New Phenomena & B Physics at D0

{ Probing the SM from all angles

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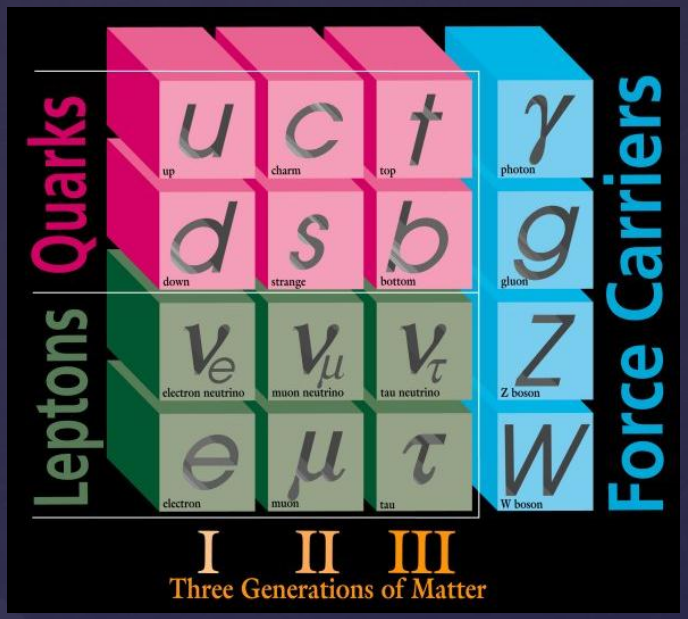
Introduction

Standard Model very successful, predicts huge range of phenomena;

However, many problems once you leave the low-energy regime:

- Hierarchy/naturalness problem;
- Dark matter;
- No unification of forces;
- Not enough CPV for baryogenesis;
- Why 3 generations?
- No Higgs boson observed yet
- …



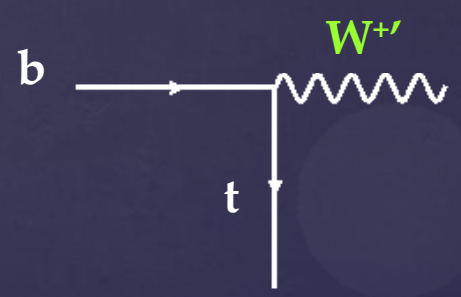
We expect 'new physics' to appear somewhere, but where?!

Many extensions to SM, which make testable predictions, generally with new particle content.

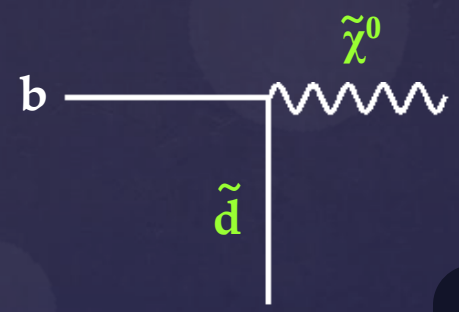
How to Find New Physics…

New Phenomena analyses: direct searches for signatures of new particles:

New Gauge Groups:

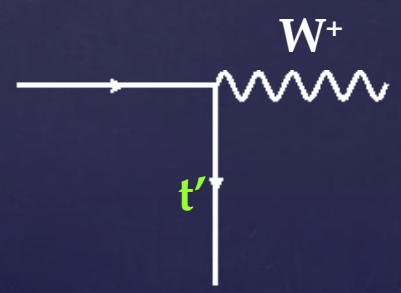


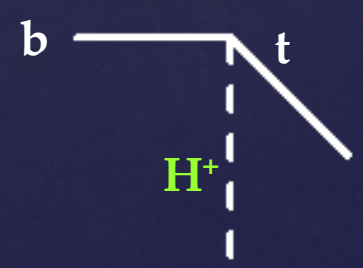
Supersymmetry:



New particles on mass shell: limited by √s

New Quarks:



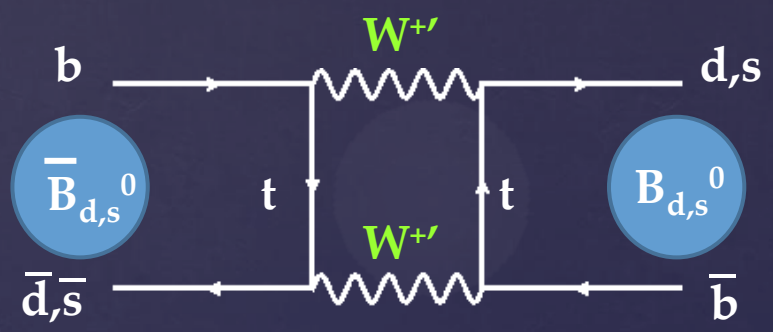


How to Find New Physics…

B Physics analyses: Measure parameters sensitive to indirect NP contributions:

New particles in loops: access to all masses

New Gauge Groups:



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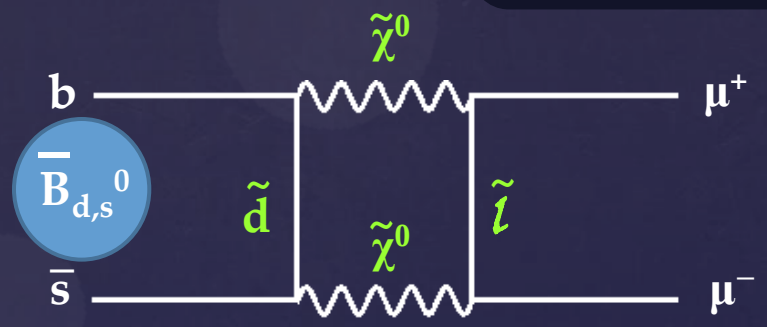
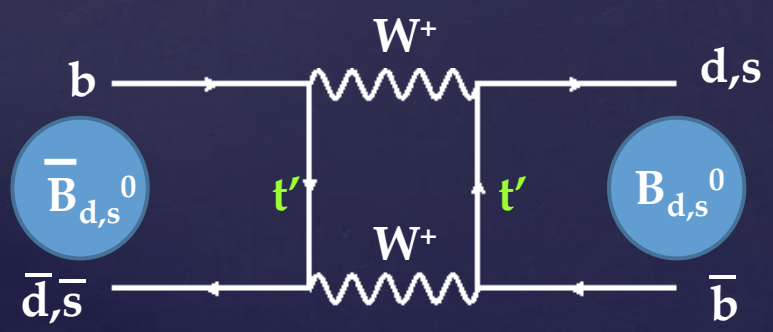
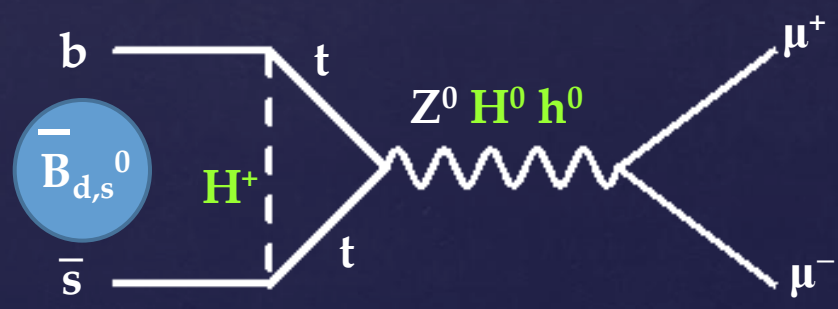


New Quarks:





TOPCITE 100+

Run I:

Inclusive μ and b-quark production cross sections (1995)

Squark and gluino search (1995)

J/ψ production (1996)

Light top squarks (1996)

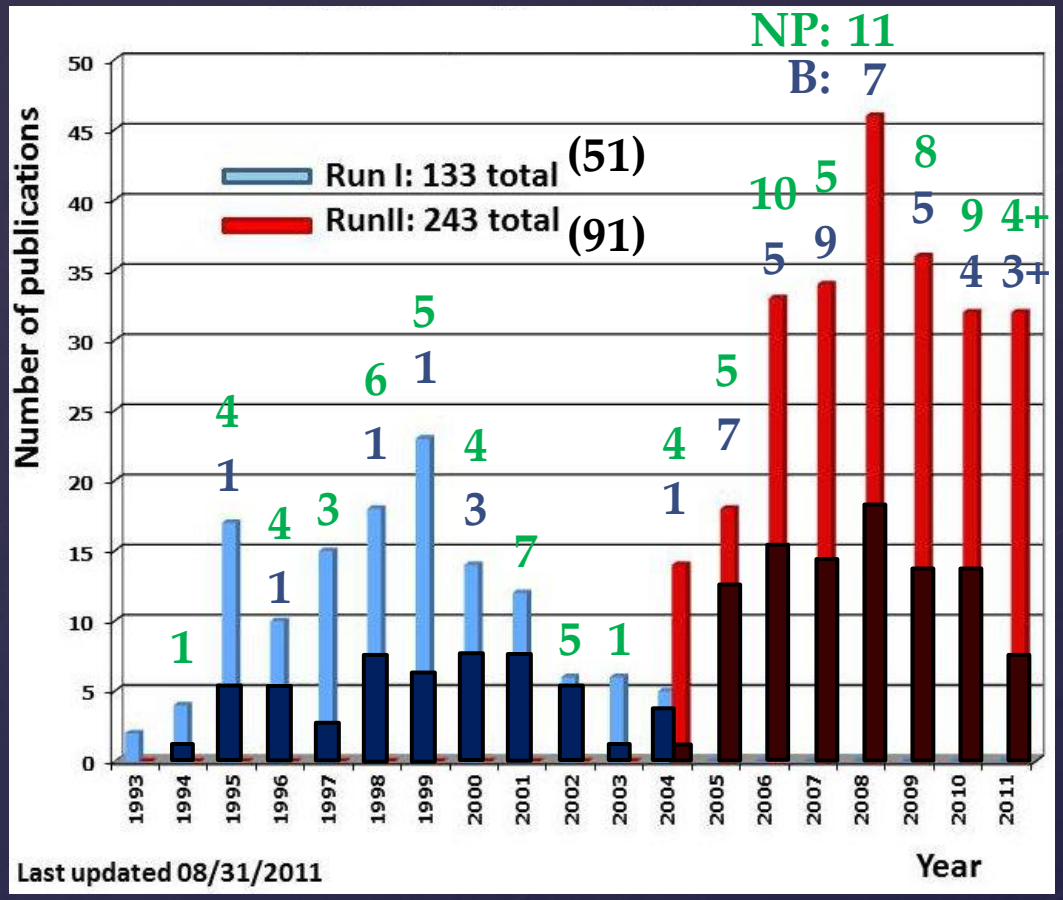
bb production cross section and angular correlations (2000)

Run II:

B_s^0 mixing parameters in channel $B_s^0 \rightarrow J/\psi\phi$ (2008)

Evidence for anomalous like-sign dimuon charge asymmetry (2010)

D0 Paper Submissions

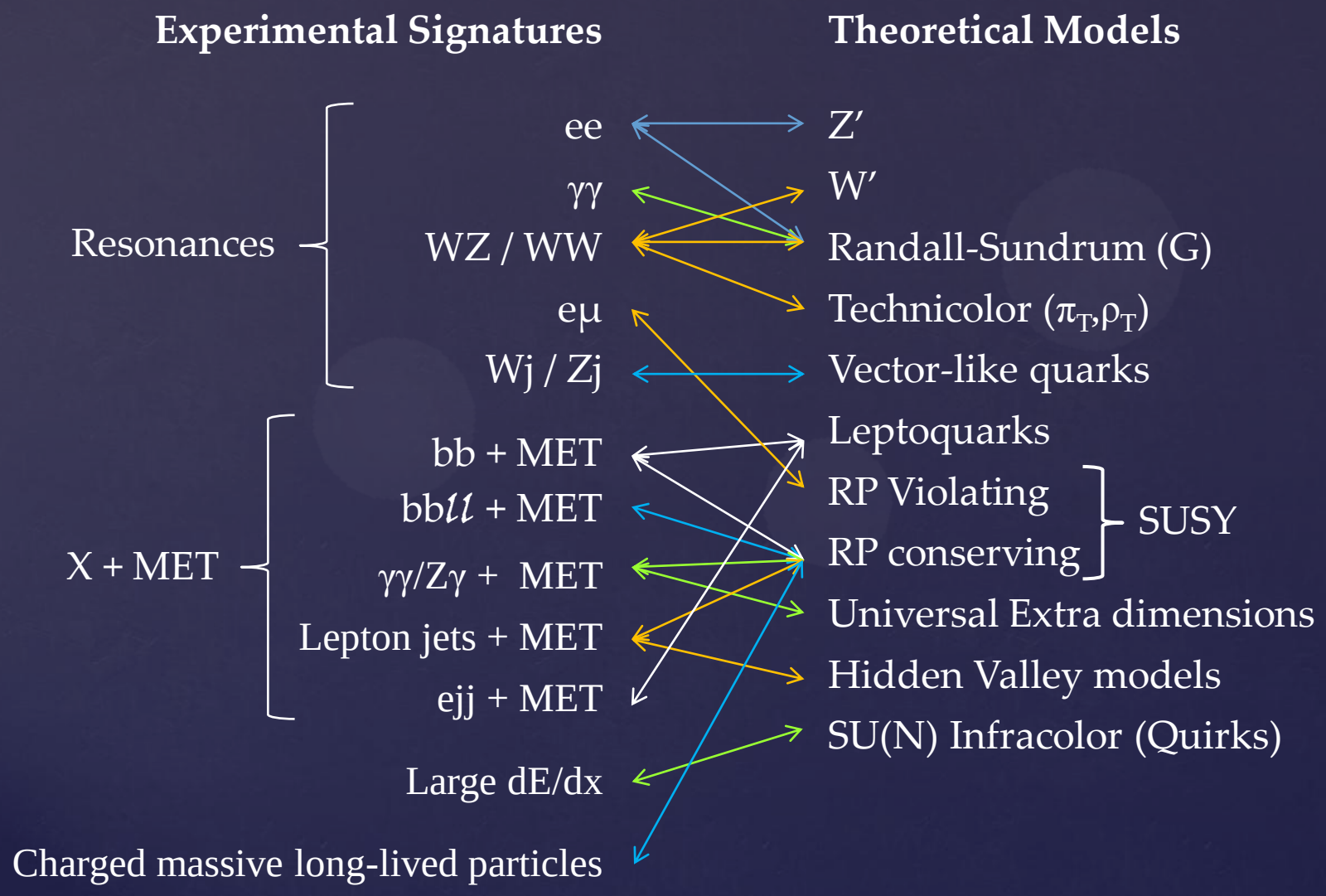


TOPCITE 250+

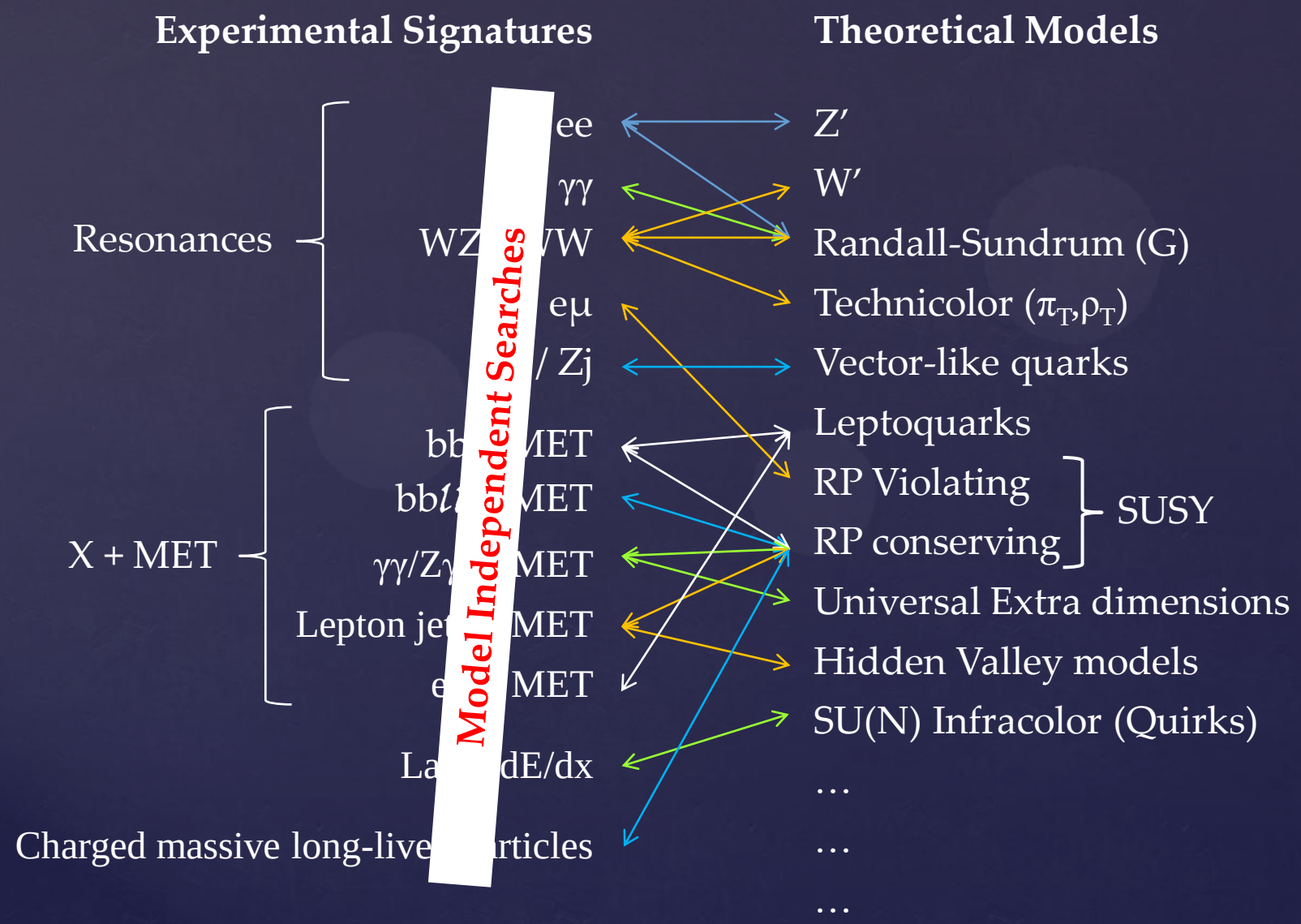
Observation and properties of the X(3872) (2004)

Direct limits on the B_s^0 oscillation frequency (2006)

Part 1: Direct Searches



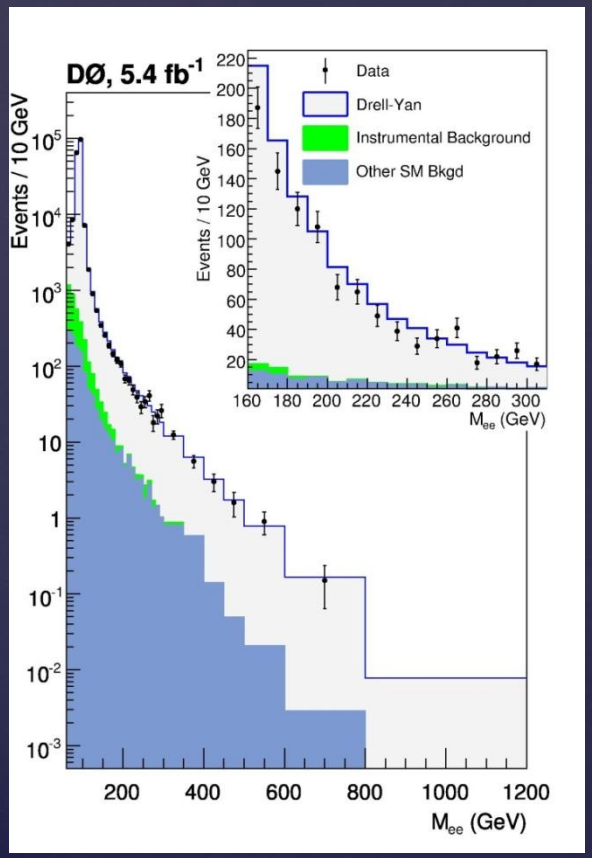
Part 1: Direct Searches



Heavy Resonances

Experimental Signature

Narrow M(ee) resonance

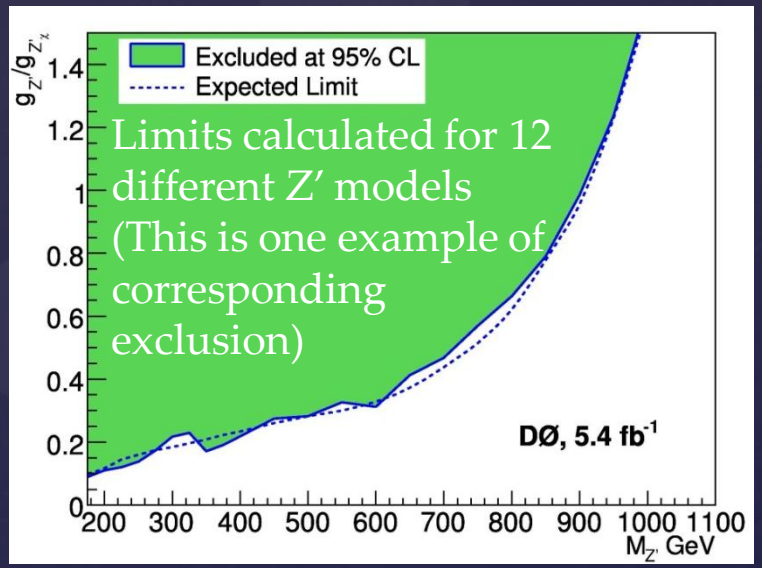


Theoretical Model

Extensions to SM with additional U(1) group, i.e. **Z′ boson**

Coupling strength $g_{Z'}$

Mass $M_{Z'}$



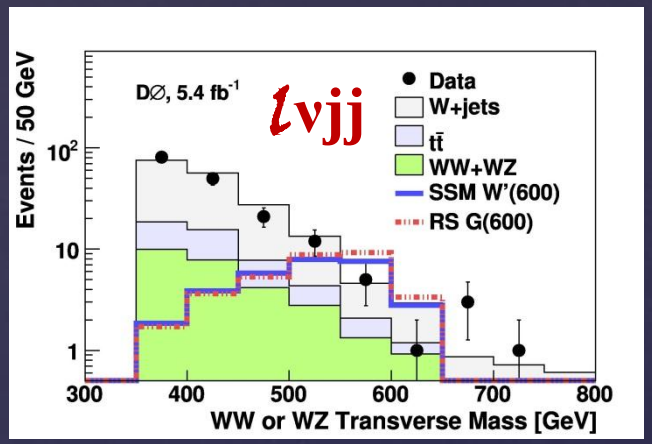
Phys. Lett. B 695, 88 (2011)

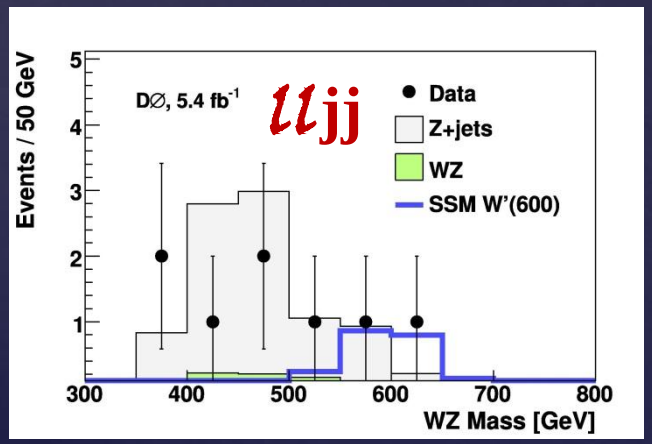
Also use M(ee), M(γγ) to place limits on KK graviton mass/coupling in Randall-Sundrum models. PRL 104, 241802 (2010)

Heavy Resonances

Experimental Signature

Resonant WW / WZ production

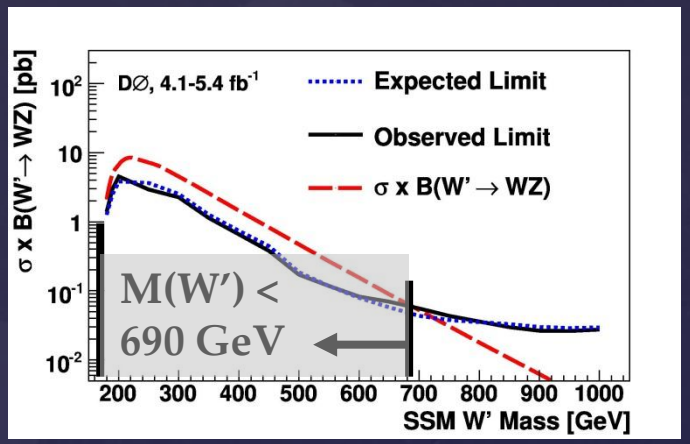


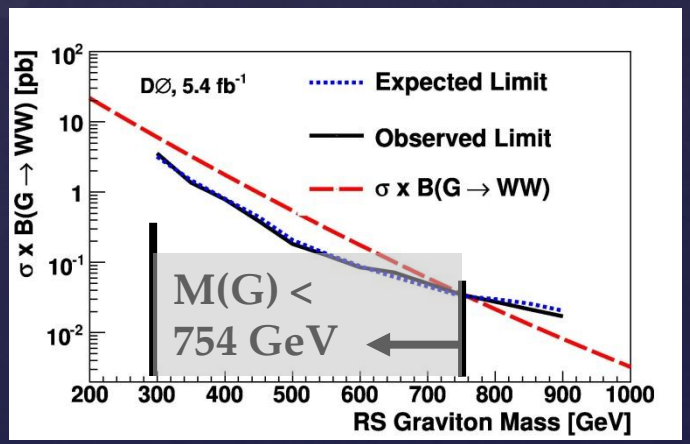


Theoretical Models

New charged boson W' ($g_{W'}$, $M_{W'}$) (sequential SM, Extra dimensions, little Higgs, technicolor…)

KK Graviton G





PRL 107, 011801 (2011)

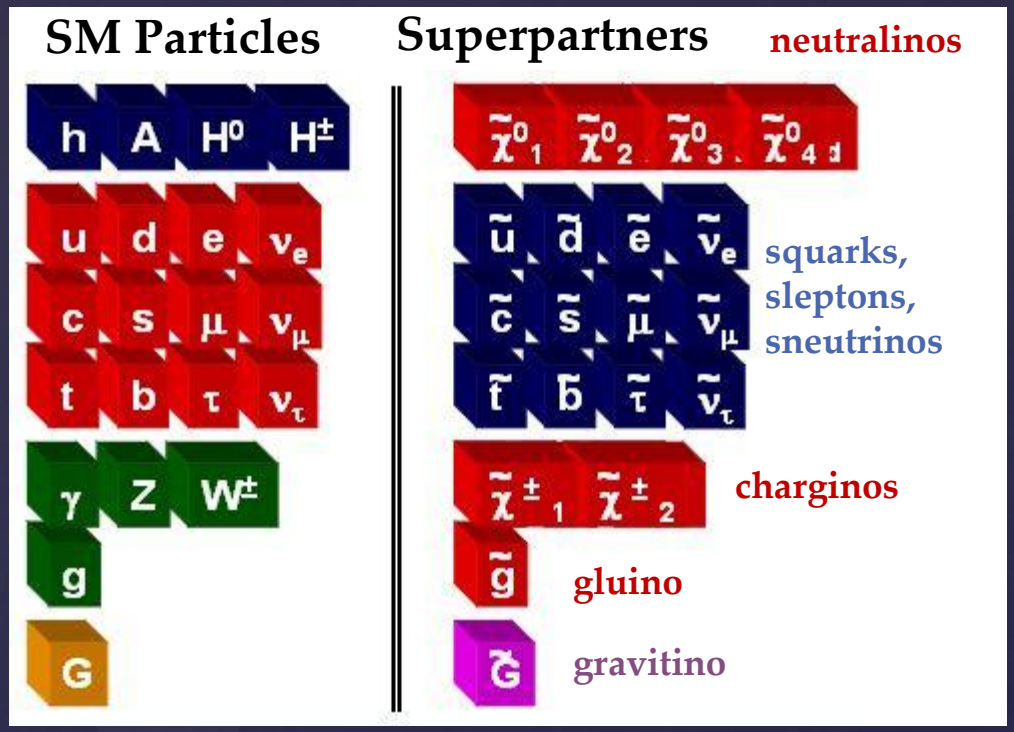
Supersymmetry

Long-time favorite of theorists – helps to address many issues with SM (naturalness, dark matter, CPV, unification…)

However, even for 'minimal' SUSY, n.d.f > 100 – huge parameter space to search.

⇒ Have to make assumptions in many cases, e.g. mass hierarchy determines kinematically-allowed decays.

Lots of choices for breaking model, e.g. mSUGRA, GMSB;



'R-parity' conservation enforced by-hand to maintain conservation of L, B;

i.e. sparticles follow SM-like conservation law, and lightest SUSY particle (LSP) cannot decay: MET!

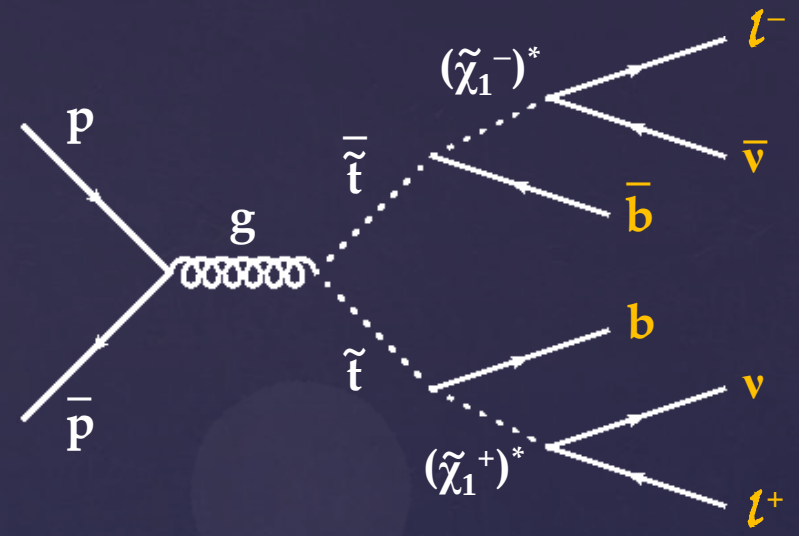
Squark Production

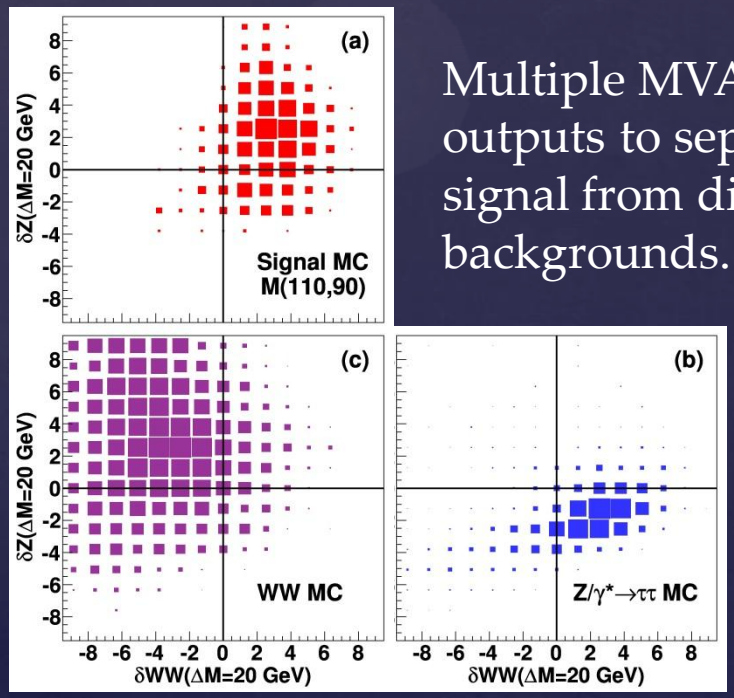
stop pair search

Signature: 2 b-jets, $e^{\pm}\,\mu^{\mp}$ + MET

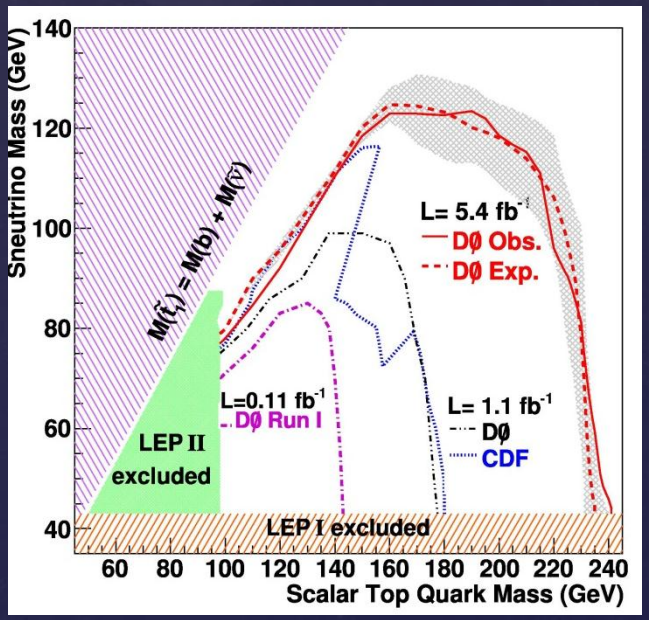
Model: $\tilde{t}\bar{\tilde{t}} \rightarrow b\bar{b}e\mu\tilde{\nu}\bar{\tilde{\nu}}$

Sneutrino $\tilde{\nu}$ is LSP, or decays invisibly





Multiple MVA outputs to separate signal from different backgrounds.



Phys. Lett. B 696, 321 (2011)

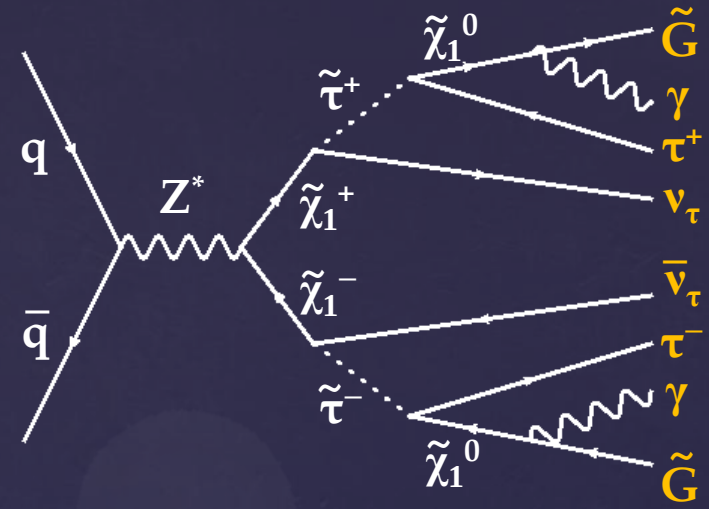
Chargino / Neutralino Production

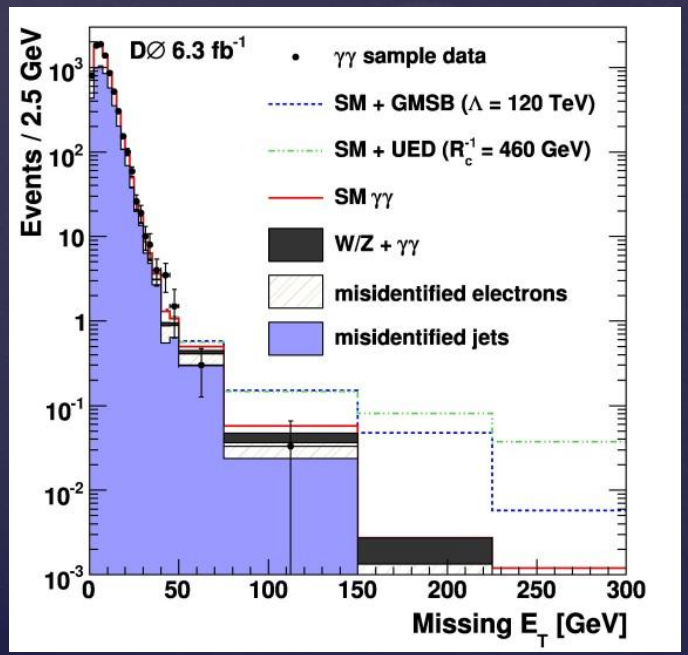
$\gamma\gamma$ + MET + X

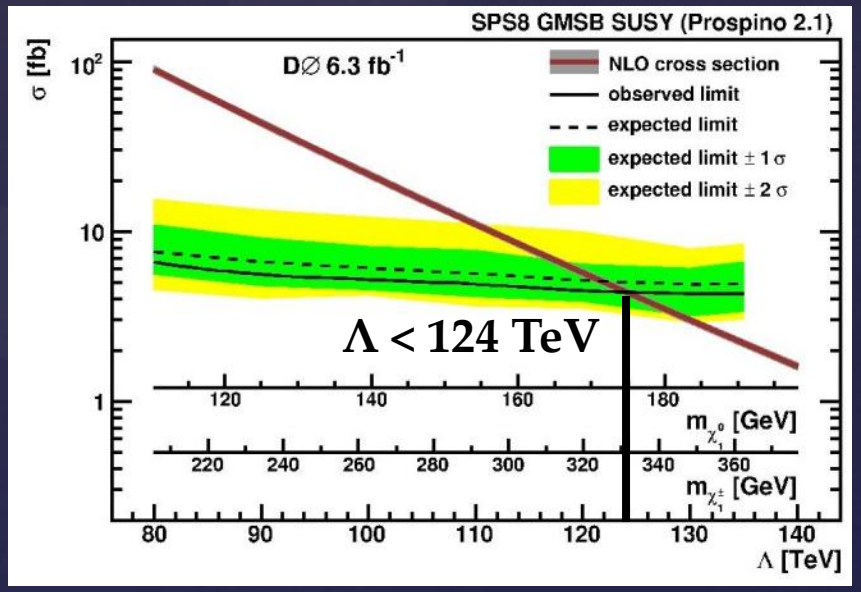
Probes SUSY breaking scale Λ in GMSB model

NLSP decays to gravitino $\tilde{G}$

$p\bar{p} \rightarrow$ gauginos $\rightarrow \gamma\gamma\tilde{G}\tilde{G}$ + X



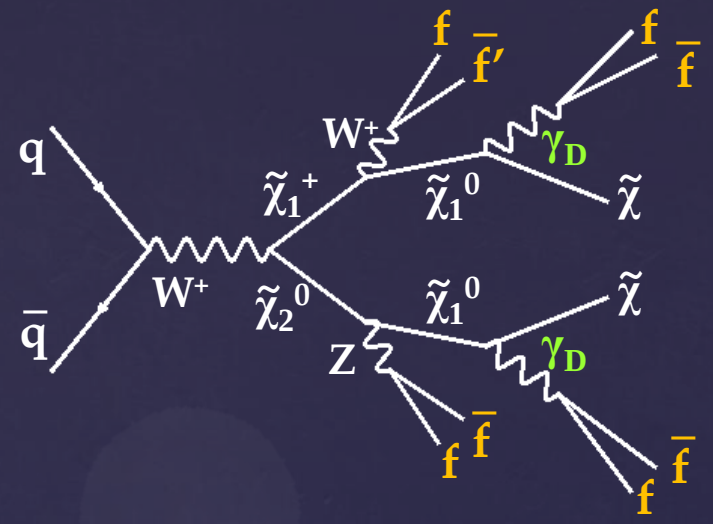




Also sets limits on UED compactification radius, R_c^{-1} < 477 GeV @ 95% C.L.

PRL 105, 221802 (2010)

Chargino / Neutralino Production



Leptonic jets + MET

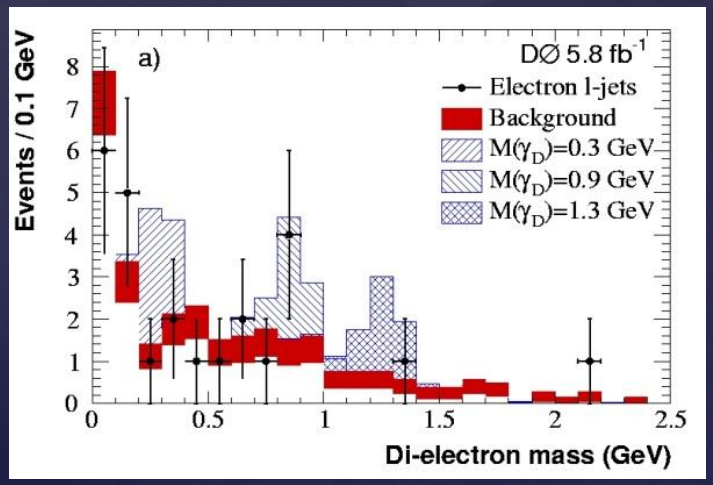
In some hidden-valley models, SUSY LSP can decay to dark photon:

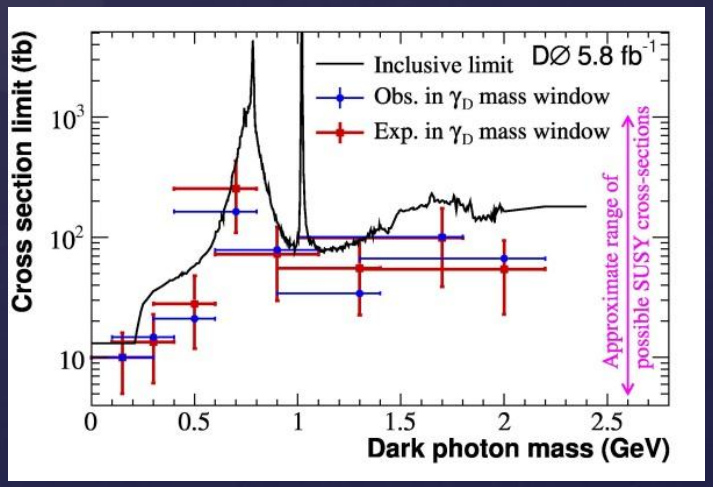
$pp \rightarrow \text{gauginos} \rightarrow \gamma_D\, \gamma_D \rightarrow \ell\bar{\ell}\, \ell\bar{\ell}$

Search for two $\ell^+\ell^-$ pairs ($e^\pm$ or $\mu^\pm$) with small opening angle, plus MET from hidden sector LSP.

Set limits on SUSY gaugino pair production versus dark photon mass.
'Inclusive' limit set from:

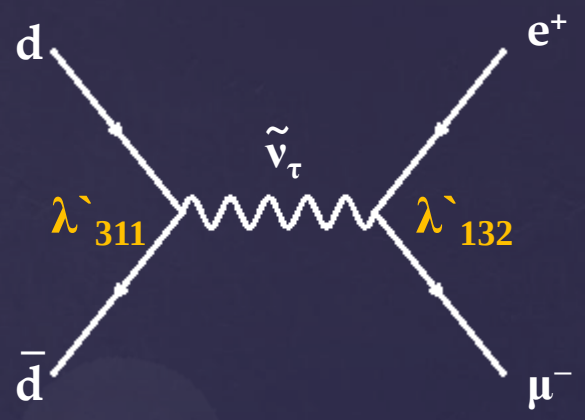
R = σ(ee→hadrons) / σ(ee→μμ)





PRL 105, 211802 (2010)

R-Parity Violating SUSY

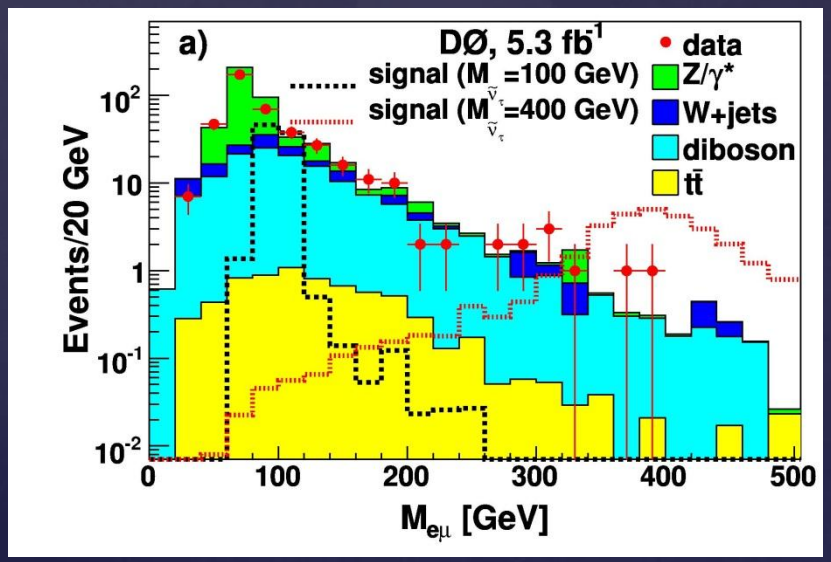


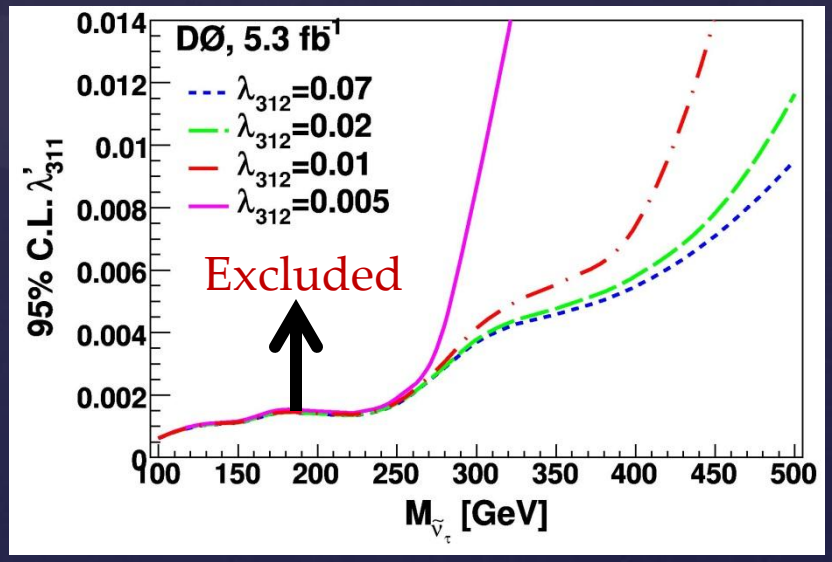
Tau sneutrino search

In RPV models, single production of sparticles possible – effects seen at lower energy.

Assume 3rd generation sneutrino is LSP, and only couplings λ_{311} and λ_{ijk} are nonzero ($i \neq j \neq k \neq i$)

Signature: high mass eμ resonance





PRL 105, 191802 (2010)

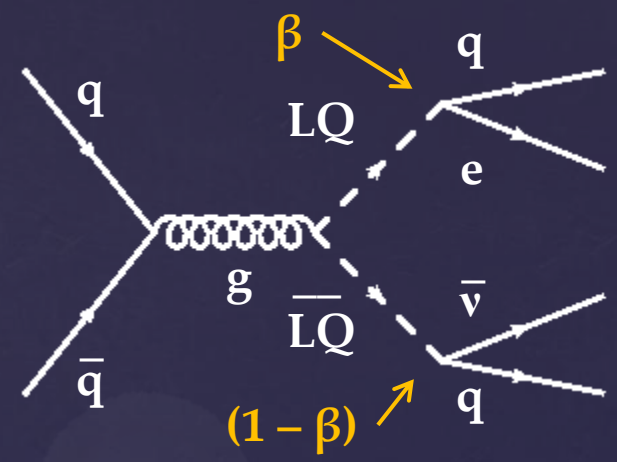
Leptoquarks

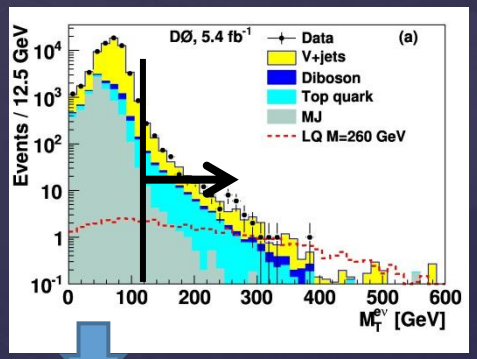
Many extensions of SM have **lepton↔quark symmetry**;

Mediating bosons, 'leptoquarks' (LQ) with both quark and lepton number.

Search for 1st generation scalar LQ pairs:

$(LQ)(\overline{LQ}) \rightarrow (e^{\pm}q)\,(\nu_e q')$

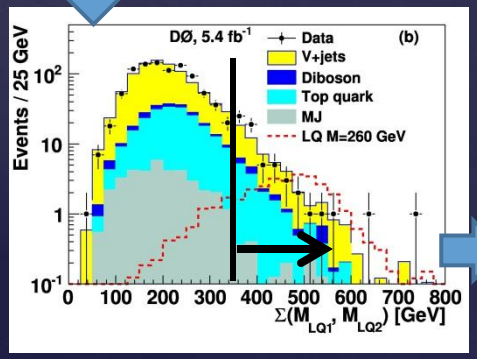


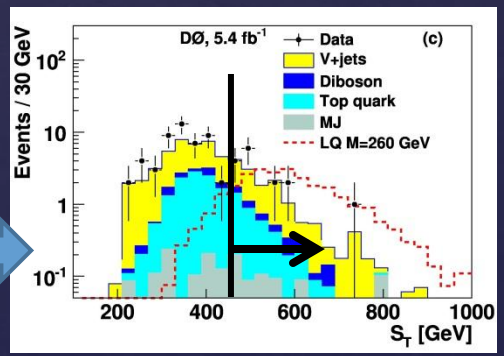


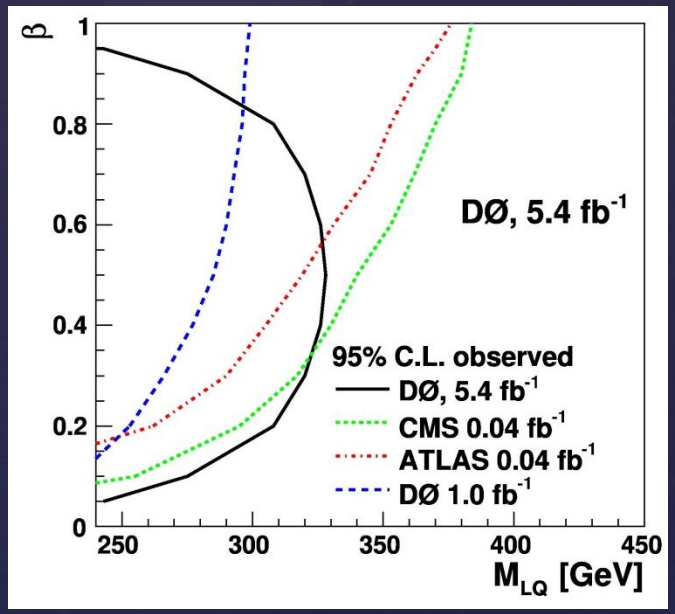
$M_T > 110$ GeV

$\sum M_{LQ} > 350$ GeV

$S_T > 450$ GeV







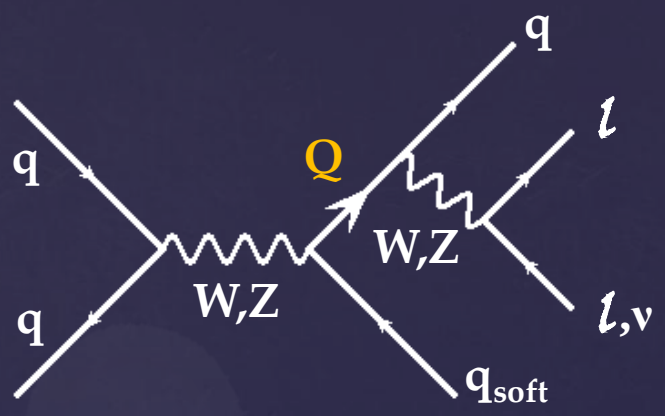
Better than published LHC results for $\beta < 0.3$

arXiv:1107.1849 [hep-ex]
Accepted by PRD-RC

Vector-like Quarks, Q

Predicted by certain little Higgs, UED, and warped ED models;

'Vector-like' = left- and right- handed components transform in same way in SU(3)×SU(2)×U(1);



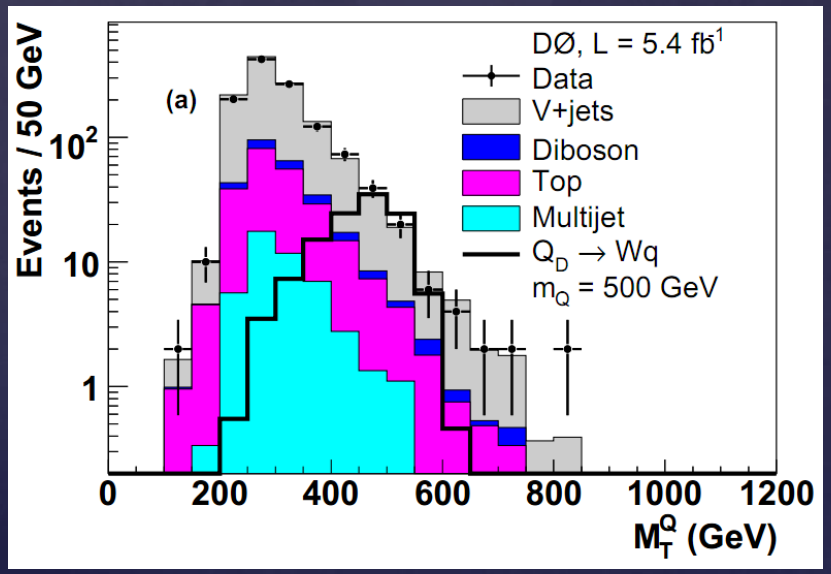
Production:

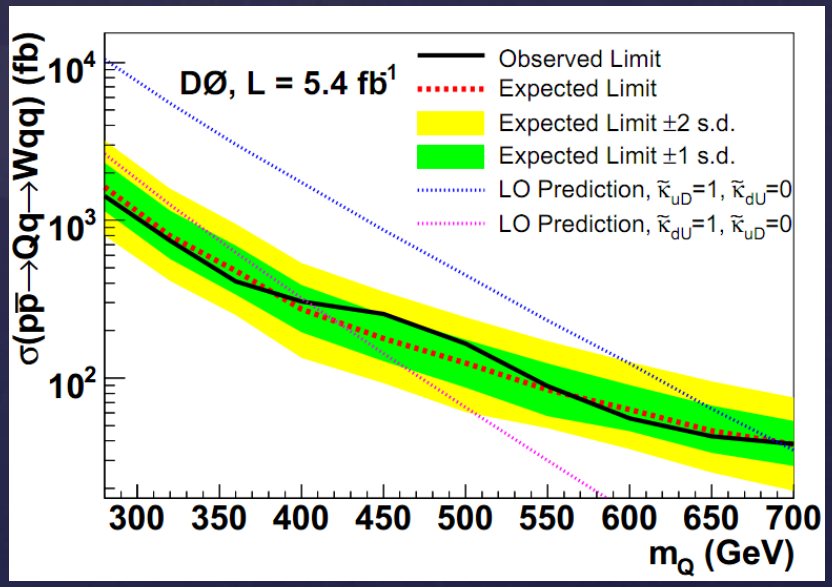
Pair: strong interaction, limited mass reach;

Single: EW interaction, mixing with SM quarks;

Final state: $q_{soft} + \ell^+\ell^- q$

or: $q_{soft} + \ell^\pm \nu q$





$M(Q_d \rightarrow Wq) < 696$ GeV

$M(Q_u \rightarrow Zq) < 449$ GeV

PRL 106, 081801 (2011)

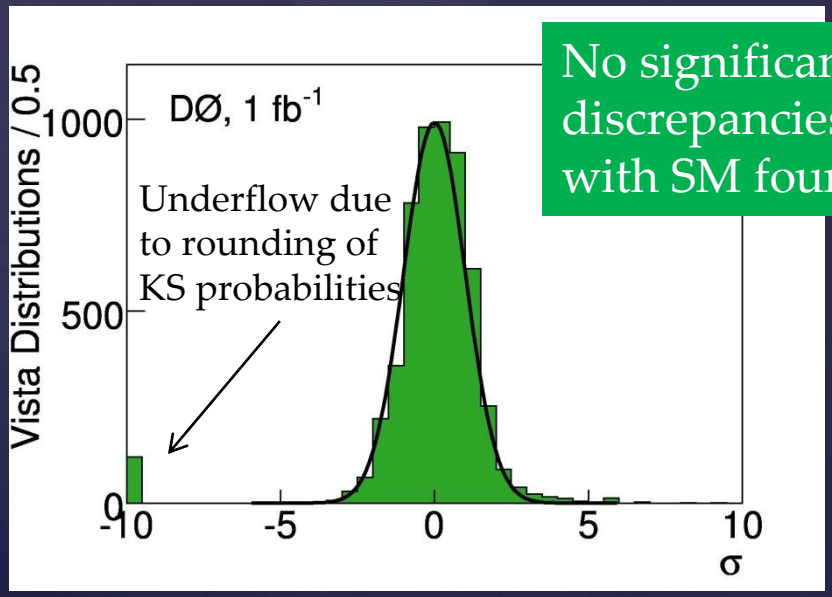
Model-Independent Search

Look for disagreement between data and SM (simulation) in 117 leptonic final states;

Sacrifice sensitivity to specific models (cannot optimise cuts, no systematics);

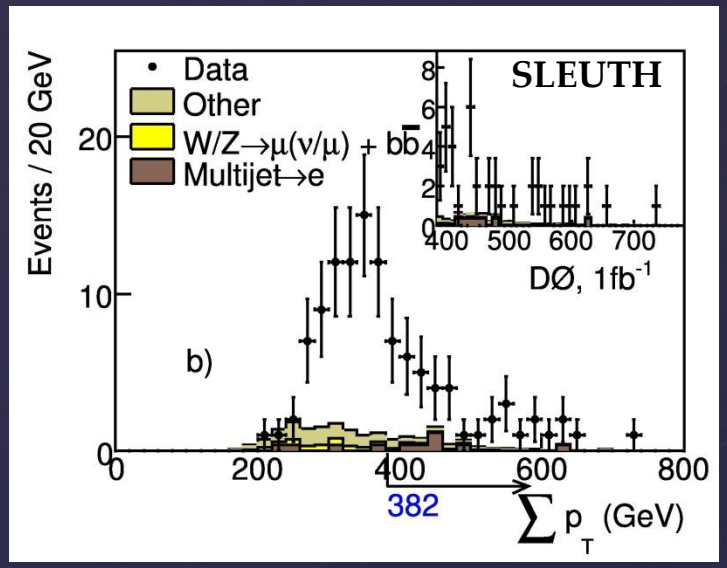
Gain acceptance to wide range of possible BSM theories, including those not yet discovered.

Final states include: **e, μ, τ, γ, $\not{E}_T$, jets, b-jets**



No significant discrepancies with SM found

Rediscovering $t\bar{t}$ in $ljjb\bar{b}\not{E}_T$ final state!



Key points:

- Apply many (>10) corrections to improve data/MC agreement;
- Normalise SM signals by fitting distributions for 'low p_T' events;
- Look for discrepancies using VISTA/SLEUTH algorithms

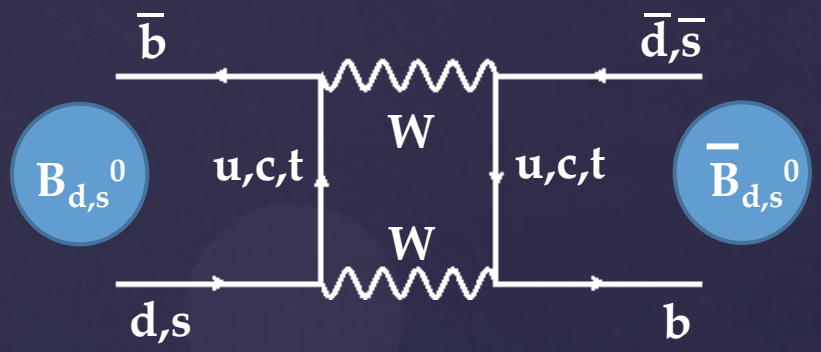
arXiv:1108.5362 [hep-ex]
Submitted to PRD

Part 2: New Physics from Flavor

B meson mixing, asymmetries and CP Violation

Neutral B mesons mix into their antiparticles;

Not CP symmetric: complex phases φ in CKM matrix, i.e. $\Gamma(\overline{B}^0 \to B^0) \neq \Gamma(B^0 \to \overline{B}^0)$



Define flavor-specific semileptonic asymmetry:

$$a^{s,d}_{sl} = \frac{\Gamma(\overline{B}^0 \to B^0 \to \mu^+ X) - \Gamma(B^0 \to \overline{B}^0 \to \mu^- X)}{\Gamma(\overline{B}^0 \to B^0 \to \mu^+ X) + \Gamma(B^0 \to \overline{B}^0 \to \mu^- X)} = \frac{\Delta\Gamma_{s,d}}{\Delta M_{s,d}} \tan\varphi_q$$

Physical parameters of $B_{s,d}^0$ system

SM prediction tiny for both B^0 and B_s^0 systems;

New particles in box diagrams can give large enhancements to asymmetry.

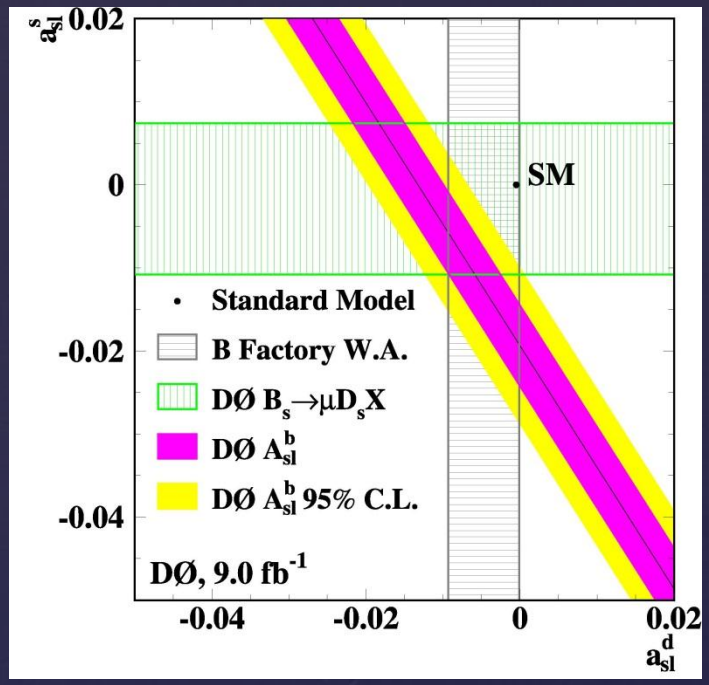
Loop integral: sensitive to new particles of **any mass**.

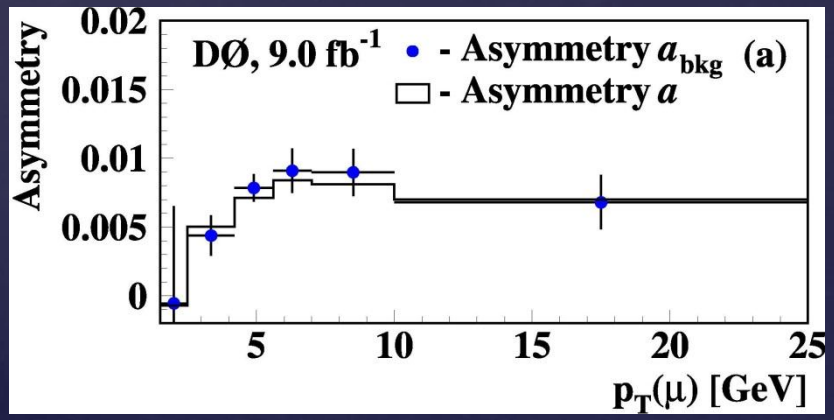
Anomalous Like-sign Dimuon Asymmetry

In same-sign dimuon sample, ~30% of muons come from decays of neutral B mesons *after mixing*.

'Flavor blind' – around 50% from B_s^0, 50% from B_d^0;

Use background-dominated single muon sample to constrain detector asymmetries and reduce systematic uncertainty.





Asymmetry 4.2σ from SM prediction;

Measurement repeated in different IP bins – gives sensitivity to a^d_{sl}, a^s_{sl} separately.

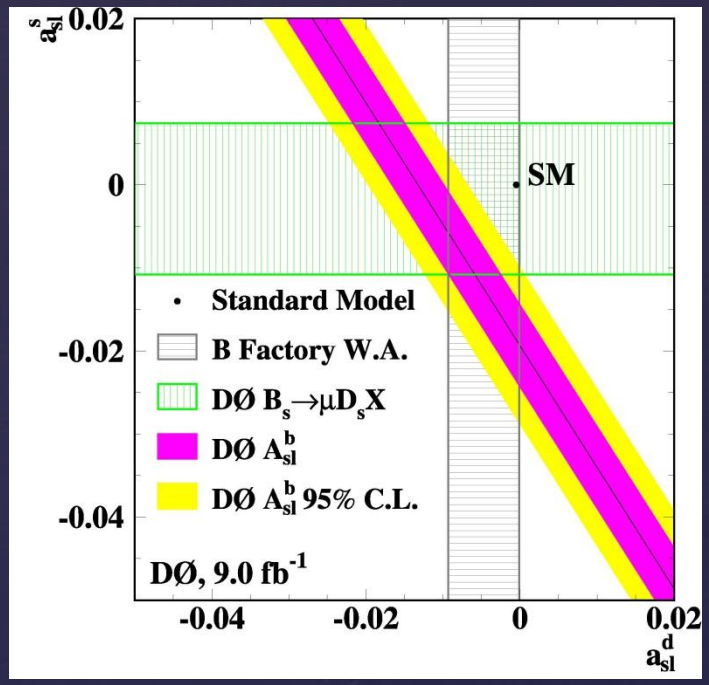
PRD 84, 052007 (2011)

Published Sep 16th

Anomalous Like-sign Dimuon Asymmetry

Now working on final 'legacy' paper:

1) Use **full dataset**. Equalise N(μμ) per polarity sample;
2) Use **'global fit'** : properly account for all correlations / dependencies;
3) Use **local muon system variables**; to constrain K/π→μ decay-in-flight fraction;
4) Extend use of **muon impact parameter**. Maximise sensitivity by separating signal and BG dominated regions;
5) Measure **integrated mixing probability χ_0.** Validation of many aspects of asymmetry measurement.



Coming soon…

Currently **no other experiments have competitive results** – unique attributes of D0 detector ($p\bar{p}$ collisions, regular magnet reversal).

Flavor-specific Asymmetries

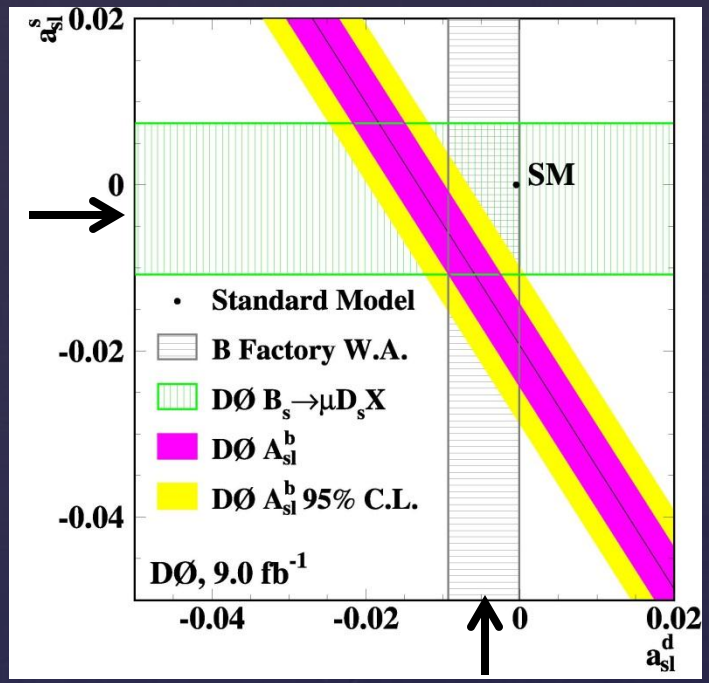
Coming soon…

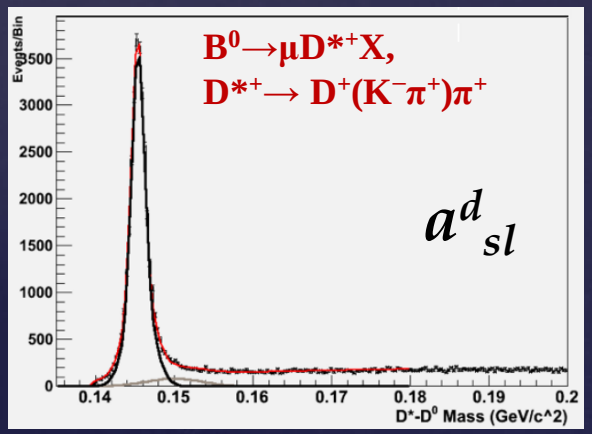
Semi-exclusive decay channels: direct extraction of raw signal asymmetry in B_d^0 and B^0_s decays;

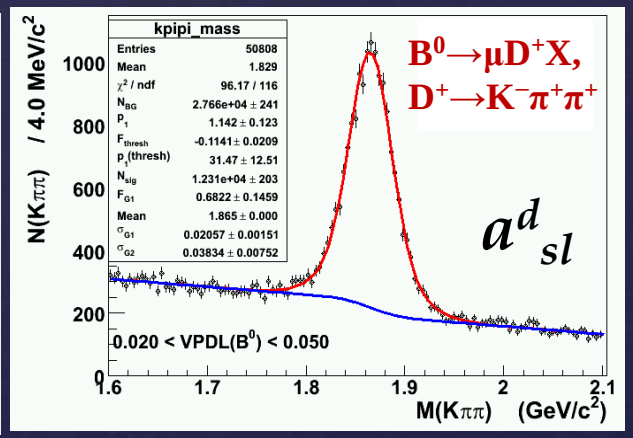
Measure reconstruction asymmetries of final state particles (muons, kaons, pions) – use data driven methods.

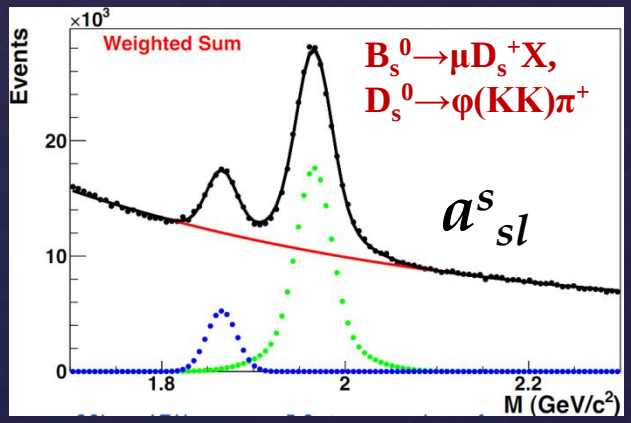
Account for dilution from charge symmetric processes.

Produce world's best measurements to narrow the constraints in the (a^d_{sl}, a^s_{sl}) plane.









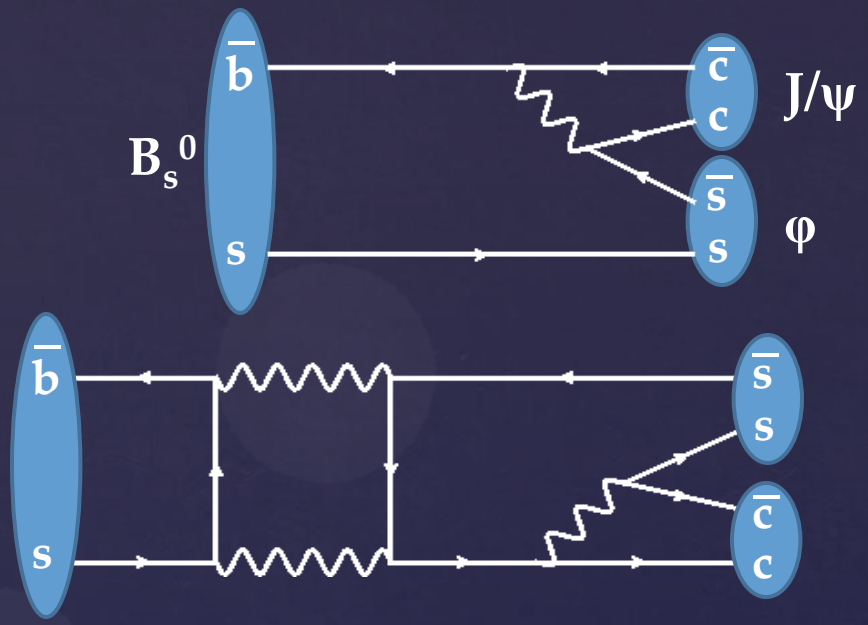
CP Violation in $B_s^0 \to J/\psi\varphi$

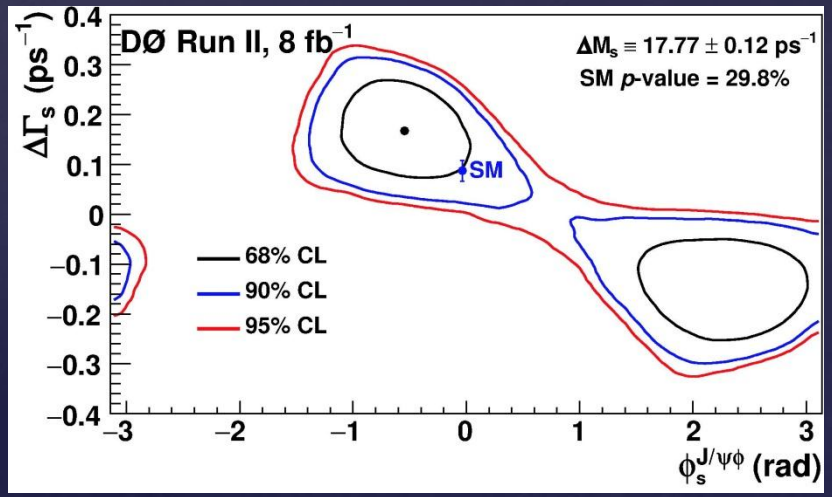
Same final states in 'mixed' and 'direct' decay $\Rightarrow$ interference between diagrams;

CPV arises from overall complex phase $\varphi_s^{J/\psi\varphi}$;

If NP enhancements present: $\varphi_s^{J/\psi\varphi} \approx \varphi_s$;

Extract physical parameters including $\varphi_s^{J/\psi\varphi}$, $\Delta\Gamma_s$, $\tau(B_s^0)$, in lifetime-dependent angular fit, including flavor tagging.





arXiv:1109.3166 [hep-ex]
Submitted to Phys. Rev. D

Final iteration of this interesting analysis at D0.

Now working on combination paper with CDF.

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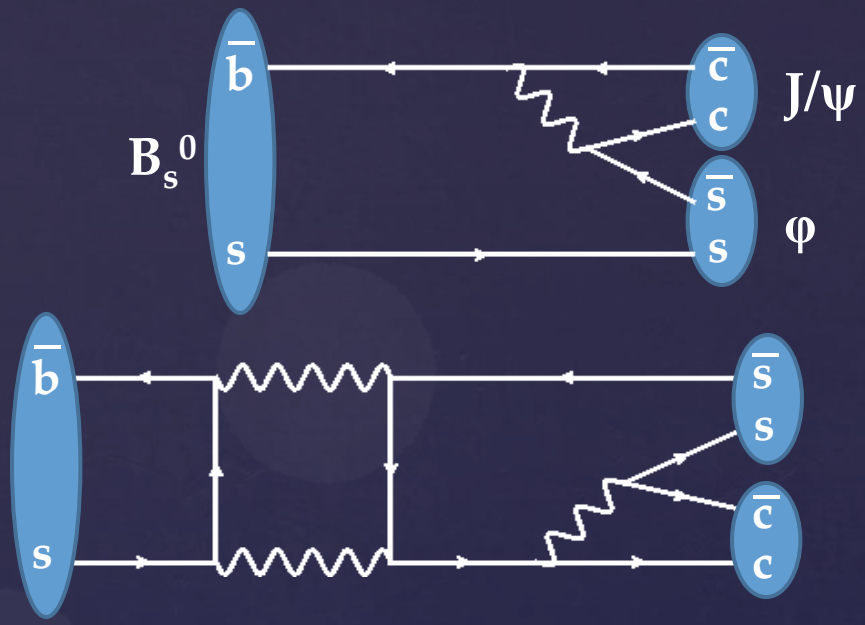

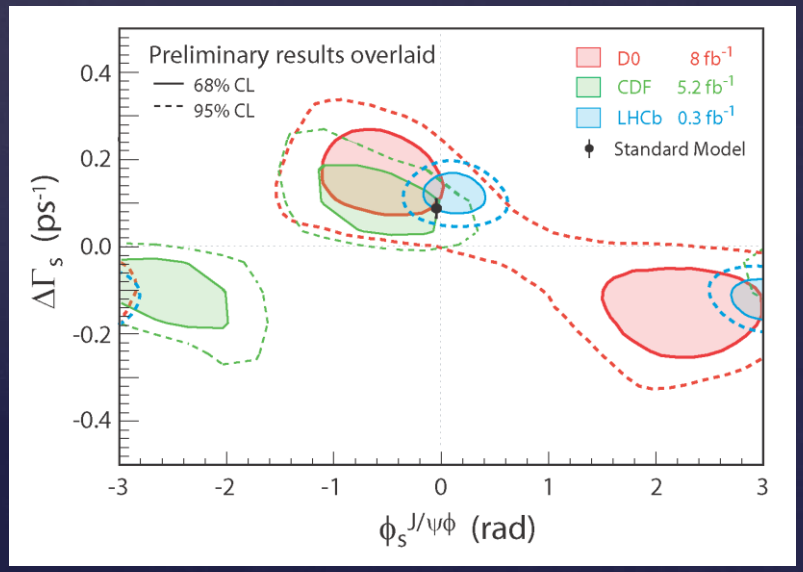

arXiv:1109.3166 [hep-ex]
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Final iteration of this interesting analysis at D0.

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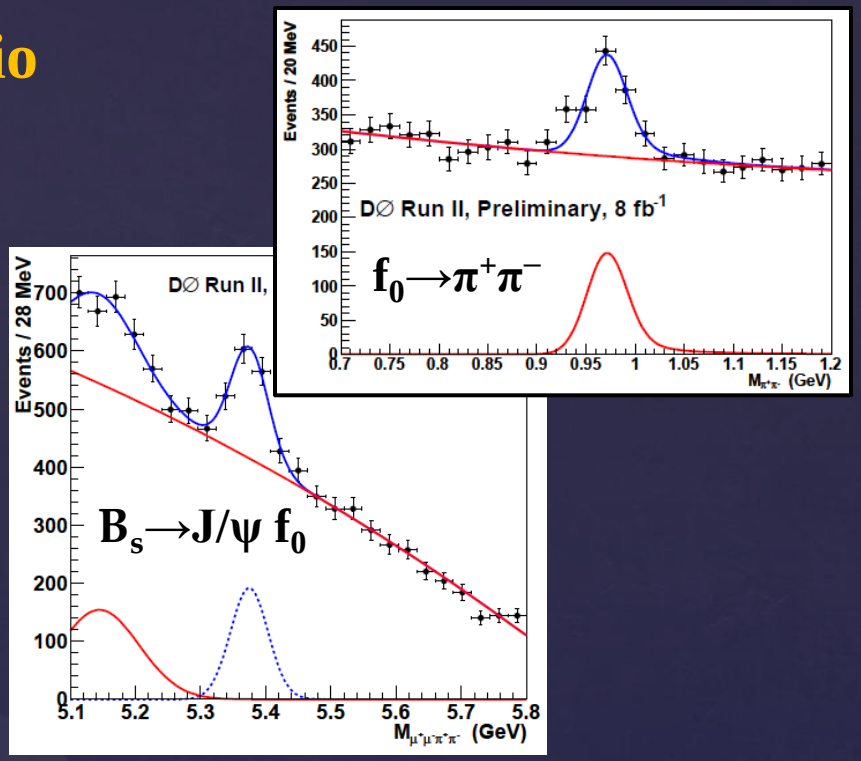
$B_s^0 \to J/\psi f_0$ Relative Branching Ratio

Same quark flow as $B_s^0 \to J/\psi\varphi$;

Final state is CP-odd, so no need for angular analysis to separate CP states;

Allows independent measurement of '$\varphi_s^{J/\psi\varphi}$': fewer events, simpler procedure.

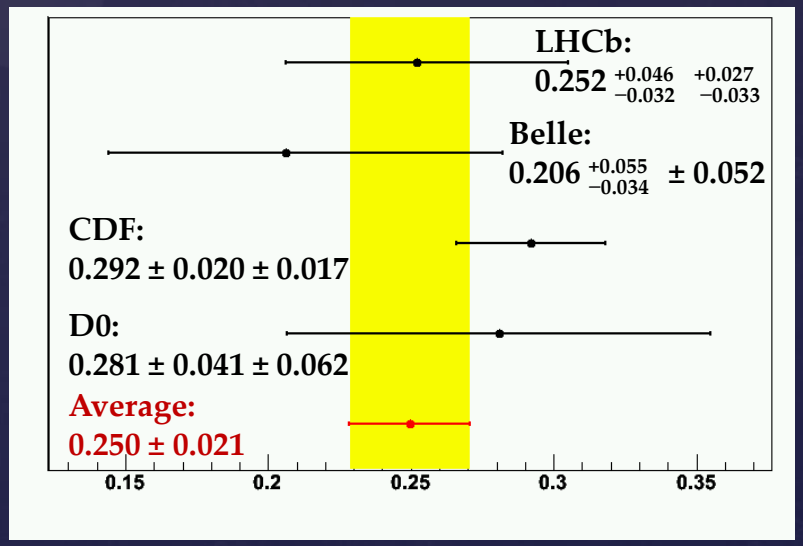
First step: measure decay branching ratio relative to $J/\psi\varphi$ channel:



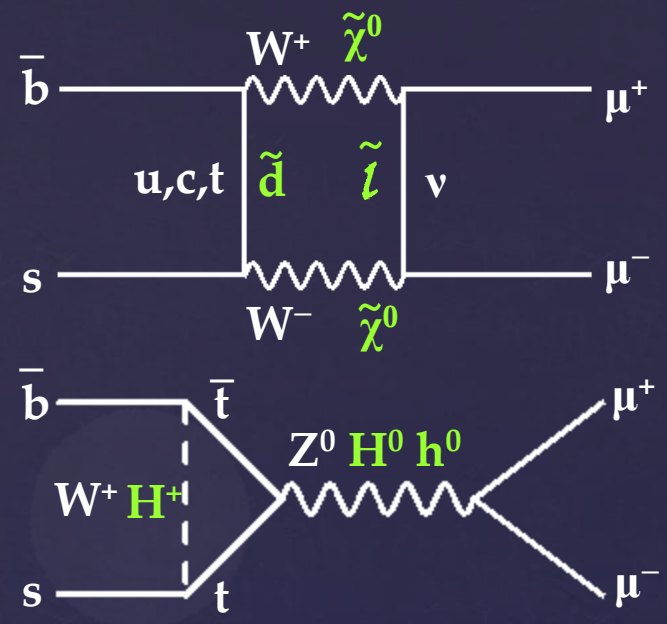
$$R = \frac{ß(B^0{}_s \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-)}{ß(B^0{}_s \to J/\psi\varphi;\ \varphi \to K^+K^-)}$$

= 0.281 ± 0.041 (stat.) ± 0.062 (syst.)

Preliminary result approved;
Paper in Collaboration review



Search for Rare Decay $B_s^0 \to \mu^+\mu^-$



High sensitivity to BSM physics;

FCNC process forbidden at 1st order in SM;

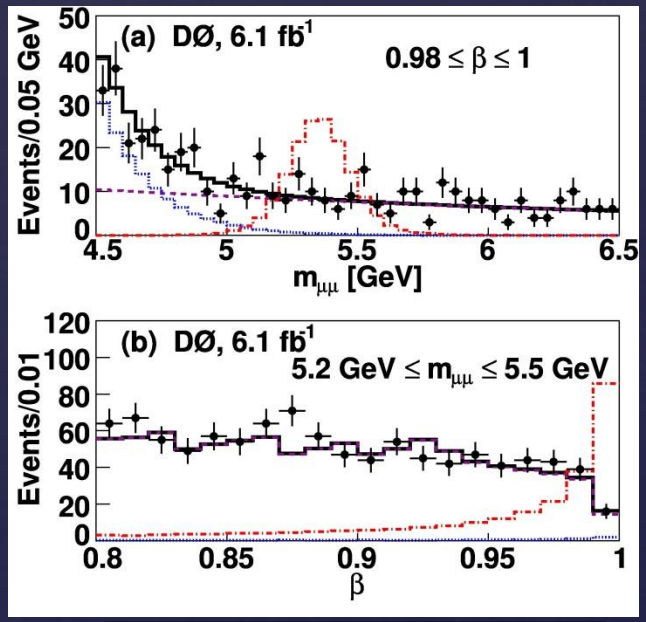
No evidence for signal, so set BR limit:

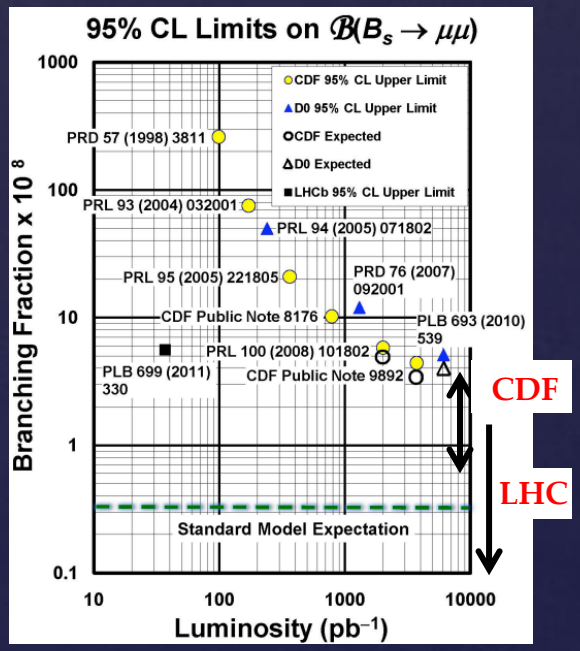
$B(B_s^0 \to \mu^+\mu^-) < 5.1 \times 10^{-8}$ at the 95% C.L.

Interesting recent result from CDF claims two-sided limit on BR;

CMS/LHCb results still see no signal;

Preliminary D0 study in progress;





Phys. Lett. B 693, 539 (2010)

Part 3: Precision B Physics

$\Lambda_b \to J/\psi\Lambda$ Branching Fraction

Particle properties (masses, decay BRs, lifetimes etc) sensitive to different models of non-perturbative QCD.

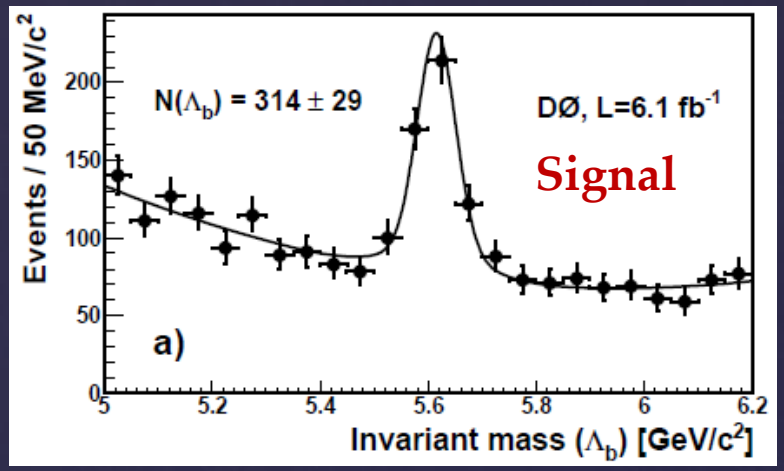
Measure BR relative to topologically similar, well-measured reference channel $B^0 \to J/\psi K_S^0$:

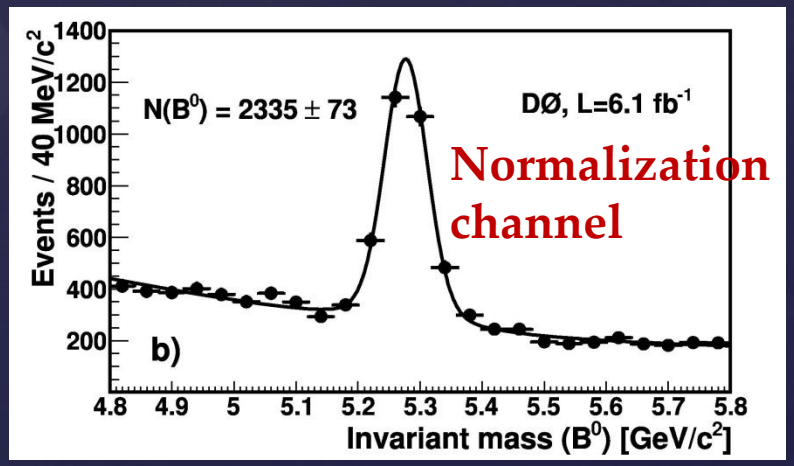
$$\sigma_R \equiv \frac{f(b\to\Lambda_b)\cdot ß(\Lambda_b\to J/\psi\Lambda^0)}{f(b\to B^0)\cdot ß(B^0\to J/\psi K_S^0)} =$$

0.345 ± 0.034 (stat.) ± 0.033 (syst.) ± 0.003 (PDG)

(existing WA: 0.270 ± 0.130)

Factor 3 improvement on previous WA precision.





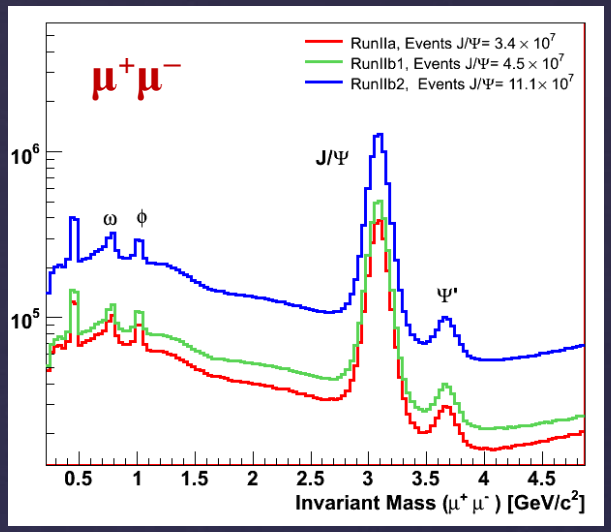
PRD-RC 84, 031102 (2011)

Future Λ_b Measurements

1) $\Lambda_b \to \psi(2S)\Lambda$ Branching Fraction

Repeat measurement for decays into the excited $c\bar{c}$ state $\psi(2S)$;

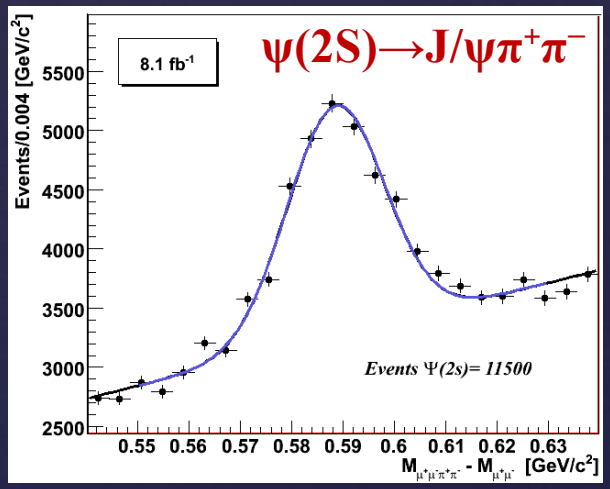
Use $\psi(2S) \to \mu^+\mu^-$ and $\psi(2S) \to J/\psi\pi^+\pi^-$ channels



2) Λ_b Lifetime in $J/\psi\Lambda$ Channel

Uses 'extended tracking' data sample: improved reconstruction efficiencies for long lived particles (70% increase in yield);

Also calculate ratio of lifetimes $\tau(\Lambda_b) / \tau(B^0)$ – very sensitive to different QCD models.

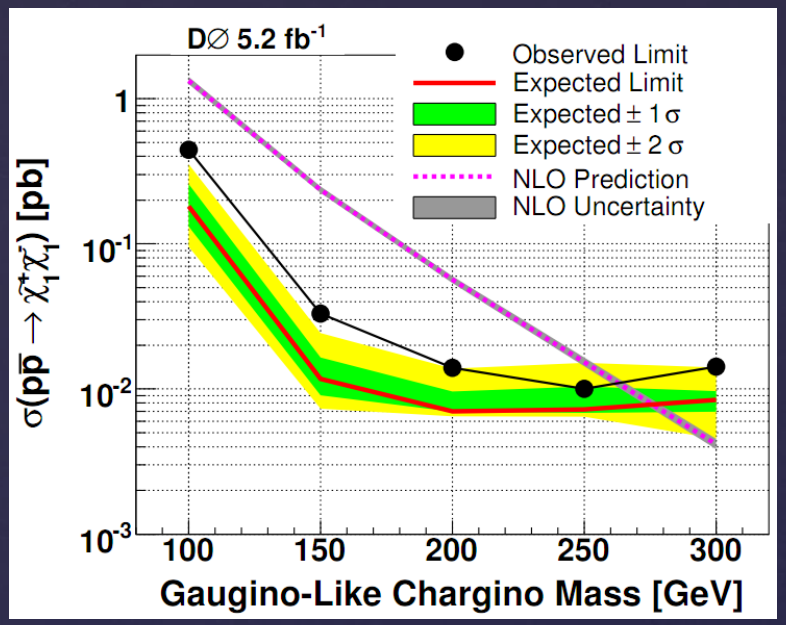


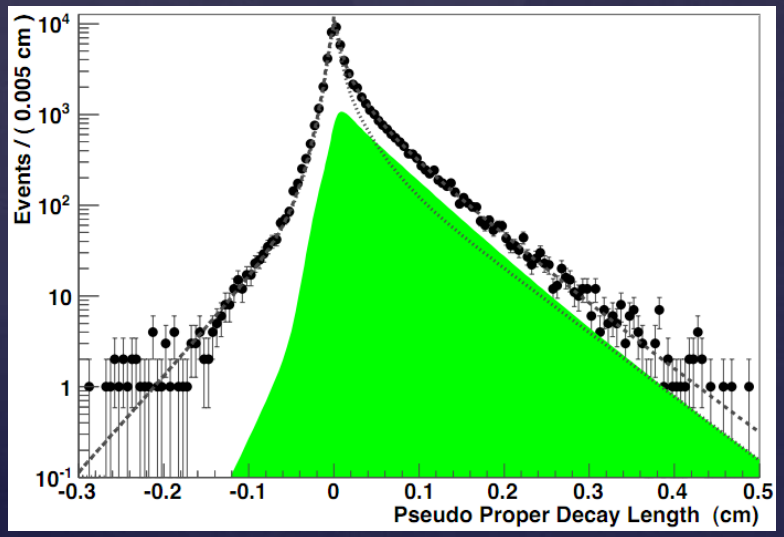
Coming soon…

Future Attractions…

- Charged massive long-lived particles (CMLLP)
- UED in Same-sign dimuons
- GMSB in Z+γ+MET (*c.f.* γγ+MET)
- Stop in bbμτ + MET (*c.f.* bbeμ+MET)
- SUSY (gaugino production) in trileptons

Preliminary summer result. Paper in final sign-off.





- B_s^0 Lifetime in Semileptonic Decays
- Searches for 'exotic' particles (X,Y,Z,…)
- ψ(2S) production cross-section
- Prompt J/ψ polarization
- B Baryon Searches

Summary

Long and fruitful history of results in NP and B physics

- Excluding BSM parameter space for almost 20 years!
- B_s^0 mixing → from first evidence that it occurs, to strong evidence that it hides new CP violating processes!

Pioneering development of next generation analysis techniques

- Novel (quirky!) searches, model-independent strategies;
- Multivariate techniques, data-driven methods;

Many more analyses to be published;

- Dimuon asymmetry already intriguing, now aiming for 5σ sensitivity. Not an easy measurement for LHC experiments.

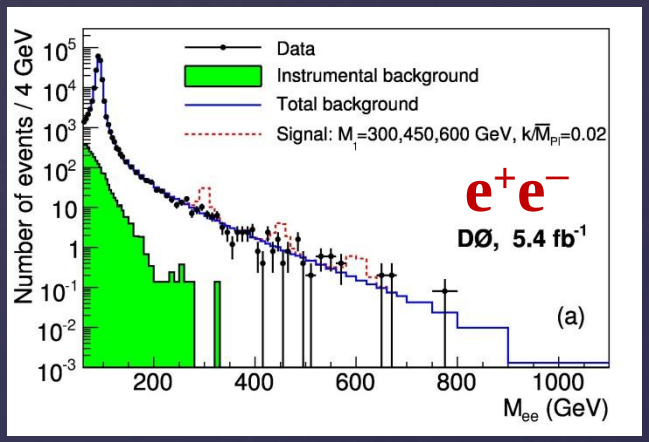
Thanks to Mike Eads, Michel Jaffre, Lidija Zivkovic for help with NP topics

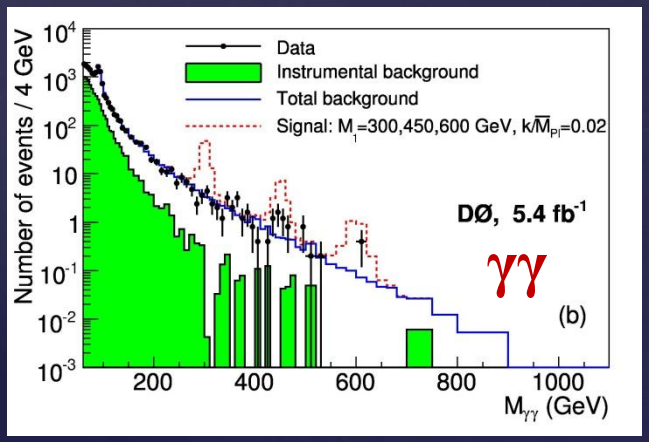
Extra Material

RS Gravity

Experimental Signature

Narrow M(ee), M(γγ) resonances

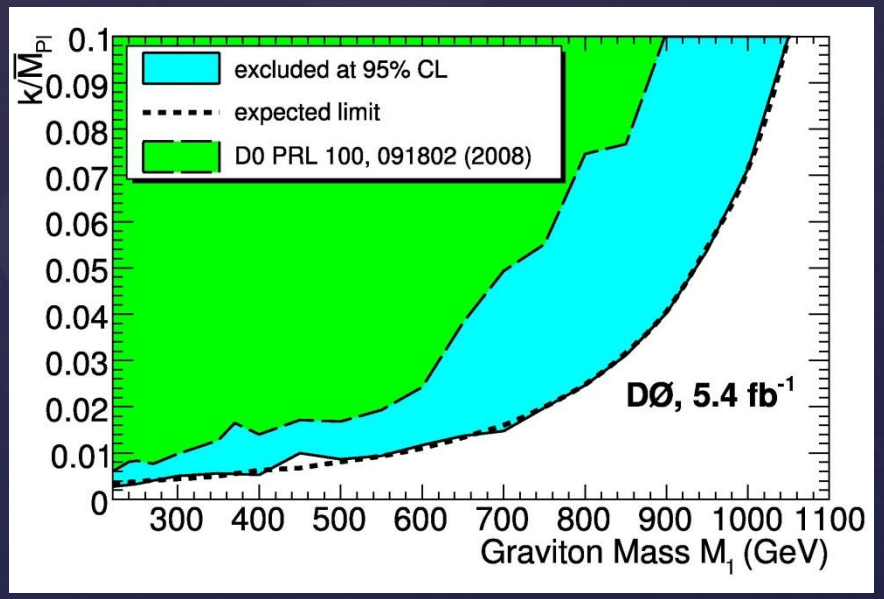




Theoretical Model

KK gravitons (G) in Randall-Sundrum Models

Coupling strength $k/\overline{M}_{pl}$
Lightest resonance mass M_1

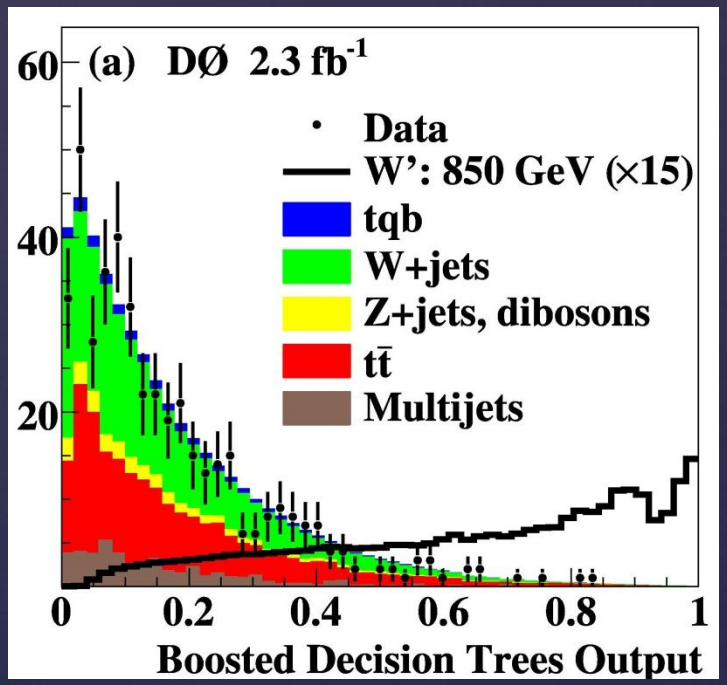


PRL 104, 241802 (2010)

Search for W′ → tb → ℓνbb

Experimental Signature

Excess of **ℓνbb** events at large values of BDT output;

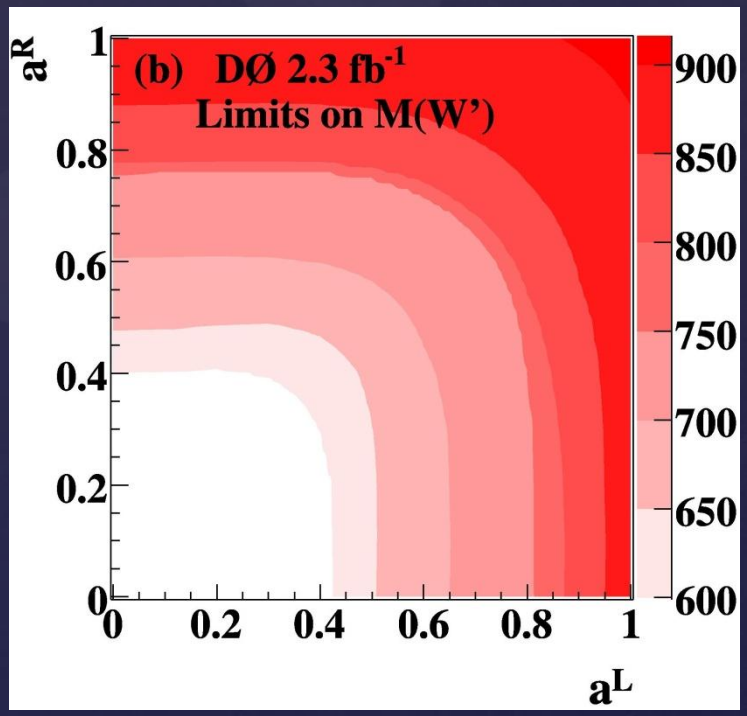


Phys. Lett. B 699, 145 (2011)

Theoretical Models

Universal extra dimensions: W′ with only LH couplings

LR symmetric models: W′ with mainly RH couplings



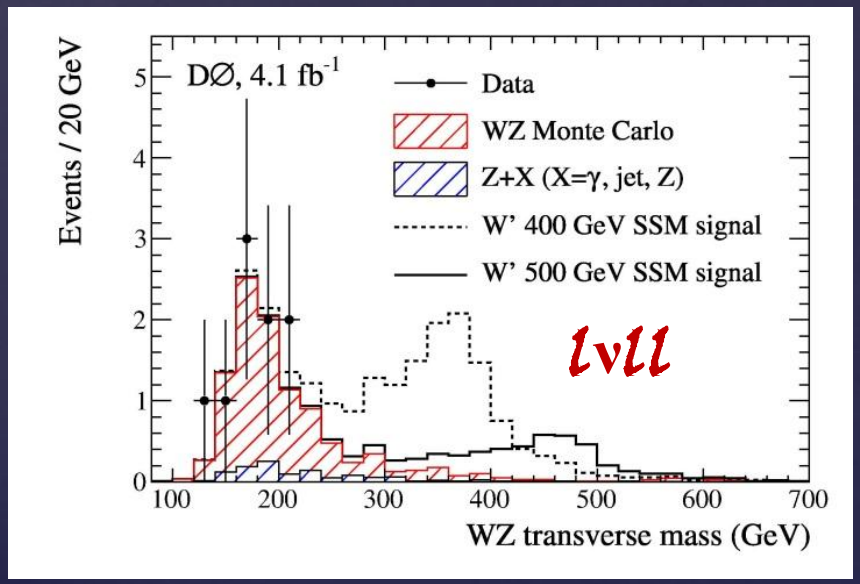
WZ Resonance in Trilepton Channel

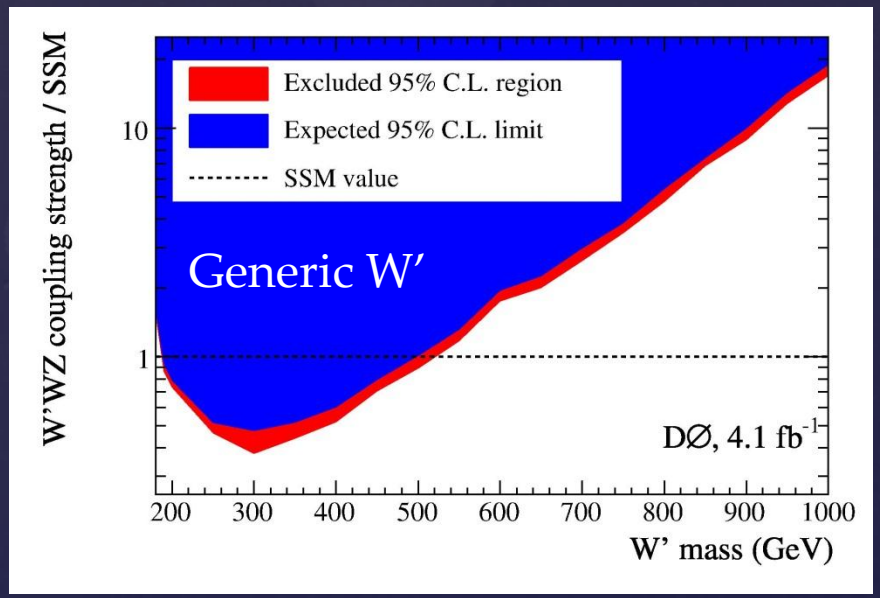
Experimental Signature

Resonant WW / WZ production

Theoretical Models

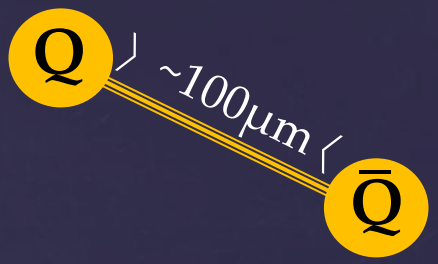
New charged boson W′ **($g_{W'}$, $M_{W'}$)** (sequential SM, Extra dimensions, little Higgs, technicolor…





PRL 104, 061801 (2010)

Quirks



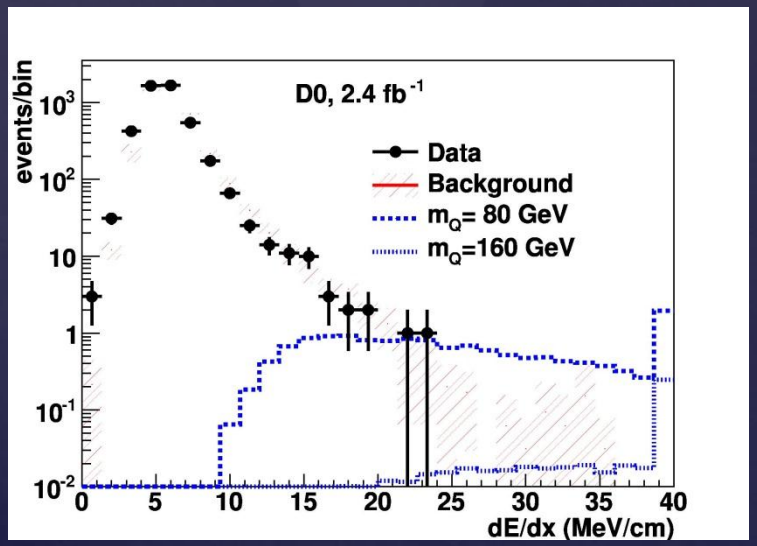
Consider new unbroken SU(N) gauge group with new fermions, 'quirks' Q.

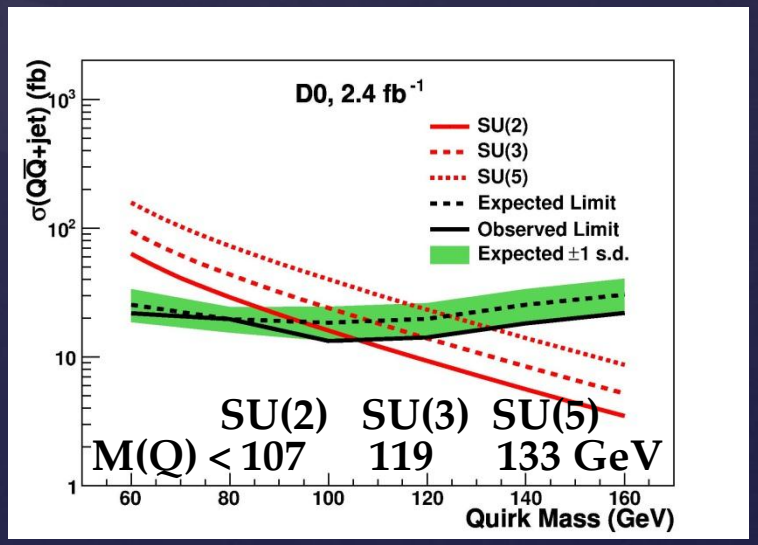
New coupling, 'infracolor' with scale Λ

For $m_Q >> \Lambda$, quirks stay connected by infracolor string (no 'hidronisation'); Assume Q carries electric charge.

Signature: neutral (straight) track with **large dE/dx**, plus associated jet.

Separation too small to be resolved in detector; large enough to have strong ionising effect.





PRL 105, 211803 (2010)

Other $B_s^0 \to J/\psi X$ States

'Inclusive' searches for:

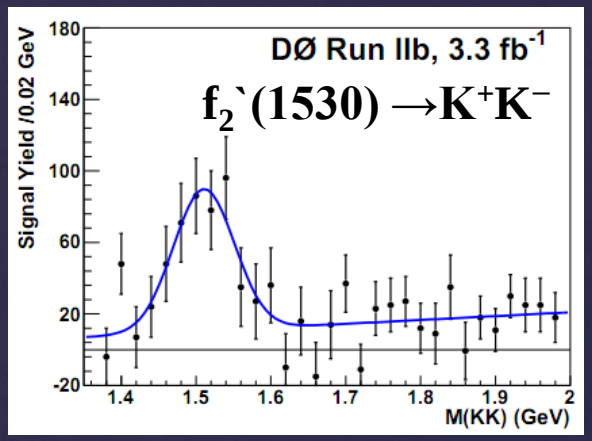
$B_s^0 \to J/\psi \pi^+\pi^-$ **$B_s^0 \to J/\psi K^+K^-$**

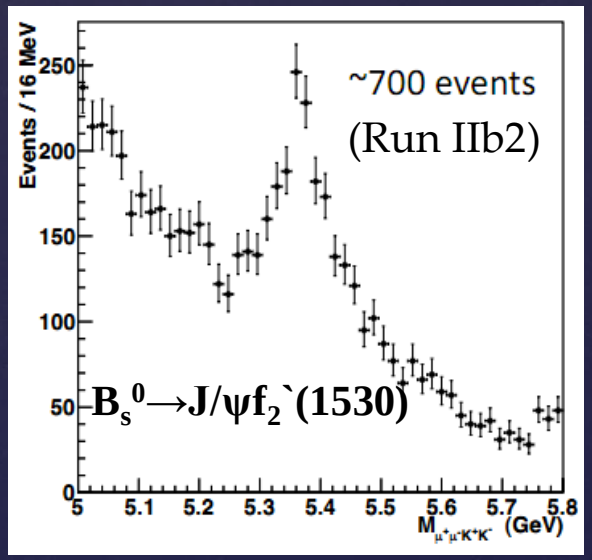
Several possible channels found, e.g. **$B_s^0 \to J/\psi f_2`(1530)$**

Could be future 'golden modes' of CPV studies;

First measure branching ratios, then investigate CPV phases.

Also working on lifetime and CPV measurement in well-established $J/\psi f_0$ mode.





Coming soon…