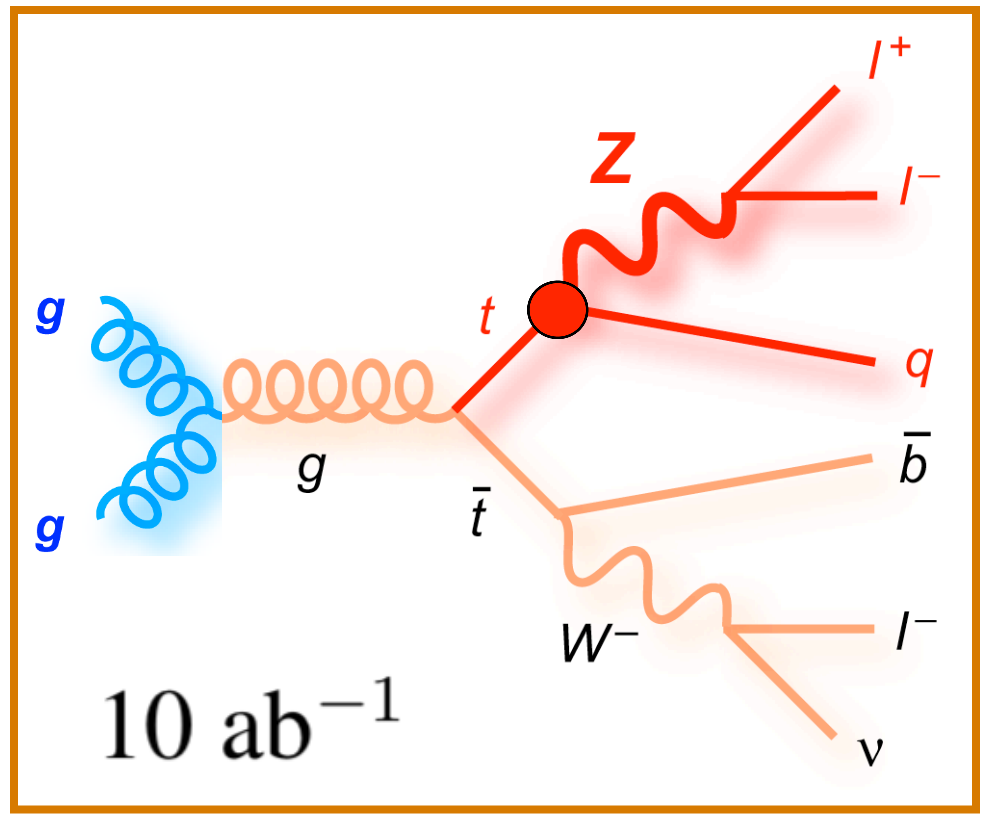
→ **test SUSY, little Higgs, technicolor…**



ILC/CLIC **FCC-ee**



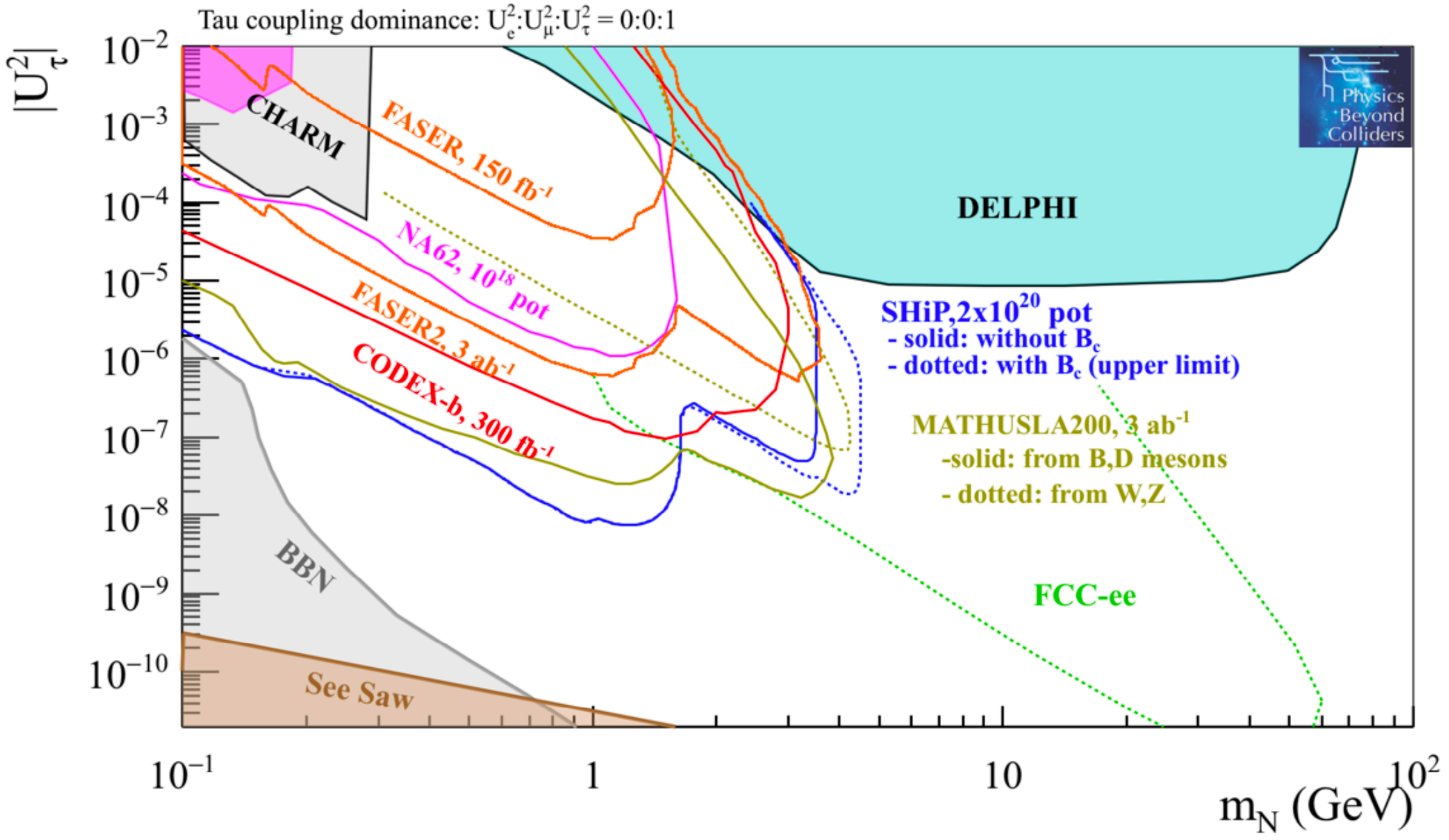
FCC-pp



Flavor Physics: Searches

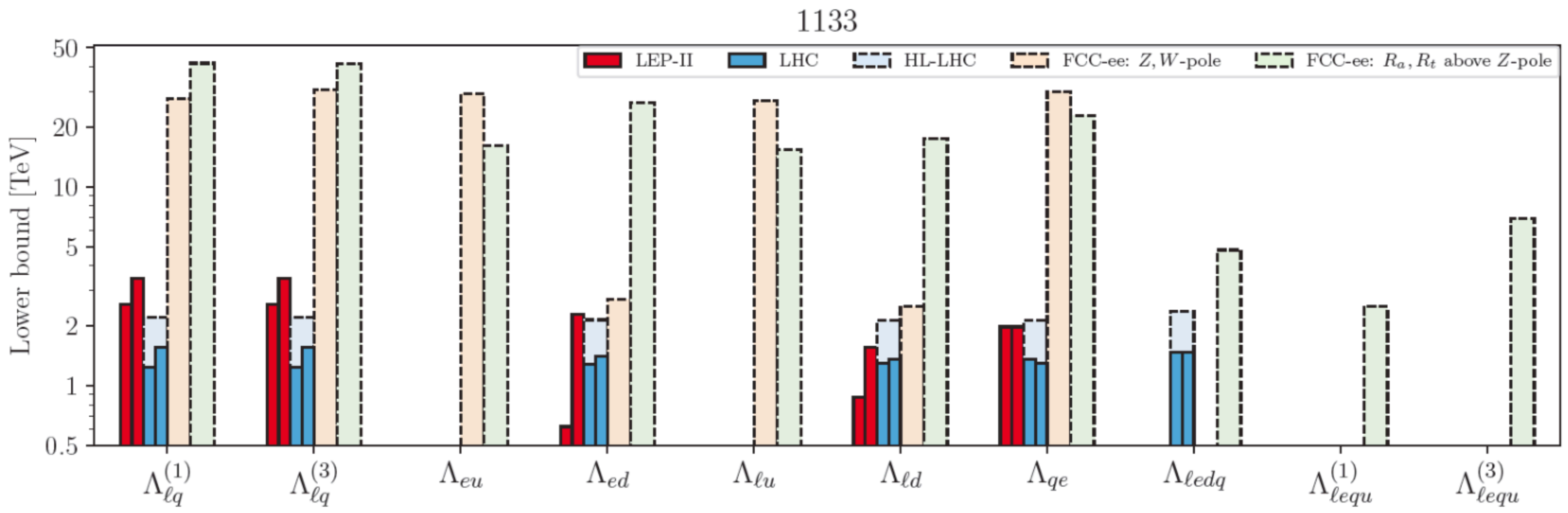
FCC-ee

- heavy dark sector searches at Z pole
- heavy neutral leptons e.g. coupling mostly to taus



arXiv:2411.02485

- what can be gained in SMEFT and concrete BSM particles from running above the Z pole



- FCC-hh configuration: best studied with a dedicated experiment à la LHCb

Summary

- future ee, ep, pp colliders have a rich and complementary analysis programme for top quark and flavor 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, EFT, FCNC, composite Higgs, …

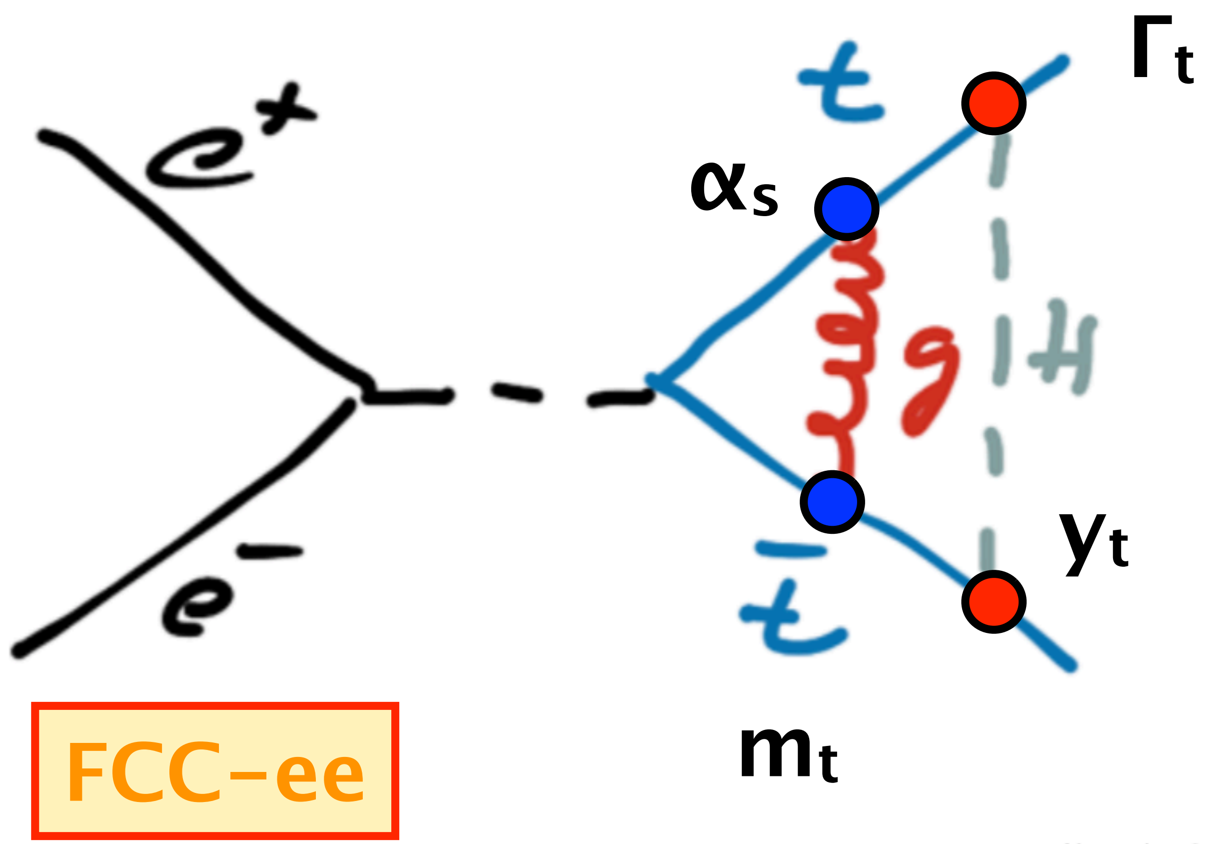
- heavy-flavour physics is expected to remain an integral part future colliders
- experiments at a future high-luminosity e^+e^- collider would perform unique heavy-flavour studies in specific channels
- Colliders operating at the Z pole can strongly contribute to develop searches for the charm Yukawa coupling and flavour-violating Higgs and Z couplings, lepton flavour violation and precision tau physics, and dark sector searches

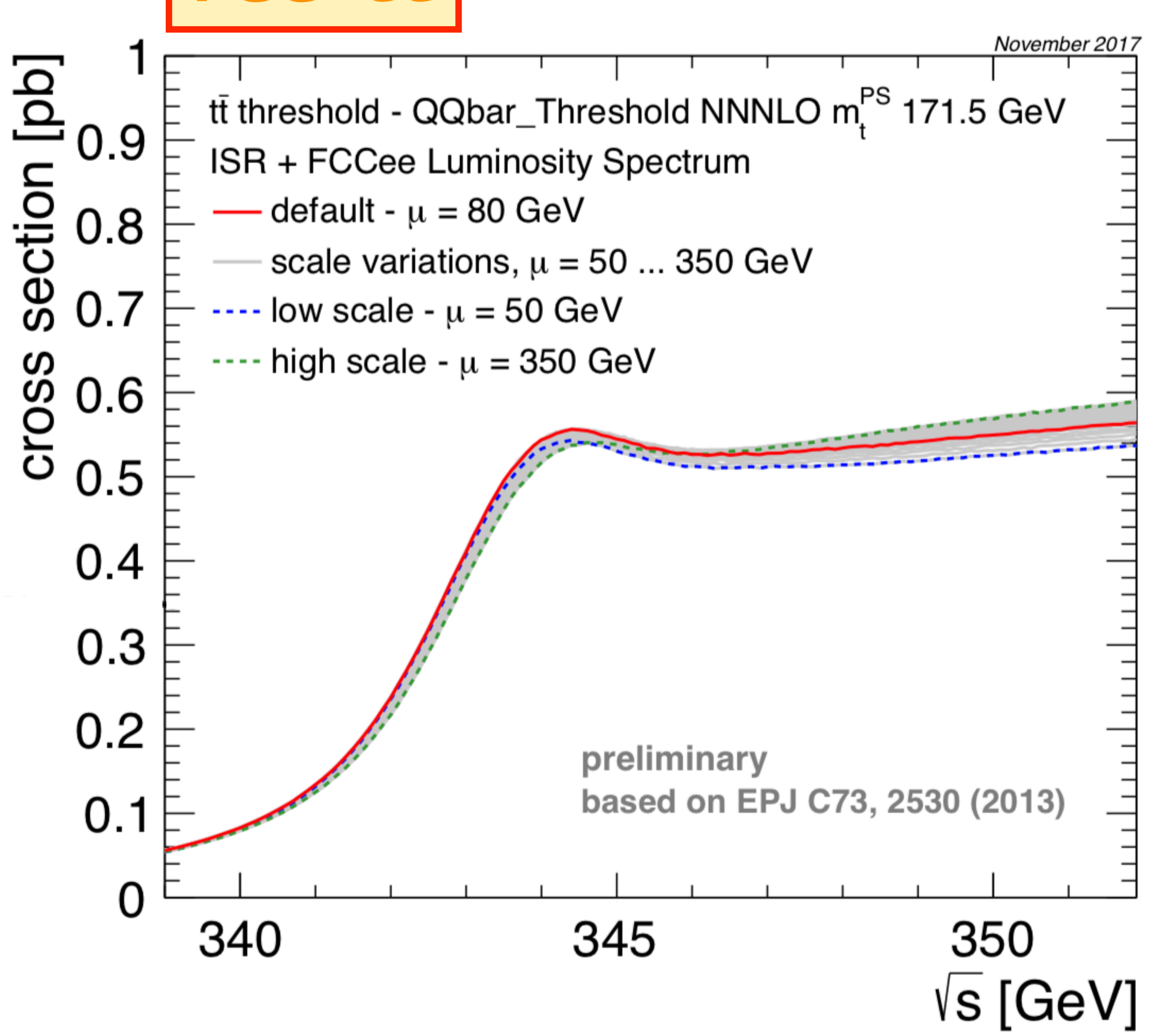
→ more exciting studies exist

→ more exciting studies to come

Backup

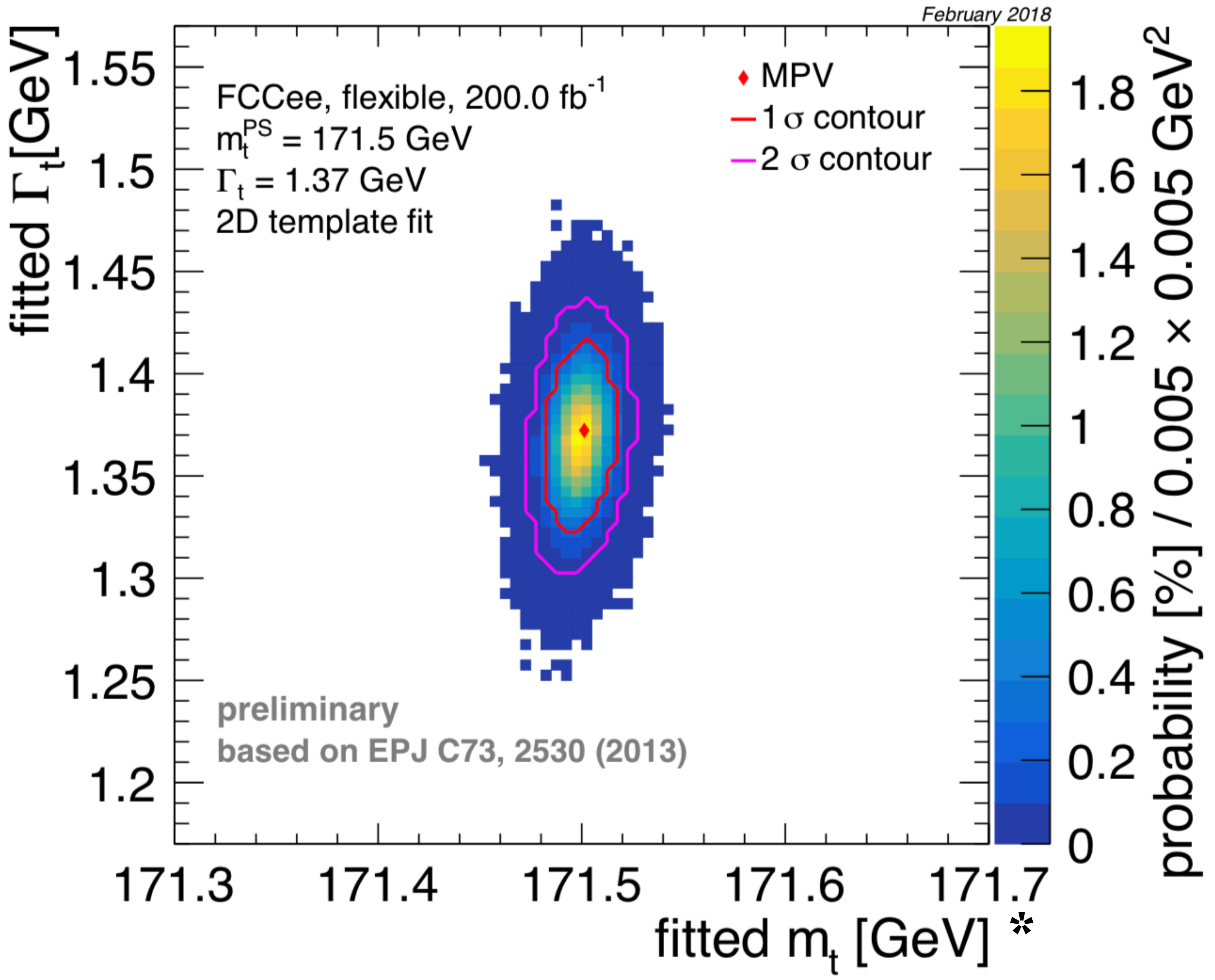
Top Quark Measurements at Threshold





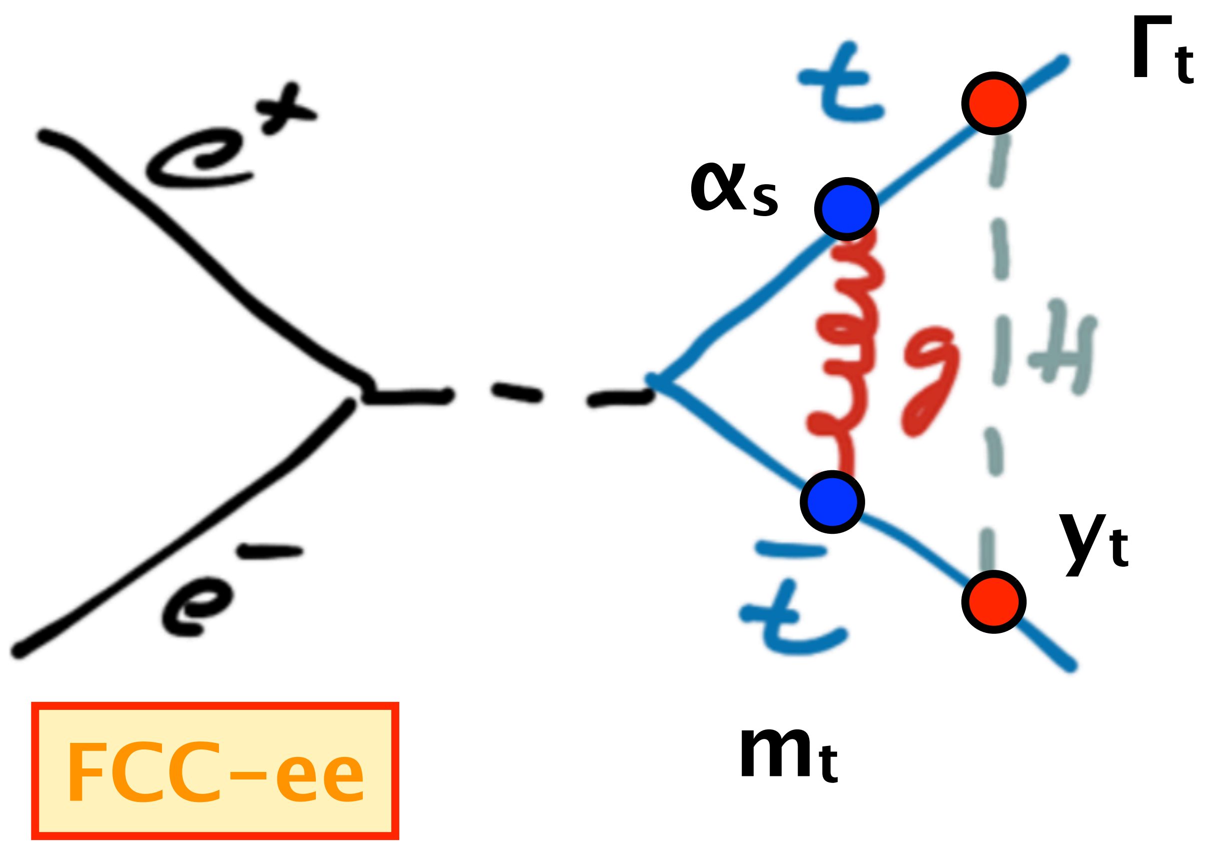
→ **mass only: 8.8 MeV** (stat), **5.4 MeV** (α_s [2 x 10^{-4}]), **44 MeV** (theo)

Top Quark Width



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

EPJC 79 (2019) 474

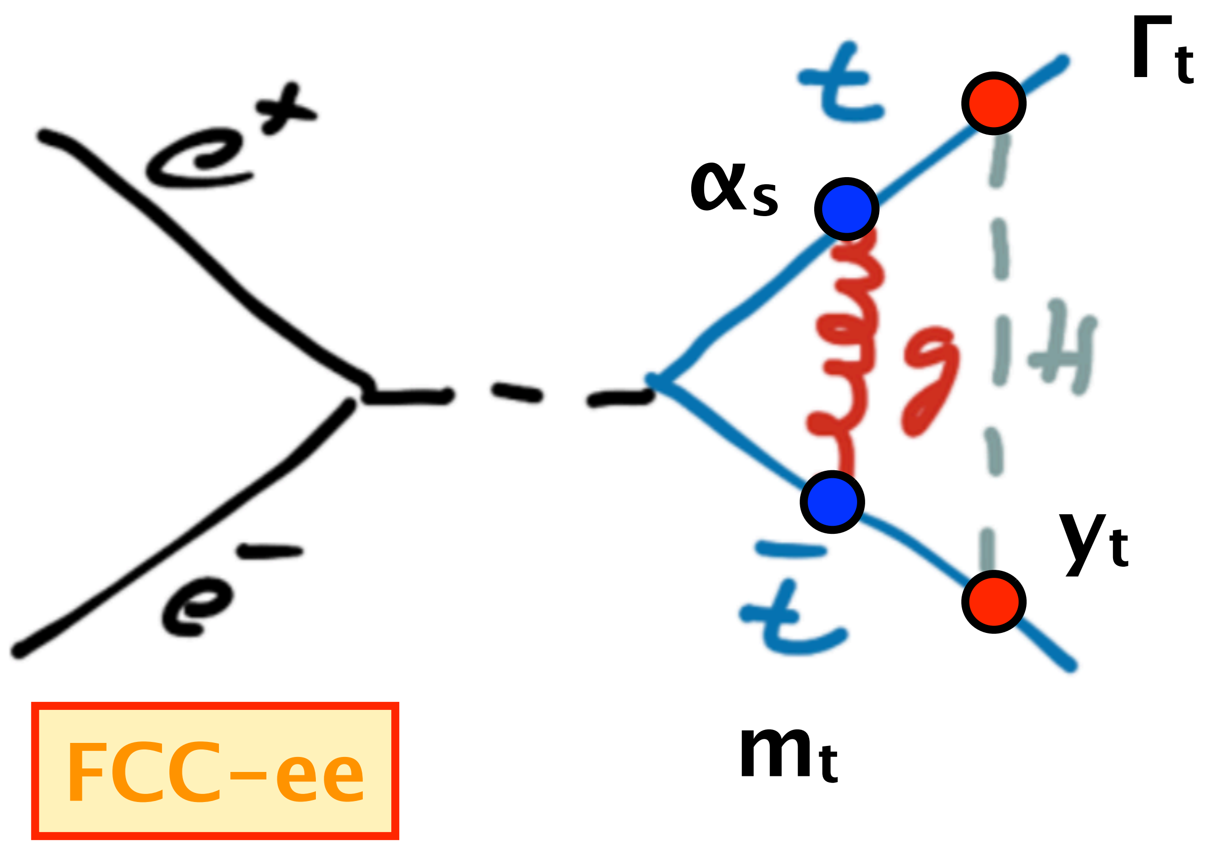


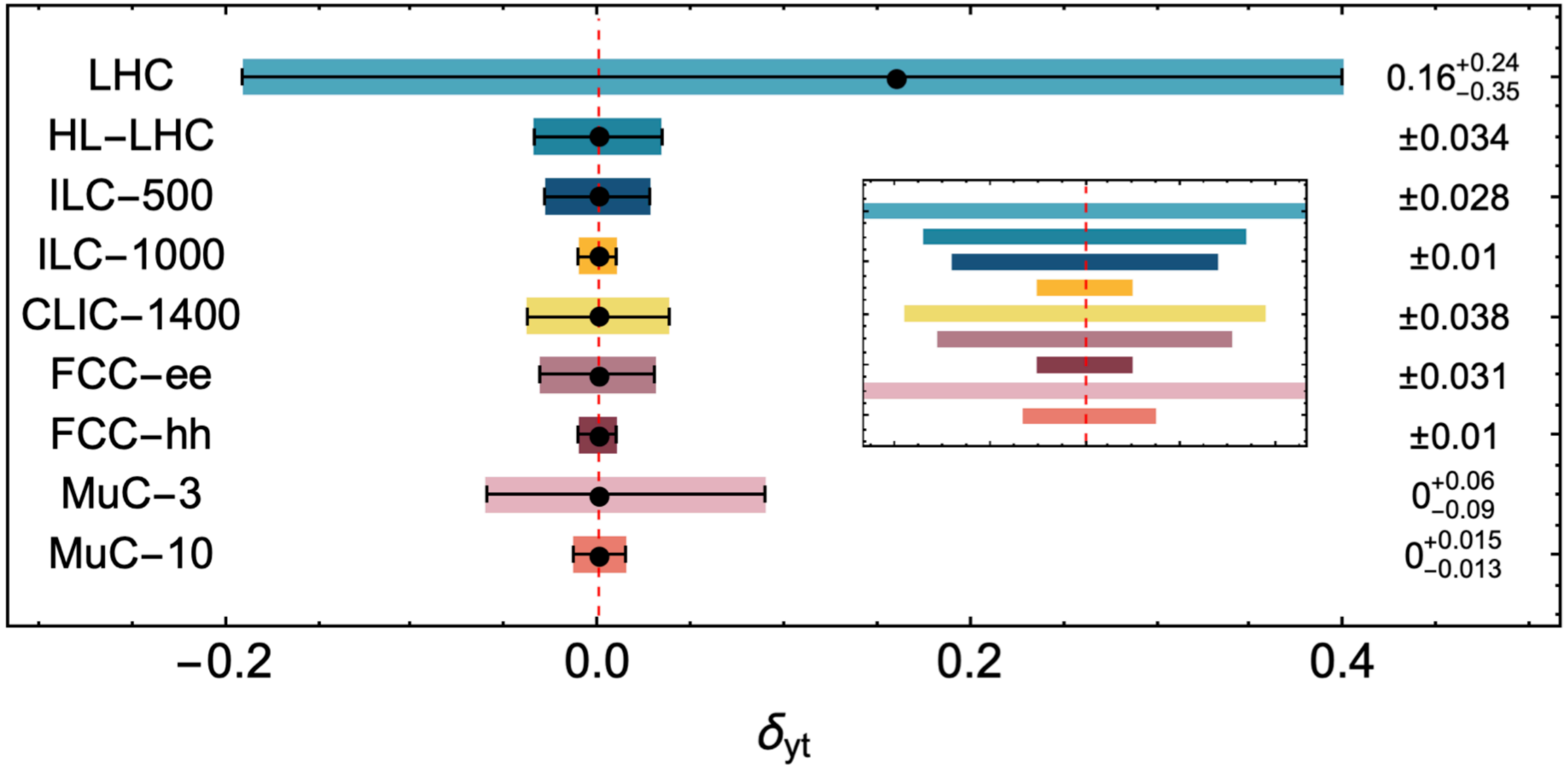
FCC-ee

- Top width **strongly depends** on the top quark mass ($\sim m_t^3$)
- **Most precise** indirect measurement of 1.36 ± 0.14 GeV
- N.B.: parton shower models treat top quarks in a **narrow width approximation**
- Towards a **simultaneous measurement** of top quark mass and width
- Expect the measurement of the width at ≈ **50 MeV** precision at FCC-ee

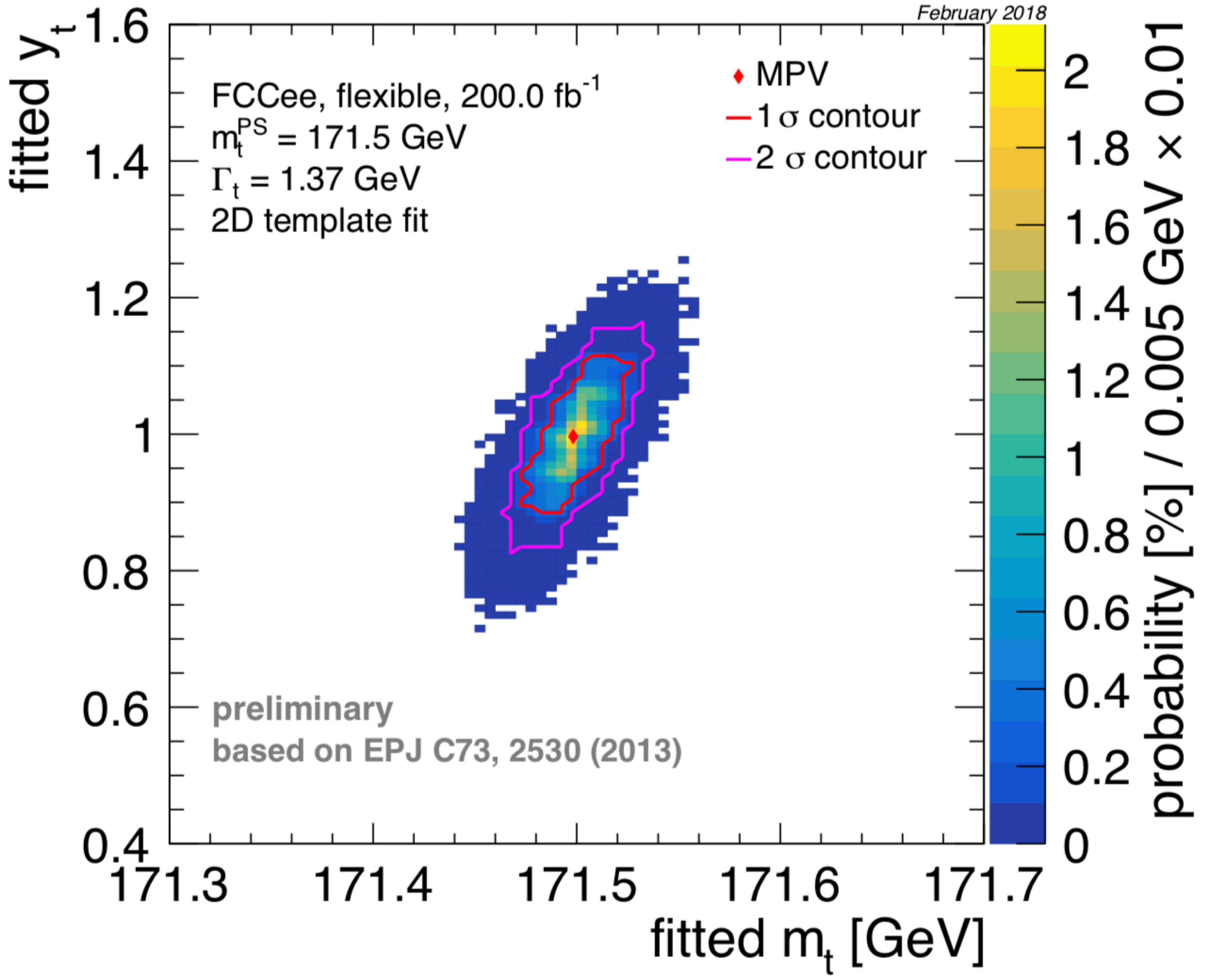
* m_t^{PS}=171.5 GeV ≙ m_t^{pole}=173.3 GeV (WA)

Top Quark Yukawa Coupling





EPJC 79 (2019) 474



Extension of 1σ contour:

mass: +29 MeV, - 26 MeV

y_t: +0.12, -0.11

Theory uncertainty (symm.):

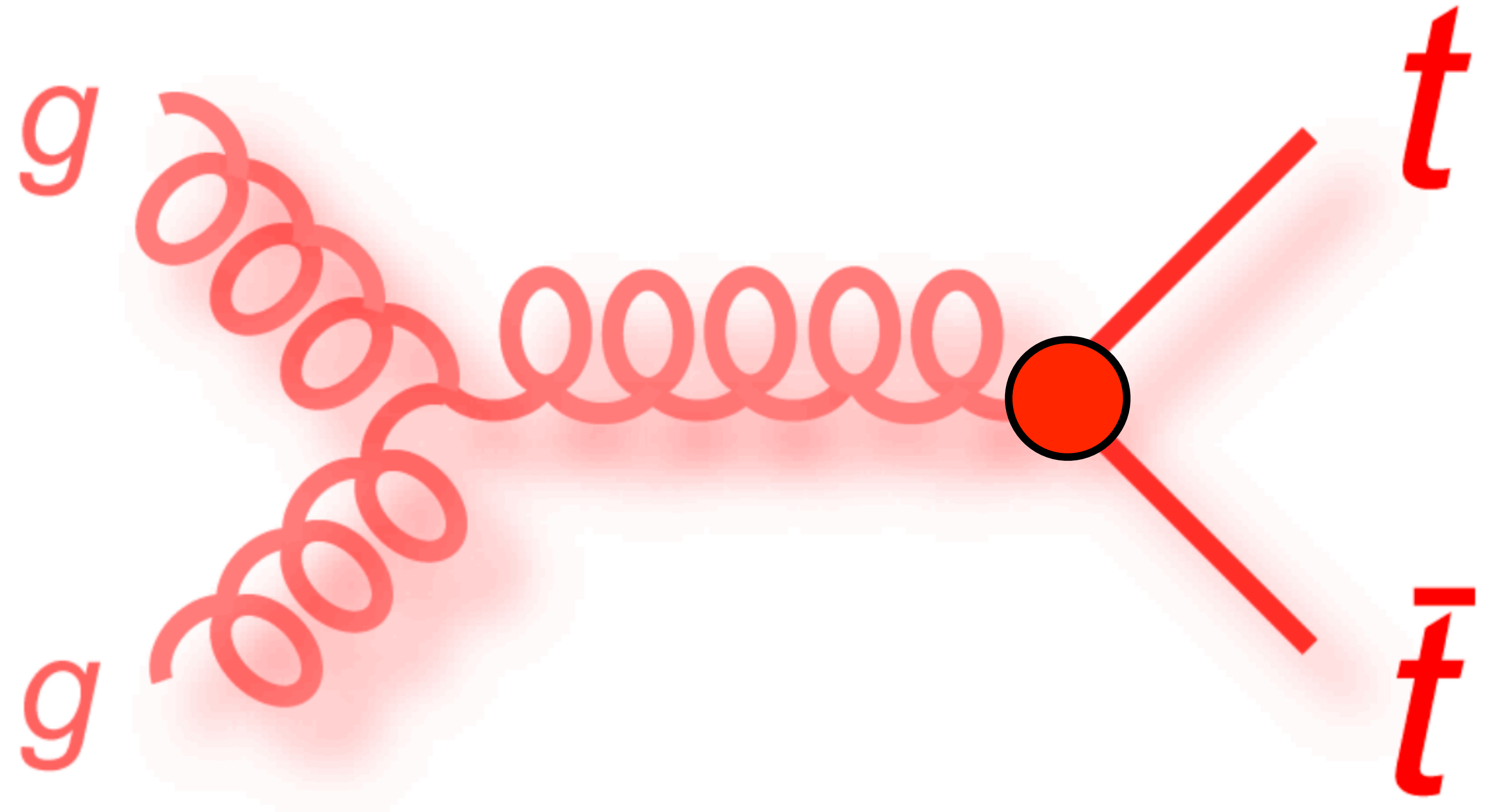
mass: 36 MeV; y_t: 0.11

α_s parametric uncertainty (0.0002)

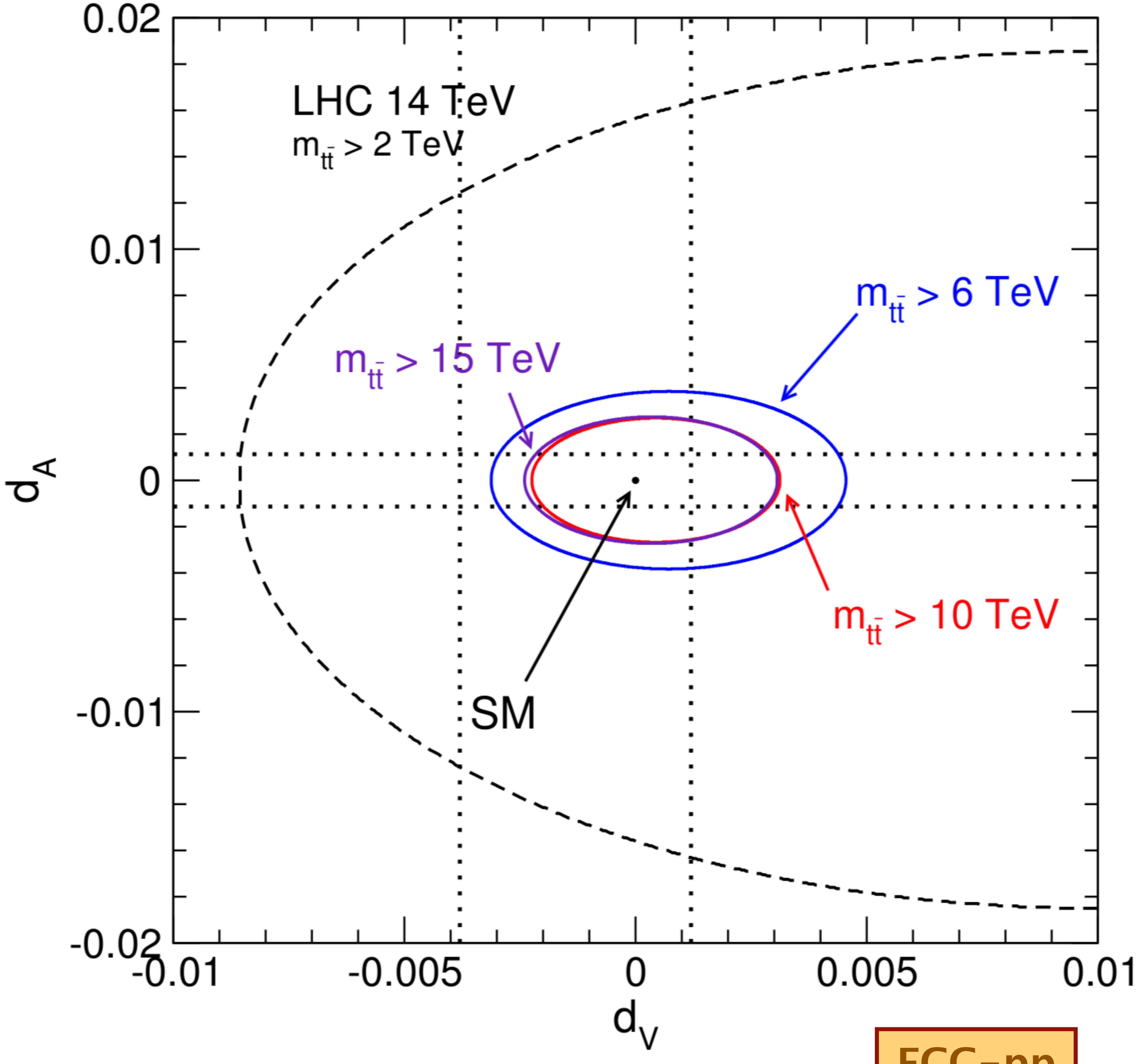
mass: 3 MeV; y_t: 0.02

Chromoelectric and Chromomagnetic Dipole Moments

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



Mangano et al., arXiv:1607.01831

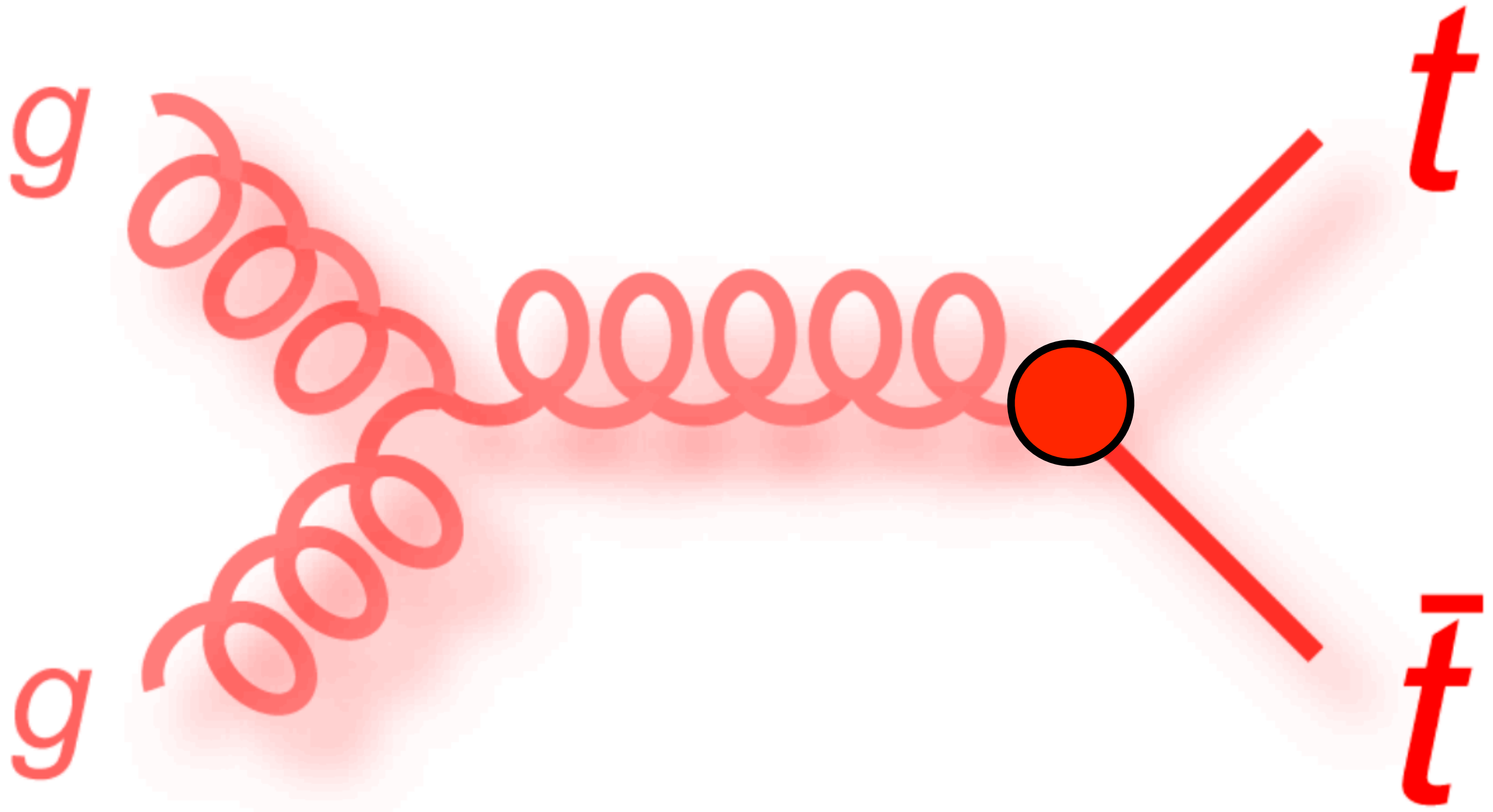


→ expected precision of order 10^{-2}

FCC-pp

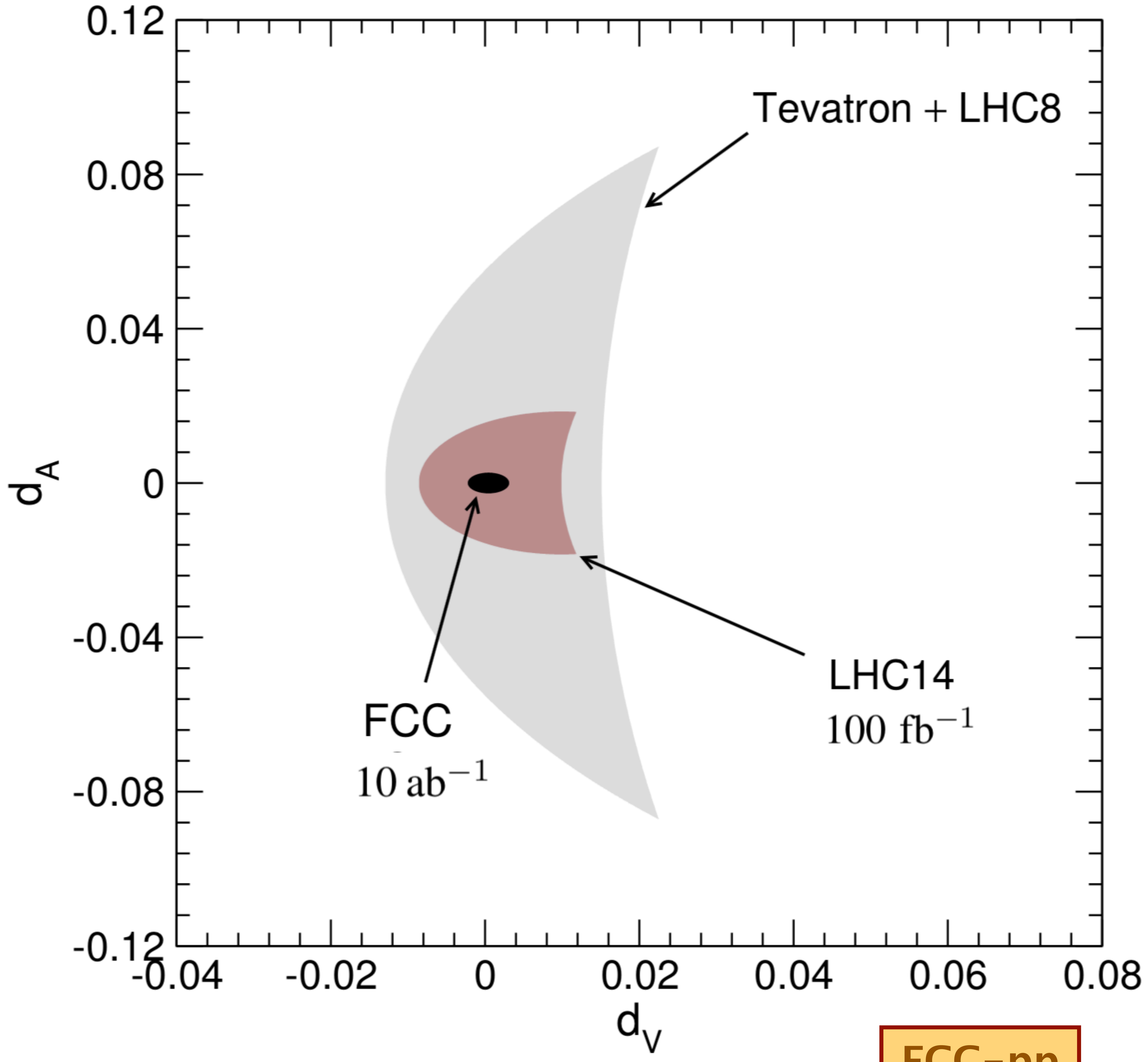
Chromoelectric and Chromomagnetic Dipole Moments

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



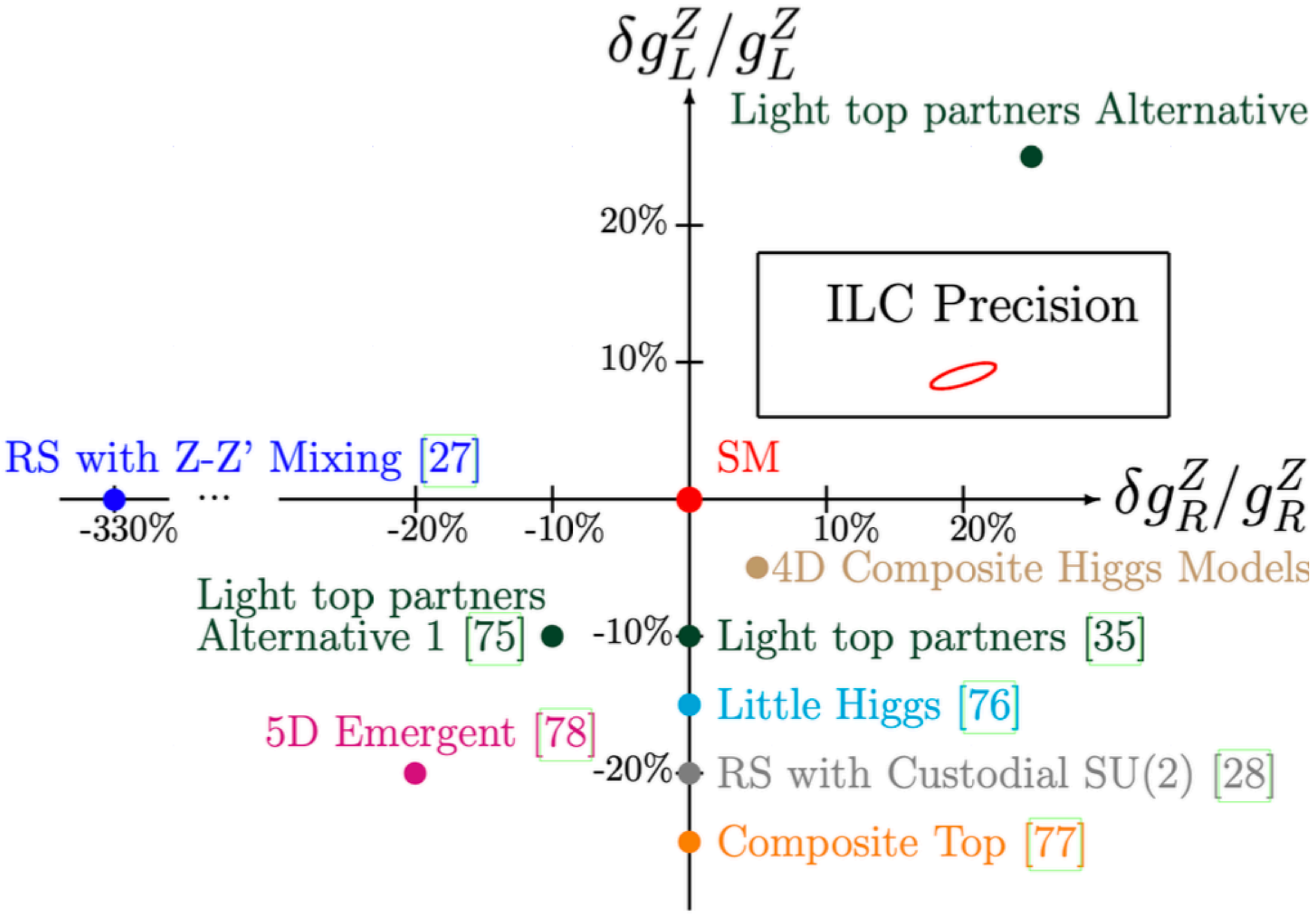
→ **expected precision of order 10^{-2}**

Mangano et al., arXiv:1607.01831

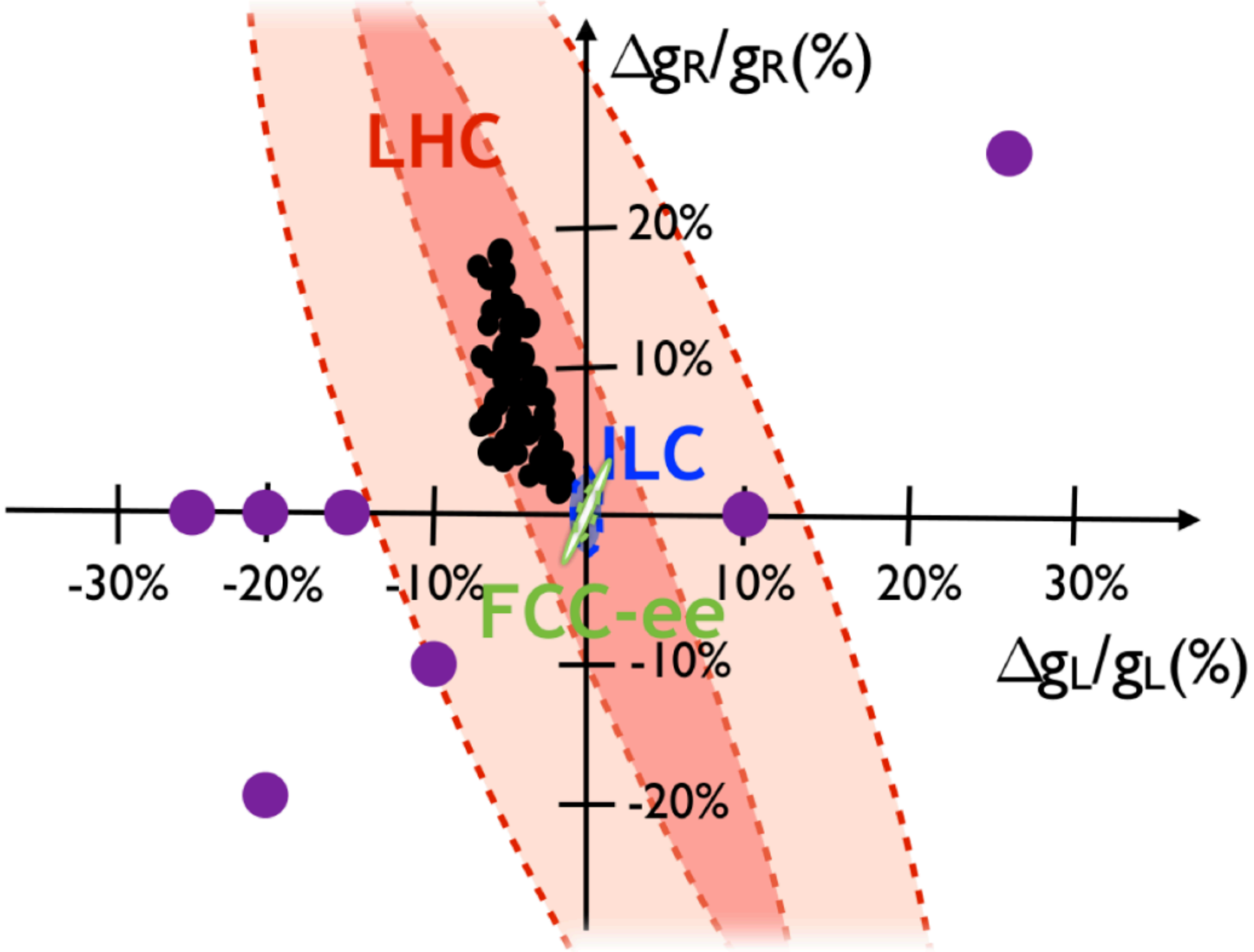


FCC-pp

Electroweak Couplings

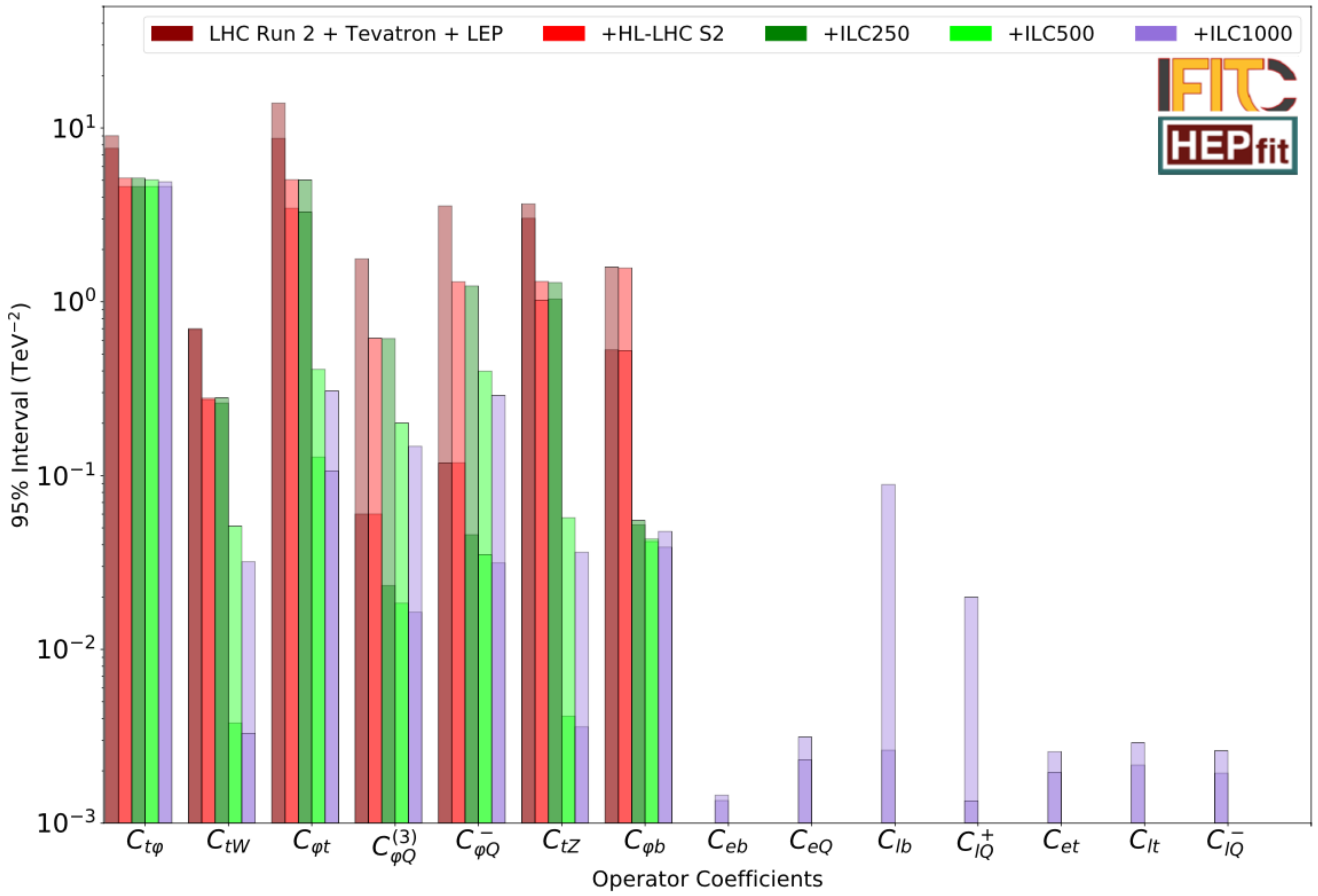


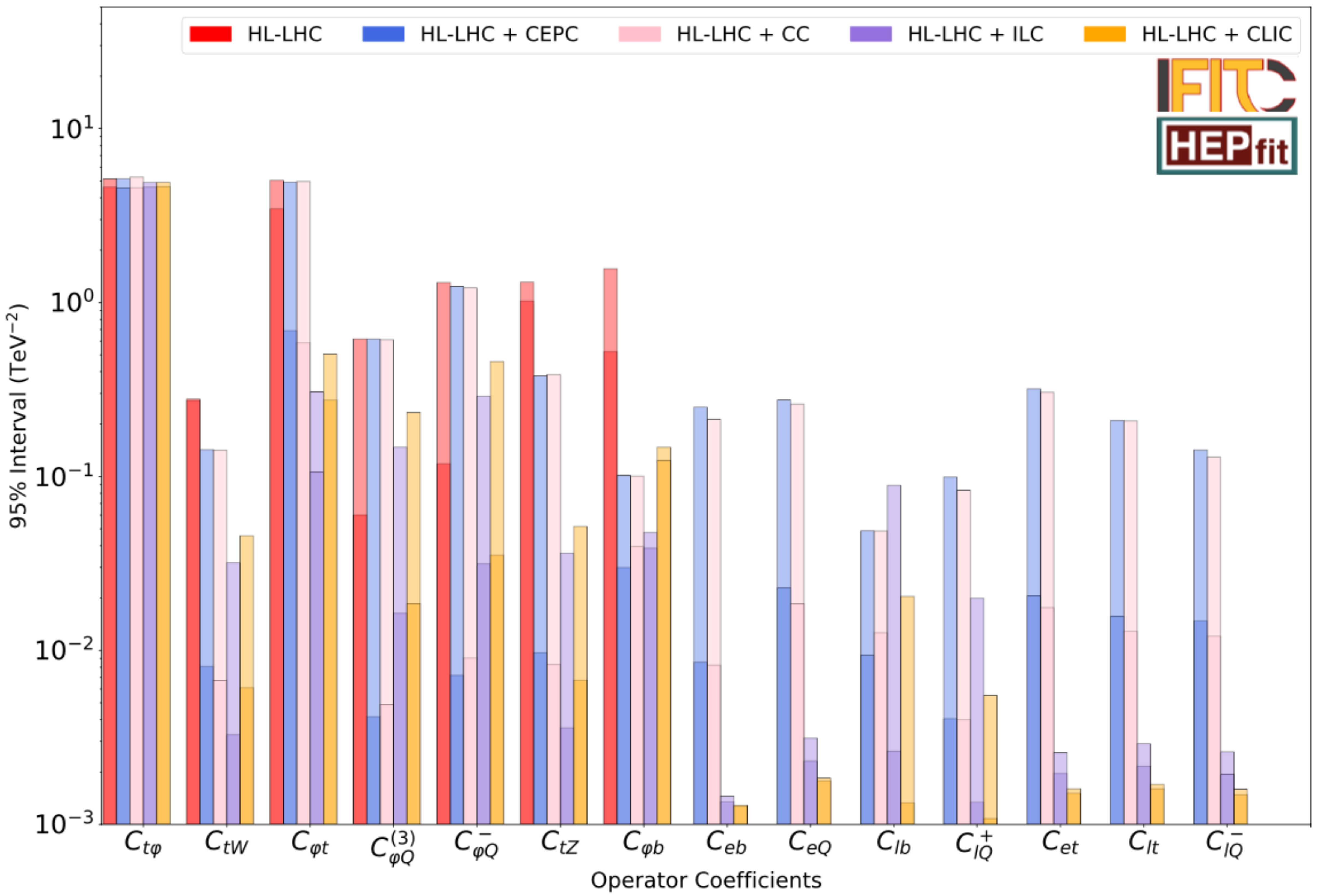
arXiv:1702.05333



JHEP 08 (2015) 127

Global Search for EFT Couplings in Top Production and Decay

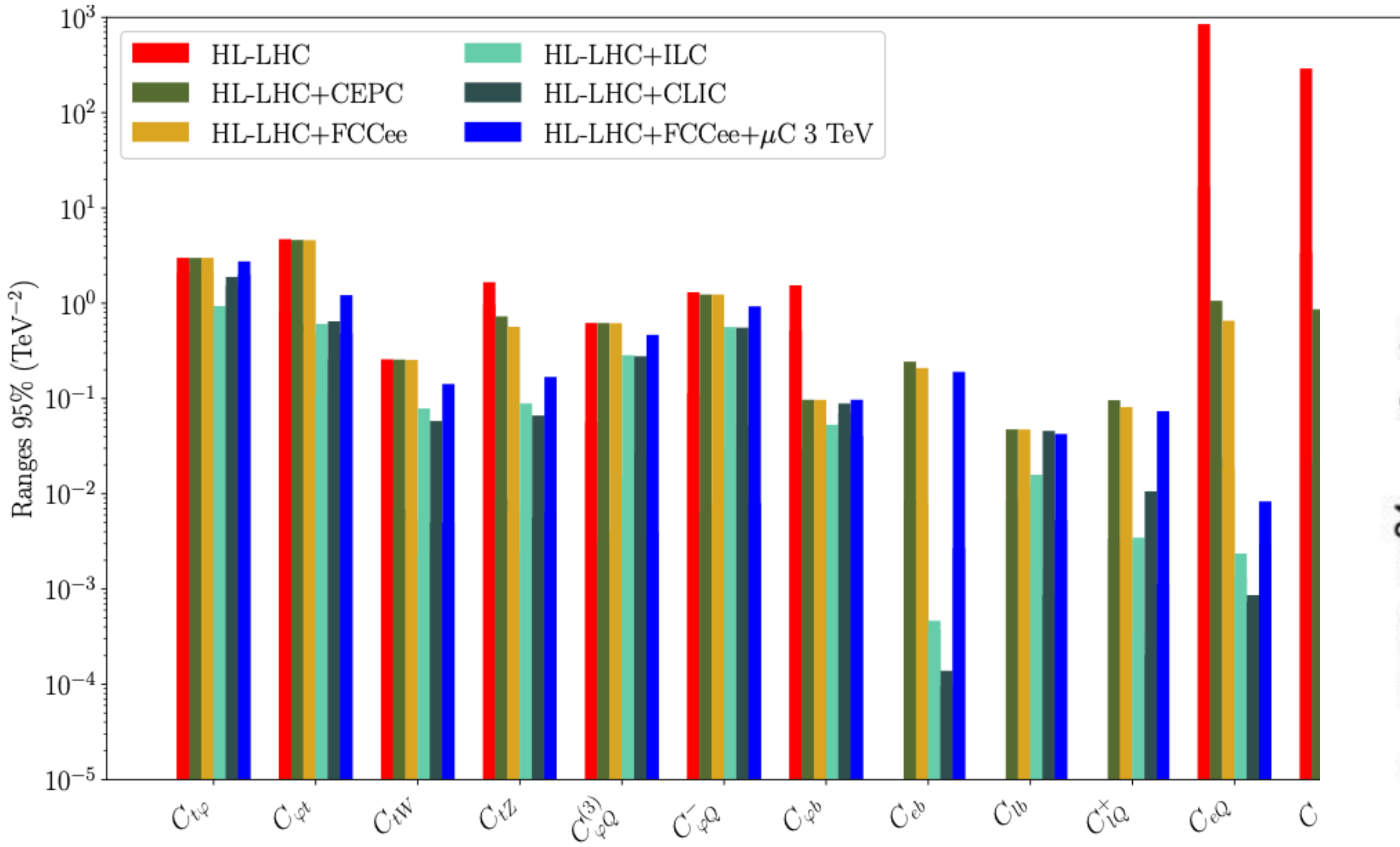


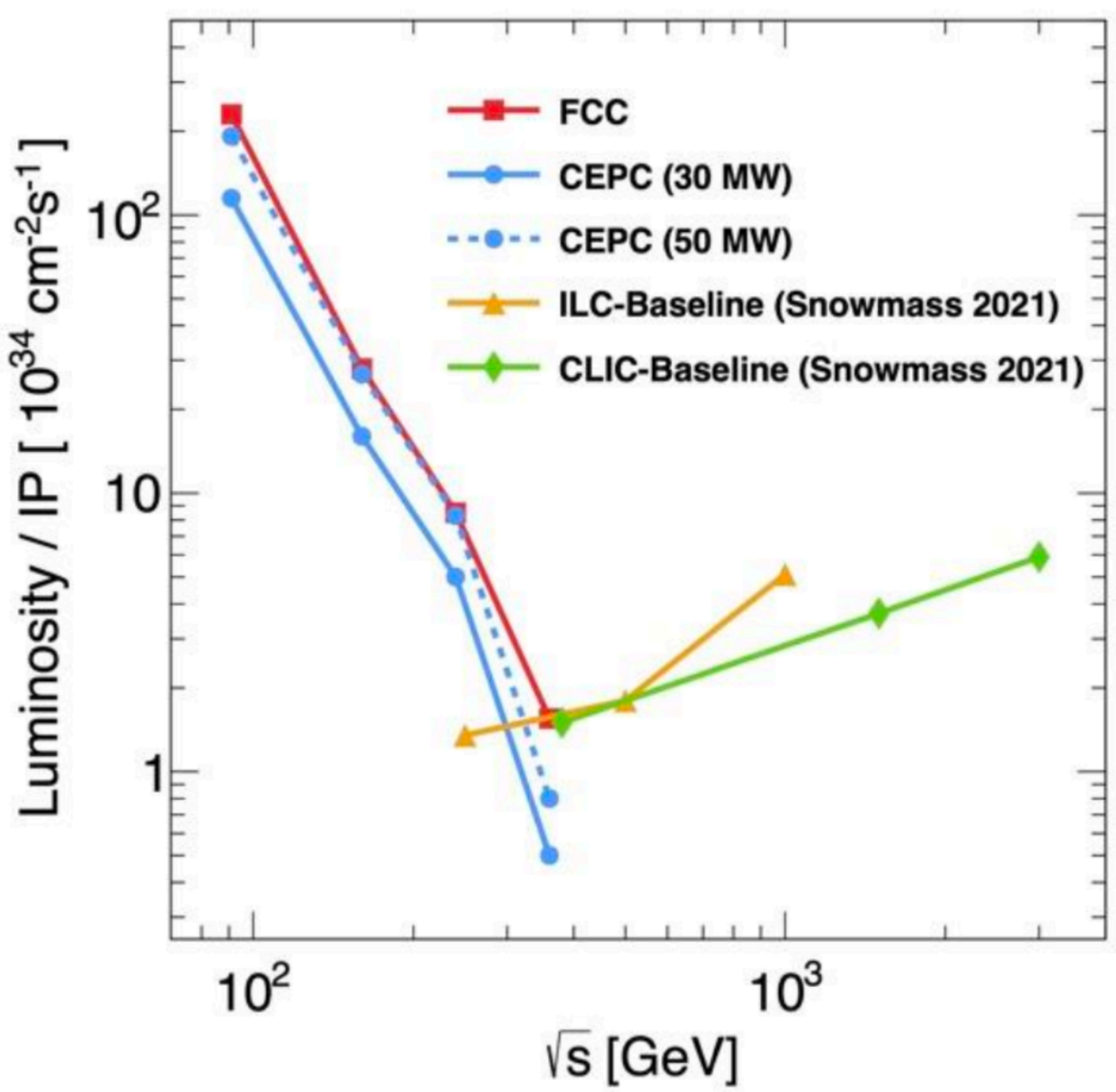


- Improve constraints x2-4 on many operators at **HL-LHC**
- Significant improvement for two-fermion electroweak operators at **FCC-ee**
- Further improvements for various two-fermion operators at higher energies at **ILC/CLIC**
- Entering a high energy regime at **FCC-hh** with an order of magnitude improvement for $q\bar{q}t\bar{t}$ with respect to HL-LHC!

arXiv:2205.02140 [hep-ph]

Global fit with NLO eett for Triple Higgs coupling





(iv) first look at the global fit with NLO eett for $\Delta\lambda_{HHH}$

by: Yong Du, Jiayin Gu, JT]

- based on a fitting program for last ESU: 23 (Higgs + WW + EWPO) + 5 (eett) operators
- take directly covariance matrix as eett bounds (from Victor Miralles)
- reproduced (almost) the NLO calculation about eett in ZH

extra uncertainty induced by eett on σ_{ZH}

$\delta\sigma_{ZH}$ ~ 0.3% (1.5%) for 240 (365) GeV

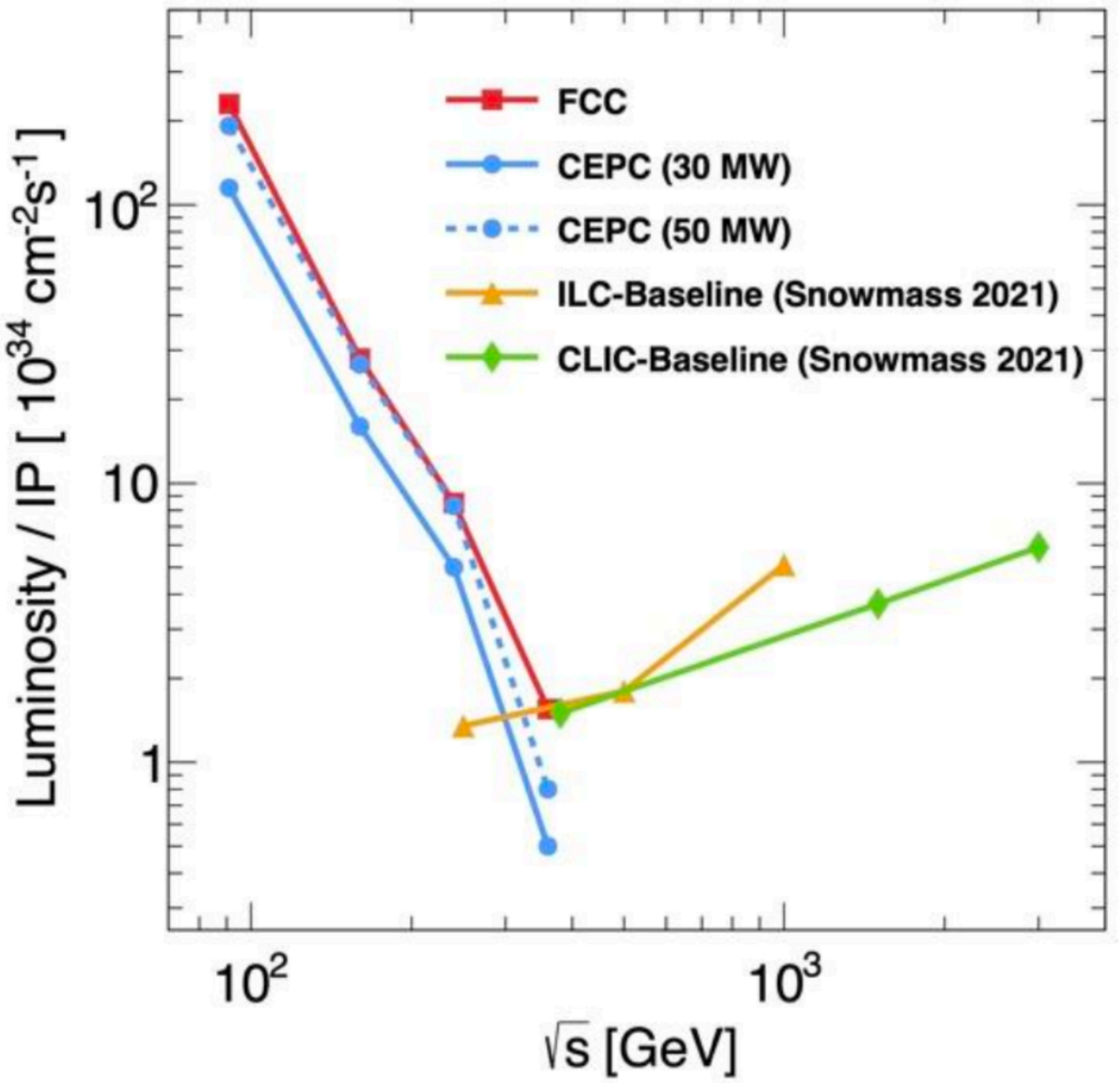
a test fit for 5000 fb^{-1} (240) + 1500 fb^{-1} (365)

$\delta\lambda_{HHH}$ mildly degraded from 57% to 77%

[warning: this is very preliminary, many things to be done, e.g. include NLO eett in other observables as well.]

Junping Tian (U.Tokyo)

Luminosity Future Colliders

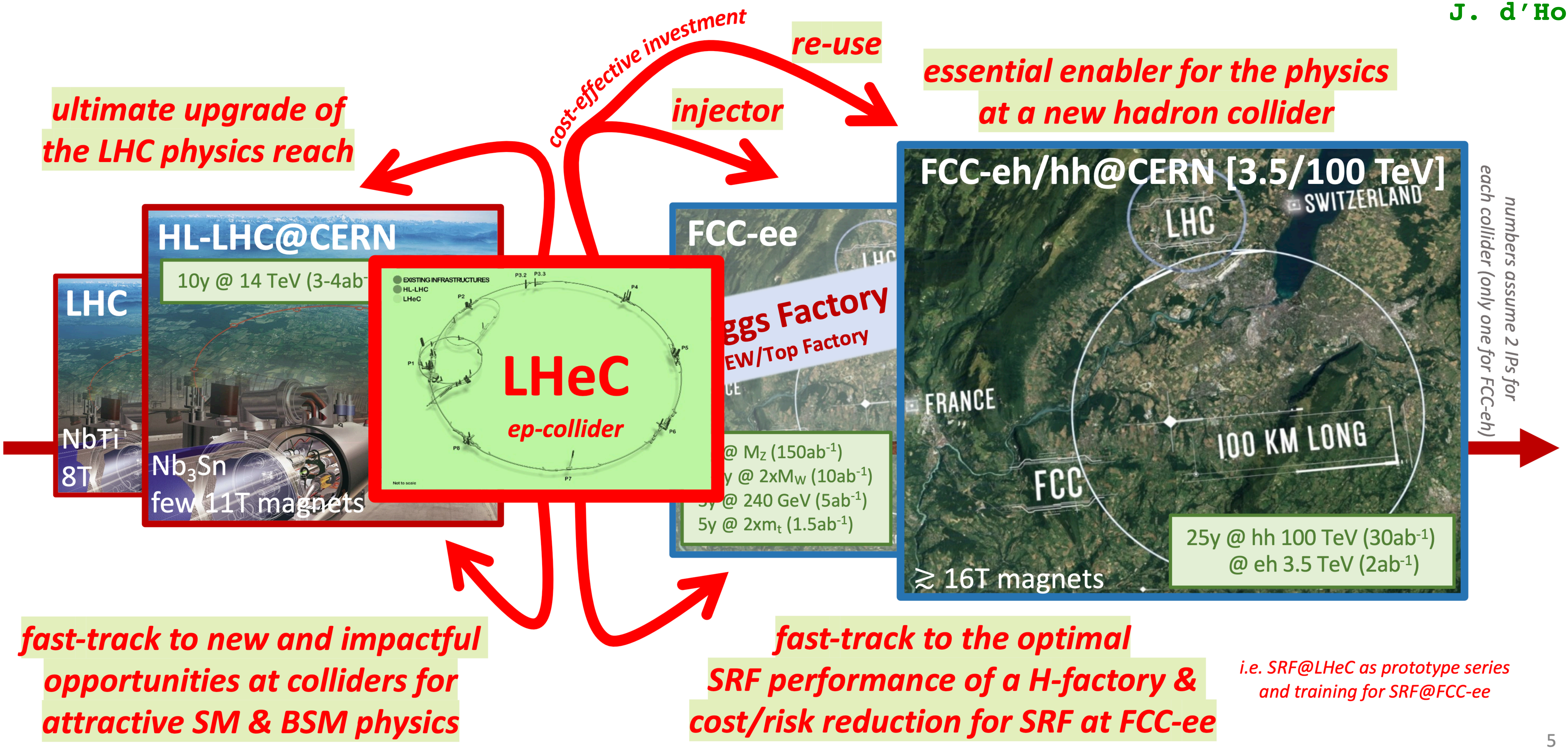


arXiv:2312.14363

More Backup

Major current & future colliders @ CERN

J. d'Hondt



ultimate upgrade of the LHC physics reach

essential enabler for the physics at a new hadron collider

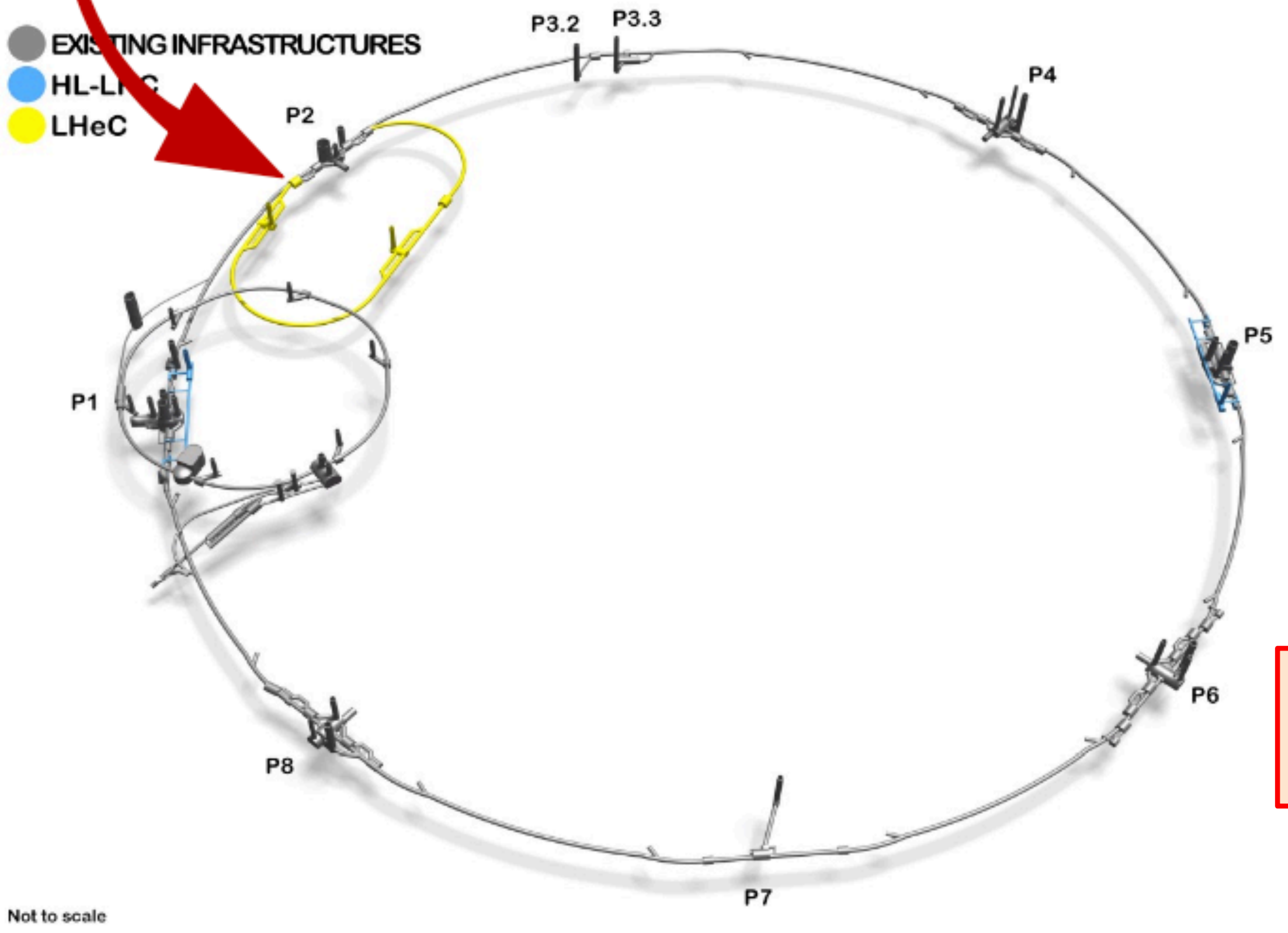
fast-track to new and impactful opportunities at colliders for attractive SM & BSM physics

fast-track to the optimal SRF performance of a H-factory & cost/risk reduction for SRF at FCC-ee

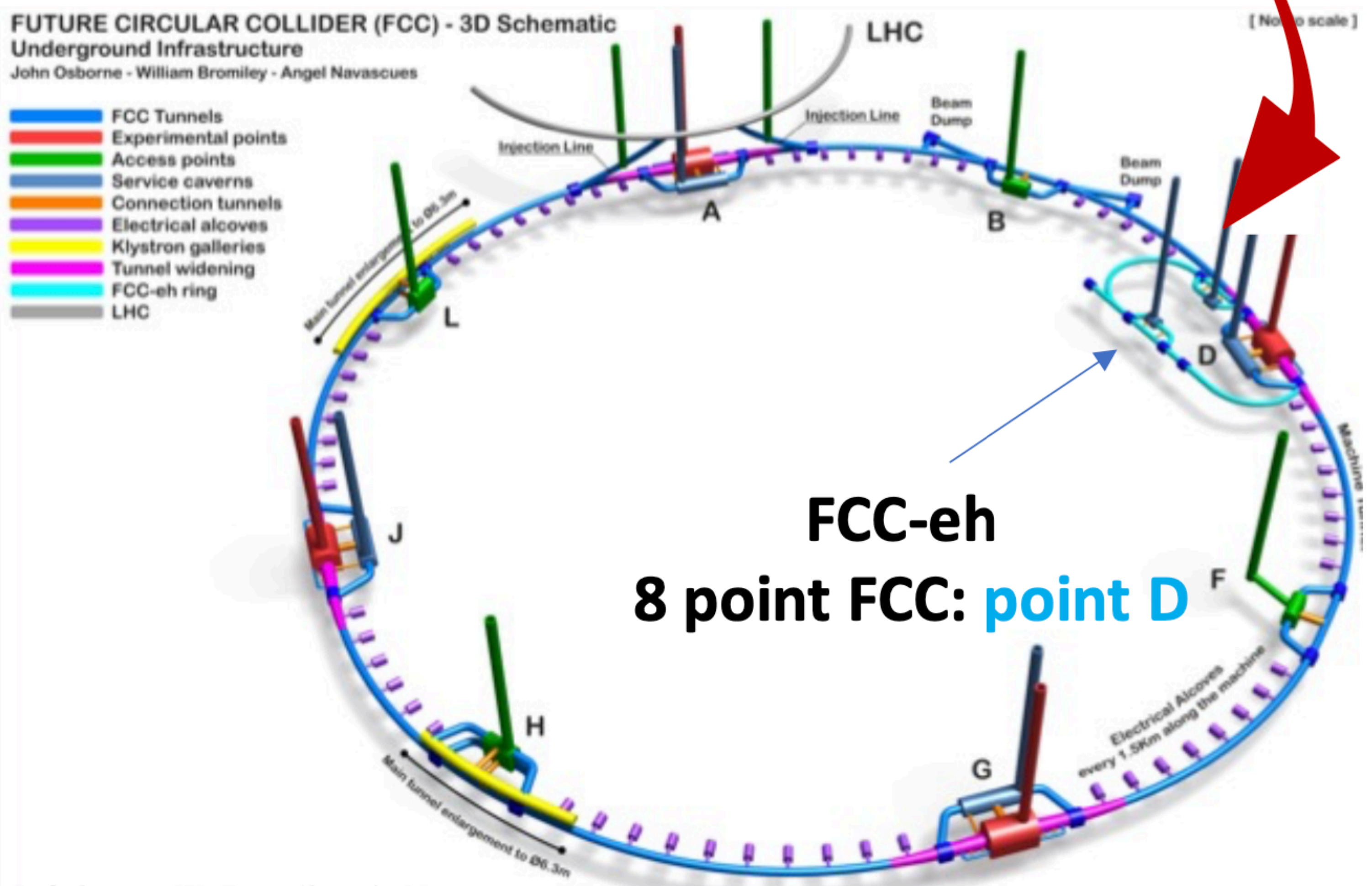
i.e. SRF@LHeC as prototype series and training for SRF@FCC-ee

Linac-Ring Collider, LHeC and FCC-eh

LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC ($\gtrsim$Run5)



FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh

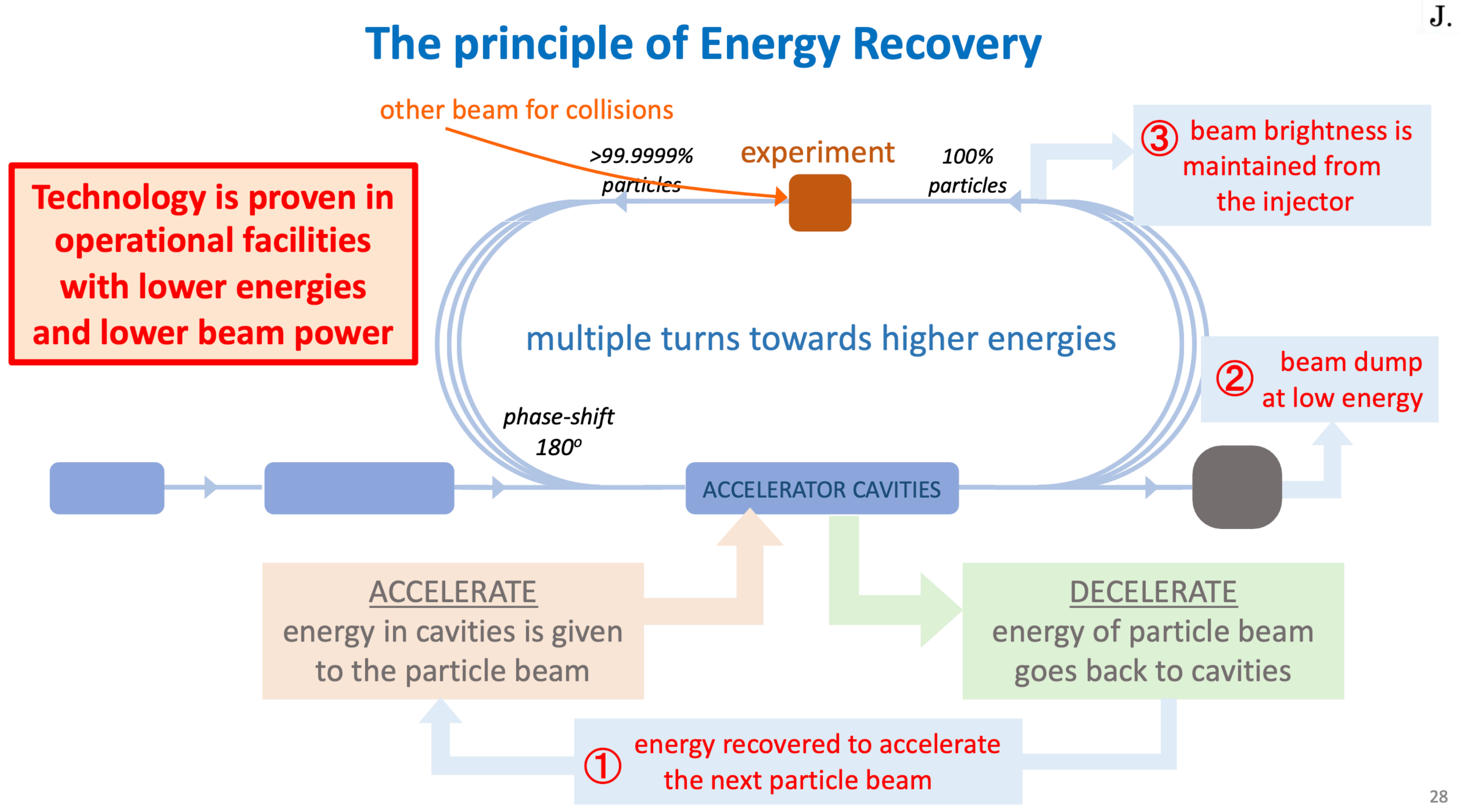


FCC-eh
8 point FCC: point D

J. Osborne, W. Bromiley, A. Navascues

L_{int} = 1-2 ab^{-1} (1000×HERA!)

Energy Recovering Linac



The principle of Energy Recovery

Technology is proven in operational facilities with lower energies and lower beam power

other beam for collisions

>99.9999% particles

experiment

100% particles

③ beam brightness is maintained from the injector

multiple turns towards higher energies

② beam dump at low energy

phase-shift 180°

ACCELERATOR CAVITIES

ACCELERATE
energy in cavities is given to the particle beam

DECELERATE
energy of particle beam goes back to cavities

① energy recovered to accelerate the next particle beam

28

FCC CDR:
Eur. Phys. J. C 79, no. 6, 474 (2019) – Physics
Eur. Phys. J. ST 228, no. 4, 755 (2019) – FCC-hh/eh

LHeC CDRs:
arXiv:1206.2913, J. Phys. G 39 075001 (2012)
arXiv:2007.14491, J. Phys. G 48, 11, 110501

LHeC Parameters

Recirculating Energy-Recovery Linac, colliding with LHC hadrons

Final upgrade to LHC

Continuity of collisions in 2040s

Bridging towards next major collider at CERN

- Potentially ‘affordable’
- Technically realisable
- Exploring sustainable acceleration with ERL and SRF-cavities
- Developing new detector technologies

- Enabling HL-LHC precision
- Complementing HL-LHC H programme
- Extending energy frontier sensitivity

Environmental cost of construction:
Annual environmental cost of operation:
Awaiting lab directors’ report. Small tunnel length & ERL / SRF technologies → relatively modest impact

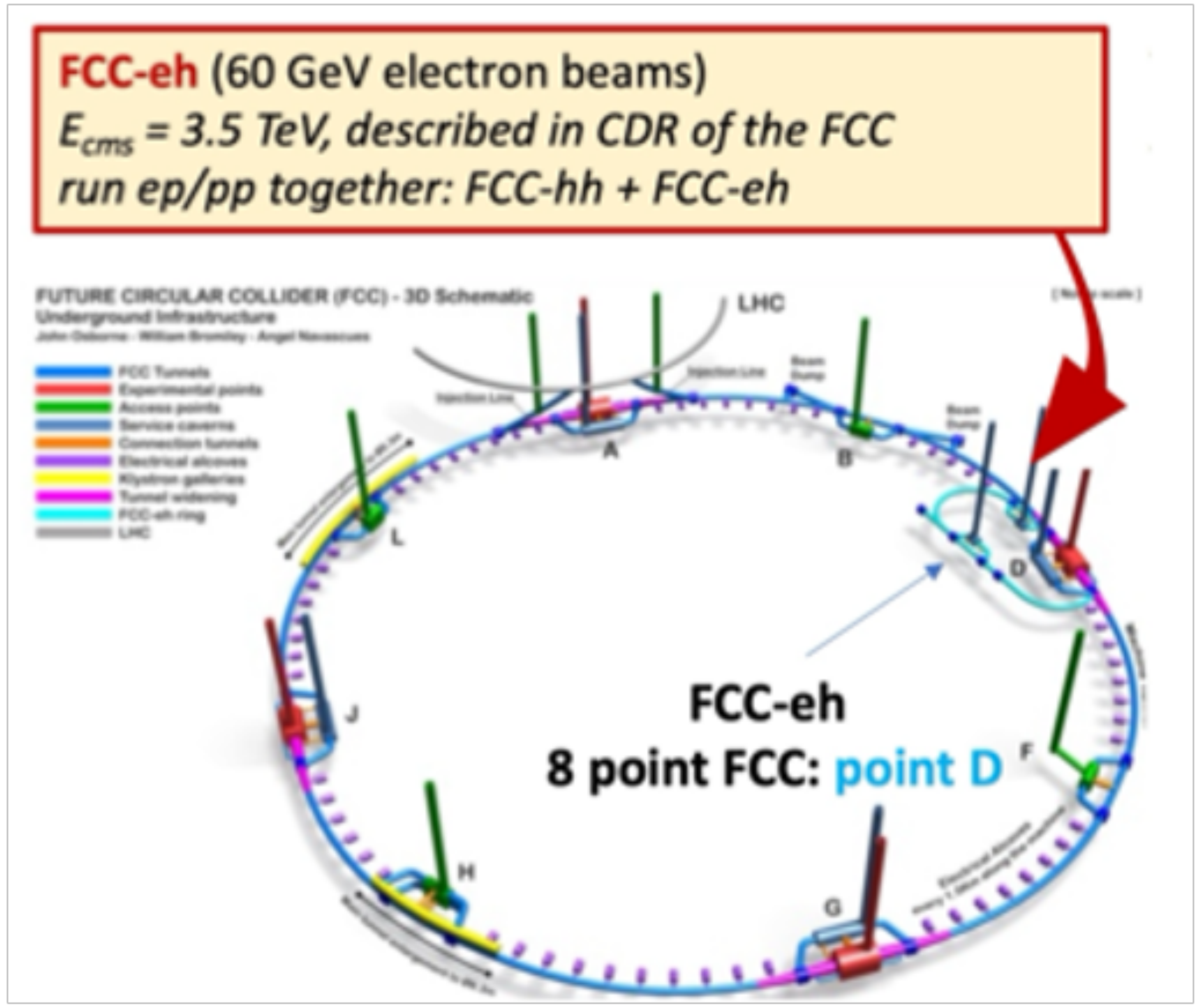
Financial cost: Baseline costed estimated in 2018 at CHF1.4B for 50 GeV electrons (1/5 of LHC circumference) [O. Bruning, CERN-ACC-2018-0061]

Dedicated submission planned to ESPPU: Yes

Centre-of-Mass Energy: 1.2 TeV for baseline 50 GeV electron option
Integrated Luminosity: A few x 100 fb^{-1} in concurrent operation with HL-LHC
Of order 1 ab^{-1} for a few years standalone operation
Number of Interaction Points: 1 (by design)
Time running: A few years
Wall power: 100 MW (by design) ~ LHC now.
Accelerator length: 5.4km for baseline 50 GeV electron option
Estimated year of 1st collisions: Late 2030s or beyond
Future upgrade paths: Very similar design for FCC-eh

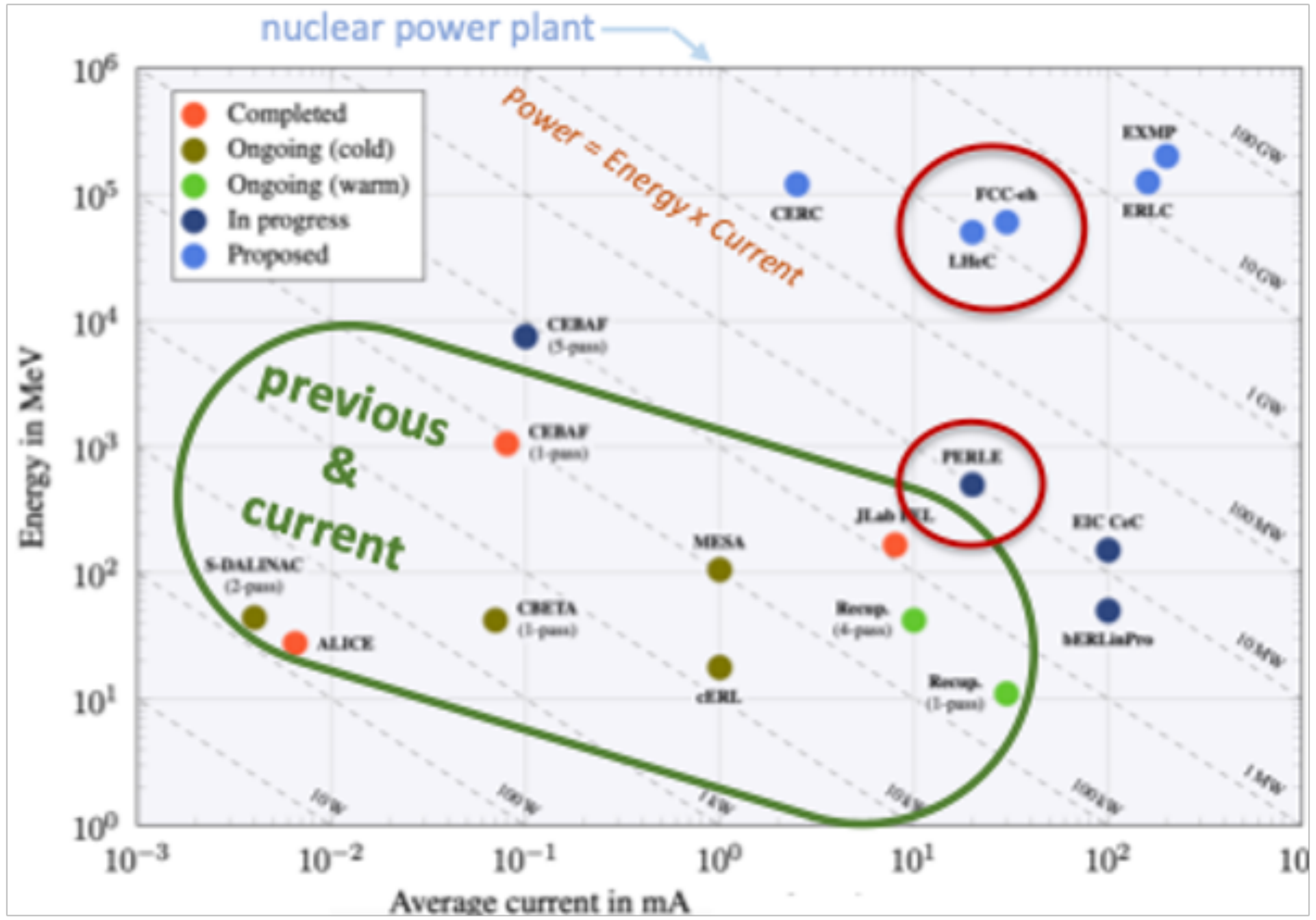
The FCC-eh Complex

- centre-of-mass energy: 3.5 TeV (assuming 60 GeV electron beam, 50 TeV proton beam)
- integrated luminosity: 1 or 2 /ab
- number of interaction points: 1
- time running at stage: 10-20 years (as many as FCC-hh)
- wall power: 100 MW for ERL?
- accelerator length: same as FCC-hh for proton beam, ERL: 2 km arc, 1 km straight-length, 3 turns
- estimated year for first collisions: 2050+
- future upgrade paths: none at the moment



FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh

ERL development in progress

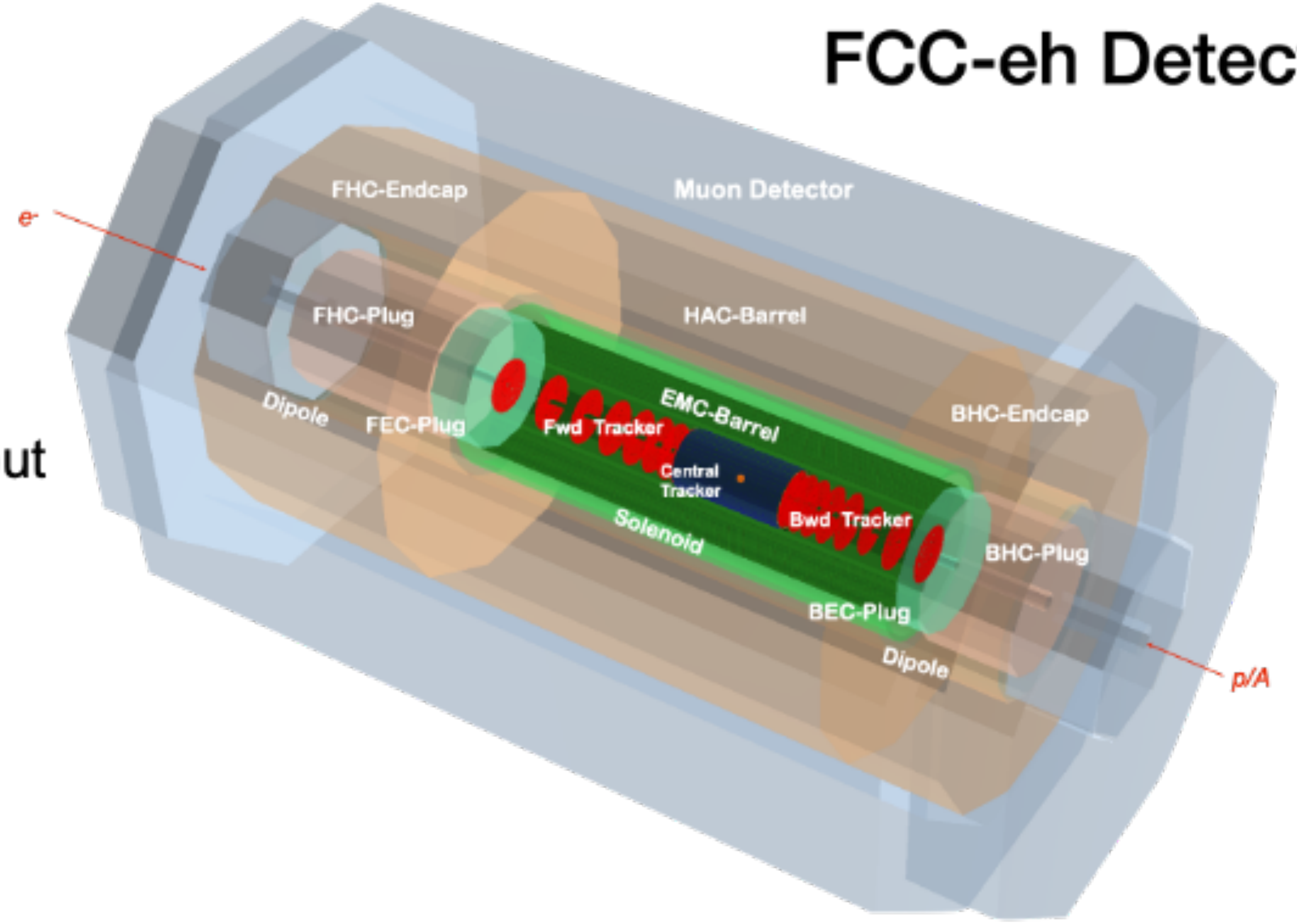


FCC-eh Detector and Operation

R=6.2 m
L=19.3 m, about CMS size

- Asymmetric, reflecting the beam energy asymmetry
- Could be built based on established technologies from ATLAS and CMS but highly benefit from advance in detector tech (e.g. FCC-ee)
- Must be highly **hermetic**
- Must have **fine segmentation** and good resolution for EM calo
- Must have **good tracking capabilities** (e.g. for b-tagging) also in forward region

FCC-eh Detector



- Environmental cost of construction (in units of tonnes of CO2 equivalent)
  - Beam:
  - Construction:
- Environmental cost of operation per year (in units of tonnes of CO2 equivalent)
  - Uses FCC-hh proton beam (no additional cost)
  - ERL
  - Detector
- Estimate of financial costs (provide separate numbers for R+D phase, construction phase and operations phase)
  - ??

Does your project plan dedicated submission(s) for the ESPPU (if so, give details)

- **Yes, a FCC-eh submission will be made (white paper in preparation)**

Signal and Backgrounds

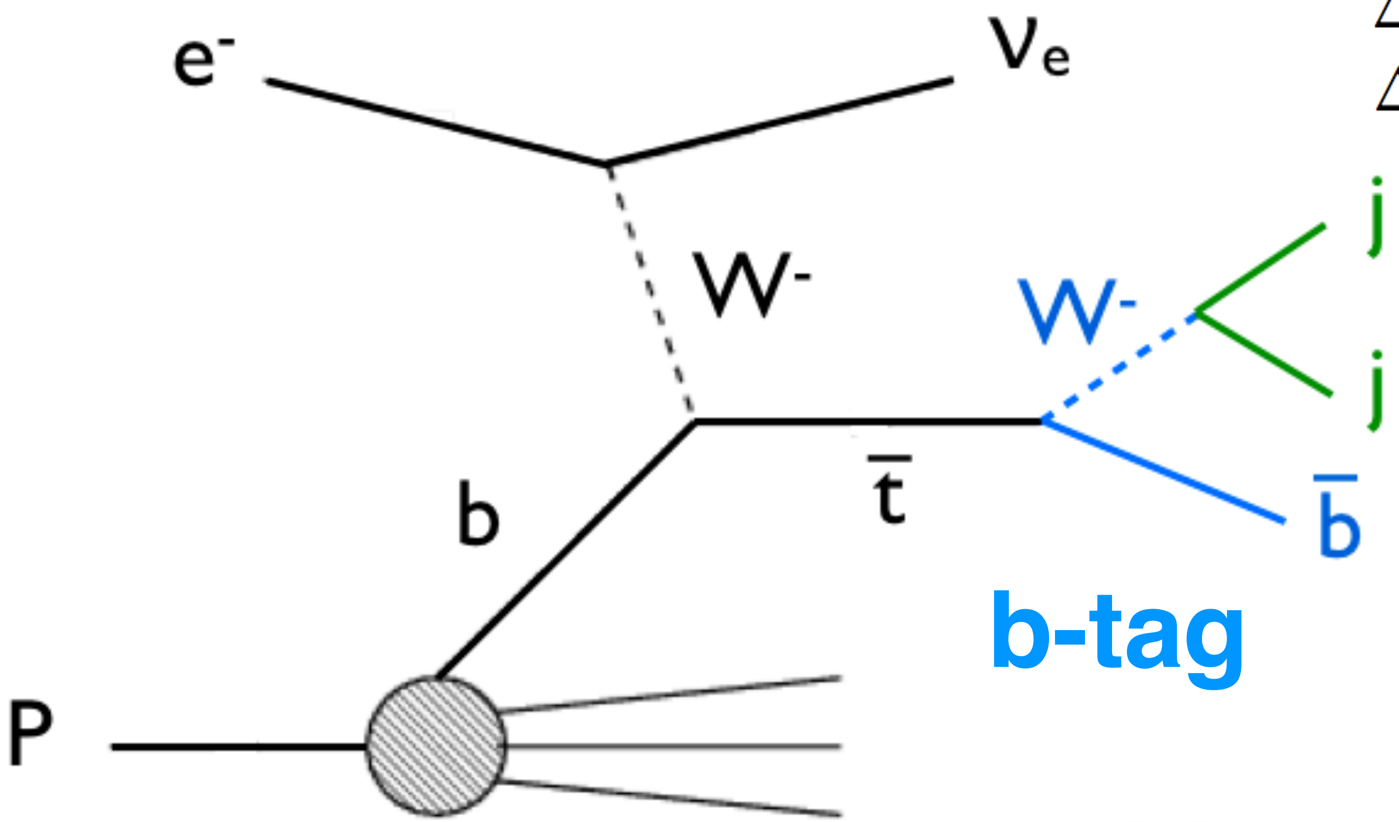
LHeC

signal

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

background

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



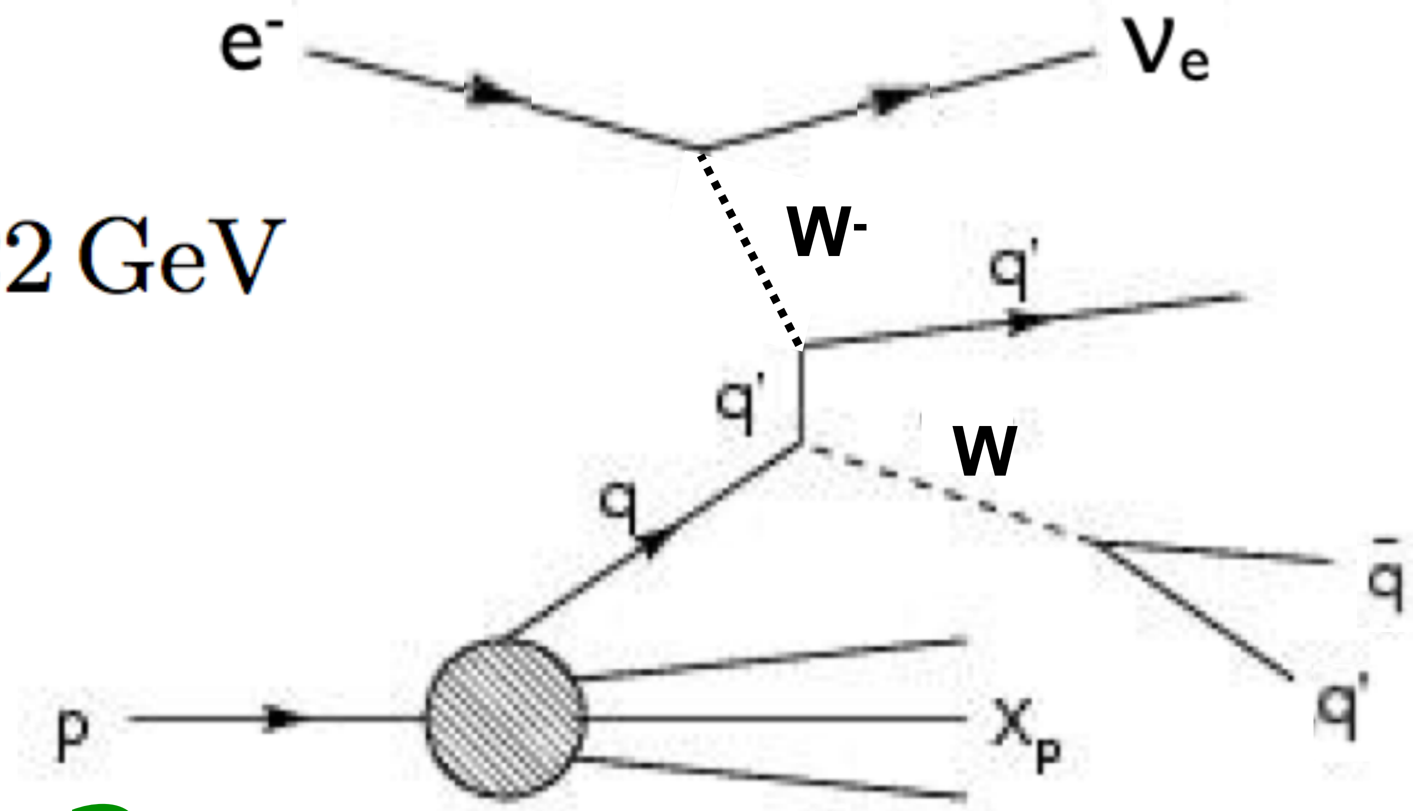
$\Delta\Phi_{\not{E},j} \geq 0.4$
$\Delta\Phi_{\not{E},b} \geq 0.4$

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

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

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

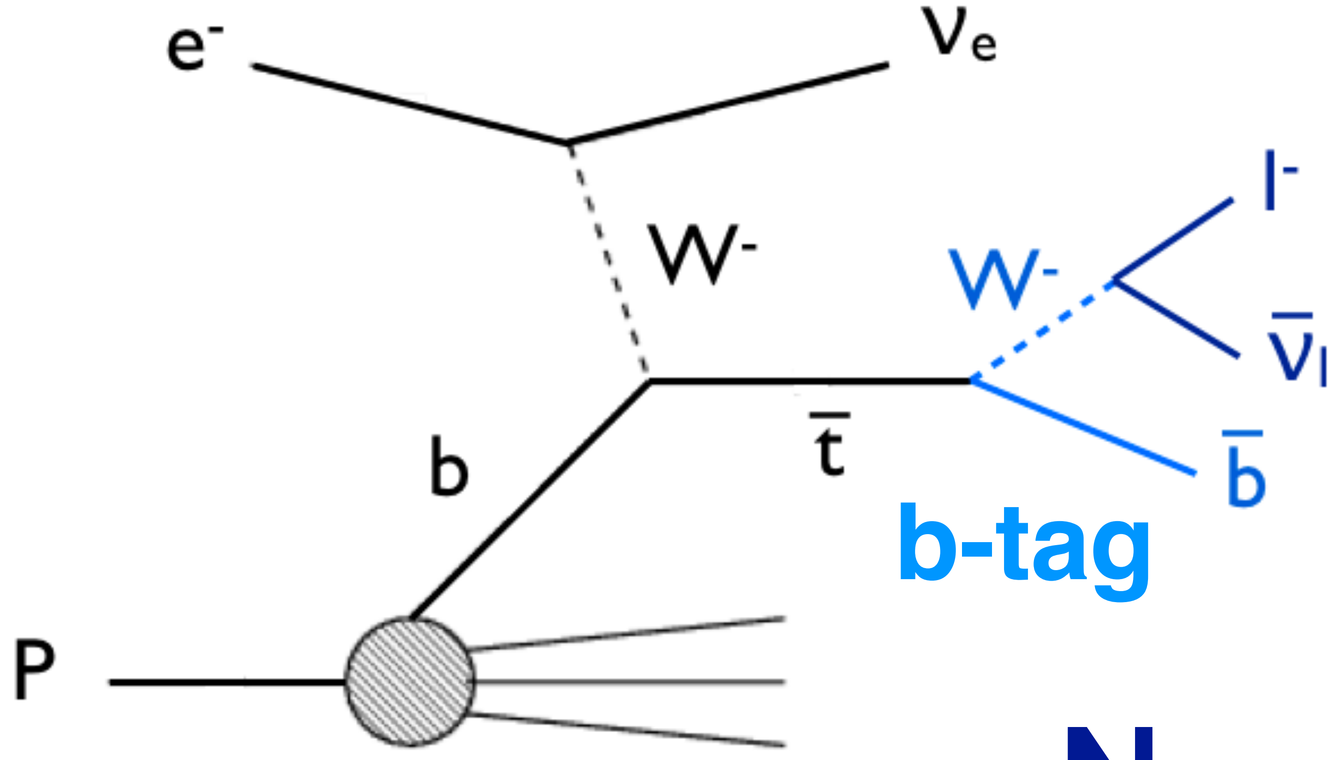
$\Delta R_{j,b/j} \geq 0.4$



N_t=220k, s/b=1.2

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

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

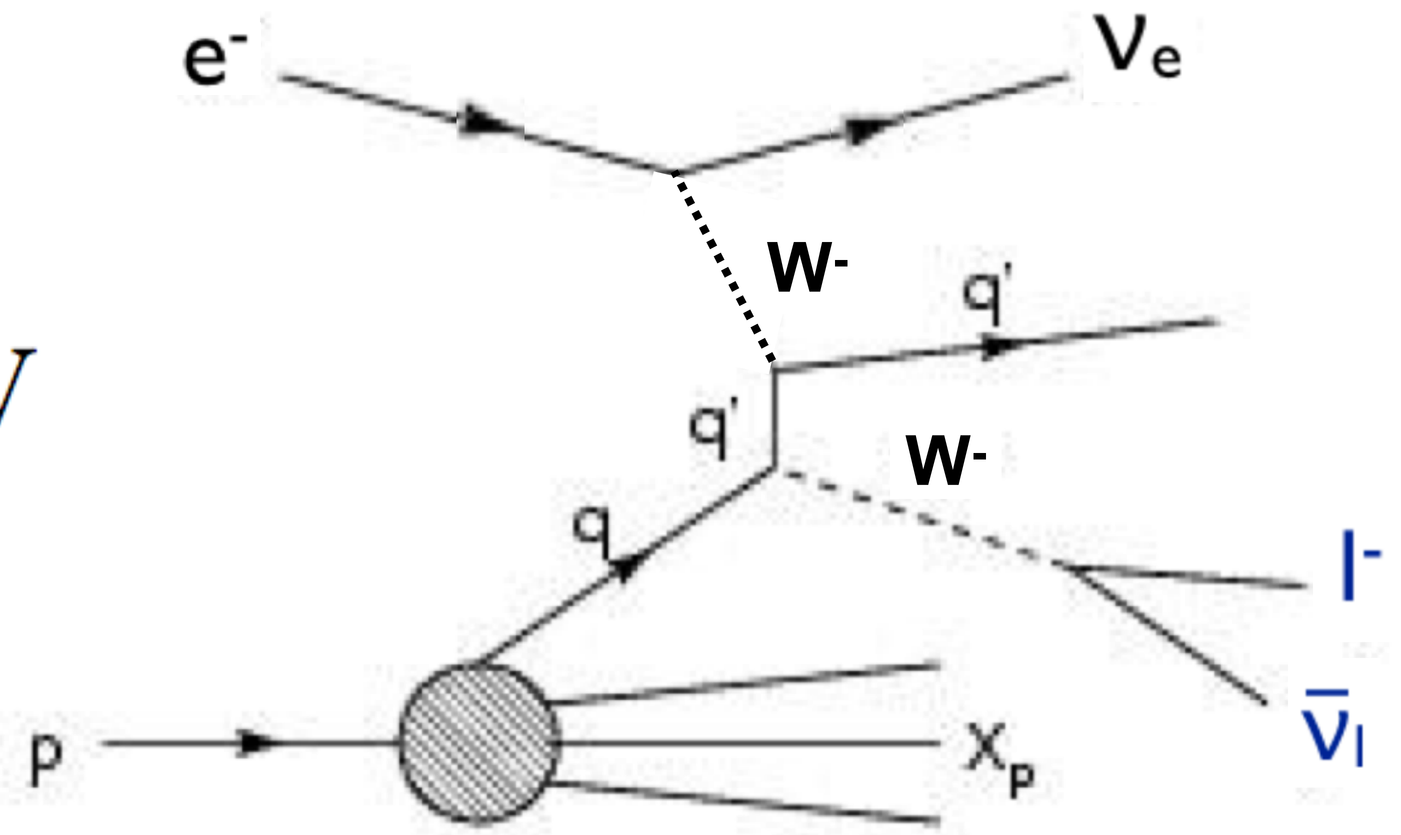


$\Delta\Phi_{\not{E},j} \geq 0.4$
$\Delta\Phi_{\not{E},b} \geq 0.4$
$\Delta\Phi_{\not{E},l} \geq 0.4$

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

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

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



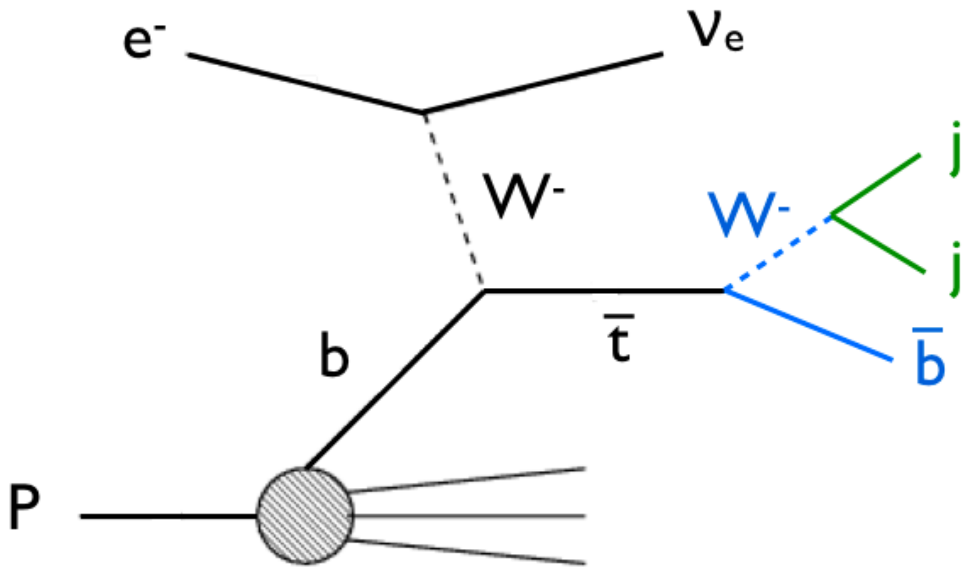
N_t=110k, s/b=11

Search for Anomalous Wtb Couplings

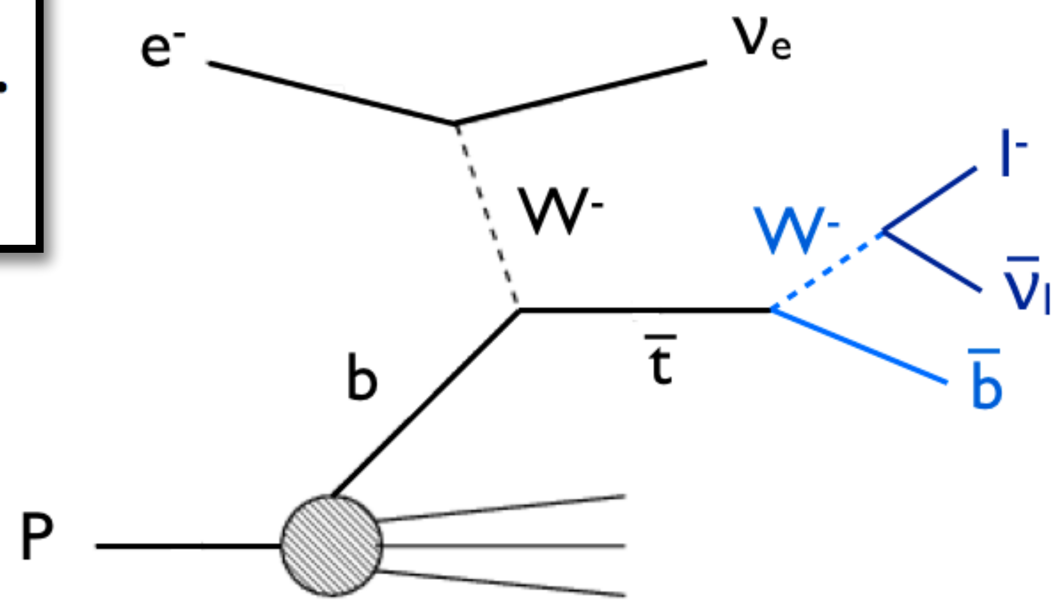
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

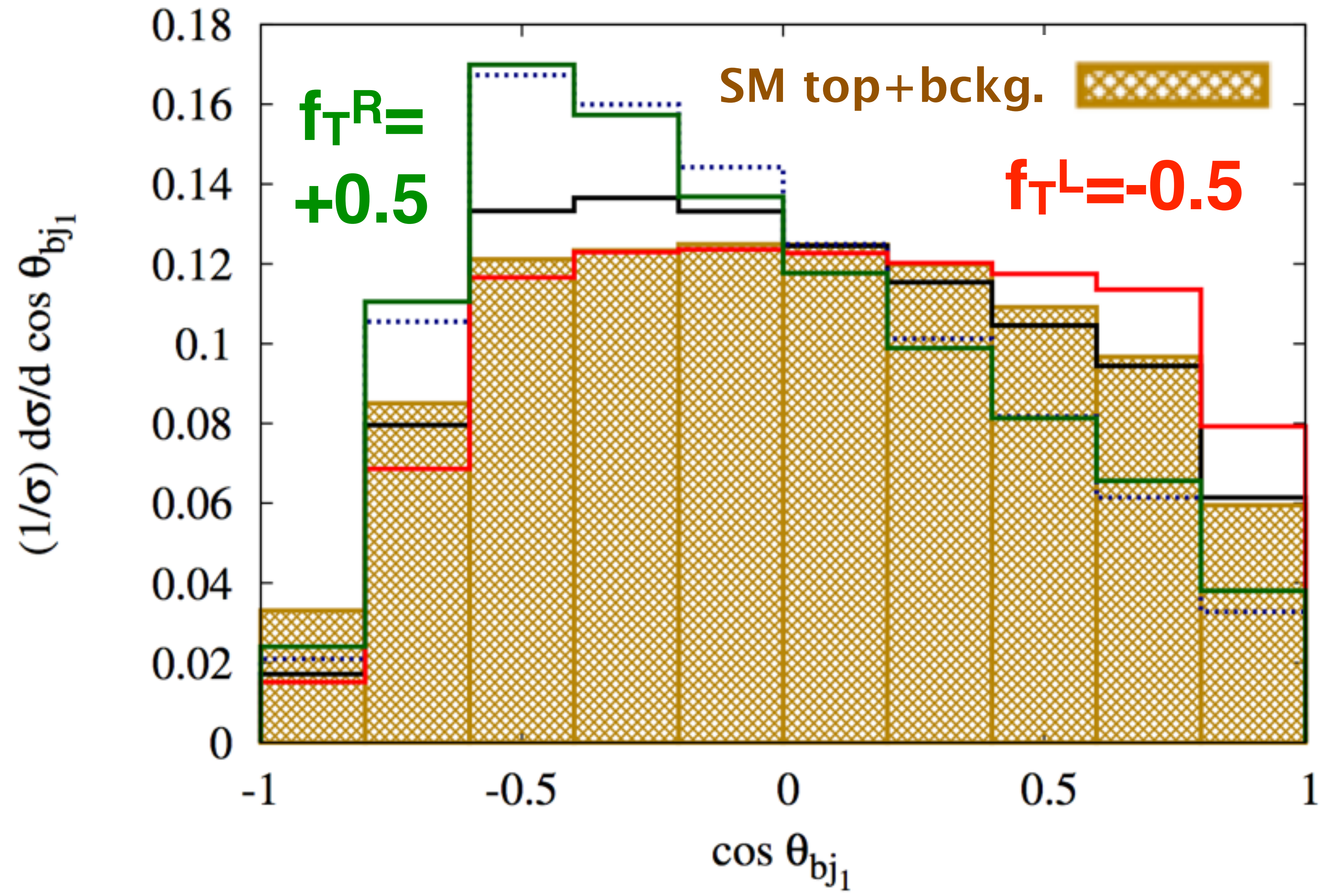
= 1 in SM

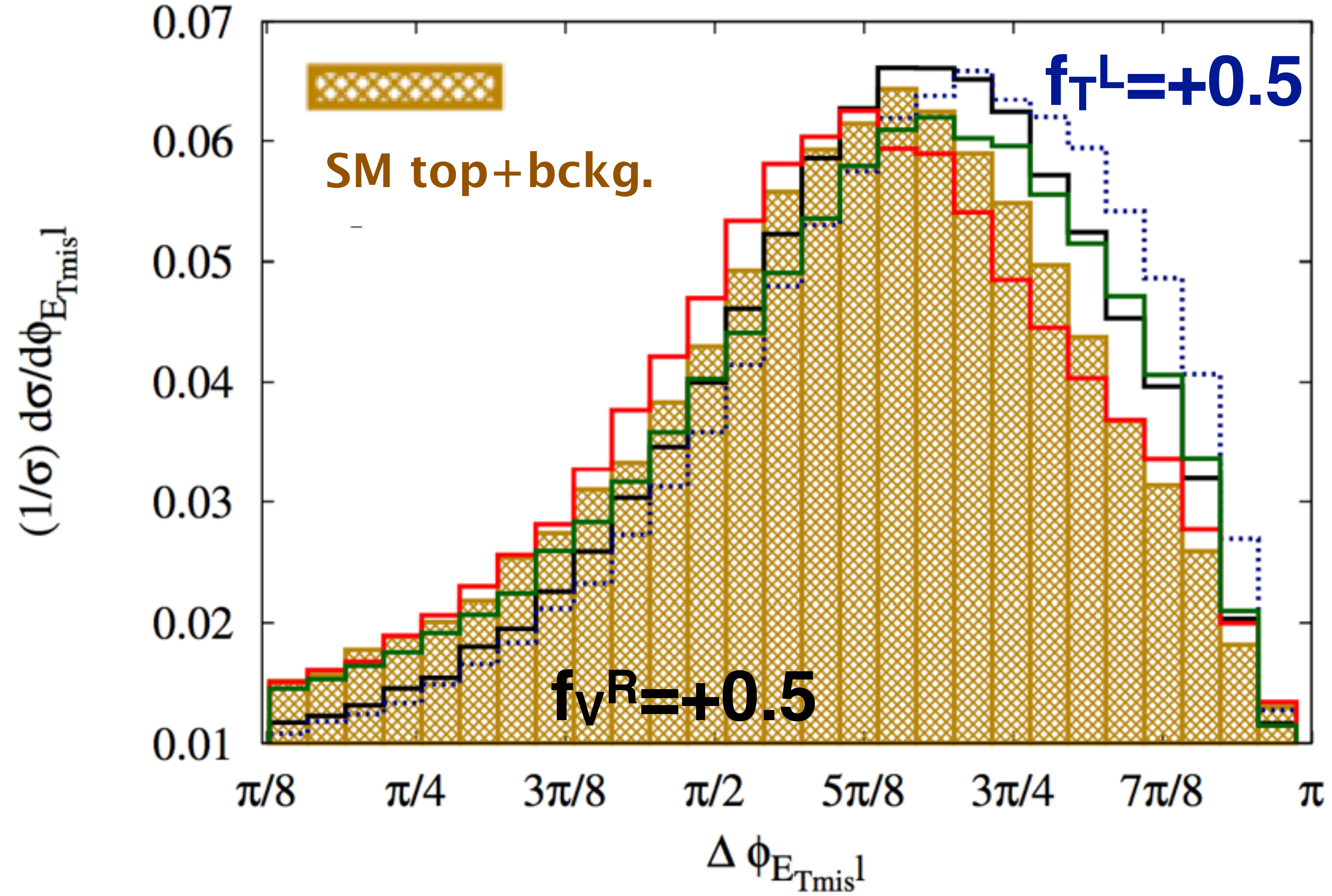
Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688



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

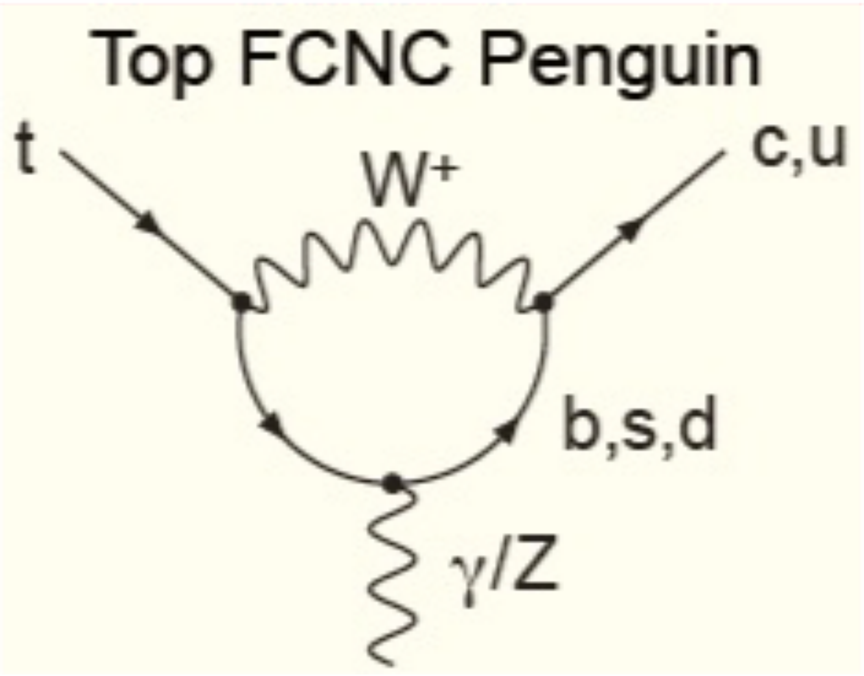


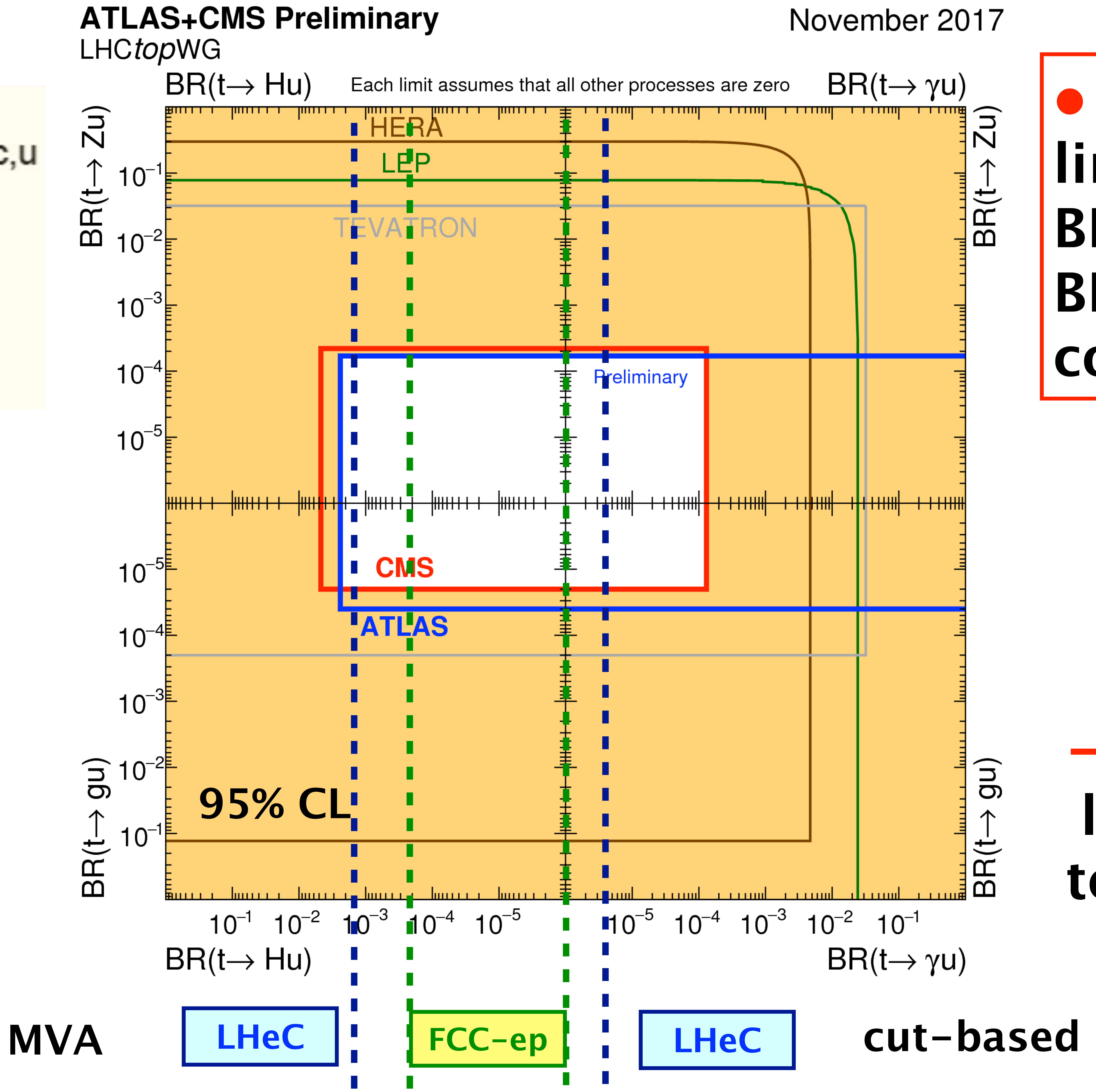




+ other variables sensitive on W helicity

FCNC Branching Ratios at Colliders





- improve limits on $BR(t \rightarrow \gamma u)$, $BR(t \rightarrow Hu)$ considerably

→ test SUSY, little Higgs, technicolor…

E_e=60 GeV
1000 fb^{-1}

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

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

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

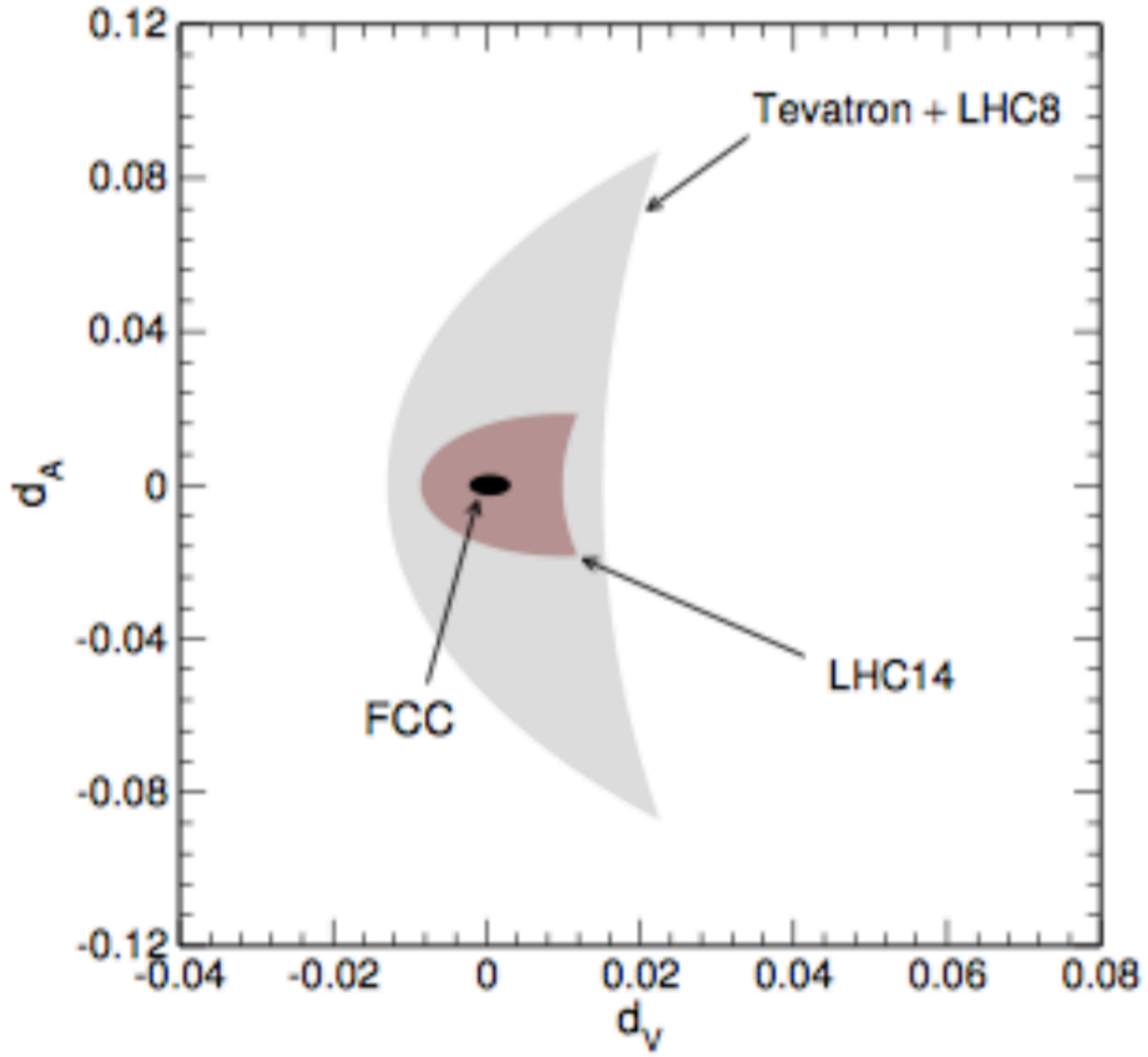
$$O^{33}_{uG\phi} = (\bar{q}_{L3}\lambda_a\sigma^{\mu\nu}t_R)\tilde{\phi}\, G^a_{\mu\nu} \qquad \Rightarrow \qquad d_V = \frac{\sqrt{2}vm_t}{g_s\Lambda^2}\mathrm{Re}\, C^{33}_{uG\phi}\,, \quad d_A = \frac{\sqrt{2}vm_t}{g_s\Lambda^2}\mathrm{Im}\, C^{33}_{uG\phi}$$

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

$-0.0022 \leq d_V \leq 0.0031$

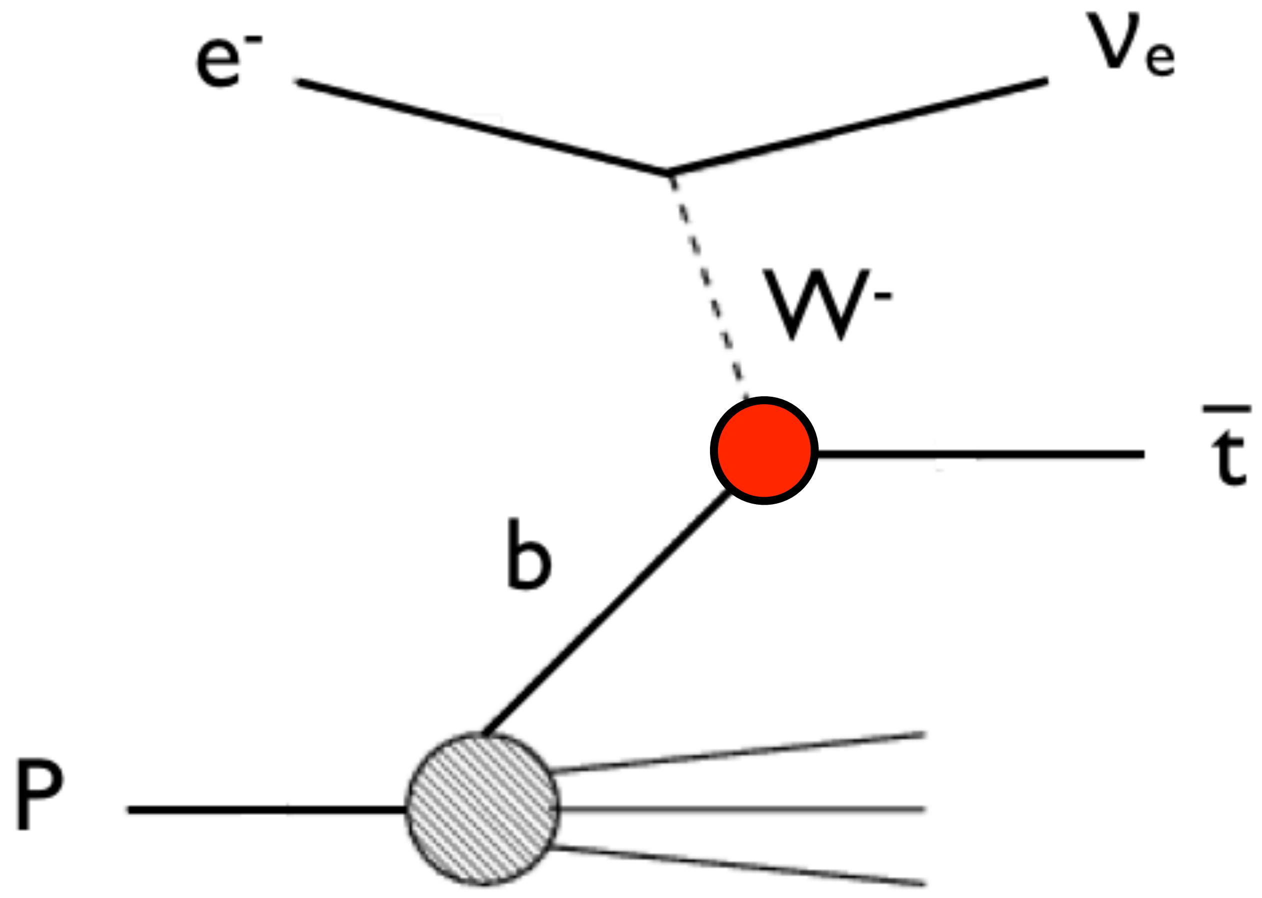
$|d_A| \leq 0.0026$

$\Rightarrow \Lambda \gtrsim 17$ TeV



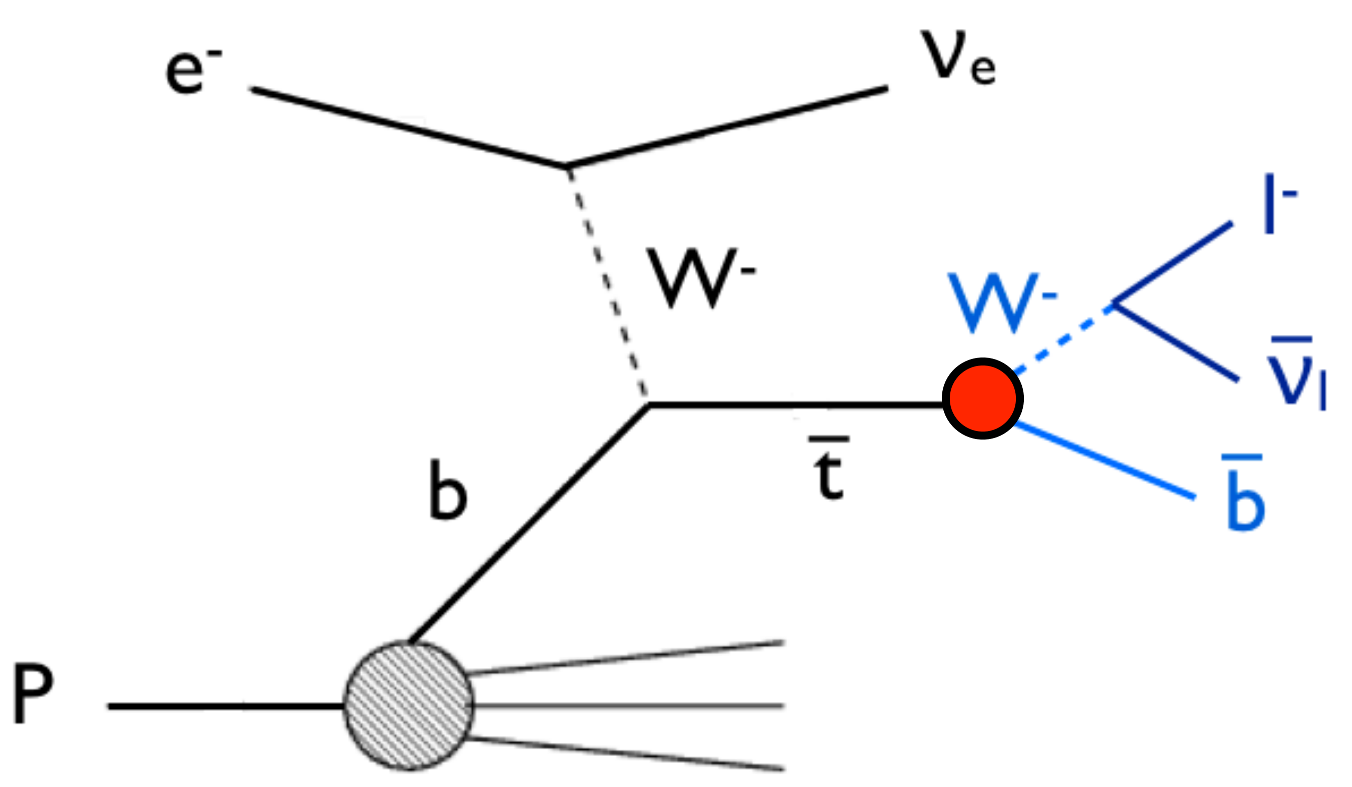
Direct Measurement of $|V_{tb}|$

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



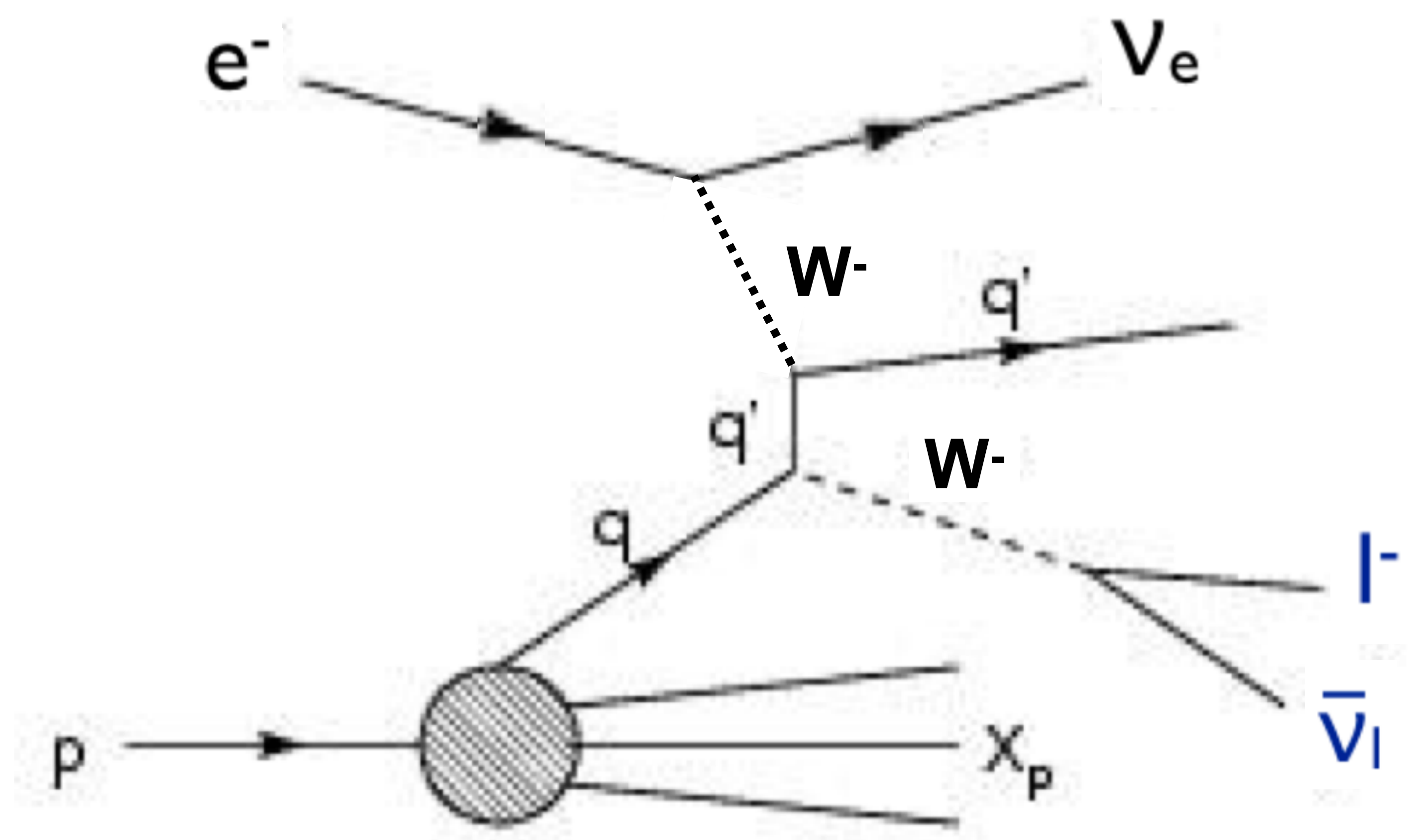
Direct Measurement of $|V_{tb}|$

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



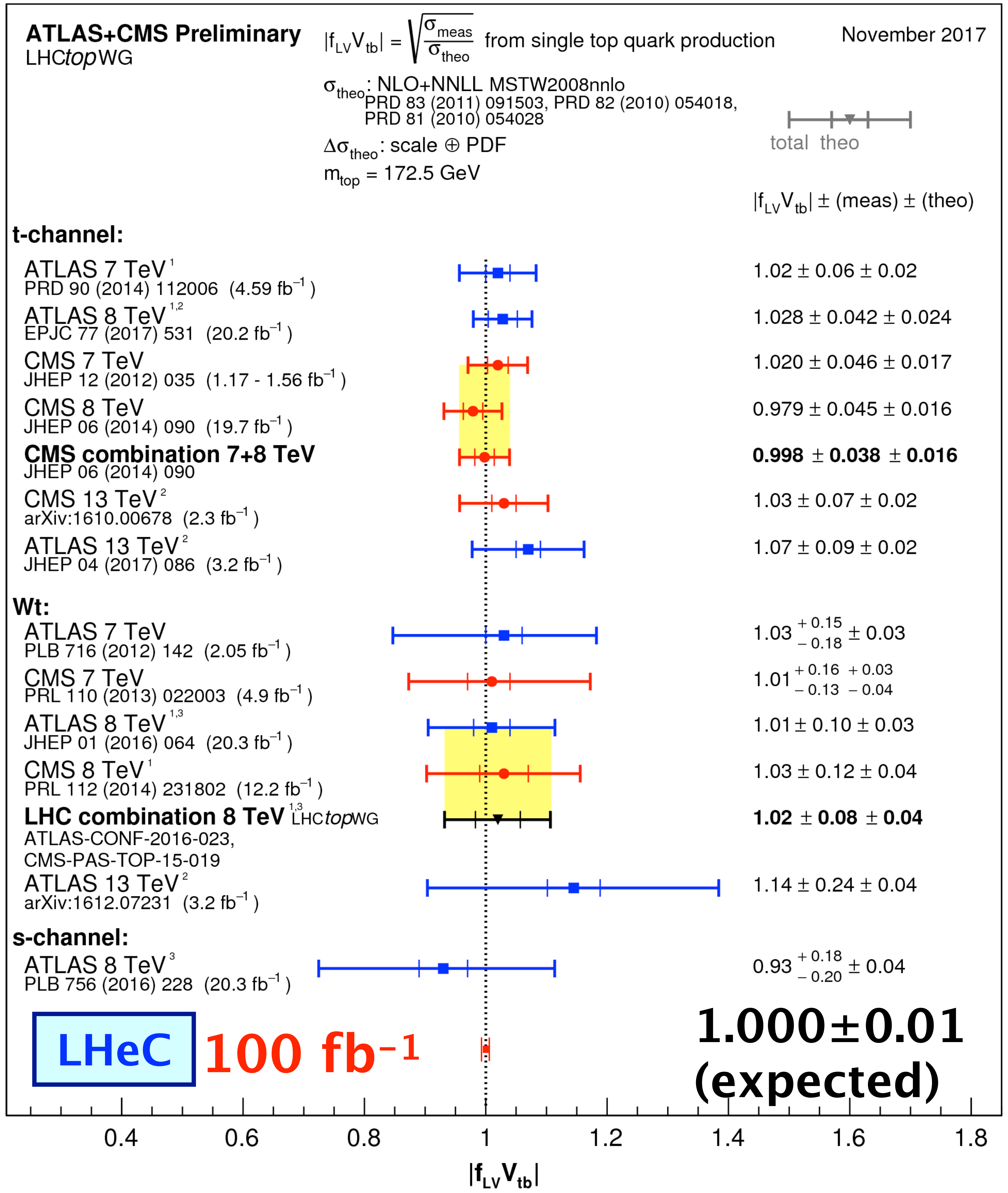
signal

s/b=11



background

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



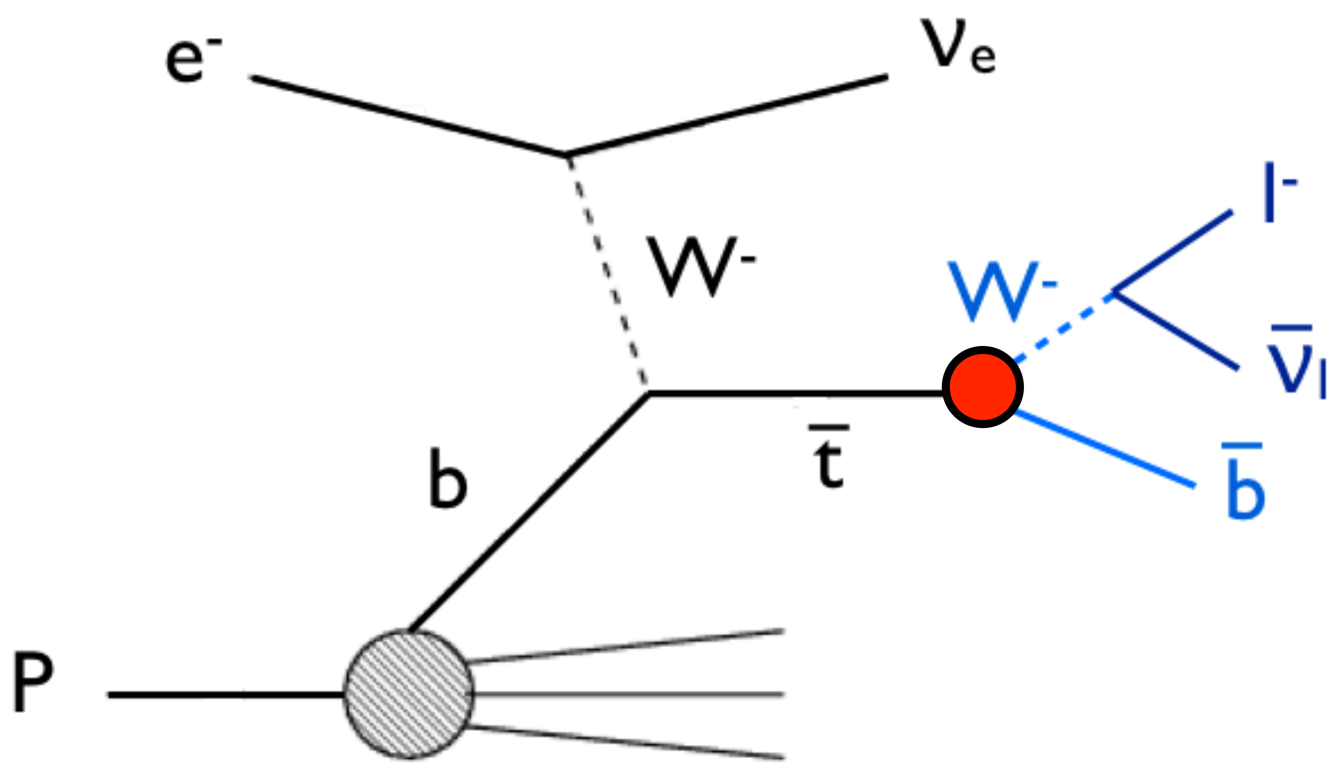
LHeC 100 fb^{-1}

1.000±0.01 (expected)

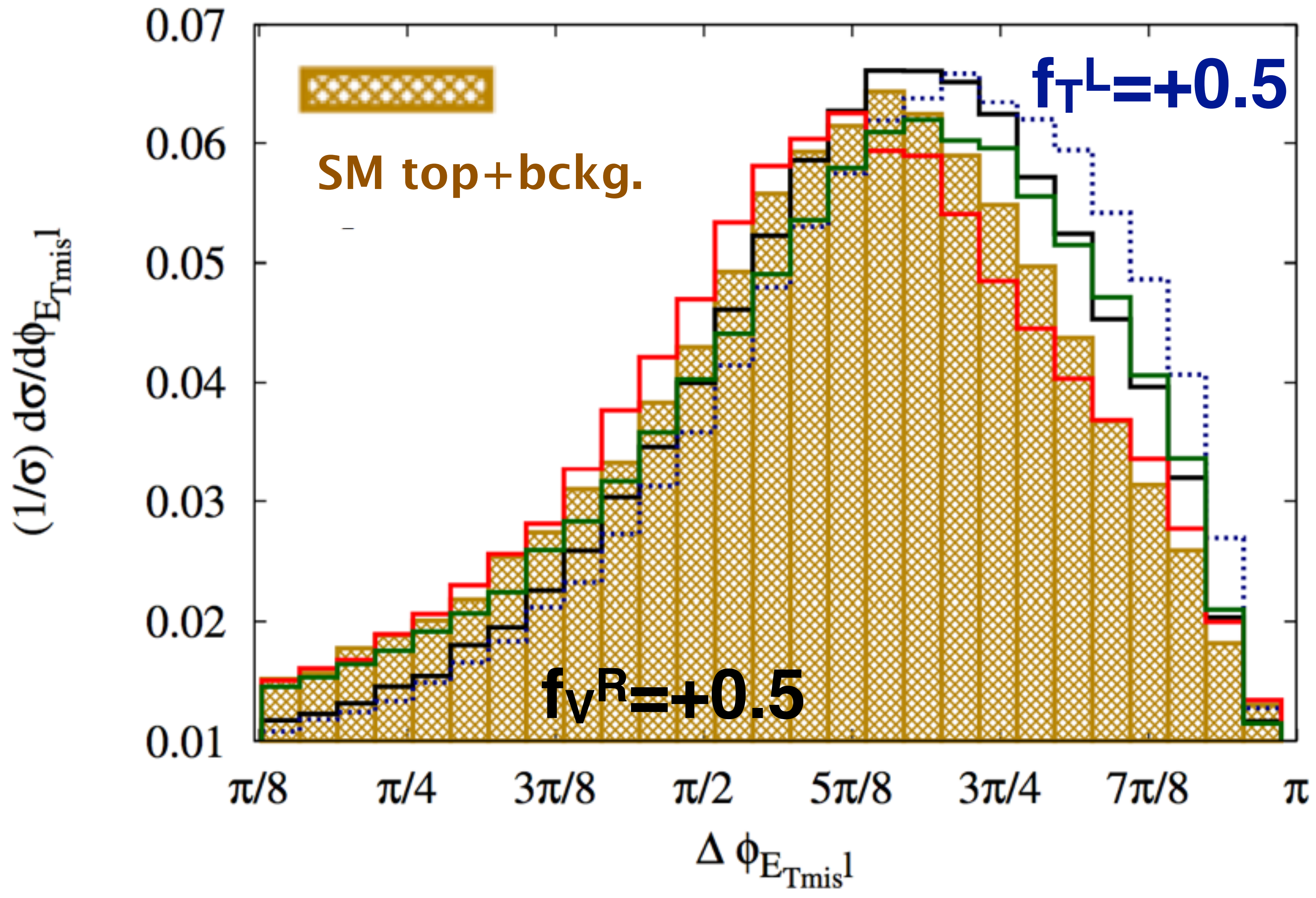
Search for Anomalous Wtb Couplings

= 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

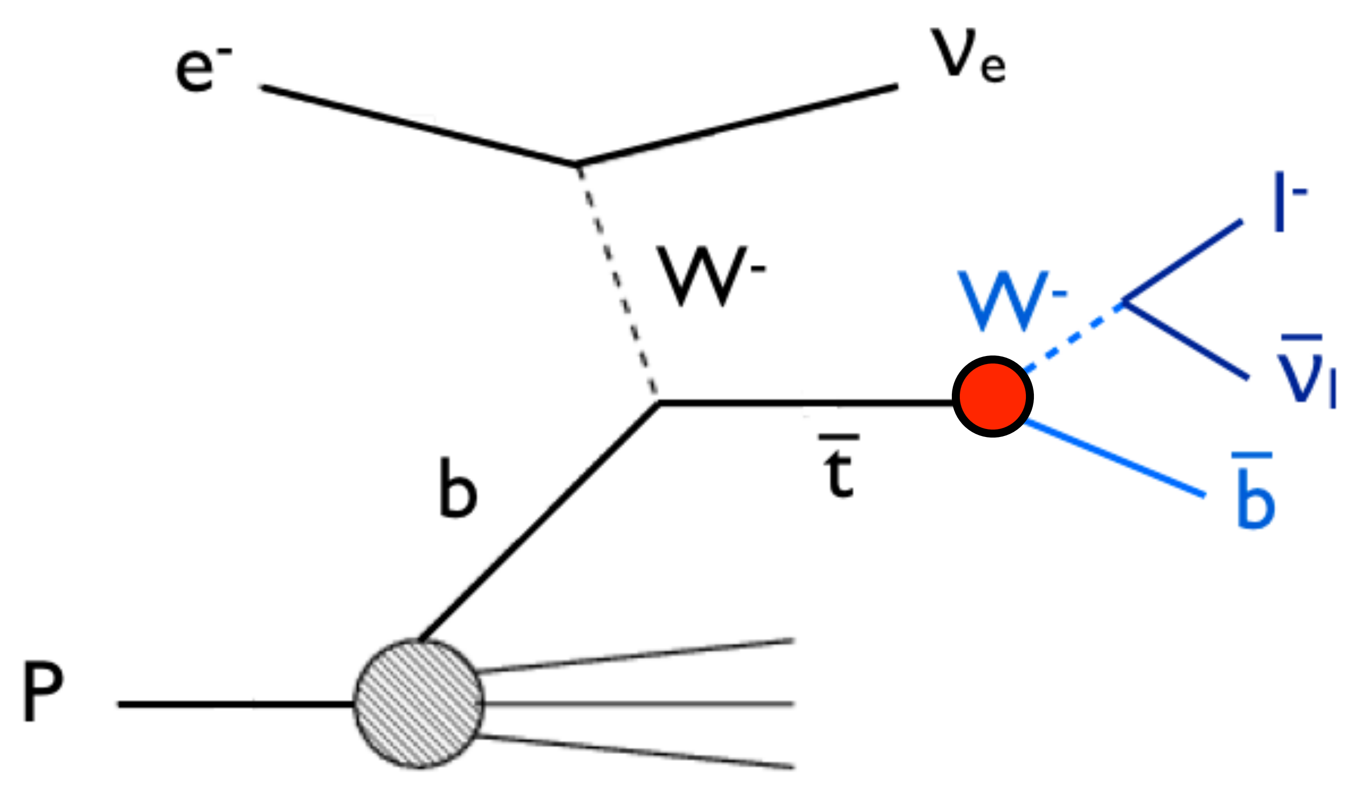


+ other variables sensitive on W helicity

Search for Anomalous Wtb Couplings

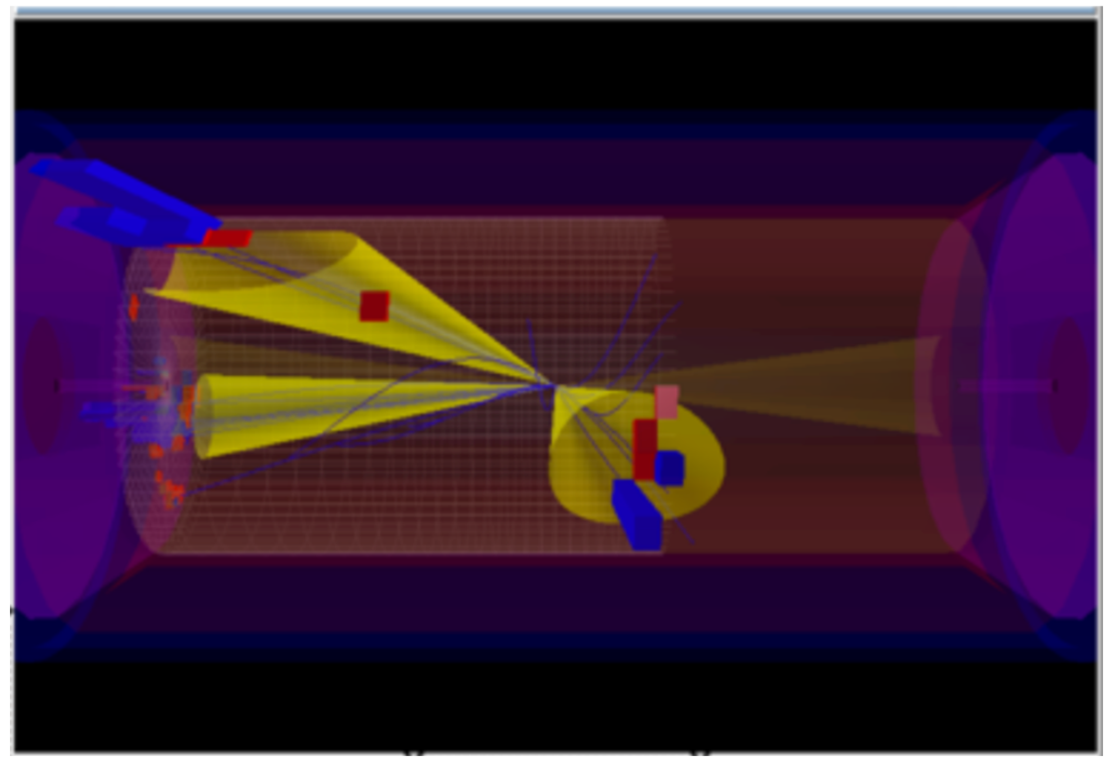
= 1 in SM

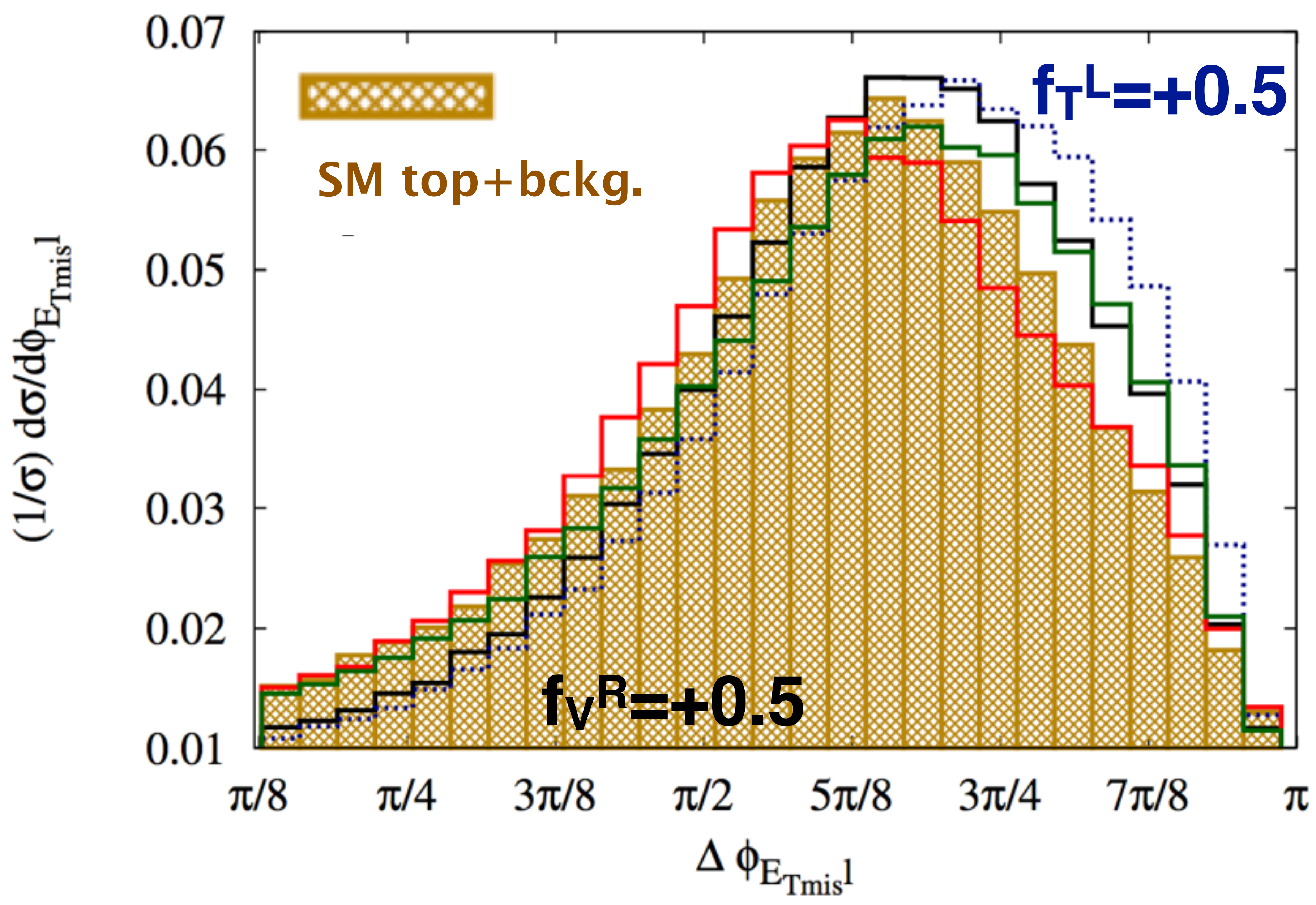
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$



signal

DELPHES

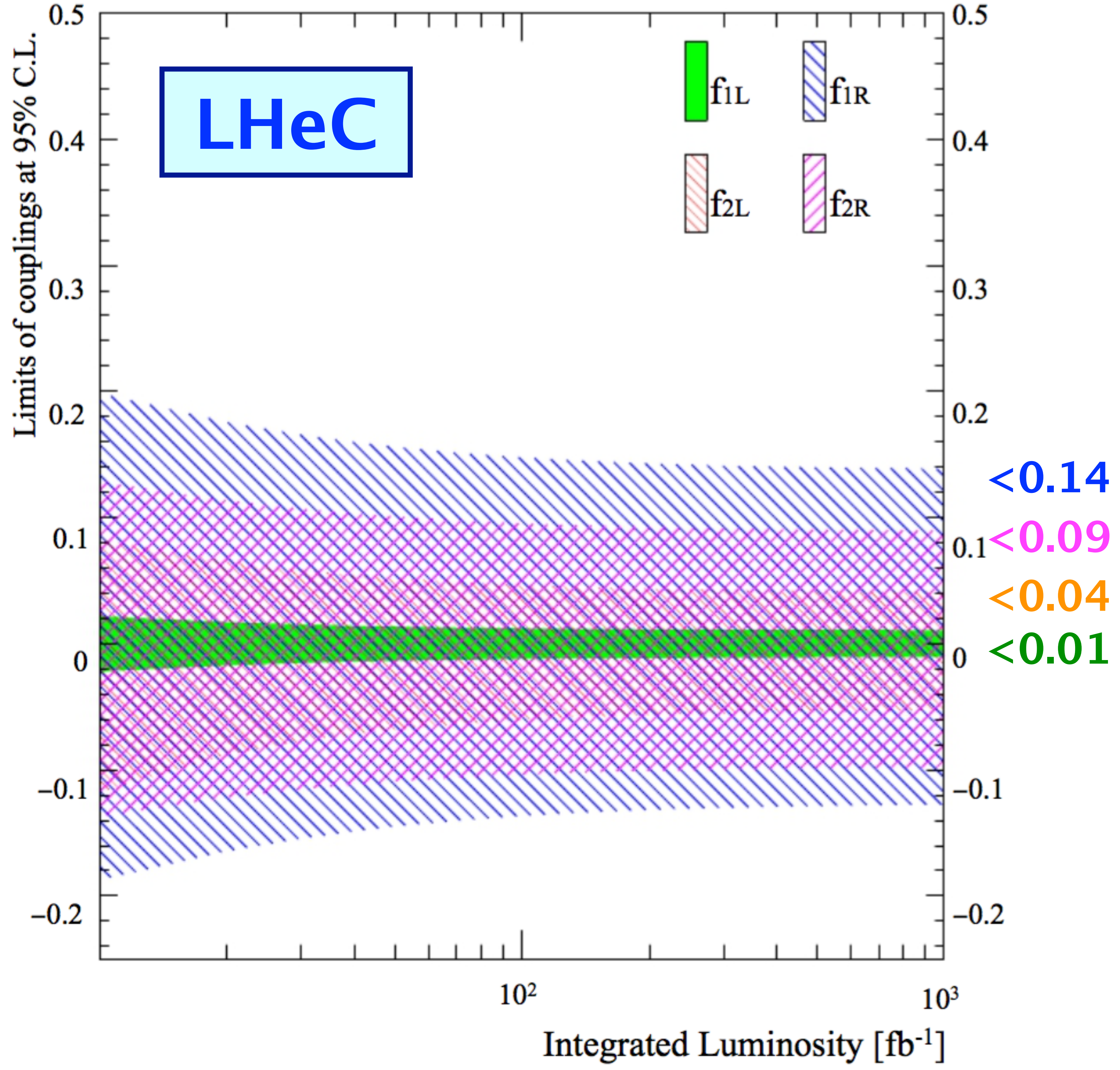




+ other variables sensitive on W helicity

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

Kumar, Ruan, to be publ.

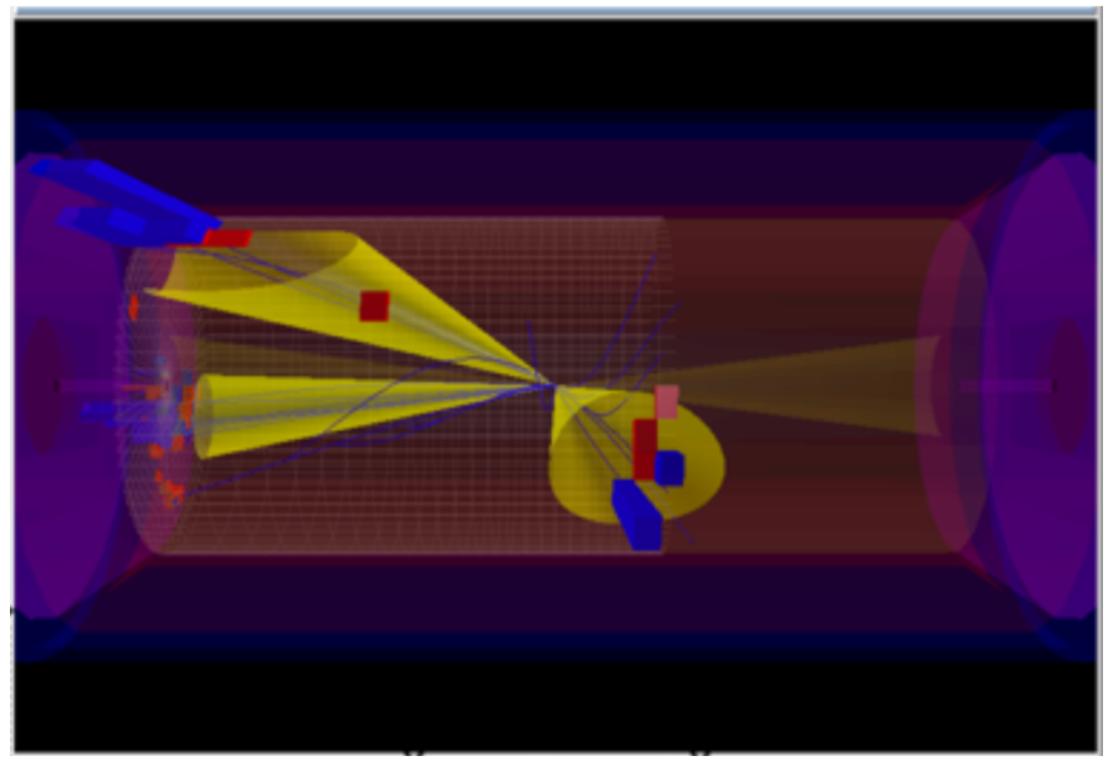


Search for Anomalous Wtb Couplings

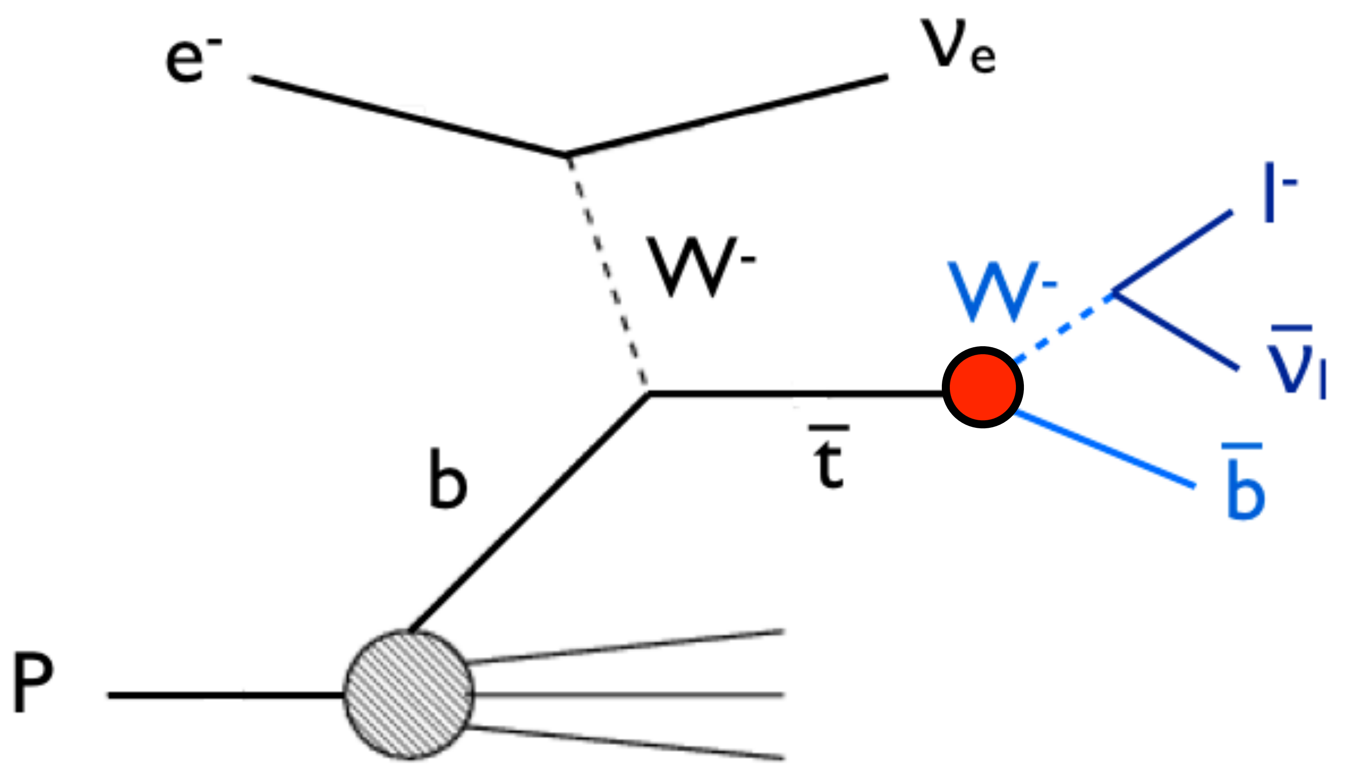
= 1 in SM

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

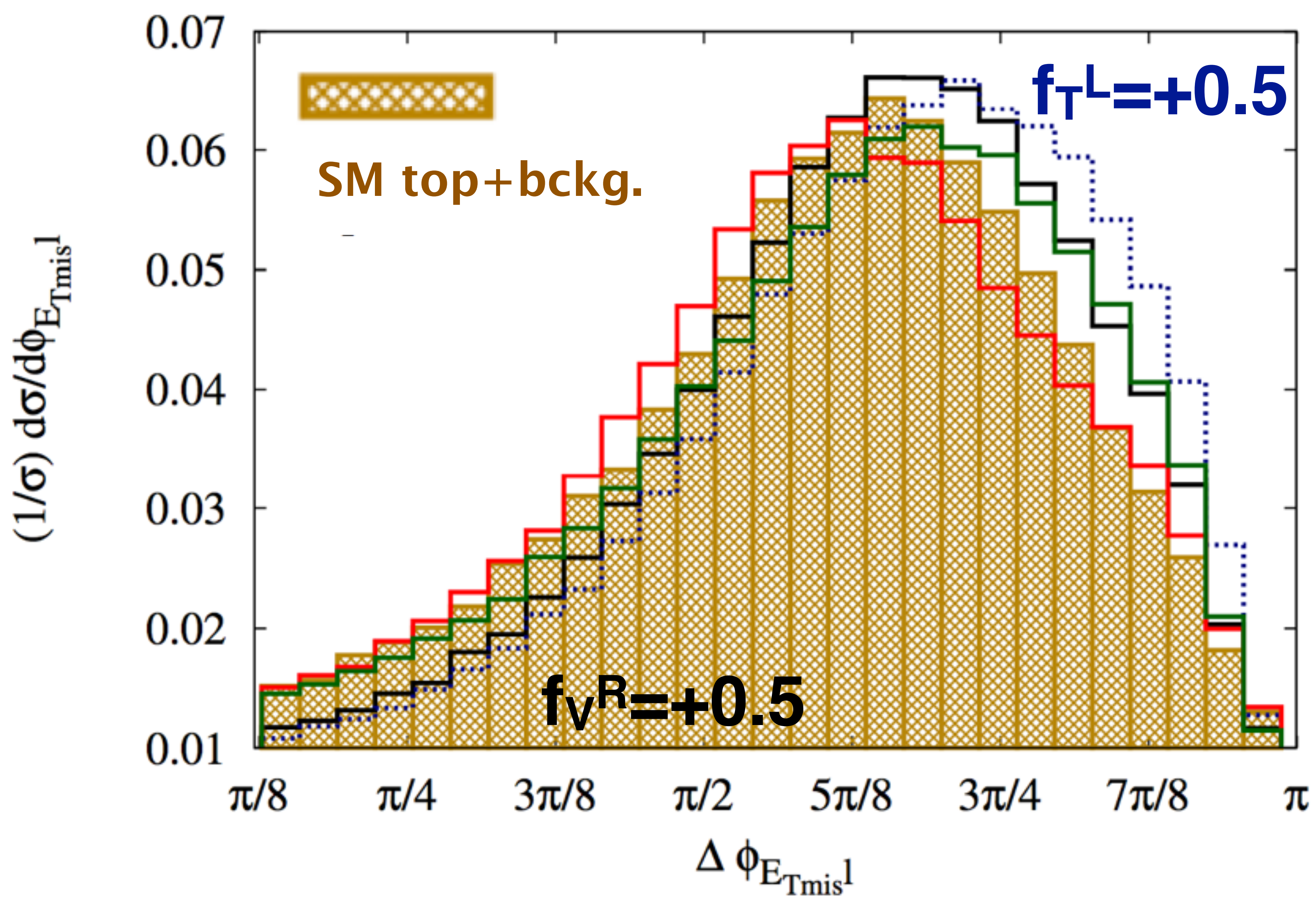
DELPHES

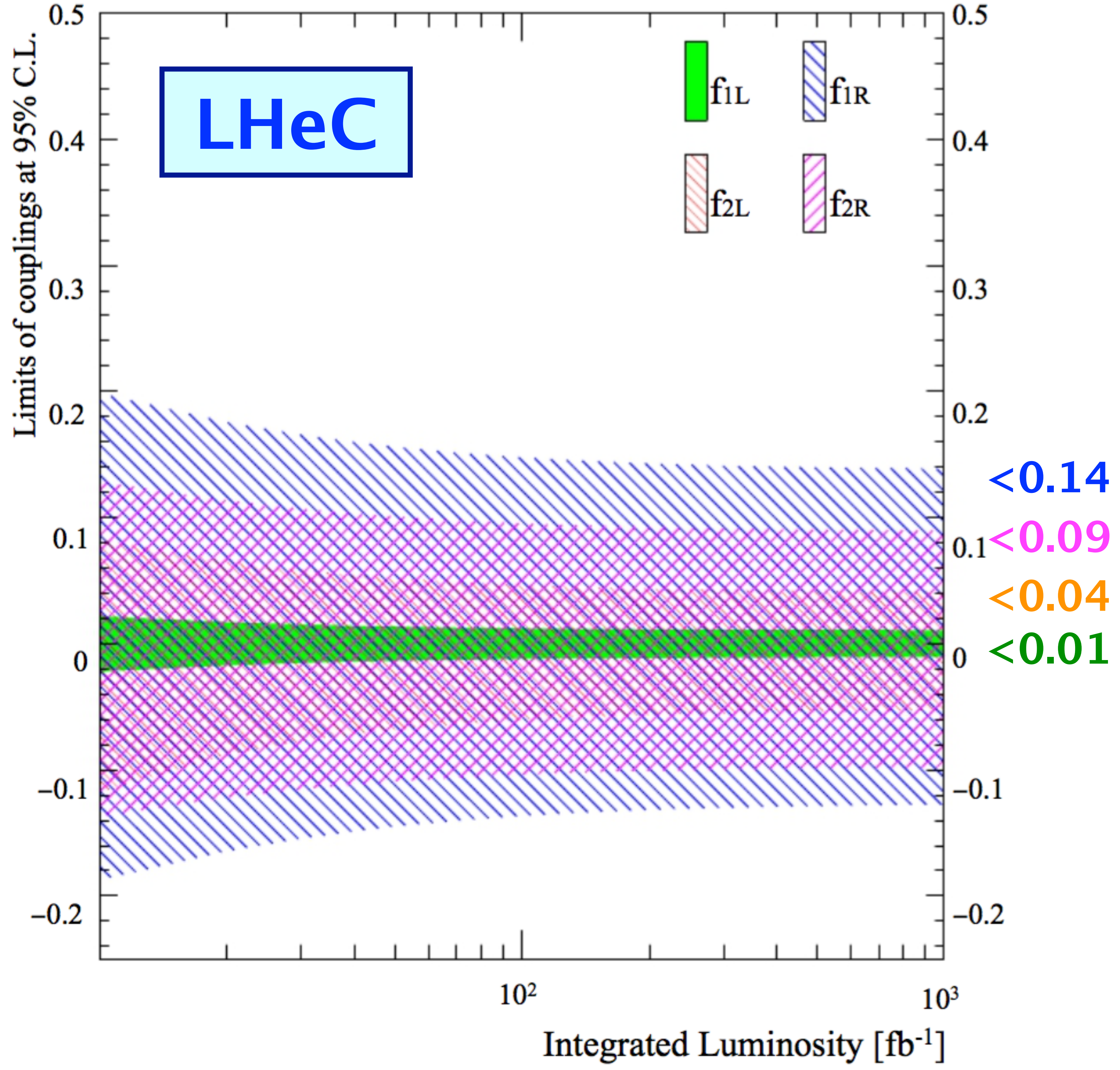


Dutta, Goyal, Kumar, Mellado,
Eur. Phys. J. C75 (2015)
no.12, 577
Kumar, Ruan, to be publ.



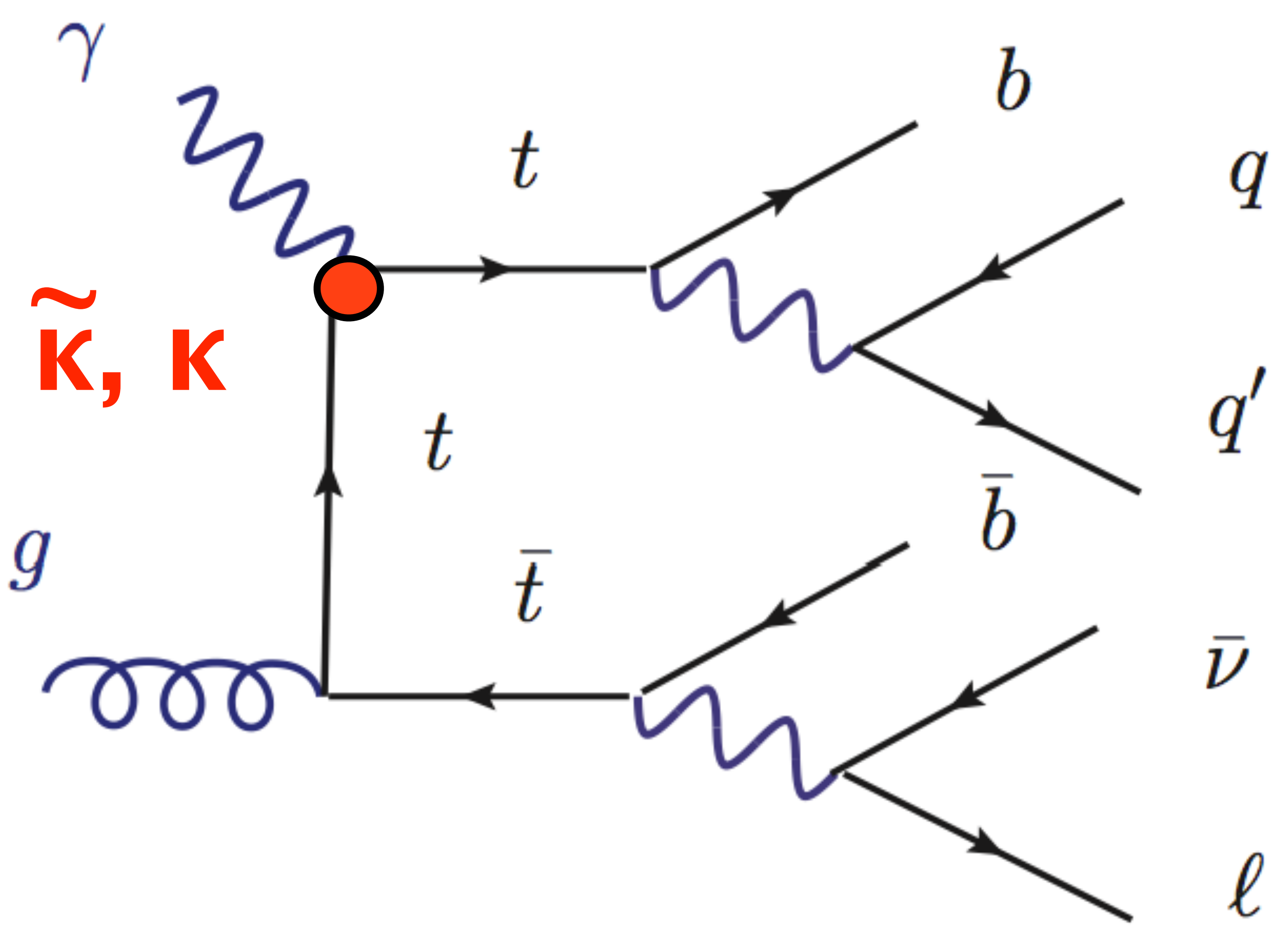
signal





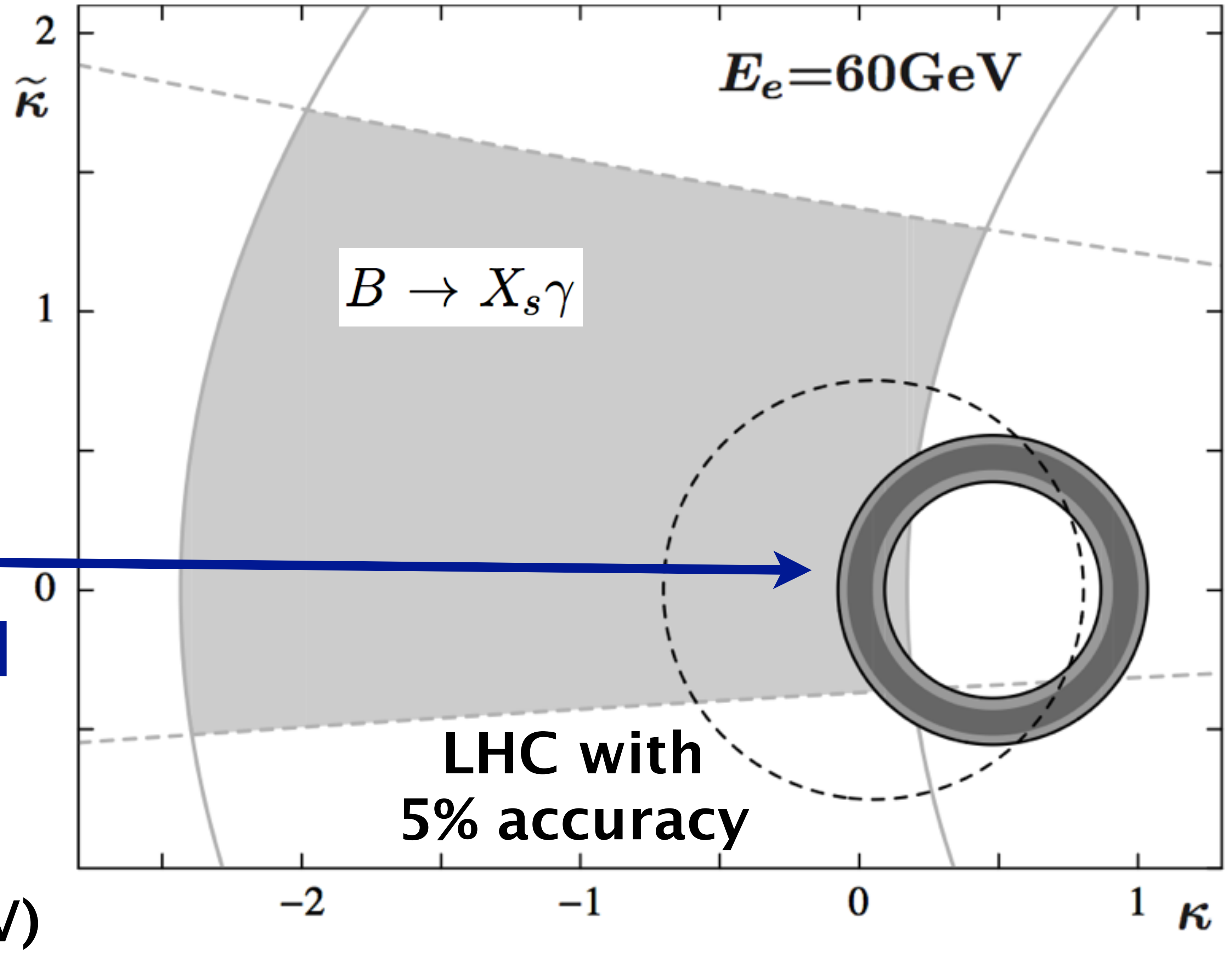
+ other variables sensitive on W helicity

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

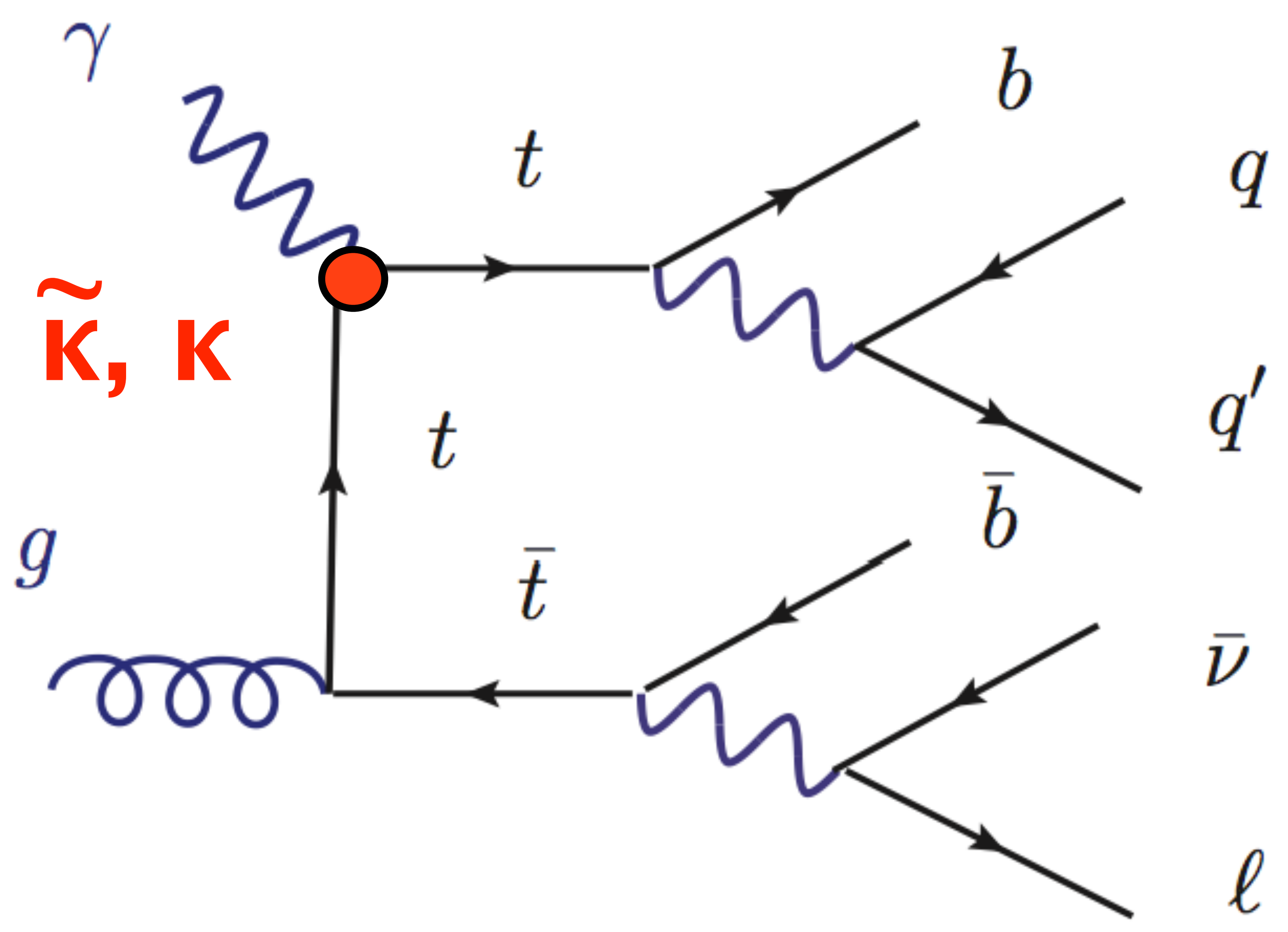
LHeC

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



LHeC

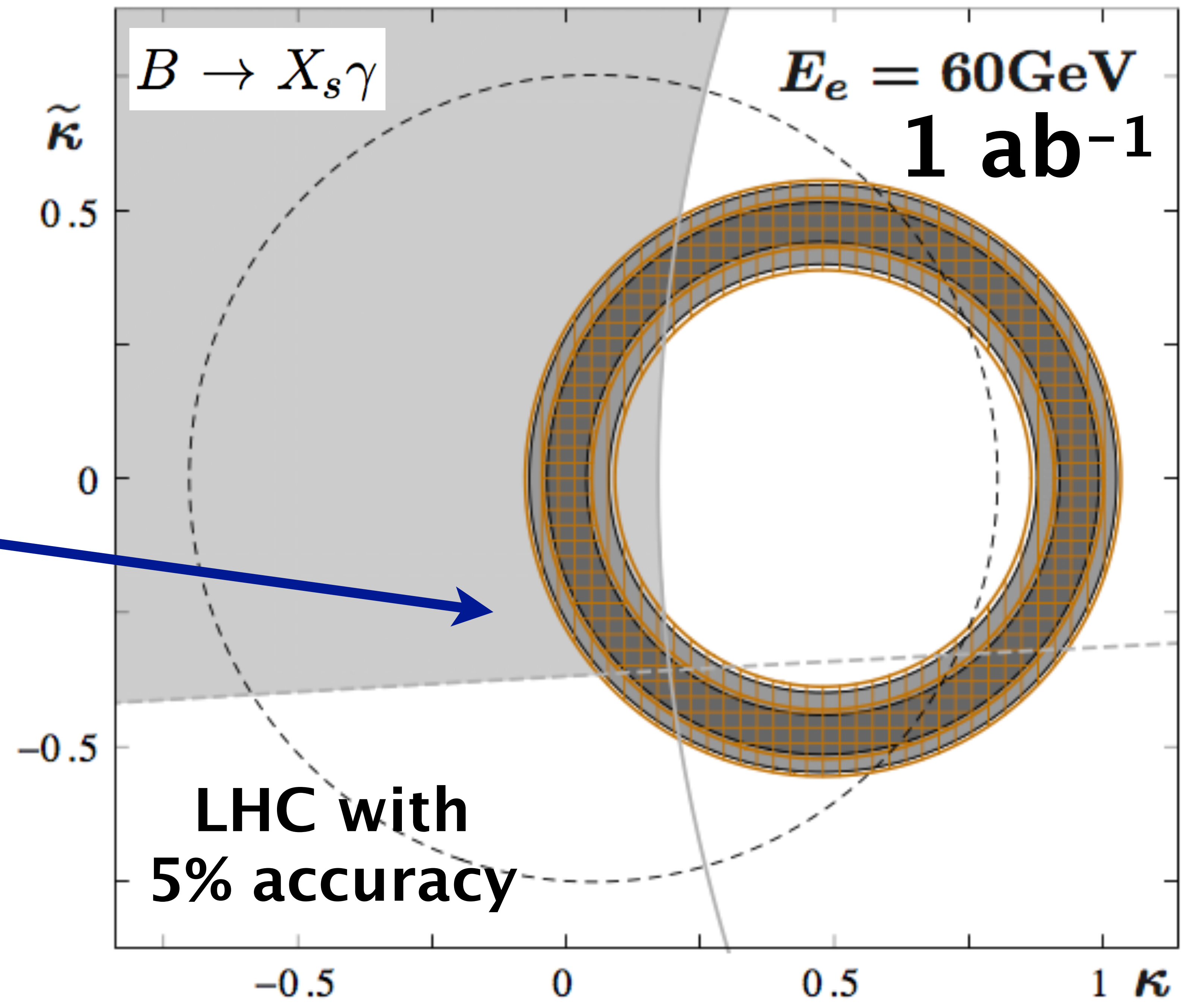
8% and 16% accuracy
10% 18%
→ systematically limited

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

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

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

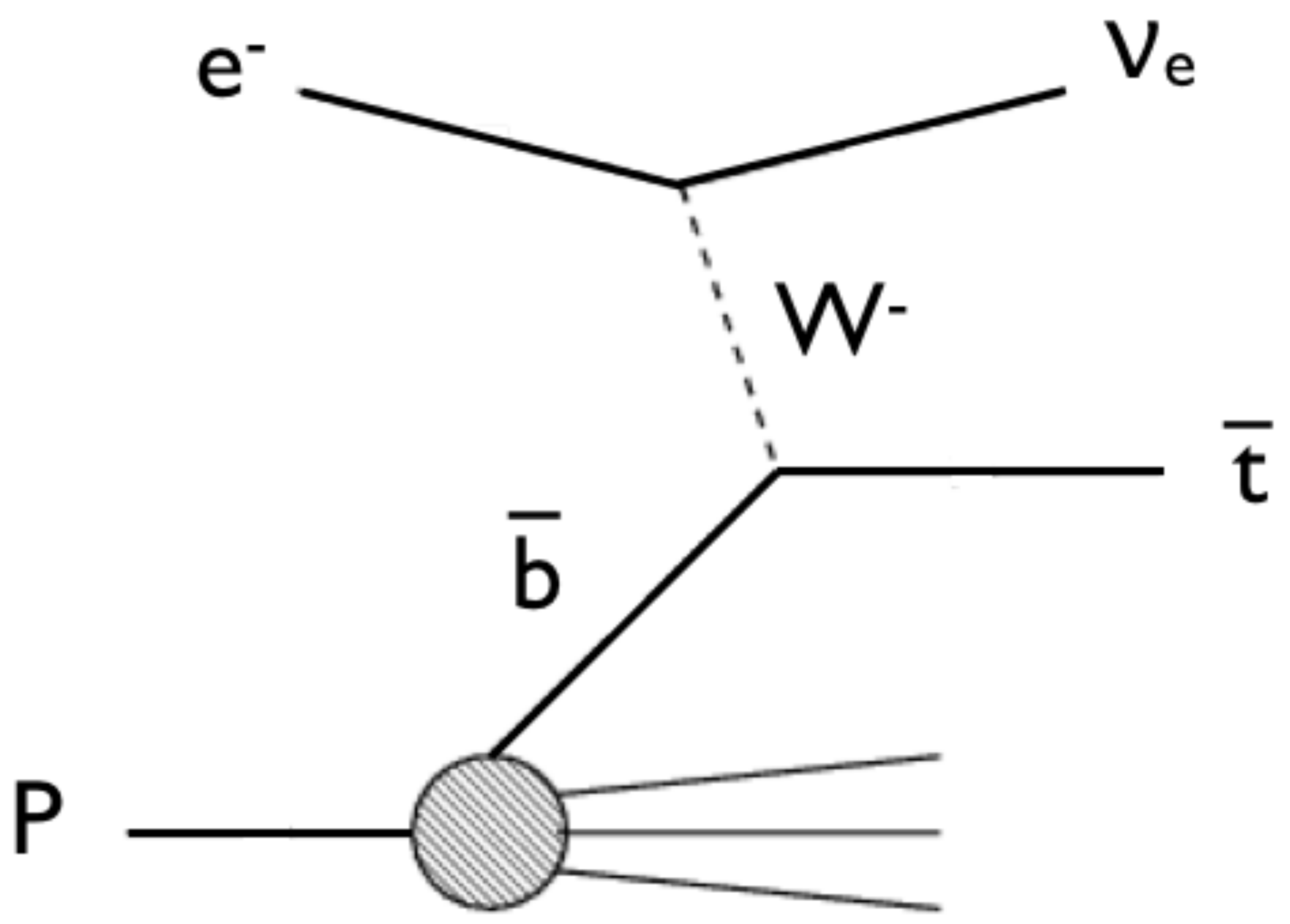
electric dipole moment: $\tilde{\kappa}$



magnetic dipole moment: κ

SM Top Quark Production

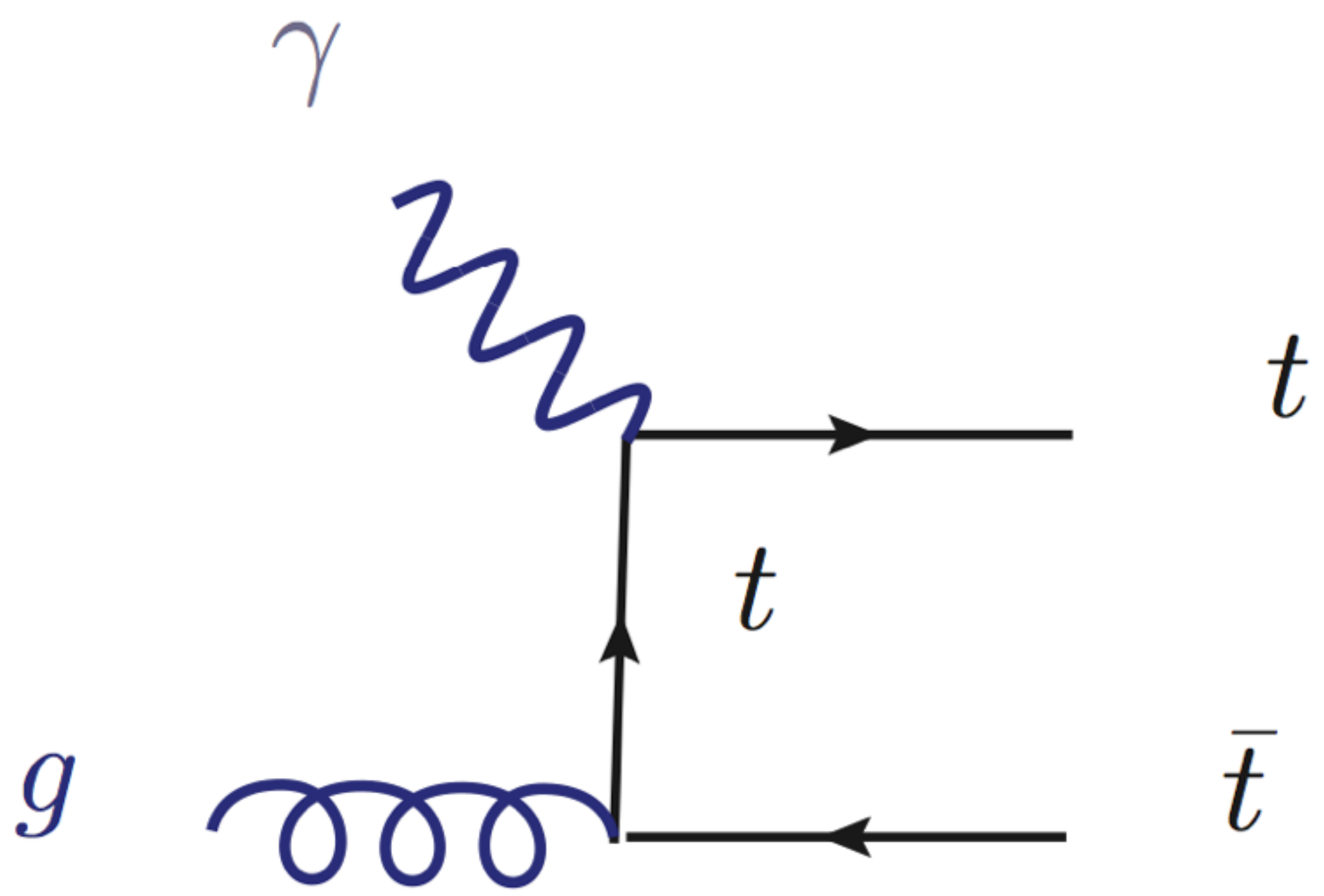
CC DIS top production



σ=1.73pb @ LHeC

σ=15.3pb @ FCC-ep

NC top photoproduction



σ=0.05pb @ LHeC

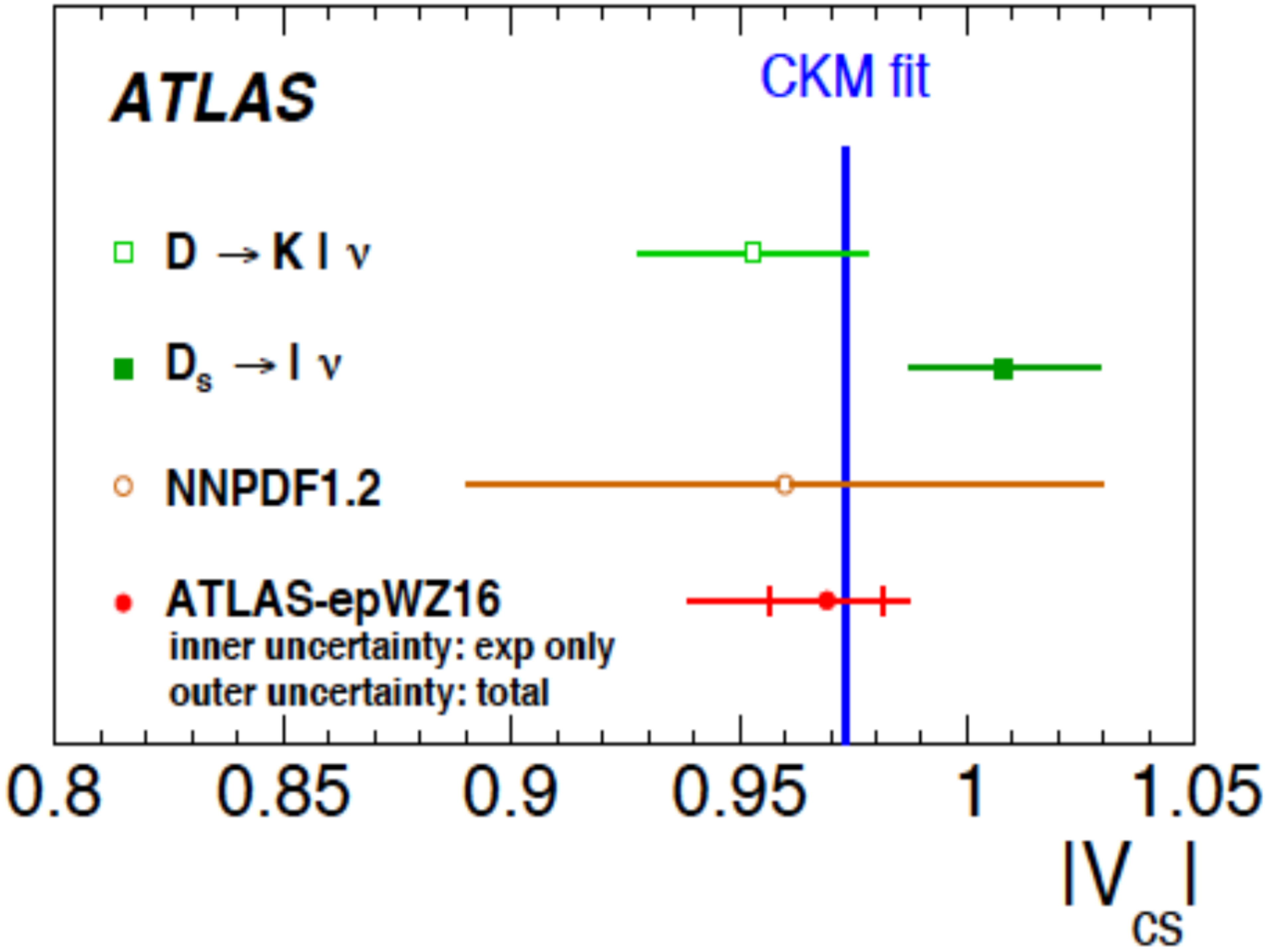
σ=1.14pb @ FCC-ep

E_e=60 GeV

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

Measurement of $|V_{cs}|$

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



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)

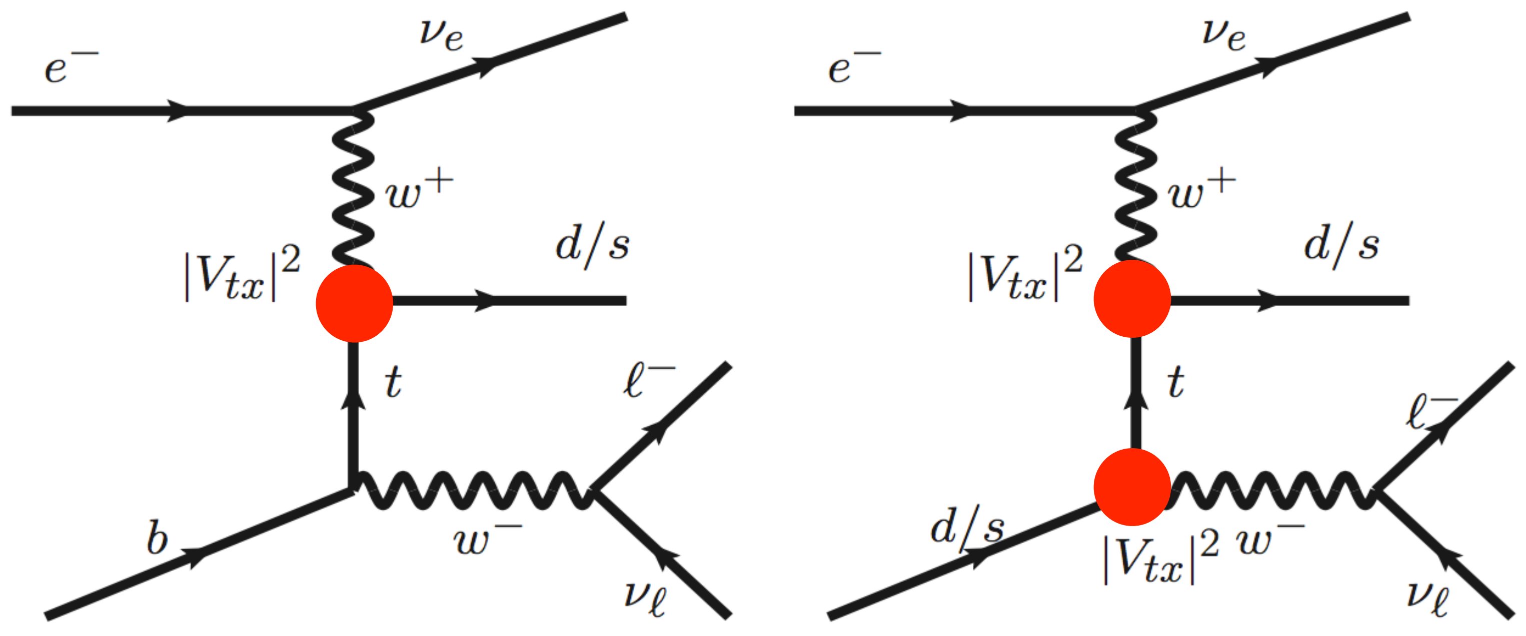
→ **heavy flavour factory**

Measurement of $|V_{td}|$

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

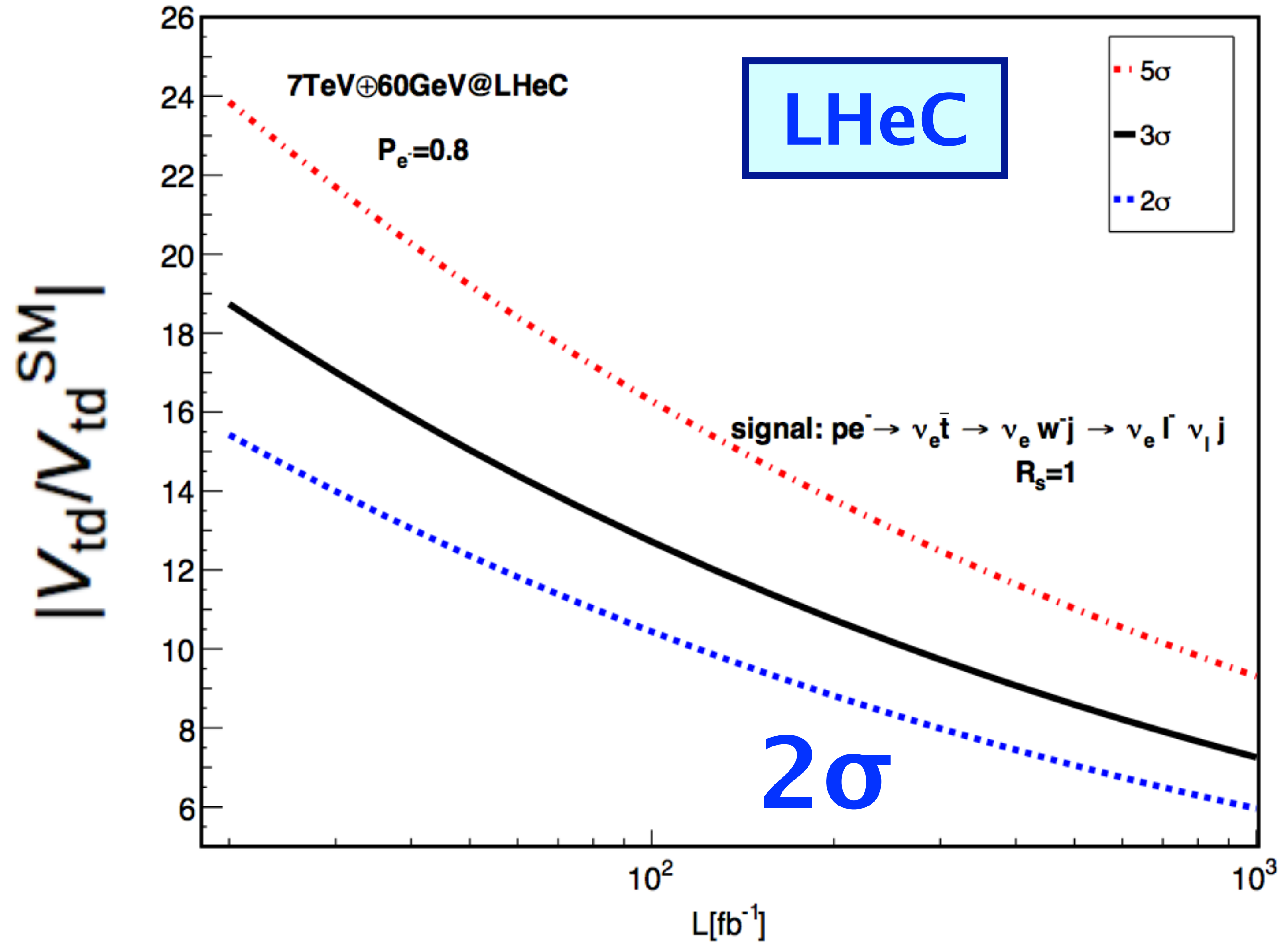
similar

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



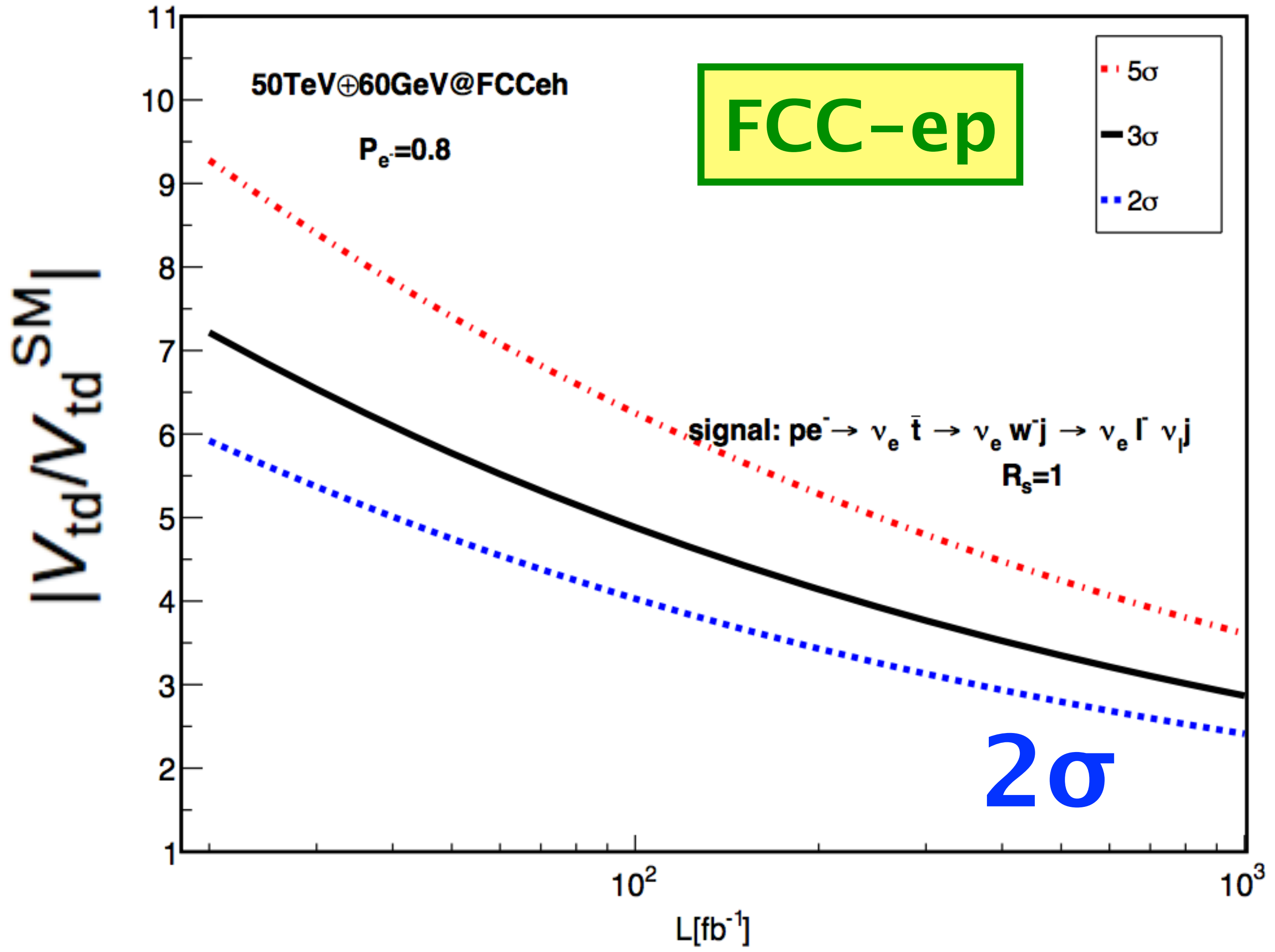
DELPHES

`Hao Sun to be publ.`



← **LHC**

→ $|V_{td}|<0.05$



→ $|V_{td}|<0.02$

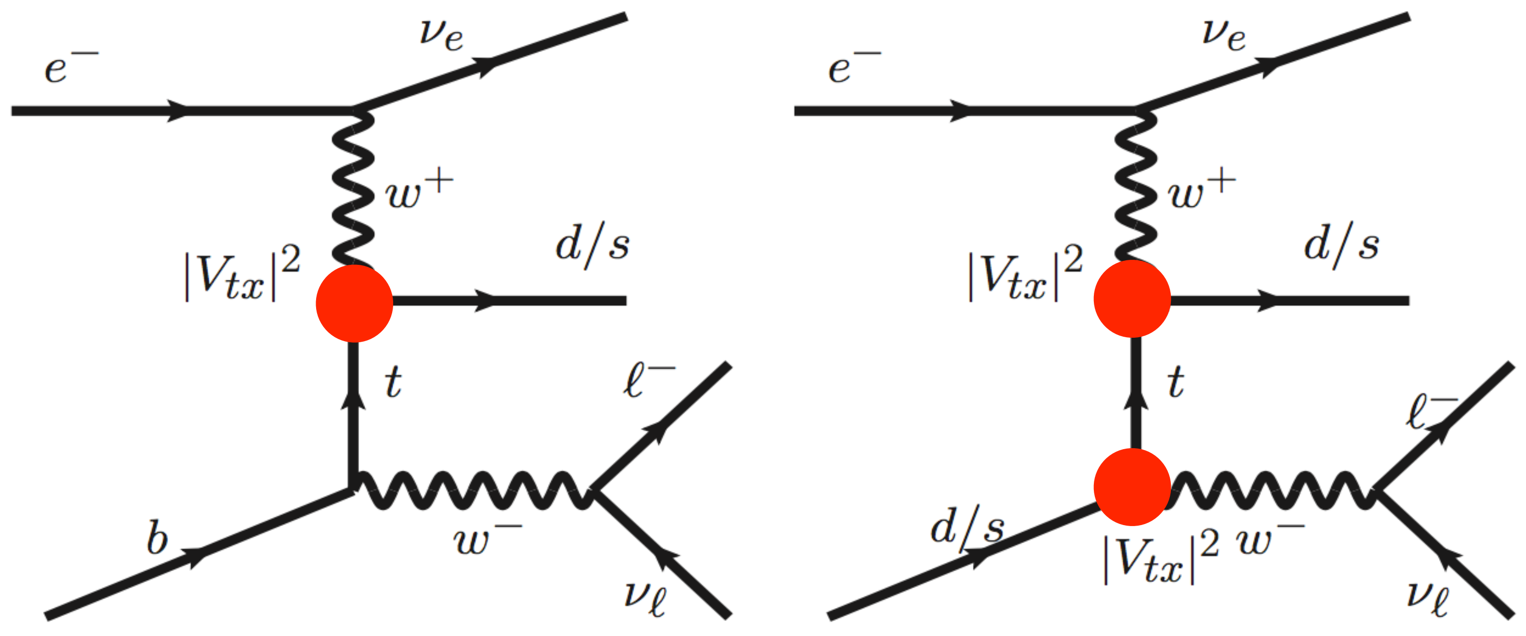
at 2σ C.L.

Measurement of $|V_{td}|$

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

similar

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

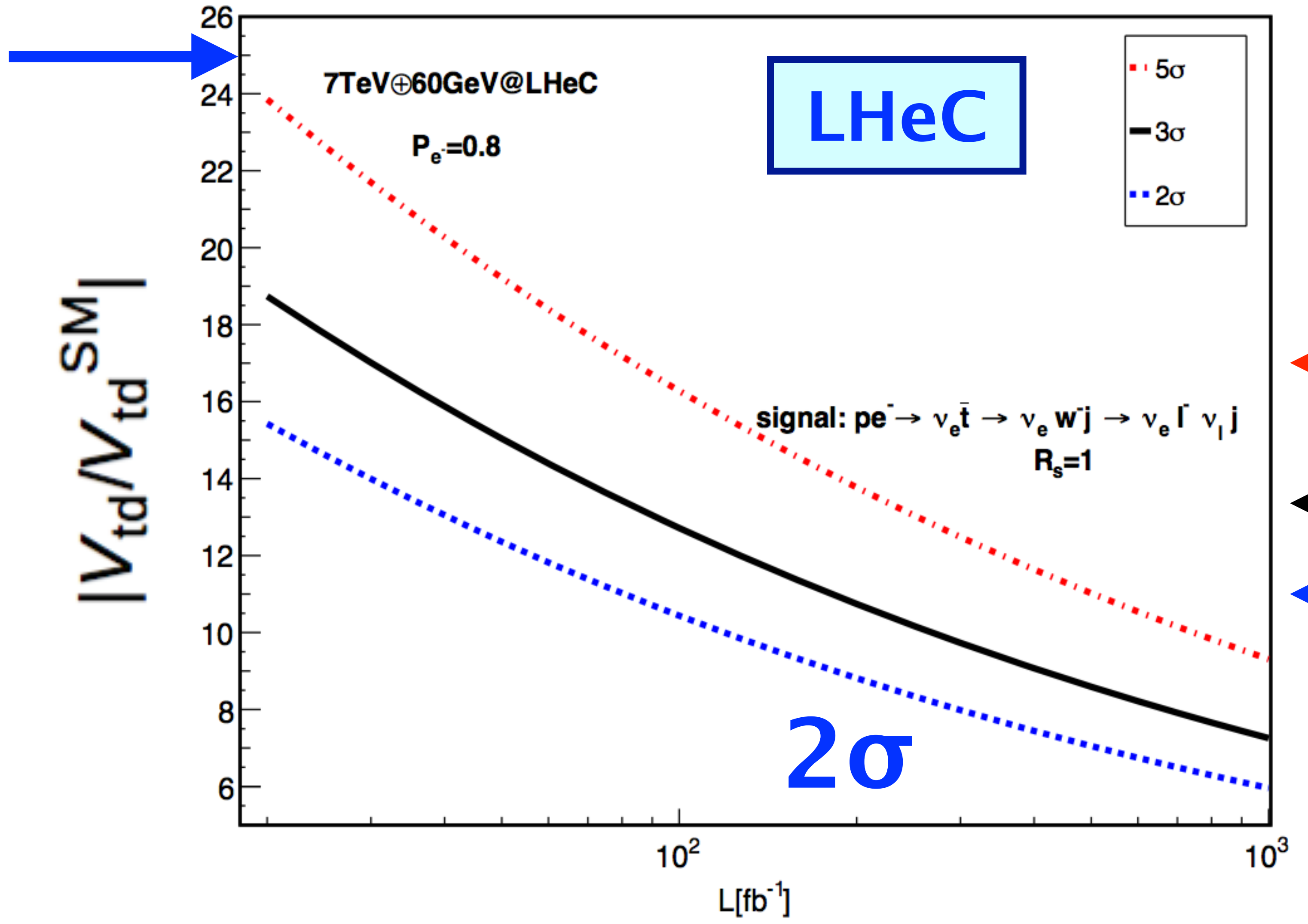


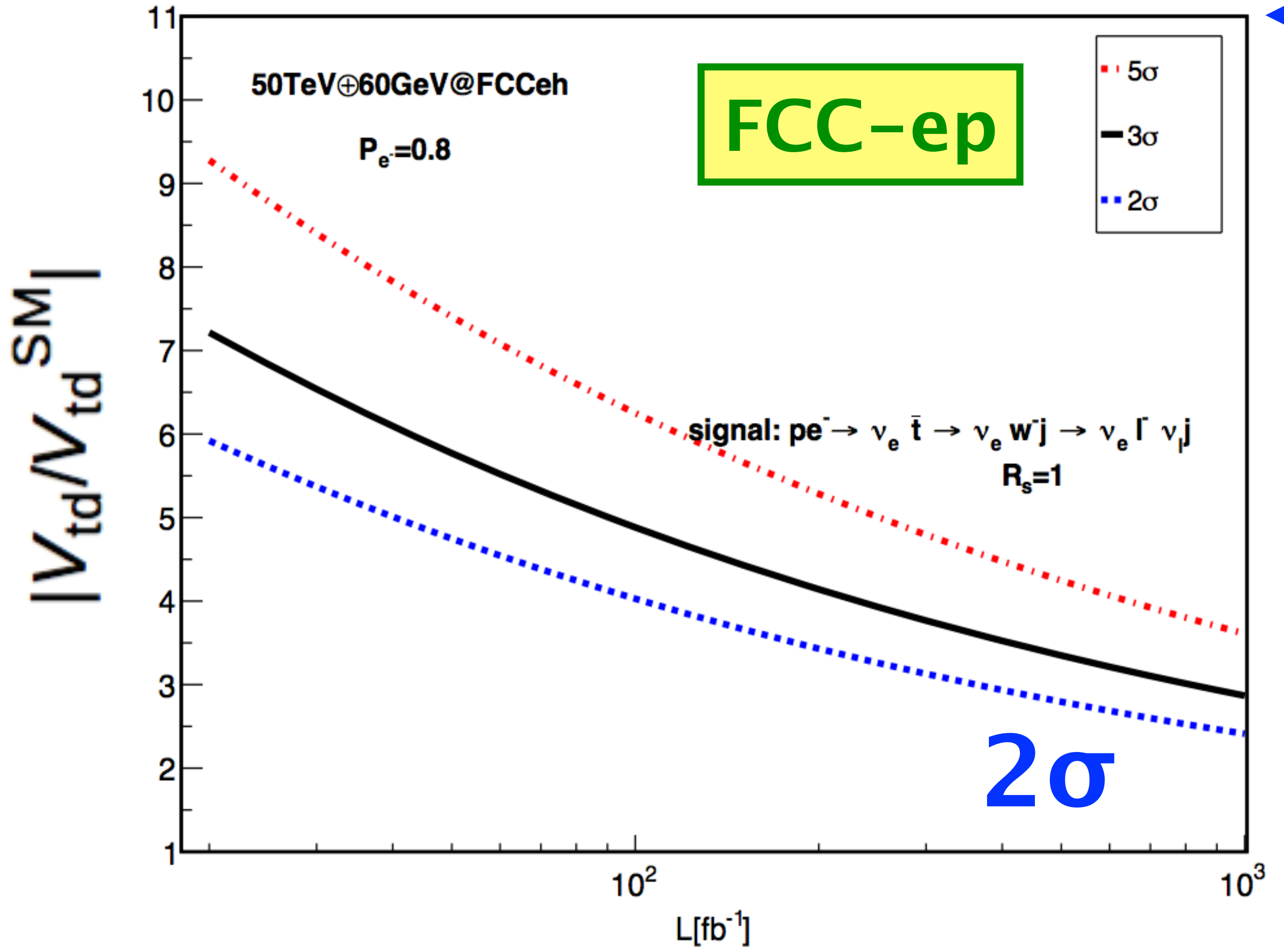
DELPHES

`Hao Sun to be publ.`

→ **extend HL-LHC limits**

LHC →





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

HL-LHC

`arXiv:1709.07887`

← **5σ**

← **3σ**

← **2σ**

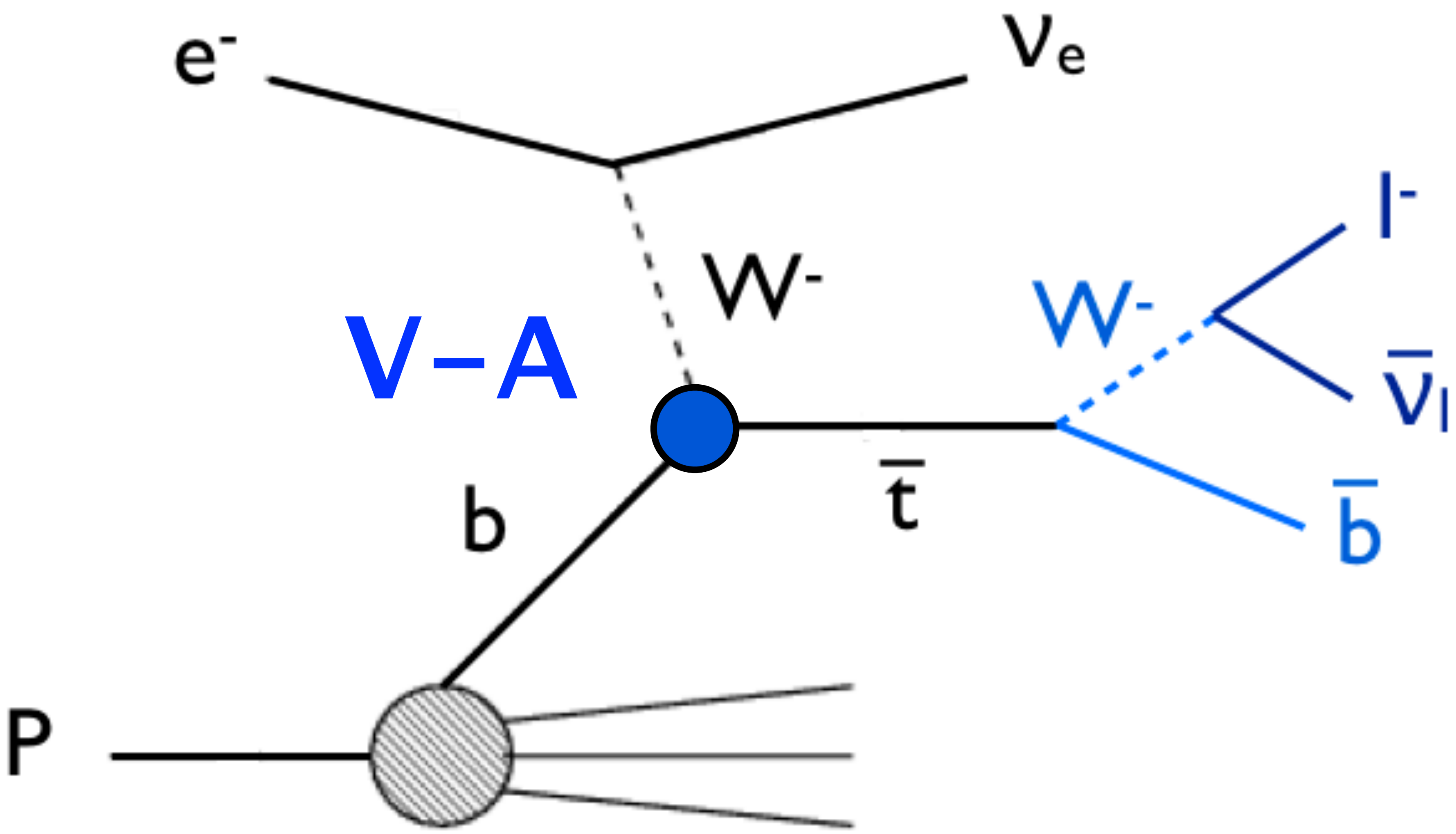
→ $|V_{td}| < 0.05$

← **2σ**

→ $|V_{td}| < 0.02$

at 2σ C.L.

Top Quark Polarisation



Atag, Sahin,
PRD 73, 074001 (2006)

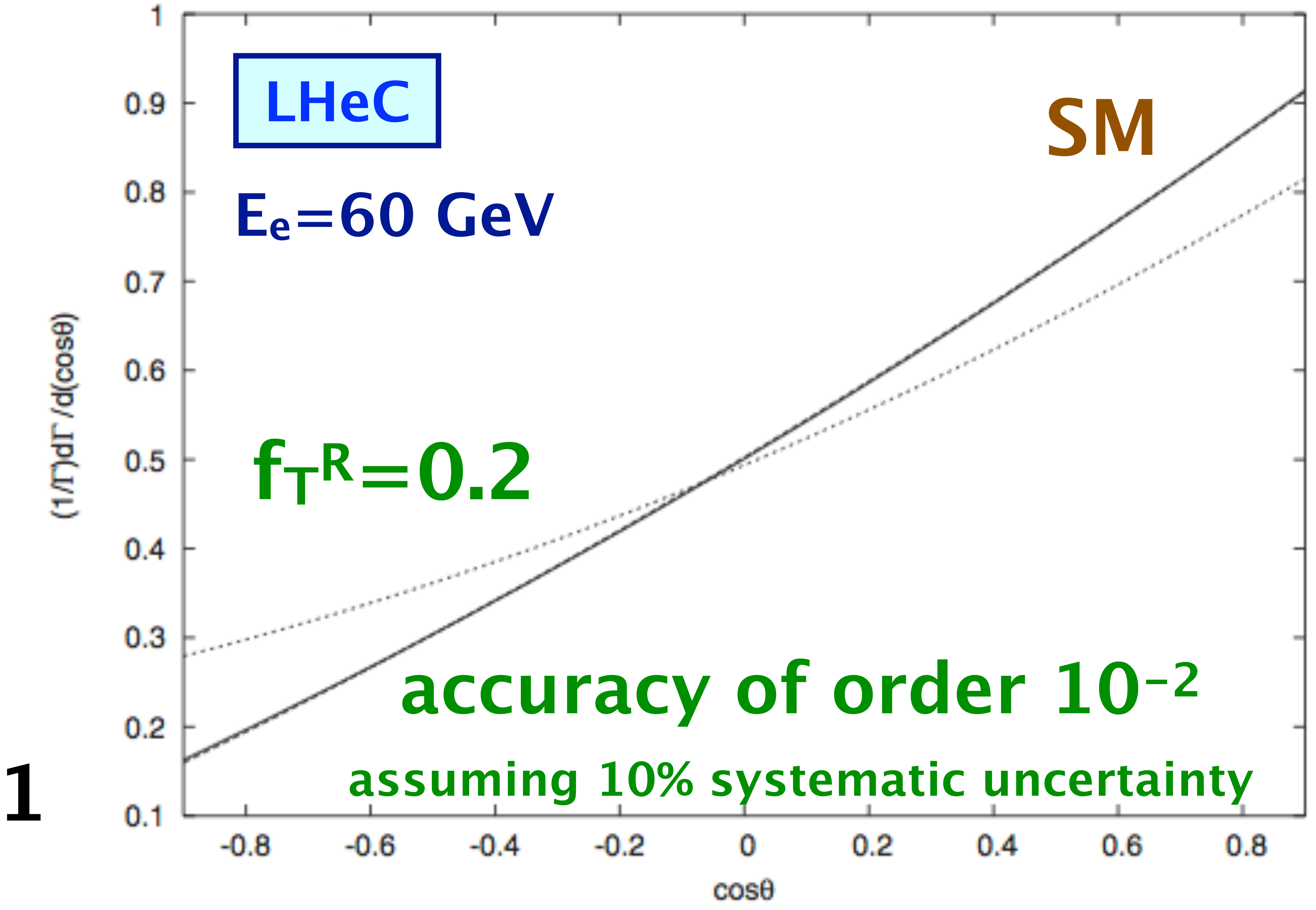
cosθ: angle between charged lepton and spin quantisation axis in top rest frame

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

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

TESLA+HERAp:

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



accuracy of order 10^{-2}
assuming 10% systematic uncertainty

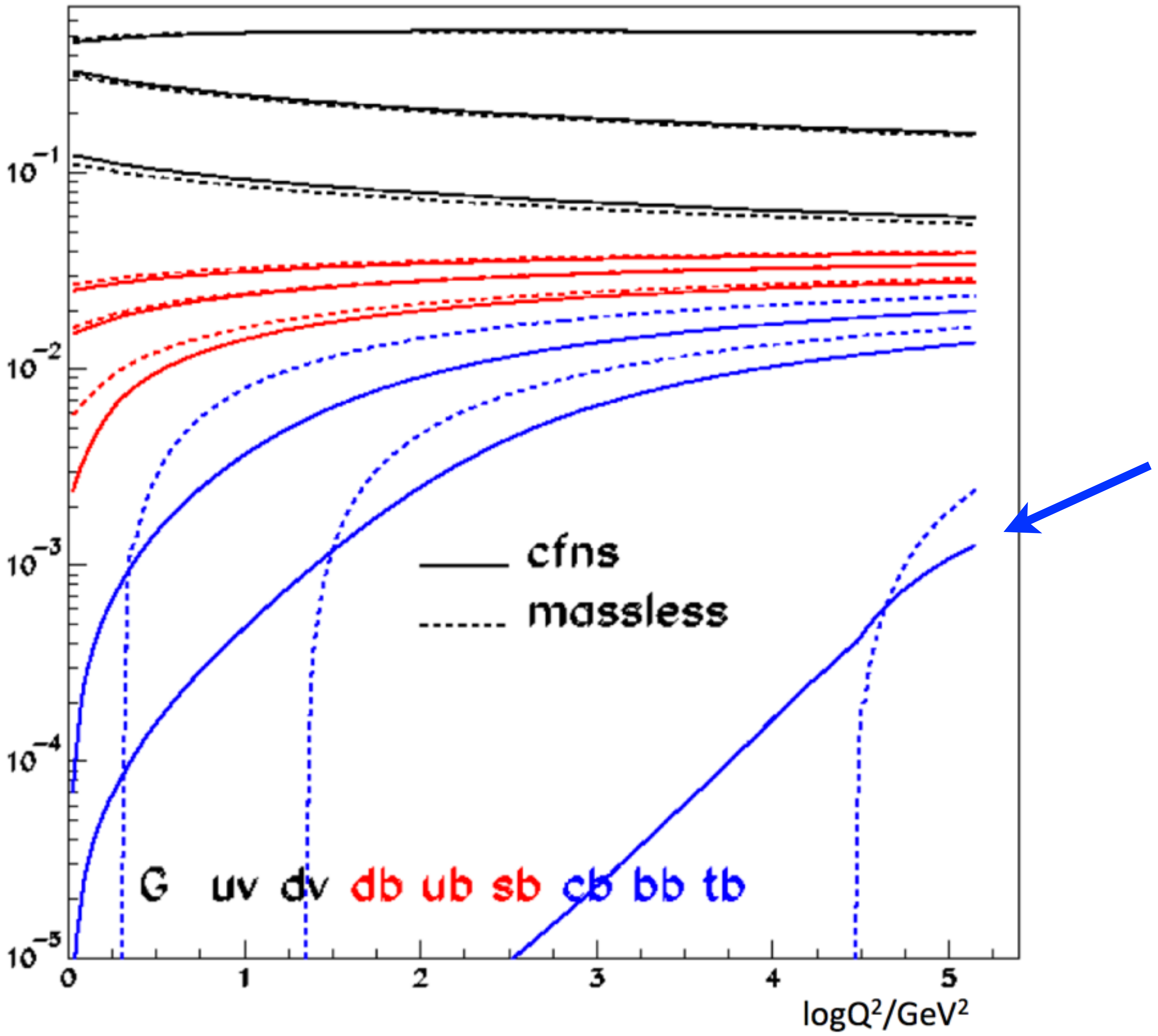
19.7 fb^{-1}: $A_{\uparrow\downarrow}$ = 0.26±0.11

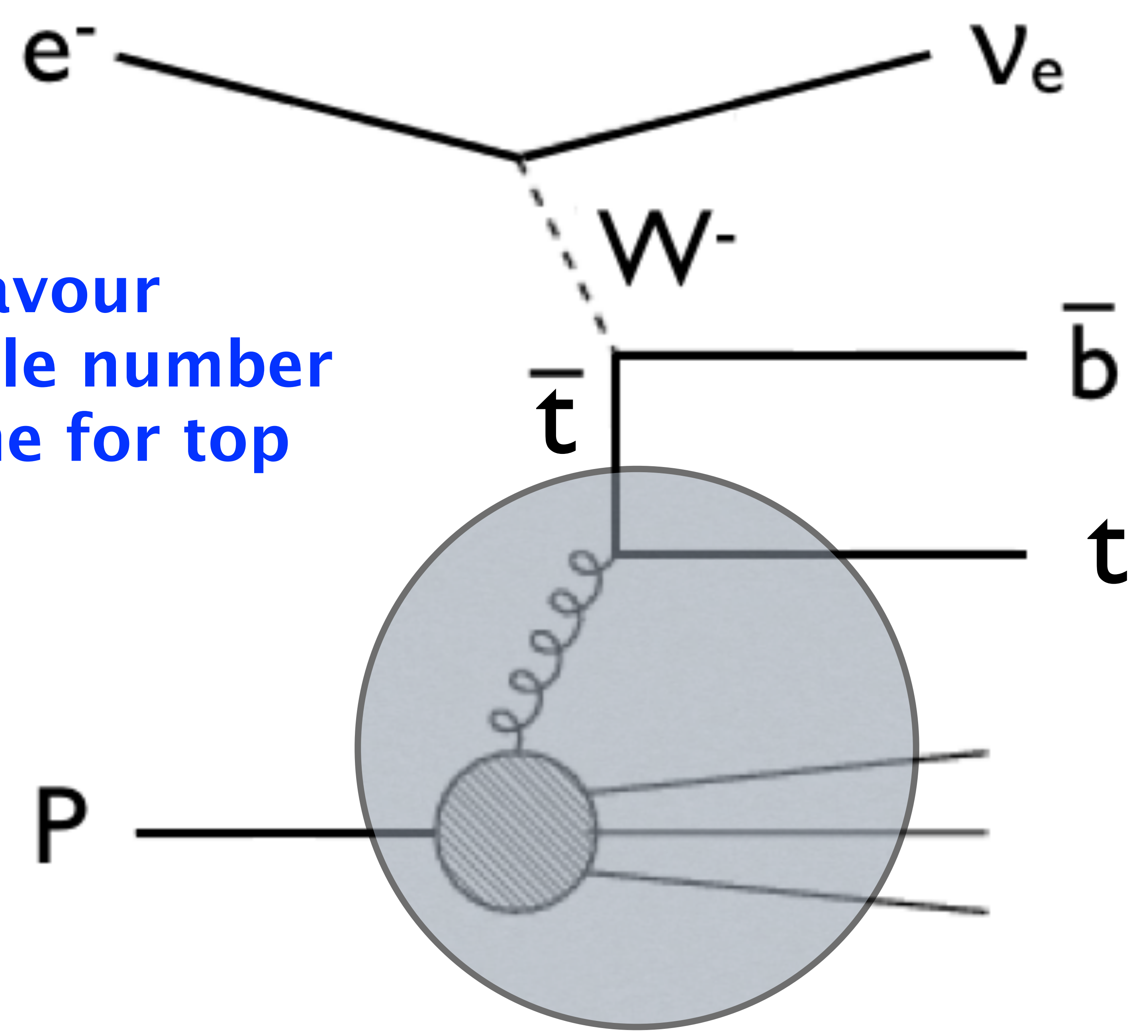
JHEP 04 (2016) 073

Top Quark Parton Density Function

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

parton momentum fraction





- 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

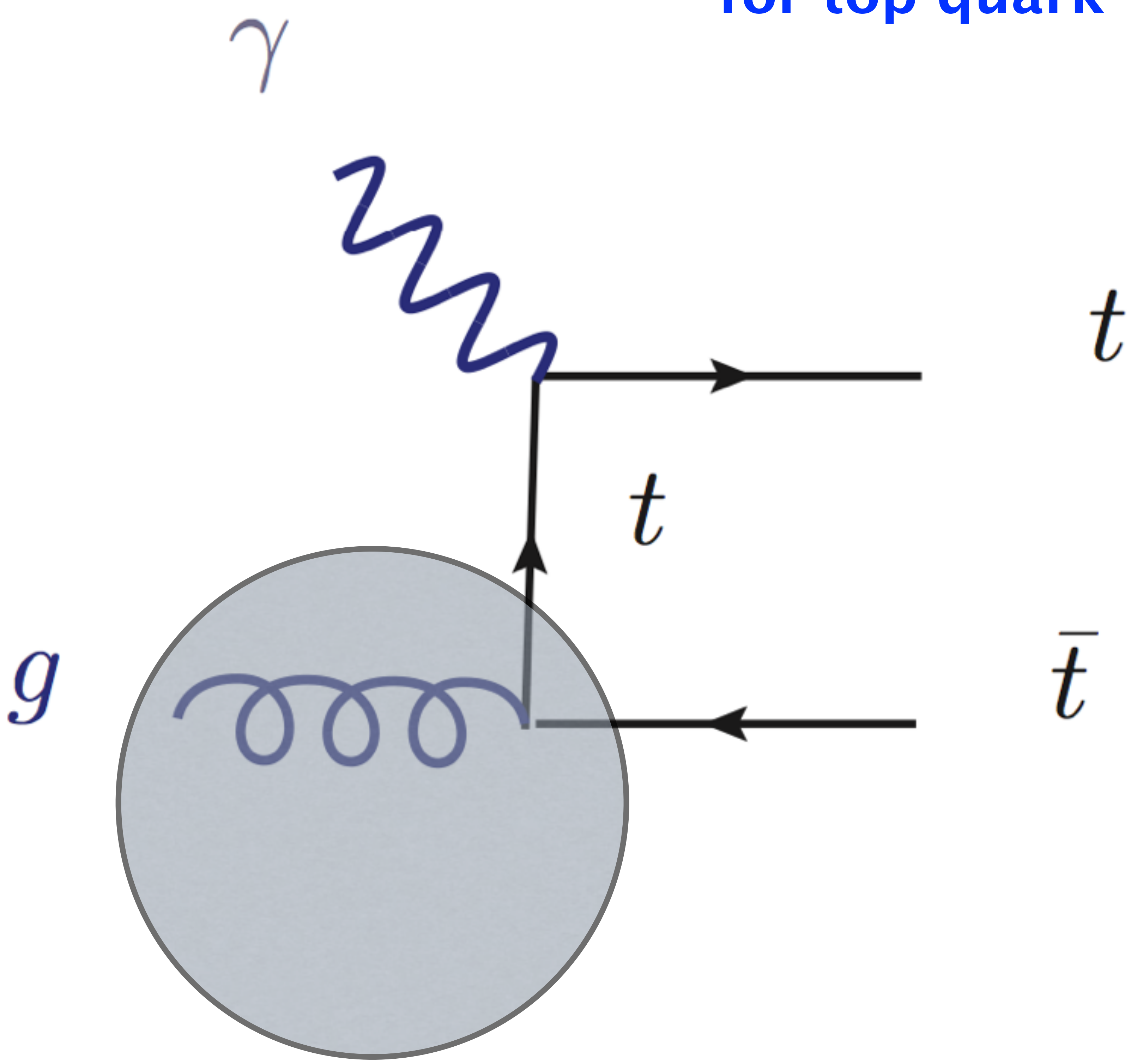
Top Quark Structure Function

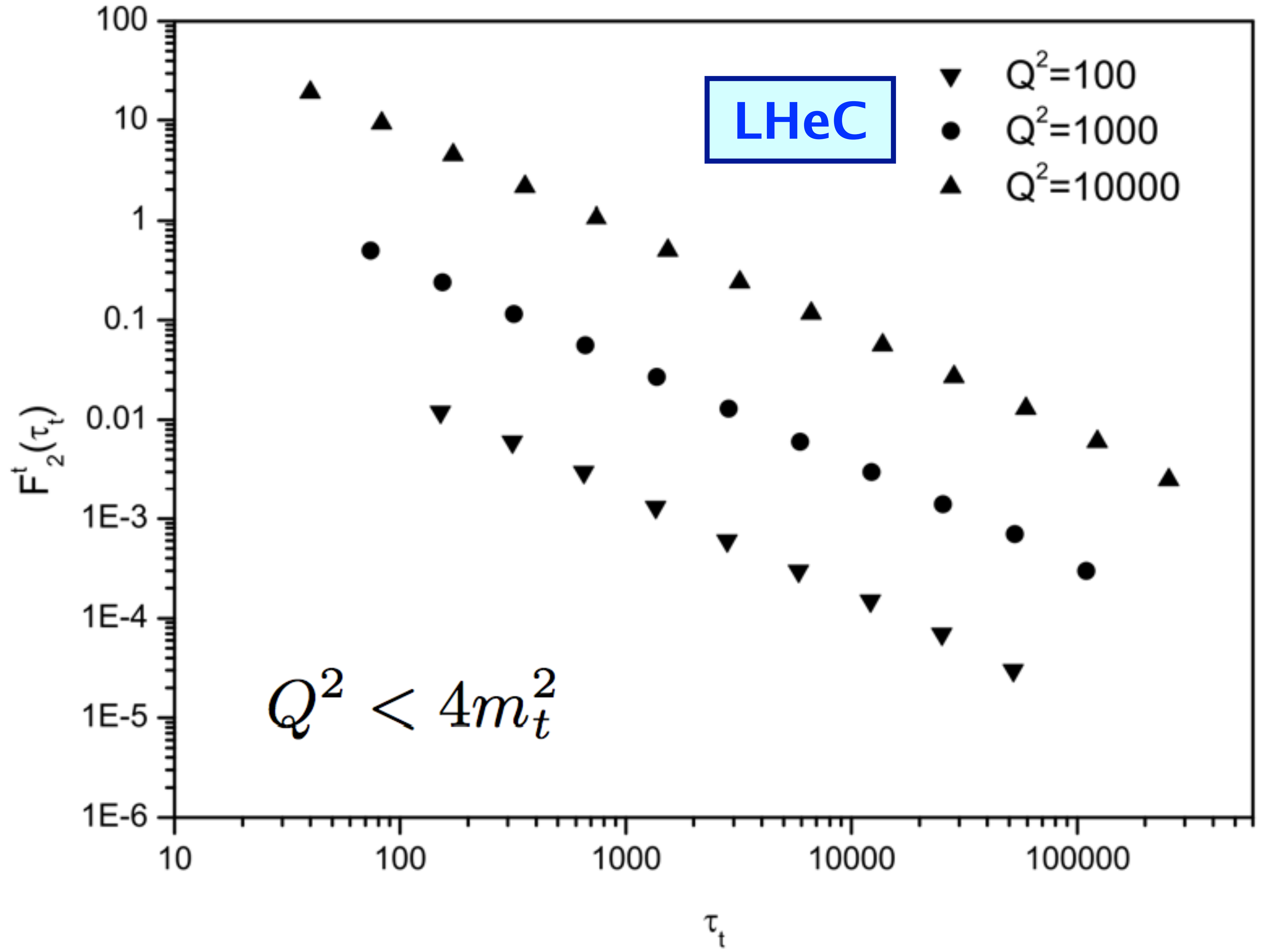
Boroun, Phys. Lett. B744, 142 (2015)

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

$E_e=60$ GeV

variable flavour number scheme for top quark





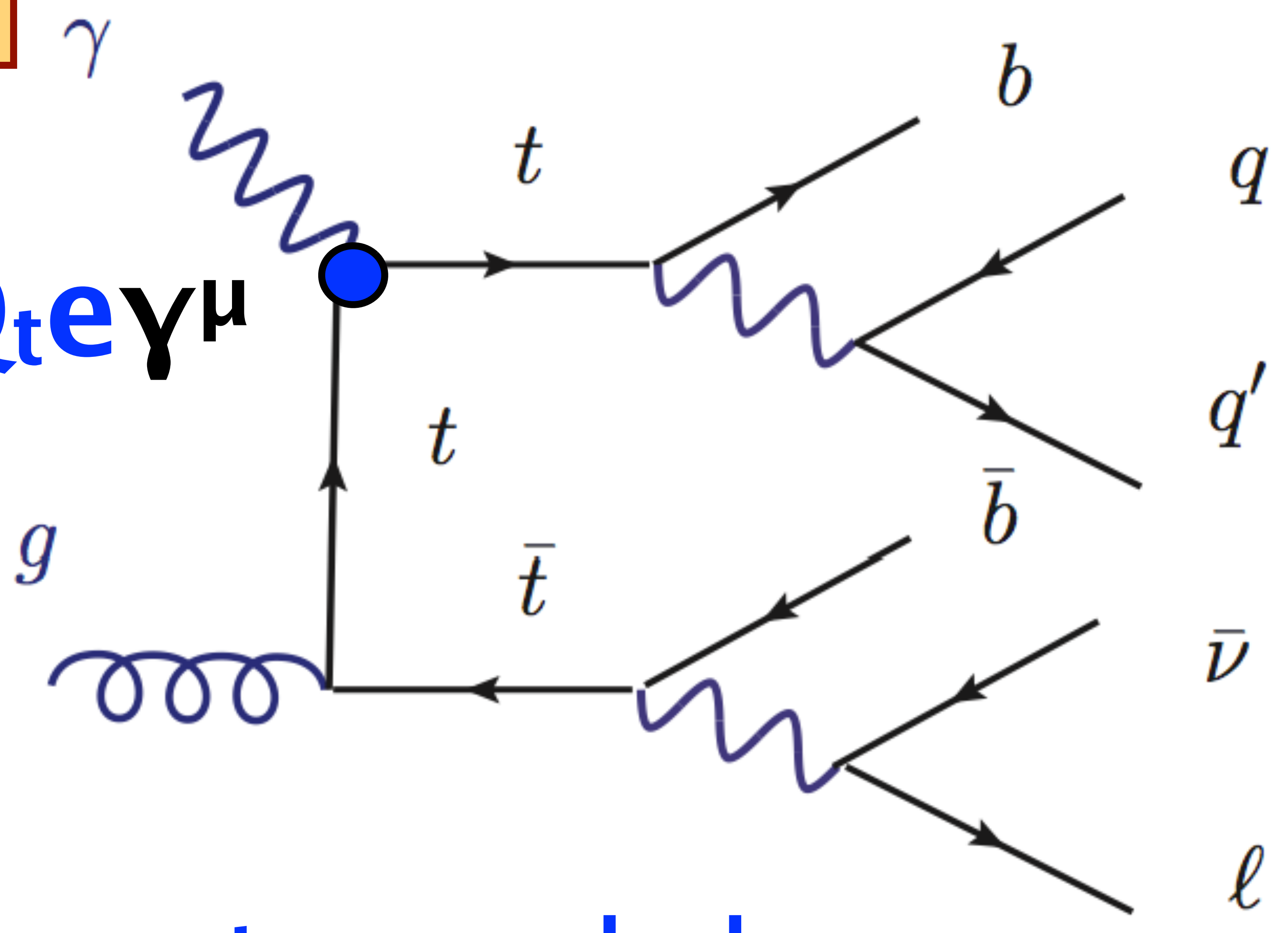
$$\tau_t = (1+\frac{4m_t^2}{Q^2})^{1+\lambda}\frac{Q^2}{Q_0^2}(\frac{x_B}{x_0})^{\lambda}$$

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

→ **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

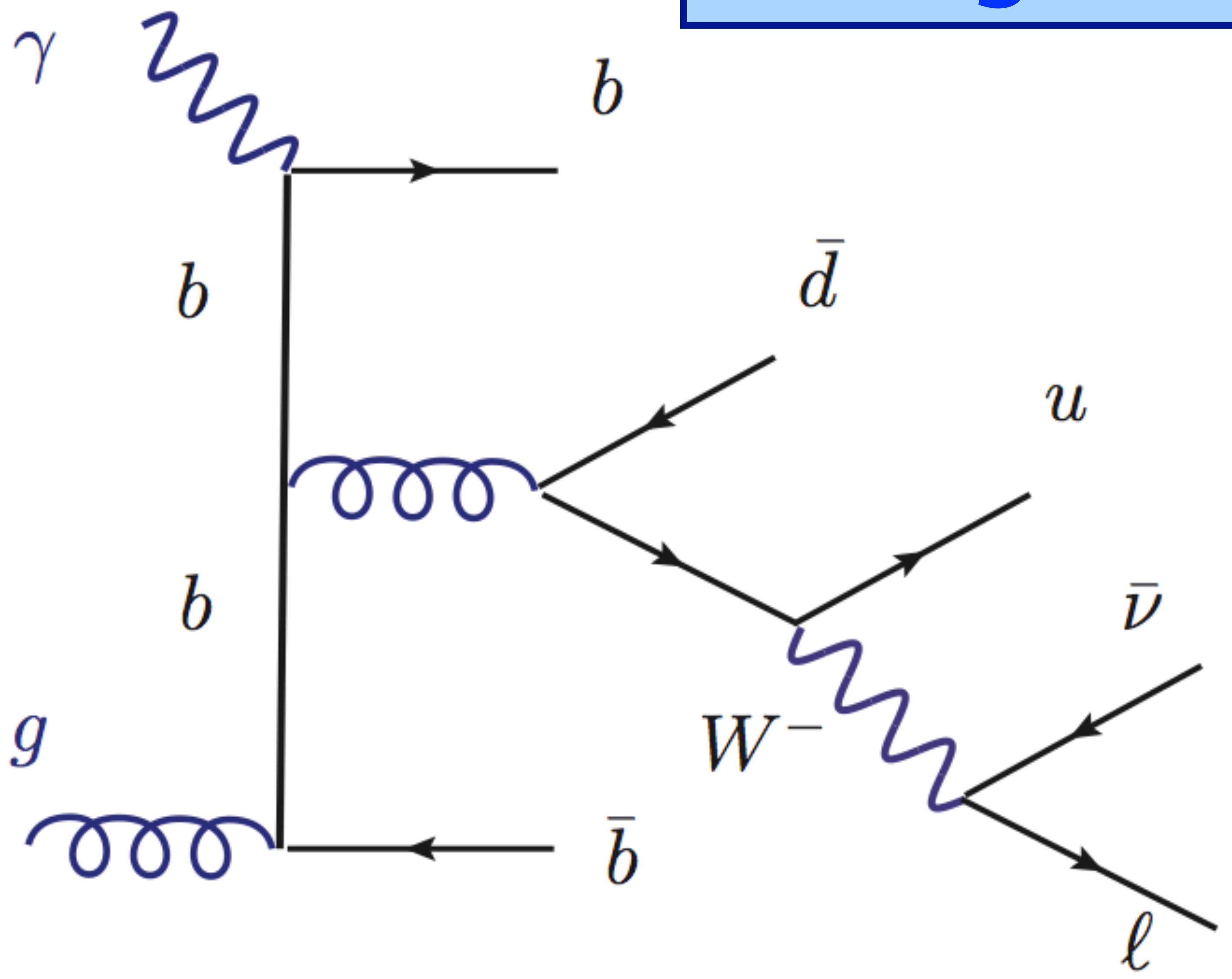
signal



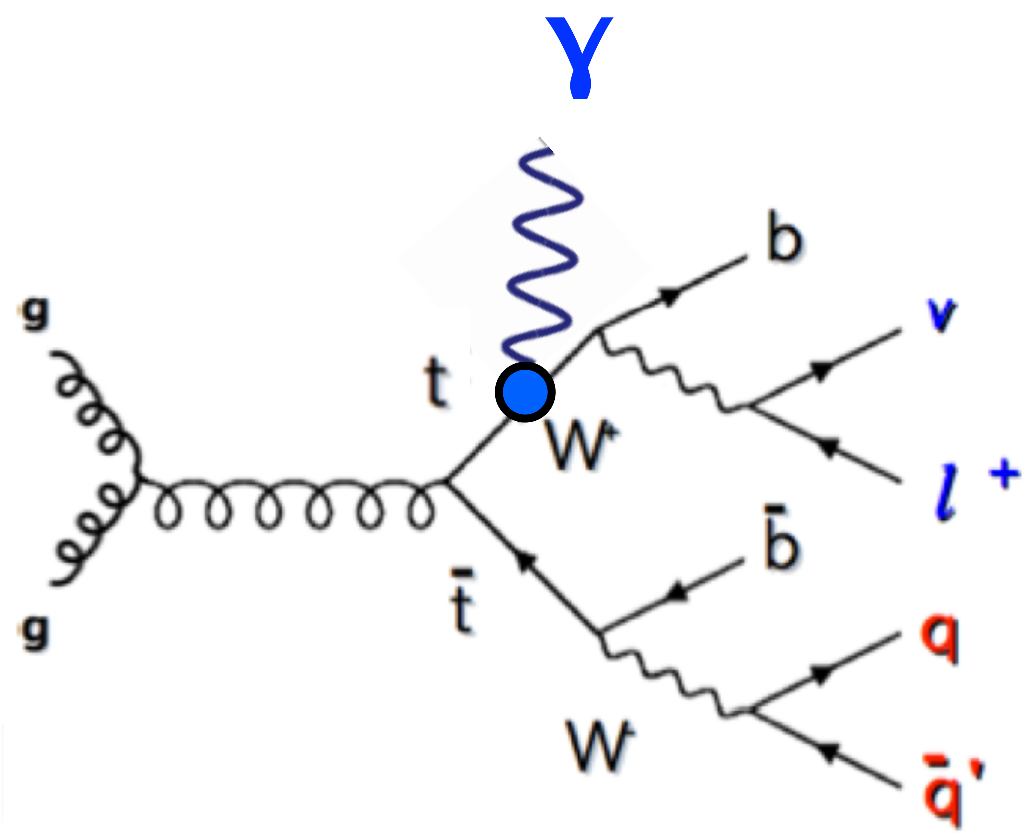
$iQ_t e\gamma^\mu$

→ measure **top quark charge**

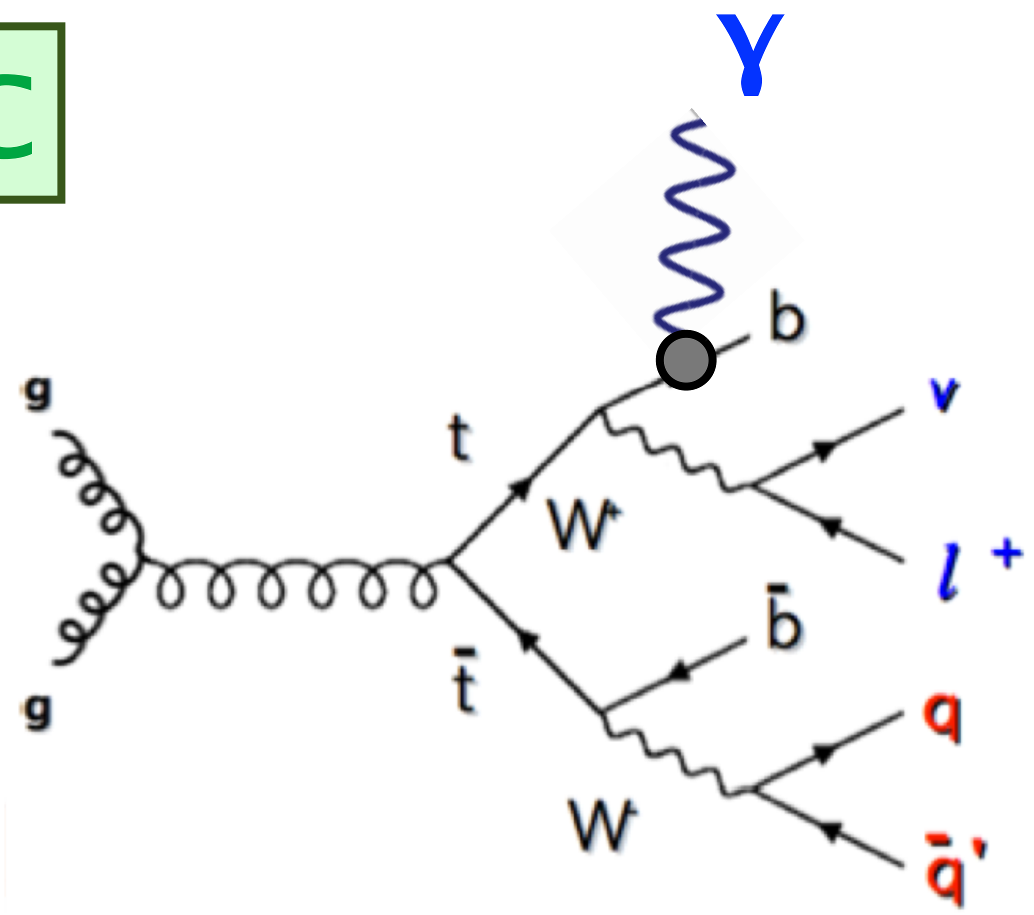
background



LHC



OR



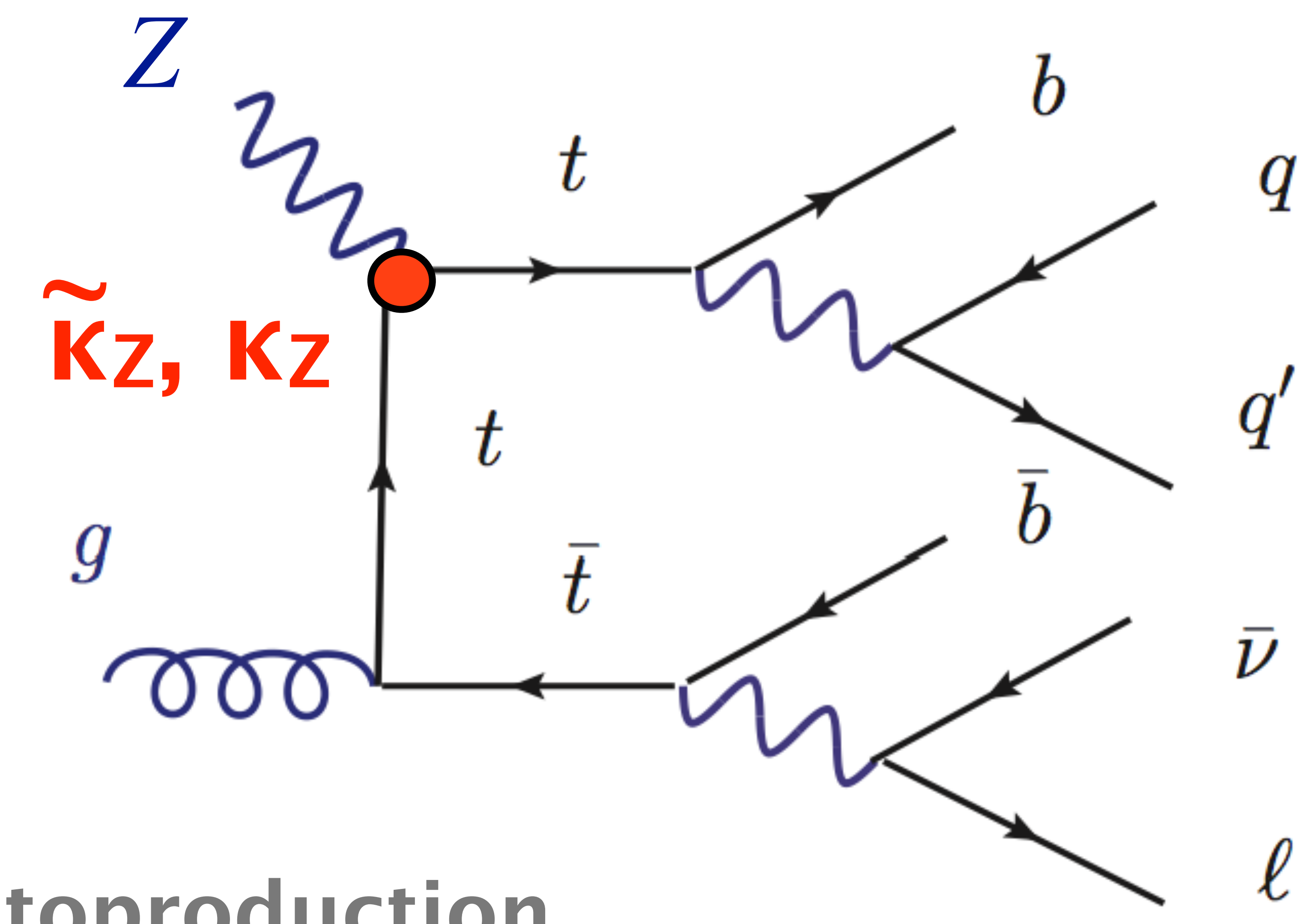
?

→ not unambiguous at the LHC

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

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

$\kappa = 2m_t \mu_t$



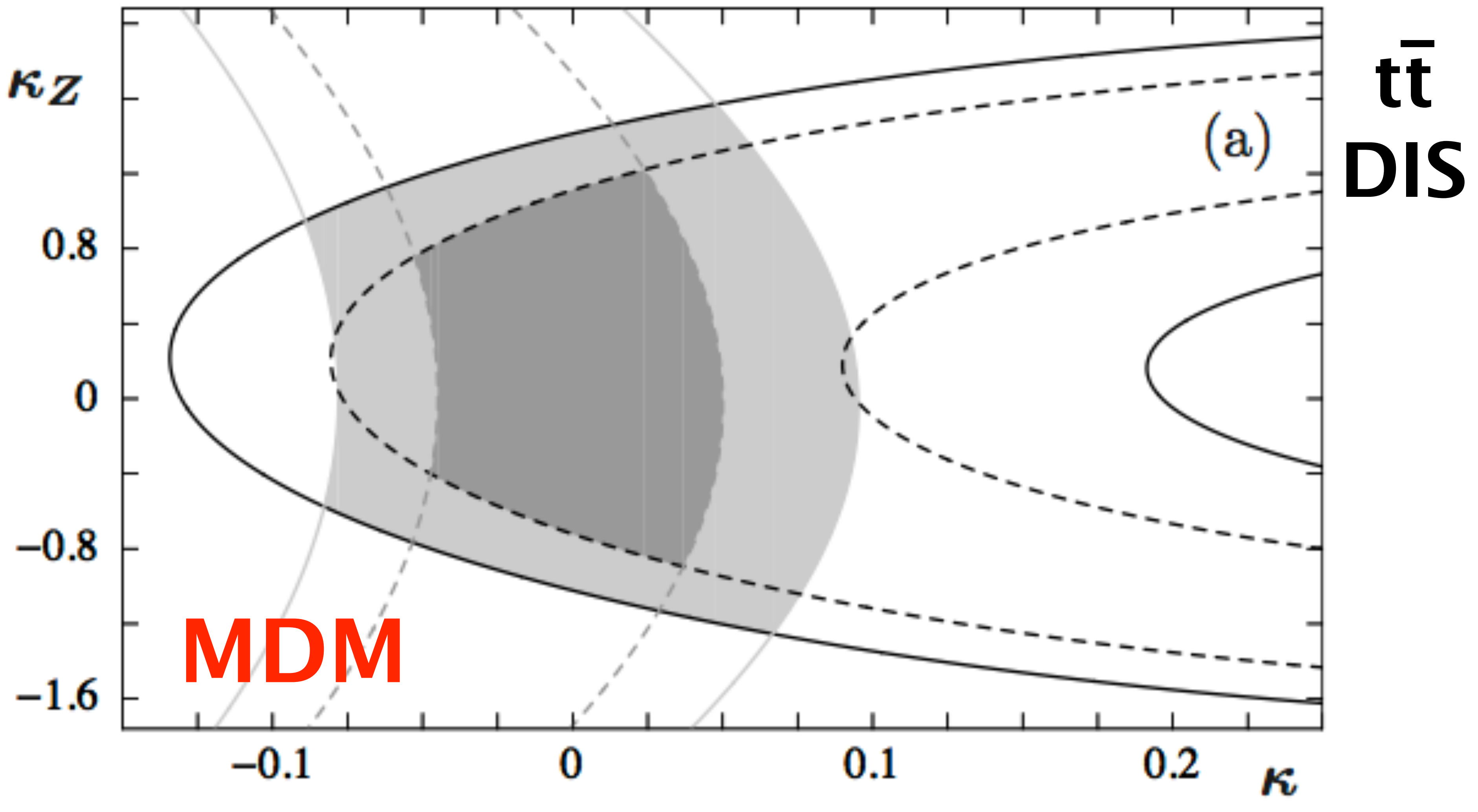
$t\bar{t}$ photoproduction

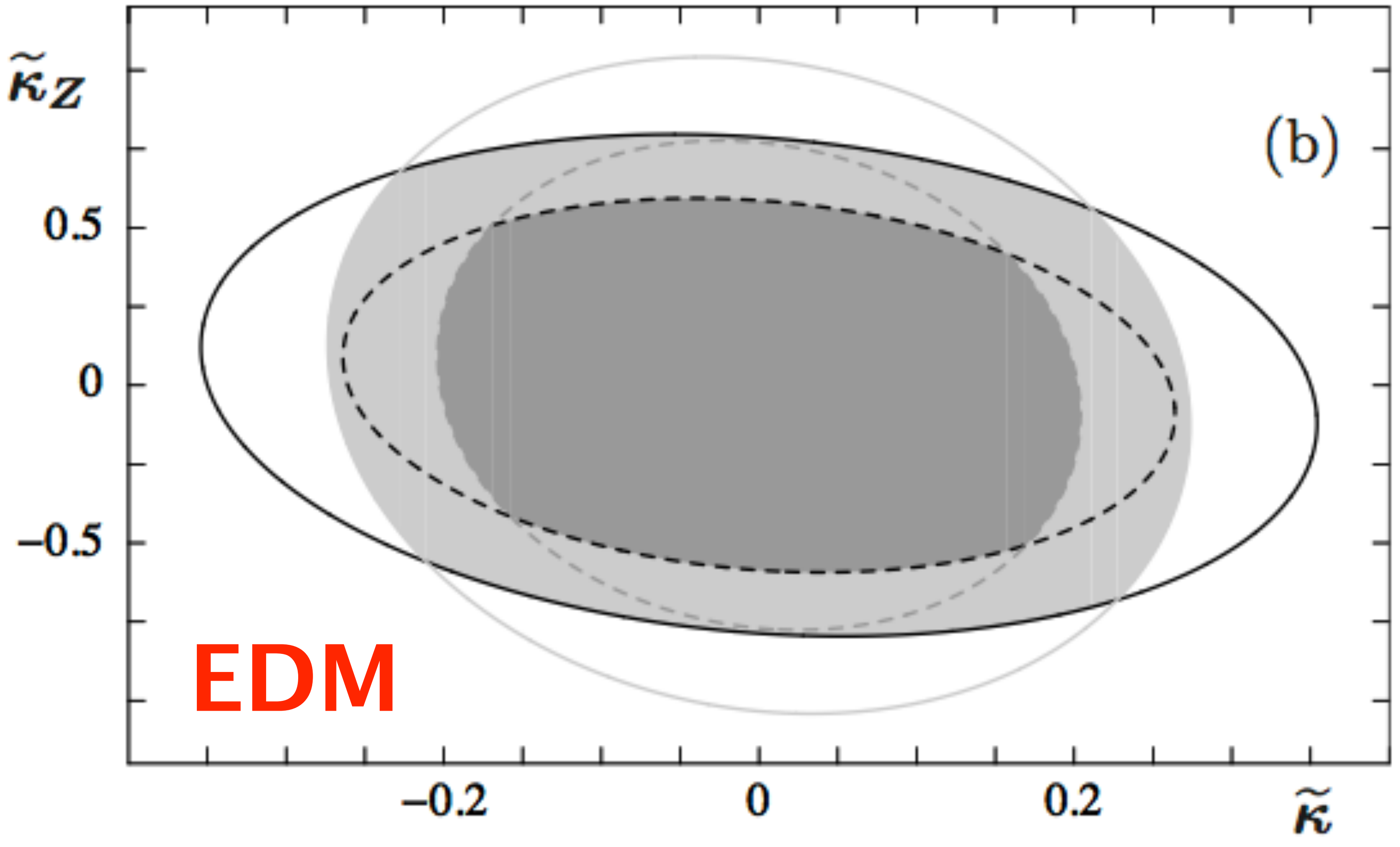
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

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

LHeC E_e=60 GeV

10% and 18% accuracy assumed



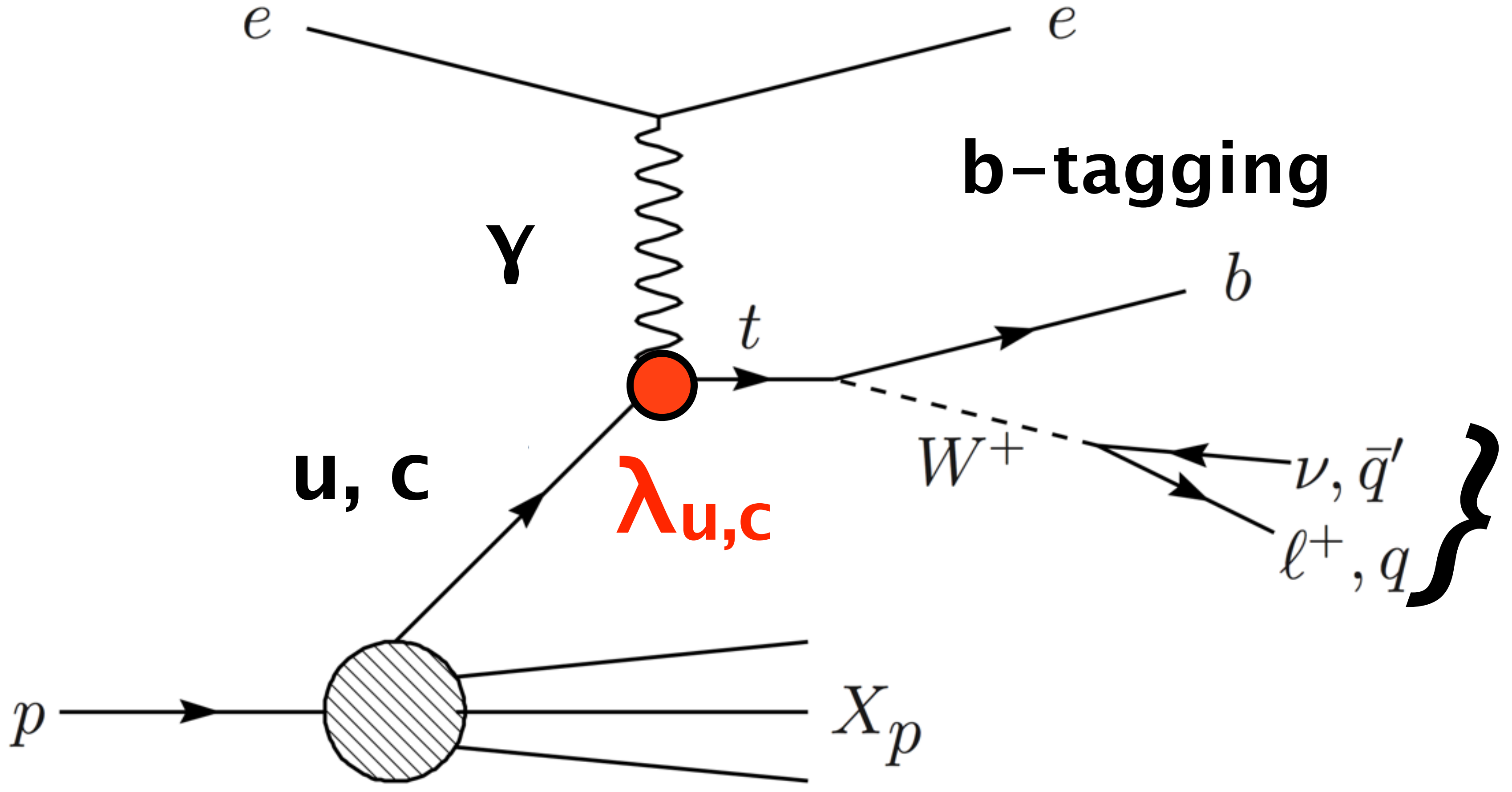


Search for Anomalous FCNC tuγ Coupling

signal

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

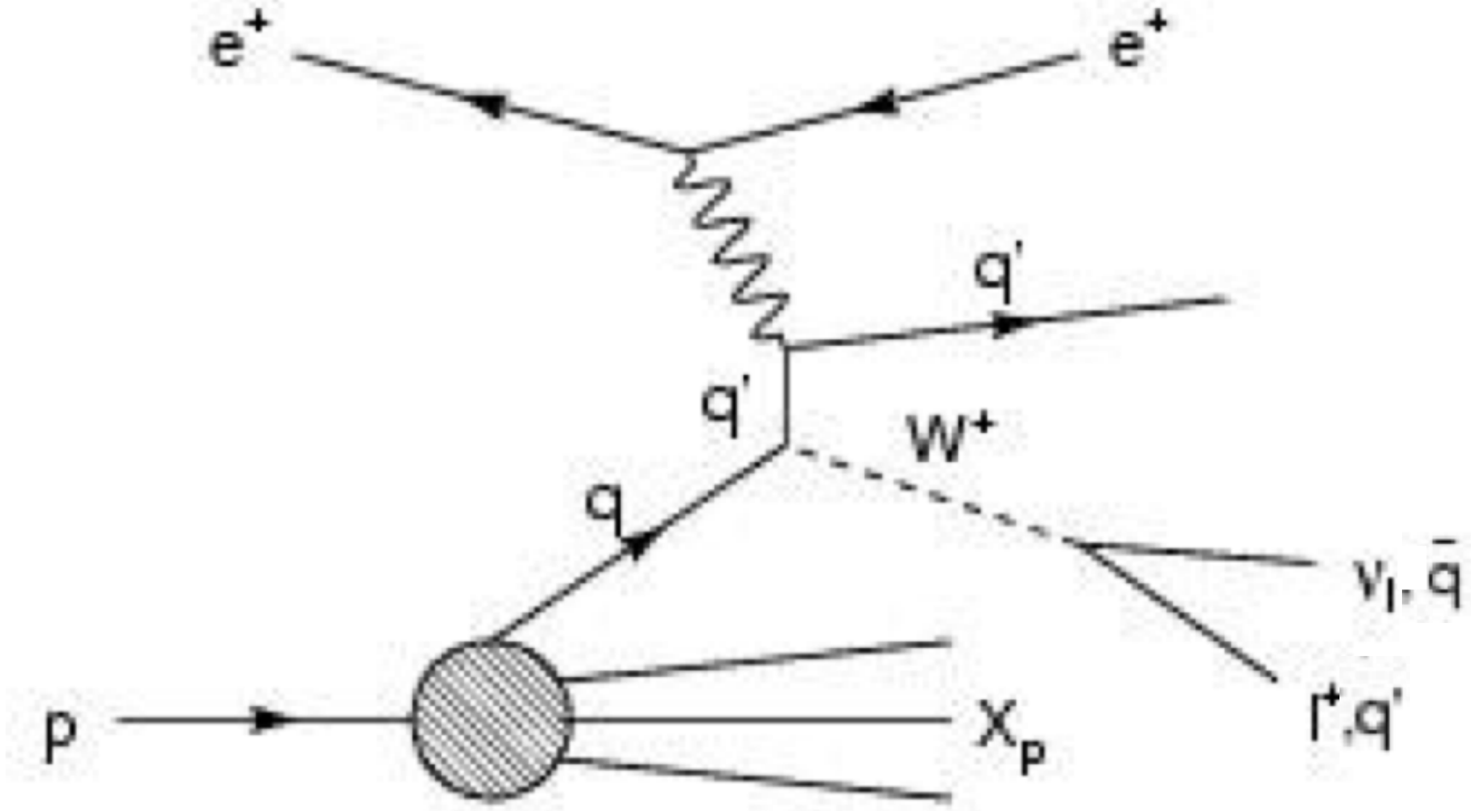
$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda_q}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_q + h_q \gamma_5) q A_{\mu\nu} + h.c.$$



b-tagging

50<M_{jj}<100 GeV

background



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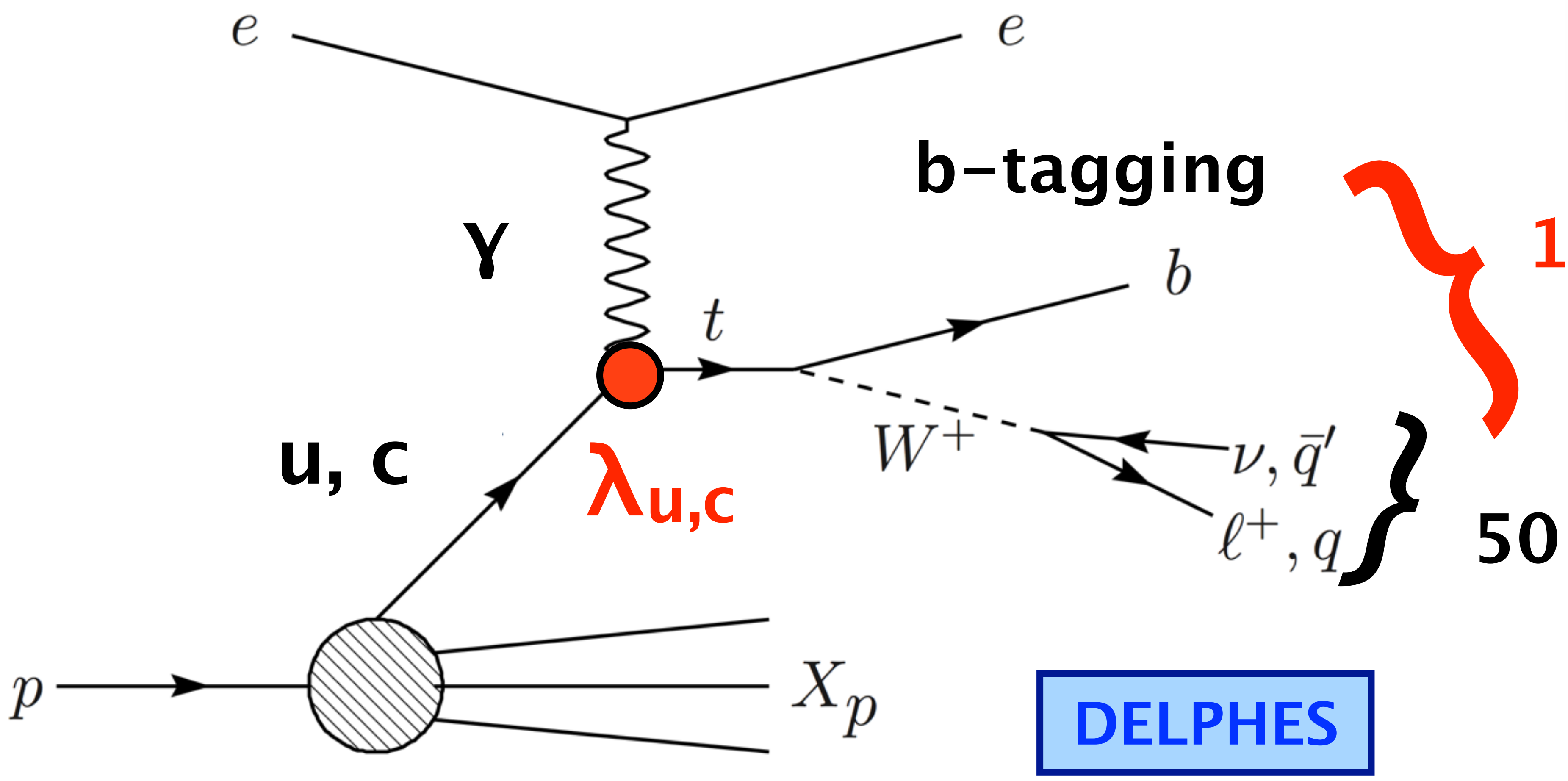
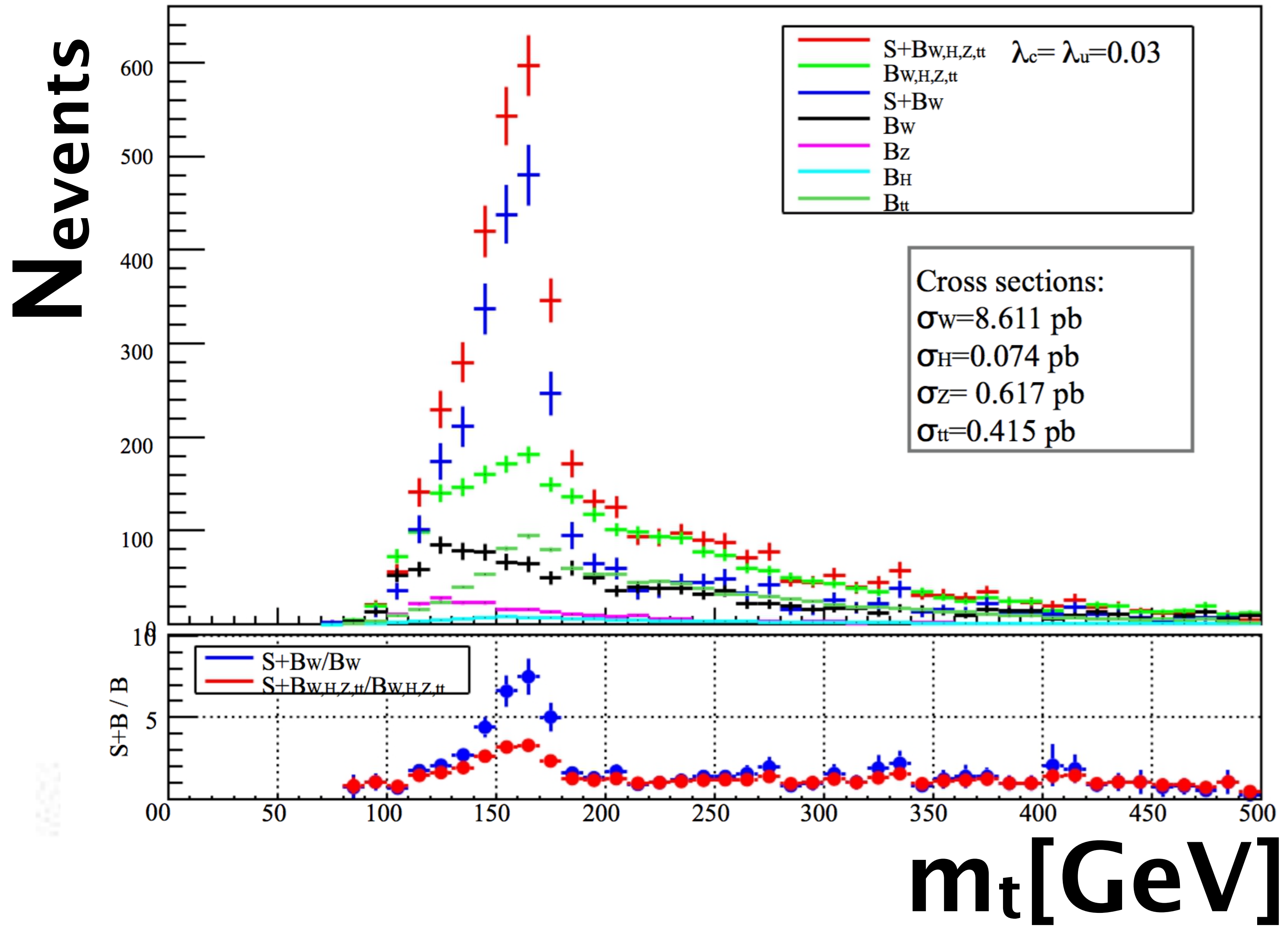


b-tagging

$130 < M_{Wb} < 190$ GeV

$50 < M_{jj} < 100$ GeV

DELPHES



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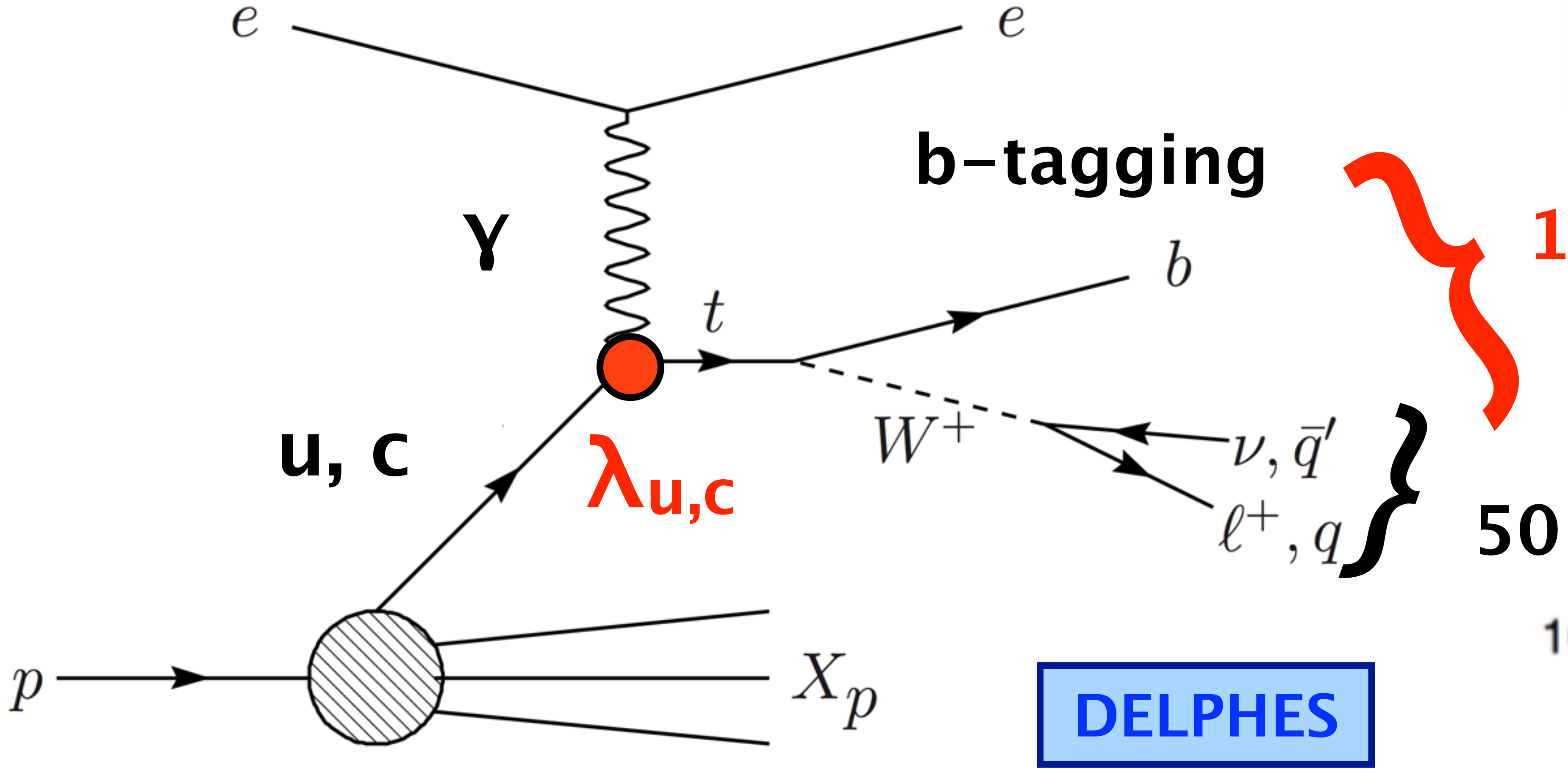

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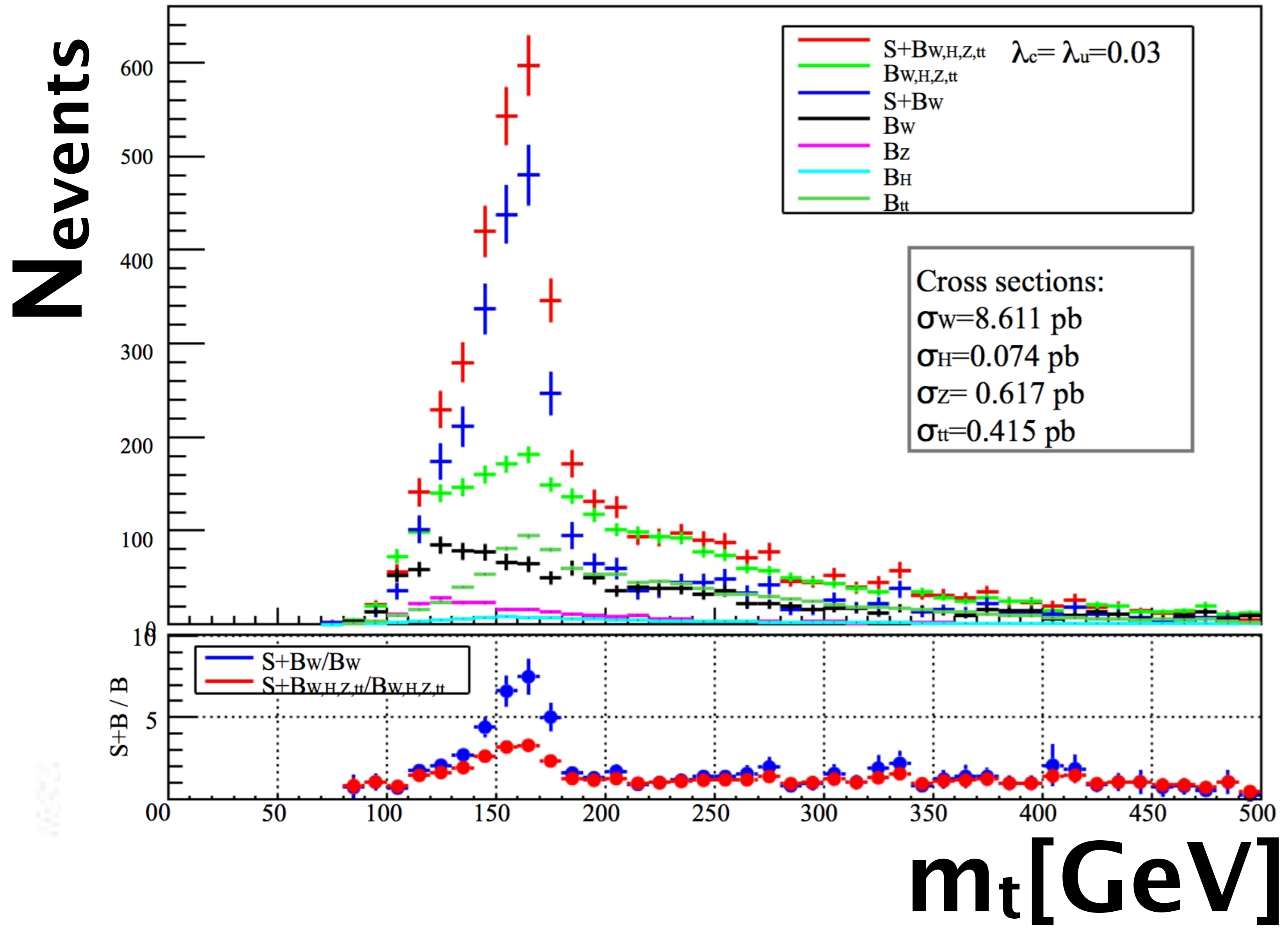
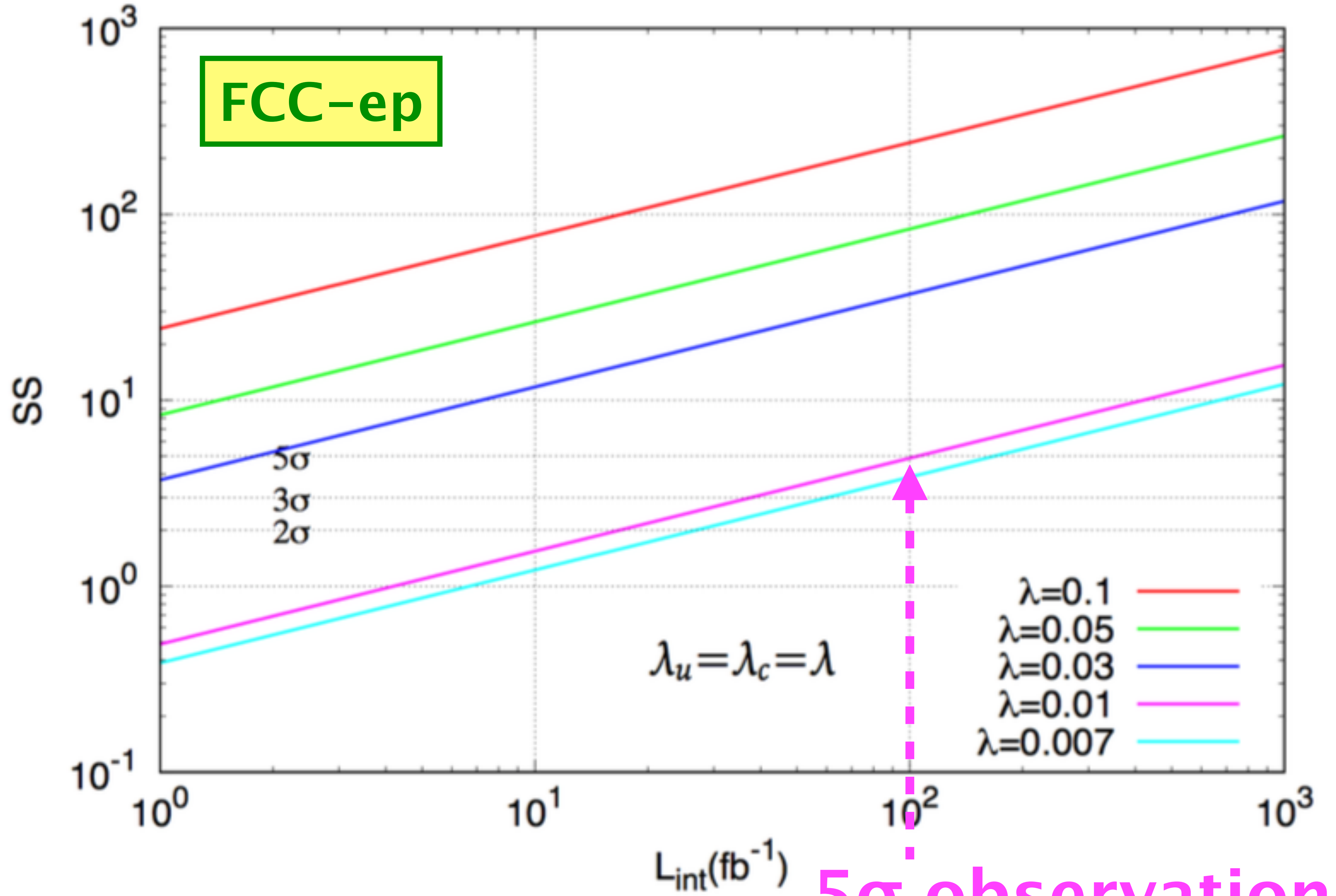
300 fb^{-1}, √s= 14 TeV:
λ<0.022 @ 95% C.L.

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

DELPHES

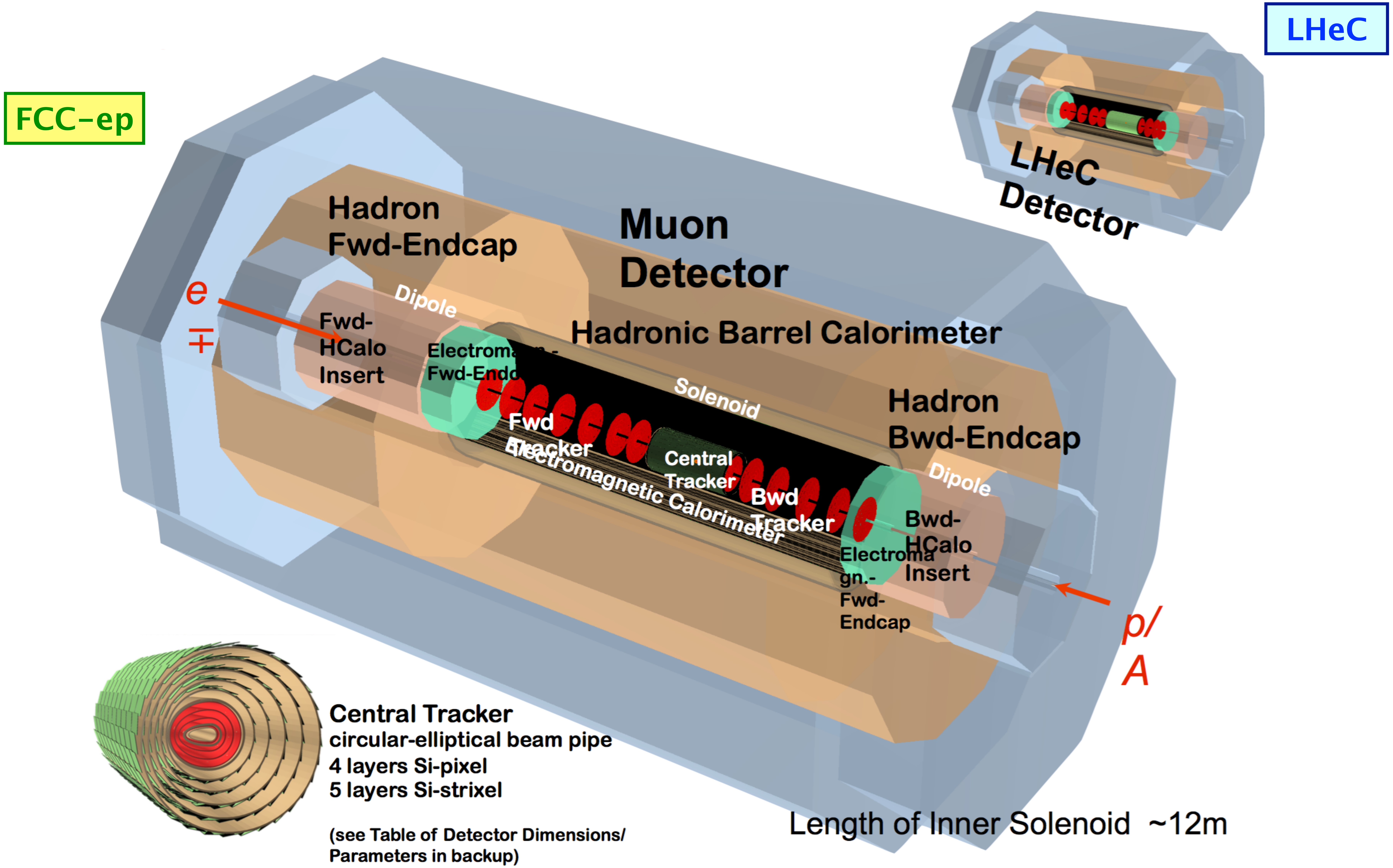


FCC-ep



5σ observation

LHeC and FCC-eh Detector Layout



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

(see Table of Detector Dimensions/ Parameters in backup)

Length of Inner Solenoid ~12m