Higgs and Top at 10TeVpCM

25/09/2024

Jay Howarth

Introduction

- **This talk is not a final summary, it is an introduction to a review that only started in the summer.**

- **Top group used the Snowmass 21 exercise as a base to update and expand.**

*(if you don't get this joke, ask your PhD students/kids)

- **Higgs group started a little later and is still performing its literature review** (more topics and material to cover)**.**

- **This talk will focus on major topic(s) for each group and propose work over the next few months.**

Review Groups

TOP TEAM

Christoph Englert
Jay Howarth
Michael Spannowsky

HIGGS TEAM

Jon Butterworth
Christoph Englert
Jay Howarth
Eleni Skorda
Tim Scanlon
Michale Spannowsky
Sarah Williams

- **Important disclaimers:**
  1. Remit is to review physics potential, not cost/env.impact/politics.
  2. The opinions attached to the numbers in this talk mostly reflect my personal interpretation.

Scenario Planning

- **Working under assumption of 'worst case scenario' for lepton collider** (i.e. assume there isn't one or that it will ONLY run in Higgs production mode, not top).

- **Also not assuming FCC$_{hh}$ is guaranteed to reach 100 TeV.**

Scenario Planning

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- **Also not assuming FCC$_{hh}$ is**

This talk works well as one of the Plan B’s Daniela mentioned:
“China builds CEPC and CERN decides to build FCChh directly, with current magnet technology.”

Scenario Planning

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- **Also not assuming FCC$_{hh}$ is guaranteed to reach 100 TeV.**

FCC lumi source, also source.

	HE-LHC	FCC$_{hh}$	FCC$_{hh}$	FCC$_{hh}$	MuC
Type	**pp**	**pp**	**pp**	**pp**	$\mu\mu$
Energy [TeV]	**27-33**	**50**	**70**	**100**	**3-10**
Lumi. per ex.	**10 ab^{-1}**	**15-20 ab^{-1}**	**15-20 ab^{-1}**	**15-20 ab^{-1}**	**10 ab^{-1}**
N $t\bar{t}$ pairs	**30 billion**	**140 billion**	**250 billion**	**430 billion**	$\mathcal{O}$**100k**
N Higgs (ggF)	**1.5 billion**	**4.8 billion**	**7.7 billion**	**12 billion**	**millions**

- **For context, 0.1(2.8 billion) $t\bar{t}$ pairs and 6(156) million H bosons in LHC Run2 (HL-LHC).**

- **Not included ep in talk but is part of review,** (lots of material for top, see Monica's talk).

Scenario Planning

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	HE-LHC	FCC$_{hh}$	FCC$_{hh}$	FCC$_{hh}$	MuC
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Lumi. per ex.					ab^{-1}
N $t\bar{t}$ pairs	30 billion	140 billion	250 billion	430 billion	100k
N Higgs (ggF)	1.5 billion	4.8 billion	7.7 billion	12 billion	millions

I'm going to be lazy and use FCChh to just mean any future proton-proton collider with a collision energy of 50-100 TeV
(there's nothing in these slides that relies on more fine-tuned details)

- **For context, 0.1(2.8 billion) $t\bar{t}$ pairs and 6(156) million H bosons in LHC Run2 (HL-LHC).**
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This Talk

TOP PHYSICS:

- ➡ Focus on mass prospects in different scenarios and implications for the field as a whole.
- ➡ Highlight a few places where we could feasibly add studies.

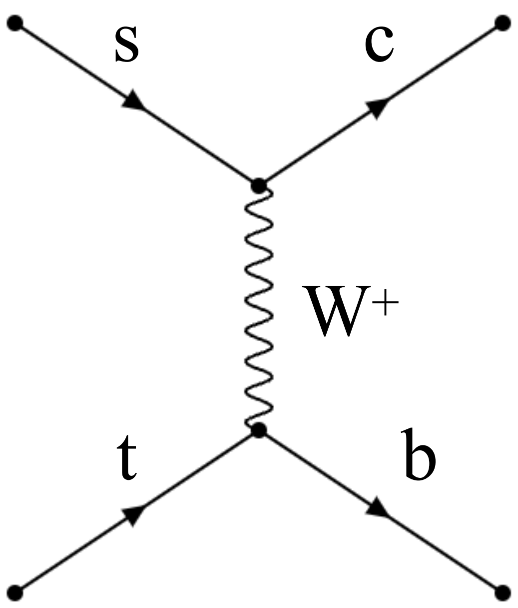
HIGGS PHYSICS:

- ➡ Focus on general prospects.
- ➡ Study suggestions mostly centre around fleshing out existing ones.

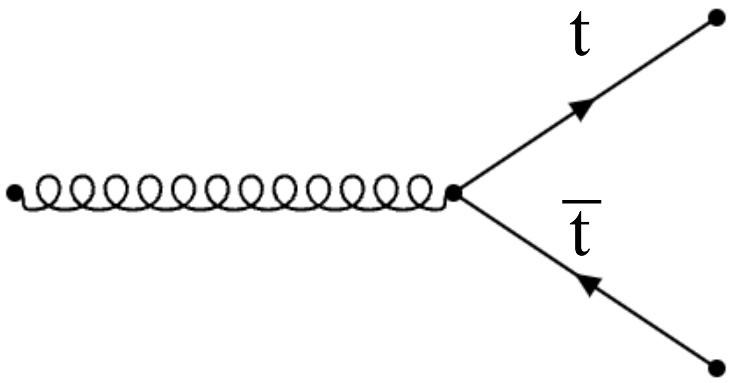
Top Physics

Top Production

- **Production at HE-LHC essentially the same as LHC** (~90% ggF, ~10% qqbar annihilation, smaller single top)**.**
- **Production at FCC$_{hh}$ introduces new** (or enhanced) **production modes:**

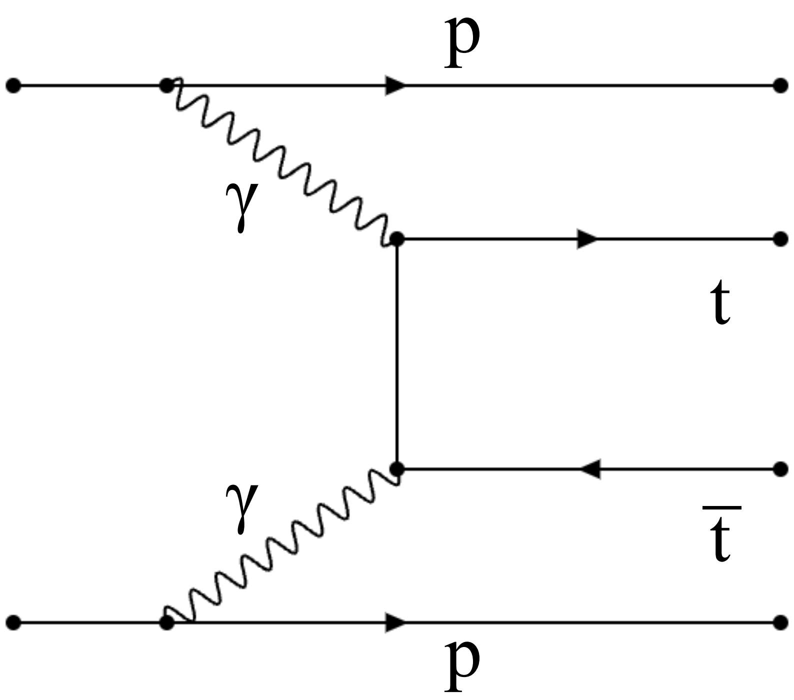


top PDF



Gluon splitting

e.g X + $t\bar{t}$ from ISR/FSR gluons

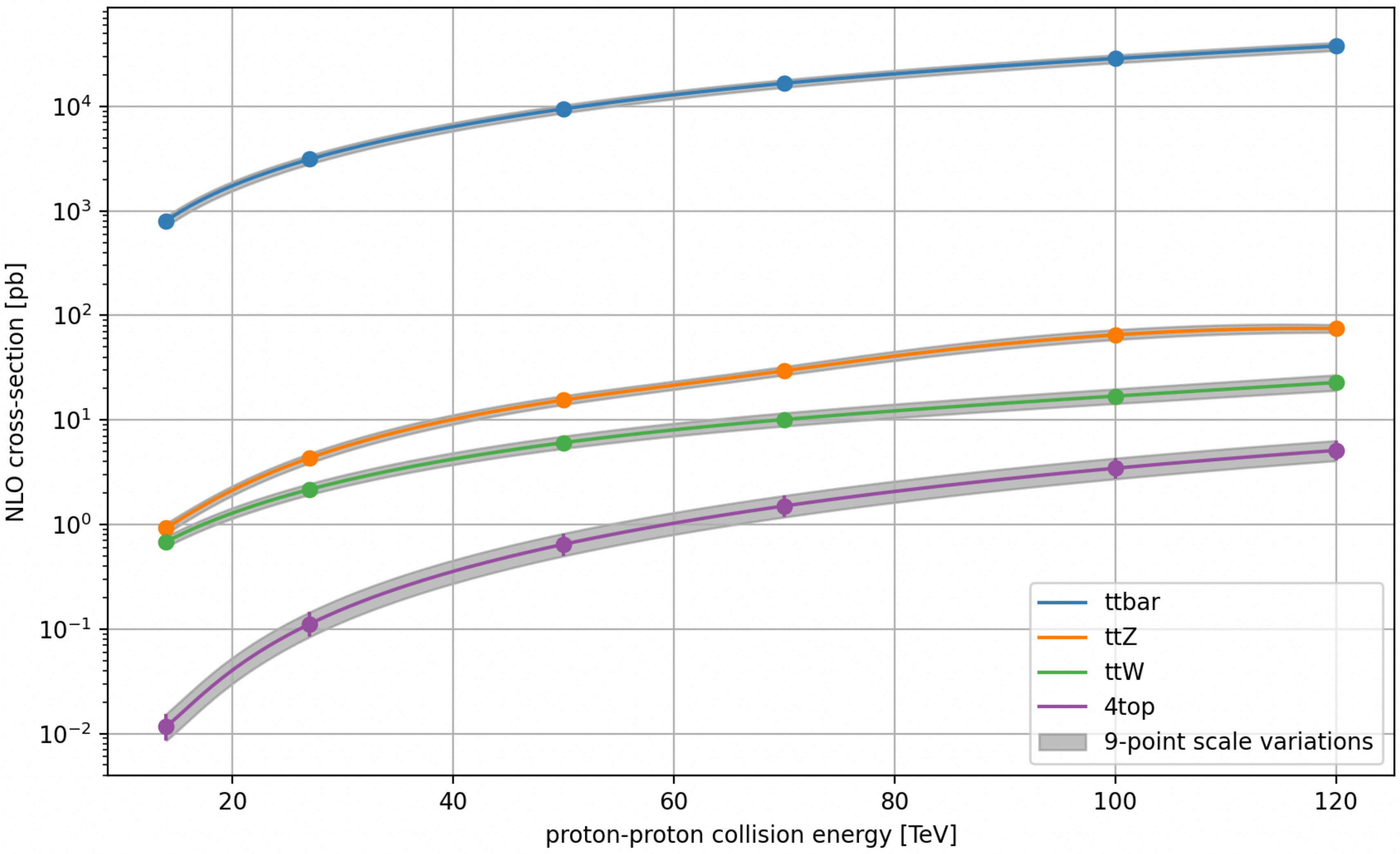


Exclusive

- **Not going to cover them in detail here, but still pretty cool.**

Top Production

- **Cross-sections of QCD production benefit most from moderate energy increases.**



Energy for order of magnitude increase in xsec, relative to LHC:

$t\bar{t}$: 50 TeV (FCC_{hh})

$t\bar{t}Z$: 50 TeV (FCC_{hh})

$t\bar{t}W$: 70 TeV (FCC_{hh})

$t\bar{t}t\bar{t}$: 27 TeV (HE-LHC)
2x **70 TeV (FCC_{hh})**

- **More stats is always nice, however, diminishing returns approaching 100 TeV.**

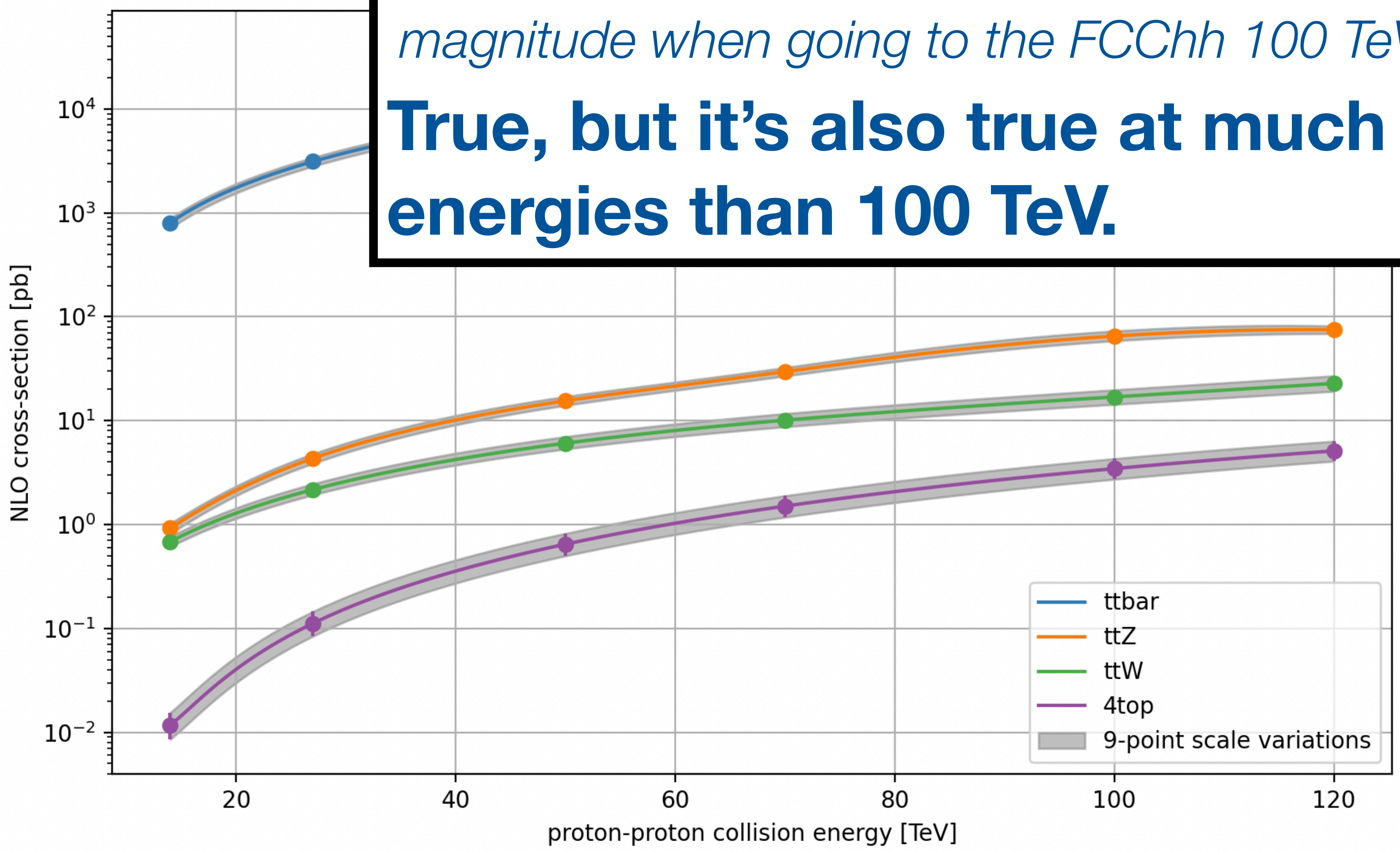
Top Production

- Cross-sec n moderate energy inc

Snow mass statement:

“[The 4top cross-section] increases by two orders of magnitude when going to the FCChh 100 TeV collider”

True, but it’s also true at much lower energies than 100 TeV.



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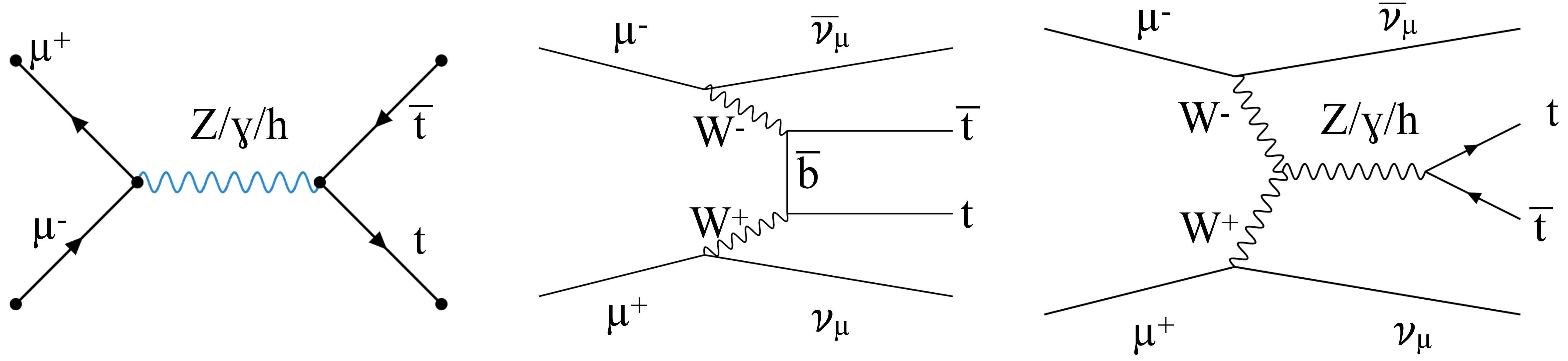
$t\bar{t}t\bar{t}$: 27 TeV (HE-LHC)
2x 70 TeV (FCC_{hh})

- More stats is always nice, however, diminishing returns approaching 100 TeV.

Top Production

- **Production at muon collider is primarily via WWF, with limited contribution from Z/γ s-channel production** (depending on energy)**.**



- **Not going to cover MuC for top physics in this talk.**

- **There is some limited material but the cross-sections are tiny and most work focuses on BSM** (e.g. top compositeness)**.**

Top Mass (goals)

- **Goal for top mass precision is set by precision EW fits due to uncertainties caused by top loop corrections to W mass:**

$$\sigma(m_t) = 500\ \text{MeV} \quad \rightarrow \quad \sigma(m_W) = 5\ \text{MeV}$$

- **Recent CMS result $\sigma(m_W)$ ~10 MeV means we need top mass precision better than 1 GeV.**

- **Have this precision now, but higher precision W mass measurements** (e.g. at a lepton collider of $\sigma(m_W)$=0.5 MeV) **will require top mass uncertainties << 100 MeV.**

- **Assuming we don't have a threshold top scan, what can we expect with future hadron machines or muon colliders?**

- **Note: This is assuming top mass in a well defined mass scheme!**

Top Mass (statistics)

- **Ignoring experimental and theoretical uncertainties for a moment, what is the limit on precision just from statistics?**
- **Extrapolating two of the most precise individual measurements, using an ‘old’ and ‘new’ technique:**

Analysis	**HL-LHC**	**HE-LHC**	**$\mathrm{FCC_{hh}}$ 50**	**$\mathrm{FCC_{hh}}$ 70**	**$\mathrm{FCC_{hh}}$ 100**
CMS Likelihood	4 MeV	1 MeV	0.6 MeV	0.4 MeV	0.3 MeV
CMS Template	19 MeV	5 MeV	3 MeV	2 MeV	1.5 MeV

- **Of course, mass measurements aren’t stat dominated, but gives a hypothetical limit on what is possible.**

Top Mass (theory uncertainties)

- **Top mass is a renormalisation scheme dependent quantity.**
  - ➡ **MS, MSR, PS, RS** (scale dependent), **pole, 1S** (scale independent)
  - ➡ Monte Carlo mass (mass from kinematics, usually what we measure),

- **Interpolating between MC mass and well-defined schemes currently comes with a theoretical uncertainty of 200-500 MeV.**
  - ➡ This has decreased during the past decade thanks to theory work, down from ~1 GeV at the start of LHC data taking.
  - ➡ **Pole mass has renormalon ambiguity but is 'close' to MC mass** (experiments using other mass schemes now as well)**.**

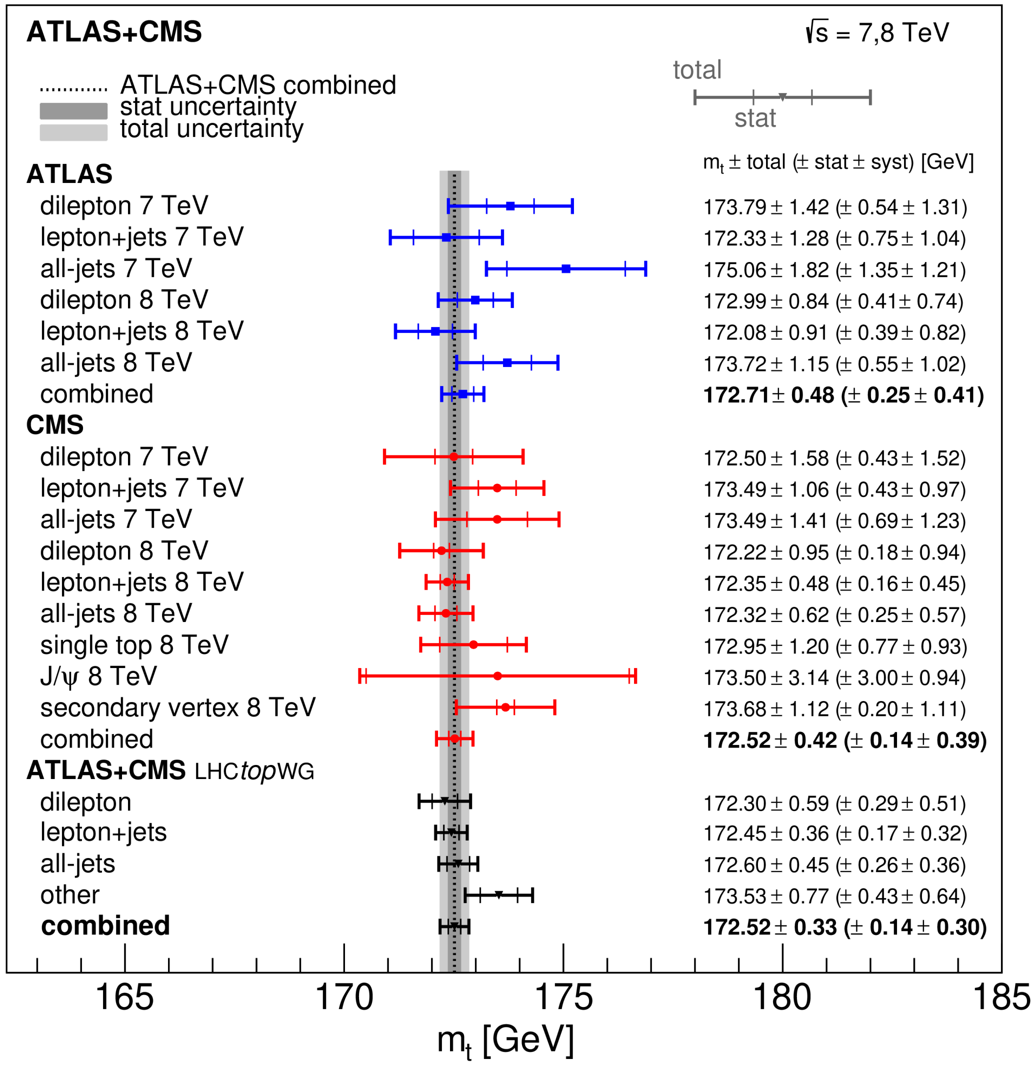
- **These theory uncertainties are fundamental to QCD but not intractable and have been studied extensively. A sustained effort of time & resources will be needed for precision top mass at future hadron machines.**

- **Is a theory uncertainty of < 100 MeV possible? I would say yes, but hard to achieve** (QCD is 50 years old, and we're projecting another 50 years ahead)**.**

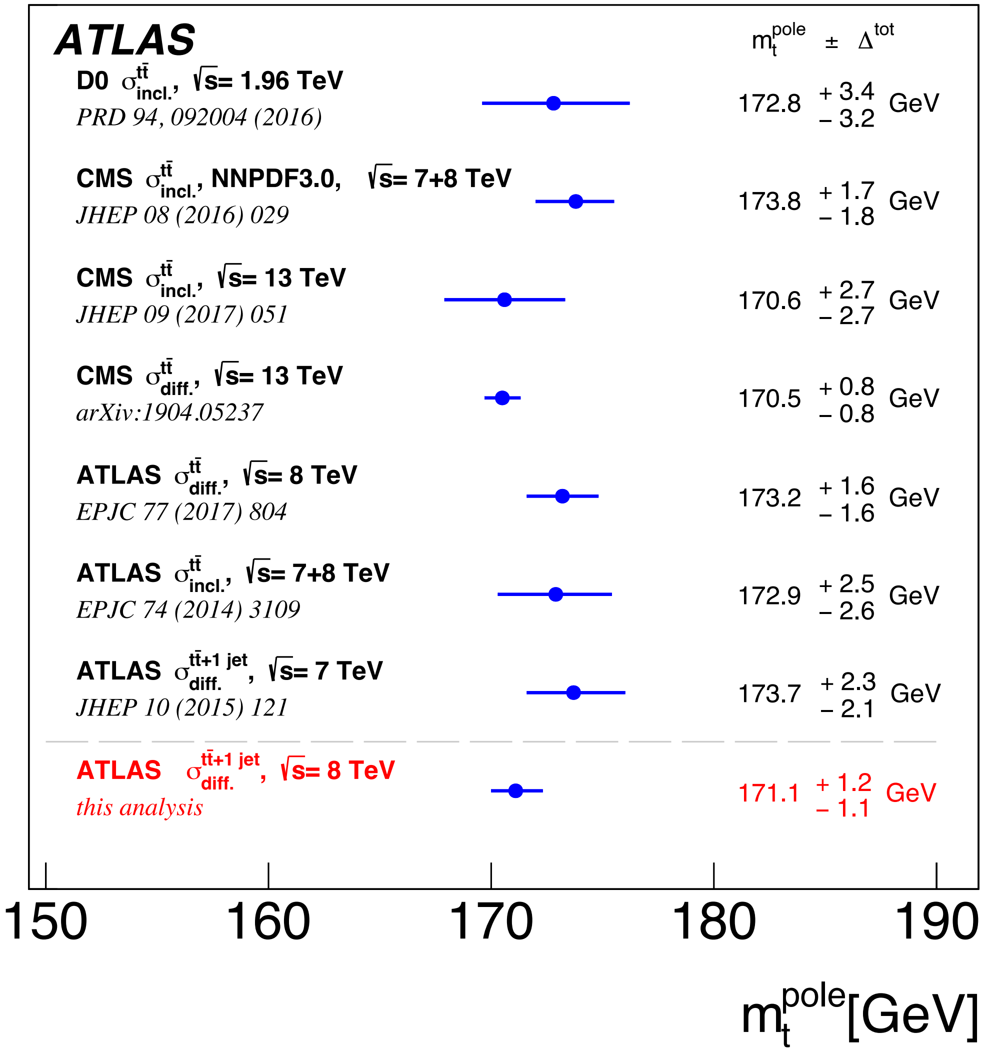
Top Mass (experimental)

- **Two types of measurements at LHC/HL-LHC:**

MC Mass
(σ ~300 MeV)

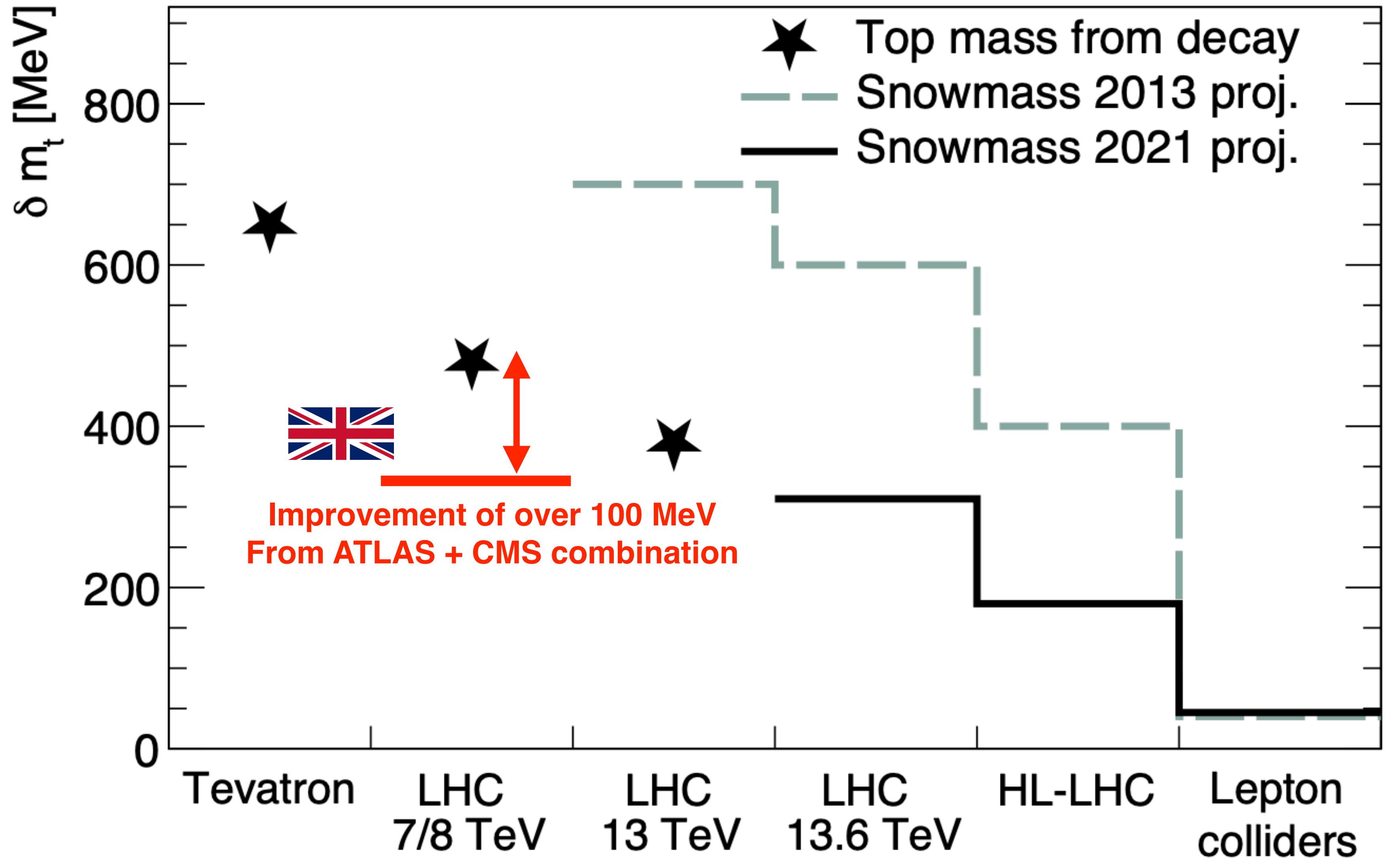


Direct Mass
(σ ~1 GeV)



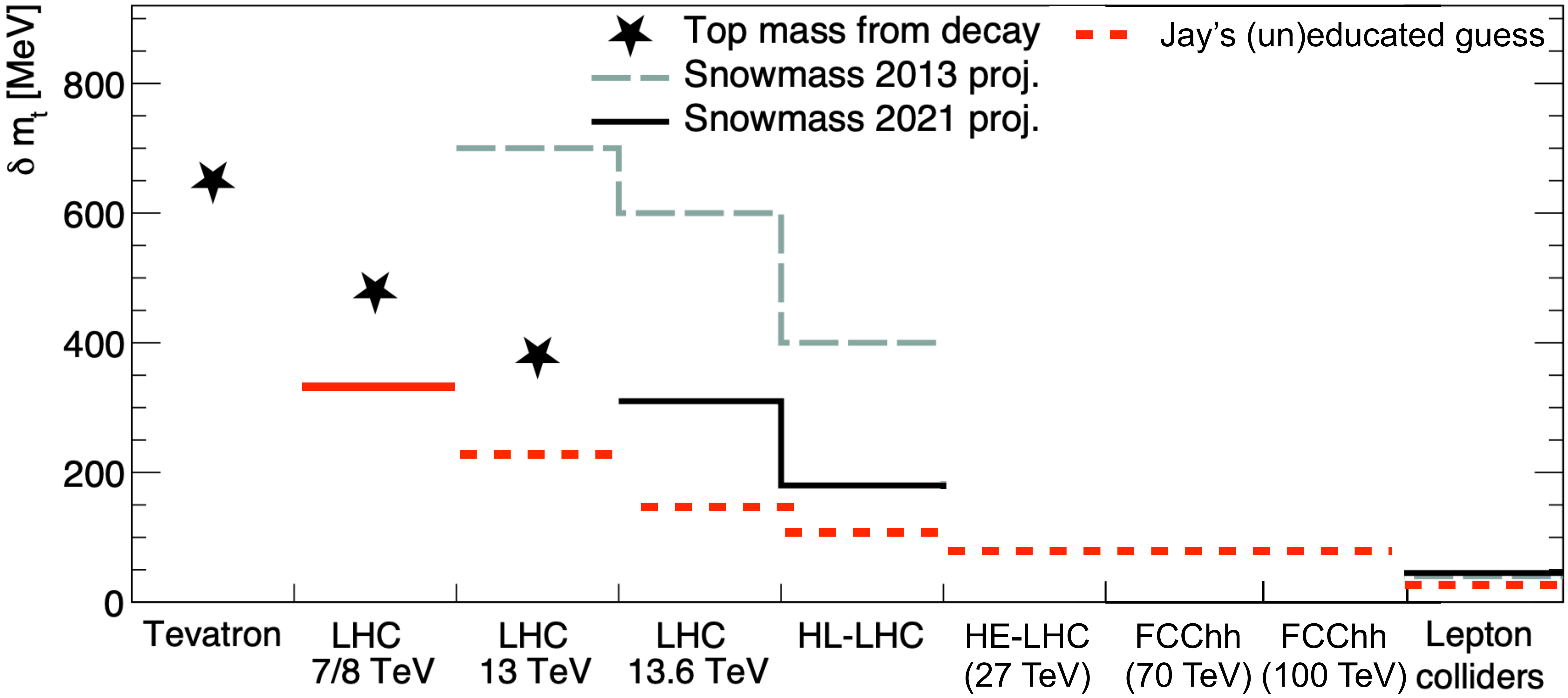
- **Both a limited by signal modelling: More stats brings benefits but** (much) **stronger assumptions if you use it to constrain systematics.**

Top (snow)Mass



- **Historically, predicting top mass has always been too conservative.**
- **Arguably, Run2/3 will already reach this precision** (even with interpretation struggles)**.**

Top (snow)**Mass**



- **Story of the LHC has been to challenge the idea that precision physics can't happen at hadron colliders.**

- **A key question is, if we don't have a top mass threshold scan, can we reach the required EW fit precision with an hh machine? Maybe.**

Top Mass from Leptons

- **Extract the top mass from leptonic observables in $t\bar{t}$ dilepton events** (avoiding many QCD uncertainties)**:**
  - ➡ **m(ll):** Has a weak kinematic endpoint (mll < 2mt) and broad peak structure.
  - ➡ **p_T(ll):** Sensitive to mt when tops produced close to threshold.
  - ➡ **p_T(l):** Sensitive to parent top's mass (think W mass recoil etc).

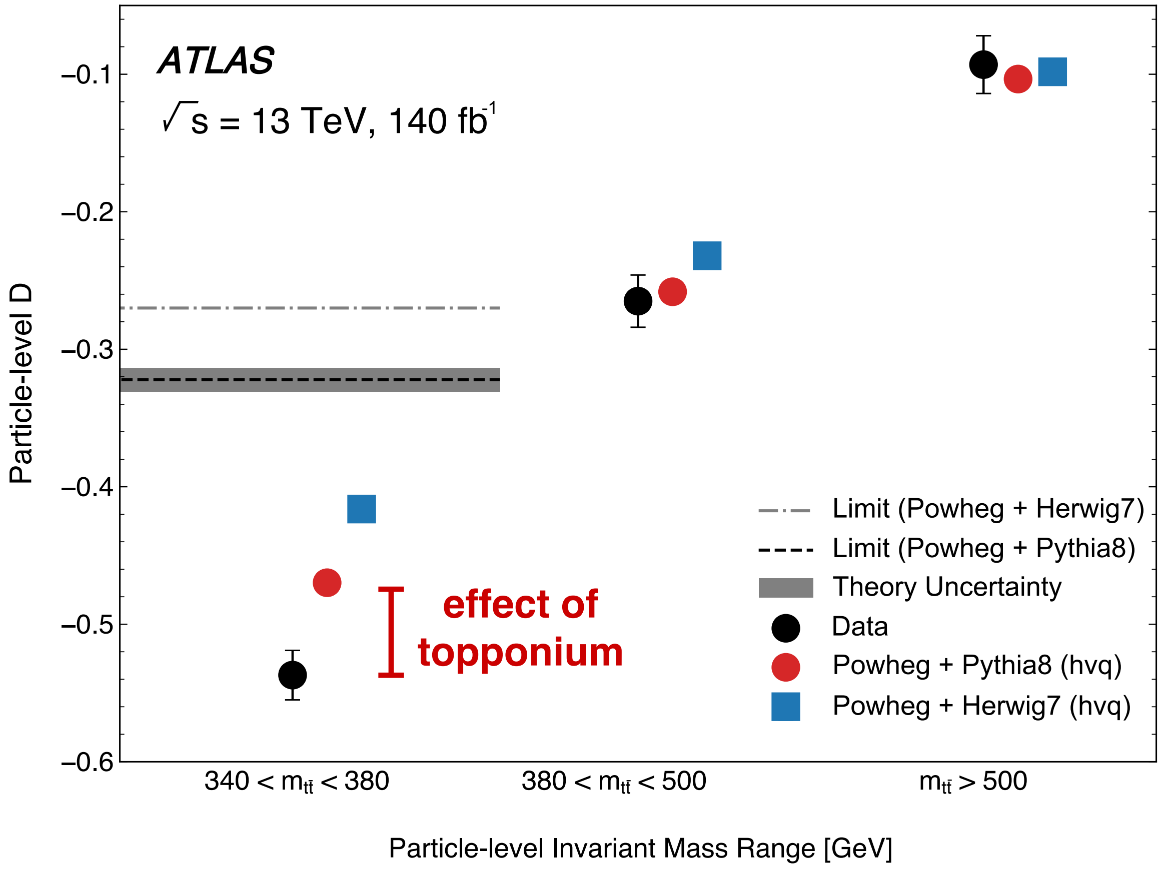
- **These observables aren't sensitive at current statistical precision, but <u>don't suffer from hadronisation uncertainties</u>. Will they be useful at FCC_{hh} statistics?**

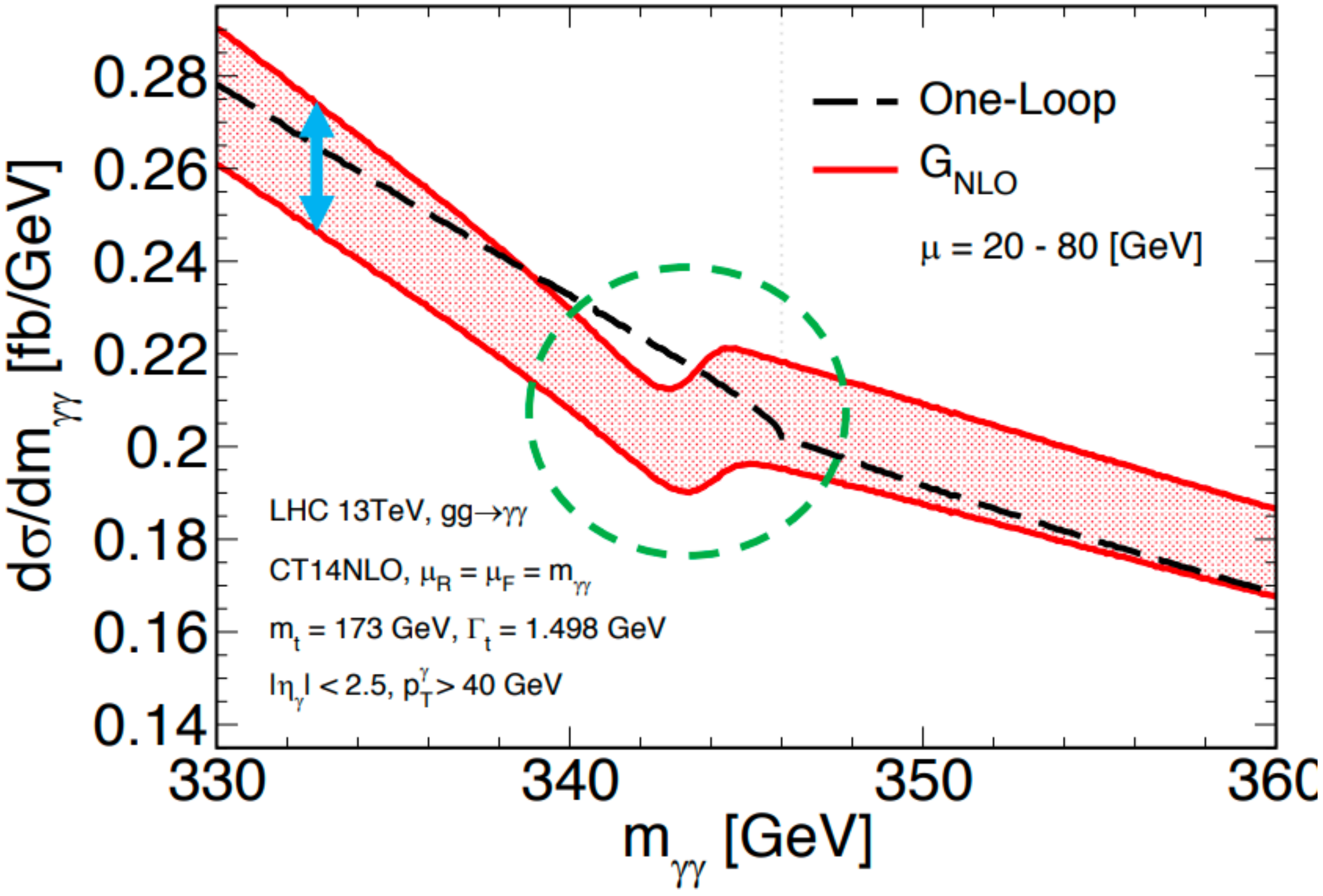
- **Two questions for this method that need to be studied:**
  - ➡ **1.** How much data are needed to reach <100 MeV in a simple combined fit to all three of these observables and individually.
  - ➡ **2.** What lepton resolution would be needed to preserve the needed sensitivity? (inform detector design)

- **Both of these could be answered on the timescale of March 25.**

Topponium

Nature 633 (2024) 542–547





- **Strong evidence of bound-state top effects in top yukawa and entanglement analyses from both ATLAS and CMS.**
- **If it is a true bound state, can decay to ɣɣ. Cross section is too low at LHC but can be found at future colliders.**

Other Top Studies

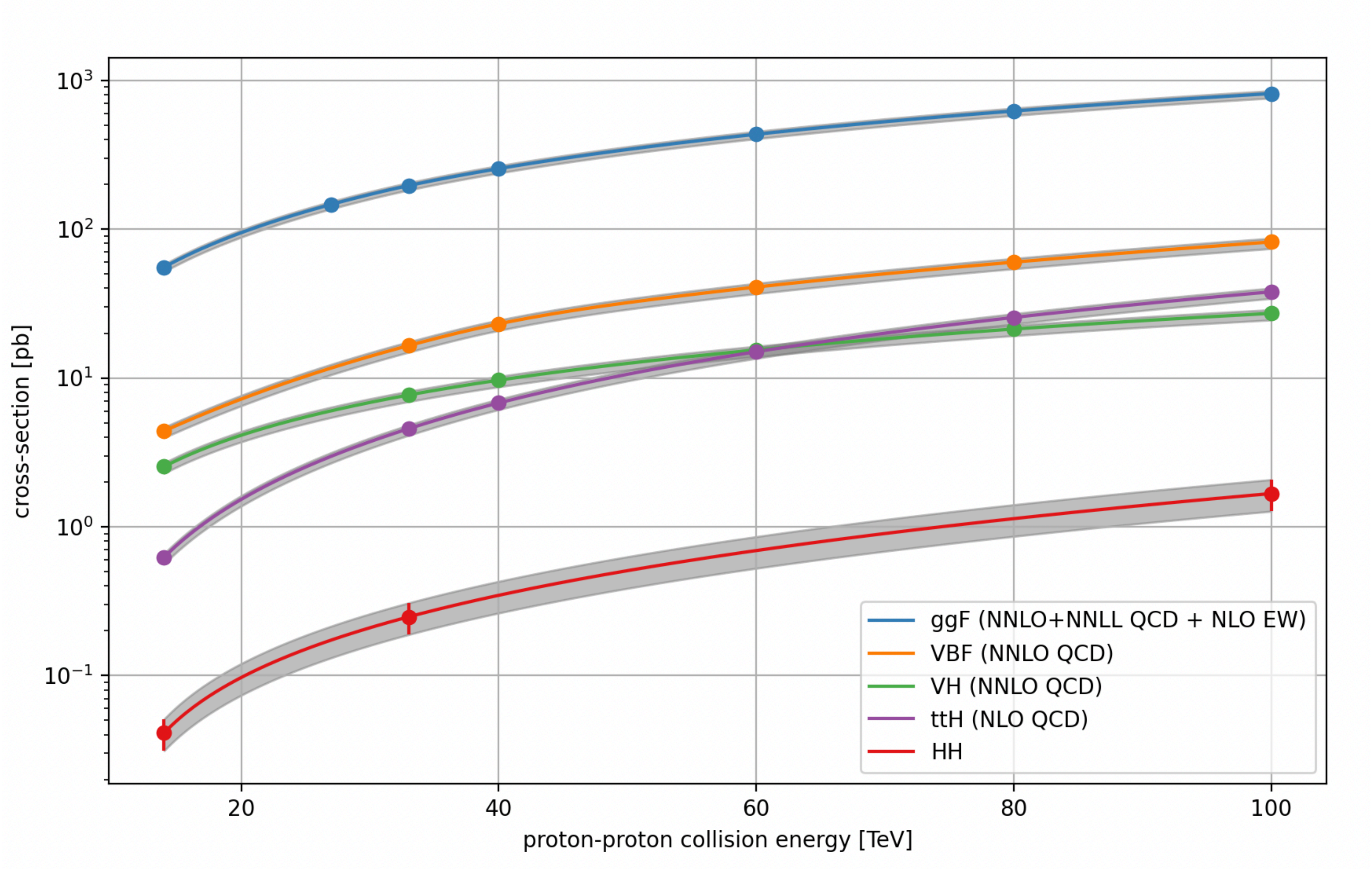
- **Plenty of other material to cover. Most follow the same story as top mass:**
  - ➡ **Top yukawa:** Several papers and analyses to extrapolate (from ttH but also 4top and $mt\bar{t}$ differential).
  - ➡ **Top properties:** Not as much material but the story is essentially the same as mass (theory uncertainties matter much more than statistics).
  - ➡ **EW top processes:** not focused on too much so far (needs expanding).
  - ➡ **Rare top processes:** Plenty of material, mostly in the context of EFT limits but also top couplings.

Higgs Physics

Jay Howarth

Higgs Production

- **Cross-sections of higgs production increase moderately with energy.**



Energy for order of magnitude increase in xsec, relative to LHC:

ggF: 70 TeV (FCC_{hh})

VBF: 65 TeV (FCC_{hh})

VH: 80 TeV (FCC_{hh})

$t\bar{t}H$: 35 TeV (HE-LHC)

HH: 45 TeV (FCC_{hh})

- **Most processes increase by order of magnitude or more by about 70 GeV but rarely 2** (ttHH does get 2 by 100, but not ttH.)

Higgs Production

- **Most gains for high p_T higgs** (where you might see anomalous couplings/Higgs substructure) **also happen lower than 100 TeV.**

$$pp \rightarrow HZ,\ Z \rightarrow \nu\nu$$

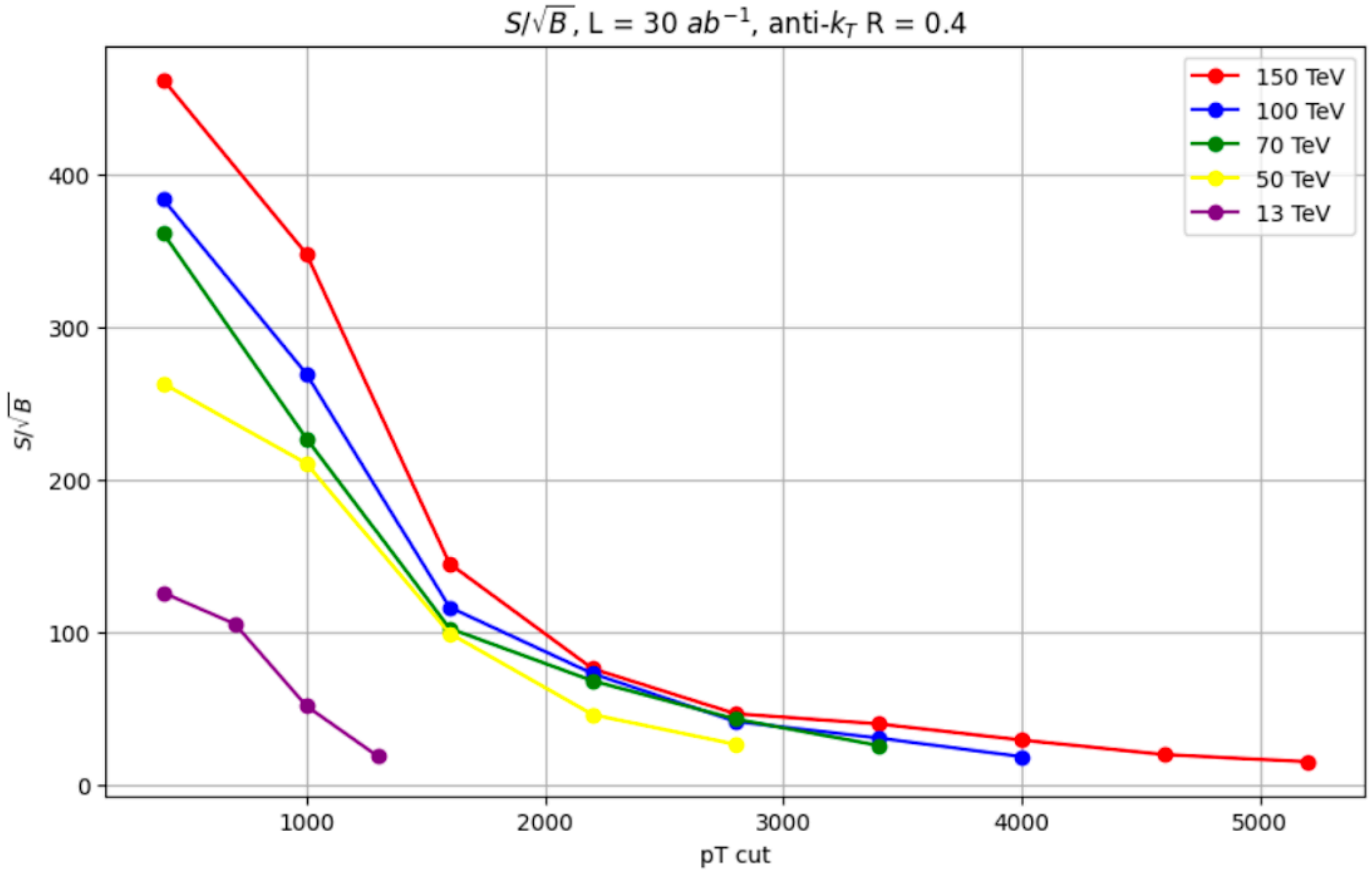


Figure 7.3: Signal-to-square-root-of-background ratio. FCC-hh integrated luminosity is applied.

J. Butterworth, B. Tan, T. Scanlon

Higgs Couplings

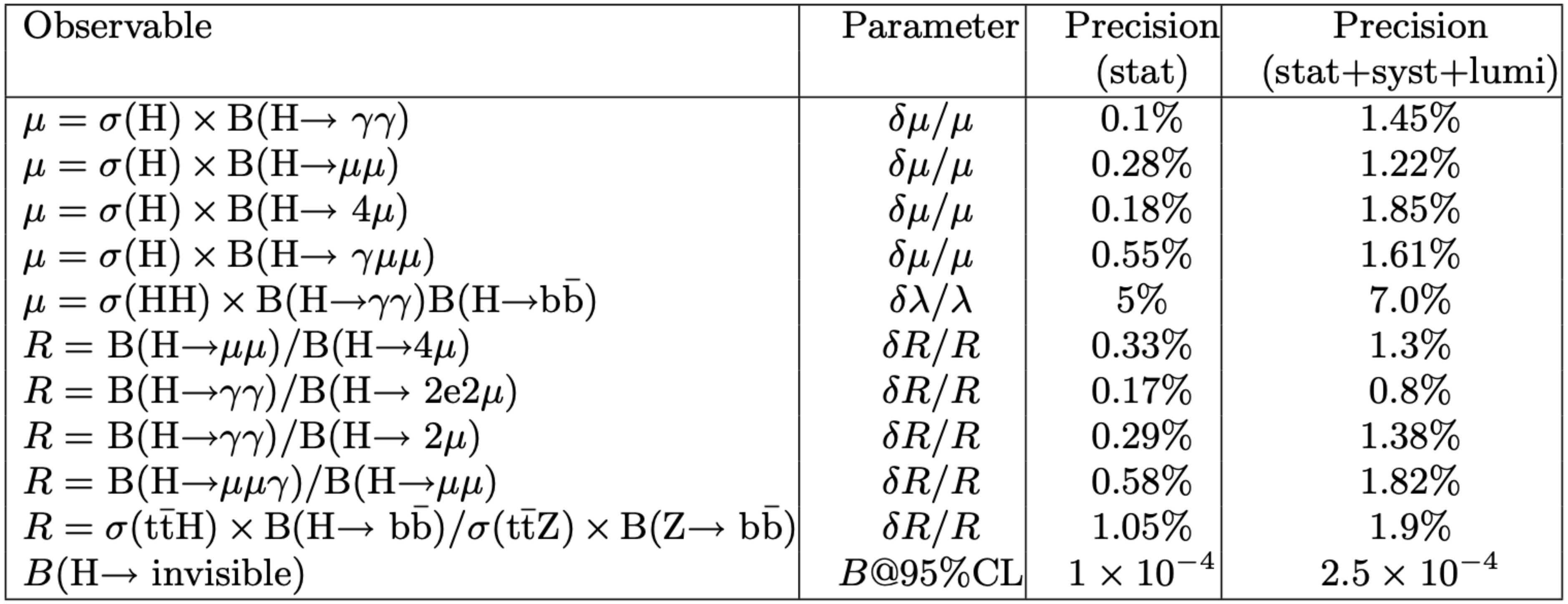
- **Mantra is that lepton colliders are unbeatable at** (most) **higgs coupling measurements. So should we consider them in FCC$_{hh}$ projections?**

- **Are we underselling the precision of hadron machines? LHC** (not even HL-LHC) **has or will have the best precision on EW parameters** (e.g. m_W, m_t, m_h, LFU, even $\sin^2\theta_W$,)**.**
  ➡ Up to us to make this argument with careful studies if so.

- **Target for next March could be to aggressively pursue literature and studies on what is possible at the FCC$_{hh}$ with most-recent analysis tools, removing the assumption of a lepton collider existing first.**

Higgs Couplings

- **Example: targets on rare Higgs couplings from FCC$_{hh}$ CDR at lower energies.**



Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(\mathrm{HH}) \times \mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)\mathrm{B}(\mathrm{H}\rightarrow\mathrm{b}\bar{\mathrm{b}})$	$\delta\lambda/\lambda$	5%	7.0%
$R = \mathrm{B}(\mathrm{H}\rightarrow\mu\mu)/\mathrm{B}(\mathrm{H}\rightarrow4\mu)$	$\delta R/R$	0.33%	1.3%
$R = \mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)/\mathrm{B}(\mathrm{H}\rightarrow 2\mathrm{e}2\mu)$	$\delta R/R$	0.17%	0.8%
$R = \mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)/\mathrm{B}(\mathrm{H}\rightarrow 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = \mathrm{B}(\mathrm{H}\rightarrow\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\rightarrow\mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(\mathrm{t}\bar{\mathrm{t}}\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow \mathrm{b}\bar{\mathrm{b}})/\sigma(\mathrm{t}\bar{\mathrm{t}}\mathrm{Z}) \times \mathrm{B}(\mathrm{Z}\rightarrow \mathrm{b}\bar{\mathrm{b}})$	$\delta R/R$	1.05%	1.9%
$B(\mathrm{H}\rightarrow \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

- **Inflating the stat uncertainties by what we would get with an FCC$_{hh}$ 50 TeV, are we losing that much?**

Higgs Couplings

- Example: targets on rare Higgs couplings from FCC_{hh} CDR at lower energies.

Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)	Precision (50 TeV) (stat+syst+lumi)	Ratio
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%	1.45%	1.00
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%	1.25%	1.03
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%	1.86%	1.00
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%	1.70%	1.06
$\mu = \sigma(\mathrm{HH}) \times \mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)\mathrm{B}(\mathrm{H}\rightarrow\mathrm{b}\bar{\mathrm{b}})$	$\delta\lambda/\lambda$	5%	7.0%	8.6%	1.23
$R = \mathrm{B}(\mathrm{H}\rightarrow\mu\mu)/\mathrm{B}(\mathrm{H}\rightarrow 4\mu)$	$\delta R/R$	0.33%	1.3%	1.3%	1.03
$R = \mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)/\mathrm{B}(\mathrm{H}\rightarrow 2\mathrm{e}2\mu)$	$\delta R/R$	0.17%	0.8%	0.8%	1.02
$R = \mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)/\mathrm{B}(\mathrm{H}\rightarrow 2\mu)$	$\delta R/R$	0.29%	1.38%	1.41%	1.02
$R = \mathrm{B}(\mathrm{H}\rightarrow\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\rightarrow\mu\mu)$	$\delta R/R$	0.58%	1.82%	1.91%	1.05
$R = \sigma(\mathrm{t}\bar{\mathrm{t}}\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow \mathrm{b}\bar{\mathrm{b}})/\sigma(\mathrm{t}\bar{\mathrm{t}}\mathrm{Z}) \times \mathrm{B}(\mathrm{Z}\rightarrow \mathrm{b}\bar{\mathrm{b}})$	$\delta R/R$	1.05%	1.9%	2.2%	1.14
$B(\mathrm{H}\rightarrow \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}	$2.7 \text{ x } 10^{-4}$	1.08

- Inflating the stat uncertainties by what we would get with an FCC_{hh} 50 TeV, are we losing that much?

- Not dramatically, <u>but could be studied in more detail.</u> Most recent studies only considers 100 TeV.

Higgs Self Couplings

- Higgs self-coupling has plenty of predictions for HL-LHC and higher energies.

- Based on the first attempts from the LHC, and usually with just one or two channels.

- Quite conservative compared to the eventual precision what will be reached by the HL-LHC.

- FCC$_{hh}$ CDR: “Target of 5% uncertainty on trilinear couplings”
  ➡ Not sure where this statement comes from. Seems perfectly reasonable but not cited.

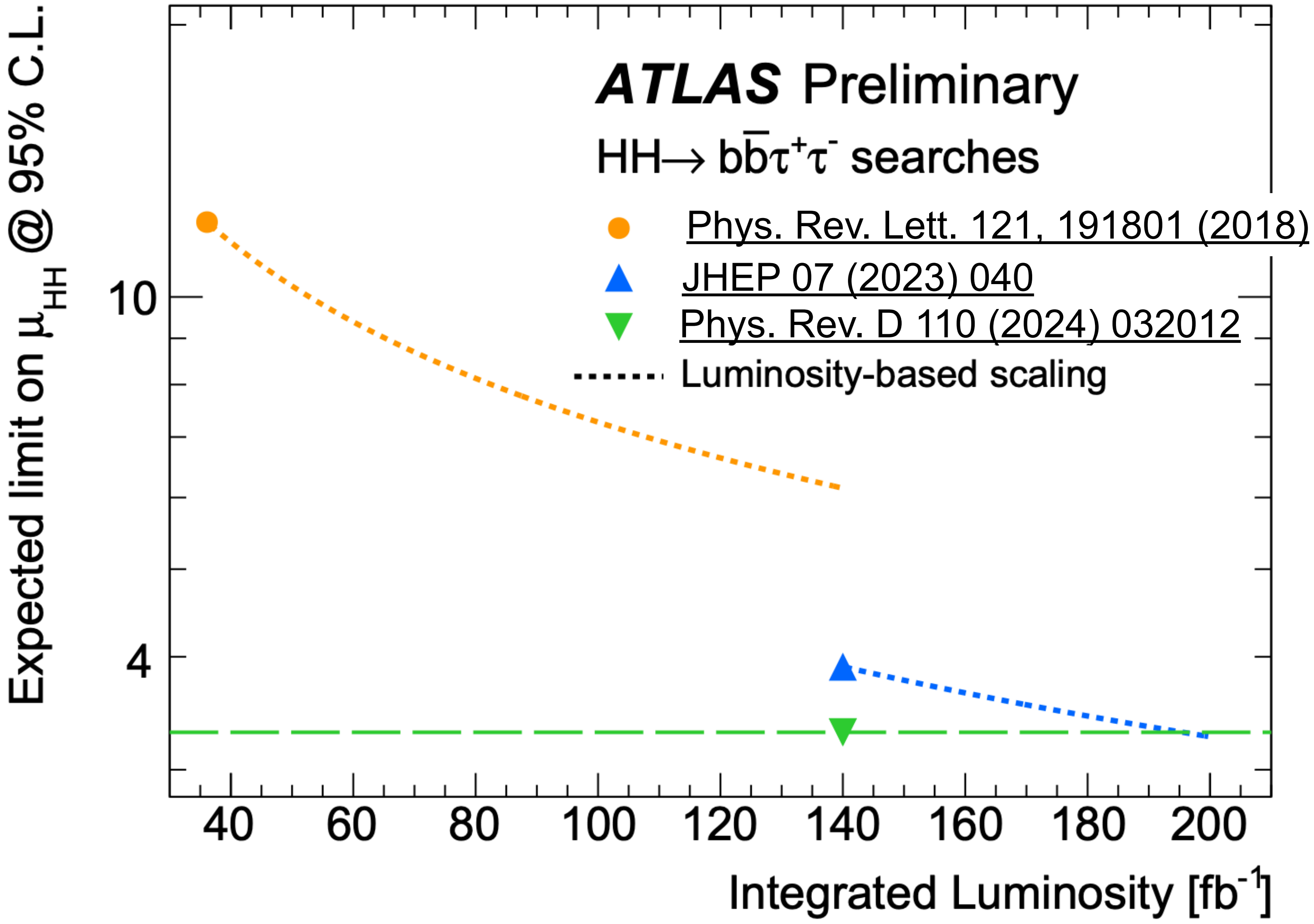
- Not clear what energy is needed to reach this precision.

- A good understanding of prospects for both at a range of energies should be a key goal to understand by March.

Higgs Self Couplings

- **New ATLAS projection of just bb$\tau\tau$, released just 5 days ago.**

ATL-PHYS-PUB-2024-016



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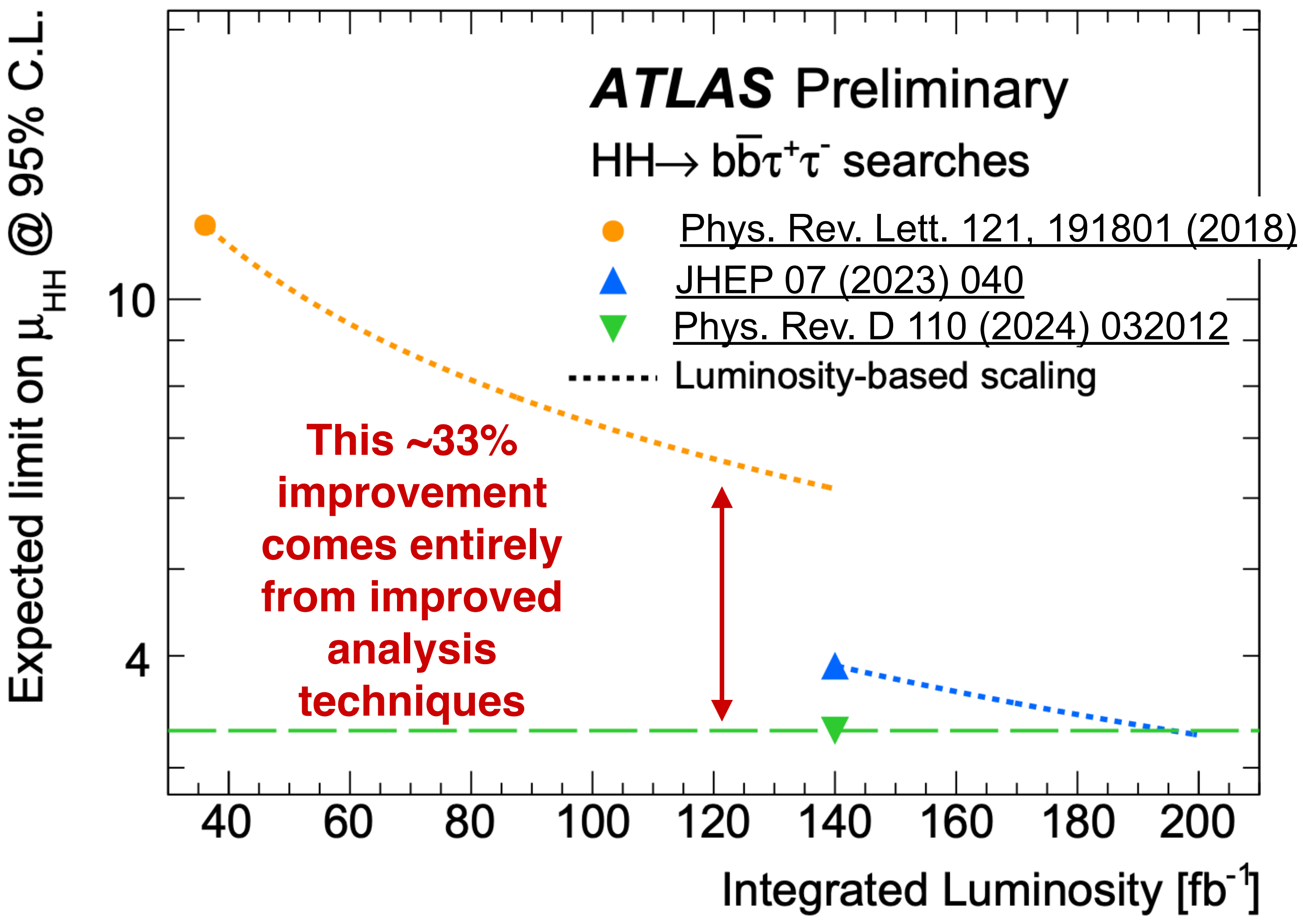
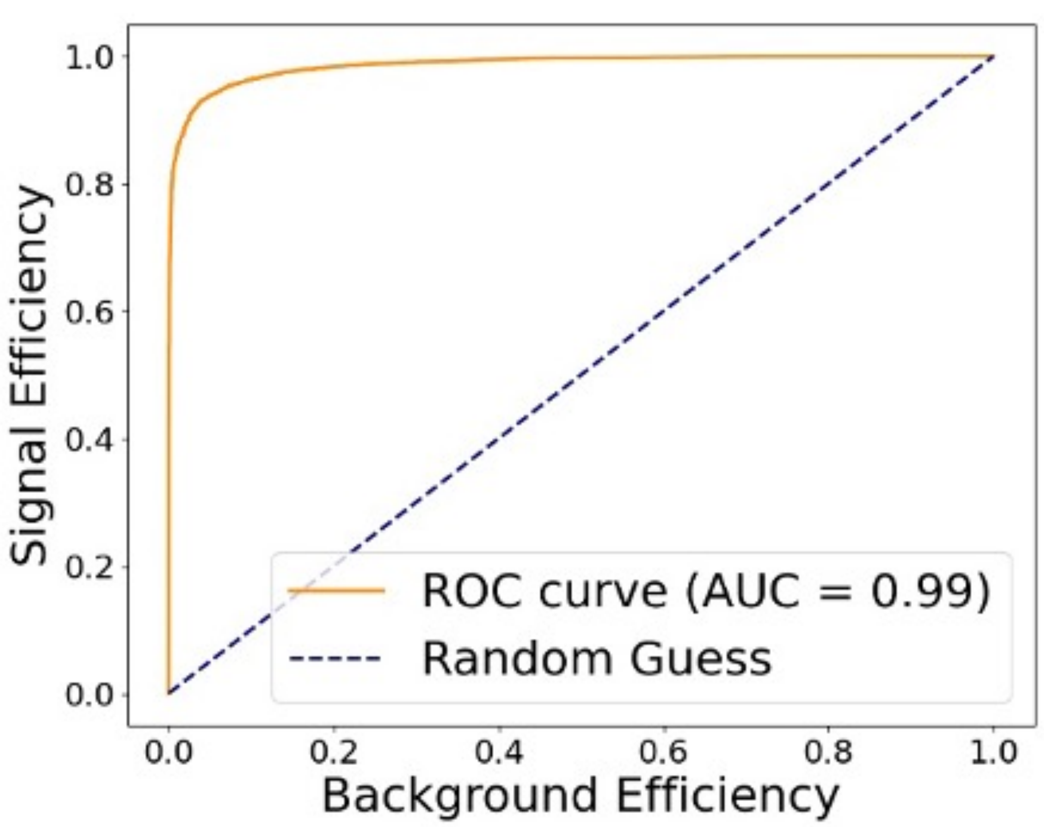


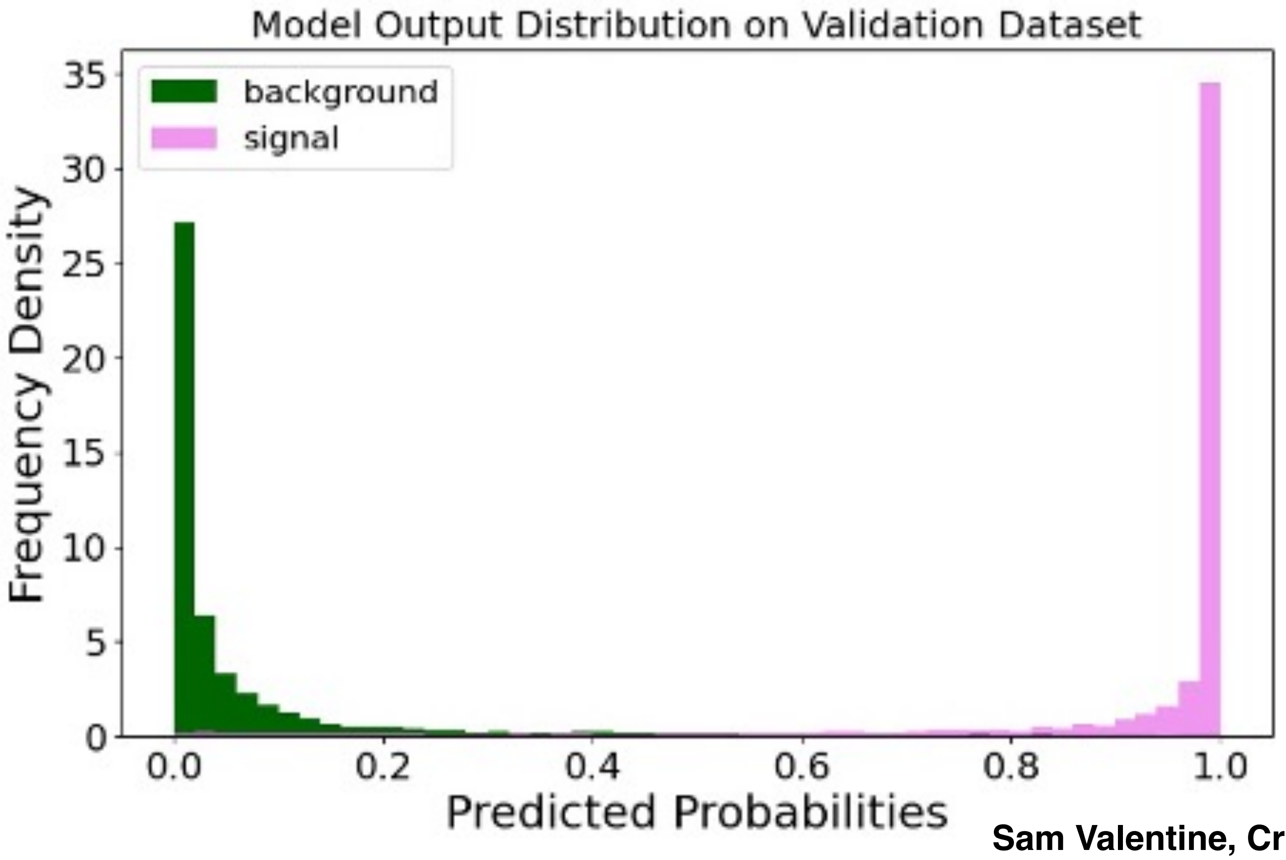
This ~33% improvement comes entirely from improved analysis techniques

- **Highlights difficulty in making meaningly projections but also highlights how we're almost always too conservative.**

Higgs Self Couplings

- **Also some dedicated work going on in the UK already (e.g. at Liverpool).**





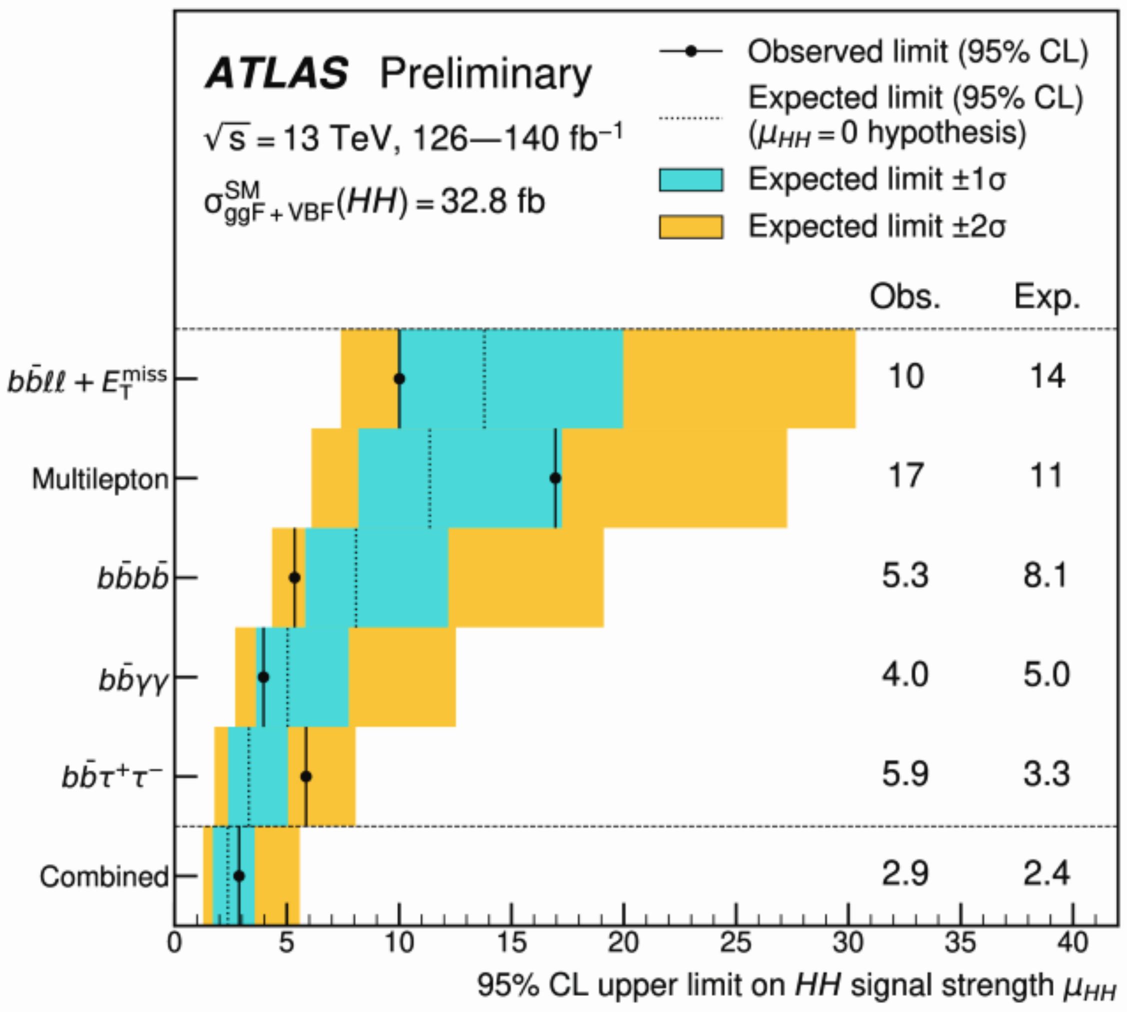
Sam Valentine, Crstiano Sebastiani, Jordy Degens, Monica D’Onofrio, Carl Gwilliam

- **Shows improvements you can gain from considering higher-level reconstructed variables in current analysis techniques.**

- **Projecting this to FCC$_{hh}$ energies** (full details in backup)**.**

Higgs Self Couplings

- **Many older extrapolations focus on one or two channels** (bbɣɣ, bb$\tau\tau$) **but other channels matter too** (bbbb, bbll, ML)**.**



PhysRevLett.133.101801

- **Though currently not as sensitive, the other channels have** (arguably) **the most scope for method improvements** (and thus, the highest uncertainty on projections)**.**

Higgs Total Width

- **Example of something that we traditionally only really consider for lepton colliders but may want to consider more for FCC$_{hh}$.**

- **You can access the higgs total width using the off-shell xsec.**

- **Extrapolating from the ATLAS Run2 result PLB 846 (2023) 138223** (CMS result also came out this week: 2409.13663 with 2 MeV uncertainty):

Scenario	Uncertainty [Mev]	Relative
Run2	3.30	73%
HL-LHC	0.50	11%
HE-LHC	0.18?	4%
FCC$_{hh}$ (50 TeV)		
FCC$_{hh}$ (70 TeV)		
FCC$_{hh}$ (100 TeV)		

source

e^+e^- Uncertainties

ILC (250) = 3.9%

ILC (500) = 1.7%

FCCee = ?%

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- **Example of something that we traditionally only really consider for lepton colliders but may want to consider more for FCC_{hh}.**
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Scenario	Uncertainty [Mev]	Relative
Run2	3.30	73%
HL-LHC	0.50	11%
HE-LHC	0.18?	4%
FCC_{hh} (50 TeV)	< 0.1?	< 2%
FCC_{hh} (70 TeV)	< 0.1?	< 2%
FCC_{hh} (100 TeV)	< 0.1?	< 2%

Note: experimental systematics would start to dominate by this point and I've ignored them here.

source

e^+e^- Uncertainties

ILC (250) = 3.9%

ILC (500) = 1.7%

FCCee = ?%

- **Trivial combination gives you 50% relative uncertainty at Run2 and 35% by the end of Run3.**

Summary

Key takeaways (so far)

- **Some of the key measurement goals** (not searches) **identified in roadmaps & strategy documents living under the remit of lepton colliders might be achievable at similar** (or sufficient) **precision at hadron colliders.**
  - ➡ But extraordinary claims require extraordinary evidence. Needs discussion on if we can provide this in time.

- **As a plan B, FCC$_{hh}$ at lower energies on a much sooner timescale could be very attractive and worth fleshing out, at least from the top and Higgs measurement point of view.**

- **It is difficult to do projections outside of collaborations on more modern measurements** (many moving parts, not trivial to extrapolate likelihood sensitivities)**.**
  - ➡ **Focusing efforts on a few measurements can work as templates for other measurement** (e.g. top mass works as a decent proxy for most properties measurements)**.**

Key takeaways (so far)

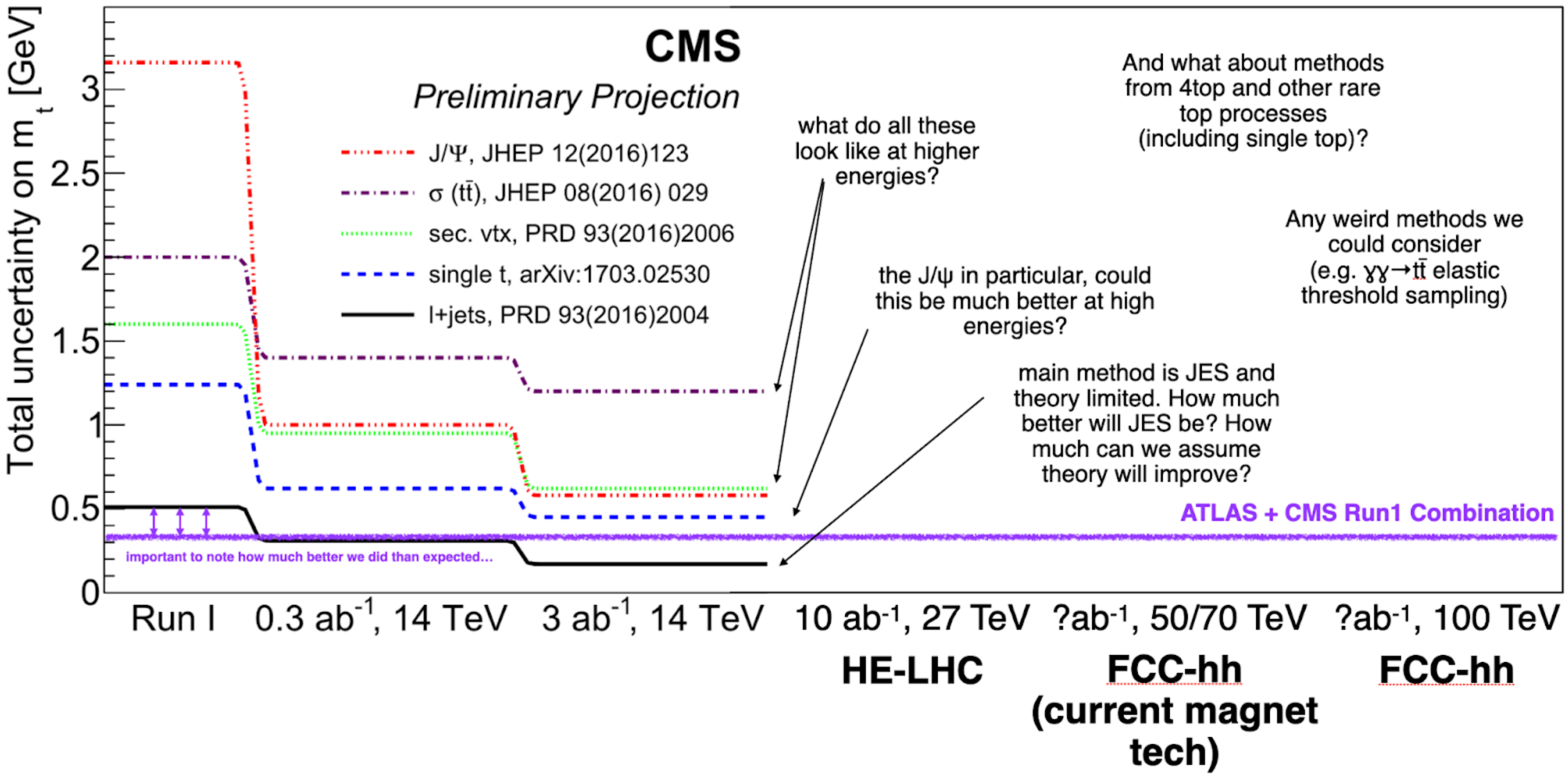
- **Top Physics:**
  - ➡ **No matter which hadron collider you consider at which energy, top physics requires significant resources on the theory side to make meaningful gains in key measurements at the HL-LHC and beyond, but have great potential at future hadron colliders.**

- **Higgs Physics:**
  - ➡ **There are places where hadron colliders obviously excel, but there could be more. Consider a bolder scope for March by focusing on understanding the potential without the assumption that some things will be covered by lepton colliders.**

- **Final Thought:**
  - ➡ **Hadron colliders are discovery machines AND precision physics machines. Best of both worlds!**

Backup

Top Mass



what do all these look like at higher energies?

the J/ψ in particular, could this be much better at high energies?

main method is JES and theory limited. How much better will JES be? How much can we assume theory will improve?

And what about methods from 4top and other rare top processes (including single top)?

Any weird methods we could consider (e.g. $\gamma\gamma \rightarrow t\bar{t}$ elastic threshold sampling)

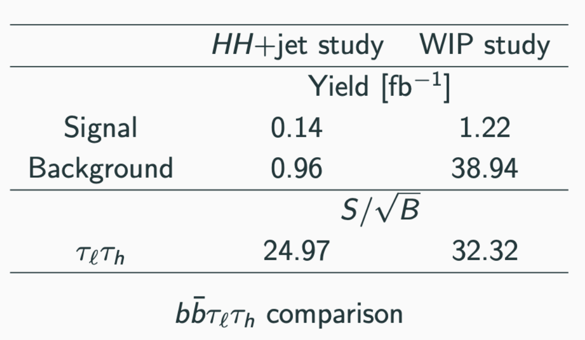
important to note how much better we did than expected…

UK $bb\tau\tau$ feasibility study

Feasibility studies for di-Higgs in $bb\tau\tau$ events

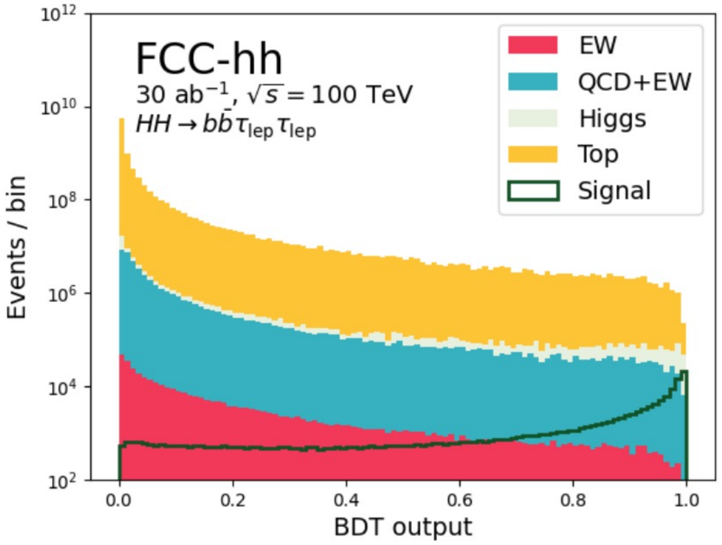
Sam Valentine (project student), Cristiano Sebastiani, Jordy Degens, Monica D'Onofrio, Carl Gwilliam

- **Previous studies** using a BDT were developed in 2022 (see presentation at Higgs pair by Matt Sullivan)
  - Results taking into account both $\tau_L - \tau_H$ and $\tau_H\,\tau_H$
  - Very good sensitivity, comparable with published studies (https://arxiv.org/pdf/2004.03505)

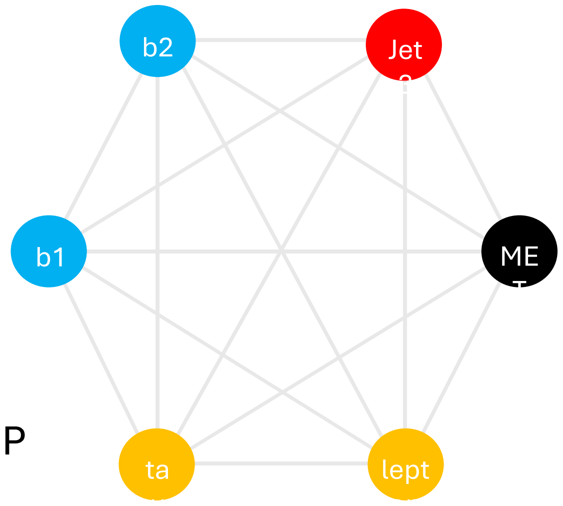


	HH+jet study	WIP study
	Yield [fb^{-1}]	
Signal	0.14	1.22
Background	0.96	38.94
	$S/\sqrt{B}$	
$\tau_\ell\tau_h$	24.97	32.32

$b\bar{b}\tau_\ell\tau_h$ comparison

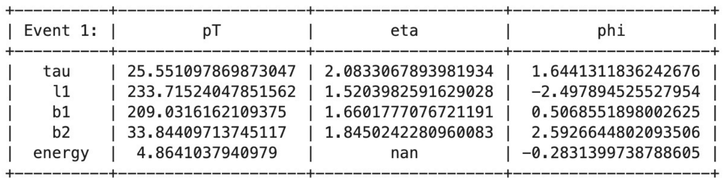


- **This work:** implement graph neural networks
  - **GNN pipeline from Alessio Devoto** (PhD Computer Scientist, University of Rome Sapienza)
  - Graph for each event, each object is a node
  - Fully connected, each node has several features
  - Different models tested (GCN, **GAT**)
  - Systematic evaluation of performance based on relevant metrics (S vs B separation, AUC)
  - Inputs and samples using official samples (EDM4HEP format) and ntuples generated with FCC analysis starterkit (same as linked in Matt's slides above)



So far:

- limited statistics used (35k events)
- $\tau_L - \tau_H$ only
- Top-pair production as background (expected to be dominant in this channel)

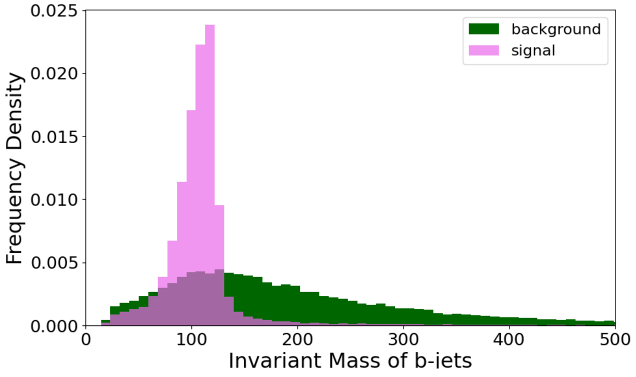


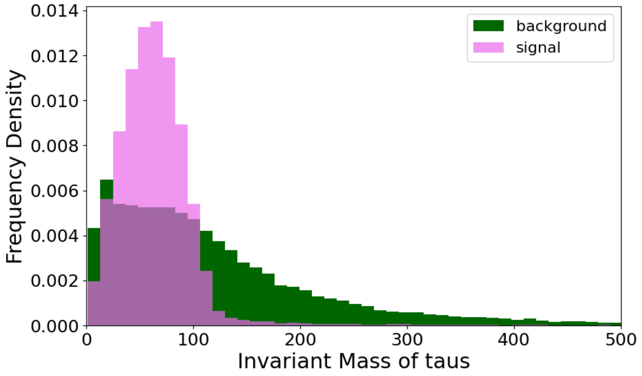
```
+-----------+---------------------+---------------------+---------------------+
| Event 1:  |         pT          |         eta         |         phi         |
+-----------+---------------------+---------------------+---------------------+
|    tau    | 25.551097869873047  | 2.0833067893981934  |  1.6441311836242676 |
|     l1    | 233.71524047851562  | 1.5203982591629028  |  -2.497894525527954 |
|     b1    |  209.0316162109375  |  1.660177076721191  |  0.5068551898002625 |
|     b2    |  33.84409713745117  | 1.8450242280960083  |  2.5926644802093506 |
|   energy  |   4.8641037940979   |         nan         | -0.2831399738788605 |
+-----------+---------------------+---------------------+---------------------+
```

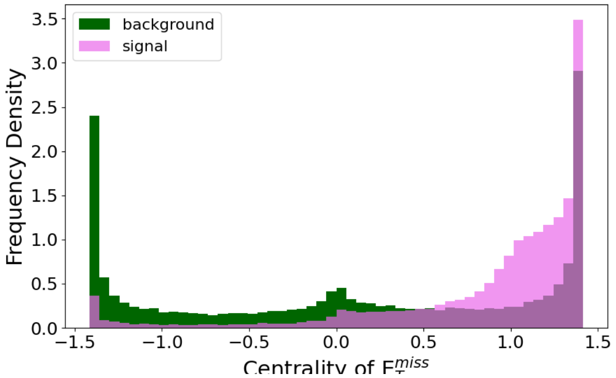
Feasibility studies for di-Higgs in bbττ events (2)

Sam Valentine (project student), Cristiano Sebastiani, Jordy Degens, Monica D'Onofrio, Carl Gwilliam

- Tested S vs B separation using only object variables and using also complex reconstructed kinematic variables
  - Performance dramatically improved when kinematic variables such as b-jet pairs invariant mass, tau-lepton invariant mass etc are passed as individual nodes
    - Area-Under-Curve in ROC curve 0.82 → 0.99
  - Use also radial distances among b and tau objects and ETMiss centrality as in ATLAS di-Higgs studies



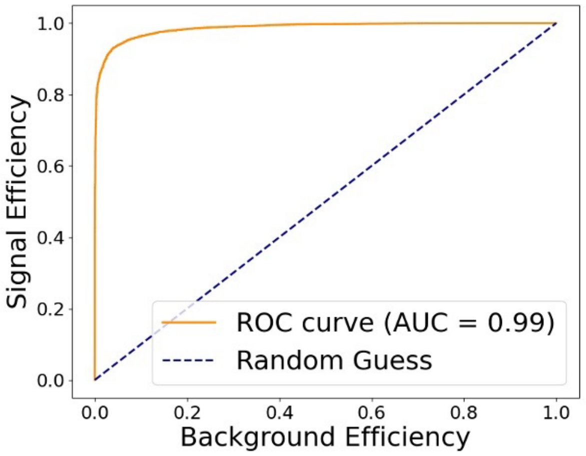




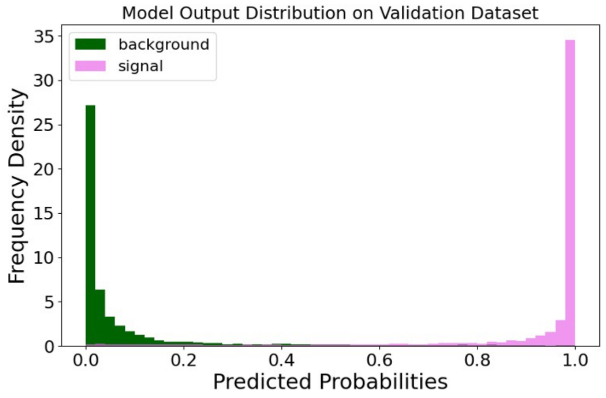
$$E_T^{miss} centrality = \frac{(x+y)^2}{\sqrt{x^2+y^2}}$$

$$x = \frac{\sin(\phi_{MET} - \phi_\tau)}{\sin(\phi_\ell - \phi_\tau)}$$

$$y = \frac{\sin(\phi_\ell - \phi_{MET})}{\sin(\phi_\ell - \phi_\tau)}$$

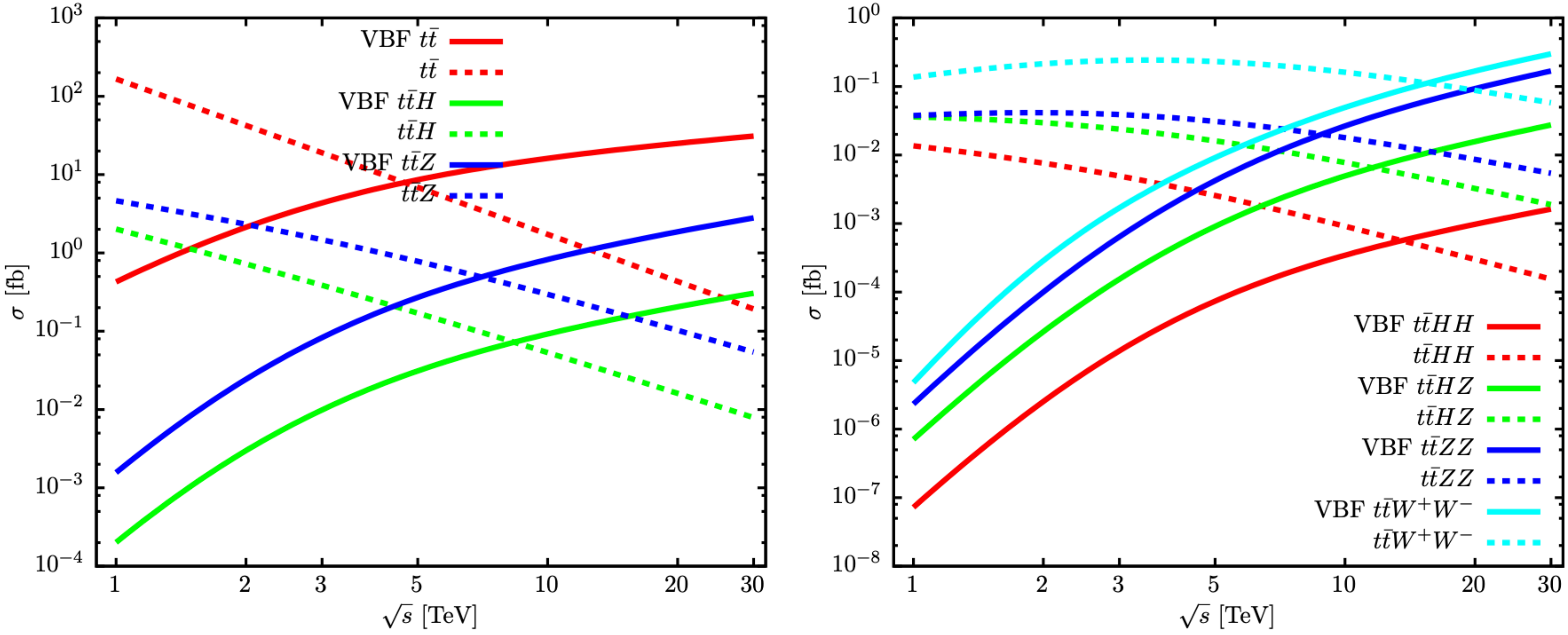


Excellent separation achieved



- First estimate of sensitivity show a significance similar to BDT-based results
- Limited by statistics, so next steps is to evaluate sensitivity with full stat ttbar and add fully hadronic channel

Muon collider cross-sections



Top Mass

- **EXECUTIVE SUMMARY:**
  - ➡ **Top mass is going to be more precise than predicted in Snowmass 21** (already approaching HL-LHC expected precision)**.**
  - ➡ **Future efforts rely on exploiting methods that can benefit from very high stats, but even with those…**
  - ➡ **Significant investment is required in all aspects of the theory if future hadron colliders are required for <100 MeV precision.**
- **FOR MARCH 2025:**
  - ➡ **Material available for an informed view point** (top mass is a good example of a story across most top measurements)**.**
  - ➡ **There are some short studies that could be nice to add.**