Boosted Objects at the Tevatron

Thomas Gadfort / BNL

BOOST 2010 Oxford

Outline

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- Brief overview of the Tevatron and CDF and DØ detectors
- What's left for new physics at the Tevatron?
- Boosted searches at the Tevatron
  - SUSY + dark photons
  - Higgs → aa → μμ + μμ(ττ)
  - NLLP → bb
- Brief comment on boosted tops
- Summary & Outlook

Fermilab Tevatron Collider

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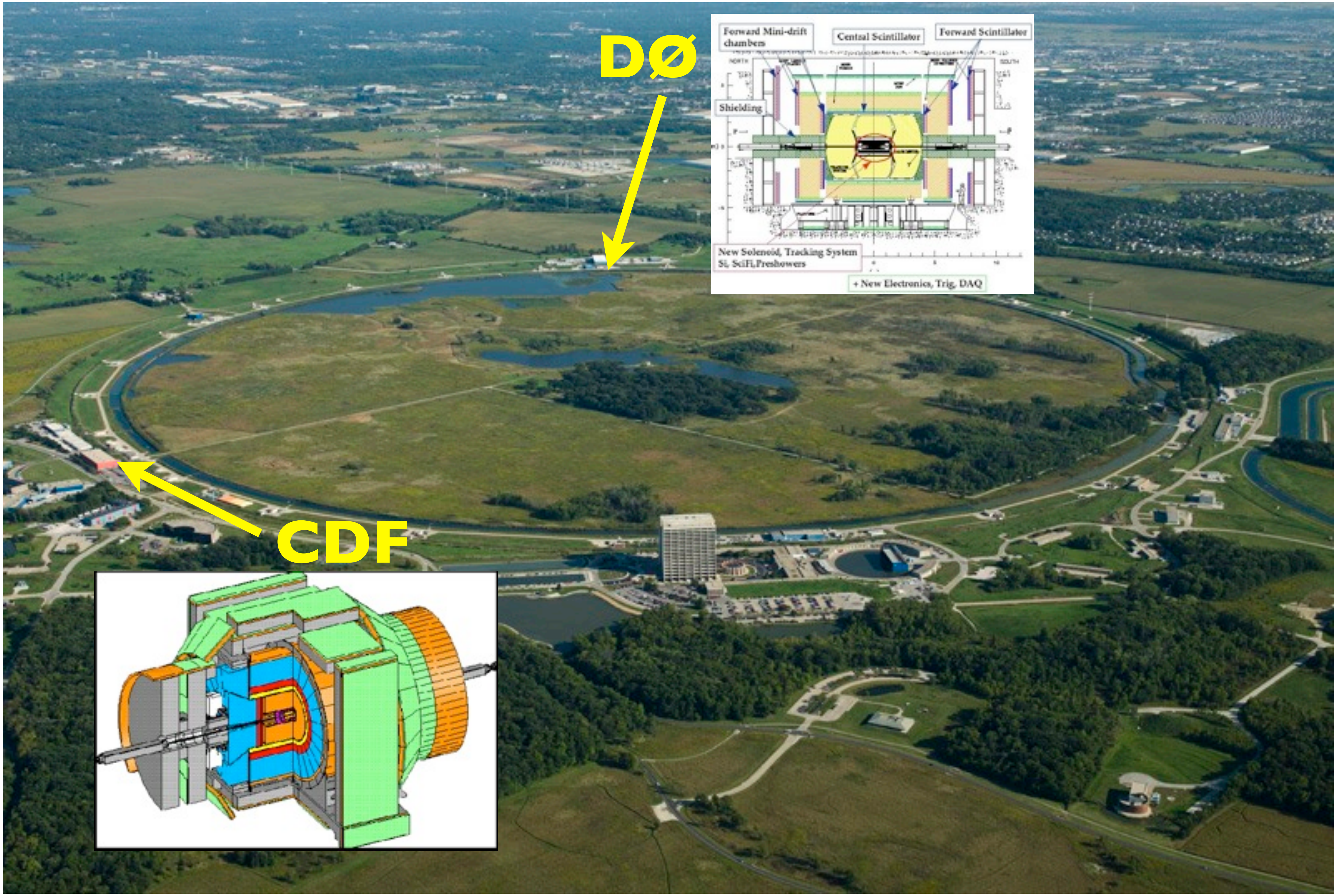

CDF and DØ Detectors

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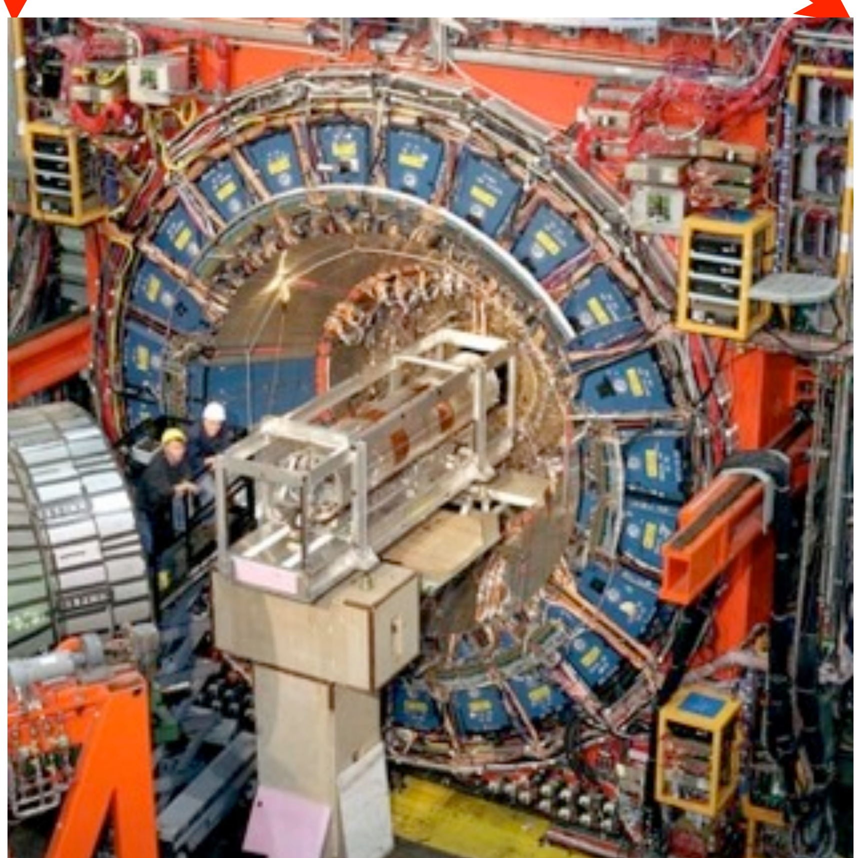
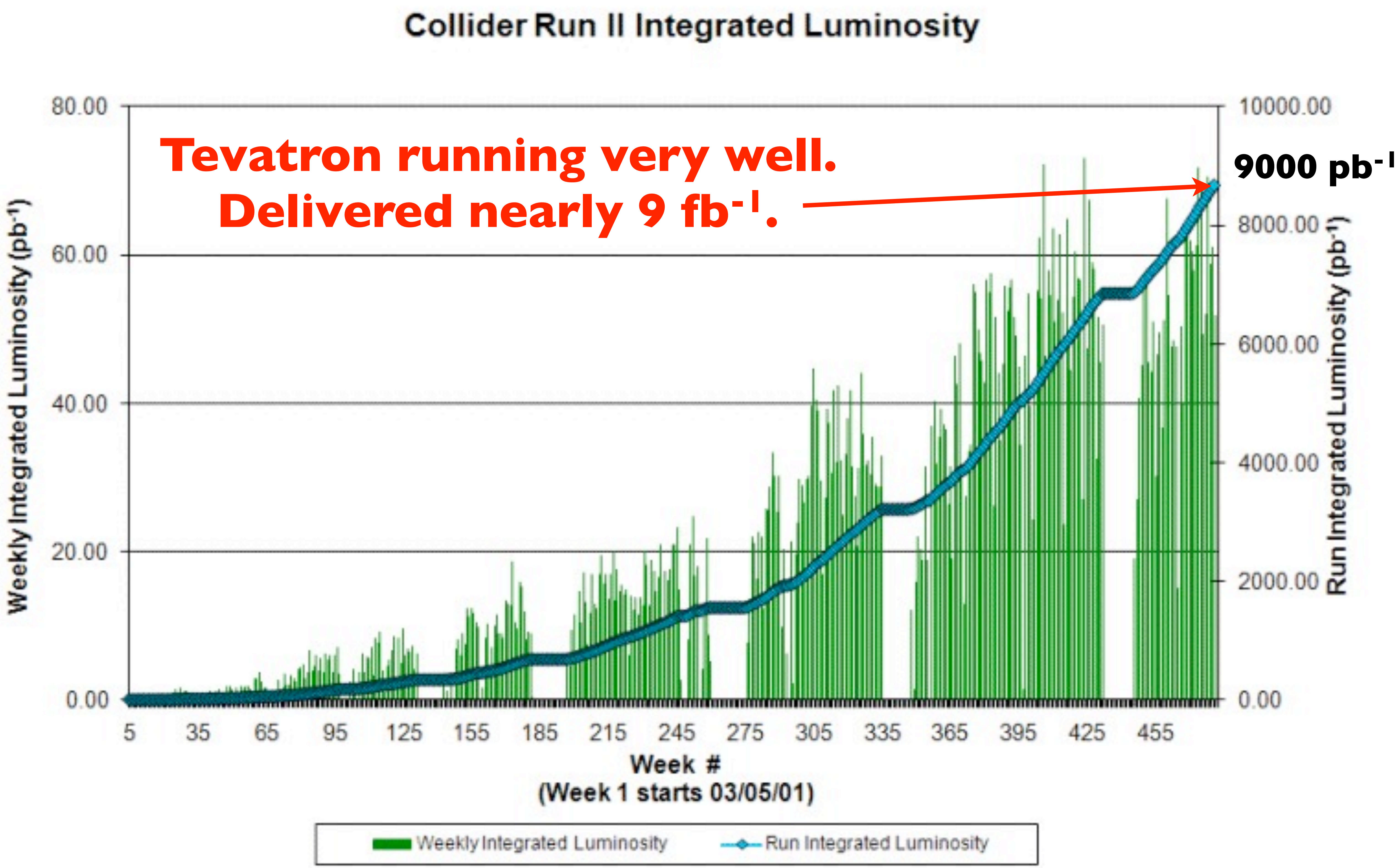


- **Highlights**
  - $\delta M_{top} / M_{top} < 1\%$
  - single top discovery
  - B_s - $\bar{B}_s$ oscillations
  - W mass
  - WZ and ZZ discovery
  - Higgs exclusion ($162 < M_H < 166$ GeV)
  - Many more...

Data Collection



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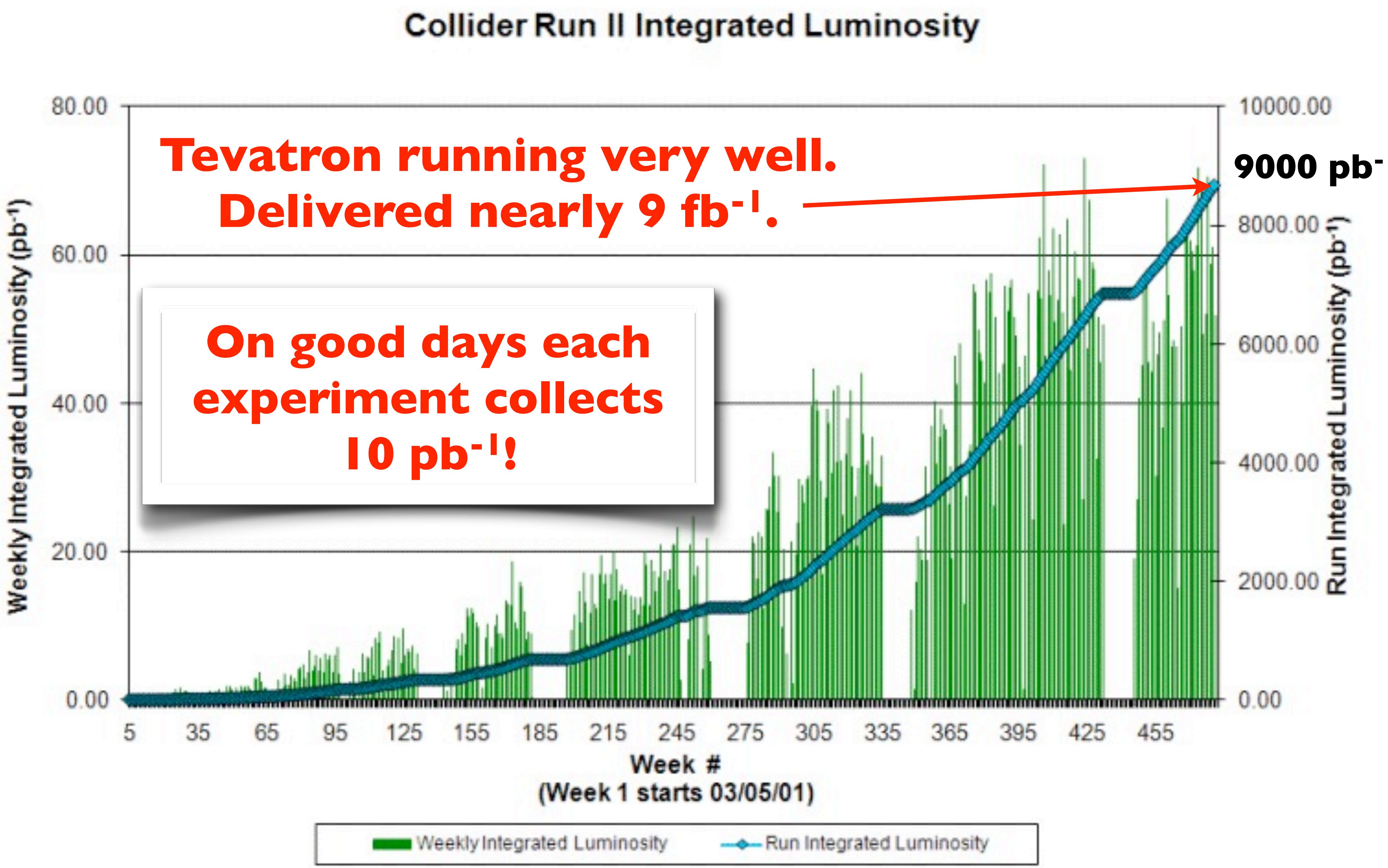
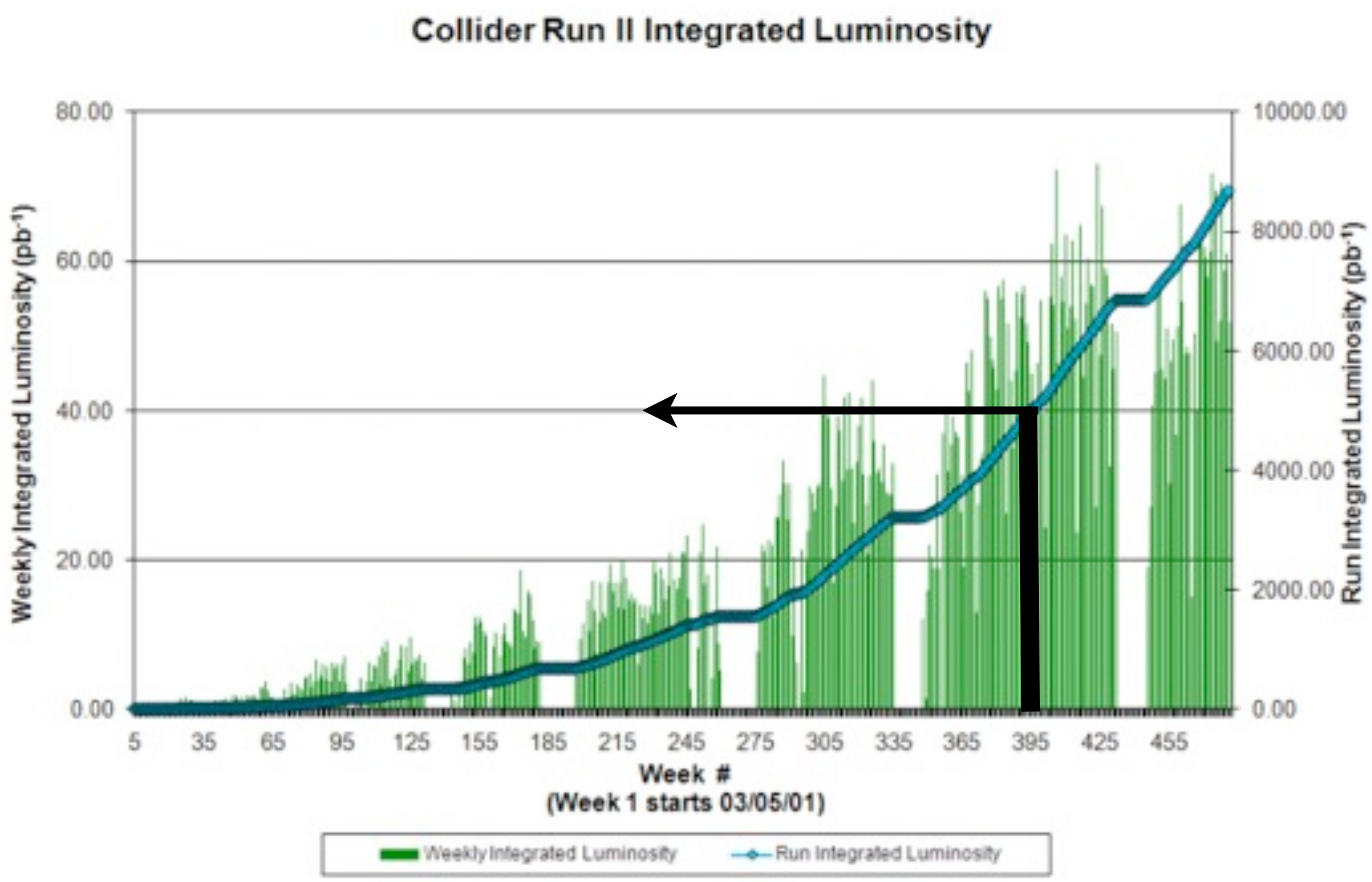


New Physics Searches

- Few hints of new TeV-scale physics at the Tevatron
  - Nothing in Squark/gluino searches, SLPIT SUSY,
    EW sector (diboson cross sections, aTGC),
    FCNC in top decays,
    W' and Z' searches, etc...
  - Exciting new results in B_S system,
    small b' and t' excess.
- Most analyses completed with $1\ fb^{-1}$ to $5\ fb^{-1}$ datasets.
- If we haven't seen anything with $5\ fb^{-1}$, is a 3σ observation likely with $10\ fb^{-1}$?



- With limited resources what is the best way to analyze Tevatron data with $10\ fb^{-1}$? Basically, how can we compete with the LHC even at $\sqrt{s} = 7$ TeV?

New Physics Searches cont.

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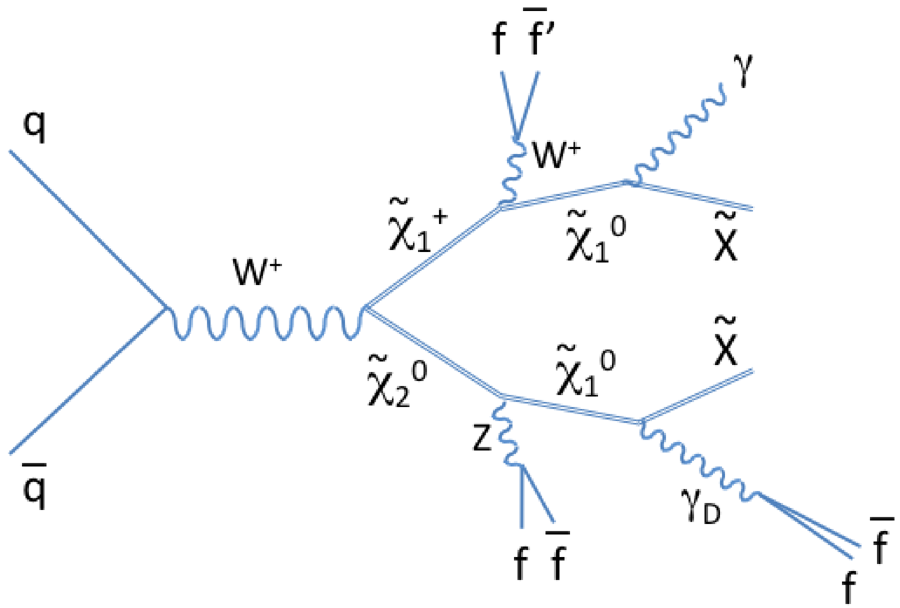
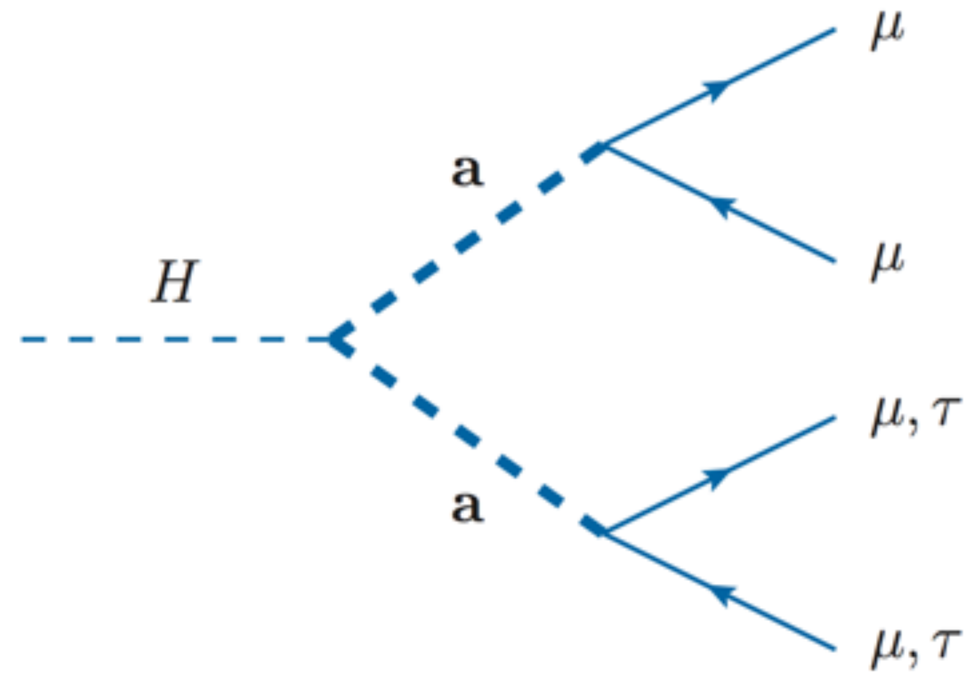
- Build upon many years of detector understanding and don't compete with LHC on high $\sqrt{s}$ searches.
  - e.g. LHC discovery potential for $W' \to l\nu$ will bypass Tevatron with $O(10\ pb^{-1})$.
- Compete with LHC on systematics-limited searches.
  - e.g. Higgs searches require serious understanding of backgrounds.
- Also, start re-analyzing data for new signatures we might have missed.
- This talk presents three analyzes we've published this past year on new physics searches.

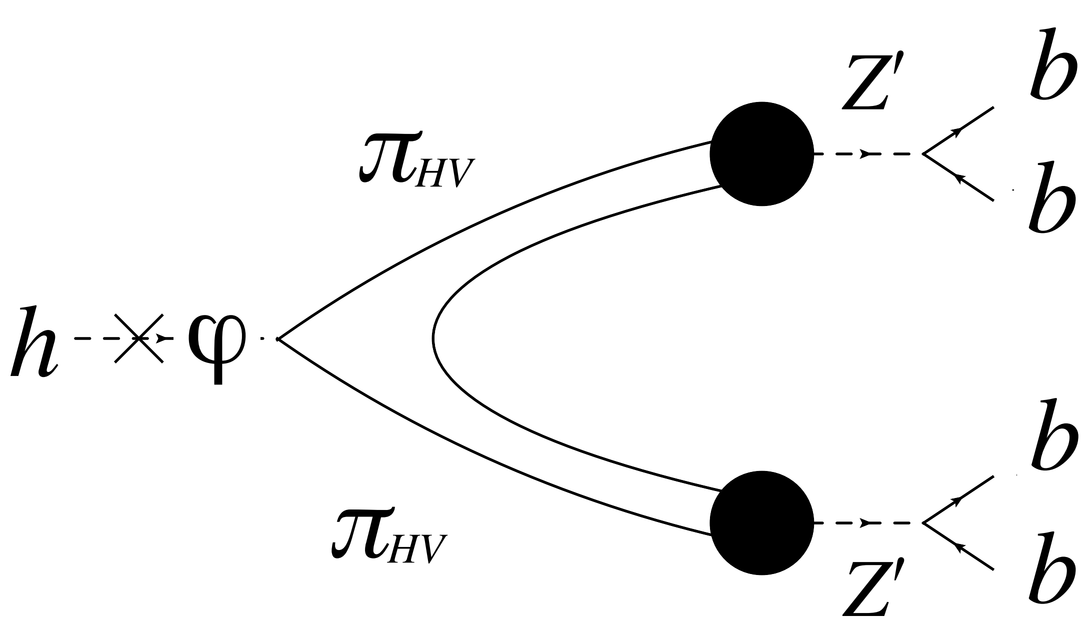
Searches w/ Boosted Objects



1). SUSY production w/ "dark" sector decays



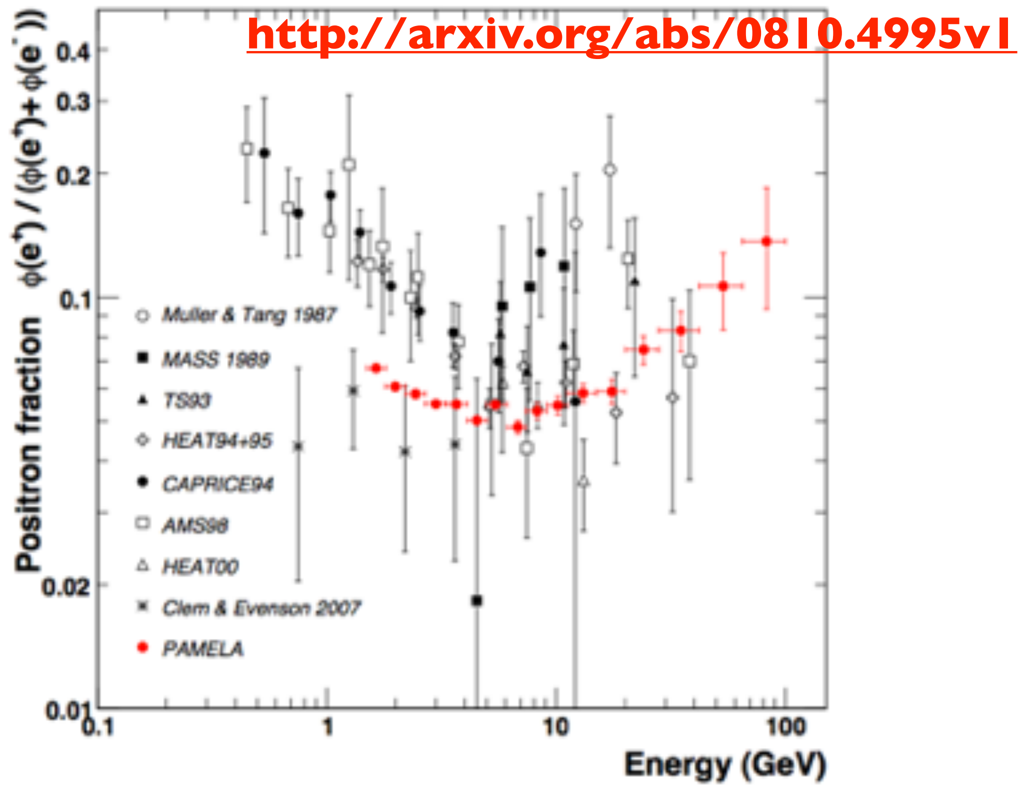
2). Light psuedoscalar production in Higgs decays.



3). Highly displaced vertices from NLLP decays.

SUSY + Dark Sector Search

- Exciting results from recent measurements of high energy positron energy spectrum.
  - No excess of antiprotons...



- High energy excess can be explained if we suppose a new weakly coupled (to SM) sector with gauge boson mass scaled of order 1 GeV. http://arxiv.org/abs/0810.5344v3
  - Boson mass explains excess in positrons and not protons.
  - Further referred to as dark sector.
- Also dark LSP (darkino) is the true LSP since M_{dark} ~ MeV.
  $M(\tilde{\chi}_{\rm dark}) < M(\tilde{\chi}_0)$
- Can we see these relatively low mass states in collider searches?

"Dark" Collider Signature

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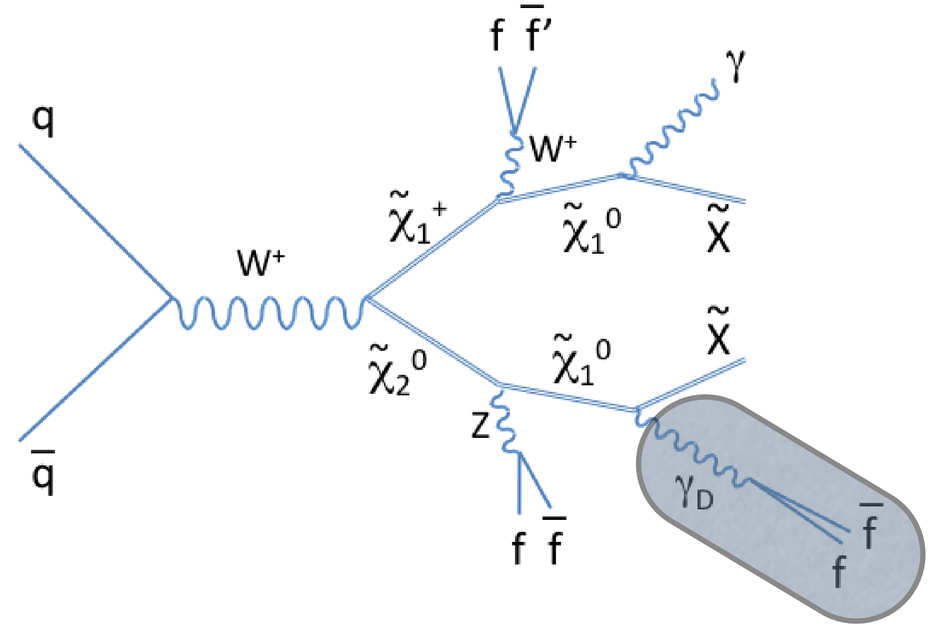
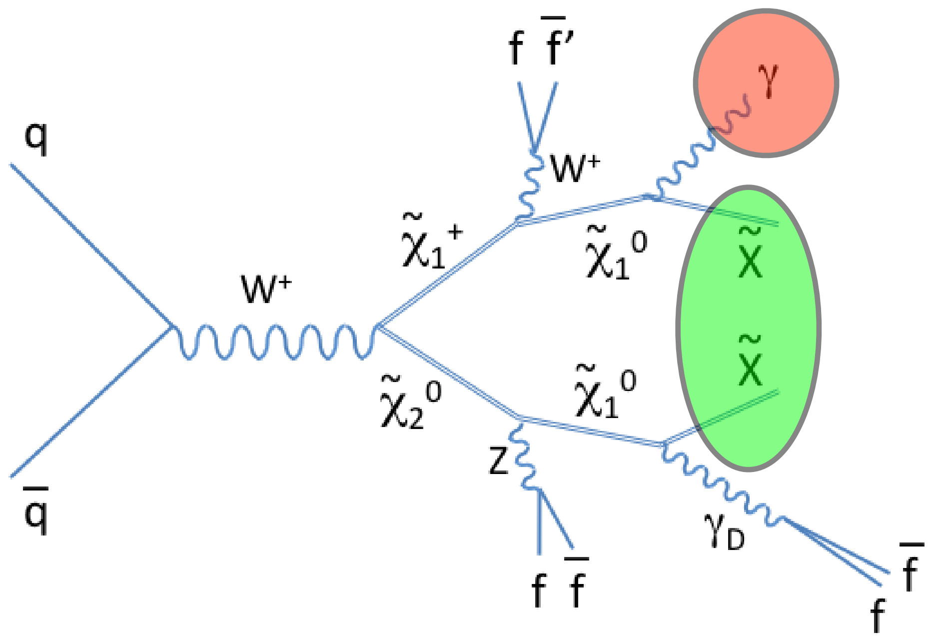
- One mechanism is SUSY chargino production with cascade decays down to a two neutralino final state.
  - Remember that $M(\tilde{\chi}_{\rm dark}) < M(\tilde{\chi}_0)$
- Neutralino will decay to true LSP (darkino) in addition to a SM photon or dark photon (γ_D)
- The dark photon will mix ($\epsilon < 10^{-3}$) with SM photon $\gamma_D \to \gamma_{\rm SM}$ and decay to highly boosted lepton pairs ($\gamma \to \ell^+\ell^-$).
  - Boosted because $M_\chi \sim 100 \times M_{\gamma_D}$



- Signature depends on neutrino branching ratio: $\mathcal{B}(\tilde{\chi}_1^0 \to \gamma_D \tilde{X})$
  - If $\mathcal{B} \sim 1$ then signature is two high p_T photons + large missing E_T.
  - If $\mathcal{B} \sim 0$ then signature is two boosted lepton pairs with M(ll) ~ GeV and large missing E_T.

Lepton-jet Event Selection

- Require ≥1 photon with $p_T > 30$ GeV and missing E_T (from undetected χ) > 20 GeV.
  - Trigger on hard photon.



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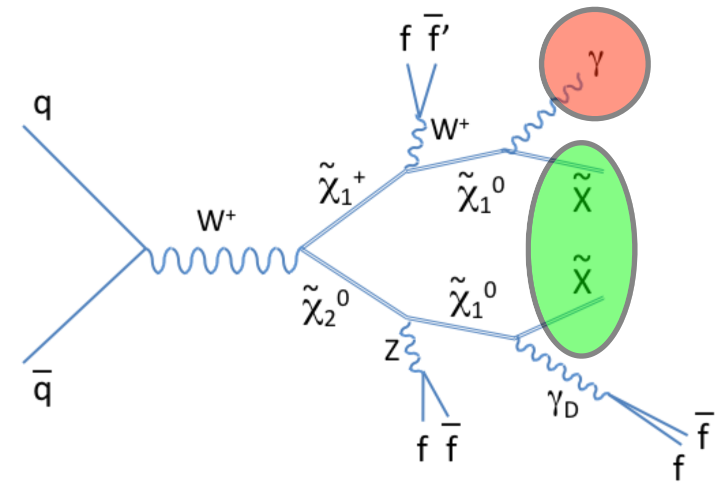
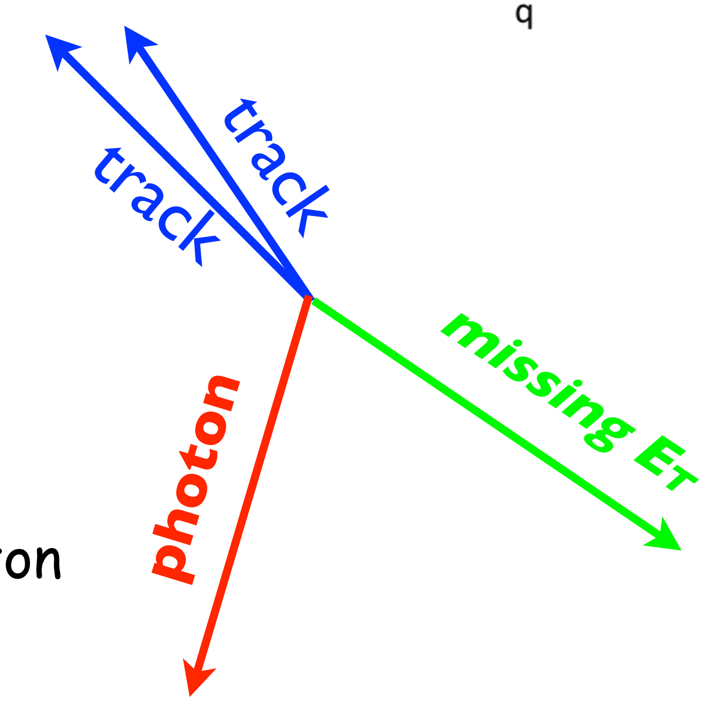


- Dark photon reconstruction:
  - Start with spatially close and oppositely charged tracks.
  - Track-pair should be isolated (<2 GeV)
  - Track-pair should be separated from photon



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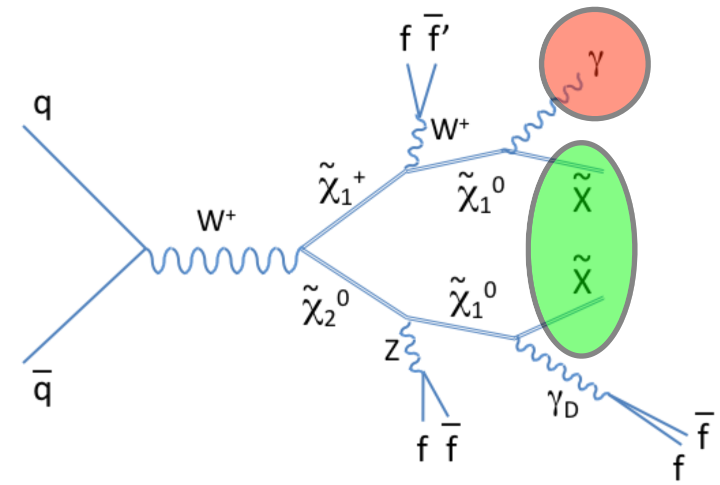

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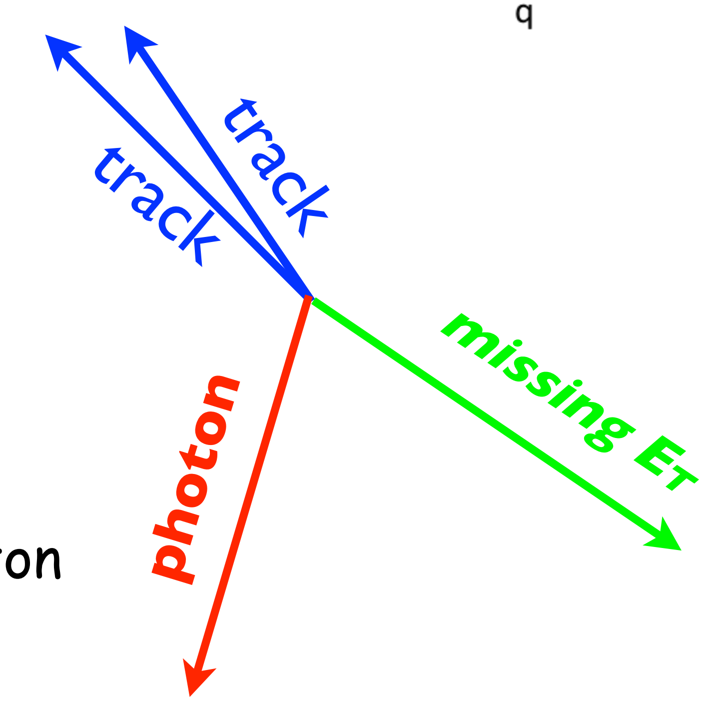

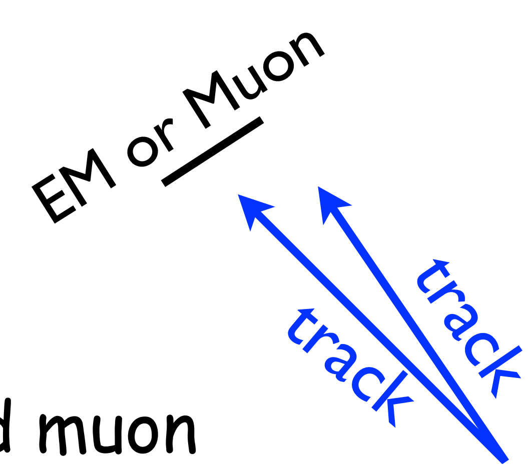

- For dielectron decay, match tracks to EM cluster.
- For dimuon decay, match at least one track to isolated muon

Backgrounds & Result

- Background dominated by multijet events with mismeasured missing E_T and photon conversions faking lepton pairs.
- Model background using low missing E_T sample (negligible signal).

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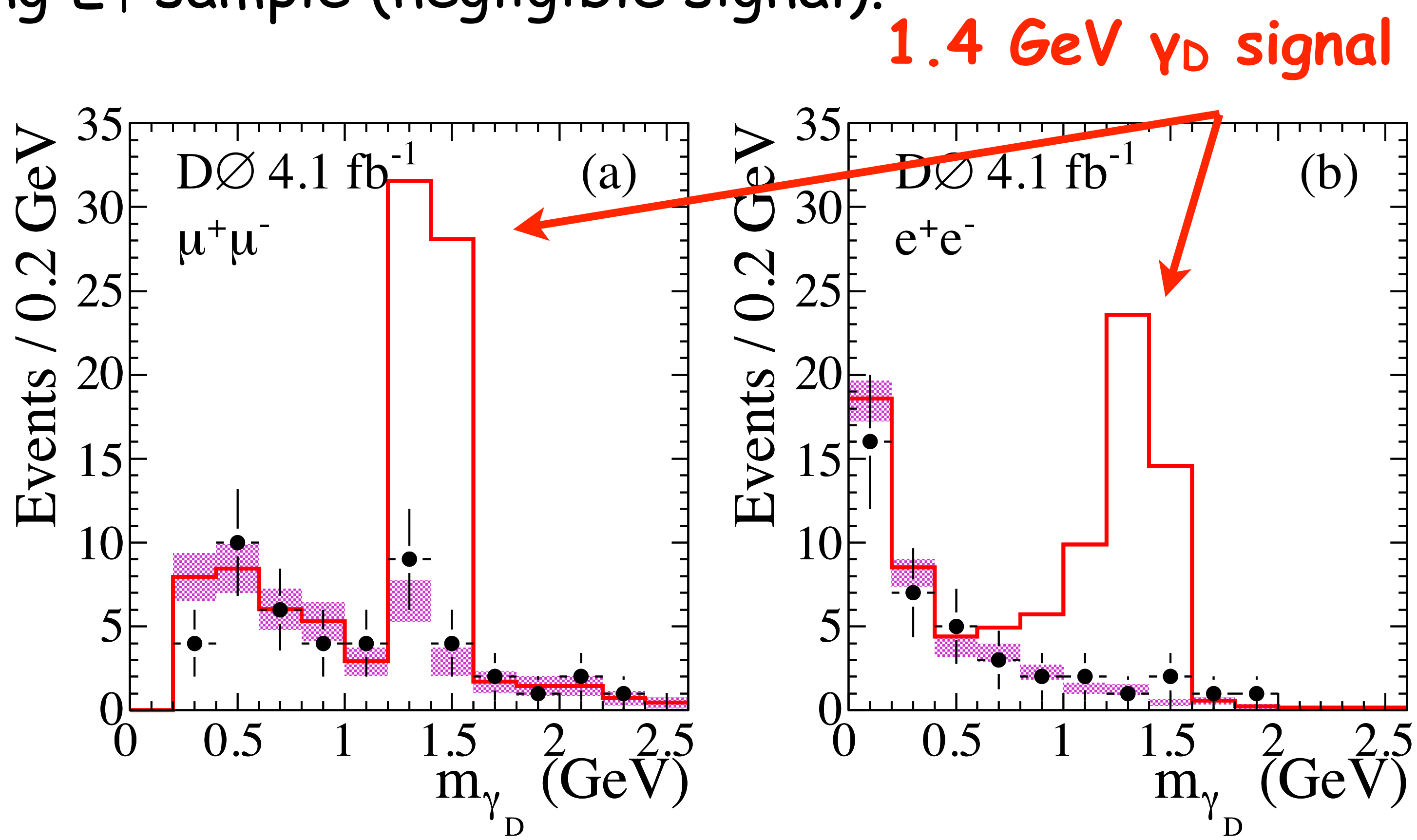

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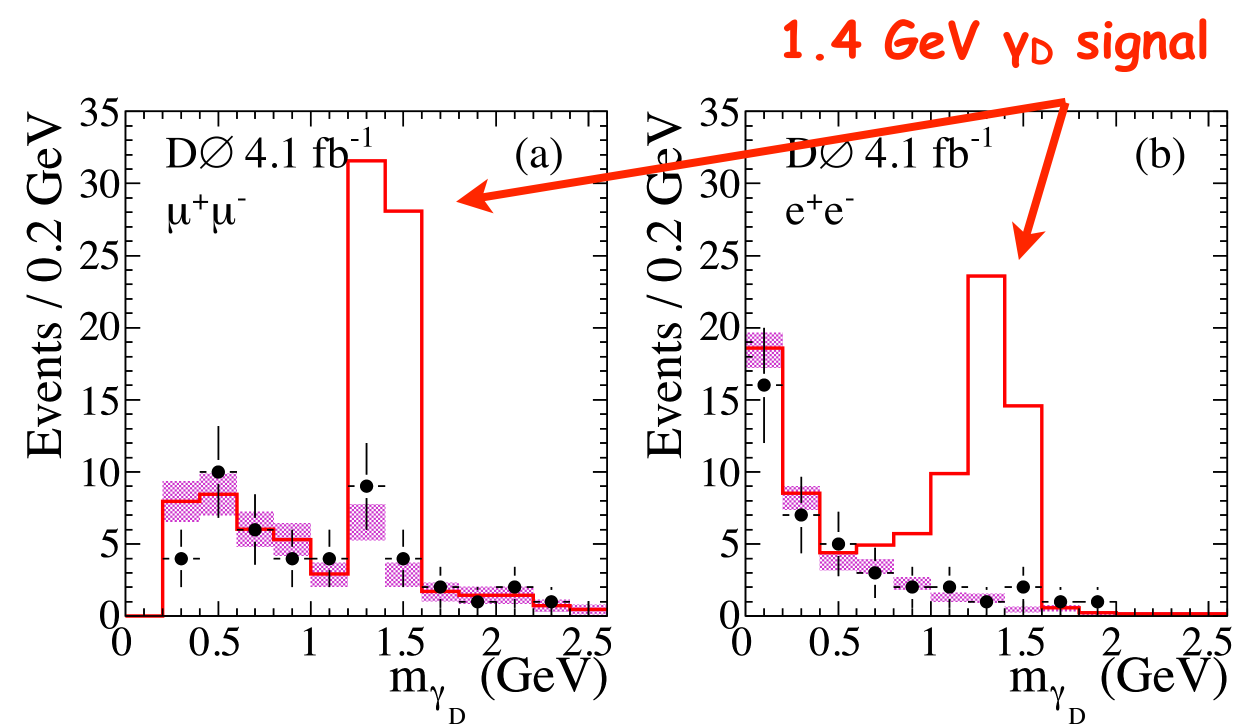
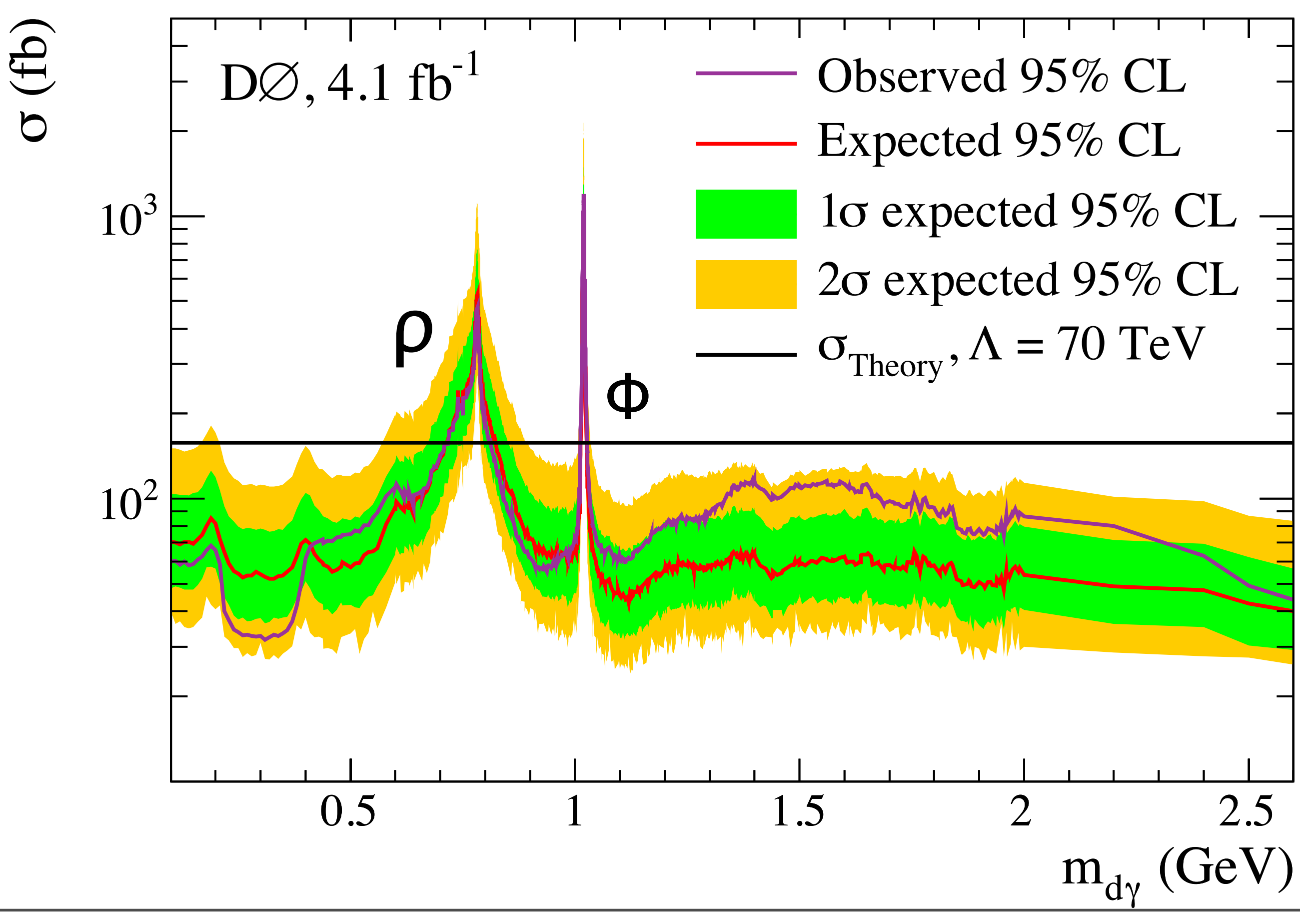
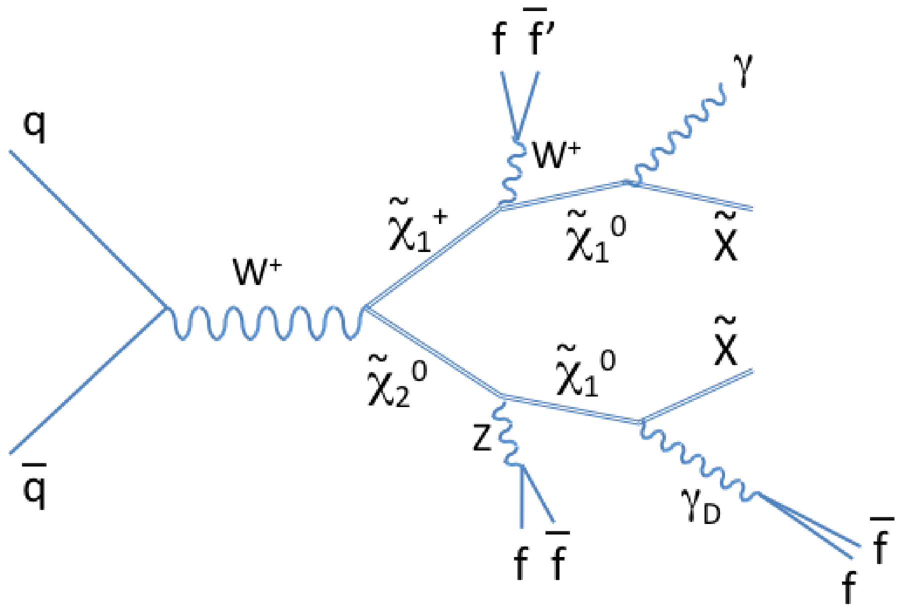
- Limits presented in model-dependent planes or as excluded production cross section.





Excluded cross section vs dark photon mass.

Searches w/ Boosted Objects



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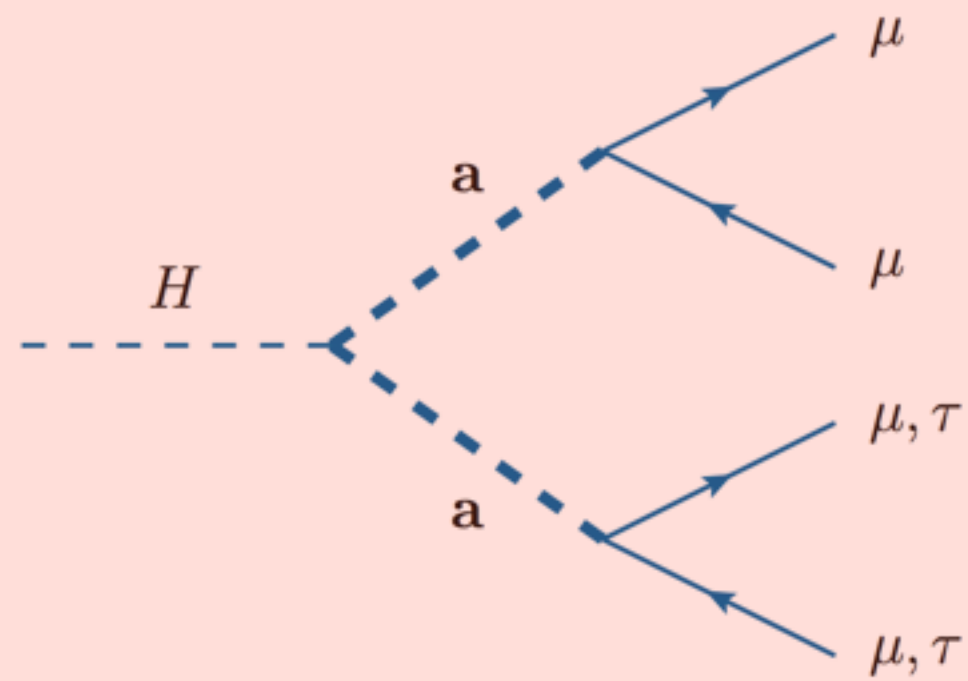

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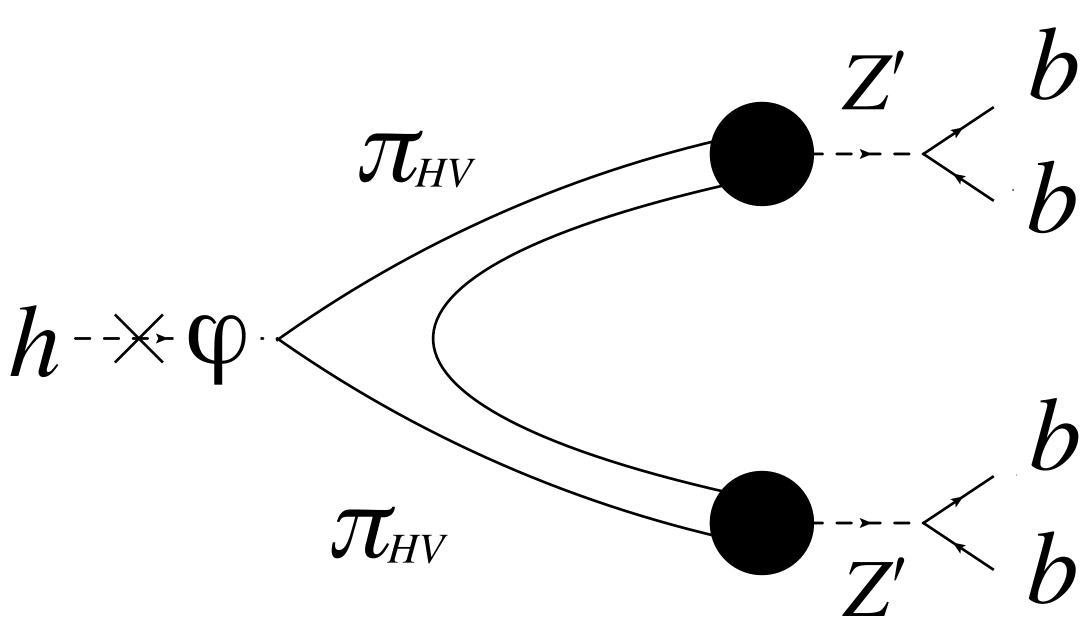

3). Highly displaced vertices from NLLP decays.

Higgs → aa Search

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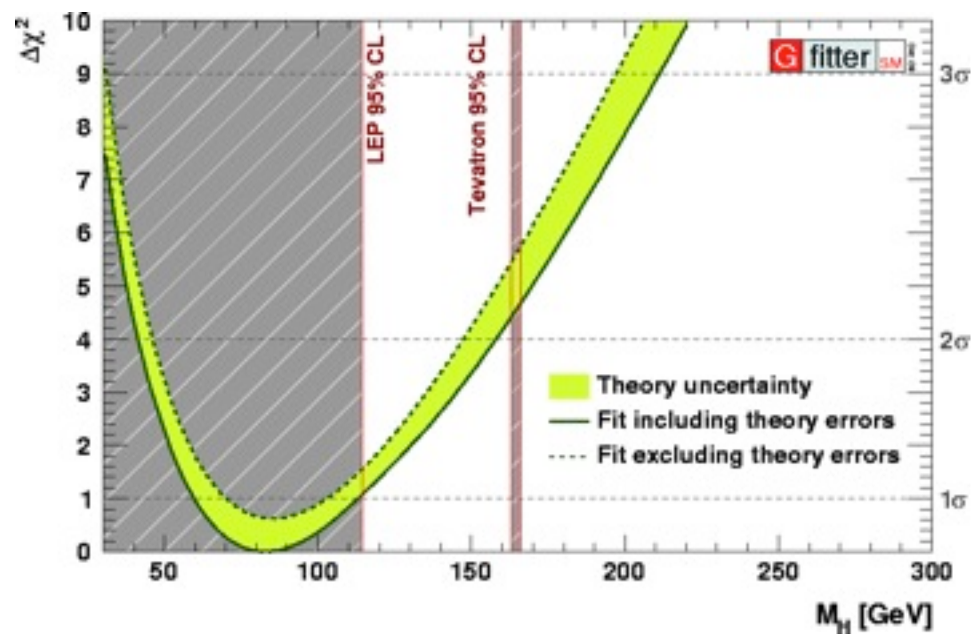
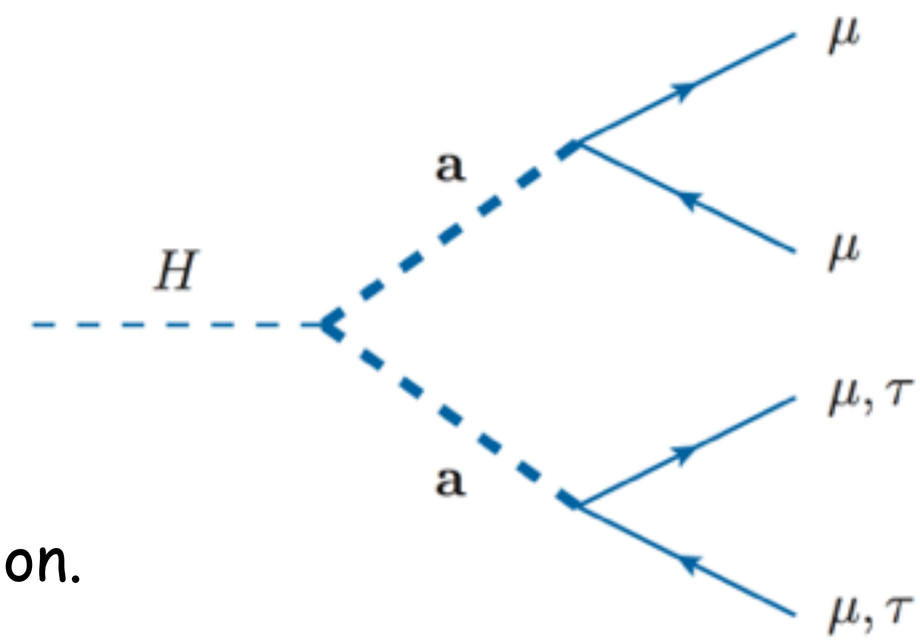
- Current Higgs exclusion limits based on Higgs → bb decays assumed Br(H→bb).



- Many reasons to move beyond SM Higgs picture
  - e.g. fine tuning to solve hierarchy problem.

- One way to keep Higgs light is the NMSSM with the price that we must augmented particle content.

- NMSSM dramatically changes Higgs branching ratio due to H → aa decays (BR ~ 90%) ⇒ Evades LEP ZH limits.
  - Recent activity in this area by ALEPH collaboration. http://arxiv.org/abs/1003.0705v2



Properties of New Pseudoscalar

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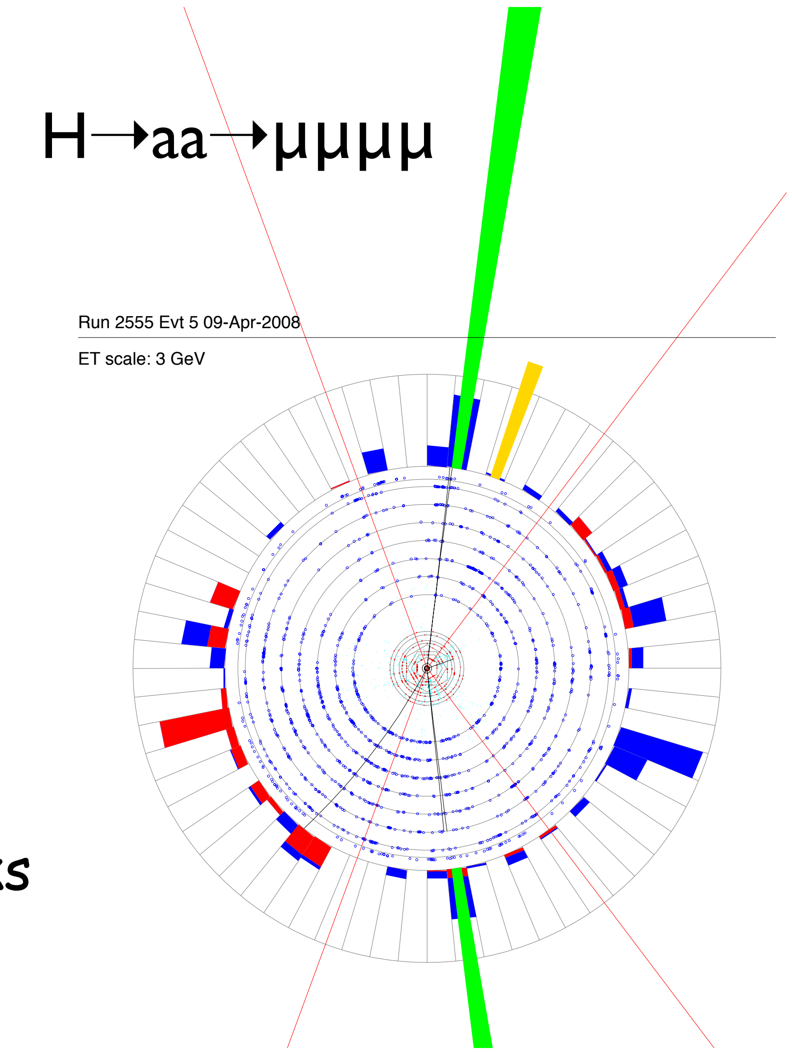
- Pseudoscalar mass (m_a) is unconstrained.
- It will decay to heaviest available fermion pairs.
  - e.g. $a < 2m_\tau \Rightarrow a \to \mu\mu$ or $2m_\tau < a < 2m_b \Rightarrow a \to \tau\tau$
- Start search with **a** decays to dimuons assuming $m_a < 2m_\tau$
- If $M_H \gg M_a$ then expect highly collinear muon pairs back-to-back in φ
- Cuts:
  - Do not explicitly require 4 muons in the event.
  - Require ≥2 muons w/ p_T > 10 GeV and M(μ,μ) > 15 GeV.
  - Each muon must have a nearby track with p_T > 4 GeV
  - Muon + track candidates must be isolated from other tracks and calorimeter energy deposits.



Background Modeling

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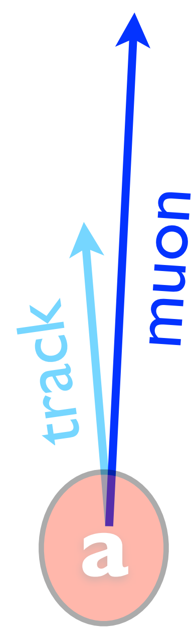
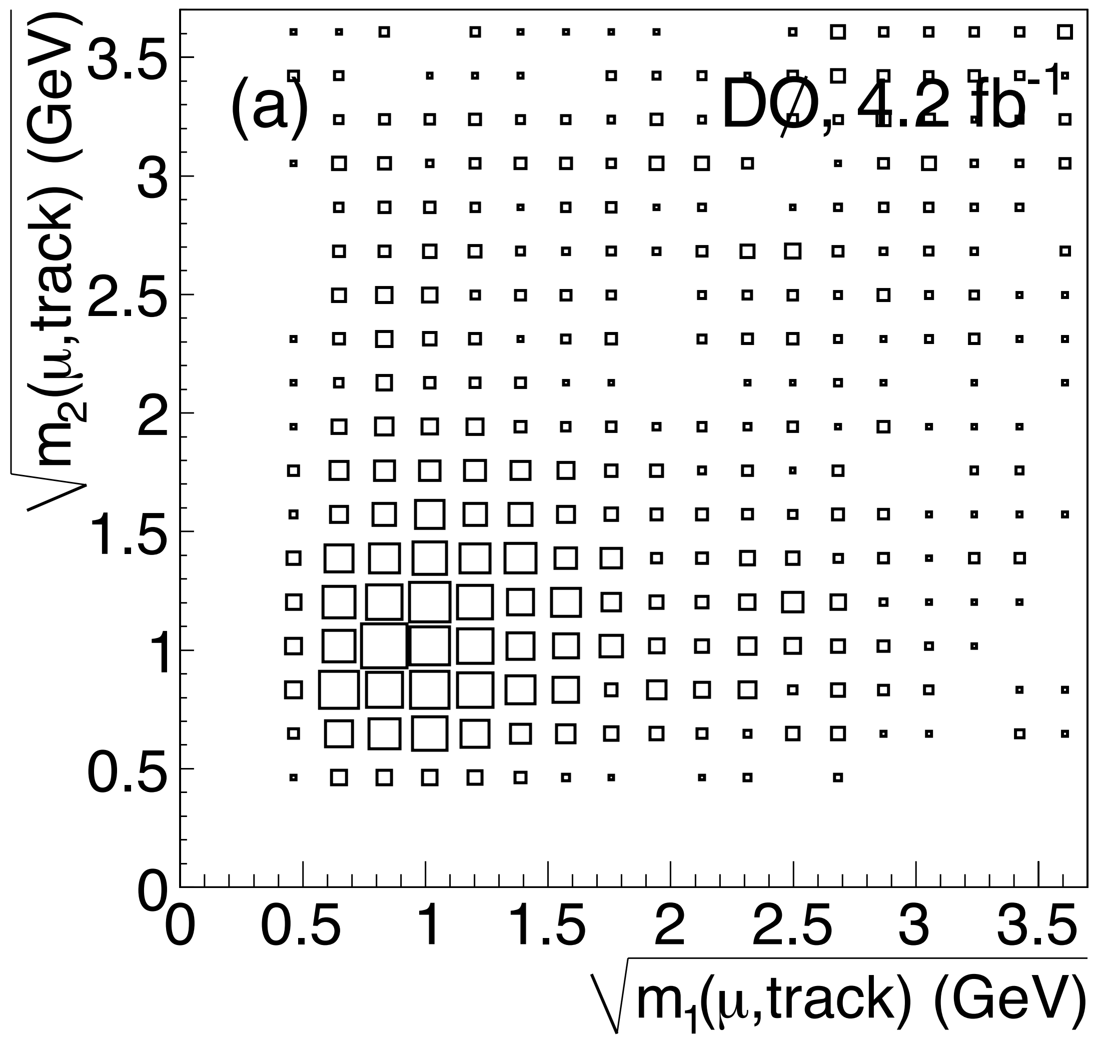
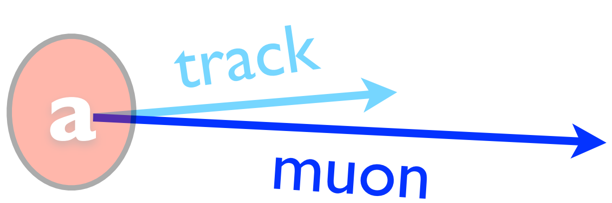
- Monte Carlo + GEANT simulation not expected to match data in this phase space.
- QCD Multijets dominate backgrounds.
- Create multijet-enriched sample by reversing muon-track calorimeter E_T cut to model background shape.
- $Z/\gamma^* \to \mu\mu$ + tracks contribute and modeled with Monte Carlo.
- Signal acceptance determined from Monte Carlo.







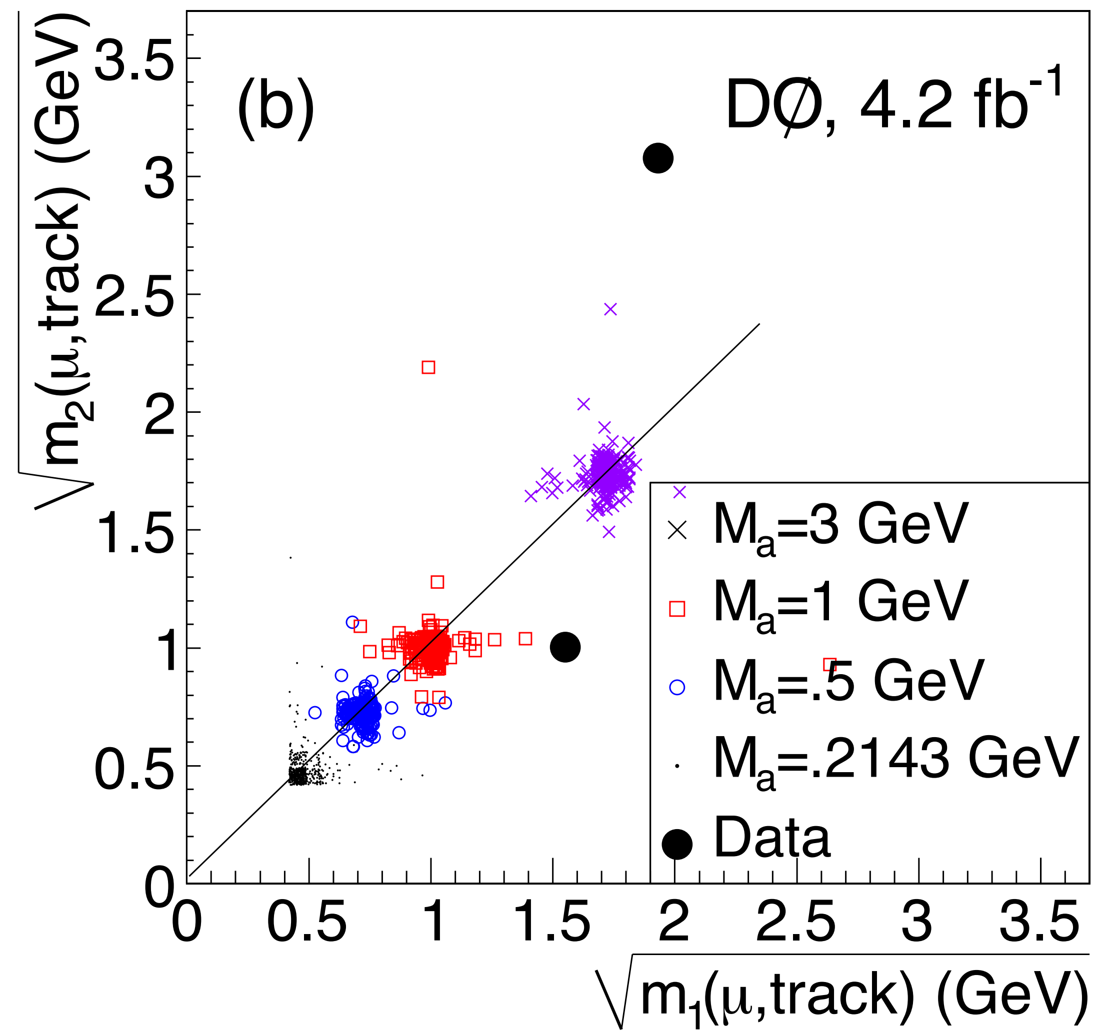
- Uncertainty on signal acceptance studied in $K_s \to \pi\pi$ decays as a function of ΔR(π,π)
  - Data / MC correction within 20% and rises to 50% for ΔR < 0.02
  - Dominant systematic on background due to limited statistics in multijet sample. (50%).

Results for Higgs → aa → μμμμ

- Look for excess of events in ±2σ mass window around assumed m_a.

Results for Higgs → aa → μμμμ

- Look for excess of events in ±2σ mass window around assumed m_a.
- Opening the box, we find 2 events passing all cuts and expect 2.2 ± 0.5 events.



- Limits set on

$$\sigma(p\bar{p} \to H) \times \mathrm{Br}(\mathrm{H} \to \mathrm{aa})$$

M_a (GeV)	Window (MeV)	Eff.	N_{bckg}	N_{obs}	$\sigma\times$BR [exp] obs (fb)
0.2143	±15	17%	0.001±0.001	0	[10.0] 10.0
0.3	±50	16%	0.006±0.002	0	[9.5] 9.5
0.5	±70	12%	0.012±0.004	0	[7.3] 7.3
1	±100	13%	0.022±0.005	0	[6.1] 6.1
3	±230	14%	0.005±0.002	0	[5.6] 5.6

Extending Mass Reach

- If $m_a > 2m_\tau$ then **a** will prefer to decay to tau pairs.
- 4-tau final state is experimentally challenging.
  - No resonance peak, tau reconstruction efficiency is low, triggering is difficult.
- 2-muon + 2-tau final state easier in many ways
  - Use muons for triggering, still some resonance peaks

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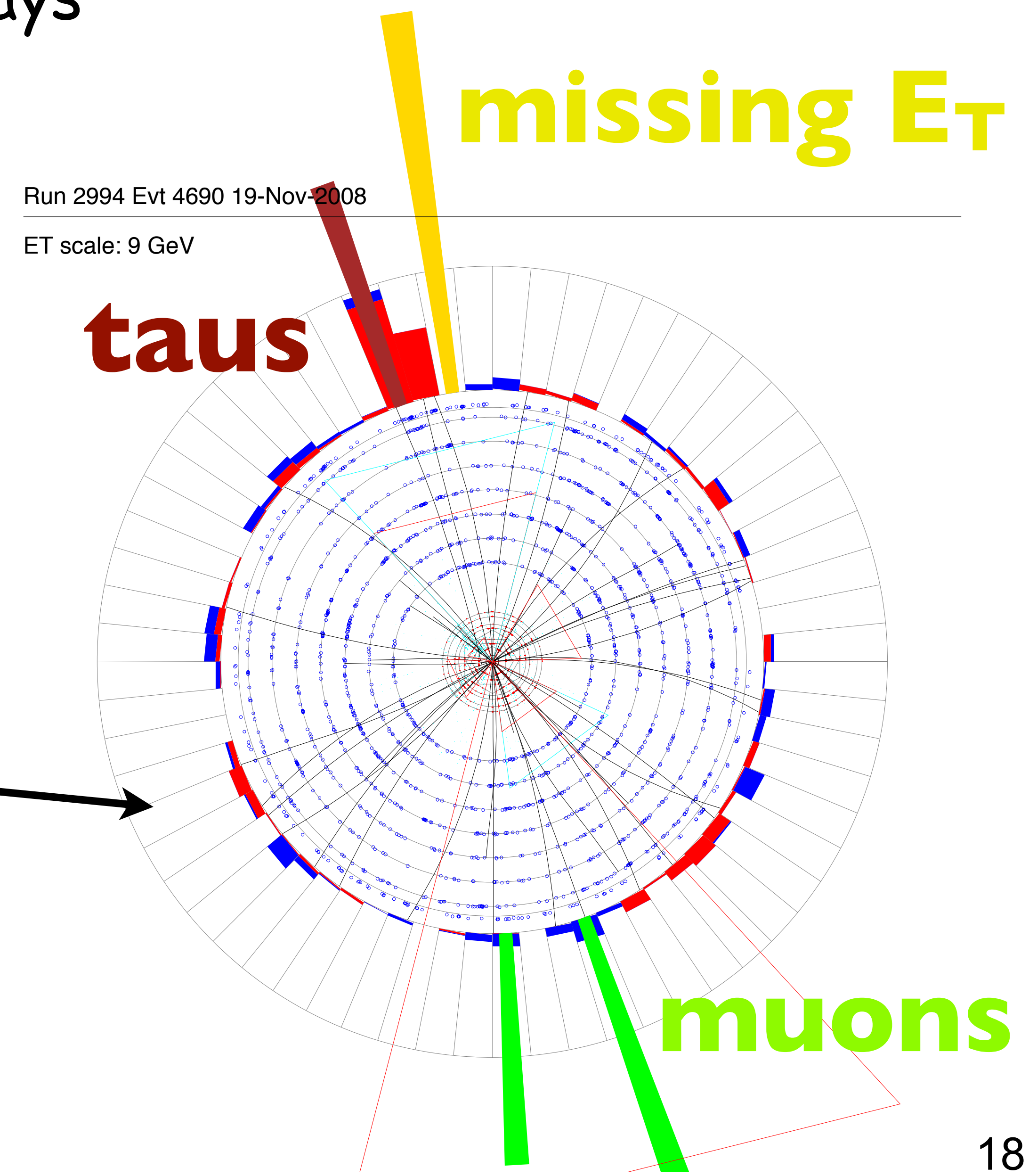
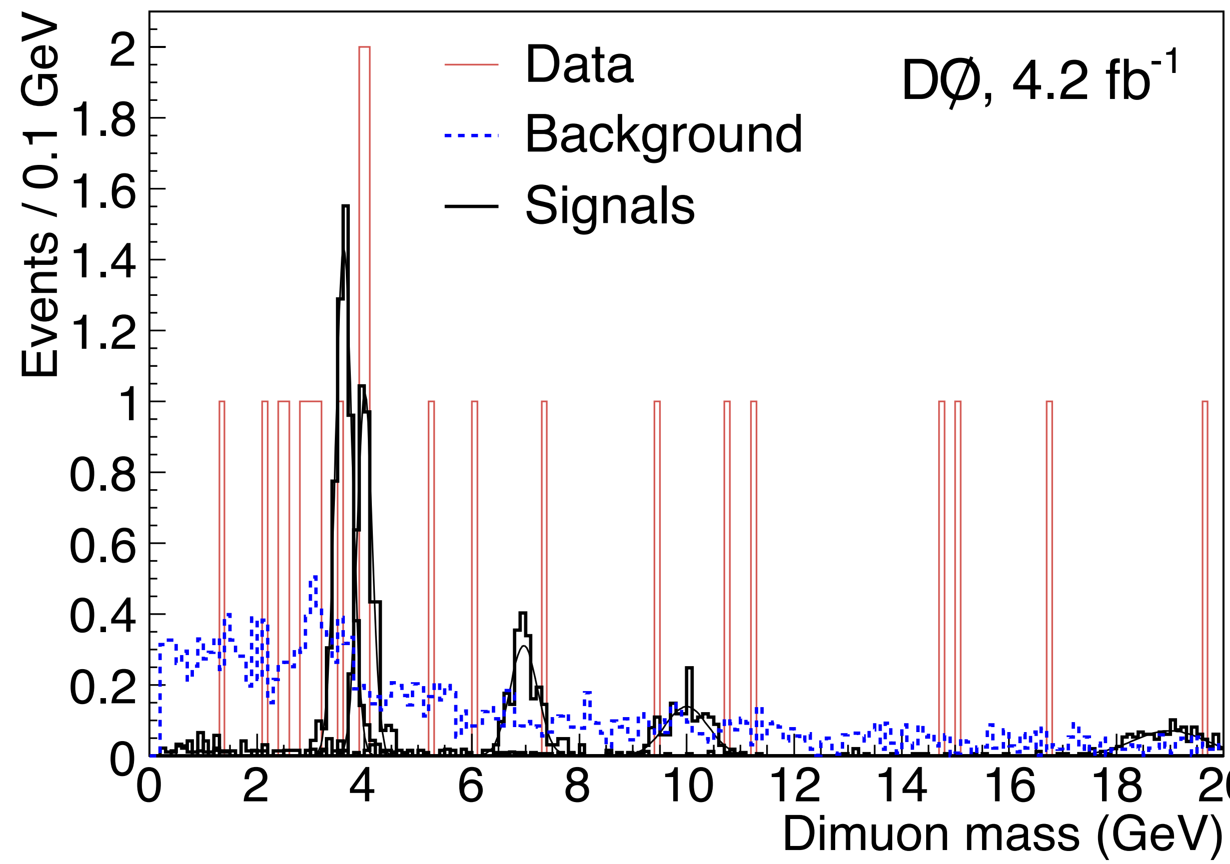
- 2-muon + 2-tau final state easier in many ways
  - Use muons for triggering, still some resonance peaks
- Taus are not explicitly reconstructed, but inferred by large missing E_T created by tau decays.
  - Monte Carlo simulation of

$$H \to aa \to \mu\mu\tau\tau$$

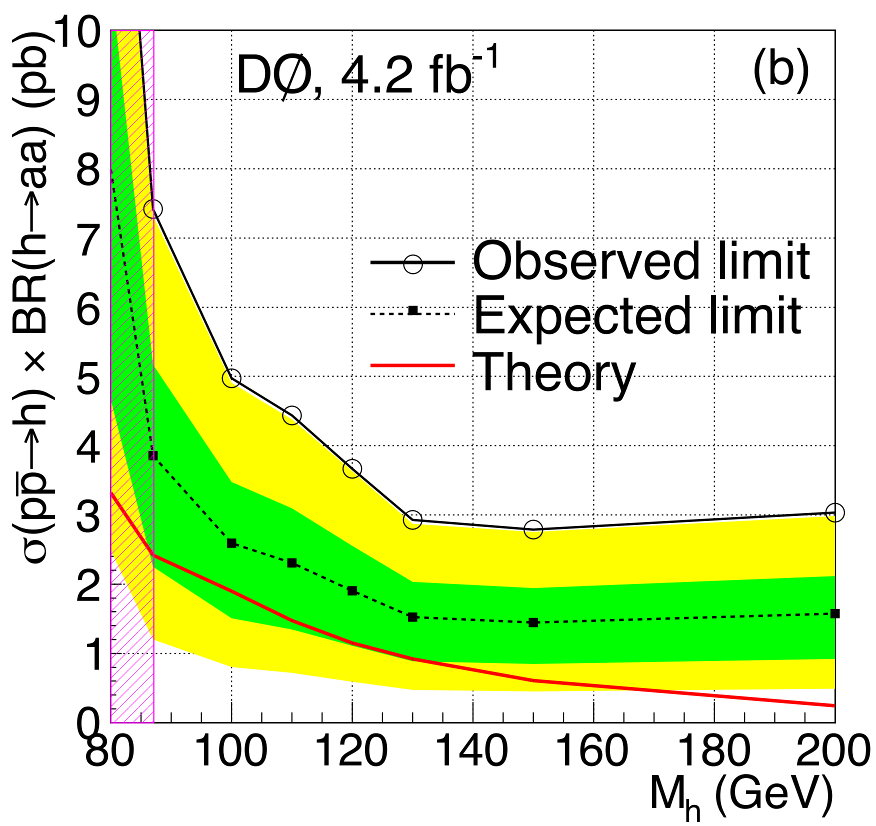


- Tau reconstructed based on 3 categories (leptonic decay, 1-prong, and 3-prong decays)
- Background modeled by reversing tau cuts.

Results for Higgs → aa



- As before, mass windows ($M_a \pm 2\sigma$) used to determine signal, background, and data yields.
- Observed data agrees with background prediction
- Limits determined versus Higgs mass and **a** mass.
  - Start to exclude some part of $p\bar{p} \to H \to aa$ phase space.



Searches w/ Boosted Objects

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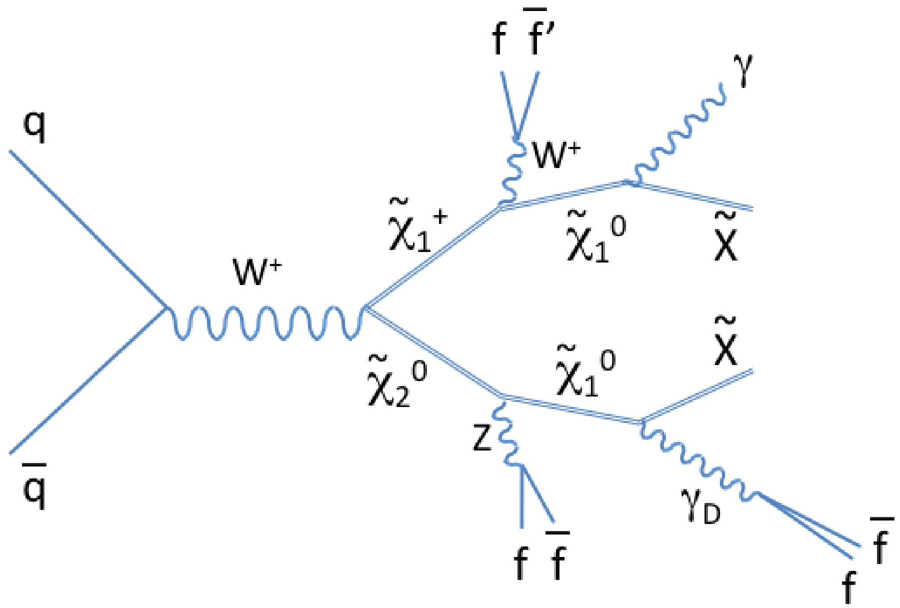
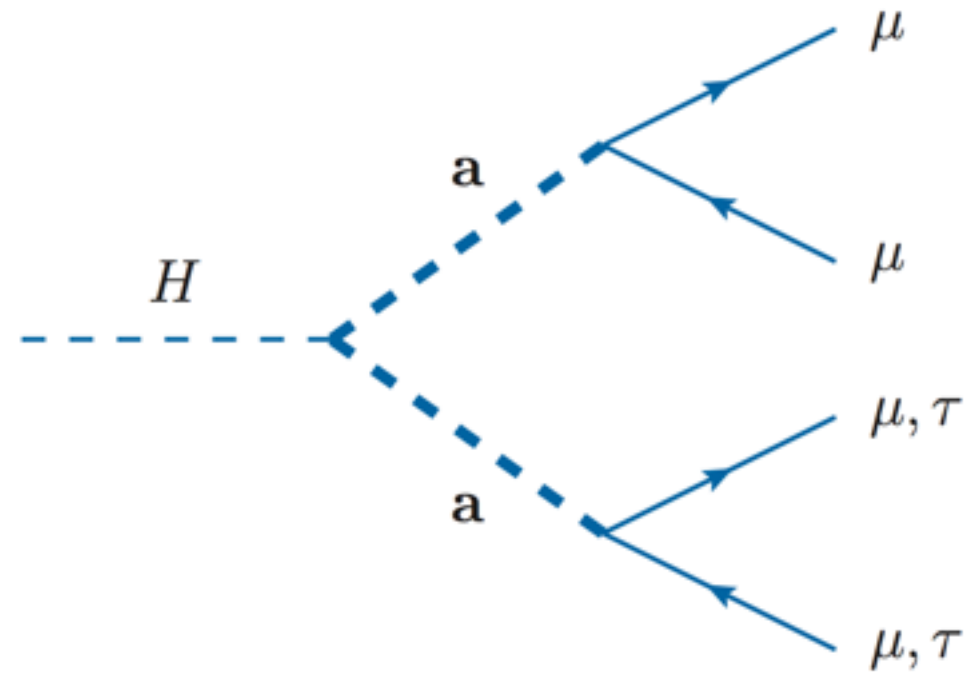
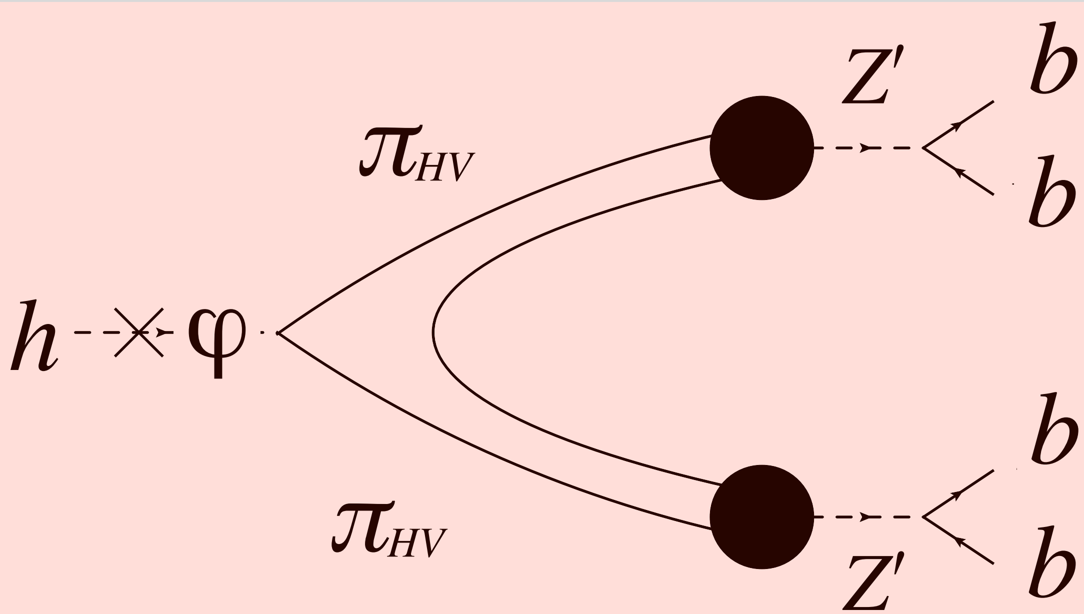


1). O(GeV) dark photon decays to fermion pairs.



2). O(GeV) **a** pair production and decays to 4 muons or 2 muon + 2 taus.

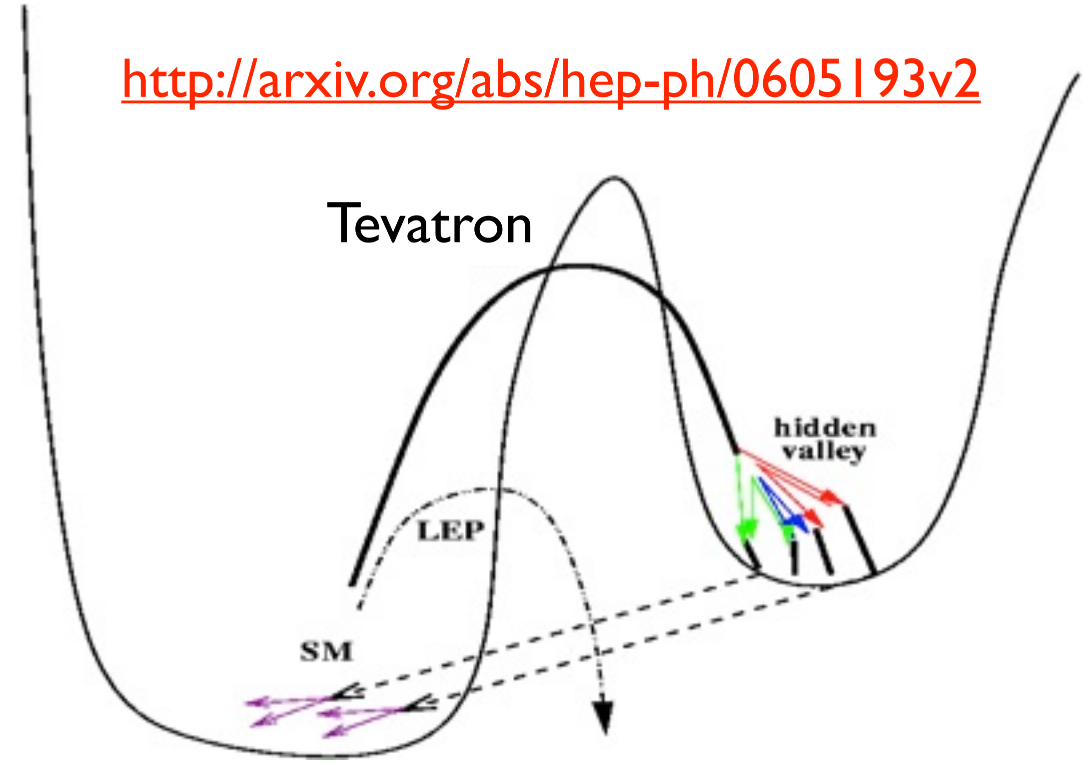


3). NLLP decaying to bb pairs (Hidden valley)

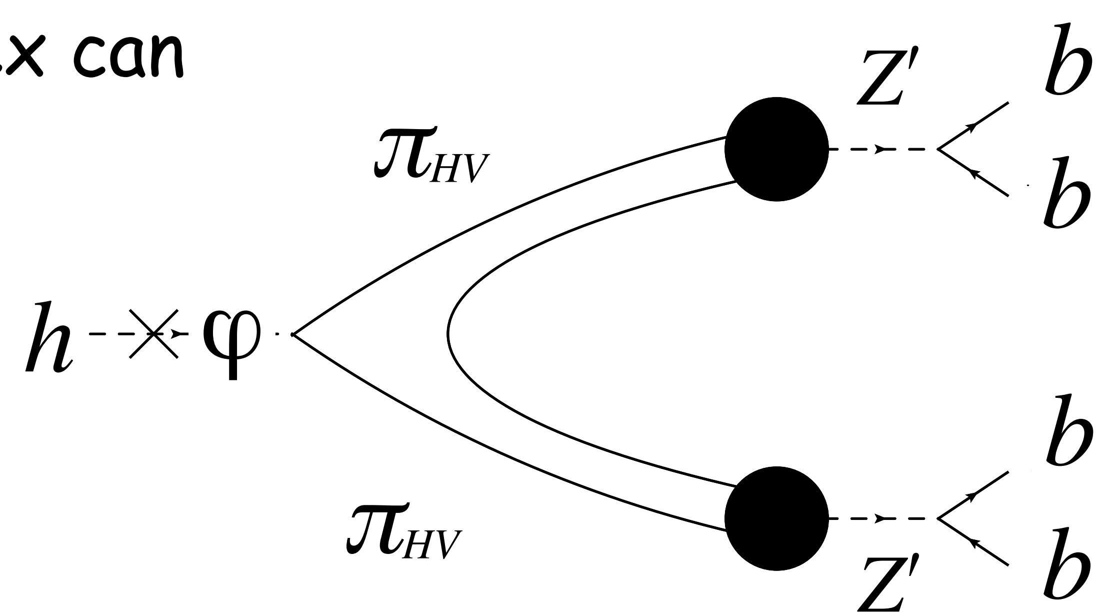
Hidden Valley Models

- Similar to SUSY + dark photon search, introduce a hidden sector that is weakly coupled to the standard model.
  - Hidden sector may have complex structure.
  - All HV particles decay to HV pions (π_{HV}).

http://arxiv.org/abs/hep-ph/0605193v2

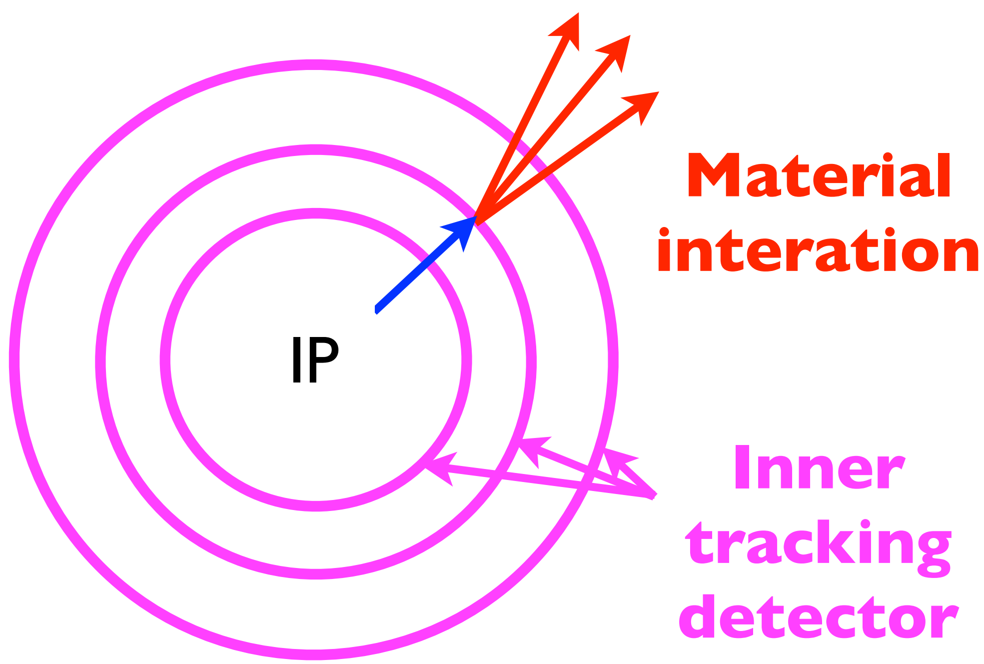


- π_{HV} will decay back to SM particles through SM-HV communicators (Z').
- Because $M_{Z'} \gg M_{\pi_{\mathrm{HV}}}$ decay vertex can be highly displaced from the IP.
- Collider signature.
  - Highly displaced vertices with large track multiplicities (2Bs).



NLLP Event Selection

- Triggering on these events is difficult.
  - Can not use dijet triggers due to overwhelming QCD rate.
  - Require one muon from semileptonic B decay. $B \to \mu + X$
  - More sophisticated trigger strategy is clear improvement for this analysis.
- Common background is nuclear interactions with detector material.
  - Signal is also displaced vertex with large charged particle multiplicity.



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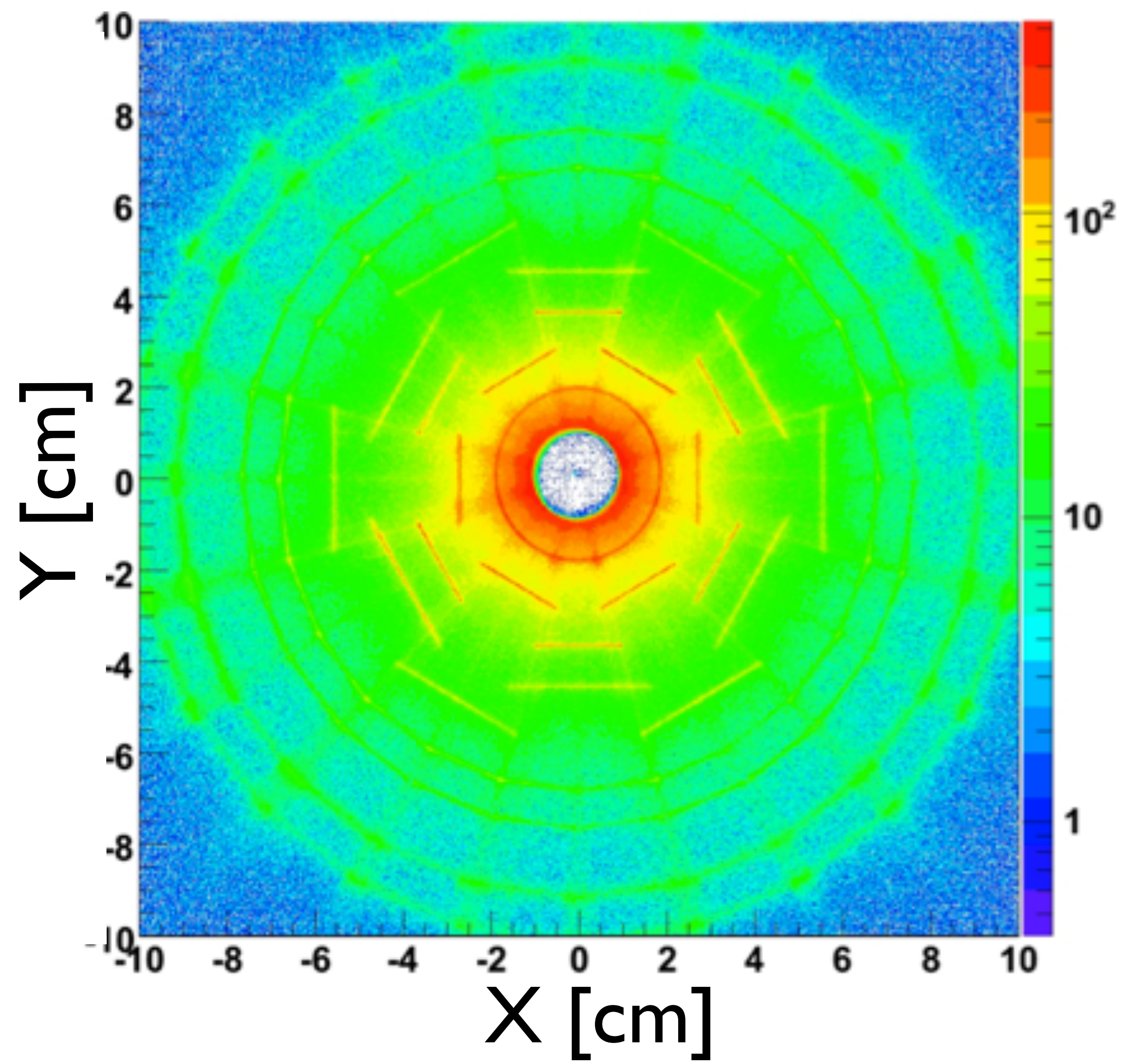
- Create material map using data and remove dense regions.



Hidden Valley Analysis

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- After removing material regions, backgrounds mostly QCD dijet production with real or fake muon.
  - Background dominated data control sample not available due to signal contamination.
- Model backgrounds with dijet Monte Carlo and reweight to data in regions with low signal fraction.
  - Background Monte Carlo statistics are dominant systematic uncertainty.
- Signal modeled with Pythia $gg \to H \to aa \to b\bar{b}b\bar{b}$ + GEANT simulation

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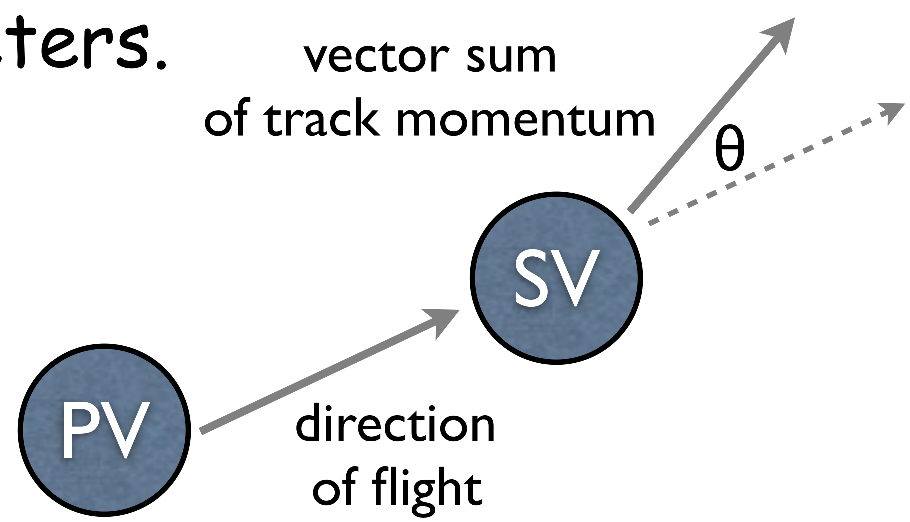
  a ⇔ π_{HV}
- Signal selection cuts depend on model parameters.
  - If $M_H \gg M_{\pi_{\rm HV}}$ then $b\bar{b}$ will be highly boosted, use cos(θ) as signal:background discriminator.
  - If $M_H \approx \frac{1}{2} M_{\pi_{\rm HV}}$ then $b\bar{b}$ tracks form large angles, use displaced vertex mass as signal:background discriminator.



NLLP Results

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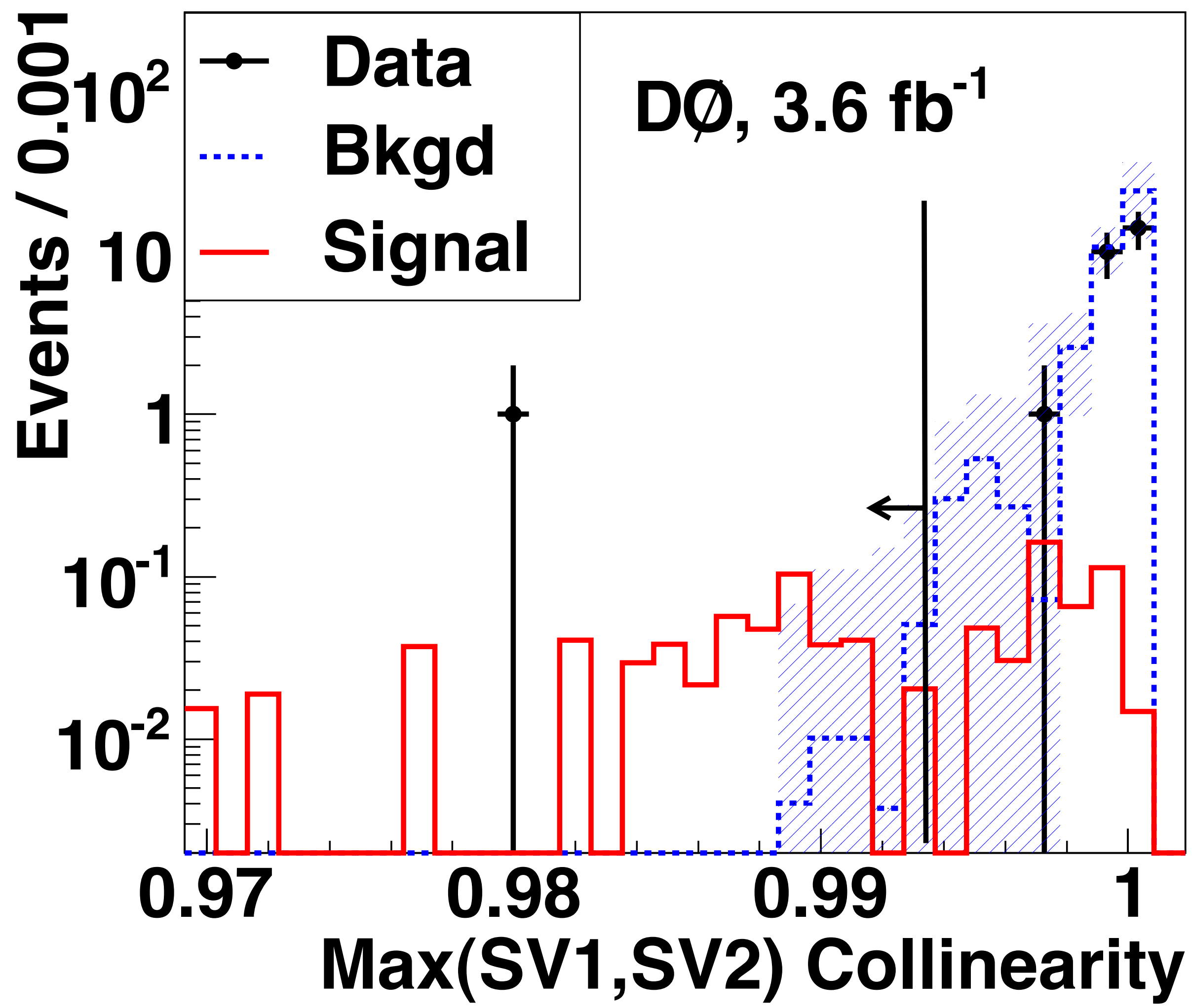
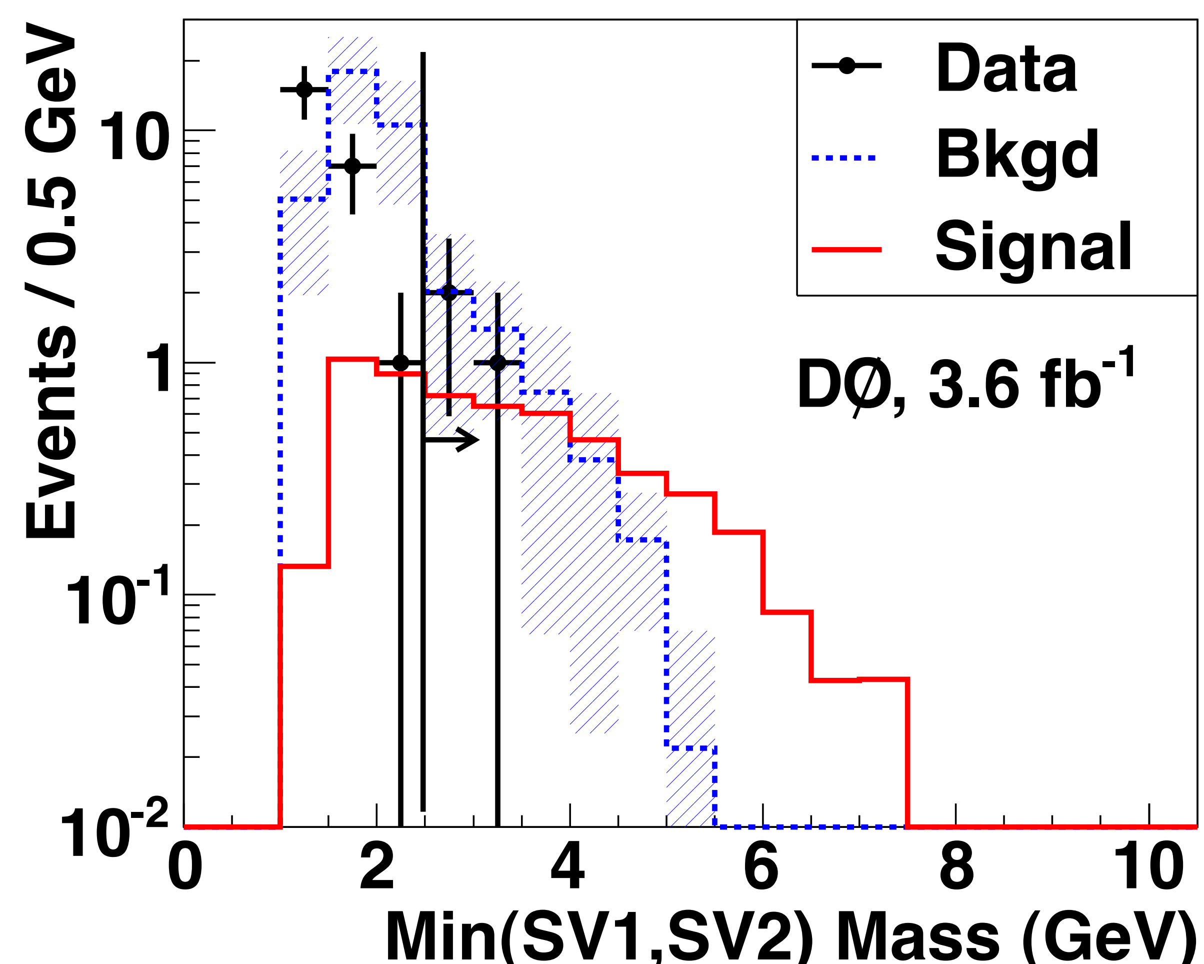
- We find statistical agreement with the standard model across the scanned parameter space.



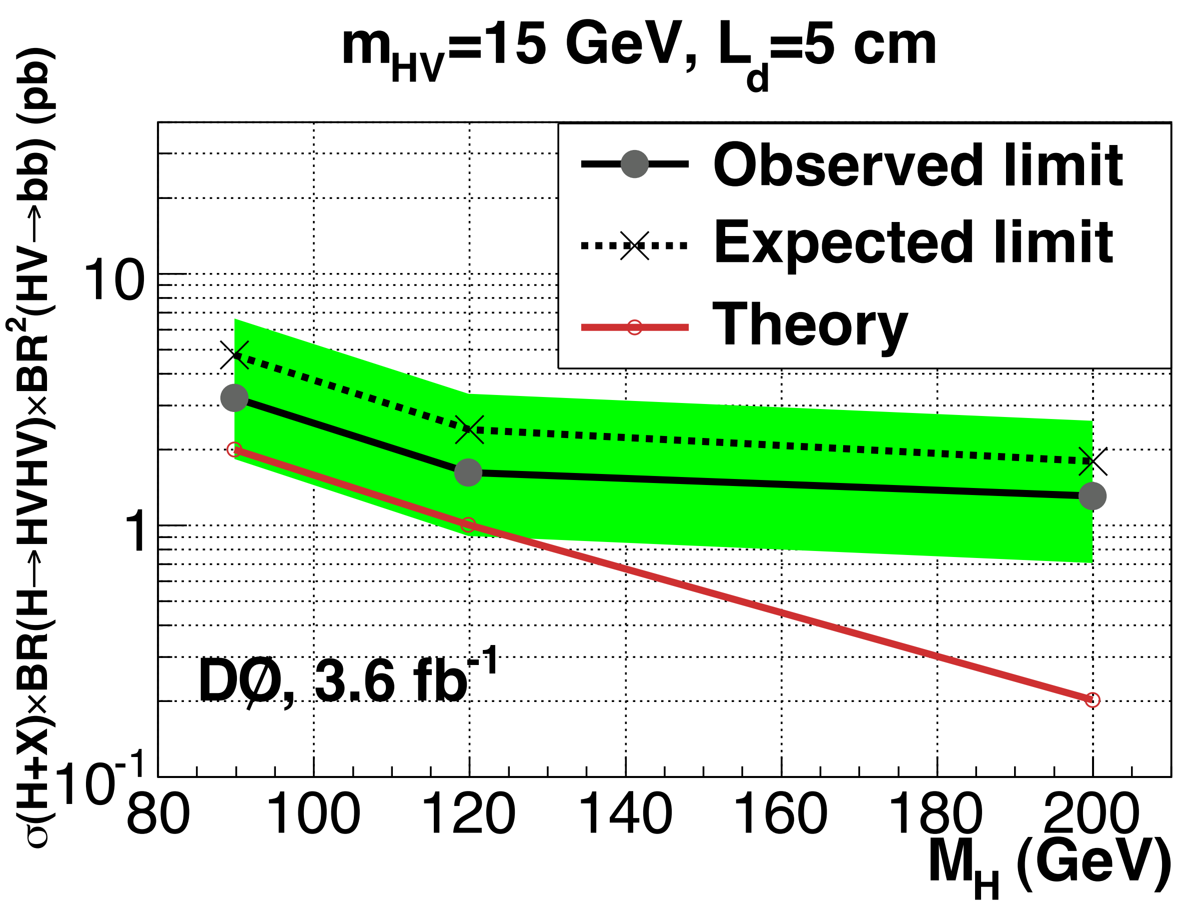
$$M_H \gg M_{\pi_{\mathrm{HV}}}$$

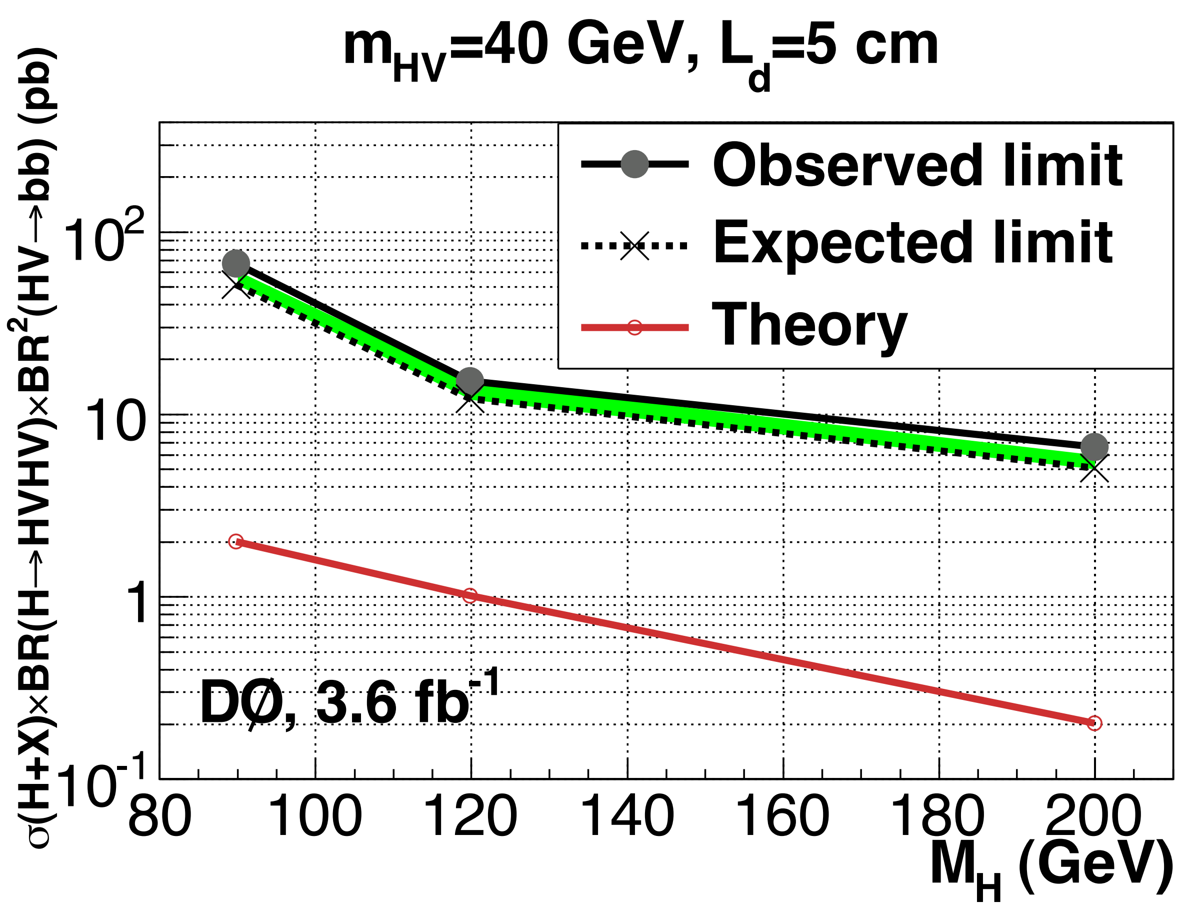


$$M_H \approx \frac{1}{2} M_{\pi_{\mathrm{HV}}}$$

Hidden Valley Limits

- 8 points in the 3D space of [M_H , $M_{\pi_{\rm HV}}$, L_{xy}].



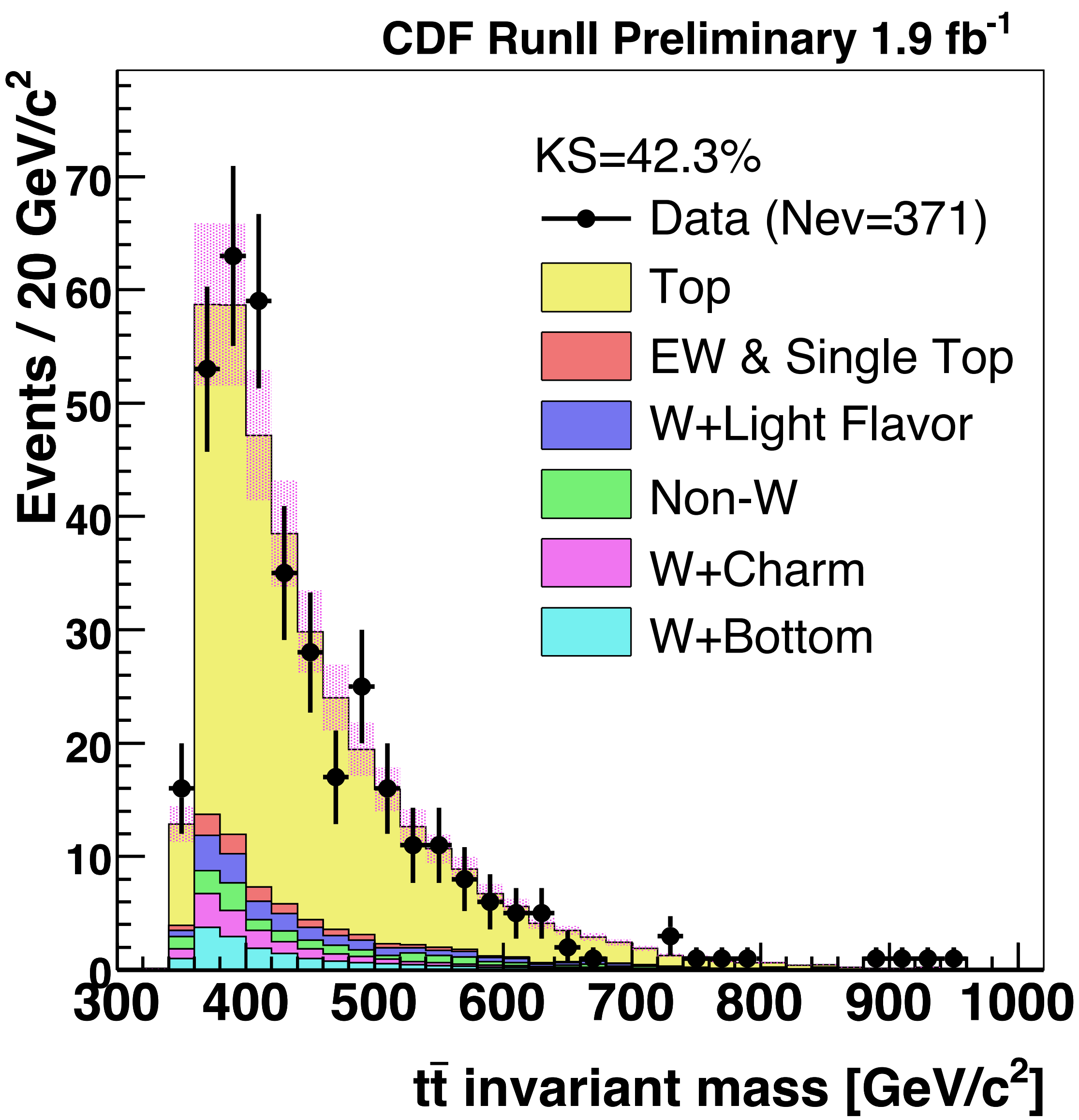


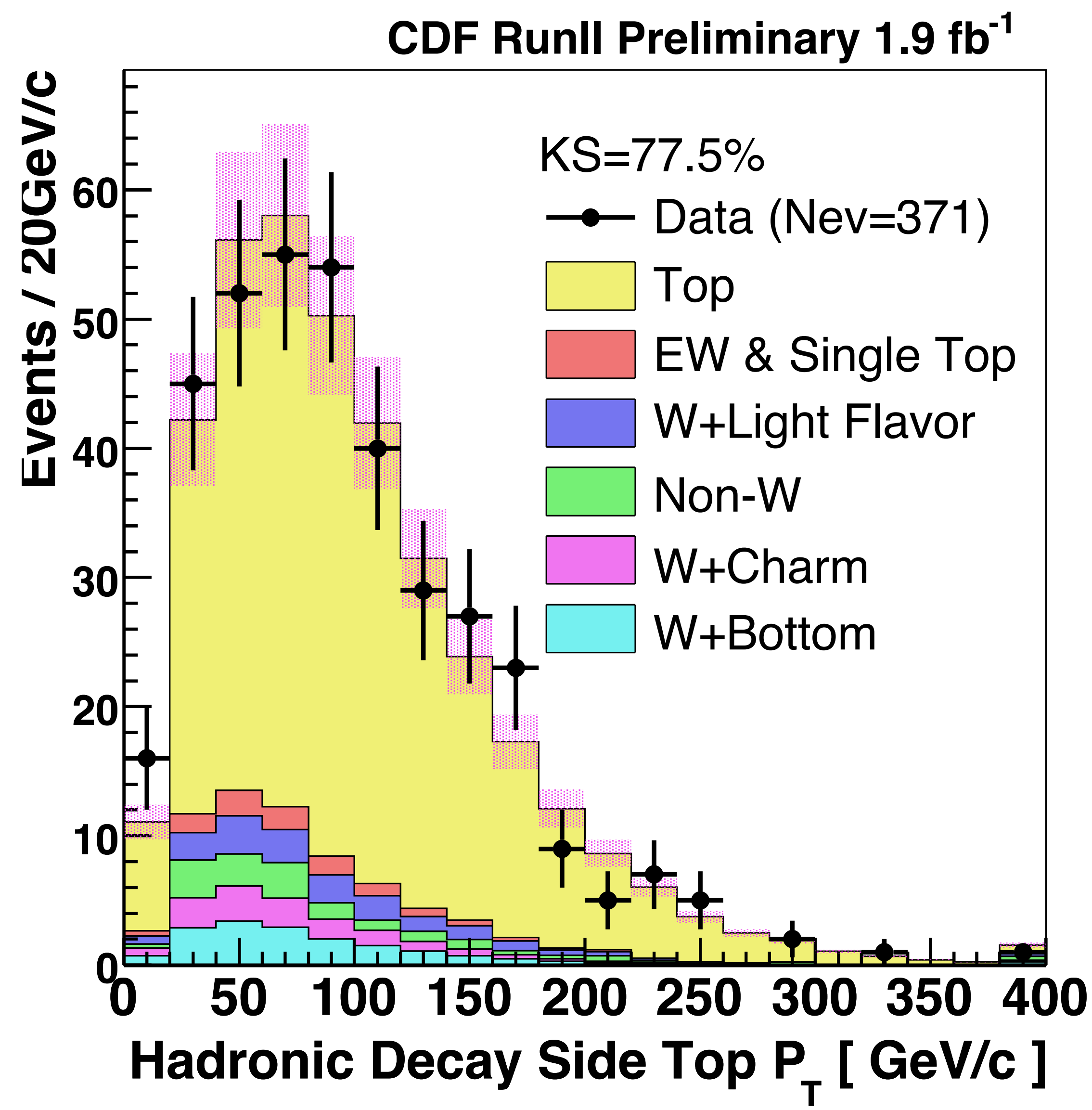
$$M_H \gg M_{\pi_{\rm HV}}$$

$$M_H \approx \frac{1}{2} M_{\pi_{\rm HV}}$$

High P_T top

- Both experiments have large ttbar samples in the lepton+jets channel.
- CDF has dedicated ttbar resonance search.
  - Unfortunately most of them are produced with little boost with current dataset.
  - May not have enough events to study boosted tops even with the fully expected dataset.





Summary & Outlook

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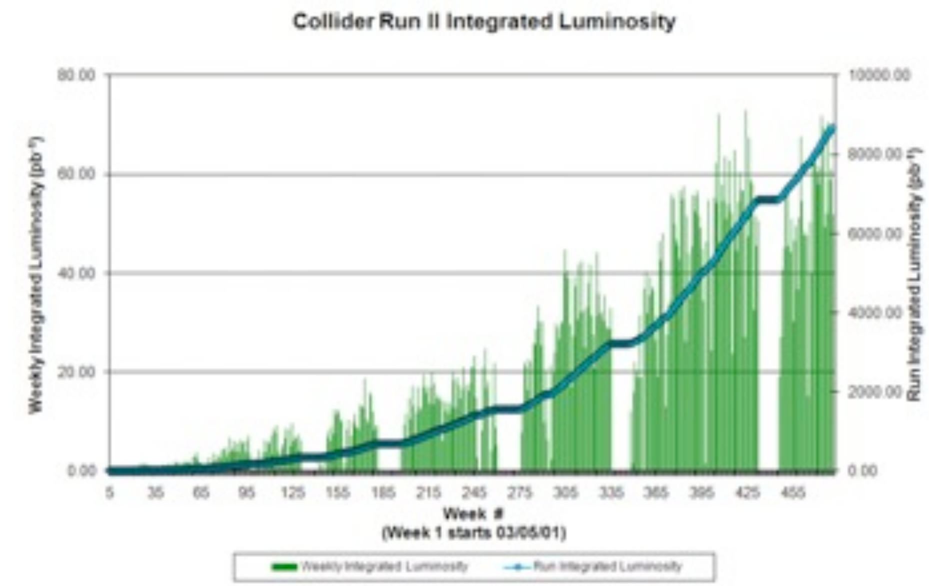
- Tevatron is performing extremely well with nearly 9 fb^{-1} delivered to both experiments.



- Most Tevatron Boosted searches focus on lepton-jets signals
  - Boosted tops (w/ high statistics) unlikely for Tevatron.

- Additional searches not mentioned:
  - Jet substructure measurement from CDF soon (ICHEP abstract).
  - Updated lepton-jets result from DØ (maybe tomorrow?).

- By end of 2010, both experiments can expect to analyze ~ 10 fb^{-1}.

- Tevatron still producing exciting results and if we're lucky we still might find new physics before LHC.

SUSY/Dark Photon Limits

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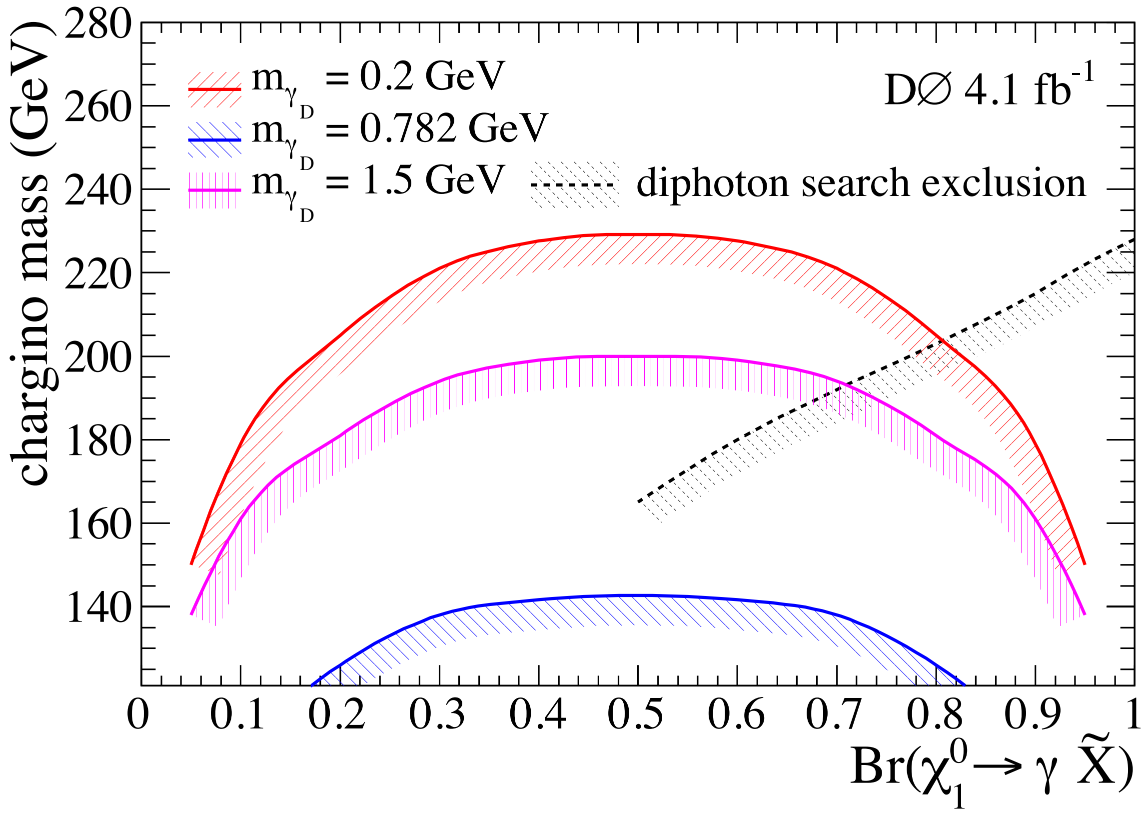
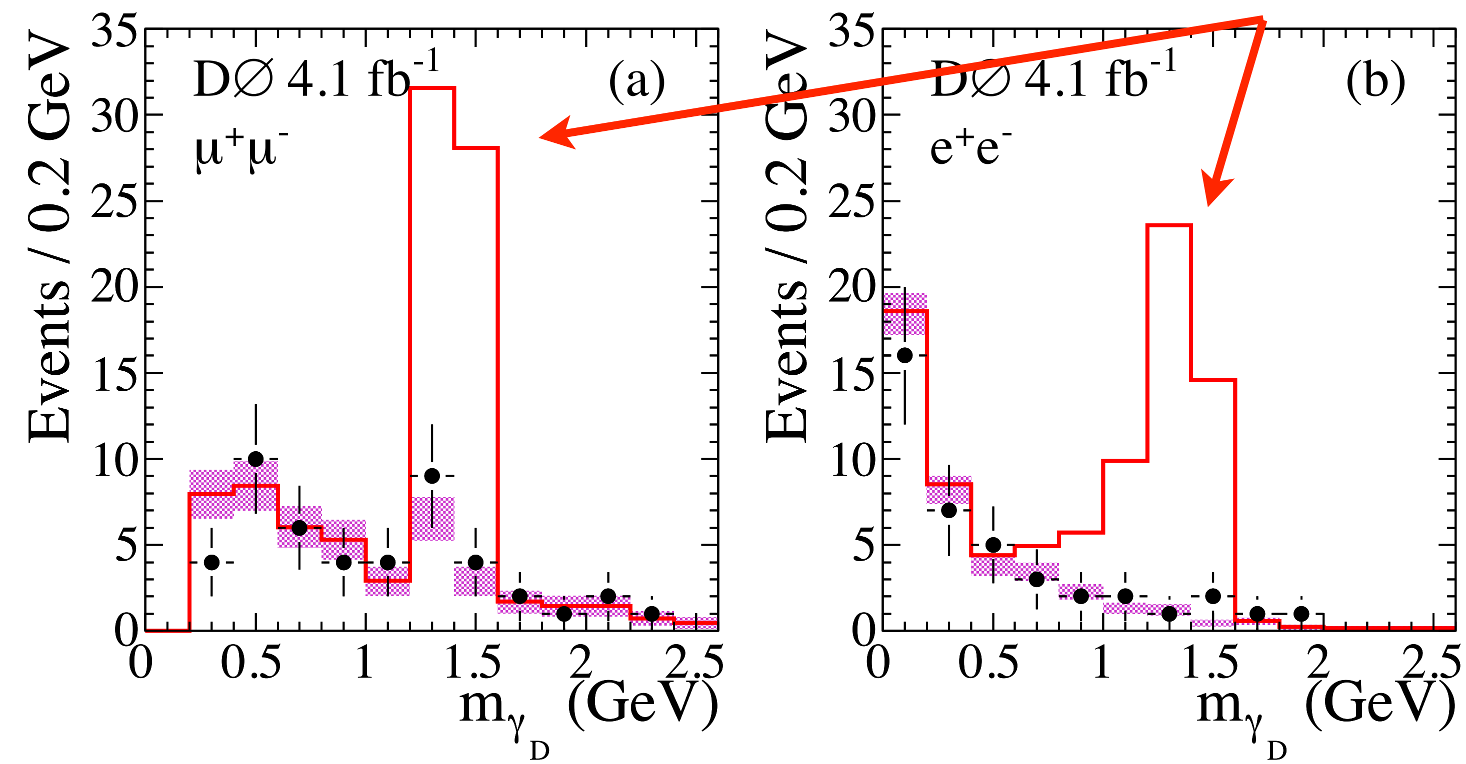
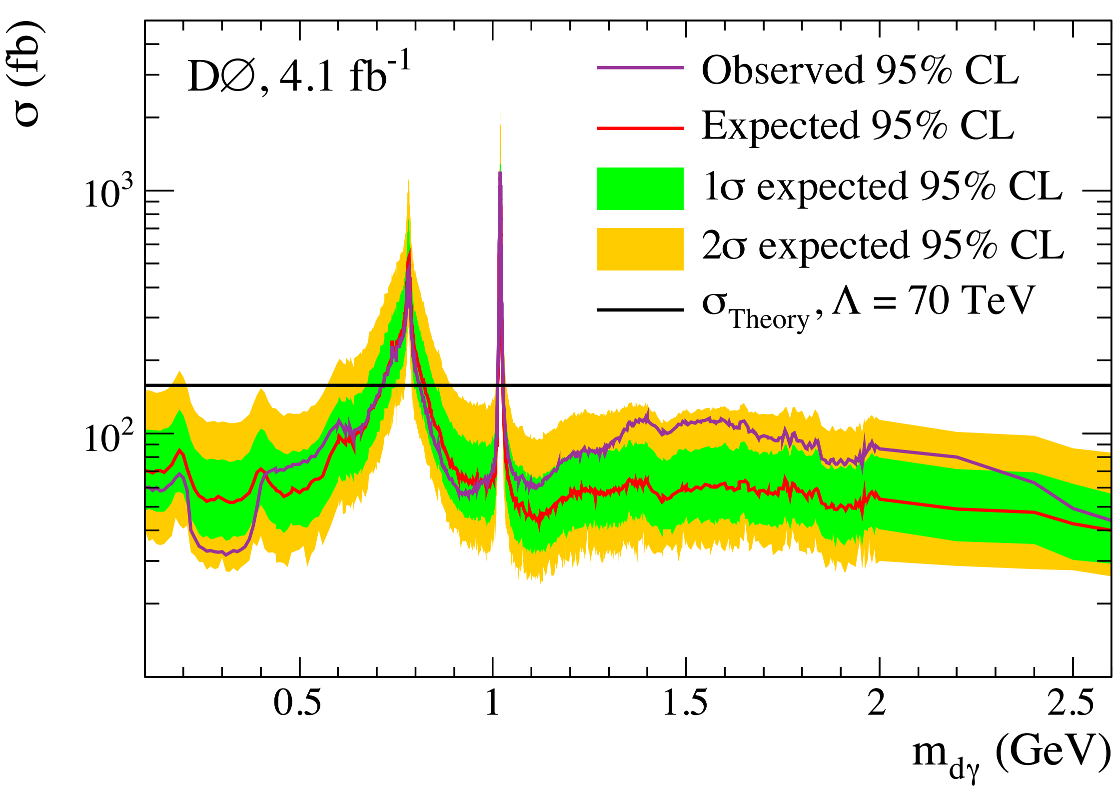
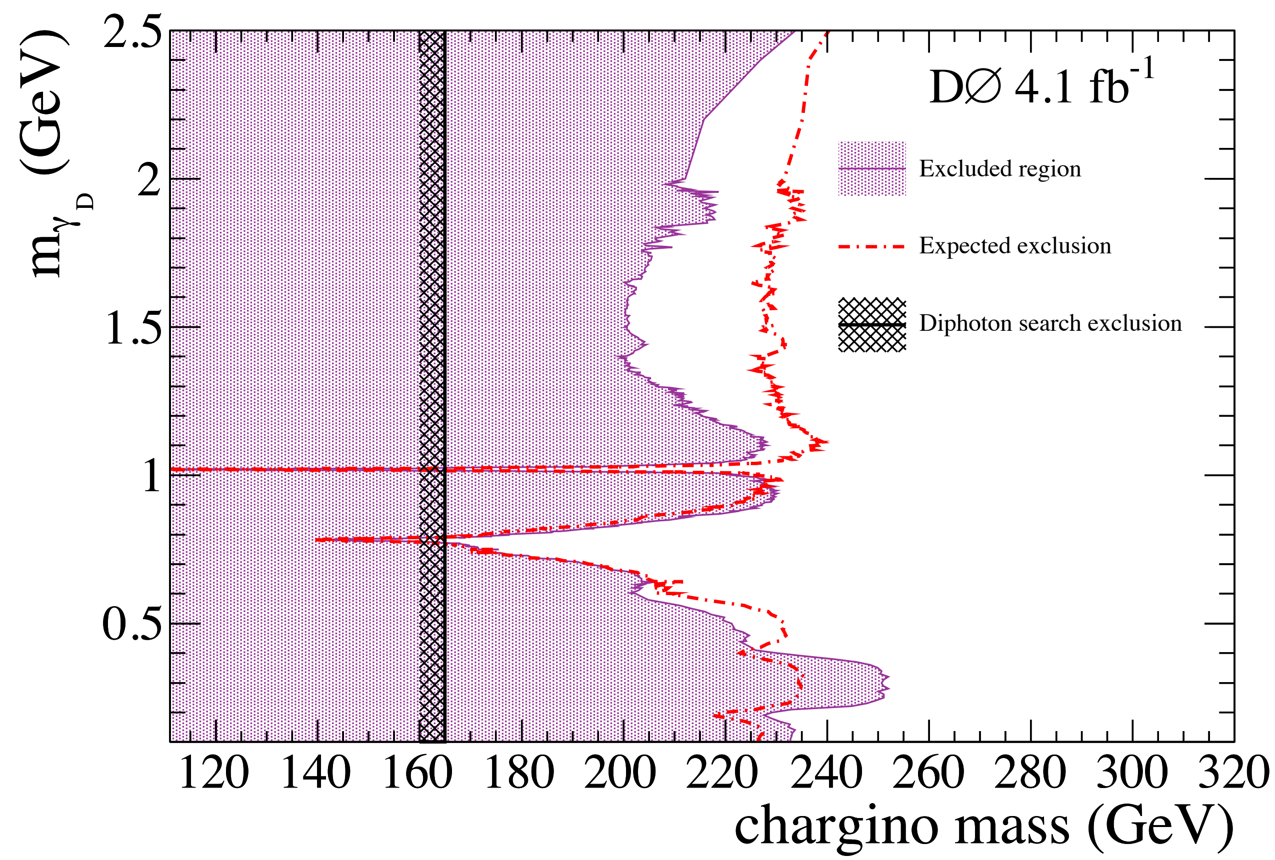
1.4 GeV γ_D signal



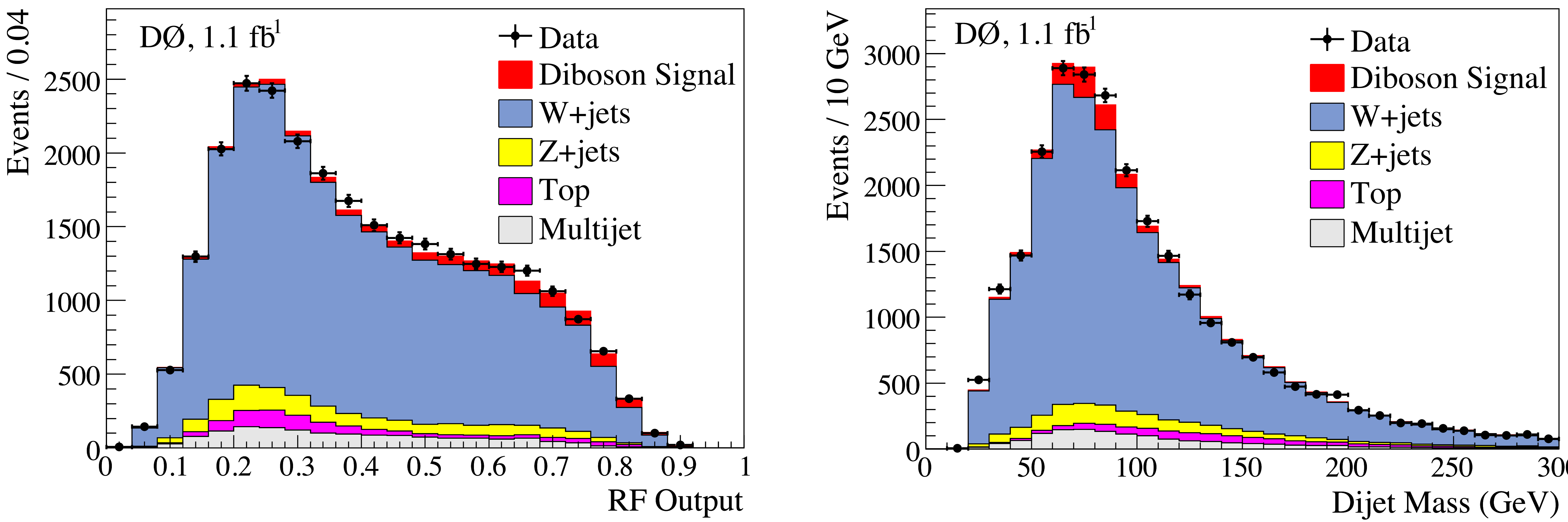






Hadronic W and Z Decays

- Both CDF and D0 see WW+WZ in the lepton+MET+jets channels.
  - W+jets a major background with large systematics.
- Both experiments use multivariate techniques to enhance signal fraction.



- CDF also see hadronically decaying W/Z in MET+jj channel.

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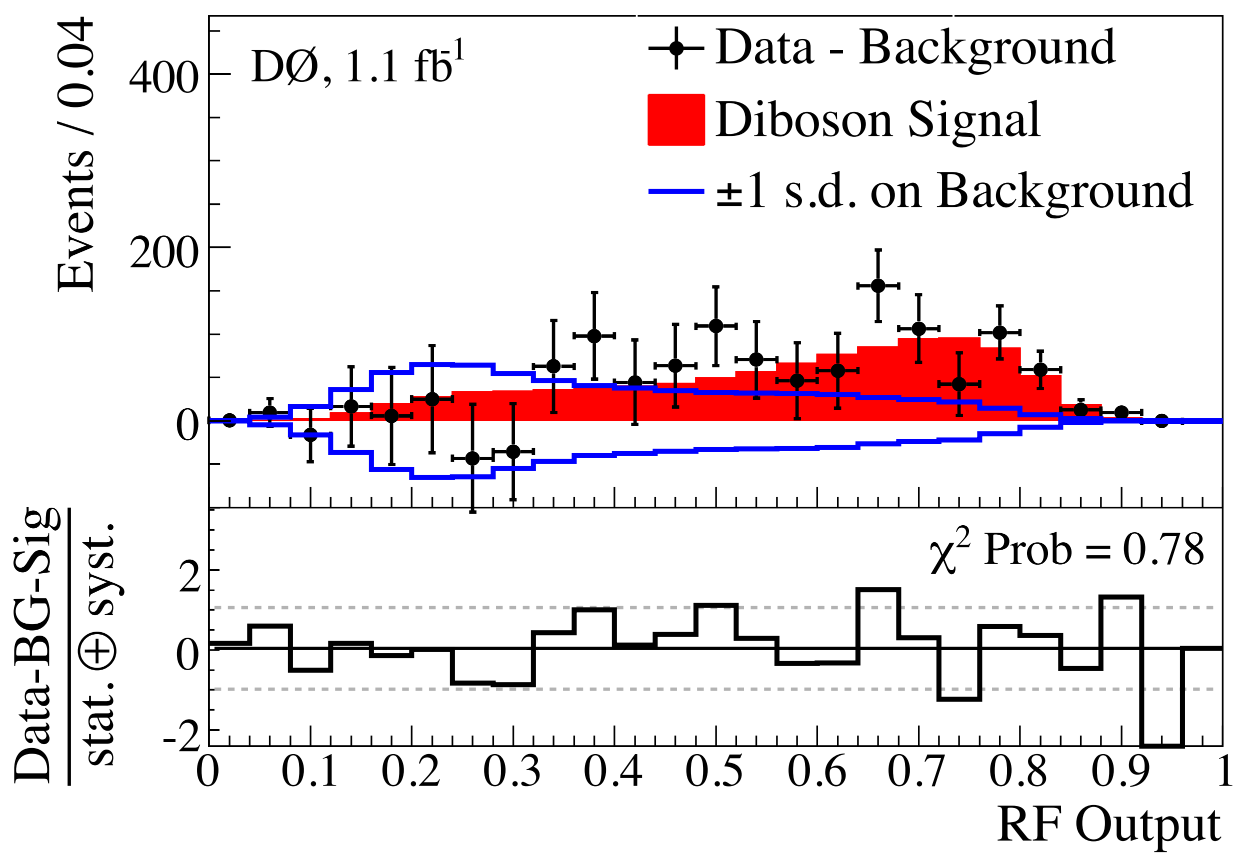

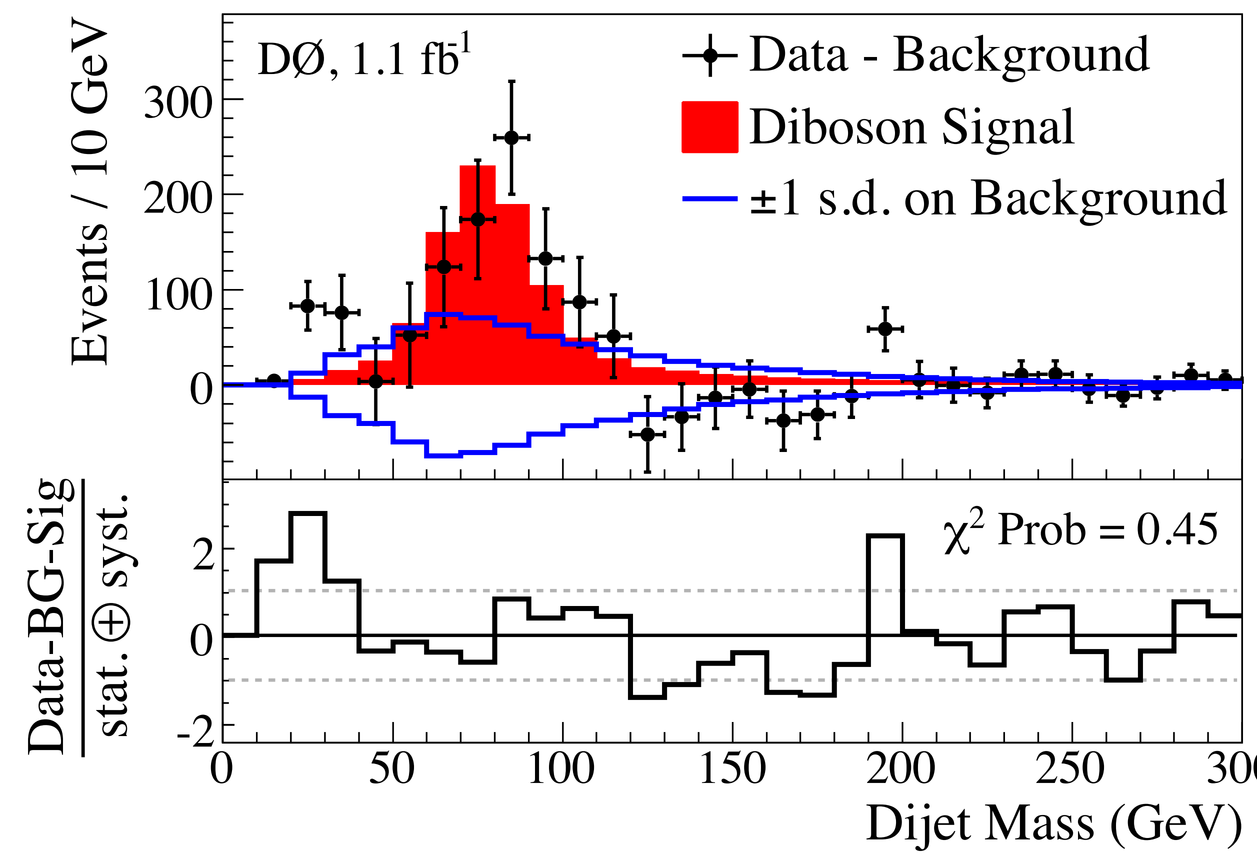

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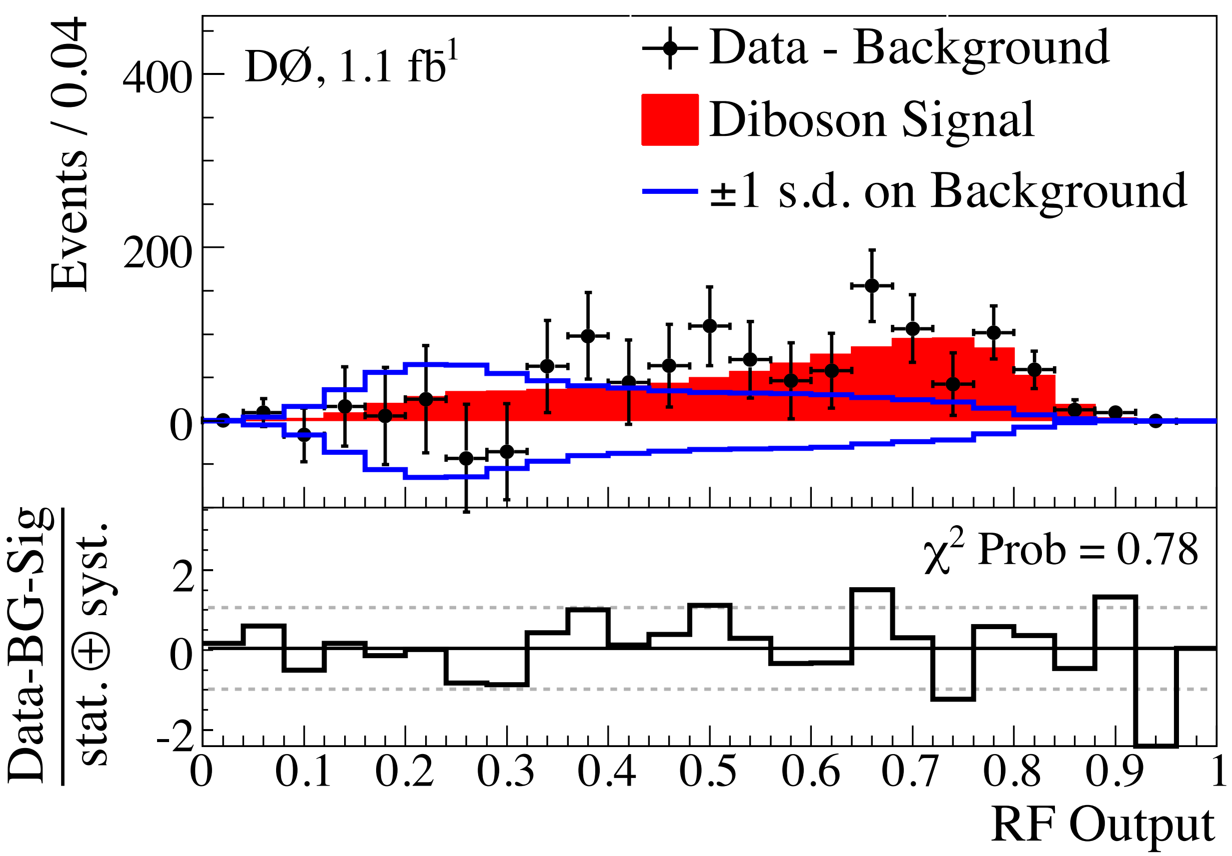

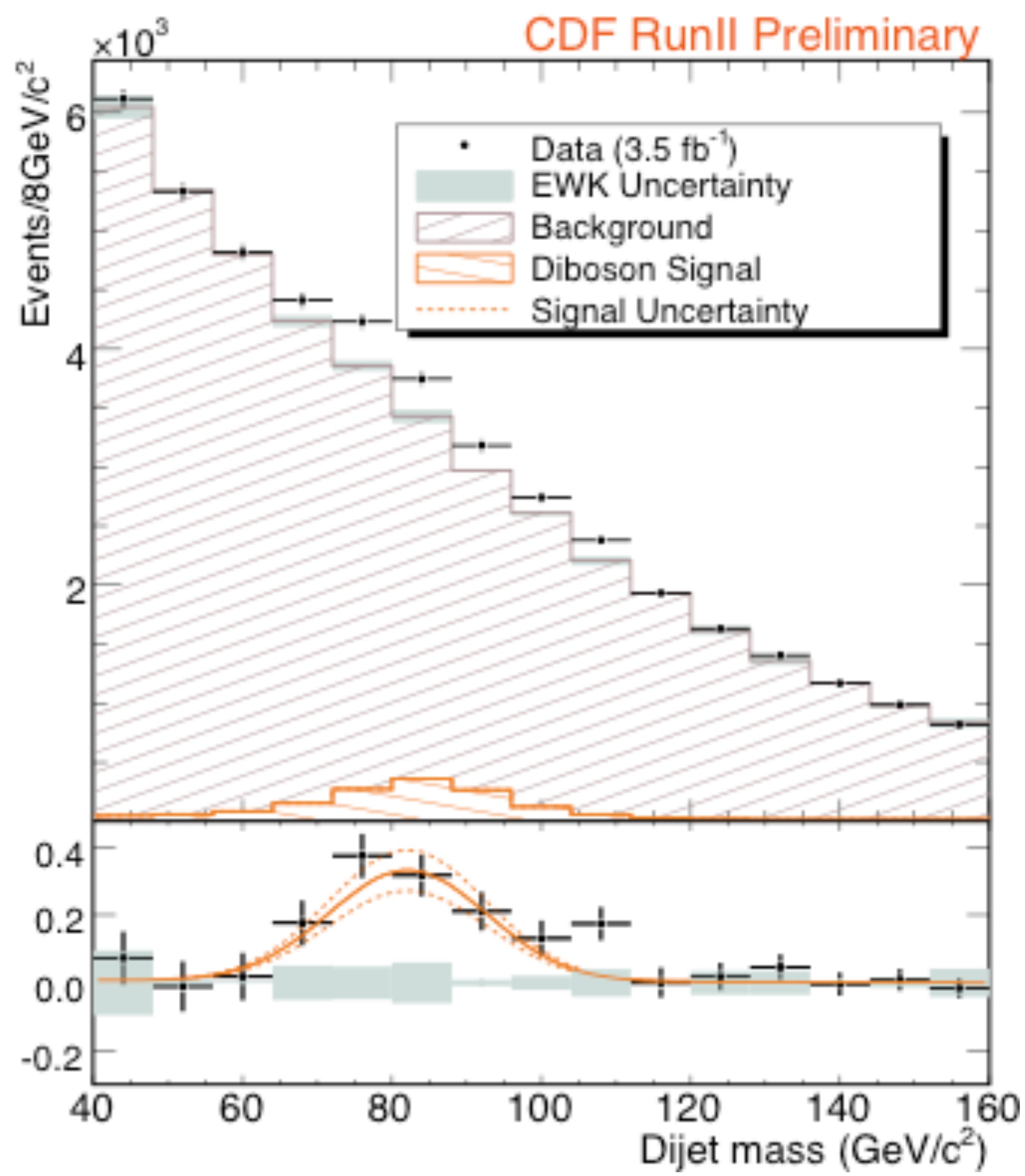

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Recent ALEPH H -> aa

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