The 6th annual Large Hadron Collider Physics conference,
Bologna, June 4-9 2018

Theoretical studies of future (hadron) colliders

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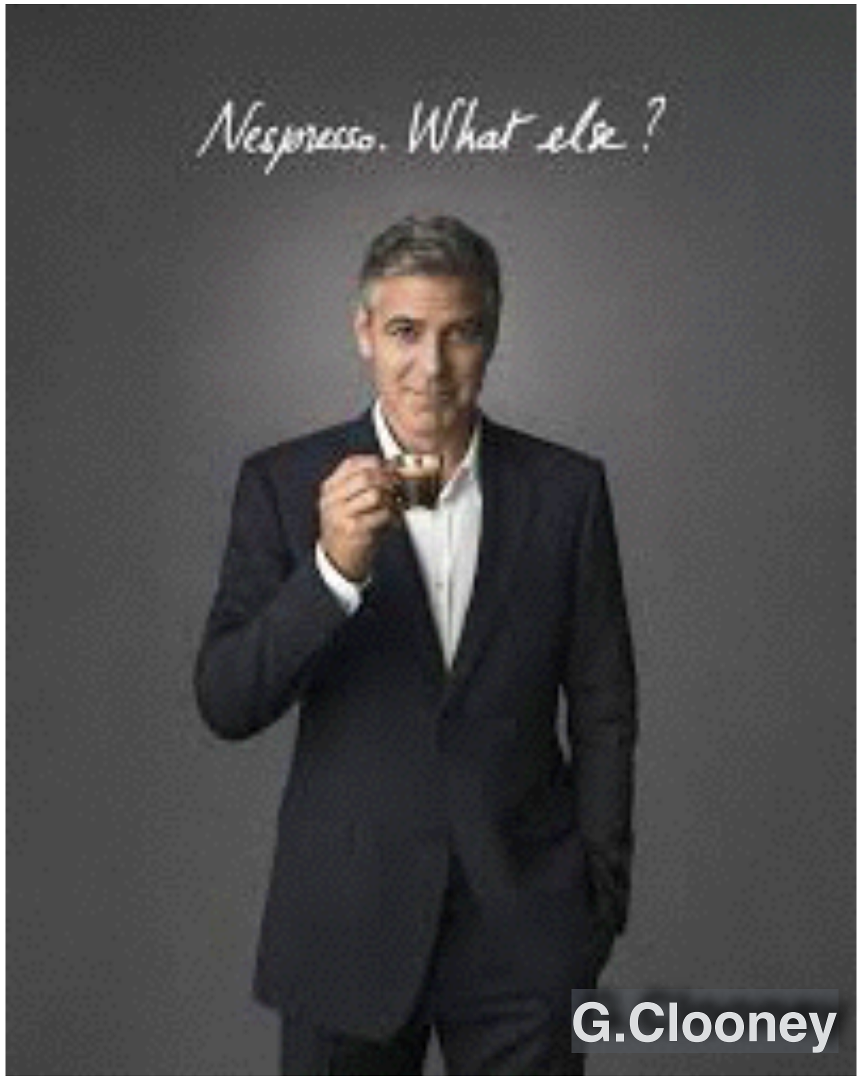
FCC-hh: *"Physics at 100 TeV"*, Report, 5 chapters:

- SM processes, arXiv:1607.01831
- Higgs and EWSB studies, arXiv:1606.09408
- BSM phenomena, arXiv:1606.00947
- Heavy Ions at the FCC, arXiv:1605.01389
- Physics opportunities with the FCC injectors, arXiv:1706.07667

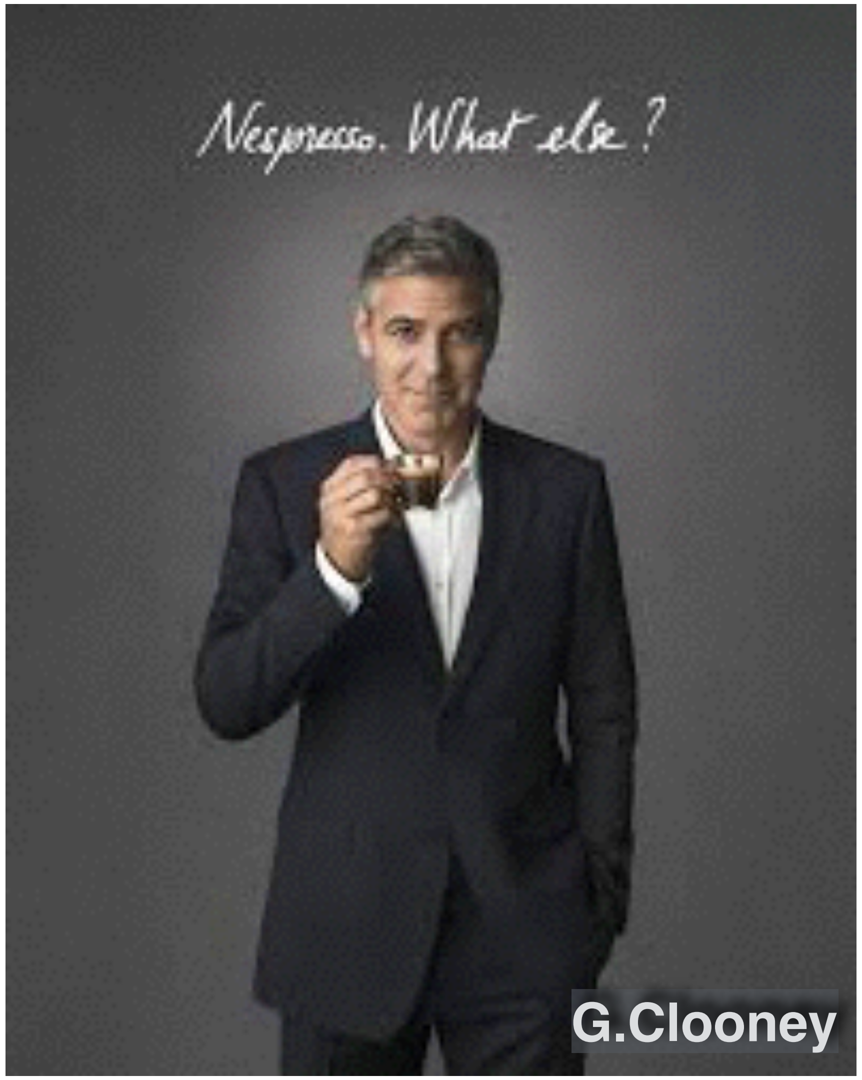
See also in the parallel sessions:

Gauthier Durieux: Physics of future lepton colliders
Giancarlo Ferrera: Physics of future hadron colliders
Steinar Stapnes: Status of ILC and CLIC projects
Rogelio Tomas Garcia: Status of FCC study



Higgs ….

what else?



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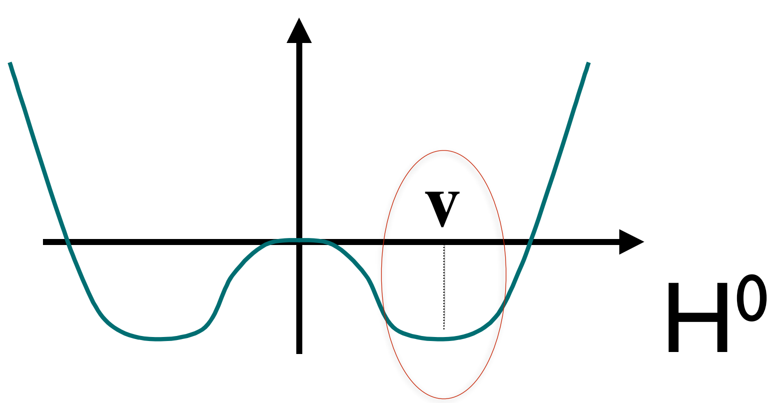

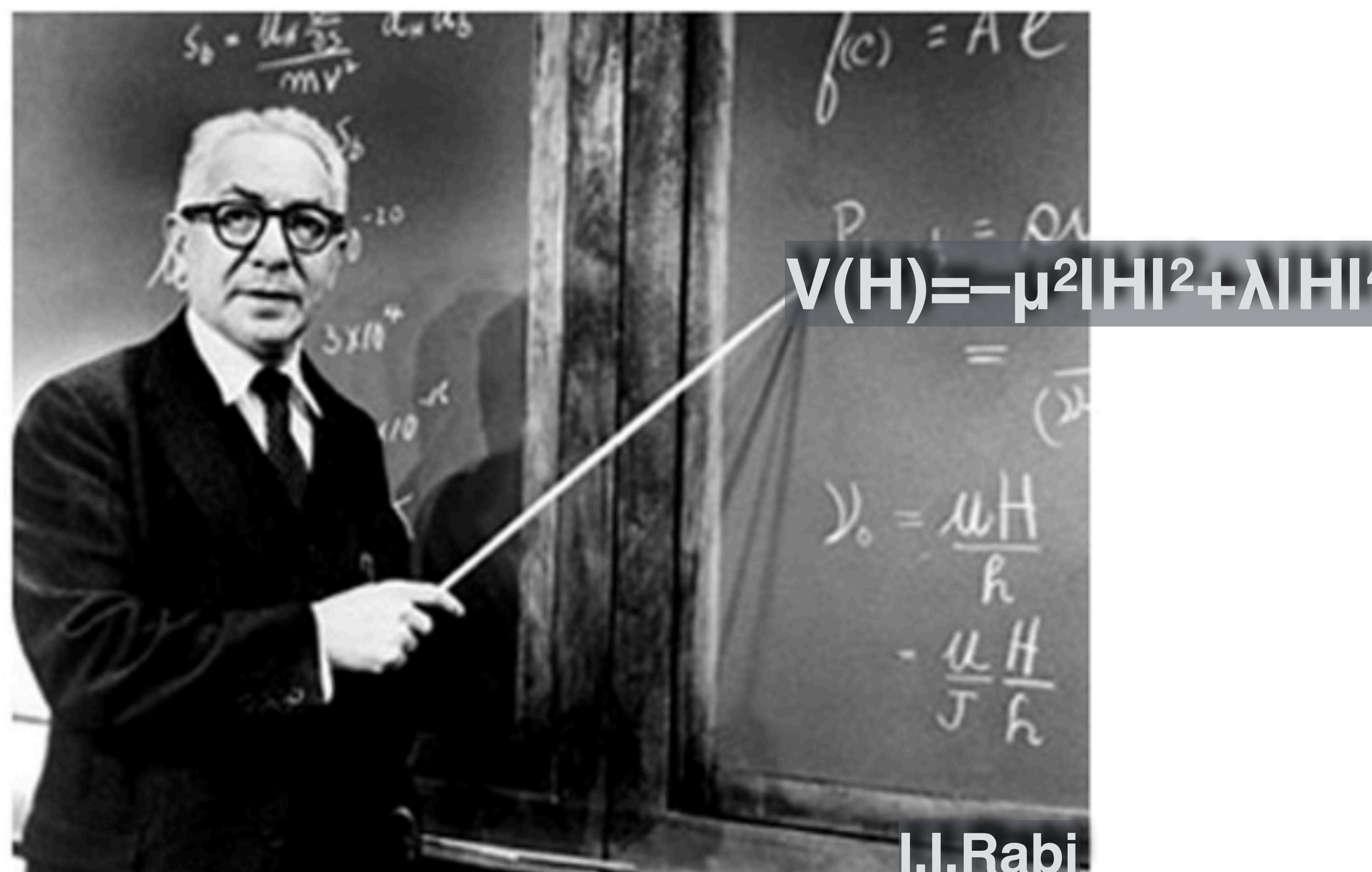

a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

what's ahead?

- HEP has two priorities:
  - **explore the physics of electroweak symmetry breaking**:
    - experimentally, via the measurement of Higgs properties, Higgs interactions and selfinteractions, couplings of gauge bosons, flavour phenomena, etc
    - theoretically, to understand the origin of the Higgs potential, the nature of the hierarchy problem and identify possible natural solutions (to be subjected to exptl test)
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Planning the future builds on the belief that
these two directions are deeply intertwined

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These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:
- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

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- Provide firm Yes/No answers to questions like:
  - is the SM dynamics all there is at the TeV scale?
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - was the cosmological EW phase transition 1st order? Cross over? ??
  - could baryogenesis take place during the EW phase transition?

Higgs properties,

some sample studies

Higgs couplings @ FCC-ee

g_{HXY}	ee [240+350 (2IP)]
ZZ	0.21%
WW	0.43%
bb	0.64%
cc	1.04%
gg	1.18%
ττ	0.81%
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uu,dd	H->ργ, under study
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BR_{inv}	< 0.45%
Γ_{tot}	1.5%

SM Higgs: event rates at 100 TeV

	$gg \to H$	VBF	WH	ZH	ttH	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

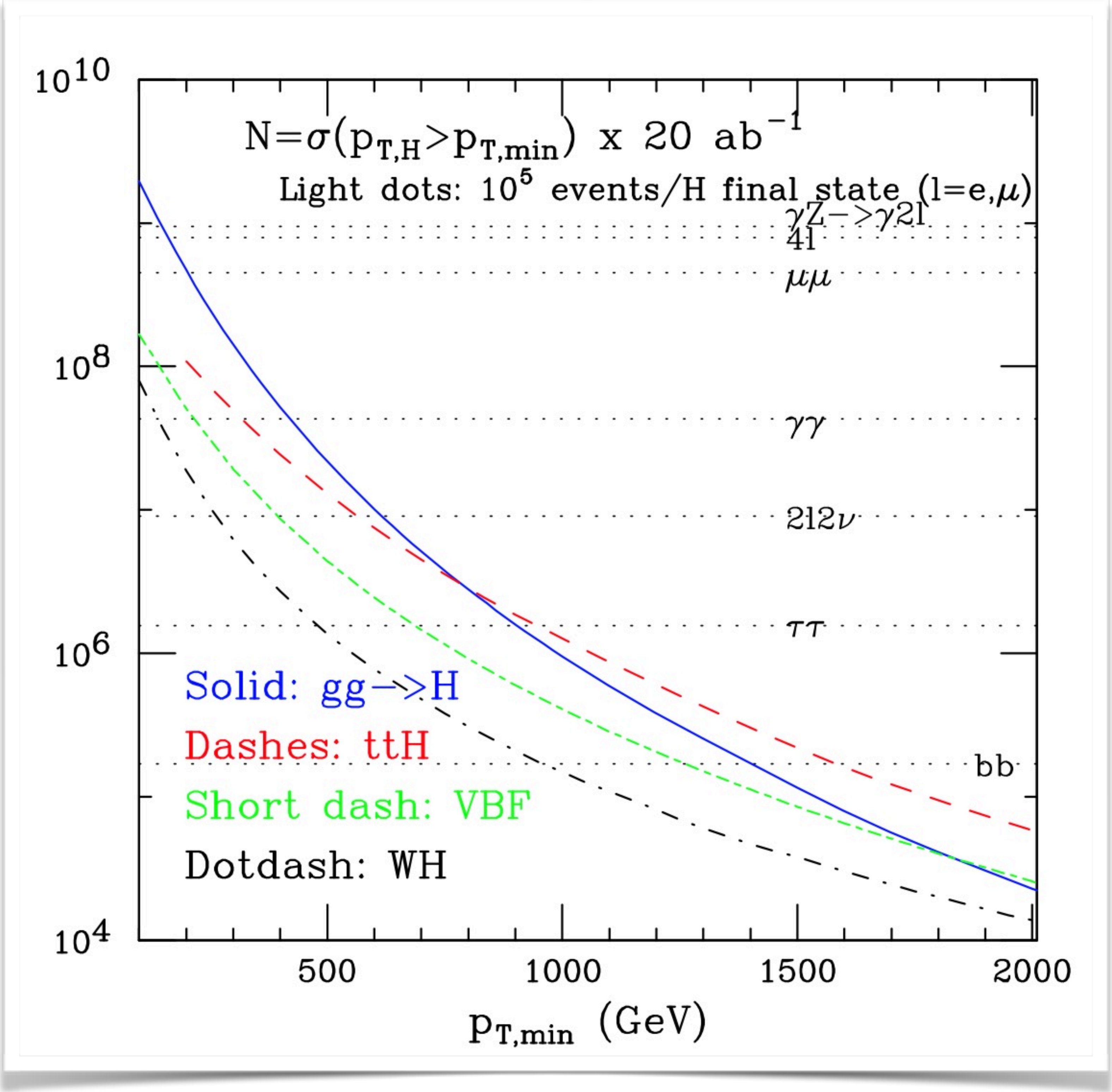
$N_{100} = \sigma_{100\,\text{TeV}} \times 30\ \text{ab}^{-1}$

$N_{14} = \sigma_{14\,\text{TeV}} \times 3\ \text{ab}^{-1}$

The uniqueness of *FCC-hh contributions to Higgs physics*

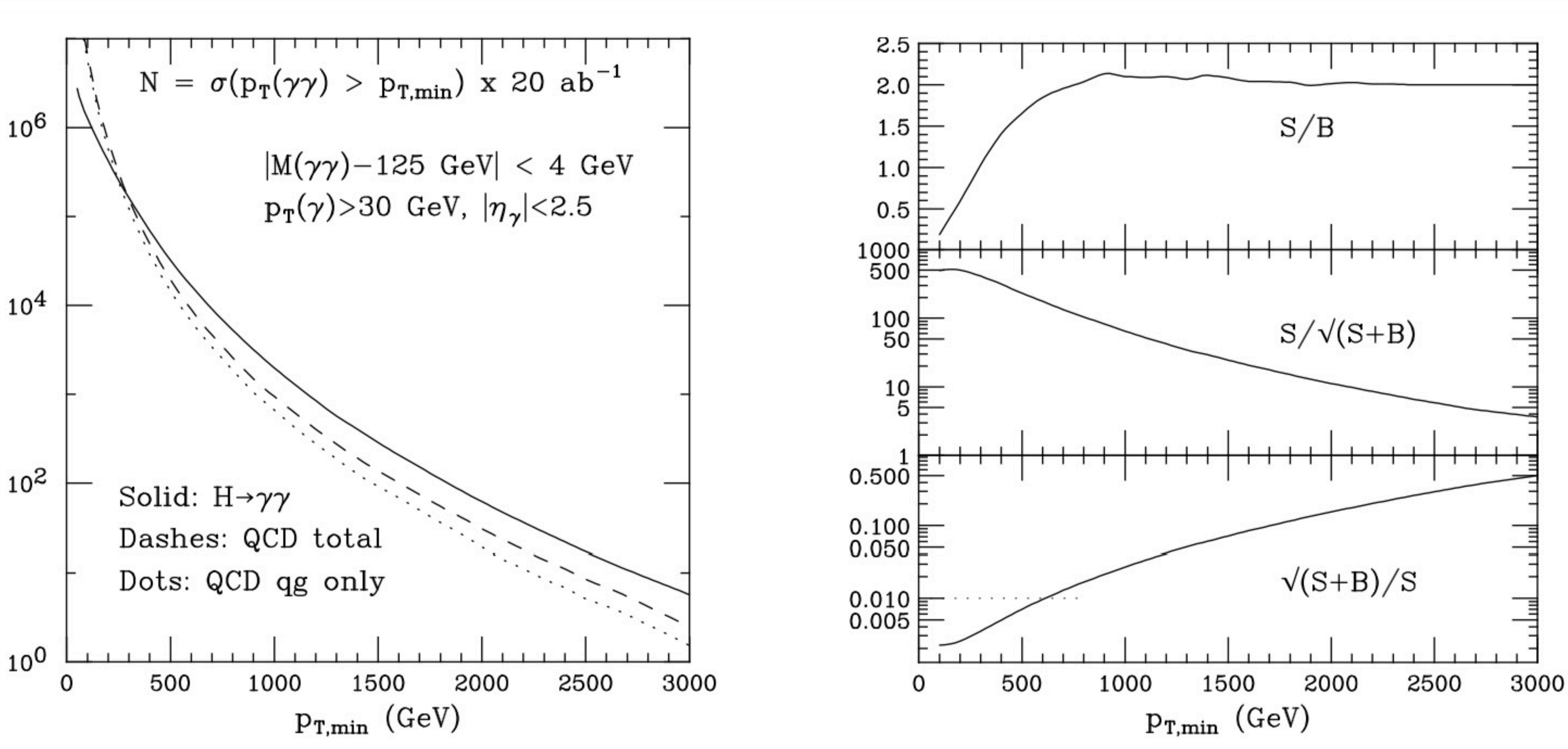
- Huge Higgs production rates:
  - access (very) rare decay modes
  - push to %-level Higgs self-coupling measurement
  - new opportunities to reduce syst uncertainties (TH & EXP) and push precision
- Large dynamic range for H production (in p_T^H, m(H+X) , ...):
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - develop indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*eg decay BRs*) at $Q \sim m_H$
- High energy reach
  - direct probes of BSM extensions of Higgs sector
    - SUSY Higgses
    - Higgs decays of heavy resonances
    - Higgs probes of the nature of EW phase transition (strong 1st order? crossover?)
    - ...

H at large p_T



- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg \to H)$ above 1800 GeV

gg→H→γγ at large p_T



- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for p_T(H)>300 GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%

Delphes-based projections

M.Selvaggi

All **signal and background samples** have been generated via the following chain (using the FCCSW): http://fcc-physics-events.web.cern.ch/fcc-physics-events/LHEevents.php

- **MG5aMC@NLO + Pythia8**
  - LO (MLM) matched samples (up to 1/2/3 jets) and global K-factor applied to account for $N^{2/3}LO$ corrections
  - full list of signal prod. modes simulated (ggH with finite m_{top})
- **Delphes-3.4.2** with baseline FCC-hh detector

Consider the following categories of uncertainties:

- δ_{stat} = statistical
- δ_{prod} = production + luminosity systematics
- $\delta_{eff}^{(i)}$ (p_T) = object reconstruction (trigger+isolation +identification) systematics
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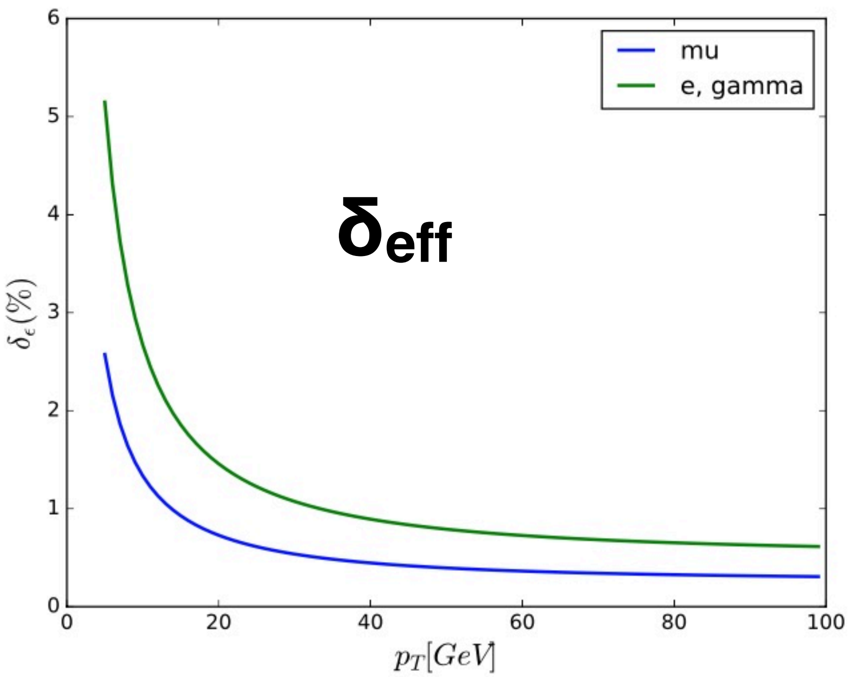

Assume (un-)correlated uncertainties for (different) same final state objects

Following scenarios are considered:

- δ_{stat} → stat. only (I)
- δ_{stat} , δ_{eff} → stat. + eff. unc. (II)
- δ_{stat} , δ_{eff} , δ_{prod} = 1% → stat. + eff. unc. + prod (III)

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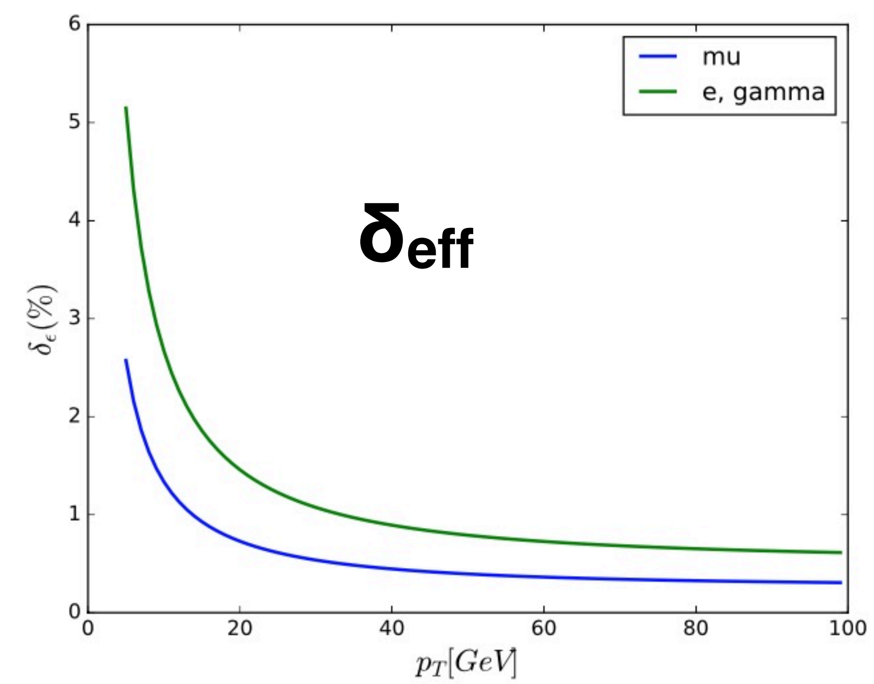

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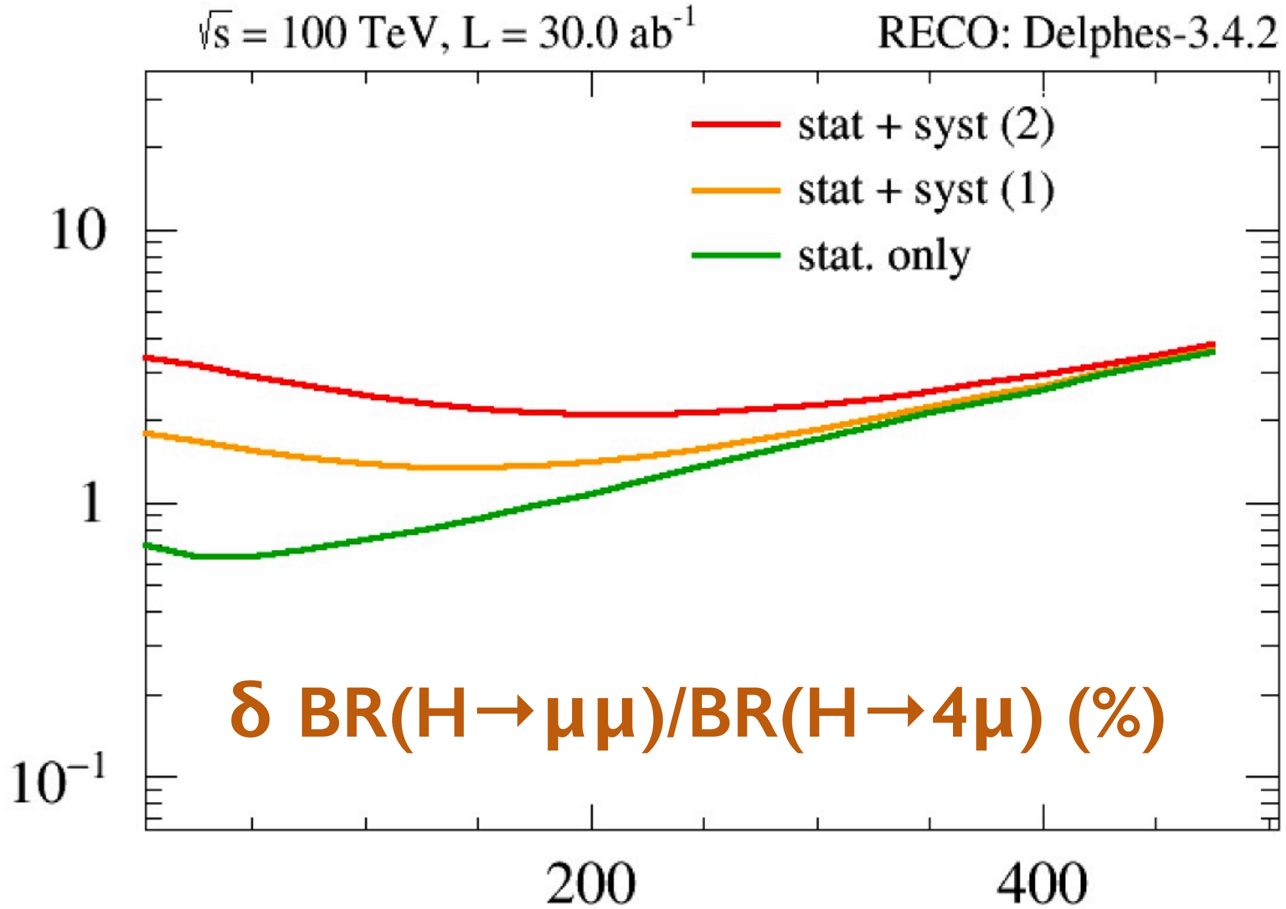
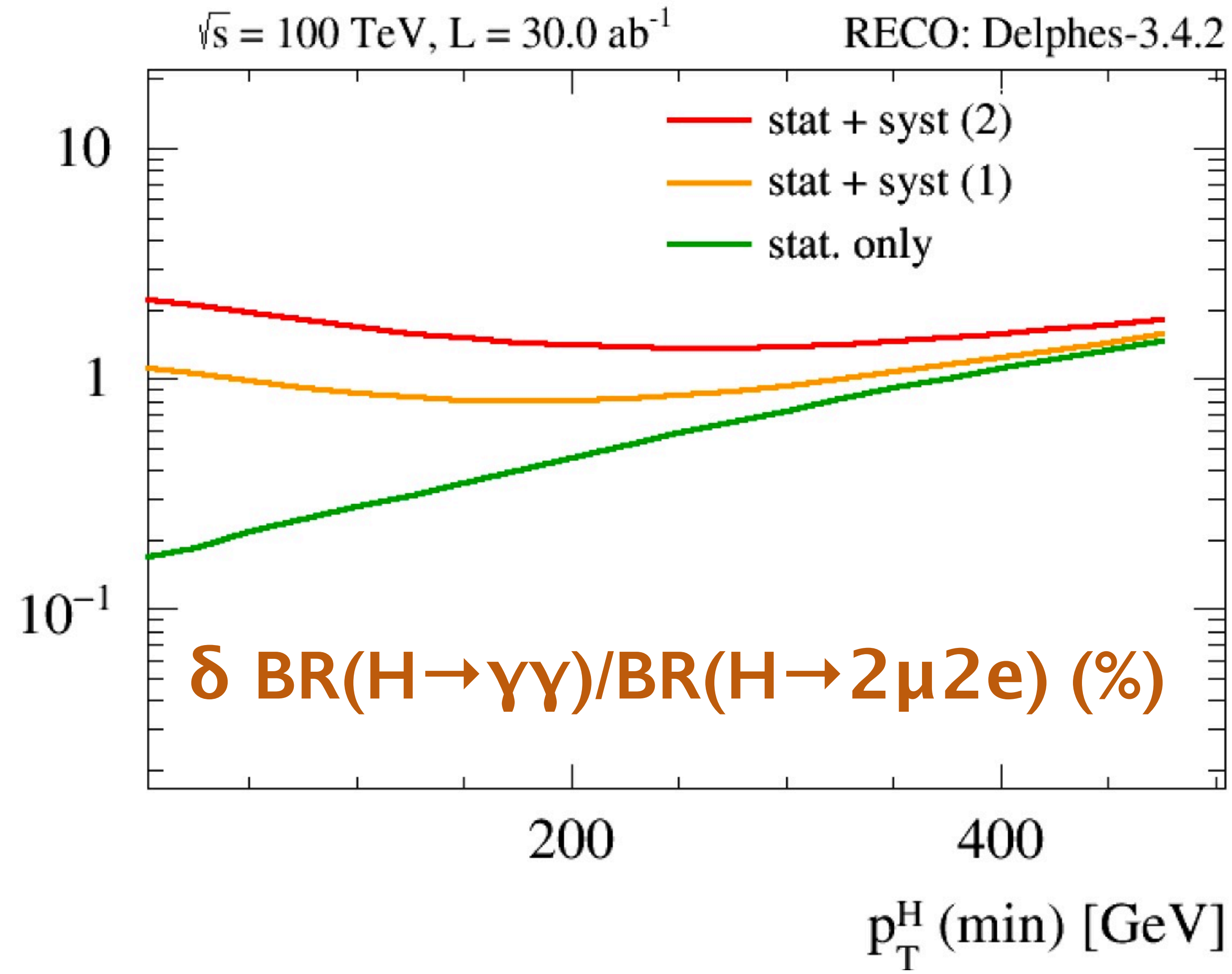
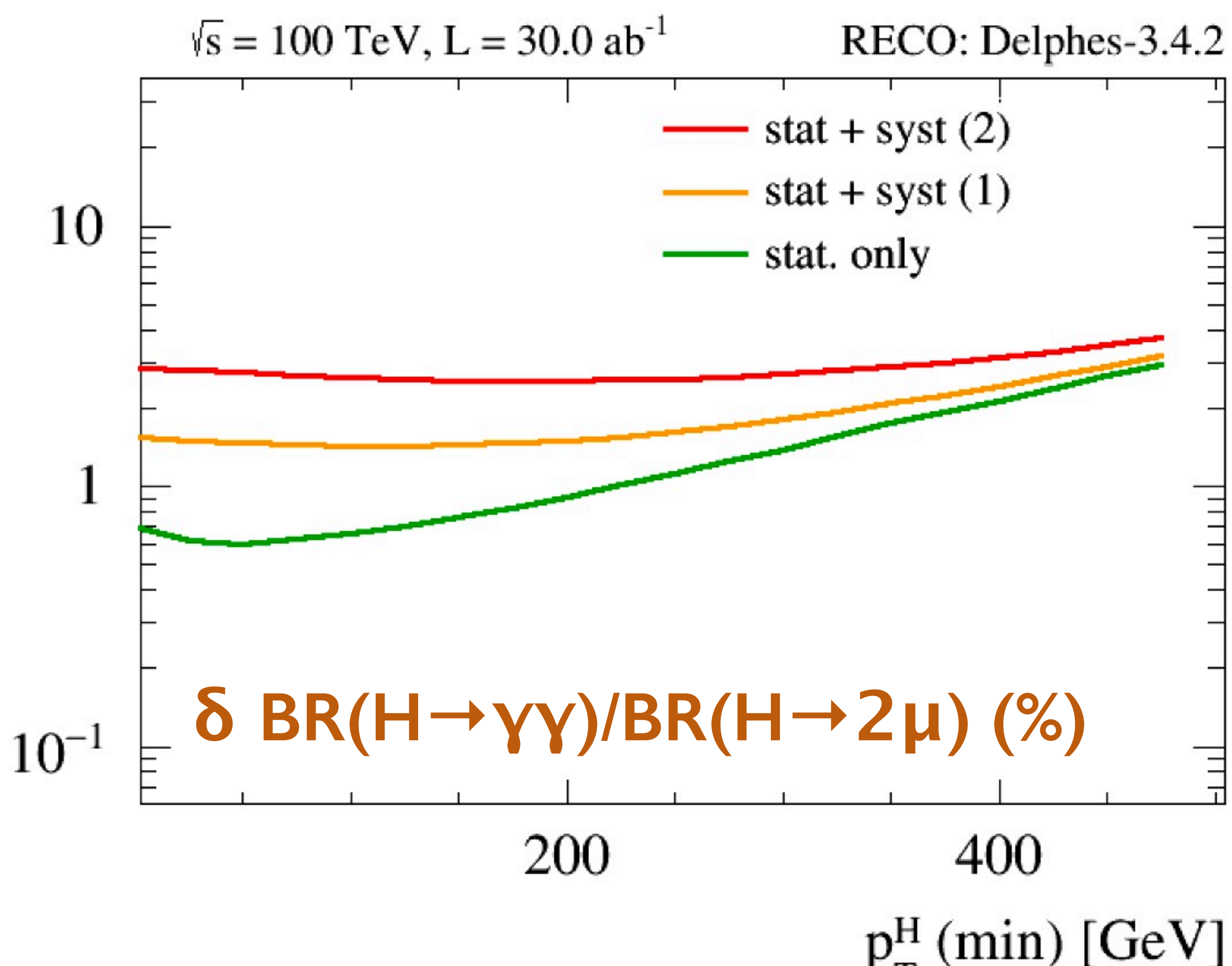
could be seen as syst in the normalization of production*lumi wrt standard candles such as pp→Z→ee





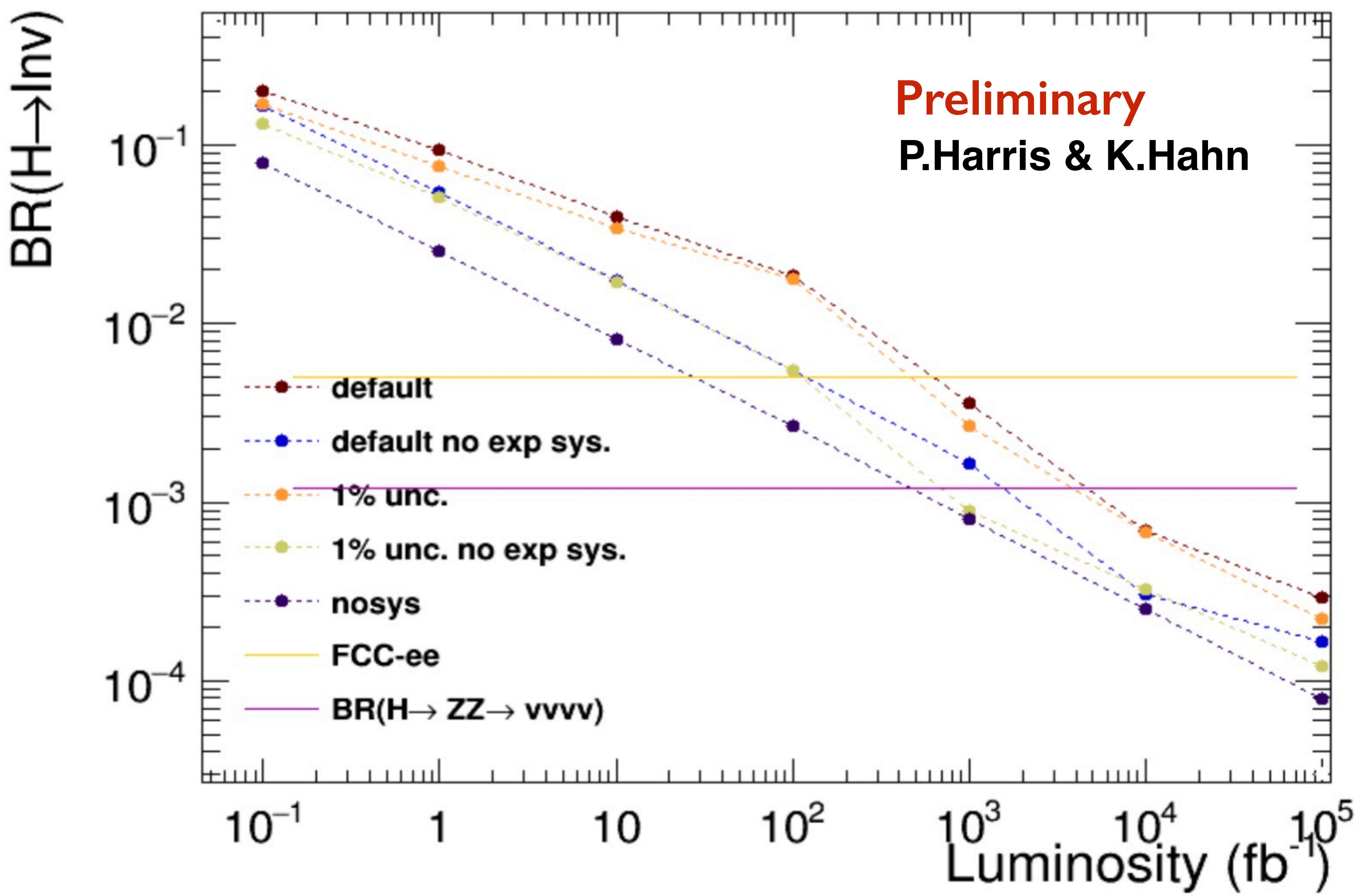


Normalize to BR(4l) from FCC-ee at 1% level => absolute sub-% for couplings

M.Selvaggi

BR(H→inv) in H+X production at large $p_T(H)$

Constrain bg pt spectrum from $Z\rightarrow\nu\nu$ to the % level using NNLO QCD/EW to relate to measured $Z\rightarrow ee$, W and γ spectra



SM sensitivity with 1ab^{-1}, can reach few x 10^{-4} with 30ab^{-1}

Table 1.2: Target precision for the parameters relative to the measurement of various Higgs couplings, the Higgs self-coupling λ, Higgs branching ratios B and ratios thereof. Notice that lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.

Observable	Parameter	Precision (stat)	Precision (stat+syst)
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$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.2%	1.6%
$\mu = \sigma(t\bar{t}H) \times B(H \to b\bar{b})$	$\delta\mu/\mu$	1%	tbd
$\mu = \sigma(HH) \times B(H \to \gamma\gamma)B(H \to b\bar{b})$	$\delta\lambda/\lambda$	3.5%	5.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.6%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
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$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

Study for $B(H \to Z\gamma)$ in progress

first probe of the Higgs potential beyond the 2-point function

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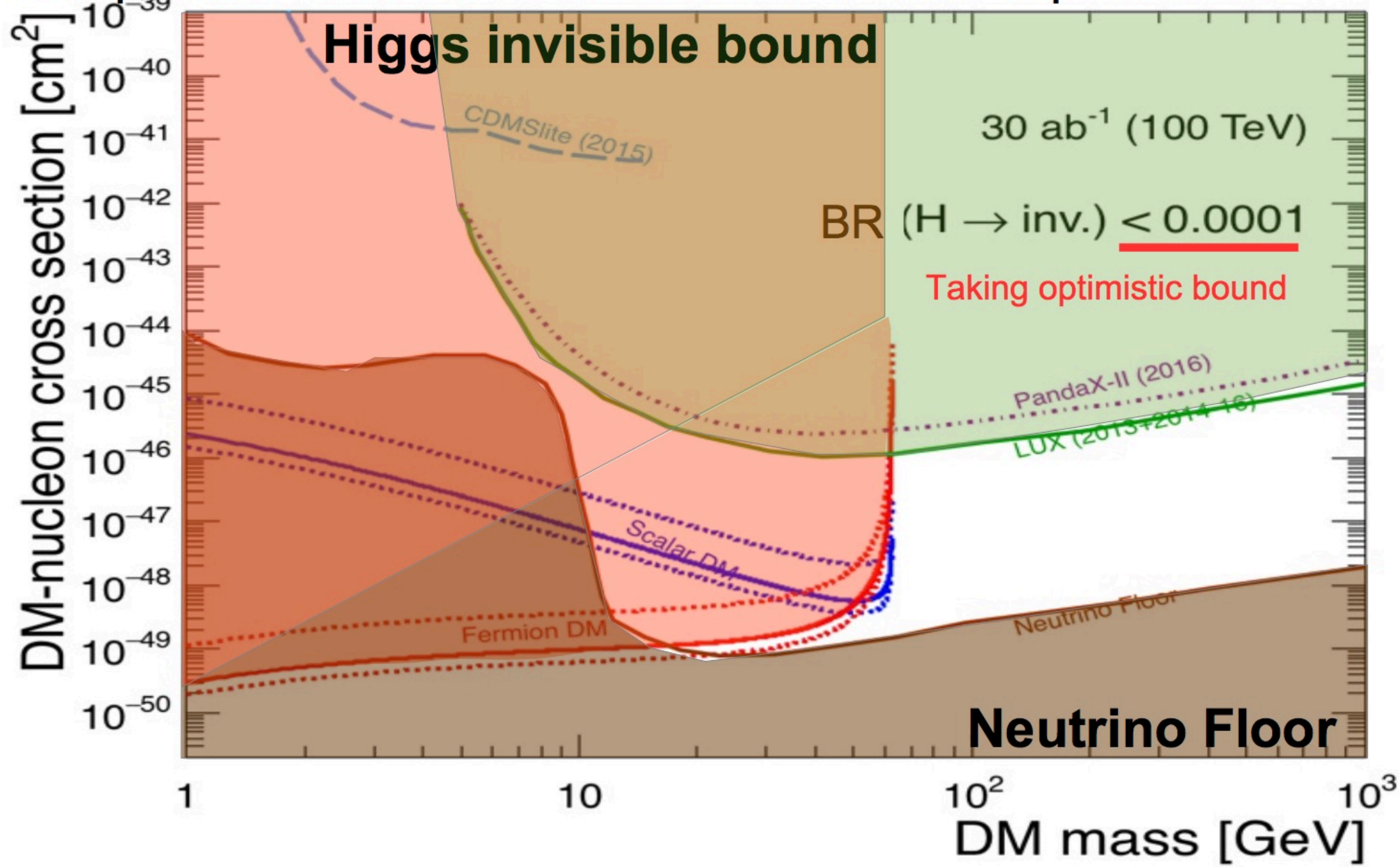
Study for B(H→Zγ) in progress

sensitive to possible Higgs-to-DM decays

P.Harris & K.Hahn

Impact on DM bounds

Competitive with the best direct detection experiments



Higgs invisible of 10^{-4} corresponds to g_{SM} from 10^{-3} to 10^{-2}

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- ***Sensitivity*** may not require extreme precision
  - Going after "sensitivity", rather than *just* precision, opens itself new opportunities …

Higgs as a BSM probe: precision vs dynamic reach

$$\boxed{L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots}$$

$$O = |\, \langle f|L|i\rangle \,|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

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⇒ **precision** probes large Λ

e.g. $\delta O = 1\% \Rightarrow \Lambda \sim 2.5$ TeV

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For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

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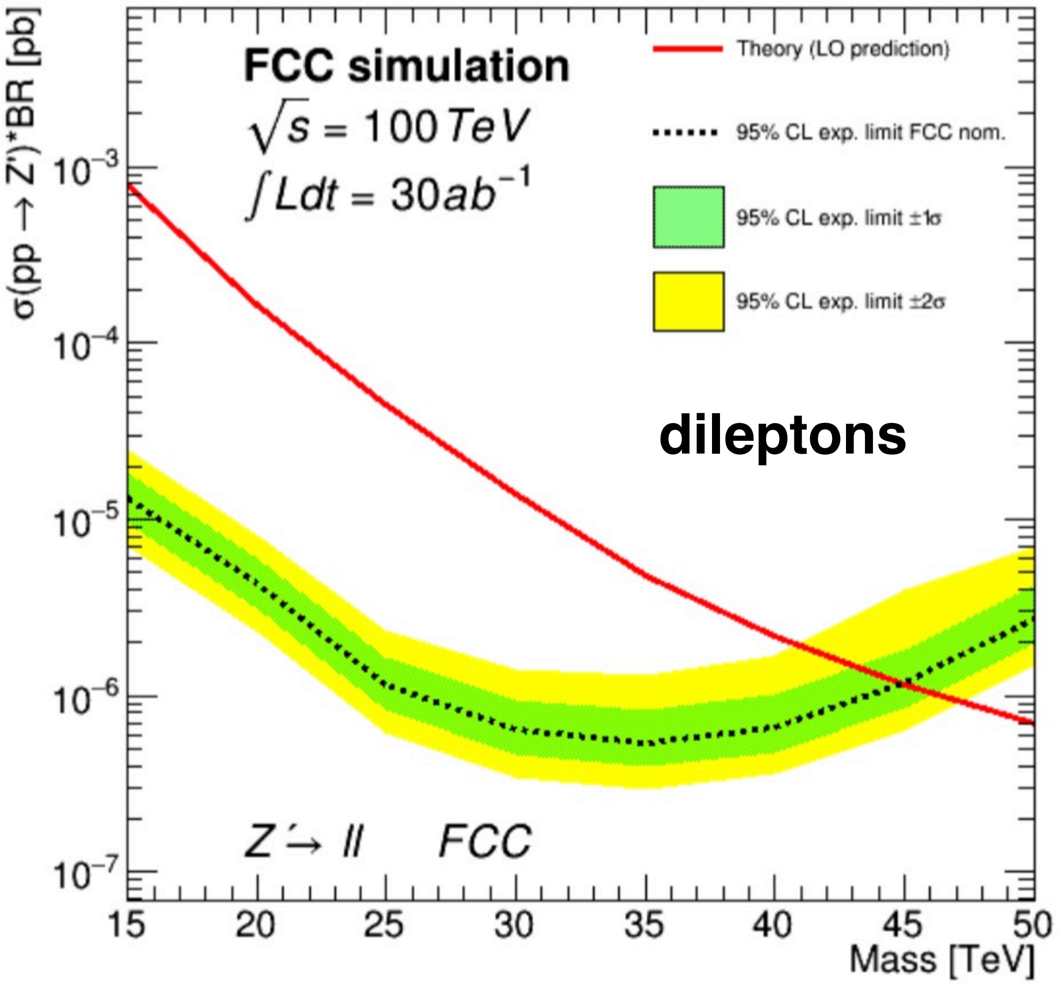
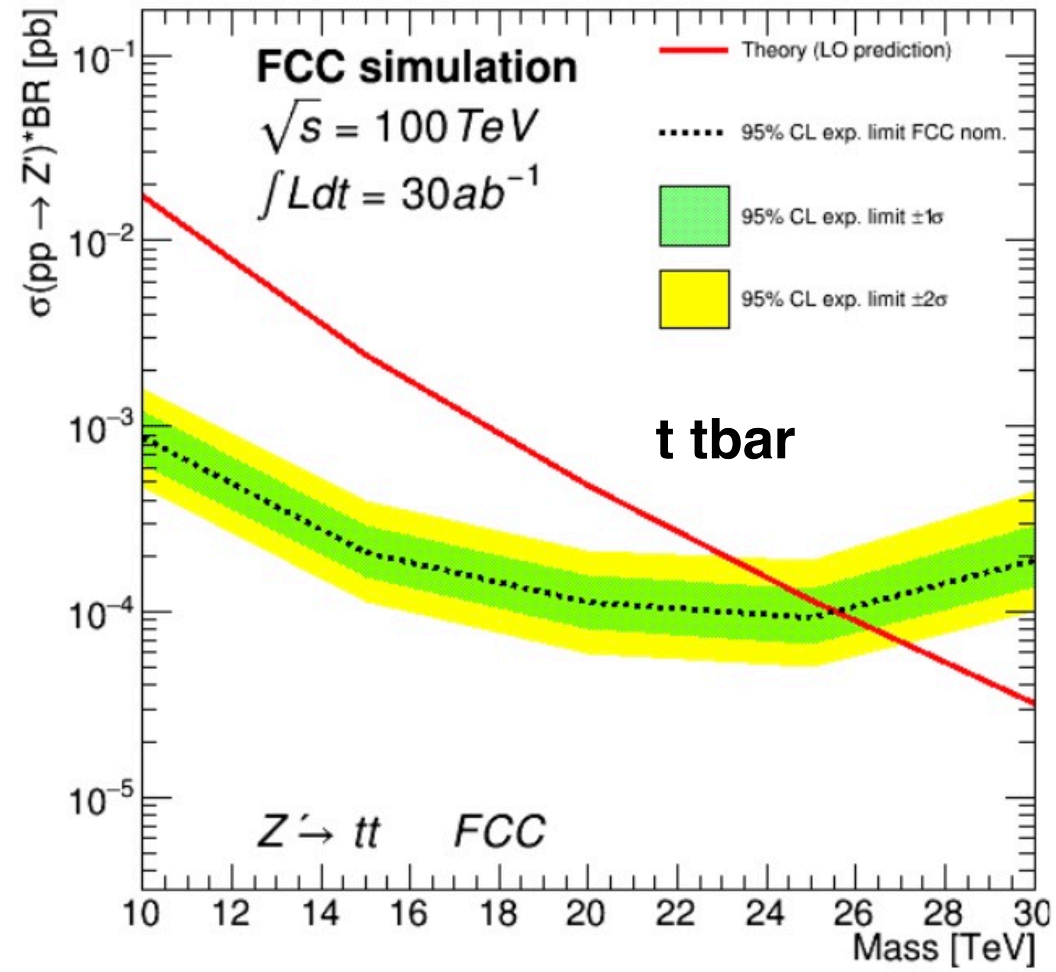
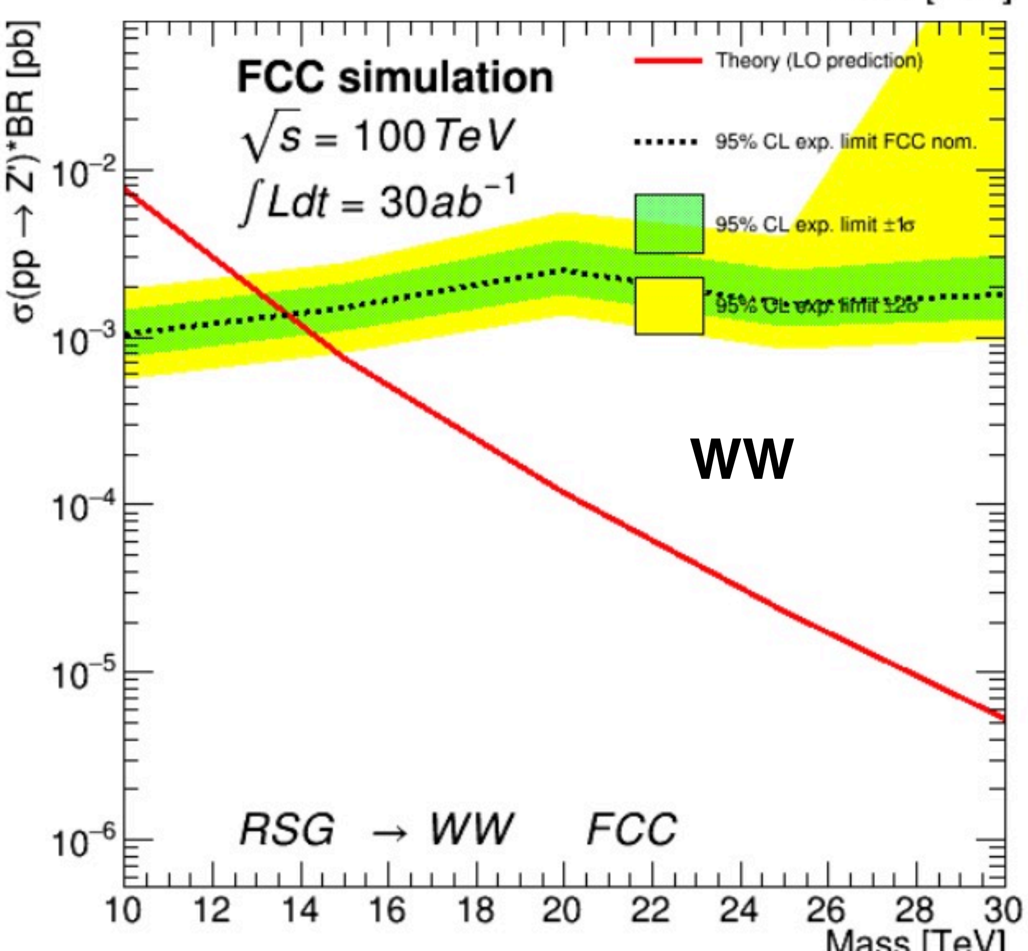
Complementarity between super-precise measurements at ee collider and large-Q studies at 100 TeV

Examples: direct discovery reach

Resonances: SSM Z'

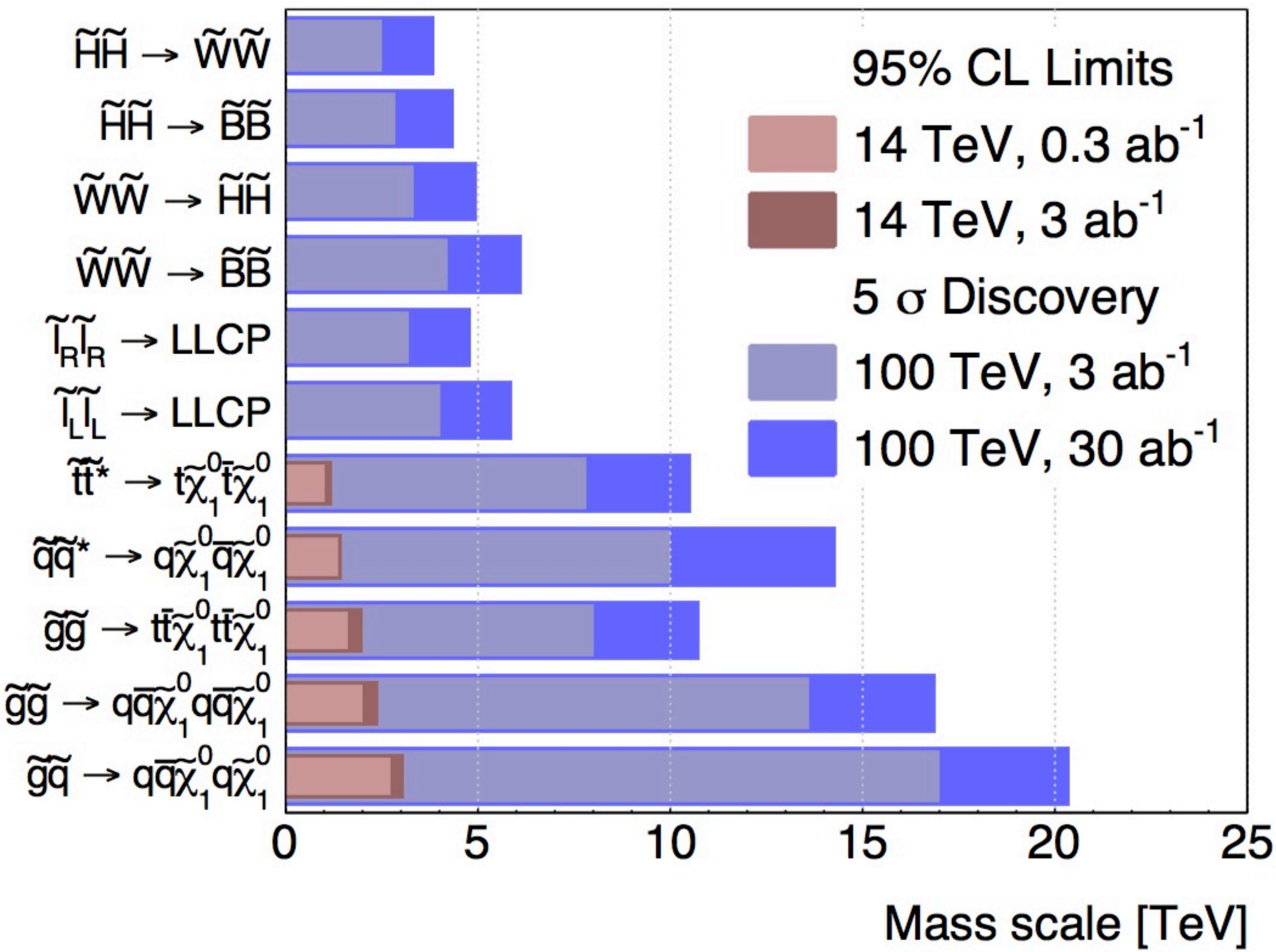




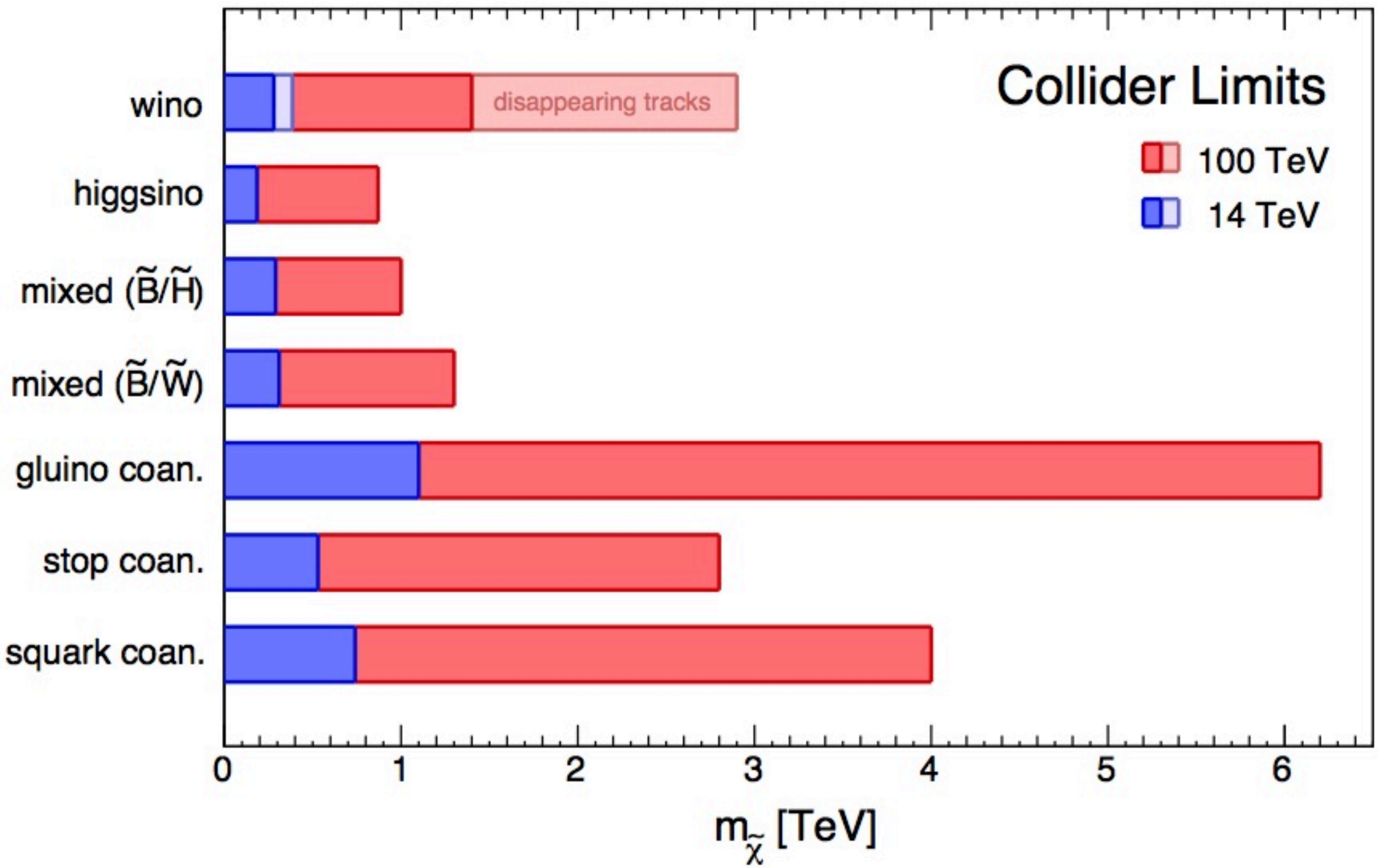


C. Helsens & M. Selvaggi + Summer students
Rachel Smith UIUC and Ine Arts UA

SUSY reach at 100 TeV



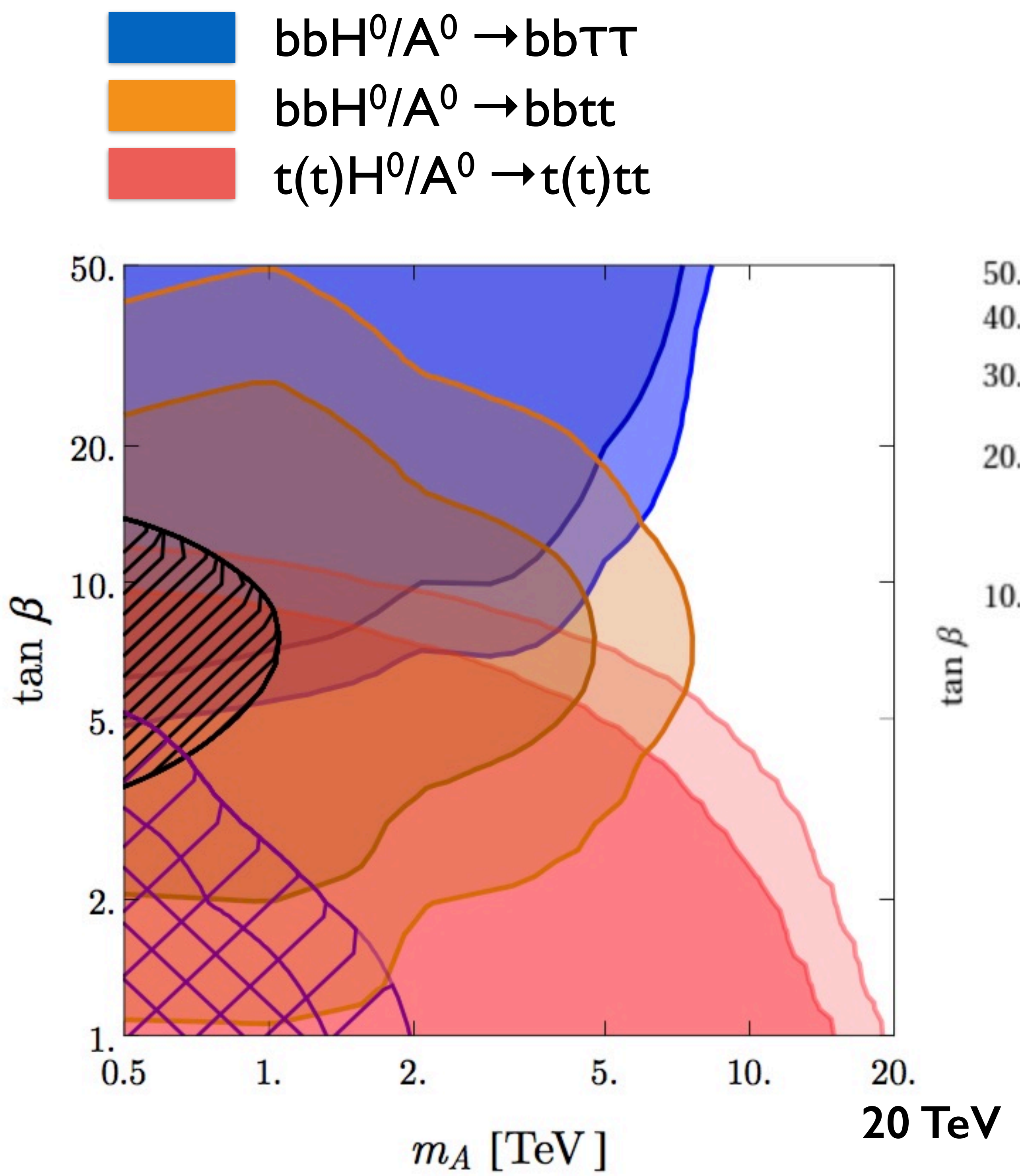
DM reach at 100 TeV

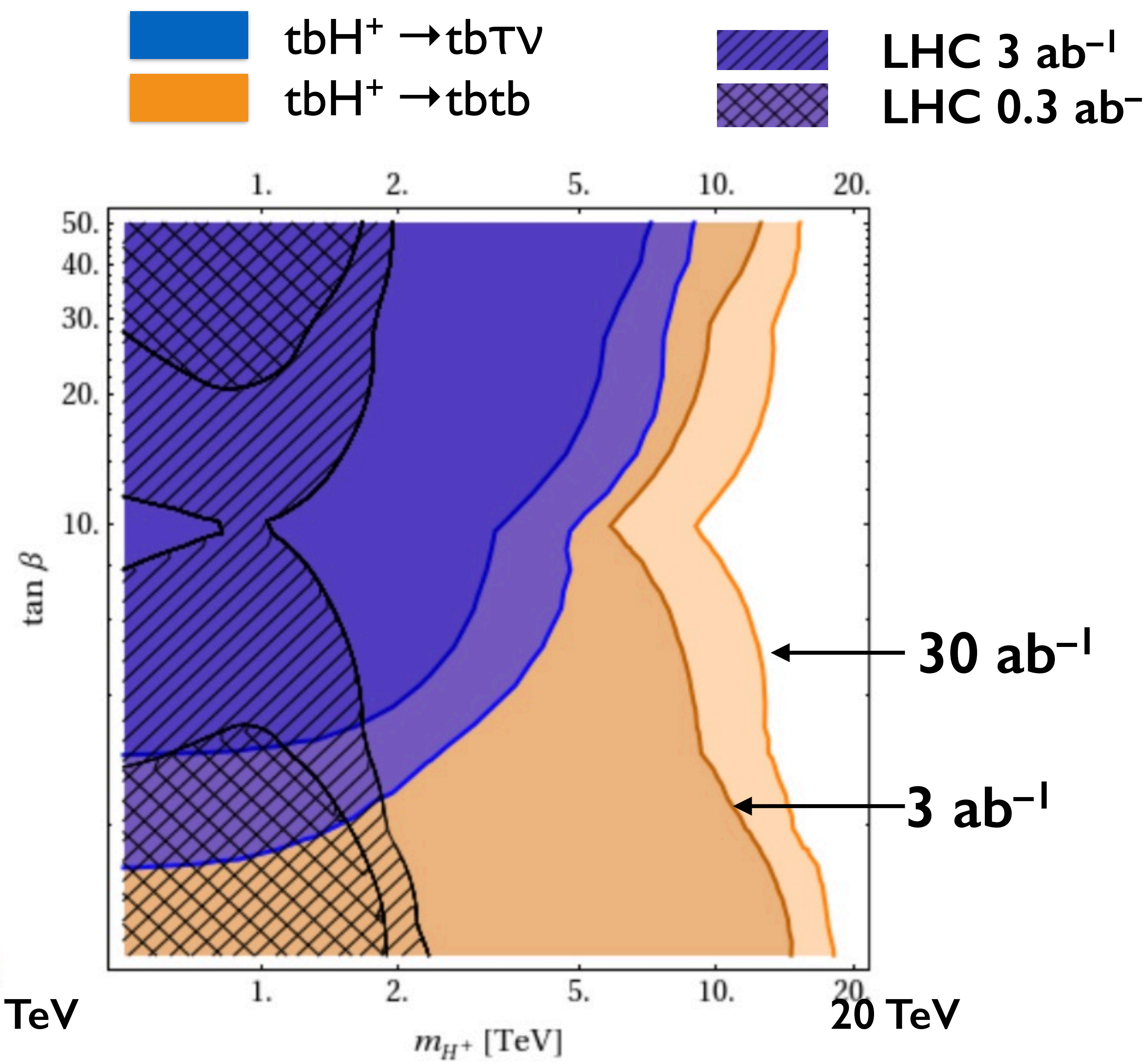


$$M_{\rm WIMP} \leq 1.8\ {\rm TeV}\left(\frac{g^2}{0.3}\right)$$

→ **possibility to find (or rule out) thermal WIMP DM candidates**

MSSM Higgs @ 100 TeV





N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang, arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617

HE-LHC physics potential: domains to be evaluated

(1) extension of the LHC direct search for new particles (approximately doubling its mass reach);

(2) the Higgs self-coupling: establishing firm evidence for the structure of the symmetry-breaking Higgs potential;

(3) increased precision in the measurements made by the LHC, and the consequent increased sensitivity to new physics (indirectly to high mass scales, and, directly, to elusive final states such as dark matter);

(4) exploration of future LHC discoveries, confirmation of preliminary signs of discovery from the LHC, or the search for the underlying origin of new phenomena revealed indirectly **(e.g. the flavour anomalies under discussion nowadays)** or in experiments other than the LHC ones (e.g. dark matter or neutrino experiments).

(1) extension of mass reach for discovery: generic results

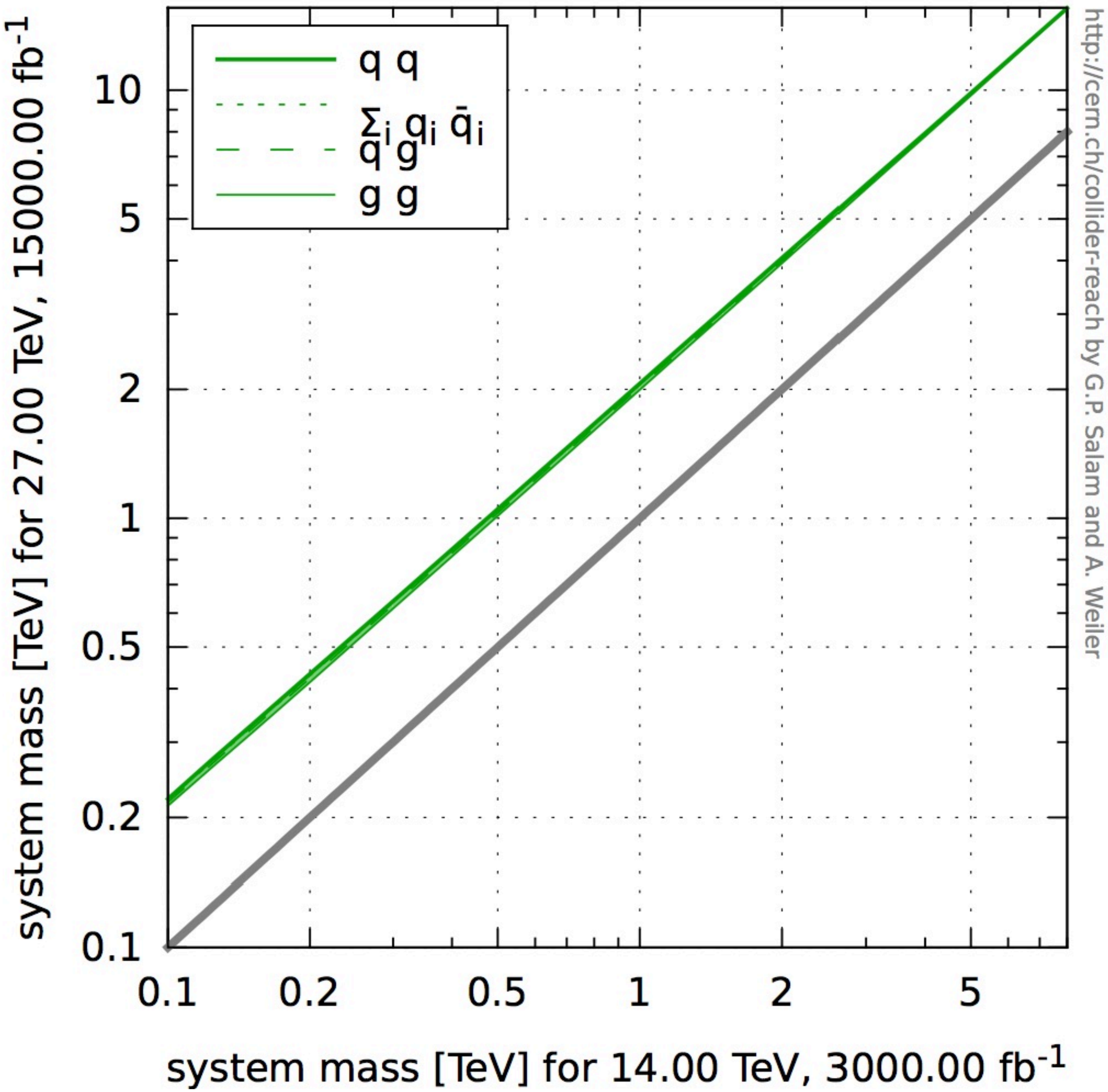


Figure 1.1: Estimate of the system mass (e.g. $m_{Z'}$ or $2m_{\tilde{g}}$) that can be probed in searches for new particles at HE-LHC, given an established system mass reach at HL-LHC.

G. Salam and A. Weiler, *Collider Reach*, `http://collider-reach.web.cern.ch/`.

(1) extension of mass reach for discovery: "natural" supersymmetry examples

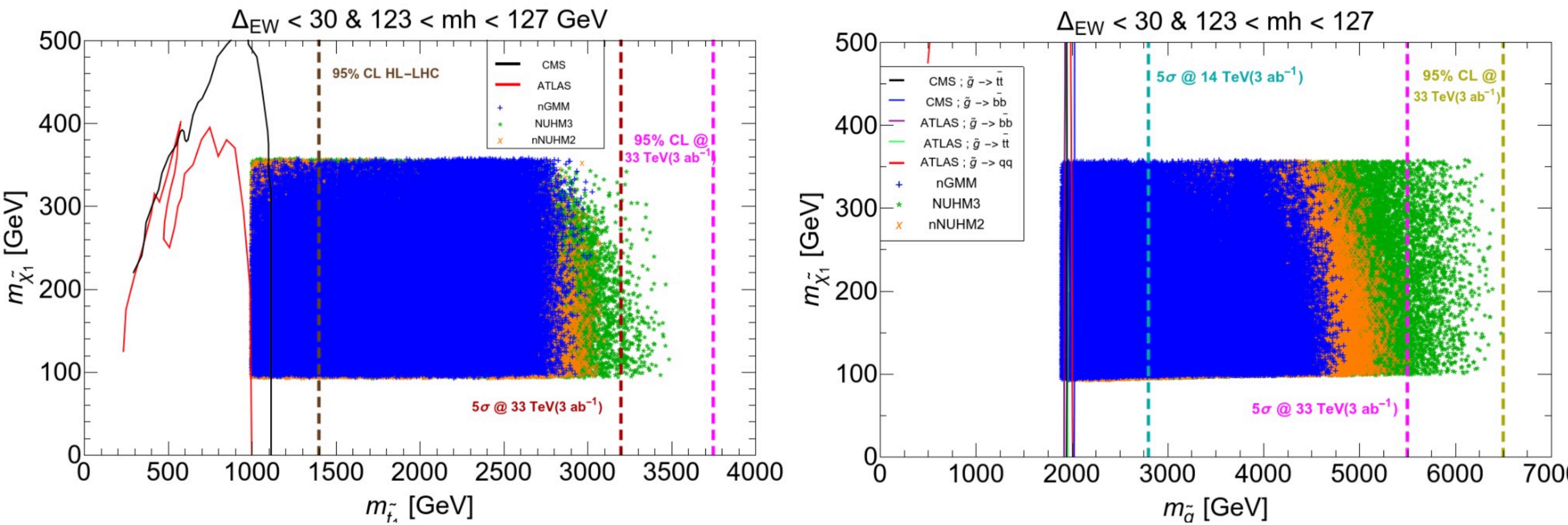


Figure 1.2: Discovery reach at the HE-LHC for gluinos and stops in various, compared to the HL-LHC reach and to the expectations of a several classes of natural supersymmetric models.

H. Baer, *talk at the Fermilab Workshop on HL-HE/LHC Physics, April 2-4 2018*, https://indico.fnal.gov/event/16151/session/4/contribution/46/.

For recent 27 TeV projections of DM WIMP searches:

T. Han, S. Mukhopadhyay, and X. Wang, *Electroweak Dark Matter at Future Hadron Colliders*, arXiv:1805.00015 [hep-ph].

(II+III) precision measurements and EWSB probes: Higgs observables

Examples of goals in the Higgs sector:

(a) improve the sensitivity to the Higgs self-coupling

(b) reduce to the few percent level all major Higgs couplings

(c) improve the sensitivity to possible invisible Higgs decays

(d) measure the charm Yukawa coupling

	$gg \to H$	WH	ZH	ttH	HH
N_{27}	2.2×10^8	5.4×10^7	3.7×10^7	4×10^7	2.1×10^6
N_{27}/N_{14}	13	12	13	23	19

$N_{27} = \sigma(27\ \mathrm{TeV}) * 15\ \mathrm{ab}^{-1}$

$N_{14} = \sigma(14\ \mathrm{TeV}) * 3\ \mathrm{ab}^{-1}$

(II+III) precision measurements and EWSB probes: Higgs observables

- First results on Higgs selfcouplings measurement:

D. Gonçalves, T. Han, F. Kling, T. Plehn, and M. Takeuchi, *Higgs Pair Production at Future Hadron Colliders: From Kinematics to Dynamics*, arXiv:1802.04319 [hep-ph].

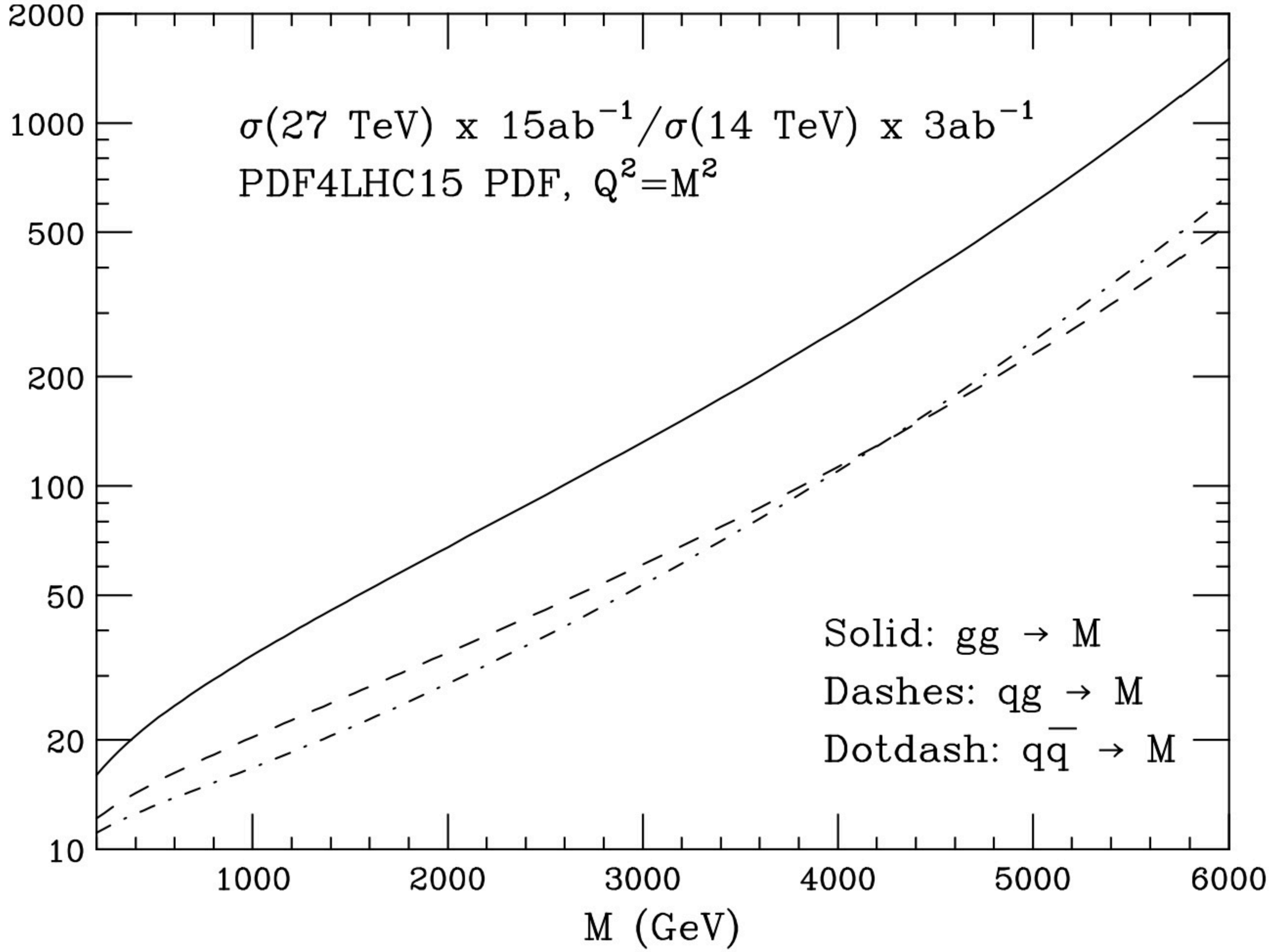
λ/λ_{SM} =1±0.3 at 95%CL (1±0.15 at 68%CL)

(compare to $-0.2 < \lambda/\lambda_{SM} < 2.6$ at HL-LHC)

F. Kling, T. Plehn, and P. Schichtel, *Maximizing the significance in Higgs boson pair analyses*, Phys. Rev. **D95** (2017) no. 3, 035026, arXiv:1607.07441 [hep-ph].

- For couplings like Hγγ, HZγ, Hμμ, Htt, … , plan to repeat studies presented at 100 TeV

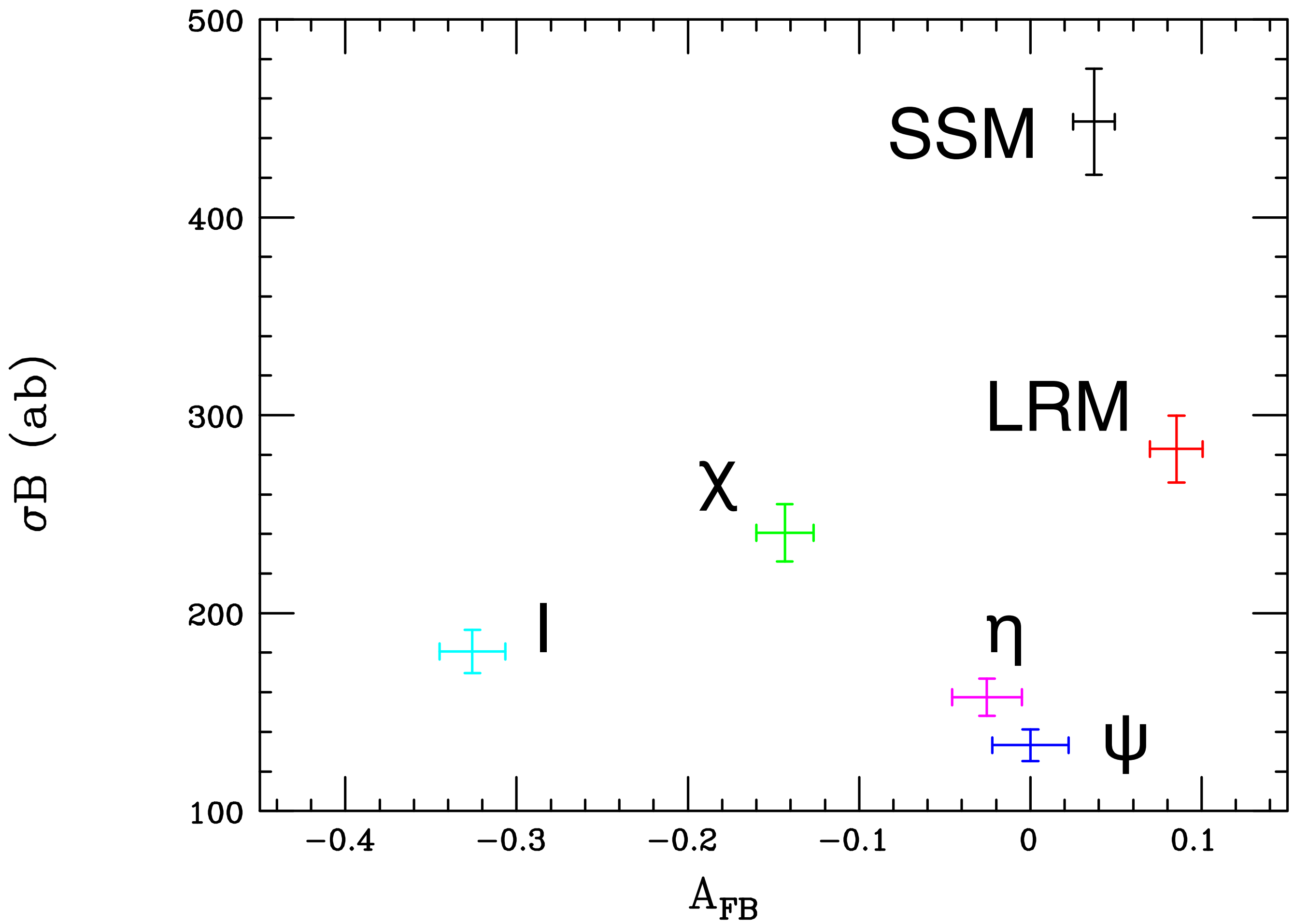
(IV) Exploration at 27 TeV of LHC discoveries: generic results

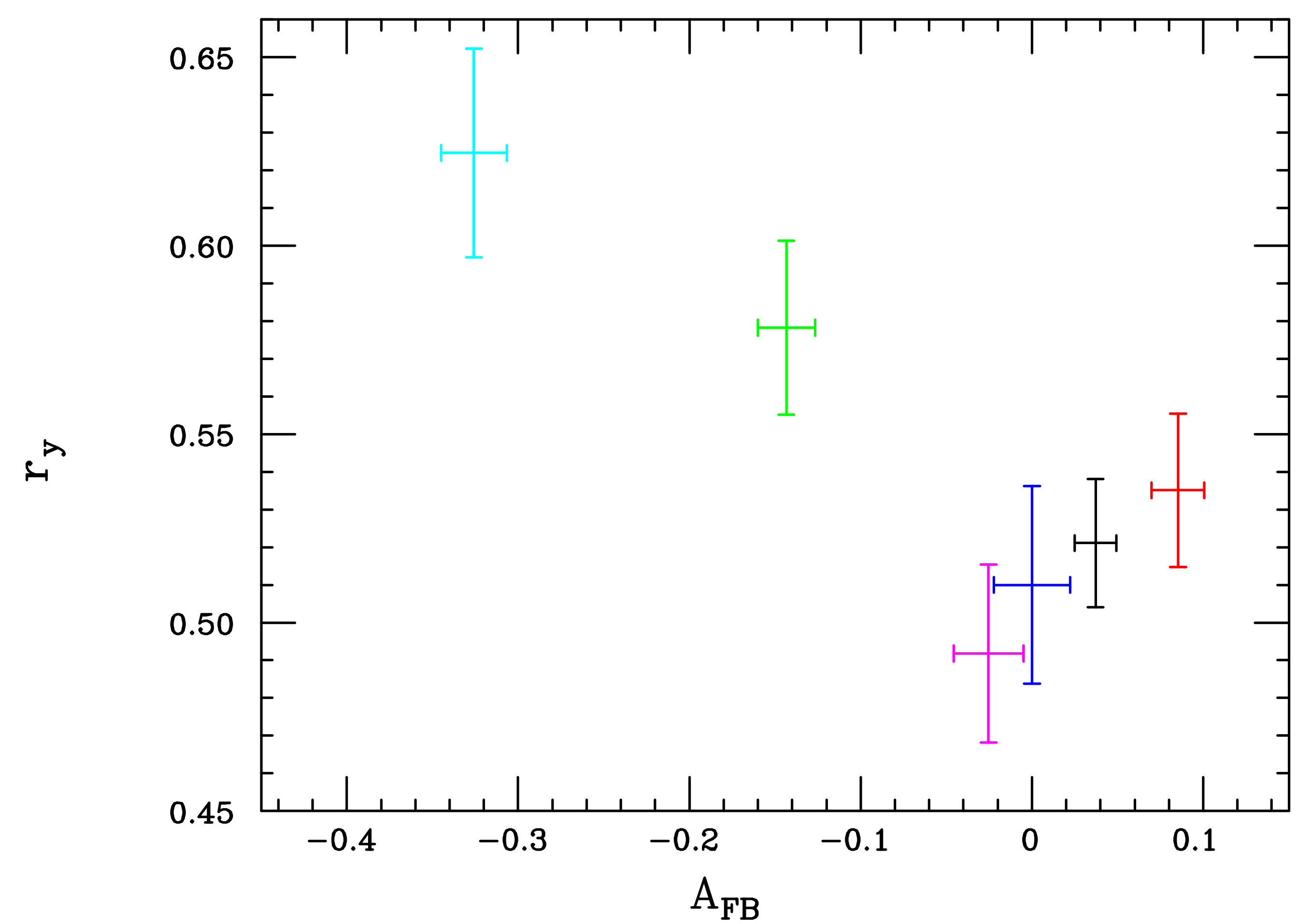


(IV) Exploration at 27 TeV of LHC discoveries: characterization of Z' models within reach of LHC observation

NB: uncertainty bars reflect very conservative syst assumptions

T. Rizzo, *work in progress,*

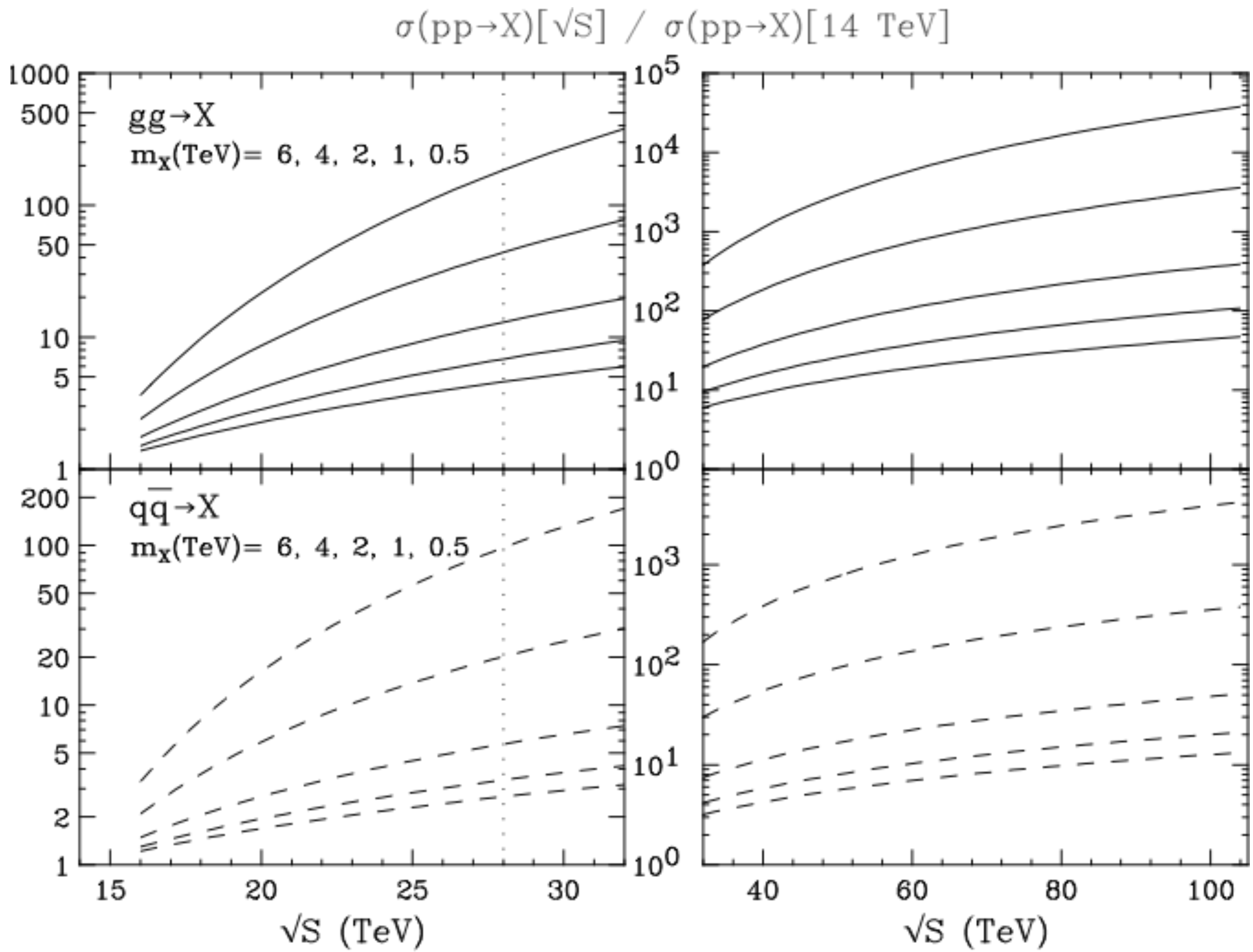




Colours: different Z' models, leading to observation at HL-LHC in Z'->dilepton decay for m(Z')=6 TeV

T. G. Rizzo, *Exploring new gauge bosons at a 100 TeV collider*, Phys. Rev. **D89** (2014) no. 9, 095022, arXiv:1403.5465 [hep-ph].

27 or 100? √S evolution of LHC discovery scenarios



Possible questions/options

- If m_X ~ 6 TeV in the gg channel, rate grows x 200 @28 TeV:
  - Do we wait to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?
  - Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$) ?
  - .... and the answers may depend on whether we expect partners of X at masses $\gtrsim 2m_X$ (⇒ *28 TeV would be insufficient ....*)
- If m_X ~ 0.5 TeV in the qqbar channel, rate grows x10 @100 TeV:
  - Do we go to 100 TeV, or push by x10 $\int L$ at LHC?
  - Do we build CLIC?
- etc.etc.

Final remarks

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- The physics case of a 100 TeV collider is very clear as a long-term goal for the field, simply because no other proposed or foreseeable project can have direct sensitivity to such large mass scales.
- Nevertheless, the precise route followed to get there must take account of the fuller picture, to emerge from the LHC as well as other current and future experiments in areas ranging from flavour physics to dark matter searches.

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

18-20 June 2018
CERN

https://indico.cern.ch/event/686494/

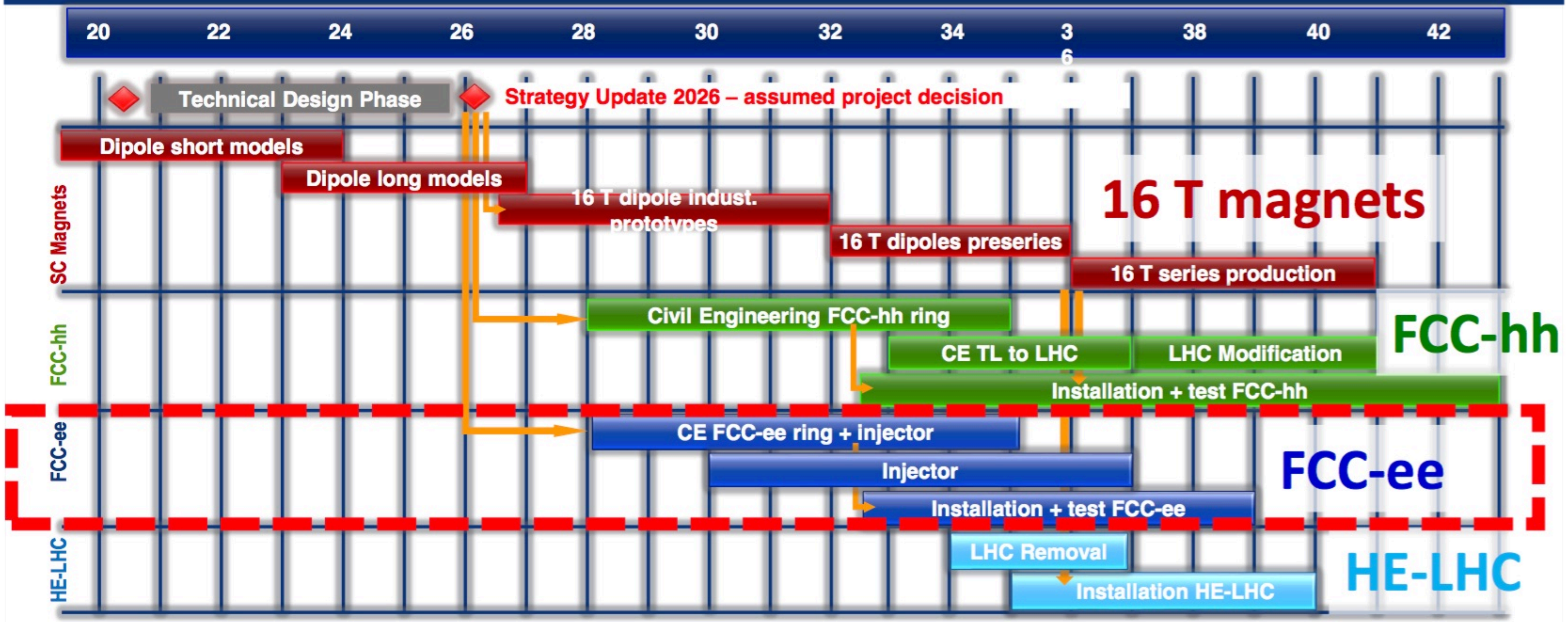
Search...

Next general mtg: June 18-20, CERN, https://indico.cern.ch/event/686494/

Workshop twiki pages: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop

To join the mailing list, click here

Technical Schedule for each the 3 Options



schedule constrained by 16 T magnets & CE
→ earliest possible physics starting dates
- **FCC-hh: 2043**
- **FCC-ee: 2039**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

M. Benedikt