U.S. Snowmass: New physics at energy frontier

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International Symposium on Higgs Physics, IHEP, Beijing. Aug. 15, 2015.

Energy frontier working groups

http://www.snowmass2013.org/tiki-index.php?page=Energy%20Frontier

- The Higgs boson.
- Precision Study of Electroweak Interaction.
- Fully understanding the top quark
- The Path Beyond the SM
- QCD and the strong force
- Flavor and CP violation at high energy

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My focus here

- QCD and the strong force
- Flavor and CP violation at high energy

The Charge:

With the completion of the Tevatron program, the High Energy Frontier is now located at CERN, where the Large Hadron Collider offers a program of discovery that may continue for twenty years or longer.

The task of the High Energy Frontier study group is to investigate the major areas of particle physics relevant to possible high energy accelerators, to review their current state, and to map the opportunities they provide for future discoveries. In addition, these studies should explore the motivations for other possible energy frontier accelerators that may complement the LHC.

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- In particular, no prioritization.

Or:

We need to articulate a scientific program and its motivation:

I. What scientific targets can be achieved before 2018 ?

II. What are the science cases that motivate the High Luminosity LHC ?

III. Is there a scientific necessity for a "Higgs Factory" ?

IV. Is there a scientific case today for experiments at higher energies beyond 2030 ?

For these issues, we must clarify in our own minds:

Where is the physics beyond the Standard Model ?

What did we learn from LHC 7/8 TeV ?

What does this tell us about the next step ?

slide from M. Peskin

Current progress of Snowmass

- Main meeting in Minneapolis, July 29 - Aug. 6.

https://indico.fnal.gov/conferenceTimeTable.py?confId=6890#20130729.detailed

- Working group reports drafted, circulating and collecting comments.
    - Will finalize on Aug. 30.

- Presentation at DPF meeting in Santa Cruz.

https://indico.bnl.gov/getFile.py/access?contribId=4&sessionId=0&resId=0&materialId=slides&confId=603

A large amount of valuable contributions

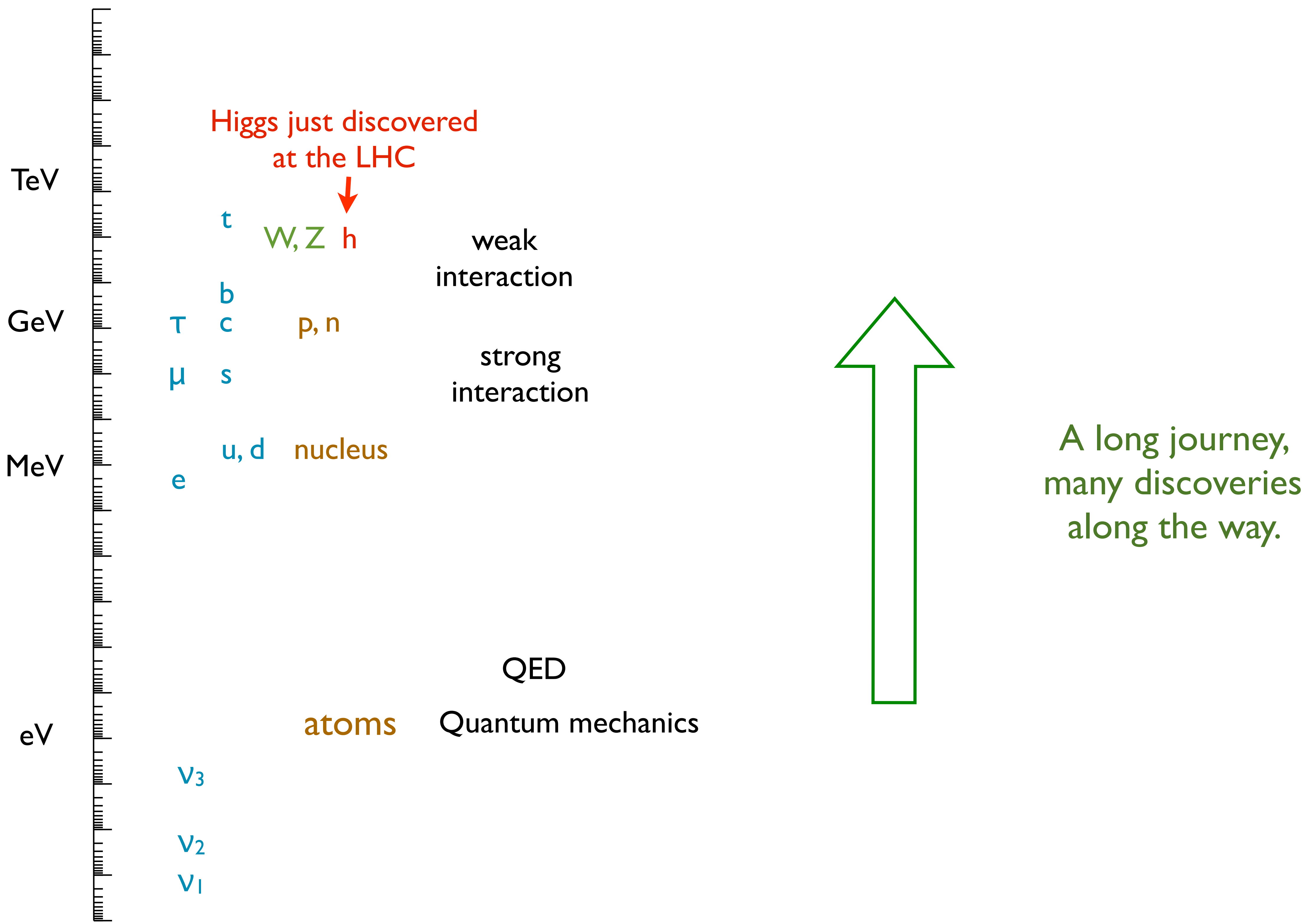
Incomplete list of contributing authors

Conveners: Yuri Gershtein, Markus Luty, Meenakshi Narain, Lian-Tao Wang, Daniel Whiteson

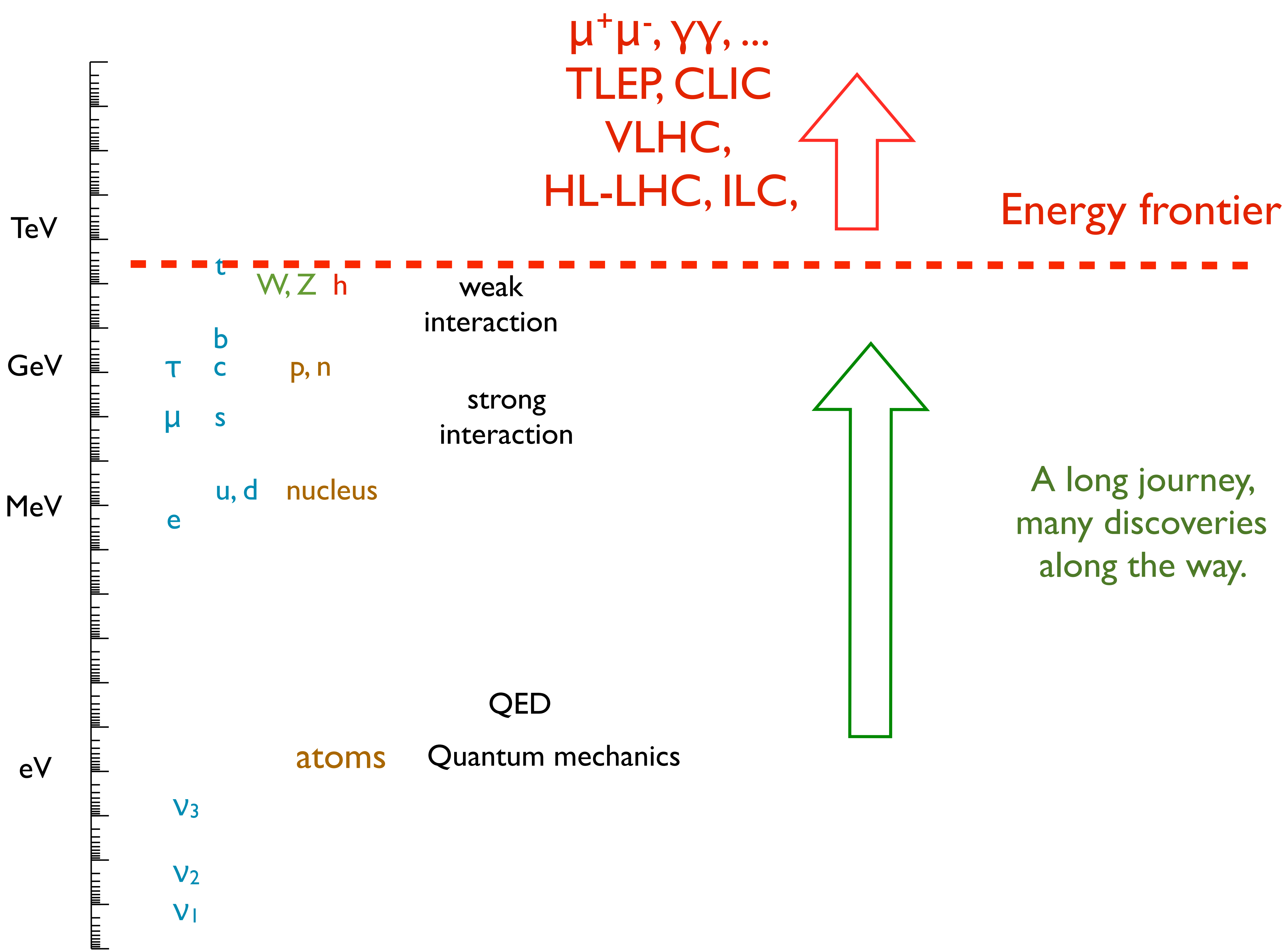
Authors: L. Apanasevich, G. Artoni, A. Avetisyan, H. Baer, C. Bartels, D. Berge, M. Berggren, S. Bhattacharya, K. Black, T. Bose, J. Brau, R. Brock, E. Brownson, M. Cahill-Rowley, A. Cakir, T. Cohen, R. Cotta, N. Craig, K. Dienes, B. Dobrescu, D. Duggan, R. Essig, J. Evans, A. Drlica-Wagner, S. Funk, Y. Gershtein, J. George, S. G., T. Golling, T. Han, A. Haas, M. Hance, D. Hayden, U. Heintz, A. Henrichs, J. Hewett, J. Hirschauer, K. Howe, A. Ismail, Y. Kats, K. Kaadze, B. Coleppa, F. Kling, D. Kolchmeyer, K. C. Kong, A. Kumar, G. Kribs, P. Langacker, A. Lath, J. List, T. Lin, L. Linssen, T. Liu, Z. Liu, J. Loyal, M. Luty, A. Martin, I. Melzer-Pellmann, M. Narain, M. M. Nojiri, S. Padhi, N. Parashar, B. Penning, M. Perelstein, M. Peskin, A. Pierce, W. Porod, C. Potter, T. Rizzo, G. Sciolla, J. Stupak III, S. Su, T.M.P. Tait, T. Tanabe, B. Thomas, S. Thomas, S. Upadhyay, N. Varelas, A. Venturini, J. Wacker, M. Walker, L.-T. Wang, D. Whiteson, M. Wood, F. Yu, N. Zhou

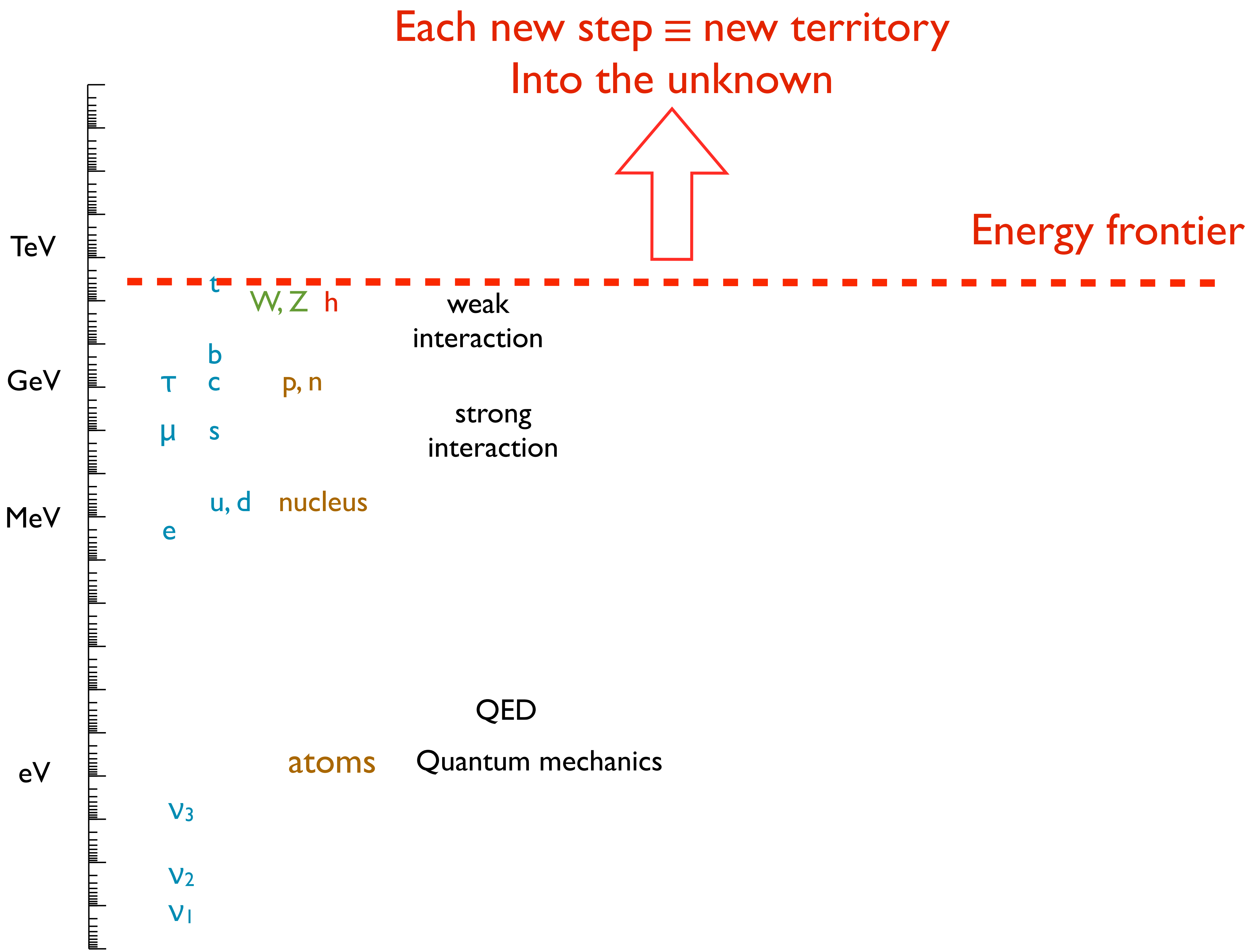
Some Highlights

EF: establishing new laws of physics



EF: establishing new laws of physics




Each new step ≡ new territory
Into the unknown
Energy frontier
TeV
GeV
MeV
eV
t
W, Z
h
weak
interaction
b
τ
c
p, n
strong
interaction
μ
s
u, d
nucleus
e
QED
atoms
Quantum mechanics
ν3
ν2
ν1

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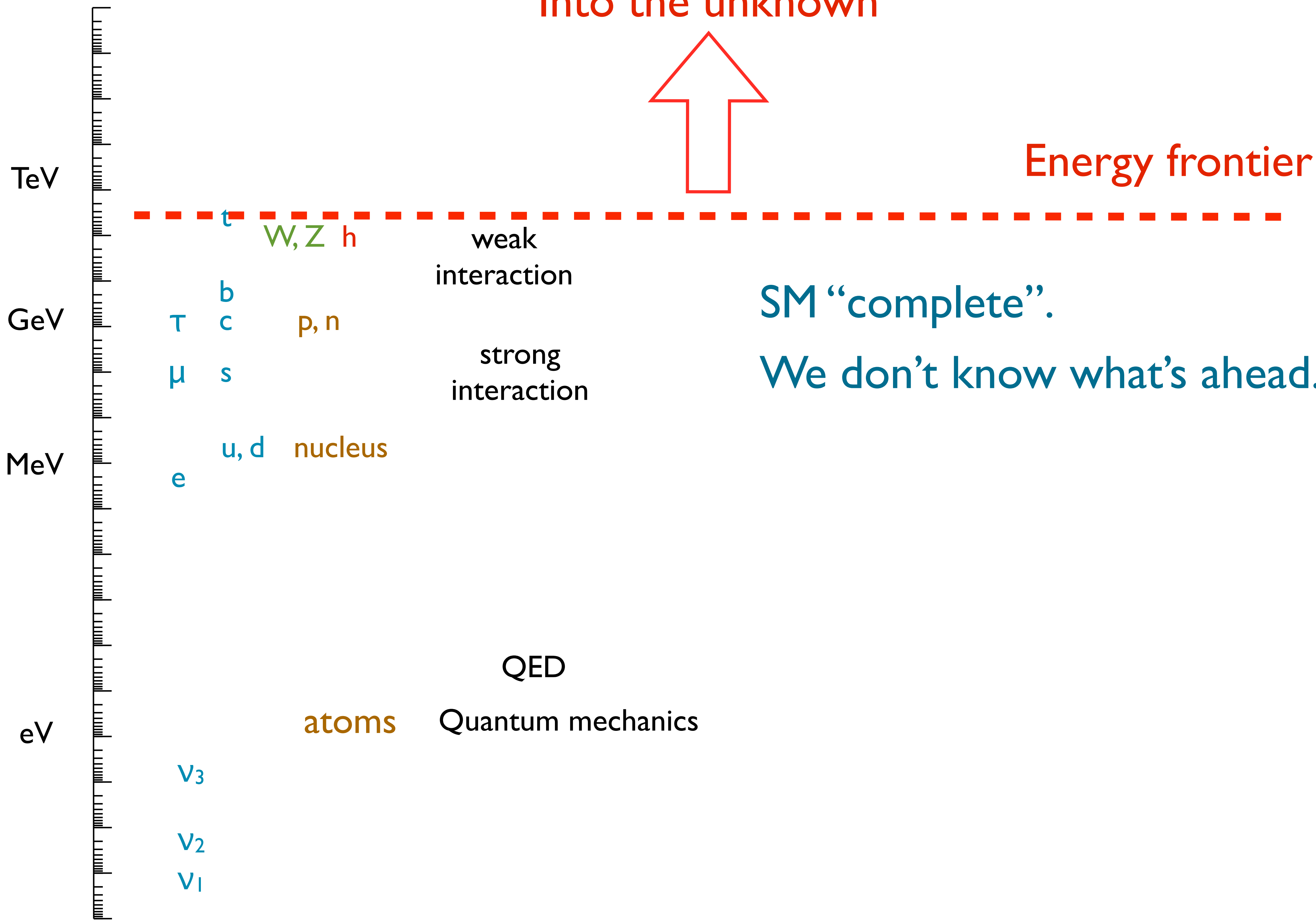

SM "complete".

We don't know what's ahead.

Each new step ≡ new territory
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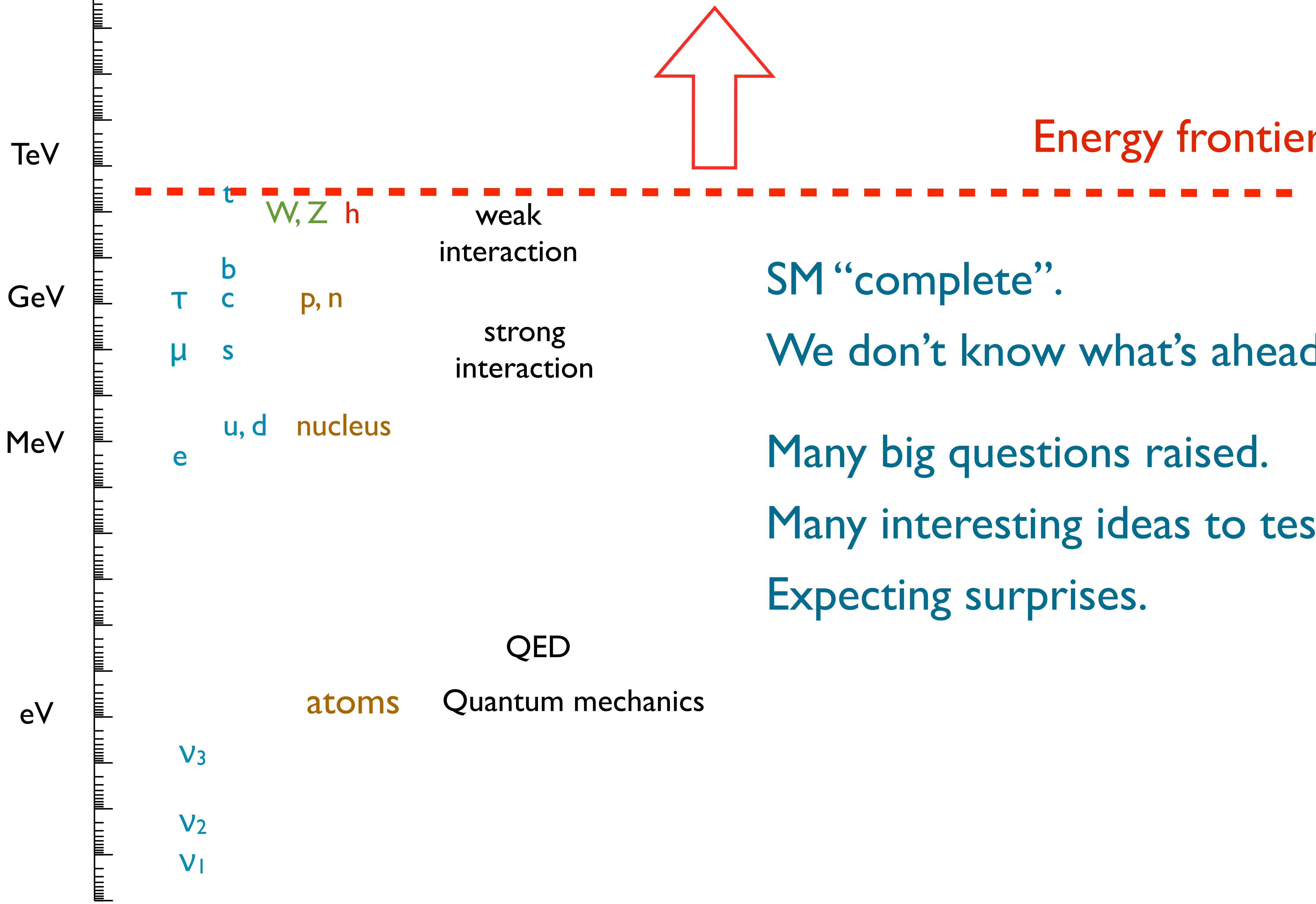

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Many big questions raised.

Many interesting ideas to test.

Expecting surprises.

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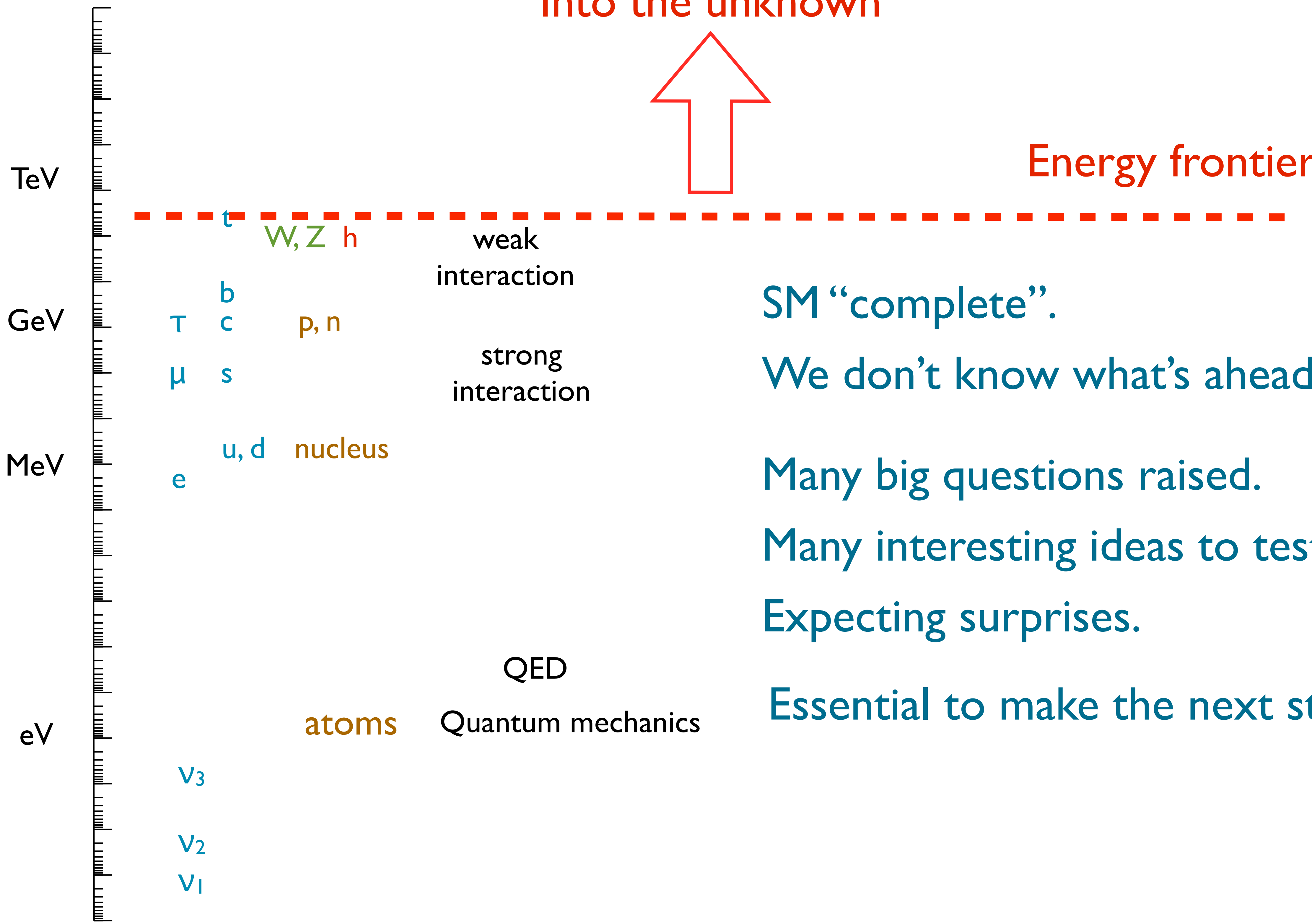

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Many big questions raised.

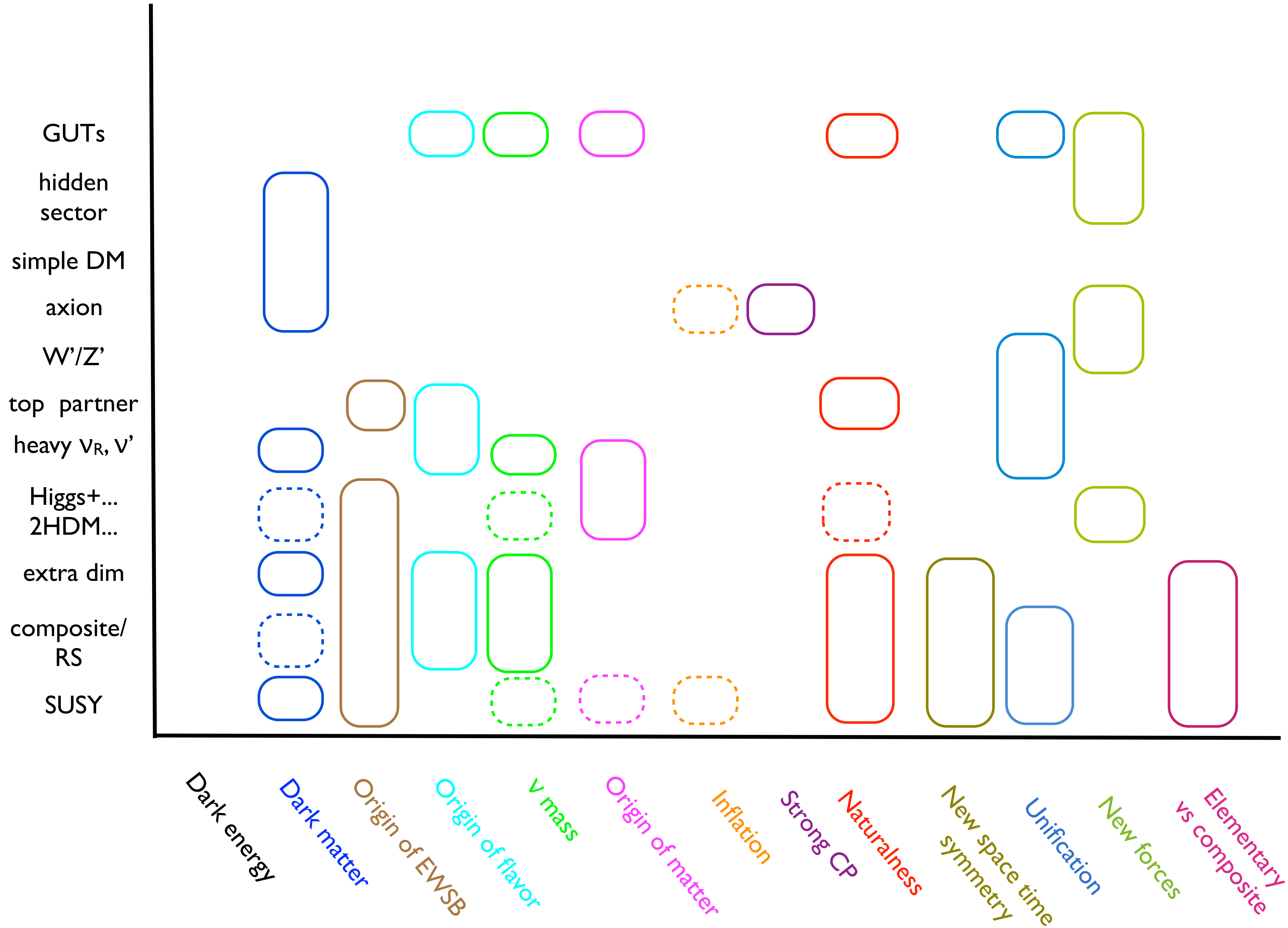
Many interesting ideas to test.

Expecting surprises.

Essential to make the next step!

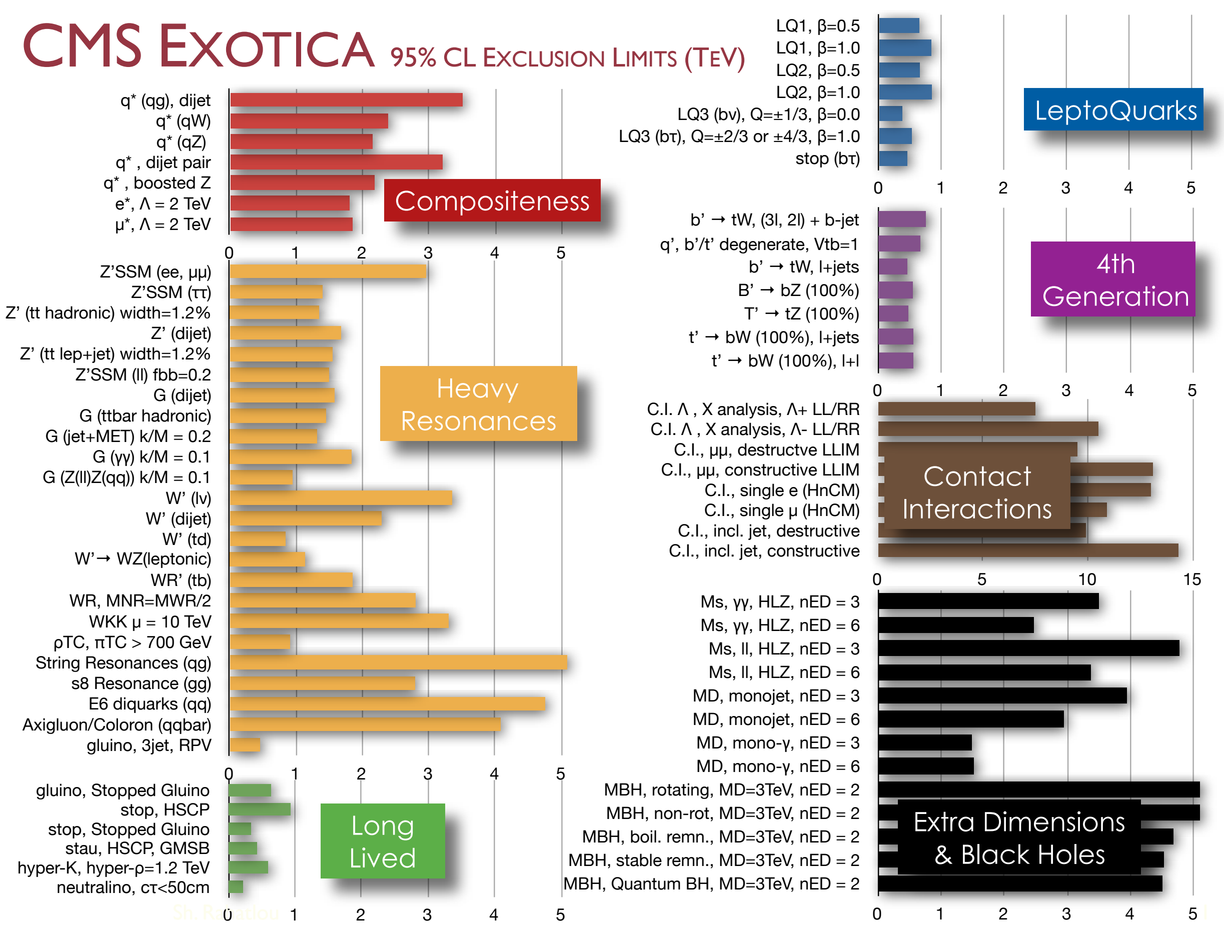
Energy frontier in 2013

- LHC Run 1 finished.
- Higgs discovered.
    - Standard Model like.
- We now have a theory which can be valid up to Planck scale.
- At the same time, many important questions remain.

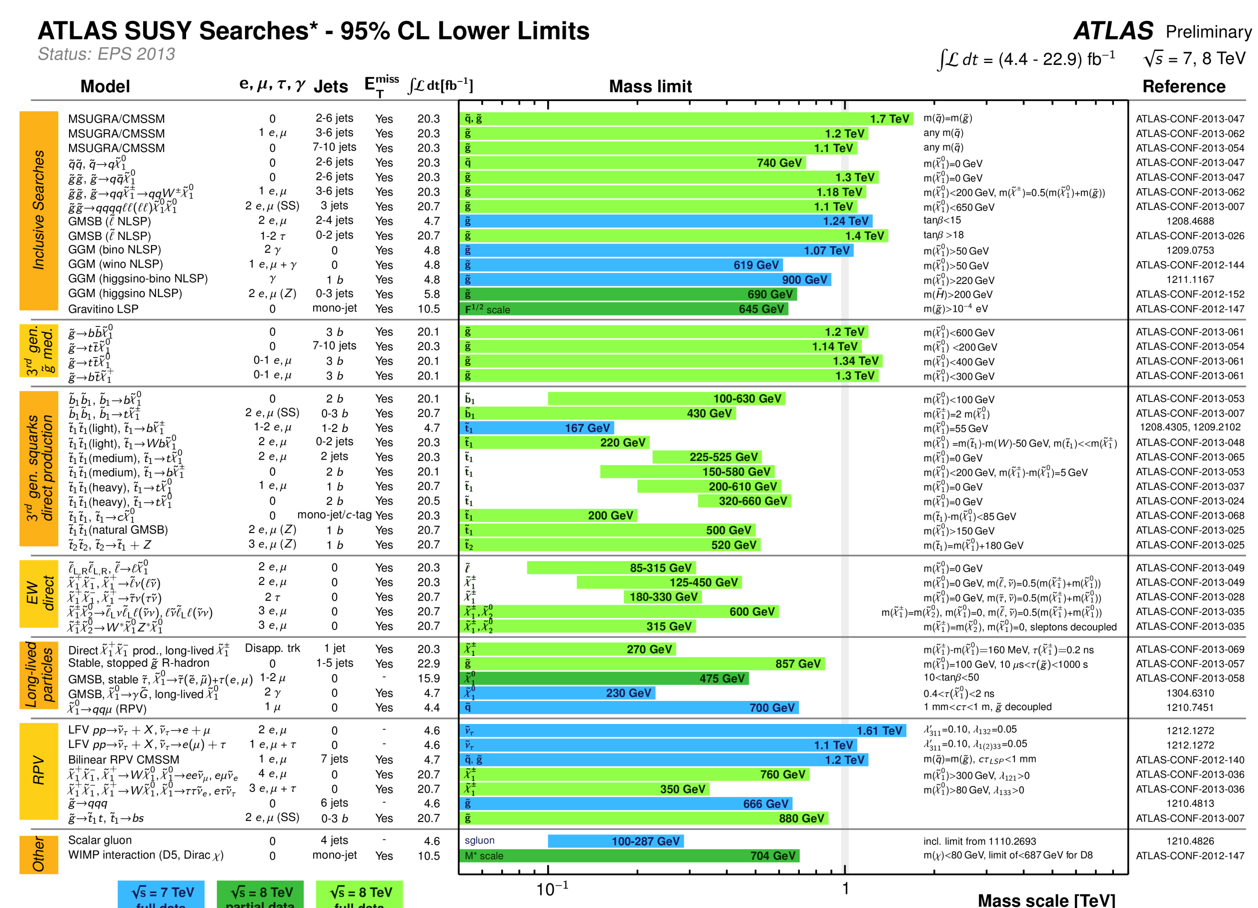

GUTs
hidden sector
simple DM
axion
W'/Z'
top partner
heavy ν_R, ν'
Higgs+... 2HDM...
extra dim
composite/ RS
SUSY
Dark energy
Dark matter
Origin of EWSB
Origin of flavor
ν mass
Origin of matter
Inflation
Strong CP
Naturalness
New space time symmetry
Unification
New forces
Elementary vs composite

LHC 7-8 TeV "Run 1" searches

- Broad physics program, out performed expectations.
  - Many innovative searches, advances in theory



*similar results obtained by ATLAS

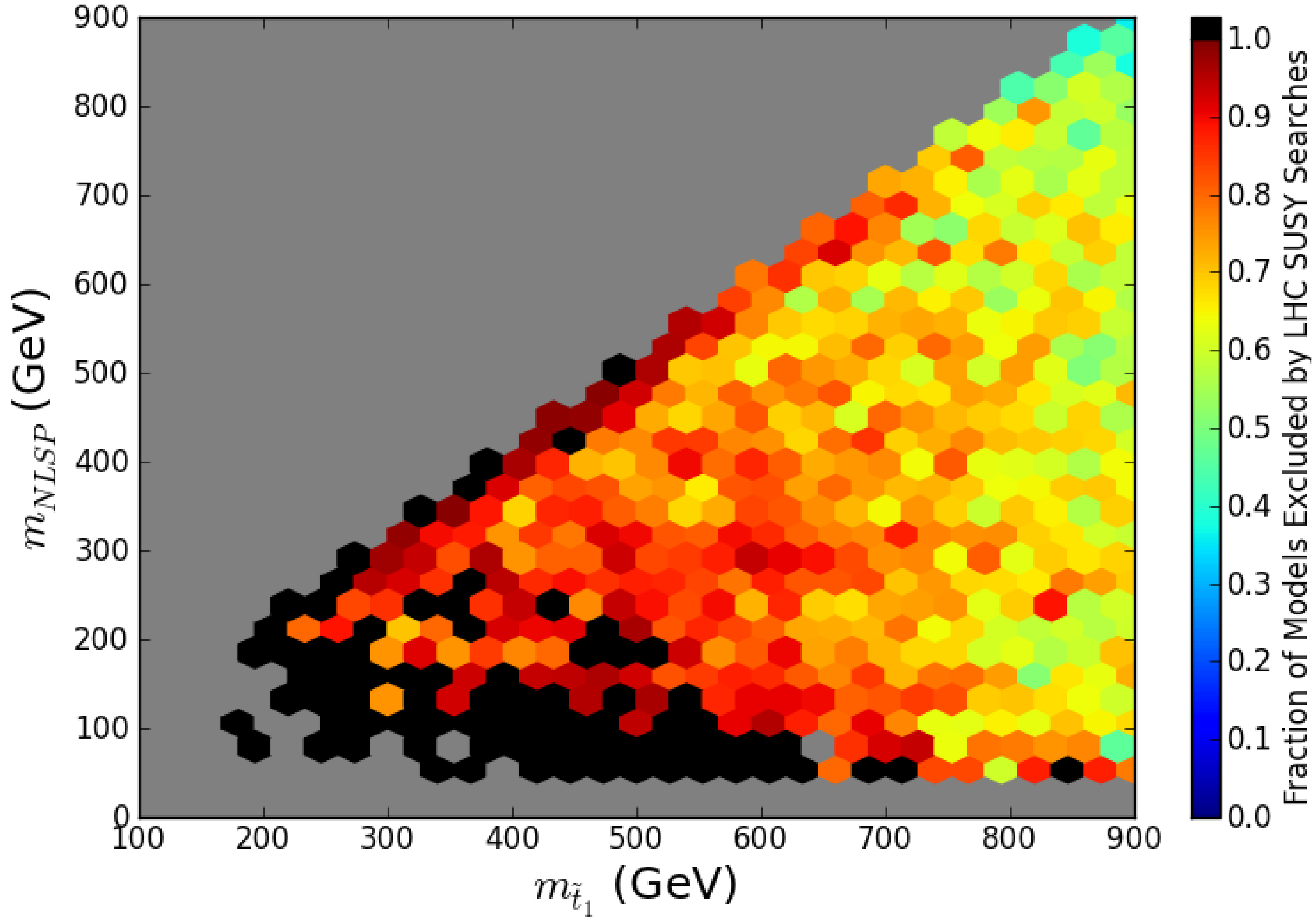


*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

*similar results obtained by CMS

However, only scratched the surface

- For example, still plenty of room for natural SUSY.
  - At the LHC, naturalness = top partner.



pMSSM scan

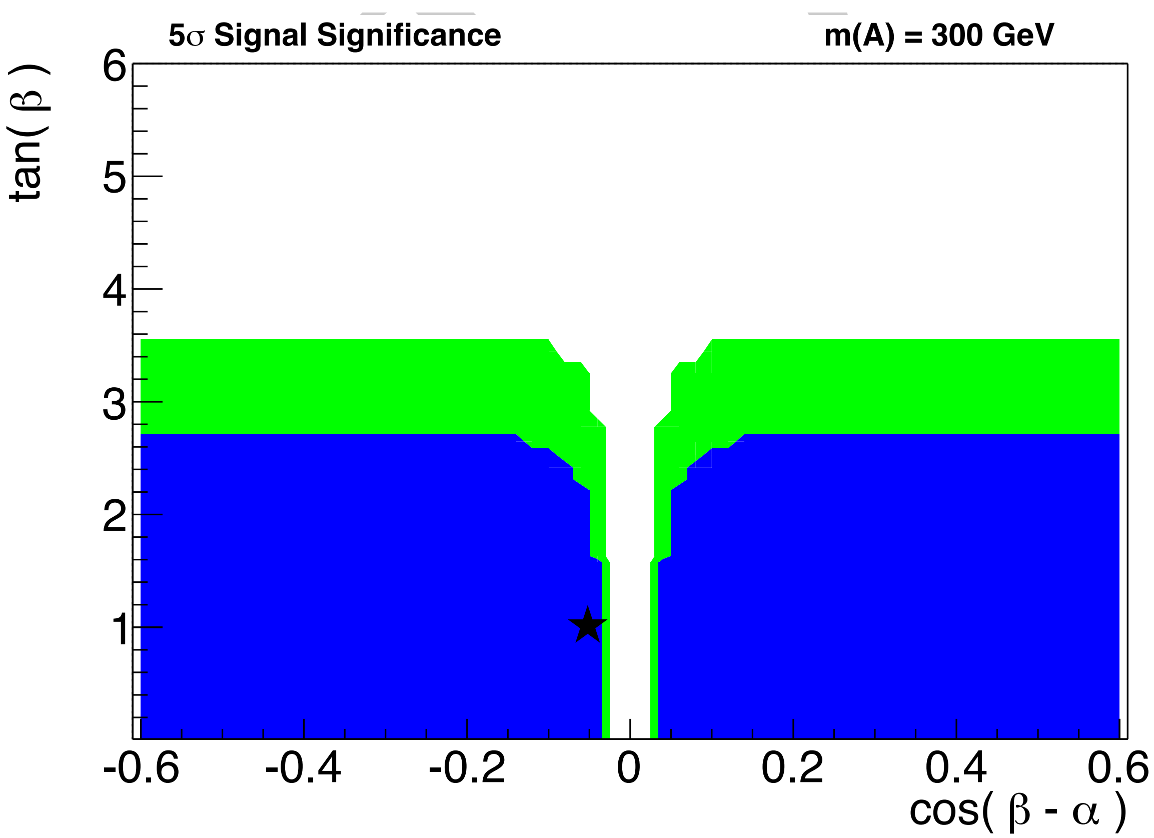
Looking towards the future: Big questions to address

Careful Study of the Higgs need to be vigorously pursued.

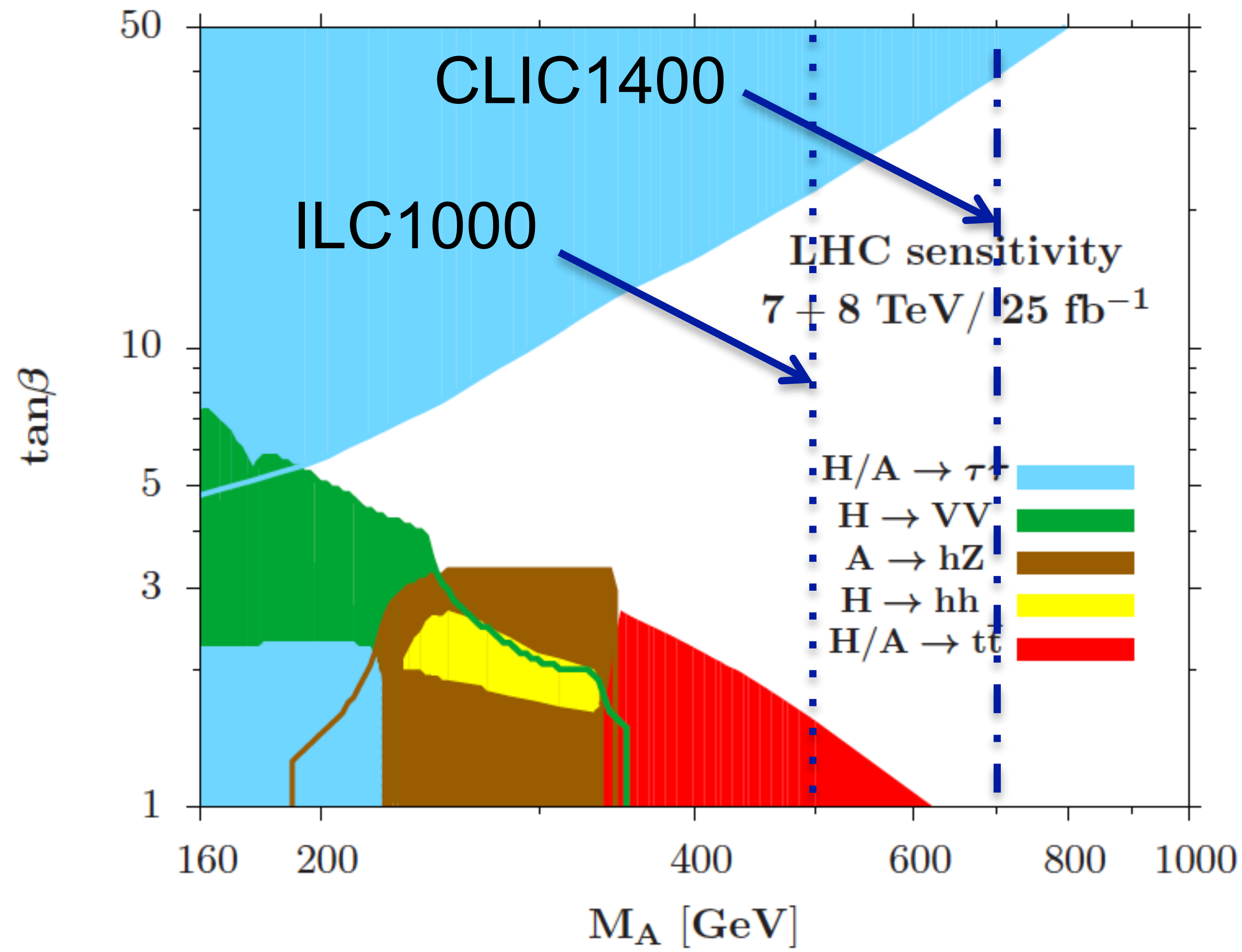
- We have a new particle, but we don't understand it very well yet!
  - A **new kind of particle**: spin-0, key role in EWSB
- High luminosity LHC, ILC, Higgs factories, CLIC, μμ...
  - shift of Higgs coupling $\delta \approx v^2/M^2_{NP}$,
    e.g. $\delta \approx 5\%$ $M_{NP} \approx$ TeV
  - Complementary to collider searches for resonances
    - Direct searches for extended Higgs sector (+VLHC)
- Possible surprises: exotic decays, connection to baryogenesis...

Search for extended Higgs sector

300 GeV A, A→ Zh



LHC 14 300 fb^{-1} LHC 14 3000 fb^{-1}



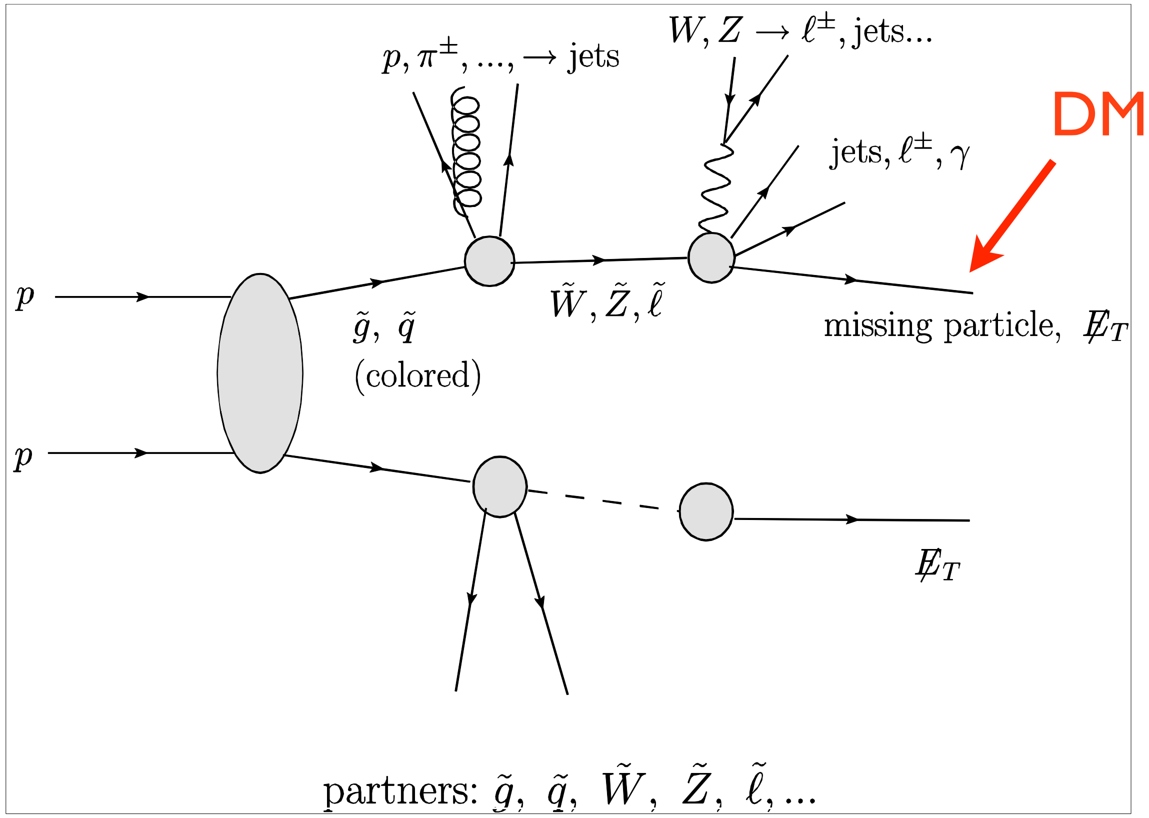
– Higher luminosity, cleaner environment helps.

Investigate the WIMP dark matter: cover all the ground

- Dark matter is the only **known** new physics beyond the Standard Model.
- $$m_{\rm WIMP} \leq 2\ {\rm TeV} \left(\frac{g_{\rm eff}^2}{0.3}\right)$$

LHC	VLHC 100 TeV	ILC/CLIC
M_{DM} ~10^2s GeV	M_{DM} ~TeV(s)	M_{DM} ~ 0.5 E_{cm} Spin, coupling Is it WIMP?

“standard” story.



- WIMP is part of a complete model at weak scale.
- It’s produced as part of the NP signal, shows up as missing energy.
  - Dominated by colored NP particle production: eg. gluino.
- The reach is correlated with the rest of the particle spectrum.
  - Can have blind spots/regions especially at pp collider.

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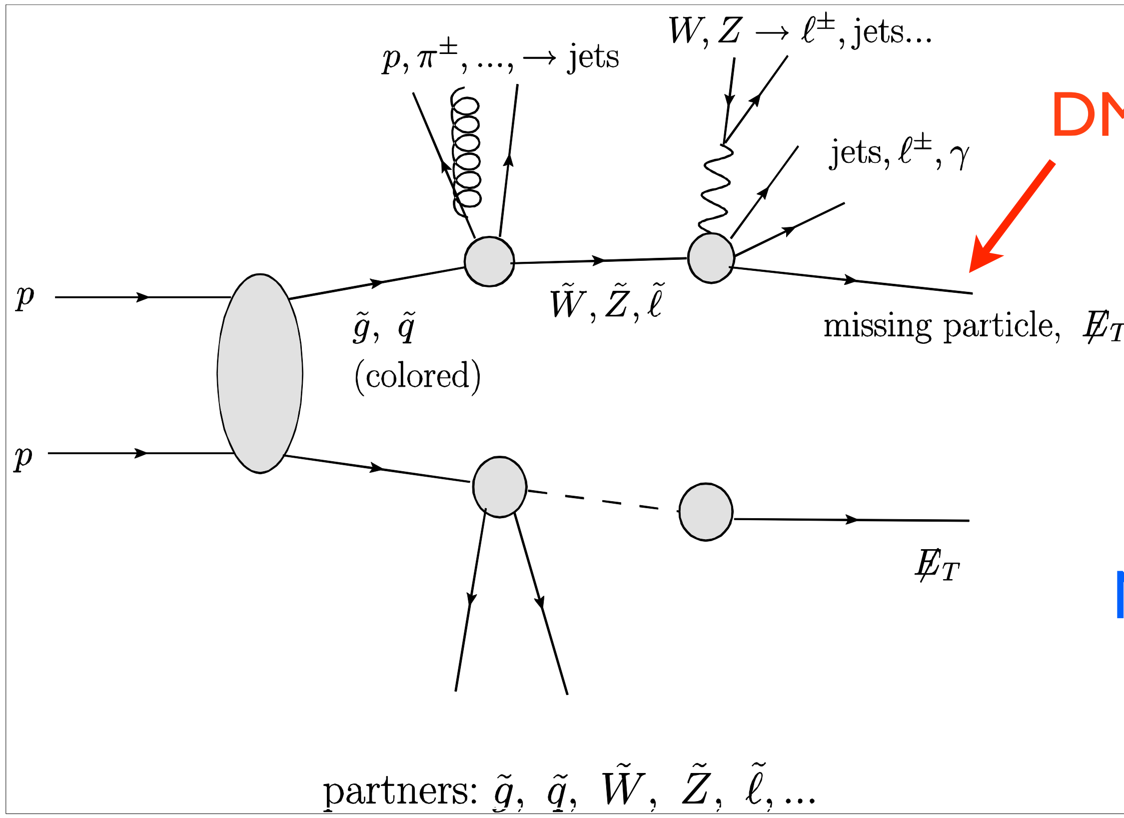
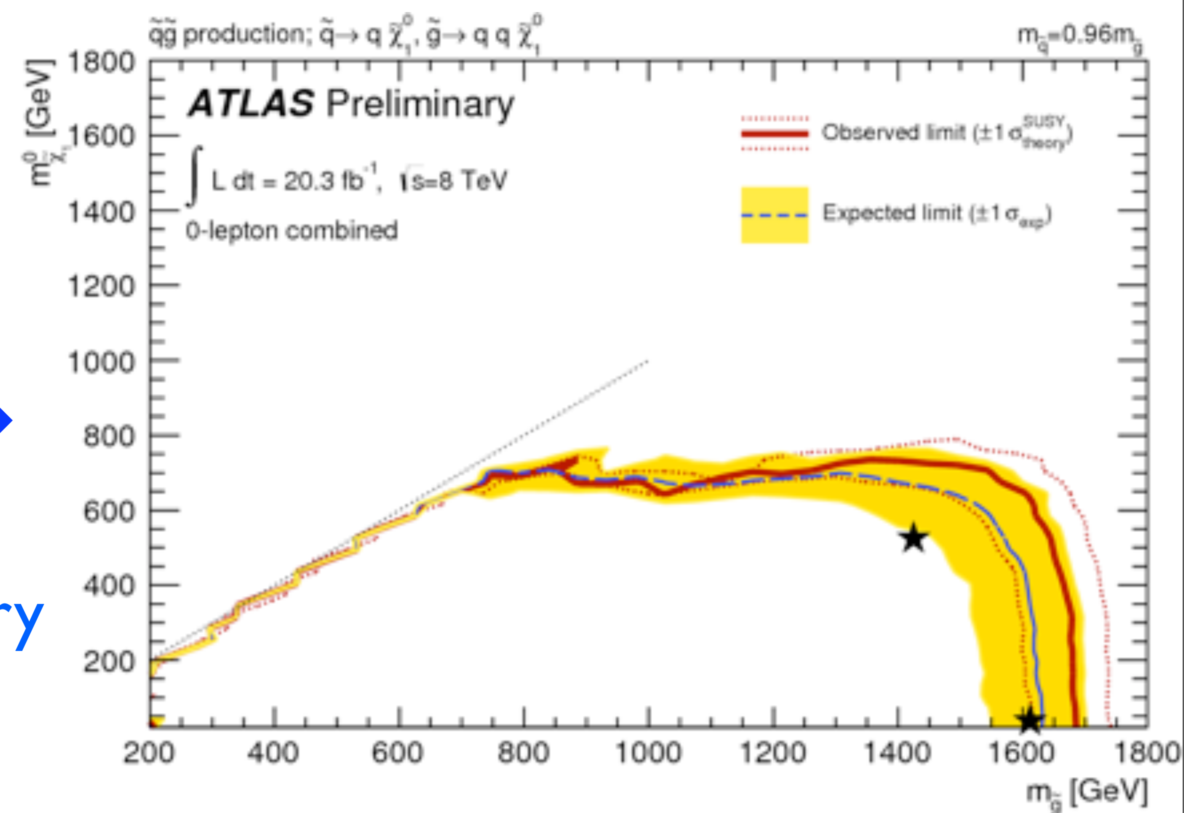


No discovery yet



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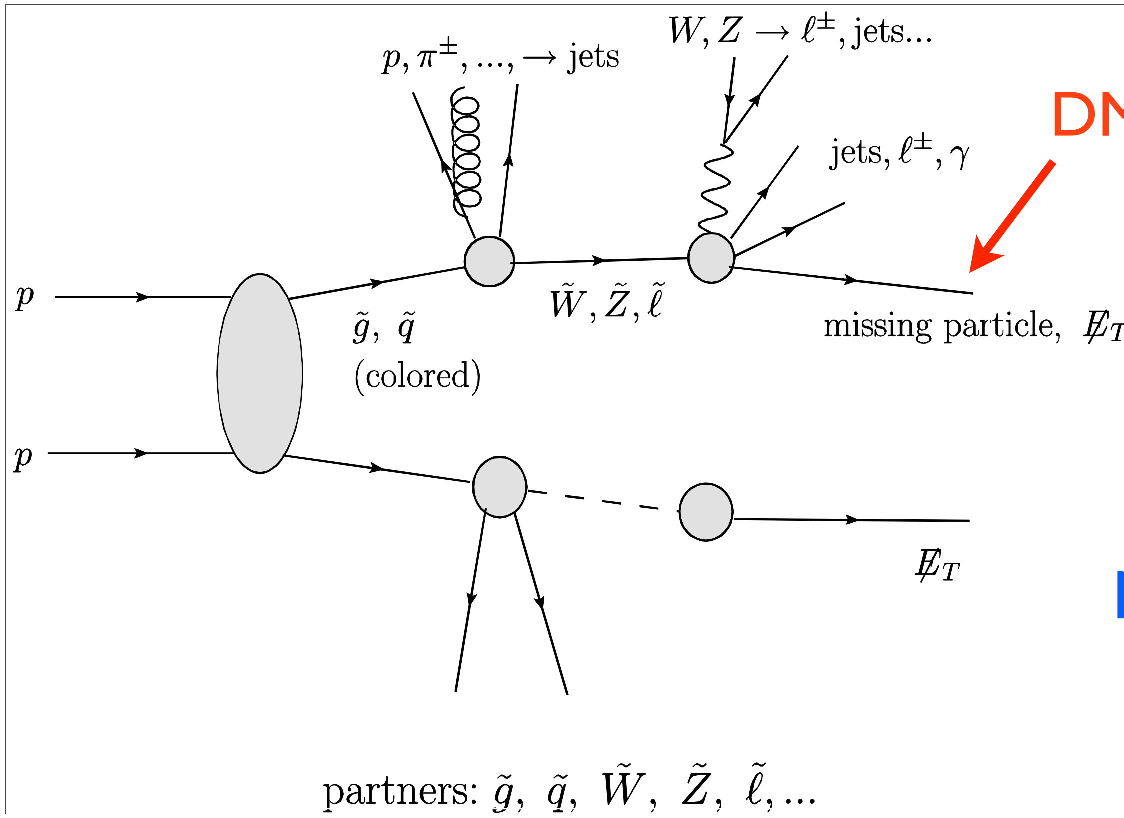

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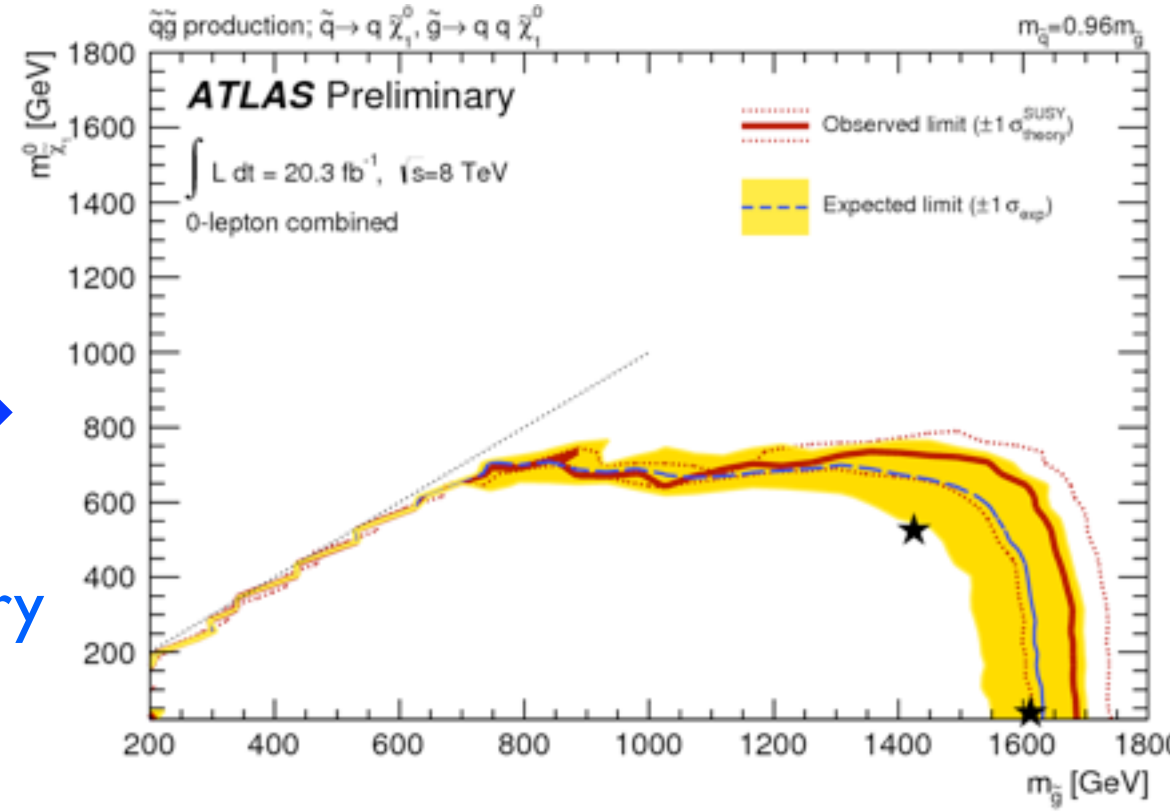
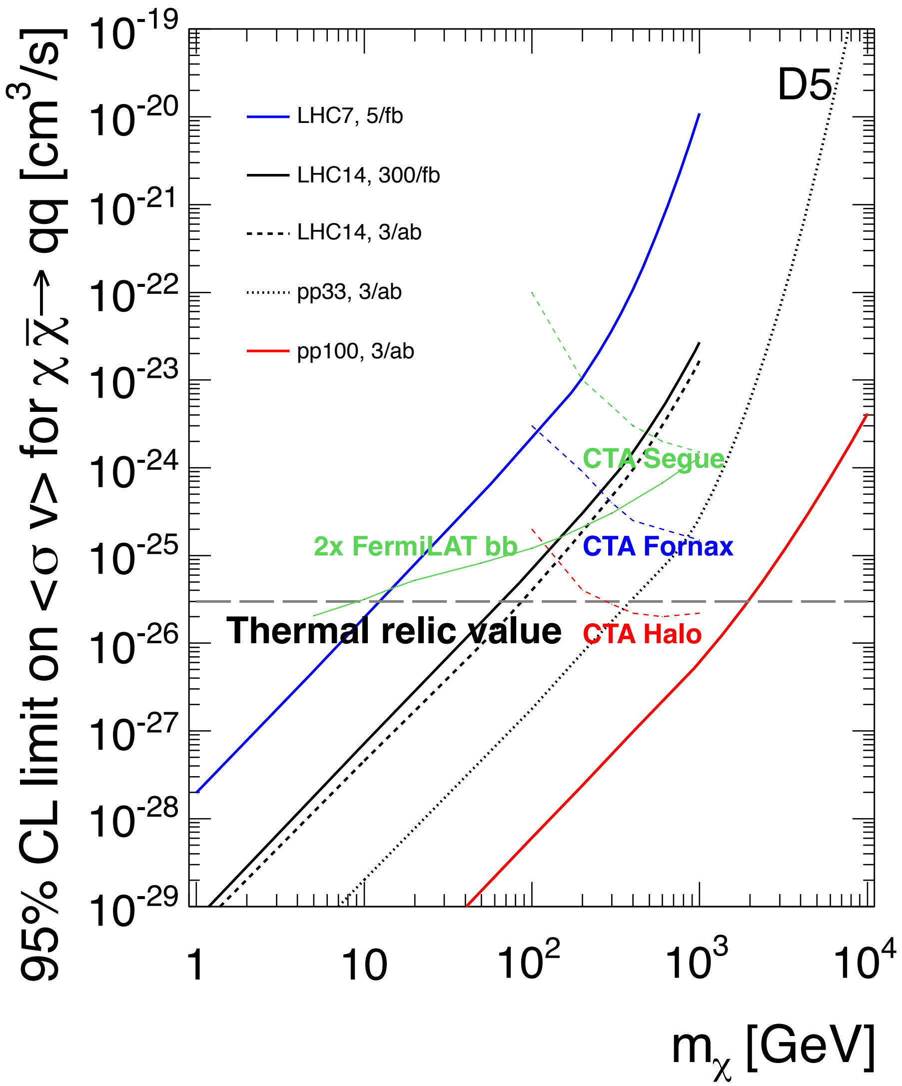


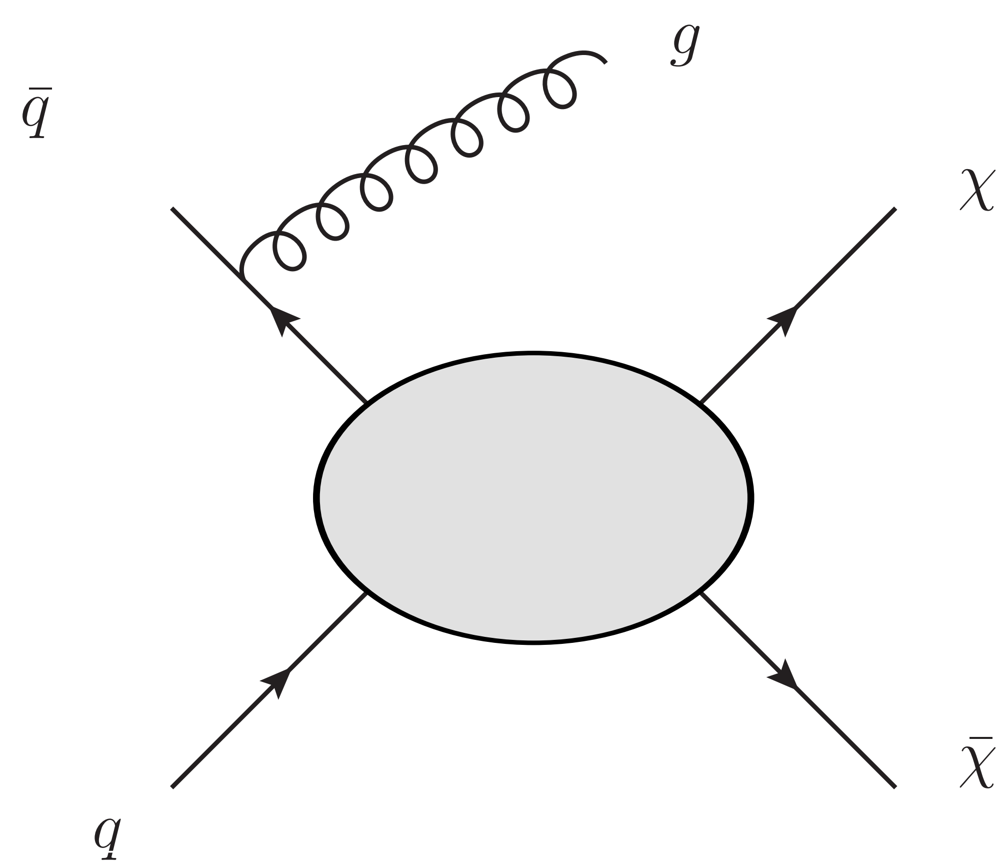
Of course, still plausible, will keep looking.
Higher energy ⇒ higher reach

Lepton collider ⇒ better cover possible blind spots

mono-jet

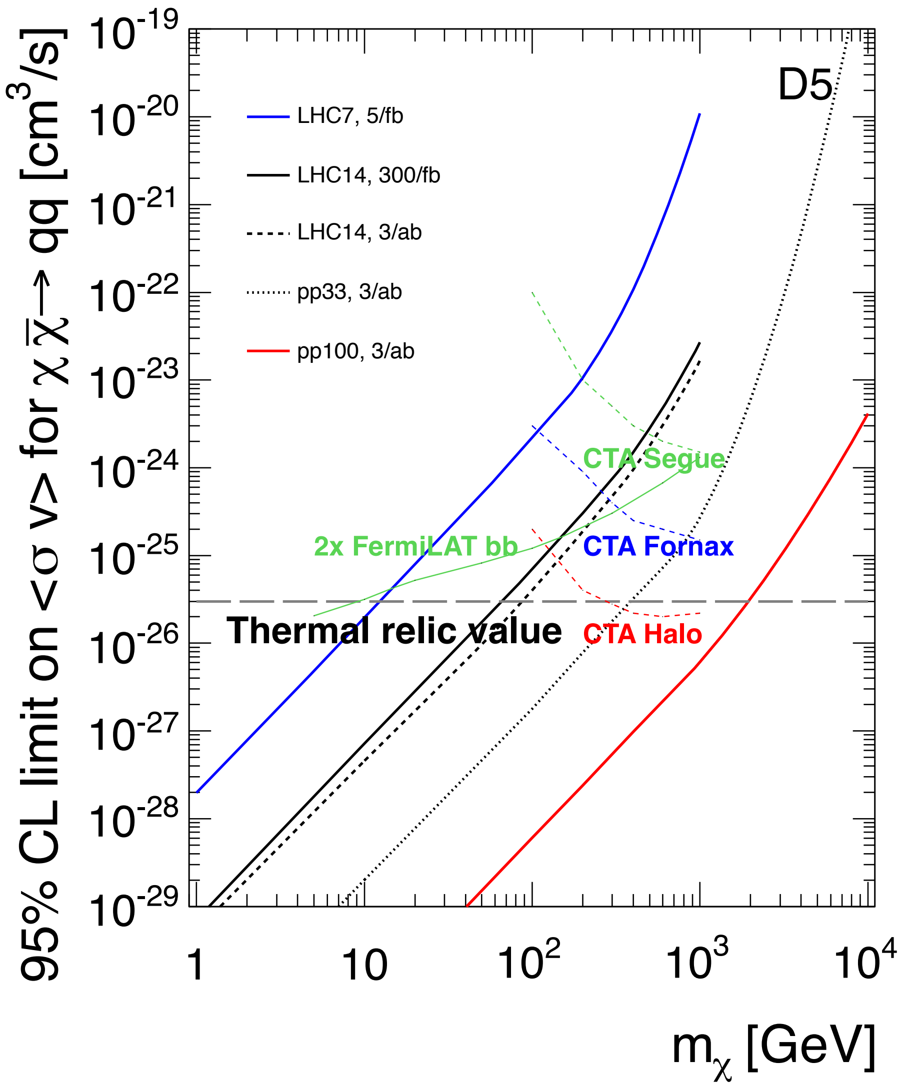


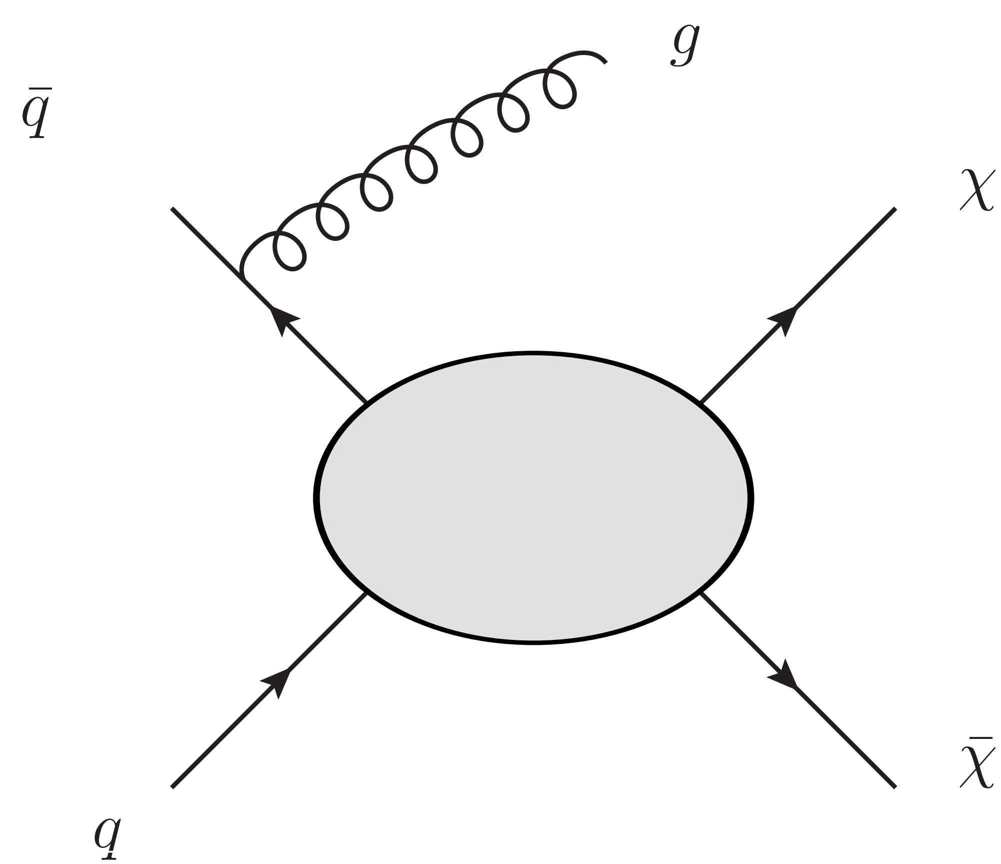
95% CL limit on <σ v> for $\chi\bar{\chi} \rightarrow$ qq [cm^3/s]
D5
LHC7, 5/fb
LHC14, 300/fb
LHC14, 3/ab
pp33, 3/ab
pp100, 3/ab
CTA Segue
2x FermiLAT bb
CTA Fornax
Thermal relic value
CTA Halo
m_χ [GeV]



$\bar{q}$
g
χ
q
$\bar{\chi}$

mono-jet





- Possible link to a possible dark sector.
- Strategy at EF strongly correlated with potential discovery at in direct/indirect detection.

Fully test the idea of naturalness

- Naturalness is at the foundation of our understanding of field theory.

- Tuning, scales with energy^{-2}
  - $\propto m^{-2}_{\text{top-partner, W/h partner}}$

- 14 TeV LHC(HL) can push fine tuning limit to at least 10^{-2}.

- 100 TeV VLHC can push this to about 10^{-4}.

- ILC/CLIC can discover and study Higgs/W partners very well.

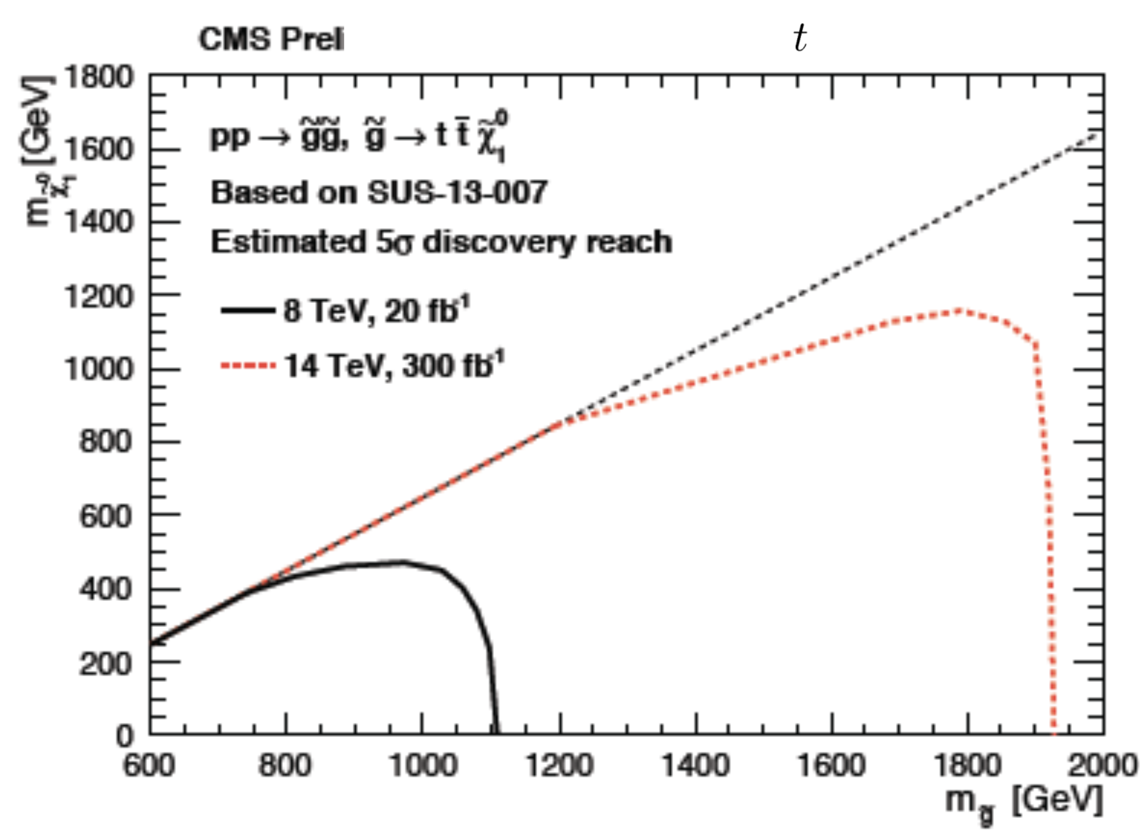
If top partner is discovered

- Discovery in tt+MET, discovery of a potential dark matter candidate at the same time!
  - DM can be studied at HL-LHC, ILC, CLIC
- We want to measure
  - spin. (SUSY or others).
  - higher luminosity pp, lepton collider with enough energy.
- Higgs coupling: addressing the naturalness?
  - Need VLHC

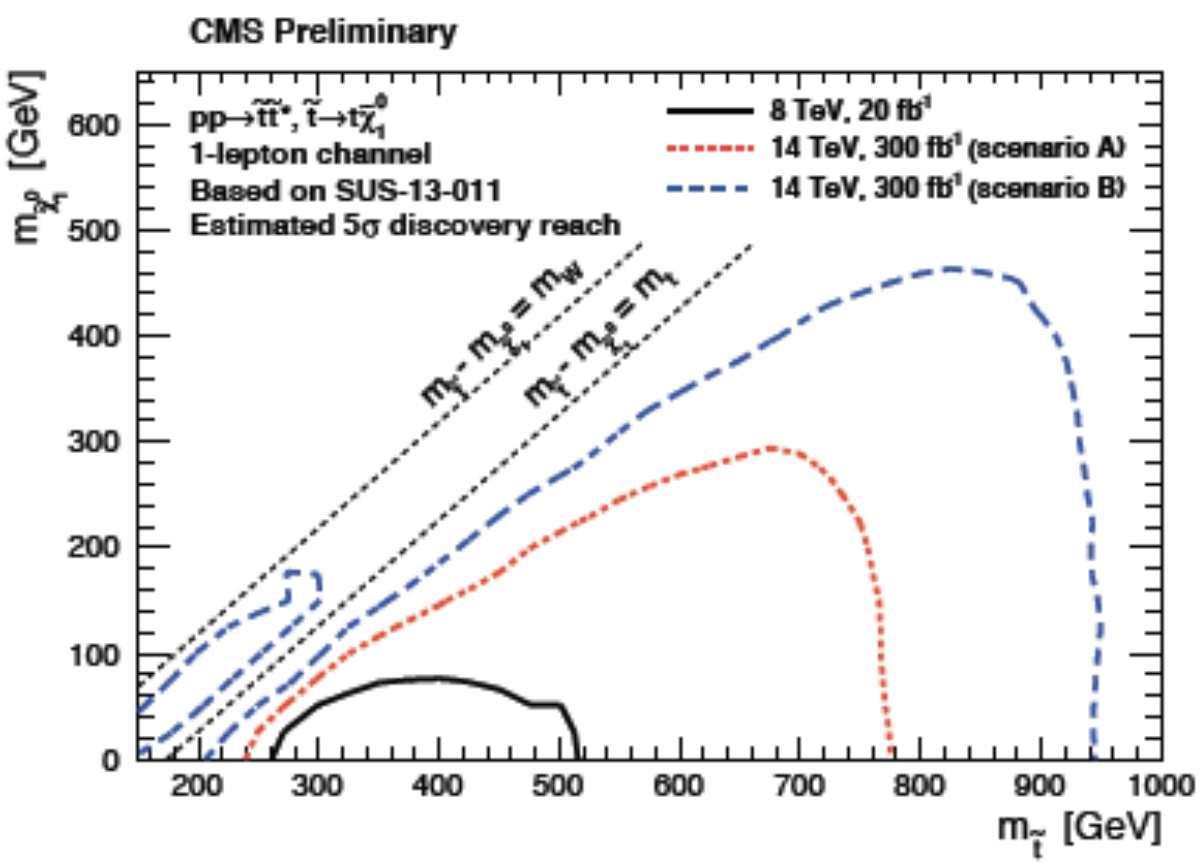
Looking towards the future: Machines and scenarios

14 TeV LHC (300 fb^{-1}). "LHC Run 2"

- Great enhancement in reach.
  - x 2-3 in mass, 10 in tuning



gluino



stop

LHC Run 2 sees nothing?

- Plenty of reason to go further!

- Fine tuning.
  - worth going further than 10^{-2}

- WIMP dark matter $m_{\mathrm{WIMP}} \leq 2\ \mathrm{TeV}\left(\frac{g_{\mathrm{eff}}^2}{0.3}\right)$
  - Can not explore most of the parameter space at 14 TeV. Need to go to higher energy.

LHC Run 2 sees nothing?

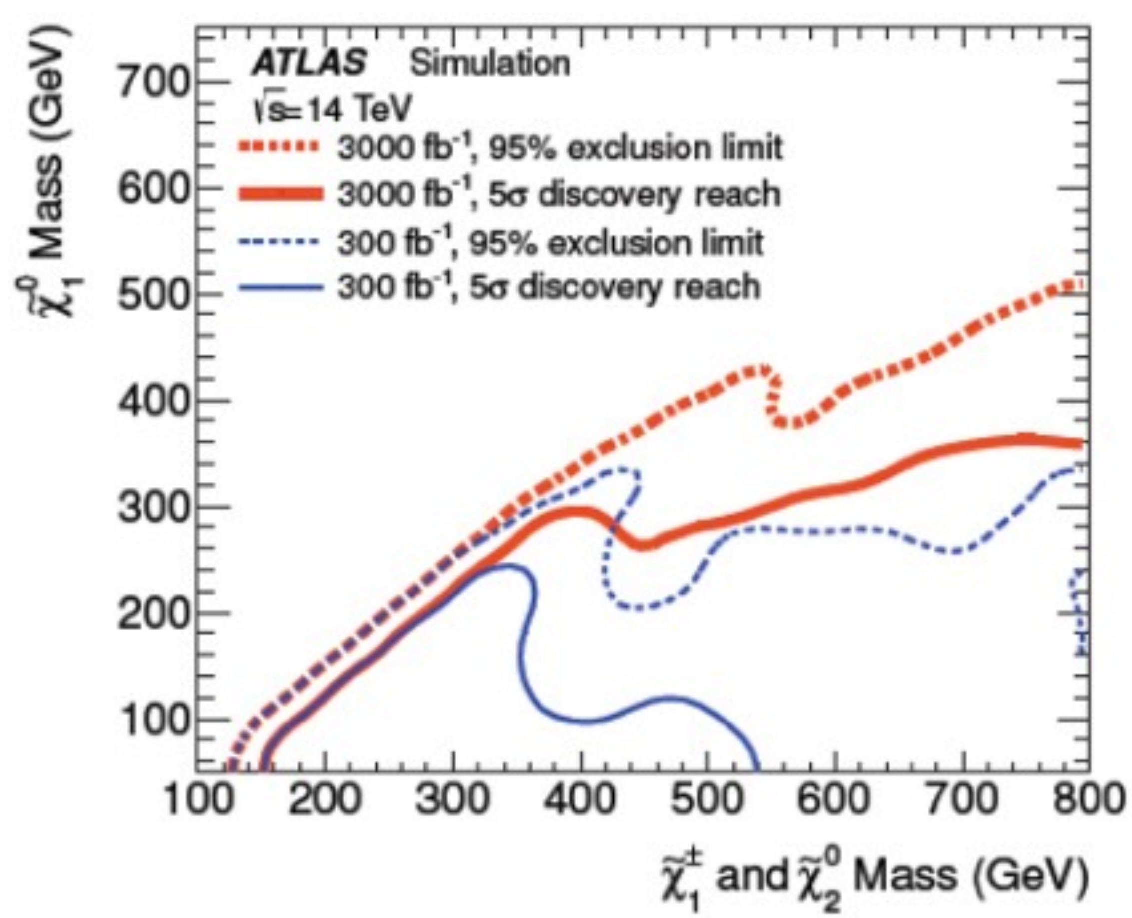
- Little Hierarchy.
  - Flavor, CP, precision measurements seem to point to a higher scale (about 10 TeV).
  - This is the reason we have seen nothing?
  - Clearly out of reach at LHC 14 $\Rightarrow$ Higher energy

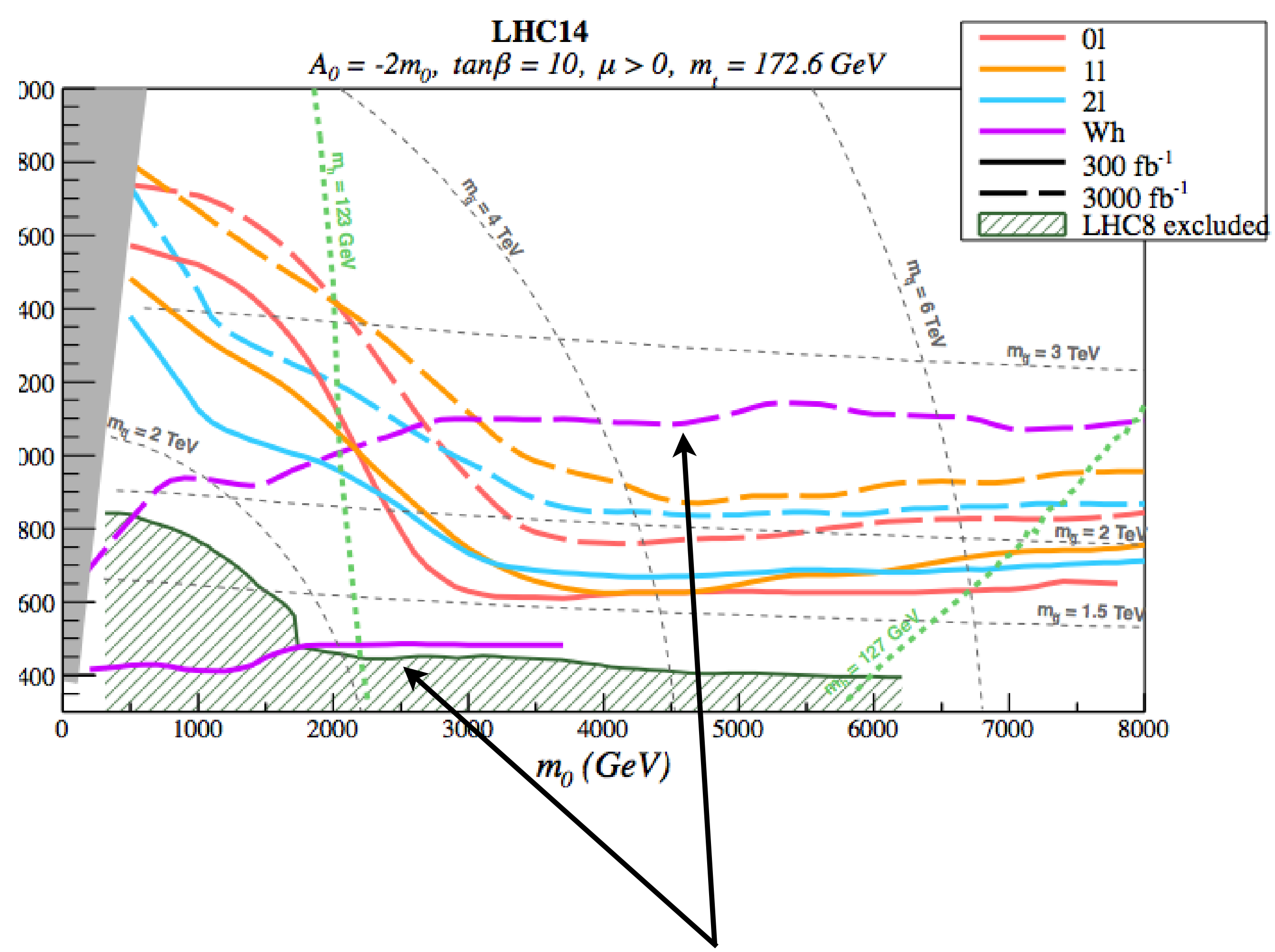
- Loopholes at the LHC.
  - Electroweak-ino, compressed spectrum, stealth...
  - ILC/CLIC, if accessible.

High luminosity LHC

- Any run 2 anomalies can be studied.

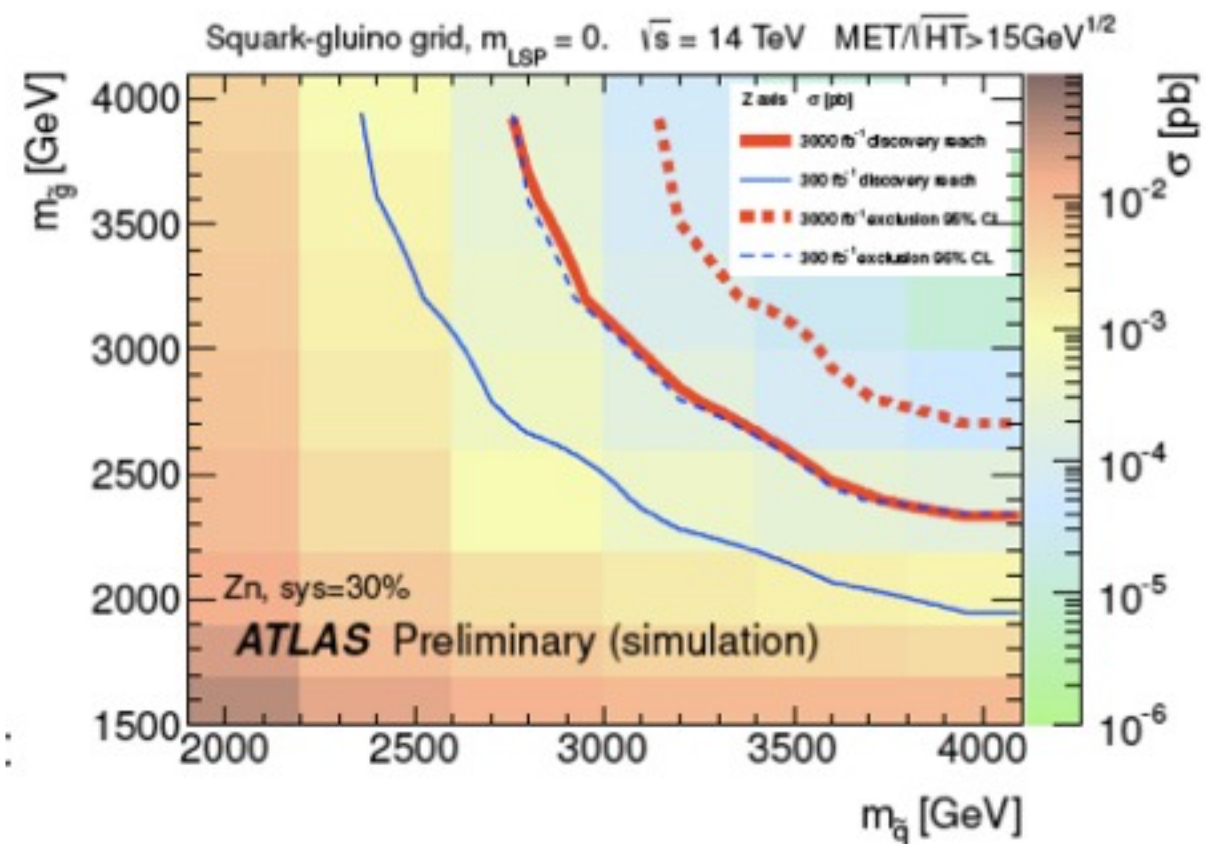
- Extends reach, especially in the EW sector.



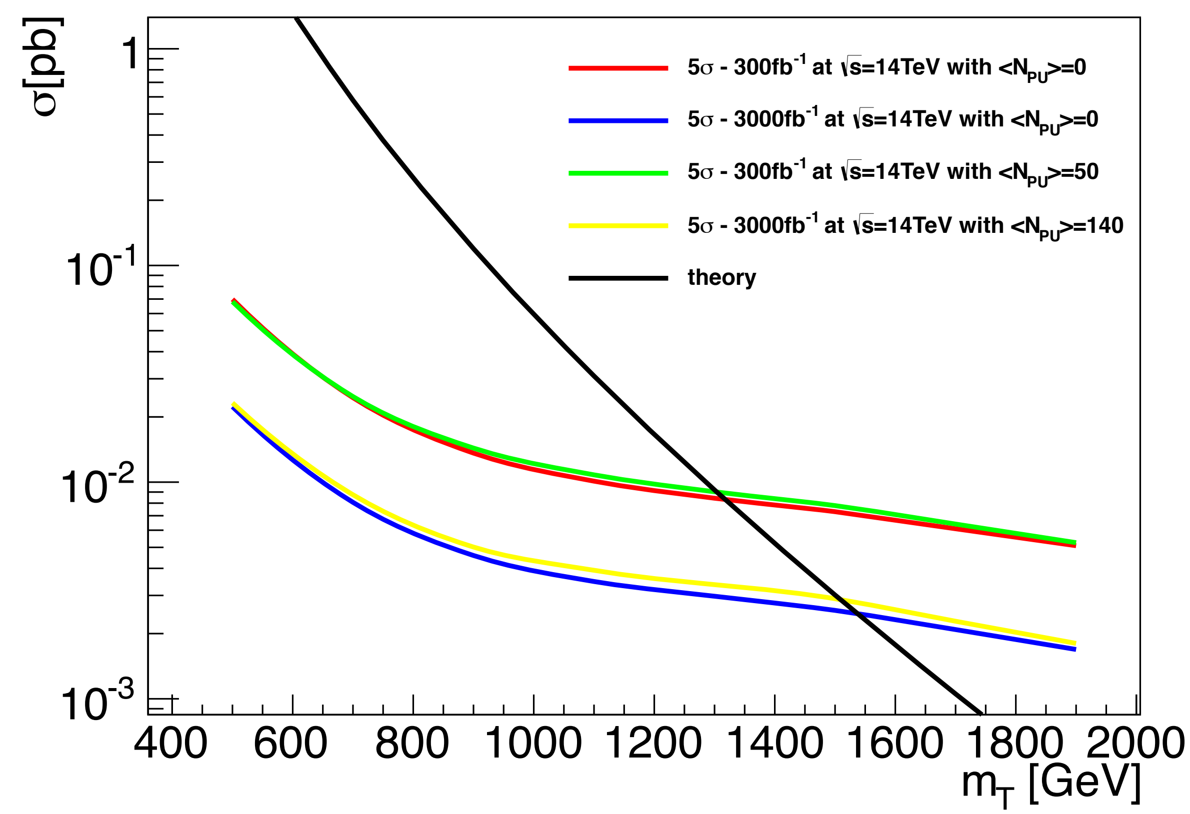


electroweak-ino

Extend the reach for colored states



gluino/squark

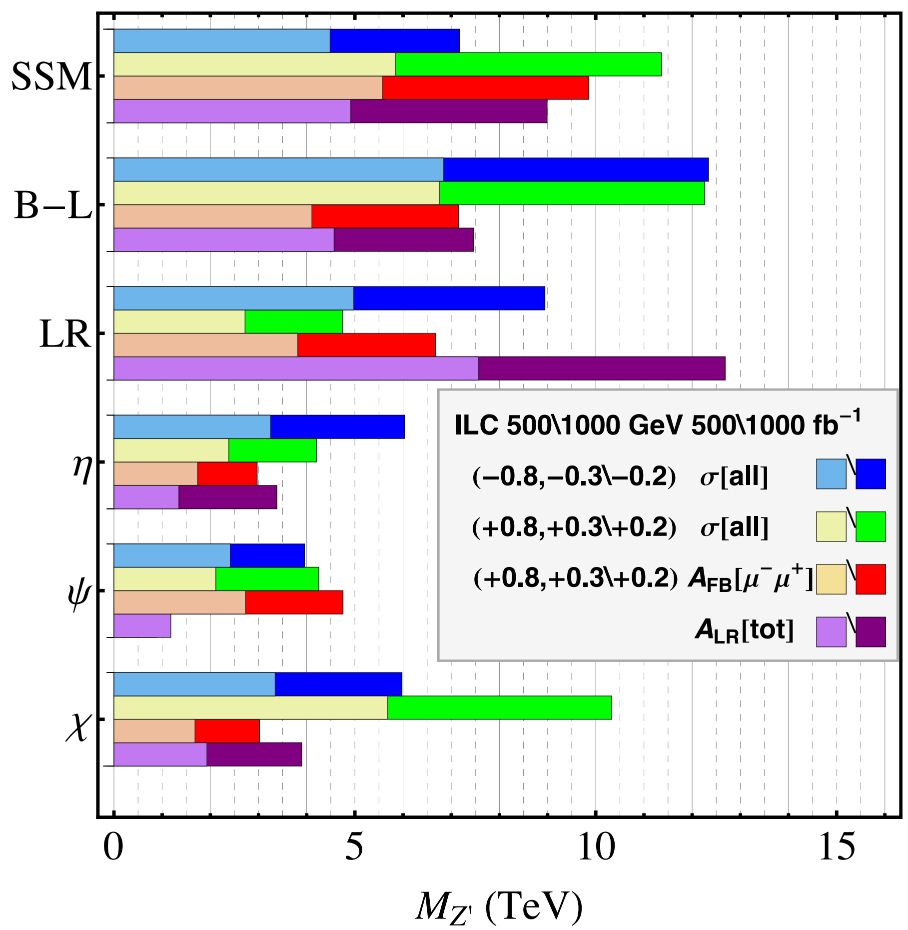


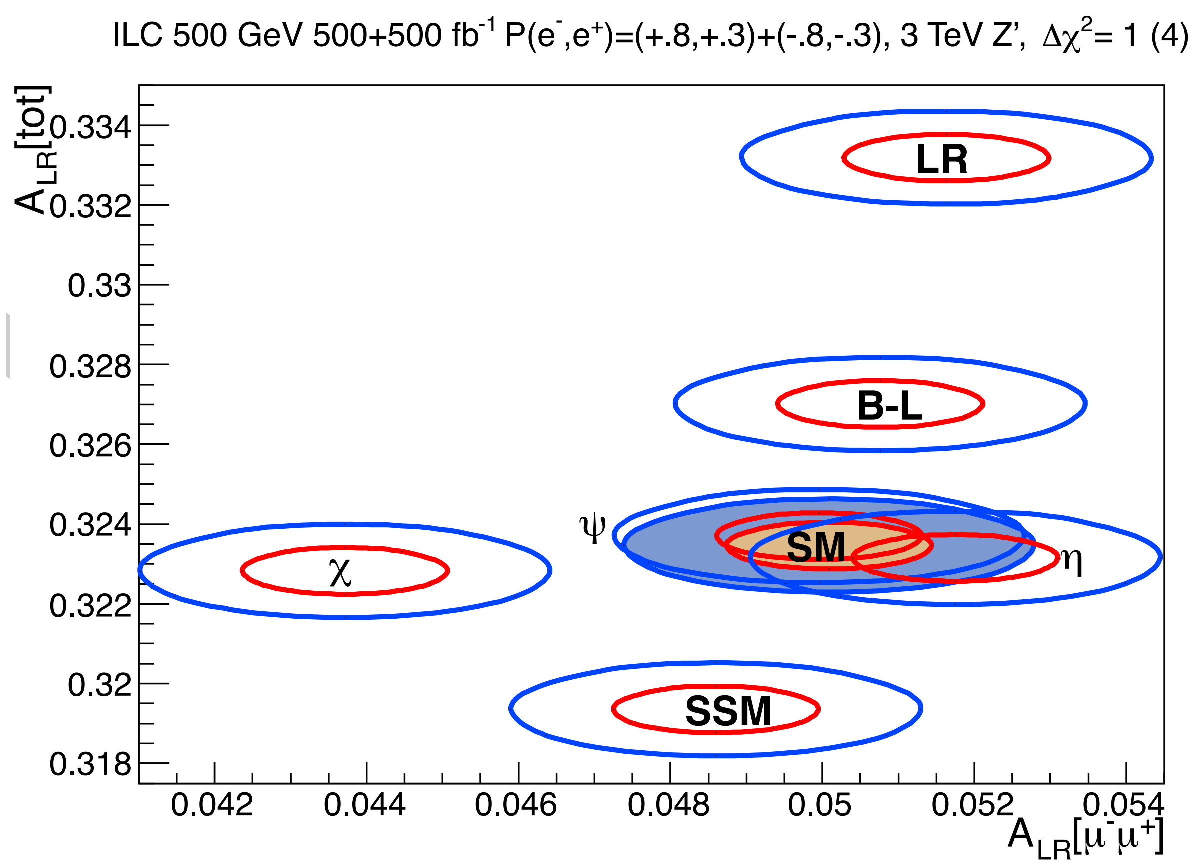
T’

- More data can make us smarter! Expecting surprises.

ILC program

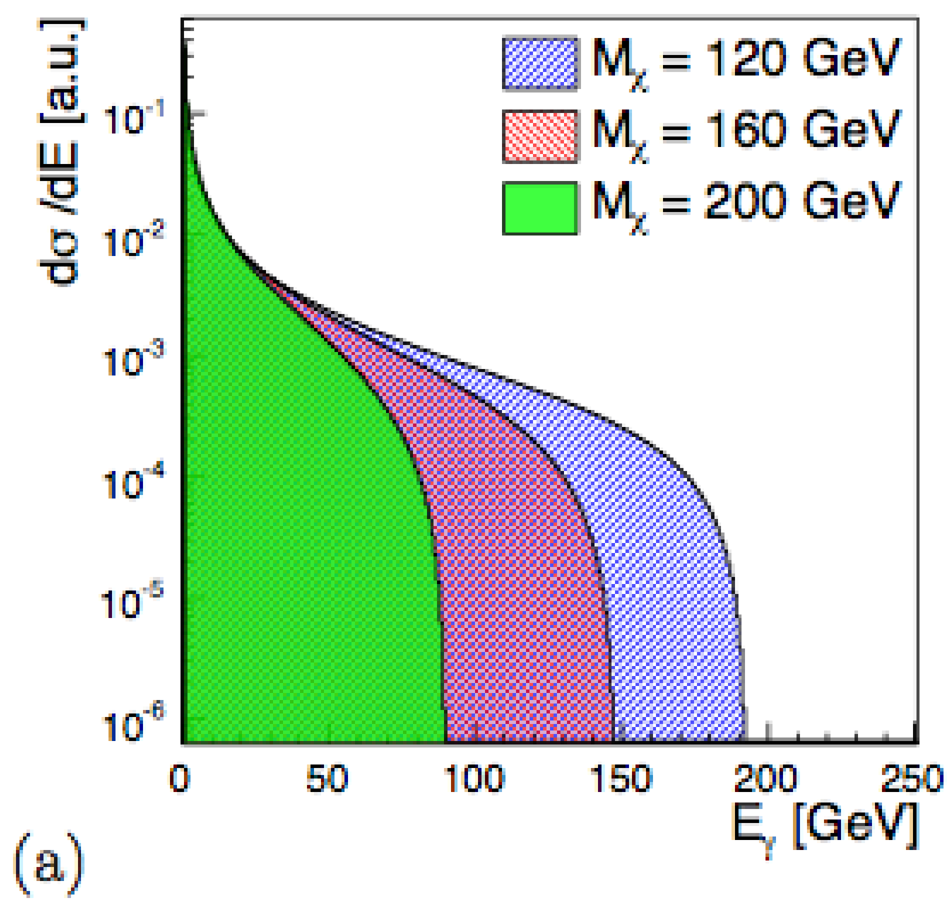
- Excellent reach for discovery and measurements.
  - Essentially loophole free within accessible energy regime.

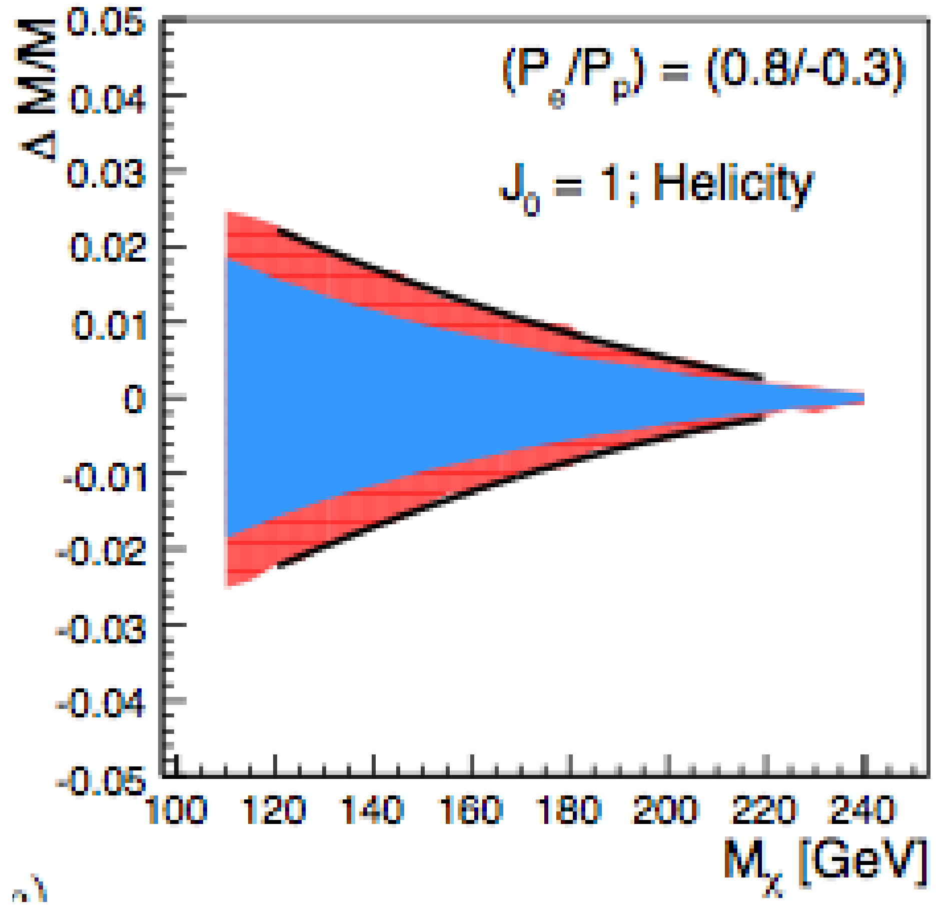




Z'

Understanding DM at the ILC

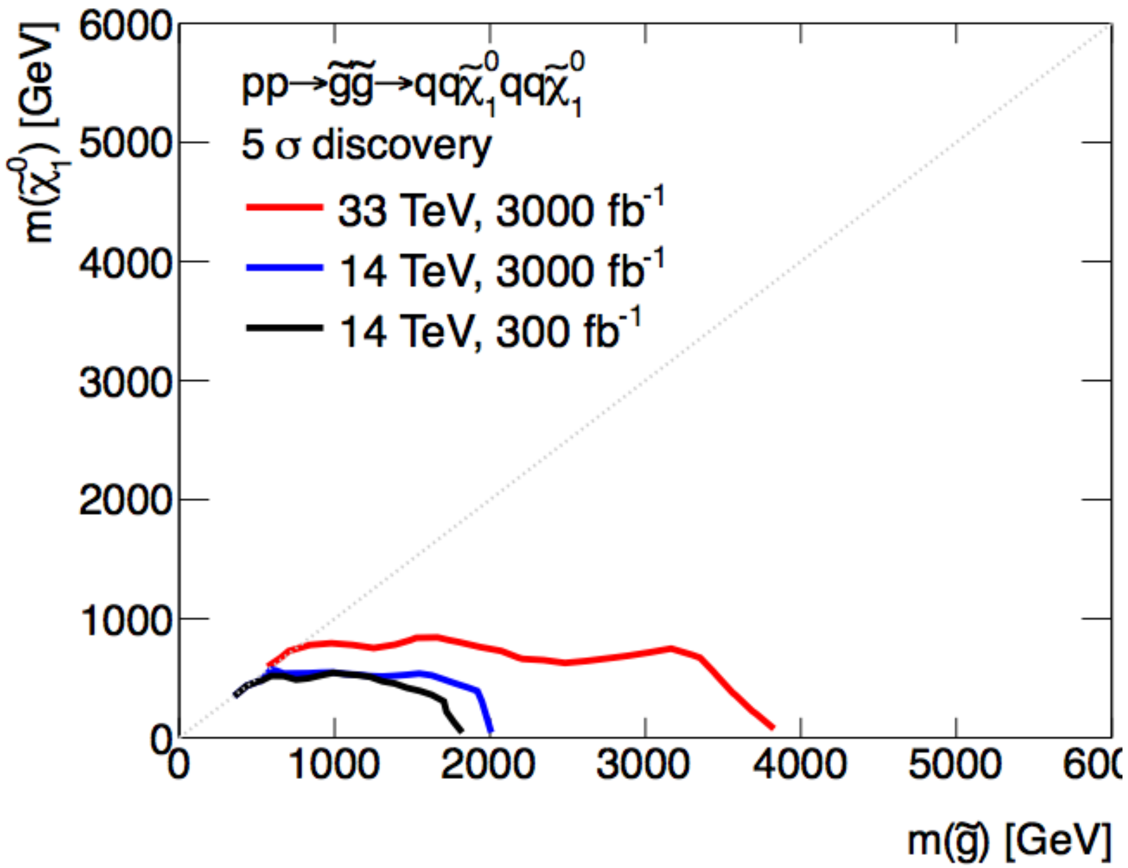


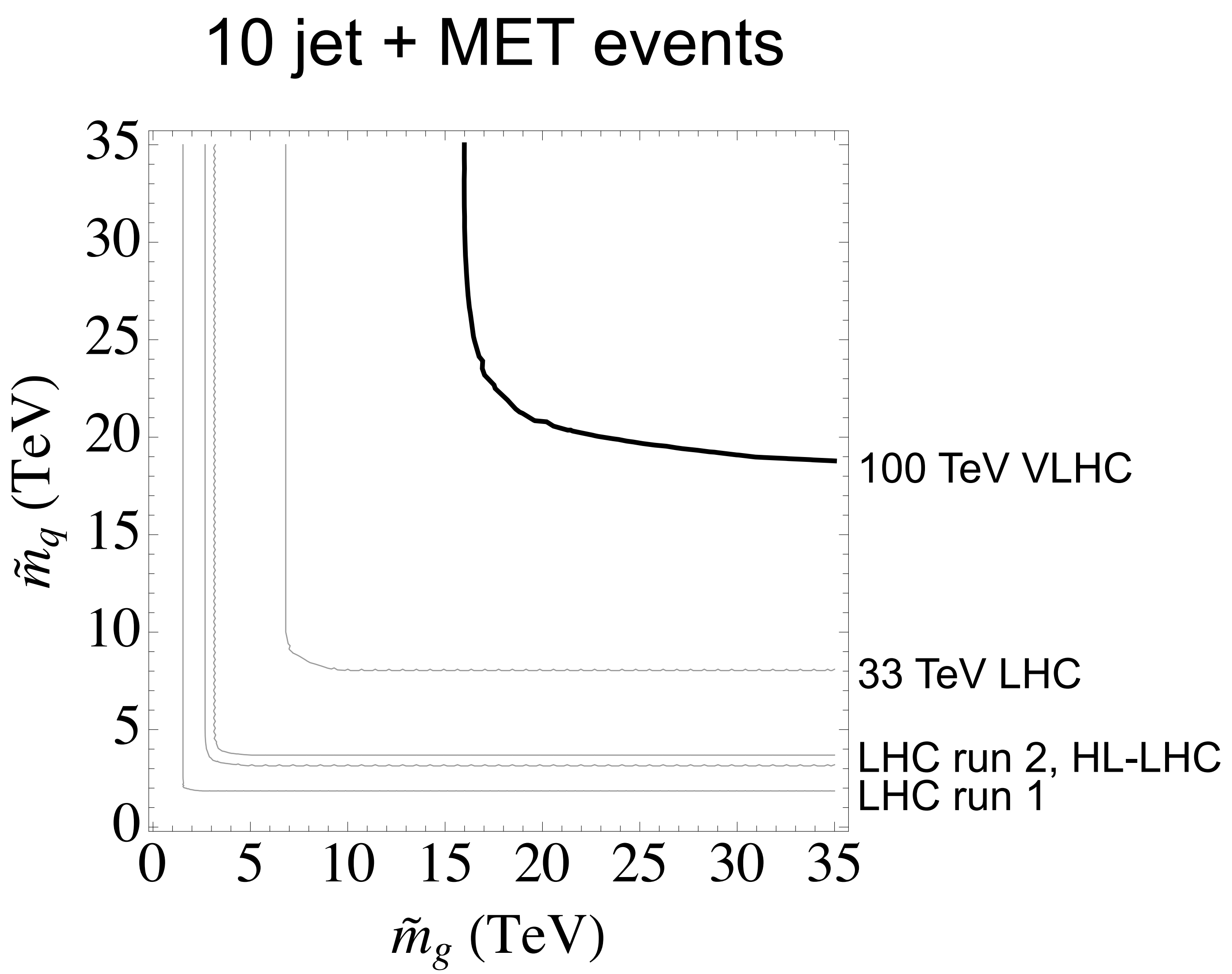


Dark matter mass

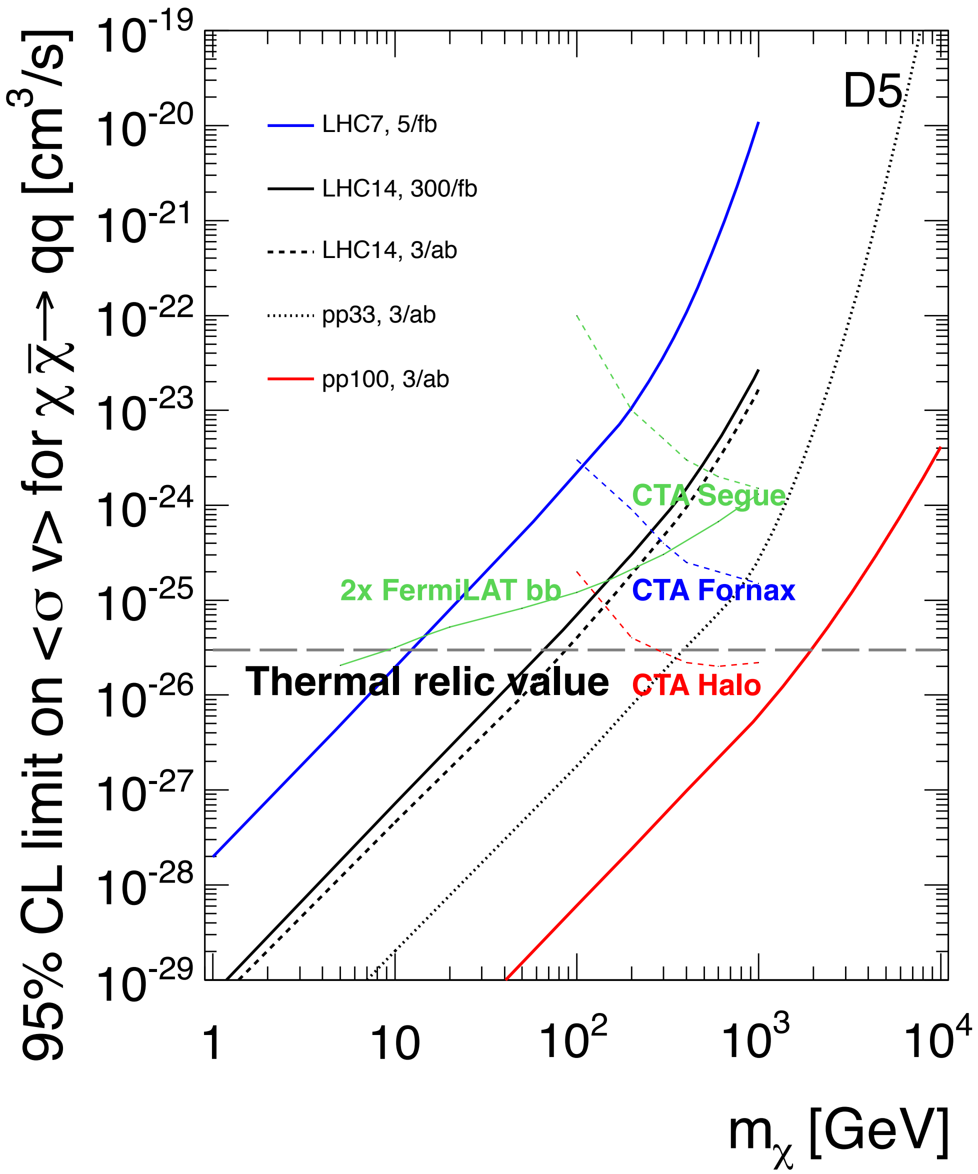
VLHC: 33 TeV and 100 TeV

- Big leap in reach.
  - fine tuning to 10^{-4}, TeV dark matter.

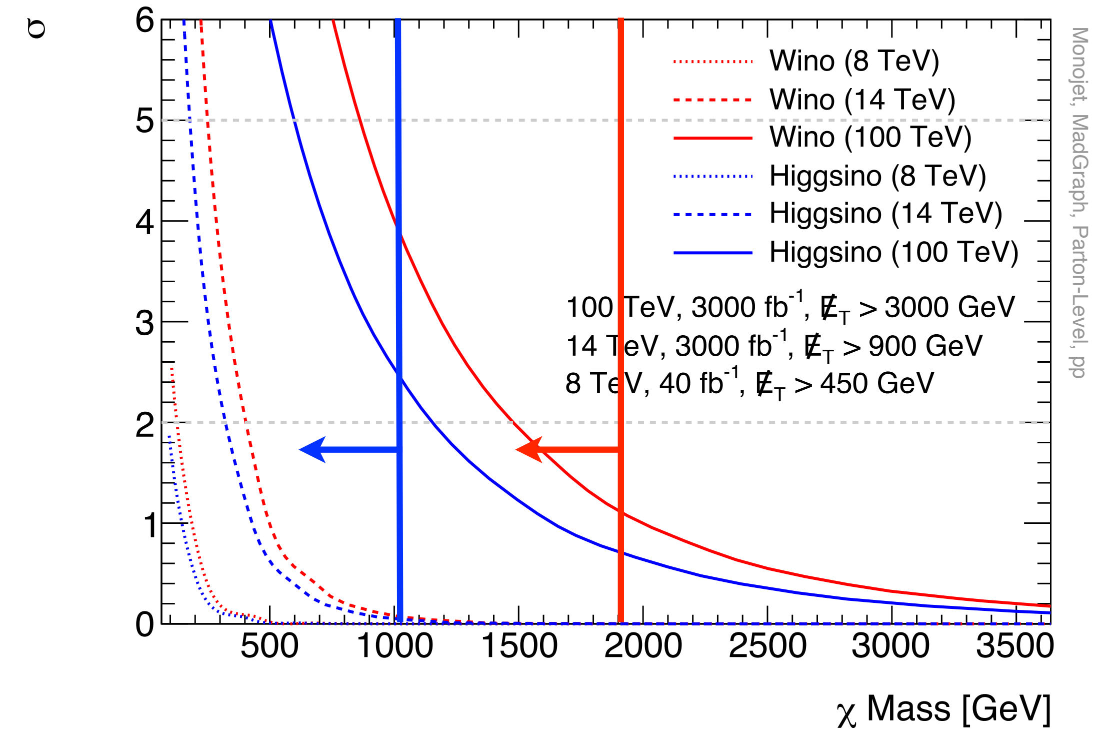




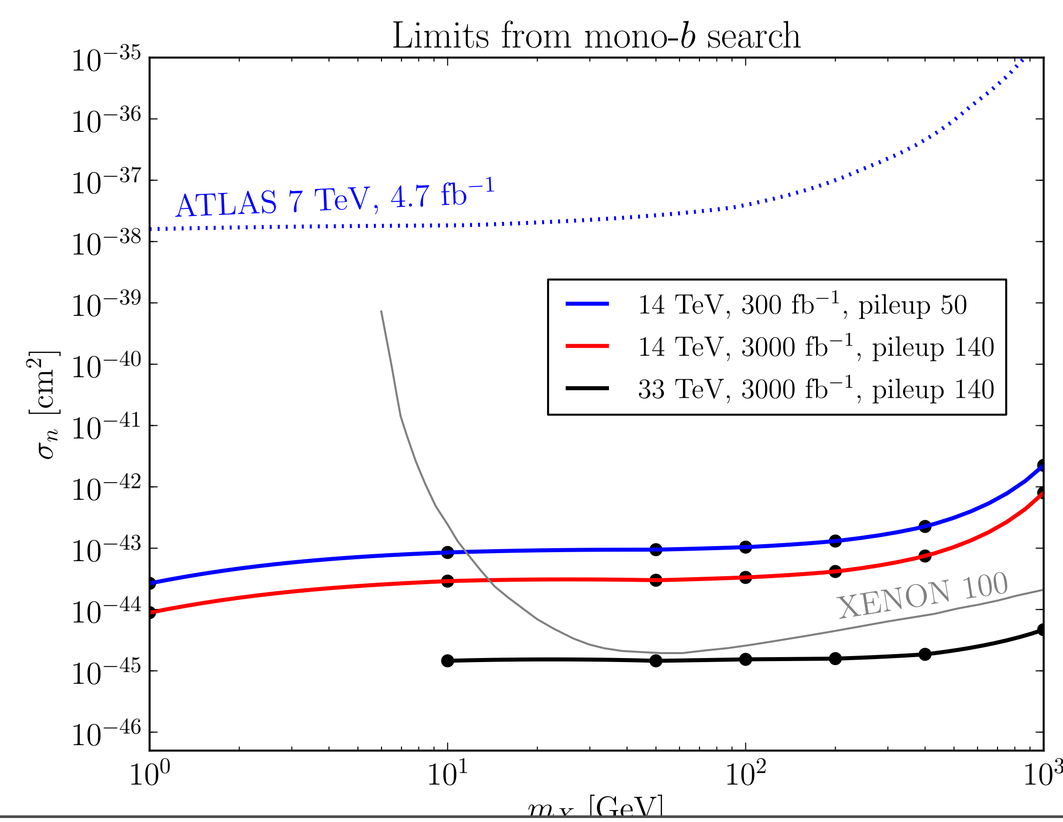
Finally, access TeV WIMPs



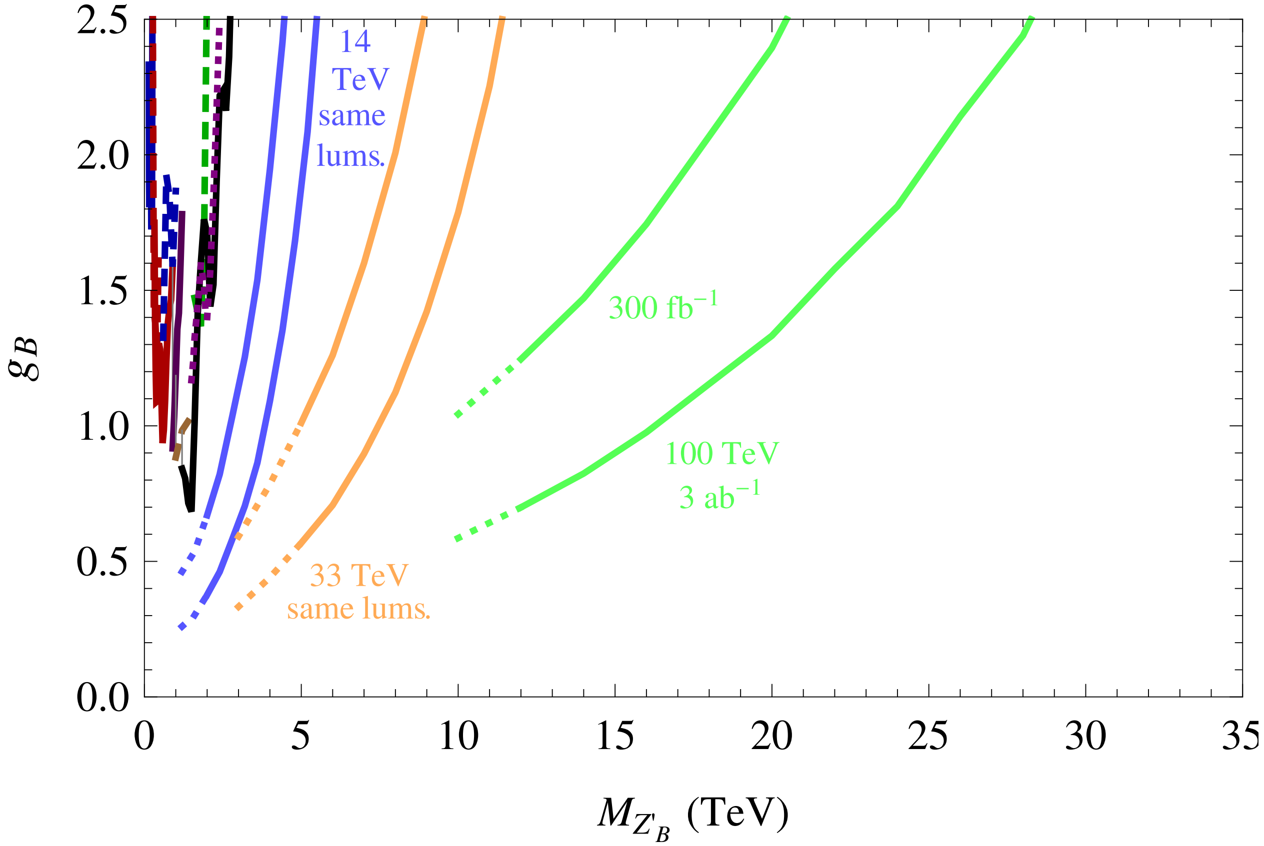
SUSY WIMP



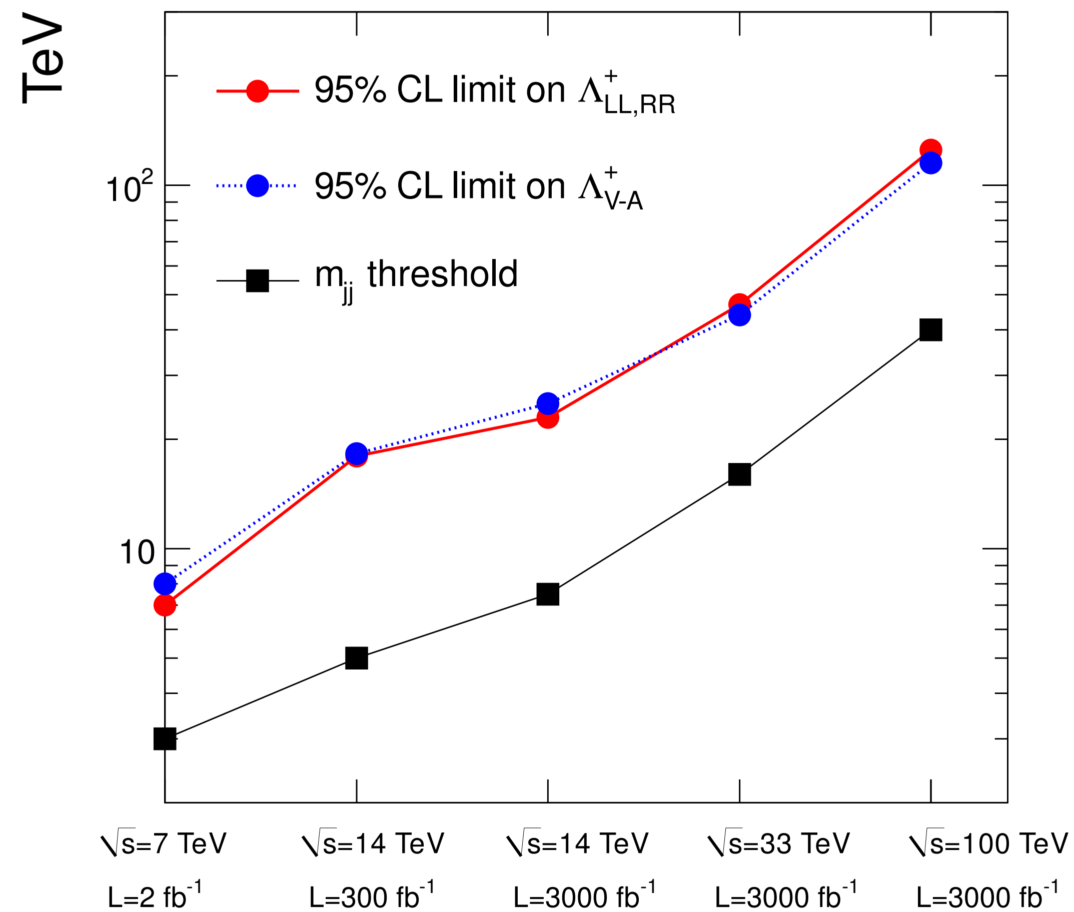
M. Low, L. Wang [preliminary]



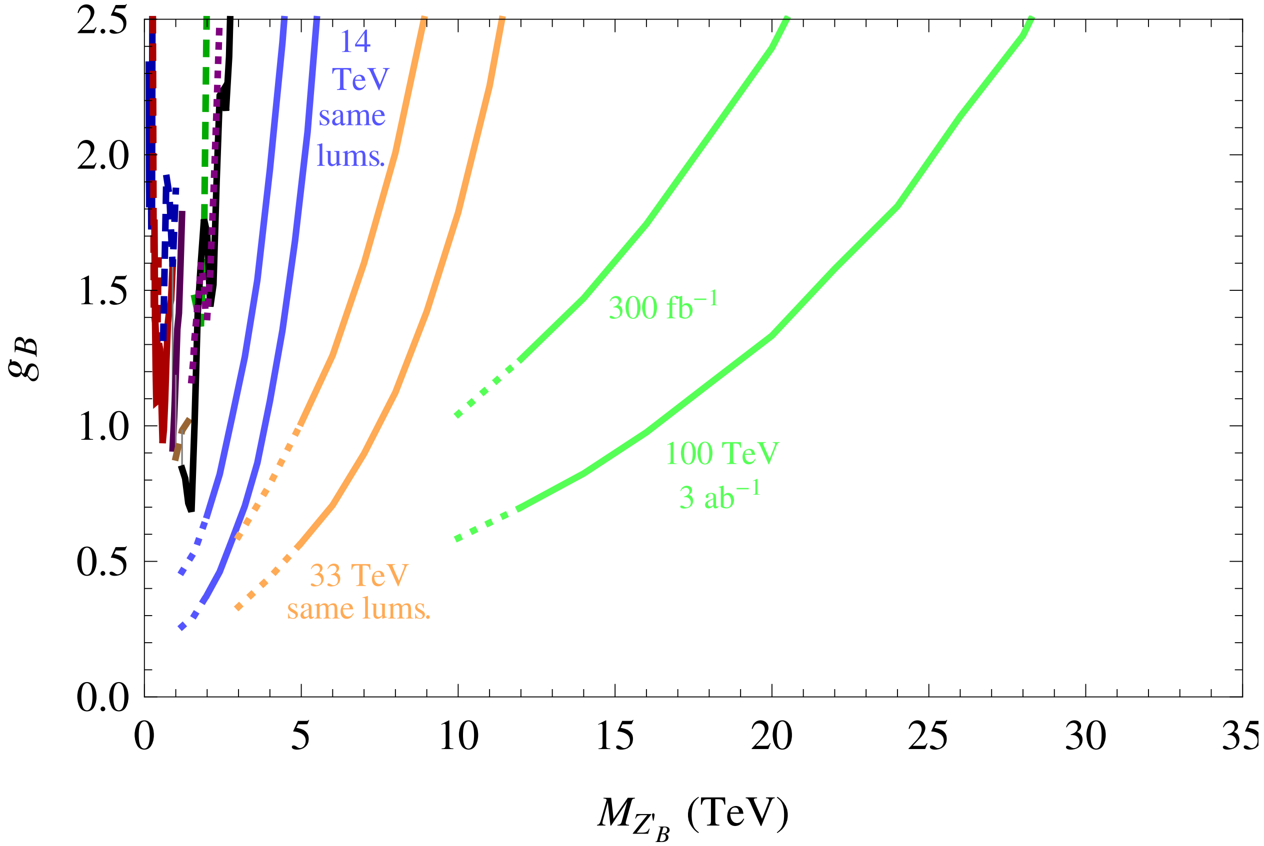
$$m_{\mathrm{WIMP}} \leq 2\ \mathrm{TeV}\left(\frac{g_{\mathrm{eff}}^2}{0.3}\right)$$

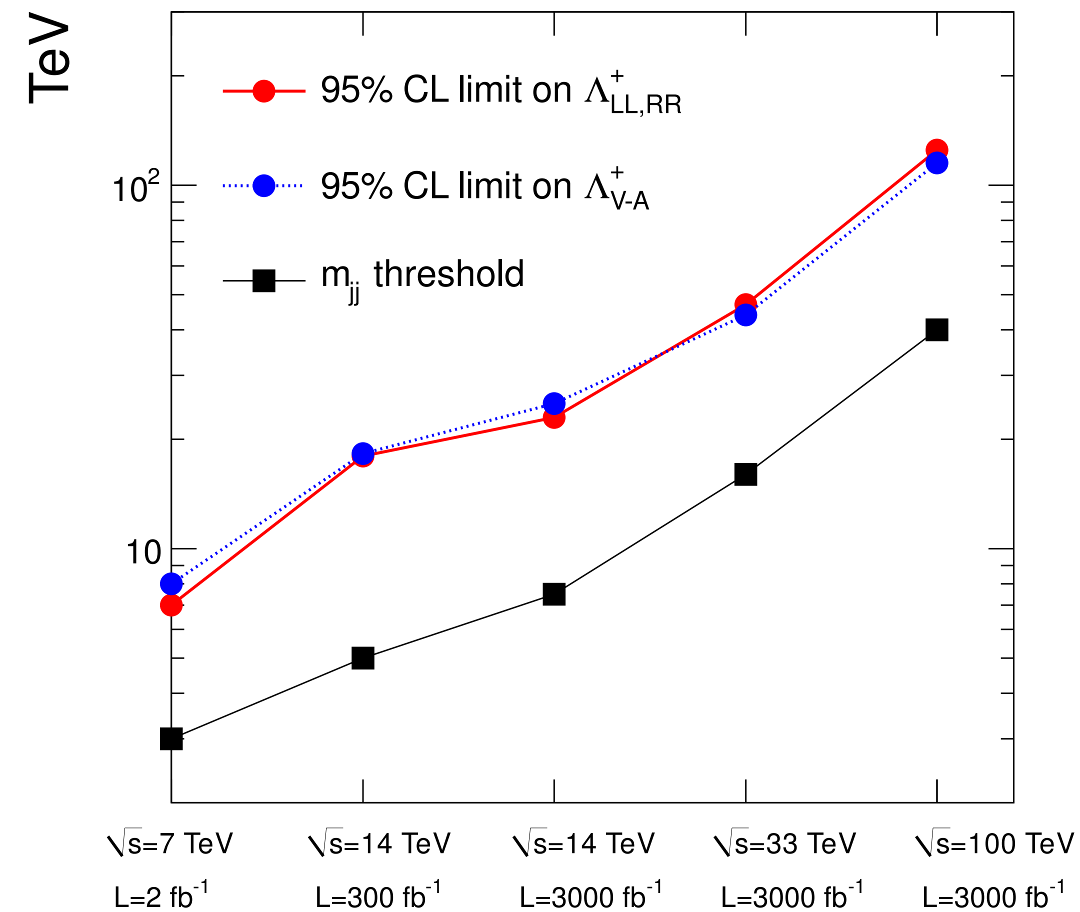


Z'B



quark compositeness





Z'$_B$

quark compositeness

- VLHC studies still preliminary.
  - Clear message already, enormous potential.

Further more,

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- Higgs factory. (Covered by Jianmin's talk)

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- Higher energy ee and muon collider offer a long term program that can extend the precision and reach of a wide range of physics.

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- Higgs factory. (Covered by Jianmin's talk)
- Higher energy ee and muon collider offer a long term program that can extend the precision and reach of a wide range of physics.
- There are interesting complementarity between direct collider searches and indirect precision measurements.
  - Connection to Flavor/CP. Complementary.


LHC
H

Go for the most exciting adventure!

extra

Energy Frontier Facilities List:

Hadron Colliders:

LHC 13 TeV, 300/fb , spacing: 25 ns (50 ns), pileup: 50 events/crossing

LHC 13 TeV, 3000/fb (HL-LHC) , spacing: 25 ns, pileup: 140 events/crossing

LHC 33 TeV, 3000/fb (HE-LHC) , spacing: 50 ns, pileup: 190 events/crossing

VHE-LHC 100 TeV, 3000/fb, spacing: 50 ns, pileup: 263 events/crossing

VLHC at 100 TeV, 1000/fb , spacing: 19 ns, pileup: 40 events/crossing

Lepton Colliders:

e+e- at 250 GeV (ILC: 500/fb , LEP3: 500/fb, TLEP: 2500/fb),
e-/e+ polarization: ILC: 80%/30%, LEP3, TLEP: 0/0

e+e- at 350 GeV (ILC: 350/fb, CLIC: 350/fb, TLEP: 350/fb) ,
e-/e+ polarization: ILC: 80%/30%, CLIC: 80%/0, TLEP: 0/0

e+e- at 500 GeV (ILC: 500/fb), e-/e+ polarization: ILC: 80%/30%

e+e- at 1000 GeV (ILC: 1000/fb) , e-/e+ polarization: ILC: 80%/20%

e+e- at 1400 GeV (CLIC: 1400/fb) , e-/e+ polarization: CLIC: 80%/0%

e+e- at 3000 GeV (CLIC: 3000/fb) , e-/e+ polarization: CLIC: 80%/ 0%

mu+mu- at 125 GeV 2/fb , 0 polarization

mu+mu- at 1500 GeV 1000/fb , 0 polarization

mu+mu- at 3000 GeV 3000/fb , 0 polarization

Gamma Colliders:

gamma-gamma at 125 GeV, 100/fb ,
80% e- polarization to generate the photon beams

gamma-gamma at 200 GeV, gamma-e at 225 GeV, 200/fb ,
80% e- polarization to generate the photon beams

gamma-gamma at 800 GeV, gamma-e at 900 GeV, 800/fb ,
80% e- polarization to generate the photon beams

Electron-Hadron Colliders:

LHeC 60 GeV e- or e+ on 7 TeV p 50/fb , 90% e- / 0% e+ polarization