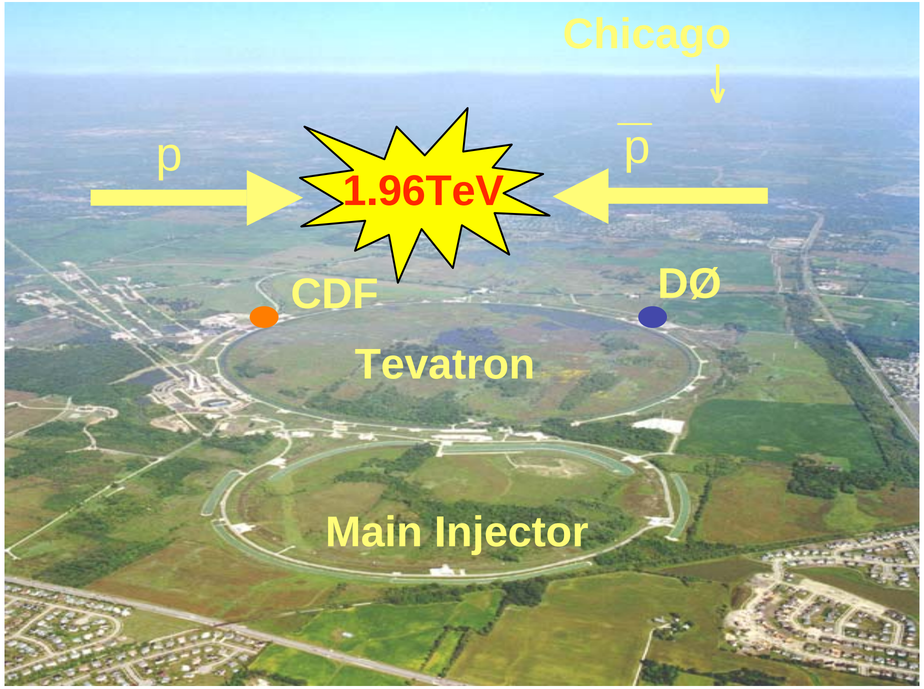
Multi-leptons: from the Tevatron to the LHC

Michele Gallinaro

LIP Lisbon

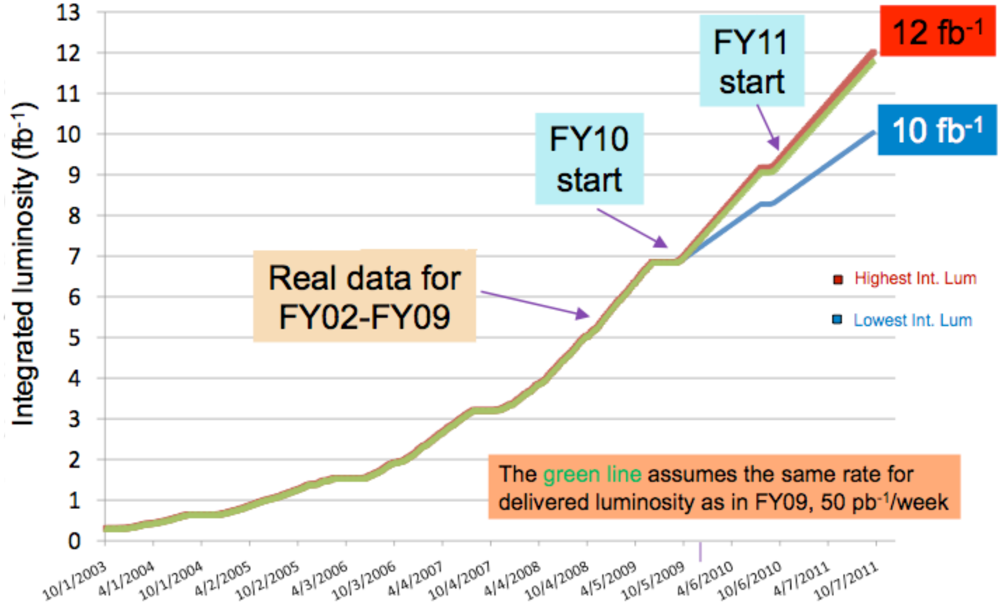
- Introduction
- Higgs and Top
- Multi-bosons
- SUSY

Tevatron



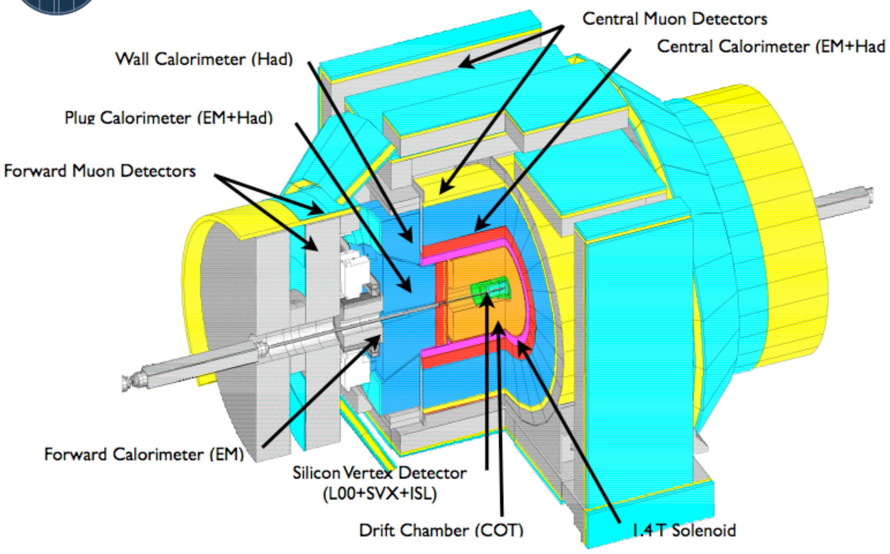
- Direct measurements are the most precise and can only be done at hadron colliders: Tevatron now, LHC in the future

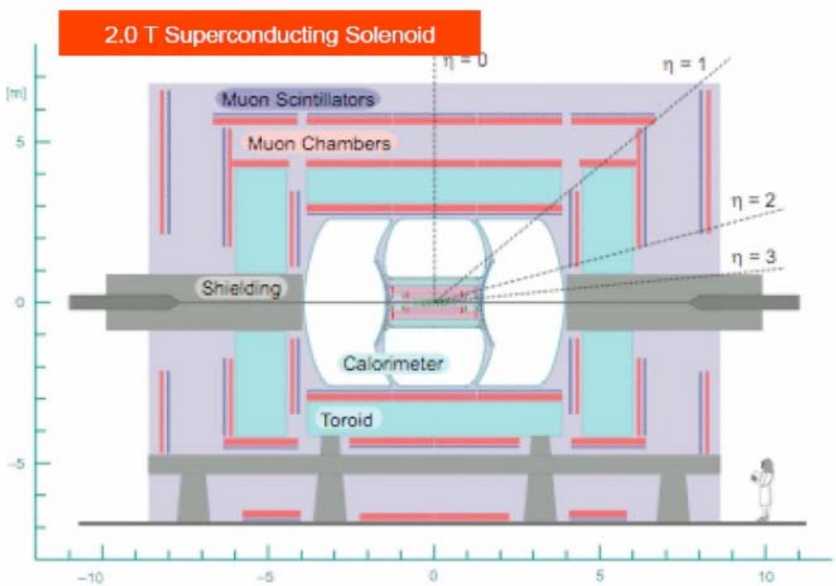
- p-pbar at 1.96 TeV since 2001
- Record luminosity: $3.6 \times 10^{32} cm^{-2} s^{-1}$
- Expected to run until 2011
- Integrated luminosity up to 12 fb^{-1}



Detectors

- Accurate tracking system with silicon detectors
- Good calorimetry to measure EM/Had energy
- Efficient b-tagging capabilities



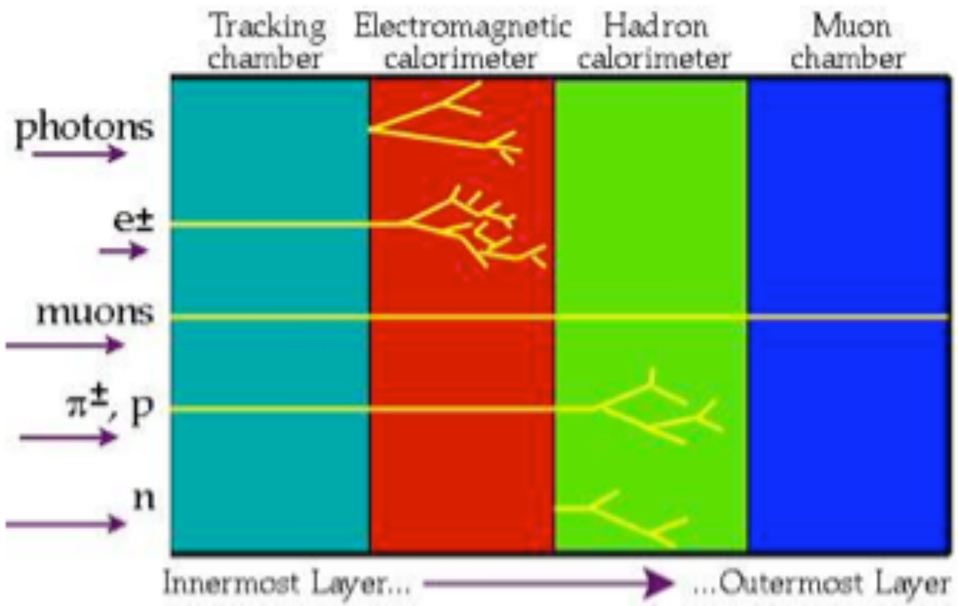


excellent tracking system

excellent muon coverage

Particle detection

- **Electrons:**
  - matching between track and EM calo
  - shower compatibility (reject π^0s)
  - isolation (reject showers from quarks)
- **Muons:**
  - matching track to muon chambers
  - isolated tracks
- **Taus:**
  - $\tau \rightarrow$ leptons through e,μ
  - $\tau \rightarrow$ hadrons through jets



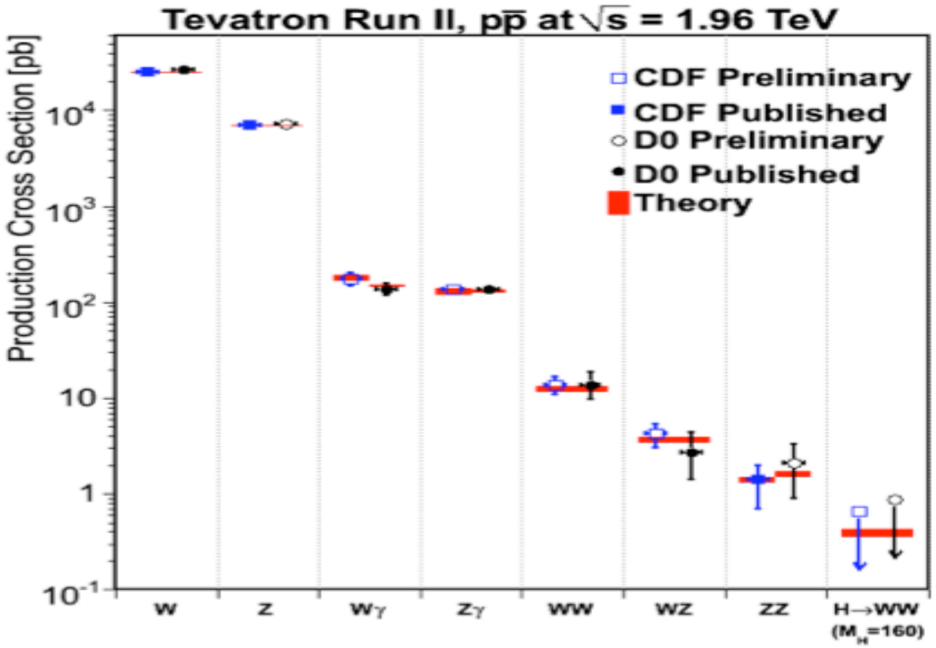
Leptons

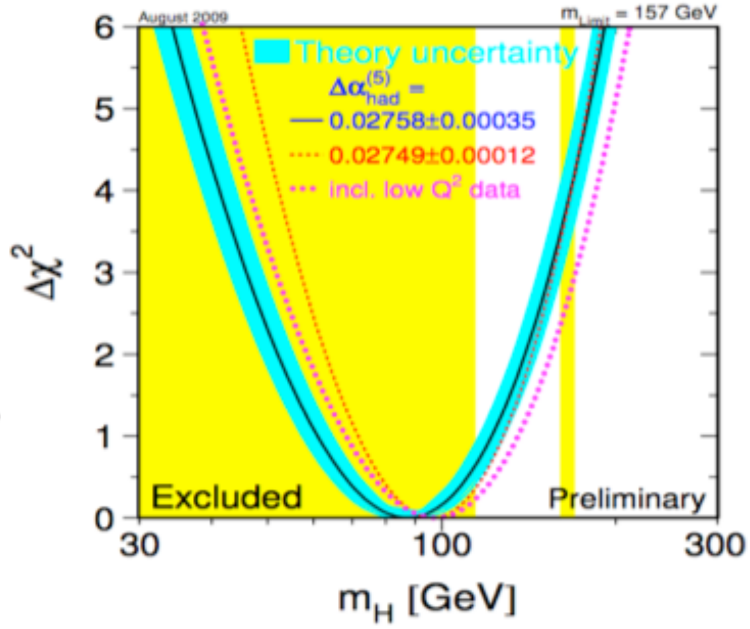
- “simple”, robust ID, small fake rate
- Cross section lower than jets, but easy to trigger (e,μ)
- Many final states contain leptons

- Start with SM signatures
- Deviations can provide hint of NP
- Using ratios may help to look for deviations

SM Higgs and beyond

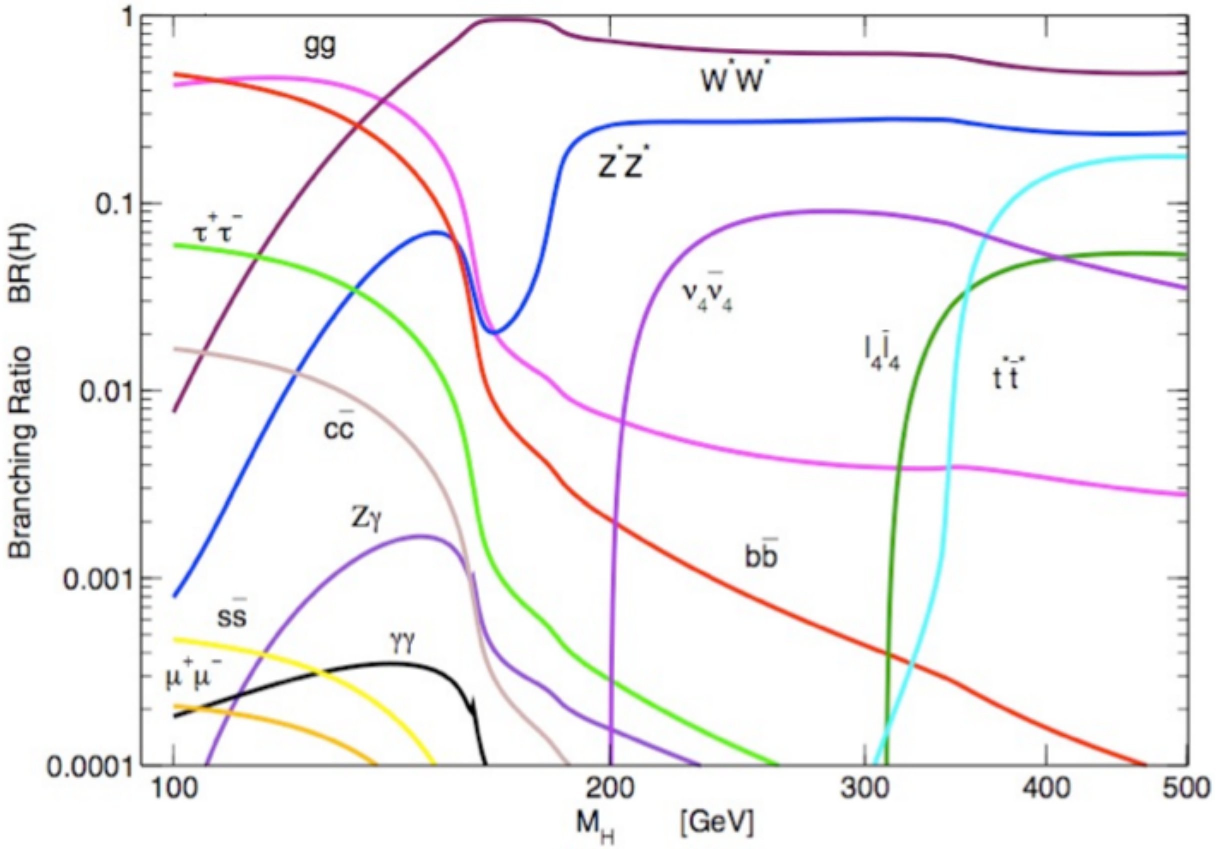
- **Higgs search is a major goal of HEP, central part of Tevatron Program.**
- With recent observations of single top and WW/WZ→lνjj Tevatron is closing in on the SM Higgs boson.
- Direct search & EW fit set: **$114.4 < m_H < 186$ GeV @ 95 % C.L.**
- **The SM Higgs is now within Tevatron reach !**





Higgs decays

- At high masses: H→WW is dominant decay mode
- At low masses: H→bbar is dominant decay mode

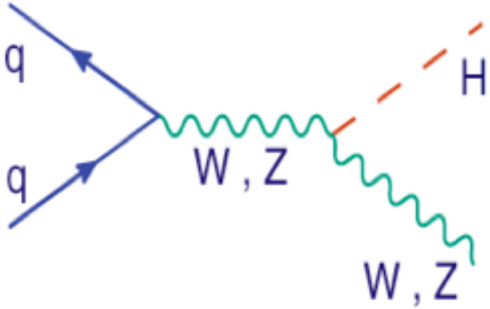


Search strategies

•Event selections are similar for the corresponding CDF and D0 analyses.

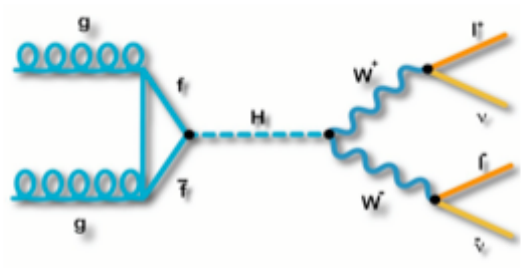
•**Search for H→bb in association with W and Z:**

- Main low mass channels
- Identify Higgs as two jets with 1 or 2 btags
- W, Z identified as leptonic or hadronic decays



•**Search for H→WW→lνlν in inclusive production:**

- Main high mass channel
- Selects on two charged leptons + missing et



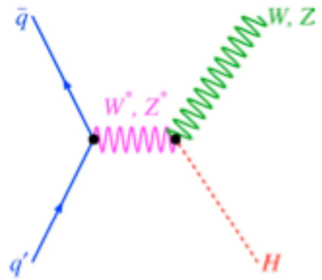
•**Search for H→ττ, γγ in inclusive production:**

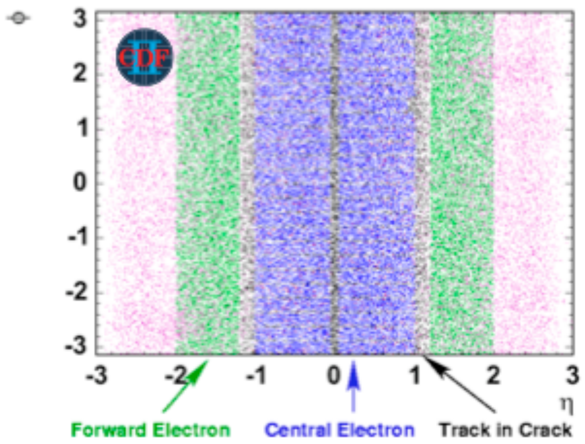
- Minor channels for Tevatron, but important for LHC
- Identify Higgs as a pair of τ or a pair of γ

•Employing "**no channel too small**" strategies to gain signal acceptances while reducing backgrounds with advanced analysis technique(**NN,ME,BDT**).

Low mass Higgs searches

- Identified leptons
  - *WH→lνbb̄, ZH→llbb̄*
- Invisible leptons
  - WH→(l)νbb̄, ZH→ννbb̄





1. Identify *W/Z*: leptons (*e*,*μ*)

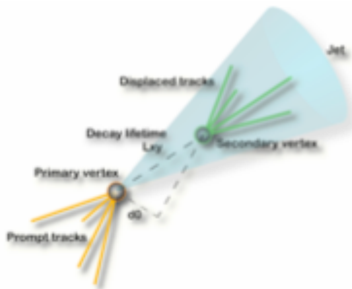
- Maximize lepton coverage
  - *e.g.* leptons not in fiducial region of calorimeter

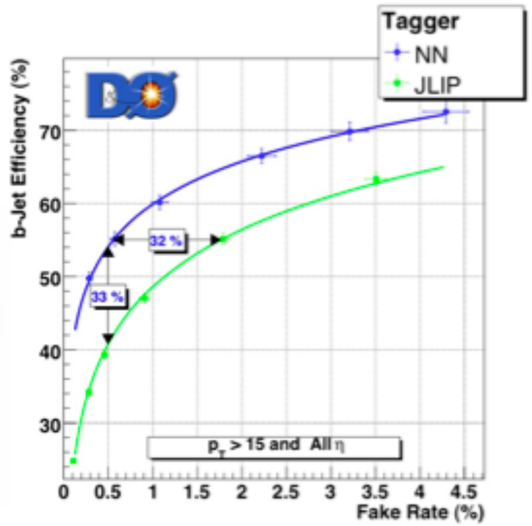
2. Identify Higgs decay: jets

- Develop NN and other advanced tagging algorithms
- Develop multivariate jet corrections

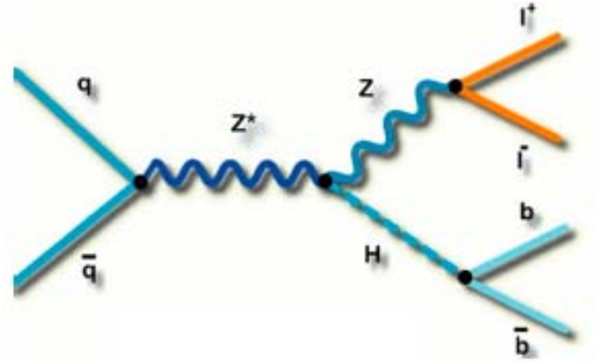
3. Reduce backgrounds

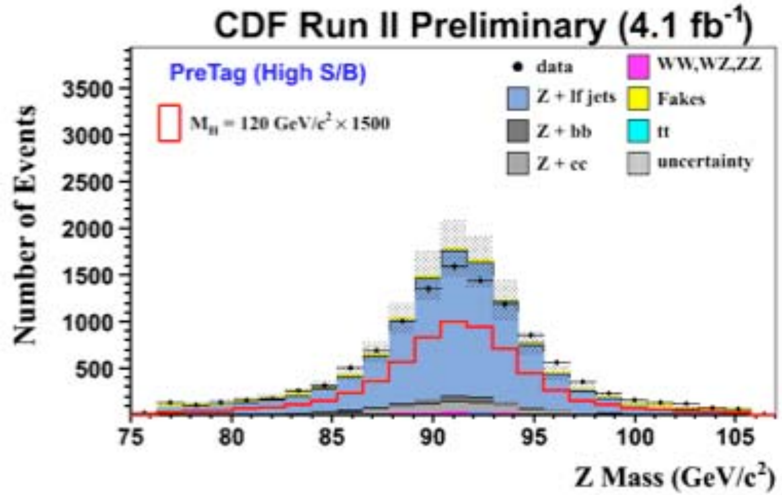
- Multijet backgrounds particularly difficult
  - Model using data
  - Use NN to separate



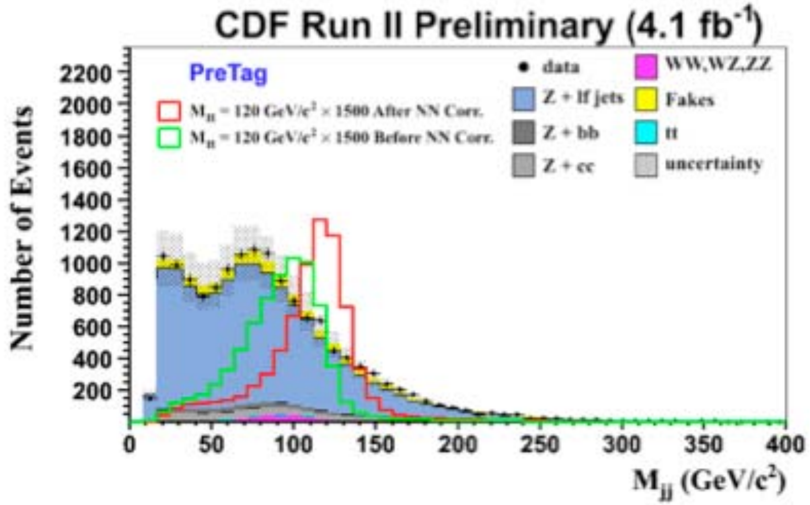


ZH channel





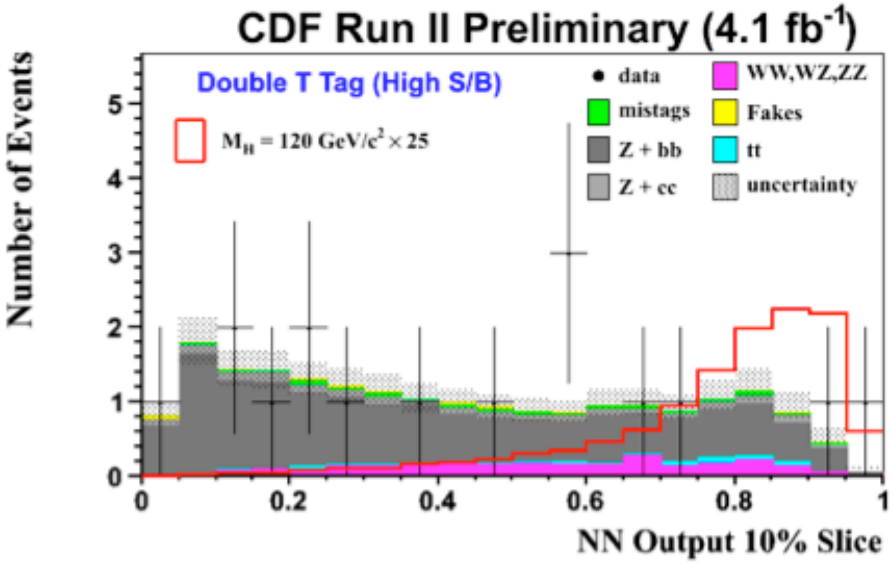
- Fully reconstructible final state
- Backgrounds primarily *Z*+jets, diboson and ttbar (little QCD)
- Very small signal rate

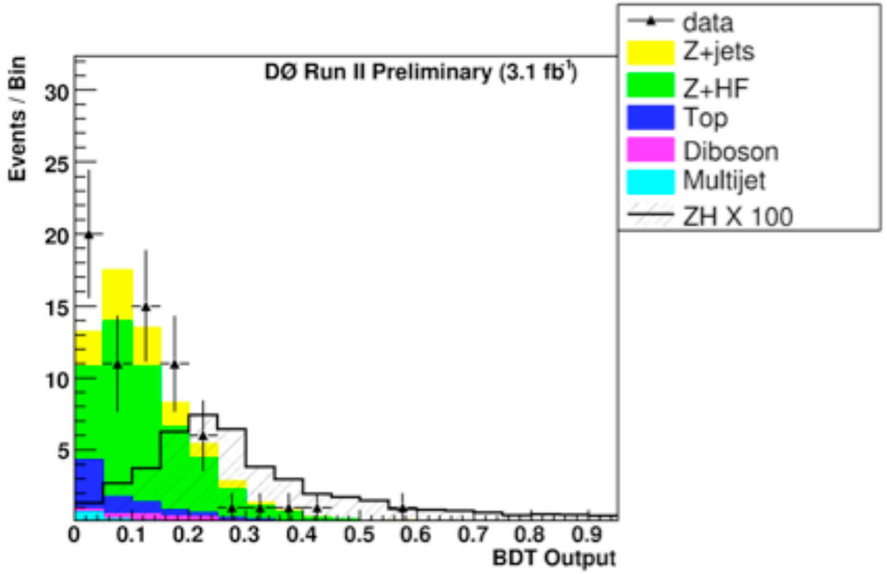


- Expand lepton selection to maximize acceptance
- Select events with 2 leptons, 2 jets, at least one of which is b-tagged
- Can use NN to improve dijet mass resolution

ZH results

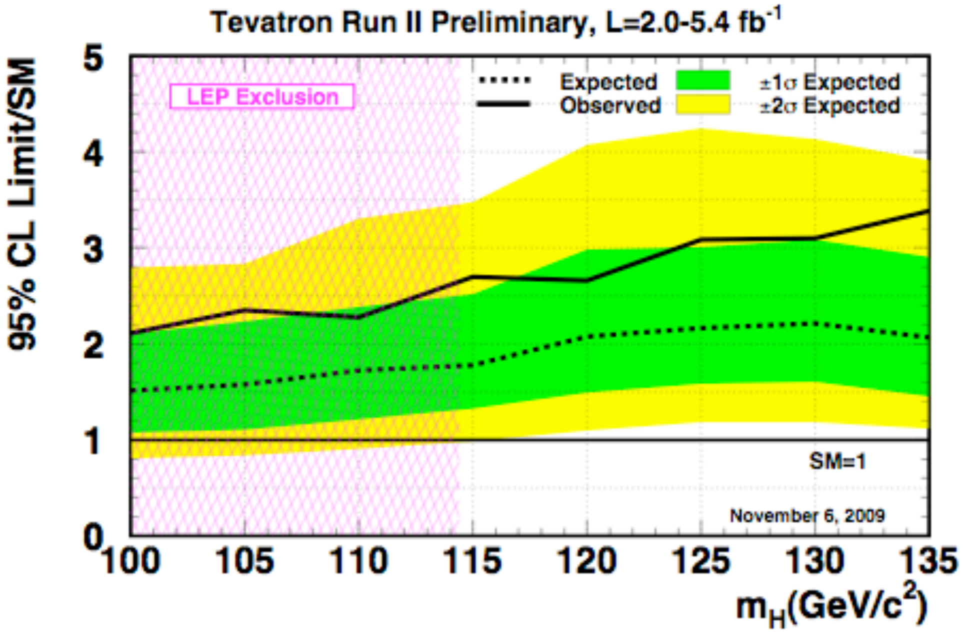
$ZH \to llb\bar{b}$





- CDF: 2D NN (ZH vs ttbar, ZH vs Z+jets), include leading order ME as input
  - 4.1 fb^{-1} Observe (expect) 5.9 (6.8)×σ_{SM} @95% CL for m_H=115 GeV
- DØ: boosted decision tree
  - 4.2 fb^{-1} Observe (expect) 9.1 (8.0)×σ_{SM} @95% CL for m_H=115 GeV

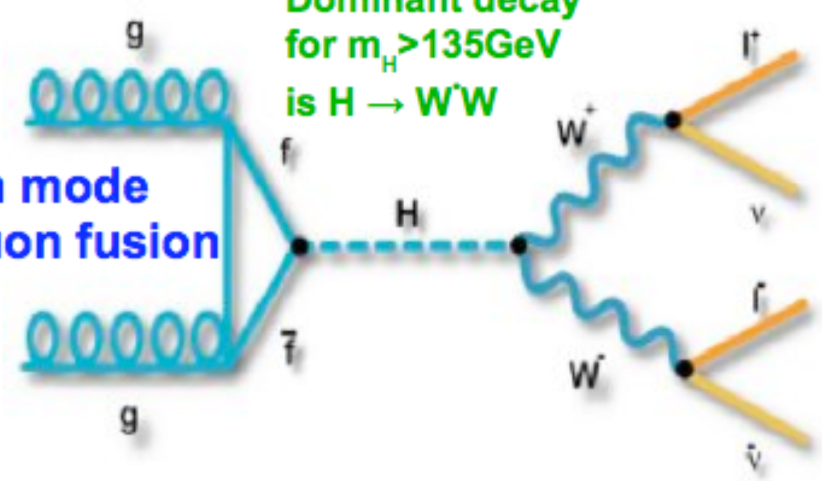
Low-mass Higgs



- Comprehensive search for low mass SM Higgs at CDF and DØ
  - Cover all associated production channels
  - High mass $H \to W^+W^-$ search also contributes at low mass
- Combined CDF+DØ sensitivity at m_H=115 GeV is now $1.78 \times \sigma_{SM}$
  - Observed limit of $2.70 \times \sigma_{SM}$ at m_H=115 GeV

High-mass Higgs search

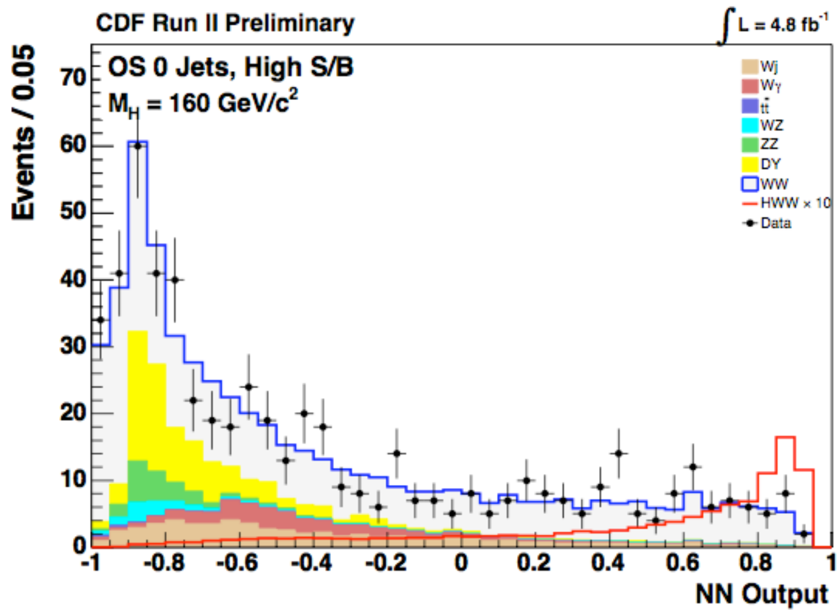
Dominant production mode at the Tevatron is gluon fusion



Dominant decay for m_H>135GeV is $H \rightarrow W^+W^-$

2 opposite charge high p_T leptons (electrons, muons)
+
Missing E_T

- Event signature:
  - two isolated high-pT leptons with opposite charge
  - large MET
- Backgrounds: dibosons (mainly WW)
  - Drell-Yan
  - Top, W+jets, W+γ, multi-jets



VH→VWW→lνlν+X

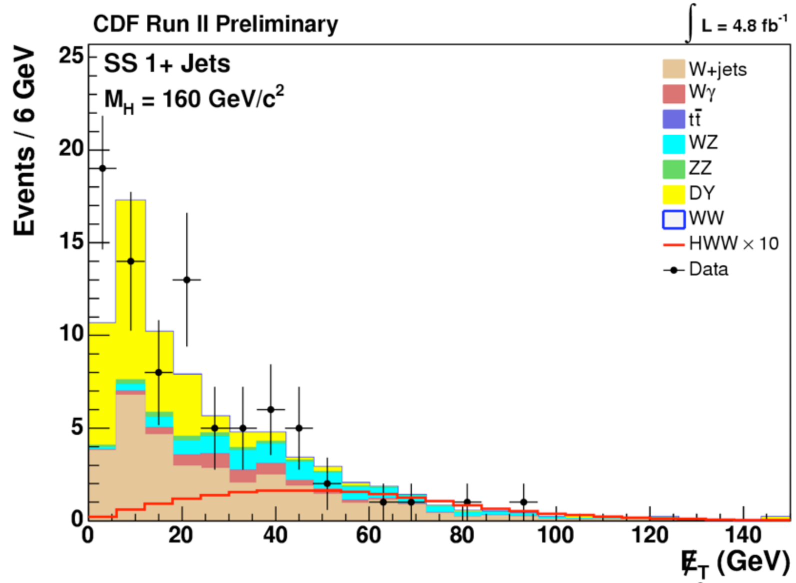
Search for Higgs signal in sample with same sign dileptons to further increase sensitivity both in the intermediate (~130GeV) and high (~160GeV) mass regions

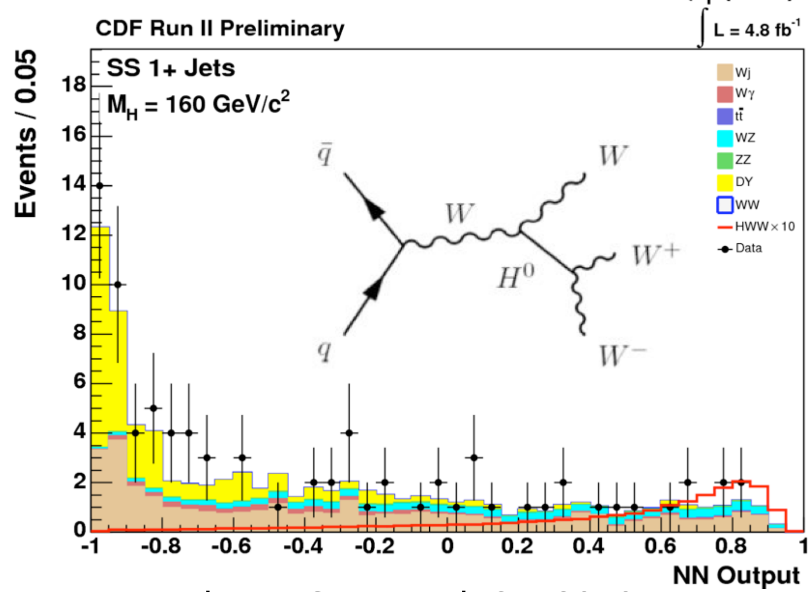
VH → VWW where V (W or Z) and one of the Ws from H decay leptonically

$VH \rightarrow VW^+W^- \rightarrow l^\pm \nu l^\pm \nu + X$

Largely reduced SM background due to like sign

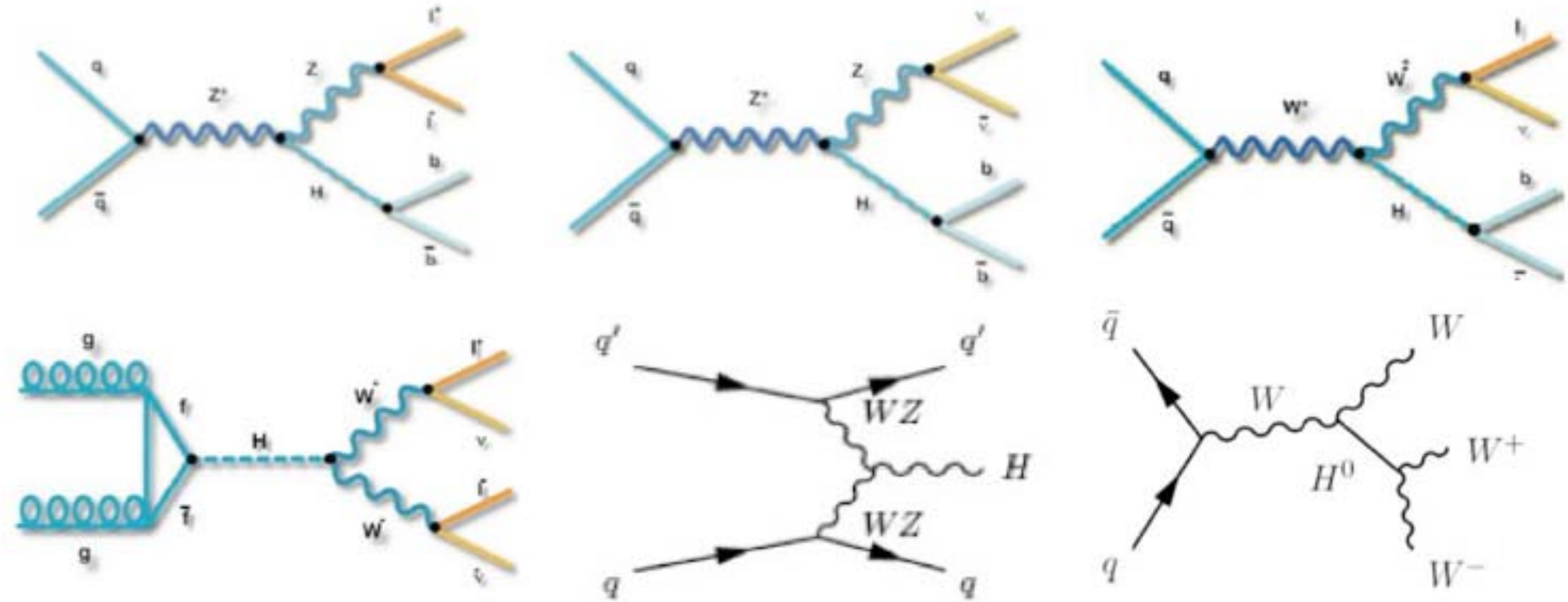
Instrumental backgrounds: Charge flips and fake leptons





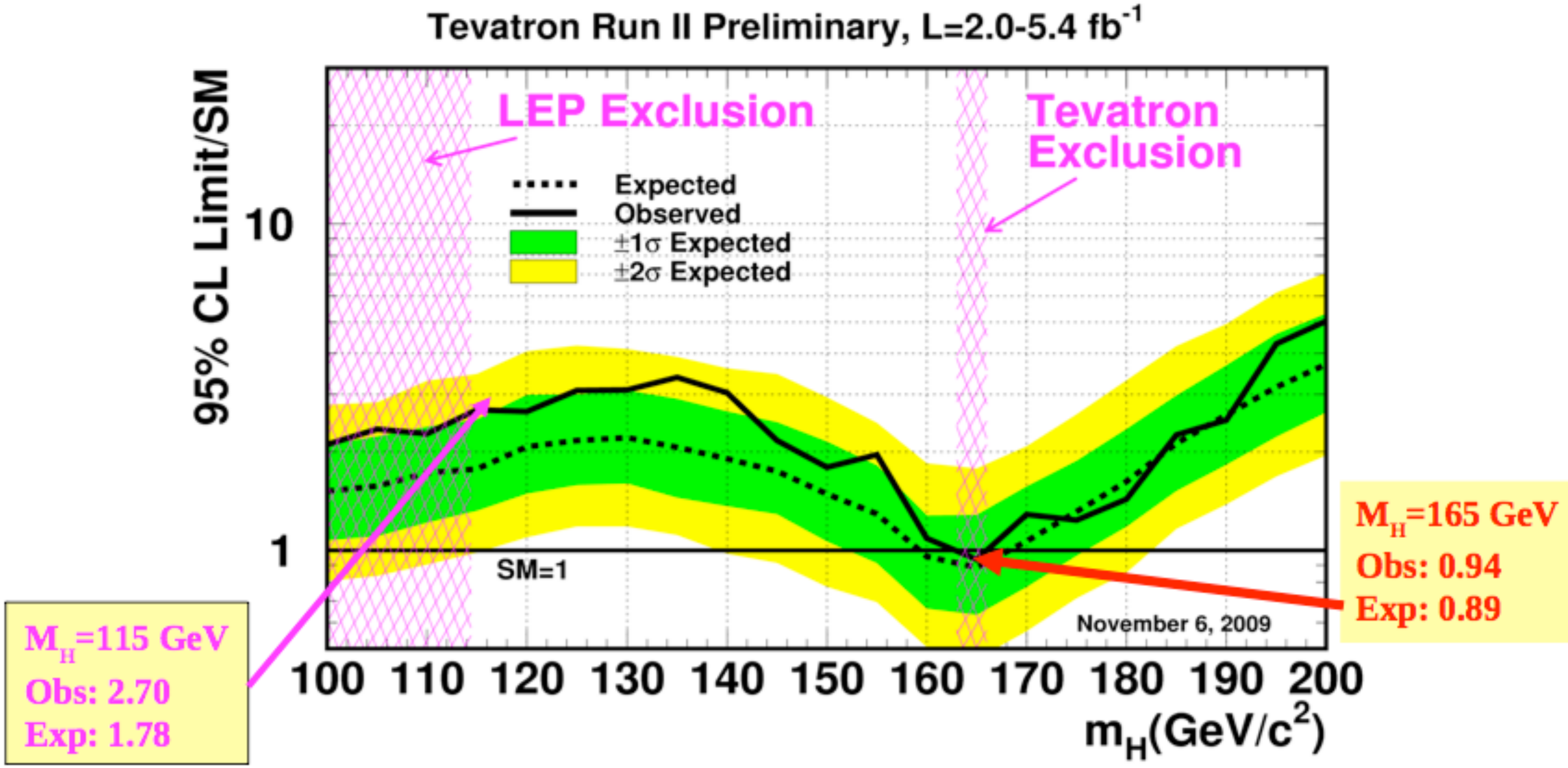
Tevatron combination

Combination of orthogonal final states to maximize sensitivity



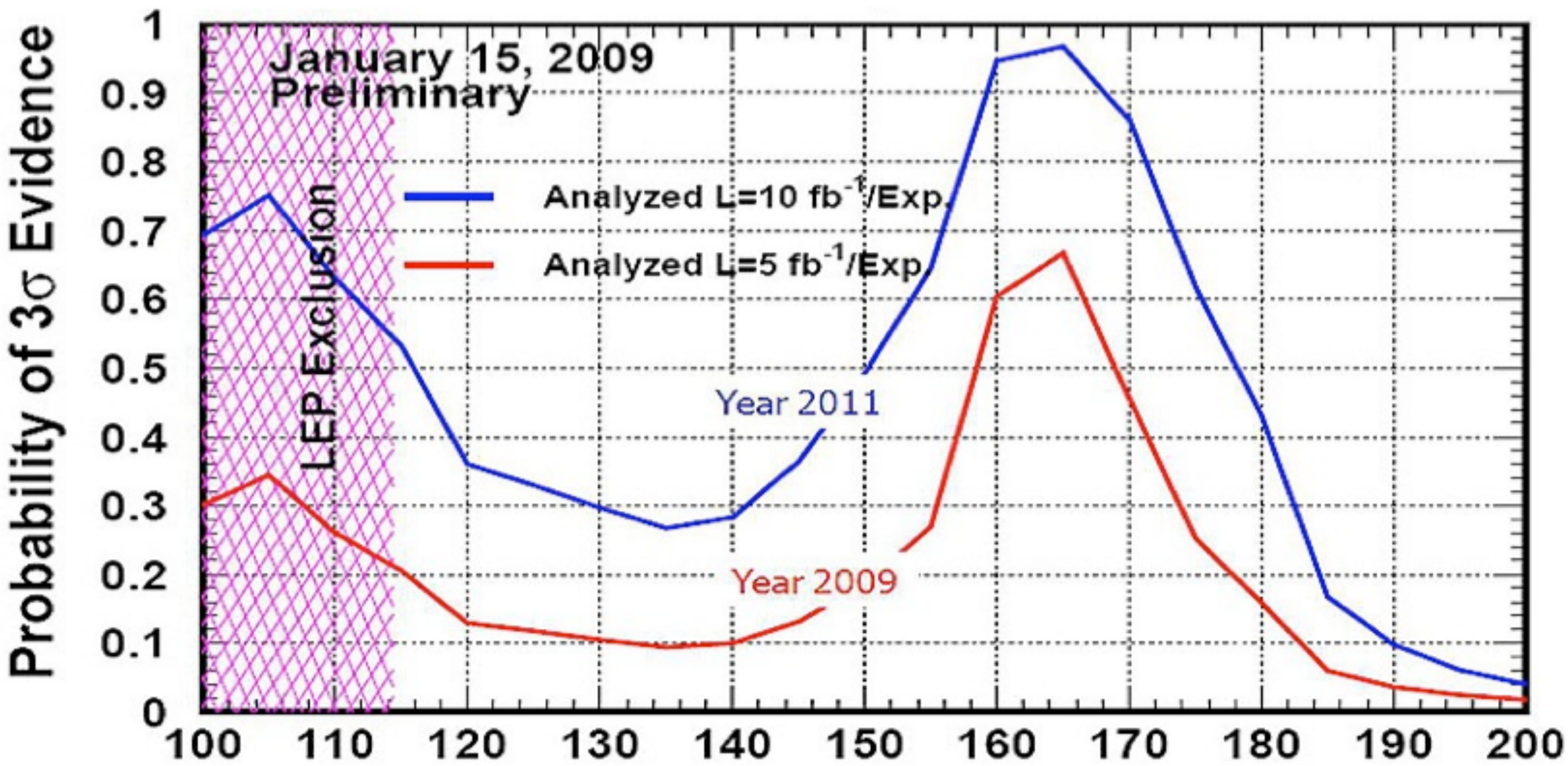
Tevatron combination

Combining CDF and D0 for maximum sensitivity



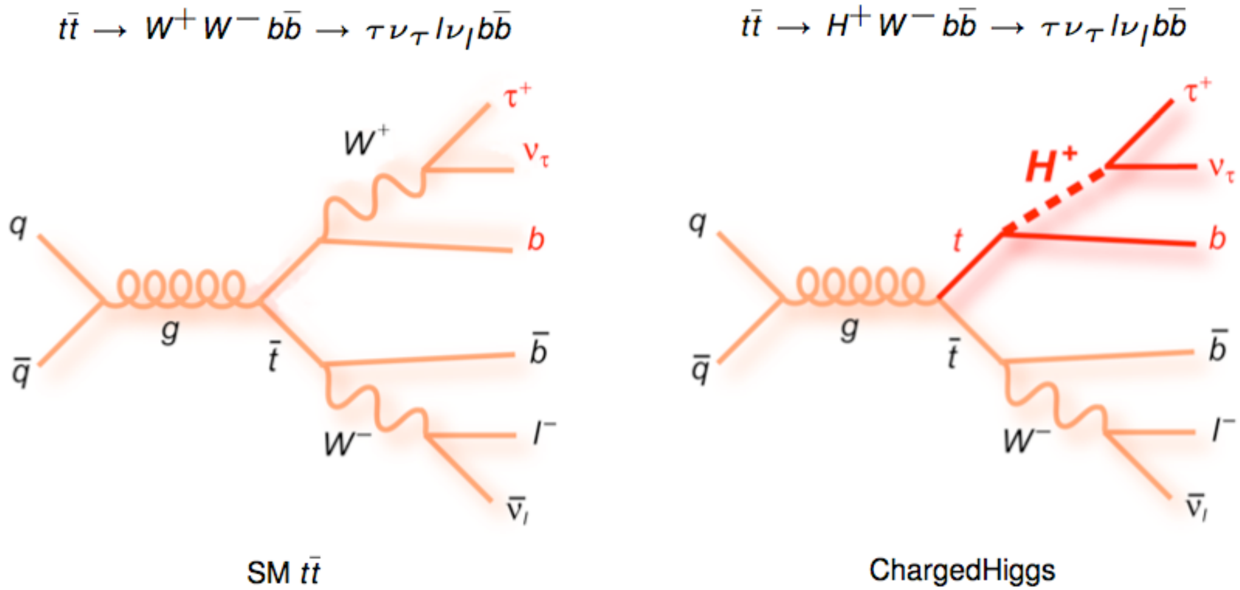
Prospects

•With 10 fb^{-1} data, Tevatron has 1/3 of chance to see some hints of SM Higgs for all m_H<180 GeV/c^2.



Higgs in Top decays

- Search for $H^{\pm}$ in ttbar events: $100 \leq M(H^{\pm}) \leq 160$ GeV/c^2, BR($H \rightarrow \tau\nu$)=1
- if the $H^{\pm}$ exists we may observe an excess of events in the $l\tau$ channel incompatible with the SM



⇨probe non-standard physics ($t \rightarrow H^{\pm}b$, …)

Measuring ratios

- Tau dilepton analysis is useful check on tau efficiency and can be sensitive to non-SM physics

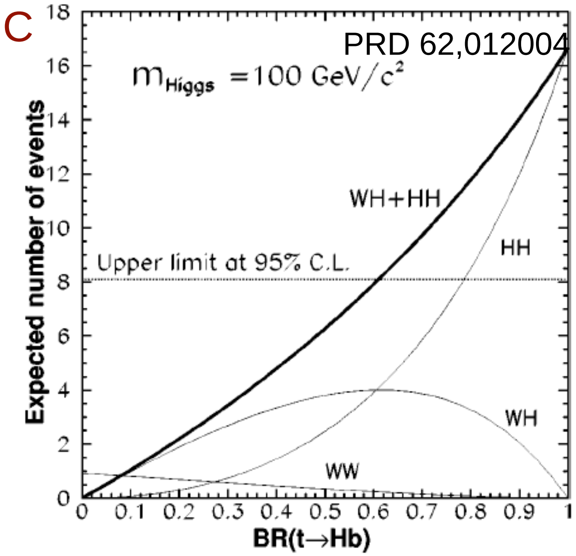
- Key is to understand relative efficiency of l/τ
- All other systematic cancel out (i.e. ISR/FSR, lumi, etc.)
- If discrepancy is found, case is more convincing

- BR($t \rightarrow H^+ b$) could be large
- $H^+ \rightarrow \tau^+ \nu_\tau$ enhanced if $\tan\beta$ large

⇨ **observe more taus**

($\tan\beta$: ratio of vacuum expectation values)

x50-100 events @LHC

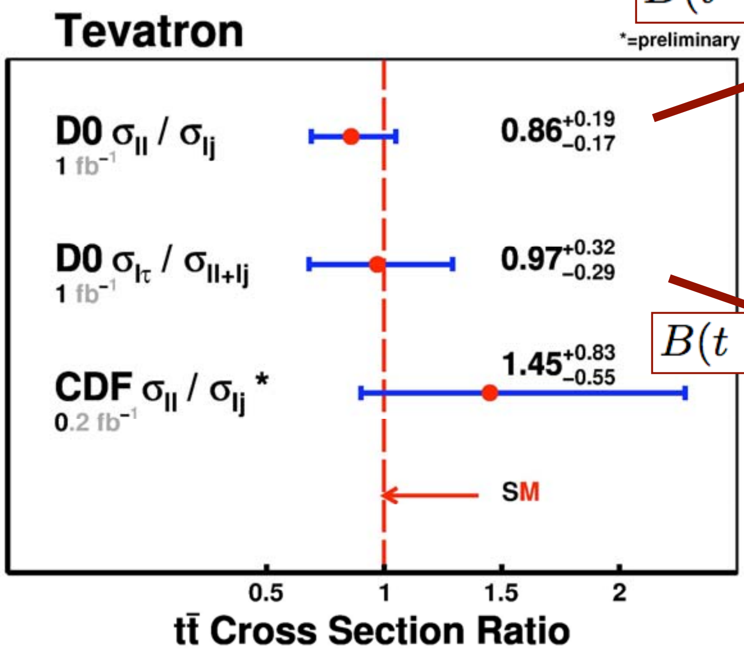


Cross section ratios

Many systematic unc. cancel in the ratio
Study of cross section ratios
⇨sensitive to BSM

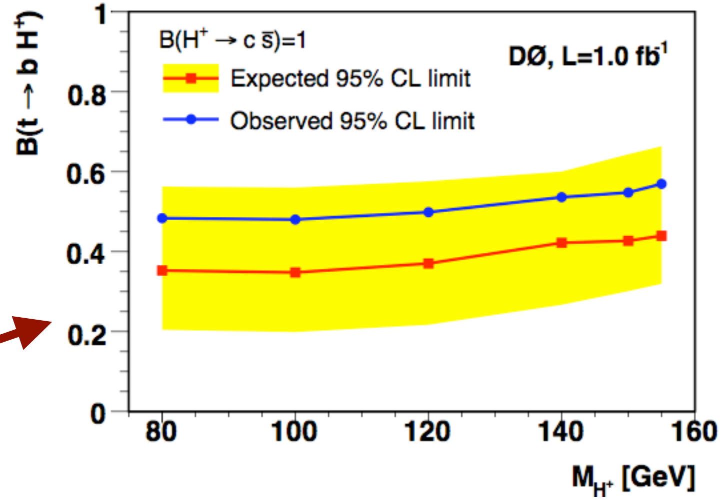
1. BR(l+jets)/BR(ll)
2. BR(l+tau)/BR(ll)

PLB 682, 278 (2009)



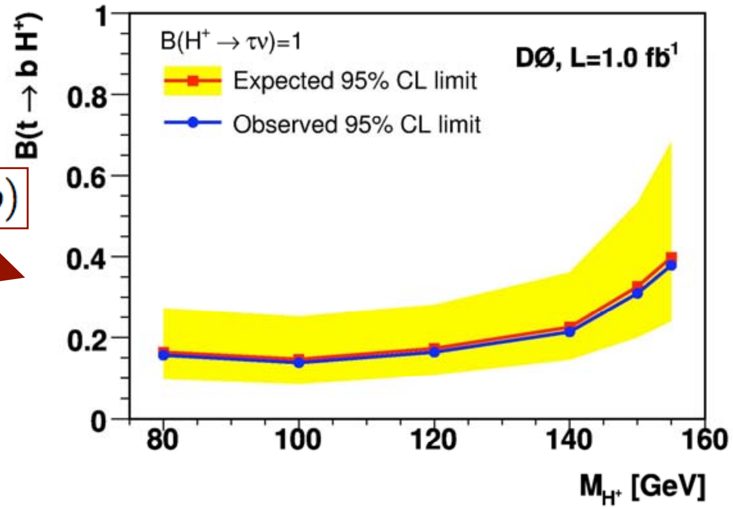
$B(t \to H^+ b \to c\bar{s}b)$

lept.+jets



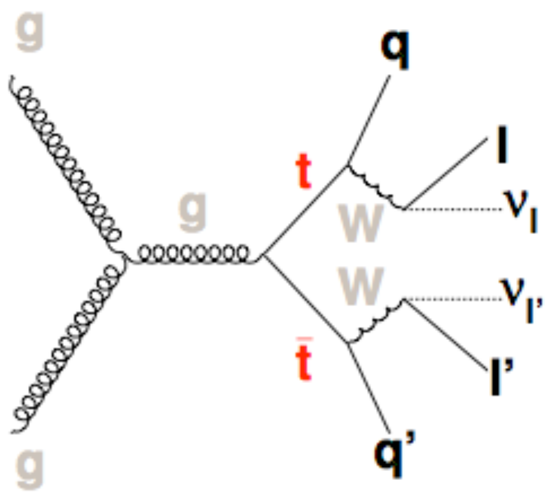
$B(t \to H^+ b \to \tau^+ \nu b)$

tau leptons

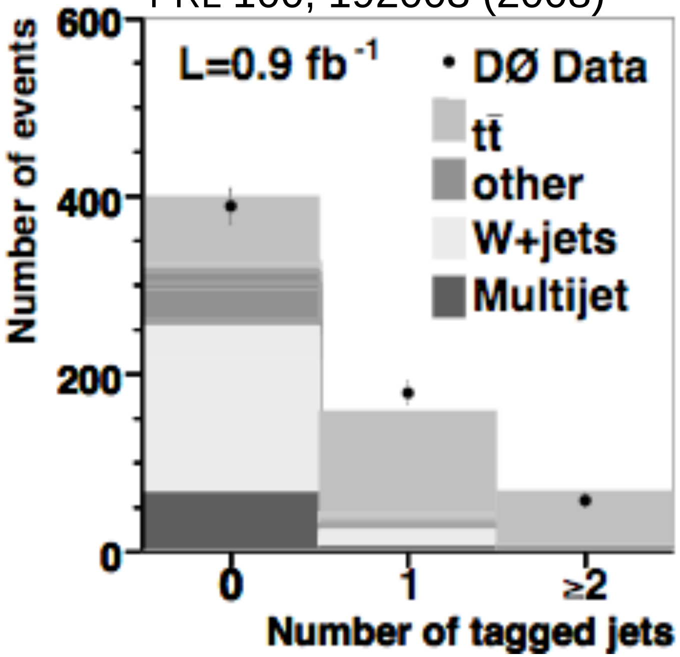


Top quark: dileptons

- Two leptons (e,μ)+2 jets+MET
- Look at jet multiplicity
- Derive b-tagging, R, cross-section



PRL 100, 192003 (2008)



$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)}$$

$R=1.03^{+0.09}_{-0.08}$ (stat+syst)

$|V_{tb}|>0.71$ @95% CL (lepton+jets)

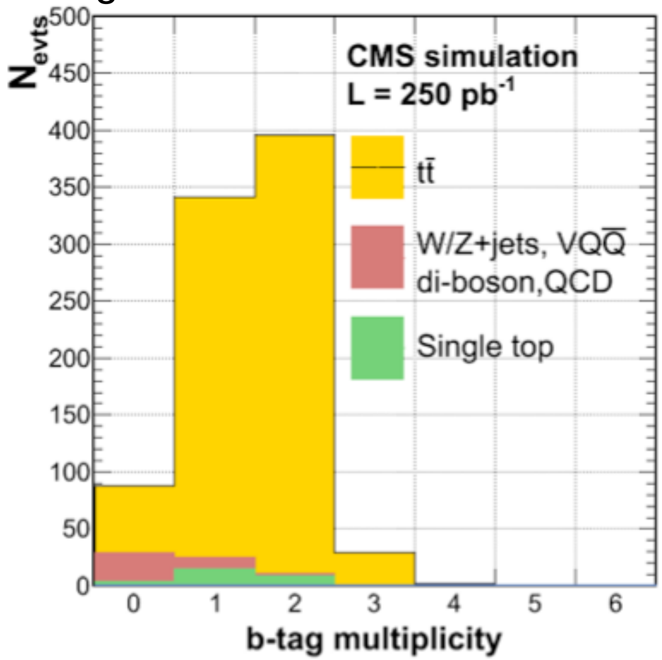
$|V_{tb}|=0.91$ (single top) (hep/ex-0612052)

Not yet sensitive to SM

⇨Simultaneous measurement of cross-section and R

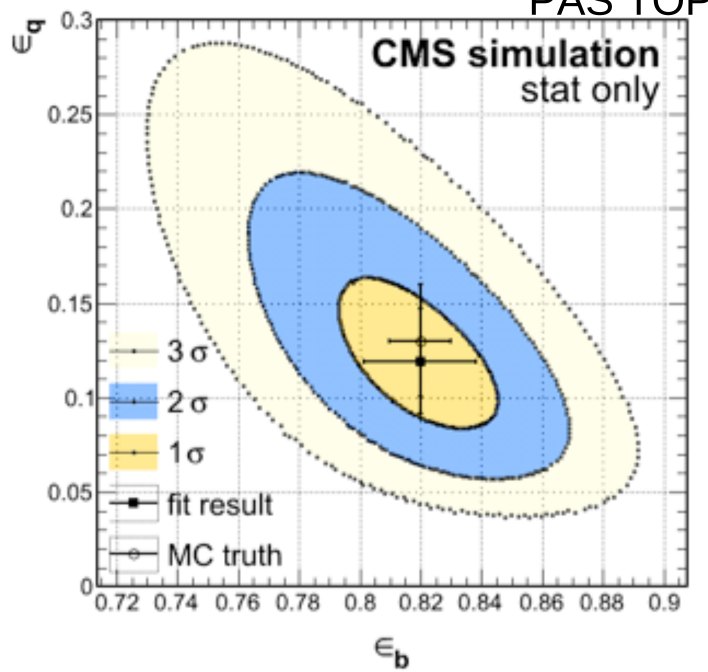
Probing heavy flavor of ttbar events

- Study dilepton channel
- Advantages:
  - less combinatorial ambiguity
  - less background
- Disadvantages:
  - lower statistics
  - jet assignment



- Selection:
  - 2 leptons+ ≥2 jets + MET
  - no b-tagging in preselection
- Clean signature
- Goals:
  - measure ε(b) and R, cross section

PAS TOP-09-001



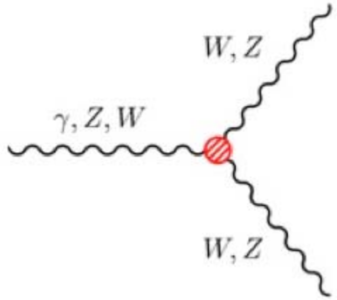
Multi-bosons

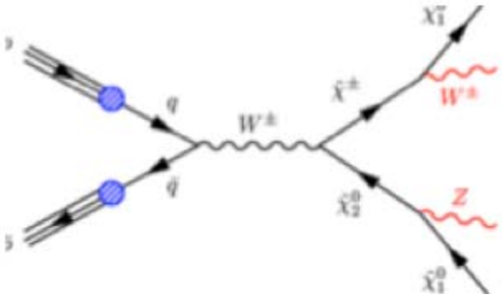
- Direct probe into the gauge structure of the SM
  - rich phenomenology with well calculated predictions:
    - ❖zero triple neutral gauge coupling
    - ❖radiation-amplitude zero
- Must-do preliminary for the Higgs
  - benchmark for experimental capabilities
  - diboson final states ~ Higgs final states
- New Physics effects
  - new couplings

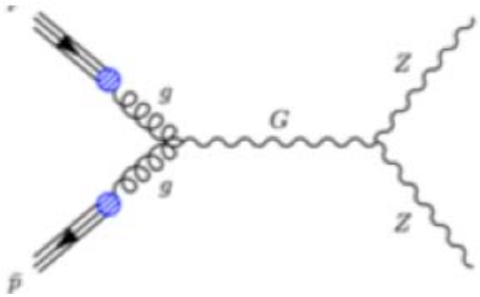
$$-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2}|\partial_\mu W^+_\nu - \partial_\nu W^+_\mu +$$

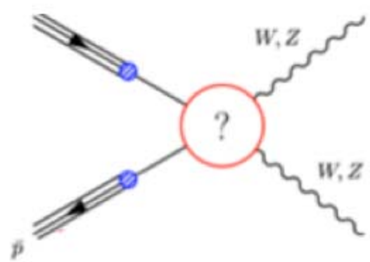
$$-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 +$$

$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 +$$

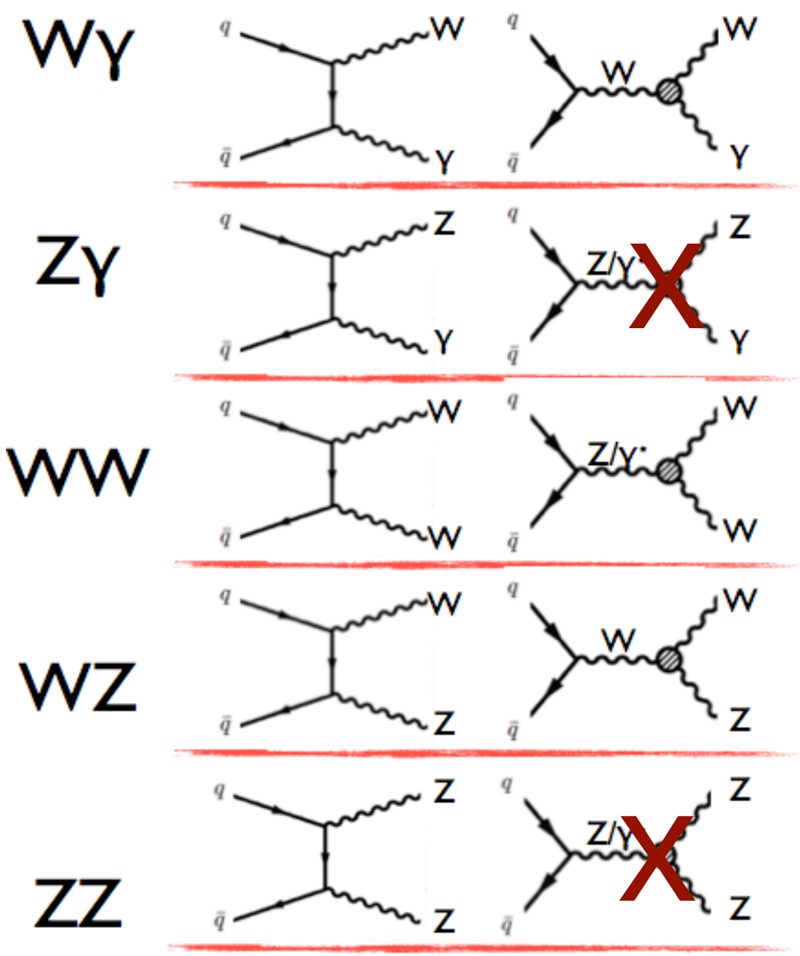


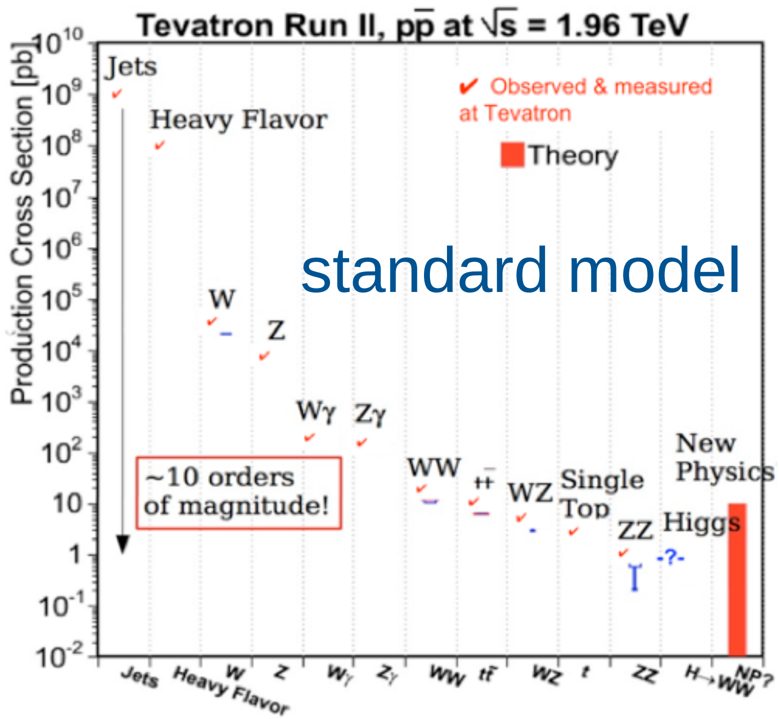






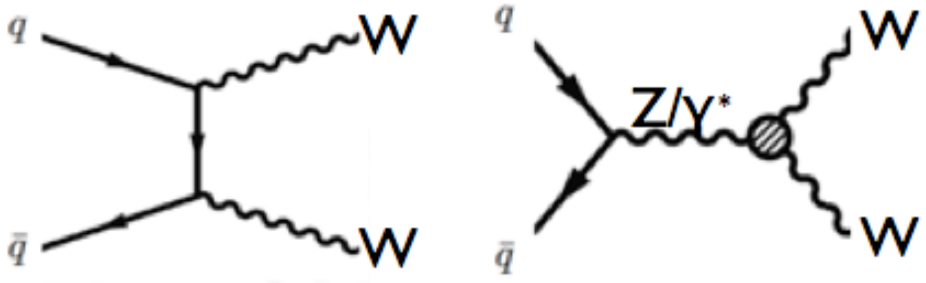
Diboson production

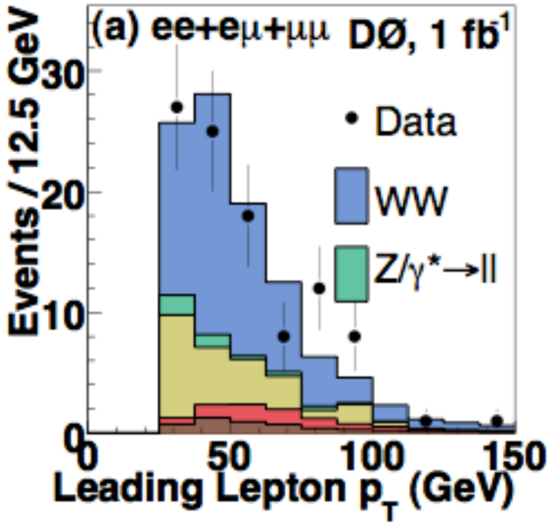




Process	Events in 5fb-1
WW→lνlν	2720
ZZ->llll	30
Zγ->llγ	1485
WZ→lνbb	599
WH→lνbb	158

Two leptons: WW



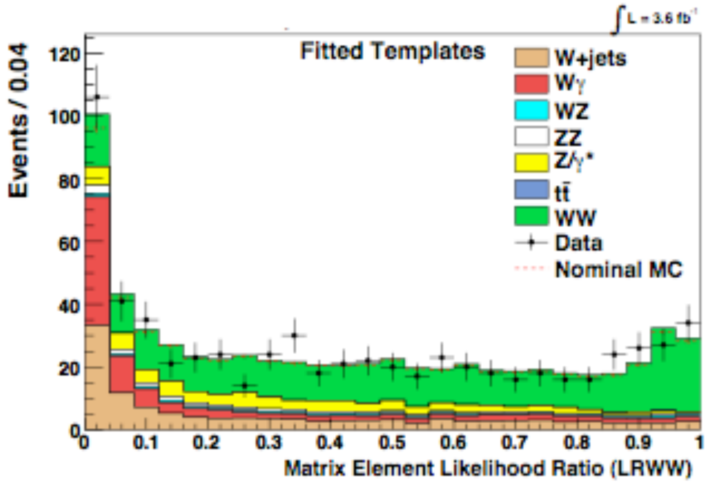


Two isolated leptons and large MET

- Easiest to observe
- Important background for the H→WW

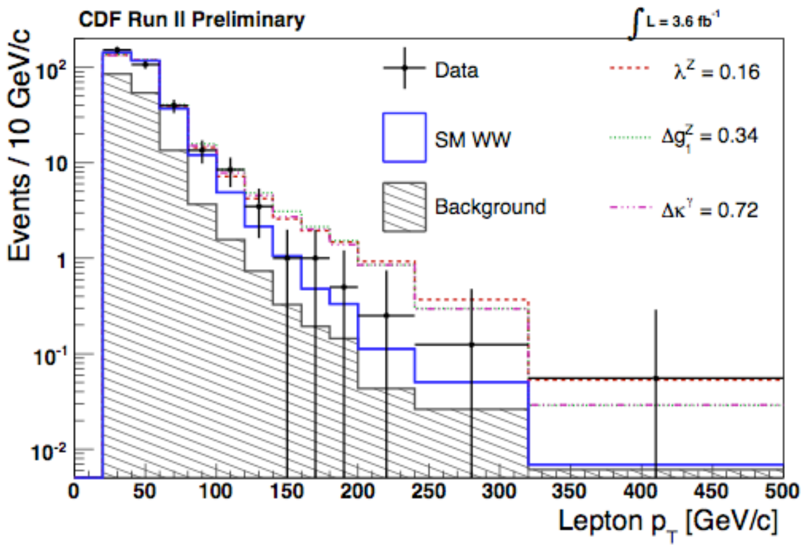
Results:

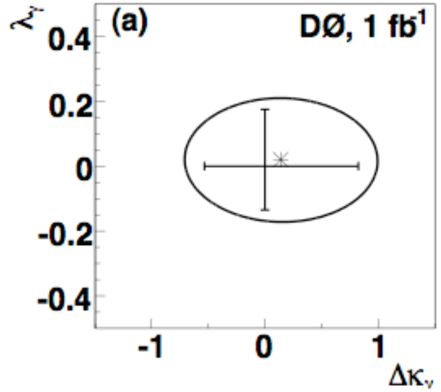
- CDF: 12.1±0.9(stat)±1.6±1.4(syst) pb
  - arXiv:0912:4500
- D0: 11.5±2.1(stat+syst)±0.7 (lumi) pb
  - PRL 103, 191801 (2009)
- NLO theory: 11.66±0.7 pb



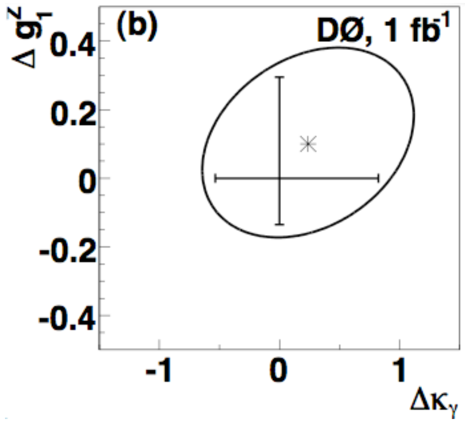
WW and TGC

Lepton p_T is sensitive to TGC





$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu} \right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu V^{\nu\lambda}$$



CDF Preliminary Results at 3.6fb^{-1}

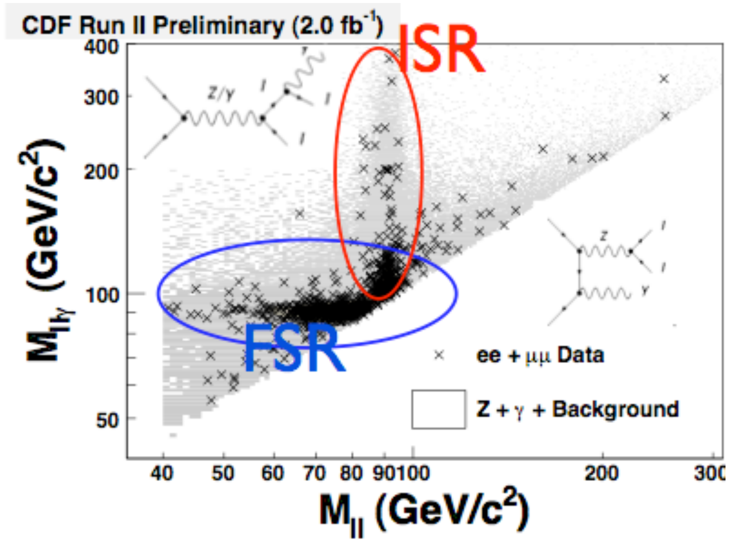
Λ	λ^Z	Δg_1^Z	$\Delta\kappa^\gamma$
2.0TeV	(-0.14,0.15)	(-0.22,0.30)	(-0.57,0.65)
1.5TeV	(-0.16,0.16)	(-0.24,0.34)	(-0.63,0.72)

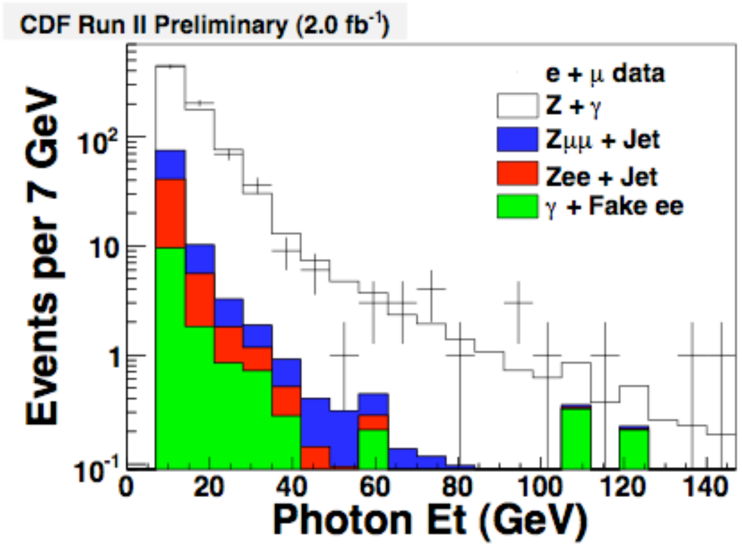
DØ Results at 1.0fb^{-1}

Λ	λ^Z	Δg_1^Z	$\Delta\kappa^\gamma$
2.0TeV	(-0.14 , 0.18)	(-0.14 , 0.30)	(-0.54 , 0.83)

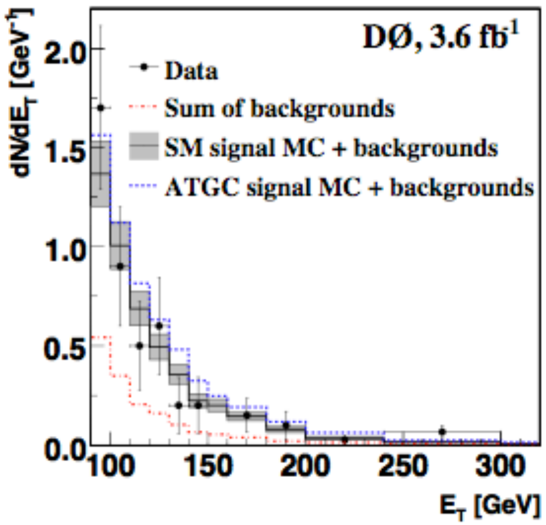
Zγ

- Two leptons and a high ET photon
- FSR and ISR only
  - New physics can contribute
  - H→Zγ
- σ=4.6±0.2(stat)±0.3(syst)±0.3(lumi)pb
- NLO = 4.5±0.4pb



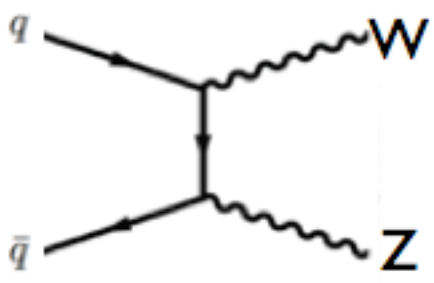


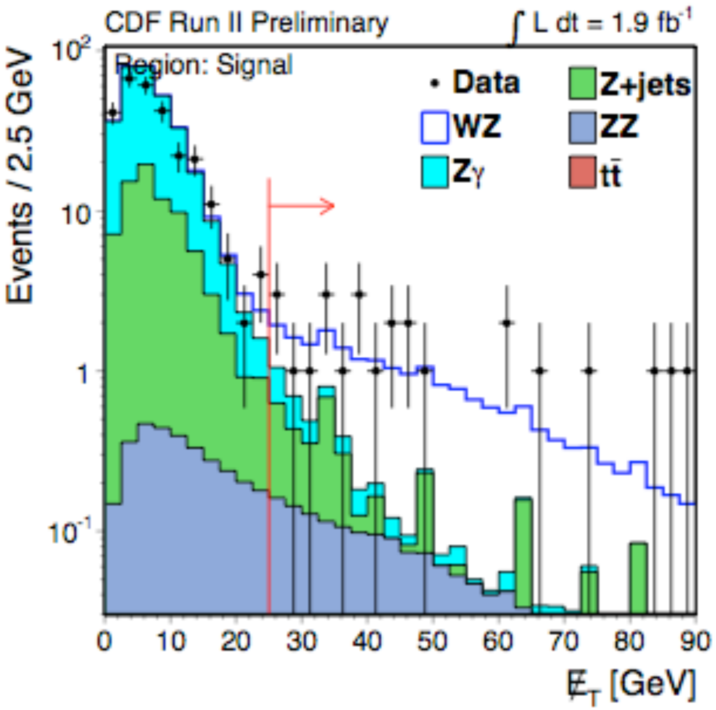
- Add MET channel
  - Z→νν+photon
  - MET+photon final state
- TGC in high Et photons



Three leptons: WZ

- Final state with three leptons
  - WZ→lνll (l=e,μ)
  - Δφ(MET,any-jet/l)>0.15



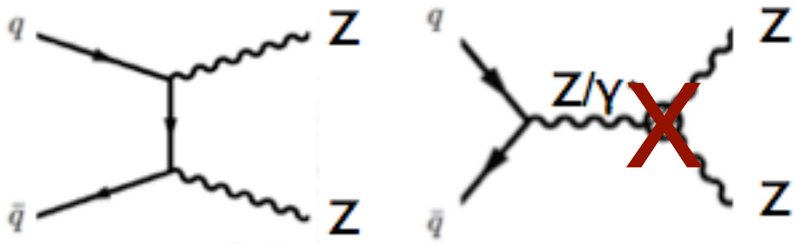


Source	Expected	± Stat	± Syst	± Lumi
Z+jets	2.45	± 0.48	± 0.48	± 0.00
ZZ	1.53	± 0.01	± 0.16	± 0.09
$Z\gamma$	1.03	± 0.06	± 0.35	± 0.06
$t\bar{t}$	0.17	± 0.01	± 0.03	± 0.01
WZ	16.45	± 0.03	± 1.74	± 0.99
Total	21.63	± 0.48	± 2.25	± 1.15
Observed	25			

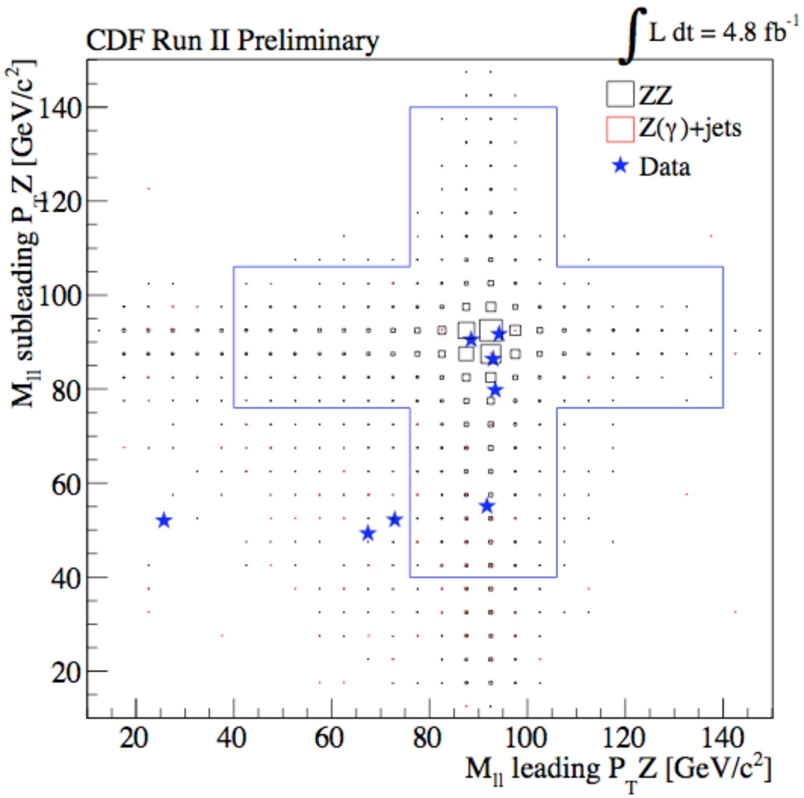
$$\sigma(p\bar{p} \rightarrow WZ) = 4.3^{+1.3}_{-1.0}\ (stat.) \pm 0.4\ (syst. + lumi.)\ pb$$

NLO: 3.7±0.3 pb

Four leptons: ZZ



- Four lepton final state

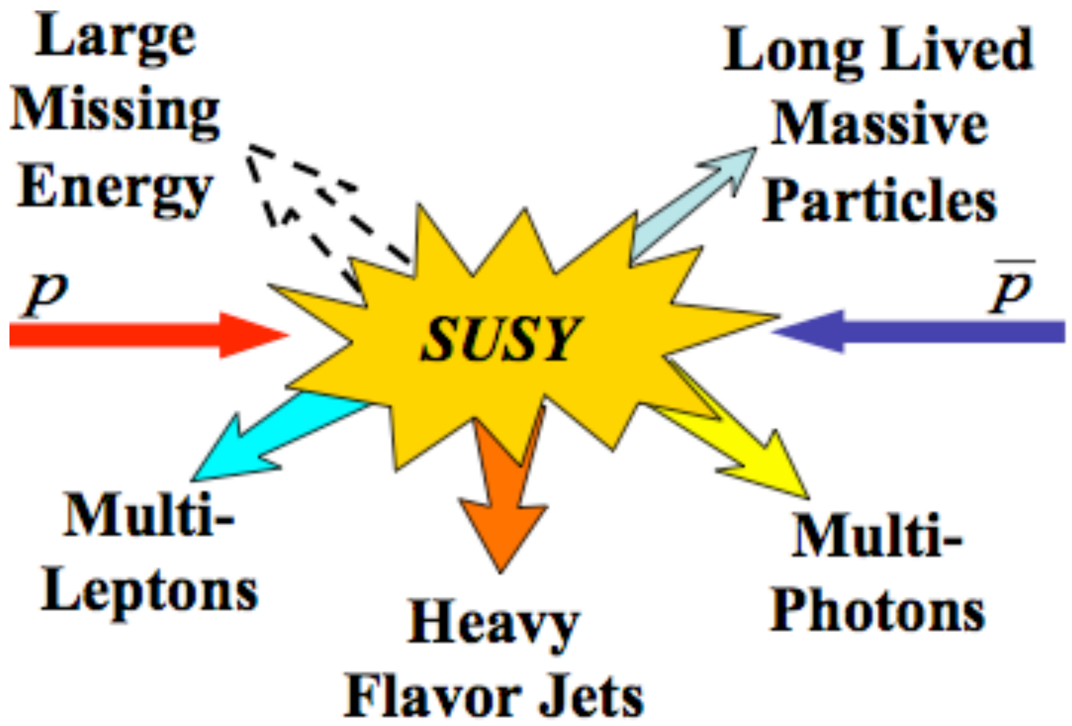


Events in $\mathcal{L} = 4.8$ fb^{-1}	
Signal	4.68 ± 0.02(stat.) ± 0.76(syst.)
Z(γ)+jets	0.041 ± 0.016(stat.) ± 0.029(syst.)
Total expected	4.72 ± 0.03(stat.) ± 0.76(syst.)
Observed	**5**

$$\sigma_{ZZ} = 1.56^{+0.80}_{-0.63}(stat.) \pm 0.25(syst.)$$

NLO: 1.4±0.1pb

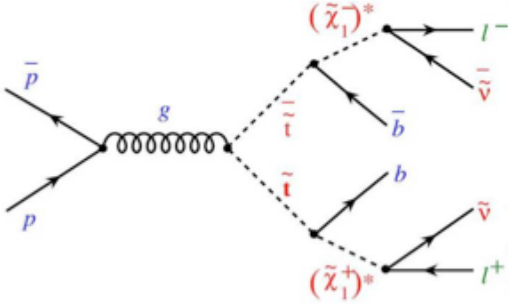
SUSY

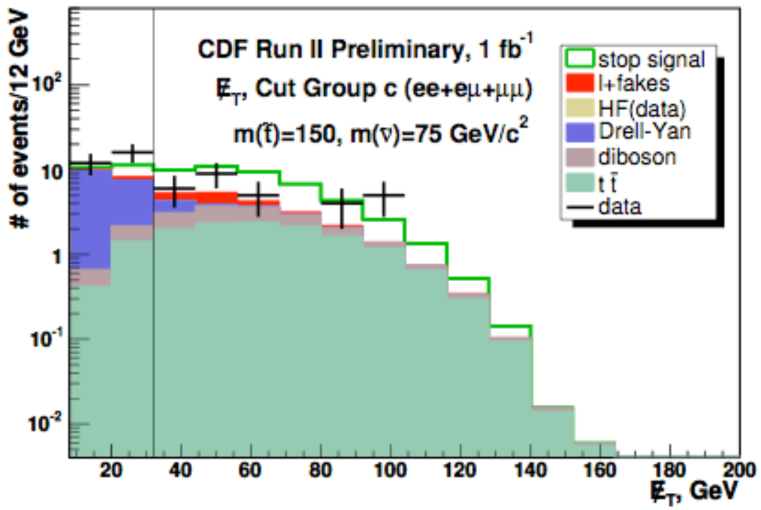


Large
Missing
Energy
Long Lived
Massive
Particles
p
SUSY
p̄
Multi-
Leptons
Heavy
Flavor Jets
Multi-
Photons

Stop searches

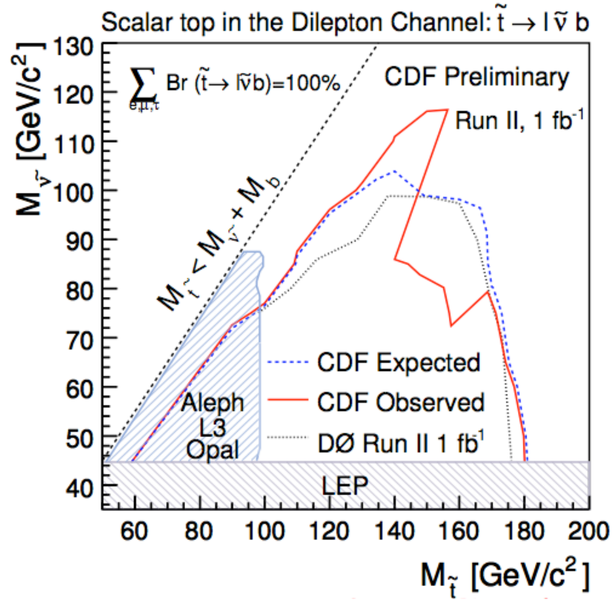
- $\tilde{t} \rightarrow \ell b \tilde{\nu}$ $(m_{\tilde{\chi}_1^\pm} > m_{\tilde{t}})$
- *DØ ee, eμ*
- CDF *ee, eμ, μμ*

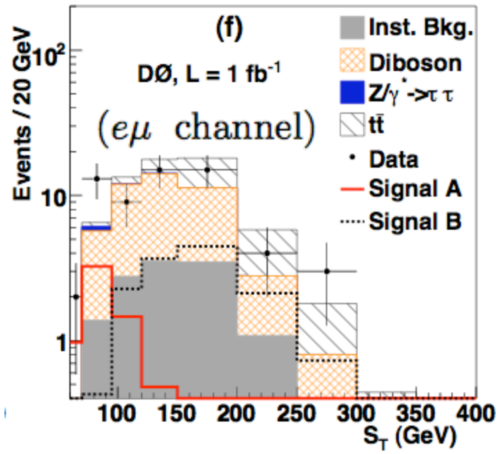


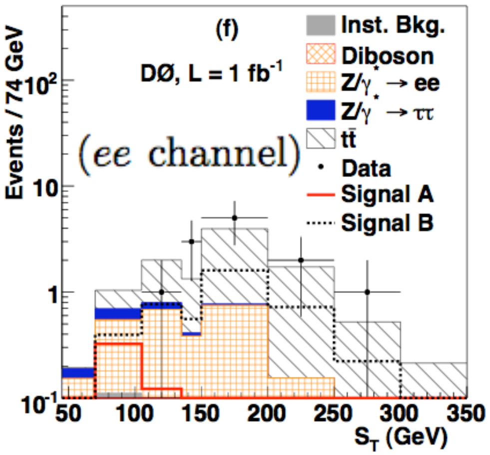


Events per 2.7 fb^{-1} in the signal region with ≥1 b-tag

Source	ee	μμ	eμ	ll
top	11.6 ± 1.8	10.4 ± 1.5	27.0 ± 3.7	49.0 ± 6.9
z/γ^*+HF	1.2 ± 0.2	0.8 ± 0.1	0.4 ± 0.1	2.4 ± 0.4
z/γ^*+LF	0.8 ± 0.1	0.5 ± 0.1	0.3 ± 0.1	1.6 ± 0.2
diboson	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.5 ± 0.1
fakeables	0.5 ± 0.2	0.5 ± 0.1	1.9 ± 0.6	2.8 ± 0.9
Total	14.3 ± 2.0	12.3 ± 1.6	29.7 ± 3.8	56.4 ± 7.2
stop	2.0 ± 0.4	2.1 ± 0.5	5.4 ± 1.1	9.5 ± 1.9
Data	15	12	30	57

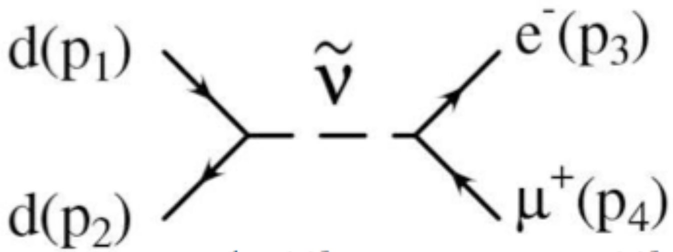


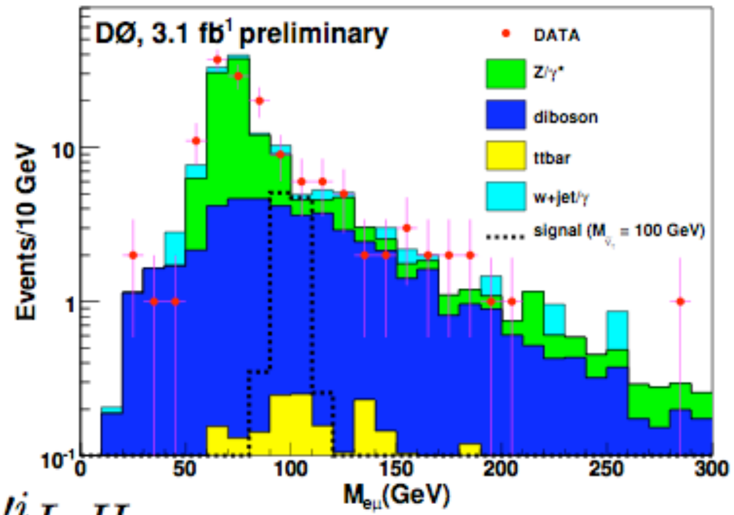




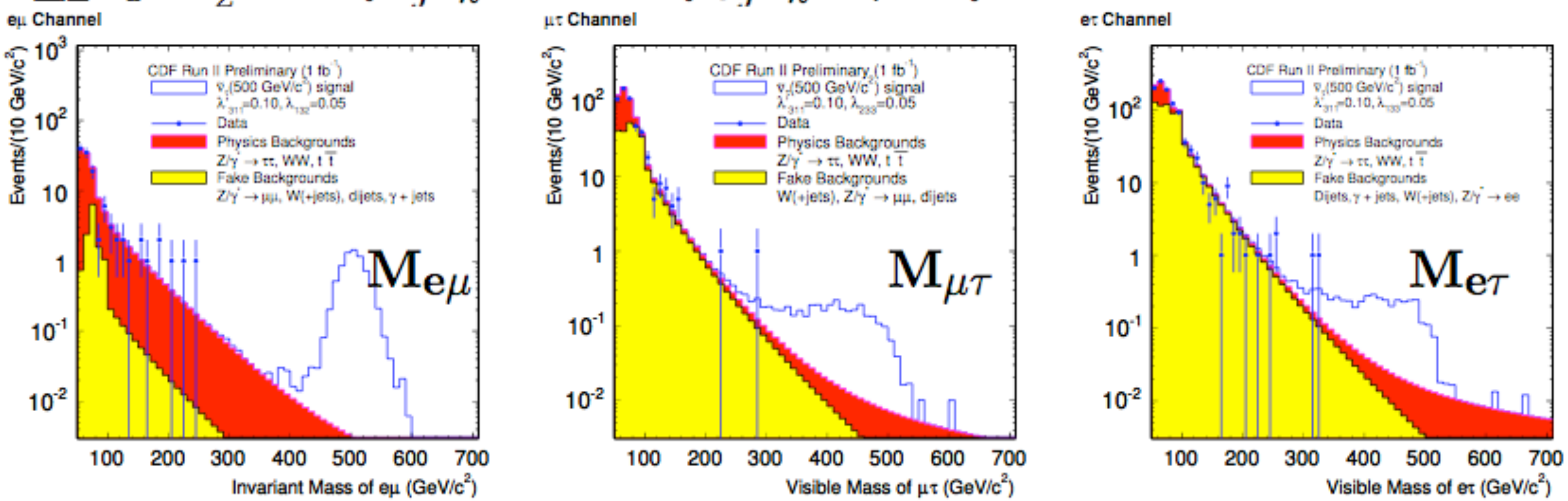
2 leptons: RPV

- CDF @ 1 fb^{-1}: $e\mu$, $\mu\tau$, $e\tau$
- DØ @ 4.1 fb^{-1}: $e\mu$

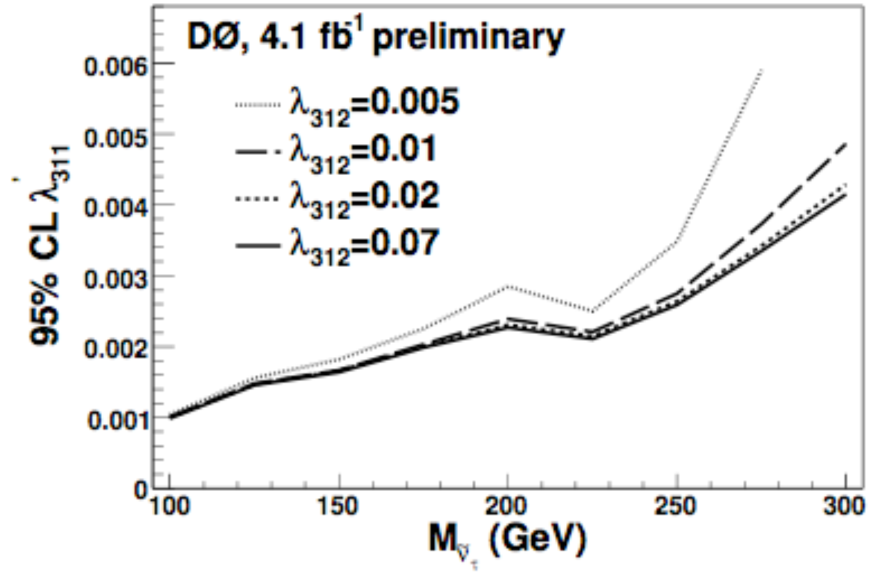


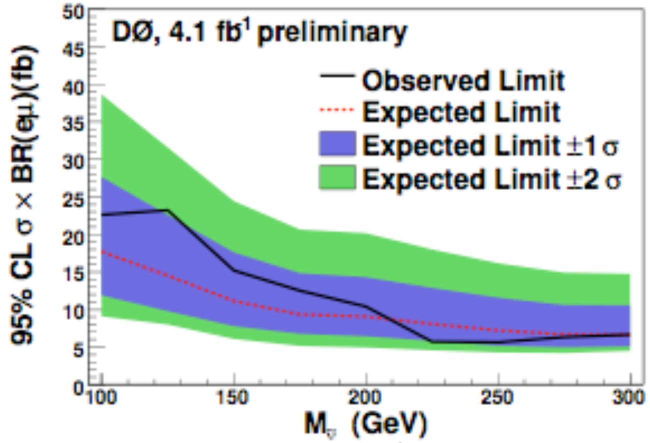


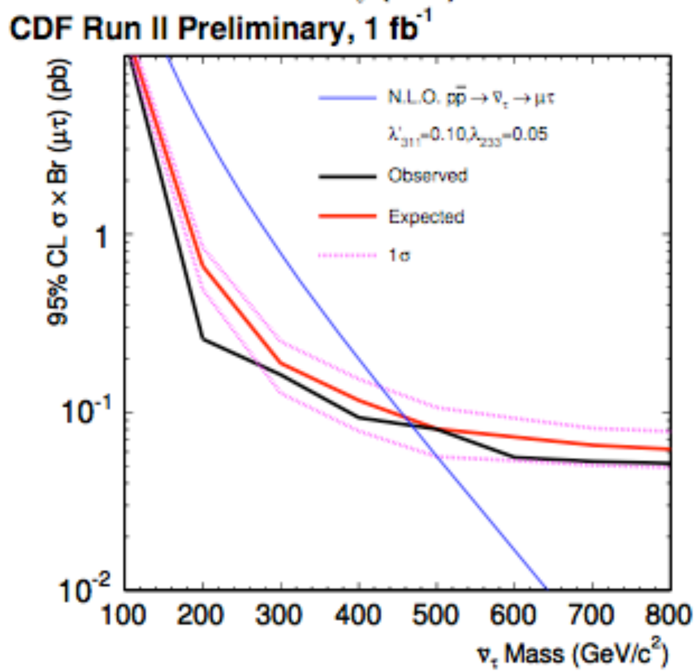
$$W_{\Delta L=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu'^i L_i H_u$$



RPV (cont.)





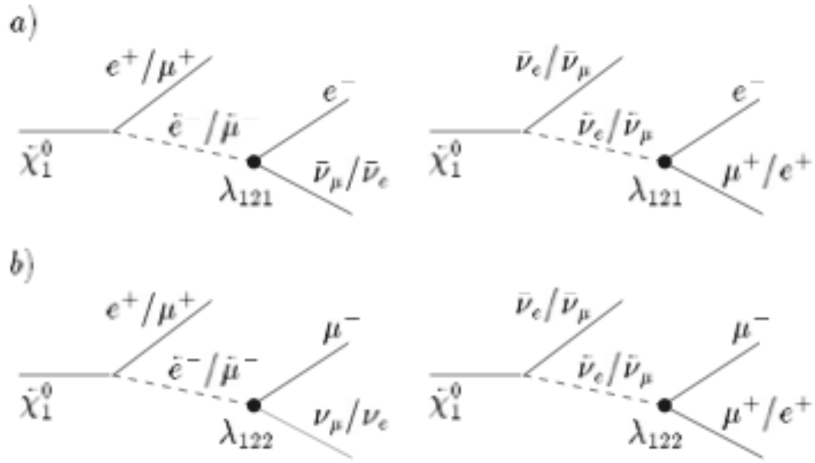


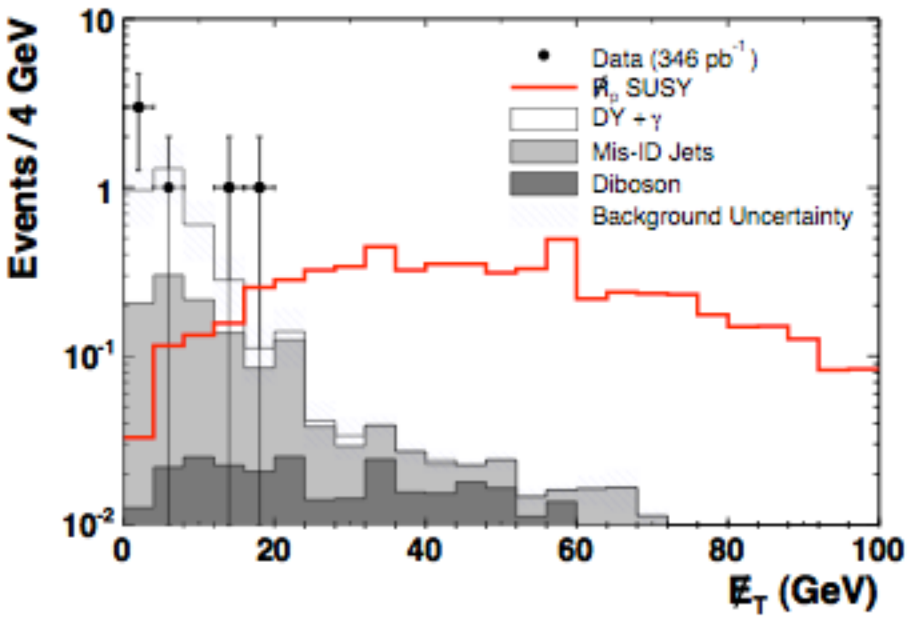
DØ:

- All RPV couplings are null but λ'_{311} and $\lambda_{321} = \lambda_{312}$
- $\lambda'_{311} \leq 0.12$, $\lambda_{321} \leq 0.07$ for $M_{\tilde{\nu}_\tau} < 100 GeV$

3/4 leptons: RPV

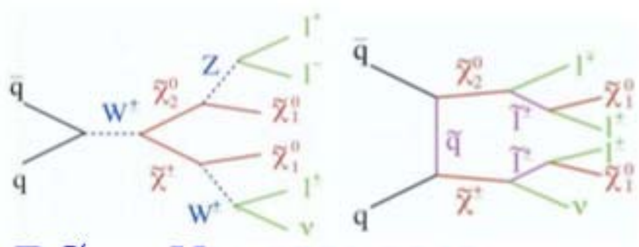
- Several models predict final states with 3/4+ leptons in the final state:
  – RPV SUSY, nMSSM, doubly-charged Higgs
- Two or more leptons: p_T>20, 8, (5) GeV





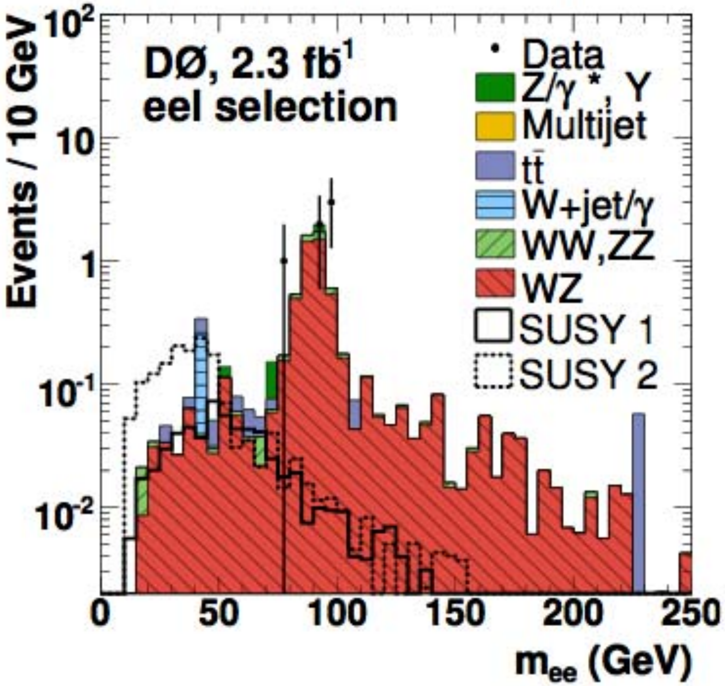
	bkg	data
Three-Lepton Signal Samples		
λ_{121} scenario	3.1 ± 0.8	5
λ_{122} scenario	1.9 ± 1.0	1
Four-or-More-Lepton Signal Sample		
λ_{121}, λ_{122} scenarios	0.008 ± 0.004	0

Trileptons: chargino/neutralino



DØ: arXiv 0901.0646

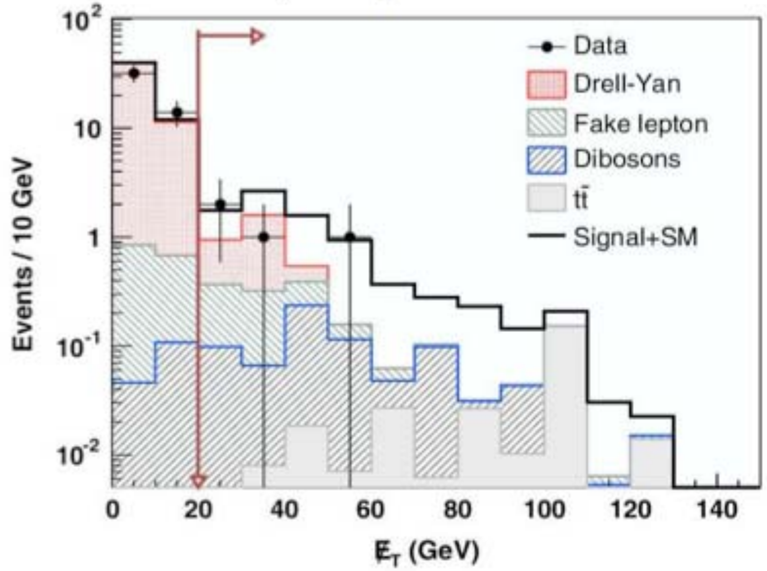
- ee, $\mu\mu$, $e\mu$, $\tau\mu$ + trk(e,μ,τ) + $\not\!\!E_T$



CDF: PRL **101**, 251801 (2008)

- 3 leptons (e, μ) + $\not\!\!E_T$
- 2 leptons (e, μ) + trk(e,μ,τ) + $\not\!\!E_T$

CDF 2fb^{-1}, dilepton+trk:

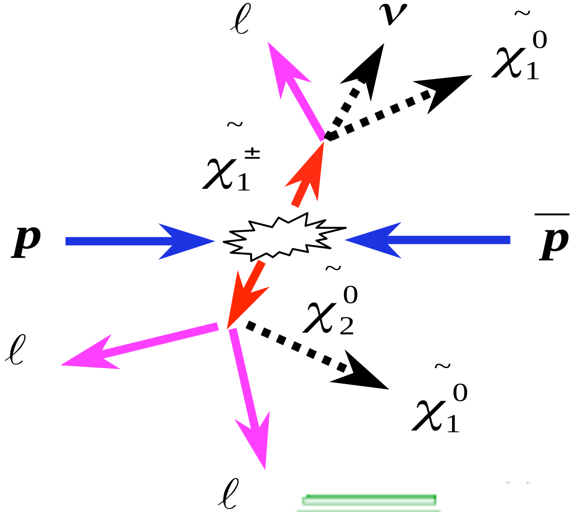


7 vs 6.4±1.1 (all channels)

fake ℓ 1.4, DY 3.0, dibosons 1.6, $t\bar{t}$ 0.5

Trileptons (cont.)

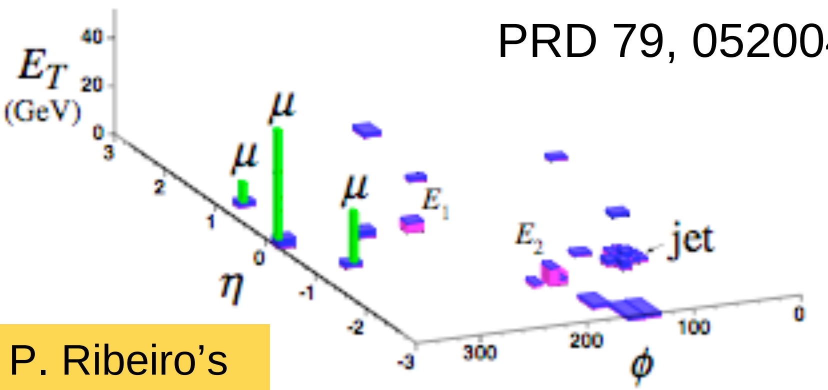
- chargino-neutralino production
- three isolated leptons (low-pT):
  - μμ+l (l=e,μ)
- low background/data-driven

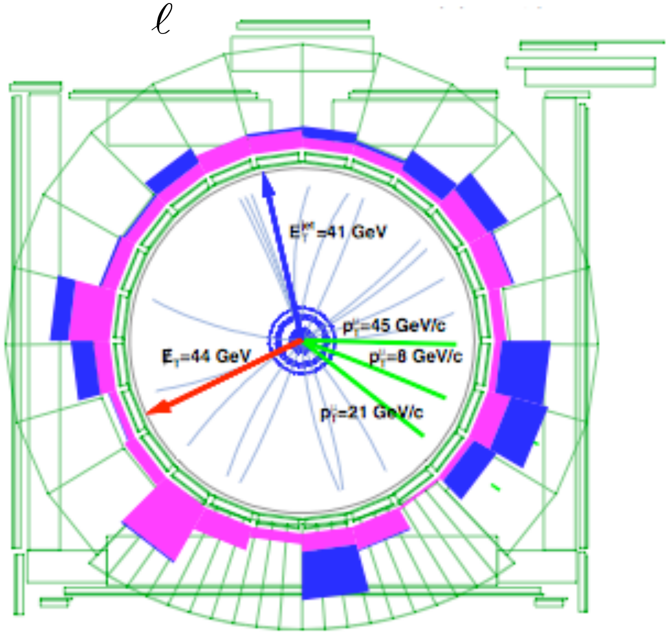


control regions (rows 1–5); signal region → (row 6)

Total SM expected	SUSY expected	Observed
3 ± 1	0.06 ± 0.01	4
14 ± 4	0.08 ± 0.02	16
0.3 ± 0.1	0.10 ± 0.03	0
5 ± 2	0.06 ± 0.02	8
0.03 ± 0.01	0.04 ± 0.02	0
0.4 ± 0.1	1.7 ± 0.4	1

PRD 79, 052004 (2009)





see P. Ribeiro's presentation

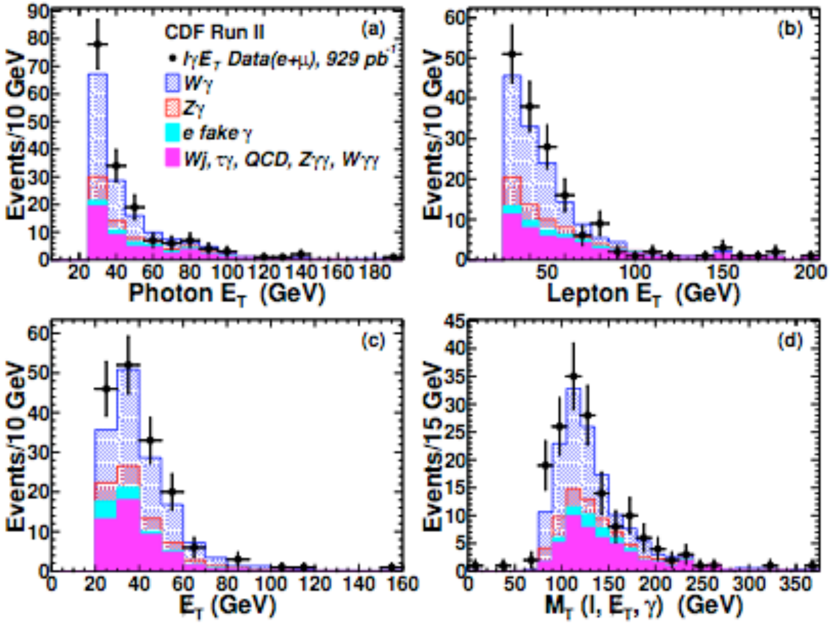
Search for l+photon+X

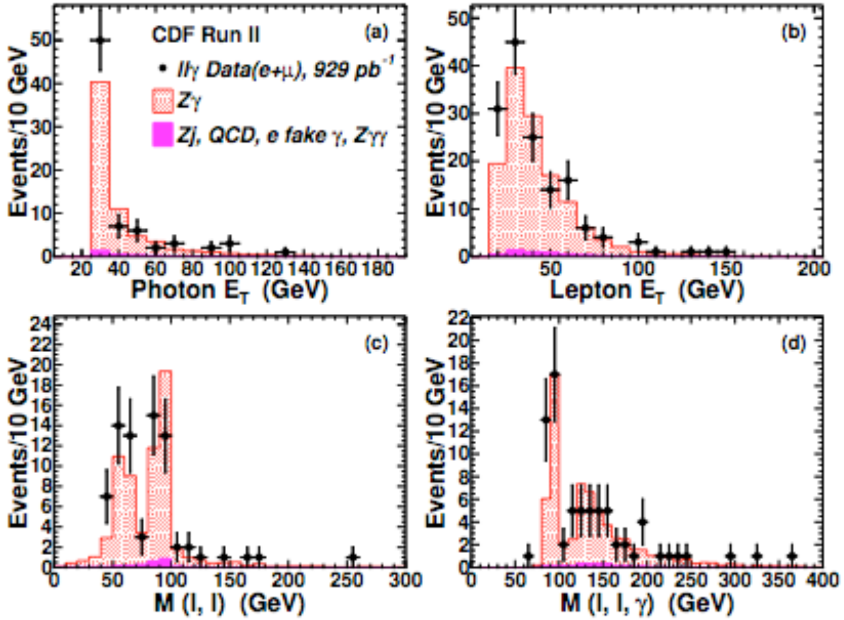
Motivation
- Run I $ee\gamma\gamma\not{E}_T$ (10^{-6} expected, 1 observed)
- $\ell\gamma\not{E}_T$: 7.6±0.7 expected, 16 observed, 2.7σ

Analysis
- Signature-Based search
- *a priori* defined cuts (same as in Run I)
- MadGraph, CompHep and Baur MC

Results

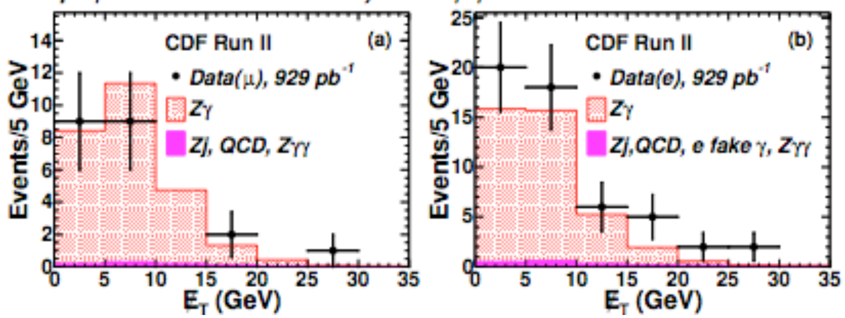
$\ell\gamma\not{E}_T$	$e\gamma\not{E}_T$	$\mu\gamma\not{E}_T$	$(e+\mu)\gamma\not{E}_T$
Predicted	94.8 ± 8.1	55.7 ± 7.1	150.6 ± 13.0
Observed	96	67	163





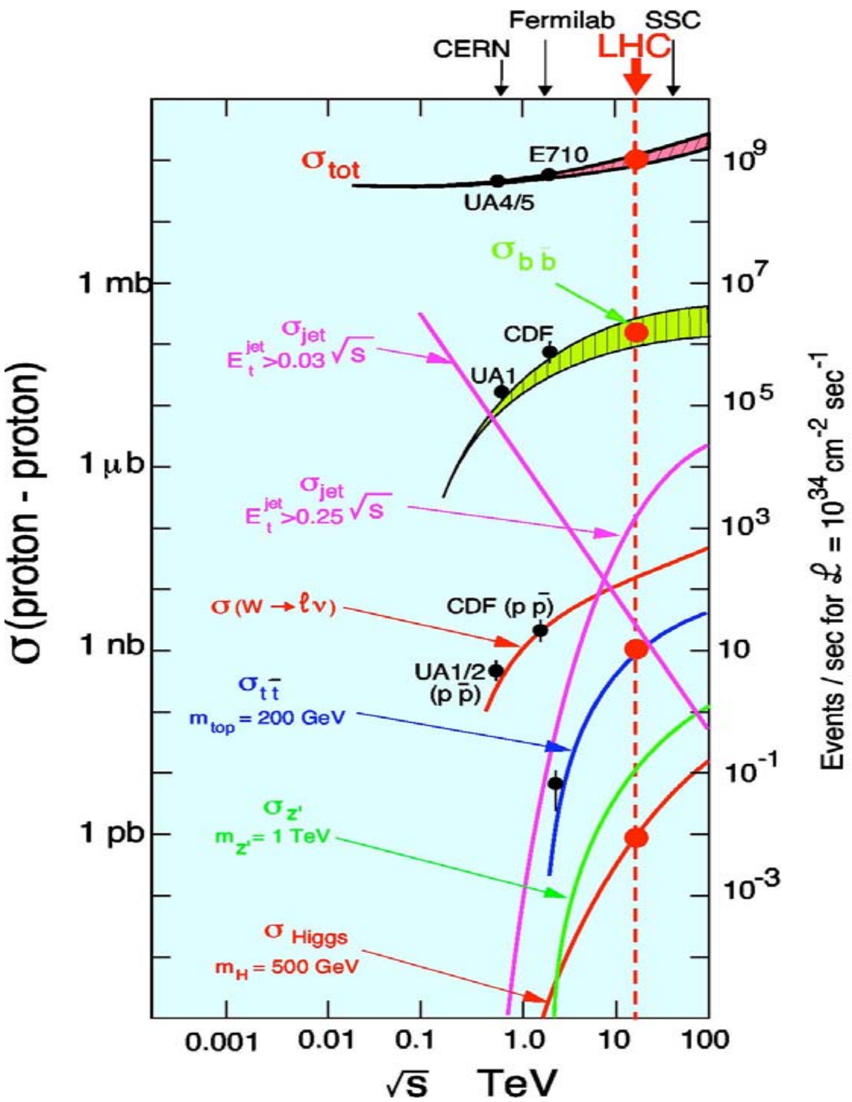
$\ell\ell\gamma$	$ee\gamma$	$\mu\mu\gamma$	$\ell\ell\gamma$
Total	39.0 ± 4.8	26.1 ± 3.1	65.1 ± 7.7
Observed	53	21	74

0 $e\mu\gamma$ vs. 1.0 ± 0.3, 0 $\ell\gamma\gamma$ vs. 0.62 ± 0.15



Cross section: TeV vs LHC

- First collisions at 0.9 and 2.36 TeV in 2009
- LHC collisions at 7 TeV in 2010 (14 TeV design)
- Top cross section goes up faster than background processes at higher sqrt{s}
- From TeV to LHC, Top cross section goes up by factor of ~20:
  - Cacciari,Frixione, Mangano, Nason, Ridolfi - arXiv:0804.2800
  - Top σ(2TeV)=8 pb
  - Top σ(7TeV)=200 pb
- Background is more “flat”



A word about QCD background

- QCD may still be large background in Top events
- From Tevatron to LHC
  - σ(ttbar) increases by 100
  - σ(W) increases by 10

…however…

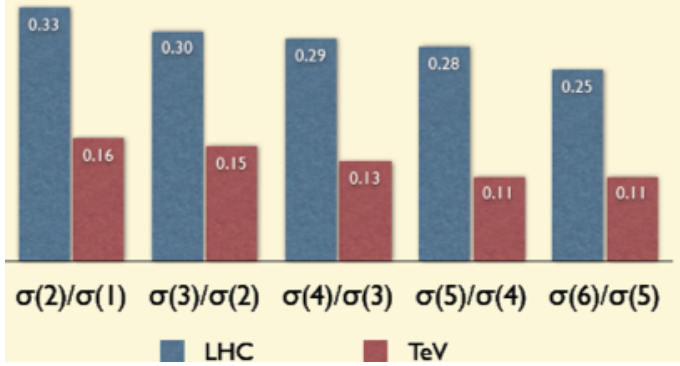
- σ(W+4 jets) increases 100 times

⇨W+jet background is large

Slide by Michelangelo Mangano

$\sigma \times B(W\to e\nu)$[pb]	N jet=1	N jet=2	N jet=3	N jet=4	N jet=5	N jet=6
LHC	3400	1130	340	100	28	7
Tevatron	230	37	5.7	0.75	0.08	0.009

E_T(jets) > 20 GeV , $|\eta|$<2.5 , ΔR>0.7



- Ratios almost constant over a large range of multiplicities
- $O(\alpha_s)$ at Tevatron, but much bigger at LHC

29

Summary

- Leptons are experimentally accessible at colliders
  - Good background rejection vs jets
  - Many multi-lepton final states in (B)SM
- Multi-lepton final states may signal New Physics
- Measurement and searches at Tevatron
  - No evidence for anomalies
  - At the limit of current experimental reach
- New LHC energy frontier soon available

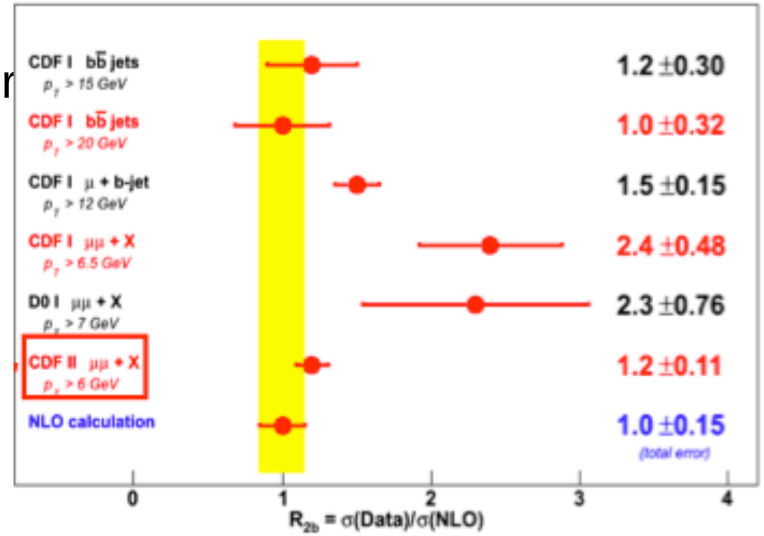
backup

A few thoughts

- The devil is in the detail…

Multi-muons

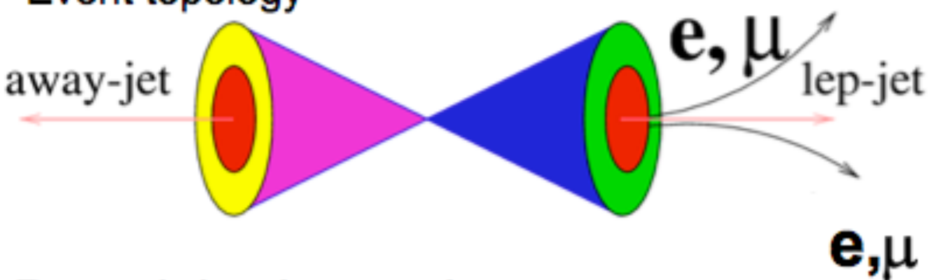
- Motivation
  - Large inclusive b-quark cross section measured in Run I
  - Problems with low-mass dimuon spectrum
  - Wrong value of time averaged mixing parameter χ



- Recent results:
  - New and very precise measurement of σ_{bb} agrees with prediction, PRD 77, 072004 (2008)
  - Study of multi-muon events responsible for previous discrepancies, arXiv:0810.5357[hep-ex]

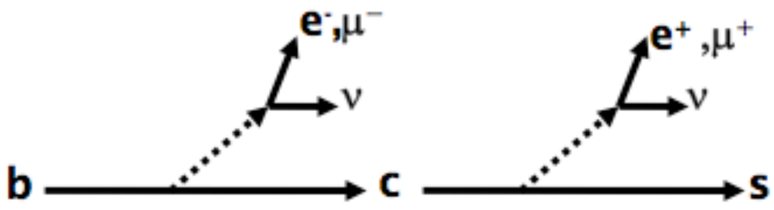
Low-mass dileptons

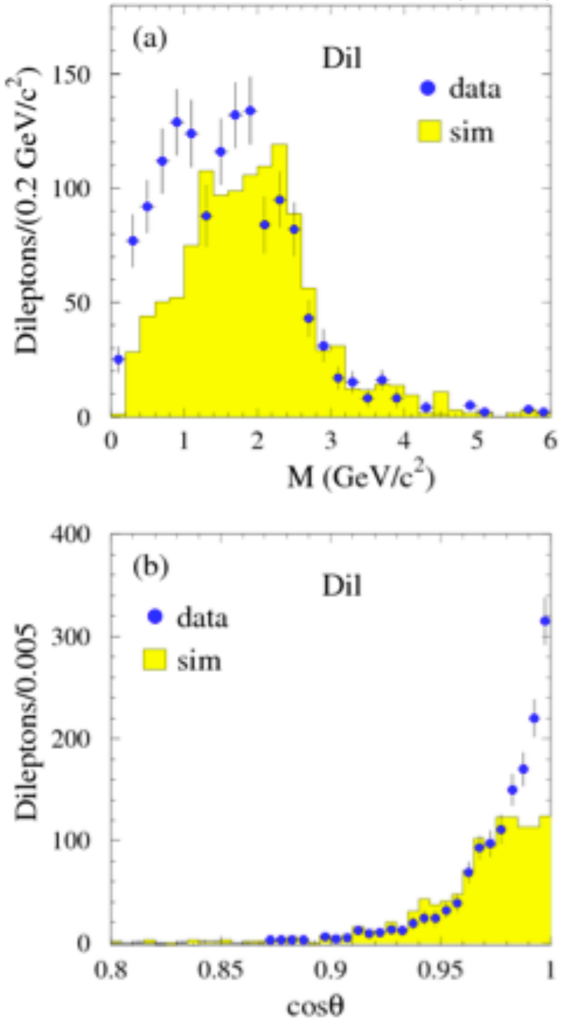
PRD 72, 072002 (2005)



B enriched sample:

the low mass di-lepton invariant mass is not well modeled by sequential semi-leptonic decays of single *b* quarks

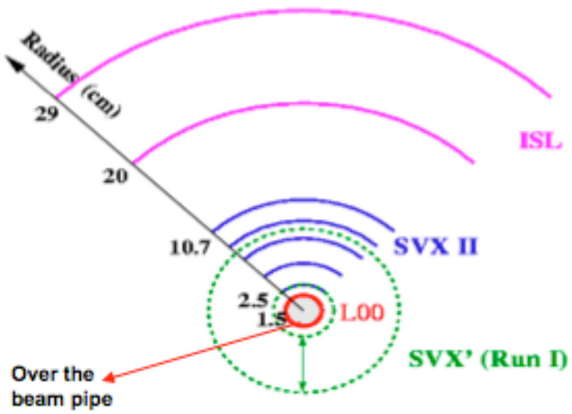


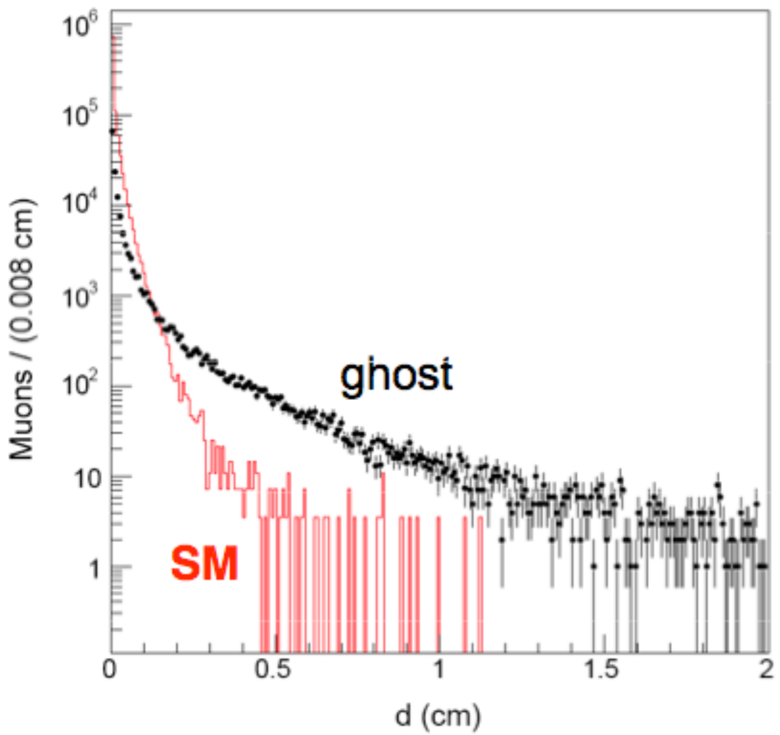


Simulation: HERWIG+EVTGEN

“Ghost” muons

- Study is about di-muon events
- Requires both muons originate inside beam-pipe





- Size of ghost sample is about the same as bb sample
- No dependence on run#/lumi
- Possible explanations:
  - Tracking reconstruction failure
  - Semi-leptonic decays of b-hadrons with large boost
  - etc.

Muon impact parameter

- Impact parameter of both muons
- Histogram is sum of templates fit to data (bottom, charm, prompt)
- Excellent agreement over 4 orders of magnitude