Energy Frontier Physics: the Big Questions

2: Experiment

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In the previous lecture, I defined what I see as the key problem for high energy physics in the next two decades:

What is the complete spectrum of particles at the TeV energy scale ?

In this lecture, I will sketch how we might find this out.

Much of the possible region for new particle searches was already covered by e+e- colliders operating before 2000. The highest energy experiments of this type were done at LEP 2.

I have some nostalgia for these searches. In e+e-, new particles and Standard Model particles have similar production rates. So signals stand out dramatically above backgrounds. Also, backgrounds are generated by electroweak cross sections and can be precisely modelled.

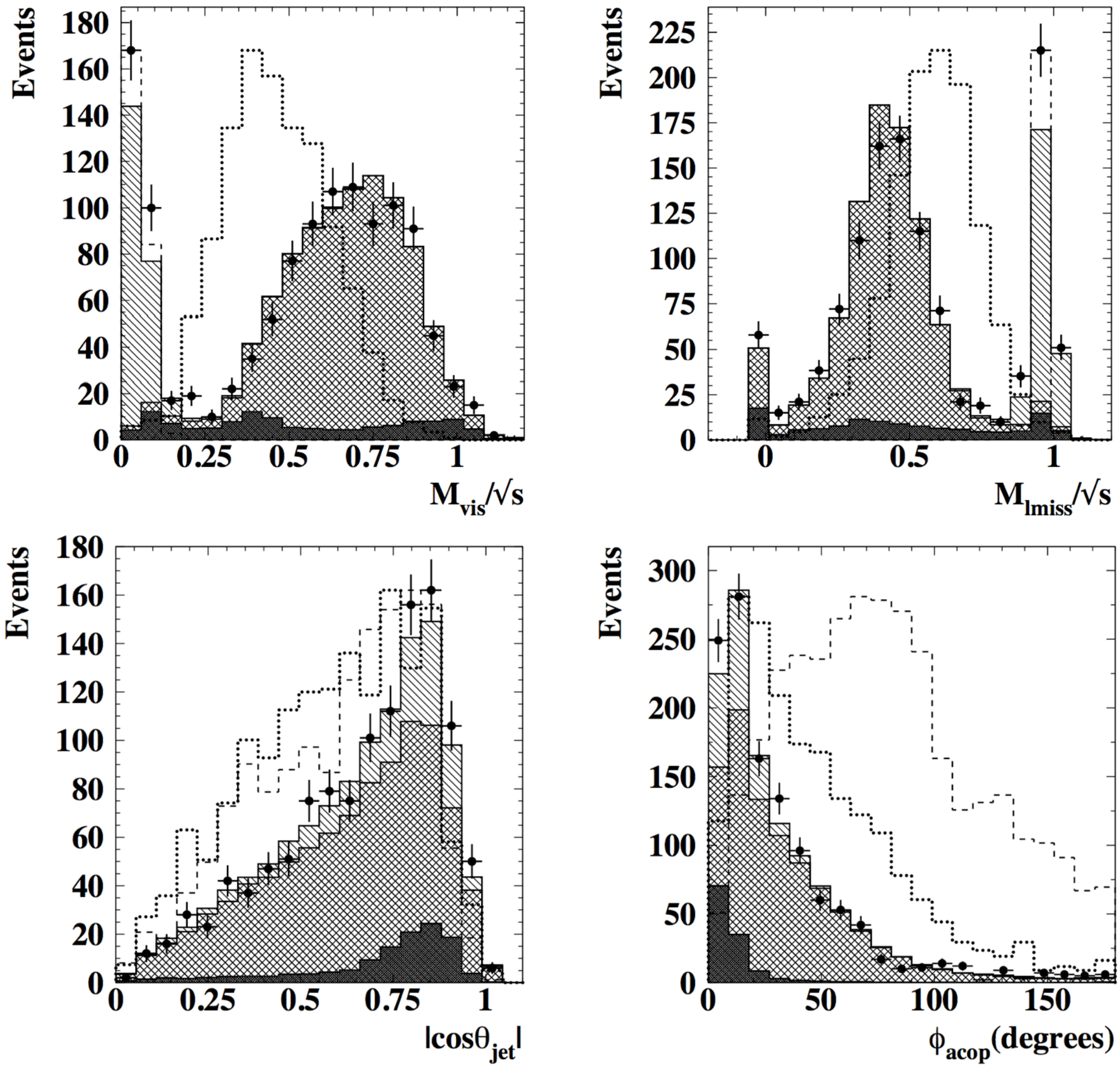
Here are some figures from the OPAL search for supersymmetry at LEP 2.

I should define:

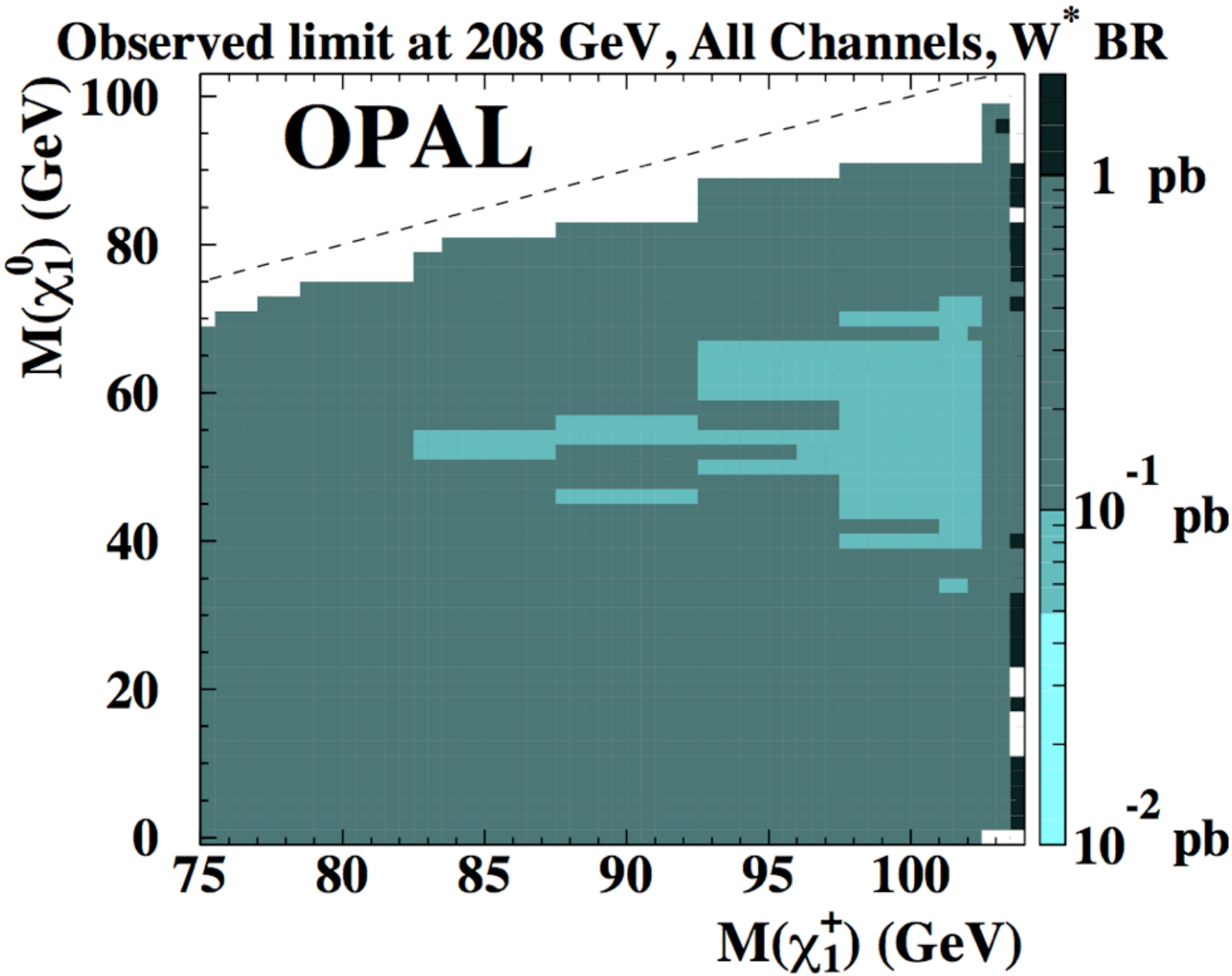
neutralino: supersymmetry partner of $(\gamma, Z, H_u^0, H_d^0)$
(4 linear combinations; Majorana fermions)

chargino: supersymmetry partner of (W^+, W^-, H_u^+, H_d^-)
(2+2 linear combinations; Dirac fermions)

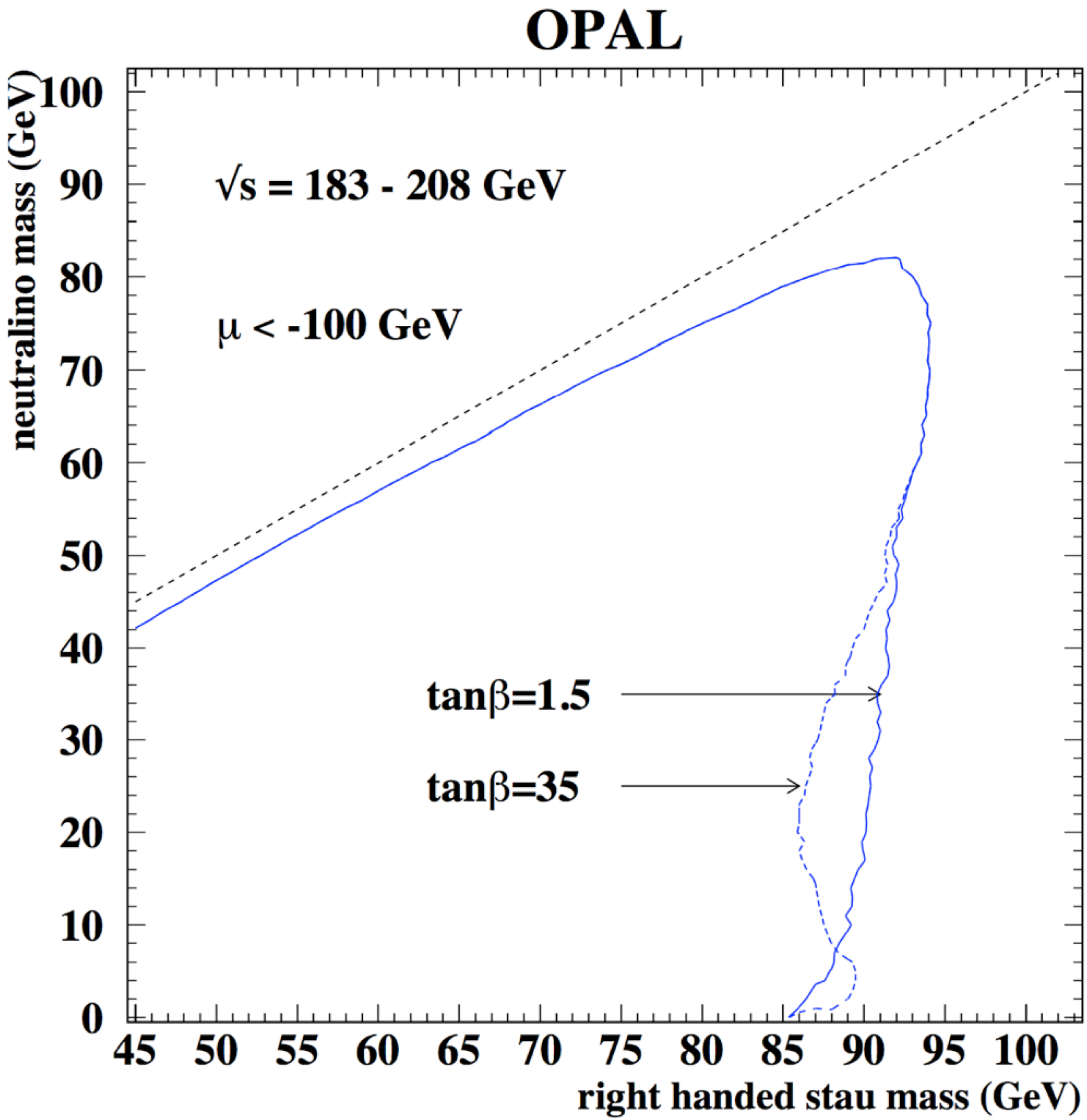
and, supersymmetry requires 2 Higgs multiplets, so it gives an extended Higgs sector


Events
$M_{vis}/\sqrt{s}$
$M_{lmiss}/\sqrt{s}$
$|\cos\theta_{jet}|$
ϕ_{acop}(degrees)

OPAL



Observed limit at 208 GeV, All Channels, W* BR
OPAL
M(χ₁⁰) (GeV)
M(χ₁⁺) (GeV)
0
20
40
60
80
100
75
80
85
90
95
100
1 pb
10⁻¹ pb
10⁻² pb



OPAL
√s = 183 - 208 GeV
μ < -100 GeV
tanβ=1.5
tanβ=35
neutralino mass (GeV)
right handed stau mass (GeV)
0
10
20
30
40
50
60
70
80
90
100
45
50
55
60
65
70
75
80
85
90
95
100

However, there is a price.   It is difficult to accelerate electrons to TeV energies. Protons can be accelerated to TeV energies with well-understood technologies.

But, there is also a price for working with protons: (14 TeV)

pp total cross section	100 mb
W, Z production	100 nb
top quark pair production	1 nb
Higgs boson production	30 pb
new particle production	$<$ 1 pb

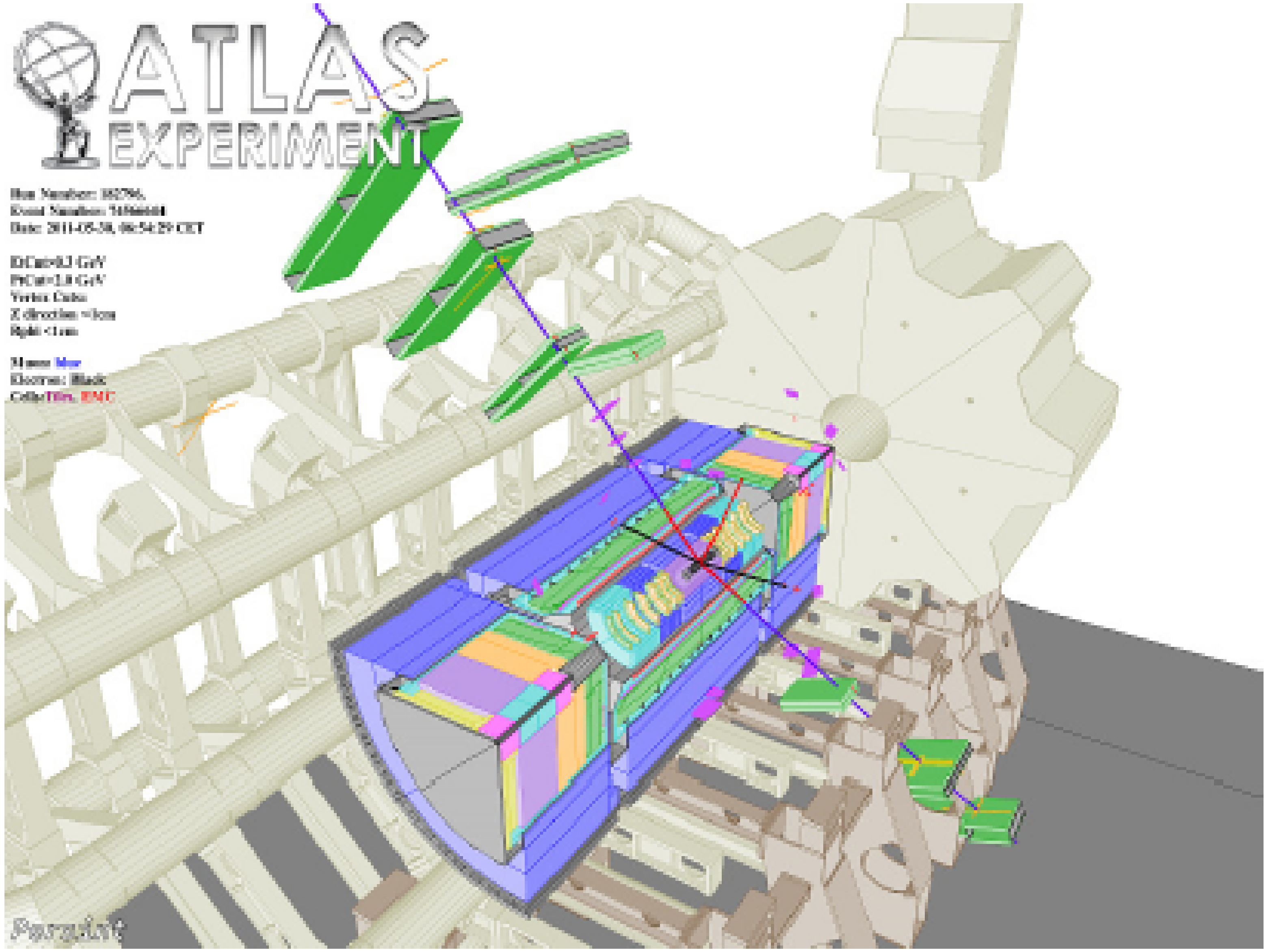
So, we need to detect processes that occur at 10^{-11} or less of the total cross section.

This requires

high luminosity,   and radiation-hard detectors
triggers that reject all but 10^{-6} of the data set without human supervision

precise understanding of complex Standard Model processes

It can be done. The top quark was discovered at the Tevatron at 10^{-11} of the total cross section. The processes actually used to discover the Higgs boson at the LHC occur at less than 1 in 2×10^{12} pp events.



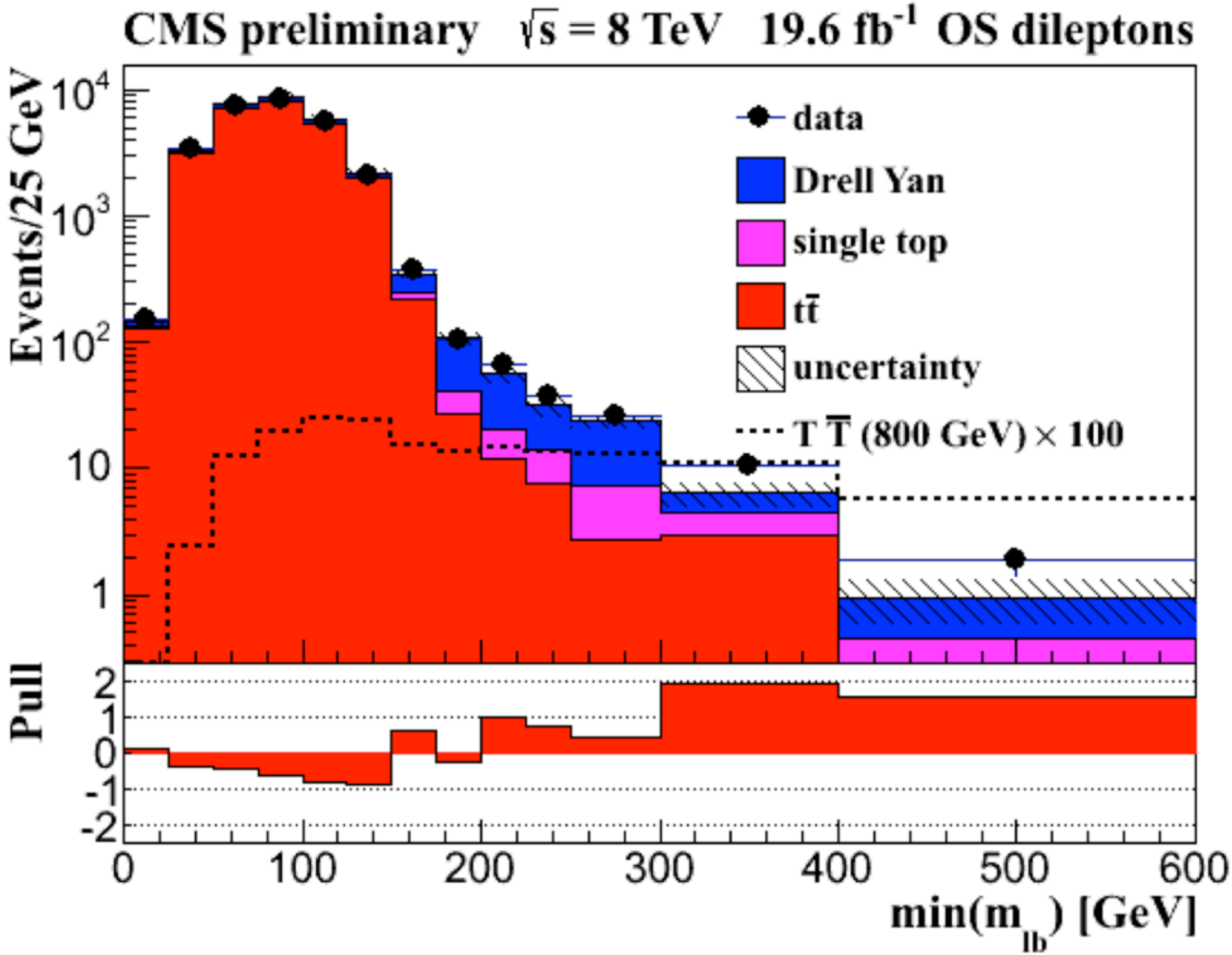
Look in more detail at the search for a vectorlike top quark, one of the key signatures of extra-dimensional and Little Higgs models.

Decay modes: $T \to bW^+, tZ, th \quad (2:1:1)$

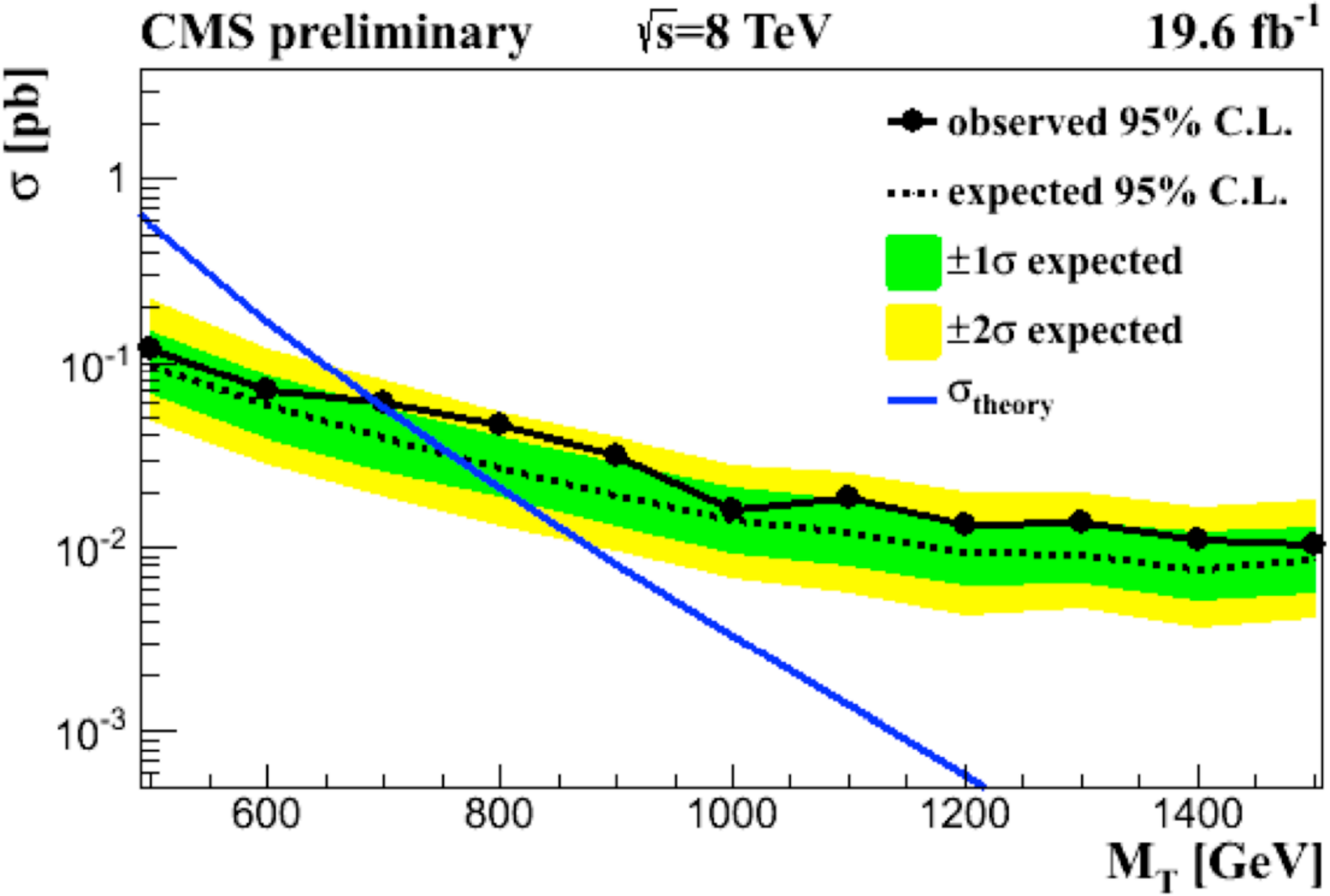
Search for these modes by looking for events with 2 isolated leptons, 2 b-tagged jets, large multijet and (jl) invariant masses.

Here is a figure from the CMS analysis:

The background must be plotted on a log scale. The dominant background comes from $pp \to t\bar{t} + ng$. This must be precisely understood.

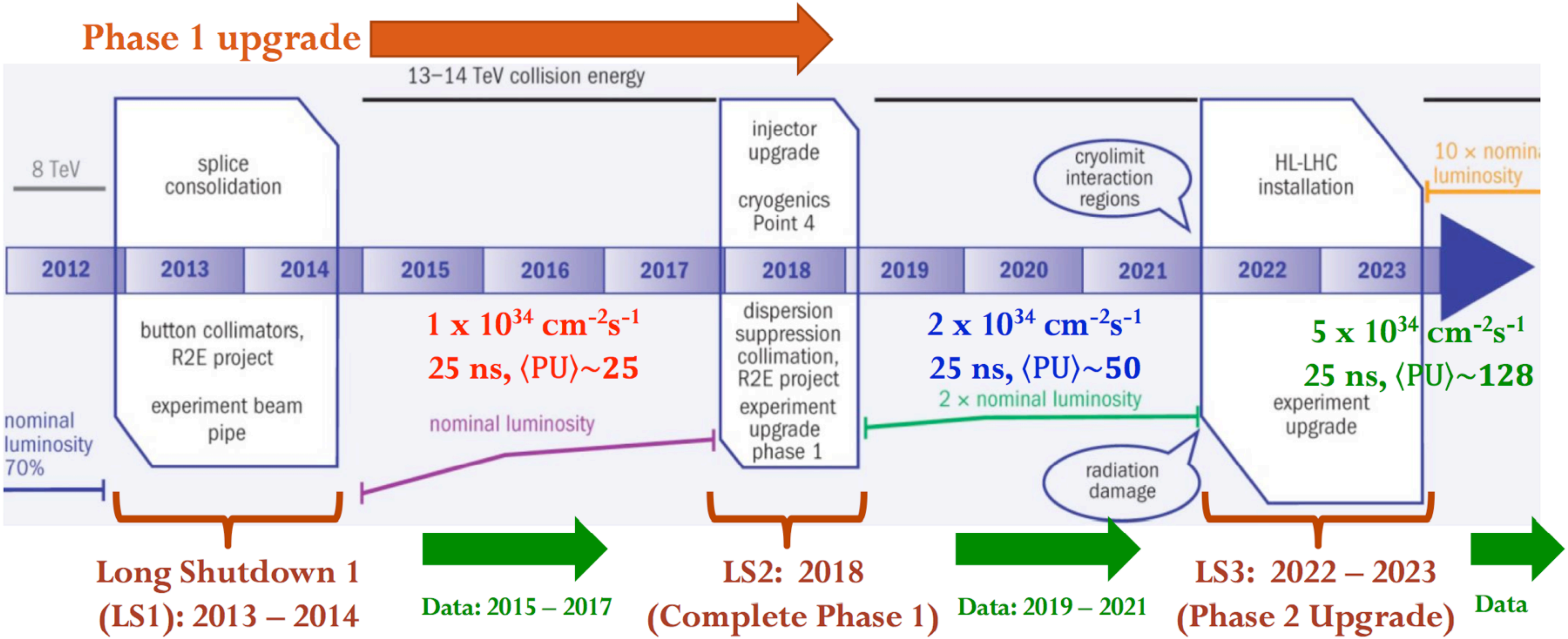


CMS preliminary √s = 8 TeV 19.6 fb-1 OS dileptons
Events/25 GeV
data
Drell Yan
single top
tt̄
uncertainty
T T̄ (800 GeV) × 100
Pull
min(m_lb) [GeV]
0
100
200
300
400
500
600



CMS preliminary
$\sqrt{s}$=8 TeV
19.6 fb^{-1}
σ [pb]
1
10^{-1}
10^{-2}
10^{-3}
observed 95% C.L.
expected 95% C.L.
±1σ expected
±2σ expected
σ_{theory}
600
800
1000
1200
1400
M_T [GeV]

With planned energy and luminosity upgrades, this search will access masses of T close to 2 TeV.   This will test the expected range of masses for the vectorlike T in extra dimension and Little Higgs models.

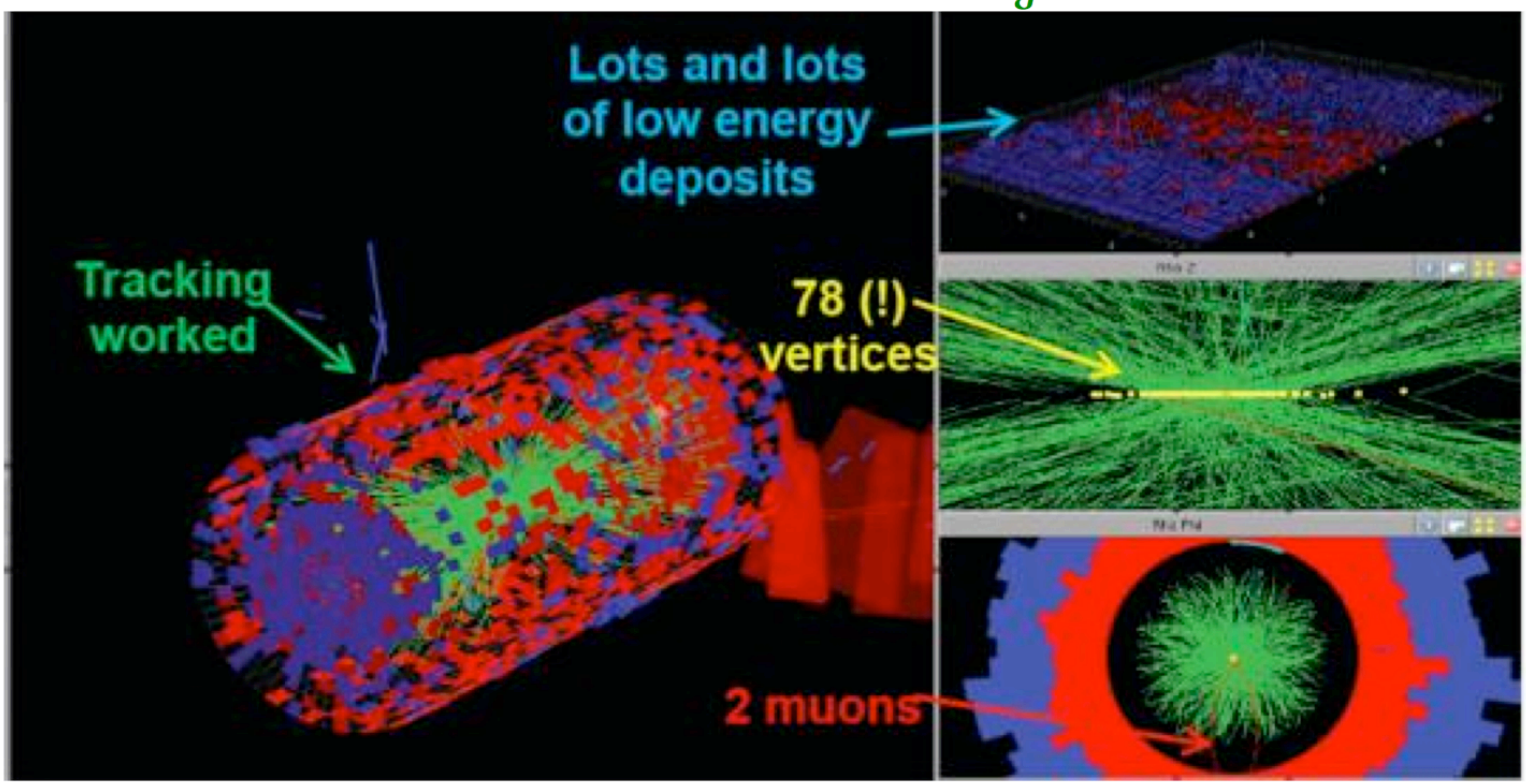

Phase 1 upgrade
13–14 TeV collision energy
8 TeV
splice consolidation
injector upgrade
cryogenics Point 4
cryolimit interaction regions
HL-LHC installation
10 × nomin
luminosity
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
button collimators, R2E project
experiment beam pipe
nominal luminosity 70%
1 x 10^34 cm^-2s^-1
25 ns, ⟨PU⟩~25
nominal luminosity
dispersion suppression collimation, R2E project
experiment upgrade phase 1
2 x 10^34 cm^-2s^-1
25 ns, ⟨PU⟩~50
2 × nominal luminosity
radiation damage
5 x 10^34 cm^-2s^-1
25 ns, ⟨PU⟩~128
experiment upgrade
Long Shutdown 1 (LS1): 2013 – 2014
Data: 2015 – 2017
LS2: 2018 (Complete Phase 1)
Data: 2019 – 2021
LS3: 2022 – 2023 (Phase 2 Upgrade)
Data

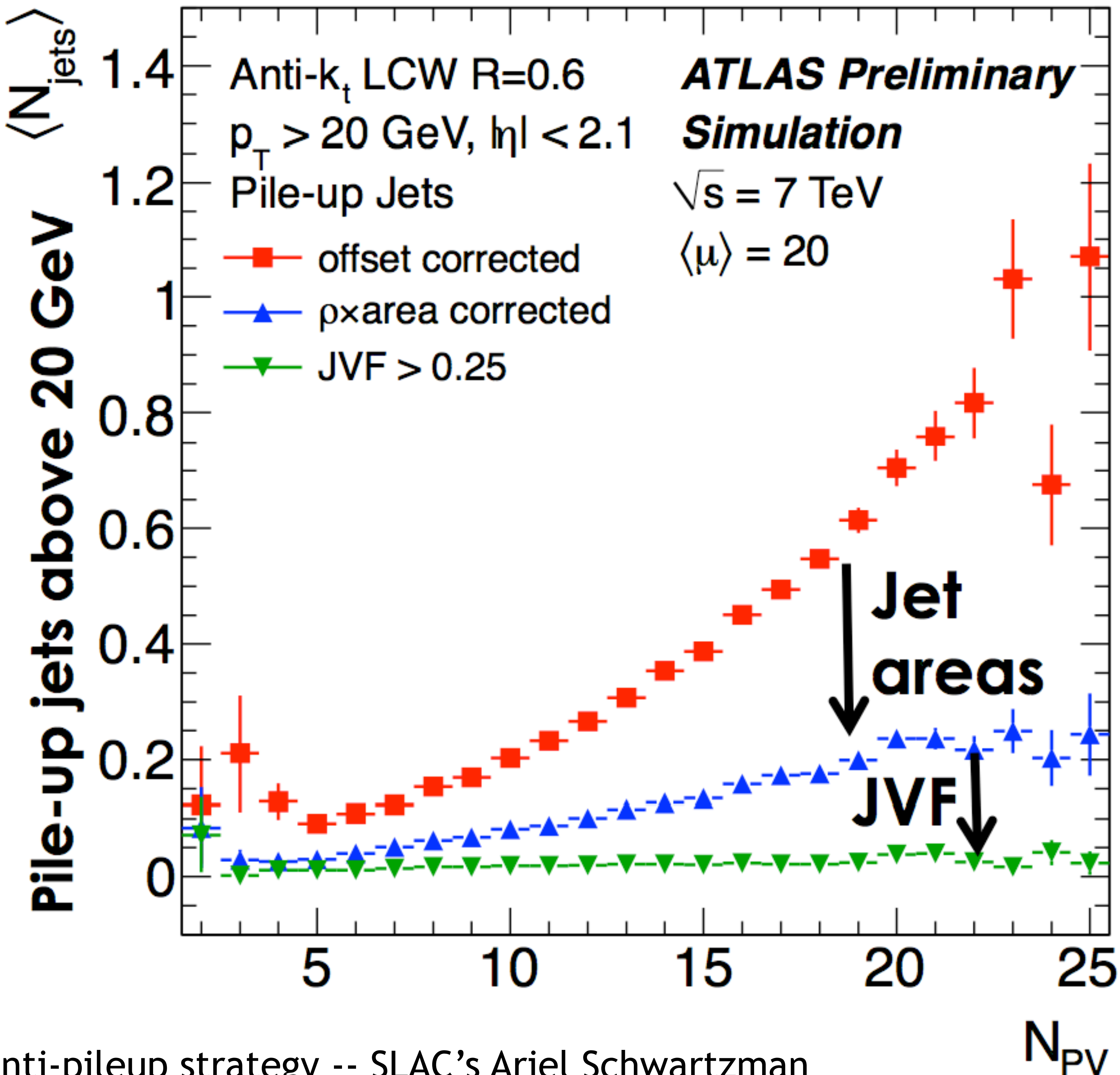
Note that high luminosity entails large numbers of collisions per proton bunch crossing -- high pileup.

It is a black art to correct observed events, using all available information, so that the effect of many soft pp collisions is subtracted and the single hard event in a bunch crossing is rendered accurately.

CMS

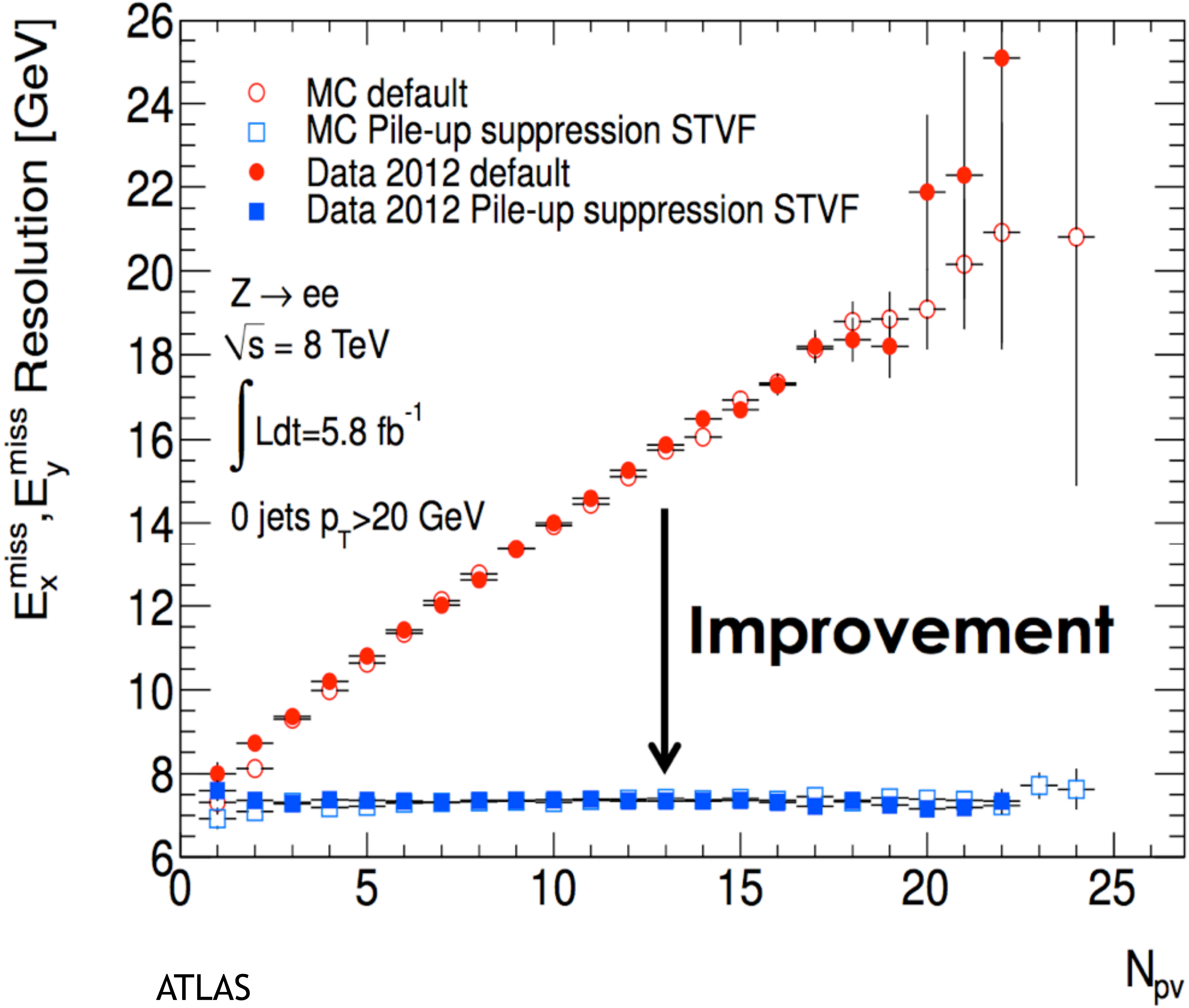
Dedicated high-PU run with 78 vertices





ATLAS anti-pileup strategy -- SLAC's Ariel Schwartzman

Missing ET resolution in events with no jets



ATLAS

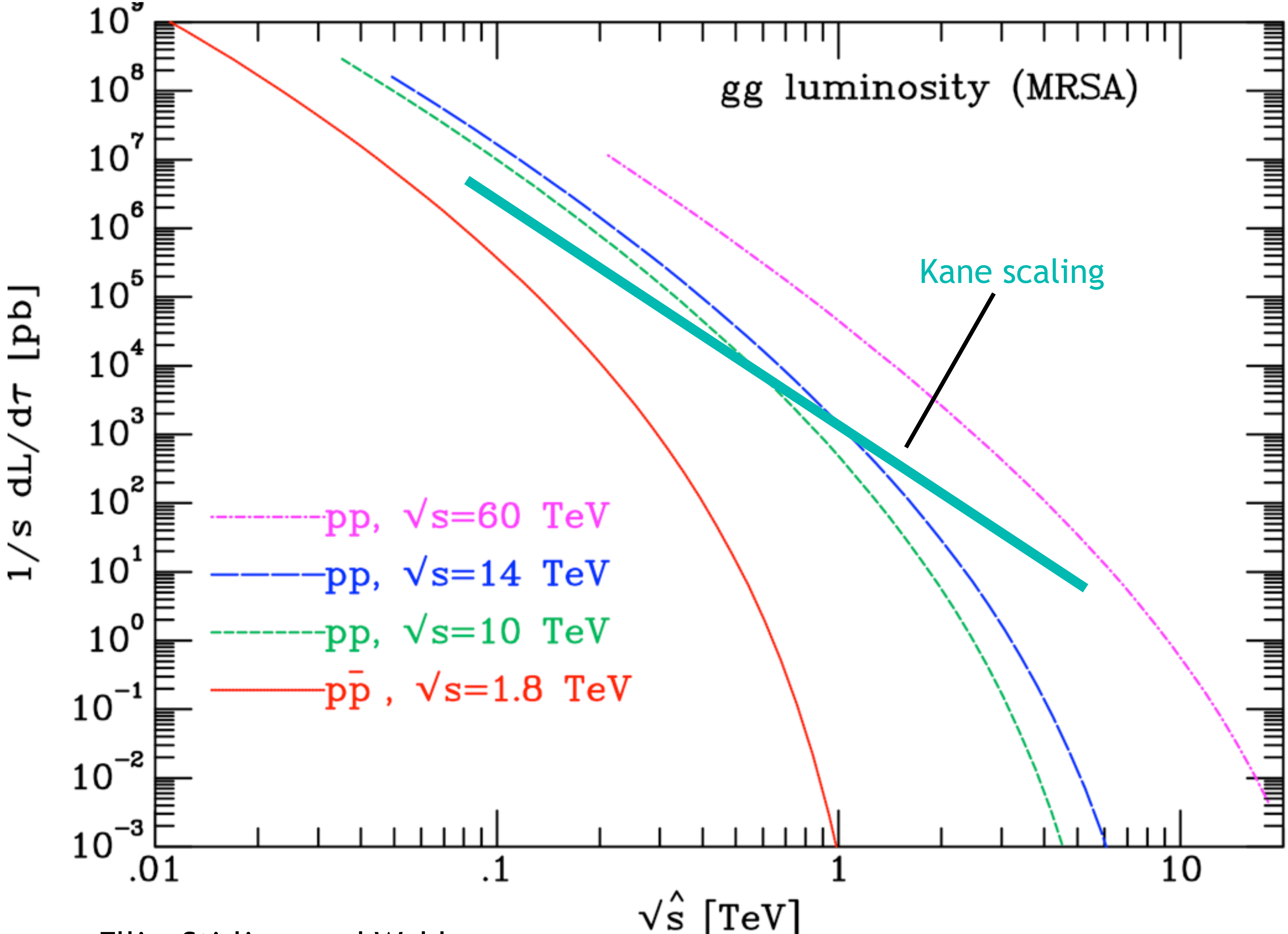
Assuming that we can do physics at high pileup,

how do we think about increasing luminosity ?

Kane’s rule of thumb:

A factor of 2 in energy is equivalent to a factor of 10 in luminosity

(as long as we are not already at the extreme values of parton distribution functions)



Ellis, Stirling, and Webber

so, luminosity is a big advantage until we reach new particle masses of ~ 2 TeV.

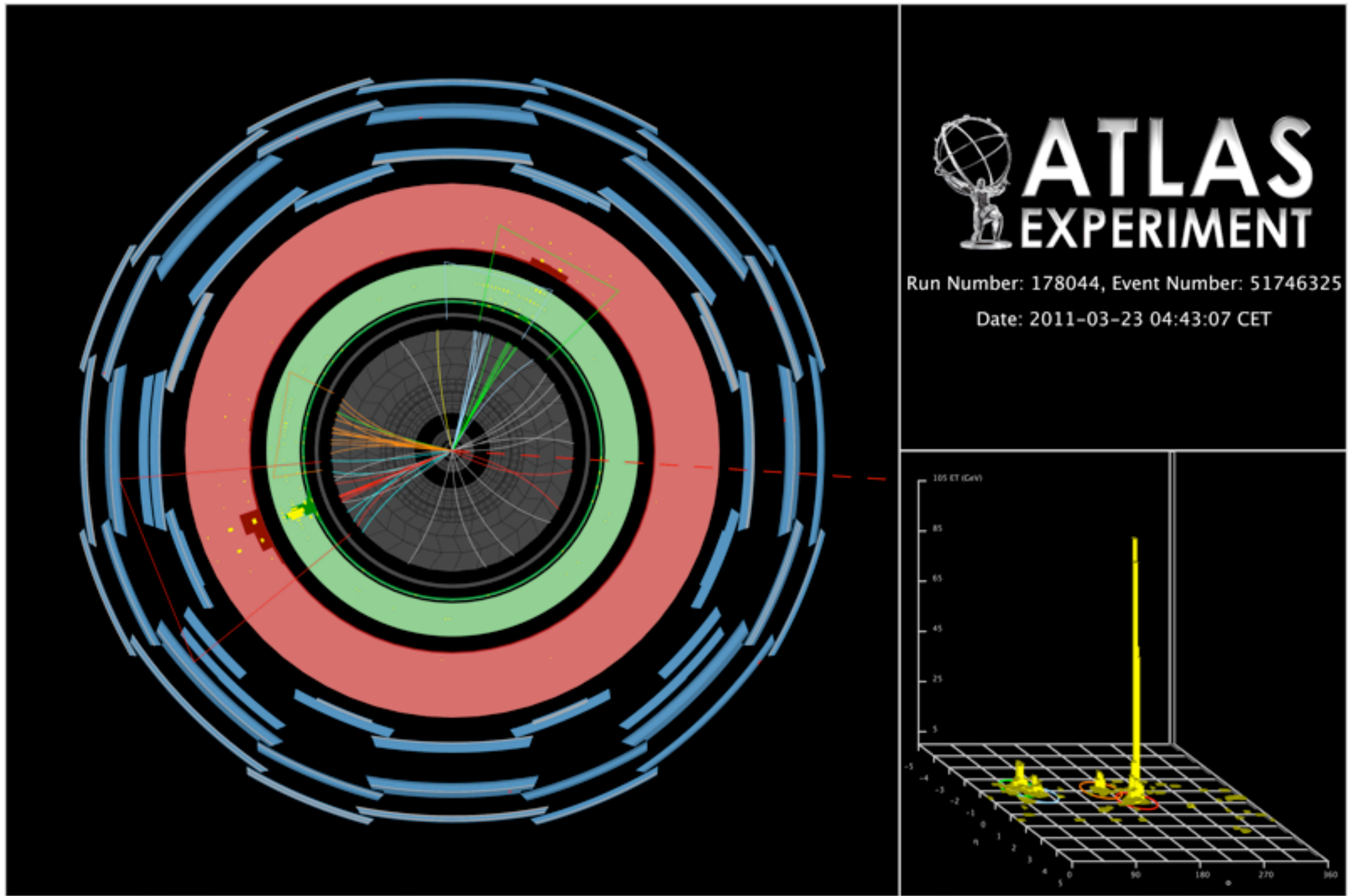
After that, gains are difficult, ~ 30% reach increase for a factor of 10 in lumi.

With this introduction, discuss searches for supersymmetry at the LHC.

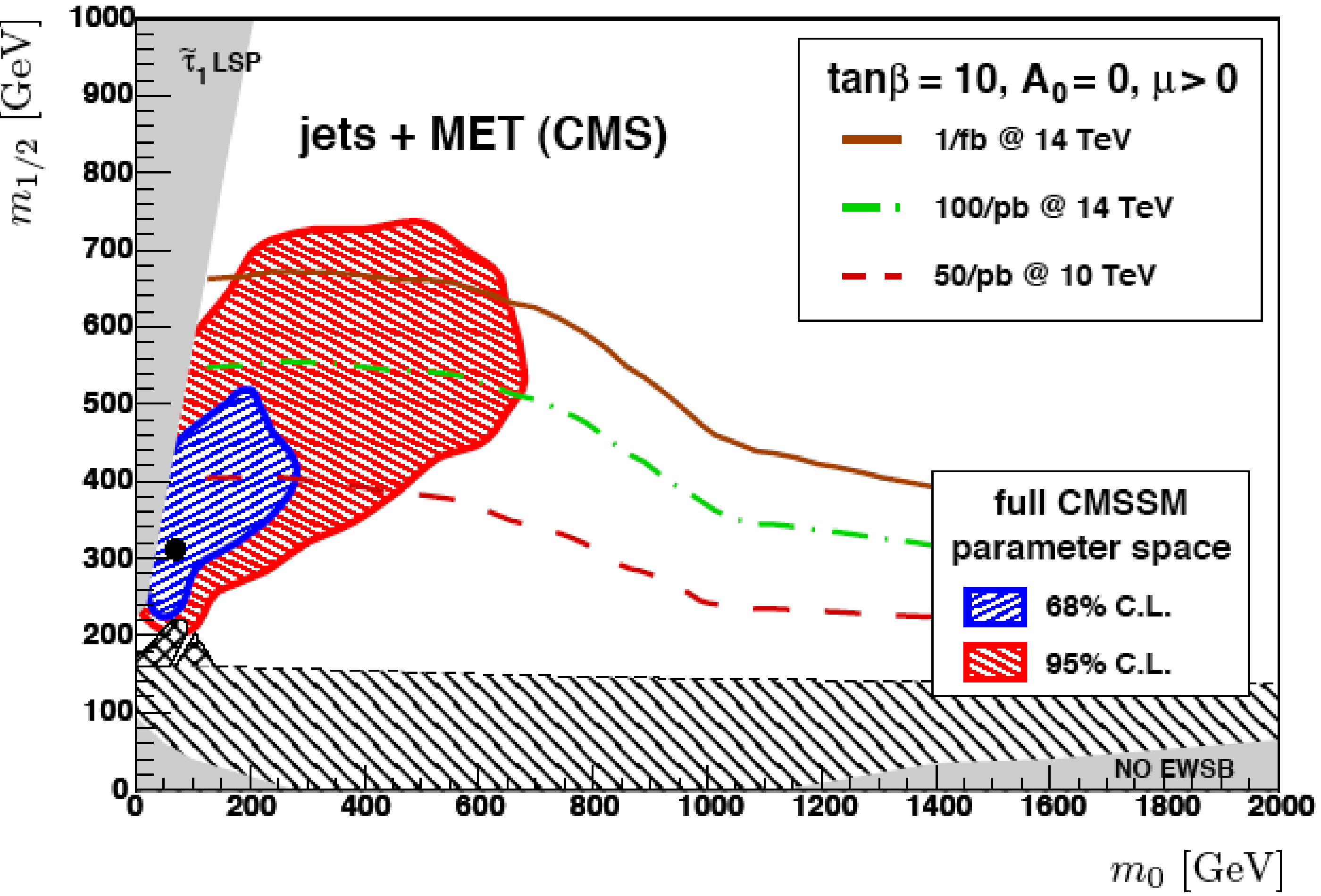
The expection, before the LHC, was that even 7 TeV running would be very powerful.

Squarks, gluinos have large QCD cross sections,   SUSY with decay to dark matter yields events with unbalanced visible momentum (“missing transverse energy”).

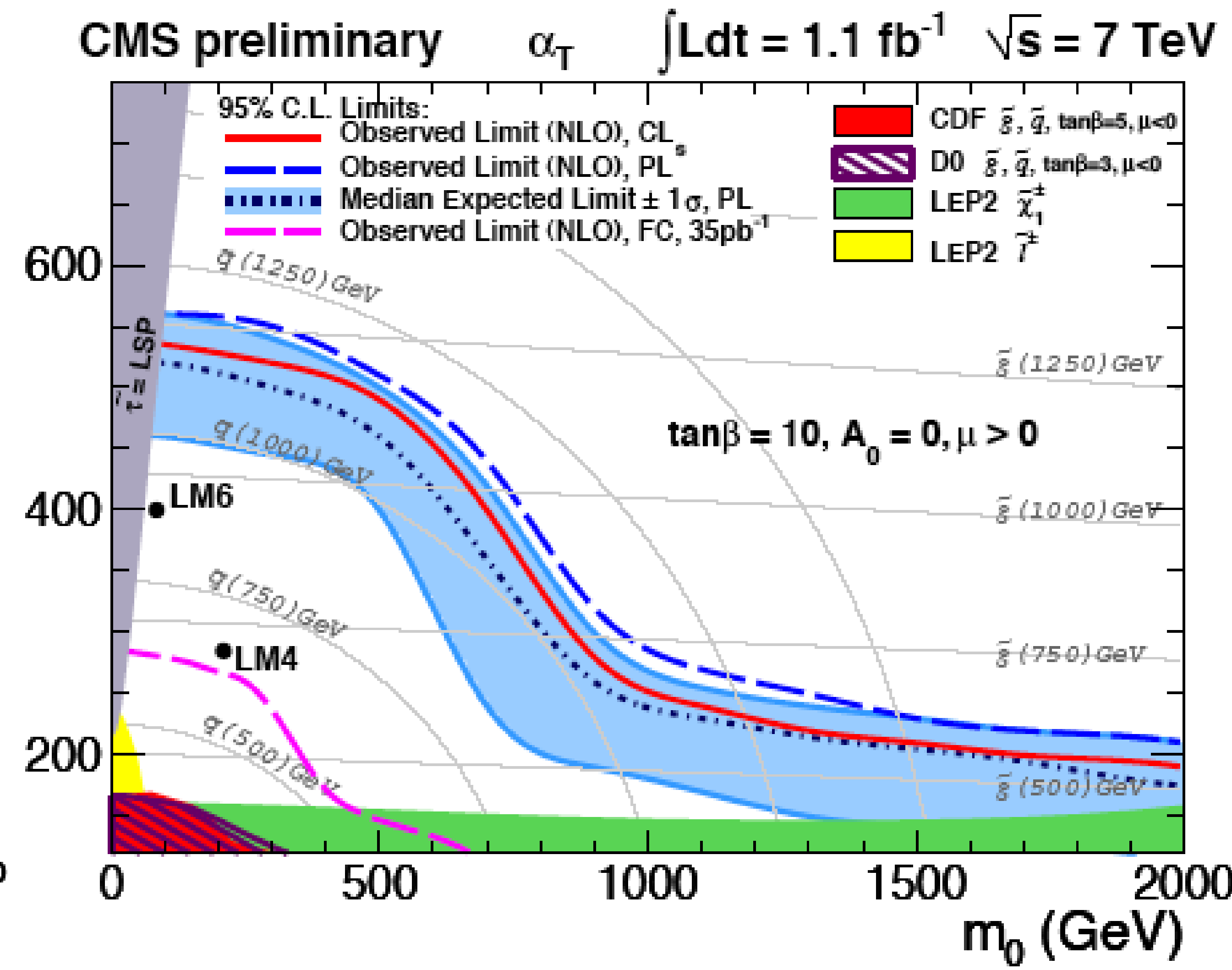
If we can control missing energy resolution for detector, pileup effects -- and, this has been a big success of ATLAS and CMS -- the experiments should look for these events very sensitively.

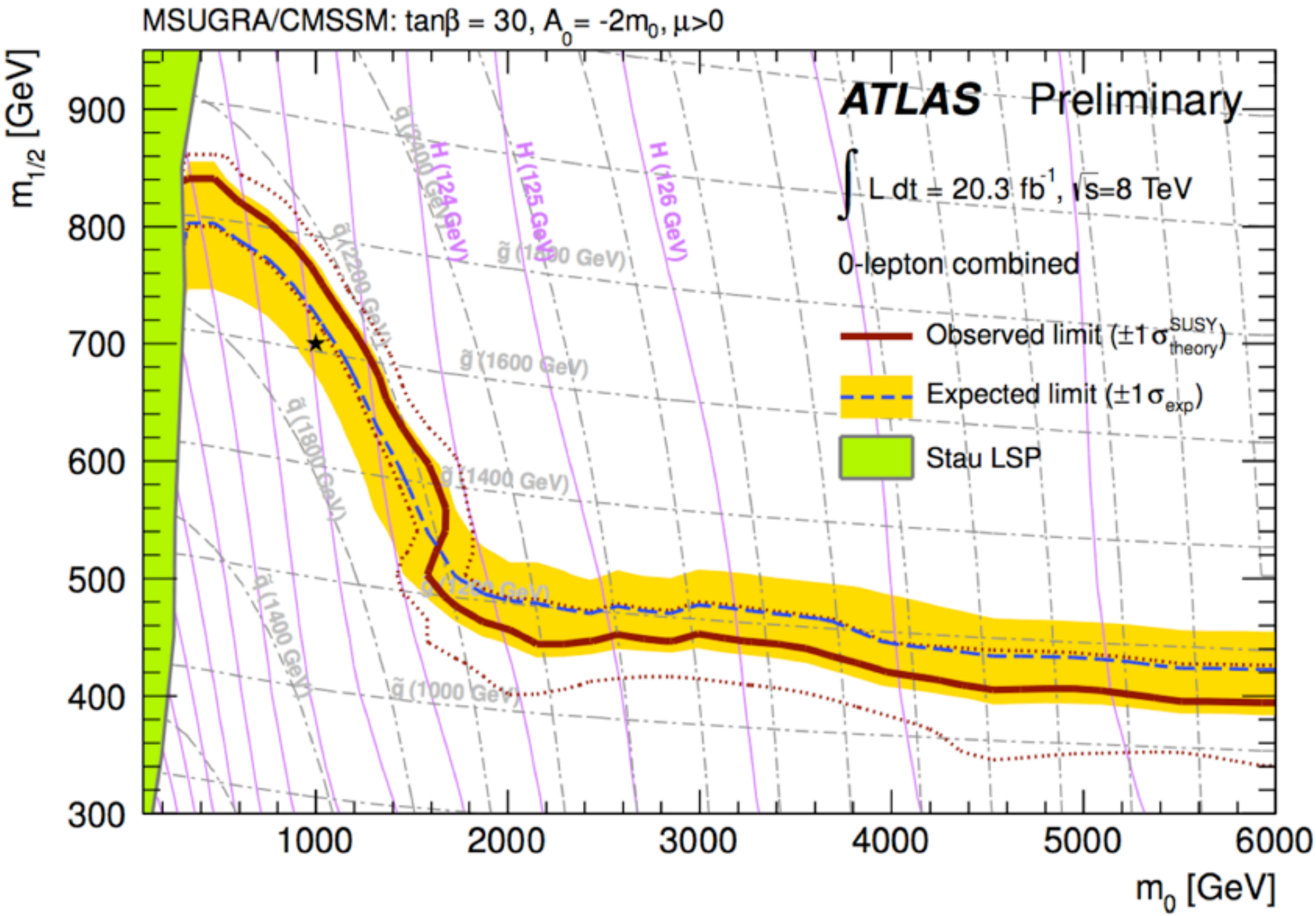


Buchmuller, … , DeRoeck, Ellis …
2008



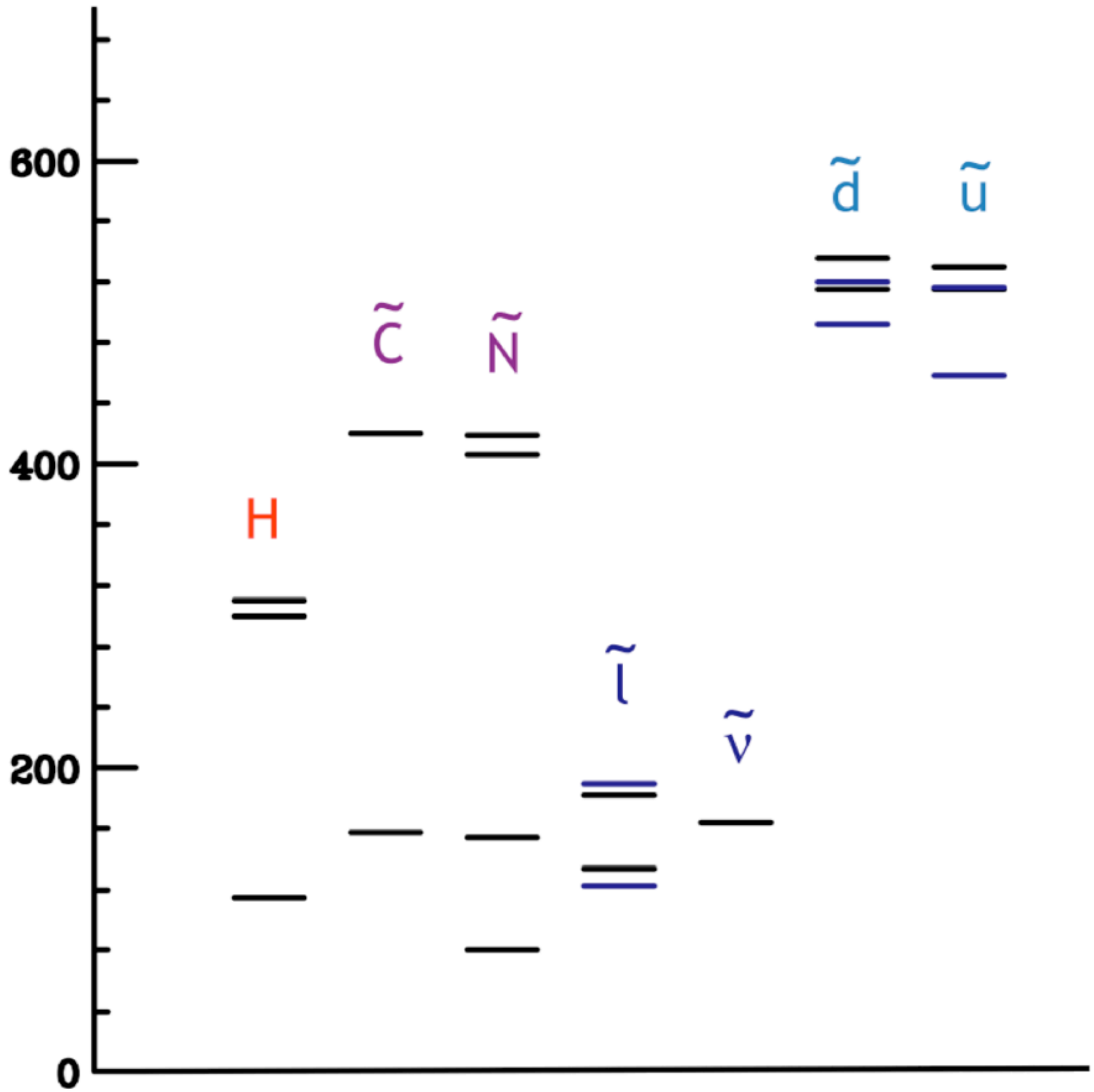
CMS LP11 α_T analysis





MSUGRA/CMSSM: tanβ = 30, A0= -2m0, μ>0
ATLAS Preliminary
∫L dt = 20.3 fb-1, √s=8 TeV
0-lepton combined
Observed limit (±1 σ SUSY theory)
Expected limit (±1 σexp)
Stau LSP
H (124 GeV)
H (125 GeV)
H (126 GeV)
g̃ (1600 GeV)
g̃ (1400 GeV)
g̃ (1000 GeV)
g̃ (2200 GeV)
g̃ (1800 GeV)
g̃ (1400 GeV)
m1/2 [GeV]
m0 [GeV]
300
400
500
600
700
800
900
1000
2000
3000
4000
5000
6000

The models discussed in these figures are generated from a hypothesis called MSUGRA. This leads to generic SUSY spectra that are relatively easy to discover or exclude.



but, perhaps, the SUSY spectrum has a different form. What does "naturalness" say?

Equation for the Higgs potential minimum v in supersymmetry:

$$m_Z^2 = 2\,\frac{M_{Hd}^2 - \tan^2\beta M_{Hu}^2}{\tan^2\beta - 1} - 2\mu^2$$

The parameters that appear are the Higgsino mass μ, the Higgs masses, and

$$\tan\beta = \langle H_u \rangle \,/\, \langle H_d \rangle$$

The top squark masses appear implicitly, since $M_{H_u}^2$ becomes negative due to a renormalization effect from these particles. The gluino appears more implicitly, because this gives a large positive correction to the stop masses.

I conclude that naturalness predicts

$\mu \lesssim 200\ \mathrm{GeV}$ $m(\widetilde{t}) \lesssim 1\ \mathrm{TeV}$ $m(\widetilde{g}) \lesssim 3\ \mathrm{TeV}$

and the 1st and 2nd generation squarks are hardly constrained.

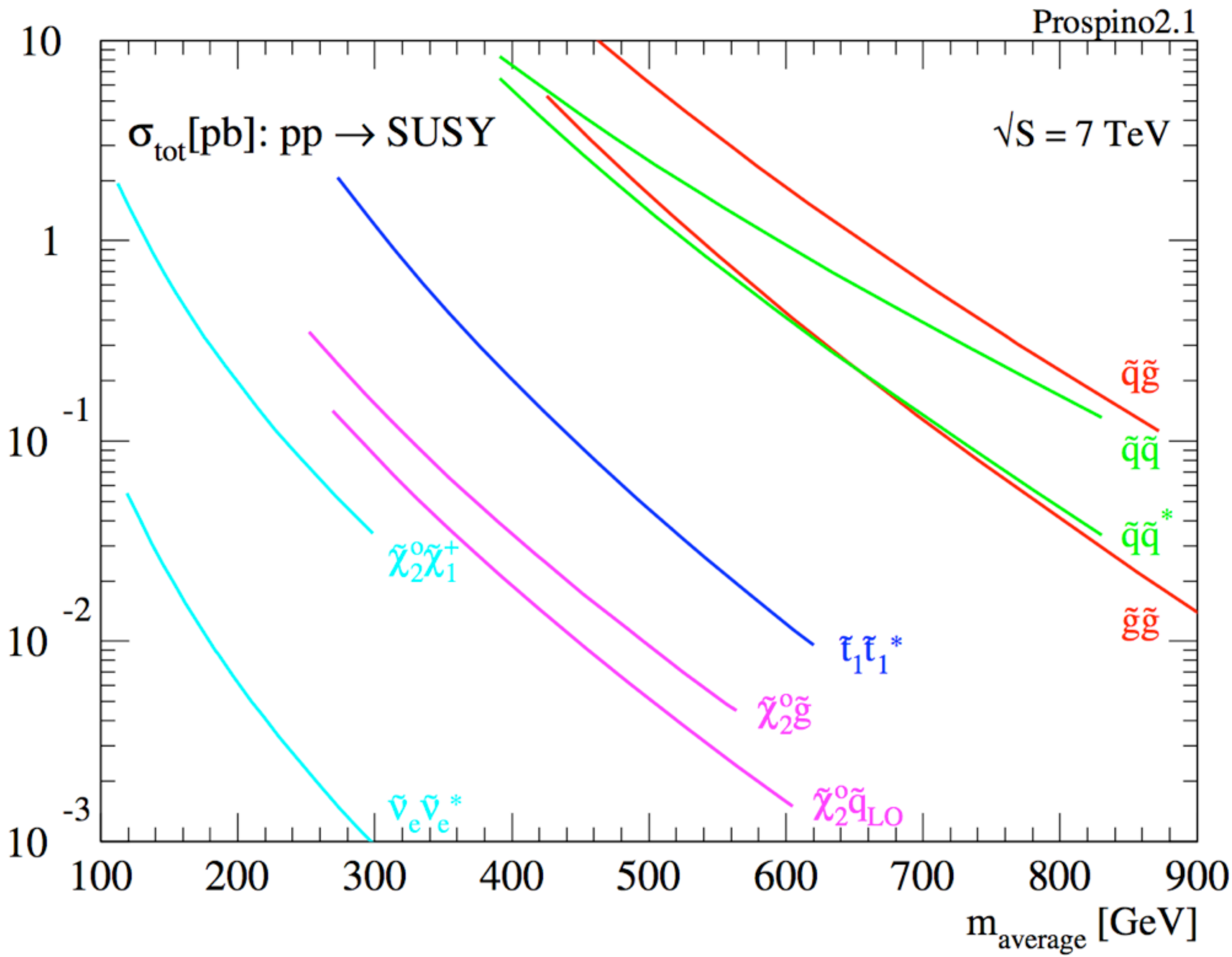
This has important implications for the visibility of SUSY at the various stages of the LHC.

If Higgsinos are the lightest supersymmetric particles, they are also quite degenerate in mass. They are very hard to detect, except maybe as missing energy in

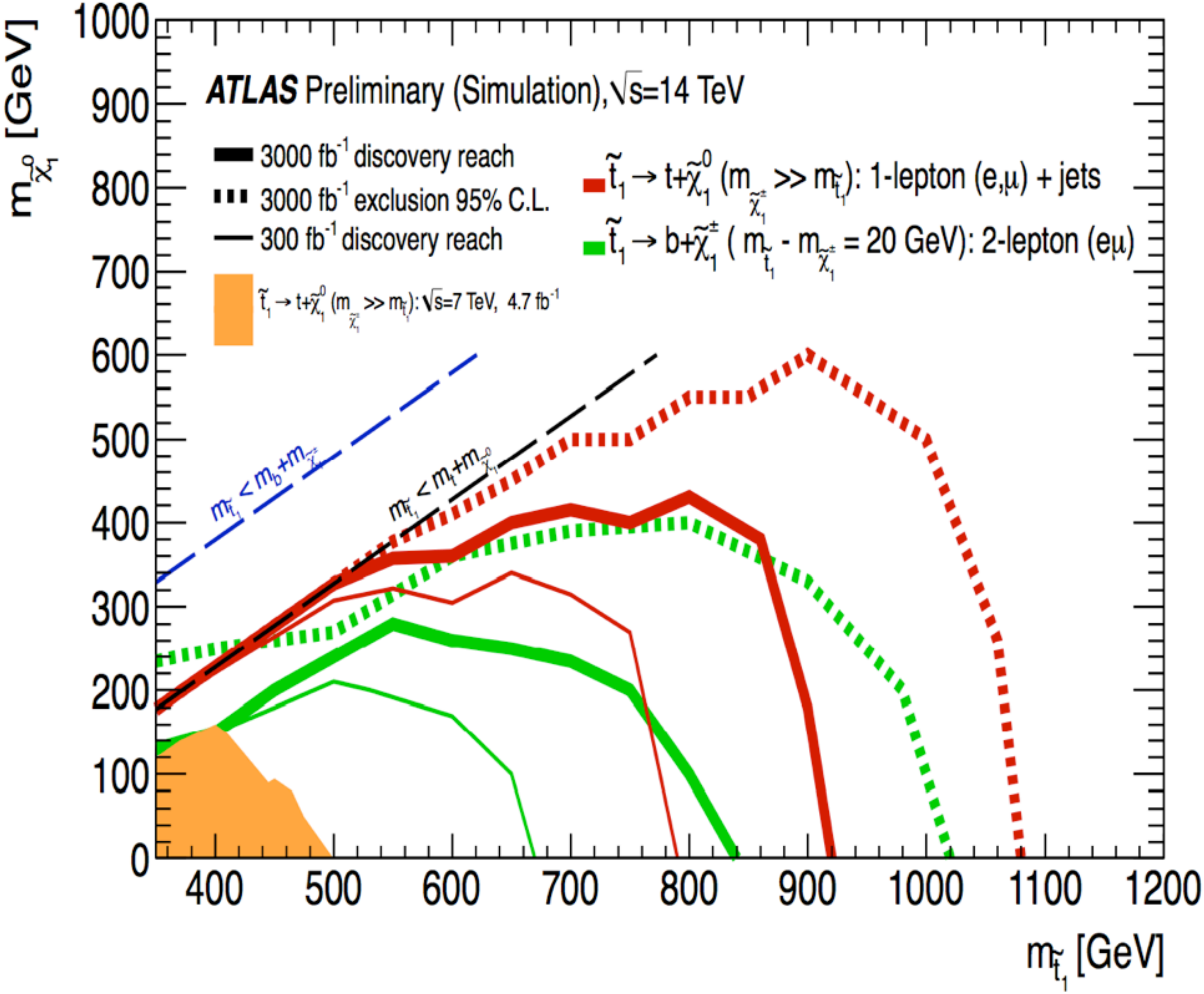
$$pp \to \text{ ISR jet} + (\text{missing})$$

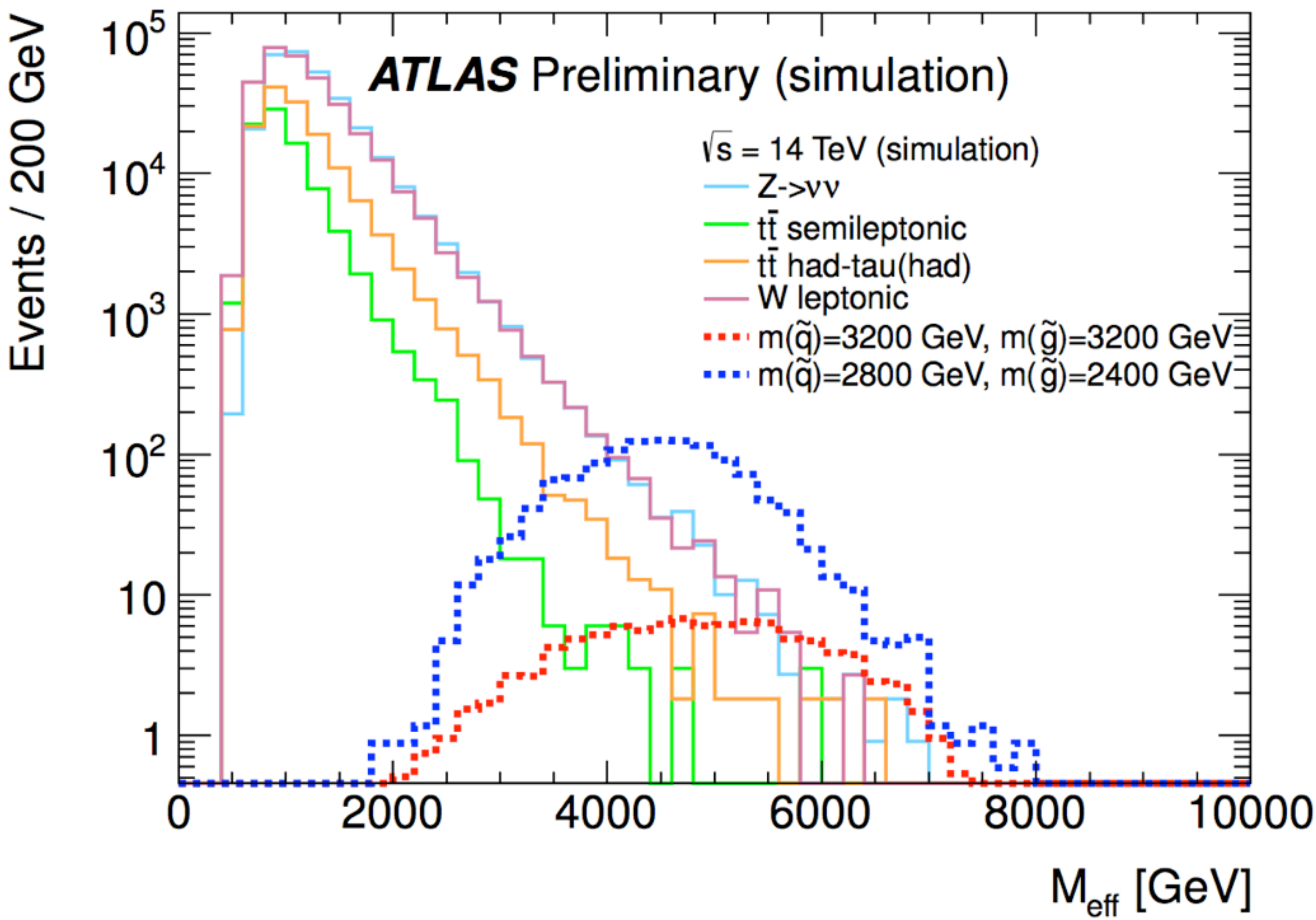
Top squarks have relatively small cross sections. Recently, ATLAS and CMS have launced dedicated searches.

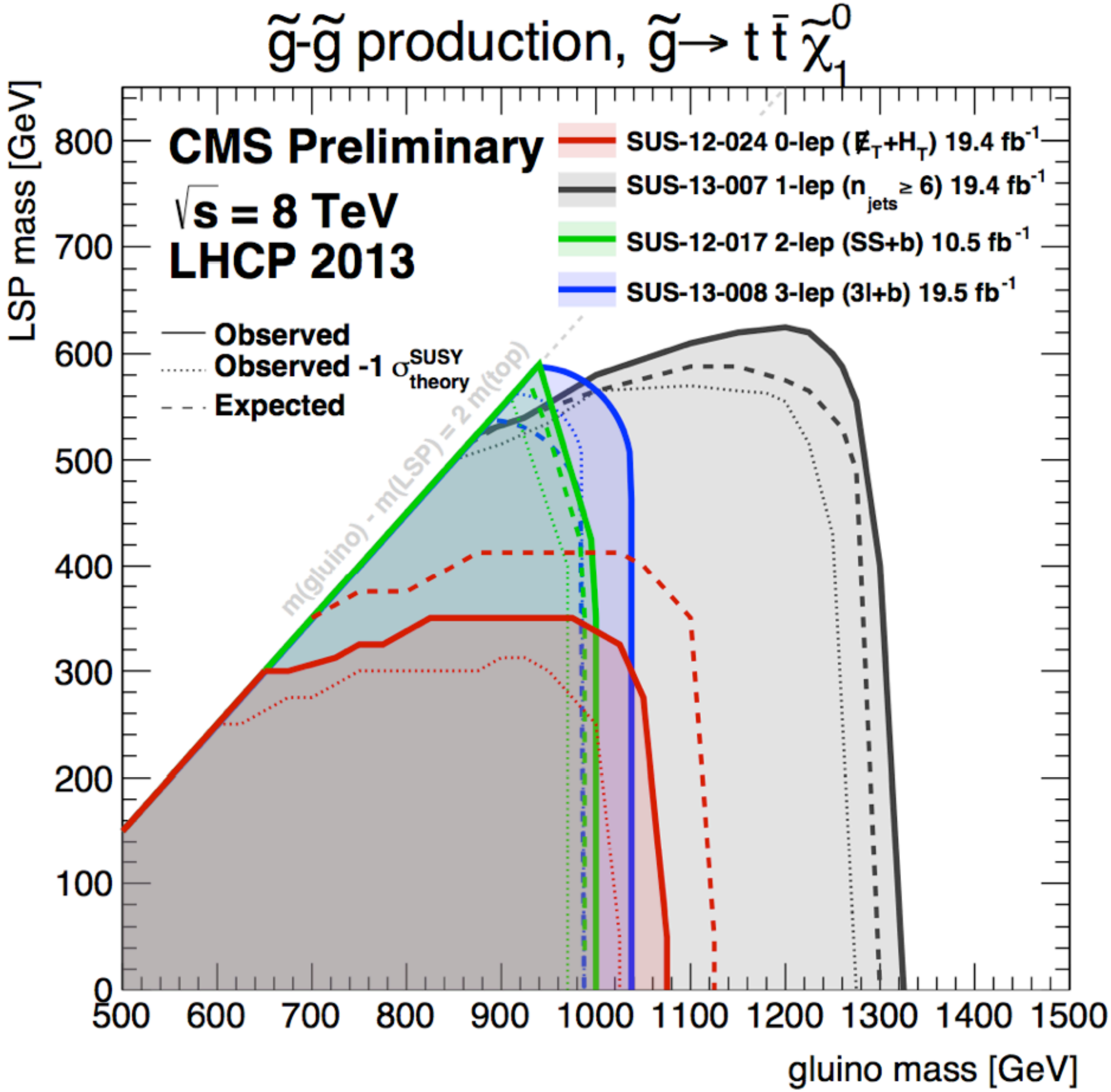
The gluino may be too heavy for LHC-8. But LHC-14 should be enough to see striking missing energy events.



Prospino2.1
σ_tot[pb]: pp → SUSY
√S = 7 TeV
10
1
10^-1
10^-2
10^-3
100
200
300
400
500
600
700
800
900
m_average [GeV]
q̃g̃
q̃q̃
q̃q̃*
g̃g̃
t̃1t̃1*
χ̃2oχ̃1+
χ̃2og̃
χ̃2oq̃LO
ν̃eν̃e*


ATLAS Preliminary (Simulation), √s=14 TeV
3000 fb-1 discovery reach
3000 fb-1 exclusion 95% C.L.
300 fb-1 discovery reach
t̃1 → t+χ̃01 (mχ̃±1 >> mt̃1): √s=7 TeV, 4.7 fb-1
t̃1 → t+χ̃01 (mχ̃±1 >> mt̃1): 1-lepton (e,μ) + jets
t̃1 → b+χ̃±1 (mt̃1 - mχ̃±1 = 20 GeV): 2-lepton (eμ)
mt̃1 < mb+mχ̃±1
mt̃1 < mt+mχ̃01
mχ̃01 [GeV]
mt̃1 [GeV]
0
100
200
300
400
500
600
700
800
900
1000
400
500
600
700
800
900
1000
1100
1200


ATLAS Preliminary (simulation)
√s = 14 TeV (simulation)
Z->νν
tt̄ semileptonic
tt̄ had-tau(had)
W leptonic
m(q̃)=3200 GeV, m(g̃)=3200 GeV
m(q̃)=2800 GeV, m(g̃)=2400 GeV
Events / 200 GeV
M_eff [GeV]



g̃-g̃ production, g̃→ t t̄ χ̃₁⁰
CMS Preliminary
√s = 8 TeV
LHCP 2013
SUS-12-024 0-lep (E̸T+HT) 19.4 fb-1
SUS-13-007 1-lep (njets ≥ 6) 19.4 fb-1
SUS-12-017 2-lep (SS+b) 10.5 fb-1
SUS-13-008 3-lep (3l+b) 19.5 fb-1
Observed
Observed -1 σ theory SUSY
Expected
m(gluino) - m(LSP) = 2 m(top)
LSP mass [GeV]
gluino mass [GeV]
0
100
200
300
400
500
600
700
800
500
600
700
800
900
1000
1100
1200
1300
1400
1500

There is much more to discuss here, but we need to move on to other subjects.

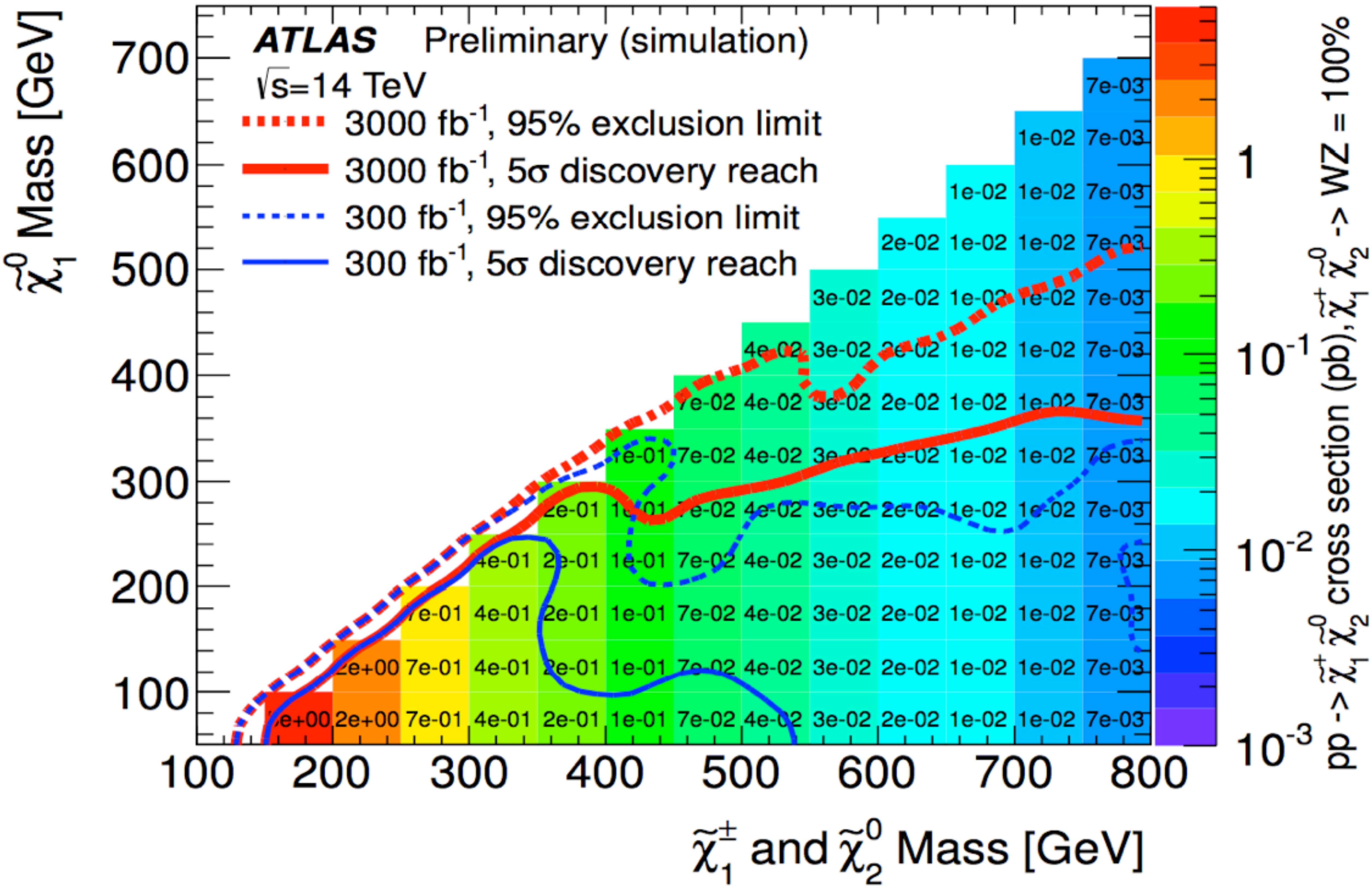
First, though, I would like to list special advantages of the high-luminosity phase of the LHC. This upgrade entails expensive upgrades of the detectors. It needs to be explicitly justified. In fact, it is strongly justified.

for searches

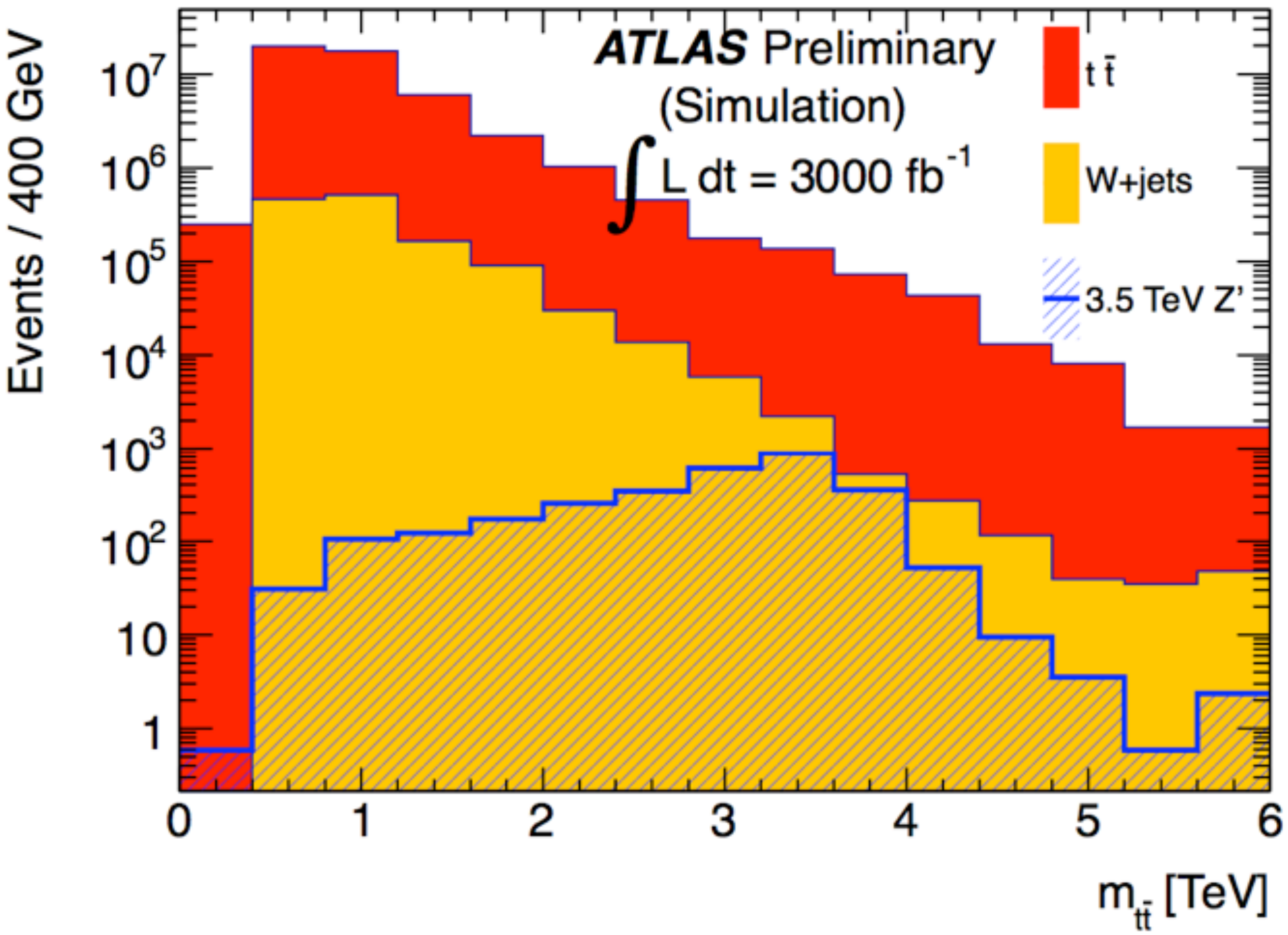
increased reach for many important searches, including
searches exploiting the tails of parton distributions
e.g. extra-dimensional resonance $G \to t_R \bar{t}_L$
electroweak production of SUSY and other partners of
W, Z, Higgs
additional Higgs bosons in $H \to b\bar{b}, \tau^+\tau^-$

for precision measurement, especially W and Z scattering processes
and Higgs processes (one billion Higgs bosons)

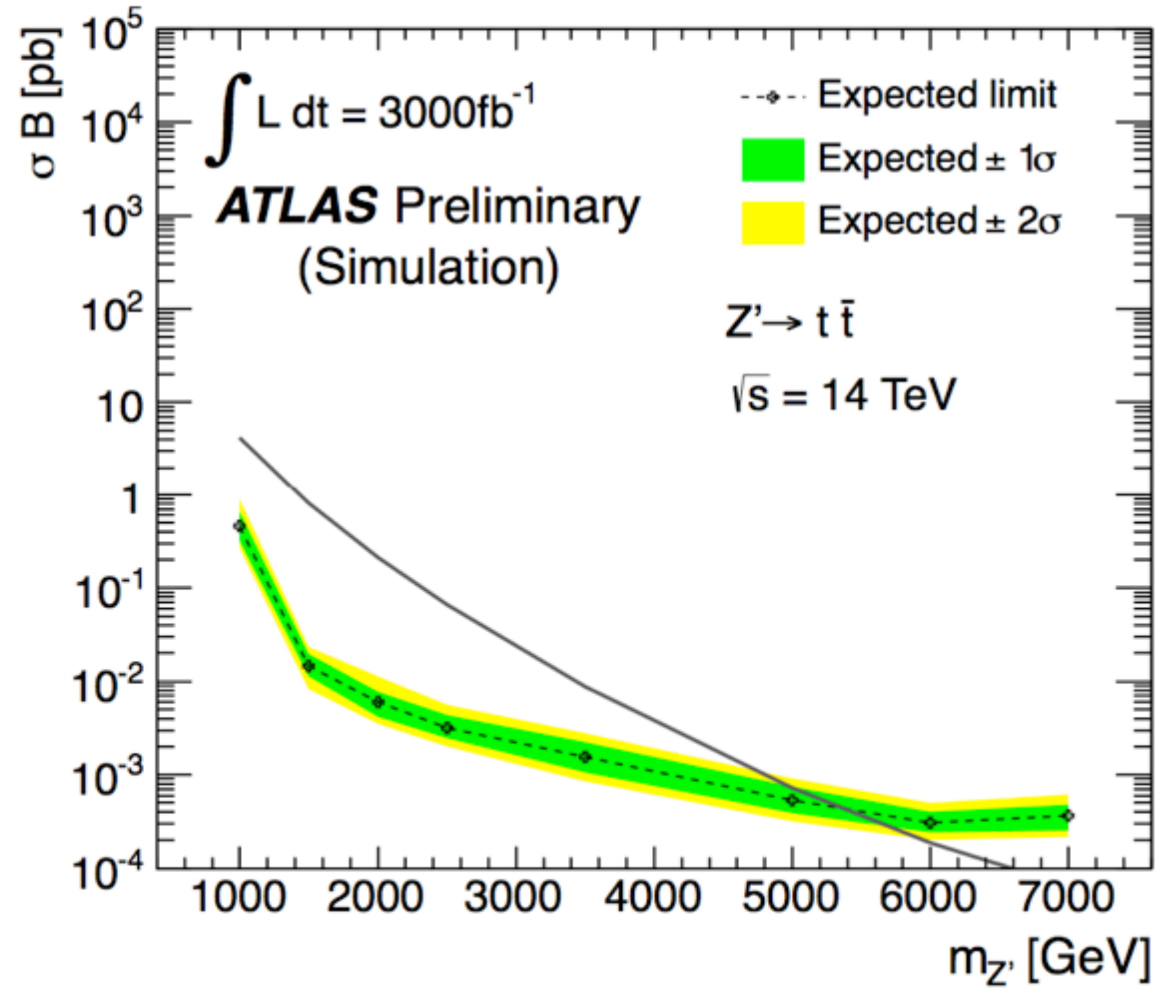
for followup of the discoveries I have predicted for LHC-14,
discovering new, rarer, decay modes, polarization studies


ATLAS Preliminary (simulation)
√s=14 TeV
3000 fb-1, 95% exclusion limit
3000 fb-1, 5σ discovery reach
300 fb-1, 95% exclusion limit
300 fb-1, 5σ discovery reach
χ̃10 Mass [GeV]
χ̃1± and χ̃20 Mass [GeV]
pp -> χ̃1± χ̃20 cross section (pb), χ̃1± χ̃20 -> WZ = 100%
100
200
300
400
500
600
700
800
1
10-1
10-2
10-3

Reconstructed ttbar mass spectrum



Expected KKgluon mass limit



model	$300\ fb^{-1}$	$1000\ fb^{-1}$	$3000\ fb^{-1}$
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{Topcolour}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)

Polland - Kotwal

Projections of Higgs coupling accuracy from LHC:

Little certainty here. No full simulations. Assumption that pileup can be controlled to the level where it plays no role.

CMS: very aggressive "scenario 2": current theoretical errors halved, experimental errors decreasing as $\sqrt{N}$.

Numbers in brackets are % uncertainties on coupling deviations for [scenario 2, scenario 1]

L (fb^{-1})	κ_γ	κ_V	κ_g	κ_b	κ_t	κ_τ
300	[5, 7]	[4, 5]	[6, 8]	[10, 13]	[14, 15]	[6, 8]
3000	[2, 5]	[2, 3]	[3, 5]	[4, 7]	[7, 10]	[2, 5]

Goal: ultimate precision of ~5% or better

There is an excellent opportunity here!

On the other hand, there is a better question to ask about the Higgs boson. Can we observe a discrepancy in Higgs couplings at the few-percent level. This requires experimental precision at 1% or below. Can this be done ?

What is the importance of percent accuracy ? This is the typical scale of deviations in the Higgs couplings if only very massive new particles are seen at the LHC.

Examples:

Supersymmetry:

$$g(\tau)/SM = 1 + 10\% \left(\frac{400 \text{ GeV}}{m_A}\right)^2$$

$$g(b)/SM = g(\tau)/SM + (1-3)\%$$

Little Higgs:

$$g(g)/SM = 1 + (5-9)\%$$

$$g(\gamma)/SM = 1 + (5-6)\%$$

Composite Higgs:

$$g(f)/SM = 1 + (3-9)\% \cdot \left(\frac{1 \text{ TeV}}{f}\right)^2$$

reach: roughly 3 TeV in new particle masses for the most sensitive deviations.

To perform these measurements properly to the required percent accuracy, we need to bring a lepton collider back into play.

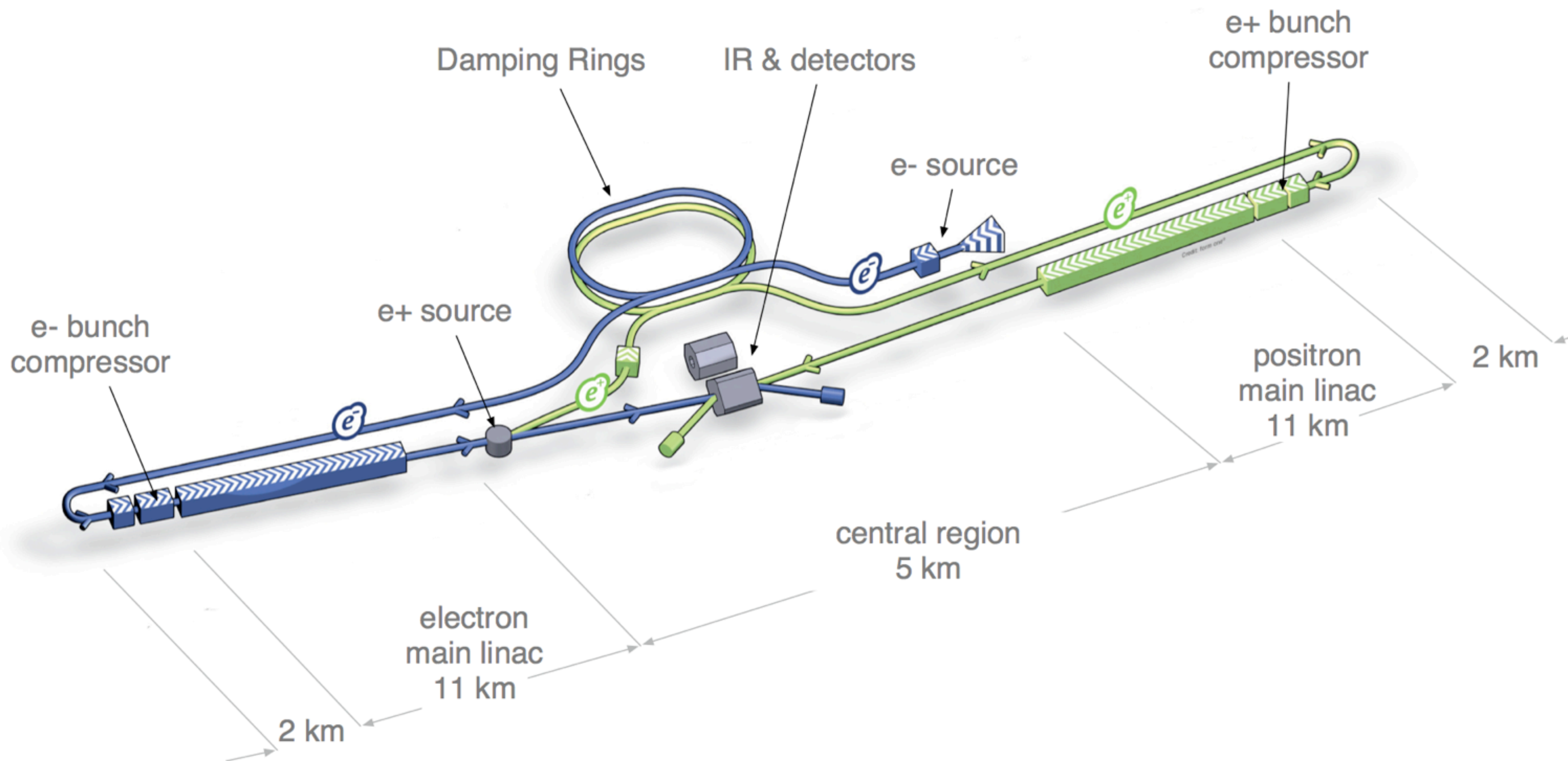
Lepton colliders bring important advantages to the study of the Higgs Boson couplings:

Higgs rates are 1% of the total cross section, not 10^{-10}.

Low backgrounds and high flavor tagging efficiency make possible the direct observation of hadronic decay channels $h \to b\bar{b}, c\bar{c}, gg$.

The reaction $e^+e^- \to Zh$ provides tagged Higgs decay. This gives a tool for measuring branching fractions and a way to discover invisible and otherwise unexpected Higgs decays.

ILC - Technical Design Report just completed



ILC appears in the LDP Election Manifesto

32　科学技術政策の強力な推進力となる 真の「司令塔」機能の再構築

資源の少ないわが国にとって、今後の社会・経済をさらに発展させるため、企業の研究開発投資が激減する中、新たな成長に向けて国主導で科学技術イノベーションをリードするのが喫緊の課題です。

しかし、年間約3.6兆円にも及ぶ科学技術関係予算については、文部科学省を中心に、経済産業省や厚生労働省等、関係省庁に予算が配分され、各省内で同様な研究が行われている事例も見受けられ、縦割りの弊害が顕著です。また、限られた予算にも関わらず、効果的な配分が行われていないのが現状です。

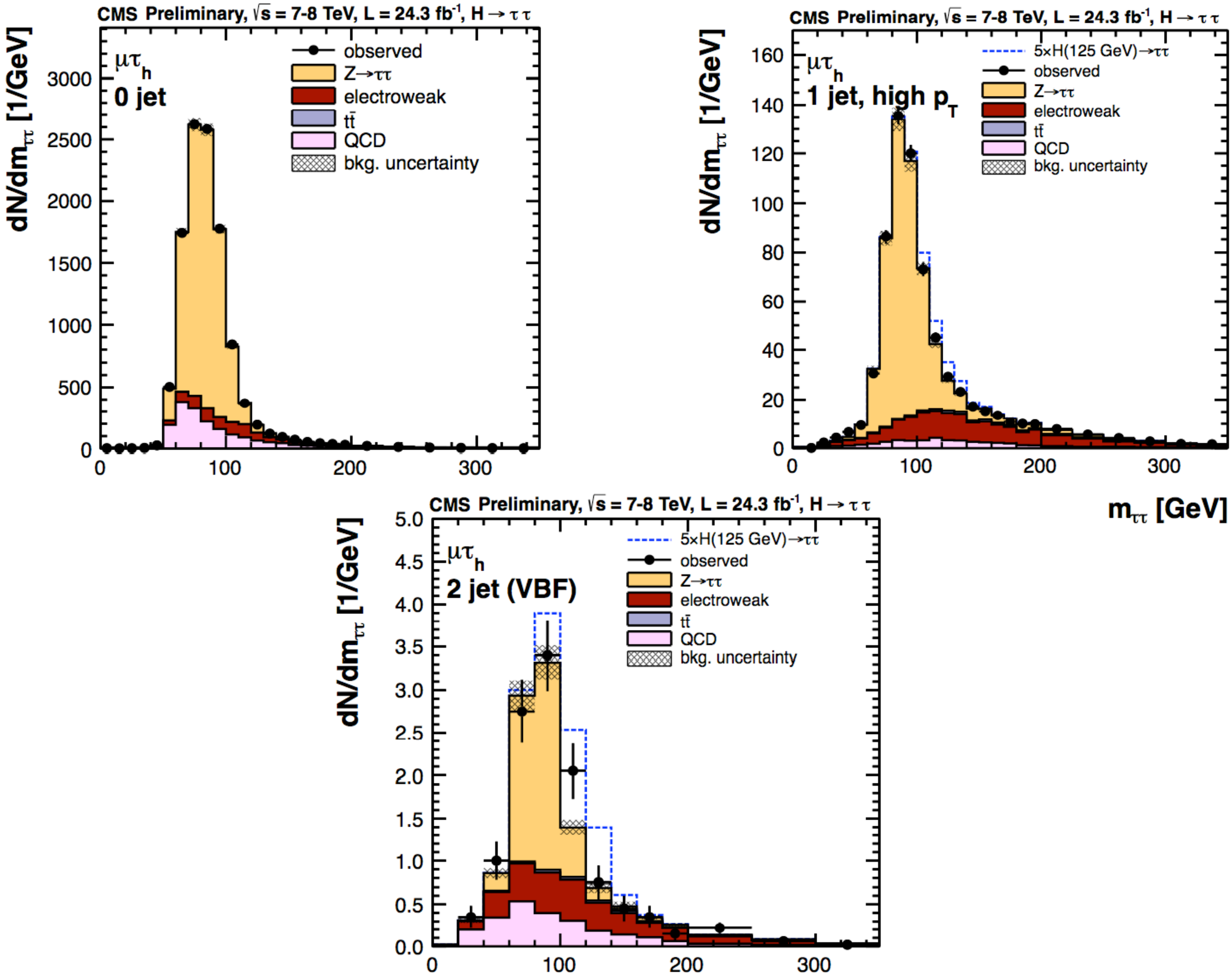
そこで、産業の生命線である科学技術を国家戦略として推進し、「価値の創造拠点」とするべく、総合科学技術会議の「権限」「体制」「予算システム」を抜本的に強化し、真の「司令塔」機能へと再構築します。

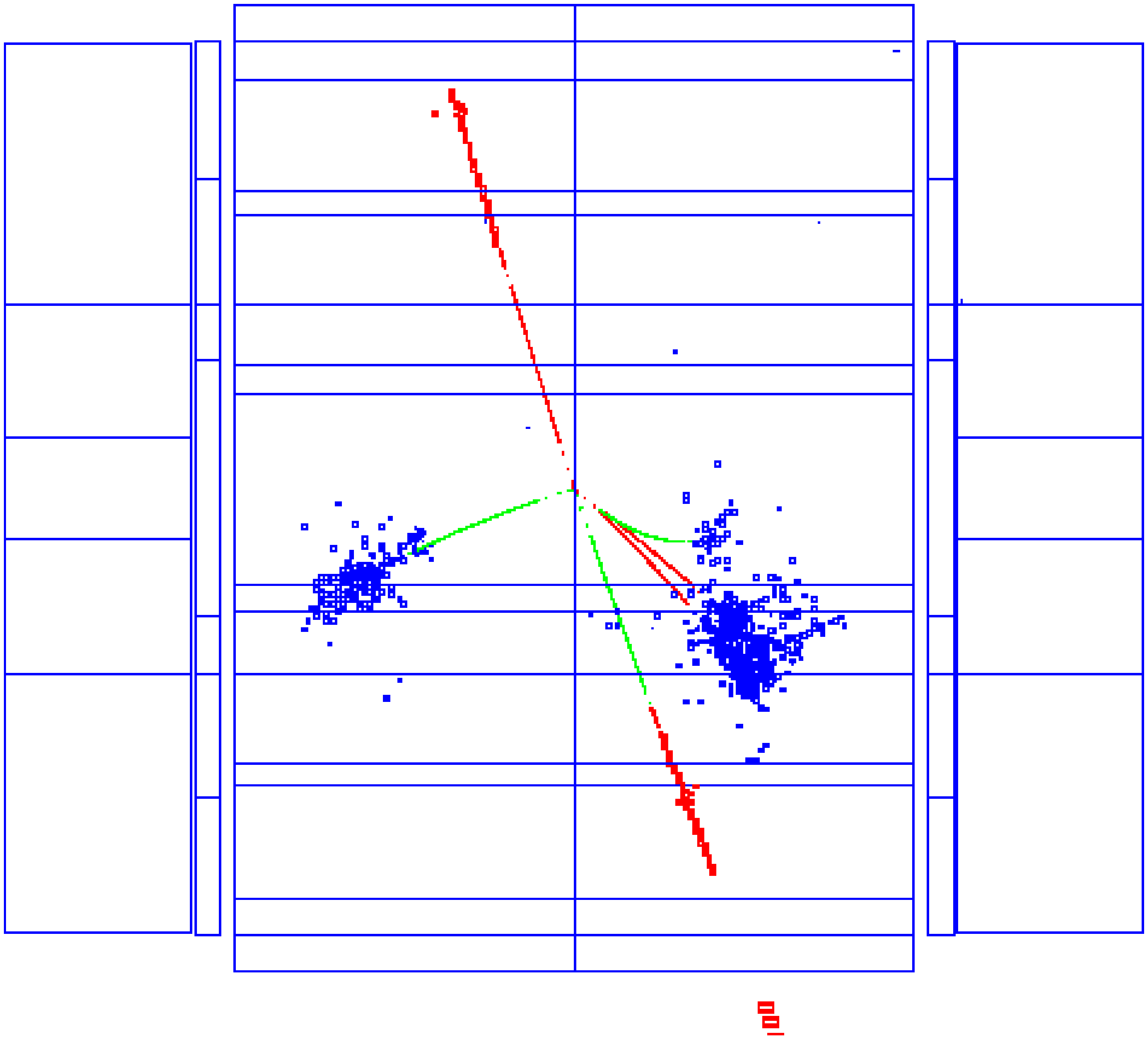
具体的には、各省庁の縦割りを排し、強力な予算配分権限を集中させ、適正な評価を行うことができる人材育成とシステムの構築を行います。例えば、素粒子物理分野の大規模プロジェクトであるILC（国際リニアコライダー※研究所建設）計画等を含む国際科学イノベーション拠点作りに日本が主導的な役割を果たせるなど、再生医療※や創エネ・省エネ・蓄エネ等の重点分野を産学の知を結集した国家戦略として強力に推進します。

A very urgent issue for the leaders of the country is to take the lead in science and technology innovation and aim for new growth in order to develop the future society and economy.

... and make Japan play a leading role in the formation of an international scientific innovation base that includes, for example, the plan for the ILC ...

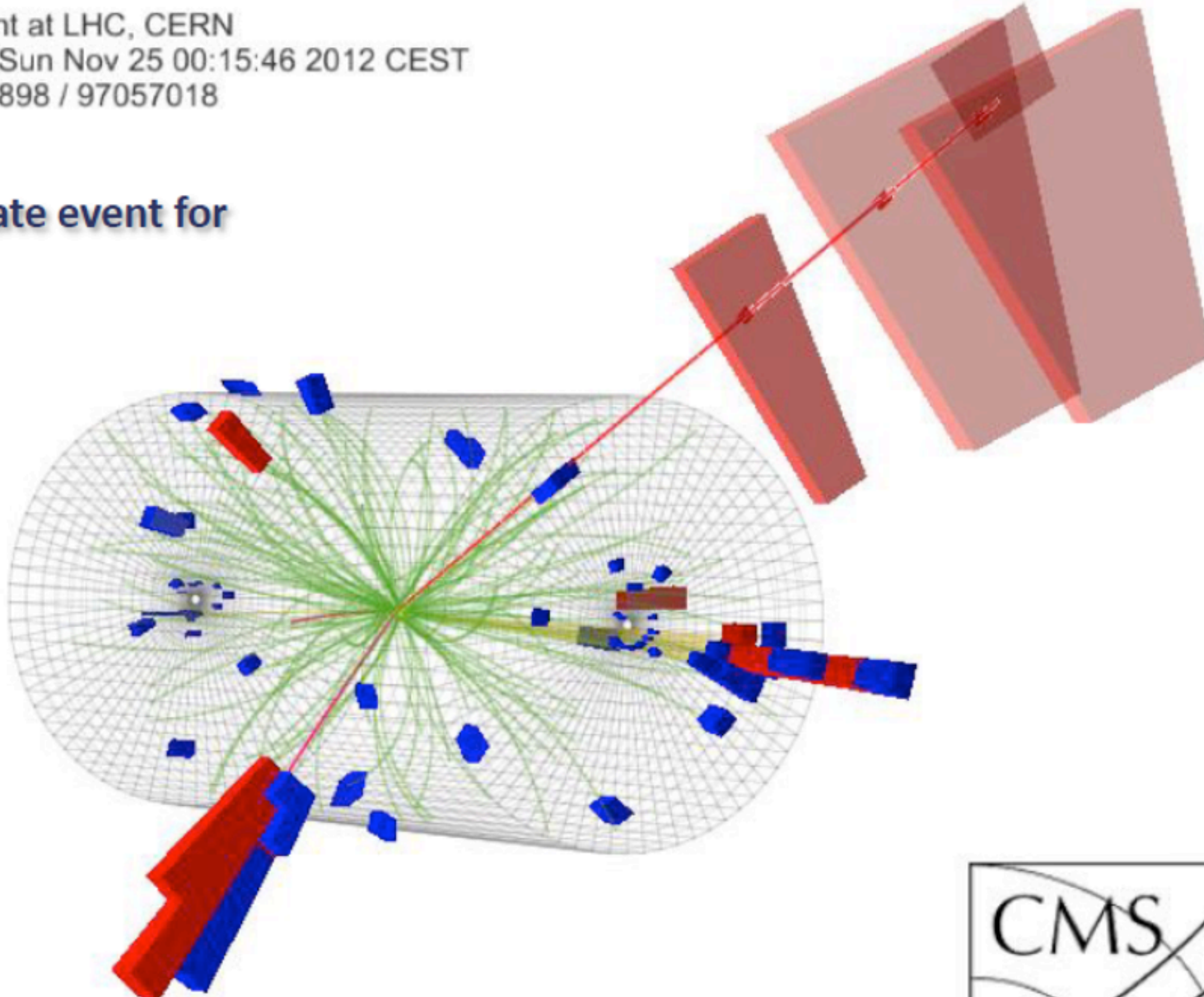
meeting of Lyn Evans and Prime Minister Abe, March 27, 2013


CMS Preliminary, √s = 7-8 TeV, L = 24.3 fb-1, H → τ τ
μτh
0 jet
observed
Z→ττ
electroweak
tt̄
QCD
bkg. uncertainty
dN/dmττ [1/GeV]
0
500
1000
1500
2000
2500
3000
0
100
200
300
CMS Preliminary, √s = 7-8 TeV, L = 24.3 fb-1, H → τ τ
μτh
1 jet, high pT
5×H(125 GeV)→ττ
observed
Z→ττ
electroweak
tt̄
QCD
bkg. uncertainty
dN/dmττ [1/GeV]
0
20
40
60
80
100
120
140
160
0
100
200
300
mττ [GeV]
CMS Preliminary, √s = 7-8 TeV, L = 24.3 fb-1, H → τ τ
μτh
2 jet (VBF)
5×H(125 GeV)→ττ
observed
Z→ττ
electroweak
tt̄
QCD
bkg. uncertainty
dN/dmττ [1/GeV]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0
100
200
300



CMS Experiment at LHC, CERN
Data recorded: Sun Nov 25 00:15:46 2012 CEST
Run/Event: 207898 / 97057018

VBF candidate event for $H \to \tau\tau \to \mu\tau_h$



CMS

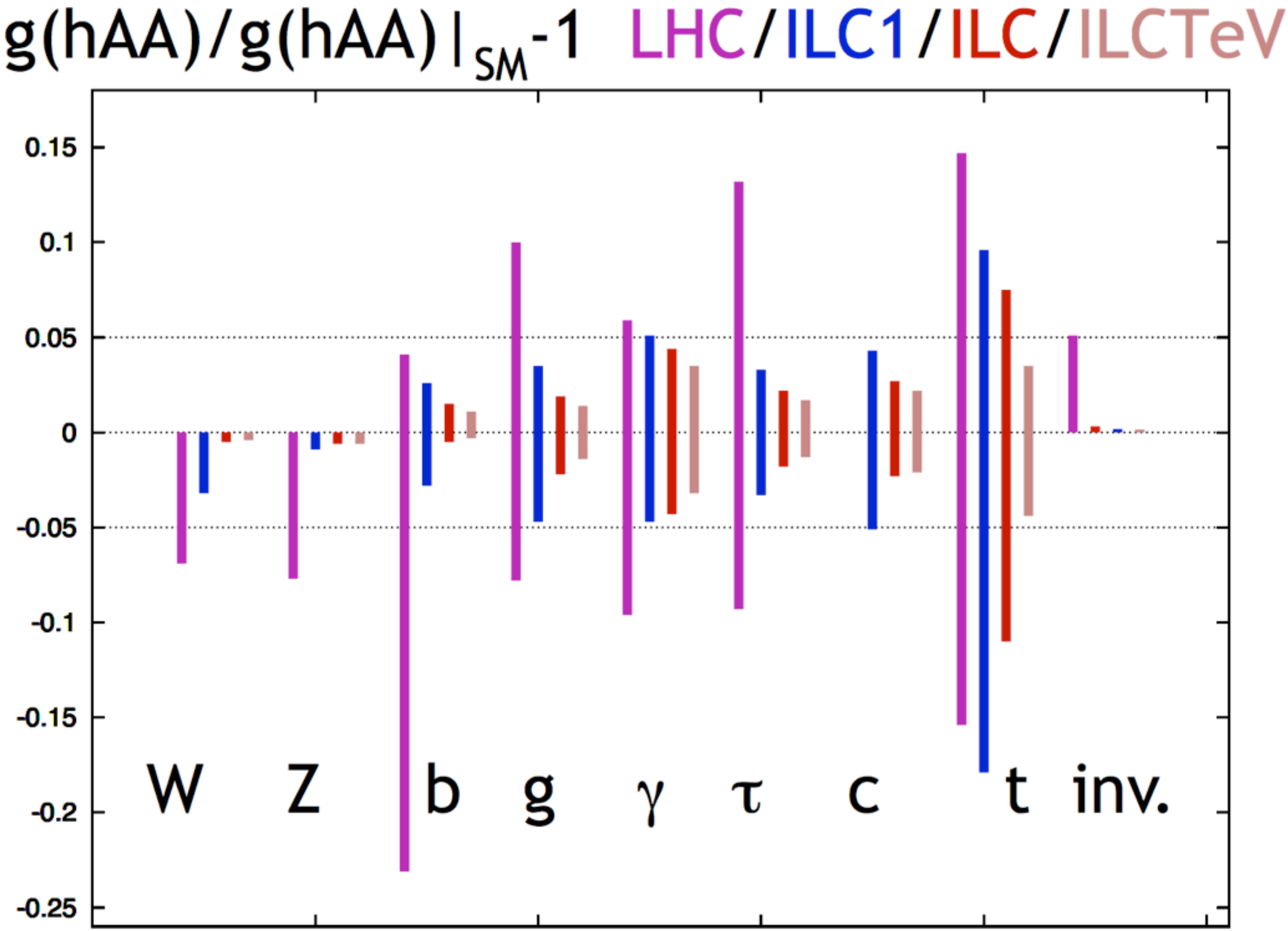
It is important to realize that a comprehensive Higgs program requires running at multiple energies. The ILC will provide this:

250 GeV: tagged Higgs, branching ratios

350-500 GeV: W fusion production, absolute normalization of the couplings

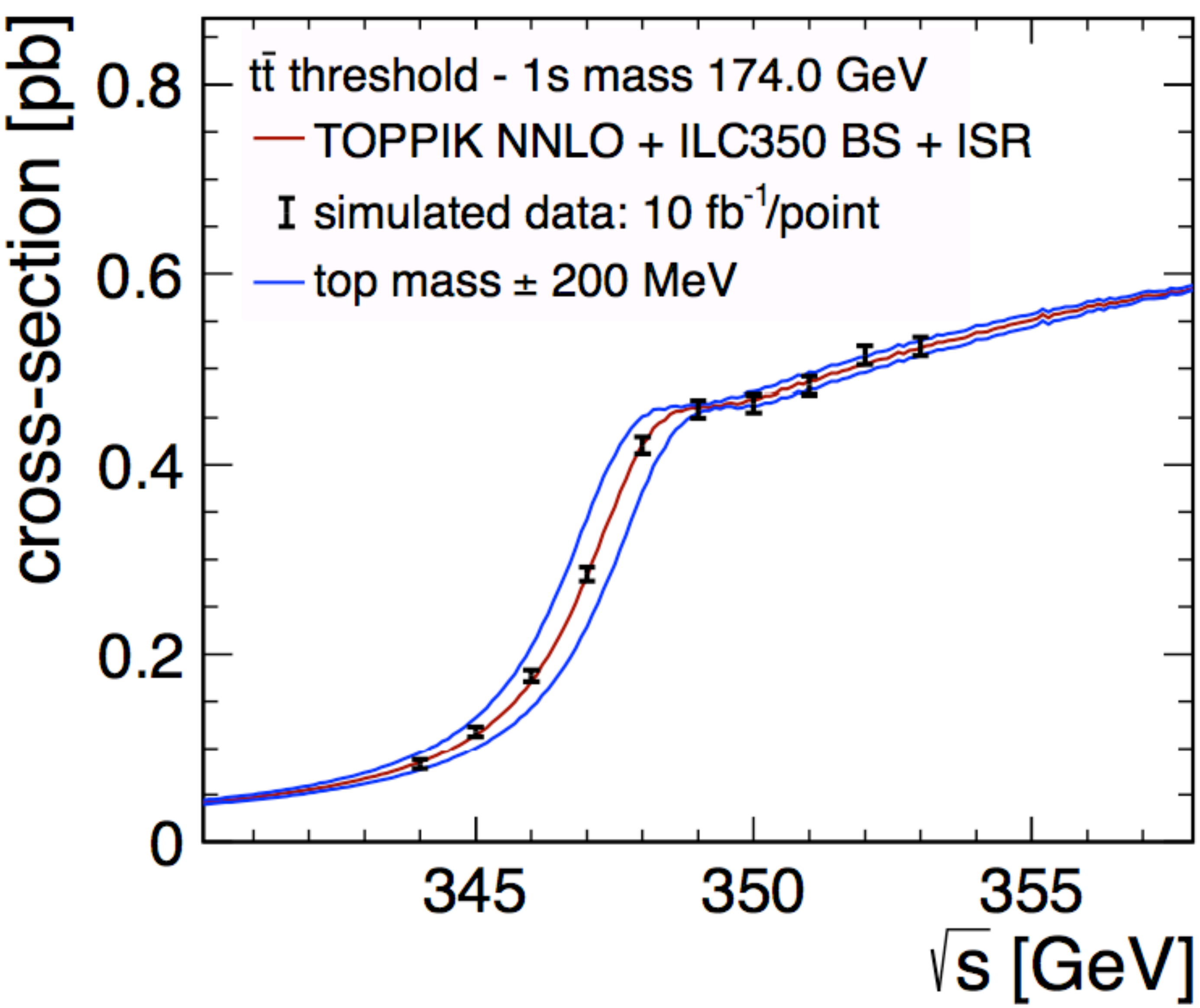
> 700 GeV: Higgs coupling to top (4%)

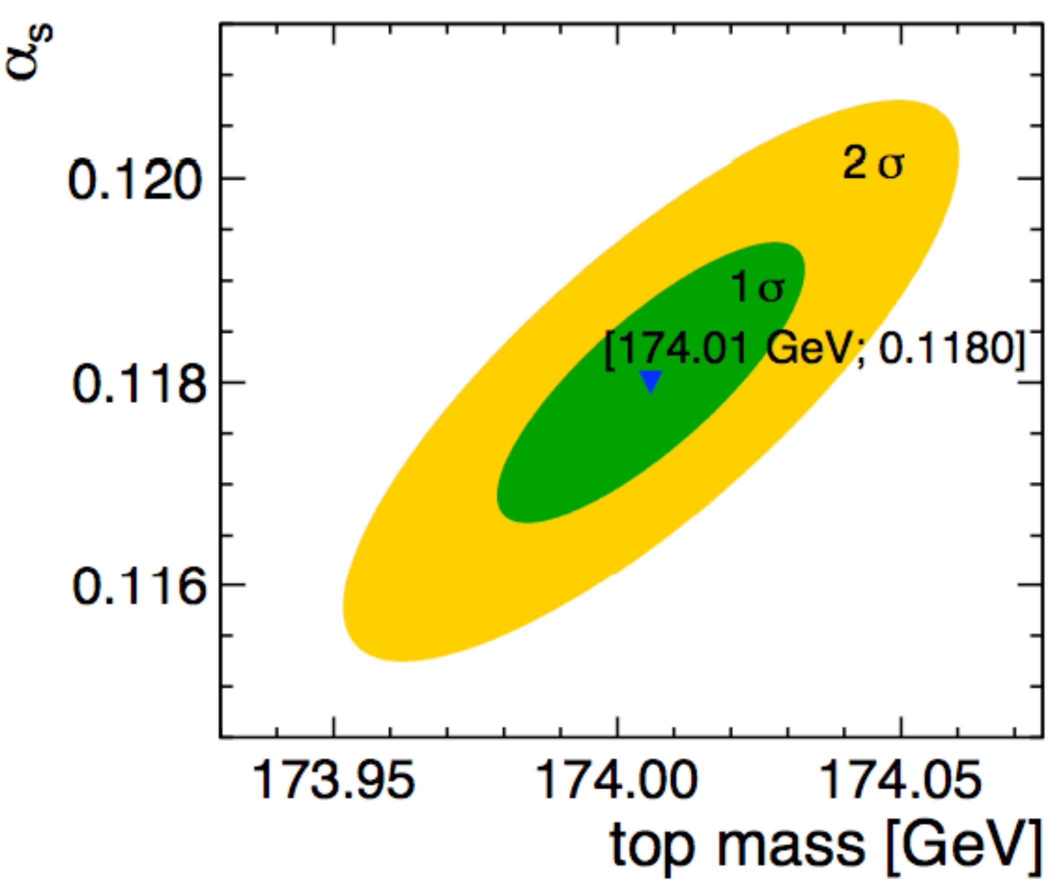
> 700 GeV: Higgs self-coupling (16%; maybe reducible to 10%)



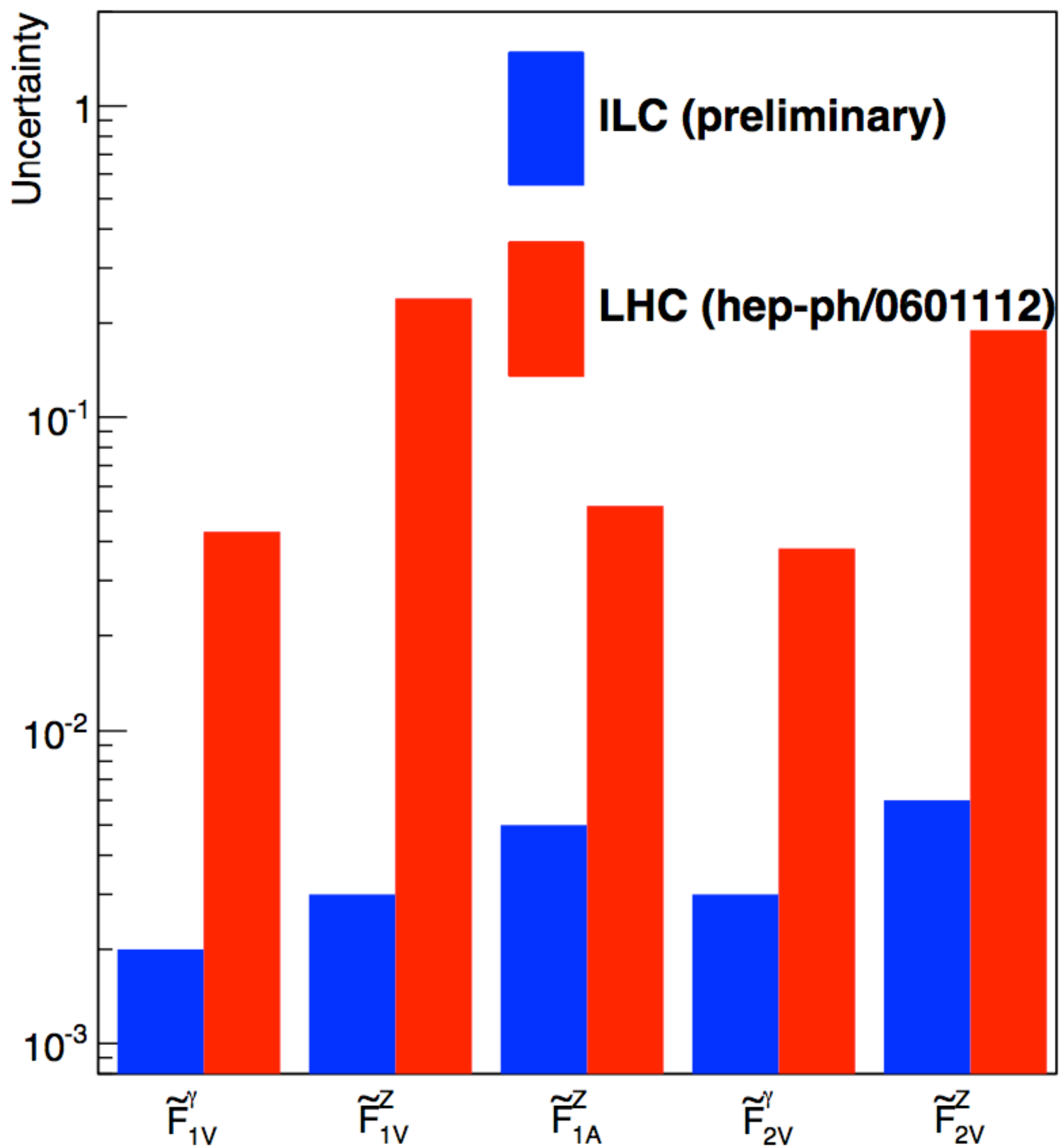
g(hAA)/g(hAA)|SM-1 LHC/ILC1/ILC/ILCTeV
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
W
Z
b
g
γ
τ
c
t
inv.

top quark: precision mass measurement and precision electroweak coupling measurement





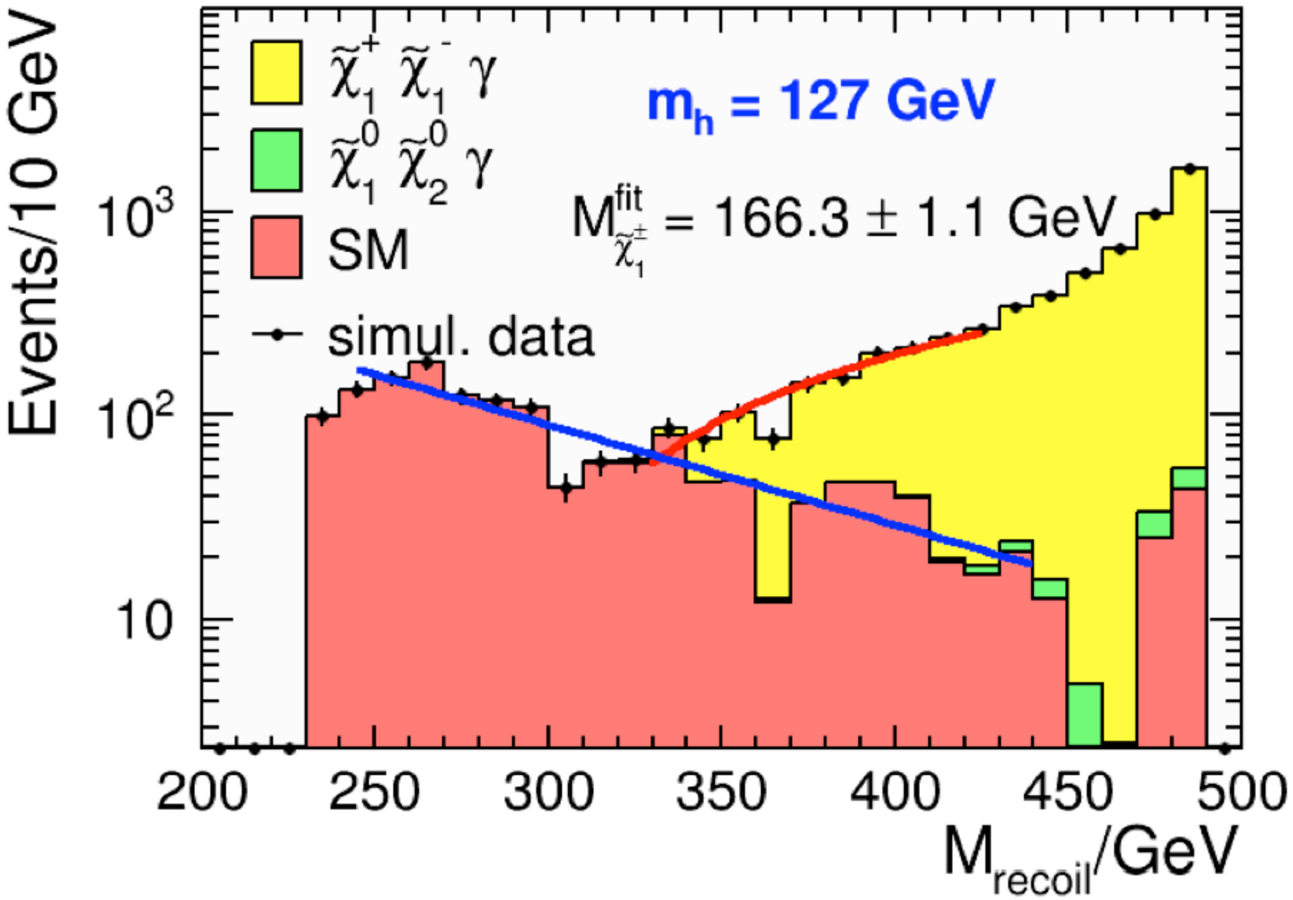
Seidel, Simon, and Tesar

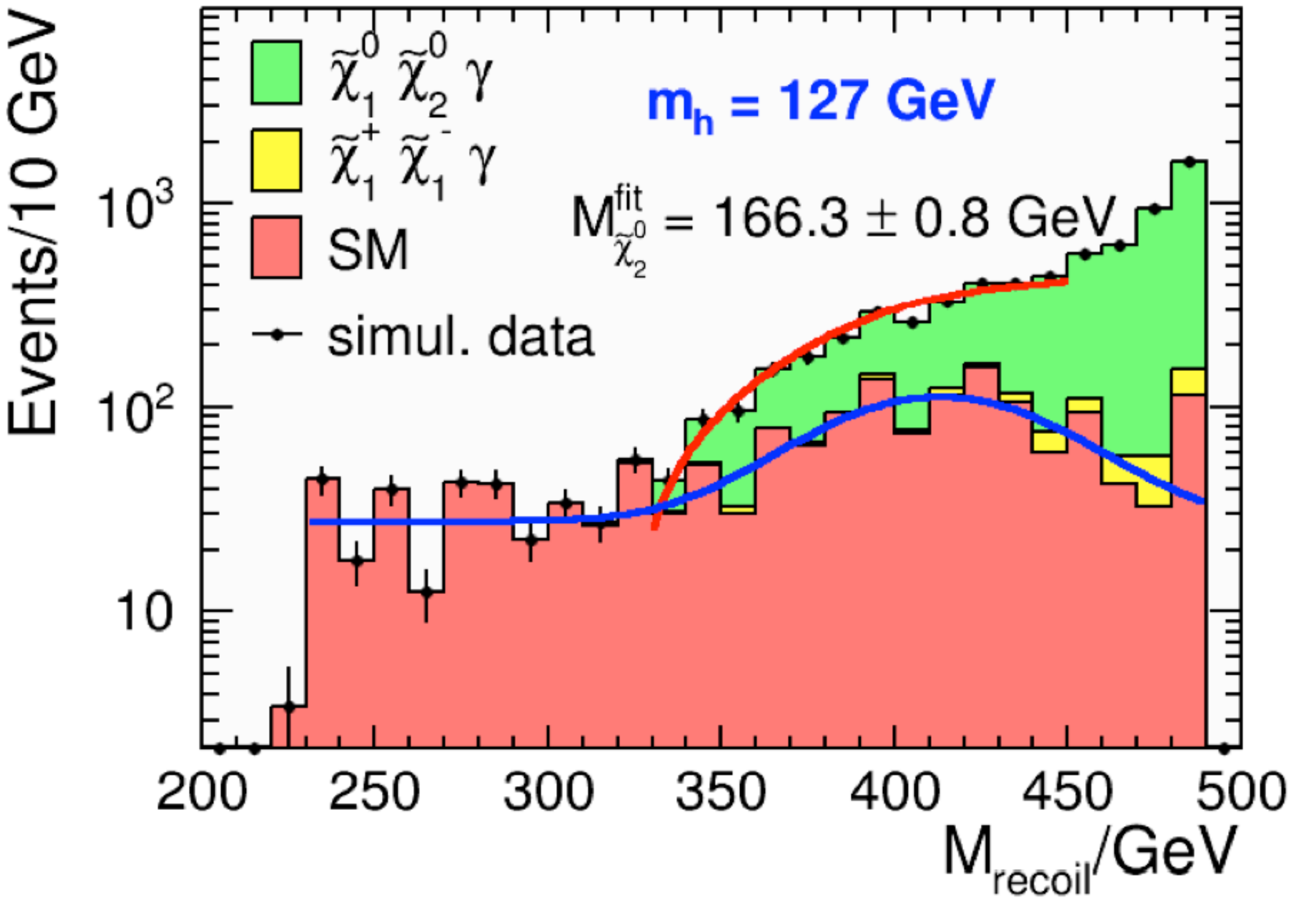


Uncertainty
1
10^-1
10^-2
10^-3
ILC (preliminary)
LHC (hep-ph/0601112)
$\tilde{F}^{\gamma}_{1V}$
$\tilde{F}^{Z}_{1V}$
$\tilde{F}^{Z}_{1A}$
$\tilde{F}^{\gamma}_{2V}$
$\tilde{F}^{Z}_{2V}$

In the natural-SUSY scenario described earlier in this lecture, the almost degenerate Higgsinos can be discovered and their properties measured at ILC.

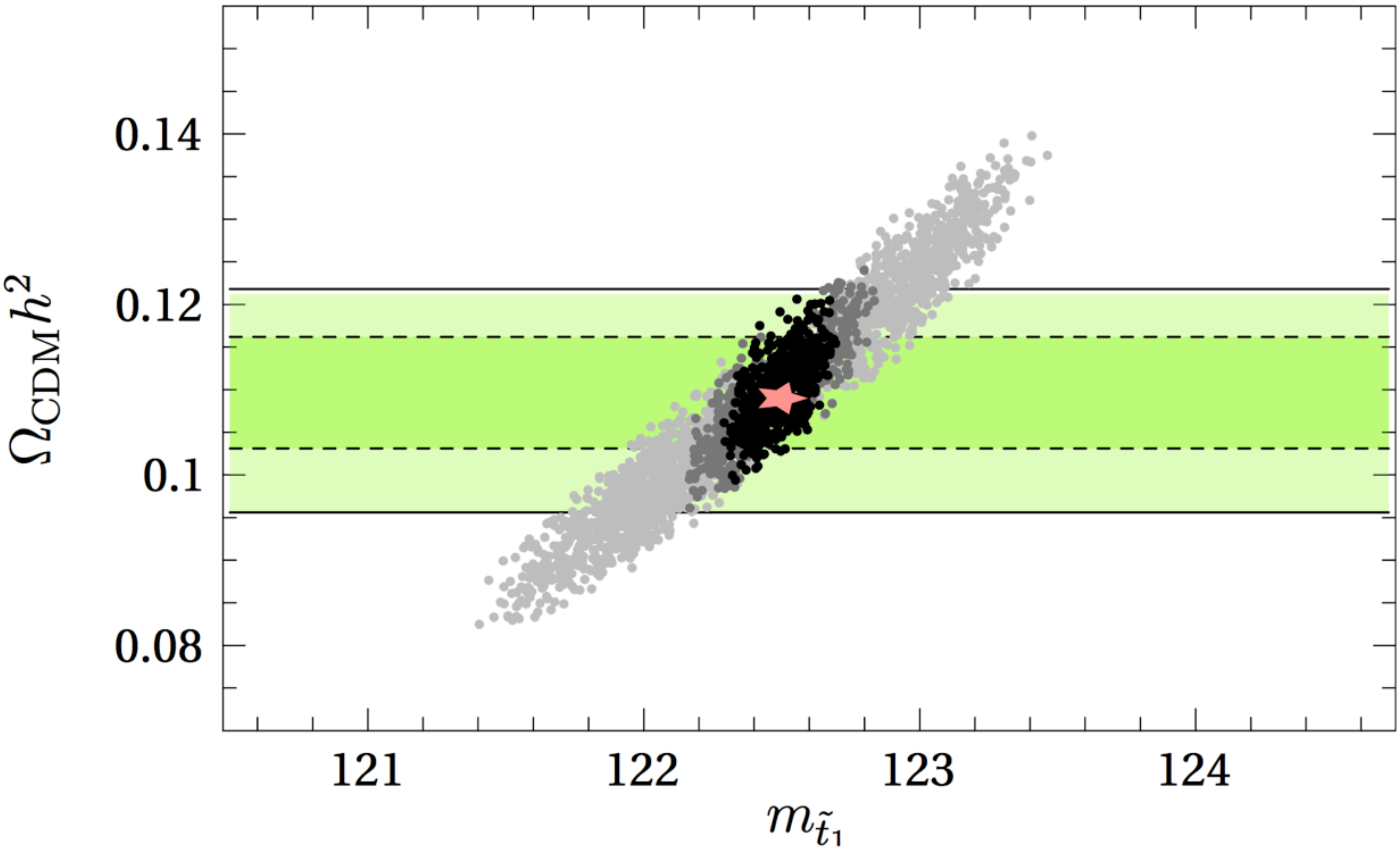
In fact, ILC will be a Higgsino factory.





Sert

example of dark matter relic density prediction in a "stop coannihilation" scenario



Many other facilities are being considered for the farther future.

I have time to discuss these only briefly:

CLIC -- "Compact Linear Collider" at CERN

extends lepton collider searches and Higgs interaction measurements to higher energy

TLEP -- e+e- synchrotron in a 100 km tunnel.

use the methods of super-B factor design to produce a 250 GeV event sample with multi-ab-1 integrated luminosity for precision Higgs studies and precision electroweak

(but limited to 350 GeV)

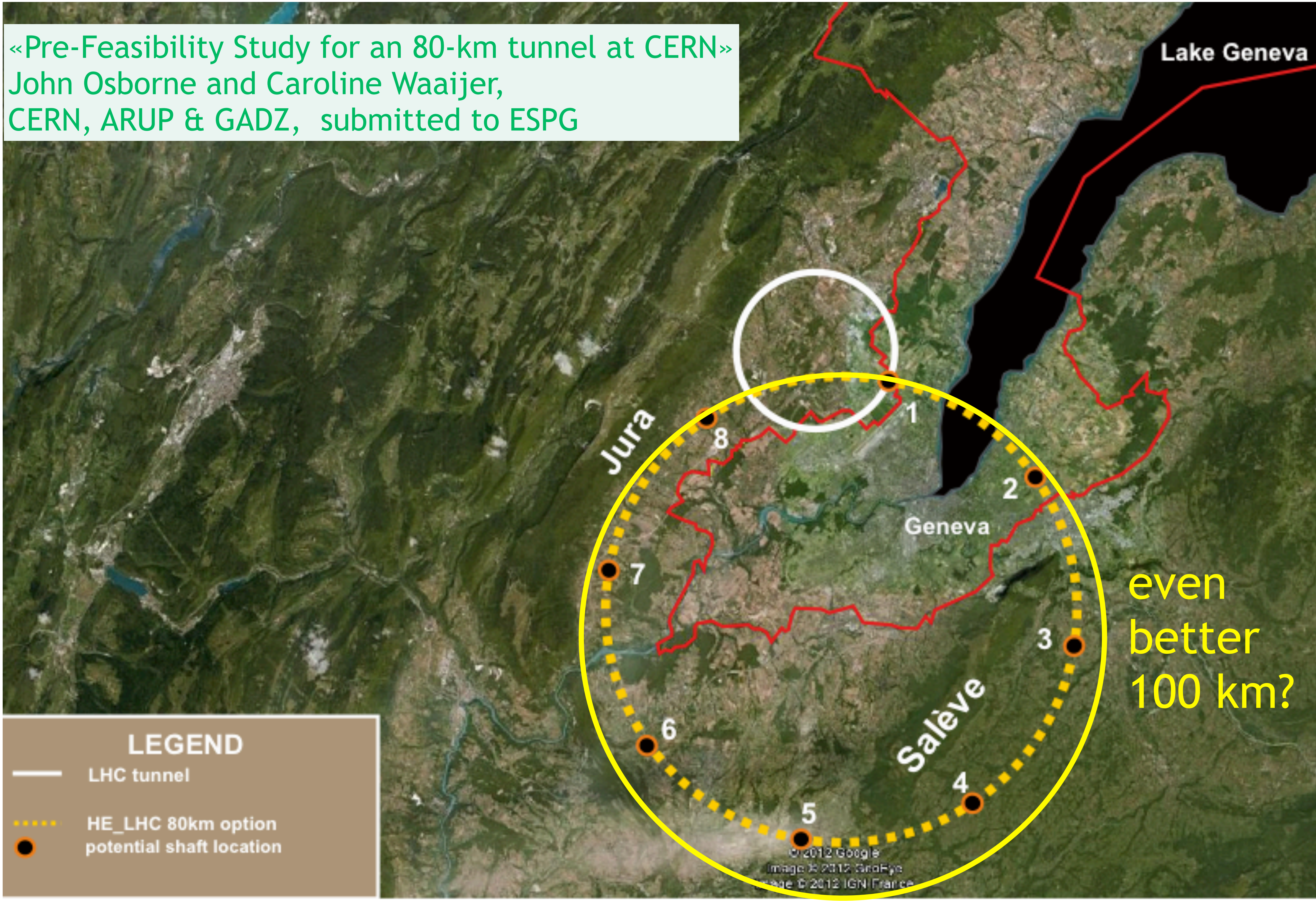
Muon Collider -- muon synchrotron at Fermilab

exploit $\mu^+\mu^- \to h$; eventually, multi-TeV lepton collisions

VLHC or VELHC -- 100 TeV pp collisions

searches for the heaviest particles of the TeV new particle spectrum

«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG



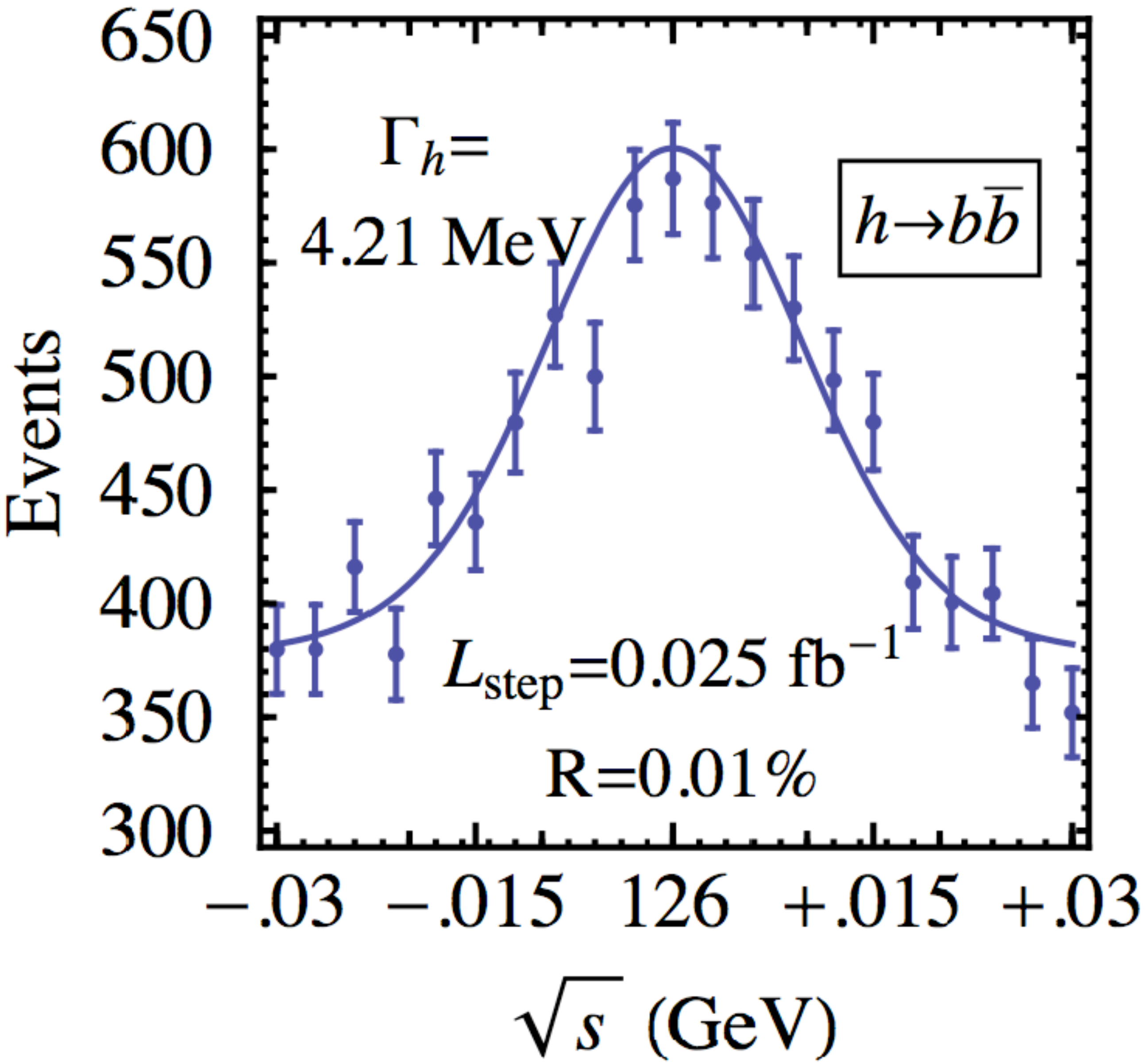
even better 100 km?

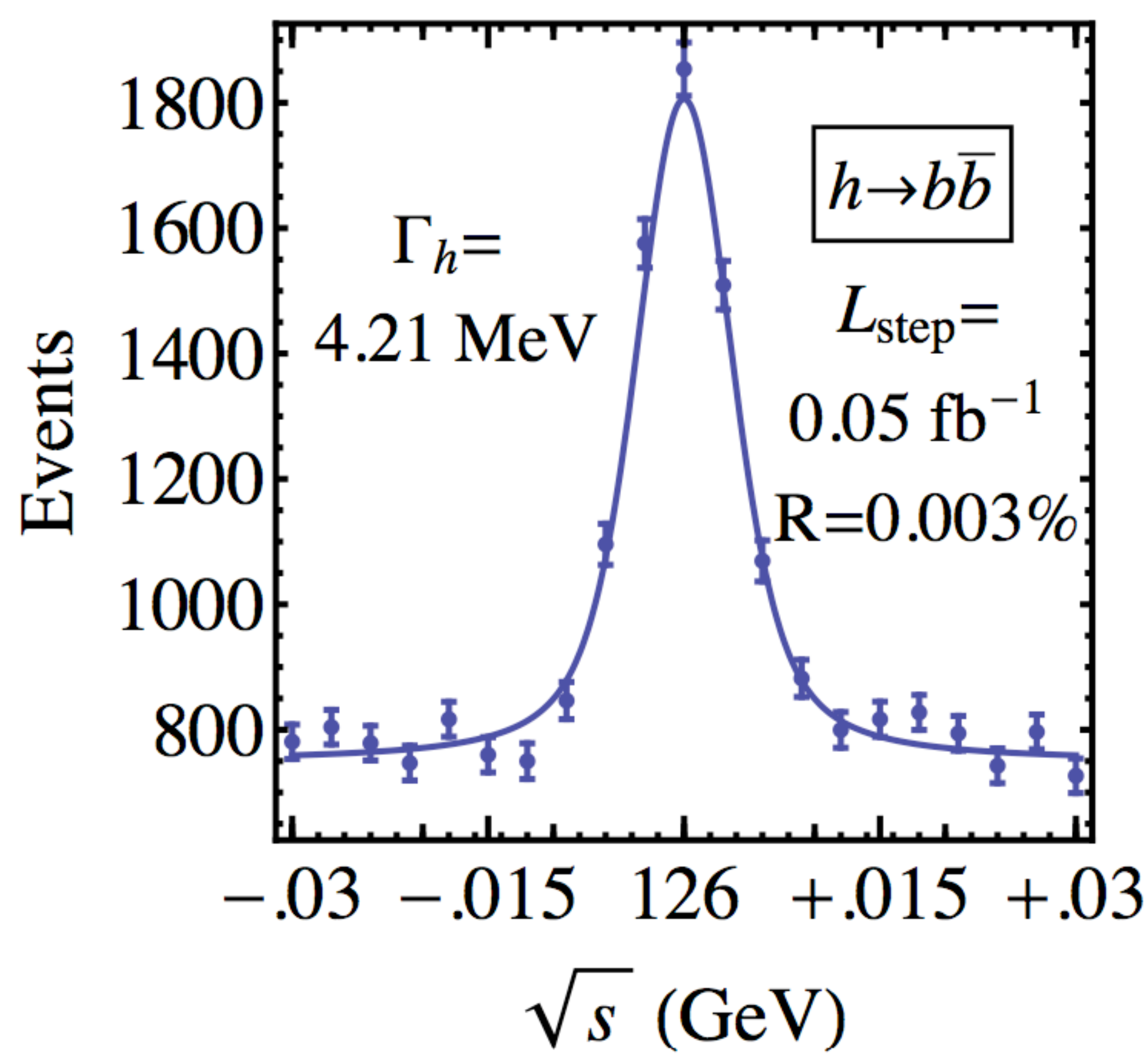
TLEP Higgs coupling predictions (Bachtis):

Coupling	g_Z	g_W	g_b	g_c	g_g	g_τ	g_μ	g_γ	BR_{exo}
LEP-240	0.16%	0.85%	0.88%	1.0%	1.1%	0.94%	6.4%	1.7%	<0.48%
LEP-350	0.15%	0.19%	0.42%	0.71%	0.80%	0.54%	6.2%	1.5%	<0.45%
ILC-350	0.9%	0.5%	2.4%	3.8%	4.4%	2.9%	45%	14.5%	<2.9%

Note: direct searches with tagged Higgs give < 0.1% here.
All couplings should improve accordingly.

muon collider at the Higgs resonance:





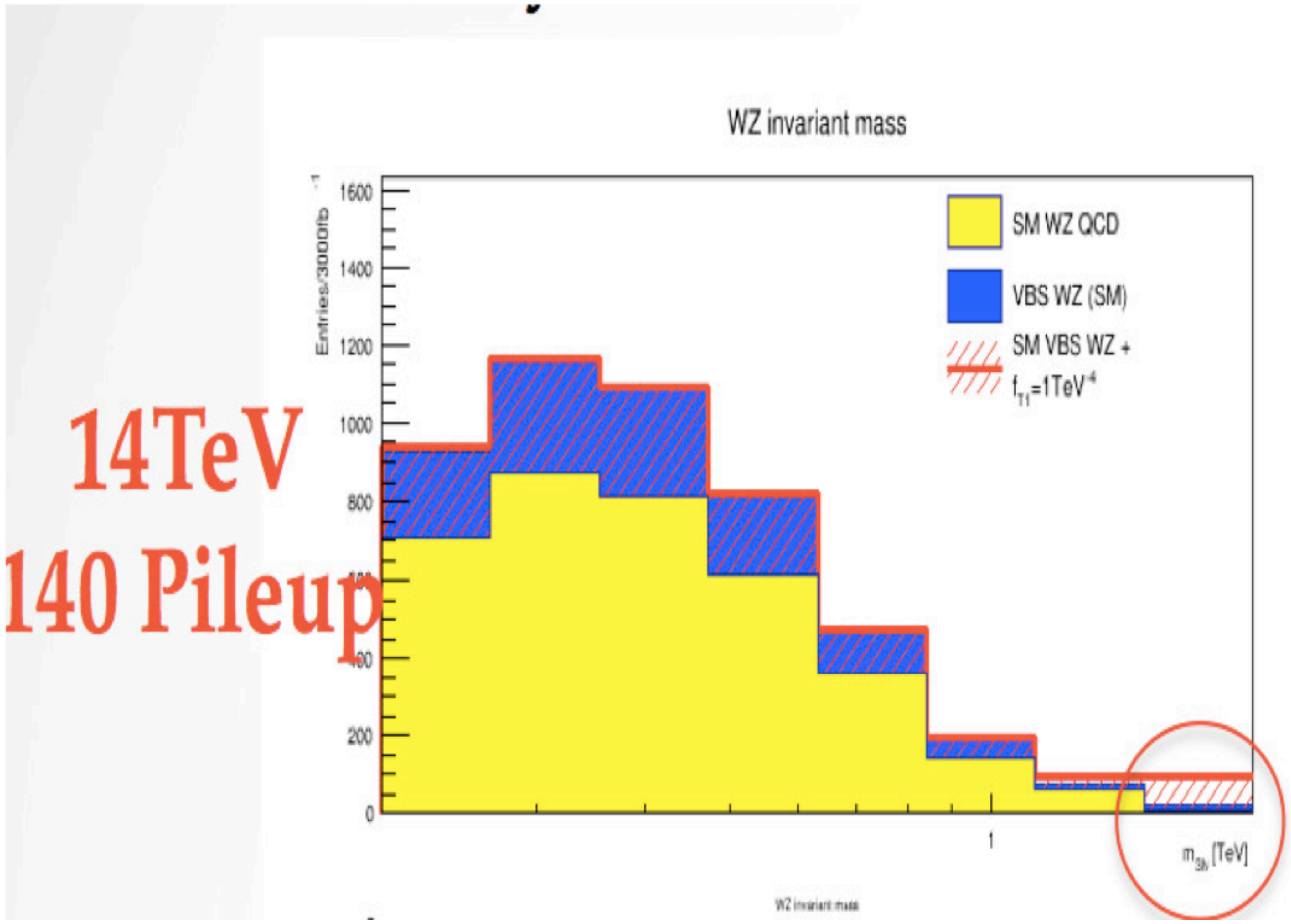
Han and Liu

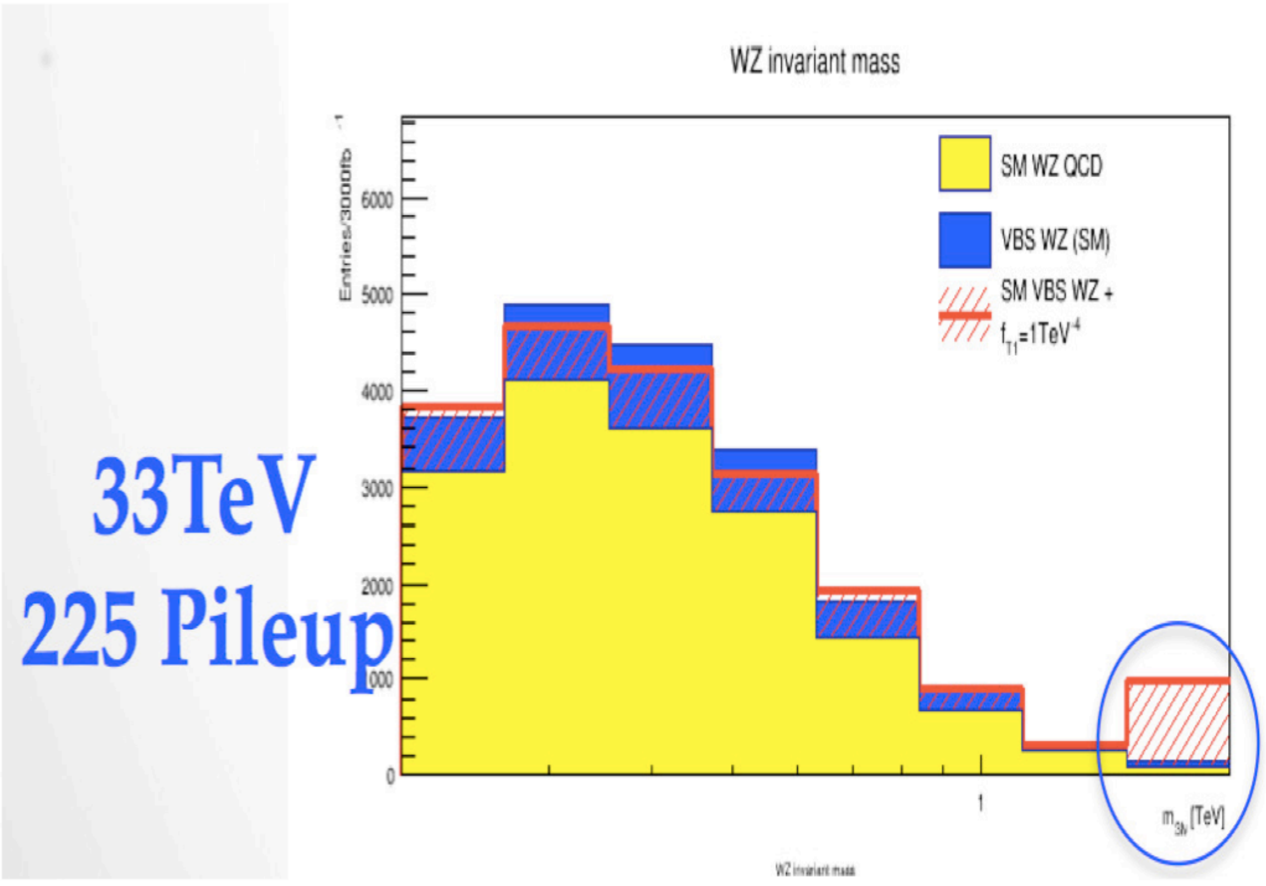
requires muon cooling by 10^6; achieved so far: 1.1

$\Gamma_h = 4.21$ MeV	L_{step} (fb^{-1})	$\delta\Gamma_h$ (MeV)	δB	δm_h (MeV)
$R = 0.01\%$	0.005	0.73	6.5%	0.25
	0.025	**0.35**	**3.0%**	**0.12**
	0.2	0.17	1.1%	0.06
$R = 0.003\%$	0.01	0.30	4.4%	0.12
	0.05	**0.15**	**2.0%**	**0.06**
	0.2	0.08	1.0%	0.03

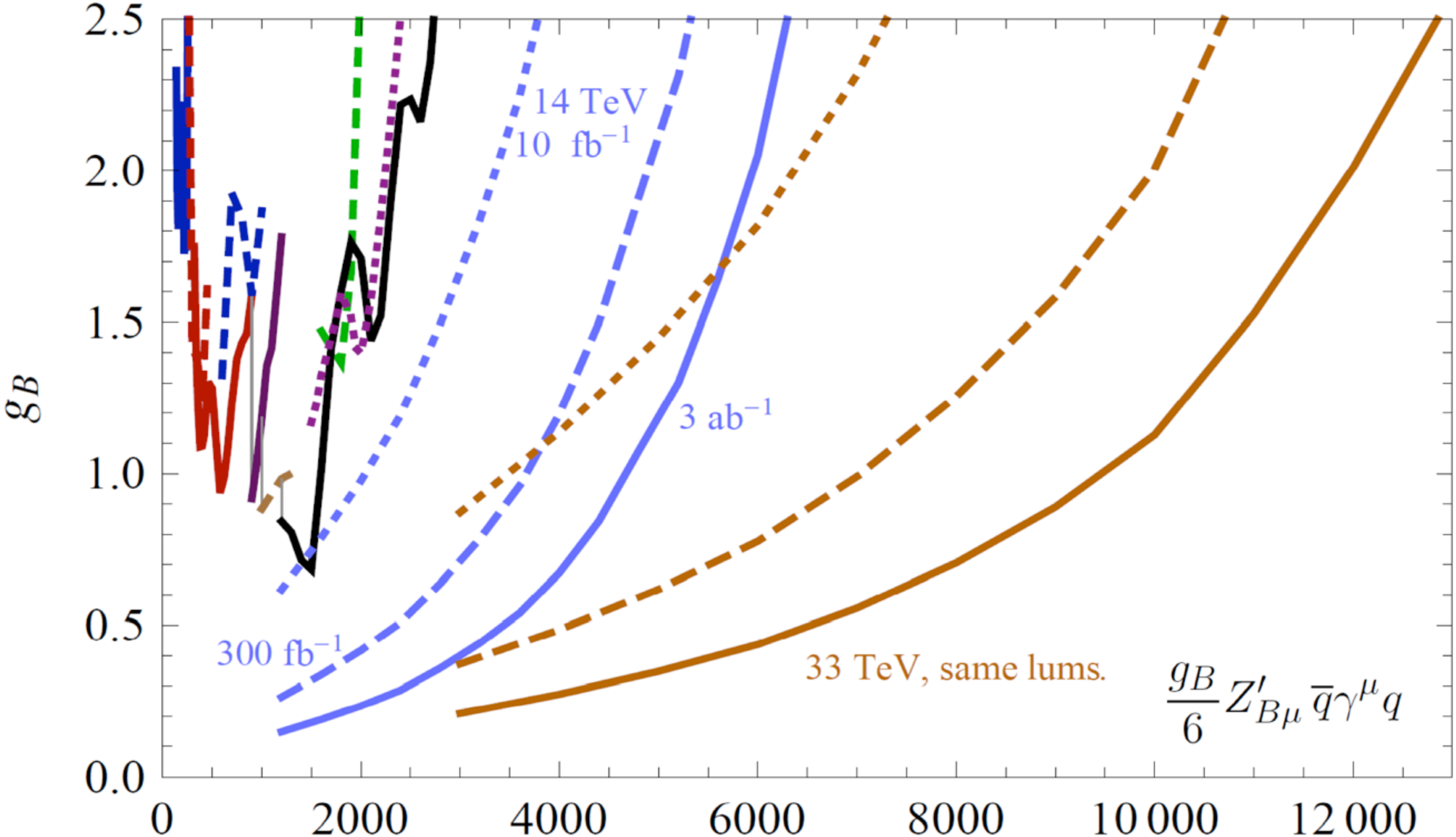
Han and Liu

HE-LHE study of WZ scattering





sensitivity to a new gauge boson



Yu

In the first lecture of this series, I told you to expect a rich new particle spectrum at the TeV mass scale.

Now you see that many tools are potentially available to discover these particles at colliders and explore their properties directly.

It is our job to bring these experiments to reality.