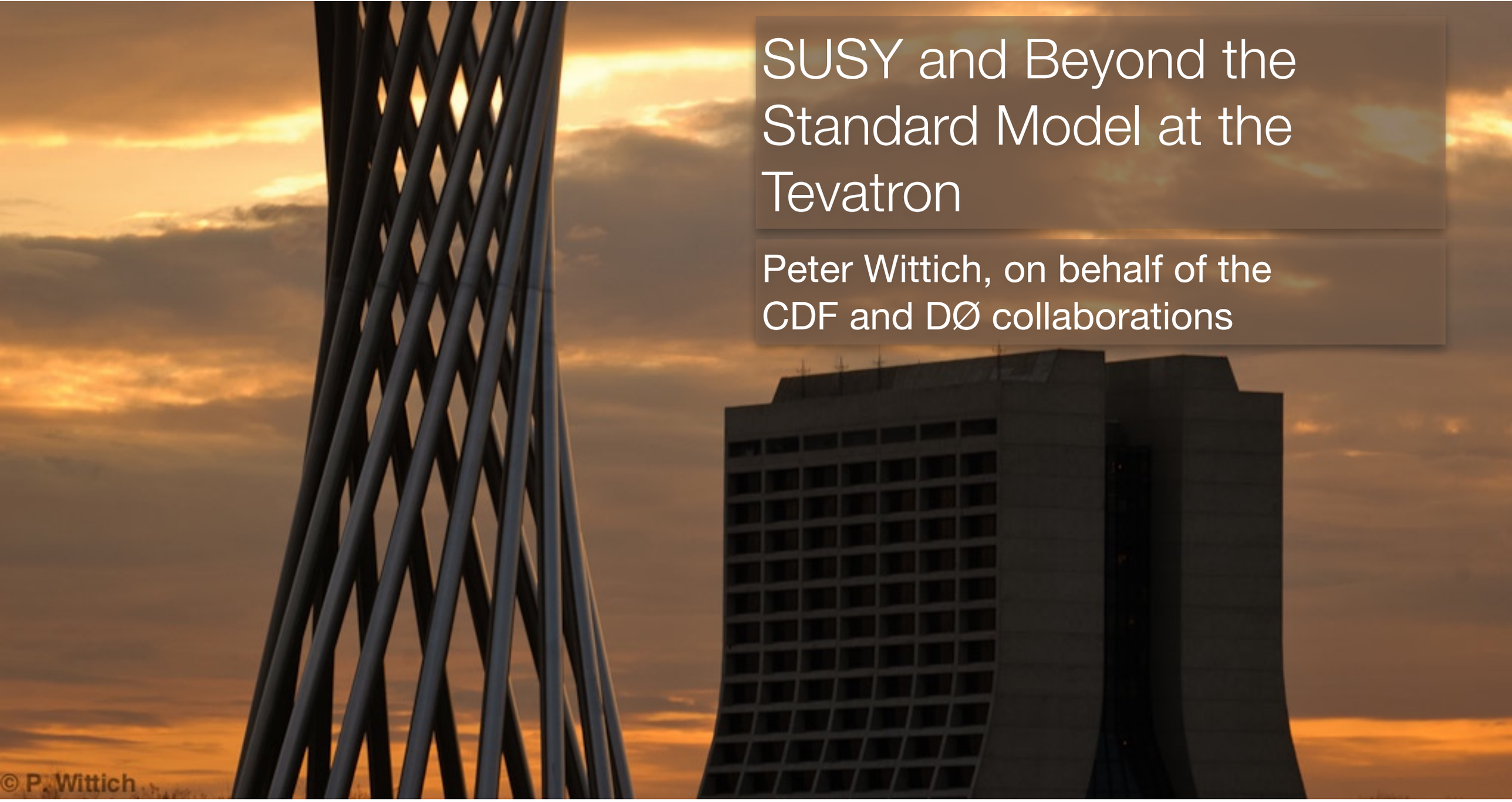
SUSY and Beyond the Standard Model at the Tevatron

Peter Wittich, on behalf of the CDF and DØ collaborations



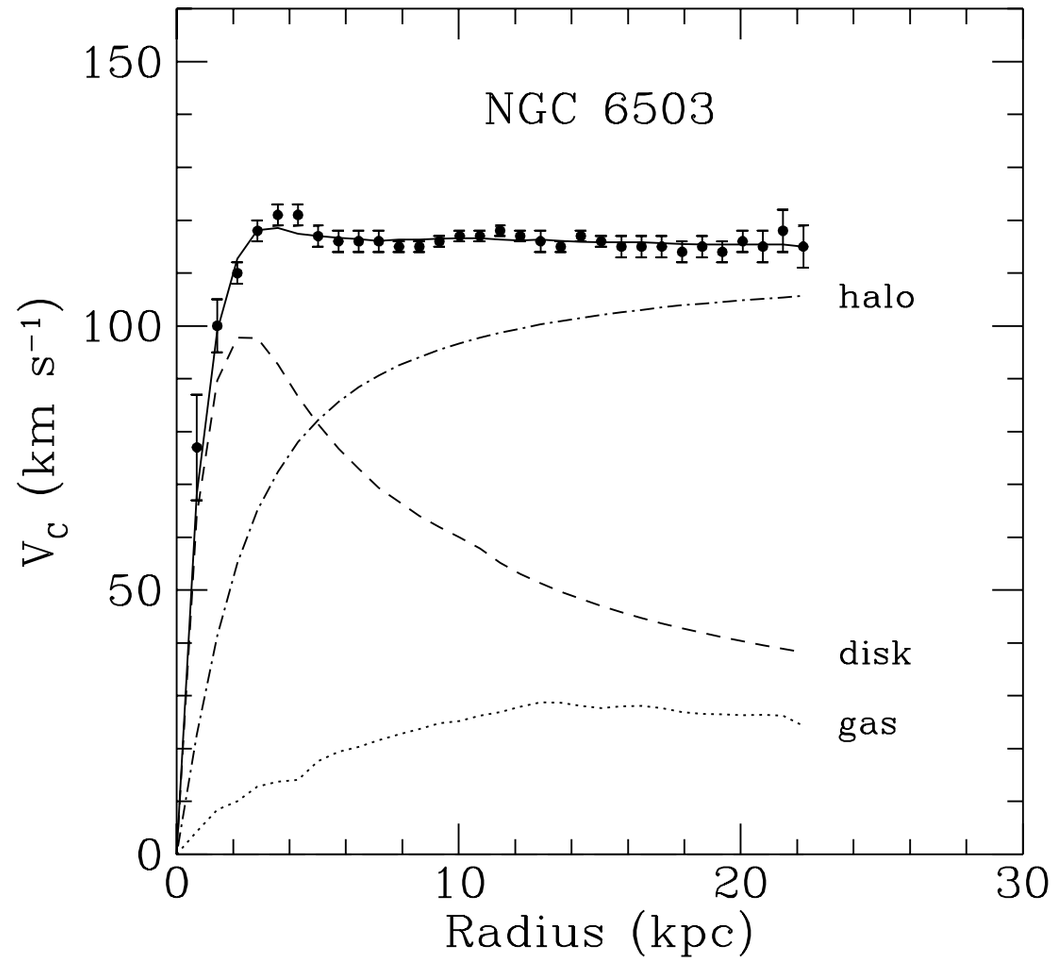
Cornell University
Laboratory for
Elementary-Particle Physics

Fermilab

New physics motivation from an exp. POV

Two Major Drivers:

- Dark Matter from Cosmology
  - heavy, long-lived neutral particle
- Hierarchy Problem
  - scale for new physics around 1 TeV



K. G. Begeman, A. H. Broeils and R. H. Sanders, 1991, MNRAS, 249, 523.

New physics motivation from an exp. POV

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New physics motivation from an exp. POV

Two Major Drivers:

- Dark Matter from Cosmology
  - heavy, long-lived neutral particle
- Hierarchy Problem
  - scale for new physics around 1 TeV

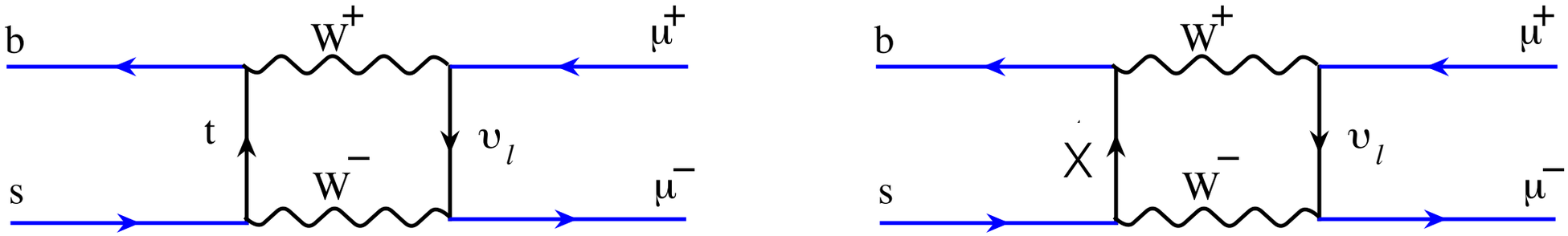
→ Tevatron Run 2 (and of course LHC!) fits the bill to explore particles with properties and mass scale

→ We're in the right place at the right time.

Interpretation of data and theoretical models

- Experiment's job: develop robust signatures; sensitive to a wide range of new physics models
- Either: *Null-hypothesis test* on standard model
  - strength: open to many possibilities
  - weakness: less sensitive to any particular model
- OR: *Optimization for a particular model*
  - Minor Optimization: better model limits
- Both methods are pursued
- Personally:
  - what ultimately matters is ***data vs SM***

Direct searches vs indirect searches



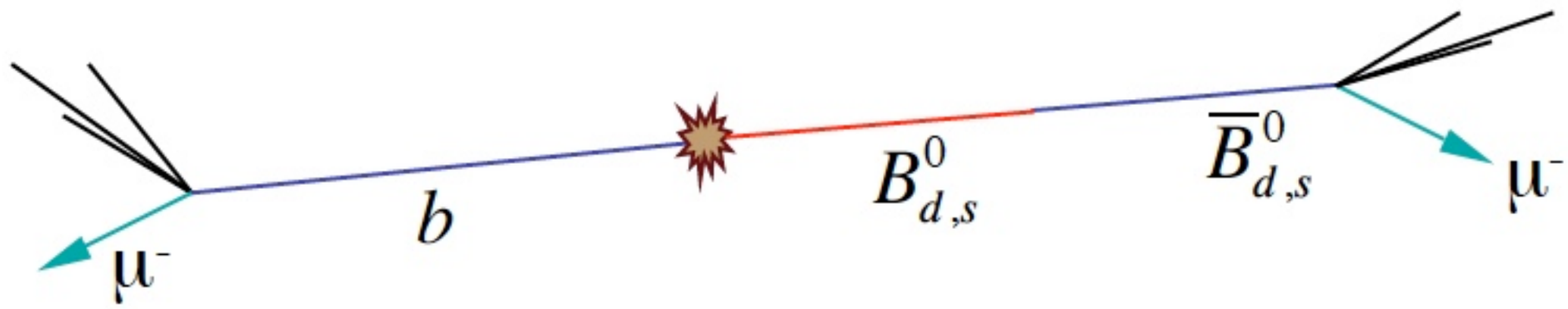
- This talk is focussed on *direct searches*
- Indirect searches are another powerful method
  - Understanding mechanism for CP violation in the *B* system
- Precision test of SM physics looking for *discrepancies* between SM prediction and data via off-mass-shell weakly produces particles

- Recently lots of buzz about one such measurement
  - Anomalous production of like-sign dimuon pairs at D0

- Michal Kreps (KIT) will cover indirect searches in *B* system in more detail during Friday Morning session at this conference, also $B_s \to \mu\mu$
- See also talk by Iain Bertram on D0 like-sign di-μ's at 15:40 on Friday.

Teaser: $\mu^{\pm}\mu^{\pm}$ asymmetry at D0

Submitted to P.R.D.
arXiv:1005.2757



- Precision measurement: Look at decay of *B* mesons to final states with μ's
- Look for *same-charge* final states

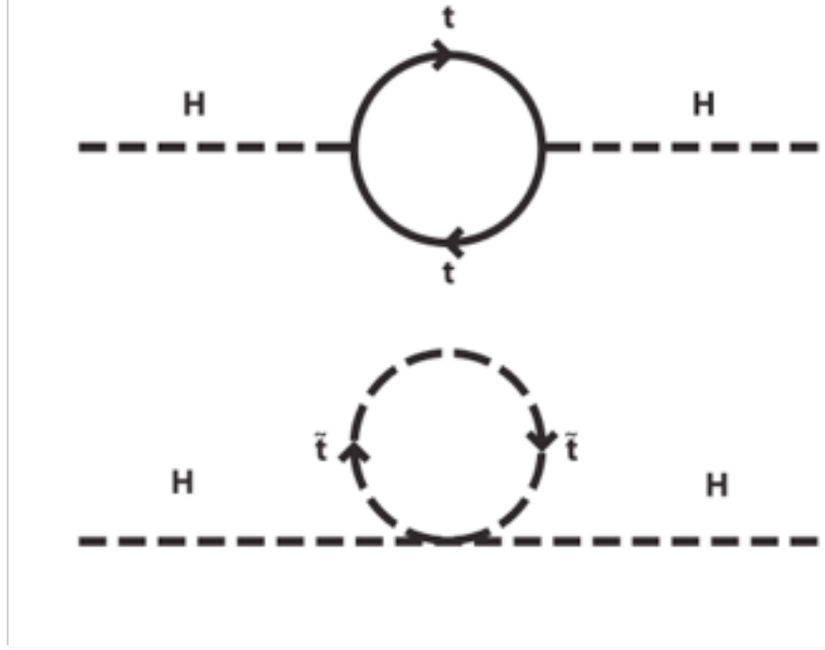
- D0 reports 3.2σ excess - see talks on Friday at this conference

$$A_{\rm sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = -2.3^{+0.5}_{-0.6} \times 10^{-4}({\rm SM})$$

$$\mathrm{D0}: A_{\rm sl}^b = -0.957 \pm 0.251\ (\mathrm{stat}) \pm 0.146\ (\mathrm{syst})\%$$

Supersymmetry: Grand Dame of NP models

- Based on fundamental symmetries
- Hierarchy Problem solved
- How: double particle spectrum
  - Worked before: postulate positron for quantum mechanics
- Introduce "super-partners" of diff spin
  - Makes theory self-consistent
  - Also provides dark matter candidate
- But: where are they?
  - Mass of positron = Mass electron
  - But not so for missing selectron
  - SUSY is a broken symmetry
- SUSY partners should be visible at Tevatron/LHC



Particle	Super-partner
e,ν,u,d	$\tilde{e},\tilde{\nu},\tilde{u},\tilde{d}$
γ,W,Z,h	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^{\pm},$ $\tilde{\chi}_1^0 \cdots \tilde{\chi}_4^0$

Dark Matter Candidate

Many other models exist too...

- Large Extra Dimensions:
  - Another formulation of the Hierarchy problem: why is Gravity so weak?
- Universal Extra Dimensions:
  - Models of many extra dimensions can mimic SUSY in some of the phenomenology
- Hidden Valley:
  - How to explain the apparent lack of new physics in the Tevatron and LEP data? They're in a hidden sector
- Technicolor models of EWK symmetry breaking...

- No questioning the fertile imagination of today's theory community!

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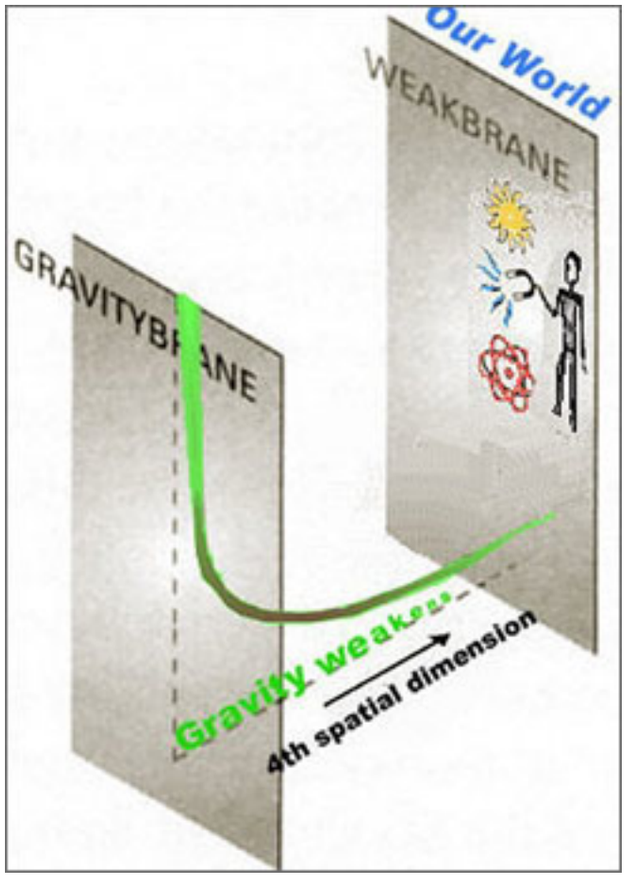

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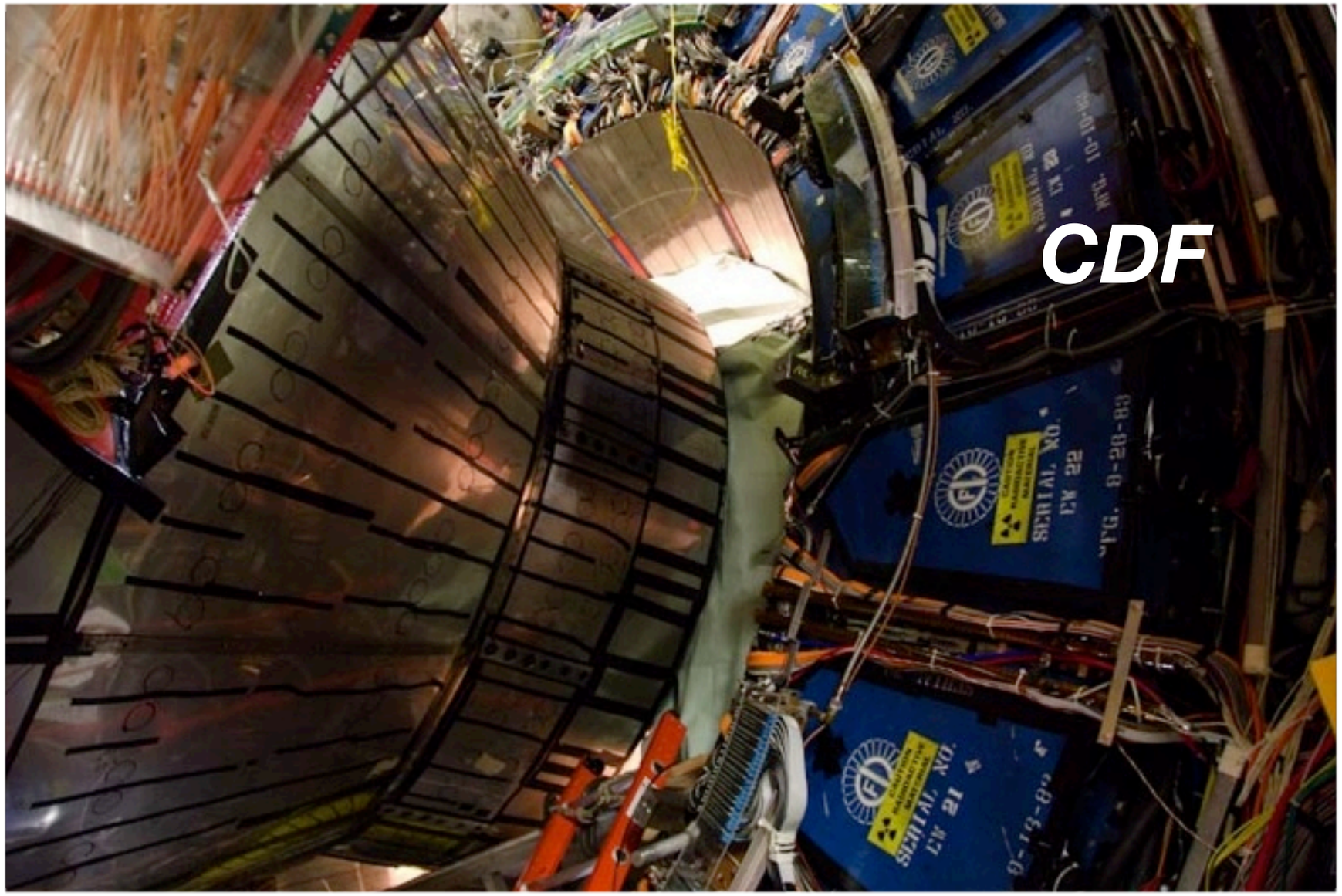
The cast of characters



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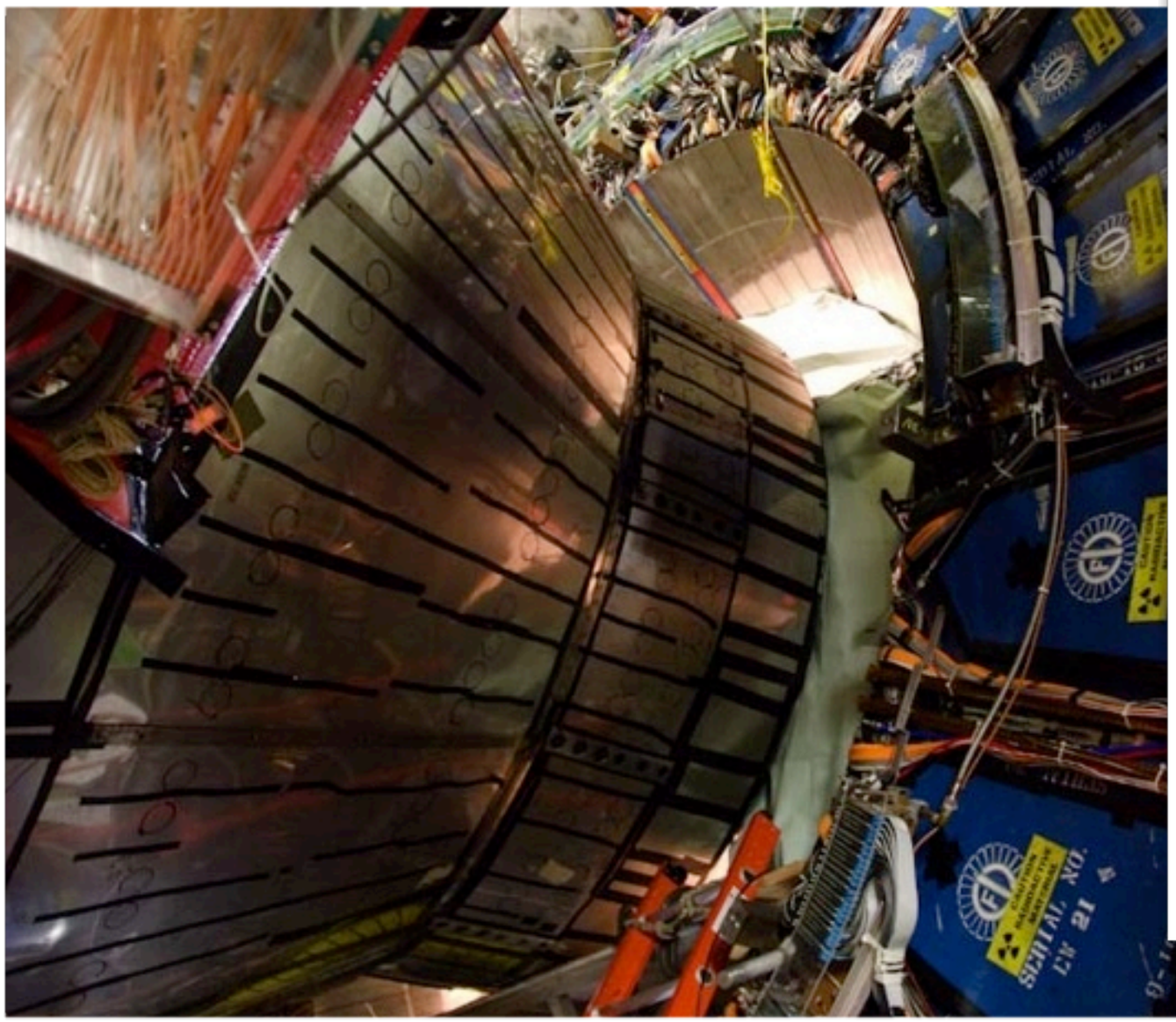

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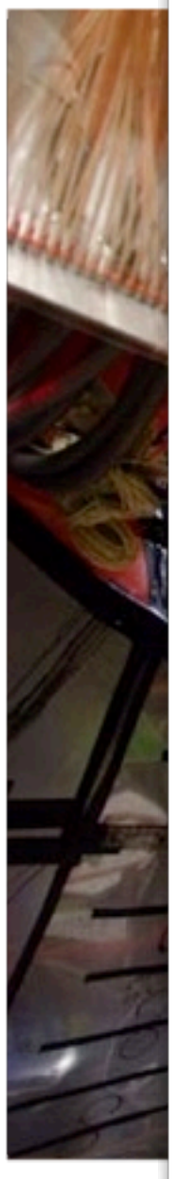
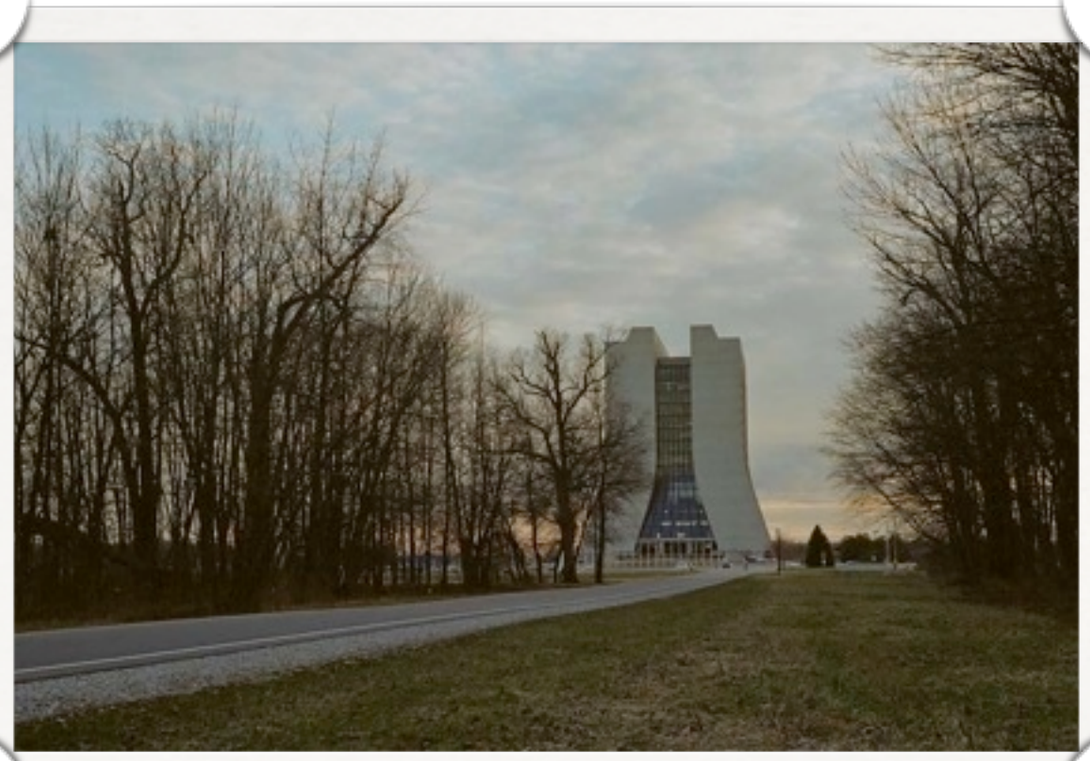
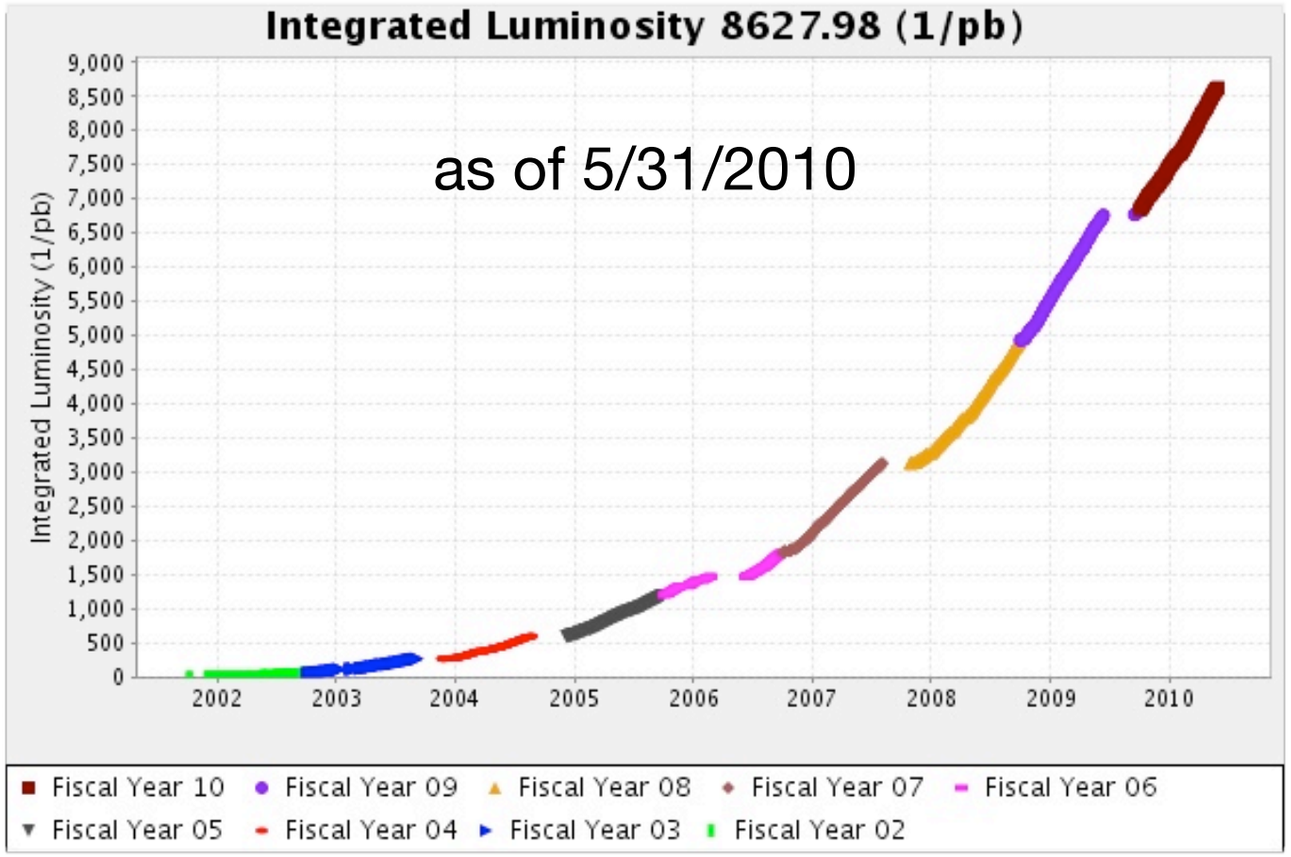
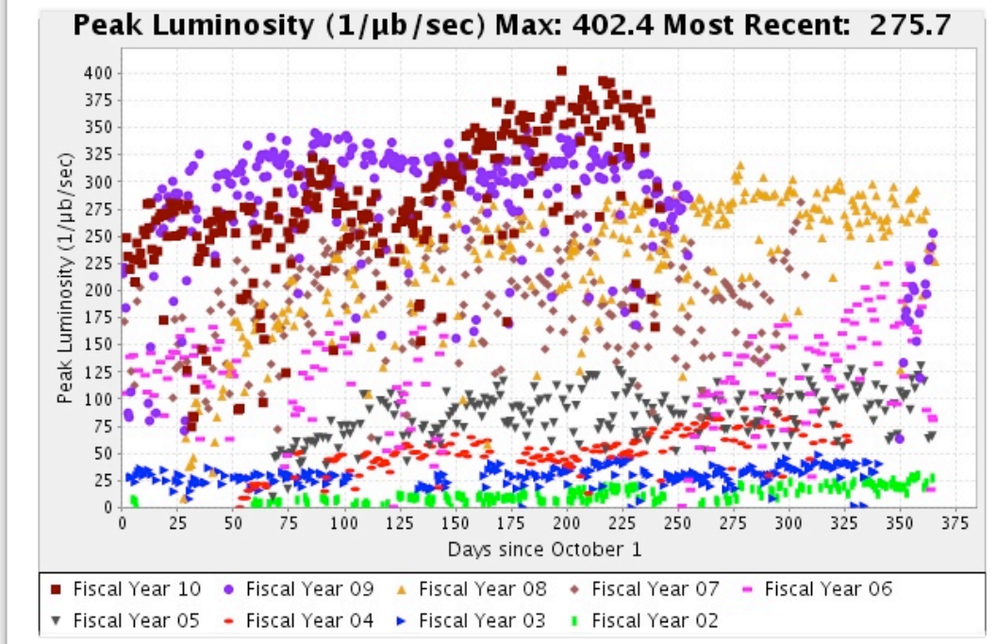


Tevatron Performance

- The machine is performing very well
  - Delivering record inst. luminosities (>400E30)
  - Integrating lots of data with high efficiency (>1.7/fb accumulated in FY10 already)
- Today: **5.4/fb**, already have **8.6/fb** in the can
- On track for a ***record-breaking year***

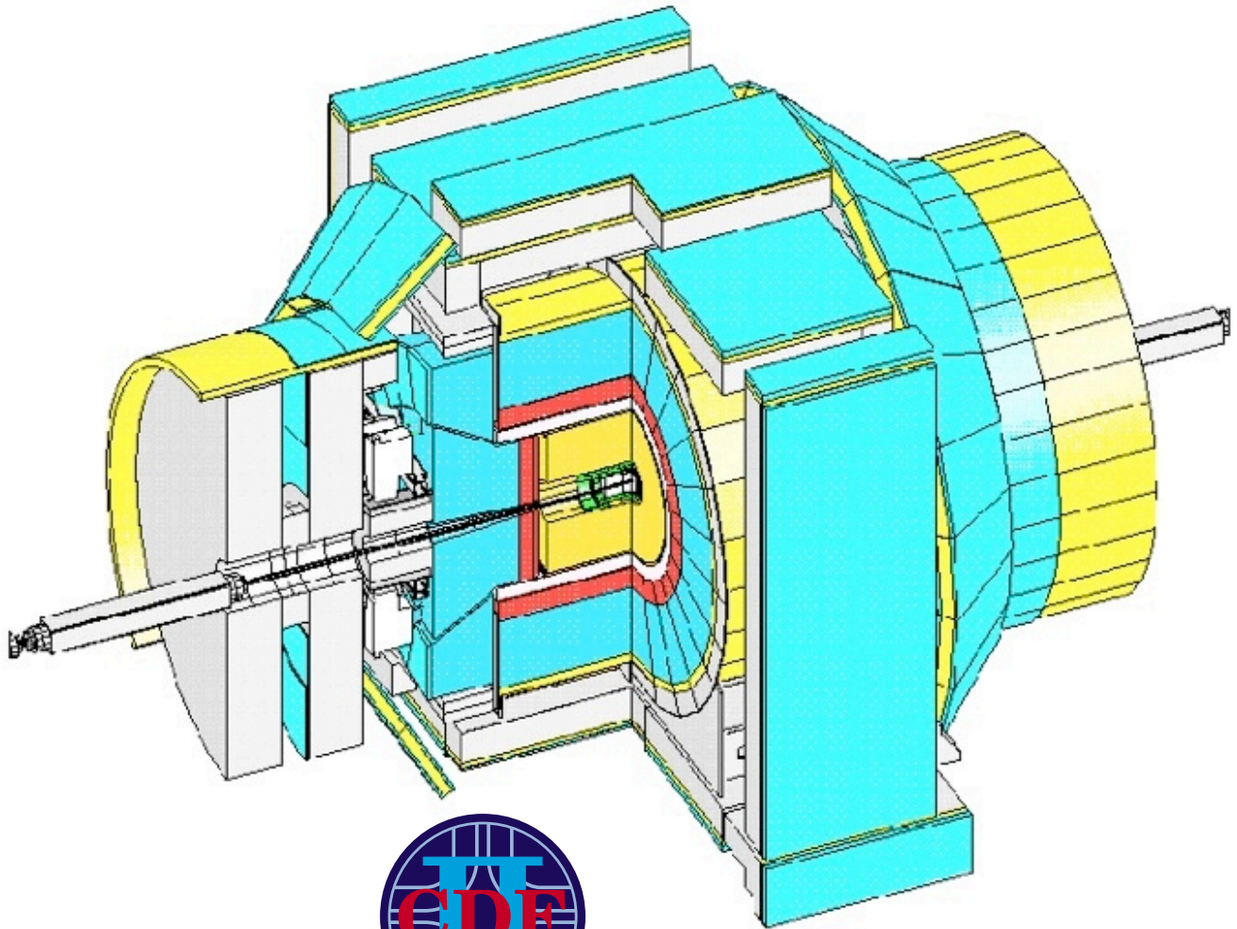


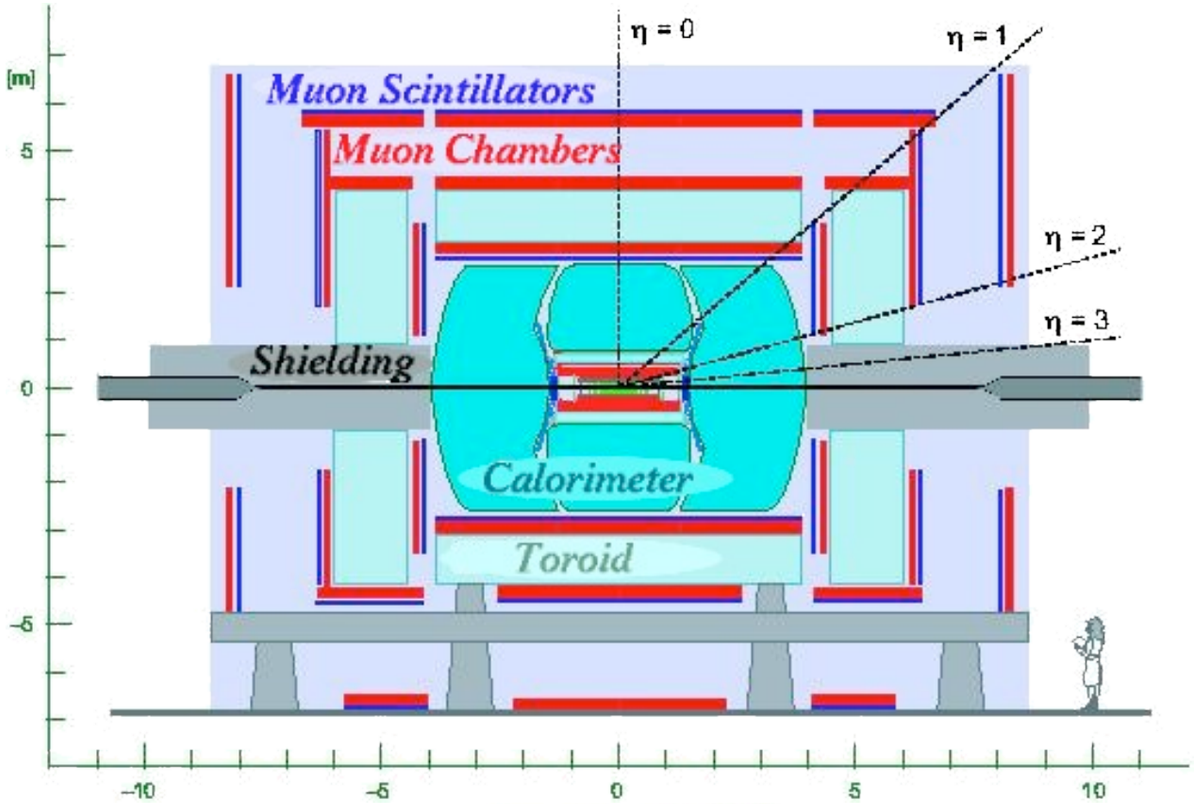




Experiments: CDF and D0

- Run 2 experiments very similar
  - strong central tracking in solenoidal field (η~1-2), Si innermost
  - good hermetic calorimetry (em & had, η ~ 2-2.5)
  - extensive muon coverage (η ~1 -2)
  - performant trigger to collect interesting events
- Very similar performance as measured by physics results





Selected Current Results

- Decays to Pairs of Gauge Boson-like objects
- Searches for quark-like particles
- Bump Hunts
- Exotic Exotica

- Highlights
- Full list available:

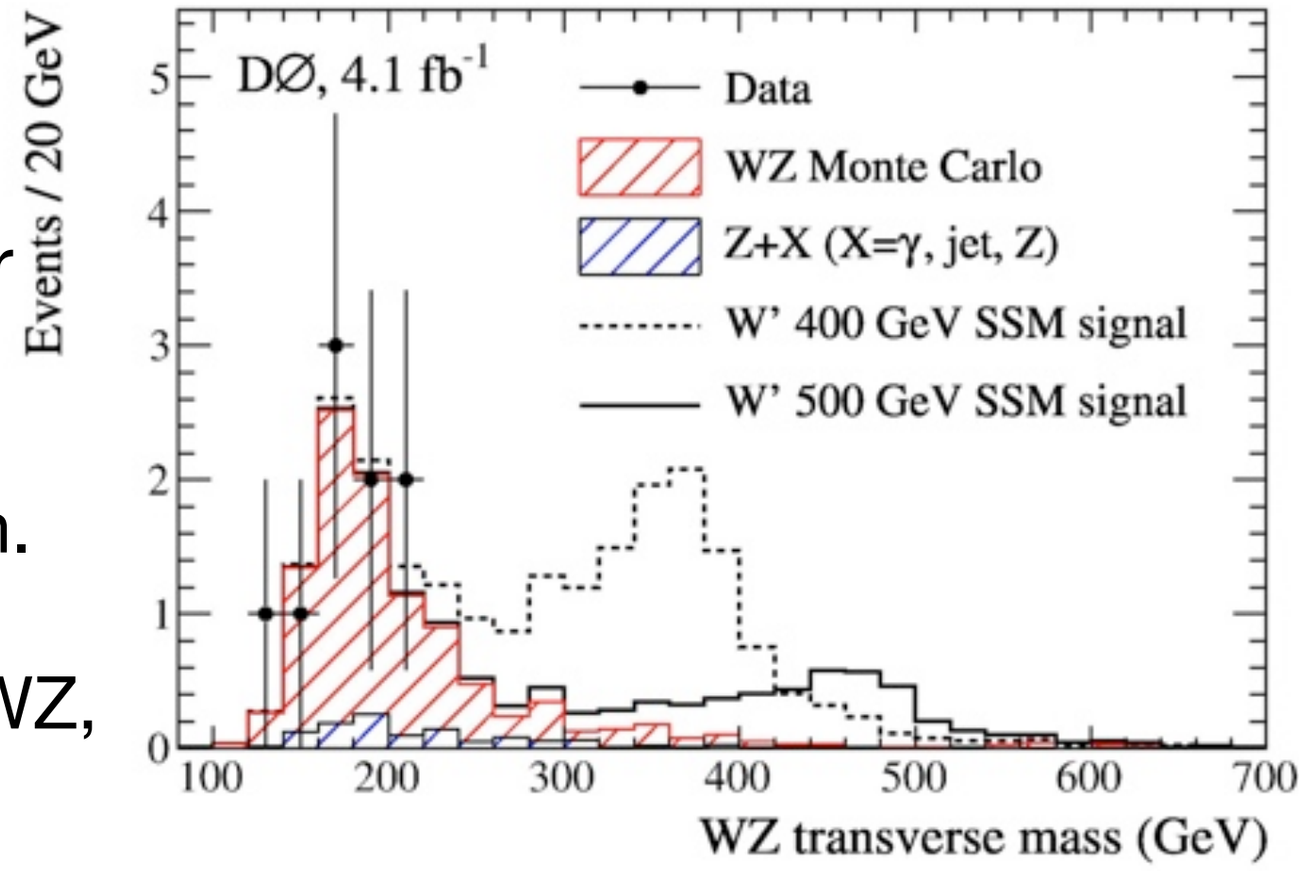
http://www-cdf.fnal.gov/physics/exotic/exotic.html

http://www-d0.fnal.gov/d0_publications/

Decays to Pairs of Gauge-boson-like Objects

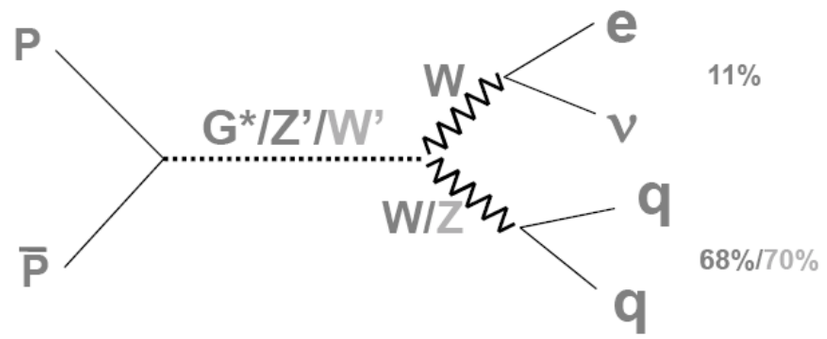
Trileptons: X→ WZ (Gauge boson pairs), 4.1/fb

- Similar to SUSY chargino/neutralion analyses, but high p_T→ not SUSY but decays to SM Gauge Boson
- require large missing E_T, same-flavor opposite-sign pair in Z mass range, separation btw pair and 3rd lepton
- data consistent with SM expectation.
- Set limit using CL_s technique in m_T(WZ, E_T^{miss})
  - next



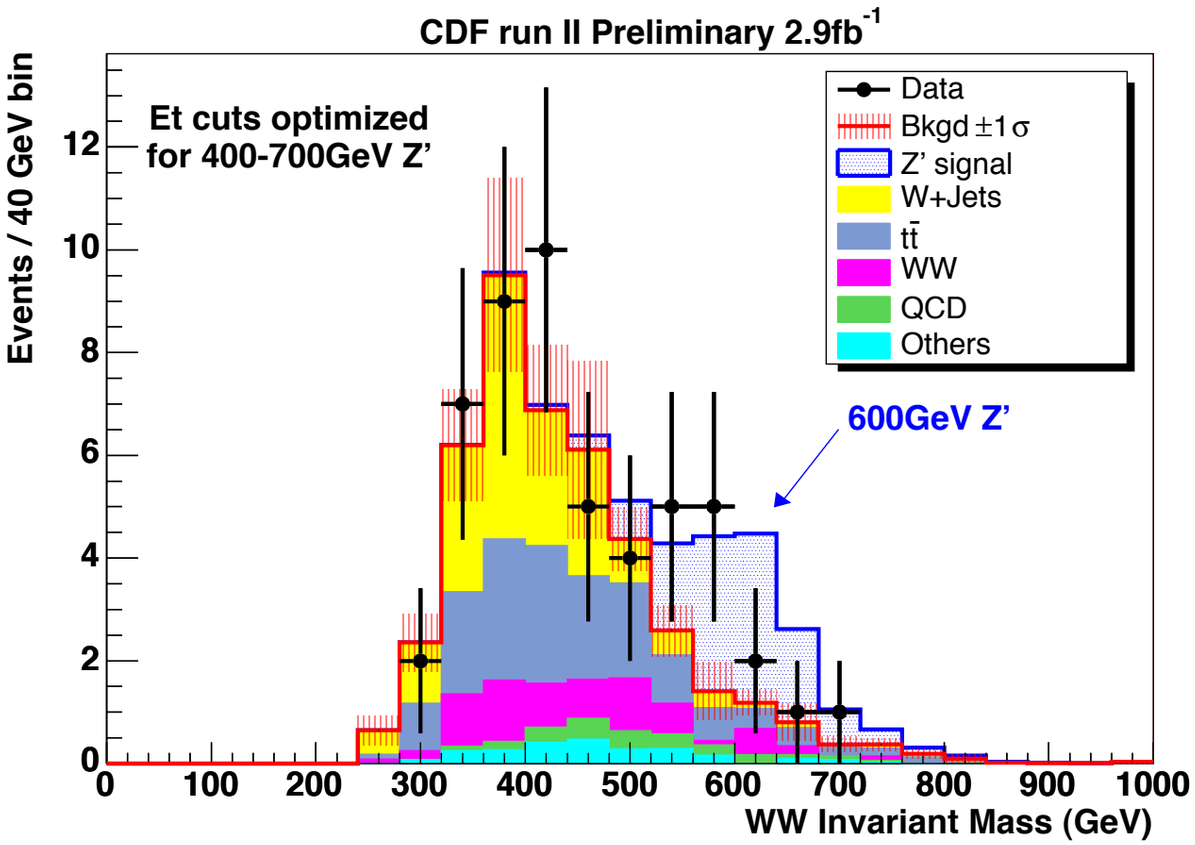
Phys. Rev. Lett. 104, 061801 (2010),

Diboson resonances in eνjj, 2.9/fb

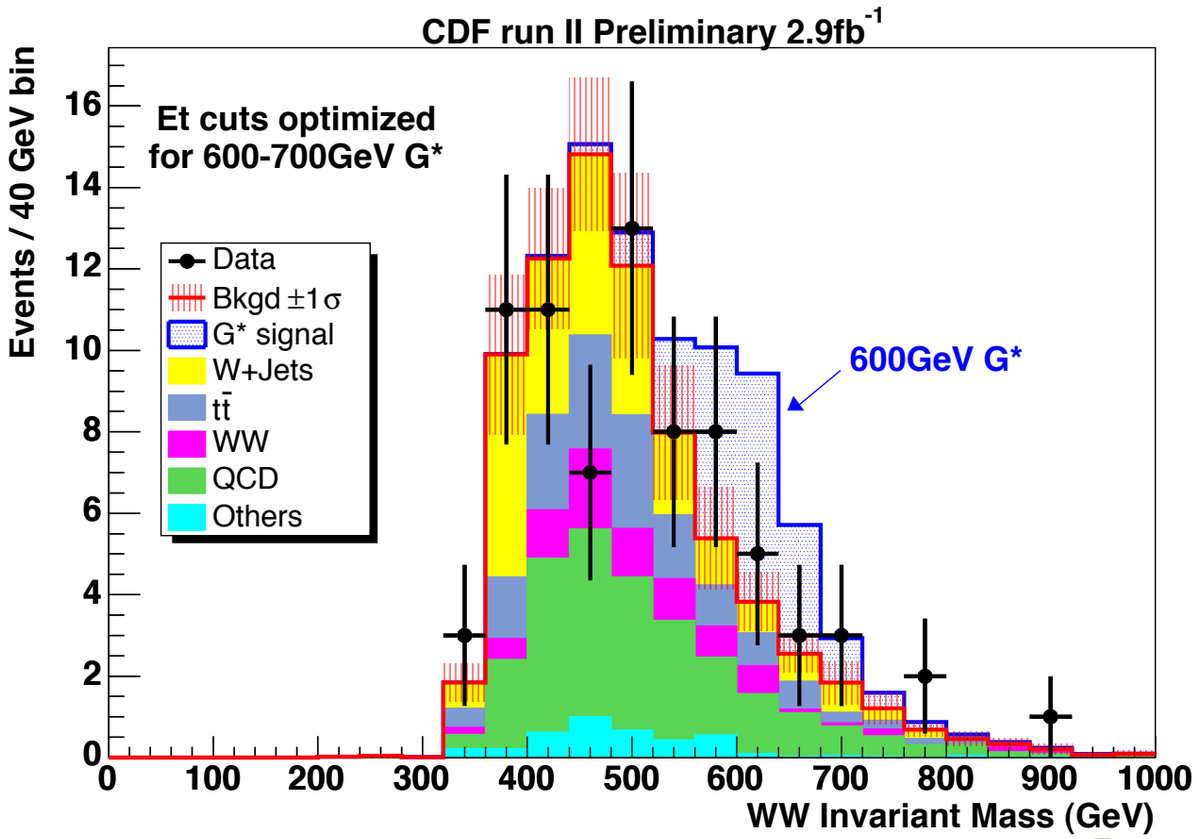


- Final state: electron+MET+ 2jets
- Dominant bkgnd: multi-jet and W+jets
- Reconstruct resonant mass
- Interpretation given in different models, optimized for expected resonance mass

W→νe with two solutions
1.Dijets in [65,95] (for WW)
2.Dijets in [70,105] (for WZ)
3-jet events also considered



signal optimized for Z*→WW, 600 GeV



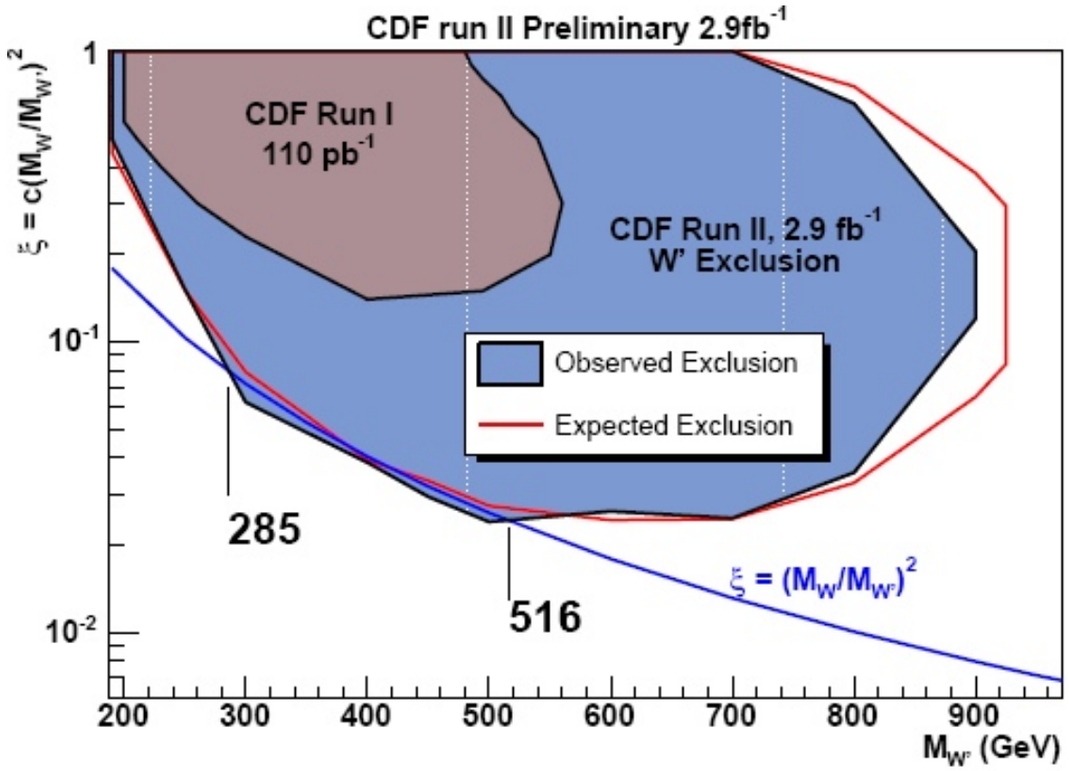
signal optimized for G*→WW, 600 GeV

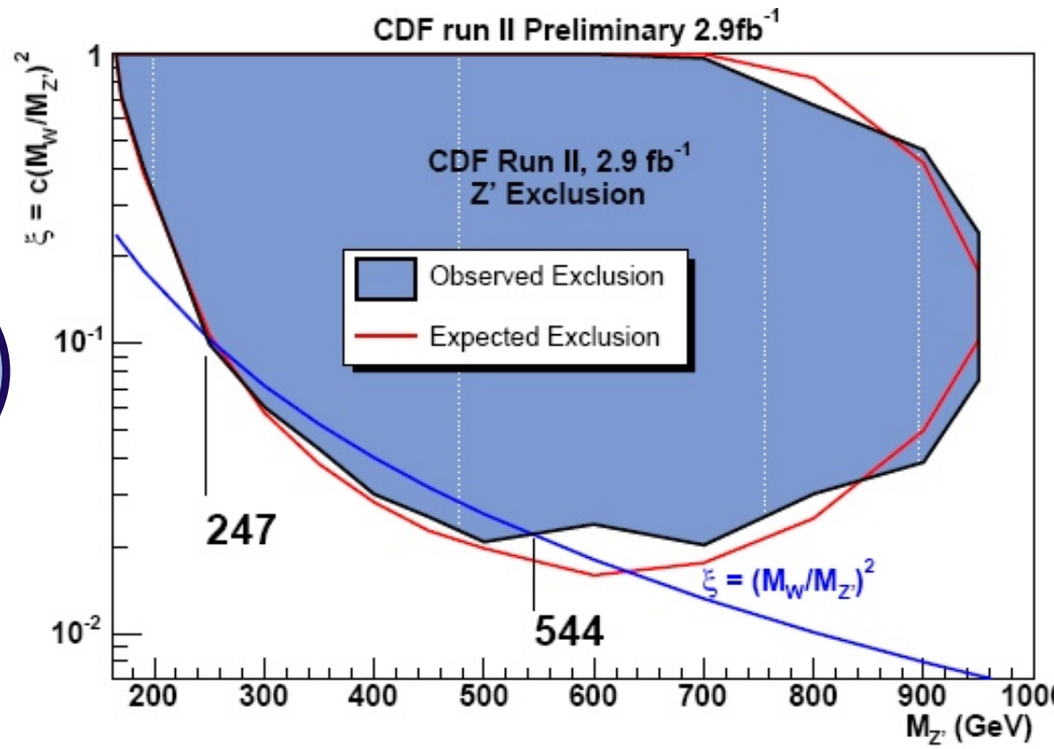
Results for X→gauge boson pairs

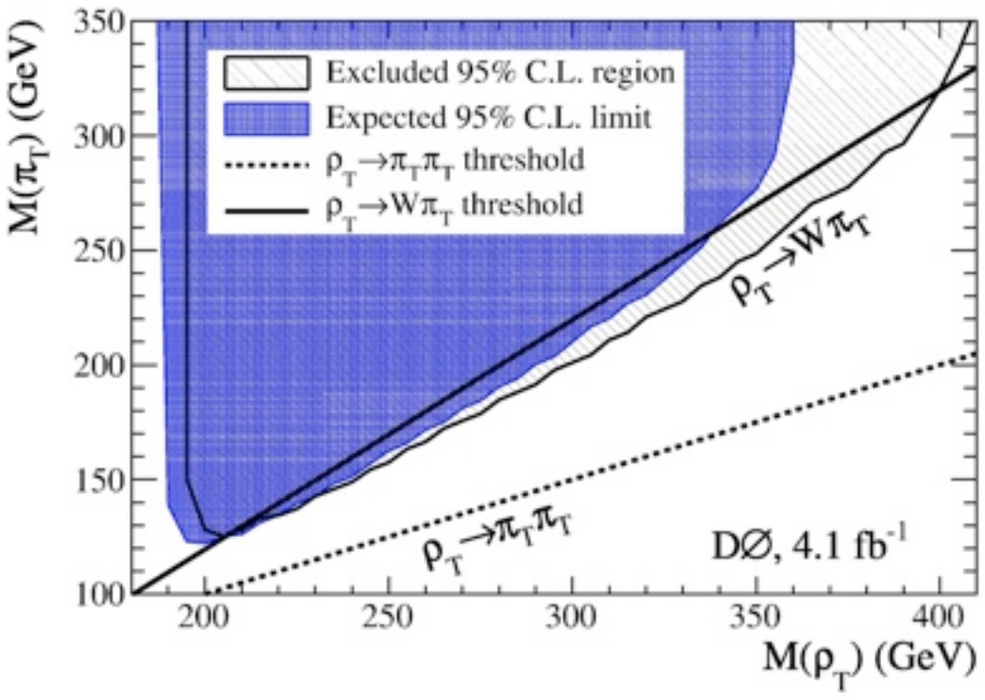
$$g\cos\theta_W \rightarrow \xi \times g\cos\theta_W$$
$$\xi = C \times (m_W/m_V)^2$$

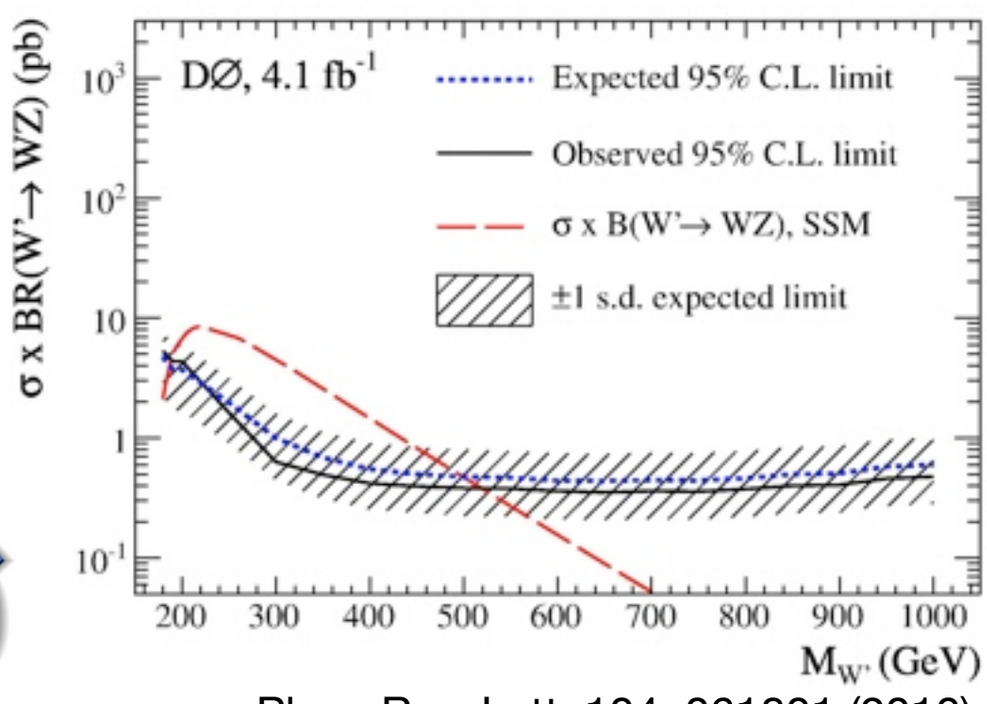
- Put limits on null result in terms of technicolor theories, generic SM-like heavy W', and RS gravitons G*

arXiv:1004.4946



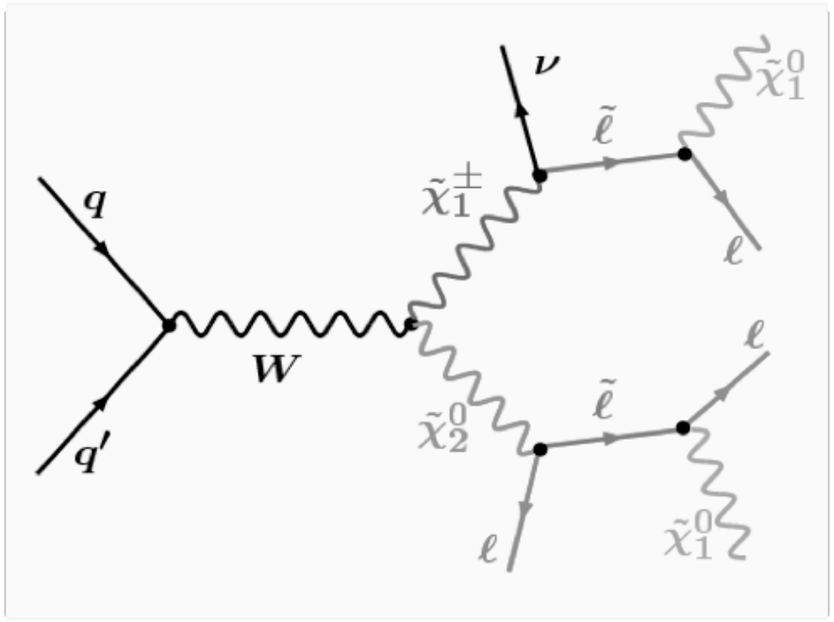






Phys. Rev. Lett. 104, 061801 (2010)

Trileptons: Chargino-Neutralino Search, 3.2/fb

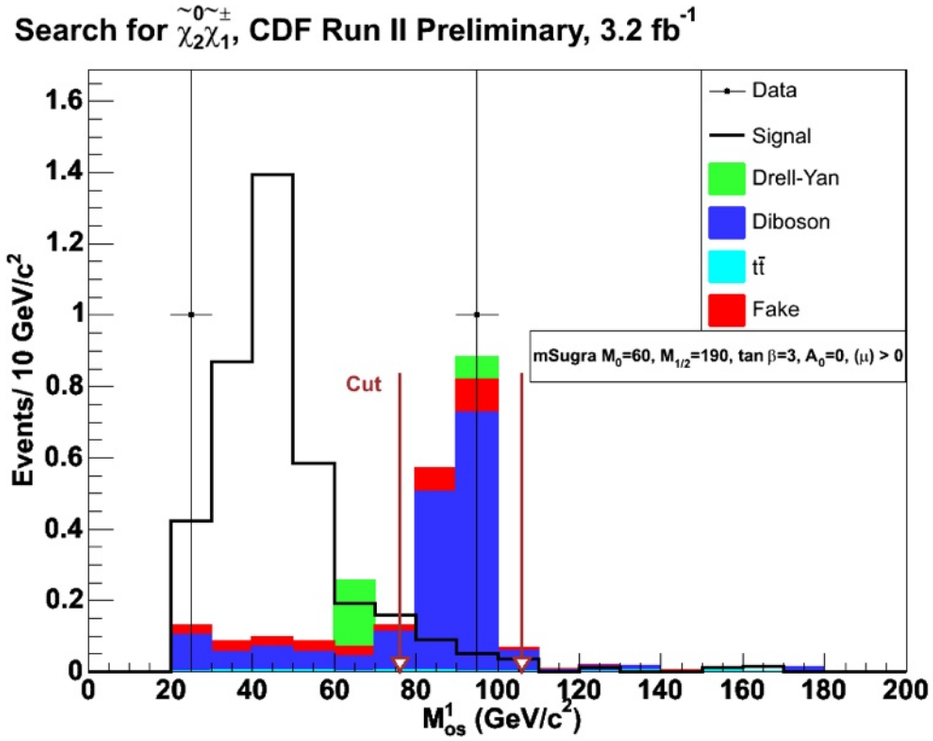


- Very clean signature:
  - Missing E_T due to undetected ν, χ^0_1
  - 3 isolated leptons, *lower momentum*

- 3 identified leptons (e,μ)
- 2 identified leptons + track *(l)*
- "Tight" and "loose" e,μ categories

- Rejection using kinematic selections on: m_{l+l-}, n_{jets}, Missing E_T, Δφ between leptons...

Good agreement between data and SM prediction → **set limit**



Channel	SM expected	Data
Trilepton	1.5 ± 0.2	1
Lepton+trk	9.4± 1.2	6

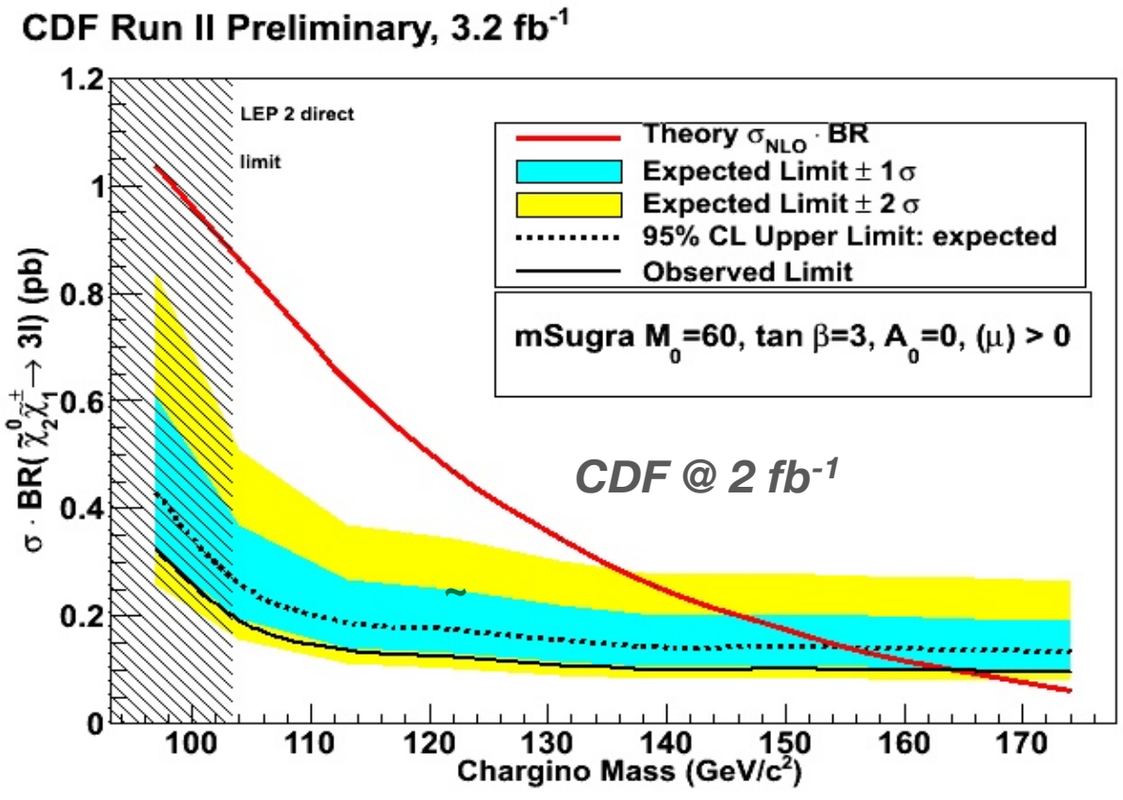
Chargino-neutralino results

PRL 101, 251801 (2008)

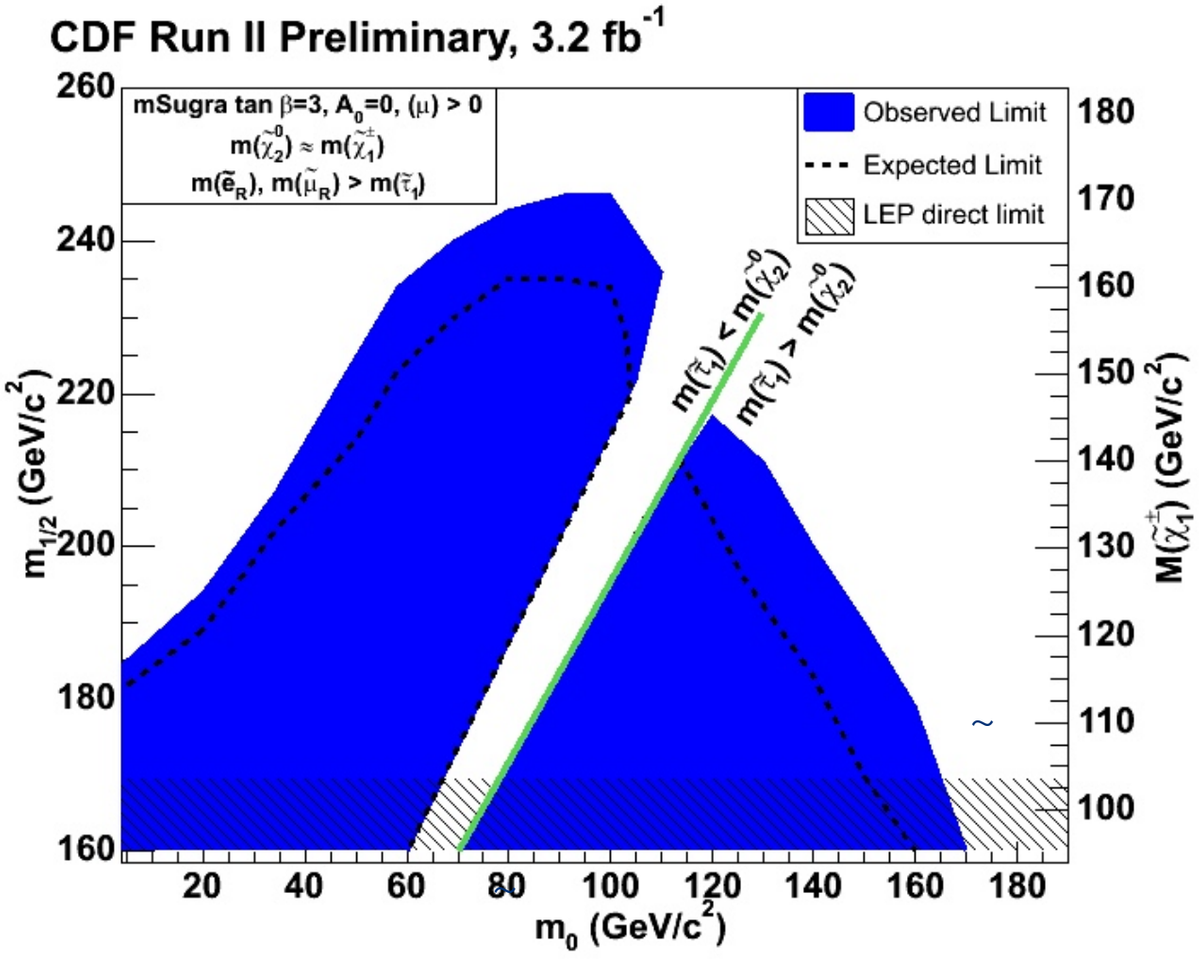
- interpret null result in mSugra SUSY scenario as a convenient/conventional benchmark

excluded region in mSUGRA m_0-$m_{1/2}$ space

m_0 = 60 GeV, tan β=3, A_0=0, μ>0



Excludes $m\chi^{\pm}_1$ < 164 (154 Exp.) **GeV/c²**

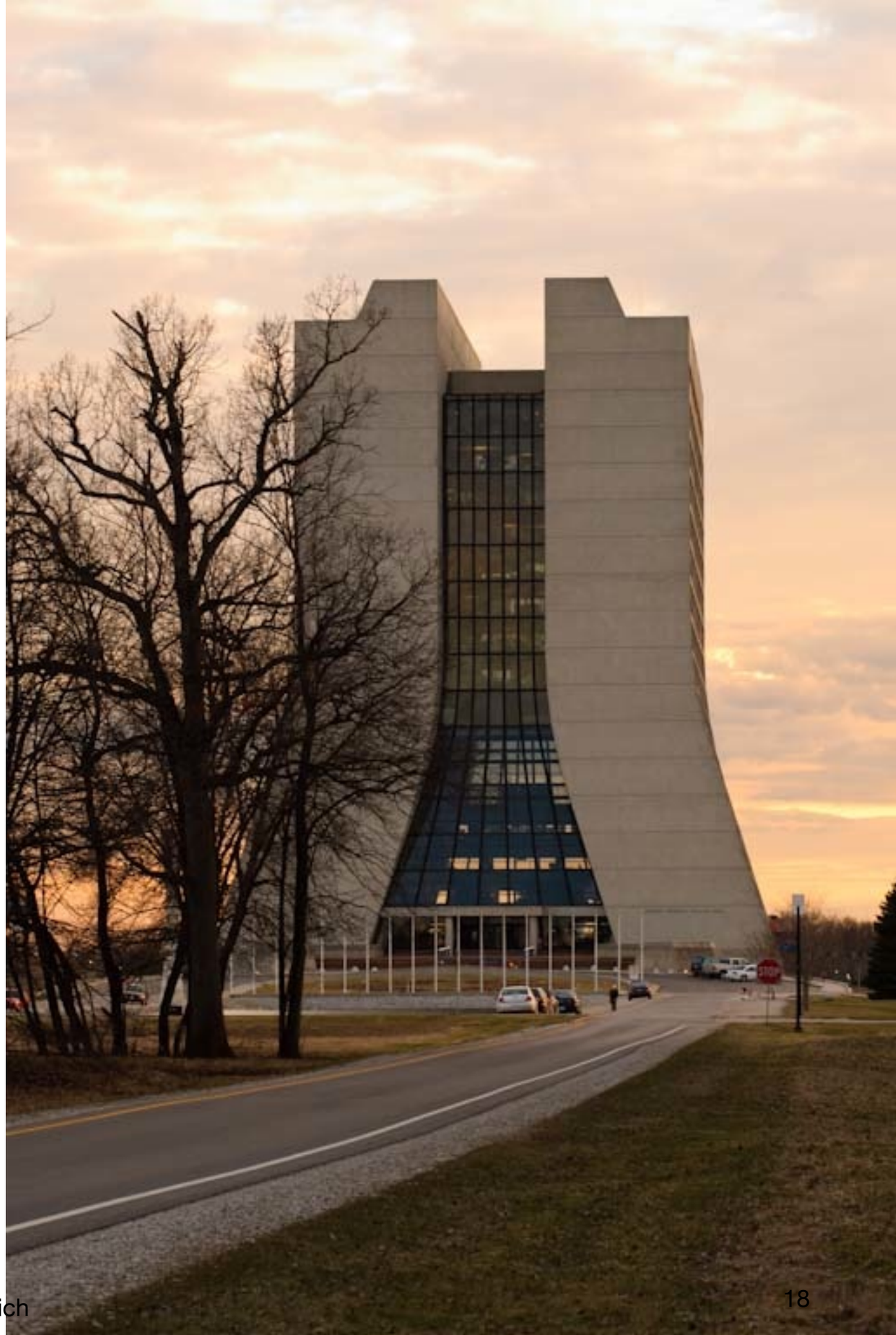


Limits depend on relative χ^0_2-ℓ masses

- $m_{\chi 2} > m_{\ell}$ increases $\mathcal{BR}$ to e/μ
- $m_{\chi 2} \approx m_{\ell}$ reduces acceptance

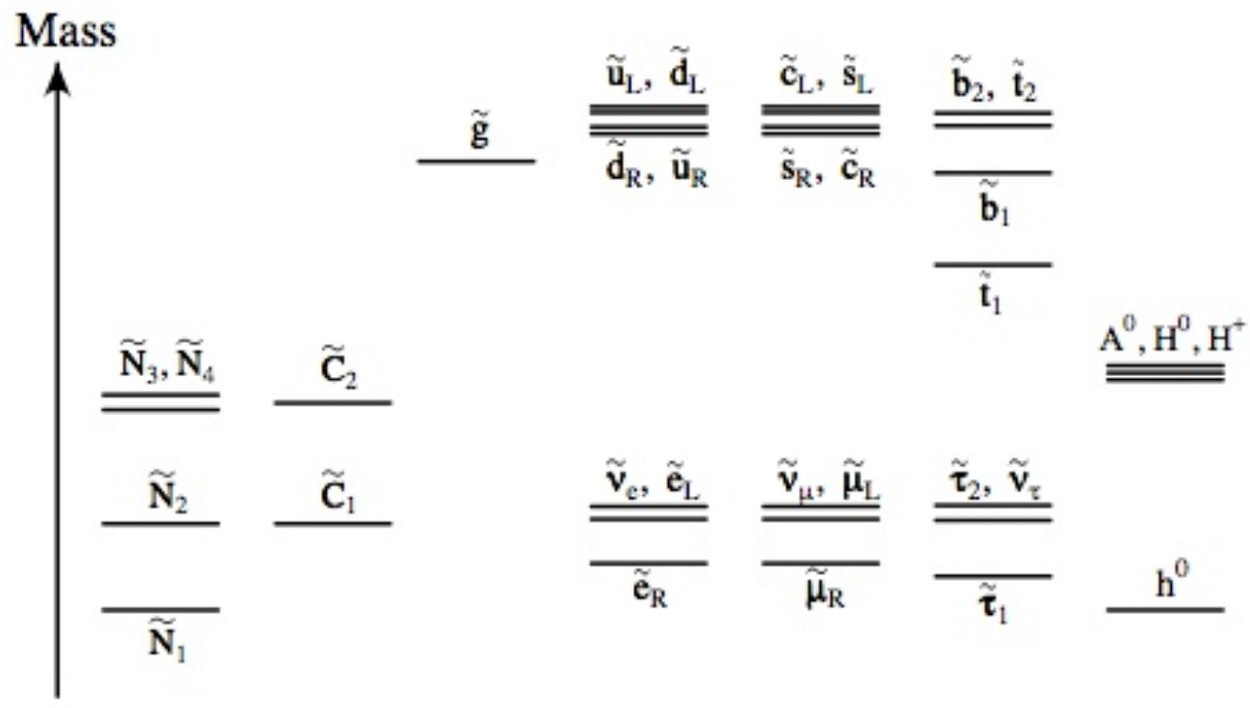
D0 limit in 2.3/fb: Phys. Lett. **B** 680, 34 (2009)

Searches for quark-like objects



Squarks in SUSY

Martin,arXiv:hep-ph/9709356, “for entertainment purposes only”

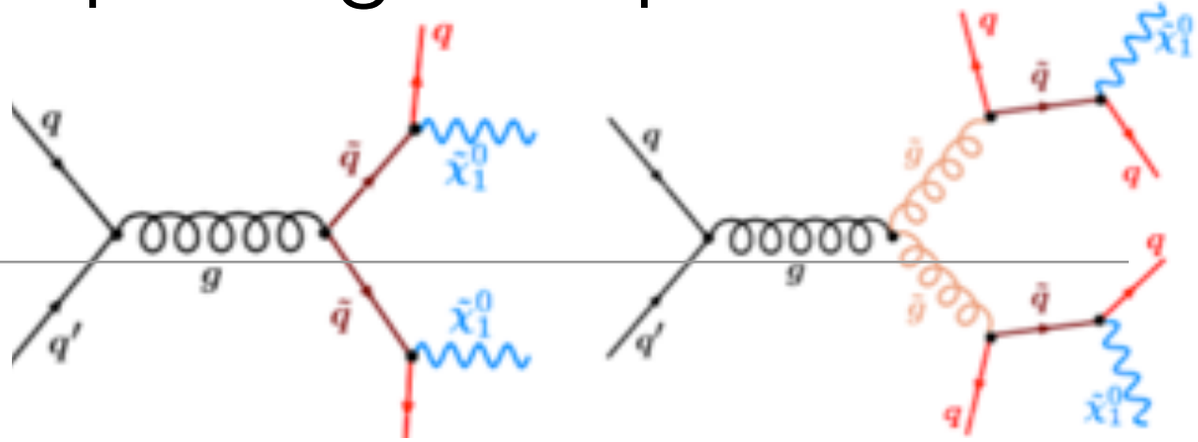


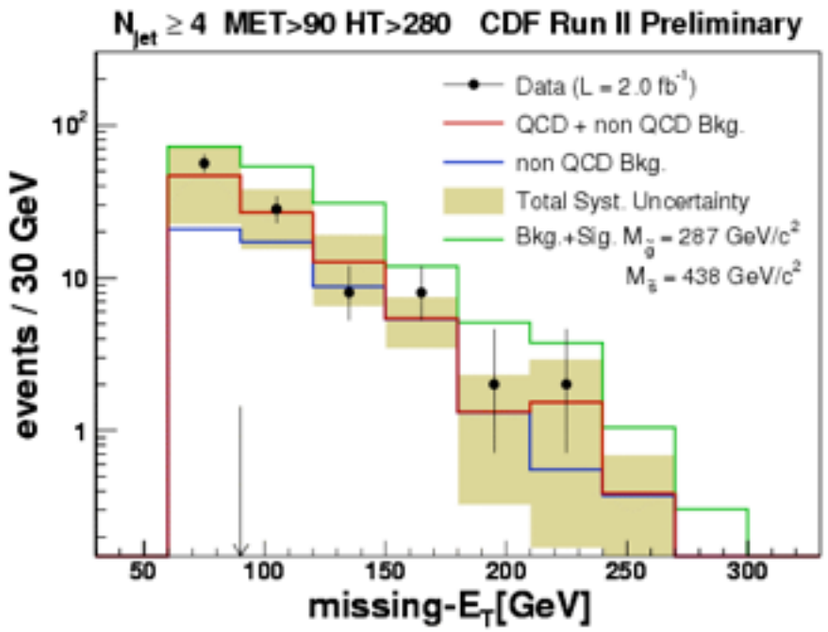
- Strong production cross section → lots of squarks and gluinos produced
  - Very powerful SUSY signature in jets + MET (LSP)
- 3rd generation is special - look for it specifically
  - *b* and *t* squarks - use *b* tagging

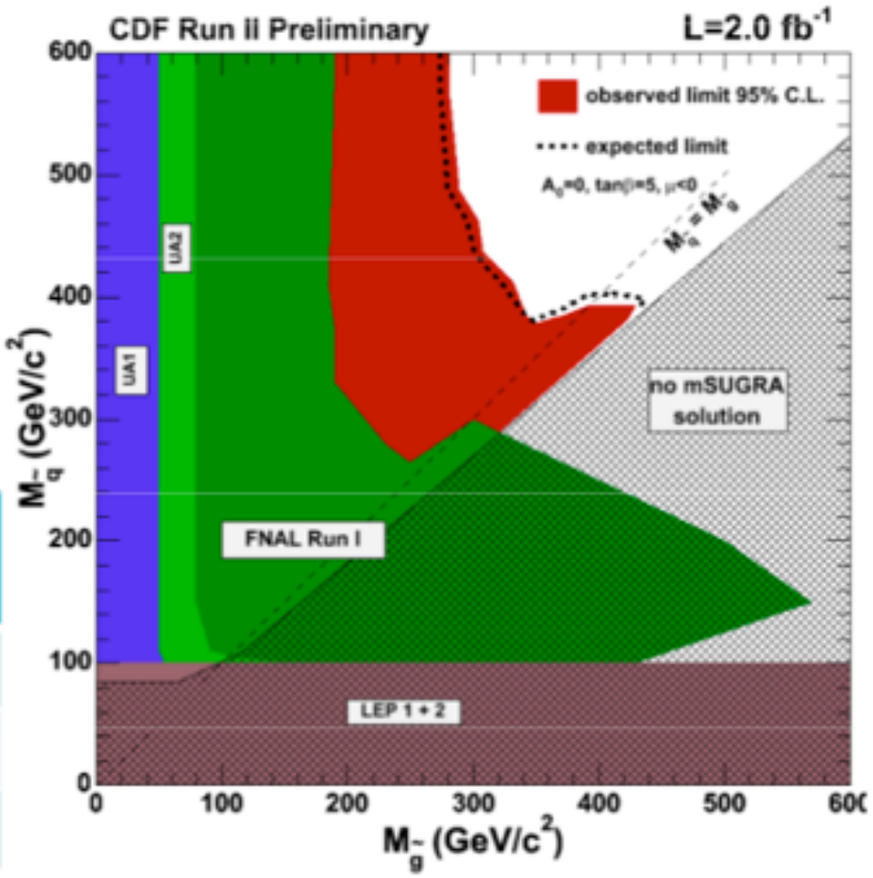
- Large multi-jet backgrounds from generic SM qcd processes make these hard measurements

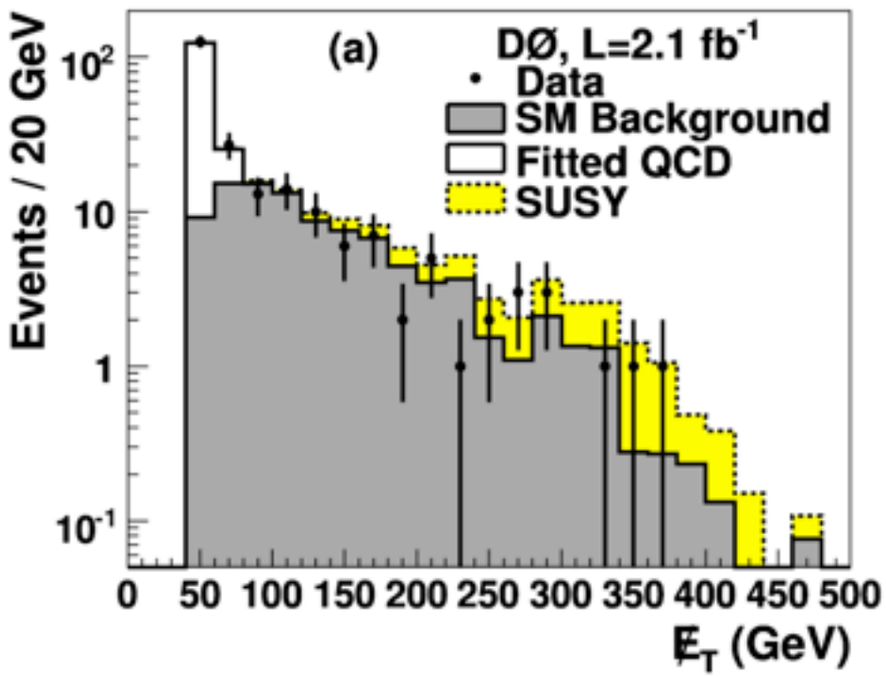
susy in jets + met:generic squark/gluino production

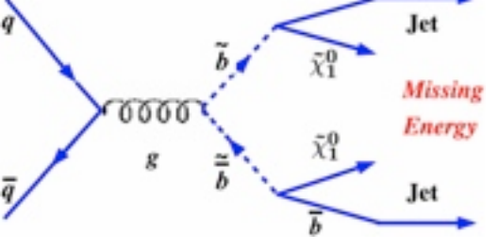
- Large production cross section, bkgnds from multi-jet, Z→νν, top
- Optimize searches as a function of (Missing E_T, n_{jet})
- No excess seen so far
- Limits for 2 (2.1)/fb of data for CDF (D0)
- interpret results in mSUGRA-like SUSY scenario











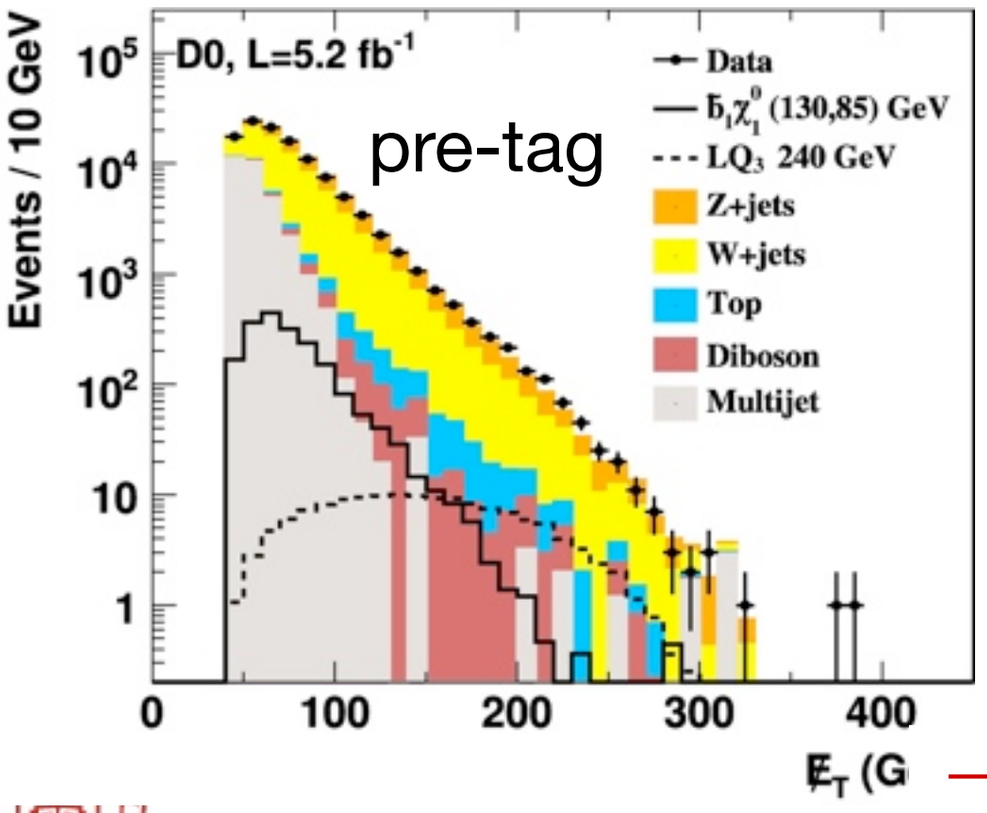
2 *b* jets + E_T^{Miss} - ~q and LQ

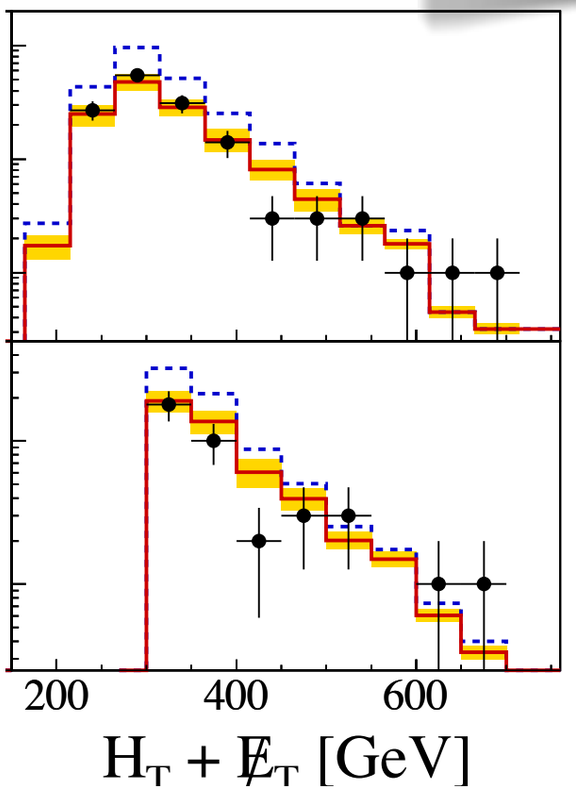
$$ZH \rightarrow \nu\bar{\nu}b\bar{b}$$

$$p\bar{p} \rightarrow \tilde{b}_1\bar{\tilde{b}}_1 \rightarrow b\tilde{\chi}_1^0\bar{b}\tilde{\chi}_1^0$$
$$LQ_3 \rightarrow \nu_\tau b$$

- Final state familiar from Higgs searches
  - missing E_T and b quarks
- Also good signal for leptoquarks and SUSY
- event selection:
  - b tagging (D0: neural-net algo)
  - two b-tagged jets, E_T^{miss}, Sign., ΣE_T
  - optimize p_T, E_T^{miss}, H_T, X_{jj} for SUSY/LQ3 signals

$$X_{jj} = \frac{p_T^{jet1} + p_T^{jet2}}{H_T}$$





low $\delta M_{(LSP,\ b\ squark)}$ ←

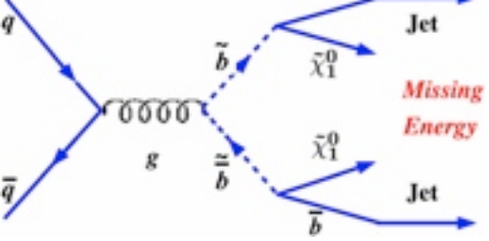
hi $\delta M_{(LSP,\ b\ squark)}$ ←

SM

Total Syst. Uncertainty

CDF RunII DATA (

SM + MSSM



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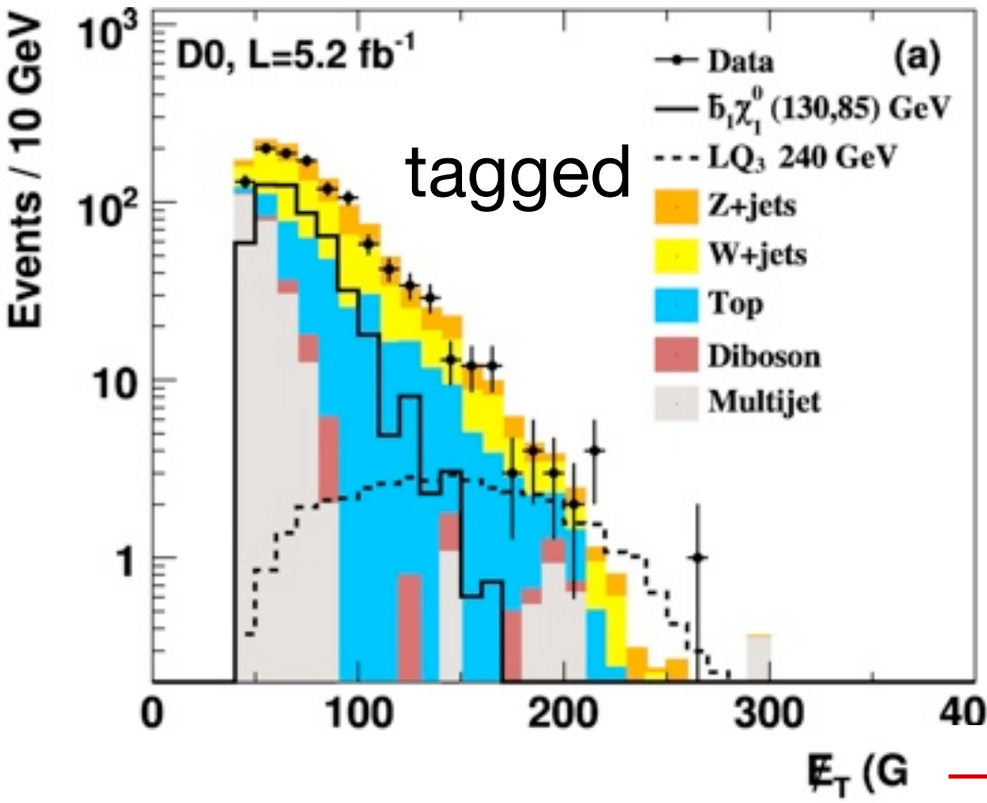
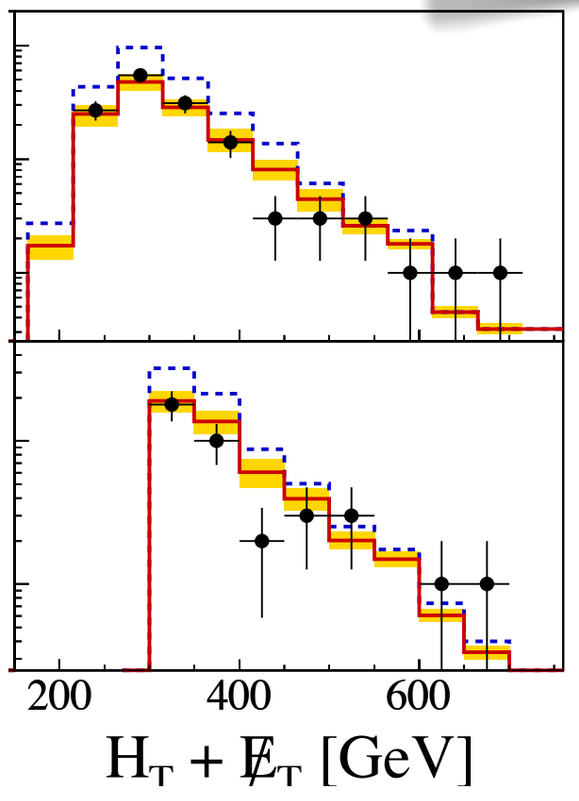
$$p\bar{p} \to \tilde{b}_1\bar{\tilde{b}}_1 \to b\tilde{\chi}_1^0\bar{b}\tilde{\chi}_1^0$$
$$LQ_3 \to \nu_\tau b$$

$$X_{jj} = \frac{p_T^{\text{jet1}} + p_T^{\text{jet2}}}{H_T}$$





low $\delta M_{(\text{LSP}, b\ \text{squark})}$

hi $\delta M_{(\text{LSP}, b\ \text{squark})}$

SM

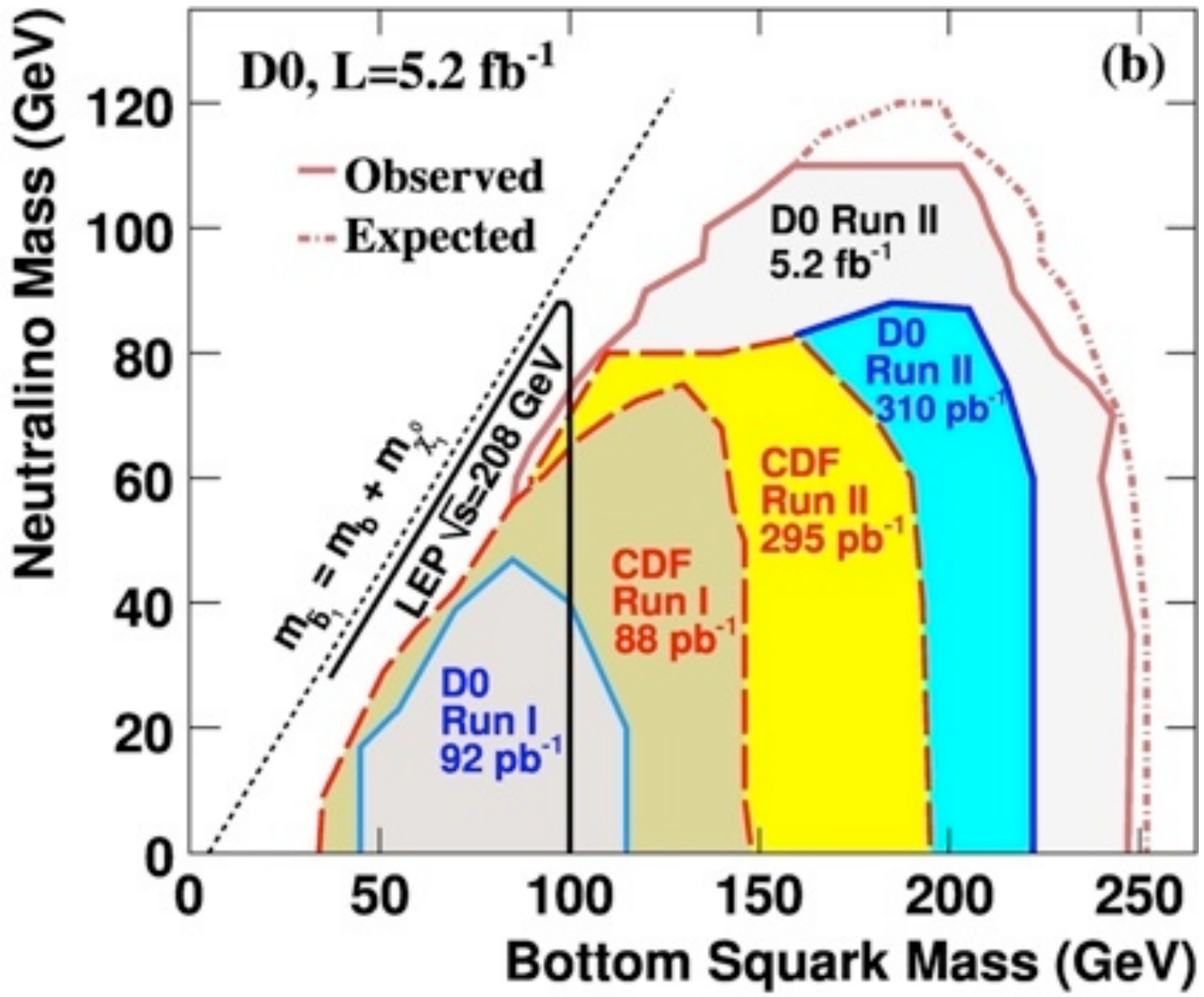
Total Syst. Uncertainty

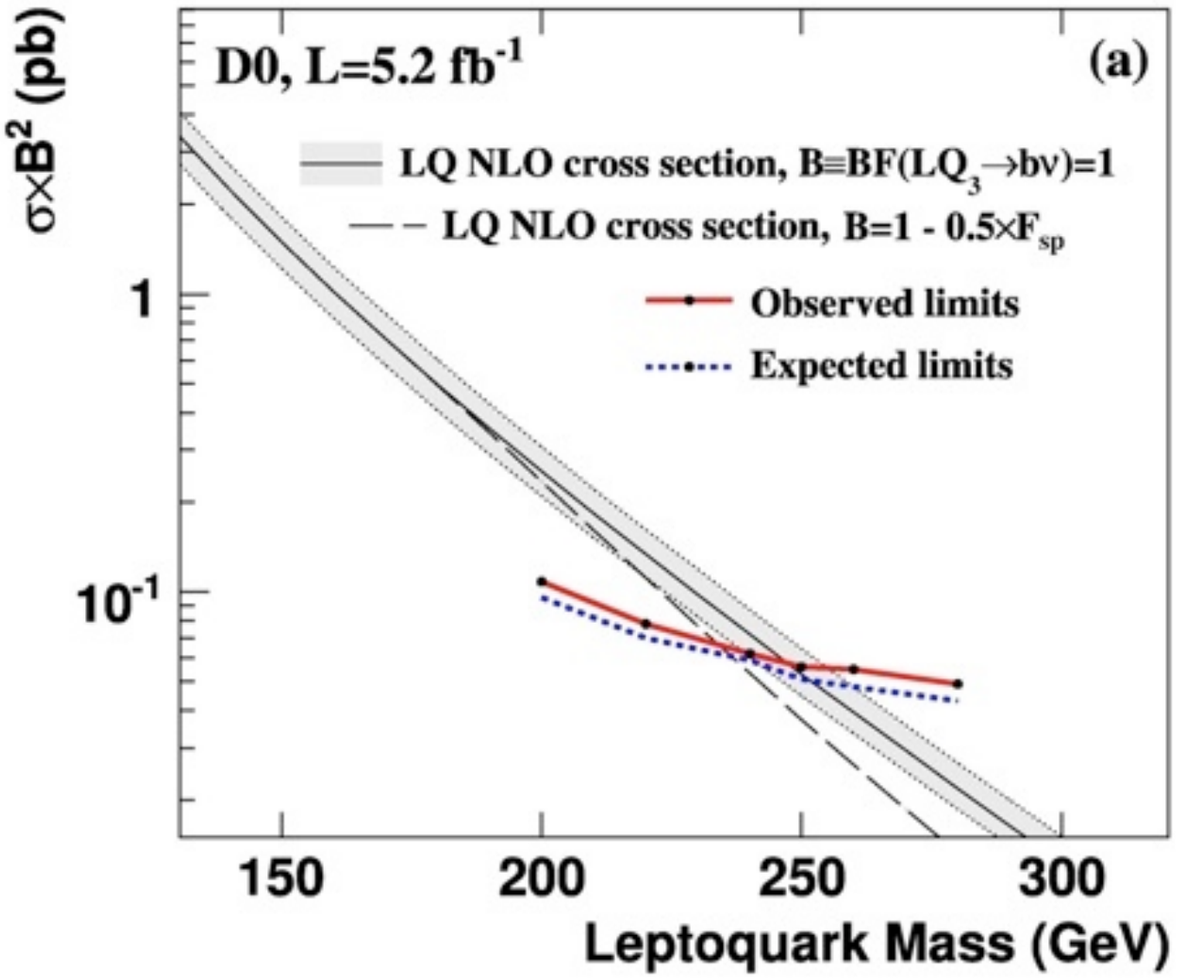
CDF RunII DATA (

SM + MSSM

Results (*b* squarks/leptoquarks)

Submitted to *Phys Lett B;* arXiv:1005.2222v2





Submitted to PRL; arXiv:1005.3600

Supersymmetric top in the e+μ+bb+MET, 3.1/fb

- 3rd generation again - special role in SUSY
- Look for decay mode in e μ final state with $\not\!\!E_T$ >18 GeV
  - Low SM backgrounds (Z→ττ,ttbar)
  - Reject with δΦ(lepton, $\not\!\!E_T$) cuts
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$$p\bar{p} \rightarrow \tilde{t}_1\bar{\tilde{t}}_1$$

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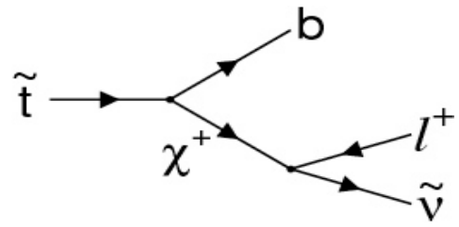

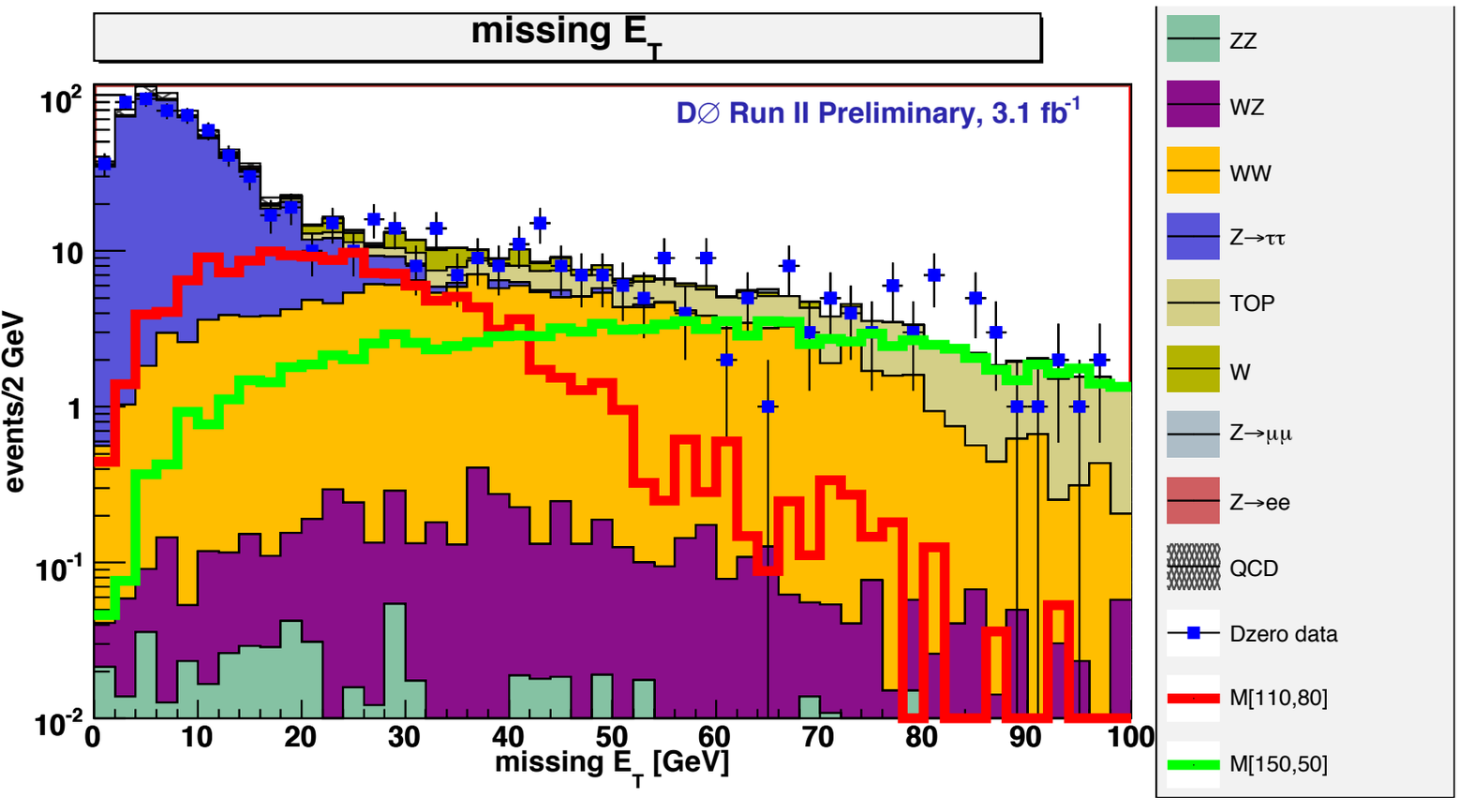

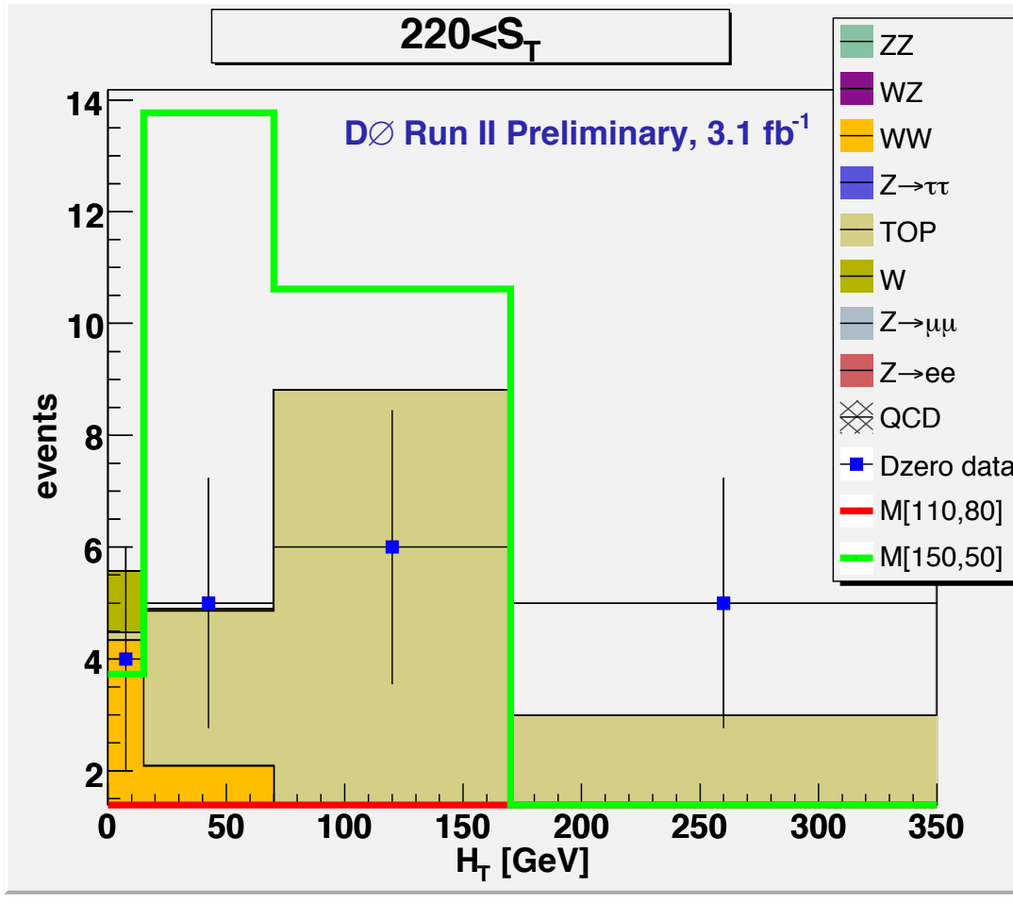

D0 Conference Note 5937-CONF

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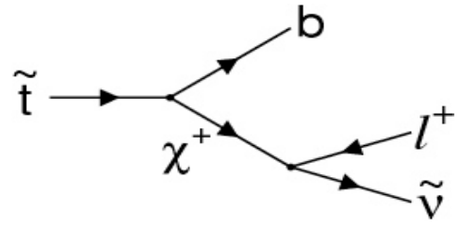

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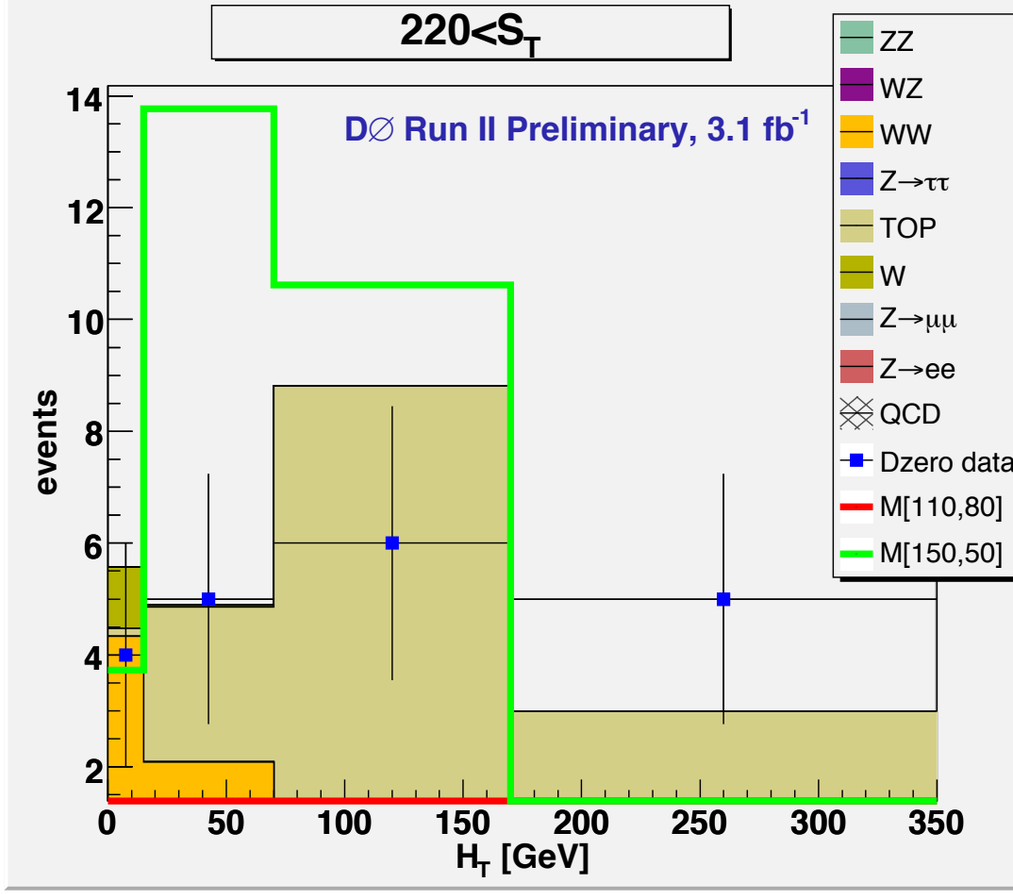

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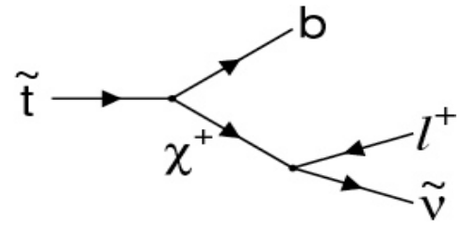

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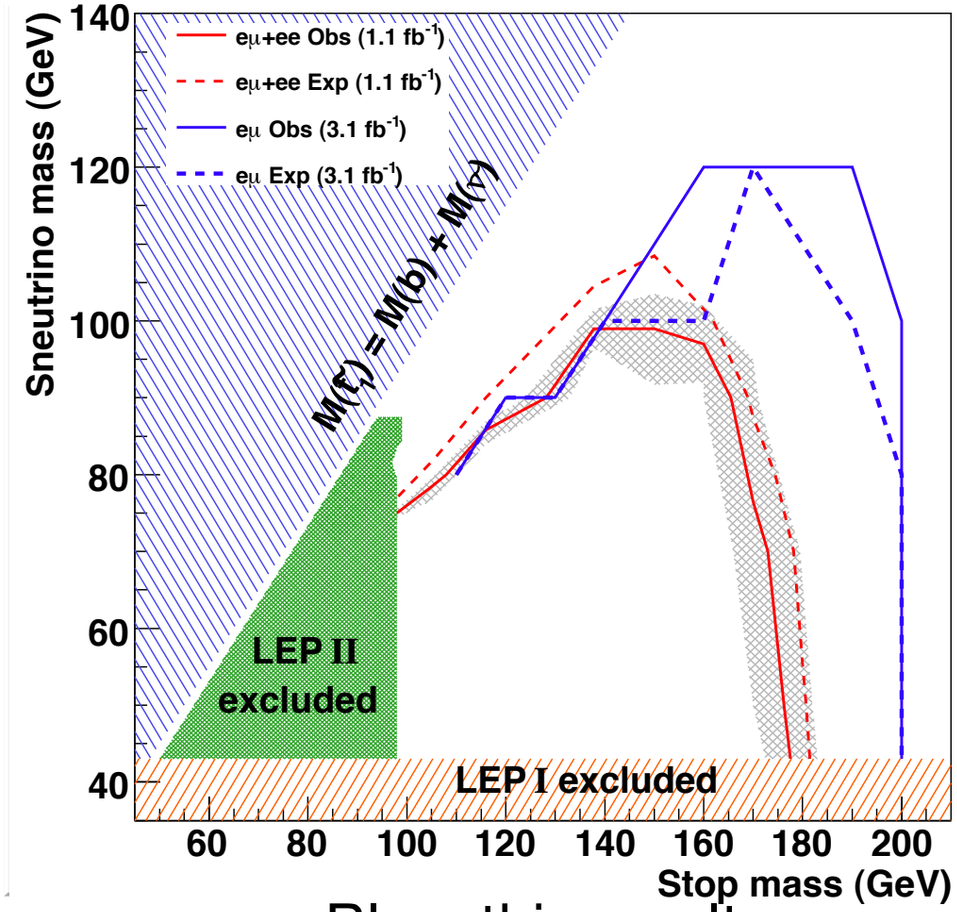


Blue: this result

D0 Conference Note 5937-CONF

Bump Hunts

Bump Hunts

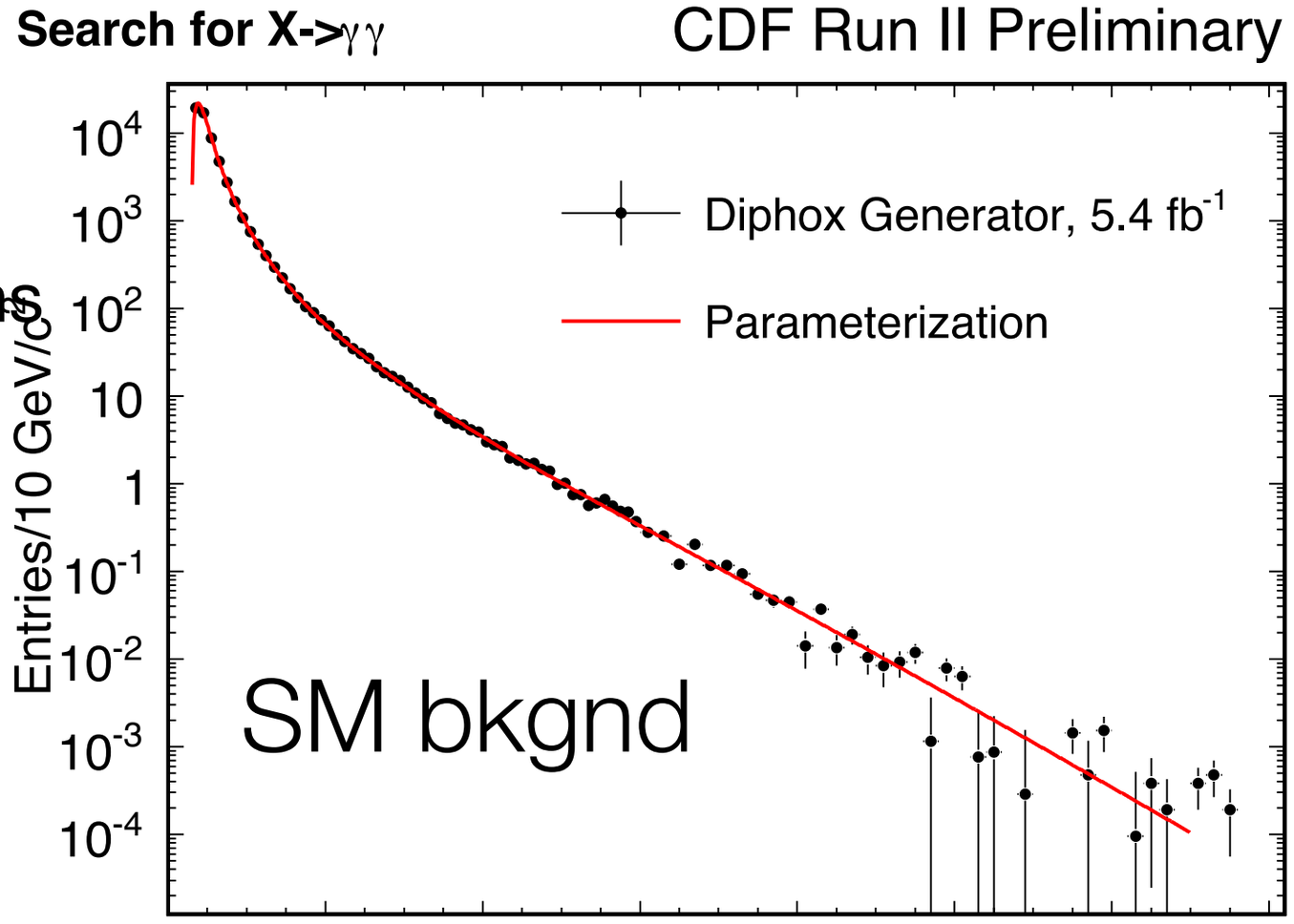
- Look for excess in invariant mass spectrum
  - an old-fashioned bump hunt

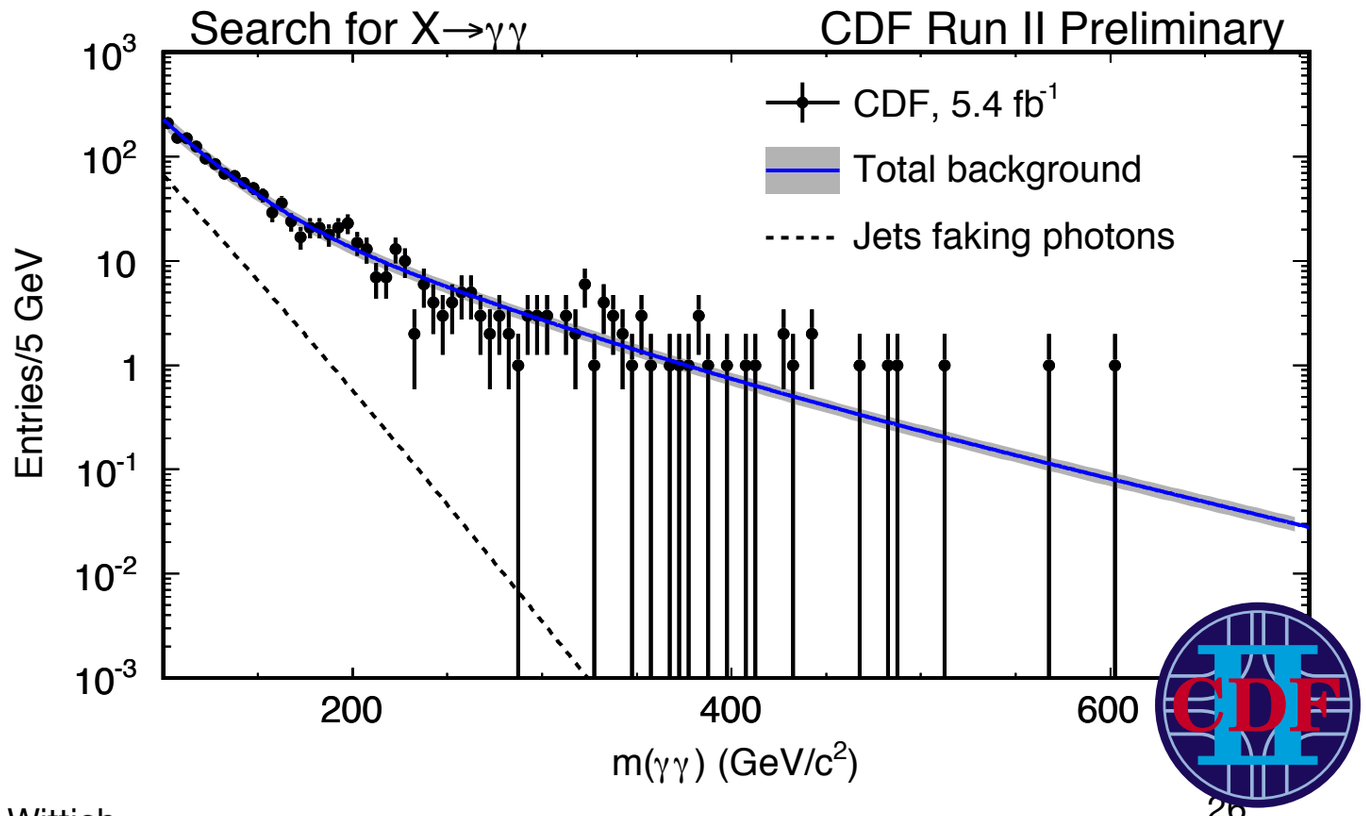
- Three new results
  - diphoton searches
  - diphoton + dielectron searches
  - dimuon searches
  - dijet searches

- Generic, powerful searches - should be some of the earliest results from the LHC experiments

di-γ bump hunt

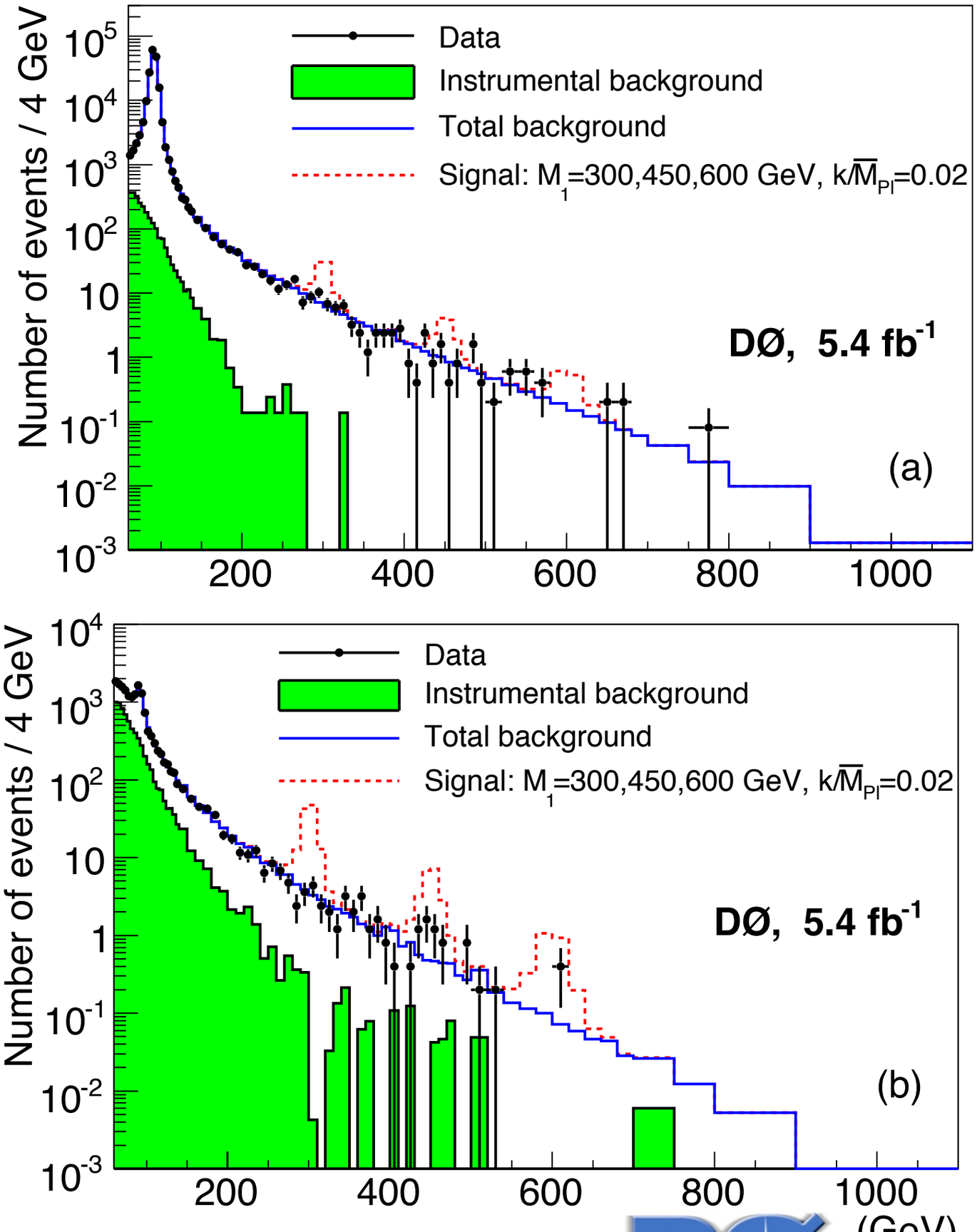
- 5.4/fb of data
- Look for events with two photons with $m_{\gamma\gamma} > 30$ GeV
- NLO DIPHOX background analytically modeled, corrected for acceptance/detector effects
- heuristic shape for instrumental backgrounds
- fit to $m_{\gamma\gamma}$ distribution
  - low mass control region, sets scale/normalization
  - extrapolate to high mass signal region
- Data is consistent with SM backgrounds





di-γ ***and*** di-e bump hunts, 5.4/fb

- Same as CDF but with a twist: add γγ and ee channels
  - RS models:
  - BR(G→ee) = ½BR(G→γγ)
- open selection:
  - two em clusters, split into photons and electrons
- estimate background
  - shape from Pythia simulation, weighted to DIPHOX NLO
  - fit scale in low-mass control region (60 GeV < *m* < 200 GeV)
- most significant excess near m≈450 GeV γγ
  - 2.3 (2.2) σ in γγ (γγ+ee)
  - Nothing in ee



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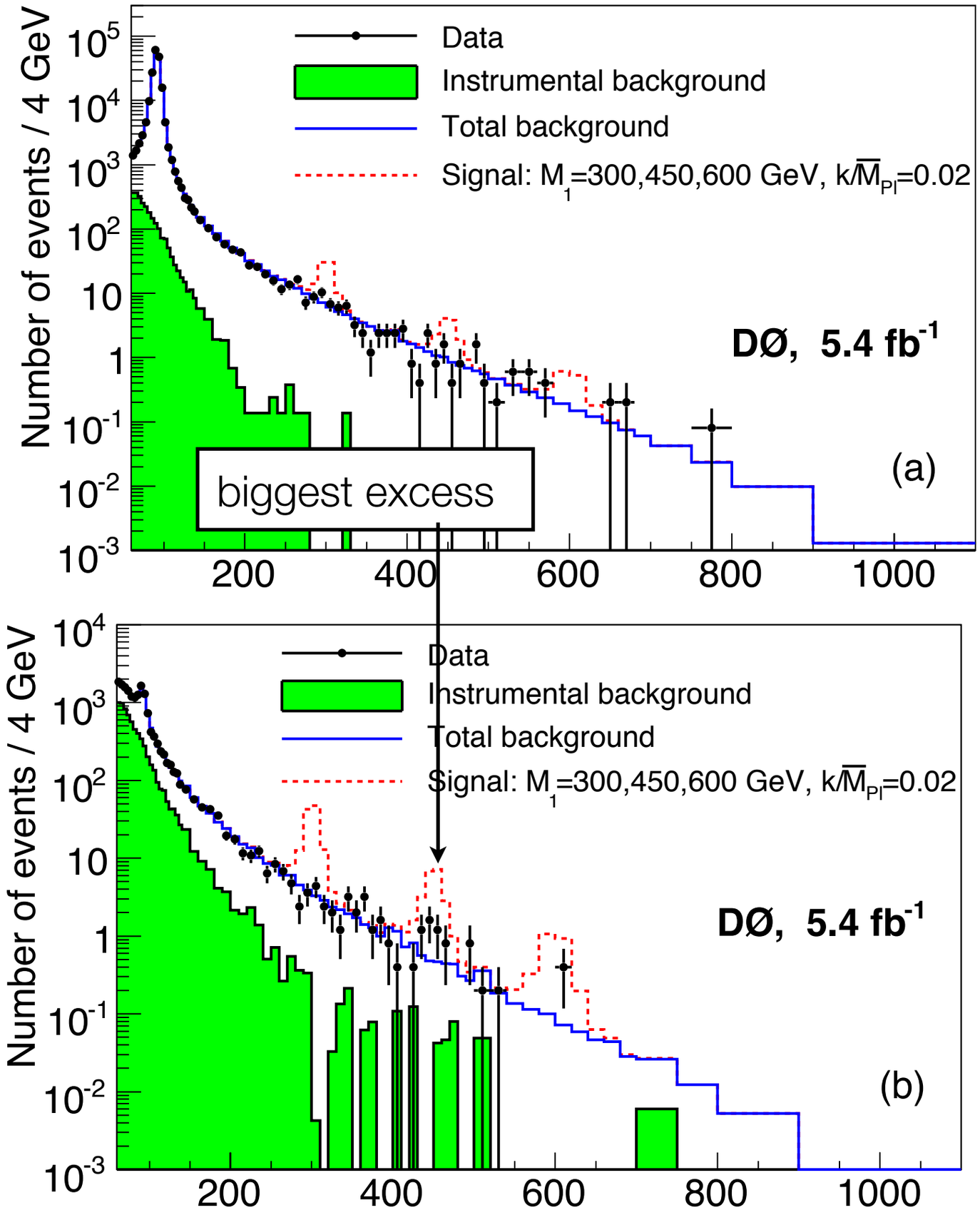
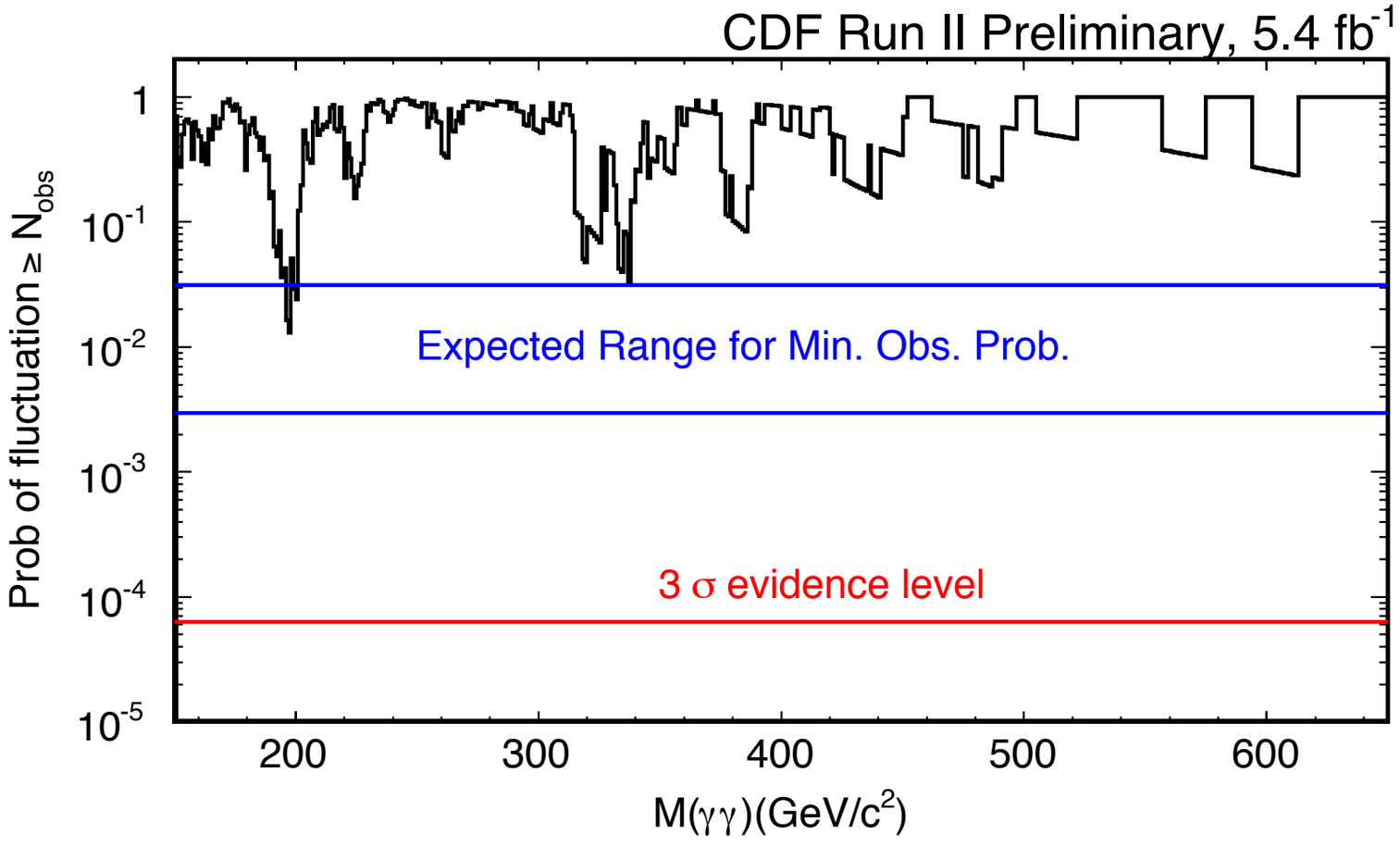


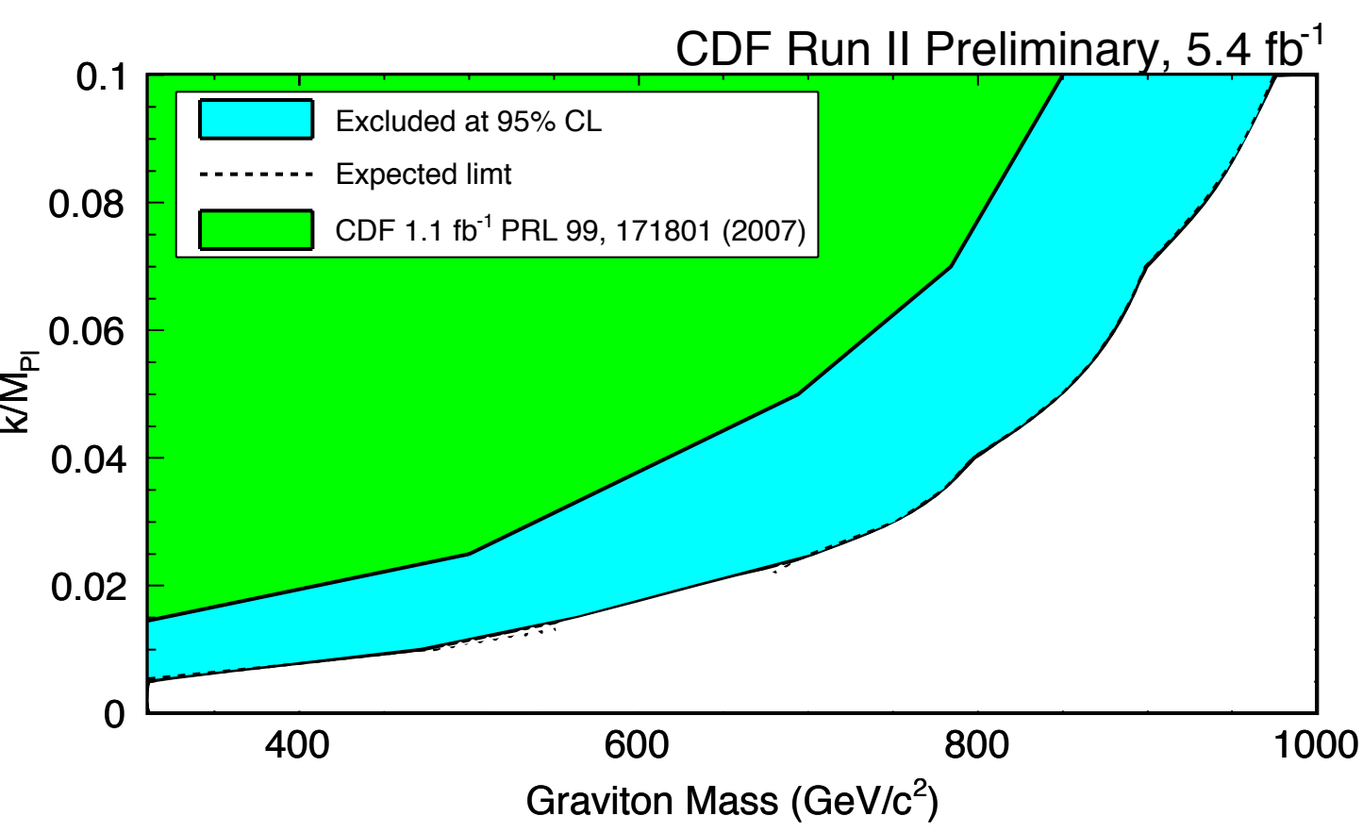


Results:

- Randall-Sundrum Graviton interpretation
- CDF limits (γγ only)

CDF public conference note

arXiv:1004.1826, accepted by PRL



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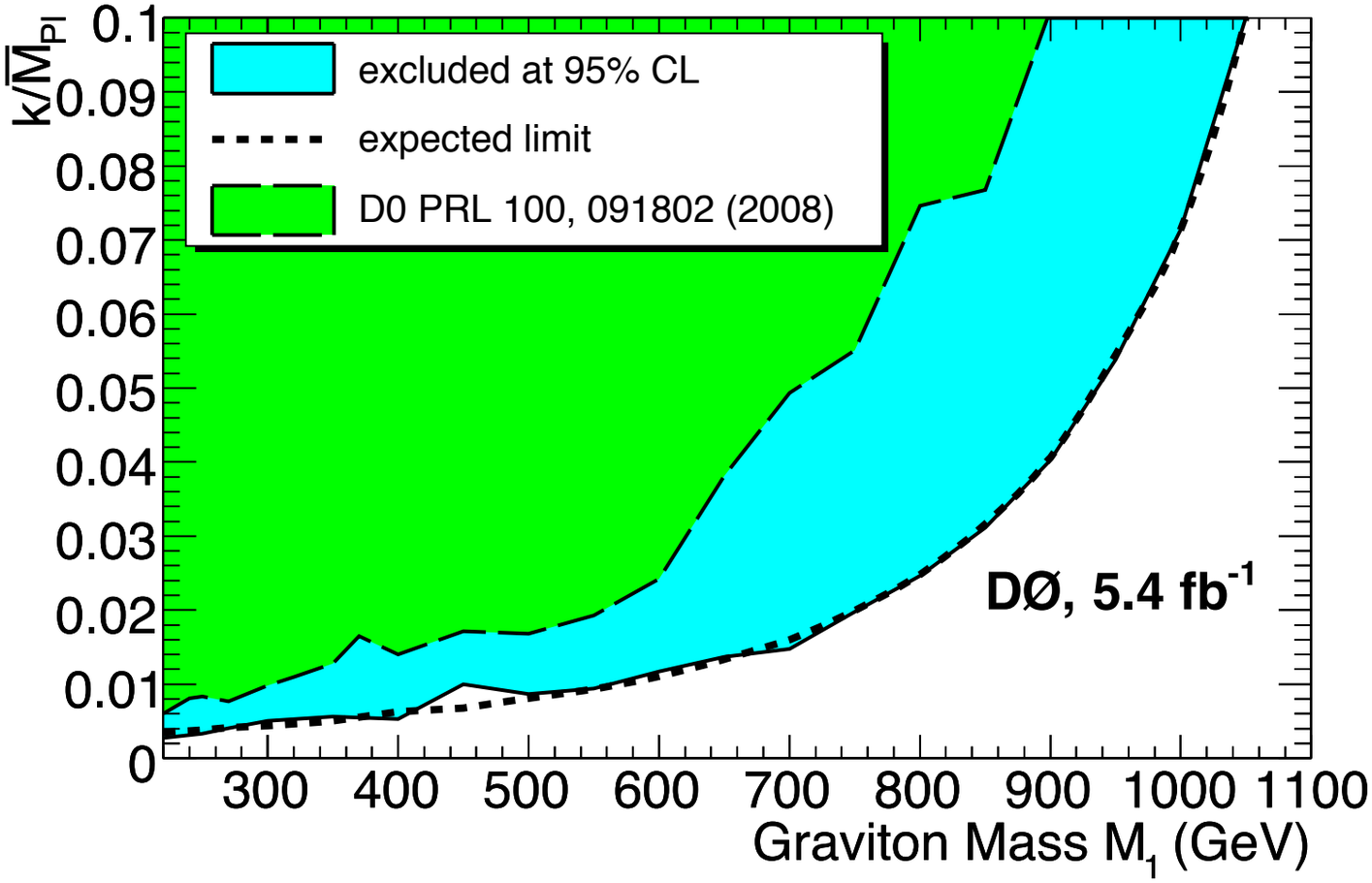
CDF public conference note

- D0 limits (γγ and ee)



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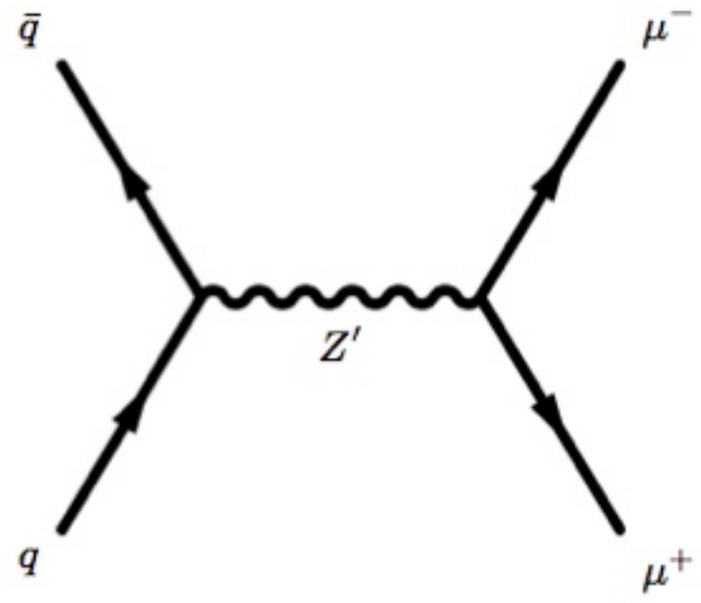
CDF: $X \rightarrow \mu^+\mu^-$, 4.6/fb

- Another signature search
- two high-momentum, opposite-sign muons from resonant production
- similar to ee/γγ
- Backgrounds: DY ppbar → μμ; pythia w/ mass-dependent k-factor; normalize to low-mass (70 GeV<$m_{\mu\mu}$<100 GeV)
- Acceptance show PDF suppression at high mass

- Data in search region looks like SM



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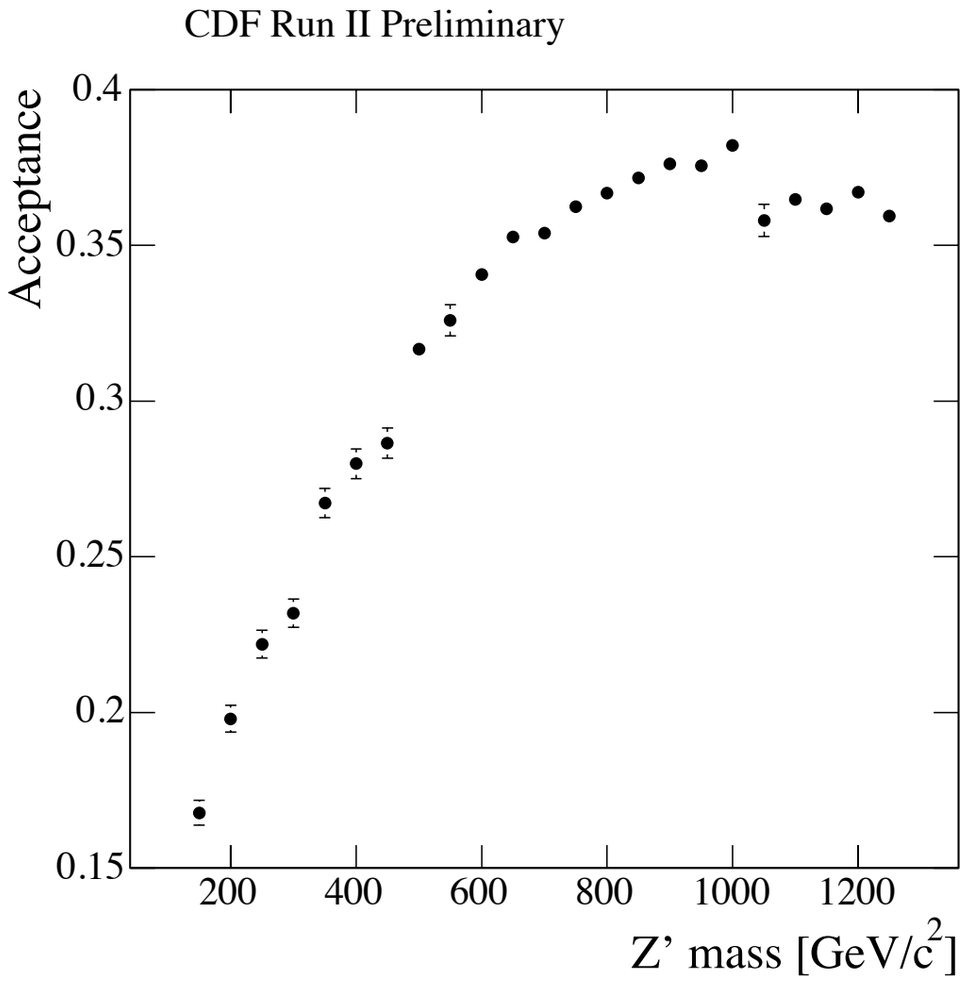

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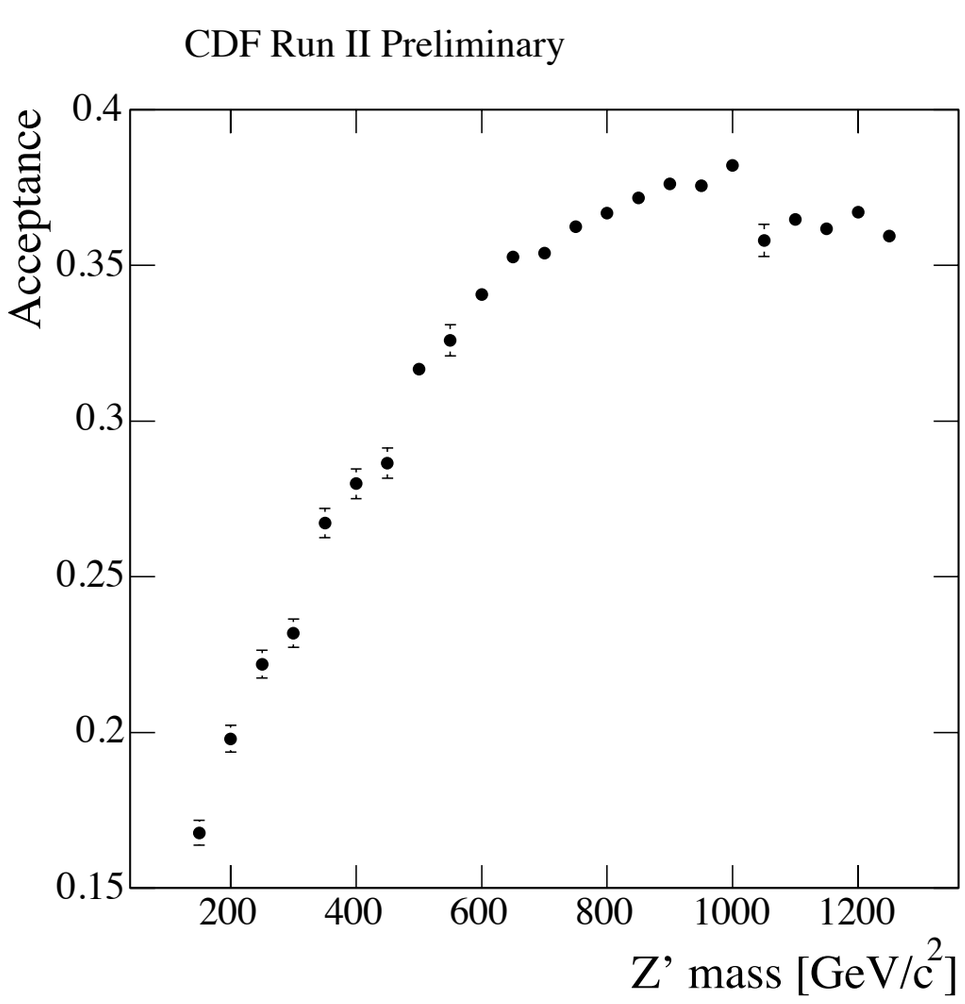

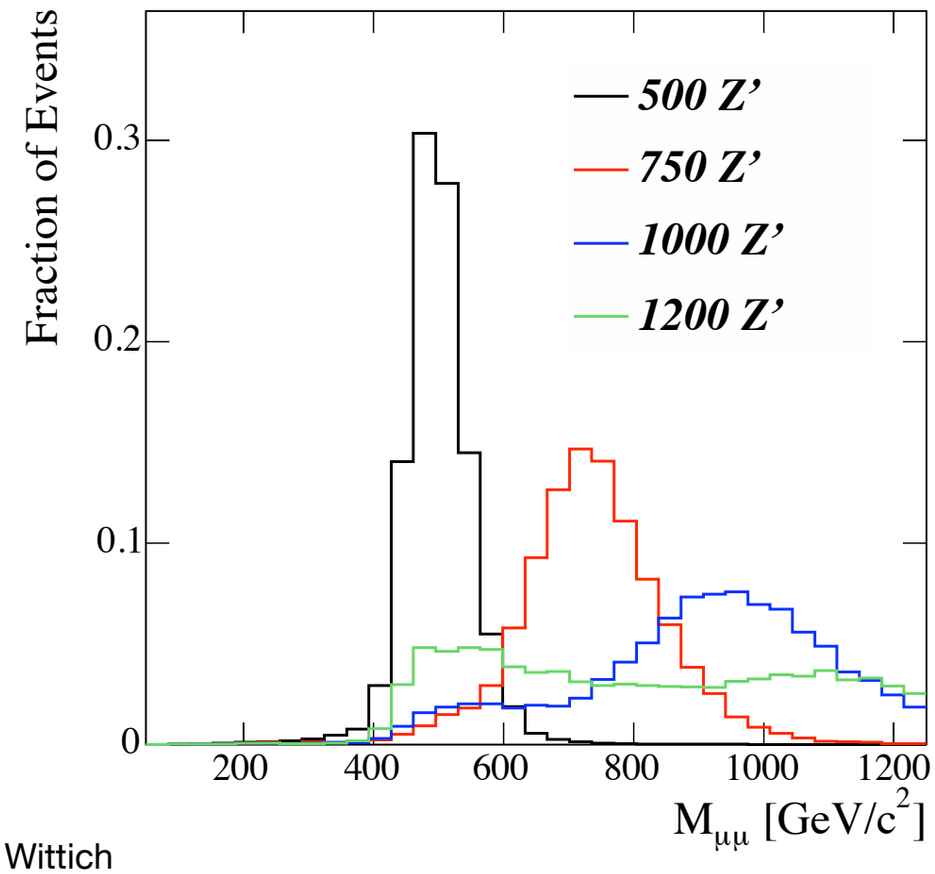

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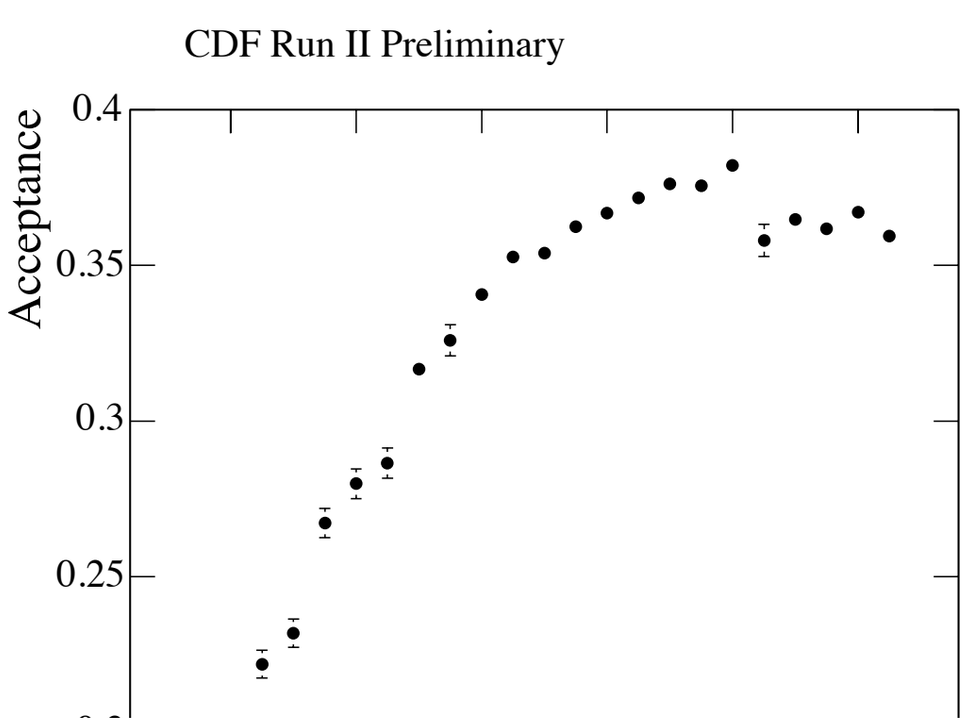
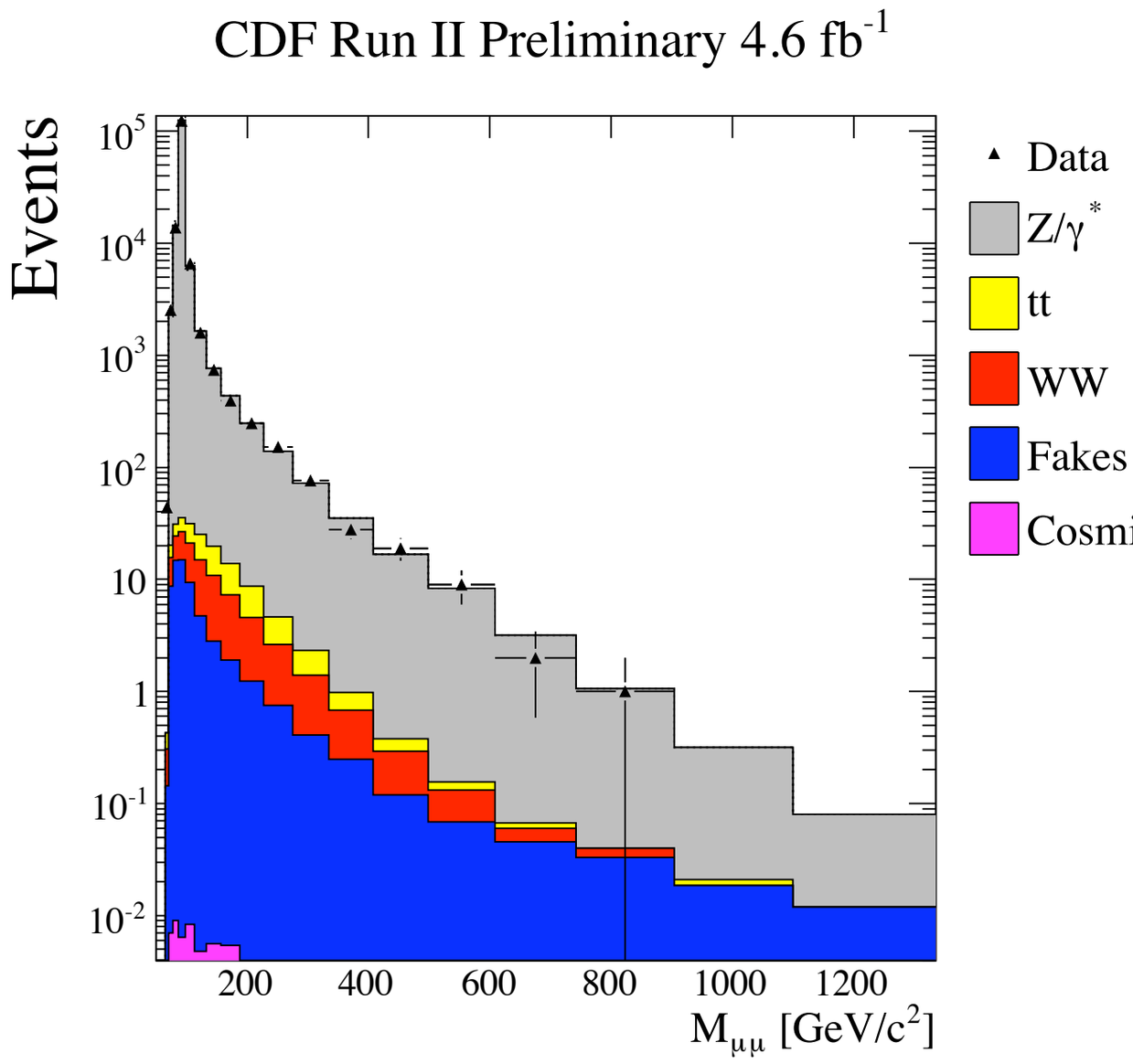
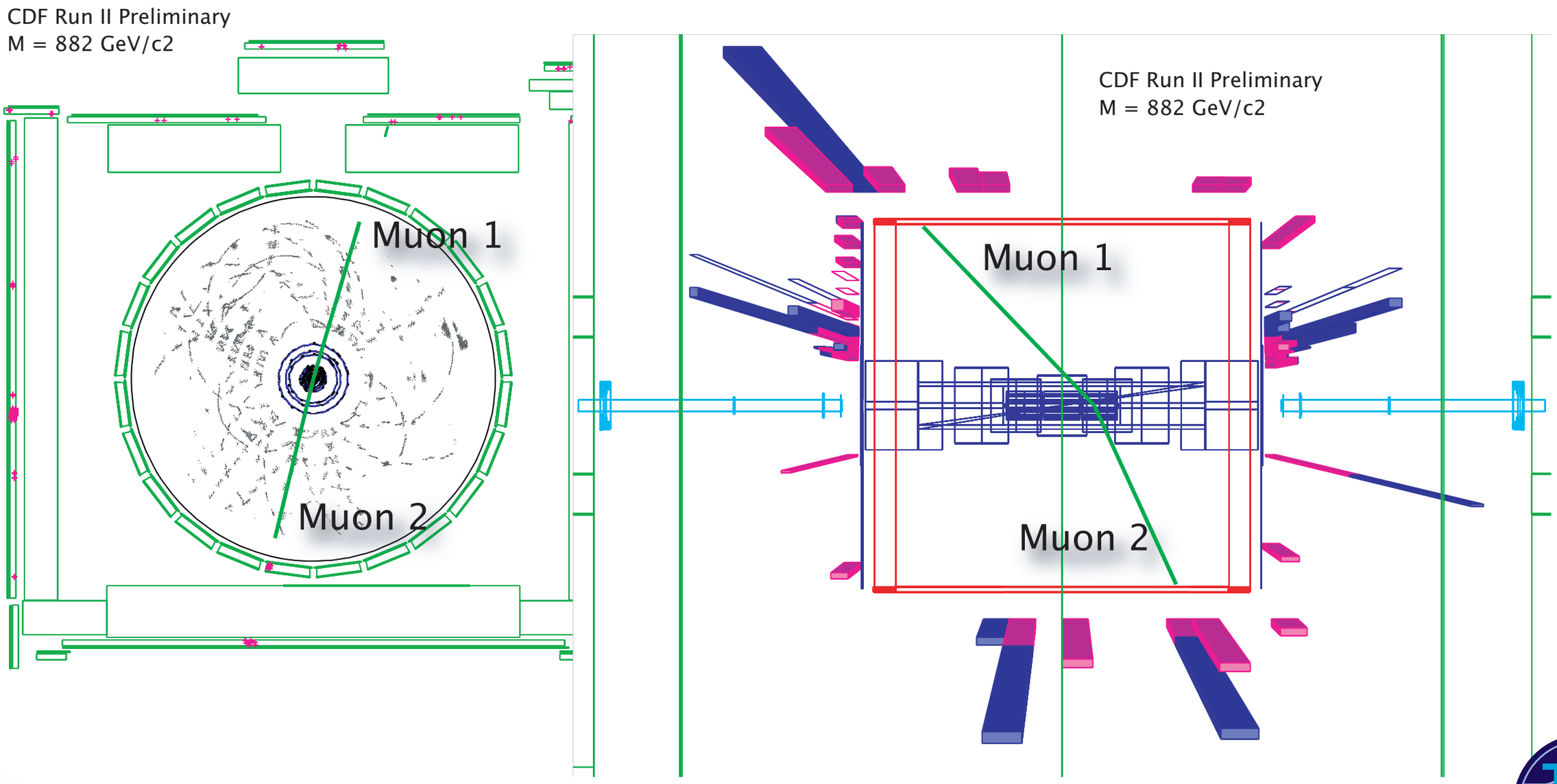




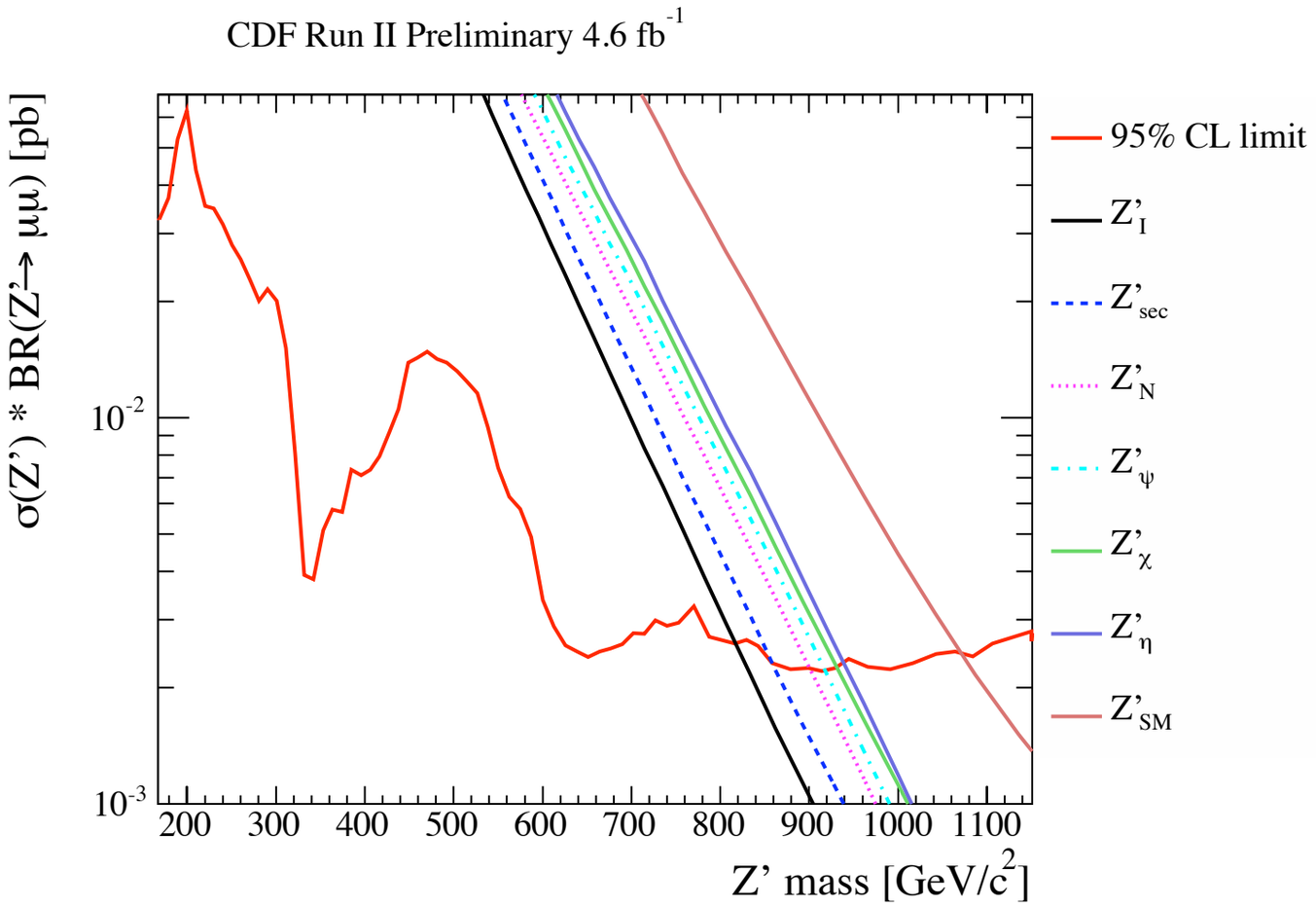
highest mass event: $m_{\mu\mu}$ = 882 GeV



CDF: Z'→$\mu^+\mu^-$, 4.6/fb

- No excess observed;
- Set limits in terms of several Z' models
- $Z'_{SM} > 1071$ GeV

- data "best fit":
  - consider fit of signal fraction (number of Z') and mass as 2d fit
- best fit at m=190 GeV, sz=1.3%
  - p-value 16%



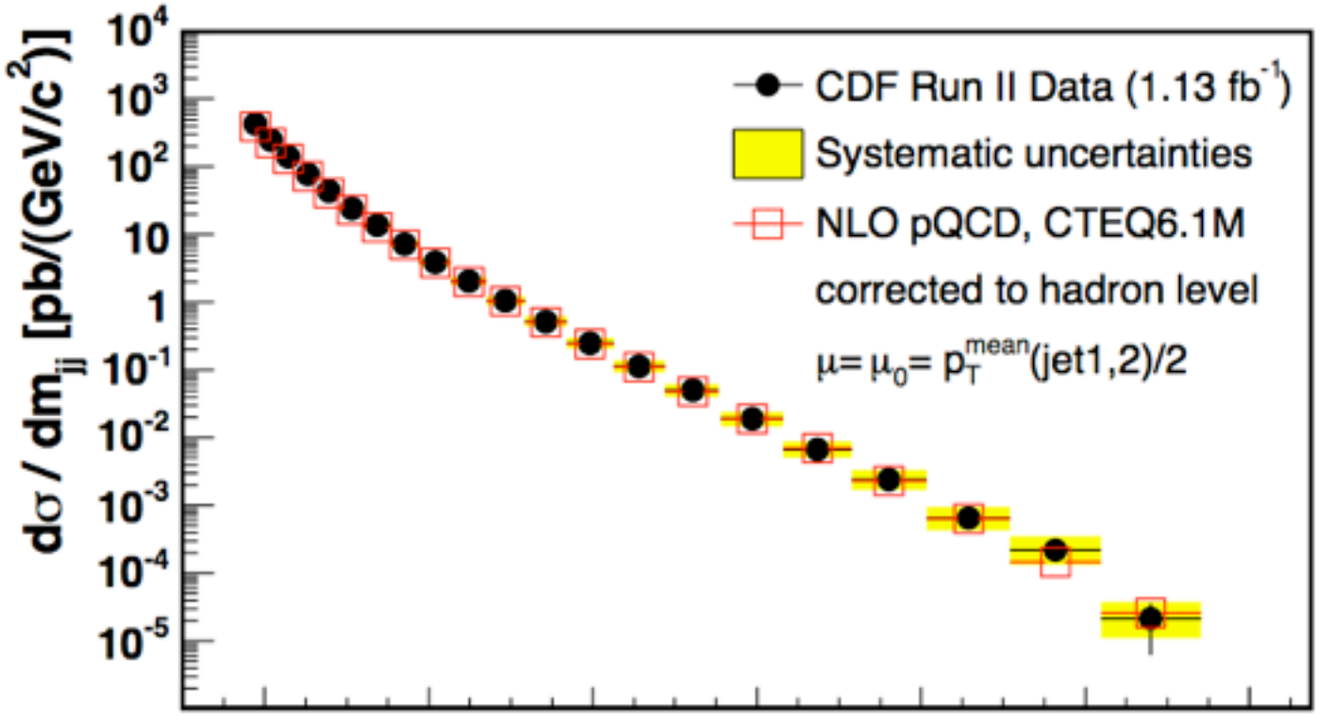
Model	Mass Limit (GeV/c^2)
Z'_l	817
Z'_{sec}	858
Z'_N	900
Z'_ψ	917
Z'_χ	930
Z'_η	938
Z'_{SM}	1071

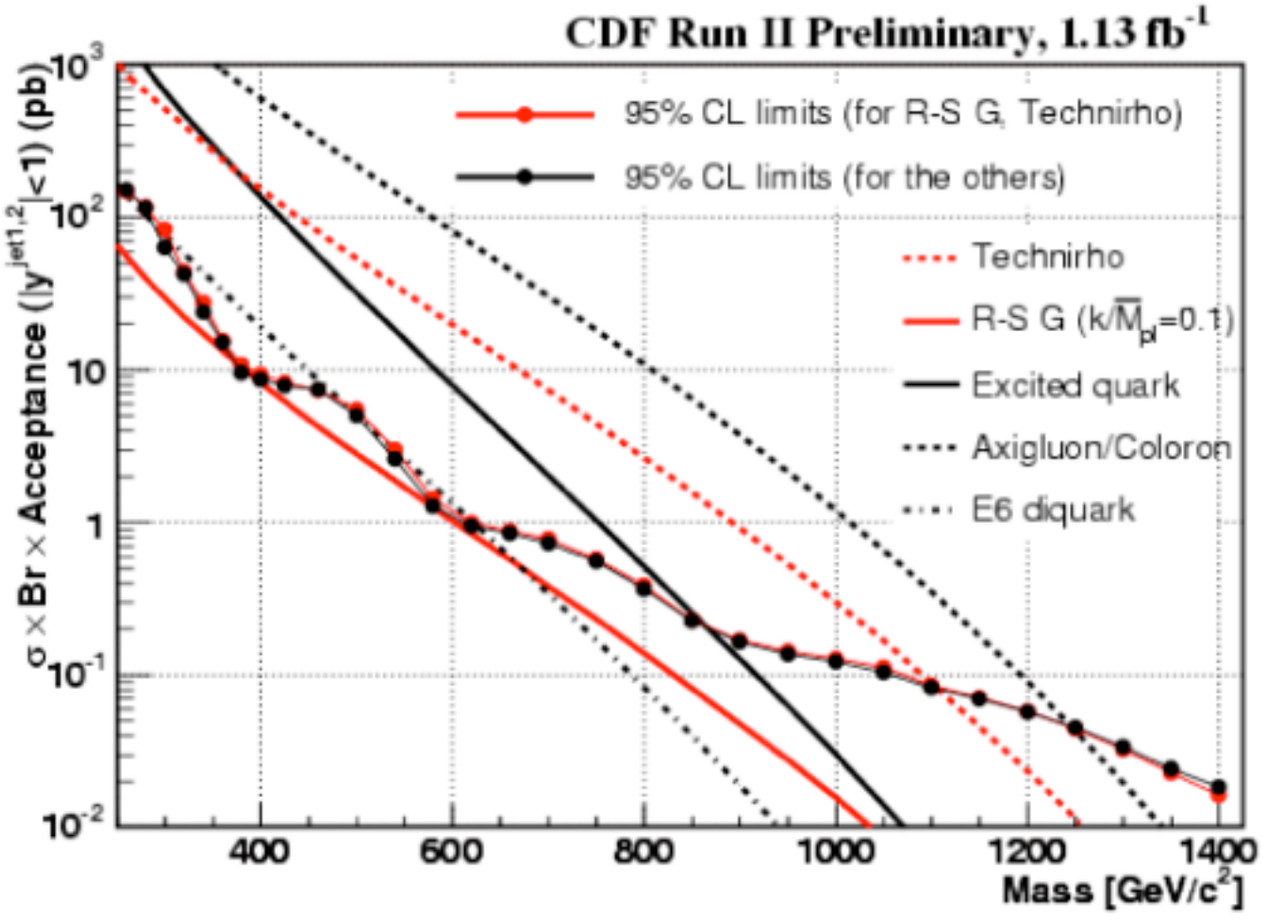
CDF Pub 10165 CDF Public Page

Dijet Mass Spectrum

- Choose events with two high-pt, central jets ($|\eta|<1.0$)
- Signal: bump in region $m_{jj}>180$ GeV
- Sensitive to all the usual resonar signal productions, with large production cross sections and decay BR's
- Functional form of dijet mass using pythia/herwig fit to data. Look for narrow excess.

- Data is consistent with SM: Set limits in various models

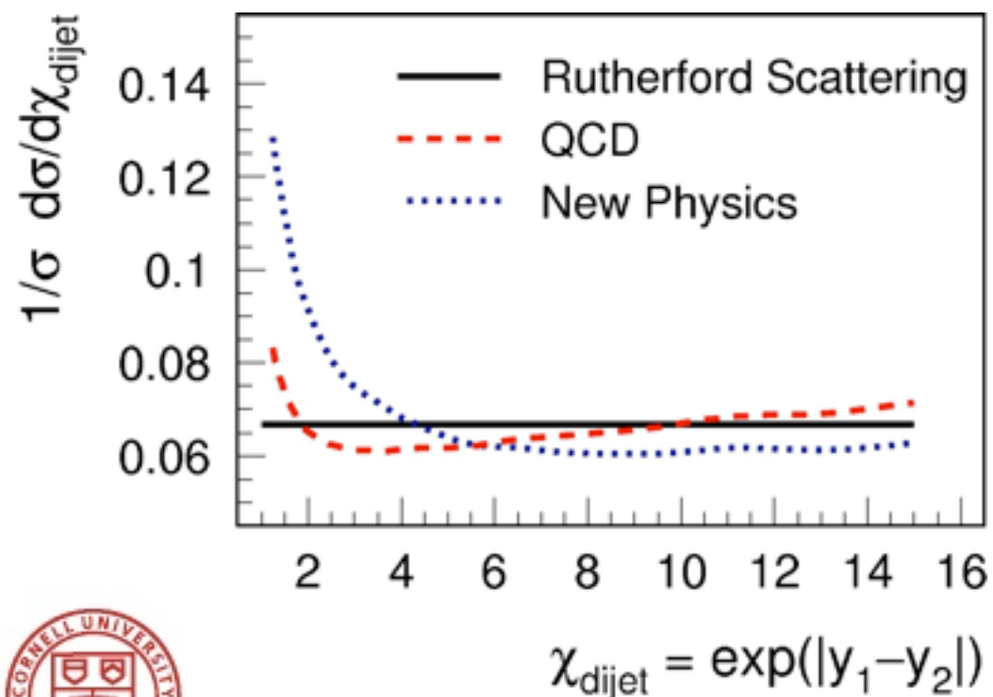


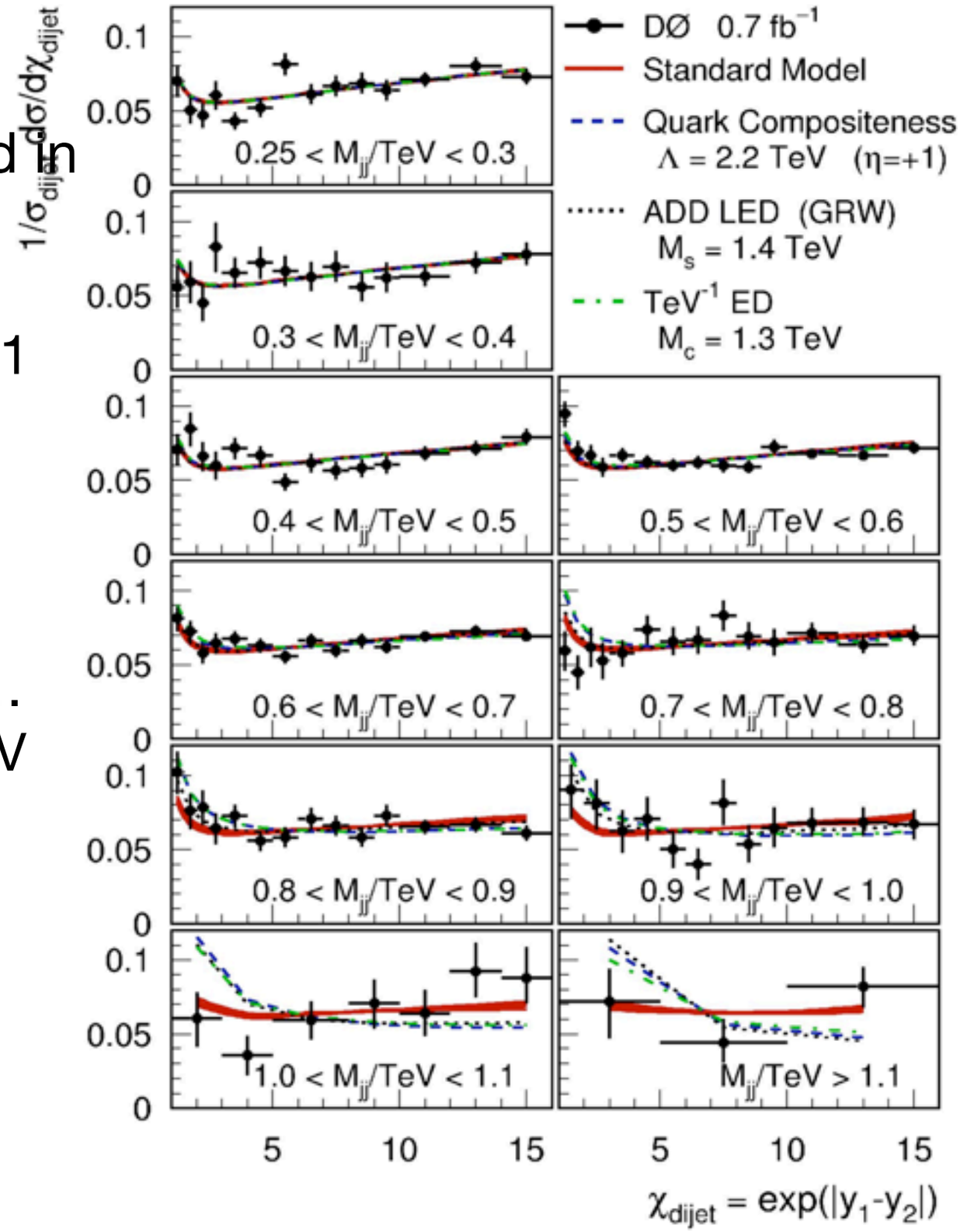


Phys. Rev. D 79, 112002(2009)

Quark Compositeness

- Dijet angular distributions is measured in bins of dijet mass
  - First differential cross section measurement at partonic energies >1 TeV!
  - Small experimental and theoretical uncertainties.
  - Sensitive to New Physics: compositeness, extra dimensions, …
    - ➡compositeness scale 2.75-3.06 TeV





Phys. Rev. Lett. 103, 191803 (2009)

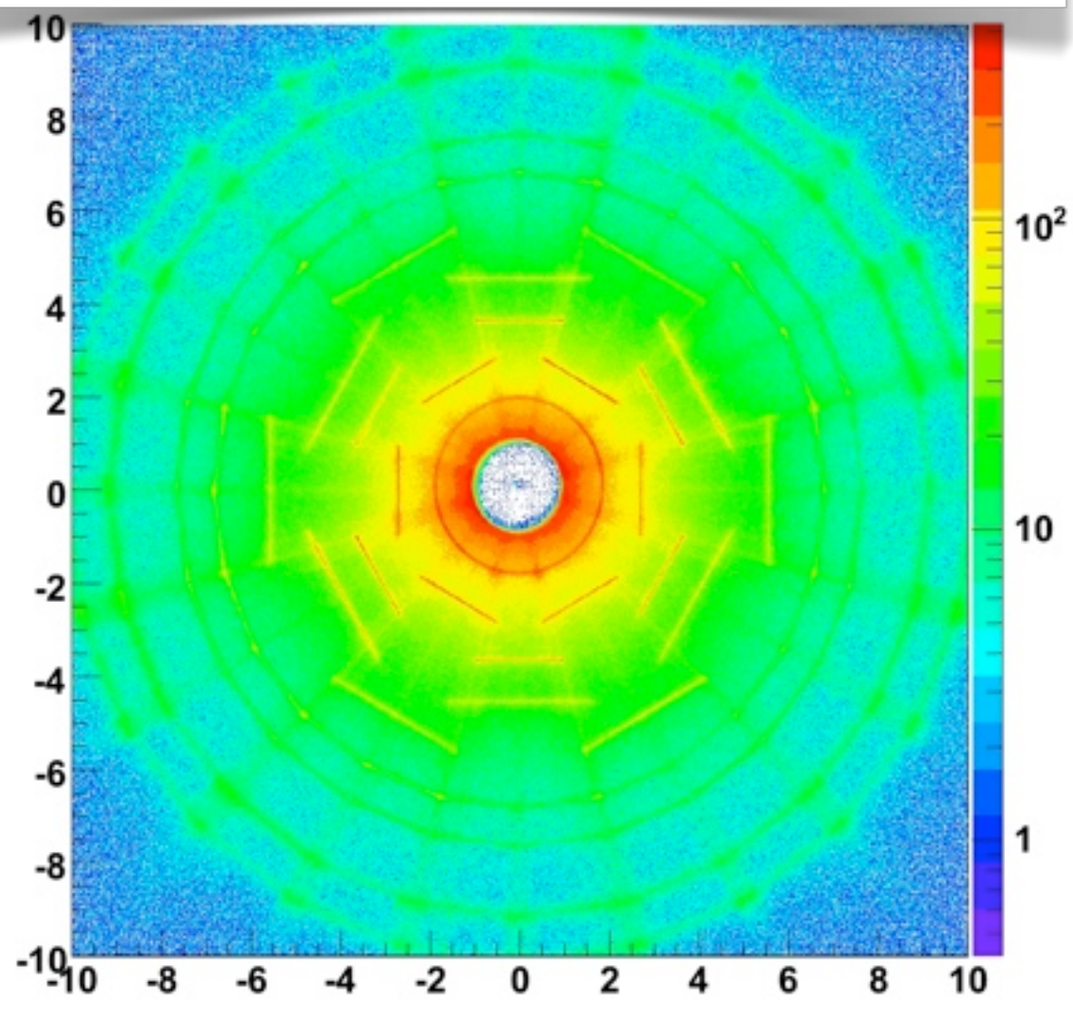
Exotic Models

Hidden Valley: resonant pair production of neutral long-lived particles

- Production of “v-particles”: possibly long-lived particles from a ‘hidden sector’
- Due to structure of theory: long-lived particles mix with SM H
- Consider b-like events
  - 1.6 cm < L_d < 20 cm
- Require:
  - ≥ 2 jets, ≥ 1 μ near jet, ≥ 2 good SV’s
- Two optimizations:
  - m_{SV}, co-linearity (low m_{HV}, high m_{HV})
- Backgrounds:
  - heavy flavor (L_{xy} cut)
  - interactions in material (region cuts)
- Set limits on m_{HV} vs m_H as fcn of L_d.

$$H \rightarrow HV\,HV$$
$$HV \rightarrow b\bar{b}$$

Co-linearity: $\mathbf{x}^{SV} \cdot \mathbf{p}_T^{SV} < .9937$



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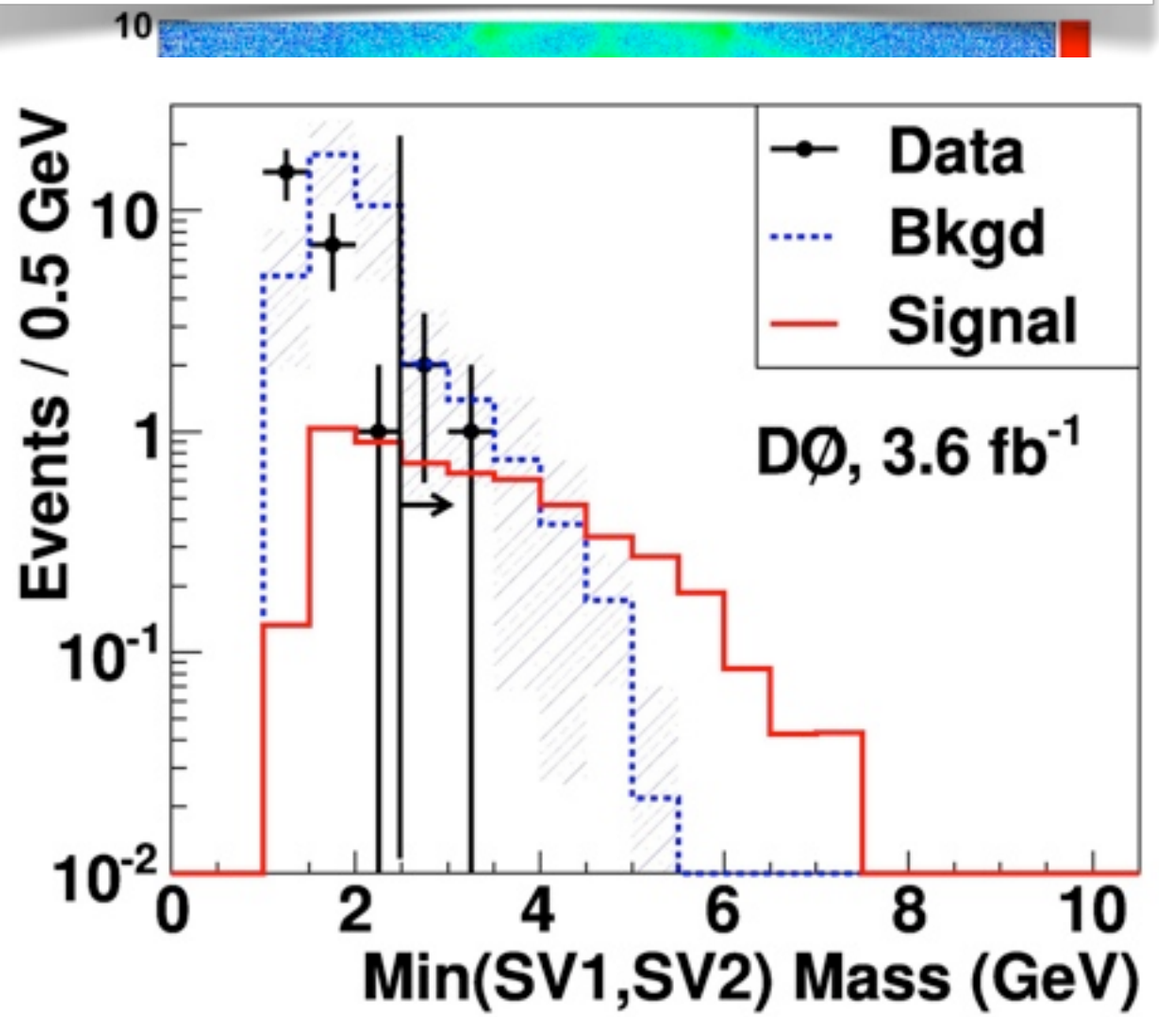

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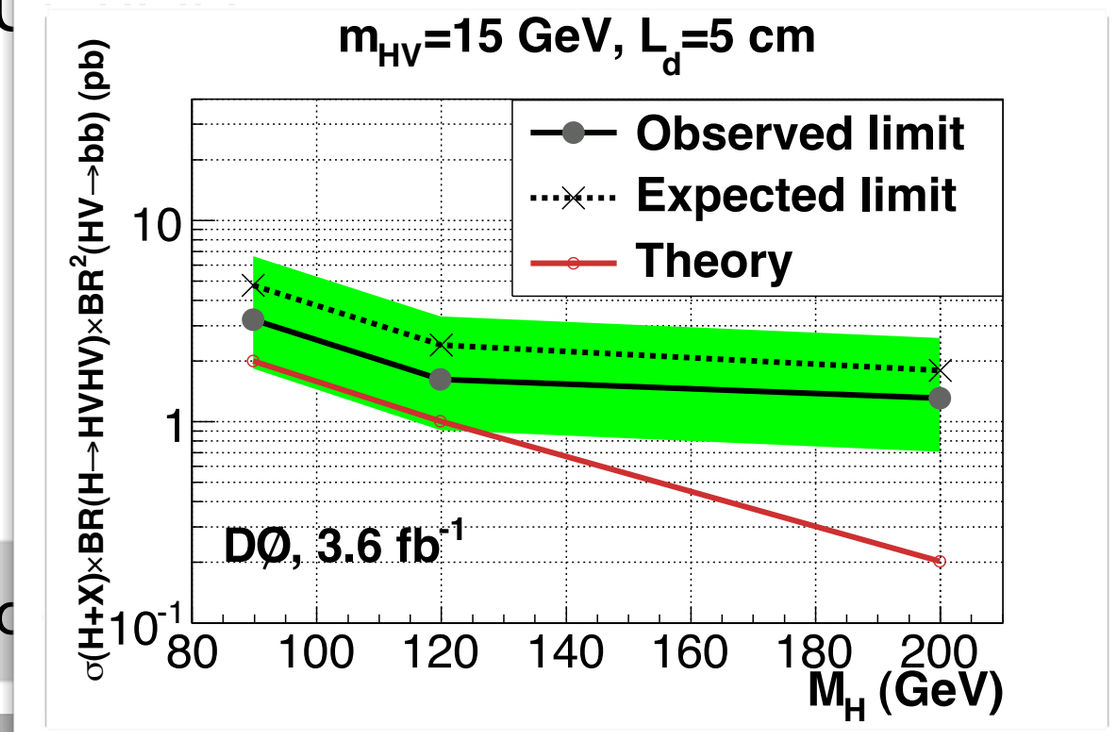
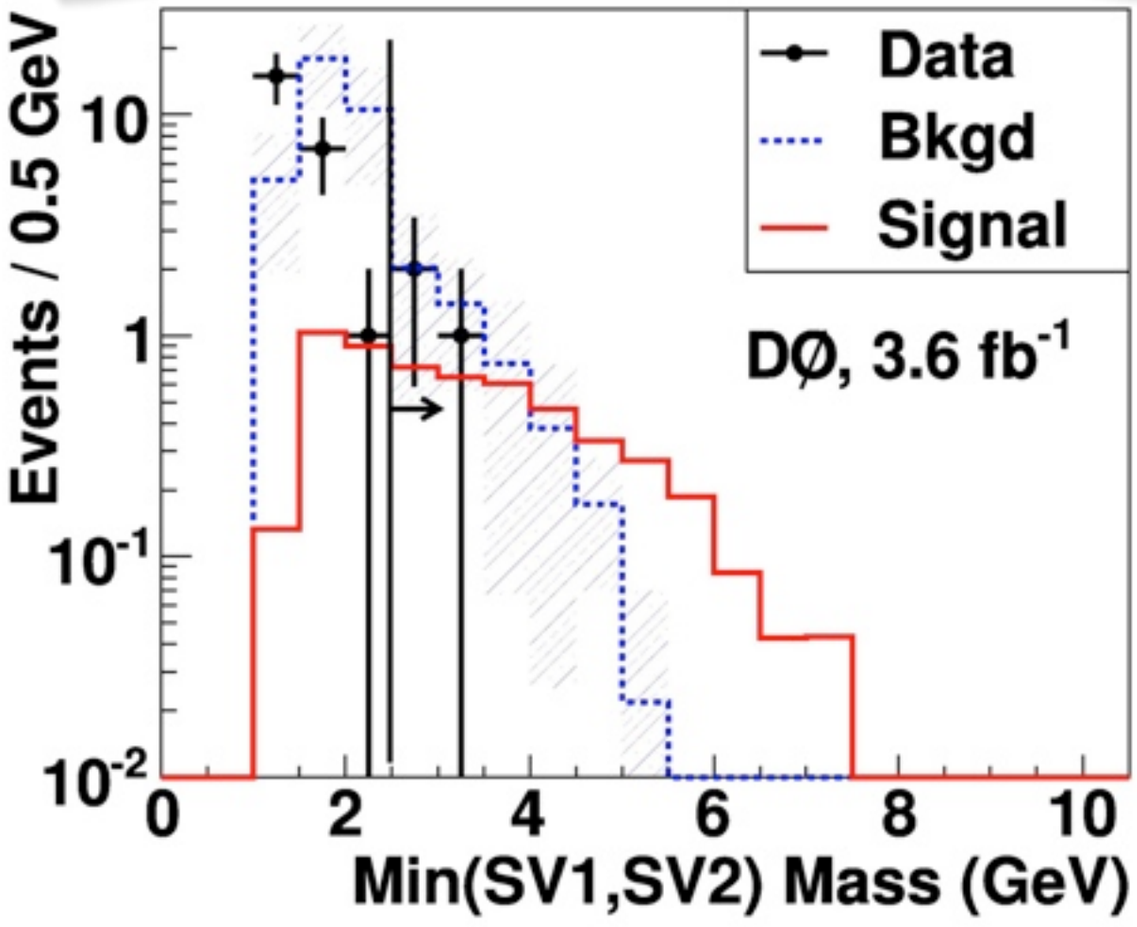
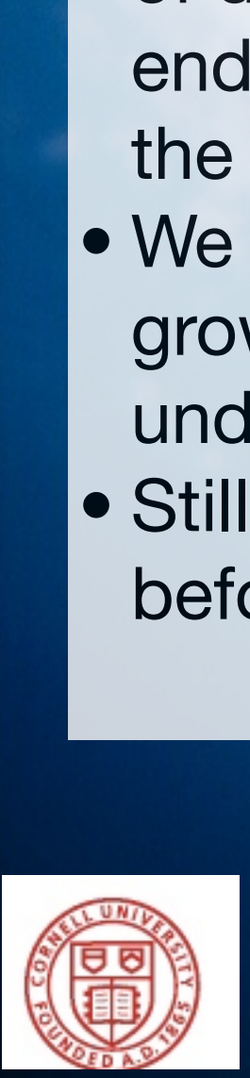




New Physics searches at the Tevatron

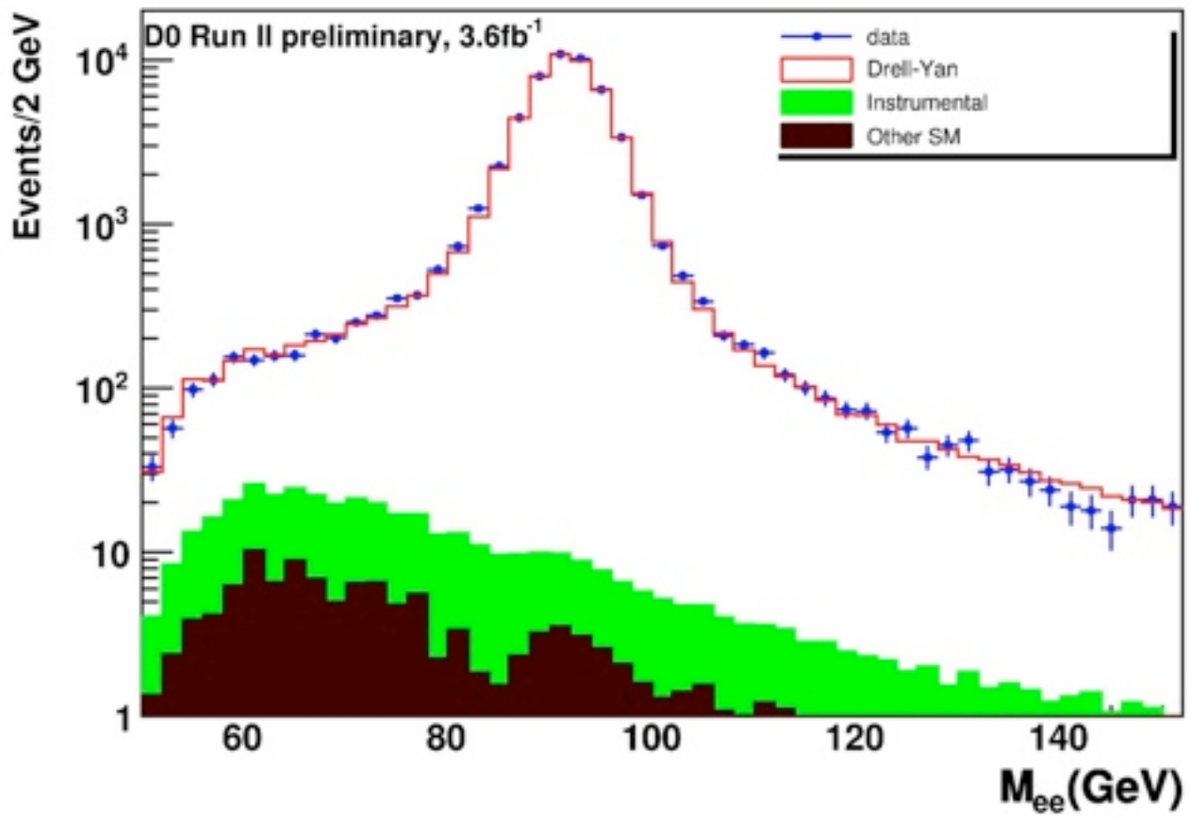
- D0 and CDF continue to mine the Tevatron dataset for hints of something new
- I've presented results with > 5/fb of data; expect to see >6/fb by end of the summer and 10+/fb by the end of Run 2
- We are exploring the large and growing datasets from our well-understood detectors
- Still a lot of fun things to be done before the LHC takes over!

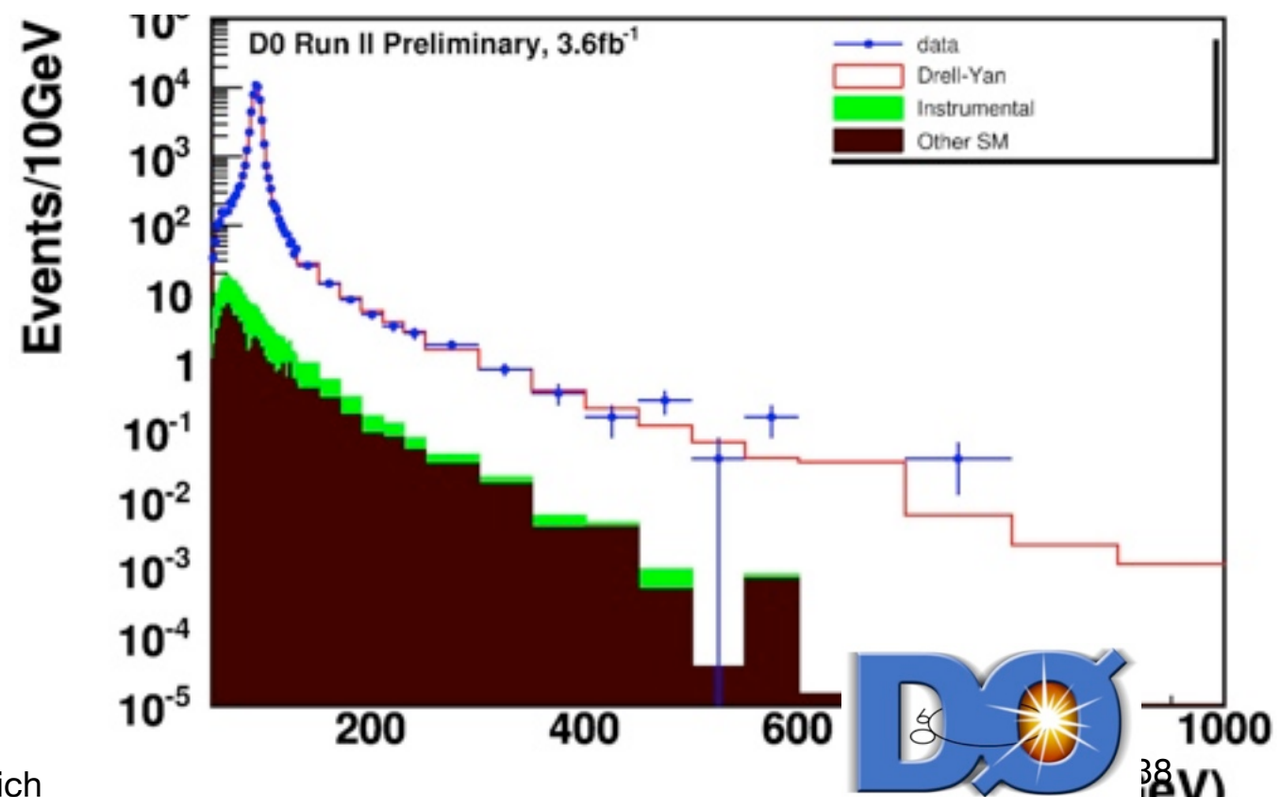


Backup Slides

Search for high-mass narrow resonances in the di-electron channel

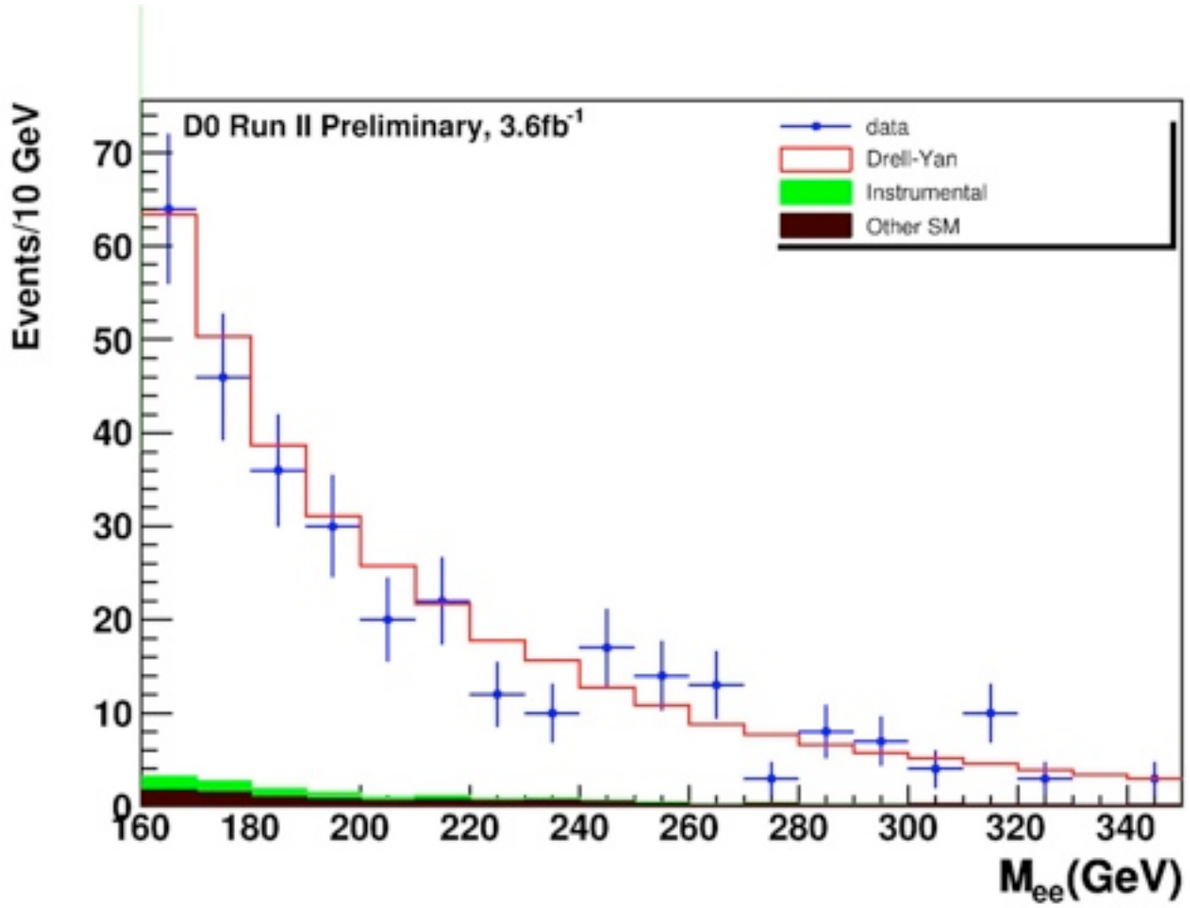
- Look for resonant production of heavy particle decaying to di-electron pair
- “bump hunt” across mass range
- Estimate non-DY and non-fake bkgnd from MC
- di-fakes biggest instrumental background from generic qcd
- normalize dy +fake to 70<mee<150 region after subtracting MC-derived estimates
- No excess observed
- Set limits in various different new physics models
  - RS gravitons
  - KK gravitons



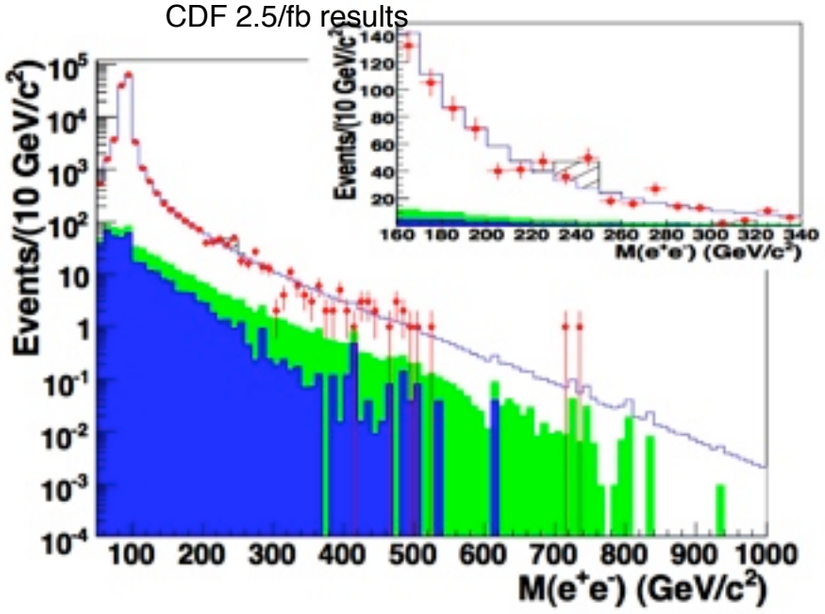


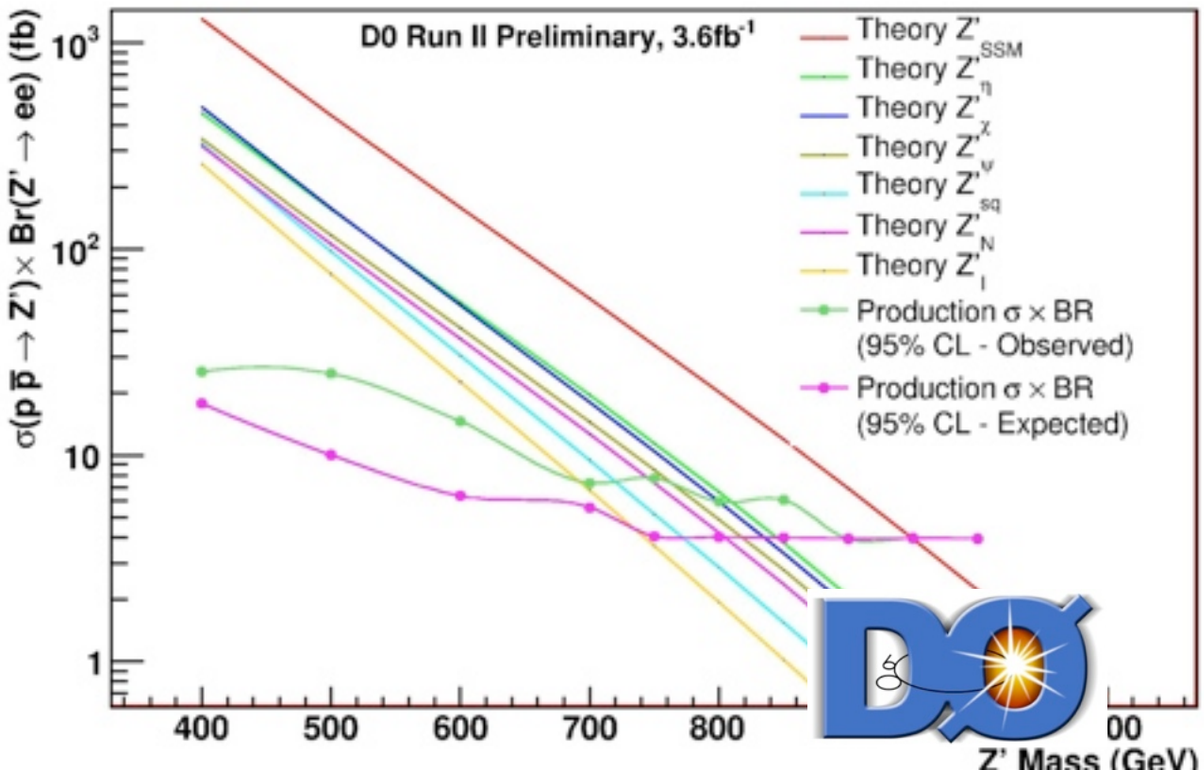
Di-electron bump hunt: results

- Nothing to see across entire mass range
- Nothing to see around ~240 GeV, either (2.5 σ CDF hint in 2.5/fb)



CDF 2.5/fb results





Tevatron parameters

TEVATRON Parameters

Parameter	Last Store	Best Store	Last 10 Stores (Ave)	Best 10 Stores (Ave)	FY Average	Previous FY (last 50)	FY End Goal (Design)	FY End Goal (Base)	
Protons per bunch	269.3	287.1	295.1	284.8	271.0	249.7	.0	.0	1e9
Pbars per bunch	60.2	96.3	68.1	93.8	77.2	66.8	.0	.0	1e9
Proton Efficiency to low ?	78.4	72.7	72.2	71.3	74.7	71.4	.0	.0	%
Pbar Efficiency to low ?	87.9	82.7	85.6	82.3	80.4	82.5	.0	.0	%
HourGlass factor	.68	.66	.67	.66	.66	.67	.00	.00	
Initial Luminosity lifetime	.0	.0	.0	.0	.0	.0	.0	.0	Hours
Asymptotic Luminosity lifetime	.0	.0	.0	.0	.0	.0	.0	.0	Hours
Effective Emittance	9.8	11.3	10.9	11.4	12.2	11.3	.0	.0	? mm mr