Search for Neutral MSSM Higgs Bosons in the Di-Tau Decay Channel at CDF

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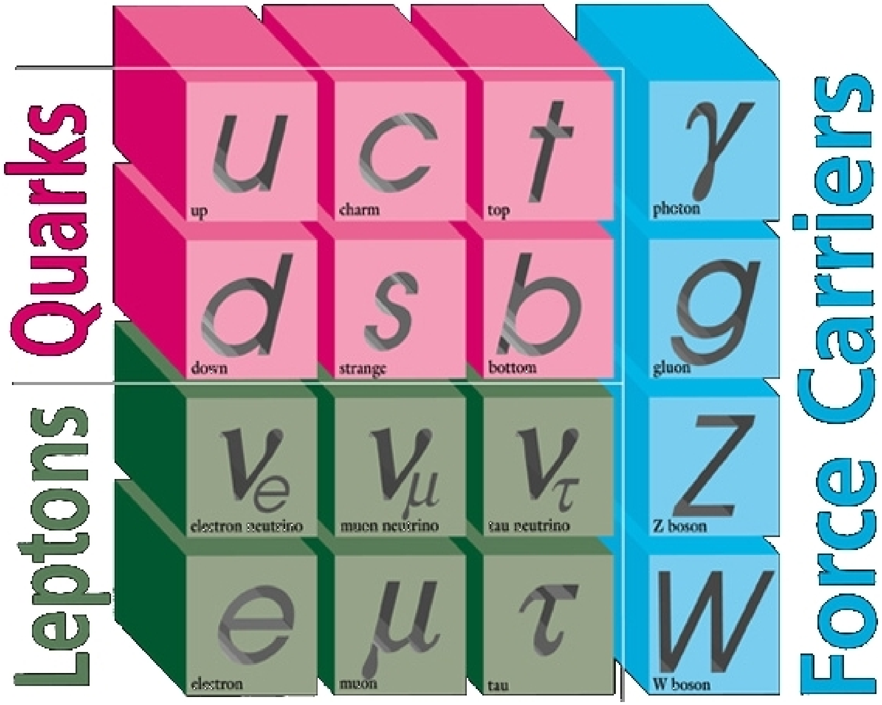
Outline

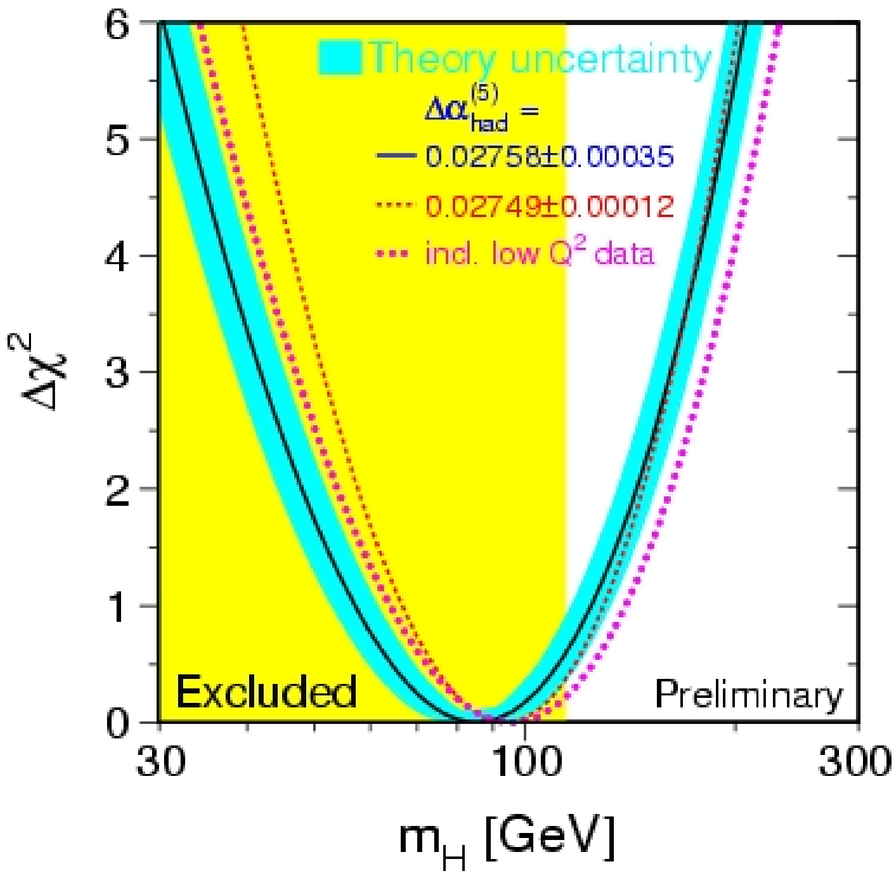
- Searching for the Higgs boson at the Tevatron
- SM vs MSSM Higgs
- The tau lepton as a tool
- Taus at CDF
- Preliminary results with $\mathcal{L}_{int} = 1\ fb^{-1}$
- Summary and outlook



- Good description of particles and their interactions
- Extensively tested
- But… need explanation of W,Z, fermion masses
- Suggested solution: the Higgs mechanism
  - Predicts the existence of a new massive neutral particle – the Higgs boson

Understanding the origin of masses is one of the priorities at the Tevatron and LHC.

- Theory does not predict the mass of the Higgs:
  - LEP limit: m_H>114 GeV @ 95% CL
  - Indirect limit from EW data:

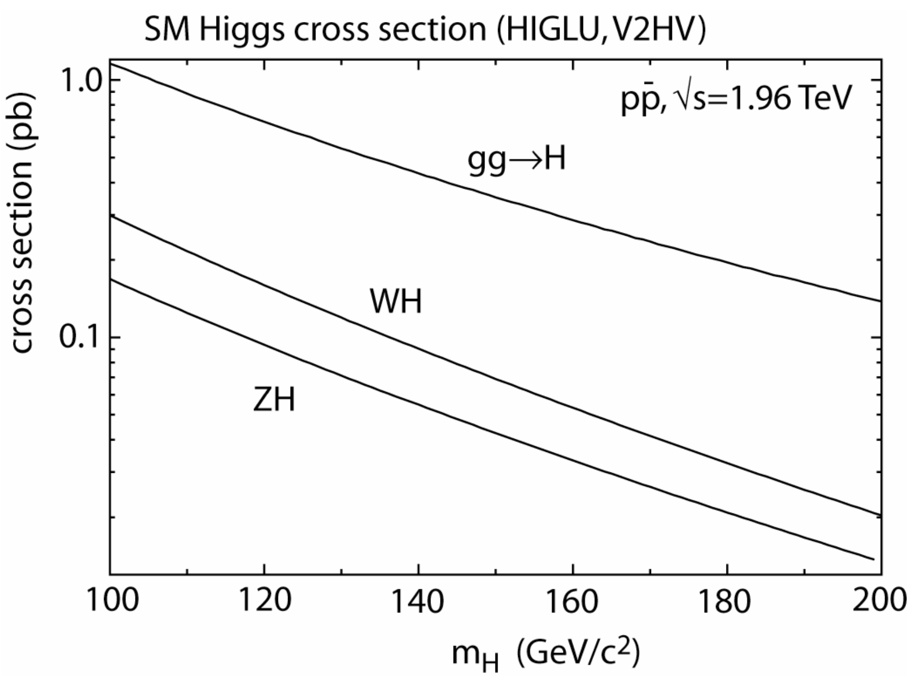


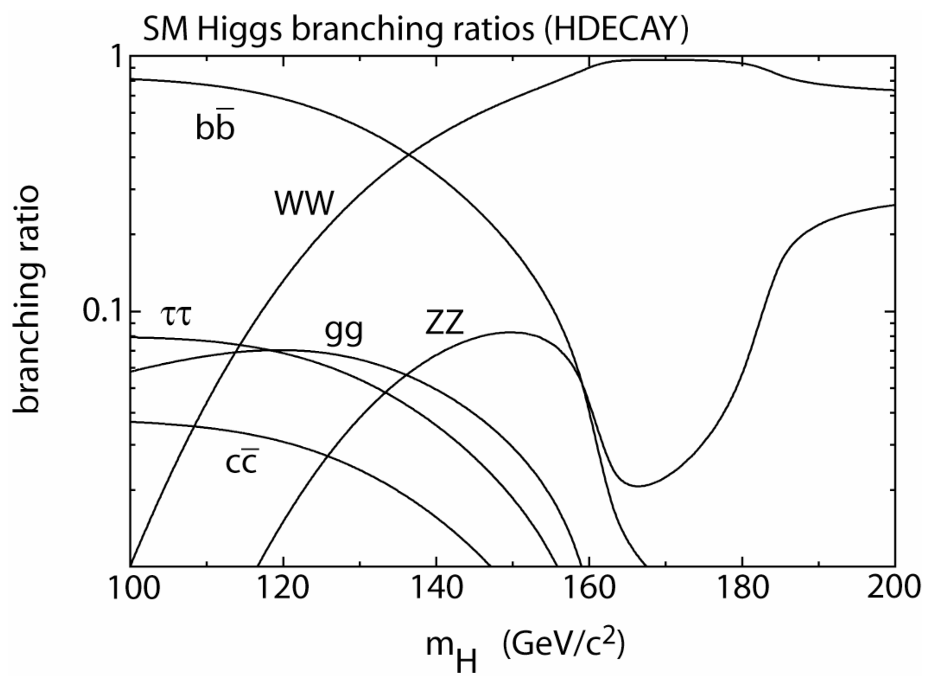
- Preferred value: $m_H = 85^{+39}_{-28}$ GeV
- m_H < 166 GeV @ 95% CL (one-sided)
- m_H < 199 GeV @ 95% CL (including LEP limit from the direct search)

Results as of Summer 2006!

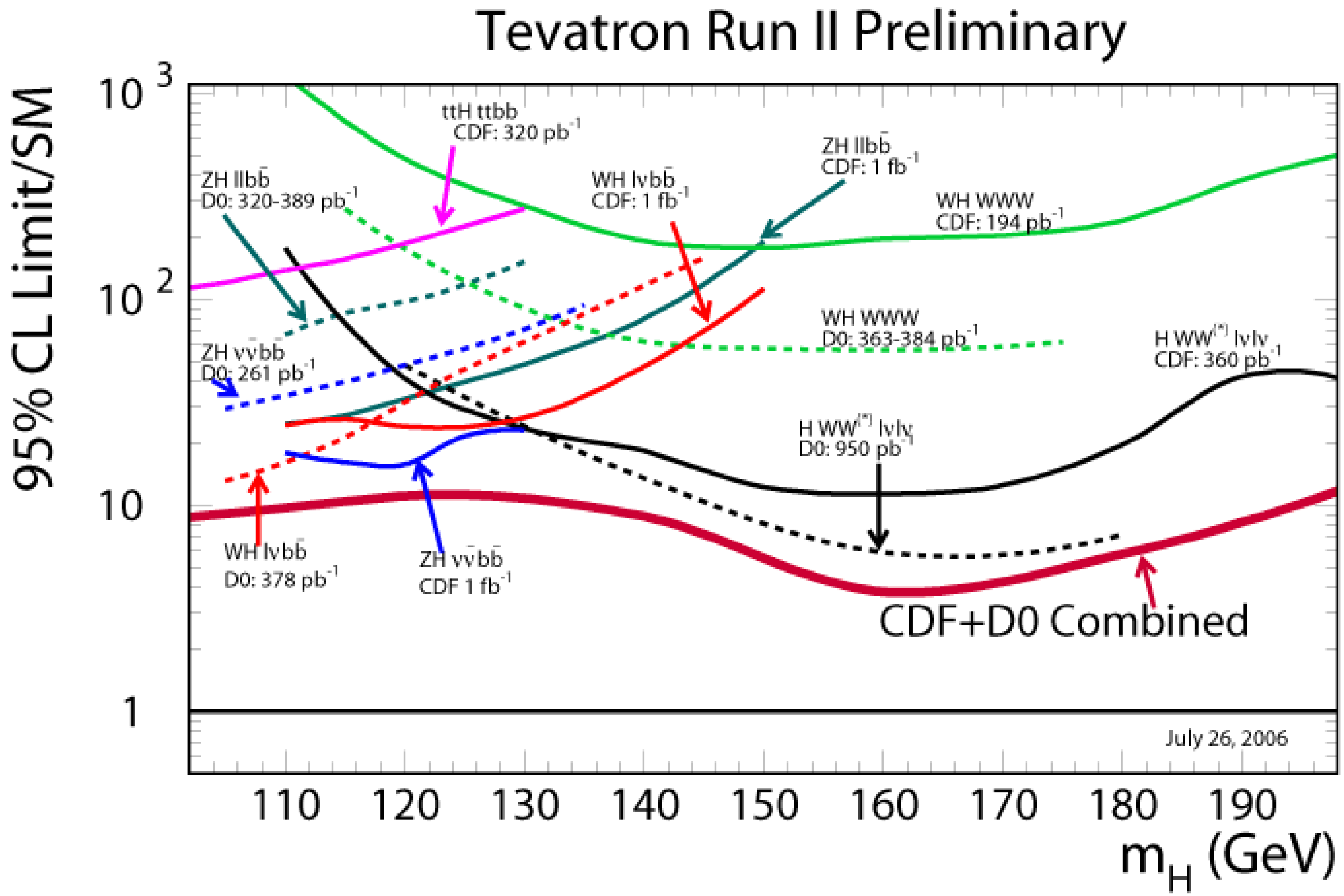
- Relatively light Higgs is favored
- The new CDF measurement of m_W pulls the estimate of m_H even lower

How to search for SM Higgs at the Tevatron



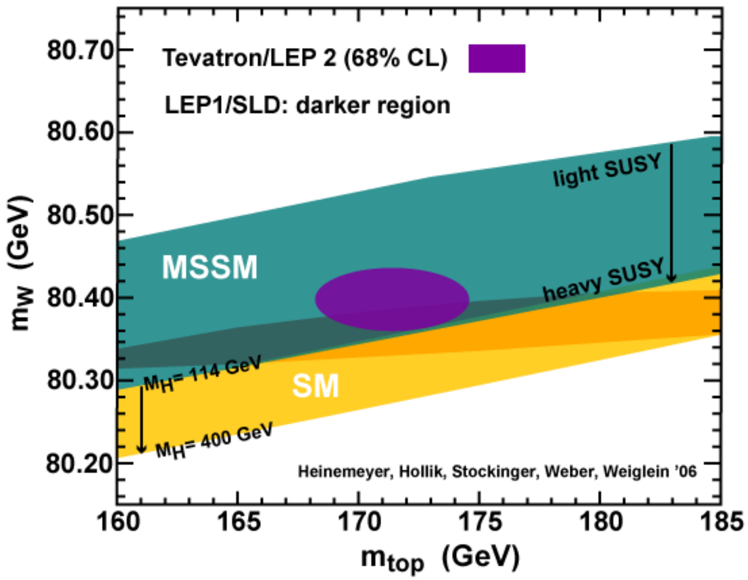


- Most promising for lower mass-range: associated production with W/Z; W→lν, Z→ll,νν; H→bb
- Higher masses: gg→H; H→WW*



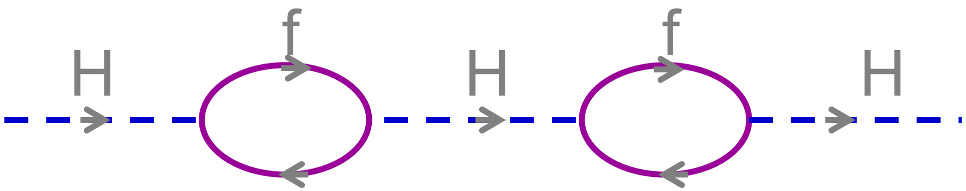
Getting closer to the SM predictions… but not there yet

Why Search for Higgs Beyond SM?



- Possible enhancement in SUSY Higgs production
- Recent results seem to prefer SUSY?

- Difficulties in the SM Higgs sector:
  - Large corrections to Higgs mass: $\delta m^2 \sim \Lambda^2$; $\Lambda = M_P$?



  - Special tuning needed (“accidental” cancellation?)

SUSY provides an elegant solution

What Do We Get from SUSY

- New symmetry: fermions (bosons) have bosonic (fermionic) partners
  - Doubles the number of particles
- Unification of forces at one scale
- Dark matter candidate (LSP)
- …
- **As far as Higgs is concerned:**

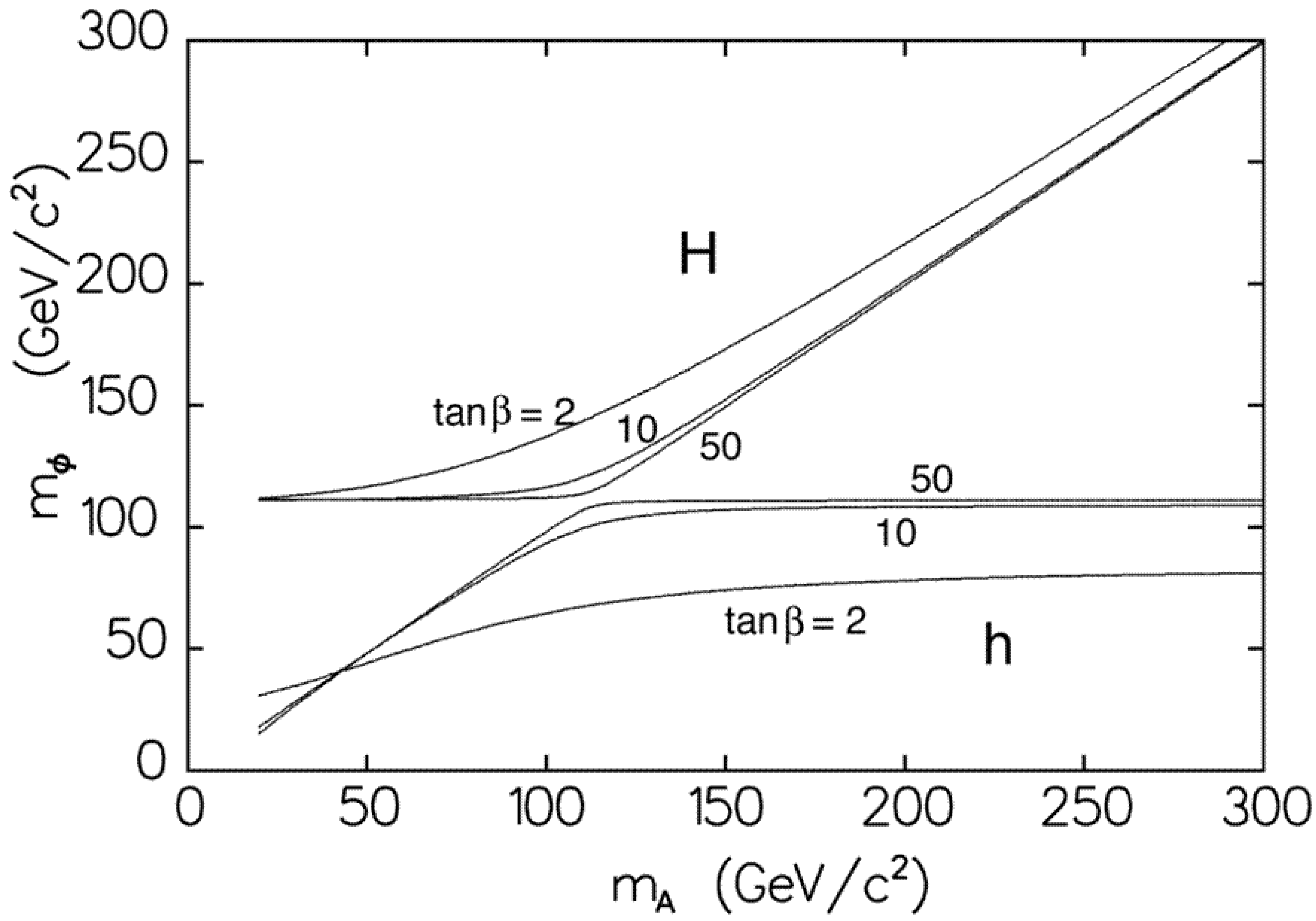
  Divergent terms in m_H calculations canceled by the *s*partners – the "accidental" cancellation has solid underlying foundation

Higgs Sector in MSSM

Minimal Supersymmetric Standard Model (MSSM): SUSY extension of SM with minimal particle content

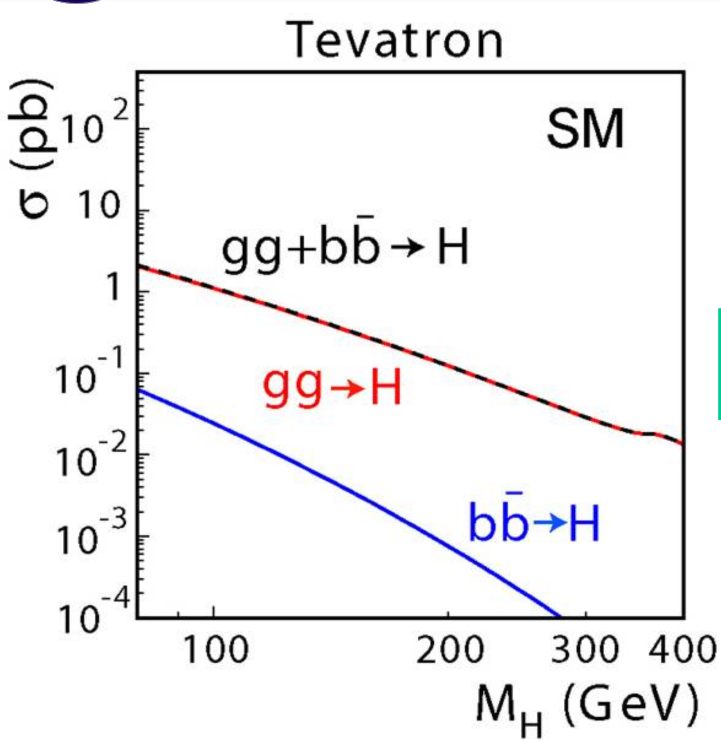
- Higgs sector in the MSSM:
  - Requires two Higgs field doublets
  - Five physical states: H, h, A; $H^{\pm}$
  - Lightest Higgs (h) mass close to EW scale
  - At tree level defined by m_A and $\tan\beta = v_u/v_d$
  - A couplings to b,τ enhanced by ~$\tan\beta$!

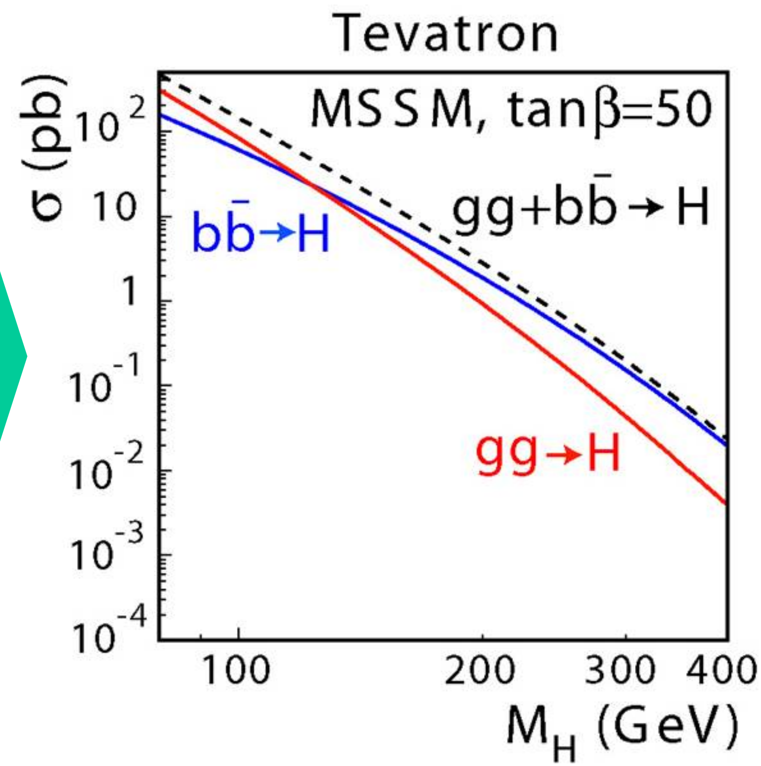
Neutral MSSM Higgs masses



- For large tanβ h or H are almost mass degenerate with A, similar couplings
- The other one is SM-like, low-mass (m<135 GeV)

MSSM Higgs production

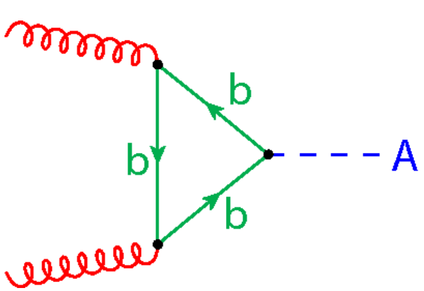




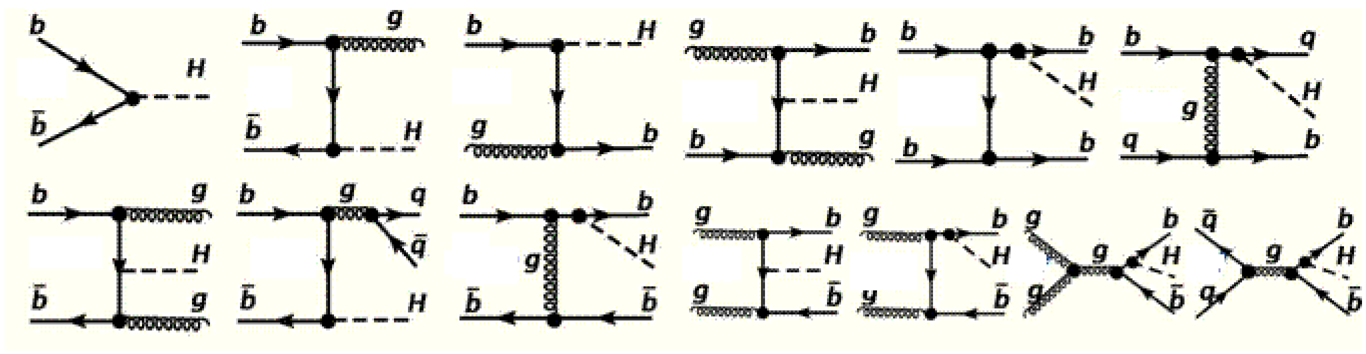
Higgs decays:

- bb (~90%)
- ττ (~10%)

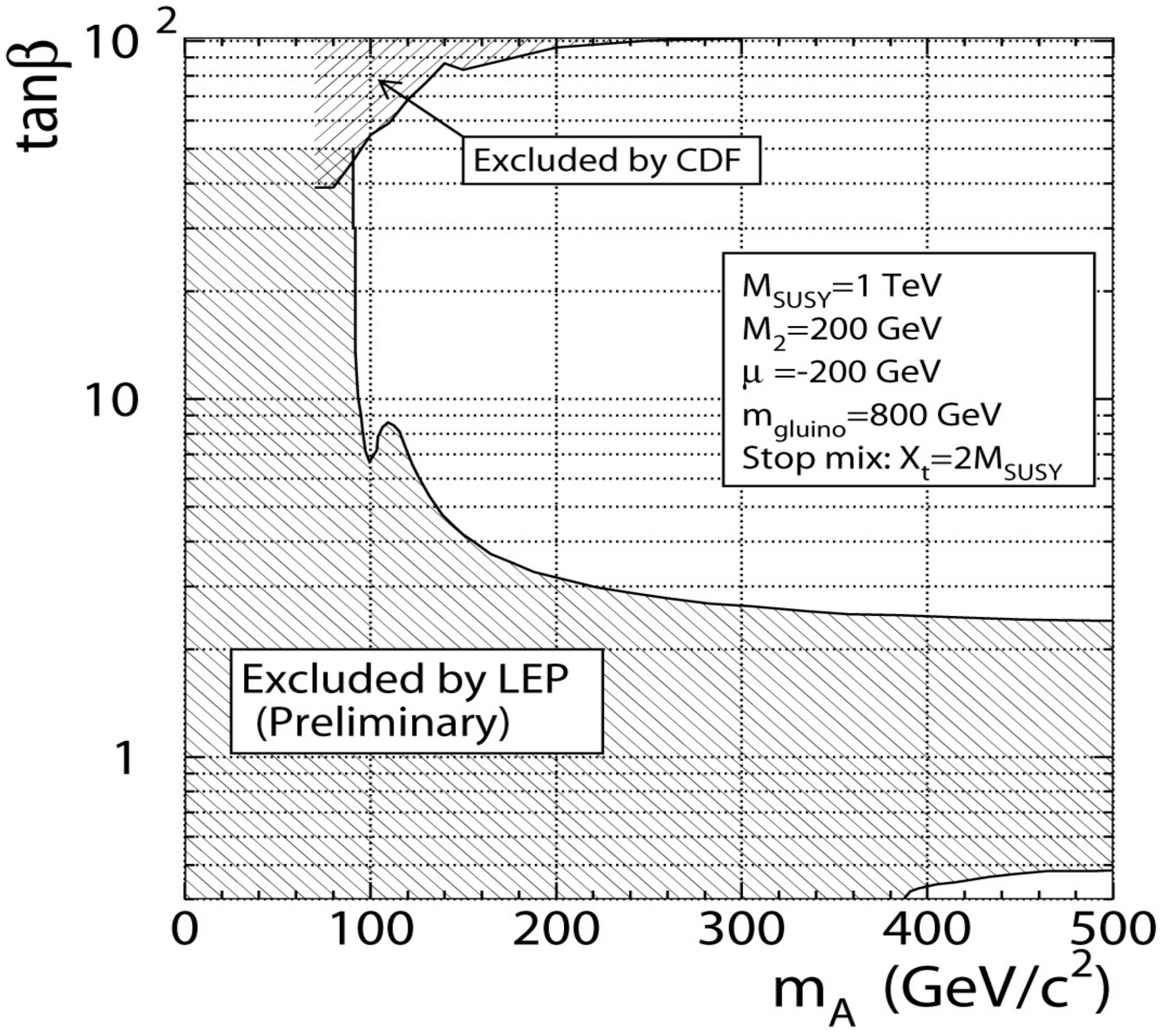
$$gg \to H$$



$$b\bar{b} \to H$$



Neutral MSSM Higgs Limits: before Run II



Large regions of parameter space remained unexcluded.

The A+b(b) →bbb(b) channel was considered the most promising search mode (Tevatron Higgs Working Group Report).

Case for MSSM Higgs→ττ Search

- BR(A→bb) is larger, *however*, the strengths of a search channel are influenced by other factors as well
- Due to large QCD backgrounds, the searches for A→bb are restricted to production mechanisms with an associated high-p_T b-jet: A+b(b)
  - Can not take advantage of gg→A
  - Explore only a subset of the bb→A
- All production mechanisms can be explored with the A→ττ channel
  - Largely compensates the BR disadvantage!

Case for MSSM Higgs→ττ Search

- MSSM Higgs production and decays can be significantly affected by radiative corrections *
- The bb channel is more sensitive to these corrections (and therefore to the SUSY scenario), while the ττ channel is more robust

$$\sigma(b\bar{b} \to A) \times BR(A \to b\bar{b}) \cong \sigma(b\bar{b} \to A)_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2 + 9}$$

$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \cong \sigma(b\bar{b}, gg \to A)_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2 + 9}$$

Δ_b is a function of SUSY parameters

A→ττ is important for MSSM Higgs searches:

- adds an extra detection mode
- sensitive to additional production mechanisms
- expands the probed SUSY parameter space

* M. Carena, S. Heinemeyer, G. Weiglein, and C.E.M. Wagner, Eur.Phys.J. C45 (2006) 797-814

The Tools of the Search: Tau Leptons

- Third generation; charged: $Q^{\tau} = \pm 1$
- Heavy: m_{τ} = 1.777 GeV
- Decays :
  - Leptonic: $\tau \to e \bar{\nu}_e \nu_\tau$, $\tau \to \mu \bar{\nu}_\mu \nu_\tau$ (~36%)
  - Hadronic: $\tau \to \pi \nu_\tau$, $\tau \to \pi \pi^0 \nu_\tau$, $\tau \to \pi\pi\pi \nu_\tau$, $\tau \to \pi \pi^0 \pi^0 \nu_\tau$ ... (~64%)

⇒ rich decay spectrum!

Taking advantage of $A \to \tau\tau$ comes at a price: reconstruction of many and sometimes complex final states!

Throughout this talk we use τ_e, τ_μ, τ_{had} as shorthand notations for $\tau \to e \bar{\nu}_e \nu_\tau$, $\tau \to \mu \bar{\nu}_\mu \nu_\tau$, and $\tau \to \mathit{hadrons}\ \nu_\tau$, respectively.

Higgs$\rightarrow \tau\tau$ Signatures

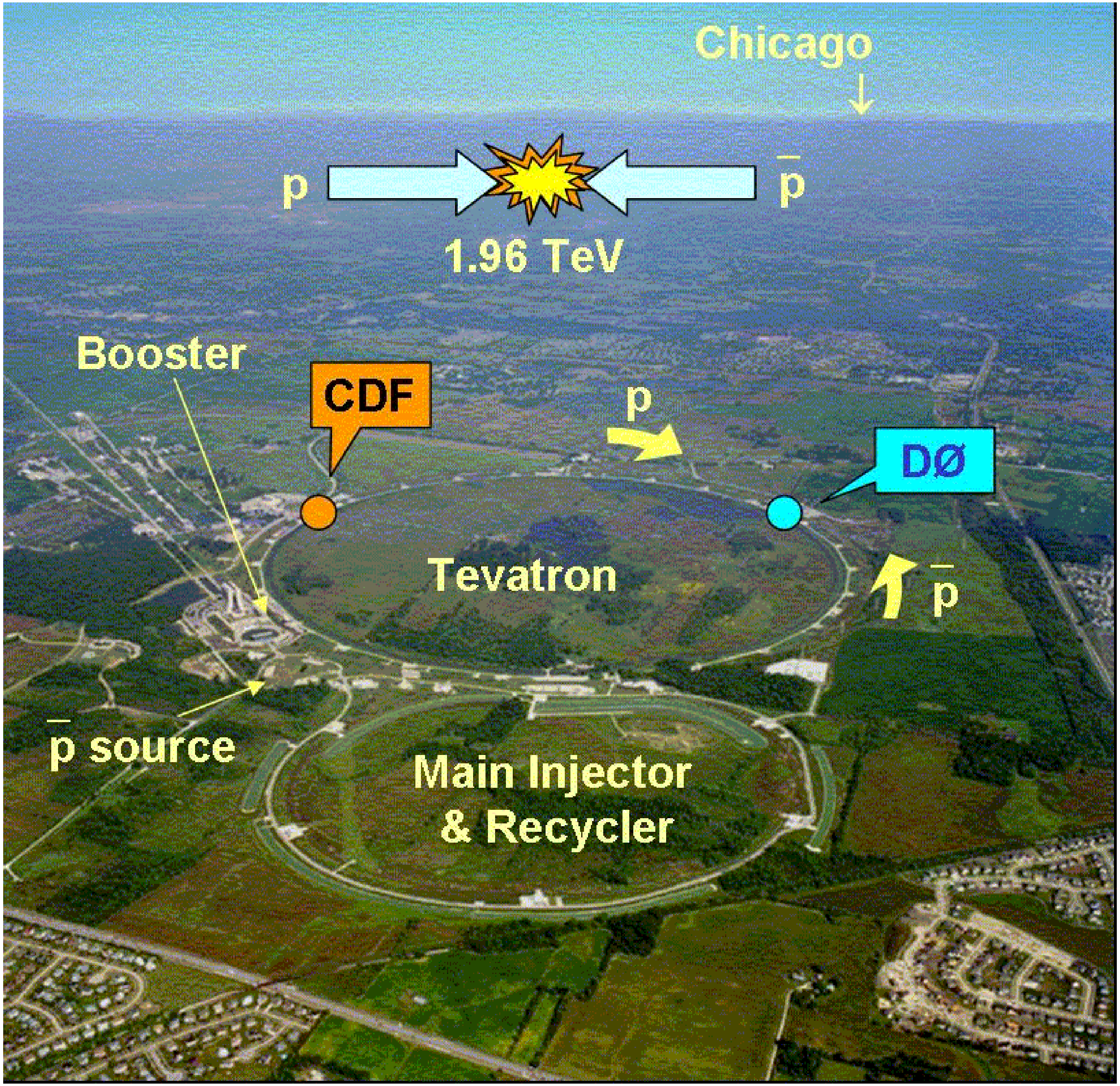
- Determined by the decay modes of the taus

Mode	Fraction (%)	Comment
$\tau_e\tau_e$	3	large $Z/\gamma^*\rightarrow ee$ bg
$\tau_\mu\tau_\mu$	3	large $Z/\gamma^*\rightarrow \mu\mu$ bg
$\tau_e\tau_\mu$	6	low jet backgrounds
$\tau_e\tau_{had}$	23	golden
$\tau_\mu\tau_{had}$	23	golden
$\tau_{had}\tau_{had}$	41	challenging (jet bg's)

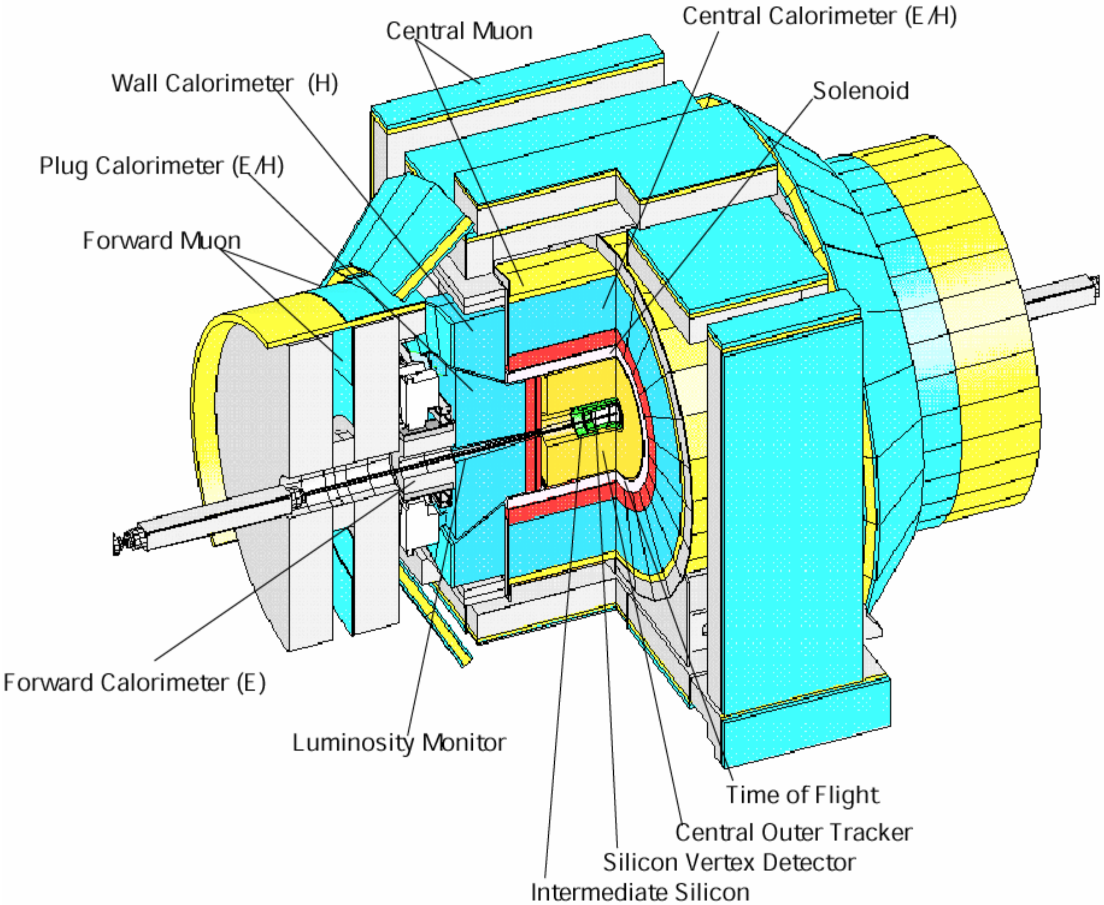
Used in this search ($\tau_e\tau_\mu$, $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$)

Strategy of the search

- Look for inclusive production of $A \rightarrow \tau\tau$:
  - Select di-tau candidate events: $\tau_e\tau_\mu$, $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$
  - No requirement on associated particle production
  - Construct a variable that gives Z/Higgs separation (m_{vis})
  - Extract signal/set limits by fitting the observed distribution with background and Higgs signal templates (various masses)

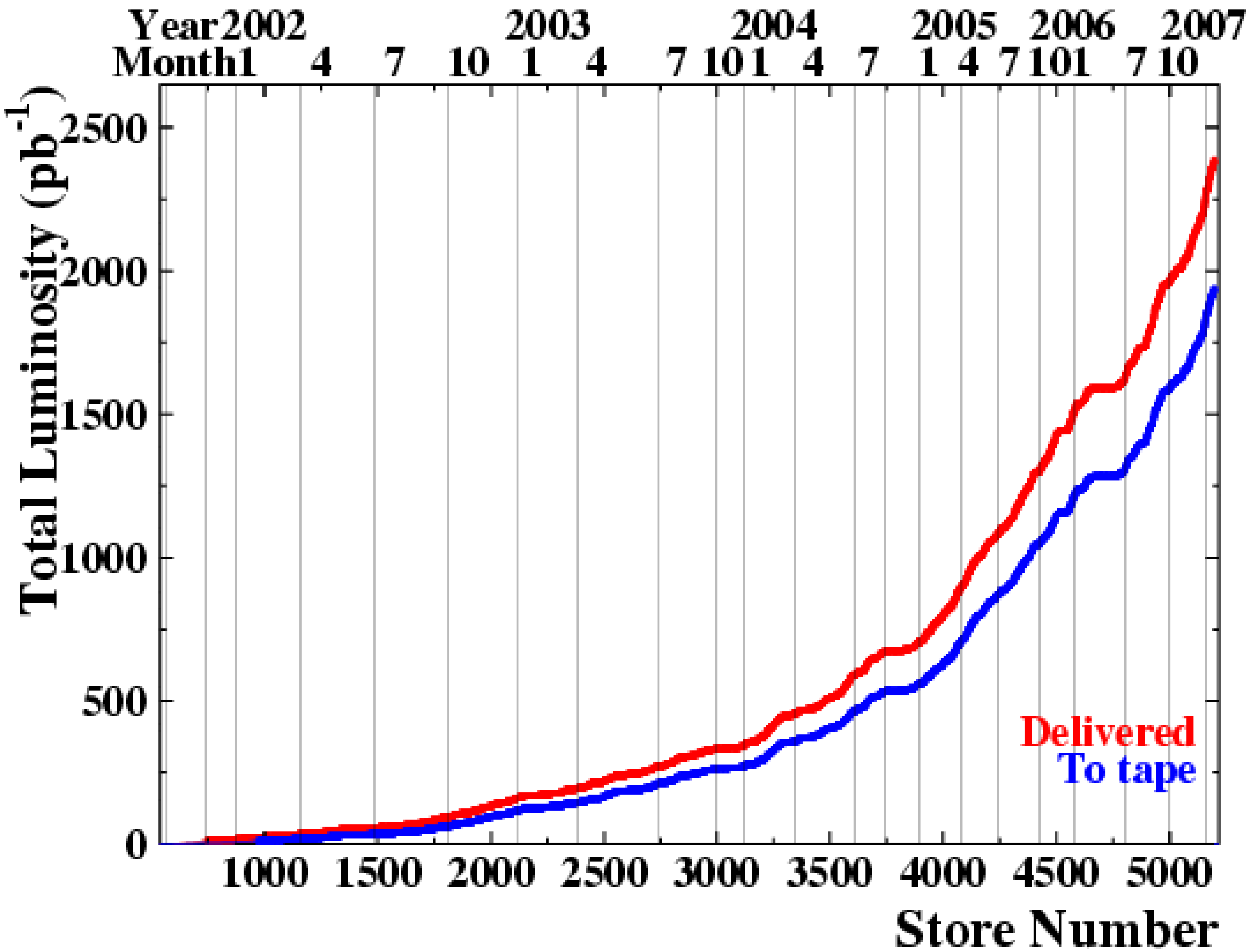

Chicago
p
p̄
1.96 TeV
Booster
CDF
p
DØ
Tevatron
p̄
p̄ source
Main Injector
& Recycler

The CDF Detector at the Tevatron



- Tracking: Silicon detectors and wire chambers
- Calorimetry: EM, Hadronic
- EM Shower Maximum detector - used in π^0 reconstruction
- Muon Detectors
- TOF System

CDF Integrated Luminosity



CDF has collected almost 2 fb^{-1} of data (Jan 2007)!
This analysis uses 1 fb^{-1}.

Triggers

- Dedicated set of tau triggers in Run 2:
  - **Electron + τ_{had}**
    - Central electron (E_T> 8 GeV) + isolated track (p_T>5 GeV)
  - **Muon + τ_{had}**
    - Central muon (p_T>8GeV) + isolated track (p_T>5 GeV)
  - **Missing Transverse Energy + τ_h**
    - $\not{E}_T$>20 GeV + narrow isolated jet
  - **Di-tau: τ_{had}+τ_{had}**
    - Two narrow, isolated jets

no tracks with p_T >1.5 GeV in isolation annulus 10-30^o

Cluster-matched track, no tracks with p_T >1.5 GeV in $\Delta\phi$ 10-30^o

- Low-p_T di-lepton triggers
  - **ee/$\mu\mu$/eμ ; p_T>4 GeV**

Electron and muon selection

Electrons

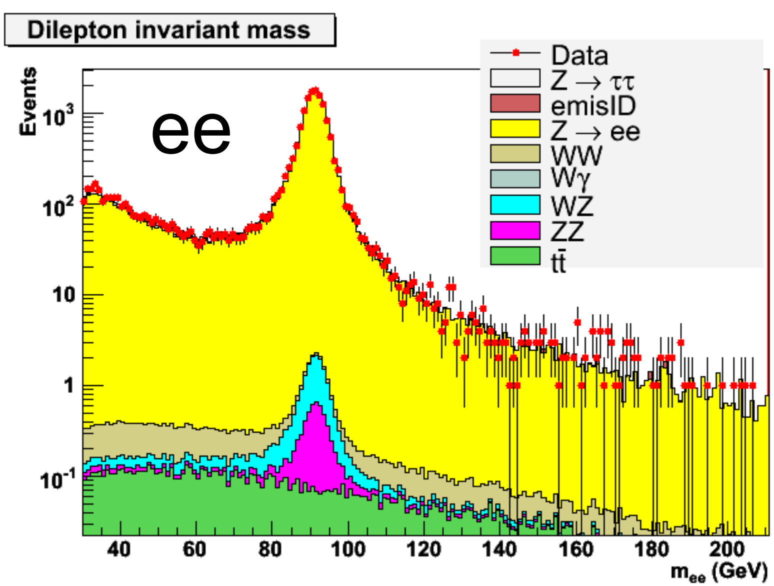
- In the central detector
- E_{HAD}/E_{EM}, E/p, and calorimeter cluster lateral shape consistent with the expectation for electrons
- Not part of a conversion pair
- $E_T > 10$ GeV (6 GeV) for $\tau_e\tau_{had}$ ($\tau_e\tau_\mu$)

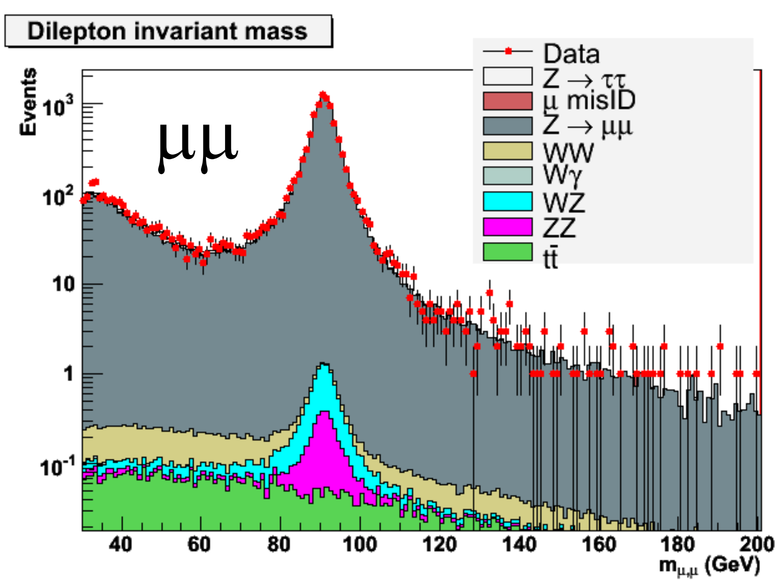
Muons:

- Fiducial in the central muon detectors
- Hits in the muon detectors associated with the track
- Small energy deposition in the calorimeter
- $p_T > 10$ GeV (6 GeV) for $\tau_\mu\tau_{had}$ ($\tau_e\tau_\mu$)

Isolation (same for e/μ) :

- $\Sigma p_T^{trk\ iso}(0.4) < 2$ GeV ($\tau_e\tau_\mu$ final state)
- $I^{cal}(0.4)<\max(2.0,\ 0.1\times\ p_T(\text{or } E_T))$ GeV (additional requrement for $\tau_{e/\mu}\tau_{had}$)





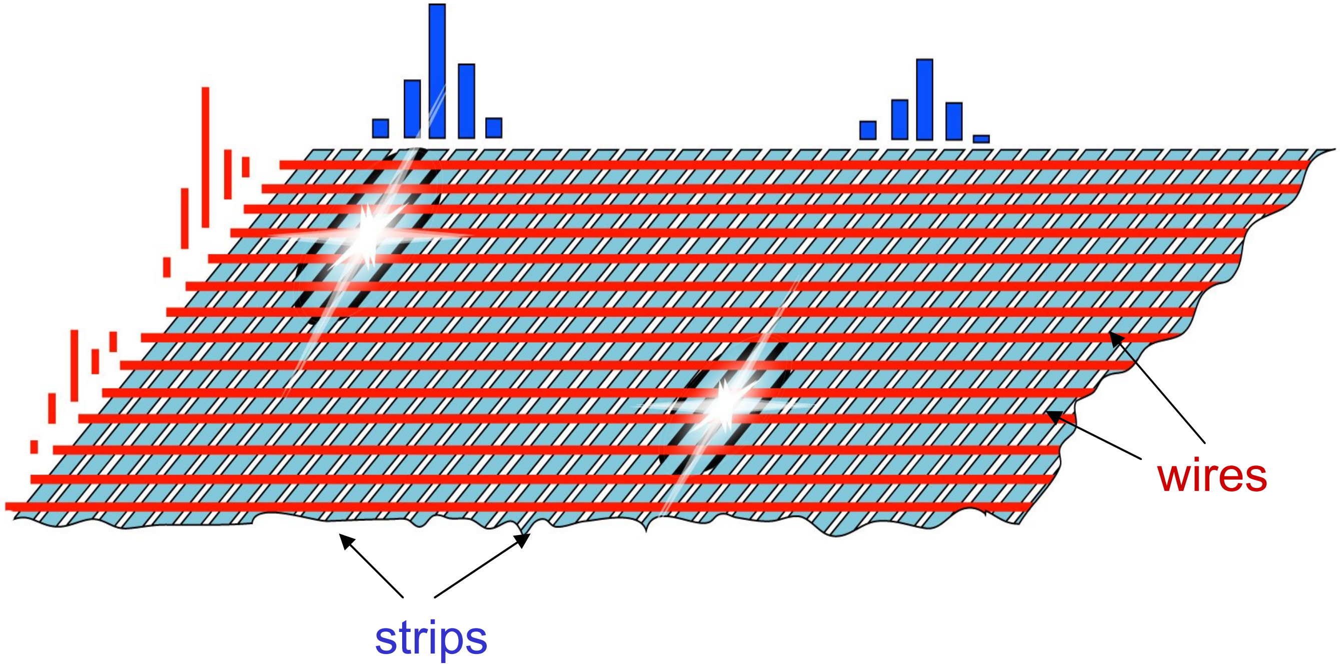
Hadronic tau decays

Throughout this presentation "tau reconstruction" refers to reconstruction of the hadronic system in $\tau \rightarrow \mathit{hadrons}\ \nu_\tau$

- Detector signature
  - Narrow jet
  - Low tracks and neutrals multiplicity
    - 1 or 3 trks, most of the time $\leq 3\pi^0$'s
    - 1-prong : 3-prong hadronic decays ~ 3:1
    - Most of the time the tracks are $\pi^\pm$ (small fraction of $K^\pm$)
  - Mass of had system $m_{had} < m_\tau$
- Tau ID requires detection of tracks and π^0's

π^0 detection

- Position from the ShowerMax detector (inside EM cal)
- Energy determined from EM energy in the tower, corrected for tracks hitting the tower



Orthogonal strips and wires, independent strip/wire clusters

Each ShowerMax “module” covers several towers

“Match” the strip to wire clusters to obtain 2D positions of hits

Forming π^0 candidates

- Find CES matched clusters (not associated with tracks)
- Assign EM energy from the calorimeter tower:

  If >1 match in the tower– split E_{EM} according to CES energy of each match

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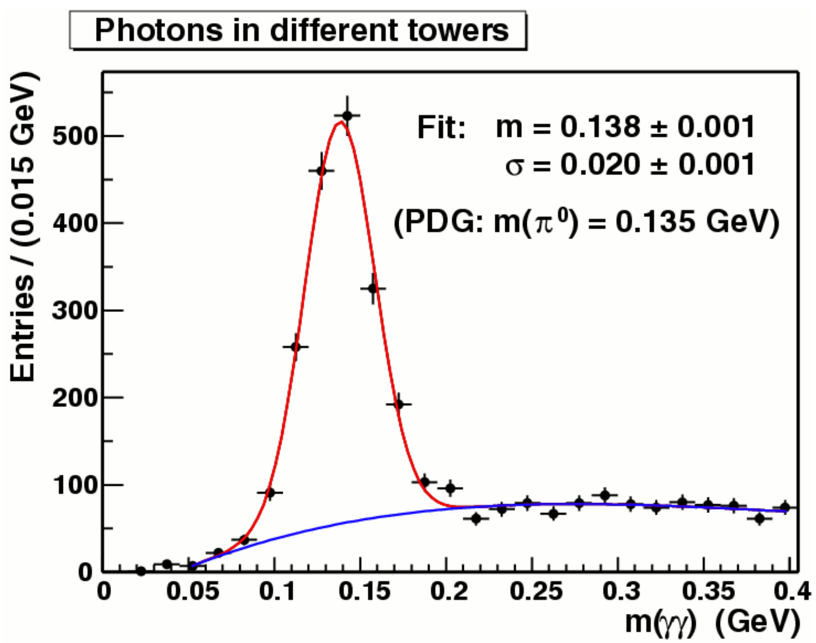
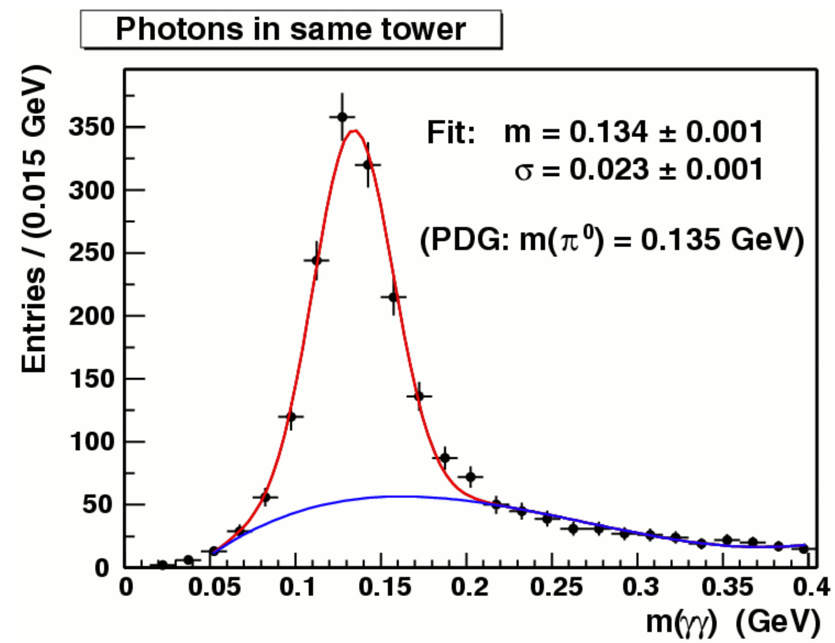
Well isolated, low-E π^0's can be reconstructed from $\gamma\gamma$ (if we really try).





Forming π^0 candidates

- Find CES matched clusters (not associated with tracks)
- Assign EM energy from the calorimeter tower:

  If >1 match in the tower– split E_{EM} according to CES energy of each match

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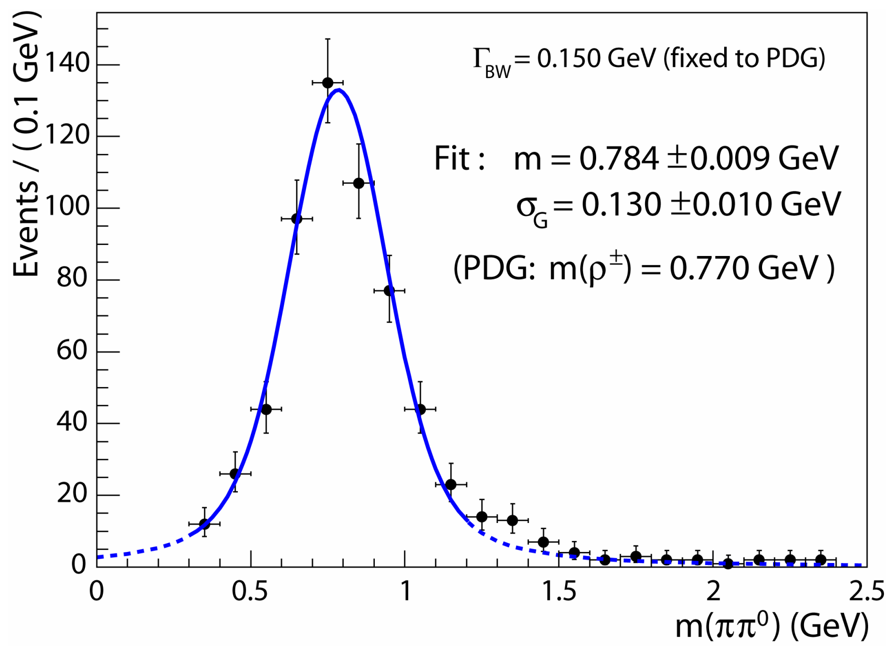
Most of the time a π^0 produces a single CES “match”.



Select ρ's from (mostly) $W \rightarrow \tau\nu$ decays (illustration from previous studies)

- Exactly one trk and one π^0
- MET > 20 GeV (QCD clean-up)
- $p_T(\pi^0)$>6 GeV (want merged γ's)
- **no** other particles in 30 degrees
- Remove candidates consistent with *e* + *brem*

Two-cone algorithm for trks and π^0's:

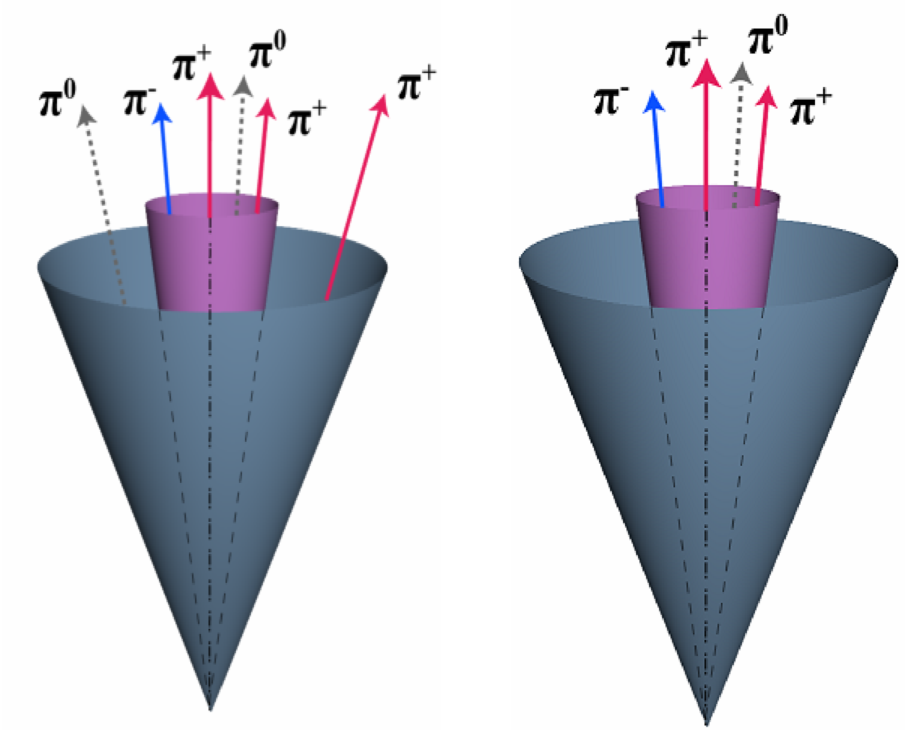
- Signal cone ⇨ reconstruct $\mathbf{p}_{had}(\mathbf{E},\vec{\mathbf{p}})$
- Iso annulus ⇨ implement g/q jet veto

•Common axis: direction of a "high-p_T" track (seed track), p_T>6 GeV

• Track points to a calorimeter cluster ($N^{twr} \leq 6$) with a seed tower with E_T > 6 GeV

Tau candidates:

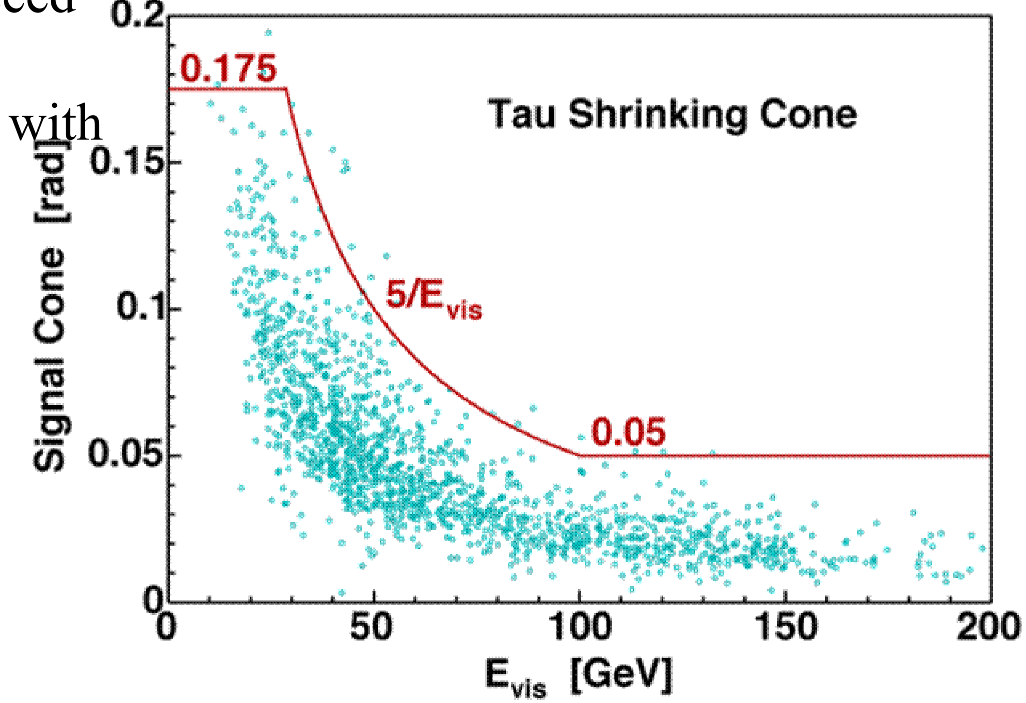
Non-isolated **isolated**



Signal cone size

$$\theta_{sig} = 5.0 \text{ (rad GeV)}/E_{cl} \text{ [rad]}$$

$$\theta_{sig}^{max} = 0.174;\ \theta_{sig}^{min}(\text{trk}) = 0.05;\ \theta_{sig}^{min}(\pi^0) = 0.1$$



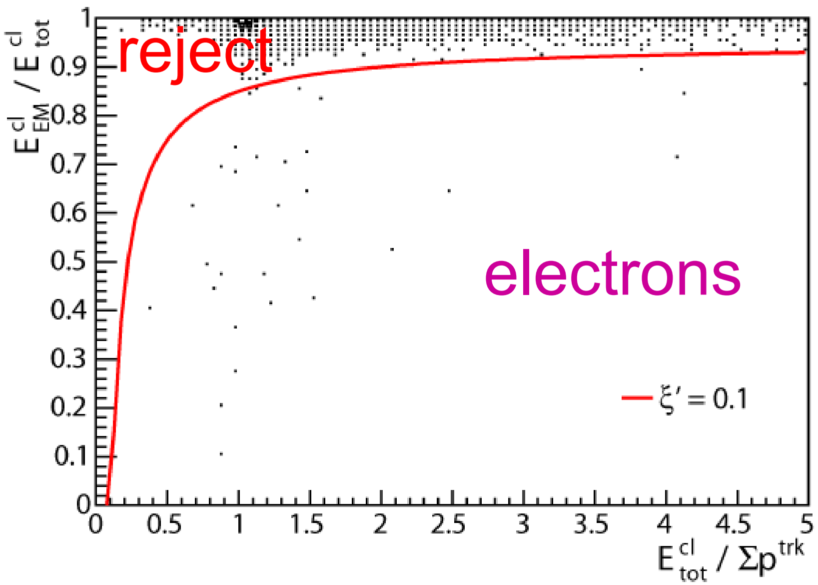
In tau reconstruction we assume that all tracks are $\pi^{\pm}$, and all reconstructed neutrals are π^0's

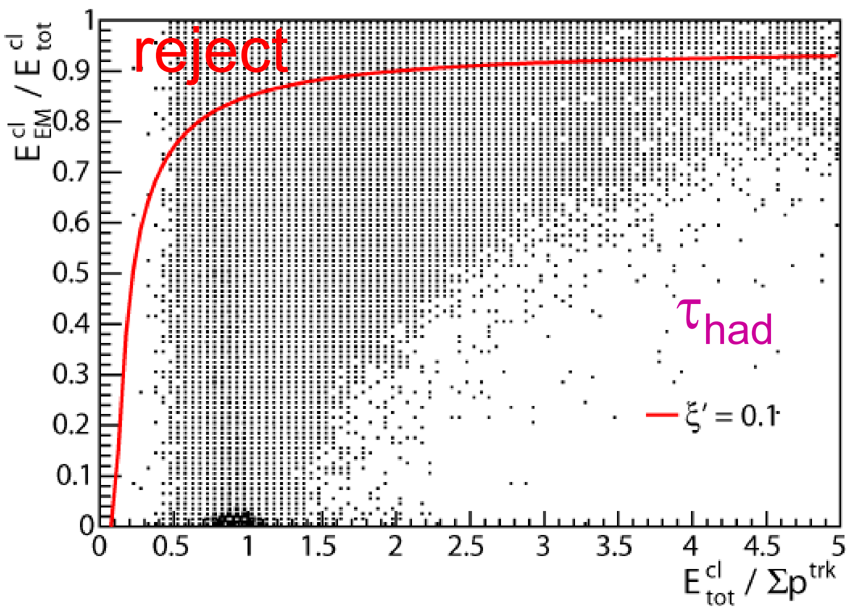
Tau selection:

- number of tracks: $N_{trk}=1,3$
- $E_T^{cl}>9$ GeV,
- $p_T>15$ (20) GeV for 1(3) prong
- $\xi' > 0.1$
- track isolation: $\Sigma_{iso}\, p_T^{trk} < 2$ GeV
- π^0 isolation: $\Sigma_{iso}\, E_T^{\pi^0} < 1$ GeV
- $m_{had} < 1.8$ (2.2) GeV for 1 (3) prong

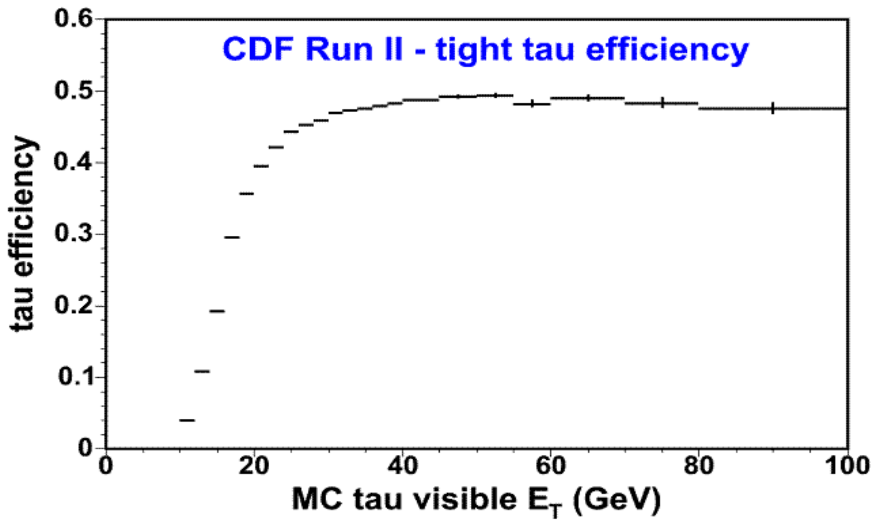
$$\xi' = \frac{E_{tot}^{cl}}{\sum |\vec{p}_{trk}|}\left(0.95 - \frac{E_{EM}^{cl}}{E_{tot}^{cl}}\right)$$

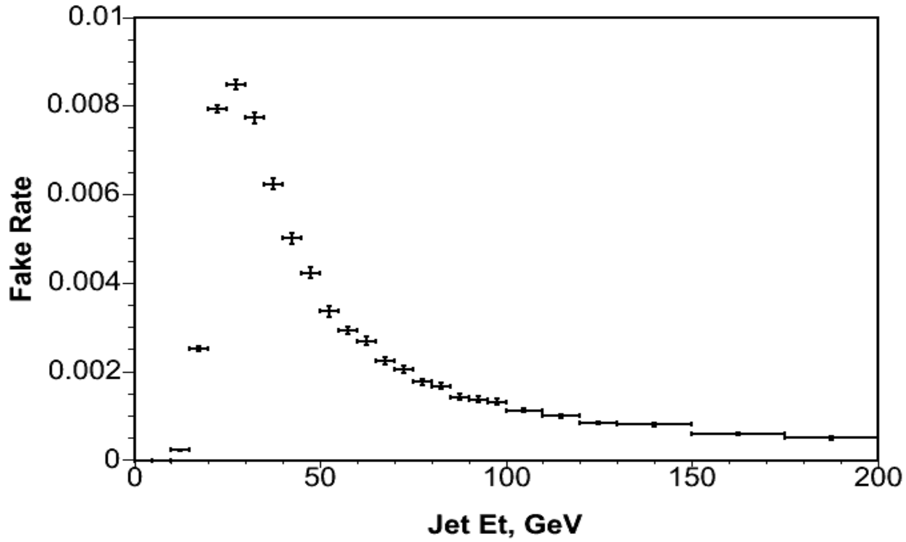
Illustration of the effect of the ξ' cut on electrons and τ_{had}





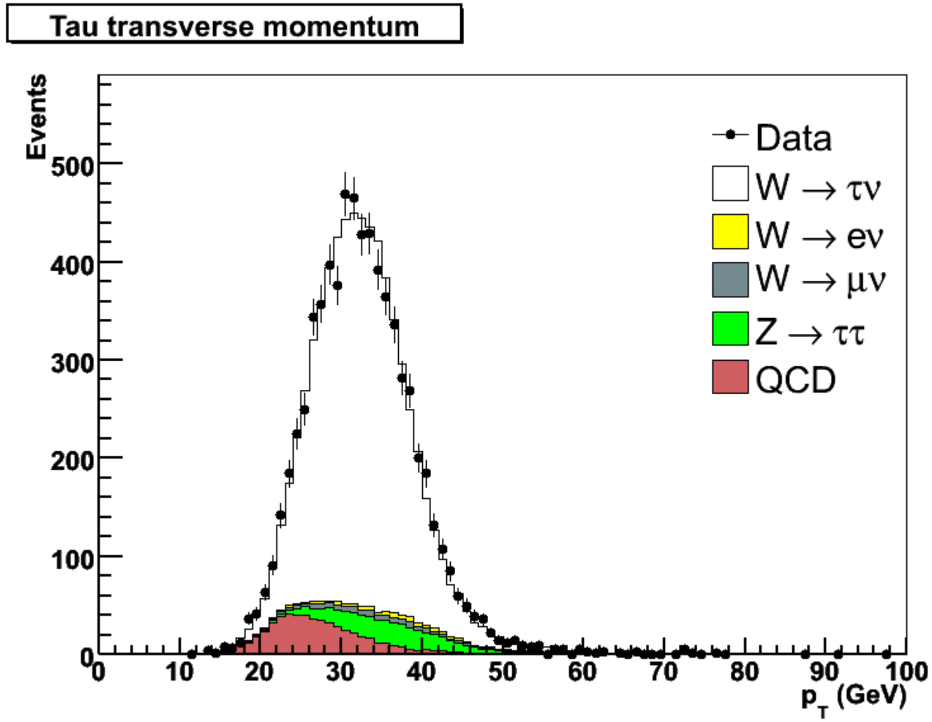
Tau efficiency and fake rate depend mostly on the isolation requirements





Data/MC energy scale

- Use taus from $W \rightarrow \tau\nu$ to compare the p_T spectra of τ_{had}
- Require one τ_{had}, E_T>25 GeV, no extra jets in the event
- Compare the p_T spectra with MC shifted templates (KS tests)
- Data/MC scale consistent within ~1%



Background Sources

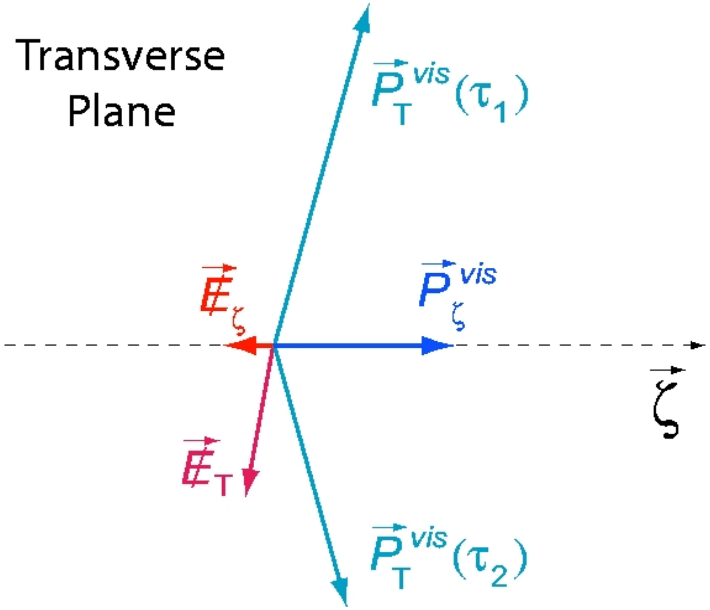
- $Z/\gamma^* \rightarrow \tau\tau$: estimated using MC
  - Largest background
  - Same final state as signal
- $Z \rightarrow \mu\mu, ee$: estimated using MC
- Misidentified jet as τ_{had}
  - multi-jet, W+jets; conversion+jet ($\tau_e\tau_{had}$ only)
    - Estimated from SS data events and W+jets MC
- Misidentified or non-isolated e/μ in the $\tau_e\tau_\mu$ channel
  - Estimated from events in the e/μ isolation sidebands
- "Other" : estimated using MC
  - ttbar, WW, WZ , ZZ, $W\gamma$, $Z\gamma$

Large number of background sources, most with small contributions

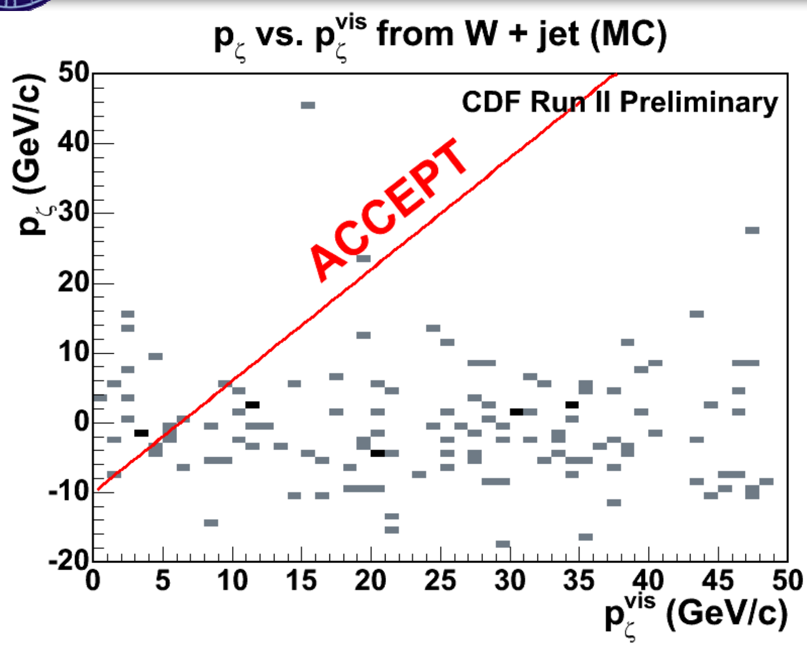
- $|z_0^{(1)} - z_0^{(2)}| < 5$ cm
- $|0.5(z_0^{(1)} + z_0^{(2)})| < 60$ cm
- $\Delta\phi(\tau^{(1)},\tau^{(2)}) > 0.5$ rad
- "Soft" QCD suppression
  - $\tau_{e/\mu}\tau_{had}$: $H_T = |p_T| + |E_t^e(p_T^\mu)| + |\not{E}_T| >$ { 55 GeV - 3-prong; 45 (50) GeV -1-prong $\tau_\mu\tau_{had}$ ($\tau_e\tau_{had}$) }
  - $\tau_e \tau_\mu$: $|E_t^e| + |p_T^\mu| > 30$ GeV
- ζ cut : di-boson, tt, W+jet(s) suppression

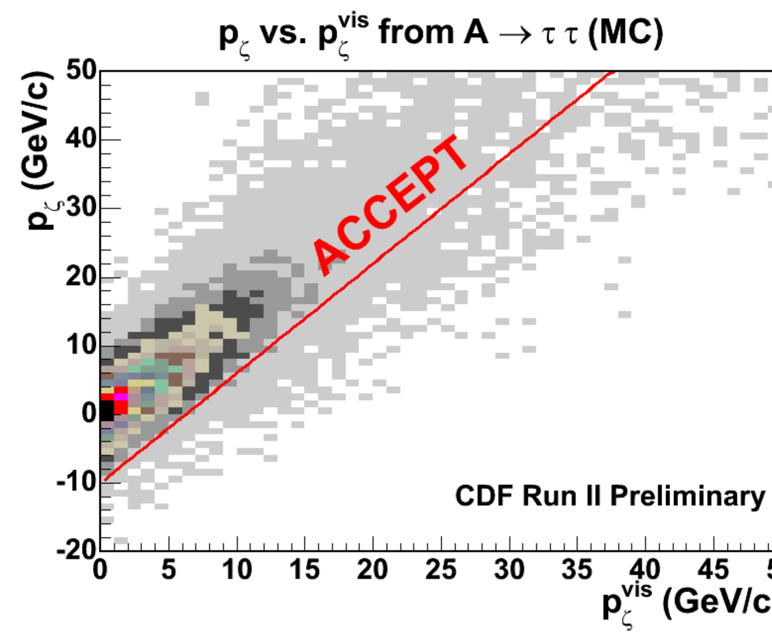
$$p_\zeta > 1.6\, p_\zeta^{vis} - 10$$

- $\vec{\zeta}$ = bisection of $\Delta\phi\,(\tau_1,\tau_2)$
- $P_\zeta = (\vec{p}_T(\tau_1)+\vec{p}_T(\tau_2)+\vec{\not{E}}_T).\,\vec{\zeta}_n$
- $p_\zeta^{vis} = (\vec{p}_T(\tau_1)+\vec{p}_T(\tau_2)).\,\vec{\zeta}_n$

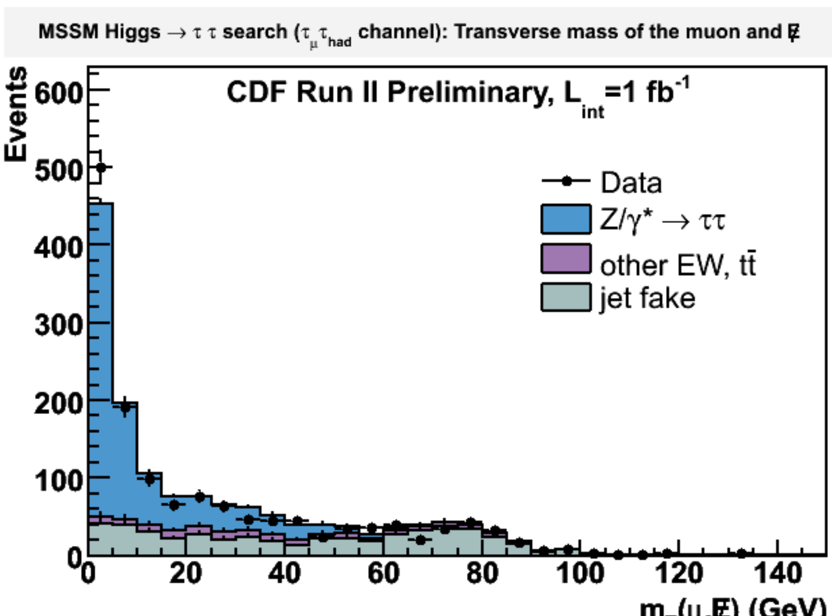


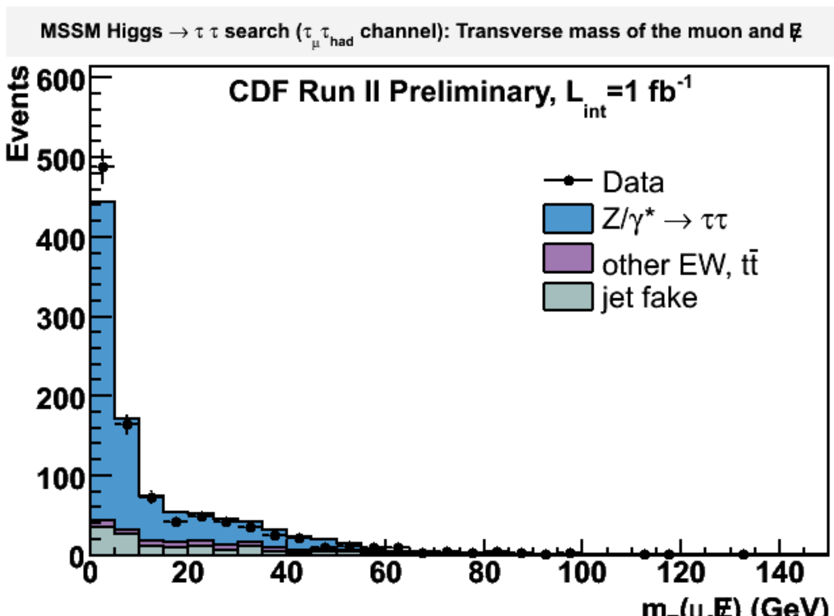
Event Selection: the z-cut





Example: effect of the ζ-cut on $\tau_\mu\tau_{had}$ candidate events



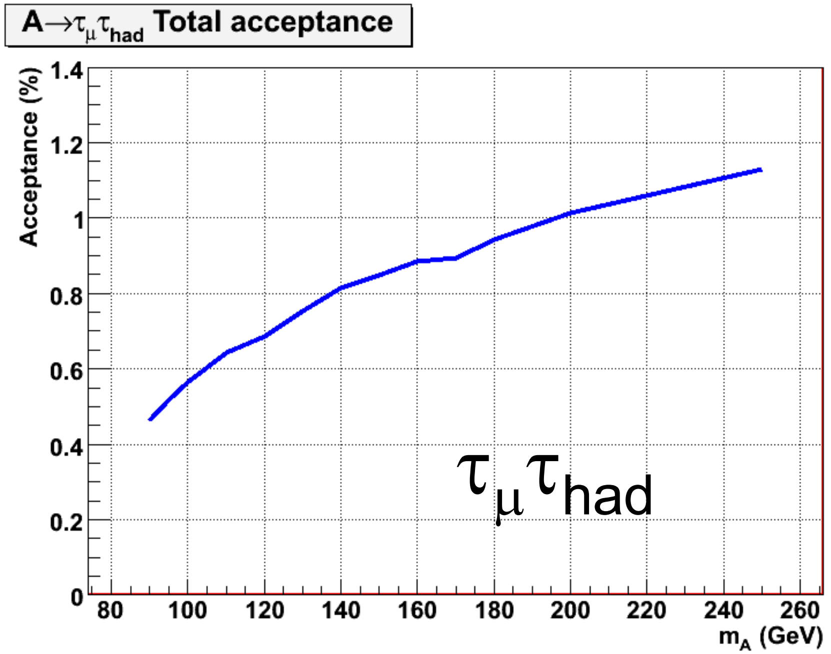


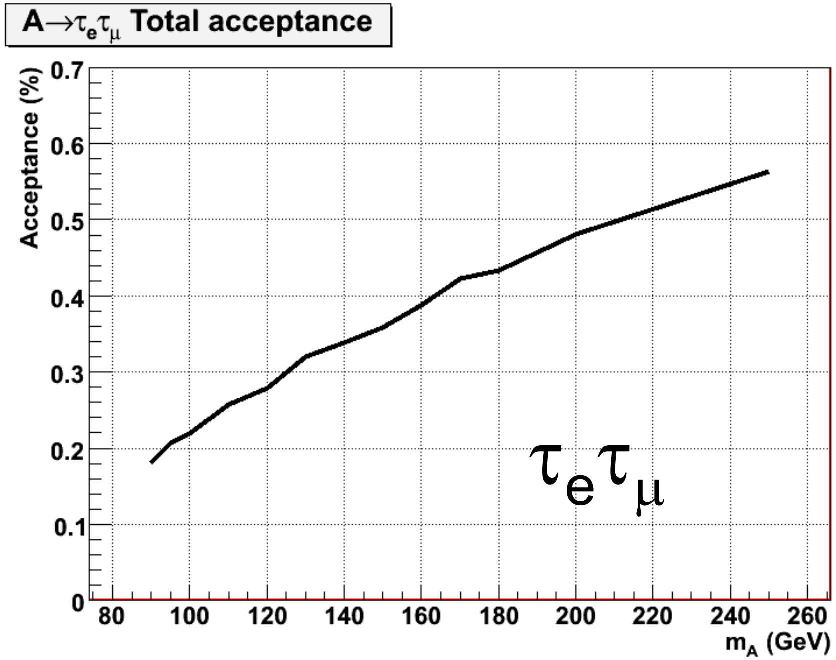
Signal detection efficiency

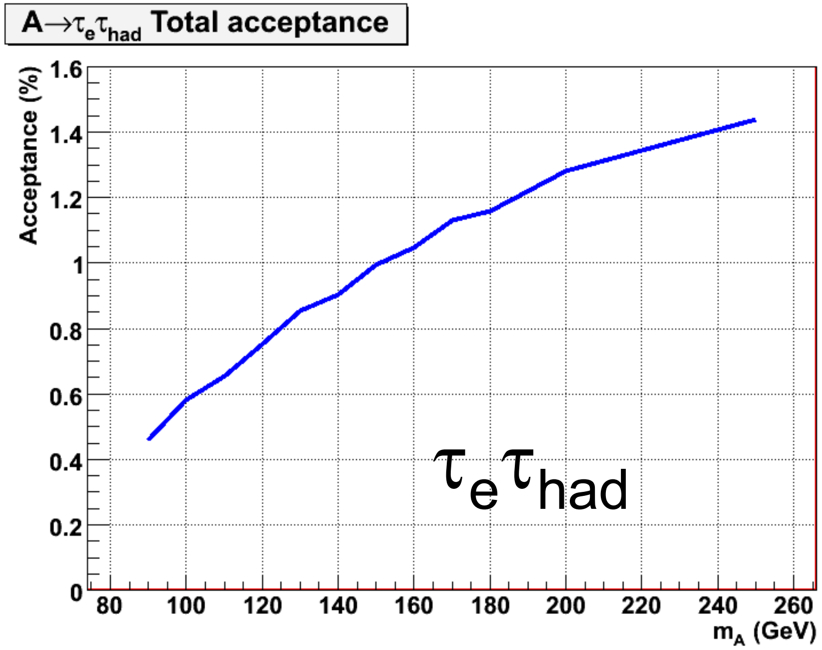
Signal MC generated with PYTHIA:
- $gg \to A$
- $bb \to A$

Higgs mass range: 90-250 GeV

Mass-dependent fractional contributions according to the expected cross sections

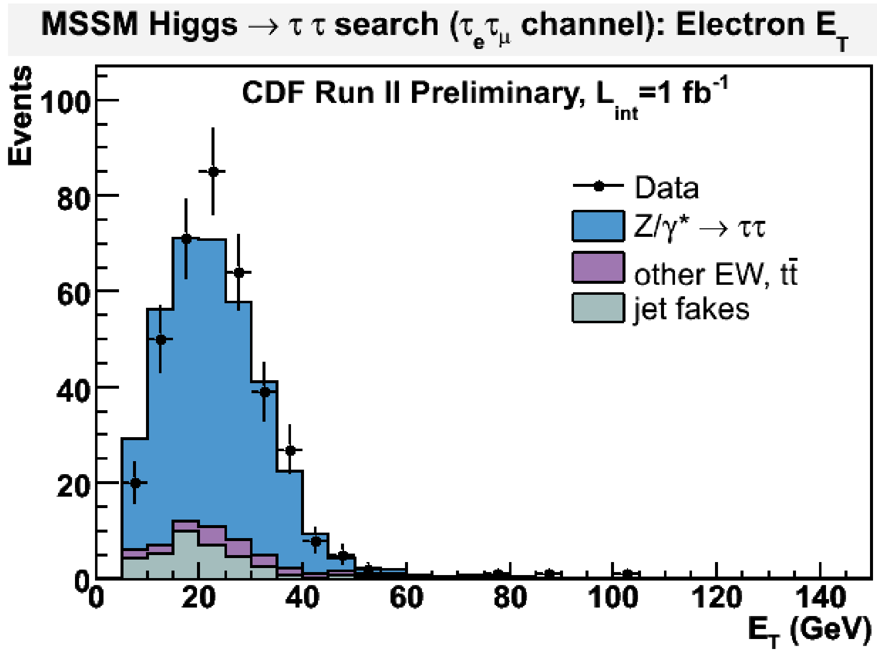


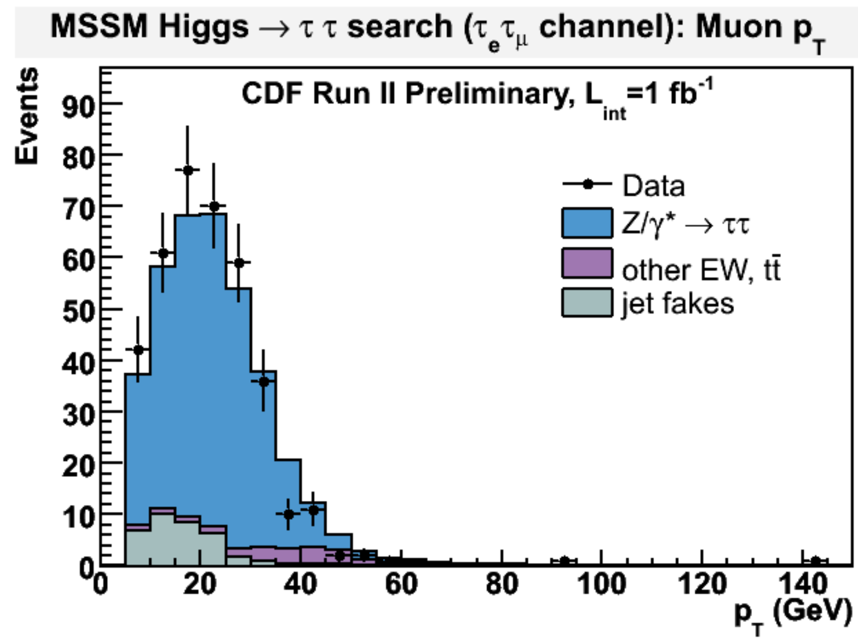


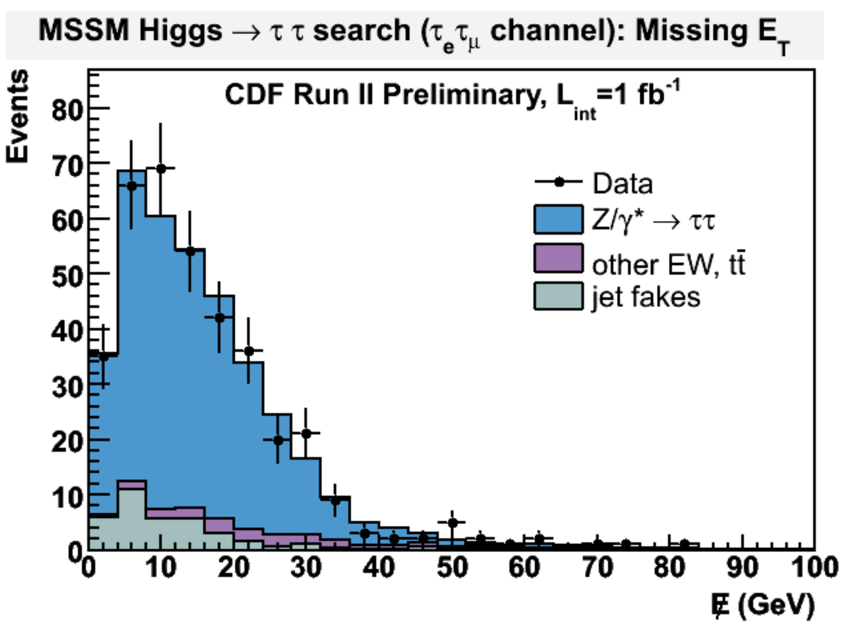


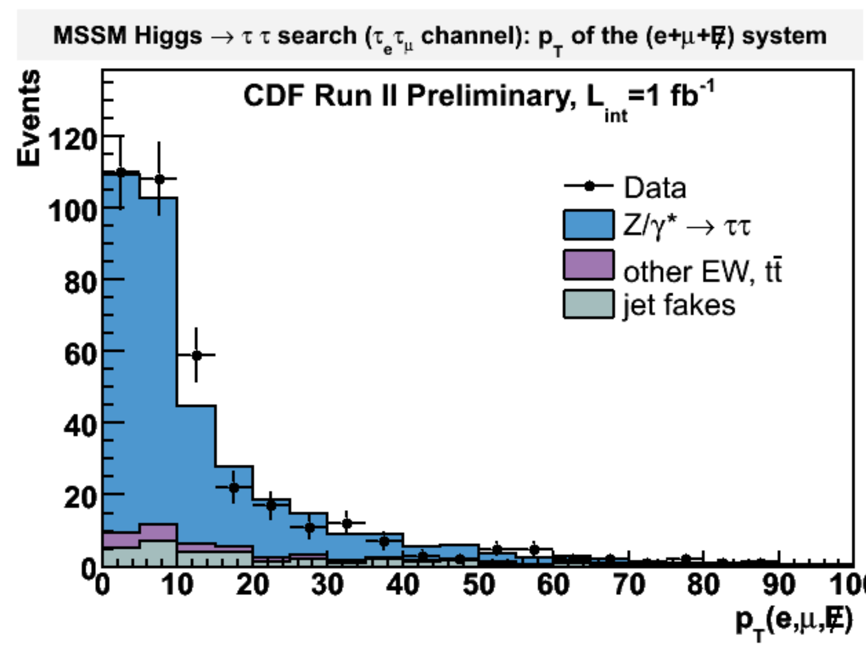
Tau BR's are in included in the calculation of the acceptance. The total acceptance is the sum of the three numbers.

Selected events in the $\tau_e\tau_\mu$ channel

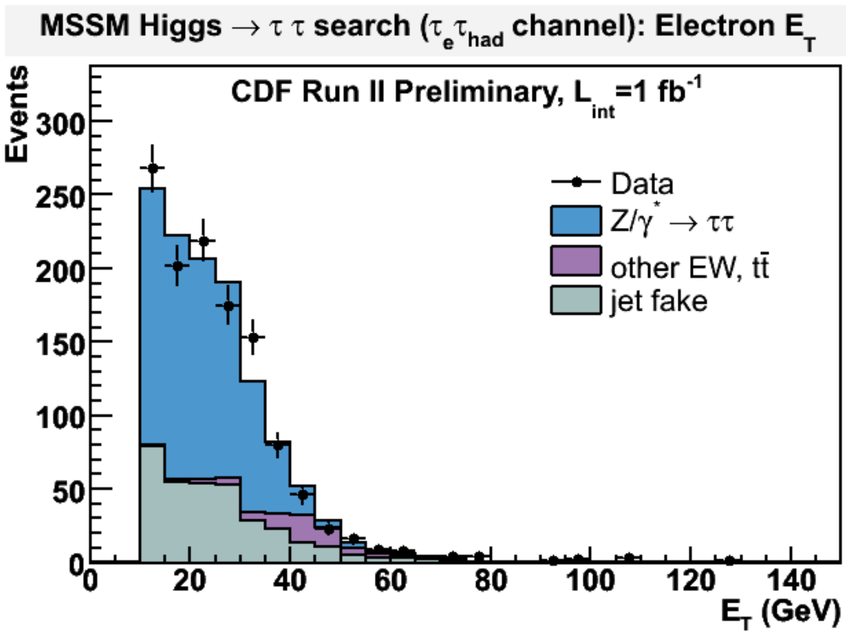


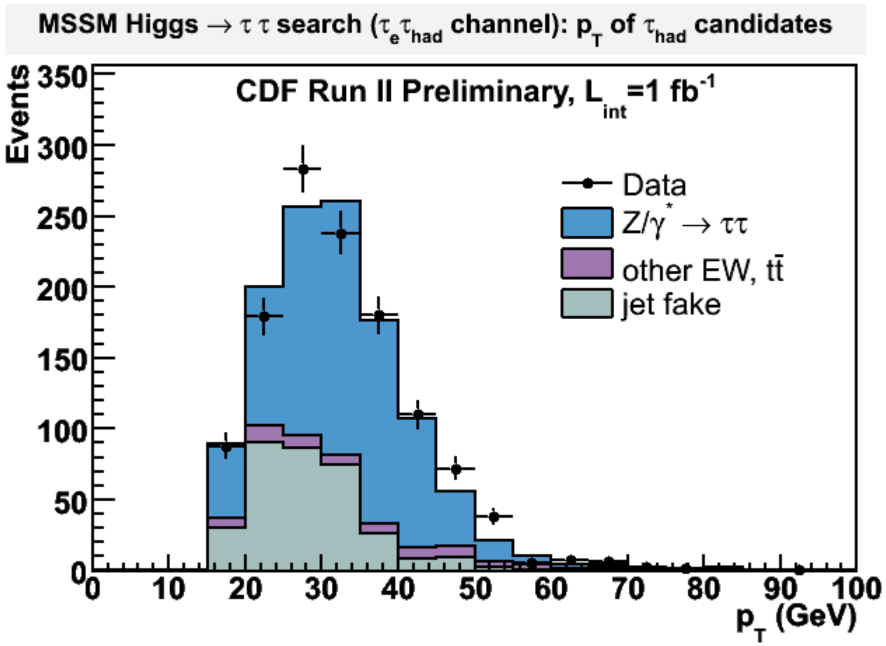


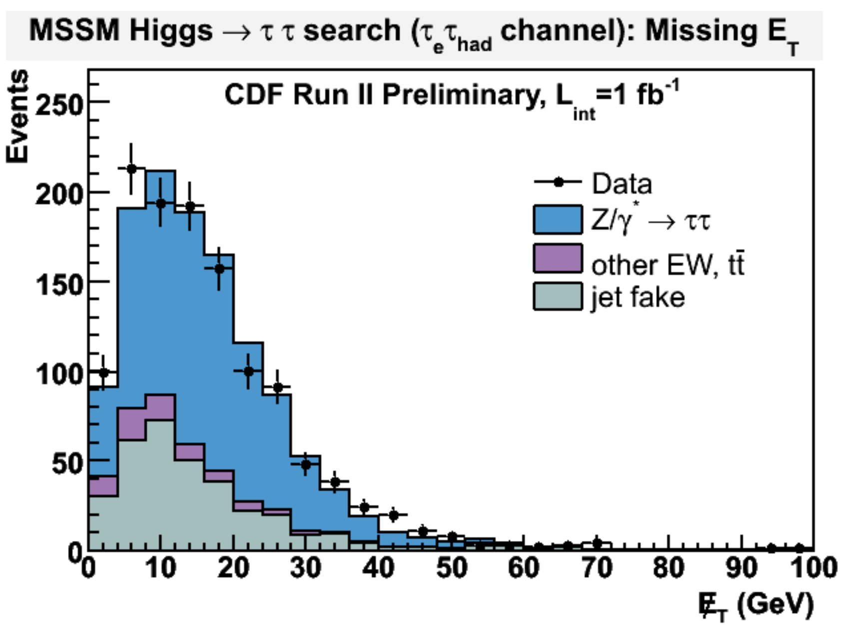


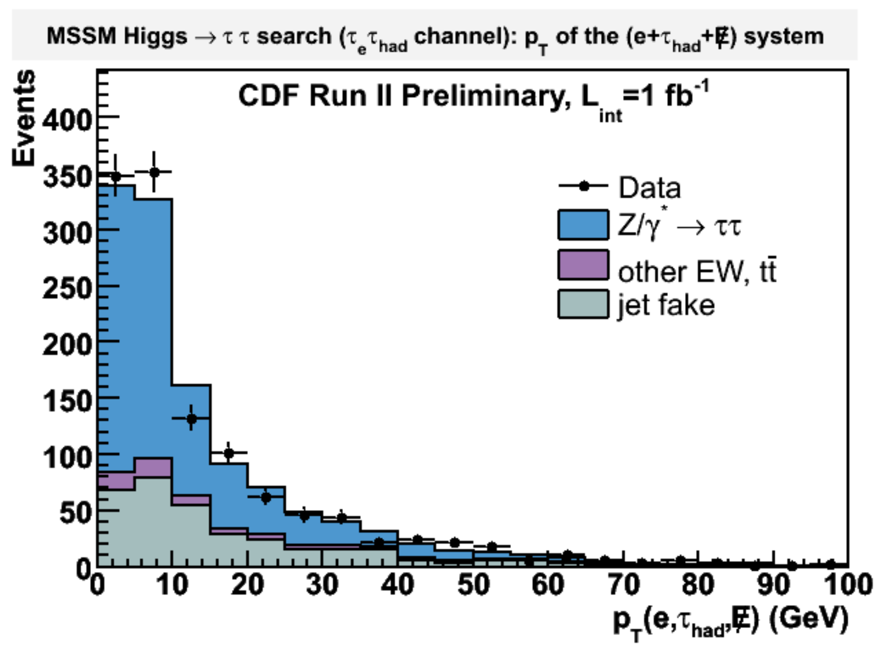


Selected events in the $\tau_e\tau_{had}$ channel

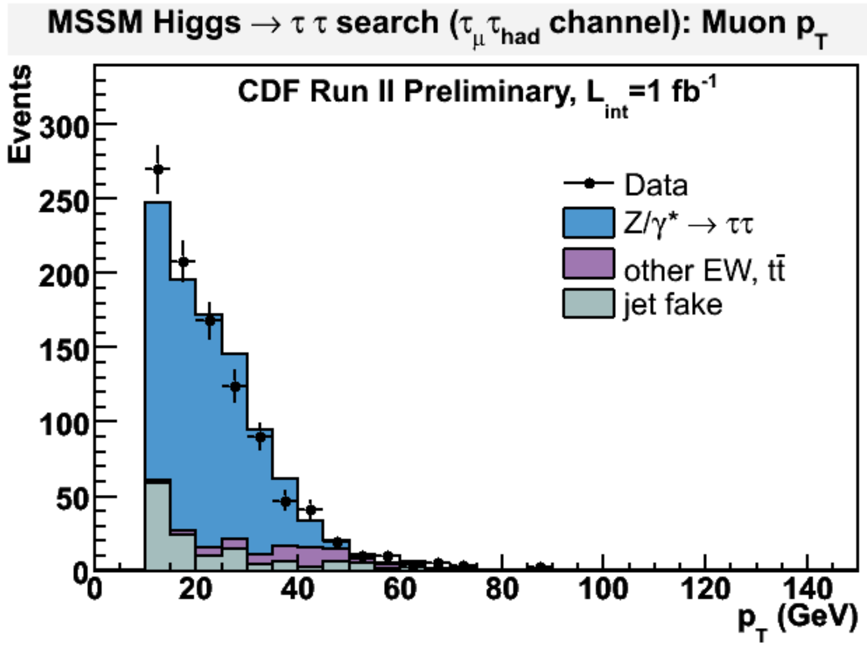


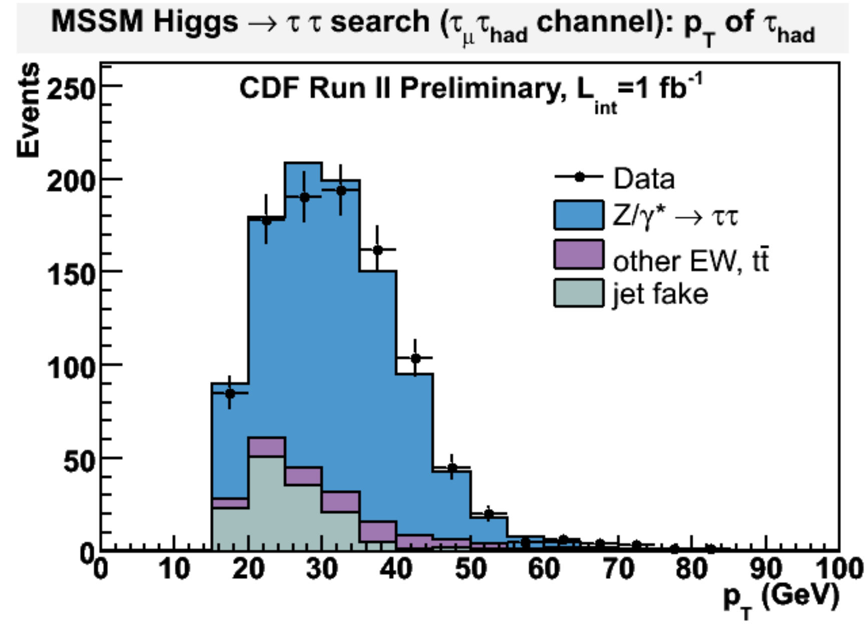


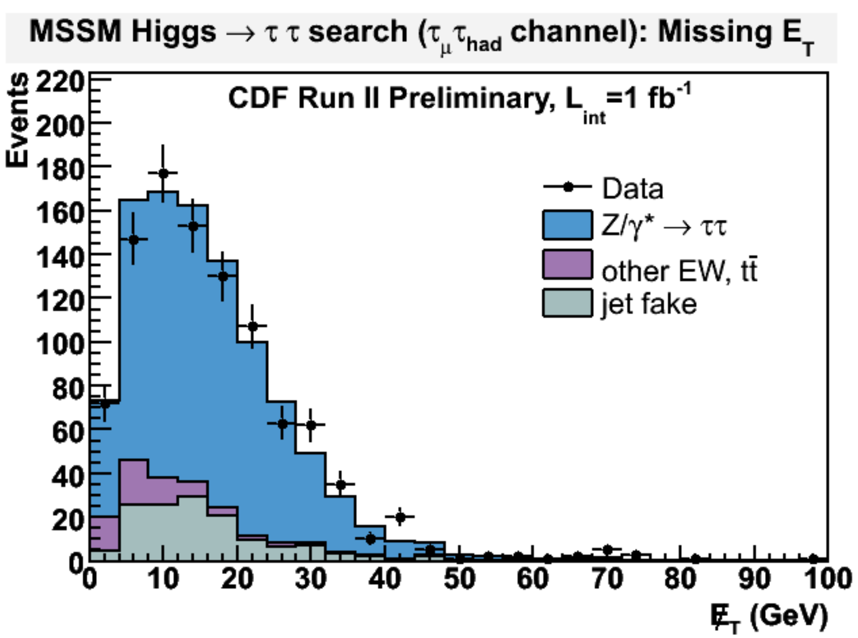


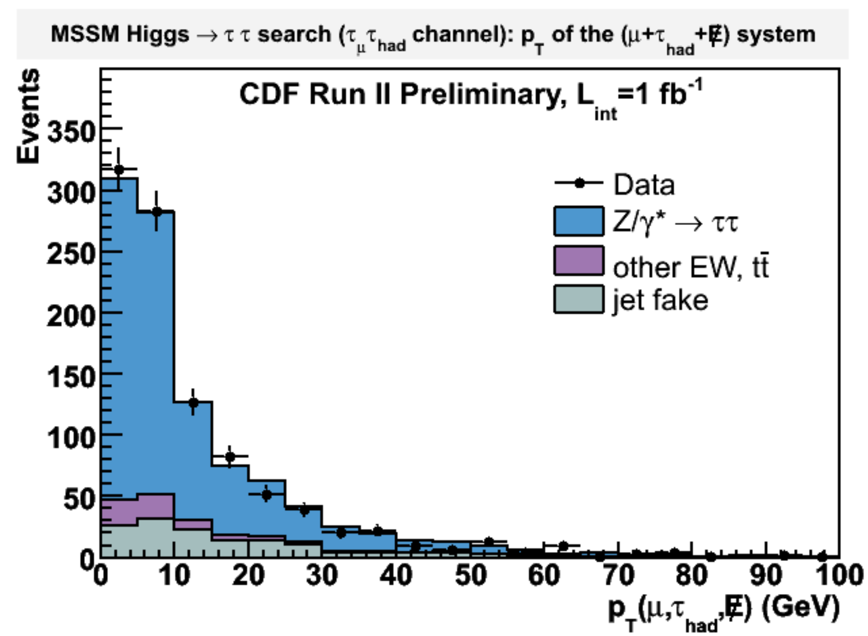


Selected events in the $\tau_\mu \tau_{had}$ channel









Observed events and expected backgrounds

Predicted bg's and observed events (stat errors only)

source	$\tau_e\tau_{had}$	$\tau_\mu\tau_{had}$	$\tau_e\tau_\mu$
$Z \to \tau\tau$	793.0 ± 4.7	796.6 ± 4.6	312.4 ± 2.9
$Z \to ee, \mu\mu$	68.3 ± 1.9	63.2 ± 1.8	11.9 ± 0.8
di-boson events	1.5 ± 0.02	1.2 ± 0.02	6.1 ± 0.1
$t\bar{t}$	1.3 ± 0.03	1.1 ± 0.03	4.7 ± 0.07
jet fakes	331.7 ± 18.2	139.4 ± 11.4	33.5 ± 3.2
Sum BG	1195.9 ± 18.9	1001.5 ± 12.5	368.6 ± 4.4
DATA	1215	1000	374

Two types of systematic uncertainties, affecting:

- rates: data/MC detection efficiency
- distribution shapes: data/MC energy scales

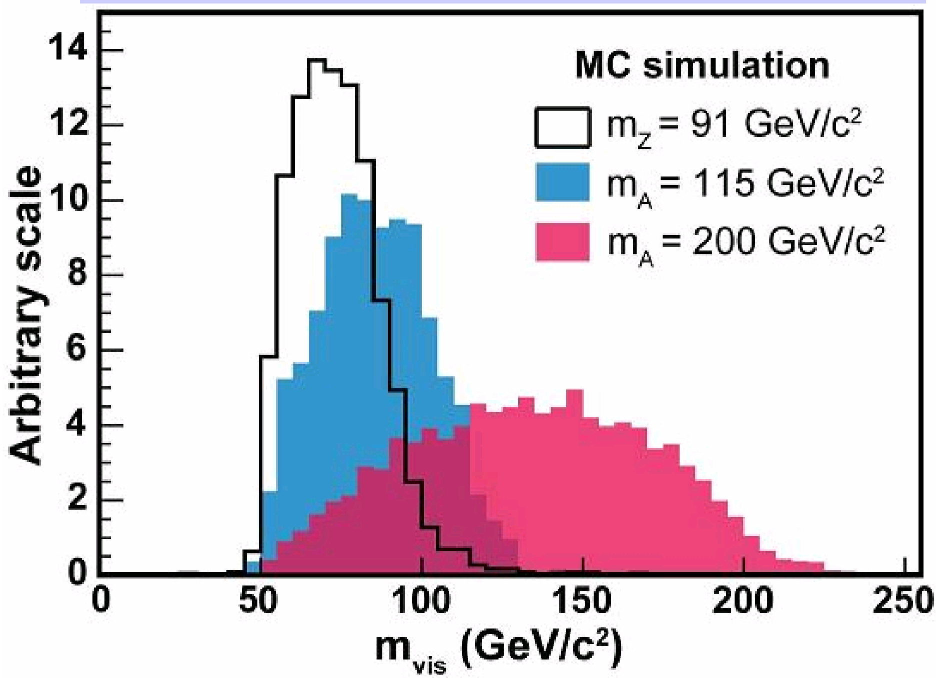
Systematic uncertainties

Parameter	type	Error(%)	applies to:
e ID	rate	2.4	e in MC
muon reco+ID	rate	2.6	μ in MC
tau ID	rate	3.0	τ in MC
e trig	rate	0.3	e in MC
muon trig	rate	1.0	μ in MC
tau trig	rate	3.0	τ in MC
z-vertex cut	rate	0.5	all MC
fake/non-iso lepton bg in $\tau_e\tau_\mu$	rate	32.0	fake/non-iso bg
fake τ_{had} in $\tau_e\tau_{had}$	rate	6.0	fake tau bg
fake τ_{had} in $\tau_\mu\tau_{had}$	rate	9.0	fake tau bg
$\sigma \times \mathcal{B}(Z \to ll)$	rate	2.2	Z MC
$\sigma(t\bar{t})$	rate	13.4	$t\bar{t}$ MC
di-boson cross sections	rate	10	di-boson MC
PDFs ($Higgs$)	rate	5.7	signal
Luminosity	rate	6.0	all MC
JES	shape	$\pm 1\sigma$ (per jet)	all MC
EM scale	shape	± 1.0	e in MC
Tau p_T scale	shape	± 1.0	τ_{had} in MC

Separating Higgs and Z

- Not enough information for exact $m_{\tau\tau}$ reconstruction:
  - Approximation: project $\not{E}_T$ onto vis τ decay products (see next slide)
  - but… significant loss of statistics
  - compromise: use partially reconstructed mass $m_{vis} = m(\tau_1^{vis}, \tau_2^{vis}, \not{E})$

Examples of m_{vis} shapes



Partial mass:

- Weaker discriminator than full mass
- Non-linear relation with mass

✓ Still, there is substantial non-overlapping region

✓ Can be calculated for all events

A look at fully reconstructed ττ masses

At this point we do not use the fully reconstructed mass to look for signal.
However, it is instructive to look at the distributions:
- for demonstrate what we expect in the future
- as a consistency check of event reconstruction

- Using projection of MET onto the direction of visible tau decay products (collinear approximation) one can reconstruct the full ττ mass *
- The mass reconstruction method of choice for large statistics
  - Taus must not be back-to-back in the transverse plane
  - MET must be pointing between the visible decay products
- The energies carried by the neutrinos are determined from the system

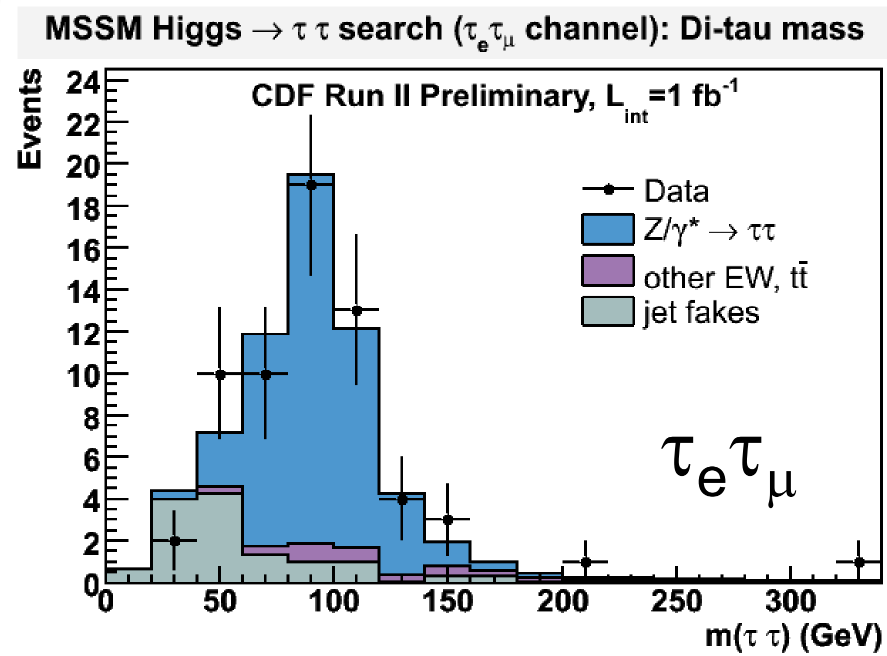
$$E_{\nu}^{(1)} \sin\theta^{(1)} \cos\phi^{(1)} + E_{\nu}^{(2)} \sin\theta^{(2)} \cos\phi^{(2)} = \not{E}_{\mathrm{x}}$$

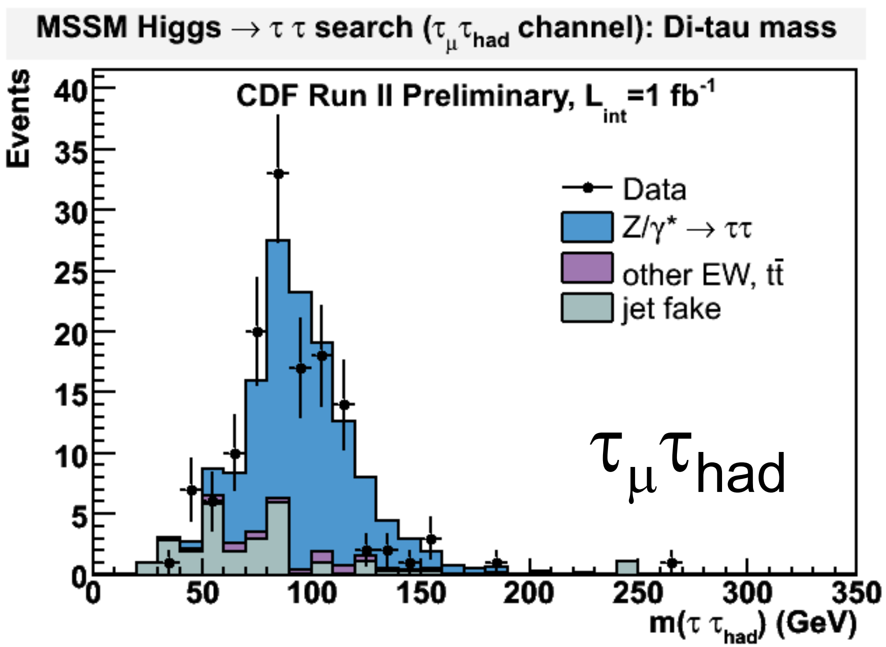
$$E_{\nu}^{(1)} \sin\theta^{(1)} \sin\phi^{(1)} + E_{\nu}^{(2)} \sin\theta^{(2)} \sin\phi^{(2)} = \not{E}_{\mathrm{y}}$$

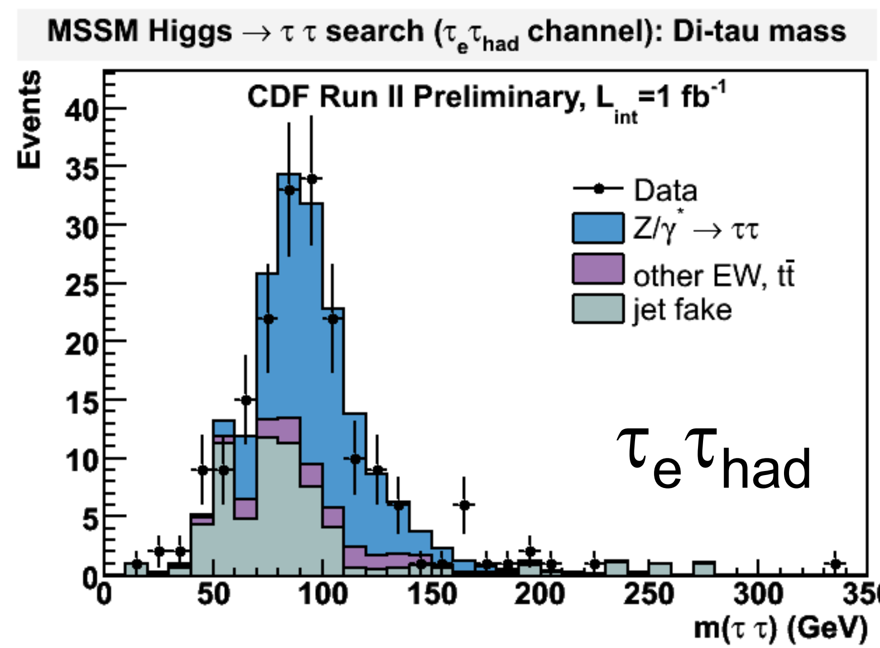
A look at fully reconstructed $\tau\tau$ masses

Non back-to-back taus: $|\sin(\Delta\phi)|>0.3$

- the distributions peak at m_Z
- good agreement between data/MC
- significant loss of statistics

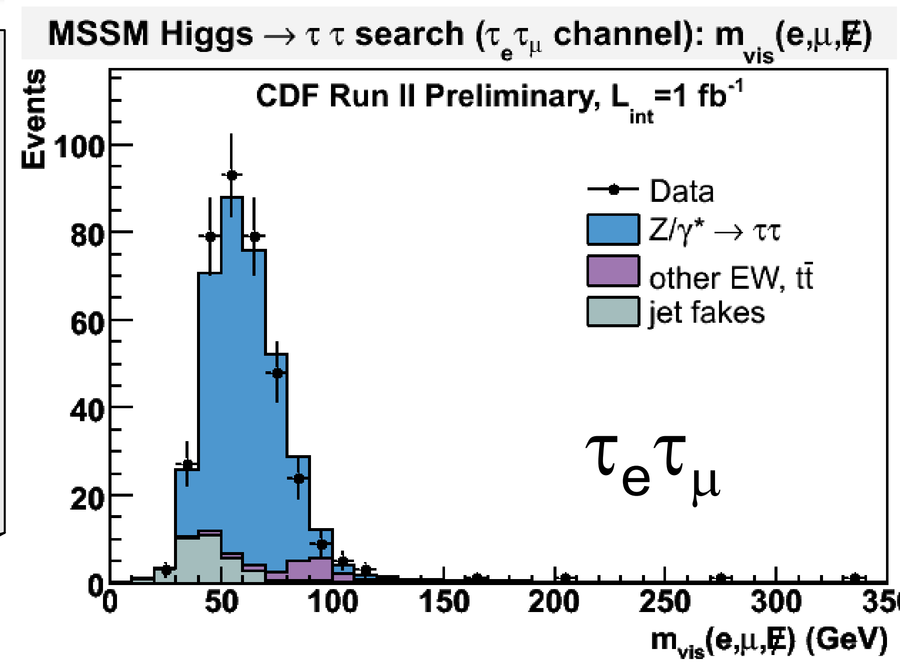


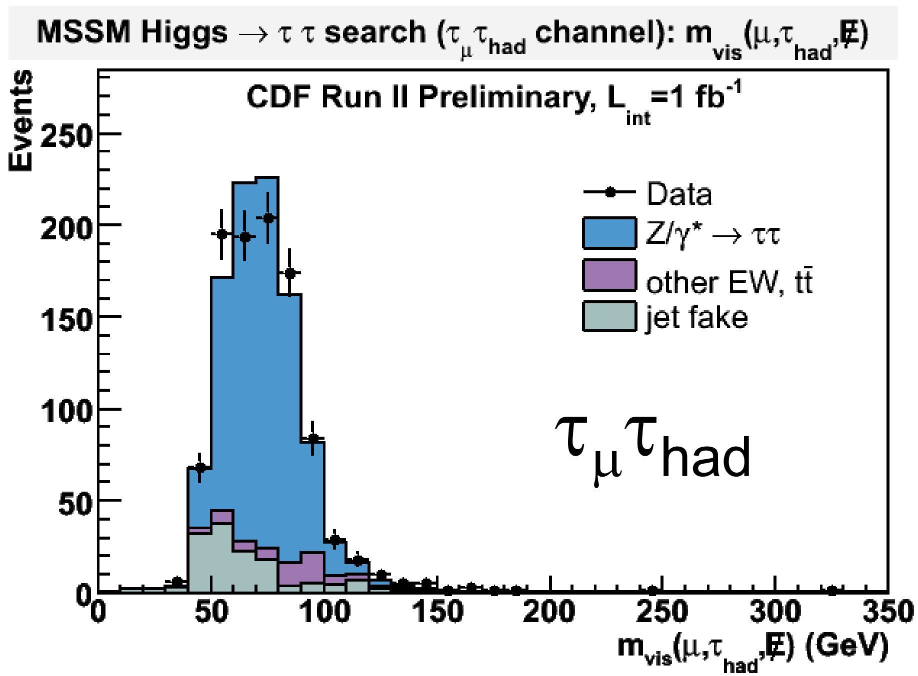


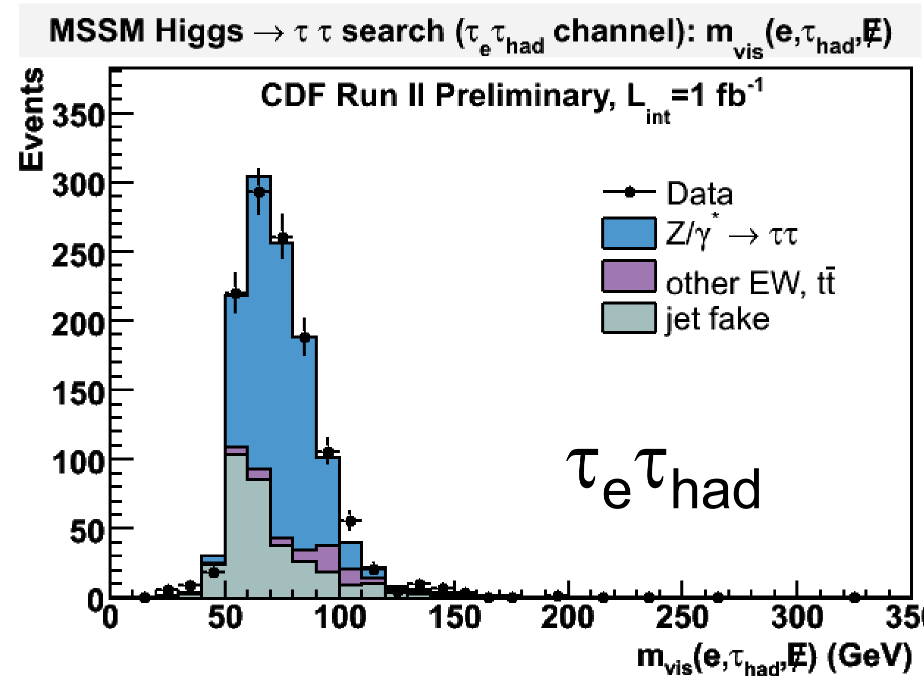


Likelihood fit to set limits:

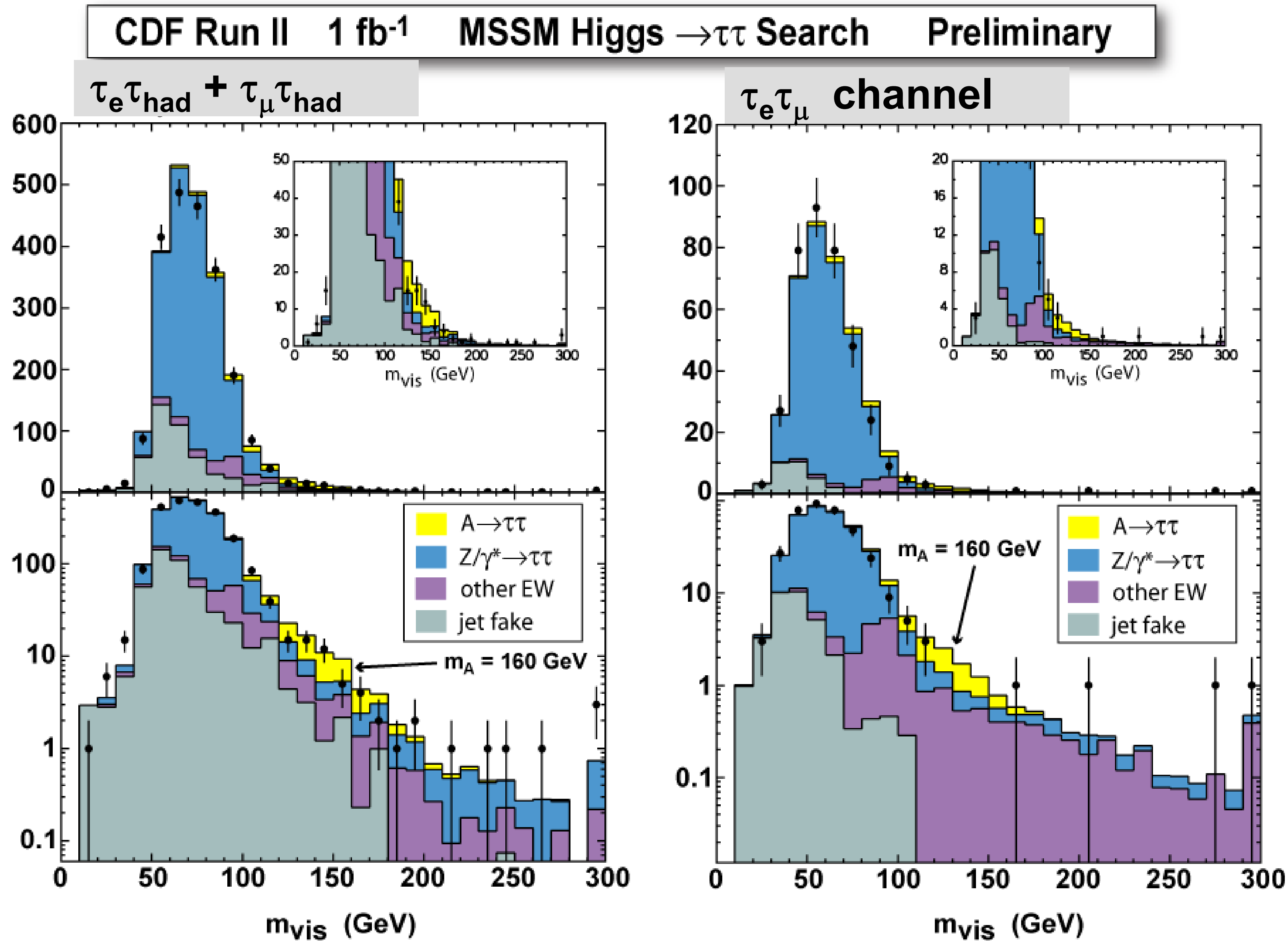
- Treat the three final states as separate channels
- Backgrounds are allowed to float subject to Gaussian constraints
- correlations between backgrounds/channels are taken into account
- shape uncertainties included via template morphing



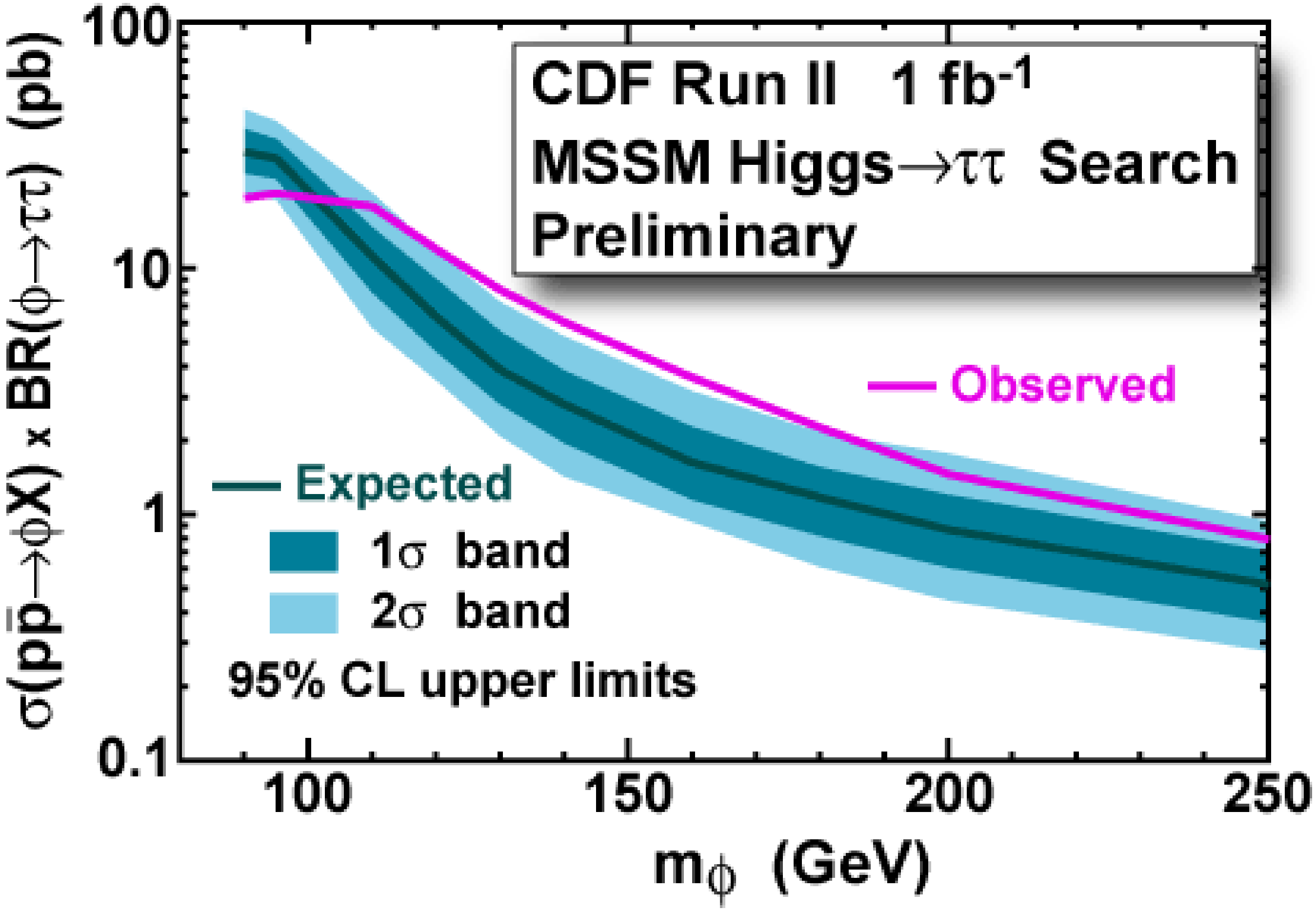




Example fit: m_A=160 GeV



The backgrounds are normalized according to the fit result. The amount of Higgs signal corresponds to the exclusion at 95% CL.



- The excess of events results in weaker limits relative to the expectation, especially for m_A=150-160 GeV
  - The broad spectrum of m_{vis} leads to propagation of the effect to a large mass range
- Taking into account that the excess could have shown anywhere in the mass range, the effect is less than 2 sigma.

Interpretation of the results in MSSM

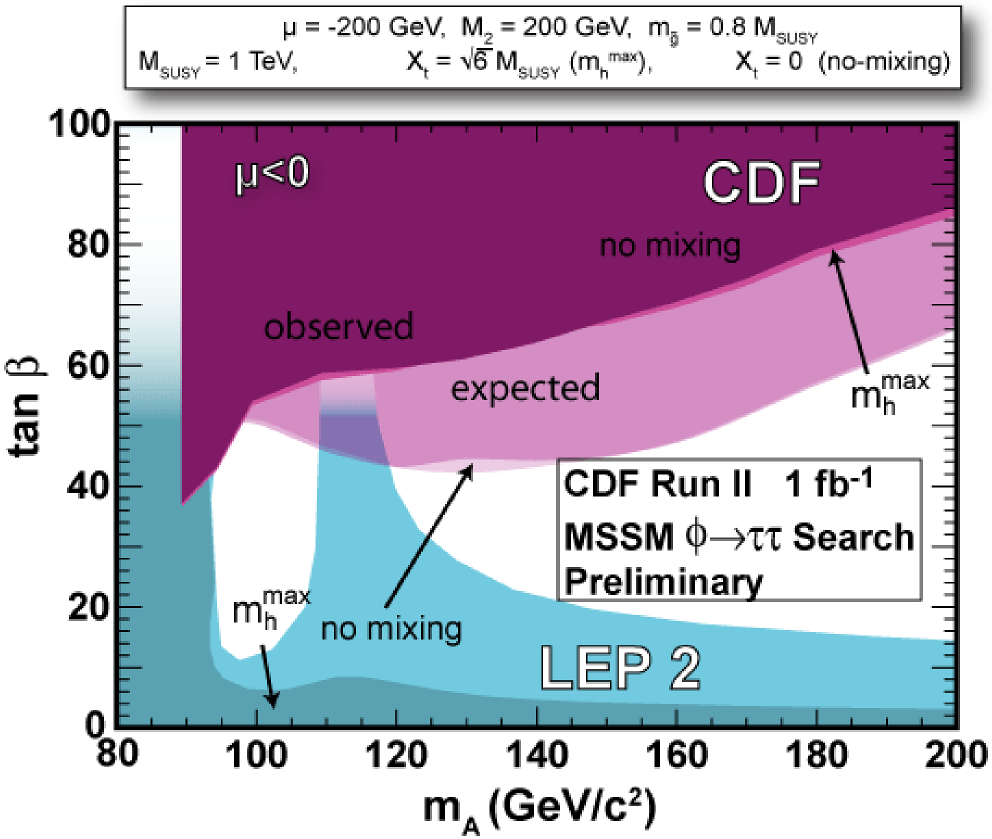
- Large MSSM parameter space, consider four benchmark scenarios [1]:

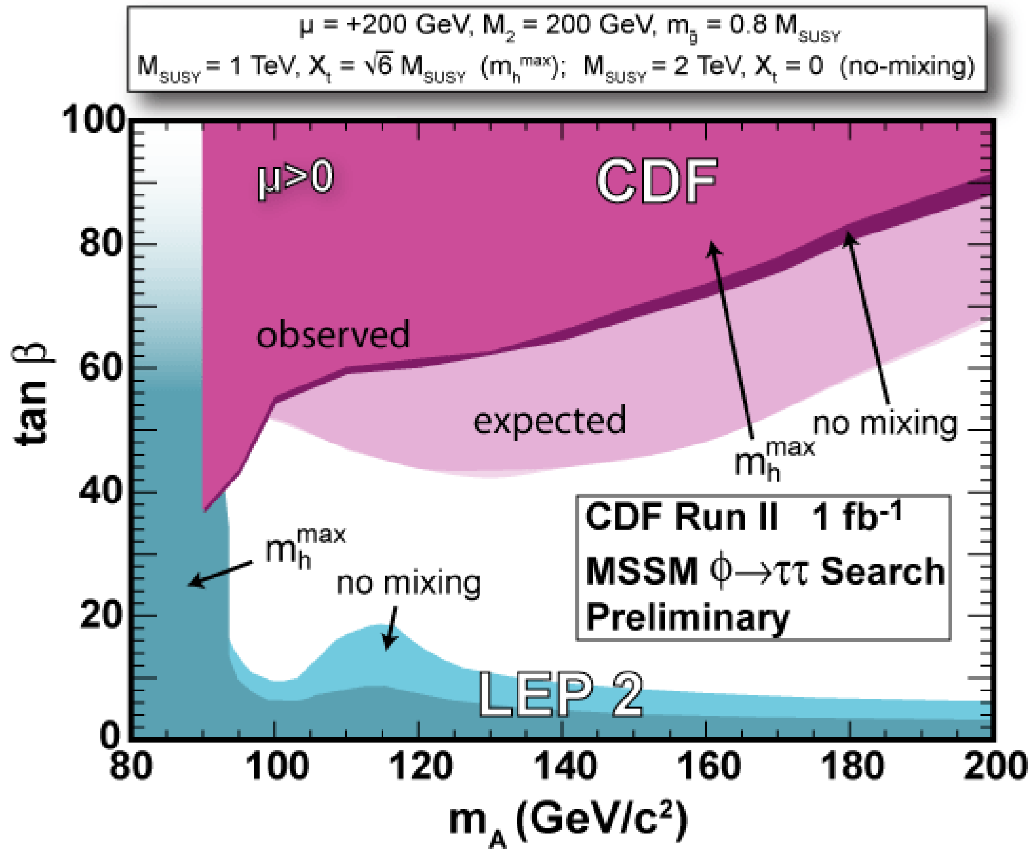
	M_{SUSY}	μ	M_2	X_t^{OS}	m_{gluino}
m_h^{max}	1 TeV	±200 GeV	200 GeV	2 M_{SUSY}	0.8 M_{SUSY}
no-mixing	2 TeV	±200 GeV	200 GeV	0	0.8 M_{SUSY}

- Follow the prescription of *Carena et al.* to get tanβ from the $\sigma \times$ BR results, using:
  - $\sigma_{SM}(gg \rightarrow \phi + X)$ from HIGLU [2]
  - $\sigma_{SM}(bb \rightarrow \phi + X)$ [3]
  - BR($\phi \rightarrow \tau\tau$) and MSSM enhancement factors from the FeynHiggs program [4]

(1) M. Carena, S. Heinemeyer, G. Weiglein, and C.E.M. Wagner., Eur.Phys.J. C45 (2006) 797-814
(2) M. Spira, Nucl. Instrum. Meth. A389, 357 (1997).
(3) R.V. Harlander, W.B. Kilgore, Phys. Rev. D68, 013001 (2003).
(4) S. Heinemeyer, W. Hollik, and G. Weiglein, Eur. Phys. J. C 9, 343 (1999); Comput. Phys. Commun. 124, 76 (2000).

tanβ vs m_A exclusions





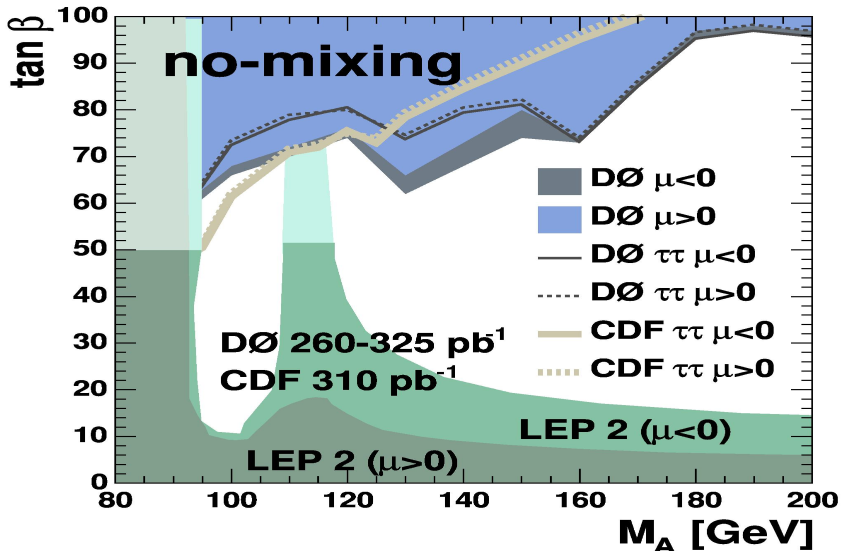
- As expected for the MSSM Higgs→ττ channel the exclusions in tanβ vs m_A plane show small variation for the four scenarios

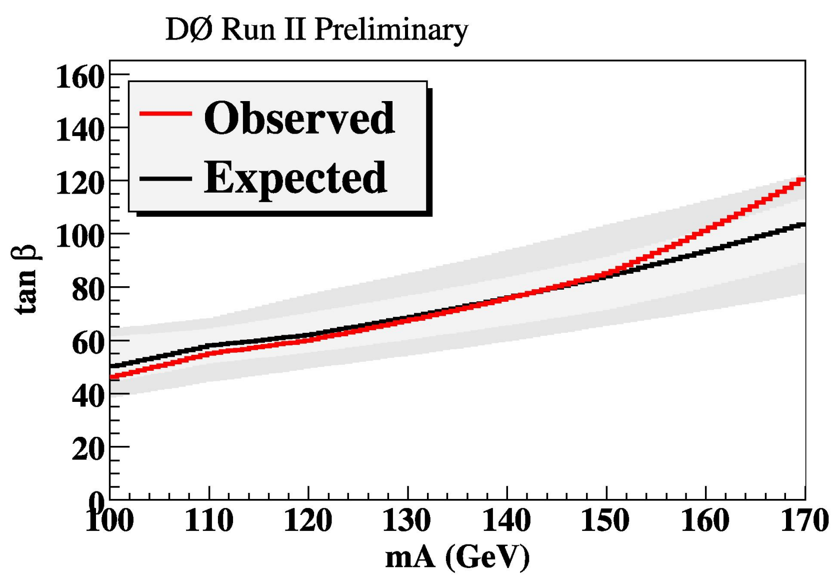
CDF Higgs$\rightarrow \tau\tau$ Search: What's next

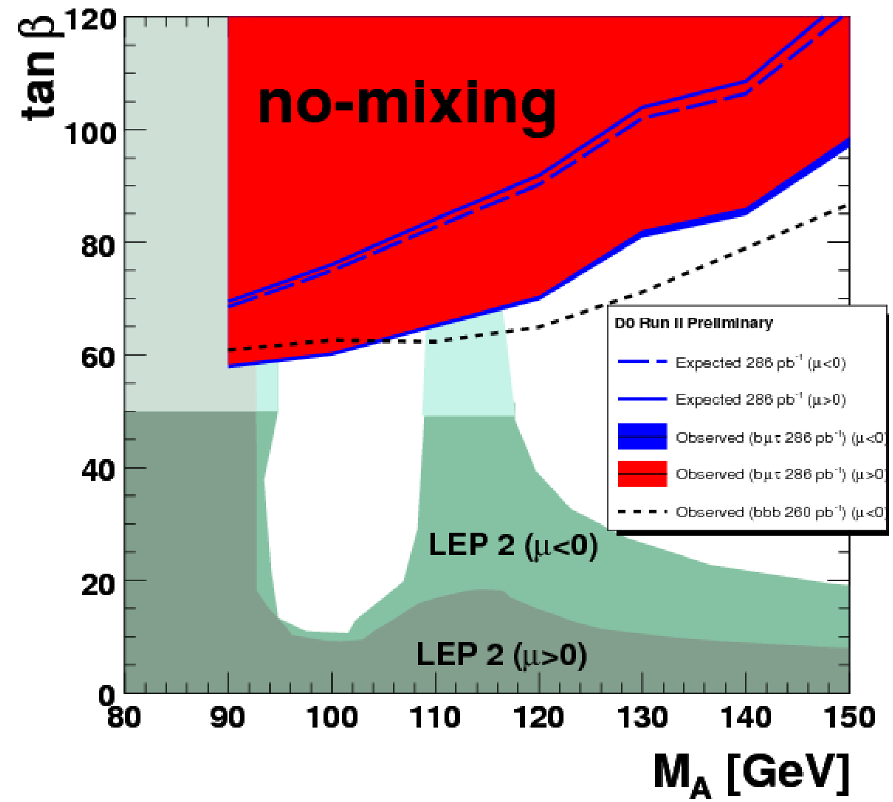
- We have observed a small, but interesting excess of events in the data
- CDF will soon have 2 fb^{-1} of data - a welcome and timely addition
- Refine the search utilizing more information, treat as separate channels events with
  - fully reconstructed $\tau\tau$ mass
  - associated high p_T b-jet

tanβ vs m_A: other results from the Tevatron

- D0 has also performed searches in the A→ττ (340 pb^{-1}), and A+b(b) →bbb(b) (260, 900 pb^{-1}) modes
- New results from D0 and CDF will follow soon







It is no longer possible to overlay all the Tevatron results on a single plot

Summary

- The Tevatron experiments have a lot to say about MSSM Higgs
- We are already probing tanβ~40
- Combination of the results in all channels from CDF and D0 will result in a significant boost in sensitivity

"The hardest thing of all is to find a black cat in a dark room, especially if there is no cat."

- Confucius