Physics on Particle Accelerators: What's Next?

Zhiqing Zhang

- Introduction
- Brief summary of the LHC Run-1 results
- Expectation for LHC runs (13/14TeV, 300fb^{-1})
- Projection for HL-LHC (3000fb^{-1})
- Future colliders
  - ILC/CLIC
  - CHEP, FCC-ee (TLEP)
  - SppC, FCC-hh
- Summary

Past
Current
Near-
Medium-
Far-future

A Brief Historical Account

Precision measurements

Late 70's, precision measurements of neutral currents
→ Prediction of W & Z bosons

90's precise measurement of W & Z properties at LEP
→ Prediction of top mass

Precise measurement of top & W masses at Tevatron
→ Constrained Higgs mass

Discovery

➔ 1983: W & Z discovery at SppS

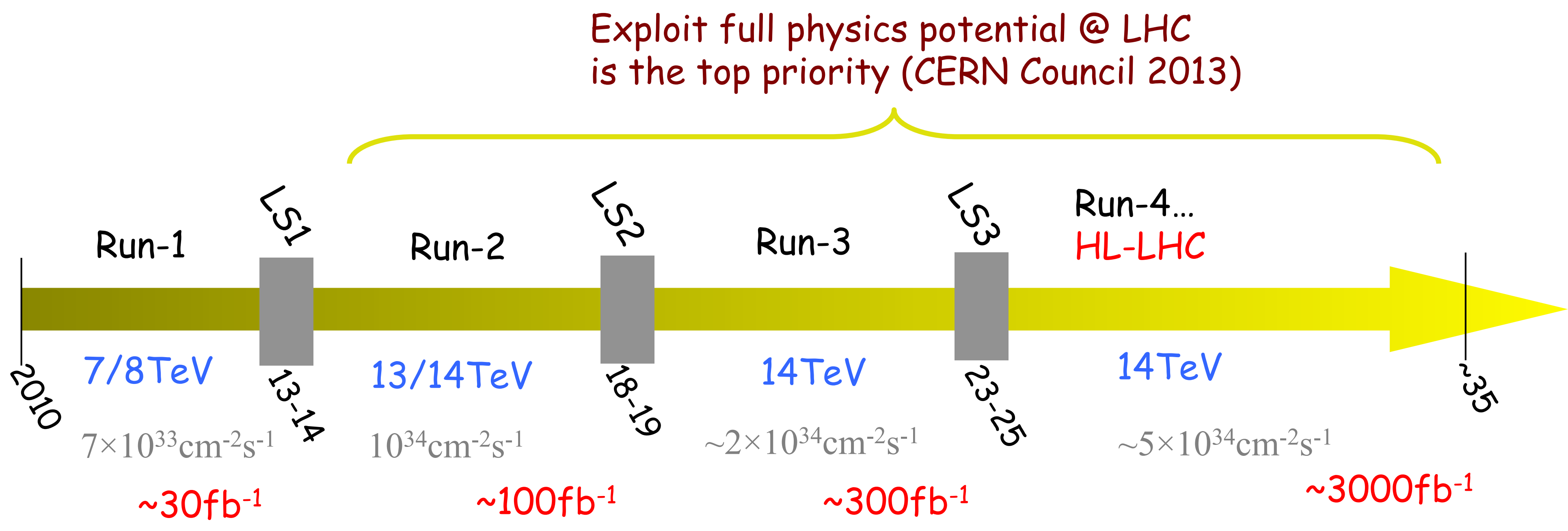
➔ 1995: top discovery at Tevatron

➔ 2012: Higgs discovery at LHC

➔ Strong interplay between precision and discovery:
Precision provides guidance for discovery
Discovery enables more observables for precision measurements

➔ Colliders played irreplaceable role in establishing the SM

LHC Runs & Current Schedule



➔ LHC will run for about 20 years!

LS1: Long Shutdown 1 ongoing for increasing √s up to 14TeV

LS2: LHC injector upgrades; phase-1 detector upgrade

LS3: Major intervention on more than 1.2km for HL-LHC (High Luminosity LHC); phase-2 detector upgrade

Main Results from LHC Run-1

- Consolidated the SM with detailed studies at $\sqrt{s}$ = 7-8 TeV, which complement wealth of measurements at lower energy by previous/present machines
  → The SM works beautifully, no deviation seen

- Completed the SM with the Higgs boson discovery
  → Yet to be verified with higher precision

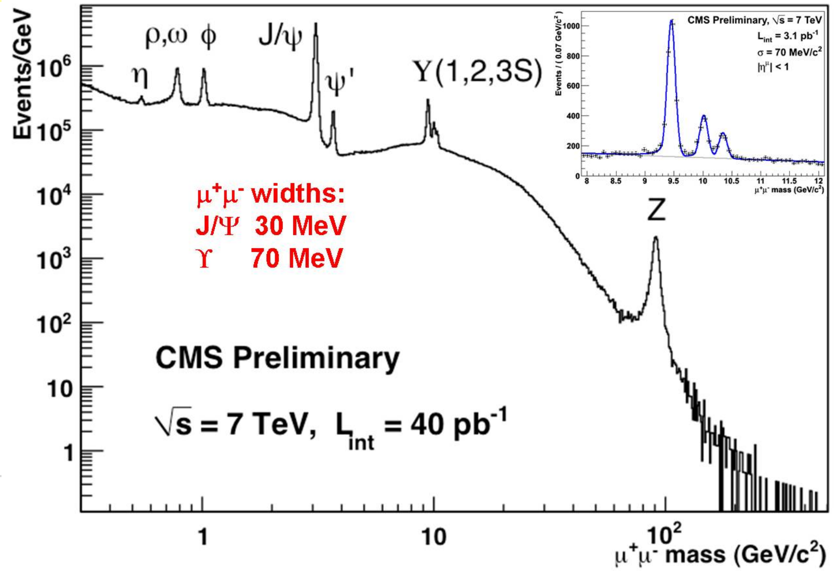
- Found no evidence of new physics (yet) but already helped in excluding some BSM scenarios & motivating others
  → need $\sqrt{s}$=13/14 TeV and high luminosity run (HL-LHC)

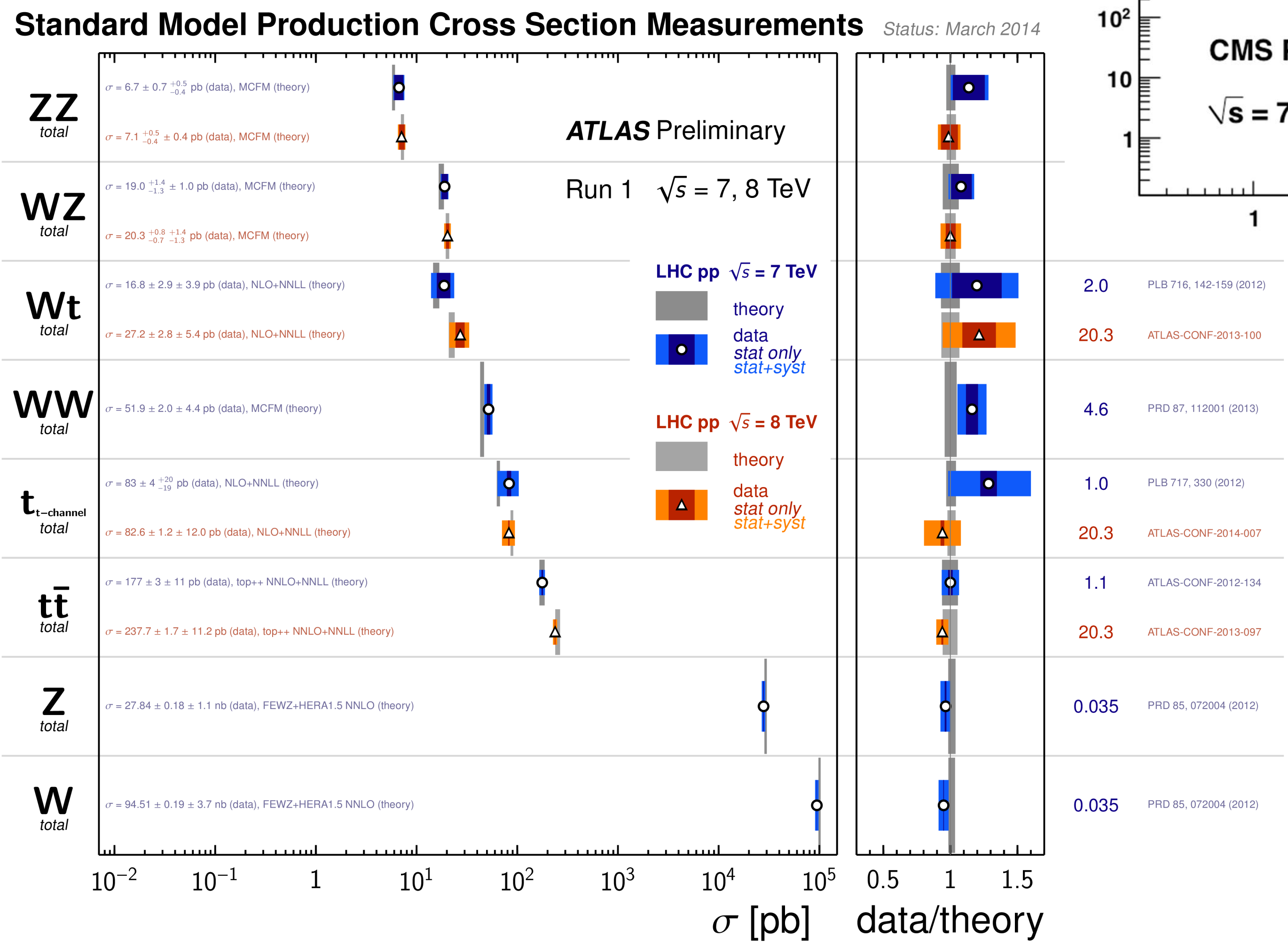
LHC had an extremely successful and fruitful start!

Extremely broad physics program outperforms expectations due to innovative analysis techniques and advances in theory

Some of the SM Results

LHC rediscovered SM particles
with a tiny early LHC data set





Need precision SM data to
- Find deviations
- Provide reliable SM background estimate for BSM searches

Combined Tevatron & LHC m_t Measurements

The 1st Tevatron and LHC combination!

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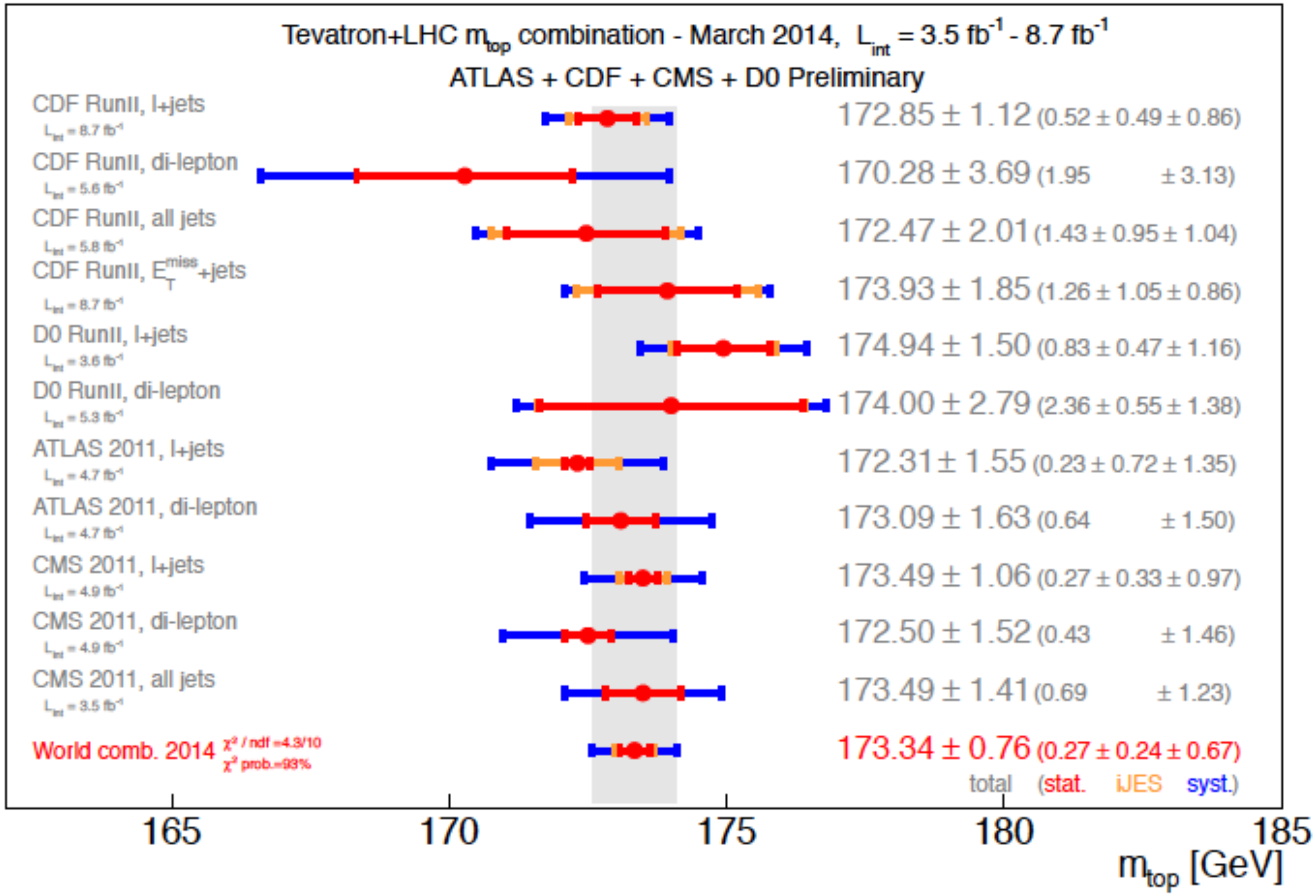


Tevatron: 300,000 top events

LHC (7TeV only): 18 millions

$\delta m_t \sim 0.4\%$

Current Knowledge on the Higgs Boson

Not yet the final Run-1 results

Mass: $\gamma\gamma$,ZZ(4l)

$$m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{syst})\ \text{GeV}$$ ATLAS: PLB726 (2013) 88

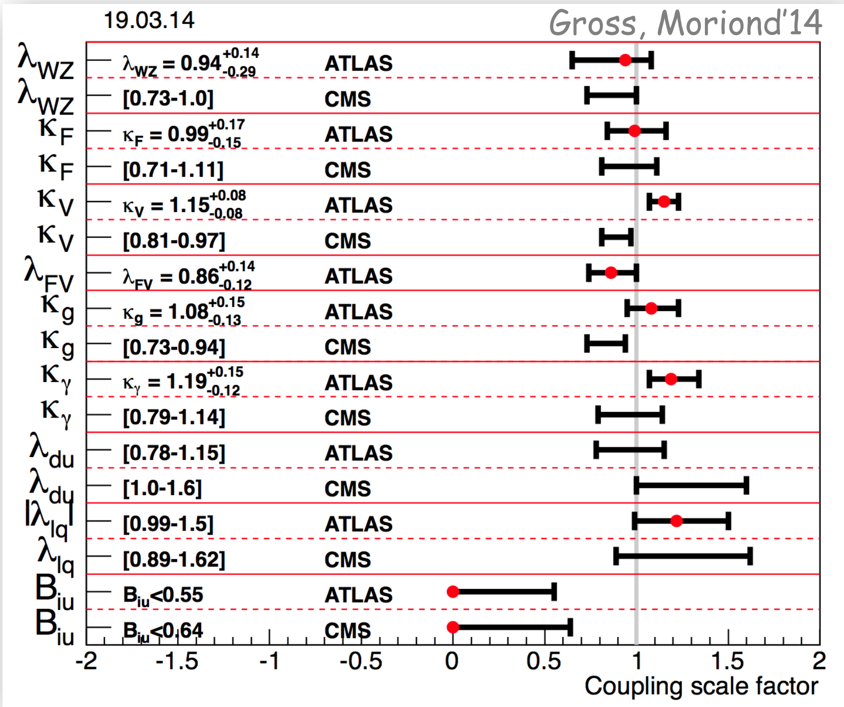
$$m_H = 125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{syst})\ \text{GeV}$$ CMS: CMS-PAS-HIG-13-005

Currently: δm_H~0.3-0.5% per expt.
Expected final Run-1 analysis: <0.2%

Width: <17.4MeV @95%CL (CMS Moriond'14)
ZZ(4l, 2l2ν) SM: 4MeV

Couplings:

$$\kappa_x = \frac{g_x}{g_x^{\text{SM}}}, \lambda_{xy} = \frac{\kappa_x}{\kappa_y}$$



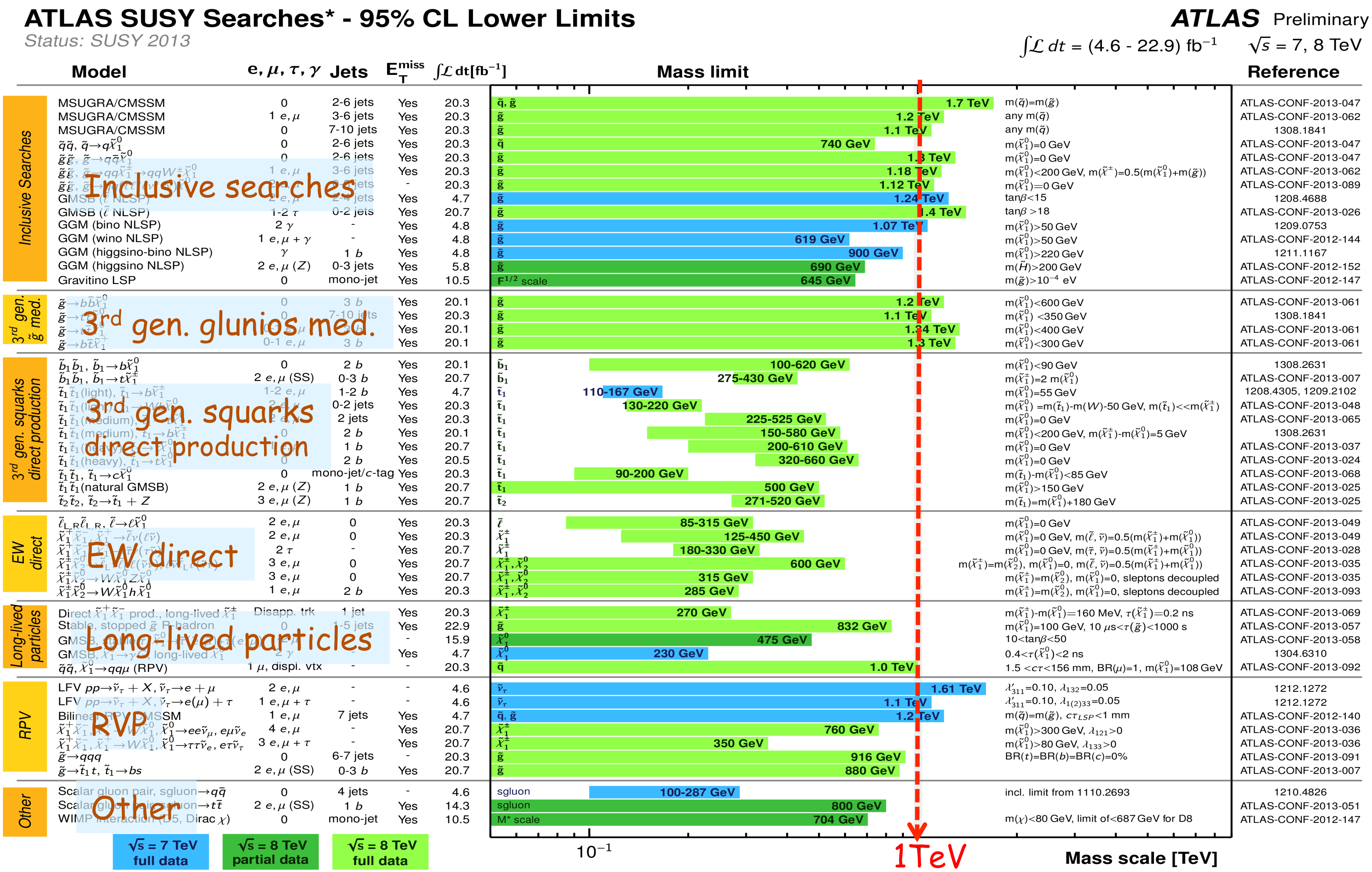
Spin-Parity: ZZ(4l), WW(lνlν), γγ

Data favors 0+
Spin-1, 0- excluded at >99%
Spin-2^+_m excluded at >95%

➔Dominant production and decay modes consistent with SM with a precision of ~20%

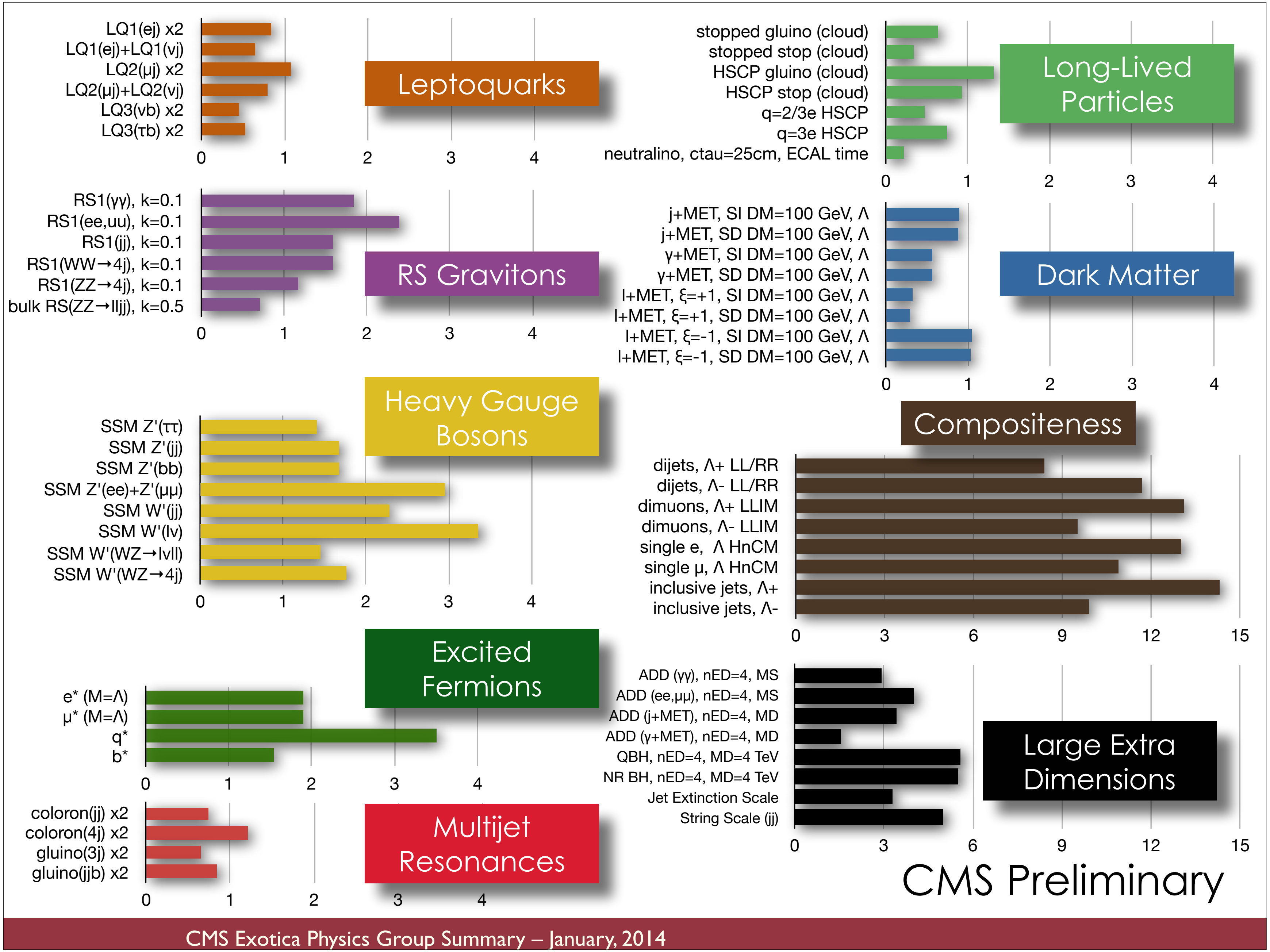
No sign of BSM Higgs so far based on
- Direct searches for extended Higgs sector
- Indirect BSM interpretations

Summary of ATLAS SUSY Searches

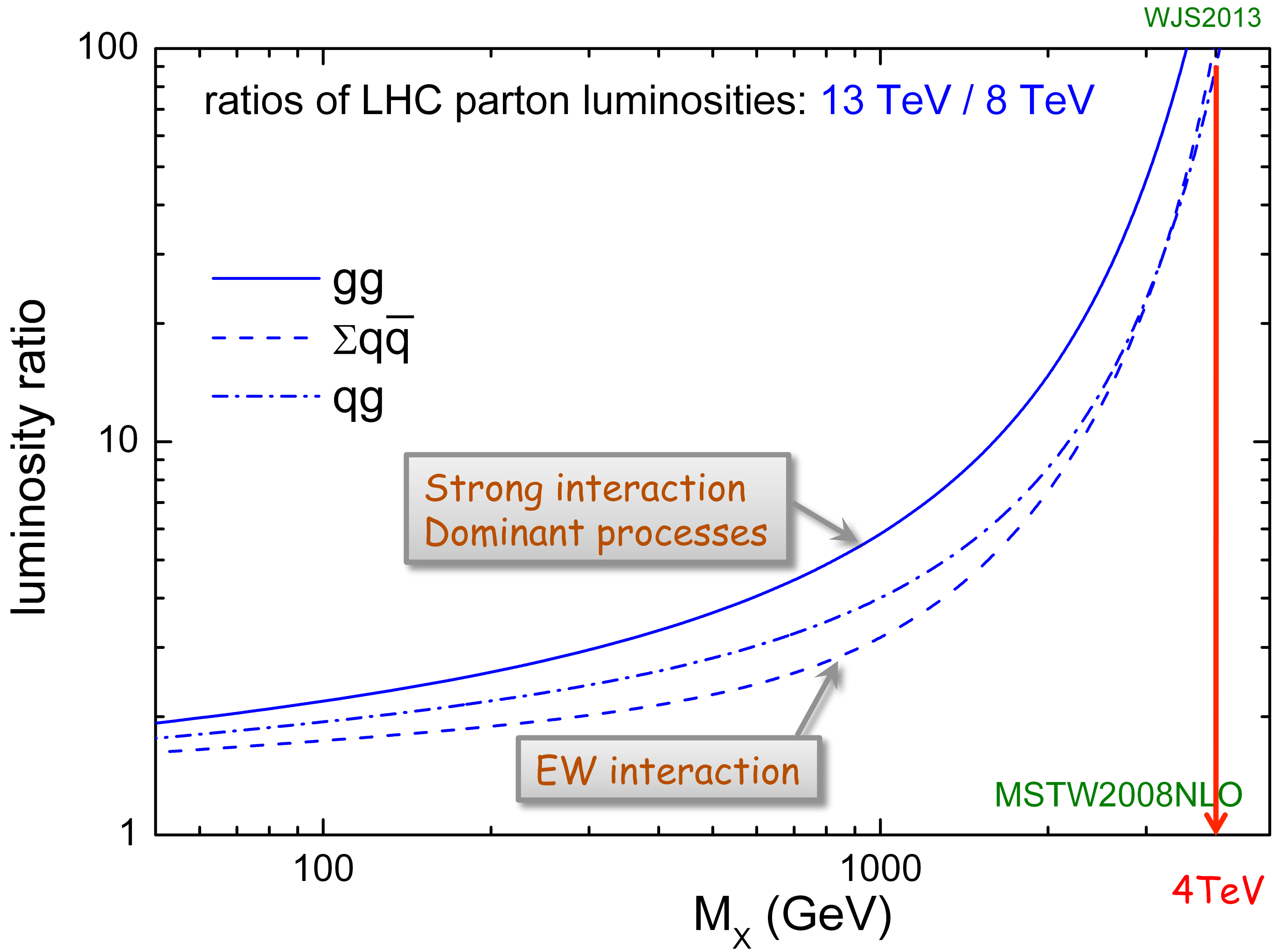


*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Summary of CMS Exotic Searches



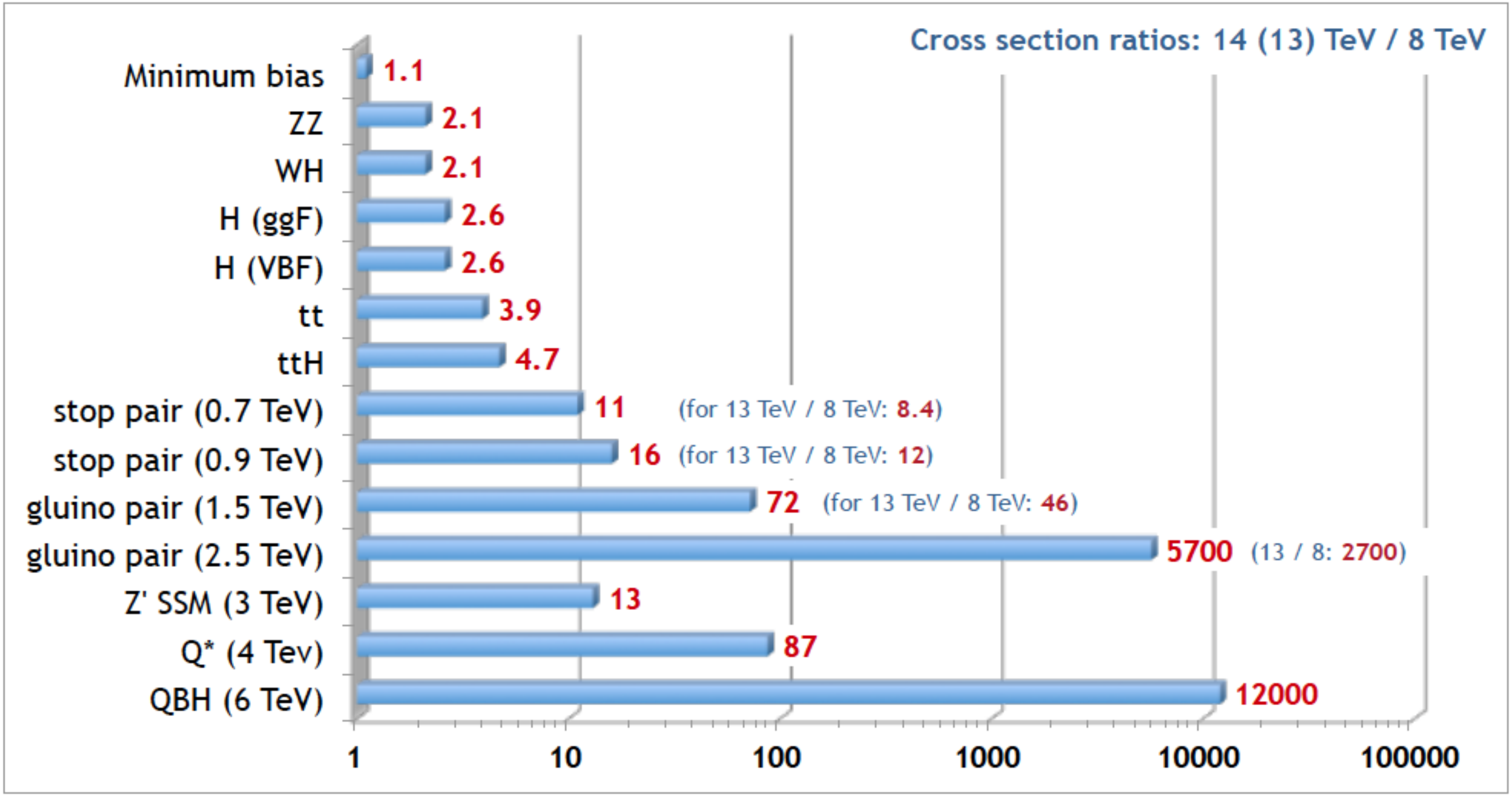
From 7/8TeV to 13/14TeV



Cross Section Ratios

for selected processes

Hugely increased potential for discovery of heavy particles at 13~14 TeV



Major Tasks at 13/14TeV & HL-LHC

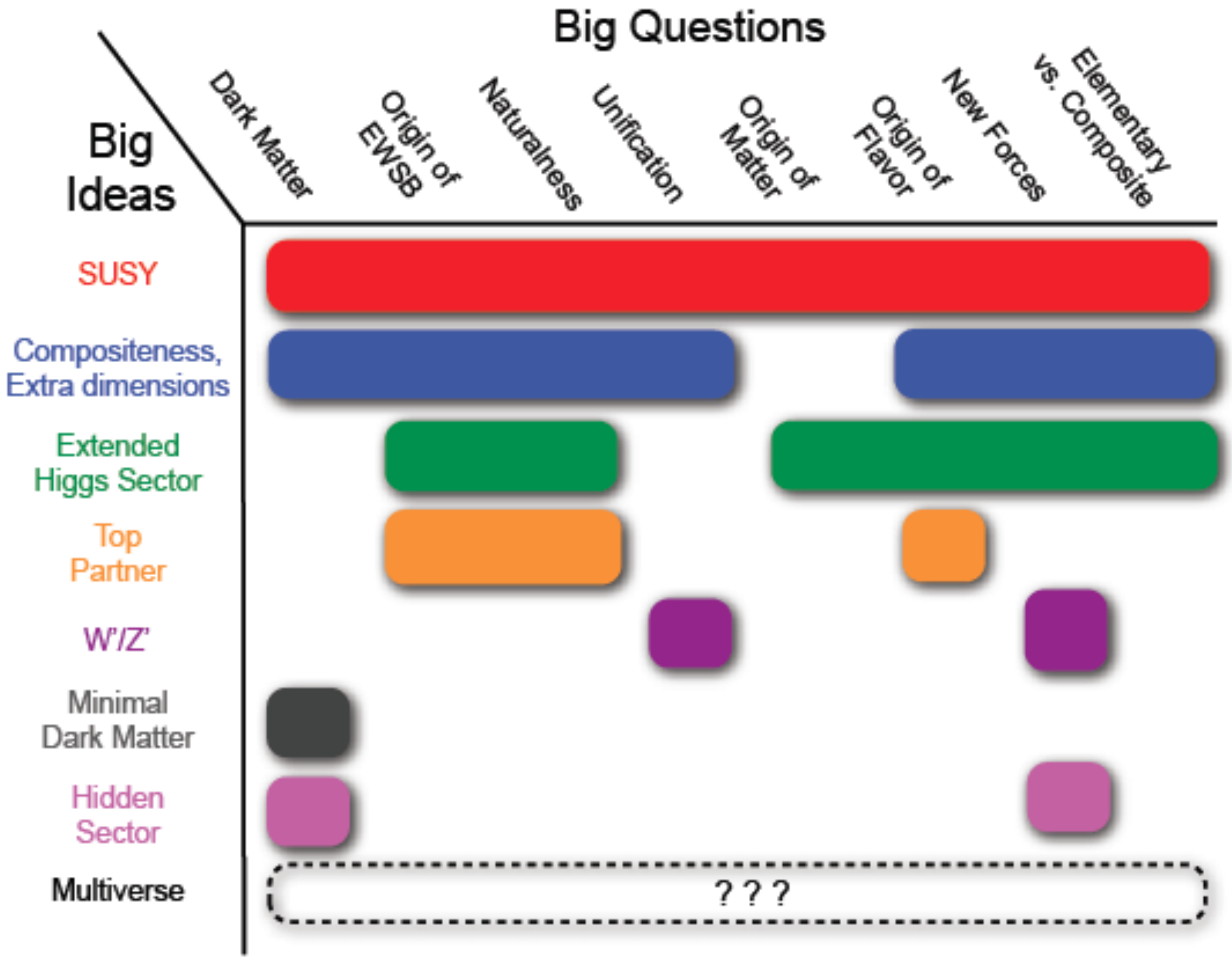
- ❑ Study in great detail the Higgs boson
- ❑ Continue searches for new particles at TeV mass scale
- ❑ Continue SM precision measurements

To address (some of) the "big" questions:

- ◆ Is the Higgs boson solely responsible for EWSB?
- ◆ Is there new physics and what's its energy scale?
- ◆ Are fundamental parameters finely tuned?
- ◆ Are "elementary" particles composite?
- ◆ Are there new fundamental forces in nature?
- ◆ What's the non-baryonic dark matter (DM)?
- ◆ What's the origin of the matter-antimatter asymmetry?
- ◆ What's the origin of q, l and ν mass hierarchies?

Big Questions vs. Big Ideas

Snowmass 1311.0299



Expectation with 13/14TeV and $300fb^{-1}$

- Higgs:
  - Measure Higgs boson mass, spin, CP and couplings to the 10% level
  - Provide the 1st measurement of t-H coupling
- Top:
  - δm_t below 600MeV
  - Measure top quark couplings to g, Z, W and γ by a factor 2-5 better (sensitive to new physics)
- Other precision measurements:
  - δm_W ~8MeV
  - 1st measurement of VV scattering
  - Provide data for a new generation of proton PDFs, a well-defined γ PDF*
- Searches:
  - Top squarks and partners
  - ttbar resonances predicted in models of composite top, Higgs
  - Other possible TeV-mass particles with × 2 better discovery reach
  - Dark Matter (DM)

PDF: Parton Distribution Function

Projection with $3000fb^{-1}$

- **Higgs:**
  - Precision era for Higgs couplings 2-10%
  - Measure rate decays $\mu+\mu-$, $Z\gamma$ with 100M Higgs bosons
  - Provide 1st evidence of Higgs self-coupling
  - Carry out powerful searches for extended Higgs bosons

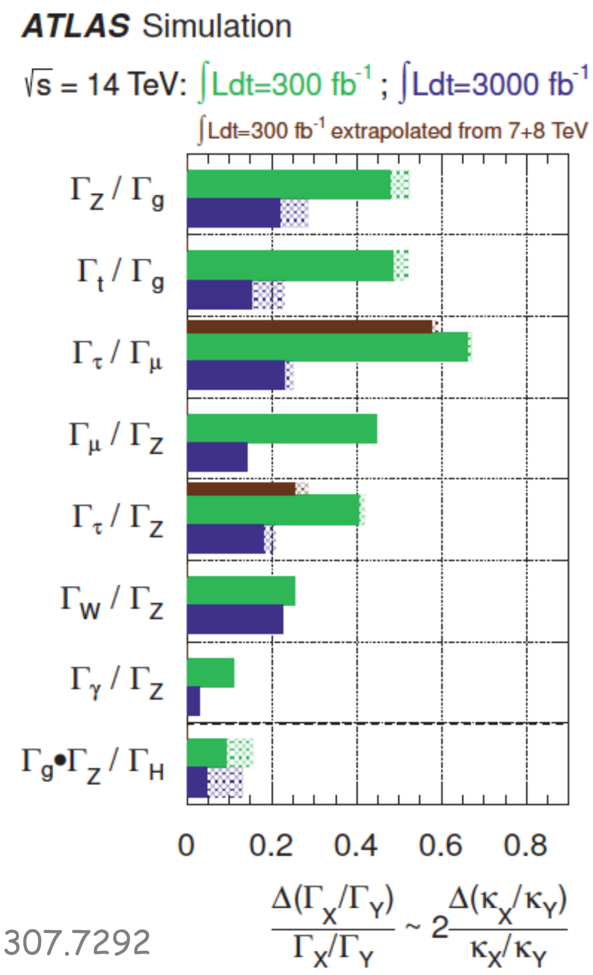
- **Top:**
  - δm_t below 500MeV
  - Intensive search for rare, flavor-changing, top quark couplings with 10B tops

- **Other precision measurements:**
  - $\delta m_W \sim$ 5MeV
  - precise measurement of VV scattering with access to Higgs sector resonances
  - Improve proton PDFs and γ PDF to higher x and Q^2

- **Searches:**
  - Top squarks and partners in extended mass range
  - 20-40% boost in discovery reach for generic new particle searches
  - Extend by × 2 the mass reach for particles produced in EW interactions

Precision Higgs Measurements

Ratio of partial decay widths



1307.7292

Snowmass Higgs report, 1310.8361

Luminosity	$300\ \text{fb}^{-1}$	$3000\ \text{fb}^{-1}$
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	$12-15\%$	$5-8\%$
	additional parameters (see text)	
$\kappa_{Z\gamma}$	$41-41\%$	$10-12\%$
κ_μ	$23-23\%$	$8-8\%$
BR_{BSM}*	$< 14-18\%$	$< 7-11\%$

Limited by theoretical systematic uncertainties,
➔ Need advance in theoretical prediction on production and decay rates

* Independent of direct search: ZH (→ invisible)

Projection for m_t at LHC

Though less well defined theoretically (pole mass vs. MSbar mass), several (complementary) methods exist (e.g. the "end-point" method):
(see 1404.1013)

CMS 1304.5783 Snowmass top report, 1311.2028

	Ref.[14]	Projections		
CM Energy	7 TeV	14 TeV		
Luminosity	$5\,fb^{-1}$	$100\,fb^{-1}$	$300\,fb^{-1}$	$3000\,fb^{-1}$
Syst. (GeV)	1.8	1.0	0.7	0.5
Stat. (GeV)	0.90	0.10	0.05	0.02
Total	**2.0**	**1.0**	**0.7**	**0.5**

Including 0.3GeV unforeseen syst

Combining different methods, a precision of 0.3-0.4GeV is feasible

However need advances in understanding the relation between the measured and fundamental quantities

The most precise known method for extracting m_t is from a threshold scan at a future lepton collider.

W Mass Measurement

An example of precision EW measurements

Snowmass report 1310.5189

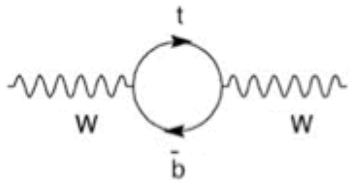
W mass is also special

- the measured value remains 1-2σ higher than the SM prediction
- δm_W currently limiting factor in the EW precision tests

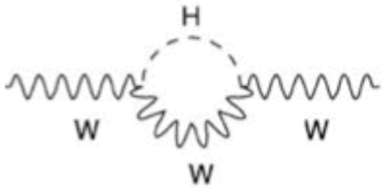
To match δm_t~0.9GeV
➔ δm_W~6MeV

ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}[\text{fb}^{-1}]$	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

PDF is the dominant syst uncertainty

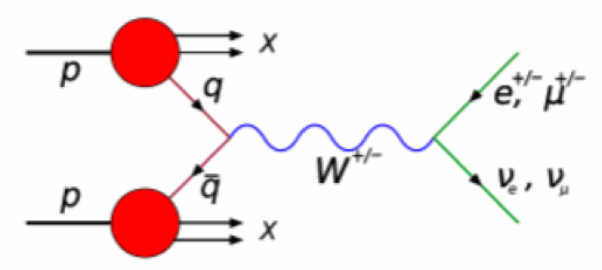


~m_t^2



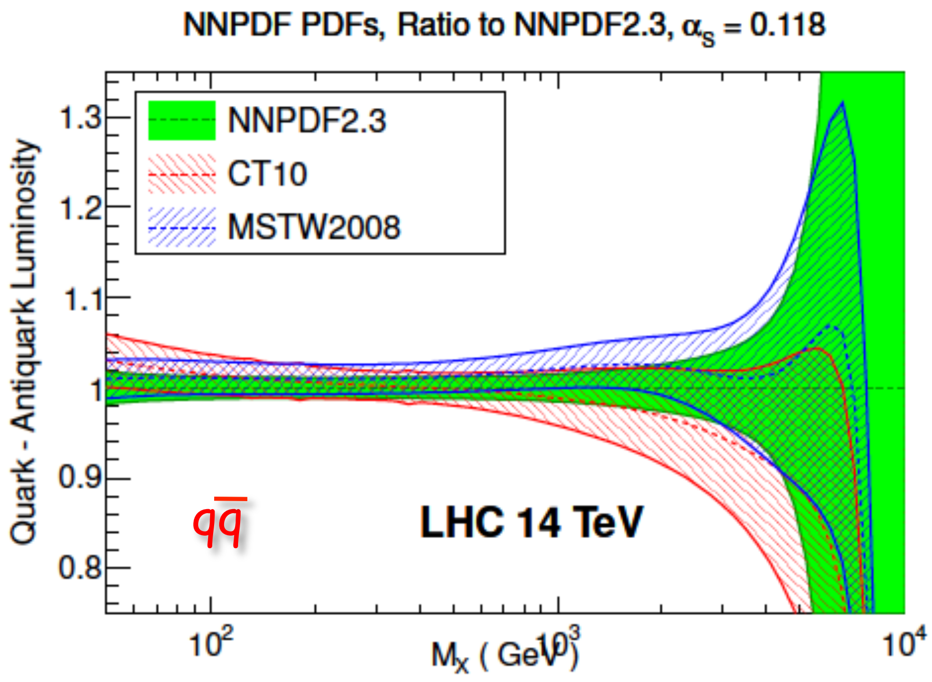
~$\log(m_H)$

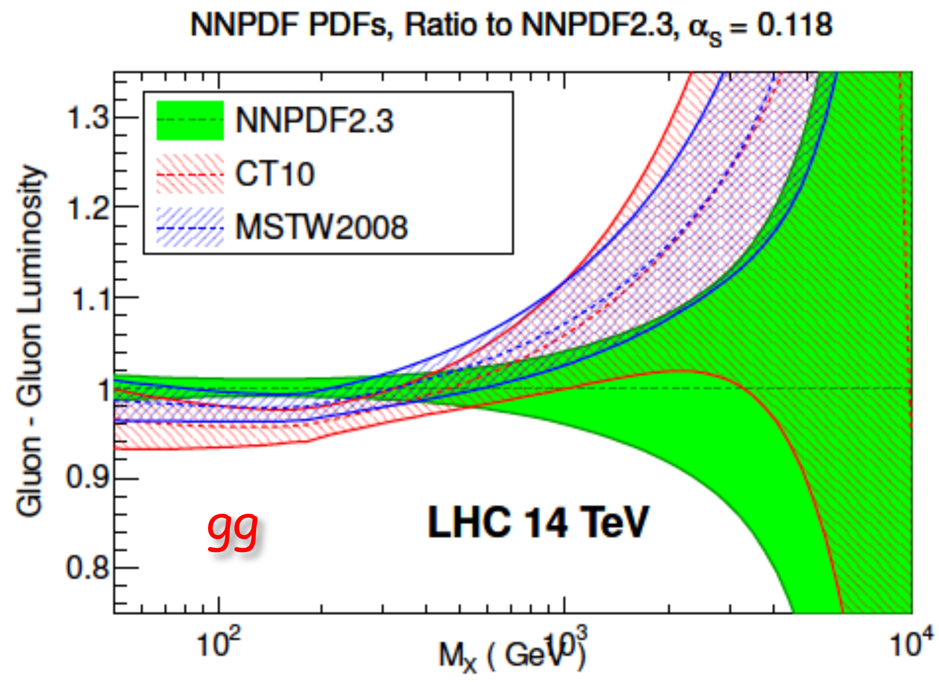
+BSM?



Our Current Knowledge on PDFs

Snowmass report 1310.5189





The PDF uncertainty:

- not only the dominant uncertainty for the W mass measurement
- but also accounts for ~8% systematic error on the Higgs cross section
- at high mass scale (high x) the uncertainty gets even larger

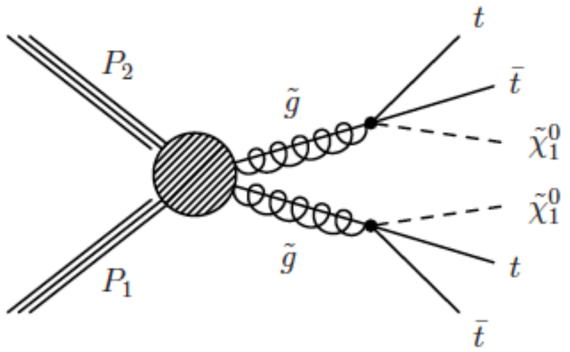
LHC do/will provide measurements for improving PDFs

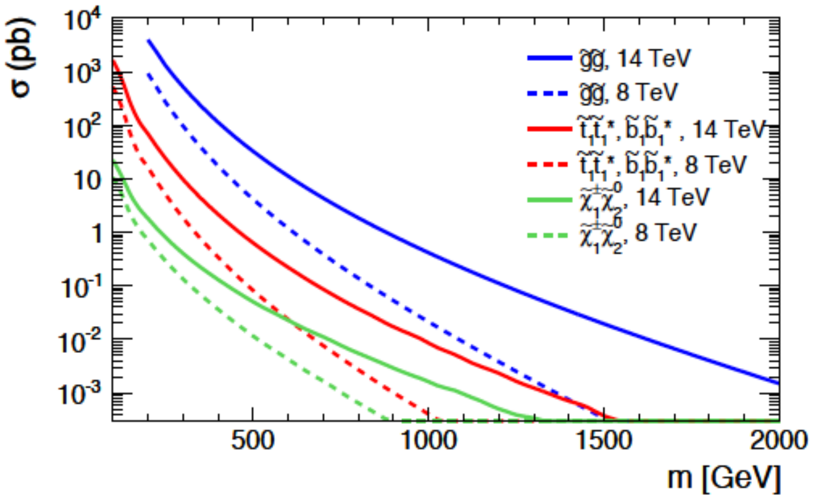
ep collider LHeC/FCC-eh would be ideal as demonstrated by HERA

An Example with Glunio Pair Production

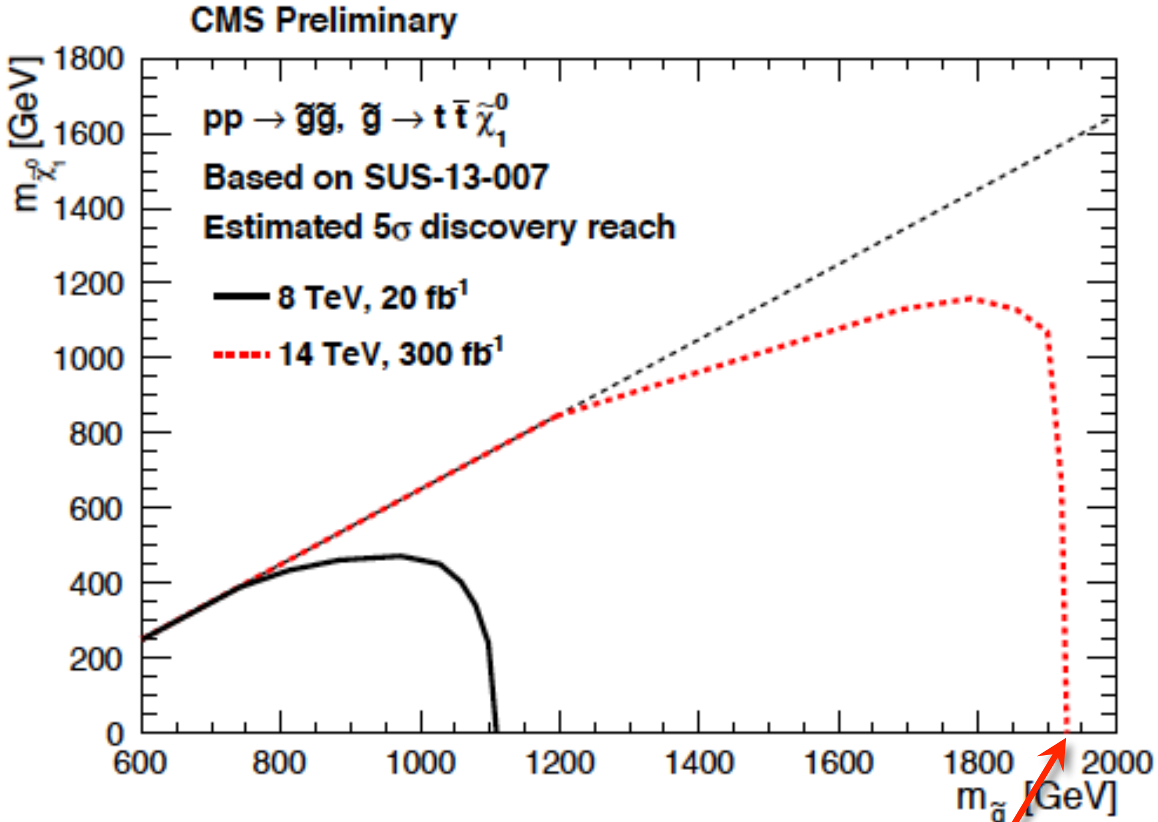
CMS 1307.7135

Dominant SUSY production mode





$$R_{\text{sig(bkg)}} = \frac{300\ \text{fb}^{-1}}{20\ \text{fb}^{-1}} \times \frac{\sigma_{\text{sig(bkg)}}(14\ \text{TeV})}{\sigma_{\text{sig(bkg)}}(8\ \text{TeV})}$$

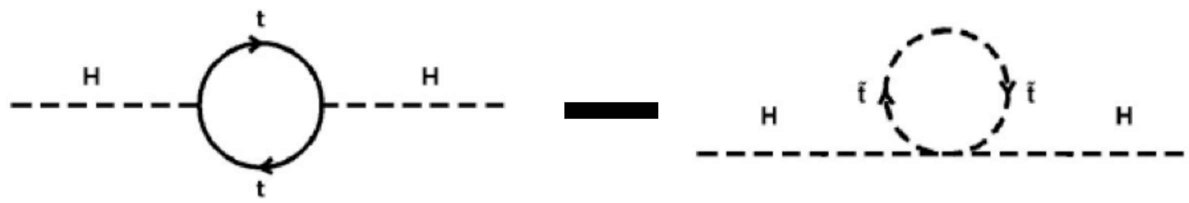


5σ discovery reach up to 1.9TeV

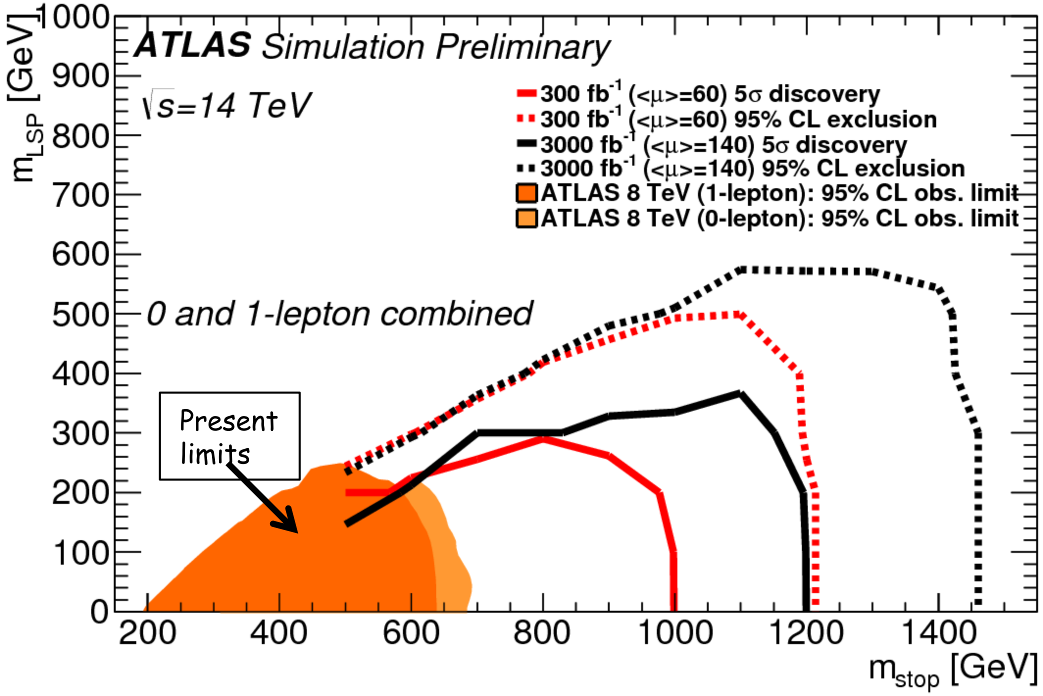
Simple extrapolation without optimization

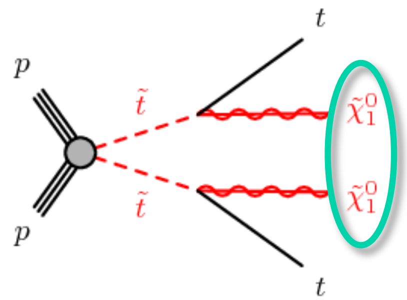
Another Example with Stop Pair Production

In SUSY, the Higgs mass is stabilized by a "light" (<1-1.5TeV) stop



Naturalness of the Higgs mass

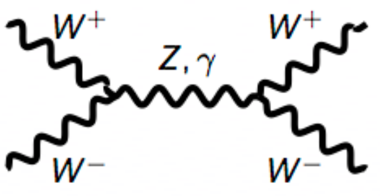


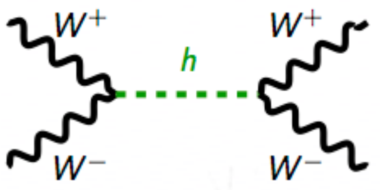


DM candidate

Mass reach extends by ~ 200 GeV from 300 to 3000 fb^{-1}
→ most of best motivated mass range will be covered at HL-LHC

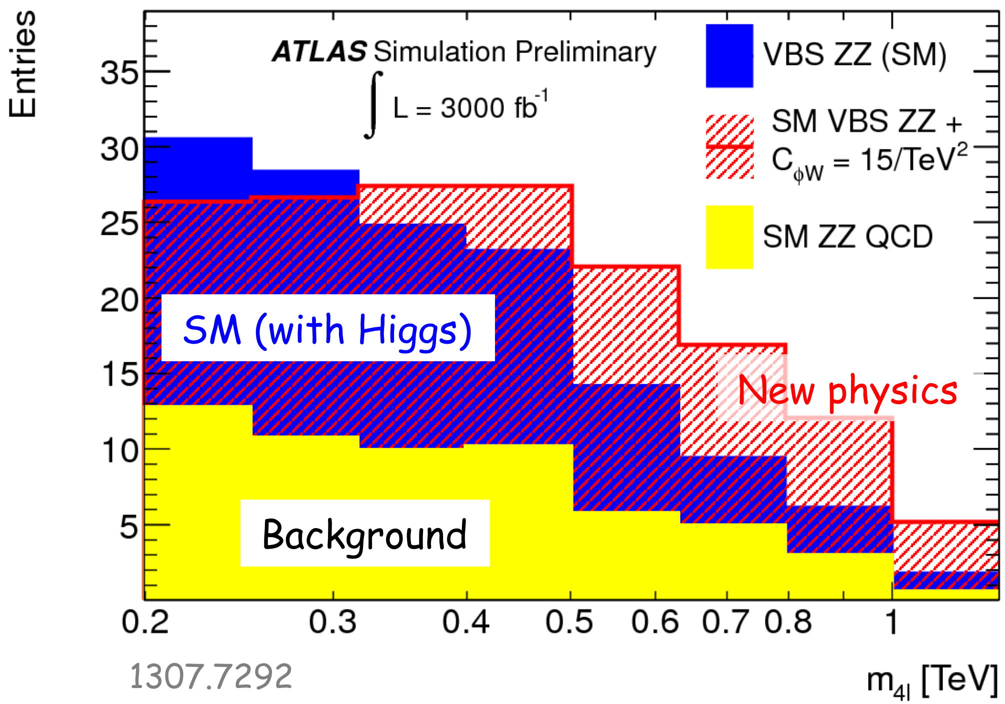
Vector Boson Scattering (VBS)





The 1st process violates unitarity: $\sigma \sim E^2$ at $m_{WW} \sim$ TeV
(divergent cross section → unphysical)
if the 2nd process does not exist

→ Important to verify that Higgs(126GeV) accomplishes this task → a crucial "closure test" of the SM
→ Need $\sqrt{s} \sim 14$ TeV and ~3000 fb^{-1}



1307.7292

If no new physics: good behavior of SM cross section can be measured to 30% (10%) with 300 (3000) fb^{-1}

If new physics: sensitivity increases by ~ 2 (in terms of scale and coupling reach) between 300 and 3000 fb^{-1}

→ HL-LHC is crucial for a sensitive study of EWSB dynamics

Possible Scenarios In Next Years/Decade

- LHC and/or HL-LHC find new physics:
  the heavier part of the spectrum may not be fully accessible at $\sqrt{s}$ ~ 14 TeV
  → strong case for a 100 TeV pp collider:
  complete the spectrum and measure it in some detail

- LHC and/or HL-LHC find indications for the scale of new physics being in the 10-50 TeV region (e.g. from dijet angular distributions → Λ Compositeness)
  → strong case for a 100 TeV pp collider:
  directly probe the scale of new physics

- LHC and HL-LHC find no new physics nor indications of next energy scale
  → Missed due to small cross sections or difficult experimental signatures?
  → A precision e+e- machine may be a good choice to find new guidance for future direction

Hadron Collider vs. e+e-(lepton)

Hadron Collider:

SppC (Super proton-proton Collider), China ←
FCC-hh (Future Circular Collider), CERN ←

e+e- Collider:

ILC (International Linear Collider), Japan?
CLIC (Compact LInear Collider), CERN
CEPC (Circular Electron Positron Collider), China
FCC-ee (TLEP), CERN
Muon collider (μC), Fermilab?

\+ Energy frontier
→ large direct discovery potential

\- Precision measurement challenging
- Pile-up
- UE, MPI*
- Composite proton → PDF uncertainty
- large theoretical (QCD) corrections

\+ Precision frontier
- Clean experimental environment
- Known $\sqrt{s}$
- Beam polarization (linear collider)
- Precise theoretical predictions

\- Lower $\sqrt{s}$
→ still large indirect scale reach

*UE: Underlying Event; MPI: Multi-Parton Interaction

A Few Machine Parameter Comparison

	ILC	CLIC	CEPC50	FCC-ee	SppC	FCC-hh
$\sqrt{s}$ (GeV)	250/500	500/3000	240	240/350	50/90TeV	80/100TeV
Length/circum (km)	➚~30	13/48	50	80/100	50/70	80/100
Lumi ($10^{34}cm^{-2}s^{-1}$)	0.75/1.8	2.3/5.9	2.6	5.9/1.8	22/29	
Polarization e-, e+ (%)	80, 30	80, 30				
#IP	1	1	2	4	2	4
Mean gradient (MVm^{-1})	14.7/31.5	150				
RF voltage (GV)			4.2	6/12		
B (T)					12/19	16/20

Physics Goal vs. √s at a e+e- Collider

ILC TDR

Circular

CEPC

FCC-ee

Multi-detector

pp → ee

Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
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

Linear

ILC

CLIC

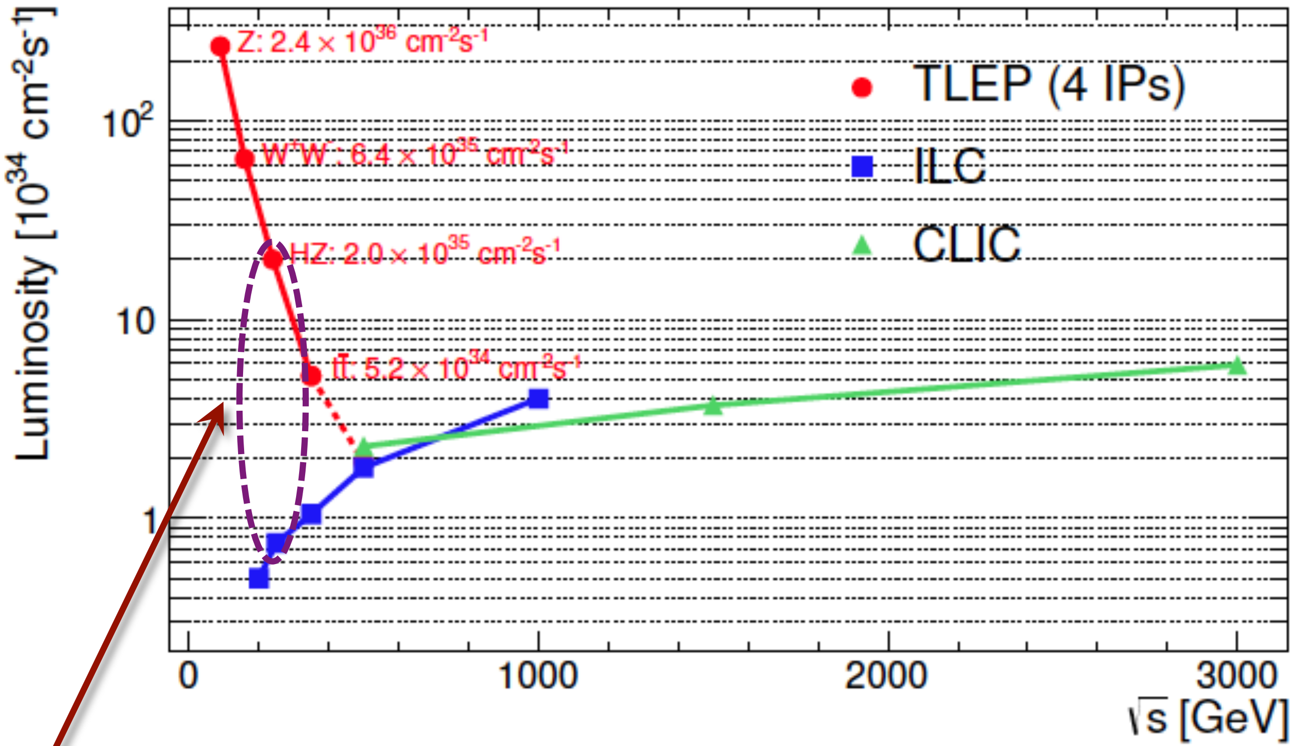
Single detector or Push-pull

Energy upgradability

3TeV

Circular vs. Linear

TLEP 1308.6176



TLEP (250) offers a factor 10 more lumi than ILC(250)

→ a factor 3 improvement in Higgs boson coupling measurements

however precision measurements are often not stat limited

Linear collider provides longitudinal beam polarization

Higgs Couplings: Why & What Precision?

Snowmass, Higgs, 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	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

➔ Up to 10% deviation from SM in different BSM models

Or in terms of new physics scale Λ (TLEP 1308.6176):

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

Larger deviation up to 20% on self-coupling,
but it's more difficult to measure experimentally

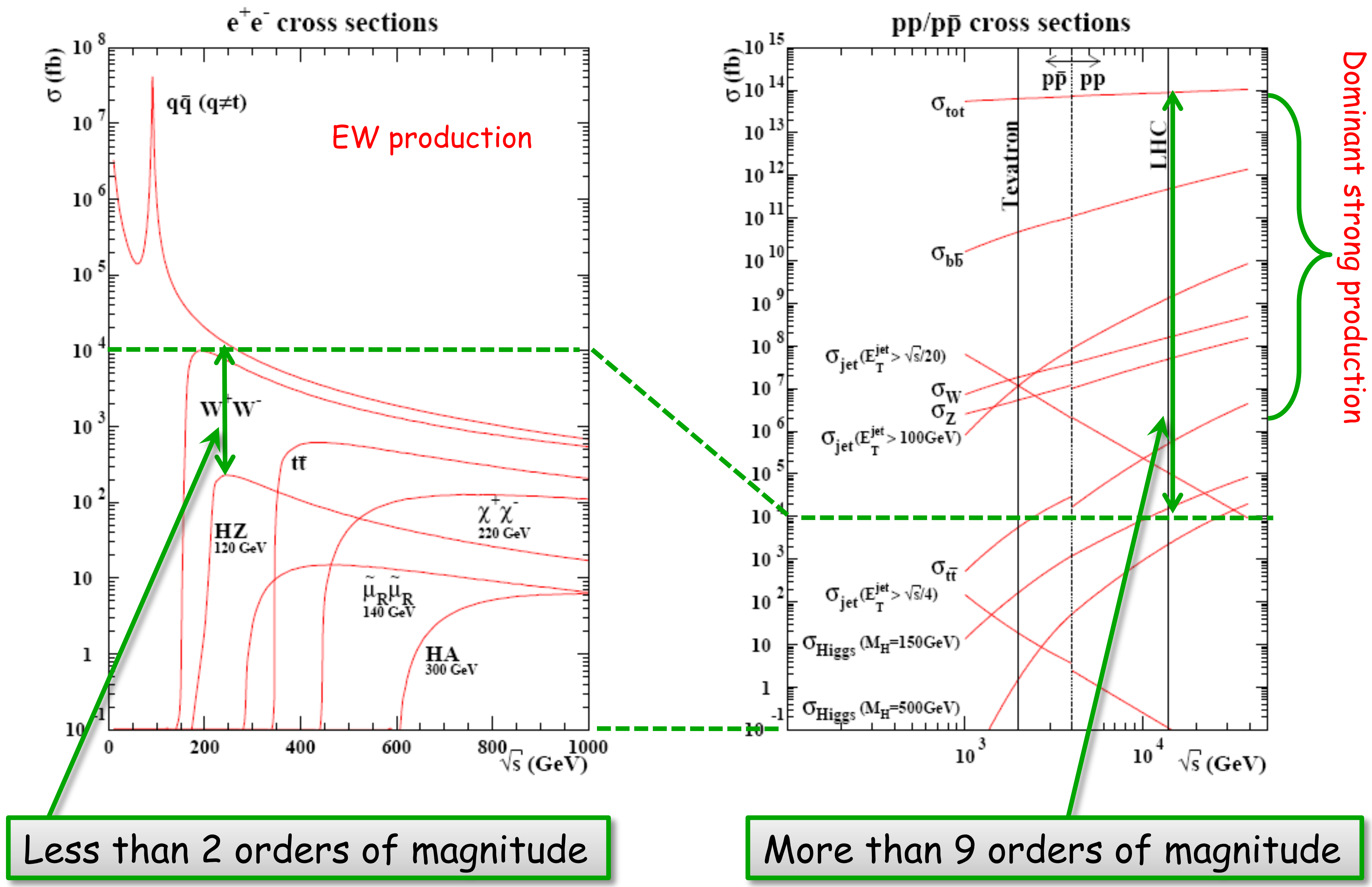
Comparison of Expected H Coupling Precision

Snowmass, Higgs, 1310.8361

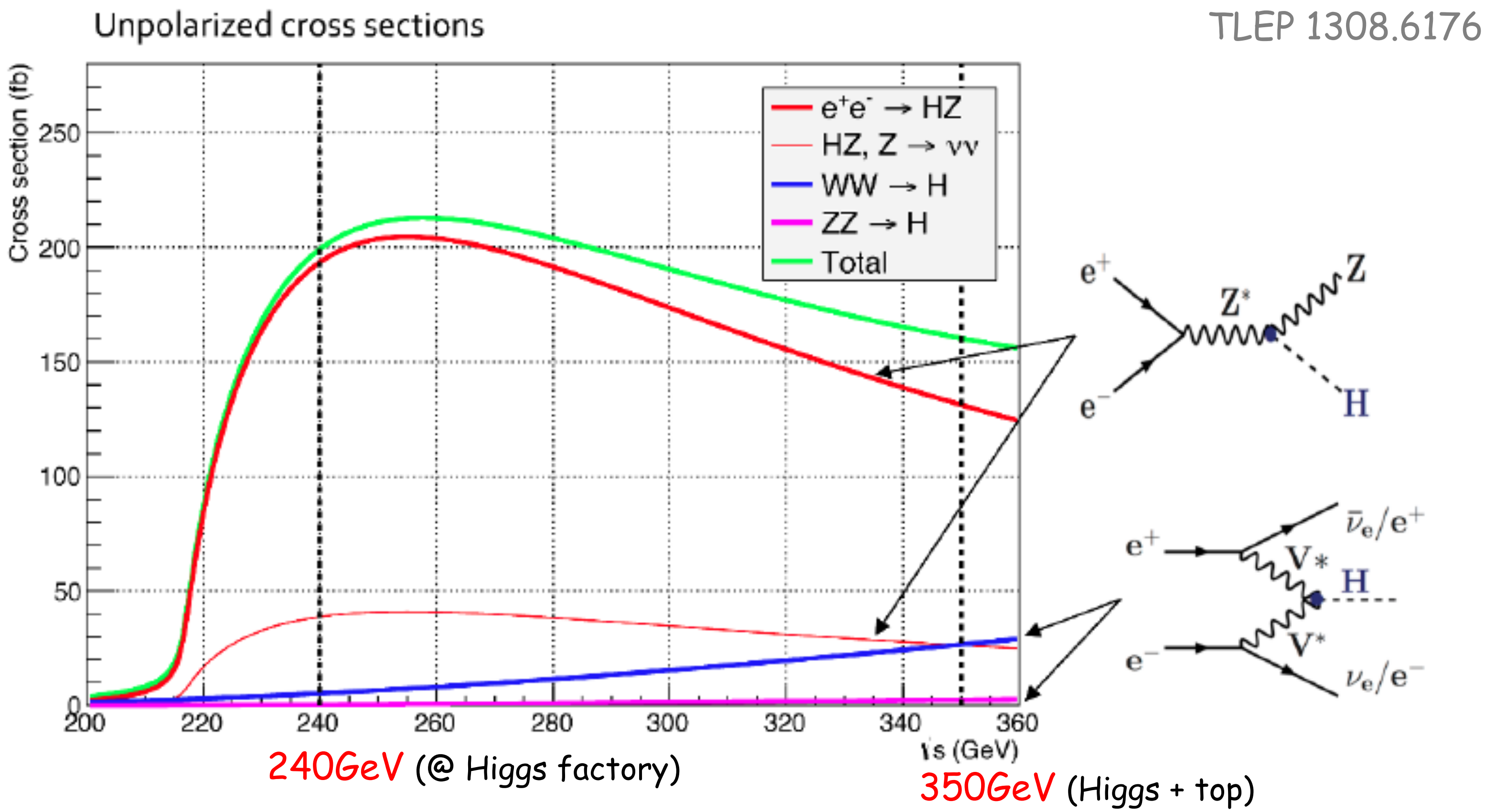
Facility	LHC	HL-LHC	ILC500	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	$3.5/1.4/<1.3\%$	0.51%
$\kappa_d=\kappa_b$	$10-13\%$	$4-7\%$	0.93%	1.7/0.32/0.19%	0.39%
$\kappa_u=\kappa_t$	$14-15\%$	$7-10\%$	2.5%	3.1/1.0/0.7%	0.69%

➔ e+e- colliders are expected to be more precise
Circular e+e- collider is doing best

Low SM Background Rate at e+e- Collider



Higgs Production at e+e- Machine



In addition to model independent λ and BR measurements, HZ process also provides a very precise Higgs mass measurement using recoil mass technique

$$m^2_{\mathrm{recoil}} = s + m^2_Z - 2E_Z\sqrt{s}$$

➔Only based on Z and √s but independent of H final state

HZ+ννH ➔ precise and model independent width measurement

Comparison of Mass and Width Measurement

Snowmass, Higgs, 1310.8361

Facility	LHC	HL-LHC	ILC500	CLIC	TLEP (4 IP)	μC
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	350/1400/3000	240/350	126
$\int \mathcal{L}dt$ (fb^{-1})	300	3000	250+500	500+1500+2000	10,000+2600	4.2
m_H (MeV)	100	50	32	33	7	0.06
Γ_H	–	–	5.0%	8.4%	1.0%	4.3%

Why precision Higgs mass measurement?

➔ Check the EW vacuum stability

➔ Check the mass relation in a BSM model

The Fate of the Universe (EW Vacuum)

Measured top and Higgs masses seem to place the SM vacuum on the very margin of stability

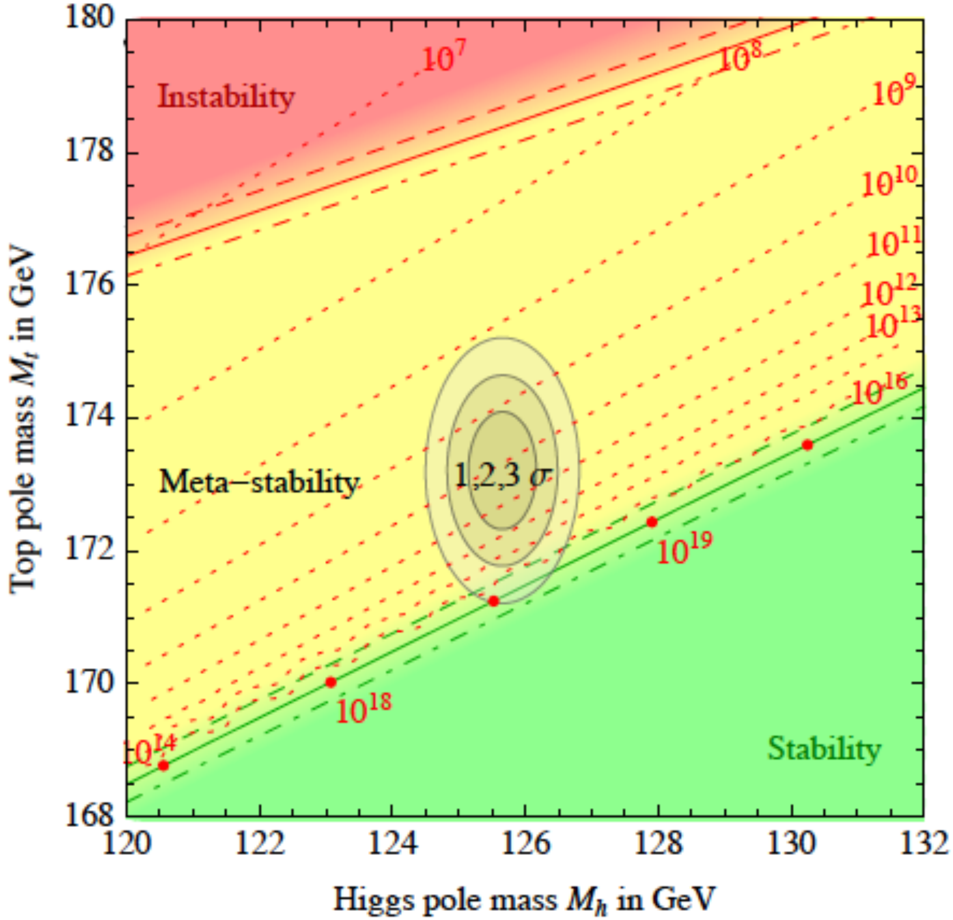
➔Precision measurement of H & top masses crucial
To match δm_H~150MeV, δm_t should be <100MeV!

If no new physics at the TeV scale to which scale the SM is valid?

Renormalization group equation
→ running of Higgs coupling $\lambda(Q)$

The instability scale Q is defined as the scale at which λ_{eff}=0

1307.3536

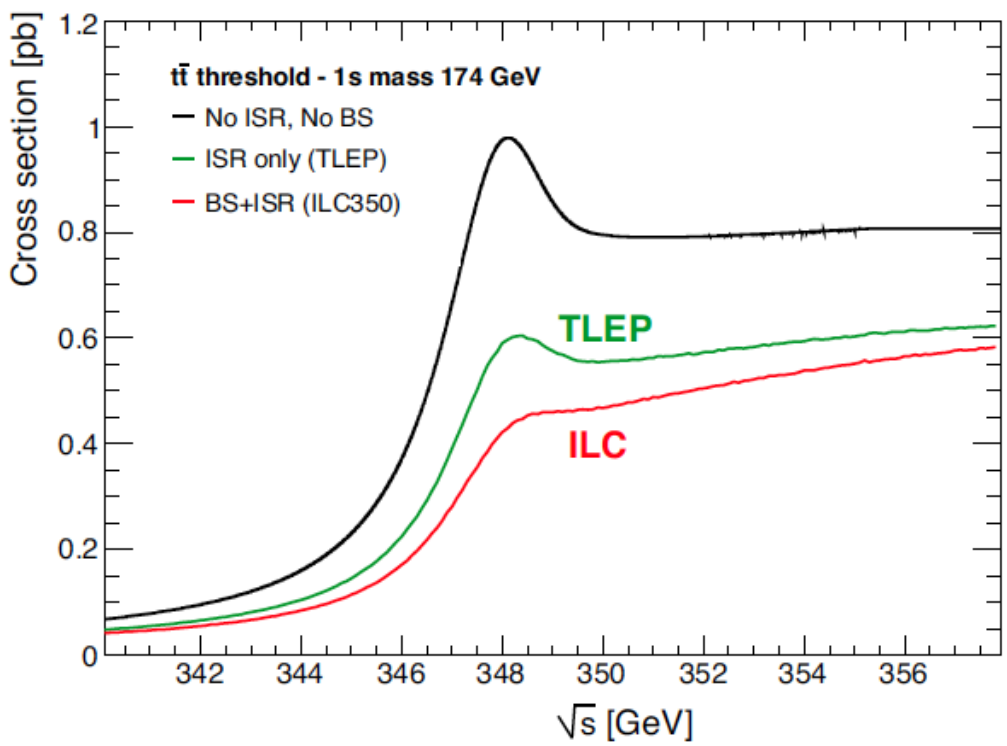


Any connection with new physical scale? If yes, it's well beyond any collider reach

Precision Top Quark Mass Measurements

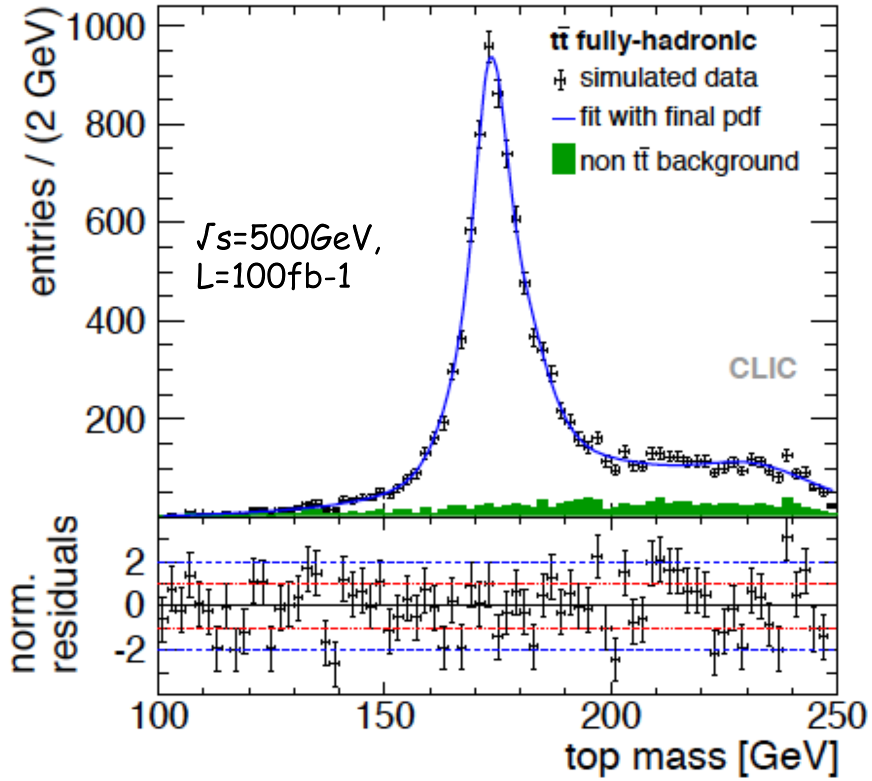
TLEP, 1308.6176

Threshold scan



Direct reconstruction above threshold

1303.3758



Precise measurement of σ at the ttbar production threshold is sensitive to

- top-quark pole mass, m_t,
- total top quark decay width,
- Yukawa coupling of the top quark to Higgs

δm_t~80MeV combining hadronic and semihadronic t→Wb decays

BS: Beamstrahlung effect

Comparison of Precision Mass Measurements

Grojean, FCC 14

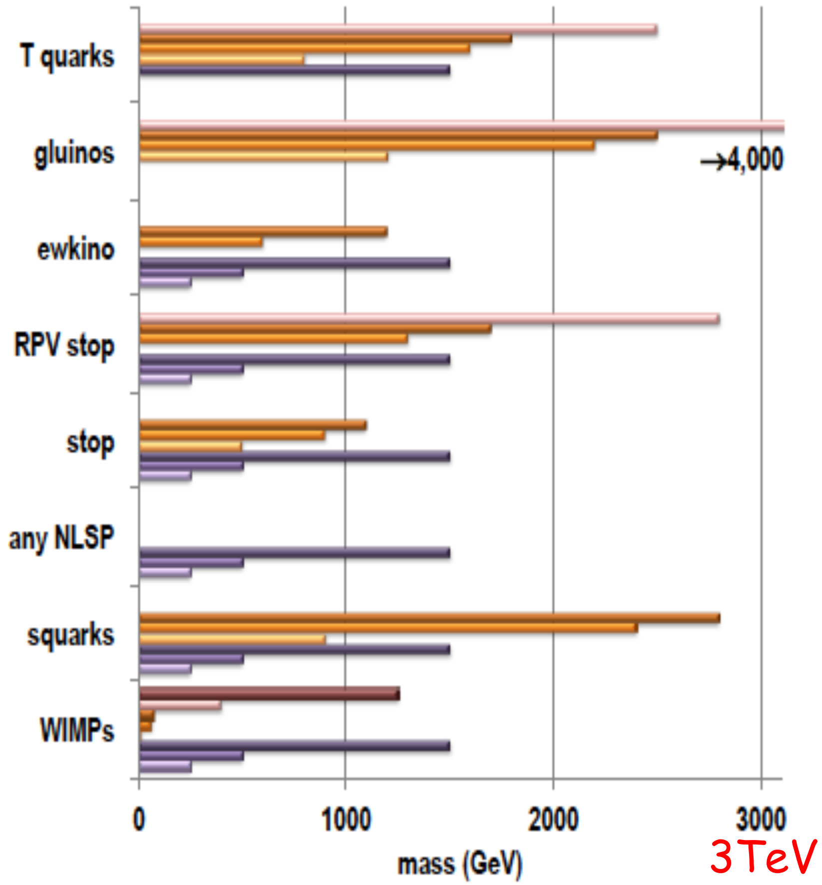
Parameter	Present	LHC	ILC/GigaZ	TLEP
M_H [GeV]	0.4	< 0.1	< 0.1	< 0.1
M_W [MeV]	15	8	5	1.3
M_Z [MeV]	2.1*	2.1	2.1	0.1
m_t [GeV]	0.9	0.6	0.1	0.08

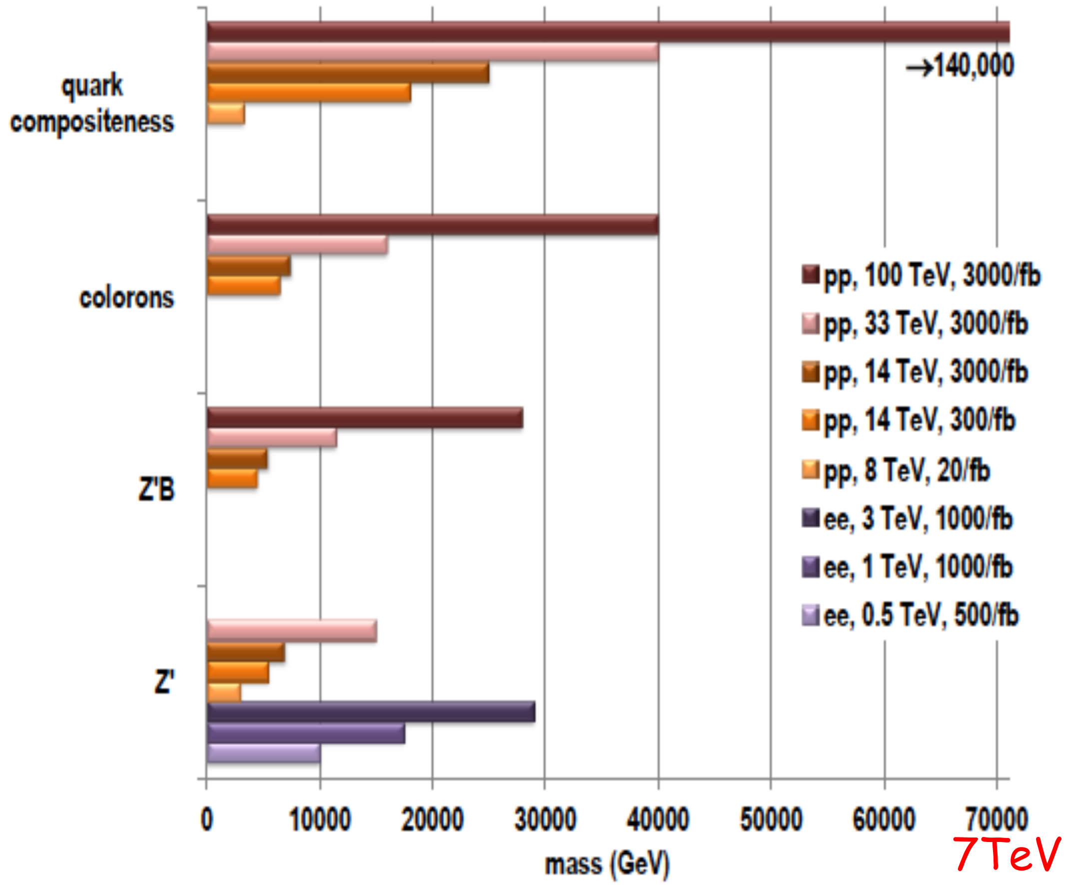
In all cases, systematic uncertainty dominates

*LEP line shape scan ($1.2_{stat}+1.7_{beam\ calib}$), TLEP improvement relies on continuous measurement with resonant depolarization of single bunches

Search Capabilities @ LHC, Future Colliders

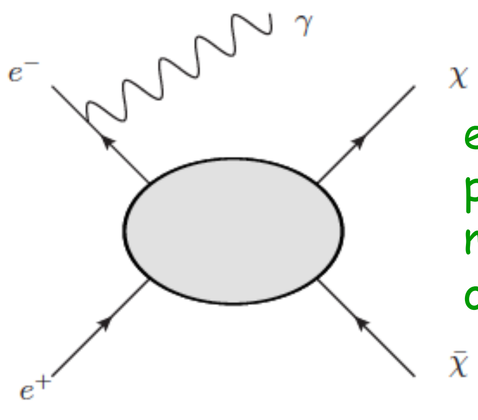
Snowmass 1311.0299



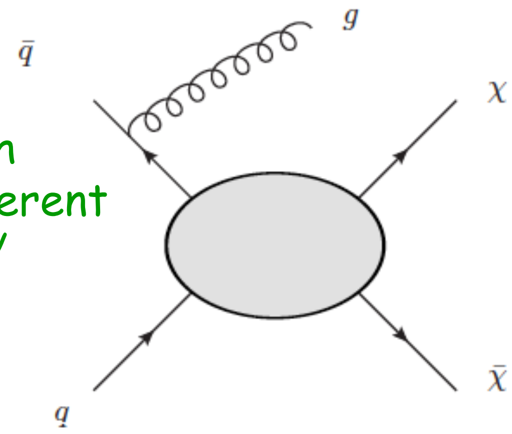


- ✓ TeV mass particles are needed in essentially all models of new physics
  →The search for them is imperative
- ✓ LHC and future colliders all give impressive capabilities for the search
- ✓ The search for TeV mass particles is integrally connected to searches for DM

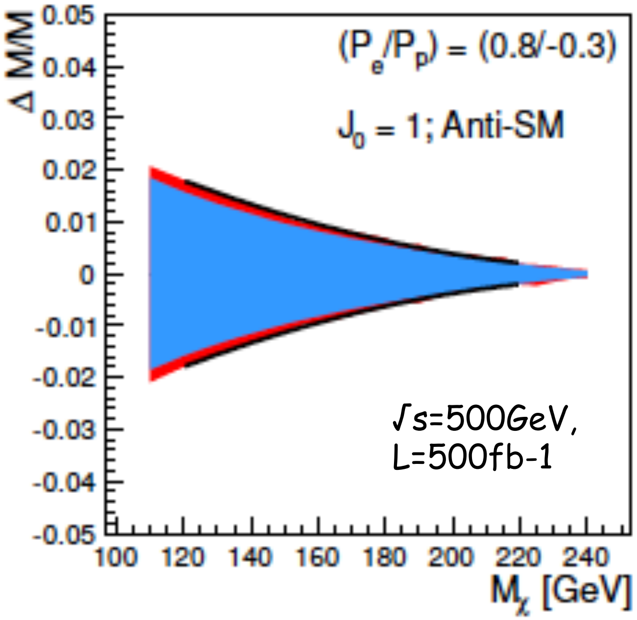
DM Search with Mono γ/jet Events



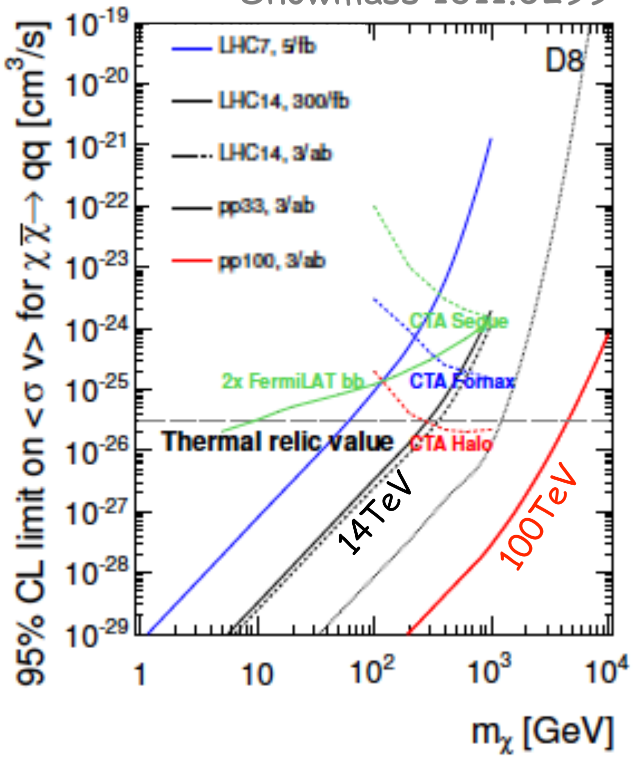
e+e- and hh probe different mediators/ operators



1206.6639



Snowmass 1311.0299



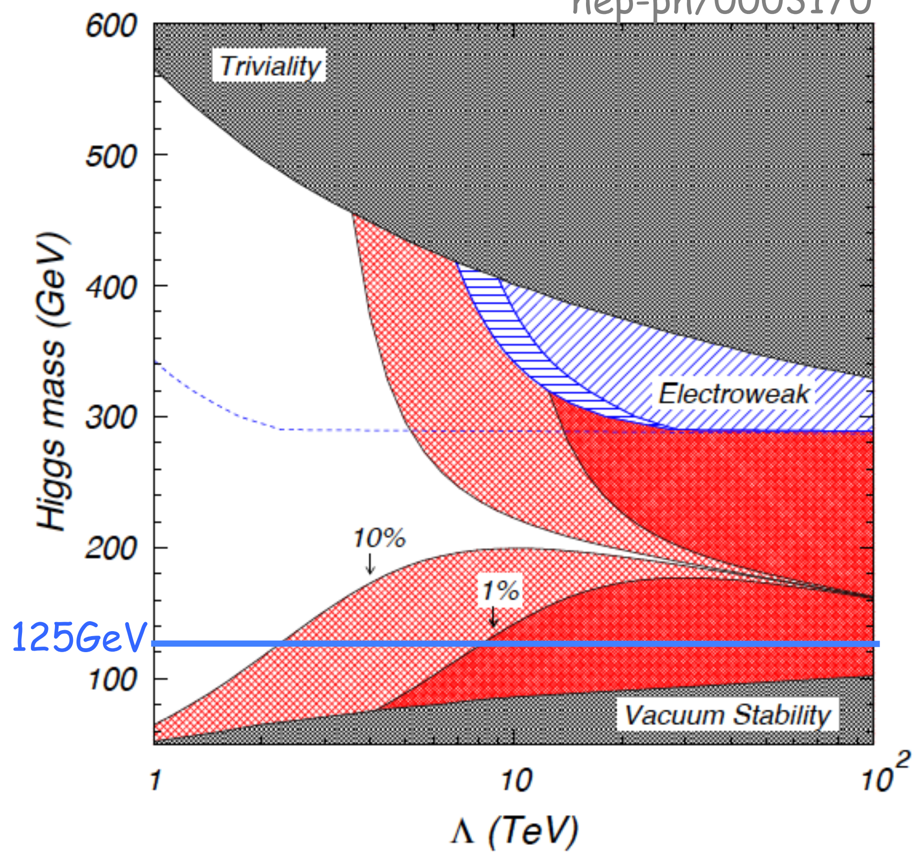
Discovery + precise mass measurement

Naturalness & Degree of Fine-Tuning

$$\varepsilon \sim \left(\frac{125}{M_{\rm NP}}\right)^2$$

- If NP* is at TeV scale, ε~1% (LHC & e+e-)
- If NP is at 10TeV scale, $\varepsilon \sim 10^{-4}$ (direct: SppC, FCC-hh; indirect: e+e-)
- If no NP up to Planck scale, $\varepsilon \sim 10^{-34}$

hep-ph/0003170



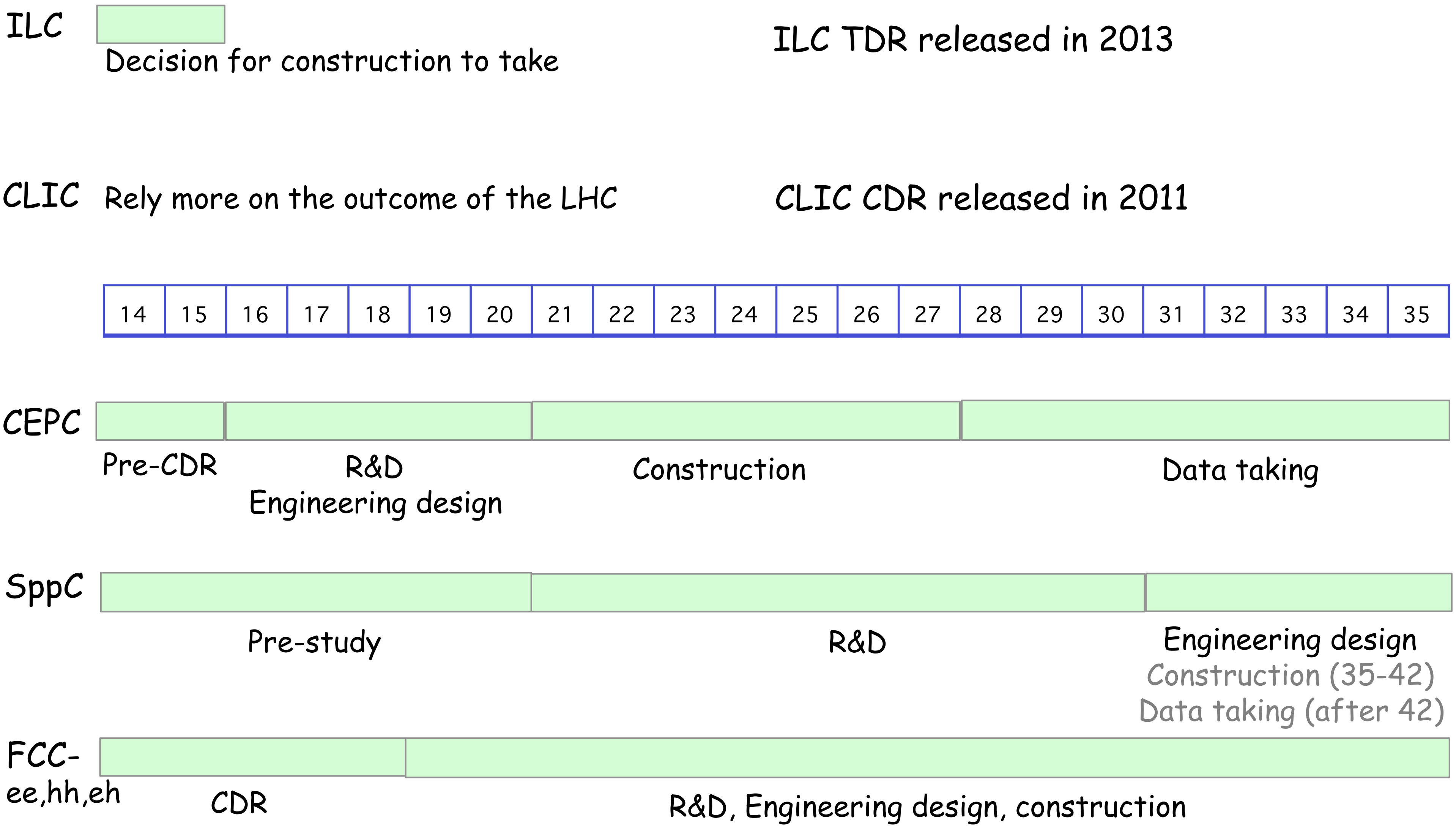
Naturalness (argument) has been a guiding principle for NP model construction

An aesthetic or physical criterion?

The key point: what's the real NP scale?

NP: New Physics

Possible Timeline



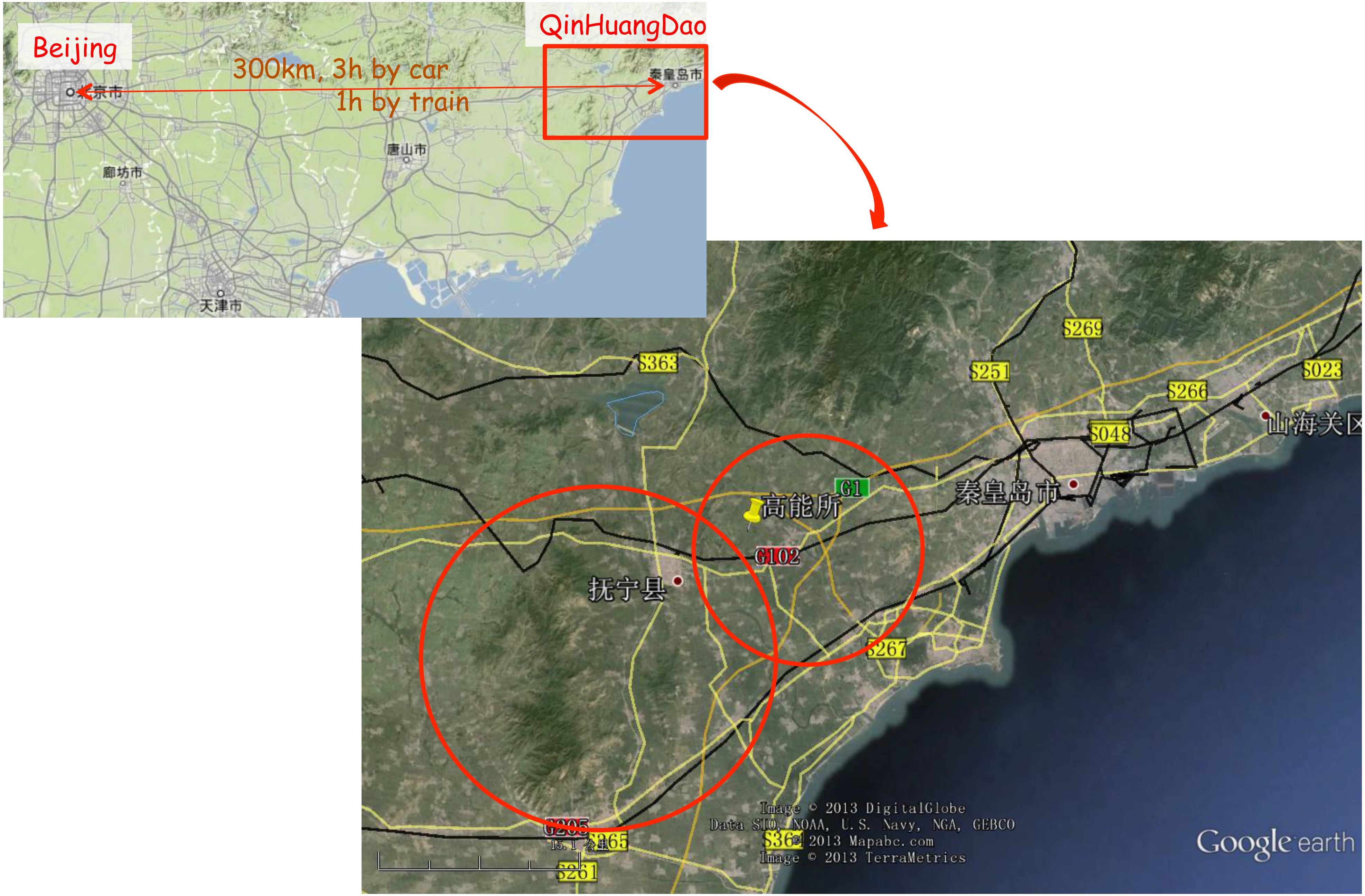
NP: New Physics

Summary

- The Higgs boson is least well studied sector in the SM
  LHC as a Higgs factory is doing a good job though not for all model-independent studies
  ➔ e+e- Higgs factory can do more/better
- If no new physics signal found at the LHC in next years/decade
  A high energy precision collider may be a good way to find a clear guidance for future
- To have several different complementary high energy colliders ideal but likely unrealistic
- Whatever the choice, we need to be prepared with active machine & detector R&D program
- Shall try all possibilities: high energy colliders, intensity-frontier experiments, astroparticle experiments, neutrino experiments, dedicated searches
  Indeed, all BSM evidences* are found so far by non-accelerator experiments!
  But high energy colliders are good for both discovery and precision measurements

*BSM evidences: non-bayonic DM, neutrino mass, dark energy, apparently acausal density fluctuations, baryon asymmetry

CEPC/SppC


Beijing
QinHuangDao
300km, 3h by car
1h by train
京市
秦皇岛市
唐山市
廊坊市
天津市
S363
S269
S251
S023
S266
S048
山海关区
G1
高能所
秦皇岛市
G102
抚宁县
S267
G205
S261
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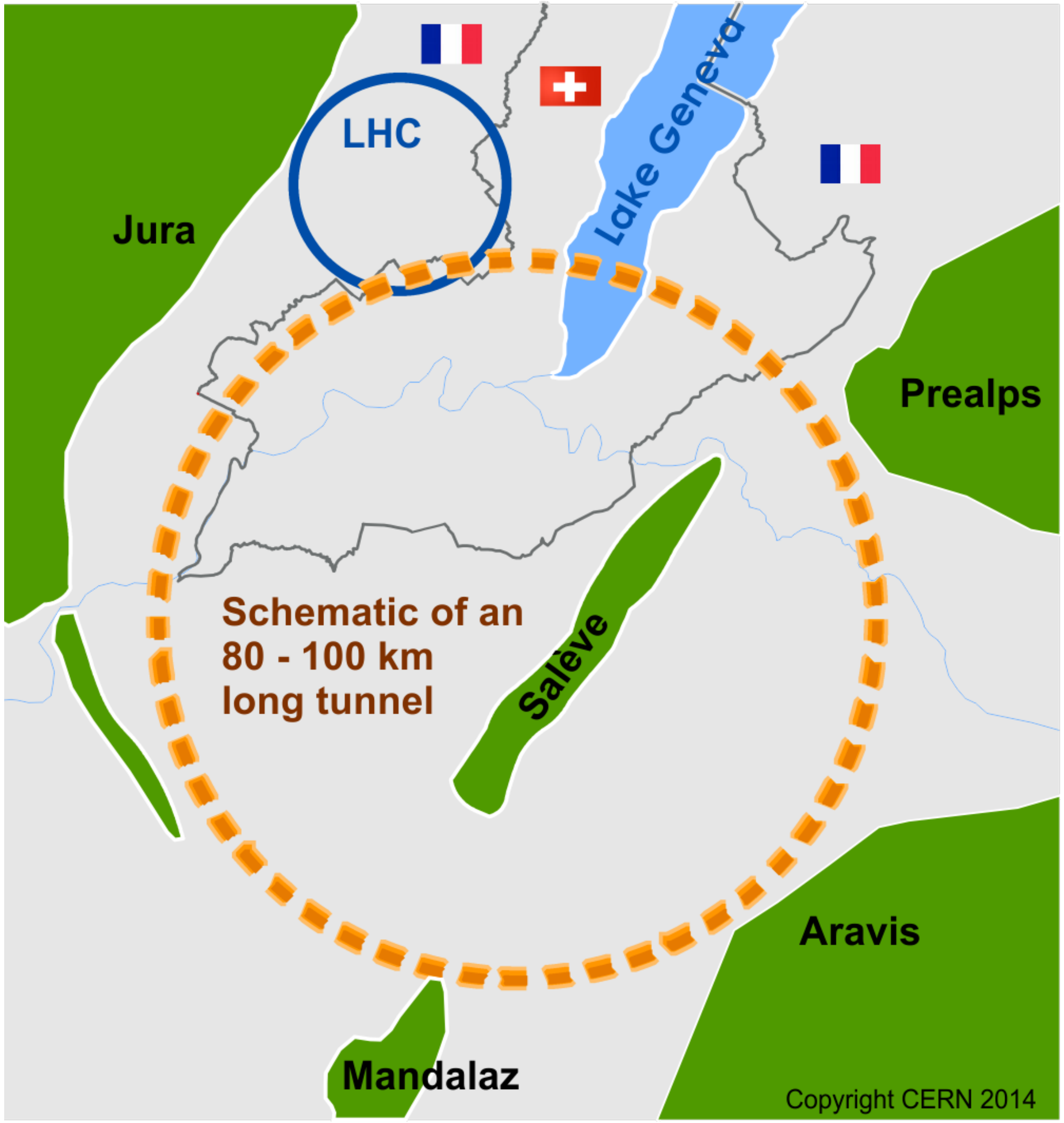
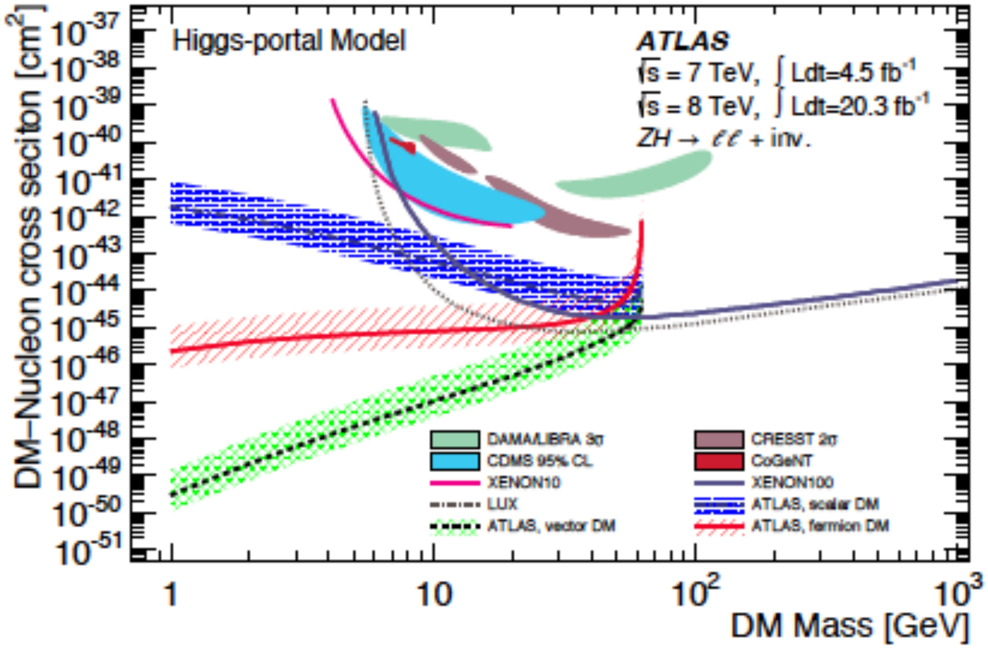
FCC-ee,hh,eh



LHC
Lake Geneva
Jura
Prealps
Schematic of an
80 - 100 km
long tunnel
Salève
Aravis
Mandalaz
Copyright CERN 2014

Higgs Portal vs. Direct DM Searches

ATLAS, 1402.3244



Interpret H→ invisible search results in Higgs portal model (hep-ph/0605188) in which the Higgs mediates interaction between DM and SM particles

CMS, 1404.1344