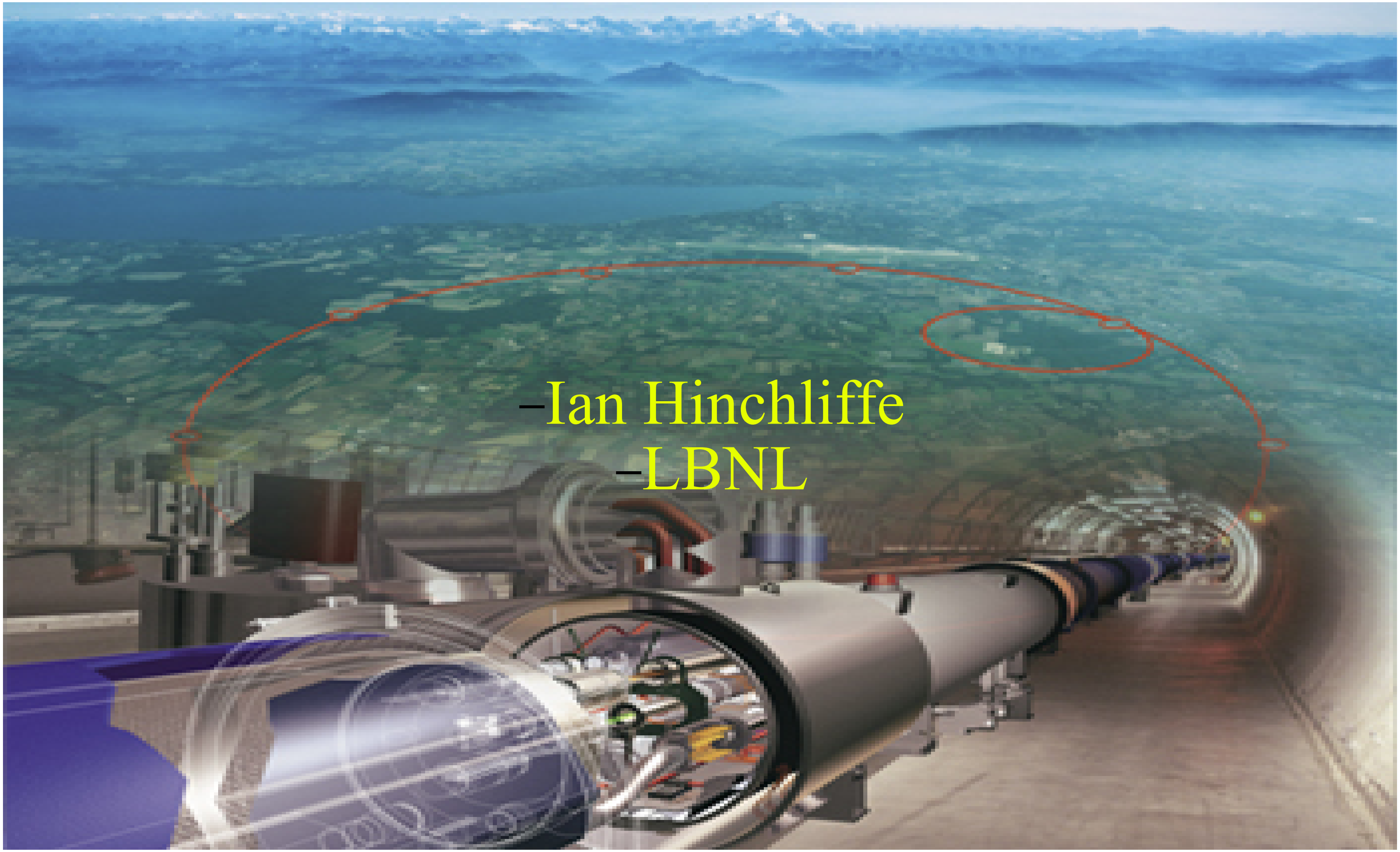
LHC and its Physics



Outline

- The Frontier energy: the long wait is over
- LHC and US program
- From 2008 to 2013 (one pb^{-1} to 100 fb^{-1})
  - I would need hrs to do justice to the program
  - Some examples of physics we will do
- Upgrades to 10^{35}
  - Depends upon what we will find: but cannot wait to get started given needed R&D and construction time
  - In any physics scenario, the upgrade will yield new important results

The Frontier energy

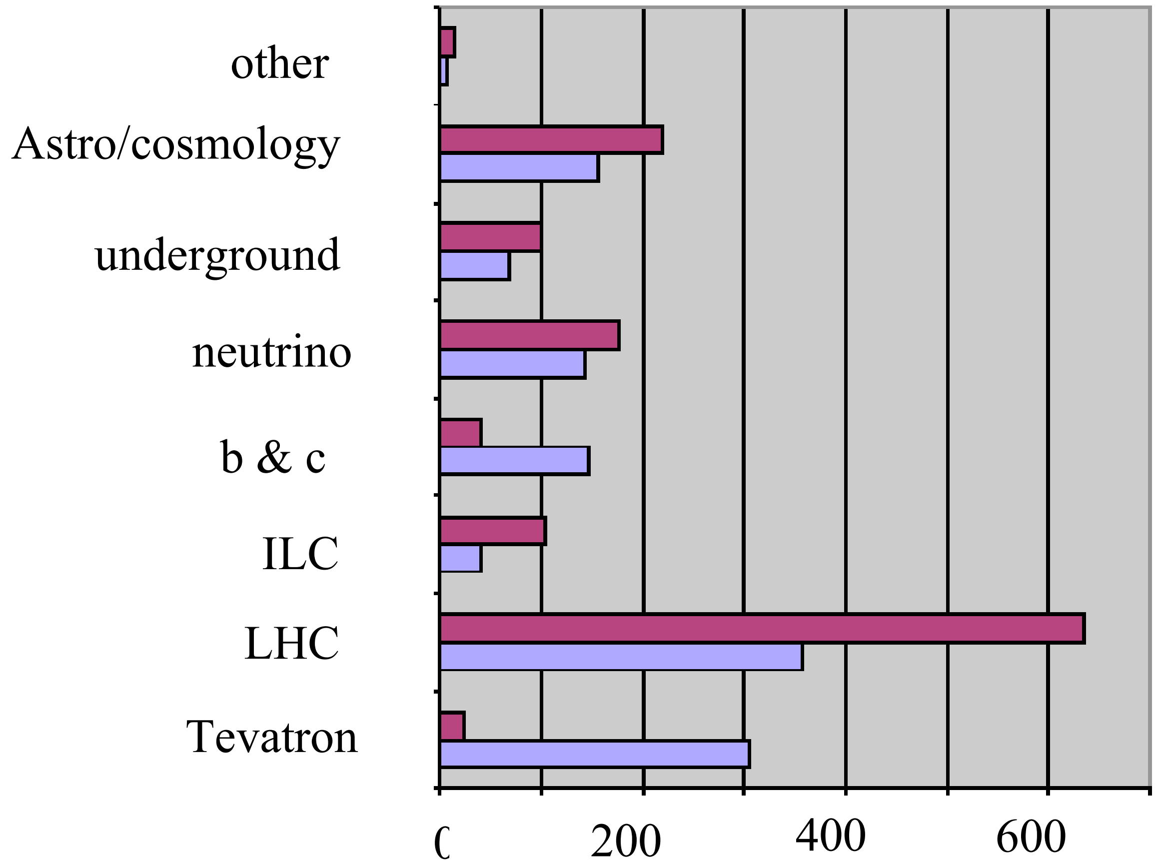
- Later this year LHC will become the frontier energy machine and will remain so for more than a decade.
- At last we should get some answers to these “old” questions
  - Where does mass come from?
  - Does the d***d Higgs exist?
  - Does low energy Supersymmetry exist: does it explain dark matter?
  - Are there extra dimensions?
  - Are quarks composite?
- The LHC is the largest step in effective energy since I was in high school.
  - Its results will shape the future of HEP

Physics program: enormous scope

- QCD: jets and hadronic properties
- Electroweak
  - W/Z production properties
  - Higgs discovery
- New Physics quests
  - SUSY (Dark matter?)
  - Extra dimensions
- Flavor physics
  - Top factory (~ 1Hz at 10^{33})
  - Rare B decays, Non standard CP violation in B sector
  - Flavor non conservation in tau decays
- Heavy Ions (LHC will run PbPb collisions)
- These are really facilities not experiments: expect hundreds of publications per year

Rich physics program
Many years needed
All available luminosity will be exploited

The LHC and the US research program



University groups only.

Half of US community in 2012

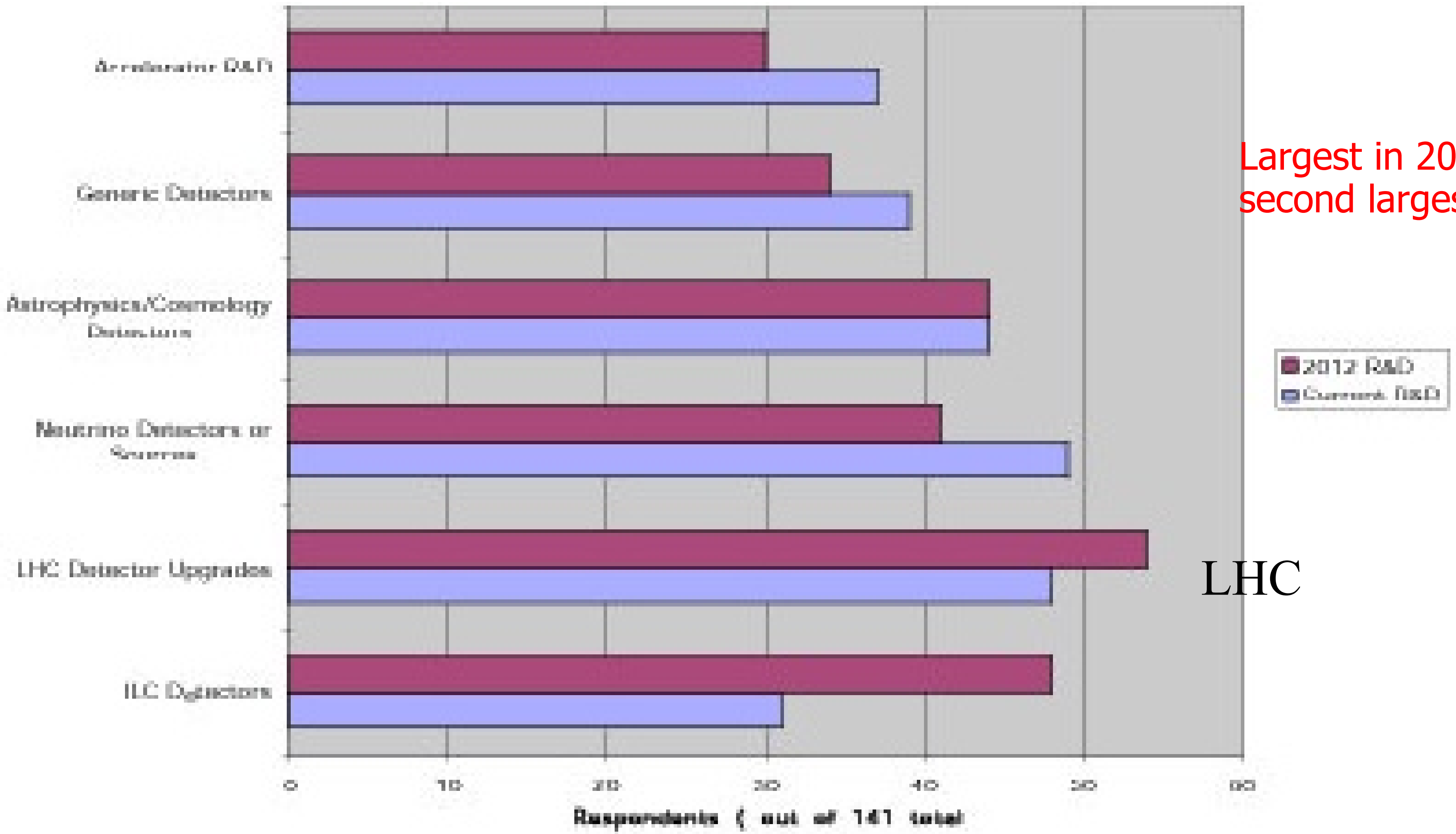
Research effort:

Now

2012

US research effort from HEPAP subpanel on University grants

The LHC upgrades: already a major activity



Largest in 2012!
second largest now!

LHC

US detector R&D from HEPAP subpanel on University grants

The LHC evolution

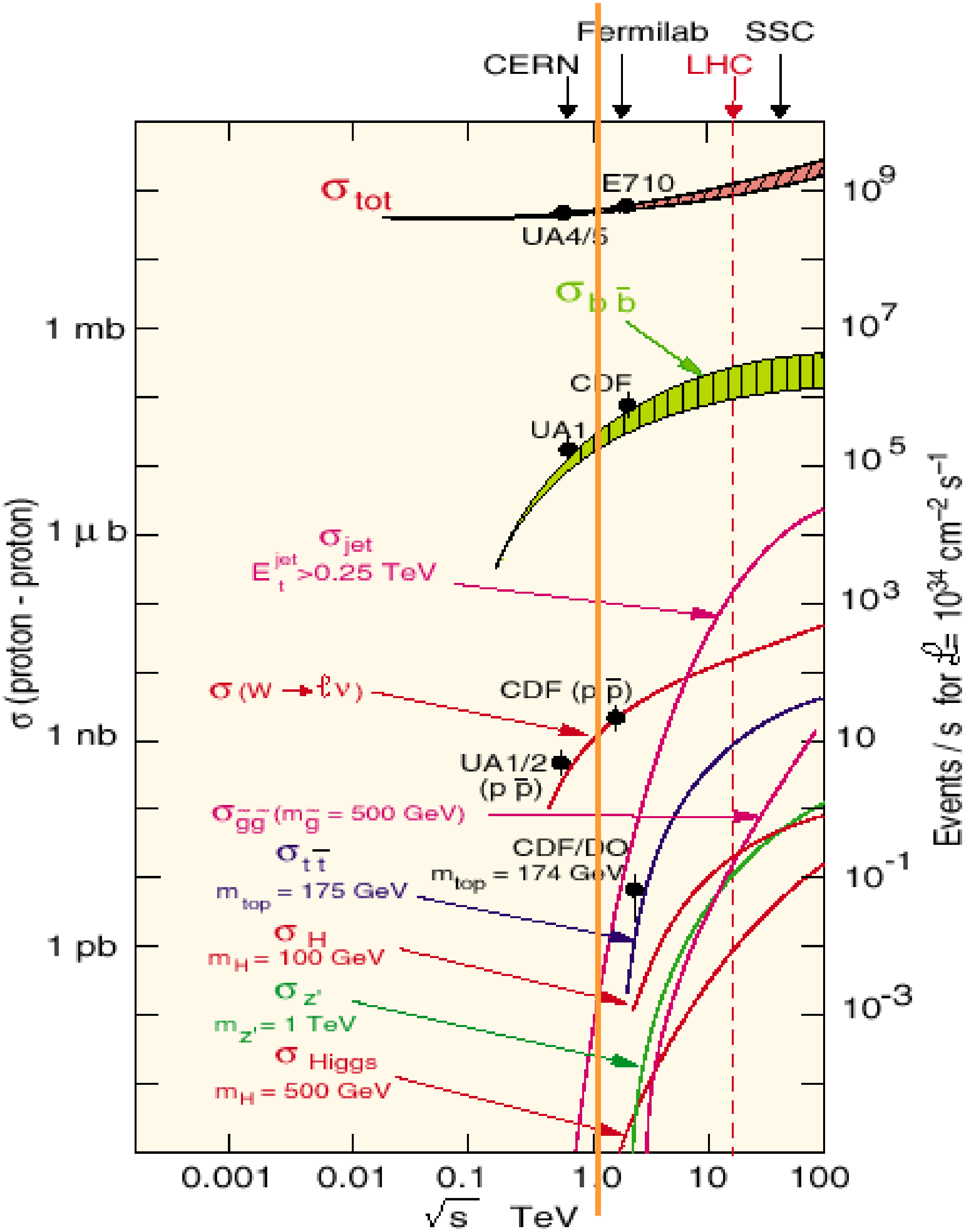
- Starts soon!
  - Luminosity will reach 10^{34} after some years operation
- CERN plan for LHC upgrades (Heuer P5@slac)
  - Phase I "reliable operation at $2x10^{34}$" ~2013
  - Phase II 10^{35} ~2016: Decision in 2011
- LHC detectors must adapt to
  - Long term running
  - Upgrades to luminosity
  - Physics discoveries
- Long term program implies long term planning
  - Tevatron started in 1987
    - CDF has had 4 tracking, one muon, one calorimeter and continual TDAQ upgrades
    - D0 upgrade was approved by FNAL-PAC before D0 took data

Physics roadmap: 2007 to 2013?

- 2008/9: QCD, jets, min bias...
- 2008/2009 Standard Model W, Z, rates, production properties
- 2008/9/10 Bphysics (no time to show examples)
- 2009/2010 Top studies: decay modes. Spin, production, mass
- 2009/2010 SUSY discovery: measurements!!
- 2009/10/11 Higgs, discovery mass and properties
- Expect several hundred papers per year

Physics examples follow

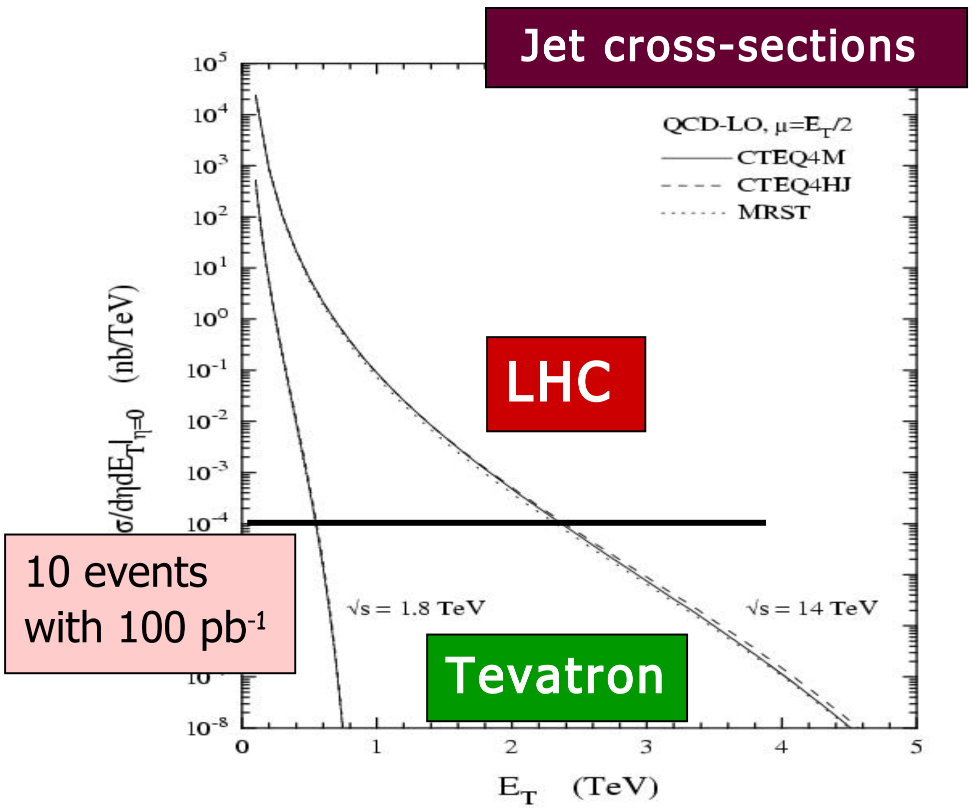
Overview of rates



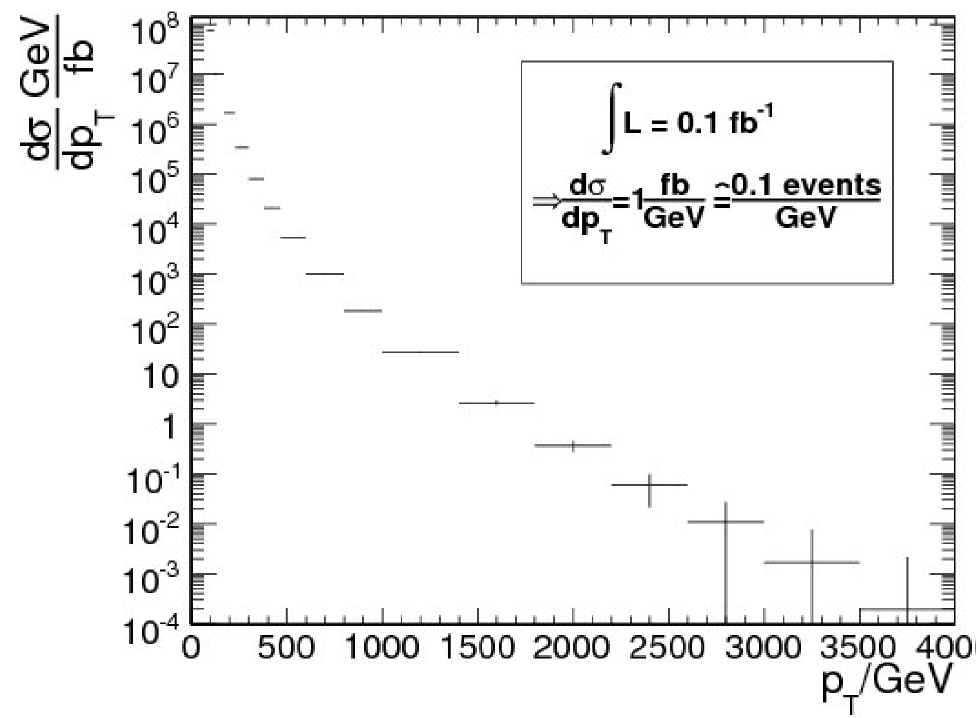
- Very large dynamic range
- 100mb total rate to ~10pb for SUSY, 1 pb for Higgs
- Major challenge for trigger
  - Reduce rate while not losing physics

Jets (2008+)

New physics may show up at high pt. Needs fully calibrated calorimeter



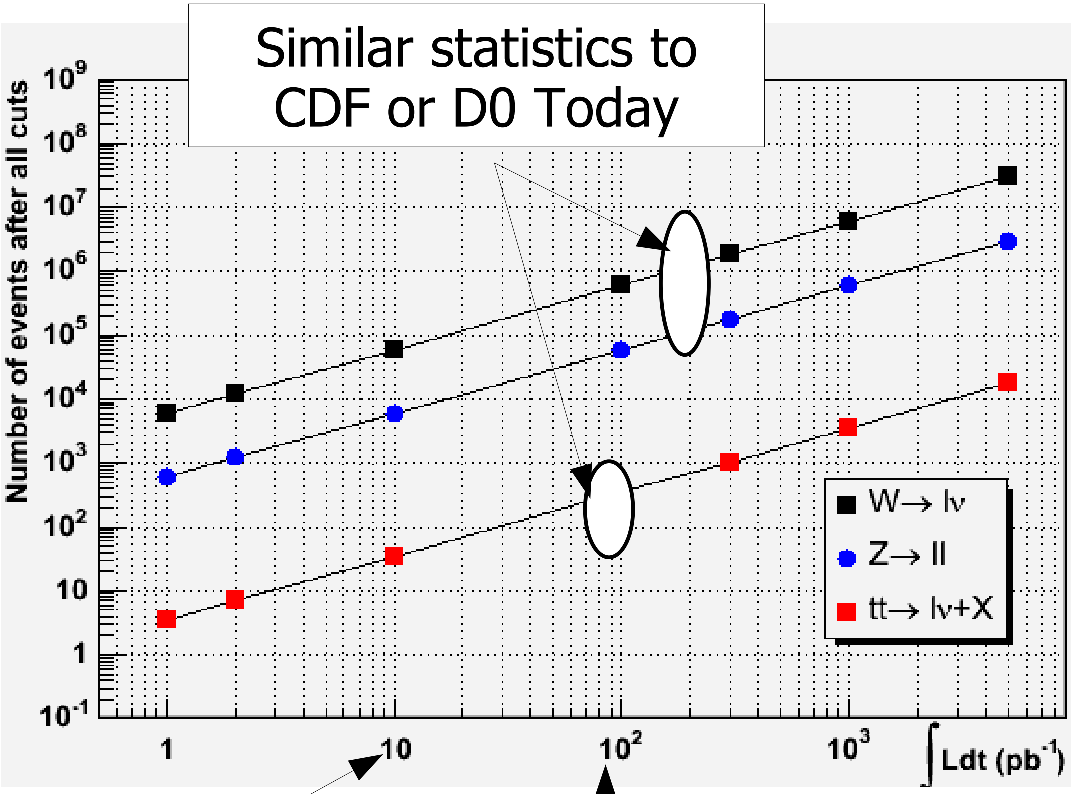
Estimated errors for 100 pb^{-1}



This program starts on day one and never ends
More data means more sensitive probe of new physics

2008 to 2009 (the start)

- Large W/Z rates
  - Measure x-section and properties
- Clean samples of e and mu
  - Calibrate e/m calorimeter, muons. tracking
  - Understand electron fakes
  - Vital for Higgs search
- Top rate: 1 Hz
  - Measure x-section and properties
  - In situ jet calibration
  - In situ b-tagging

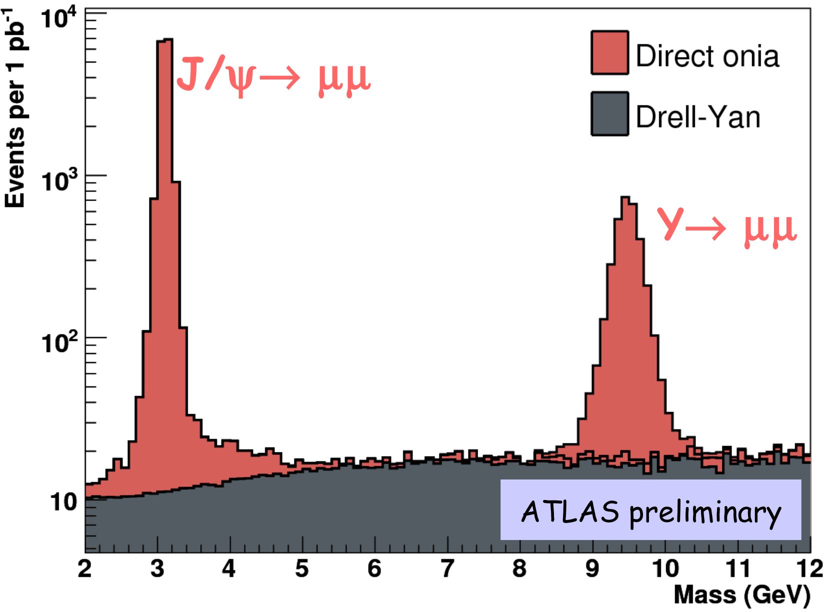


~10 pb^{-1} :1 month at 10^{30} and < 2 weeks at 10^{31} effic=50%

100 pb^{-1} few days at 10^{32}, effic=50%

More high rate processes

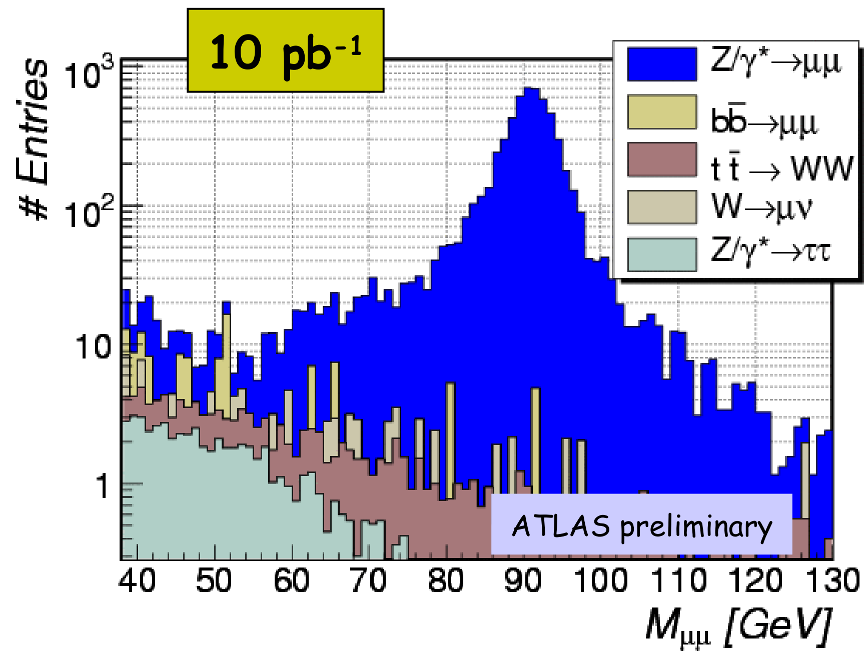
1 pb^{-1} ≡ 3 days at 10^{31} at 30% efficiency



After all cuts:
~ 4200 (800) J/ψ (Υ) $\to \mu\mu$ events per day at L = 10^{31}
(for 30% data taking efficiency)

→ tracker momentum scale, trigger performance, detector efficiency, QCD papers…

After all cuts:
~ 160 $Z \to \mu\mu$ evts per day at L = 10^{31}
Note: σ_Z(LHC)/σ_Z(Tevatron) ~ 10

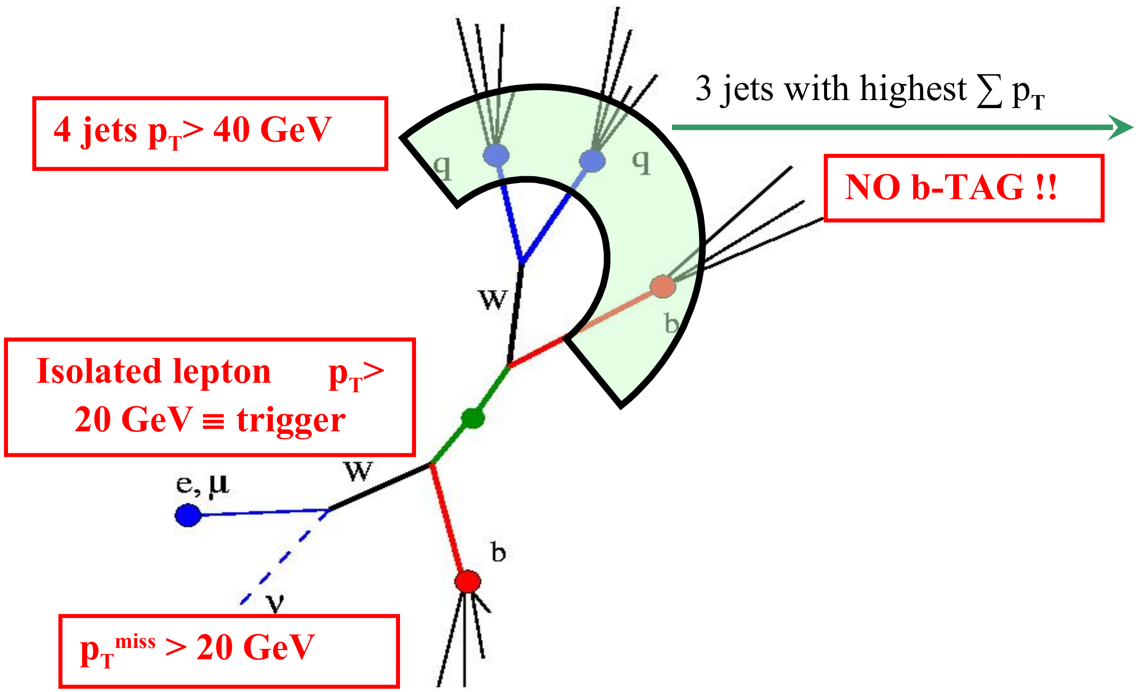


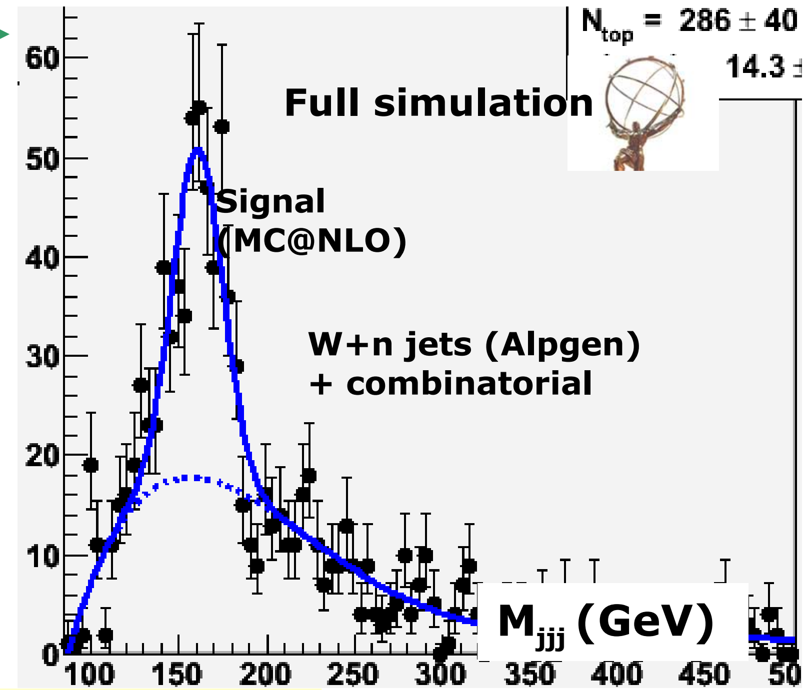
Muon Spectrometer alignment, ECAL uniformity,
energy/momentum scale of full detector,
lepton trigger and reconstruction efficiency,
physics papers!!

BERKELEY LAB

Top (2009/2010)

L=100 pb^{-1}



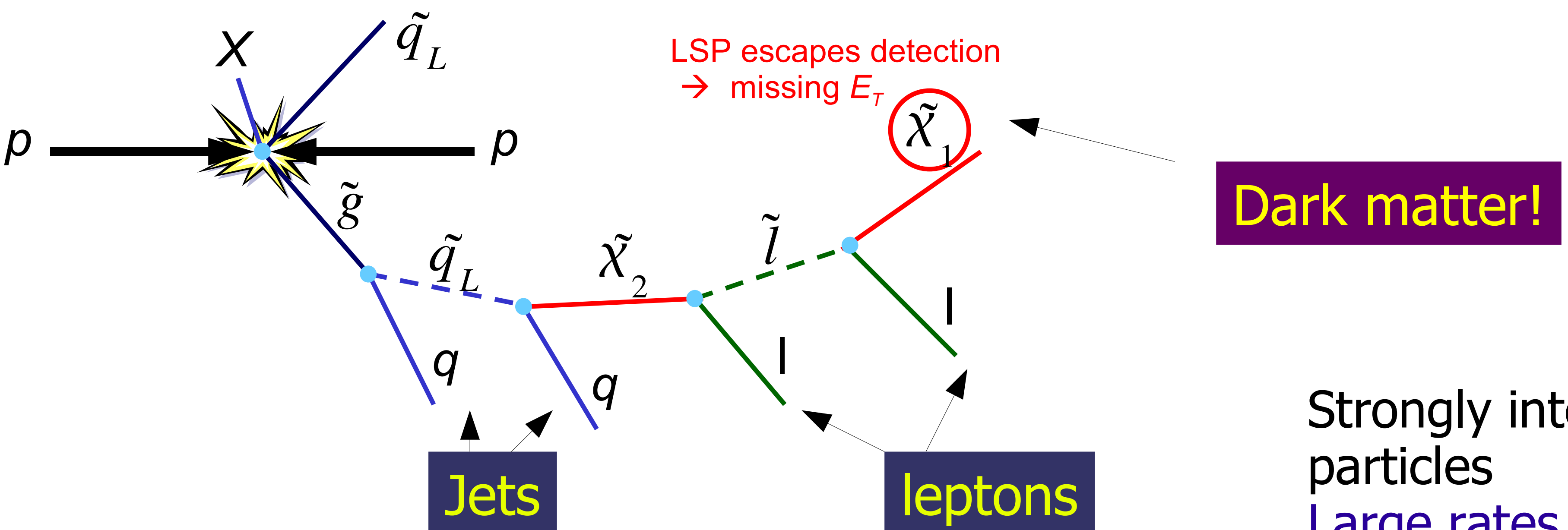


Now we have sample of bjets selected without using tracker
Use these to calibrate the b-tagging
In situ jet calibration from known W mass

Top physics results: Mass, rates, decay modes, spin, pt spectrum, peaks in ttbar mass....

SUSY: phenomenology in one page

- Conserved ***R*-parity** requires existence of a **lightest stable SUSY particle (LSP)**. Since no exotic strong or EM bound states (isotopes) have been observed, the LSP should be neutral and colourless **WIMP:** LSP signature just as heavy neutrino
- The LSP is typically found to be a spin- **neutralino**, a linear combination of gauginos (in much of the SUSY parameter space the neutralino is a mixture of photino and zino)
- With *R*-parity: **SUSY** production in **pairs requires energy 2 > SUSY mass** !



Strongly interacting particles
Large rates

"Typical" SUSY decay chain at the LHC

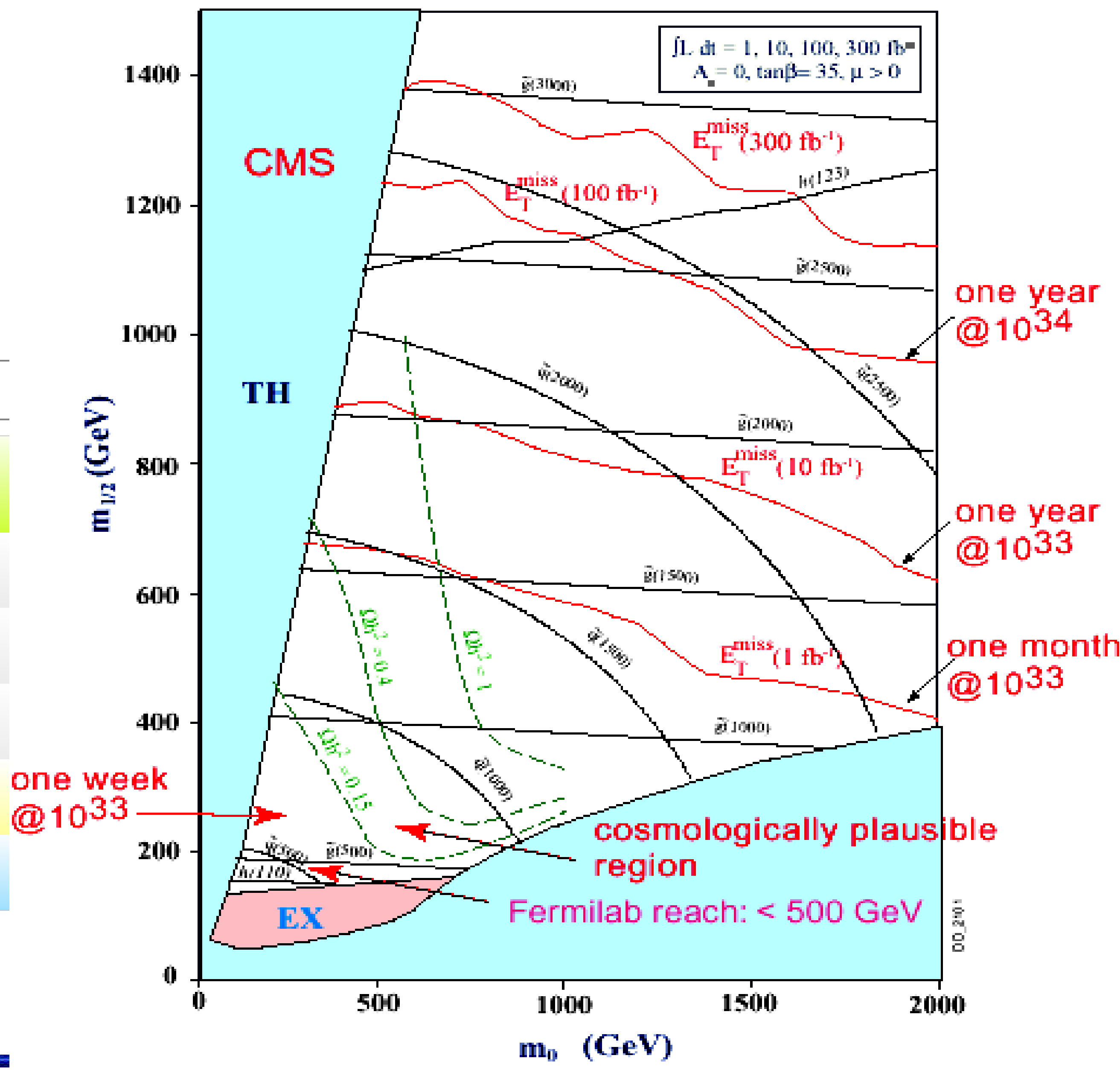
SUSY reach

- Experiments evaluate their SUSY discovery potential using some “standard” mSUGRA

5σ discovery reach for SUSY:

Time period	Luminosity [$cm^{-2}s^{-1}$]	squark/gluino masses
1 month	10^{33}	~1.3 TeV
1 year	10^{33}	~1.8 TeV
1 year	10^{34}	~2.5 TeV
Ultimate	$\int$ = 300 fb^{-1}	~2.5–3 TeV
D0 & CDF	$\int$ = 0.3 fb^{-1}	$>_{(2\sigma)}$ 0.35 TeV

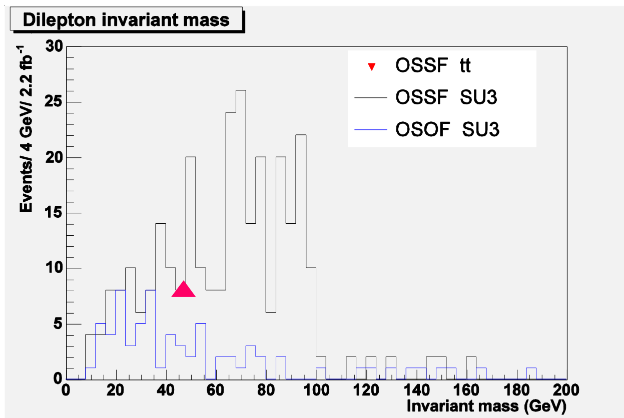
5 standard deviations discovery contours

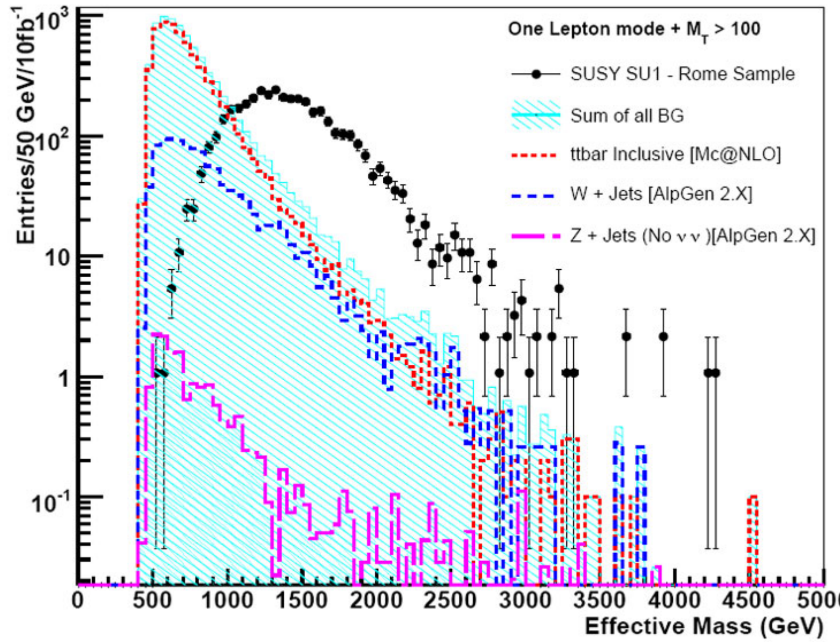


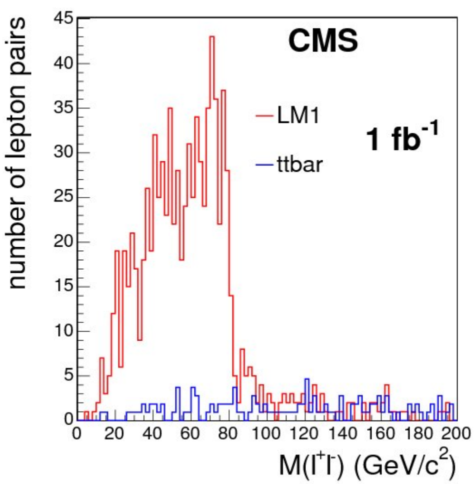
SUSY discovery then measure it!

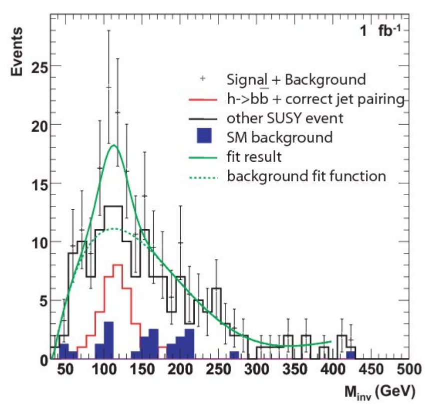
- 12 squarks, 9 sleptons, 5 Higgs, 6 gauginos
  - Measure masses
  - Measure decays and couplings
  - History redux (1950's)
  - Can never have enough data for this
  - Nobody cares about anything else if this is true
    - All other upgrade motivations are irrelevant
    - Whole conferences will be devoted to this

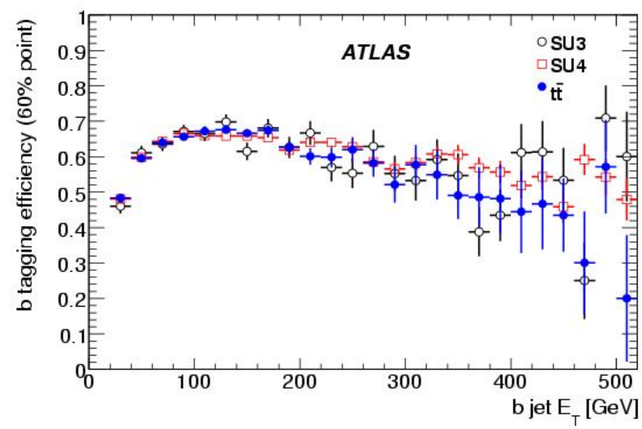
LHC →The Bevatrino: masses and couplings





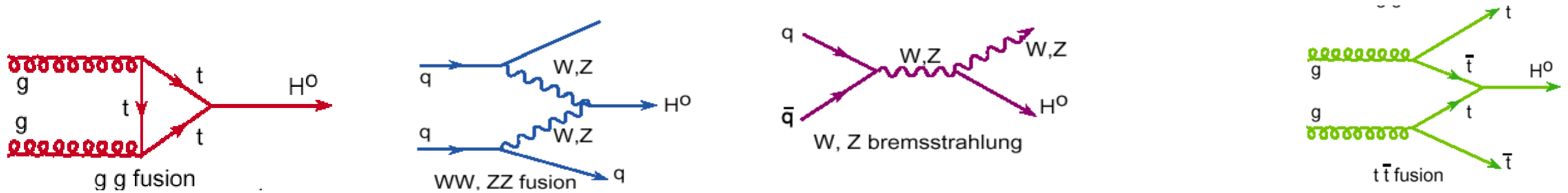


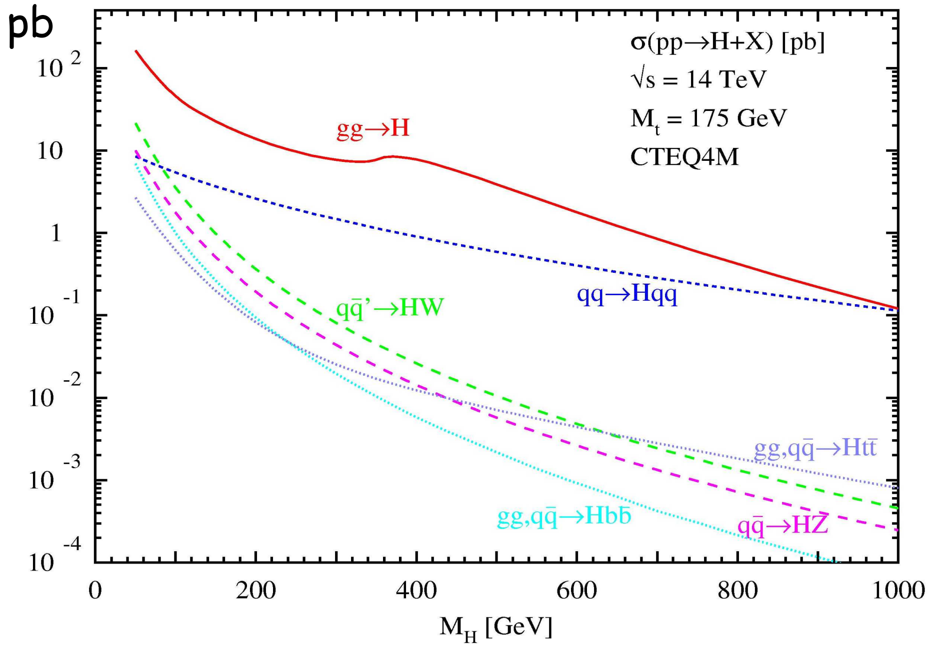


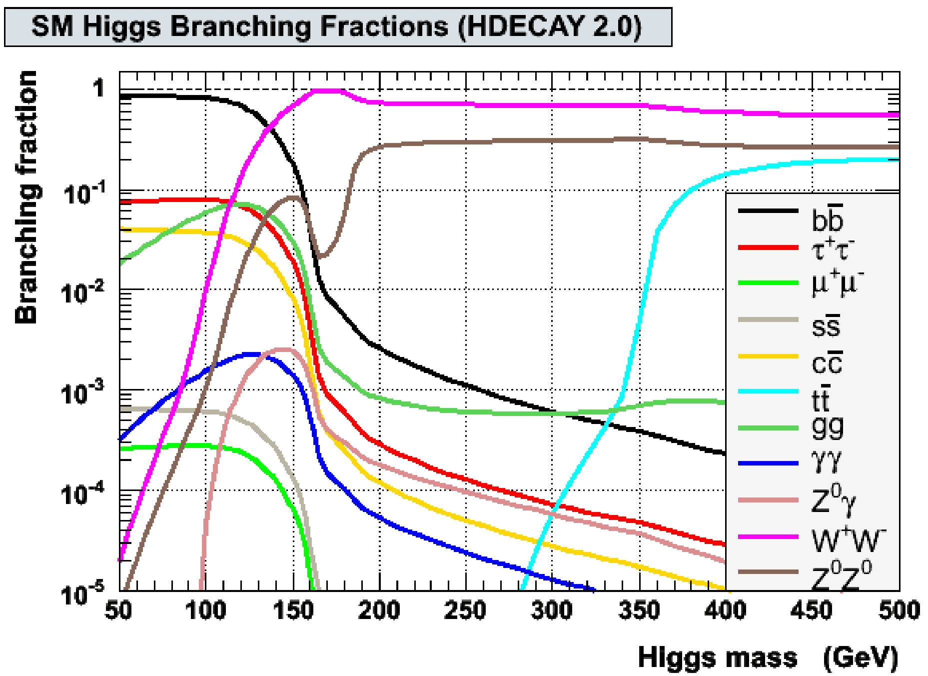


Give me 2hrs and I'll explain these!

Higgs Physics in one slide







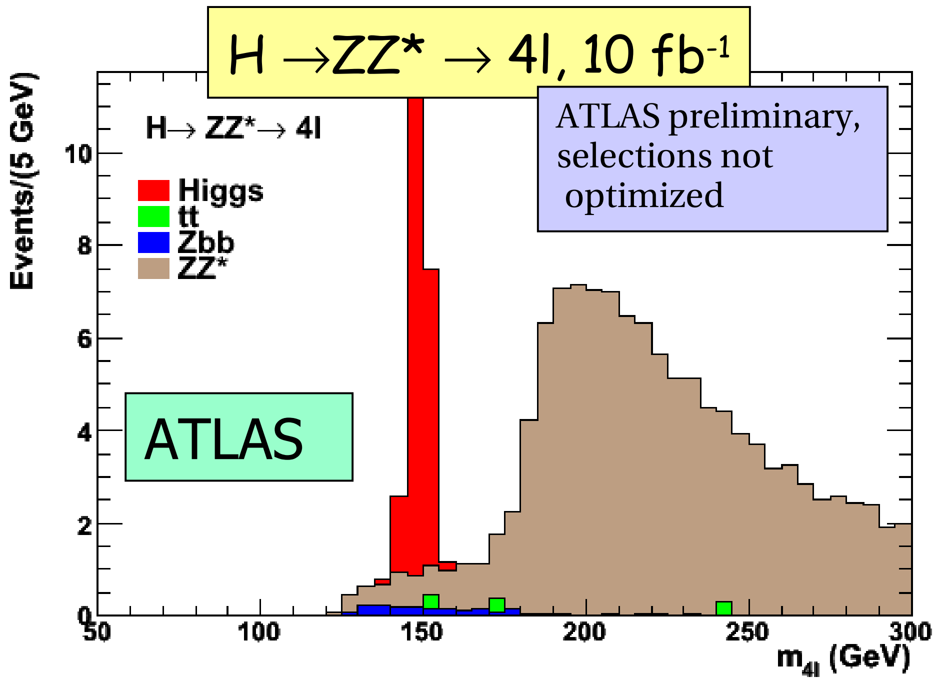
m_H < 130 GeV : H → bb, ττ dominate

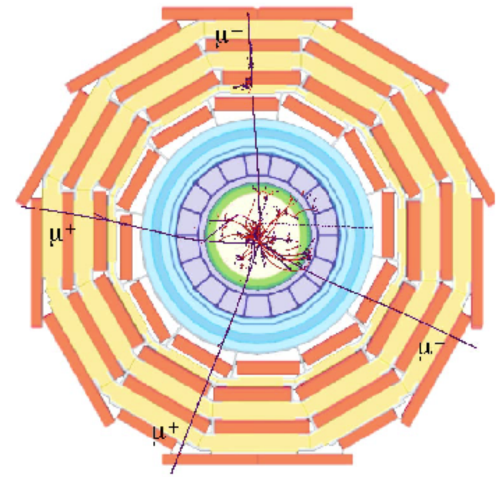
Best channels at LHC: qqH → qqττ, ttH→ lbbX, H →γγ

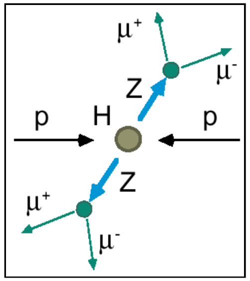
m_H > 130 GeV : H → $WW^{(*)}$, $ZZ^{(*)}$ dominate

best search channels at LHC: H → $ZZ^{(*)}$ → 4l (gold-plated), H → $WW^{(*)}$ → lν lν

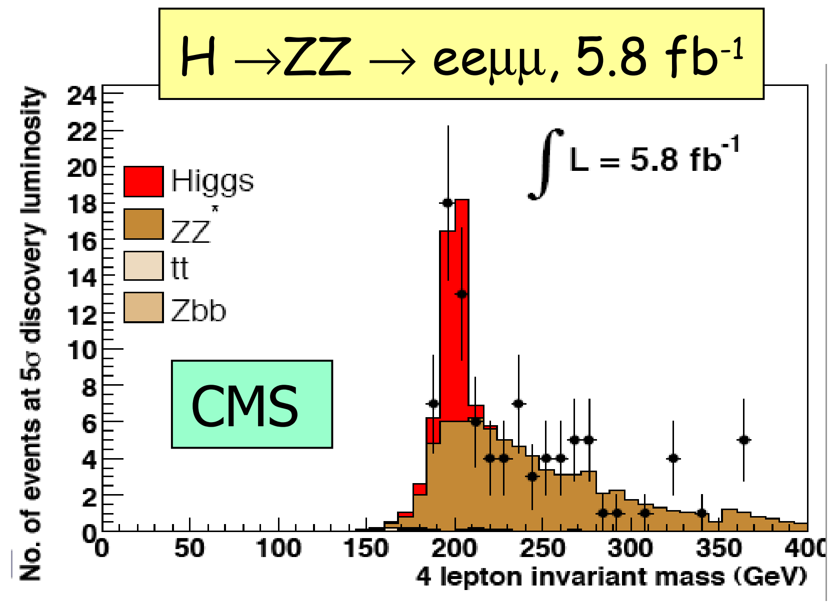
Higgs discovery?







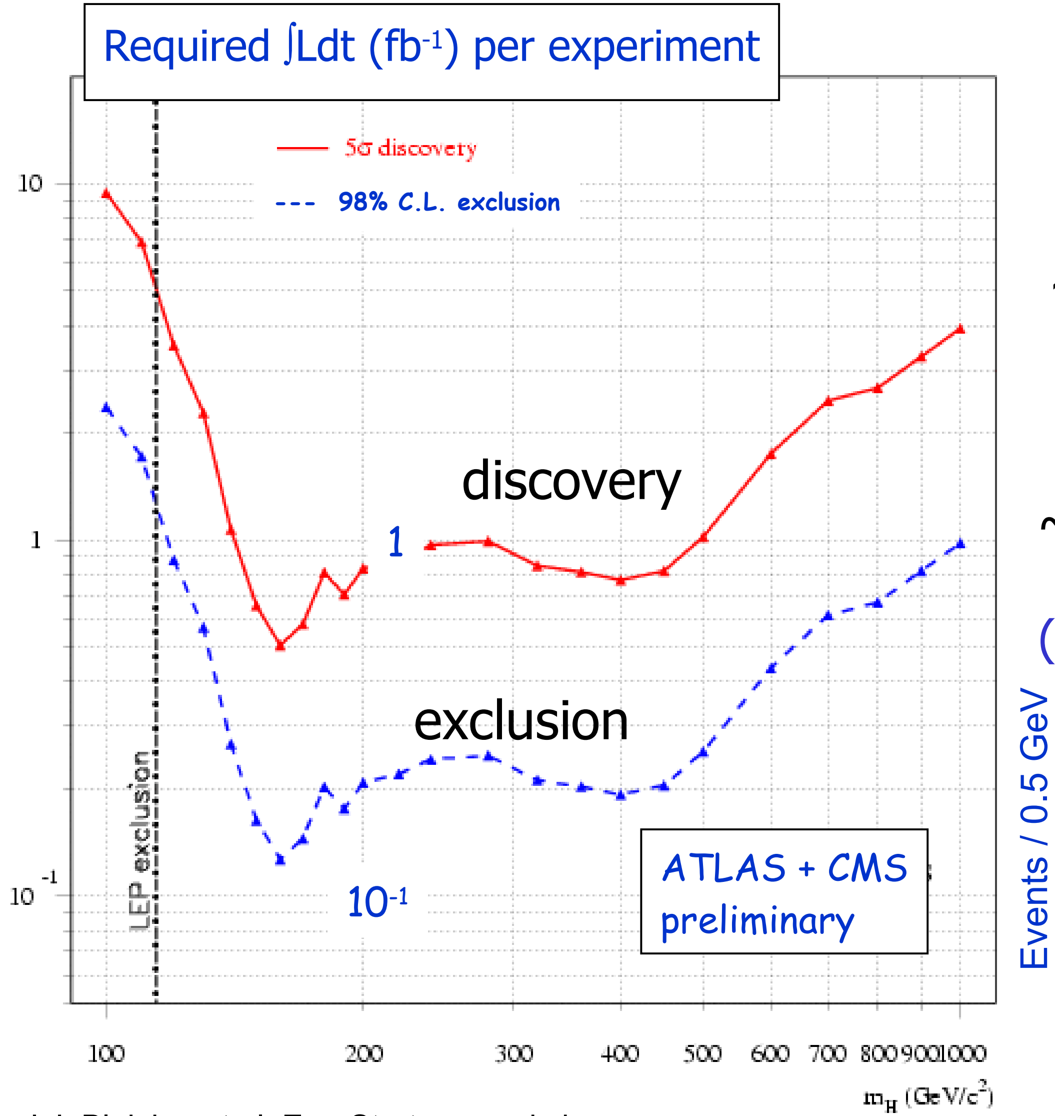
Gold-plated channel at LHC
(~ background free …)



Other channels γγ etc are more demanding of detectors

Combined ATLAS + CMS discovery potential

- Luminosity required for a 5σ discovery or a 95% CL exclusion -



J.J. Blaising et al, Eur. Strategy workshop

~ 5 fb^{-1} needed to achieve a 5σ discovery over entire mass range (well understood/calibrated detector)

~ < 1 fb^{-1} needed to set a 95% CL limit (low mass ~ 115 GeV/c^2 most difficult)

Physics of LHC upgrades

- It will depend on what we find, but
  - Contrast three scenarios
    - Extending search limits
    - Measurements limited by statistics
    - More detailed understanding via more final states
  - I will illustrate each of these with an example
    - SUSY limits, Higgs to $\mu\mu$
    - Strong coupled electro weak sector, SUSY example
    - Higgs branching ratios
  - Not mutually exclusive

Detector issues important for physics

- Heavy new objects near the limit of LHC reach
    - Triggering probably not critical as thresholds are high
- Lighter objects that need more statistics
    - May need more complex (selective) trigger strategy
- Some physics is sensitive to pile up
    - There may be 400 interactions per crossing (50ns bunches and 10^{35}): Most critical are
        - B tagging: track density degrades this
        - Jet tagging/vetoing for "low" pt jets: jet measurements degrade

Physics studies for 10^{35}

- Studies were done 2001/2002 in response to requests from CERN management
- Also included discussion of energy upgrade that I will not discuss
- No prospect of new studies at this time
  - Too busy with detector installation and commissioning
  - Depends on what LHC finds: too many options
- Issues focused at 10^{35}
  - Triggers
  - Impact of Pile up
    - Warning, studies assumed 12.5ns bunch spacing (100 interactions per crossing). This is “off the table” 50 ns is now default (400 interactions per crossing)
- Hep-ph 2002-078 (atlas+cms) (compared energy and luminosity upgrades)
- http://www.iop.org/EJ/abstract/0954-3899/28/9/309/ (atlas)

Extending searches I: Rare Higgs decays

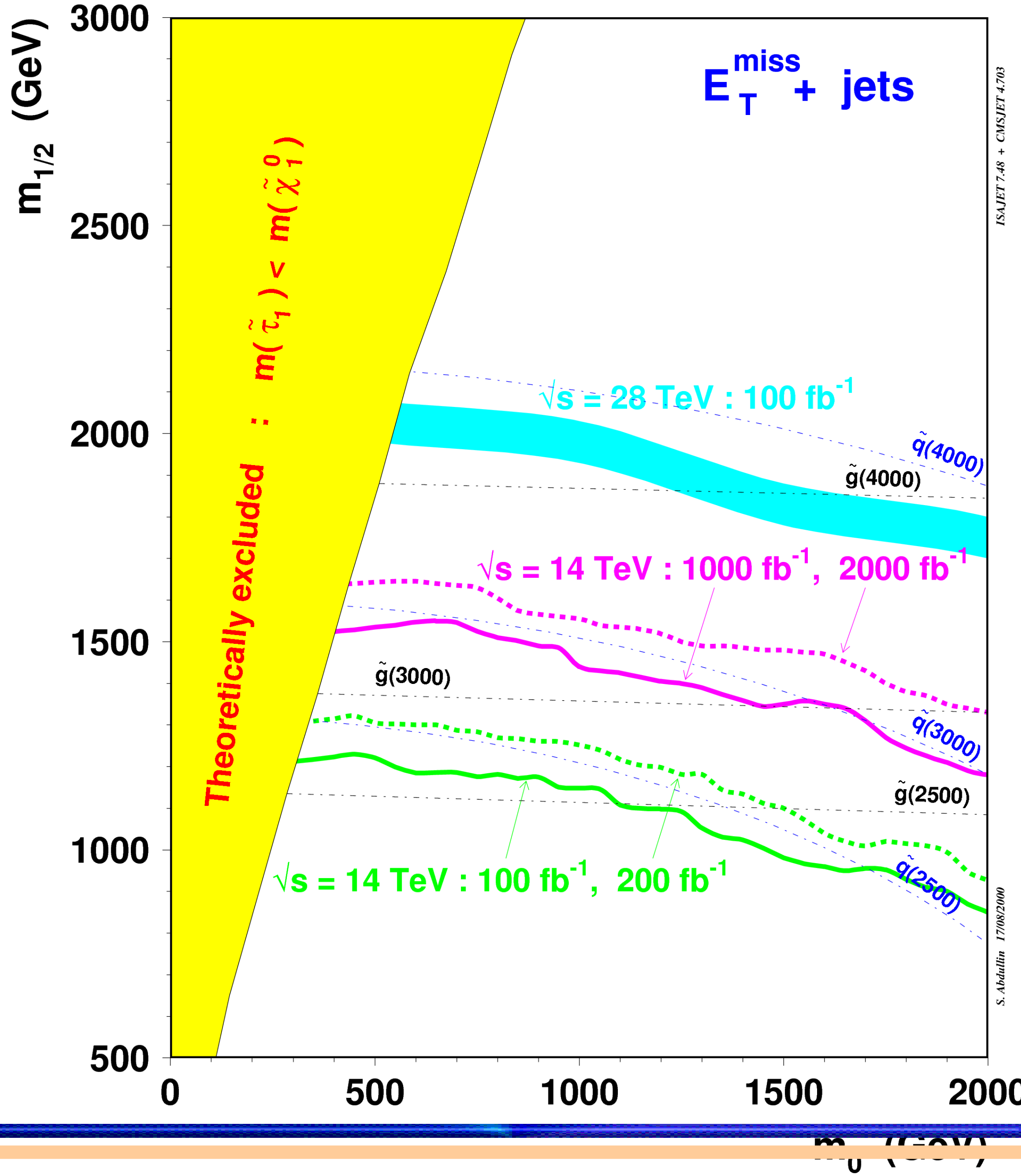
- H to Z gamma marginal with LHC if M(H) 120-160 GeV
  - 300 inverse fb yields 3 sigma in (ee or $\mu\mu$)+gamma (2.5 fb cross section) (130 GeV)
    - Not limited by trigger
    - Does not need jet tagging or veto
  - Would be clearly seen and measured with SLHC (11σ)
- Higgs to $\mu\mu$: no trigger or jet issue: Clean observation

Table 6: Expected signal significance of a SM $gg \to H \to \mu\mu$ signal for various mass values, as obtained by combining ATLAS and CMS and for an integrated luminosity of 3000 fb^{-1} per experiment [19]. The expected statistical accuracy on the measurement of the product of cross-section times BR is also given.

m_H (GeV)	$S/\sqrt{B}$	$\frac{\delta\sigma \times BR(H \to \mu\mu)}{\sigma \times BR}$
120 GeV	7.9	0.13
130 GeV	7.1	0.14
140 GeV	5.1	0.20
150 GeV	2.8	0.36

Extending searches: Heavy SUSY

- Mass reach for gluinos extends from 2.5 to 3.5 TeV
  - Insensitive to pileup
  - Straightforward trigger
- However I hope SUSY has been found and we are adding to the measurements on slide 17!



Measurement limited by statistics Higgs: strongly coupled WW

If there is no light Higgs then, WW scattering becomes "strong" at high energies

Rate limited counting experiment: study ZZ,ZW and WW final states. May not be any "peaks"

Expect to establish signal at LHC (2012??)

But not easy to constrain underlying physics

Rate limited: will need more data to get minimal understanding of underlying mechanism

No Higgs: strongly coupled WW (example)

W^+W^+ final state: cleanest from background aspects

More luminosity would unambiguously measure process

Caveat: jet tagging needed: would be easier with more bunches and less pileup

Table 10: Expected numbers of reconstructed events above an invariant mass of 600 GeV (for $\sqrt{s}$=14 TeV) and 800 GeV (for $\sqrt{s}$=28 TeV) for models with a strongly-coupled Higgs sector and for the background. The significance was computed as $S/\sqrt{S+B}$.

Model	300 fb^{-1} 14 TeV	3000 fb^{-1} 14 TeV	300 fb^{-1} 28 TeV	3000 fb^{-1} 28 TeV
Background	7.9	44	20	180
K-matrix Unitarization	14	87	57	490
Significance	3.0	7.6	6.5	18.9
Higgs, 1 TeV	7.2	42	18	147
Significance	1.8	4.5	2.9	8.1

Upgrade summary

- LHC will remain the frontier machine for at least a decade
- US a major contributor to detectors and accelerator
  - Expect to be major contributor to physics
- Upgrades necessary, independent of physics scenariox
  - Stage I Upgrades: 2 x 10^{34} in ~2013
  - Decision on Stage II Upgrades in 2012: 10^{35} in ~2016
- Urgent need to start R&D to meet this schedule
- Requires aggressive construction schedule: Details from Joel and Abe

World Class Physics Program Bound to Bring Surprises

??2010 Abstract???

The CMATLAS experiment operating at LHC has observed an excess of 9 dimuon and 11 dielectron events in events selected to have 4 jets with pt>50 GeV. The invariant mass if the lepton pair is below 109 GeV and has no peak. These events are inconsistent with the standard model expectation of 2 events. They are consistent with the cascade decay of two or more new particles. This signal could due for example, to SUSY or Universal extra dimensions

Backup

Critical issue #I: low pt jets

- Important as tool for cleaning up S/B in some processes
  - Direct production of new electroweak objects: Example SUSY winos
    - Less QCD radiation means "quiet" environment
    - Backgrounds often come from strong interacting things such as top
      - More QCD radiation
    - Vetoing events with low pt jets can help S/B
  - Higgs via VBF: qq to qqH
    - Needed to measure some final states such as tau tau at low mass
    - Provides more information on Higgs couplings
    - Need to extract this
    - Signal has two forward jets and "quiet" central region
    - Background is QCD: lots of jets flat in rapidity
    - S/B enhanced by presence for forward jets and absence of central jets
- More pileup can make jets from pileup and raise pt of existing jets
  - Makes both vetoing and tagging less effective
  -

Critical issue #2 b-tagging

- No reason to expect significant degradation of performance for **isolated** high pt tracks:
  - Assume same as current detector for e and mu with pt>20 GeV: studies gave few per cent degredation
- Btagging is harder
  - High pt is in dense environment: pileup makes it worse
  - Low pt depends on soft tracks: pileup makes it worse
  - May be needed for Higgs physics and SUSY measurements

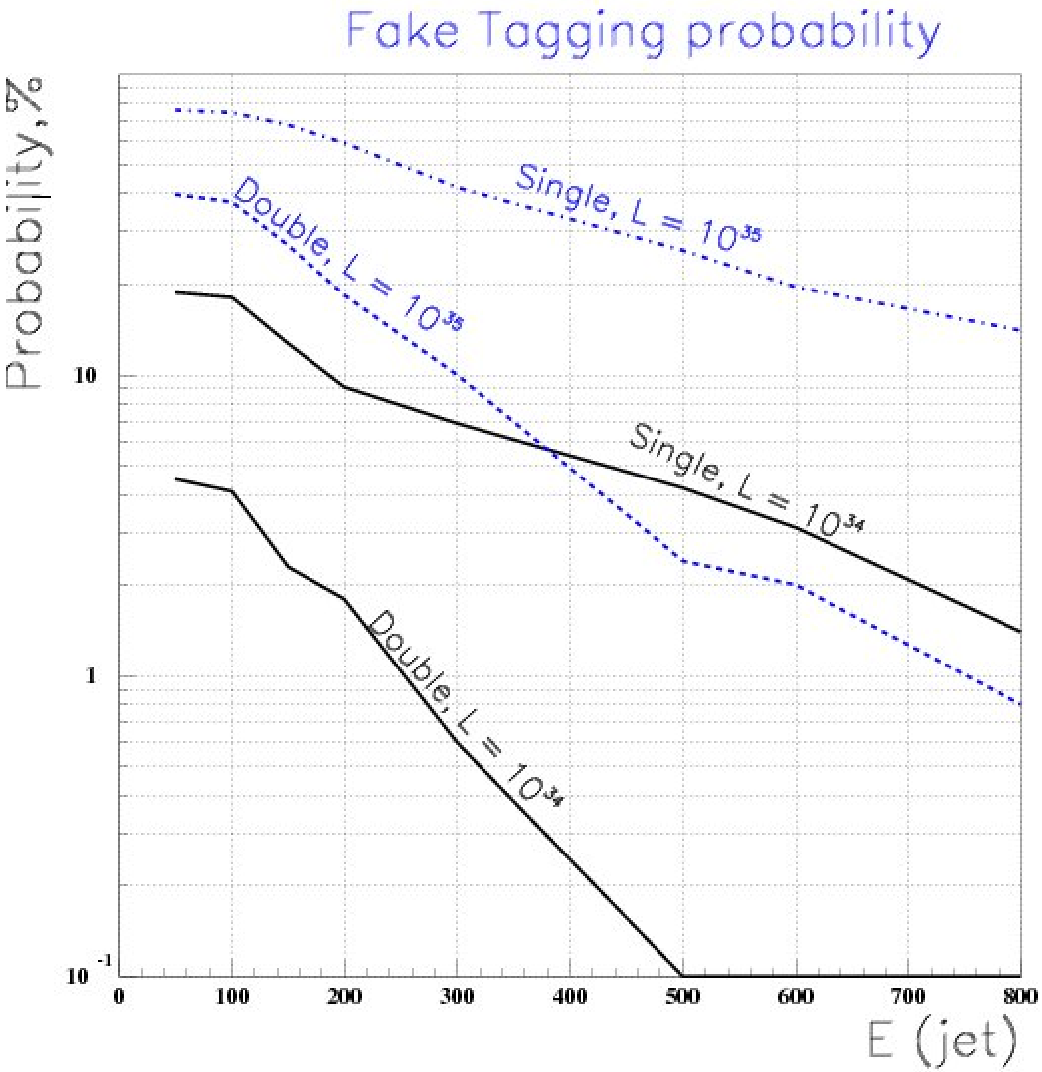
Table 1: Rejection against u-jets (R_u) for a b-tagging efficiency of 50% and in various p_T bins, as expected in ATLAS at the LHC design luminosity and with the upgraded luminosity.

p_T (GeV)	R_u at 10^{34} cm^{-2}s^{-1}	R_u at 10^{35} cm^{-2}s^{-1}
30-45	33	3.7
45-60	140	23
60-100	190	27
100-200	300	113
200-350	90	42

Recall that these are 100 events/crossing: too optimistic

Critical issue #I: low pt jets

- Jets from "garbage"
-
-



Look for 1 or two jets
at abs(eta)>2

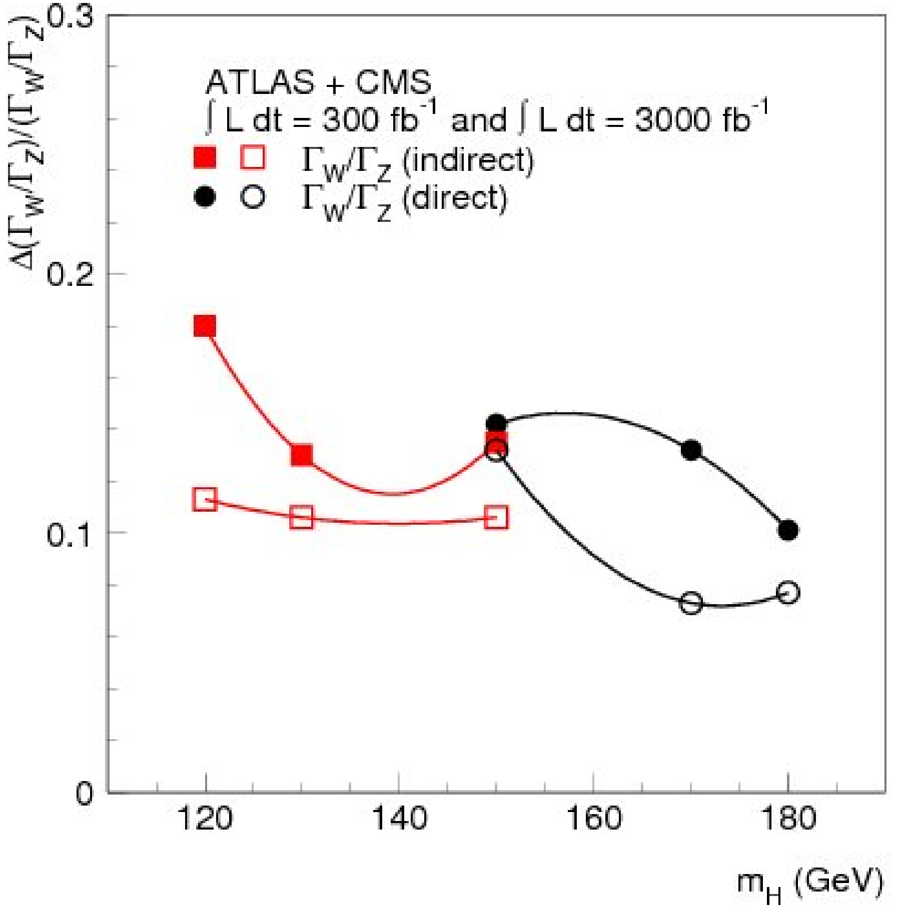
Cone of 0.4 used

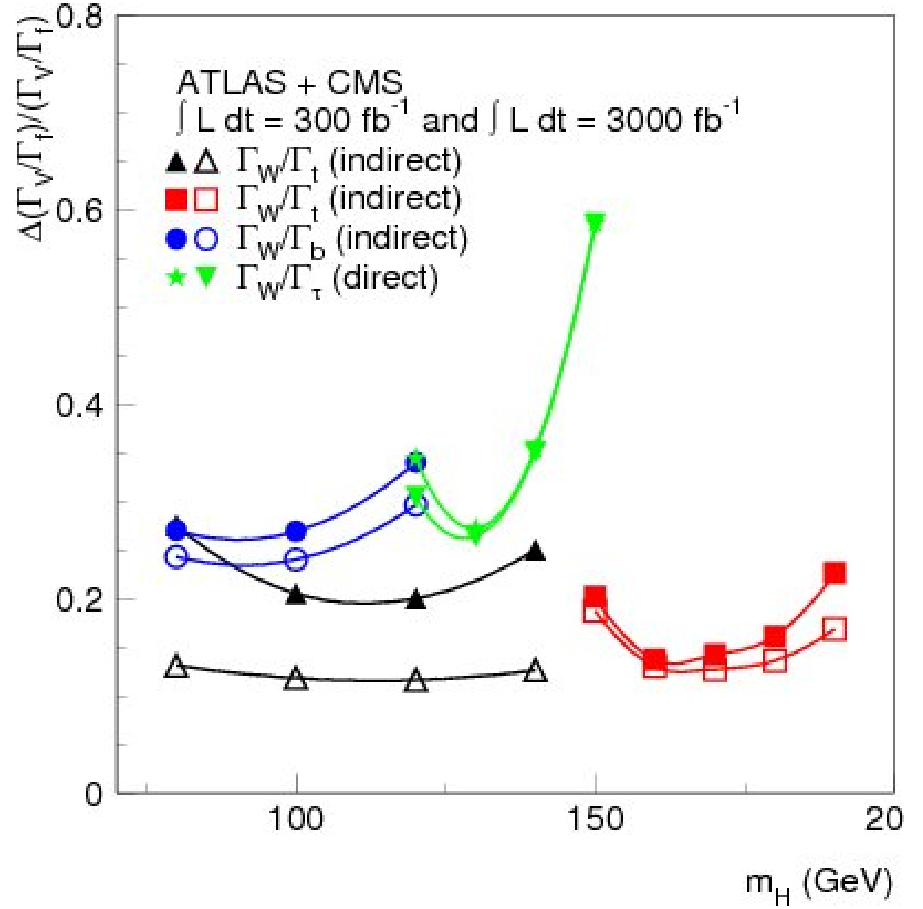
Very large fraction of
event will have single tag

Higgs: Couplings

- These cannot be measured directly at LHC
- Must be inferred by comparing σ BR for many modes
  - Ratios remove luminosity issues
- Look at processes that are rate limited at 10**34
- Measurements limited by worst channel
  - Direct means “no theory”: example qq≫ qqτ and qq>>qqWW measures ratio of τ and WW couplings direclty
  - Indirect means “theory” is needed: example H >>γ constrains H>> WW
- Only interesting if Higgs is light

Higgs: Couplings

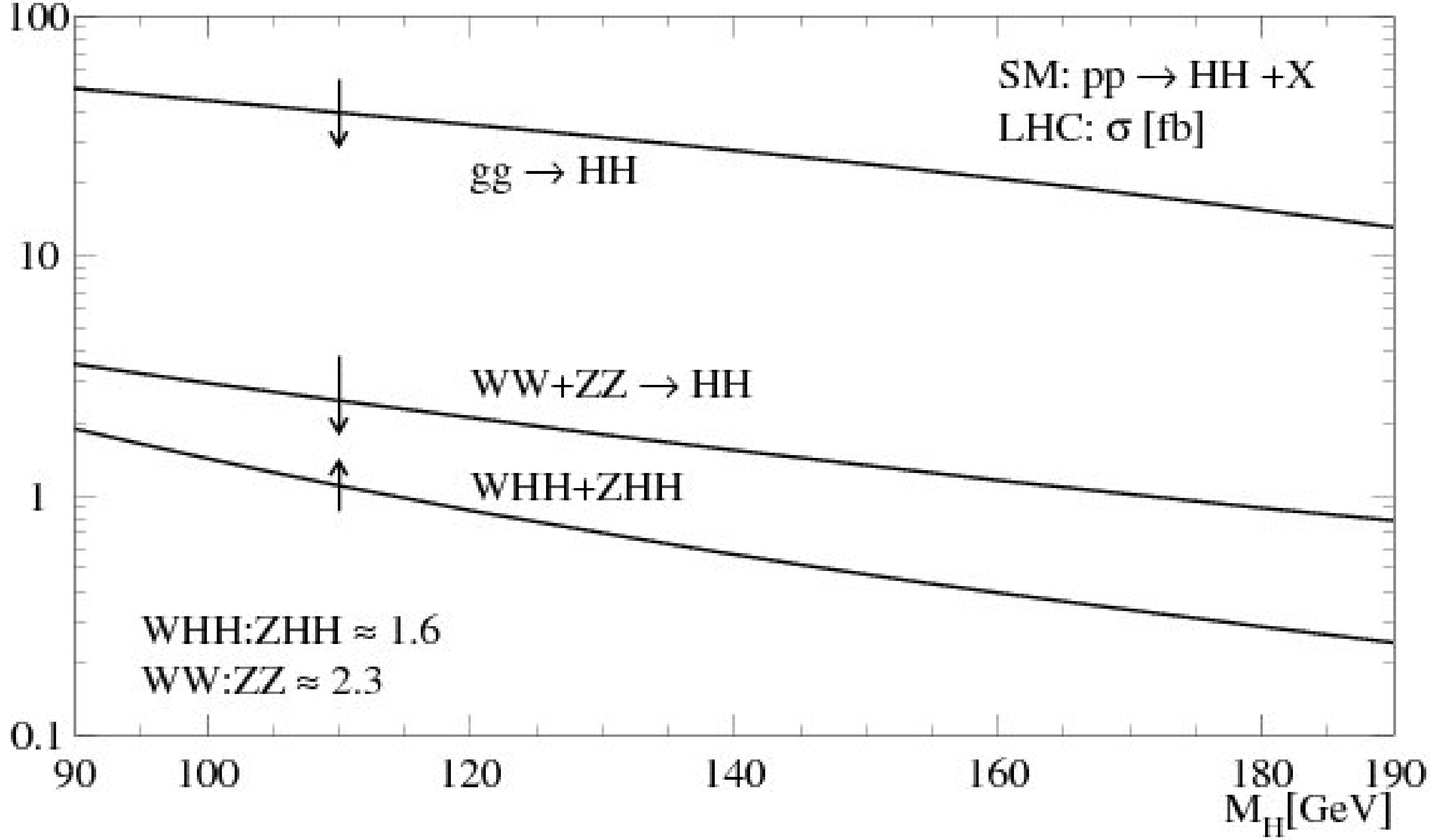




Higgs: self couplings

•

- Must observe Higgs pair production: impossible without upgrade



femtobarns!!

Arrow range corresponds to factor of 2 in HHH coupling

Higgs: self couplings

- Studies with an upgrade are inconclusive
- Rates are low: final states are mass dependent: don't know what mass is yet
- "easiest" is WW for M>160 GeV
  - Final state of WWWW to lνlν 4 jets
  - Backgrounds are complex and hard to estimate
    - Will improve when we get data
  - Not able to claim now that this is observable
- Theoretical claims that bbγ may work for lower masses
  - Not evaluated in full simulation