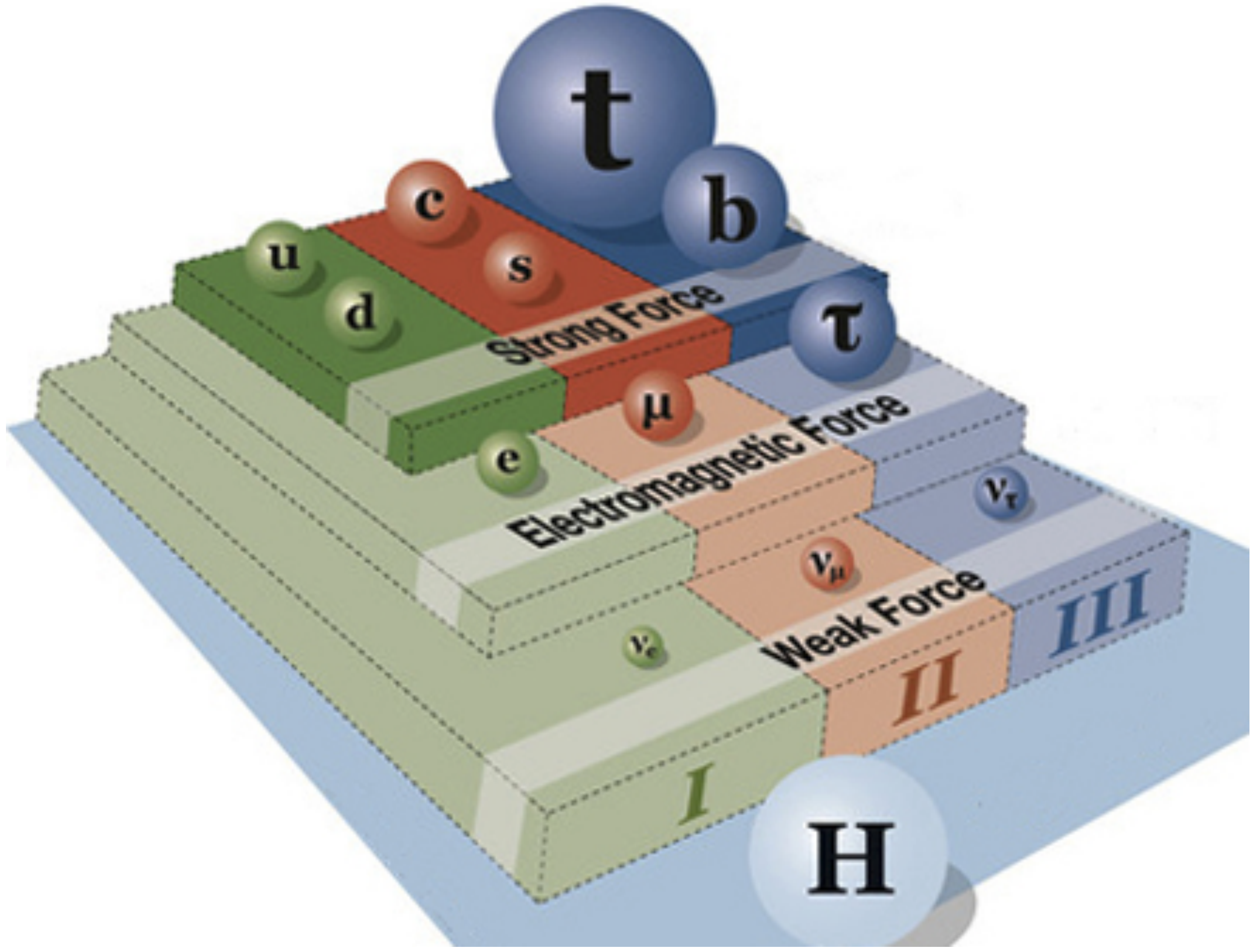
FUTURE
CIRCULAR
COLLIDER
STUDY

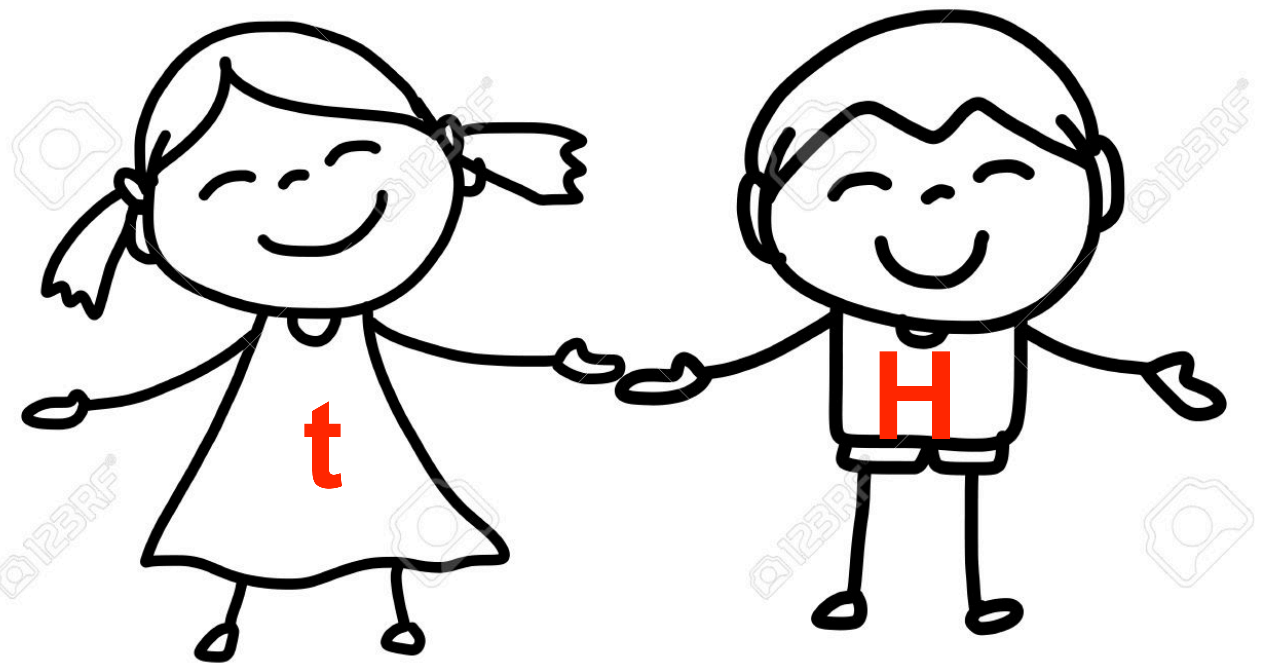
TOP PHYSICS @FCC

PATRIZIA AZZI - INFN PADOVA (ITA)
On behalf of the FCC Collaboration

NEED MORE TOP PHYSICS!

- ➤Top being the heaviest quark (and particle) in the SM is the one that most strongly influences the Higgs and its potential
- ➤Its mass leads to a yukawa coupling of about 1. Coincidence?
- ➤Top mass also close to the critical value between the region where the Higgs potential is stable up to the Plack scale (or not)





FCC will complete redefine the landscape of top studies and measurements: each machine providing the ultimate precision for various flagship measurements, greatly improving over HL-LHC precision studies.

THE SHOPPING LIST

- Mass and Width
- (anomalous) Couplings: y_t, g_{tWb}, g_{Ztt}, $g_{\gamma tt}$
- FCNC and rare decays
- Asymmetries & other properties
- multi-top+multi-boson production
- single top measurements
- tops in the initial state (top_{PDF})
- physics with/of (hyper)-boosted tops

Not discussing here top production from decay of NP particles

HL-LHC will extend significantly the current top precision results (see YR WG1 report https://arxiv.org/abs/1902.04070) however the FCC projects goes order(s) of magnitudes beyond in precision and can reach completely unexplored parameter space.

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The FCC project with its three complementary machines can achieve in a coherent way the ultimate precision on measurement of top properties

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HOW MANY TOPS?

➤ the total number is not the only thing that matters

Collider	Energy	total # of tt pairs	Integrated Luminosity	
TEVATRON	2 TeV	100K	$10fb^{-1}$	+0 extra interactions
LHC	7, 8, 13 TeV	300M	$300fb^{-1}$	+30 extra interactions
HL-LHC	14 TeV	3B	$3000fb^{-1}$	+200 extra interactions
FCC-pp	100 TeV	1T	$20ab^{-1}$	
FCC-ep	3.5 TeV	10M (single t)	$1ab^{-1}$	
FCC-ee	365GeV	1M	$1.5ab^{-1}$	

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TOP PRODUCTION @FCC COLLIDERS

E_{com}=365 GeV

L_{int}=1.5 ab^{-1}

1M tt pairs

E_{com}=100 TeV

L_{int}=20 ab^{-1}

1T tt pairs

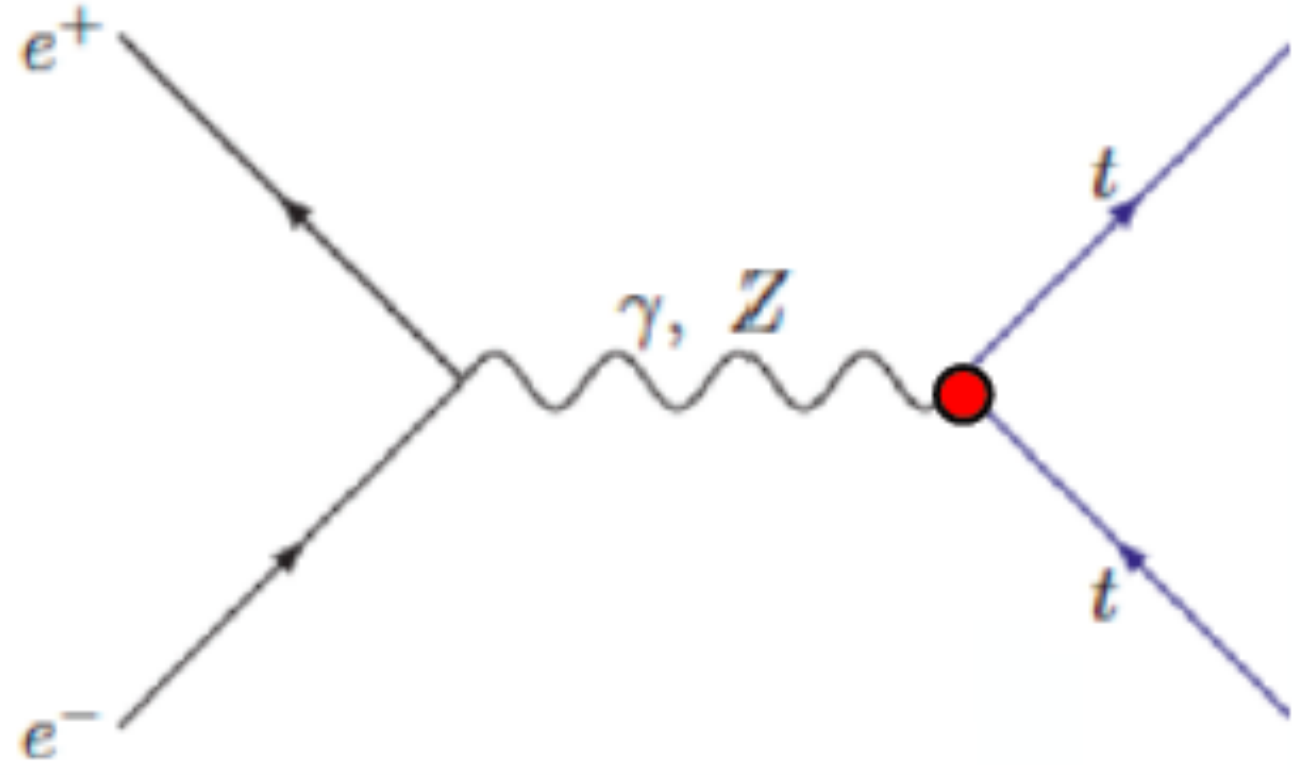
E_{com}=3.5 TeV

L_{int}=1 ab^{-1}

10M single top

TOP PRODUCTION @FCC COLLIDERS

FCC-ee



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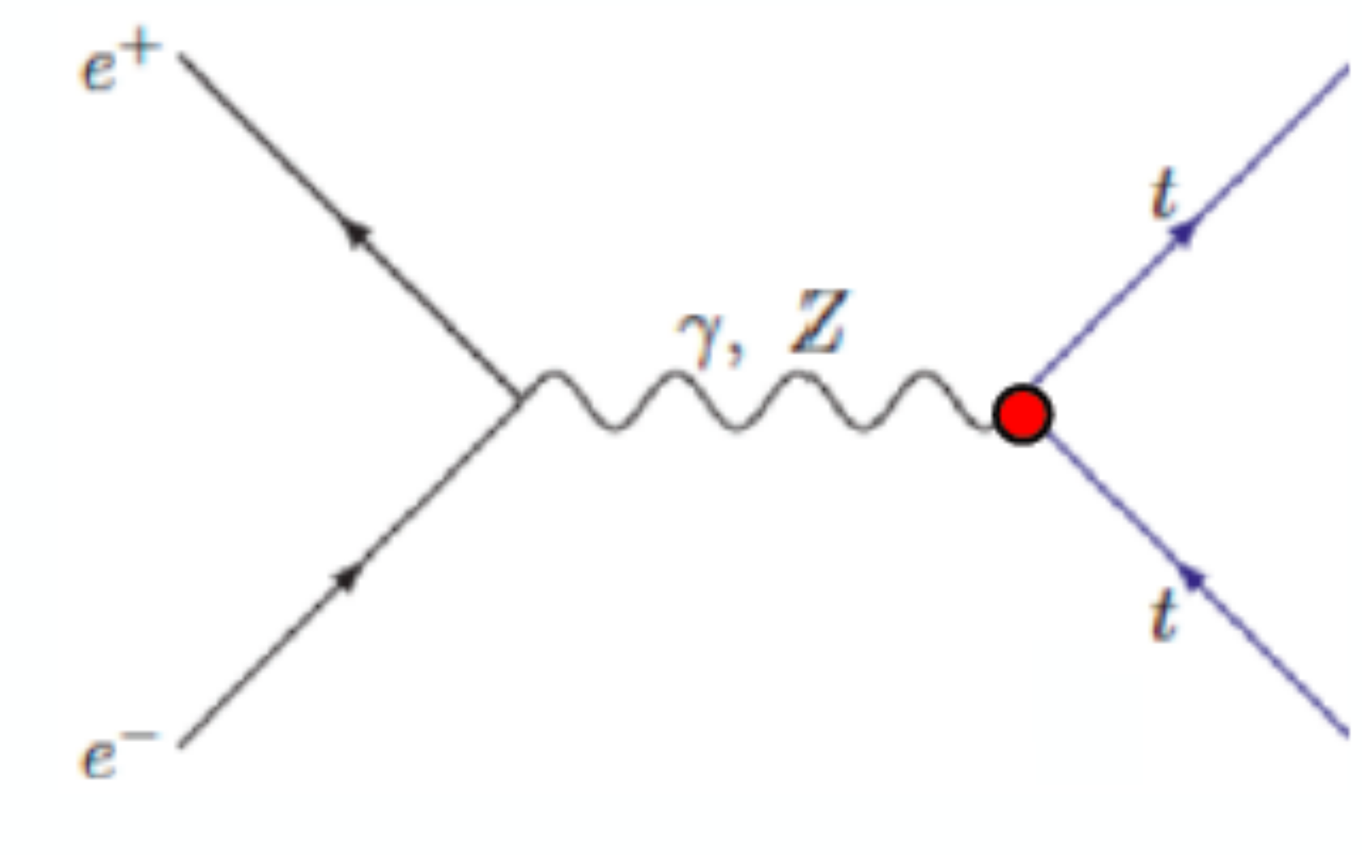
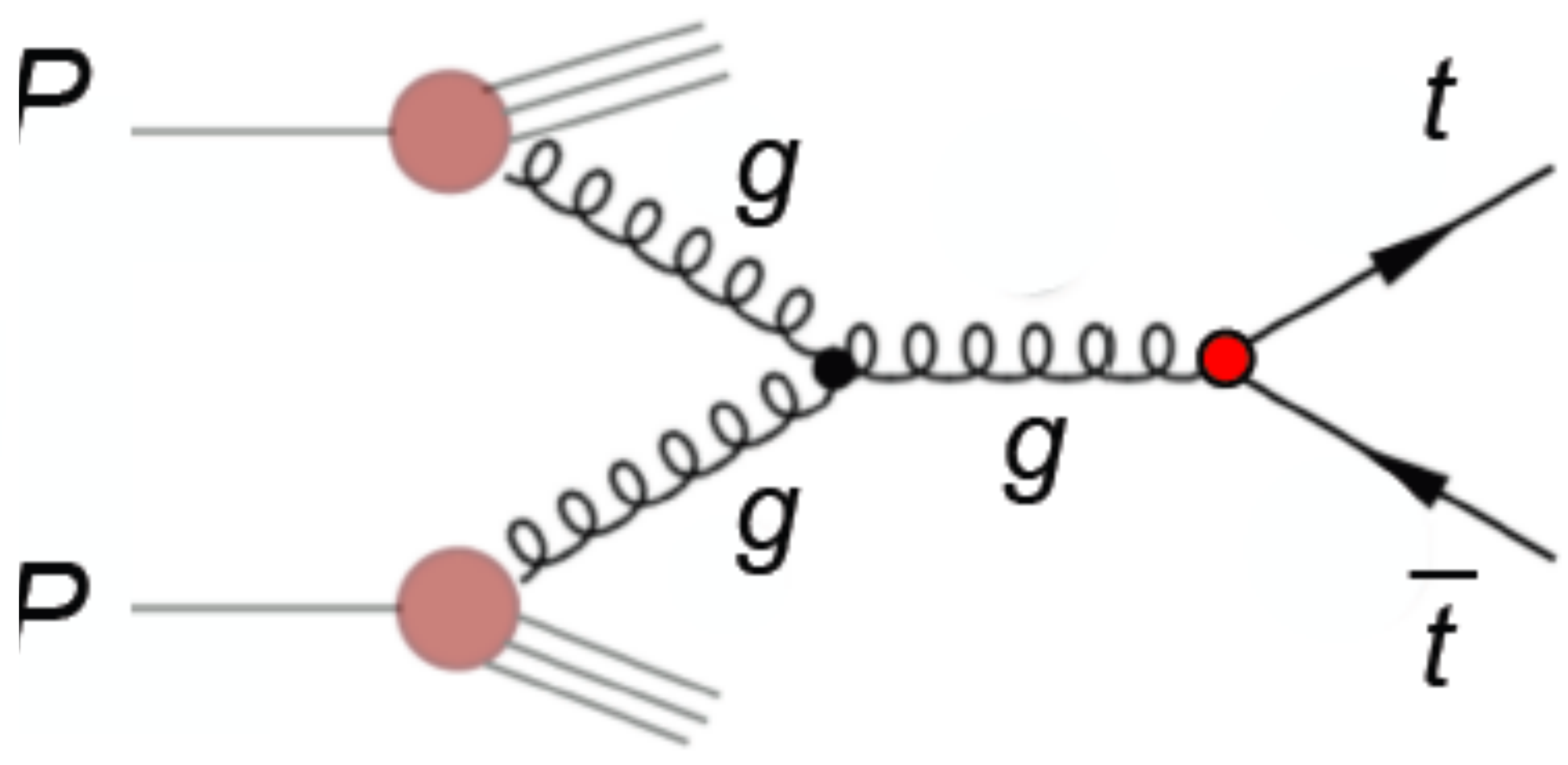
FCC-pp





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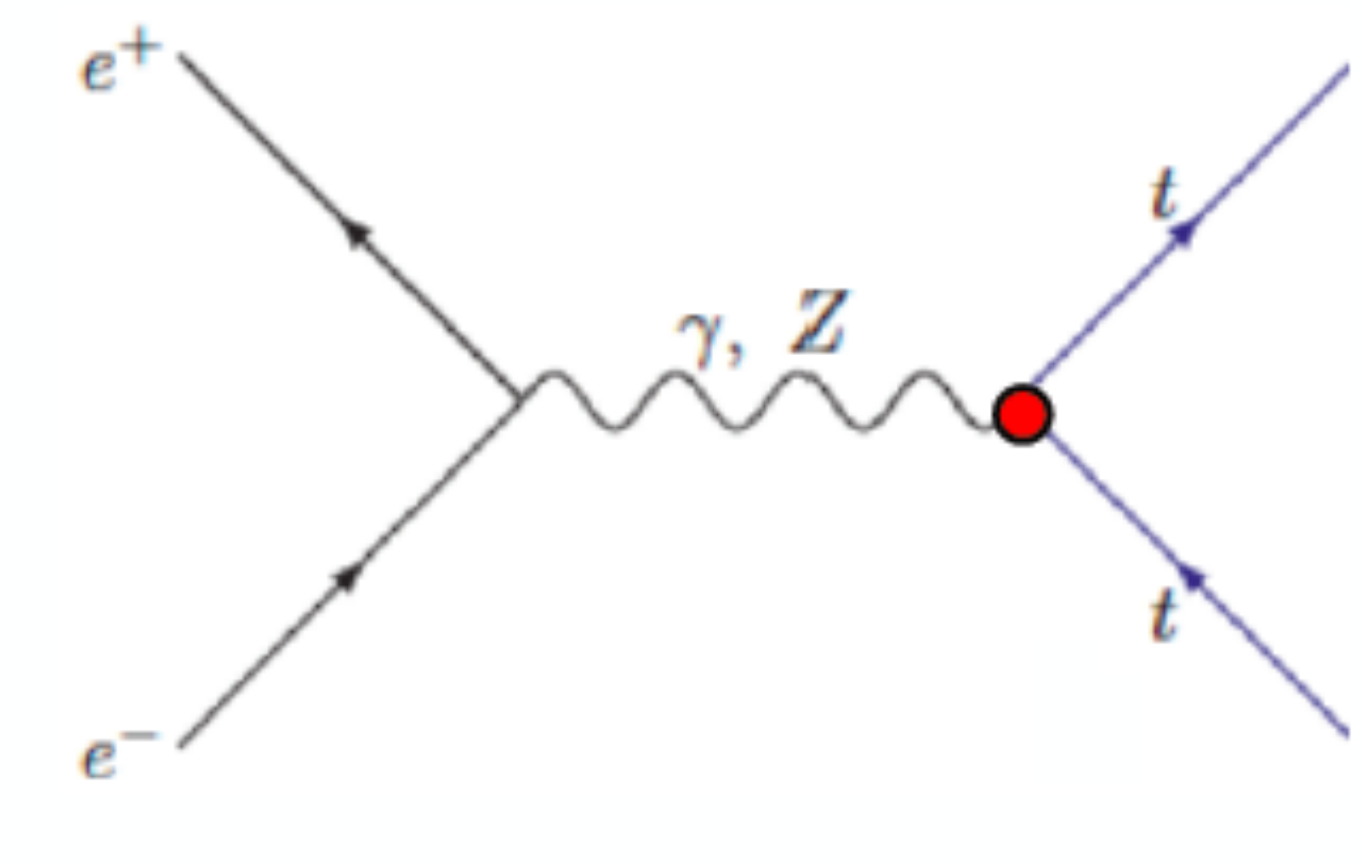
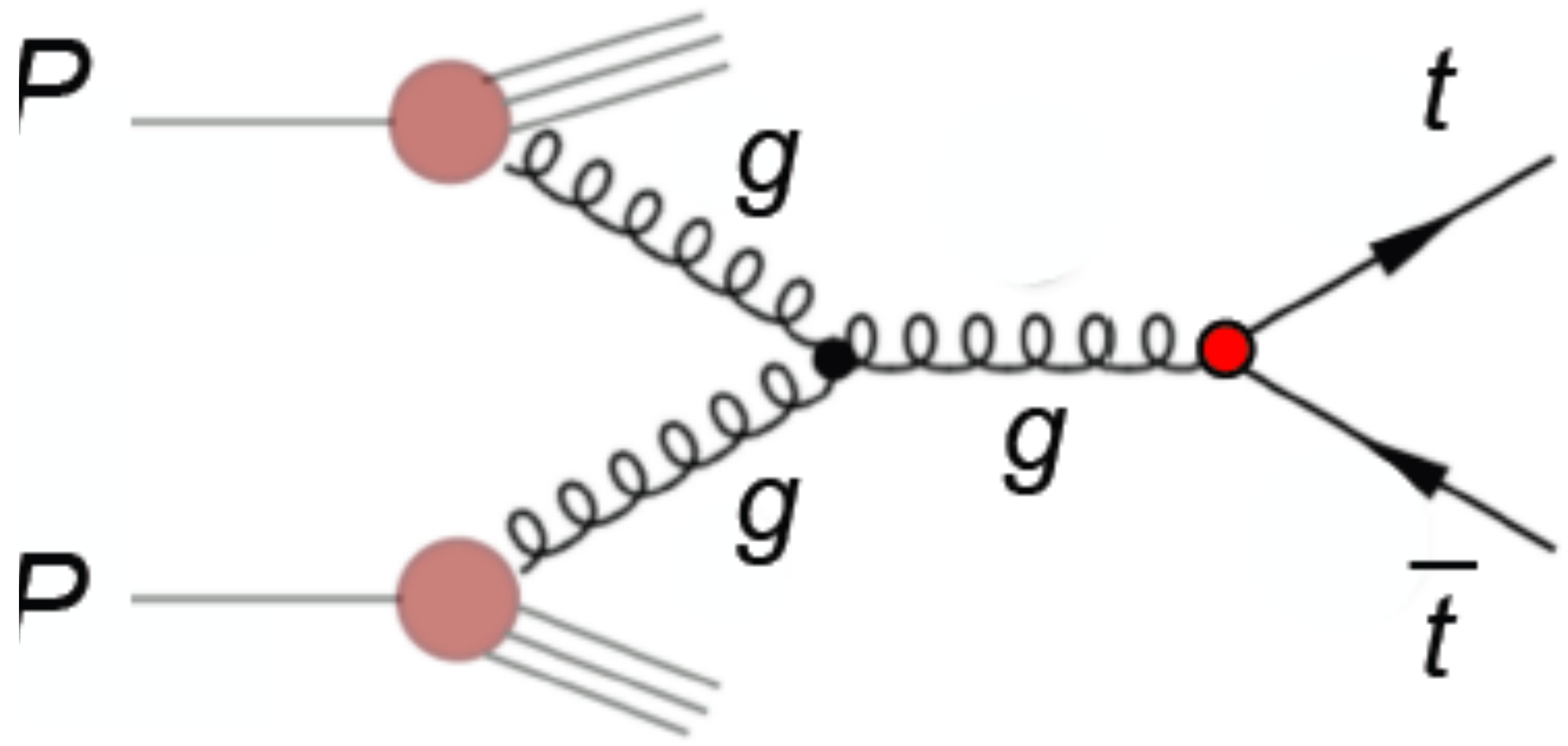
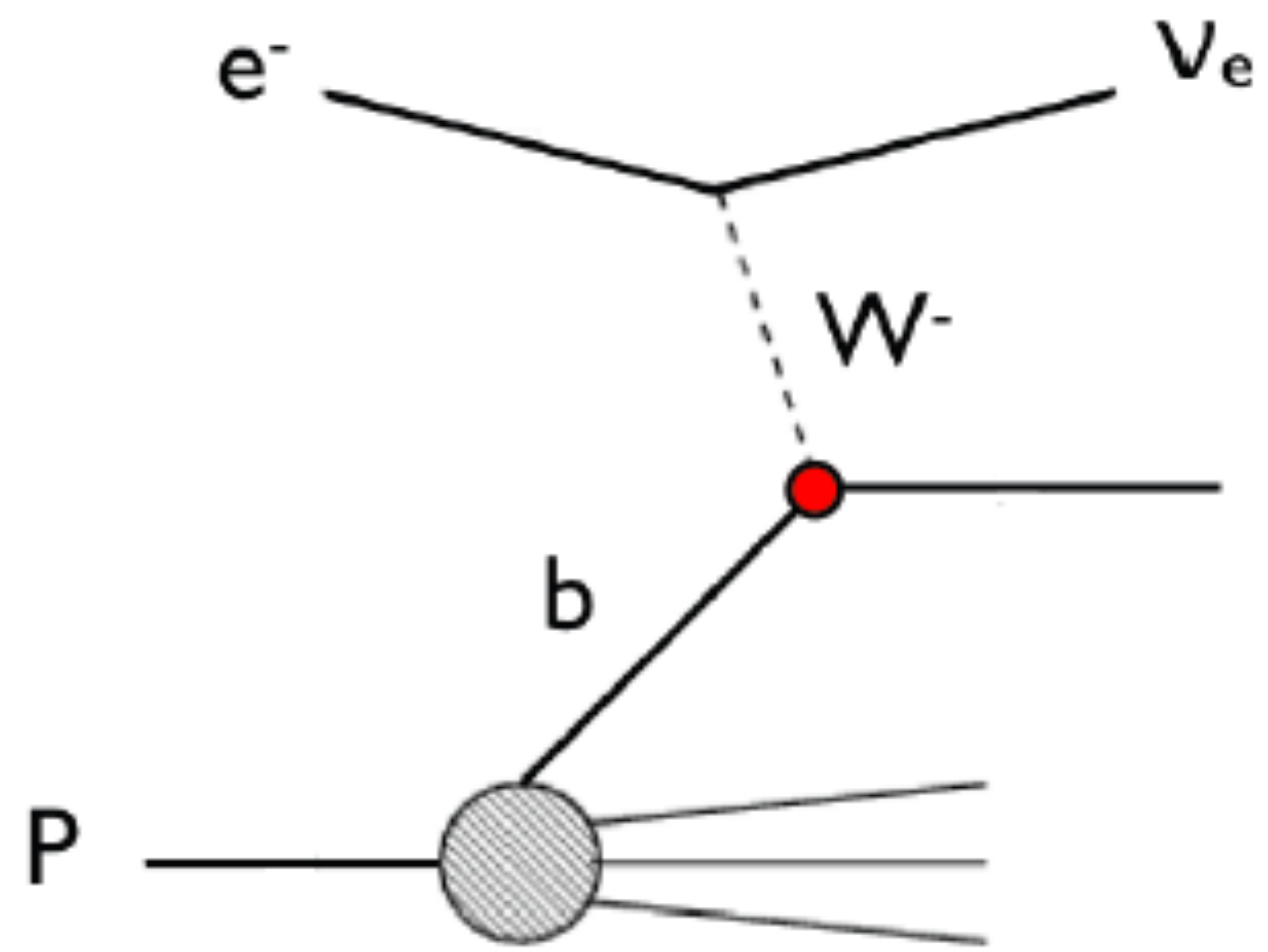


FCC-pp



FCC-ep



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1M tt pairs

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1T tt pairs

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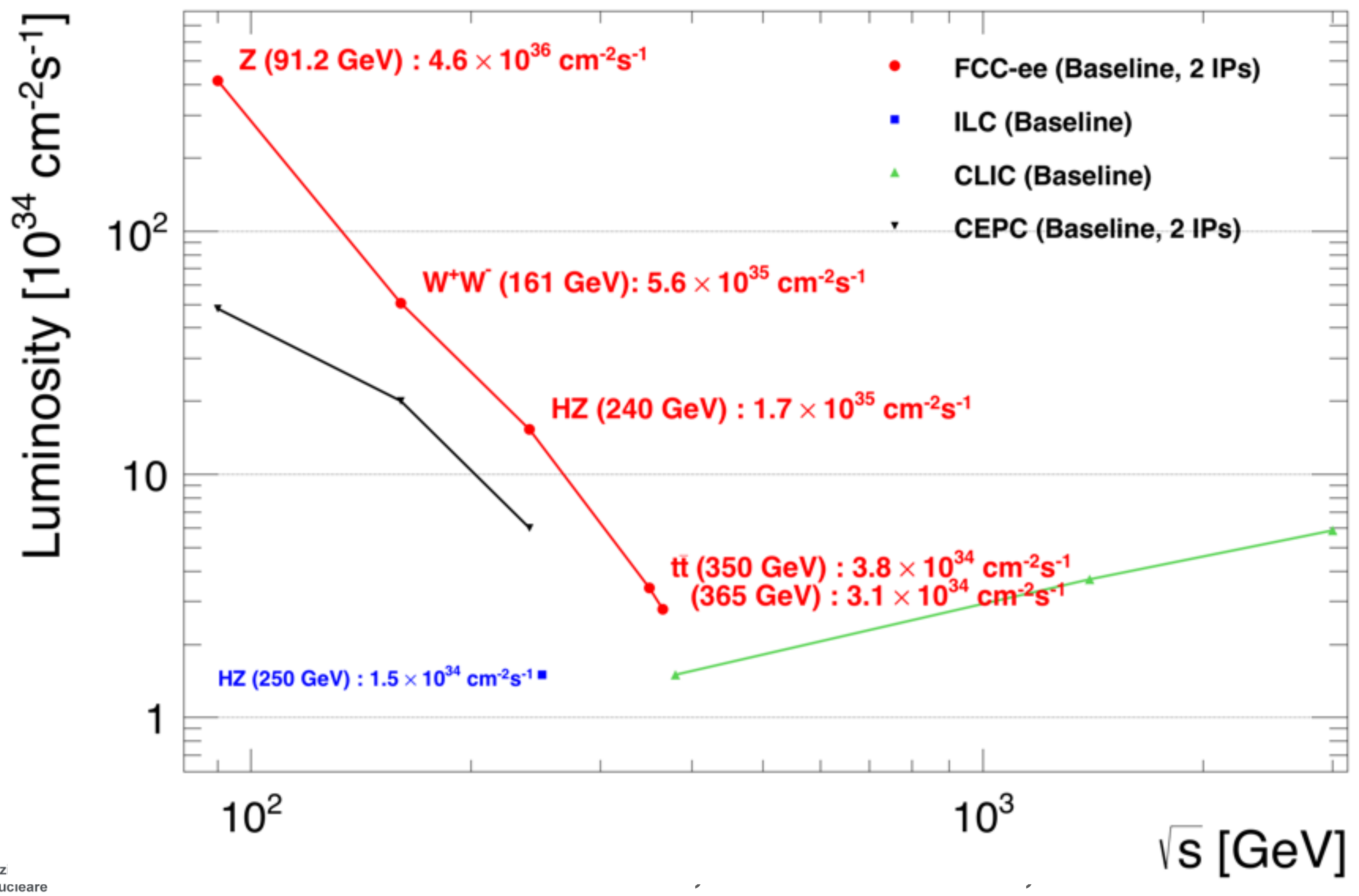
10M single top

FCC-ee

TOP PHYSICS RUN @FCC-ee

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$ threshold	365 GeV
Lumi/IP (10^{34} $cm^{-2}s^{-1}$)	100	200	31	7.5	0.85	1.5
Lumi/year (2 IP)	26 ab^{-1}	52 ab^{-1}	8.1 ab^{-1}	1.95 ab^{-1}	0.22 ab^{-1}	0.39 ab^{-1}
Physics goal	150		10	5	0.2	1.5
Run time (year)	2	2	1	3	1	4



Strength of the FCC-ee program is the ability to span several centre of mass energies at high luminosities

Top physics comes in the program in several places

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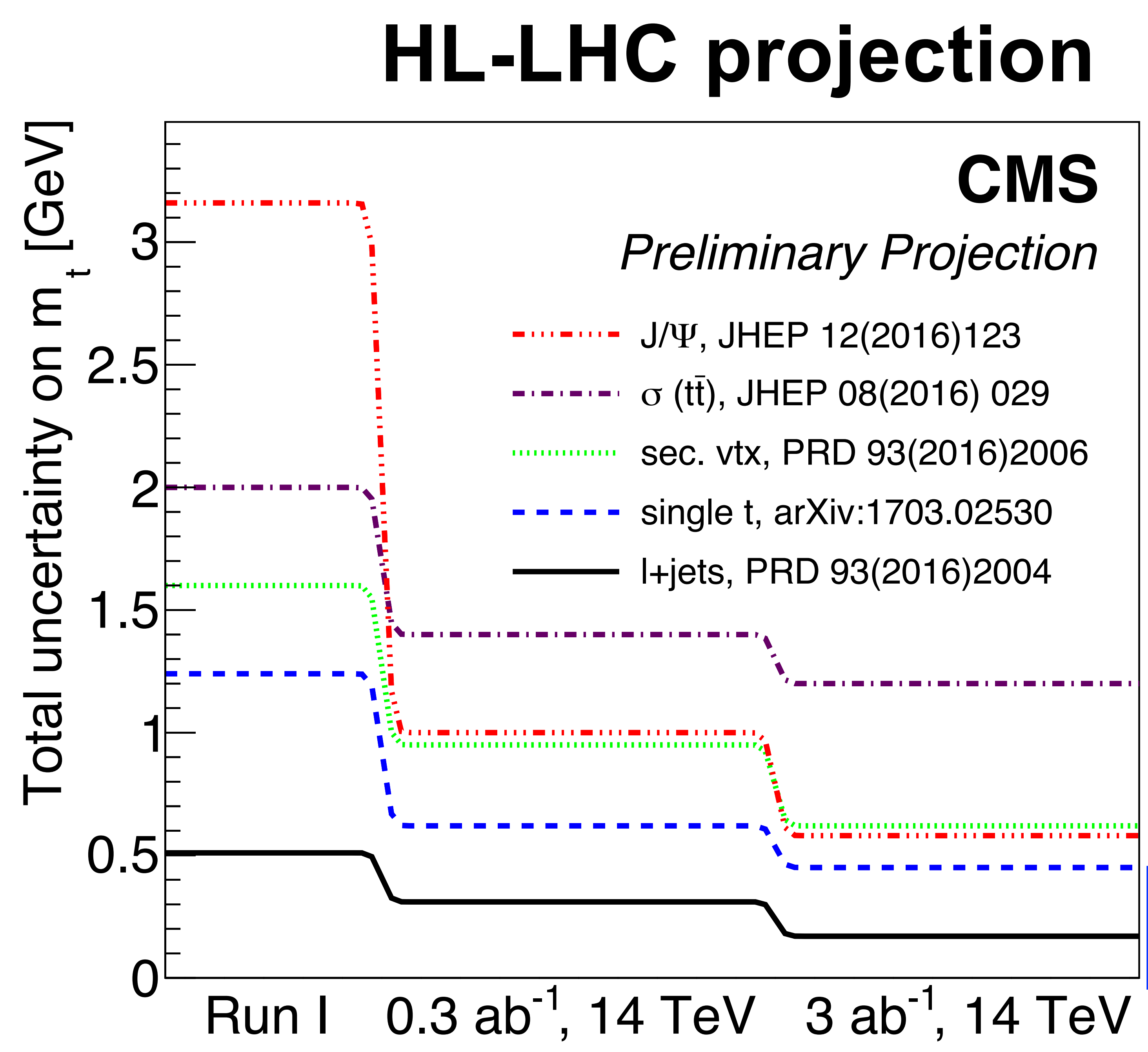
- Dedicated run of ~1.5 ab^{-1} at and around tt threshold @350GeV « Mega-Top »
  - 0.2 ab^{-1} for mass measurement from threshold scan
  - higher energy runs for top coupling measurement (ttZ,ttγ,ttH)
- Can profit of the run at 240GeV (5ab^{-1}) dedicated to HZ production for studies with single top
  - periodic returns at the Z-peak in « FCC-ee top » conditions for calibration

FCC-ee

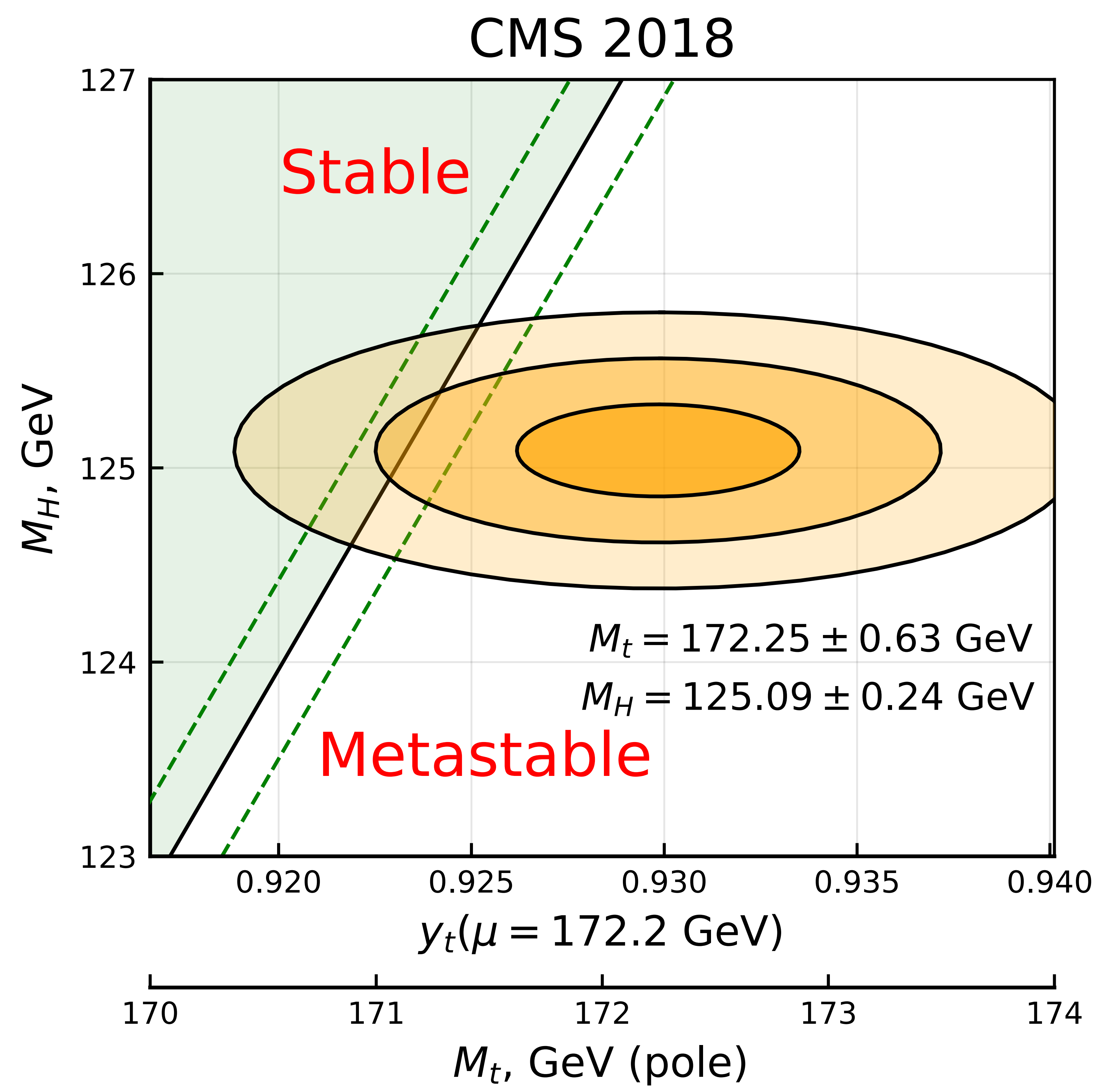
PRECISION TOP MASS MEASUREMENT

➤Precision measurements are a **portal to new physics effects at high scales**, the clean environment and large statistics at FCC-ee will allow to probe effects at much higher energies.

➤In particular the SM fits need a precise knowledge of the **top quark mass** (in a well defined scheme) possibly below the 100MeV which is extremely difficult to achieve at a pp collider even with the statistics of the HL-LHC.

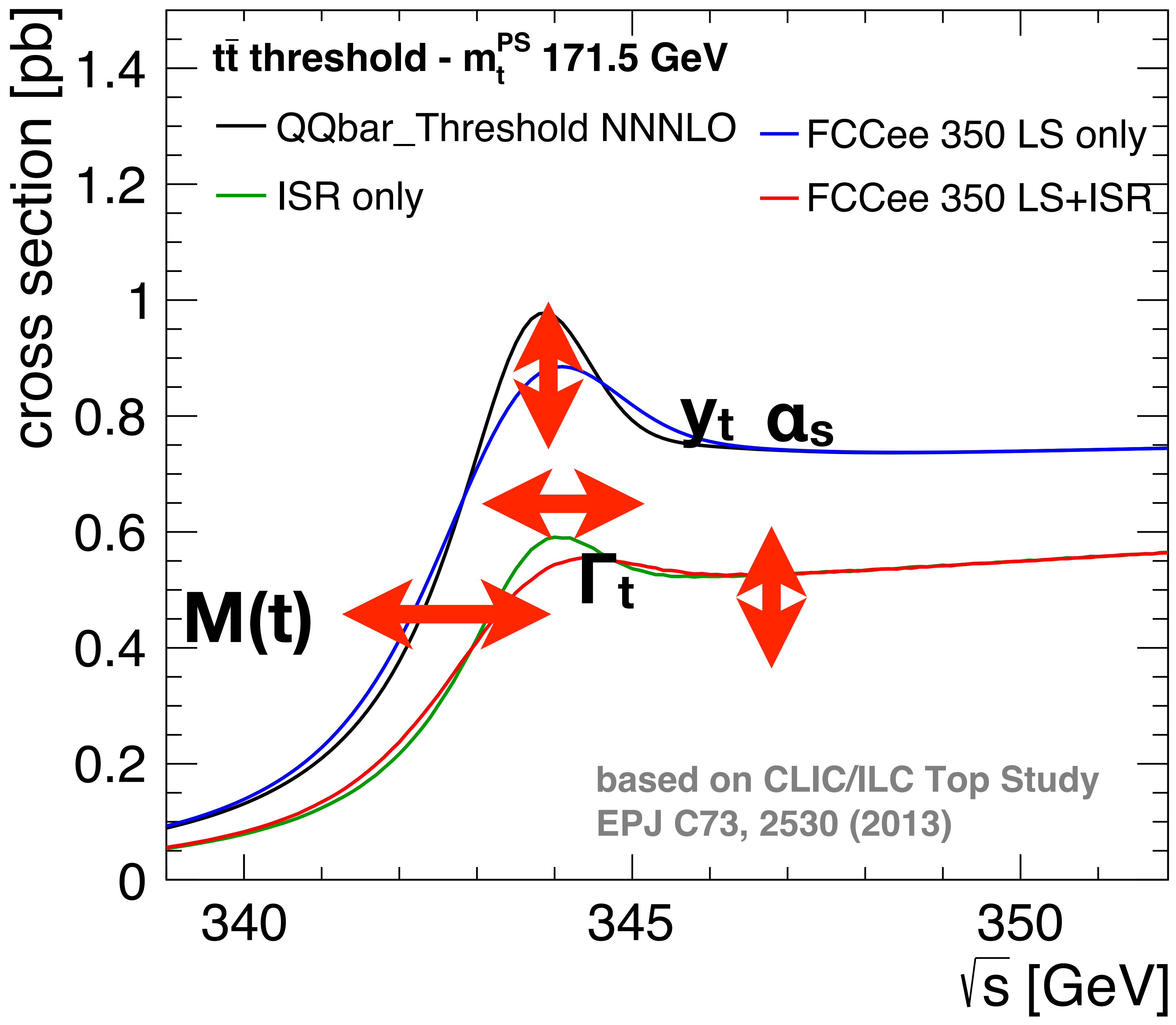


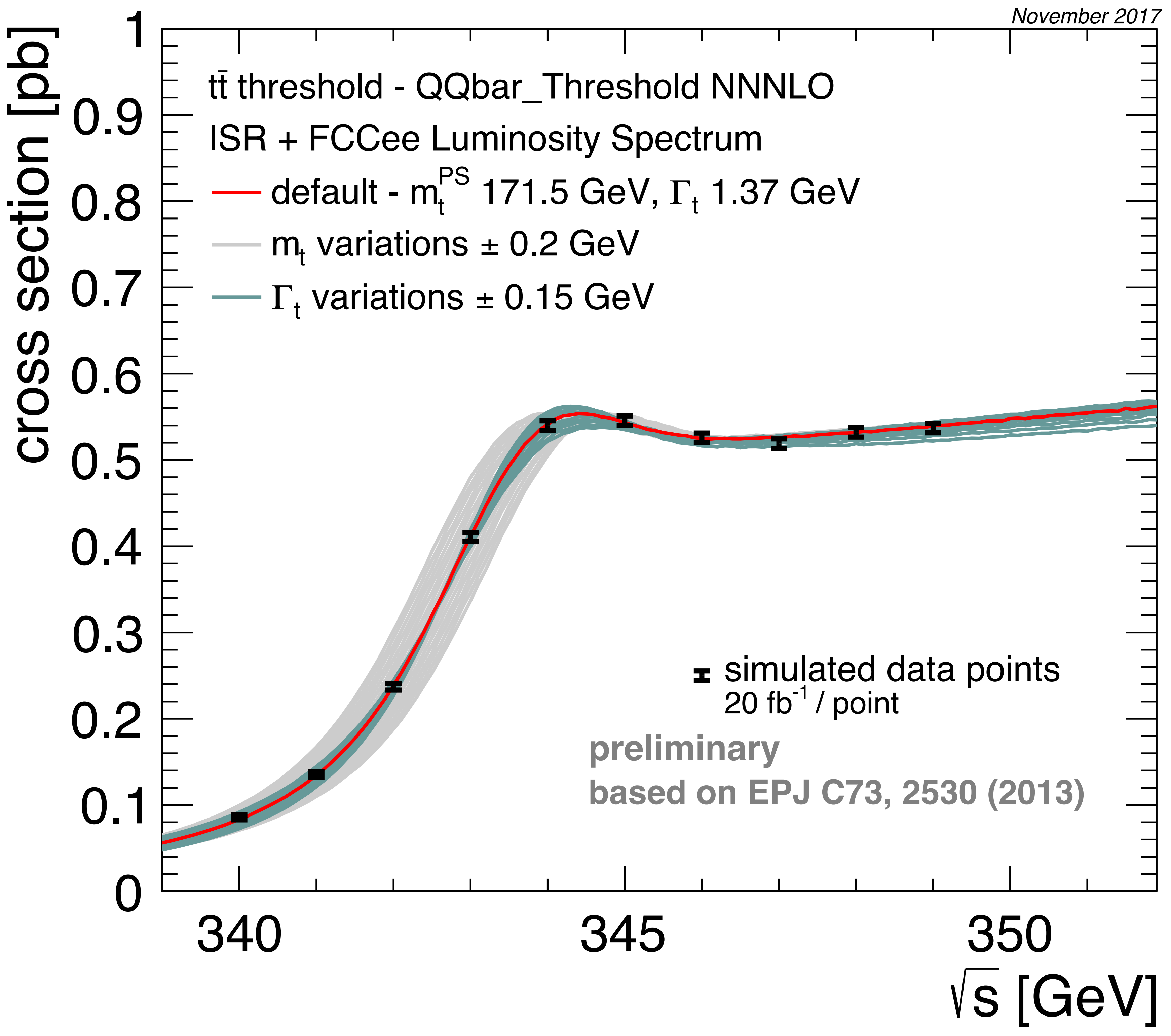
l+jets Δm~0.17GeV



FCC-ee

TOP MEASUREMENTS FROM THRESHOLD SCAN @FCC-ee



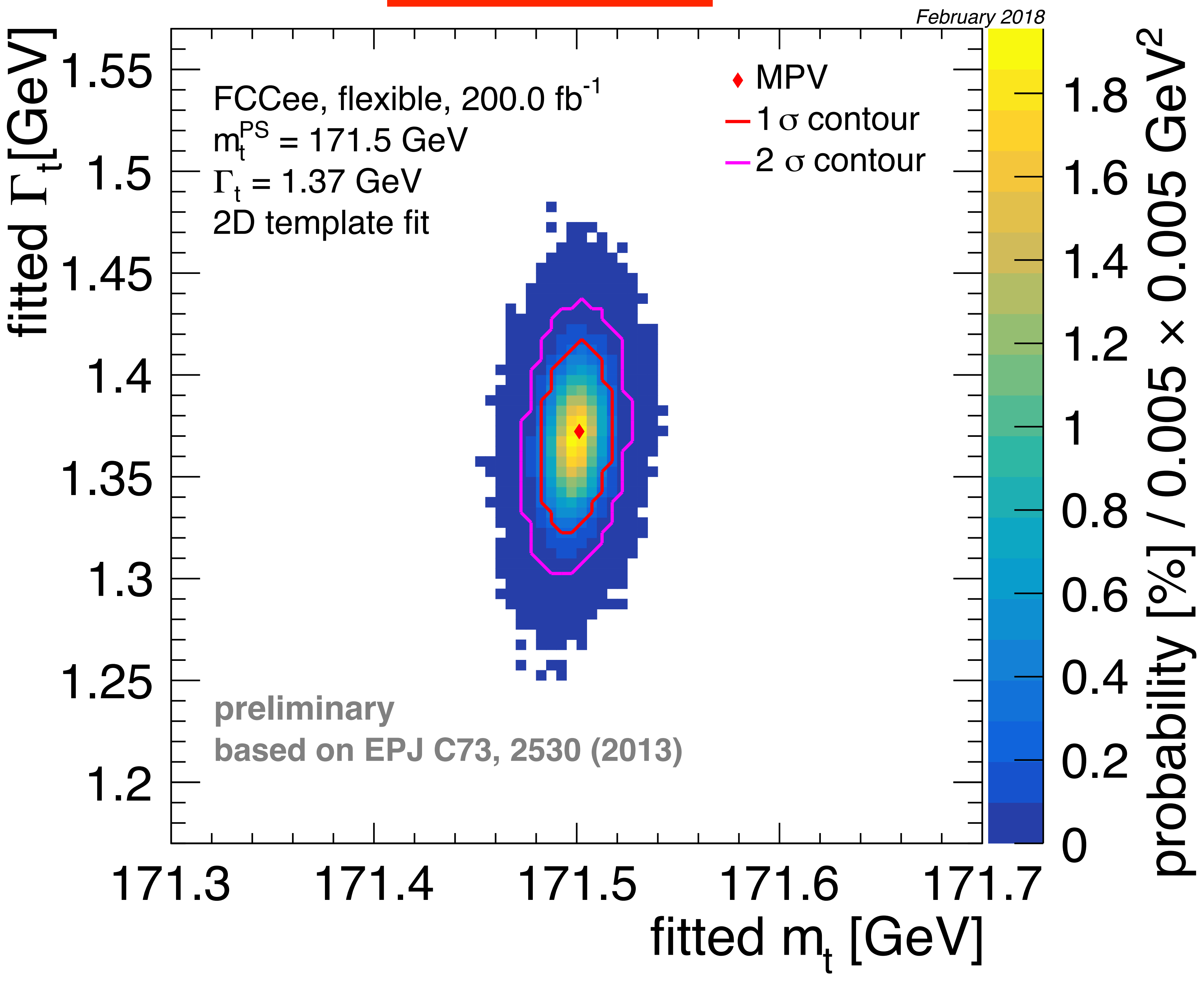


- Cross section shape depends strongly on top quark mass, width, α_s and Y_t allowing to extract directly these quantities with a threshold scan
  - choice of fit points optimized based on theory uncertainties (F. Simon arXiv:1611:03399v1(2016))
  - Threshold shape affected by ISR and machine beam energy spread

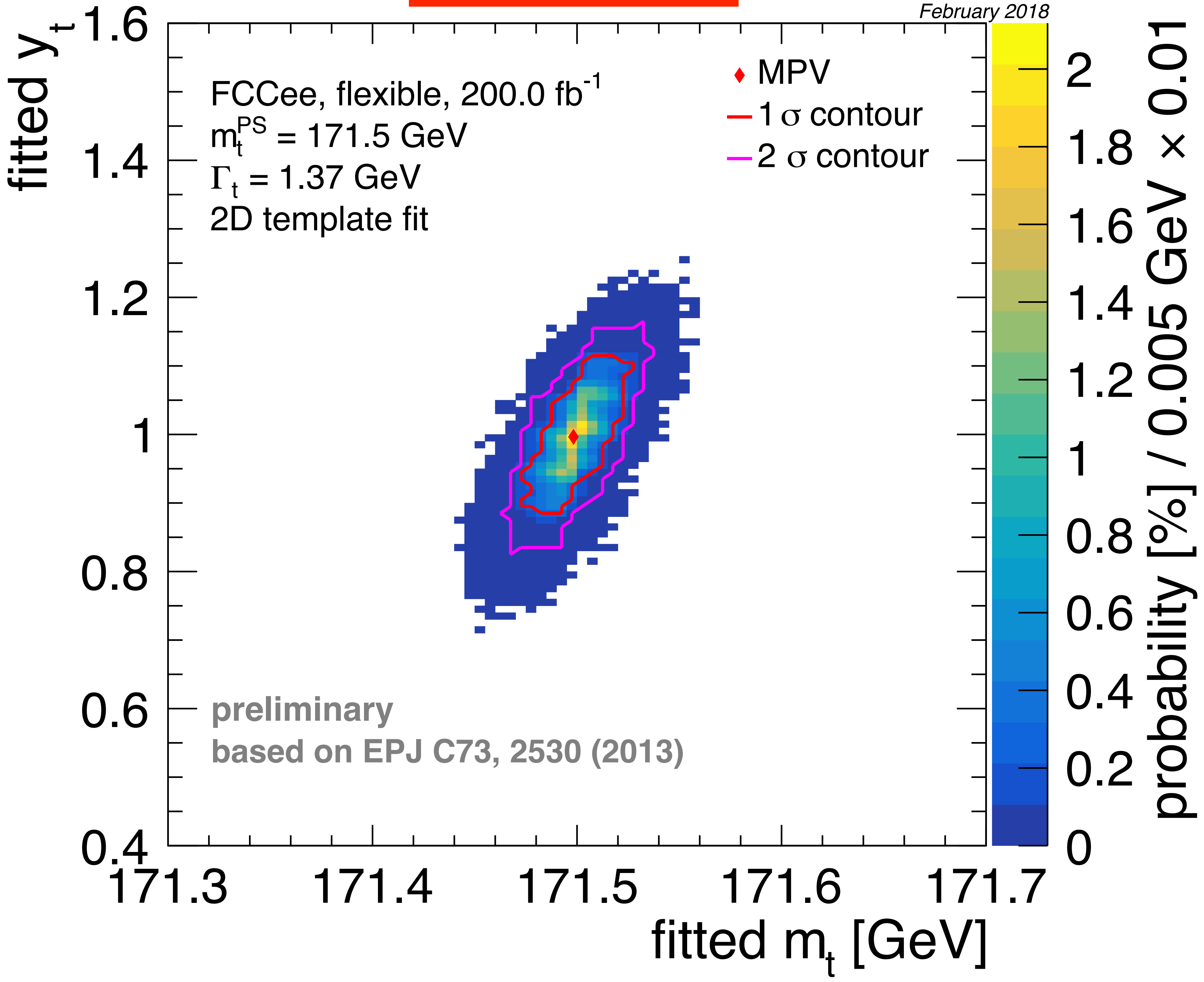
FCC-ee

TOP MEASUREMENTS FROM THRESHOLD SCAN @FCC-ee

Γ_t vs m_{top}



Y_t vs m_{top}



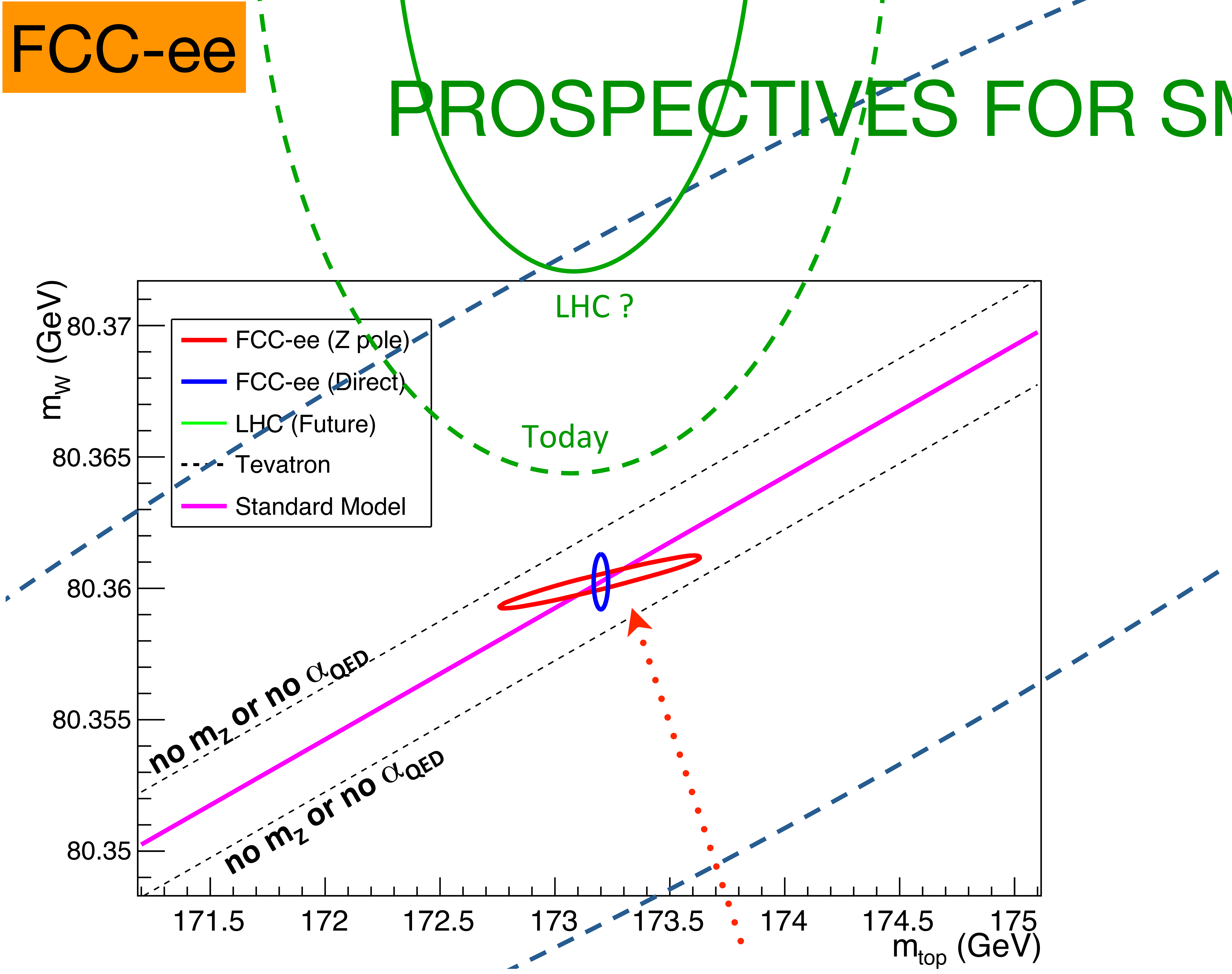
Y_{top} can be extracted with a10% uncertainty

see talk by P. Janot

With 200 fb^{-1} FCC-ee can measure $m_{top}(\Gamma_{top})$ with ~17(45) MeV statistical accuracy.

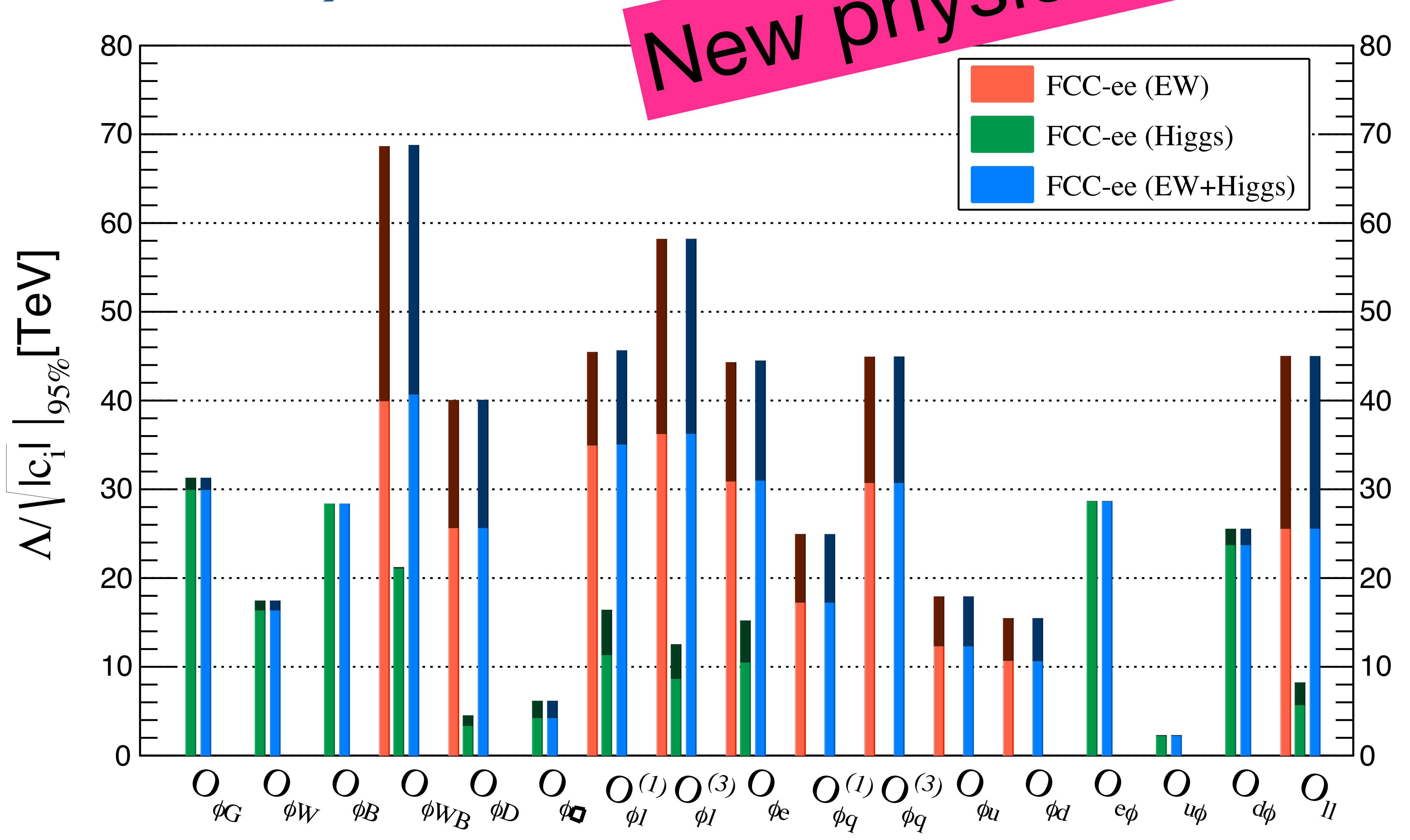
Systematics: 3MeV from center of mass energy, 5MeV from α_s ($2x10^{-4}$ as measured at lower energy) and ~40MeV from theory uncertainties (NNLO)

PROSPECTIVES FOR SM FITS AFTER @FCC-ee



Requires 10-fold improvement in theory calculations

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

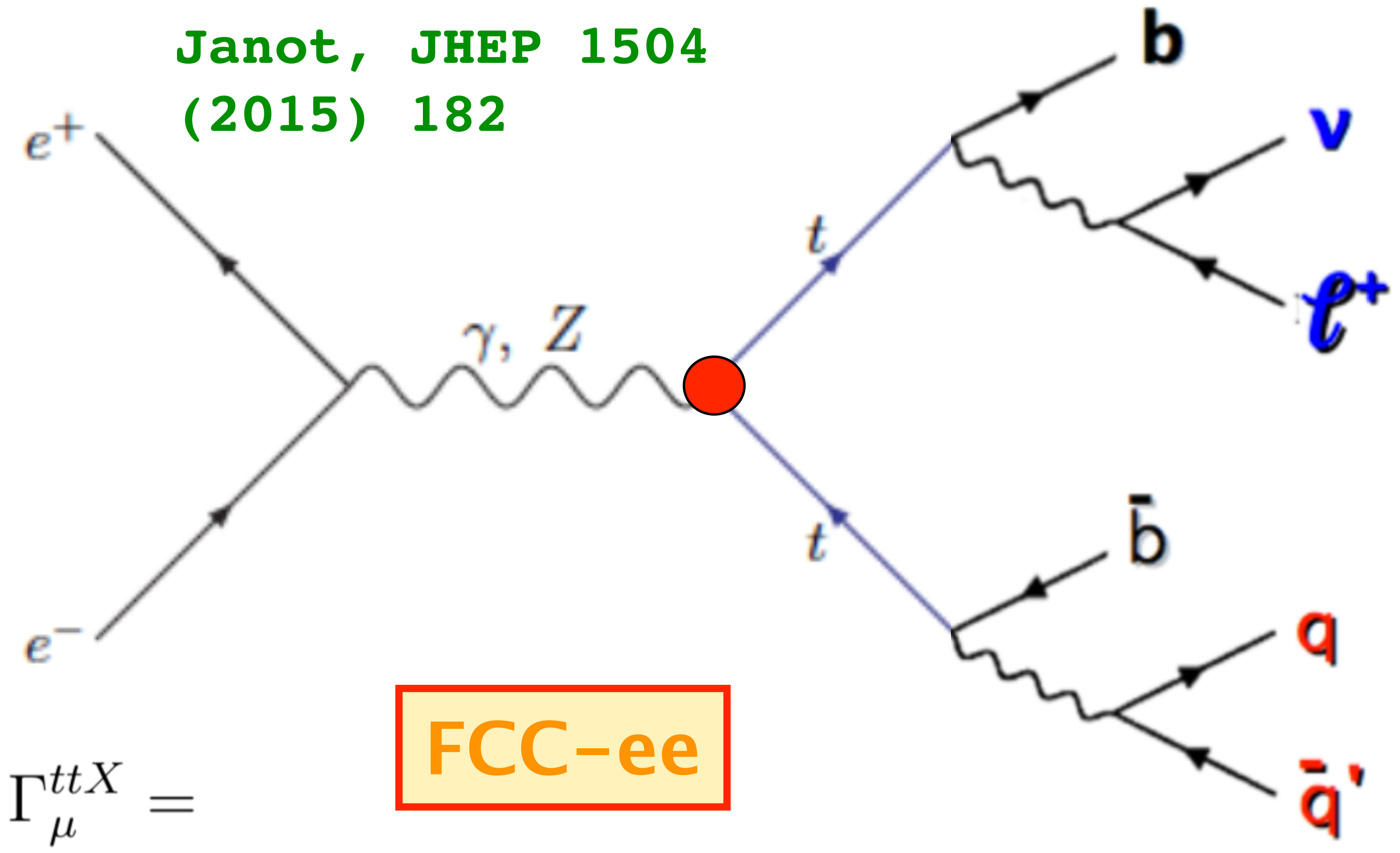


- ➤Improvements in m_{top}, α_S, M_W at FCC-ee will improve understanding consistency SM in top-W-H radiative corrections
- ➤Strongly pushing the sensitivity for NP at high scale

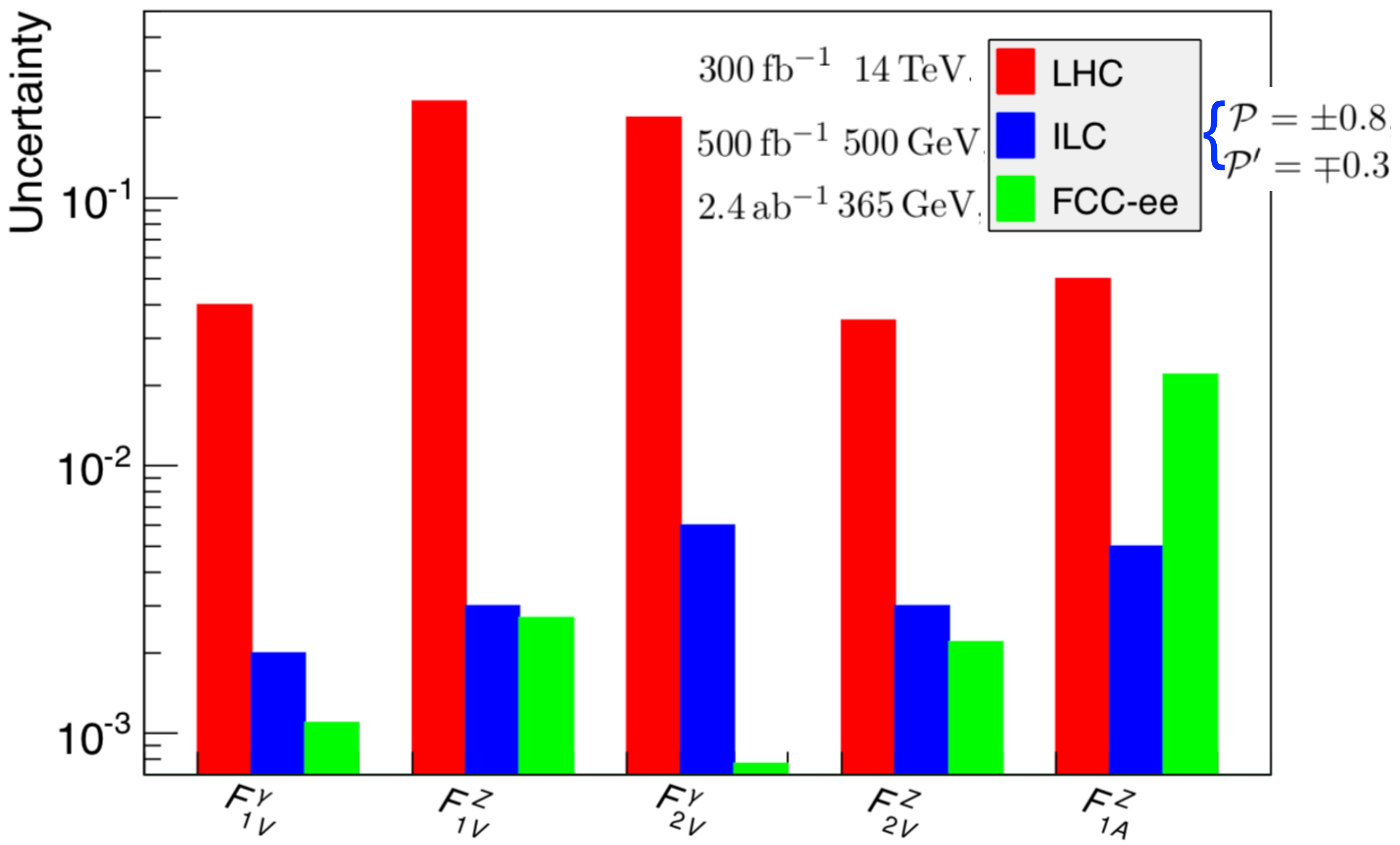
FCC-ee

ELECTROWEAK COUPLINGS OF THE TOP QUARK @FCC-ee

Janot, JHEP 1504 (2015) 182

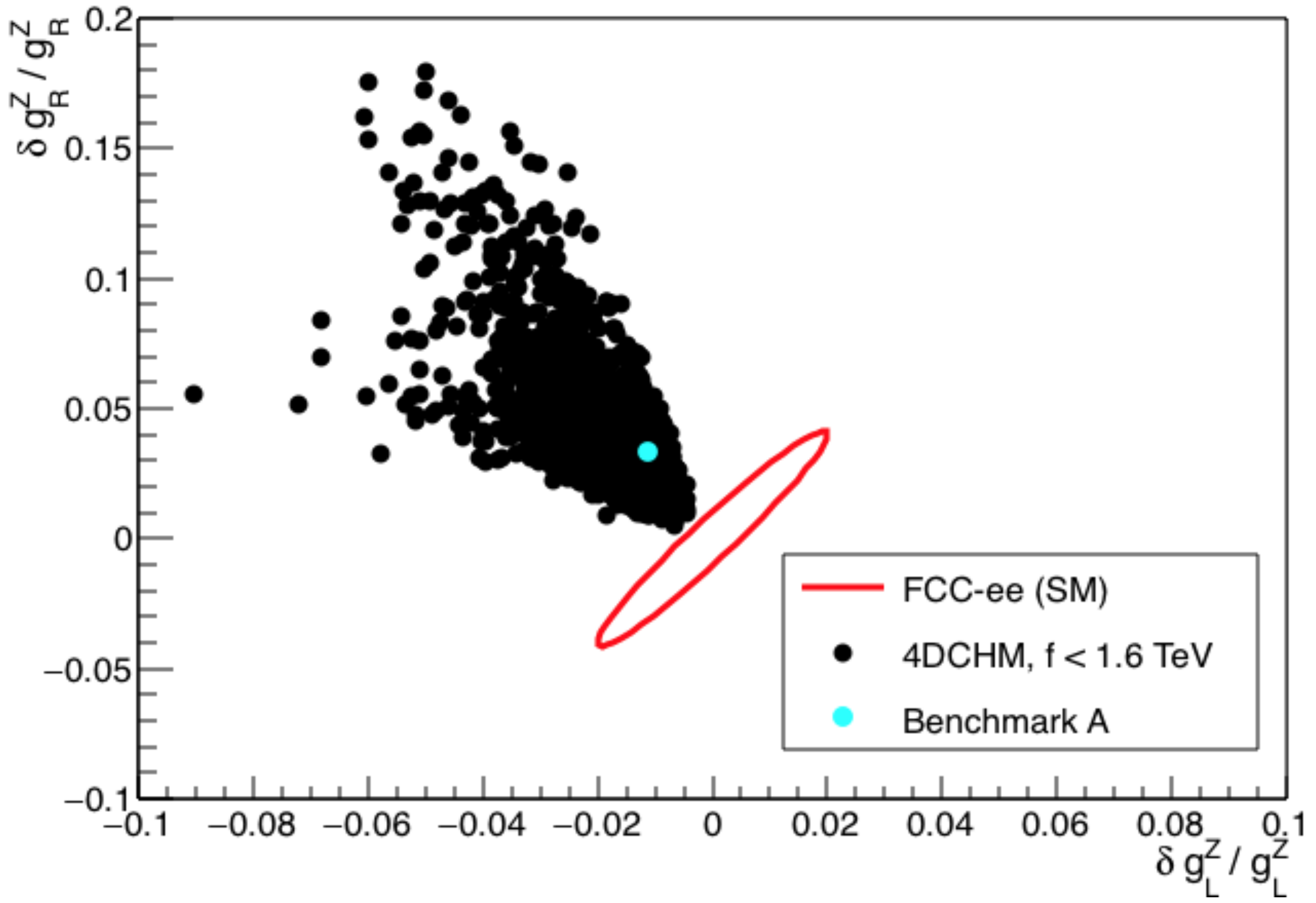


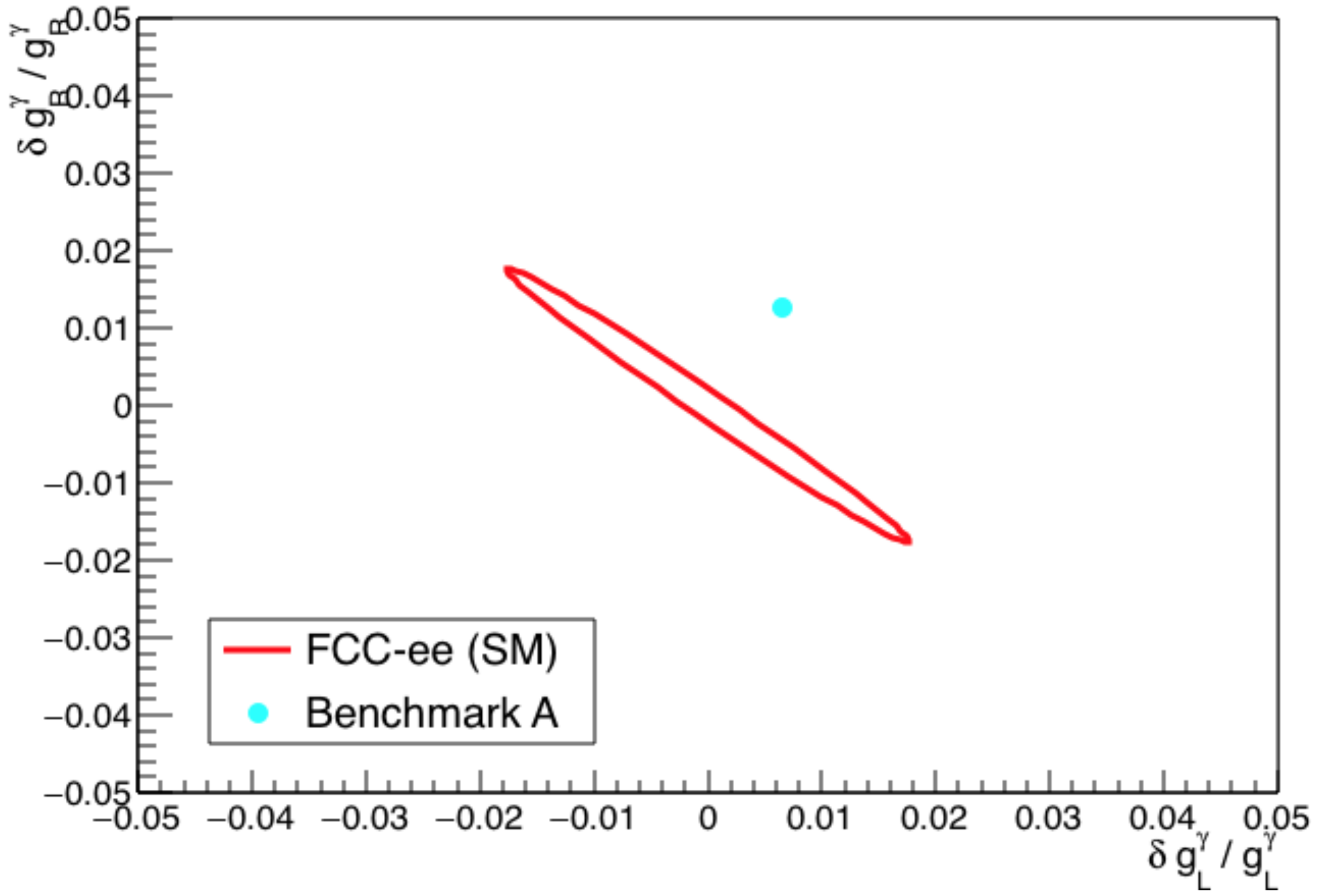
$$\Gamma_\mu^{ttX} = -ie\left\{\gamma_\mu\left(F_{1V}^X + \gamma_5 F_{1A}^X\right) + \frac{\sigma_{\mu\nu}}{2m_t}(p_t + p_{\bar{t}})^\nu\left(iF_{2V}^X + \gamma_5 F_{2A}^X\right)\right\}$$



- **ttZ, ttγ couplings can be directly probed in the tt production process at FCC-ee**
- Large statistics and final state polarization allow a full separation of the ttZ/γ couplings with **NO need for (long.) polarization in the initial state.**
- Optimal $\sqrt{s}$= 365 GeV

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





some CHDM FCC-ee precision sensitivity up to 4TeV Z' mass

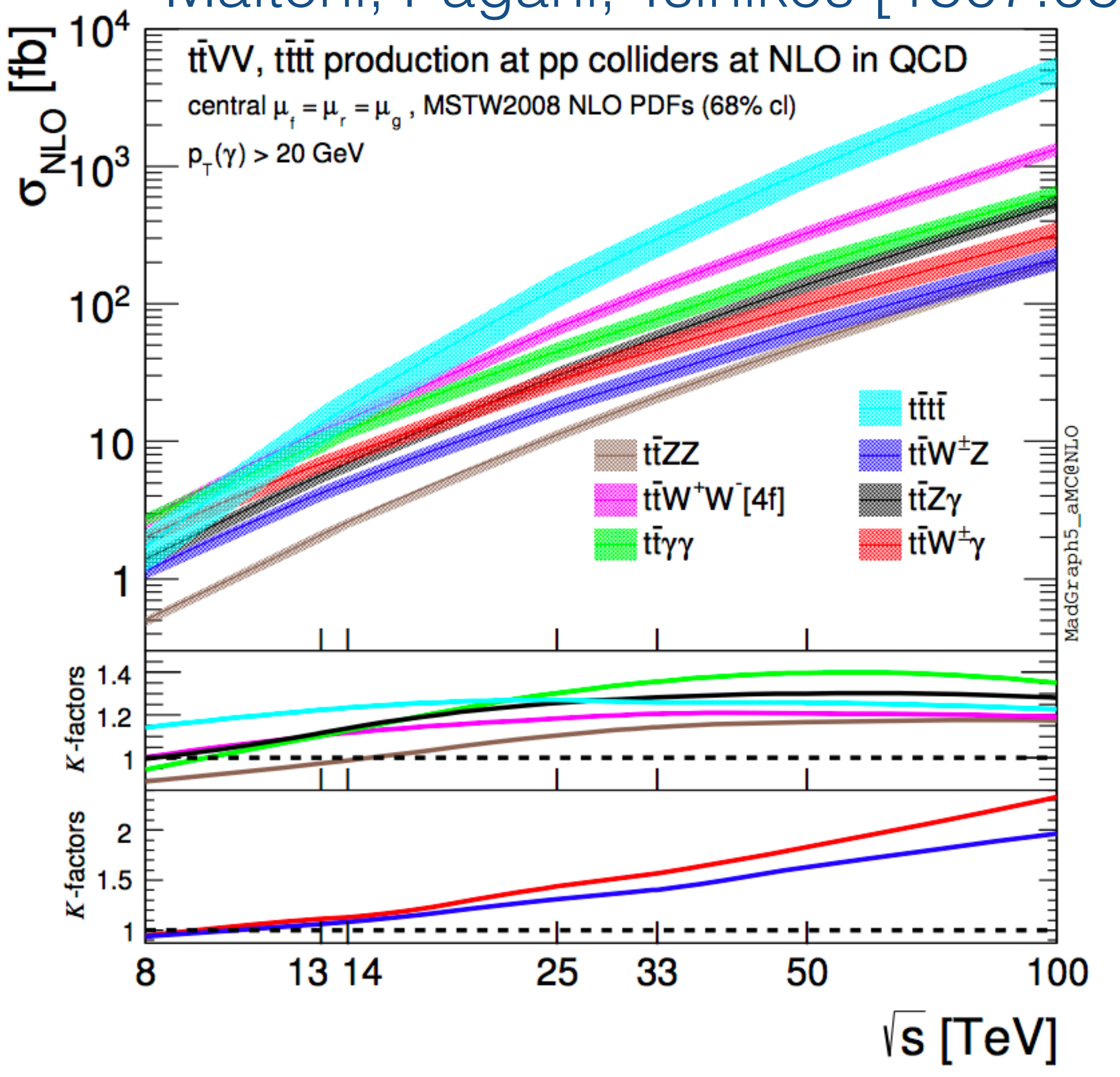
FCC-hh

TOP PRODUCTION @FCC-hh

10^{12}	top quarks
10^{12}	W bosons
10^{12}	b-hadrons
10^{11}	t->W->tau
$3x10^{11}$	t->W-charm
10^{10}	Higgs bosons
10^{9}	ttH
10^{6}	tttt

Top events precious sample of clean Ws, for measurement of properties and rare decays

Maltoni, Pagani, Tsinikos [1507.05640]



Large increase in production rate for multi-top, multi top+(multi) bosons production

FCC-hh

TOP PRODUCTION @FCC-hh

Tera-Top

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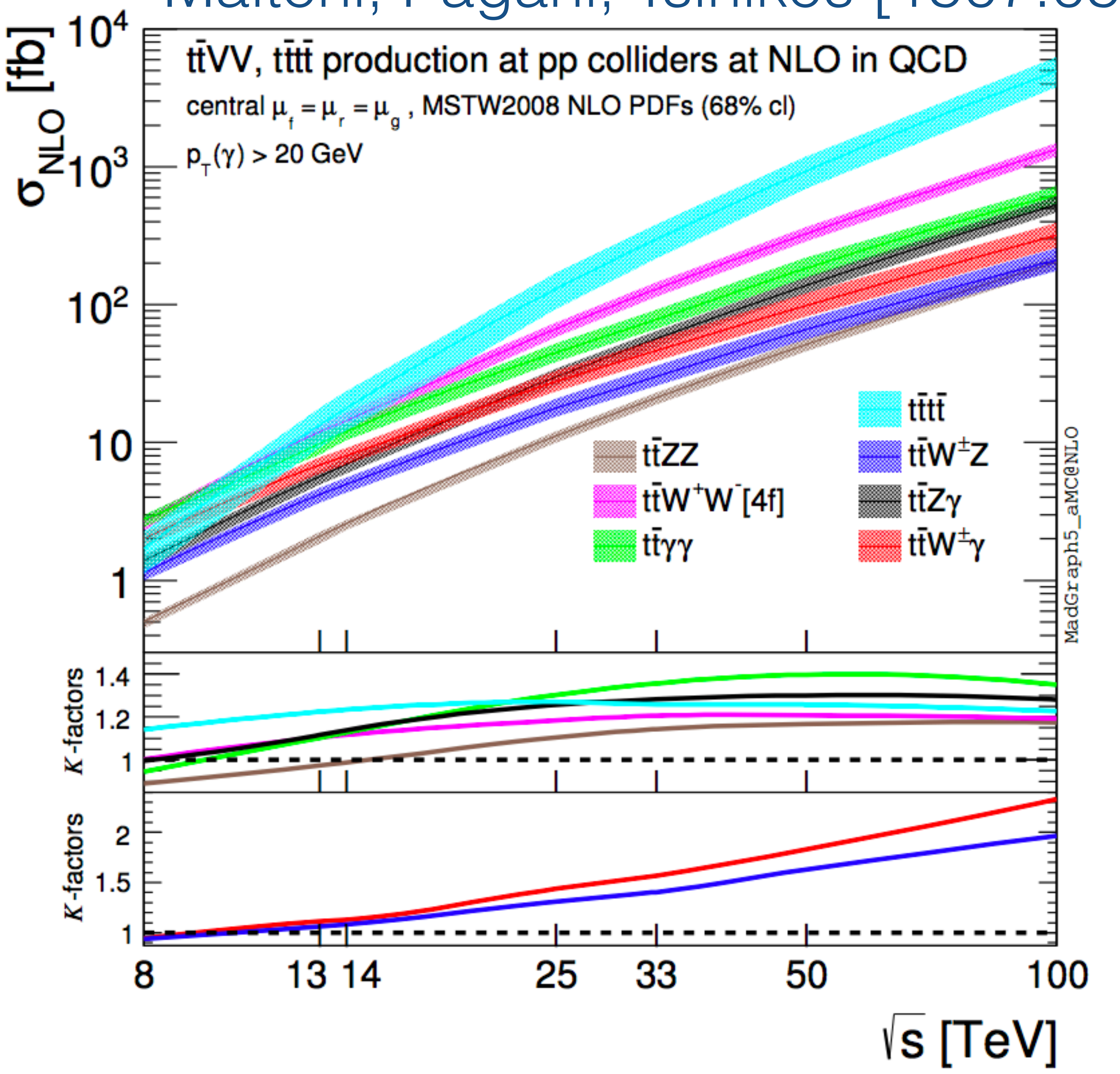

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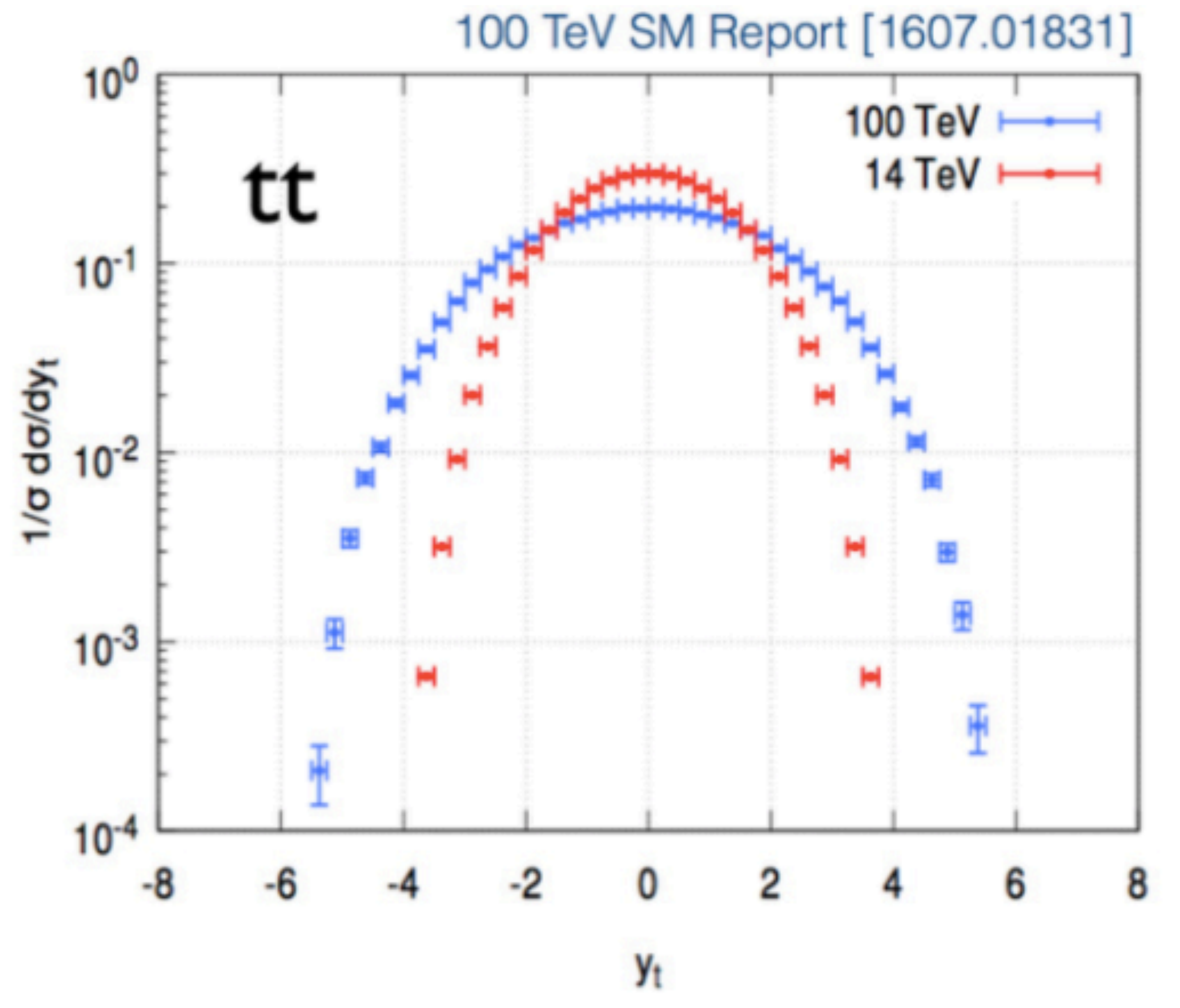
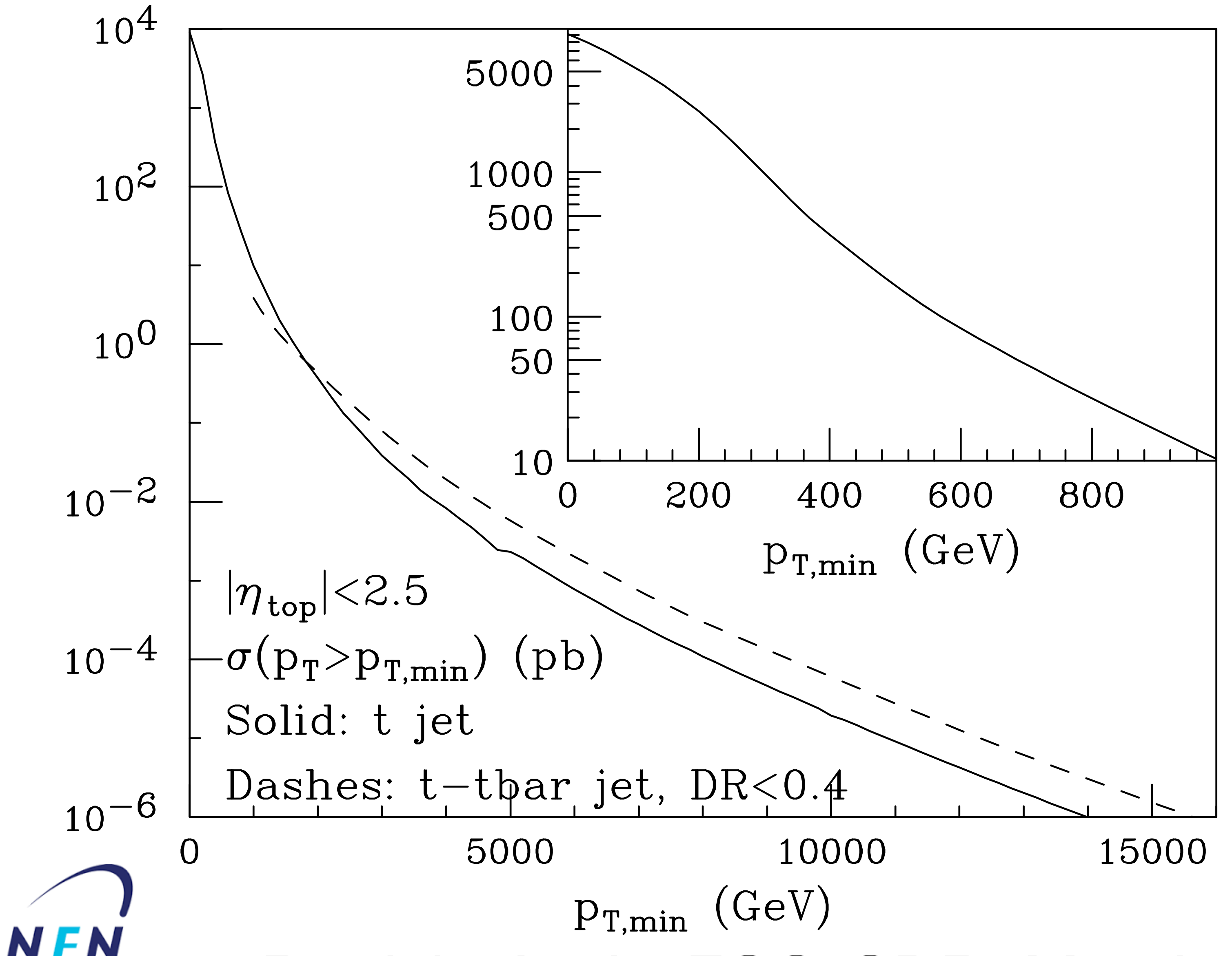
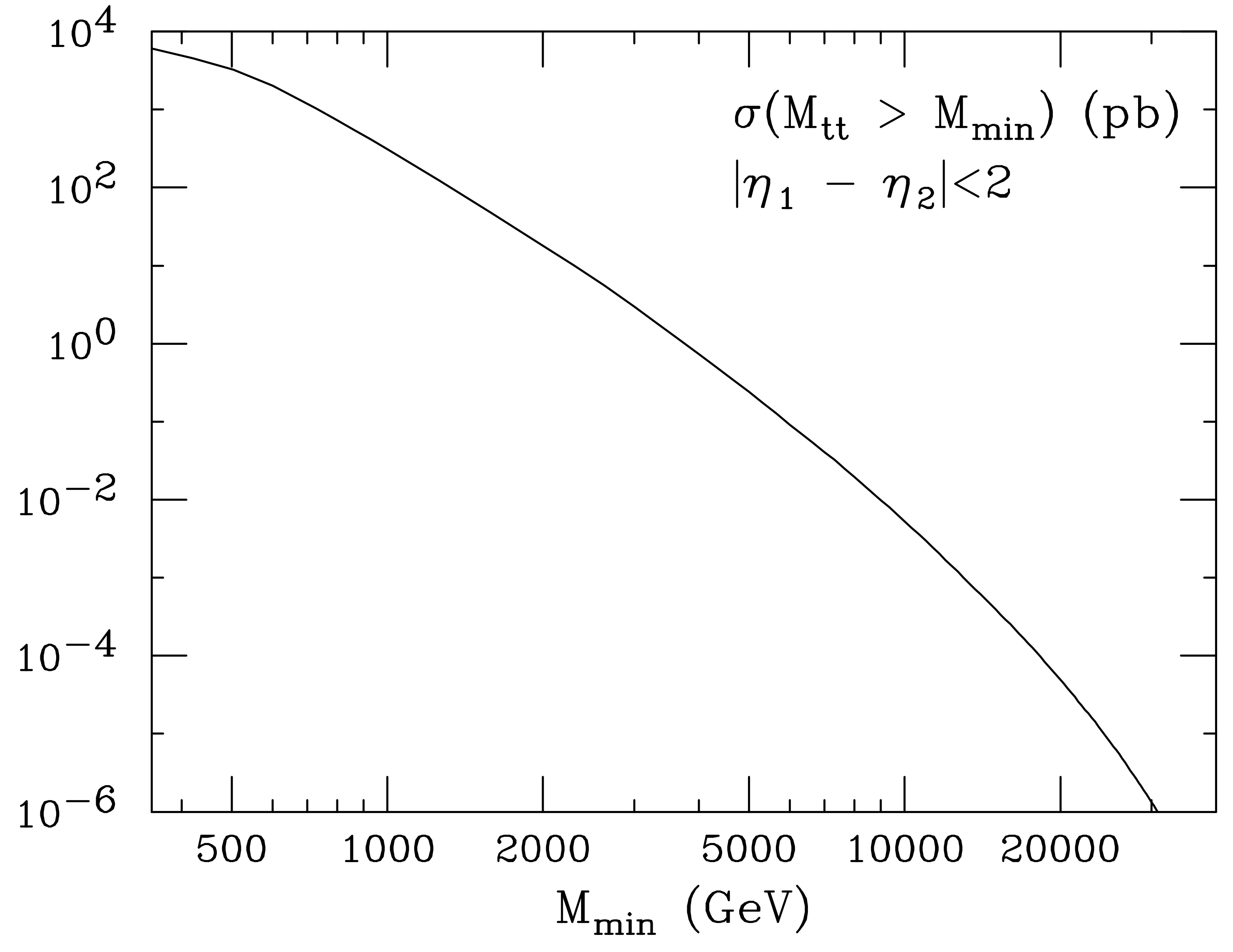
NEW KINEMATIC REGIME @FCC-hh

- Large Q²:
  - study the rapidity dependence: larger rapidity for final state particles (leptons) and larger rapidity gap
  - either one boosted top or a single jet containing the top pair from a gluon splitting recoiling against a gluon.







Large statistcs of events with large M(tt) irreducible background for NP heavy resonances, also helpful for improving sensitivity of top properties measurements

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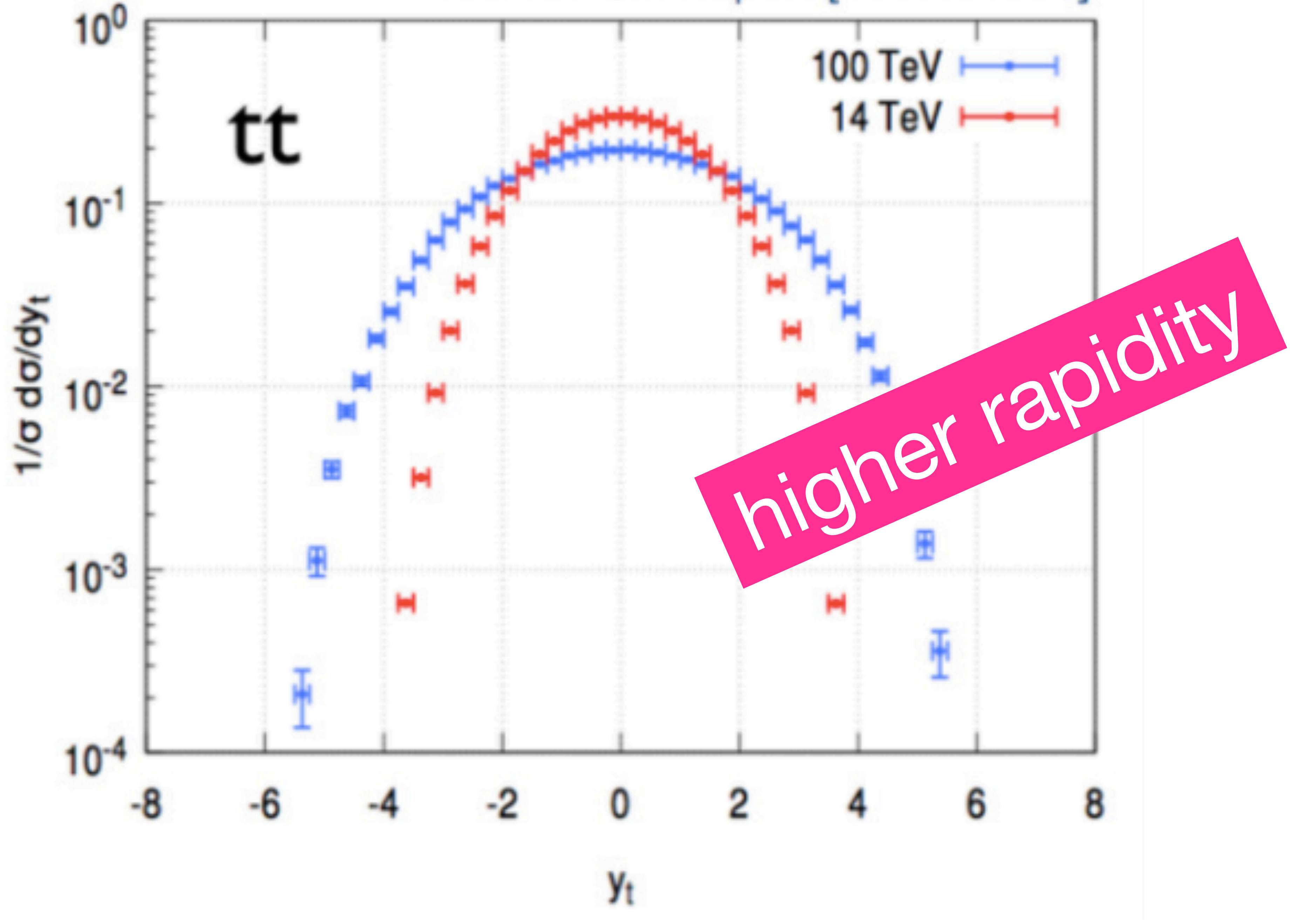
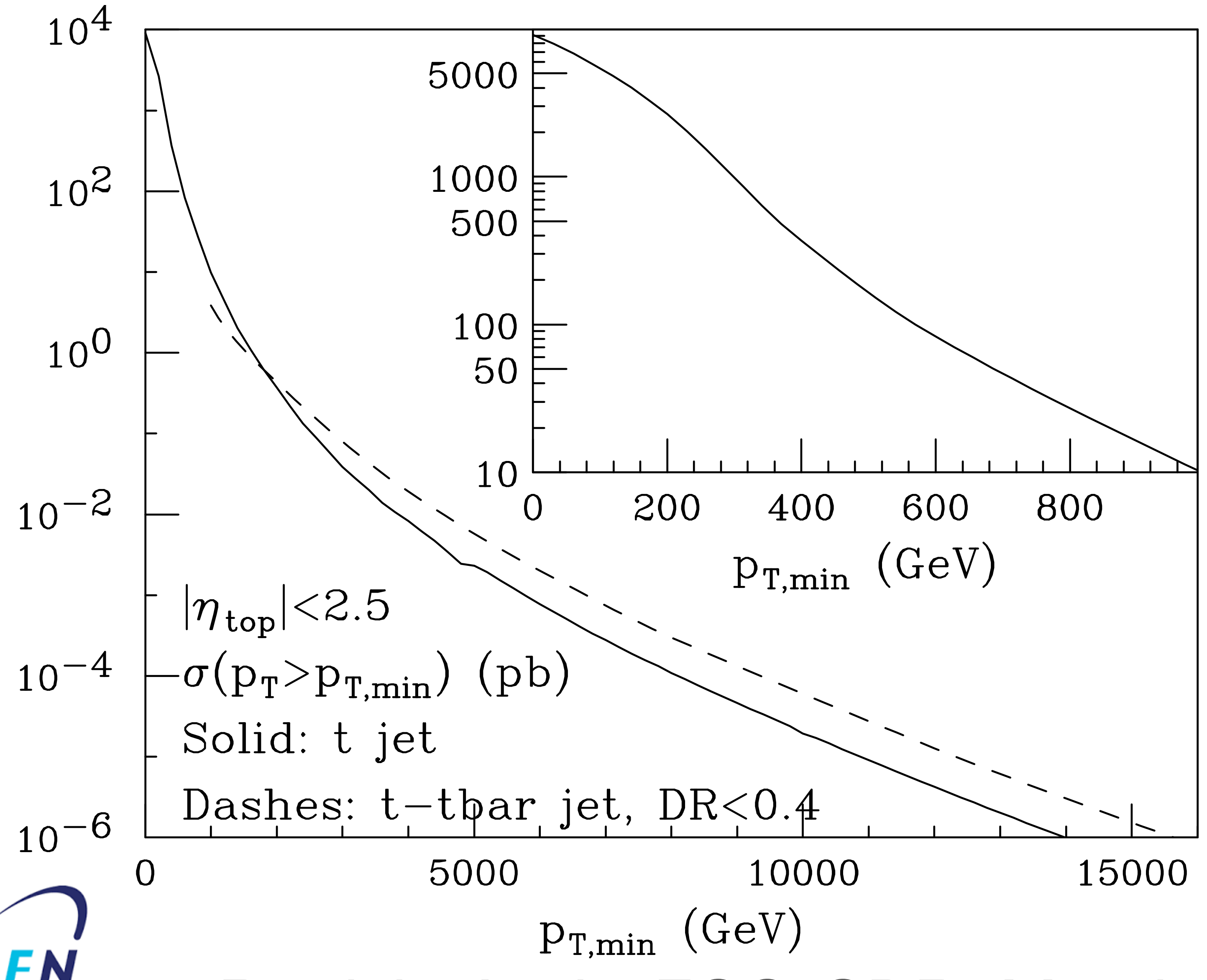
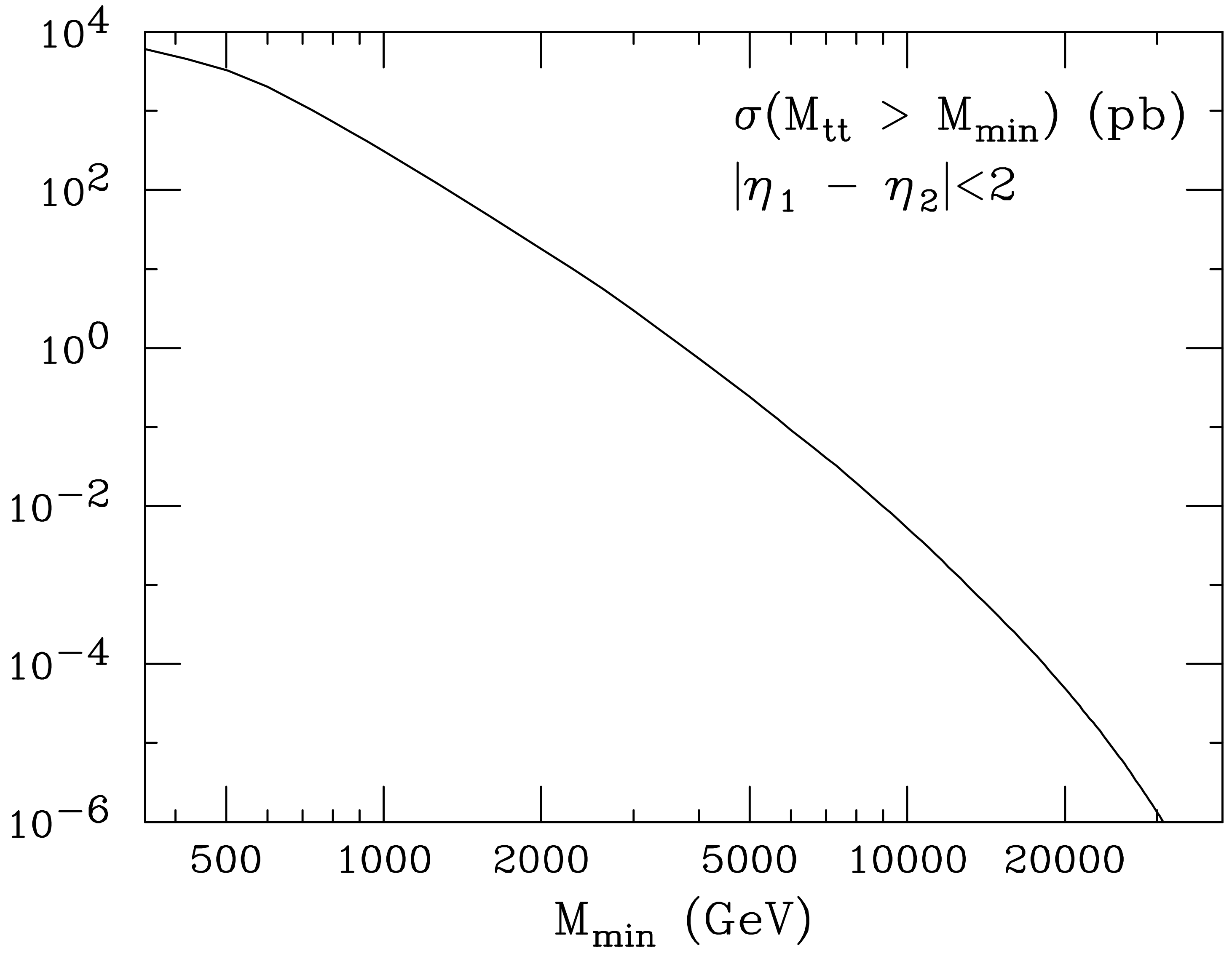
100 TeV SM Report [1607.01831]







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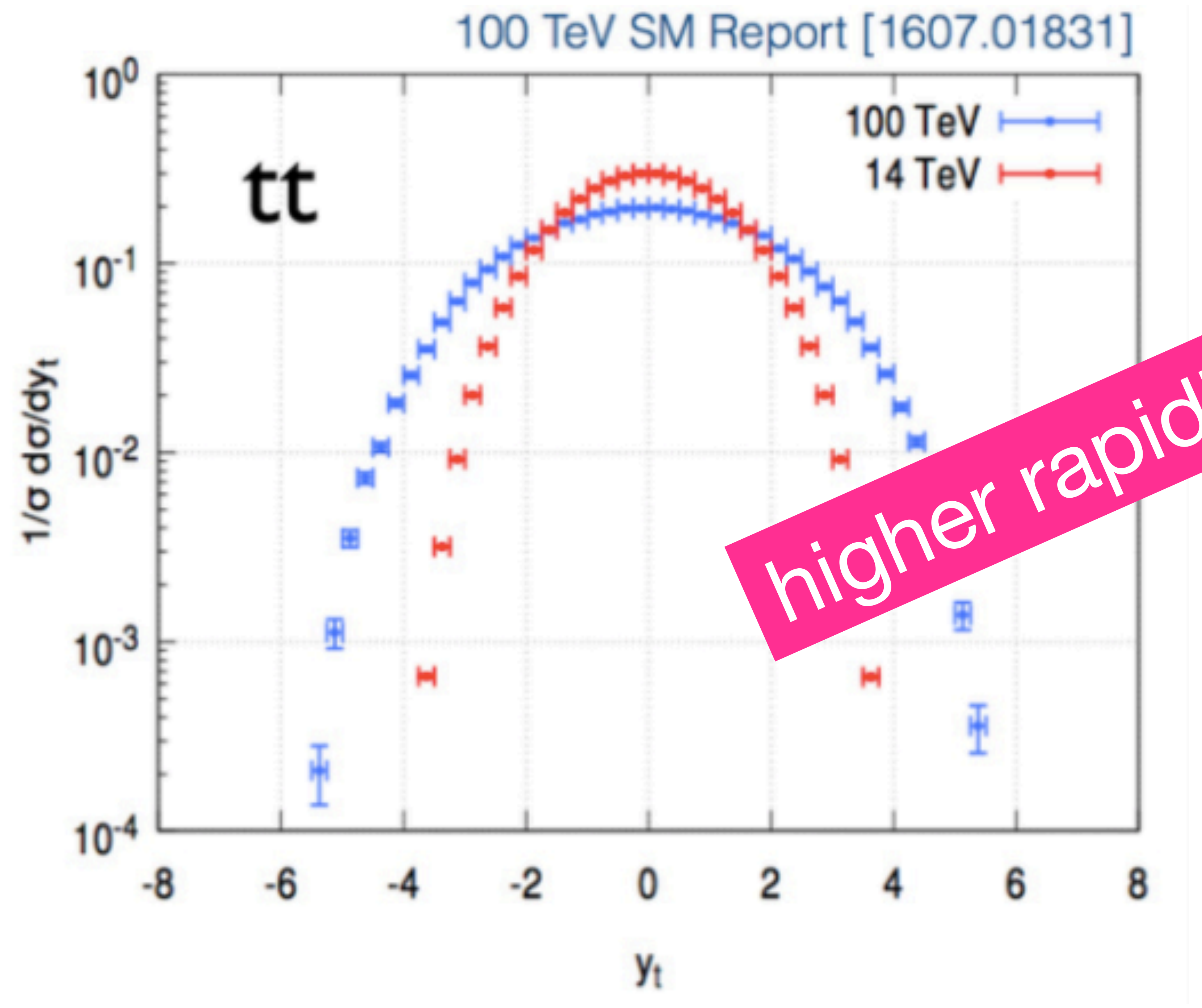

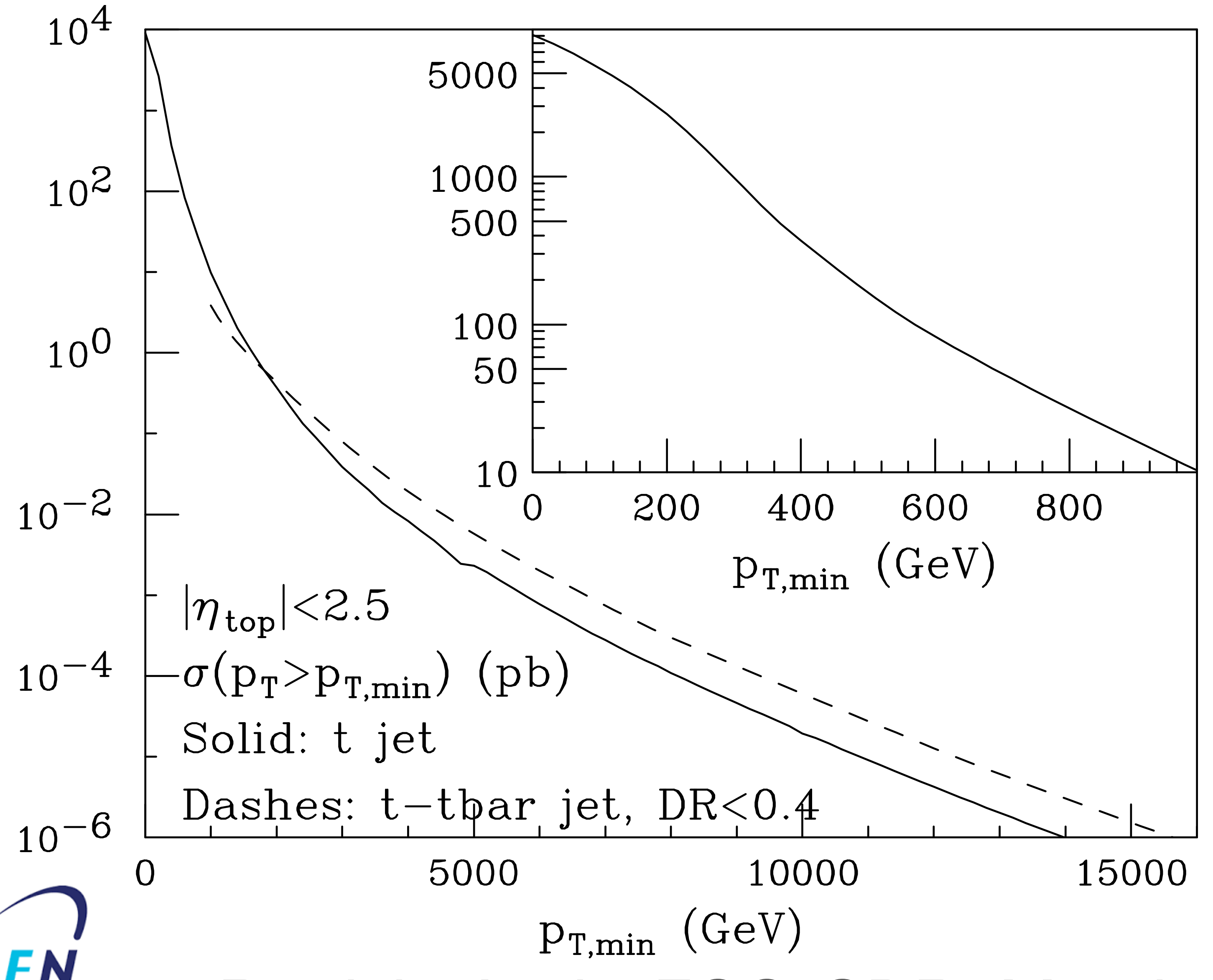

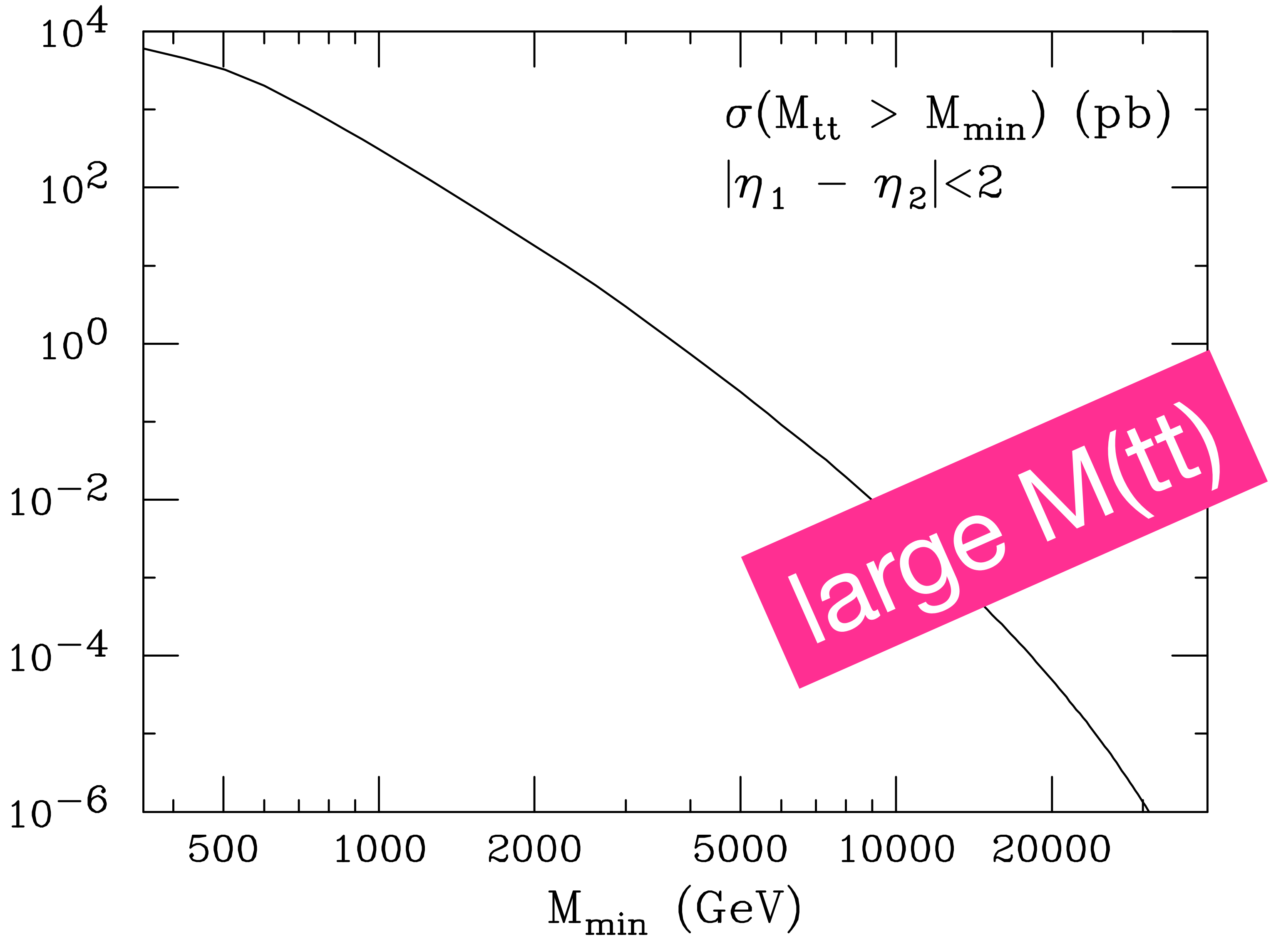

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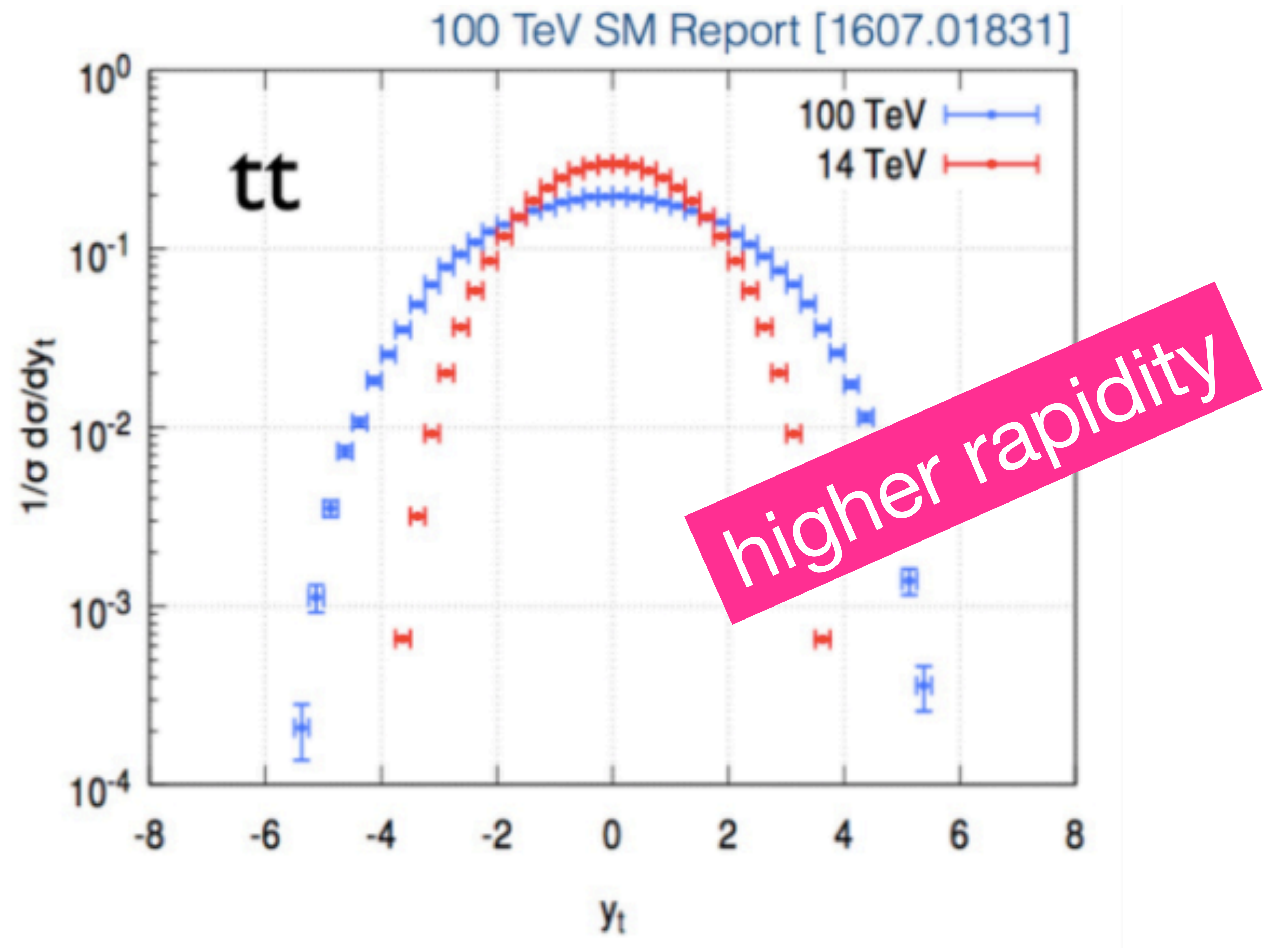

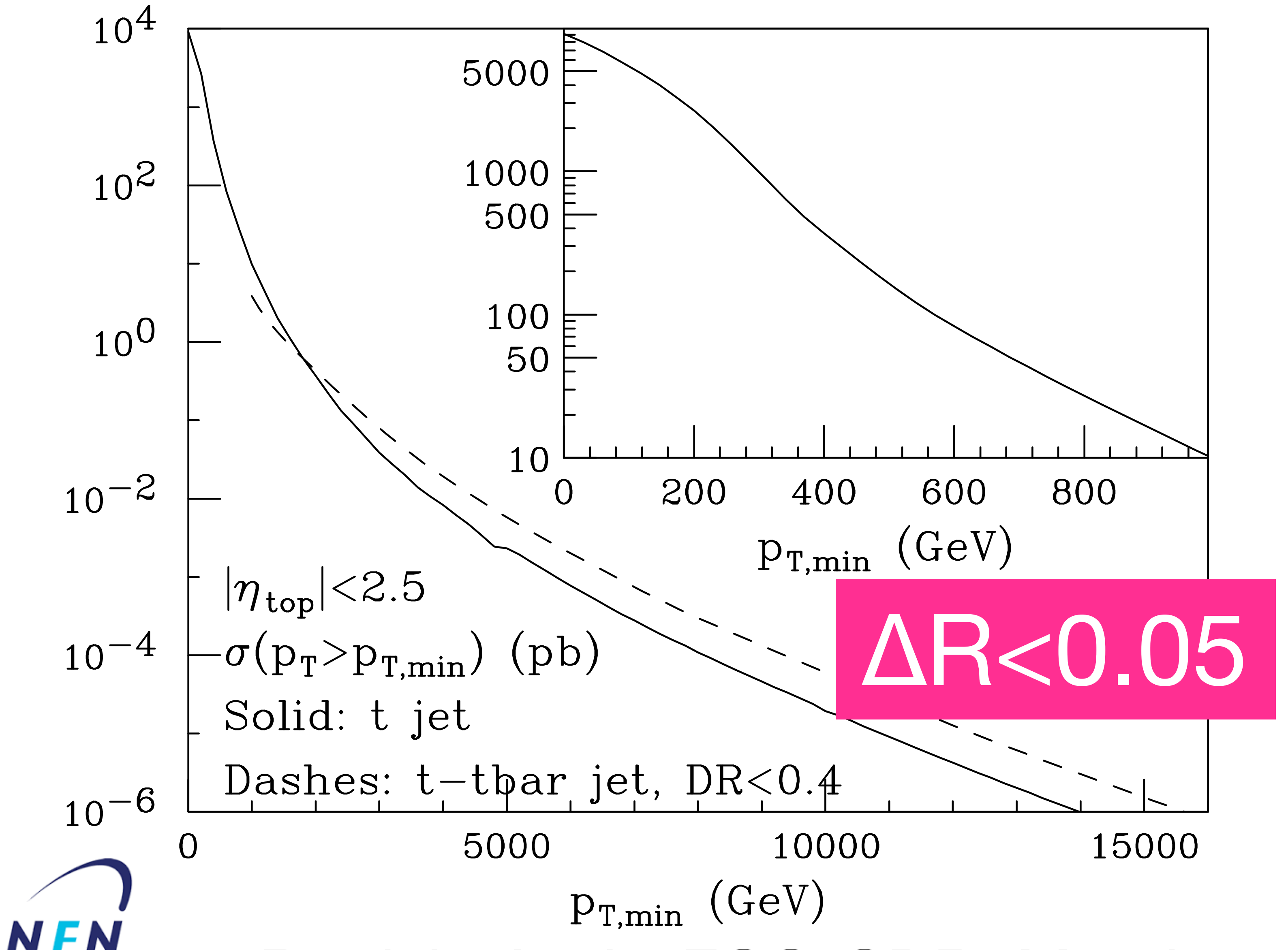

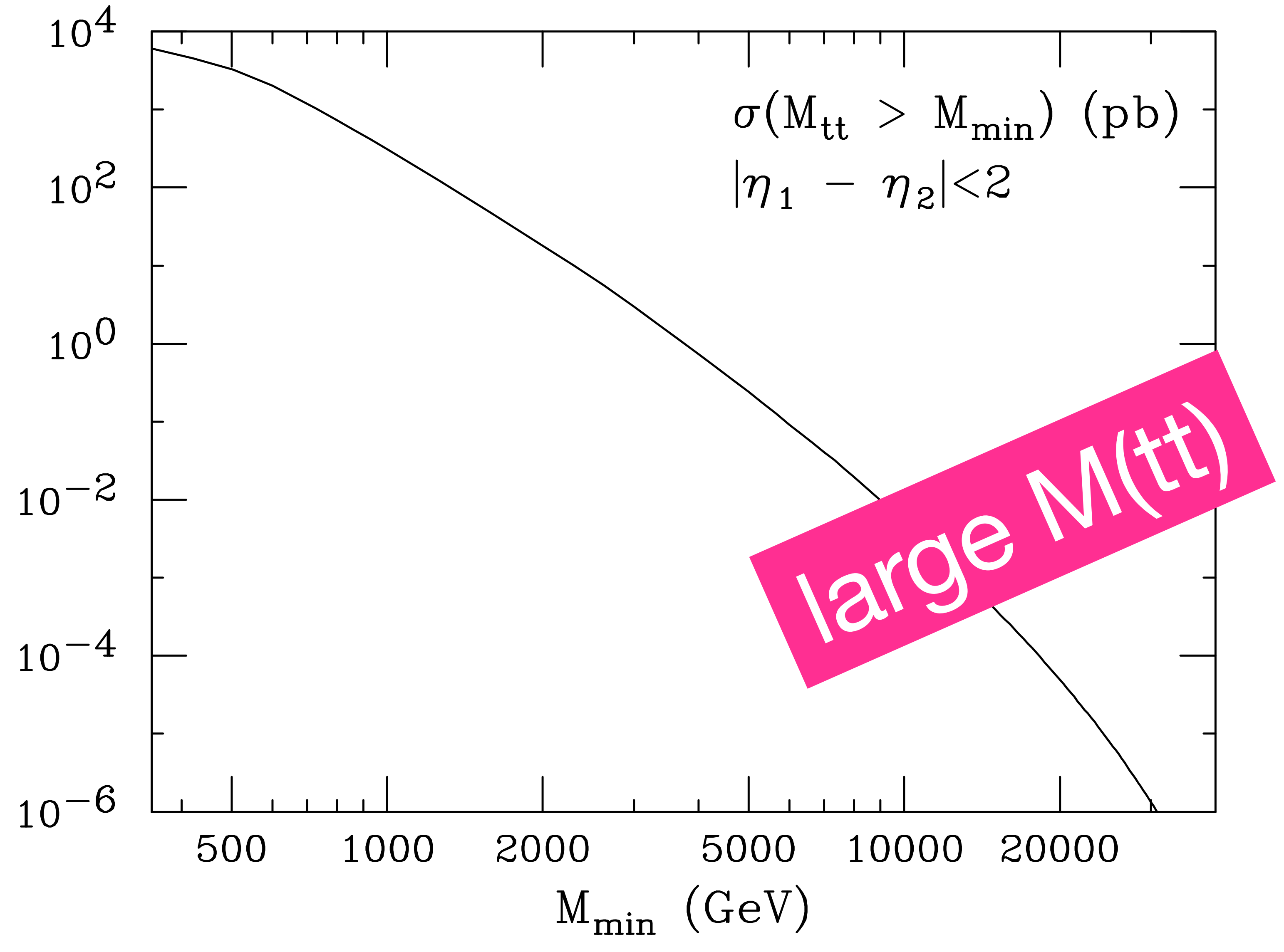

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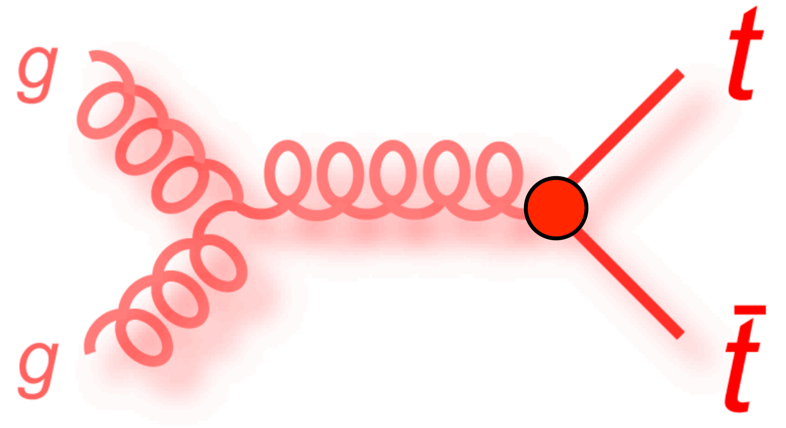
FCC-hh

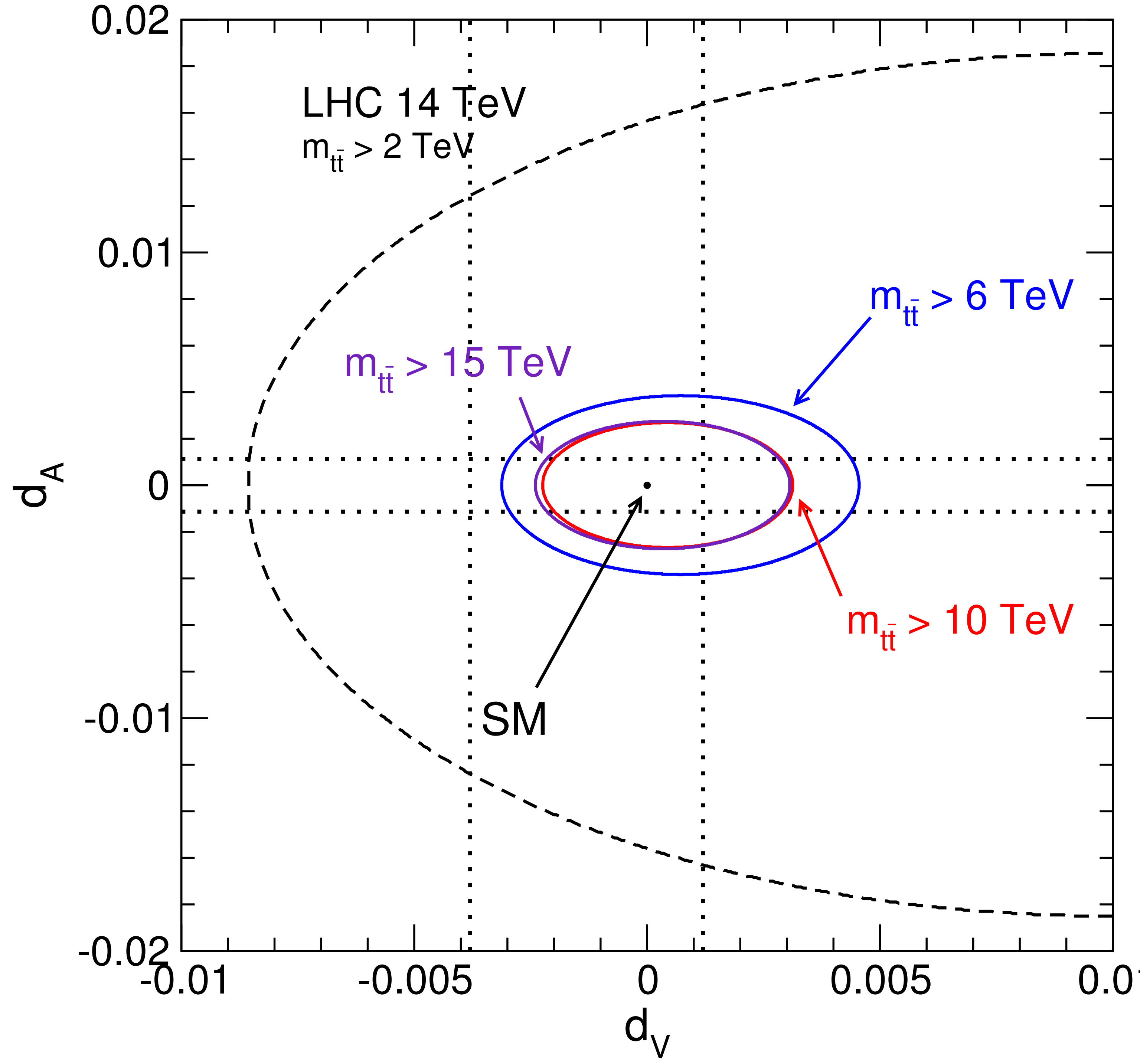
CHROMODIPOLE MOMENTS @FCC-hh

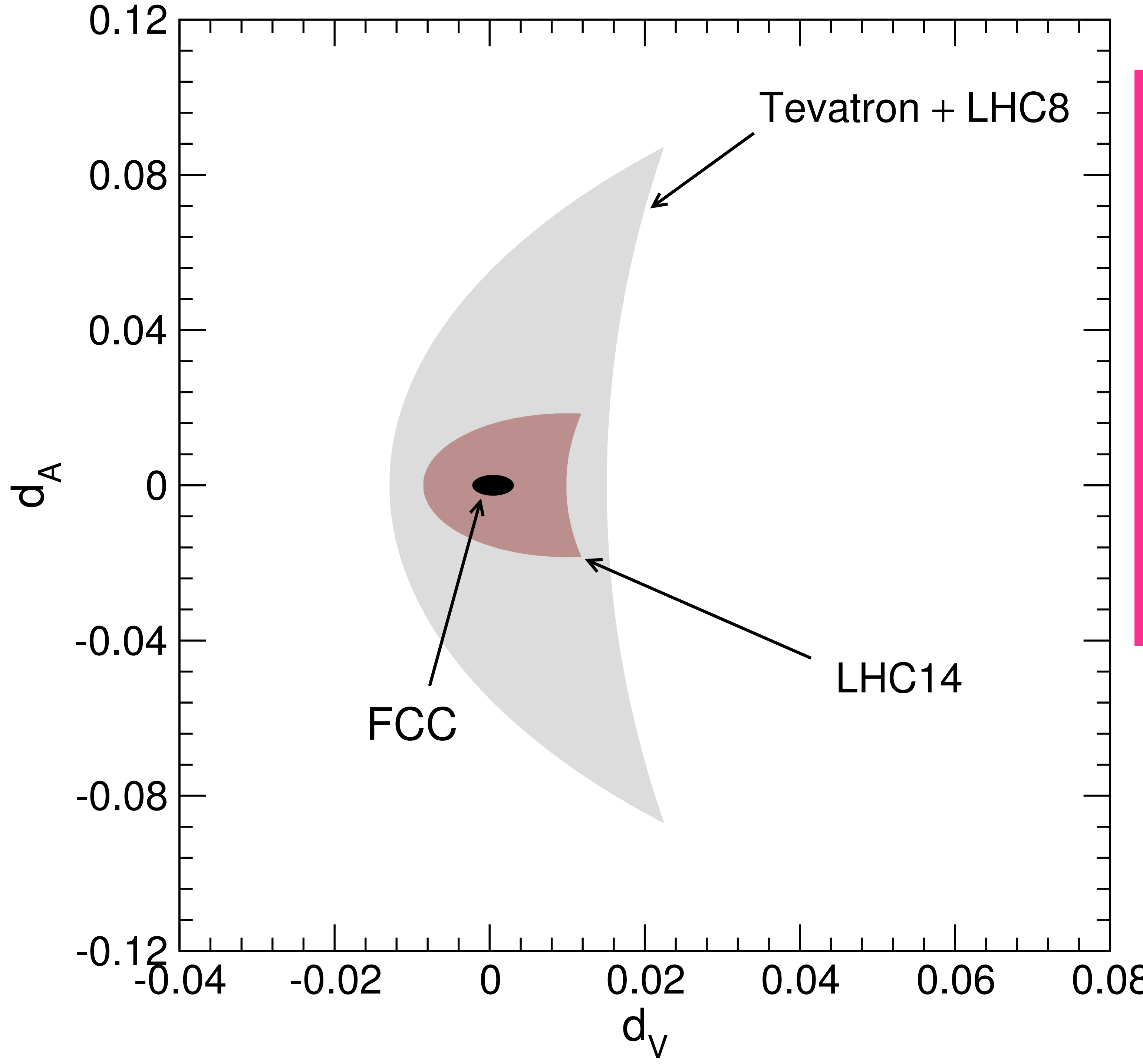
- High mass top pairs can be used for probing **anomalous couplings of the top to the gluon** with interactions such as:



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

- Cross section analysis suggests m(tt)>10TeV optimal choice.
- Improvement of an order of magnitude of the constraints on the chromodipole moment compared to HL-LHC





chromo-electric

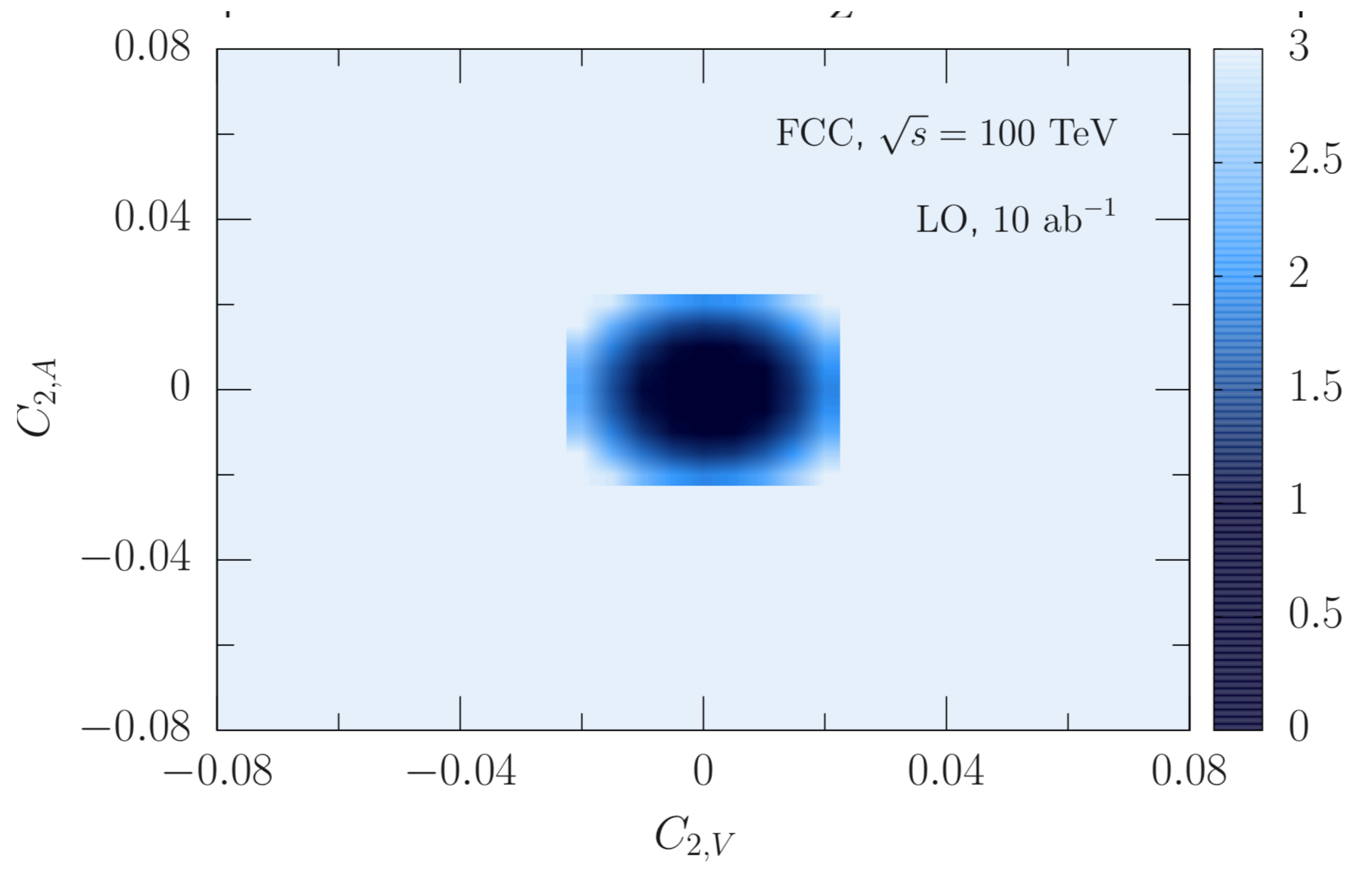
chromo-magnetic

ASSOCIATED PRODUCTION ttV @FCC-hh (1)

Associated production of top quarks and gauge bosons offer additional handles to study top properties

	$t\bar{t}\gamma$	$t\bar{t}W^{\pm}$	$t\bar{t}Z$	$t\bar{t}WW$	$t\bar{t}W^{\pm}Z$	$t\bar{t}ZZ$
σ(pb)	76.7	20.7	64.1	1.34	0.21	0.20

NLO production cross-section



Complementary: precision on SM coupling $C_{1,V/A}$ from FCC-ee

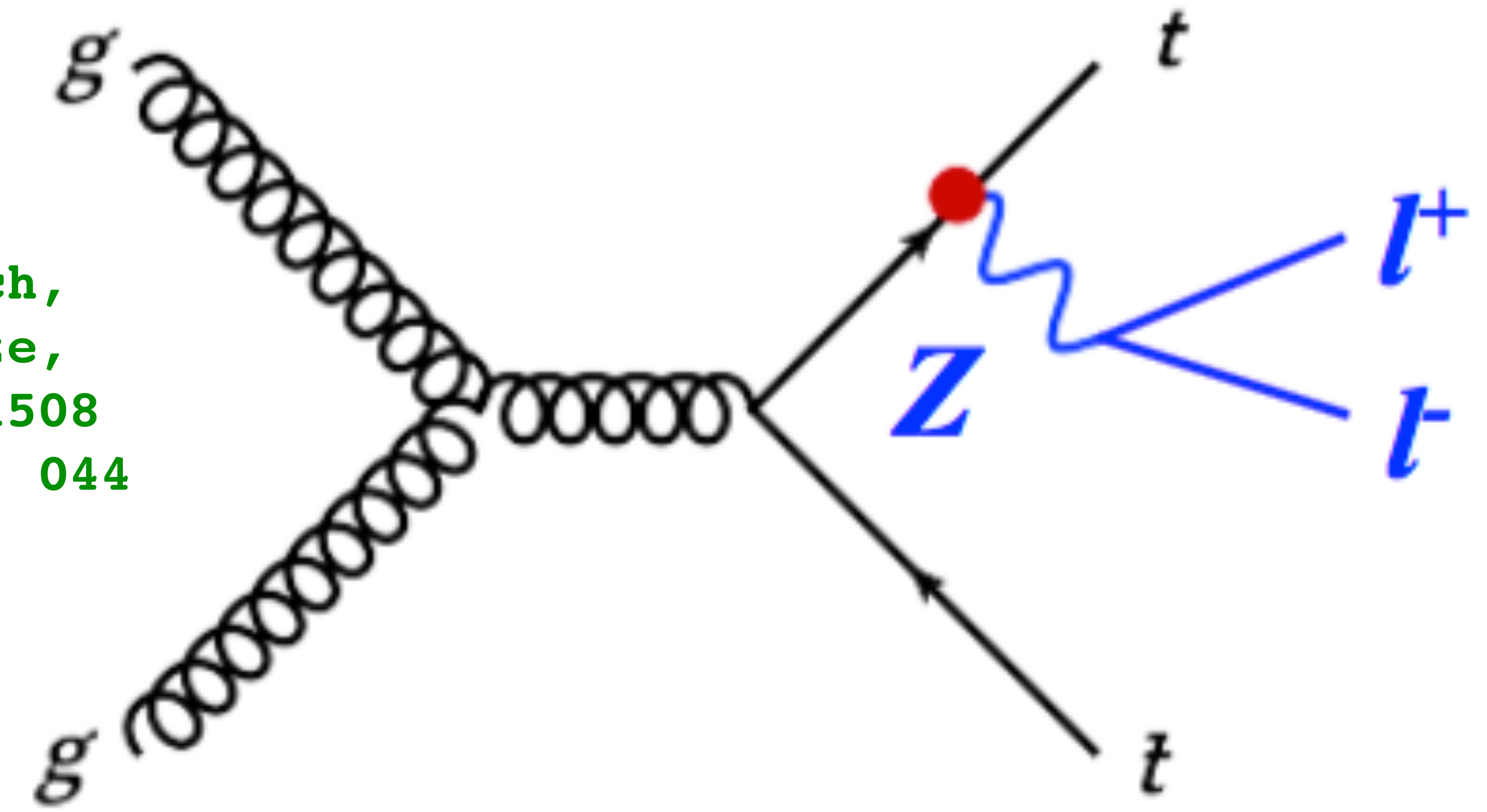
ASSOCIATED PRODUCTION ttV @FCC-hh (1)

Associated production of top quarks and gauge bosons offer additional handles to study top properties

	$t\bar{t}\gamma$	$t\bar{t}W^{\pm}$	$t\bar{t}Z$	$t\bar{t}WW$	$t\bar{t}W^{\pm}Z$	$t\bar{t}ZZ$
σ(pb)	76.7	20.7	64.1	1.34	0.21	0.20

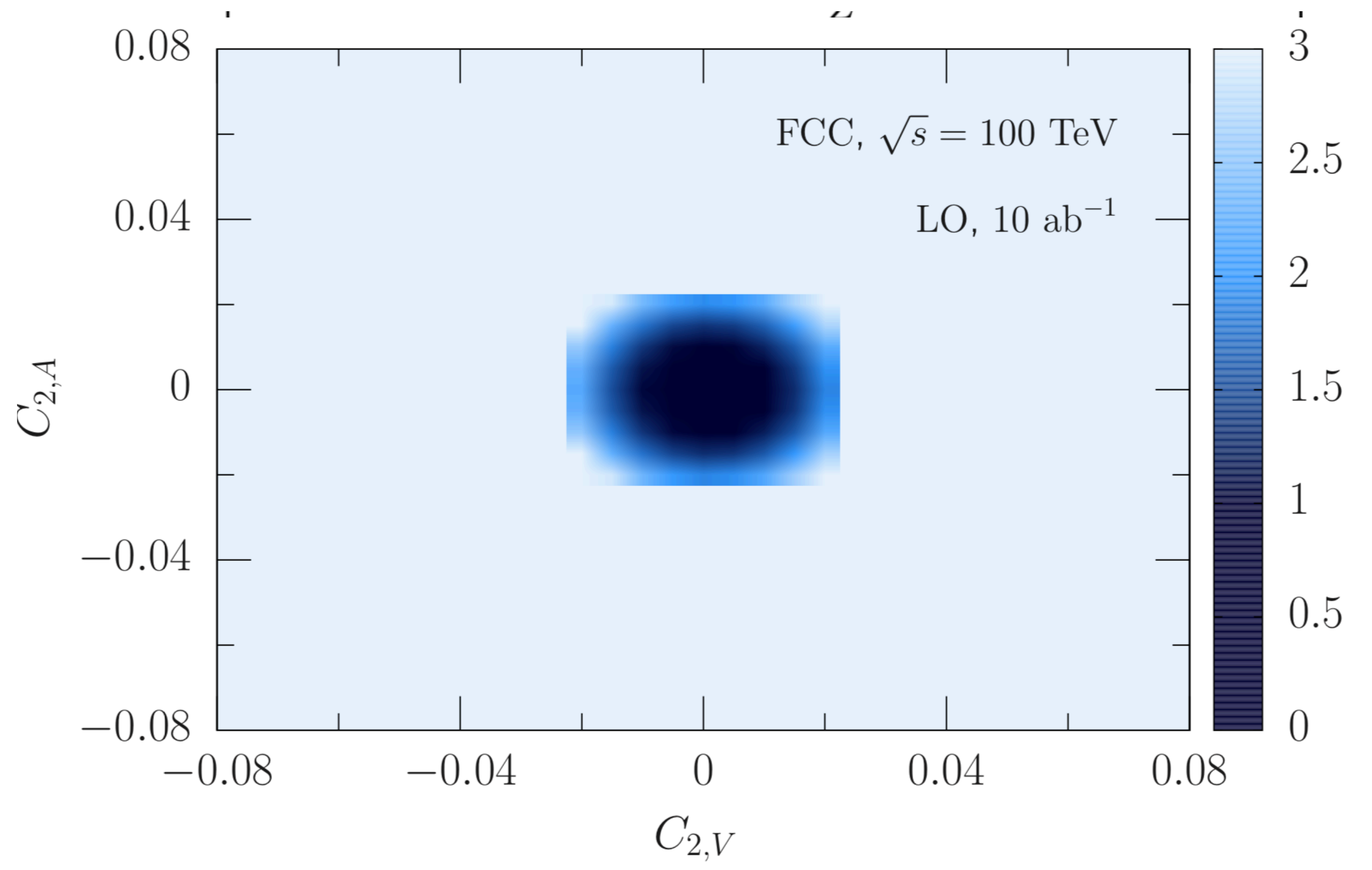
NLO production cross-section

Röntsch, Schulze, JHEP 1508 (2015) 044



FCC-pp

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



Complementary: precision on SM coupling $C_{1,V/A}$ from FCC-ee

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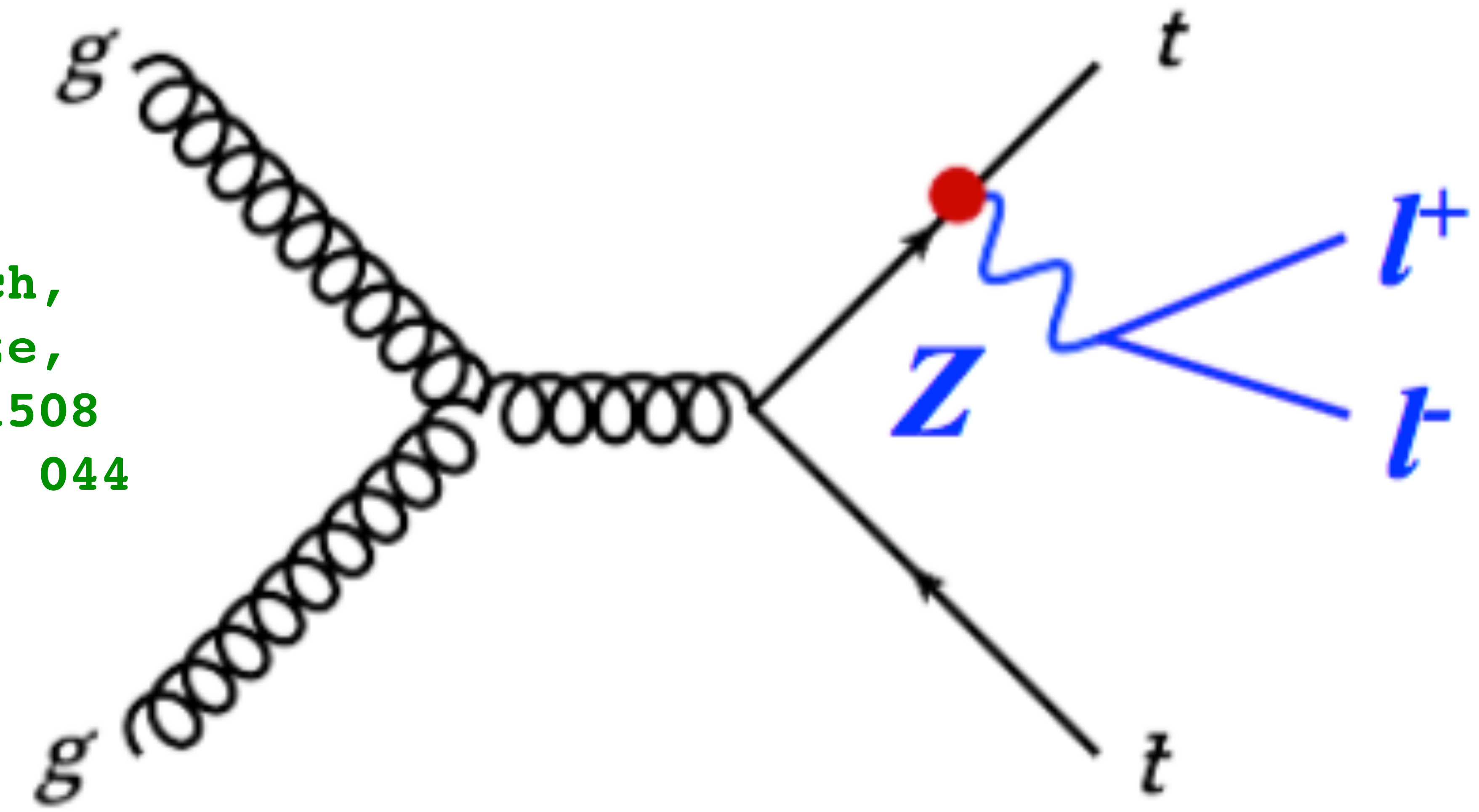

FCC-pp

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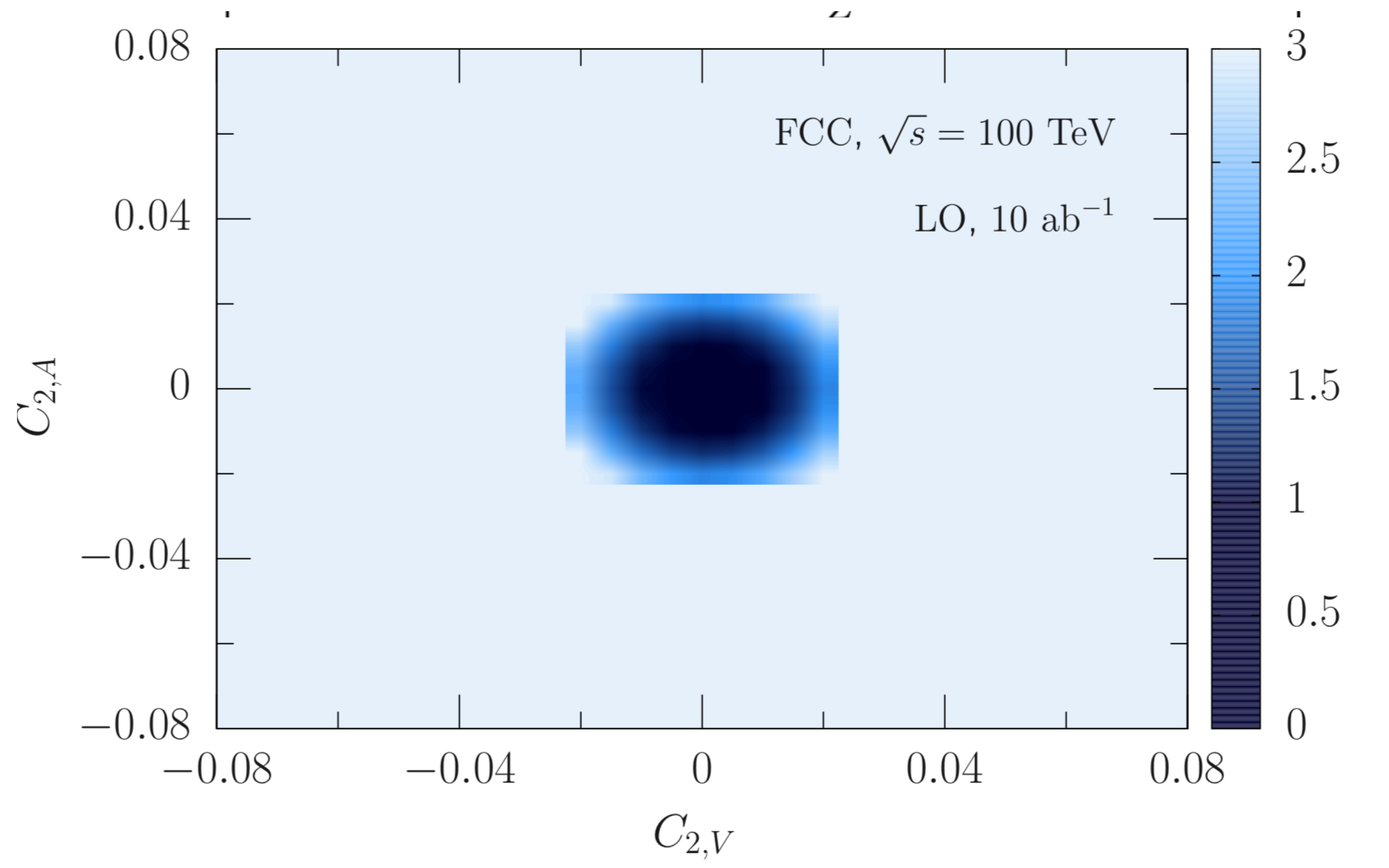
- **ttZ** production via gg process increases more than $ttW^{\pm}$
  - ttZ and ttγ can be used for the measurement of the anomalous EW couplings $C_{2,V/A}$ with comparable or better precision than at the FCC-ee.



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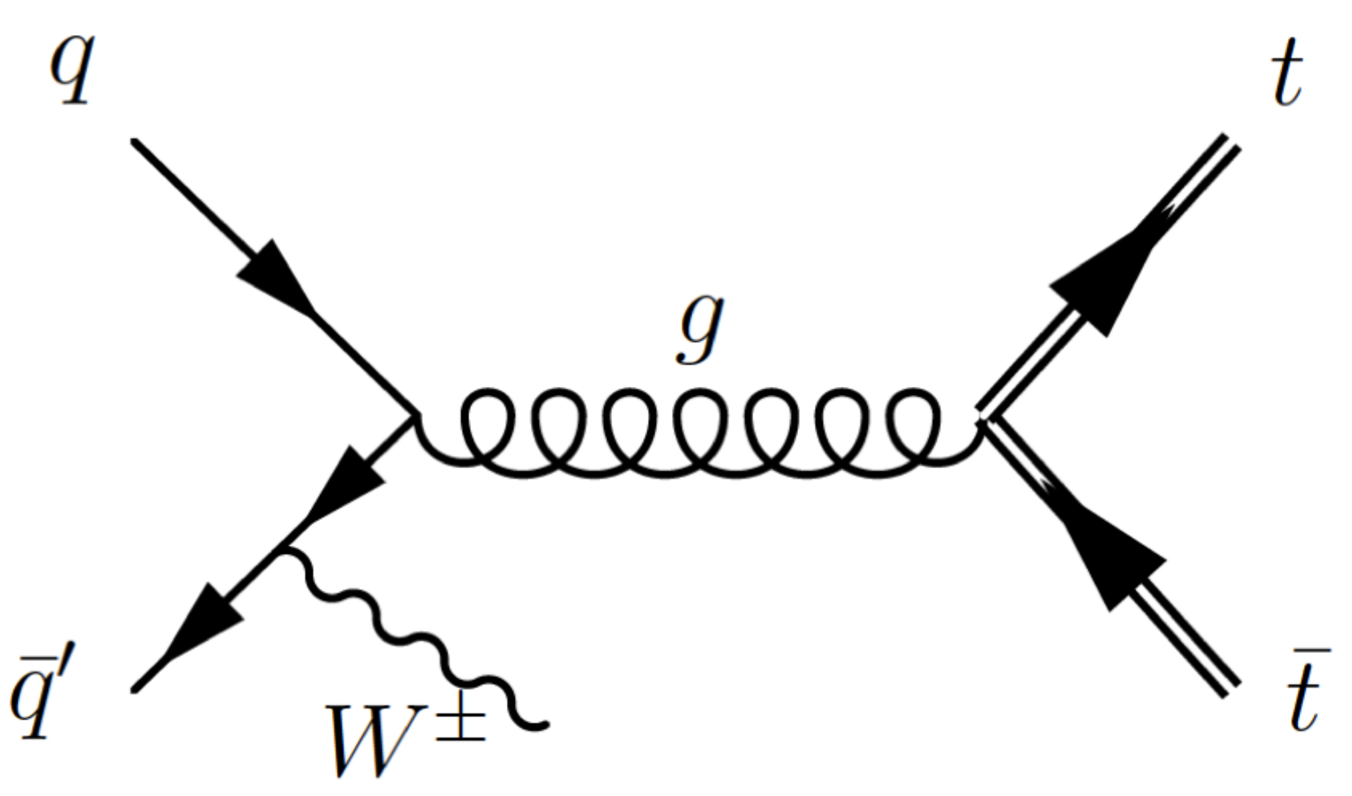
FCC-hh

ASSOCIATED PRODUCTION ttV @FCC-hh (2)

ttW & ASYMMETRIES

	$t\bar{t}W^{\pm}$	$t\bar{t}\gamma$	$t\bar{t}Z$
$A_c(\%)$ at FCC-hh	$1.3\,^{+0.23}_{-0.16}\,^{+0.05}_{-0.03}$	$-0.45\,^{+0.05}_{-0.04}\,^{+0.01}_{-0.02}$	$0.22\,^{+0.06}_{-0.04} \pm 0.01$

- The qq initial state to tt production generates a central/forward asymmetry (preferential/reduced emission of top/anti-top in the direction of the initial state quark/anti-quark)
- Asymmetry can be sensitive to BSM effects! Remember the Tevatron anomaly…



- At 100TeV is greatly diluted by the dominance of gg production to A_c=0.12%
- It is enhanced by a factor 10 in the ttW± process dominated by a qq' initial state
- **Estimate of $\delta_{rel}A_c$~3%(14%) with 3ab^{-1} at the FCC-hh(HL-LHC) in leptonic final states**

ASSOCIATED PRODUCTION ttV @FCC-hh (2)

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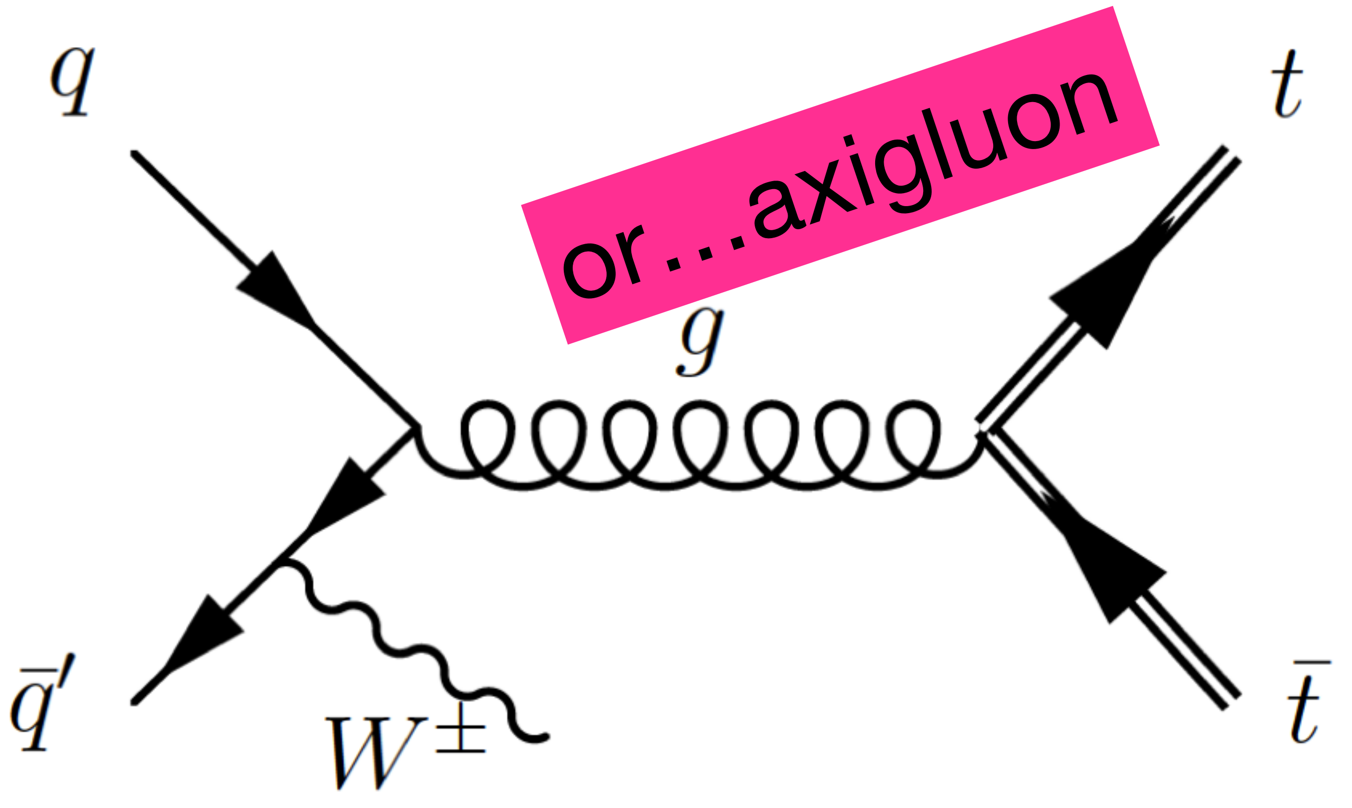

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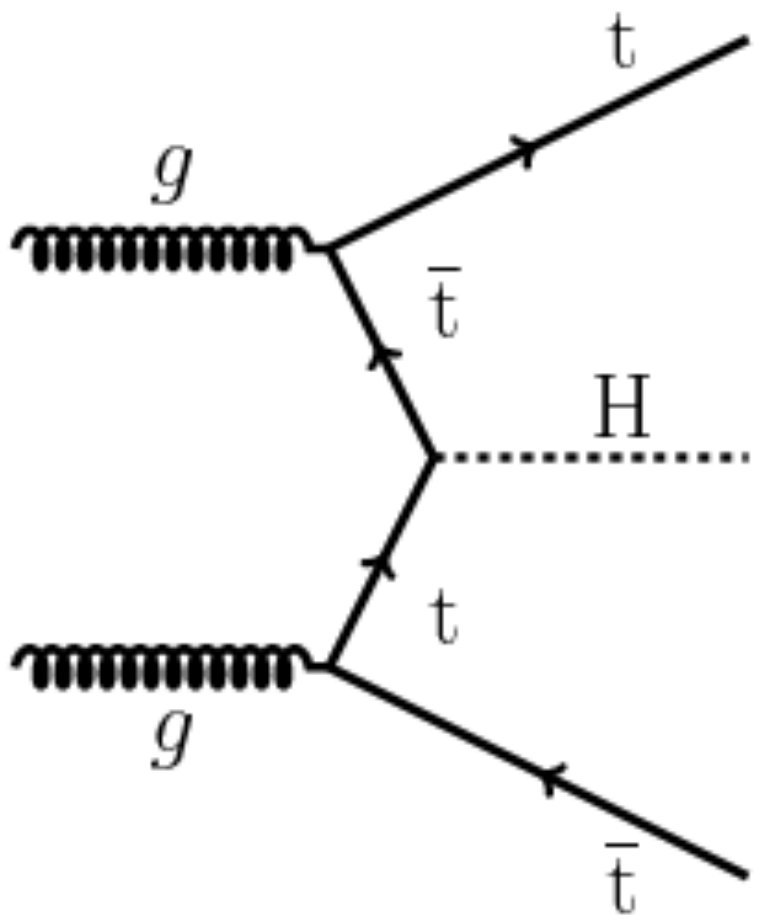
arxiv1406.3262

FCC-hh

TOP YUKAWA COUPLING @FCC-hh

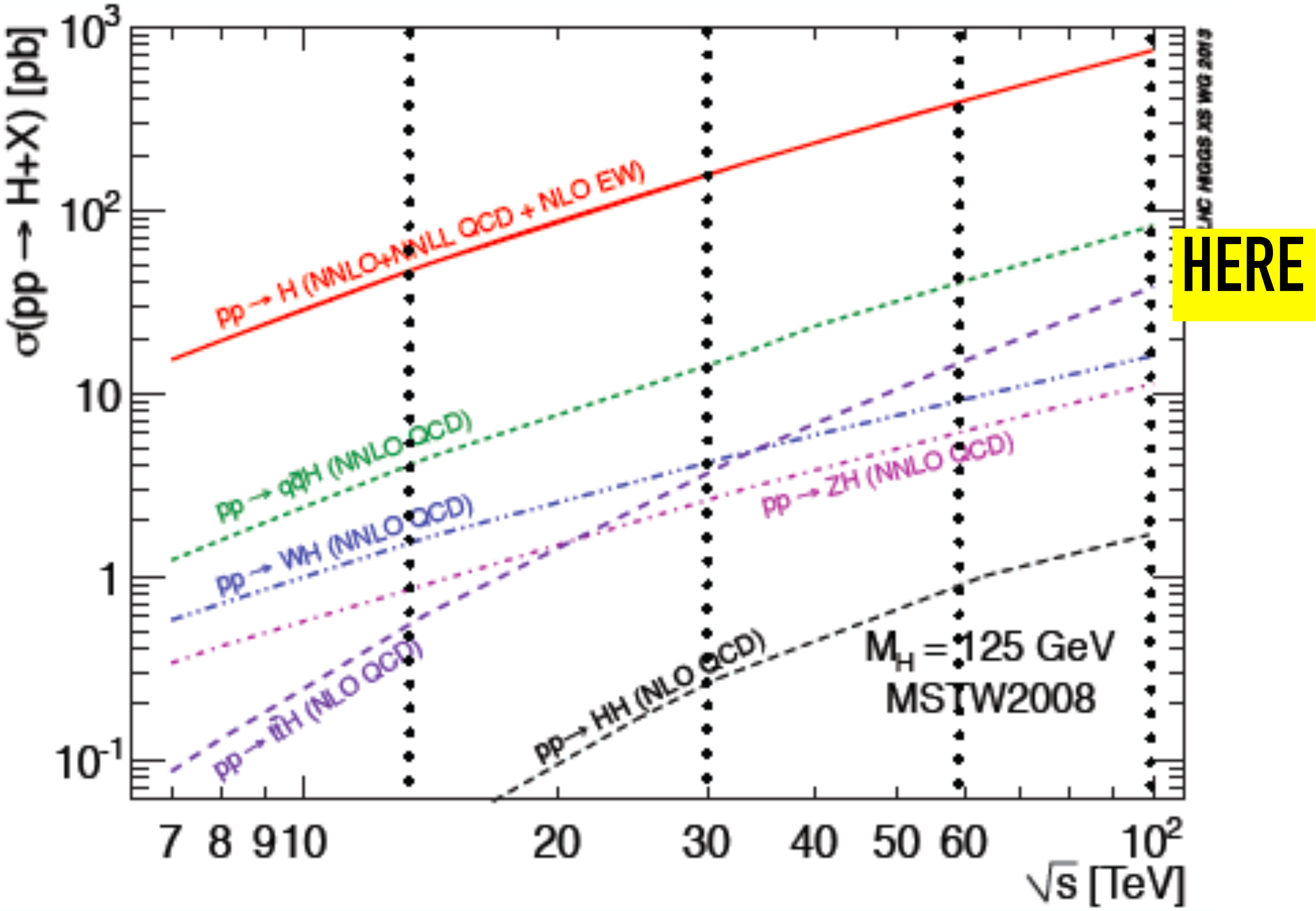
see talk by Michele Selvaggi

- need high energy and statistics to measure y_t with precision
- at FCC-hh 10^9 gg->ttH events



Large cross-section increase with √s

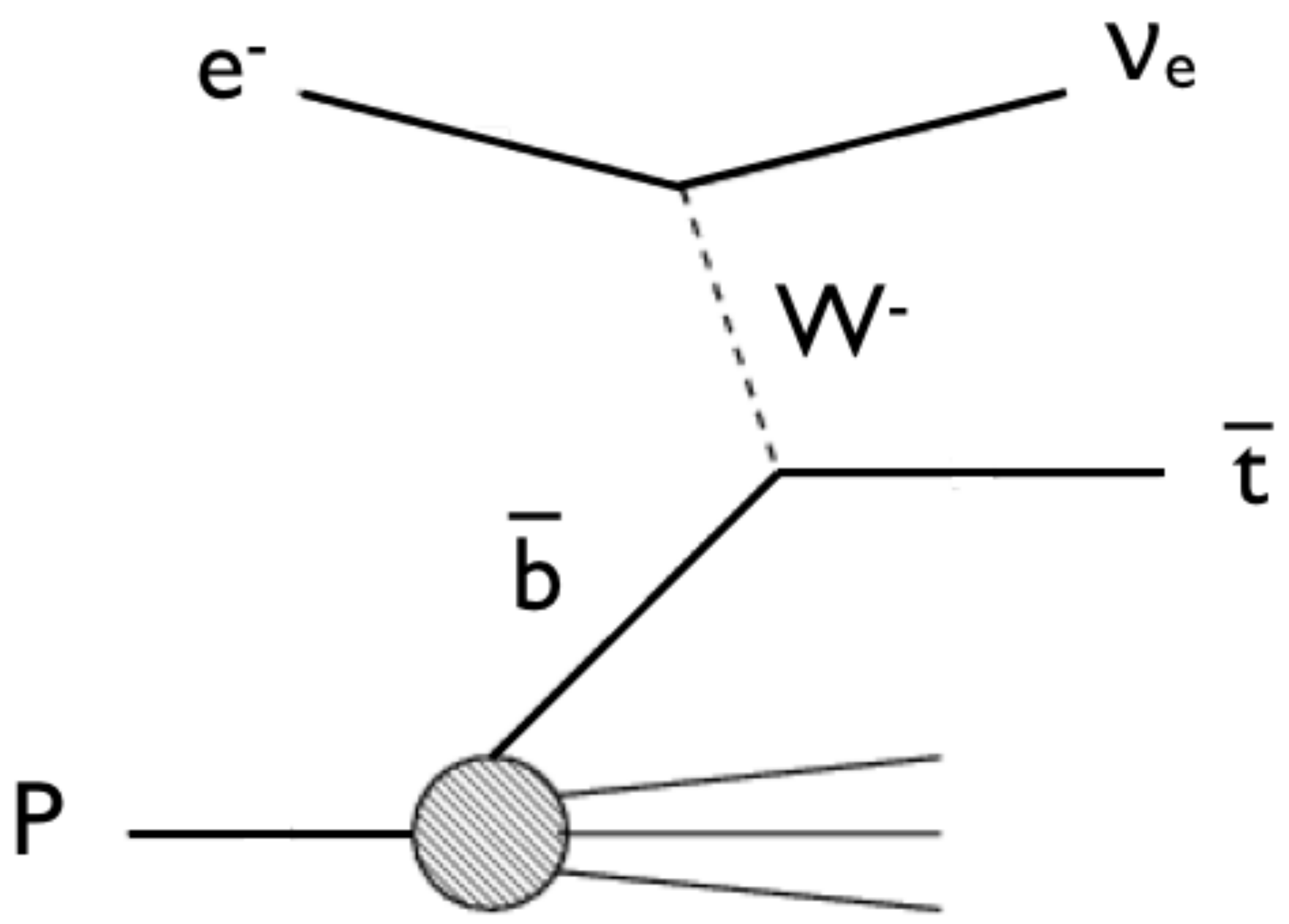
Process	14 TeV	33 TeV	100 TeV
gg → ttH	0.62 pb	4.5 pb × 7.3	37.8 pb × 61



- only way to reach a ~1% precision
  - using σ(ttZ)=1.5% from FCC-ee

TOP PRODUCTION @FCC-eh

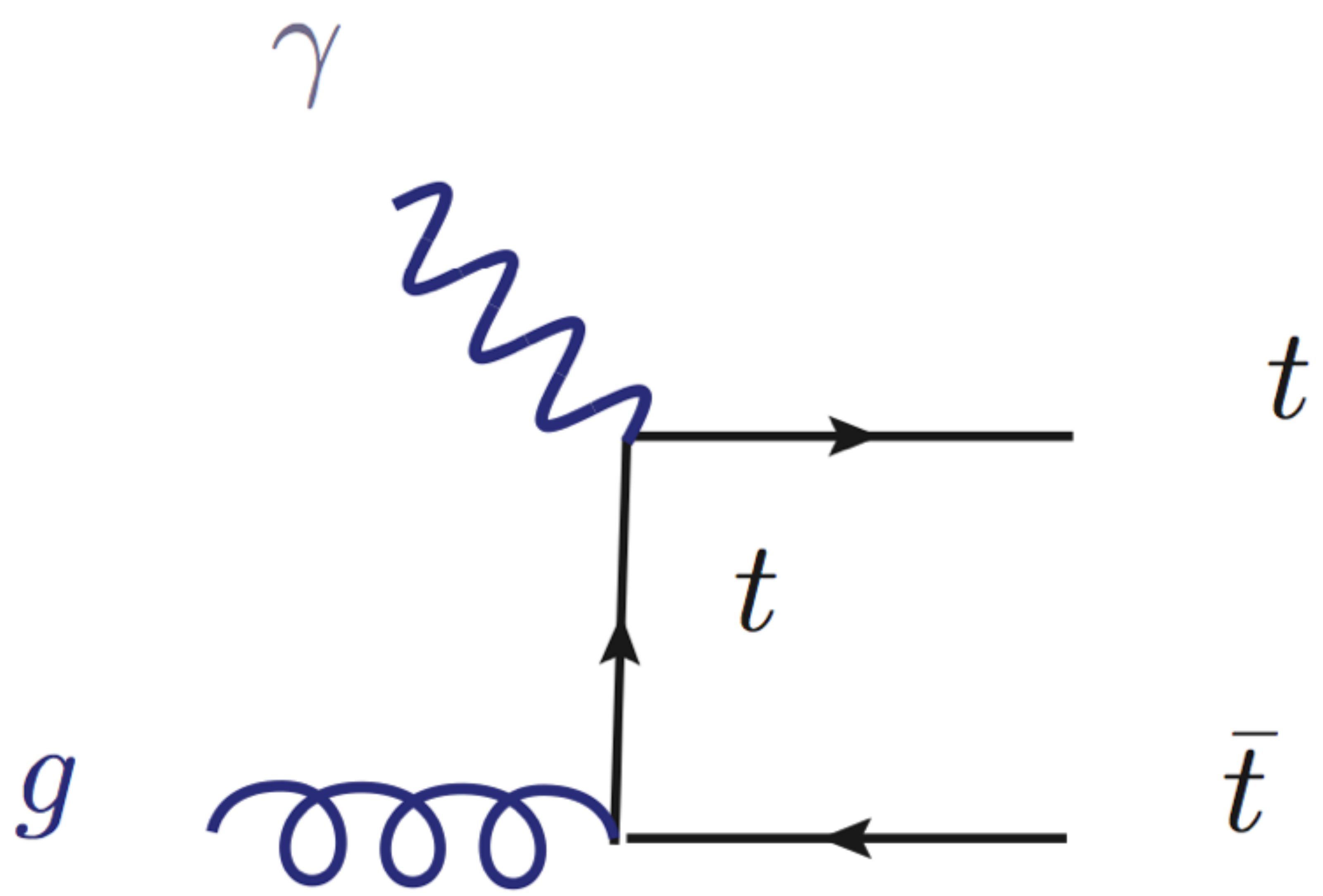
CC DIS top production



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**

FCC-eh

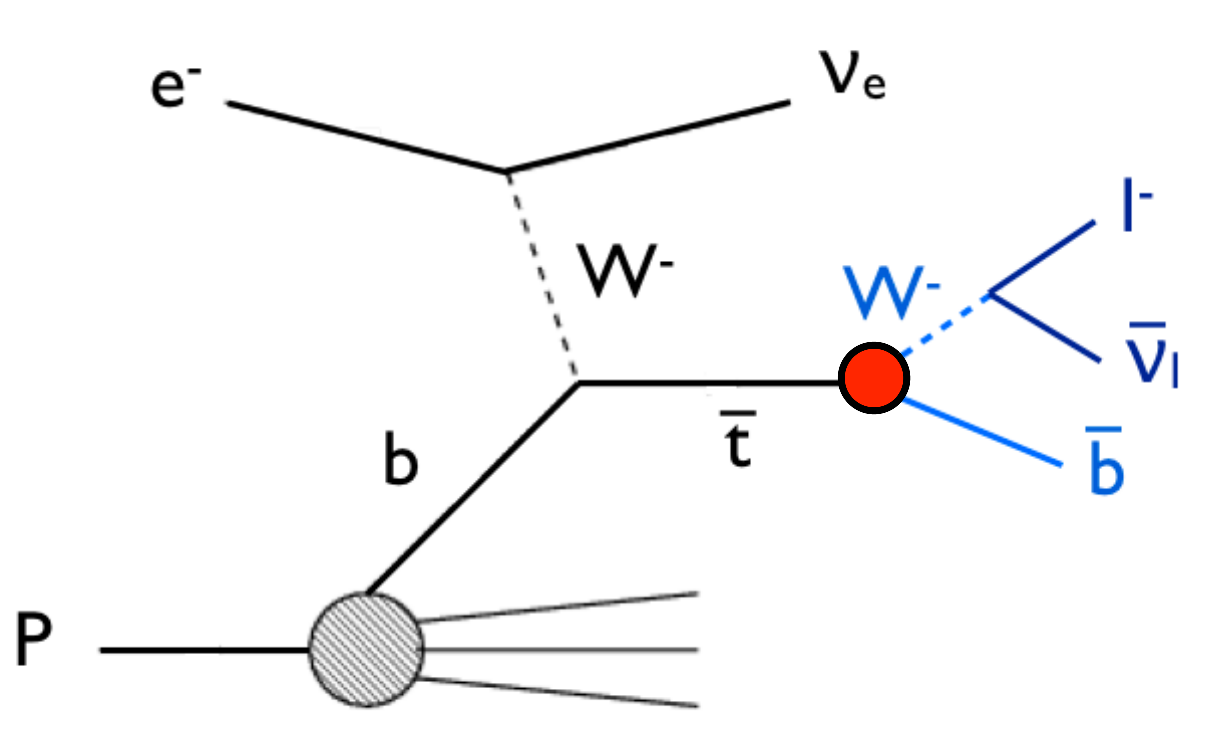
DIRECT MEASUREMENT OF V_{tb} & ANOMALOUS Wtb COUPLINGS

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

= 1 in SM

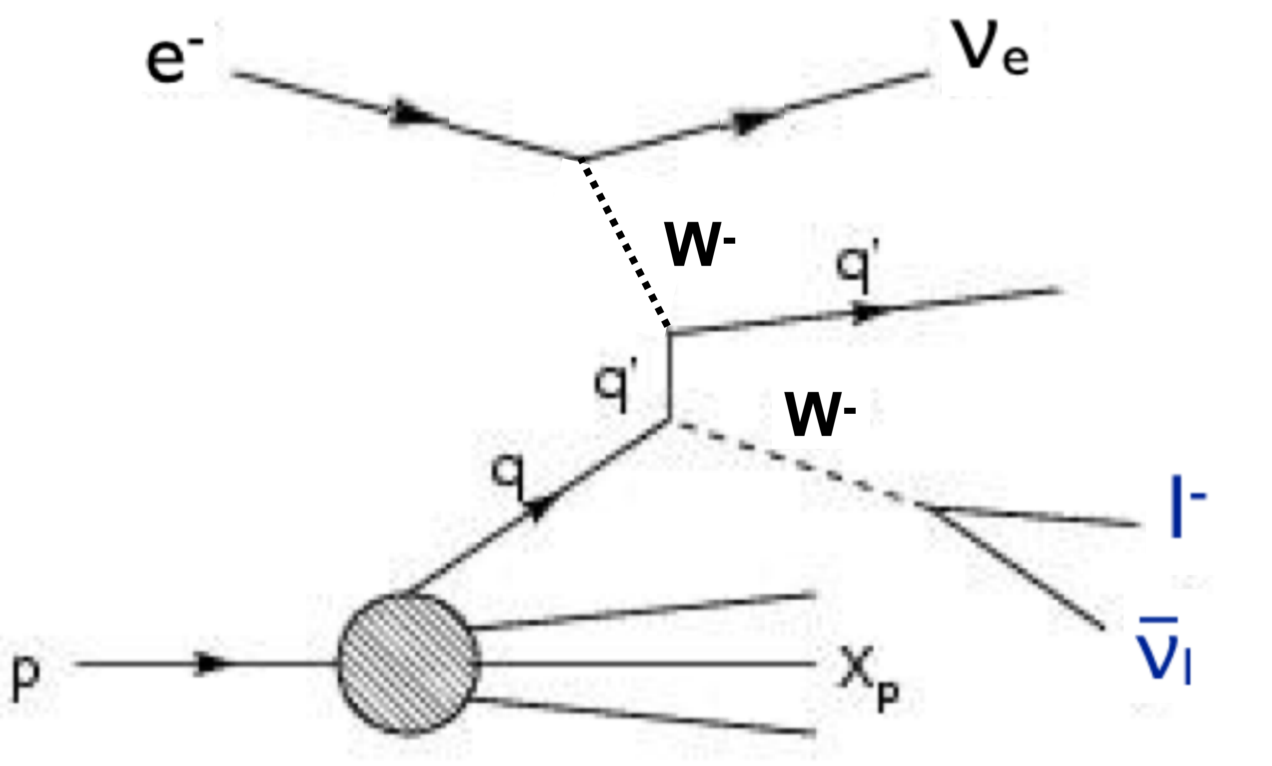
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^- + h.c.$$

V_{tb} 1% with 100fb^{-1} without assumption (LHeC)

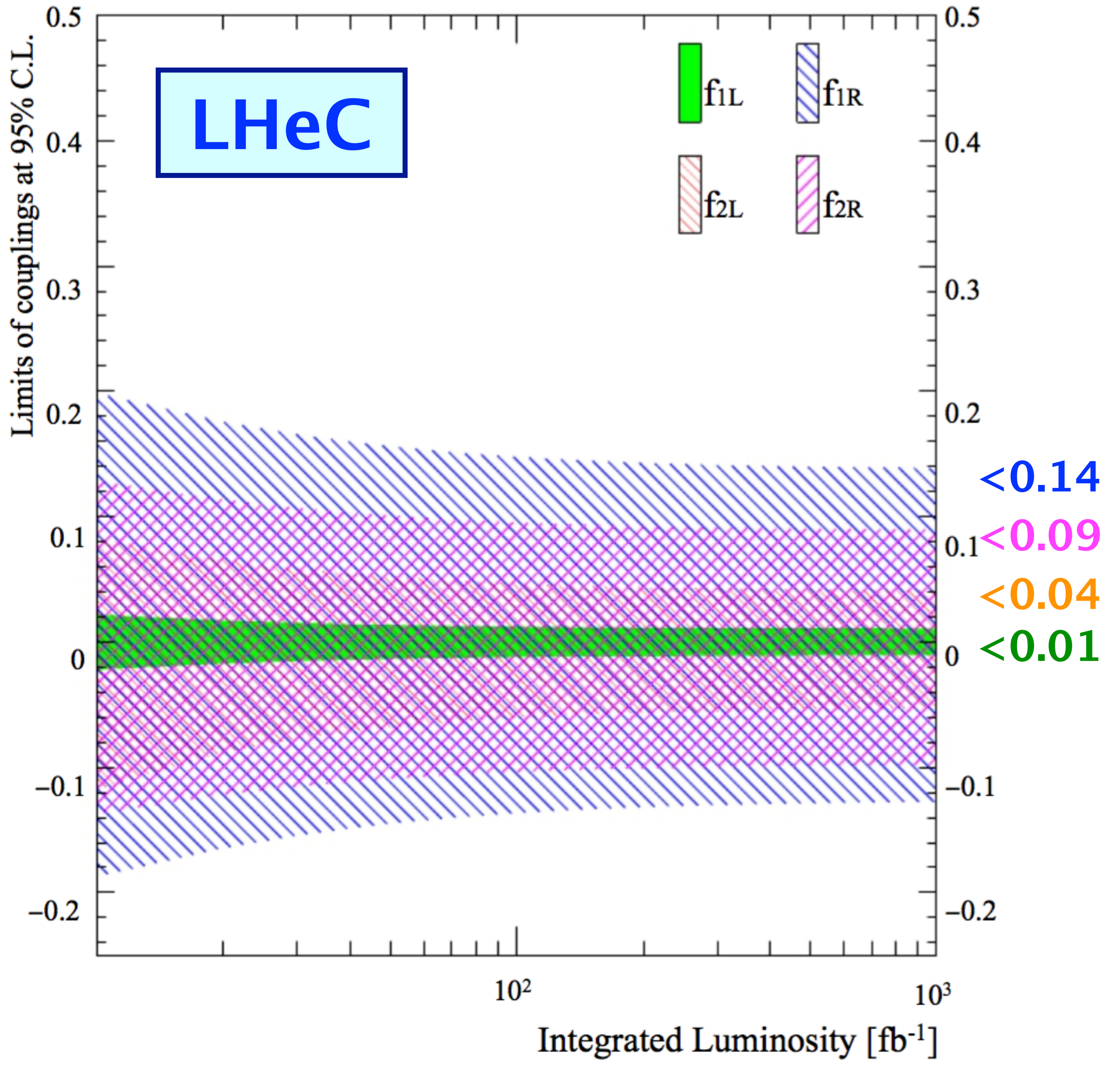


signal

s/b=11



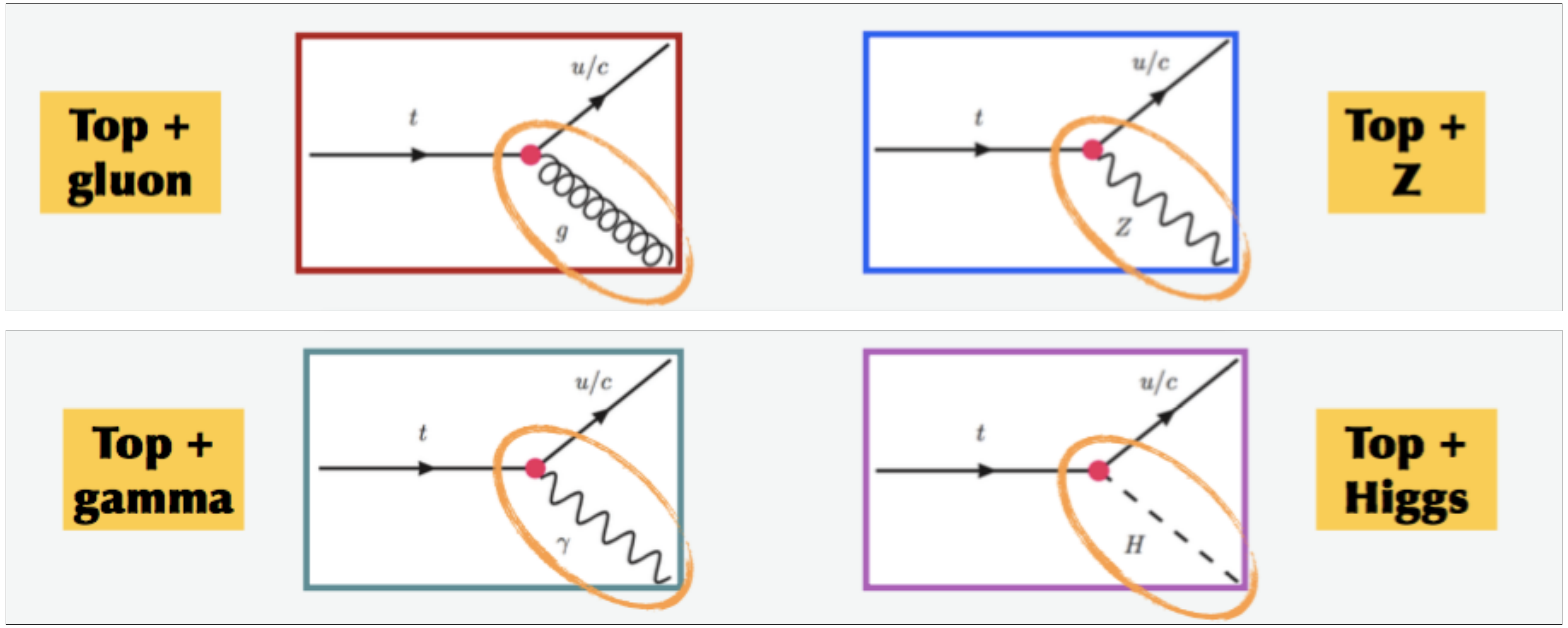
background



Other CKM elements V_{ts} V_{td} will become accessible extending HL-LHC sensitivity (extrapolation to FCC-eh)

TOP FLAVOR CHANGING NEUTRAL CURRENTS

- **FCNC is a process where the top decays via a neutral exchange (Z,γ,g) instead of a W**
- It is forbidden at tree level in the SM and so highly suppressed
- Enhancements from new physics!



	SM	2HDM	MSSM
$BR(t\to cg) \simeq$	5×10^{-12}	$10^{-8} - 10^{-4}$	$10^{-7} - 10^{-6}$
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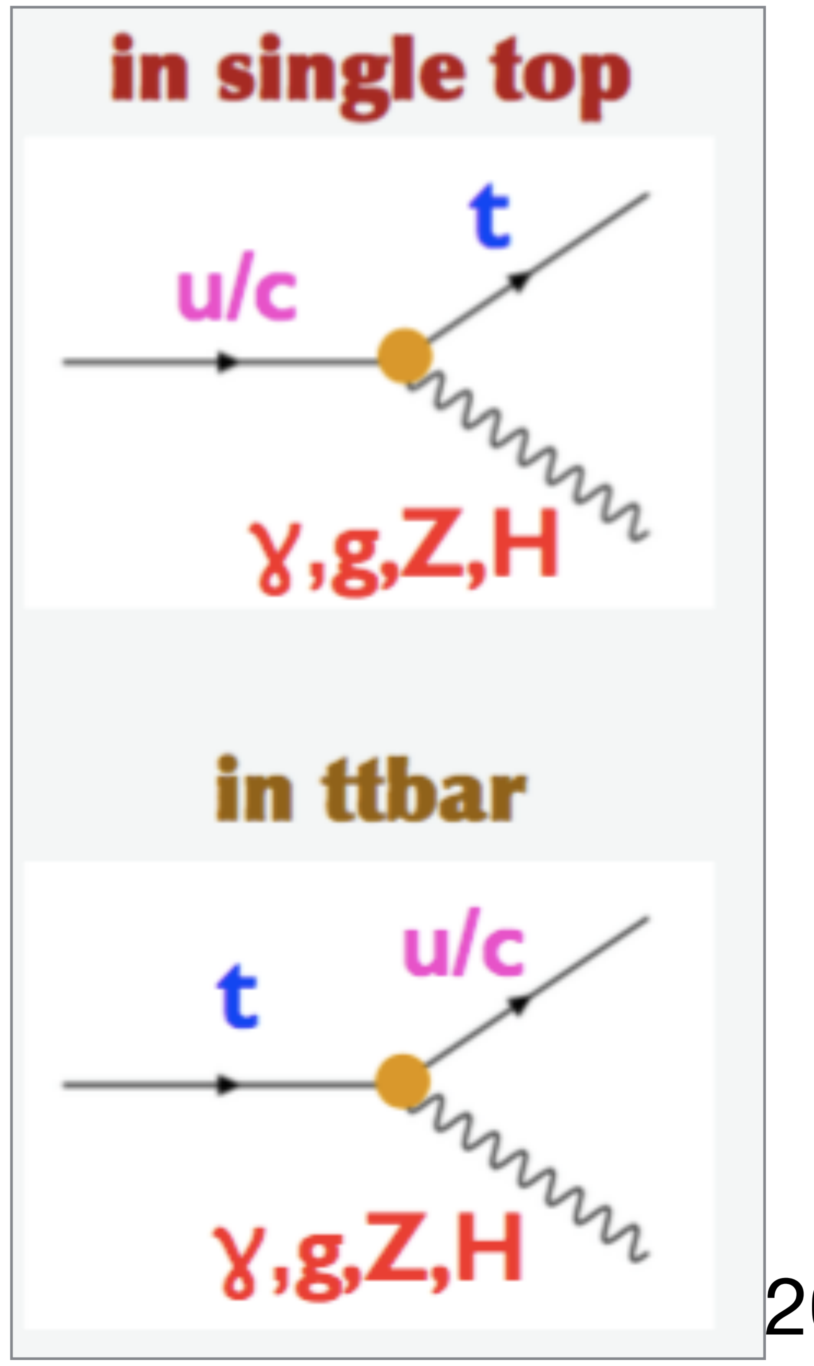

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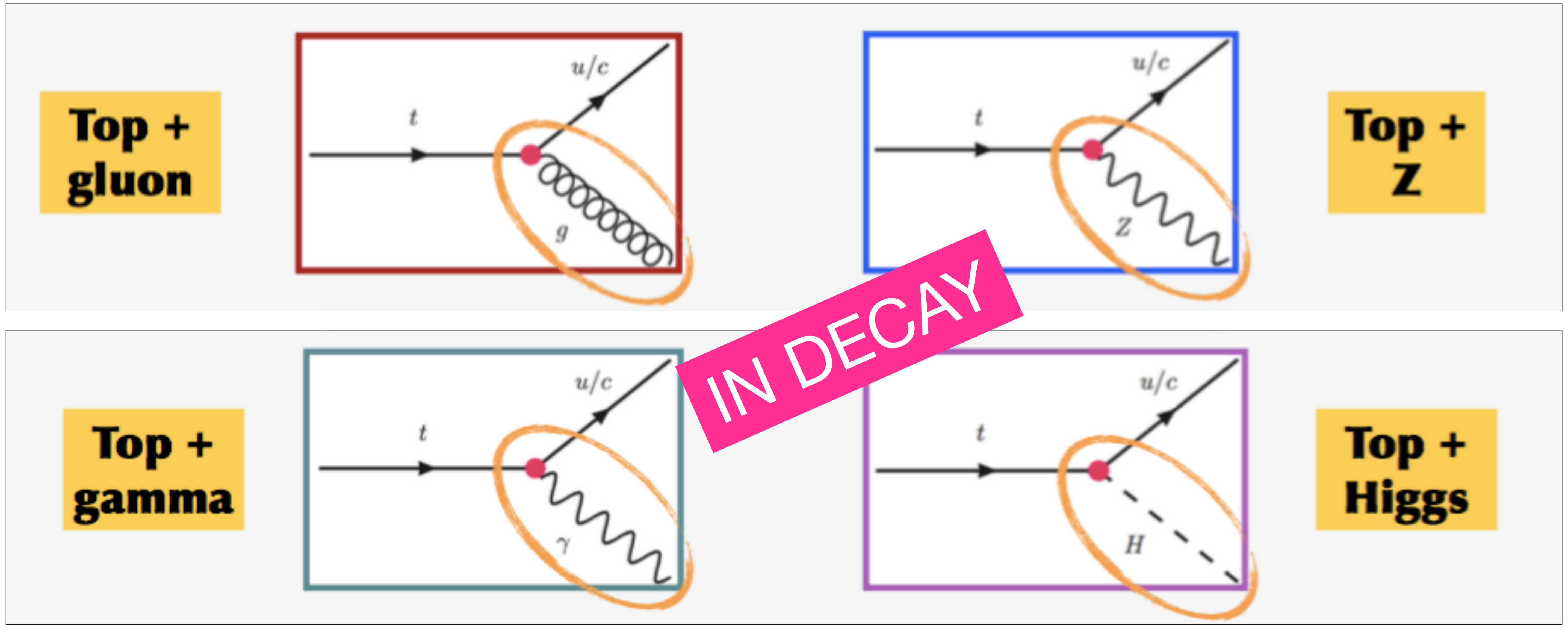

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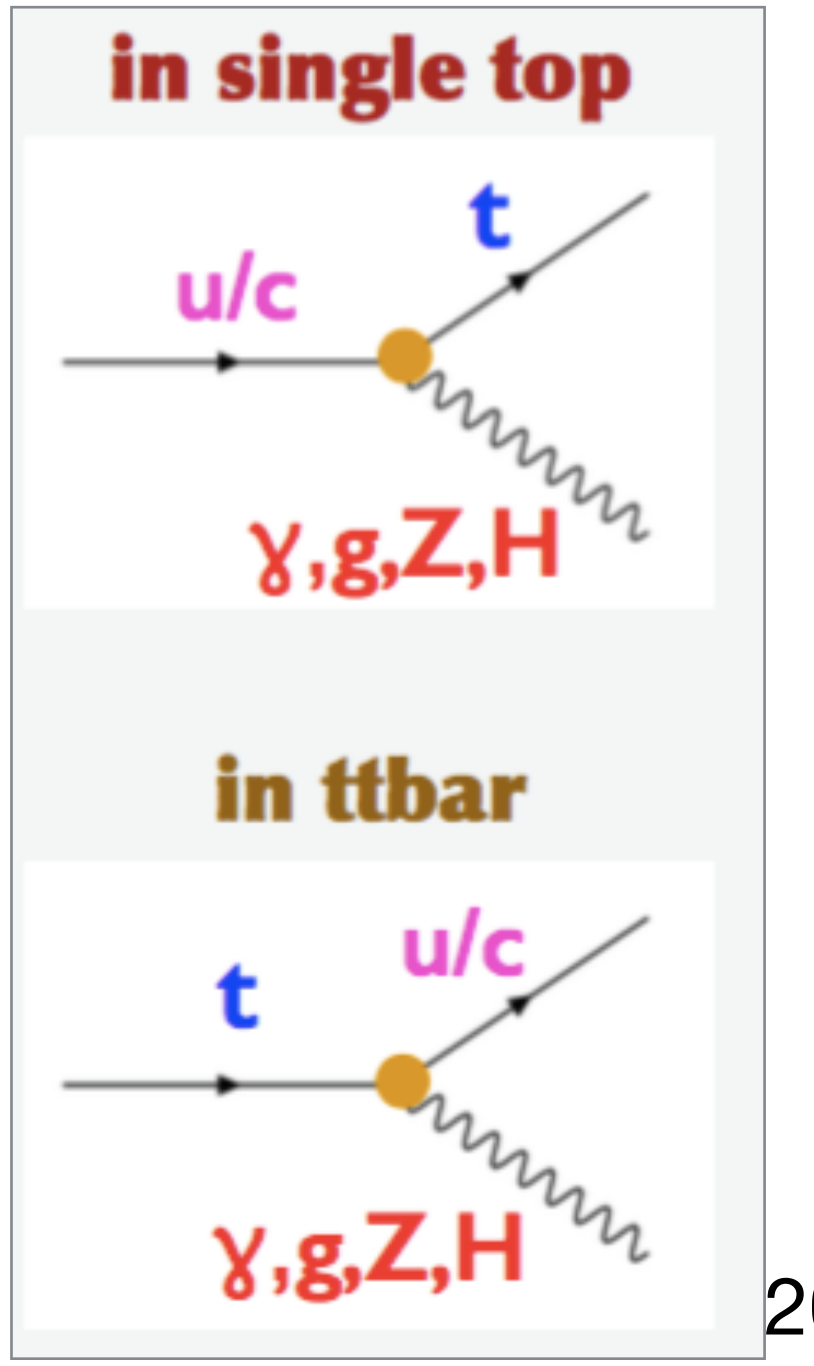

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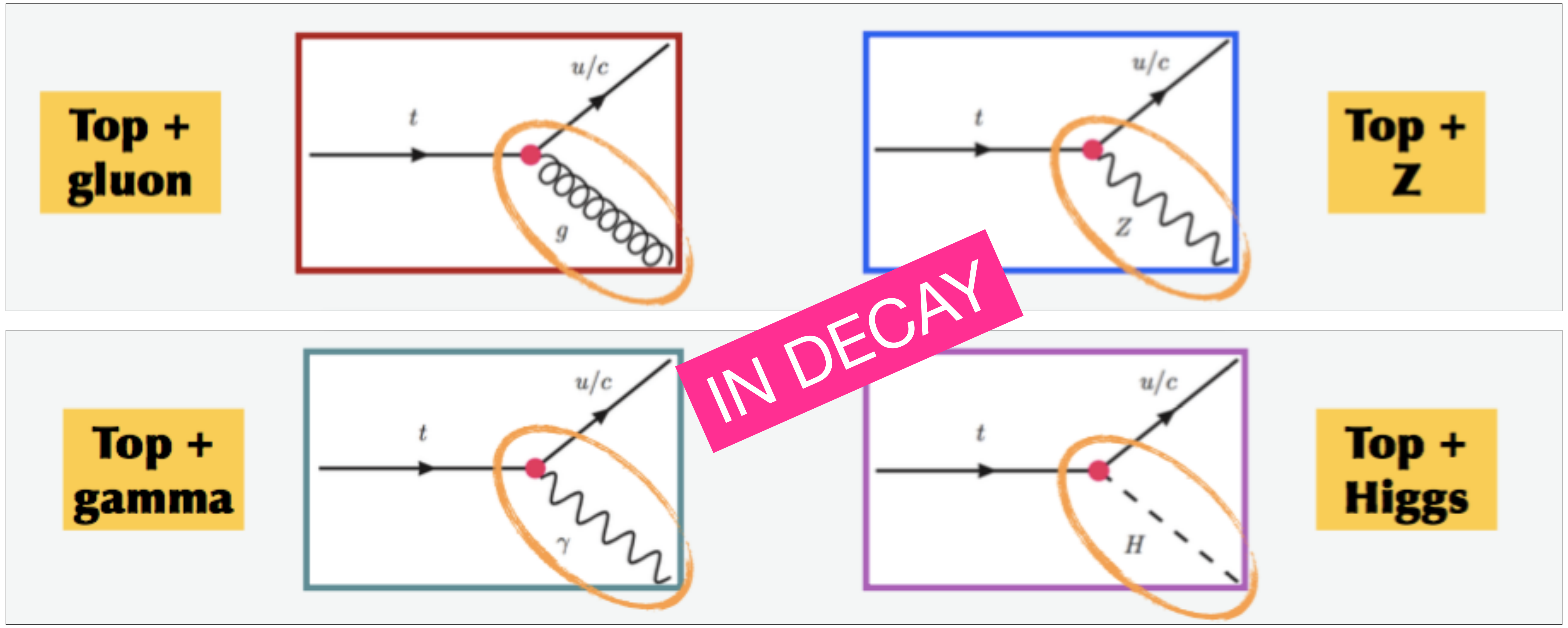

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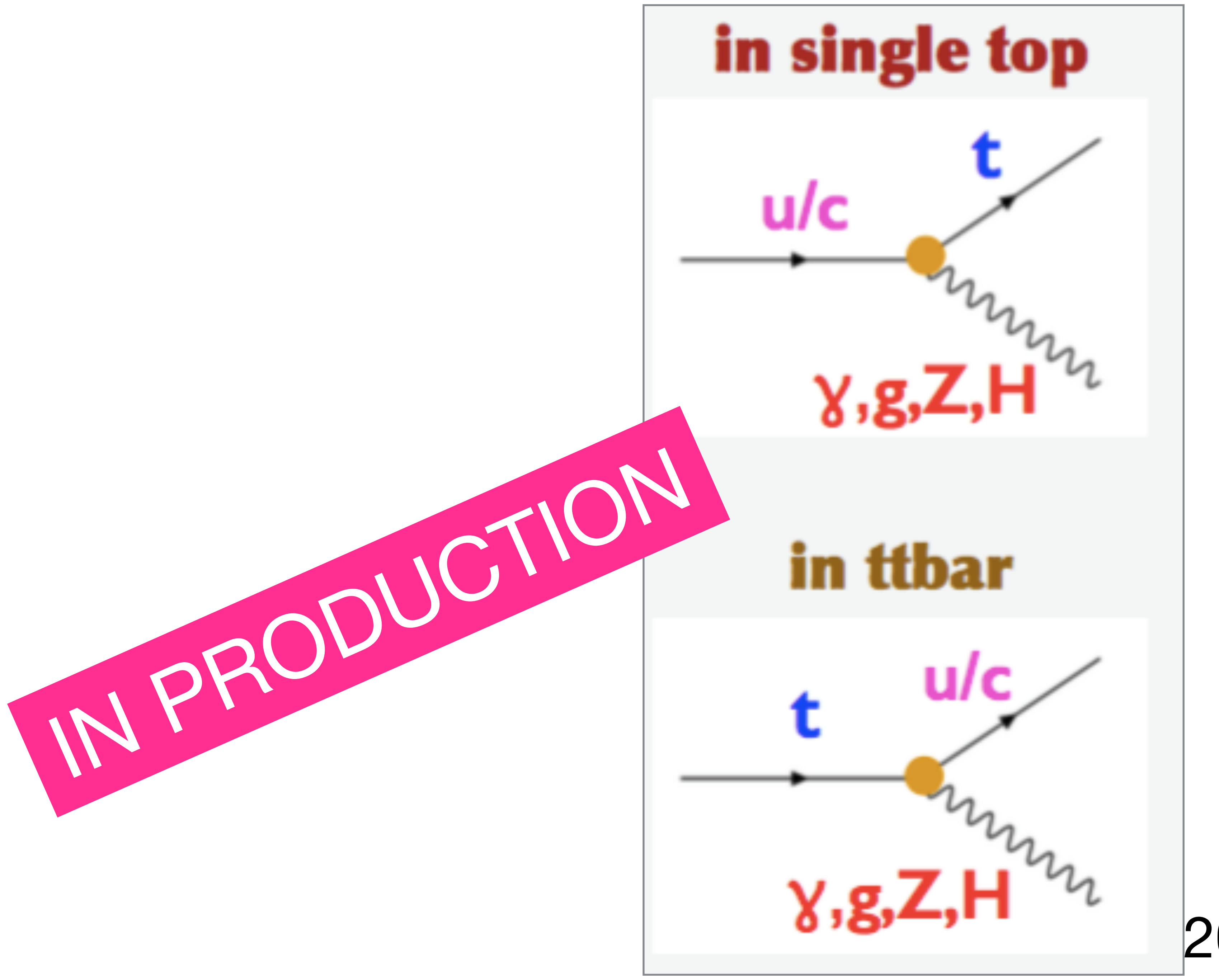
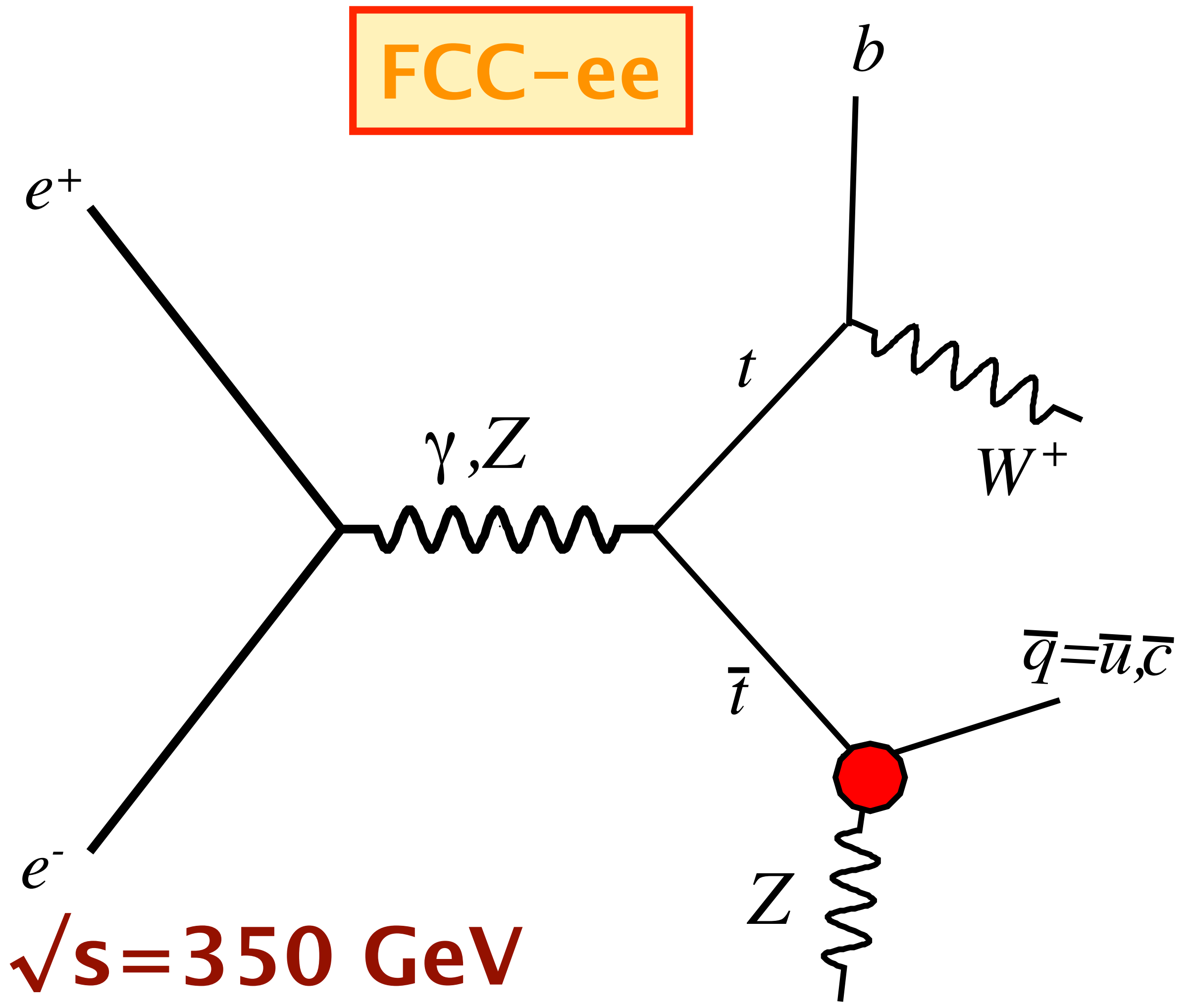
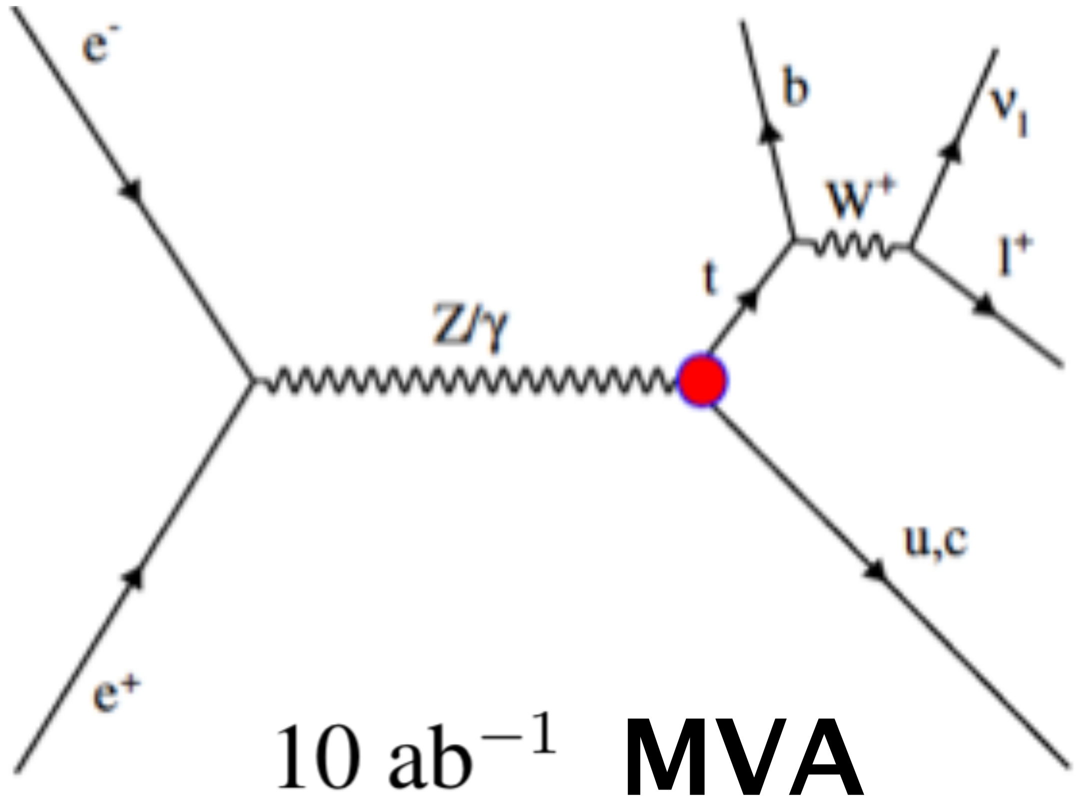


TOP FCNC ANALYSES @FCC

FCC-ee



$\sqrt{s}$=350 GeV

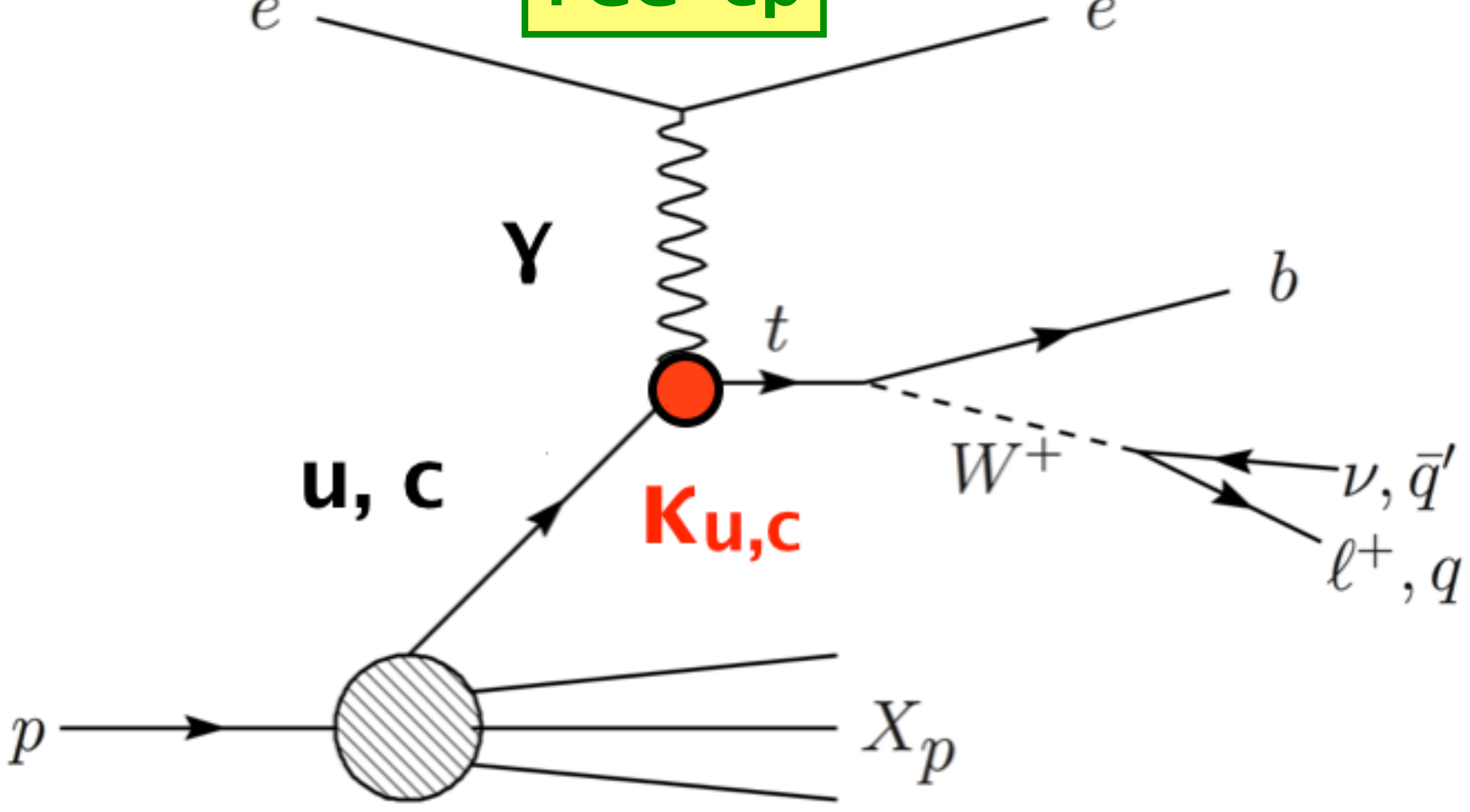


$10\ \mathrm{ab}^{-1}$ **MVA**

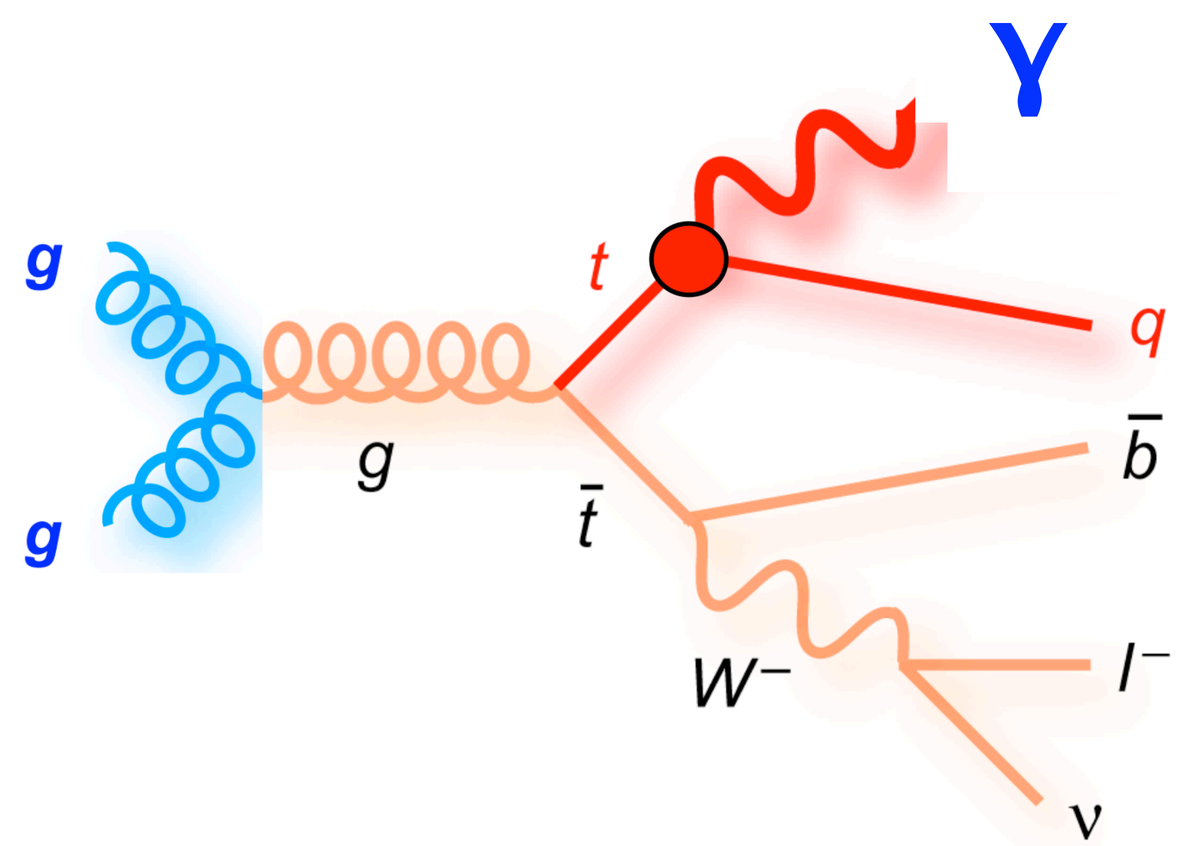
$\sqrt{s}$=240 GeV and $\sqrt{s}$=350 GeV

Br(t→qγ), Br(t→qZ)<O(10^{-6}–10^{-5})

FCC-ep



BR(t→qγ)<O(10^{-6})
with 2ab^{-1}

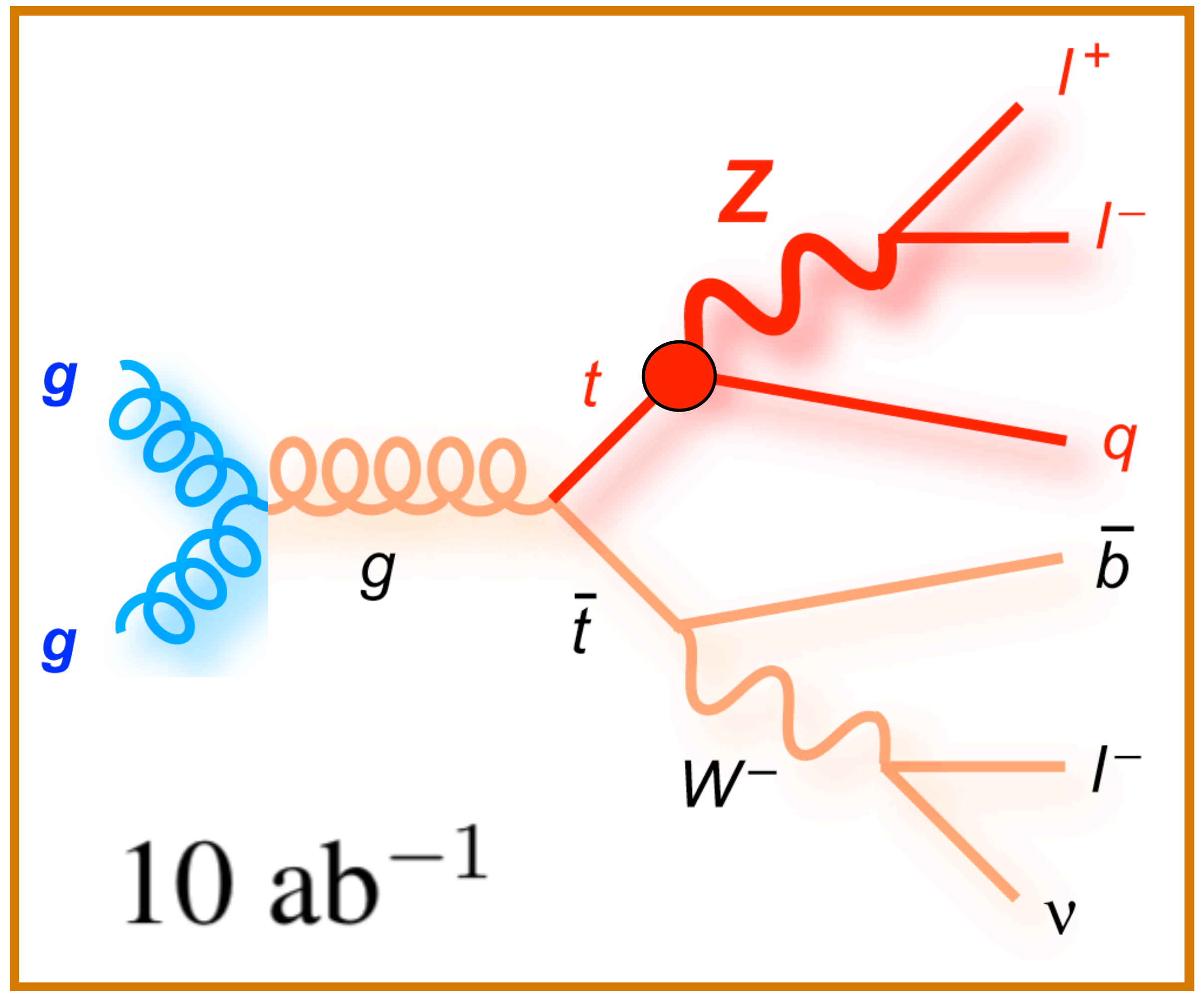


Br(t→qγ)<10^{-7}

(rescaling of the LHC expectations)

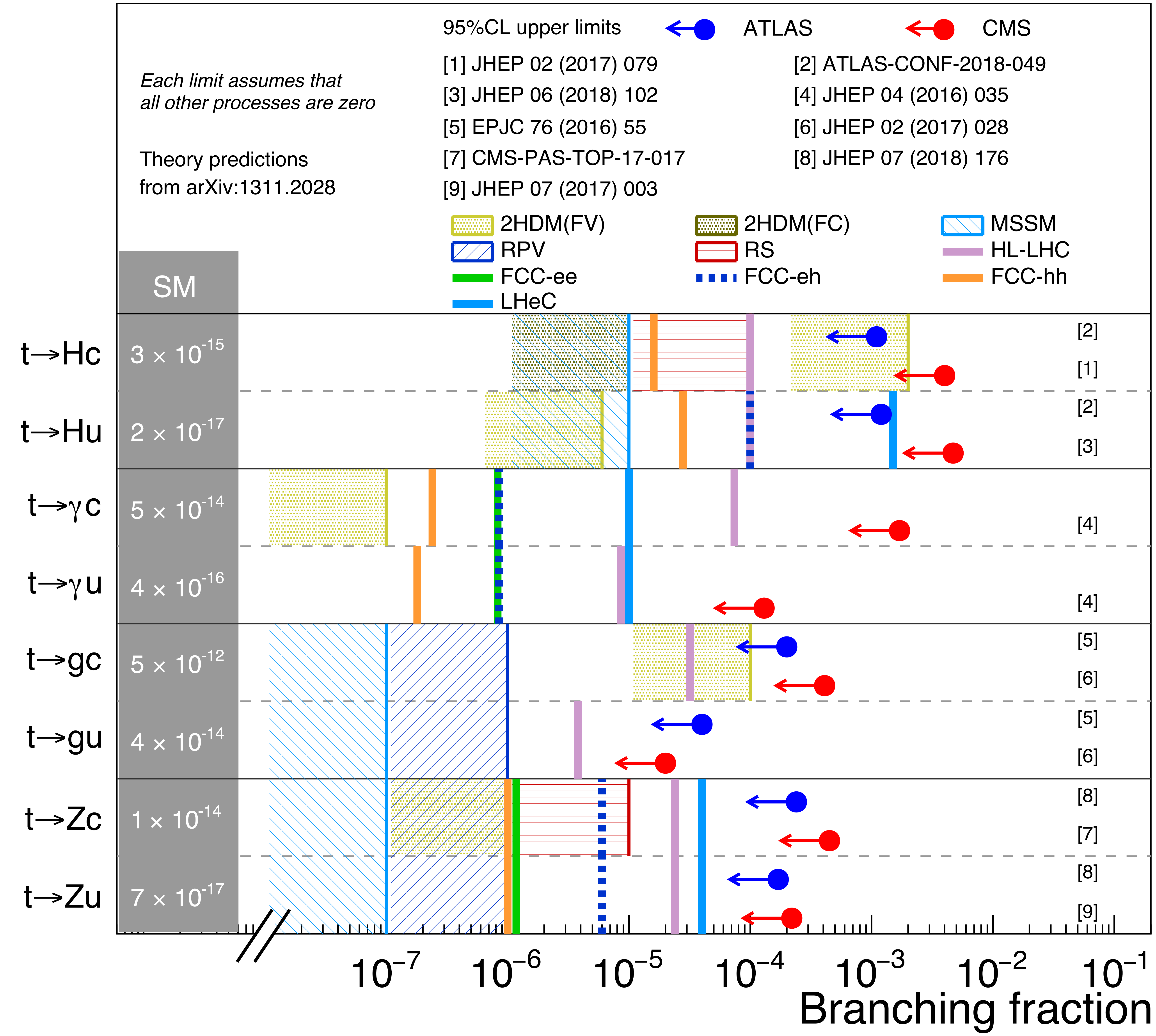
$10\ \mathrm{ab}^{-1}$

FCC-pp



Increasing sensitivity

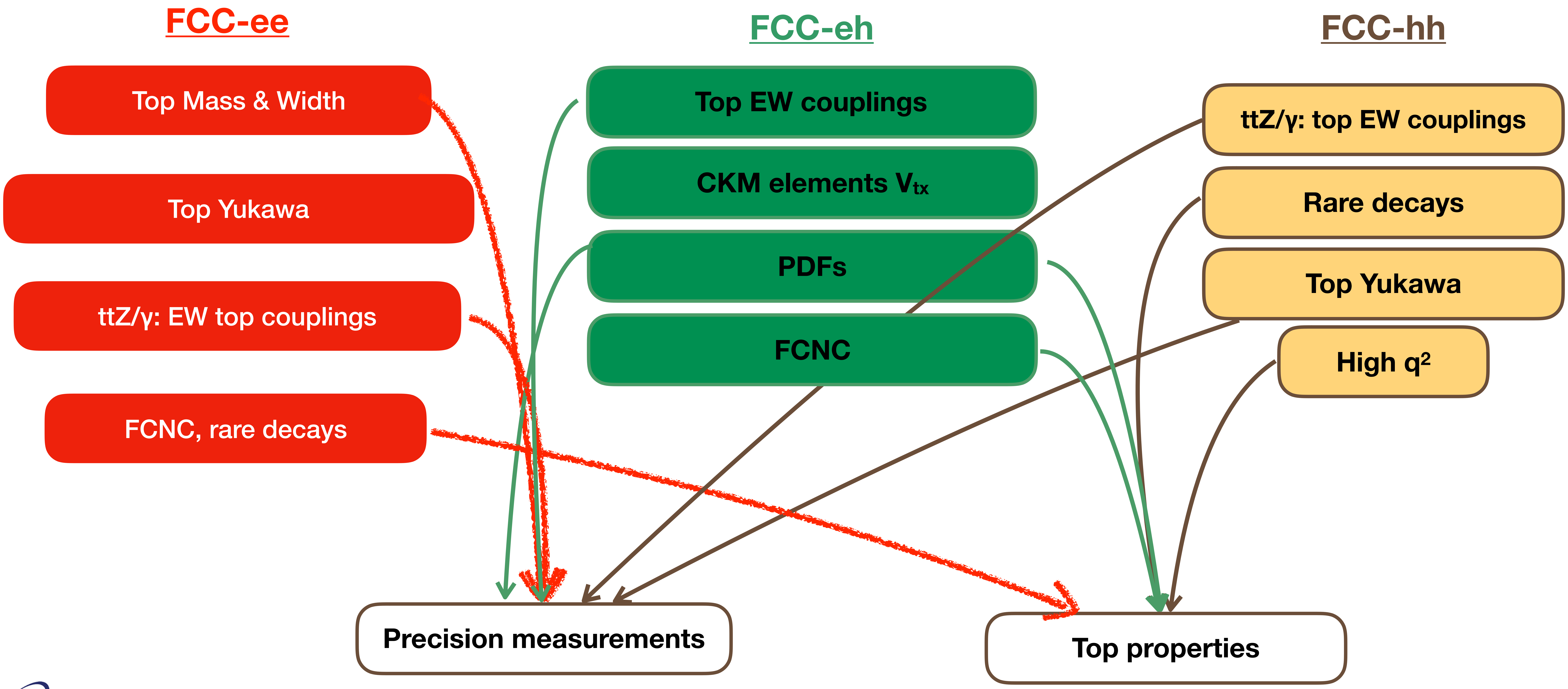
FCNC GRAND SUMMARY



- FCC-ee similar reach to HL-LHC: can provide studies in case of observation
- FCC-eh: higher sensitivity than HL-LHC
- FCC-hh: best reach due to the very large statistics available. Exploiting boosted topologies to compensate large pileup

FCC program can start probing anomalous BR from BSM models

SYNERGIES & COMPLEMENTARITIES



CONCLUSIONS

- The top physics program at FCC colliders is extremely compelling:
  - achieve ultimate precision on fundamental SM parametes
  - extend the sensitivity to study more top properties
  - access a completely new kinematic parameter space
- …and all this without considering the importance of top physics knowledge as:
  - **background for searches**
  - **decay product of new BSM particles**
  - **production in heavy ion collisions**

top mass precision <100MeV

ttZ/ttγ couplings at ~%

V_{tb} at ~%

ttH coupling at 1%

FCNC limits up to 10^{-7}

sensitivity to NP scales O(100 TeV)

…and much more!

A dream project to discover the ultimate role of top quark!

GENERAL REFERENCES

- FCC CDR Volume 1, Physics Opportunities, https://fcc-cdr.web.cern.ch/
- FCC CDR Volume 2, The Lepton Collider, https://fcc-cdr.web.cern.ch/
- Physics case of FCC-ee, arxiv:1308.6176
- Physics at the FCC-hh, a 100 TeV pp collider, arxiv:1710.06353
- LHeC CDR, arxiv:1206.2913
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- Standard Model Physics at the HL-LHC and HE-LHC, axiv: 1902.04070
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