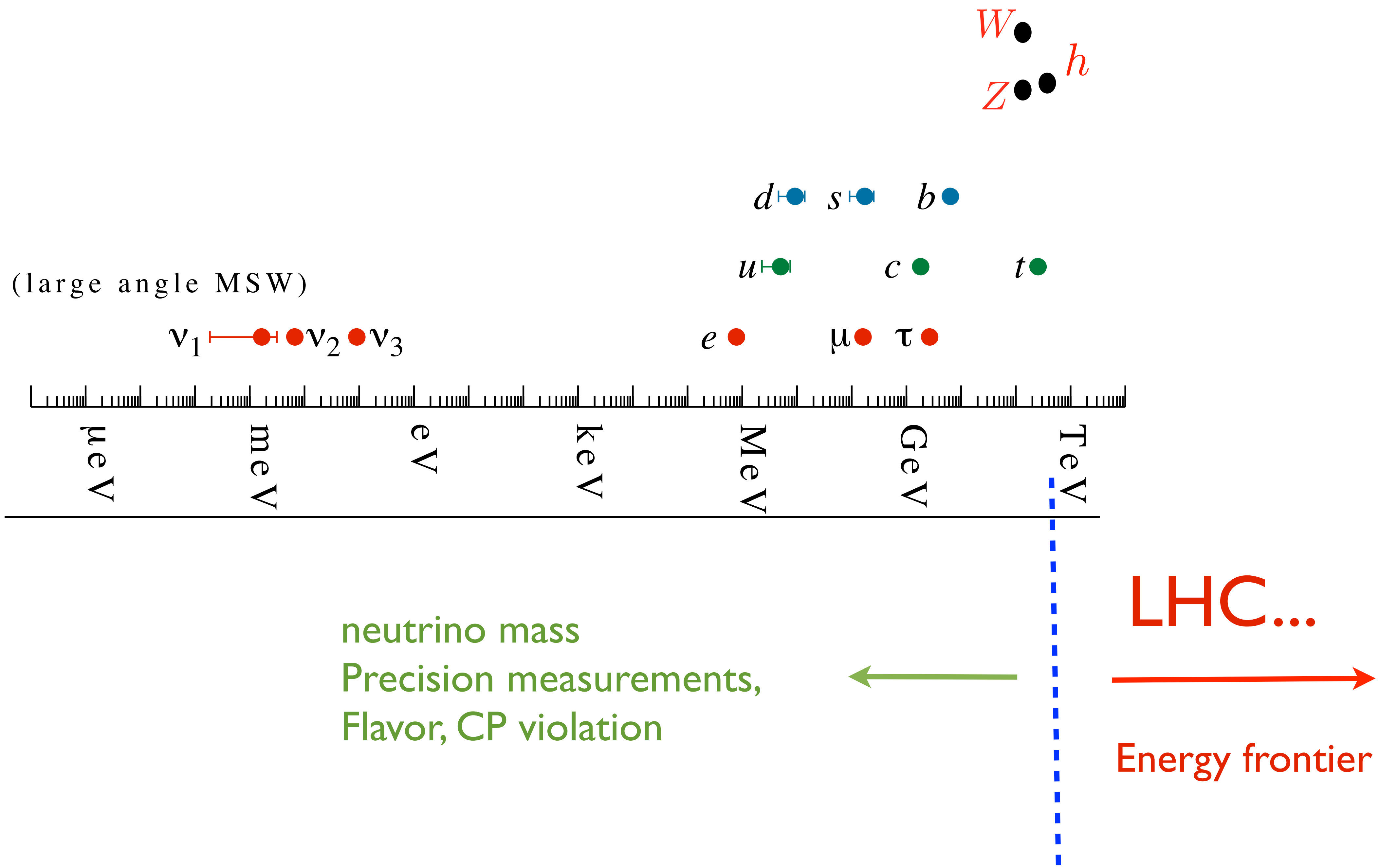
# The View From the Energy Frontier

Lian-Tao Wang

ANL Snowmass intensity frontier workshop, April 26, 2013

# Expanding the horizon:



# This talk

- Overview of our plan for Snowmass study.

  https://indico.bnl.gov/conferenceDisplay.py?confId=571

- Connections with the intensity frontier.

# 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

# Our goals

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

See the backup slides for the list of facilities we plan to consider

# Community Goals: the context for this science

## I. Articulate to scientific audiences

*To other Particle Physicists:*

EF science in the context of the Intensity and Cosmic Frontiers' goals

*To other scientists*

## II. Justify to governmental audiences

*OHEP, EPP, OSTP, Congress...beyond our direct agencies*

*Not only science, but the internationalization of science*

## III. Explain to non-specialist audiences

*Universities*

*Public*

Lectures
Written documentation
Attractive on-line presence

slide from Chip Brock

# Plan to tell "discovery stories"

slide from Chip Brock

## Take a handful of plausible discovery channels

*which might show up as anomalous observables*

## Flesh them out as a sequence of events:

- What would an experiment need to do to be convincing?
  *highlights detector capabilities*
- What could it be?
  *highlights the variety of physics directions*
- What other measurements should show evidence?
  *highlights the whole program, cross-frontier?*

Some ideas: $M_W$, tt resonance, h→bb, Z', WIMP....

# Timeline

April 3 meeting of all working groups at Brookhaven

https://indico.bnl.gov/conferenceDisplay.py?confId=571

finalization of fast simulation framework, definition of projects that must be completed for the reports

June 30 meeting of all working groups at UW, Seattle

due date for white papers from the community and talks on these white papers

draft bulleted lists of conclusions from each working group for public discussion and comment

July 29 working group reports completed; presentation at Snowmass/Minnesota

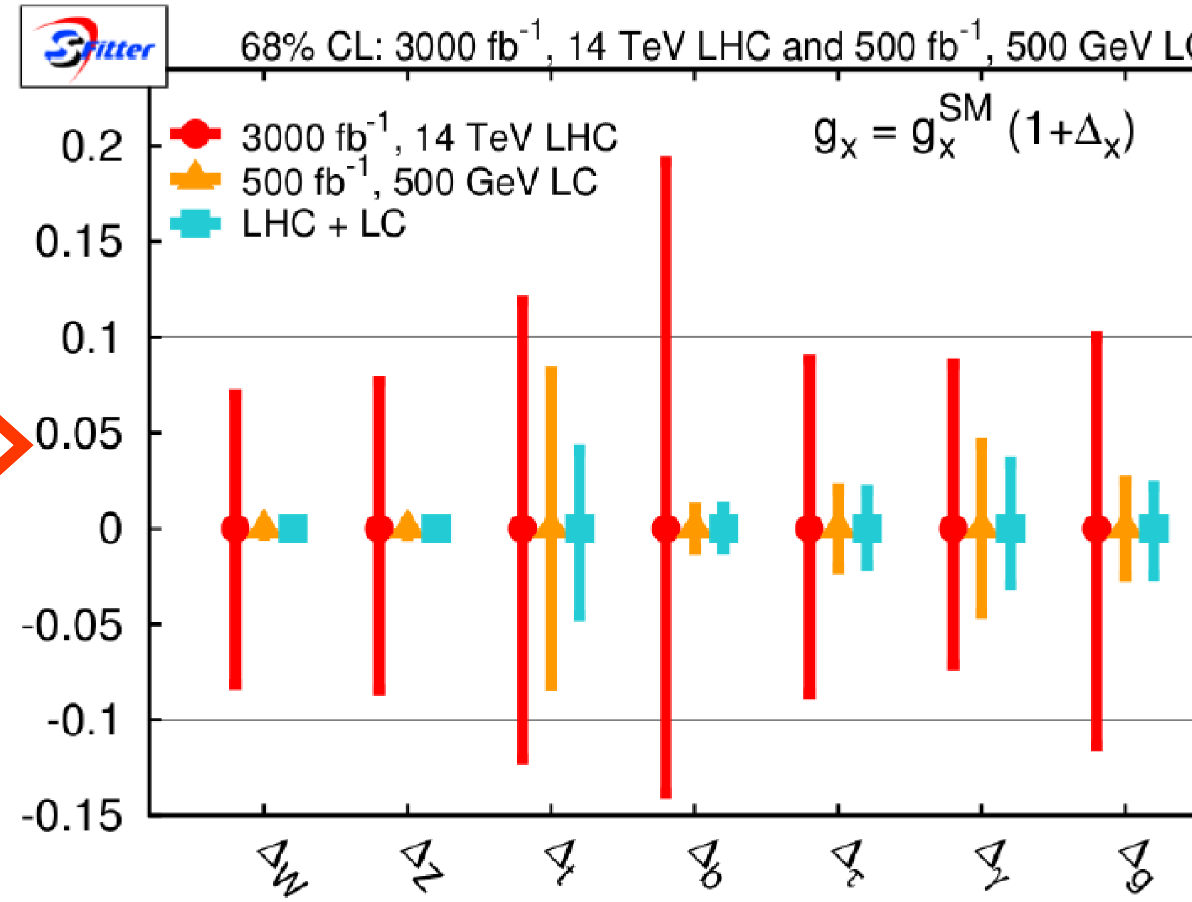
August 16 presentation of final conclusions at DPF

August 30 finalization of all reports

slide from M. Peskin

The studies we are doing.

# Understanding the Higgs




- After the discovery:
  - How well can we fully understand the properties of the Higgs boson
  - A Higgs? SM-like? Anything else? ...

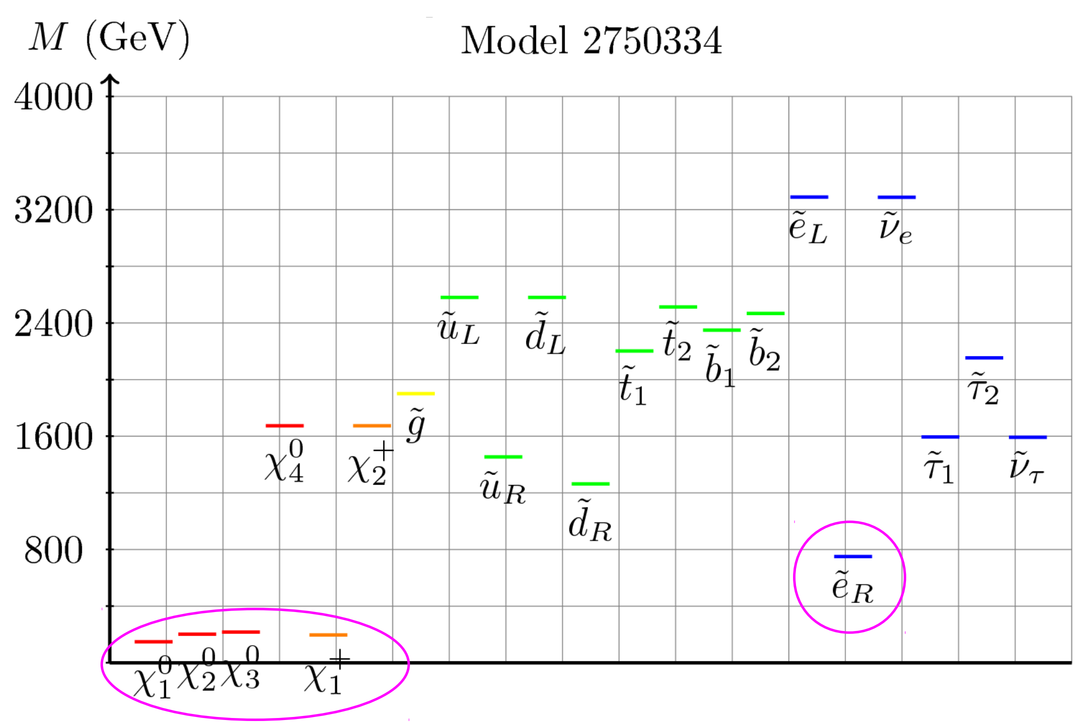
# Understanding the Higgs

## 4-Prong Approach

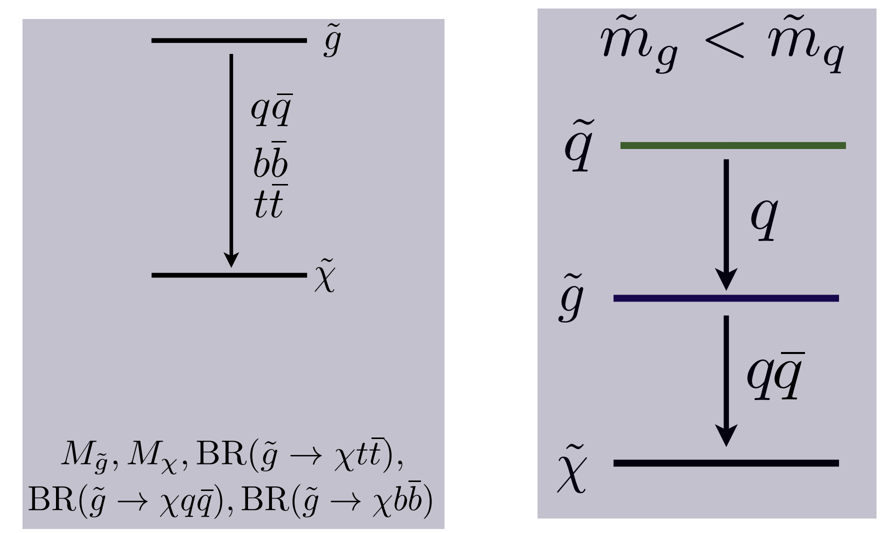
- Look for extra Higgs particles present in many models
- Look for exotic and rare decays of Higgs
- Precision measurements of Higgs couplings
- Other precision measurements of Higgs properties, such as spin, CP admixtures, Higgs self coupling from HH production, total Higgs width, invisible width, mass

slide from Sally Dawson

# Naturalness: Supersymmetry



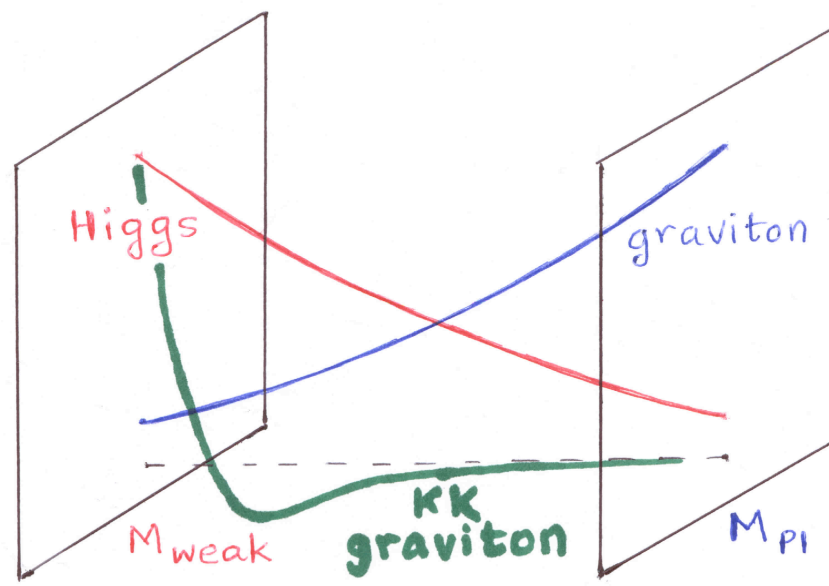

pMSSM benchmarks, J. Hewett's talk

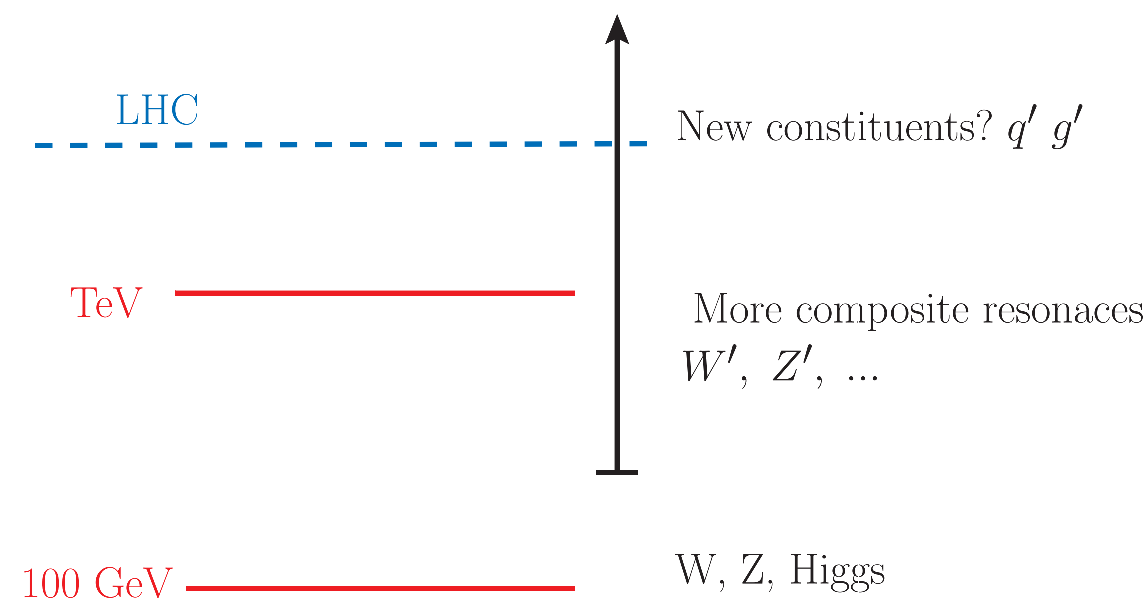



simplified models

- Our best idea to address naturalness problem.
- Many channels, model space still to be explored.
- Trying to cover as much as possible.
  - gluino/squark, electroweak-ino, dark matter motivated, nautral-SUSY

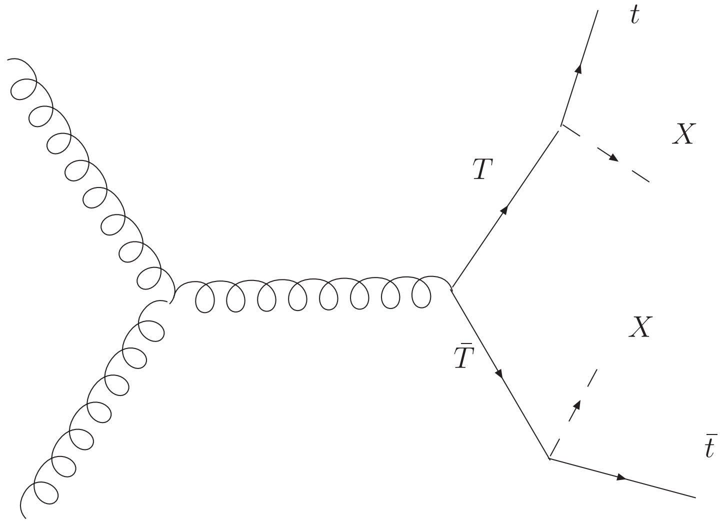
# Naturalness: RS/compositeness

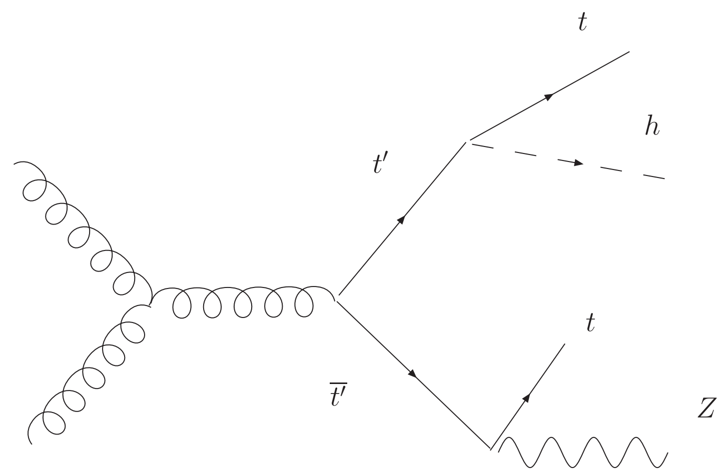


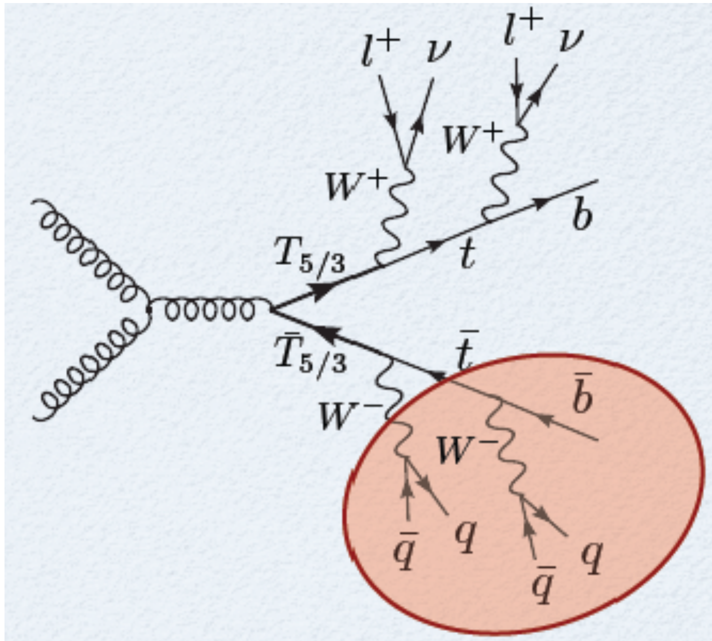




- Complete benchmarks in RS.
- Potential of discovering the resonances (e.g. through vector boson fusion).
- Corrections to Higgs couplings, TGC, $O(v^2/M_{NP}^2)$.
  - Connection to ILC.

# top, top partner

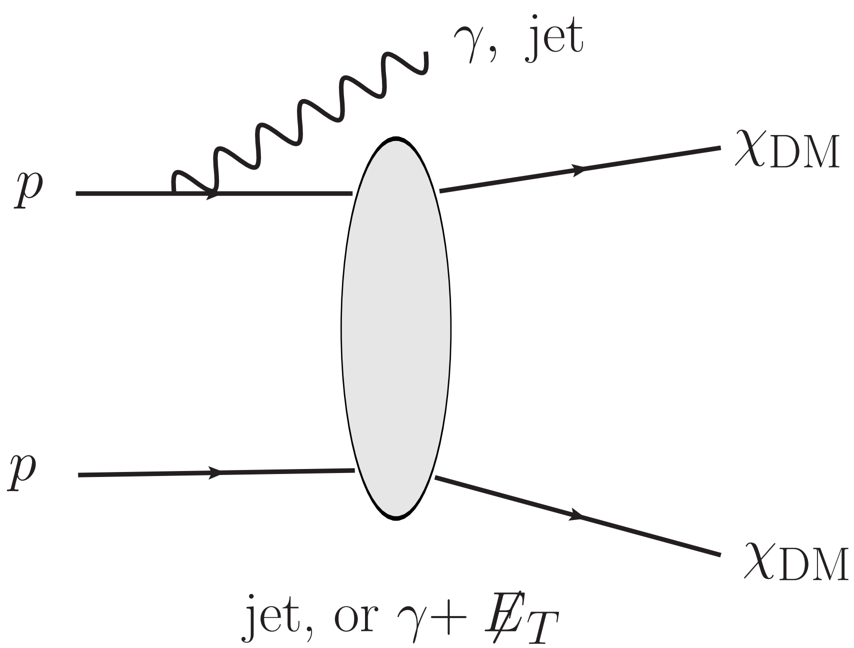


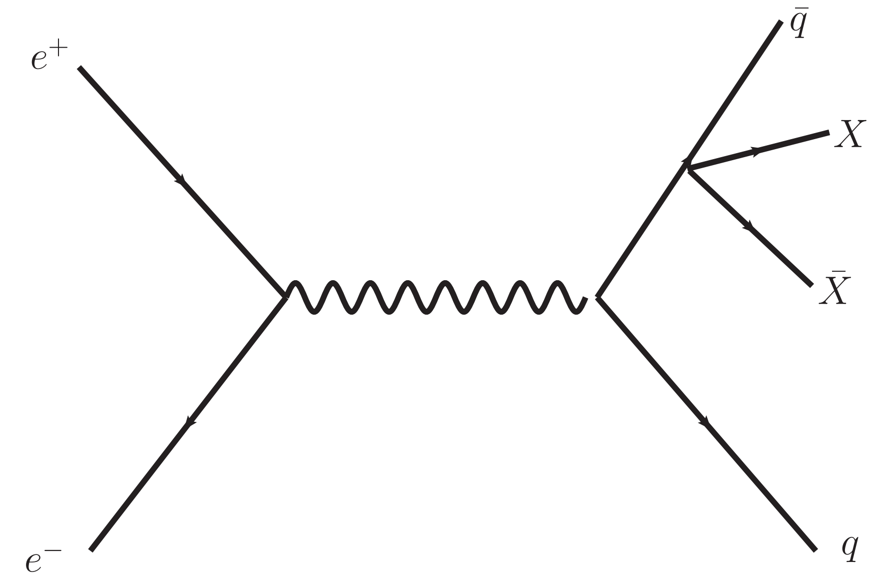




- Are there top partners (for naturalness)?
- Covering all possible top partner signals. Simplified model approach.
- More exotic top-like states?

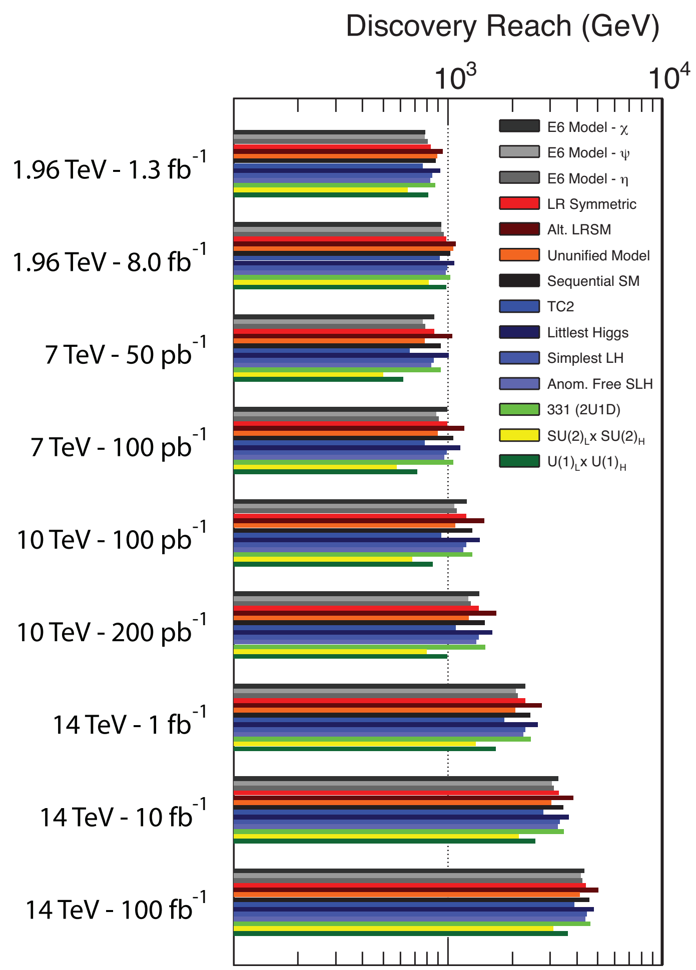
# Dark Matter

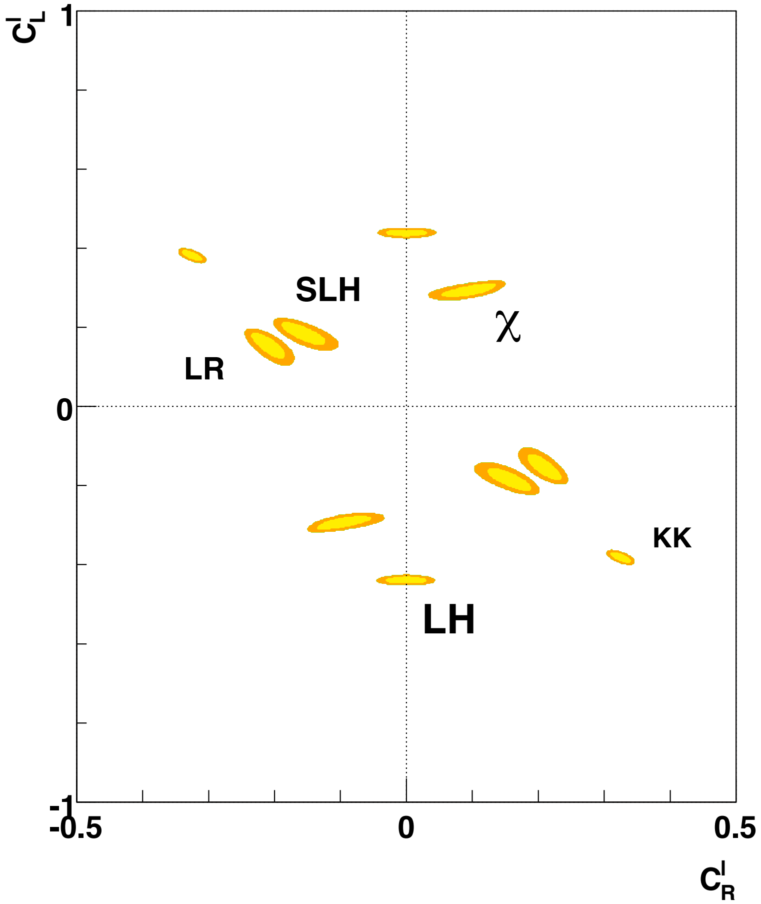



- Simplified EFT approach.
  - In addition to dark matter in the "usual" cases: LSP, LKP....
- Connection to direct detection.

# New interactions, such as Z′




- If a heavy Z′ is discovered at the LHC:
  - How well can we understand it, and at ILC?
- Discovery potential beyond LHC: ILC, higher energy?

# Many other directions

- Non-``standard" SUSY:
    - RPV, R-symmetric, compressed spectrum.
- Universal extra dimension.
- Deviations in triple gauge boson couplings.
- Long lived particles.
- Better use of jets.
- $m_W$, $m_t$
- .....

Clearly, many of these questions can not be solved by only one approach. Need to be attacked from multiple angles.

Clearly, many of these questions can not be solved by only one approach. Need to be attacked from multiple angles.

Connections to in Intensity Frontier: highlight some examples

# The interplay

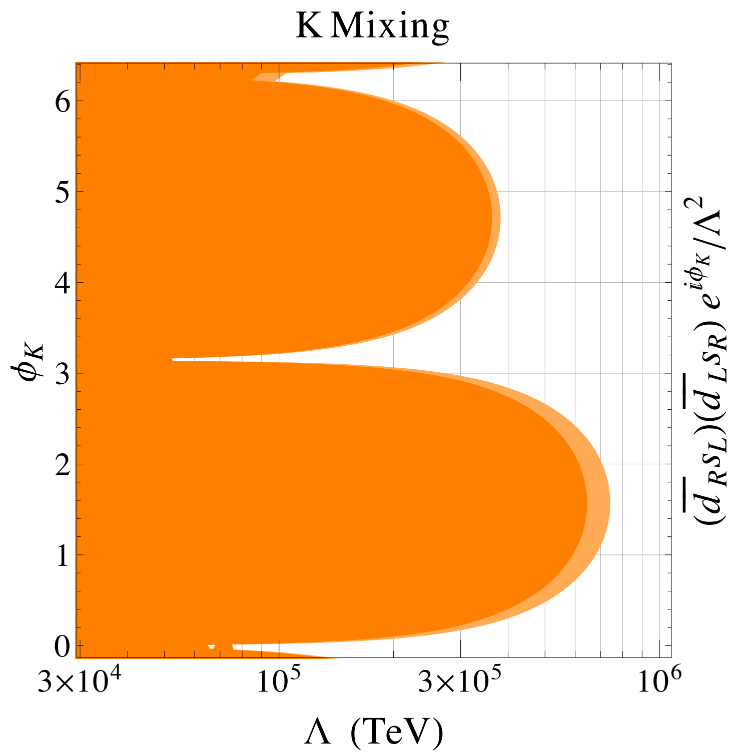
- Precise measurement sensitive to

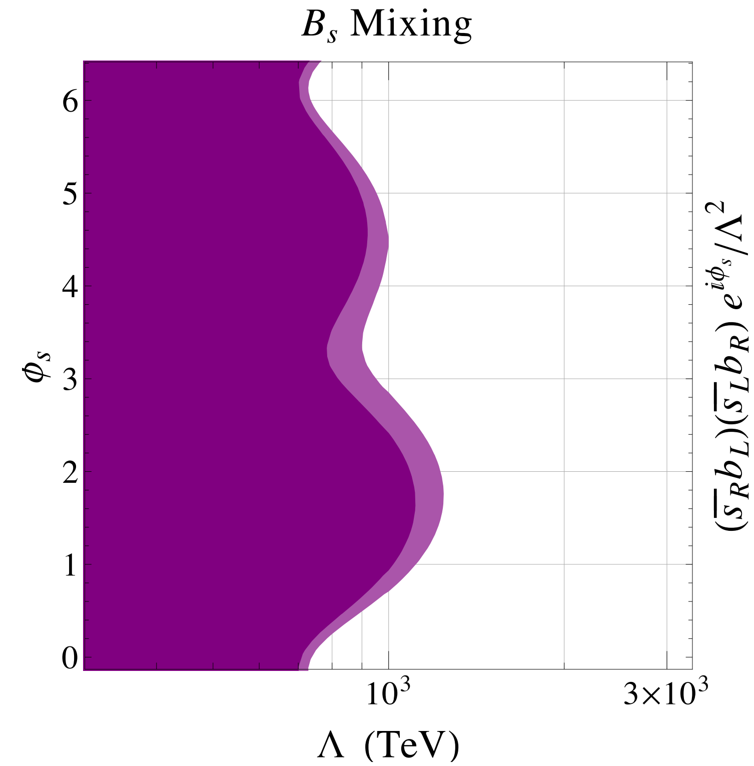
$$\frac{\text{coupling}^{\#}}{M_{\text{NP}}^{\#'}}$$

- Scenario 1: a deviation observed by precise measurements. ⇒ rough estimate of scale. If NP discovered at collider as well, couplings measured.

- Scenario 2: no deviation observed. Very special (tuned) low mass new physics, or push NP scale higher.

- Scenario 3: ...




+

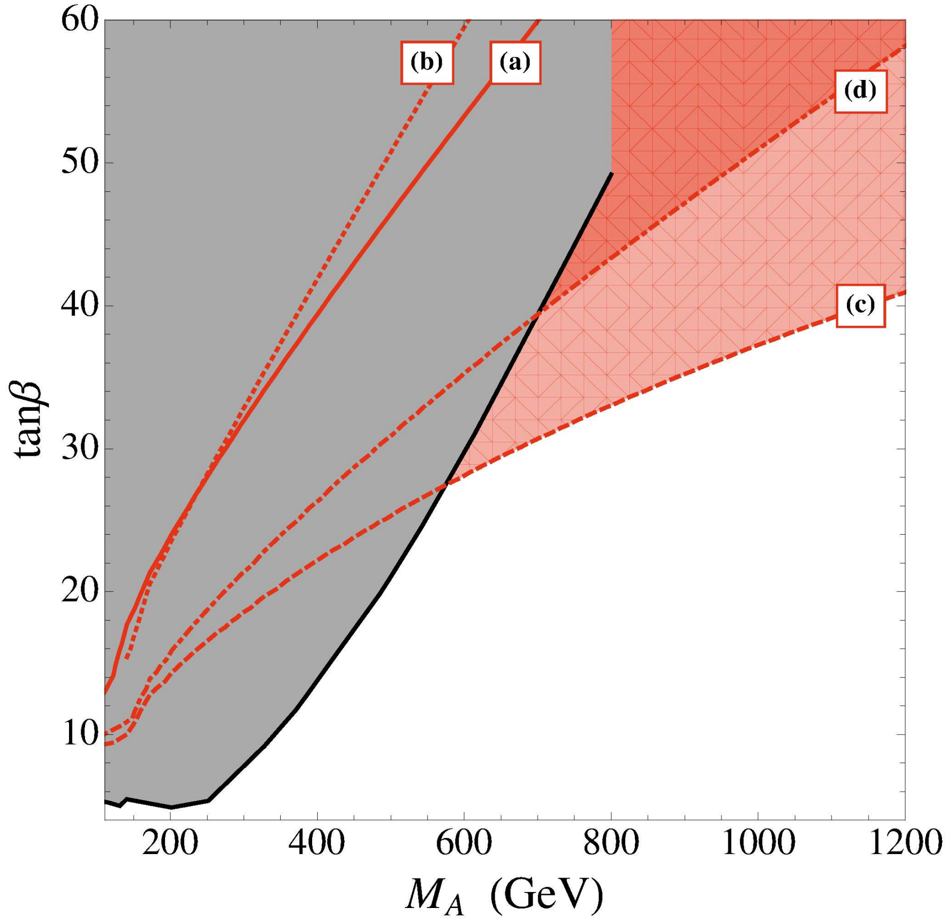
D-mixing
$b \to s\gamma$
$B_s \to \mu\mu$
$K \to \pi\,\nu\nu$
....

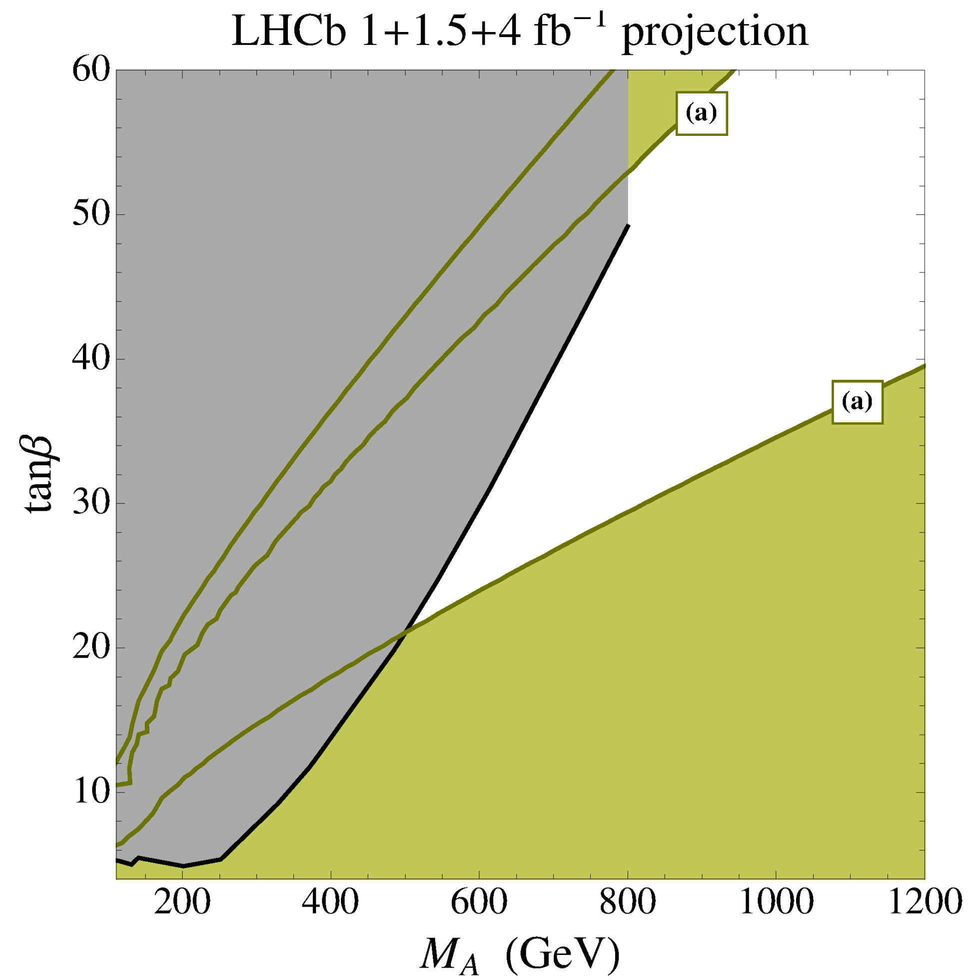
$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} + \sum_i \frac{c_i}{\Lambda_{\rm NP}^2}\mathcal{O}_i$$

- xx flavor/CP problem. (xx = SUSY, composite, ...)
  - e.g. study this in pMSSM (talk by J. Hewett)
- Symmetries, tricks ⇒ lower $c_i$
- Deviation could be around the corner.
  - Can also be probed at colliders?

# $B_s \to \mu\mu$ in SUSY Higgs

Altmanshofer, Carena, Shah, Yu, 2012



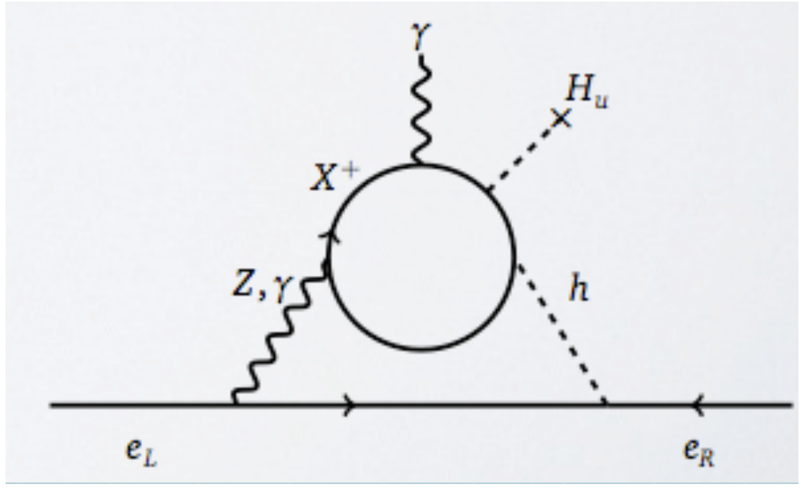



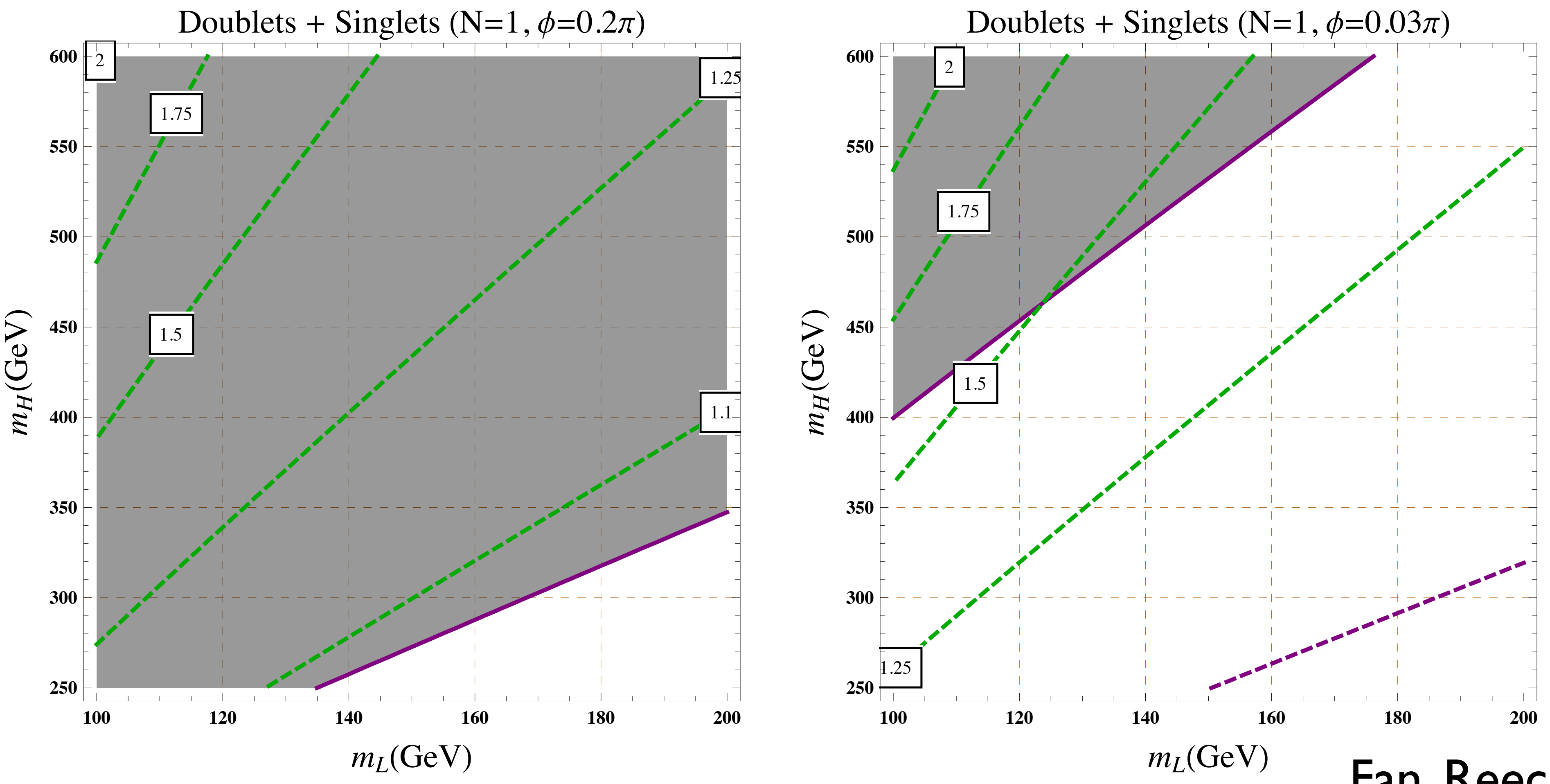

(a) $\mu = 1$TeV, $A_t > 0$ (c) $\mu = -1.5$TeV, $A_t > 0$
(b) $\mu = 4$TeV, $A_t > 0$ (d) $\mu = 1$TeV, $A_t < 0$

all squarks degenerate $\tilde{m} = 2$TeV , $|A_t|$ such that $M_h = 125$GeV

- Interesting complementarity.
- Can we close all the gaps in the future?

# h →γγ vs EDM



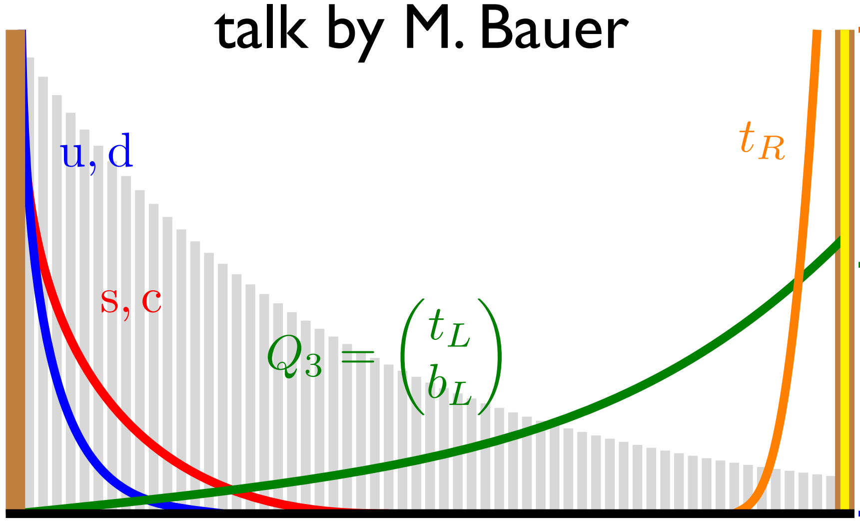



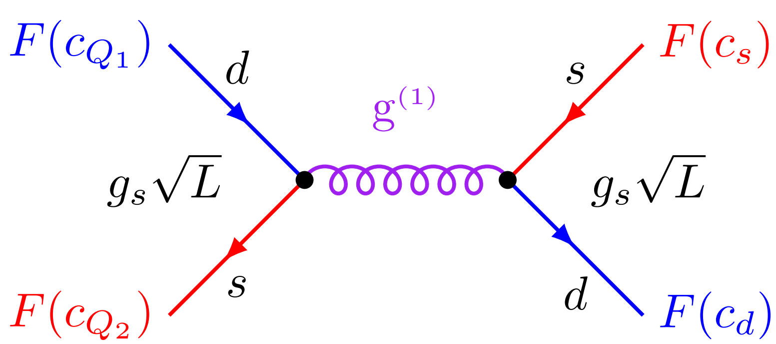

Fan, Reece, 2013

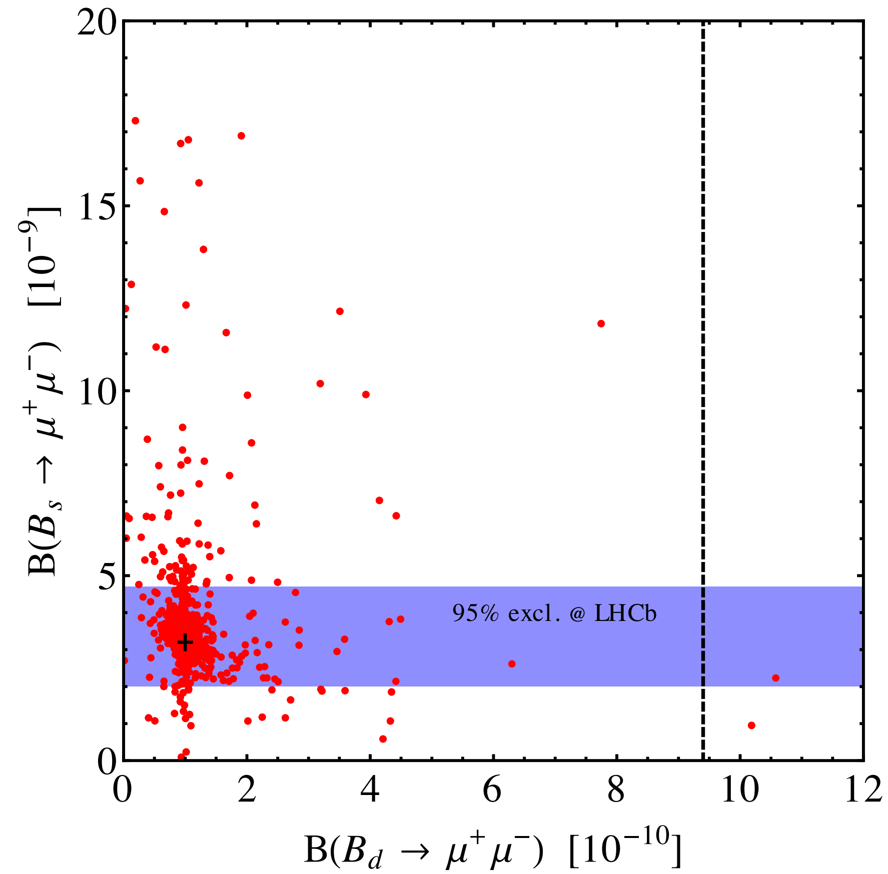
— $\mu_{\gamma\gamma}$ — EDM ruled out above

# RS(composite)-flavor

talk by M. Bauer

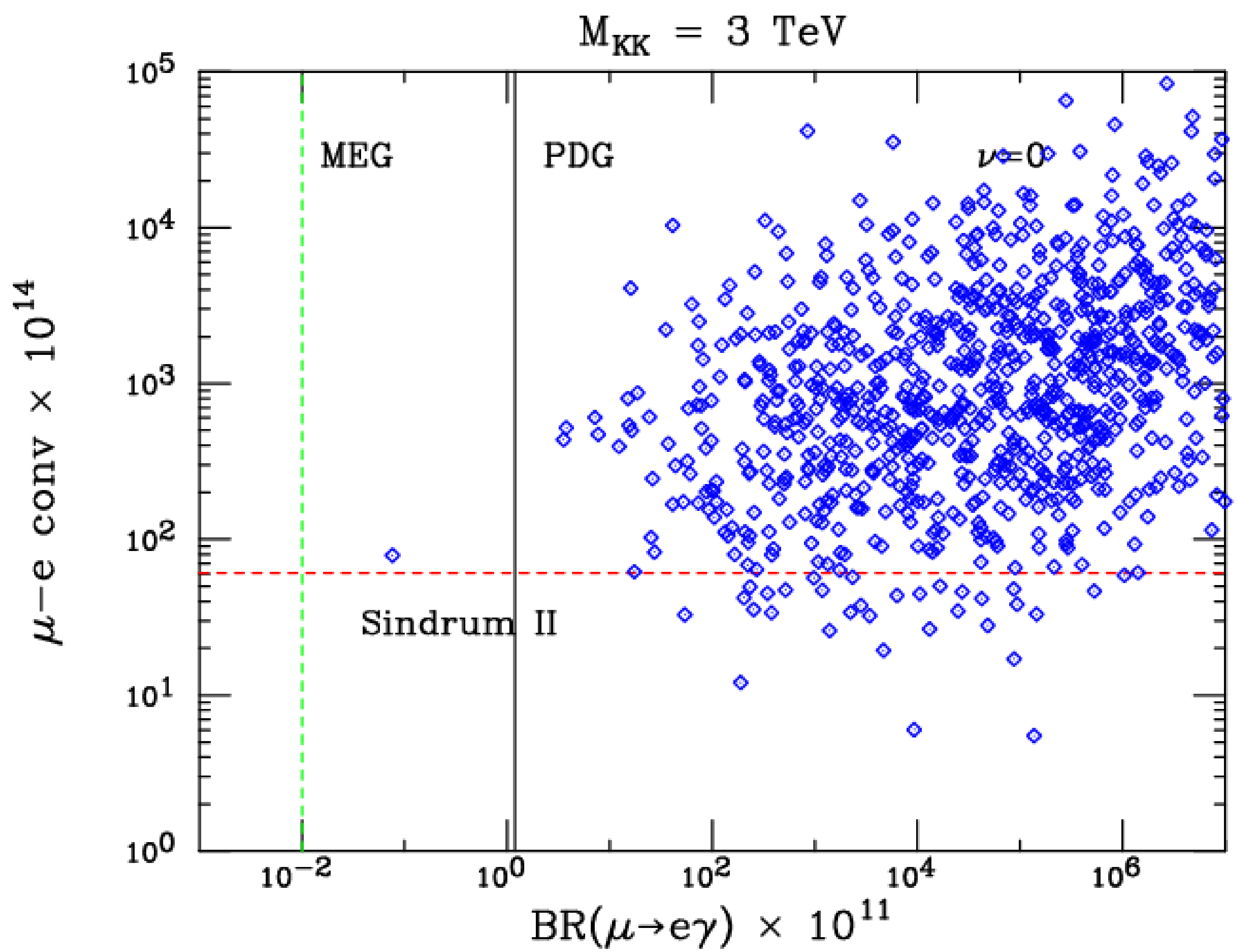



- Interesting predictions for flavor physics.
- Benchmarks: anarchy, flavor symmetry...
- Can be combined with LHC resonance searches.
- Rich lepton flavor physics too.

# RS-lepton flavor




Agashe et al, 2006

# R-parity violation:

$$P_R = (-1)^{3(\mathrm{B-L})+2s}$$

RPV: $$W' = \lambda L L \bar{e} + \lambda' Q L \bar{d} + \lambda'' \bar{u} \bar{d} \bar{d} + \bar{\mu} L H_u$$

- R-parity ⇒ stable LSP ⇒ MET.
- RPV could be where SUSY is.
- One can get rid of R-parity, and "turn on" some couplings without letting proton decay.
- There have been recent progresses on implementing RPV with symmetry principles.
- RPV violates SM accidental symmetries.
  - Strong constraints from precision low energy measurements.

# Limits

- Proton decay constrains product λλ″

$$p \to K^+ \bar{\nu} \quad \longrightarrow |\lambda_{133}\lambda''^*_{112}|, |\lambda_{233}\lambda''^*_{112}| < 10^{-21}$$

- lepton flavor violation μ→e transitions or μe final states, λ′ related constraints.

$$|\lambda^*_{i12}\lambda'_{i11}| < 10^{-8}\left(\frac{m_{\tilde{\nu}_i}}{100\ \mathrm{GeV}}\right)^2$$

$$|\lambda^*_{i21}\lambda'_{i12}| < 10^{-9}\left(\frac{m_{\tilde{\nu}_i}}{100\ \mathrm{GeV}}\right)^2$$

$$|\lambda'^*_{2j1}\lambda'_{1j1}| < 10^{-8}\left(\frac{m_{\tilde{u}_{Lj}}}{100\ \mathrm{GeV}}\right)^2$$

  - Limits flavor dependent, e.g., $|\lambda^*_{233}\lambda'_{313}| < 10^{-3}\left(\frac{m_{\tilde{\ell}_i}}{100\ \mathrm{GeV}}\right)^2$

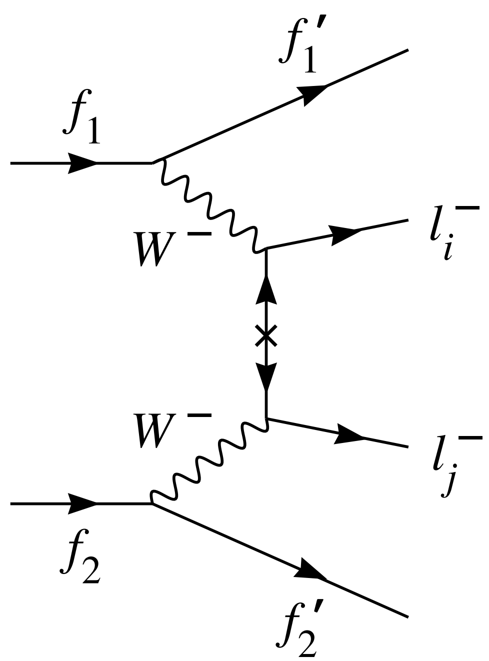
# Some limits on single couplings

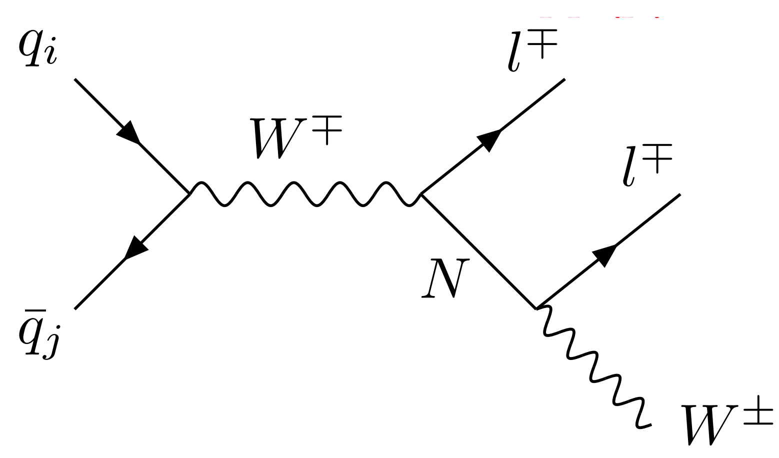
- Limits on Baryon # violating couplings
  - Neutron oscillation: $\lambda''_{11k} < 10^{-8}$ ....
- Limits on Lepton number violating coupling from neutrino mass (< eV).
  - e.g.: $\lambda_{i33} \lesssim 10^{-2}$, $\lambda'_{i33} \lesssim 10^{-3}$ $M_{SUSY}$~100s GeV
- bilinears constrained by neutrino mass.
  - $\mu_i/\mu \sim 10^{-4}$, with $\mu \sim$ 100s GeV
- Couplings are related by flavor rotations.
  - Limits strong on others as well, or flavor symmetry.
- Size of RPV controls collider pheno
  - Single production? Displaced vertices?

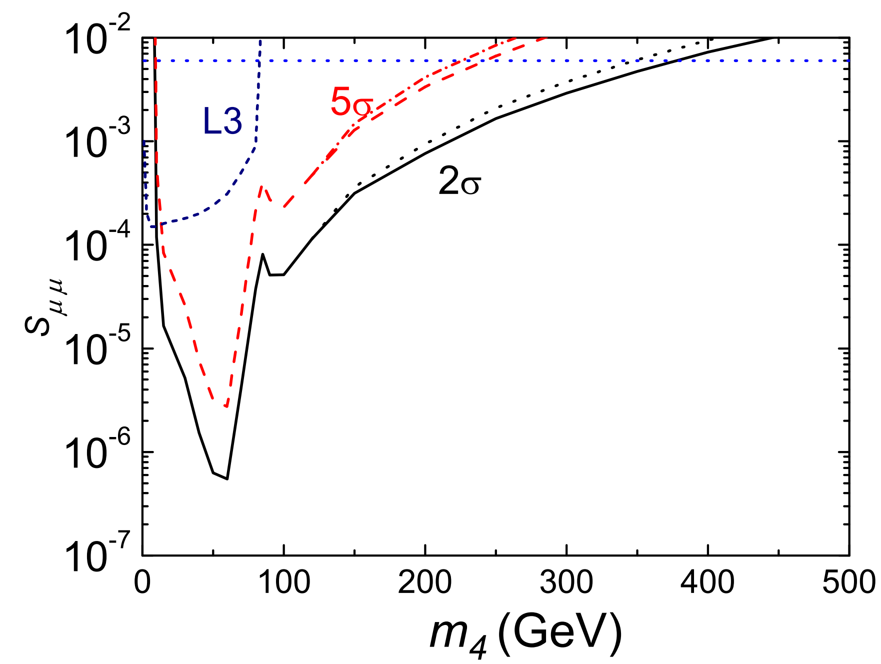
# A possible connection to ν mass?

Atre, Han, Pascoli, Zhang, 2009

14 TeV, 100 fb$^{-1}$




$$\frac{1}{\Lambda}(y_\nu LH)(y_\nu LH) + h.c. \qquad \Lambda \Rightarrow \begin{cases} 10^{14} \text{ GeV for } y_\nu \sim 1; \\ 100 \text{ GeV for } y_\nu \sim 10^{-6}. \end{cases}$$

# More connections

- Flavor violating $Z'$.
- Learn more about dark matter + dark sector.
- Flavored SUSY breaking
- R-symmetric
- Top FCNC.
- .....

# Would be useful to know from you

- The exp. reach of many channels, and the implication on the model space.
  - EDM, $g_\mu$-2
  - $\mu \to e$, $\tau \to \mu(e)\,\gamma$, $B_s \to \mu\mu$, $B_d \to \mu\mu$
  - ...
- Other possible connections?
- And of course, what would you like to hear from us? What else should we be doing at EF?

# Extras

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

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