XXXIII INTERNATIONAL SEMINAR OF NUCLAR AND SUBNUCLEAR PHYSICS “FRANCESCO ROMANO” 2022

Physics @Future Colliders - 3

Patrizia Azzi - INFN-PD/CERN
patrizia.azzi@cern.ch

PHYSICS AT e+e- COLLIDERS

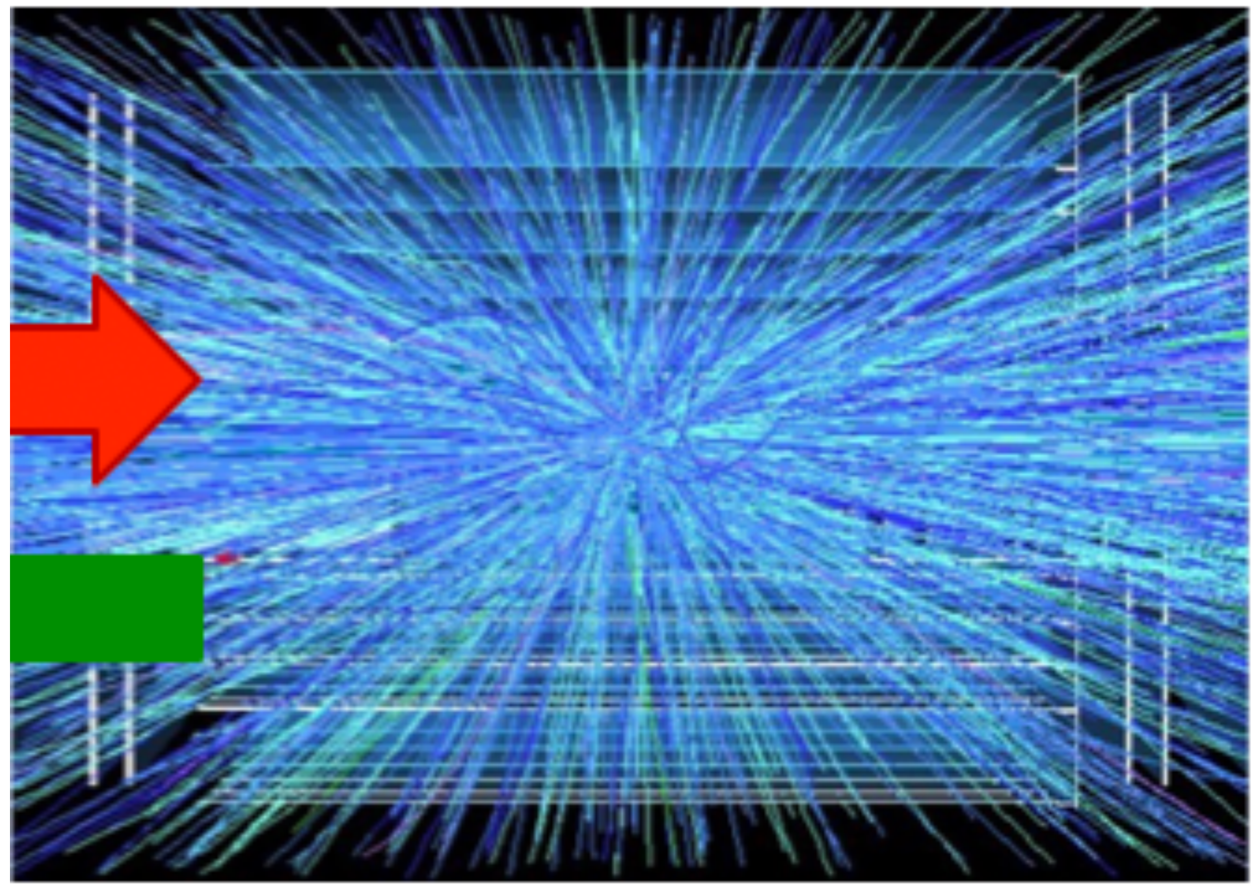
$\sqrt{s}$	Processes	Physics Goals	Observables
91 GeV	• $e^+e^- \to Z$	ultra-precision EW physics **flavour BSM**	$\sin^2\theta_{eff}$ M_Z, Γ_Z, N_ν α, α_S
125 GeV	• $e^+e^- \to H$	*limit on s-channel H production?*	y_e
160 GeV	• $e^+e^- \to W^+W^-$	ultra-precision W mass	M_W, Γ_W
>160 GeV	• $e^+e^- \to W^+W^-$ • $e^+e^- \to qq, \ell\ell\ (\gamma)$	precision W mass and couplings precision EW (incl. Z return)	M_W, aTGC N_ν
250 GeV	• $e^+e^- \to ZH$	ultra-precision Higgs mass precision Higgs couplings	M_H κ_V, κ_f, Γ_H
360 GeV	• $e^+e^- \to tt$	ultra-precision top mass	M_{top}
>360 GeV	• $e^+e^- \to tt$ • $e^+e^- \to ZH$ • $e^+e^- \to H\nu\nu$	precision top couplings precision Higgs couplings	
500+ GeV	• $e^+e^- \to ttH$ • $e^+e^- \to ZHH$ • $e^+e^- \to Z' \to ff$ • $e^+e^- \to XX$ • $e^+e^- \to AH, H^+H^-$	Higgs coupling to top Higgs self-coupling search for heavy Z' bosons search for supersymmetry (SUSY) search for new Higgs bosons	y_{top} λ_{HHH}

Special program

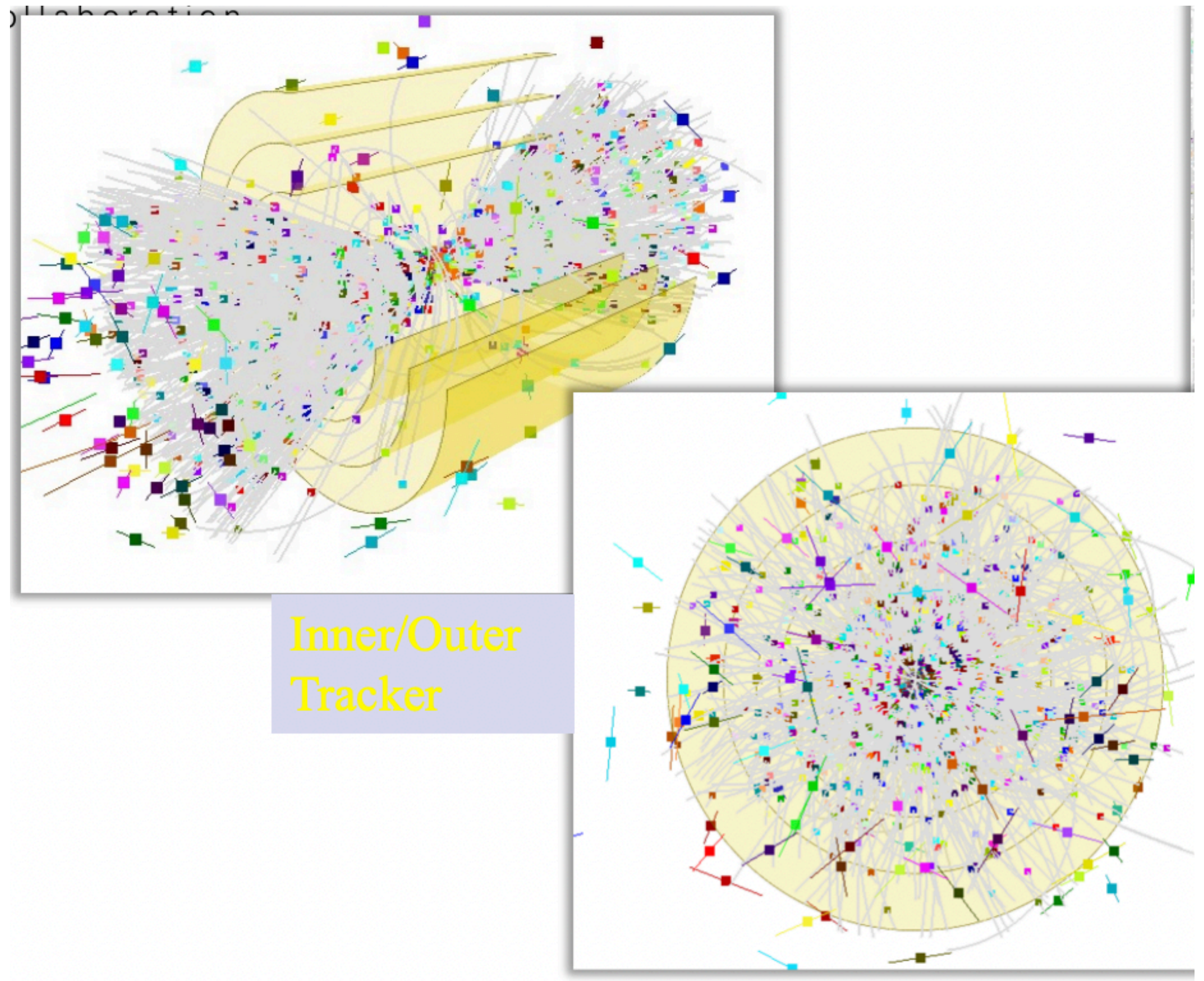
BACKGROUNDS VS PRECISION

- Electron/muons are ELEMENTARY particles. No spectators. No PDF. The $\sqrt{s}$ of the process is known. This LIMITS ULTIMATE PRECISION
- Various machines at high energy have processes that create noise and occupancy in the detector: analyses assume this will be OK

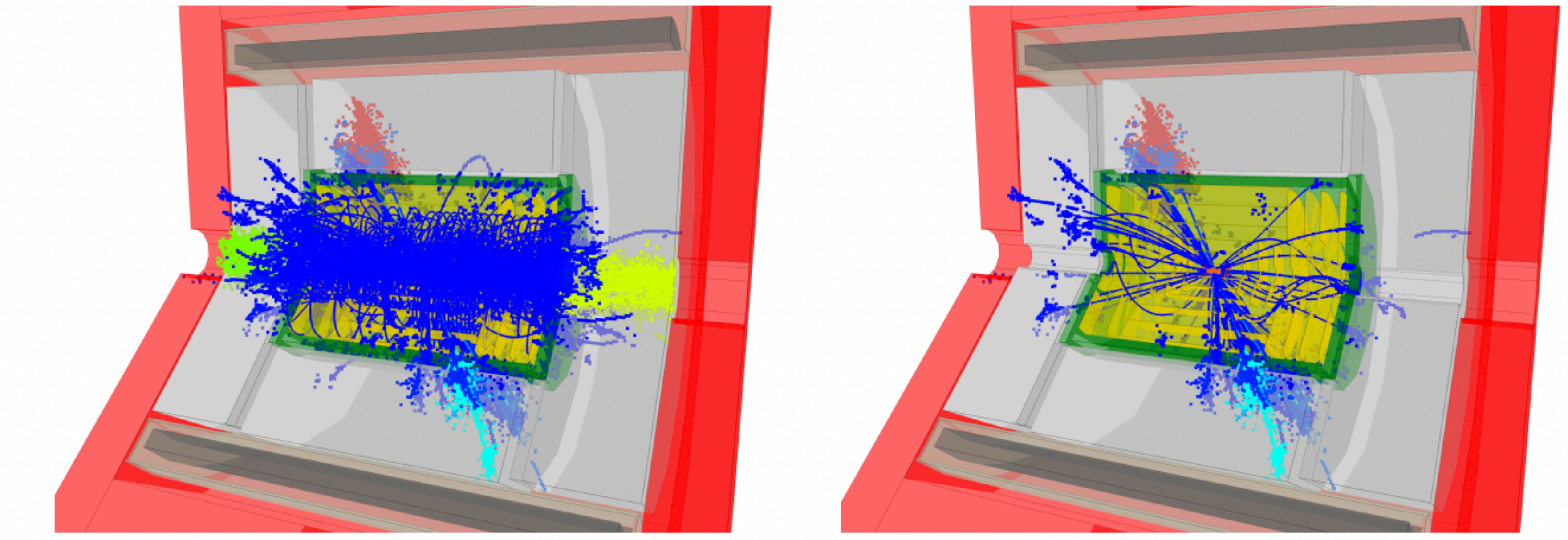
FCC-hh 100 TeV
~1000 pileup



Muon Collider 10TeV
Beam Induced Background

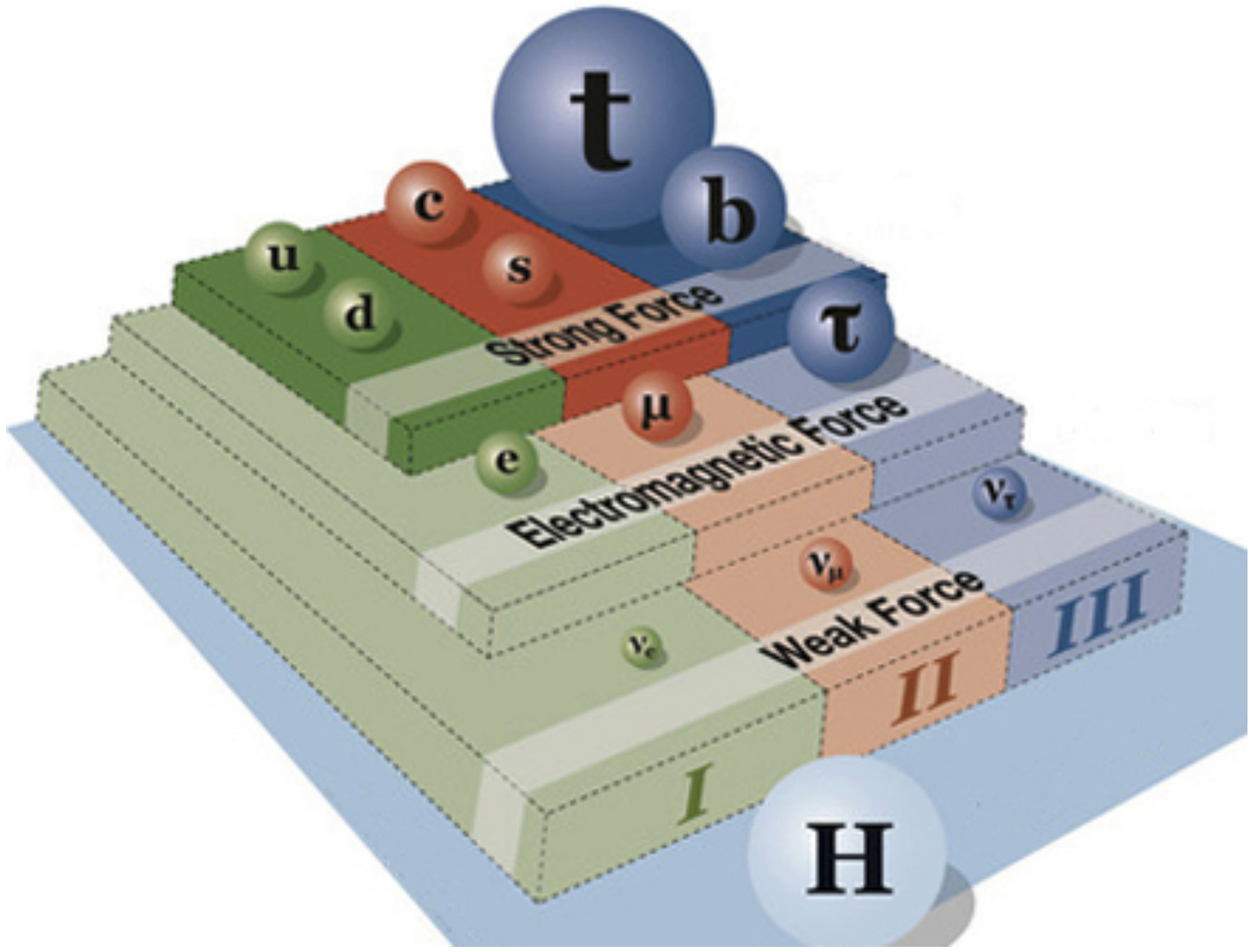


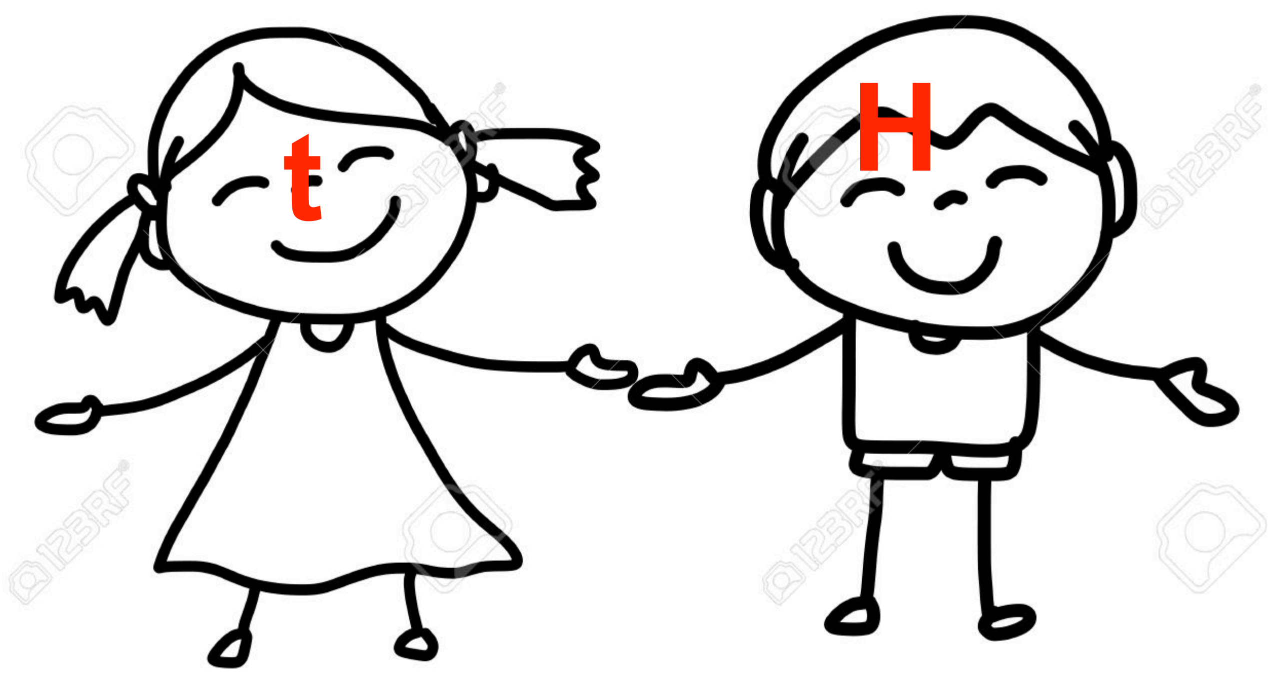
CLIC 3TeV
Beamstrahlung Background



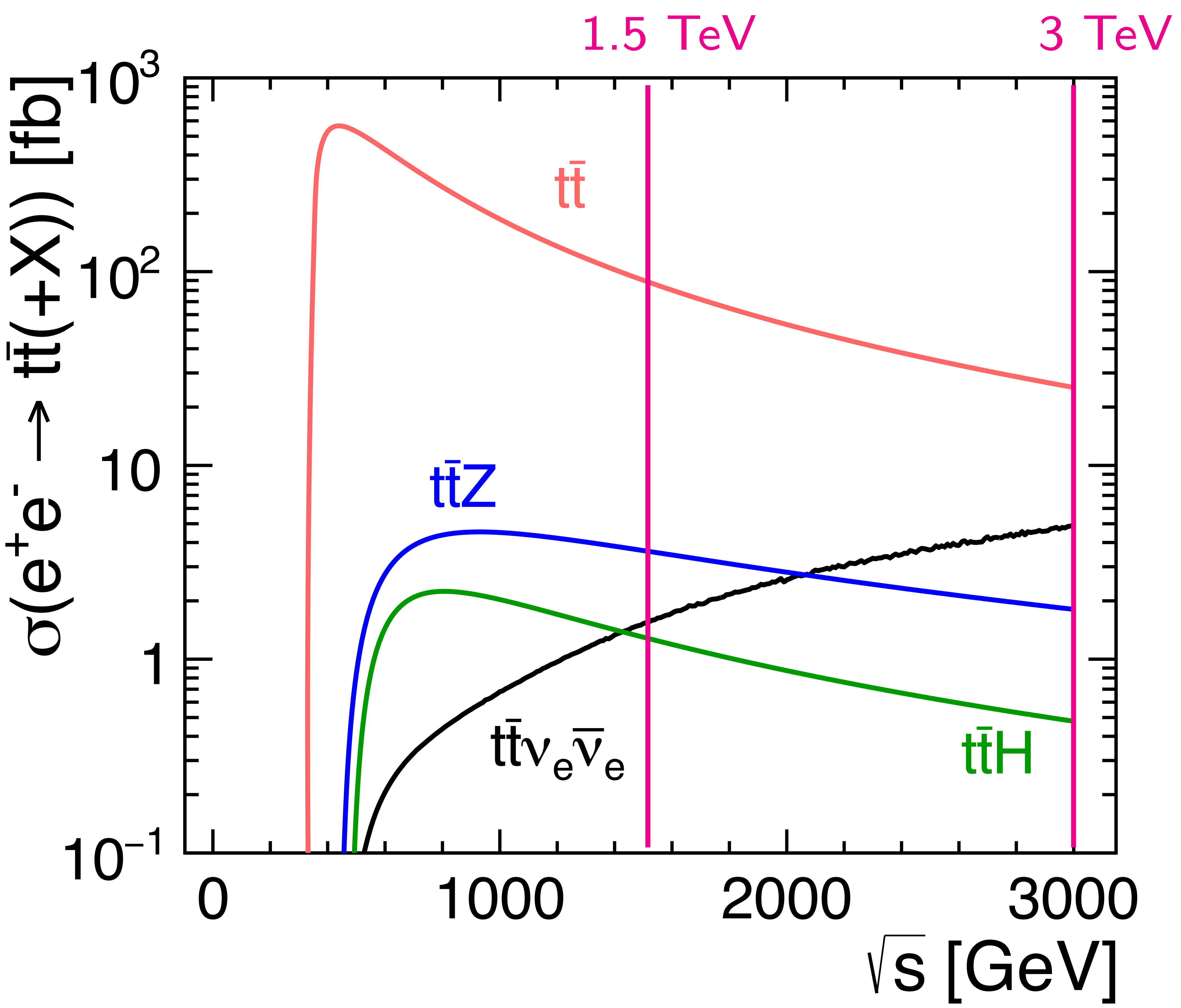
NEED MORE TOP PHYSICS!

- 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)





Future Colliders 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.



Top pair-production at and above the threshold (380 GeV)

- top-quark mass
- rare decays
- electroweak couplings

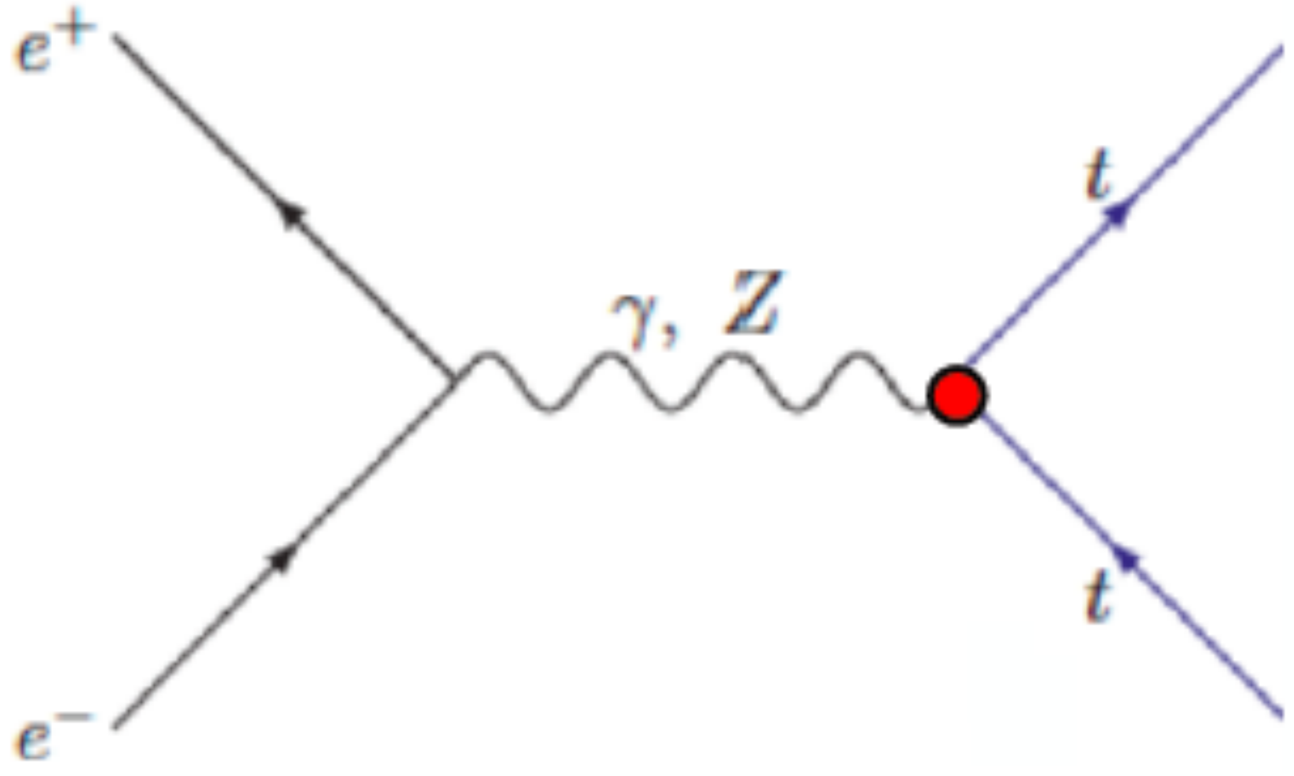
Additional processes open at high energies

- $t\bar{t}H \Rightarrow$ Yukawa coupling and CP properties
- $t\bar{t}\nu_e\bar{\nu}_e$ vector-boson fusion $\Rightarrow$ BSM constraints

Doubled at high energy: total of over 2.8 million (anti)top quarks

TOP PRODUCTION @FUTURE COLLIDERS

FCC-ee

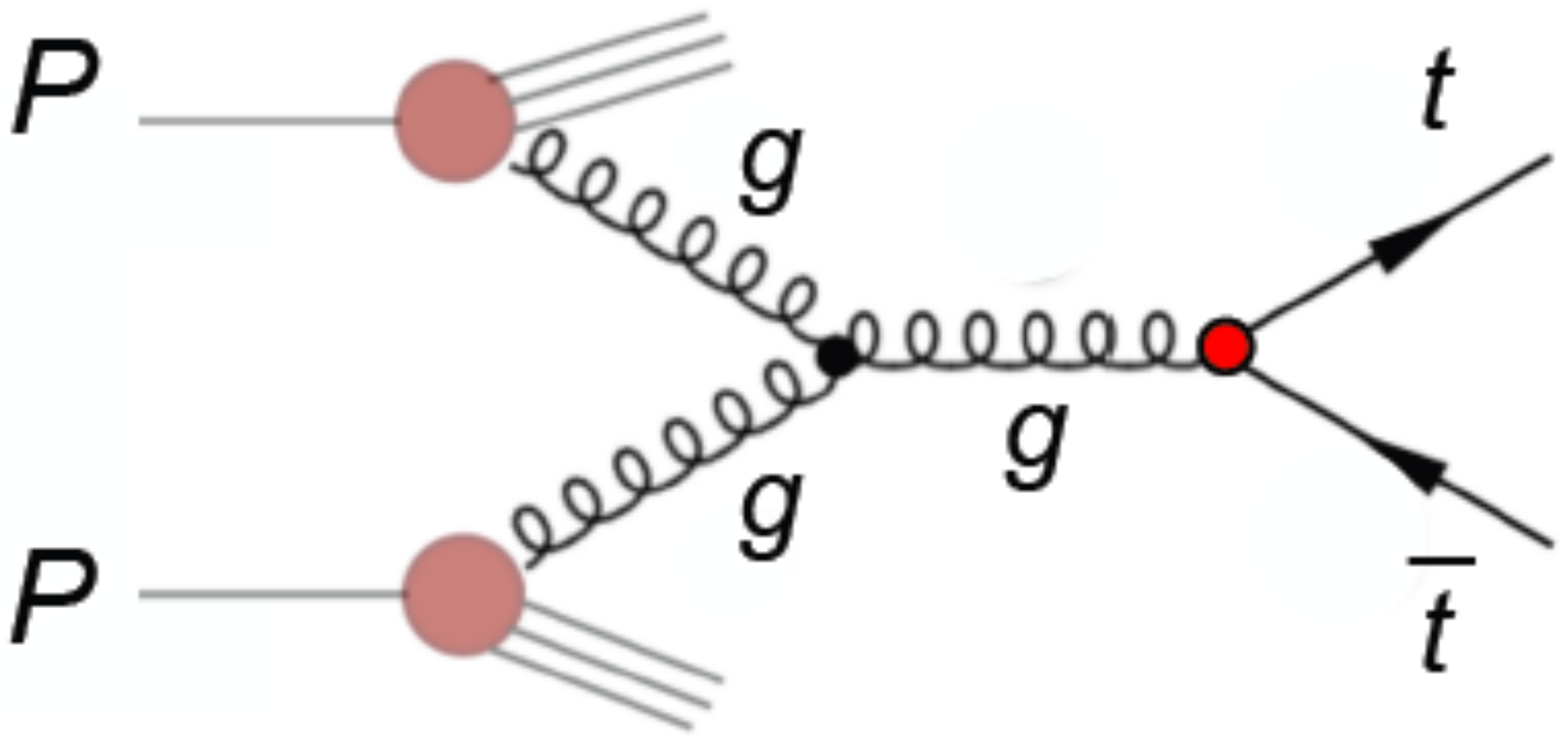


E_{com}=365 GeV

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

1M tt pairs

FCC-pp

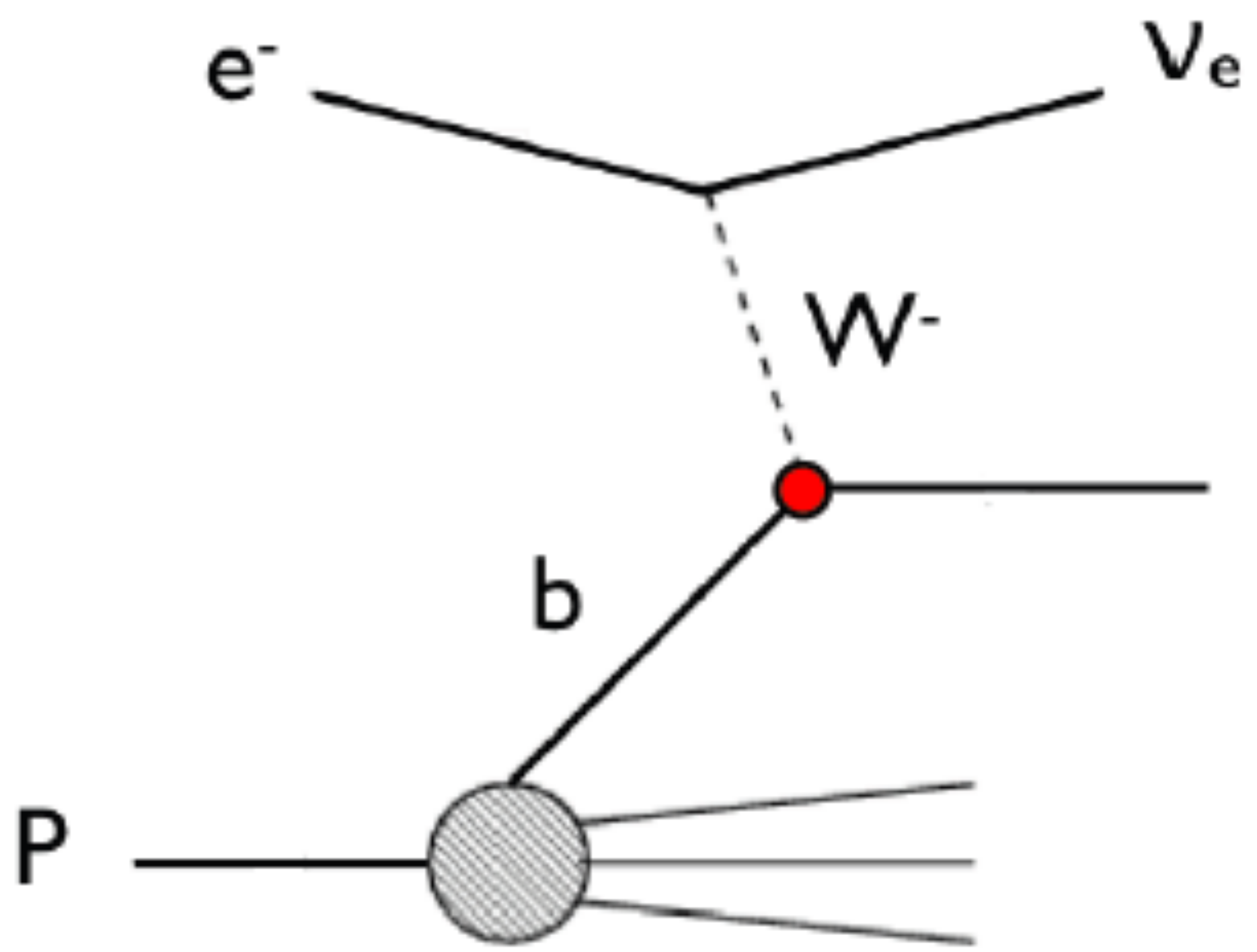


E_{com}=100 TeV

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

1T tt pairs

FCC-ep



E_{com}=3.5 TeV

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

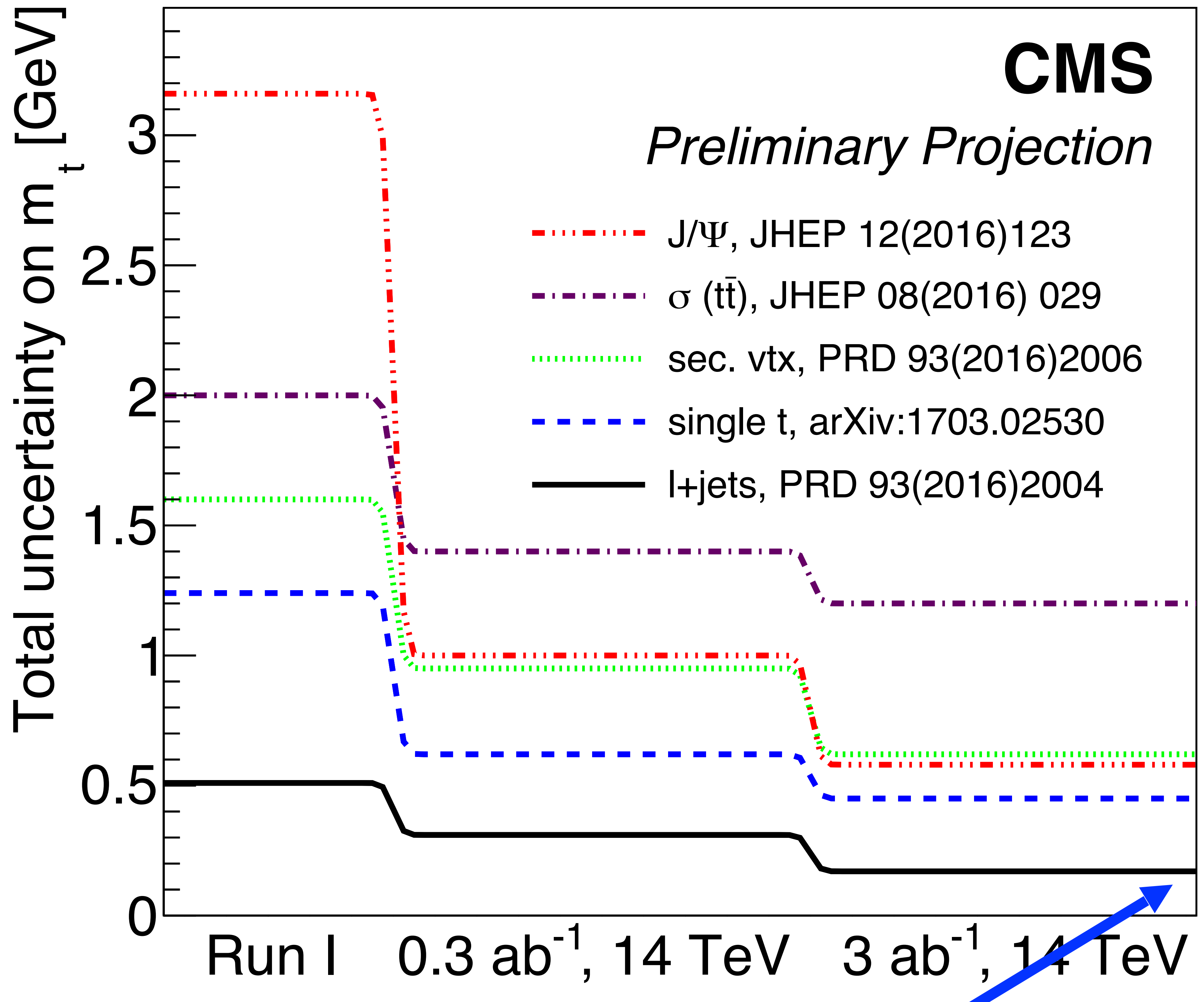
10M single top

STATUS OF TOP MASS MEASUREMENT

- Reconstructed mass: fit to the decay products
  - Most precise way (for now) at hadron colliders. Well defined experimentally, not so well theoretically.
  - New HL-LHC extrapolation ~0.17 in l+jets
  - at lepton collider could obtain precision of ~80MeV (CLIC study)
- other methods considered for HL-LHC could reach ~500MeV with different systematics.

Experiments catching up with predictions already!
New CMS top mass 171.77 ± 0.38 GeV

Projections for HL-LHC



l+jets Δm/m~0.17

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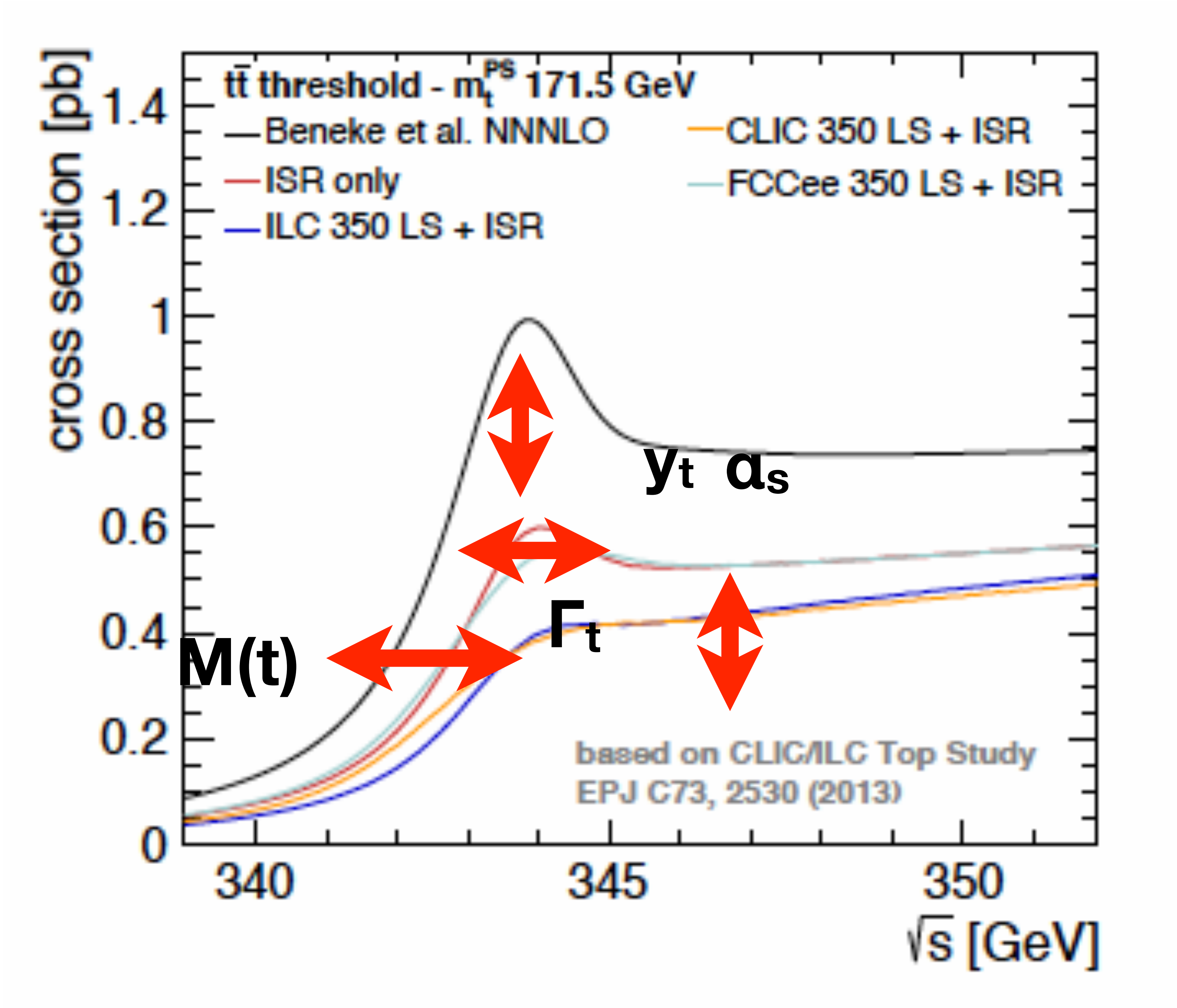
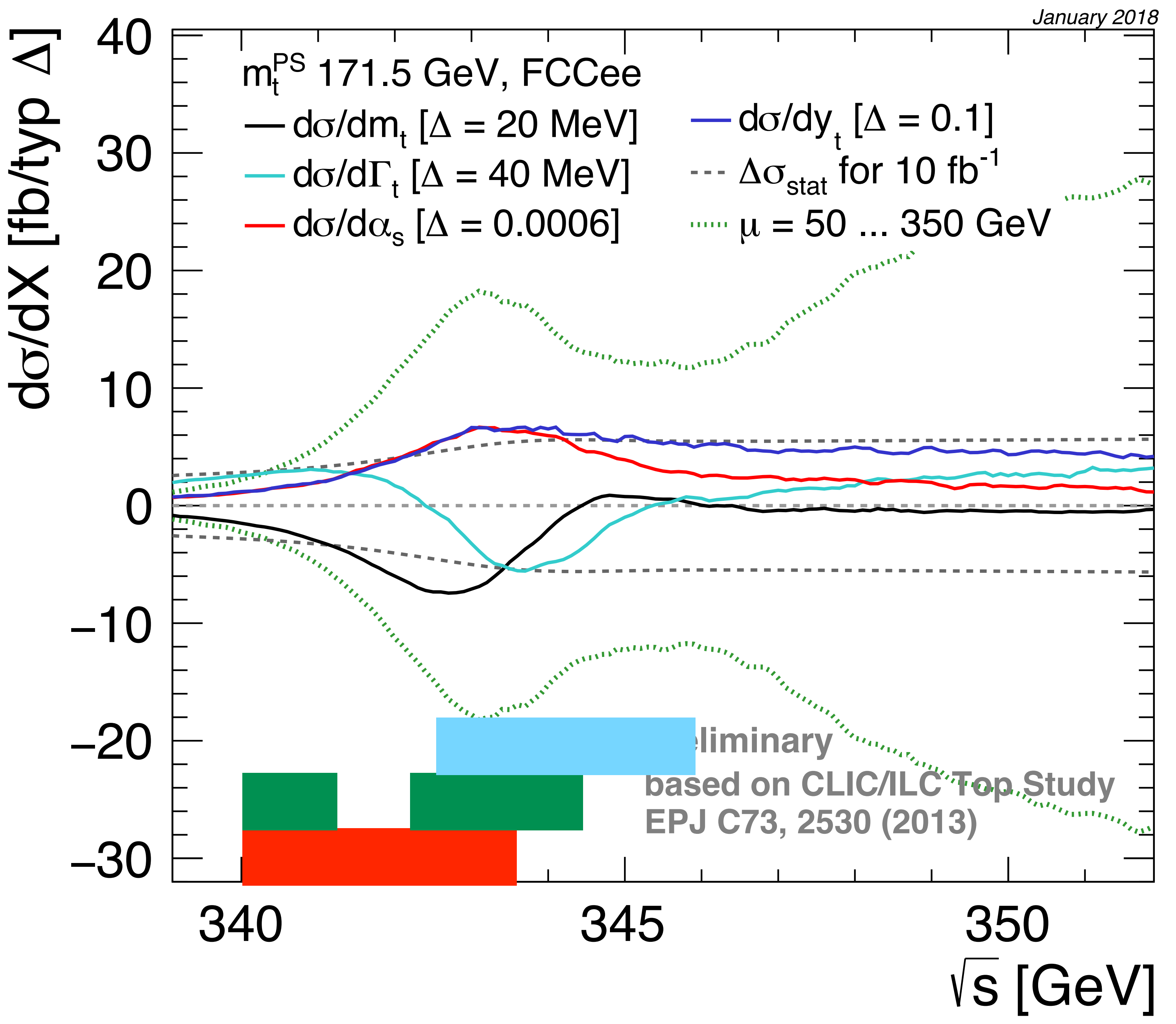
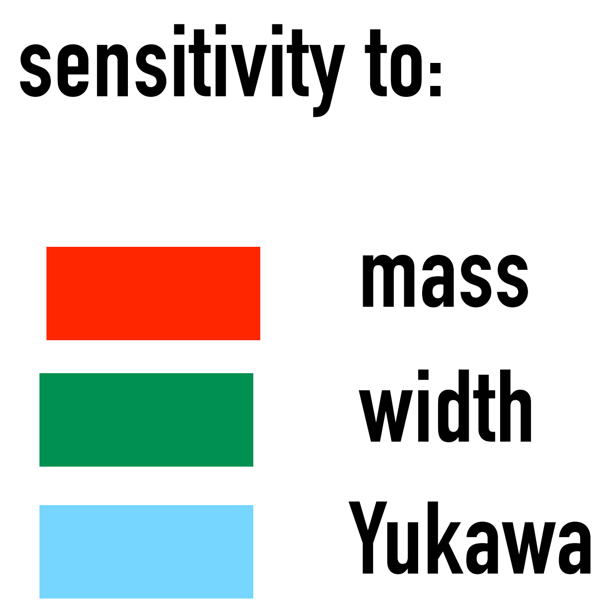
THE THRESHOLD SCAN REGION





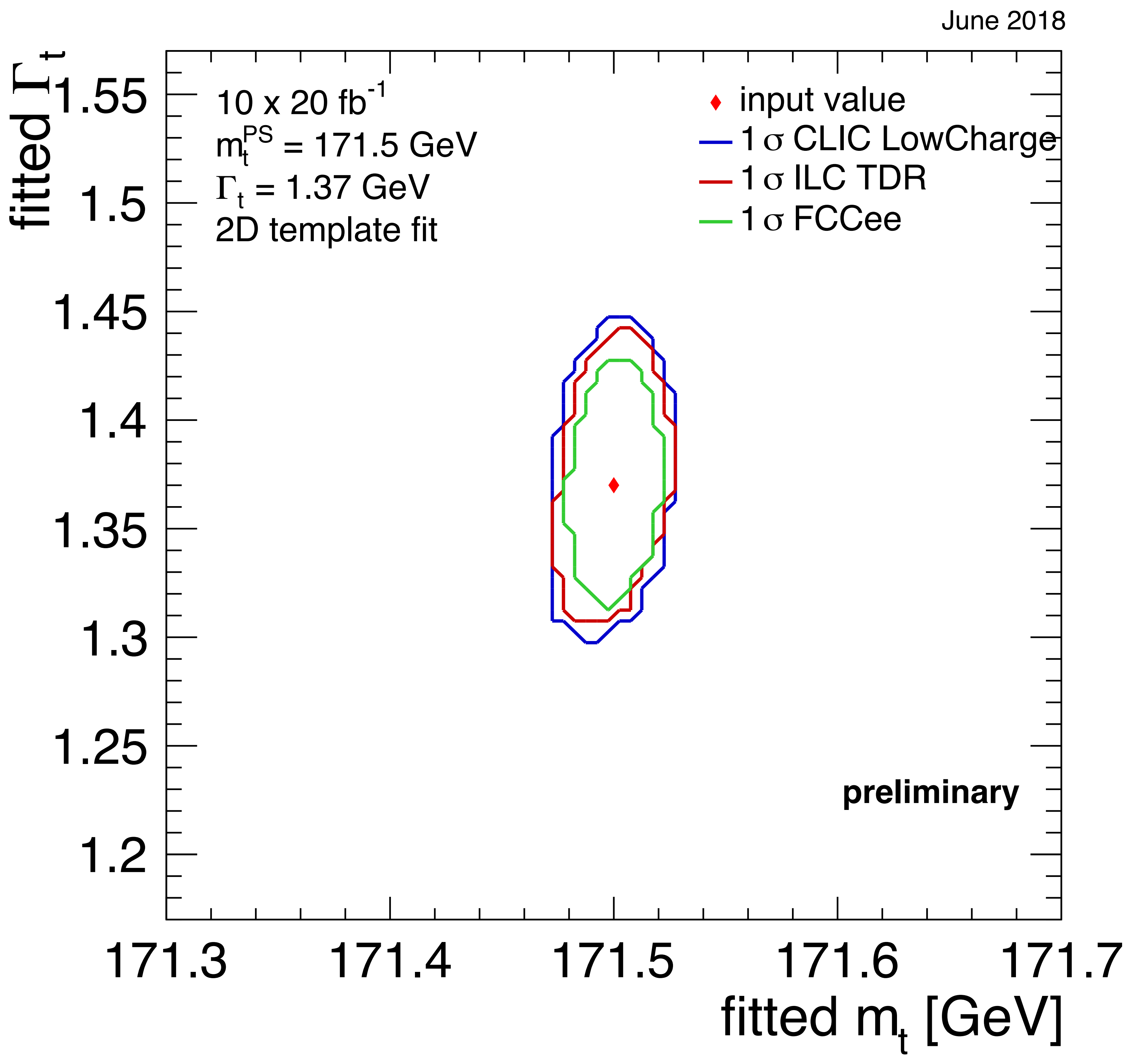


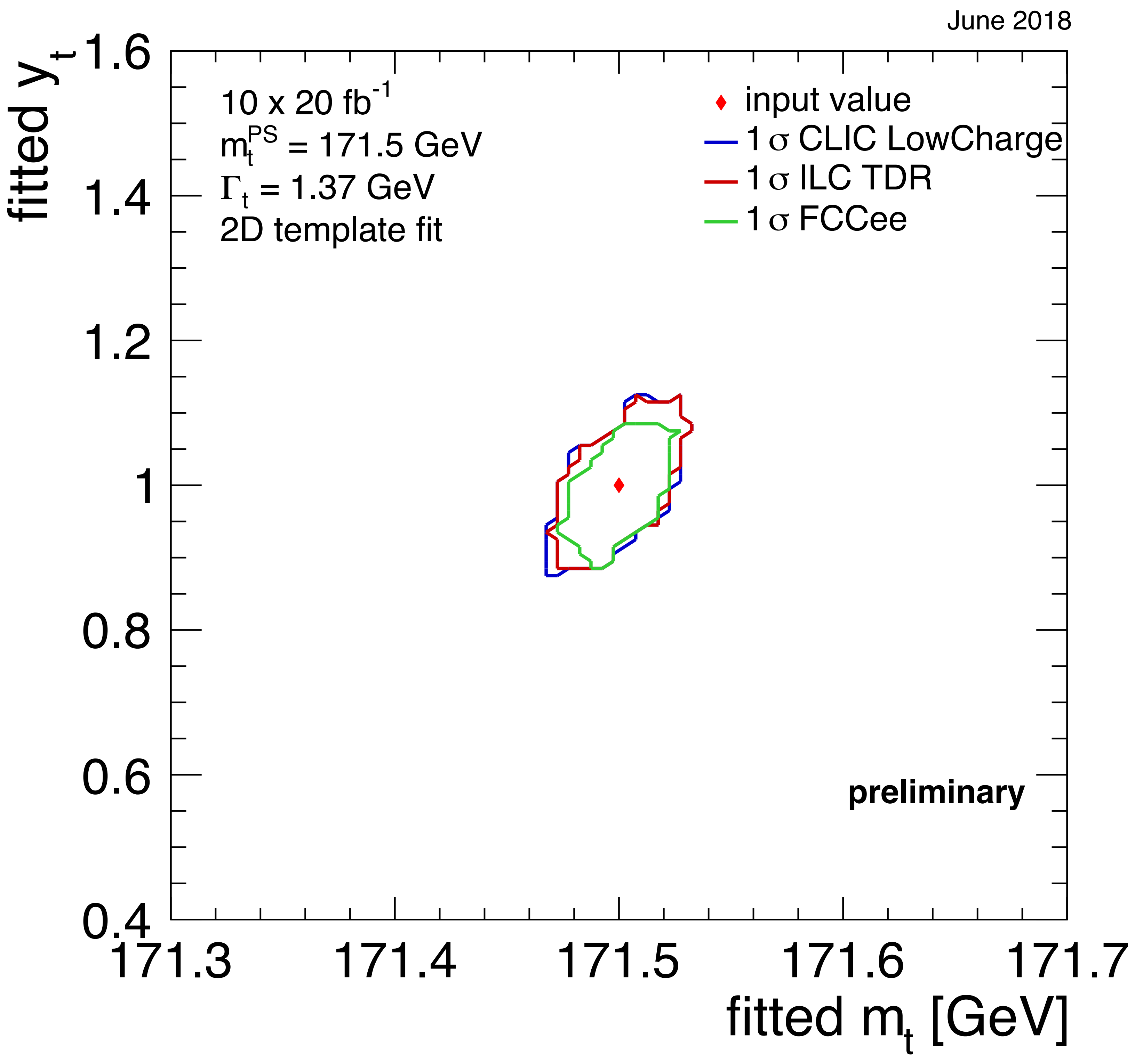
- Cross section shape depends strongly on top quark mass, width, α_s and Y_t
  - Top mass can then be extracted directly with a threshold scan
- The threshold shape is affected by ISR and machine beam energy spread
  - The FCC-ee has very steep luminosity profile, enhancing size of top sample
    - corresponds to about a 20% improvement in statistics compared to ILC

2D FIT OVERALL COMPARISON

- Assuming an integrated luminosity of 200 fb^{-1} (default for ILC, FCCee, x2 of CLIC standard scenario)
- Standard fit of mass only: ILC 12.2 MeV [stat] CLIC 13.3 MeV [stat] FCCee 10.4 MeV [stat]

- 2D fits of mass & width, mass & Yukawa





- FCCee with the assumption of a perfectly gaussian spectrum gives best performance
- Small energy spread of main lumi peak of ILC an advantage
- CLIC LowCharge in the same general ballpark as ILC

GLOBAL VIEW OF UNCERTAINTIES ON TOP MASS

A multi-parameter fit can extract the PS mass with excellent precision

Statistical uncertainty:	~20 MeV	*100 fb^{-1}*
Scale uncertainty:	~40 MeV	*N^3LO QCD, arXiv:1506.06864*
Parametric uncertainty:	~30 MeV	*α_s world average, arXiv:1604.08122*
Experimental systematics:	25-50 MeV	*including LS, arXiv:1309.0372*

Exp. Syst for CC: beam energy and spread give: Δm/m~3MeV

This threshold mass can be converted to the $\overline{\text{MS}}$ scheme with ~10 MeV precision

Marquard et al., PRL114, arXiv:1502.01030

A very competitive top quark mass measurement: Nearly machine independent

$\Delta m_t \sim 50$ MeV (= 3 x 10^{-4}, cf. Δ**m**$_b$ **~1%**)

Important: if α_s precision improves with the Z pole and WW threshold runs:
$\Delta\alpha_s < 0.0002$ then Δm/m ~5MeV
Improved α_s drastically improves correlations m_t, Γ_t and Y_t

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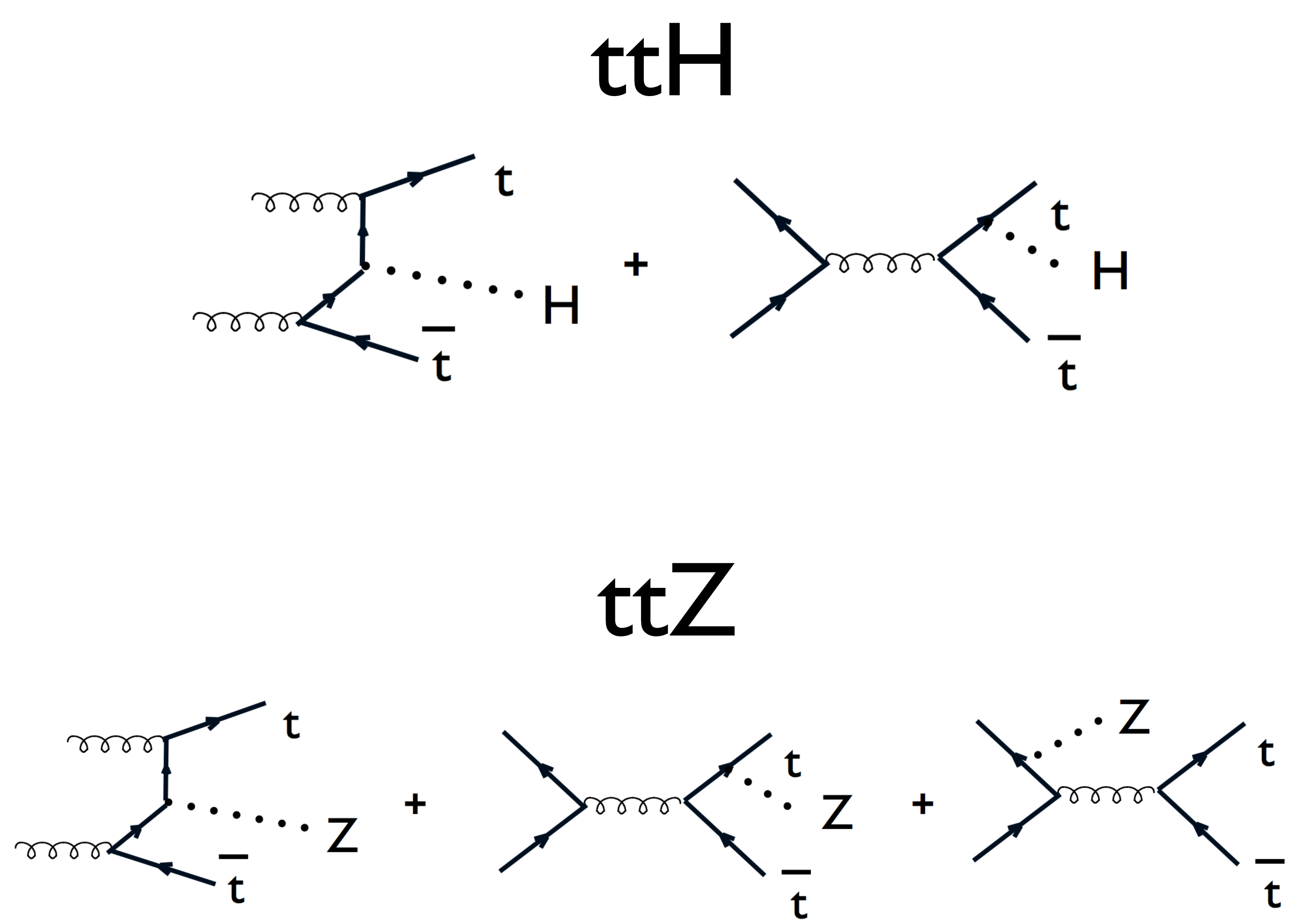
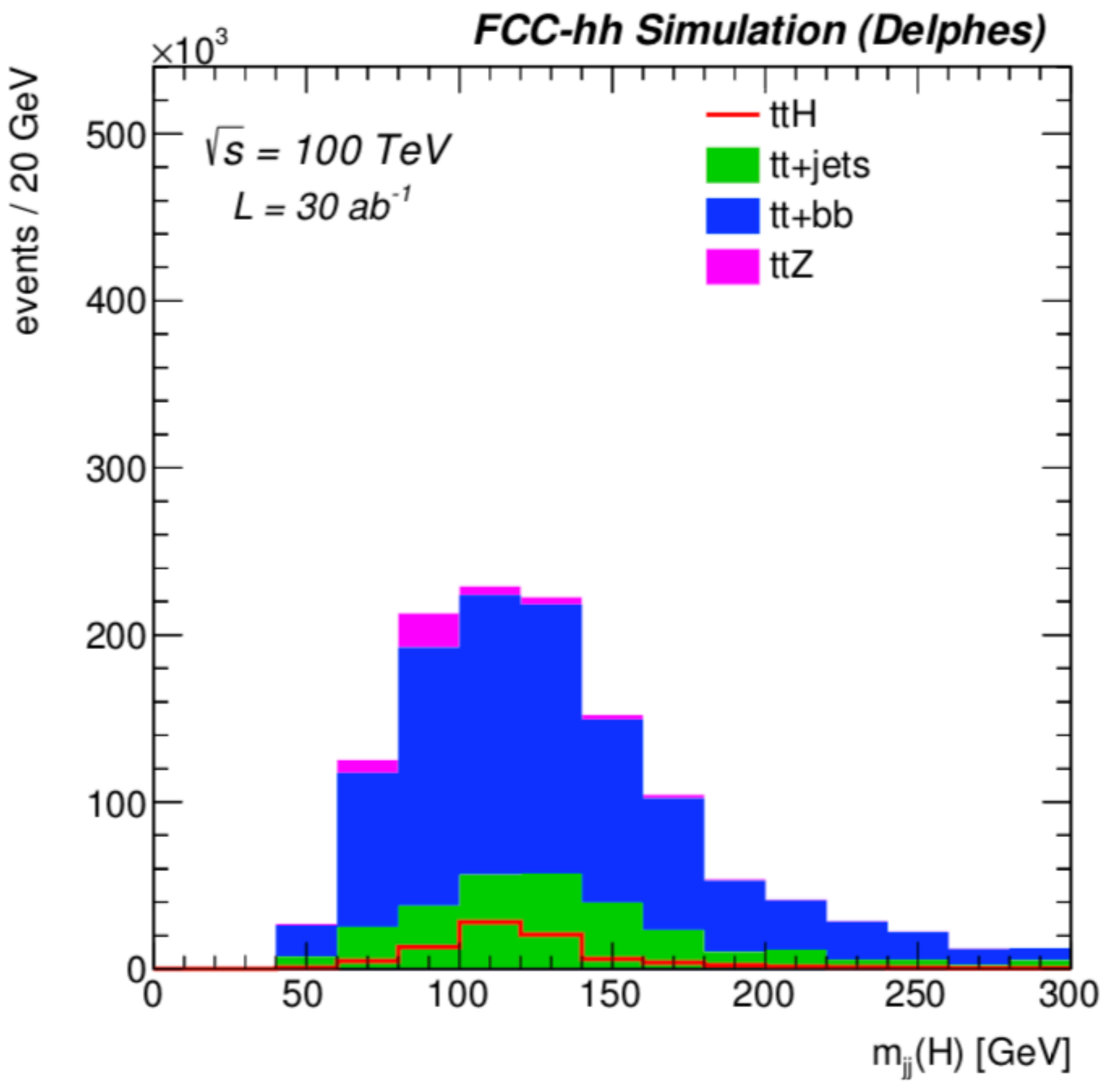
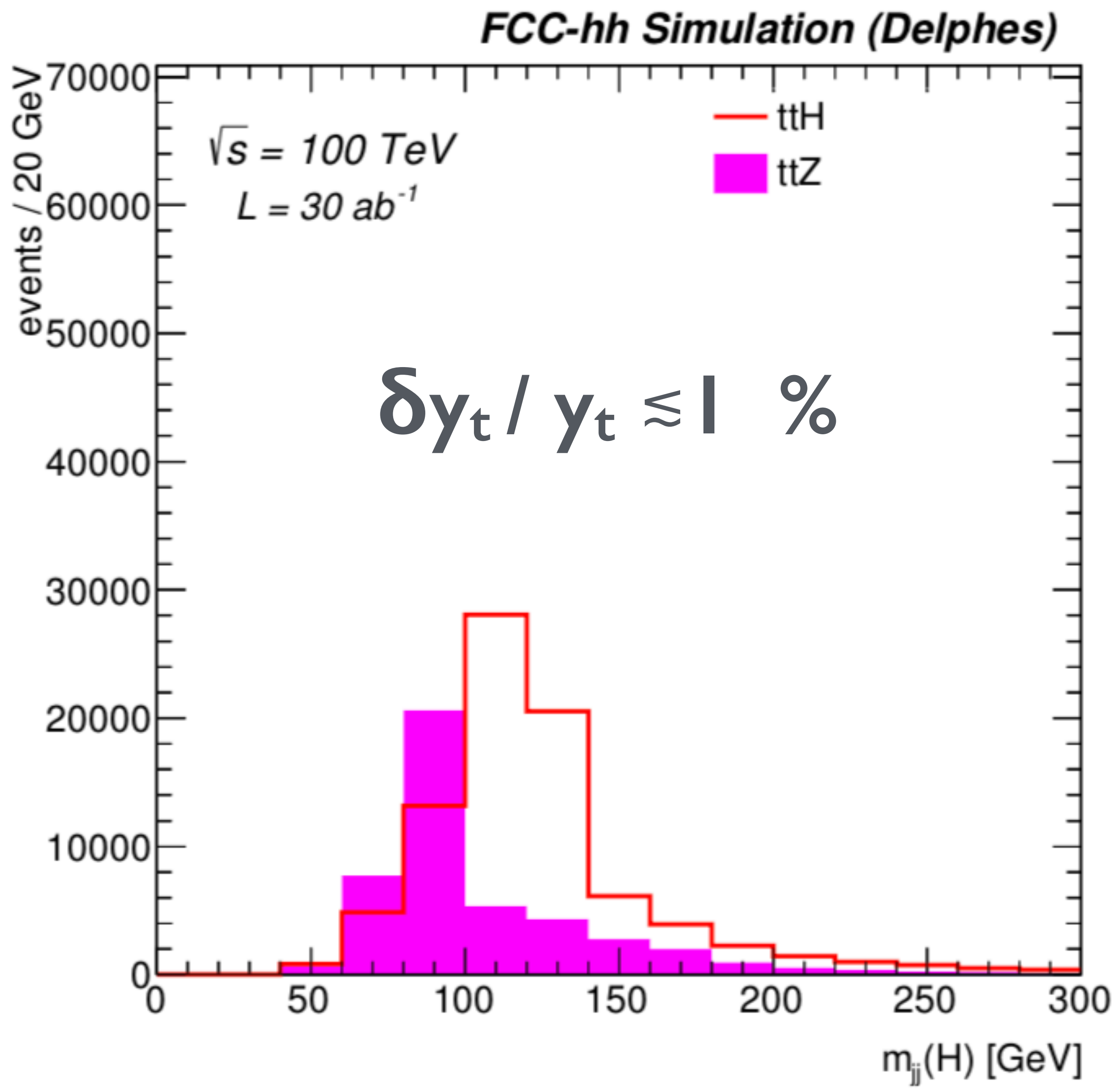
COMPLEMENTARITY: TOP YUKAWA COUPLING AT FCC-hh

- Measure the production ratio $\sigma(t\bar{t}H)/\sigma(t\bar{t}Z)$ in the boosted regime for $H \to b\bar{b}$ and in the semi-leptonic top channel. Lumi, PDF, efficiency uncertainties cancel in the ratio
- Perform simultaneous fit of Z and H peak
- **Using g_{ttZ} and k_b measured at 1% by FCC-ee.**
- **Top Yukawa can be measured at 1% and model independent at the FCC-hh**





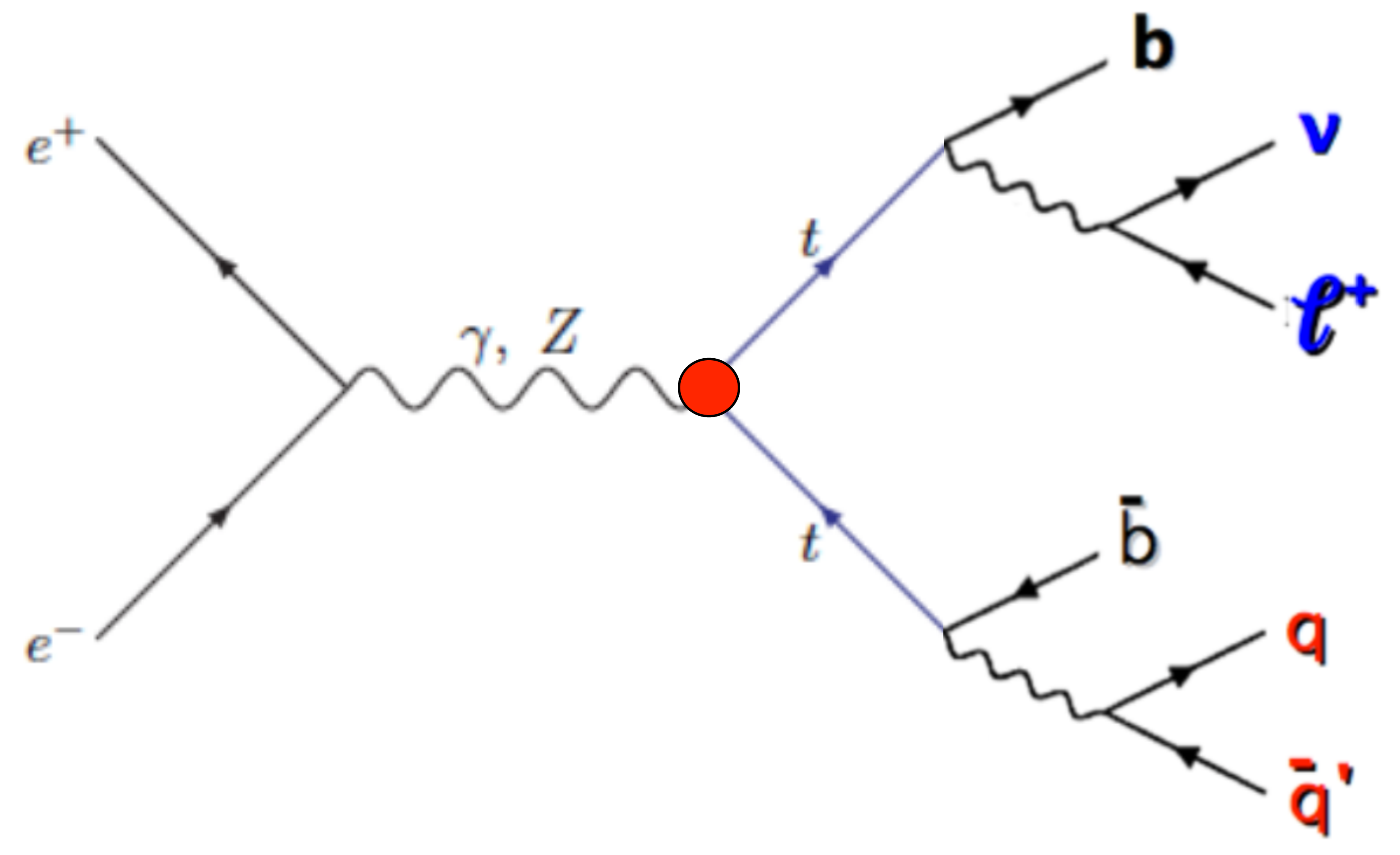


- **Run at 365 GeV used also for measurements of top EWK couplings (at the level of 10^{-2}-10^{-3}) and FCNC in the top sector.**

ELECTROWEAK COUPLING OF THE TOP QUARK @CC

arXiv: 1503.01325

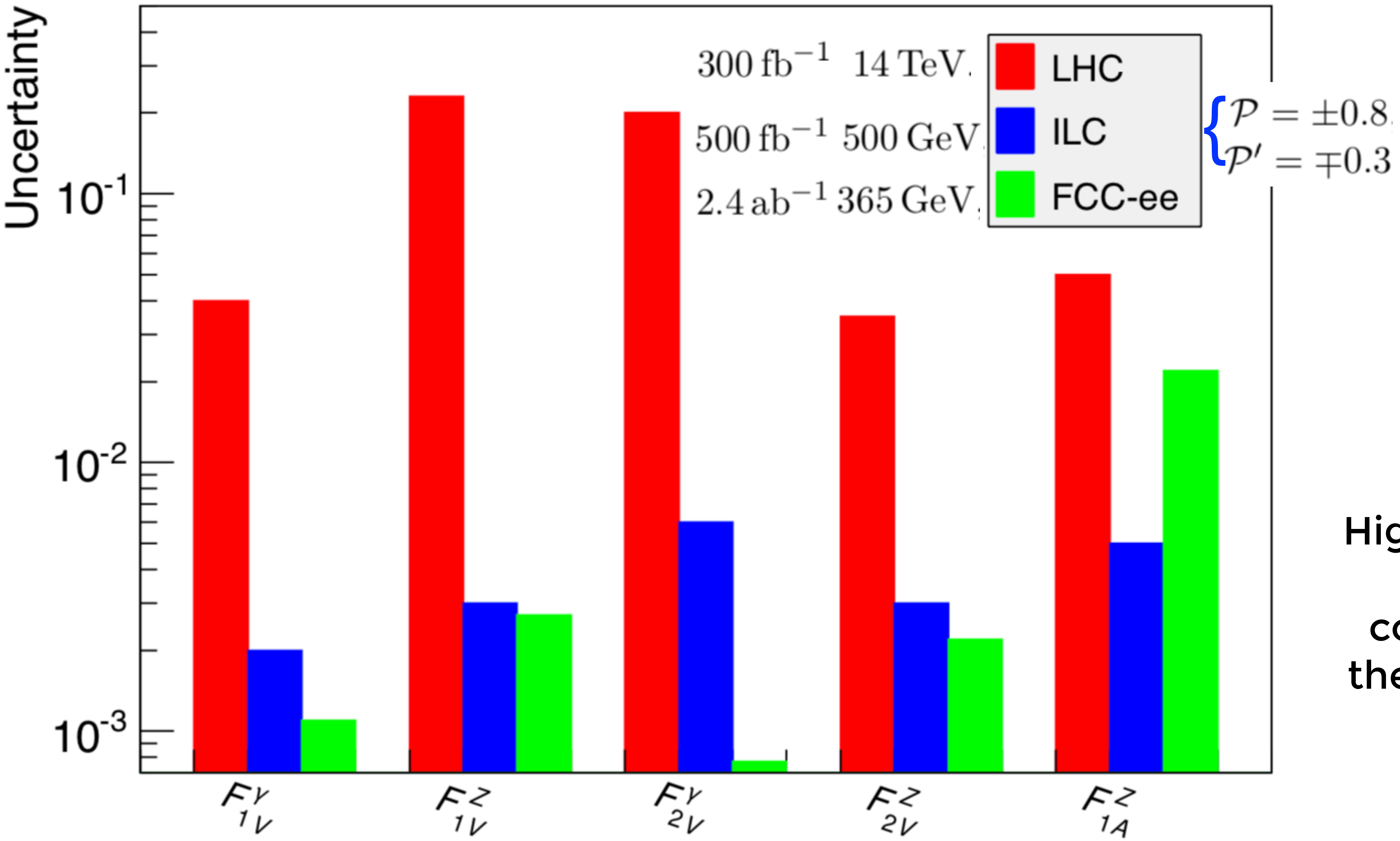
- Final state top quarks are produced with non-zero polarization (ttZ)
  - the top polarization and the total rate depend on the ttZ/γ couplings
  - the top polarization is maximally tranferred to its decay products $t \to Wb$
  - This affects the energy and angular distribution of these decay products
- ttZ, ttγ couplings can be enhanced in extra dimensions and (particularly) composite Higgs models



Study of the lepton energy and angular distribution as a function of √s in semi-leptonic events

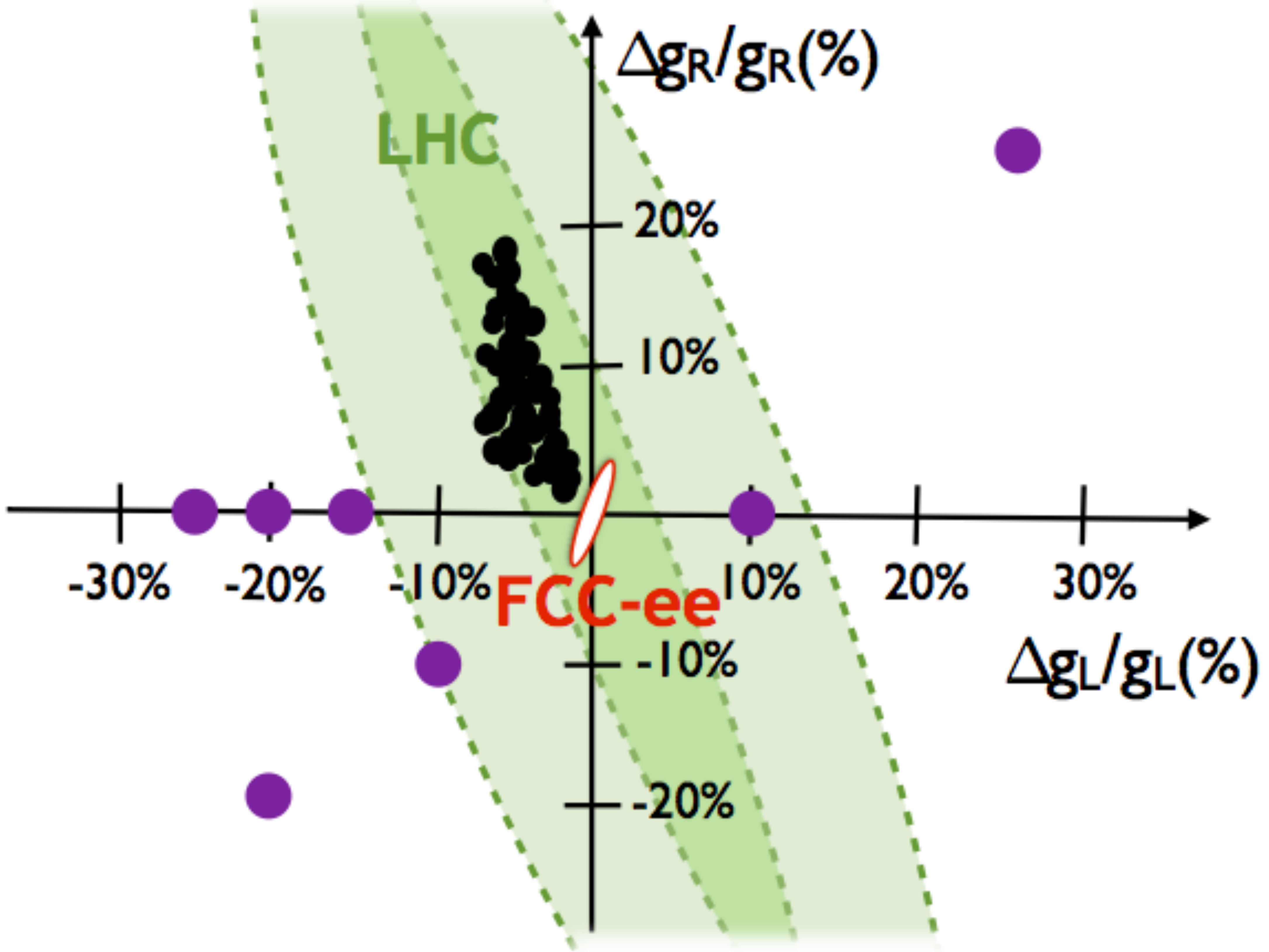
$t\bar{t} \to \ell\nu b\bar{b}q\bar{q}$

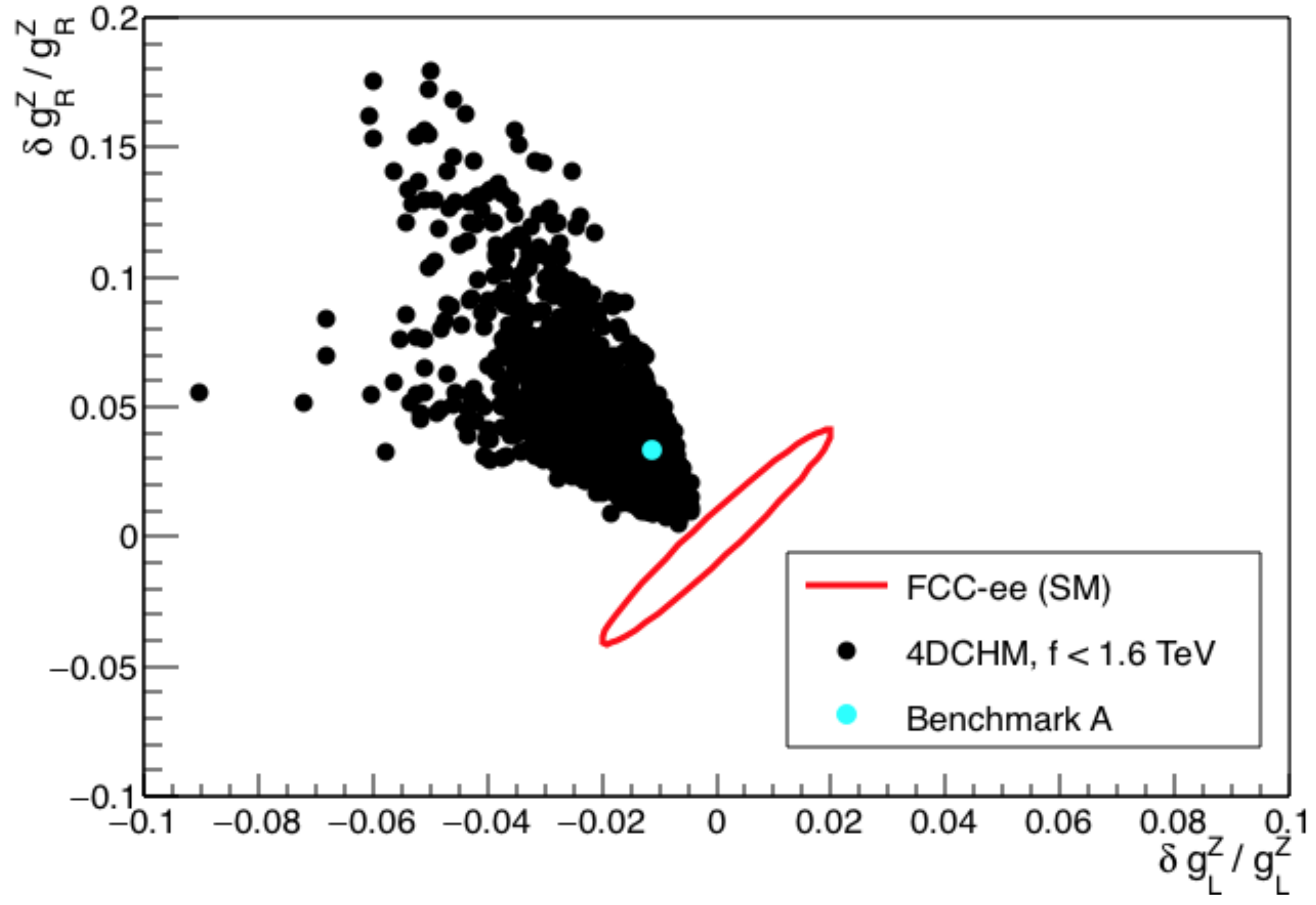
TOP EWK COUPLINGS - COMPARISON AMONG LEPTON COLLIDERS

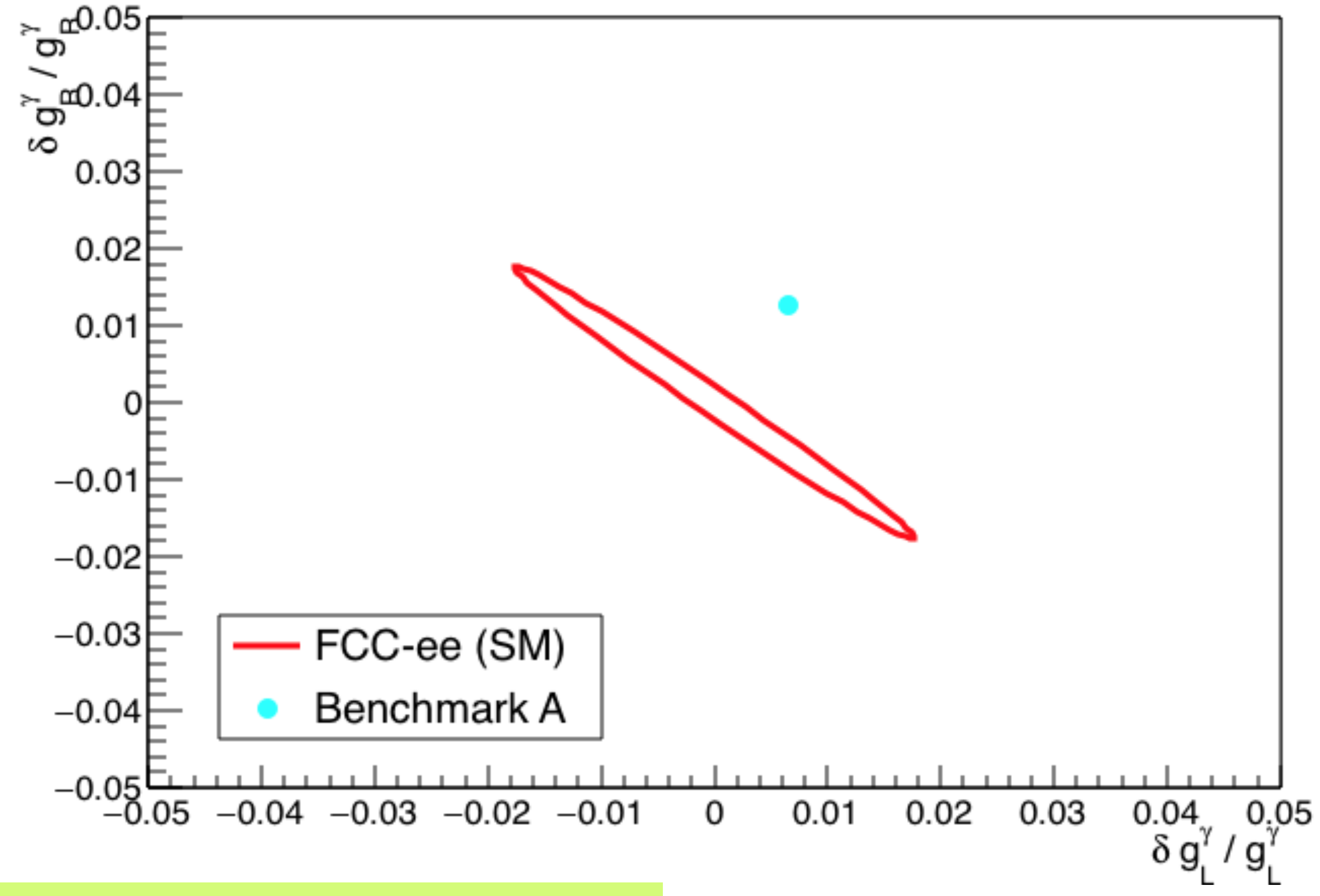


Higher statistics at CC compensates the polarisation of a LC

NEW PHYSICS SENSITIVITY: COMPARISON WITH BSM MODELS



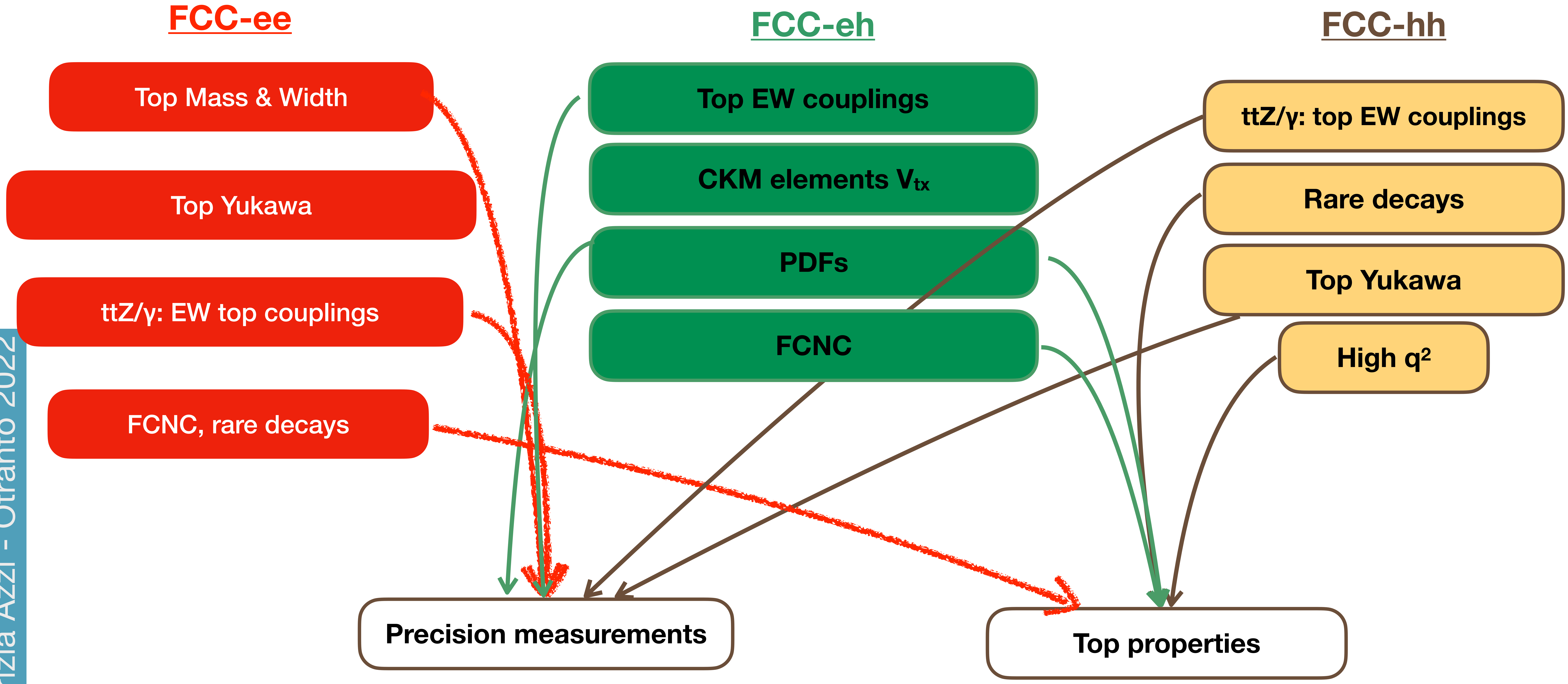




FCC-ee expected precision of order 10^{-2} to 10^{-3}

With FCC-ee precision sensitivity up to 4TeV Z' mass on a specific model

SYNERGIES & COMPLEMENTARITIES AMONG COLLIDERS FOR TOP PHYSICS



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PHYSICS AT e+e- COLLIDERS

$\sqrt{s}$	Processes	Physics Goals	Observables
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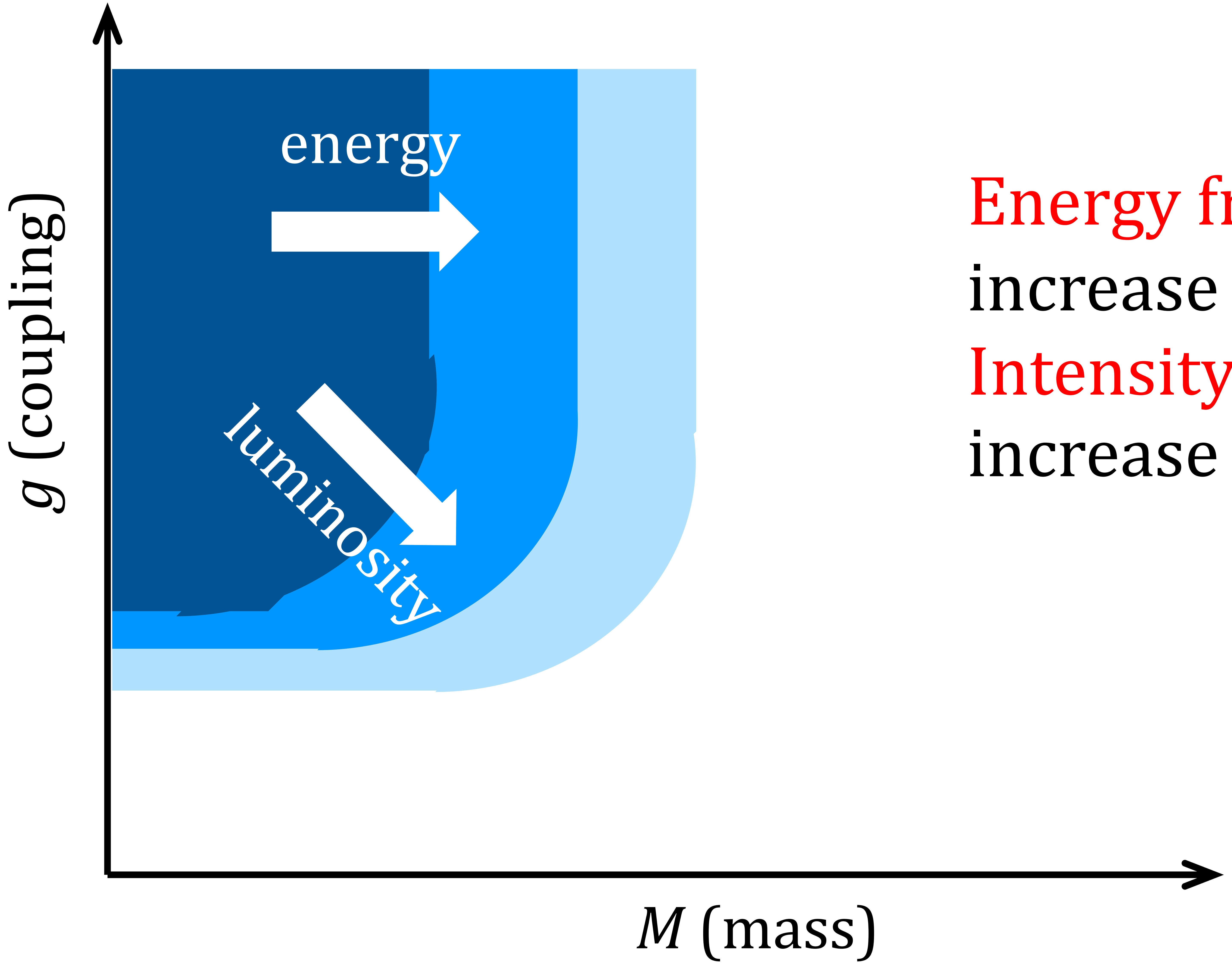
160 GeV	• $e^+e^- \to W^+W^-$	ultra-precision W mass	M_W, Γ_W
>160 GeV	• $e^+e^- \to W^+W^-$ • $e^+e^- \to q\bar{q}, \ell\ell\ (\gamma)$	precision W mass and couplings precision EW (incl. Z return)	M_W, aTGC N_ν
250 GeV	• $e^+e^- \to ZH$	ultra-precision Higgs mass precision Higgs couplings	M_H κ_V, κ_f, Γ_H
360 GeV	• $e^+e^- \to t\bar{t}$	ultra-precision top mass	M_{top}
>360 GeV	• $e^+e^- \to t\bar{t}$ • $e^+e^- \to ZH$ • $e^+e^- \to H\nu\nu$	precision top couplings precision Higgs couplings	
500+ GeV	• $e^+e^- \to t\bar{t}H$ • $e^+e^- \to ZHH$ • $e^+e^- \to Z' \to f\bar{f}$ • $e^+e^- \to \chi\chi$ • $e^+e^- \to AH, H^+H^-$	Higgs coupling to top Higgs self-coupling search for heavy Z' bosons search for supersymmetry (SUSY) search for new Higgs bosons	y_{top} λ_{HHH}

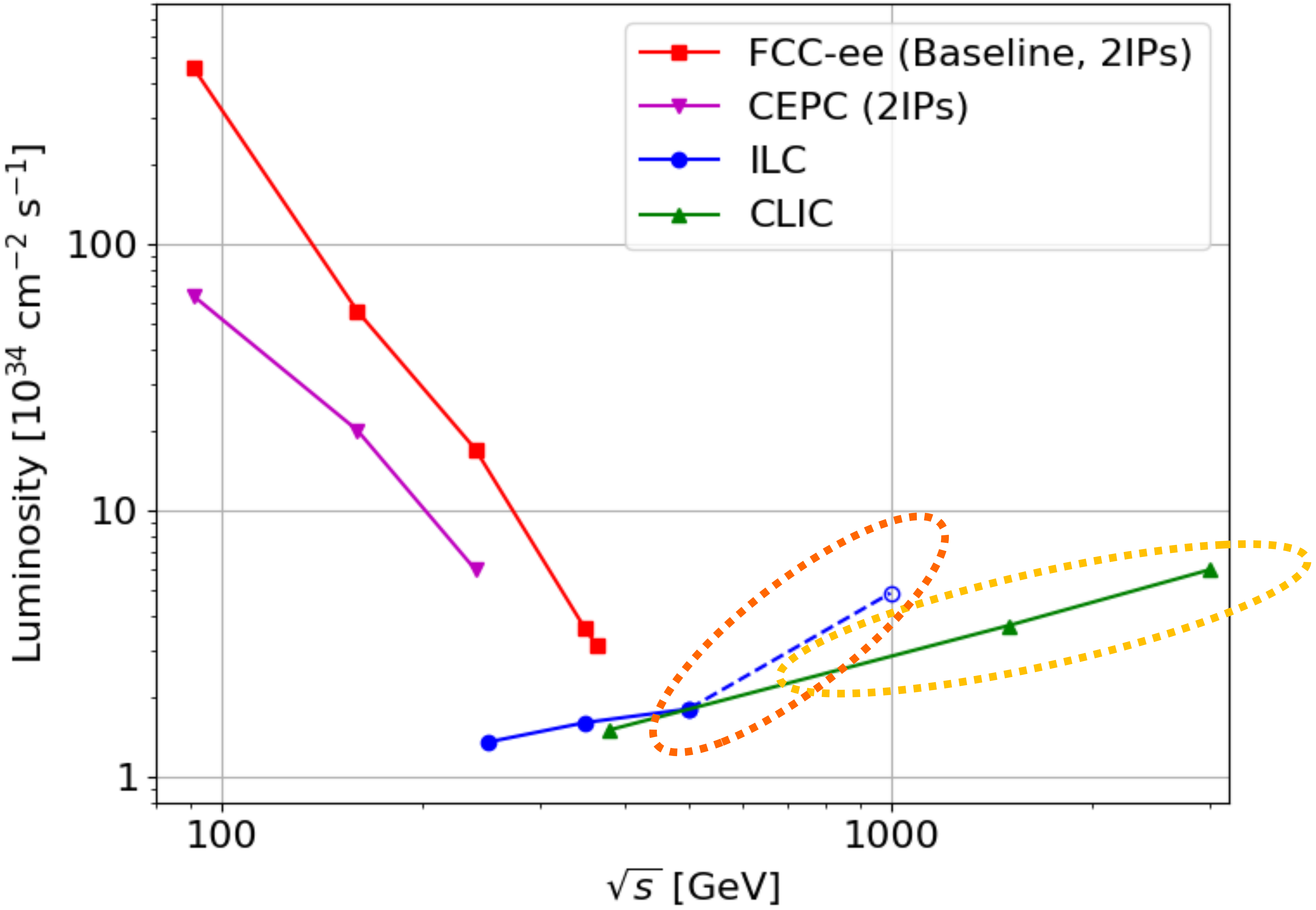
Special program

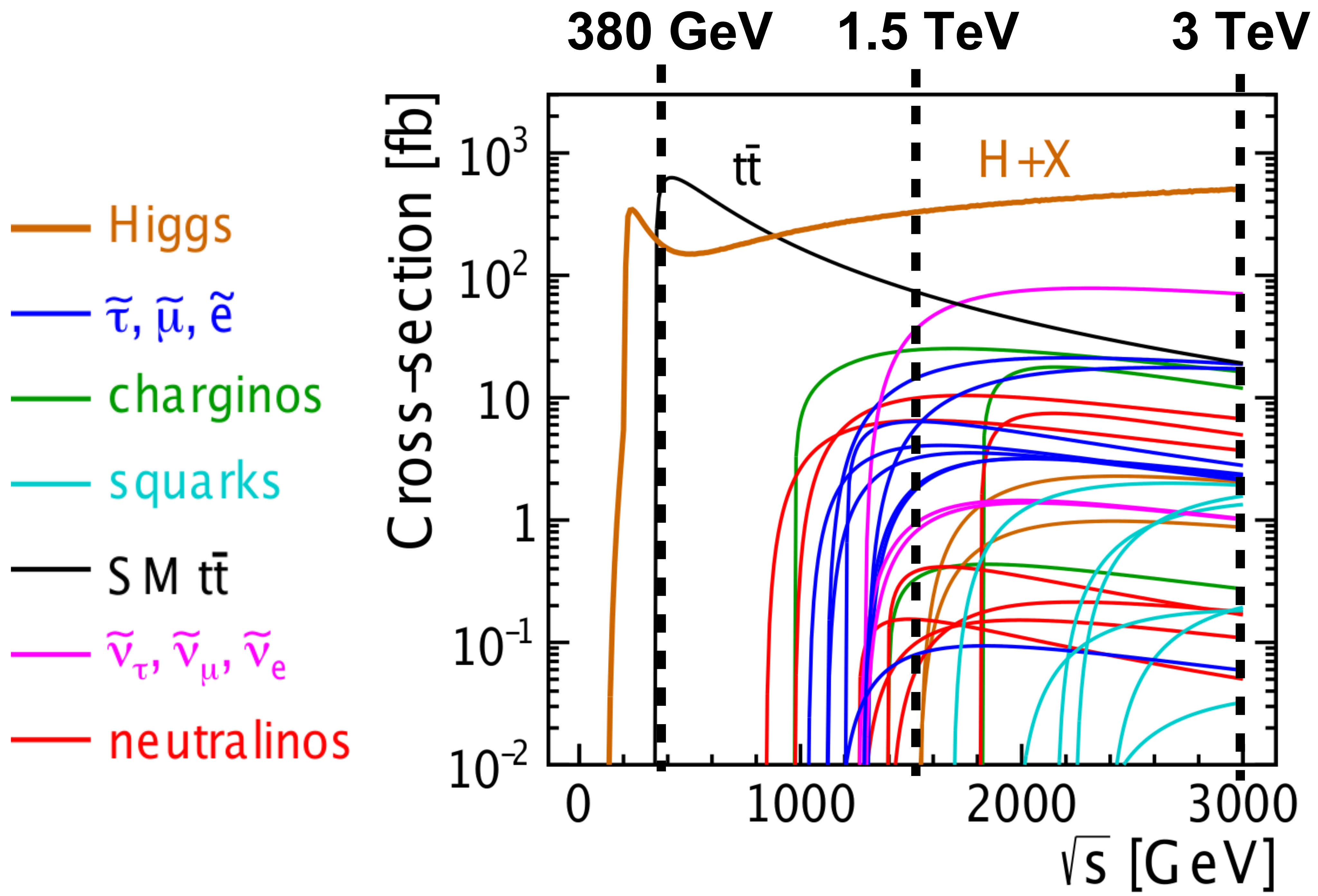
And MuColl



Energy frontier:
increase $\sqrt{s}$ to explore larger M
Intensity frontier:
increase $\mathcal{L}$ to explore smaller g

PHYSICS AT HIGH ENERGY e^+e^- - LINEAR COLLIDERS



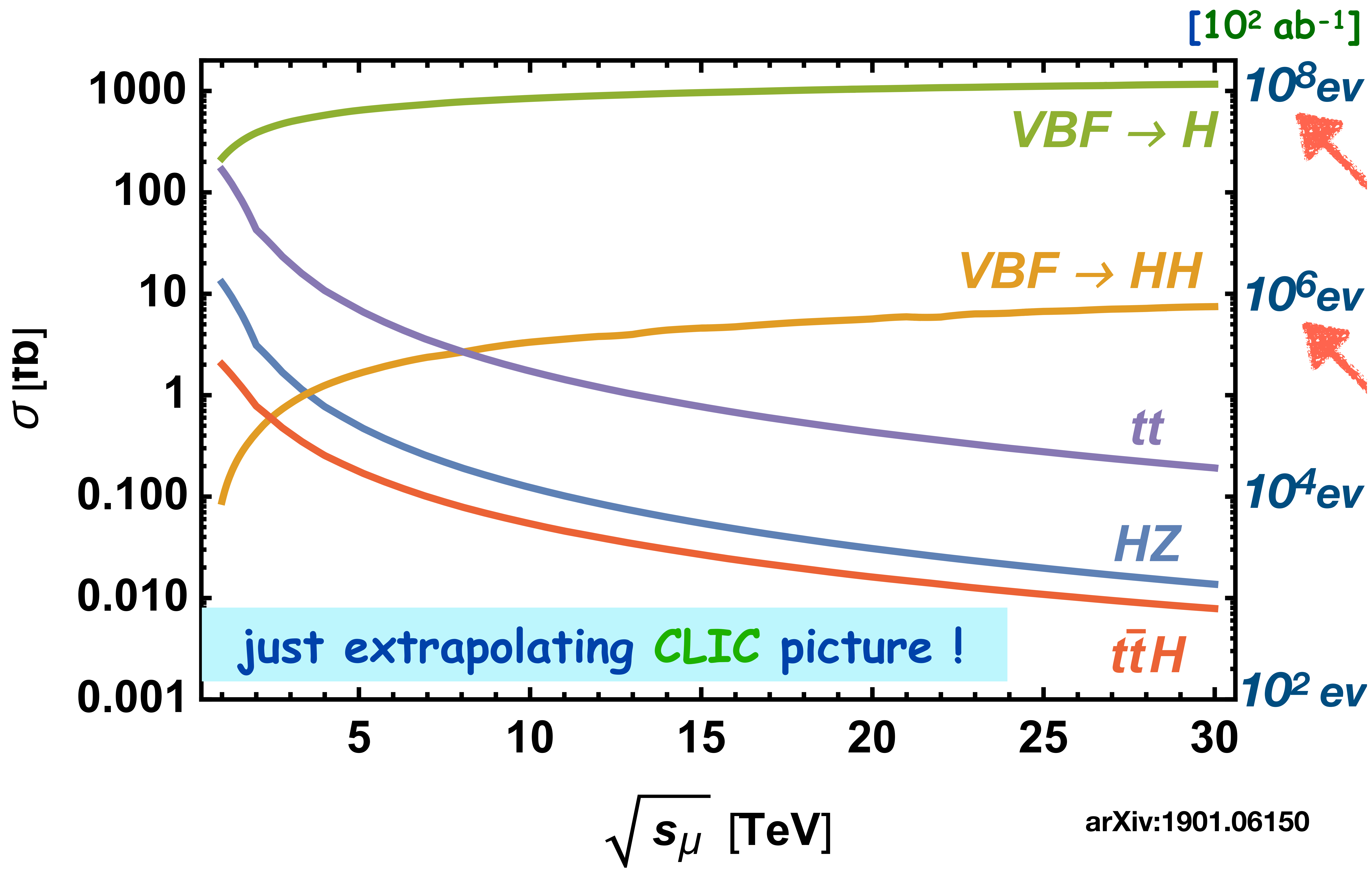


PRODUCTION CROSS SECTIONS FOR SUSY PARTICLES

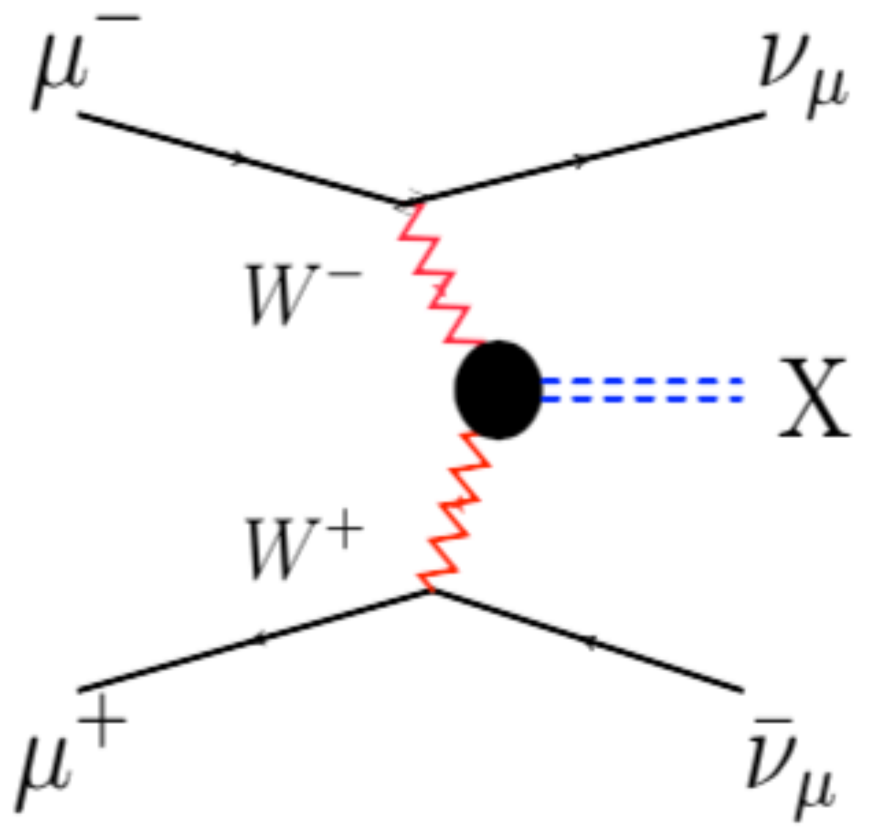
In general, **O(1%)** precision on masses and production cross sections found

CERN-2012-003 CERN-2012-007

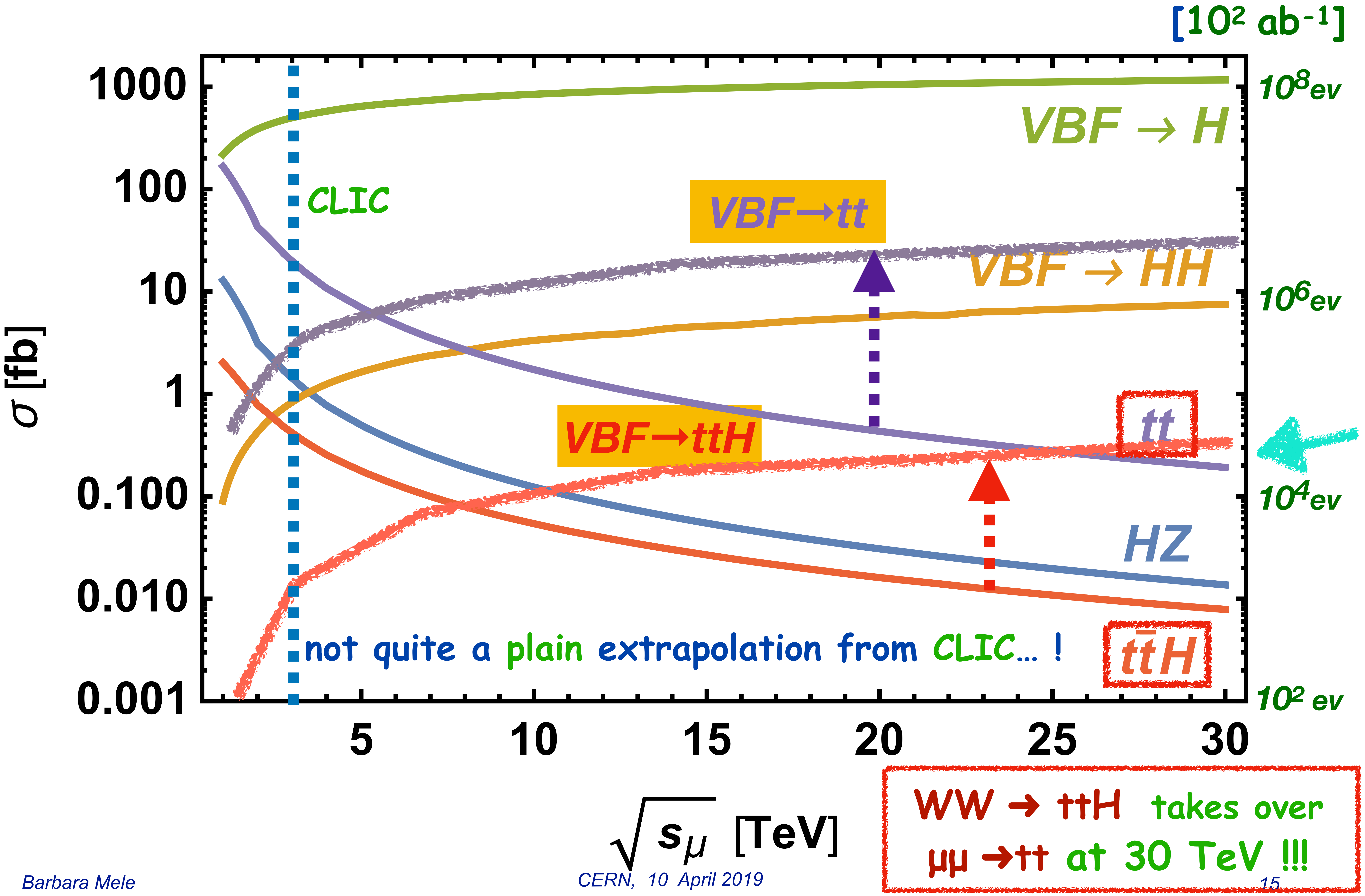
VBF DOMINATES AT LARGE √S ENERGIES 10-30 TEV



arXiv:1901.06150



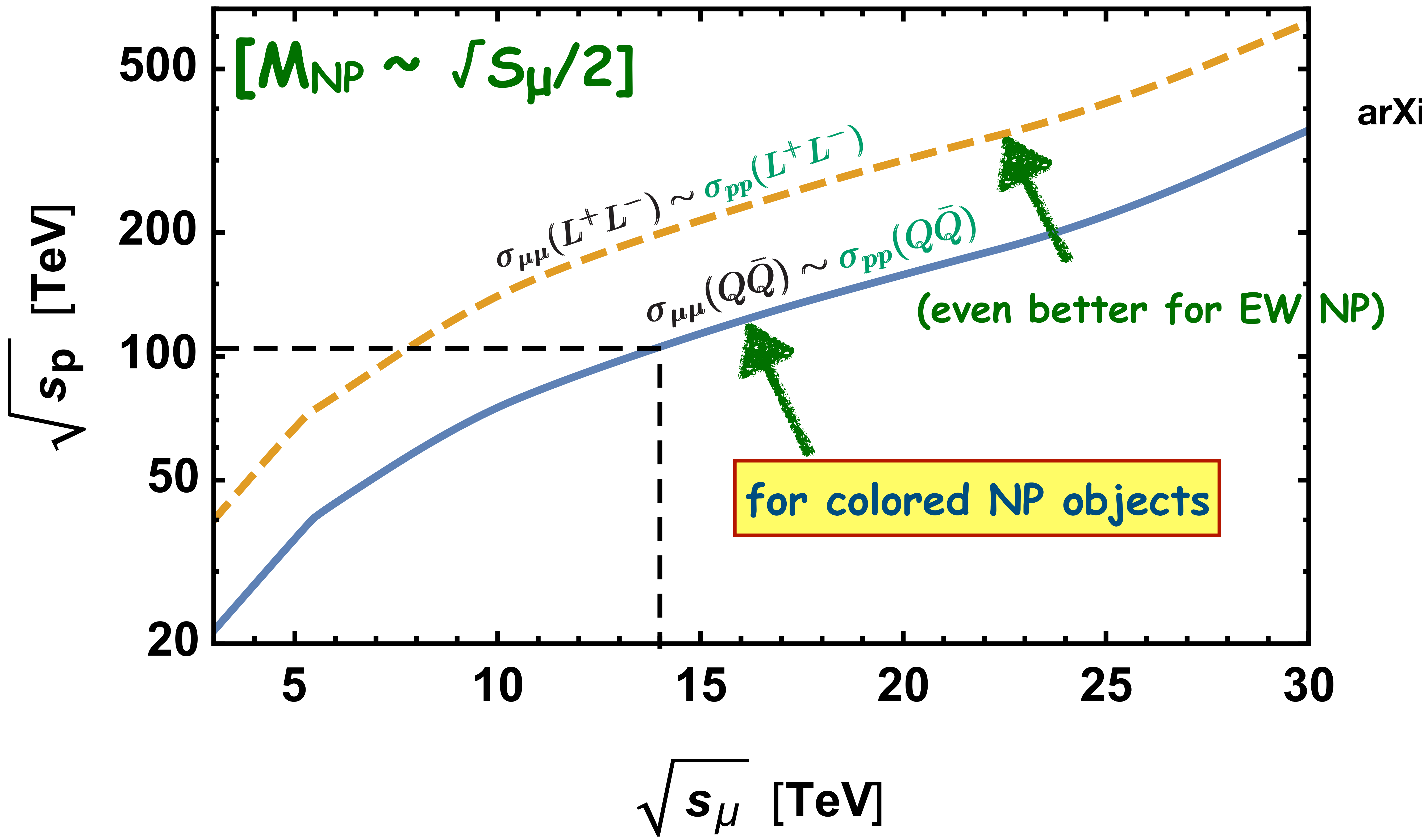
$\ell\ell \to t\bar{t}(H)$ vs. $WW \to t\bar{t}(H)$



WW → ttH takes over
μμ → tt at 30 TeV !!!

BSM COMPARISON OF COLLIDERS REACH: MUCOLL VS hh

- Compare the reach for the production of new heavy particles.
- Hadron colliders pay the price of the exponentially falling PDFs



arXiv:1901.06150

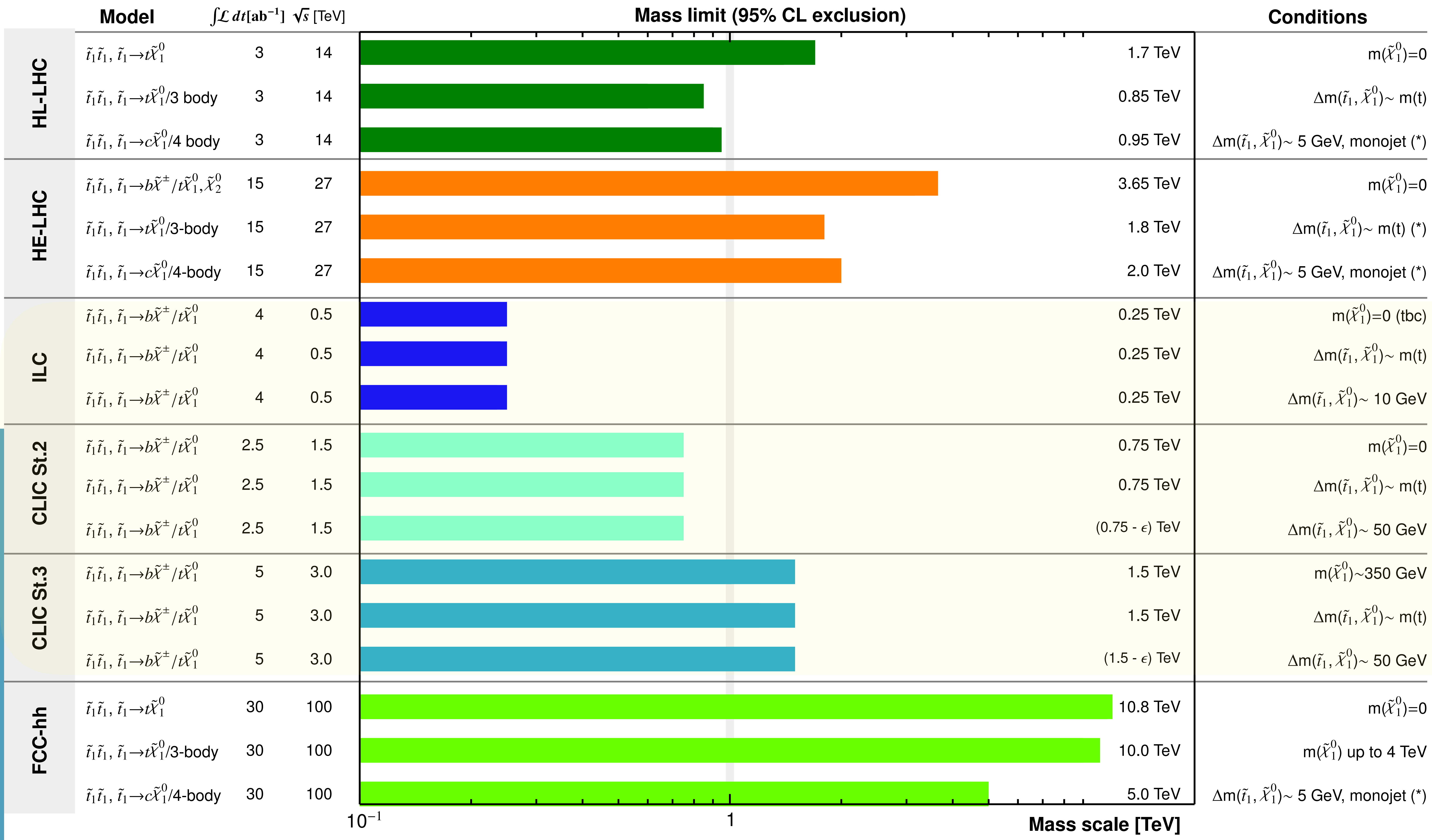
Showing the energy at which pp collider cross-section equals the muon collider one
Continuos line includes a factor 10 enhancement in pp production for colored objects.

- μμ @ 14 TeV → pp @ 100 $(200)_{EW}$ TeV !
- μμ @ 30 TeV → pp @ 350 $(600)_{EW}$ TeV !!

FUTURE PROSPECTS FOR SEARCHES - SUSY

- Many variants to be considered (MSSM, NMSSM, gauge mediation, stealth…)
  - phenomenology depends on the model and sparticle mass hierarchy
- **Strong Production** (gluino, 1st and 2nd generation squarks, top squarks: dominated by hadron colliders.
- Lepton Colliders help in the case of compressed scenarios
- **Weak production** (charginos, neutralinos, sleptons): complementarities among colliders (compressed scenarios)
  - R-Parity conserving SUSY considered here (i.e. R-parity prevents the decay of the lowest neutralino to SM particles, gives rise to missing energy in the final state)

SUMMARY RPC STOP SQUARK SEARCH AT FUTURE COLLIDERS



(*) indicates projection of existing experimental searches
ϵ indicates a possible non-evaluated loss in sensitivity

Discovery potential HL/HE-LHC ~ up to 1.4/3.2 TeV

Discovery potential e+e- ~ up to sqrt(s)/2
(with possible exception for compressed scenarios)

Discovery potential FCC-hh ~ up to 8 TeV

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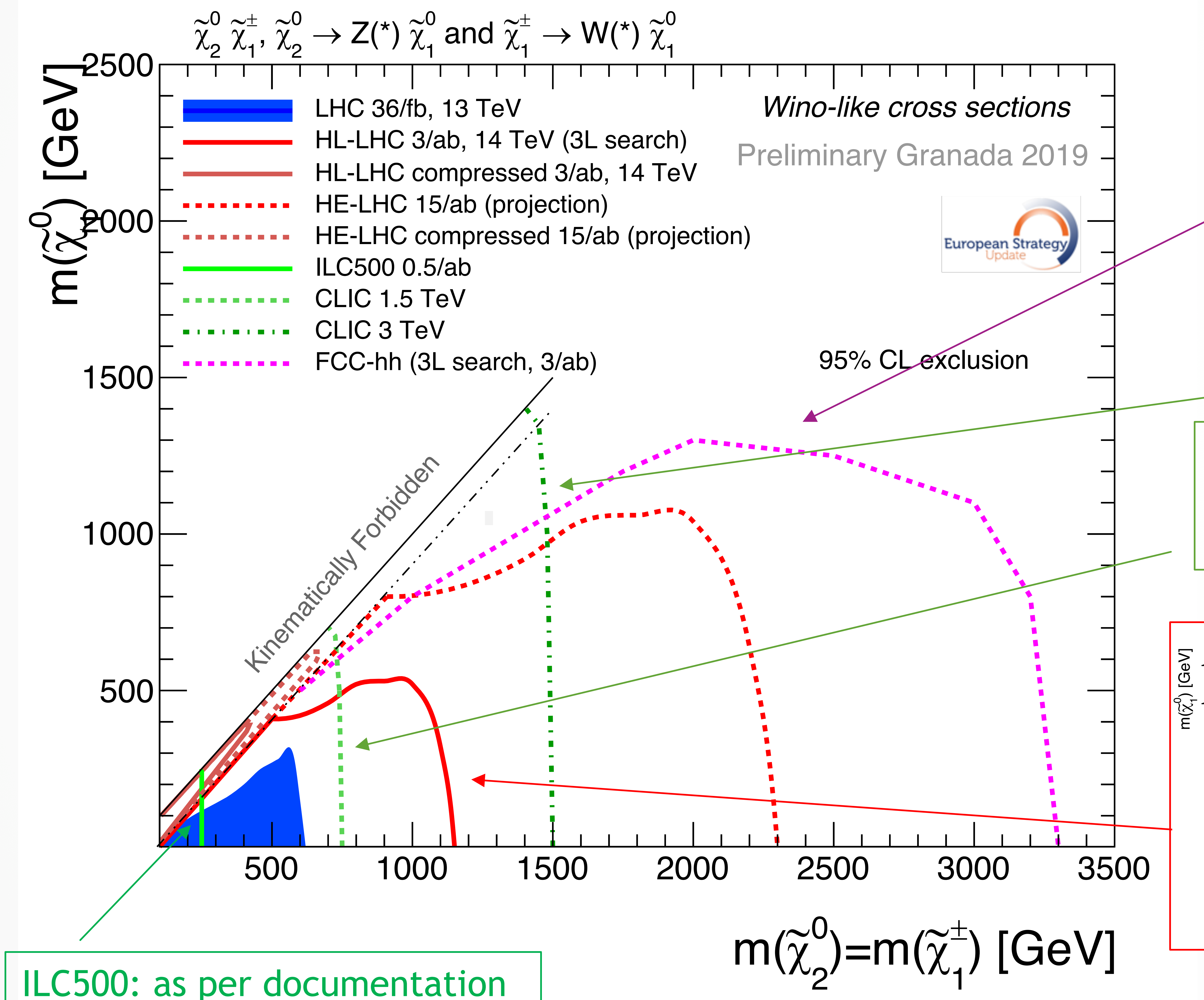
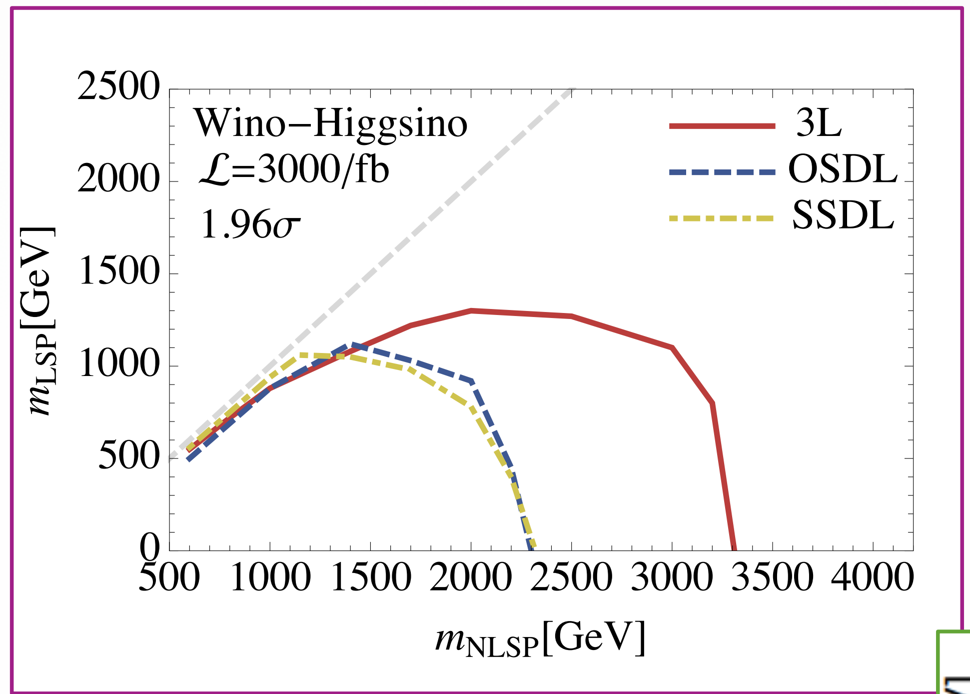
SUSY - CHARGINO & NEUTRALINO PHENOMENOLOGY

- Mass and hierarchy of the four neutralinos and the two charginos, as well as their production cross sections and decay modes, depend on the M_1, M_2, μ (bino, wino, higgsino) values and hierarchy
  - EWK phenomenology broadly driven by the LSP and Next-LSP nature

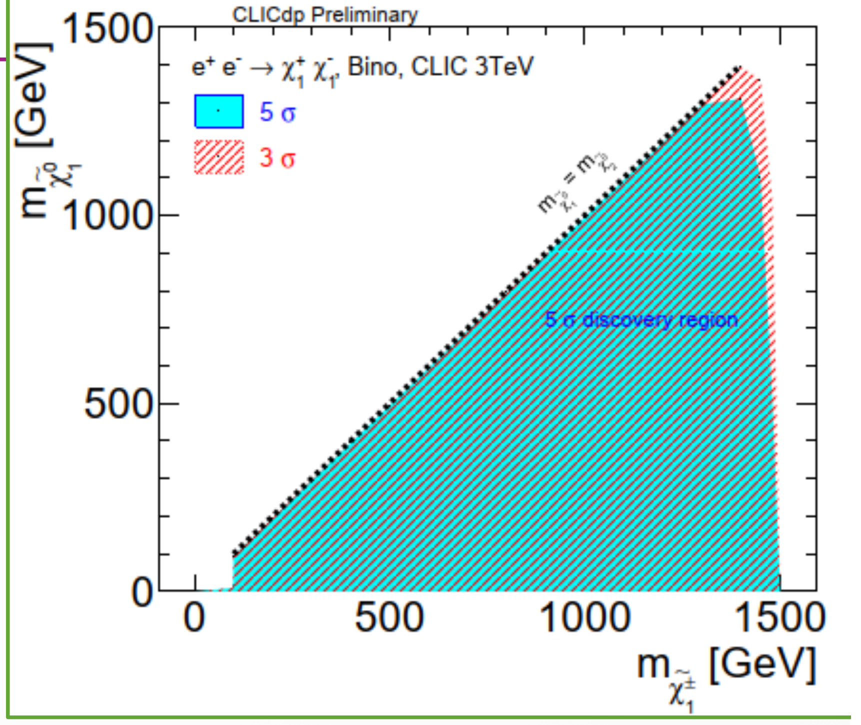
- For lepton colliders the dominant processes are $e^+e^- \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0\tilde{\chi}_1^0$.
- The large mass difference bewteen the LSP and the NSLP allows to exploit multi-leptons final states.
- Often leptons are low-pt. Compressed spectra can be exploited at hadron colliders with the use of leptons recoiling against an ISR jet.
- Lepton colliders are competitive in these cases: sensitive to $\Delta m \approx \Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ as low as 1 GeV

EWKINOS AT FUTURE COLLIDERS

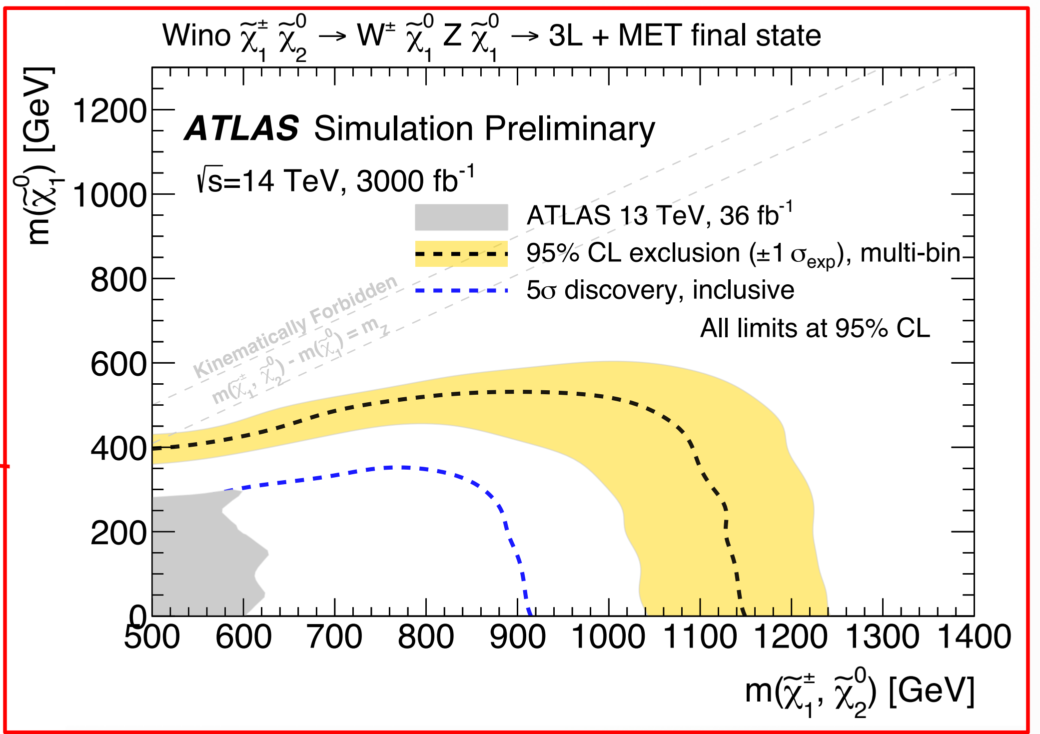




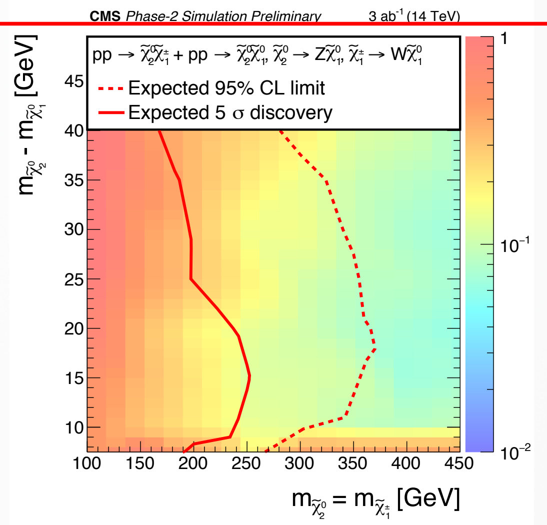
FCC-hh Contour of the 3-lepton search



CLIC: Assume reach for $\chi^+{}_1\chi^-{}_1$ and $\chi^{\pm}{}_1\chi^0{}_2$. CLIC 1.5 TeV reach / 2 up to ΔM~5 GeV



HL-LHC compressed: reinterpretation of higgsino $\chi^{\pm}{}_1\chi^0{}_2$ results



HE-LHC → projections with ColliderTool Reach

ILC500: as per documentation

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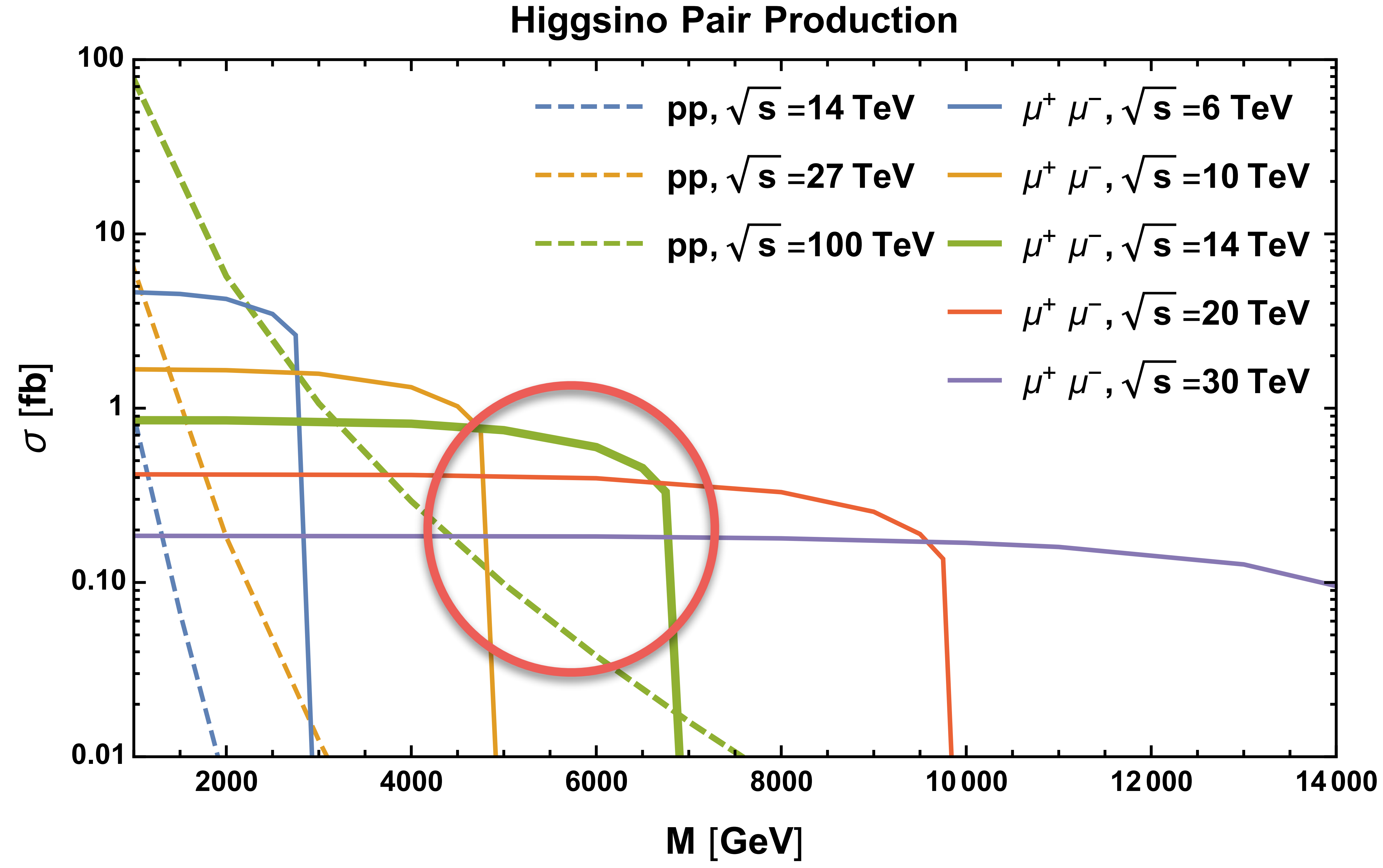
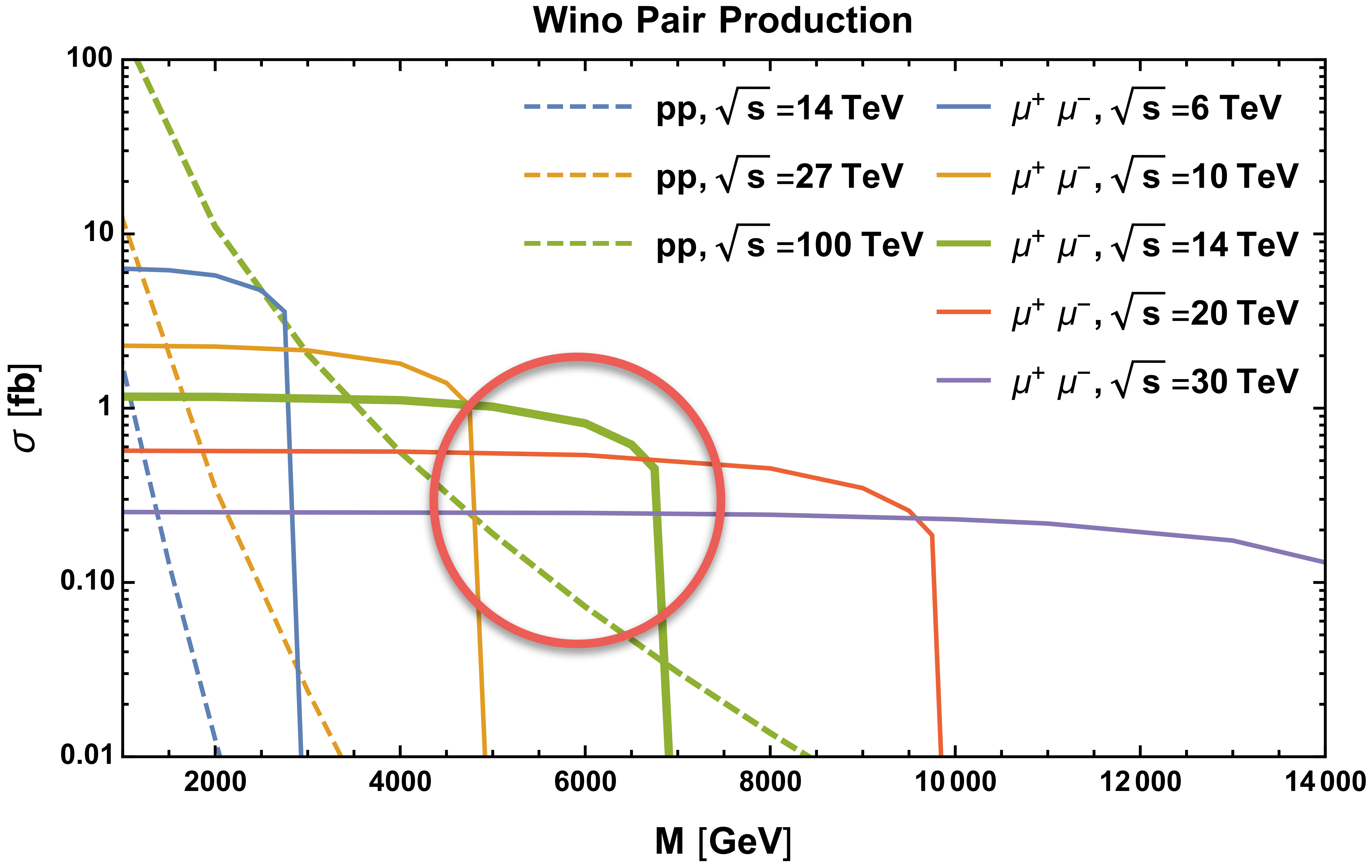
BSM Ewkinos at Muon Collider





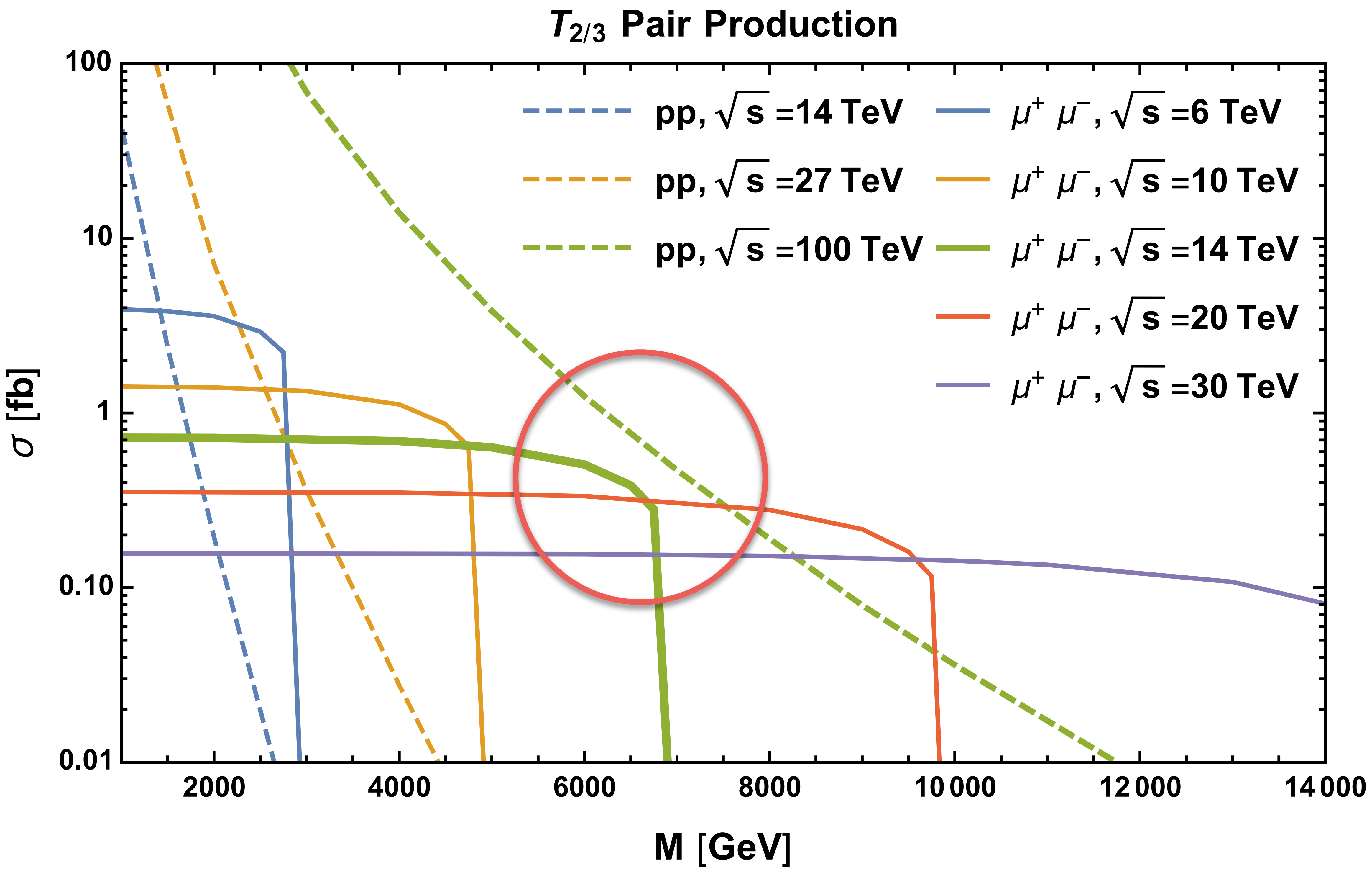
Much much better than proton collider for EW-only particles like Higgsino/EWKino/Sleptons …

BSM Colored Objects at Muon Collider

Typical Muon Collider Cross-Section:

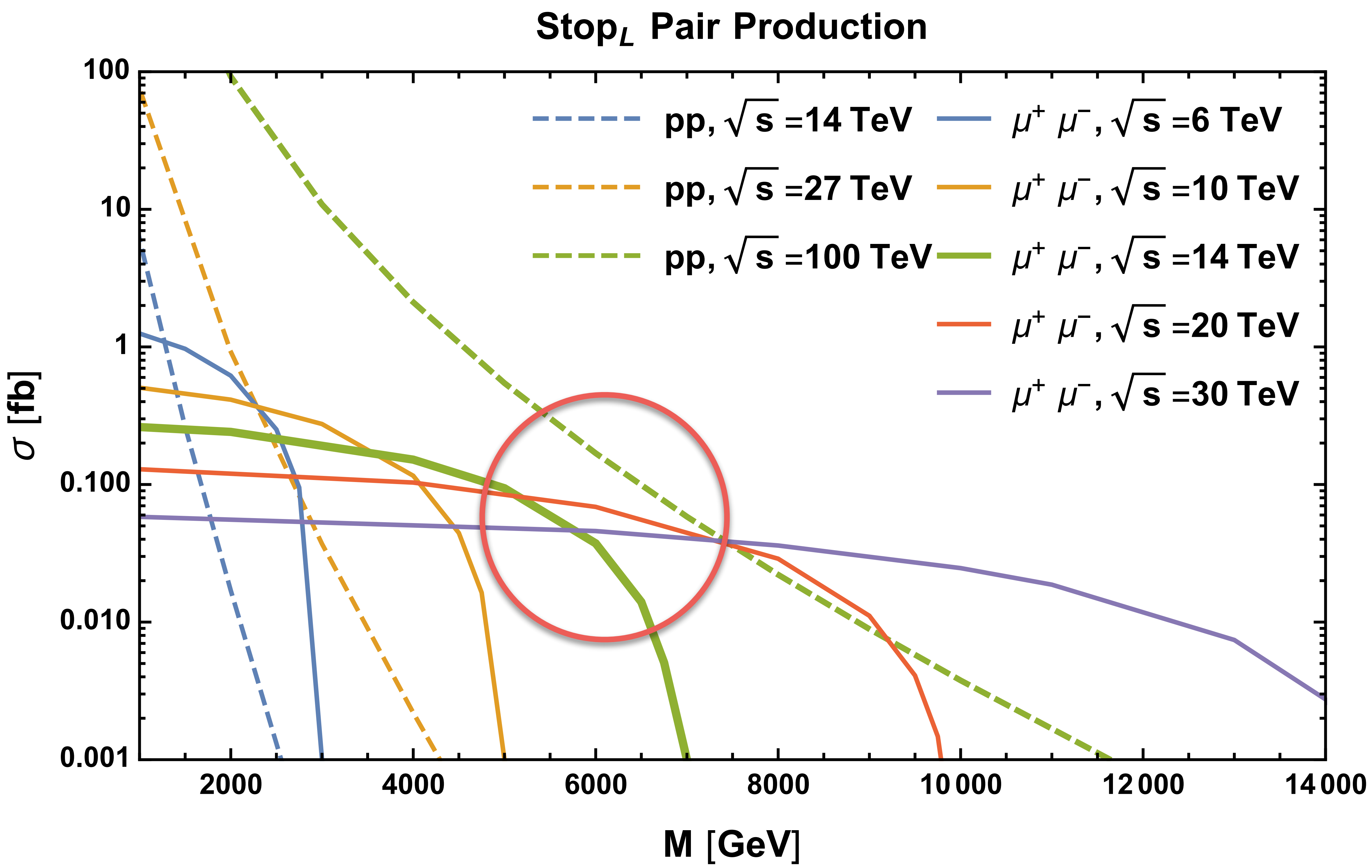
$$\sigma_\mu = \left(\frac{10\,\mathrm{TeV}}{\sqrt{s}}\right)^2 \cdot 1\mathrm{fb}$$

for benchmark processes



Composite Higgs model Top Partner

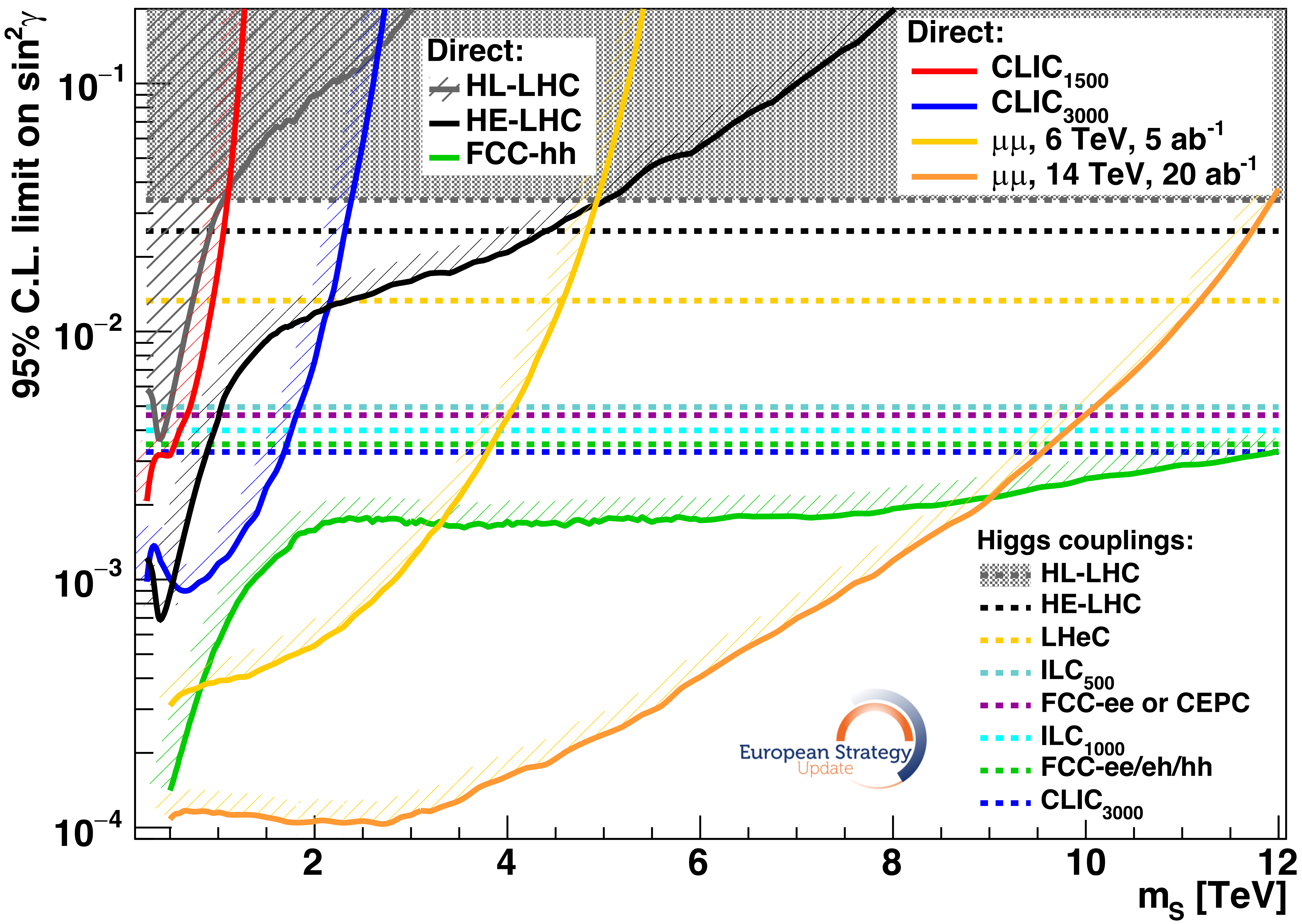
SUSY Top Partner



SUMMARY OF THE DISCOVERY REACH IN THE EWK SECTOR

- HL-LHC analyses now target also compressed scenarios with soft-lepton + ISR analyses and/or monojet
  - Good prospects, but discovery potential is limited (~ 200 GeV for higgsino-like models)
- ILC500 (→ CLIC 1.5 TeV, 3 TeV) might allow discovery in case deviations are observed at HL-LHC
  - Characterization of the EWK sector possible at e^+e^- for sparticles with masses below ~ sqrt(s)/2
- FCC-hh has certainly a high potential for EWK particles (with mass up to 3-4 TeV)
  - Together with CLIC 3 TeV, FCC-hh could go beyond ~ 1 TeV for higgsino scenarios
- Potential of monojet searches at pp colliders might be further exploited to evaluate exclusion reach. However:
  - What if a deviation in monojet final states is observed at the HL-LHC? → multiple interpretations are possible → additional EWK processes (i.e. from heavier charginos/neutralinos) must be searched for (see some examples in back-up for e+e- and pp).

BENCHMARK: SM + EXTRA SCALAR SINGLET

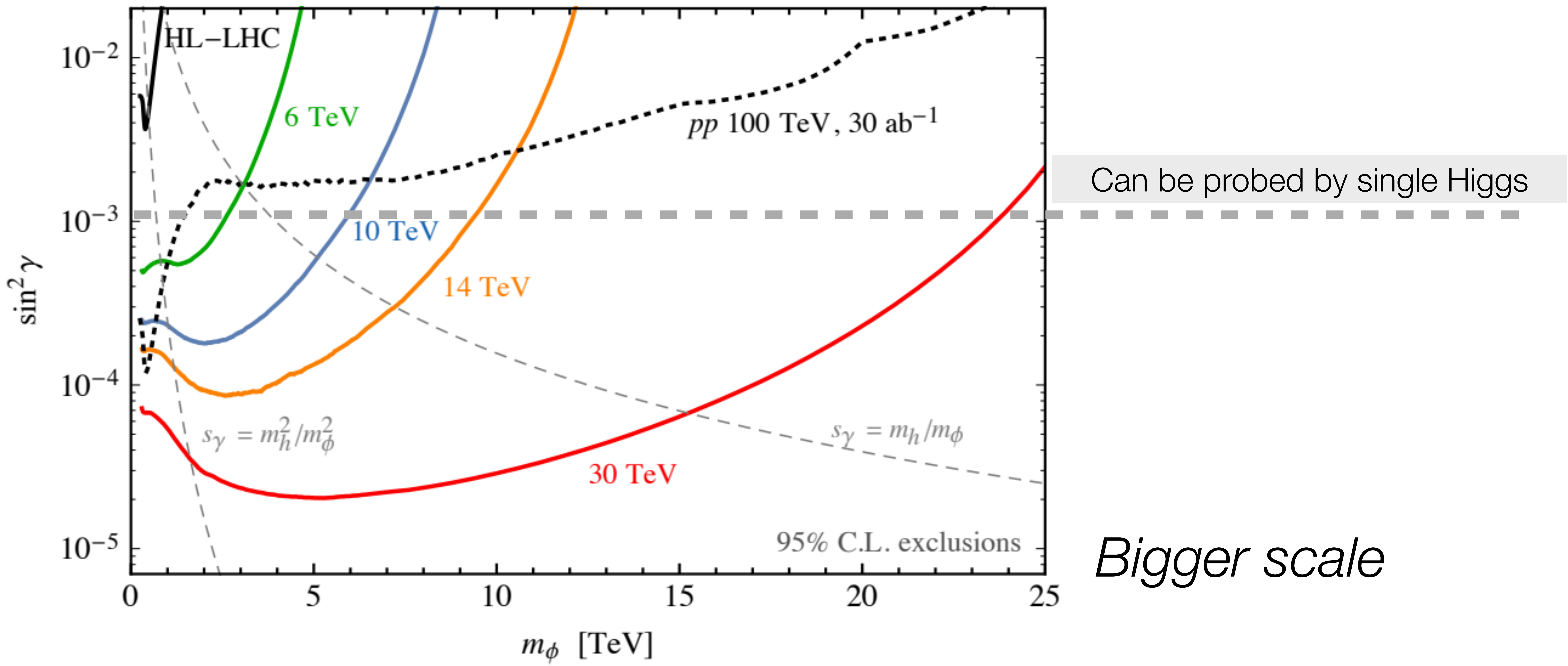


Comparison of direct and indirect searches

SCALAR SINGLET: DIRECT VS INDIRECT REACH

Compare the reach of very high energy lepton & hadron colliders

$$\sin^2\gamma \approx \Delta\mu_h/\mu_h^{SM} \approx \sigma_{VV\to\phi}/\sigma_{VV\to h}^{SM}$$

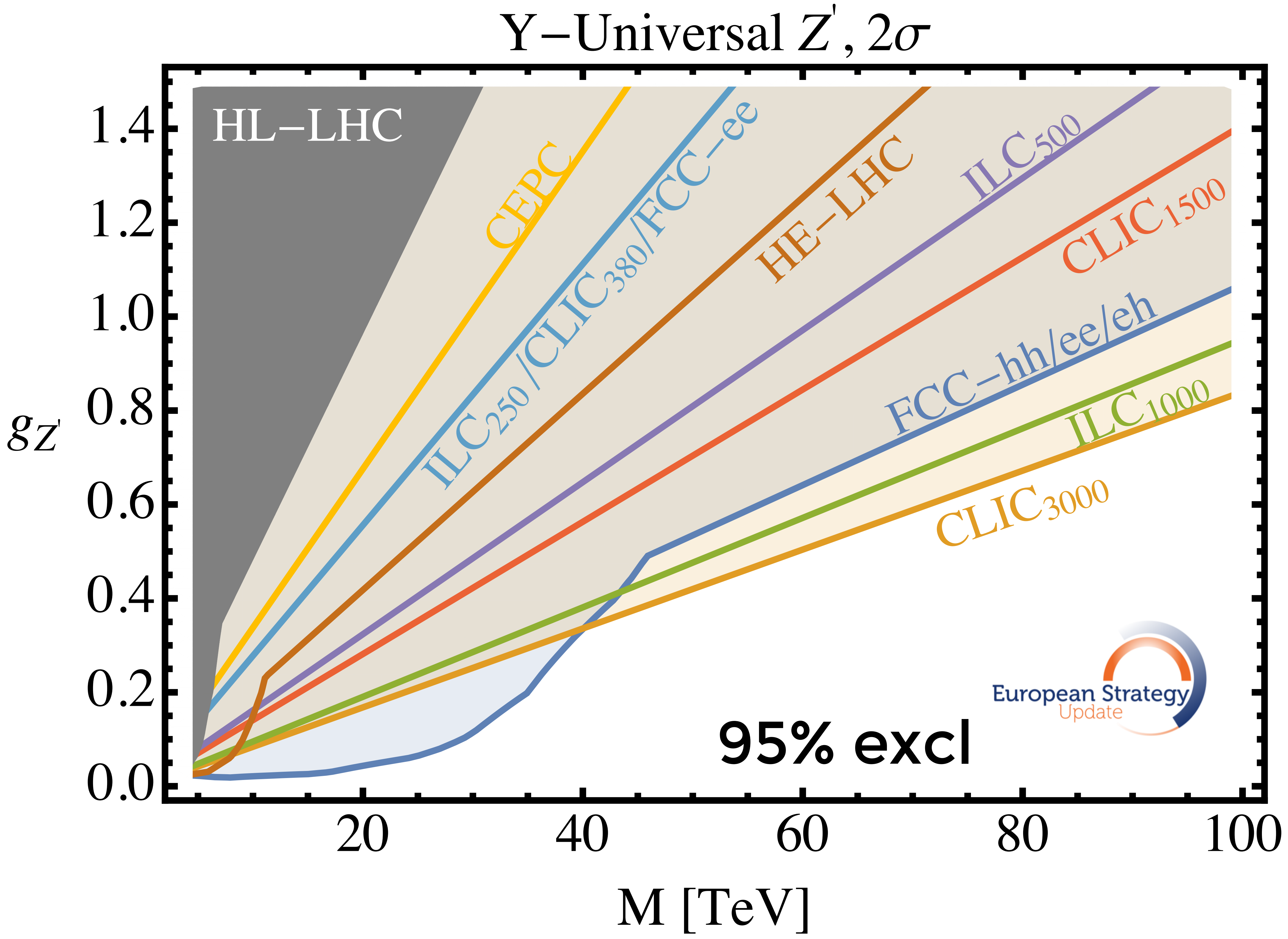


Bigger scale

For this class of models, a high-energy $\mu^+\mu^-$ collider has an amazing reach if compared to single Higgs meas. or direct searches at a 100 TeV pp collider

BENCHMARK: THE UNIVERSAL Z' MODEL

- Model consists of a neutral gauge boson Z' with mass M and charges to the SM particles equal to the hypercharge.
- The coupling $g_{Z'}$ is a free parameter.
- Model chosen by the EPSSU for comparison of future colliders as couplings to quarks and leptons are similar (also bc connected to one EFT operator that is available for all colliders)



Straight lines: indirect limits, better at higher g.
Better with higher energy machines

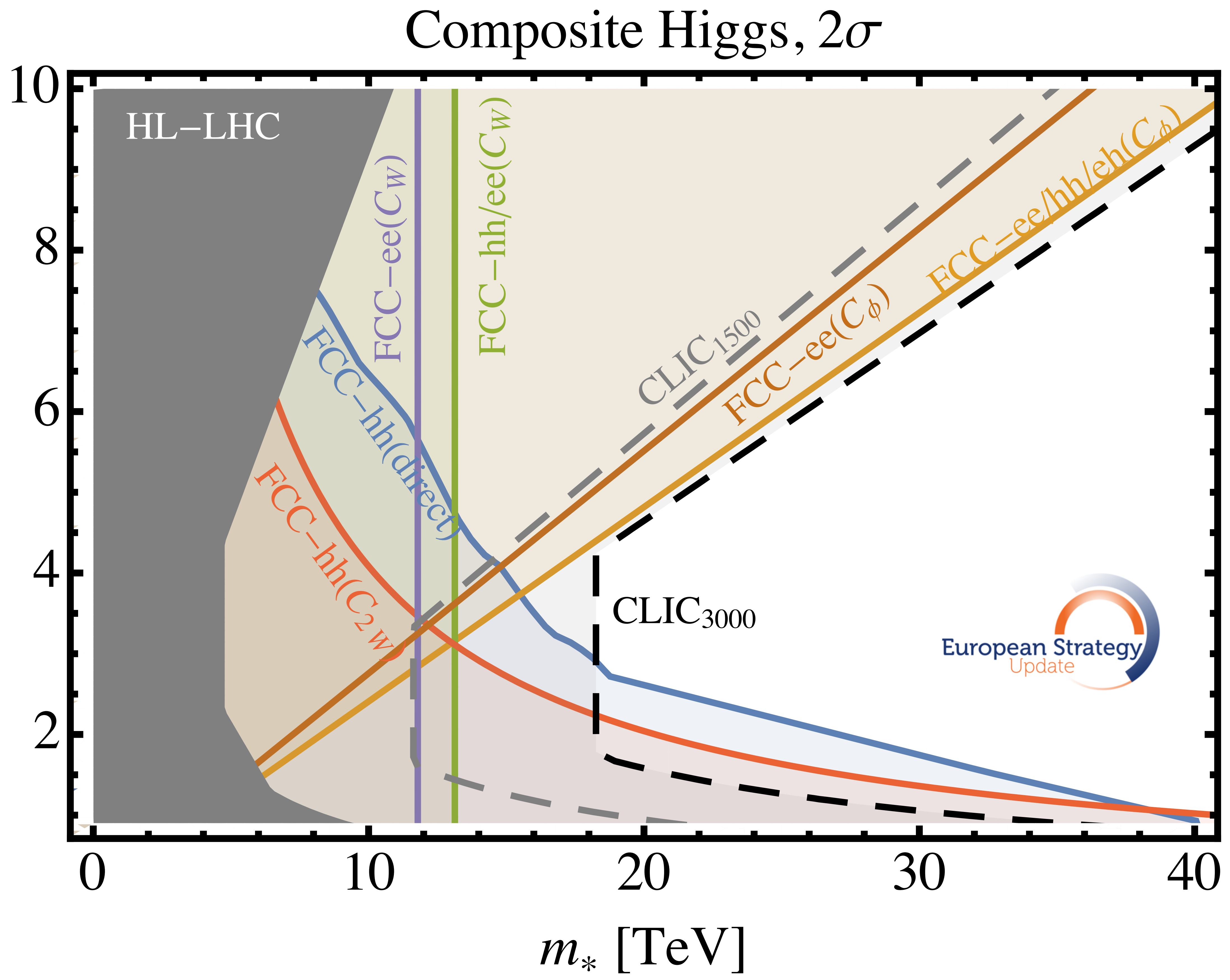
Curved contour: direct limit

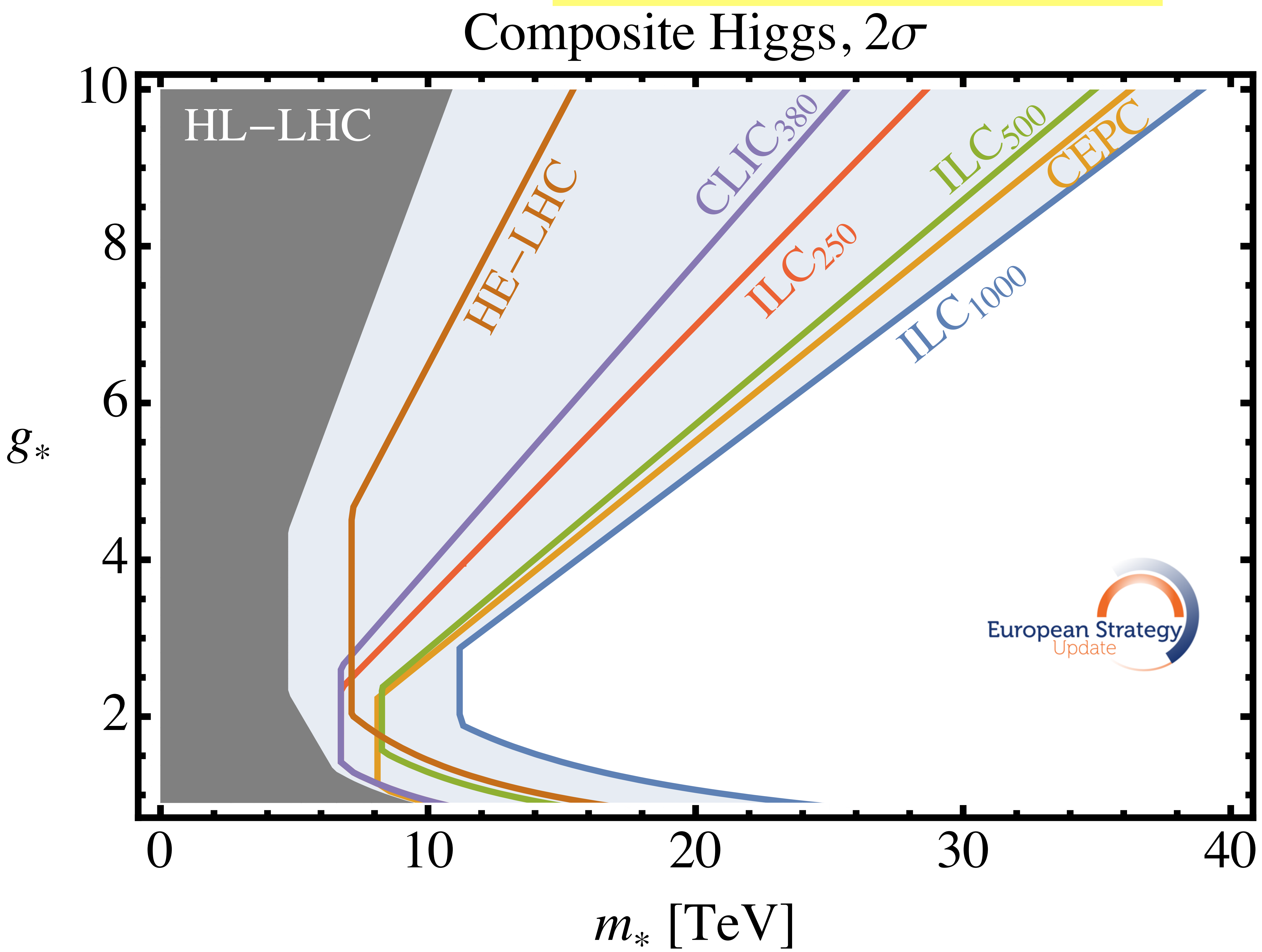
- **Strongly coupled new physics is better probed indirectly**

BENCHMARK: COMPOSITE HIGGS MODEL

- Higgs as a bound state of a new strongly-interacting confining Composite Sector. Parameters: mass scale m* (compositeness scale) and coupling g*
- Note: $\ell_H = 1/m^*$ (« size » of the composite Higgs)

95% exclusion limits





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DARK MATTER CANDIDATES: DARK PHOTON

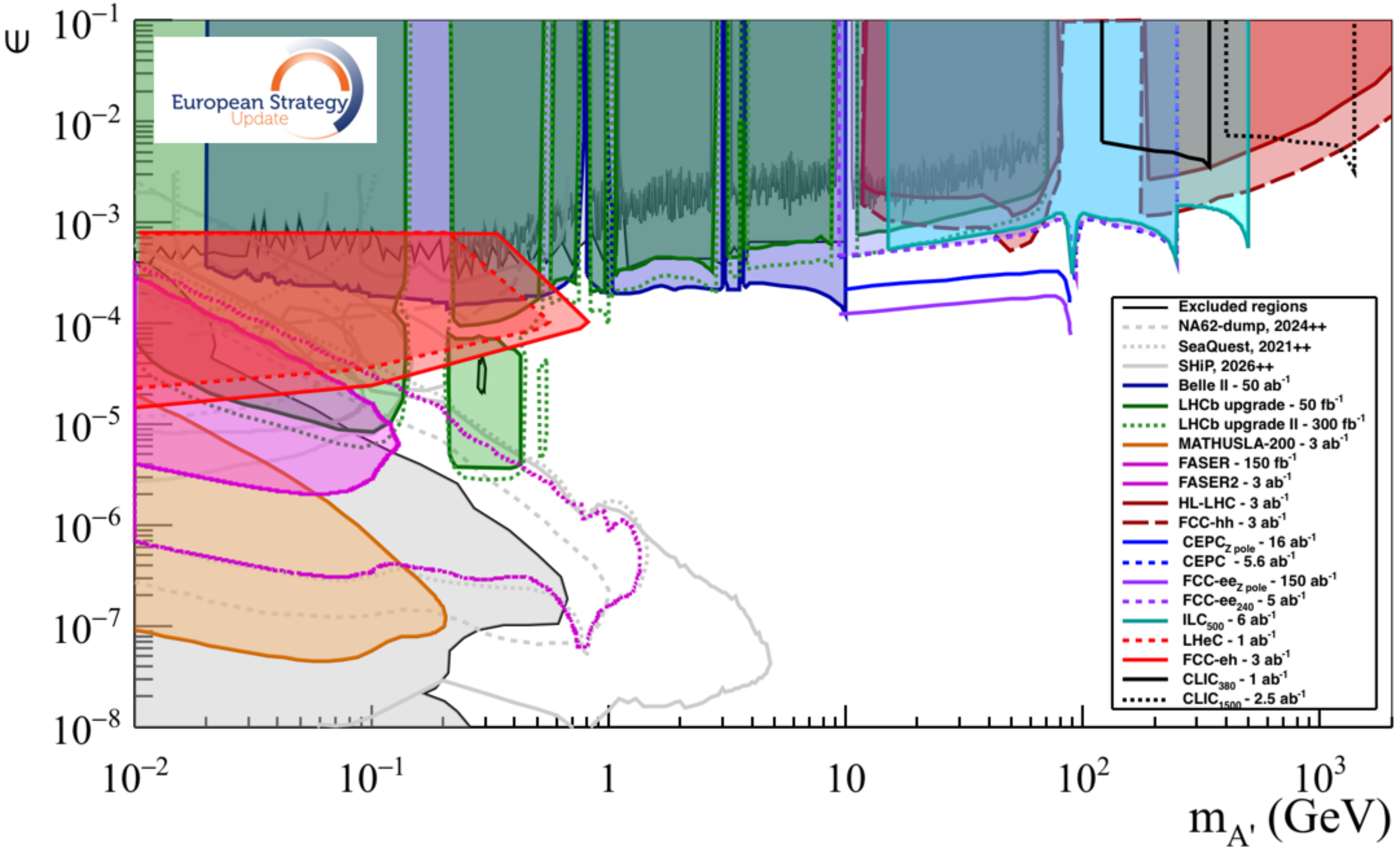
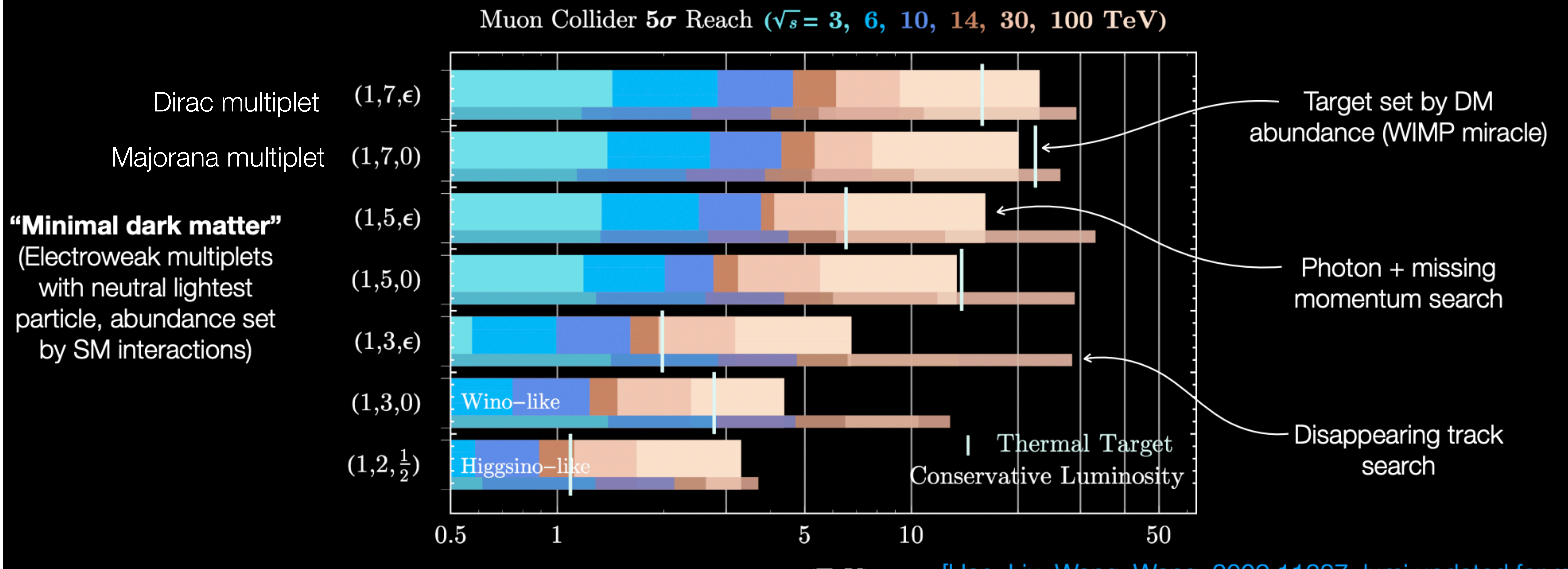


Fig. 8.16: Sensitivity for Dark Photons in the plane mixing parameter ε versus Dark Photon mass. HL-LHC, CEPC, FCC-ee and FCC-hh curves correspond to 95% CL exclusion limits, LHeC and FCC-eh curves correspond to the observation of 10 signal events, and all other curves are expressed as 90% CL exclusion limits. The sensitivity of future colliders, mostly covers the large-mass, large-coupling range, and is fully complementary to the the low-mass, very low-coupling regime where beam-dump and fixed-target experiments are most sensitive.

DARK MATTER AT MUON COLLIDER

Powerful prospects for a μC in final states with missing energy:
large electroweak production rates, low backgrounds compared to hadron colliders



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[Han, Liu, Wang, Wang, 2009.11287, lumi updated for μSG]
see also [Capdevilla, Meloni, Simoniello, Zurita 2102.11292]

SUMMARY

$\sqrt{s}$	Processes	Physics Goals	Observables
91 GeV	• $e^+e^- \to Z$	ultra-precision EW physics **flavour BSM**	$\sin^2\theta_{eff}$ M_Z, Γ_Z, N_ν α, α_S
125 GeV	• $e^+e^- \to H$	*limit on s-channel H production?*	y_e
160 GeV	• $e^+e^- \to W^+W^-$	ultra-precision W mass	M_W, Γ_W
>160 GeV	• $e^+e^- \to W^+W^-$ • $e^+e^- \to q\bar{q}, \ell\ell\ (\gamma)$	precision W mass and couplings precision EW (incl. Z return)	M_W, aTGC N_ν
250 GeV	• $e^+e^- \to ZH$	ultra-precision Higgs mass precision Higgs couplings	M_H κ_V, κ_f, Γ_H
360 GeV	• $e^+e^- \to t\bar{t}$	ultra-precision top mass	M_{top}
>360 GeV	• $e^+e^- \to t\bar{t}$ • $e^+e^- \to ZH$ • $e^+e^- \to H\nu\nu$	precision top couplings precision Higgs couplings	
500+ GeV	• $e^+e^- \to t\bar{t}H$ • $e^+e^- \to ZHH$ • $e^+e^- \to Z' \to f\bar{f}$ • $e^+e^- \to \chi\chi$ • $e^+e^- \to AH, H^+H^-$	Higgs coupling to top Higgs self-coupling search for heavy Z' bosons search for supersymmetry (SUSY) search for new Higgs bosons	y_{top} λ_{HHH}

Special program

+Muon Collider

So much physics I have not shown you!

FOOD FOR THOUGHT

- We would like to have intensity frontier and energy frontier.
  - It is impossible to achieve both with a single machine.
- Several complementarities between different machines, in particular lepton colliders and hadron colliders.
  - Note: hadron colliders can collide also heavy ions
- Currently only precision measurements of SM EWPO and Higgs can point the way to the scale of new physics and possibly the type of new physics.
  - A high energy hadron collider without a lepton collider before might not be able to achieve the desired precision or model independence needed
  - A muon collider of high energy might have access to new particle masses as a 100TeV hadron collider, but might be limited if coloured
- Integrated projects that try to optimise the use of the infrastructure (circular tunnel) for different and complementary machines and offer places for many detectors seem very appealing at the moment.