Going Beyond the Standard Model

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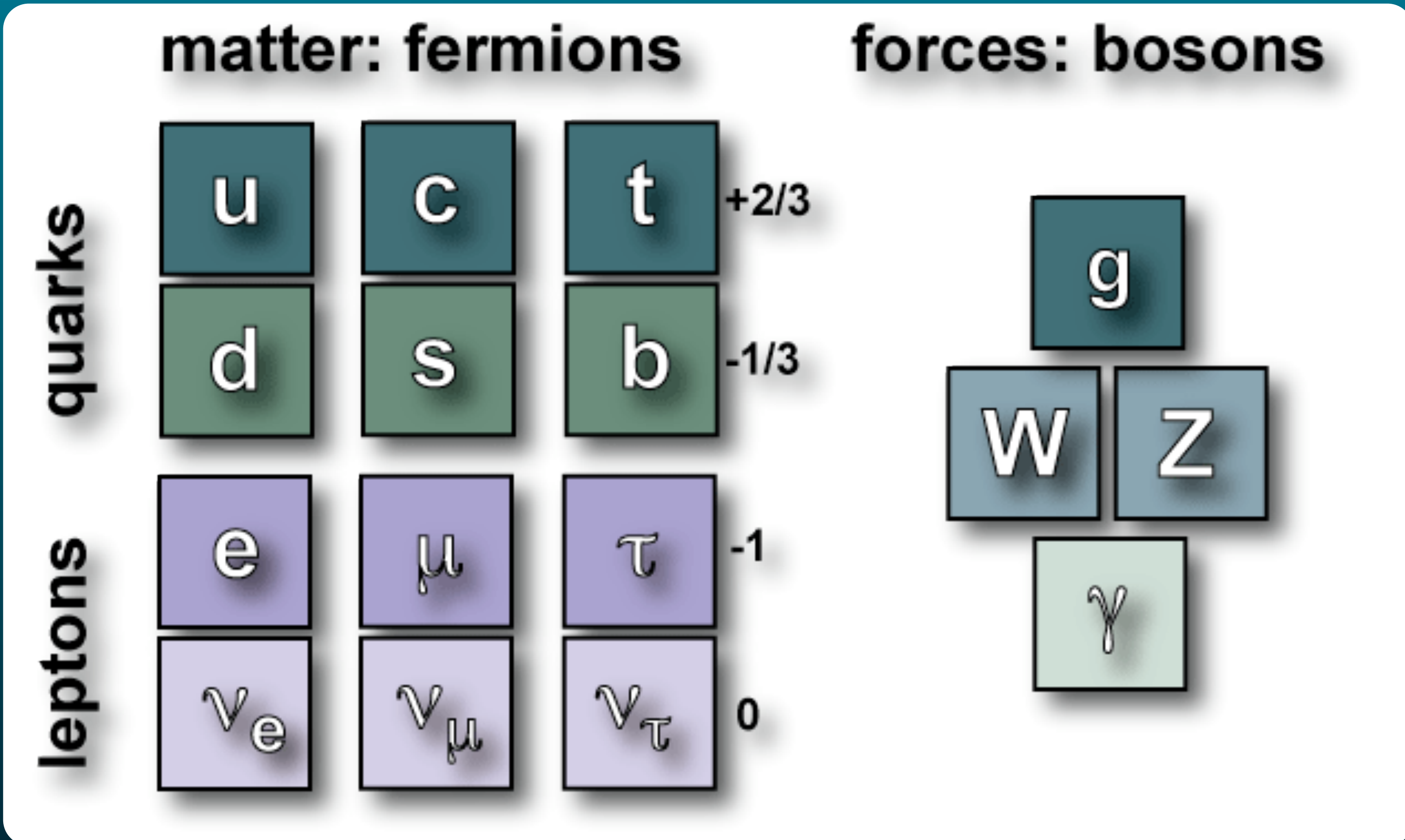
Overview

This is a vast subject! I can only cover a few selected topics that I find particularly interesting:

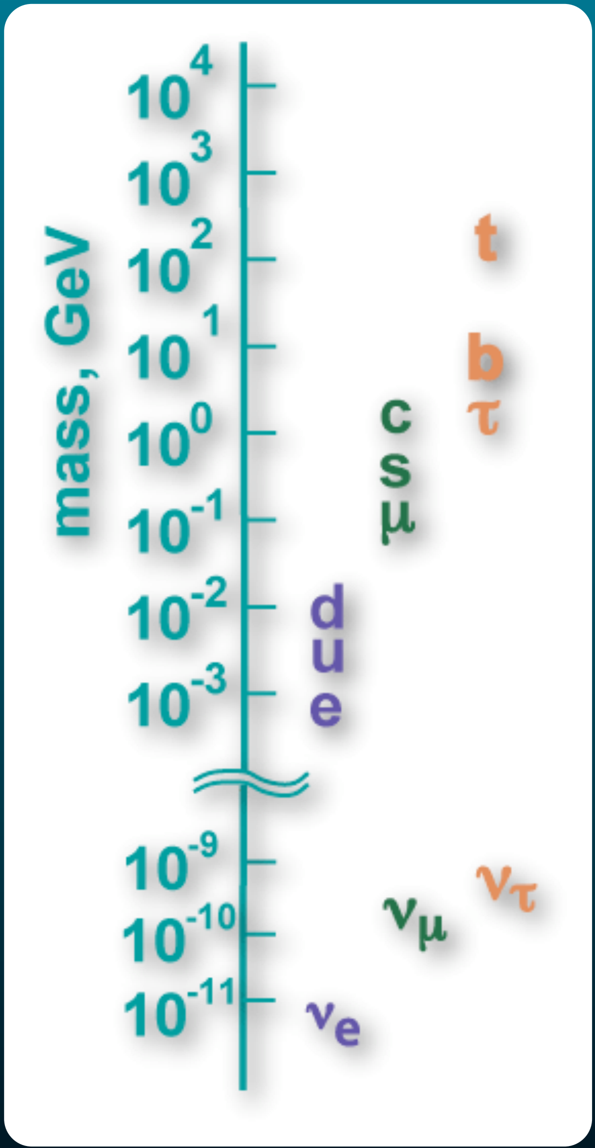
- Standard Model: Higgs
- First Steps Beyond: Supersymmetry
- New Fermions and Bosons
- Extra Dimensions, New Forces
- Casting a Broad Net
- The Unexpected

Emphasis on Tevatron/CDF with an eye toward the LHC

The Standard Model



Questions the SM Raises



Why three generations?

Is there a fourth generation?

Have we arranged them properly?

Why the huge disparity in masses?

Are they composite or elementary?

Why the odd charges?

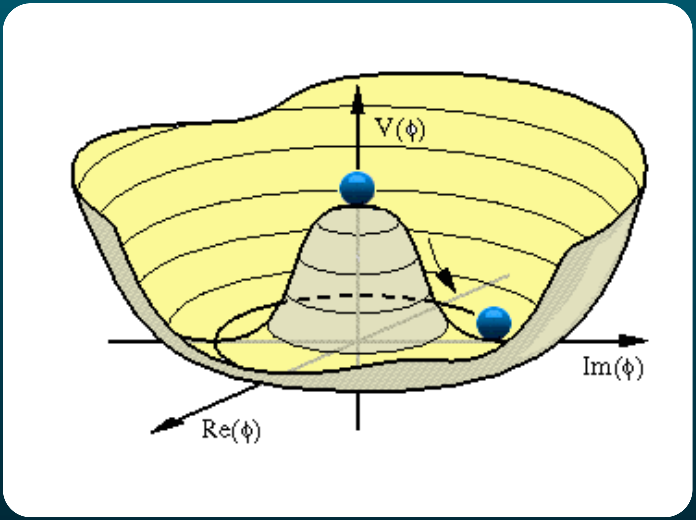
No fundamental matter bosons?

What are the neutrino masses/mixings?

Where are the dark matter particles?

SM Higgs Boson

- Central feature of the Standard Model: electroweak unification, with electroweak symmetry broken by a single Higgs doublet
- Higgs potential has a degenerate minimum in complex plane
- This miraculously gives us the photon, and massive vector gauge bosons W, Z
- Interactions of fermions understood with phenomenal precision



SM Higgs Boson

- Just for fun, the SM Lagrangian:

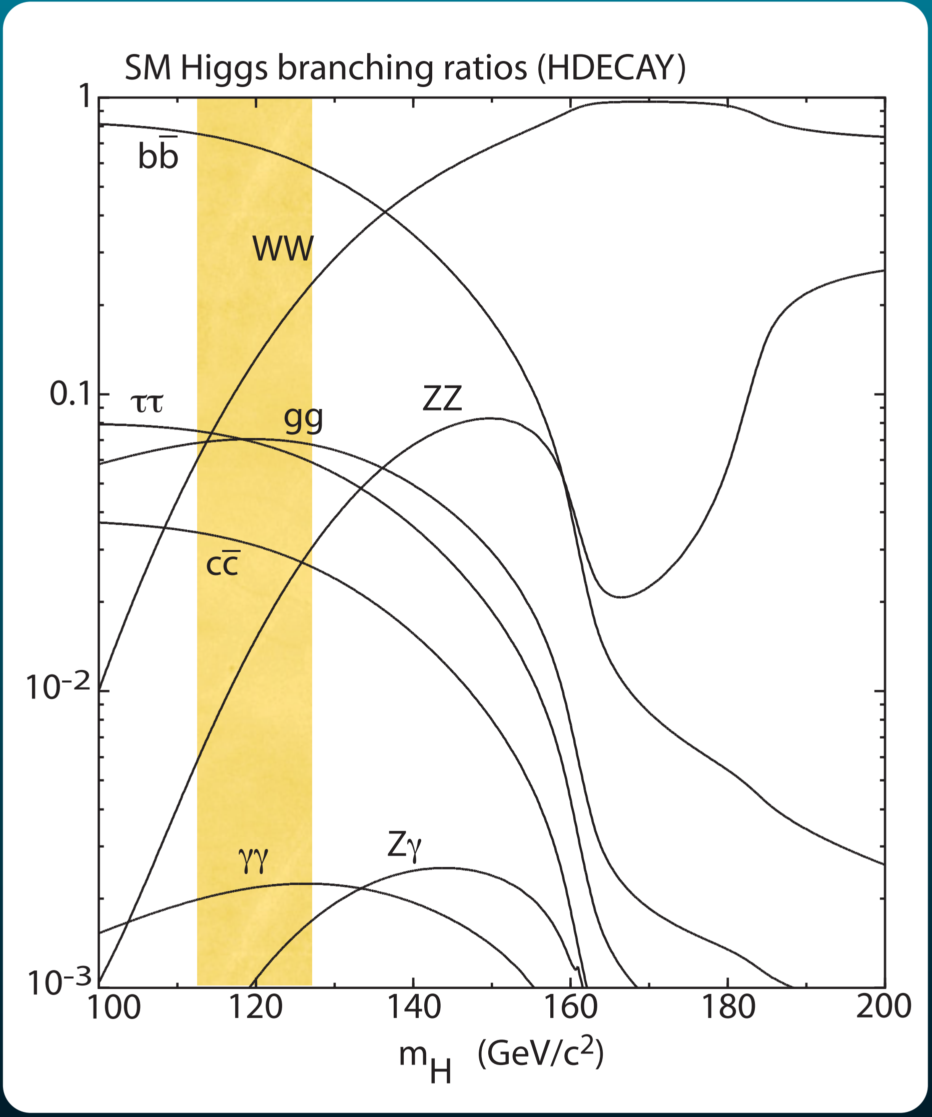
$$
\begin{aligned}
\mathcal{L}_{GWS} = & \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) + \\
& + \frac{g}{\sqrt{2}} \sum_i (\bar{a}_L^i \gamma^\mu b_L^i W_\mu^+ + \bar{b}_L^i \gamma^\mu a_L^i W_\mu^-) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I_f^3 - 2s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z_\mu + \\
& - \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 - \frac{1}{2} |\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ + \\
& - ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu|^2 + \\
& - \frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 + \\
& - \frac{1}{2} M_\eta^2 \eta^2 - \frac{g M_\eta^2}{8 M_W} \eta^3 - \frac{g'^2 M_\eta^2}{32 M_W} \eta^4 + |M_W W_\mu^+ + \frac{g}{2} \eta W_\mu^+|^2 + \\
& + \frac{1}{2} |\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta
\end{aligned}
$$

Higgs mass

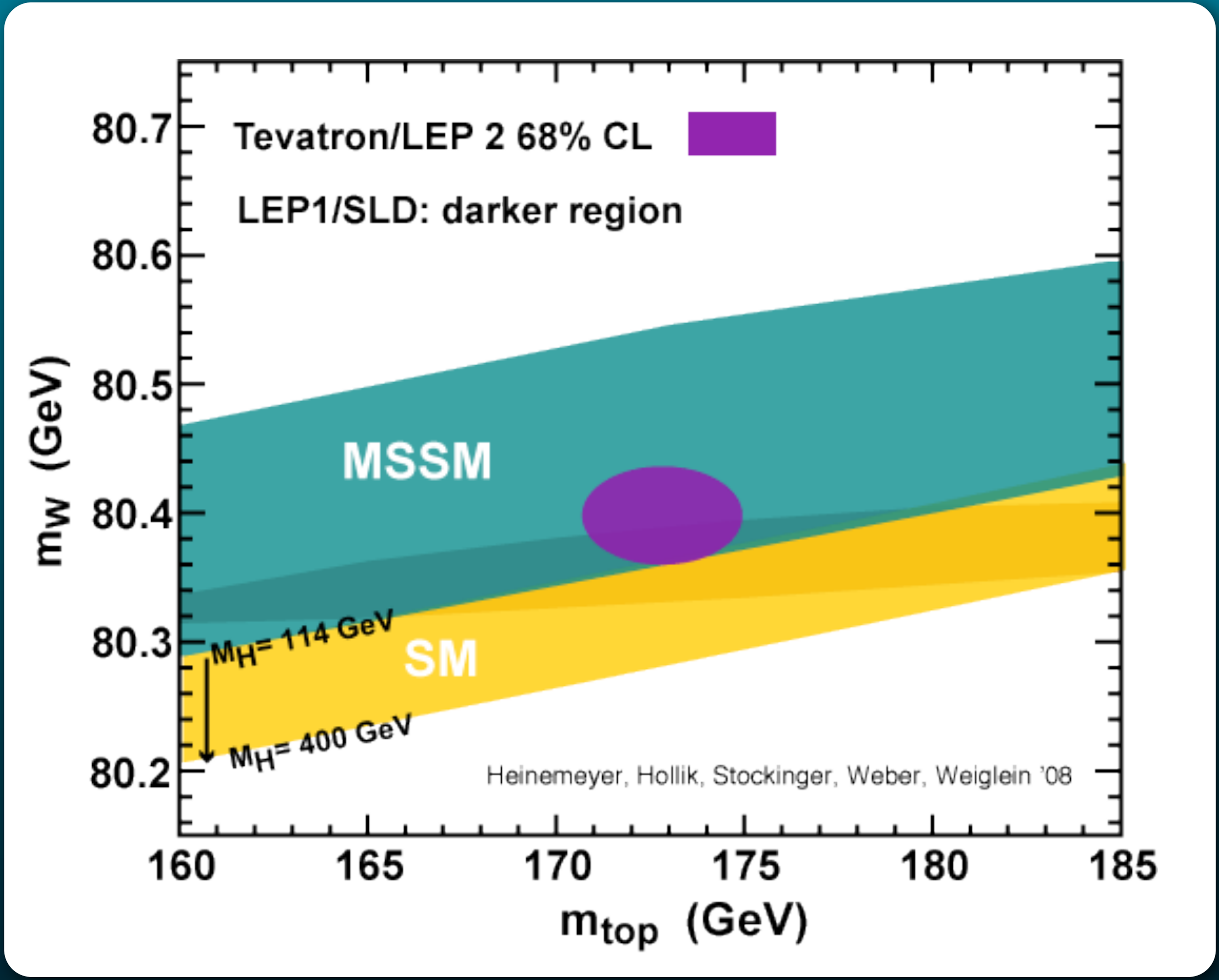
$Hf\bar{f}$ coupling

SM Higgs Decays

- H decays to heaviest fermion pair it can
- Interesting range m_H~120 GeV:
  - bb ~ 70%
  - ττ ~ 7%
  - γγ ~ 0.2%

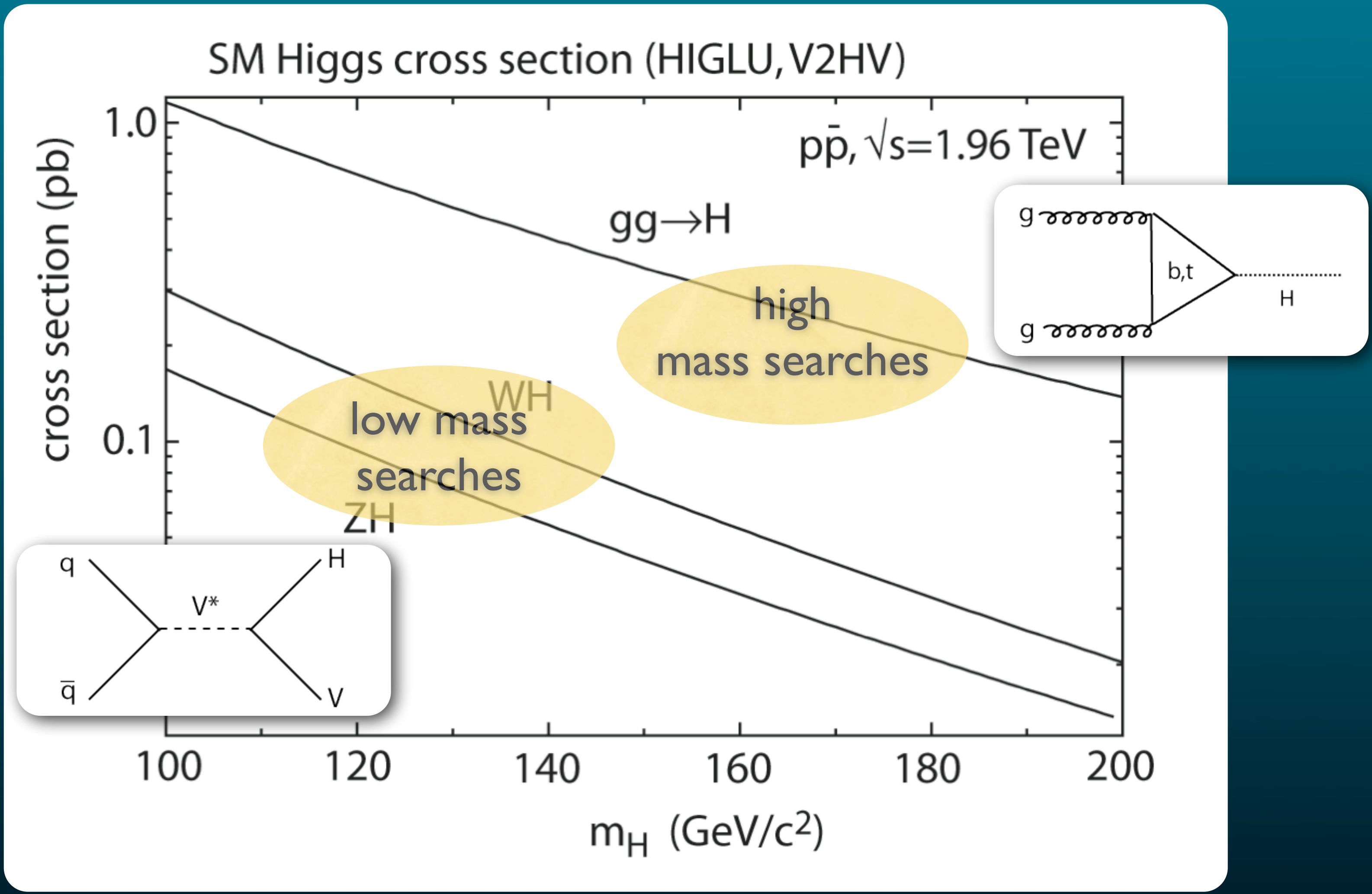


Combined Electroweak Fit

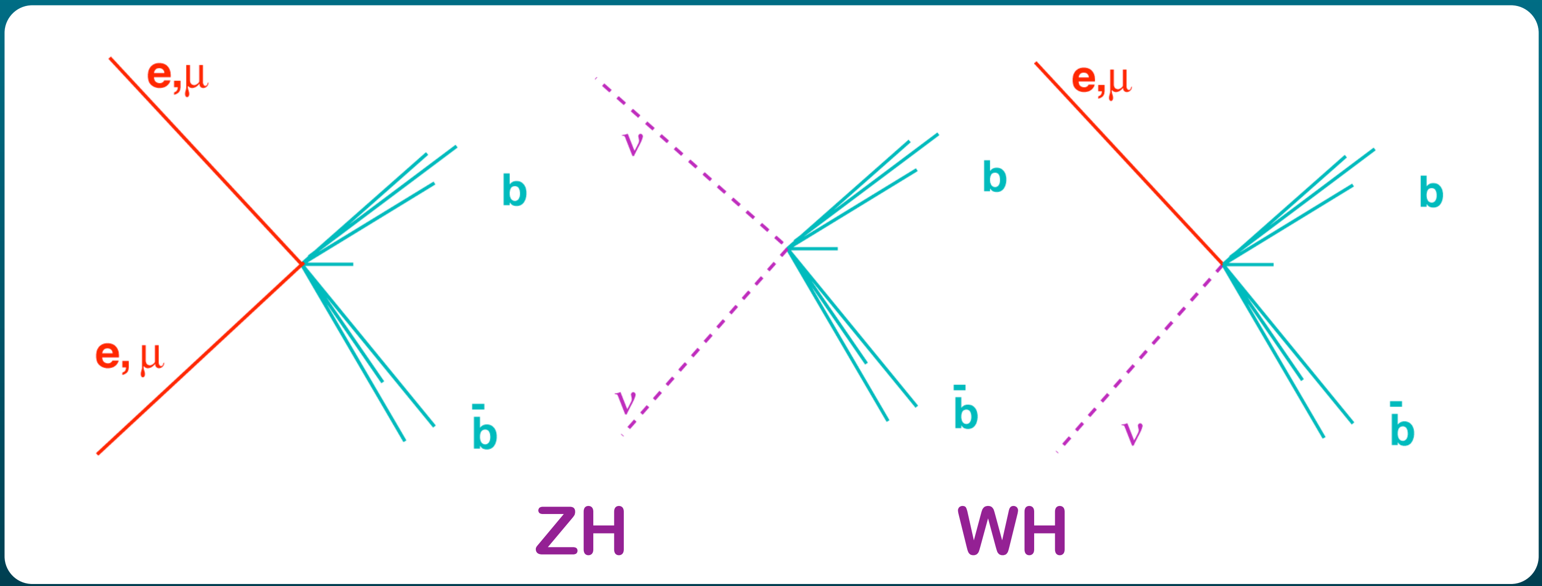


The situation is getting very interesting!

Tevatron SM Higgs Production



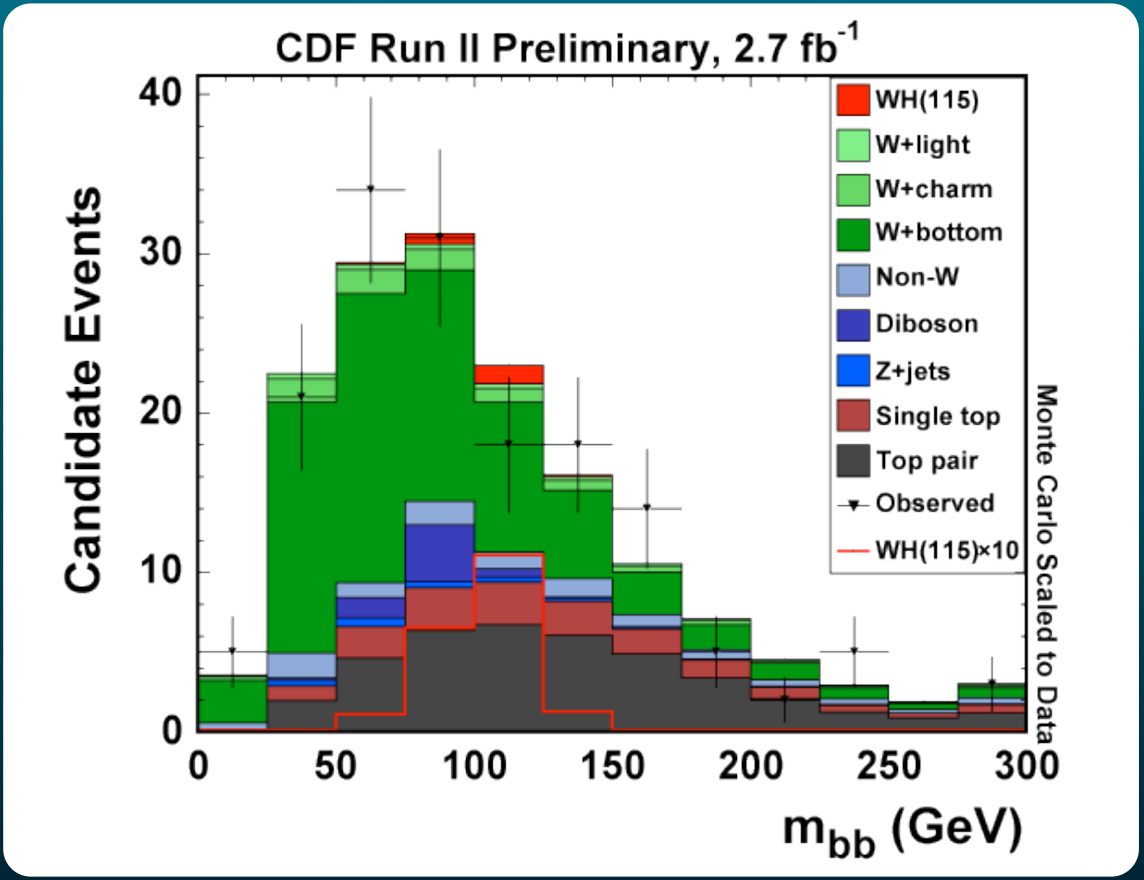
SM Higgs at the Tevatron



- main low-mass (< 130 GeV) search modes all employ bb decays
- need excellent b tagging (60-70% efficiency) and bb mass resolution (10%)

SM Higgs at the Tevatron

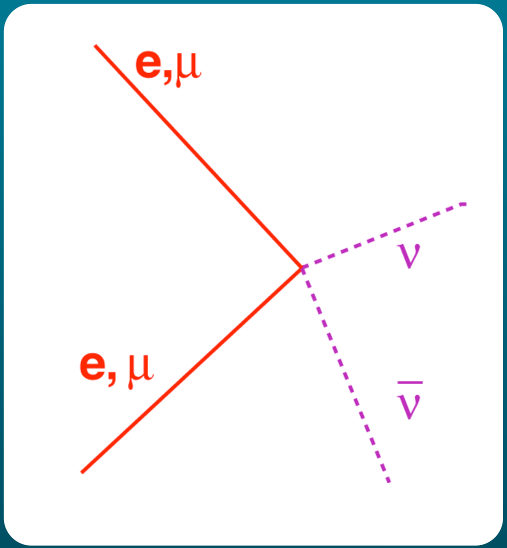
- just one plot: bb mass in case where both jets are tagged:

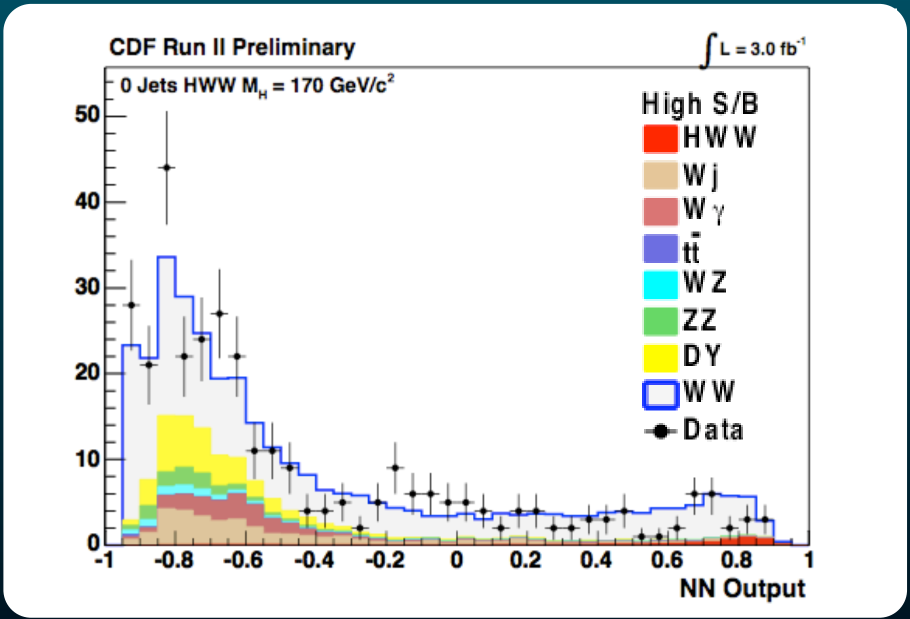


It is going to take a while to see a Higgs signal!

SM Higgs at the Tevatron

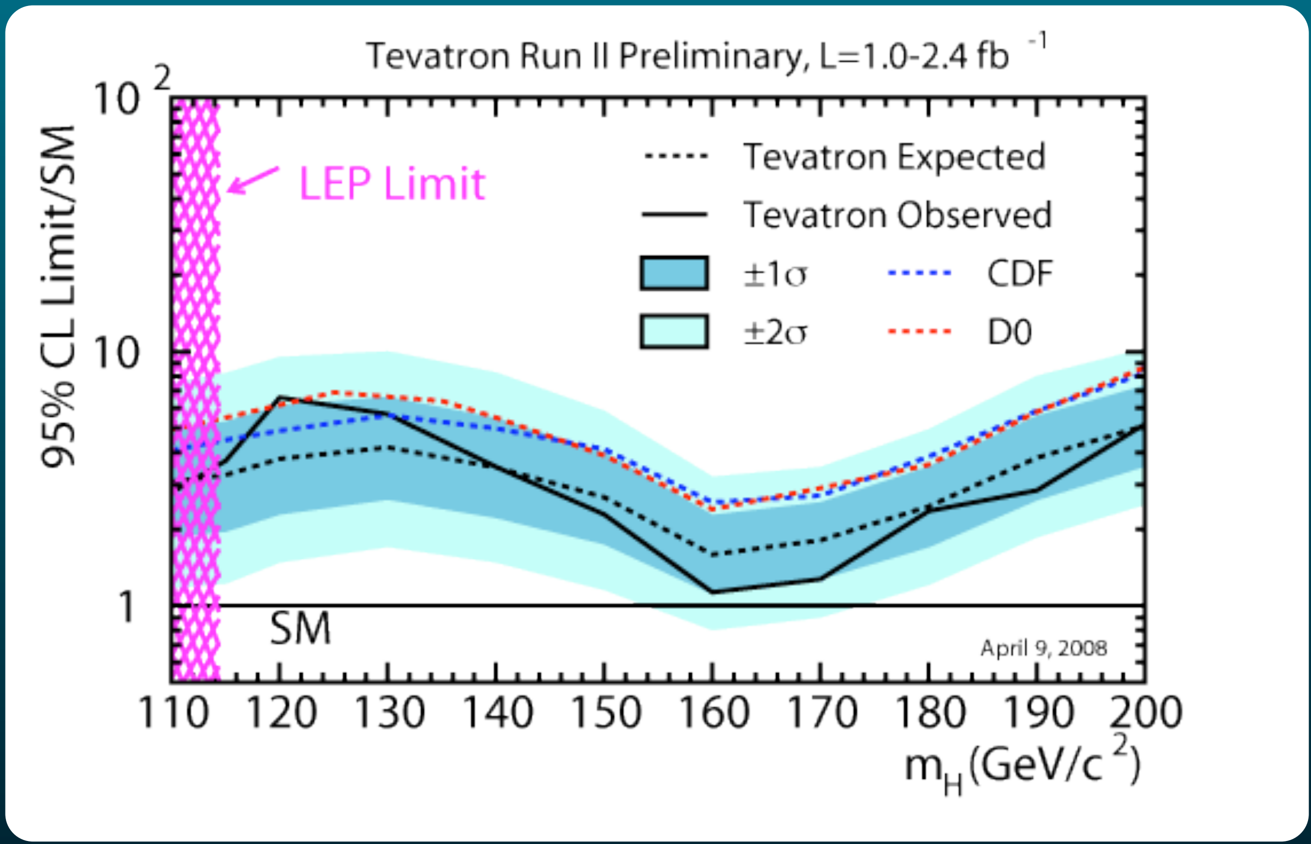
- high mass (> 140 GeV) search uses gg→H→WW where W's decay leptonically
- main background is continuum WW production
- remove WW background by relying on spin correlations
- separately analyze WW+0, 1, 2 jets channels using neural network discriminator





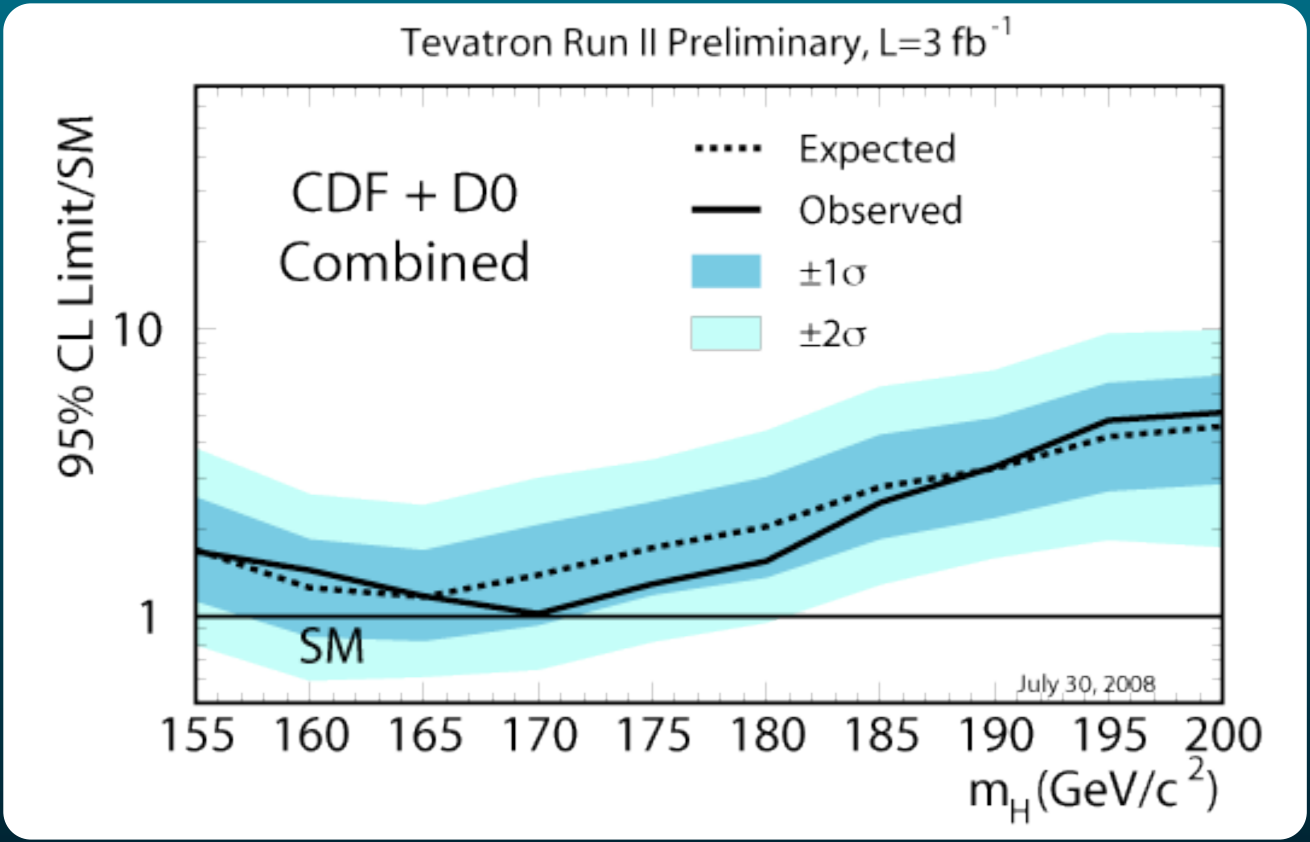
CDF + D0 Combined SM Higgs

- Tevatron needs many times more integrated luminosity to begin to rule out low mass Higgs:



CDF + D0 Combined SM Higgs

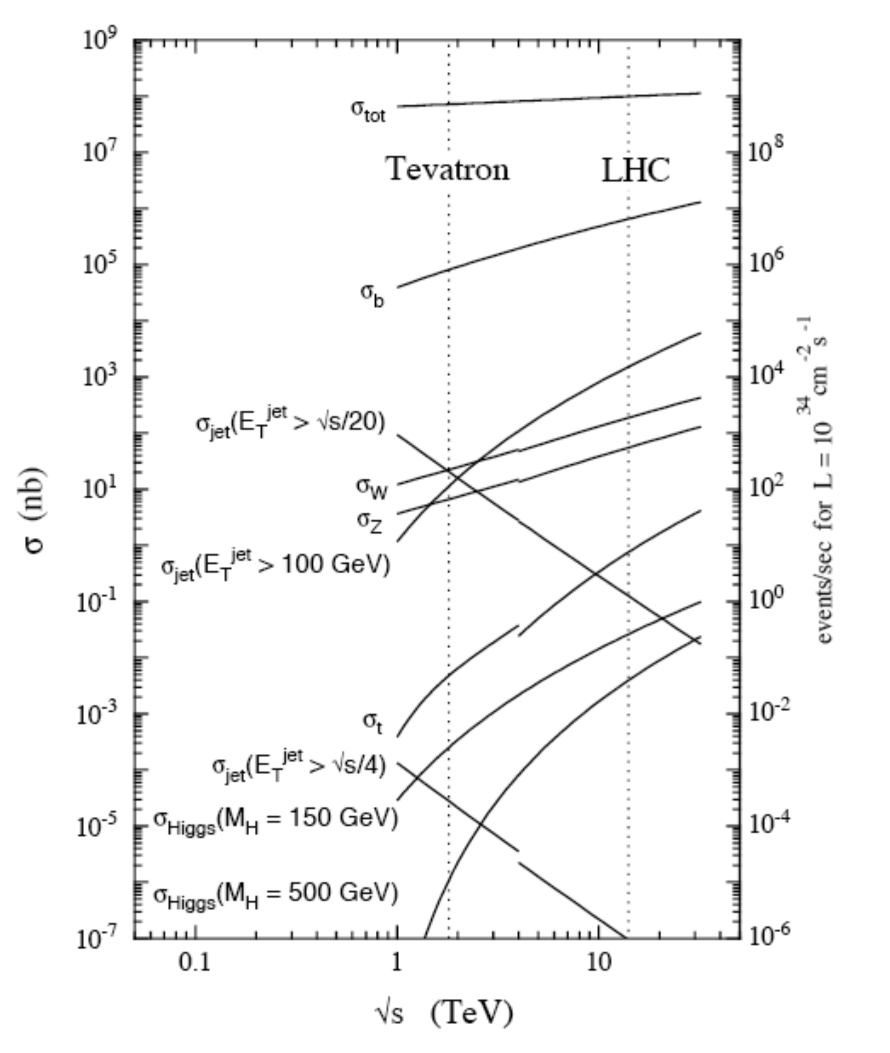
- New result: first time we have been able to rule out any SM Higgs mass at the Tevatron!



"If m_H is 170 GeV, then probability is < 5% of seeing something even less signal-like"

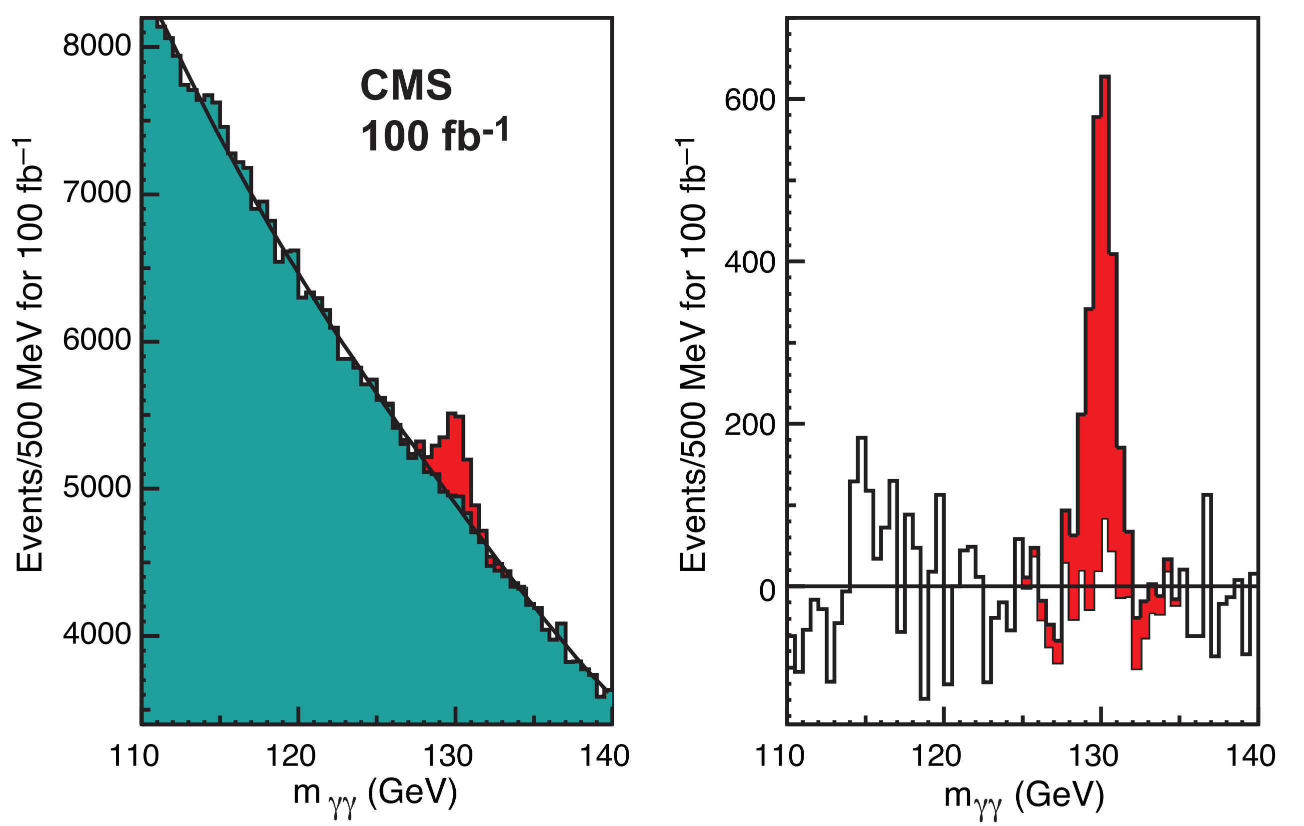
SM Higgs at the LHC

- Cross section is orders of magnitude larger at the LHC!
- W, Z backgrounds don't rise as much
- Very difficult to use bb or tau tau decay modes
- LHC relies on the very small γγ branching ratio for initial discovery and mass measurement



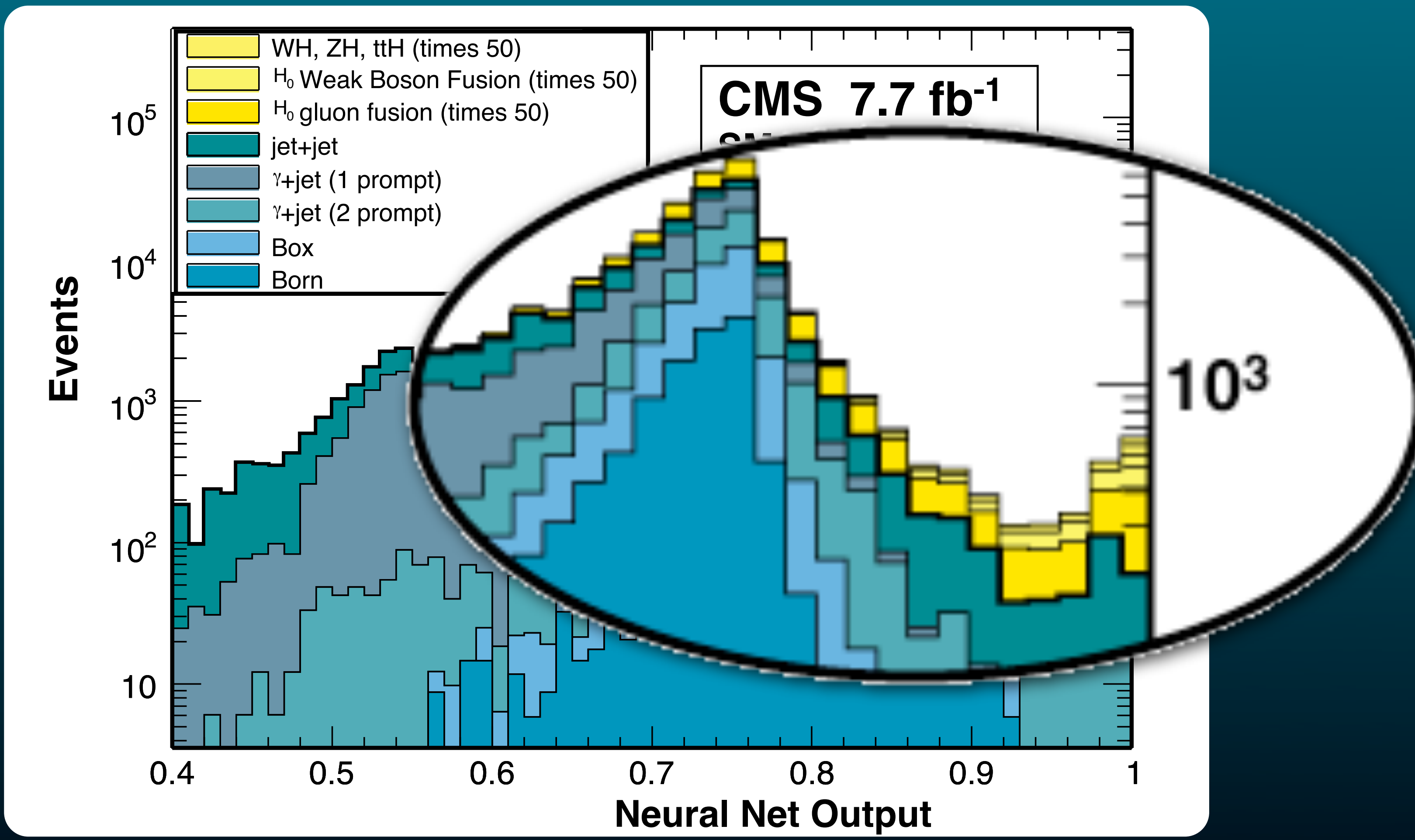
$H \to \gamma\gamma$ at the LHC

- CMS optimized neural net analysis can deliver signal with < 10 fb^{-1}; here is the 100 fb^{-1} signal

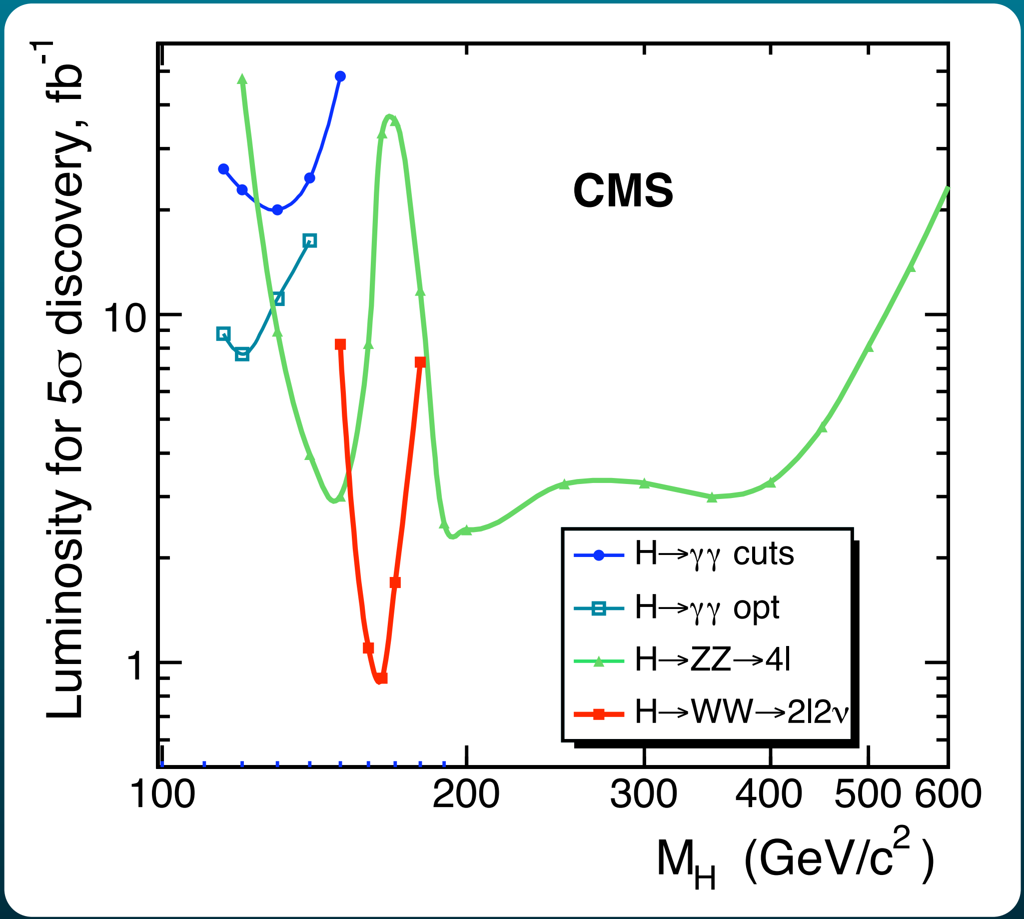


H →γγ at the LHC

- CMS optimized neural net analysis can deliver signal with < 10 fb^{-1}; here is the NN output

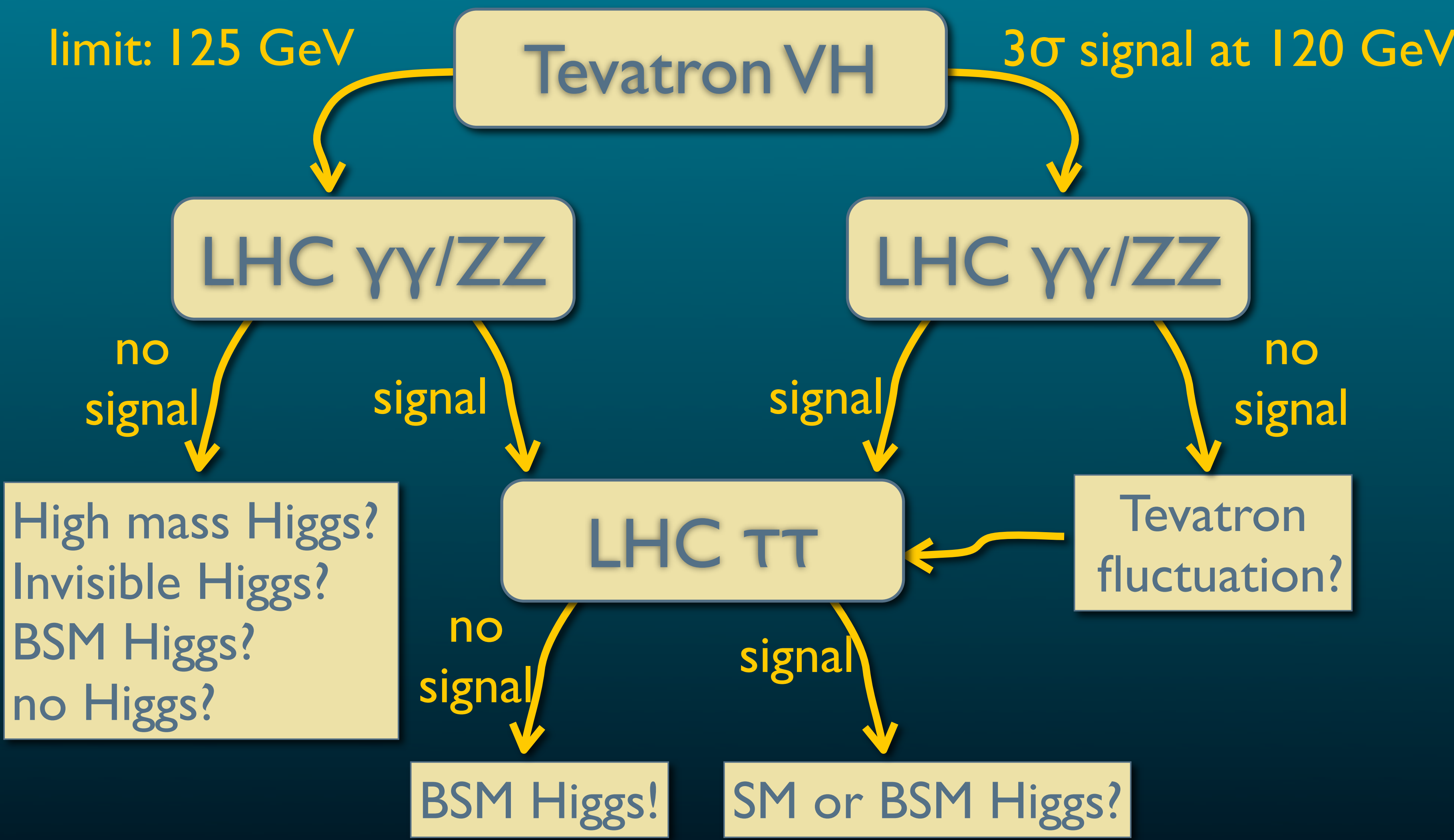


SM Higgs reach in CMS



Can make a 5σ discovery at low mass within the first $10\ \mathrm{fb}^{-1}$ probably in 2010 (this plot needs updating!)

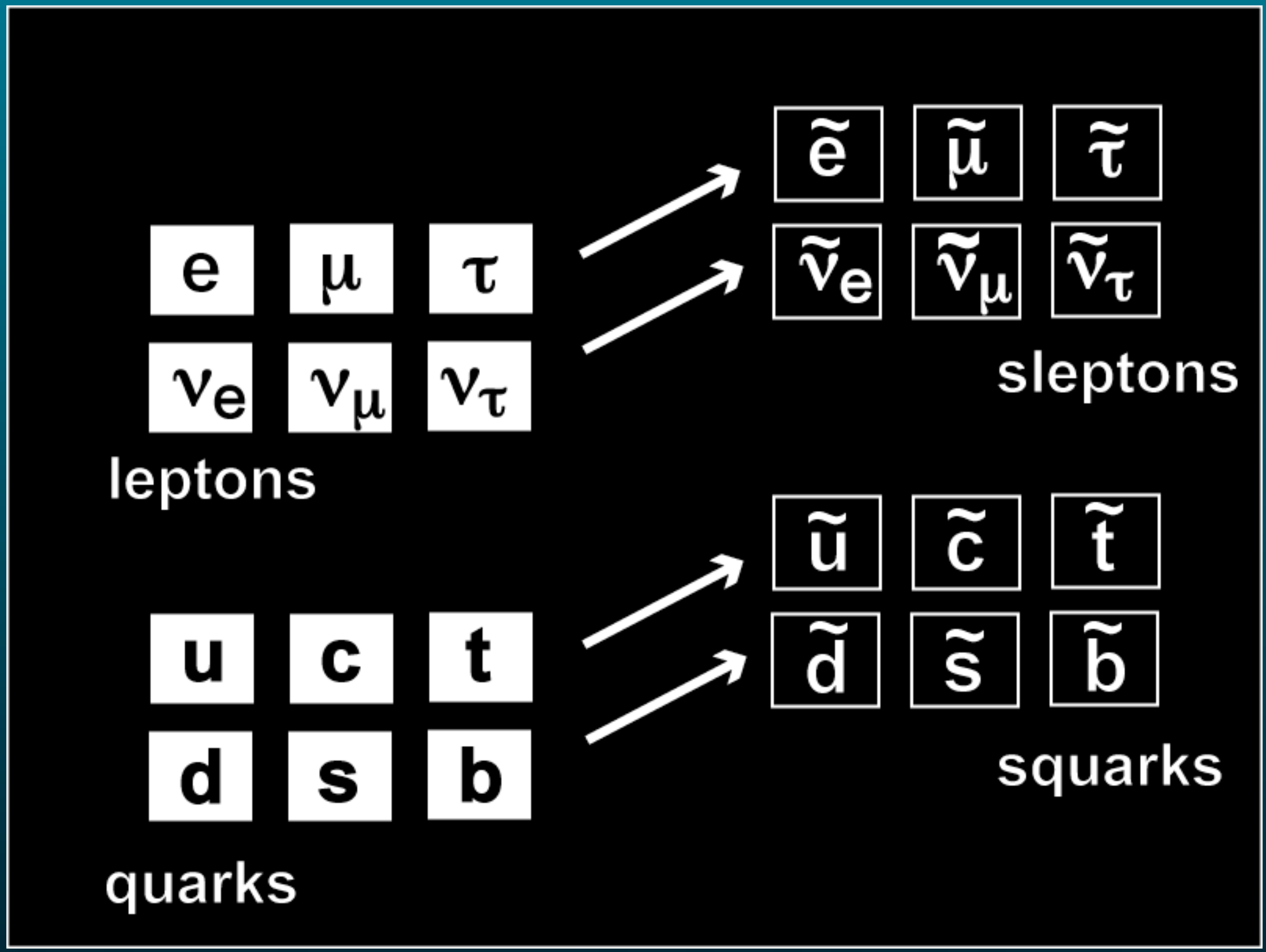
SM or BSM Higgs?



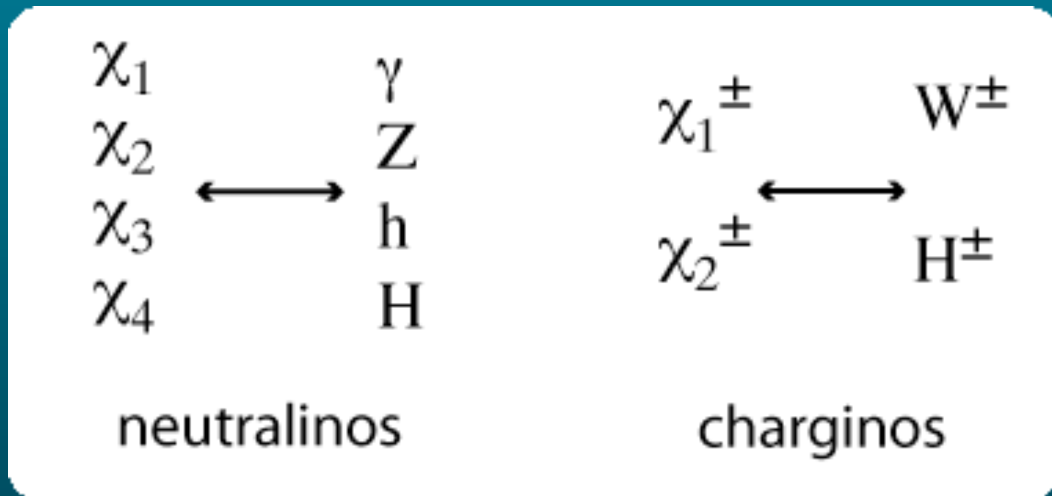
First Steps Beyond: SUSY

- we really don't expect that the only new particle awaiting us is a SM Higgs boson
- hierarchy problem: Higgs mass unstable against large, extremely finely tuned corrections
- supersymmetry solves the hierarchy problem, at least partly, in that the presence of scalar partners for every SM fermion cancels the quadratic divergences
- MSSM: the minimal version of supersymmetry requires at least two Higgs doublets, one giving mass to the up-type quarks and the other giving mass to the down-type quarks and leptons

SUSY partners



SUSY partners



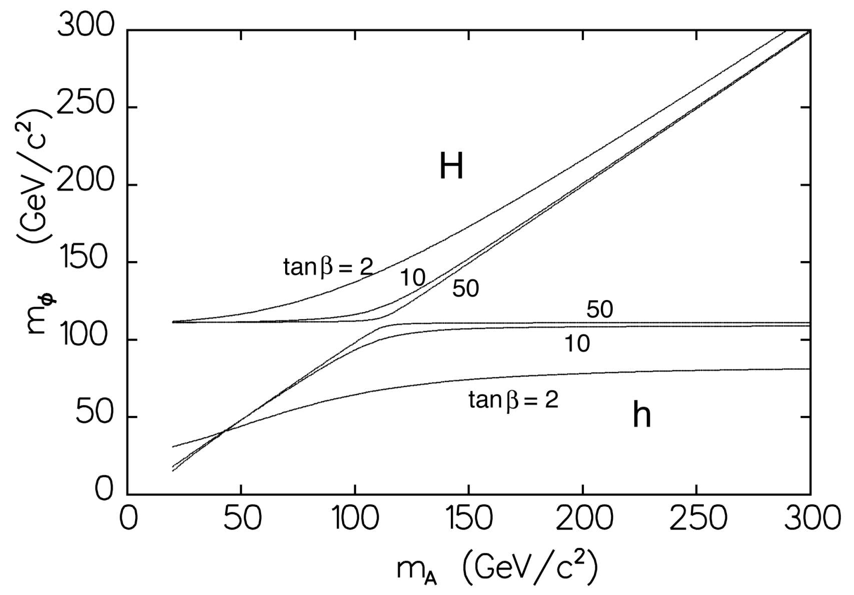
- mixing determines mass hierarchy and couplings for gauginos
- R-parity conserved ⇒ sparticles are pair-produced

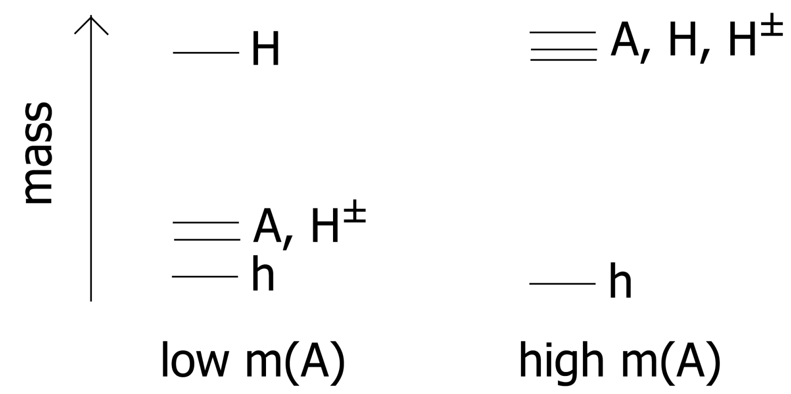
  ⇒ lightest SUSY particle stable
- LSP (neutralino or sneutrino?) is dark matter candidate

MSSM Higgs Bosons

- there are five physical Higgs boson states in the MSSM

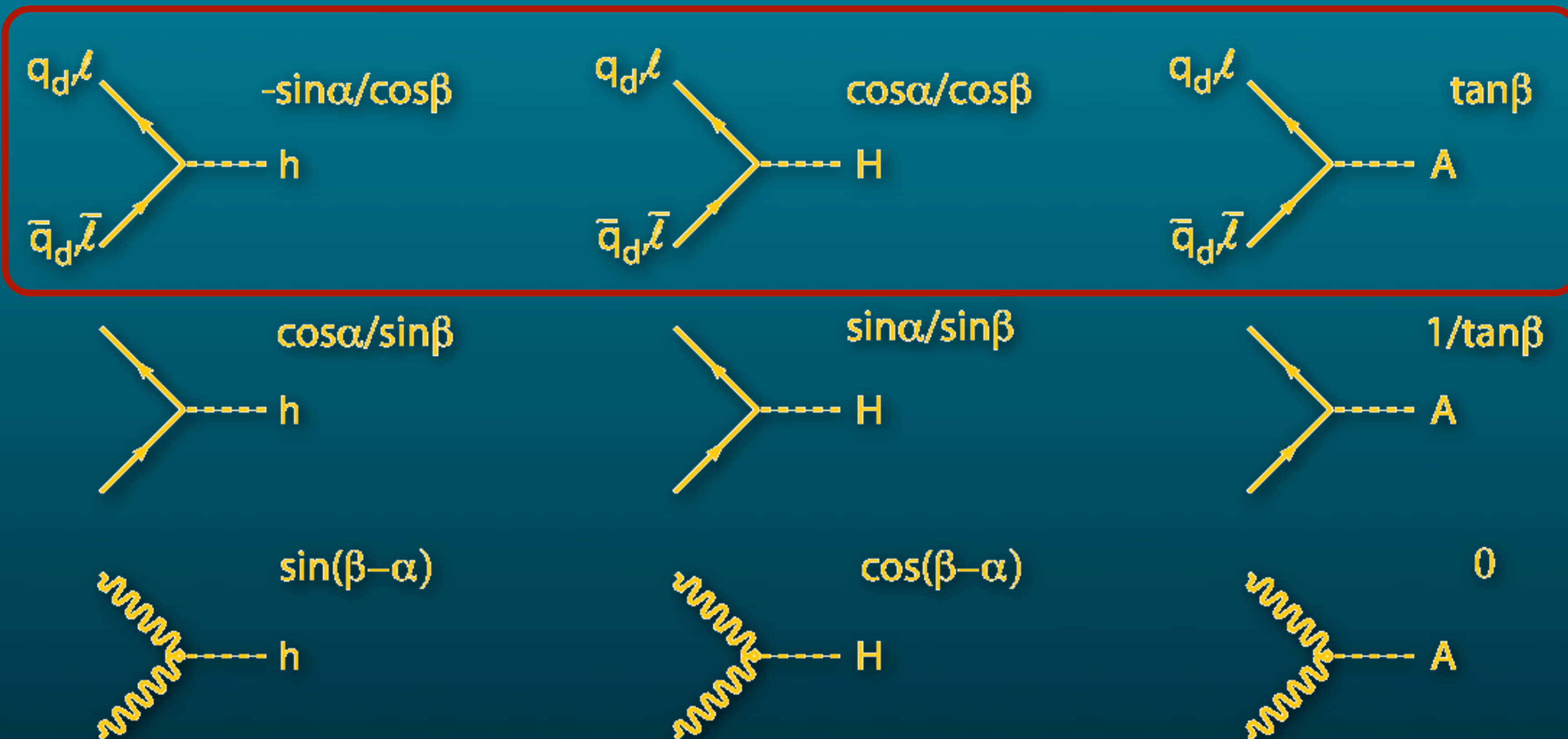
H heavy scalar
A pseudoscalar
h light scalar
$H^{\pm}$ charged Higgs





- masses determined by two parameters, tanβ and m_A
- h can be SM-like!

MSSM Higgs Couplings

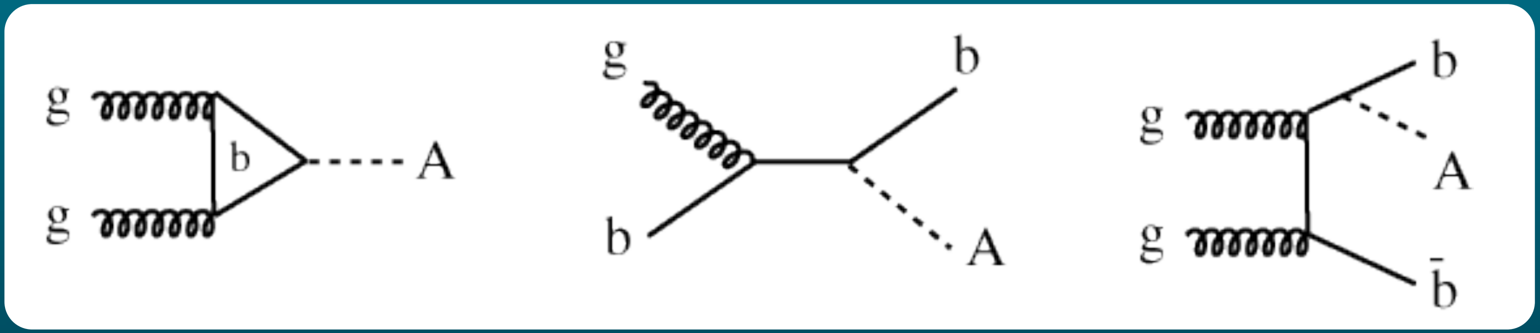


$\tan\beta$: ratio of vev of the two Higgs doublets

$\tan\beta \sim m_t/m_b \sim 35 \;\Rightarrow$ strong enhancements

MSSM Higgs: Tau Pair Mode

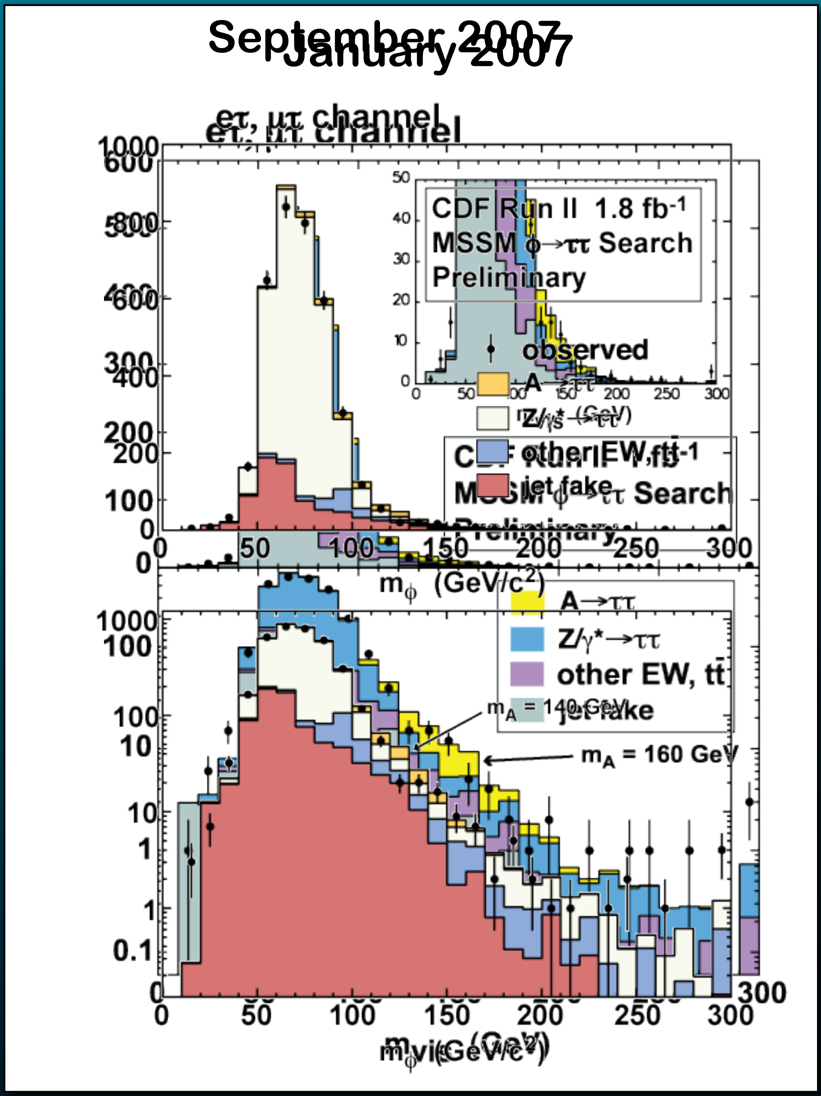
- gg, gb, modes are all enhanced by $\tan^2\beta$:



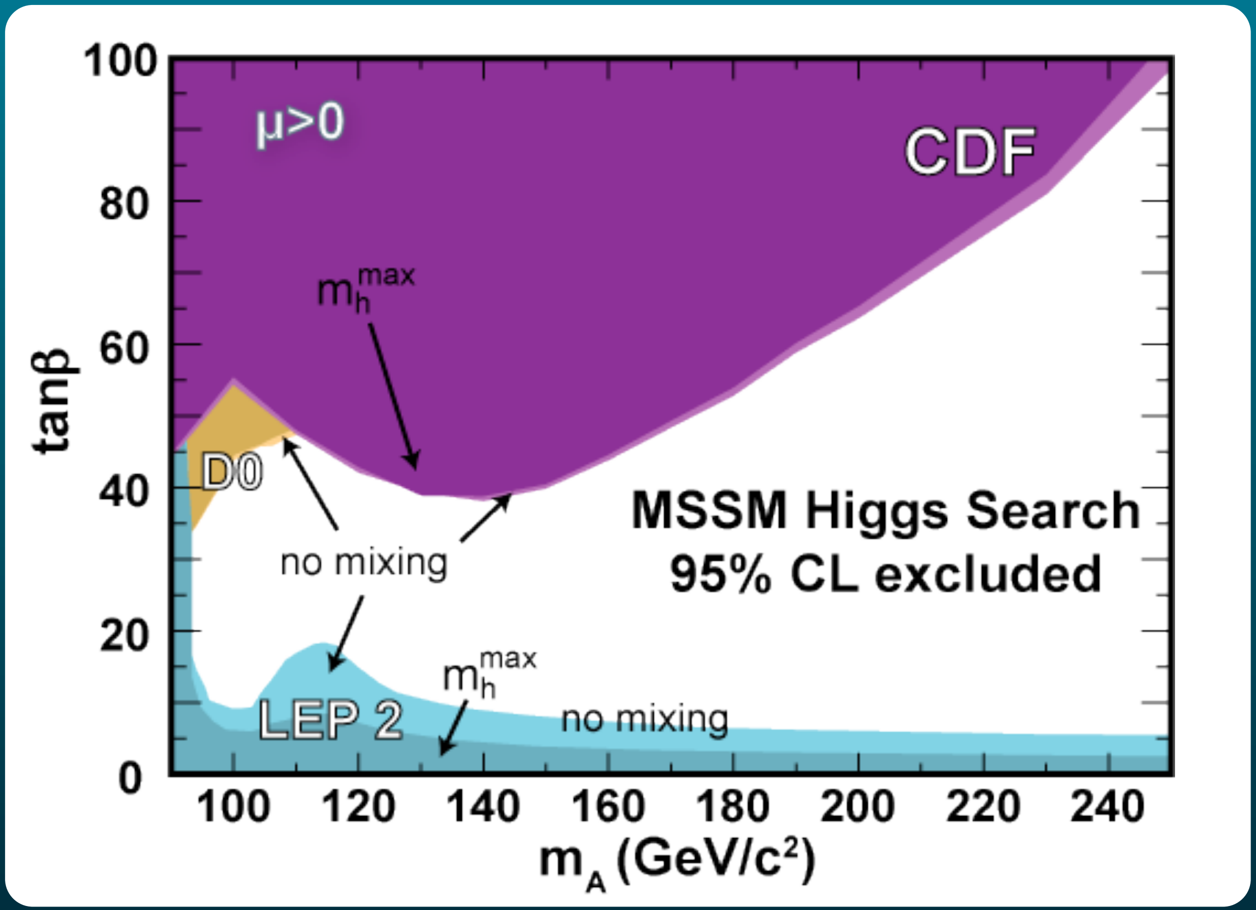
- can look at either bb (harder) or ττ (easier) decay modes of the h/A/H
- always have at least two nearly degenerate states at large $\tan\beta$

MSSM Higgs: tau pair mode

- January 2007: did we have the beginnings of a signal?
- only a 2σ excess...
- September 2007: with 80% more data, “signal” proved to be a fluctuation...

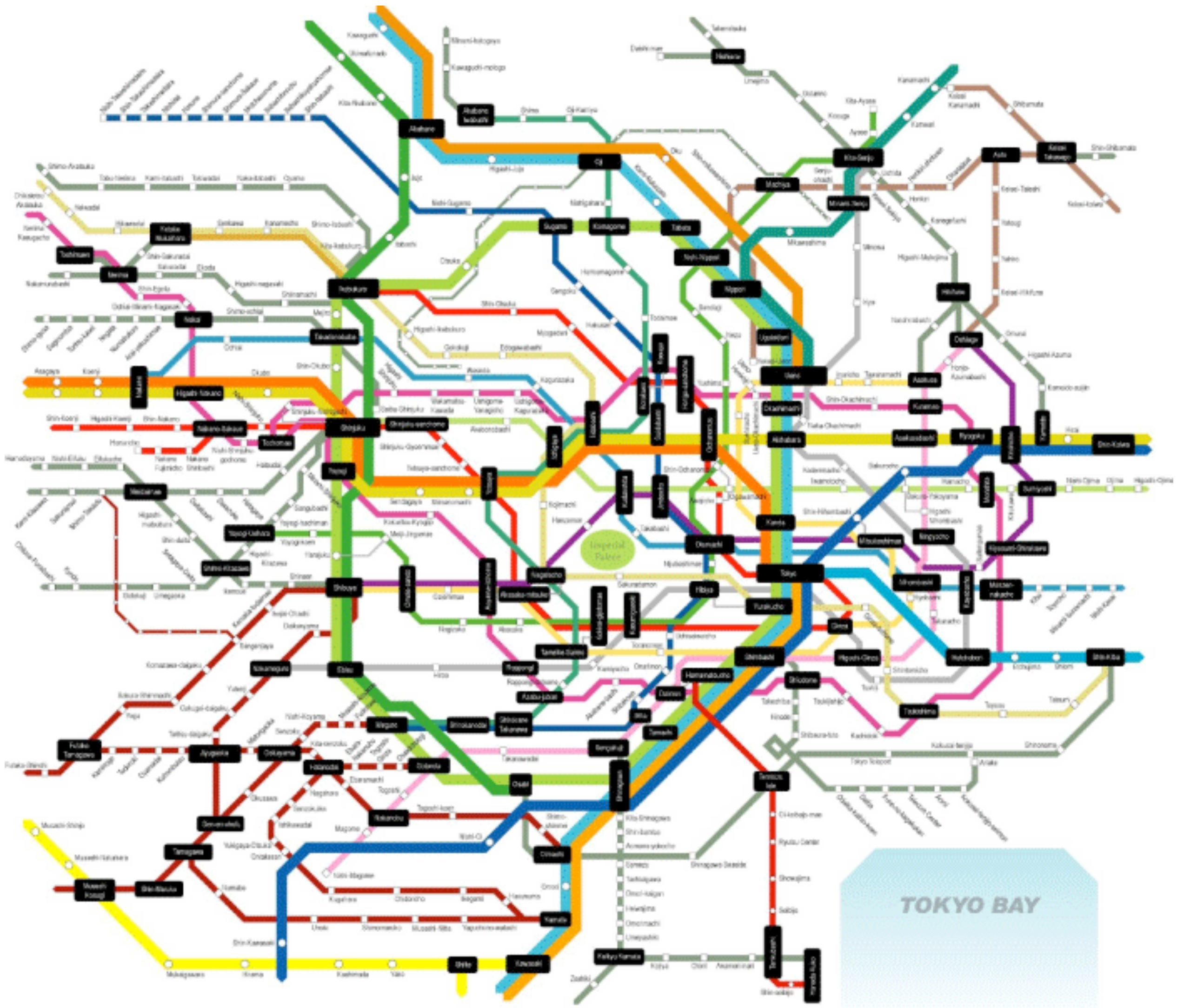


World knowledge on MSSM Higgs



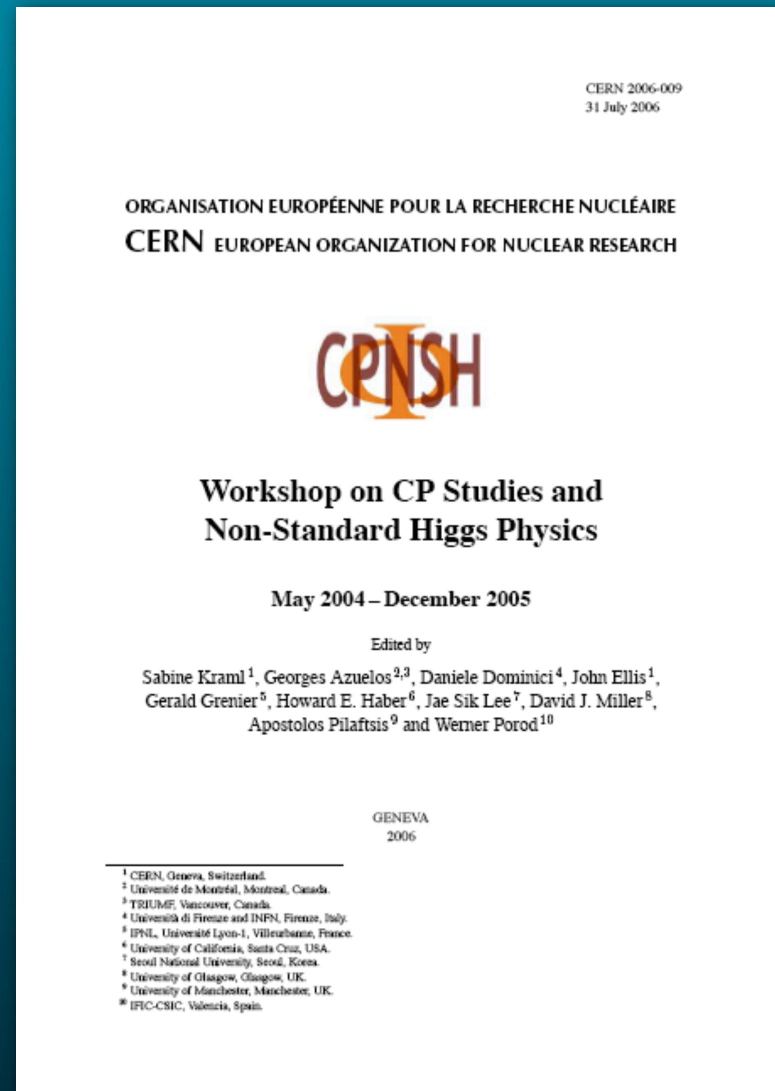
- we are getting into the interesting regime!
- limited only by statistics - will soon get much better

MSSM Higgs at the LHC



Beyond the MSSM

- SUSY models have greatly multiplied in recent years
- CPNSH workshop report:
  - ~~CP~~ 2HDM
  - MSSM with CP phases
  - NMSSM (MSSM+singlet)
  - RPV MSSM
  - Extra gauge groups
  - Little Higgs models
  - Large extra dimensions
  - Warped extra dimensions
  - Higgsless models
  - Strongly interacting Higgs
  - Technicolor
  - Higgs triplets


CERN 2006-009
31 July 2006

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CPNSH

Workshop on CP Studies and Non-Standard Higgs Physics

May 2004 – December 2005

Edited by

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2006

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http://kraml.web.cern.ch/kraml/cpnsh/

"Higgs Hunters Guide to non-standard Higgs"

Search for SUSY: Tevatron

- two classic collider signatures for SUSY partners

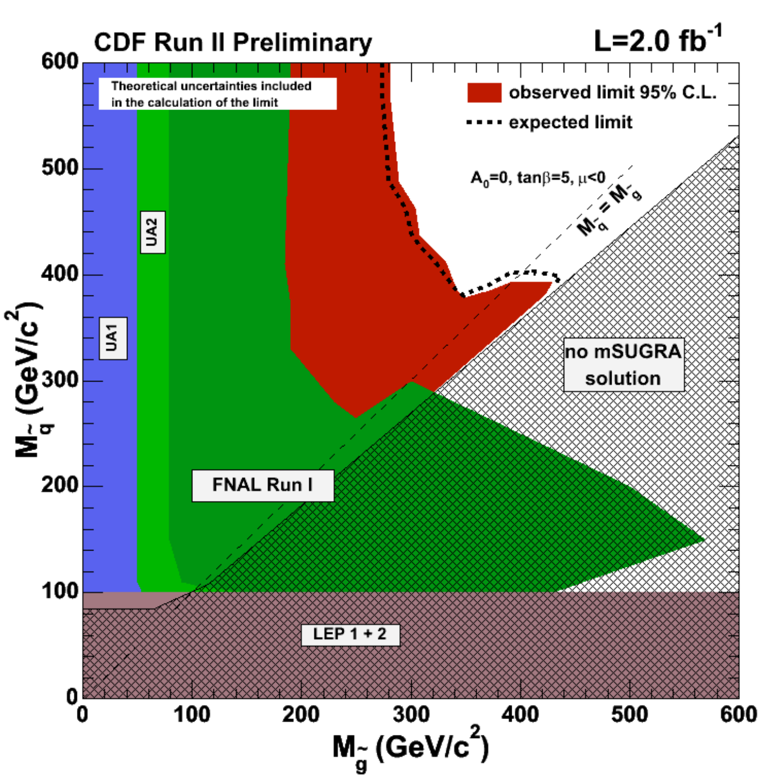
1. jets + $\not{E}_T$ from squark/gluino production
2. "trileptons" from $\chi^{\pm}\chi^{0}$ production

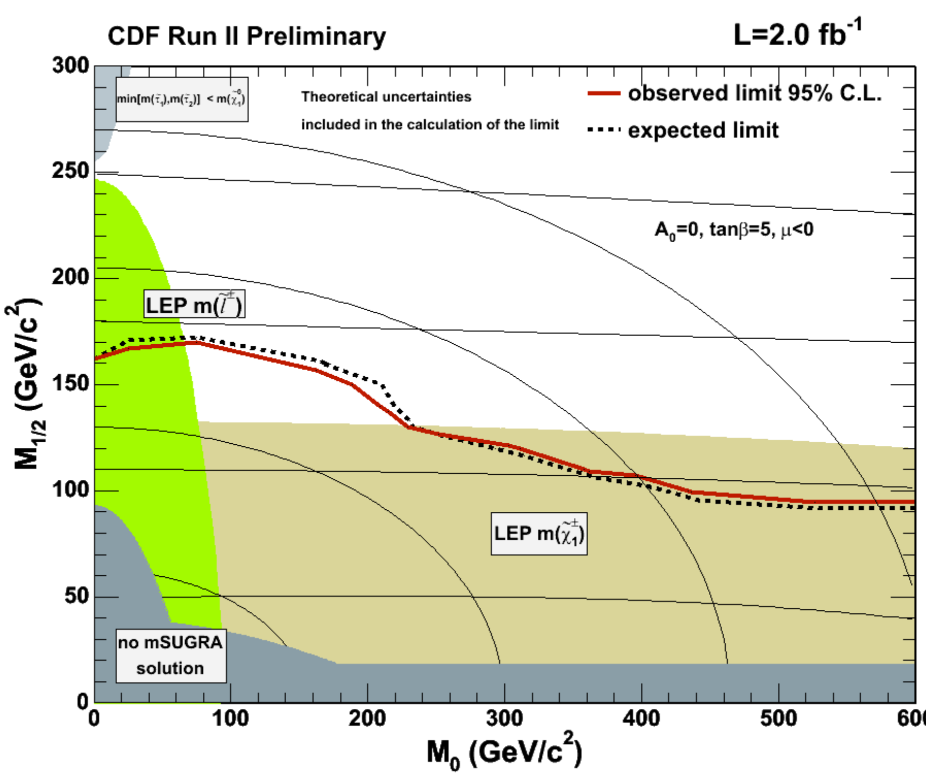
CDF RUN II Preliminary $\int \mathcal{L}dt = 2.0\ \mathrm{fb}^{-1}$: Search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$

Channel	Signal	Background	Observed
3tight	$2.25 \pm 0.13(\mathrm{stat}) \pm 0.29(\mathrm{syst})$	$0.49 \pm 0.04(\mathrm{stat}) \pm 0.08(\mathrm{syst})$	1
2tight,1loose	$1.61 \pm 0.11(\mathrm{stat}) \pm 0.21(\mathrm{syst})$	$0.25 \pm 0.03(\mathrm{stat}) \pm 0.03(\mathrm{syst})$	0
1tight,2loose	$0.68 \pm 0.07(\mathrm{stat}) \pm 0.09(\mathrm{syst})$	$0.14 \pm 0.02(\mathrm{stat}) \pm 0.02(\mathrm{syst})$	0
Total Trilepton	$4.5 \pm 0.2(\mathrm{stat}) \pm 0.6(\mathrm{syst})$	$0.88 \pm 0.05(\mathrm{stat}) \pm 0.13(\mathrm{syst})$	1
2tight,1Track	$4.44 \pm 0.19(\mathrm{stat}) \pm 0.58(\mathrm{syst})$	$3.22 \pm 0.48(\mathrm{stat}) \pm 0.53(\mathrm{syst})$	4
1tight,1loose,1Track	$2.42 \pm 0.14(\mathrm{stat}) \pm 0.32(\mathrm{syst})$	$2.28 \pm 0.47(\mathrm{stat}) \pm 0.42(\mathrm{syst})$	2
Total Dilepton+Track	$6.9 \pm 0.2(\mathrm{stat}) \pm 0.9(\mathrm{syst})$	$5.5 \pm 0.7(\mathrm{stat}) \pm 0.9(\mathrm{syst})$	6

SUSY Limits from Tevatron

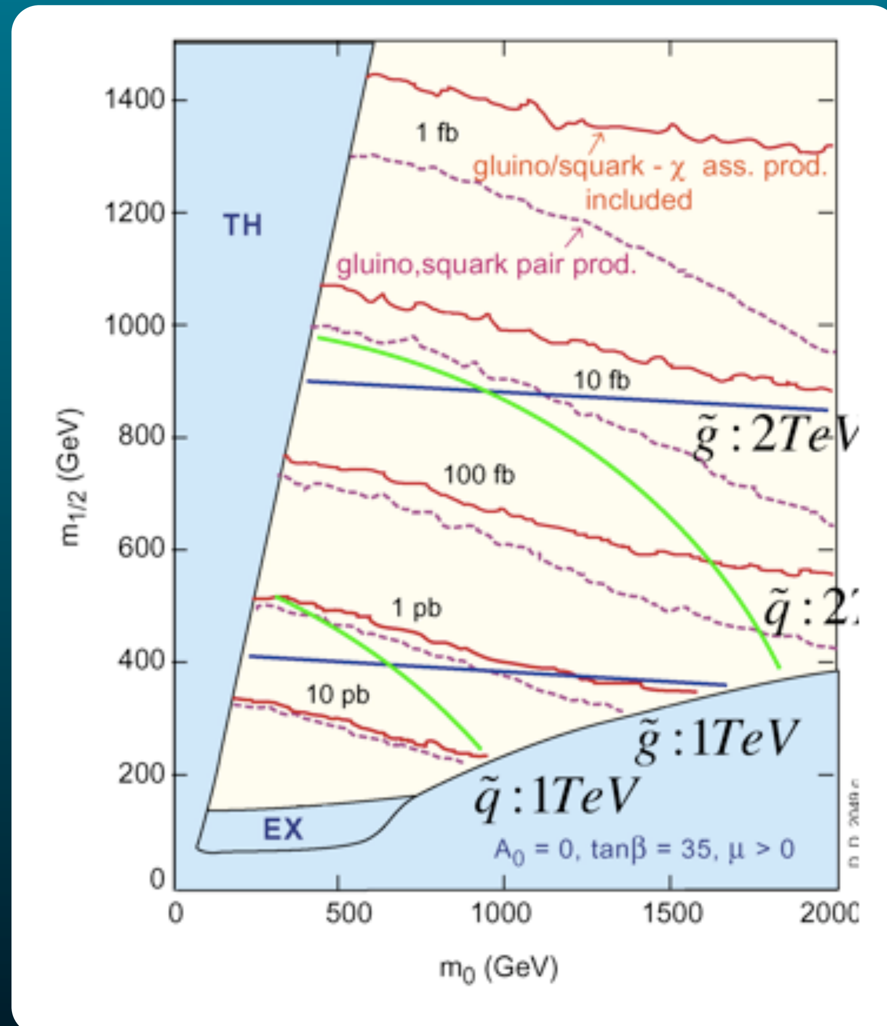
- can show limits in squark-gluino mass plane, or in terms of mSUGRA $M_{1/2}$ versus M_0





Search for SUSY: LHC

- the much larger energy of the LHC translates into greatly improved SUSY mass reach
- can move beyond Tevatron reach with the very first data sample
- will rely on getting good calibration for missing E_T very quickly after startup
- can use kinematic edges to measure gaugino masses



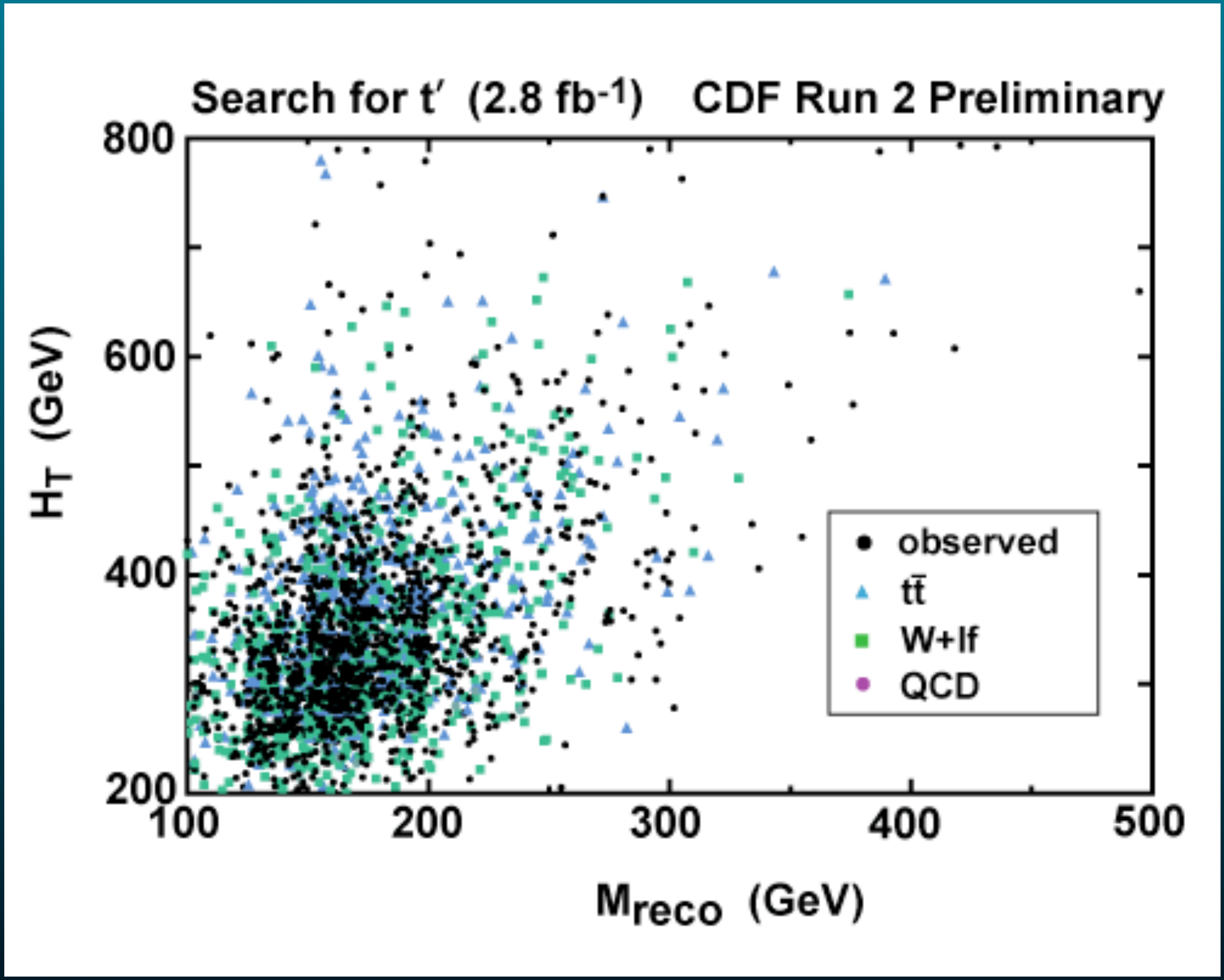
New Fermions/Bosons

- can there be a fourth generation of fermions?
- perhaps quark generations aren't linked to lepton ones?
- can there be new, heavy gauge bosons Z',W' ?
- constraints:
  - EW precision measurements
  - direct SM Higgs searches
- new fermions/bosons appear in a wide variety of BSM models: best strategy is to search broadly

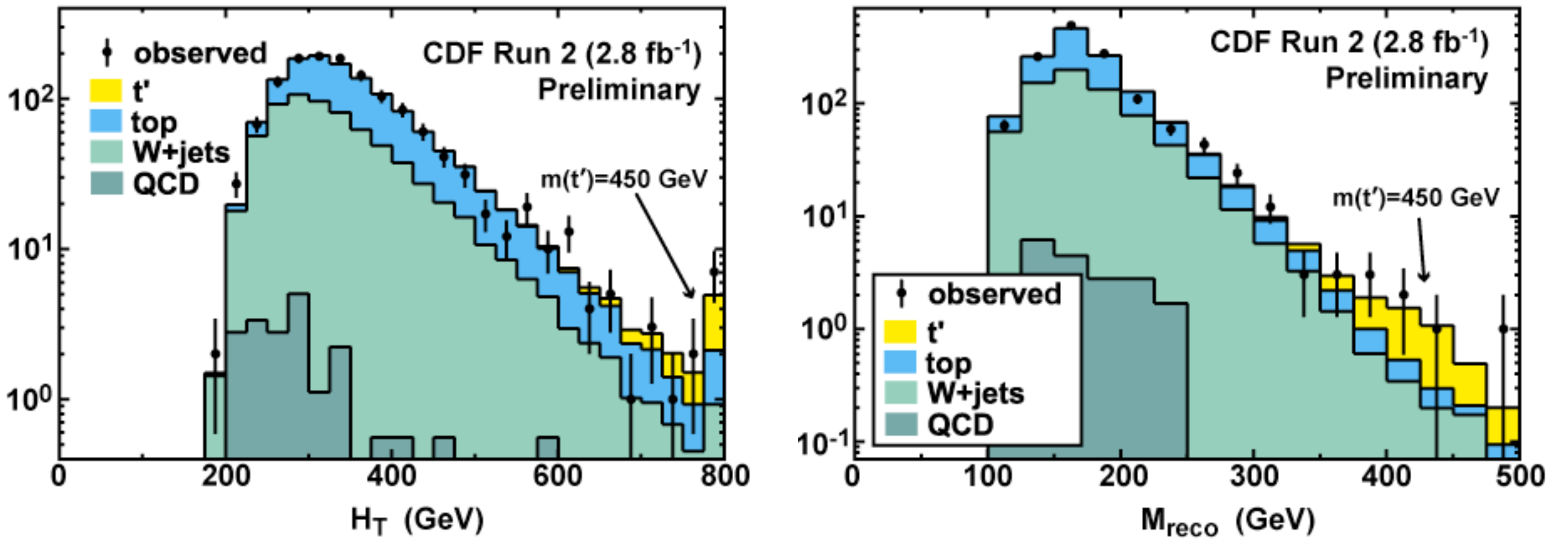
Search for t′

- CDF looks for new heavy top-like quark decaying via $t' \rightarrow Wq$ (probably q = b)
- pair-production would lead to final states with a lepton, 4 jets, and missing E_T
- can use standard top mass fit to reconstruct mass of t′ on event-by-event basis
- perform binned search in plane of M_{reco} and H_T
- search is sensitive to any new phenomena which show up in the extremes of these two variables

Search for t′ at the Tevatron

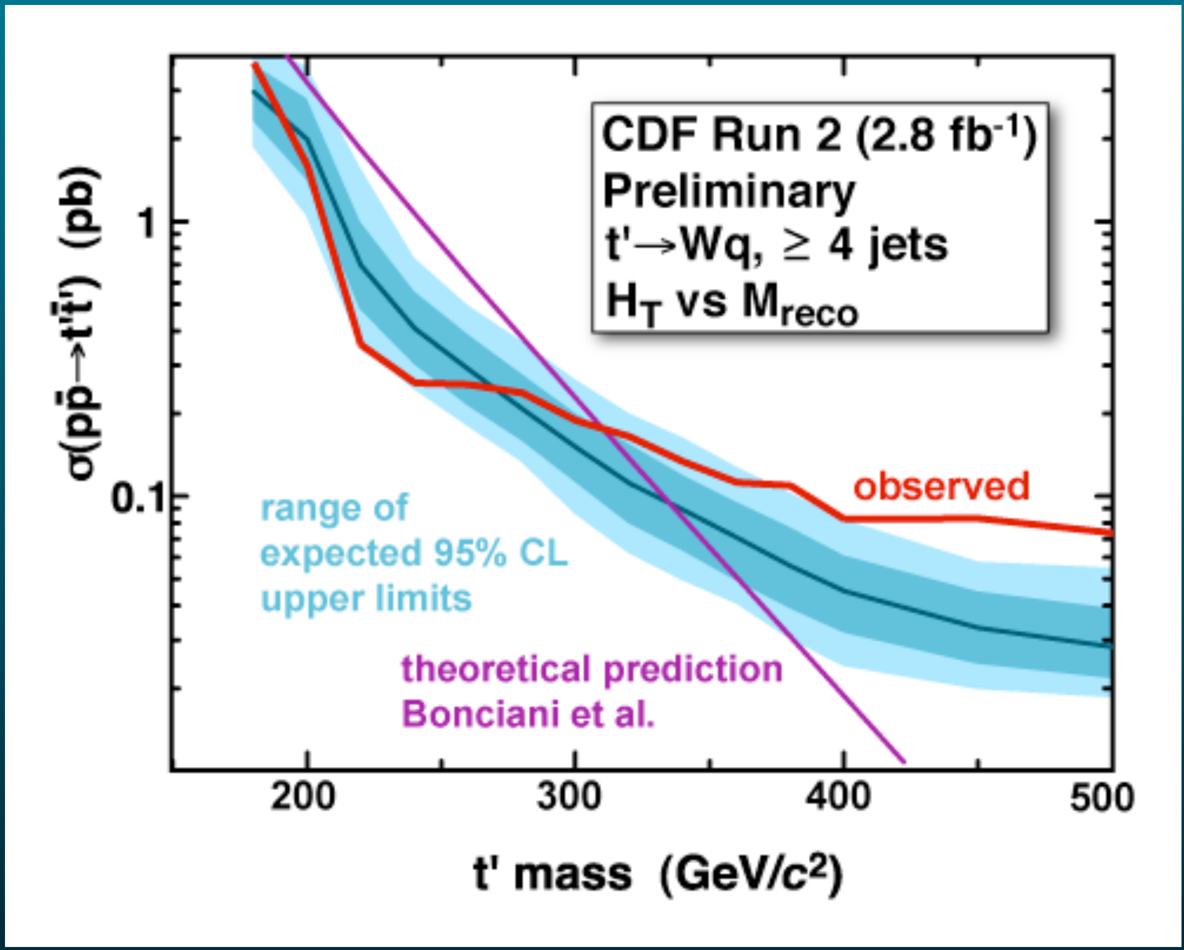


Search for t′ at the Tevatron



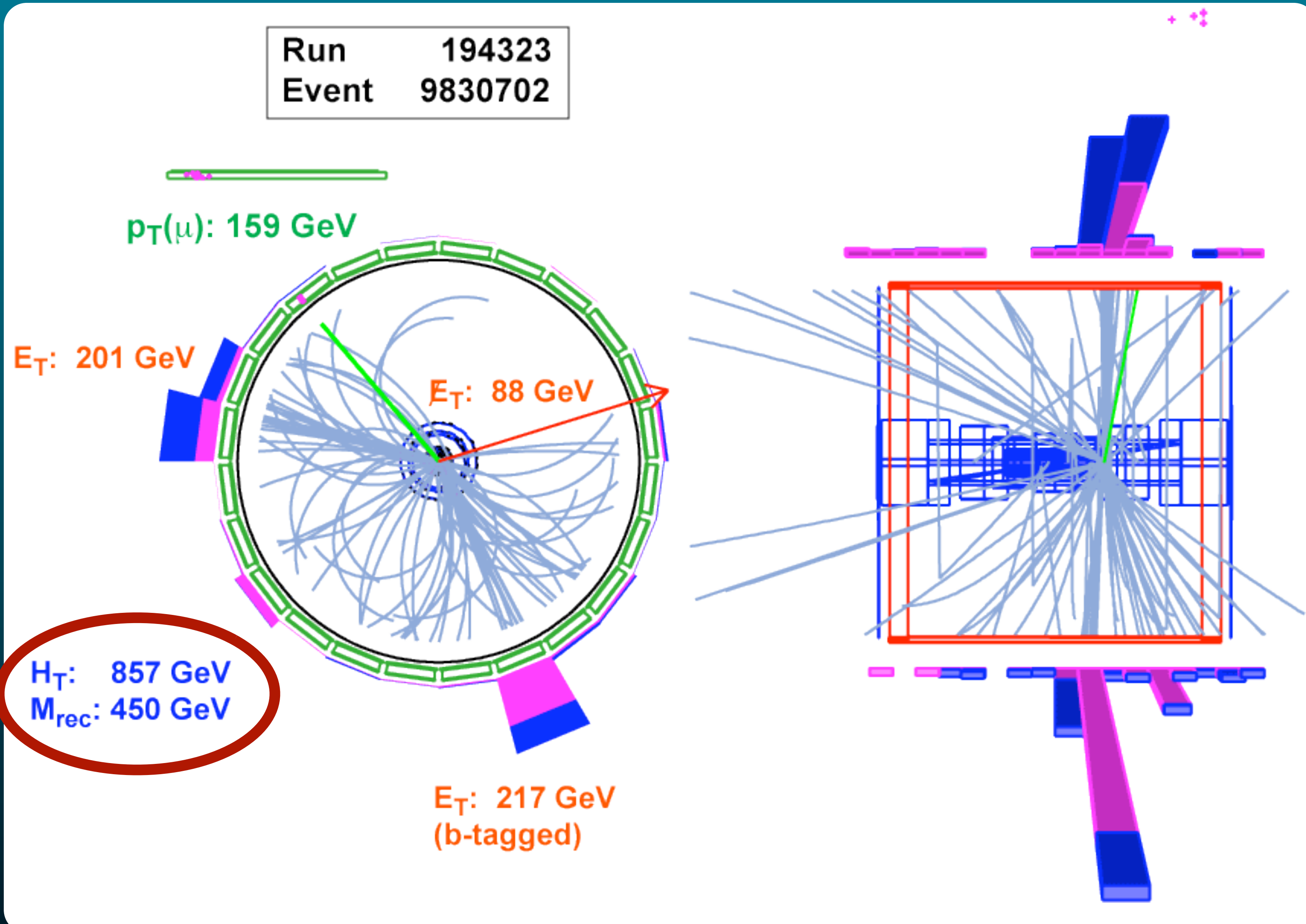
- projections of the two variables show amazing agreement over orders of magnitude
- excess at highest H_T, M_{reco}~450 GeV is intriguing but far too large to be explained by t′

Search for t' at the Tevatron



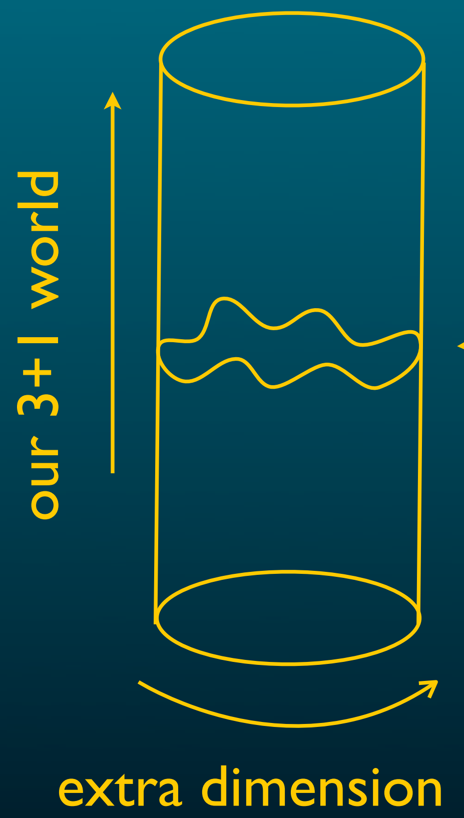
- final result rules out t' with mass less than 311 GeV
- the excess is under investigation!

Search for t′ at the Tevatron



Extra Dimensions: ADD model

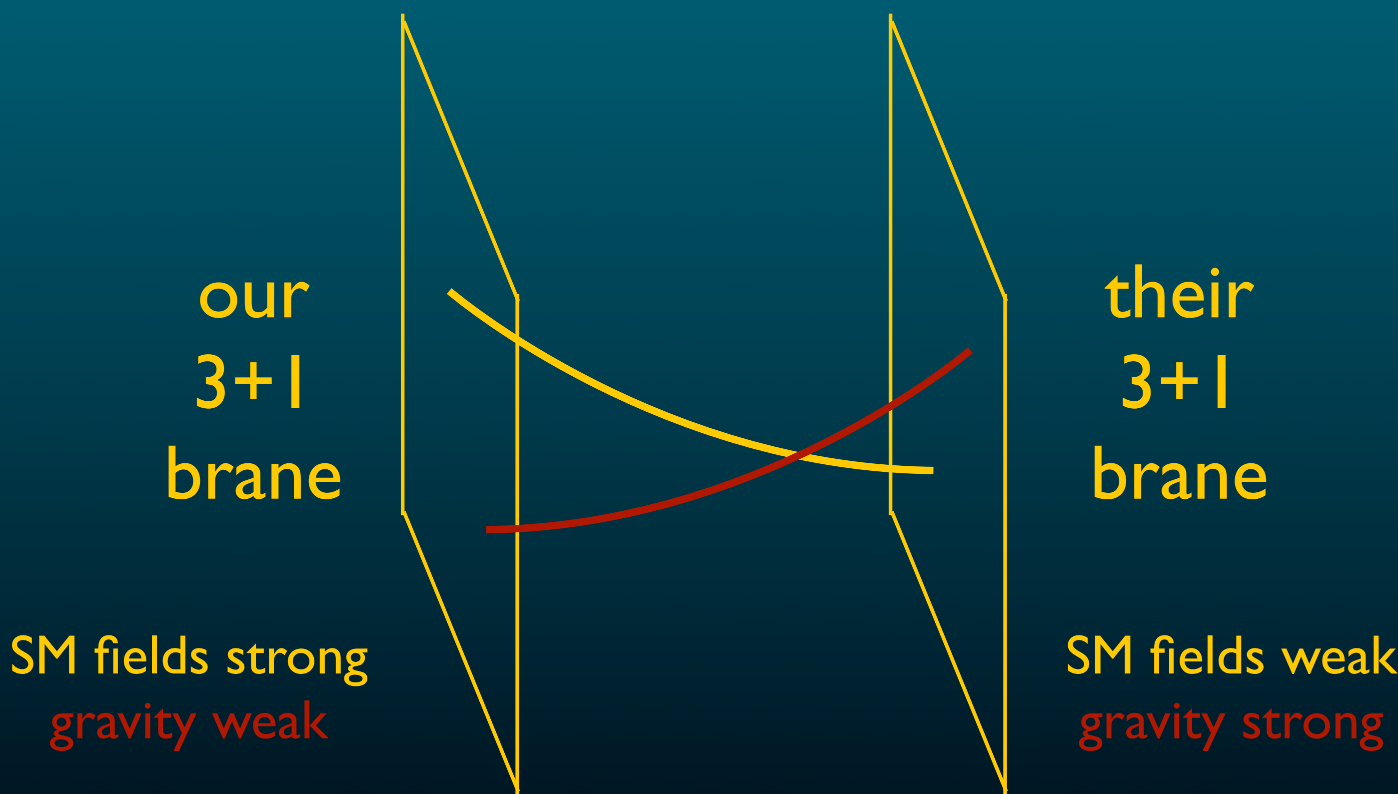
- can our world have extra, small (yet "large") dimensions?



Kaluza-Klein mode in extra dimension can carry away momentum; manifest as graviton only?

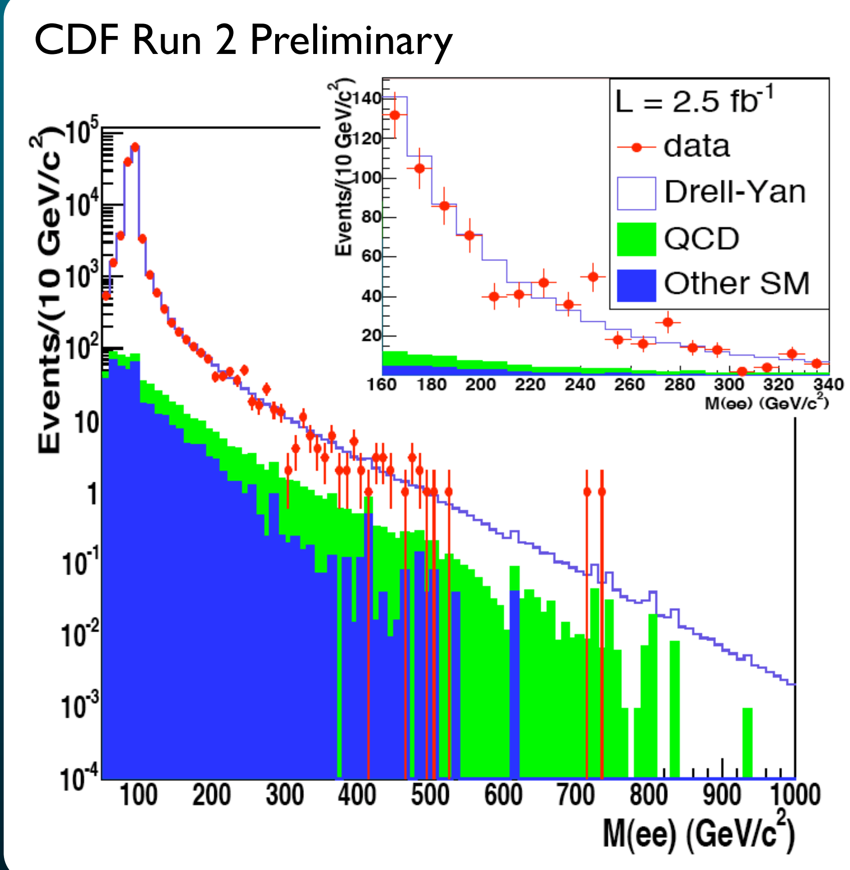
Extra dimensions: RS model

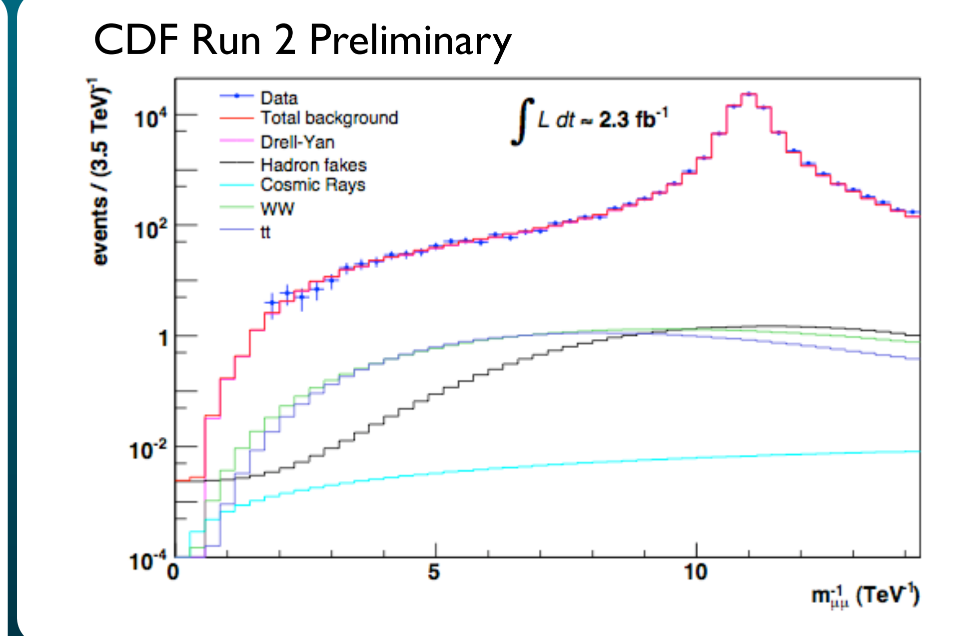
- more recently popular is the Randall-Sundrum model in which our 3+1 world brane has a parallel 3+1 world separated from ours by a tiny extra dimension:



Lepton Pair Resonances: Tevatron

- new gauge bosons (Z′), extra dimension theories predict resonances at large $\ell^+\ell^-$ invariant masses

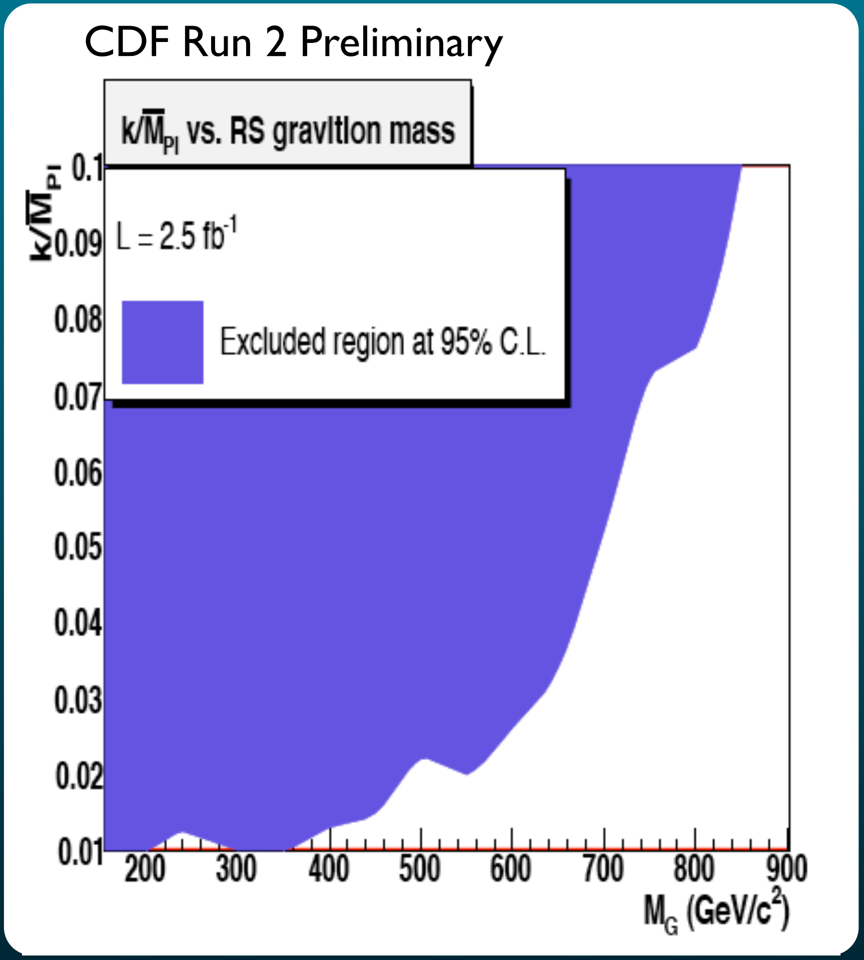




Teaching moment: why do we show m_{ee} spectrum, but for muon pairs show $1/m_{\mu\mu}$?

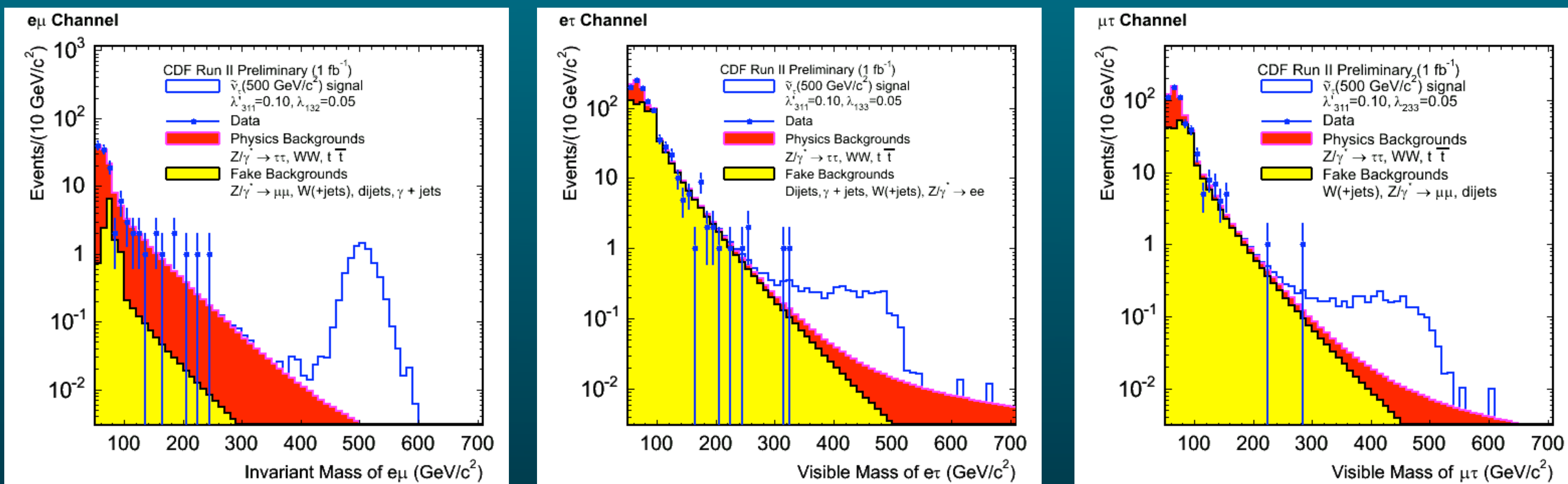
Lepton Pair Resonances: Tevatron

- can use the non-observation of bumps in these spectra to set limits on
  - Z′
    mass > 1.03 TeV if Z′ has SM couplings
  - RS gravitons:
    mass limits depend on curvature parameter



LFV in CDF?

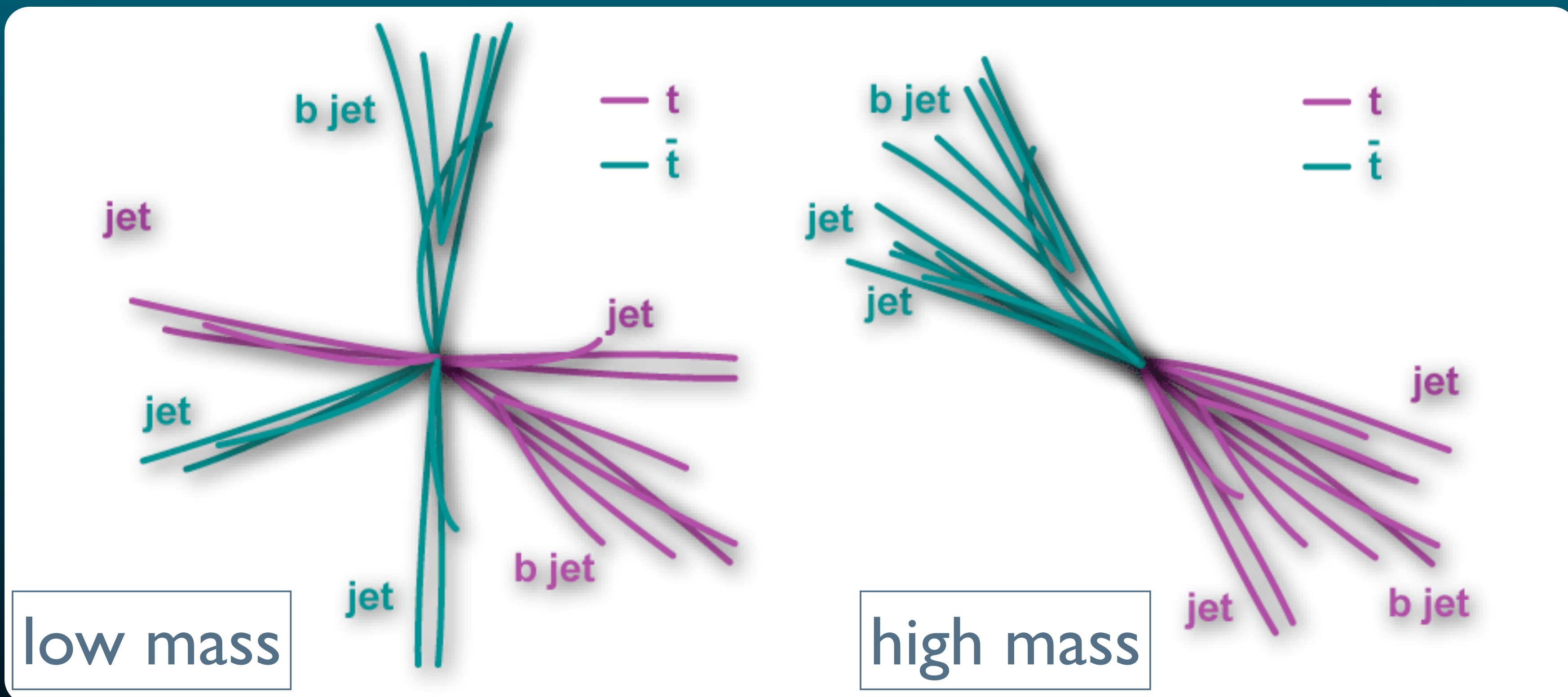
- look at e+μ, e+τ, μ+τ final states for resonances:



- set limits on
  - RPV sneutrinos
  - LFV Higgs (J.L. Diaz-Cruz)

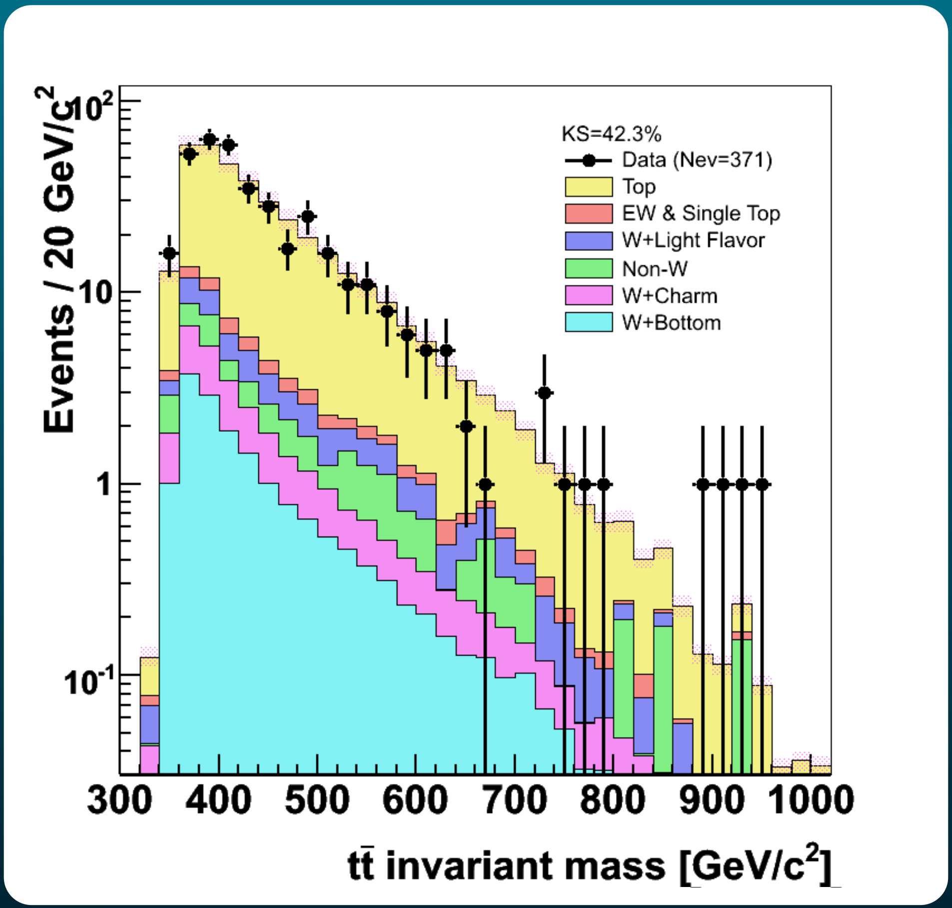
Search for $t\bar{t}$ Resonances

- some new resonances may prefer to decay to top quark pairs (Agashe et al. Phys.Rev.D77:015003,2008)
- search at lower mass is less easy than high mass:



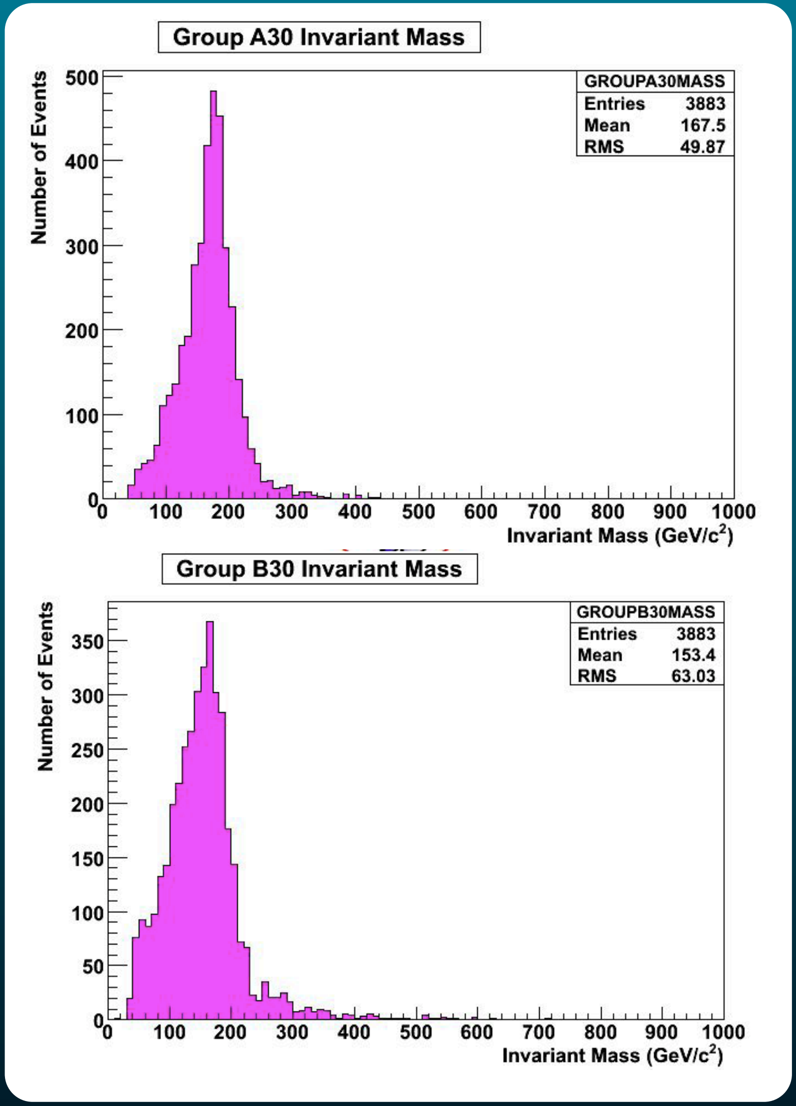
Search for $t\bar{t}$ Resonances

- CDF has searched for $t\bar{t}$ resonances in 1.9 fb-1
- no signal yet!
- a great deal of work is underway at the LHC experiments
- can see signals with the very first data from the experiments up to several TeV mass

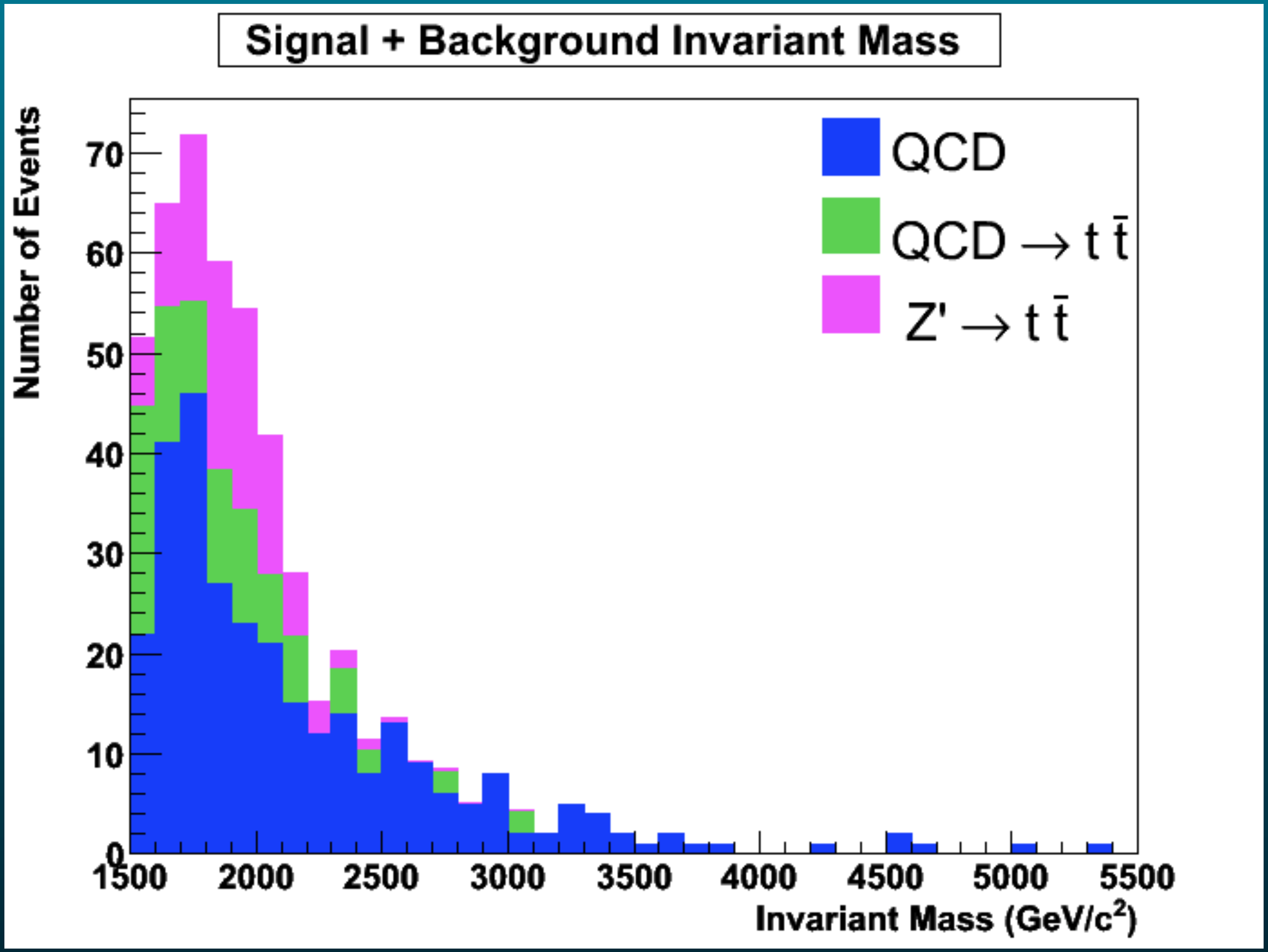


$t\bar{t}$ Resonances at the LHC

- with high mass resonances, combinatorics is not a problem
- my group is studying whether we can use the all-hadronic mode to see heavy resonances
- we simply look for back-to-back groupings of jets, and take the invariant mass on each side
- require both cones to be consistent with top - greatly reduces QCD background



$t\bar{t}$ Resonances at the LHC



- can get quite good resolution and S/B!

Casting a Broad Net

- there are so many possible new physics models - how do we cover all of them in our searches?
- our prejudice is that new physics could, and probably should, show up as new high-energy processes
- experiments are now doing very broad, generic searches for new physics
- CDF: the Vista/Sleuth approach, pioneered by Bruce Knuteson and a team from MIT
- results are in from over 2 fb^{-1} !

Vista/Sleuth in CDF

- start by identifying high-p_T final state objects in each event:
  - γ, e, μ, τ, jet, b-jet, $\not{E}_T$
- create categories of pairs, triplets, etc. of these objects: 399 different final states
- create huge inclusive background MC samples
- then compare:
  - numbers of events, kinematic shapes
  - high sum-p_T tails
  - mass bumps

Vista/Sleuth in CDF

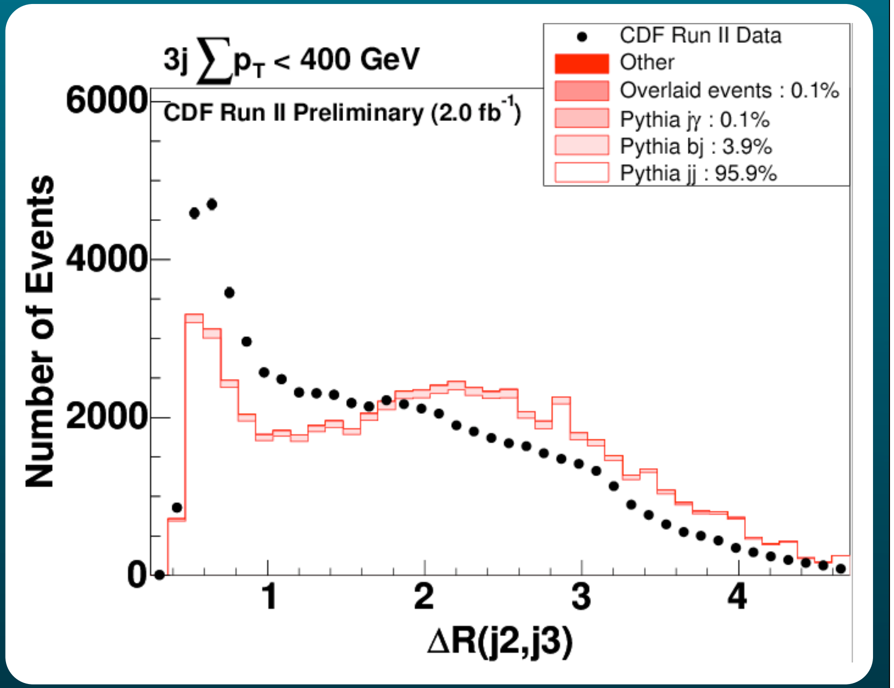
- result from 2 fb^{-1} shows 10 most discrepant channel rates
- ostensibly we have a 4.3σ deficit in be$\not{E}_T$
- however, must take into account "trials factor" which effectively makes this 2.7σ
- next look at kinematic distributions

CDF Run II Preliminary (2.0 fb^{-1})

Final State	**Data**	**Background**	σ
$\mathrm{b}e^{\pm}\not{p}$	690	817.7 ± 9.2	-4.3
$\gamma\tau^{\pm}$	1371	1217.6 ± 13.3	$+4.0$
$\mu^{\pm}\tau^{\pm}$	63	35.2 ± 2.8	$+3.7$
b2j$\not{p}$ high-Σp_T	255	327.2 ± 8.9	-3.7
2j$\tau^{\pm}$ low-Σp_T	574	670.3 ± 8.6	-3.6
3j$\tau^{\pm}$ low-Σp_T	148	199.8 ± 5.2	-3.5
$e^{\pm}\not{p}\tau^{\pm}$	36	17.2 ± 1.7	$+3.5$
2j$\tau^{\pm}\tau^{\mp}$	33	62.1 ± 4.3	-3.5
$e^{\pm}$j	741710	764832 ± 6447.2	-3.5
j2$\tau^{\pm}$	105	150.8 ± 6.3	-3.4

Vista/Sleuth in CDF

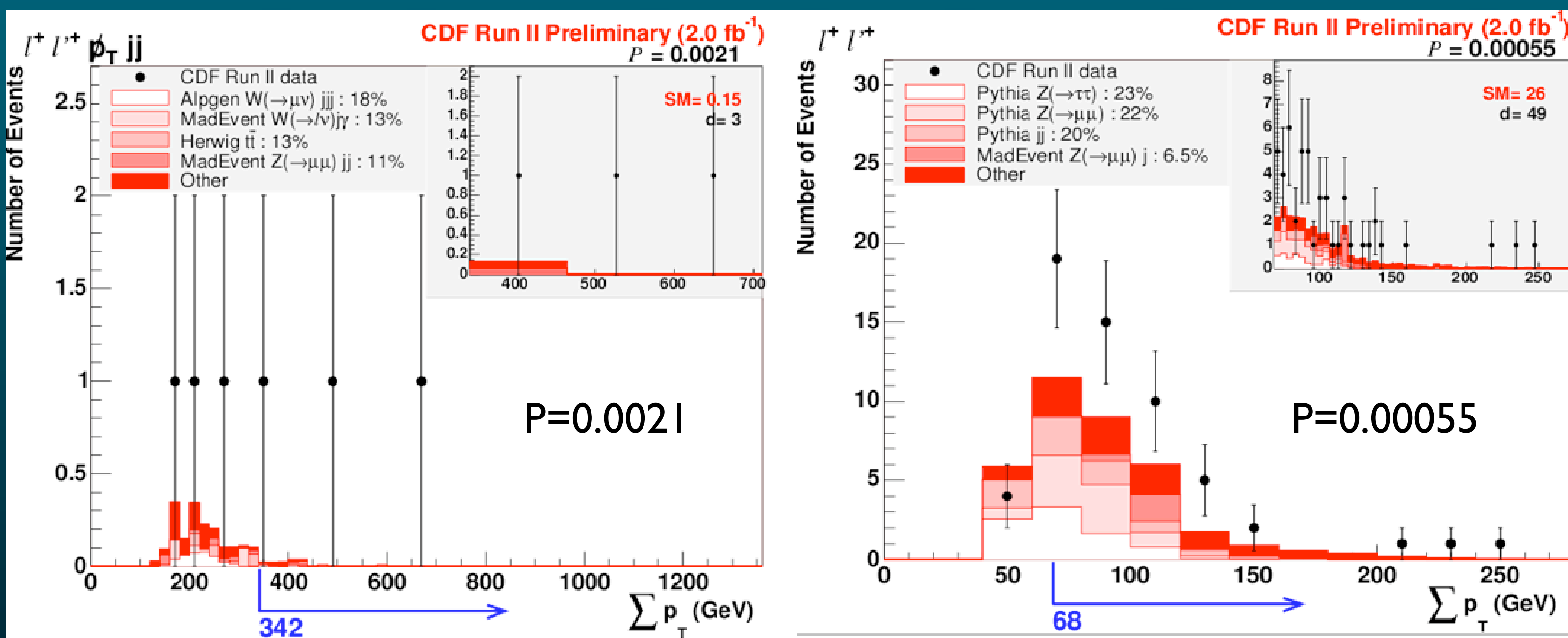
- algorithm studies 19560 kinematic distributions derived from the 399 channels: p_T, masses of combinations, ΔR, etc.
- of these, in the 2 fb^{-1} sample, 555 show a discrepancy of 5σ or more (one would expect essentially none if the model were perfect!)
- investigations of these reveals some systematic modeling problems, like the one at right



Refinements made to PYTHIA after this was seen

Vista/Sleuth in CDF

- Sleuth tries to look for the biggest discrepancies by fnding that cut for the Σp_T distribution which results in the biggest excess :



- though these look improbable, their significances are 27% and 8.5% after trials factor

Vista/Sleuth in CDF

- Here is the remarkable thing: <u>all</u> of the top five most discrepant Σp_T distributions involve like-sign dileptons:

channel	P
$e^{\pm}\mu^{\pm}$	0.00055
$e^{\pm}\mu^{\pm}jj\not{E}_T$	0.0021
$e^{\pm}\mu^{\pm}\not{E}_T$	0.0042
$\ell^{+}\ \ell^{-}\ \ell'^{\pm}\not{E}_T$	0.0047
$\ell^{\pm}\tau^{\pm}\not{E}_T$	0.0065

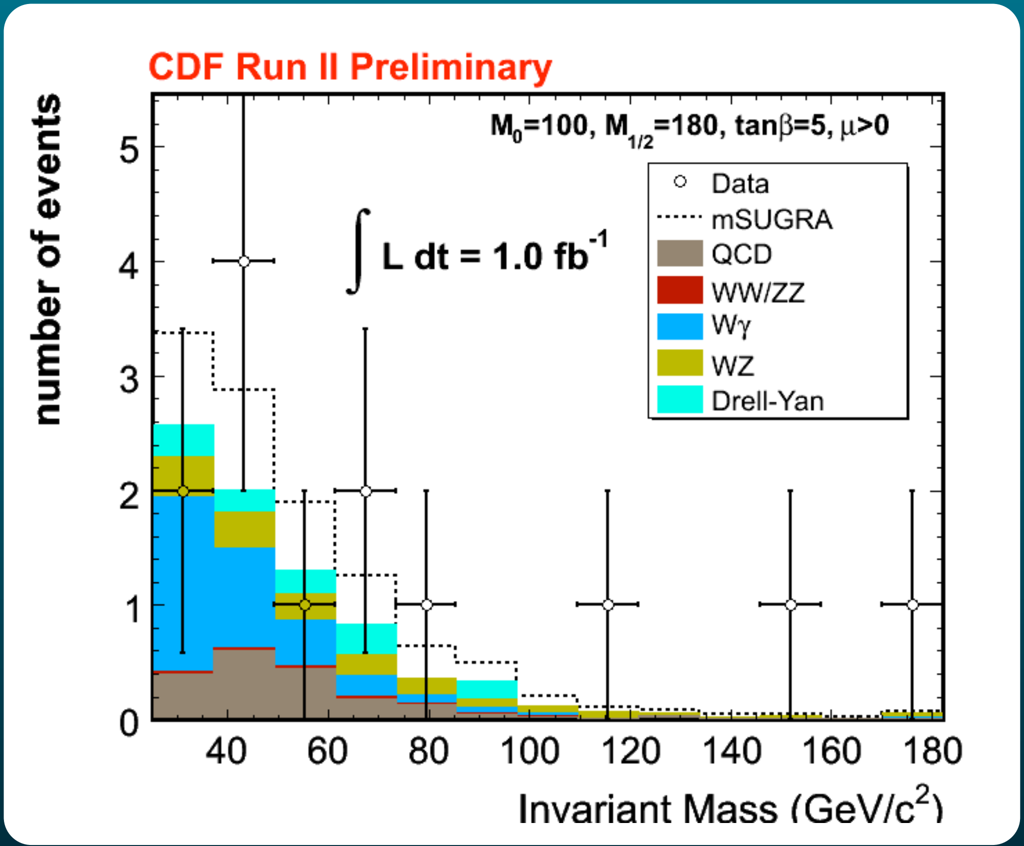
8% after trials factor

- Four have $\not{E}_T$ also! I find this to be quite exciting!

Vista/Sleuth → dedicated channel study → model test

LS Dilepton Excess in CDF?

- In fact, the 1 fb^{-1} dedicated search for LS dileptons revealed a tantalizing excess at large lepton p_T
- excess is not consistent with SUSY!



new results from 3 fb^{-1} sample coming soon!

The Unexpected

- Have we missed something at the Tevatron?
- Is the new BSM physics what we think it is?
- Are we throwing away a major discovery at the trigger level?
- Did we build LHC detectors for the right thing?

"Now, my own suspicion is that the Universe is not only queerer than we suppose, but queerer than we <u>can</u> suppose."

- J.B.S. Haldane

One example: quirks

- Markus Luty (Davis) proposes an extremely simple, and completely unmotivated example:

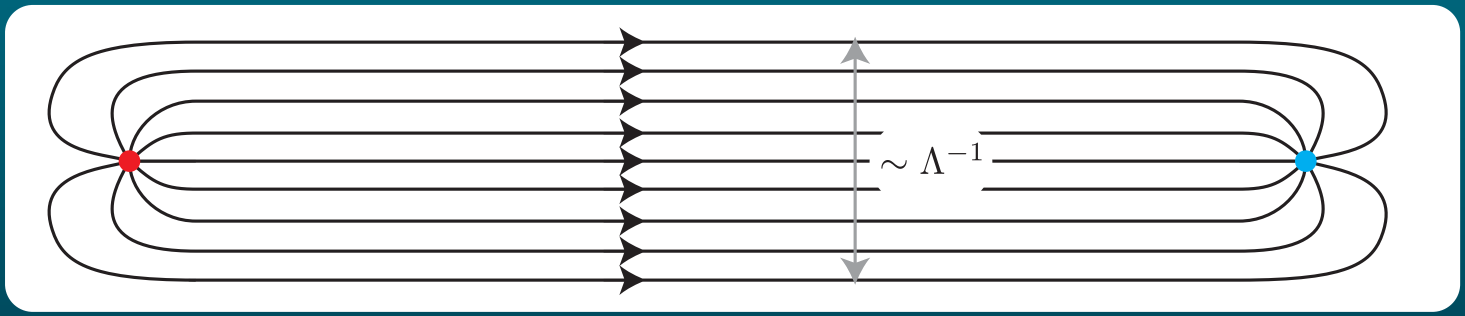
$$\underbrace{SU(N)'}_{\Lambda} \quad < \quad \begin{matrix} Q, \bar{Q} \\ m_Q \sim \mathrm{TeV} \end{matrix}$$

+ discrete choice of $Q, \bar{Q}$ charges

- new force is weak compared with the mass scale of the new fermions, which we call "quirks"
- quirks could carry color charge in addition (why not?)

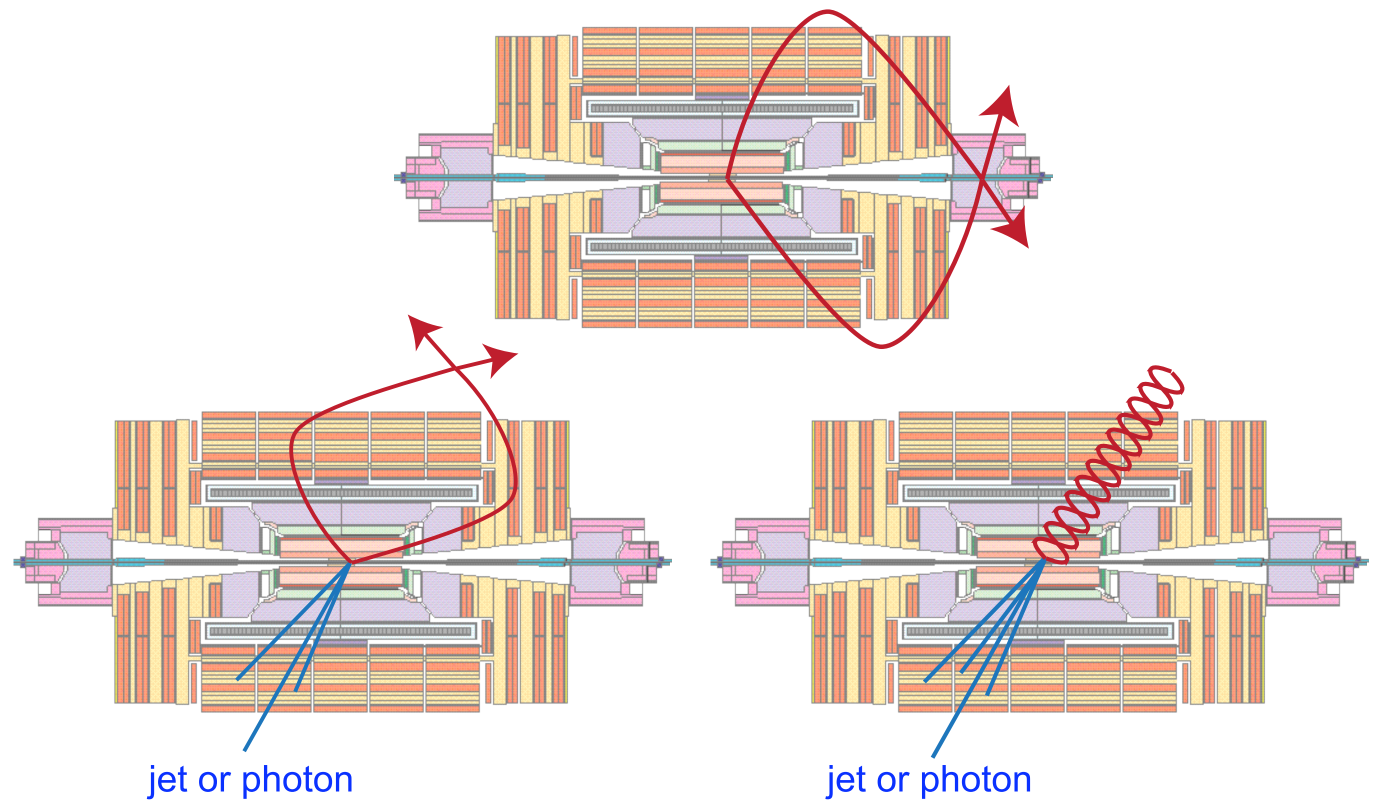
Quirks

- if quirks are pair-produced, they fly apart and create a long, unbroken flux tube between them:



- quirks fly apart until the tube reaches a maximum, then they start flying back towards each other
- quirk pair oscillates tens of times before quirk pair annihilates

Quirks



- hard to predict just what quirks signals would look like in the detector
- what about the "QCD brown muck" around quirks?

Quirks

- Each quirk surrounded by QCD color field
- As quirk pair passes near each other, a few pions of ~GeV scale energy are produced
- The oscillation process is fast, therefore we would see
    - several hundred $\pi^{\pm}$, π^{0} produced isotropically
    - dijet from final quirk pair annihilation
- "dijet plus glow-ball" signature - can we distinguish it from QCD multijet background?
- trigger is probably efficient if m_Q is large

Summary - Tevatron

- no SM Higgs discovery at the Tevatron soon
- have begun to rule out SM Higgs at high masses
- BSM Higgs search at Tevatron continues to break new scientific ground
- searches for SUSY, new fermions/gauge bosons, and more are so far negatie
- tantalizing excesses in ℓ+jets at high HT and in like-sign dilepton channels - more data soon

Summary - LHC

- first physics data in summer 2009
- with the first sample we can look for resonances (if they're big enough), SUSY with missing E_T, ...
- will LHC go beyond 10 TeV in 2009?
- SM Higgs: need ~10 fb^{-1} at 14 TeV: 2010?
- may not be able to know at the LHC if SM Higgs is actually BSM!

This is the most interesting time in particle physics for decades - enjoy it!