International School Cargese 2012: Across the TeV Frontier with the LHC

August 20 – September 1st, 2012

Searches for new phenomena at the Tevatron

Lecture 2

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ICREA/IFAE, Barcelona

Outline

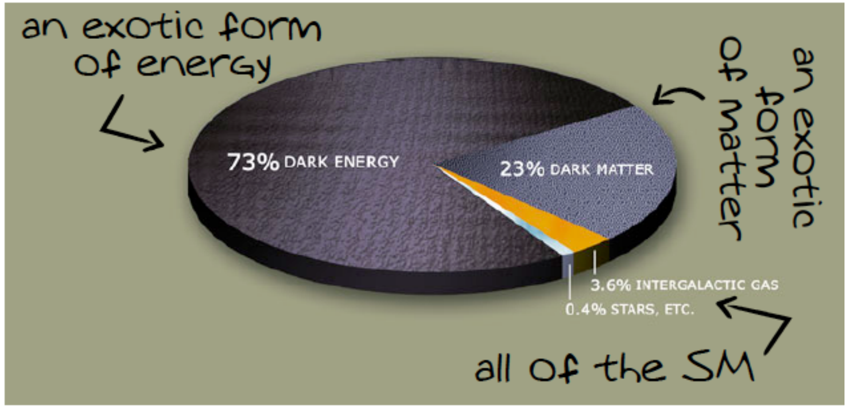
- Lecture 1
  - Preliminaries
    - The Tevatron, CDF and D0
    - Trigger and object reconstruction
  - Probing the electroweak sector
    - Forward-backward asymmetry in $Z/\gamma^* \rightarrow l^+l^-$
  - Probing the top quark sector
    - Forward-backward asymmetry in $t\bar{t}$

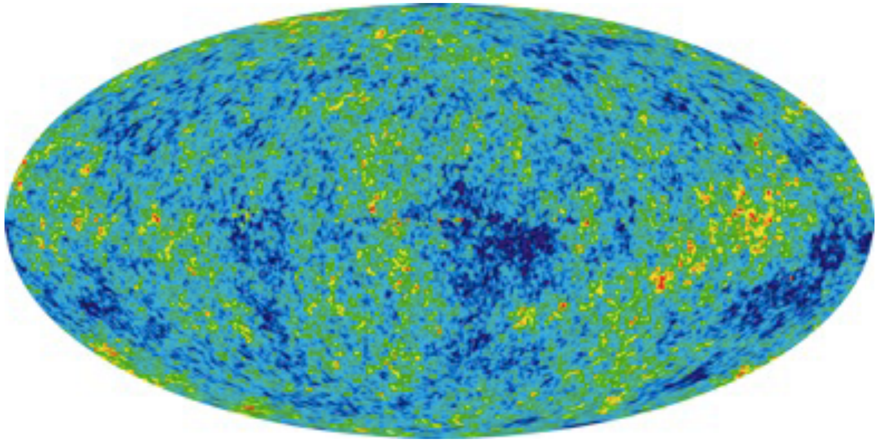
- Lecture 2
  - Probing the dark sector
    - Searches for dark matter
  - Probing the b-quark sector
    - Measurement of the dimuon charge asymmetry
  - Probing the EWSB sector
    - Searches for the SM Higgs boson

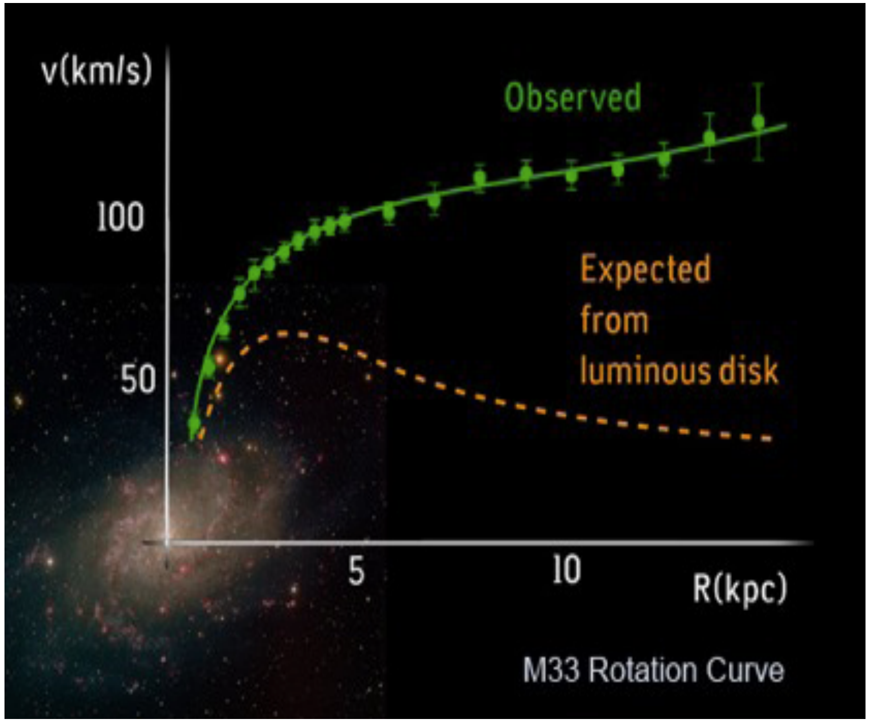
Searching for Dark Matter

Dark Matter Abundance and Distribution

- Compelling cosmological evidence for the existence of dark matter:
  - Combination of CMB data with Hubble expansion data from SNIa







  - Deviations from ~$1/\sqrt{r}$ expectation in galaxy rotation curves.
  - Estimated galactic abundance: ρ_{DM}~0.3 GeV/cm^3 (± a factor of 2)

Dark Matter Properties

Lectures by: N. Toro

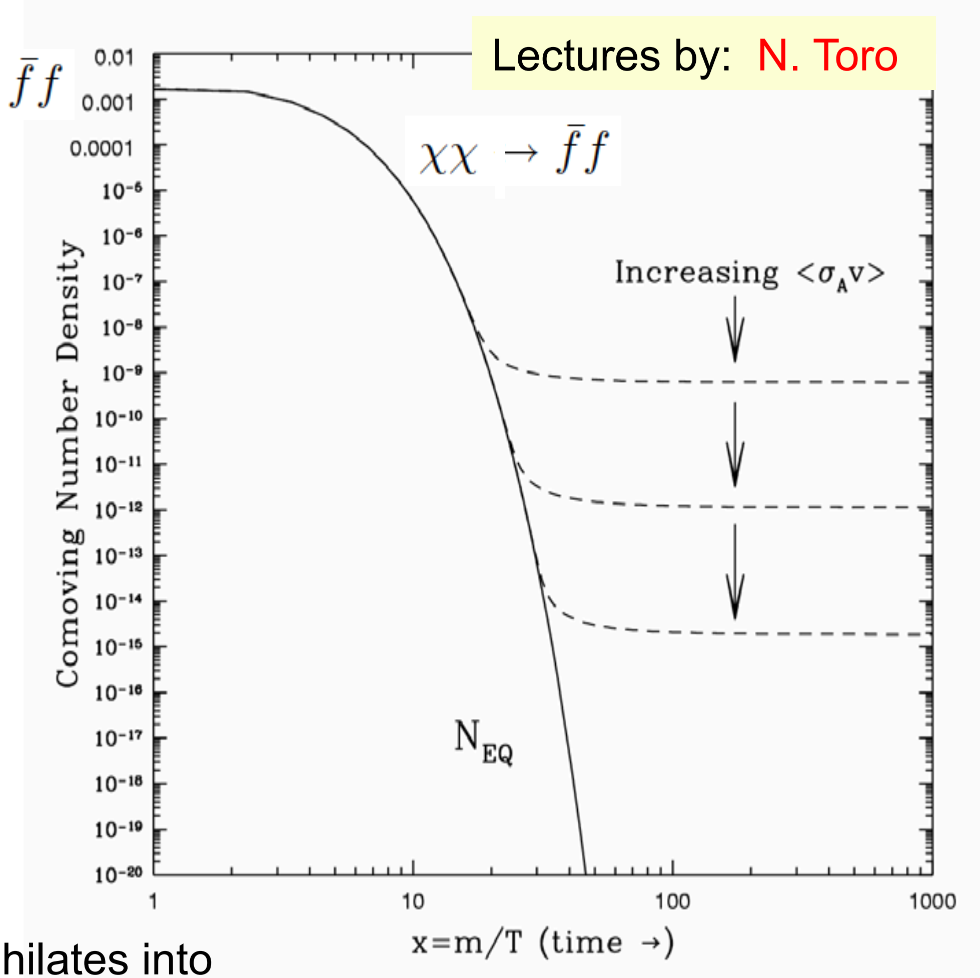
- "Cold" (i.e. non-relativistic)
- Non-baryonic
- Stable on cosmological time scales
- "Dark", i.e. neutral under SM

- Possible candidates:
  - Axions
  - Gravitinos
  - Primordial black holes
  - WIMPs (e.g. SUSY neutralino,…)
  - …

  Not all of them "weakly interacting"!

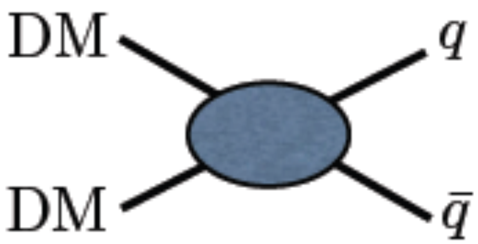
- The "WIMP miracle":
  - Initially DM in thermal equilibrium
  - As T drops below DM mass, DM annihilates into SM particles and abundance begins to drop
  - At some point, DM particles won't find each other to annihilate: abundance is set (freeze-out)
  - A weak-scale particle freezes out to give the correct relic abundance!

$\chi\chi \leftrightarrow \bar{f}f$

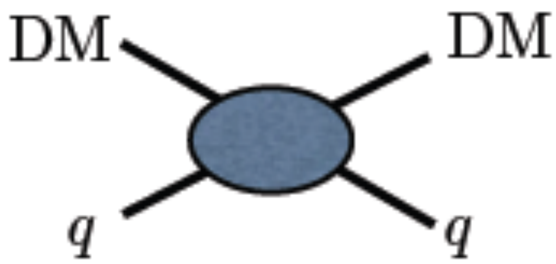


$$\langle\sigma v\rangle \sim \frac{\alpha_W^2}{M_W^2} \sim 1\,\mathrm{pb} \sim 3\times10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}$$

Searching for Dark Matter



Indirect detection



Direct detection

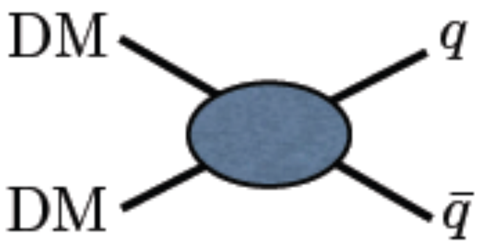
Look up

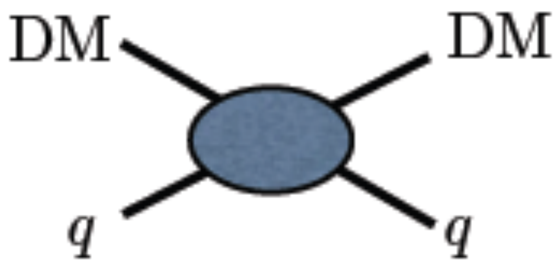
Annihilation in our galaxy
Antimatter excesses in
cosmic rays, photons
from centre of galaxy

Look down

Scattering off a nucleus
Low rate, low energy
recoil events in
underground labs

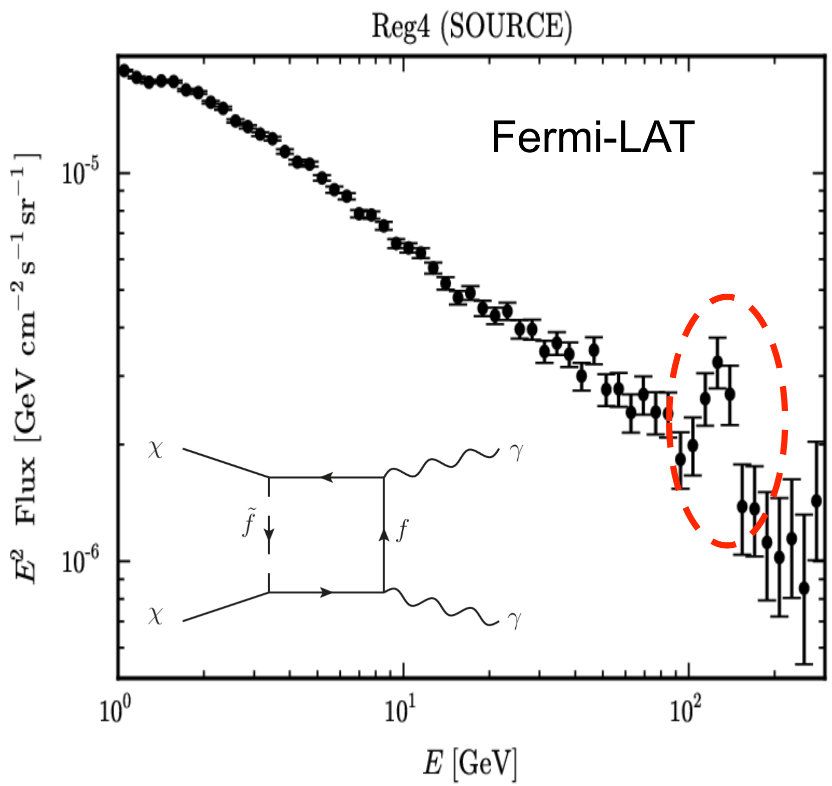
Searching for Dark Matter

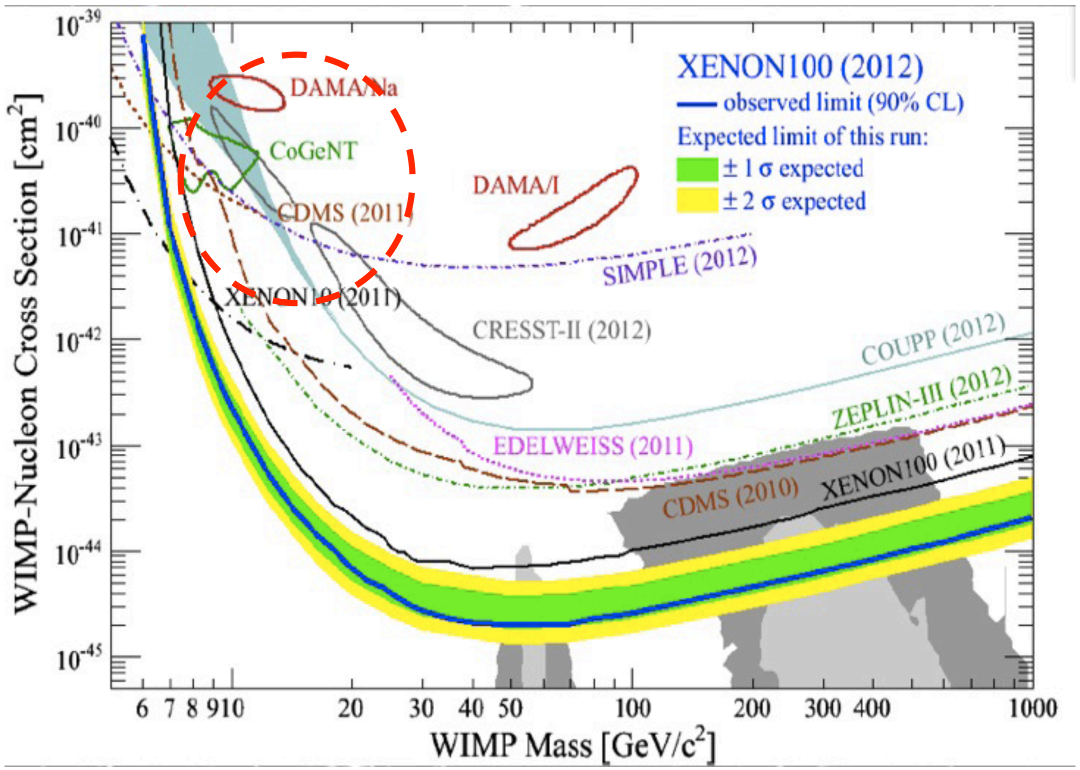




Indirect detection

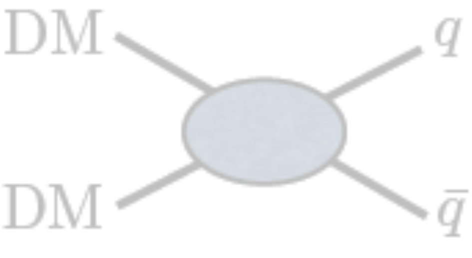
Direct detection





Excesses in several experiments. Strong limits from others. Open question!

Searching for Dark Matter



Indirect detection

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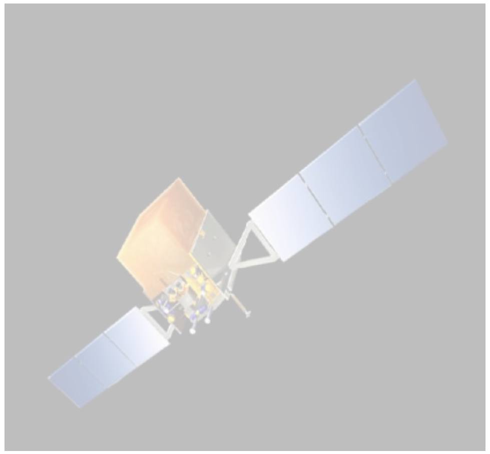
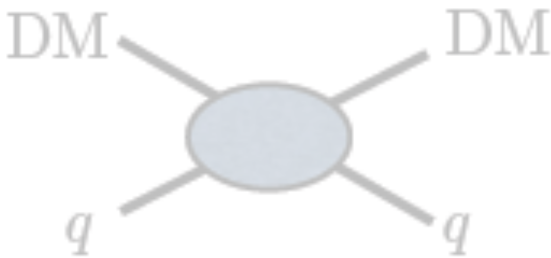
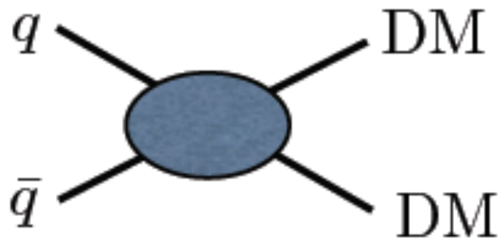




Direct detection

Look down

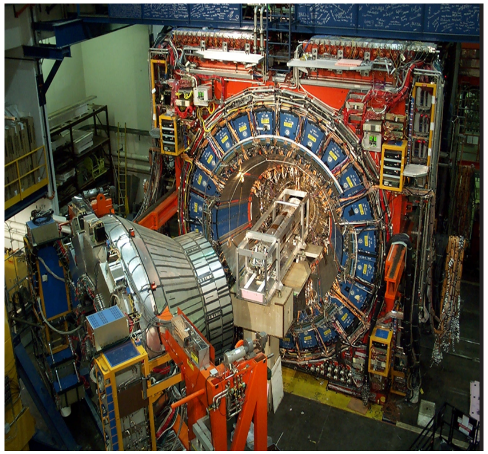
Scattering off a nucleus
Low rate, low energy recoil events in underground labs



Collider searches

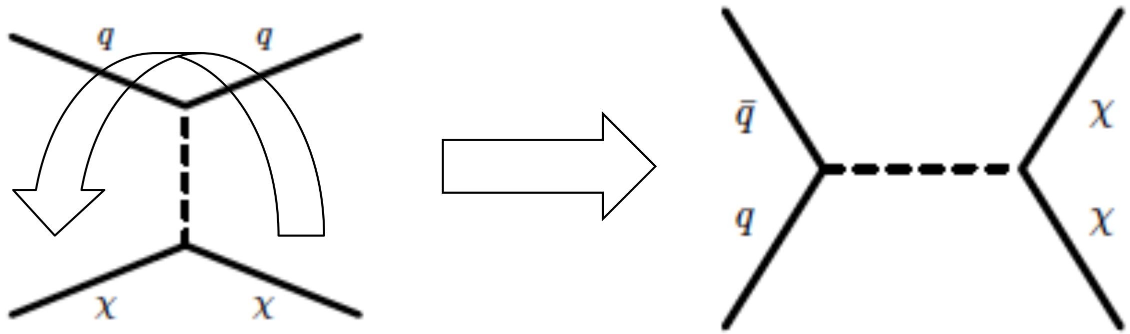
Look small

Missing energy events at a collider experiment



Collider Production

- Assuming dark matter couples to the SM (quarks and gluons), we can relate direct detection experiments to production of dark matter at hadron colliders:



- Problem: in collider production, dark matter leaves no trace in the detector!

Collider Production

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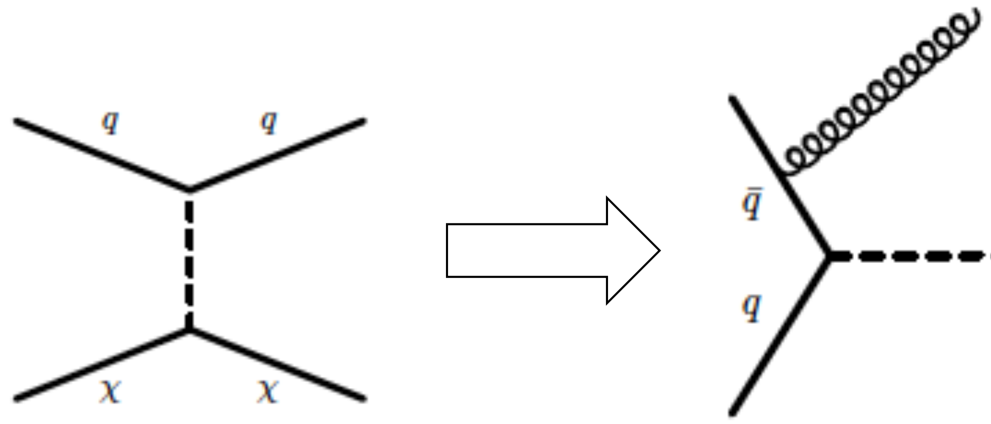
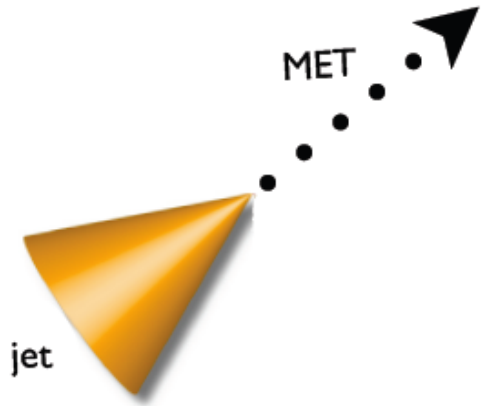


- When produced in association with a ISR jet it is possible to detect and analyze these events
  ➔ signature of mono-jet plus MET

- Could also consider a mono-photon plus MET search! (hasn't been done yet).



Back-of-the Envelope Calculation

Consider massive mediator:

$$\mu = \frac{m_\chi m_n}{m_\chi + m_n}$$

$(p_T \sim 100\,\mathrm{GeV})$ $\qquad$ $(\mu \sim 1\,\mathrm{GeV})$

$$\sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{p_T^2}{M^4} \qquad \sigma_{\mathrm{DD}} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$$

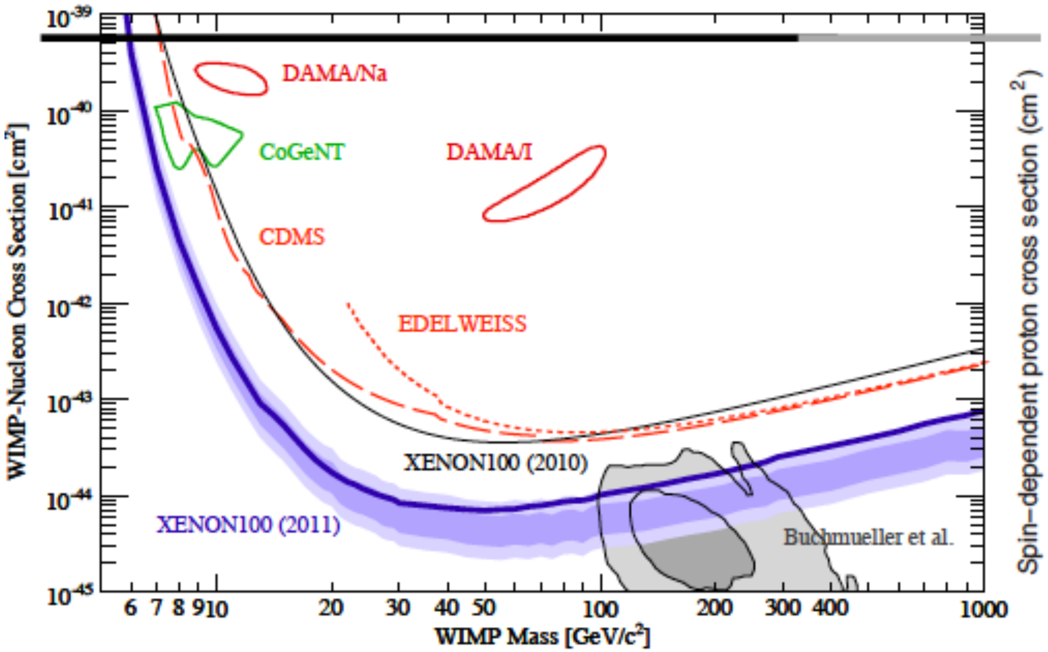
$$\frac{\sigma_{1j}}{\sigma_{DD}} \sim \mathcal{O}(1000)$$

In 1 invfb CDF saw 8449 mono-jet events, expected 8663 ± 332 $\quad \Rightarrow \quad \sigma_{1j} \lesssim 500\,\mathrm{fb}$

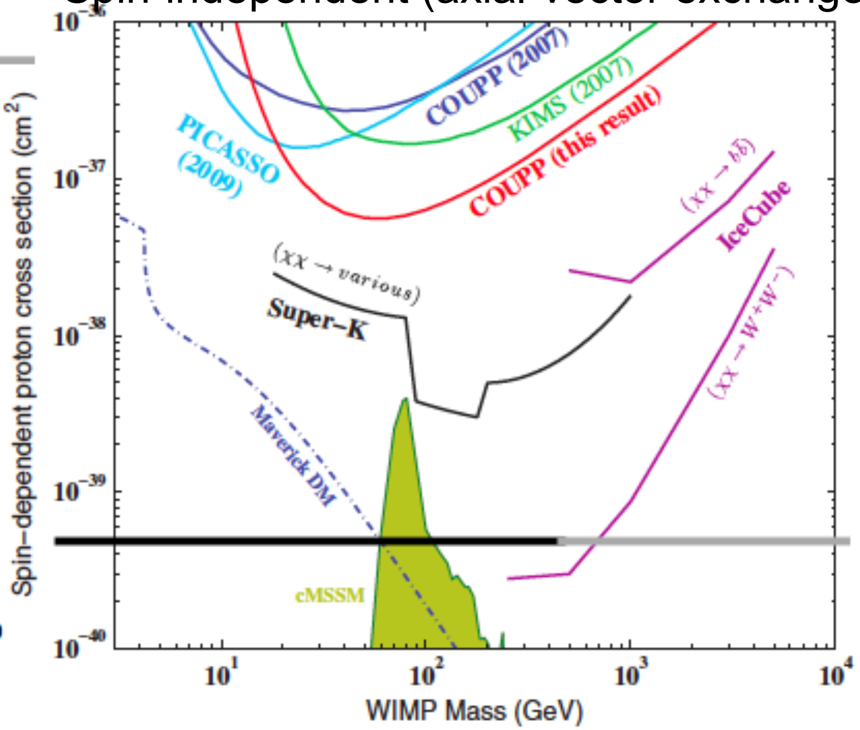
$$\sigma_{DD} \lesssim 0.5\,\mathrm{fb} = 5 \times 10^{-40}\mathrm{cm}^2$$

Collider Advantages

Spin-independent (scalar/vector exchange)



Spin-independent (axial-vector exchange)



- Advantage #1: No detection threshold. In contrast, ~1 GeV DM-recoil can fail below detection threshold in DD search experiments.
- Advantage #2: “model independent” (no spin-indep vs spin-dep interaction) and astrophysics independent (DD results assume local abundance is ρ_{DM}~0.3 GeV/cm^3).

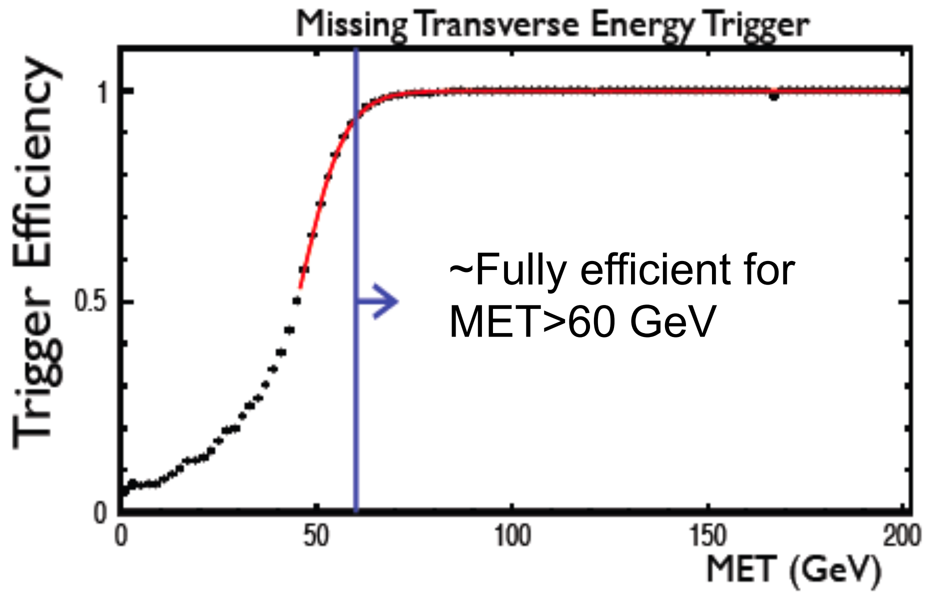
➔ Expect competitive bounds at low mass for spin-independent interactions and over all masses for spin-dependent interactions.

➔ For light mediators (M<<100 GeV) expect DD searches to win (except at low m_χ):

$$\sigma_{DD} \sim g_\chi^2 g_q^2 \frac{\mu^2}{M^4} \qquad \text{vs} \qquad \sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{1}{p_T^2}$$

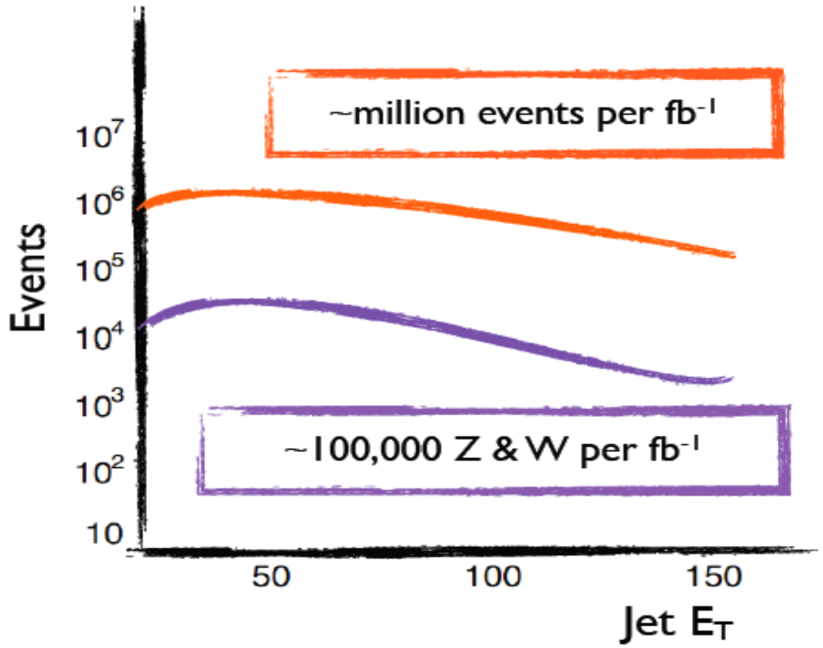
Event Selection

- 6.7 fb^{-1} of data selected with MET triggers (MET>40 GeV).
- Offline selection cuts:
  - =1 jet with p_T>60 GeV
  - ≤1 additional jets with p_T<30 GeV
  - MET>60 GeV



- Easy on the paper, but real life is a bit more complicated..
  ➔ background is HUGE!
  - W/Z+jets
  - QCD multijets
  - Non-Collision backgrounds

Total data ~ QCD multijet+non-collision

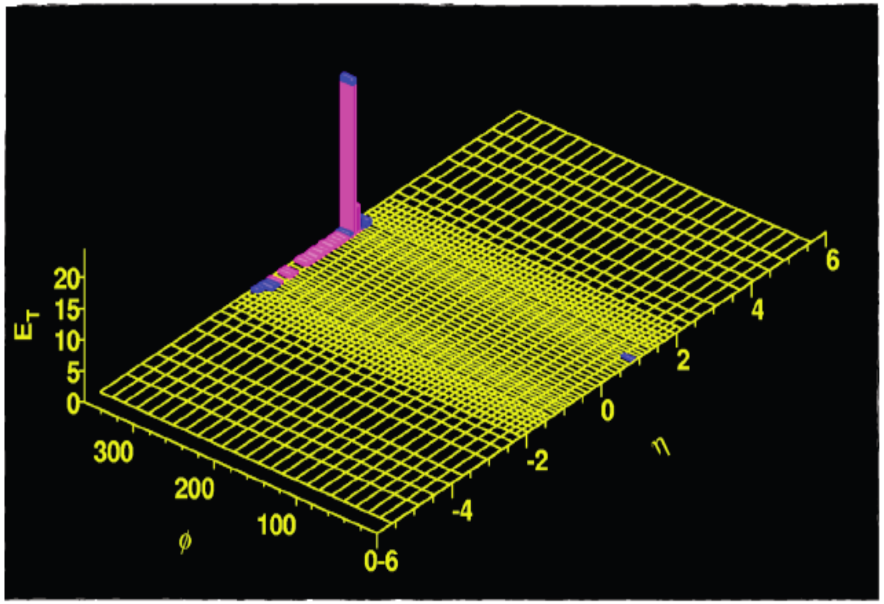


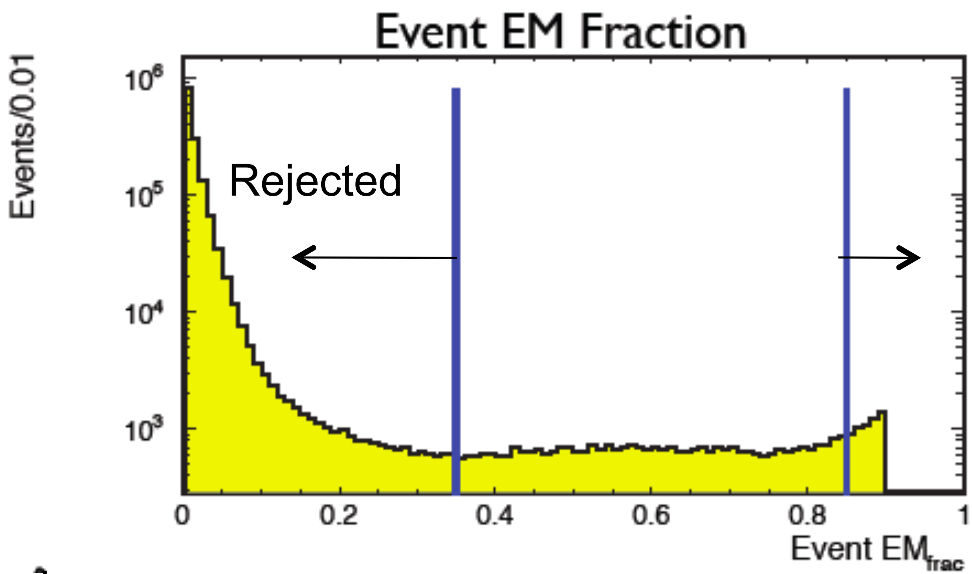
Non-Collision Backgrounds

- Consists mainly of cosmics and beam-halo (dominant contribution).
- Comics:
  - Mostly rejected by vetoing evens with cosmic track candidate in muon system or out-of-time calorimeter deposits wrt the bunch crossing.
- Beam-halo:
  - Detector-gas interactions can produce muons that travel through the calorimeter parallel to the beam
- Typically have low fraction of energy deposited in the electromagnetic calorimeter:

$$\text{Event } EM_{frac} = \frac{\sum_{jets} E_T * EM_{frac}^{jet}}{\sum_{jets} E_T}$$

➔ rejects 99% of non-collision background

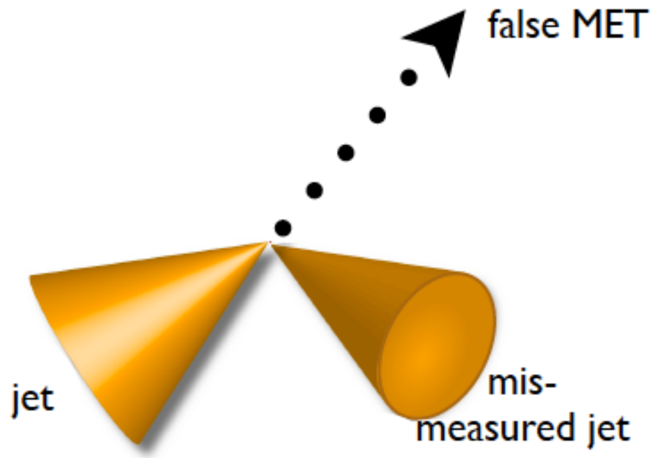


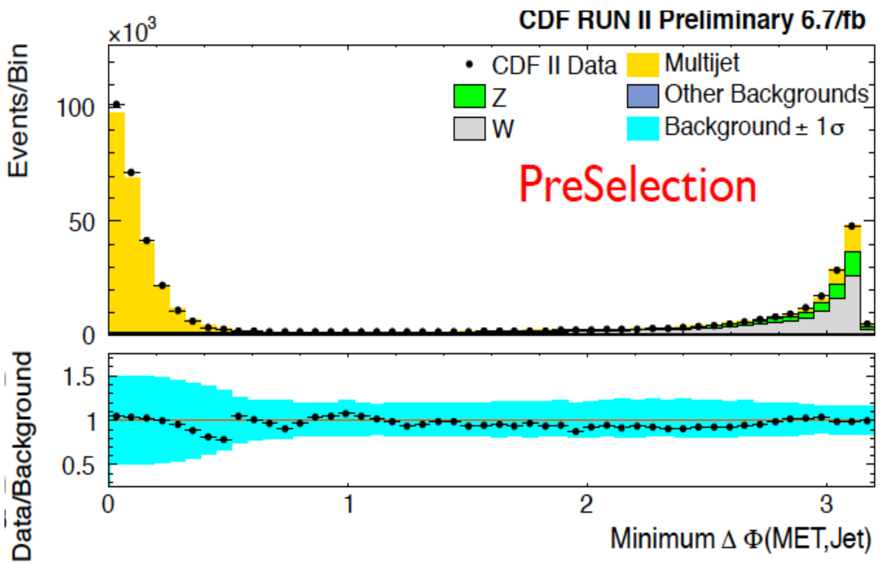


QCD Multijet Background

- QCD multijet events enter mono-jet selection due to misreconstruction or mismeasurement of jets in 2- or 3-jet events.

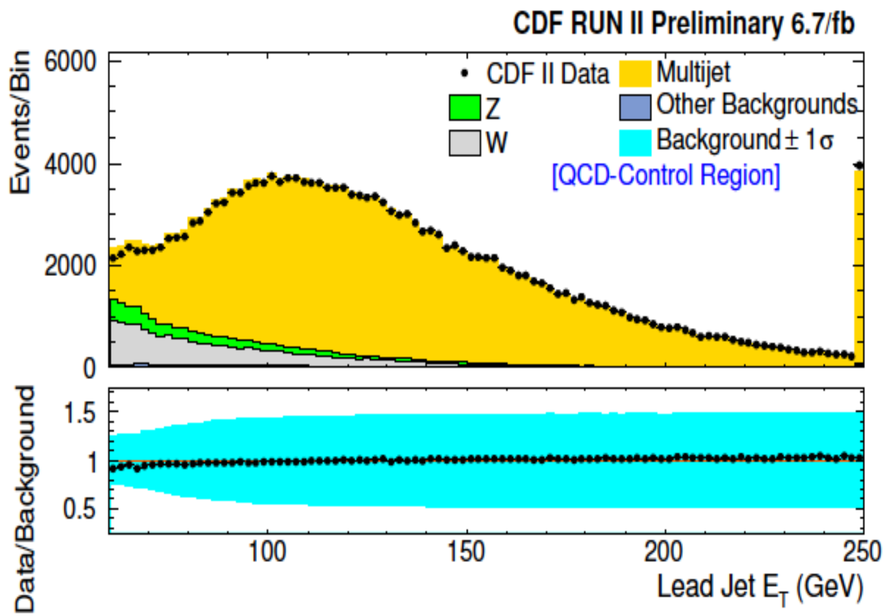
  Key characteristics:
  - Imbalance in ratio of p_T(jet 1)/MET
  - MET aligned with a jet in transverse plane





- Use this a other kinematic distributions to train a NN to discriminate between QCD multijet background from W/Z+jet events.

  A cut on this NN has 90% signal efficiency and rejects 80% of the multijet background.



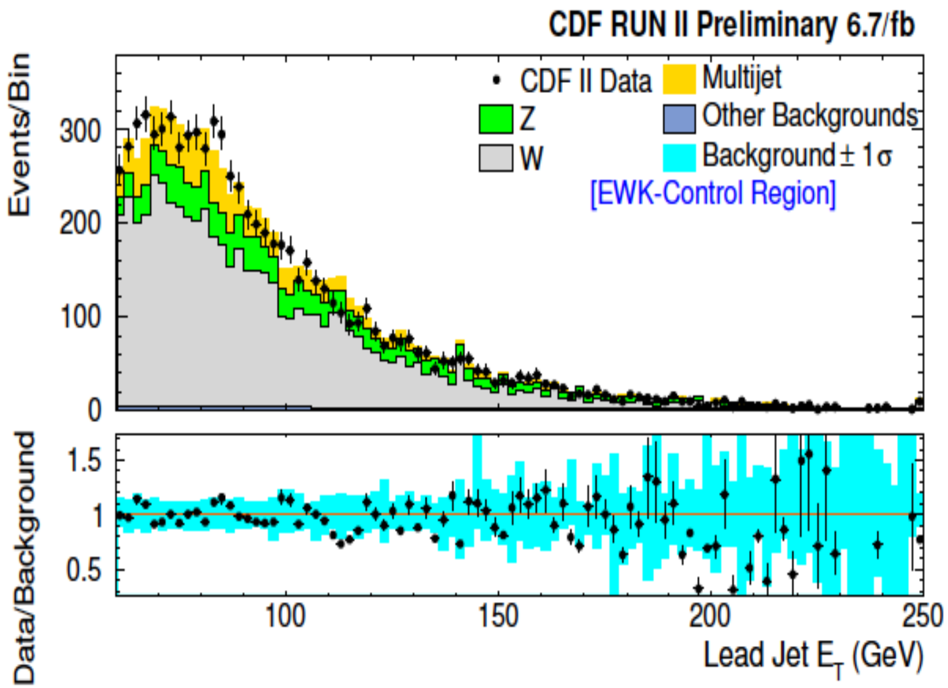
Data-driven modeling validated in QCD-enriched control region

EW Background

- Dominant background after non-collision and QCD multijet background rejection cuts.
  Main contributions from:
  - Z(→νν)+jets: real MET; irreducible
  - W(→lν)+jets: real MET: reducible by vetoing events with at least one isolated track with p_T>10 GeV.

- Modeled via the MC simulation (ALPGEN - matrix element+parton shower – in the case of W/Z+jets).

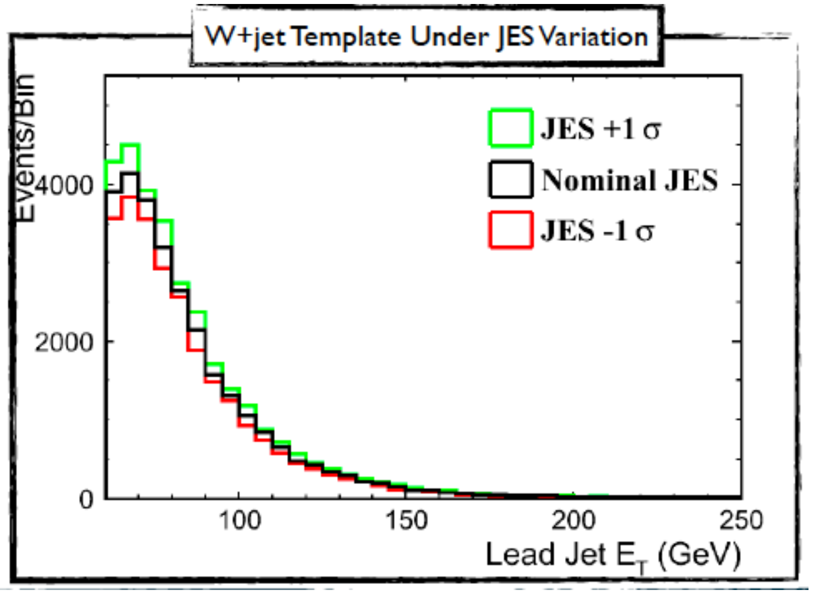
- Define control region with same analysis cuts except for requiring at least one isolated track with p_T>10 GeV.

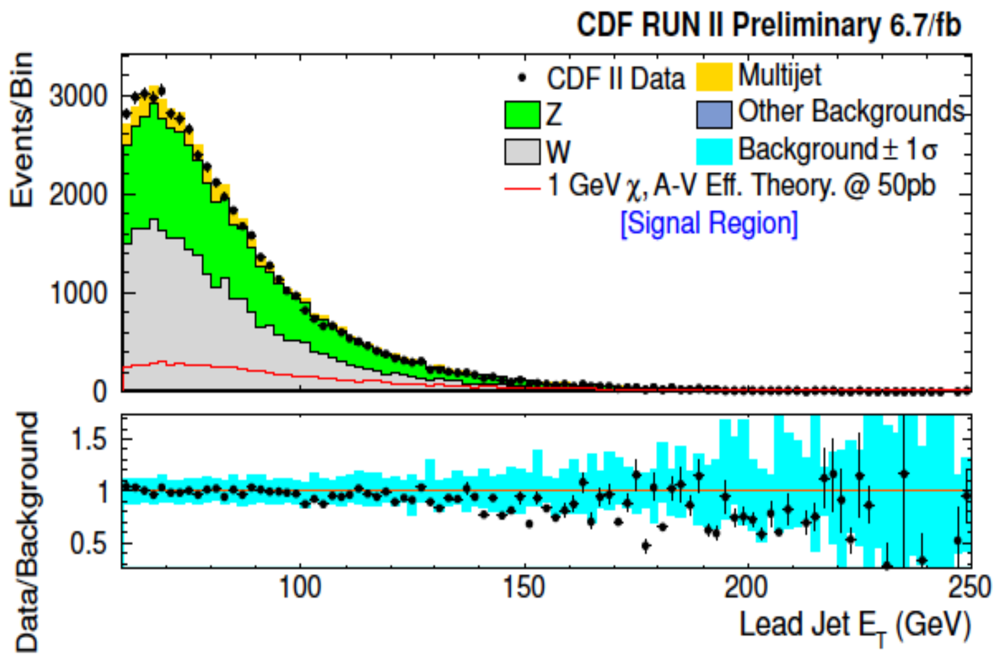


Signal Region

- Good agreement between data and total background prediction (90% W/Z+jets).
- Will use leading jet p_T distribution as main observable to perform the search.
- Main W/Z+jets background systematic uncertainties:
  - Cross section: ~10%
  - JES uncertainty: both normalization and shape.

Contribution	Signal Region
non-collision	6 ± 6
Z	22191 ± 2681
W	27892 ± 3735
diboson	412 ± 36
$t\bar{t}$	23 ± 4
single-top	104 ± 14
multijet	3278 ± 1639
total model	53904 ± 6022
A-V$[\mathcal{M}_{10\,\mathrm{TeV}}, \chi_{1\,\mathrm{GeV}}]$@ 50 pb	151 ± 11
data	52633



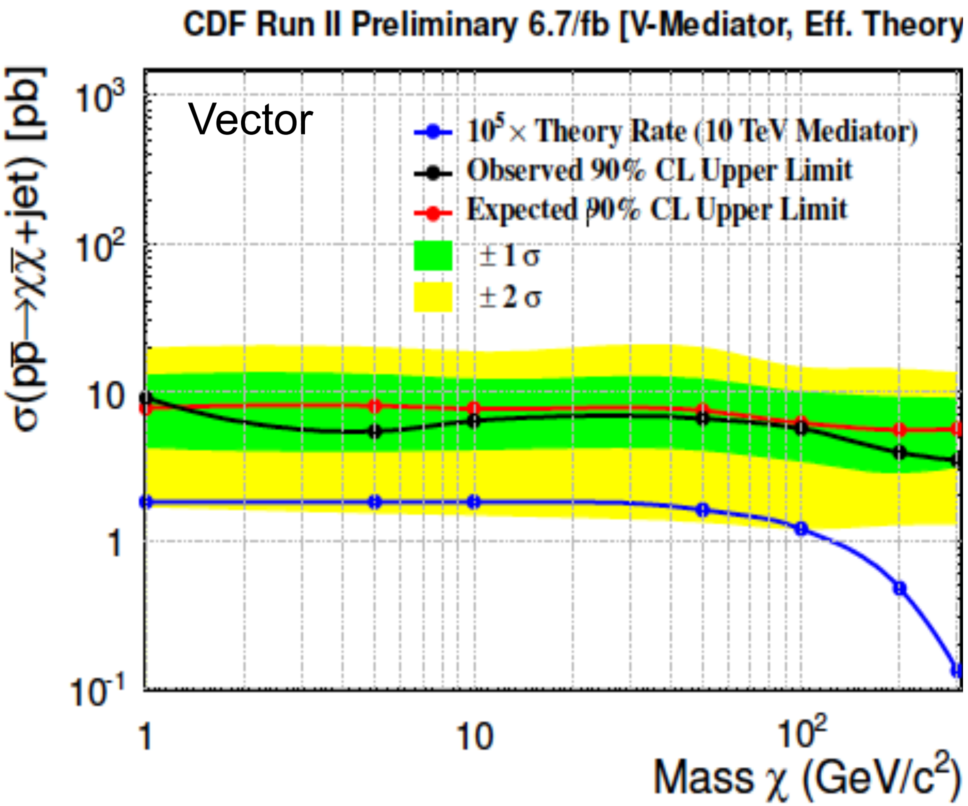


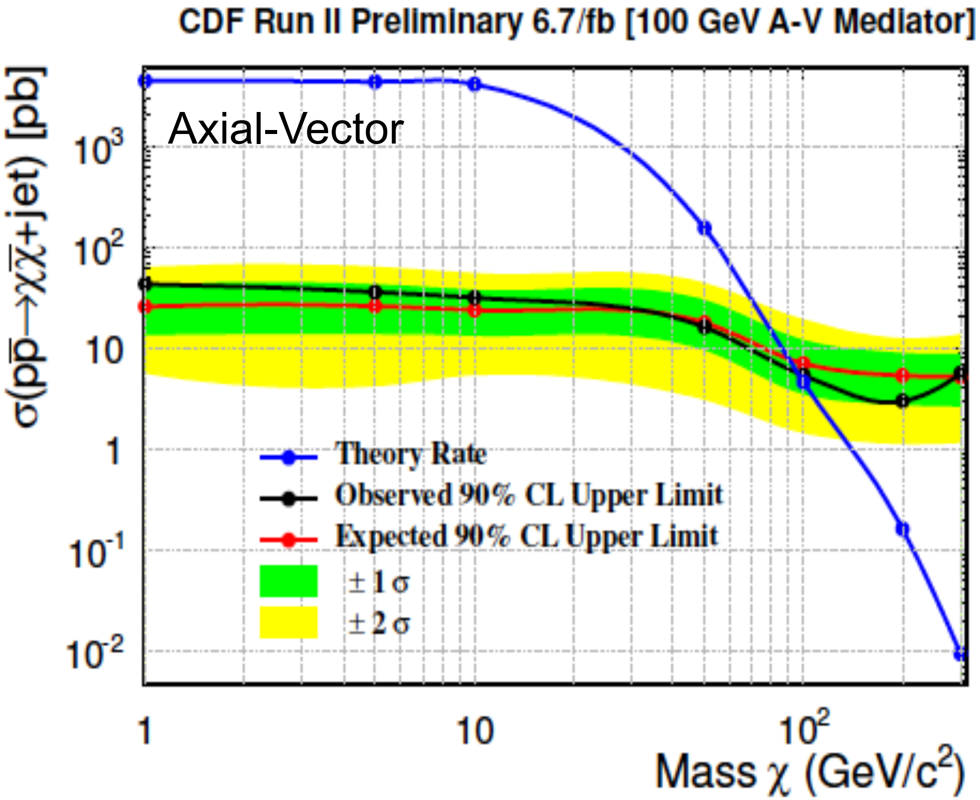
Cross Section Limits

- Set 90% upper limits on $\sigma(p\bar{p} \rightarrow \chi\chi+\text{jet})$ as a function of m_χ for different production modes (axial-vector mediated, vector mediated, t-channel mediated) and different values of the mediator mass.

  Examples:

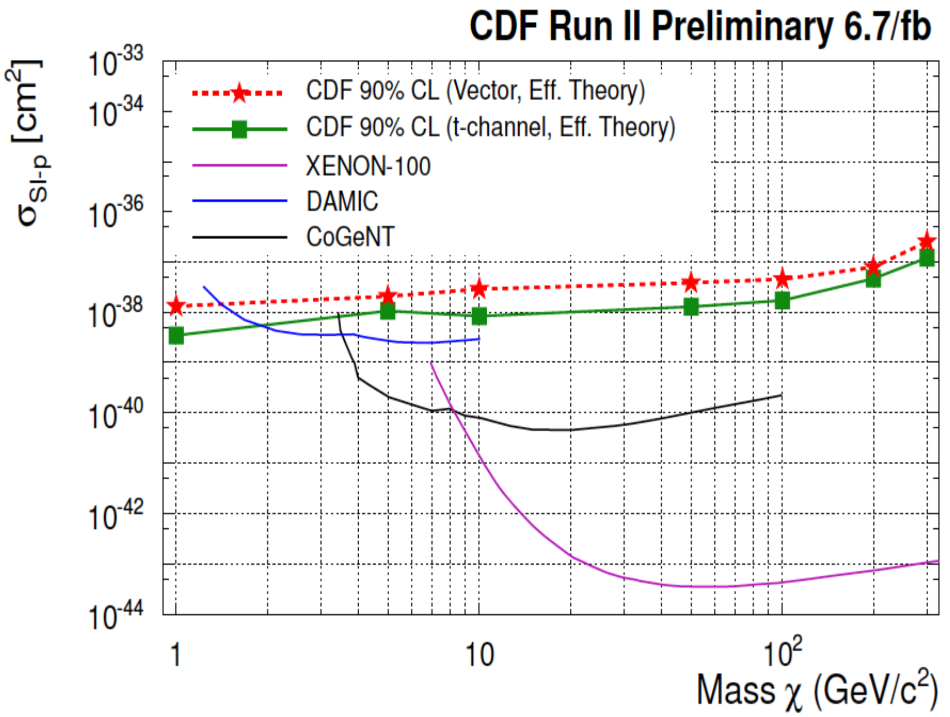
Lectures by: G. Cowan

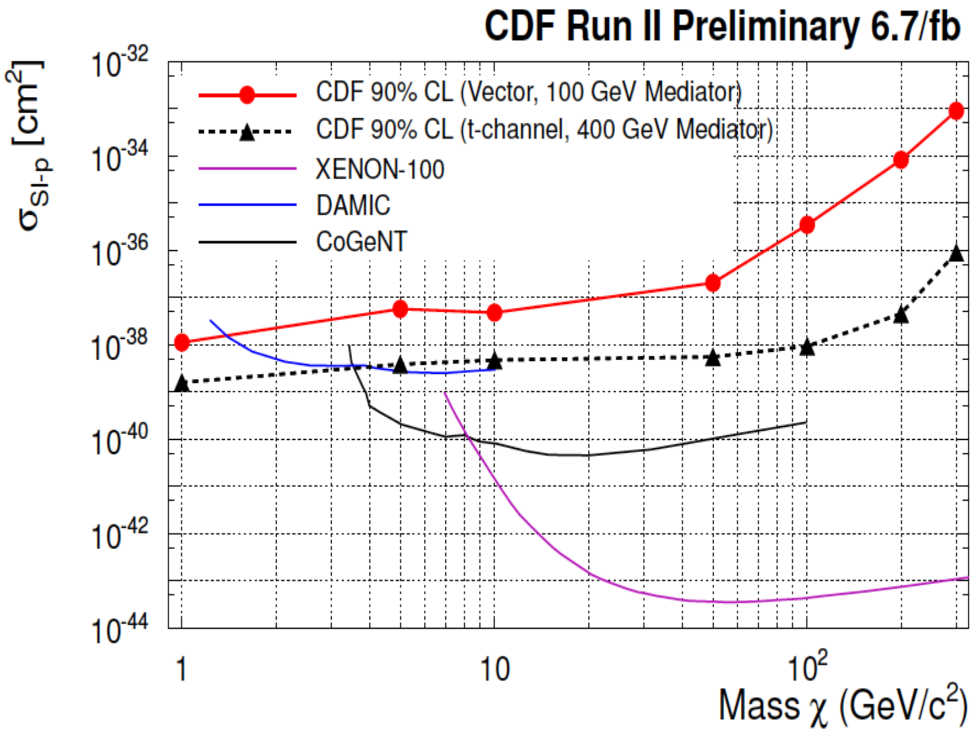




Comparison to Direct Detection

- Translation to spin-independent bounds on DM-nucleon scattering cross section:





(CoGeNT), Phys. Rev. Lett. 106, 131301 (2011), astro-ph.CO/1002.4703
(DAMIC) 2011, astro-ph.IM/1105.5191
(XENON100), Phys. Rev. Lett. 105, 131302 (2010), astro-ph.CO/1005.0380

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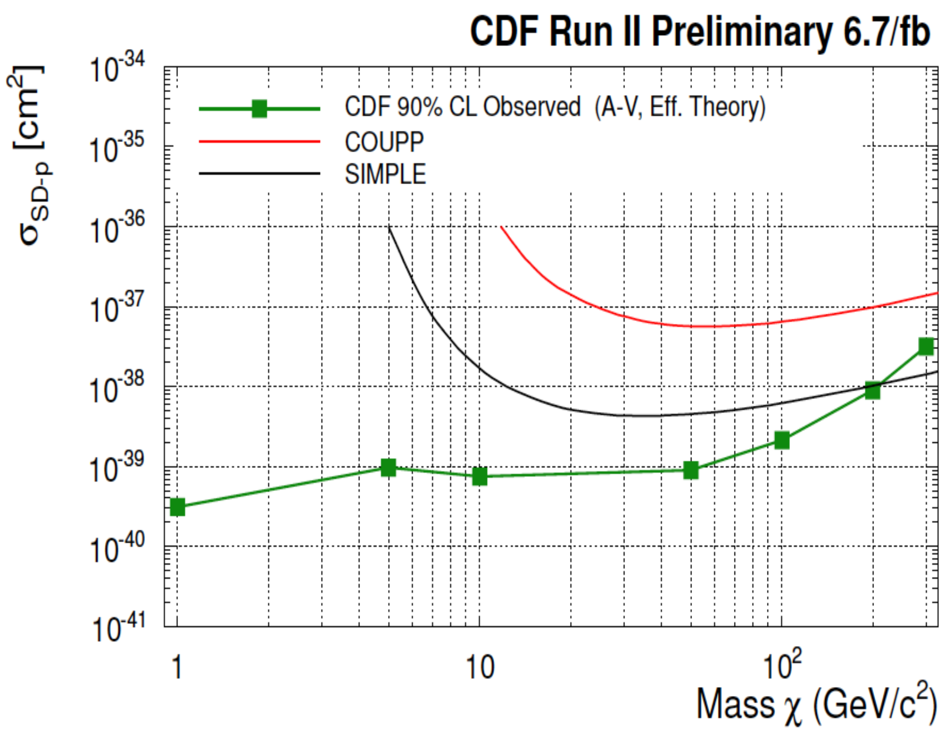
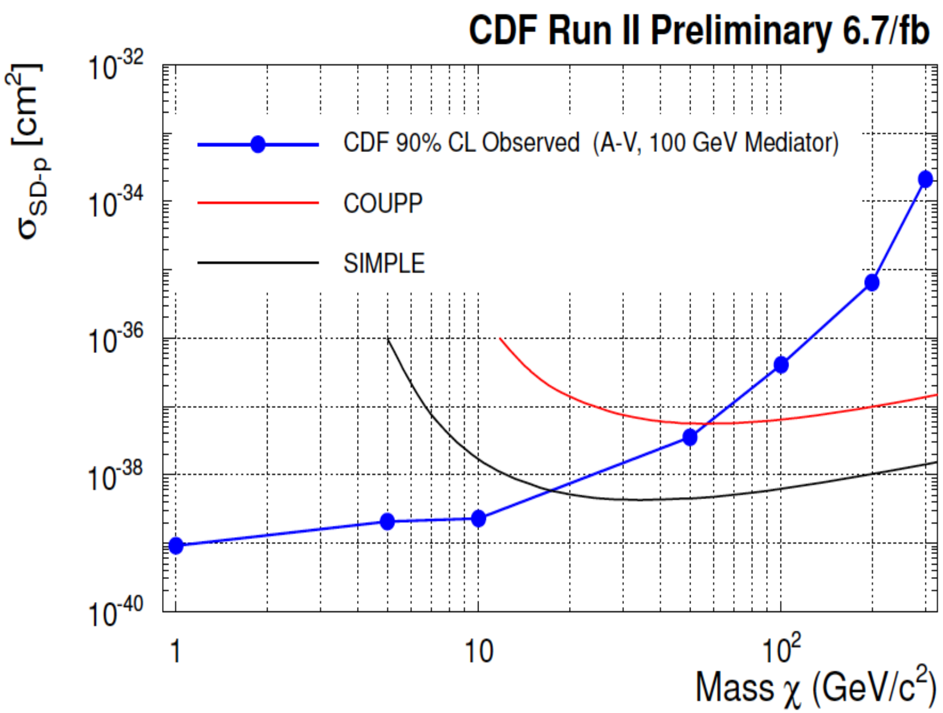
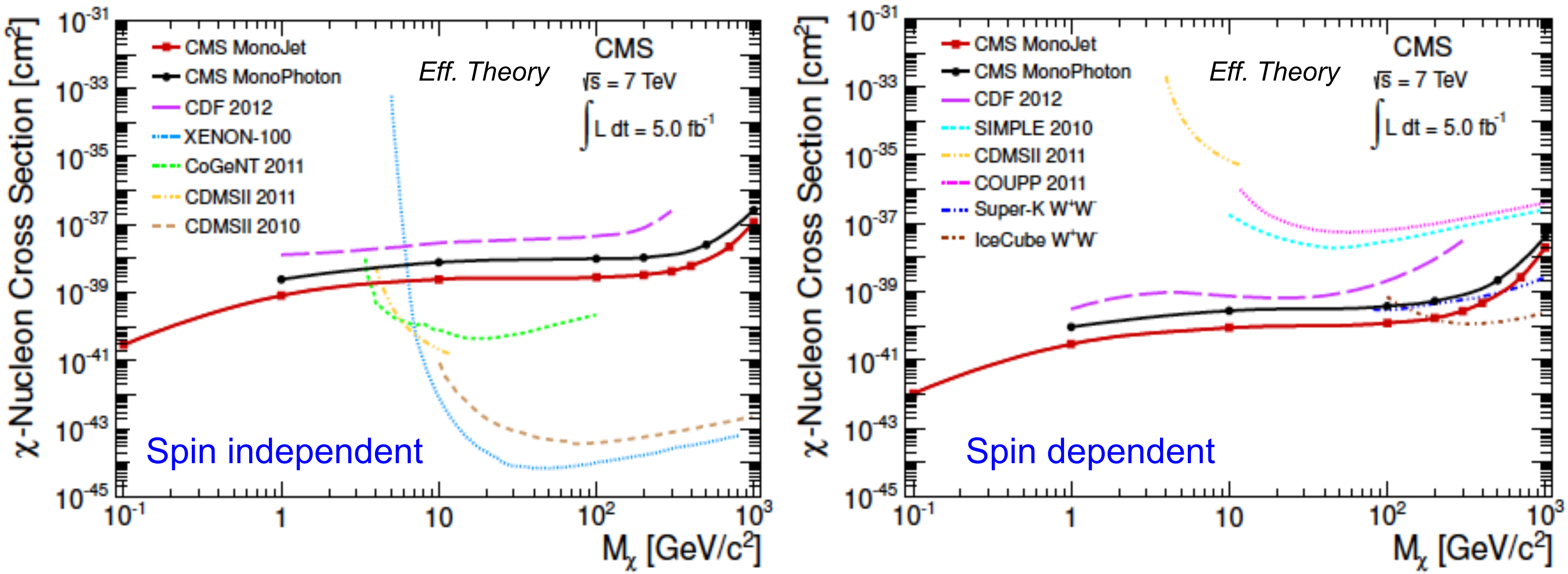




(SIMPLE) 2011, astro-ph.CO/1106.3014
(COUPP) Phys. Rev. Lett. 106, 021303 (2011), astro-ph.CO/1008.3518

Summary and Prospects

- Recent LHC results on mono-jet/photon+MET supersede the Tevatron:



And still great potential for improvement!

- Limits demonstrate that hadron-collider experiments can contribute an important piece of information to solve the dark-matter puzzle.
- However, we need to keep in mind that there are many dark-matter-unrelated BSM theories that can predict similar signatures (e.g. extra-dimensions)

It'd be very hard to disentangle the various possibilities!

Measurement of the

dimuon charge asymmetry

CP Violation

- The universe that we observe is matter-dominated, but we expect that the Big Bang produce matter/antimatter equally.

  What happened to the antimatter?

- Theories of baryogenesis can explain this asymmetry, but they require several ingredients, one of which is CP violation (CPV).

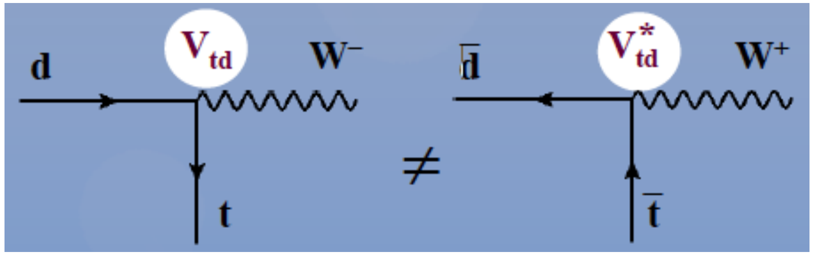
- CPV is naturally included in the SM through a single phase in the quark mixing matrix.

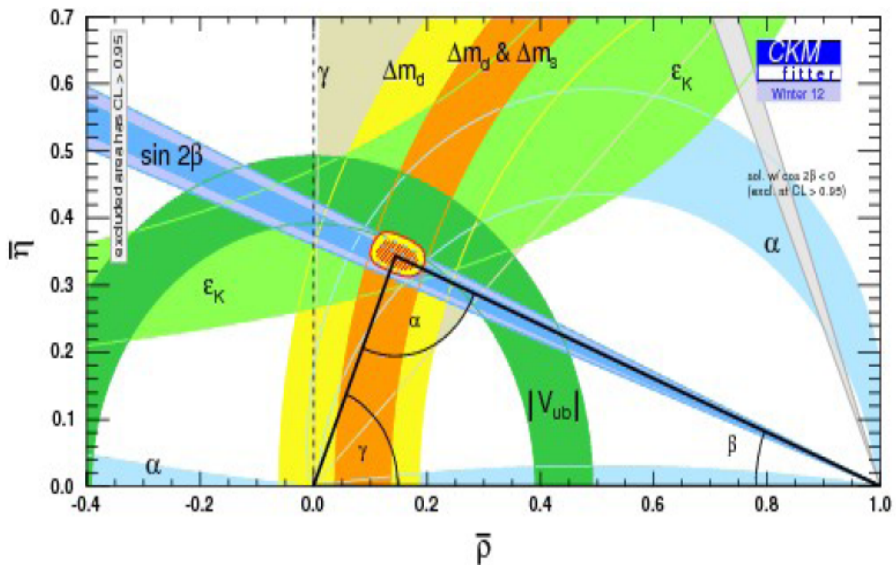
- Many different measurement of CPV phenomena are in excellent agreement with the SM.

- However, the level of CPV predicted by the SM is far too small to explain the observed matter dominance!

Lectures by: A. Weiler

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



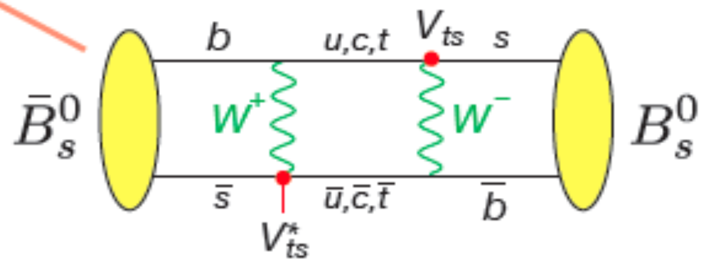


Searches for anomalous CPV are a sensitive probe of New Physics!

B_s Meson Mixing

Weak Eigenstates:

$$i\frac{d}{dt}\begin{pmatrix}|B_s^0\rangle \\ |\bar{B}_s^0\rangle\end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2}\end{pmatrix}\begin{pmatrix}|B_s^0\rangle \\ |\bar{B}_s^0\rangle\end{pmatrix}$$



Mass Eigenstates: $|B_s^{\mathrm{H}}\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$ $|B_s^{\mathrm{L}}\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$

Heavy *Light*

If CP ***not*** conserved in mixing, $p \neq q$:

$$\Delta m_s = M_H - M_L \simeq 2|M_{12}|$$

Sets oscillation frequency:
17.77 ± 0.12 ps^{-1} (CDF)
17.63 ± 0.11 ps^{-1} (LHCb)

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \simeq 2|\Gamma_{12}|\cos\phi_s$$

Sets lifetime difference
0.09 ± 0.02 ps^{-1} (SM prediction)
0.12 ± 0.06 ps^{-1} (World Average)

$$\phi_s = \arg\left[-\frac{M_{12}}{\Gamma_{12}}\right] \simeq 0.004 \text{ in SM}$$

CP violating!

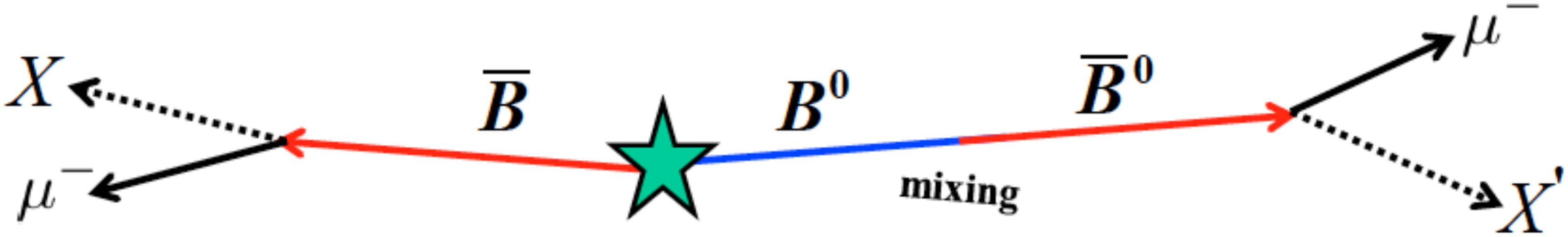
$$\mathrm{Prob}(B_s^0 \to \bar{B}_s^0) \neq \mathrm{Prob}(\bar{B}_s^0 \to B_s^0)$$

?

$$\phi_s^{SM} + \phi_s^{NP}$$

Dimuon Charge Asymmetry

- IDEA: measure CPV in neutral B meson mixing using the same-sign dimuon charge asymmetry of semileptonic B decays:

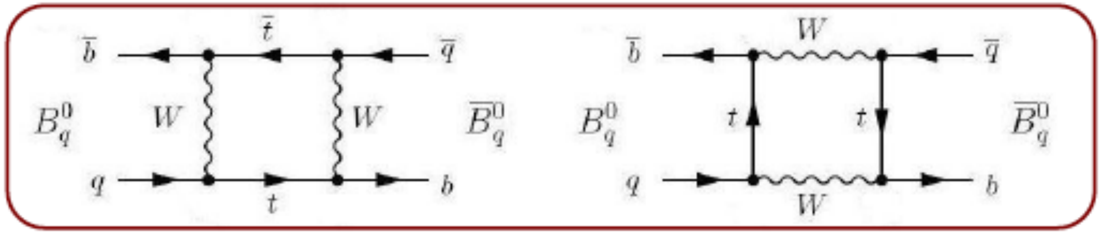


One muon comes from direct semileptonic decay $b \rightarrow \mu^- X$

Second muon comes from direct semileptonic decay after neutral B meson mixing: $B^0 \rightarrow \overline{B}^0 \rightarrow \mu^- X$

$$\boxed{A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}}$$

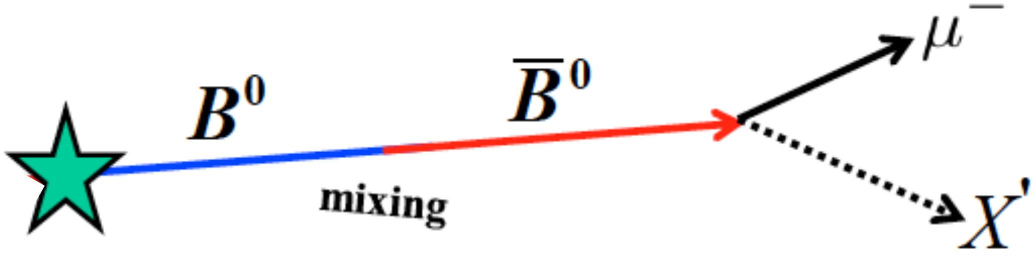
An asymmetry can occur if mixing rates are different: $R(B^0_{(s)} \rightarrow \overline{B}^0_{(s)}) \neq R(\overline{B}^0_{(s)} \rightarrow B^0_{(s)})$



Inclusive Muon Charge Asymmetry

- Because any dimuon asymmetry arises from the meson mixing, A^b_{sl} is equal to the charge asymmetry a^b_{sl} of "wrong sign" (i.e. oscillated) semileptonic B decays:

No 'opposite side' muon requirement: more events, more background processes.



$$a^b_{sl} \equiv \frac{\Gamma(\overline{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\overline{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)} = A^b_{sl}$$

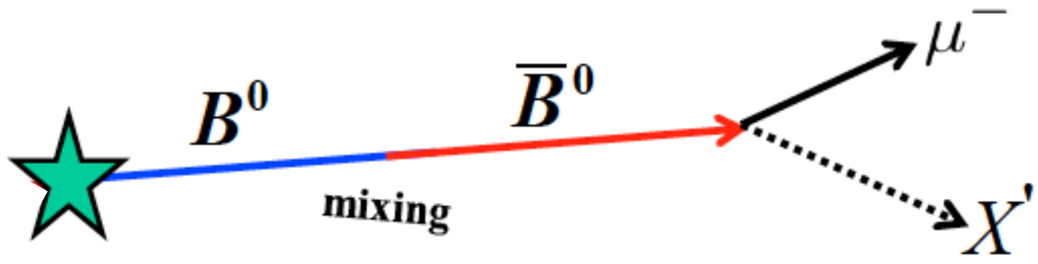
- The inclusive muon charge asymmetry can also be defined separately for specific flavors, $B^0_{(d)}$ and B^0_s, and related to the meson mixing parameters ΔM, ΔΓ, φ:

$$a^q_{sl} \equiv \frac{\Gamma(\overline{B}^0_q \to \mu^+ X) - \Gamma(B^0_q \to \mu^- X)}{\Gamma(\overline{B}^0_q \to \mu^+ X) + \Gamma(B^0_q \to \mu^- X)} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan(\varphi_q)$$

Inclusive Muon Charge Asymmetry

- Because any dimuon asymmetry arises from the meson mixing, A^b_{sl} is equal to the charge asymmetry a^b_{sl} of "wrong sign" (i.e. oscillated) semileptonic B decays:

No 'opposite side' muon requirement: more events, more background processes.



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- Both B^0_d and B^0_s are produced at the Tevatron, so both contribute to A^b_{sl}, yielding the SM prediction:

$$A^b_{sl} = (0.506 \pm 0.043) a^d_{sl} + (0.494 \pm 0.043) a^s_{sl} = (-0.023^{+0.005}_{-0.006})\ \%$$

(*) More B^0_d produced, but most decay before mixing.

SM prediction is negligible compared to current experimental precision
➔ any significant deviation from zero is an unambiguous signal of new physics.

Raw Asymmetries

- Experimentally two quantities are measured (simple event counting):

Inclusive muon charge asymmetry

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}$$

Like-sign dimuon charge asymmetry

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

Event Selection:

- Track-matched muon ($|\eta|<2.2$);
- **1.5 < pT < 25 GeV**;
- $p_T > 4.2$ GeV *or* $|p_z| > 6.4$ GeV;
- Distance to primary vertex **< 3mm (5mm)** in transverse (beam) direction.

- Both muons must pass inclusive muon selection;
- Same charge, same PV;
- **M(μμ) > 2.8** GeV to suppress events where muons are from same B decay.

a=(+0.688 ± 0.002 (stat.))%
(from 2.041 x 10^9 muons)

A=(+0.126 ± 0.041 (stat.))%
(from 6.019 x 10^6 muons)

What's the relationship to A^b_{sl}?

Extracting A^b_{sl}

- Both raw asymmetries depend linearly on A^b_{sl}:

$$a = kA^b_{sl} + a_{bkg}$$
$$A = KA^b_{sl} + A_{bkg}$$

(recall that $A^b_{sl} = a^b_{sl}$)

- The coefficients K and k are small (<1) due to the effect of charge symmetric background processes diluting the semileptonic asymmetry.

  Decays contributing to the dilution (assumed to conserve CP!):
  - $b \rightarrow \mu^- + X$ (including possible oscillations)
  - $b \rightarrow c \rightarrow \mu^+ + X$ (including possible oscillations)
  - $b \rightarrow c\bar{c}q$
  - $c\bar{c}$ and $b\bar{b}c\bar{c}$ production
  - η, ω, ρ_0, $\varphi(1020)$, J/ψ, ψ' decaying to $\mu^+\mu^-$

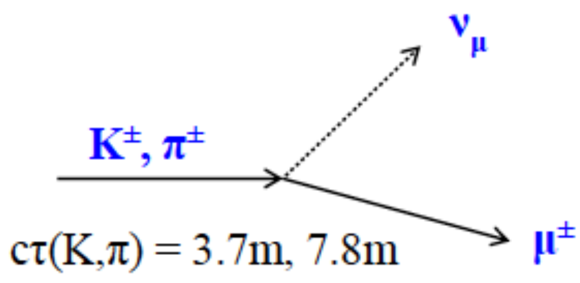
    ➔ known to very good precision (see PDG); estimated from the simulation

$k = 0.061 \pm 0.007$ << $K = 0.474 \pm 0.032$

(many more non-oscillating b- and c-quark decays contributing to inclusive asymmetry)

Detector Asymmetries: A_{bkg}, a_{bkg}

$$a = kA^{b}_{sl} + a_{bkg}$$
$$A = KA^{b}_{sl} + A_{bkg}$$



- A_{bkg} and a_{bkg} are detector-related background contributions to the measured asymmetry.
- These terms include asymmetric contributions from:
  - Decays $K^\pm \to \mu^\pm \nu$, $\pi^\pm \to \mu^\pm \nu$
  - Hadronic punch-through to the muon detector
  - Muon reconstruction efficiency, asymmetries in tracks wrongly associated with muons.

➔ measured directly in data, with reduced input from the simulation

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

kaon fraction asymmetry

pion

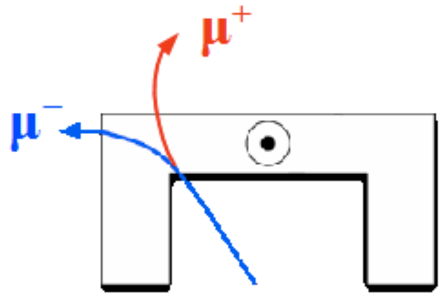
Proton (+ 'fakes')

Muon reconstruction asymmetry

Reversal of Magnet Polarities

- A major limitation for this measurement can be any charge asymmetries induced by the detector and/or the reconstruction.

  Example: for a given magnet polarity, there is a charge asymmetry from muons bending out of the muon detector acceptance.



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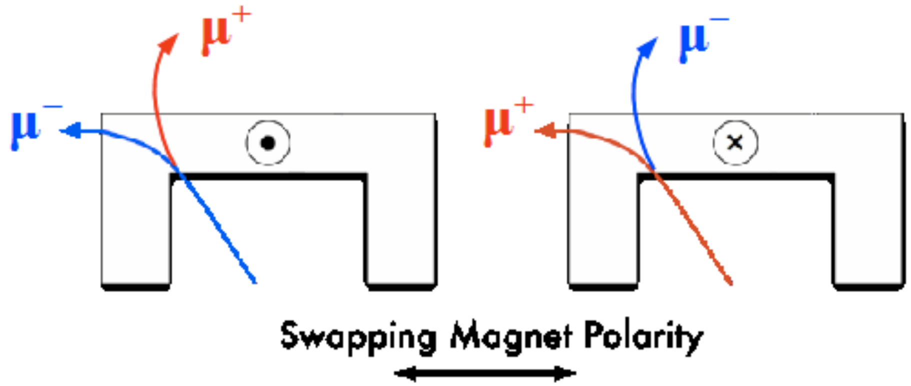


- Important observation: the trajectory of a negative particle in a given magnet polarity is exactly the same as the trajectory of the positive particle with the magnet polarity reversed.

- The D0 detector regularly changed the polarities of the solenoid/toroid, resulting in four different configurations (++, --, +-, -+) with approximately the same integrated luminosity.

  ➔ overall difference in the reconstruction efficiency between positive and negative particles is minimized.

Example: Asymmetry from Kaons

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

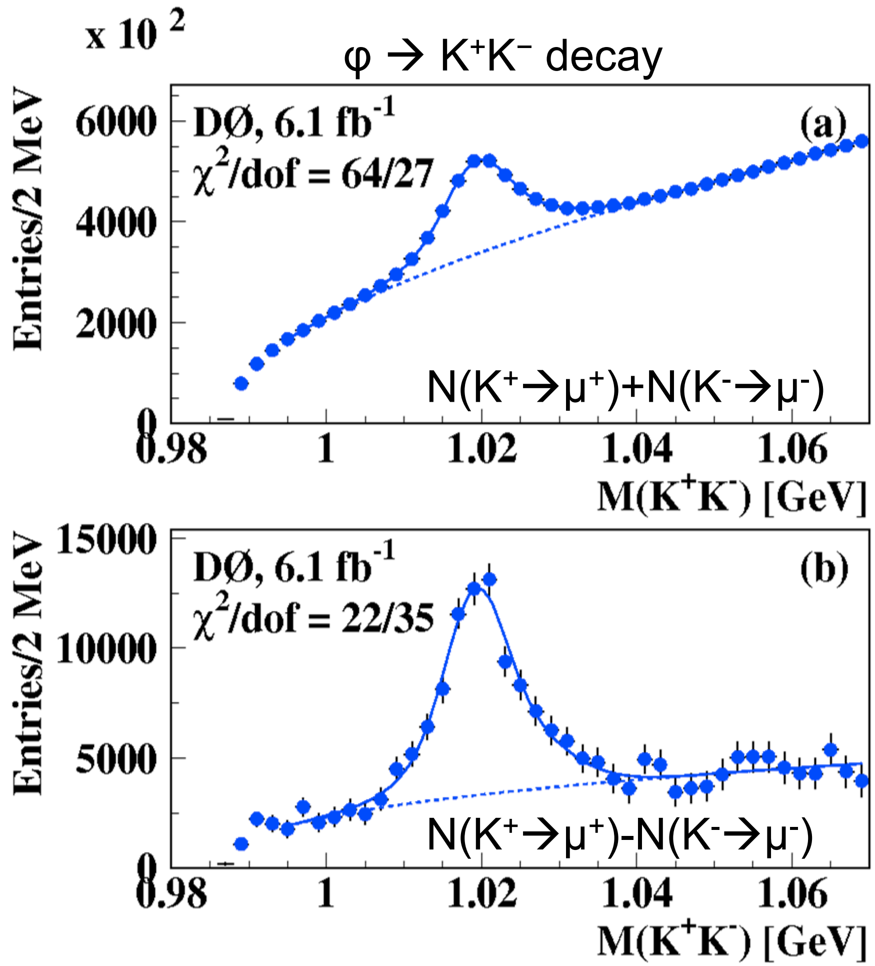
- To determine a_{bkg} and A_{bkg}, need to know 7 parameters (3 fractions and 4 asymmetries) for each.

  ➔ Measured in data in bins of muon p_T

- Example: Kaon asymmetry measured using $\varphi \to K^+K^-$ and $K^{*0} \to K^+\pi^-$.

$$a_k = \frac{N(K^+ \to \mu^+) - N(K^- \to \mu^-)}{N(K^+ \to \mu^+) + N(K^- \to \mu^-)} \approx 6\%!!$$

a_k is positive because "antimatter" kaons (K^-) are more likely to interact with matter in the detector, so have less chance of decaying to muons before interaction.



Summary of Background Contributions

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

Source	inclusive muon	like-sign dimuon
$(f_K a_K$ or $F_K A_K) \times 10^2$	$+0.776 \pm 0.021$	$+0.633 \pm 0.031$
$(f_\pi a_\pi$ or $F_\pi A_\pi) \times 10^2$	$+0.007 \pm 0.027$	-0.002 ± 0.023
$(f_p a_p$ or $F_p A_p) \times 10^2$	-0.014 ± 0.022	-0.016 ± 0.019
$[(1 - f_{\text{bkg}})\delta$ or $(2 - F_{\text{bkg}})\Delta] \times 10^2$	-0.047 ± 0.012	-0.212 ± 0.030
$(a_{\text{bkg}}$ or $A_{\text{bkg}}) \times 10^2$	$+0.722 \pm 0.042$	$+0.402 \pm 0.053$
$(a$ or $A) \times 10^2$	$+0.688 \pm 0.002$	$+0.126 \pm 0.041$
$[(a - a_{\text{bkg}})$ or $(A - A_{\text{bkg}})] \times 10^2$	-0.034 ± 0.042	-0.276 ± 0.067

- Quoted uncertainties are statistical only.
- Dominant asymmetry is from kaons, as expected.
- Comparing asymmetries in inclusive muon and dimuon samples:
  - Background contribution comparable: $a_{bkg} \approx A_{bkg}$
  - Background-subtracted asymmetry: $a\text{-}a_{bkg} \approx 0$ whereas $A\text{-}A_{bkg} \neq 0$

Results

- A^b_{sl} extracted separately from both inclusive muon (a) and dimuon (A) samples:

From a: A^b_{sl}= [-1.04 ± 1.30 (stat.) ± 2.31 (syst.)] %
From A: A^b_{sl}= [-0.81 ± 0.20 (stat.) ± 0.22 (syst.)] %

Limited by systematics

- **Here is the clever part**: the background asymmetries (a_{bkg} and A_{bkg}) are strongly correlated (same sources), so can construct a linear combination such that the total uncertainties are minimized:

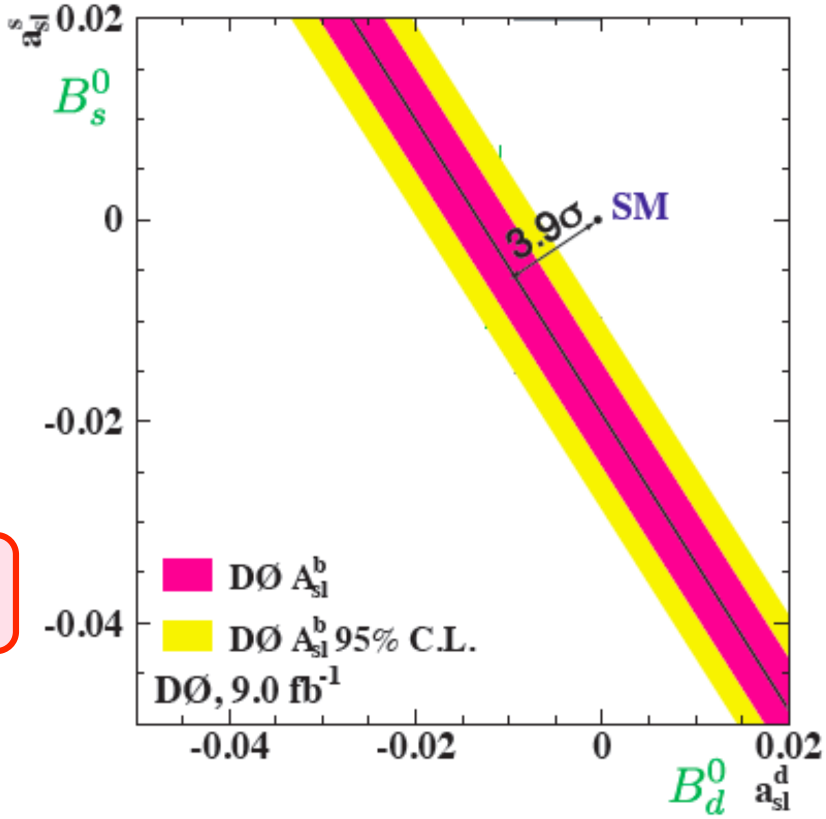
$$A' \equiv A - \alpha \cdot a = (K - \alpha \cdot k)A^b_{sl} + (A_{bkg} - \alpha \cdot a_{bkg})$$

(optimal α=0.89)

- Final result:

A^b_{sl}= [-0.787 ± 0.172 (stat.) ± 0.093 (syst.)] %

Differs from the SM prediction by 3.9σ
Pointing to a new source of CP violation?

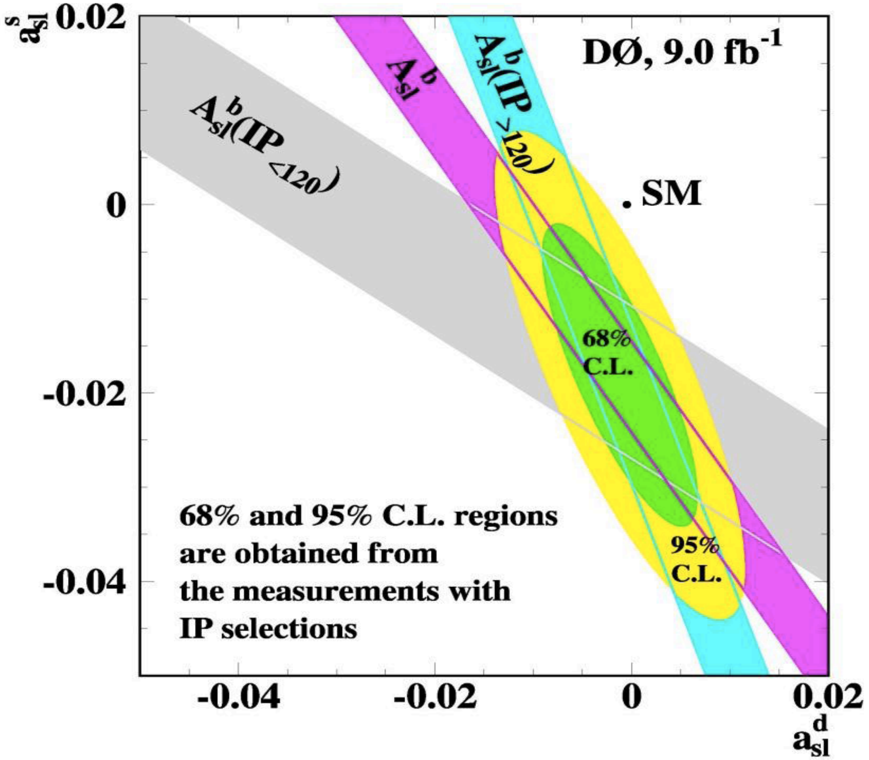


Results: Dependence on Impact Parameter

- By dividing into two samples based on muon impact parameter, IP(μ), can:

  1) confirm stable result in background-enhanced and suppressed samples.

  2) test for larger asymmetry from B^0_d or B^0_s

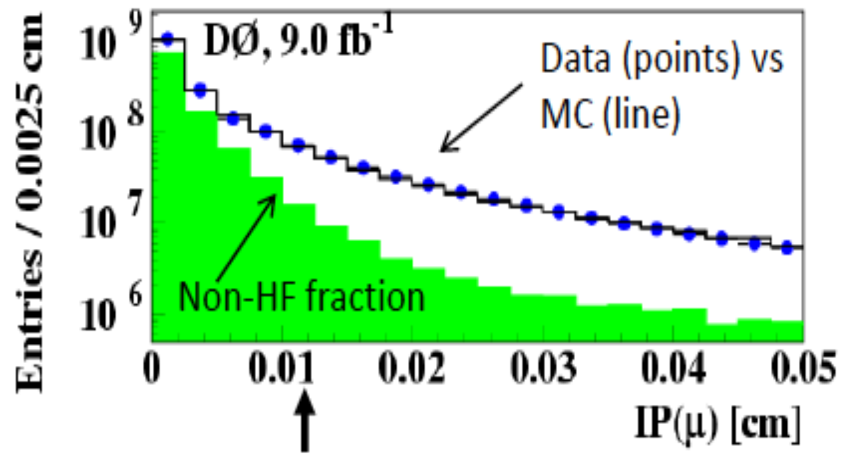


$a^d_{sl} = (-0.12 \pm 0.52)\%$

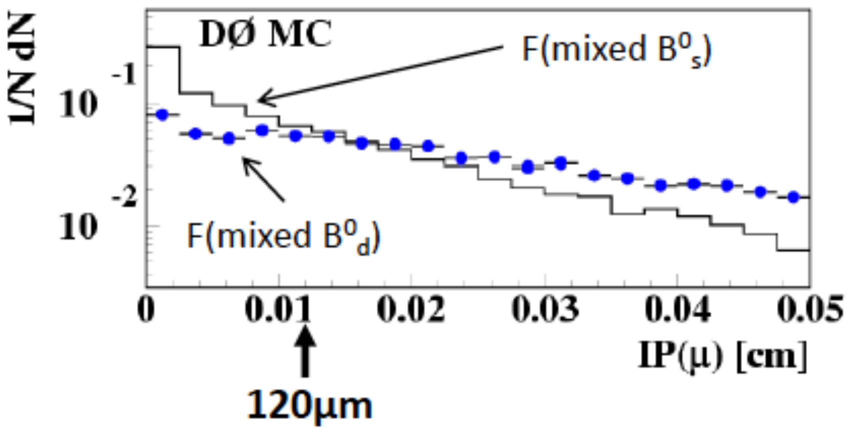
$a^s_{sl} = (-1.81 \pm 1.06)\%$

correlation $\rho_{ds} = -0.799$

Heavy flavor fraction



Fraction of \`oscillated' B^0_q mesons

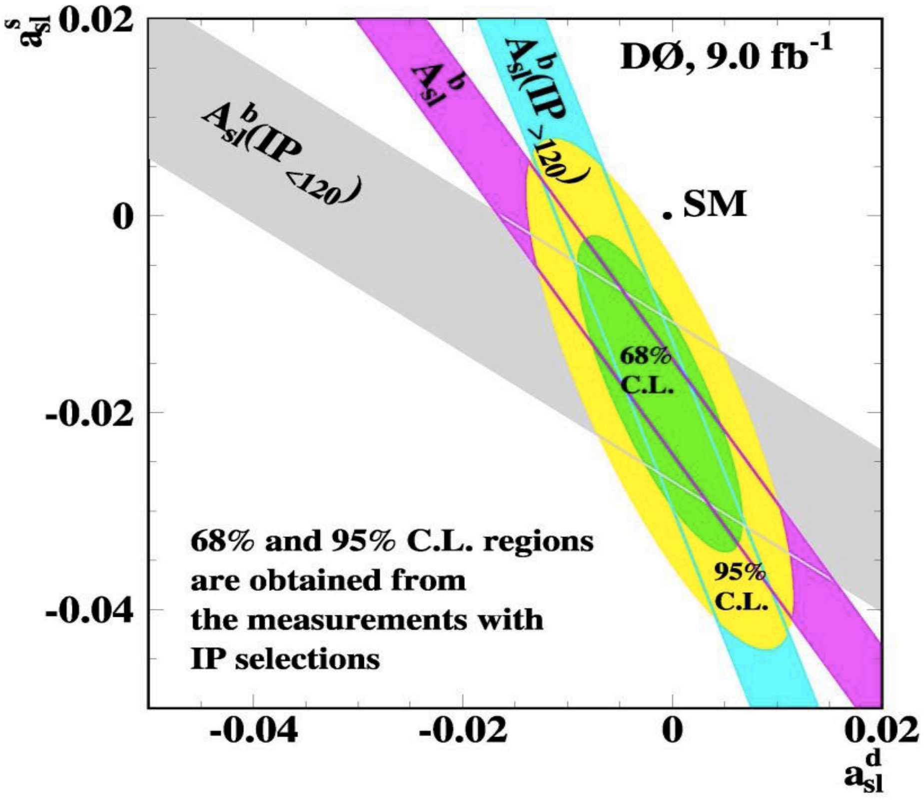


IP(μ) < 120 μm: $A^b_{sl} \approx 0.40\, a^d_{sl} + 0.60\, a^s_{sl}$

IP(μ) > 120 μm: $A^b_{sl} \approx 0.73\, a^d_{sl} + 0.27\, a^s_{sl}$

Summary and Prospects

- Dimuon charge asymmetry offers a tantalizing possibility for New Physics in B meson mixing and/or semileptonic decays:
  - Current measurement inconsistent with the SM at the 3.9σ level.
  - D0 planning to update it in the near future with more use of IP information.
  - Need independent confirmation by other measurements!



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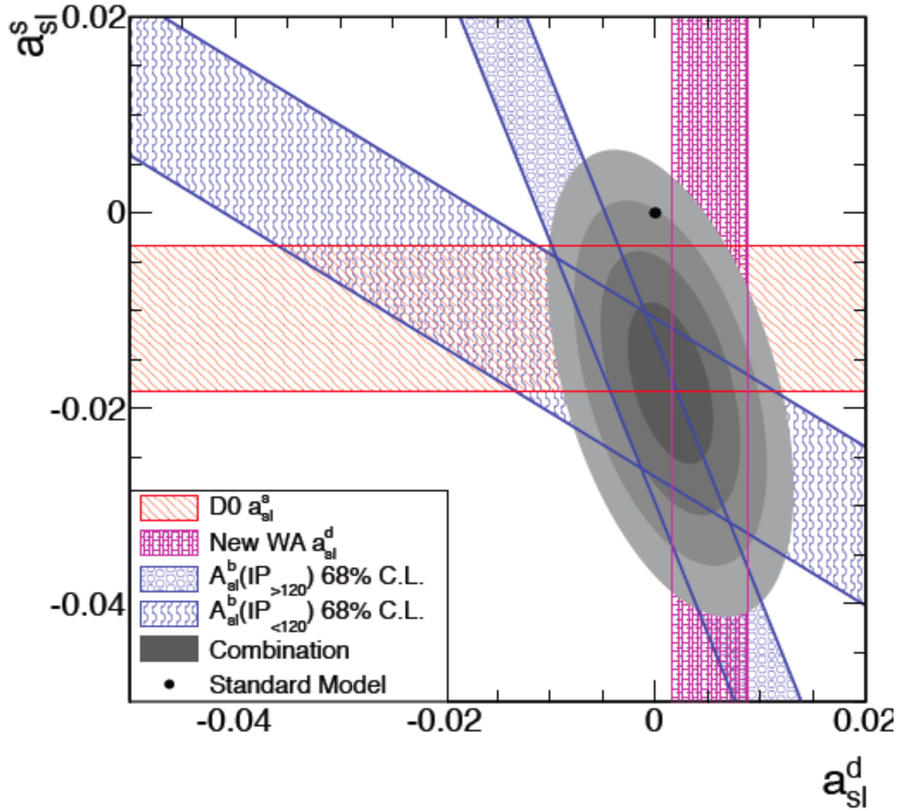
- Compare to measurements of flavor-specific semileptonic charge asymmetries:
  - a^d_{sl}: B-factories, D0
  - a^s_{sl}: D0

➔ All measurements found in agreement



$$a^s_{sl} = (-1.74 \pm 0.54)\,\%$$
$$a^d_{sl} = (0.14 \pm 0.27)\,\%$$
$$\rho = -0.46$$

2.94σ deviation from SM

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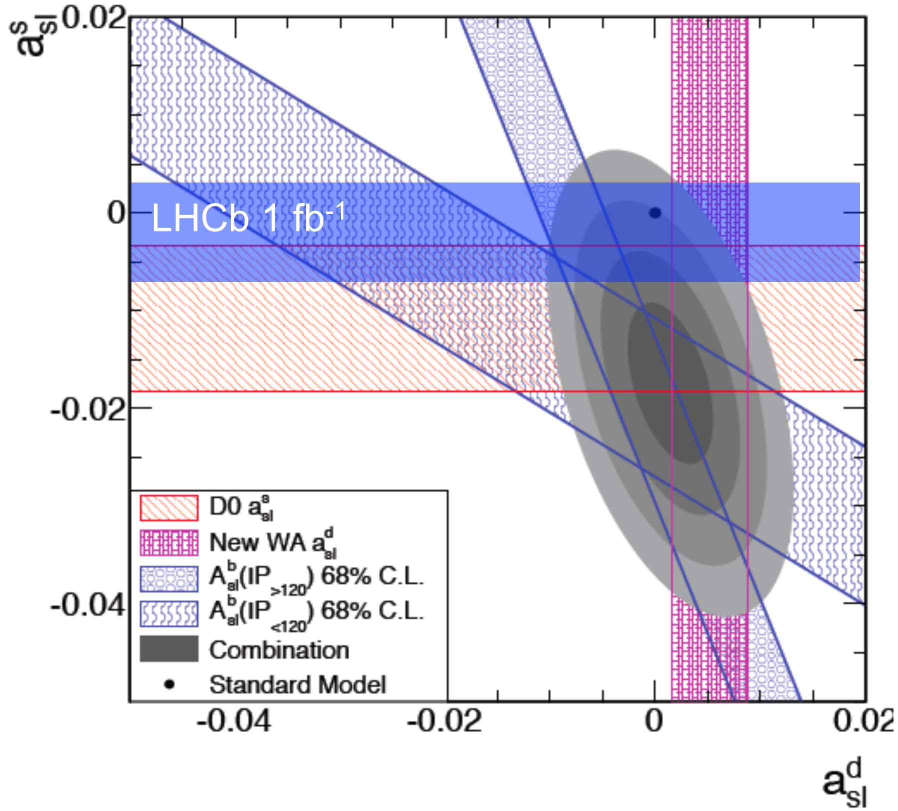
However, recent LHCb measurement of a^s_{sl} in agreement with SM:

$$a^s_{sl} = (-0.24 \pm 0.54 \pm 0.33)\%$$

End of story?



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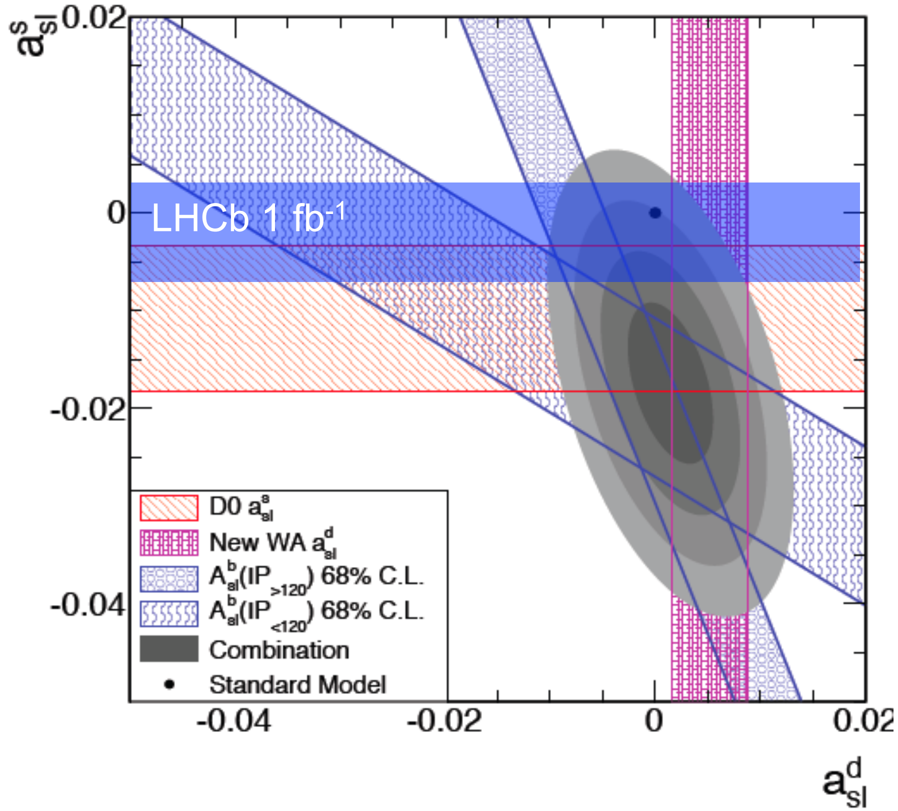
  However, recent LHCb measurement of a^s_{sl} in agreement with SM:

$$a^s_{sl} = (-0.24 \pm 0.54 \pm 0.33)\%$$

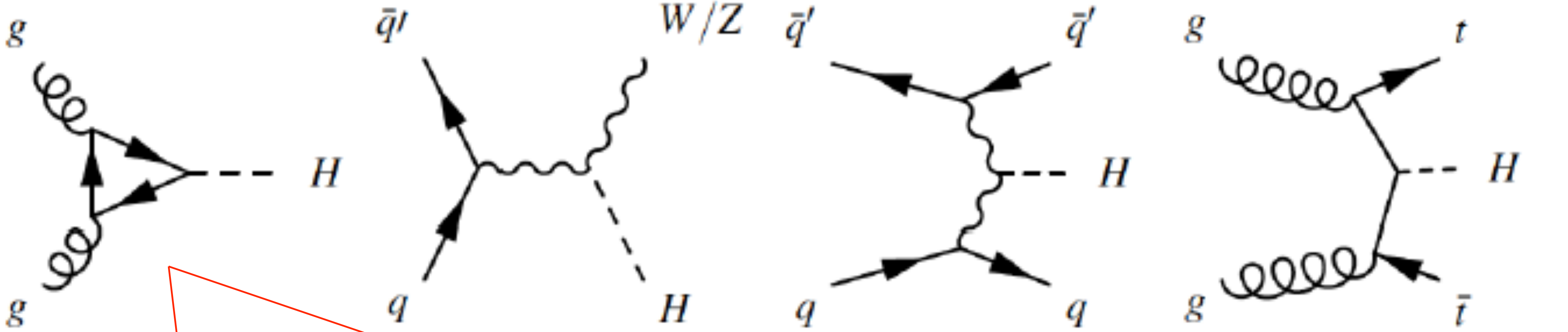
End of story? **NO!**



- Some tension but still consistent.
- Further improved measurements expected from LHCb, Belle ϒ(5S).
- All measurements can be reconciled in there is O(0.3-1%) mixing in direct b and/or c decays. *arXiv:1207.4483*

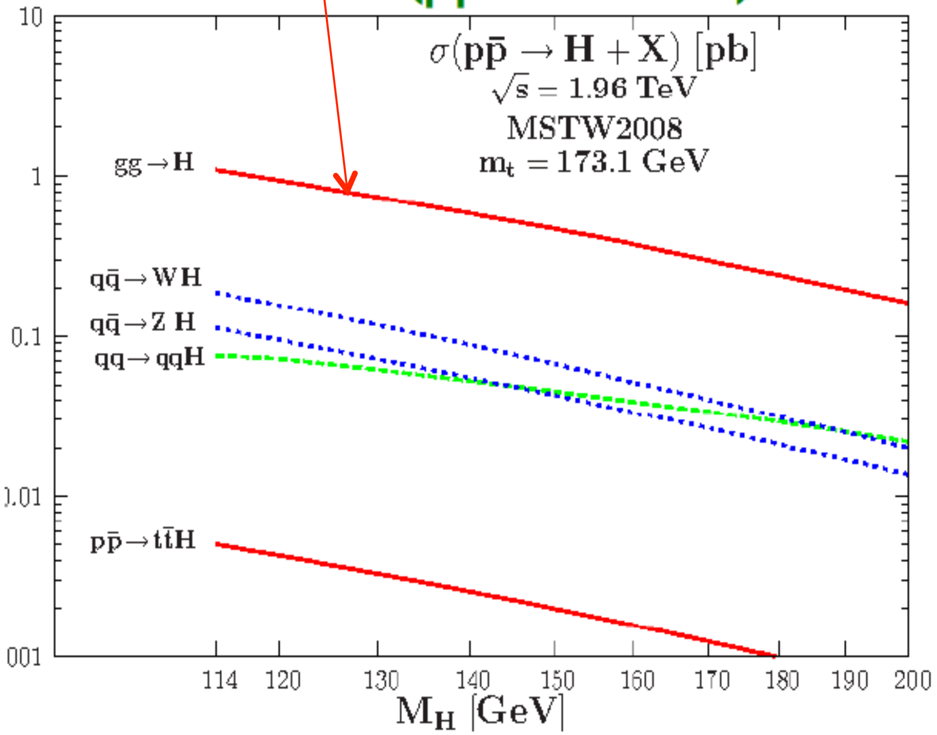
Searches for the SM Higgs Boson

SM Higgs Production at Hadron Colliders

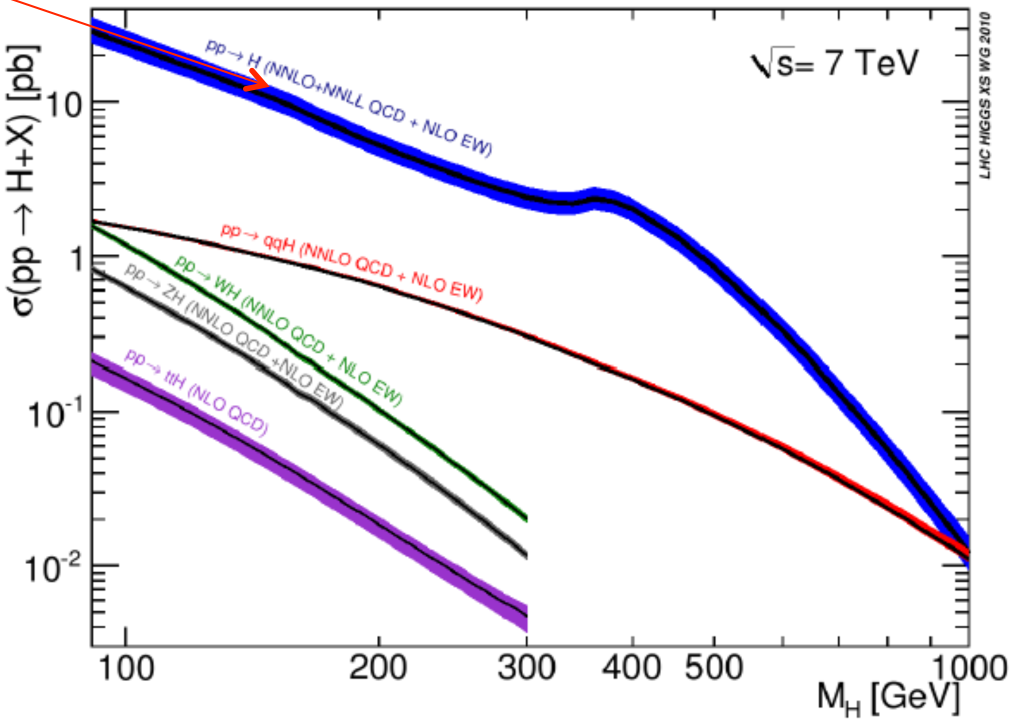


Main production mechanism

Tevatron ($p\bar{p}$ @ 1.96 TeV)



LHC (pp @ 7 TeV)



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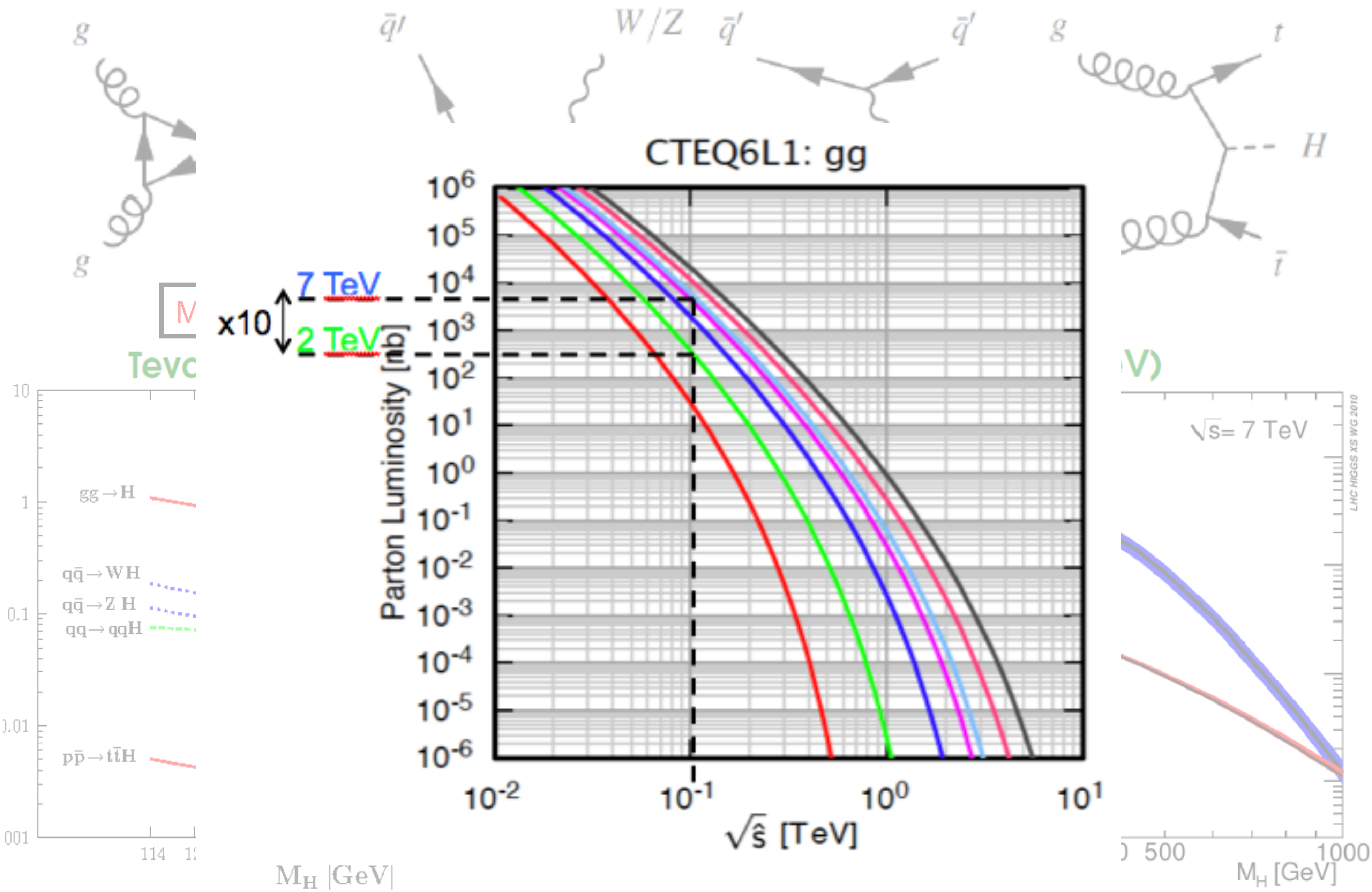

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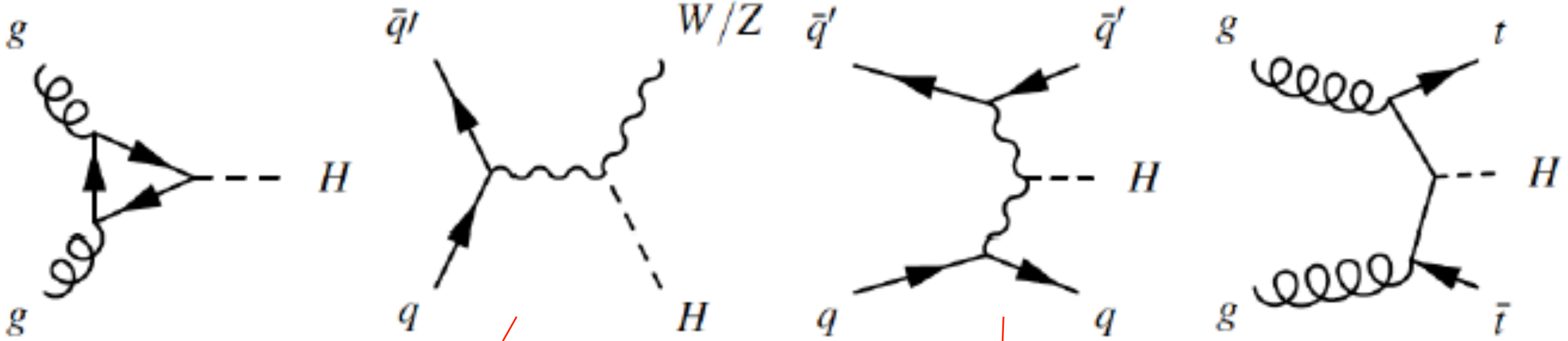
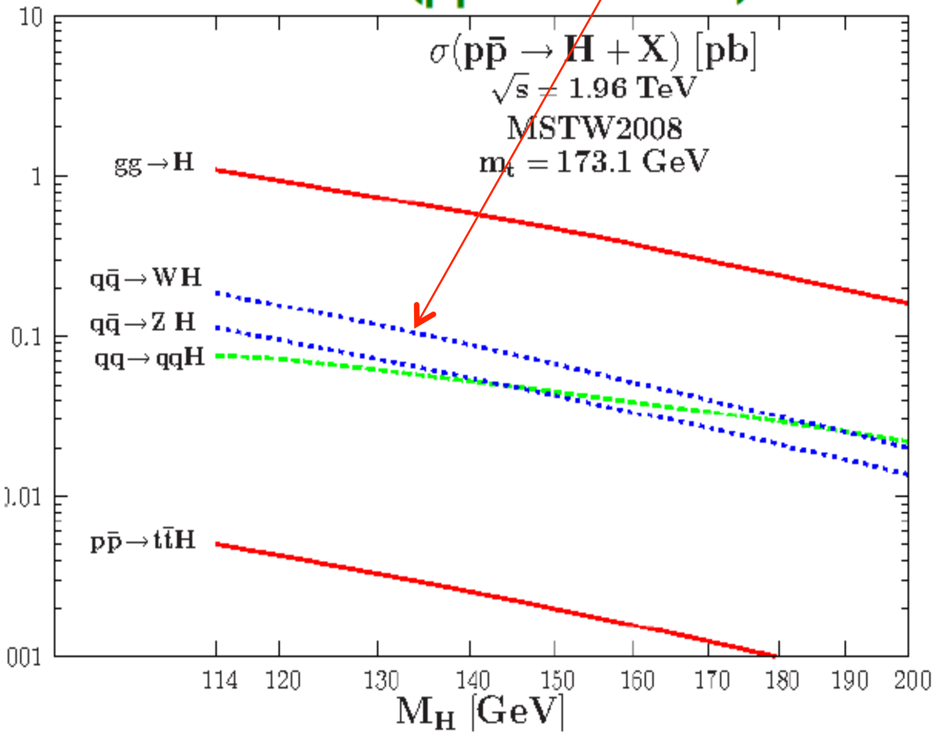
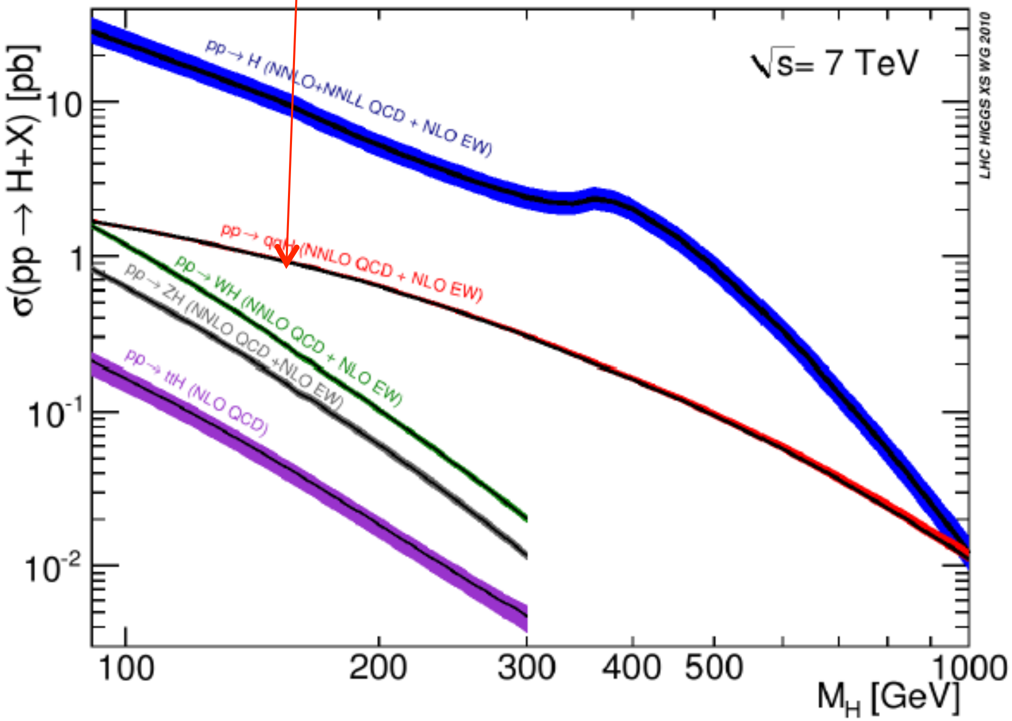


Next most important production mechanism

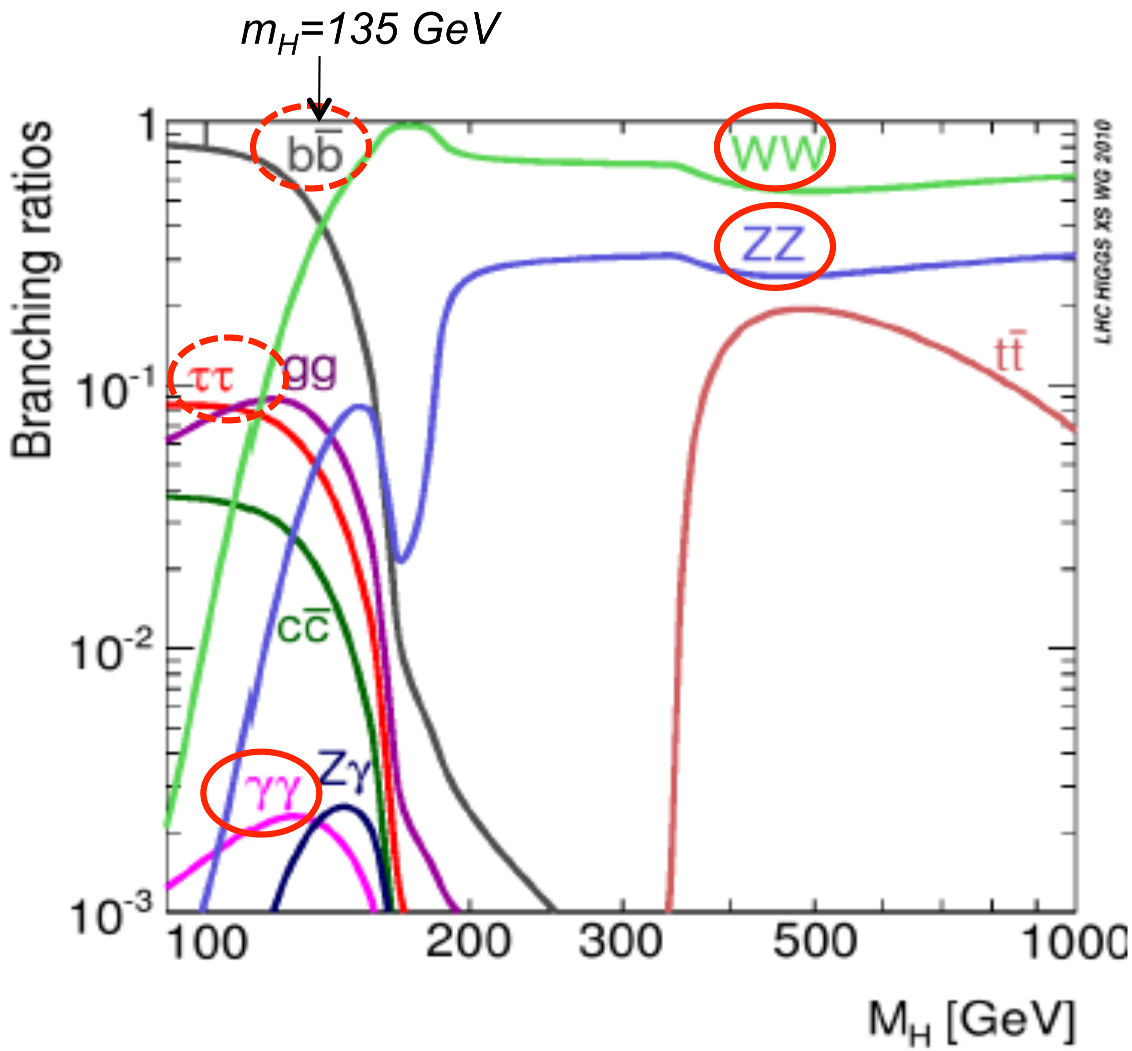
Tevatron (pp̄ @ 1.96 TeV)



LHC (pp @ 7 TeV)



SM Higgs Decay Modes



m_H<135 GeV: H→bb dominates

m_H>135 GeV: H→WW dominates

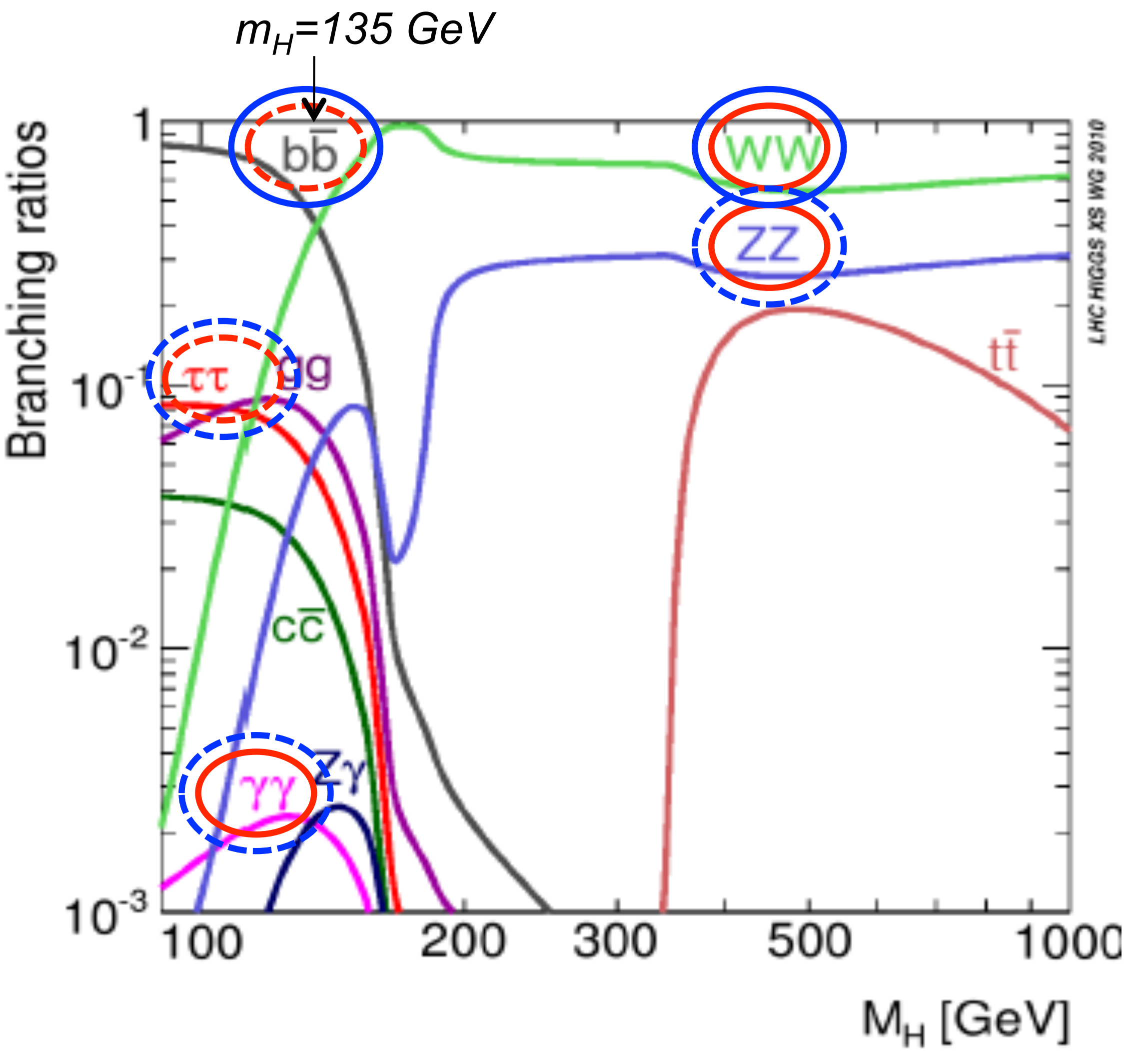
Main mode

Supporting mode

LHC

➔ Many decay modes being explored to increase the sensitivity of the search to the SM Higgs boson, but also to a non-SM one!

SM Higgs Decay Modes



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—— Main mode

- - - - Supporting mode

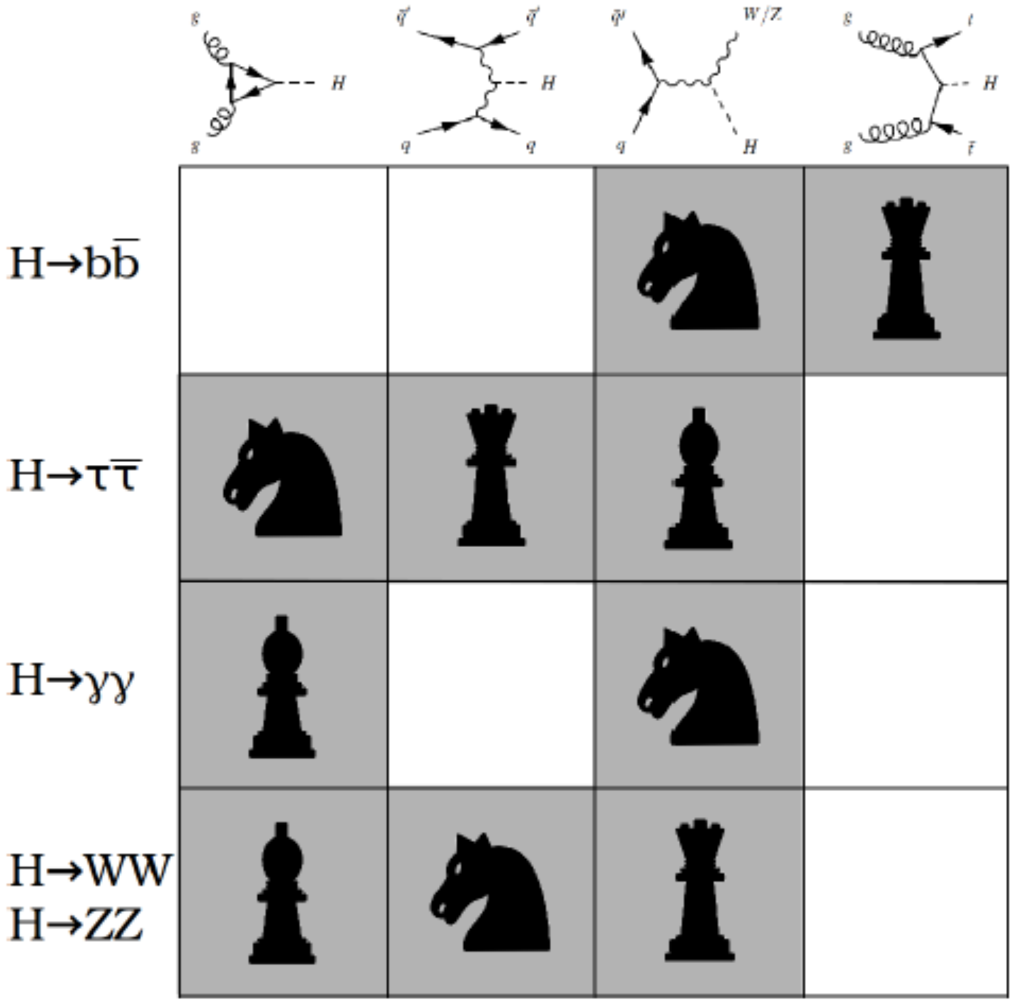
LHC

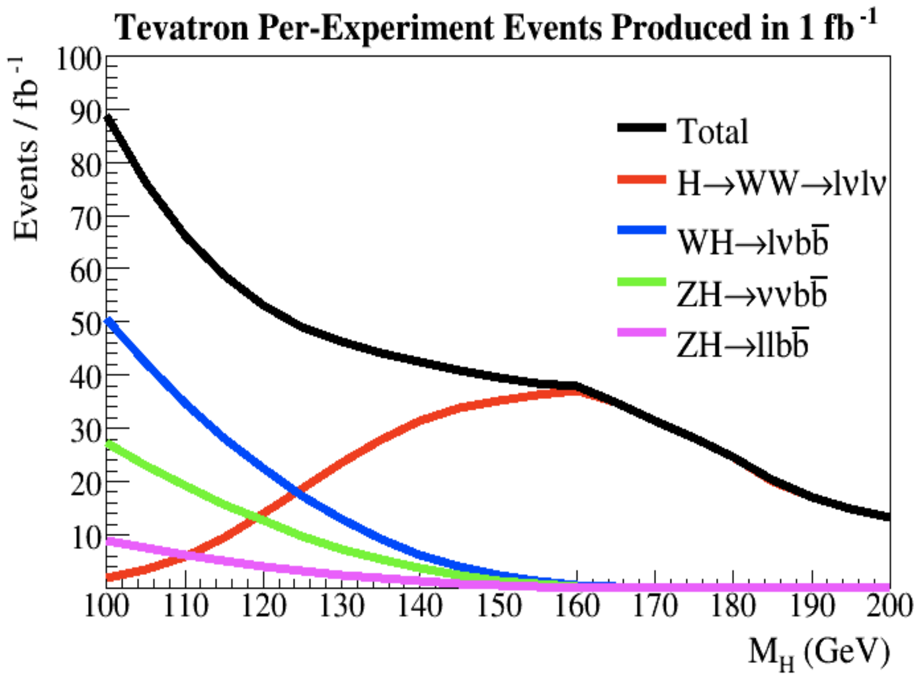
Tevatron

➔ Many decay modes being explored to increase the sensitivity of the search to the SM Higgs boson, but also to a non-SM one!

Search Strategies

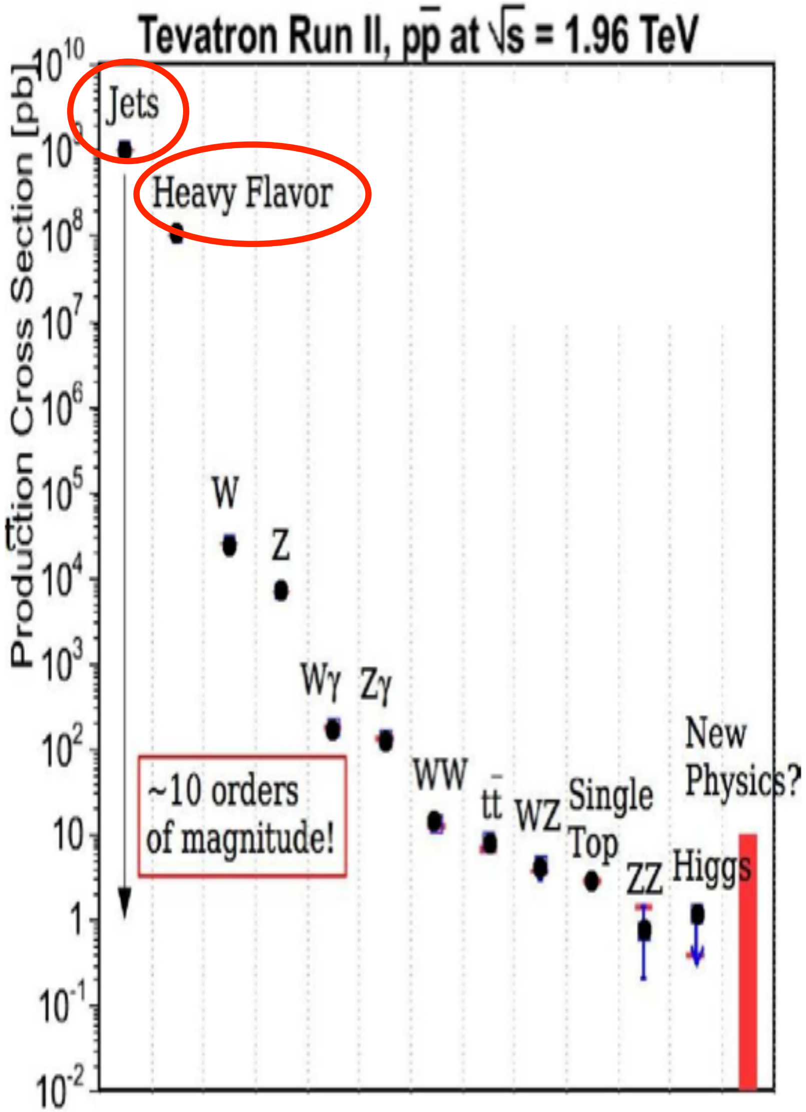
- Defined by a combination of theoretical and experimental considerations (large σxB but experimentally feasible: trigger, backgrounds….).



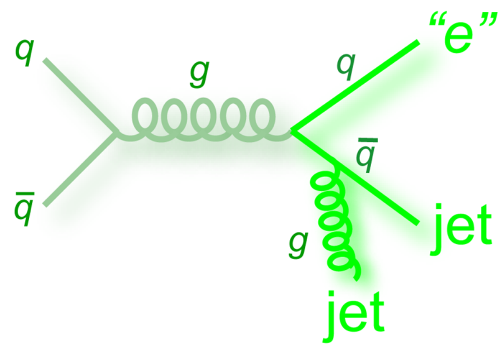


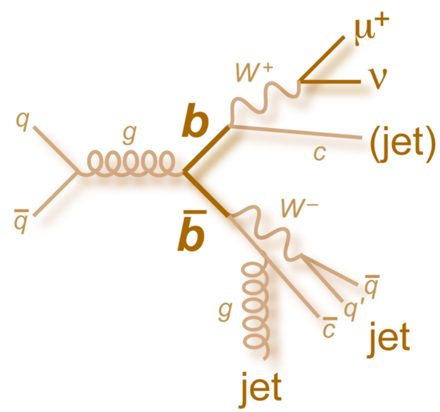
~600-1200 Higgs events produced at the Tevatron in the main search channels with 10 fb^{-1}!

Backgrounds are Ferocious



- Instrumental backgrounds: measured directly from data
  - QCD multijet production with mismeasured jets leadings to missing transverse energy or jets misidentified as leptons.





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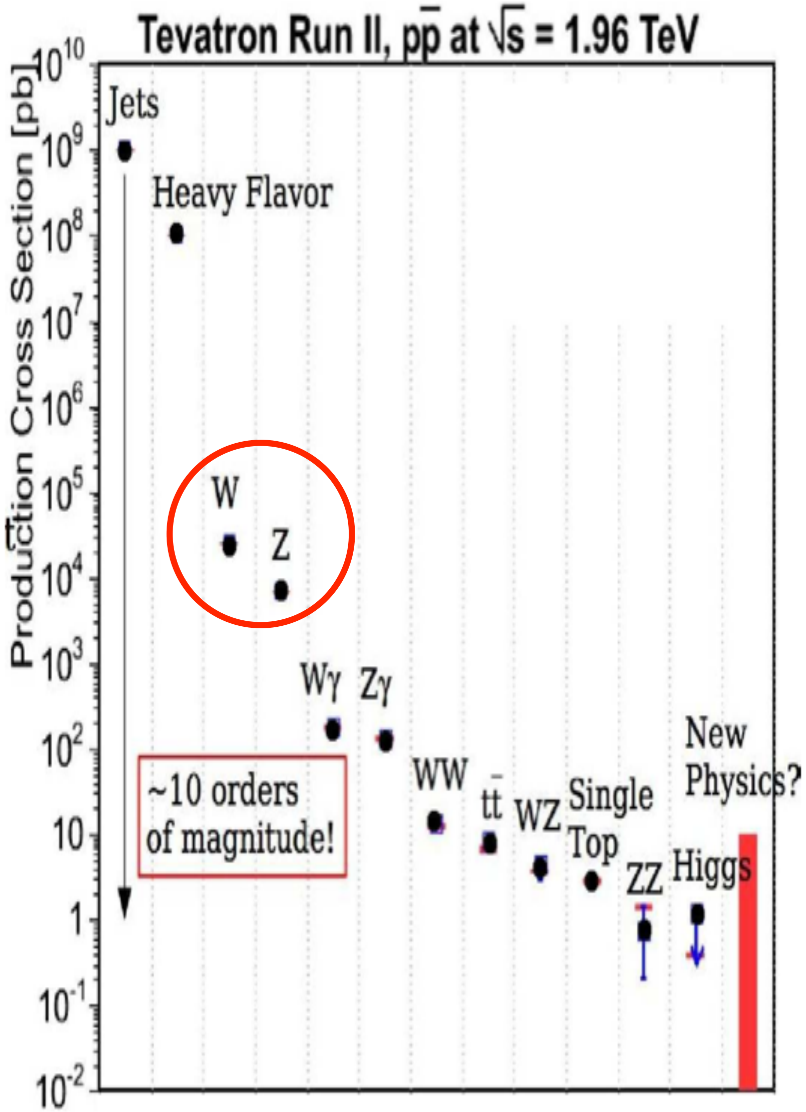

- Instrumental backgrounds: measured directly from data
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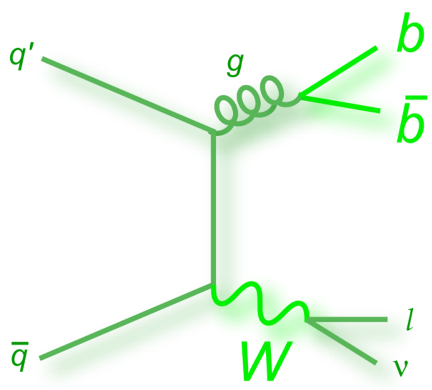
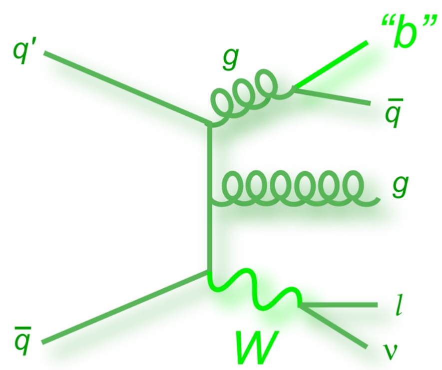
- Physics backgrounds: estimated using simulation and state-of-art theoretical predictions
  - W/Z+jets production (w/ real or misidentified heavy flavor jets)





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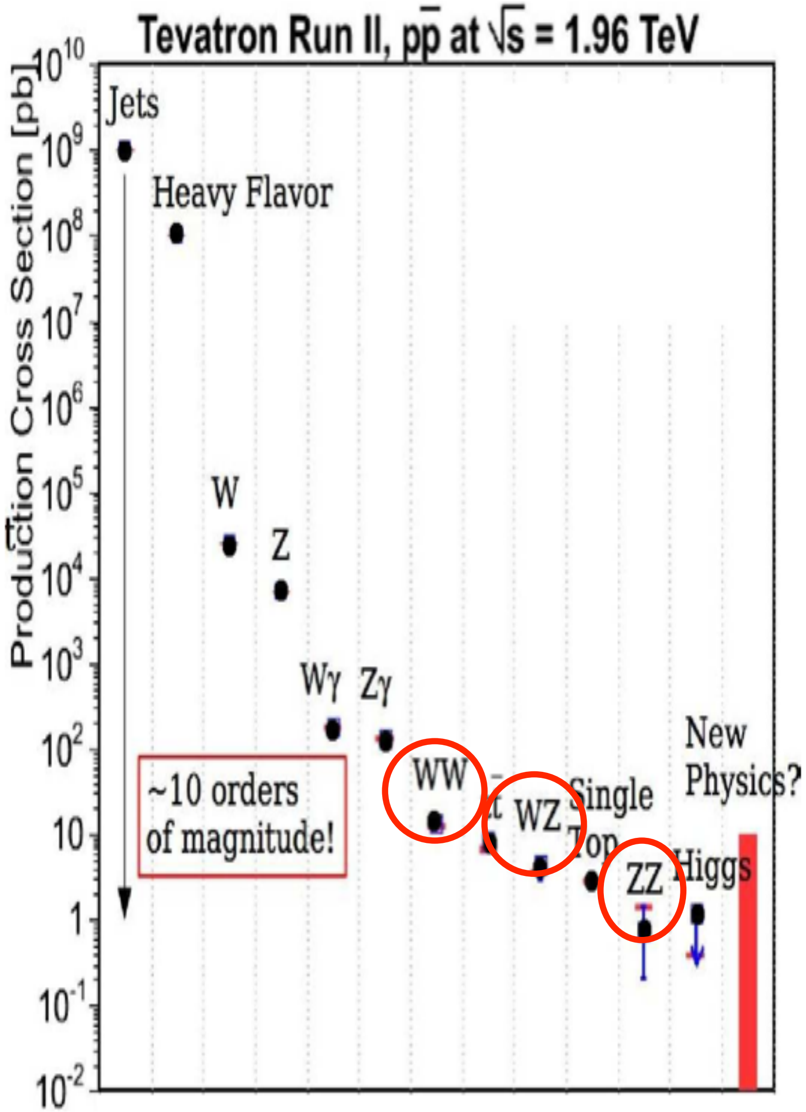

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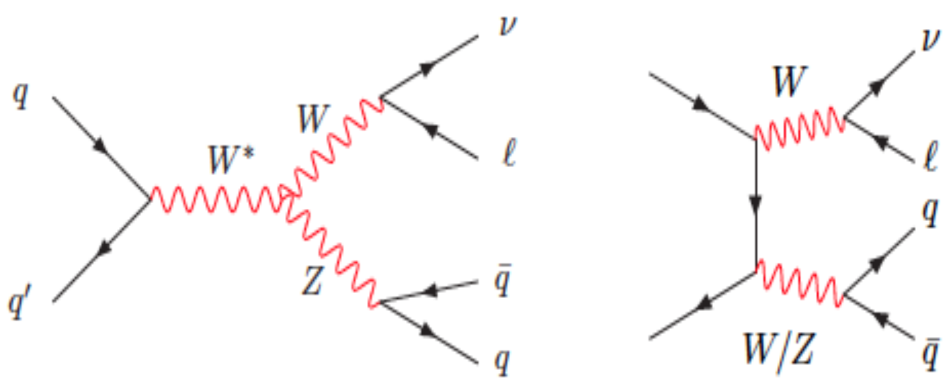
  - Diboson production



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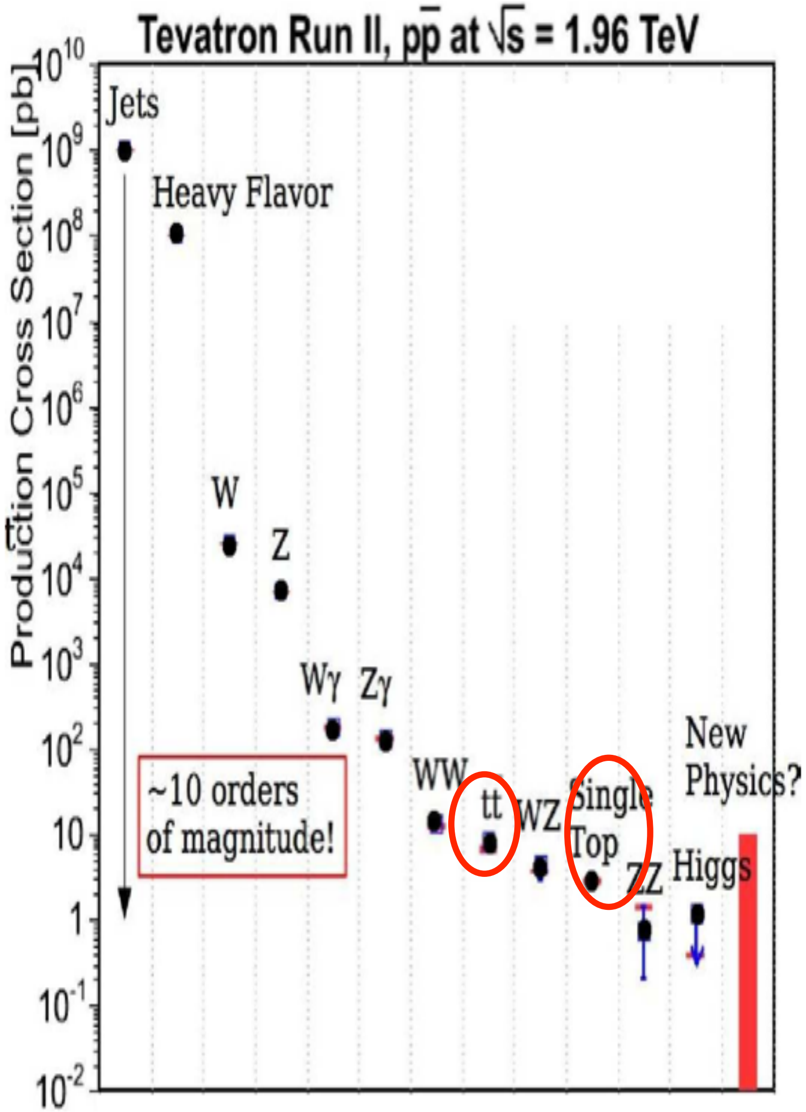

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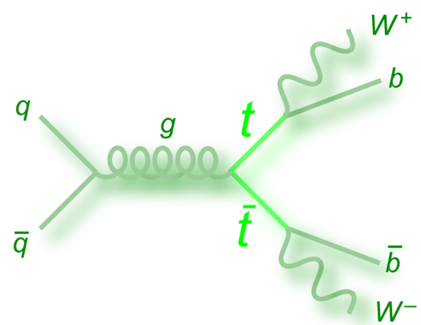
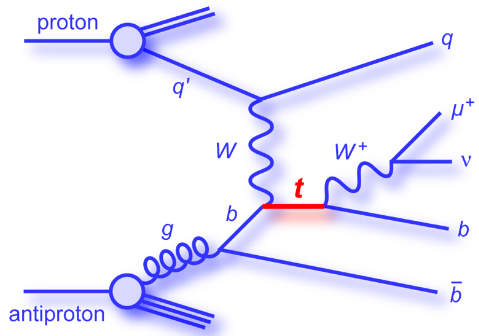
- Physics backgrounds: estimated using simulation and state-of-art theoretical predictions
  - W/Z+jets production (w/ real or misidentified heavy flavor jets)
  - Diboson production
  - Double and single top quark production

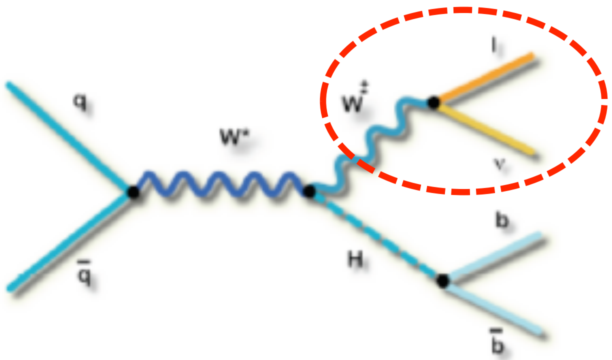


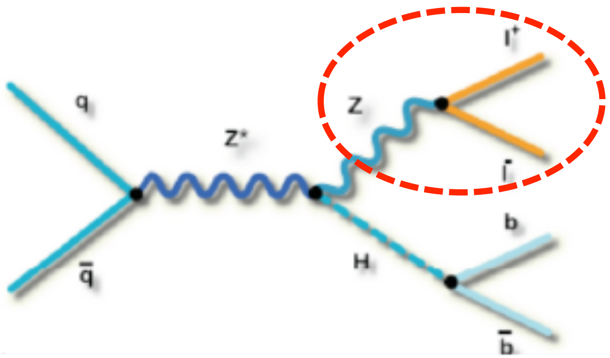


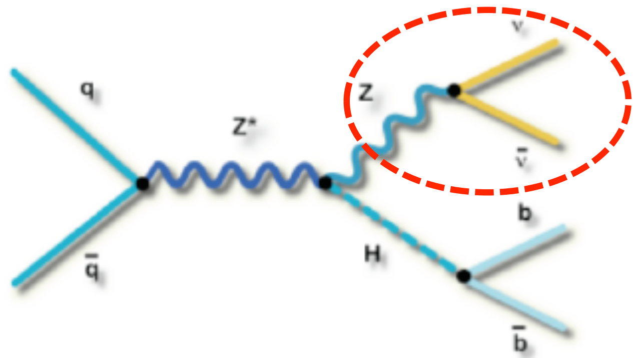
➔ Further constrain data modeling in "sideband regions"

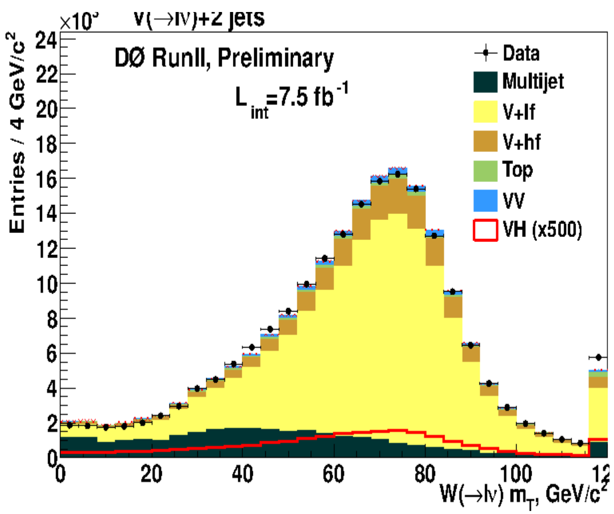
Searching for H→bb

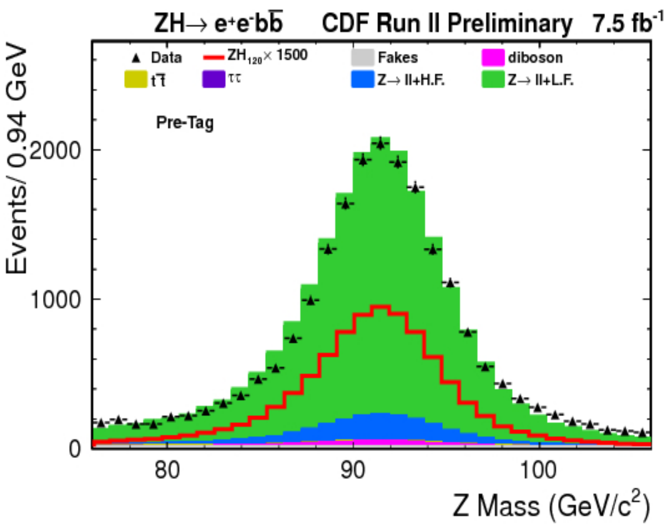
- Highest sensitivity channel at the Tevatron for m_H<130 GeV.
- Identify events consistent with leptonic W/Z decays in association with jets
  - Trigger on high p_T electrons, muons or missing transverse energy ($\not{E}_T$)
  - W→lν: e or μ and high $\not{E}_T$
  - Z→ll: ee or μμ consistent with Z resonance
  - Z→νν: no charged leptons; two acoplanar jets and $\not{E}_T$

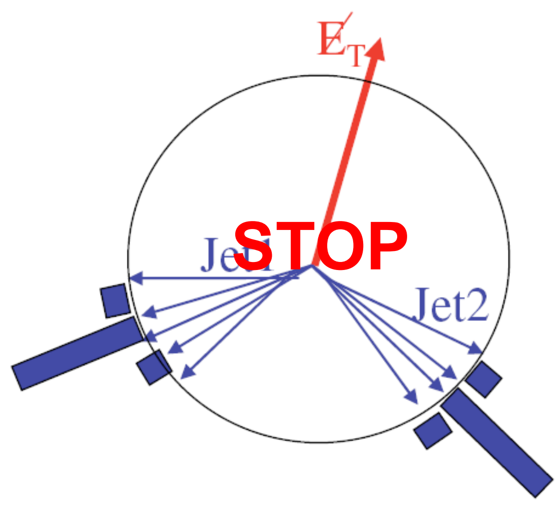






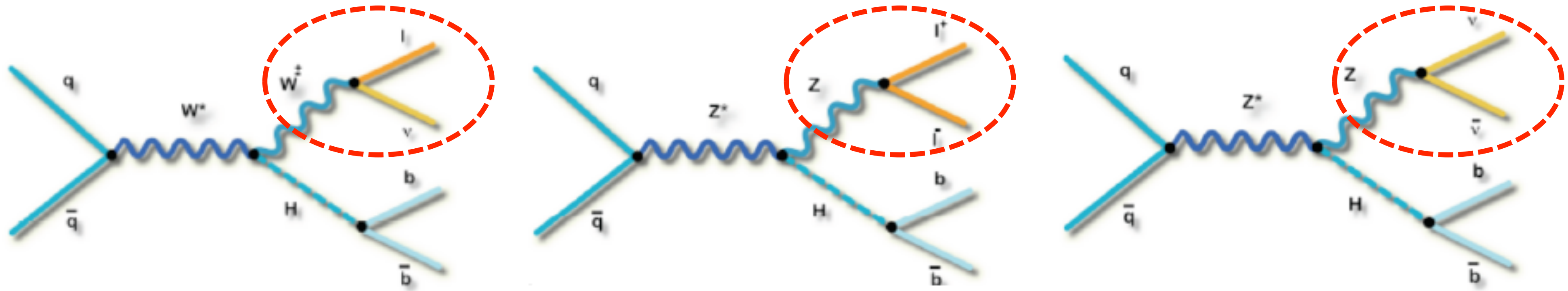


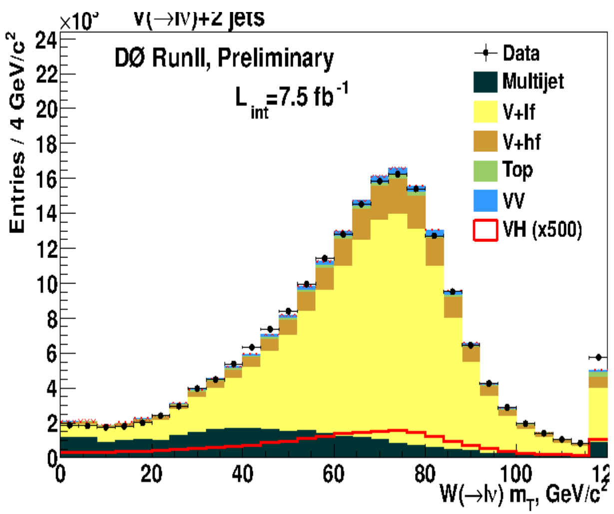


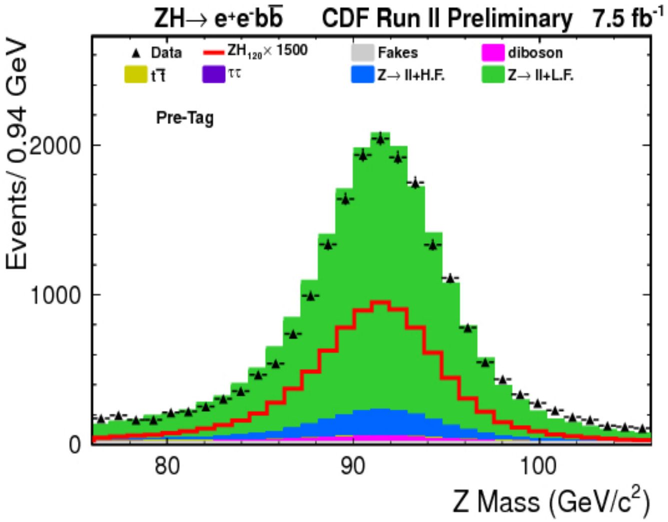


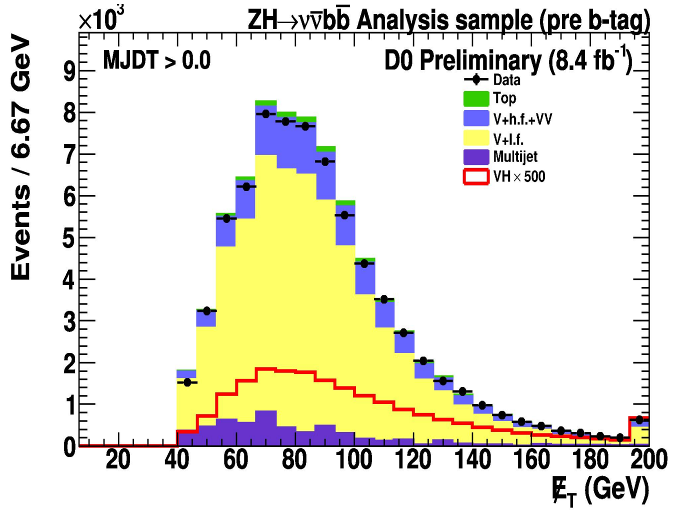
Searching for H→bb

- Highest sensitivity channel at the Tevatron for m_H<130 GeV.
- Identify events consistent with leptonic W/Z decays in association with jets
  - Trigger on high p_T electrons, muons or missing transverse energy ($\not\!\!E_T$)
  - W→lν: e or μ and high $\not\!\!E_T$
  - Z→ll: ee or μμ consistent with Z resonance
  - Z→νν: no charged leptons; two acoplanar jets and $\not\!\!E_T$









Heavy Flavor Identification

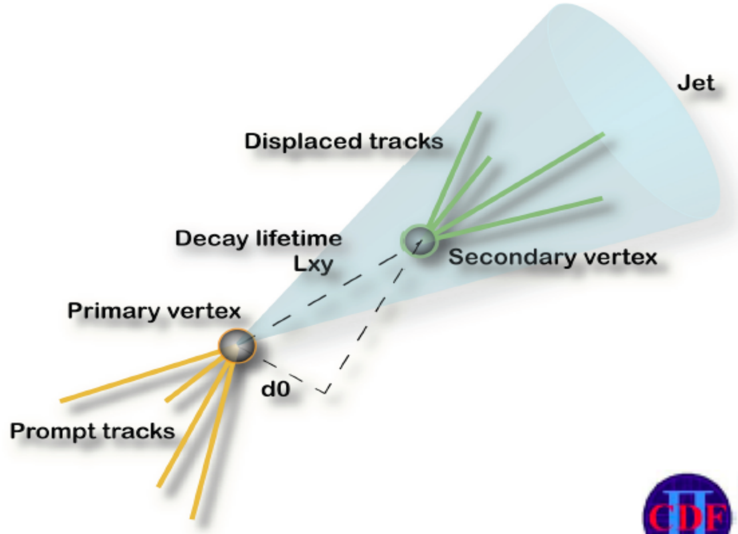
- Critical for searches involving H→bb.
- B-tagging exploits information on:
  - Lifetime: displaced tracks and/or vertices
  - Mass: secondary vertex mass

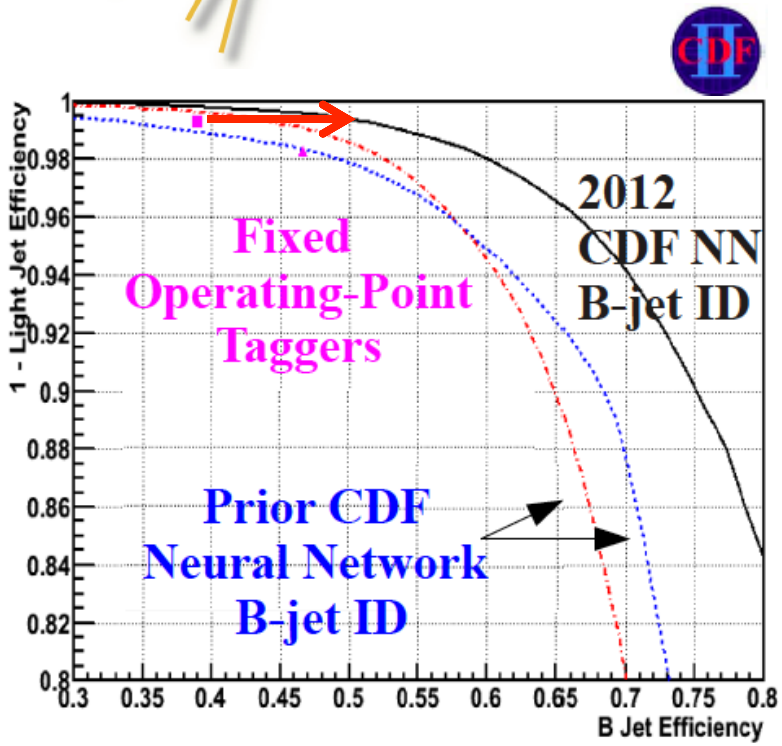
- Both experiments use multivariate techniques for improved performance:
  - b-to-light discrimination: continuous tagger (multiple operating points)
  - b-to-c discrimination

- Typical performance:
  - B-tagging efficiency: ~50-80%
  - Mistag rate: ~0.5-10%
  - Calibrated in data control samples.

- Winter 2012: major progress at CDF by using new NN b-tagger.
  E.g. ε_b~39%→54% @ 1.4% fake rate

38% increase in per-jet b-tagging efficiency!





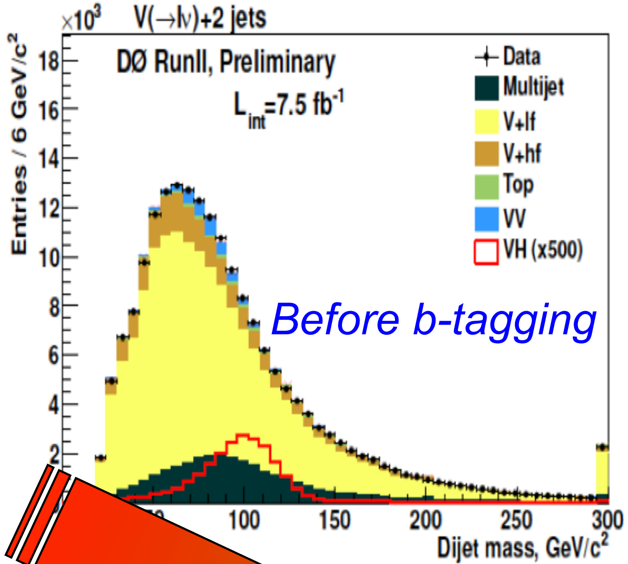
Searching for H→bb: After B-Tagging

B-tagging brings significant improvement to S:B

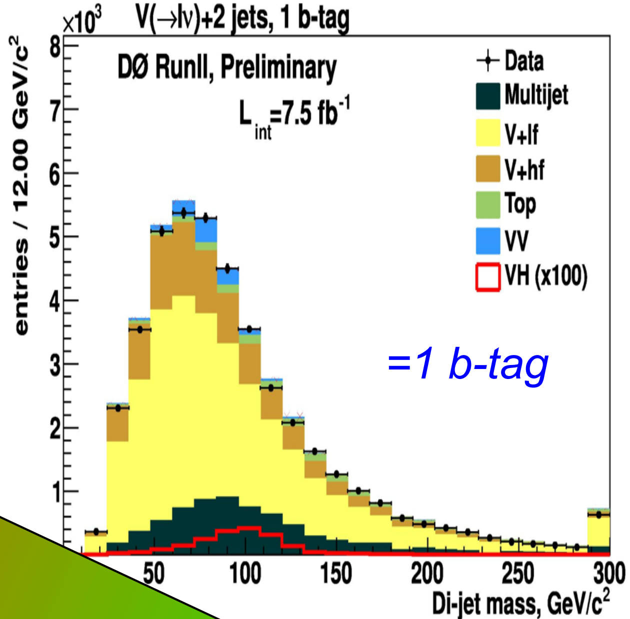
WH→lνbb

Dijet invariant mass

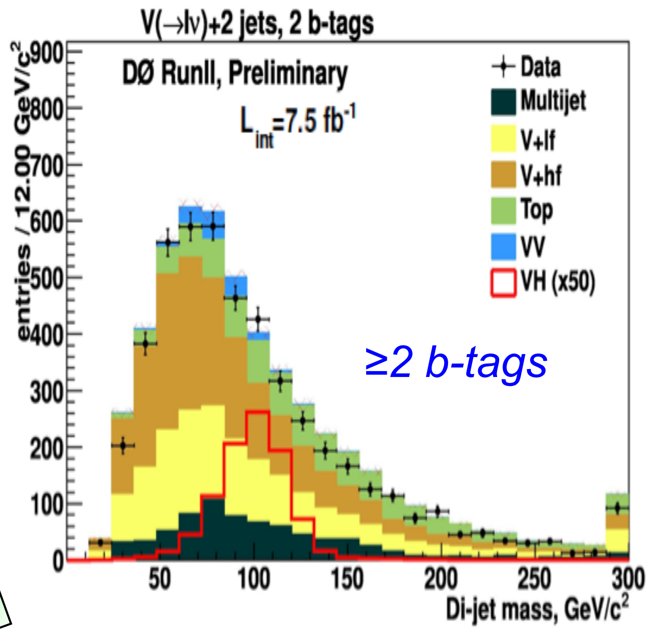
➔ single most discriminant variable



S:B ~ 1:4000

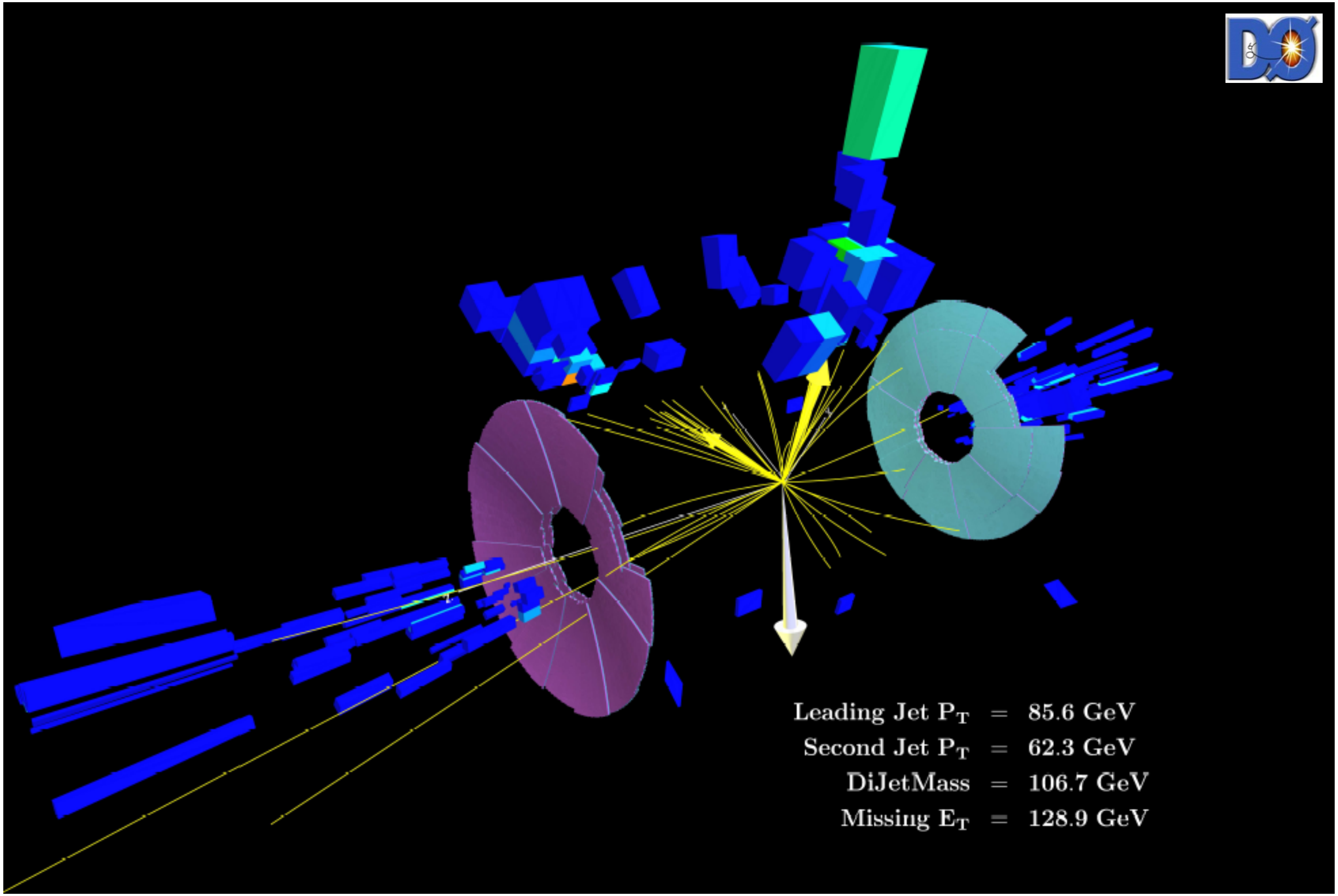


S:B ~ 1:400



S:B ~ 1:75

MET + 2 b-jets



Leading Jet P_T = 85.6 GeV
Second Jet P_T = 62.3 GeV
DiJetMass = 106.7 GeV
Missing E_T = 128.9 GeV

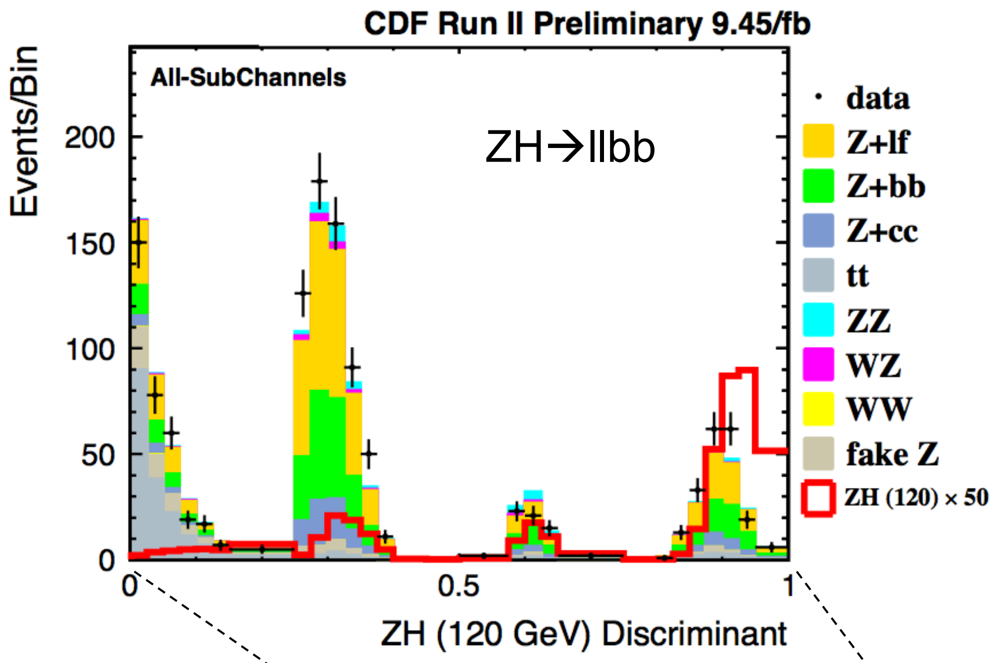
Signal-to-Background Discrimination

Most Higgs analyses use multivariate analysis (MVA) techniques:

- Used against:
  - **Instrumental backgrounds**: increase signal acceptance in event selection
  - **Physics backgrounds**: as final discriminant. Typical sensitivity gain compared to single variable ~15-20%.

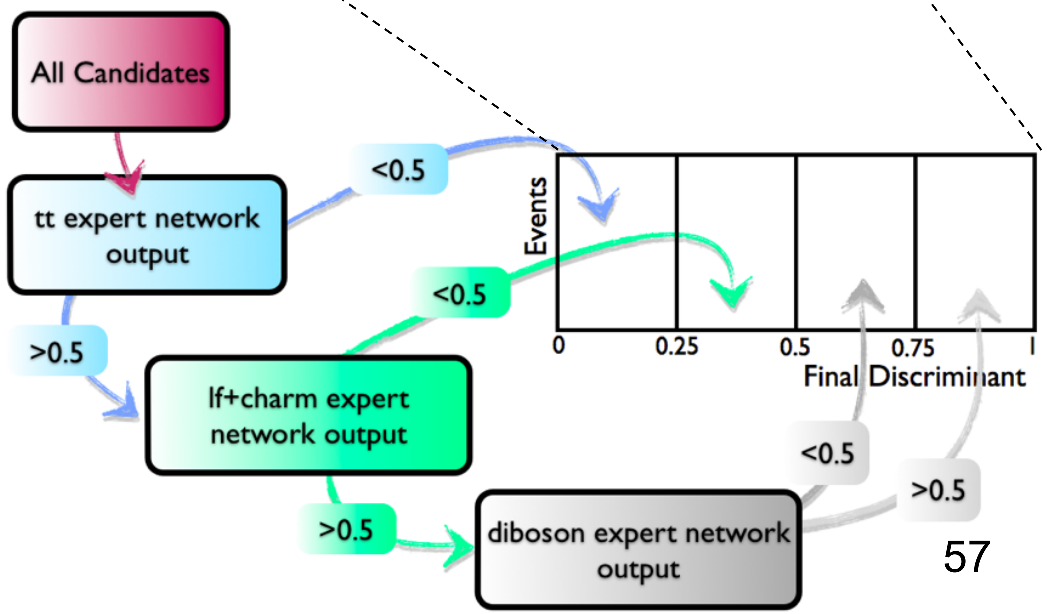
➔ Typically achieve S/B of ~1/1-1/25

S/B ~1/100 for dijet mass alone



Increase sensitivity by splitting analysis into subchannels with different S:B

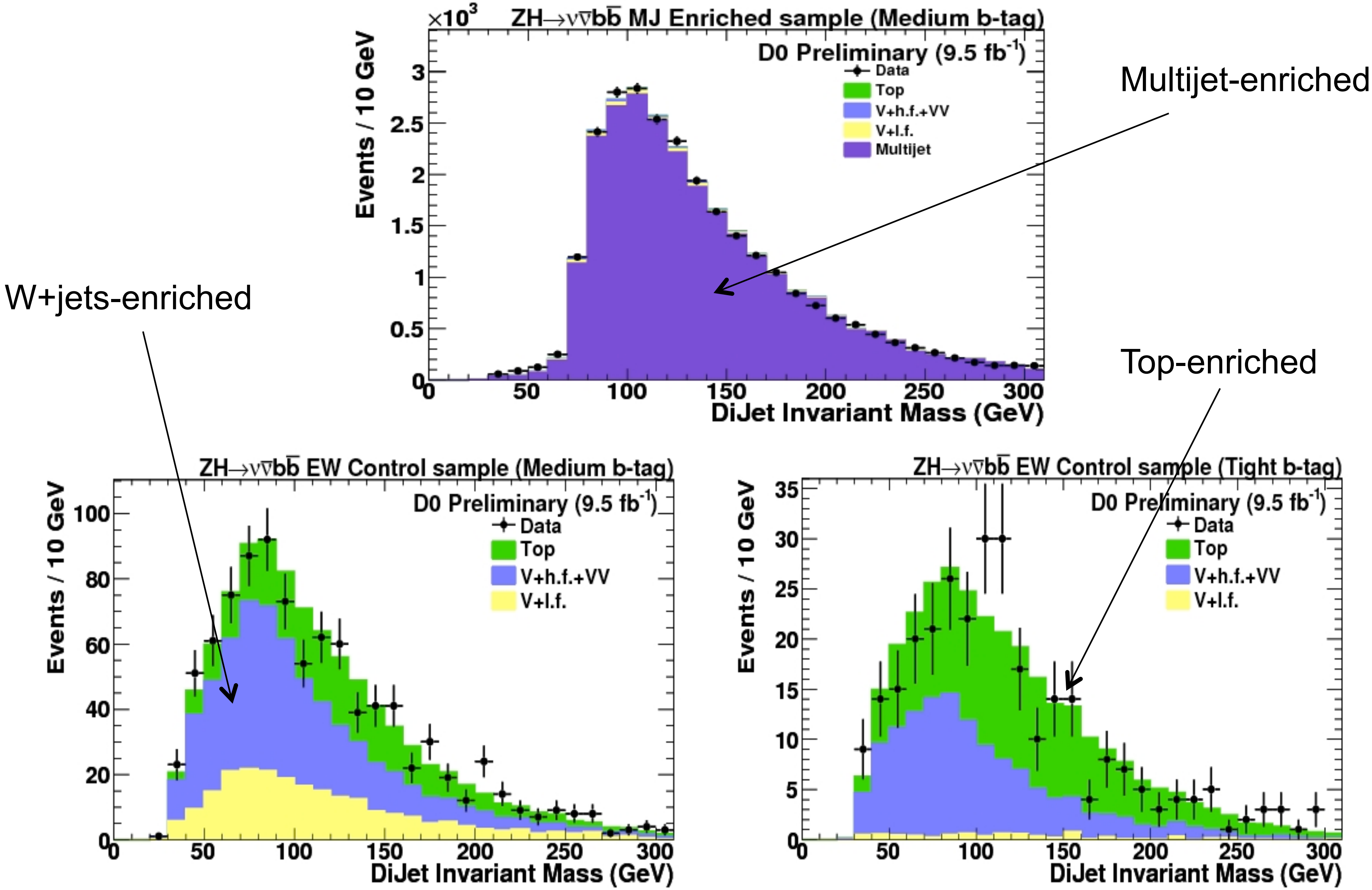
(e.g. by lepton quality, number of jets,..) and combine at the end.



Control Regions

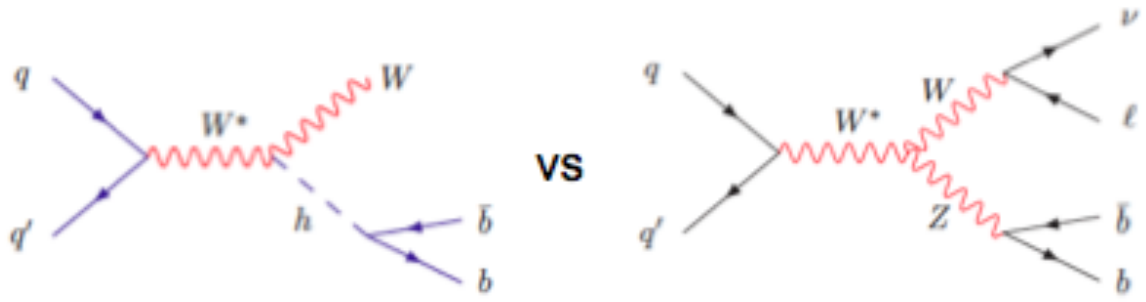
Validate background modeling in signal depleted “side-bands”

Example: $\not{E}_T$+2 b-jets



Validation of H→bb Search Techniques

Validate search strategy by looking for a known SM signal with similar signature



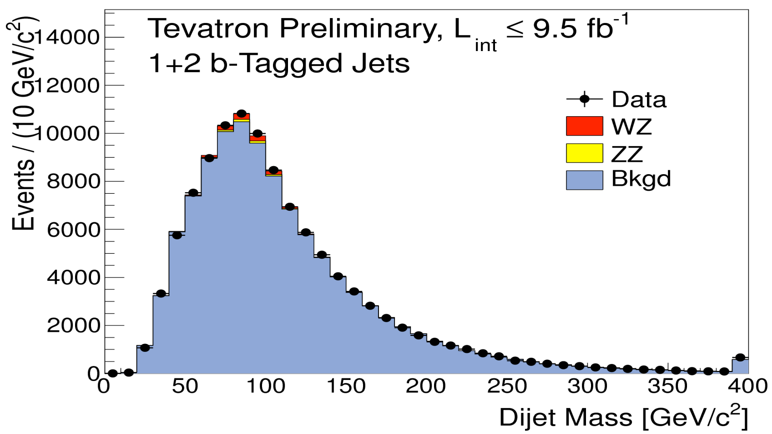
For (W/Z)H with mH = 115 GeV:		
WH → lνbb:	27 fb	(l=e,μ)
ZH → llbb:	5 fb	(ll=ee,μμ)
ZH → ννbb:	15 fb	
Total:	46 fb	

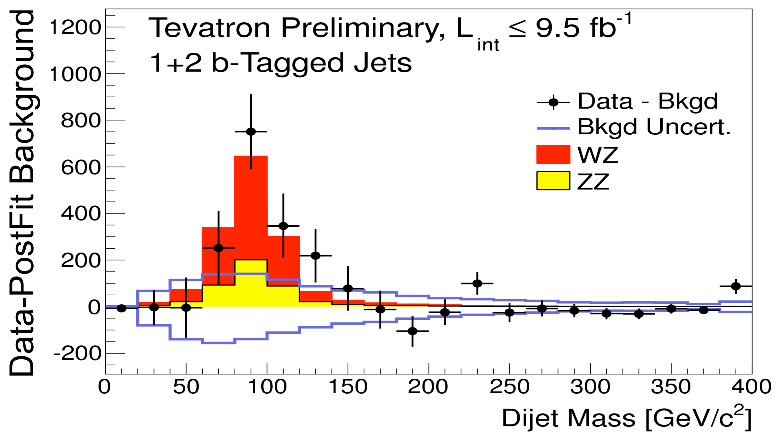
For (W/Z)Z:		
WZ → lνbb:	105 fb	(l=e,μ)
ZZ → llbb :	24 fb	(ll=ee,μμ)
ZZ → ννbb:	73 fb	
Total:	202 fb	

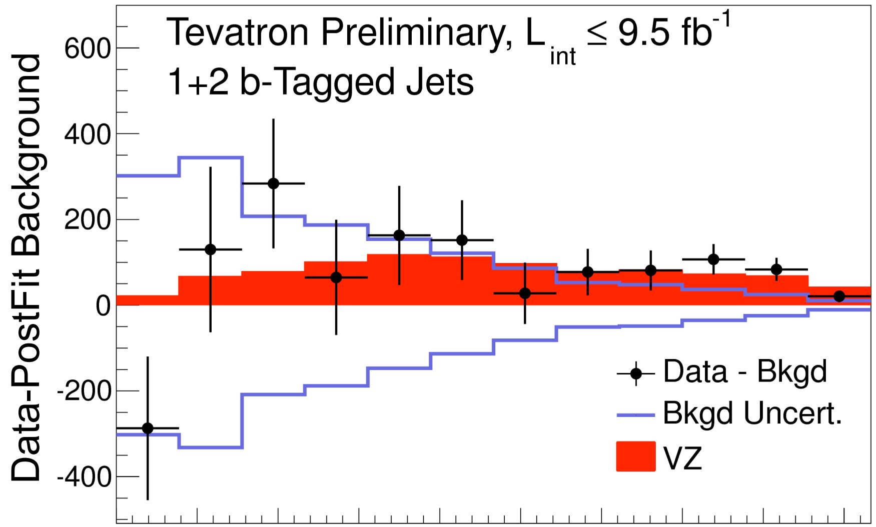
- Differences:
  - Cross section for diboson production is x4.5 larger than for W/ZH.
  - There is relatively more signal contribution from Z→cc than from H→cc.
  - Diboson signal sits at low mass where there is a significant peaking background from WW→lνcs and systematic uncertainties are larger.

Validation of H→bb Search Techniques

- Combination of CDF and DØ searches for WZ/ZZ in lνbb, llbb, ννbb
  - Exact copies of the corresponding Higgs analysis.
  - Global fit to the final discriminant distributions in all subchannels.







MVA ordered by s/b

Measured cross section in good agreement with the SM:

$$\sigma_{WZ+ZZ} = (1.01 \pm 0.21)\ \sigma_{SM}$$

Obs. significance of 4.6 s.d (4.8 s.d. exp.).

Constraining Systematic Uncertainties

LEP: small background, small systematic uncertainties

Tevatron: large background, large systematic uncertainties (particularly at low mass)

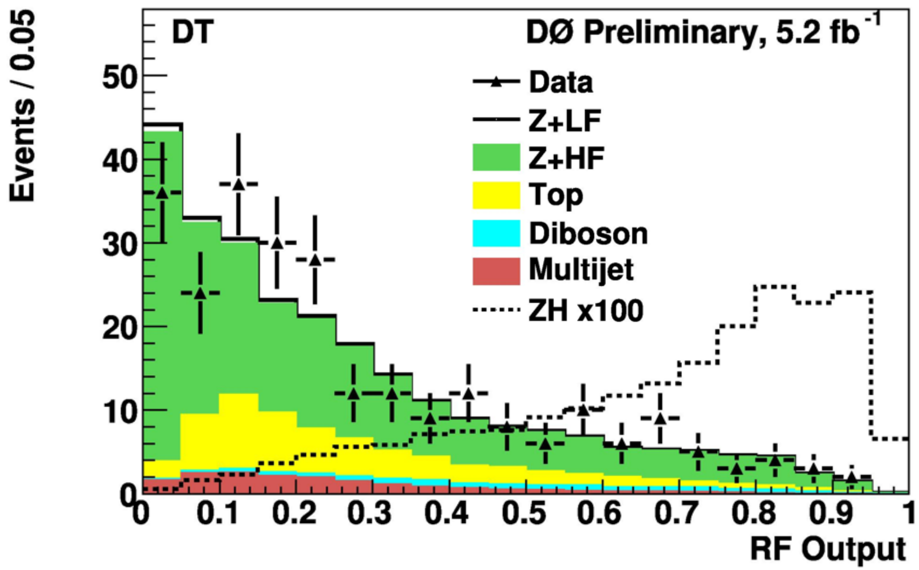
NEW wrt LEP: to counteract the degrading effects of systematic uncertainties, we use a "profile likelihood", obtained by fitting MC expectations to data for each outcome (analogous to "side-band fitting").

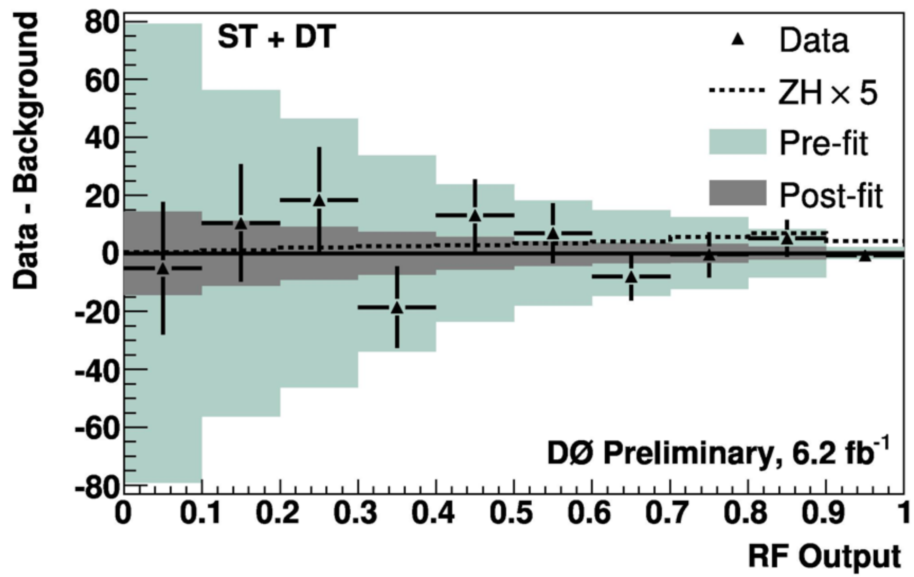
$$LLR = -2\ln Q = -2\ln\left(\frac{L(data\,|\,s+b;\ \hat{\theta})}{L(data\,|\,b;\ \hat{\theta})}\right)$$

Lectures by: G. Cowan

- Capitalizes on shape and statistics of data to constrain background uncertainties.

ZH→llbb

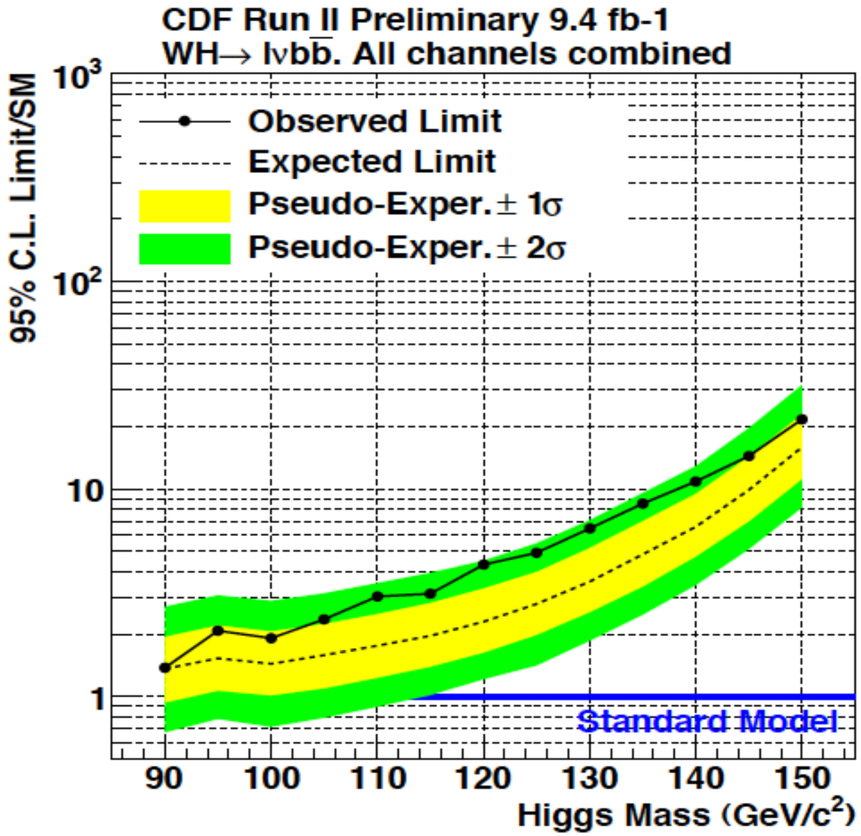




Summary of H→bb Results

95% CL Limits at m_H = 125 GeV

Channel	Exp/obs Limit (σ/SM)
WH→lνbb (9.4 fb^{-1})	2.8/4.9
ZH→ννbb (9.4 fb^{-1})	3.6/6.8
ZH→l^+l^-bb (9.4 fb^{-1})	3.6/7.2
WH→lνbb (9.7 fb^{-1})	4.7/5.2
ZH→ννbb (9.5 fb^{-1})	3.9/4.3
ZH→l^+l^-bb (9.7 fb^{-1})	5.1/7.1
VH/VBF→jjbb (9.4 fb^{-1})	11.0/9.0
ttH→l+jets (9.4 fb^{-1})	12.4/17.6
ttH→jets (5.7 fb^{-1})	26.2/36.2



- Limits from individual VH, H→bb channels at ~3-5xSM at m_H=125 GeV and quickly degrading towards high mass.
- Important to consider additional channels with different mass dependence.

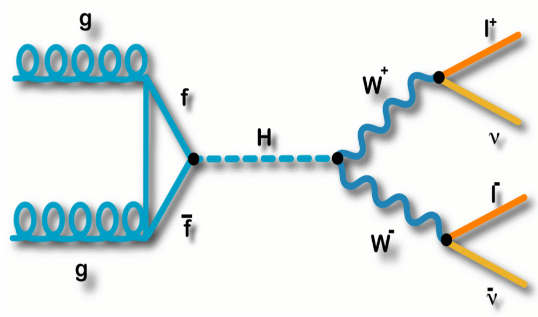
Searching for H→WW→lνlν

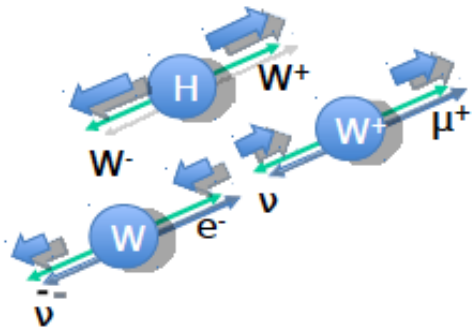
- Highest sensitivity channel in m_H~130-200 GeV range.
- Clean dilepton+$\not{E}_T$ signature.
- Main backgrounds after $\not{E}_T$ cut: WW, W/Z+jets.
- After final selection expect (m_H=165 GeV):

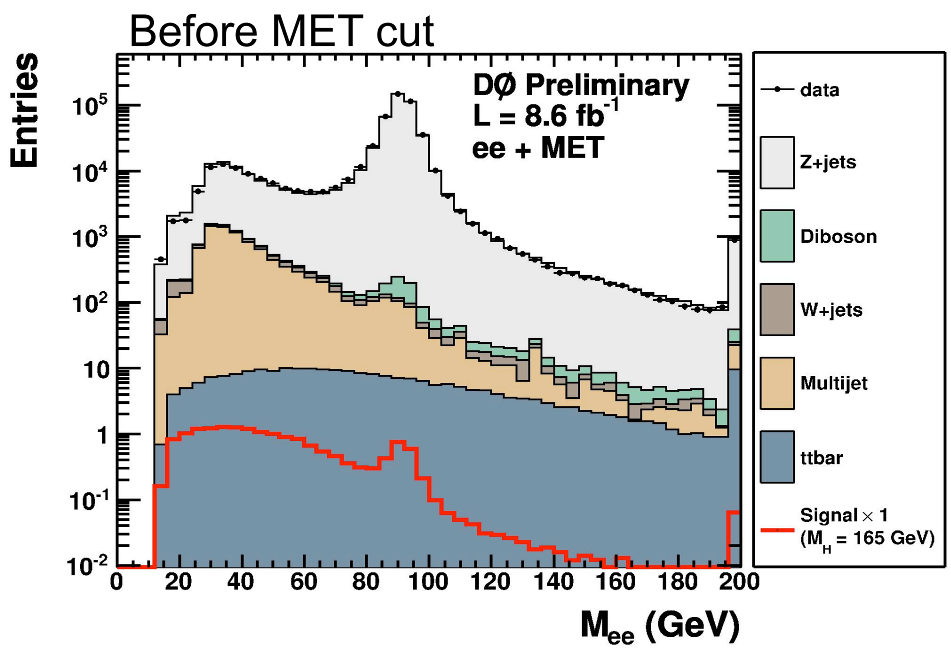
  ~7 signal events/fb^{-1}/experiment with S:B~1:50-1:100

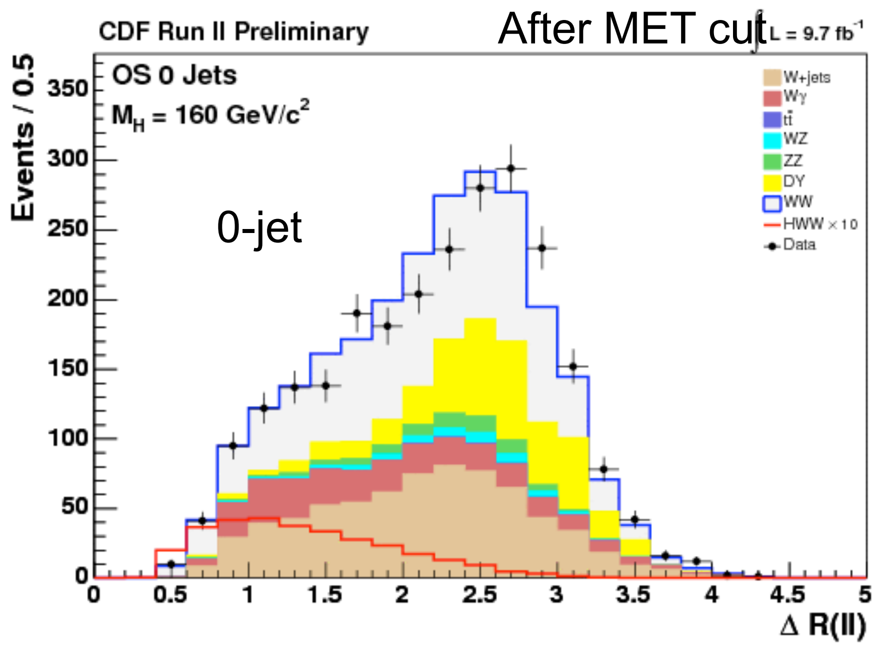
- Exploit spin correlation between dibosons.

  ➔ Small angular separation between leptons





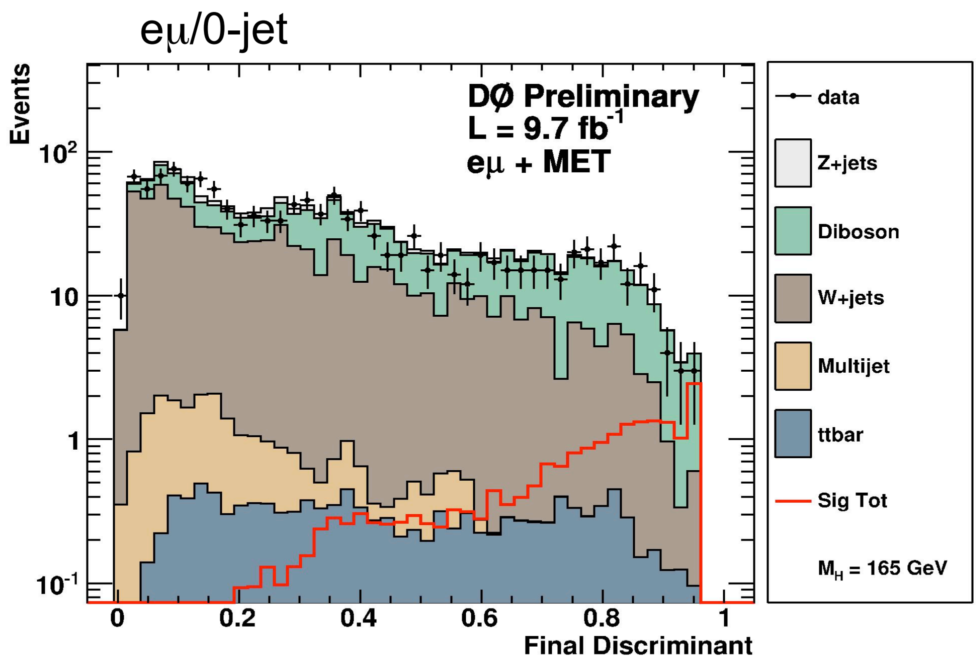


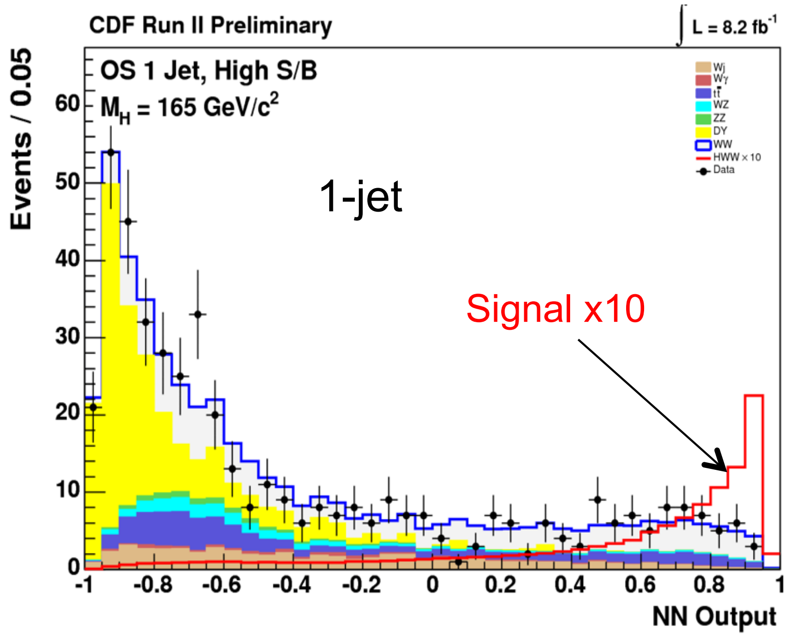


Searching for H→WW→lνlν

To increase the sensitivity:

- Build multivariate discriminants combining several variables
- Split samples with different S:B and combine at the end:
  - by lepton flavor (DØ) or quality (CDF)
  - by jet multiplicity
- Add additional requirements for particular subsamples:
  - Suppress $Z/\gamma^* \rightarrow e^+e^-, \mu^+\mu^-$ by cutting on dedicated MVA variable (DØ)
  - Suppress top quark pairs by vetoing b-tag in 2-jet events (CDF)

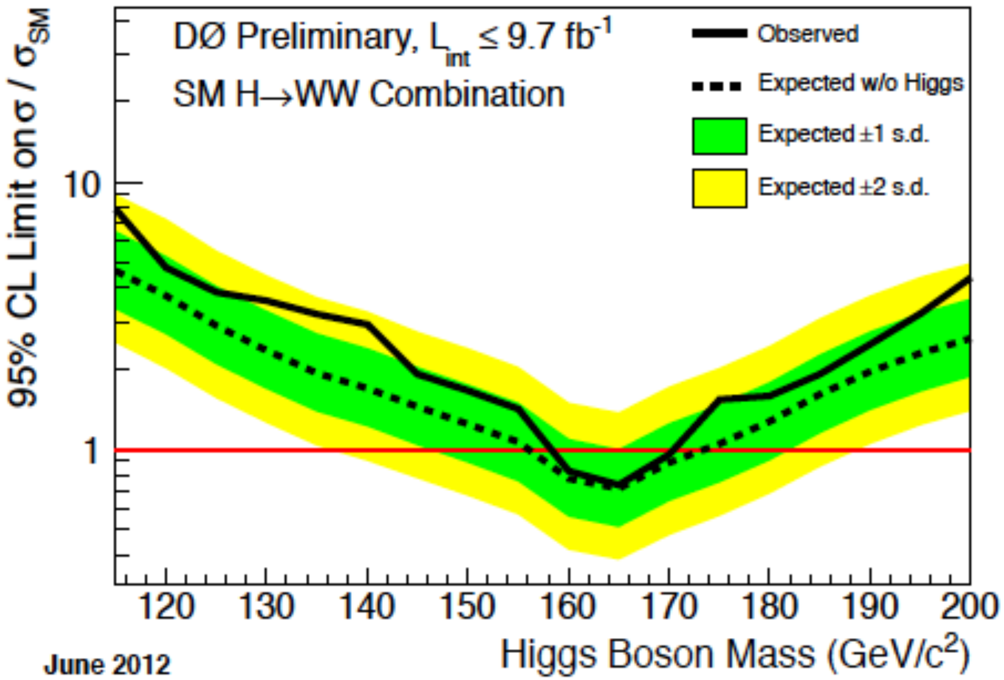




Low Mass Results from H→WW,ττ,γγ

95% CL Limits at m_H = 125 GeV

Channel	Exp/obs Limit (σ/SM)
H→WW→lνlν (9.7 fb^{-1})	3.1/3.0
H→WW→lνlν (9.7 fb^{-1})	3.2/4.6
H+X→ττ+jets (8.3 fb^{-1})	14.8/11.7
VH→ττl(l) (6.2 fb^{-1})	23.3/26.5
H+X→ττjj (6.2 fb^{-1})	11.5/17.9
VH→ττμ (7.0 fb^{-1})	17.6/13.1
H→γγ (10.0 fb^{-1})	11.7/20.5
H→γγ (9.7 fb^{-1})	8.2/12.6



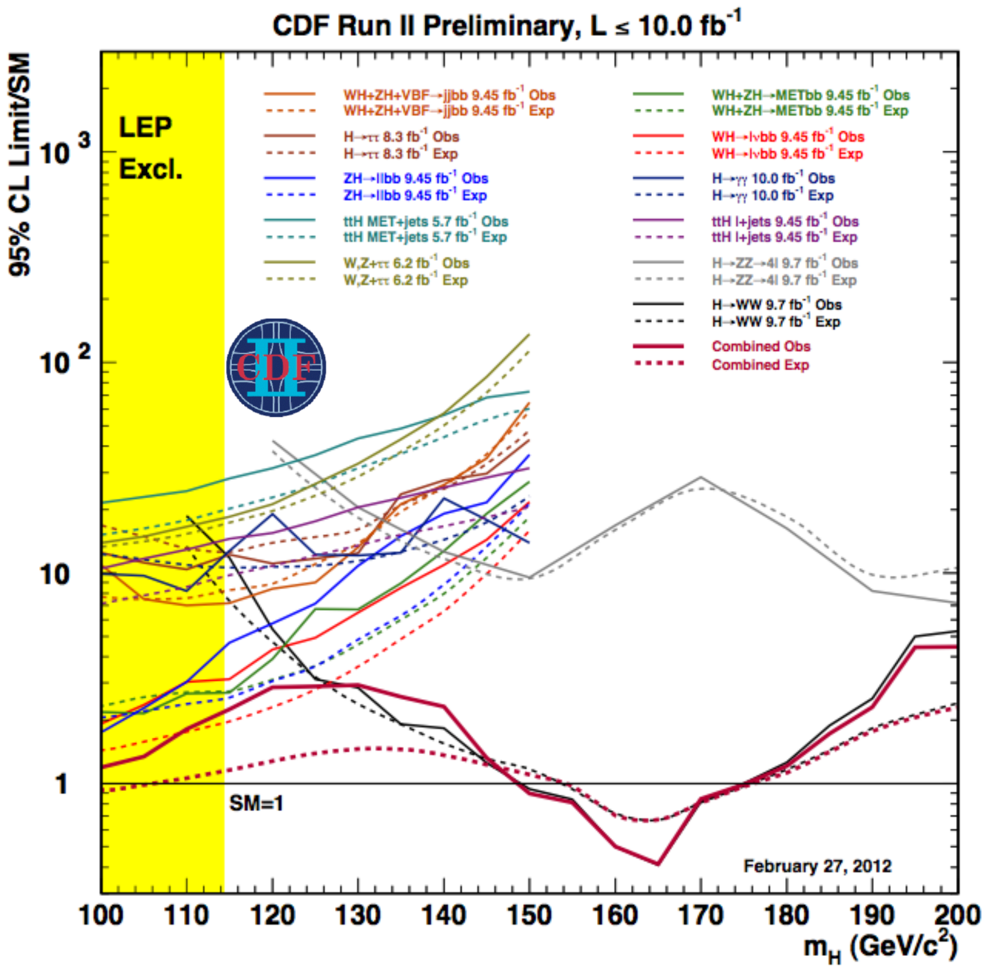
Additional channels contribute useful sensitivity at low/intermediate m_H:

- H→WW→lνlν: improving towards high m_H.
- H+X→ττjj, H→γγ : ~flat vs m_H.

→ Combination of all contributing channels crucial

Combined Limits on SM Higgs Production

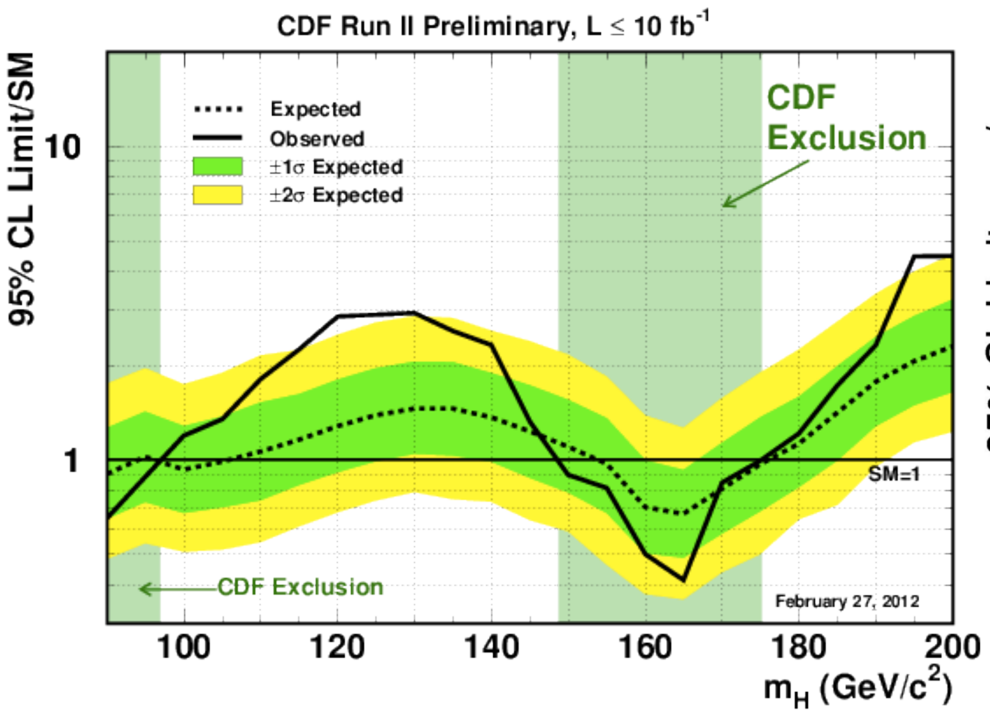
- Combination of multiple channels (and experiments!) yields the greatest sensitivity.

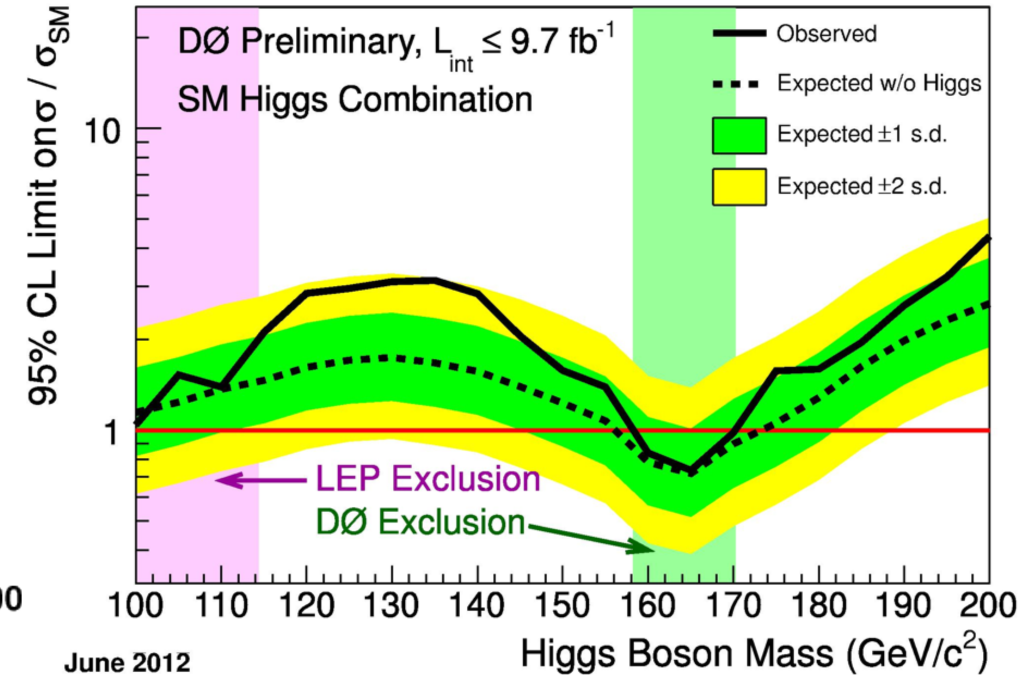


- Assumes SM prediction for ratio of production cross sections and branching ratios.
- More than 50 different sources of systematic uncertainties are considered (including correlations among channels and experiments), and constrained in sidebands.
- Use different techniques to cross check calculations (Bayesian, modified frequentist)

  ➔ results agree within ≤5%.

CDF and DØ Individual Results





At m_H = 125 GeV:

Exp. limit: 1.39 x SM
Obs. limit: 2.89 x SM

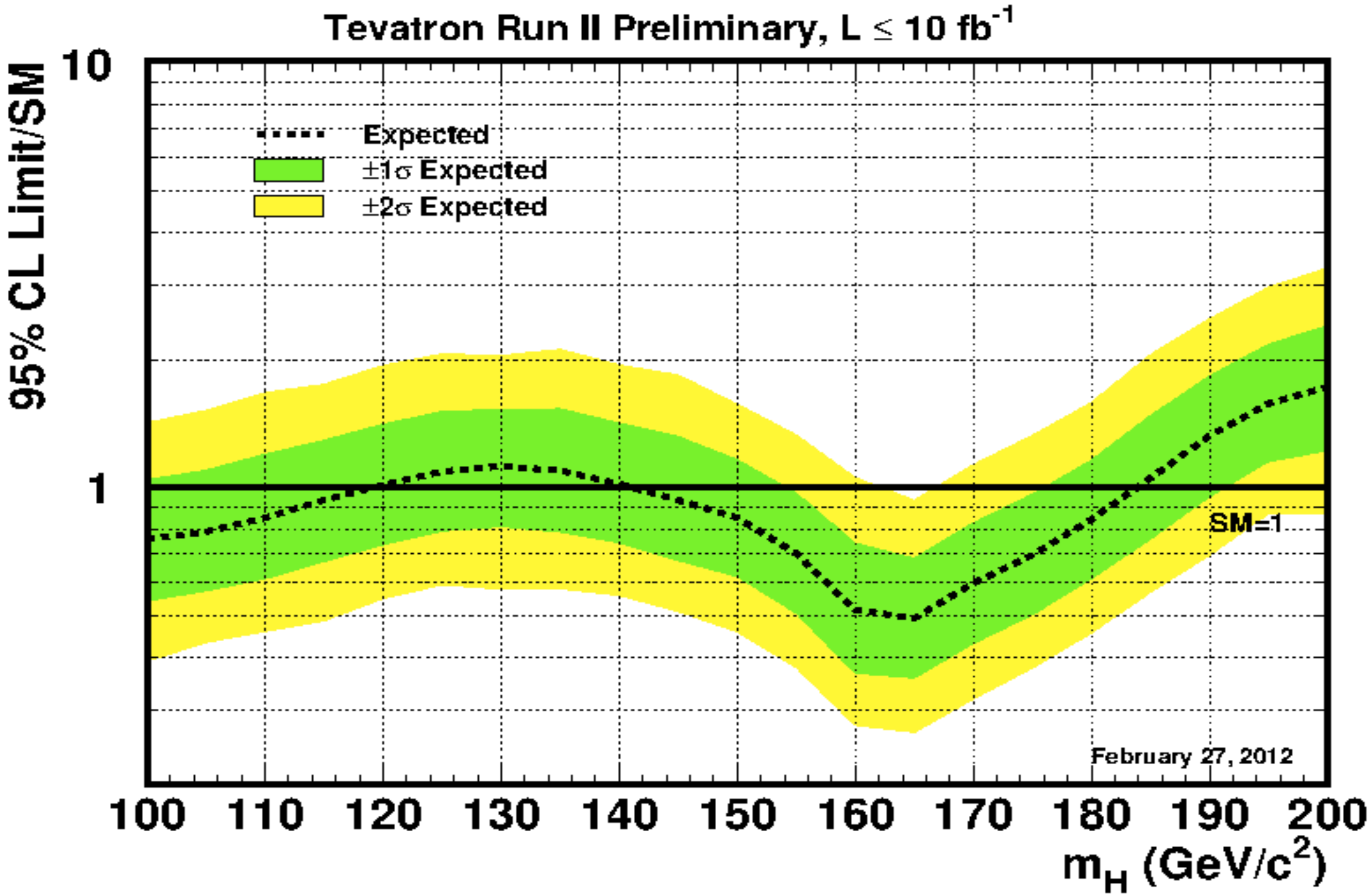
At m_H = 125 GeV:

Exp. limit: 1.70 x SM
Obs. limit: 2.94 x SM

95% CL exclusion: 147 < m_H < 175 GeV

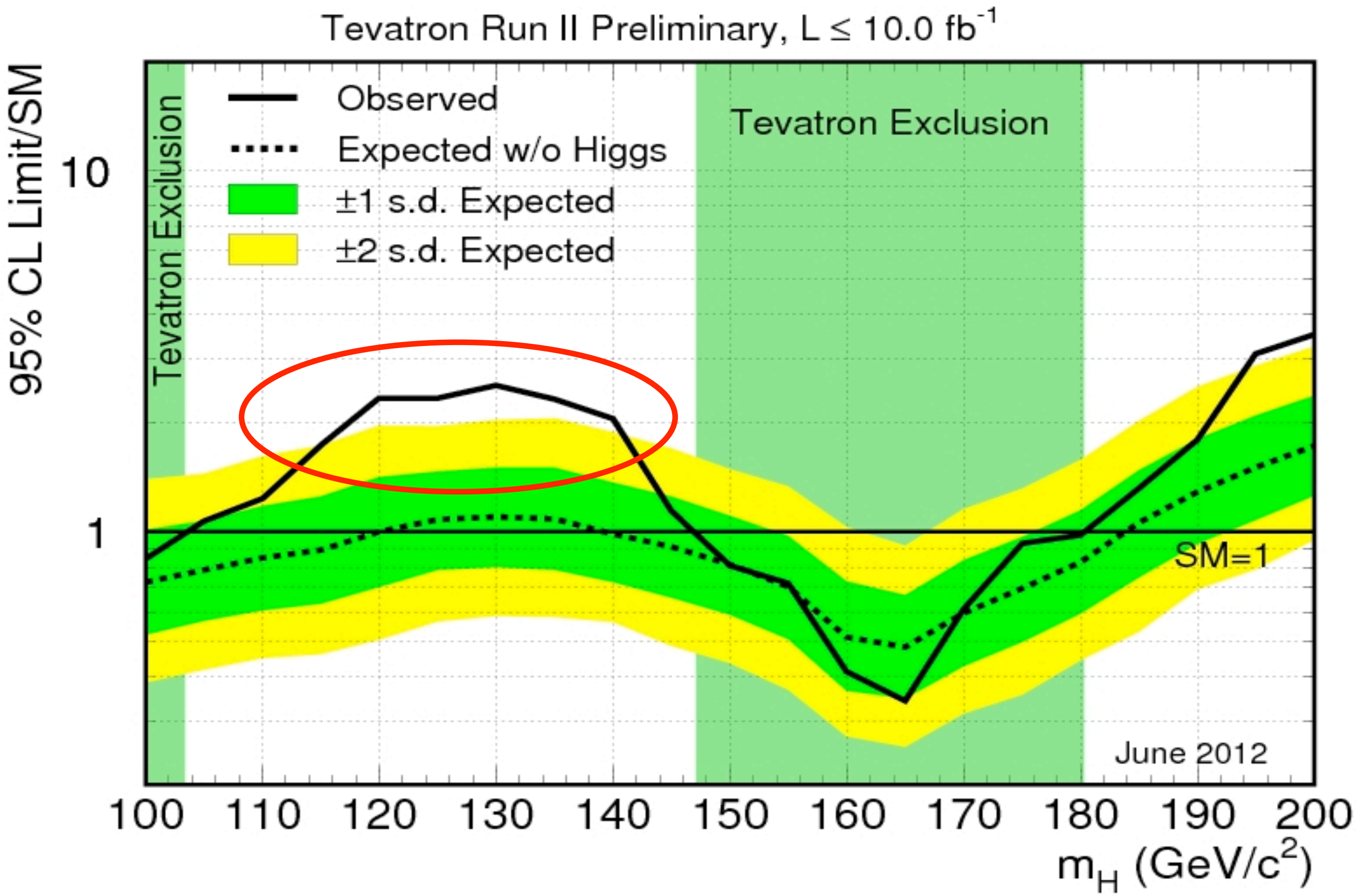
95% CL exclusion: 159 < m_H < 17 GeV

Combined Tevatron Expected Limits



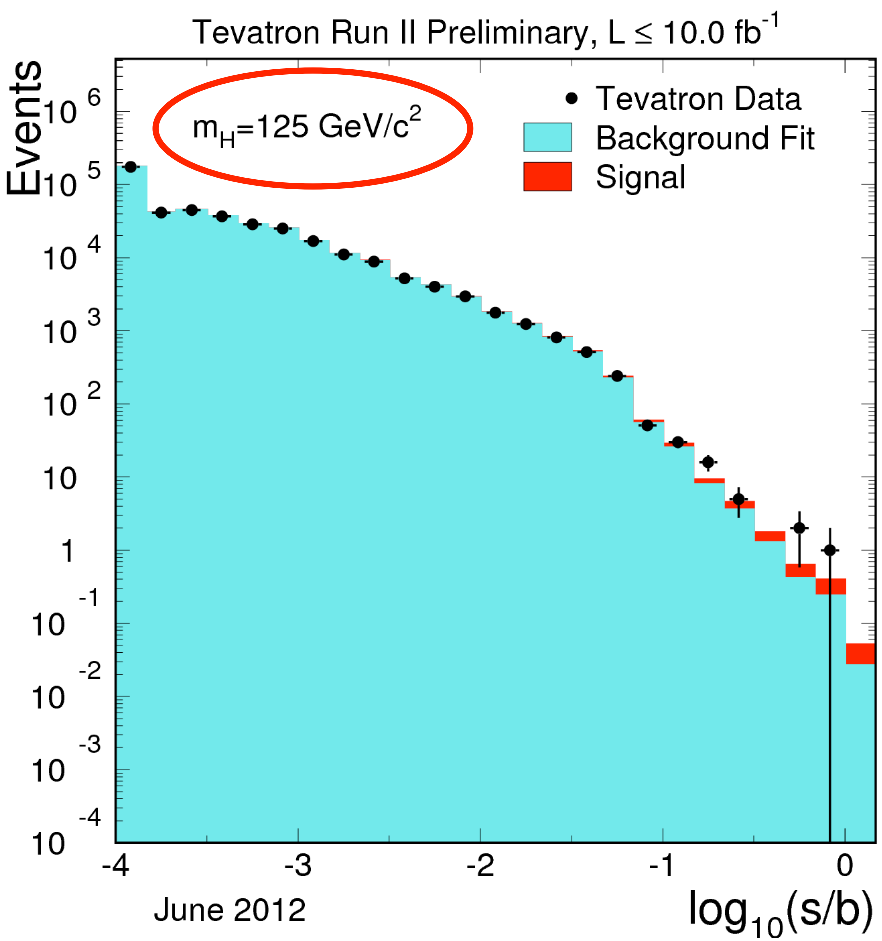
- Expected exclusion: 100 < m_H < 120 GeV, 139< m_H < 184 GeV
- 95% CL limit at m_H=125 GeV: 1.08xSM (expected)

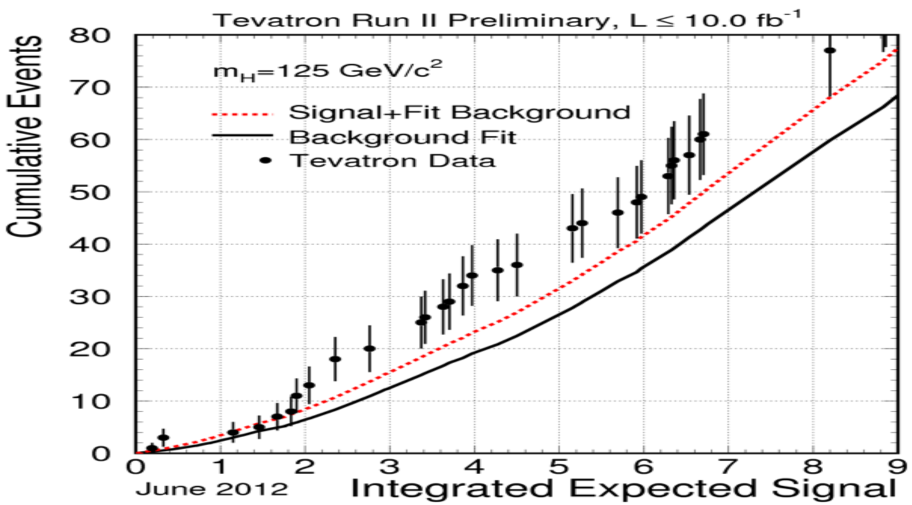
Combined Tevatron Observed Limits

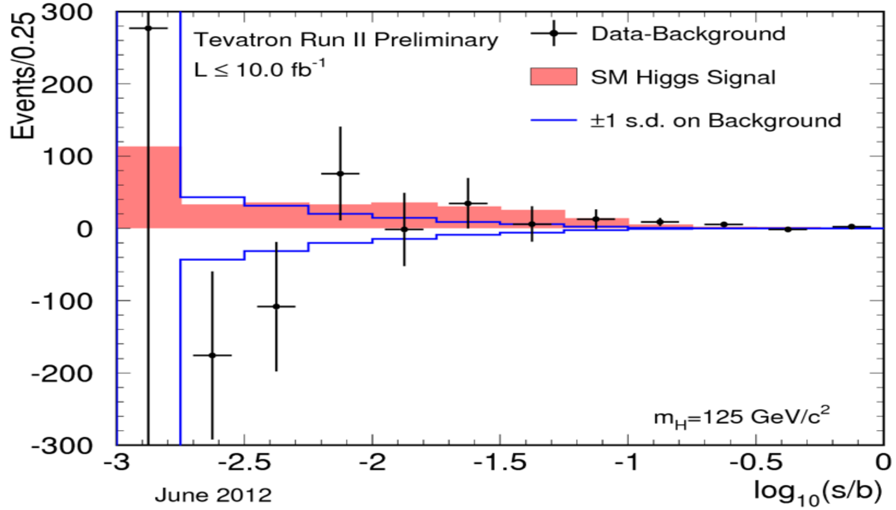


- Expected exclusion: $100 < m_H < 120$ GeV, $139 < m_H < 184$ GeV
  Observed exclusion: $100 < m_H < 103$ GeV, $147 < m_H < 180$ GeV
- 95% CL limit at m_H=125 GeV: 1.08xSM (expected), 2.35xSM (observed)

Visualizing the Excess



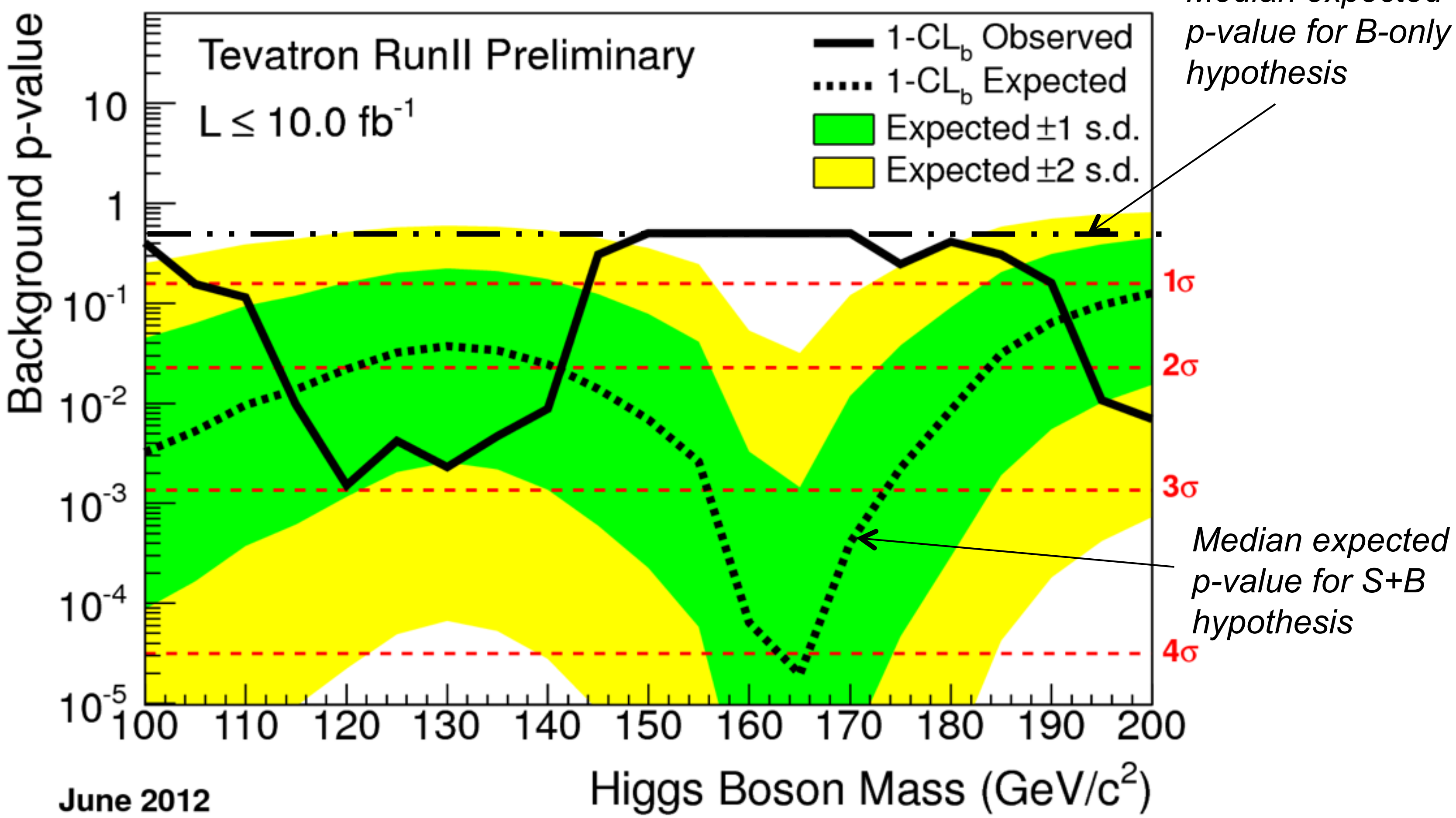




- Display all input histogram bins ordered according to S/B in one plot.
- The background model has been constrained by the data.

Quantifying the Excess: p-values

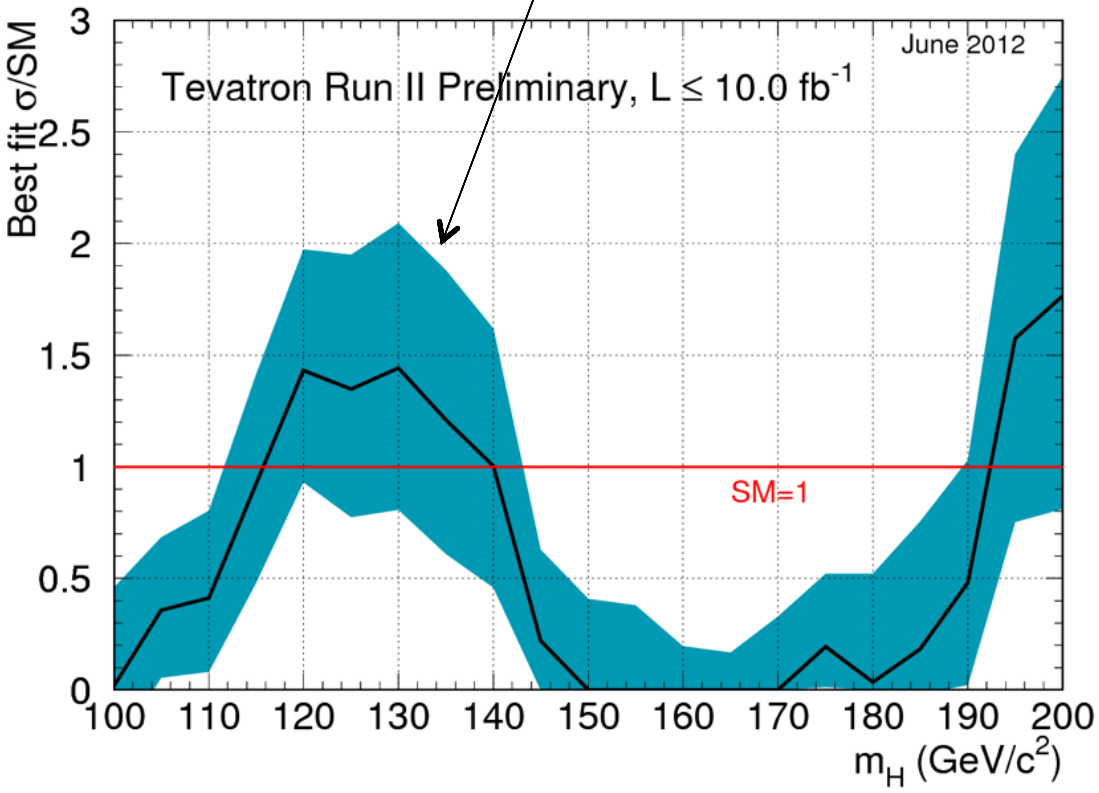
- Local p-value distribution for background-only hypothesis:

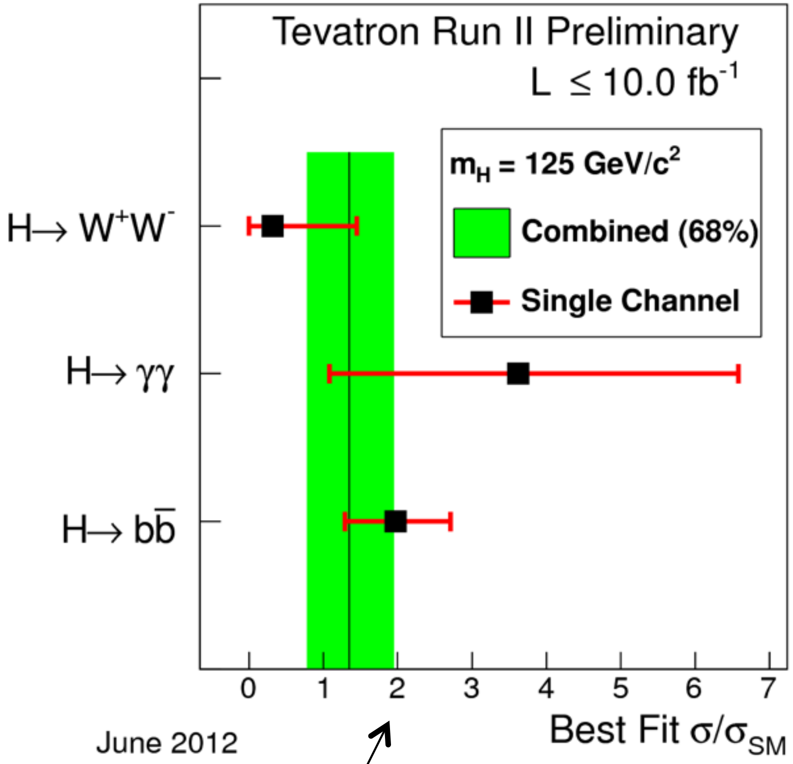


- Minimum local p-value at M_H=120 GeV: 3.0σ (2.0σ expected)
  [Minimum global p-value with look-elsewhere factor of 4: 2.5σ]

Quantifying the Excess: Best Fit Signal Rate

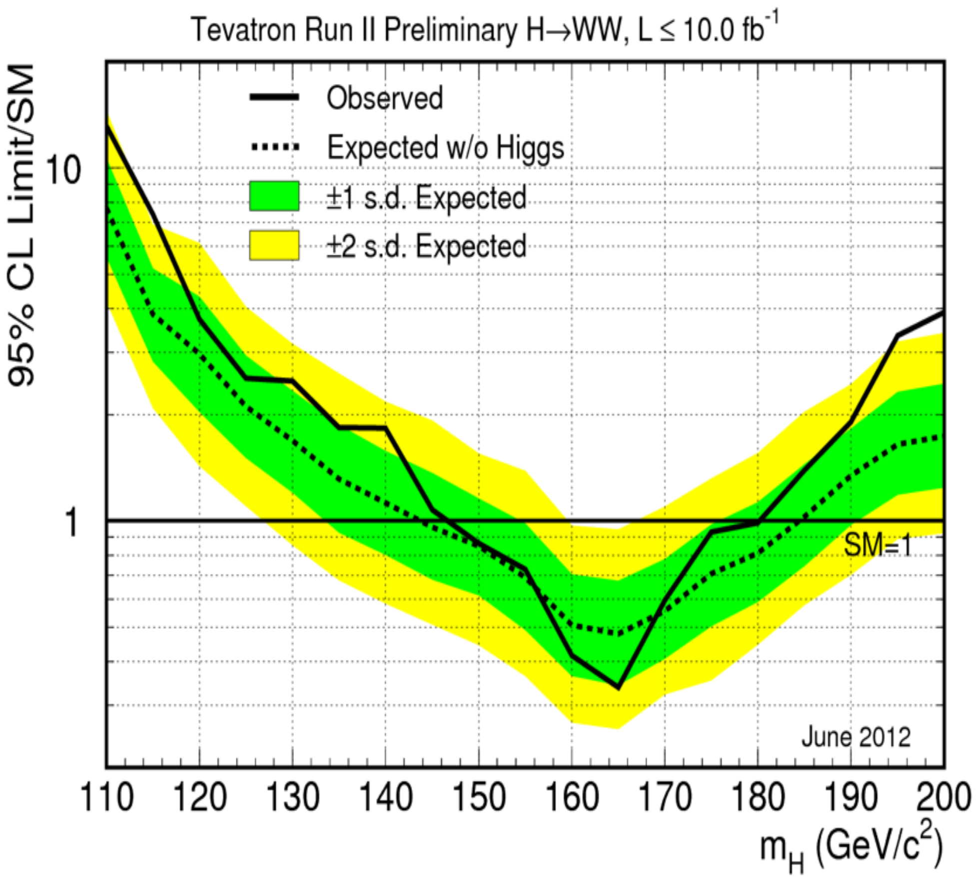
Maximum likelihood fit to data with signal rate as free parameter

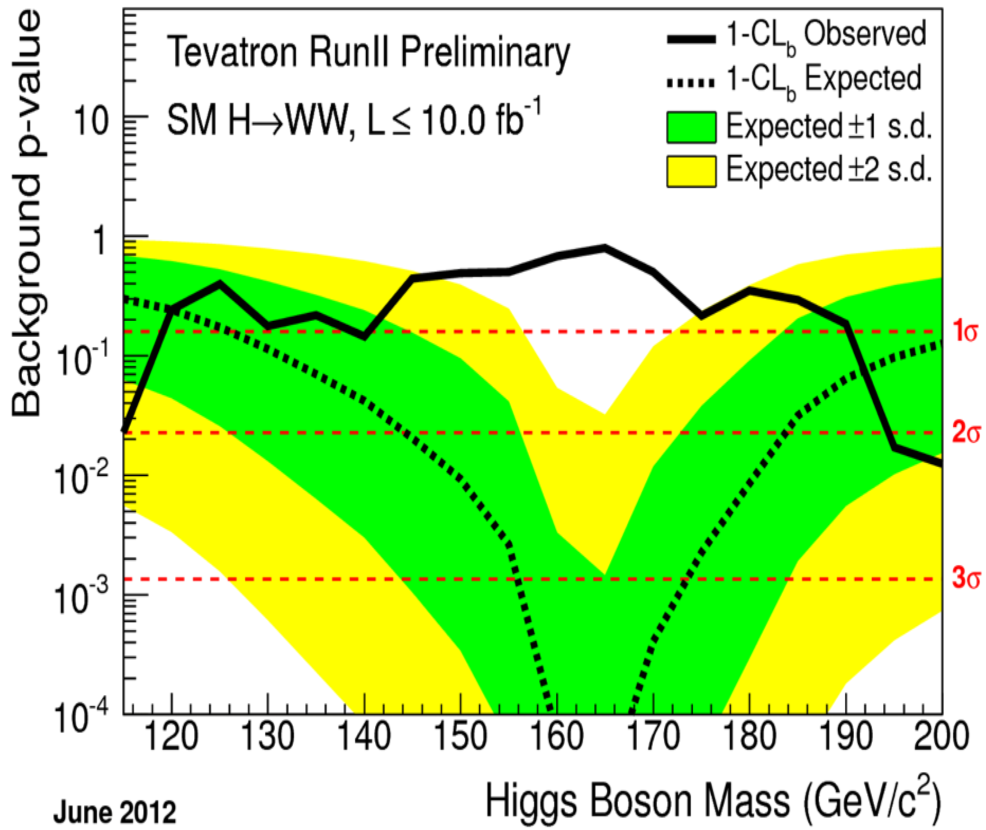




Split by decay channel

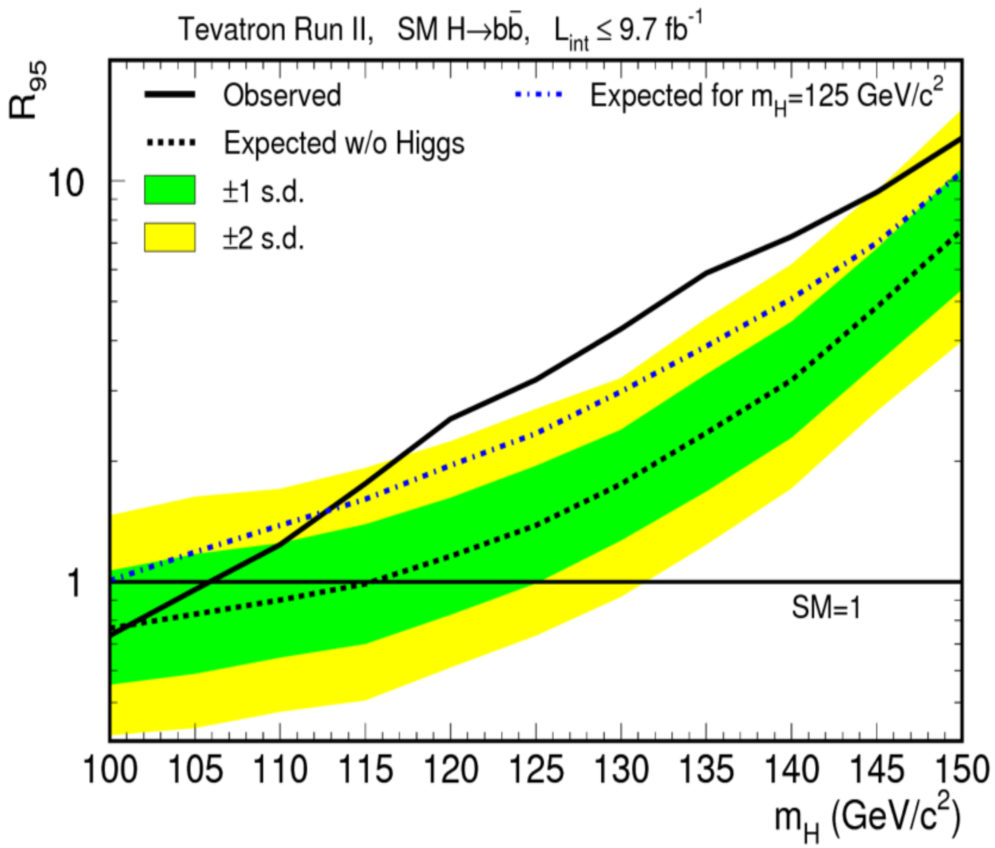
Results by Channel: H→WW

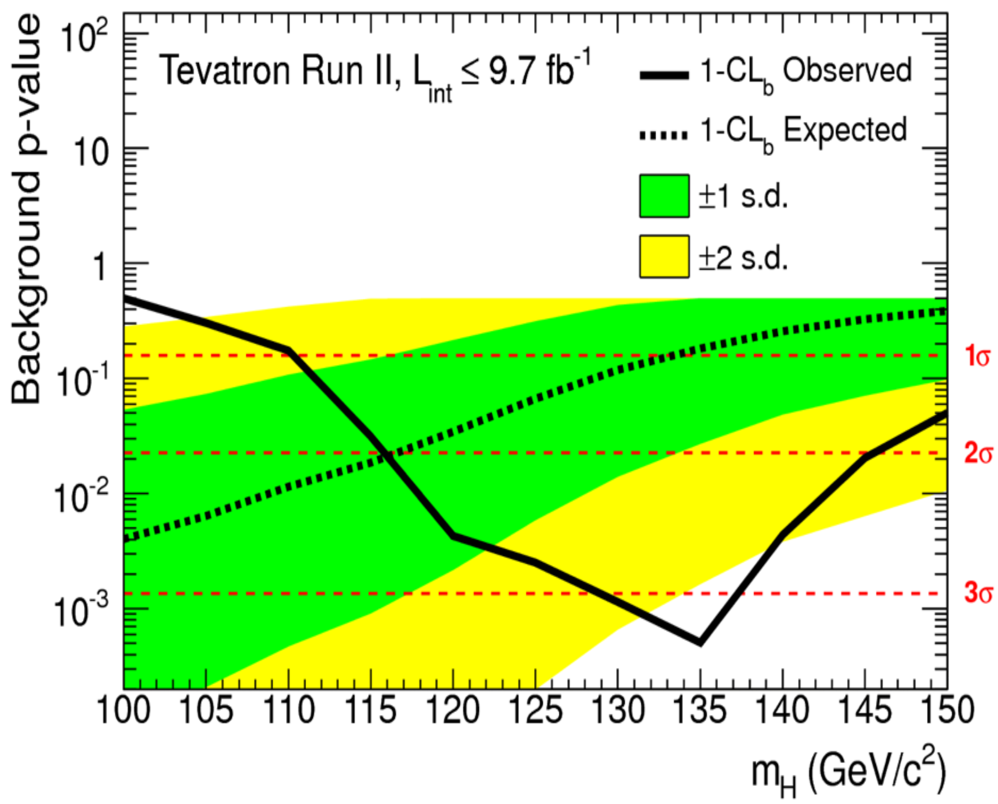




- No significant excess in $115 < m_H < 135$ GeV region

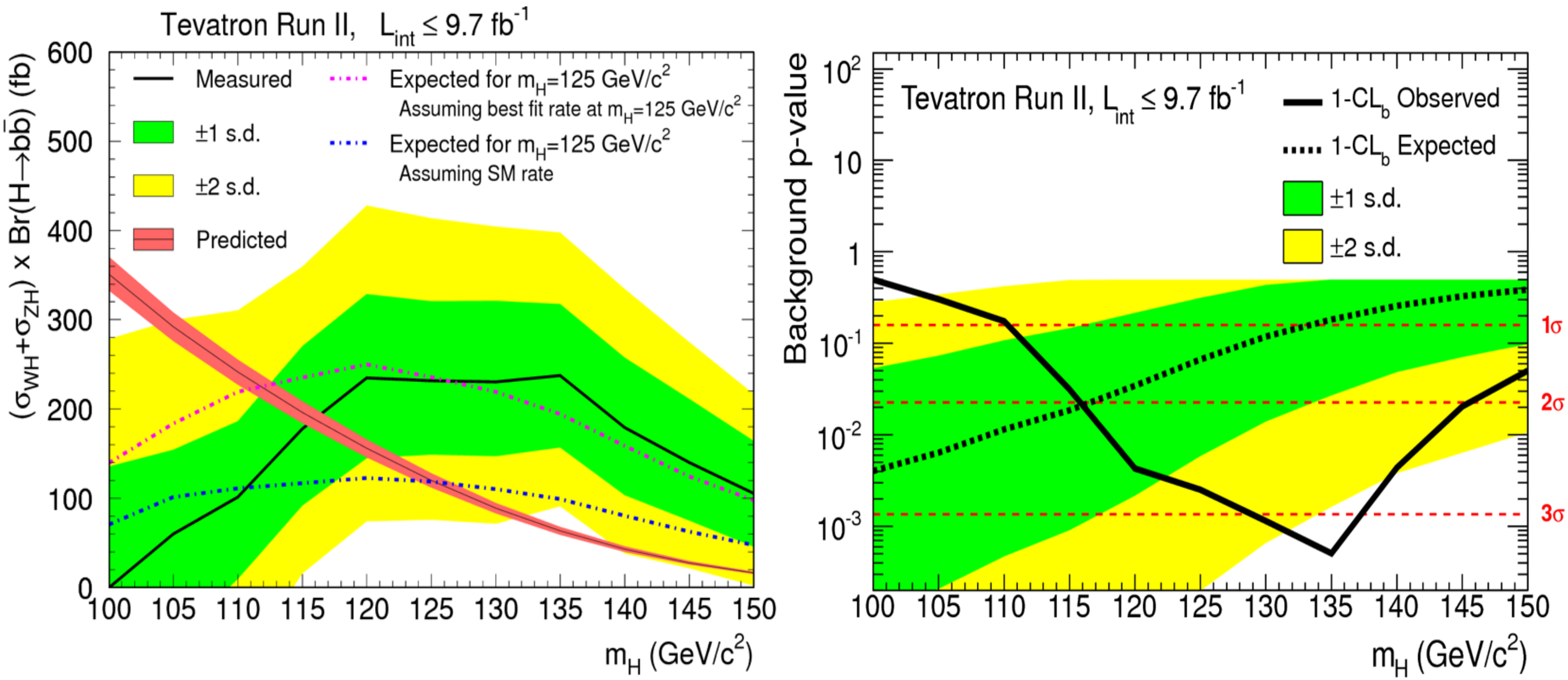
Results by Channel: H→b$\bar{b}$





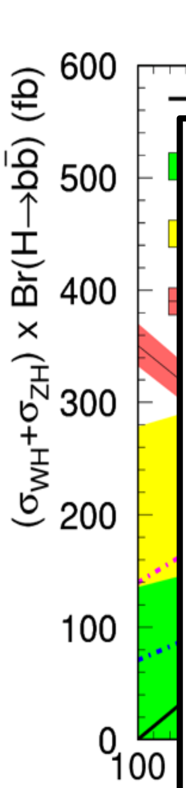
- Main contribution to excess in 115<m_H<135 GeV region
- Minimum local p-value at M_H=135 GeV: 3.3σ (2.8σ at 125 GeV)
  [Minimum global p-value with look-elsewhere factor of 2: 3.1σ]

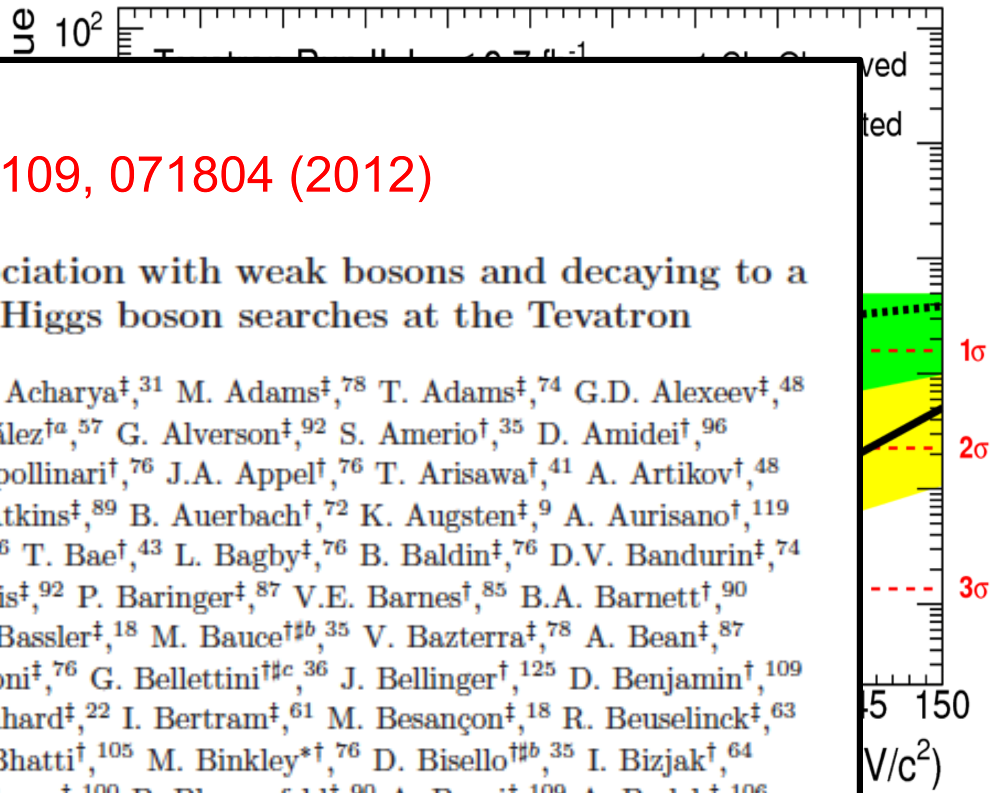
Results by Channel: $H \rightarrow b\bar{b}$



- Main contribution to excess in $115<m_H<135$ GeV region
- Minimum local p-value at M_H=135 GeV: 3.3σ (2.8σ at 125 GeV)
  [Minimum global p-value with look-elsewhere factor of 2: 3.1σ]
- Perform measurement of σ_{VH} x $BR(H \rightarrow b\bar{b})$

Results by Channel: H→b$\bar{b}$





Phys. Rev. Lett. 109, 071804 (2012)

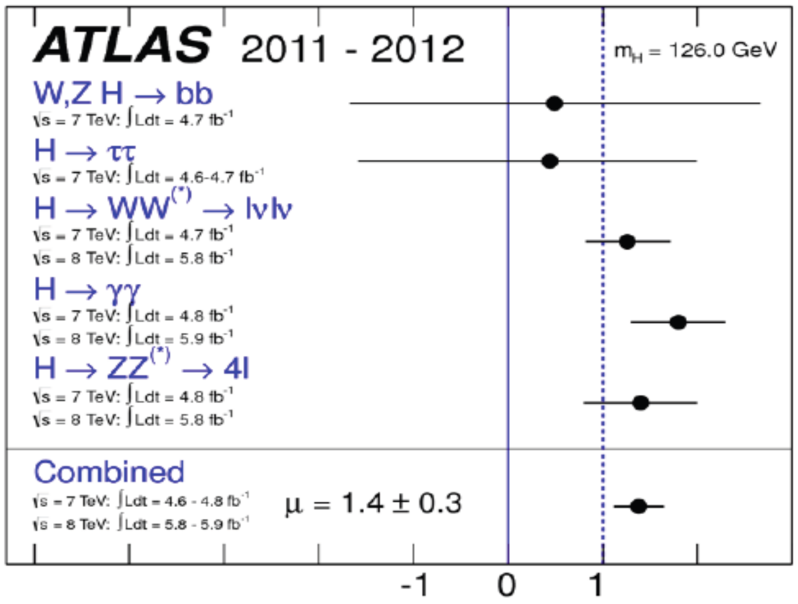
Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson searches at the Tevatron

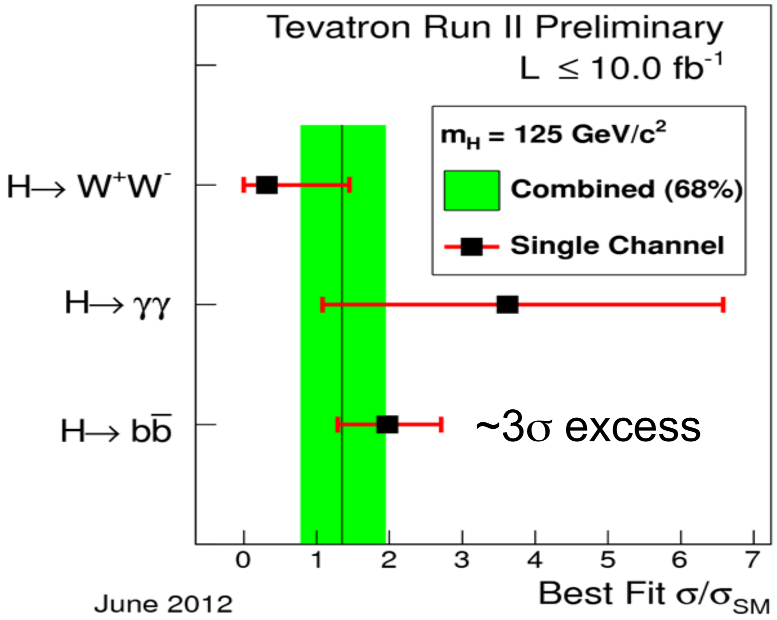
T. Aaltonen[†,12] V.M. Abazov[‡,48] B. Abbott[‡,112] B.S. Acharya[‡,31] M. Adams[‡,78] T. Adams[‡,74] G.D. Alexeev[‡,48] G. Alkhazov[‡,52] A. Alton[‡a,96] B. Álvarez González[†a,57] G. Alverson[‡,92] S. Amerio[†,35] D. Amidei[†,96] A. Anastassov[†b,76] A. Annovi[†,34] J. Antos[†,53] G. Apollinari[†,76] J.A. Appel[†,76] T. Arisawa[†,41] A. Artikov[†,48] J. Asaadi[†,119] W. Ashmanskas[†,76] A. Askew[‡,74] S. Atkins[‡,89] B. Auerbach[†,72] K. Augsten[‡,9] A. Aurisano[†,119] C. Avila[‡,7] F. Azfar[†,66] F. Badaud[‡,13] W. Badgett[†,76] T. Bae[†,43] L. Bagby[‡,76] B. Baldin[‡,76] D.V. Bandurin[‡,74] S. Banerjee[‡,31] A. Barbaro-Galtieri[†,68] E. Barberis[‡,92] P. Baringer[‡,87] V.E. Barnes[†,85] B.A. Barnett[†,90] P. Barria[†‡d,36] J.F. Bartlett[‡,76] P. Bartos[†,53] U. Bassler[‡,18] M. Bauce[†‡b,35] V. Bazterra[‡,78] A. Bean[‡,87] F. Bedeschi[†,36] M. Begalli[‡,2] S. Behari[†,90] L. Bellantoni[‡,76] G. Bellettini[†‡c,36] J. Bellinger[†,125] D. Benjamin[†,109] A. Beretvas[†,76] S.B. Beri[‡,29] G. Bernardi[‡,17] R. Bernhard[‡,22] I. Bertram[‡,61] M. Besançon[‡,18] R. Beuselinck[‡,63] P.C. Bhat[‡,76] S. Bhatia[‡,99] V. Bhatnagar[‡,29] A. Bhatti[†,105] M. Binkley[*†,76] D. Bisello[†‡b,35] I. Bizjak[†,64] K.R. Bland[†,122] G. Blazey[‡,79] S. Blessing[‡,74] K. Bloom[‡,100] B. Blumenfeld[†,90] A. Bocci[†,109] A. Bodek[†,106] A. Boehnlein[‡,76] D. Boline[‡,107] E.E. Boos[‡,50] G. Borissov[‡,61] D. Bortoletto[†,85] T. Bose[‡,91] J. Boudreau[†,116] A. Boveia[†,77] A. Brandt[‡,118] O. Brandt[‡,23] L. Brigliadori[†‡a,33] R. Brock[‡,98] C. Bromberg[†,98] A. Bross[‡,76] D. Brown[‡,17] J. Brown[‡,17] E. Brucken[†,12] J. Budagov[†,48] X.B. Bu[‡,76] H.S. Budd[†,106] M. Buehler[‡,76] V. Buescher[‡,25] V. Bunichev[‡,50] S. Burdin[‡b,61] K. Burkett[†,76] G. Busetto[†‡b,35] P. Bussey[†,60] C.P. Buszello[‡,58] A. Buzatu[†,4]

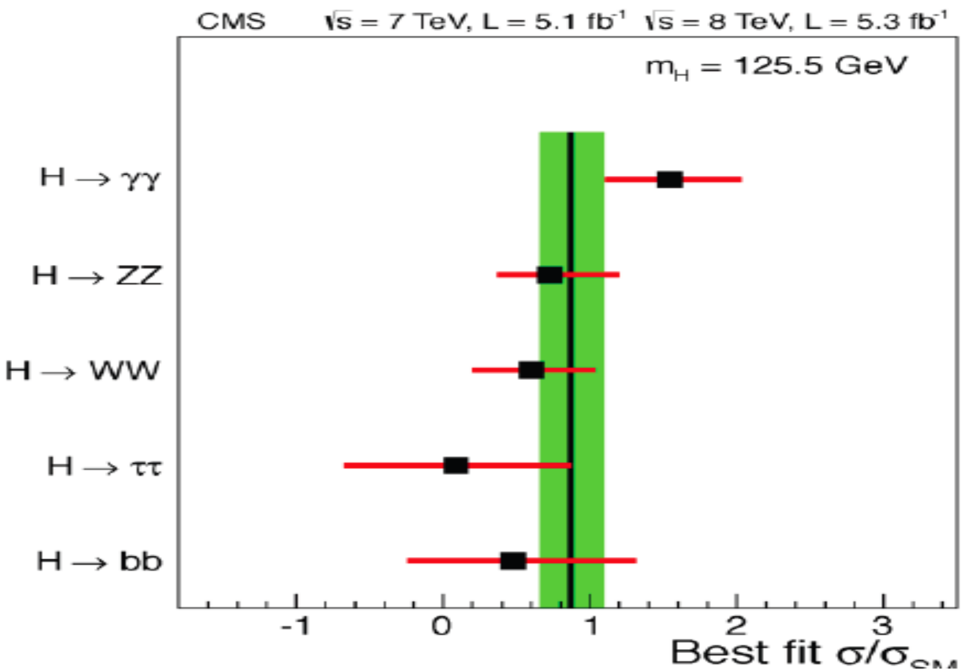
- [Minimum global p-value with look-elsewhere factor of 2: 3.1σ]
- Perform measurement of σ_{VH} x BR(H→b$\bar{b}$)

Conclusion

- The particle discovered at the LHC looks like the SM-Higgs, but is it the SM Higgs?
  - $H \rightarrow \gamma\gamma$ rate above SM
  - $H \rightarrow WW/ZZ$ rate close to SM
  - No apparent excess in $H \rightarrow \tau\tau$, $b\bar{b}$
- Despite the impressive progress on $H \rightarrow b\bar{b}$ at the LHC, the Tevatron will contribute important additional information on this channel till the 2015 run. Further improvements expected.

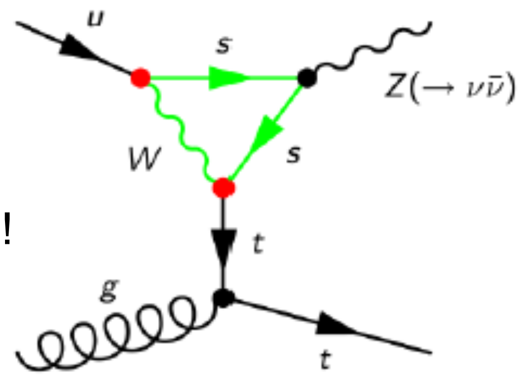






Backup

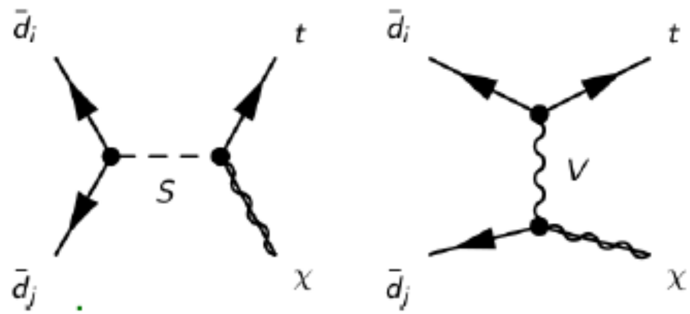
A novel signature: monotop+MET



- Monotop production in the SM:
  - Loop-suppressed
  - CKM-suppressed

➔ sounds like a promising signature to search for New Physics!

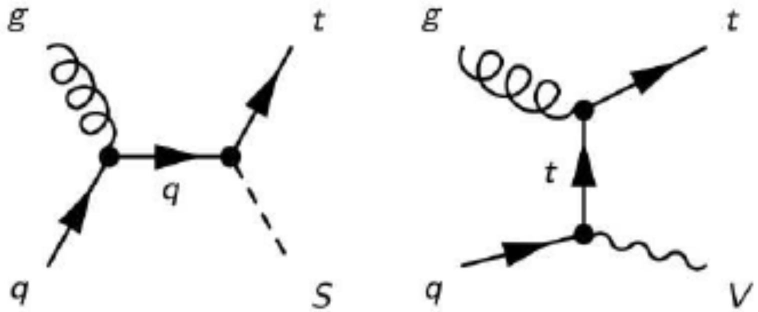
- Monotop production beyond the SM. A bottom-up approach:
  Two broad classes of models:
  - Fermionic missing energy state: baryon number violating interaction



arXiv:1106.6199

s-, t-, and u-channel exchange of a new state (scalar or vector)

  - Bosonic missing energy state: flavor-changing interaction



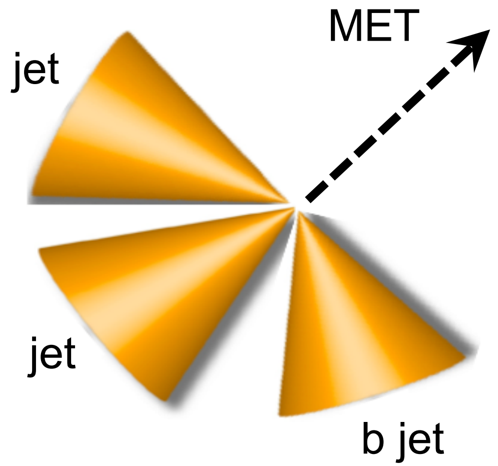
with a new neutral scalar, vector or tensor field either long-lived or decaying invisibly

Event Selection and Backgrounds

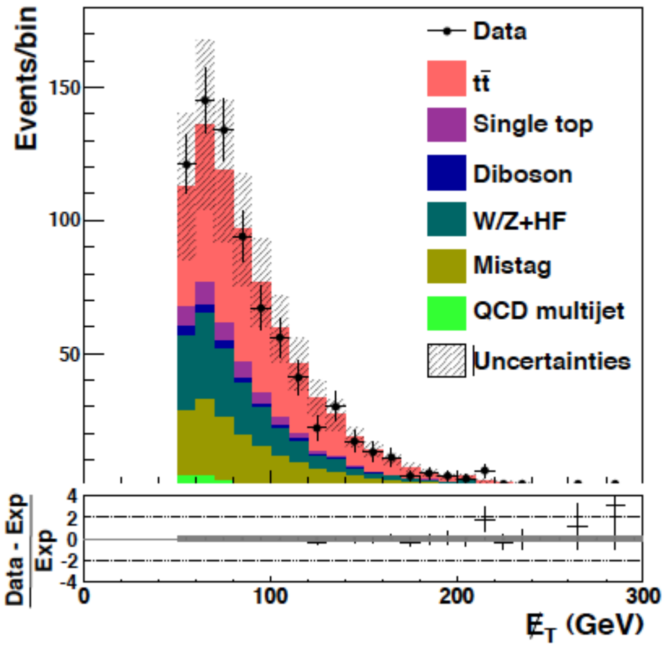
- Strategy: focus on hadronic top quark decay mode
  - Largest BR
  - Full reconstruction of top quark candidate
  - MET uniquely assigned to invisible particle
    ➔ main observable

- Event selection:
  - Jets+MET trigger (MET>30 GeV requirement)
  - 3 jets with p_T>35/25/15 GeV, =1 b-tagged jet
  - MET>50 GeV, $\Delta\phi$(jet2, MET)>0.7
    MET significance>3.5
  - Hadronic top quark candidate:110<m_{jjj}<200 GeV
  - Veto events with electron or muon

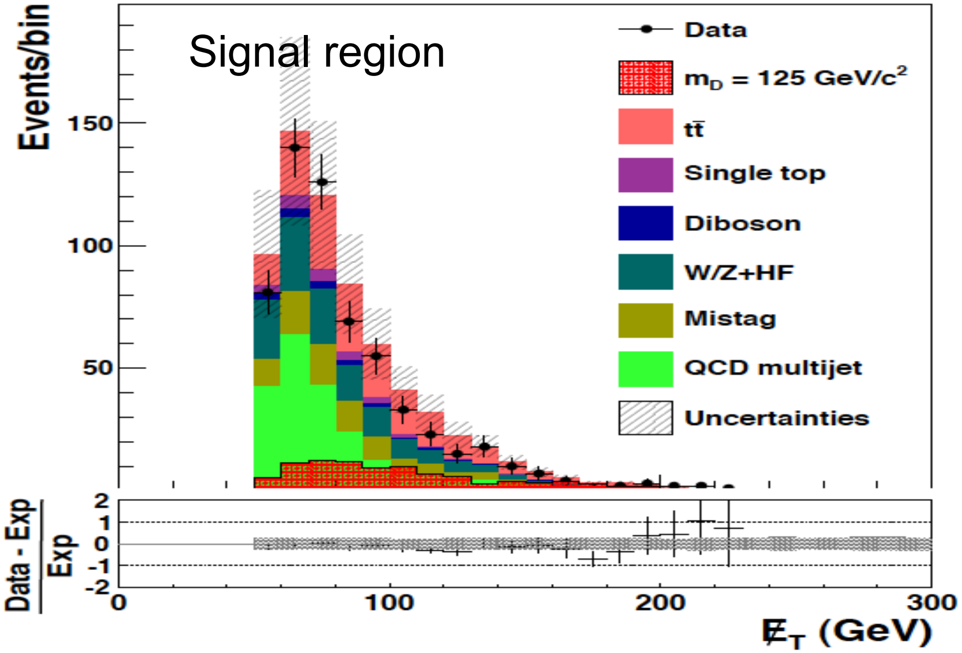
- Main backgrounds:
  - $t\bar{t}$: real hadronic top, MET from leptonic W with non-reconstructed lepton
  - W/Z+jets: fake hadronic top (combinatorial bkg), MET from leptonic W with non-reconstructed lepton
  - QCD multijet: fake hadronic top, MET from jet p_T mismeasurement



Control region requiring identified electron or muon



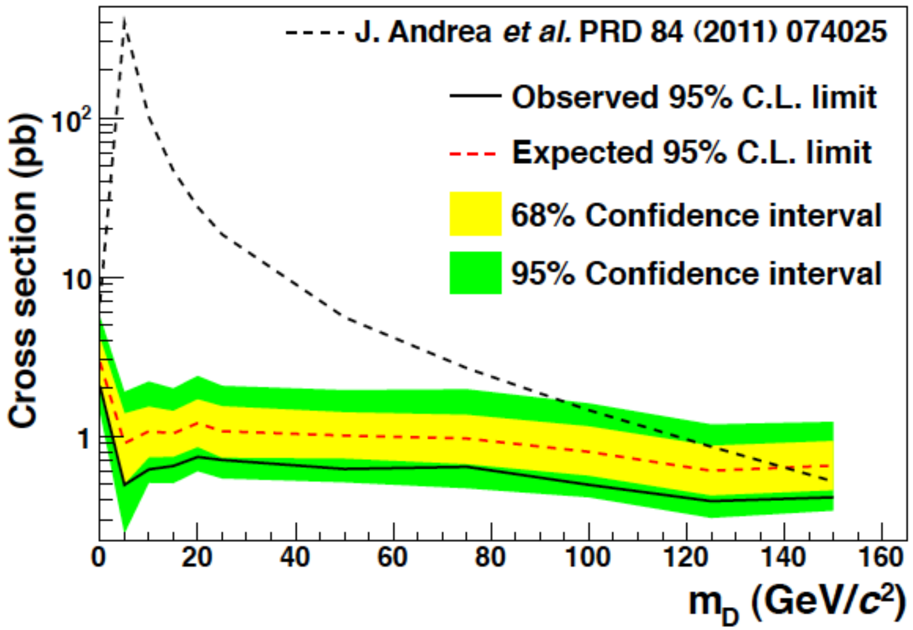
Result



Processes	Events
$p\bar{p} \to t + D$	
$m_D = 20$ GeV$/c^2$	2116.9 ± 121.4
$m_D = 75$ GeV$/c^2$	232.3 ± 22.9
$m_D = 100$ GeV$/c^2$	129.8 ± 12.5
$m_D = 125$ GeV$/c^2$	94.5 ± 9.3
$t\bar{t}$	182.8 ± 20.2
Single top	24.3 ± 4.5
Diboson	15.7 ± 2.7
W/Z+HF	130.5 ± 33.8
Mistag	96.9 ± 39.4
QCD multijet	210.2 ± 54.5
Total background	660.2 ± 78.1
Data	592

- Data found in good agreement with SM expectations.
- Signal modeled as a flavor-violating process ug→tD with Madgraph.

- Set limits 95% CL upper limits of σ(ug→tD)<0.4-2.0 pb as a function of m_D.
- Exclude m_D<150 GeV in the highest-cross section model.



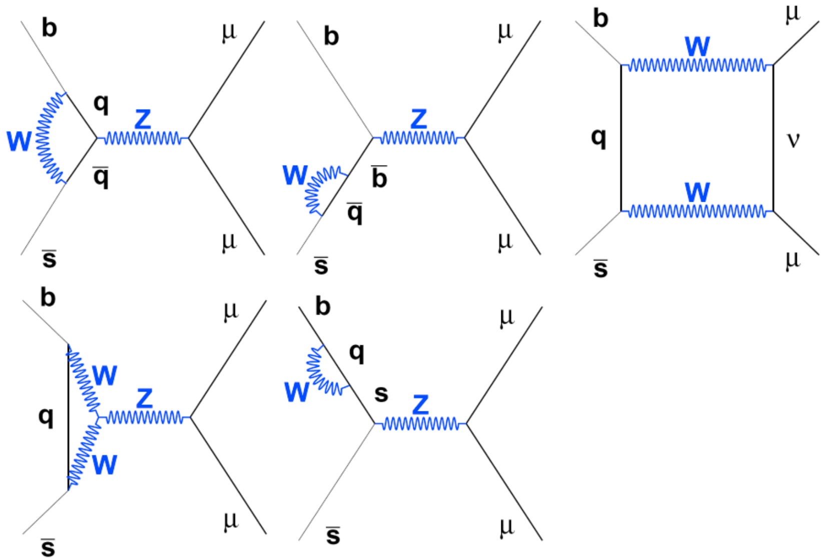
Searches for $B_{s/d} \rightarrow \mu^+\mu^-$

A Golden Mode for FCNC Searches

- In the SM the $B_{s(d)} \rightarrow \mu^+\mu^-$ process is very rare:
  - Cabibbo and helicity suppressed
  - Accesible via EW loop diagrams

$$BR(B_s \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$
$$BR(B^0 \rightarrow \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$$

A. J. Buras et al., JHEP 1010:009,2010



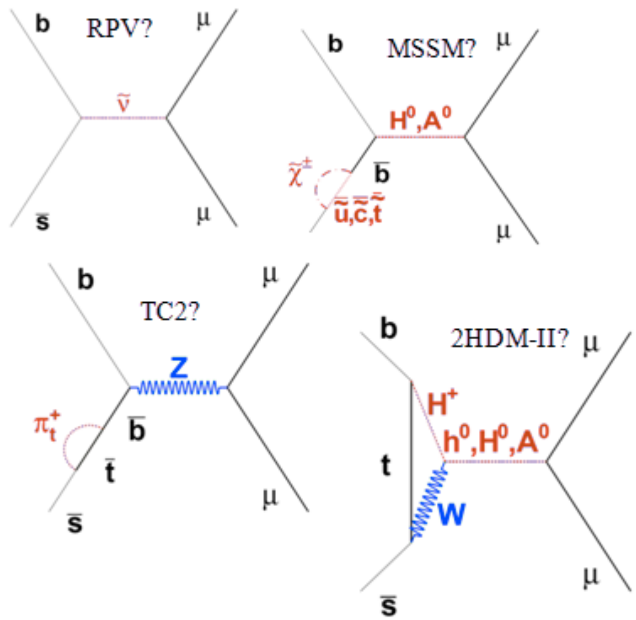
- Many New Physics models predict large enhancements, in particular those with new scalar operators:

  e.g. $\tan^6\beta$ enhancement in the MSSM.

  In NP models without new scalar operators, $BR(B_s \rightarrow \mu^+\mu^-) > 10^{-8}$ are unlikely.

- Ratio $BR(B_s \rightarrow \mu^+\mu^-)/BR(B_d \rightarrow \mu^+\mu^-)$ highly informative on whether NP significantly violates flavor or not.

- Very simple and robust experimental signature!



What Could be Learned?

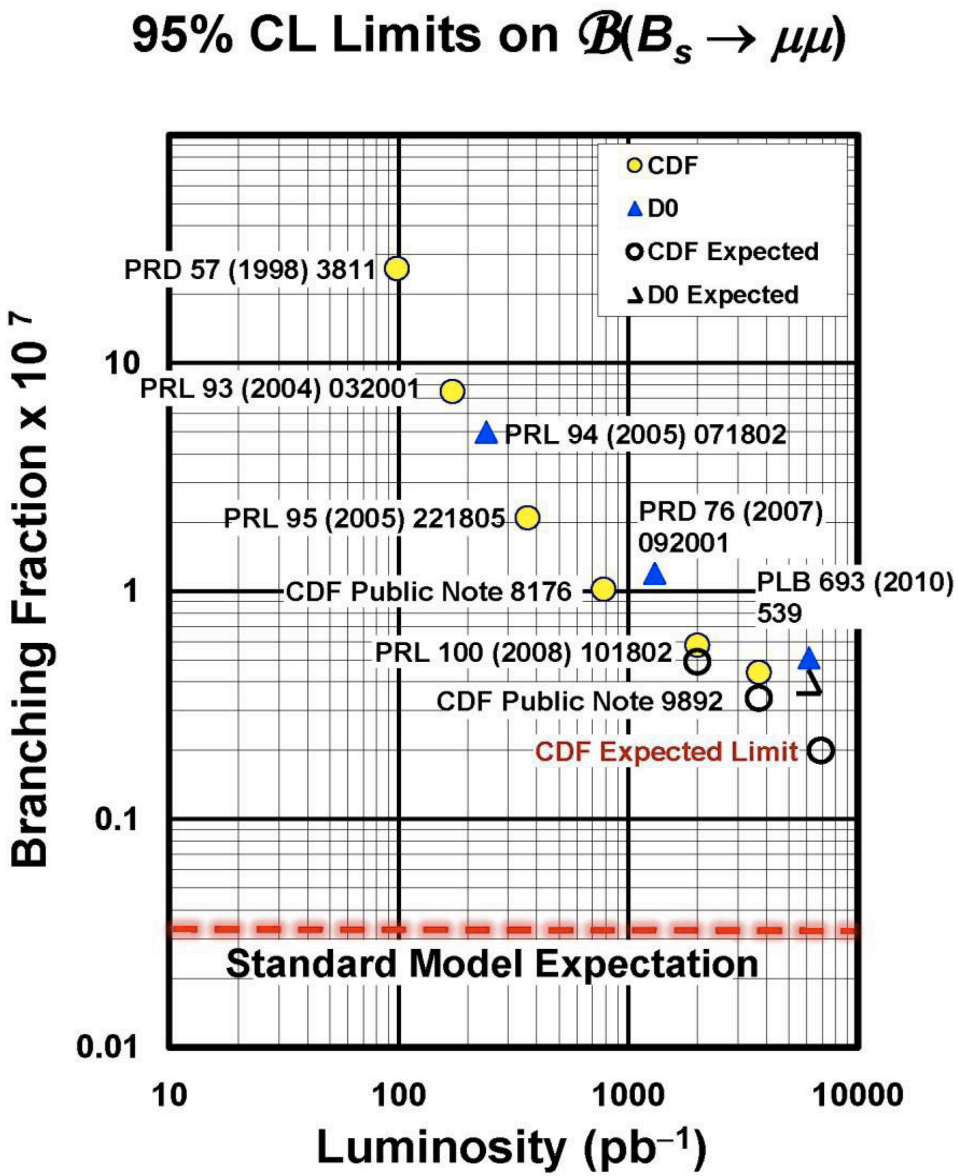
Scenario	*would point to ...*
$BR(B_s \to \mu\mu) >> SM$	*Big enhancement from NP in scalar sector, SUSY high tanβ*
$BR(B_s \to \mu\mu) \neq SM$	*SUSY (C_S, C_P) , ED's, LHT, TC2 (C_{10})...*
$BR(B_s \to \mu\mu) \sim SM$	*Anything (→ rule out regions of parameter space that predict sizable departures from SM. Obviously)*
$BR(B_s \to \mu\mu) << SM$	*NP in scalar sector, but full MSSM ruled out. NMSSM (Higgs singlet) good candidate*
$BR(B_s \to \mu\mu) / BR(B_d \to \mu\mu) \neq SM$	*CMFV ruled out. New FCNC sources fully independent of CKM matrix (RPV SUSY, ED's etc...)*

A Search with Tradition

- This is a search with a long-standing tradition at the Tevatron.

- The high integrated luminosity during Run 2, improved detectors and triggers and increasingly more sophisticated experimental techniques have improved the sensitivity by ~2 orders of magnitude wrt Run 1.

- Racing against the 400 pound gorilla…



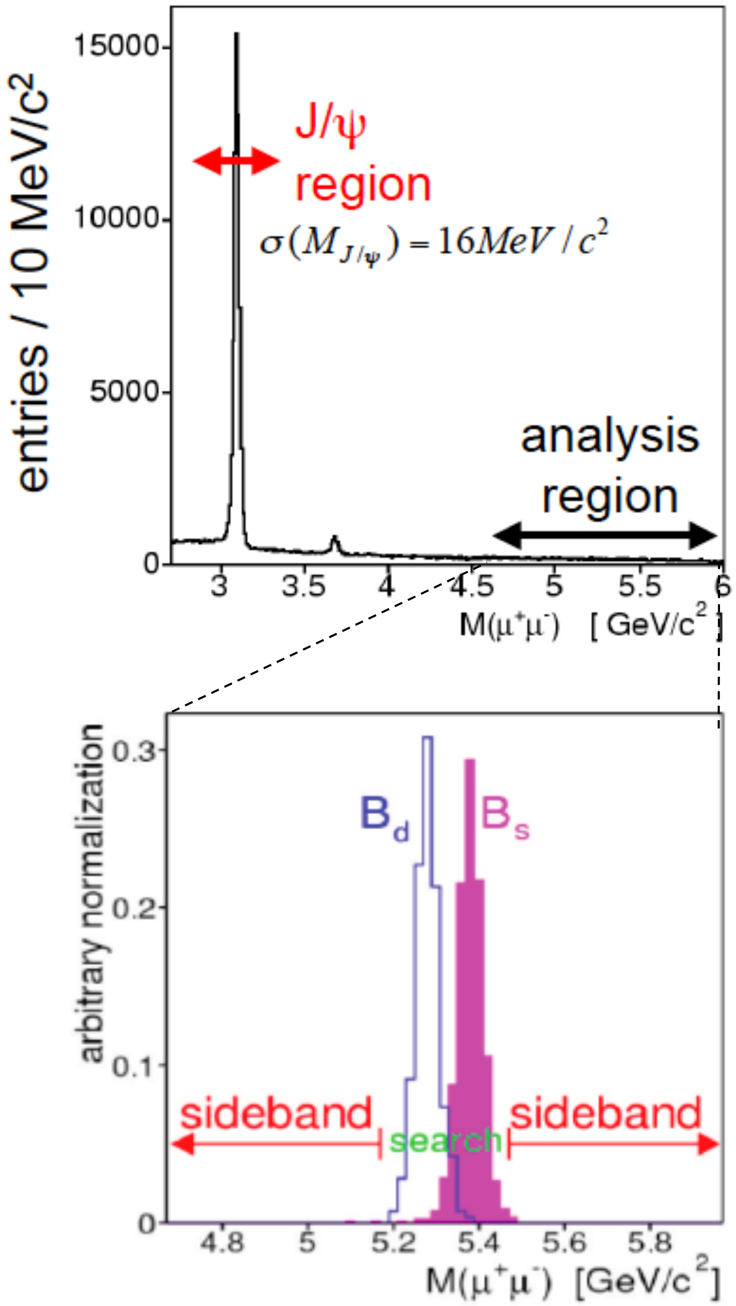
Search Strategy

- This is a relatively simple analysis:
  - Find events with 2 muons
    - Using dimuon triggers (7 fb^{-1})

      E.g. 2 muons, $p_{T\mu}$>1.5 GeV, $|\eta|$<0.6

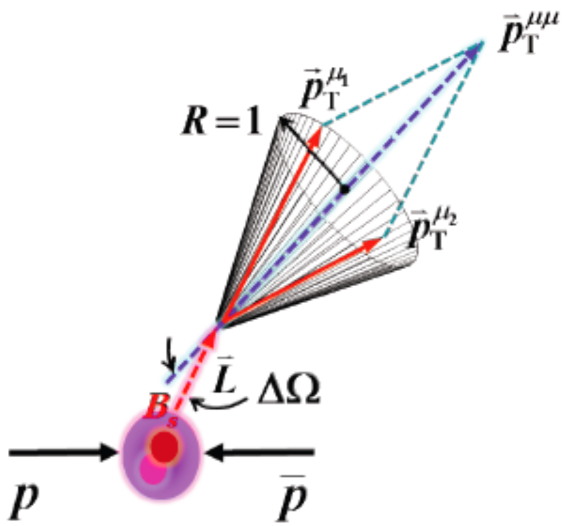
      $p_{T\mu1}+p_{T\mu2}$>4 GeV, 2.7<$m_{\mu\mu}$<6.0 GeV
  - Identify means to suppress background while keeping as much signal as possible
  - Look for a bump in the $m_{\mu\mu}$ distribution

- To avoid biasing the result:
  - "Blind" signal region: 5.169<$m_{\mu\mu}$<5.469 GeV
    - Corresponds to $\pm 6\sigma_m$, σ_m~24 MeV (2-track invariant mass resolution)
  - Use $m_{\mu\mu}$ sidebands to estimate dominant background in signal region:
    - Additional 0.5 GeV on either side
  - Employ an a-priori optimization to choose final selection criteria
  - Build confidence in background estimate using control regions prior to "opening the box"



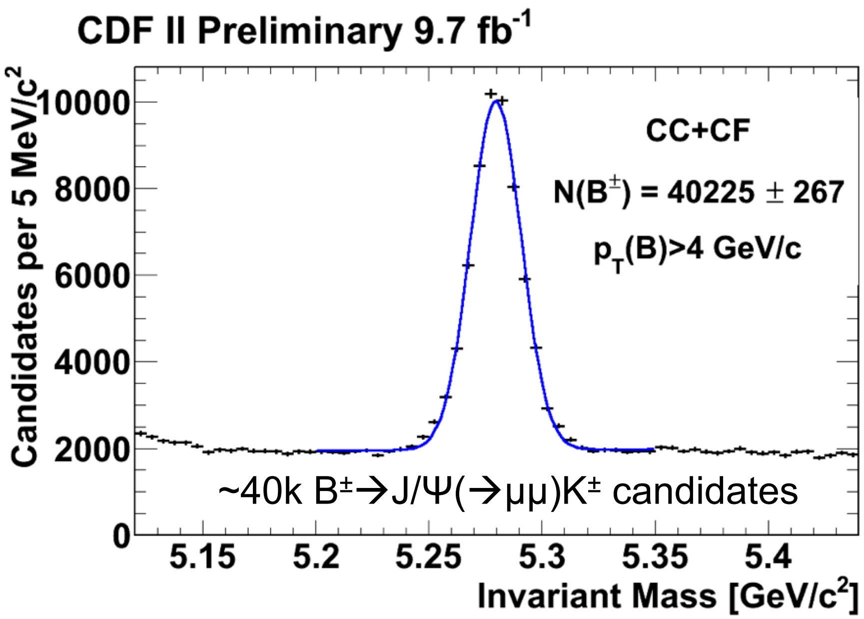
Preselection

- Apply loose preselection to identify sample containing $B_{s/d}$ and $B^{\pm}$ candidates:
    - Good-quality tracks constrained to common 3D vertex
    - p_T of B candidate and muon tracks
    - Isolation of B candidate and pointing angle ($\Delta\Omega$)
    - Significance of proper decay time
    - Invariant mass of B candidate
- Large sample of $B^{\pm} \to J/\Psi(\to \mu\mu)K^{\pm}$ used as normalization mode to cancel common systematic uncertainties



$$\text{Isolation} = \frac{p_T(\mu\mu)}{\sum p_T(tracks) + p_T(\mu\mu)}$$

all tracks within a cone of R=1 around $p_T(\mu\mu)$ considered



$$BF(B_{s,d} \to \mu^+\mu^-) = \left(\frac{N_{Bs,d}}{N_{B+}}\right)\left(\frac{\alpha_{B+}\varepsilon_{B+}}{\alpha_{Bs,d}\varepsilon_{Bs,d}}\right)\left(\frac{f_u}{f_s}\right) BF(B^+ \to J/\psi K^+)$$

From fits to the data.

From the PDG 2010:

$$\frac{f_u}{f_s} = 3.55 \pm 0.47$$

$$BF(B^+ \to J/\psi K^+) BF(J/\psi \to \mu^+\mu^-) = (6.01 \pm 0.21) \times 10^{-5}$$

Preselection

- Apply loose preselection to identify sample containing $B_{s/d}$ and $B^{\pm}$ candidates:
  - Good-quality tracks constrained to common 3D vertex
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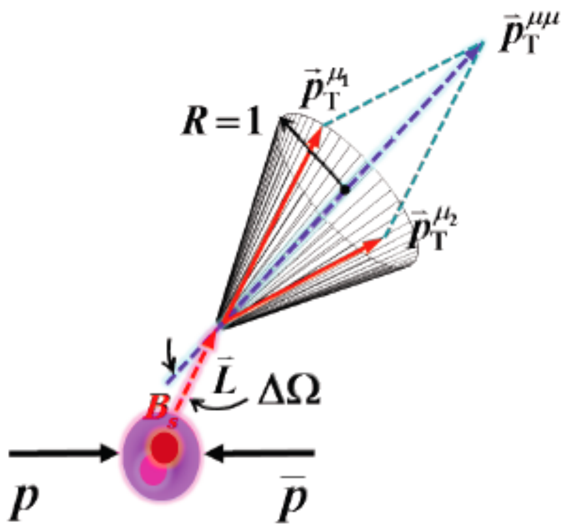
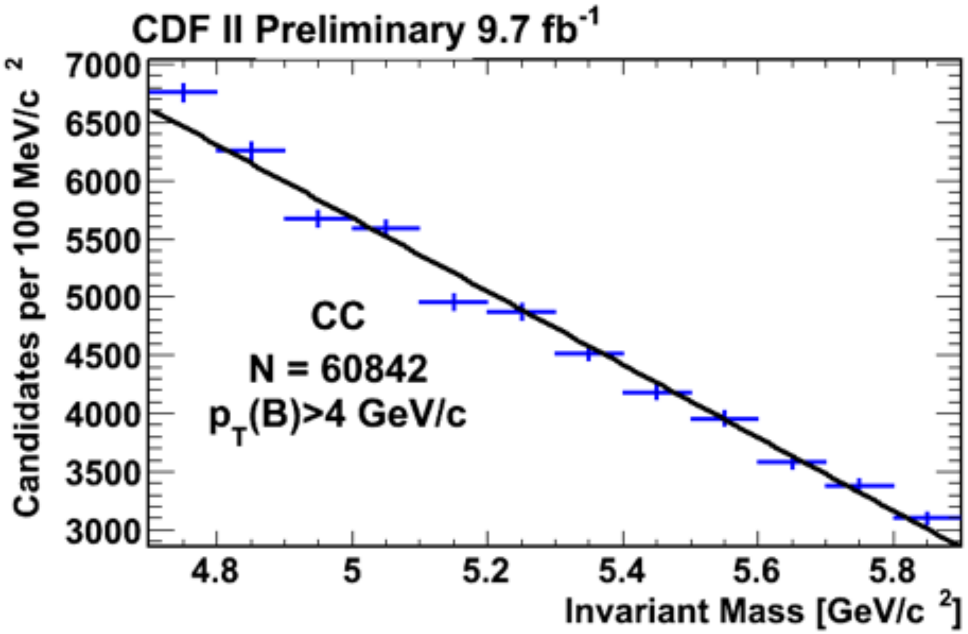


Isolation = $\frac{p_T(\mu\mu)}{\sum p_T(tracks) + p_T(\mu\mu)}$

all tracks within a cone of R=1 around $p_T(\mu\mu)$ considered

- At this stage the $B_{s(d)}$ search sample is background-dominated:



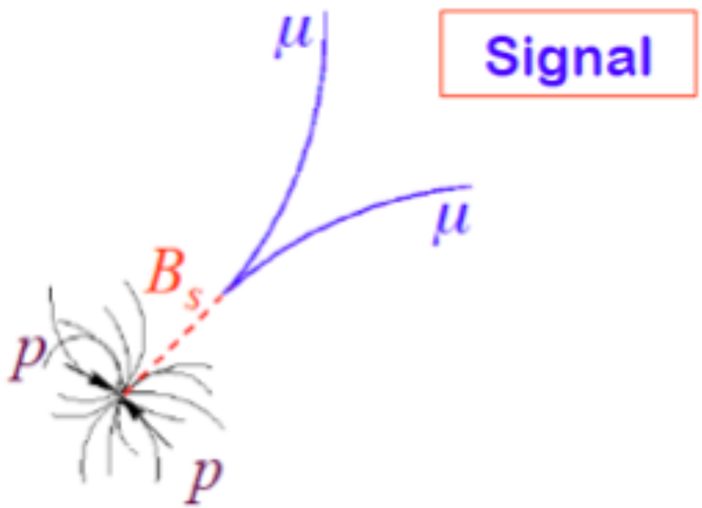
~125k candidates

Assuming SM production, ~2 signal events expected

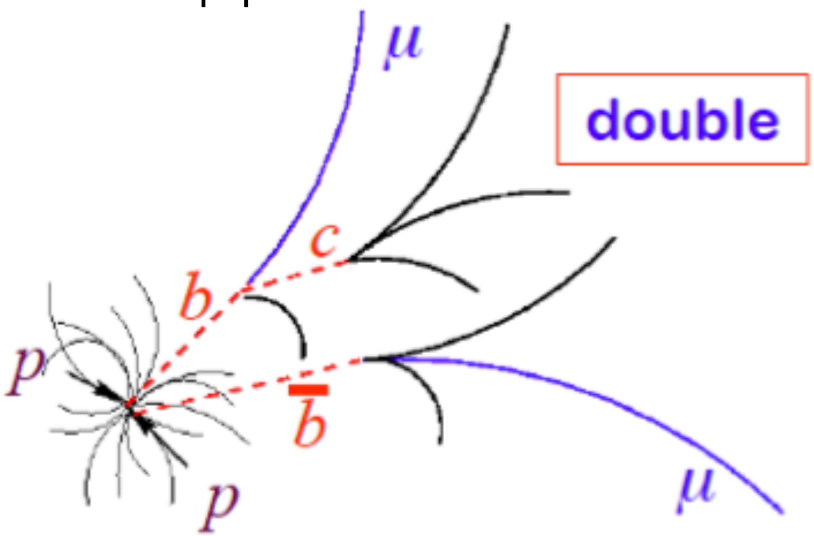
➔ Need to reduce background by 10^5!

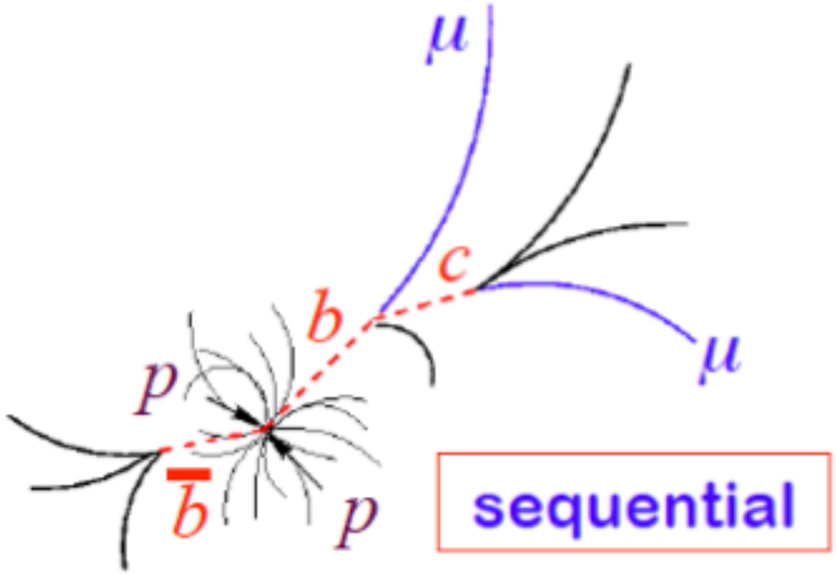
$B_{s(d)}$ Signal vs Background

- Signal characteristics:
  - Final state fully reconstructed
  - B-fragmentation is hard: few extra tracks, L and $p_T(\mu\mu)$ are collinear
  - $B_{s(d)}$ has long lifetime, ~1.5 ps



- Backgrounds:
  - Sequential semi-leptonic decay: $b \rightarrow c\mu^{-}X \rightarrow \mu^{+}\mu^{-}X$
  - Double semileptonic decay: $bb \rightarrow \mu^{+}\mu^{-}X$





$B_{s(d)}$ Signal vs Background

- Signal characteristics:
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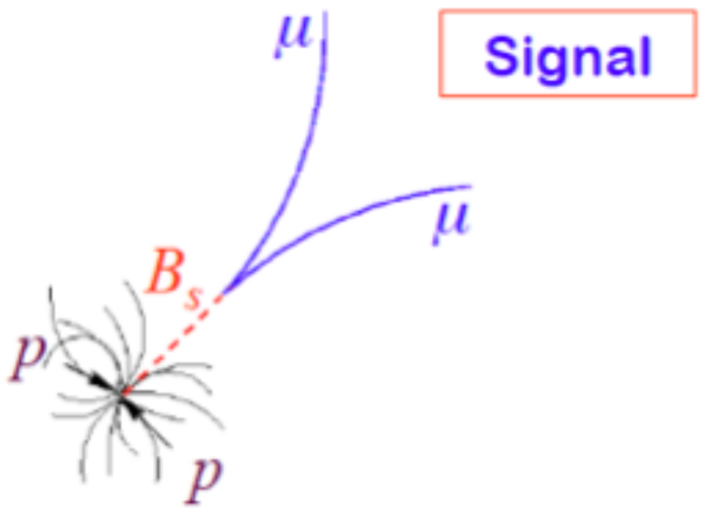
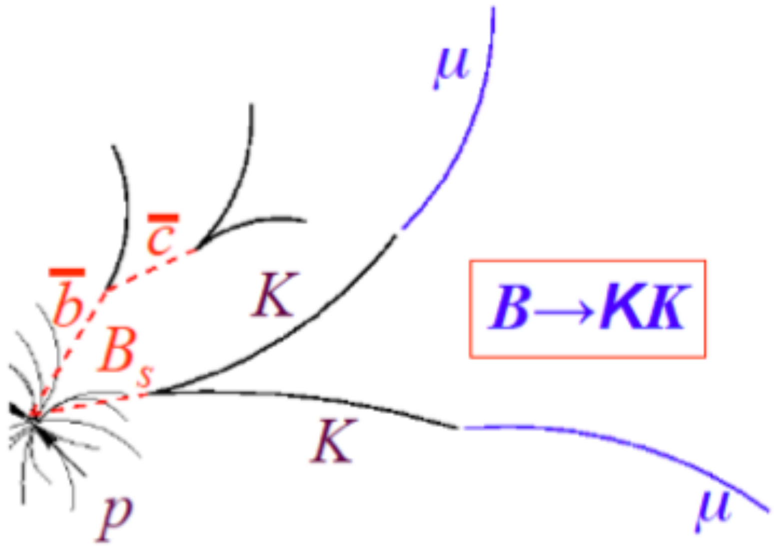


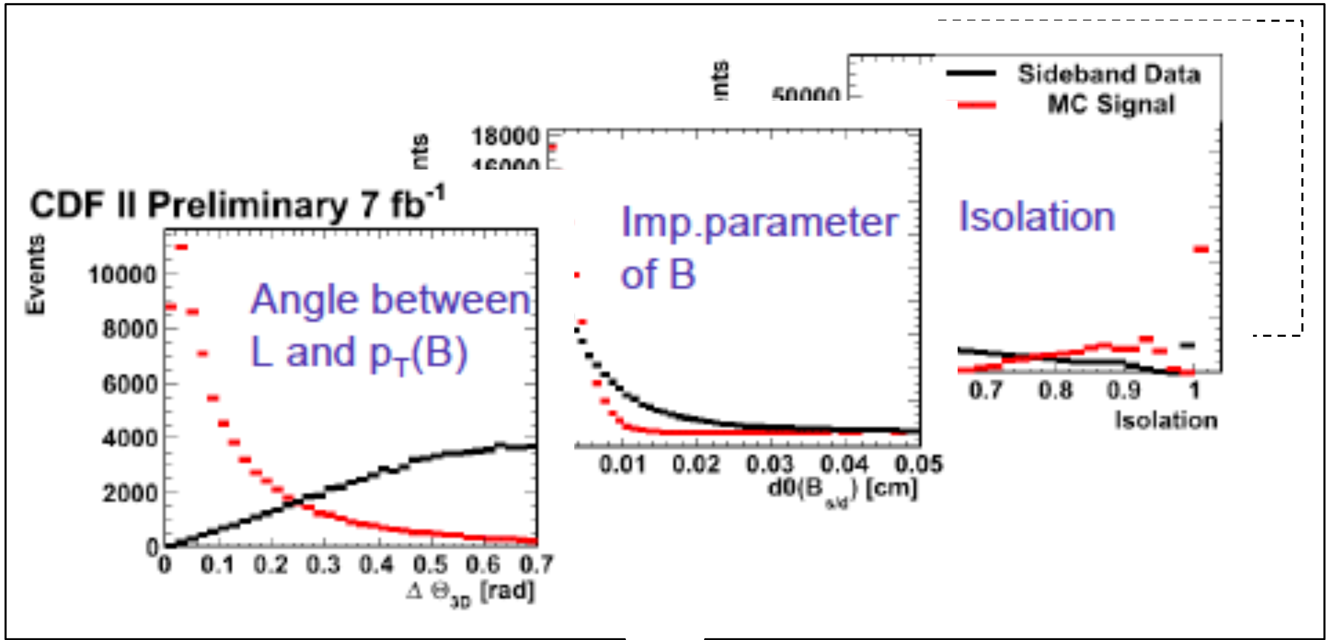
- Backgrounds:
  - Sequential semi-leptonic decay:
    $b \to c\mu^- X \to \mu^+\mu^- X$
  - Double semileptonic decay:
    $bb \to \mu^+\mu^- X$
  - Continuum $\mu^+\mu^-$
  - μ+fake, fake+fake

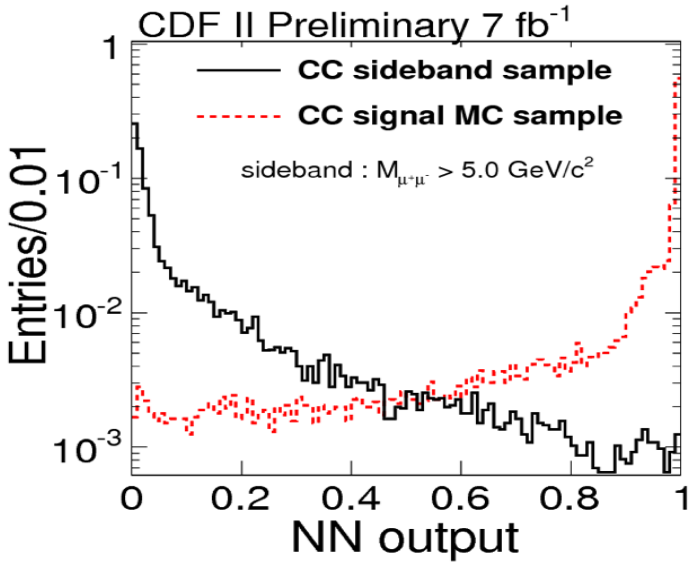


- Good discriminators: isolation, mass, lifetime, p_T , how well p_T aligns with L

Signal-to-Background Discrimination

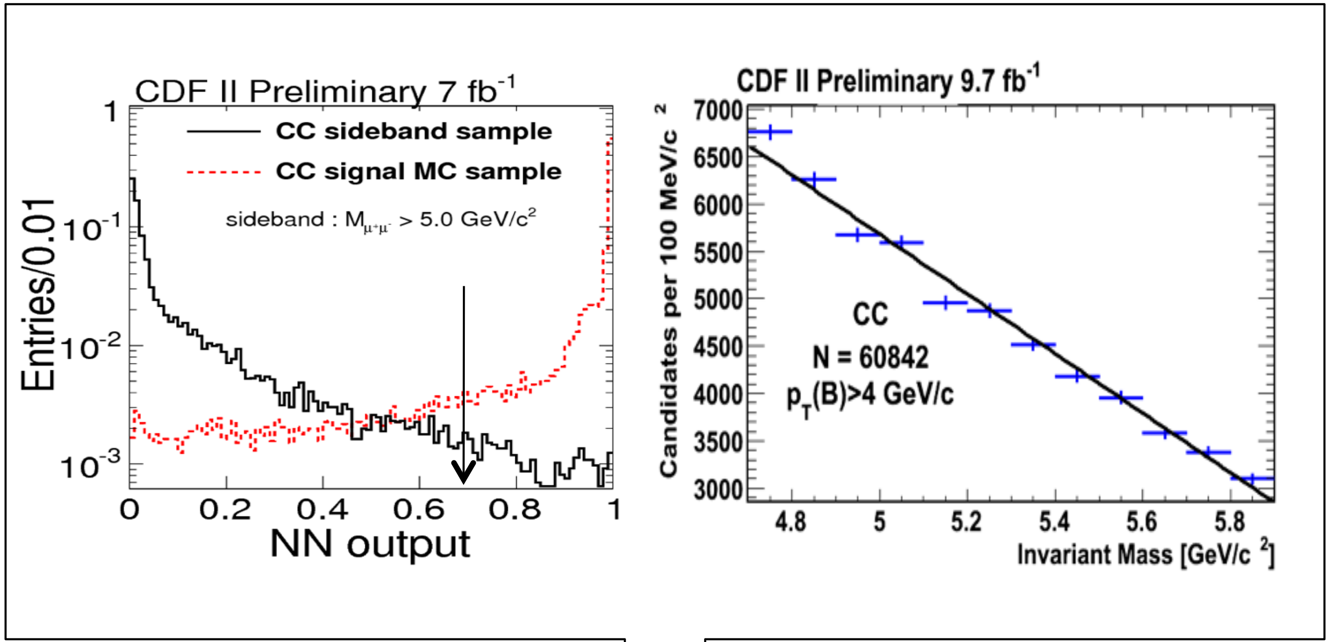
- 14 variables are combined into a Neural Network (except $M_{\mu\mu}$).
- NN trained to separate signal MC and sideband data.

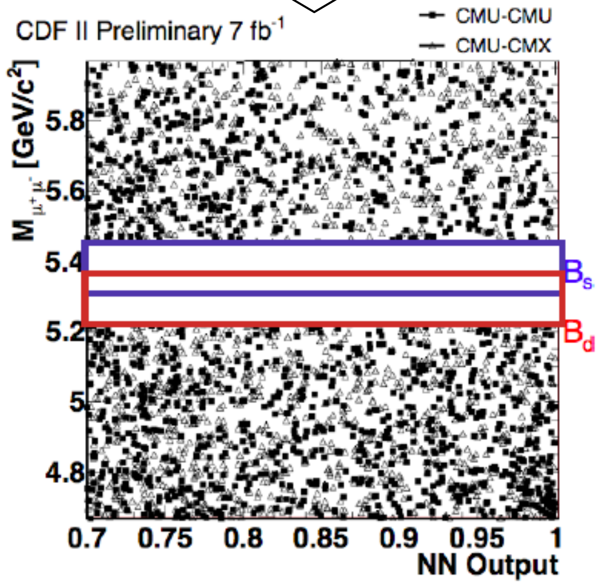




Signal-to-Background Discrimination

- 14 variables are combined into a Neural Network (except $m_{\mu\mu}$).
- NN trained to separate signal MC and sideband data.
- NN>0.7 cut is applied to reduce background independent of $m_{\mu\mu}$.
- Analysis will be performed in 2D plane of NN vs $m_{\mu\mu}$.
  - $B_{s(d)}$ mass windows remain blinded
  - Binning choice optimized for best expected limit.





Background Estimation

- Two main backgrounds:
  1. Combinatoric backgrounds:
     - bb → $\mu^+\mu^- X$
     - Continuum $\mu^+\mu^-$
     - b/c→μ+fake μ (K/π)

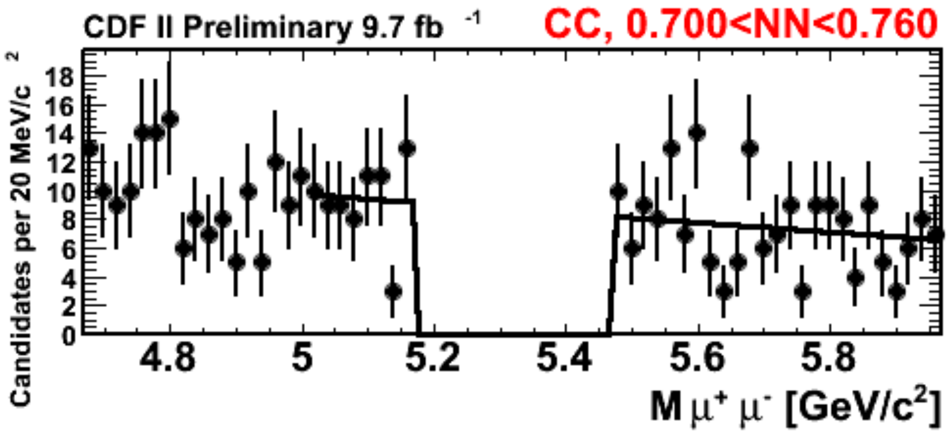
     ➔ estimated from sideband fit in each NN bin
  2. 2-body hadronic B decays:

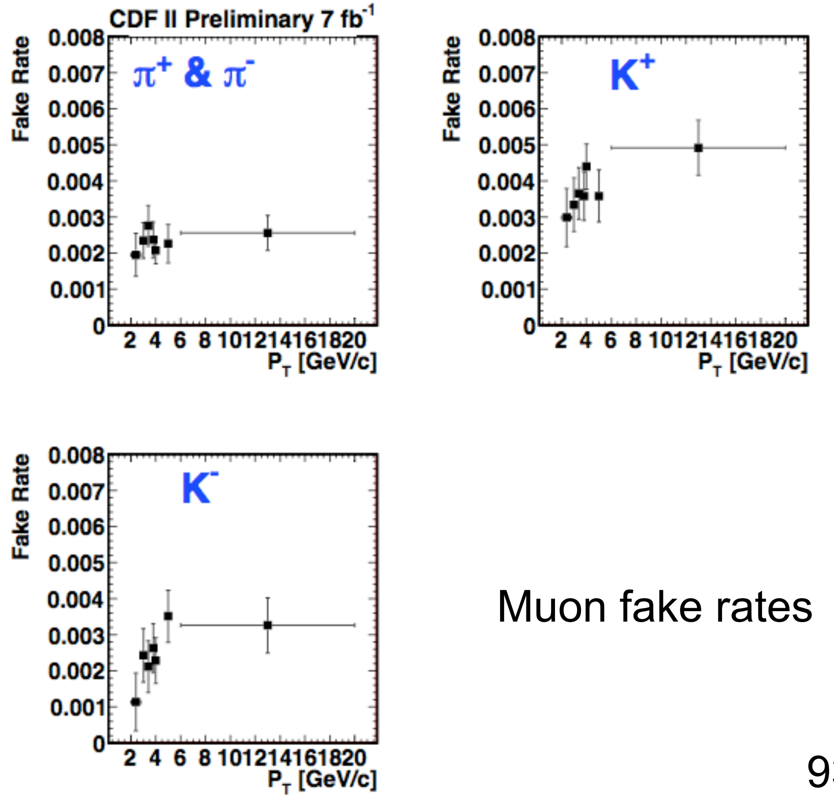
     B→hh where h→fake μ (K/π)

     ➔ peaking in signal region

     ➔ estimated by applying fake muon rates measured in $D^0 \to K^-\pi^+$ data to B→hh MC.

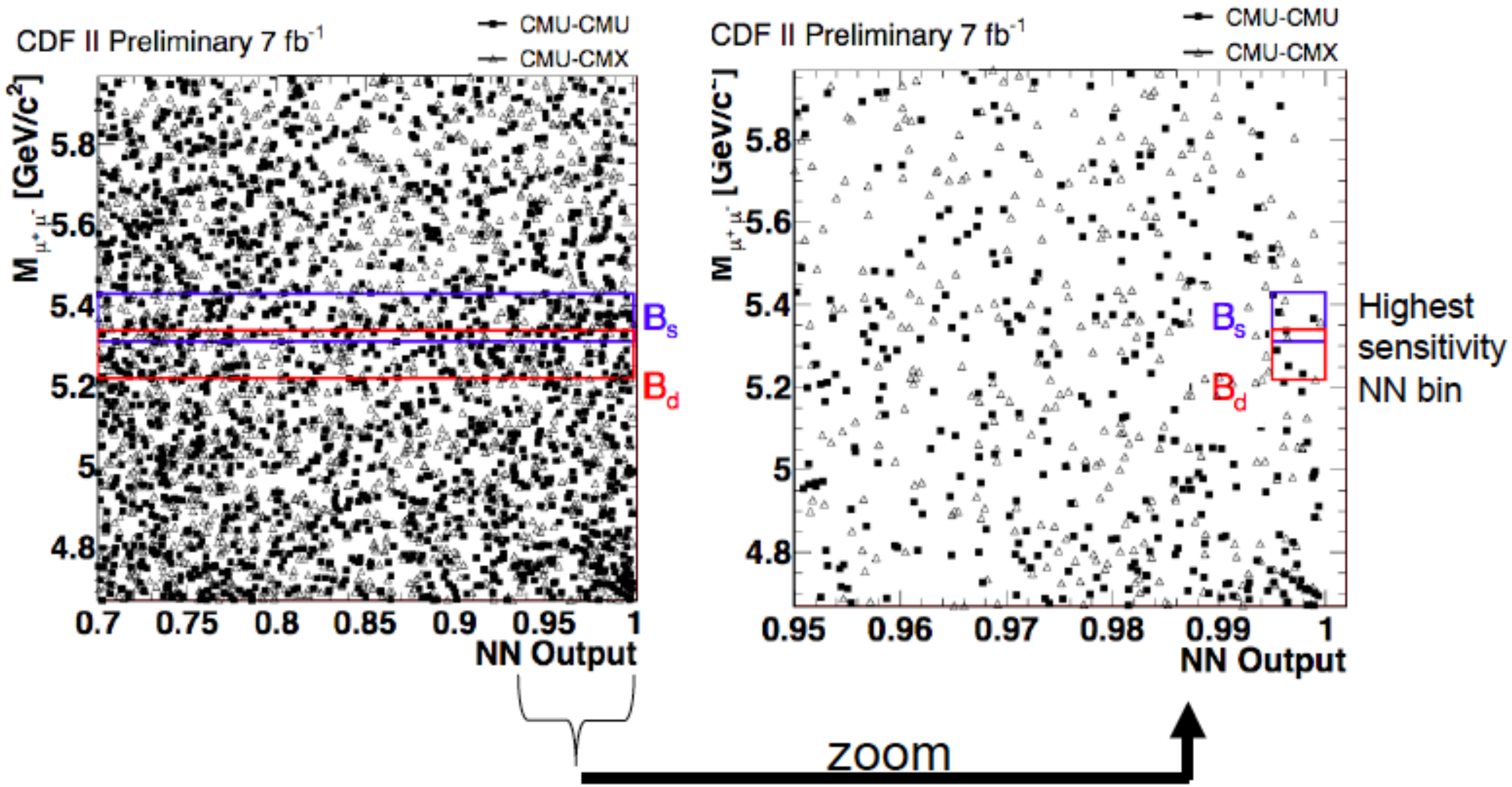
- Background modeling validated in a number of statistically-independent control samples.



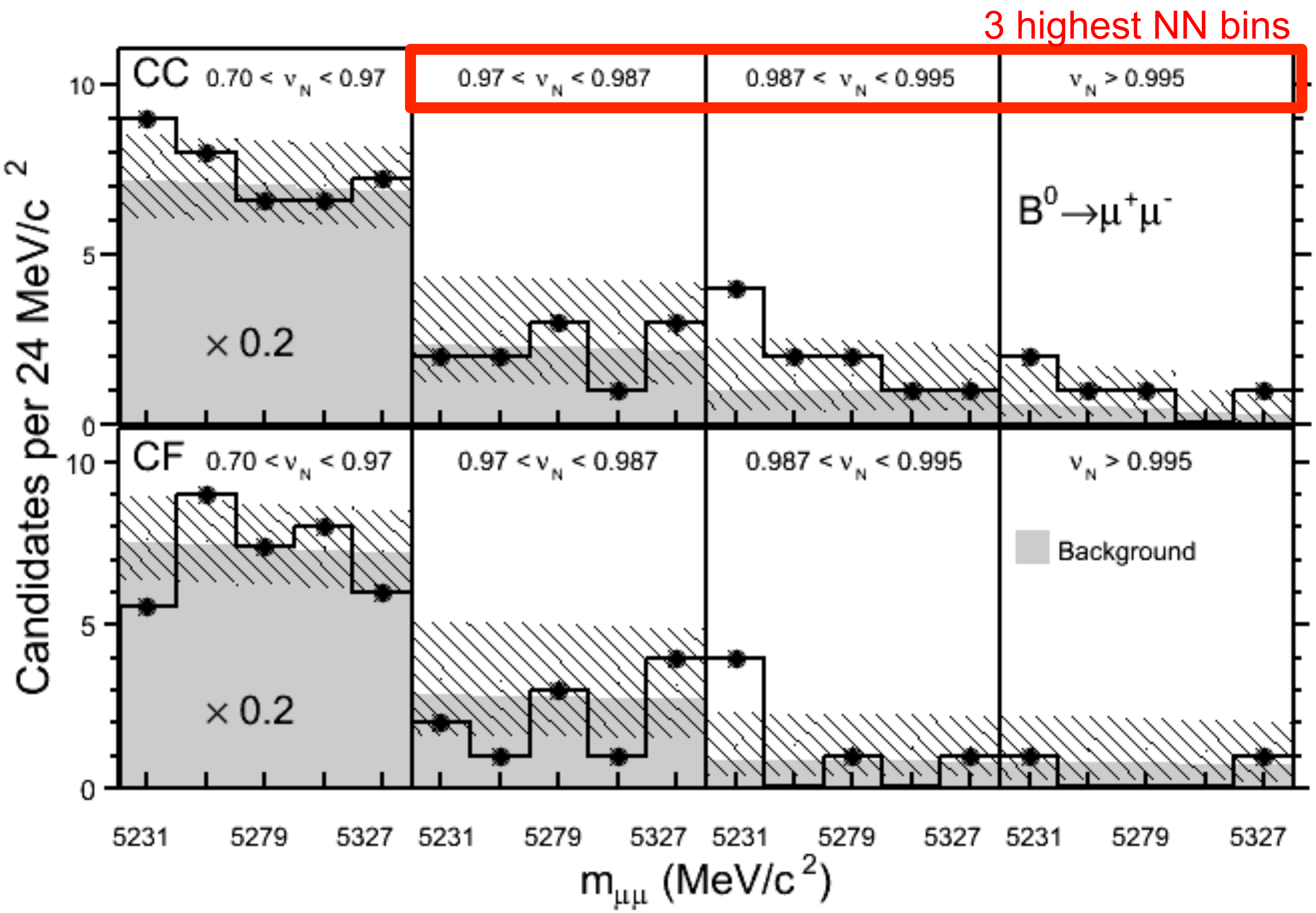


Muon fake rates

Opening the Box



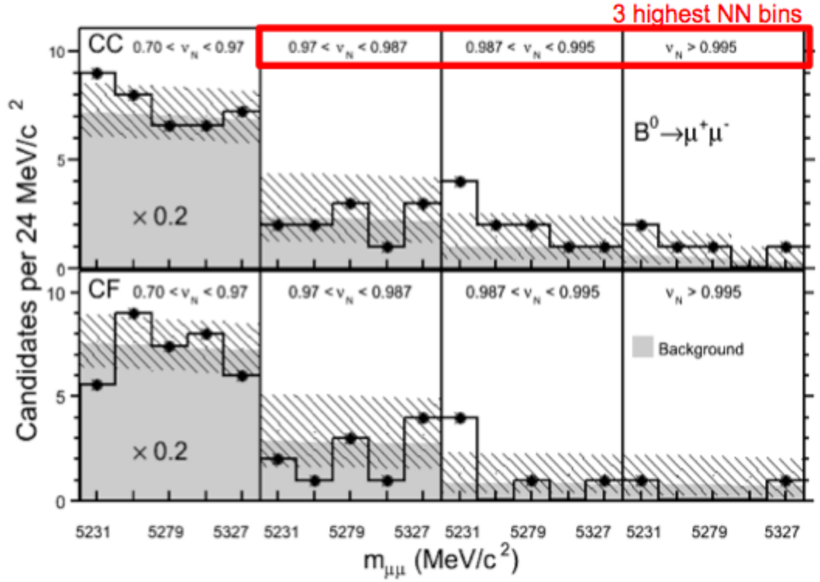
$B_d \rightarrow \mu^+\mu^-$ Search: Opened Box



- Data and background expectation are in good agreement.
- What have learned about $BR(B_d \rightarrow \mu^+\mu^-)$?

Interpreting the Data

- Use the final discriminant distributions to perform hypothesis testing (S+B vs B-only).
- In absence of an excess, typically set limits using:
  - The CL_s method or
  - A Bayesian method



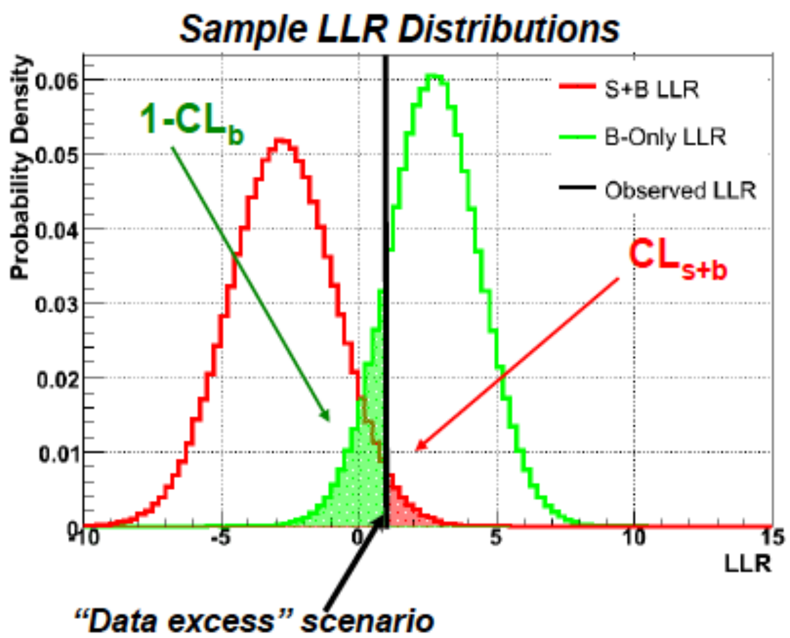
CL_s method

1. Compute the likelihood ratio for S+B ("test") vs B-only ("null") hypothesis using Poisson statistics:

$$Q(\vec{d};\vec{s},\vec{b}) = \prod_{i=1}^{N_{chan}} \prod_{j=1}^{N_{bins}} \frac{(s+b)_{ij}^{d_{ij}} e^{-(s+b)_{ij}}}{d_{ij}!} \Big/ \frac{b_{ij}^{d_{ij}} e^{-b_{ij}}}{d_{ij}!}$$

$$LLR = -2\ln Q$$

2. Generate pseudo-experiments for S+B and B-only hypotheses via Poisson trial.
   - Systematics are folded in via Gaussian marginalization
   - Correlations held amongst signals and backgrounds



Interpreting the Data

CL_s method (cont'd)

3. Compute two confidence levels:

$$CL_{s+b} = P_{s+b}(LLR > LLR_{obs})$$
$$CL_{b} = P_{b}(LLR > LLR_{obs})$$

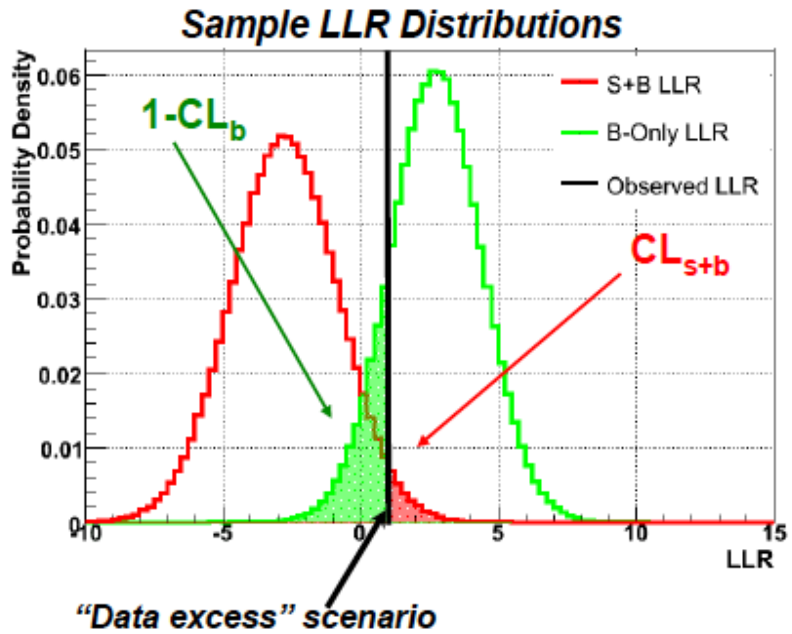
4. Define CL_s as:

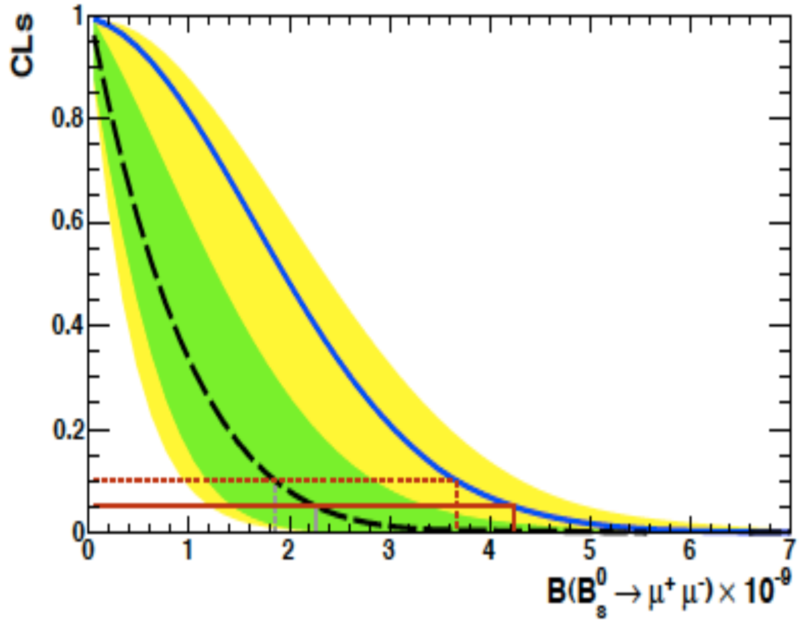
$$CL_s = \frac{CL_{s+b}}{CL_b}$$

<u>Note:</u> *CL_s is a ratio of confidence levels (not a CL itself). This construction avoids exclusions of the null hypothesis due to downward background fluctuations.*

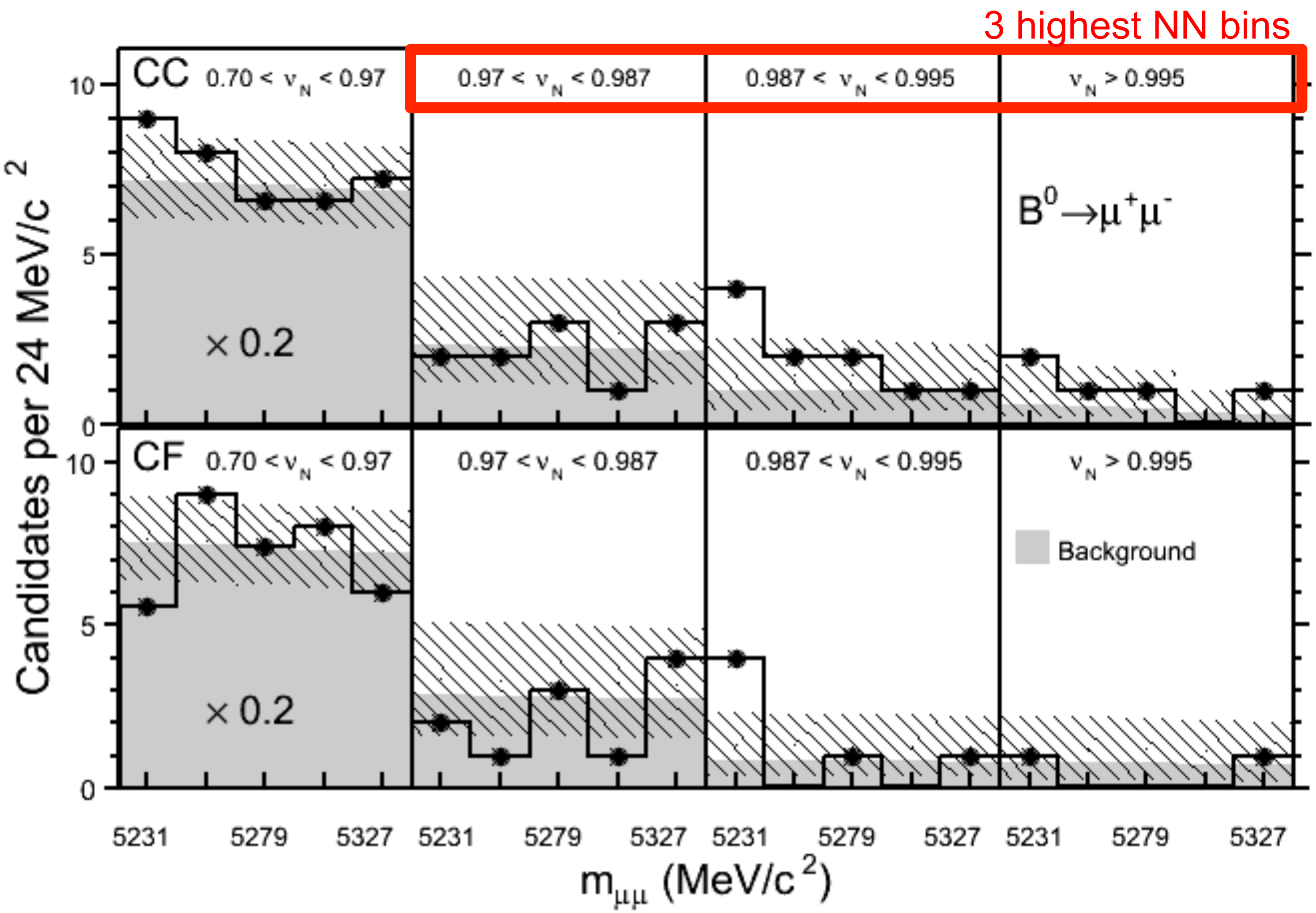
5. If CL_s<0.05, the test hypothesis is deemed excluded at ≥95% CL. (CL_s<0.1 for 90% CL exclusion).

   If instead of LLR_{obs}, use median LLR under the null hypothesis, set expected limit.



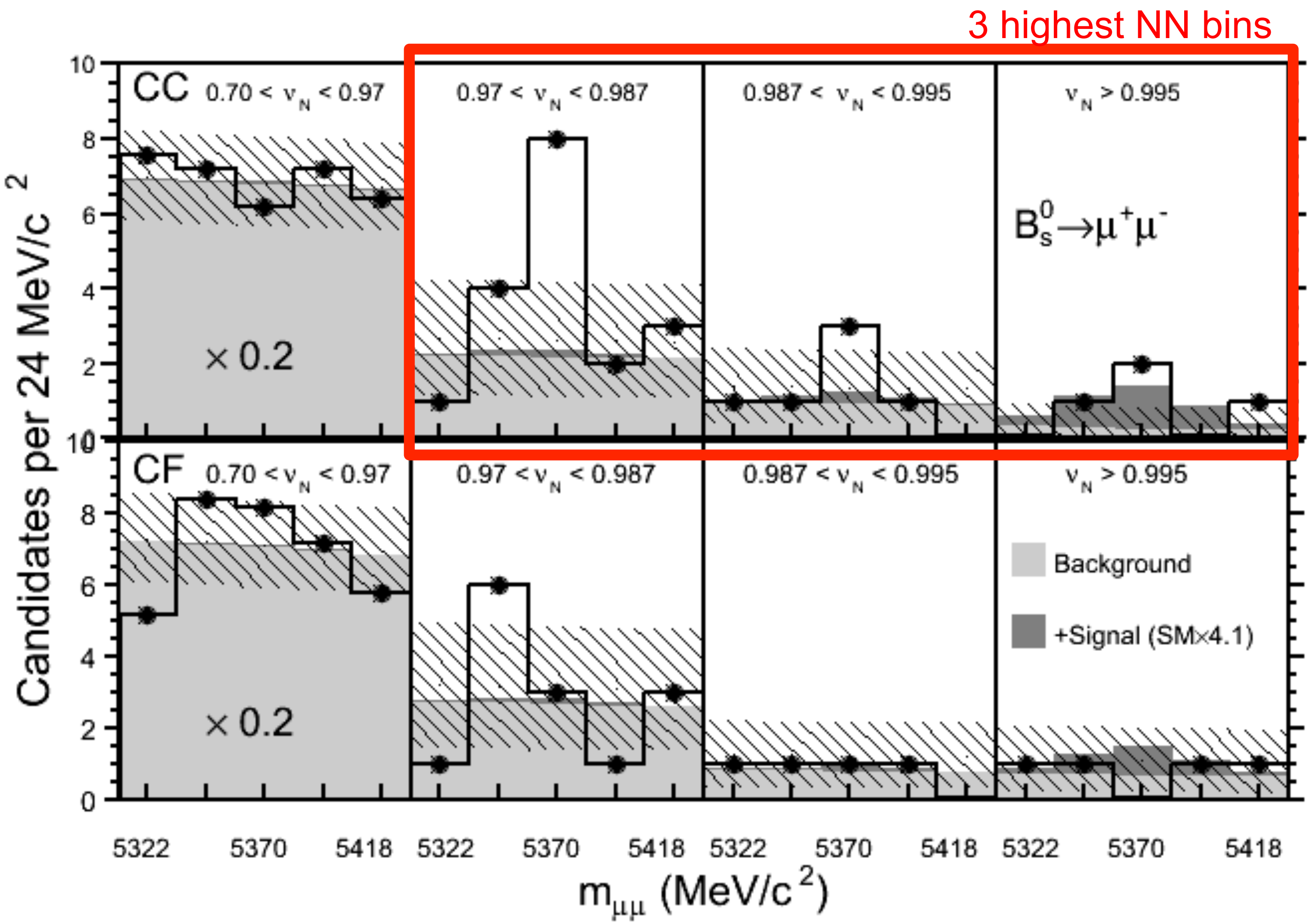


$B_d \to \mu^+\mu^-$ Search: Observed Limit



- Data and background expectation are in good agreement.
- Set 95% CL upper limit: BR($B_d \to \mu^+\mu^-$)<4.6x10^{-9} (expected: 4.0x10^{-9})
- Limit still a factor of ~46 above the SM prediction of BR($B_d \to \mu^+\mu^-$) = (1.0±0.1)x10^{-10}

$B_s \to \mu^+\mu^-$ Search: Opened Box



- Observe an excess above background expectation, concentrated in the 3 highest NN bins of the CC sample.

$B_s \rightarrow \mu^+\mu^-$ Search: Observed Limit

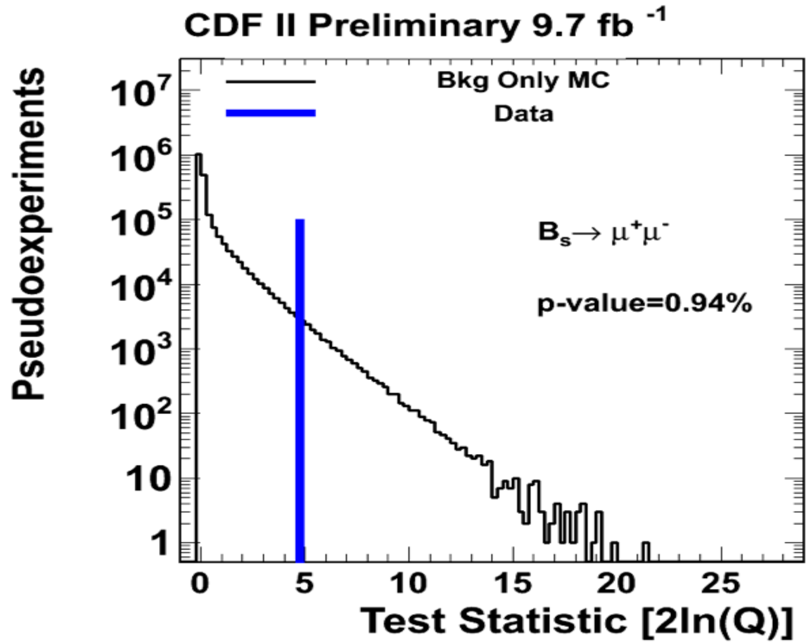
- Observed 95% CL upper limit:
  $BR(B_s \rightarrow \mu^+\mu^-) < 3.1\times10^{-8}$ (expected: 1.3×10^{-8})

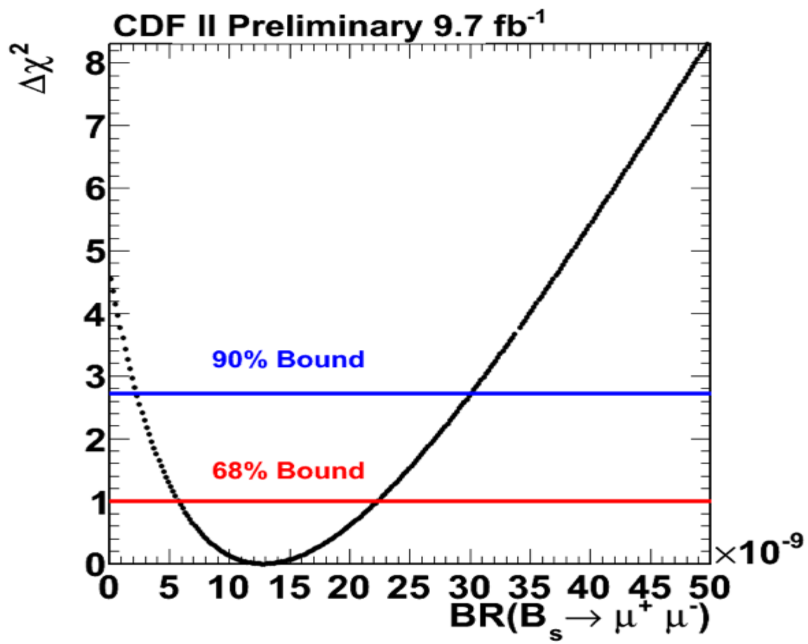
- Need statistical interpretation of the observed excess:
  - what is the level of inconsistency with the background?
    Observed CL_b=0.94% ➔ 2.4σ discrepancy
  - what does a fit to the data in the B_s search window yield?

    Best fit (68% CL):
    $BR(B_s \rightarrow \mu^+\mu^-) = (1.3^{+0.9}_{-0.7})\times10^{-8}$

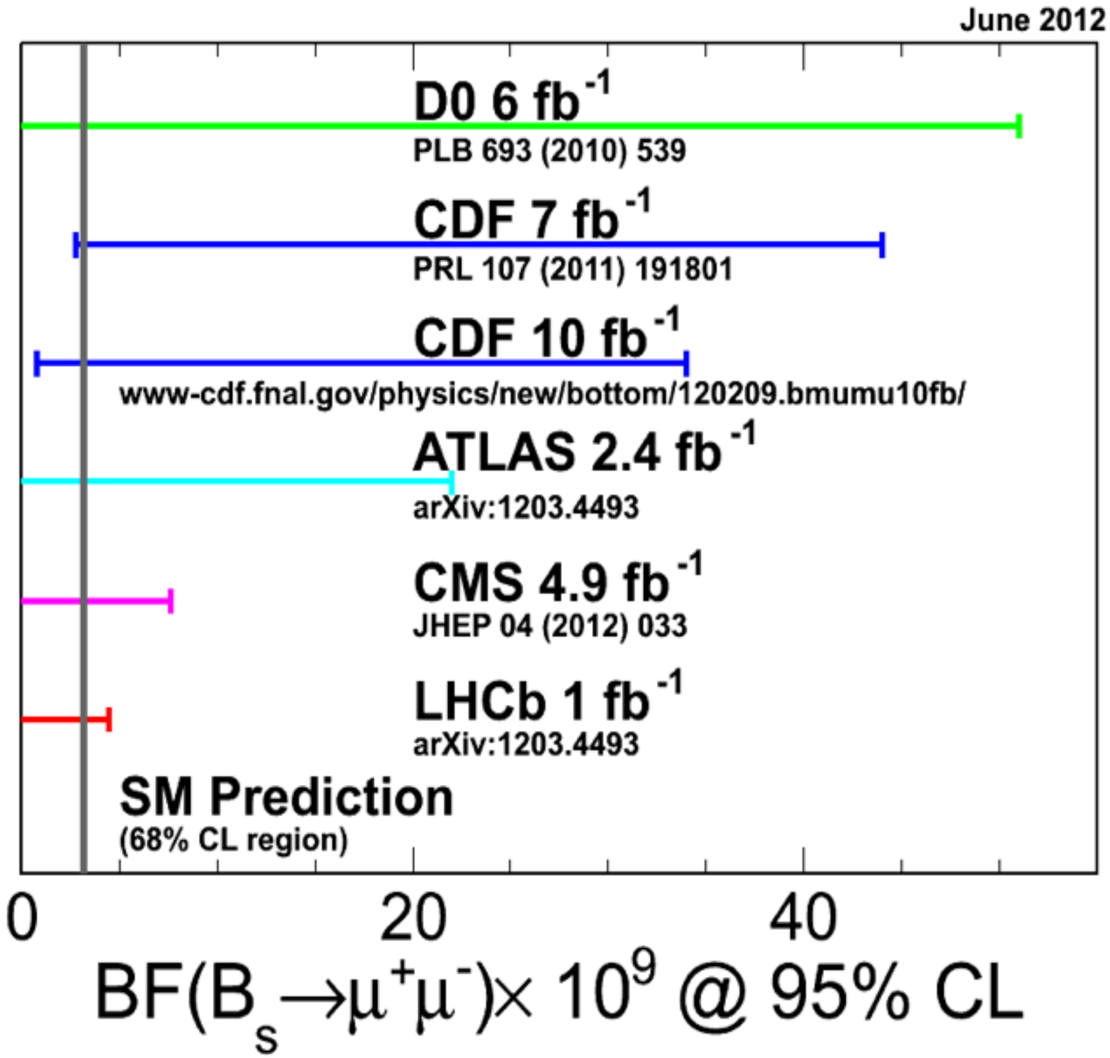
    Two-sided limit (95% CL):
    $0.8\times10^{-8} < BR(B_s \rightarrow \mu^+\mu^-) < 3.4\times10^{-8}$

- SM prediction: $BR(B_s \rightarrow \mu^+\mu^-) = (3.2\pm0.2)\times10^{-9}$





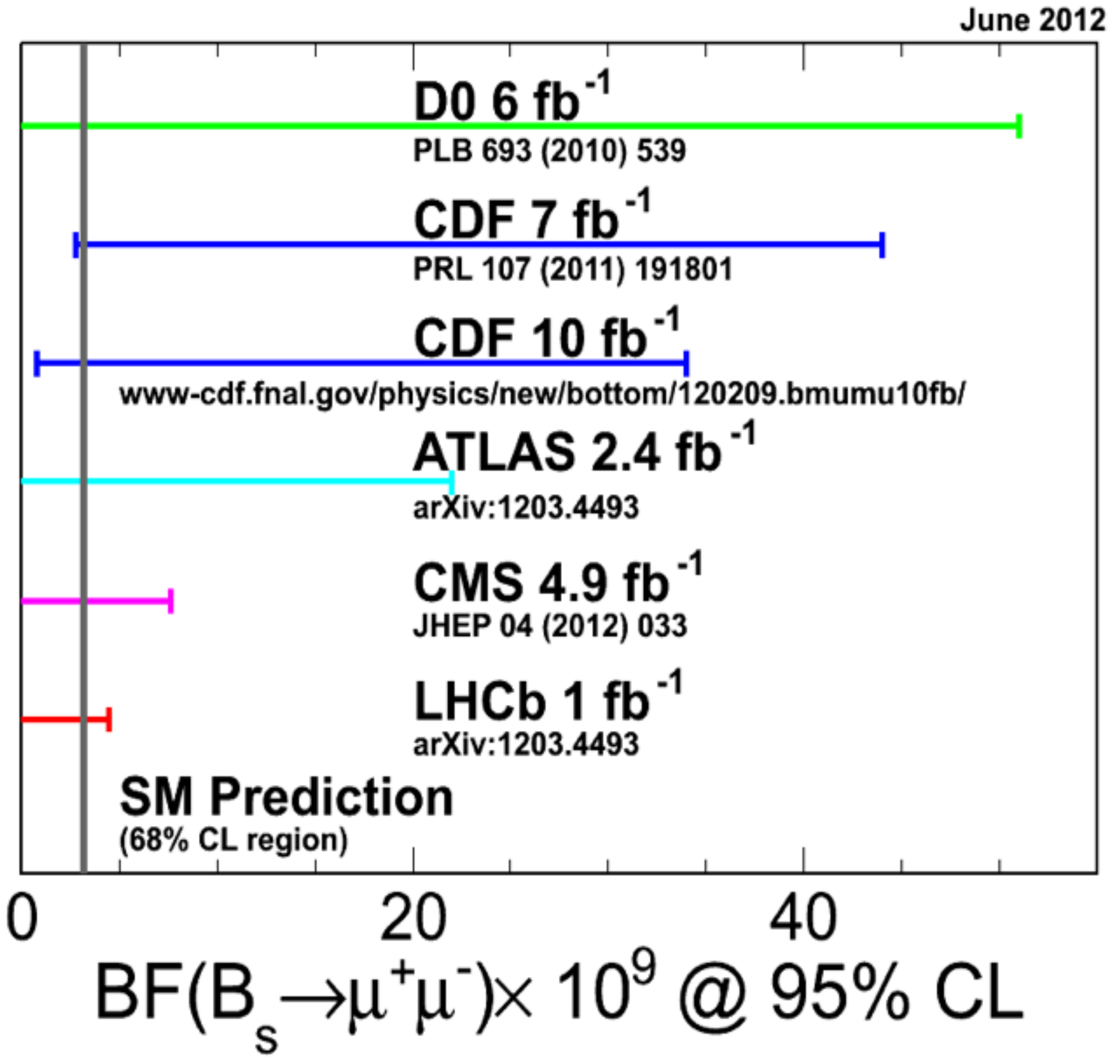
Current Status and Outlook

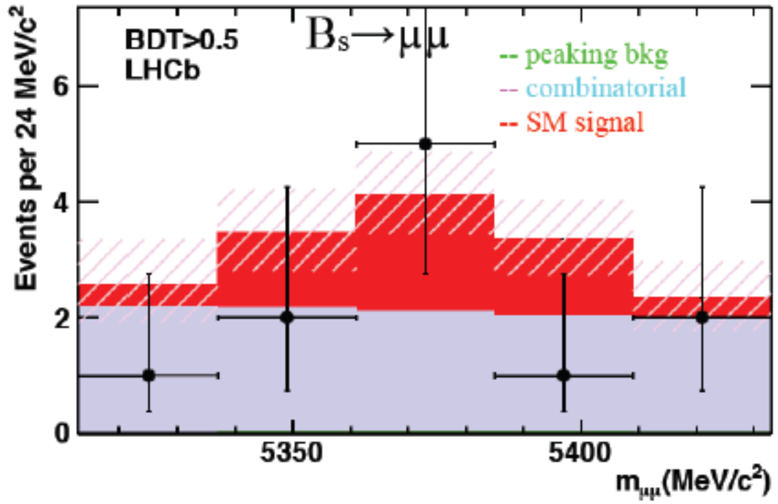


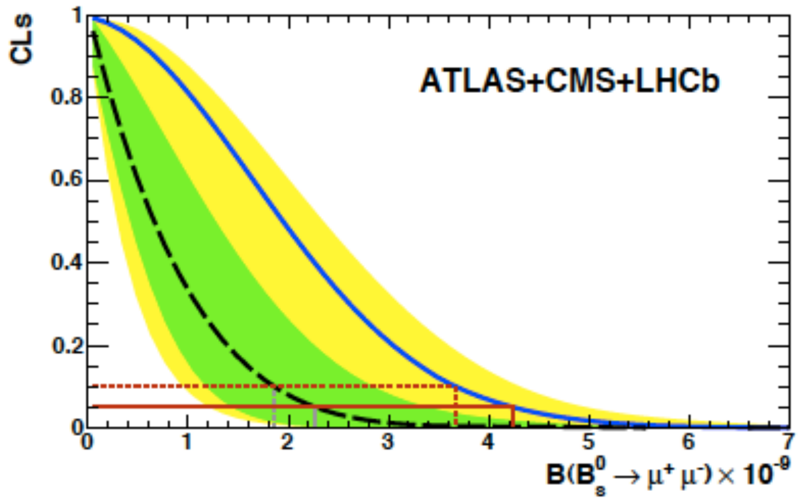
The gorilla is out...

LHC:
ATLAS, CMS,
LHCb

Current Status and Outlook







$BR(B_s \to \mu^+\mu^-) < 4.2 \times 10^{-9}$ @ 95%CL

With 2.5 fb^{-1} (end of 2012) LHCb should see a SM signal at 3σ (if it exists...)