Beyond SM and Heavy Flavor Physics Results from Tevatron

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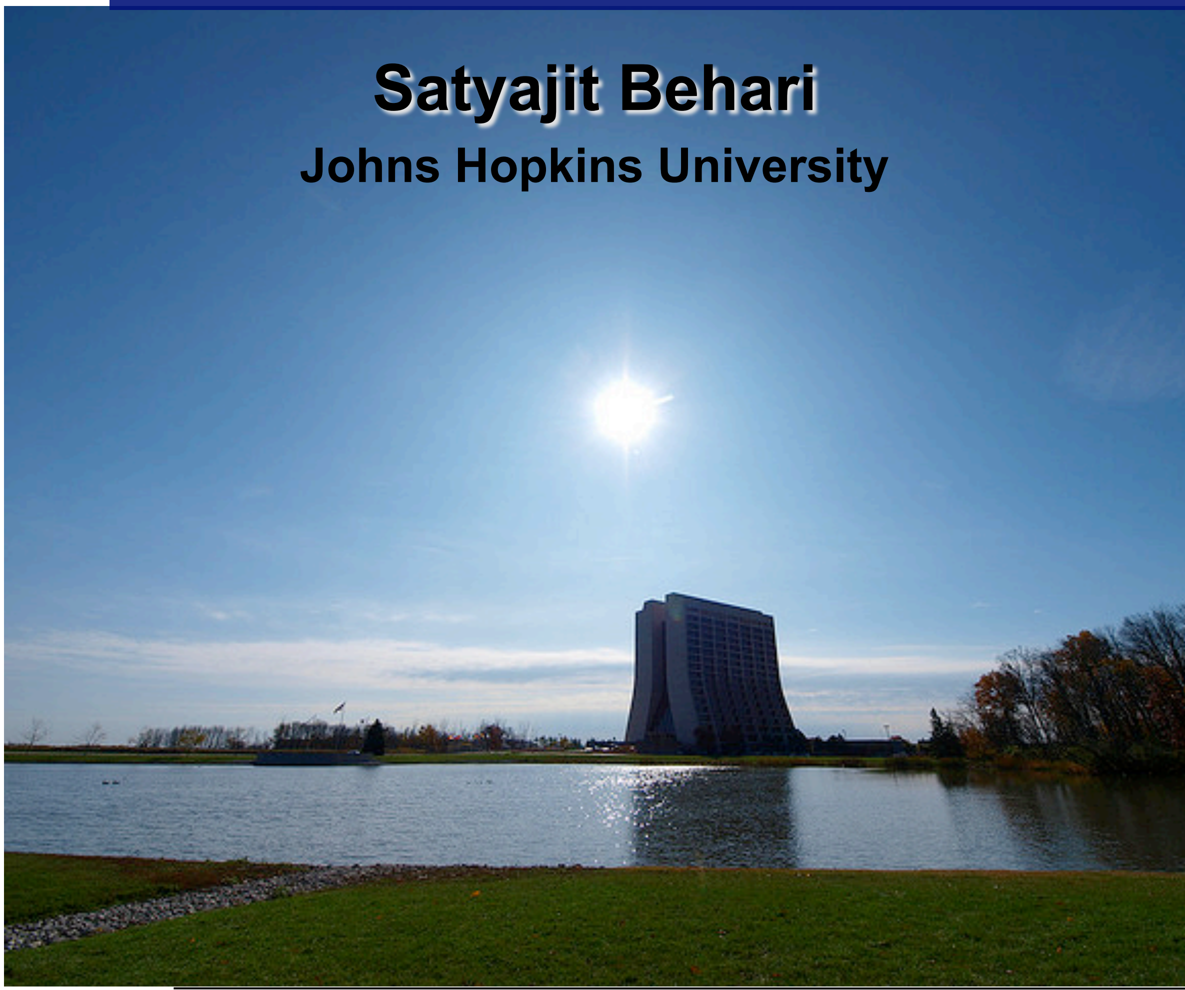

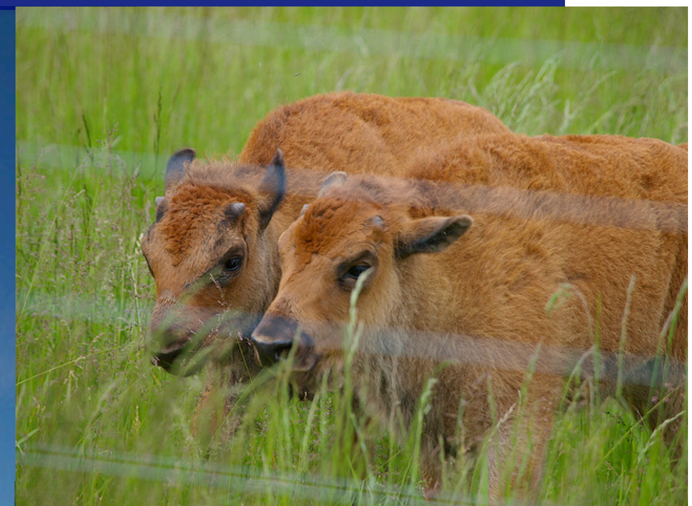

44th Annual Fermilab Users' Meeting
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Introduction

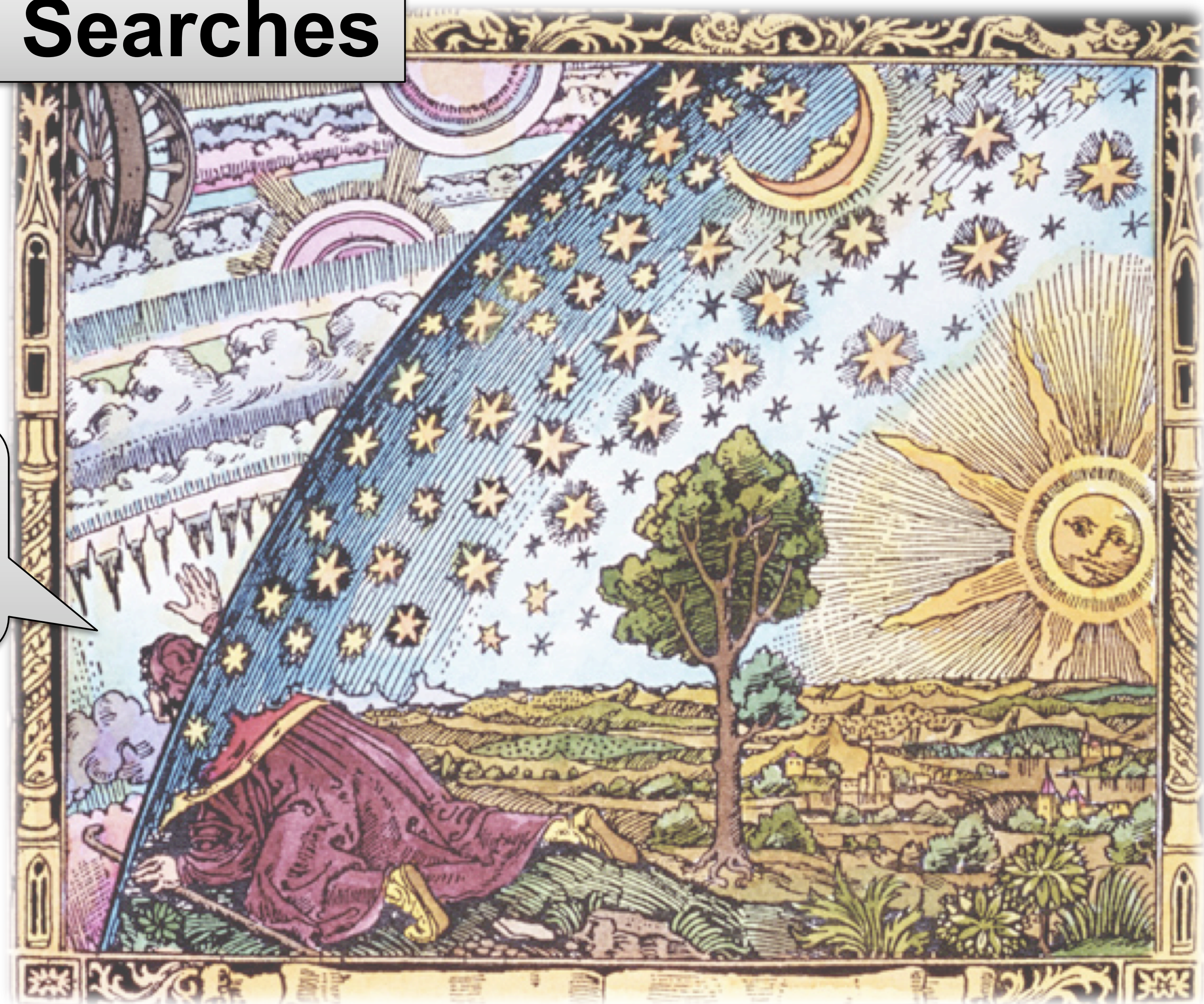
- Collider experiments support a synergy between **exotics searches** and **heavy flavor physics** in their quest for physics Beyond Standard Model.
- **Exotics searches** exploit direct production of new states of matter / couplings which can manifest themselves as excesses over expected backgrounds.
- **Heavy Flavor analyses** probe higher energy scales indirectly through exploration of effects of virtual massive particles that could alter the phenomenology of SM processes. In absence of NP, they provide precision measurement of SM fundamental parameters (e.g. CKM couplings...)

Contents of this talk

- **Exotics:** **Assorted measurements from CDF and DØ, based on 5.4 – 6.3 fb^{-1} data:**
  - **Search for Extra Dimensions**
  - **Inclusive searches for BSM physics in like-sign dileptons and Photon+Jets+MET events.**
- **Heavy Flavor:** **Recent measurements from CDF and DØ, based on 1.4 – 8 fb^{-1} data:**
  - **Search for BSM physics in B_s sector**
  - **Results competitive with B factories in B/charm sector**

NOTE: **These topics form a tiny fraction of analyses carried out at CDF and DØ. Apology to my colleagues whose work I couldn't cover here.**

Exotic Searches



Medieval pilgrim exploring the Extra Dimension!

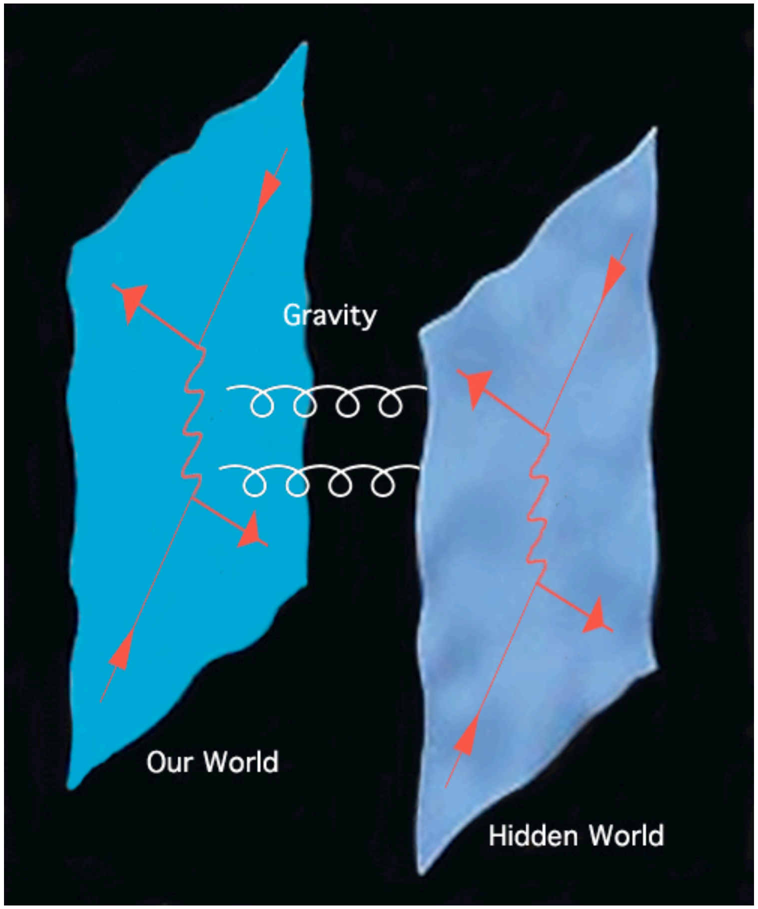
Motivation for Extra Dimensions (ED)

- A fundamental (hierarchy) problem in Standard Model:
  - Electroweak and Planck scales are O(10^{16}) apart.

- **Randall-Sundrum ED:**
  - Fixes the hierarchy problem by introducing one extra dimension (5 total)
  - SM processes are localized to one membrane (our 4-D world). Only gravity propagates between ours and the ED.
  - Gravity is much weaker than other forces of nature.

- **Universal Extra Dimensions (UED):**
  - SM processes can also propagate in the extra dimensions

- Phenomenology of these models lead to Kaluza-Klein resonances (spin-2 Gravitons) of a pair of SM particles (leptons, photons, jets or gauge bosons) we wish to detect.

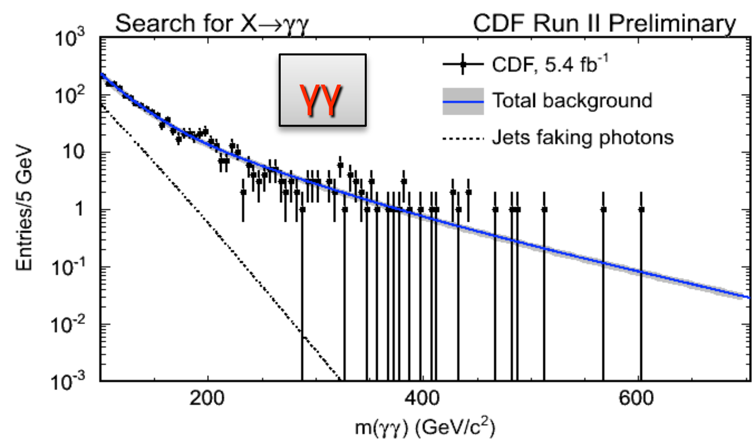


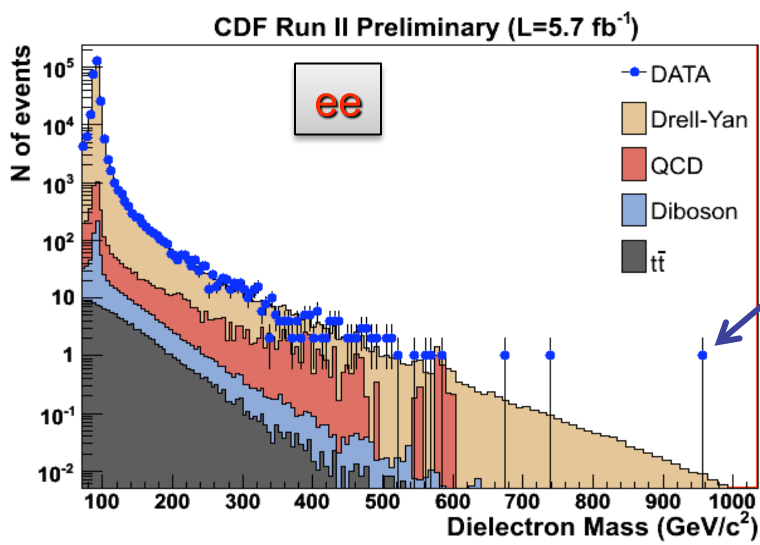
L. Randall, R. Sundrum, Phys. Rev. Lett. 83, 3370 (1999)

Search for RS-Gravitons

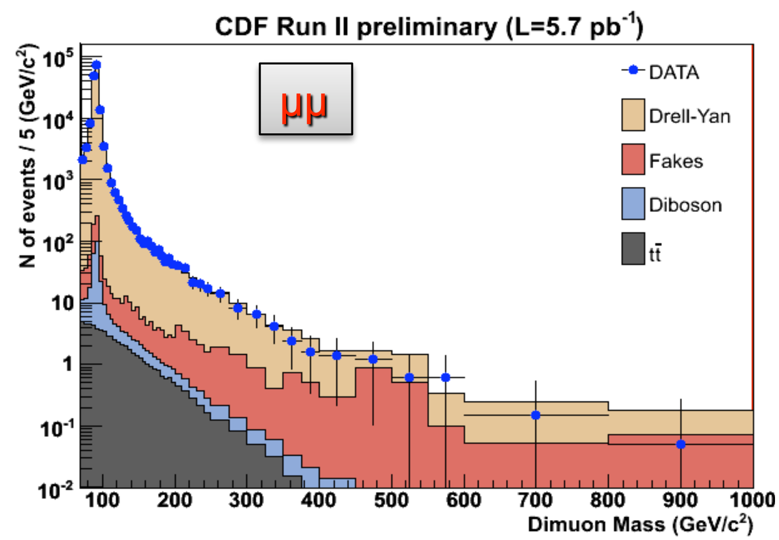
arXiv:1103.4650 (Submitted to PRL)

- Analyze 5.4 – 5.7 fb^{-1}
- Search for gravitons decaying to **γγ**, **ee** and **μμ** pairs.
- Mass spectra understood very well.
- Look for bumps in mass spectra. In absence set cross-section and graviton-mass limits for the three modes.
- Combine the 3 analyses to set the strongest RS-graviton limit.



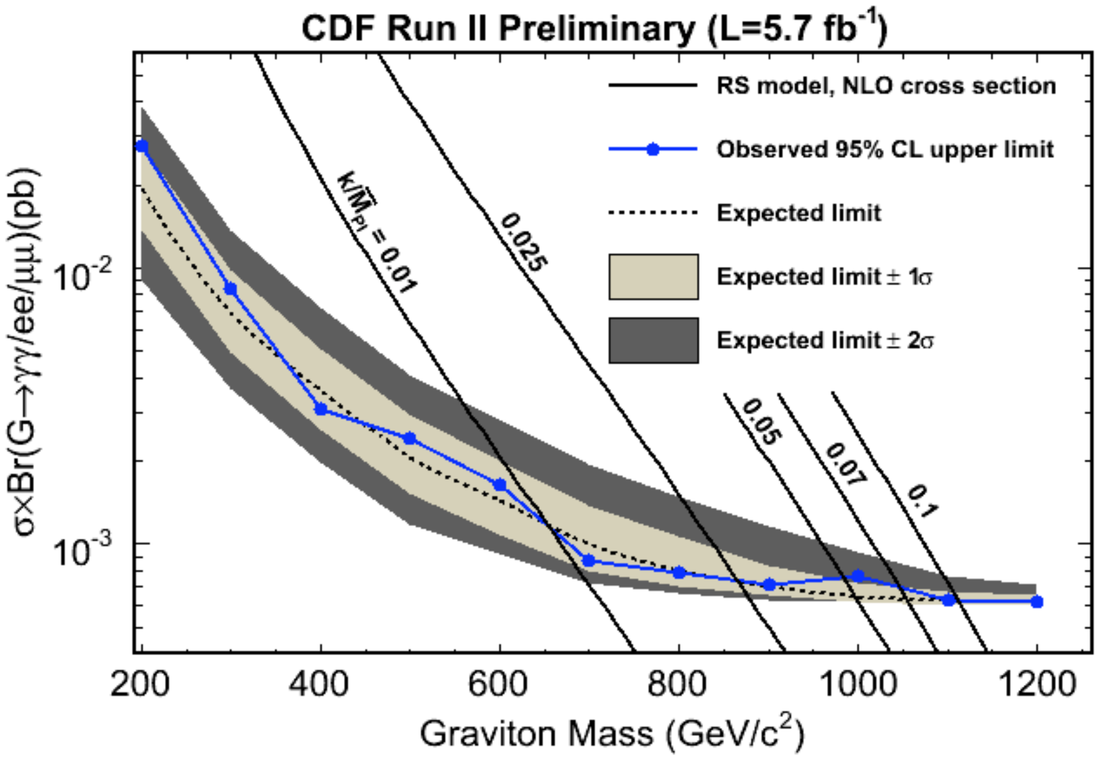


Highest Di-electron mass (960 GeV) ever!



Combined γγ+ee+μμ RS-Graviton Limit

arXiv:1103.4650

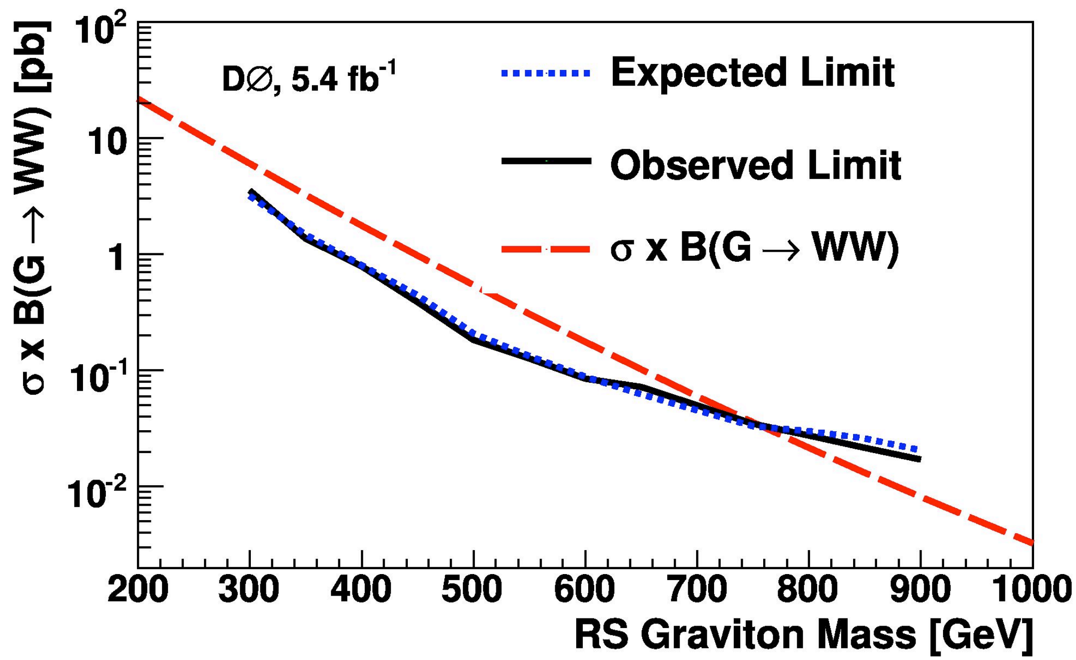


- **Combined γγ, ee, μμ RS-graviton limit:**
  M_G>1111 GeV/c^2 at 95% CL
  - for $k/\overline{M}_{PL}$=0.1
  - realistic variable k-factor)
- **Currently best in the world**

- **DØ: 1050 GeV/c^2**
  - 5.4fb^{-1}, ee+γγ, k-factor=1.54, **PRL 104, 241802 (2010)**
- CMS: 1079 GeV/c^2 (40 pb^{-1}, dileptons, k-factor=1.6, arXiv:1103.0981)
  ATLAS: 920 GeV/c^2 (40 pb^{-1}, diphotons, k-factor=??, ATLAS-CONF-2011.044)

Search for RS-Gravitons (Di-bosons)

arXiv:1011.6278 (Accepted by PRL)



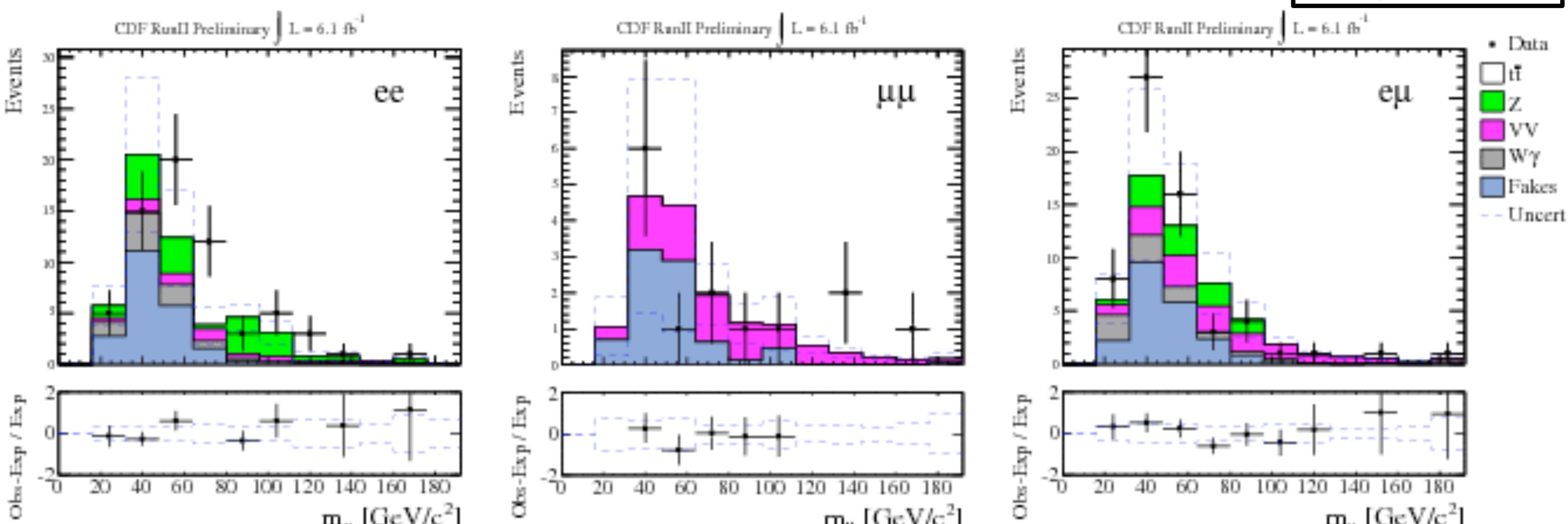
- RS gravitons can also decay to boson pairs.
- Use *WZ* search to also set limits on RS-gravitons.
- Exclude RS-graviton between 300 - 754 GeV @ 95% CL.

Like-sign Di-lepton Search

CDF Public Note 10464

- Very rare in SM
- Many NP models predict same-sign dileptons, e.g. SUSY, 4th generation quarks, heavy neutrino etc.
- Data: 6.1 fb^{-1}, Single e or μ trigger.
- Checked various kinematic variables
  - ➲ **Found consistent with SM**.

Dilepton Mass

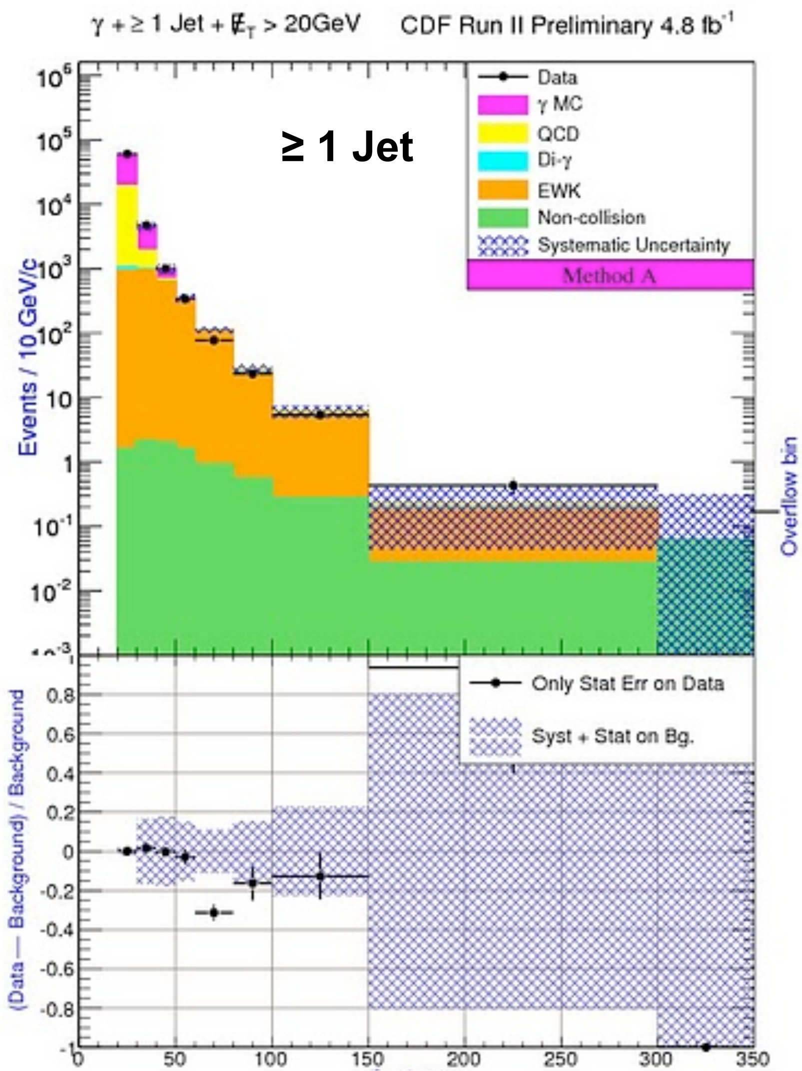


Photon + Jets + MET Search

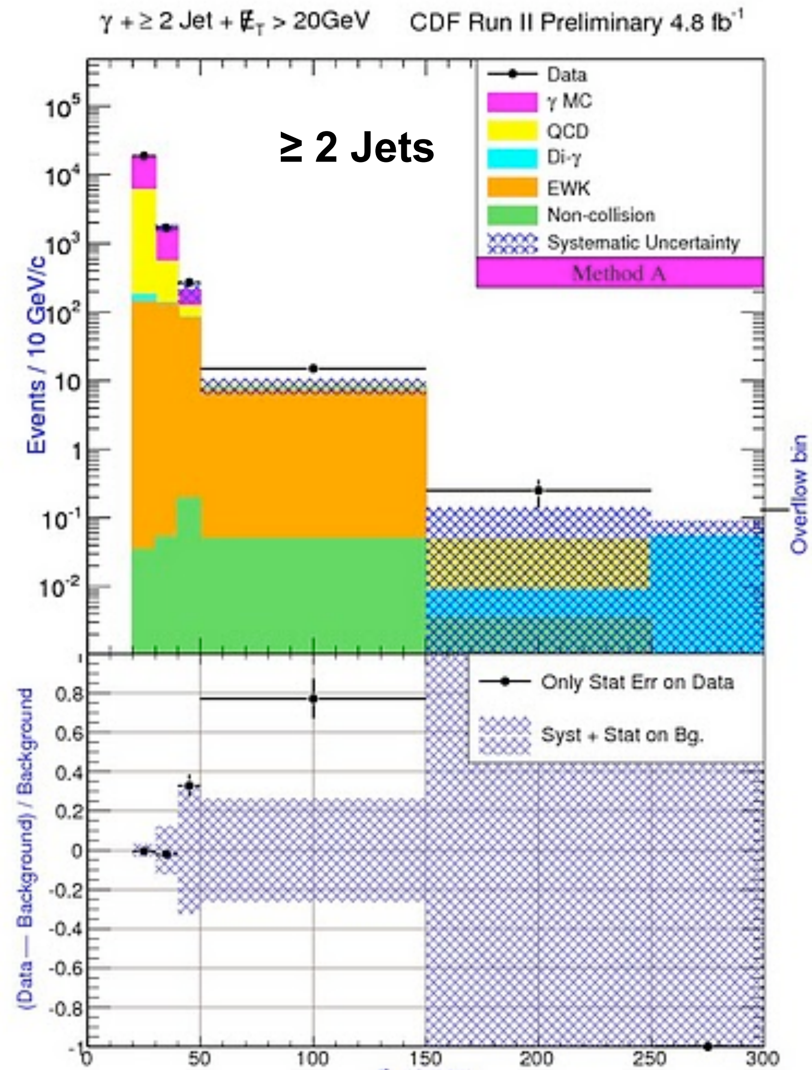
CDF Public Note 10355

- A model-independent, signature-based search for anomalous photon+jets or photon+jets+MET
- Data used: **4.8 fb^{-1}**
- Examine several kinematic variables in events with a photon + ≥1 or ≥2 jets with/without MET
- Look for deviations from SM, which may point to:
  - A heavy particle decaying to photon+jets OR
  - A new physics mechanism, e.g. Gauge-Mediated SUSY Breaking (GMSB) or Technicolor, is in play.

Photon + Jets + MET Search



MET



MET

Consistent with SM.

A Heavy Flavor Treat!

Mashed potato, gravy and sausage ice-cream

Search for NP in B_s decays

- B_s mixing phase is expected to be tiny in SM ($\beta_s^{SM} \approx 0.02$) and unconstrained by the 2006 measurement of the B_s mixing frequency.
  - ➲ Presence of NP can lead to large values of the phase, not experimentally excluded

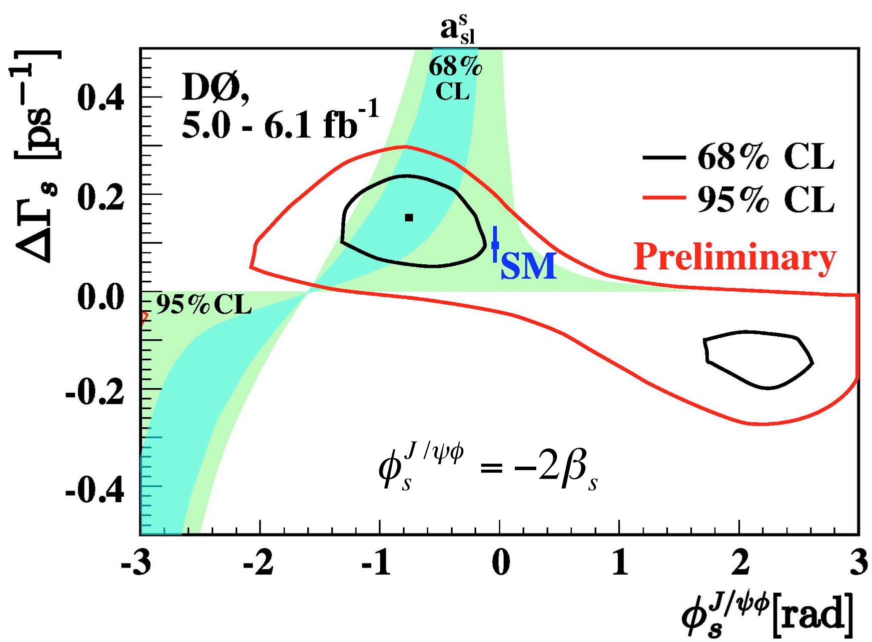
- Access β_s^{SM} through:
  1) Time evolution of flavor tagged $B_s \to J/\psi\varphi$ decays
  2) Inclusively, by measuring anomalous mixing rate difference between B_s and $\overline{B}_s$ (A^b_{SL})

- Both the methods are pursued at CDF and DØ. Initial results indicate departure from SM by 1.5σ and 3.2σ, respectively.
  - ➲ Call for more scrutiny through independent measurements.

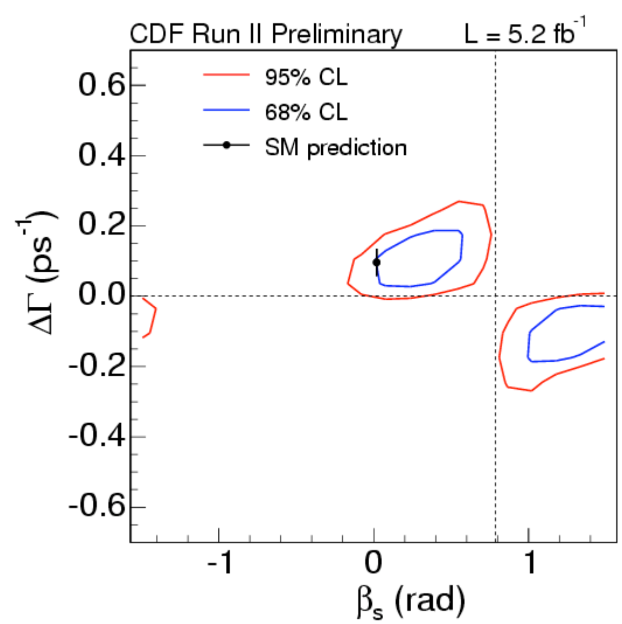
1) CPV from mixing in $B_s \rightarrow J/\psi\phi$ decays

- Best way of probing CPV due to NP in B_s mixing
- BUT.. angular analysis to disentangle CP even and odd components.

- DØ: 6.1 fb^{-1} data
  - Sees 1.1σ deviation from SM



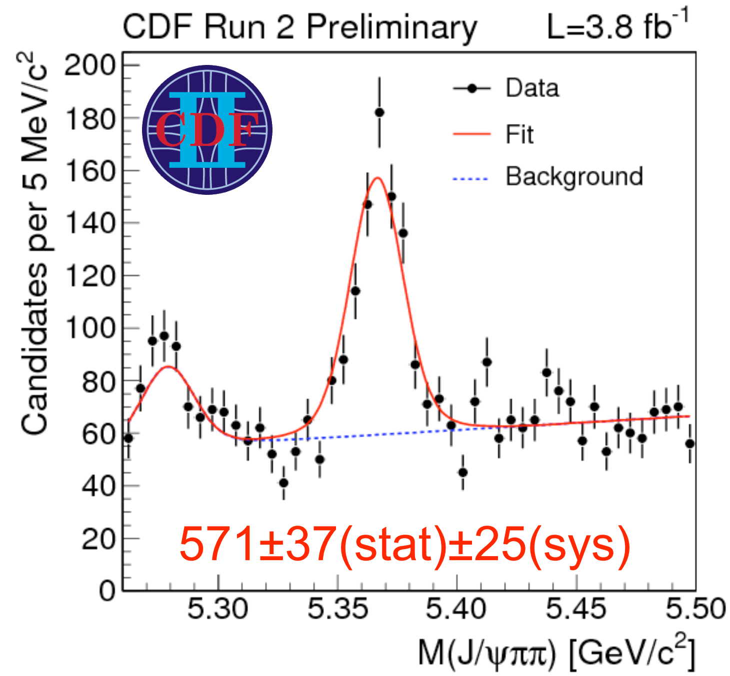
- CDF: 5.2 fb^{-1} data
  - Sees 0.8σ deviation from SM



Need updated measurements and new ways to measure the phase.

A simpler way: $B_s \to J/\psi\ f_0(980)$ BR

- Use multivariate techniques to suppress background. Then perform a log-likelihood fit on signal and normalization mode, $B_s \to J/\psi\ \Phi$, simultaneously.



- Measured:

$$R_{f^0/\phi} = \frac{\mathrm{BF}(\mathrm{B_s} \to J/\psi f_0(980)) \cdot BF(f_0(980) \to \pi^+\pi^-)}{\mathrm{BF}(\mathrm{B_s} \to J/\psi\phi) \cdot BF(\phi \to K^+K^-)}$$

$$= 0.292 \pm 0.020(\mathrm{stat}) \pm 0.017(\mathrm{sys})$$

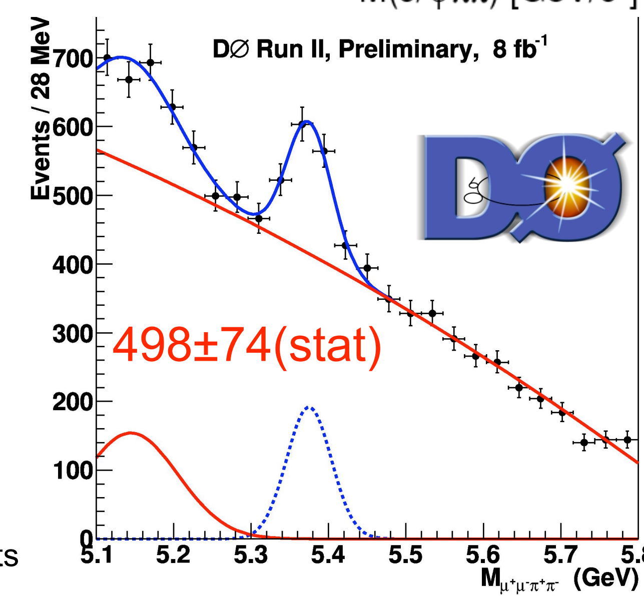
Most precise!

CDF Public Note 10404

$$= 0.210 \pm 0.032(\mathrm{stat}) \pm 0.036(\mathrm{sys})$$

DØ Public Note 6152

(Theory: 0.1 – 0.5)



2) Dimuon charge asymmetry recap

V. A. Abazov et al, Phys. Rev. Lett. 105, 081801 (2010)

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

- Where, $N_b^{++,--}$ are number of same sign dimuon events produced due to the b hadrons decaying semileptonically, one before and the other after mixing.
- Is close to zero if mixing rates $B \to \overline{B} = \overline{B} \to B$ (SM expectation is a few 10^{-4}).

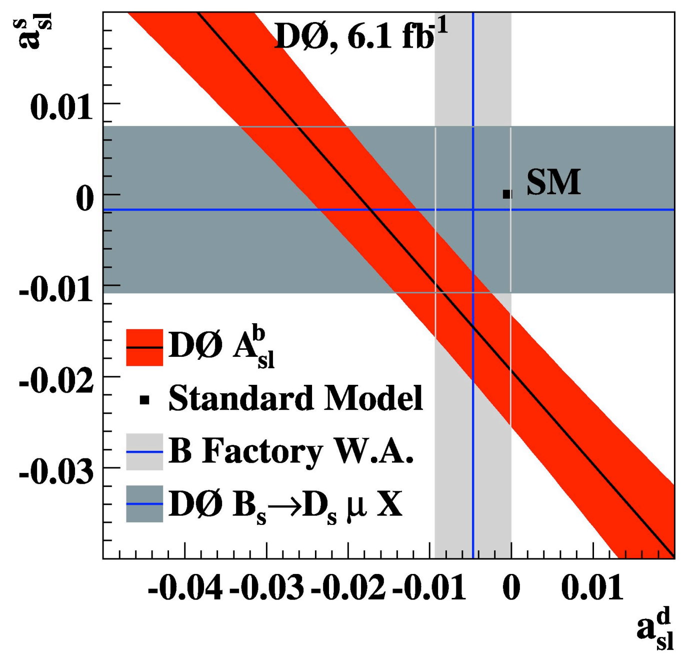
- DØ 6.1 fb^{-1} result:

$$A_{sl}^{b} = (-0.957 \pm 0.251(\text{stat}) \pm 0.146(\text{syst}))\%$$

- Differs from SM by ~3.2σ:

$$A_{sl}^{b}(\text{SM}) = (-0.023^{+0.005}_{-0.006})\%$$

- Indication of large B_s mixing phase?



Need independent verification

CDF on the way to measuring A^b_{sl}

- CDF is pursuing an alternate path for independent verification of the interesting DØ result.
- Use muon impact parameter (IP) information to fit for sample composition, separating same-sign dimuons $\mu^+\mu^+$ and $\mu^-\mu^-$ that originate from B decays (i.e. are long lived).
- IP fitter is a standard robust technique demonstrated in the correlated $B\bar{B}$ cross-section measurement: *PRD 77, 072004 (2008).*
- As a first step: measure time-integrated mixing probability $\bar{\chi}$
  - Comparison to LEP $\bar{\chi}$ validates the IP fitter.

Time integrated mixing prob. measurement

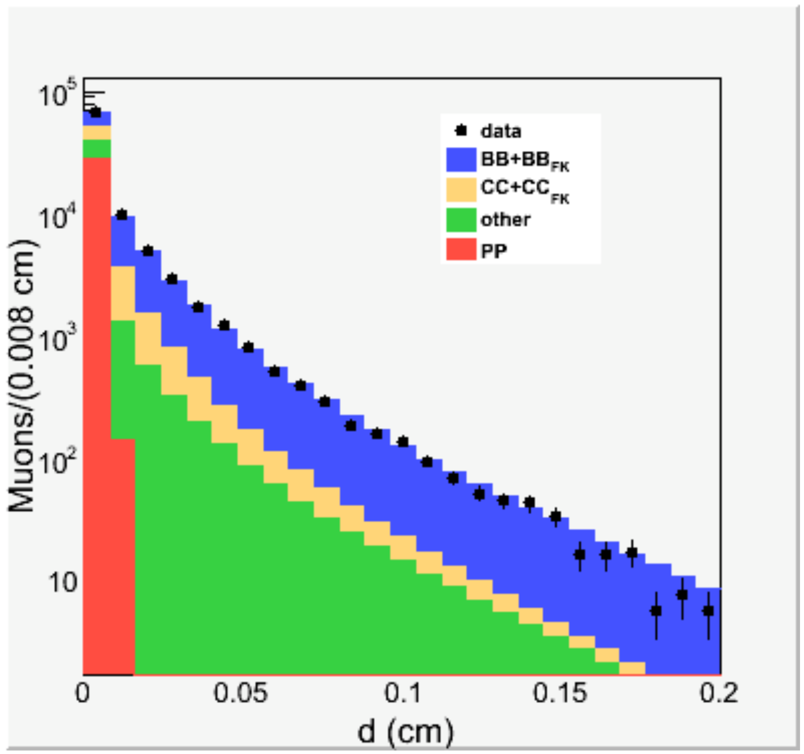
CDF Public Note 10335

- Data sample: 1.45 fb^{-1} from CDF di-muon trigger
- Ratio of like-sign (LS) to opposite-sign (OS) di-muons, **R**, measure the average time-integrated mixing probability ($\bar{\chi}$) of the mixture of semileptonic decays of B and $\bar{B}$ mesons.

- Fit the observed impact parameter distribution for muon pairs simultaneously to extract: $\bar{\chi} = 0.126 \pm 0.008$

- Good agreement with LEP measurement of 0.1259±0.0042

➲IP fitter is ready for A^{b}_{sl} extraction.



Evidence for $B_s \rightarrow \pi^+\pi^-$ decays

NEW!

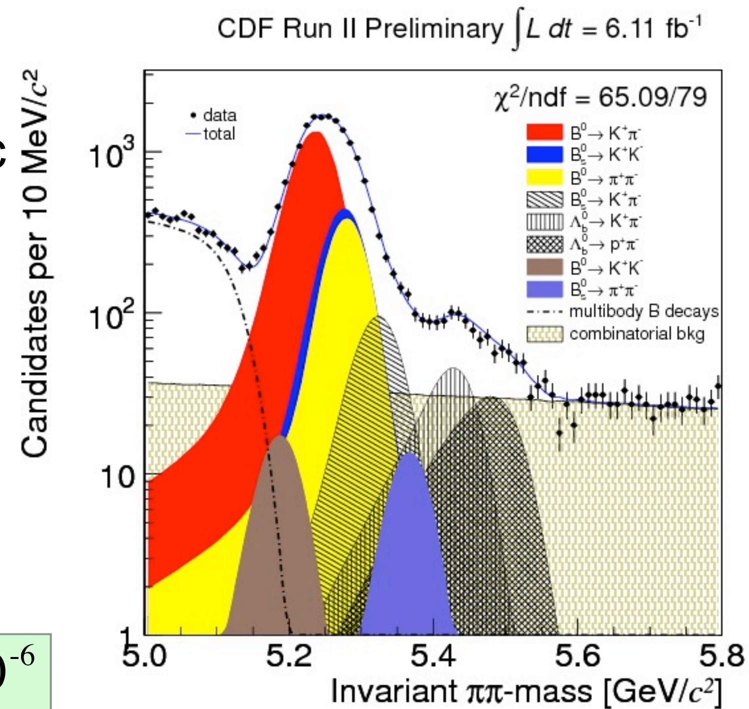
- Study of charm-less $B \rightarrow h^+ h^-$ decays have been a key part of CDF heavy flavor program, employing the displaced track trigger.
- **Latest entry:** evidence of $B_s \rightarrow \pi^+\pi^-$, the rarest B_s ever seen.
- **Importance:** b and s quark annihilate each other yielding new set of quarks in final states
  - Very hard to predict decay amplitudes and a source of large uncertainties in predictions for many hadronic B decays.
  - Experimental input is crucial to constrain their magnitude.
- The as yet unobserved $B^0 \rightarrow K^+K^-$ mode is similar and has a larger predicted BR.

Evidence for $B_s \to \pi^+\pi^-$ decays

CDF Public Note 10498

- Data analyzed: **6.1 fb^{-1}**
- Use an unbinned likelihood fit with kinematic and particle ID information to obtain each fraction.
- Observed 94±28(stat)±11(sys) $B_s \to \pi^+\pi^-$ and 120±49(stat)±42(sys) $B^0 \to K^+K^-$ events.
- Using PDG 2010 obtained:

$$BR(B_s^0 \to \pi^+\pi^-) = [0.57 \pm 0.15(stat) \pm 0.10(sys)] \cdot 10^{-6}$$
$$BR(B^0 \to K^+K^-) = [0.23 \pm 0.10(stat) \pm 0.10(sys)] \cdot 10^{-6}$$
$$BR(B^0 \to K^+K^-) \in [0.05, 0.46] \cdot 10^{-6} \ @90\% \ C.L.$$



- $B_s \to \pi^+\pi^-$: 3.7σ signal
- $B^0 \to K^+K^-$: 2.0σ signal. Excludes a NULL BR @90% CL.

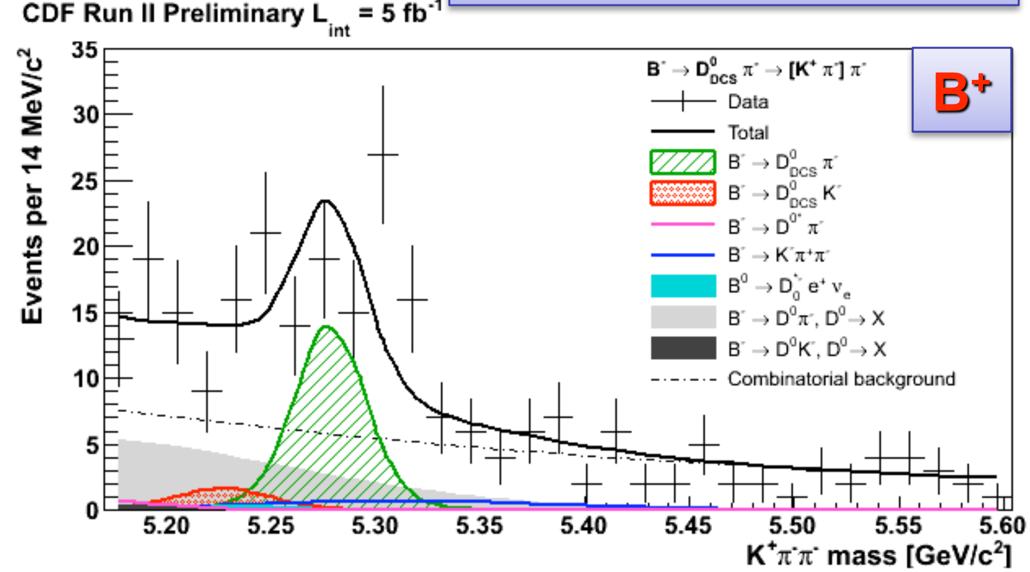
BR and A_{CP} in $B^{\pm} \rightarrow D^0 h^{\pm}$ decays

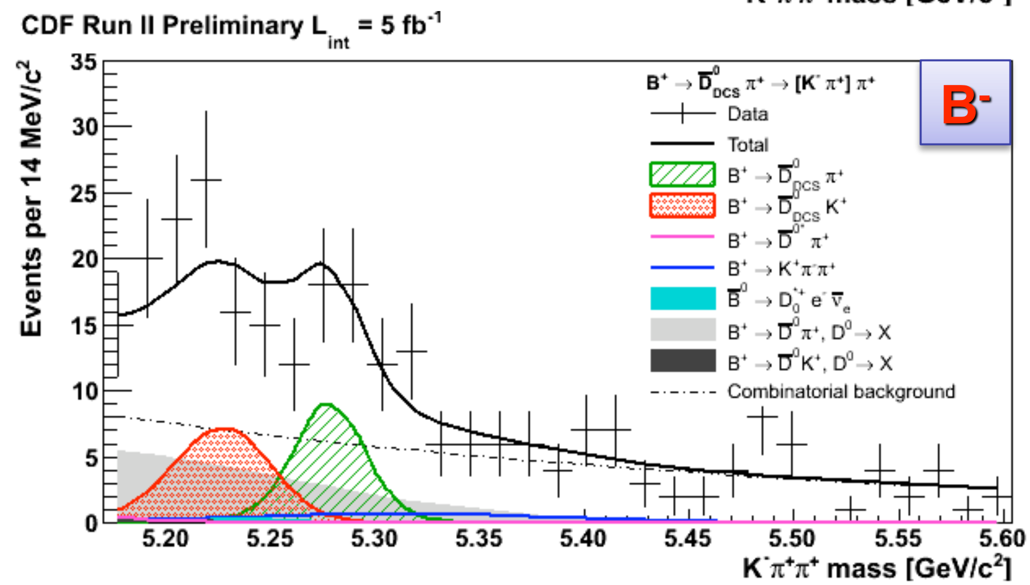
- The angle γ is the least well determined angle of CKM matrix
  - Not sure yet if the triangle closes properly
- The cleanest measurement method uses highly suppressed $B^- \rightarrow D^0 K^-$ decays:
  - Technique pioneered at e^+e^- colliders (Atwood-Dunietz-Soni method)
  - Deemed unfeasible in hadron collider experiments
- CDF measures of $B^- \rightarrow D^0$ ($K^+\pi^-$ or $K^-\pi^+$) K^-, where interference between D^0 or $\bar{D}^0$ is sensitive to γ through a combination of decay rates and some inputs from other experiments.

BR and A_{CP} in $B^{\pm} \to D^0 h^{\pm}$ decays

CDF Public Note 10309

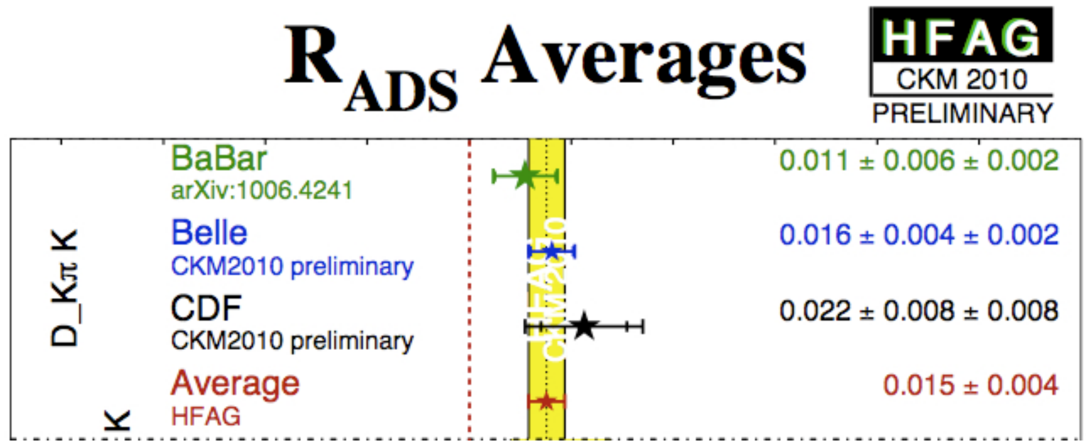
- Data analyzed: **5 fb^{-1}**
- First measurement in a hadron collider experiment
- Perform an unbinned maximum likelihood fit, that combines mass and particle ID (dE/dx) information, to separate signal (π, K) from backg.
- Reconstructed DCS modes:
  - $B \to D^0\pi$: **73 ± 16** events and
  - $B \to D^0K$: **34 ± 14** events





ADS Method: Results

First time in a hadron machine!

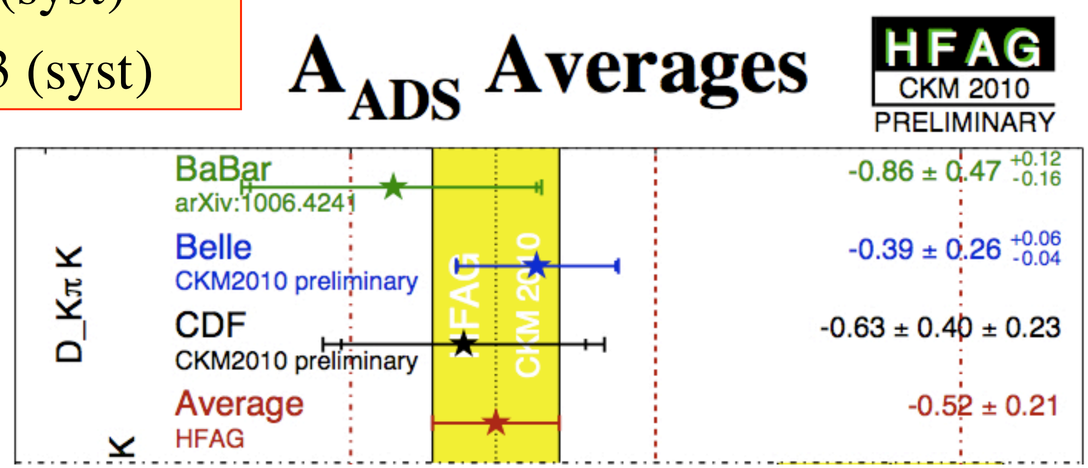


$$R_{ADS}(\pi) = (4.1 \pm 0.8\ (\text{stat}) \pm 0.4\ (\text{syst})) \cdot 10^{-3}$$

$$R_{ADS}(K) = (22.5 \pm 8.4\ (\text{stat}) \pm 7.9\ (\text{syst})) \cdot 10^{-3}$$

$$A_{ADS}(\pi) = 0.22 \pm 0.18\ (\text{stat}) \pm 0.06\ (\text{syst})$$

$$A_{ADS}(K) = -0.63 \pm 0.40\ (\text{stat}) \pm 0.23\ (\text{syst})$$



Time Integrated A_{CP} in $D^0 \to h^+ h^-$ Decays

- Negligible penguin contribution to the charm decays in SM
  - CPV larger than ~0.1% in charm would point to new physics
  - Unique probe of the up quark sector.
- Asymmetry:

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)}$$

- Use self-tagged $D^{*\pm} \to D^0 \pi_s^{\pm} \to [h^+ h^-] \pi_s^{\pm}$ decays to select clean $D^0 \to h^+ h^-$ samples.

CPV in charm

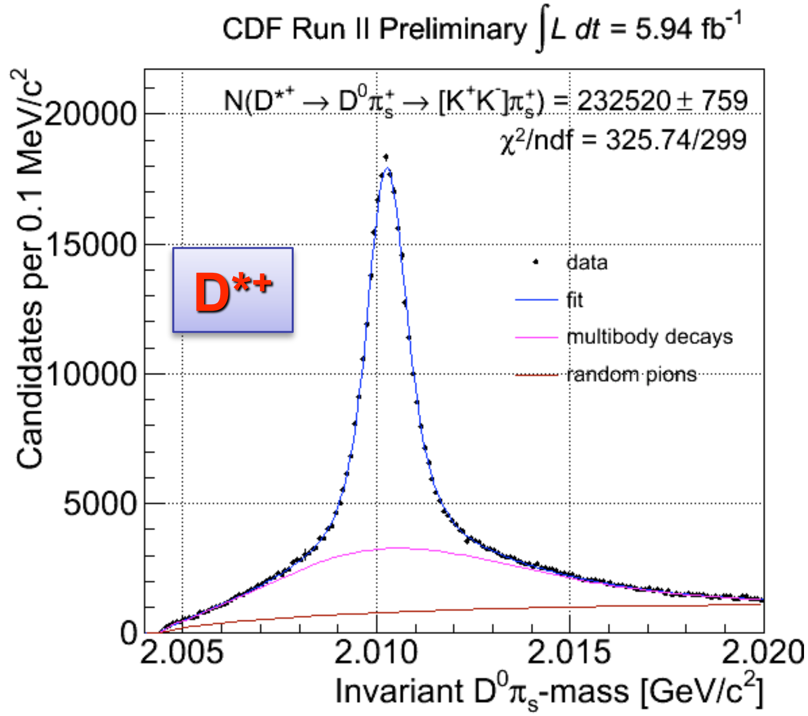
- Data sample: 5.94 fb^{-1}, with CDF two displaced track trigger.
- Measure asymmetry in $\pi^+\pi^-$ and K^+K^- samples and correct for instrumental asymmetry using $K\pi$ samples.
  - **$A_{CP}(D^0 \rightarrow \pi^+\pi^-)$=**

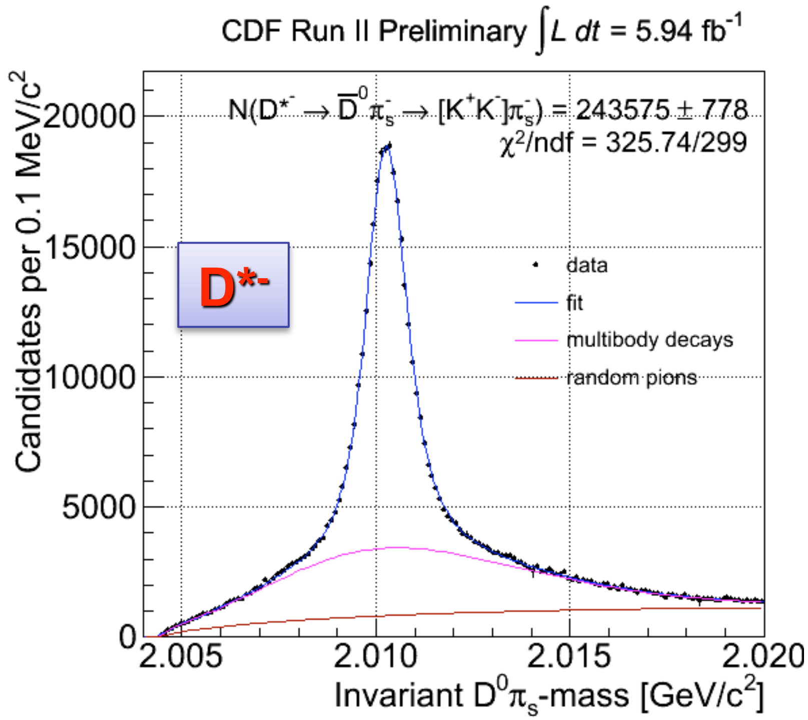
    +0.22±0.24 ±0.11 %

    Belle 2008: [+0.43±0.52(stat.)±0.12(syst.)]%
  - **$A_{CP}(D^0 \rightarrow K^+K^-)$=**

    -0.24±0.22 ±0.10 %

    Belle 2008: [-0.43±0.30(stat.)±0.11(syst.)]%





Beyond SM + HF Outlook

Exotics

- The LHC experiments would weigh-in on most of the traditional BSM exotics searches by summer 2011.
- Tevatron experiments would wrap-up / publish current work with as much statistics as possible.

Heavy Flavor

- Tevatron has pioneered Heavy Flavor physics in hadron collisions and has led the field through crucial measurements, B_s mixing, $\sin 2\beta_s$ and A^b_{sl} to name a few.
- HF programs continue to have a major share in the Tevatron physics output
  - Many results over the last year.

Heavy Flavor Outlook (*continued..*)

- By the end of 2011 CDF/DØ plan on publishing high profile measurements, e.g. $B \to \mu\mu$., with maximum data samples.
- Between summer 2011 to winter 2012 several world's best measurements would be overtaken by LHCb.
- Beyond that the focus moves to measurements unique to $p\bar{p}$ collisions at 2TeV, e.g.
  - Production and polarization (quarkonia, exotic hadrons, baryons, …)
  - Very high precision CPV (where CP-symmetry of initial state matters).

Summary

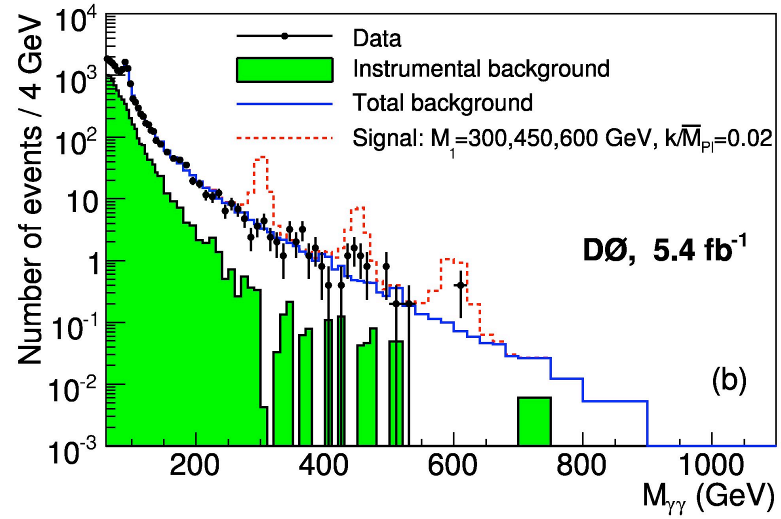
- Very rich BSM exotics and heavy flavor program at the Tevatron. With about 10 fb^{-1} data to be accumulated per experiment by the end of Run II, more precision results are yet to come.
- Beyond 2011 Tevatron experiments would focus on measurements complementary to those from the LHC experiments, especially those which thrive on the $p\bar{p}$ intial state.
- For more results visit our web pages:
  - CDF: http://www-cdf.fnal.gov/physics/physics.html
  - DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results.htm

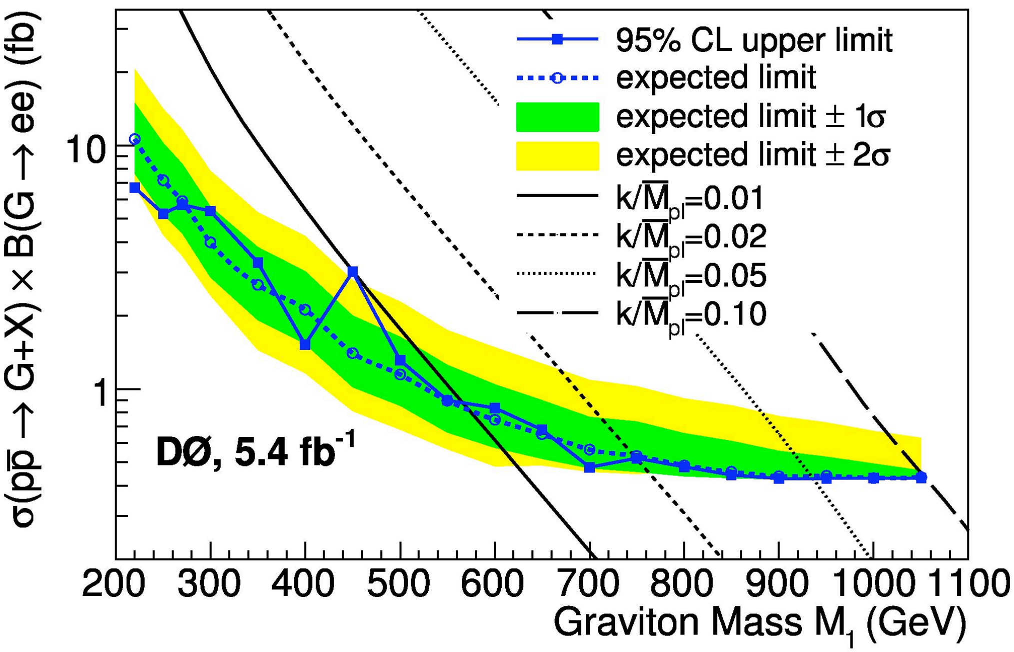
BACKUP SLIDES

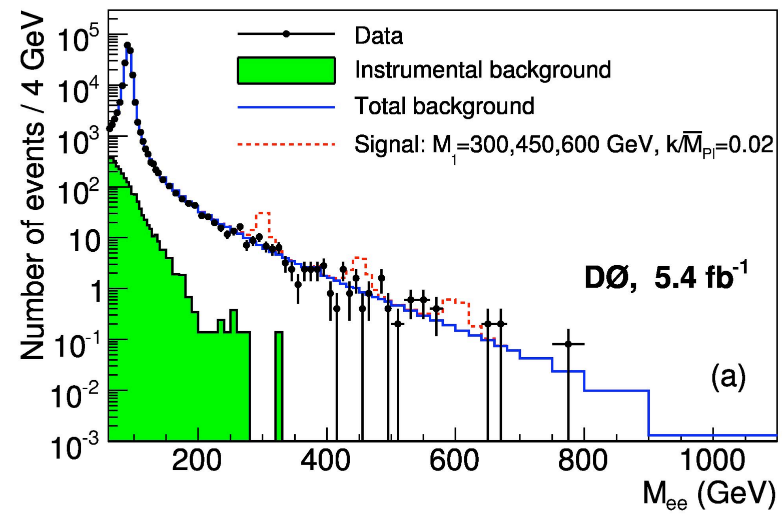
DØ Search for RS Gravitons

Phys. Rev. Lett 104, 241802 (2010)

- Exclude RS graviton below 1050 GeV for $k/\overline{M}_{PL}=0.1$.

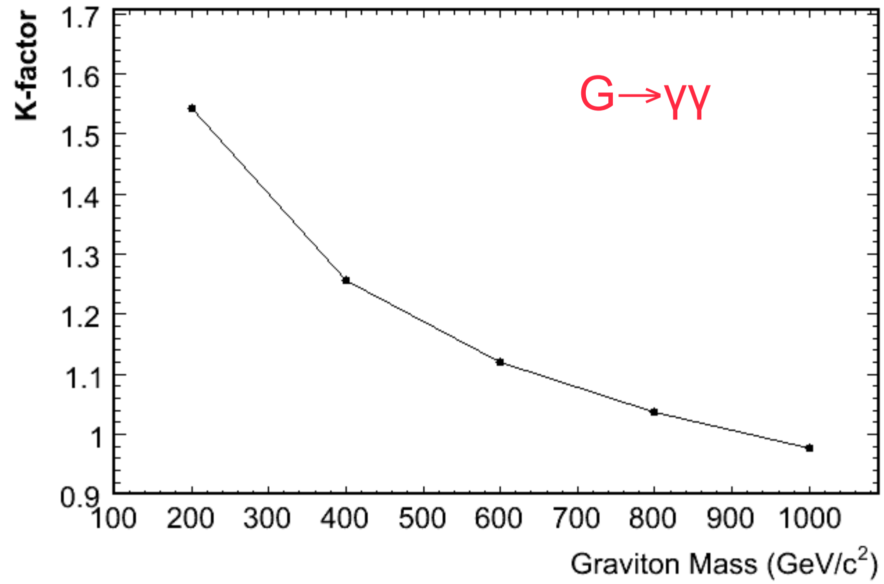


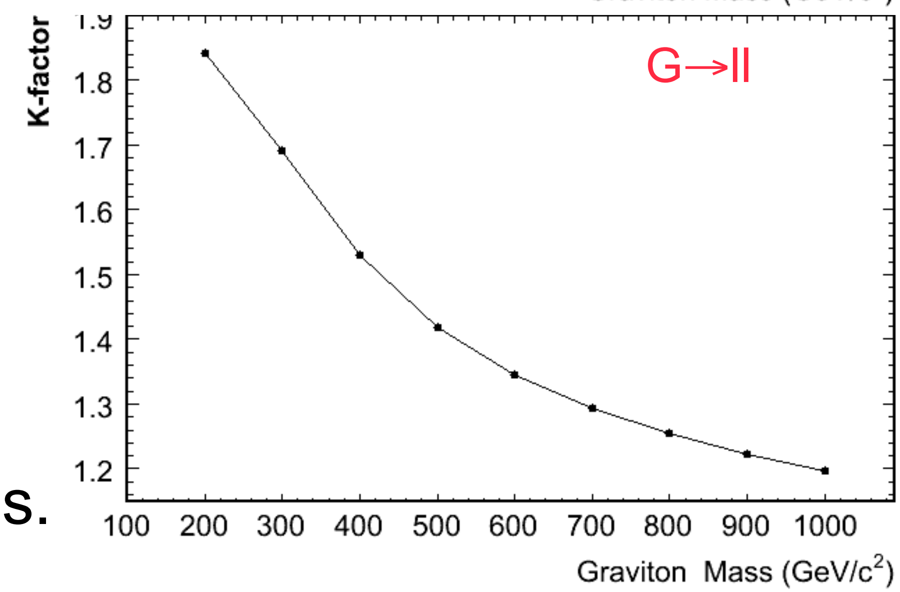




Graviton mass-dependent k-factors

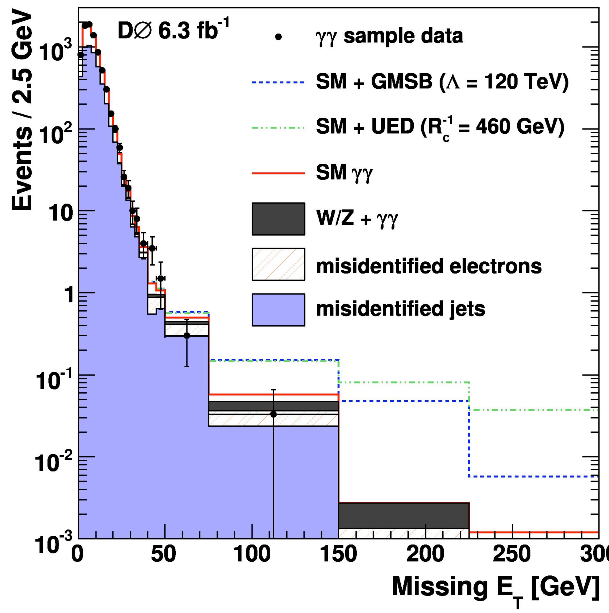
- K-factors are used to scale the LO Pythia cross-sections to include NLO effects.
- For Tevatron energy the k-factors are graviton mass dependent.
- CDF uses a calculation by P. Mathews, V. Ravindran, and K. Sridhar made specifically for CDF.
- These variable k-factors are more realistic and give smaller value of limit than the fixed ones.



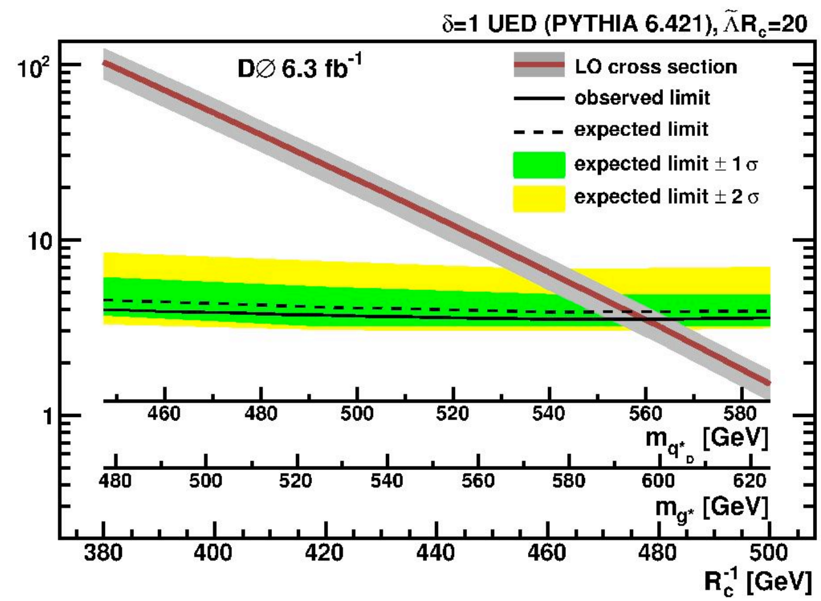


Search for Universal ED

Phys. Rev. Lett. 105 221802 (2010)



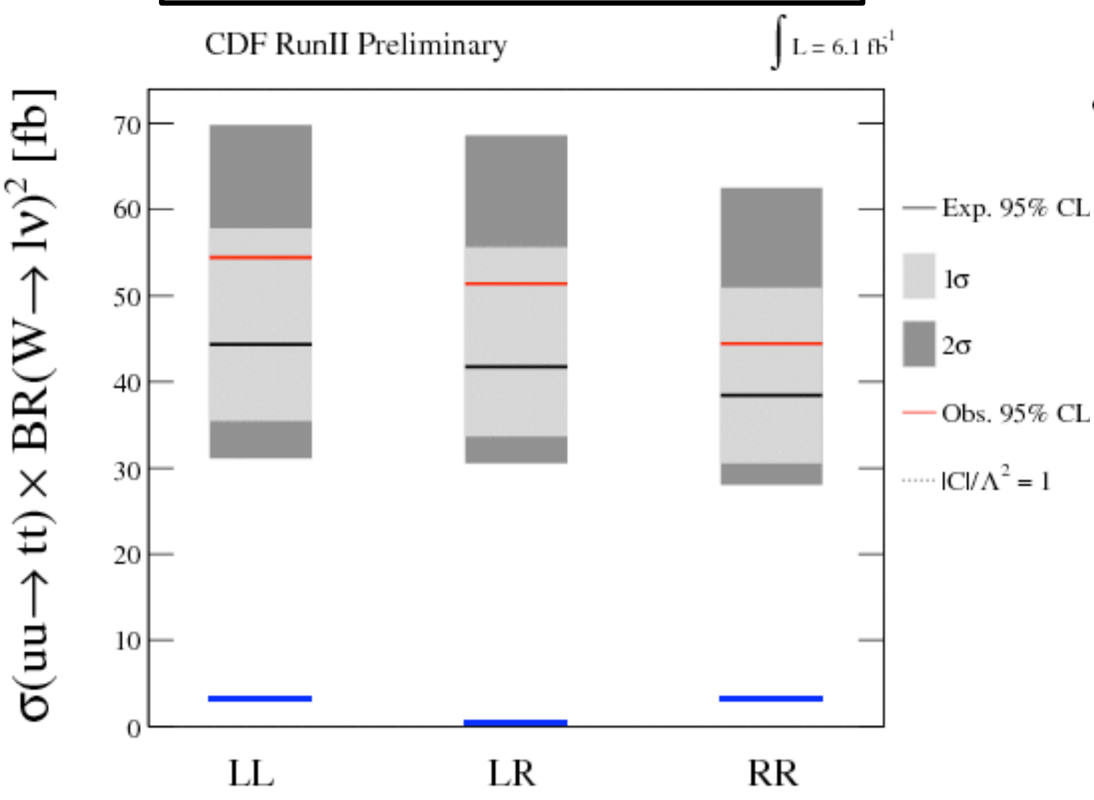
- Assume a single compactified ED.
- Search for a pair of Kaluza-Klein photons which decay to a photon and a graviton each.
  - Look for events with a two photons + ME_T signature.
- Exclude compactification radius below 477 GeV. Also set limit on Gauge-Mediated SUSY Breaking (GMSB) models.



Like-sign Di-lepton Search

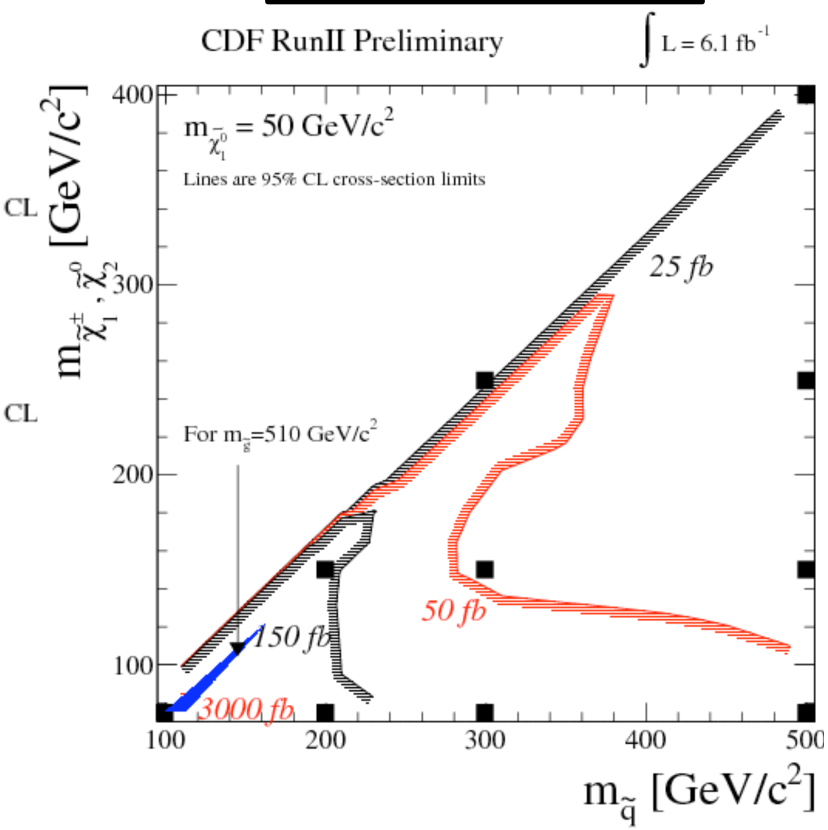
- Similar analyses also set…

Limits on like-sign top quark pair production



Chirality Mode

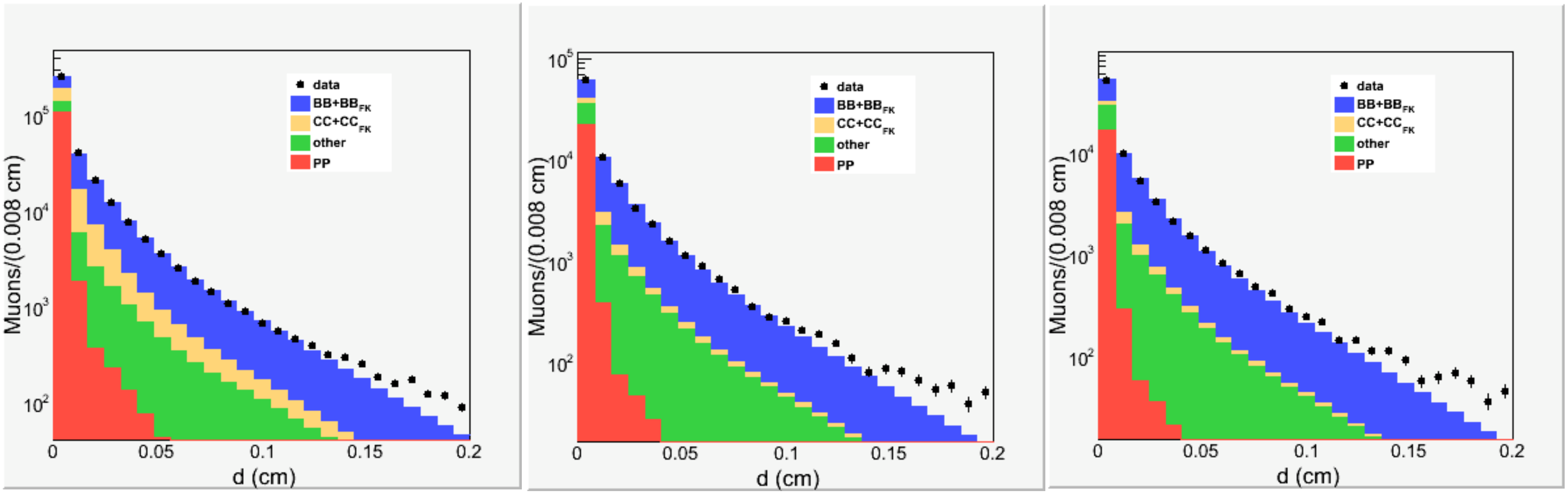
Limits on squark pair production



A simpler way to access β_s

- In early searches for CP violation $B_s \to J/\psi\varphi$ decays a 1.5σ deviation from standard model was observed.
- It is suggested that the decay $B_s \to J/\psi f_0(980)$, $f_0(980) \to \pi^+\pi^-$ (pure CP odd state) can be used to measure CP violating phase $\beta_s^{J/\psi\varphi}$ without need for angular analysis.
- Although not statistically competitive with $B_s \to J/\psi\varphi$ it can provide an important cross-check of the $\beta_s^{J/\psi\varphi}$ measurement.
- As a first step:
  - **CDF** searched for this suppressed decay mode using a 3.8 fb^{-1} di-muon trigger data sample.
  - **DØ** searched for the same using an 8.0 fb^{-1} single- or di-muon trigger data sample.

Chi-bar: IP fit projections (with standard silicon requirements)



OS **LS ++** **LS --**

- When muons are selected with standard silicon requirement, the tail region of data is not fitted well.
- This is understood as the source of discrepancy between Run I and LEP results.

Evidence for $B_s \rightarrow \pi^+\pi^-$ decays

- Effective models used in predictions of hadronic B meson decay amplitudes provide accurate results for decays dominated by tree-level amplitudes, but suffer from significant uncertainties when penguin amplitudes intervene.
- One of the largest sources of uncertainty is the size of penguin-annihilation topologies, e.g $B^0_s \rightarrow \pi^+\pi^-$.
  - ➲ Experimental input is crucial to constrain their magnitude.
- The as yet unobserved $B^0 \rightarrow K^+K^-$ mode is similar and has a larger predicted BR.
  - ➲ A measurement of both modes would provide an even more accurate determination of the strength of penguin-annihilation.
- CDF exploits its large displaced track trigger sample and particle ID capabilities to extract the BRs from inclusive $B \rightarrow h^+h^-$ decays.

BR and A_{CP} in DCS $B^{\pm} \to D^0 h^{\pm}$ decays

- BR and A_{CP} in $B^- \to D^0 K^-$ allow for a theoretically-clean way of measuring the CKM angle γ (known to 10-20° level)

- Atwood-Dunietz-Soni method: Interference between
  - $B^- \to D^0 K^-$ (color allowed); $D^0_{DCS} \to K^+\pi^-$
  - $B^- \to \bar{D}^0 K^-$ (color suppressed); $\bar{D}^0_{CF} \to K^+\pi^-$

  can lead to large A_{CP}.

- Define DCS fractions and asymmetries:

$$R_{ADS}(K) = (BR(B^- \to [K^+ \pi^-]_D K^-) + BR(B^+ \to [K^- \pi^+]_D K^+)) / (BR(B^- \to [K^- \pi^+]_D K^-) + BR(B^+ \to [K^+ \pi^-]_D K^+))$$
$$= r_D^2 + r_B^2 + r_D r_B \cos\gamma \cos(\delta_B + \delta_D)$$
$$A_{ADS}(K) = (BR(B^- \to [K^+ \pi^-]_D K^-) - BR(B^+ \to [K^- \pi^+]_D K^+)) / (BR(B^- \to [K^+ \pi^-]_D K^-) + BR(B^+ \to [K^- \pi^+]_D K^+))$$
$$= 2\, r_B r_D \sin\gamma \sin(\delta_B + \delta_D) / R_{ADS}(K)$$

$r_B = |A(b \to u)/A(b \to c)|$ and $\delta_B = \arg[A(b \to u)/A(b \to c)]$

r_D and δ_D: For D decays

[Similar for $R_{ADS}(\pi)$ and $A_{ADS}(\pi)$]

A_{CP} in $D^0 \rightarrow h^+ h^-$: Extraction method

- Asymmetry of signal sample:
  - $A(h^+h^-,\pi_s) = A_{CP}(h^+h^-) + \delta(\pi_s)$

$\delta(X)$: Detector induced asymmetry due to the particle/state X

- Asymmetry of D* tag in CKM favored mode:
  - $A(K^-\pi^+,\pi_s) = A_{CP}(K^-\pi^+) + \delta(K^-\pi^+) + \delta(\pi_s)$
- Using asymmetry from $D^0 \rightarrow K^-\pi^+$ (without a D* tag):
  - $A(K^-\pi^+) = A_{CP}(K^-\pi^+) + \delta(K^-\pi^+)$
- Derive:
  - $A_{CP}(h^+h^-) = A(h^+h^-,\pi^*) - A(K^-\pi^+,\pi^*) + A(K^-\pi^+)$
- Measure the three asymmetries