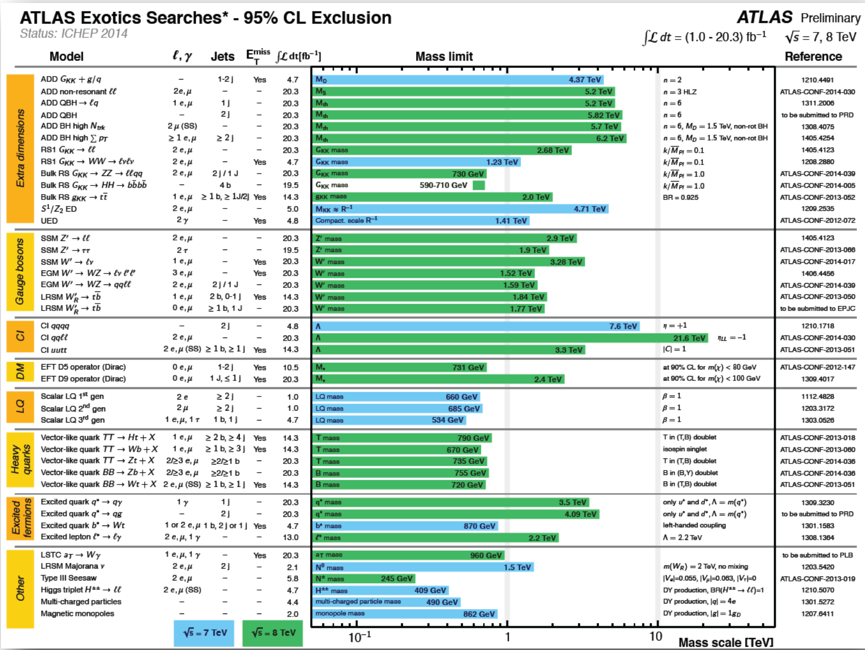
FCC/SppC Physics Studies

Shufang Su • U. of Arizona

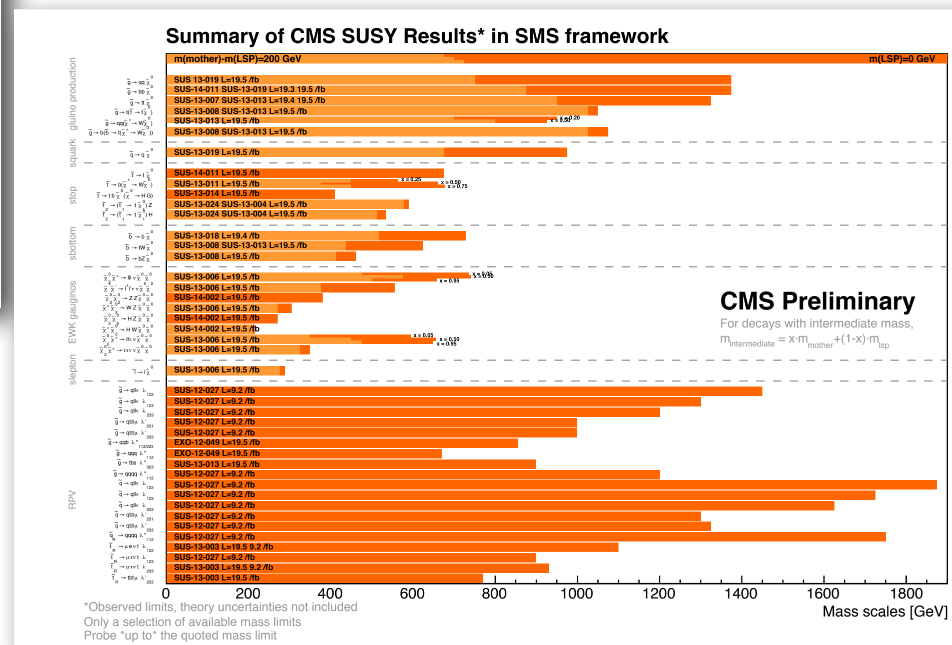
MC4BSM

July 24, UCAS

New Physics Searches



ATLAS exotic



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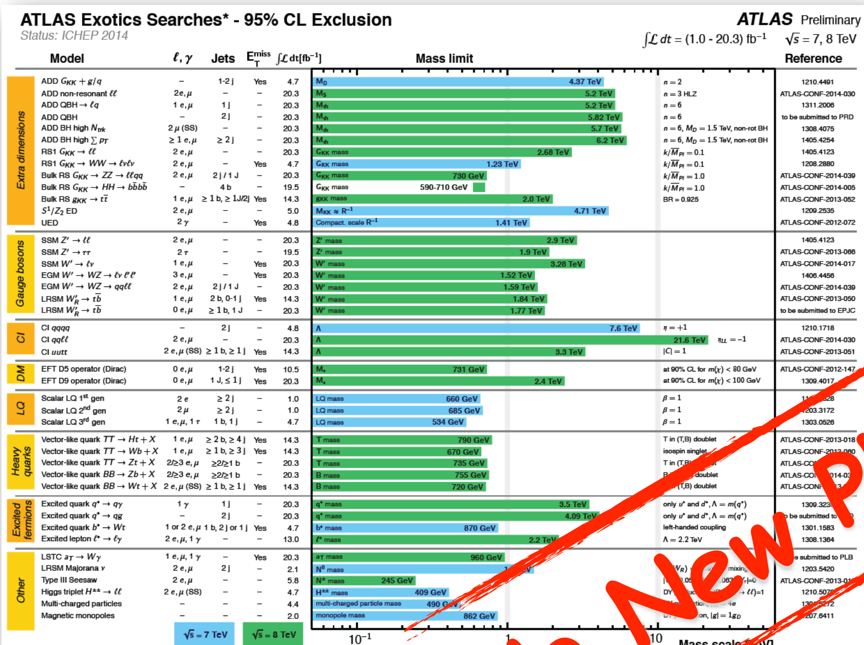
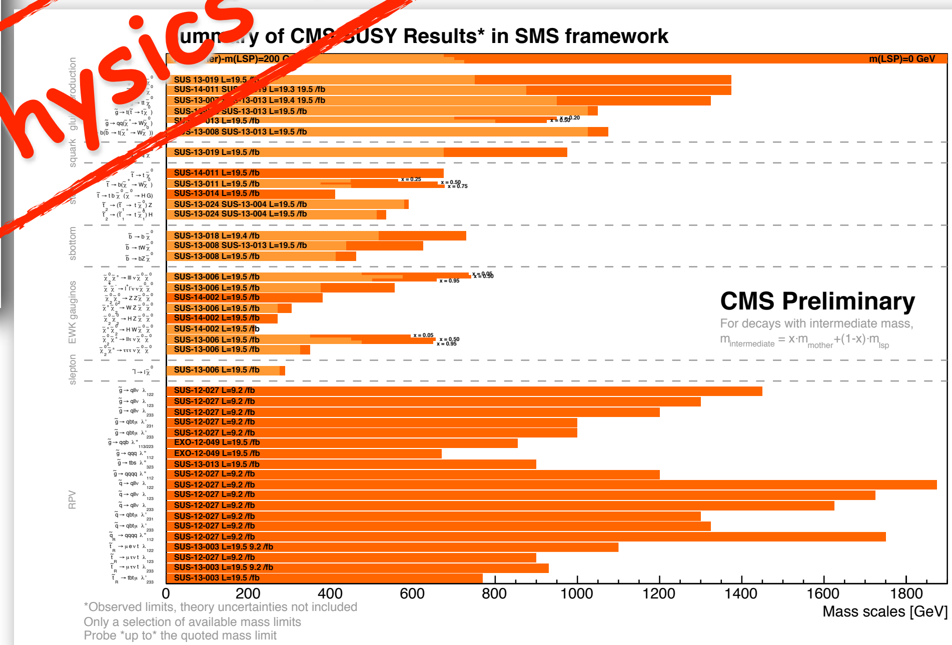
CMS SUSY

New Physics Searches



ATLAS exotic

No New Physics Yet!



CMS SUSY

Where Are We Now?

- Our wish list has not change much from 10 years ago.
- Discovery of Higgs
  - ➡ Exclude technicolor
  - ➡ Narrow down parameter space
- Non-discovery of anything else
  - ➡ New physics gets heavier
  - ➡ A bit uncomfortable, big picture unchanged

Then What?

Where is New Physics?

larger mass? Small Coupling? Too much BG?

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  Need colliders/measurements with unprecedented accuracy

  (e+e- or pp with high luminosity)

FCC-pp/SppC

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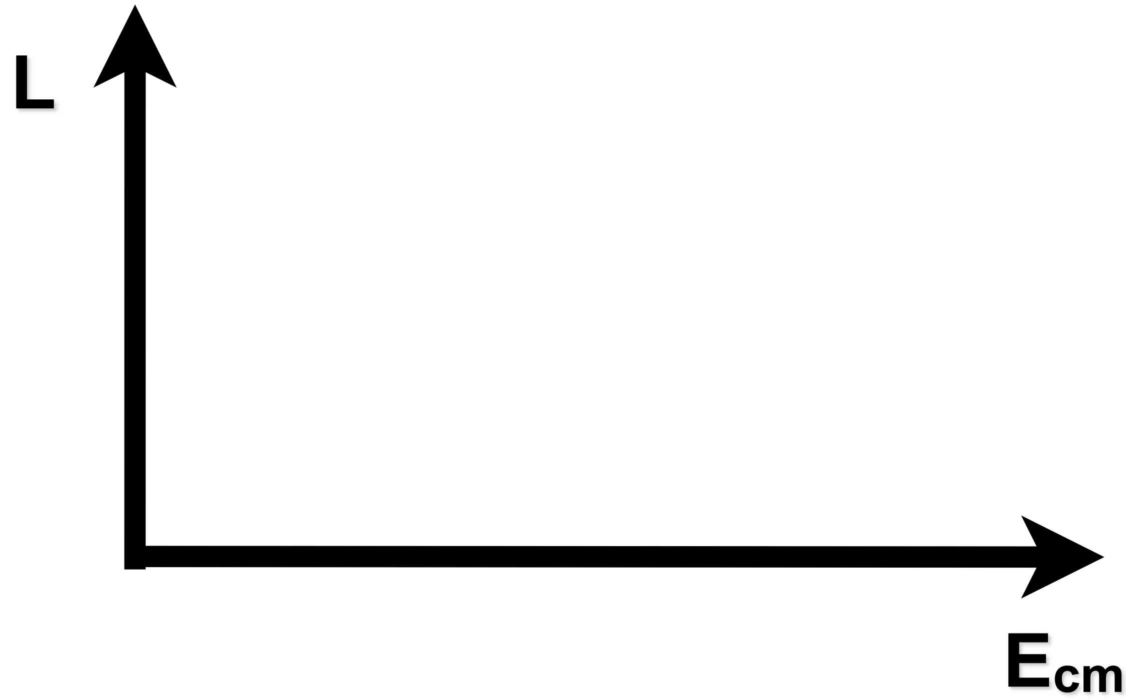

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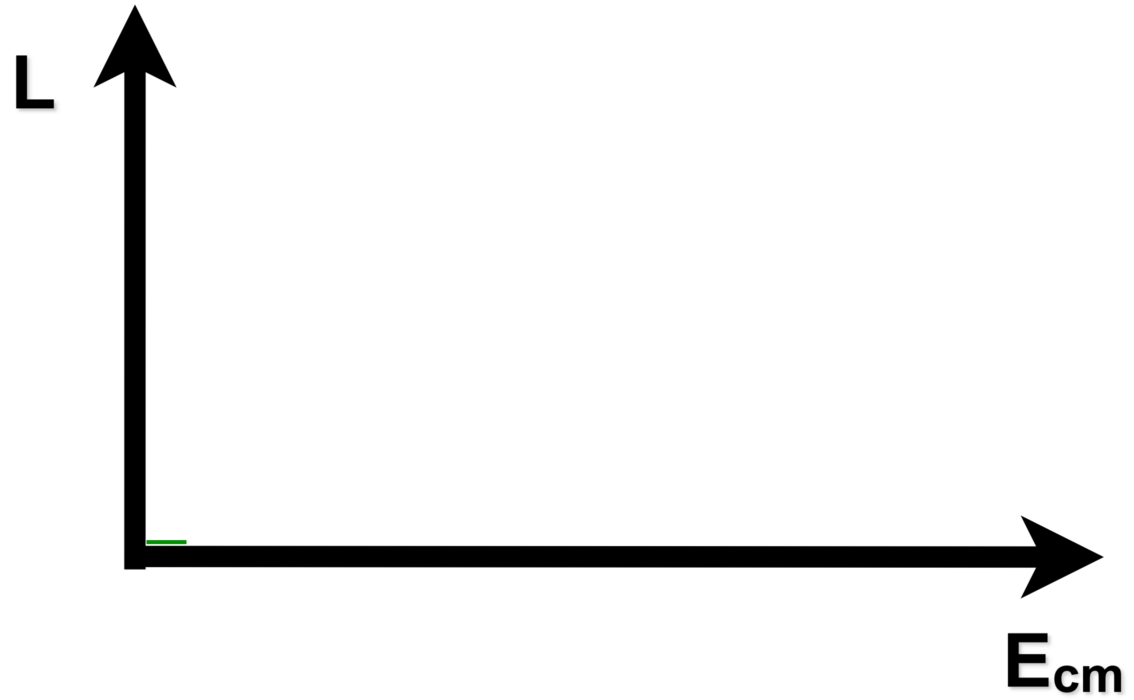

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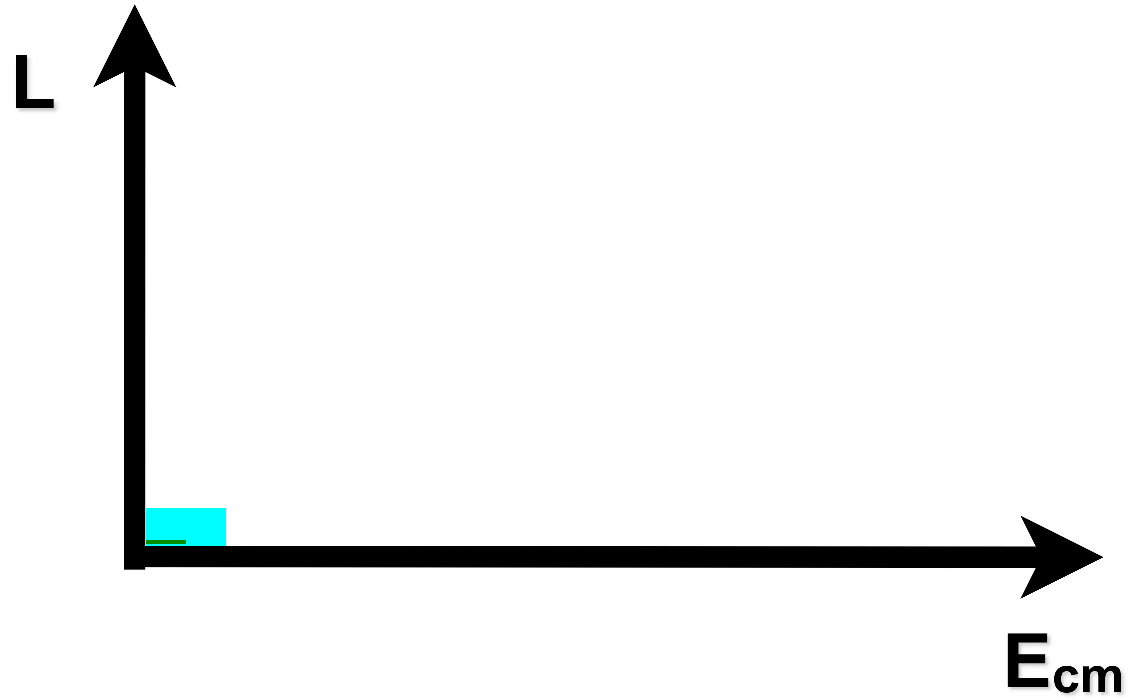

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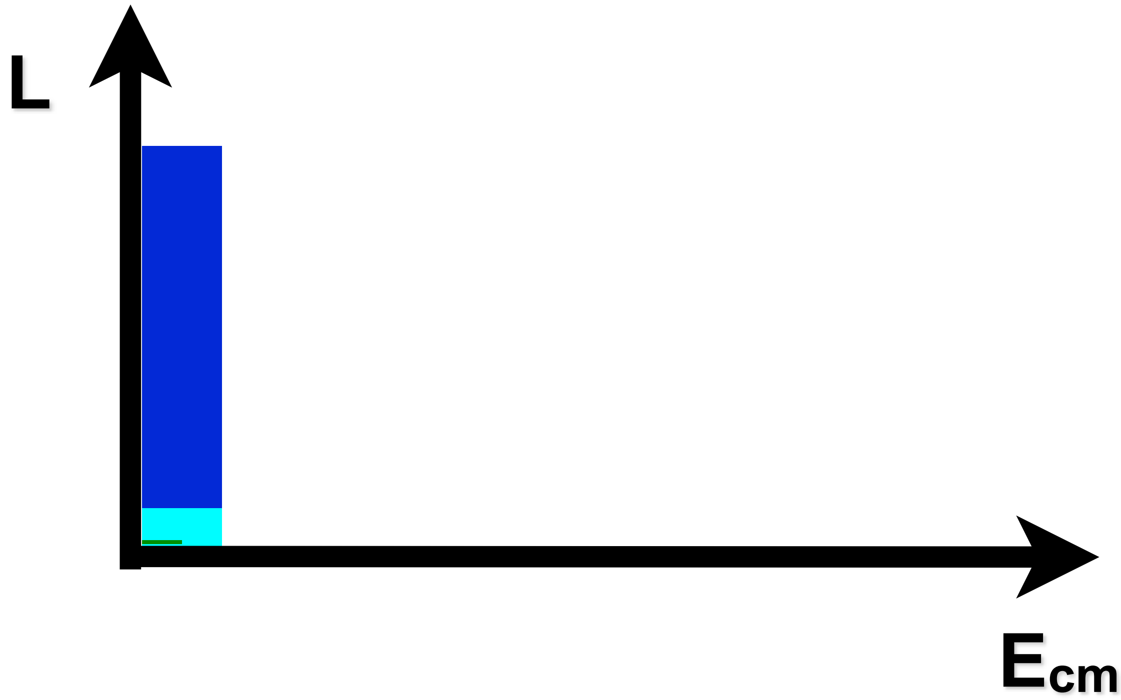

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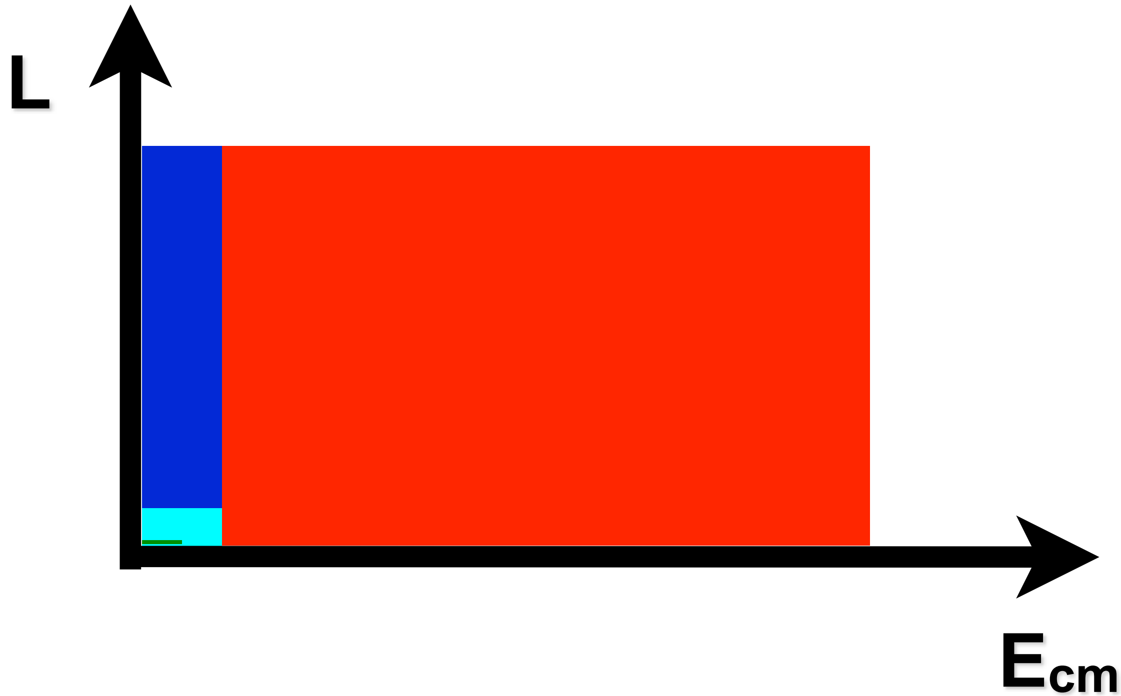

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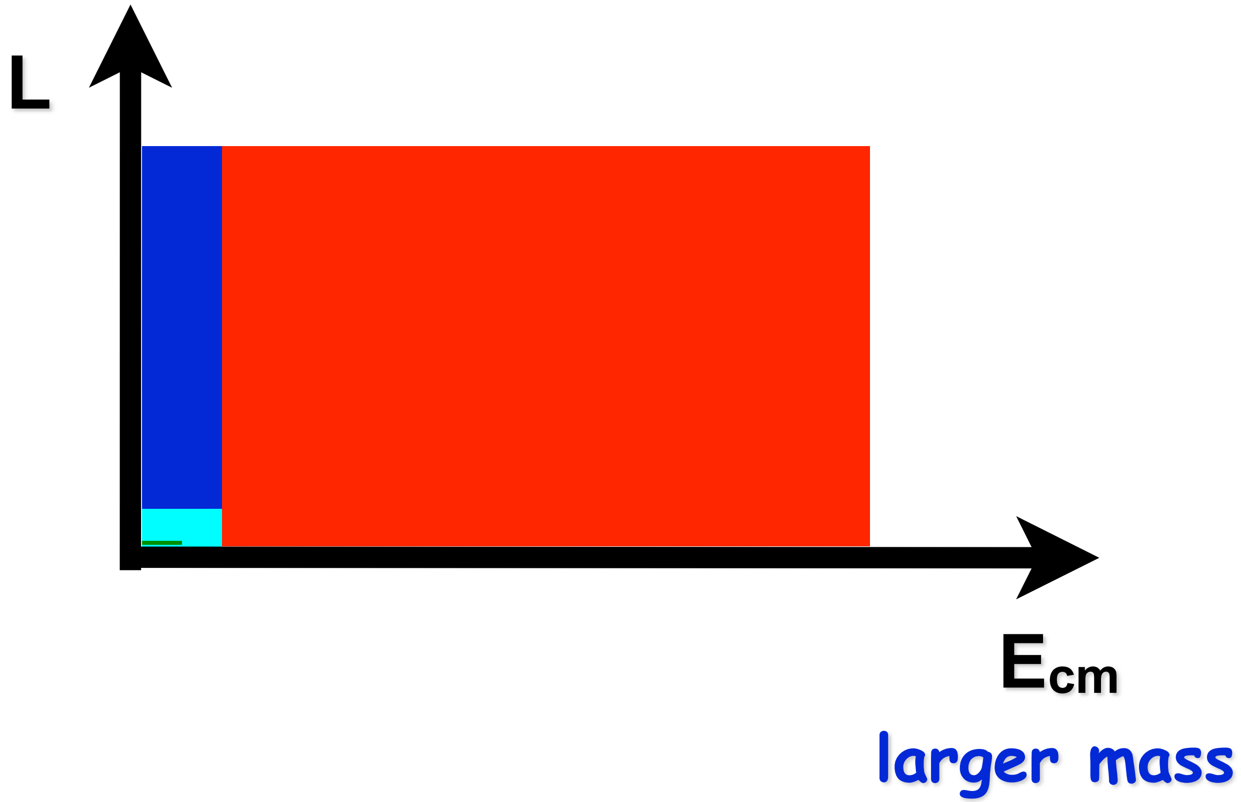

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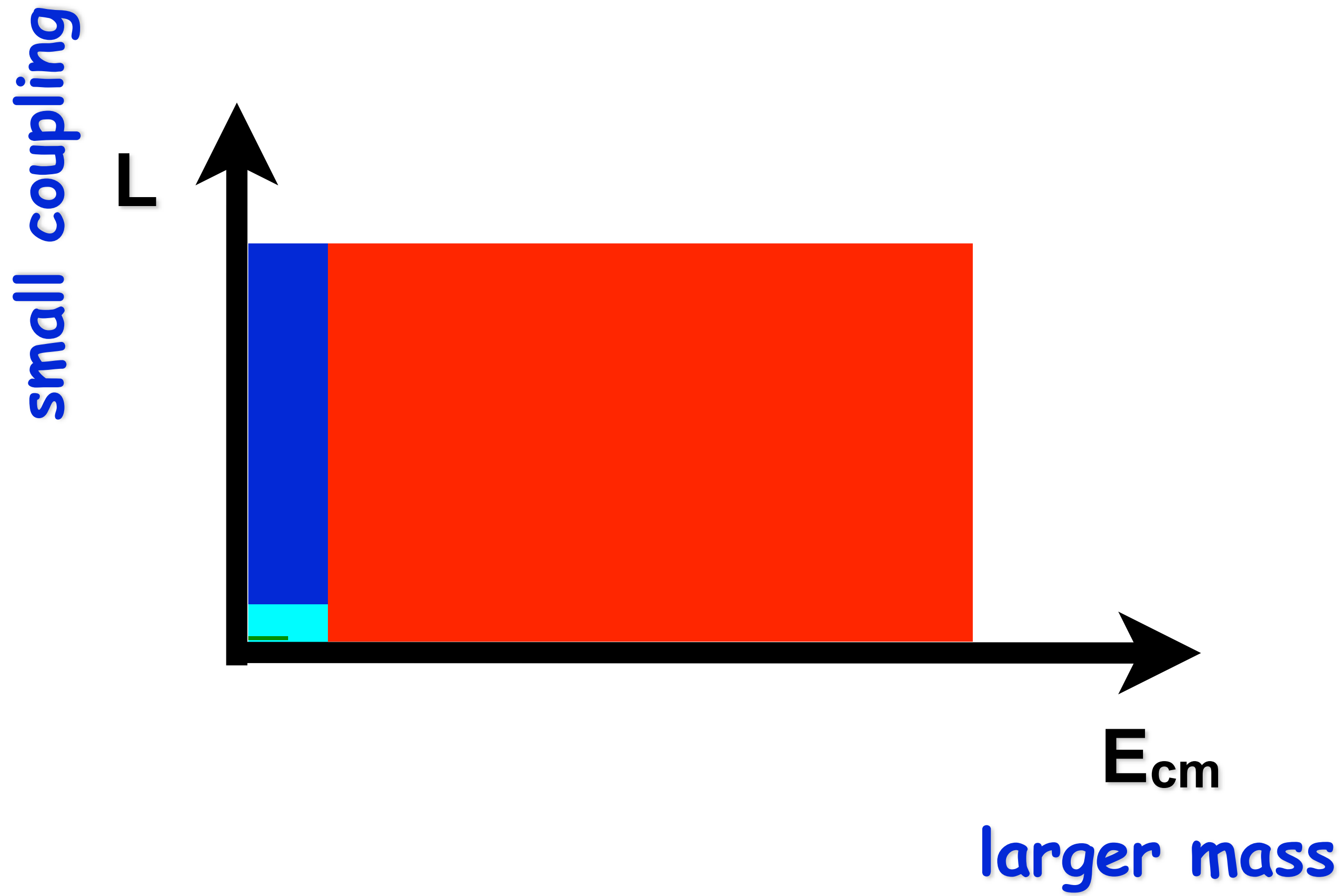
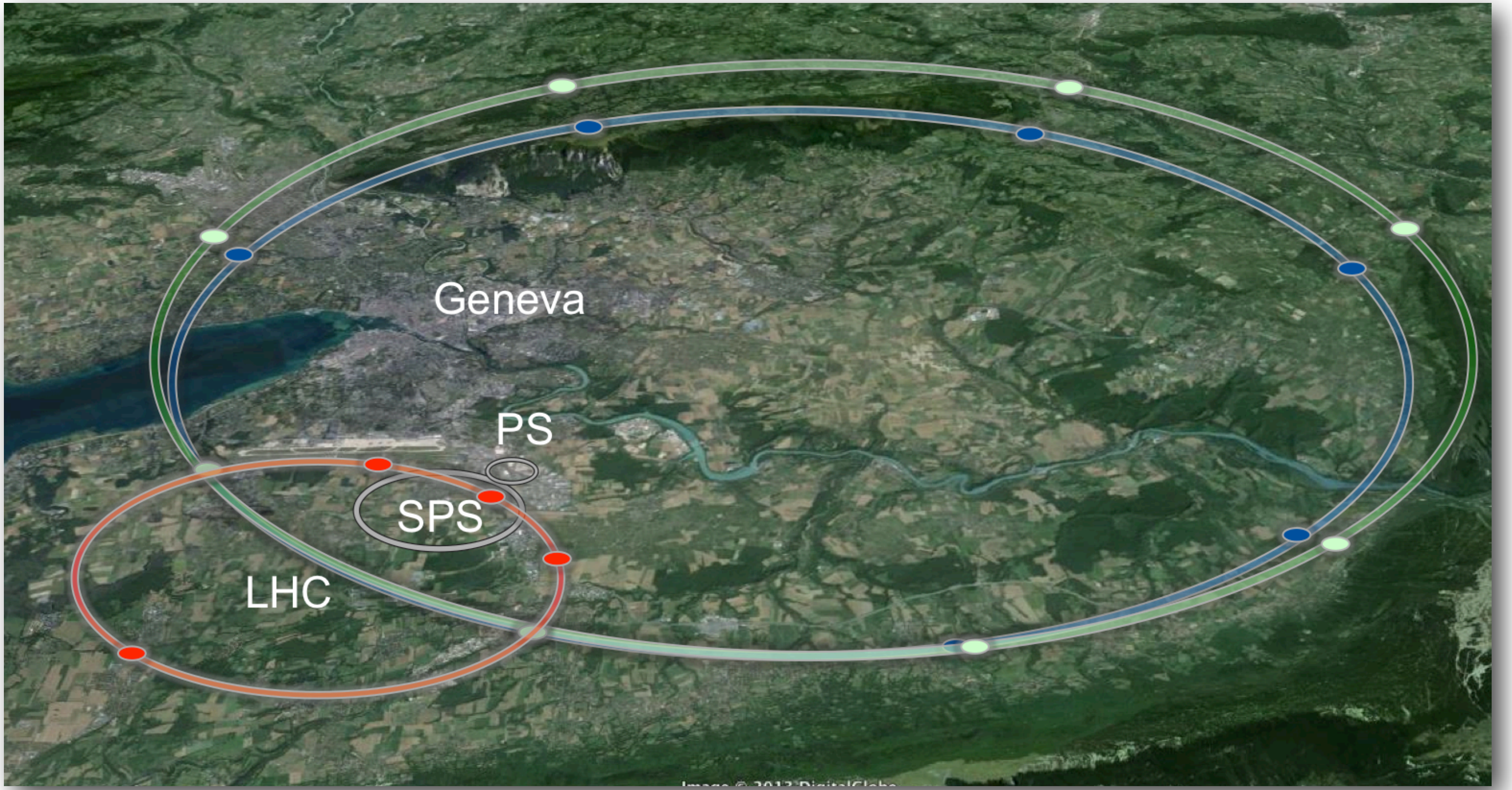


FCC

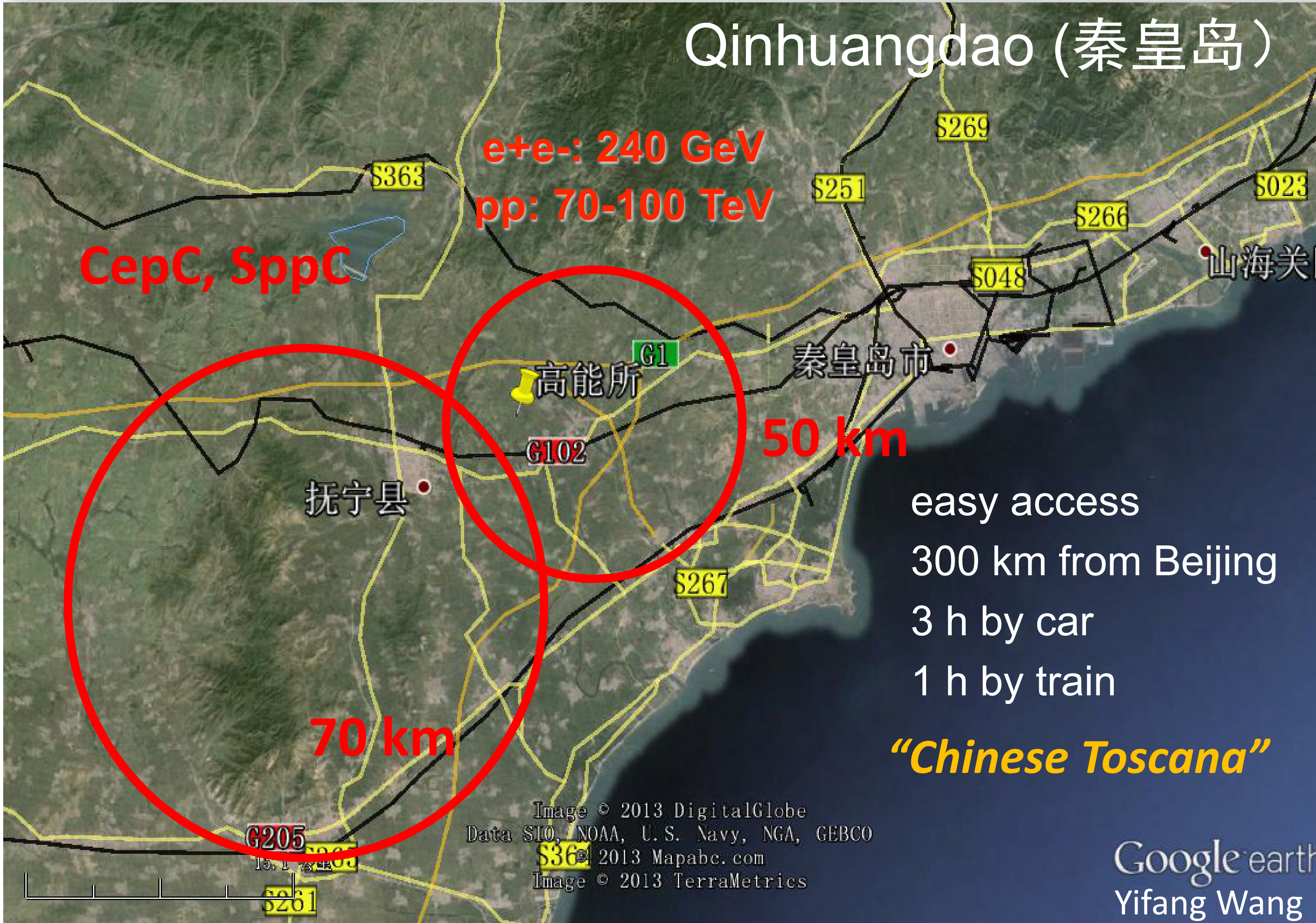


HE-LHC
27 km, 20T
33 TeV

FCC-ee
80/100 km
90 - 400 GeV

FCC-hh
80 /100 km, 16/20T
100 TeV

CEPC-SPPC



Qinhuangdao (秦皇岛）
e+e-: 240 GeV
pp: 70-100 TeV
CepC, SppC
50 km
70 km
高能所
秦皇岛市
抚宁县
山海关区
S363
S269
S251
S266
S023
S048
G1
G102
S267
G205
S261
easy access
300 km from Beijing
3 h by car
1 h by train
"Chinese Toscana"
Image © 2013 DigitalGlobe
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2013 Mapabc.com
Image © 2013 TerraMetrics
Google earth
Yifang Wang

CEPC-SPPC

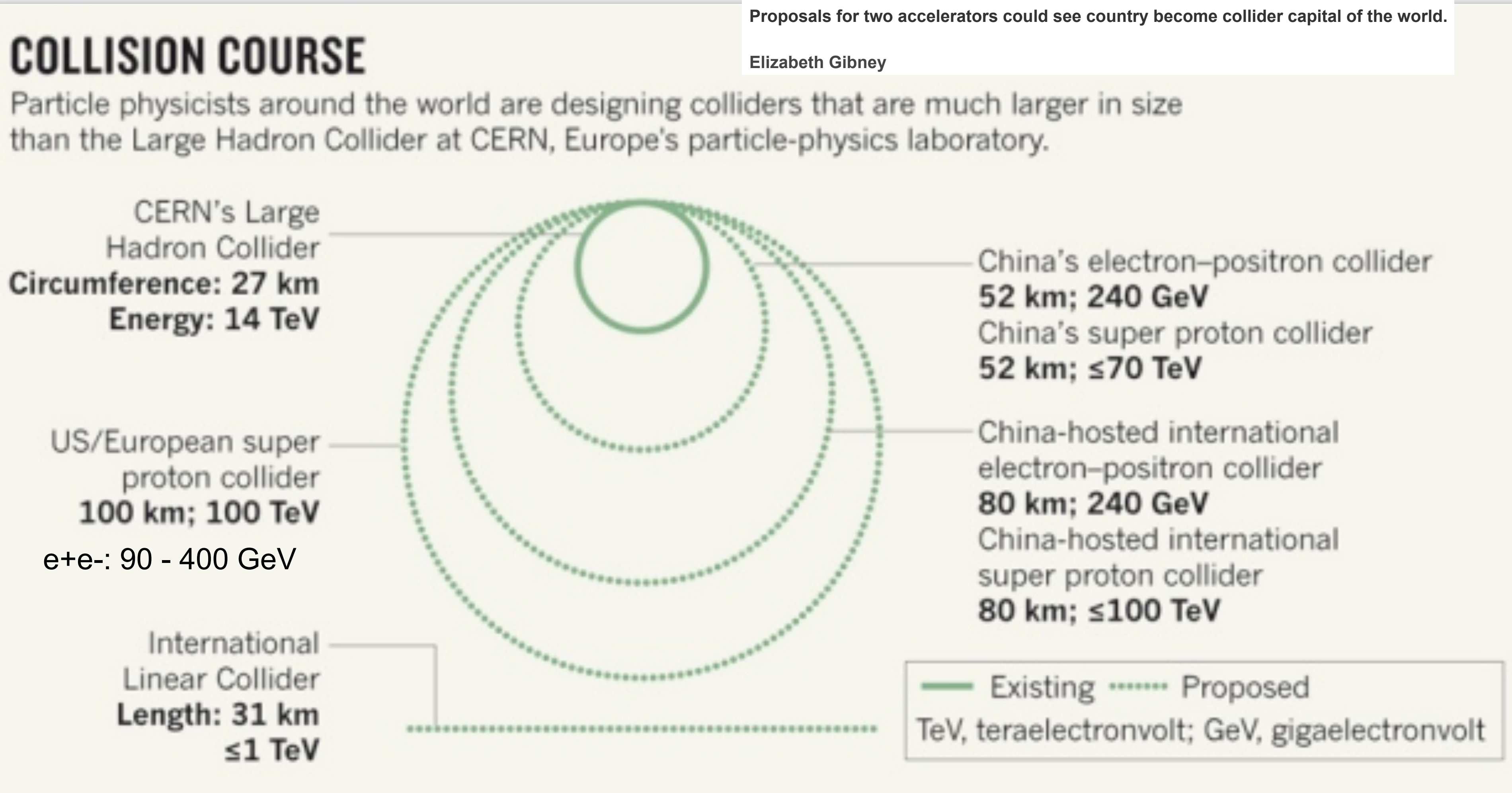
ao (秦皇岛)
PRe-CDR
CepC, SppC
抚宁
70
S023
S266
S048
山海关
G205
S261
y access
km from Beijing
by car
by train
inese Toscana"
Google earth
Yifang Wang

Machine Options

China plans super collider — Nature News, July

Proposals for two accelerators could see country become collider capital of the world.

Elizabeth Gibney



e+e-: 90 - 400 GeV

Physics opportunity at FCC-pp/SppC

Physics opportunity at FCC-pp/SppC

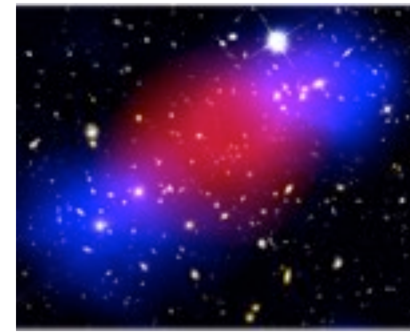
- new particles: a few TeV - 30 TeV, beyond LHC reach
- increased rate for sub-TeV particle: increased precision wrt LHC: Z, W, top,...
- rare process in sub-TeV mass range
- Higgs and EWSB: more Higgs couplings, WW scattering, Higgs self-coupling,...

FCC-pp
SppC

- SM physics

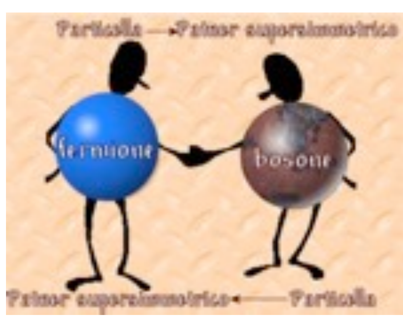
- other BSM

- dark matter



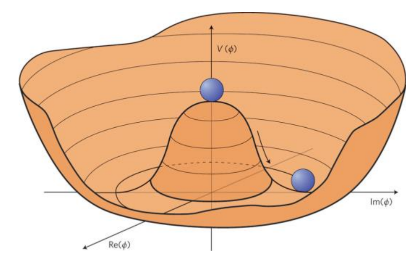
- precision tests

- top partners (naturalness)



- Higgs-related

- Cosmo connection



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- other BSM

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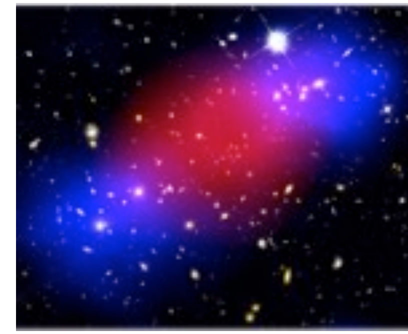
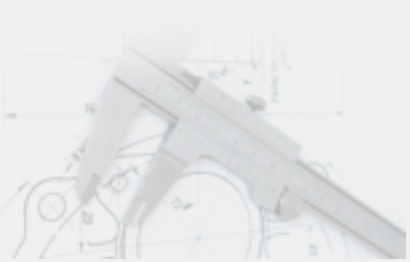


FCC-pp
SppC

- precision tests



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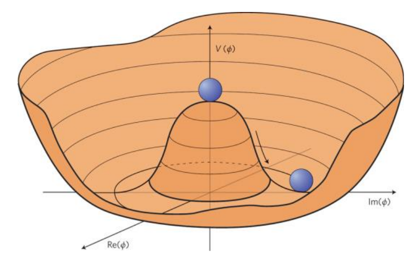
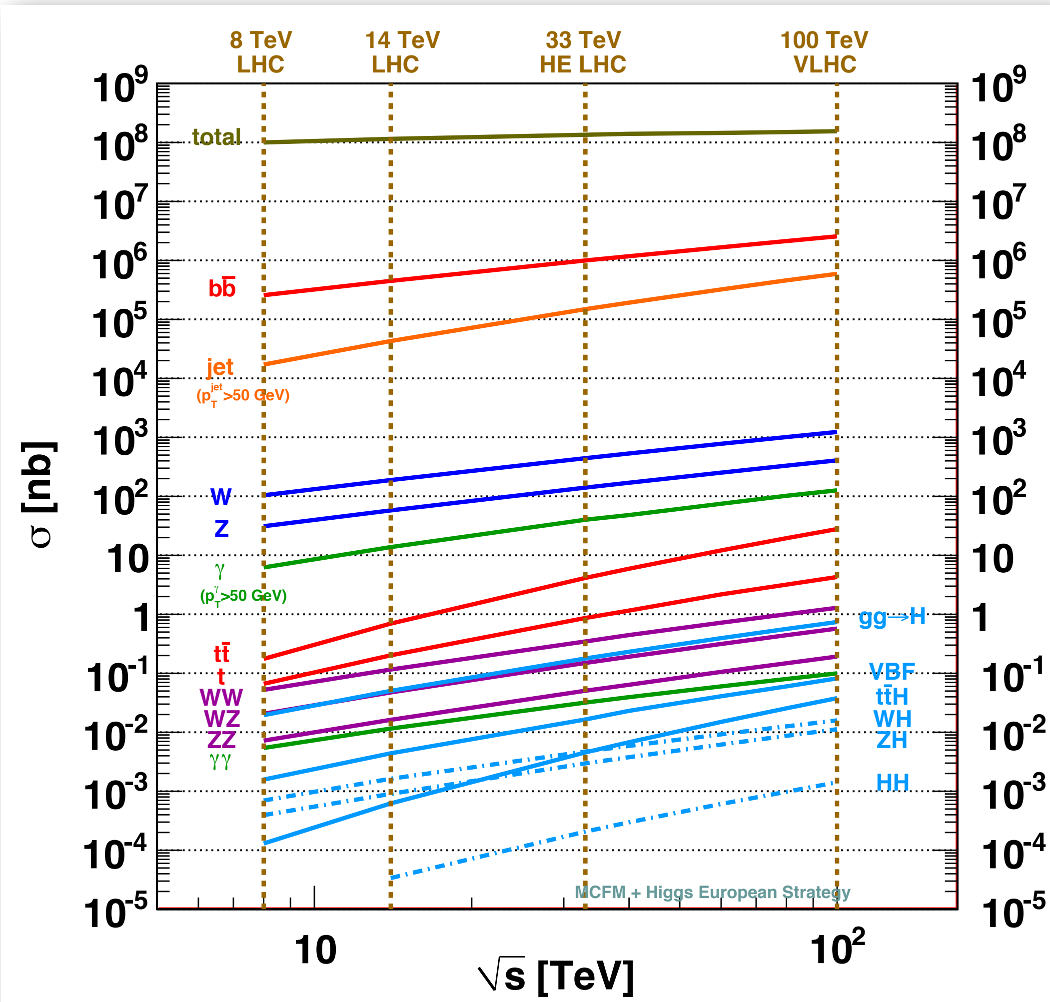
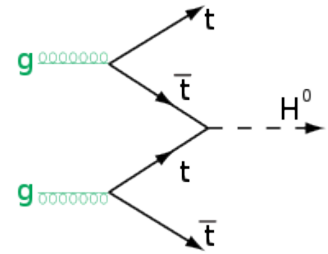


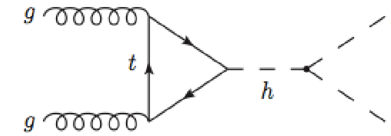
Higgs related

- SM-like Higgs
  - ➡ Deviation of SM Higgs couplings
  - ➡ New coupling structures, beyond the SM
  - ➡ Higgs couples to new particles
- non-SM like Higgs sector

Higgs Production @ pp







Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	$\sim 10^3$

λ_t : 1%

λ : 8%

Snowmass QCD Working Group: 1310.5189

non-SM Higgs

- Models with extended Higgs sector

  Discovery of extra Higgs: direct evidence for BSM new physics

- Conventional search channel (even for non-SM neutral Higgs):

  $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb, tt

- Charged Higgs is challenge! $H^\pm \to \tau\nu$, tb

- New Higgs decay modes open for (non-)SM Higgs decay

  ➡Higgs → light Higgs + gauge boson

  ➡ Higgs → two light Higgses

Complementary to conventional channels

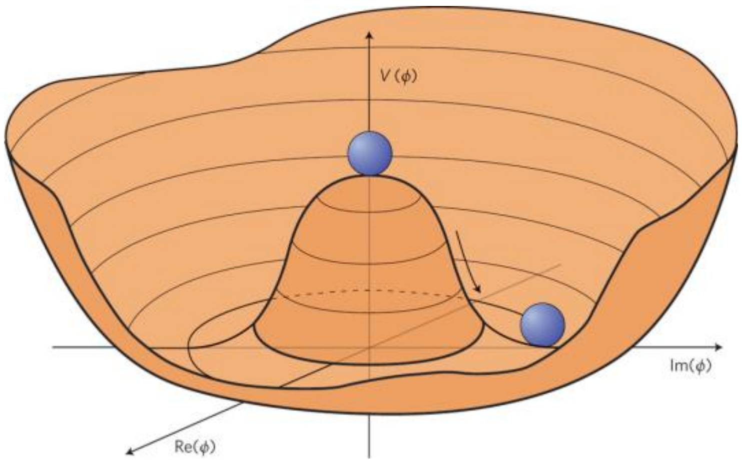
Searching for Other Higgses

New channels open up for non-SM Higgs decay

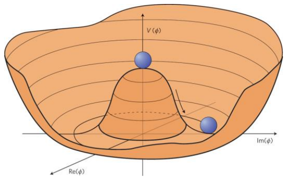
neutral Higgs	HH type	$(bb/\tau\tau/WW/ZZ/\gamma\gamma)(bb/\tau\tau/WW/ZZ/\gamma\gamma)$	$h_{SM} \to AA$ $H \to AA$
	H^+H^- type	$(\tau\nu/tb)(\tau\nu/tb)$	$H \to H^+H^-$
	ZH type	$(ll/qq/\nu\nu)(bb/\tau\tau/WW/ZZ/\gamma\gamma)$	$H \to ZA$ $A \to ZH, Zh$
	$WH^\pm$ type	$(l\nu/qq')\ (\tau\nu/tb)$	$H/A \to WH^\pm$
charge Higgs	WH type	$(l\nu/qq')(bb/\tau\tau)$	$tH^\pm$ production, $H^\pm \to WH$ $H^\pm \to WA$

B. Coleppa, F. Kling, T. Li, A. Pyarelal, SS (2014, 2015, 2016)

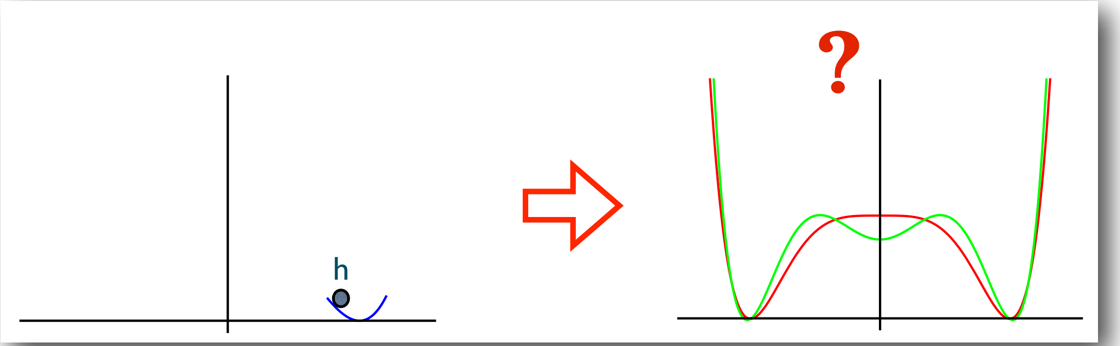
Cosmo Connection



Cosmo Connection: Shape of Higgs Potential



Nature of electroweak phase transition

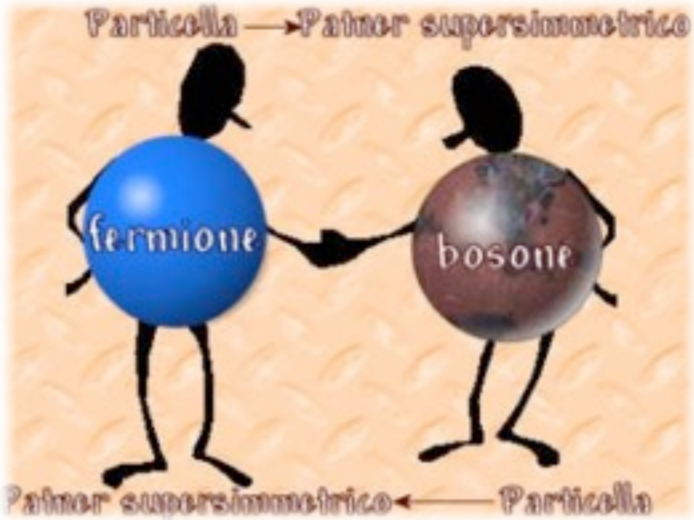


- baryon asymmetry ⬅ baryogenesis ⬅ strong 1st order EWPT
- SM: 125 GeV, 2nd order EWPT ➡ no EW baryogenesis
- BSM with strong 1st order EWPT ➡ large deviation in HHH

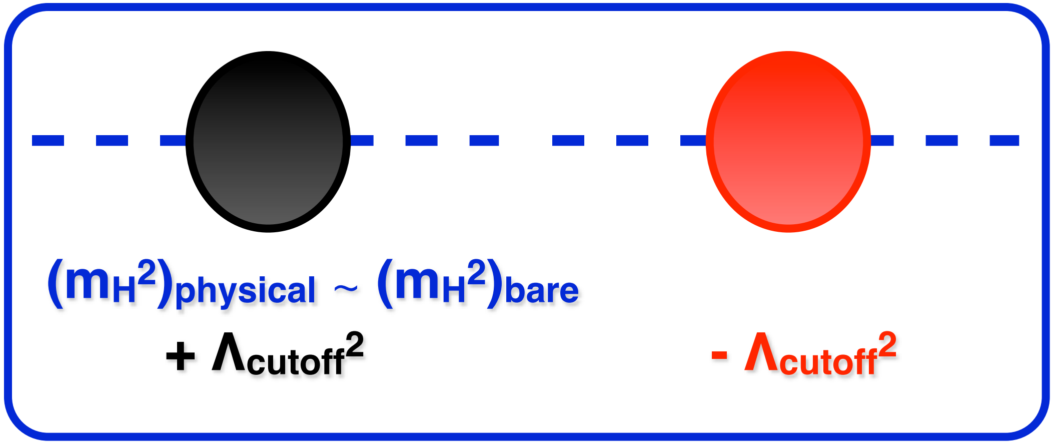
➡ HHH > 20% or more, 100 TeV pp

pp collider @ 100 TeV: HHH coupling : 8%
determine the shape of Higgs potential.

Top Partners: Naturalness



Naturalness and Top Partner

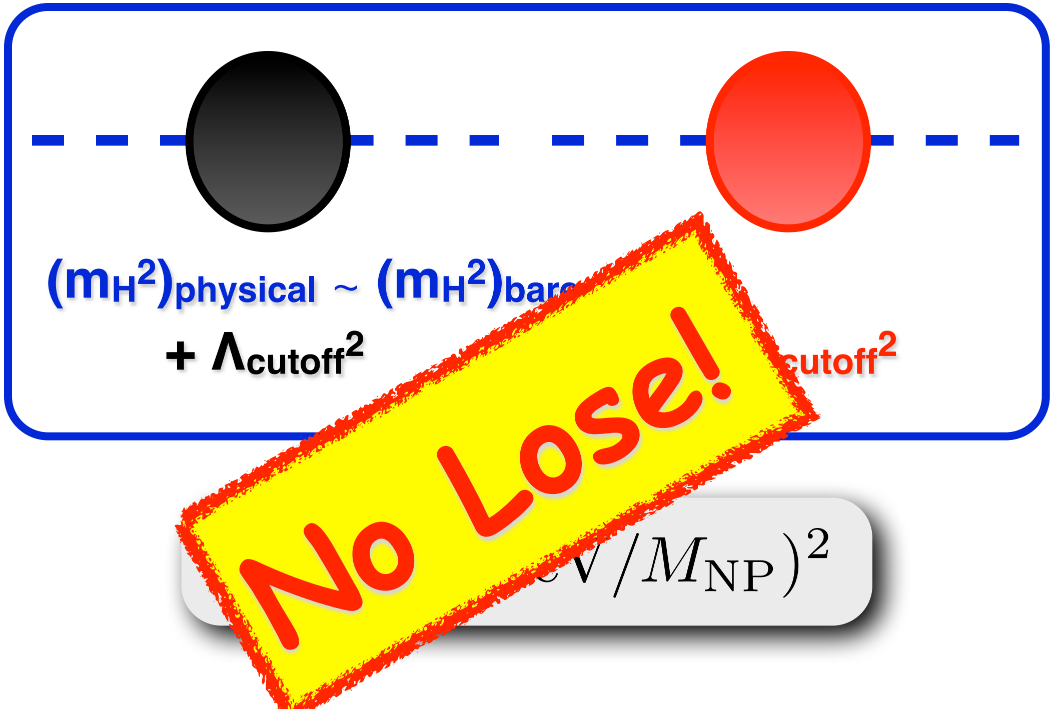


$$\epsilon \sim (125\ \text{GeV}/M_{\text{NP}})^2$$

- **LHC:** TeV scale for top partner, $\varepsilon \sim 1\%$
- **HL-LHC:**

  increase the reach by 10-20%, measure top partner property
- **100 TeV FCC-pp/SppC:** 10 TeV level, $\varepsilon \sim 10^{-4}$

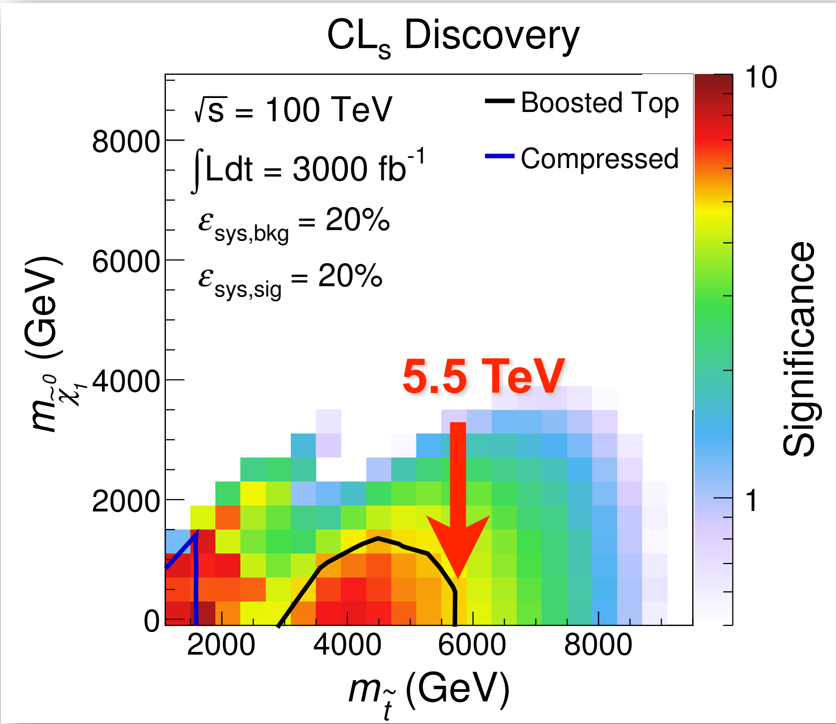
Naturalness and Top Partner

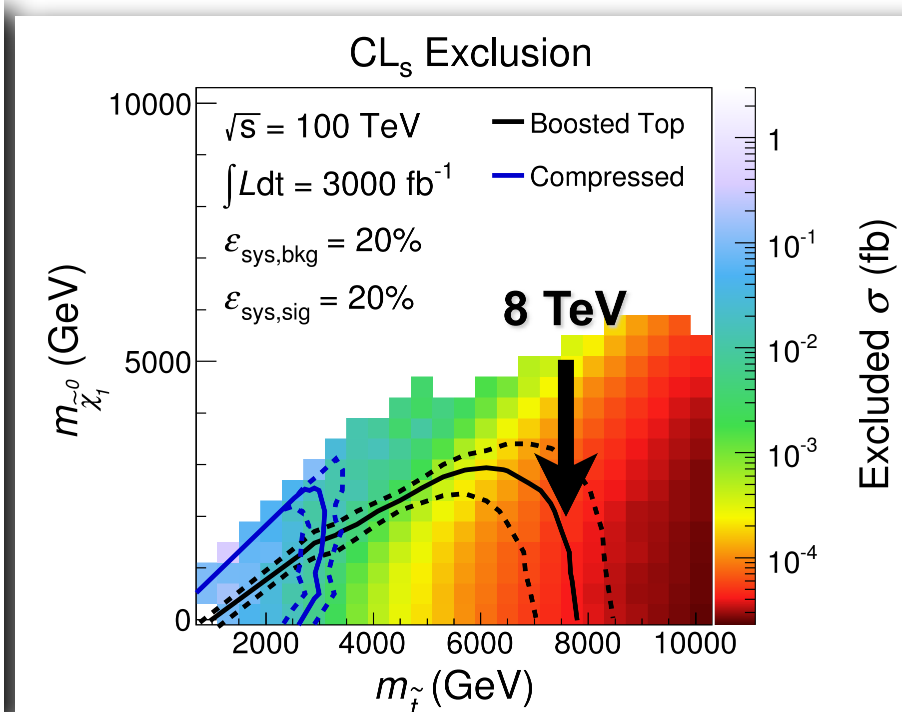


- **LHC:** TeV scale for top partner, ε~1%
- **HL-LHC:**

  increase the reach by 10-20%, measure top partner property
- **100 TeV FCC-pp/SppC:** 10 TeV level, ε~10^{-4}

100 TeV pp: Stop





T. Cohen et. al, 1406.4512

- 100 TeV pp: stop-stop-h production

100 TeV pp: SUSY

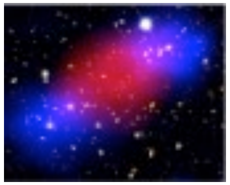
T. Cohen et. al, 1311.6480, 1406.4512

		exclusion		discovery	
		14 TeV 300 fb^{-1}	100 TeV 3000 fb^{-1}	14 TeV 300 fb^{-1}	100 TeV 3000 fb^{-1}
$\tilde{g} \rightarrow q\,\bar{q}\,\tilde{\chi}_1^0$	uncompressed	2.3 TeV	13.5 TeV	1.9 TeV	11 TeV
	compressed	600 GeV	4.8 TeV	900 GeV	5.7 TeV
$\tilde{q} \rightarrow q\,\tilde{\chi}_1^0$	uncompressed	1.5 TeV	10 TeV	800 GeV	8 TeV
	compressed	650 GeV	4 TeV	500 GeV	3 TeV
$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$	msq=mgluino	2.8 TeV	16 TeV	2.5 TeV	15 TeV
	mgluino	2.4 TeV	16 TeV	2 TeV	15 TeV
	msq	2.1 TeV	14 TeV	1.5 TeV	12 TeV
$\tilde{g} \rightarrow t\,\bar{t}\,\tilde{\chi}_1^0$	mgluino	1.9 TeV	8 TeV	1.6 TeV	6.4 TeV
$\tilde{t} \rightarrow t\,\tilde{\chi}_1^0$	mstop		8 TeV		5.5 TeV

Dark Matter

$$M_{\rm DM} < 1.8\ {\rm TeV}\left(\frac{g_{\rm eff}^2}{0.3}\right)$$

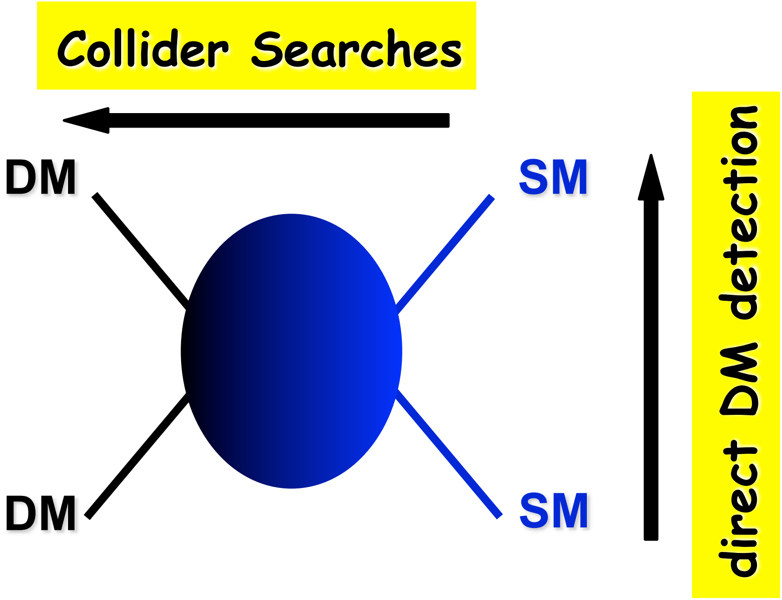
Effective operator



- effective operator approach
- monojet, monophoton, mono-...

"Standard" LHC searches

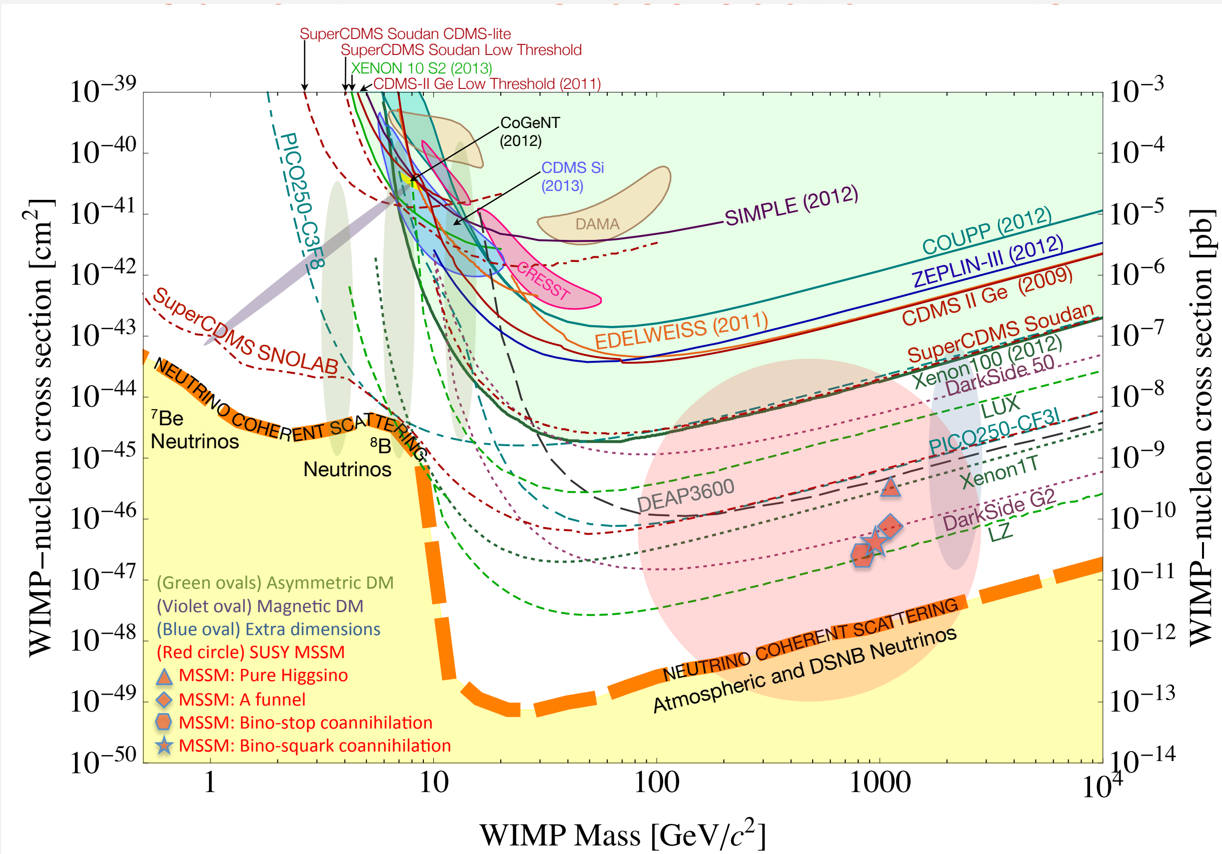
$$M_{\rm DM} < 1.8 \text{ TeV} \left(\frac{g_{\rm eff}^2}{0.3}\right)$$



complementary
to DM direct detection

Direct detection versus collider reach

LUX collaboration, 2013



Direct detection versus collider reach

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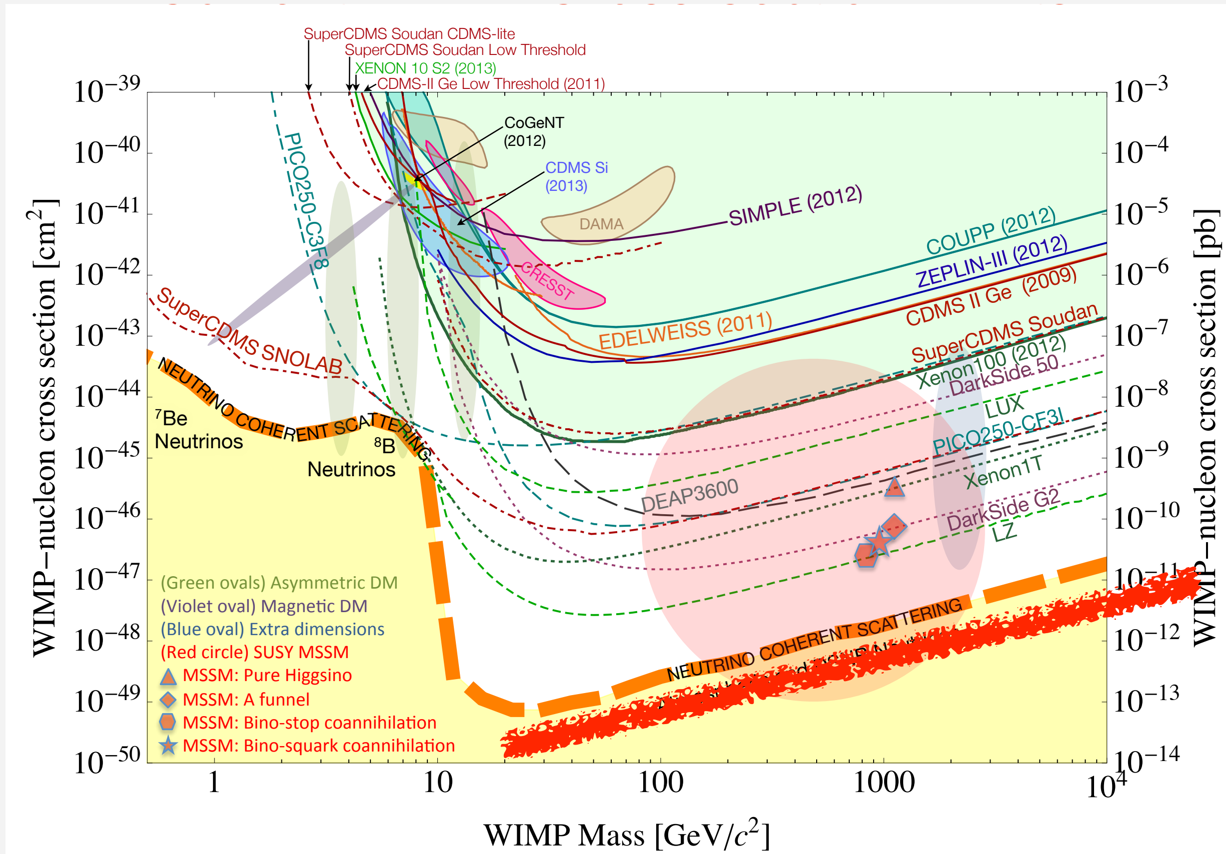
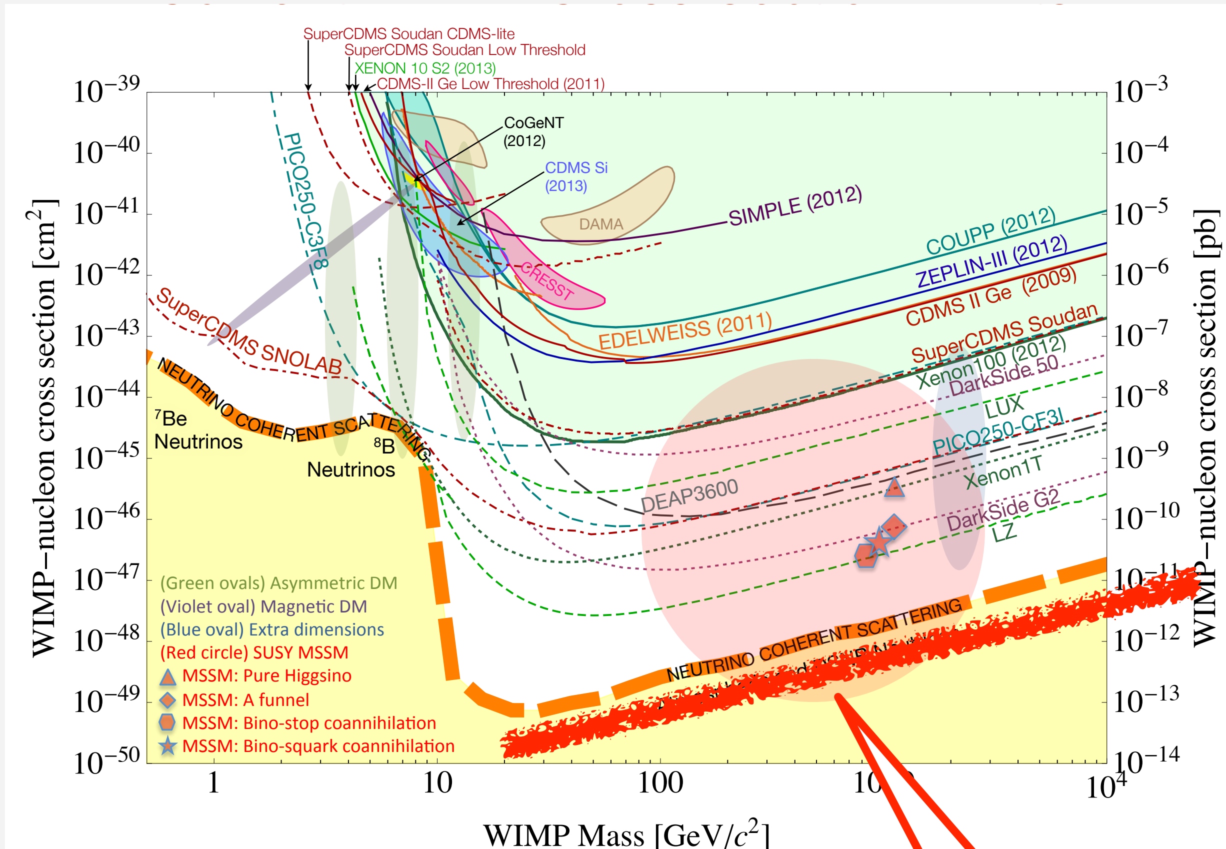


Direct detection versus collider reach

LUX collaboration, 2013



O(100) GeV DM, typical DM range

S. Su

Direct detection versus collider reach

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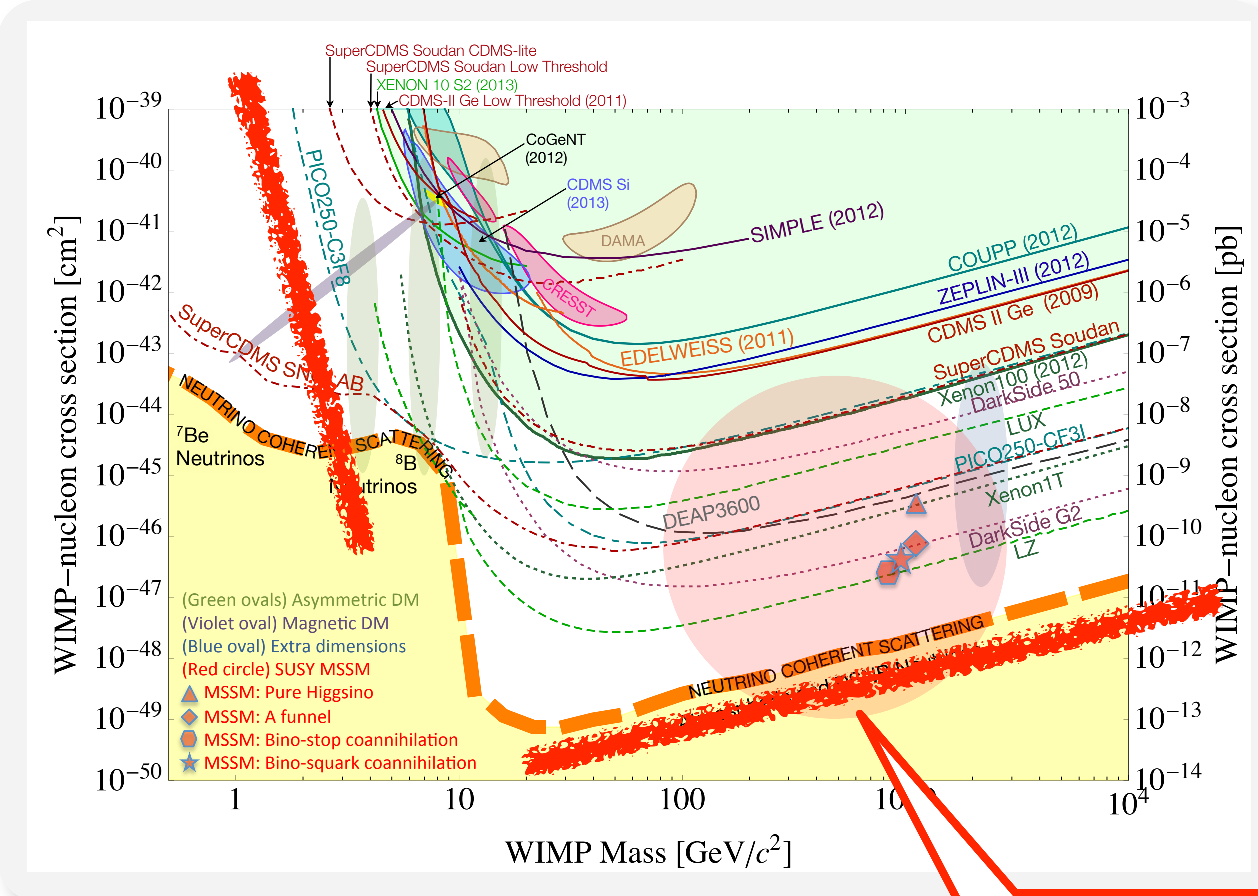

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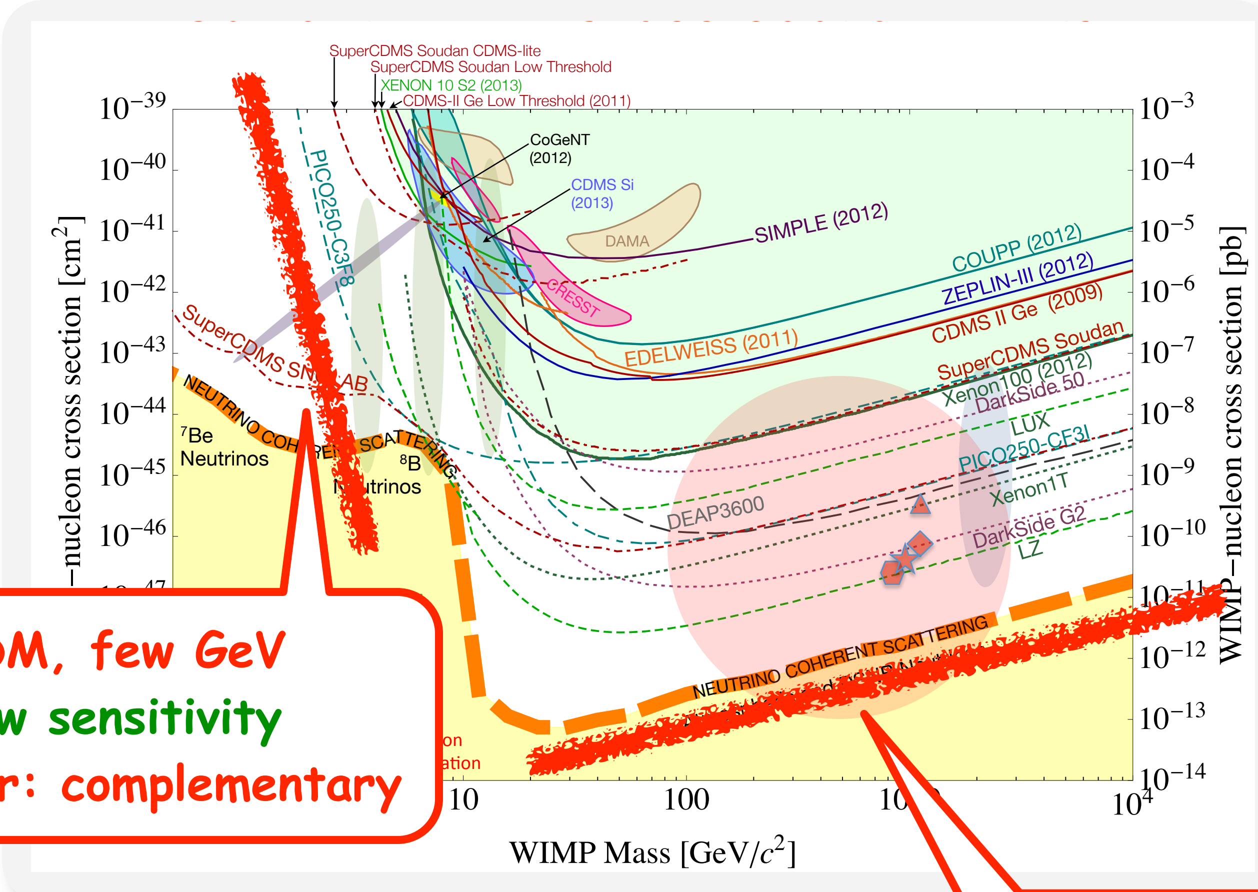
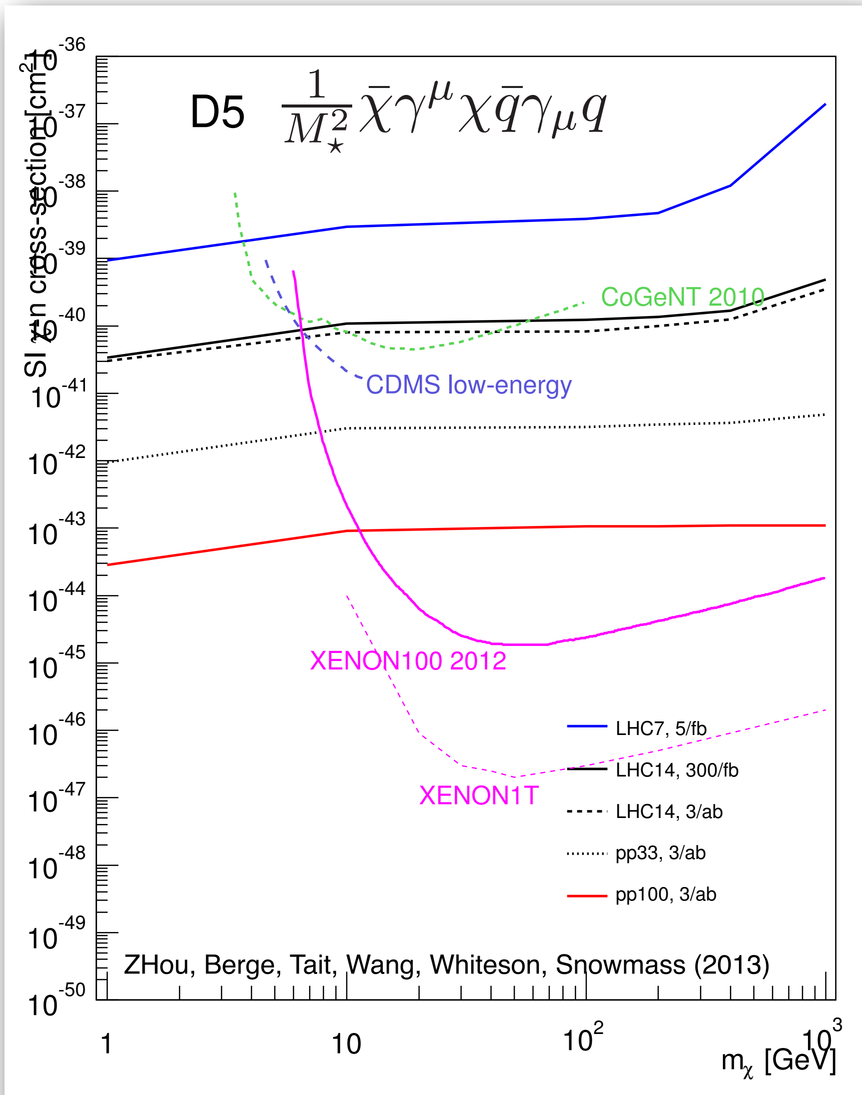


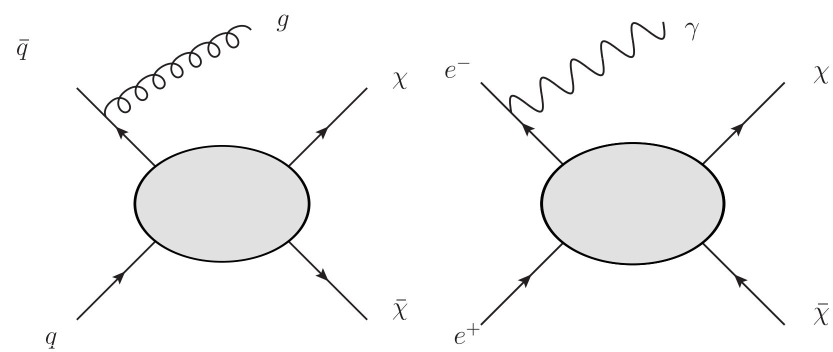
light DM, few GeV
DD: low sensitivity
Collider: complementary

O(100) GeV DM,
typical DM range

S. Su

LHC/100 TeV: Higgs

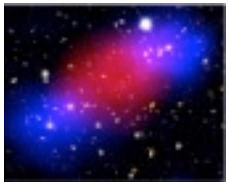




monojet, monophoton, monoZ, monoW, mono-b,...

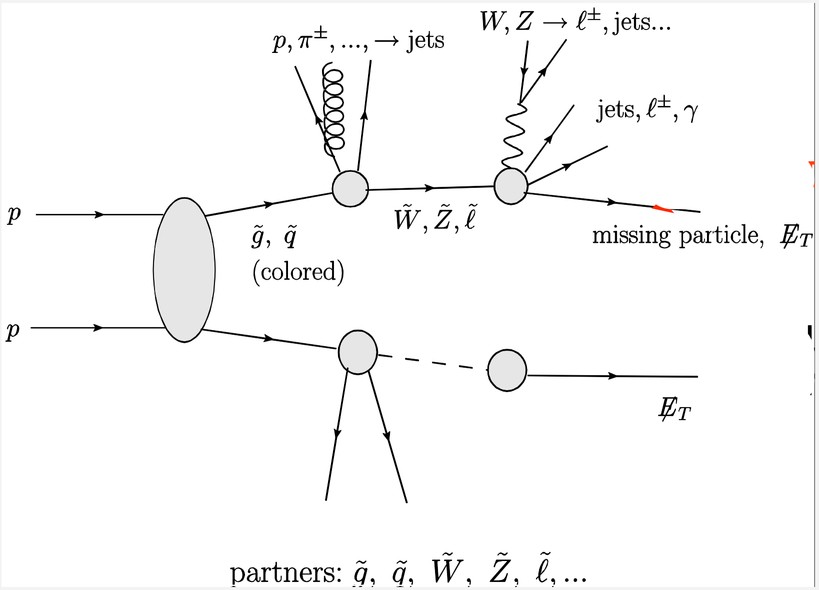
Collider better:
small m_χ region, spin-dependent

Model Dependent DM Searches



- WIMP: part of a complete model
- Last particle in the cascade decay chain of parent particle, MET

$$M_{\rm DM} < 1.8\ {\rm TeV}\left(\frac{g_{\rm eff}^2}{0.3}\right)$$

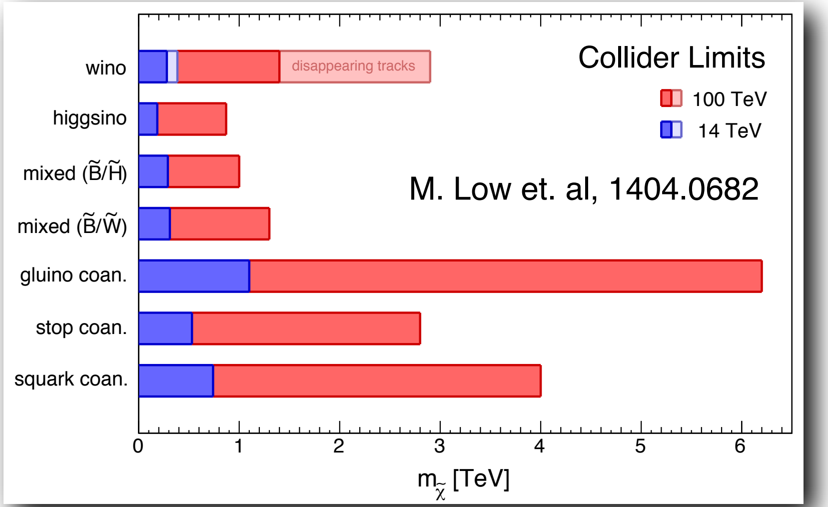


Very challenging.

weak discovery @ 14 TeV, 3 ab-1

Dark Matter

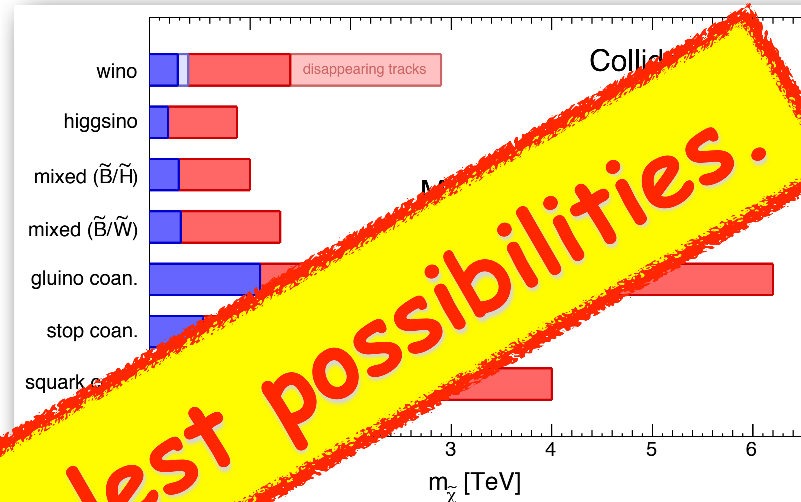
$$m_{\rm WIMP} \leq 2\ {\rm TeV}\left(\frac{g_{\rm eff}^2}{0.3}\right)$$



- Dark matter at TeV scale (Wino or Higgsino LSP)
  - ➡ can not be explored at LHC 14 with 300 fb^{-1}
  - ➡ enhanced reach of 1 TeV or higher at pp 100 TeV
- Smaller dark matter mass
  - ➡ low mass loopholes of suppressed coupling or compressed spectrum, small MET
  - ➡ e+e- collider, reach $E_{cm}/2$.

Dark Matter

$$m_{\mathrm{WIMP}} \leq 2\ \mathrm{TeV} \left(\frac{g_{\mathrm{eff}}^2}{0.3}\right)$$



See or rule out simplest possibilities.

- Dark matter at TeV s… Higgsino LSP)
  - ➡ can not be e… 14 with 300 fb^{-1}
  - ➡ enhanc… TeV or higher at pp 100 TeV
- Small… er mass
  - … loopholes of suppressed coupling or compressed … m, small MET
  - ➡ e+e- collider, reach $E_{cm}/2$.

SM Physics: New Phenomena

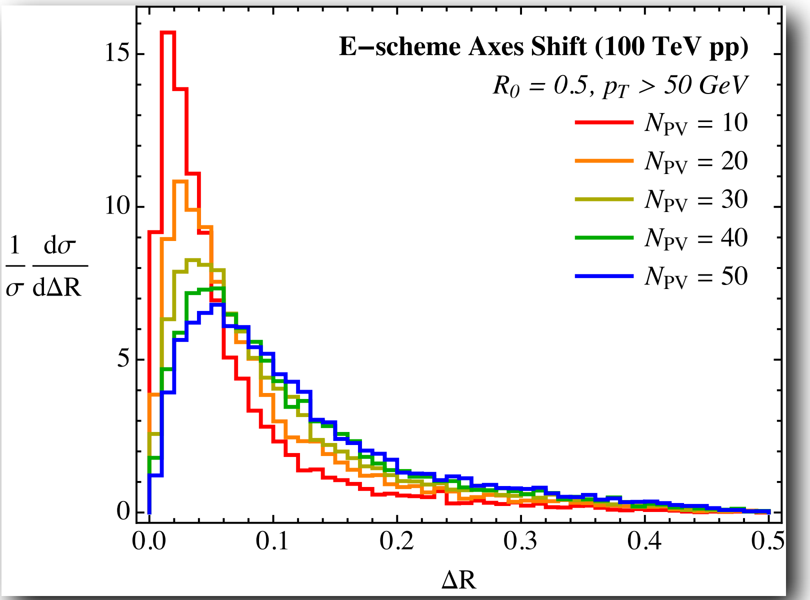
- jets
- W/Z/H/t radiation

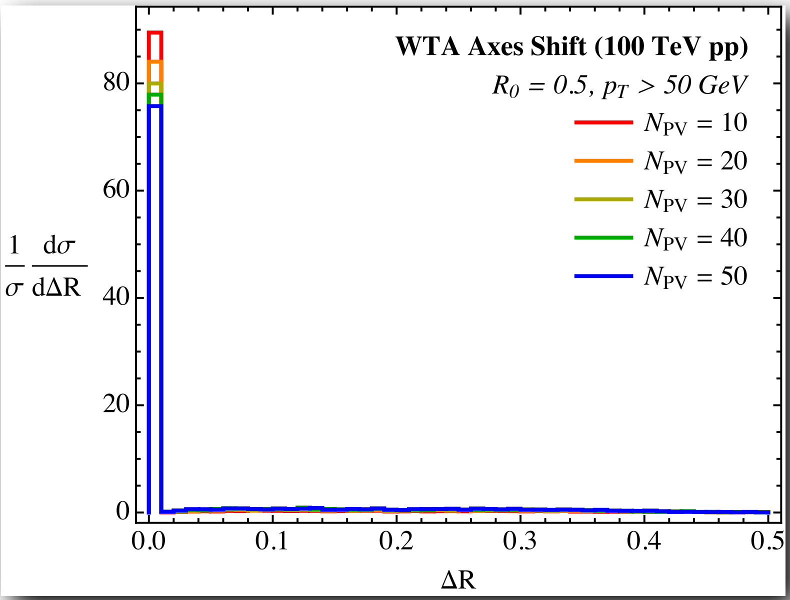
Jet Physics

- understanding QCD
- search for new physics

100 TeV: significant pileup, more than 200 (LHC Run I: 30)

affect energy and direction of jet





Larkoski et. al. (2013)

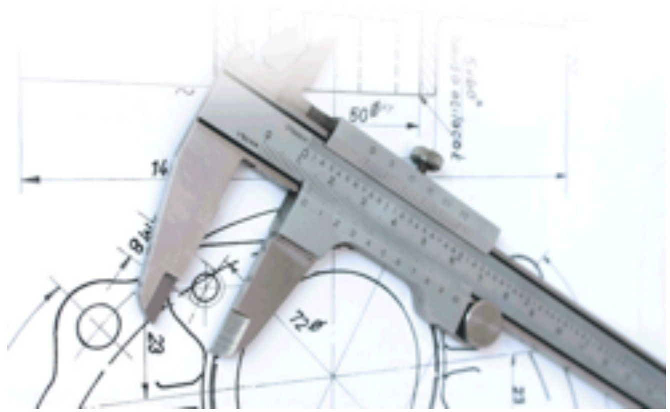
W/Z/H/t radiation

electroweak splitting rate

Process	$\mathcal{P}(p_T)$	$\mathcal{P}(1\ \text{TeV})$	$\mathcal{P}(10\ \text{TeV})$
$f \to V_T f$	$(3\times 10^{-3})\left[\log\frac{p_T}{m_{\rm EW}}\right]^2$	1.7%	7%
$f \to V_L f$	$(2\times 10^{-3})\log\frac{p_T}{m_{\rm EW}}$	0.5%	1%
$V_T \to V_T V_T$	$(0.01)\left[\log\frac{p_T}{m_{\rm EW}}\right]^2$	6%	22%
$V_T \to V_L V_T$	$(0.01)\log\frac{p_T}{m_{\rm EW}}$	2%	5%
$V_T \to f\bar{f}$	$(0.02)\log\frac{p_T}{m_{\rm EW}}$	5%	10%
$V_T \to V_L h$	$(4\times 10^{-4})\log\frac{p_T}{m_{\rm EW}}$	0.1%	0.2%
$V_L \to V_T h$	$(2\times 10^{-3})\left[\log\frac{p_T}{m_{\rm EW}}\right]^2$	1%	4%

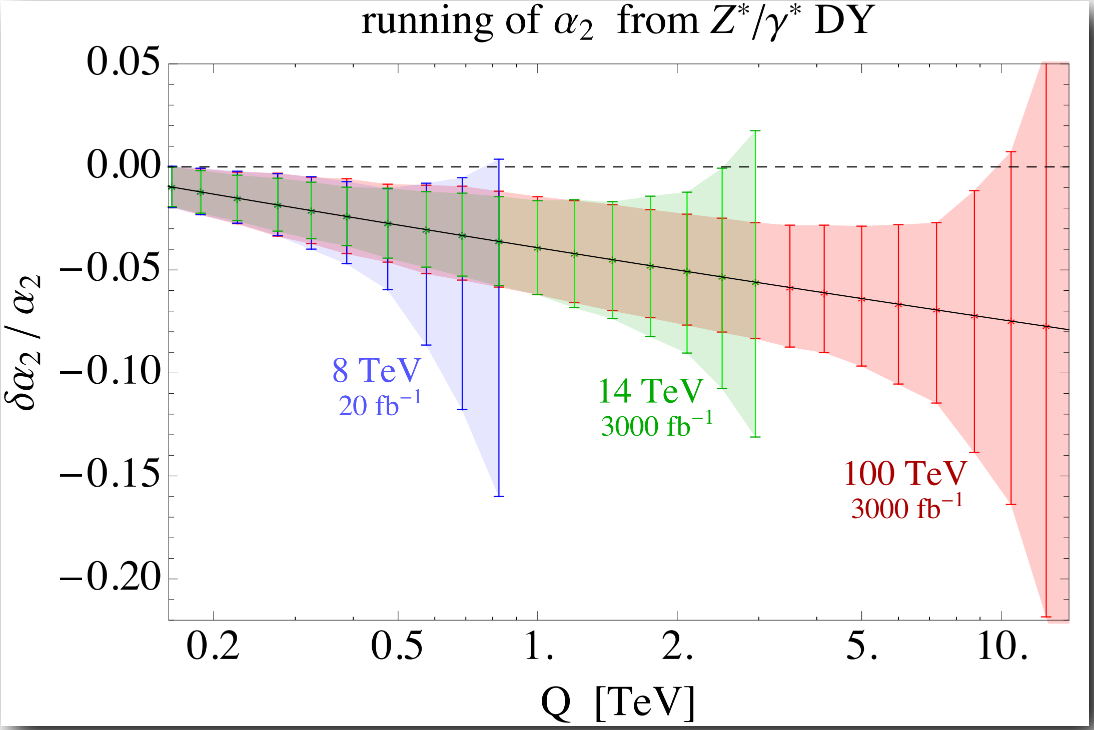
Chen et. al. (2015)

SM tests



Running EW Couplings

	1 TeV	10 TeV
$\alpha_1/\alpha_1(m_Z)$	2.7%	5.5%
$\alpha_2/\alpha_2(m_Z)$	3.9%	7.4%

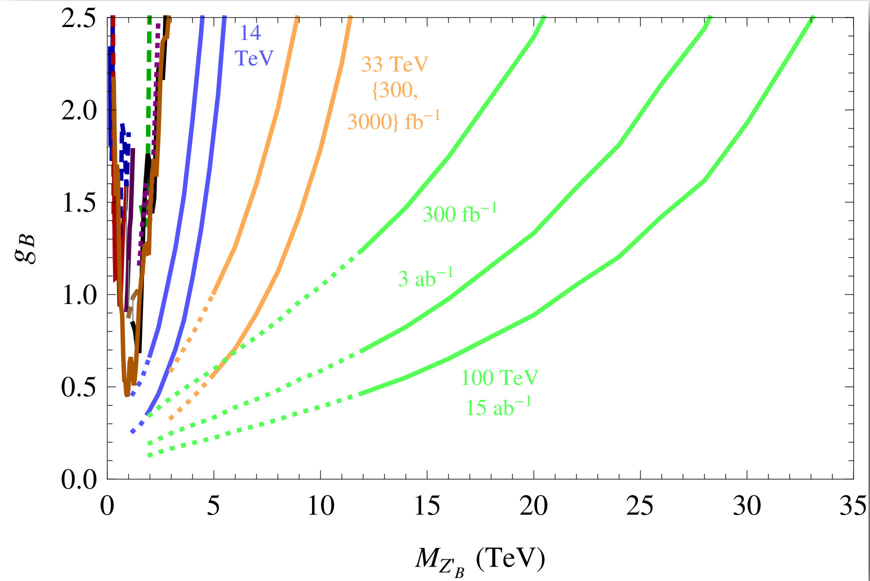


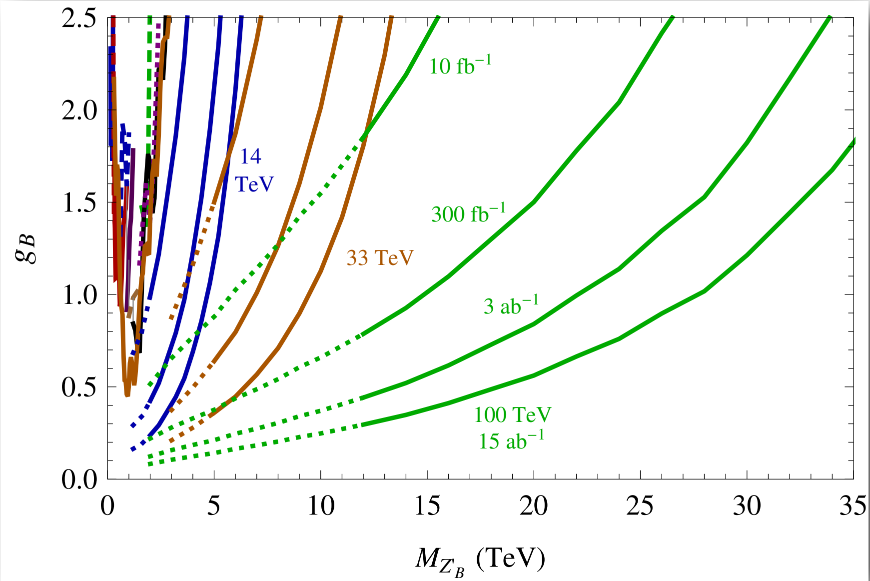
Alves et. al. (2014)

Other BSM Physics

New Resonance

- dijet resonance:
  color singlet, color octet, UED KK gluon, RS gluon, quark compositeness
- minimal requirement on machine luminosity and trigger
- calibrating detector response in hadronic environment



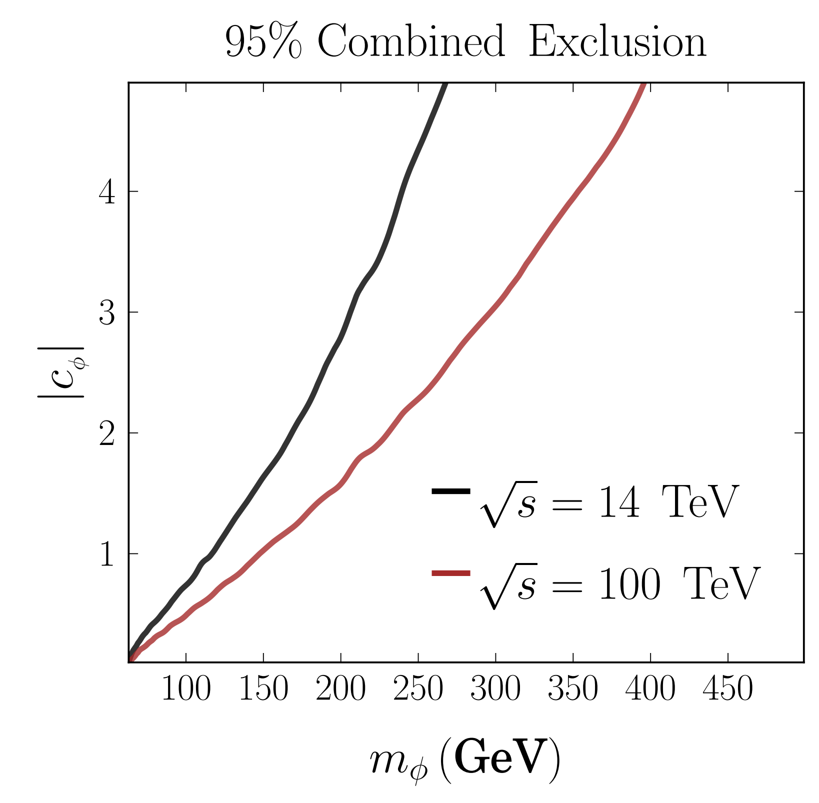


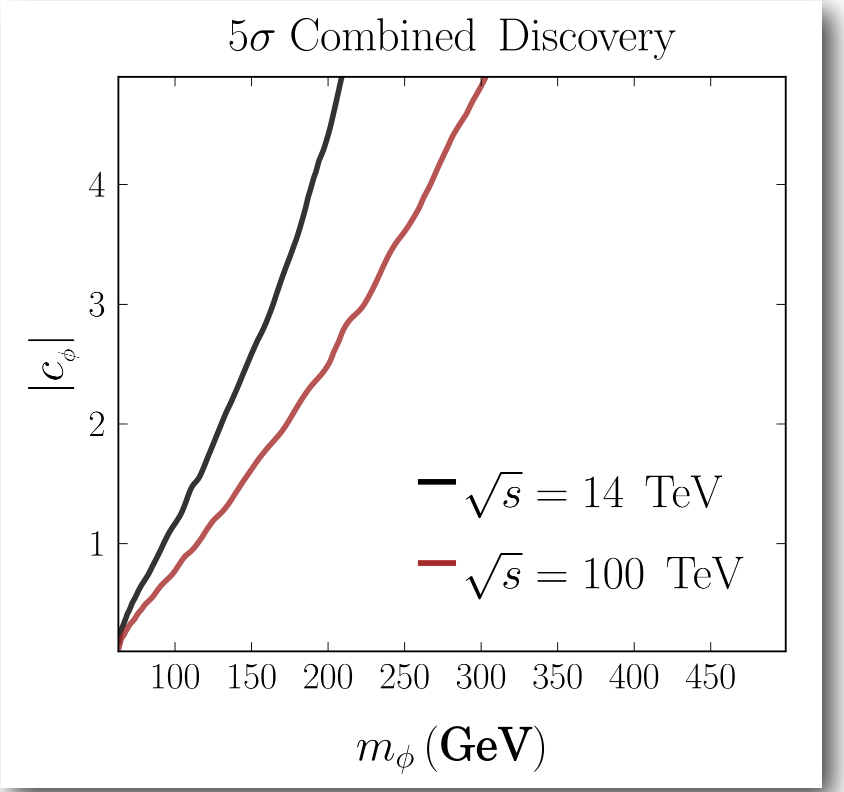
S. Su

Yu et. al. (2013)

Higgs Portal

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$



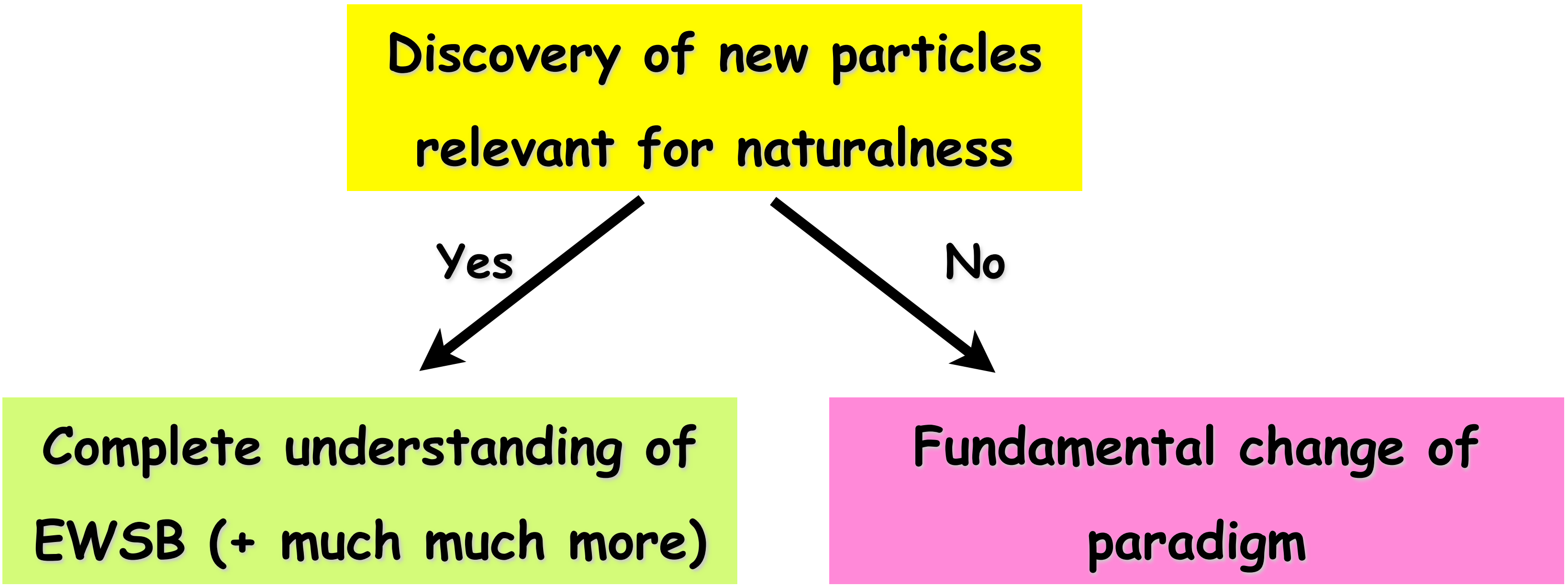


Curtin et. al. (2014)

What if still nothing else @ 100 TeV pp?

What if still nothing else @ 100 TeV pp?

Naturalness ???


Discovery of new particles relevant for naturalness
Yes
No
Complete understanding of EWSB (+ much much more)
Fundamental change of paradigm

Conclusion

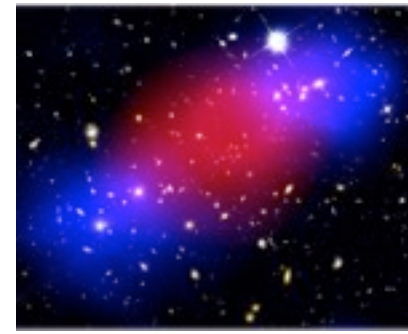
- the discovery of Higgs is a remarkable triumph in particle physics
- a light weakly coupled Higgs argues for new physics beyond SM
- Search for new physics calls for both high precision machine and high energy machine
- 100 TeV pp machine:
  - probe energy frontier: non-SM Higgs, naturalness connection, dark matter, BSM particles,...
  - precision, H coupling, V^3,V^4 couplings (cosmo connection), EW couplings
  - SM physics: new phenomena

An exciting journey ahead of us!

- SM physics

- other BSM

- dark matter

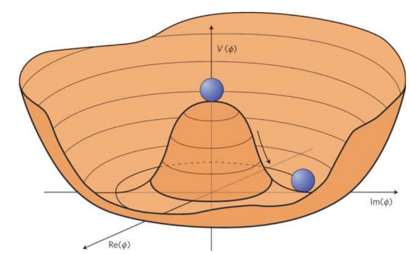


Future Colliders

- SM tests

An exciting journey ahead of us!

- Cosmo connection



- top partners (naturalness)

- Higgs-related

Conclusion

An exciting journey ahead of us!

Conclusion

LHC

An exciting journey ahead of us!

Conclusion

LHC

FCC-ee/CEPC

An exciting journey ahead of us!

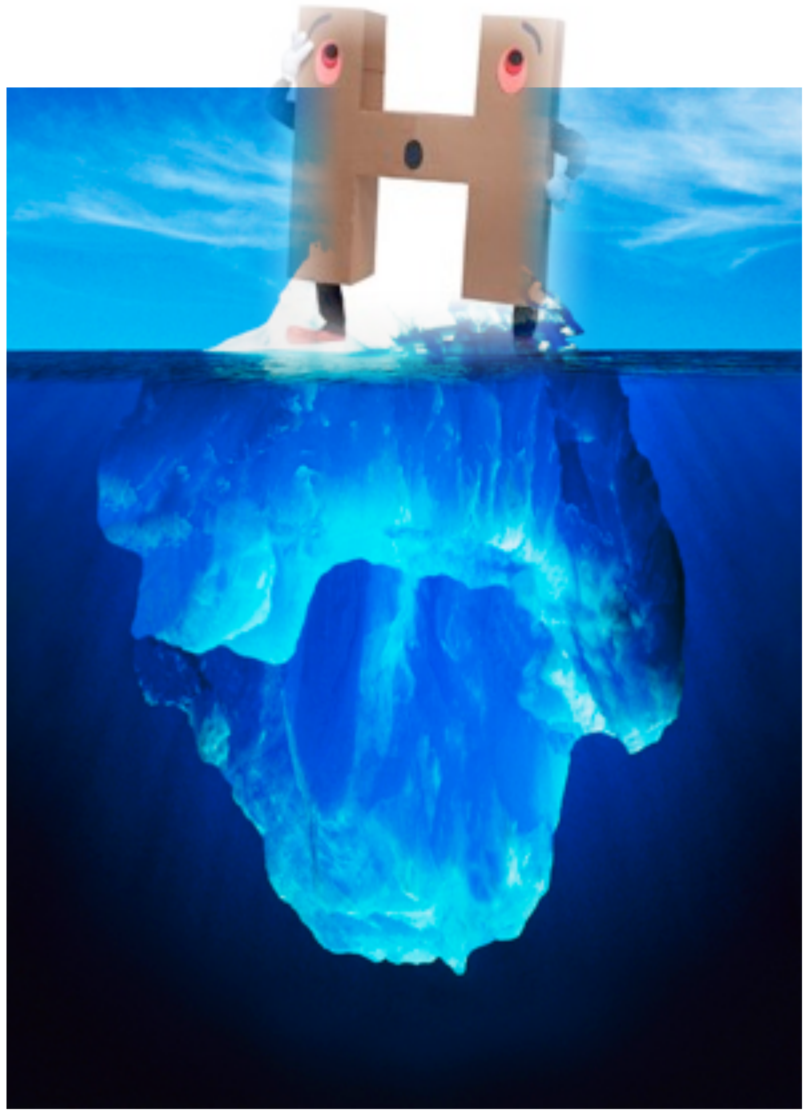
Conclusion

LHC

FCC-ee/CEPC

FCC-pp/SppC

An exciting journey ahead of us!



Beginning of new era ...

Beginning of new era ...

Thank you !