Future Colliders

Shufang Su • U. of Arizona

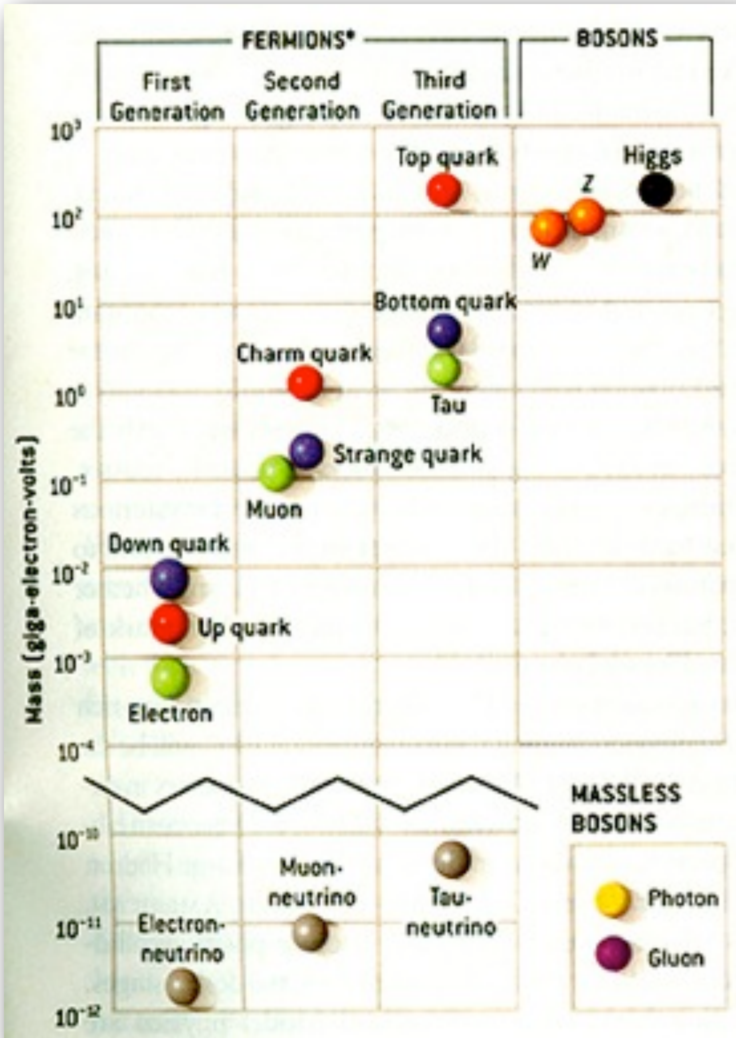
US ATLAS Physics Workshop 2014

University of Washington, Seattle

August 4, 2014

Standard Model

Image credit: Gordon Kane, Scientific American, June 2003.



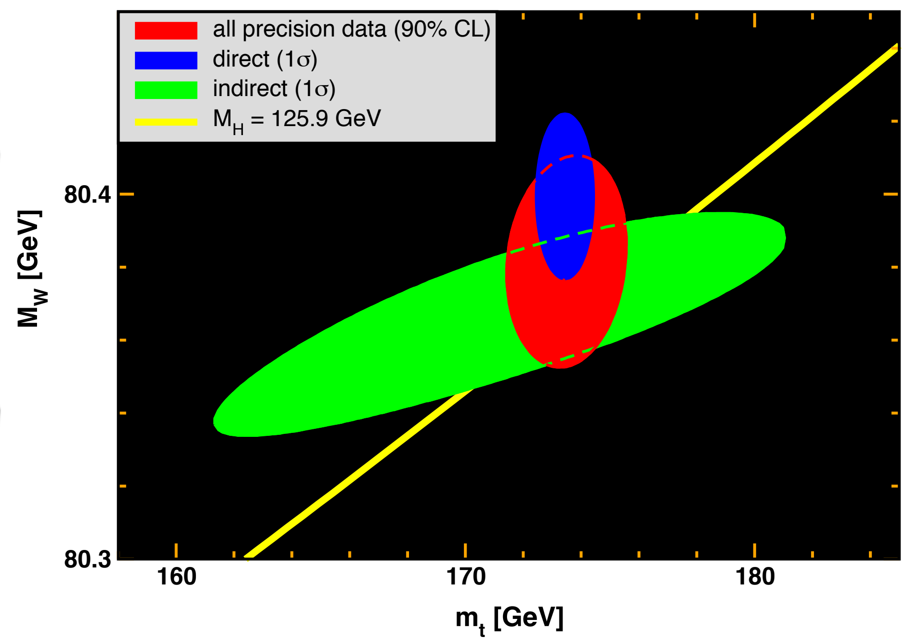
TeV

GeV

MeV

eV

Erler, Su (2013)



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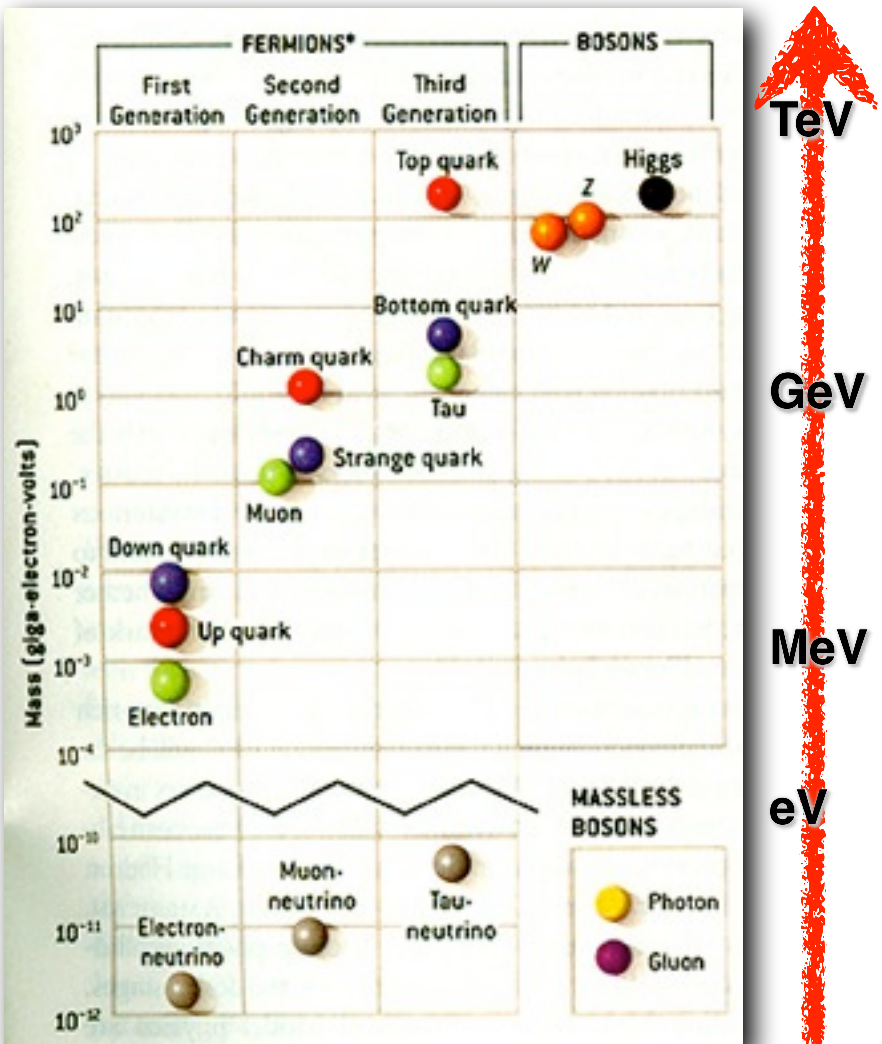

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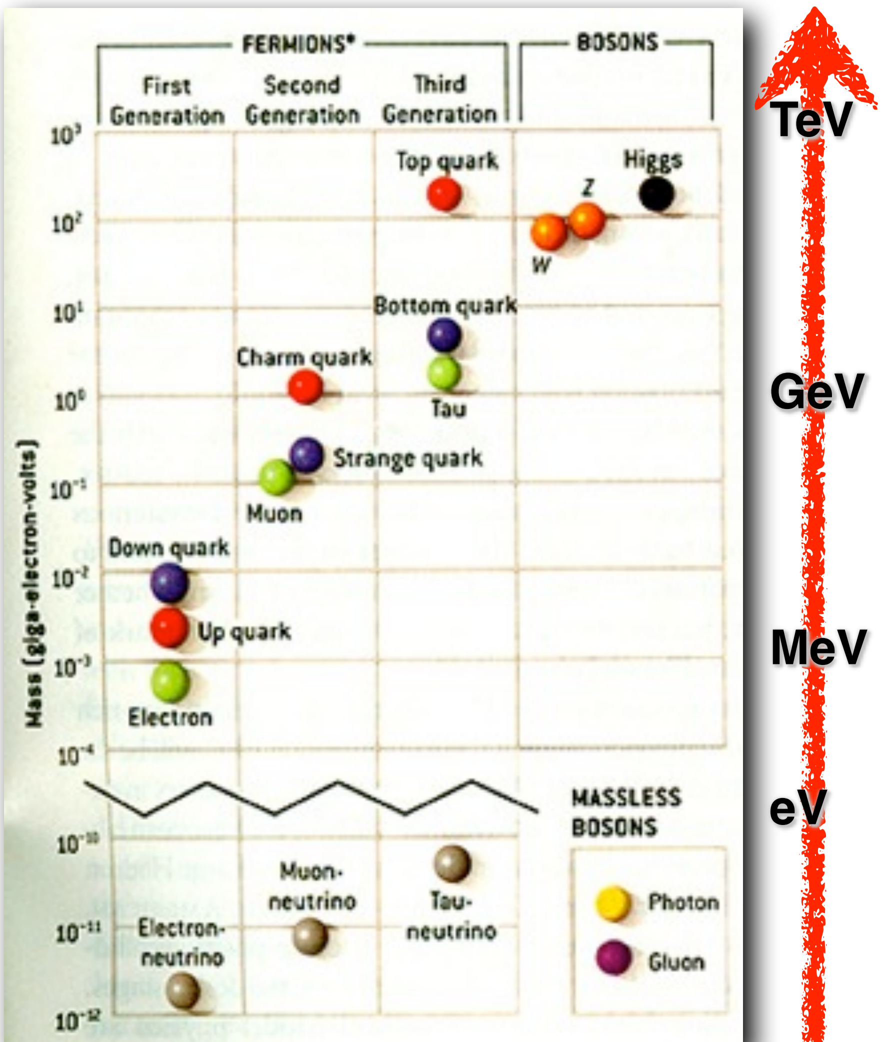

- SM complete

  valid up to Planck scale

Standard Model

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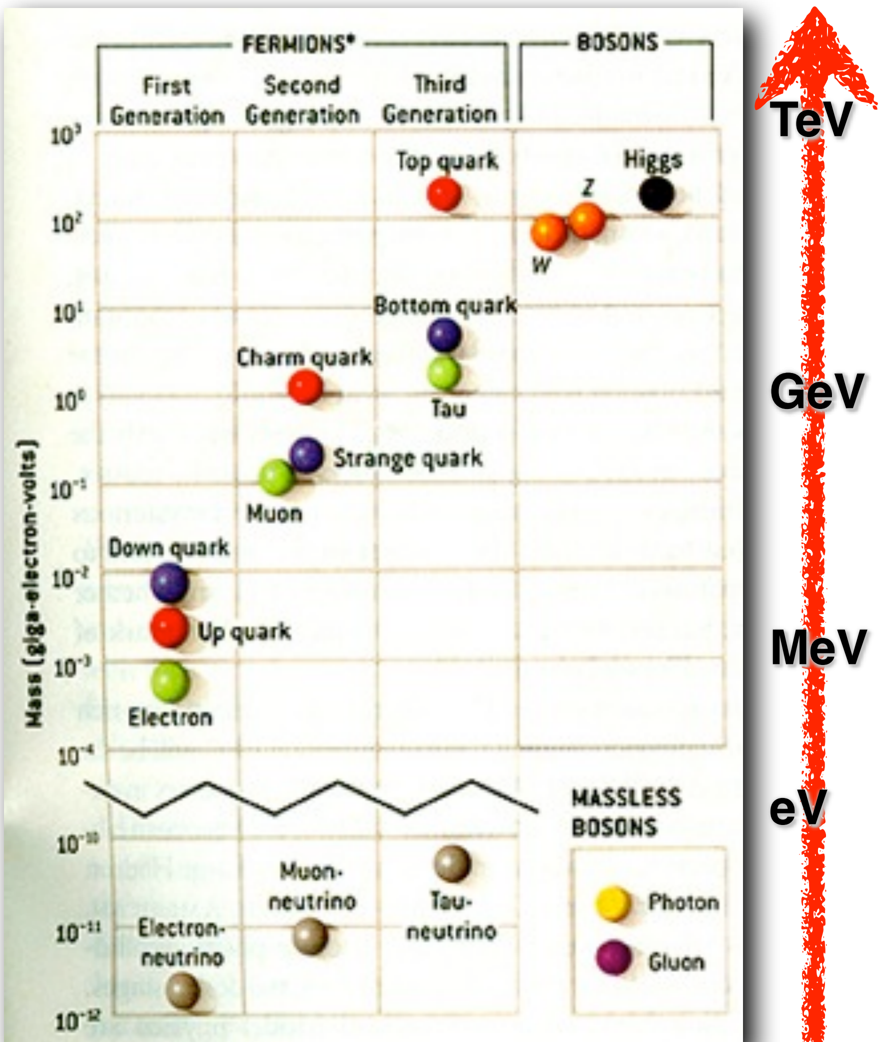

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- Big questions

Standard Model

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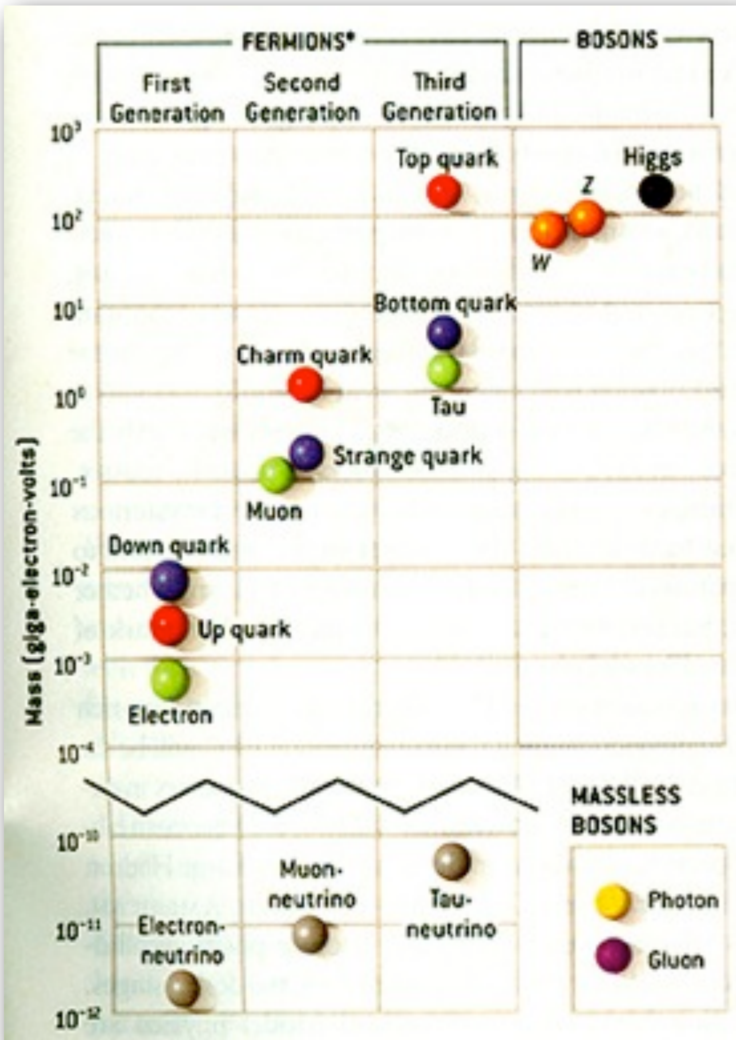

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- Big questions
- Big ideas

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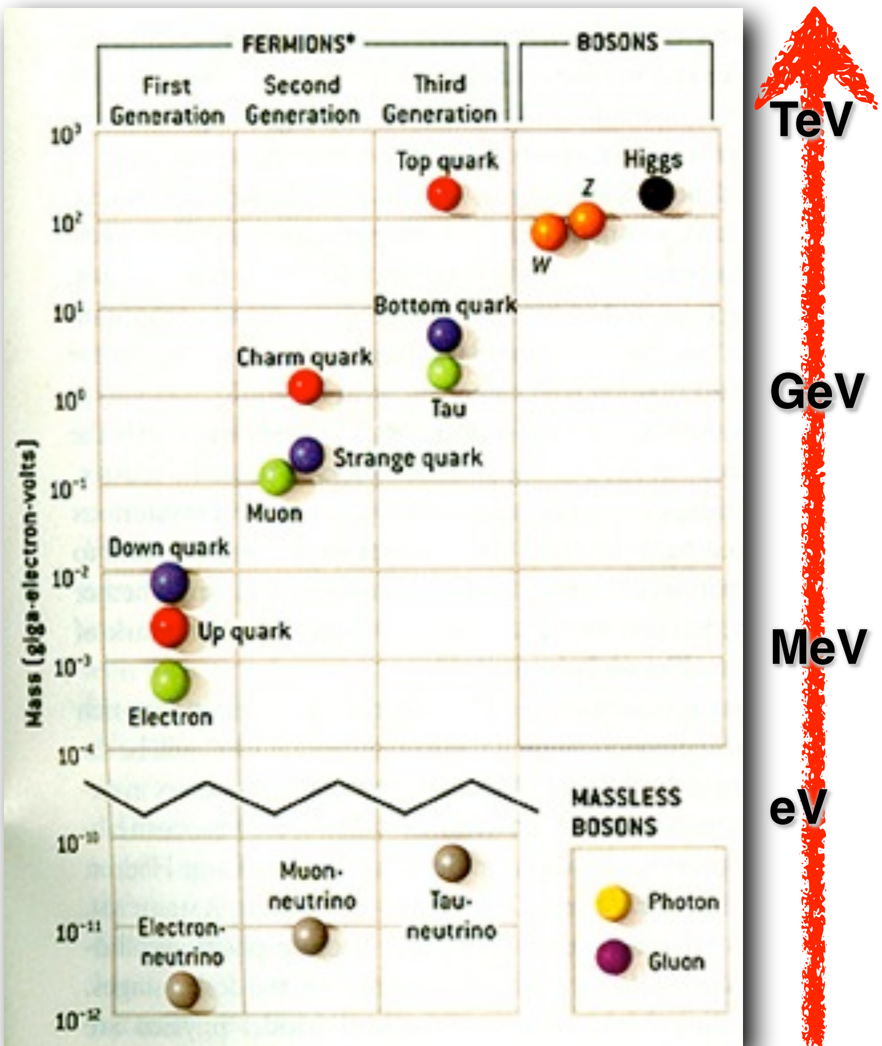
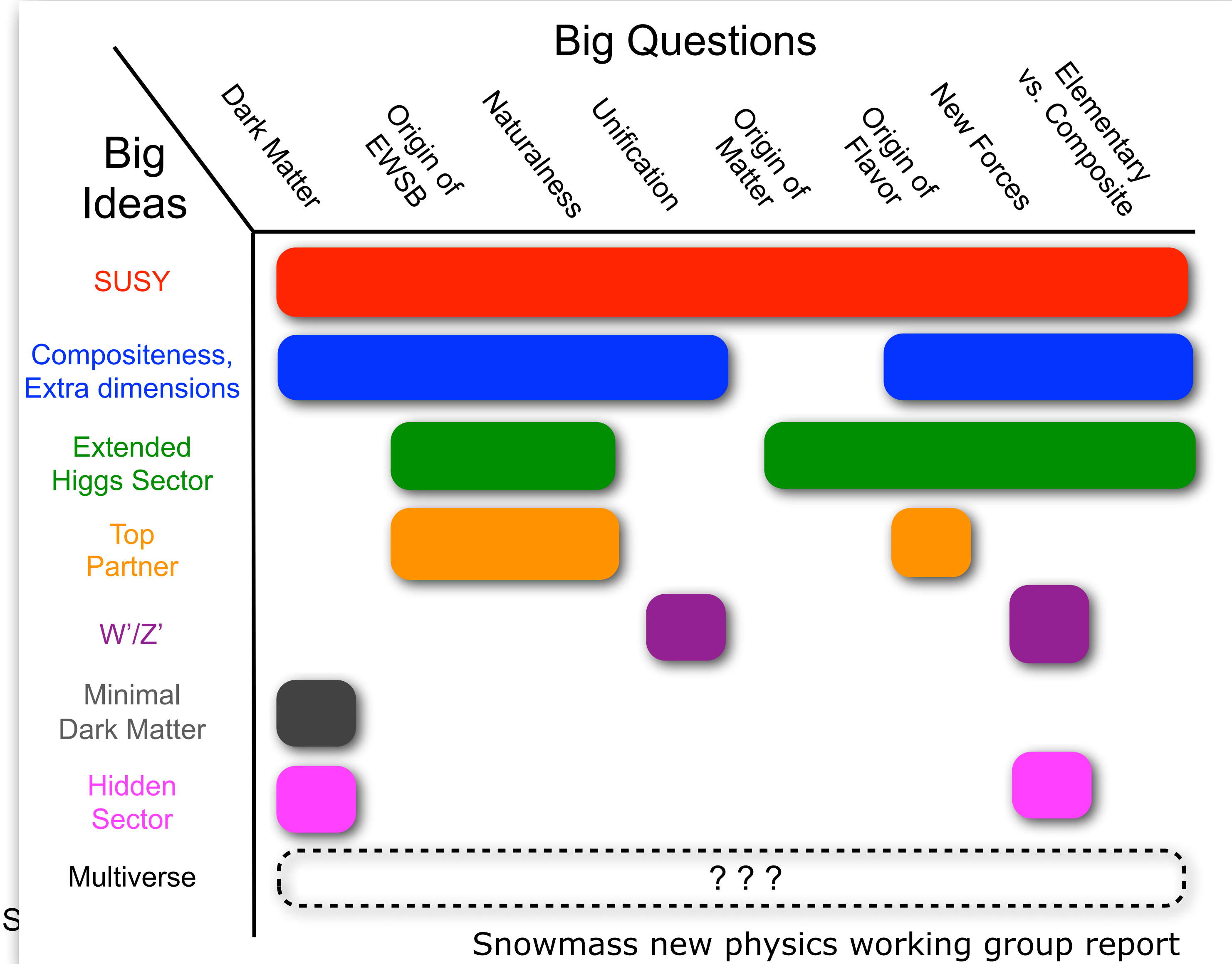


- SM complete

  valid up to Planck scale
- Big questions
- Big ideas
- unexpected...

New Physics beyond the SM



S. S

What did we learn from LHC 7/8 TeV ?

A Light Higgs is Puzzling...

- Light, weakly coupled boson: m_h = 125-126 GeV, Γ < 1 GeV
  - ➡ spin 0, a new kind of fundamental particle
  - ➡ Nothing protects its mass ⇒ New physics beyond the SM

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Then What? Still a lot of hard, but fun work to do!

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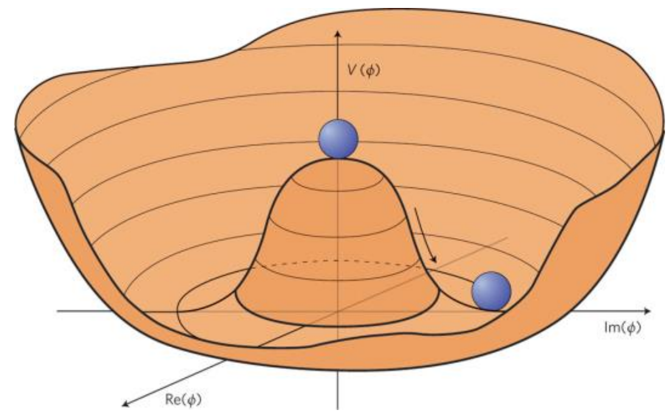

$$V(\phi) = \frac{1}{2}\mu_h^2\phi^2 + \frac{\lambda}{4}\phi^4$$

$$\langle\phi\rangle \equiv v \neq 0 \quad \rightarrow \quad m_W = g_W\frac{v}{2}$$

$$M_H^2 = -2\mu^2 = 2\lambda v^2$$

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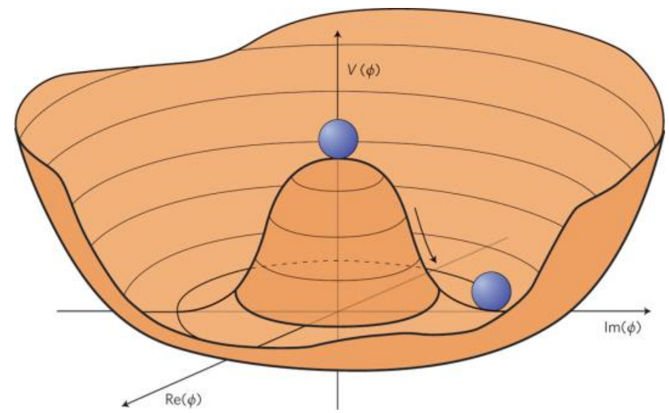
A new force of nature? $\lambda \sim 1/8$



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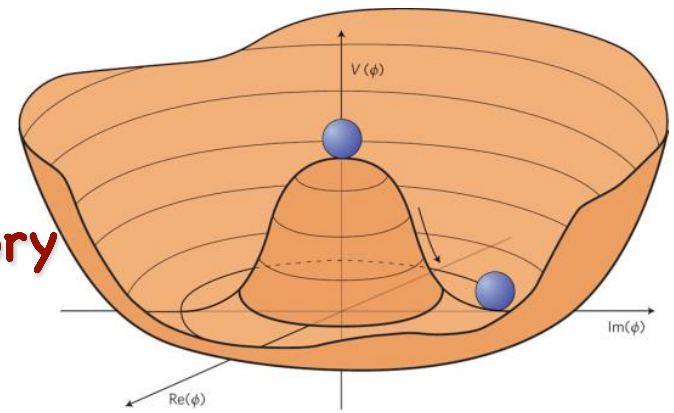
At the verge of uncovering a deep theory

- λ determined by guage couplings?

  e.g., SUSY, $\lambda = (g_1^2+g_2^2)/8$ ...

- or dynamically generated by a new strong force?

  e.g., technicolor, composite Higgs, Higgsless, extra dimensions,...



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Then What? **experimentally...**

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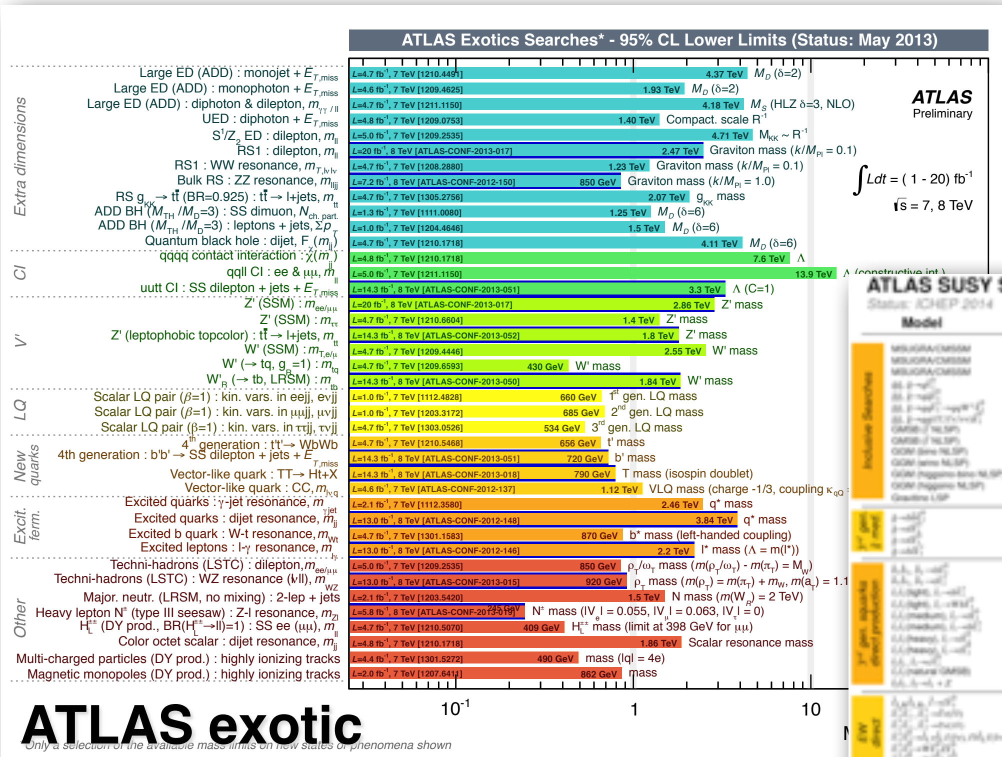
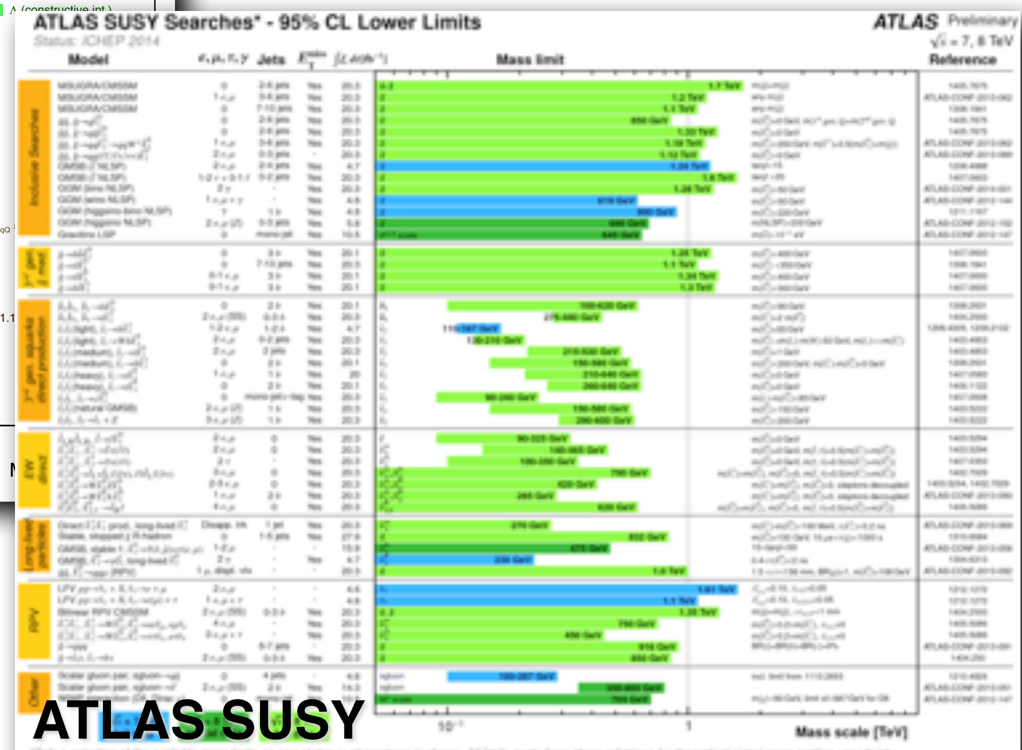
New Physics Searches

- No new physics beyond the SM has been discovered yet





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Then What?

<u>**Where is New Physics?**</u> **larger mass? Small Coupling? Both?**

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  (pp with high luminosity or e+e-)

Outline

Physics case for future colliders

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- Available options for future colliders

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- Precision

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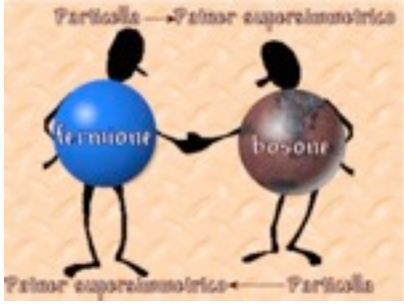
◉ Precision

◉ top partners (naturalness)



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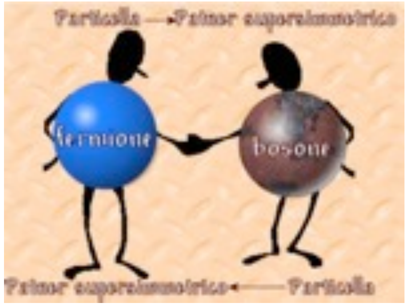
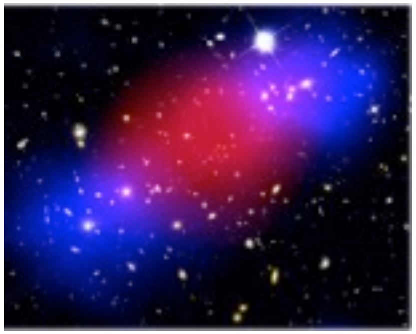
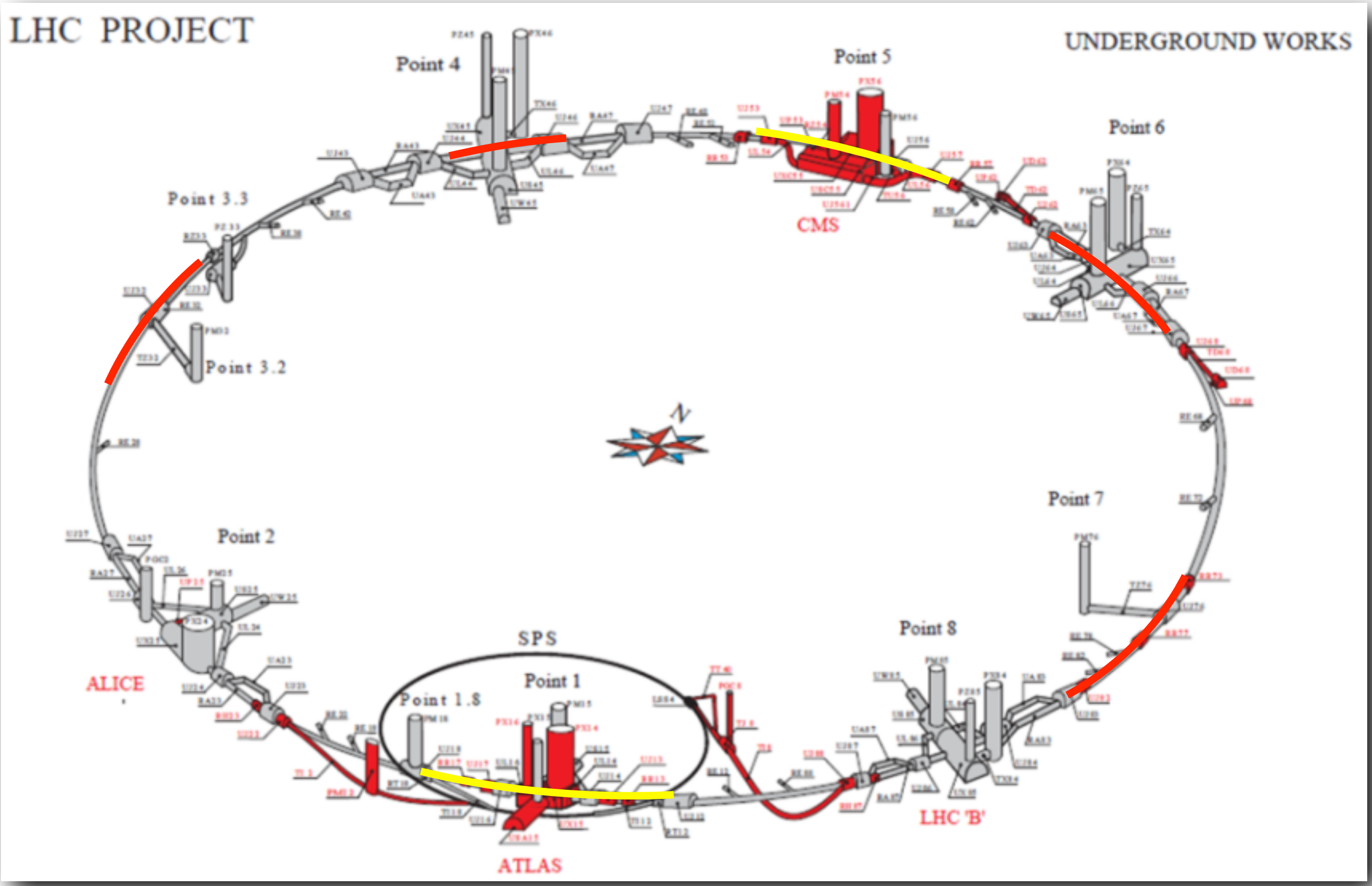


- dark matter



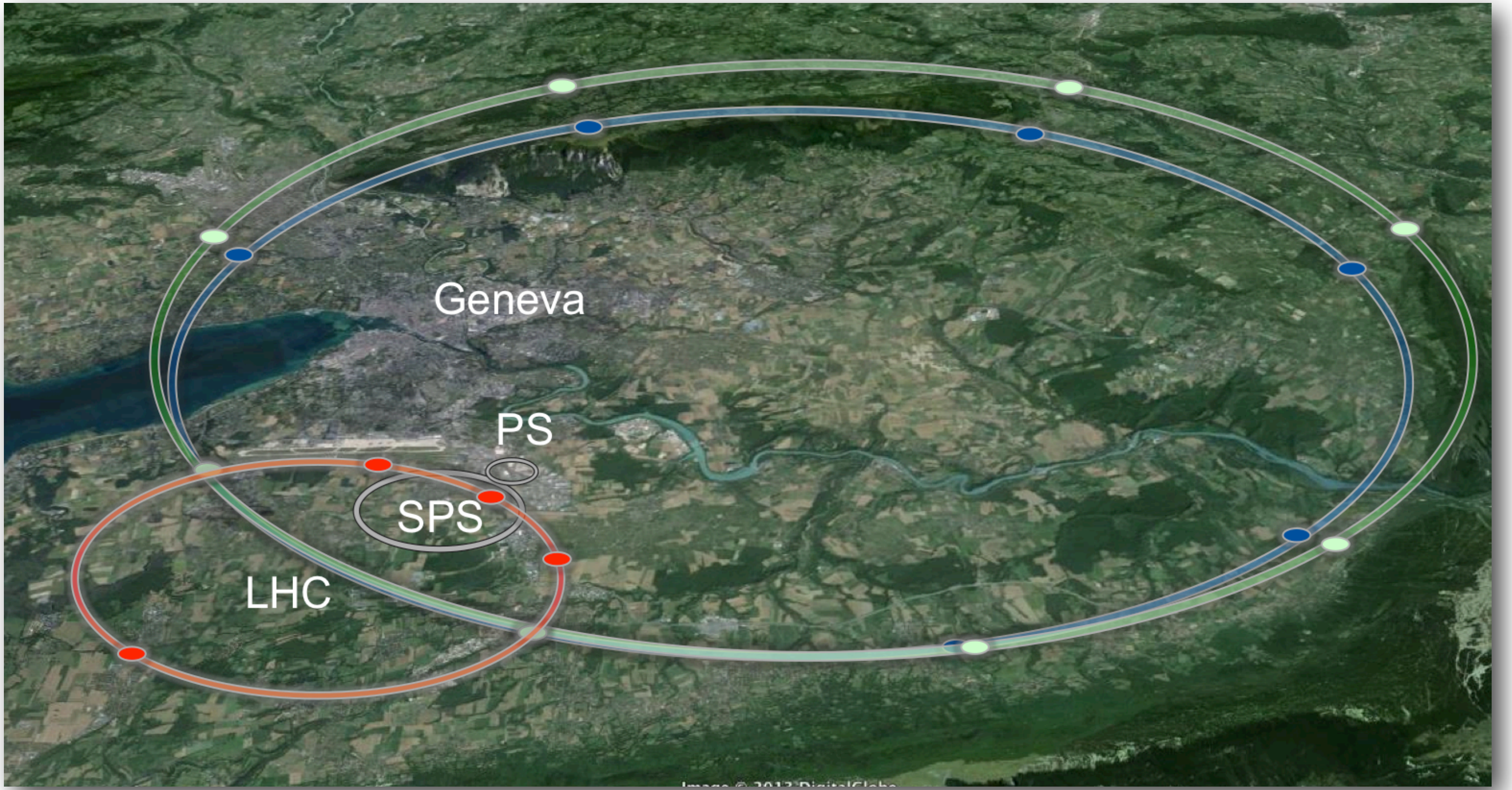
Available Options for future colliders

HL-LHC



LHC @ 14 TeV, 3 ab^{-1} by 2035

FCC

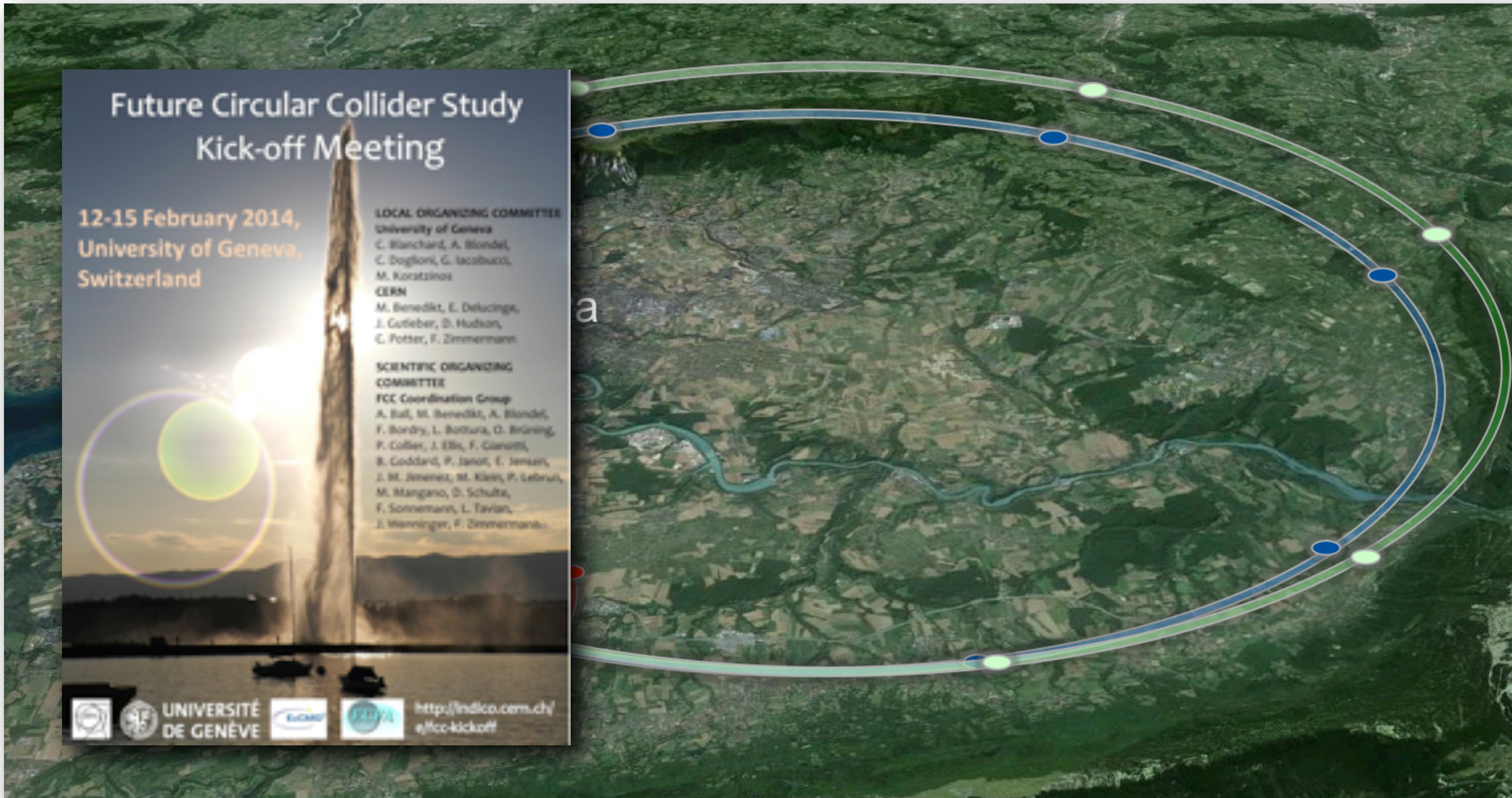


HE-LHC
27 km, 20T
33 TeV

FCC-ee
80/100 km
90 - 400 GeV

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

FCC



HE-LHC	FCC-ee	FCC-hh
27 km, 20T	80/100 km	80 /100 km, 16/20T
33 TeV	90 - 400 GeV	100 TeV

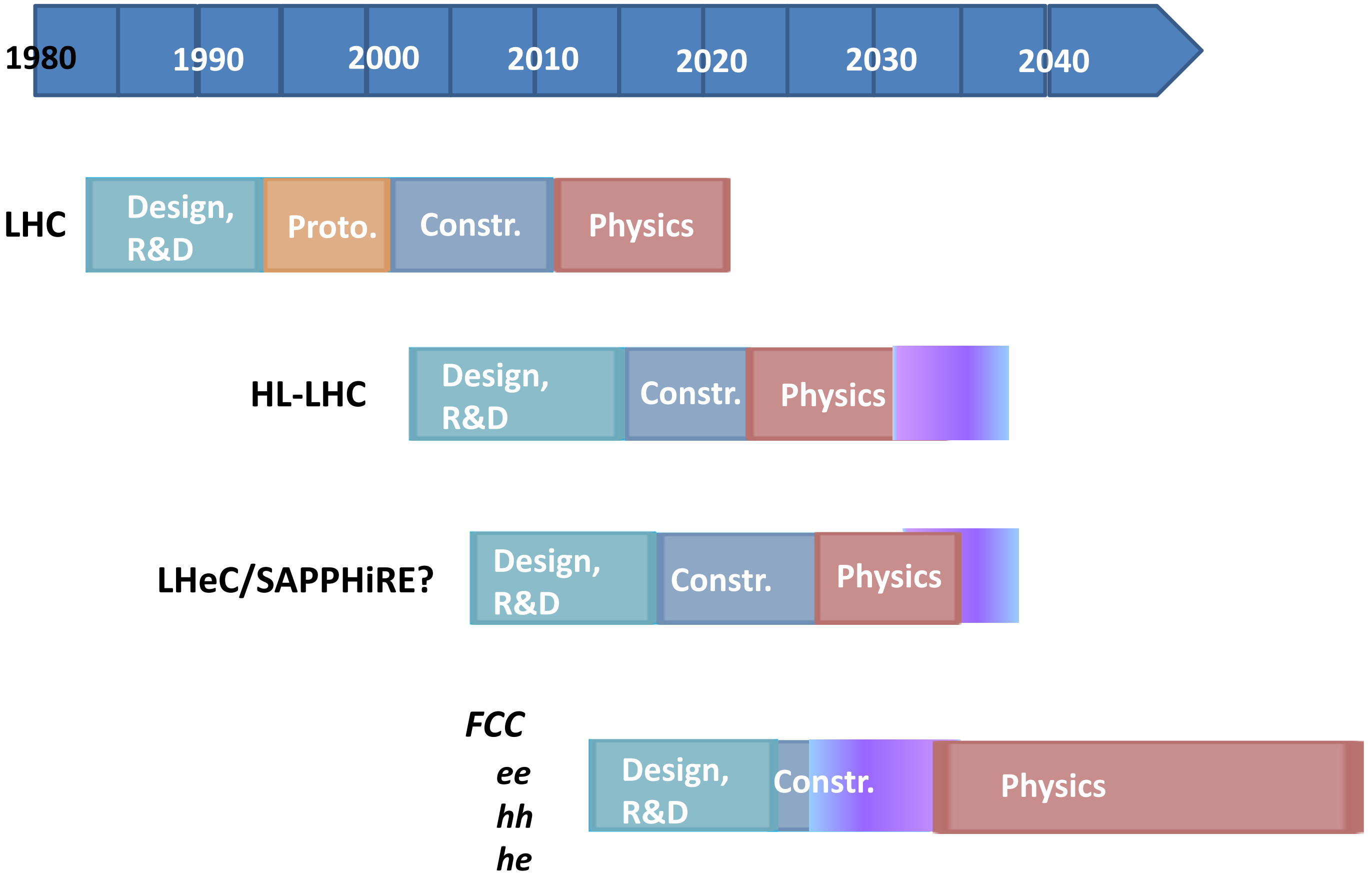
FCC

HE-LHC
27 km, 20T
33 TeV

FCC-ee
80/100 km
90 - 400 GeV

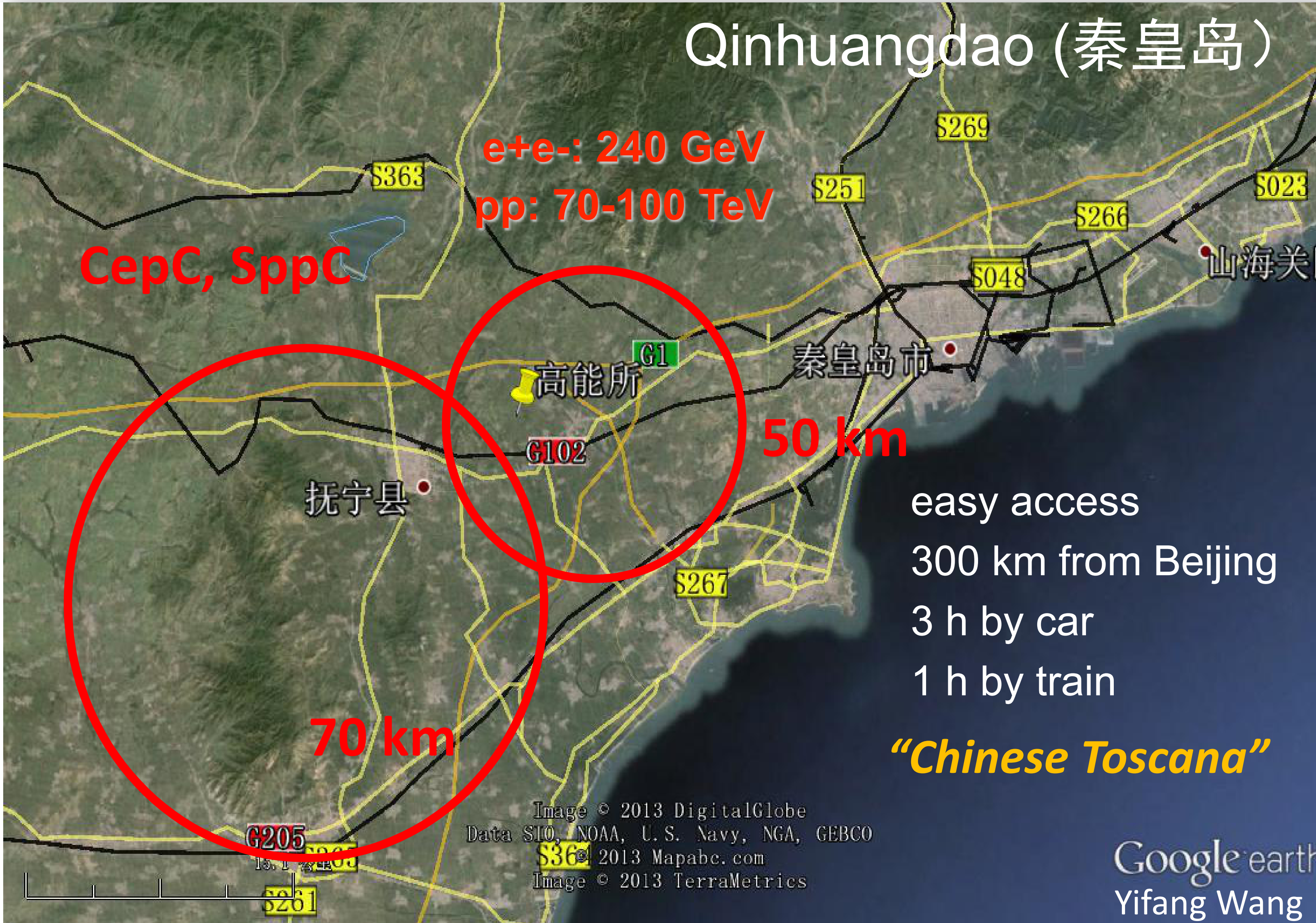
FCC-hh
80 /100 km, 16/20T
100 TeV

FCC Timeline



M. Benedikt

CEPC-SPPC



Qinhuangdao (秦皇岛）
e+e-: 240 GeV
pp: 70-100 TeV
CepC, SppC
高能所
秦皇岛市
山海关区
抚宁县
50 km
70 km
S363
S251
S269
S266
S023
S048
G1
G102
S267
G205
S261
easy access
300 km from Beijing
3 h by car
1 h by train
"Chinese Toscana"
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Google earth
Yifang Wang

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Ce
岛）
S023
山海关区
抚宁县
easy access
环行正负电子对撞机—超级质子对撞机
(CEBC-SPPC) 项目启动会
2013.9.13—14, 北京


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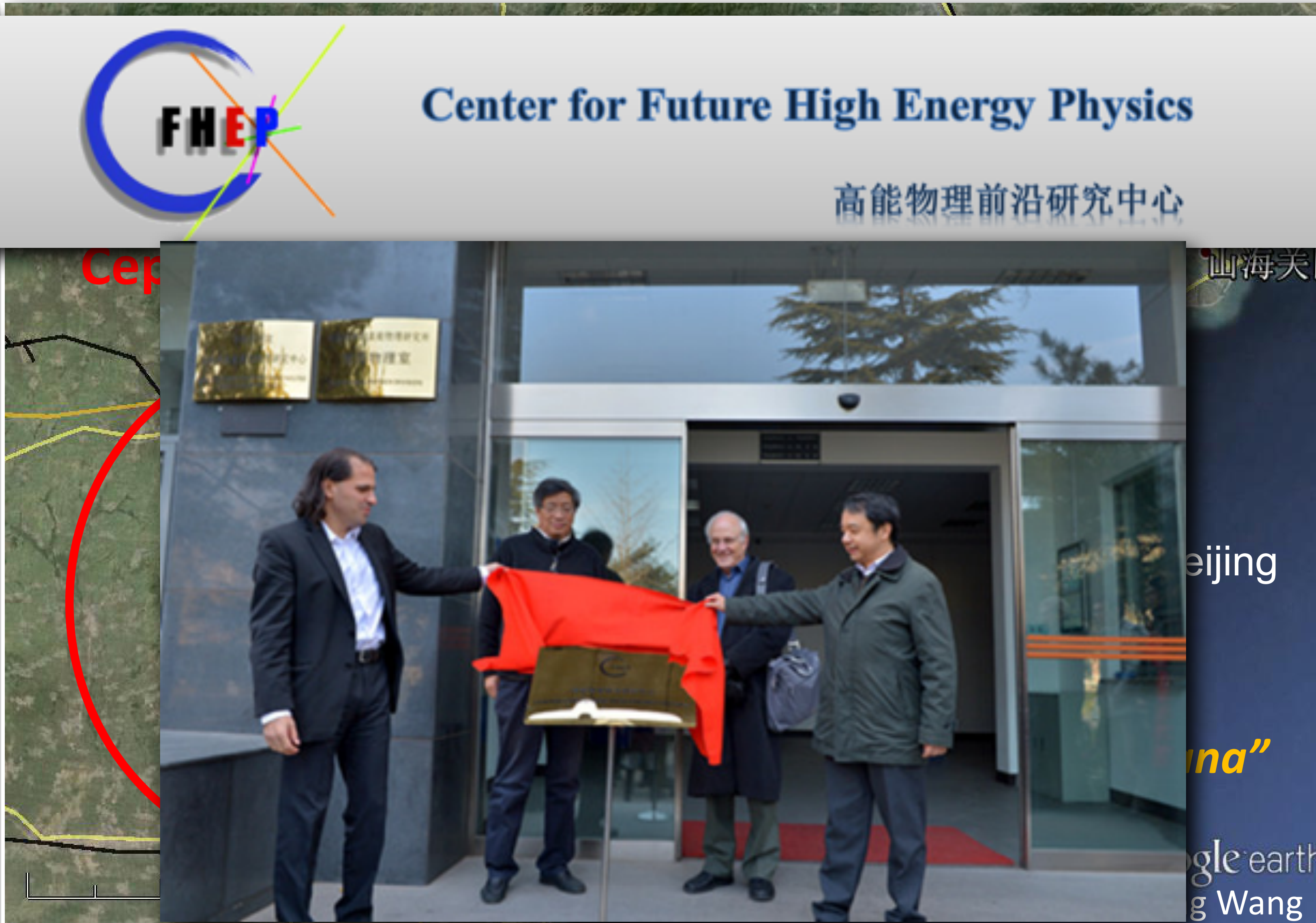
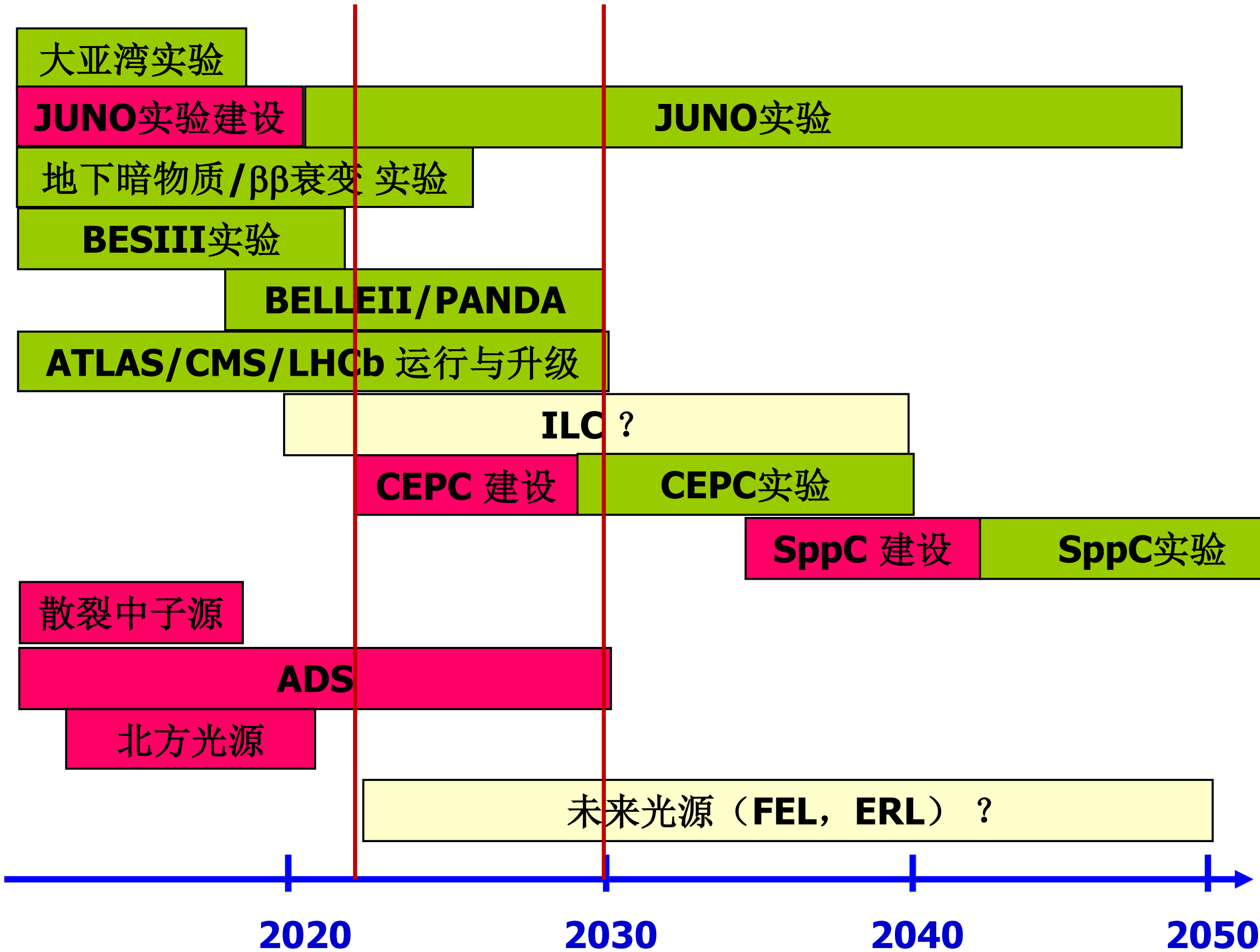


Center for Future High Energy Physics

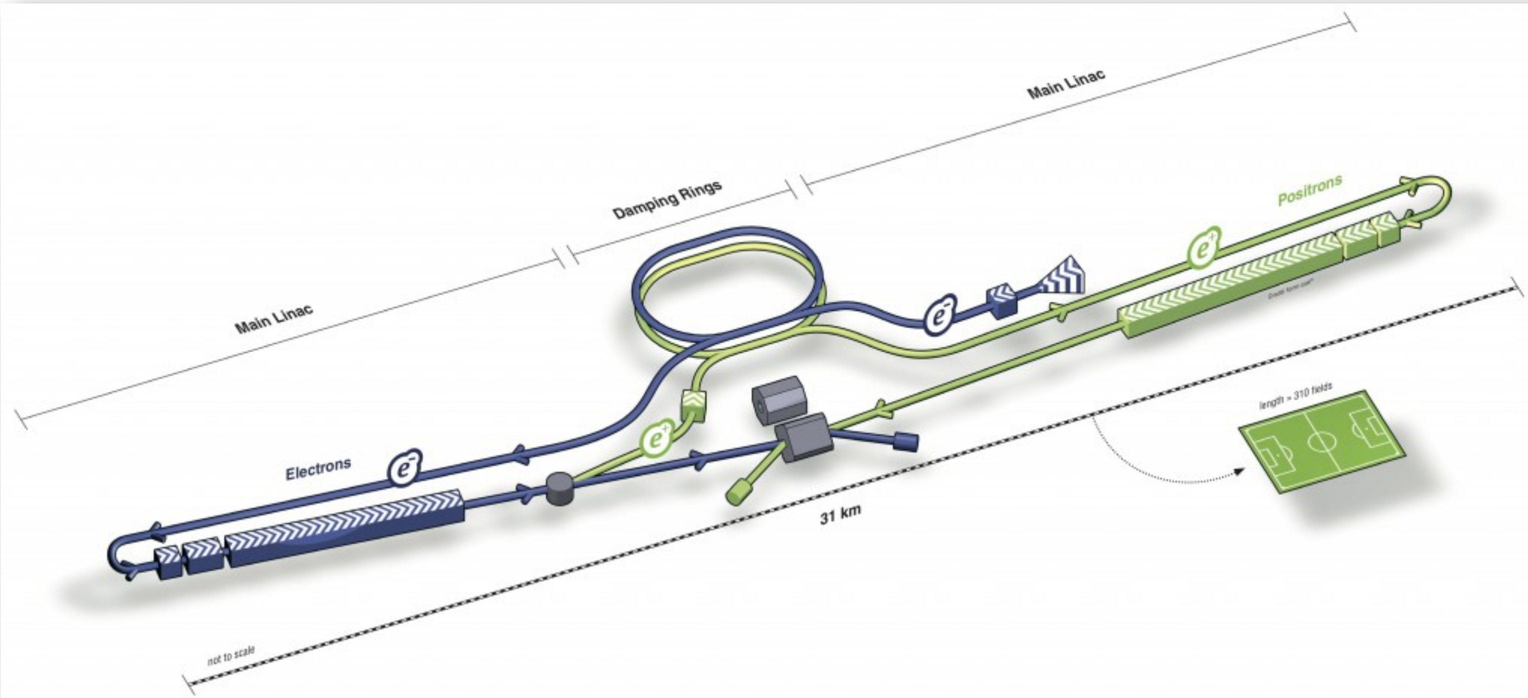
高能物理前沿研究中心

CEPC-SPPC Timeline



Y. Wang

ILC

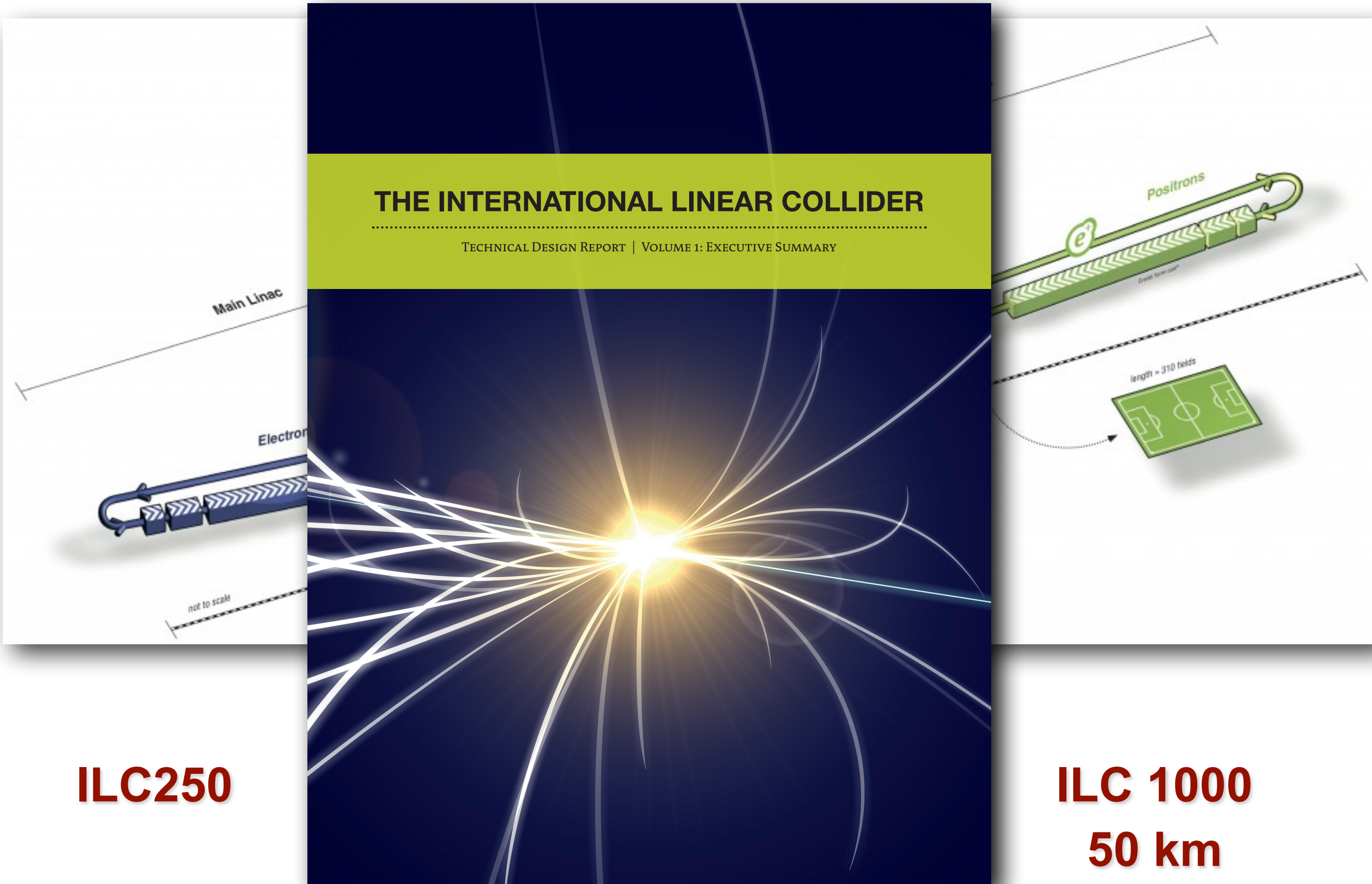


ILC250

ILC 500
31 km

ILC 1000
50 km

ILC



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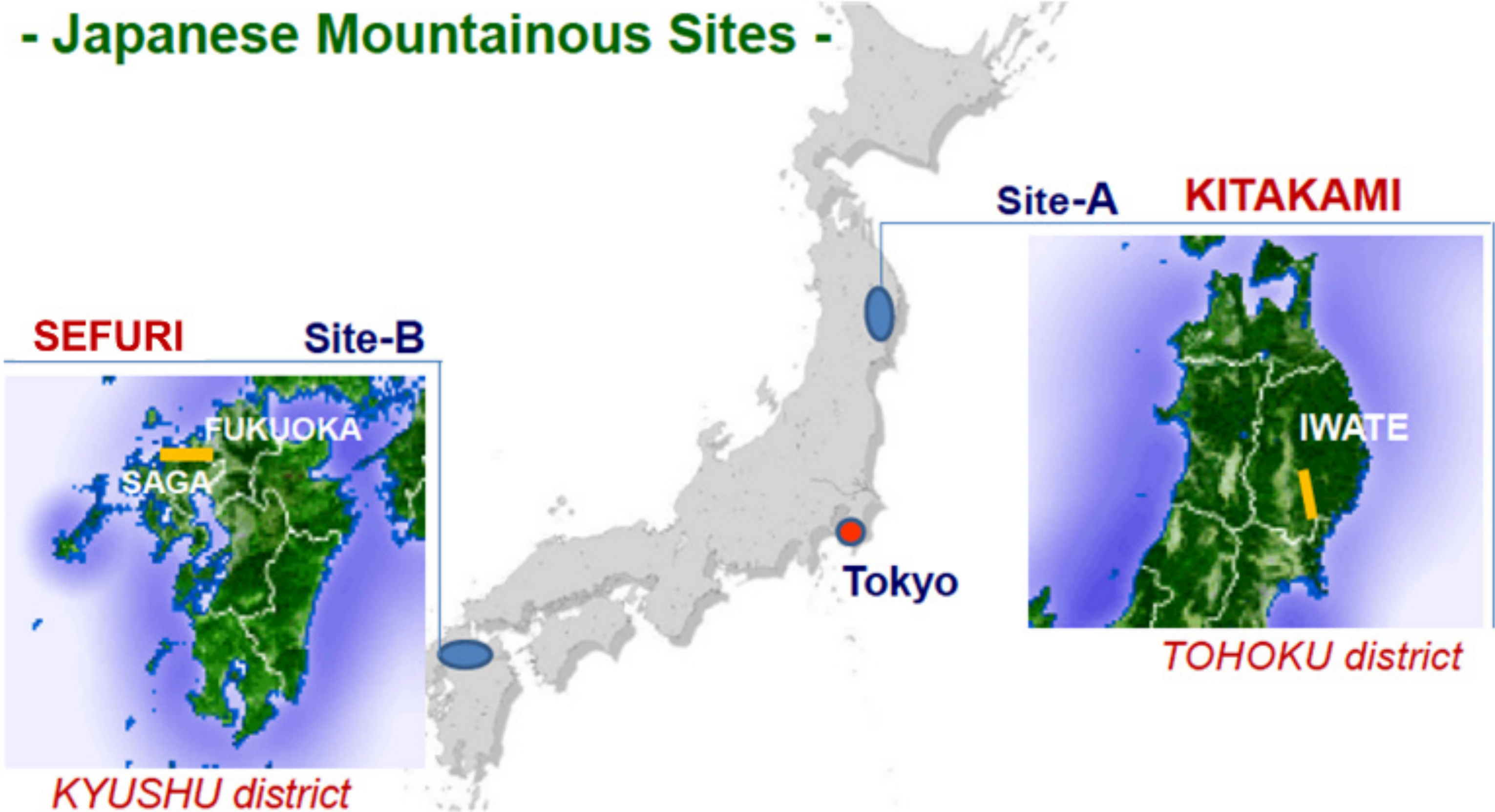
50 km

ILC



- relatively conservative approach, could start soon
- Japan ponders (physics, money, global HEP, etc…) – decision in 2016

Machine Options

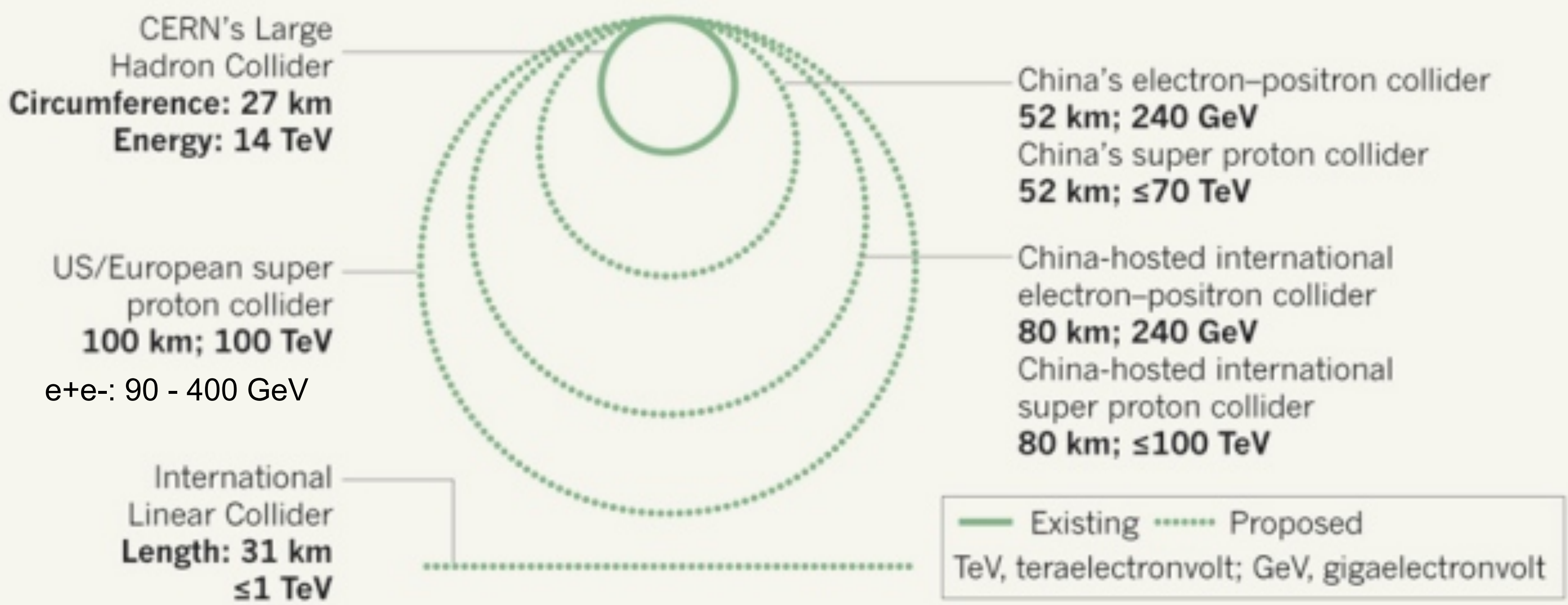
China plans super collider Nature News, July

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

Elizabeth Gibney

COLLISION COURSE

Particle physicists around the world are designing colliders that are much larger in size than the Large Hadron Collider at CERN, Europe's particle-physics laboratory.



e+e-: 90 - 400 GeV

Physics opportunity for HL-LHC

14 TeV with 3 ab-1

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14 TeV with 3 ab-1

- **EW Physics:**

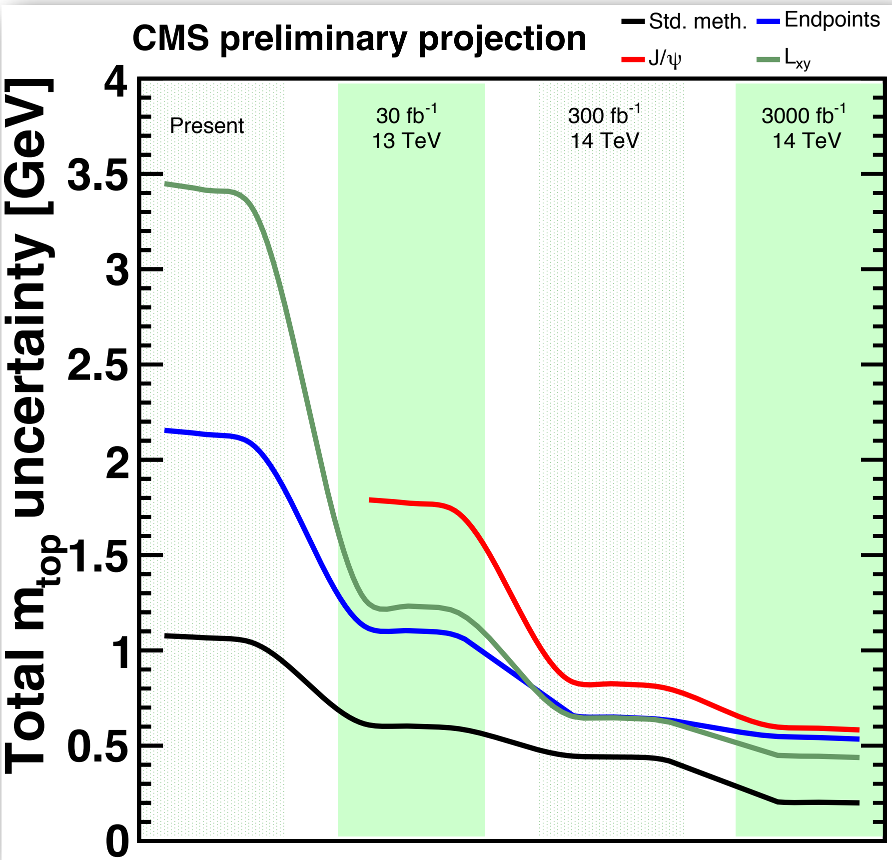
  m_t, m_W, rate top decay, VVV/VVVV couplings, WW scattering,...

- **Higgs Physics**

  mass, width, CP, coupling, rare decay, self-coupling

- **New heavy particles**

HL-LHC: top



P. Janot, XVII LNF Spring School

Projected uncertainties

- Reduction by a factor 2

after the first data of LHC Run2 (1yr)

after the LHC Run3 (5 yr)

after 3 ab^{-1} (10 yr)

- Ultimate reach: ~ 200 MeV (exp.)

Theory uncertainties ~ 500 MeV need to be reduced as well.

HL-LHC: Higgs

Higgs factory

- 170 M Higgs produced in each experiment, ~ 2 M events after selection
- access to rare decays: μμ, Zγ

Luminosity	300 fb^{-1}	3000 fb^{-1}
Coupling parameter	7-parameter fit	
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_u	$14-15\%$	$7-10\%$
κ_d	$10-13\%$	$4-7\%$
κ_ℓ	$6-8\%$	$2-5\%$
Γ_H	$12-15\%$	$5-8\%$

Factor of 1.5-2 better.

New physics contribution

$$\frac{\delta g_{\mathrm{HXX}}}{g^{\mathrm{SM}}_{\mathrm{HXX}}} \leq 5\% \times \left(\frac{1\mathrm{TeV}}{\Lambda}\right)^2$$

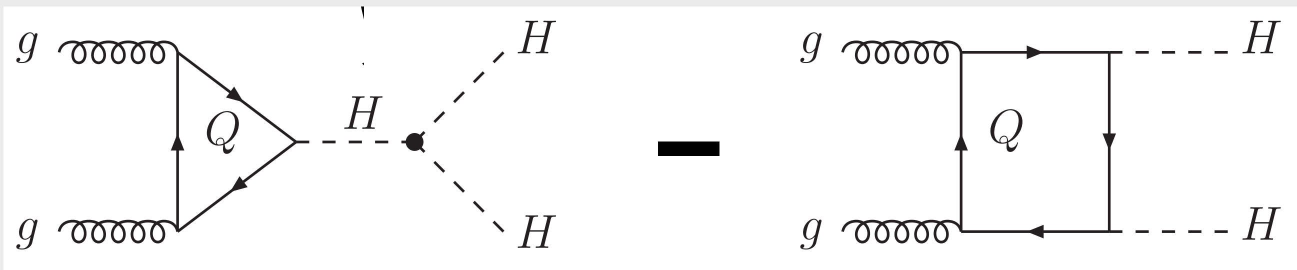
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Might be good for some new physics with scale < 1 TeV

Snowmass Higgs Working Group, 1310.8361

HL-LHC: Higgs self-coupling

Negative interference reduces the sensitivity to g_{HHH}



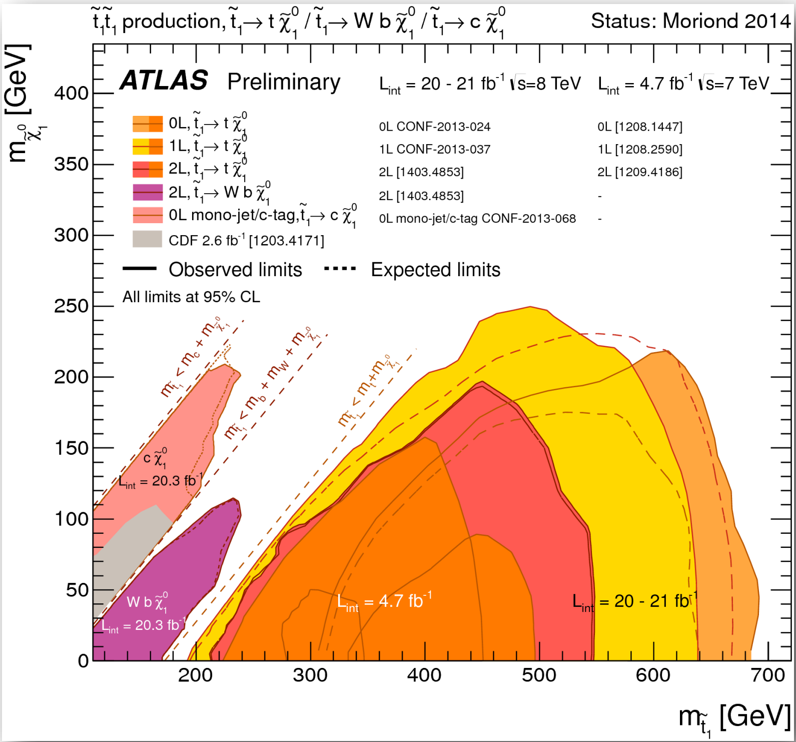
With 3 ab^{-1}

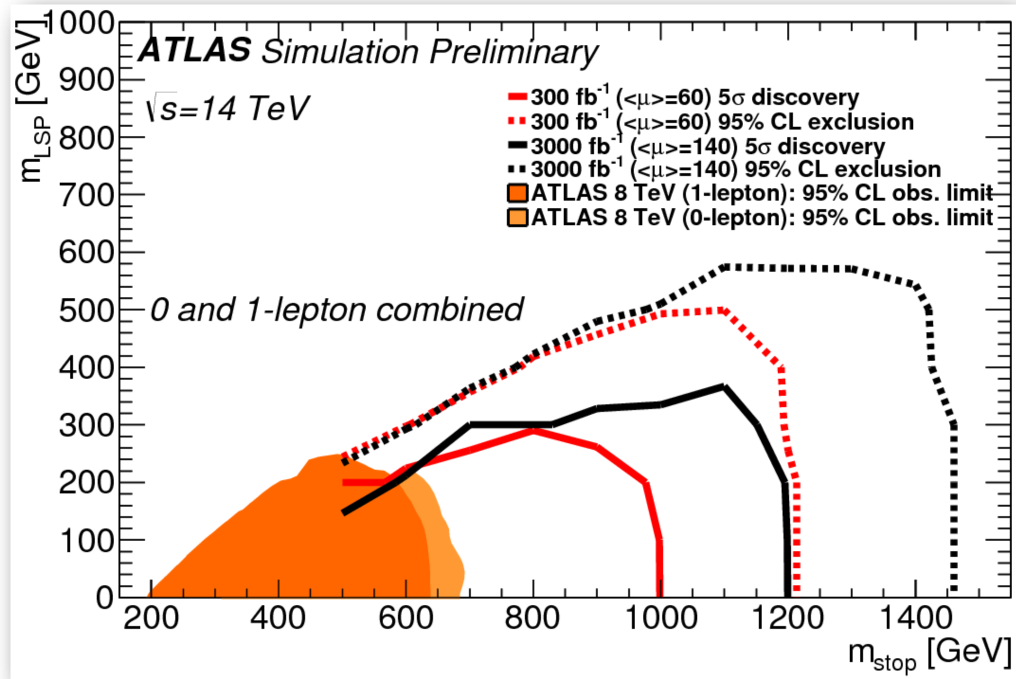
Expected events

bbWW	30000
bbττ	9000
WWWW	6000
γγbb	320
γγγγ	1

- A sensitivity of 30% might be achieved for bbγγ
- New physics deviation typically less than 20%

HL-LHC: stop





- Mass reach extended by a factor of 2 at 14 TeV, 300 fb^{-1}
- further extended by 20% at 3 ab^{-1}
- If no excess seen at 300 fb^{-1}, can not be seen at 3 ab^{-1}

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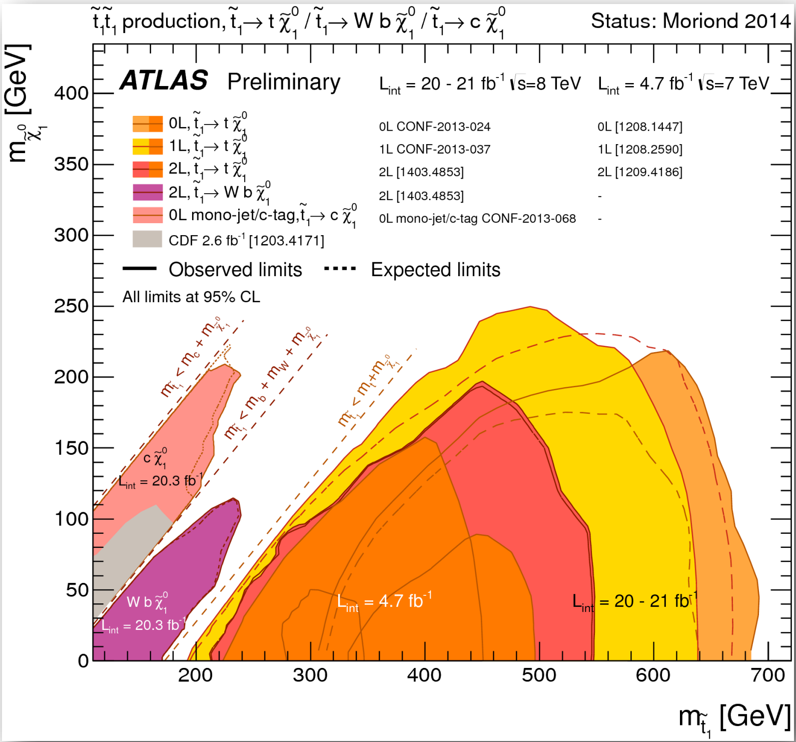

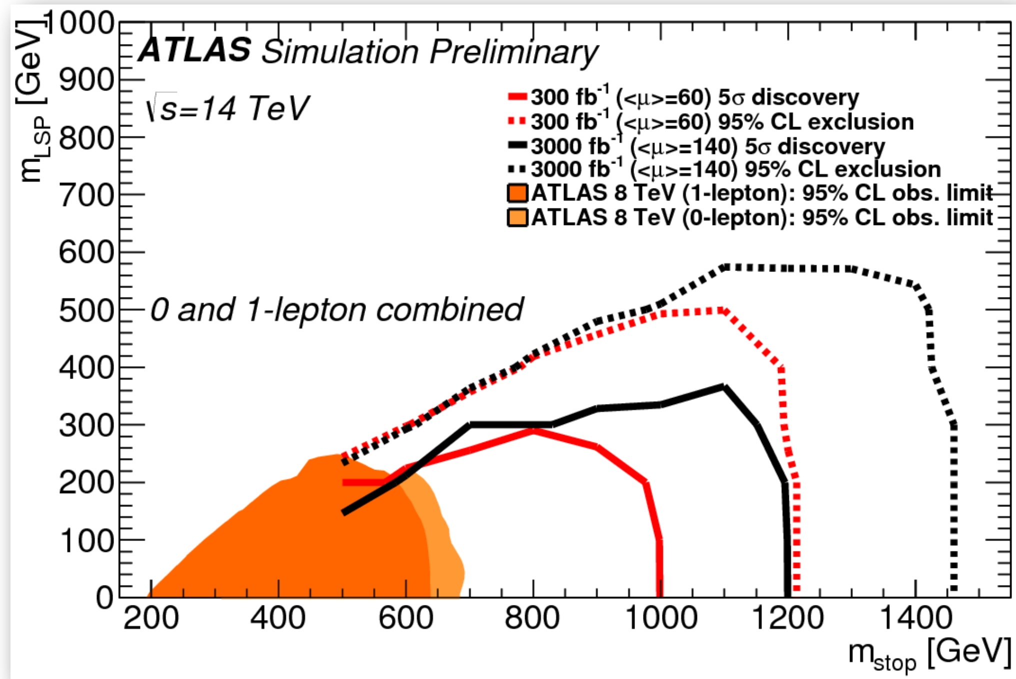

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S. Su

True for many other new particle searches as well.

Physics opportunity at e+e- machine

90 - 500 GeV or 1 TeV

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90 - 500 GeV or 1 TeV

- ◉ precision test (Z, W, H, t)
- ◉ invisible decay of Z and H: dark matter
- ◉ rare decay
- ◉ direct new physics search: $E_{cm}/2$

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90 - 500 GeV or 1 TeV

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◉ invisible decay of Z and H: dark matter

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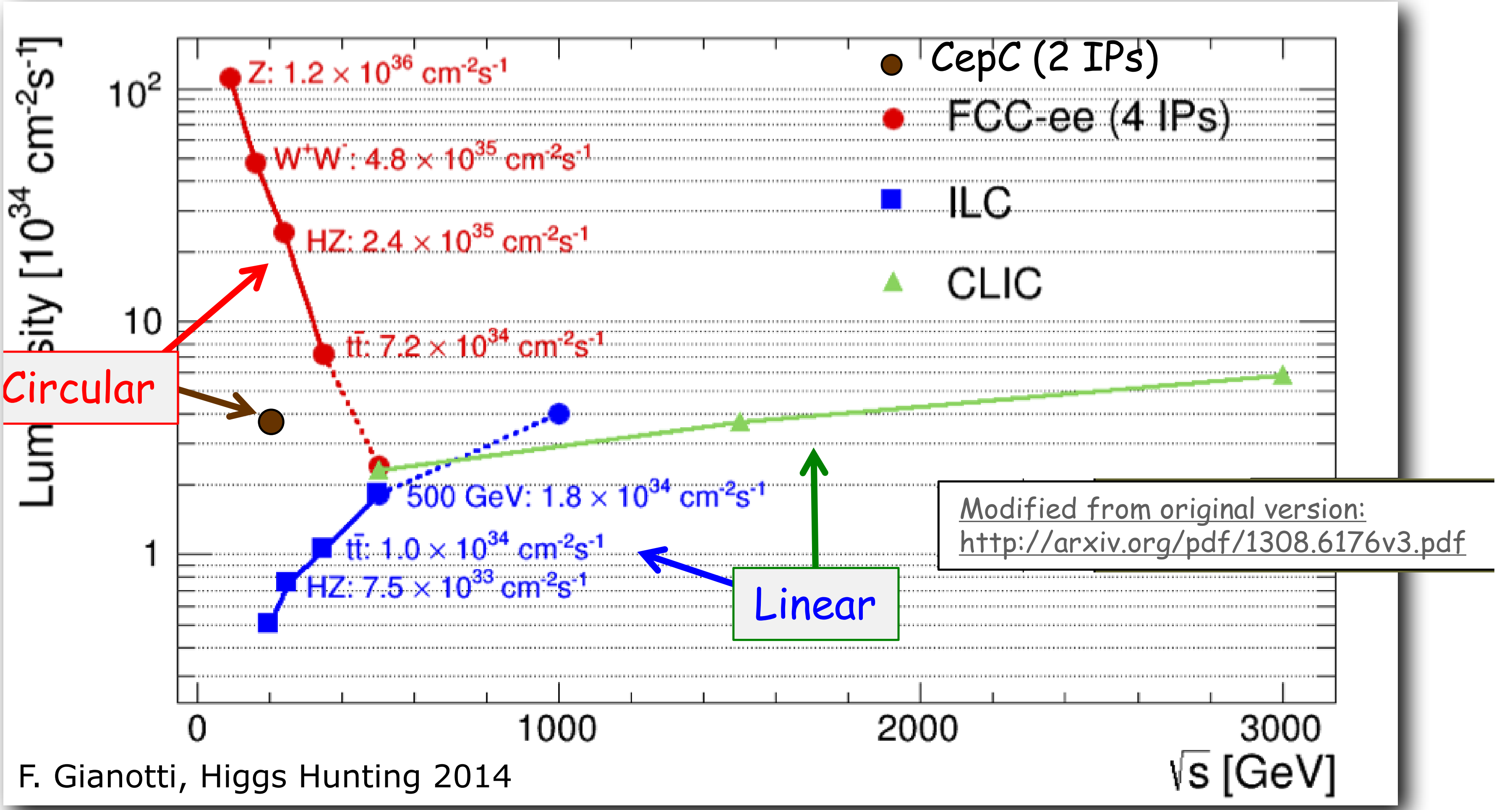
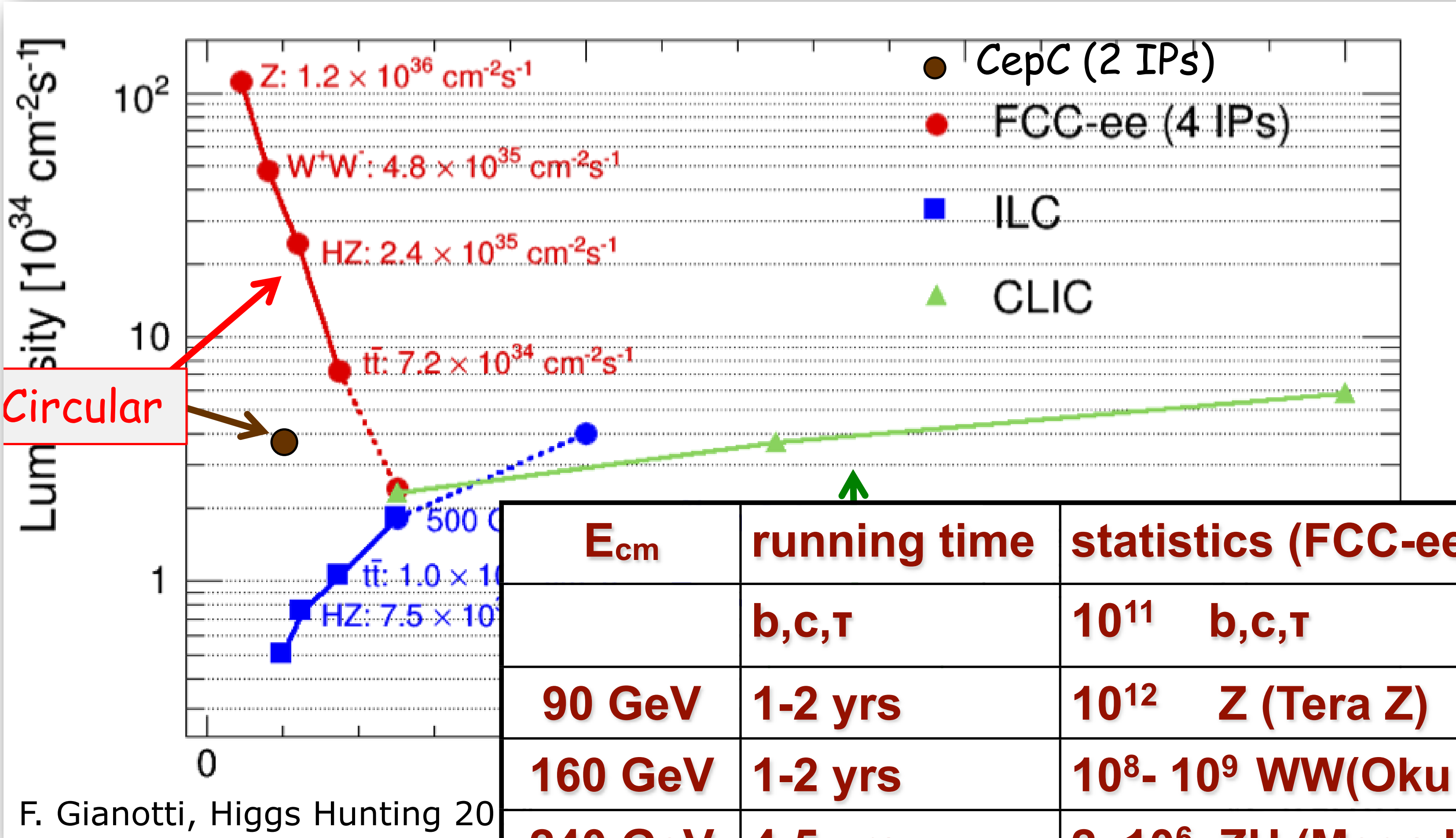
e+e- Machine: Lum vs. E_{cm}



e+e- Machine: Lum vs. E_{cm}

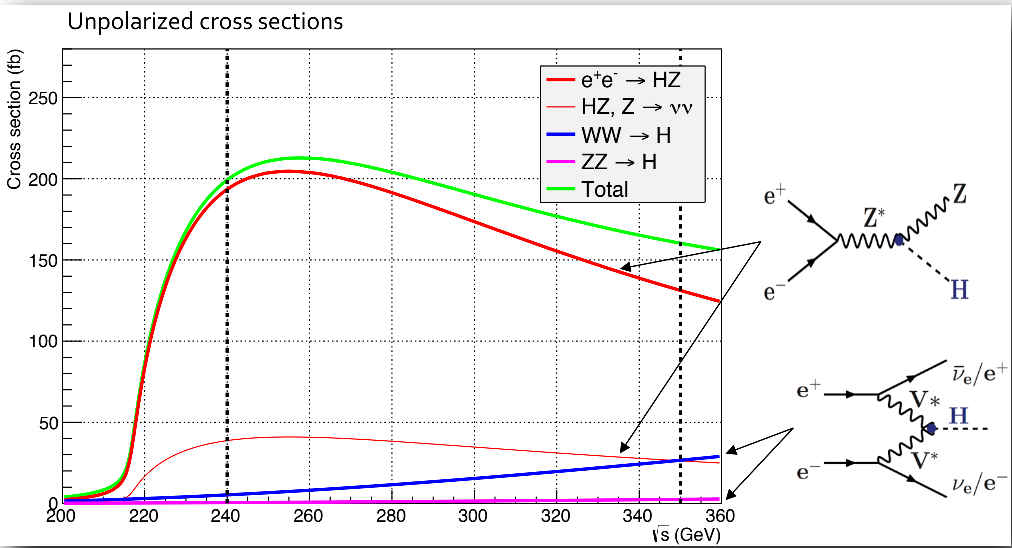


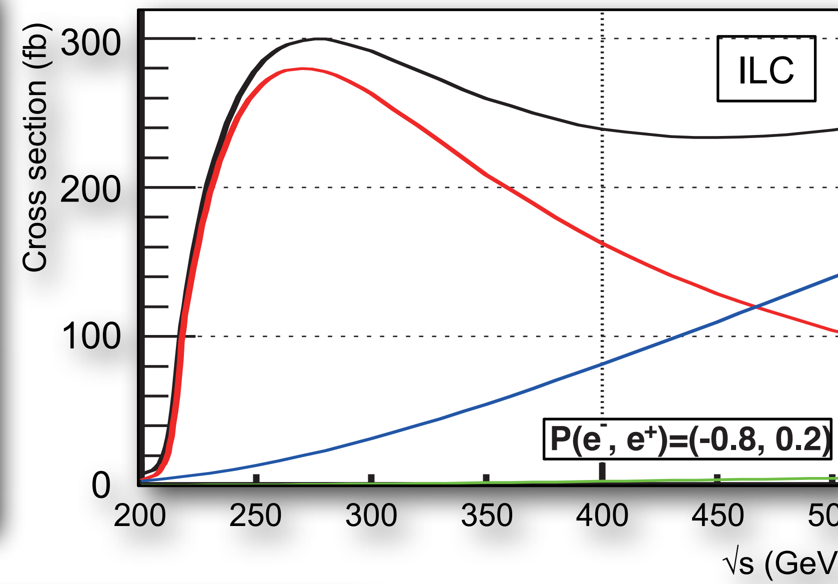
F. Gianotti, Higgs Hunting 20

E_{cm}	running time	statistics (FCC-ee)
	b,c,τ	10^{11} b,c,τ
90 GeV	1-2 yrs	10^{12} Z (Tera Z)
160 GeV	1-2 yrs	10^8- 10^9 WW(Oku W)
240 GeV	4-5 yrs	2×10^6 ZH (Mega H)
350 GeV	4-5 yrs	10^6 tt (Mega top)

S. Su

Higgs Production @ e+e-





$$\sigma(e^+e^- \to H + X) \times BR(H \to YY)$$

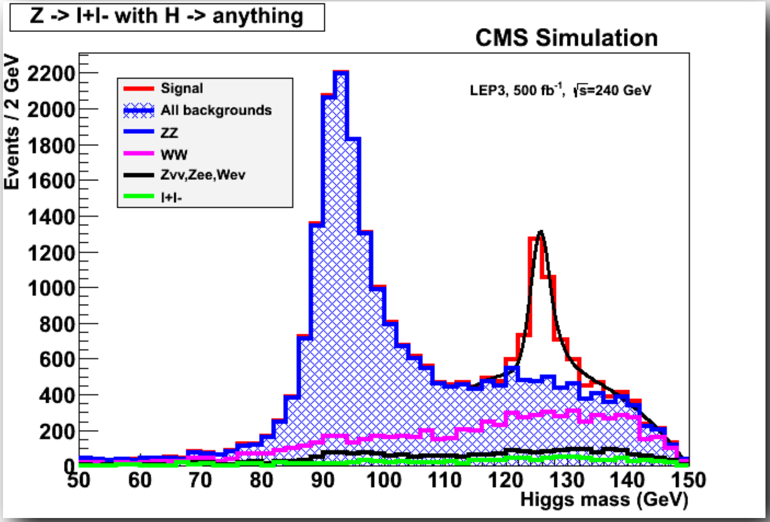
Y=b,c,g,W,Z,γ,τ,μ

- **Determine all Higgs couplings (model-independent)**
- **Infer Higgs total decay width**
- **probe invisible Higgs decay**

Higgs

Model-independent measurement of σ_{HZ} and κ_Z

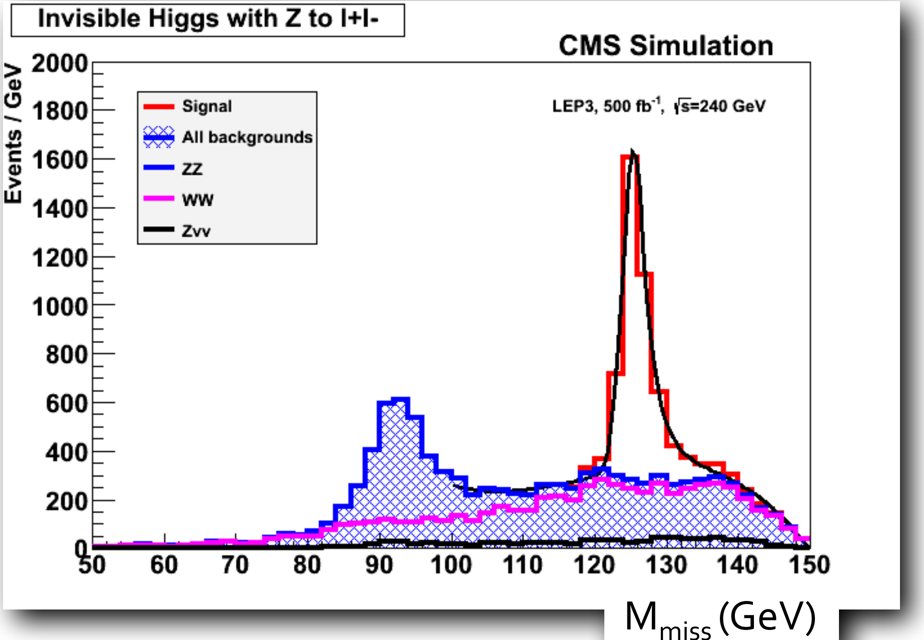
- $Z \rightarrow ee, \mu\mu$
- $H \rightarrow$ anything
- Higgs recoil mass



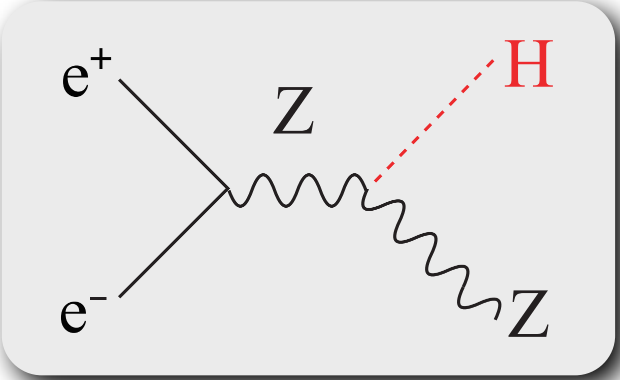
TLEP 1308.6176

Invisible Higgs decay

- $ZH \rightarrow ll$ + nothing



Higgs: total width

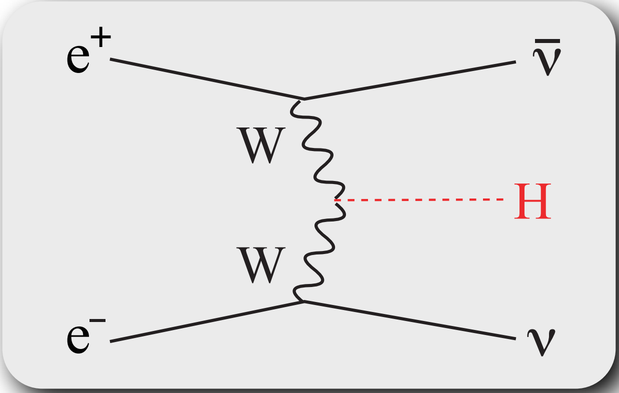


@ 240 GeV

$\sigma_{HZ} \times BR(H \to ZZ) \propto \kappa_Z^4 / \Gamma_H$

@ 350-500 GeV

$WW \to H \to bb$



$$\Gamma_H \propto \sigma_{WW\to H} / BR(H \to WW) = \sigma_{WW\to H\to bb} / BR(H \to WW) \times BR(H \to bb)$$

Higgs Couplings

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Snowmass Higgs Working Group, 1310.8361

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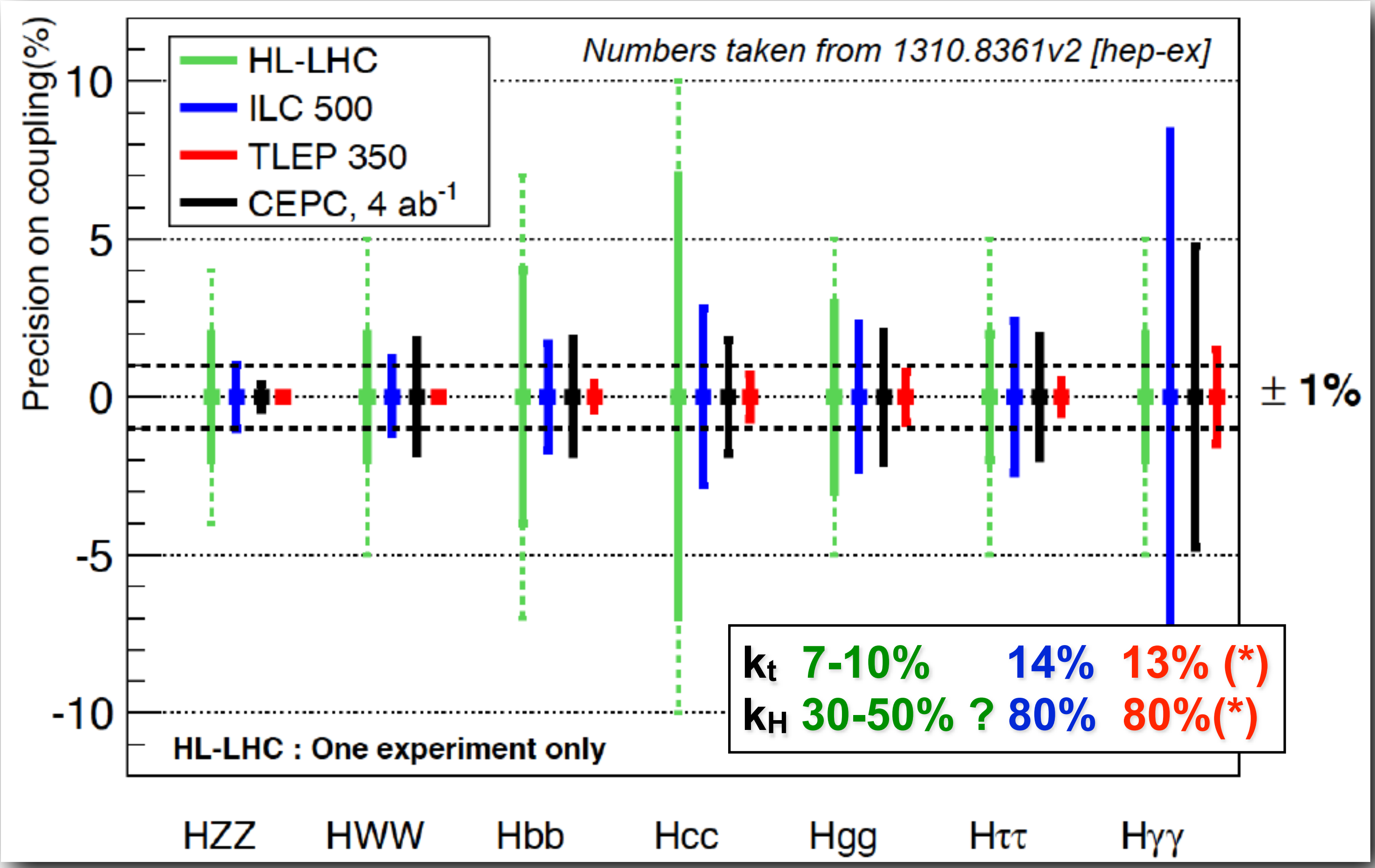


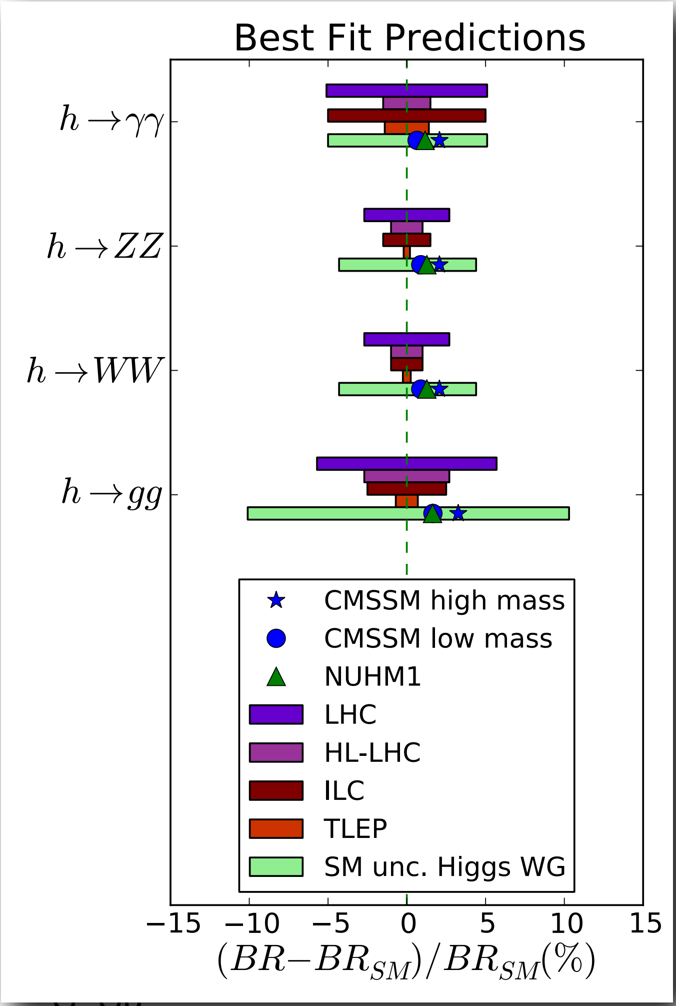
HL-LHC(3 ab^{-1}, 1 detector) with **assumption** ~ $g(HVV) \leq g(HVV)|_{SM}$, g(Hcc) ~ g(Huu)

ILC 500: 250 fb^{-1} @ 250 GeV, 500 fb^{-1} @ 500 GeV
TLEP 350: 10 ab^{-1} @ 240 GeV, 2.6 ab^{-1} @ 350 GeV
CEPC, 4 ab^{-1} @ 250 GeV

S. Su

Higgs Factory: New Physics

- Sensitivity to new physics



- Need FCC-ee precision to be sensitive to new physics
- Theoretical uncertainty need to be reduced.

TLEP, 1308.6176

Z Factory

Tera Z, clean environment, E_{cm} knows < 1 MeV, possible longitudinal polarization

- Z lineshape:
  high precision M_Z and Γ_Z
- Z partial width:
  N_ν to 0.001 with $Z\gamma$, sterile neutrino, rare decay
- Long. polarized beam
  A_{LR} and $\sin^2\theta_W$

- 10^5 more statistics than LEP
  reduction of statistical uncertainty of a factor of 300
- exp systematic uncertainty
- Uncertainty in theoretical interpretation

Z and top Factory

- **targeted precision**

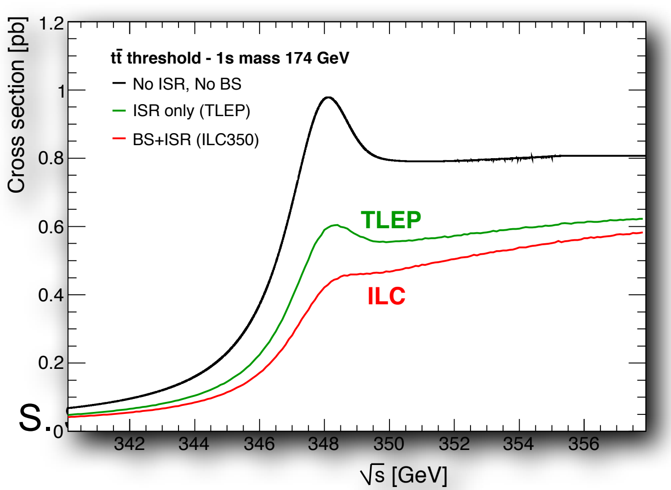
TLEP: 1308.6176

Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6) keV	< 100 keV
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{had}$)	2495200 ± 2300	Z Line shape scan	8 (10) keV	< 100 keV
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004
N_ν	... and sterile ν's	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.0010 (12)	< 0.001
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060
A_{LR}	$\Delta\rho, \epsilon_3, \Delta\alpha_{had}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015
m_W (MeV)	$\Delta\rho$, $\epsilon_3, \epsilon_2, \Delta\alpha_{had}$	80385 ± 15	WW threshold scan	0.3 (0.4)MeV	< 0.5 MeV
m_{top} (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 (12) MeV	< 10 MeV

m_Z<100 keV

$\sin^2\theta_W$<2x 10^{-6}

m_W<500 keV



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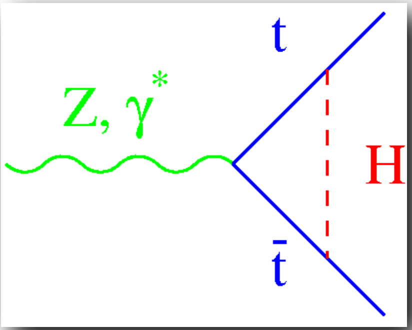
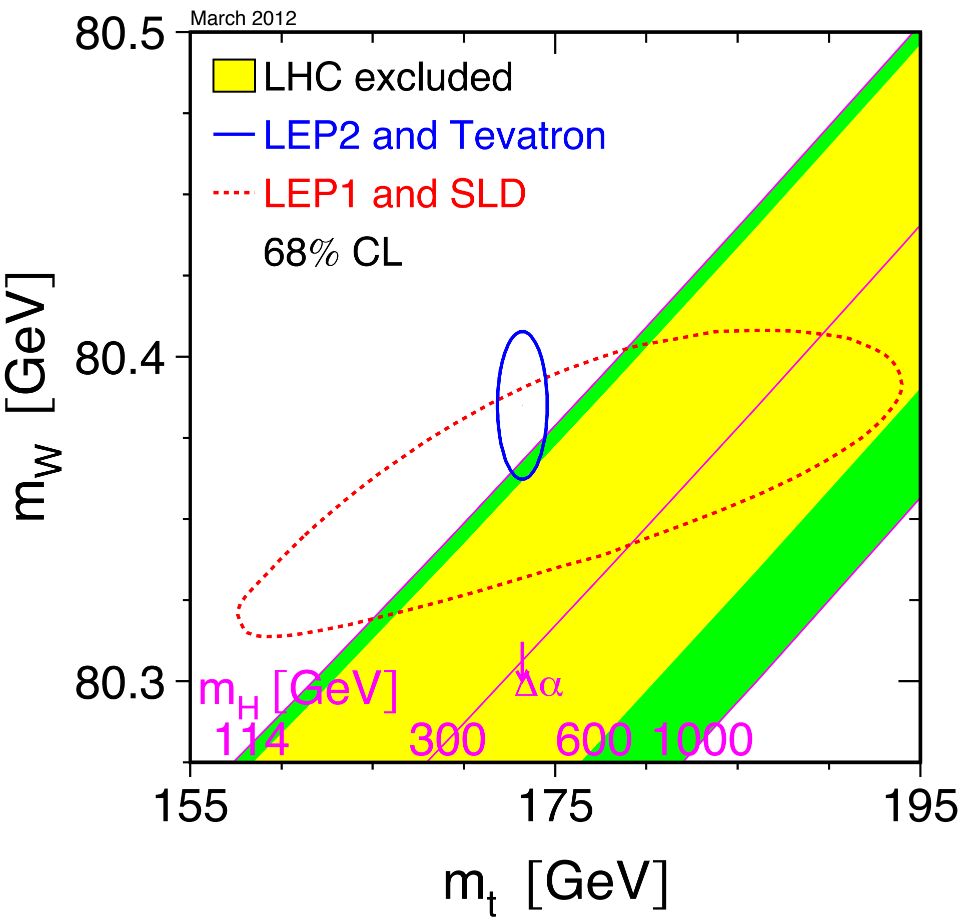


m_t < 10 MeV
Γ_t < 12 MeV
λ_t : 13%

Eletroweak Precision



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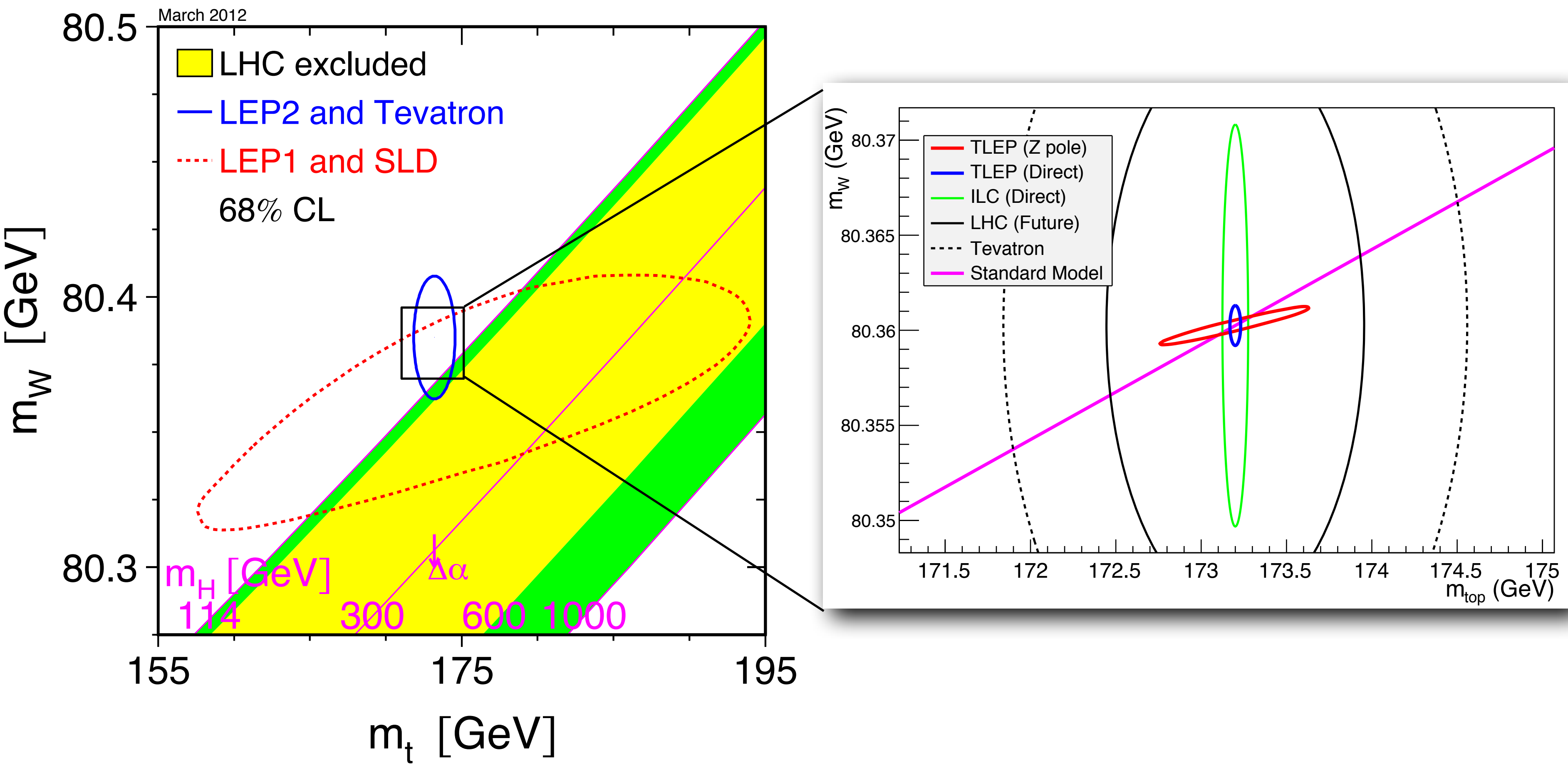
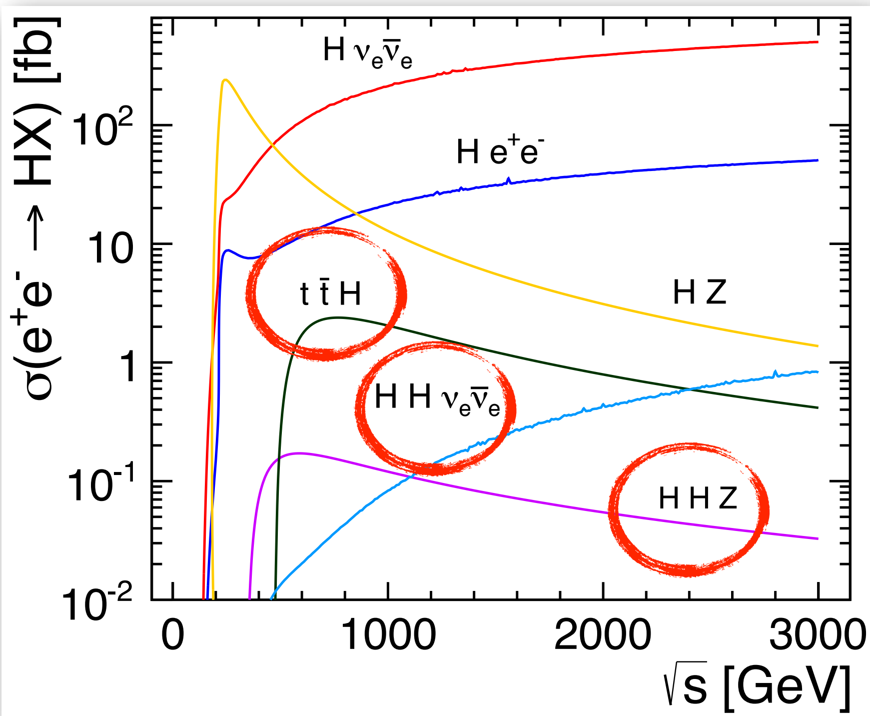


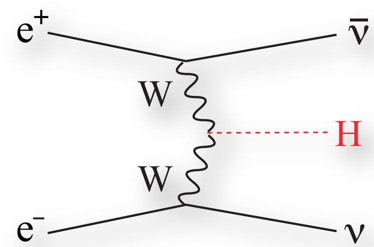
ILC 500 - 1 TeV

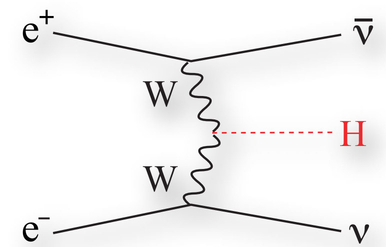
- **ILC as a discovery machine**
- **probe new particle up to Ecm/2**
- **probe challenging final states: degenerate state**
- **precise measurement of the particle mass, coupling, mixing.**

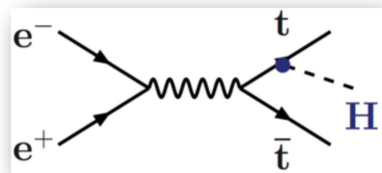
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings
	$e^+e^- \to WW$	precision W couplings
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top
	$e^+e^- \to Zhh$	Higgs self-coupling
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry

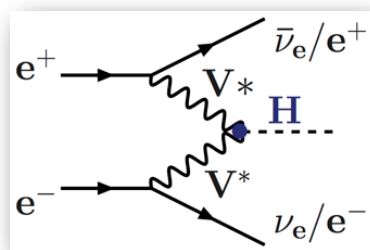
ILC/CLIC

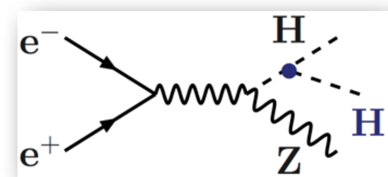

$\sigma(e^+e^- \to HX)$ [fb]
$\sqrt{s}$ [GeV]
$H\,\nu_e\bar{\nu}_e$
$H\,e^+e^-$
$t\,\bar{t}\,H$
$H\,Z$
$H\,H\,\nu_e\bar{\nu}_e$
$H\,H\,Z$
10^2
10
1
10^{-1}
10^{-2}
0
1000
2000
3000


e^+
$\bar{\nu}$
W
H
W
e^-
ν


e^+
$\bar{\nu}$
W
H
W
e^-
ν


e^-
t
H
e^+
$\bar{t}$


e^+
$\bar{\nu}_e/e^+$
$V*$
H
V^*
e^-
ν_e/e^-


e^-
H
H
e^+
Z

Physics opportunity at pp machine

80 - 100 TeV

Physics opportunity at pp machine

80 - 100 TeV

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

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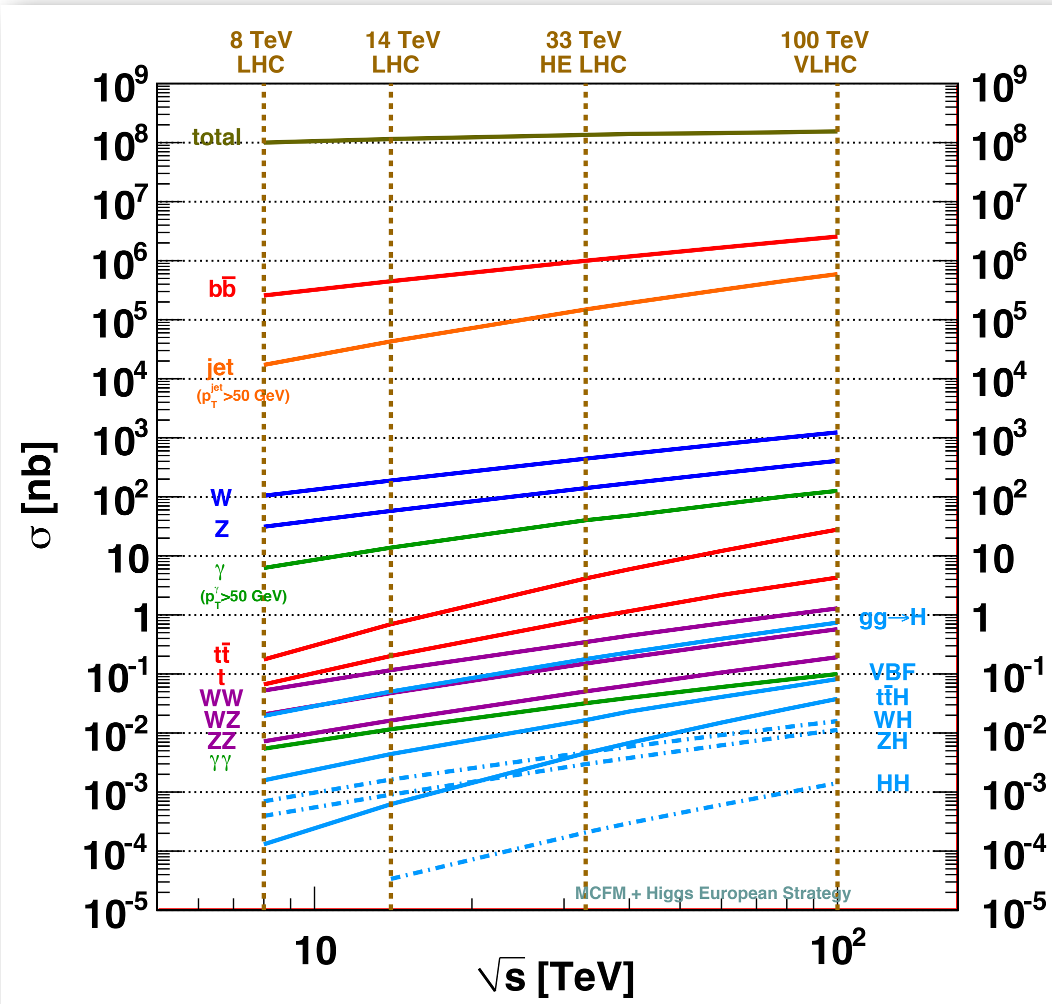
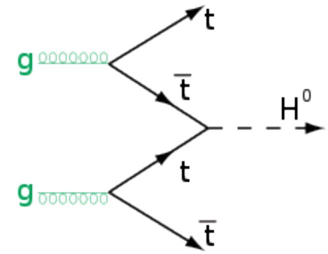
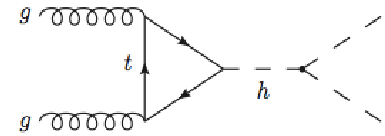
Higgs Production @ pp







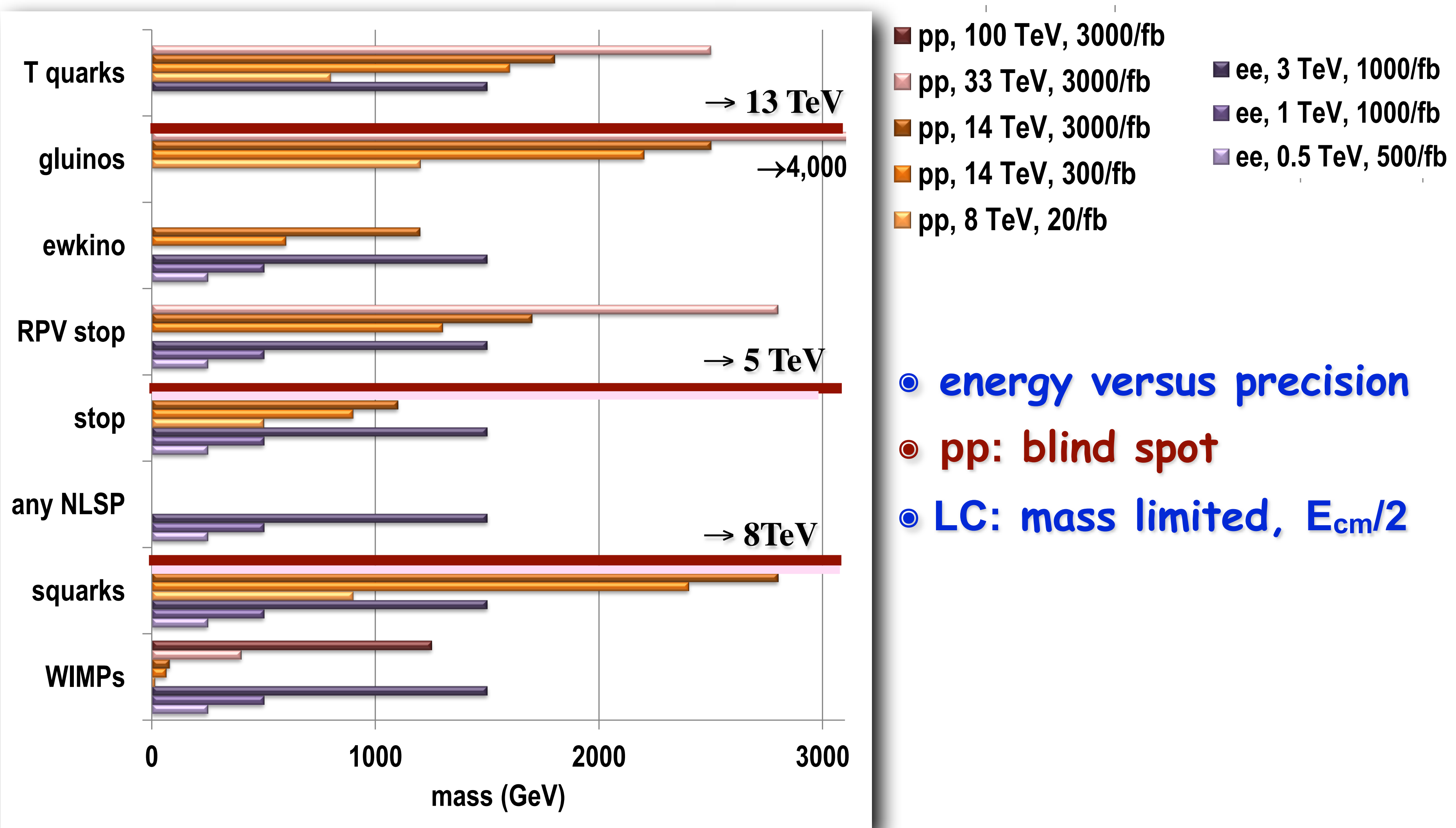
Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

λ_t : 1%

λ : 8%

Snowmass QCD Working Group: 1310.5189

BSM: Collider Reach

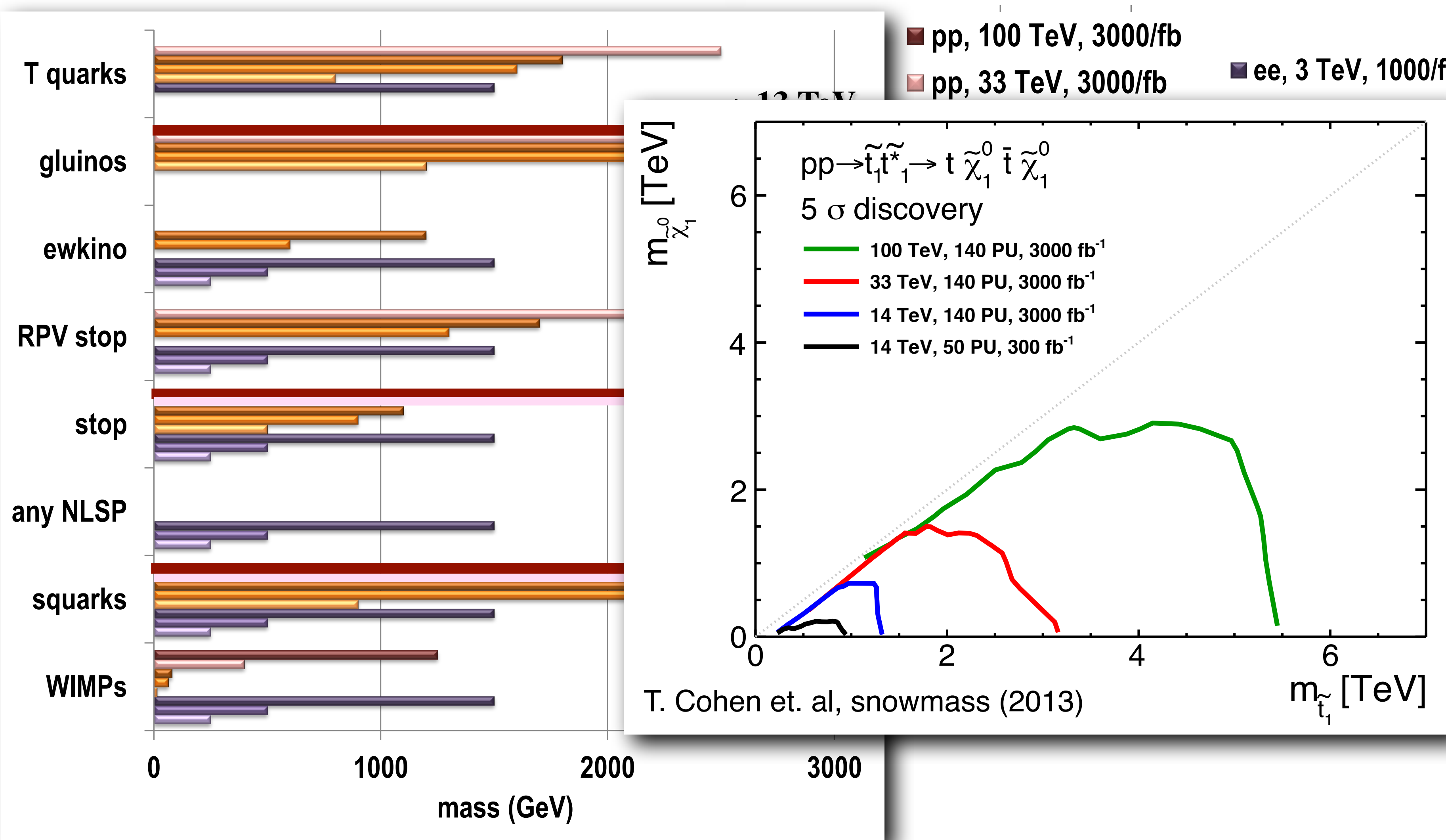


- energy versus precision
- pp: blind spot
- LC: mass limited, $E_{cm}/2$

S. Su

Snowmass new physics working group report

BSM: Collider Reach



Snowmass new physics working group report

Naturalness

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

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

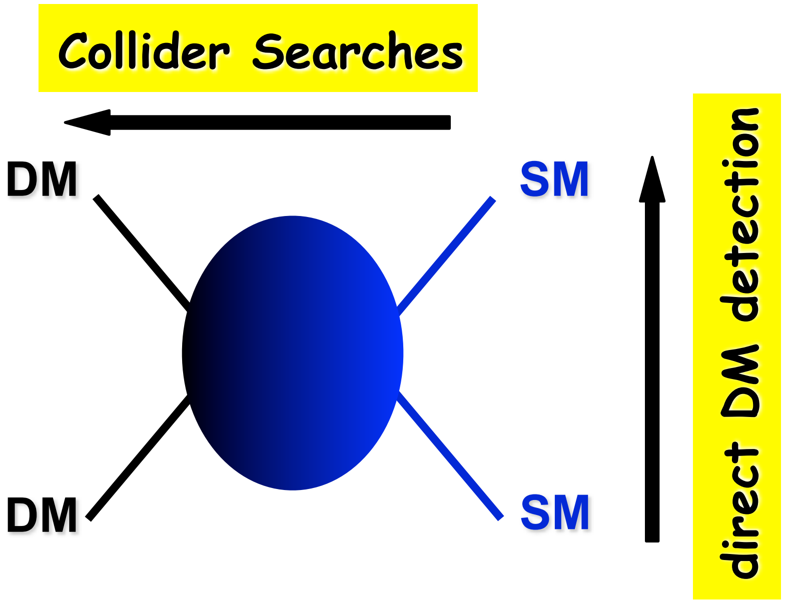
  increase the reach by 10-20%, measure top partner property
- **100 TeV VLHC:** 10 TeV level, $\varepsilon \sim 10^{-4}$
- **ILC:** $E_{cm}/2$, 1 TeV machine, ε~1%

  Precision measurements, multi TeV level

Effective operator

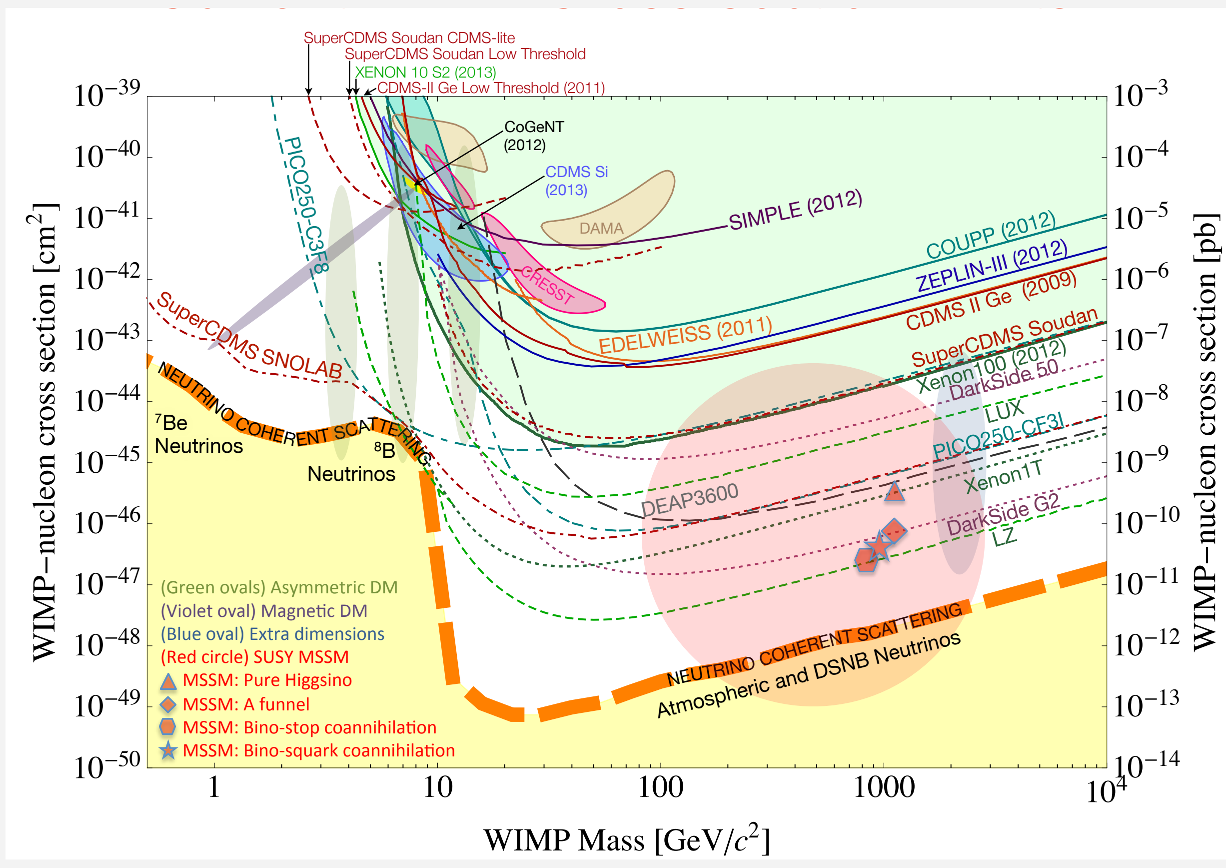
- relax relic density requirement
- study effective operators that couples DM to SM quarks/gluons
- same operator also contribute to DM direct detection: complementary

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



Direct detection versus collider reach

LUX collaboration, 2013



Direct detection versus collider reach

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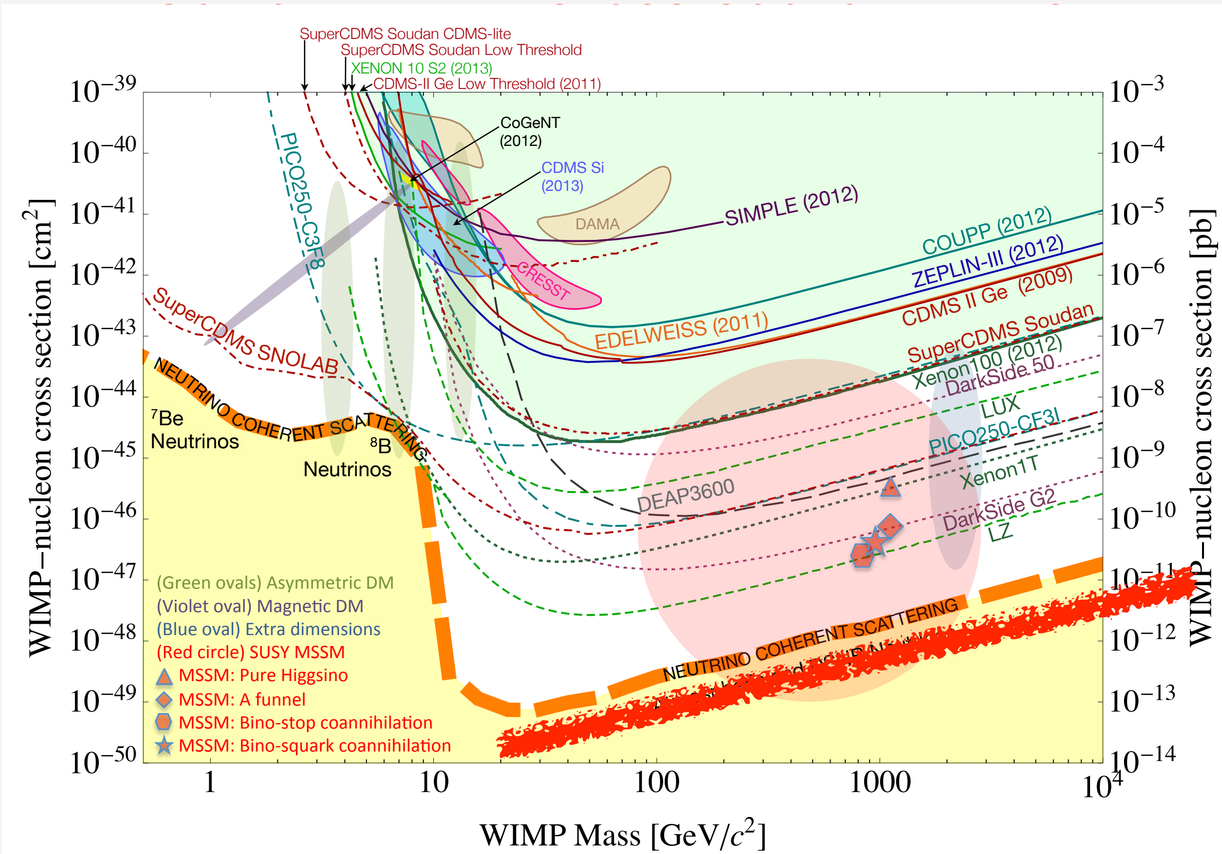

Direct detection versus collider reach

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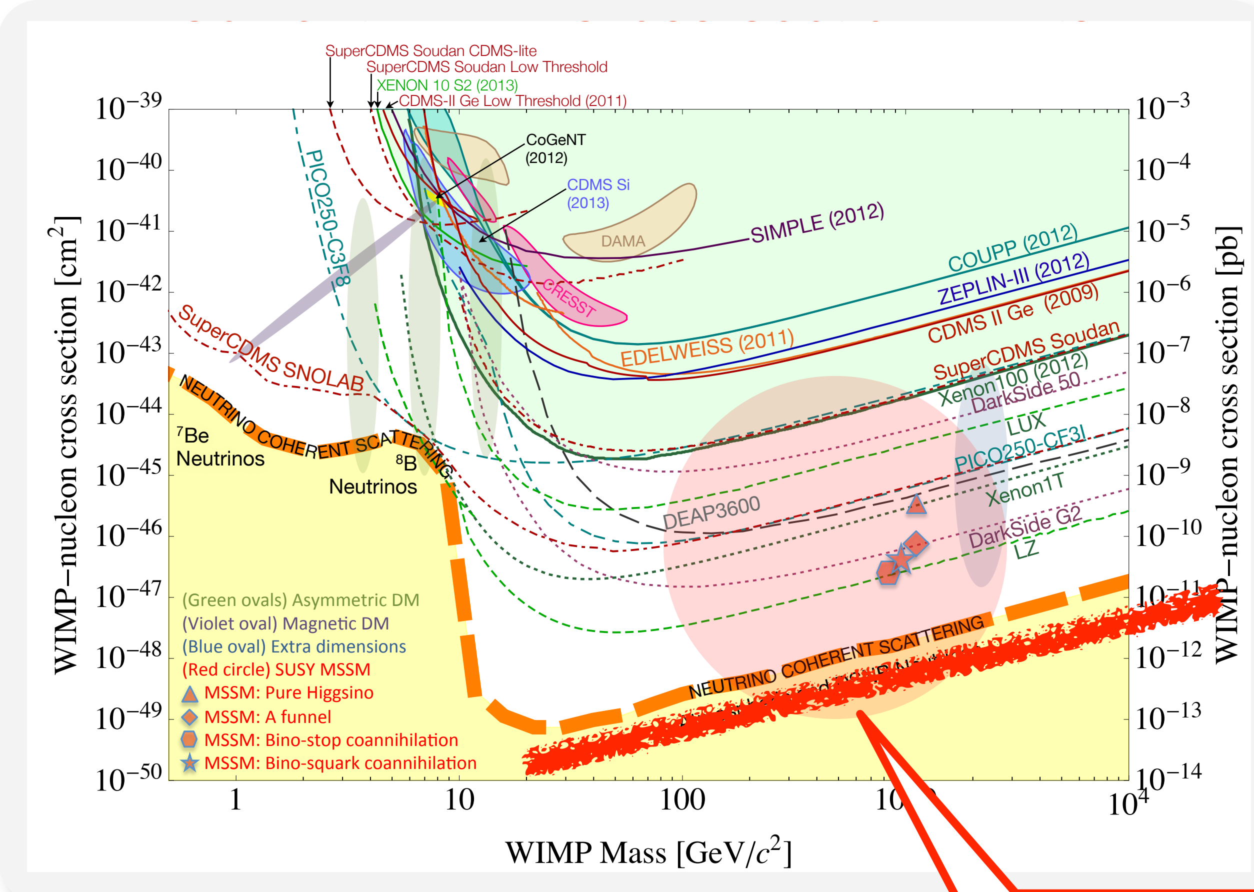

O(100) GeV DM, typical DM range

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Direct detection versus collider reach

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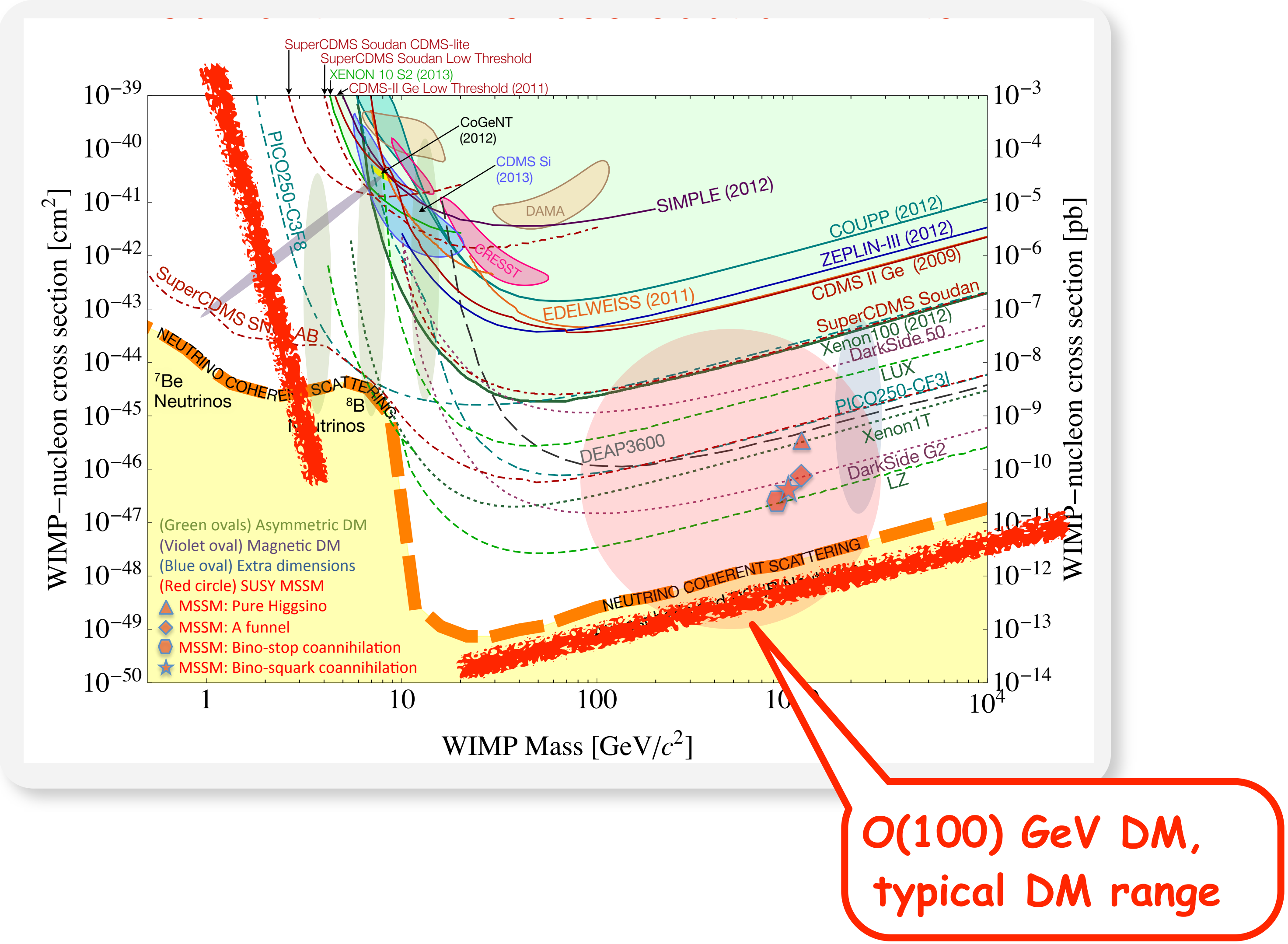

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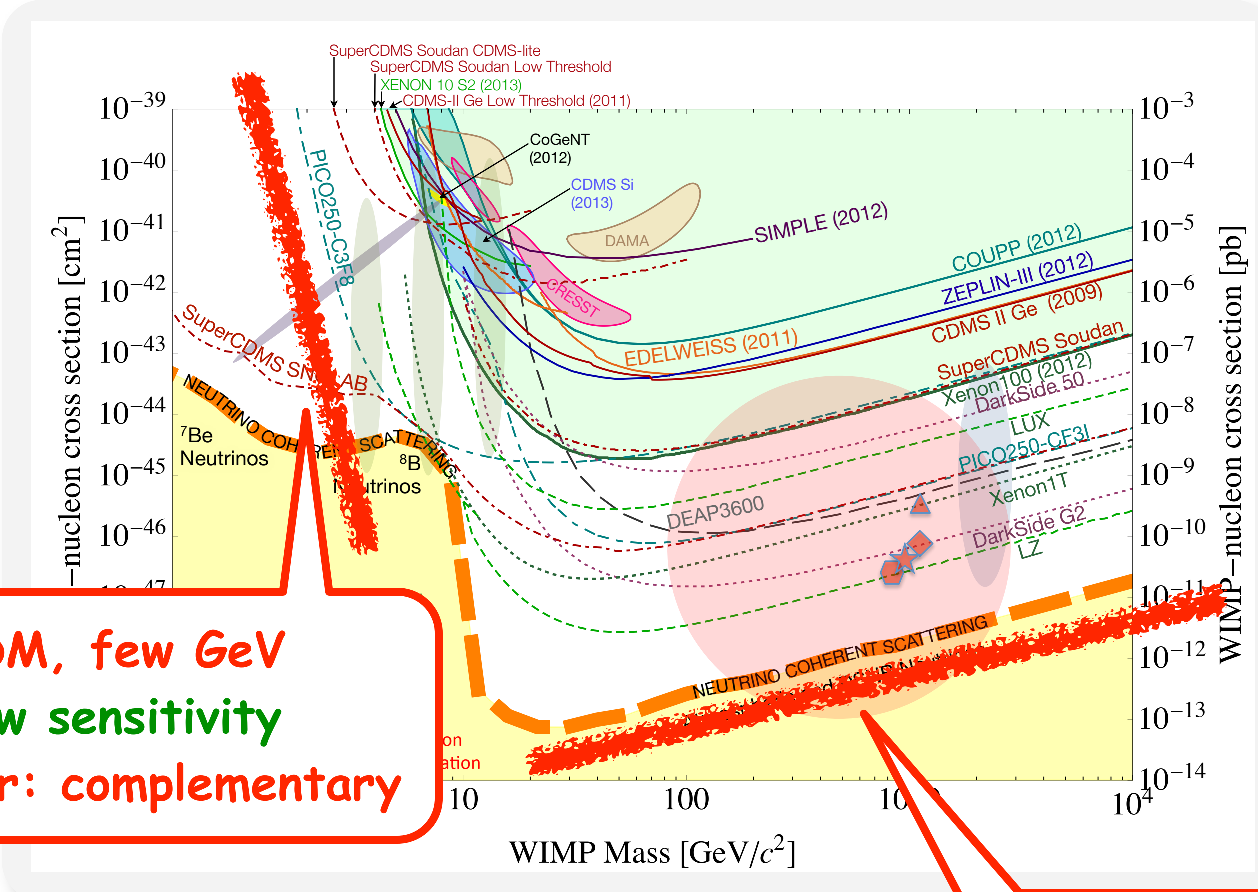

light DM, few GeV
DD: low sensitivity
Collider: complementary

O(100) GeV DM,
typical DM range

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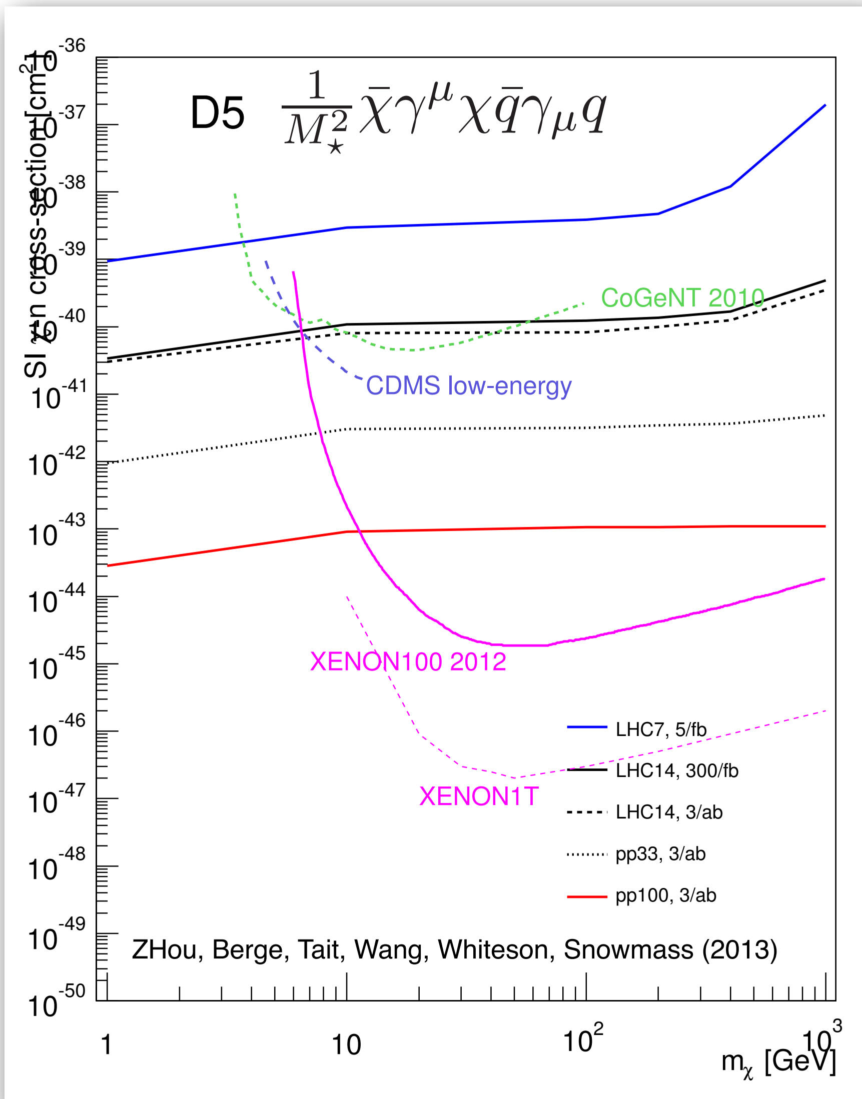
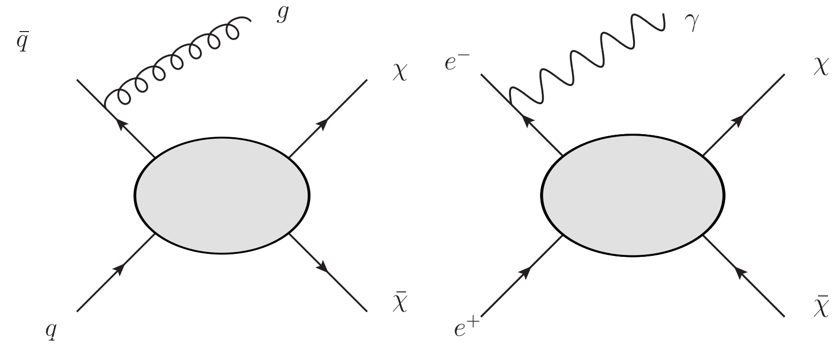
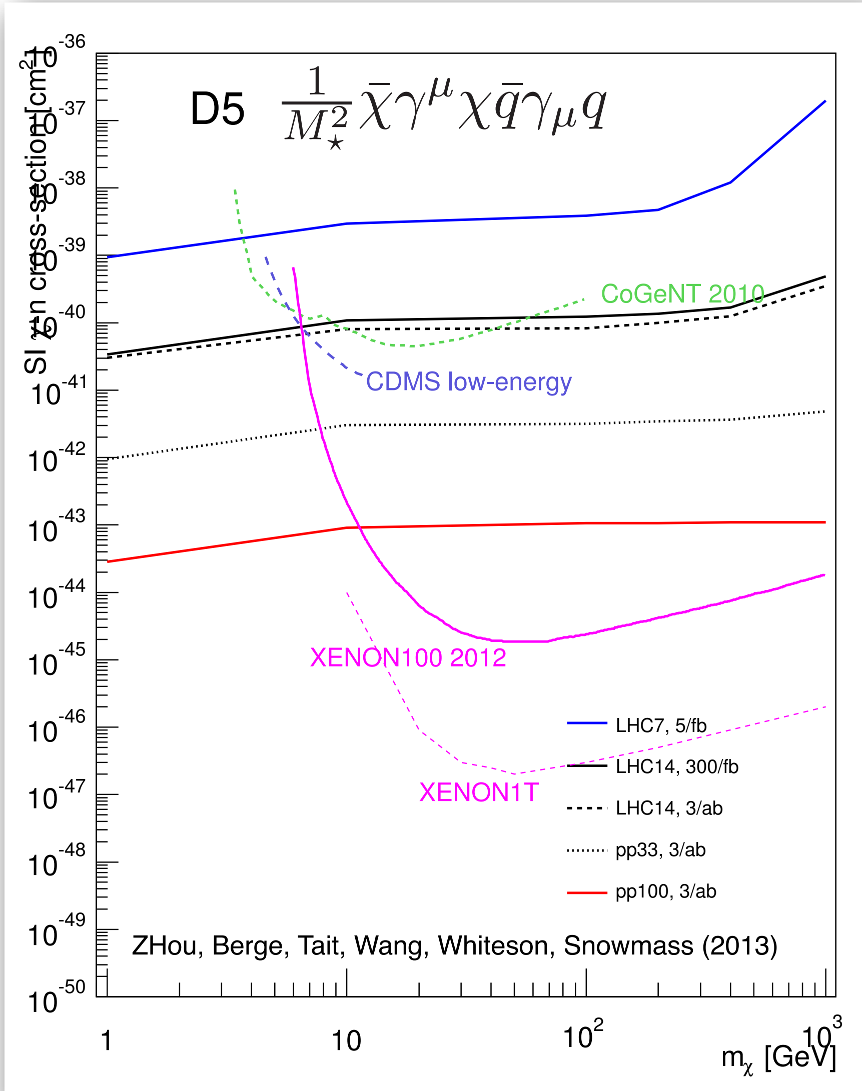
DM: Collider vs. Direct Direction

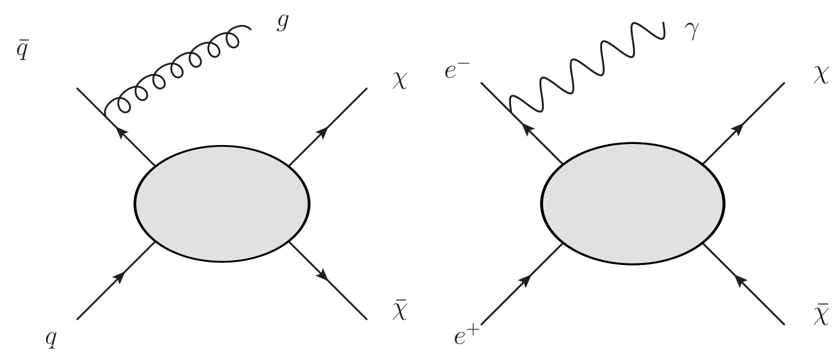




monojet, monophoton, monoZ, mono-b,...

DM: Collider vs. Direct Direction



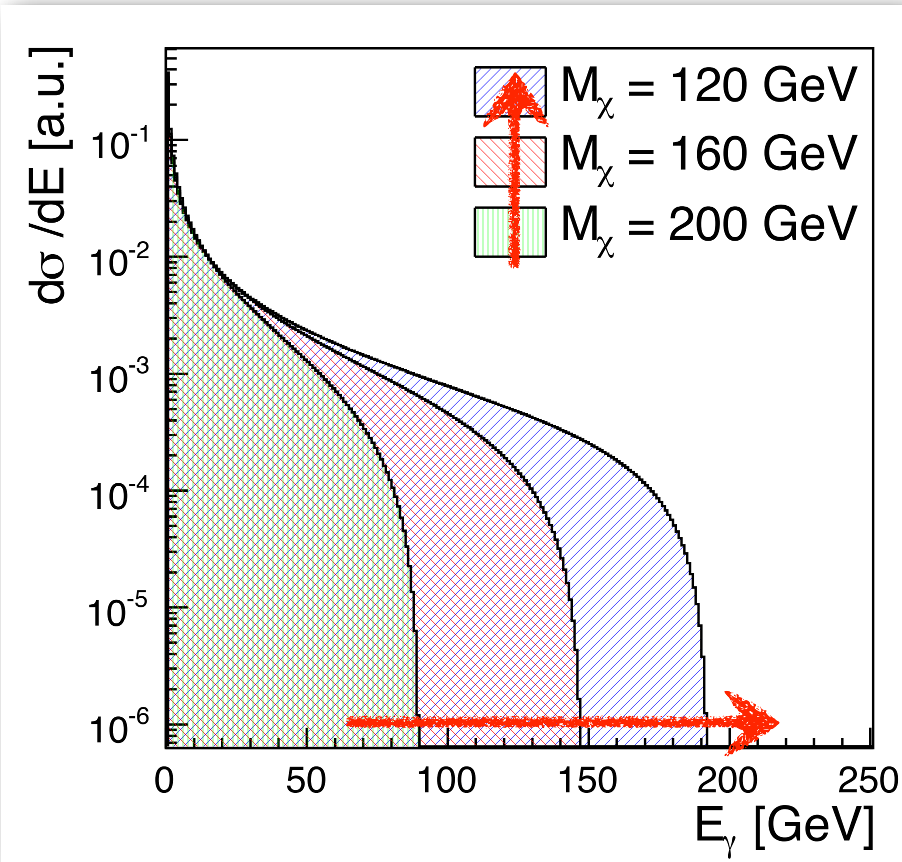


monojet, monophoton, monoZ, mono-b,...

Collider better:
small m_χ region, spin-dependent

DM: ILC

Bartels, Berggren, List, (2012)



ILC:

- beam polarization

  signal vs. BG

- WIMP mass

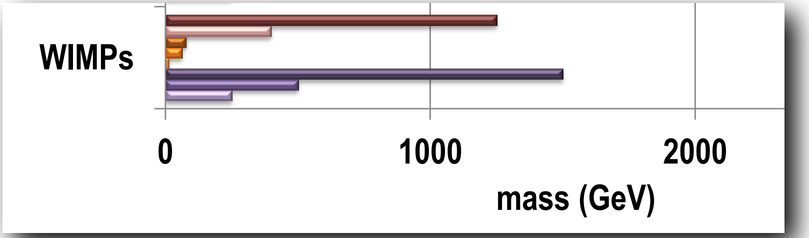
  photon energy

- photon spectrum, CS@ different polarization

  helicity structure of WIMP interaction, partial wave

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 at VLHC 33 or 100 TeV
- Smaller dark matter mass
  - ➡ low mass loopholes of suppressed coupling or compressed spectrum, small MET
  - ➡ e+e- collider, reach $E_{cm}/2$.

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
- HL-LHC: probe Higgs precision few% (factor of 2 increase), search for new physics limited (20% increase)
- e+e- machine: tera-Z, Oku-W, Mega-H, Mega-t factory, ILC 1 TeV discovery machine
- pp machine: probe energy frontier
- FCC-ee/hh, CEPC/SPPC, ILC/CLIC...

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An exciting journey ahead of us!

Conclusion

LHC

HL-LHC

VLHC

Lepton Collider

An exciting journey ahead of us!