FCC Complementarity: BSM

First FCC Physics Workshop

Jan 10th 2017

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Plan

Complementarity: "A relationship or situation in which two or more different things improve or emphasize each other's qualities."

Synergy: "The interaction or cooperation of two or more organizations, substances, or other agents to produce a combined effect greater than the sum of their separate effects."

Plan

This talk will be structured around four interpretations of physics complementarity/synergy:

FCC Complementarity: "Different FCC Colliders...

...explore the same parameter space of a model in physically distinct ways."

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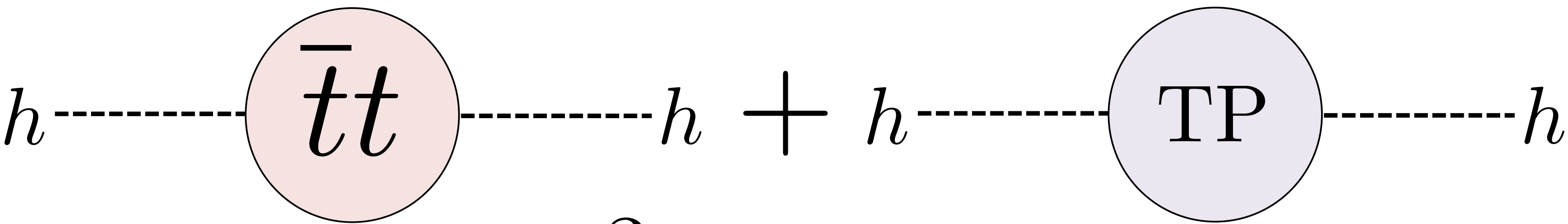
…require different BSM theory assumptions, giving a more "model independent" result in combination."

To finish: some unanswered questions.

Comprehensive Complementarity

Hierarchy problem solutions typically involve a "Top Partner":



$$\approx \frac{3}{8\pi^2} m_{TP}^2 \log \Lambda$$

If top partner is near the weak scale, Higgs mass corrections logarithmically sensitive to new physics scales, hence naturally light Higgs.

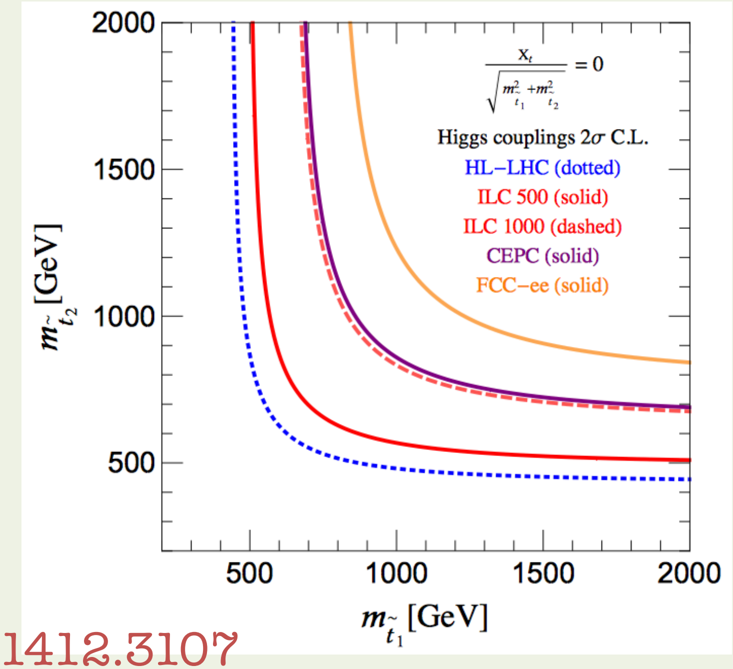
For naturalness expect $m_{TP} \lesssim 400 \text{ GeV}$.

Comprehensive Complementarity

In supersymmetry this is the "stop squark".

FCC-ee

Coloured and charged, stops modify Higgs couplings:



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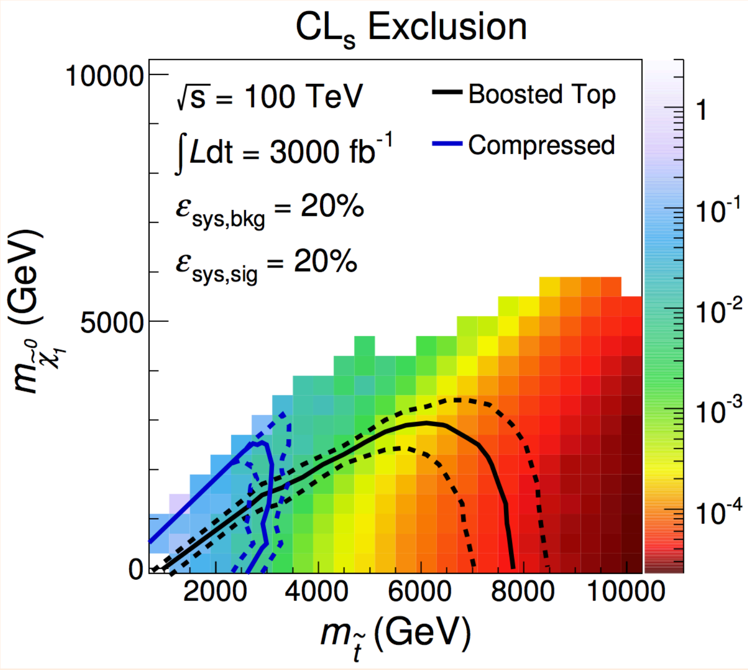
FCC-hh

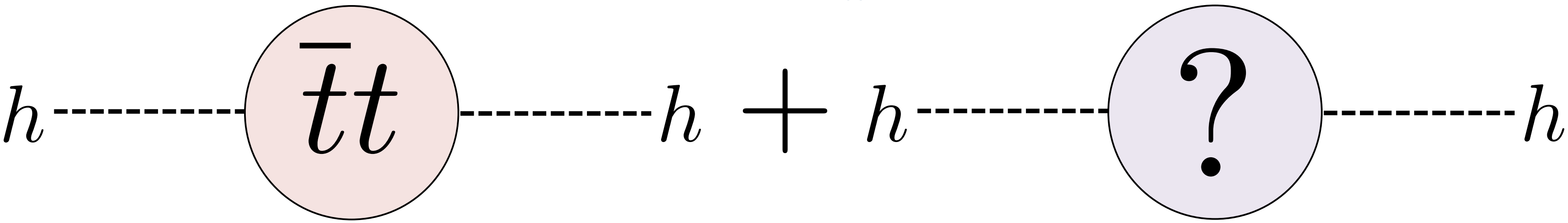
And show up directly at hadron colliders:



FCC-ee: Indirect, but more "spectrum independent", for a model.
FCC-hh: Direct confirmation, but direct might be hidden.

Comprehensive Complementarity

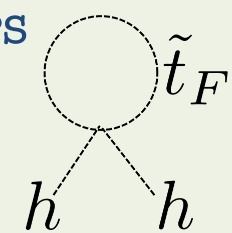
Could there be a hidden "Top Partner"?



Much attention now to alternative ideas:

Folded SUSY hep-ph/0609152

Theory where EW-charged uncoloured scalars are top partners

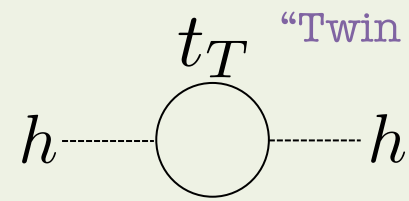


"Folded Stops"

...but they must be charged under new hidden QCD'.

Twin Higgs hep-ph/0506256

Theory where top partners are SM gauge neutral fermions



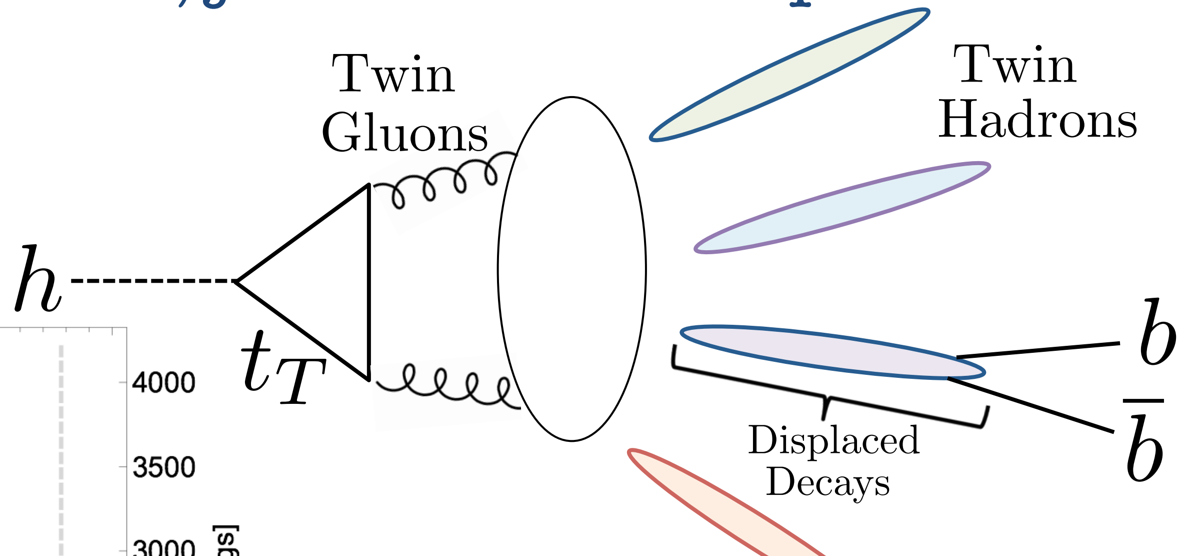
"Twin Tops"

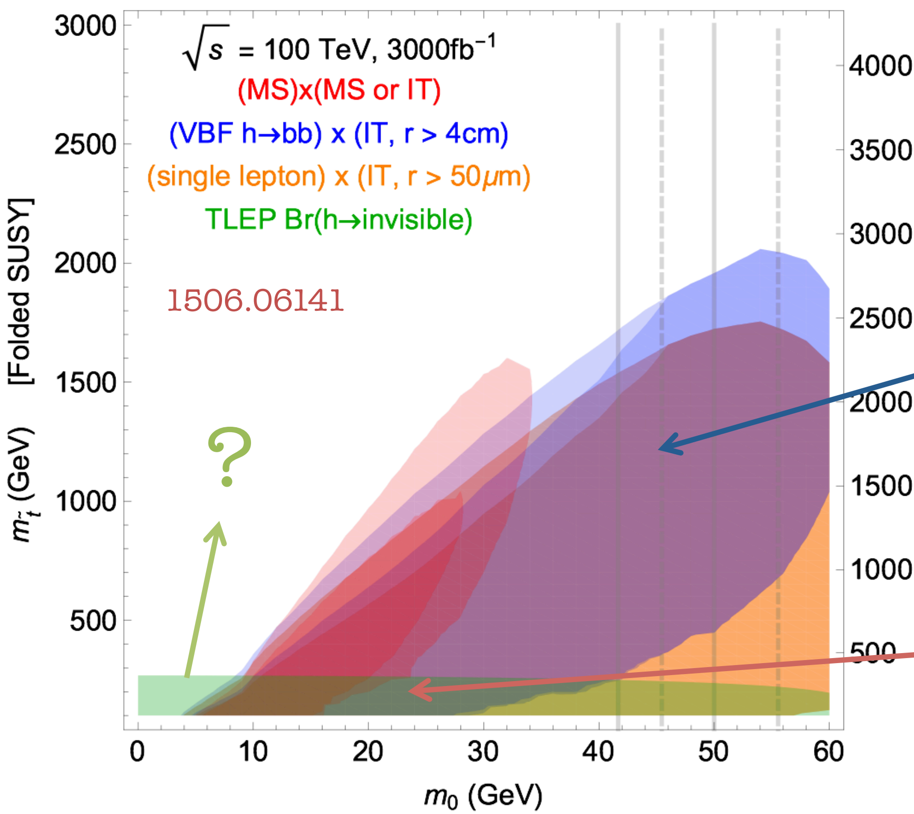
...but they must be charged under new hidden QCD'.

Comprehensive Complementarity

Naturalness not hidden, just look in new places...

New hidden sector introduces exotic Higgs decays:



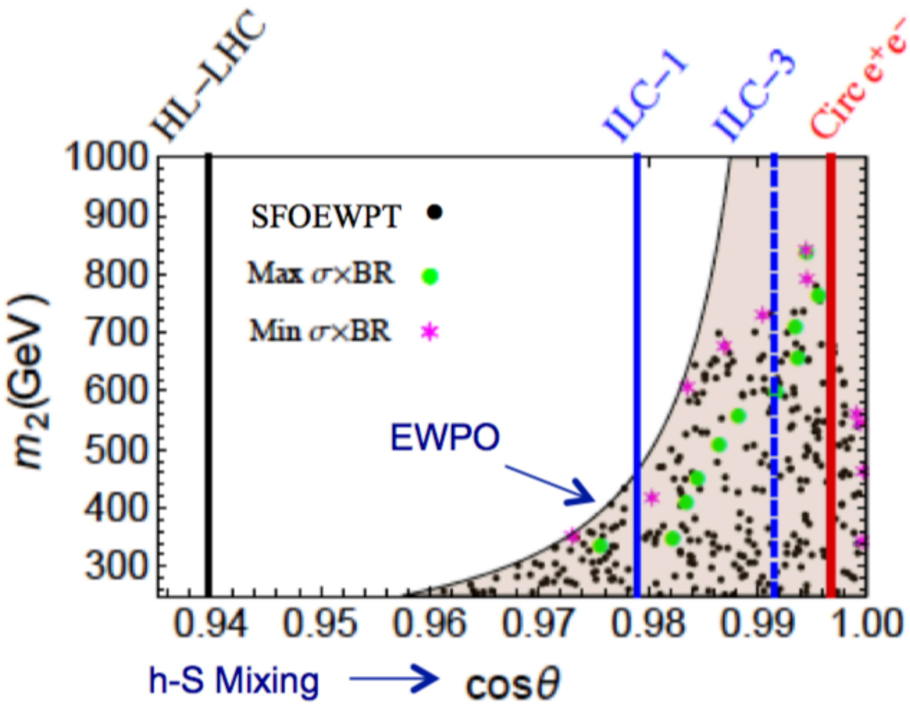


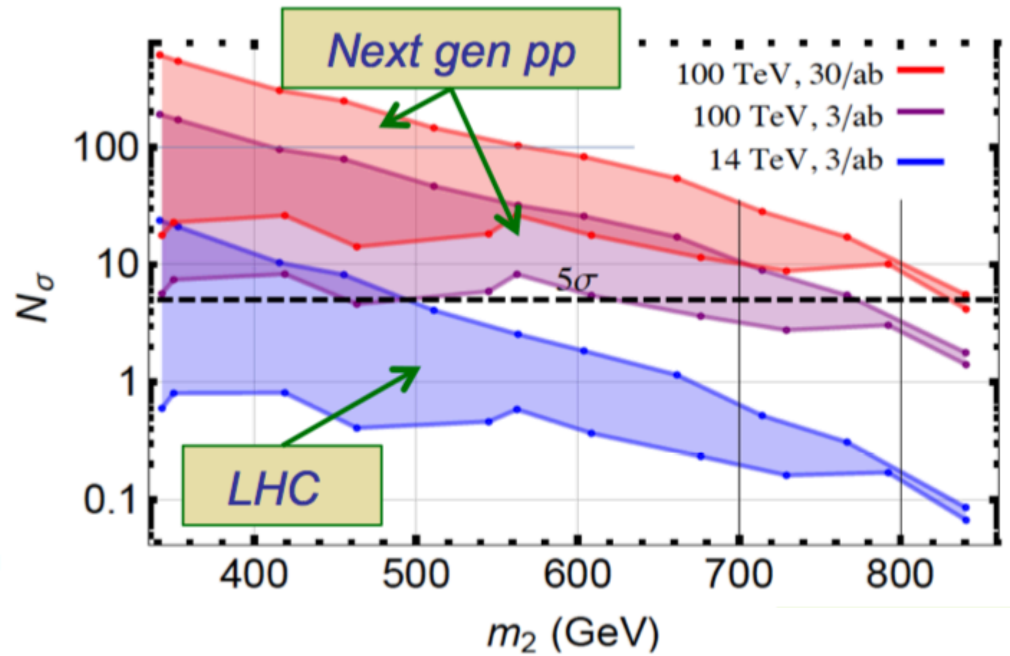
FCC-hh can thoroughly probe larger Twin confinement scales through displaced searches.

FCC-ee has access for light top partners, including for well-motivated low confinement scales.

Comprehensive Complementarity

A similar story also plays out for some models of electroweak baryogenesis…

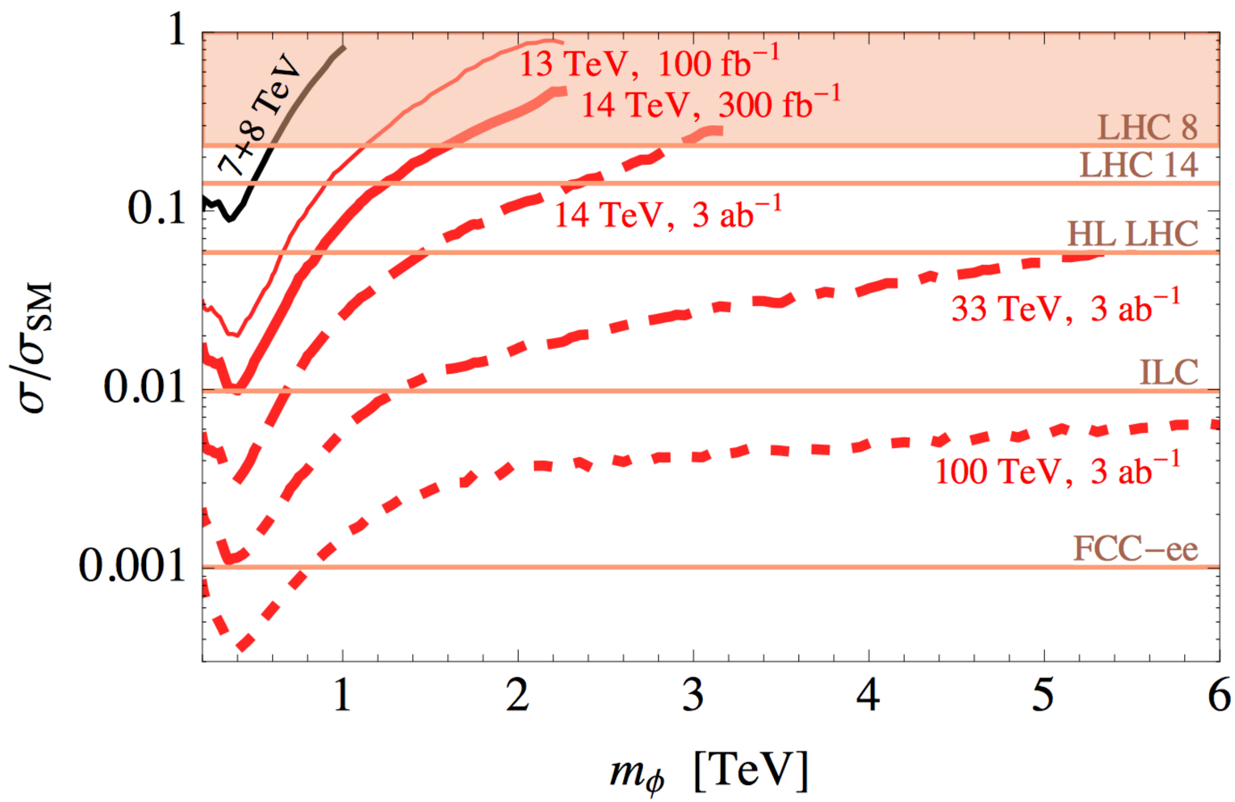




See the earlier talk by Ramsey-Musolf.

Comprehensive Complementarity

And in more general setup, sense of complementarity to high masses for FCC-ee!



See the earlier talk by Buttazzo.

Comprehensive Complementarity

Thus returning to the second notion of complementarity: "Different FCC Colliders explore the same parameter space of a model in physically distinct ways."

Through precision Higgs coupling measurements and precision electroweak constraints FCC-ee will have indirect sensitivity to theories of naturalness.

FCC-hh can also directly probe similar parameter ranges of the same models, to expose the underlying cause of any indirect hints for new physics at FCC-ee.

Comprehensive Complementarity

Thus returning to the second notion of complementarity: "Different FCC Colliders explore the same parameter space of a model in physically distinct ways."

Similar story for FCC-eh for BSM scenarios. See talks on BSM neutrinos, top physics, RPV SUSY etc.

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FCC-hh can also directly probe …
ranges of the same models, to expose the … ng
cause of any indirect hints for new physics at FCC-ee.

Parametric Complementarity

There are models in which there is no preferred mass scale for new particles.

An "Axion-like particle" (ALP) is a canonical example:

$$V_a \approx \frac{\lambda}{4}\left(|(f+\rho)e^{\frac{ia}{f}}|^2 - f^2\right)^2 + \frac{m^2}{2}\left((f+\rho)e^{\frac{ia}{f}}\right)^2 + h.c.$$

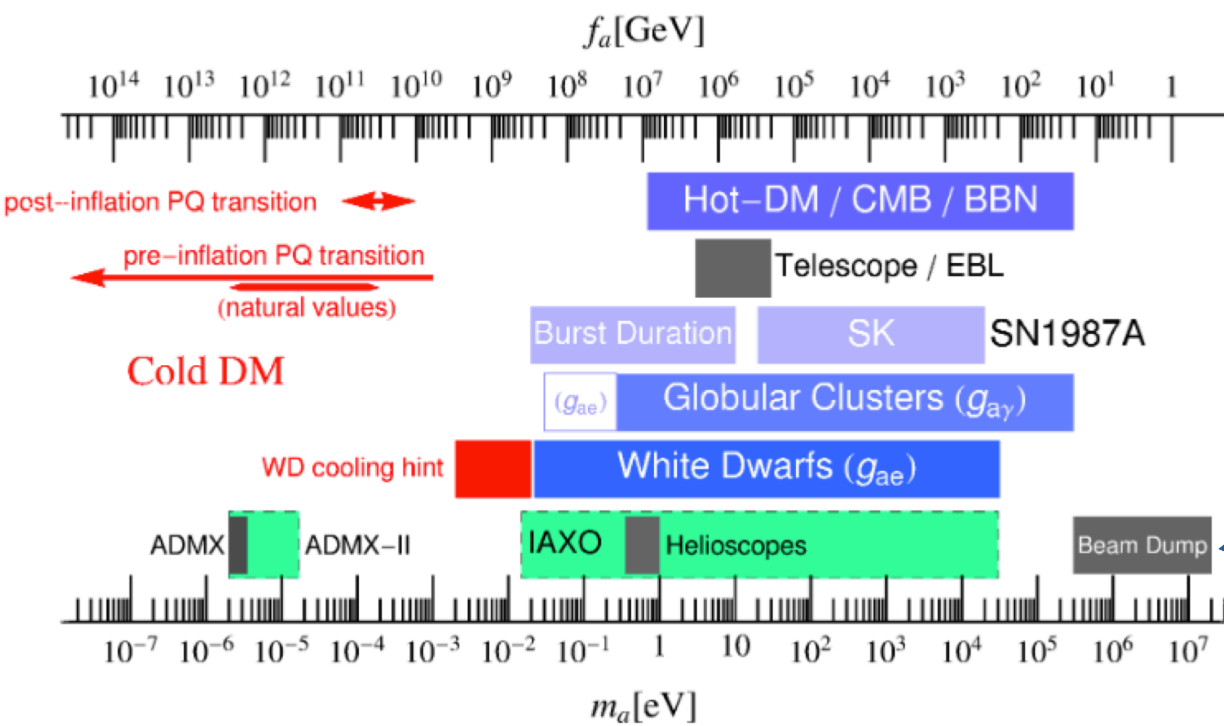
ALPs emerge as pseudo-Goldstone bosons of spontaneously broken global symmetries.

Since the parameter that gives mass breaks a symmetry, it can be naturally small.

Parametric Complementarity

ALPs can also couple to photons, gluons etc,

$$\mathcal{L} \supset \frac{a}{f} B^{\mu\nu} \widetilde{B}_{\mu\nu}$$

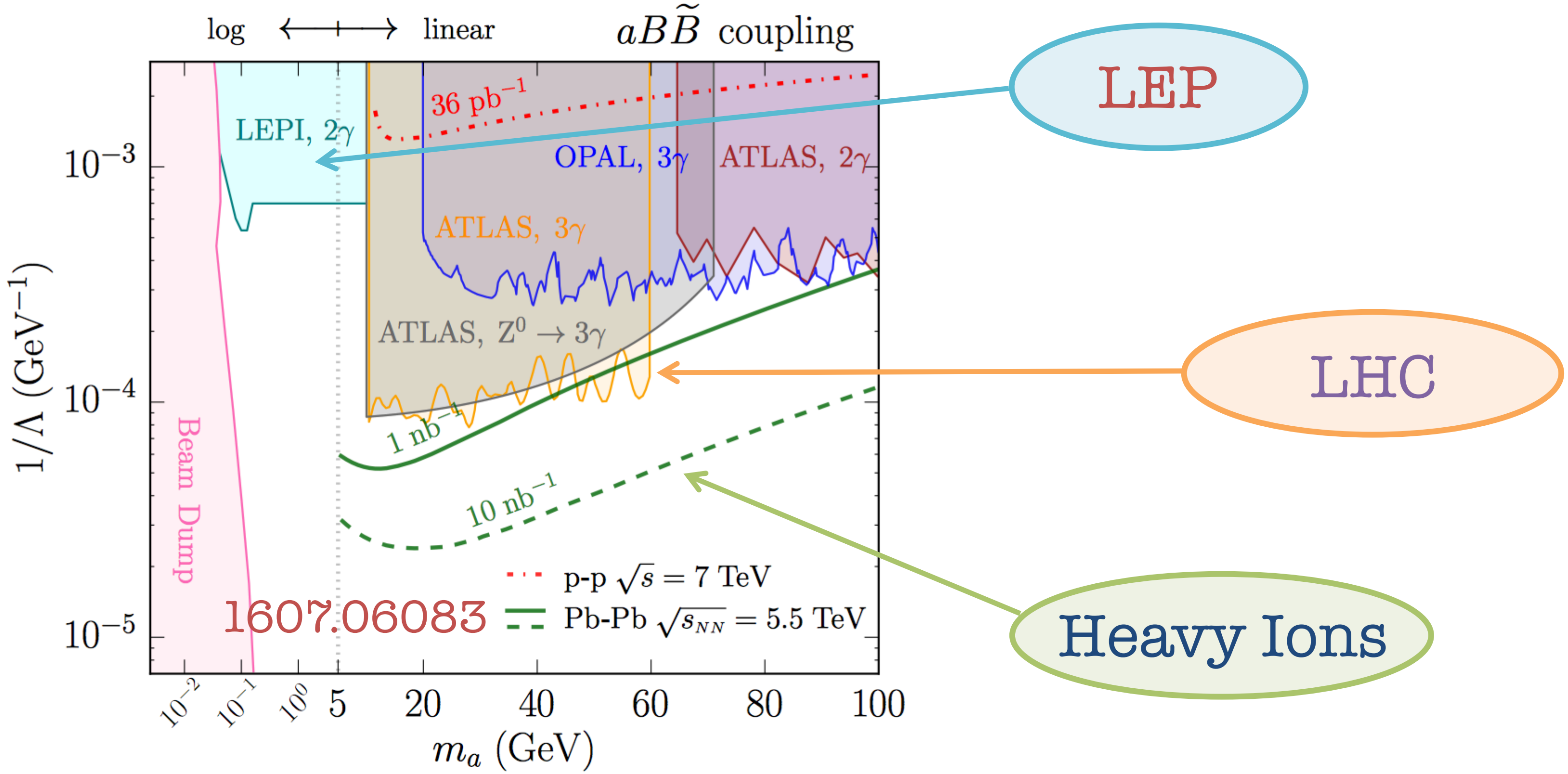


This is why we consider ALPs searches over many orders of magnitude...

But why do so many plots end here?

Parametric Complementarity

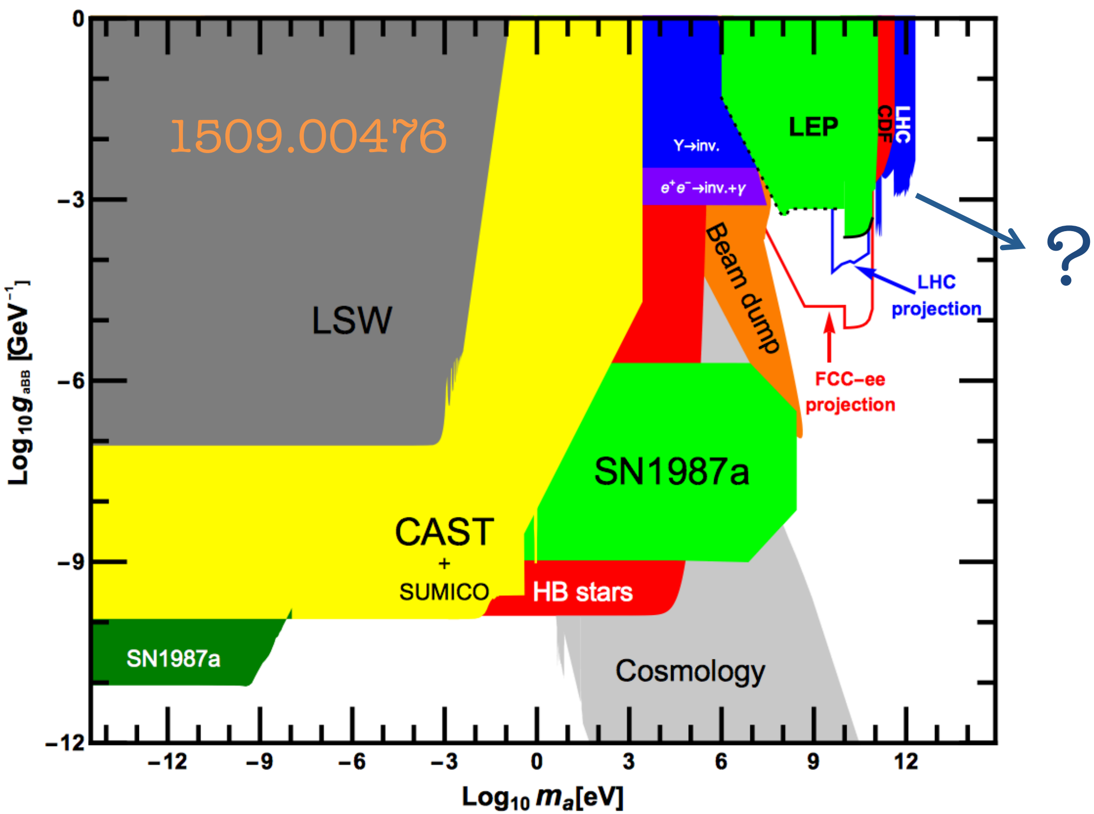
LEP+LHC already proven complementary



Together they fill the gap from beam dumps to weak scale, but not at “intensity frontier”-level cross sections...

Parametric Complementarity

The extra two orders of magnitude luminosity at FCC-ee would push this further, to "intensity frontier level"!



Where should FCC-hh go on this plot?

Due to:

a) CM energy
b) Huge PDFs
c) Large L_{int}

FCC-hh would perform as "intensity frontier": Lower couplings than LHC, and higher masses than FCC-ee.

Parametric Complementarity

Thus returning to the second notion of complementarity: "Different FCC Colliders probe different parameter regions of a model, giving greater exploration of new physics."

Although not yet studied fully, FCC-ee and FCC-hh could push the intensity frontier of searches for axion-like particles (and probably also Z' bosons), to higher masses and weaker interactions.

Systematic Complementarity

To search for BSM physics at FCC-hh, in many not "bump hunt" cases, one must compare with precision Standard Model predictions.

Examples include:

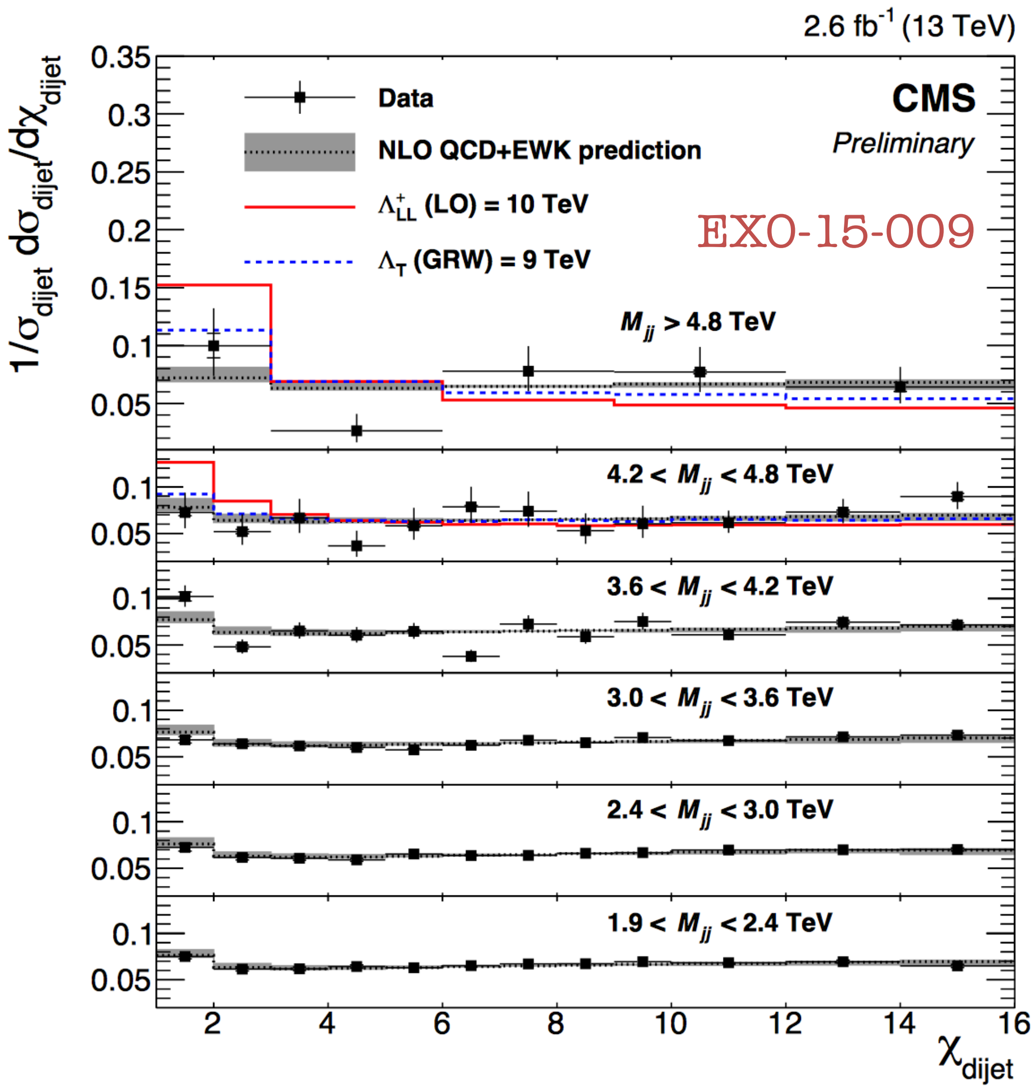
- Searches for extra dimensions.
- Modifications of Higgs physics.
- …

Many examples such as these will benefit greatly from N^NLO QCD calculations…

Not to mention that collider predictions for BSM models will require precise knowledge of cross sections etc.

Systematic Complementarity

Extra dimensions



Kaluza-Klein gravitons in extra dimensional scenarios can give rise to excesses in tails of distributions.

Which may also have interesting angular dependence. This is a recent search based on multijets.

Systematic Complementarity

Extra dimensions

EXO-15-009

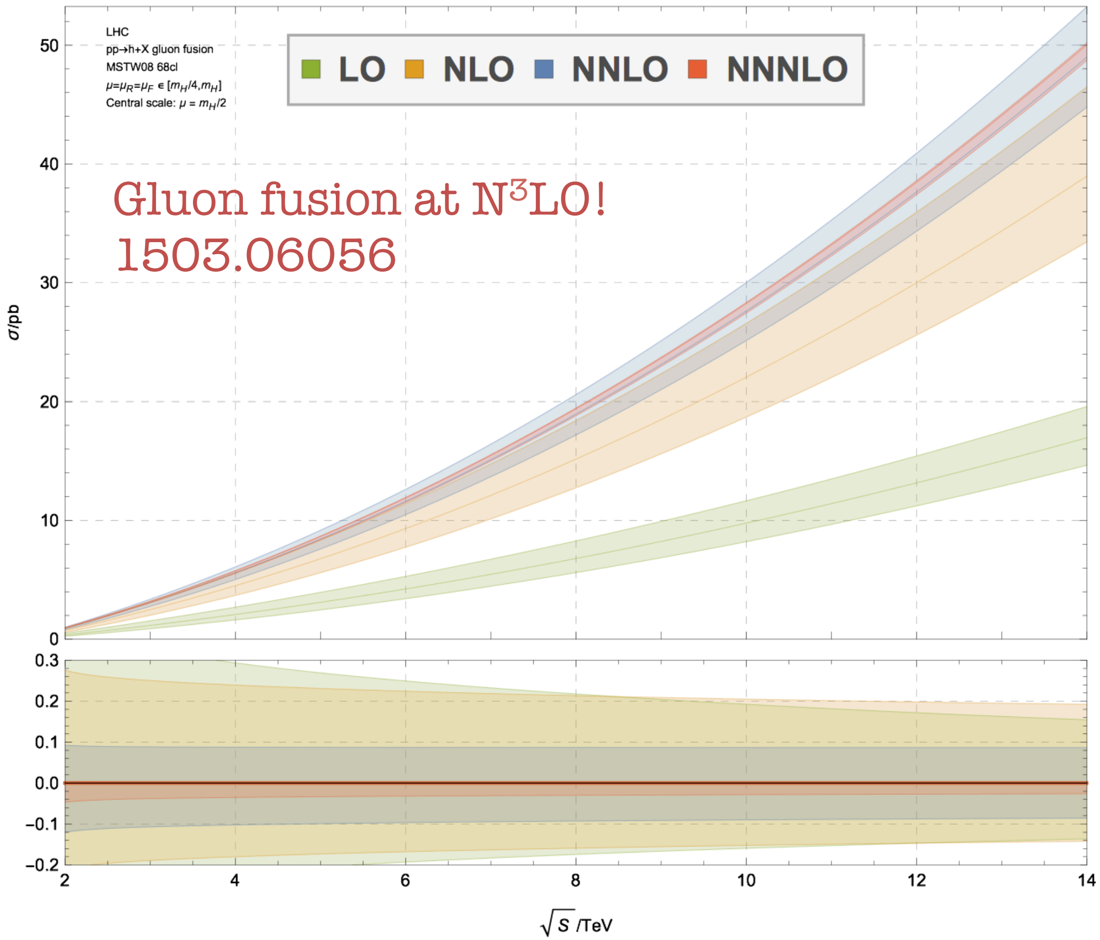
Uncertainty	$1.9 < M_{jj} < 2.4$ TeV	$M_{jj} > 4.8$ TeV
Statistical	1.6%	24%
Jet energy scale	3.0%	9.5%
Jet energy resolution (core)	<1%	2.0%
Jet energy resolution (tails)	<1%	2.5%
Unfolding, MC modeling	<1%	<1%
Unfolding, detector simulation	1.0%	3.0%
Pileup	<1%	<1%
Total experimental	9.7%	26%
NLO scale (6 variations of μ_R and μ_F)	$^{+7.9\%}_{-2.8\%}$	$^{+13\%}_{-4.9\%}$
PDF (CT14 eigenvectors)	0.15%	0.4%
Non-perturbative corrections (Pythia8 vs. Herwig++)	<1%	<1%
Total theoretical	7.9%	13%

An important systematic uncertainty is NLO theory uncertainty. This will also affect FCC-hh searches, so progress will be crucial.

However QCD $N^N LO$ progress has a limit…

Systematic Complementarity

A recent lesson from (spectacular) $N^{N}LO$ progress in Higgs physics at the LHC.



The march towards higher orders significantly improved our predictions in Higgs physics, and hence our ability to search for new physics in the Higgs sector!

Systematic Complementarity

A recent lesson from (spectacular) $N^{N}LO$ progress in Higgs physics at the LHC.

E_{CM}	σ	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
2 TeV	1.10 pb	$^{+0.04\text{pb}}_{-0.09\text{pb}}\left(^{+4.06\%}_{-7.88\%}\right)$	$\pm$ 0.03 pb ($\pm$ 3.17%)	$^{+0.04\text{pb}}_{-0.04\text{pb}}\left(^{+3.36\%}_{-3.69\%}\right)$
7 TeV	16.85 pb	$^{+0.74\text{pb}}_{-1.17\text{pb}}\left(^{+4.41\%}_{-6.96\%}\right)$	$\pm$ 0.32 pb ($\pm$ 1.89%)	$^{+0.45\text{pb}}_{-0.45\text{pb}}\left(^{+2.67\%}_{-2.66\%}\right)$
8 TeV	21.42 pb	$^{+0.95\text{pb}}_{-1.48\text{pb}}\left(^{+4.43\%}_{-6.90\%}\right)$	$\pm$ 0.40 pb ($\pm$ 1.87%)	$^{+0.57\text{pb}}_{-0.56\text{pb}}\left(^{+2.65\%}_{-2.62\%}\right)$
13 TeV	48.58 pb	$^{+2.22\text{pb}}_{-3.27\text{pb}}\left(^{+4.56\%}_{-6.72\%}\right)$	$\pm$ 0.90 pb ($\pm$ 1.86%)	$^{+1.27\text{pb}}_{-1.25\text{pb}}\left(^{+2.61\%}_{-2.58\%}\right)$
14 TeV	54.67 pb	$^{+2.51\text{ pb}}_{-3.67\text{ pb}}\left(^{+4.58\%}_{-6.71\%}\right)$	$\pm$1.02 pb ($\pm$ 1.86%)	$^{+1.43\text{pb}}_{-1.41\text{pb}}\left(^{+2.61\%}_{-2.59\%}\right)$

However, this progress revealed an important bottleneck in higher order QCD predictions, the strong coupling constant uncertainty.

Systematic Complementarity

A recent lesson from (spectacular) N^{N}LO progress in Higgs physics at the LHC.

E_{CM}	[illegible]	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
2 Te[illegible]	[illegible]	[illegible]	[illegible] (± 3.17%)	$^{+0.04\text{pb}}_{-0.04\text{pb}}\left(^{+3.36\%}_{-3.69\%}\right)$
7 T[illegible]	[illegible]	[illegible]	[illegible]	[illegible] (+2.67% [illegible]6%)
8 TeV	21.42 pb	[illegible]	[illegible]	[illegible]5% [illegible]62%
13 TeV	48.58 pb	$^{+2.22\text{pb}}_{-3.27\text{pb}}\left(^{+4.56\%}_{-6.72\%}\right)$	± [illegible]	[illegible].61% [illegible].58%
14 TeV	54.67 pb	$^{+2.51\text{ pb}}_{-3.67\text{ pb}}\left(^{+4.58\%}_{-6.71\%}\right)$	±1.02 pb (± 1.86%)	[illegible]2.61% [illegible]2.59%

> "Finally, the computation of the hadronic cross-section relies crucially on the knowledge of the strong coupling constant and the parton densities. After our calculation, the uncertainty coming from these quantities has become dominant."

However, this progress revealed an important bottleneck in higher order QCD predictions, the strong coupling constant uncertainty.

Systematic Complementarity

The $\alpha_S(M_Z)$ uncertainty will thus affect:

- Higgs physics, and our ability to search for BSM in the Higgs sector
- and potentially many other BSM searches at FCC-hh, such as extra dimensions etc.

World average (PDG):

$$\alpha_S(M_Z^2) = 0.1181 \pm 0.0011 (0.9\%)$$

Which gives an idea of the uncertainties introduced to predictions.

- This could limit the impact of theoretical progress in some final states.

Systematic Complementarity

Thus returning to the third notion of complementarity: "Different FCC Colliders enhance the exploratory power of one another, when a measurement at one reduces a systematic uncertainty in another."

One can see that the estimated FCC-ee determination, from runs at the Z-pole and at higher energies, of

$$\Delta\alpha_S(M_Z^2) \sim \pm 0.0001 (0.08\%)$$

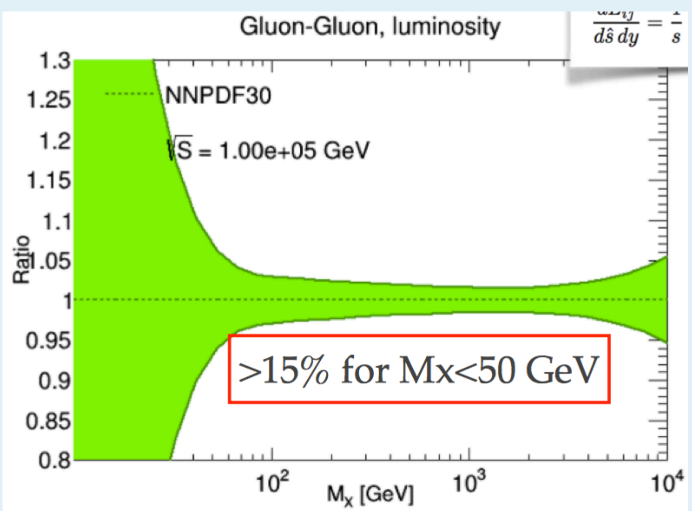
Would reduce systematic uncertainties in BSM searches at FCC-hh, both direct (e.g. extra dimensions) and indirect (e.g. Higgs couplings).

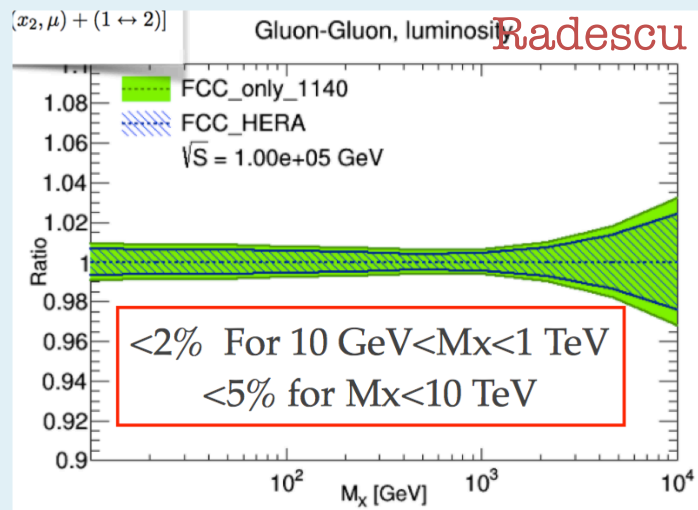
Systematic Complementarity

Thus returning to the third notion of complementarity: "Different FCC Colliders enhance the exploratory power of one another, when a measurement at one reduces a systematic uncertainty in another."

PDFs a similar story at FCC-eh

Camarda Radescu

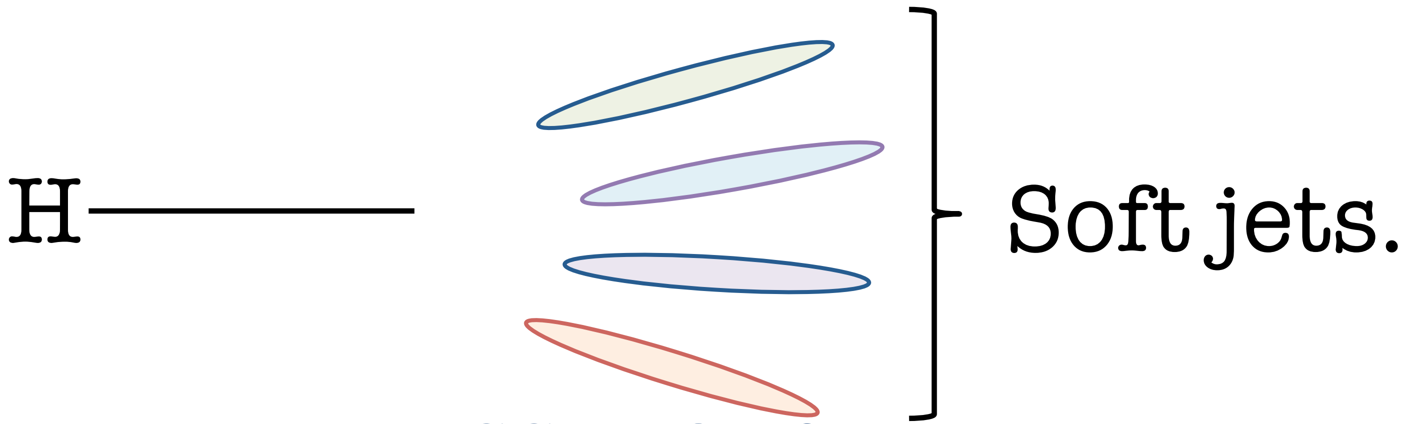




Improvement in low-x predictions for FCC-hh.

Assumptive Complementarity

Finally, consider a new decay process of the Higgs, for example to multiple soft jets…



Could we catch this at FCC-hh? If not directly observed this would show up as a reduction in Higgs signal strength:

$$\sigma_h \times BR_{ij} < \sigma_h^{\rm SM} \times BR_{ij}^{\rm SM}$$

But would be hard to tell if reduced coupling, or larger width.

Assumptive Complementarity

However FCC-ee would allow a direct measurement of the production cross section

$$\sigma_{Zh} = \sigma_{Zh}^{\mathrm{SM}}$$

Distinguishing between reduced couplings and additional width. And the decay could be measured directly! (See talk by LianTao.)

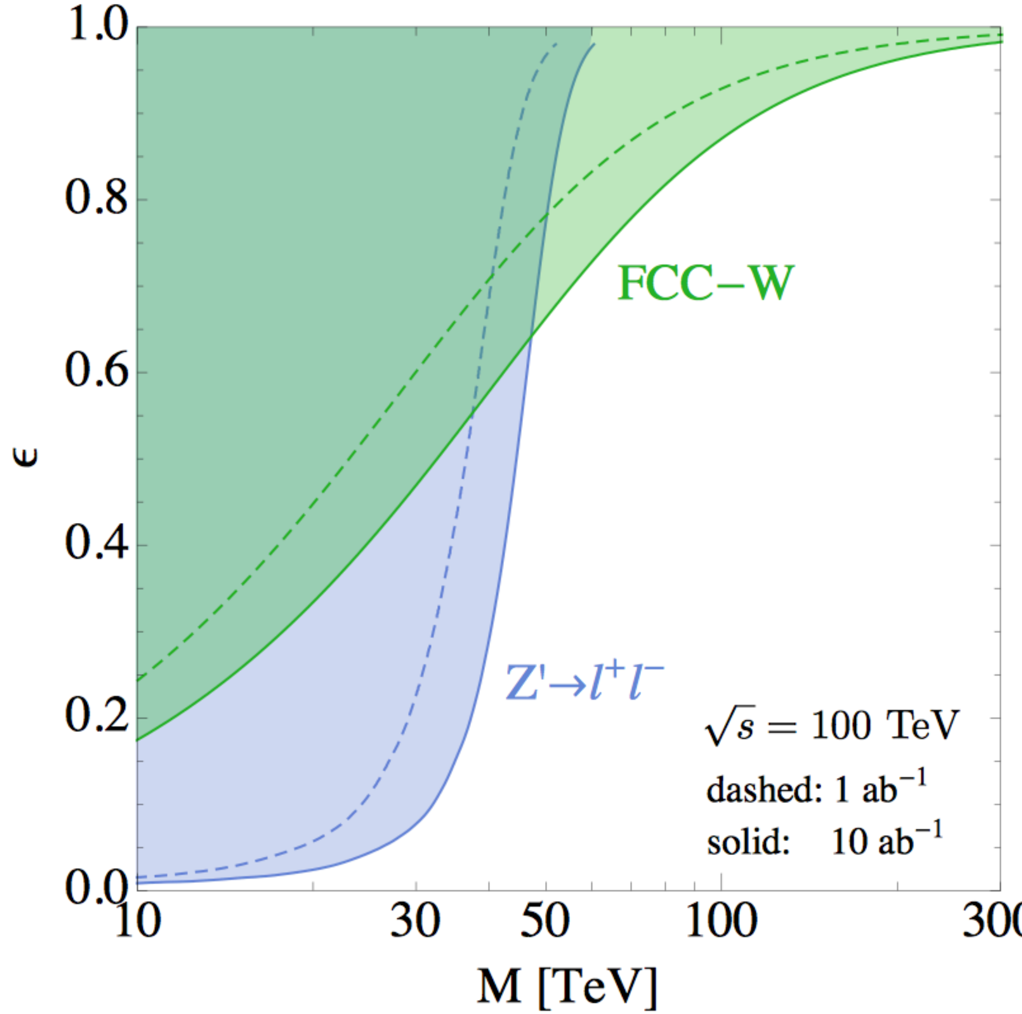
Thus returning to the third notion of complementarity: "Different FCC Colliders require different BSM theory assumptions, giving a more "model independent" result in combination."

Summary

There are clearly many respects in which different FCC machines are complementary in a BSM context.

And many respects in which they are not:

Models in Josh's talk best probed <u>directly</u> and <u>indirectly</u> at FCC-hh.



Summary

Specific questions:

- Indirect probes stand out at FCC-ee, but have we yet leveraged the high luminosity and clean environment for exotic/rare signatures in proximity of the weak scale?

- Direct probes stand out at FCC-hh, but have we yet leveraged capabilities for precision indirect probes?

- Progress in $N^{N}LO$, and $NL^{N}L$ is pretty much guaranteed, but inputs must also be at commensurate level. What goals does this set for the most successful BSM programs at FCC?

Summary

Specific questions:

- Indirect probes stand out at FCC-ee, but have we yet leveraged the high luminosity and clean environment for exotic/rare signatures i... ...imity of the weak scale?

Until these and many more questions are answered, the full complementarity of all machines will remain unclear...

- ... ...h, but have we ye... indirect probe...

- Progress in $N^{N}LO$, and $NL^{N}L$ is pretty ...ch guaranteed, but inputs must also be at commensurate level. What goals does this set for the most successful BSM programs at FCC?