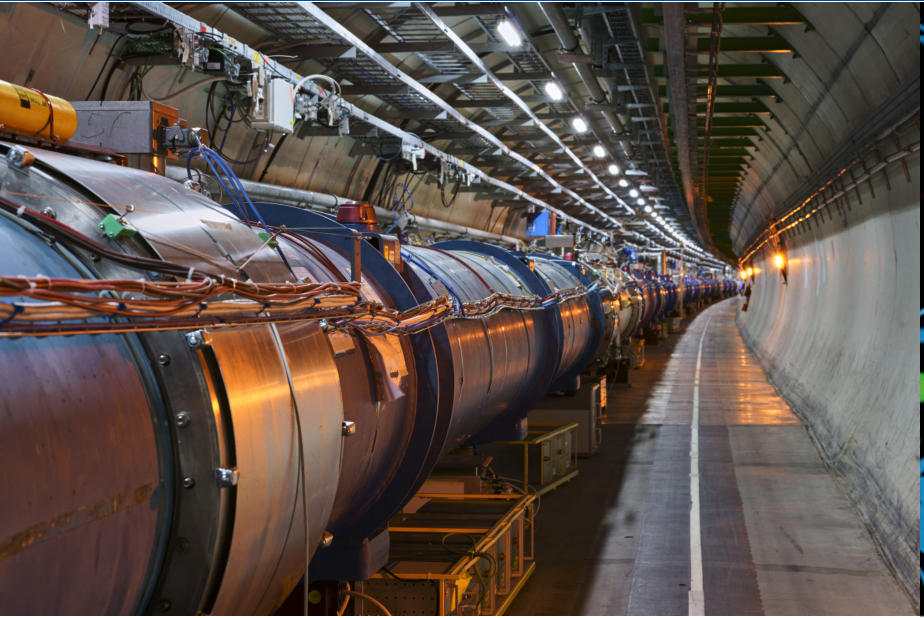
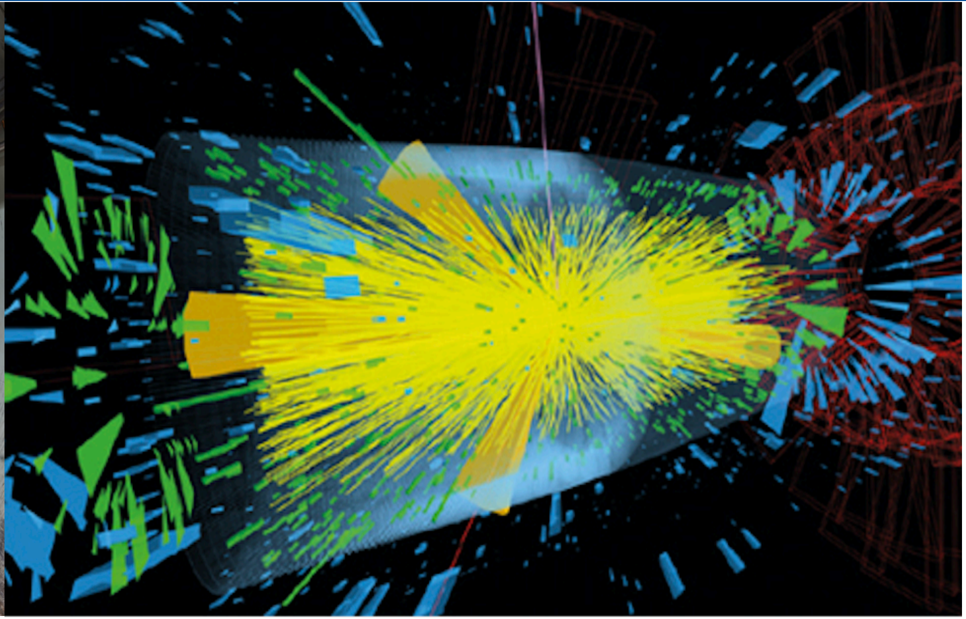




Physics at HL-LHC and Beyond

Sergo Jindariani (Fermilab)

LHCP

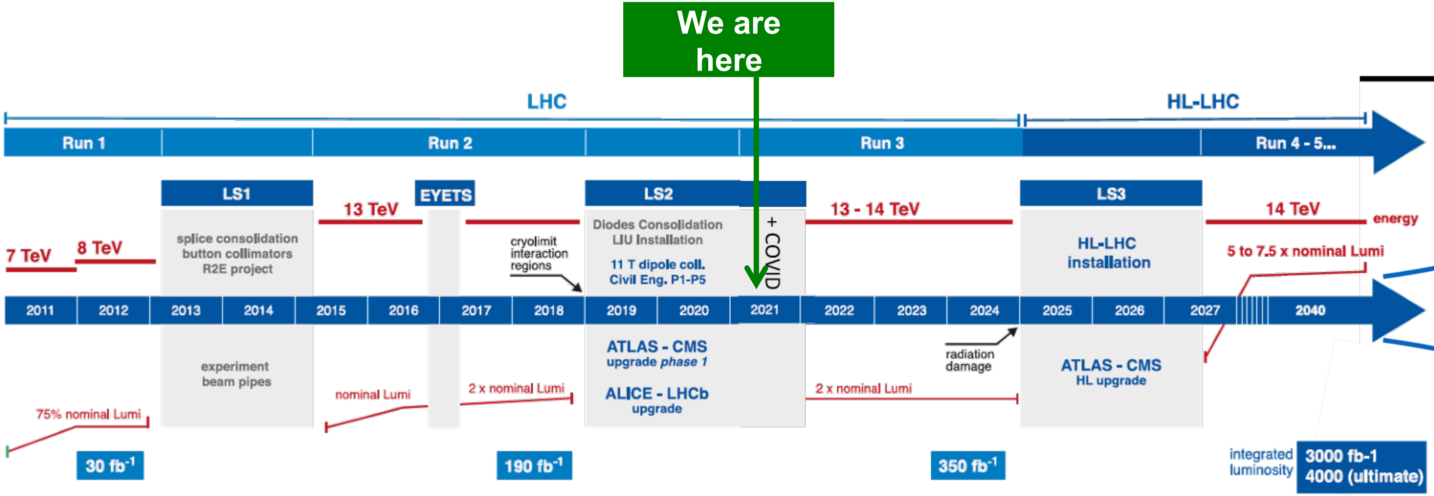
June 12th, 2021

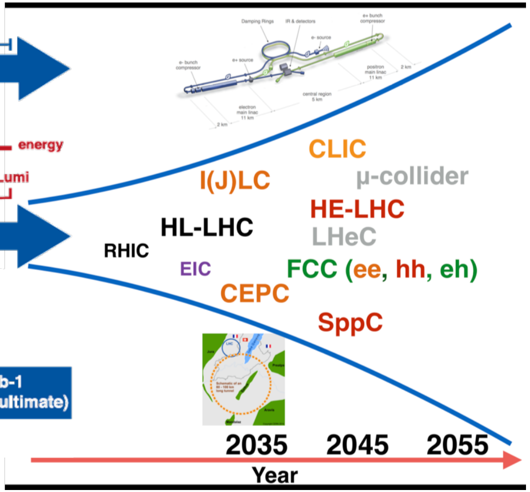
Outline

- Highlights of physics at High Luminosity LHC
- Post-LHC Colliders
- Challenges of detectors for future colliders
- Summary

This is not a comprehensive, quantitative review of future physics (impossible in 20 mins), rather an attempt to lay out the big picture using personal choices

Collider Landscape





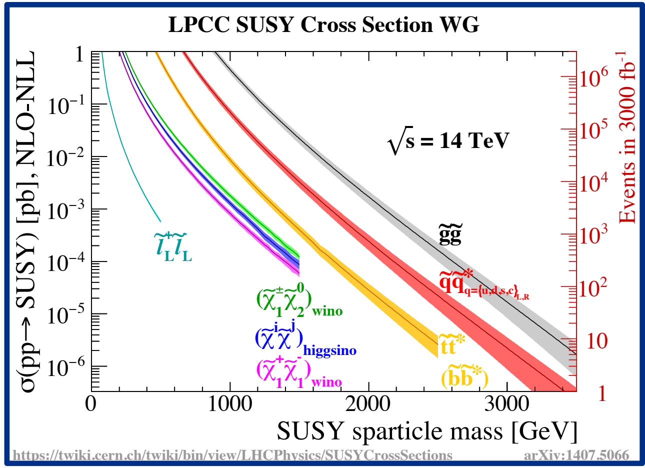
LHC + HL-LHC is the largest **pp** dataset for the next few decades

Variety of post-LHC colliders proposed globally

Pursuit for New Physics

- The LHC will deliver 3 ab^{-1} of data over the next 20 years
  - Incredibly rich dataset (x20 more than we have now)
  - But the doubling size is becoming longer → slower gains in many direct searches for BSM physics
- Precision to probe New Physics indirectly:
  - Higgs boson – a particle like no other
- BSM processes with small rates and challenging final states (e.g. Higgsinos in SUSY)
- Previously unexplored signatures (e.g. highly boosted, long-lived)

arXiv:1407.5066

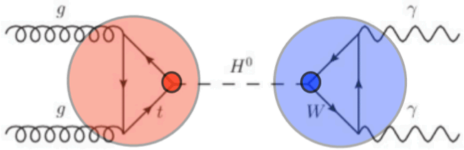


Rapidly falling cross-section

Higgs Couplings

New physics can modify Higgs couplings to SM particles

arXiv:1209.0040
arXiv:1210.3342



$$(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

How big are the modifications ?

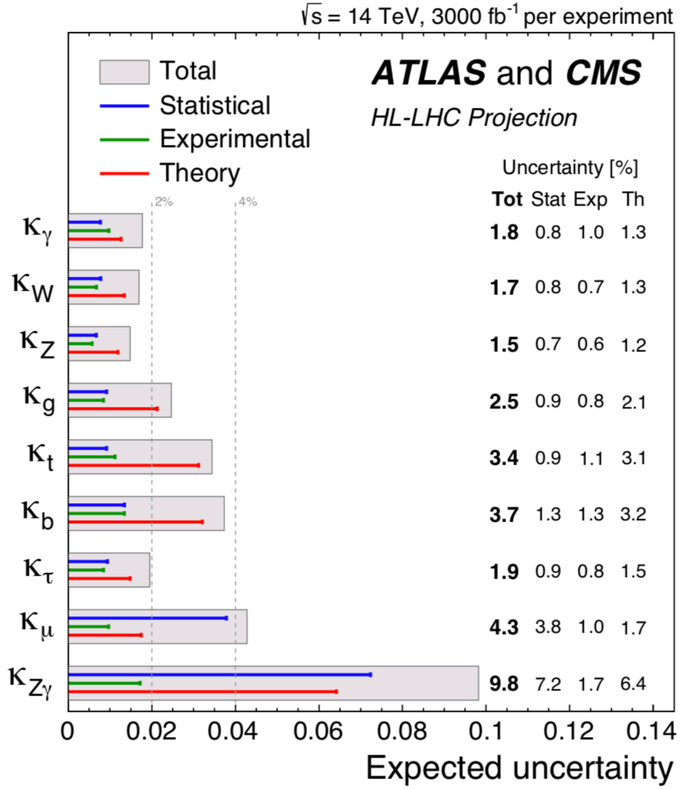
- Different physics models considered in the Higgs Working Group report

arXiv:1310.8361

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

- $M_{NP} \sim 1$ TeV and mixing angles satisfy precision electroweak fits
- Typical deviation of O(few %)
- **Target 1% accuracy**

Higgs Couplings at HL-LHC



Uncertainty assumptions:

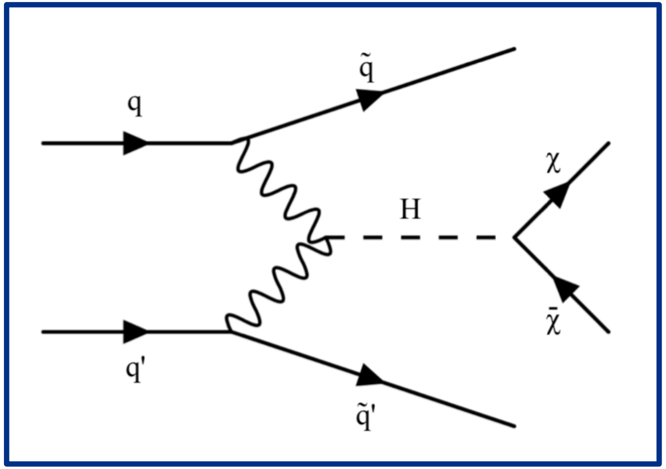
- Data statistics as sqrt(L)
- Theory uncertainties halved
- Detector limitations remain constant

Precision on kappas of 2-4% can be reached with 3 ab^{-1} for the non-statistically dominated modes

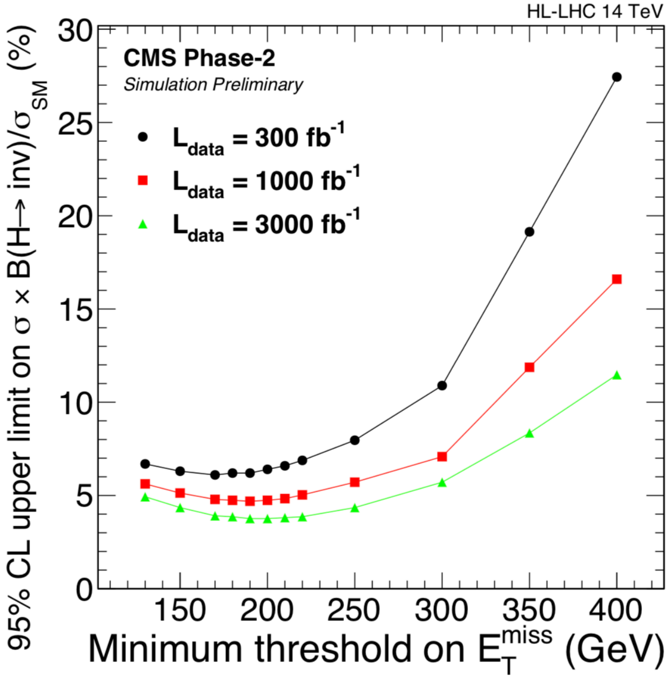
Measurements become systematically limited rather quickly

Higgs to Unknown

Connection with **Dark Matter**

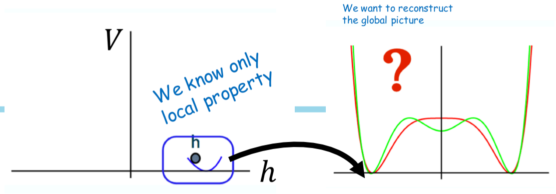


Run-2 Limit ~20% @ 95%CL (dominated by VBF)



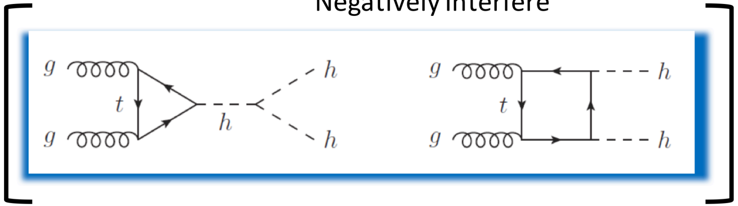
CMS projection for VBF BR(inv): < 3.8% at 95%
Sensitive to E_T^{miss} thresholds

Higgs Self-Coupling at HL-LHC



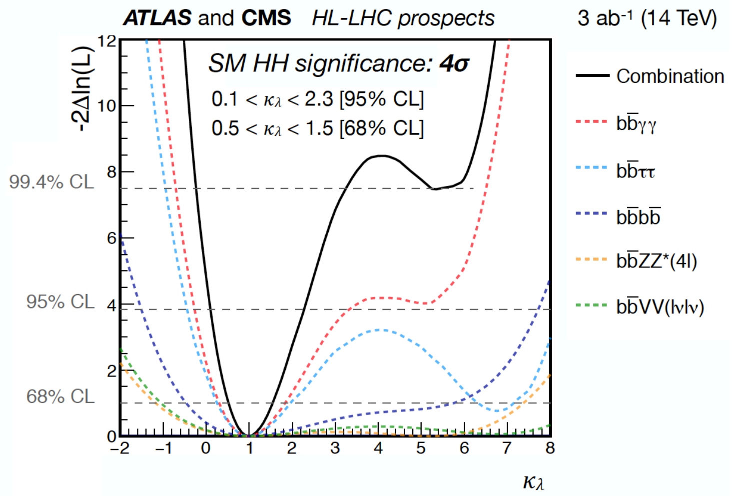
$$V_h = \frac{m_h^2}{2}h^2 + (1+\boxed{\kappa_3})\lambda_{hhh}^{SM} v h^3 + \frac{1}{4}(1+\boxed{\kappa_4})\lambda_{hhhh}^{SM} h^4$$

Negatively Interfere

σ  $\sim$ 40 fb @14 TeV

$\times$ BR

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

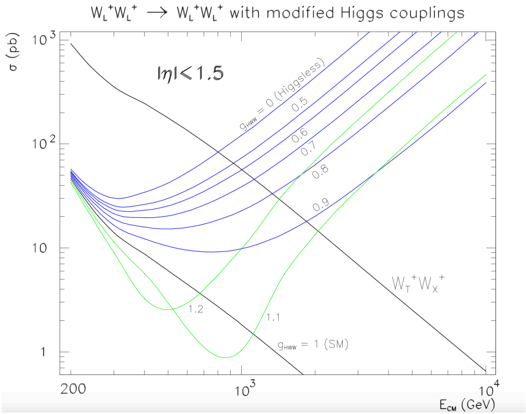


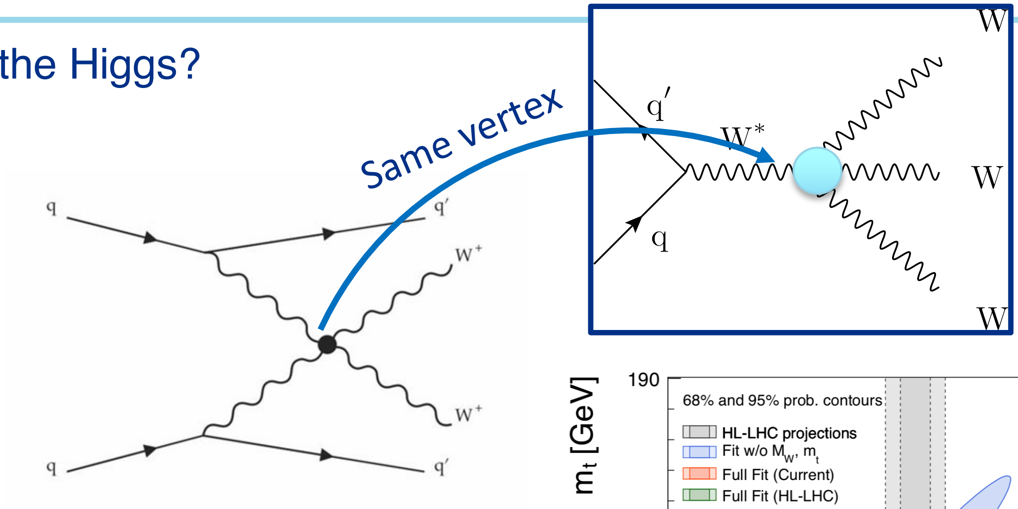
Statistically limited!

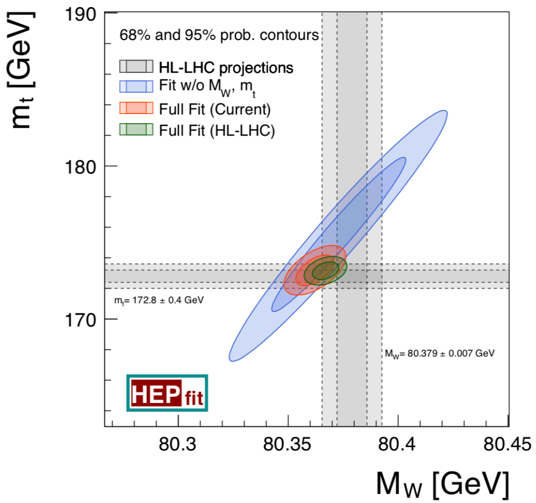
Fermilab

Plethora of SM Measurements

W_LW_L Unitarized by the Higgs?





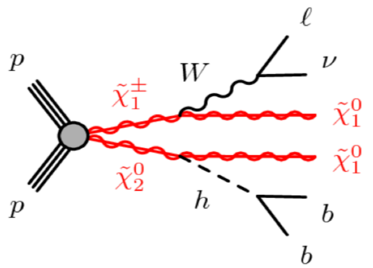


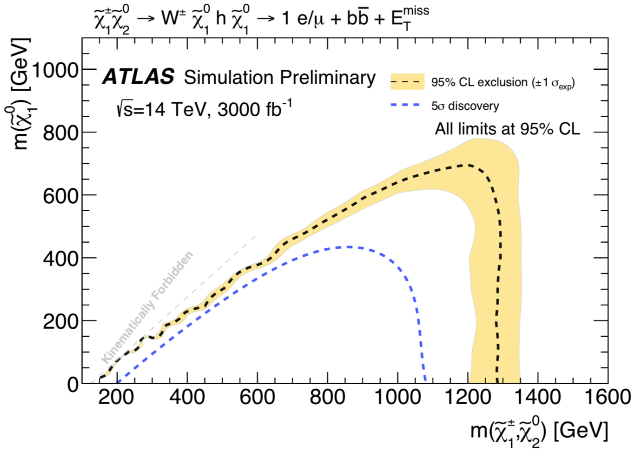
- ATLAS+CMS: evidence for W_LW_L production
- Quartic Gauge Coupling in VVV
- Goal Δm(W)~7 MeV (combination + ultimate PDF)
- $\sin^2(\theta_{eff})$ total uncertainty of better than $20*10^{-5}$

Fermilab

SUSY (as an example of BSM)

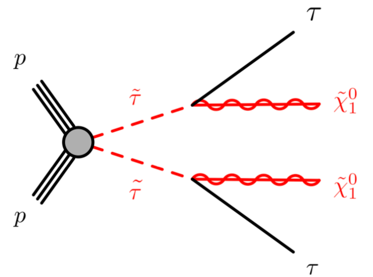
Chargino/Neutralino

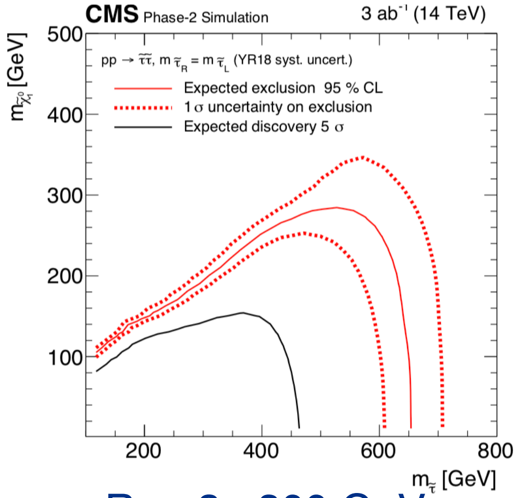




Run-2 ~800 GeV

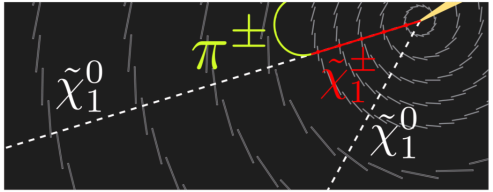
sTaus



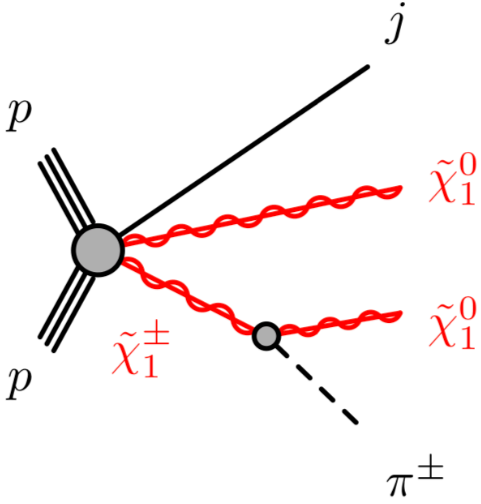


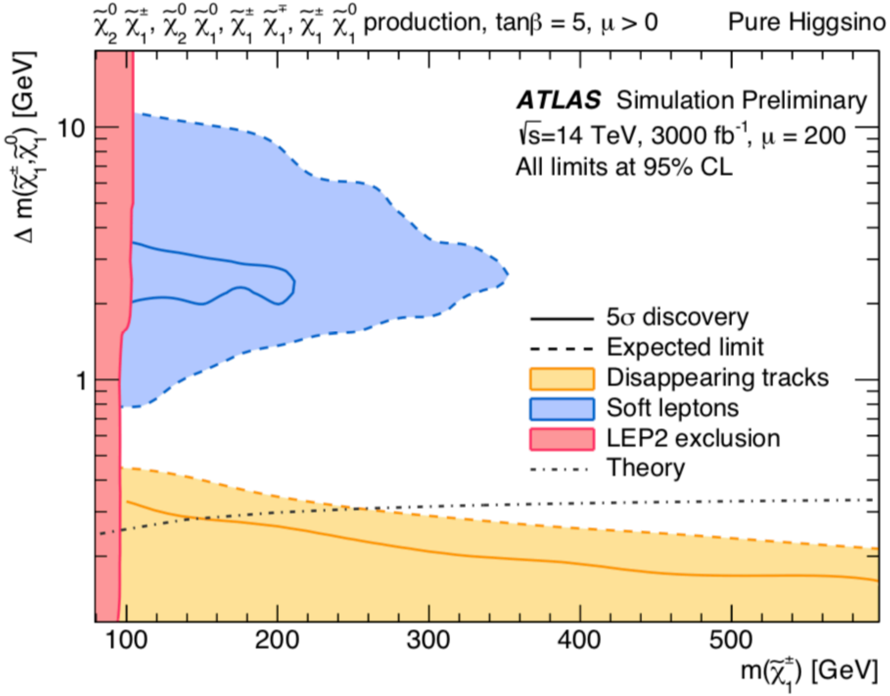
Run-2 ~300 GeV

Long Lived at HL-LHC



- Disappearing track targets very small mass splitting
- E.g. Higgsino/Wino motivated
- Connection with Dark Matter

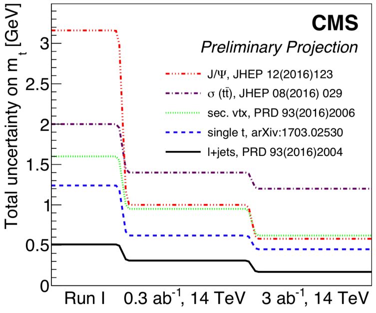


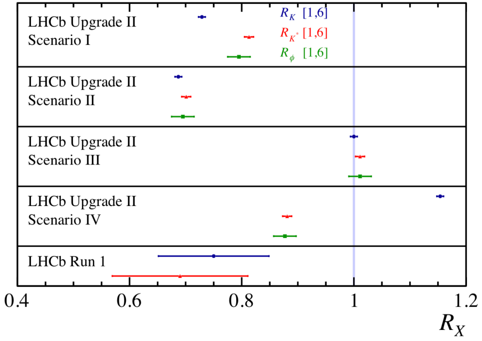


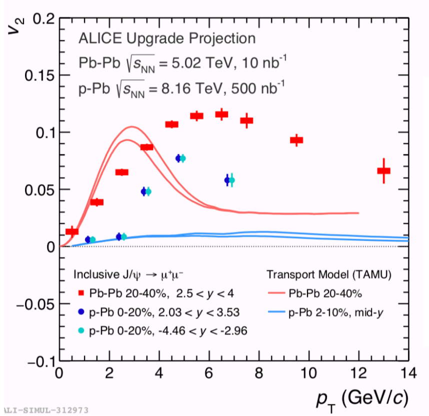
Things I did not talk about

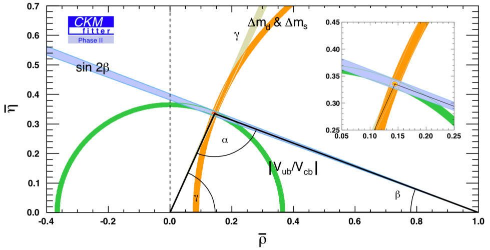
- Differential measurements
- Top mass, properties, FCNC, etc
- Heavy flavor, CKM unitarity tests
- Prospects for B-anomalies
- Hadron Spectroscopy
- PDFs
- Heavy Ion program

- A very exciting and rich physics program!







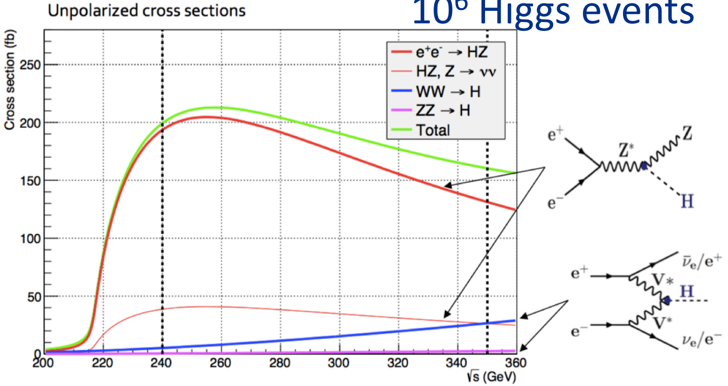


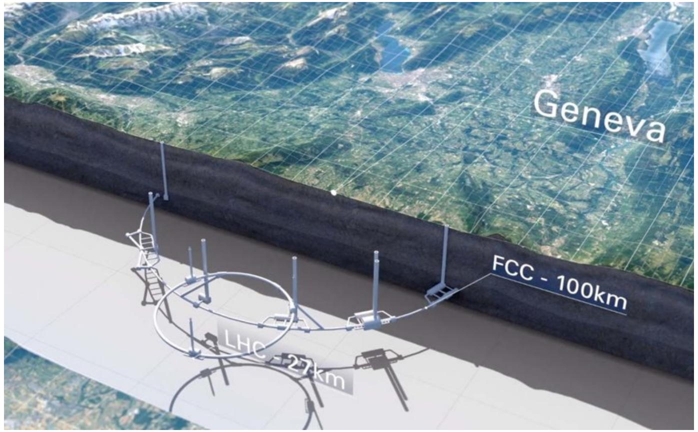
Beyond the LHC

- Electron-positron colliders to make precision measurements of the SM:
  - CepC, CLIC, FCC-ee, ILC
  - Produce Higgs events in large quantities
  - Collider colorless particles → smaller backgrounds
- Proton-proton colliders with energy above LHC for extended reach to BSM (FCC-hh, SppC)
- Can Muon Colliders do both?

- ESPP gives the preferred direction for future collider(s) at CERN:
  - 100 km ring with e+e- Higgs factory followed by a 100 TeV proton-proton collider in the same tunnel

10^6 Higgs events





Fermilab

Higgs Precision

FCC CDR

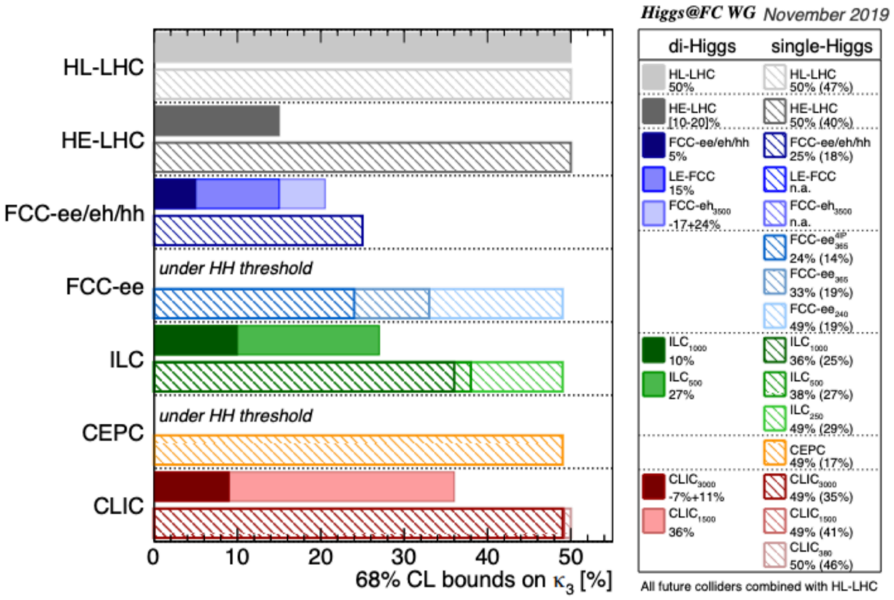
Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{Hmm}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	$<$ **1.0**	$<$ **1.0**

Sub % precision for most couplings

There is much more than Higgs at the e+e- colliders…

Higgs Self Coupling

$$V_h = \frac{m_h^2}{2}h^2 + (1+\boxed{\kappa_3})\lambda_{hhh}^{SM} v h^3 + \frac{1}{4}(1+\boxed{\kappa_4})\lambda_{hhhh}^{SM} h^4$$



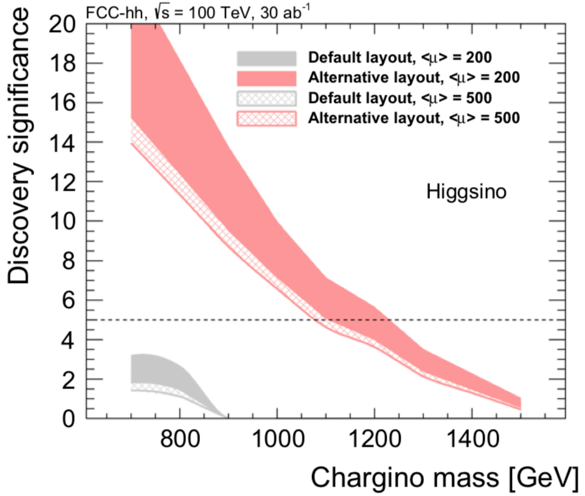
k_3 needs higher energies! Precision from 50% at HL-LHC down to 5% (FCC)

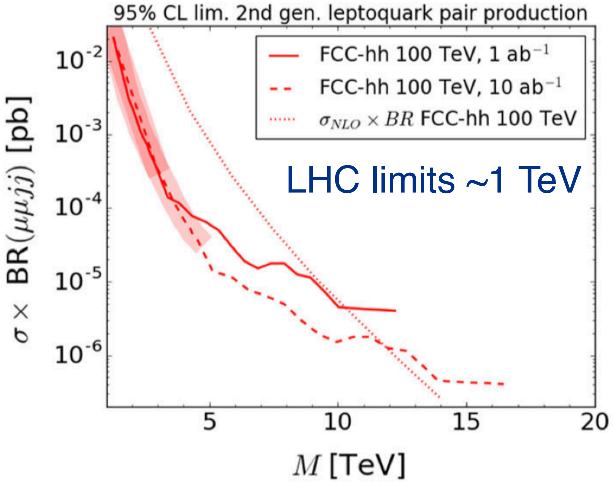
100 TeV pp Collider (FCC-hh example)

- Direct BSM Reach:
  - Strongly produced resonances → up to 40 TeV
  - Wino/Higgsino like DM up to 4 TeV/1 TeV
  - Leptoquarks up to 10-12 TeV

- Higgs
  - Improved determination of couplings
  - Trilinear couplings, potential access to quartic coupling
  - Invisible decay 10^{-4}

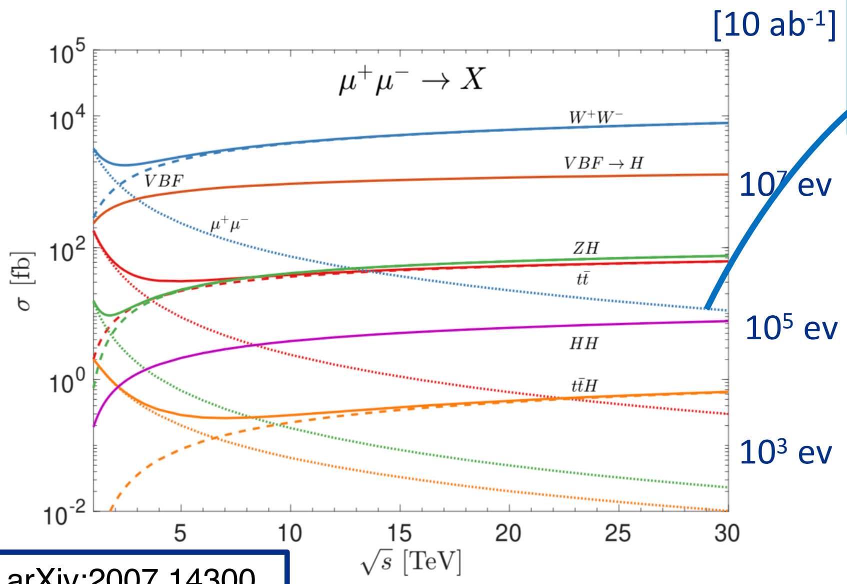
- Rich top and flavor physics program: 10^{12} top quarks 10^{17} bottom quarks





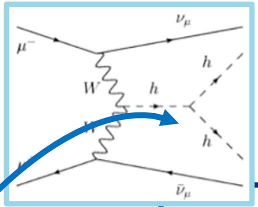
Muon Collider: Higgs

- Colliding elementary, colorless particles (alike electrons)
  - No synchrotron radiation compared to e+e- → can reach high energies
  - Large beam induced backgrounds - further studies and mitigation strategies needed



arXiv:2007.14300

[T. Han, Y. Ma, K.Xie 2007.14300]



High Energy Muon Collider is a VBF Higgs Factory

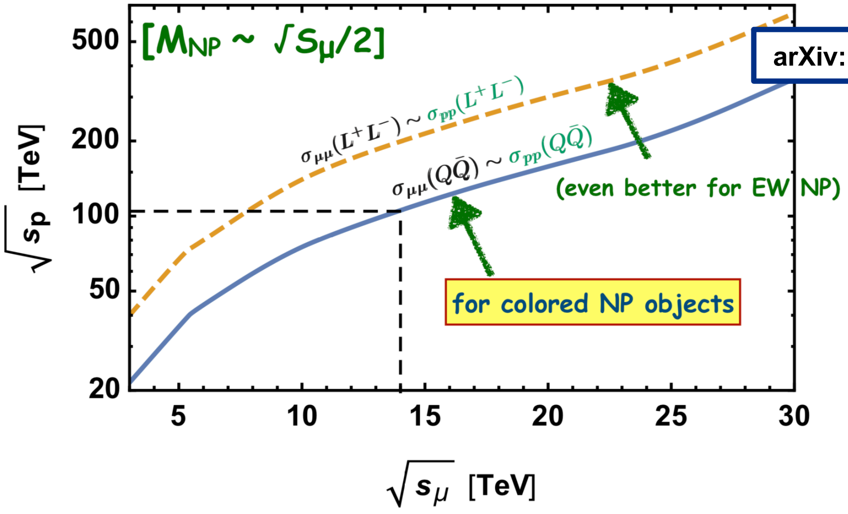
arXiv:2103.14043

	Fit Result [%]		
	10 TeV Muon Collider	with HL-LHC	with HL-LHC + 250 GeV e^+e^-
κ_W	0.06	0.06	0.06
κ_Z	0.23	0.22	0.10
κ_g	0.15	0.15	0.15
κ_γ	0.64	0.57	0.57
$\kappa_{Z\gamma}$	1.0	1.0	0.97
κ_c	0.89	0.89	0.79
κ_t	6.0	2.8	2.8
κ_b	0.16	0.16	0.15
κ_μ	2.0	1.8	1.8
κ_τ	0.31	0.30	0.27

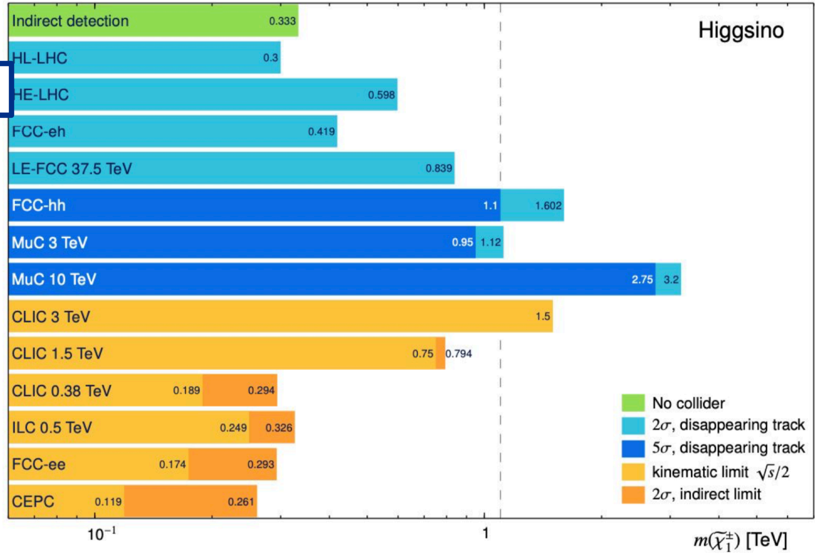
Muon Collider: BSM

Great reach for BSM particles

arXiv: 1901.06150



arXiv: 2102.11292

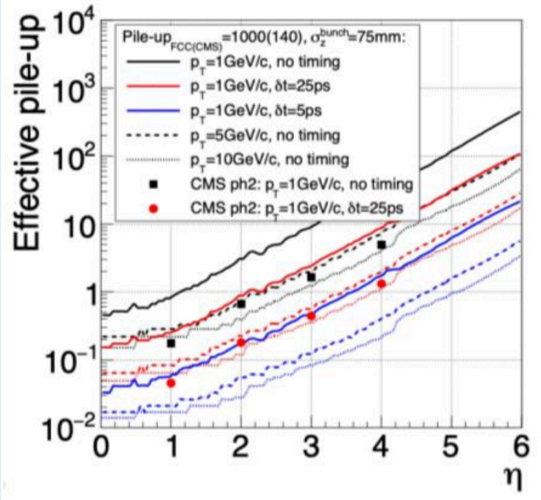


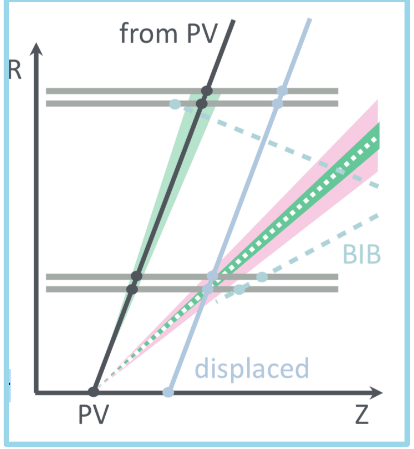
Colored particles: 10 TeV mumu ~ 70 TeV pp
Colorless particles 10 TeV mumu ~ 140 TeV pp

DM reach via disappearing track rivals FCC-hh, covers thermal target

Detector Challenges

- Future Collider detectors face challenges
- Electron-positron: high precision (low mass) Si tracking, 3D imaging and/or dual readout calorimetry, control of systematics
- Proton-proton: radiation-hard tracking and calorimetry, large bore solenoid, high granularity and precision timing for pile-up rejection, challenging data rates
- Muon Colliders: most of the above





Summary and Outlook

- HL-LHC will provide the largest pp dataset for decades
  - Few % level Higgs couplings precision
  - Significantly advance BSM searches, in particular those with small x-sections and unconventional signatures
  - Very rich physics program!

- Future Colliders will greatly advance our understanding of Nature
  - Improve precision and energy reach by ~an order of magnitude wrt to the LHC
  - Big projects take time to realize, now is the time to get engaged

- Collider physics has yielded many discoveries. History shows that will likely do better than we think today. **Look forward to many more discoveries to come!**