Snowmass 2013
Energy Frontier working group

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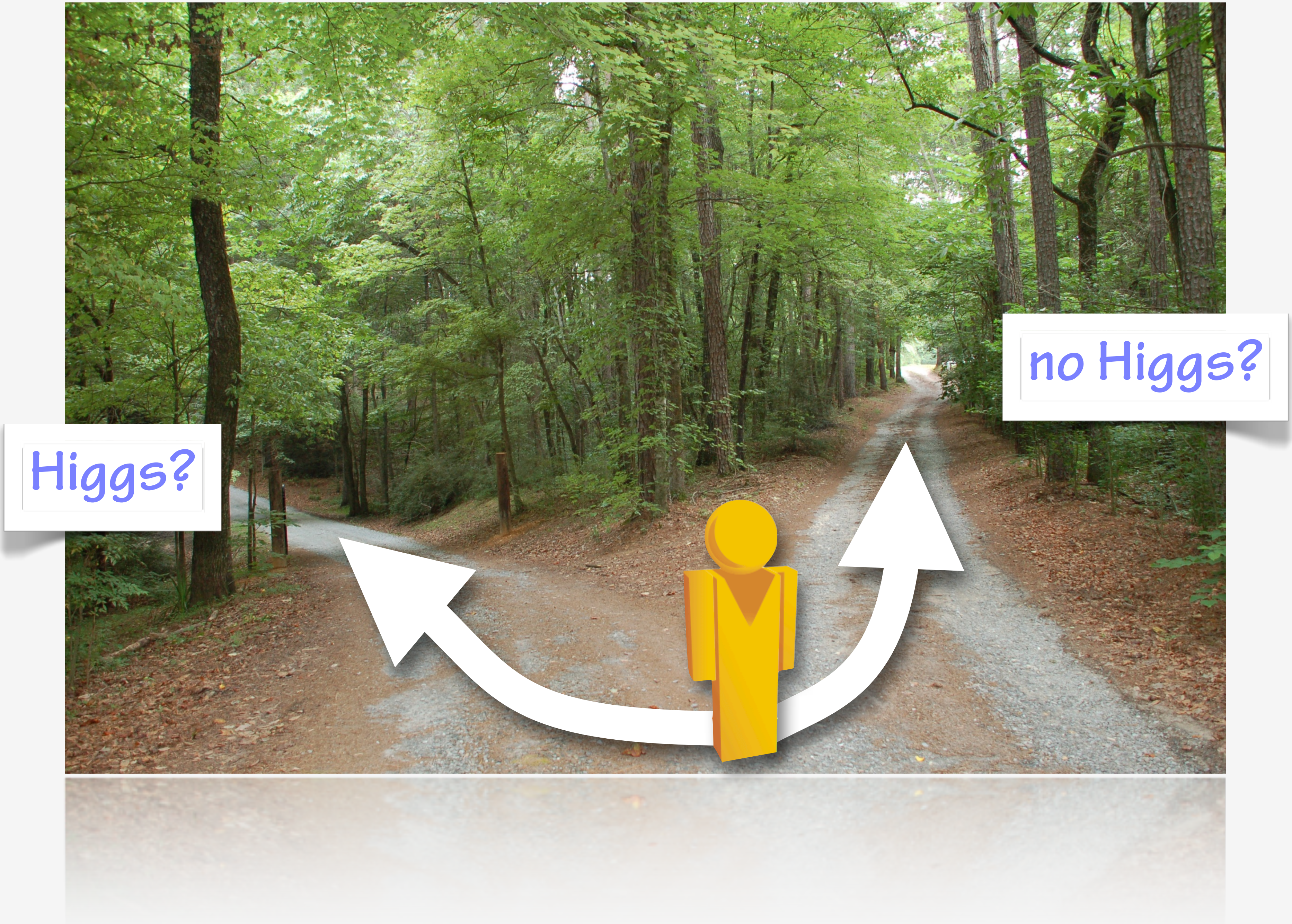
SLAC
Chip Brock
Michigan State University

HEPAP September 5, 2013

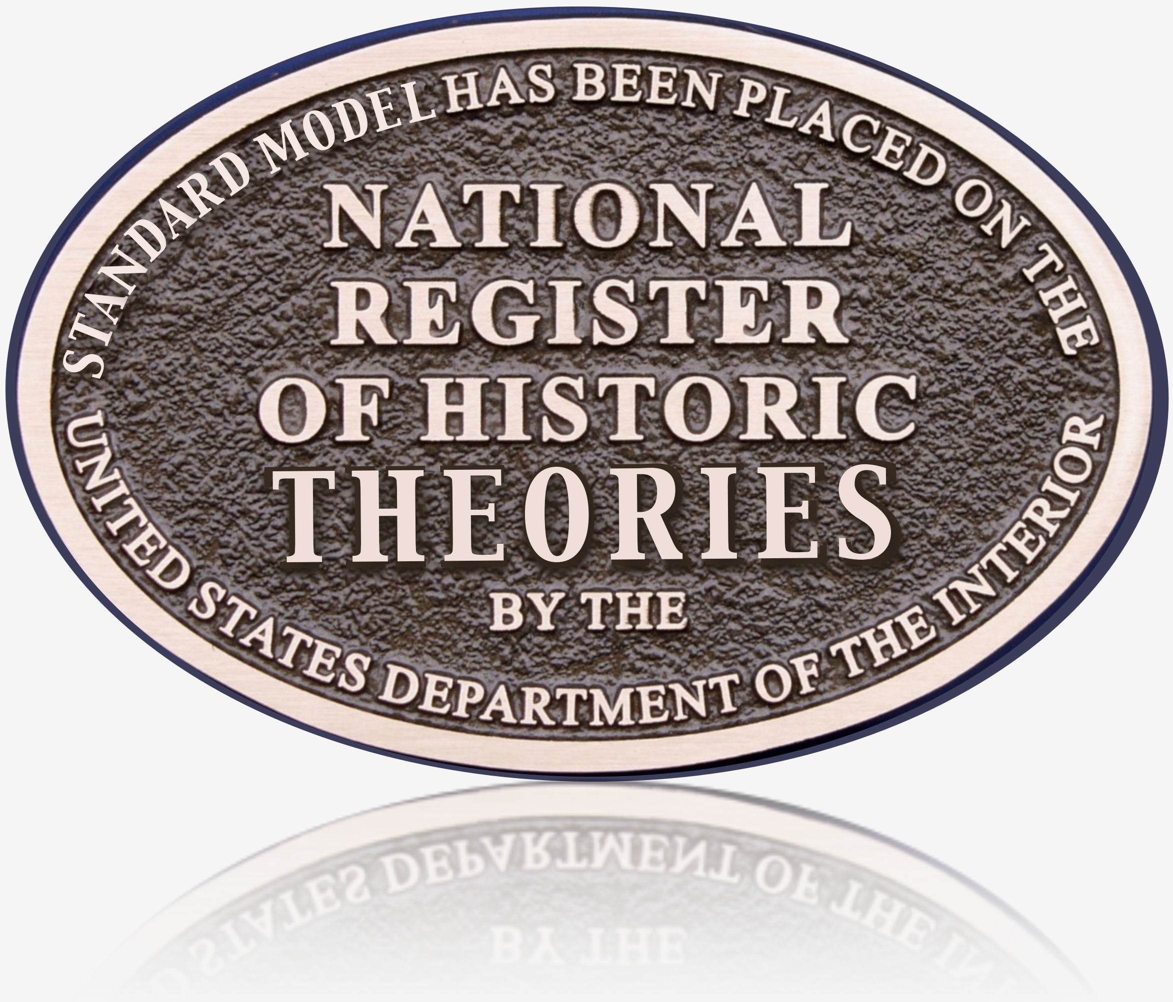
- the stakes
- the energy frontier process
- reports from the subgroups
  - themes
  - content
  - message
- cases for future programs

imagine a couple of years ago




H

now


STANDARD MODEL HAS BEEN PLACED ON THE
NATIONAL
REGISTER
OF HISTORIC
THEORIES
BY THE
UNITED STATES DEPARTMENT OF THE INTERIOR

what embodies the

?

- the Gauge Principle

What's odd about the Standard Model?

- the Potential.

  Much of our work is unpacking it:

$$V = V_0 - \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 + \left[y_{ij} \bar{f}_{Li} f_{Rj} \phi + HC \right]$$

vacuum energy

Higgs mass

instability?

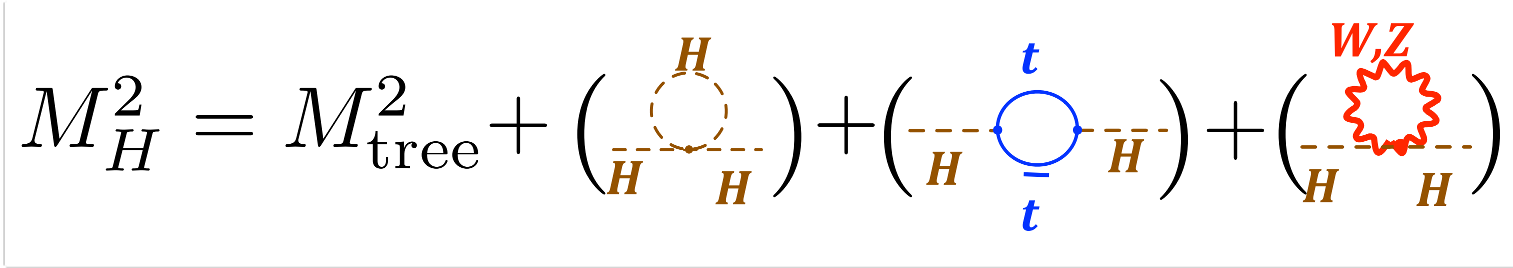
Yukawa couplings

particle physics


HIGGS
ticl
e p
phys
HIGGS

- We know of BSM physics.

First-ever spin 0 elementary particle.



- leads to perplexing quantum

  additive, quadratic cut-offs...

  in mass-squared, by the way

$$V(\text{Higgs}) = \boxed{-\mu^2\Phi^\dagger\Phi} + \lambda(\Phi^\dagger\Phi)^2$$

to many


POST CARD
Correspondence
Address
A Hint
To: 2013
From: Nature
#5064 BOPR
ROBERT H. LORD
BOSTON

Serious experimental anomalies

- The Higgs Boson mass is small.
- *ν*'s flavor, mass, symmetry properties not SM.
- Dark Matter needs a quantum.
- Primordial antimatter needs an explanation.
- (g-2)μ results need confirmation or disconfirmation

Serious experimental anomalies

- The Higgs Boson mass is small.
- *ν*'s flavor, … symmetry properties not SM.
- Dark M… …uantum.
- Primordial a… …an explanation.
- (g-2)μ results need… …or disconfirmation

Dramatically influence the EF

Conclusions from the Energy Frontier

A three-pronged research program:

- Measure properties of the Higgs boson.
- Measure properties of the: *t*, *W*, and *Z*
- Search for TeV-scale particles

A three-pronged research program:

Mass, CP, and especially couplings

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A three-pronged research program:

They talk to the Higgs Field

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Scale inspired by naturalness

The Snowmass Energy Frontier Process

EF working groups

EF1: The Higgs Boson

- *Jianming Qian (Michigan), Andrei Gritsan (Johns Hopkins), Heather Logan (Carleton), Rick Van Kooten (Indiana), Chris Tully (Princeton), Sally Dawson (BNL)*

EF2: Precision Study of Electroweak Interactions

- *Doreen Wackeroth (Buffalo), Ashutosh Kotwal (Duke)*

EF3: Fully Understanding the Top Quark

- *Robin Erbacher (Davis), Reinhard Schwienhorst (MSU),Kirill Melnikov (Johns Hopkins), Cecilia Gerber (UIC), Kaustubh Agashe (Maryland)*

EF4: The Path Beyond the Standard Model–New Particles, Forces, and Dimensions

- *Daniel Whiteson (Irvine), Liantao Wang (Chicago), Yuri Gershtein (Rutgers), Meenakshi Narain (Brown), Markus Luty (UC Davis)*

EF5: Quantum Chromodynamics and the Strong Interactions

- *Ken Hatakeyama (Baylor), John Campbell (FNAL), Frank Petriello (Northwestern), Joey Huston (MSU)*

EF6: Flavor Physics and CP Violation at High Energy

- *Soeren Prell (ISU), Michele Papucci (LBNL), Marina Artuso (Syracuse)*

Organization:

Created necessary correlations among groups

- Technical groups, accelerators, simulations
  - *Eric Prebys, Eric Torrence, Tom LeCompte, Sanjay Padhi, Tor Raubenheimer, Jeff Berryhill, Markus Klute, and Mark Palmer*

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Additional group "infrastructure"

- established direct connection with the established collaborations:
  - *"Advisors":*

    ATLAS: Ashutosh Kotwal; CMS: Jim Olsen; LHCb: Sheldon Stone; ILD: Graham Wilson; SiD: Andy White; CLIC: Mark Thomson; Muon Collider: Ron Lipton; VLHC: Dmitri Denisov

Energy Frontier Goals:

What are the scientific cases which motivate HL LHC running:

“Phase 1”: circa 2022 with ∫ L dt of approximately 300 fb -1

“Phase 2”: circa 2030 with ∫ L dt of approximately 3000 fb -1

- *How do the envisioned upgrade paths inform those goals?*
- *Specifically, to what extent is precision Higgs Boson physics possible?*

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Is there a scientific necessity for a precision Higgs Boson program?

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Is there a scientific necessity for a precision Higgs Boson program?

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

- *High energy lepton collider?*
- *A high energy LHC?*
- *Lepton-hadron collider?*
- *VLHC?*

EF meetings:

the allovertheplace workshop.

snowmass@Batavia

snowmass@Princeton

snowmass@Durham

snowmass@Brookhaven 

snowmass@Dallas

snowmass@SantaBarbara

snowmass@Boston

snowmass@Tallahassee

snowmass@Boulder

snowmass@Geneva

snowmass@Seattle 

snowmass@Minneapolis

We simulated against a defined set of accelerators

- This included:

  LHC 14 TeV running at 300/fb and 3000/fb

  LHC at 33 TeV

  linear and circular e+e- colliders

  muon collider

  gamma-gamma colliders

  pp collider at 100 TeV

Fast simulation tools

- LHC simulation strategies

  A Generic DELPHES 3 “Snowmass detector”

  Background simulations

- The LC community

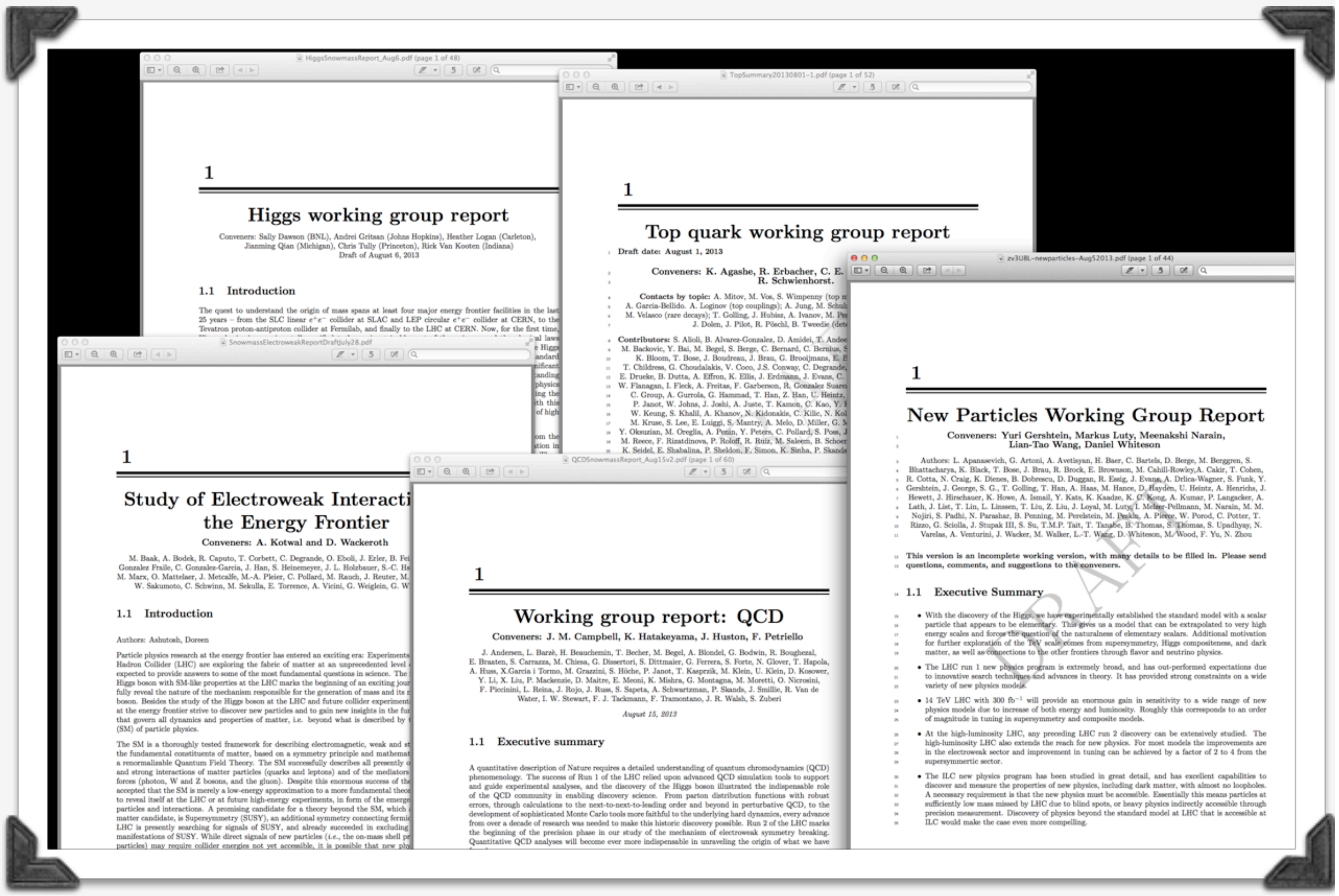
  Snowmass-specific analyses beyond the CLIC CDR & ILC TDR.

  Signal & complete SM background samples

Reports are being finished up

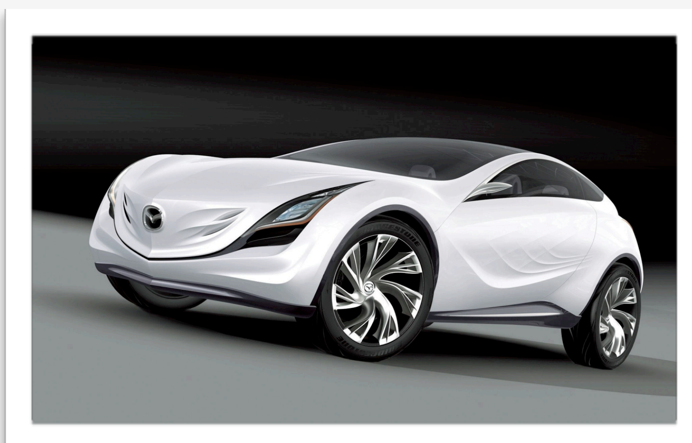
- 300 pages of technical detail

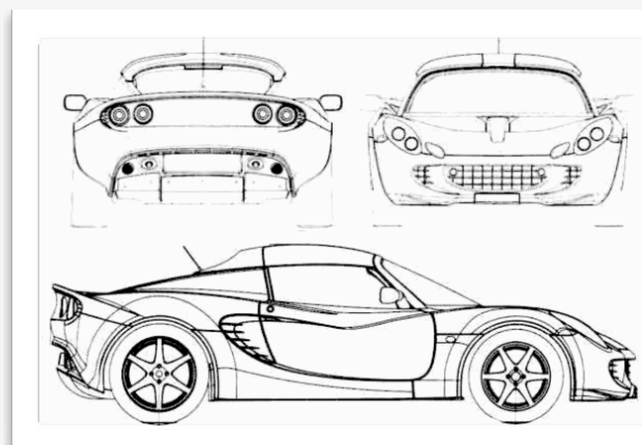
  http://www.snowmass2013.org/tiki-index.php?page=Energy%20Frontier



- two points

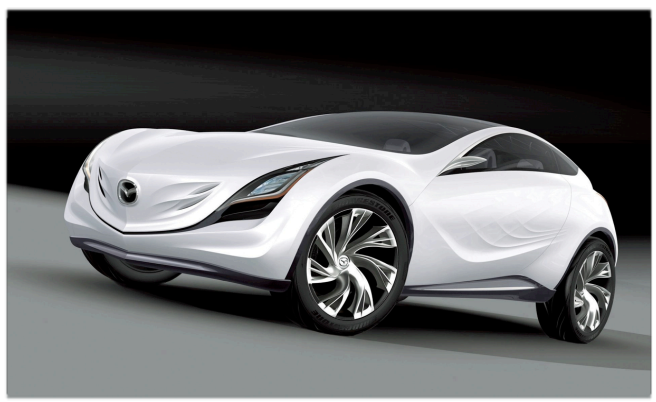
the Proposal Frontier

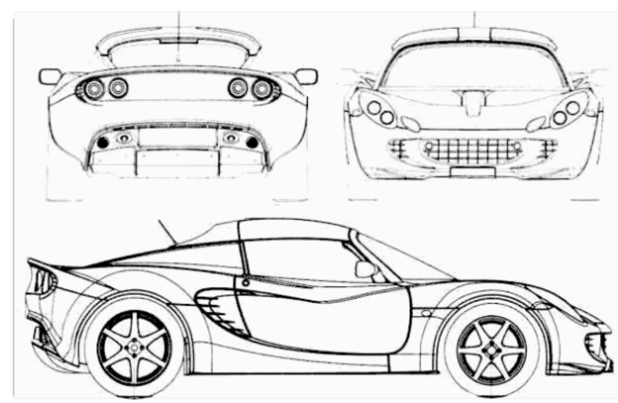




Comments:

LHC 100/fb	LHC 300/fb	LHC 3/ab	ILC 250-500GeV	ILC 1TeV	CLIC >1TeV	MC	TLEP	VLHC
years beyond TDR	TDR	LOI	TDR	TDR	CDR			





Exclusion

- we always speak of "exclusion plots"

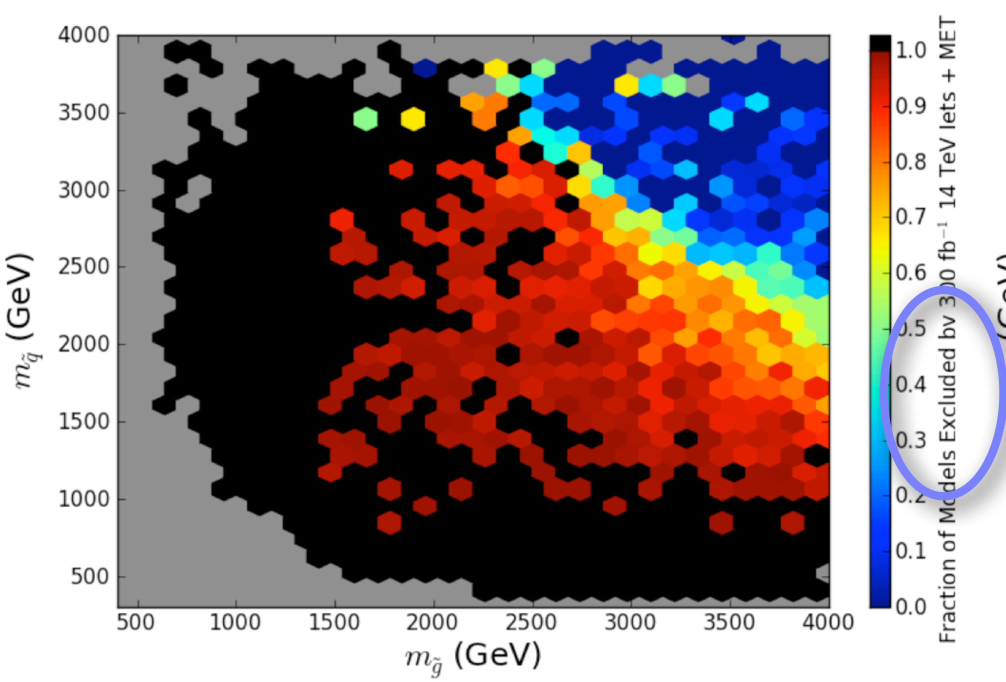
implying that the goal is to eliminate any place for new physics!

Not exclusion.

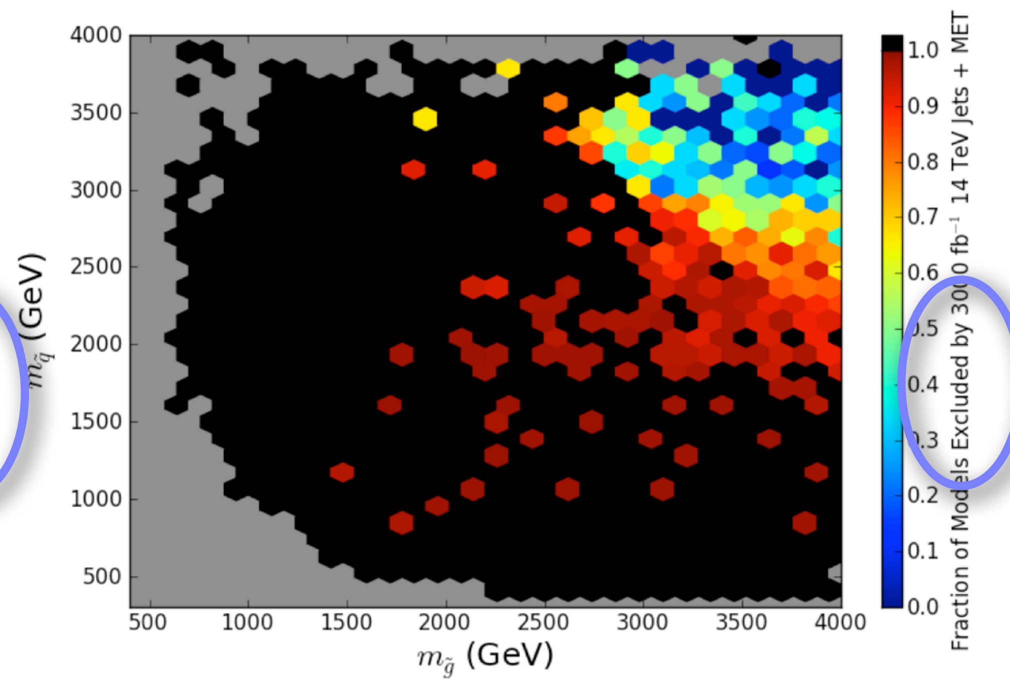
Discovery

- We've all seen these nice Cahill-Rowley, Hewett, Rizzo grids

300/fb



3000/fb



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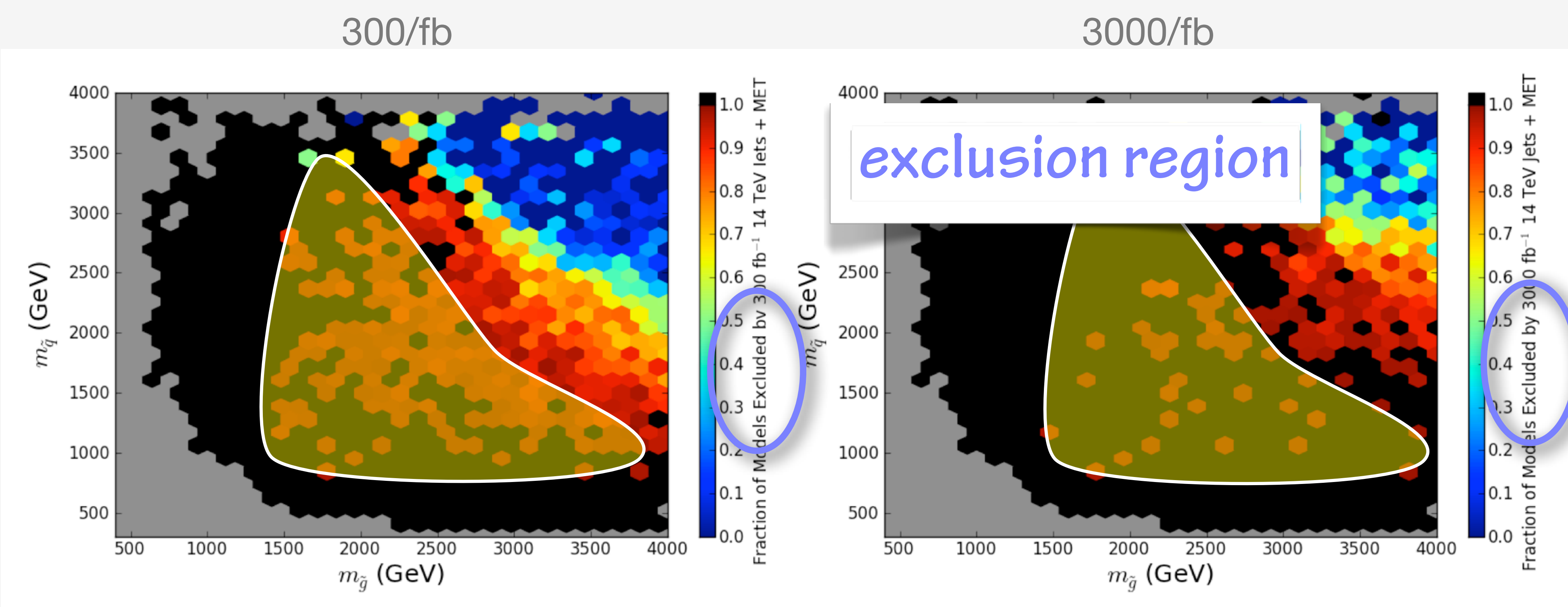

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Discovery

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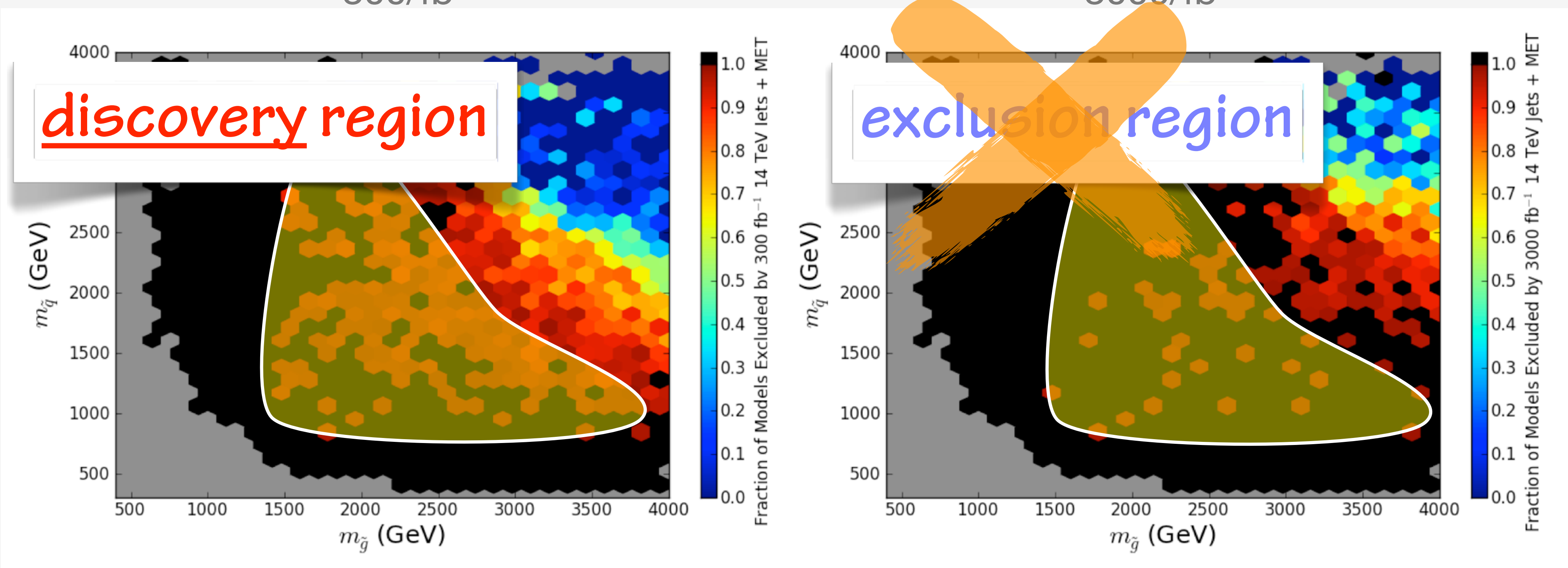
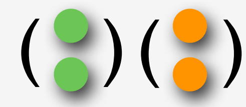
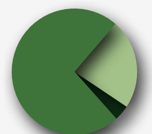
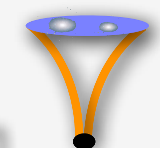
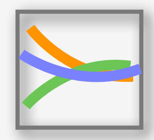
300/fb

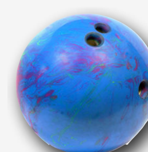
3000/fb



Working Group Results

Big Questions

1. How do we understand the Higgs boson? 
2. How do we understand the multiplicity of quarks and leptons? 
3. How do we understand the neutrinos? 
4. How do we understand the matter-antimatter asymmetry of the universe? 
5. How do we understand the substance of dark matter? 
6. How do we understand the dark energy? 
7. How do we understand the origin of structure in the universe? 
8. How do we understand the multiplicity of forces? 
9. Are there new particles at the TeV energy scale? 
10. Are there new particles that are light and extremely weakly interacting? 

11. Are there extremely massive particles to which we can only couple indirectly at currently accessible energies? 

- The Higgs Boson

Higgs Boson Group Themes:

1. outline a precision Higgs program

   mystery of Higgs, theoretical requirements
2. projections of Higgs coupling accuracy

   measurement potential at future colliders
3. projections of Higgs property studies

   mass, spin-parity, CP mixture
4. extended Higgs boson sectors

   phenomenology and prospects for discovery

couplings

$$V(\text{Yukawa}) = [y_{ij}\bar{f}_{Li}f_{Rj}\phi + HC]$$

Higgs discovery spawned an industry

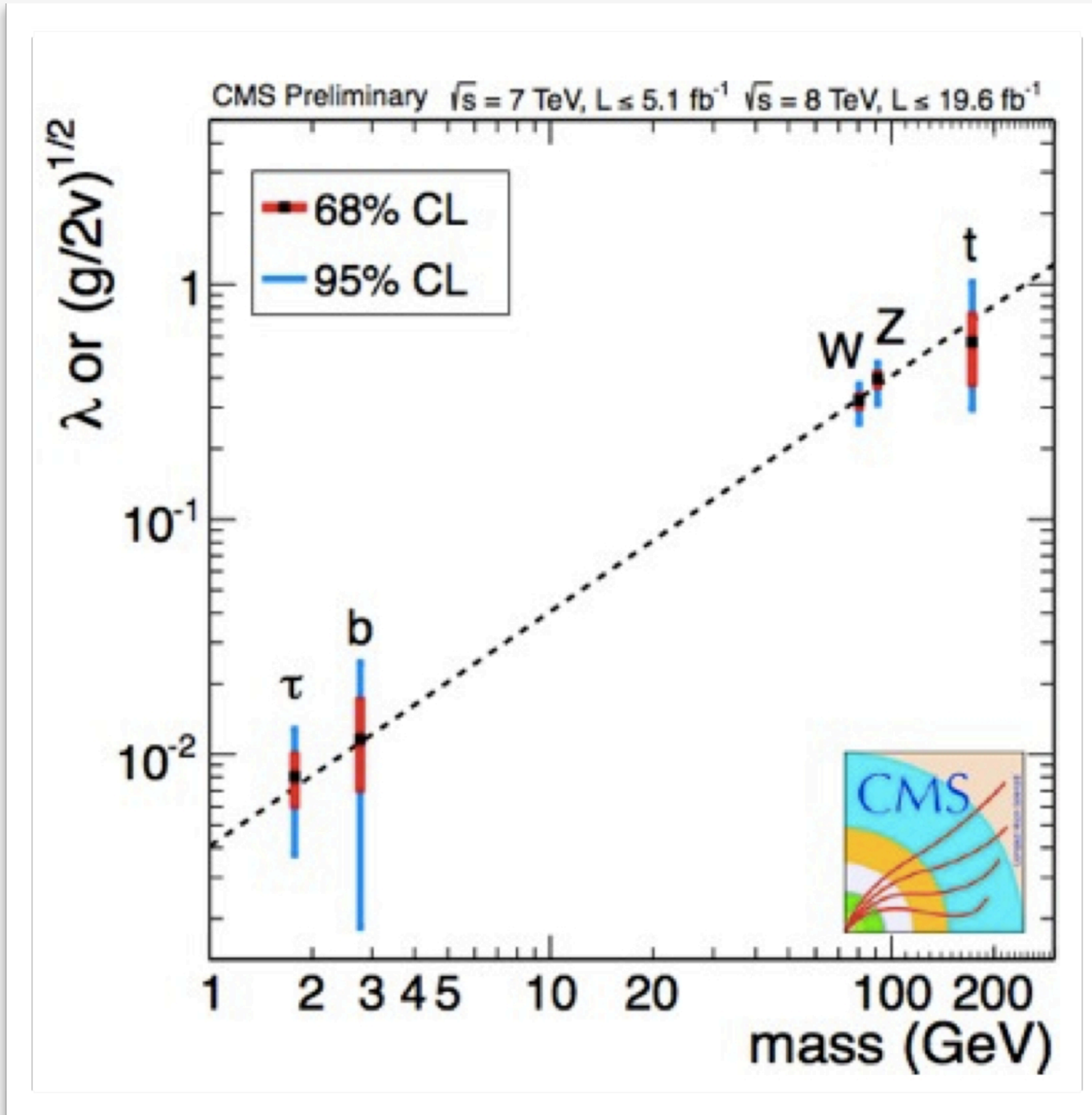
- precision fitting of couplings,

  eg for fermions

couplings

Early results are in line

- for fermions and VBs



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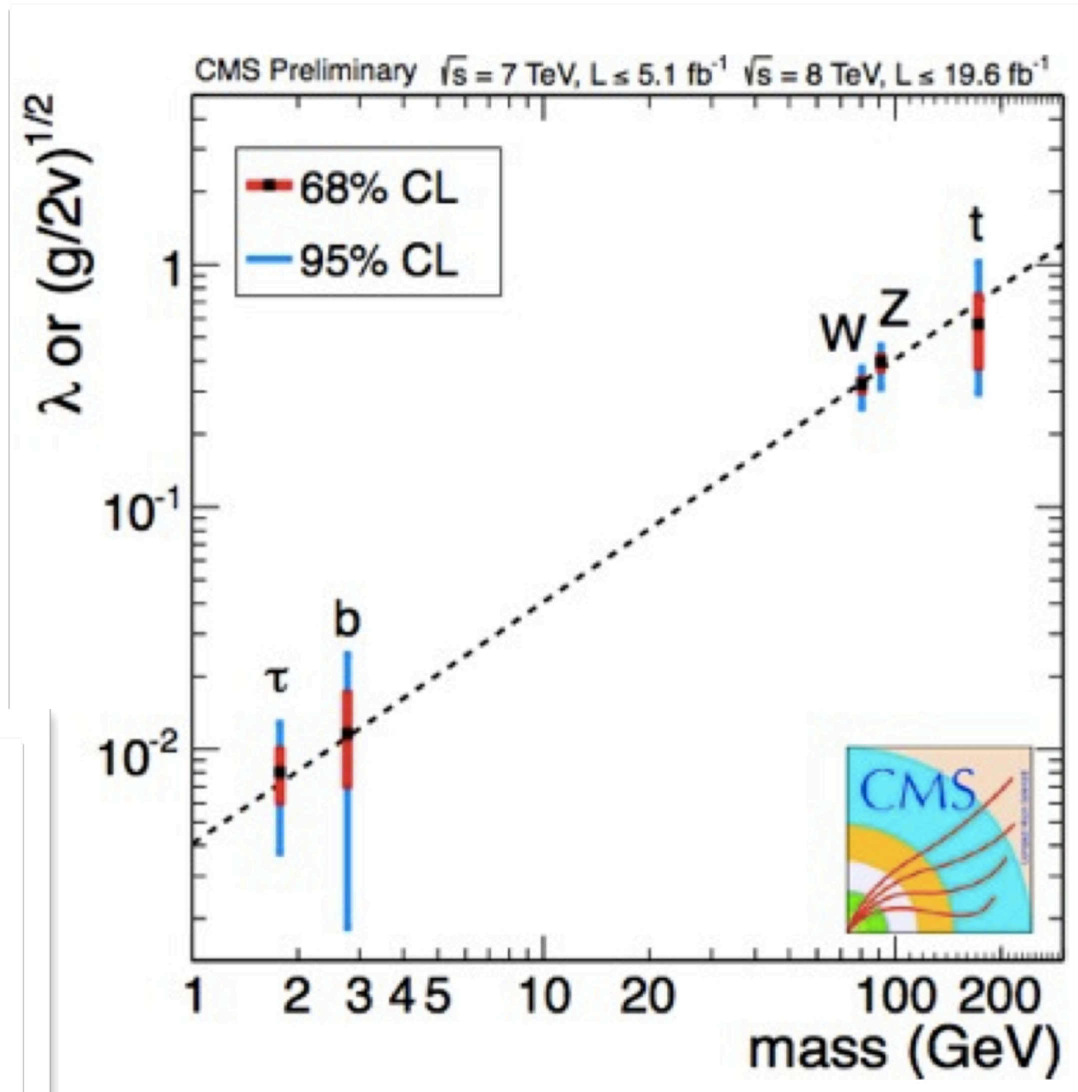


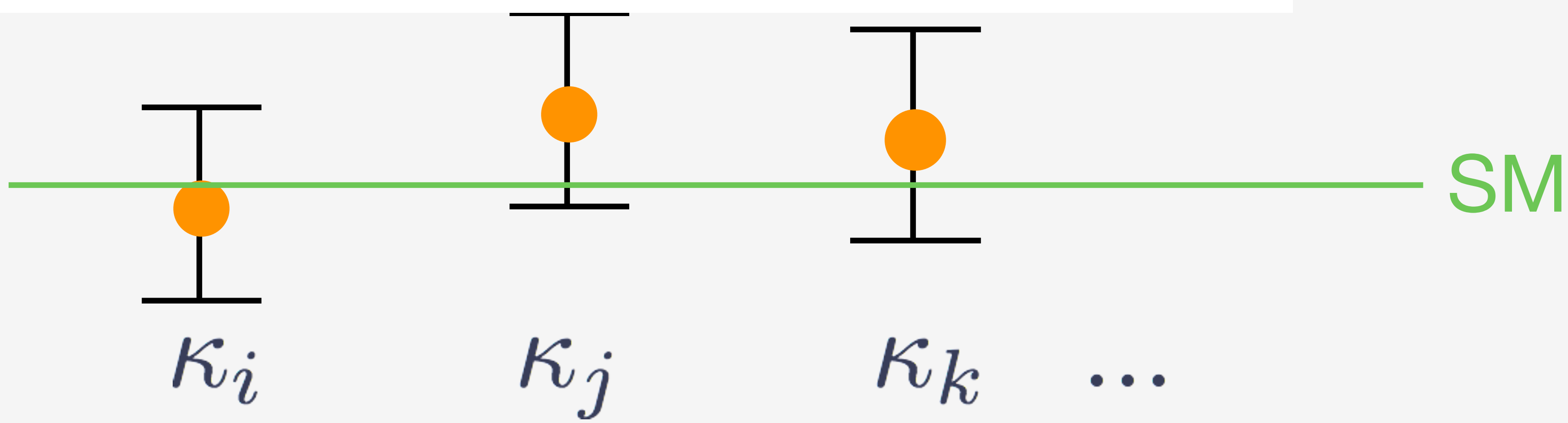
The precision Higgs boson program has begun.

How well do we need to know couplings?

Higgs group evaluated models

- when new particles are ~1TeV:

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



precision for precision's sake?

No - this is a discovery search

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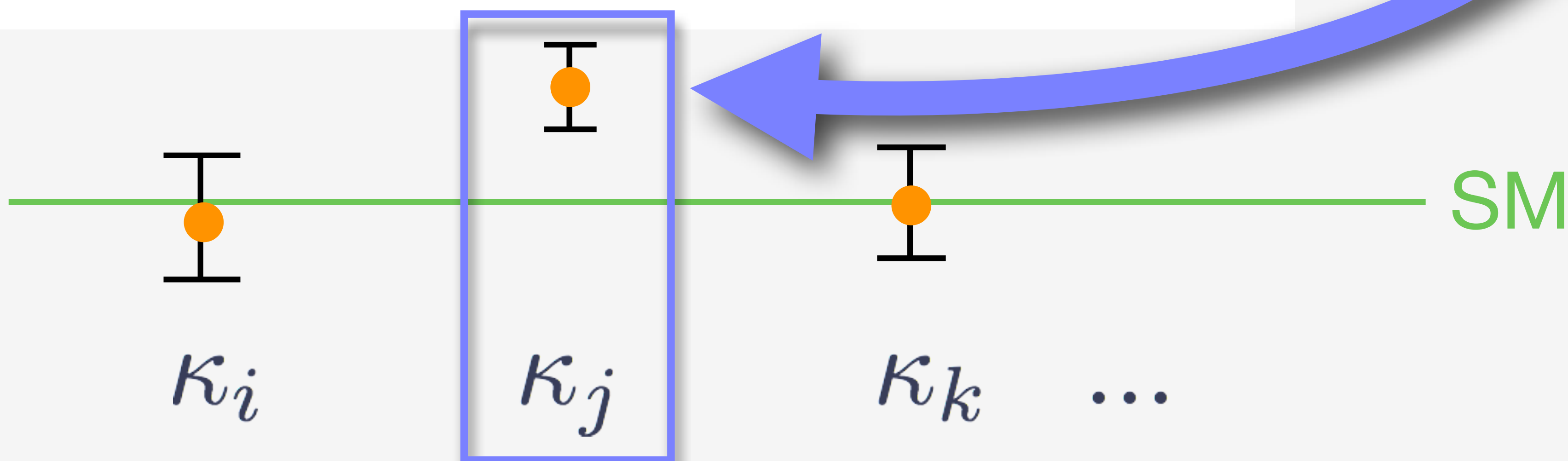
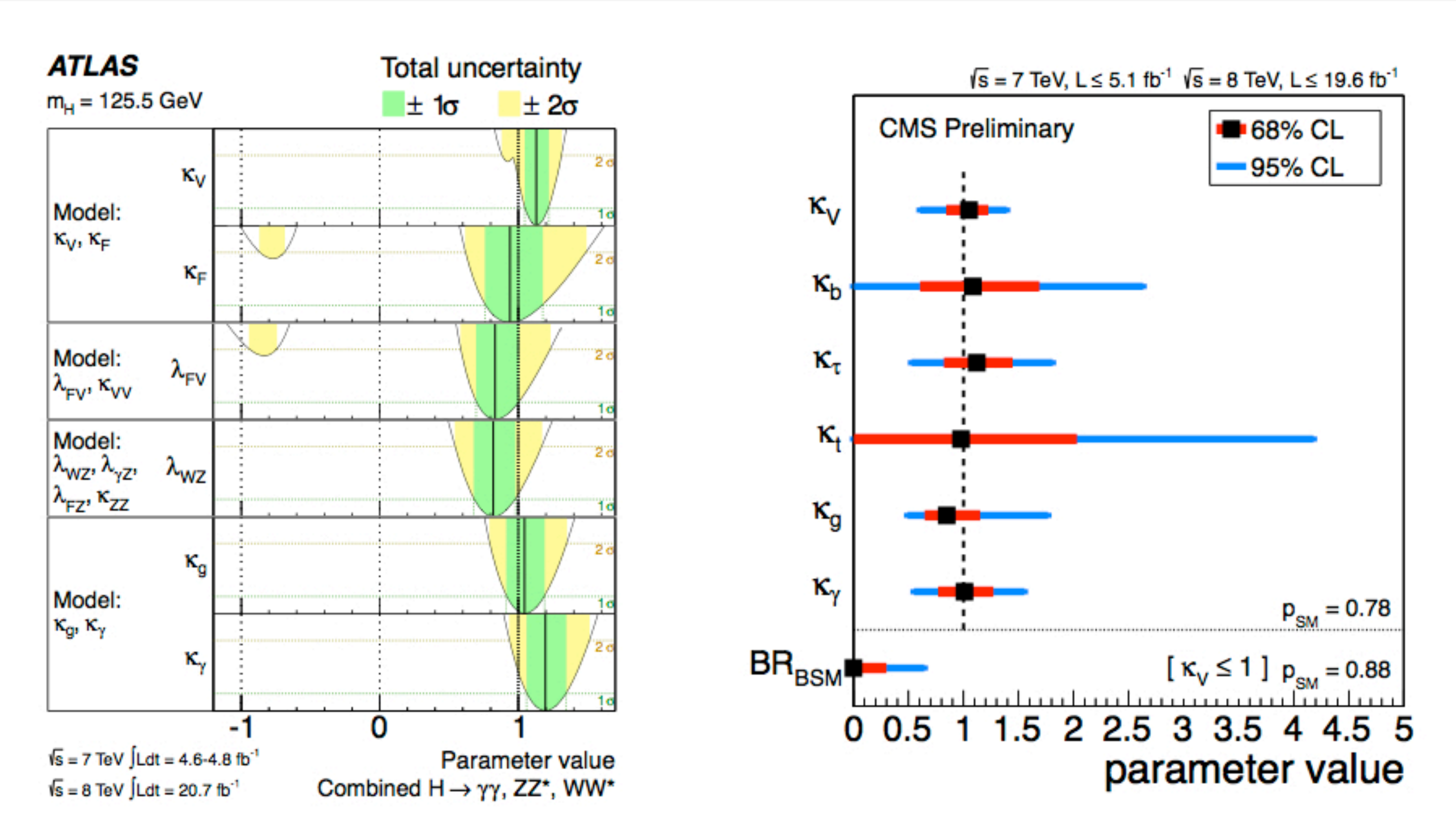
Benchmark for discovery is few % to sub-%



Current precision is multiple 10's%.



Evaluation of coupling extrapolations

Extrapolating LHC requires a strategy

- 2 numbers shown:*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
κ_d	10 – 13%	4 – 7%	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

*$$\delta(\text{sys}) \propto \frac{1}{\sqrt{\mathcal{L}}}$$

and

$$\delta(\text{theory}) \downarrow 1/2$$

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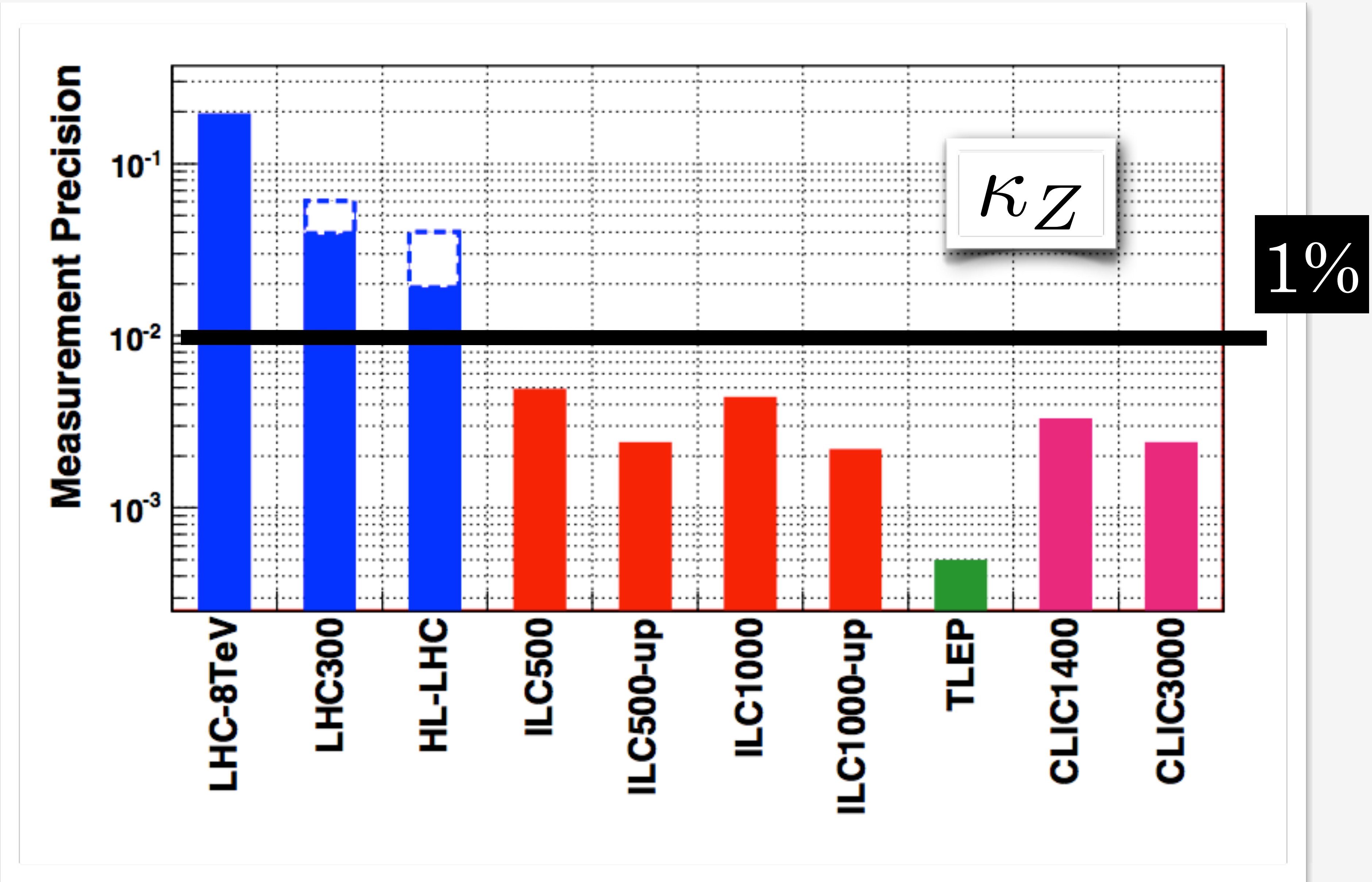
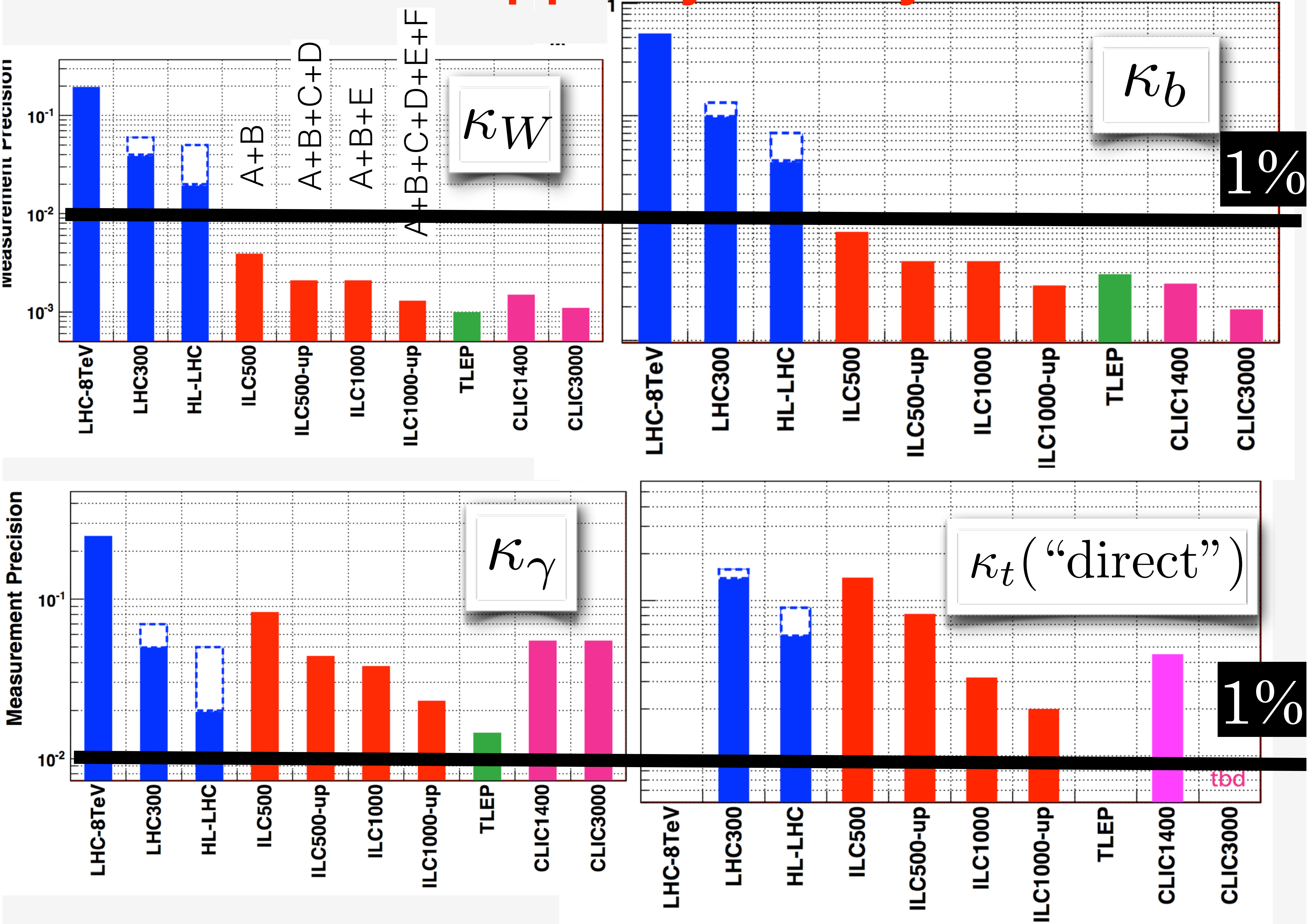
example precision by facility



Precision in kappa by facility

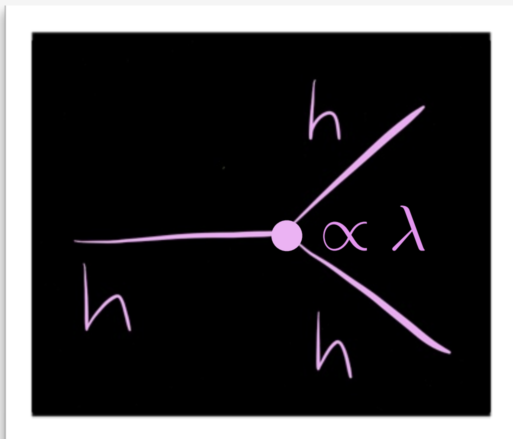


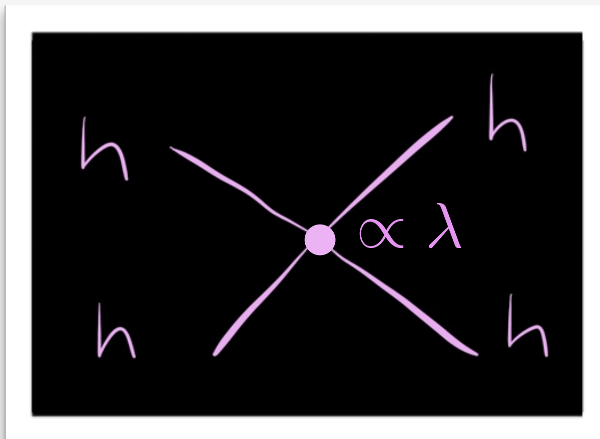
Higgs Self-Coupling

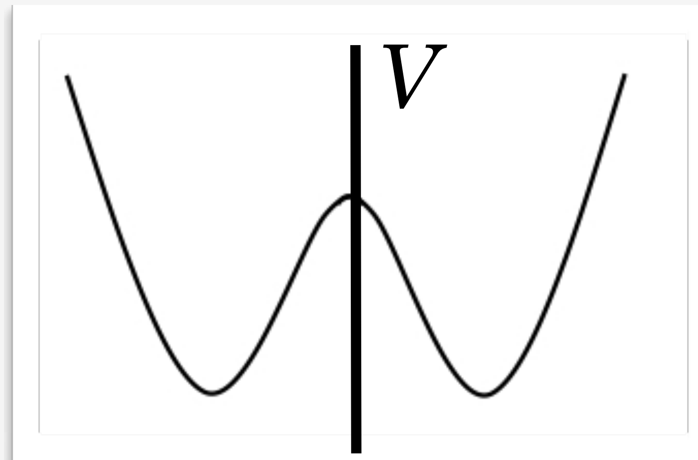
Critical feature of SM

$$V(\text{Higgs}) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

- extremely challenging







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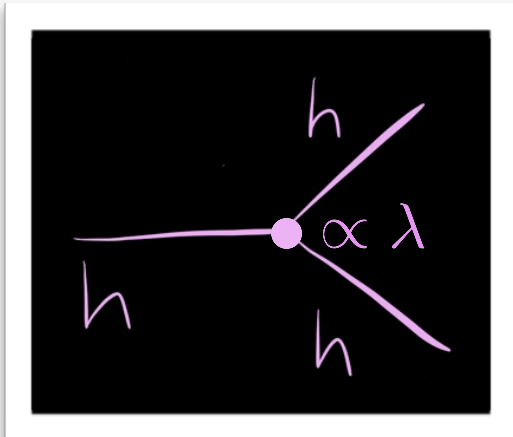

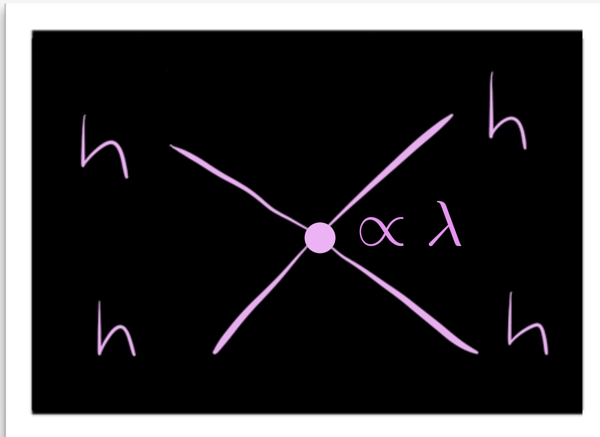

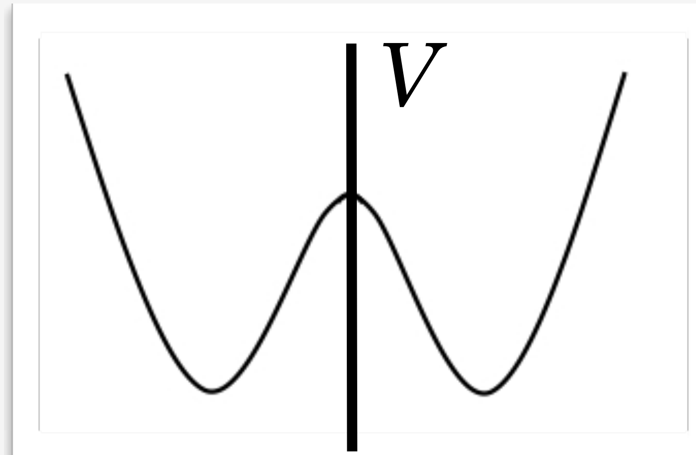

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600[‡]	500/1000	1600/2500[‡]	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

Higgs self-coupling is difficult to measure precisely at any facility.

m_H & Γ_H can be determined to a few %

Mass

- LHC: 50 MeV/c^2
- ILC: 35 MeV/c^2

m_H & Γ_H can be determined to a few %

Mass

- LHC: 50 MeV/c^2
- ILC: 35 MeV/c^2

Total Width

- LHC: limits on Γ
- ILC: model-independent
- MC: direct

Facility	LHC	HL-LHC	ILC500	ILC1000	ILC1000-up	CLIC	TLEP (4 IP)	μC
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350	126
$\int \mathcal{L}dt$ (fb^{-1})	300	3000	250/500	250/500/1000	1150/1600/2500	500/1500/2000	10,000/1400	
m_H (MeV)	100	50	35	35	?	33	7	0.03–0.25
Γ_H	–	–	5.9%	5.6%	2.7%	8.4%	0.6%	1.7–17%

Γ_W to few %

Higgs Properties & extensions

1. SM Higgs spin will be constrained by LHC
2. Many models anticipate multiple Higgs'

   LHC has begun the direct search

   - *The LHC can reach to 1 TeV, with a gap in tan beta*
   - *Lepton colliders can reach to sqrt(s)/2 in a model-independent way.*

   Evidence for CP violation would signal and extended Higgs sector

   - *Specific decay modes can access CP admixtures.*
   - *An example is h-> tau tau at lepton colliders.*
   - *Photon colliders and possibly muon colliders can test CP of the Higgs CP as an   s-channel resonance.*

The Higgs Boson message

1. Direct measurement of the Higgs boson is the key to understanding Electroweak Symmetry Breaking.

   The light Higgs boson must be explained.

   An international research program focused on Higgs couplings to fermions and VBs to a precision of a few % or less is required in order to address its physics.

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2. Full exploitation of the LHC is the path to a few % precision in couplings and 50 MeV mass determination.

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2. Full exploitation of the LHC is the path to a few % precision in couplings and 50 MeV mass determination.
3. Full exploitation of a precision electron collider is the path to a model-independent measurement of the width and sub-percent measurement of couplings.

- Precision Study of Electroweak Physics

Electroweak: Themes

1. precision measurements:

   traditional electroweak observables: M_W, $\sin^2\theta_{eff}$

   sensitive to new TeV particles in loops

2. studies of vector boson interactions

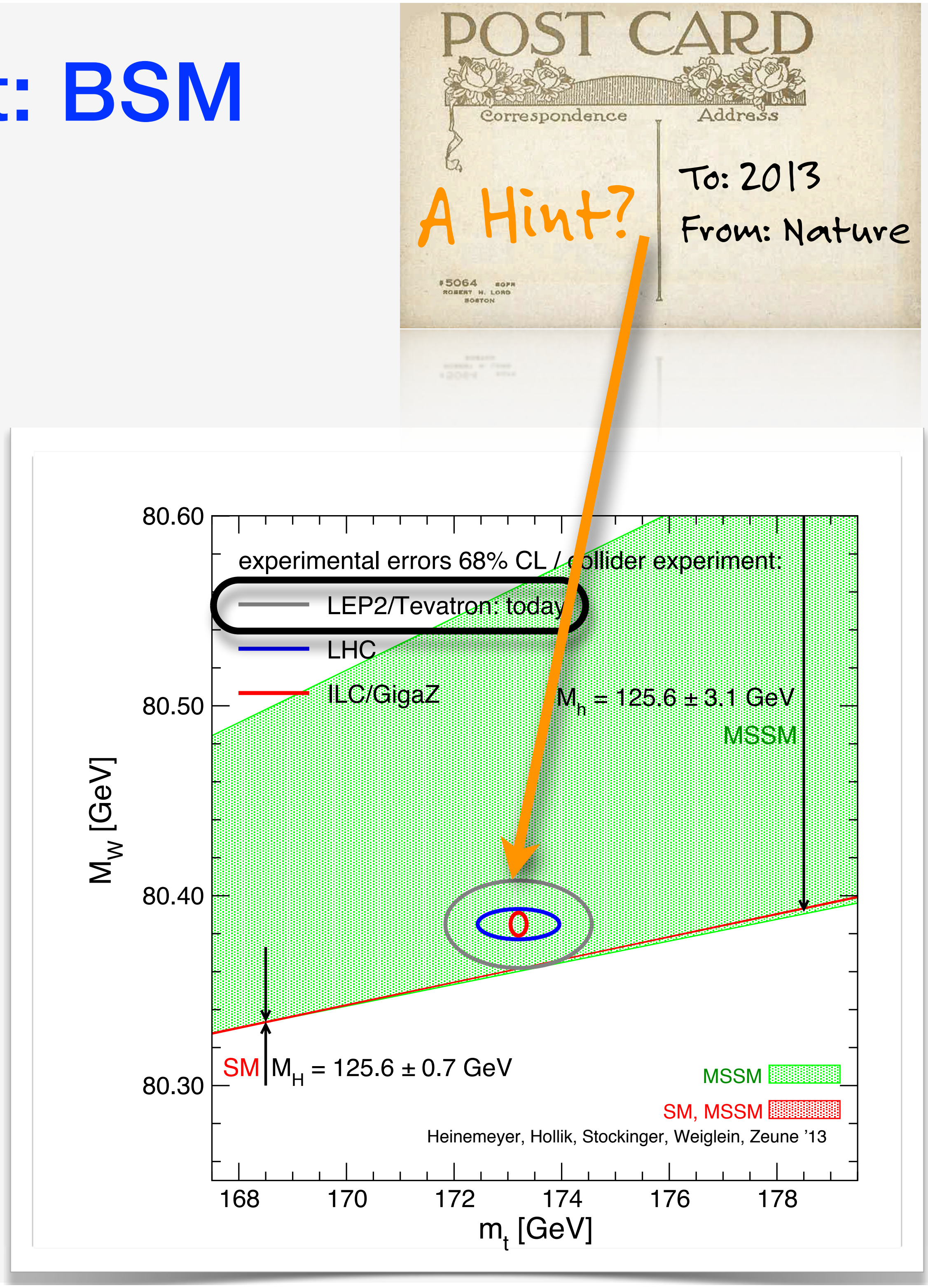
   triple VB couplings, VB scattering

   - *Effective Field Theory approaches*
   - *sensitive to Higgs sector resonances*

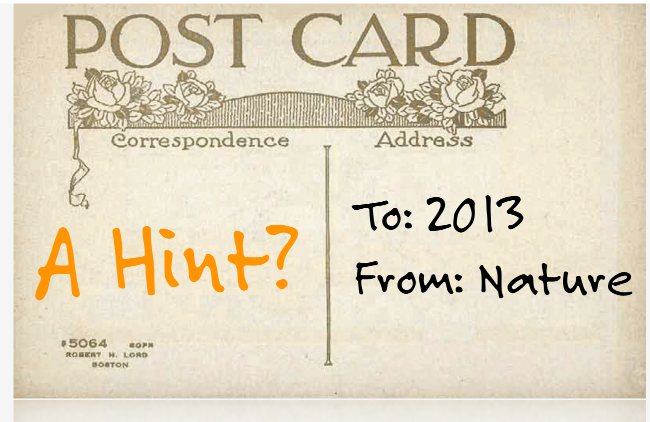
Now...a new target: BSM

Premium on M_W

- Now fits include M_h



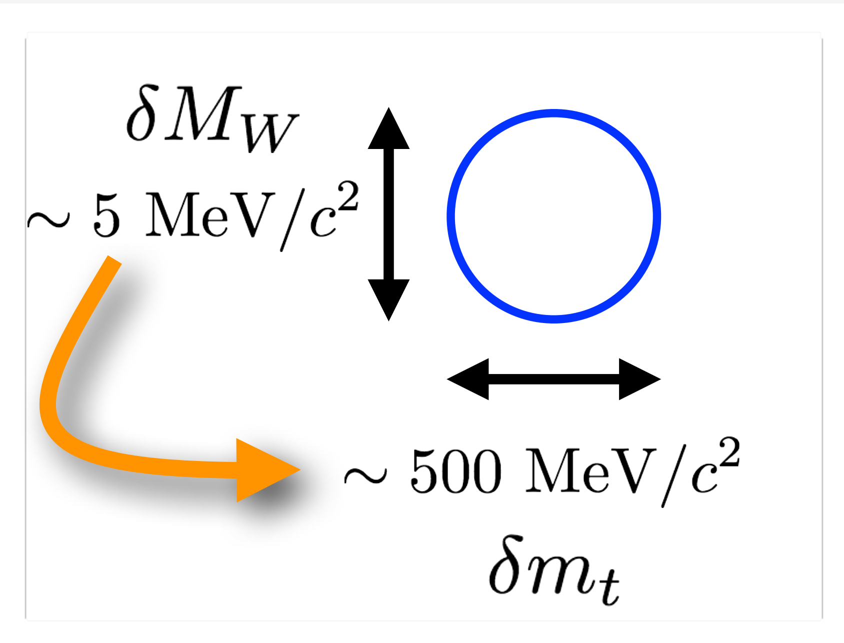
Now...a new target: BSM



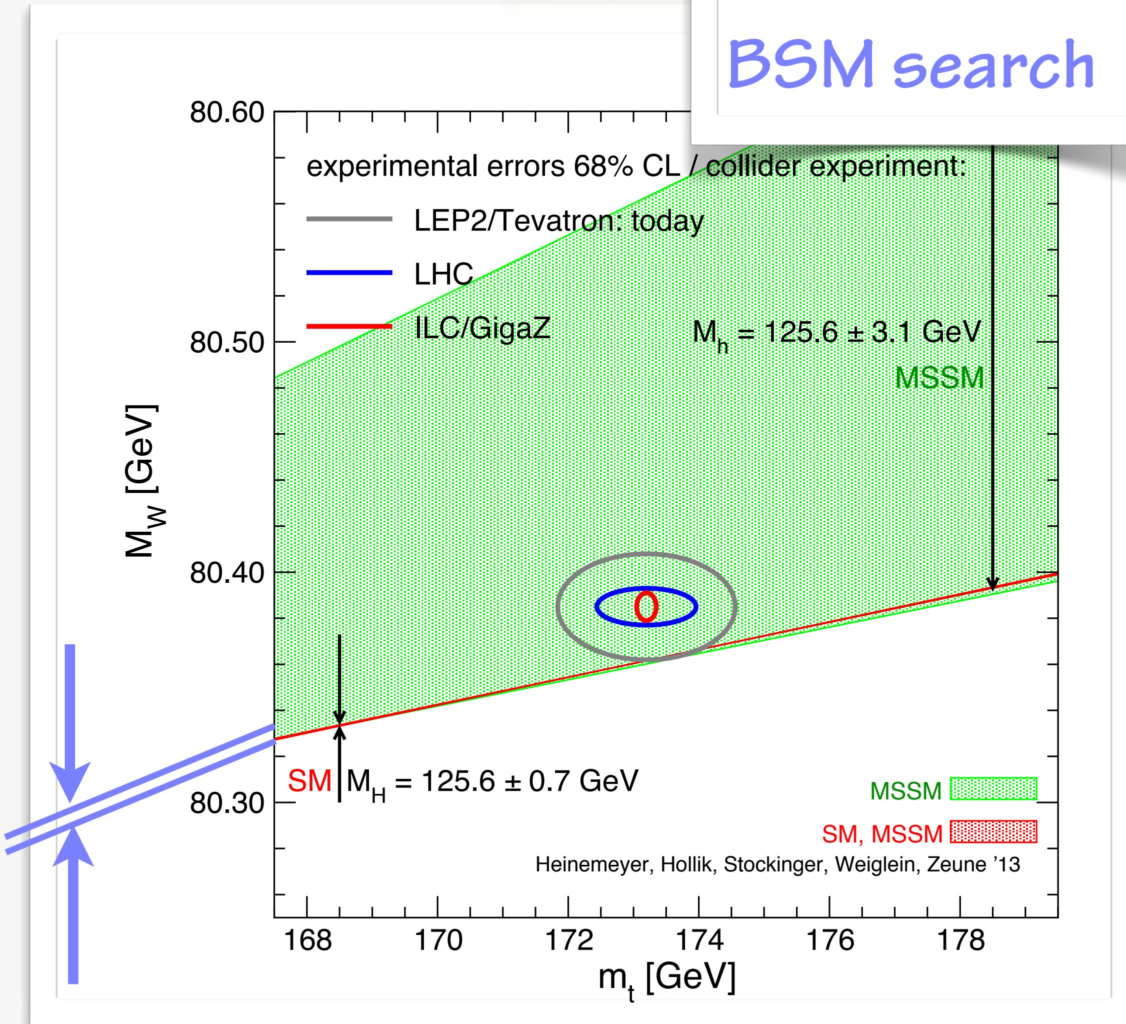
Premium on M_W

- Systematics goal of $M_W = \pm\, 5\ \mathrm{MeV}/c^2$

This is now a BSM search



$\delta M_W \sim 5\ \mathrm{MeV}/c^2$



achievable M_W precision: few MeV/c^2

1. M_W at the LHC

   δM_W ~ 5 MeV requires x7 improvement in PDF uncertainty

   - *a critical need*

2. M_W at the lepton colliders

   A *WW* threshold program: δM_W ~ 2.5 – 4 MeV at ILC, sub-MeV at TLEP.

3. Furthermore: $\sin^2\theta_{\mathrm{eff}}$

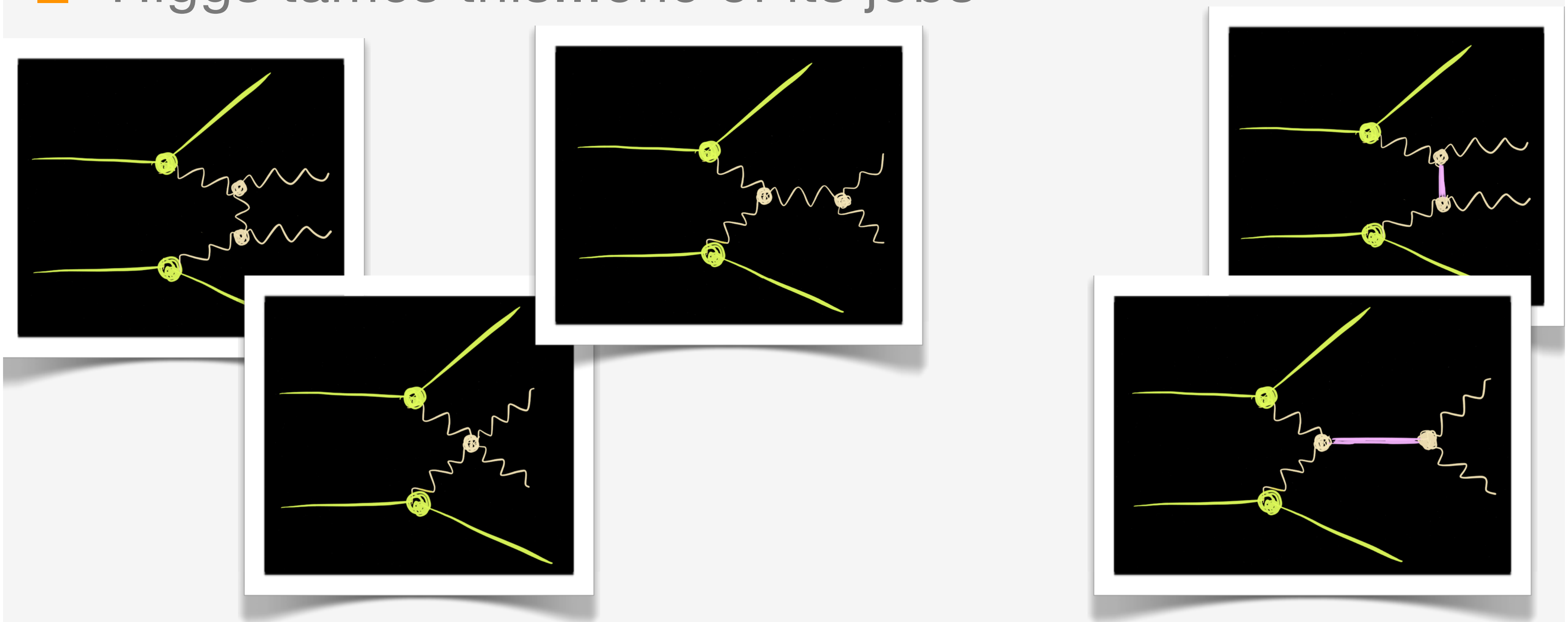
   Running at the *Z* at ILC (Giga-Z) can improve $\sin^2\theta_{\mathrm{ef}}$f by a factor 10 over LEP/SLC;

   - *TLEP might provide another factor 4.*

EW scale - TeV?

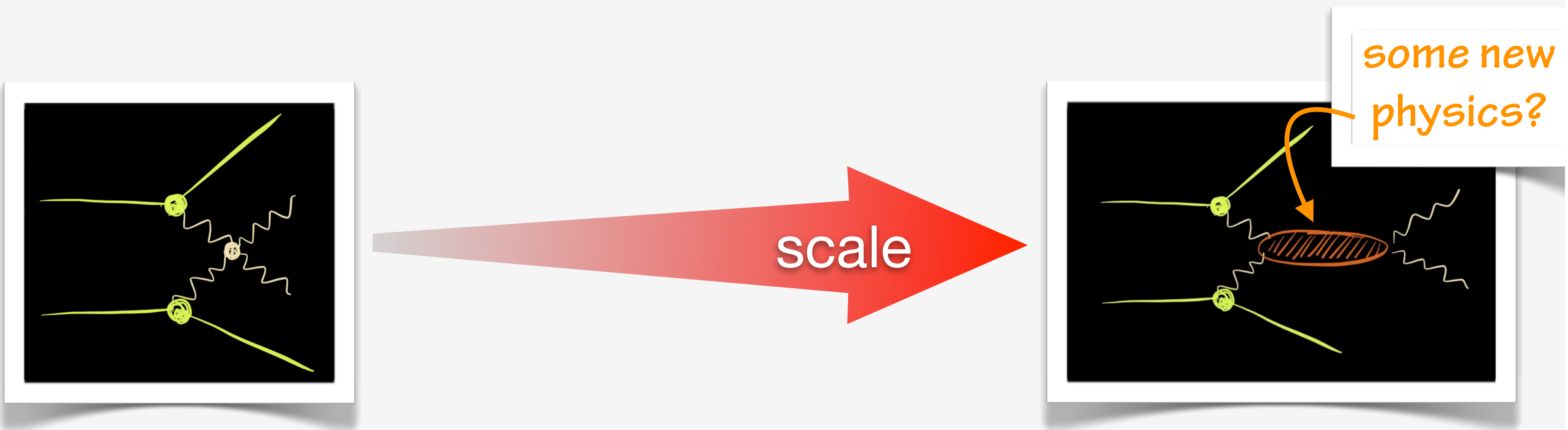
Weak Interaction theory broke down at TeV scale

- Higgs tames this...one of its jobs



searching beyond: quartic VB scattering

- Effective Operator Machinery built into Madgraph specifically for the Snowmass EW group

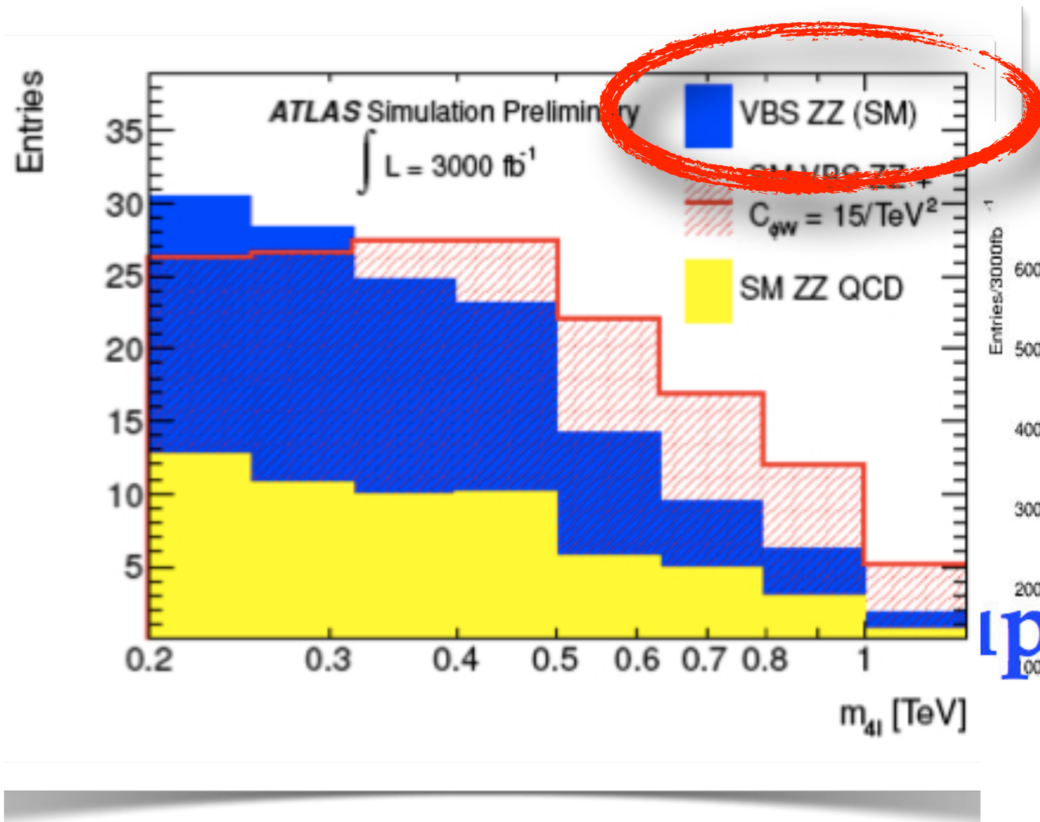


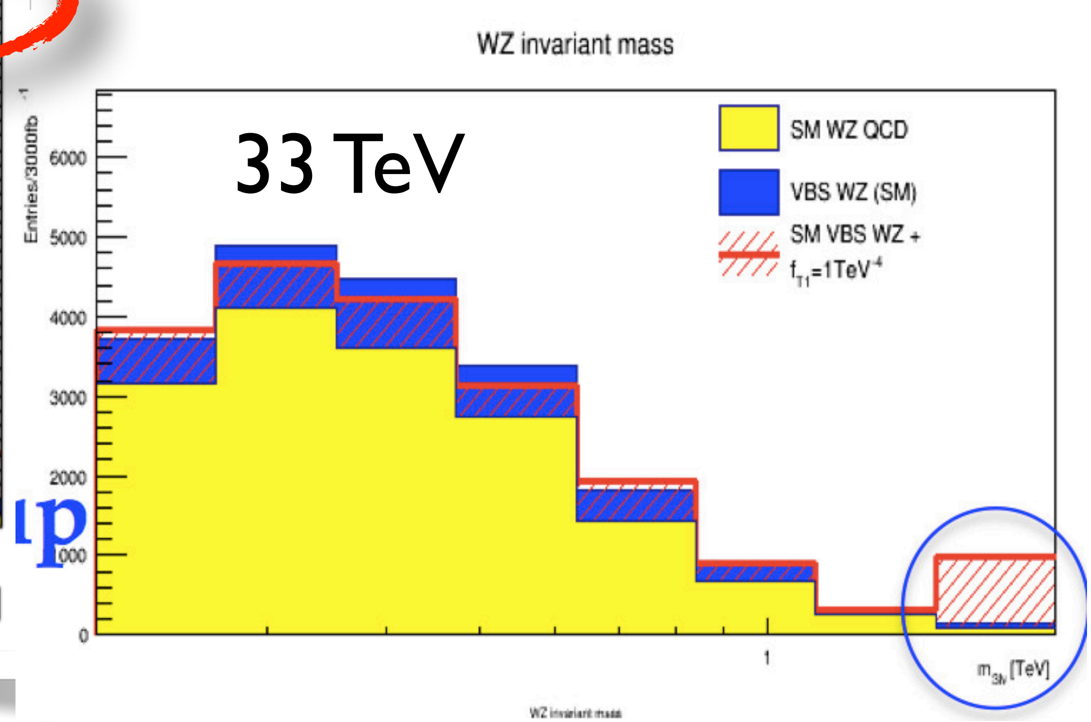
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_i \frac{f_j}{\Lambda^4}\mathcal{O}_j + \cdots$$

Comments:

Effective Operator Machinery built into Madgraph for Snowmass

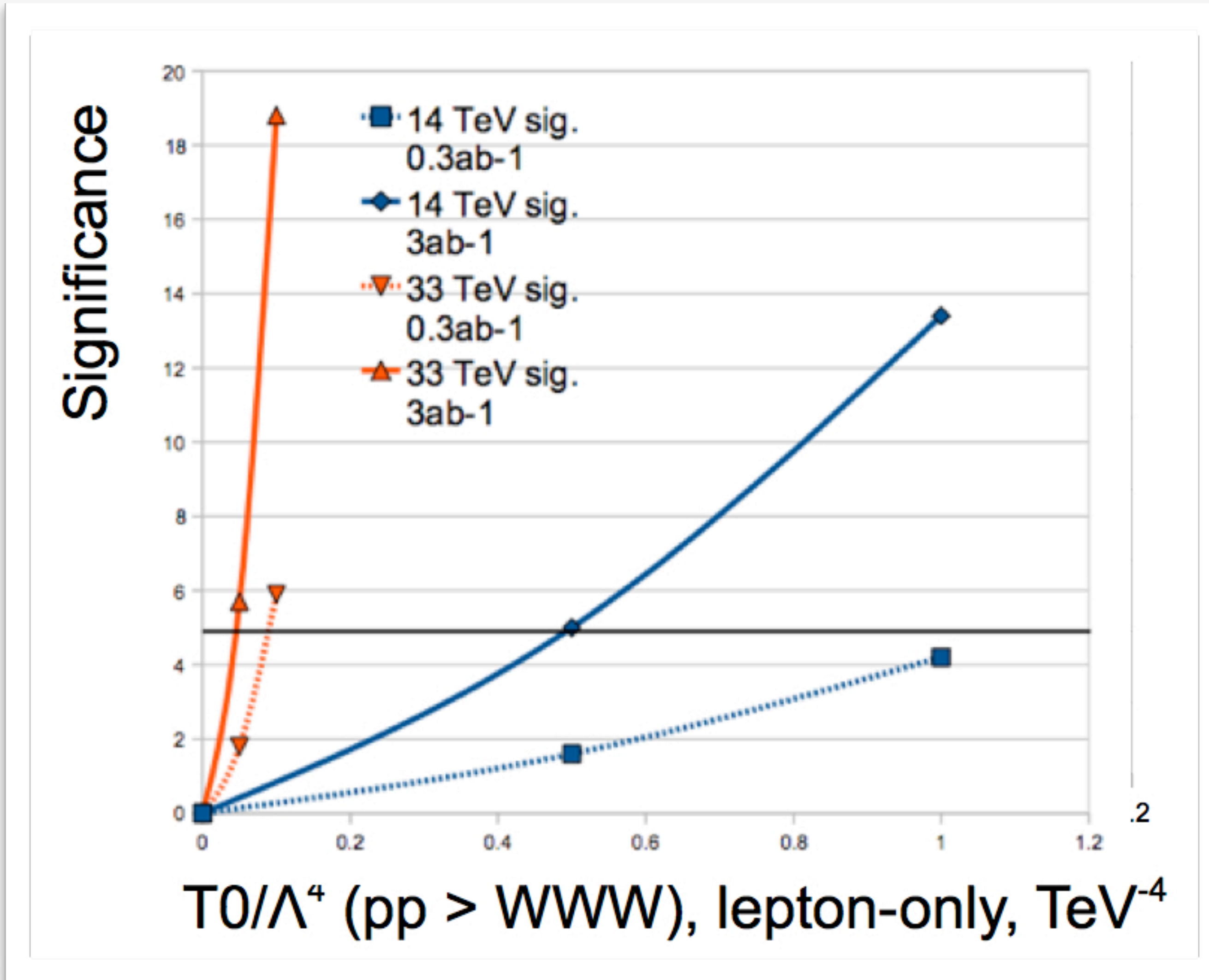
- Sensitivity to non-standard gauge interactions





VB Scattering

Luminosity and Energy win.



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The EW physics message

1. The precision physics of W's and Z's has the potential to probe indirectly for particles with TeV masses.

   This precision program is within the capability of LHC, linear colliders, TLEP.

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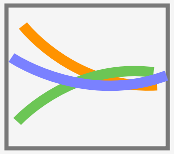
   This precision program is within the capability of LHC, linear colliders, TLEP.

2. Measurement of VB interactions probe for new dynamics in the Higgs sector.

   In such theories, expect correlated signals in triple and quartic gauge couplings.





- Fully Understanding the Top Quark

Top: Themes

1. Top Quark Mass
   - *theory targets and capabilities*
2. Top Quark Couplings
   - *strong and electroweak couplings*
3. Kinematics of Top Final States
   - *top polarization observables and asymmetries*
4. Top Quark Rare Decays
   - *Giga-top program; connection to flavor studies*
5. New Particles Connected to Top
   - *crucial study for composite models of Higgs and top;*
   - *stop plays a central role in SUSY*
6. Boosted-top observables

Mass: why measure m_t precisely?

- EWPOs

  “keep up with” M_W precision

- fundamental parameter

  Yukawa coupling to Higgs

  close to weak scale

  stability argument sensitivity

why measure m_t precisely?

$$V(\text{Higgs}) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

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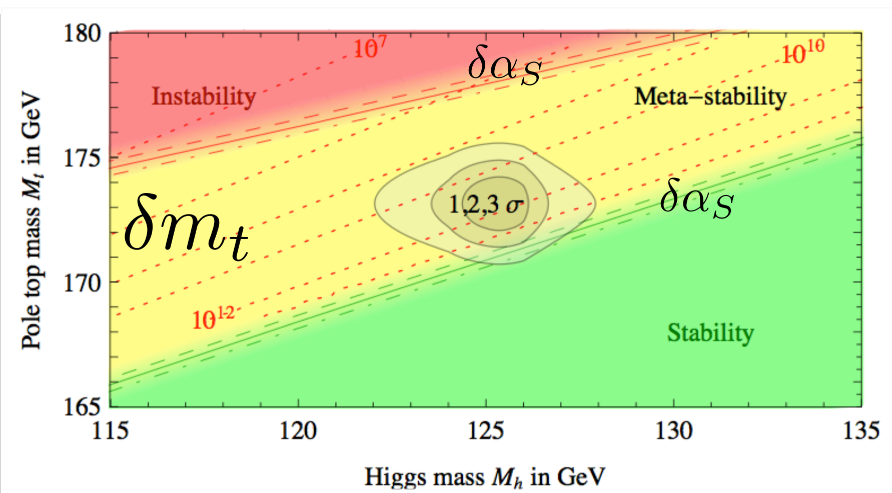

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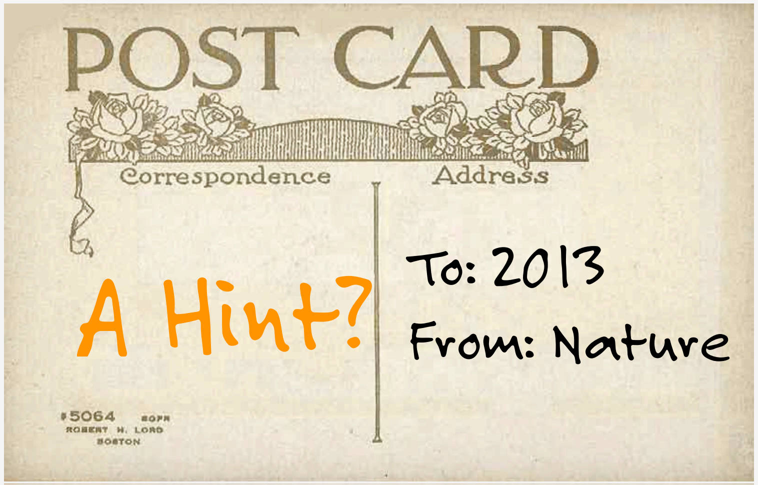

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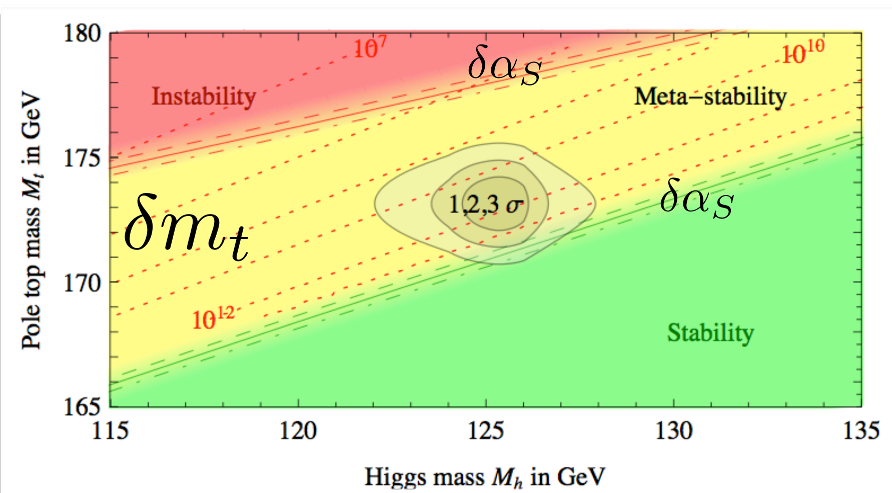
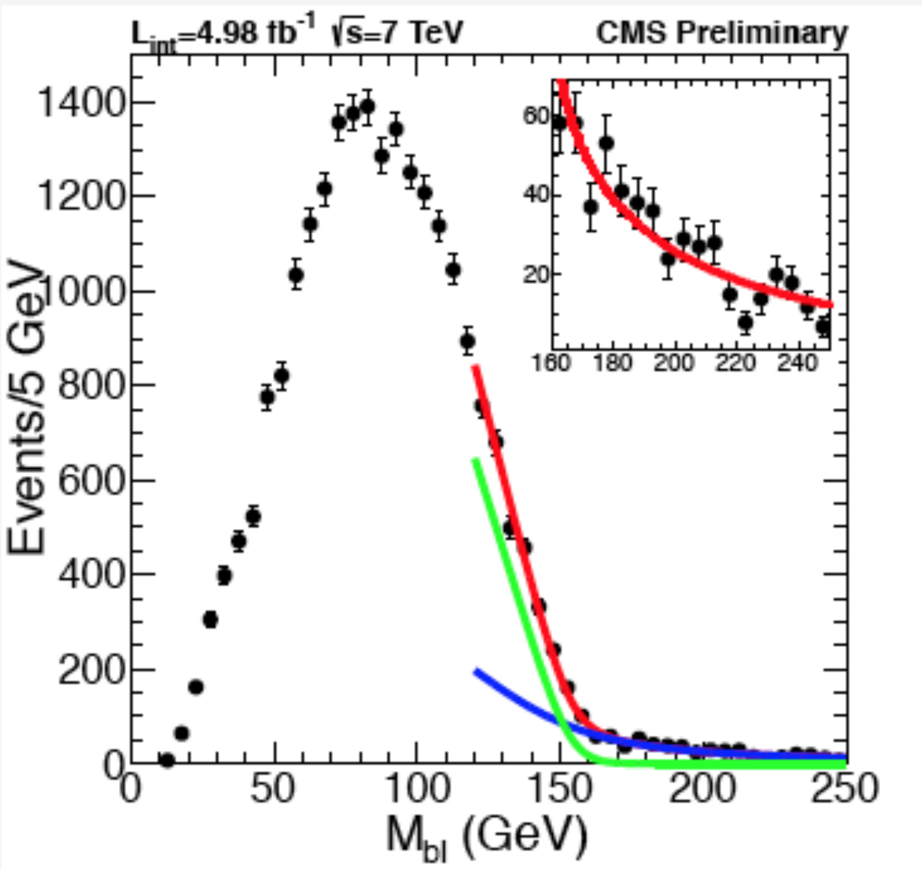


A precision, theoretically sound m_t is doable at LHC

$m(b\ell)$ endpoint method for m_t at LHC

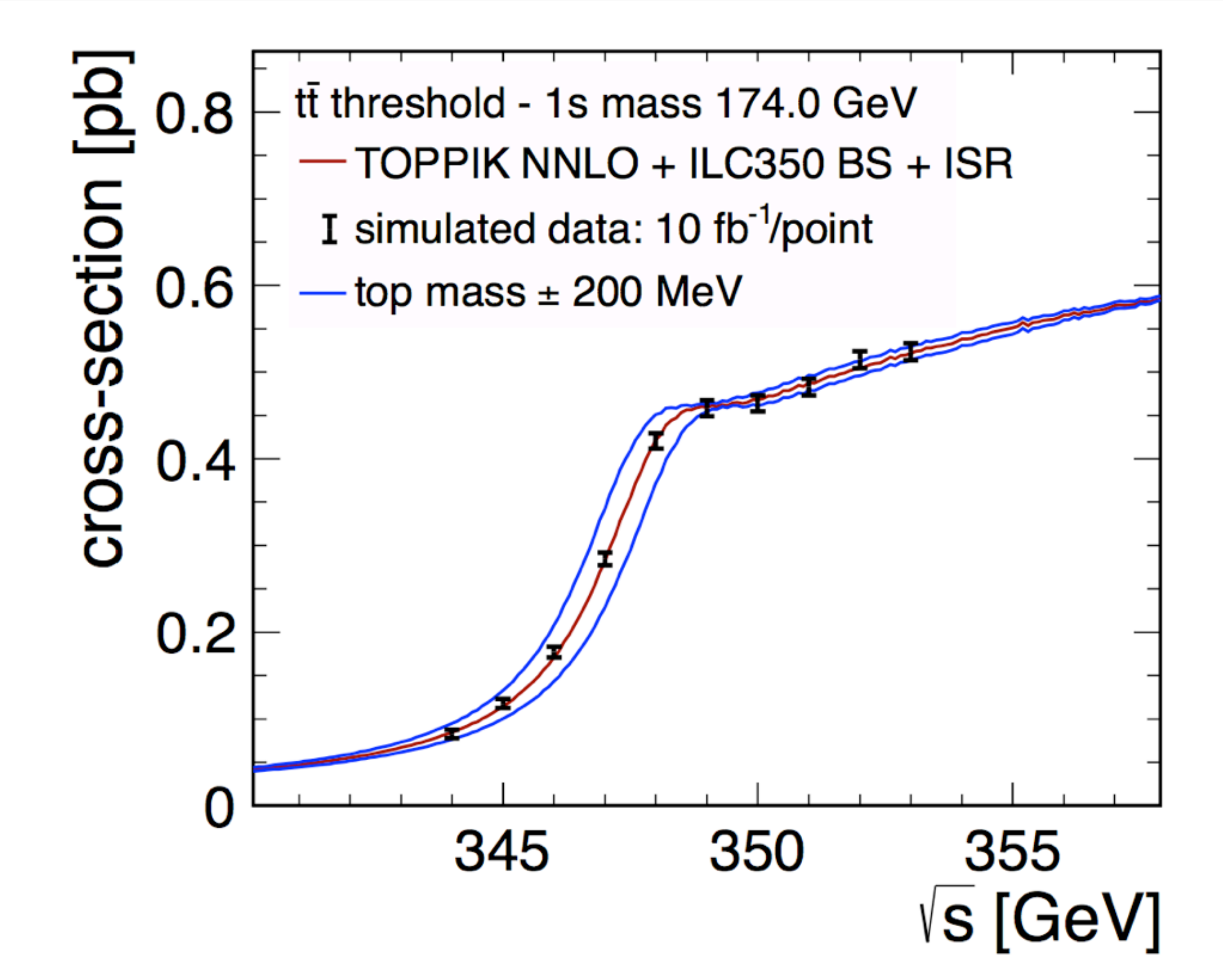


- δm_t ~ 500 MeV/c^2 ultimately

matching the 5 MeV/c^2 precision goal of MW

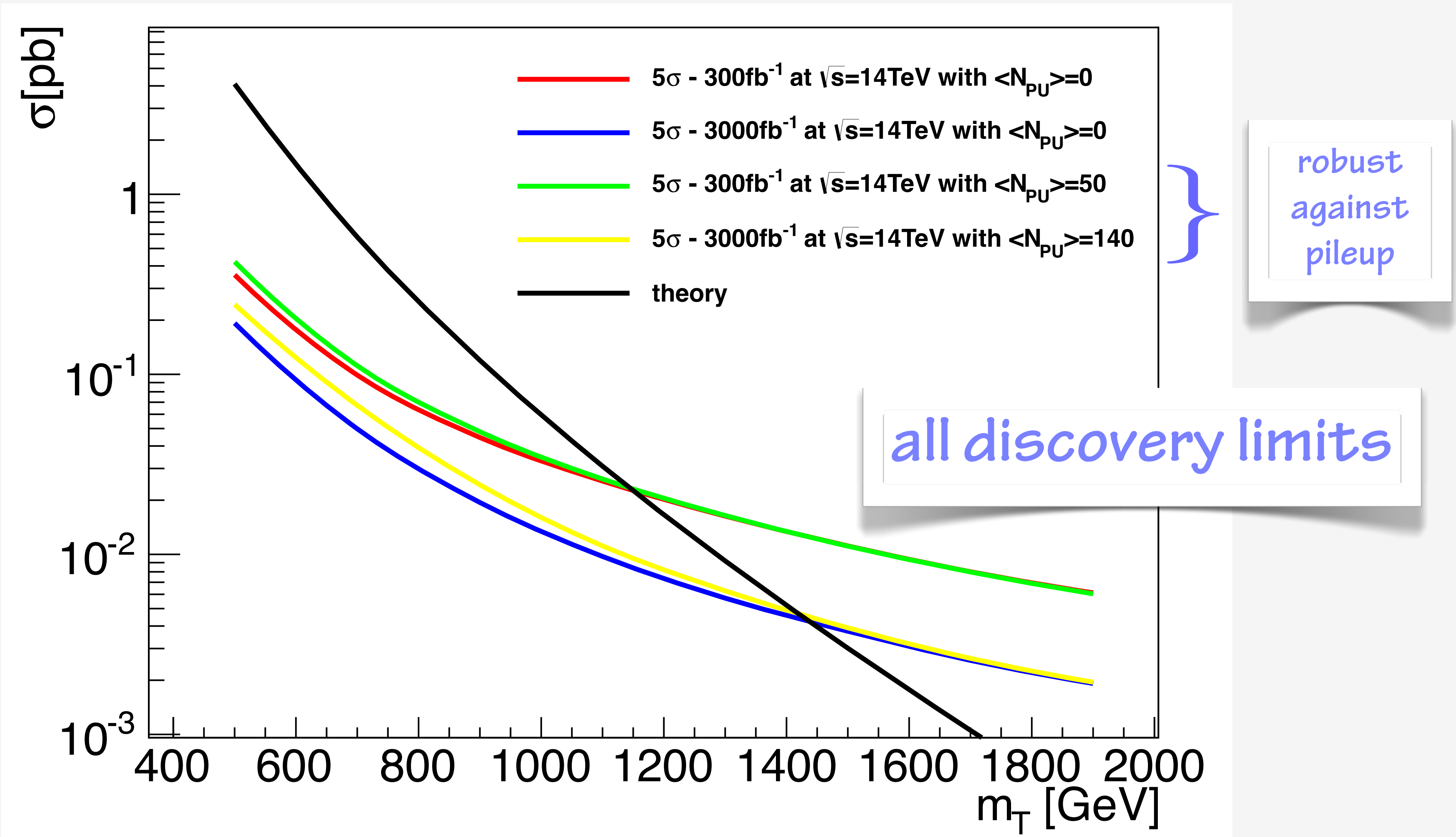
Precision m_t at Lepton Colliders

theoretically clean 100 MeV accuracy in $m_t(\overline{MS})$, matching the needs of Giga-Z precision electroweak fit



Top partner searches to 1.2-1.5 TeV

search reach for vectorlike top partners at LHC 300 and 3000/fb

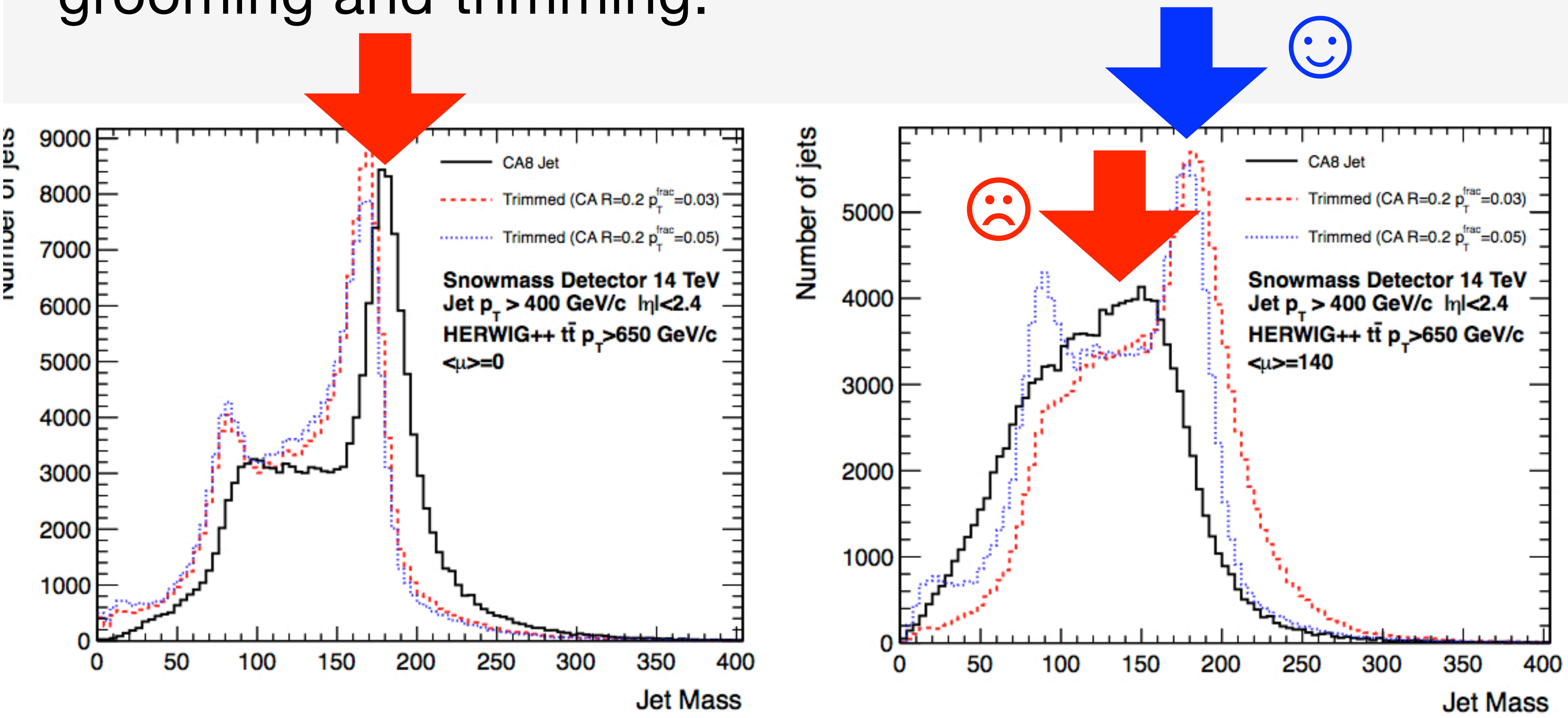


additionally

- EW top-Neutral VB couplings
- Top quark spin correlations
- Flavor-changing top decays

Analysis techniques inoculate against pileup

Restore the performance with boosted techniques of grooming and trimming.



pileup = 0 = 140

The Top Quark physics message

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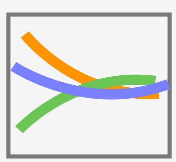
1. Top is intimately tied to the problems of symmetry breaking and flavor
2. Precise and theoretically well-understood measurements of top quark masses are possible both at LHC and at e+e- colliders.
3. New top couplings and new particles decaying to top play a key role in models of Higgs symmetry breaking.

   LHC will search for the particles;

   Linear Colliders for coupling deviations.



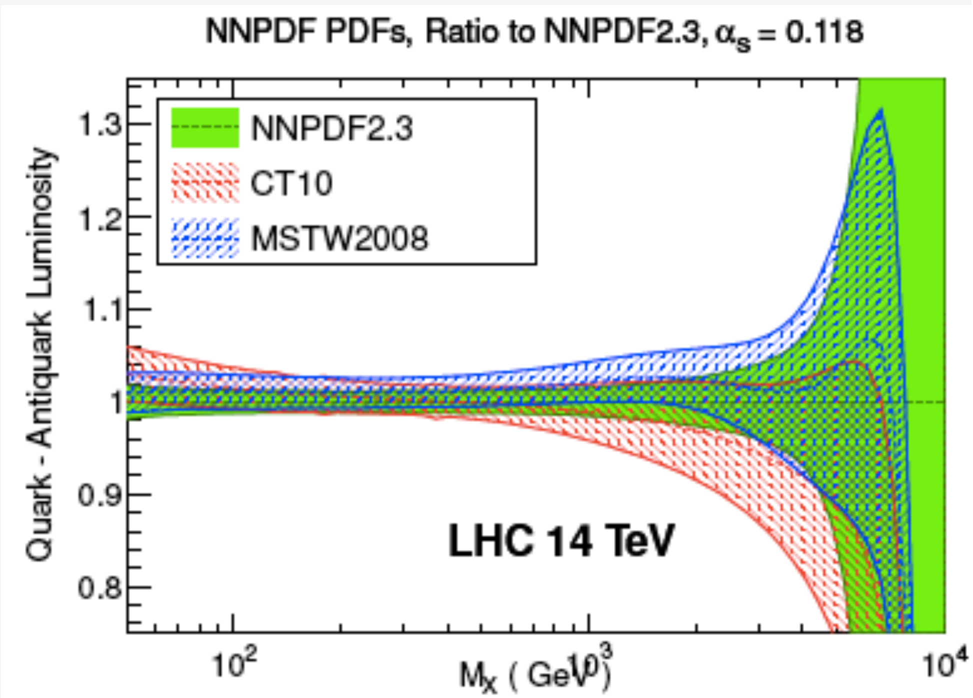
- Quantum Chromodynamics and the Strong Force

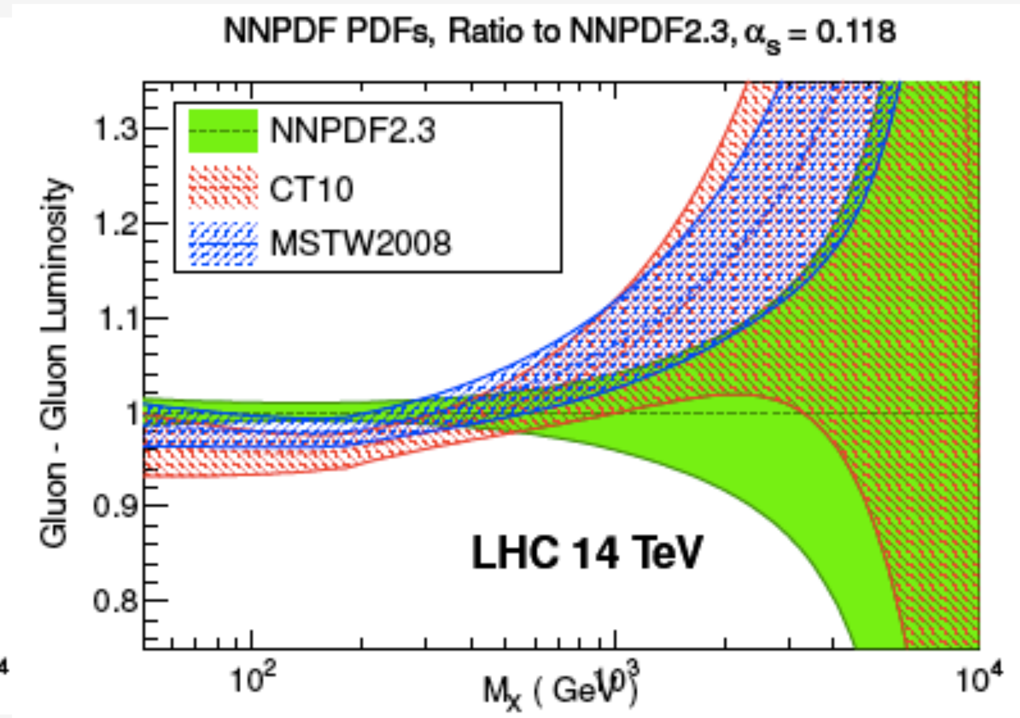
QCD: Themes

1. Improvement of PDFs and α_S
2. Event structure at hadron colliders
   - *needed to enable all measurements*
   - *mitigation of problems from pileup at high luminosity*
3. Improvement of the art in perturbative QCD
   - *key role in LHC precision measurement, especially for Higgs*

PDF uncertainties must improve

significant in regions relevant to Higgs, EWPOs, & new particle searches



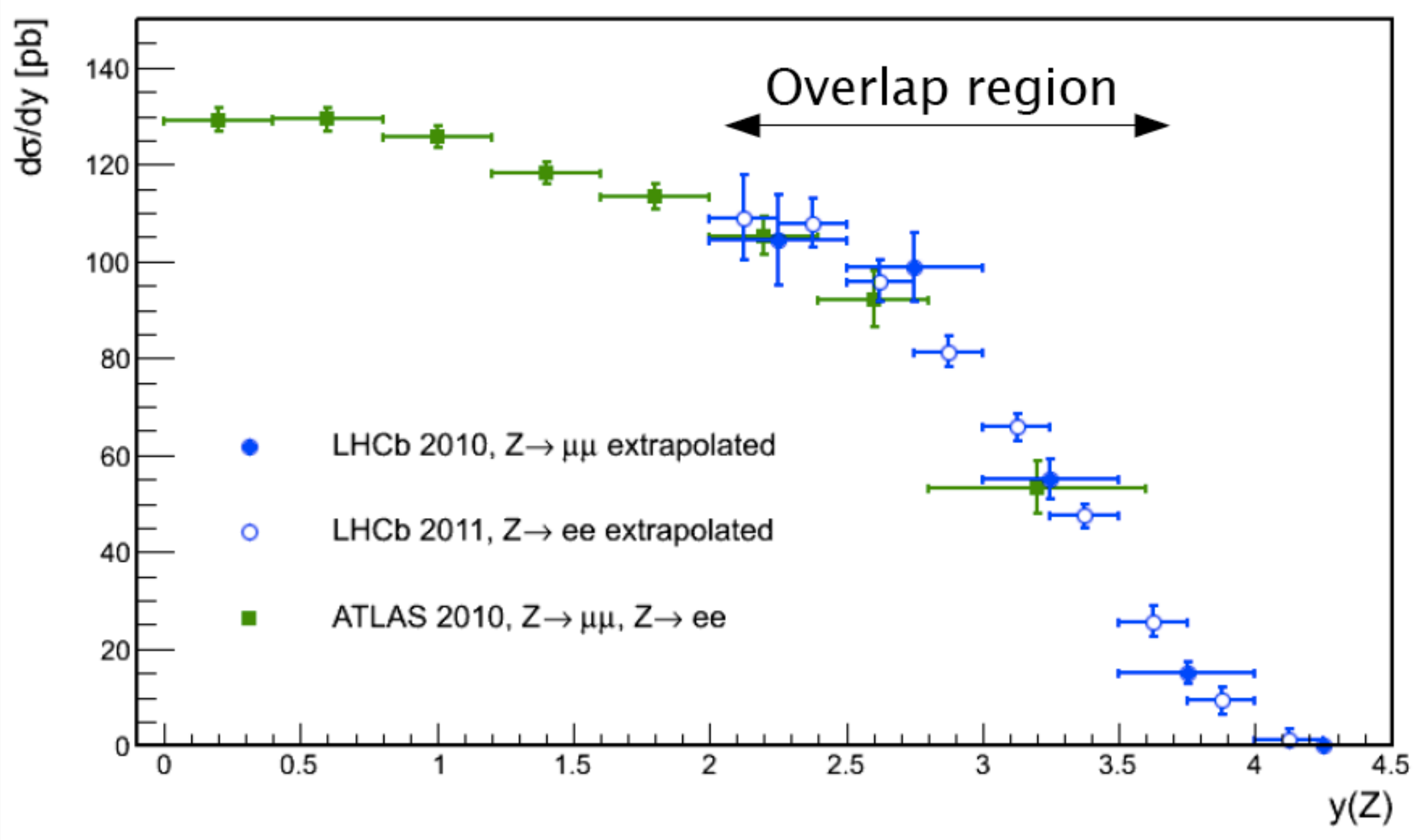


Juan Rojo

- Improve at LHC with W, Z, top rapidity distributions

full rapidity coverage required

complementary role of ATLAS,CMS and LHCb



additionally

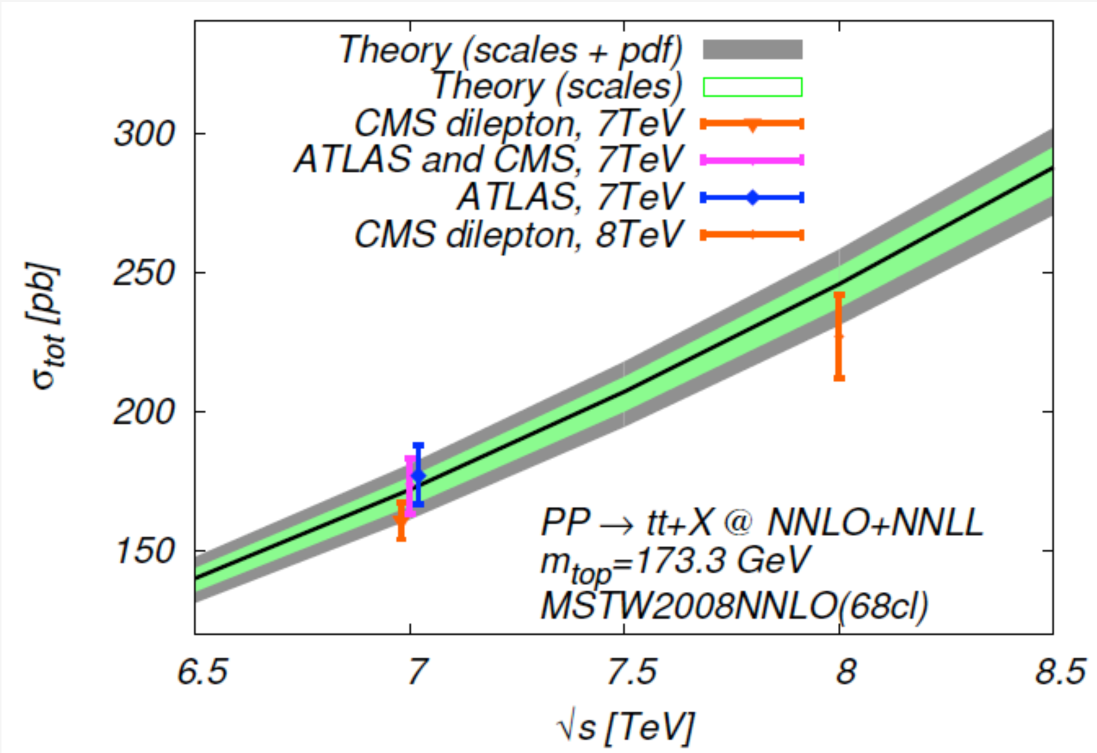
- importance of photon distribution function
- need to incorporate full EW resummation
- lattice contributions, esp aS

NNLO

Landmark NNLO calculation of the top quark pair production cross section.

- Soon for 2->2 & some 2->3 processes.

Higgs and many other LHC analyses.



Czakon-Mitov

The QCD Physics Message

1. Improvements in PDF uncertainties are achievable.
   - *There are strategies at LHC for these improvements.*
   - *QED and electroweak corrections must be included in PDFs and in perturbative calculations.*

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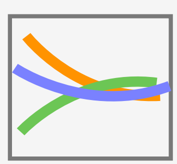
   - *QED and electroweak corrections must be included in PDFs and in perturbative calculations.*
2. alphas error ~ 0.1% is achievable
   - *lattice gauge theory + precision experiments*
3. Advances in all collider experiments, especially for Higgs boson physics & M_W

require continued advances in perturbative QCD.






- The Path Beyond the Standard Model – New Particles, Forces, and Dimensions

NP: Themes

1. Necessity for new particles at TeV mass

the questions of fine tuning and dark matter are still open

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2. Candidate TeV particles
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   - *strongly coupled/composite: Randall-Sundrum, KK and Z' resonances, long-lived particles*
   - *evolution of robust search strategies*

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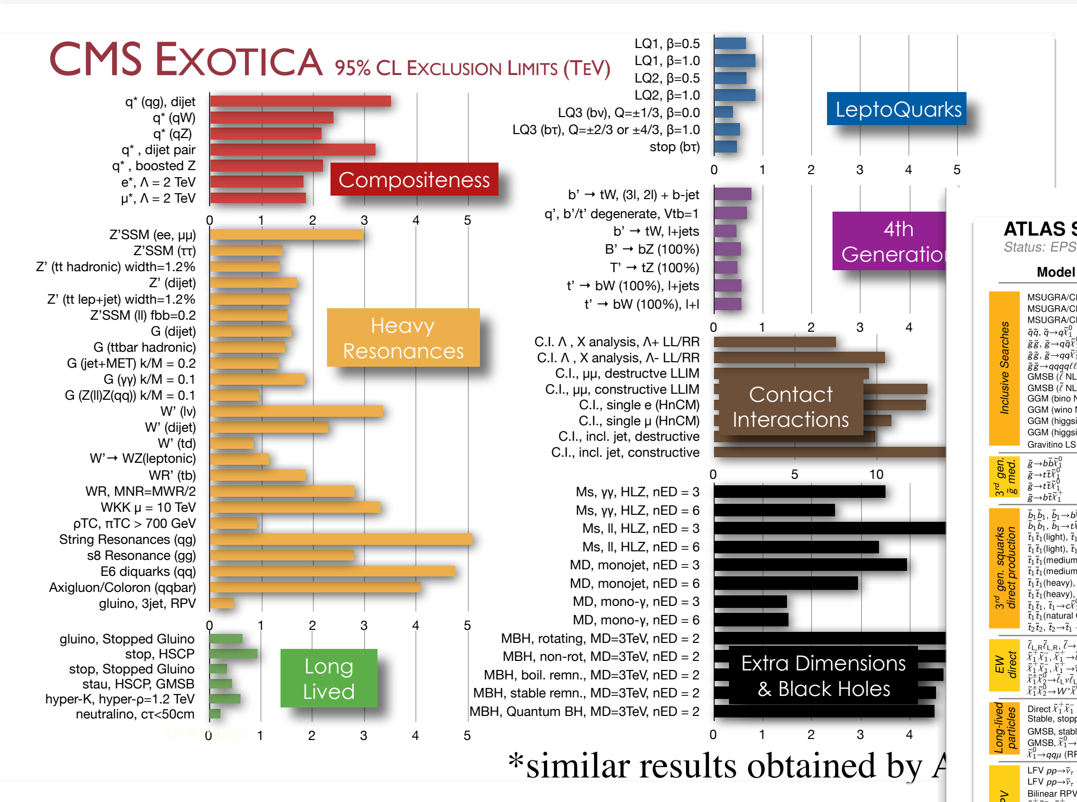
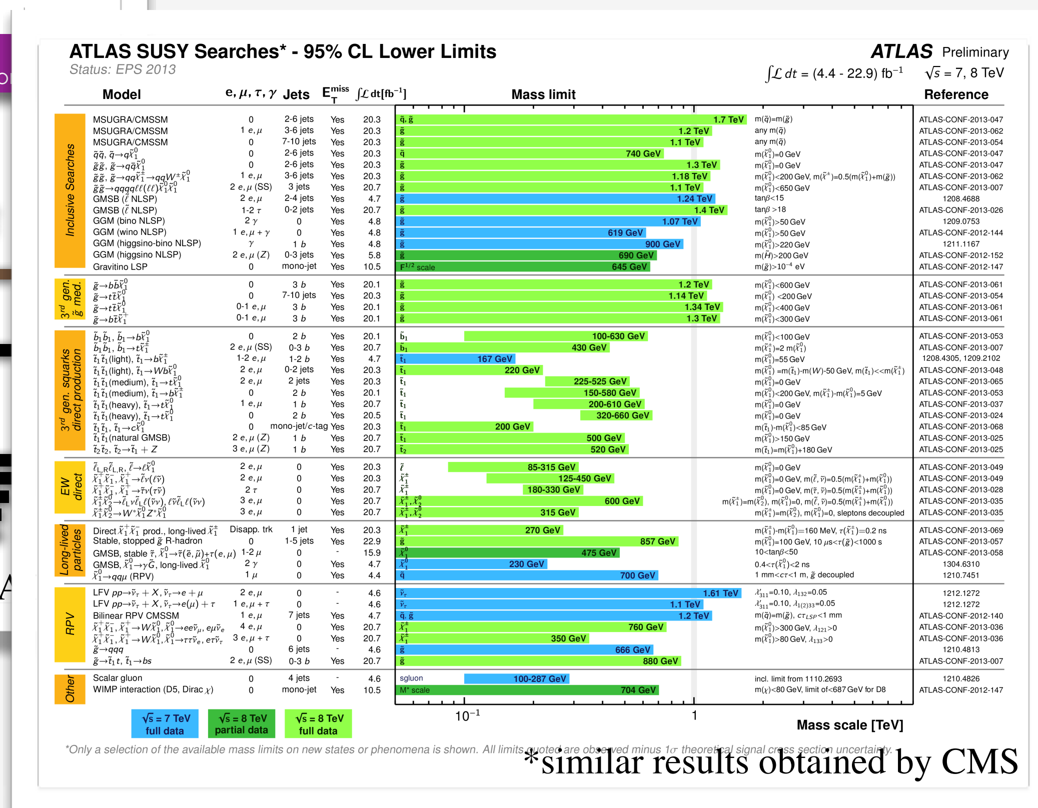
    - *evolution of robust search strategies*
3. Connection to dark matter problem
4. Connection to flavor issues

current LHC searches

New particle searches at the current LHC.



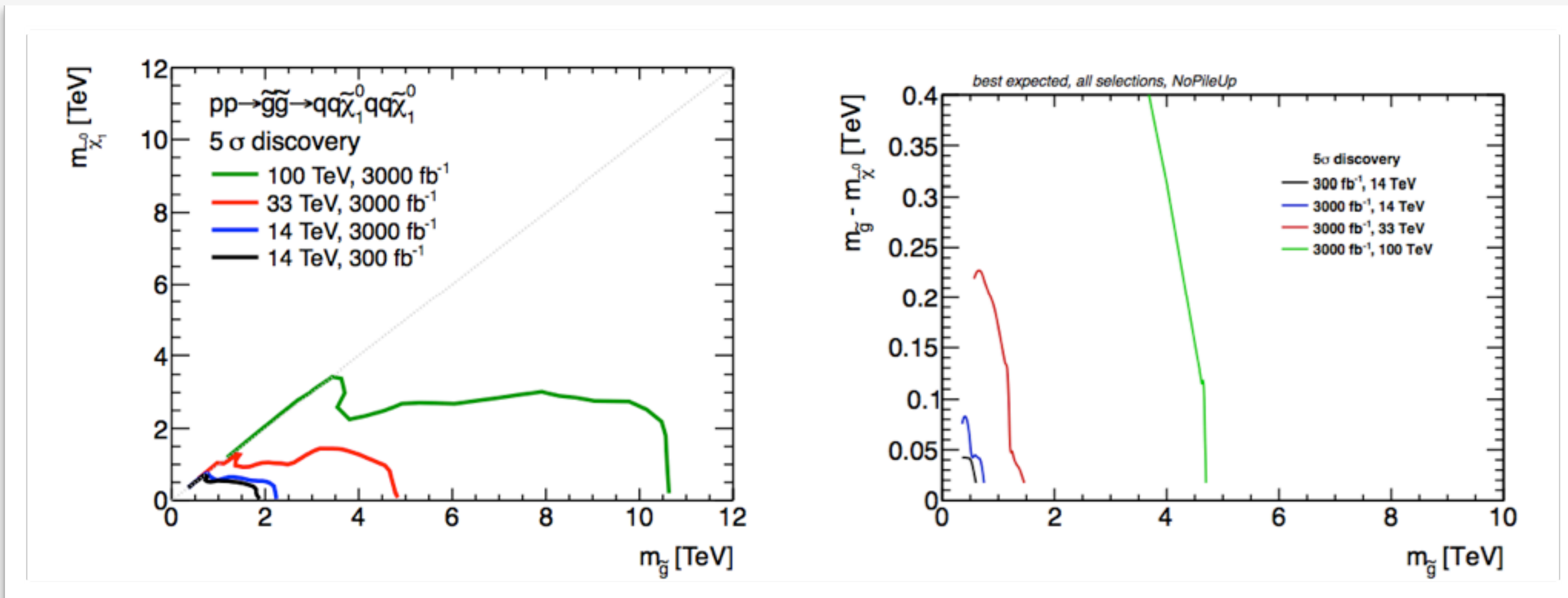


gain from now to 300/fb & beyond

x2 in gluino mass reach 8-14 TeV,

- 30% more with 300/fb - 3000/fb @14 TeV

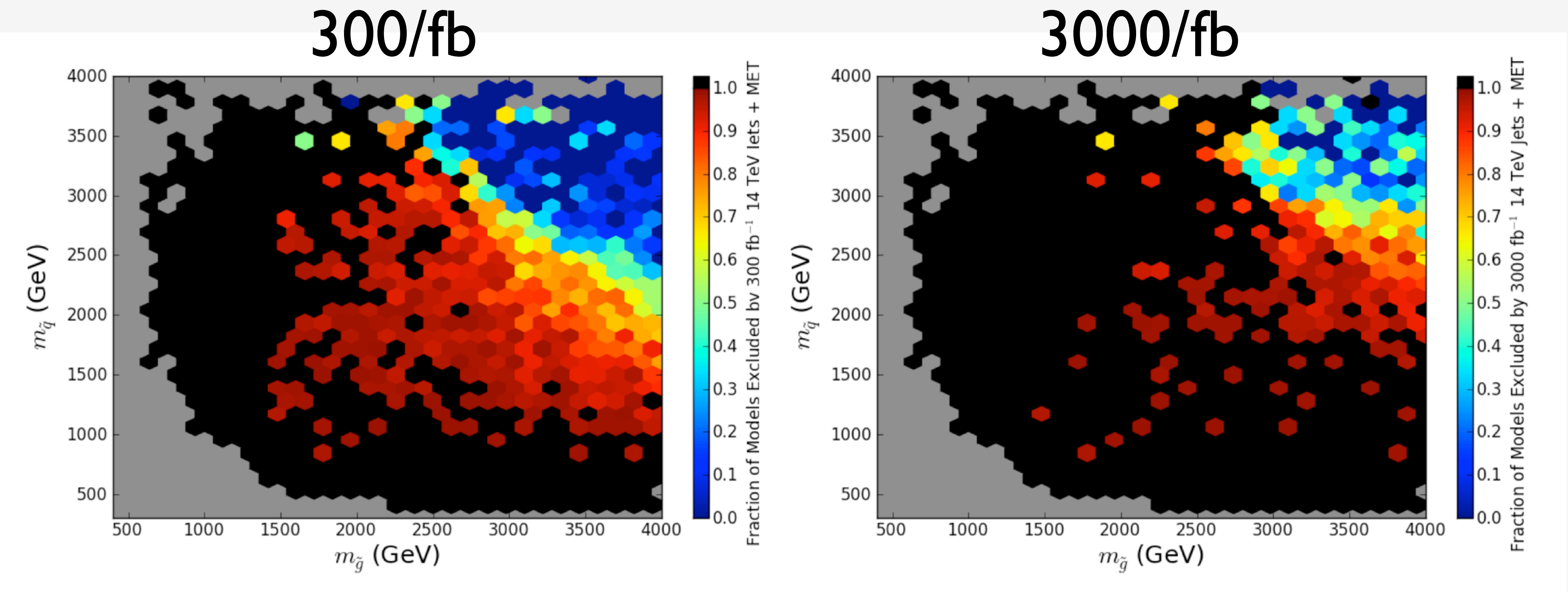
factors of 2 for 33 TeV and 100 TeV



SUSY reach: x2 from E_{cm}, 1.3 in $\mathcal{L}$

In the pMSSM survey of SUSY models

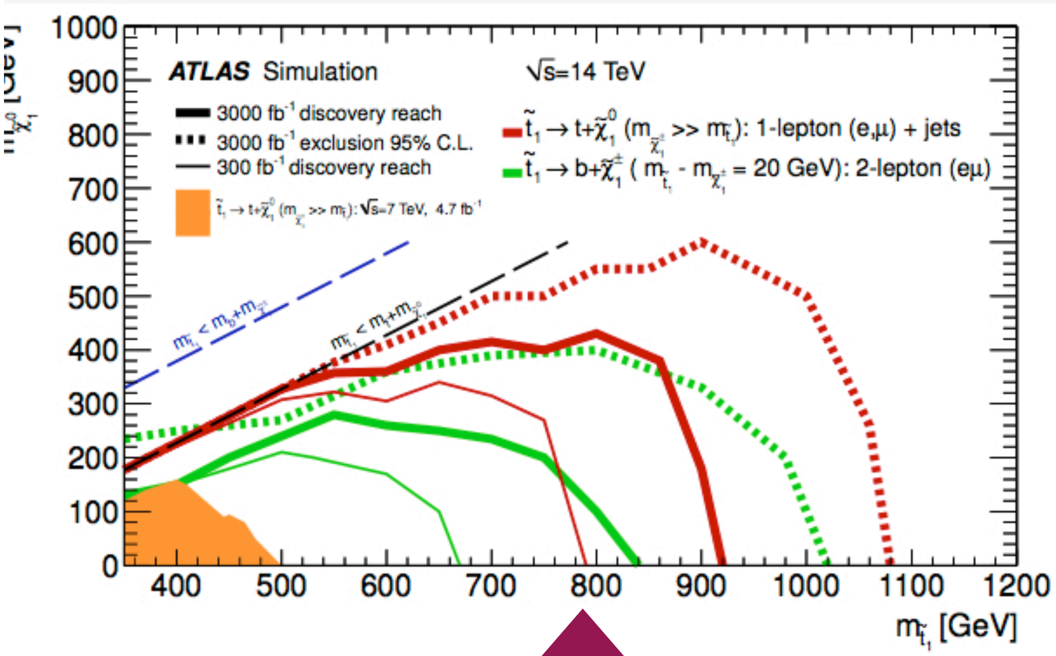
- squark/gluino mass plane

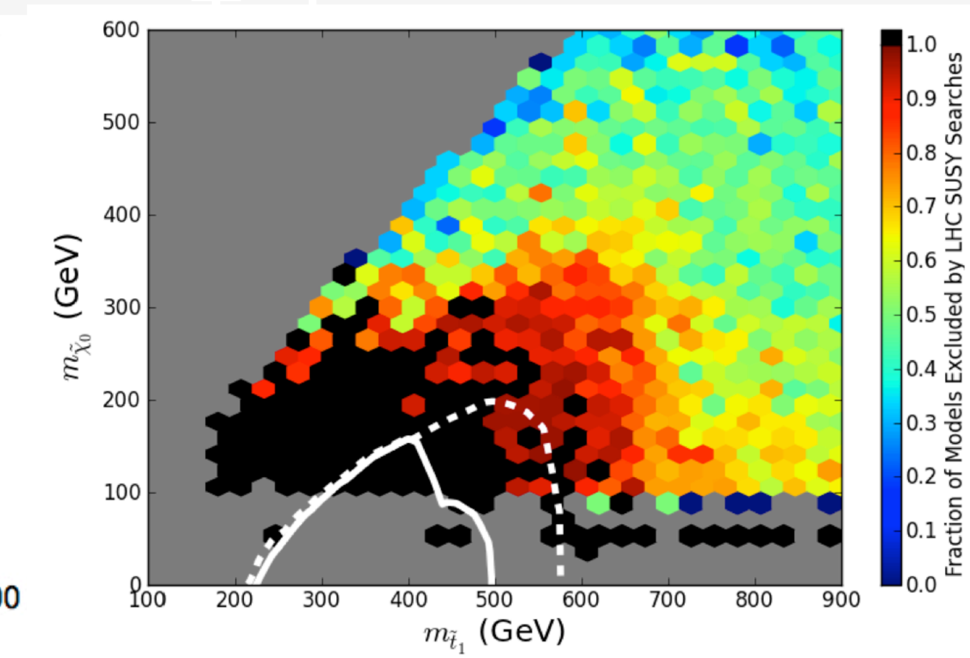


Note closing of loopholes in addition to increased energy reach.

Cahill-Rowley et al.

m_{stop} reach: ~50% from E_{cm}, 1.5 in $\mathcal{L}$



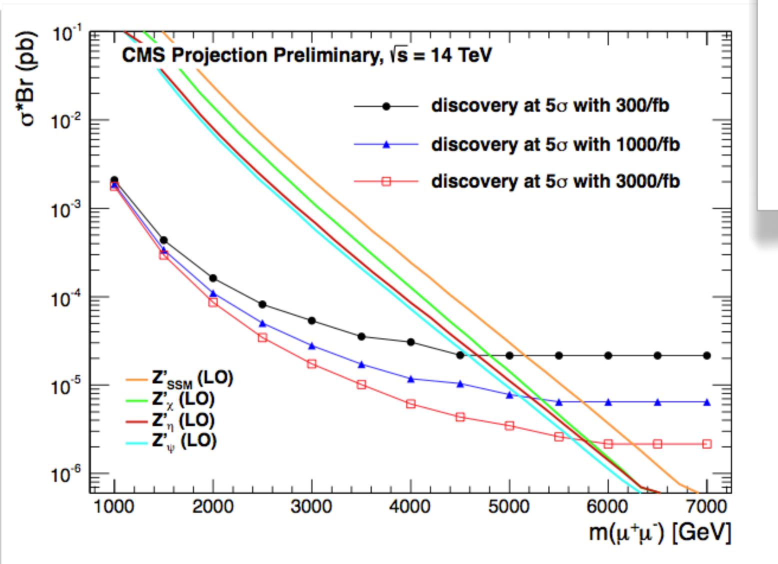


300/fb reach
stop-> t + neutralino

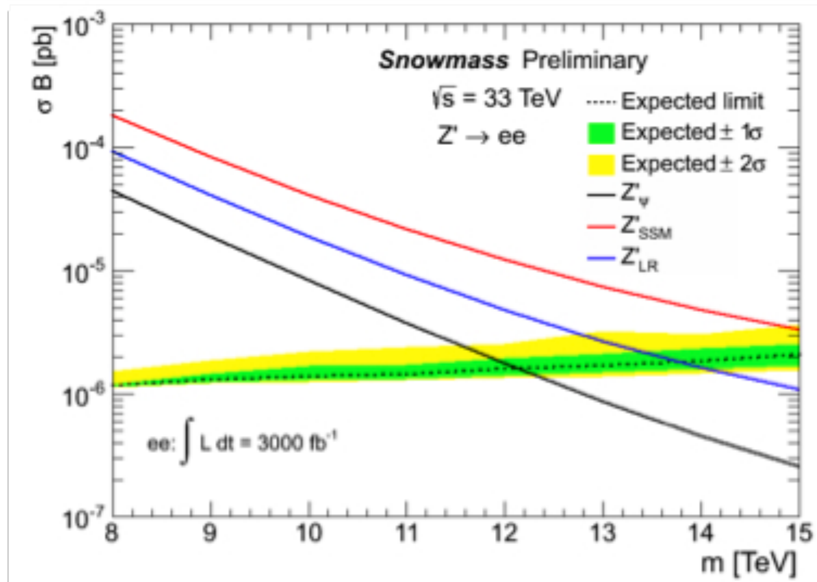
3000/fb reach
stop-> t + neutralino

Cahill-Rowley et al.

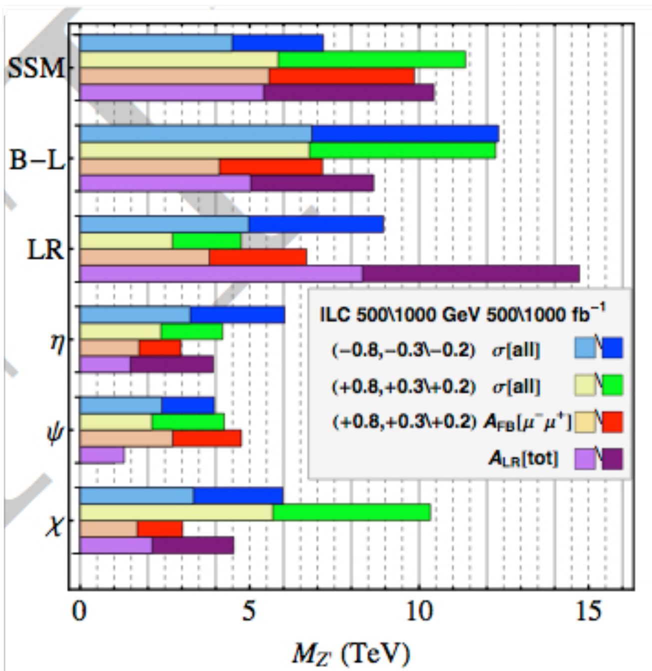
Z’ sensitivity



5-6+ TeV Discovery range at 14 TeV LHC



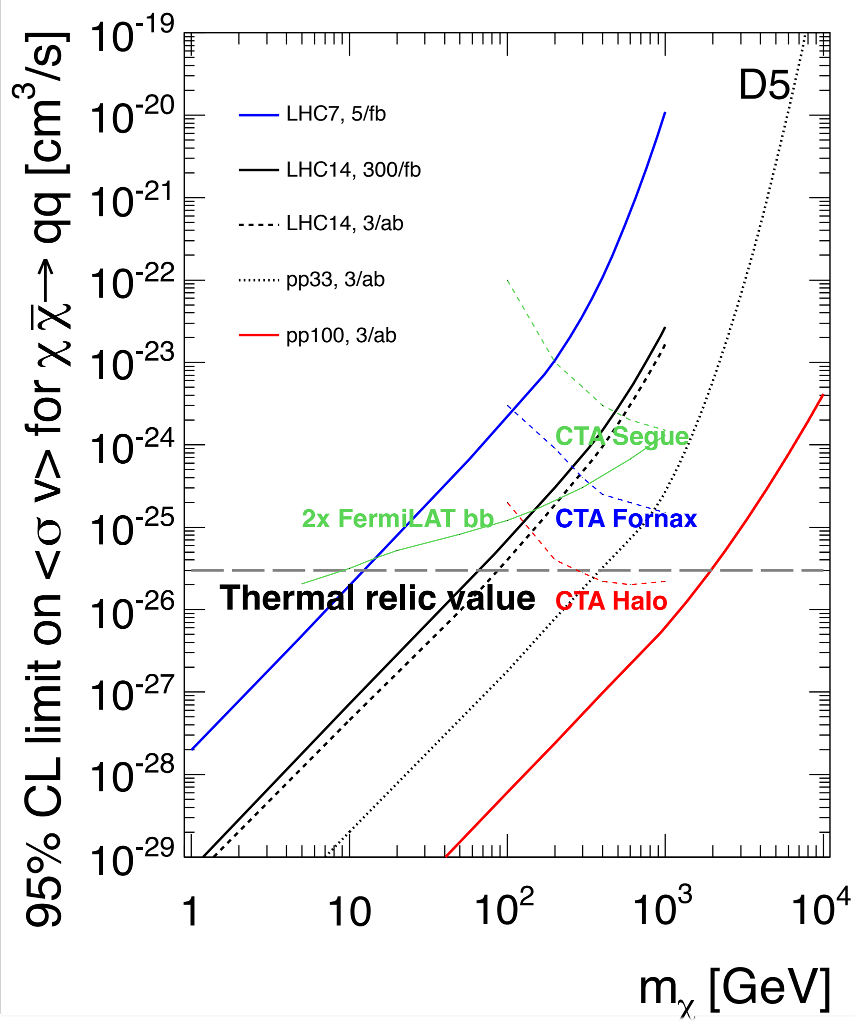
12-15 TeV limit range at 33 TeV pp



ILC asymmetry interference, beyond LHC

Dark Matter Connection

nearly close the thermal relic range?



progressive increase in sensitivity

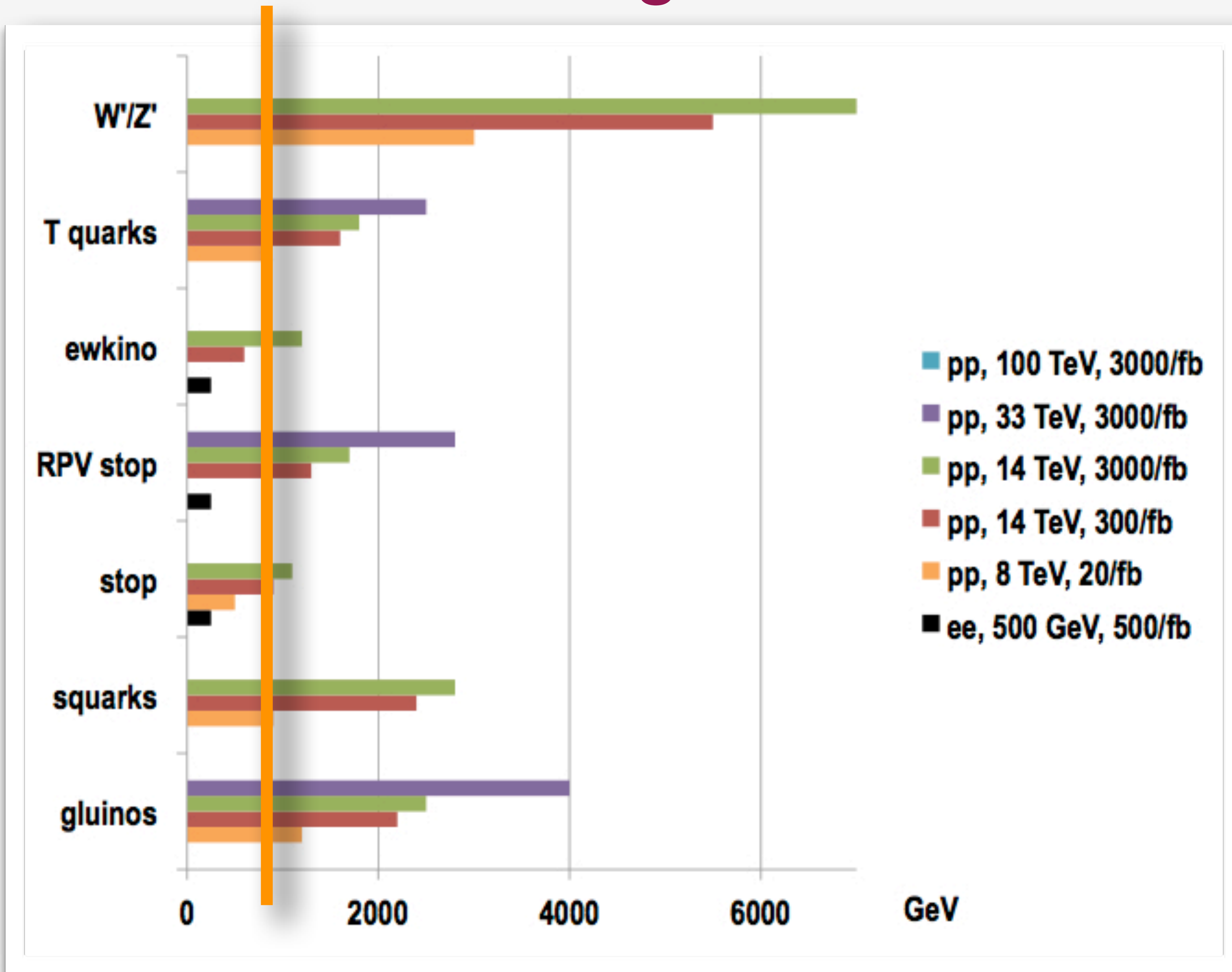
VLHC (100 TeV) can probe WIMP DM candidacy up to 1-2 TeV

Likewise, VLHC closes the fine tuning requirement to 10^{-4}

additionally

- model discrimination in Z' discovery
- WIMP sensitivity in ILC
  $$e^+e^- \to \gamma + \chi + \chi$$
- SUSY neutralino decaying $\tilde{\chi}_1^0 \to W + \tau$
- electroweak-inos, x2 sensitivity in 2015

The TeV scale is in sight



The NP Physics Message

1. TeV mass particles are needed in essentially all models of new physics. The search for them is imperative.

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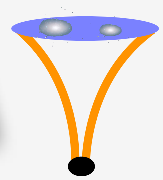
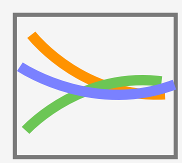
1. TeV mass particles are needed in essentially all models of new physics. The search for them is imperative.
2. LHC and future colliders will give us impressive capabilities for this study.
3. This search is integrally connected to searches for dark matter and rare processes.
4. A discovery in any realm is the beginning of a story in which high energy colliders play a central role.






Scientific Cases for:

LHC upgrades: 300, 3000/fb

Linear ee collider: 250/500, 1000 GeV

CLIC: CLIC: 350 GeV, 1 TeV, 3 TeV

muon collider

photon collider

Circular ee collider: up to 350 GeV

pp Collider: 33/100 TeV

an obvious point

- cases for machine B

  are usually written as if machine A found nothing.

an obvious point

- cases for machine B

  are usually written as if machine A found nothing.

- The most important cases for machine B?

  to study the discoveries of machine A with more precision.

  and to find additional particles or forces

LHC: 300 fb^{-1}

Higgs EW Top QCD NP/flavor

1. Clarification of Higgs couplings, mass, spin, CP to the 10% level.

5. Theoretically and experimentally precise top quark mass to 600 MeV

10. x2 sensitivity to new particles: supersymmetry, Z’, top partners – key ingredients for models of the Higgs potential – and the widest range of possible TeV-mass particles.

LHC: 300 fb^{-1}

Higgs EW Top QCD NP/flavor

1. **Clarification of Higgs couplings, mass, spin, CP to the 10% level.**
2. First direct measurement of top-Higgs couplings
3. Precision W mass below 10 MeV.
4. First measurements of VV scattering.
5. **Theoretically and experimentally precise top quark mass to 600 MeV**
6. Measurement of top quark couplings to gluons, Zs, Ws, photons with a precision potentially sensitive to new physics, a factor 2-5 better than today
7. Search for top squarks and top partners and ttbar resonances predicted in models of composite top, Higgs.
8. New generation of PDFs with improved g and antiquark distributions.
9. Precision study of electroweak cross sections in pp, including gamma PDF.
10. **x2 sensitivity to new particles: supersymmetry, Z', top partners – key ingredients for models of the Higgs potential – and the widest range of possible TeV-mass particles.**
11. Deep ISR-based searches for dark matter particles.

LHC: 3000 fb^{-1}

Higgs EW Top QCD NP/flavor

1. The precision era in Higgs couplings: couplings to 2-10% accuracy, 1% for the ratio gamma gamma/ZZ.

3. First measurement of Higgs self-coupling.

6. Precise measurements of VV scattering; access to Higgs sector resonances

12. EW particle reach increase by factor 2 for TeV masses.

13. Any discovery at LHC–or in dark matter or flavor searches–can be followed up

LHC: 3000 fb^{-1}

Higgs EW Top QCD NP/flavor

1. **The precision era in Higgs couplings: couplings to 2-10% accuracy, 1% for the ratio gamma gamma/ZZ.**
2. Measurement of rare Higgs decays: mu mu, Z gamma with 100 M Higgs.
3. **First measurement of Higgs self-coupling.**
4. Deep searches for extended Higgs bosons
5. Precision W mass to 5 MeV
6. **Precise measurements of VV scattering; access to Higgs sector resonances**
7. Precision top mass to 500 MeV
8. Deep study of rare, flavor-changing, top couplings with 10 G tops.
9. Search for top squarks & partners in models of composite top, Higgs in the expected range of masses.
10. Further improvement of q, g, gamma PDFs to higher x, Q^2
11. A 20-40% increase in mass reach for generic new particle searches - can be 1 TeV step in mass reach
12. **EW particle reach increase by factor 2 for TeV masses.**
13. **Any discovery at LHC–or in dark matter or flavor searches–can be followed up**

ILC, up to 500 GeV

Higgs EW Top QCD NP/flavor

1. Tagged Higgs study in e+e–> Zh: model-independent BR and Higgs Γ, direct study of invisible & exotic Higgs decays
2. Model-independent Higgs couplings with % accuracy, great statistical & systematic sensitivity to theories.

4. Giga-Z program for EW precision, W mass to 4 MeV and beyond.

7. Sub-% measurement of top couplings to gamma & Z, accuracy well below expectations in models of composite top and Higgs

10. No-footnotes search capability for new particles in LHC blind spots -- Higgsino, stealth stop, compressed spectra, WIMP dark matter

ILC, up to 500 GeV

Higgs EW Top QCD NP/flavor

1. **Tagged Higgs study in e+e–> Zh: model-independent BR and Higgs Γ, direct study of invisible & exotic Higgs decays**
2. **Model-independent Higgs couplings with % accuracy, great statistical & systematic sensitivity to theories.**
3. Higgs CP studies in fermionic channels (e.g., tau tau)
4. **Giga-Z program for EW precision, W mass to 4 MeV and beyond.**
5. Improvement of triple VB couplings by a factor 10, to accuracy below expectations for Higgs sector resonances.
6. Theoretically and experimentally precise top quark mass to 100 MeV.
7. **Sub-% measurement of top couplings to gamma & Z, accuracy well below expectations in models of composite top and Higgs**
8. Search for rare top couplings in e+e- -> t cbar, t ubar.
9. Improvement of αS from Giga-Z
10. No-footnotes search capability for new particles in LHC blind spots -- Higgsino, stealth stop, compressed spectra, WIMP dark matter

ILC 1 TeV

Higgs EW Top QCD NP/flavor

2. Higgs self-coupling, 13% accuracy

5. Model-independent search for new particles with coupling to gamma or Z to 500 GeV

7. Any discovery of new particles dictates a lepton collider program:

   search for EW partners, 1% precision mass measurement, the complete decay profile, model-independent measurement of cross sections, BRs and couplings with polarization observables, search for flavor and CP-violating interactions

ILC 1 TeV

Higgs EW Top QCD NP/flavor

1. Precision Higgs coupling to top, 2% accuracy
2. **Higgs self-coupling, 13% accuracy**
3. Model-independent search for extended Higgs states to 500 GeV.
4. Improvement in precision of triple gauge boson couplings by a factor 4 over 500 GeV results.
5. **Model-independent search for new particles with coupling to gamma or Z to 500 GeV**
6. Search for Z' using e+e- -> f fbar to ~ 5 TeV, a reach comparable to LHC for similar models. Multiple observables for Z' diagnostics.
7. **Any discovery of new particles dictates a lepton collider program:**

   search for EW partners, 1% precision mass measurement, the complete decay profile, model-independent measurement of cross sections, BRs and couplings with polarization observables, search for flavor and CP-violating interactions

CLIC: 350 GeV, 1 TeV,

Higgs EW Top QCD NP/flavor

2. Higgs self-coupling, 10%

or

6. Model-independent search for new particles with coupling to gamma or Z to 1500 GeV: the expected range of masses for electroweakinos and WIMPs.

8. Any discovery of new particles dictates a lepton collider program as with the 1TeV ILC

CLIC: 350 GeV, 1 TeV,

Higgs EW Top QCD NP/flavor

1. Precision Higgs coupling to top, 2% accuracy
2. **Higgs self-coupling, 10%**
3. Model-independent search for extended Higgs states to 1500 GeV.
4. Improvement in precision of triple gauge boson couplings by a factor 4 over 500 GeV results.
5. Precise measurement of VV scattering, sensitive to Higgs sector resonances.
6. **Model-independent search for new particles with coupling to gamma or Z to 1500 GeV: the expected range of masses for electroweakinos and WIMPs.**
7. Search for Z' using e+e- -> f fbar above 10 TeV
8. **Any discovery of new particles dictates a lepton collider program as with the 1TeV ILC**

muon collider: 125 GeV, 350 GeV,1.5 TeV, 3 TeV

2. **Ability to produce the Higgs boson, and possible heavy Higgs bosons, as s-channel resonances.**

   This allows sub-MeV Higgs mass measurement and direct Higgs width measurement.

Higgs EW Top QCD NP/flavor

muon collider: 125 GeV, 350 GeV,1.5 TeV, 3 TeV

1. Similar capabilities to e+e- colliders described above.

   (Still need to prove by physics simulation that this is robust against machine backgrounds.)

2. **Ability to produce the Higgs boson, and possible heavy Higgs bosons, as s-channel resonances.**

   This allows sub-MeV Higgs mass measurement and direct Higgs width measurement.

Higgs	**EW**	**Top**	**QCD**	**NP/flavor**

photon collider

Higgs EW Top QCD NP/flavor

2. Ability to study CP mixture and violation in the Higgs sector using polarized photon beams.

photon collider

1. An ee collider can be converted to a photon-photon collider at ~ 80% of the CM energy.

   This allows production of Higgs or extended Higgs bosons as s-channel resonances, offering percent-level accuracy in gamma gamma coupling.

2. **Ability to study CP mixture and violation in the Higgs sector using polarized photon beams.**

TLEP, circular e+e-

Higgs EW Top QCD NP/flavor

1. **Possibility of up to 10x higher luminosity than linear e+e- colliders at 250 GeV. Higgs couplings measurements might still be statistics-limited at this level.**

   (Note: luminosity is a steeply falling function of energy.)

TLEP, circular e+e-

Higgs EW Top QCD NP/flavor

1. **Possibility of up to 10x higher luminosity than linear e+e- colliders at 250 GeV. Higgs couplings measurements might still be statistics-limited at this level.**

   (Note: luminosity is a steeply falling function of energy.)

2. Precision electroweak programs that could improve on ILC by a factor 4 in sstw, factor 4 in mW, factor 10 in mZ.
3. Search for rare top couplings in e+e- -> t cbar, tubar at 250 GeV.
4. Possible improvement in alphas by a factor 5 over Giga-Z, to 0.1% precision.

pp Collider: 33/100 TeV

Higgs EW Top QCD NP/flavor

5. Increased search reach over LHC, proportional to the energy increase, for all varieties of new particles (if increasingly high luminosity is available). Stringent constraints on “naturalness”.
6. Ability to search for electroweak WIMPs (e.g. Higgsino, wino) over the full allowed mass range.

pp Collider: 33/100 TeV

Higgs EW Top QCD NP/flavor

1. High rates for double Higgs production; measurement of triple Higgs couplings to 8%.
2. Deep searches, beyond 1 TeV, for extended Higgs states.
3. Dramatically improved sensitivity to VB scattering and multiple vector boson production.
4. Searches for top squarks and top partners and resonances in the multi-TeV region.
5. **Increased search reach over LHC, proportional to the energy increase, for all varieties of new particles (if increasingly high luminosity is available). Stringent constraints on "naturalness".**
6. **Ability to search for electroweak WIMPs (e.g. Higgsino, wino) over the full allowed mass range.**
7. Any discovery at LHC -- or in dark matter or flavor searches -- can be followed up by measurement of subdominant decay processes, search for higher mass partners. Both luminosity and energy are crucial here.

- **Let’s be clear.**

  We collider types say we know about Mass.

Really?

- As long as we know

  nothing about the neutral fermions

  &

  nothing about 85% of the gravitating universe

- We don’t know the Mass story.

This is serious.

The very light neutrino mass **is BSM physics:**

- is it Dirac? – it's a tiny coupling to v
  - *then the Higgs sector could be expanded*
- is it Majorana? – it might talk to a different Higgs!
  - *then we have to find it*
- do they get mass differently... because it's tiny?
  - *neutral fermions and charged fermions with different mass generation? Completely bizarre*

Andre de Gouvea keeps making this point

This is serious.

The very light neutrino mass **is BSM physics:**

is it Dirac? – it's a tiny coupling to v

- *then we need to find [illegible] and expand the Higgs sector*

is it Majorana? – it might talk to a different Higgs!

- *then we have to find it*

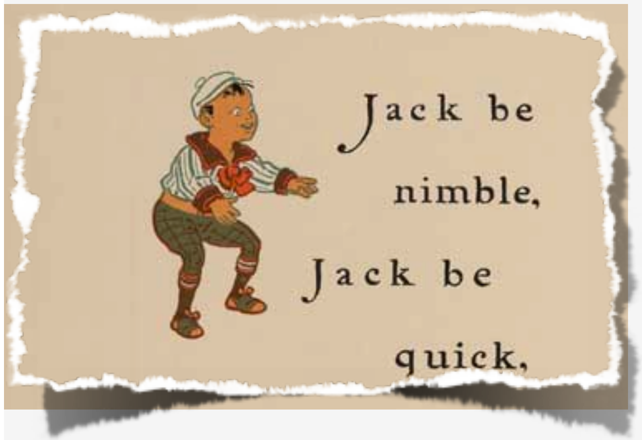
do they get mass differently... because it's tiny?

- *neutral fermions and charged fermions with different mass generation? Completely bizarre*

Understanding Mass is still "all hands on deck" physics – EF, IF, and CF!

Andre de Gouvea keeps making this point

Energy Frontier: precision, mass reach, and surprise



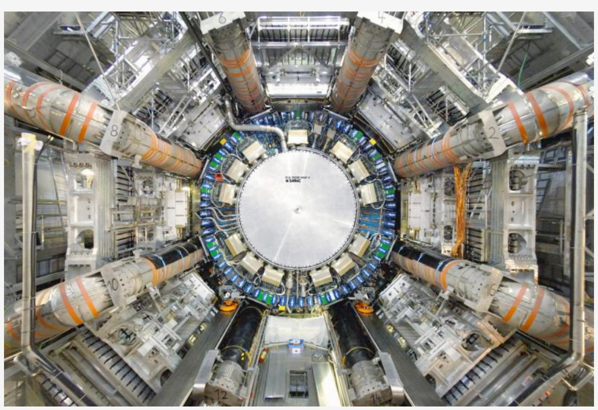
- LHC: exquisite instruments

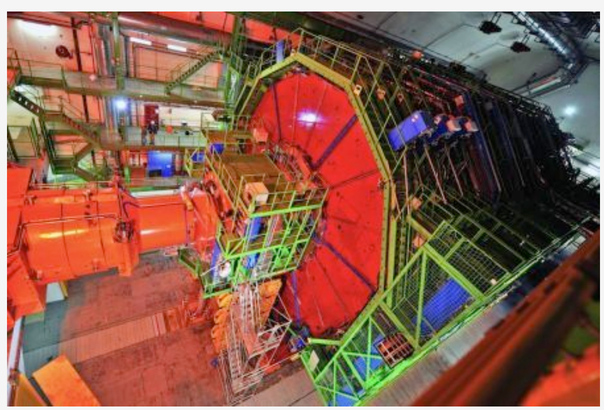
  proven capability

    precision and surprise

- Will point to the EF future at

  ILC, Muon Collider, CLIC, TLep, $\gamma\gamma$, ep, or VLHC





by incrementally:

- Measuring the properties of the Higgs boson.
- Measuring the properties of the: *t*, *W*, and *Z*
- Searching for TeV-scale particles

- The Higgs particle changes everything.

why?

- **Confirming the SM?**

  No longer a goal

- **Now we're exploring.**

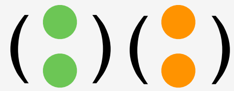
  The real meaning of

"Frontier"

[redacted]

1. How do we understand the Higgs boson?

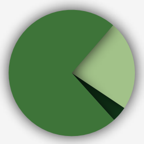
2. How do we understand the multiplicity of quarks and leptons?



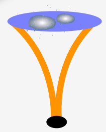
3. How do we understand the neutrinos?

4. How do we understand the matter-antimatter asymmetry of the universe?

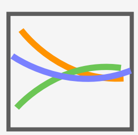
5. How do we understand the substance of dark matter?



6. How do we understand the dark energy?

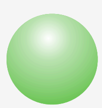


7. How do we understand the origin of structure in the universe?



8. How do we understand the multiplicity of forces?

9. Are there new particles at the TeV energy scale?



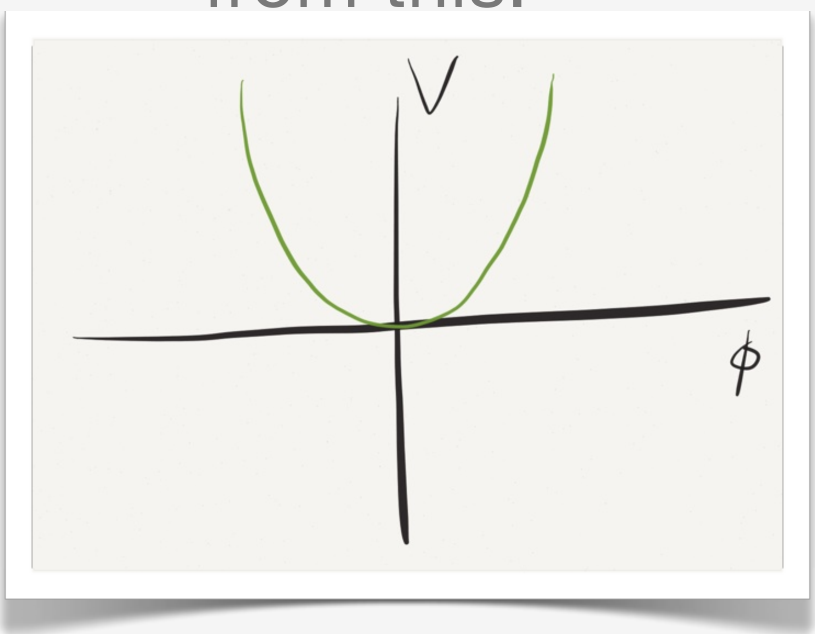
10. Are there new particles at higher energies?

But we know that the Standard Model is

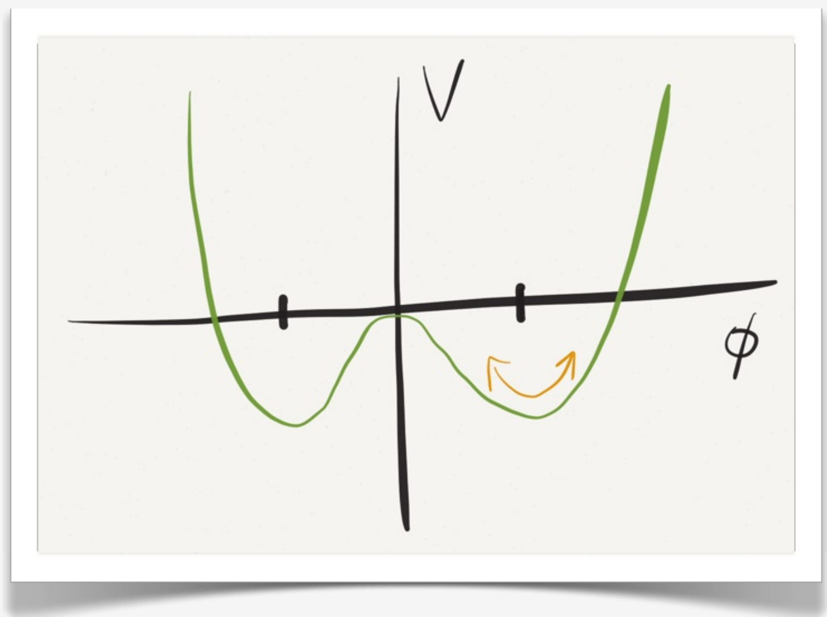
- It's only an effective model

  It lacks dynamics to explain the change of potential

  from this:



to this:



EW top-Neutral VB couplings

projected precision of $t-\gamma,\ t-Z^0$ couplings

Collider	LHC		ILC/CLIC
CM Energy [TeV]	14	14	0.5
Luminosity [fb^{-1}]	300	3000	500
SM Couplings			
photon, F_{1V}^{γ} (0.666)	0.042	0.014	0.002
Z boson, F_{1V}^{Z} (0.24)	0.50	0.17	0.003
Z boson, F_{1A}^{Z} (0.6)	0.058	?	0.005
Non-SM couplings			
photon, F_{1A}^{γ}	0.05	?	?
photon, F_{2V}^{γ}	0.037	0.025	0.003
photon, F_{2A}^{γ}	0.017	0.011	0.007
Z boson, F_{2V}^{Z}	0.25	0.17	0.006
Z boson, ReF_{2A}^{Z}	0.35	0.25	0.008
Z boson, ImF_{2A}^{Z}	0.035	0.025	0.015

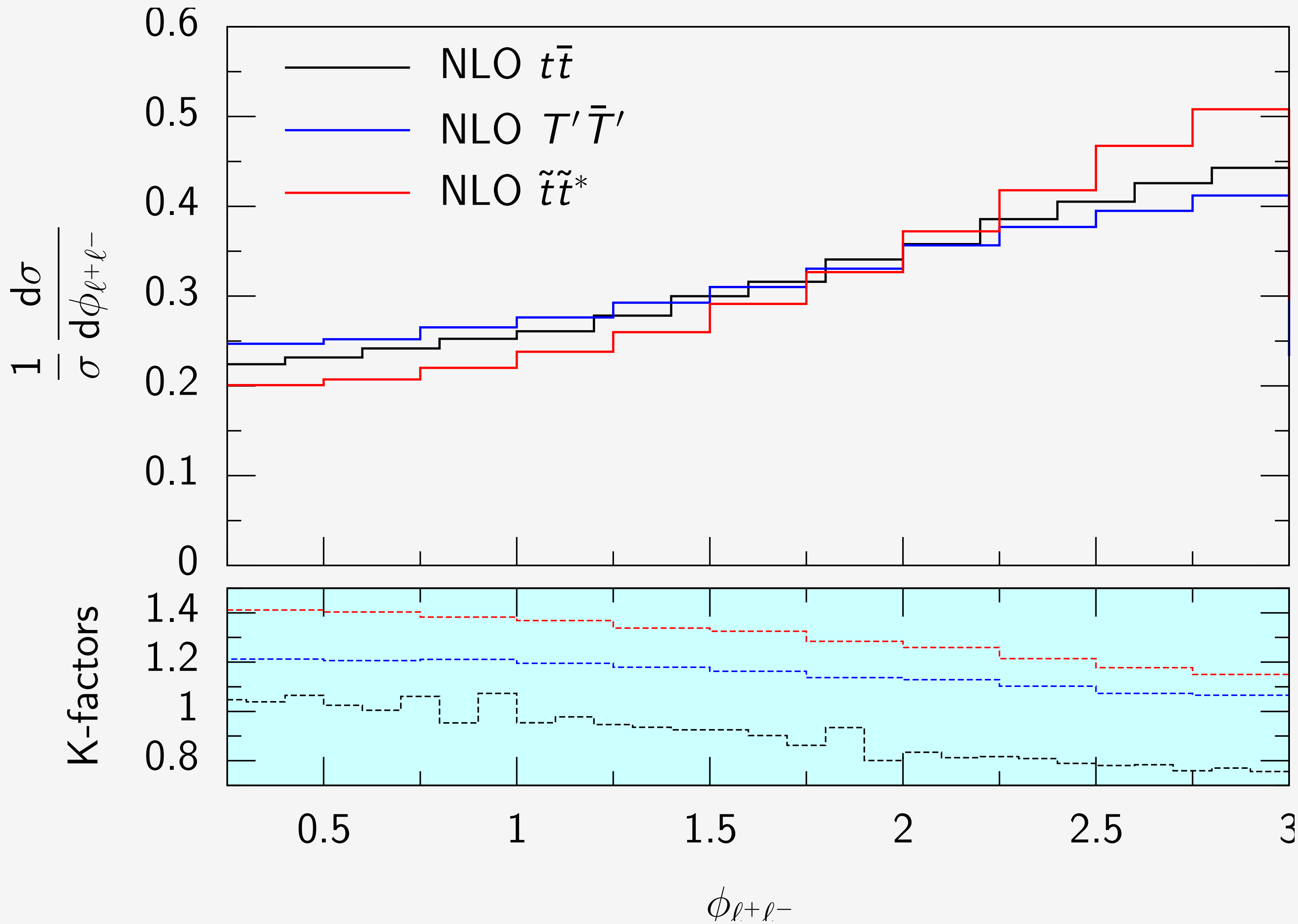
BSM: 2-10 %

LHC : few %

ILC/CLIC: sub-%

Top quark spin correlation

diagnostic of top polarization;
a sensitive probe for top partners, esp stealthy stop



Flavor-changing top decay

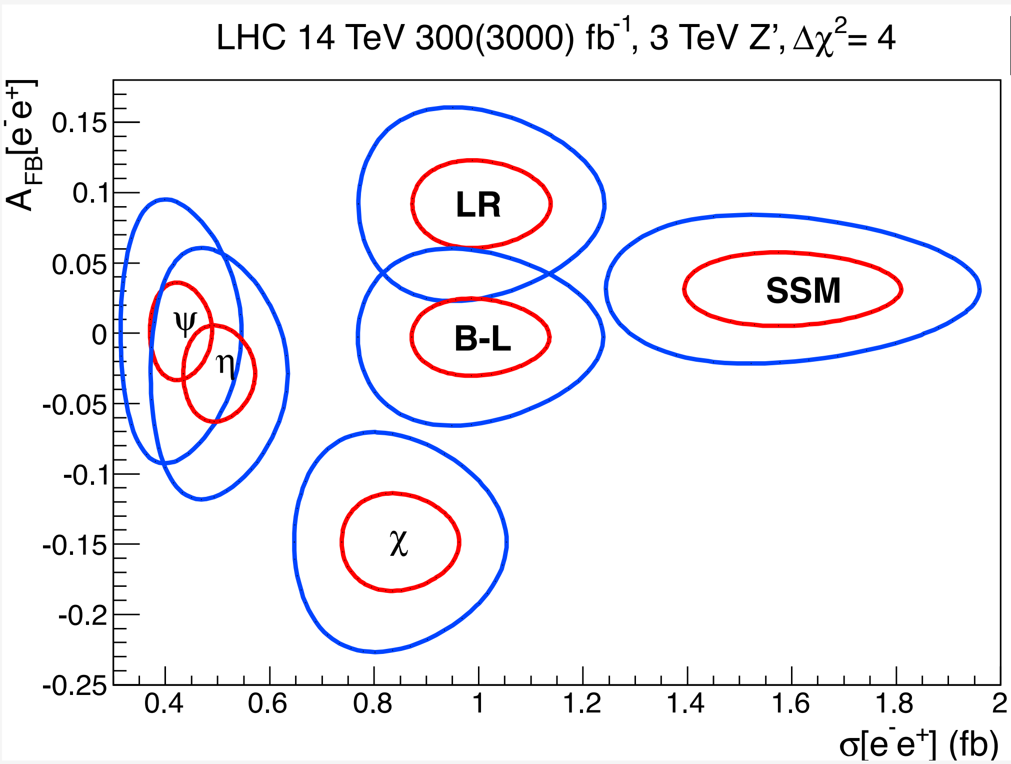
10^{-4} level probes BSM top decay models

projected limits for FCNC top decay processes

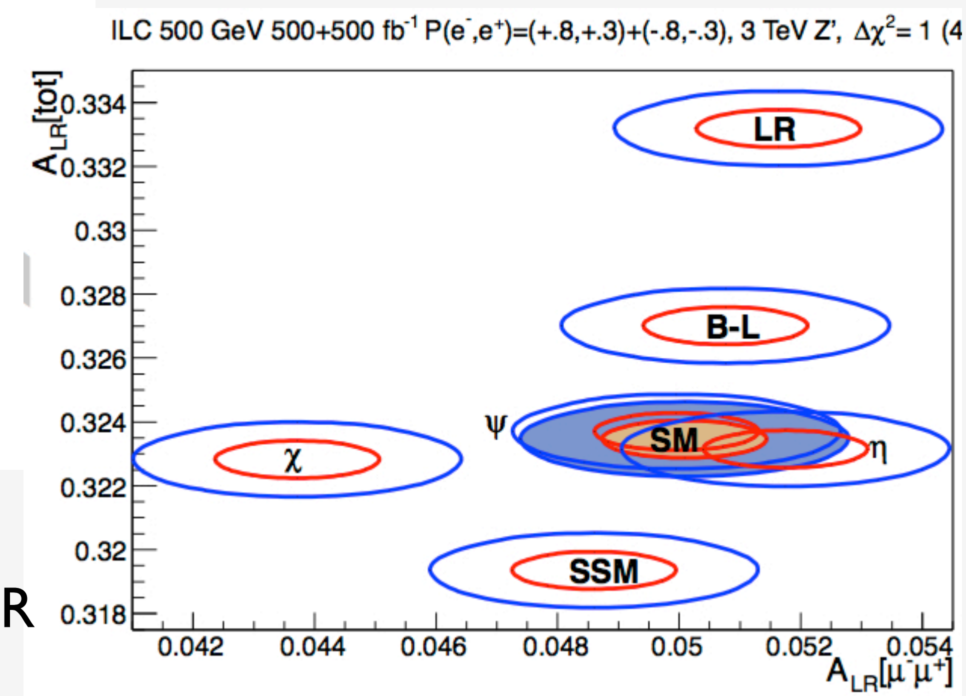
Process	Br Limit	Search	Dataset	Referenc
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV	[136]
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV	[136]
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 250 GeV	Extrap.
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV	[137]
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV	[137]
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV	[136]
$t \to \gamma q$	2.5×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV	[136]
$t \to \gamma q$	6×10^{-5}	ILC single top	500 fb^{-1}, 250 GeV	Extrap.
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1}, 500 GeV	[137]
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1}, 500 GeV	[137]

Finding the identity of a Z’

Many more diagnostic observables are available in e+e-, similar reach.



E6 from LR, etc LHC A_{FB}

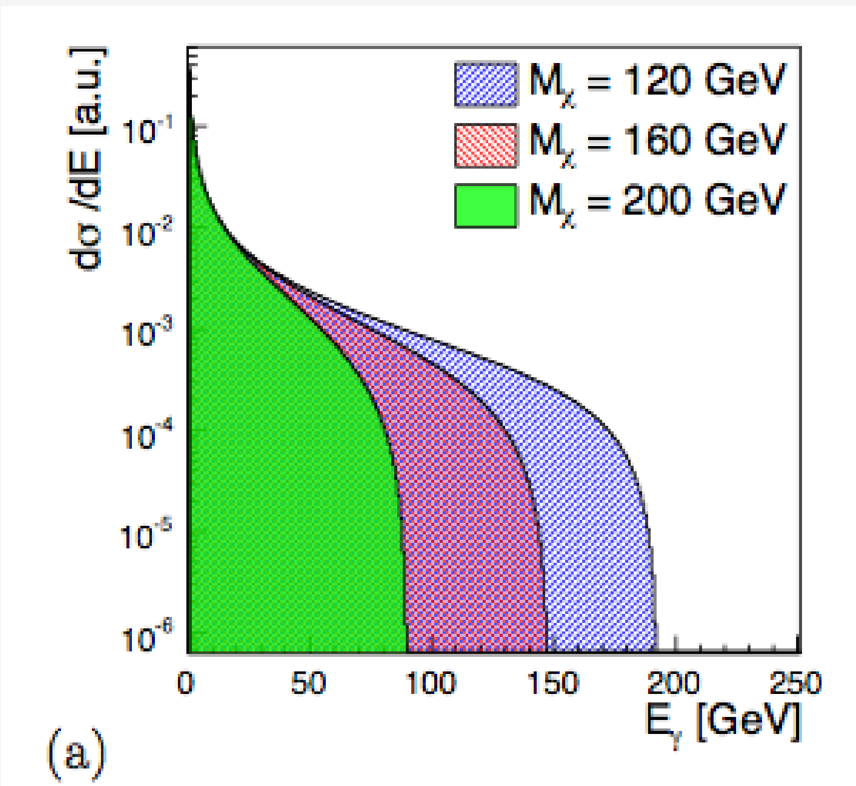


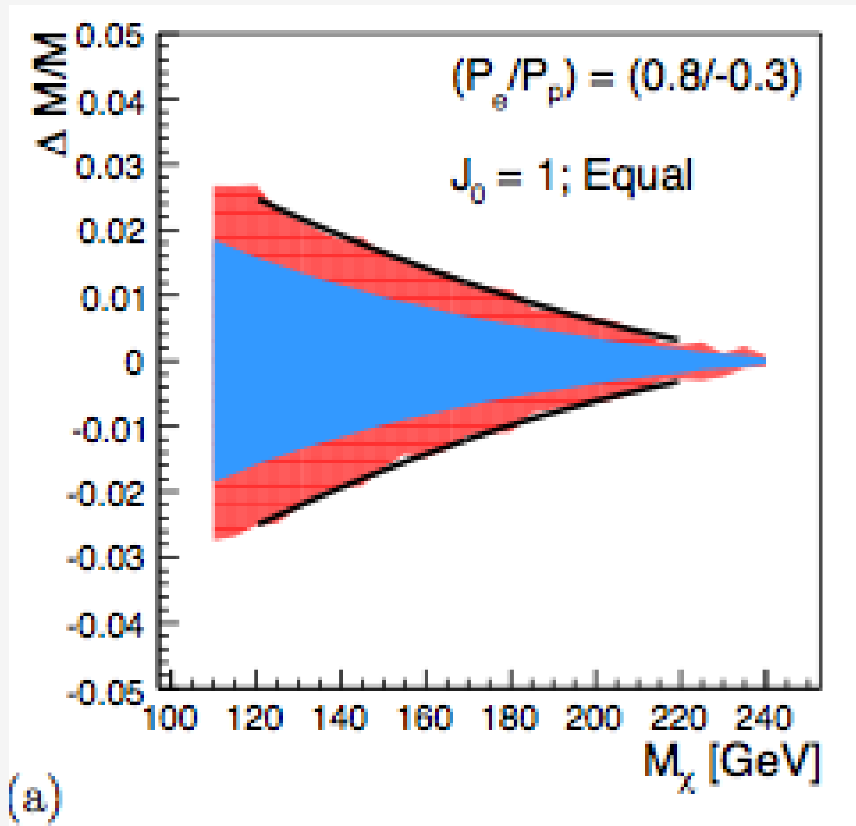
E6 from LR, etc ILC A_{LR}

Dark matter connection

WIMP search at ILC in $e^+e^- \rightarrow \gamma + \chi + \chi$

polarization significant in controlling backgrounds

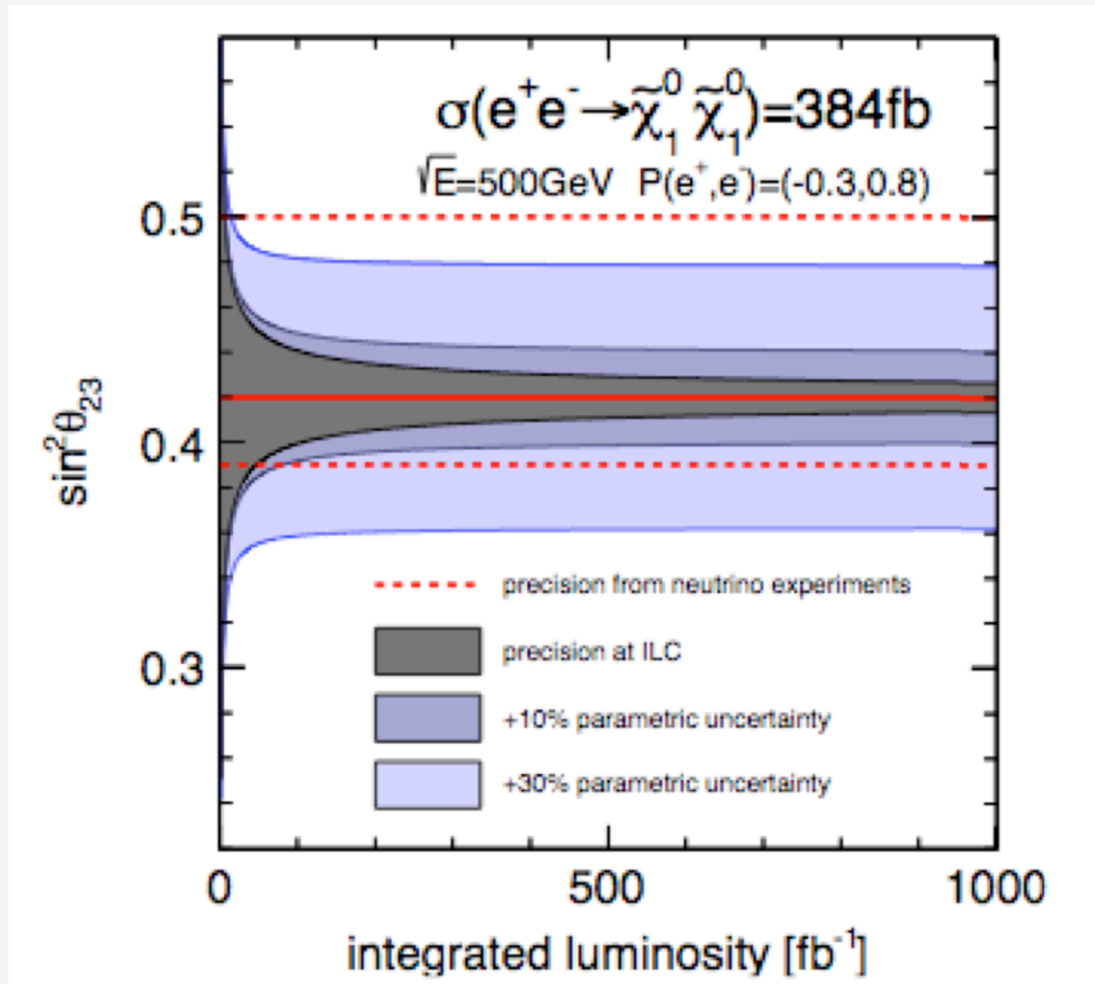




Neutrino connection

Discover the SUSY neutralino decaying $\tilde{\chi}_1^0 \to W + \tau$ via ....through the R-parity violating SUSY coupling.

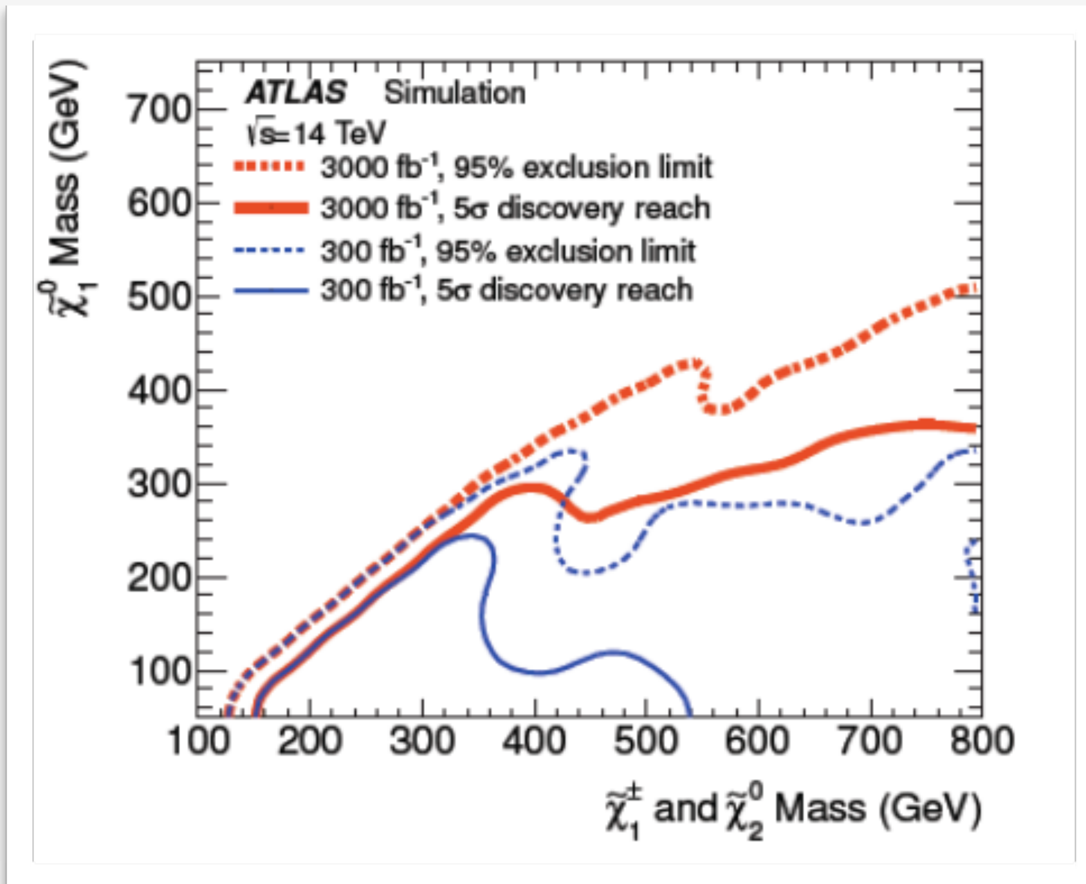
In "Type III seesaw," the θ23 controls the rate of the subleading $\tilde{\chi}_1^0 \to W + \mu$ decay ....
In this model, with neutralino accessible at ILC, this prediction is directly testable.



electroweakinos

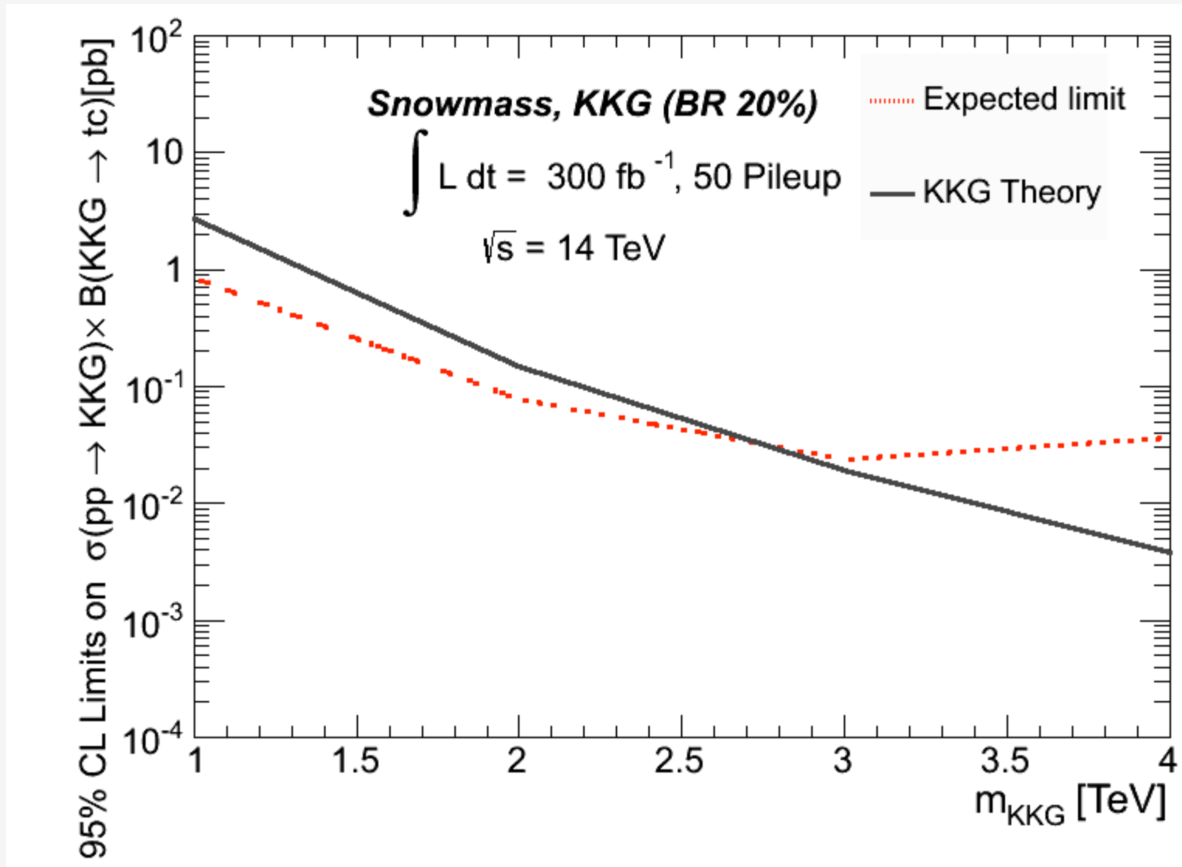
x 2 again...300/fb to 3000/fb

- for lighter states with more difficult searches, in particular, states with only electroweak production at pp colliders.



Flavor connection

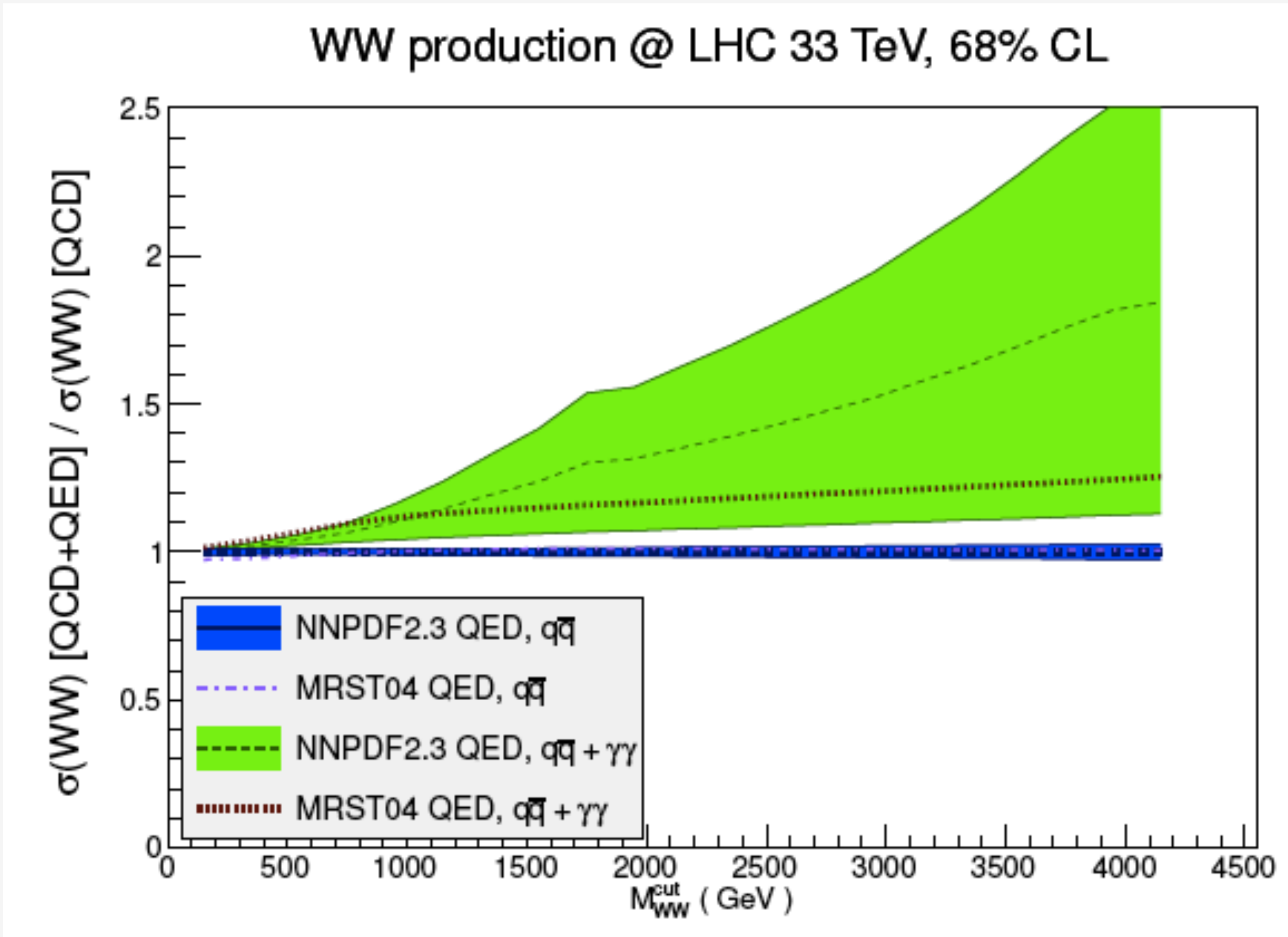
Discover KK resonance -> t tbar, search for decay to t cbar



Schoenrock, Drueke, Alavarez-Gonzalez, Schwienhorst

Photon PDF and QED

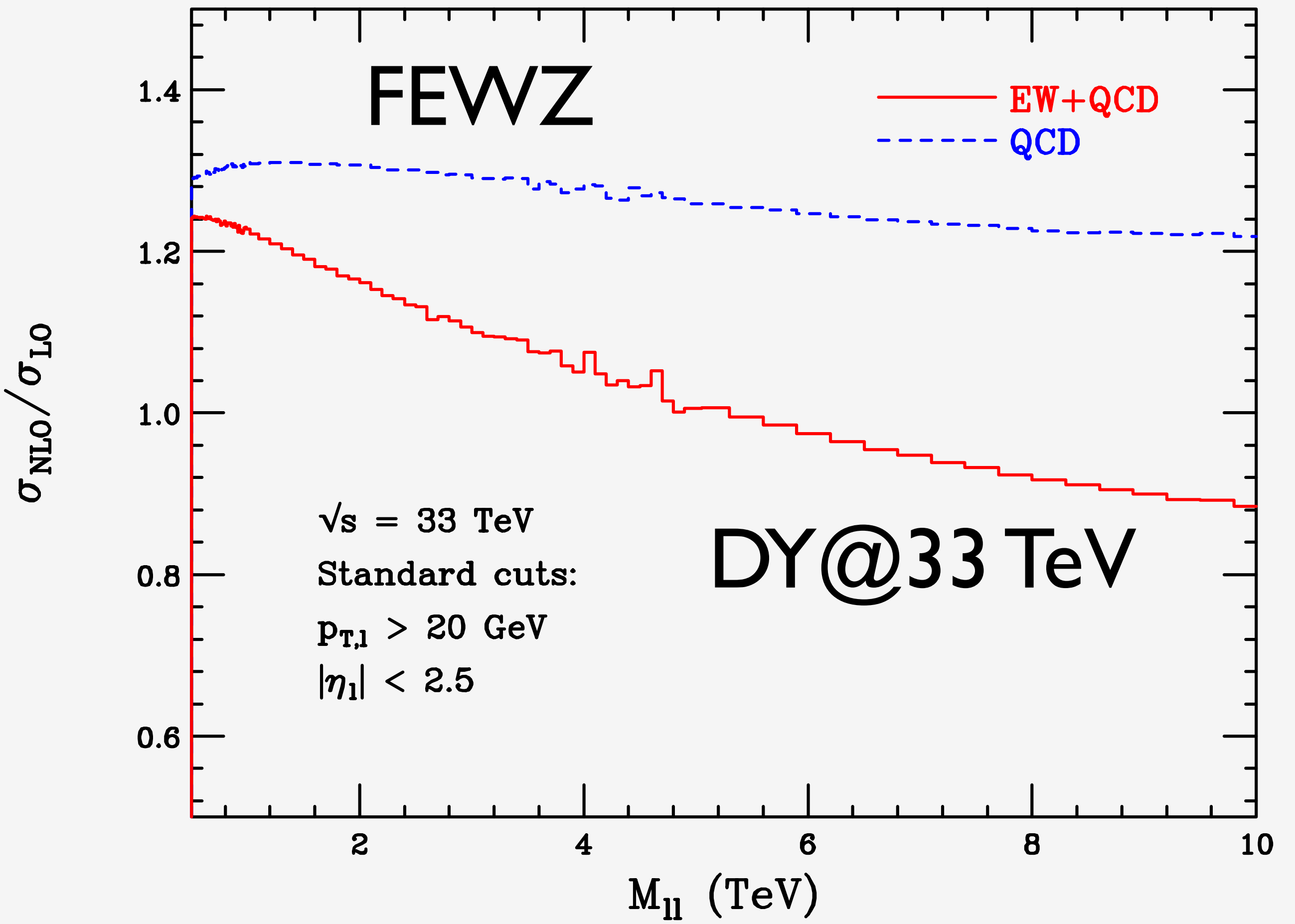
Photon-induced processes are increasingly important; need to extend the current state of the art in PDFs to QED.



Juan Rojo

Electroweak Sudakov

Electroweak corrections and Sudakov EW logs must be incorporated into event simulation.



Kaland Mishra

Precision inputs from Lattice

Improvement in alphas and quark masses will come from lattice gauge theory.

- These are necessary inputs to precision Higgs theory and other precision programs.

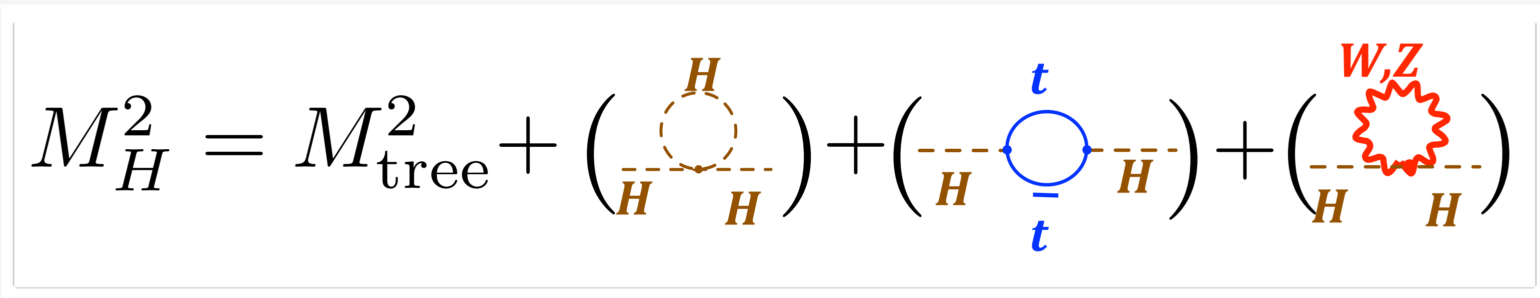
	Higgs X-section Working Group [34]	PDG[1]	Non-lattice	Lattice (2013)	Lattice (2018)	Prospects from ILC/TLEP/LHeC
$\delta\alpha_s$	0.002	0.0007	0.0012 [1]	0.0006 [24]	0.0004	0.0001–0.0006 [8, 27, 28]
δm_c (GeV)	0.03	0.025	0.013 [31]	0.006 [24]	0.004	-
δm_b (GeV)	0.06	0.03	0.016 [31]	0.023 [24]	0.011	-

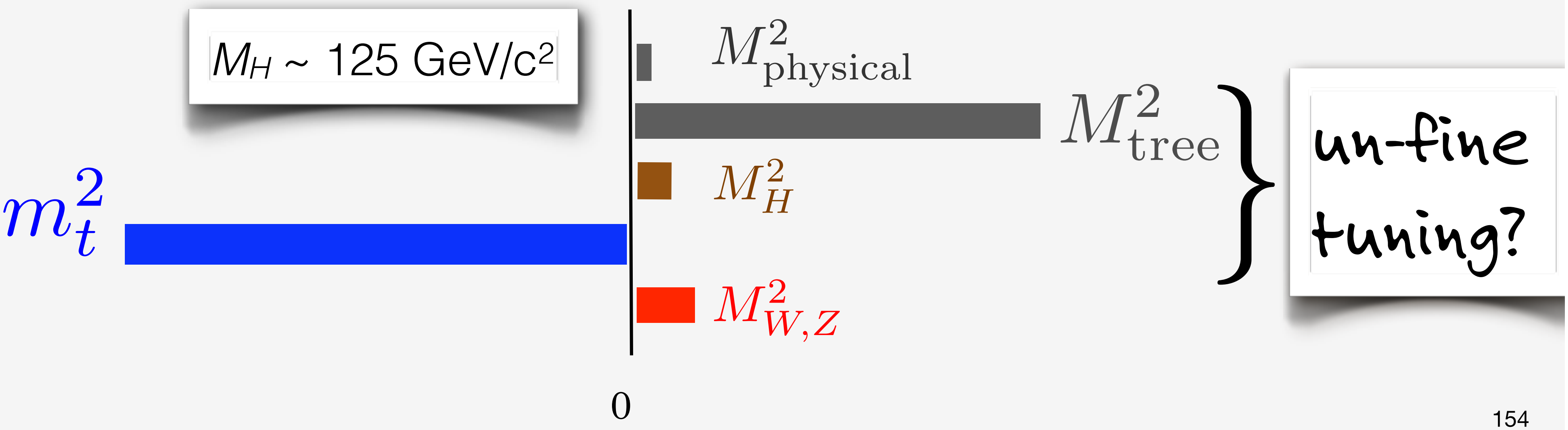
Paul Mackenzie,
Snowmass QCD report

Light scalar mass = mass confusion

"hierarchy" problem

additive, quadratic cut-offs...in mass-squared, by the way

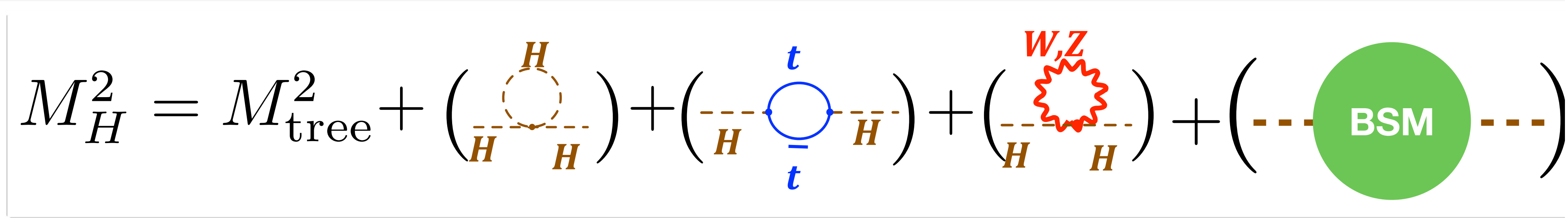


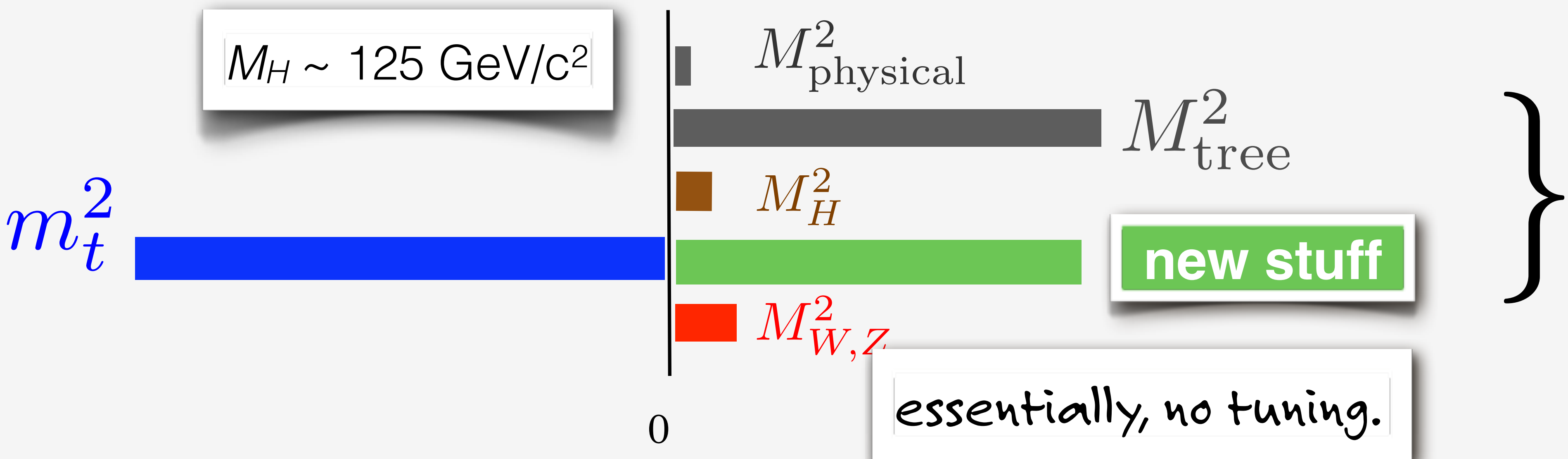


Perhaps a huge hint?

of something “BSM”?

- no shortage of ideas

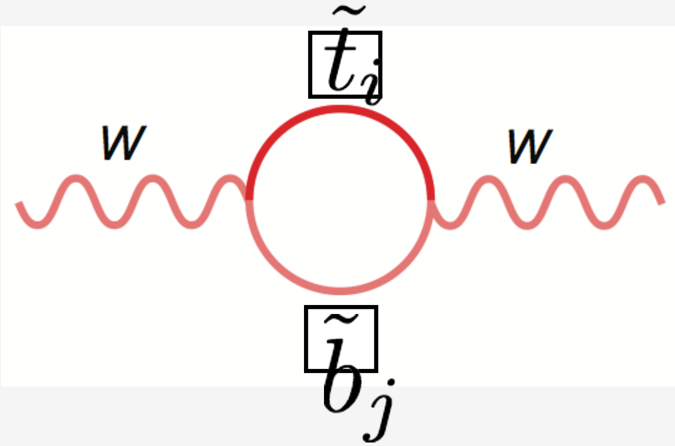




M_W, the old fashioned way

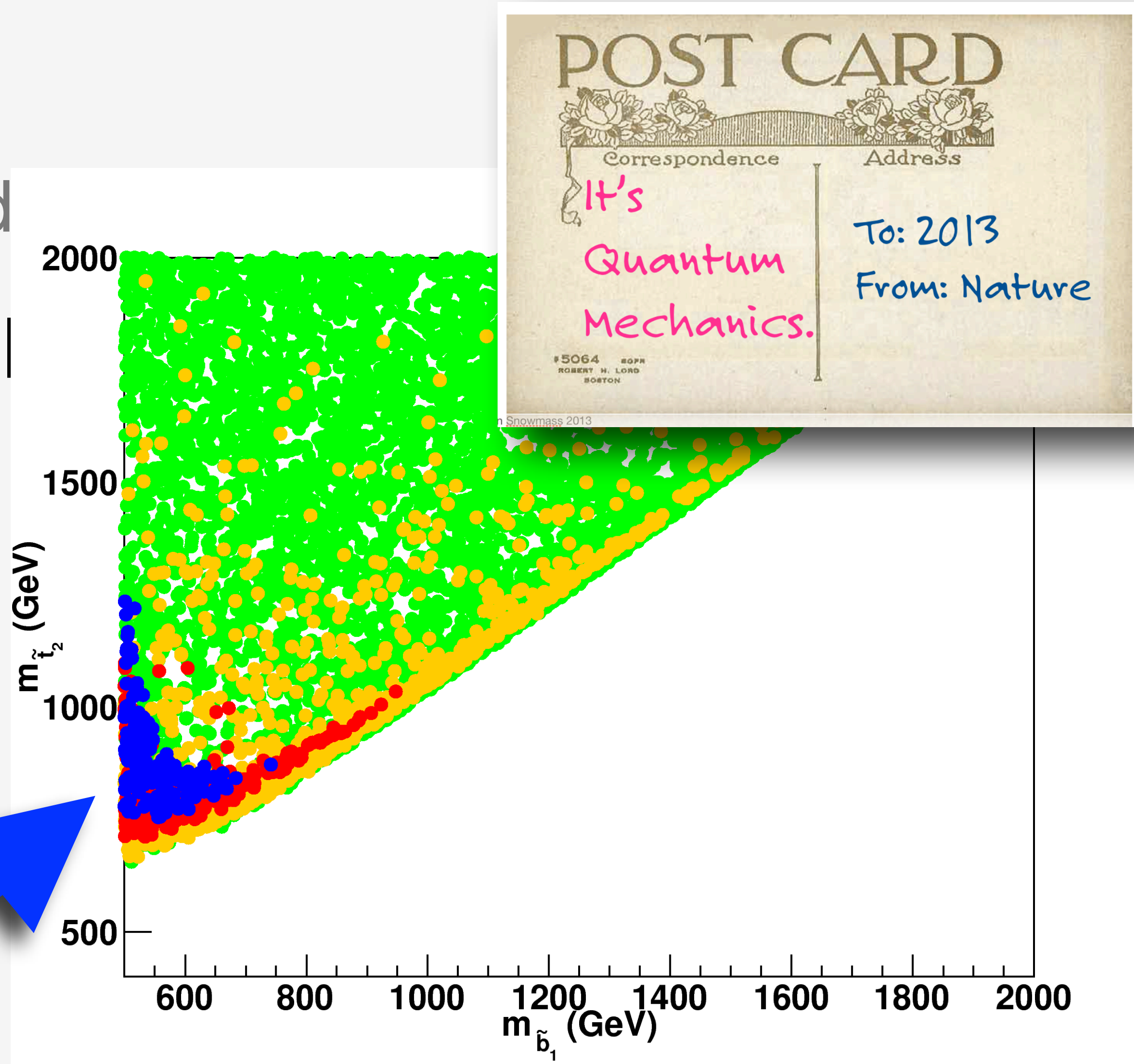
Imagine we knew:

- the stop1 mass, and



n t

$$\delta M_W \sim 5\ \mathrm{MeV}/c^2$$



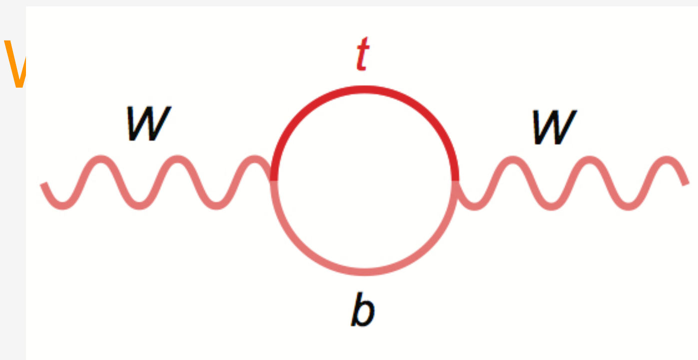
MSSM scenarios in mstop2 vs msbottom1 plane with

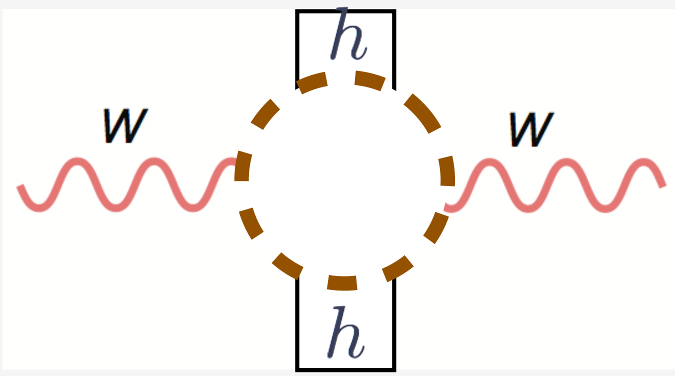
EWPOs

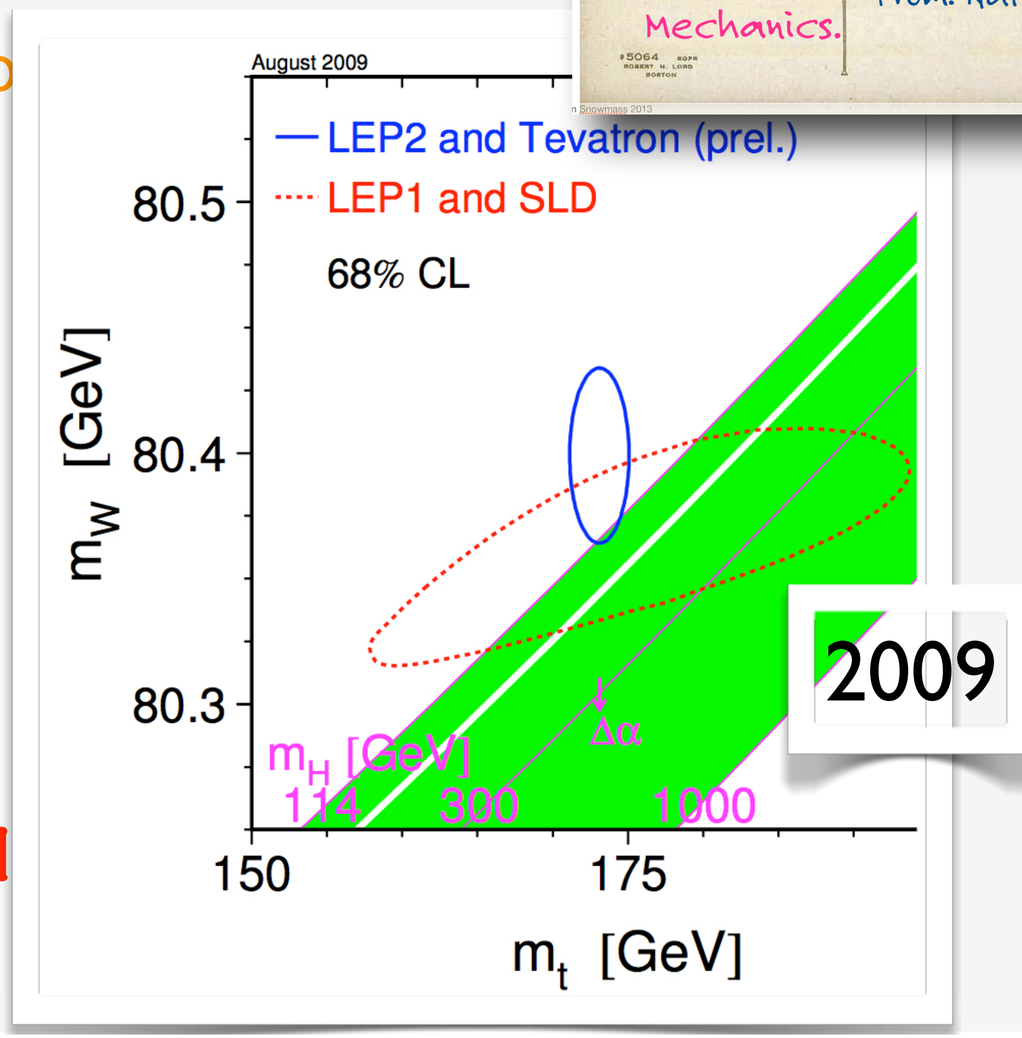
Electroweak Precision Observables

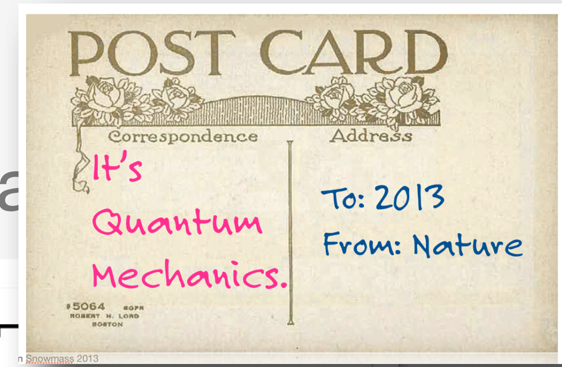
- We knew where to look for the Top Qua

V   fo



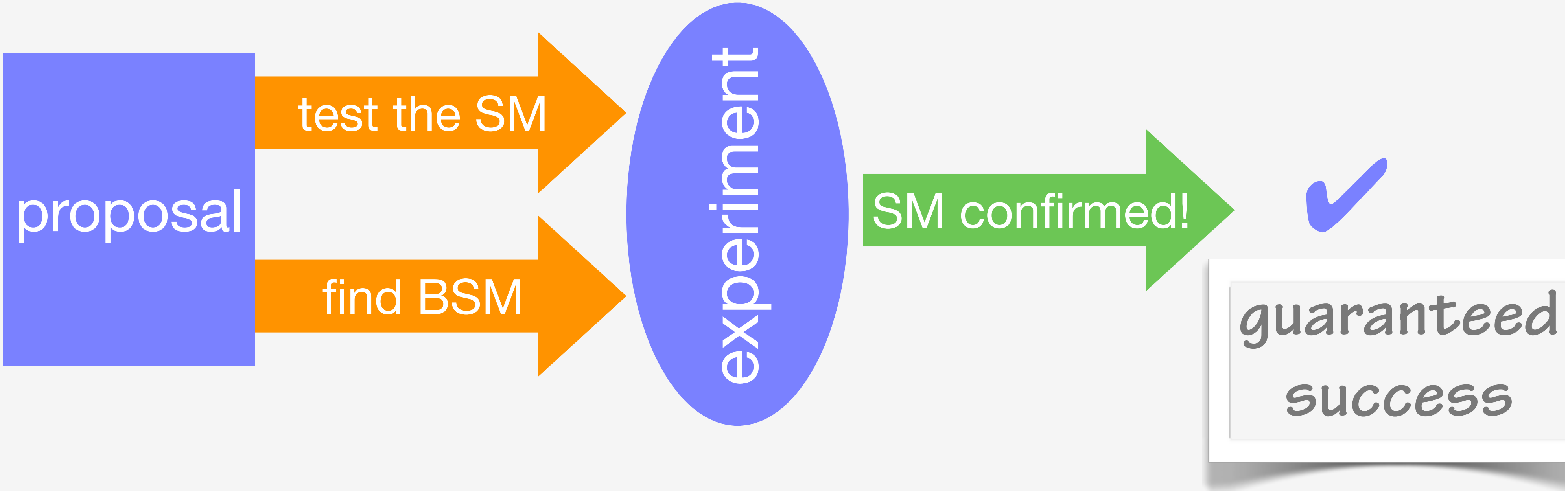






EWPOs are a well
trusted probe

In the past:



Now: