(New) New Phenomena with DØ

- Supersymmetry
  - Squarks / Gluinos → Jets + MET
  - Charginos / Neutralinos → Trileptons
- RS Gravitons
- Extra gauge bosons: W'
- Excited fermions: e*
- Leptoquarks: second generation
- Perspective

Arnd Meyer

RWTH Aachen

16. March 2007

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RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

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Großgeräte der physikalischen Grundlagenforschung

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Not as random as it seems!

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DØ Run II NP Publications (excl. Higgs)

- **~ 20 publications** on a wide variety of topics
  - 8 x Supersymmetry
  - 4 x Leptoquarks
  - 2 x Excited fermions
  - 2 x Extra dimensions
  - 2 x Signature based
  - 1 x Extra gauge bosons
  - 1 x Technicolor
- > 50 conference results

Continued new results in all areas

Beating "$\sqrt{\mathcal{L}}$" in many cases

The Physics Landscape

Beyond SUSY, there are many other possible models of new physics that could easily produce results in 1 fb^{-1}.

While SUSY may be popular, all that is certain is a high probability for some sort of new physics “just around the corner”.

- Radiative corrections to the Higgs mass
- If there is one
- Gravitation?
- Unification of couplings?
- Three generations?
- Dark matter?
- .....

New Phenomena is Approximately:

Supersymmetry	**Bread and butter RPC MSSM**
	→ Jets + MET, 3rd Gen., lepton(s) from cascade decays, ...
	R-Parity Violation
	Long-Lived Particles (AMSB, split SUSY, RPV, ...)
	Gauge Mediated SUSY Breaking
Extra Dimensions	**Monojets, di-leptons and di-photons**
Extra Gauge Bosons	**W´, Z´**
Leptoquarks	**1st, 2nd, 3rd Generation**
Compositeness	**Lepton and Quark Substructure**
Alternatives	**Technicolor, Little Higgs, ...**
Unknown	**Signature Based Searches**

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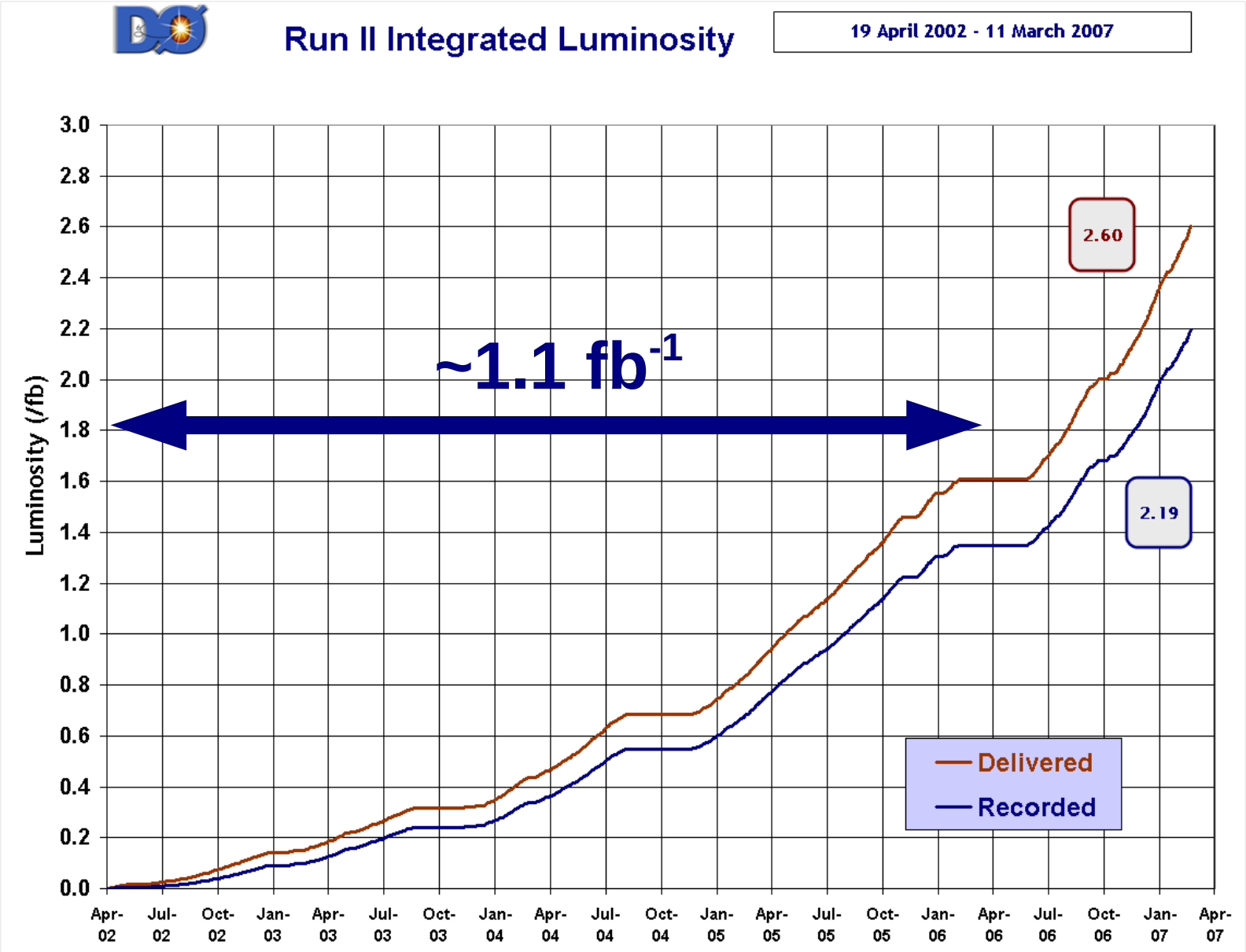
The Path to Discovery...

- **Trigger chain** defined and studied, and trigger efficiencies measured and understood, with appropriate dataset definitions
- **Extracting backgrounds and efficiencies**, from data wherever possible. Definition of triggers and data sets needed for data-based efficiency and background measurements
- Full **systematics** for backgrounds, signal, luminosity dependence, ...
- Justified selection criteria
- Methods of demonstrating **robustness** of potential signal and correctness of background prediction

Standard tools for faster turnaround

(trigger efficiencies, PDF systematics, etc.)

Data Set = “Run IIa”



Supersymmetry

- Most studied extension of the Standard Model to solve some (many, most, all) of its shortcomings
- A whole new zoo of new (s)particles, differing from their SM partners by spin 1/2

Quark	q	*Squark*	$\tilde{q}_R, \tilde{q}_L$	
Lepton	l	*Slepton*	$\tilde{l}_R, \tilde{l}_L$	
Neutrino	ν	*Sneutrino*	$\tilde{\nu}$	
Photon	γ	*Photino*	$\tilde{\gamma}$	**4 Neutralinos**
W-,Z-Boson	$W^{\pm}, Z$	*Wino, Zino*	$\tilde{W}^{\pm}, \tilde{Z}$	$\tilde{\chi}^0$
Higgs	$H^{\pm}, H^0$	*Higgsino*	$\tilde{H}_1^0\ \tilde{H}_2^+$	**2x 2 Charginos**
	h, A		$\tilde{H}_1^-\ \tilde{H}_2^0$	$\tilde{\chi}^{\pm}$
Gluon	g	*Gluino*	$\tilde{g}$	

R-Parity $R_p = \begin{cases} +1 & \text{SM} \\ -1 & \text{SUSY} \end{cases}$

- Different ways proposed to break supersymmetry, often with strikingly different phenomenology
- Popular benchmarks in mSUGRA

m0	**Scalar mass at GUT scale**
m1/2	**Gaugino mass at GUT scale**
tanß	**Ratio of Higgs vacuum expectation values**
mu	**Higgsino mass parameter**
A0	**Trilinear coupling**

Supersymmetry: Squarks and Gluinos

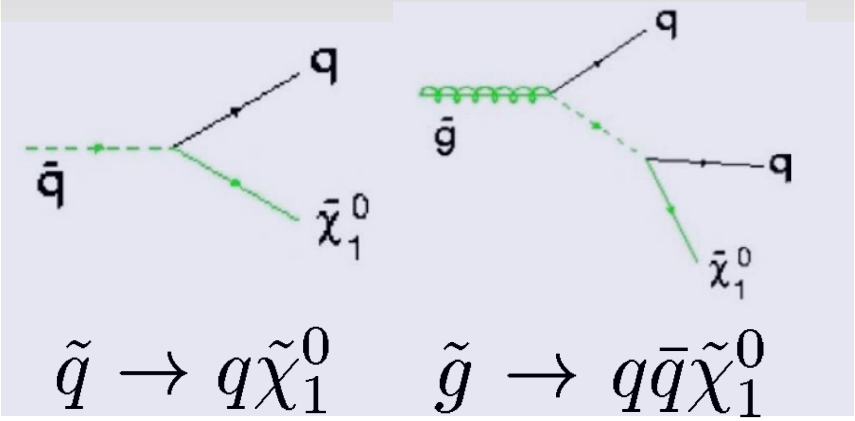
Hadron collider:

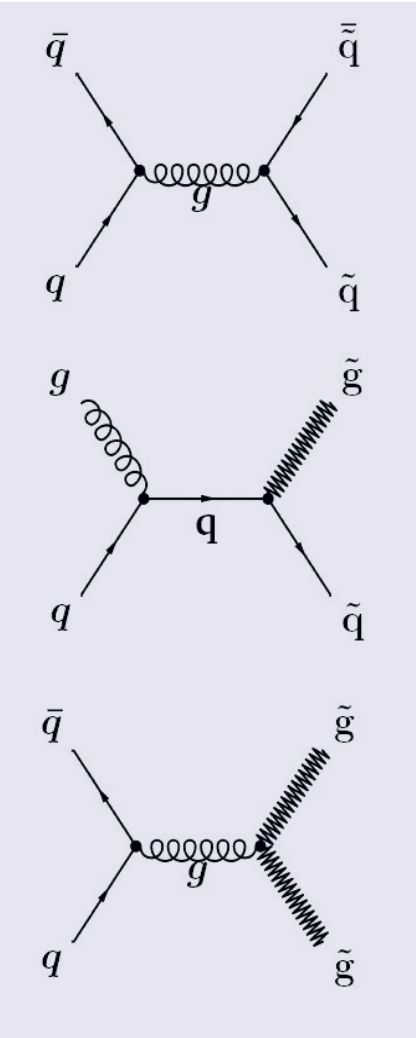
large squark-gluino cross sections

LSP assumed stable

(R_p conserved)

→ ≥ 2 jets + $\not{E}_T$ ("MET")





Low m_0, m(squark)<m(gluino) **"di-jet"**

(at least 2 jets)

Medium m_0, m(squark)~m(gluino) **"3-jet"**

(at least 3 jets)

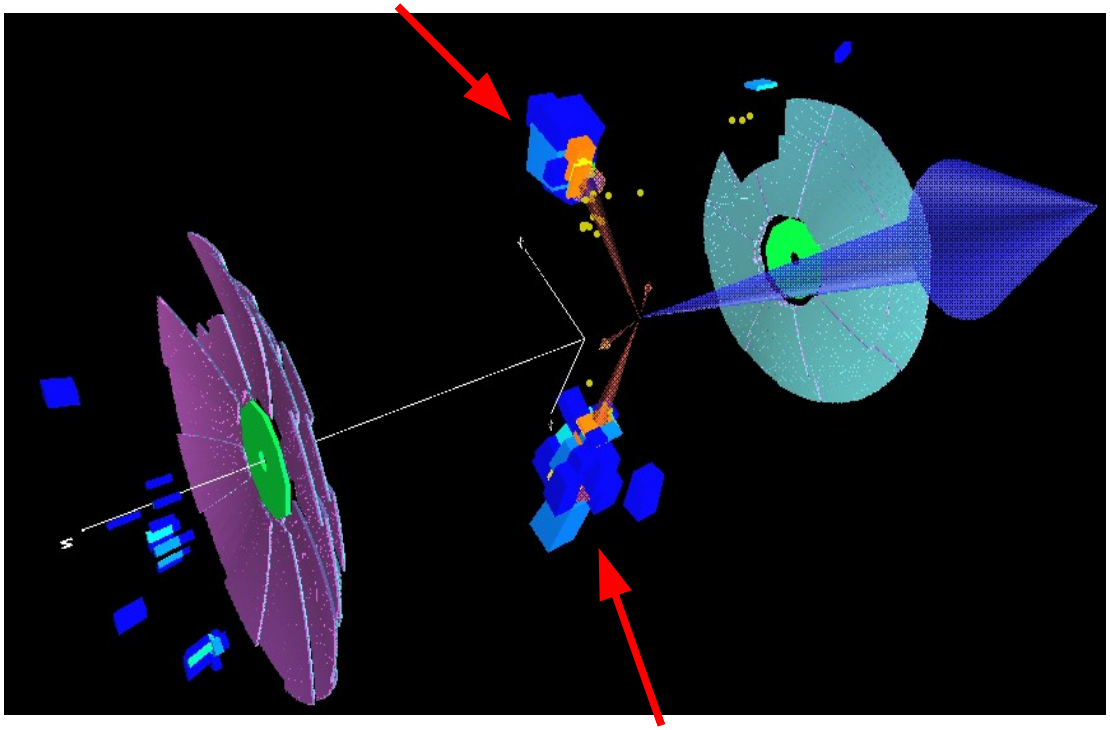
High m_0, m(squark)>m(gluino) **"gluino"**

(at least 4 jets)

Squarks and Gluinos: Candidates

Di-jet and multi-jet event with largest MET

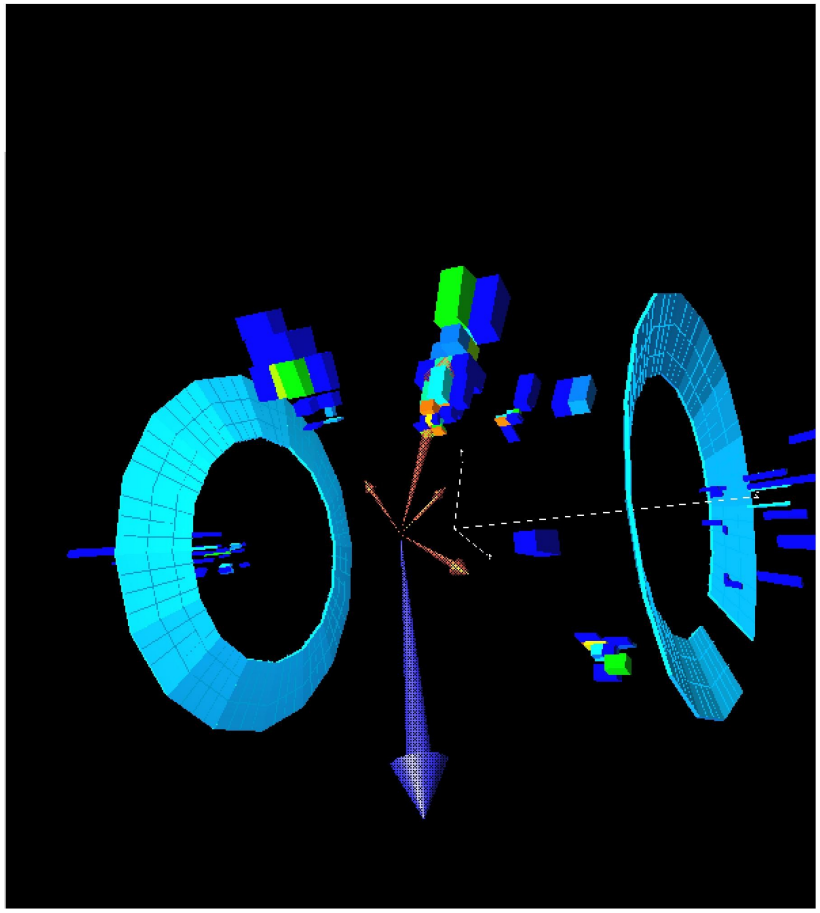
Jet 2: (174 GeV, -0.37, 0.12)



Jet 1: (282 GeV, -0.18, 1.52)

MET = 368 GeV

H_T = 489 GeV (= sum of jet E_T)



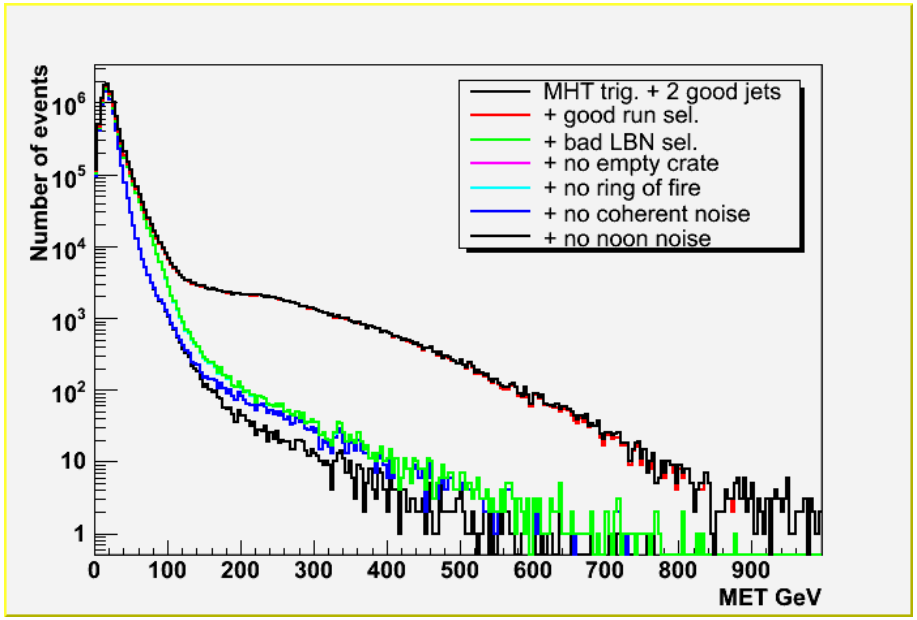
4 jets

MET = 321 GeV

H_T = 464 GeV

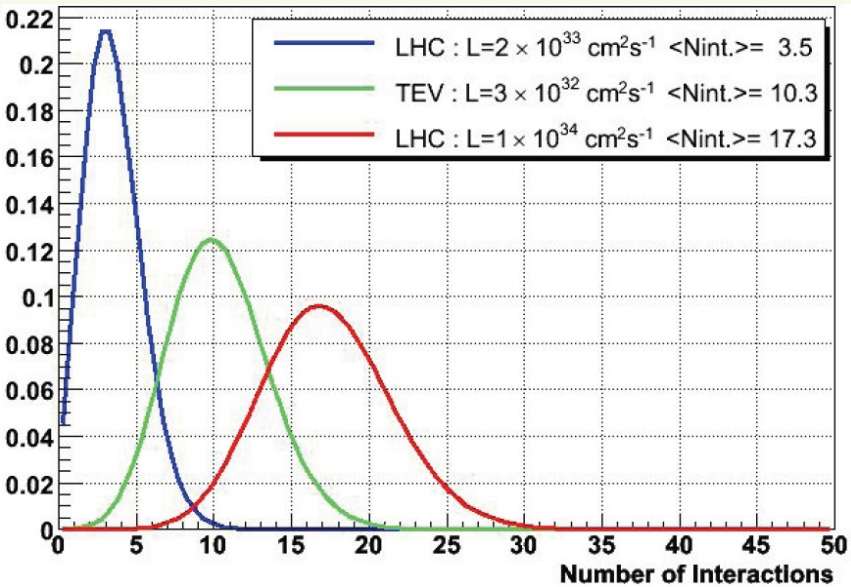
Squarks and Gluinos / MET

- Most of the time, a problem in online data taking will generate “fake” MET
- Excellent detector operations obligatory
- A perfect understanding of the calorimeter is required to control the MET tail
- A huge amount of work, online and offline, prior to physics analysis



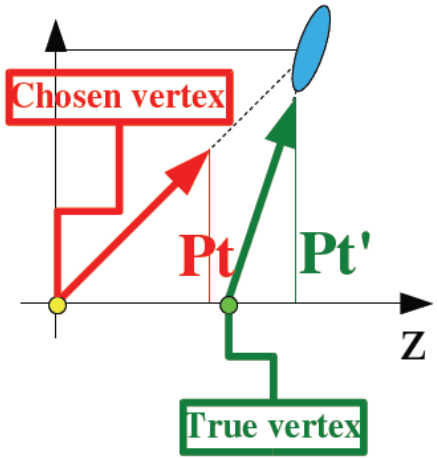
- Reject runs (and parts of runs) with detector problems
- Flag events with well known and identified noise pattern (mainly based on calorimeter occupancy per layer, per crate, in phi rings, ...)
- Some data quality problems are as rare as the new physics we are searching!

Squarks and Gluinos / Jets and MET



Choosing the wrong vertex is often the main source of QCD background in analyses where MET is important

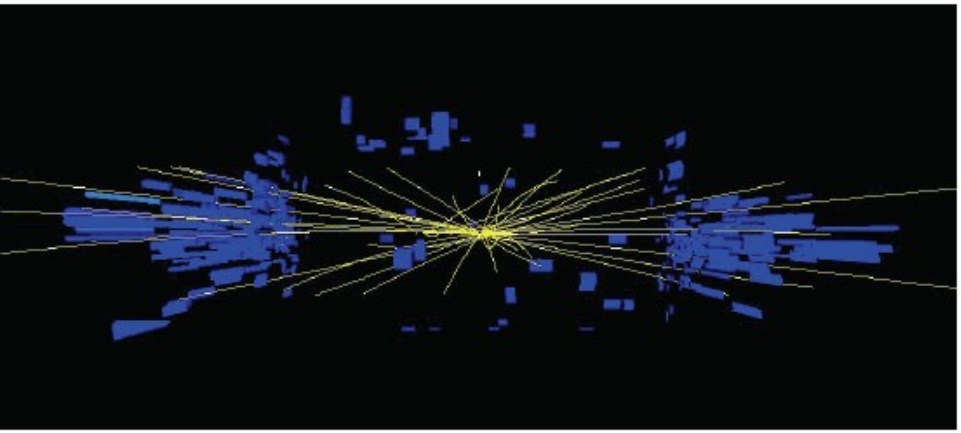
P. Verdier



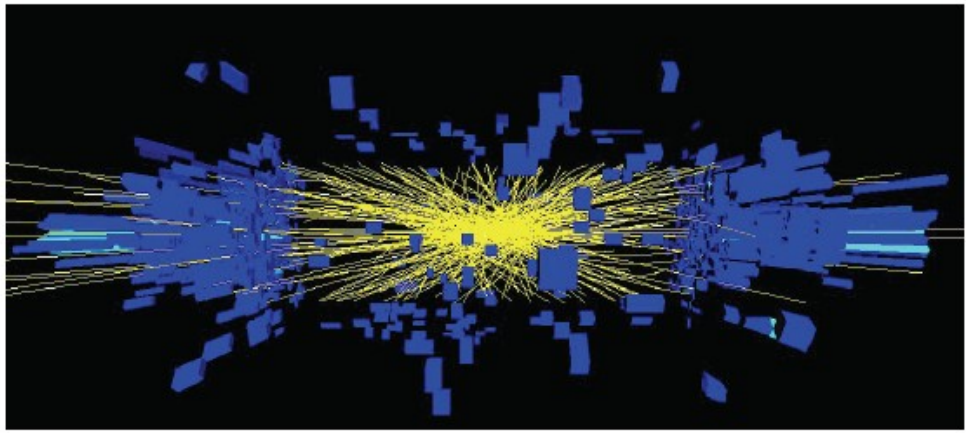
<u>Jet track confirmation:</u> Require tracks associated to jets

- For two leading jets, >85% of ΣpT (tracks) from primary vertex
- Also rejecting cosmic muon and beam related backgrounds

A zero bias event @ 60E30 cm^2s^{-1}



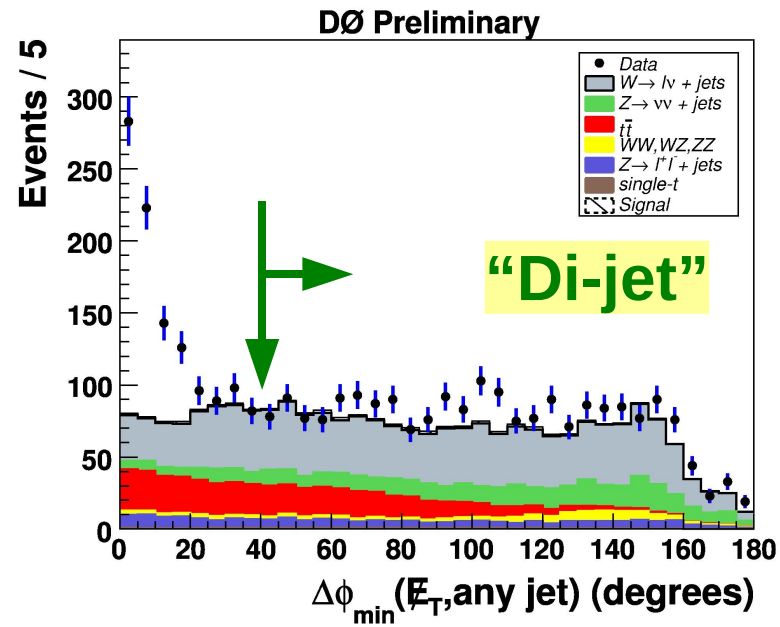
... and @ 240E30 cm^2s^{-1}

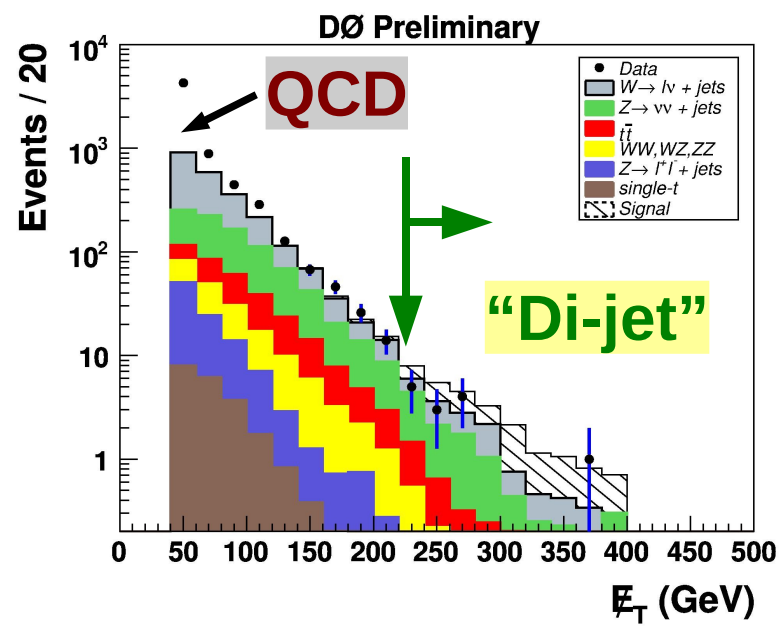


Squarks and Gluinos: Selection

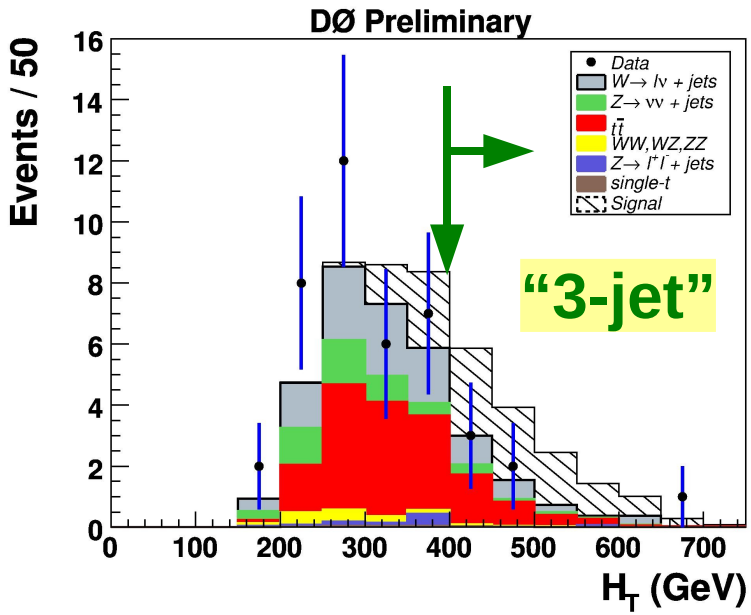
- Main backgrounds: $Z \rightarrow \nu\nu$ + jets, ttbar, W+jets (Alpgen)
- QCD negligible in the end
- Common preselection:
  - 2 acoplanar jets ($\Delta\varphi < 165^{o}$) with E_T>35 GeV and $|\eta|$<0.8, confirmed by tracks
  - MET > 40 GeV
- Jet 3 / 4: $|\eta| < 2.5$, E_T > 35 / 20 GeV
- MET isolated from jets
- Veto isolated electrons and muons
- Optimize final cuts on MET and H_T for best expected limit:

"Di-jet"	MET > 225 GeV	HT > 300 GeV
"3-jet"	MET > 150 GeV	HT > 400 GeV
"Gluino"	MET > 100 GeV	HT > 300 GeV

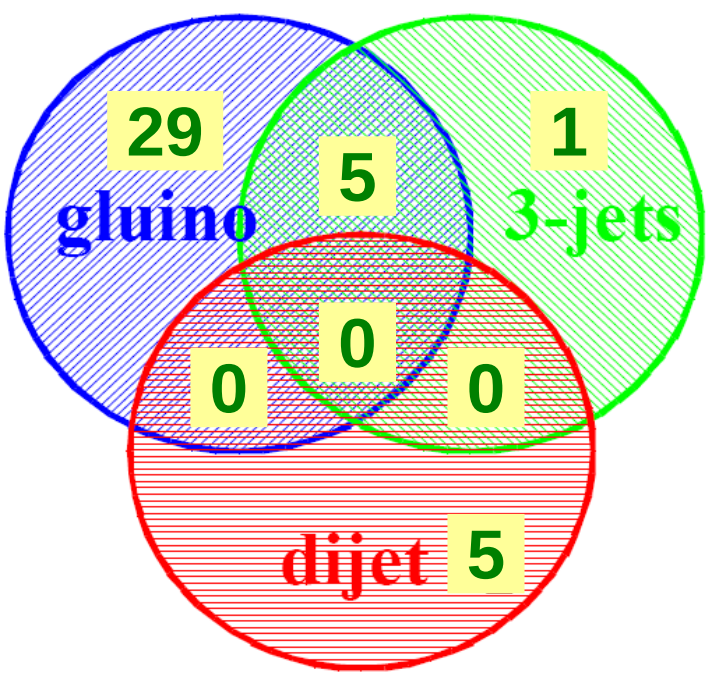




Squarks and Gluinos: Results

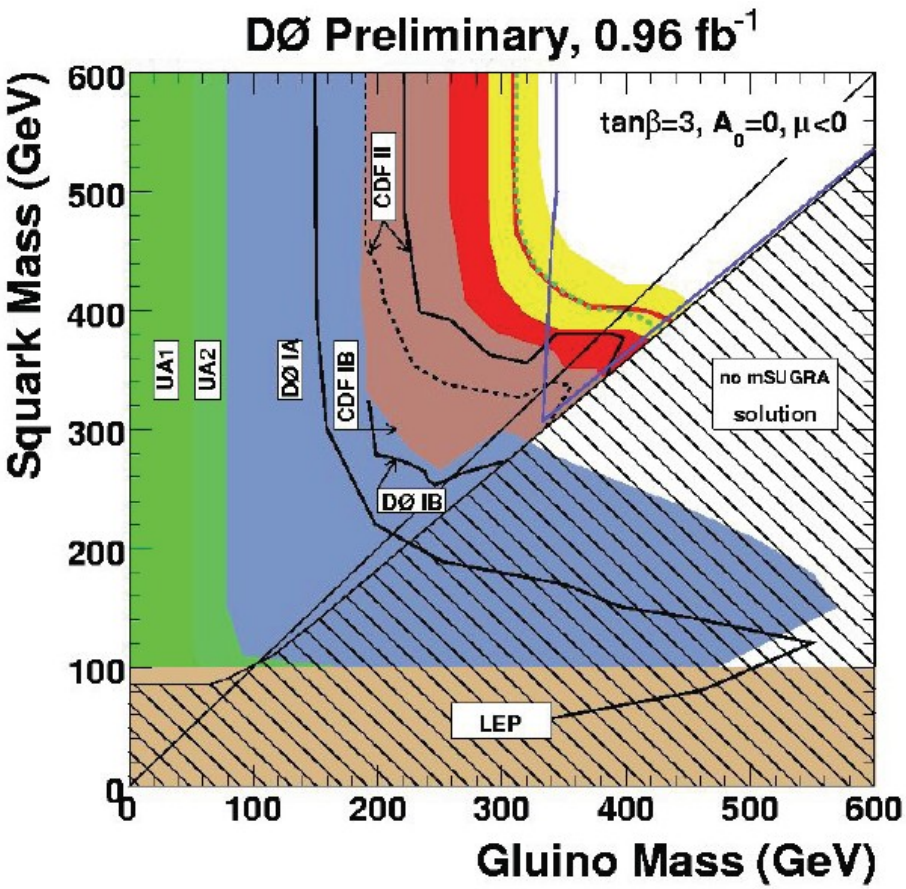


	Data	SM Expectation
"Di-jet"	5	7.5 ± 1.1 + 1.3 - 1.0
"3-jet"	6	6.1 ± 0.4 + 1.3 - 1.2
"Gluino"	34	33.4 ± 0.8 + 5.6 - 4.9



- Signal efficiencies up to ~10%, higher for large squark-gluino masses
- Main systematic uncertainties
  - Jet energy scale (6 – 17%)
  - Background cross sections (15%)
  - Other detector: 5 – 7% (jet ID, resol., track conf.)
  - Luminosity (6.1%)
  - Signal acceptance: PDF's (6%)
- Combination: seven orthogonal analyses

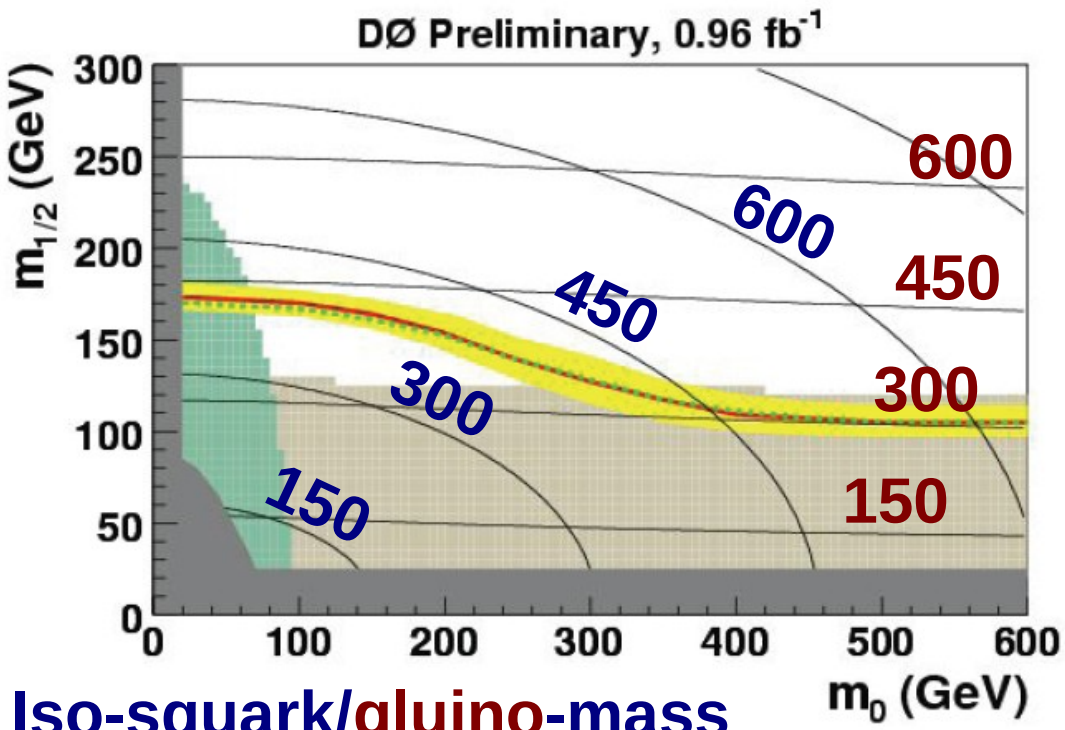
Squarks and Gluinos: Limits



Using minimal cross sections:

$m(\tilde{q},\tilde{g}) > 383$ GeV for $m(\tilde{q}) = m(\tilde{g})$
$m(\tilde{q}) > 375$ GeV
$m(\tilde{g}) > 289$ GeV

~50 GeV higher than previous limits



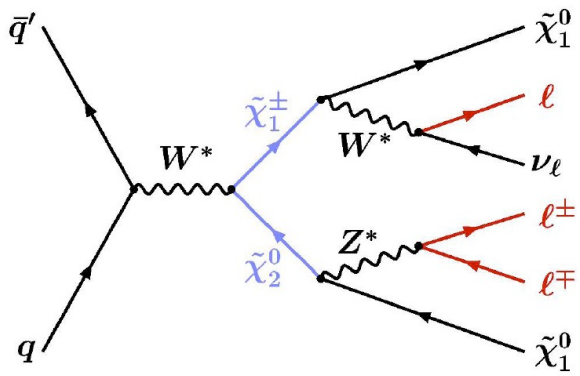
Iso-squark/gluino-mass

Yellow band: variation due to

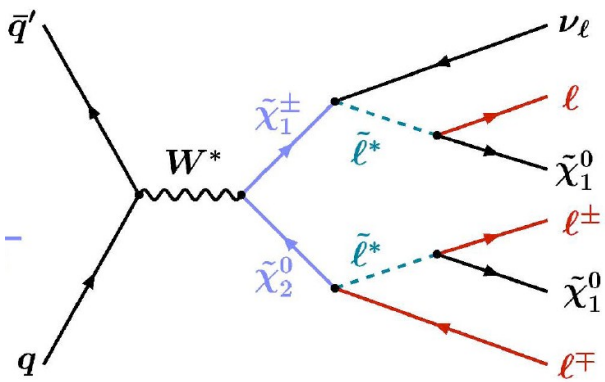
- PDF (CTEQ 6.1M error PDF's)
- Renormalization/factorization scale

Charginos / Neutralinos: Trilepton Final State

Heavy sleptons:



Light sleptons:

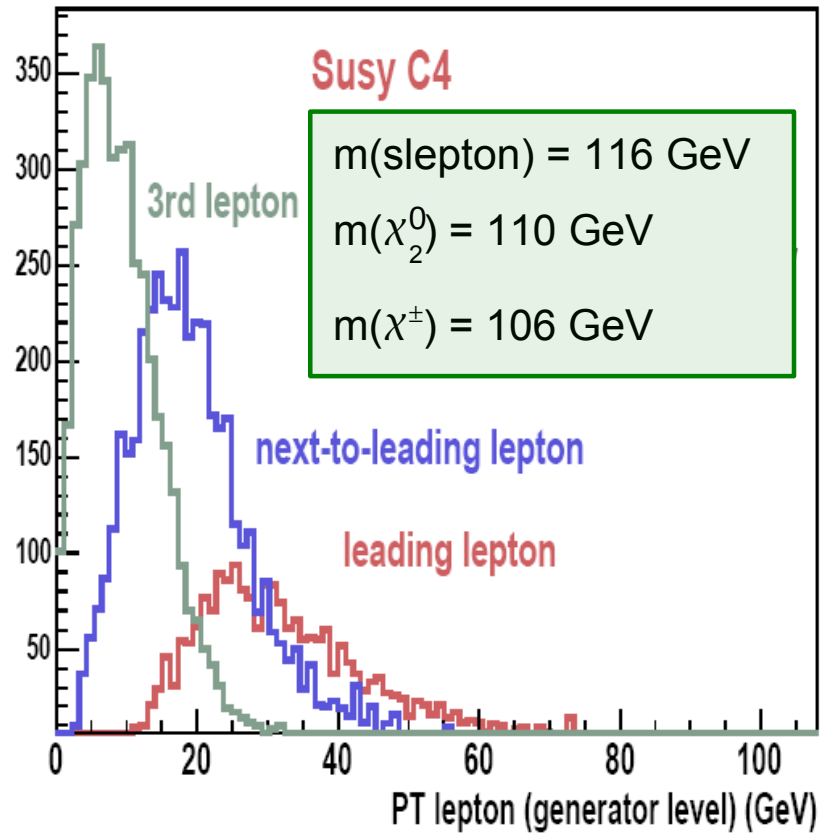


- Gaugino pair production via EW interaction
  - Small cross sections, ~0.1 – 0.5 pb
- Charginos and neutralinos decay via gauge bosons or sfermions to LSP and SM particles.
- R-parity conserving models ⇒ LSP stable
- LSP escapes detection in the detector
- SUSY signature
  - 2 electrons or muons
  - Third lepton
  - Large missing E_T

Very clean signature, but very small cross sections

Trileptons Outline

- Look for high quality track or like-sign muons to increase efficiency
- Four channels updated with full Run IIa data set
  - ee + track
  - μμ + track
  - eμ + track
  - Like-sign μμ
- Earlier results based on ~0.3 fb^{-1}
- **Selection outline:**
  - Two leptons
  - Additional isolated track (except LS μμ)
  - Missing transverse energy
  - Veto events with $Z \rightarrow ll$ decays
- Sophisticated criteria to discriminate a multitude of backgrounds!



Trileptons: Backgrounds

	# leptons	true MET	xsec(pb)	Remarks
Signal	3	Yes	0.18	
WZ -> lllν	3	Yes	0.11	signal like
ZZ -> ll XX	2 – 4	Both	0.07	lepton misid. / MET mismeas.
WW-> ll νν	2	Yes	1.24	fakes
W-> lν+γ/jet	1	Yes	2500	fakes
(Z /γ->ll)+γ/jet	2	No	250-400	fakes, mismeasurement
ttbar -> ll +2jets	2	Yes	0.73	fakes, mismeasurement
qqbar -> jets	0	No		fakes, mismeasurement

Two leptons in acceptance:

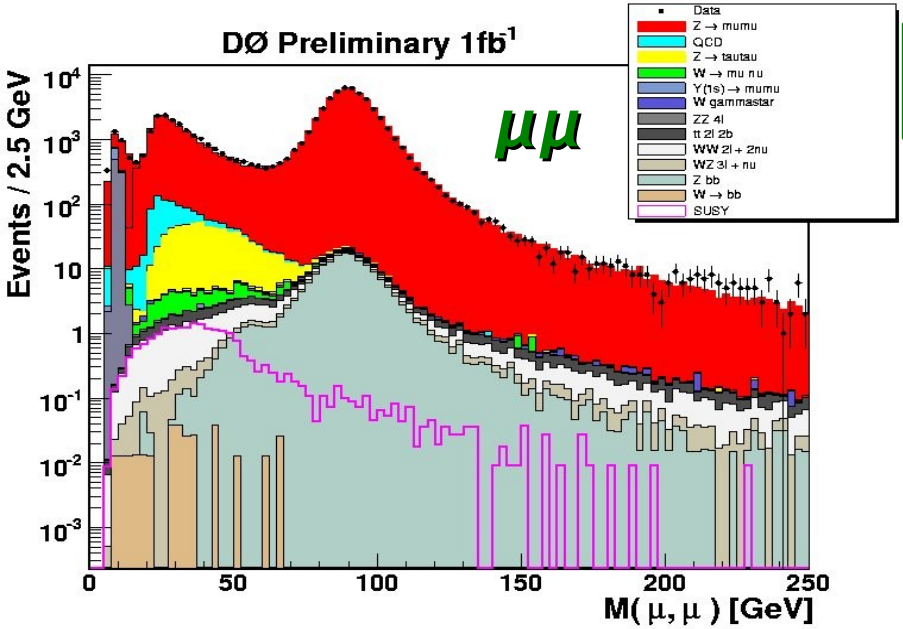
ee + Track p_T **> 12 GeV** **> 8 GeV**

μμ + Track p_T **> 12 GeV** **> 8 GeV**

eμ + Track p_T **> 12 GeV** **> 8 GeV**

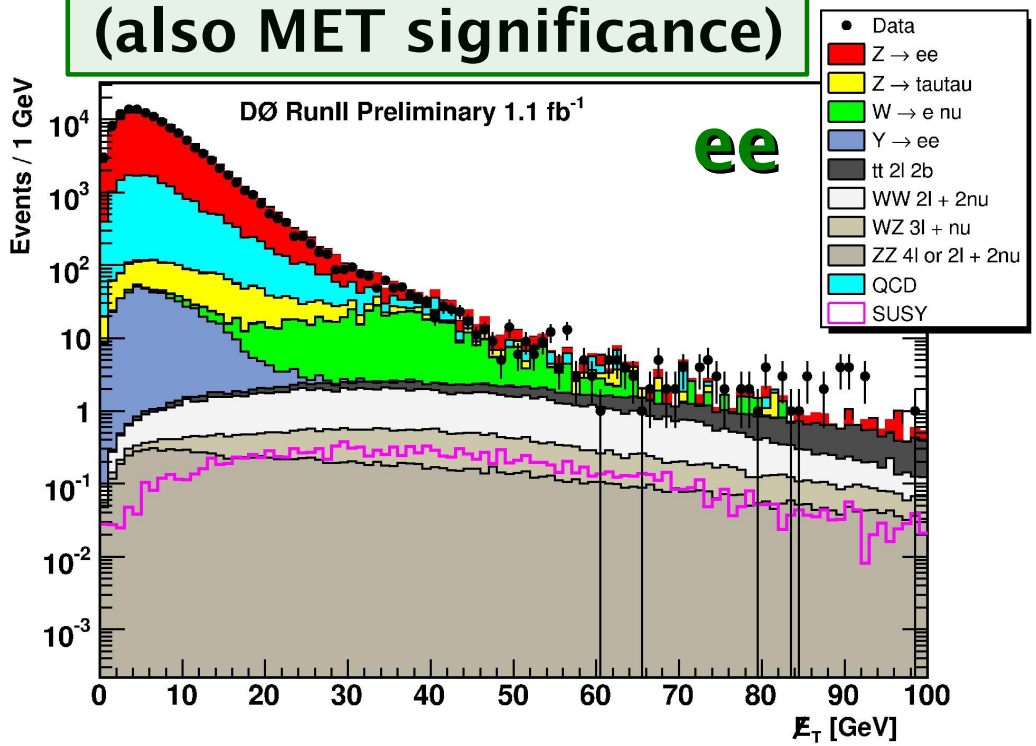
LS μμ p_T **> 13 GeV, < 35 GeV** **> 8 GeV**

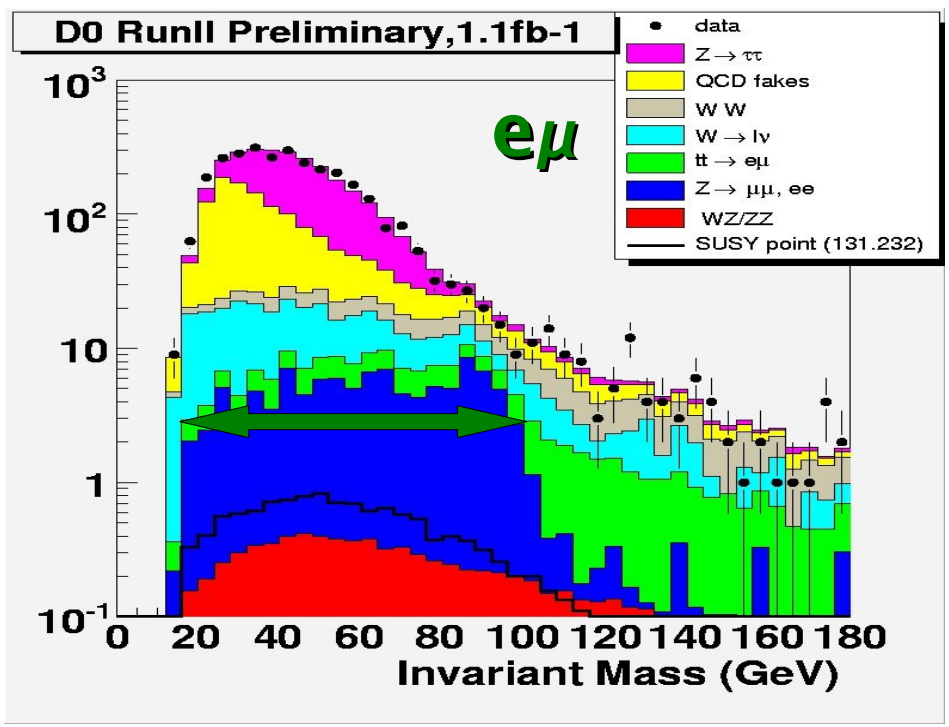
Trileptons: Dilepton Distributions



24 GeV < M($\mu\mu$) < 60 GeV

MET > 22 GeV
(also MET significance)

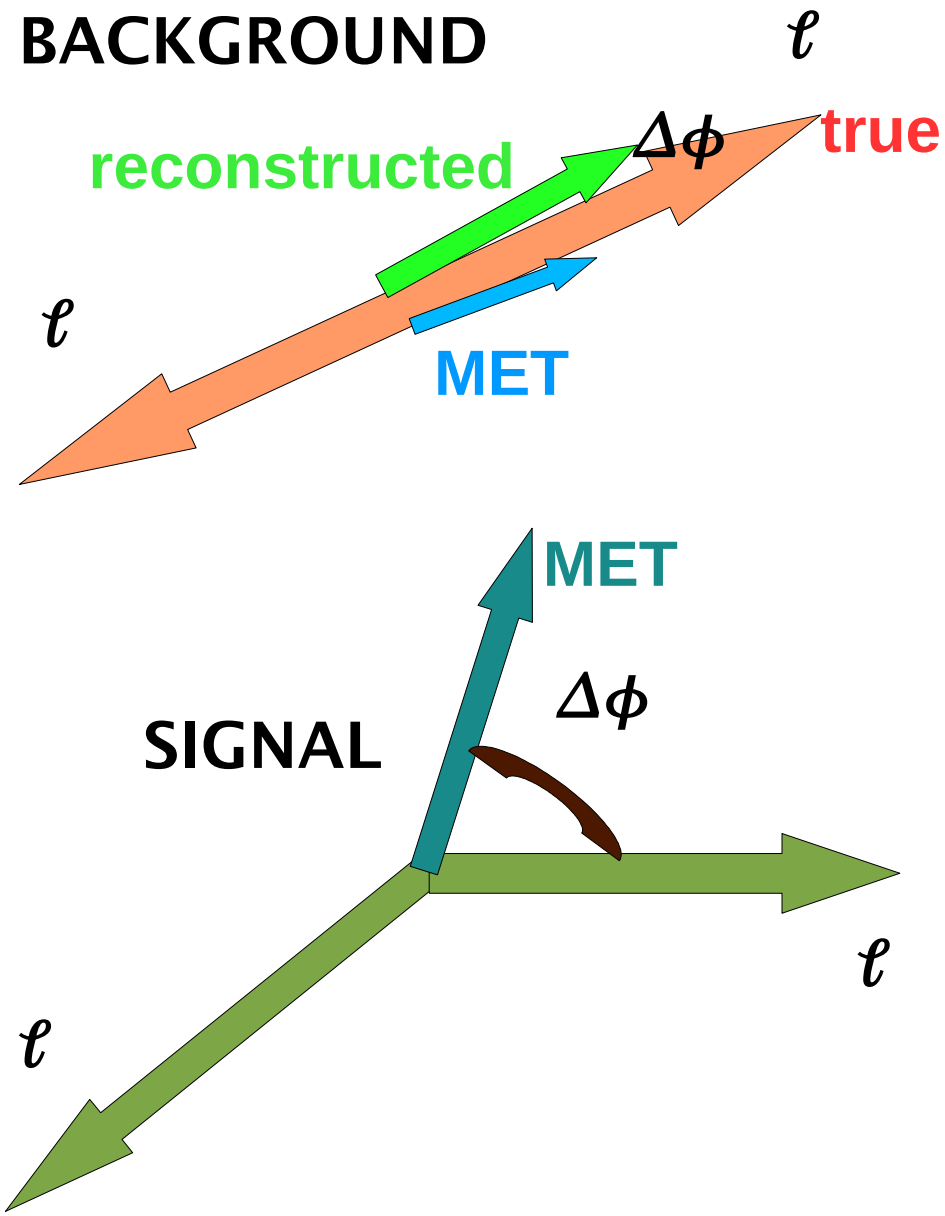




15 GeV < M(eμ) < 100 GeV

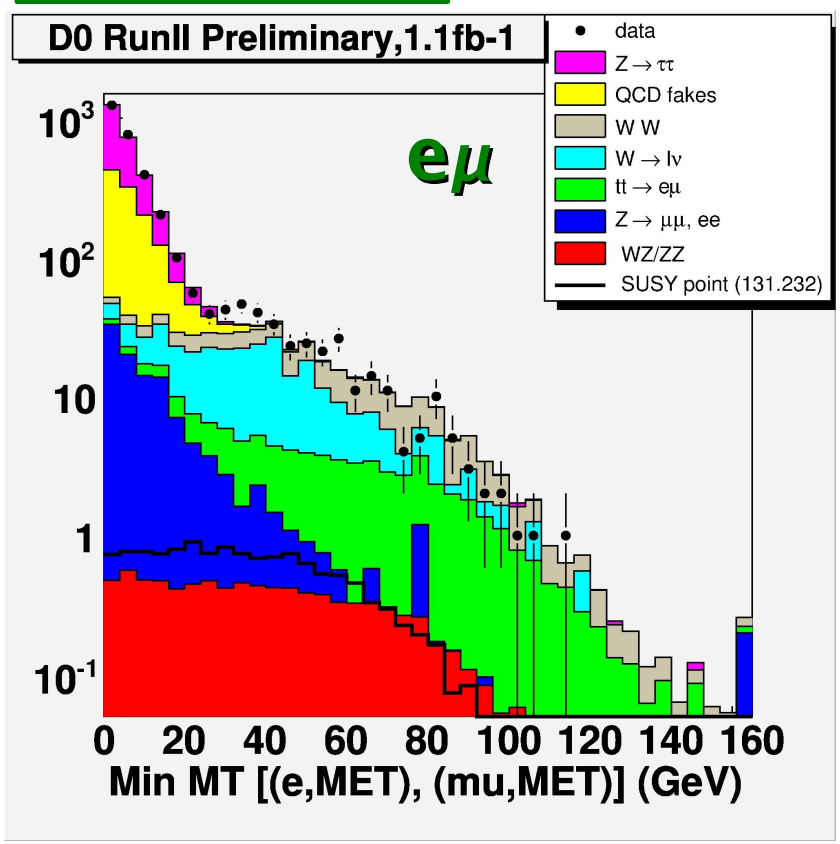
(and reject ee/$\mu\mu$ with M(ll)>70 GeV)

Mismeasured MET



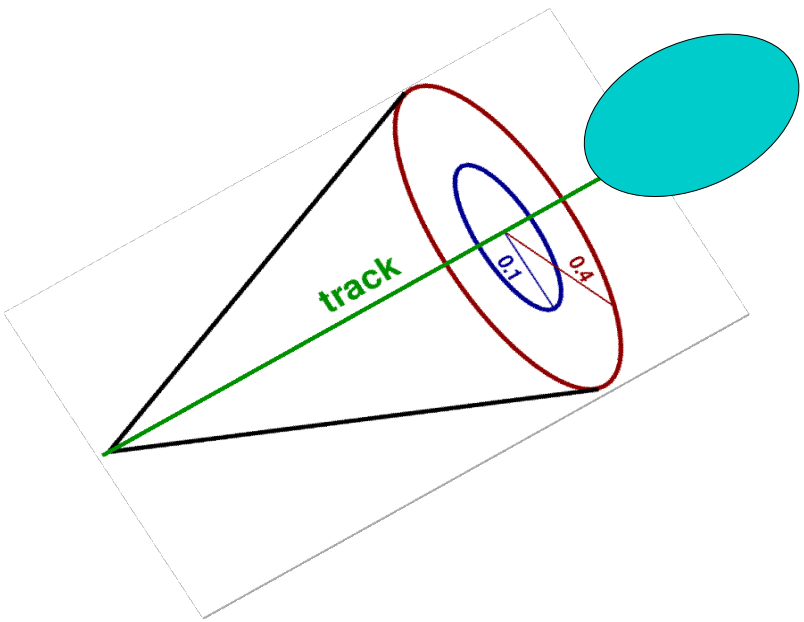
- large MET caused by poorly measured lepton energy will be in the same direction as the lepton ⇒ small values of M_T
- $M_T^2 = 2MET * p_T * (1-\cos(\Delta\varphi(MET, p_T))$

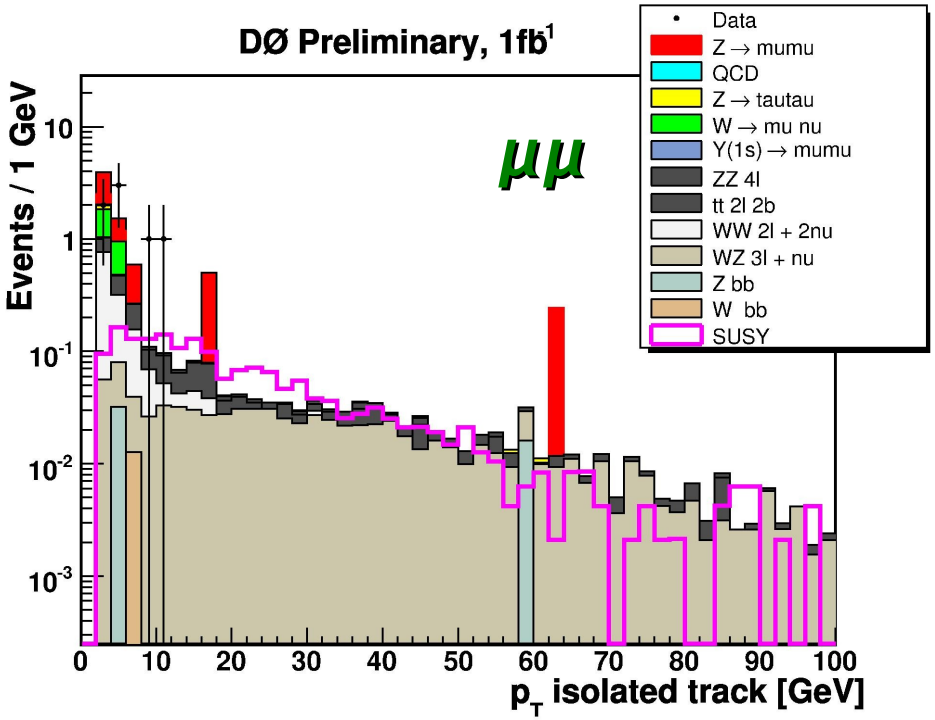
$M_T > 20$ GeV



Third Lepton

- To increase efficiency, require track instead of an identified lepton
- $p_T > 4 – 5$ GeV
- Isolation in tracker and calorimeter to reject background from jets
  - ΣpT of other reconstructed tracks in a hollow cone around track < 1 GeV
  - efficient for e, μ, τ(1 prong, 3 prong)





ee + Track

(stat. errors only)

Cut	Data	SM Expected	MSUGRA example
Preselection	118518	113592±175	18
Anti-Z	17459	18306±89	13
Third track	776	650±18	7.6
MET	2	1.97±0.73	4.6
MET x PT(3rd track)	0	0.76±0.67	3.5

42%	$Z \rightarrow \tau\tau$
33%	WZ
9%	WW
6%	ZZ
8%	ttbar

m($\tilde{\chi}^{\pm}$) = 125 GeV:

Signal efficiency 2.6% relative to lepton events with all flavour combinations

$e\mu/\mu\mu$ + Track

$e\mu$ Cut	Data	SM Expected	MSUGRA example
Preselection	3105	3080±34	14.4
MET-related	303	287±7	9.2
Isolated Track	5	5.1±0.9	4.6
Anti-Diboson	0	0.9±0.4	2.2

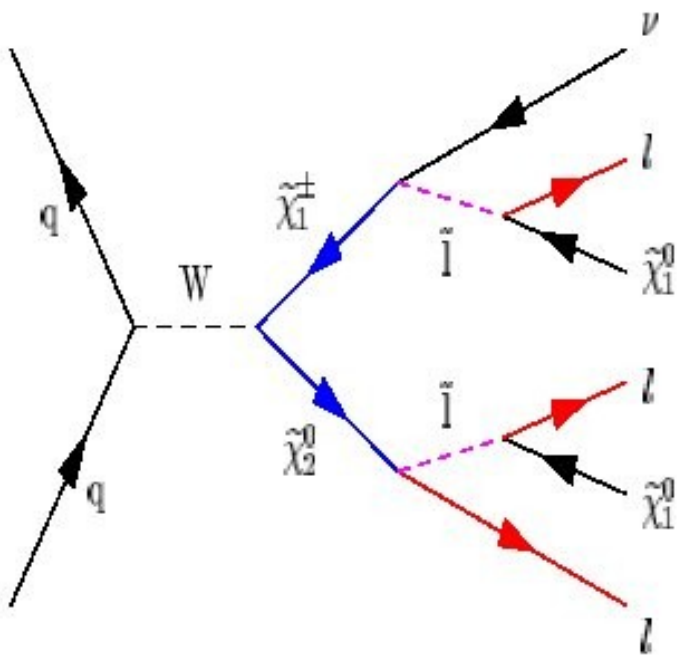
$\mu\mu$ Cut	Data	SM Expected	MSUGRA example
Preselection	81927	80373±130	12.1
Anti-Z	7486	8099±53	7.8
MET-related	51	54±4	4.9
Isolated track	4	2.6±1.2	2.9
MET x PT(3rd track)	2	0.3+0.7-0.0	1.8

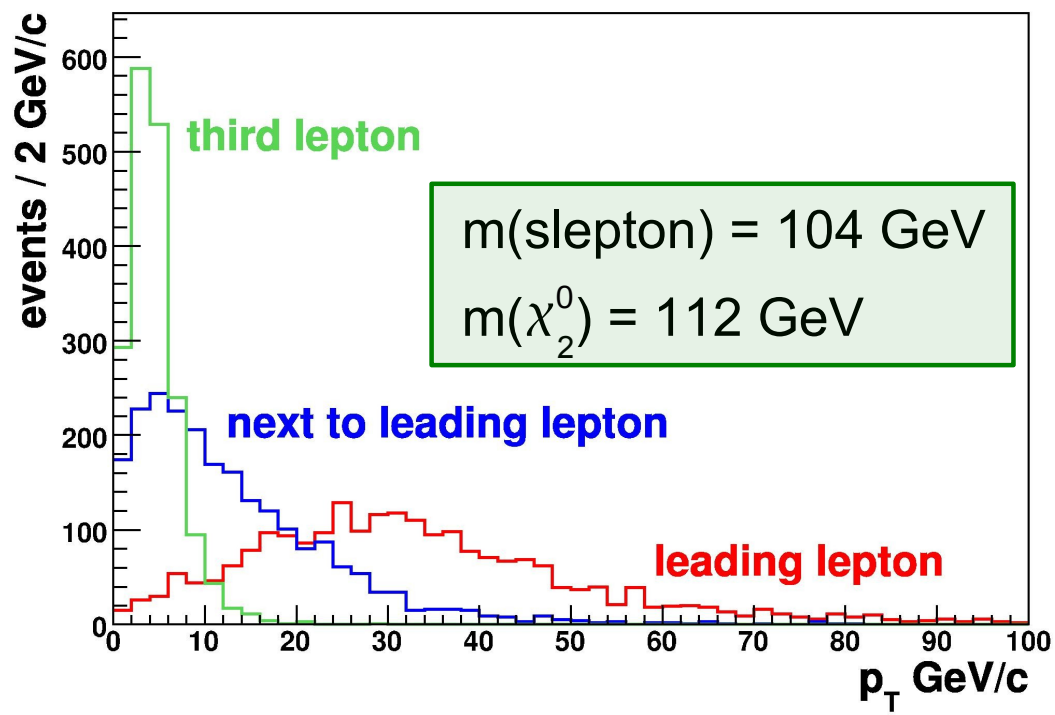
(stat. errors only)

Like-sign $\mu\mu$

m(sleptons) < m($\tilde{\chi}^0_2$): two body decays of $\tilde{\chi}^0_2 \rightarrow$ slepton + lepton

very soft third lepton possible

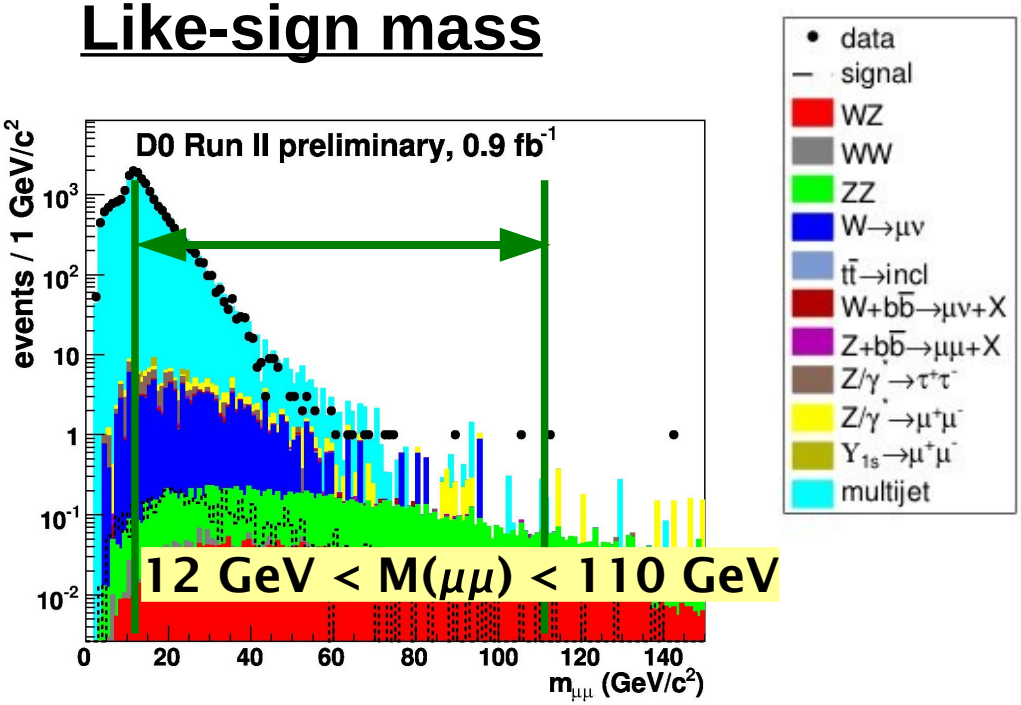




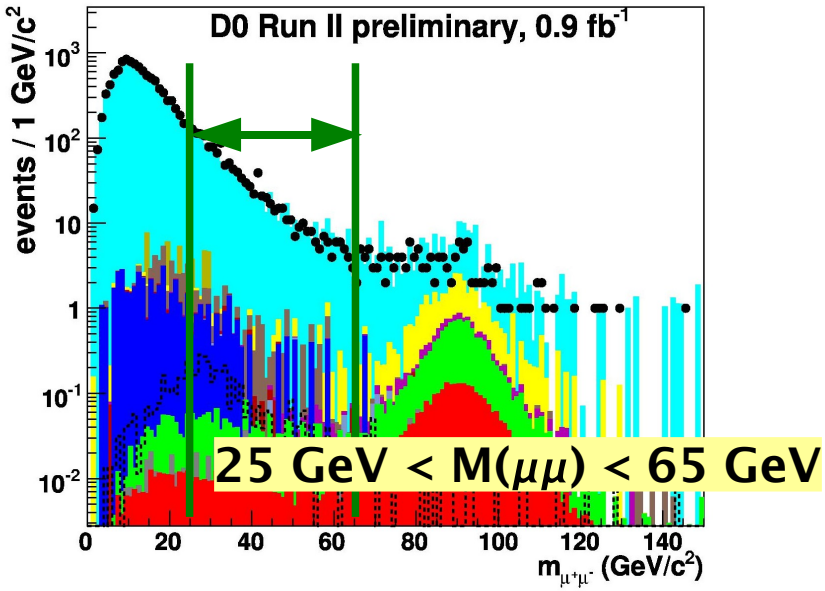
- Instead of requiring two leptons + track
  - Require two leptons of same charge
  - Reduces background significantly

Like-sign $\mu\mu$

Like-sign mass



Opposite-sign mass



Cut	Data	SM Expected	MSUGRA example
Preselection	15234	14922±981	8.4±0.6
Minv OS	3569	3479±232	7.6±0.6
Minv LS	2	2.9±0.8	5.7±0.5
MET	1	1.7±0.6	4.6±0.4
MET x PT(μ2)	1	1.1±0.4	4.0±0.4

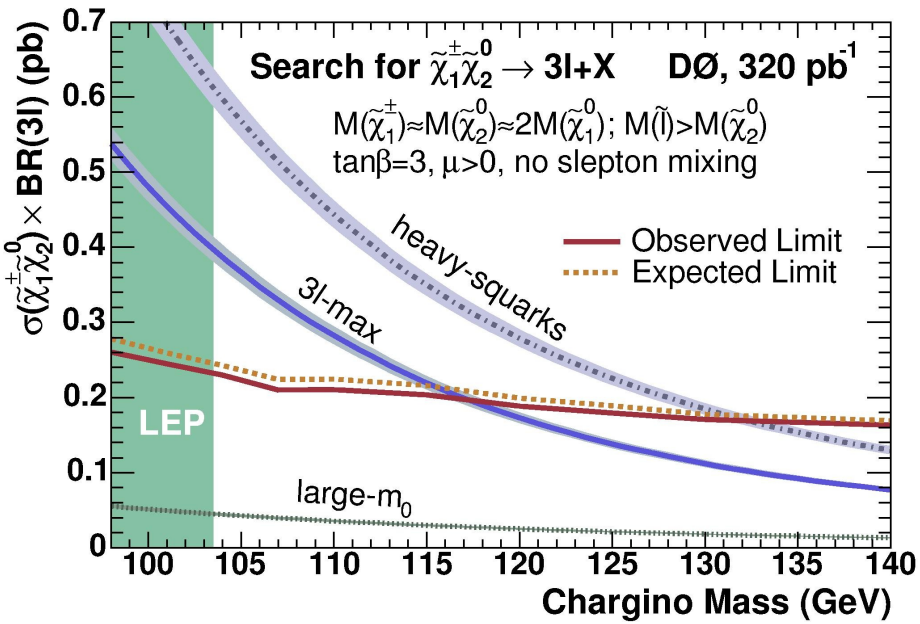
17%	QCD
18%	W
19%	Z
18%	WZ
14%	ZZ
14%	Z+bb

(stat. errors only)

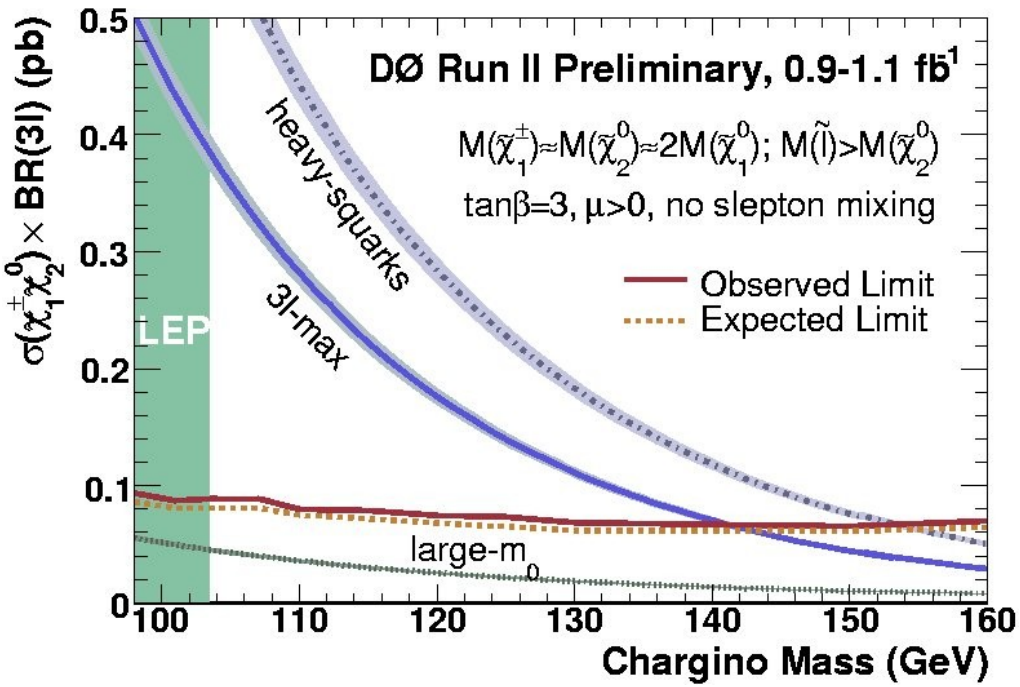
Trilepton Result I

- Combine by subtracting overlap from weakest analysis
- upper limit σ x BF(3l)

- Chargino mass limit of 141 GeV in scenario with enhanced BF into leptons
  - "3l-max": mSUGRA with light sleptons, but heavier than $\tilde{\chi}_2$



Published result

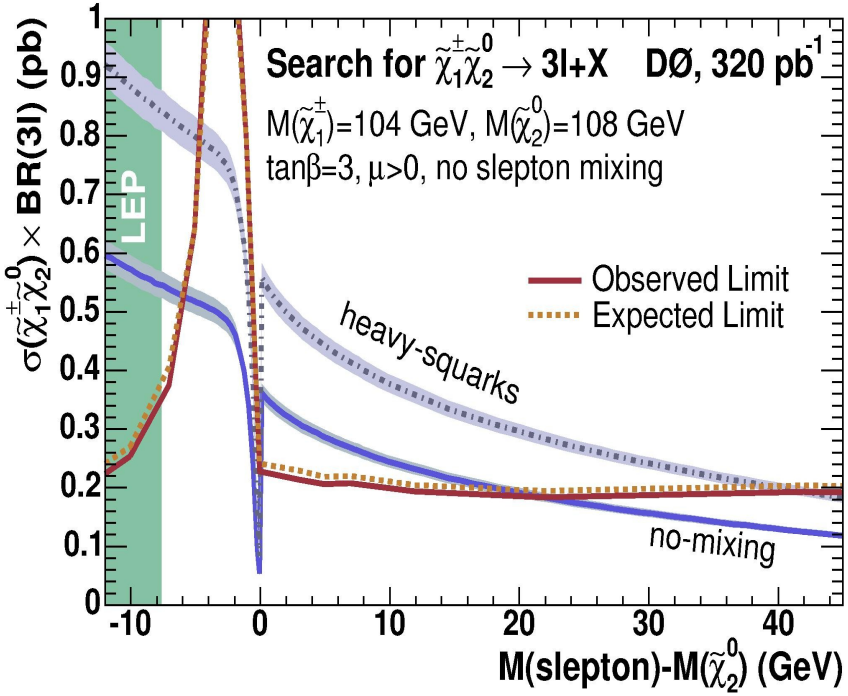


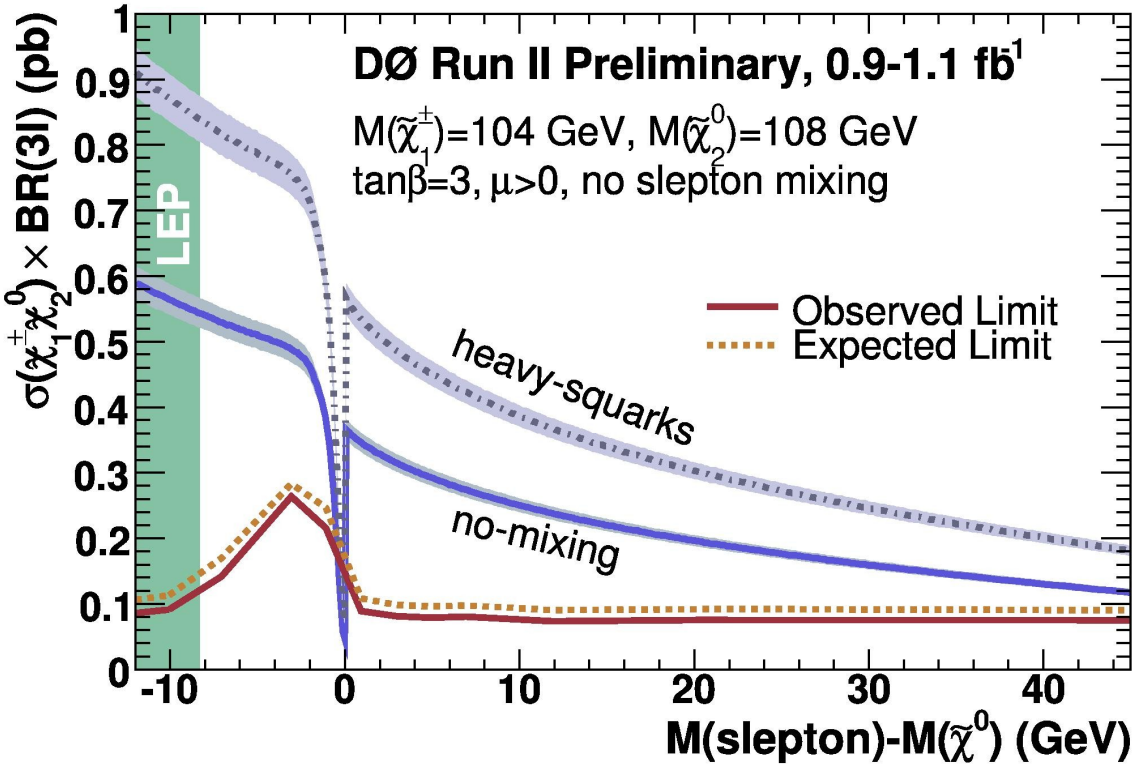
New combination

– "large m_0": W / Z exchange dominates (small BF(3l))

– "heavy-squarks": maximal cross section, no interference

Trilepton Result II





Published result **New combination**

- Significant improvement
- Limit stable as a function of mass

Randall-Sundrum Gravitons

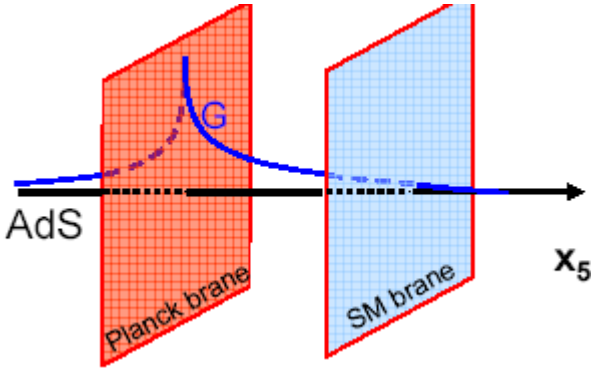
Use extra dimensions to address hierarchy problem

RS model:

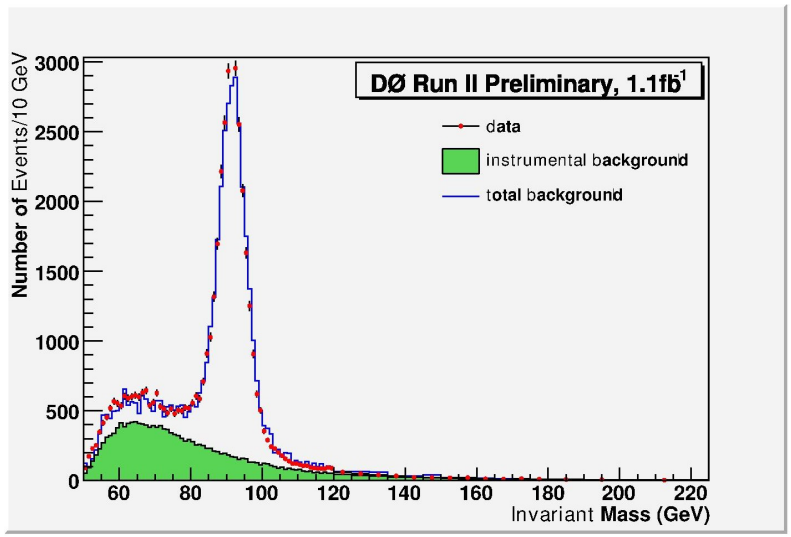
One 5th (infinite) ED with warped geometry

Gravity is localized on a brane other than the SM

KK excitations have spacings of order TeV



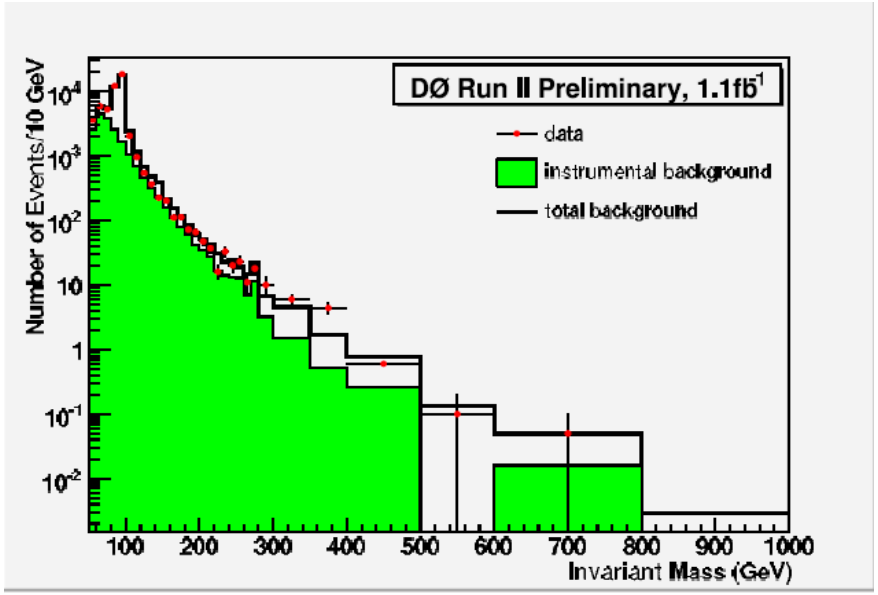
Signature: **narrow, high mass resonances**



Combined ee + γγ:

- 2 central ($|\eta|<1.1$) electromagnetic objects with $E_T > 25$ GeV
- Background: DY and di-photon
- QCD background estimated from data

Randall-Sundrum Gravitons – Result

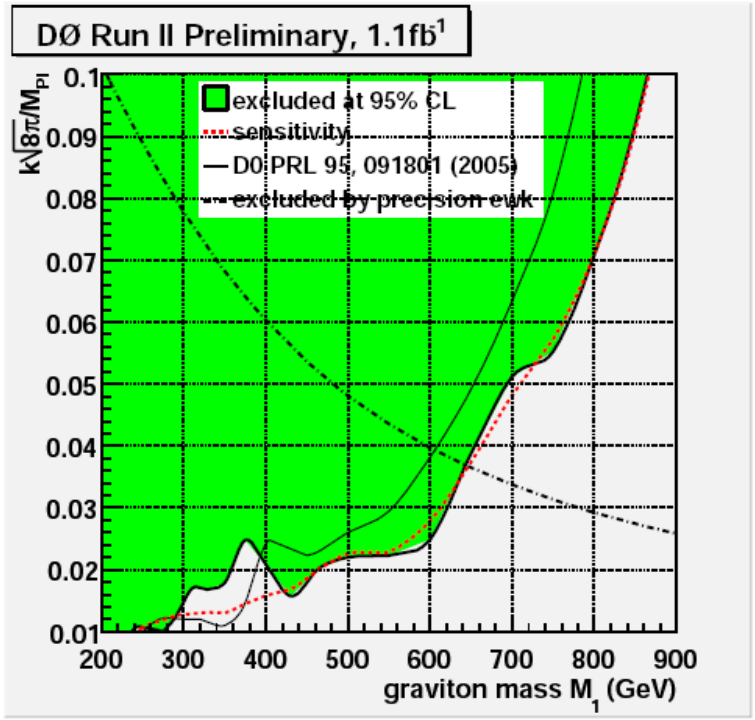


Sliding mass window

Most of the sensitivity is in di-photons (BF = 2 * ee)

Two model parameters:

Mass and coupling (κ/M_{Pl}) →



(similar CDF result)

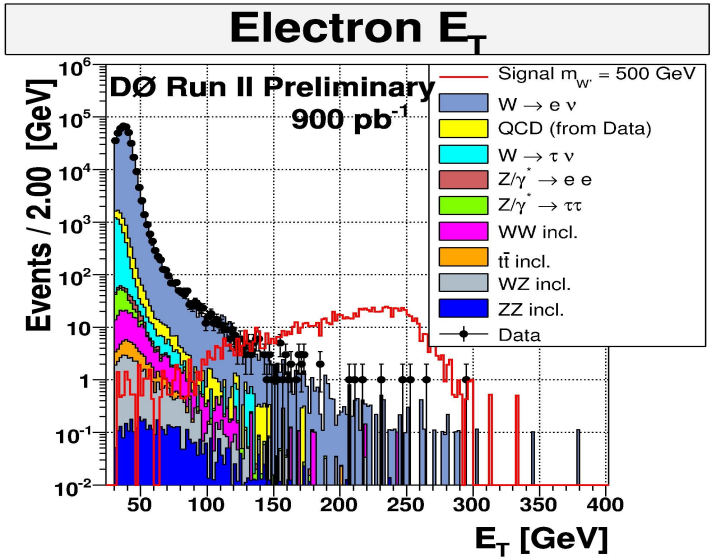
Previously: 785 GeV based on 260 pb^{-1}

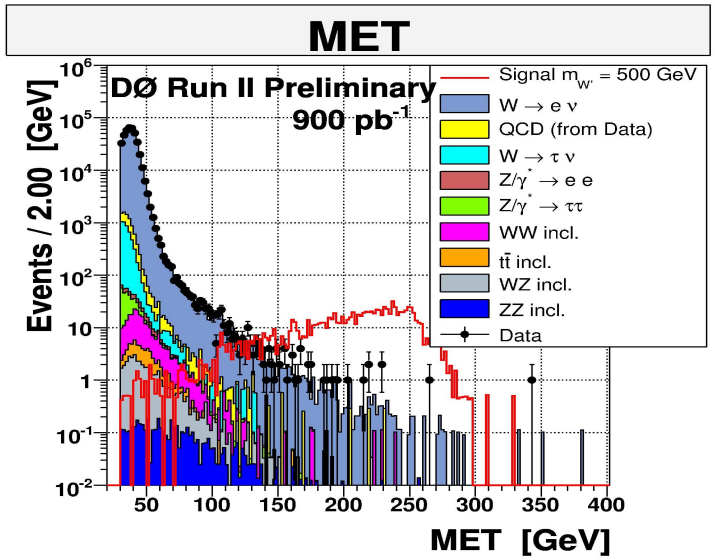
For κ/M_{Pl} = 0.1: M_1 > 865 GeV

New Gauge Bosons: W' → e ν

- Predicted in many beyond-SM scenarios, GUT's, e.g. left-right symmetric models ($SU(2)_L$ x $SU(2)_R$)
- Benchmark: a SM-like W'
- Selection: isolated central electron with E_T>30 GeV
- MET>30 GeV, M_T>150 GeV
- Estimate QCD background from low M_T region

$M_T = M(p_T(e), MET)$





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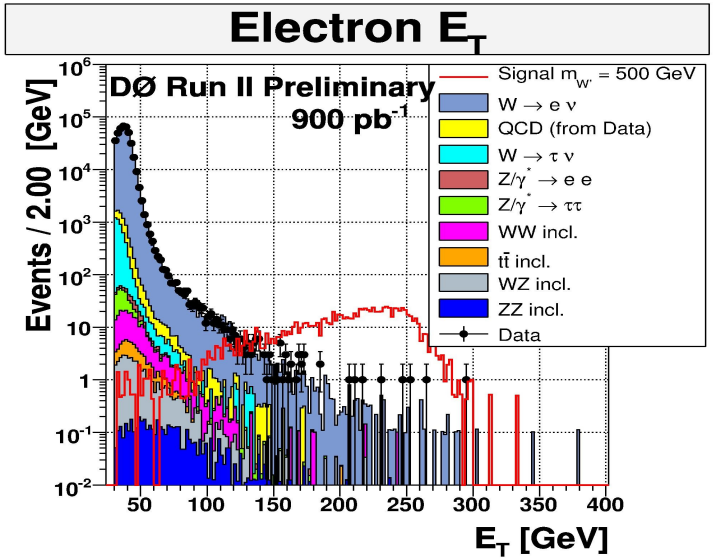

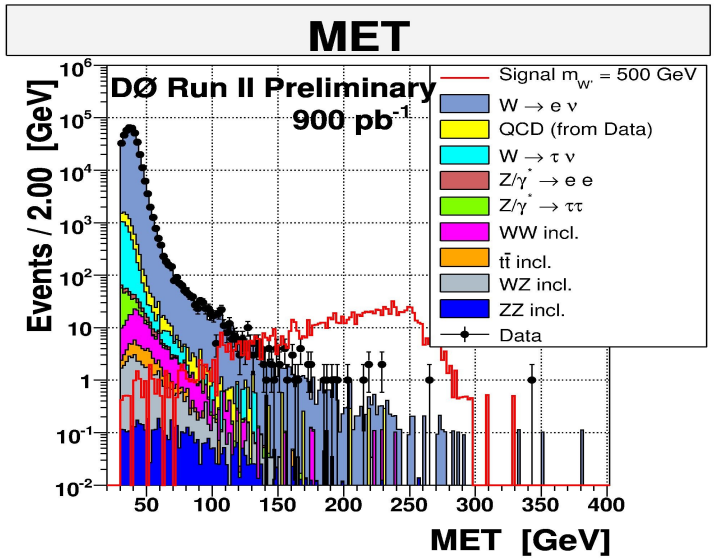

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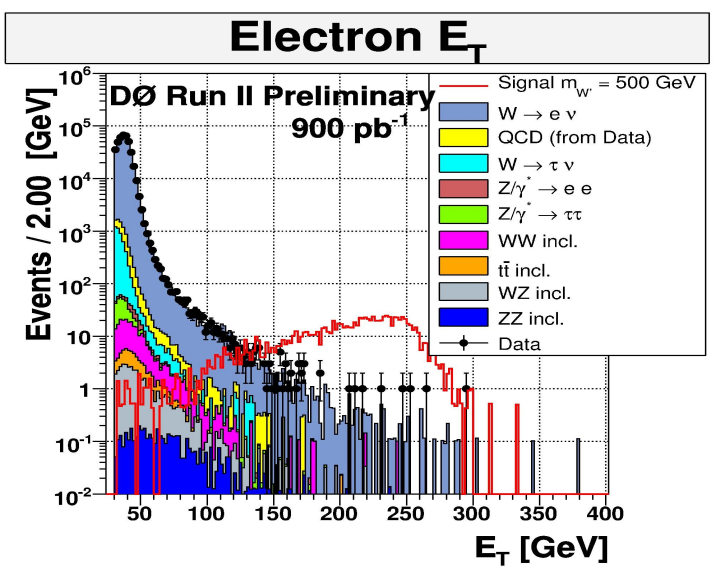
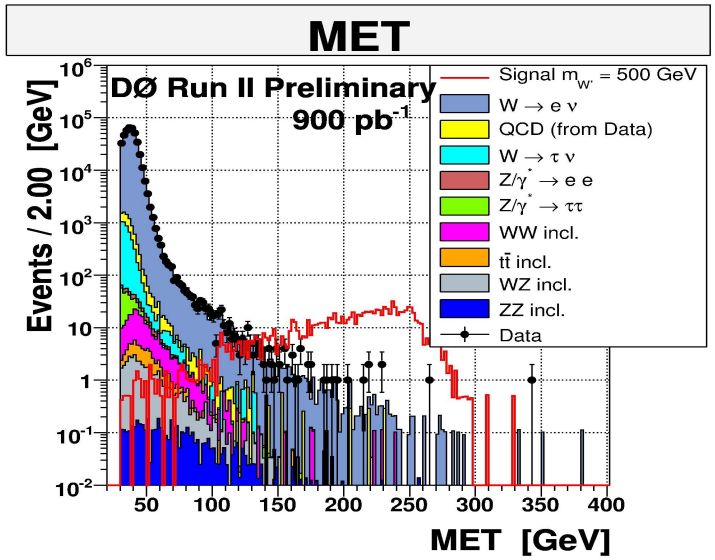
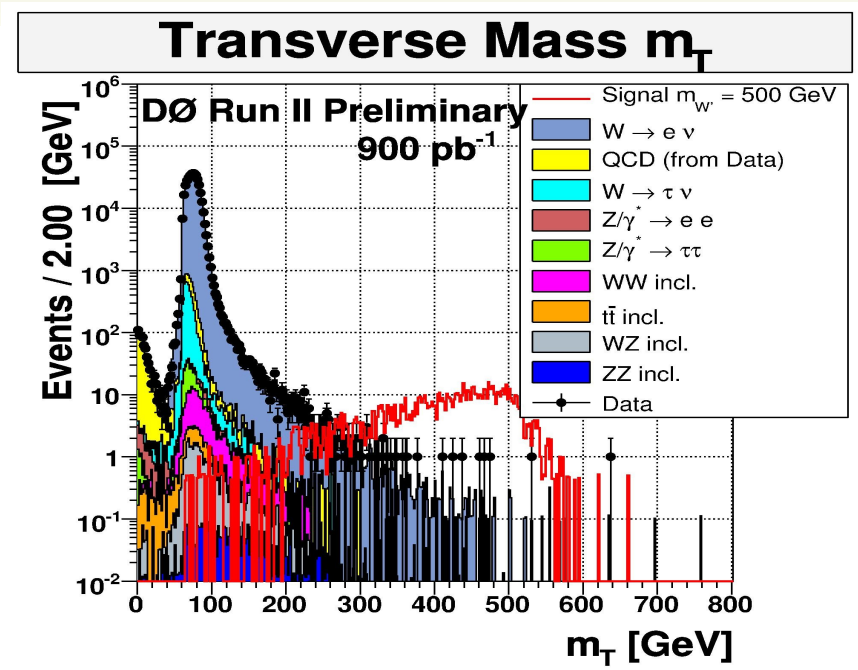
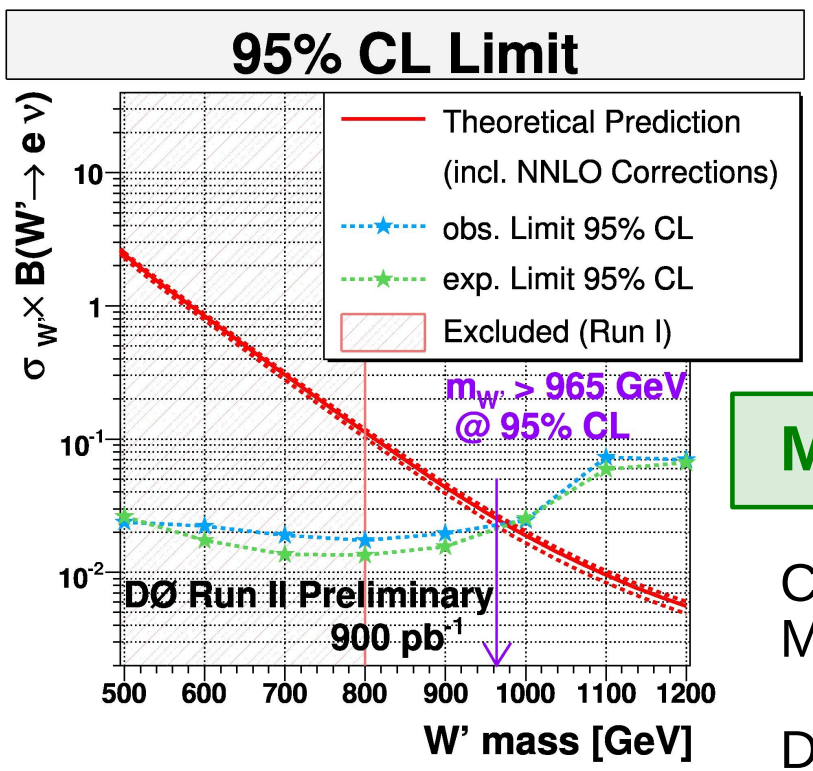




New Gauge Bosons: W' – Result

- Data:
  630 events
- SM expectation:
  623 ± 18 (stat) + 83 – 75 (syst) events
- Use M_T distribution to derive limits

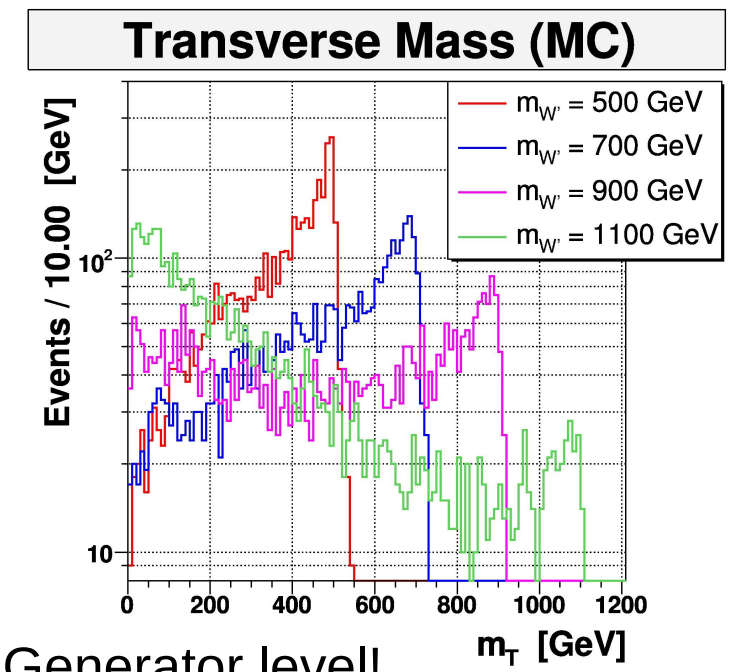




M(W') > 965 GeV

CDF Run II (e ν):
M(W') > 788 GeV

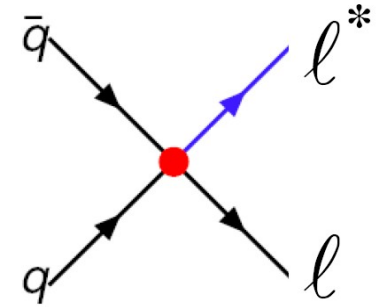
D0 Run I (di-jets):
M(W') > 800 GeV



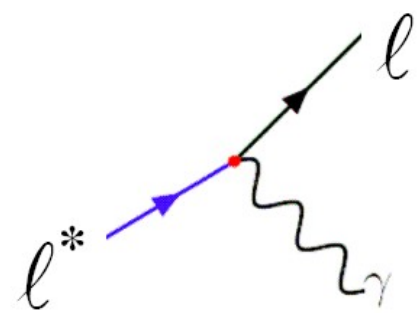
Generator level!

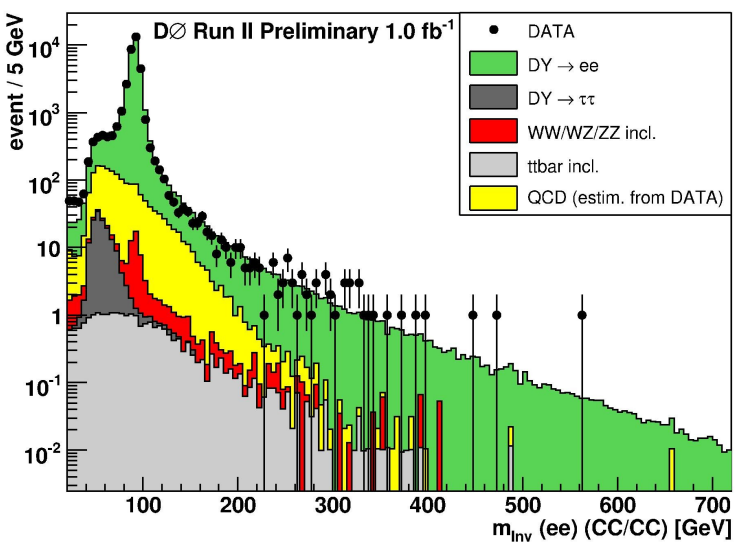
Lepton Compositeness: e*

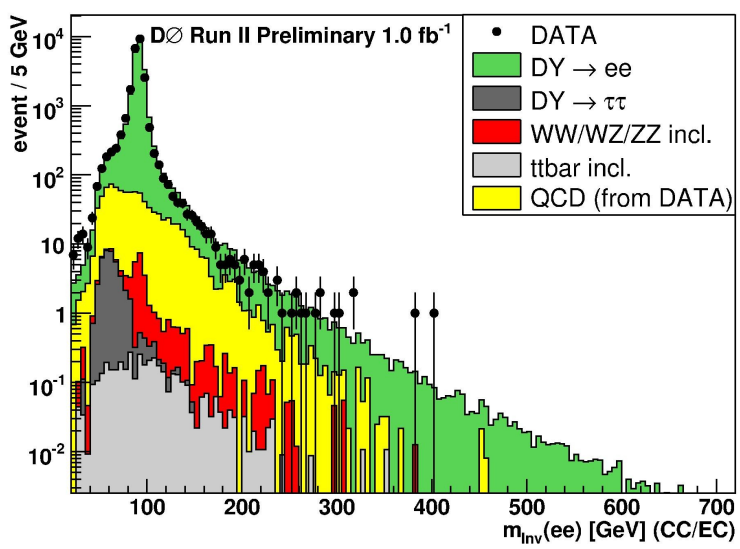
- Learning from thousands of years of history, quarks and leptons may be made of smaller pieces ("preons")
  - Allows excited states (e^*, μ^*, q^*)
  - Describe as contact interaction
  - e* for the first time at DØ



- Decay: gauge interaction ($e^* \to e\,\gamma$, ν W, e Z) or CI ($e^* \to e\,f\,\bar{f}$)
- Search in e e γ







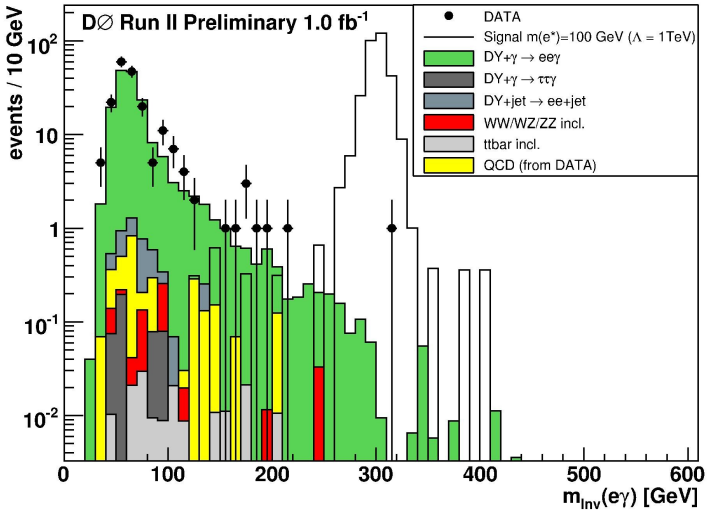
Two isolated electrons with

E_T > 25 GeV and

E_T > 15 GeV

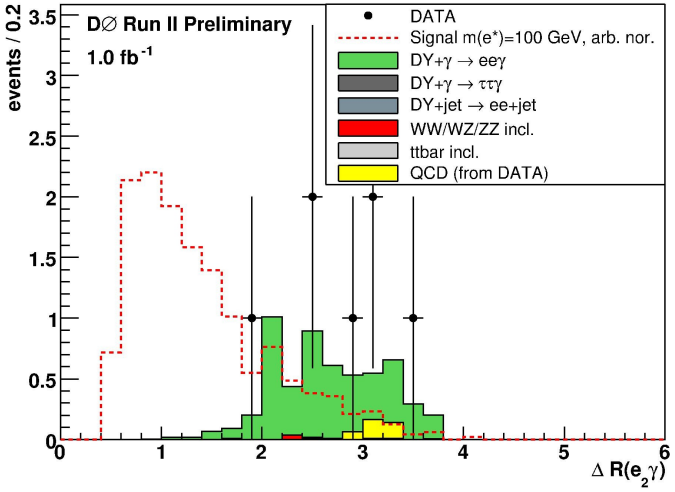
Excited Fermions: e*

- Require **isolated photon with E_T > 15 GeV**
- Observe **259 events with expectation 232 ± 3 ± 29 events**



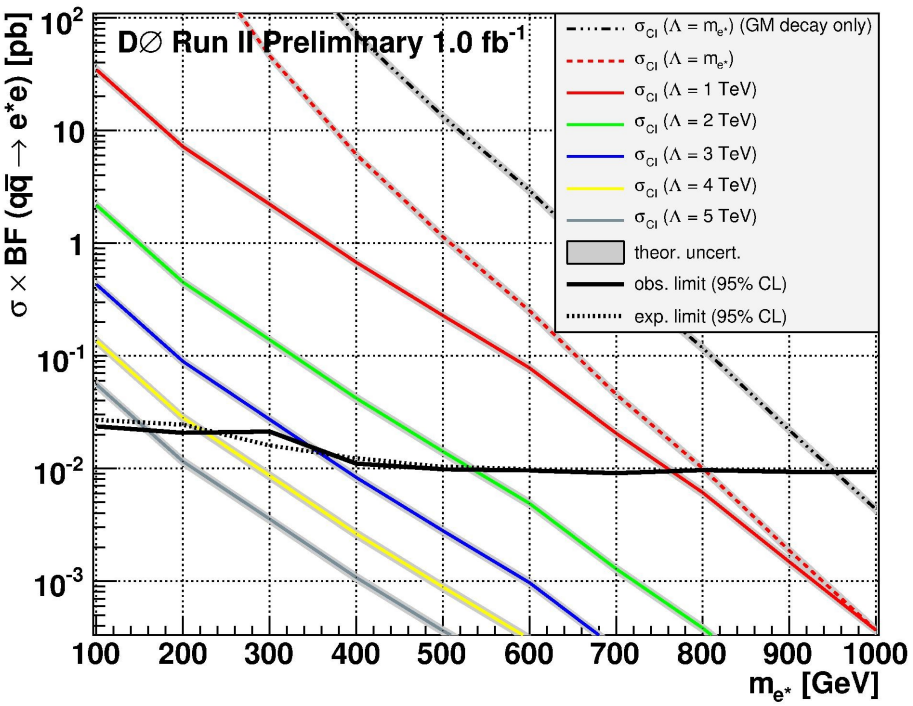
- Search for peak in e+γ invariant mass
- Optimize selection criteria
  - Combination e1+γ or e2+γ
  - Mass window / <u>single sided cut</u>
  - |η| acceptance (for small m(e*))
  - Separation (for small m(e*))
- Signal efficiency 13 – 33%

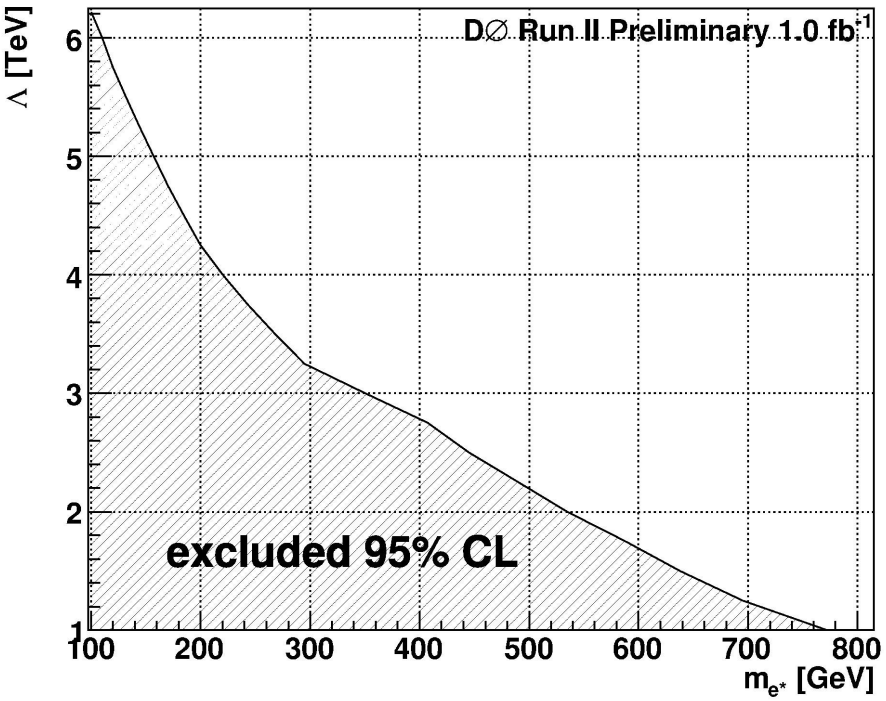
m_{e^*} [GeV]	Data	SM Expectation
100	0	$0.31 \pm 0.08 \pm 0.03$
200	0	$0.20 \pm 0.09 \pm 0.02$
300	1	$0.28 \pm 0.10 \pm 0.03$
400	0	$0.22 \pm 0.17 \pm 0.02$
500	0	$0.018 \pm 0.012 \pm 0.002$
600	0	$0.0026 \pm 0.0006 \pm 0.0003$
700	0	$0.0008 \pm 0.0004 \pm 0.0001$
800	0	$0.0005 \pm 0.0003 \pm 0.00006$
900	0	$0.0002 \pm 0.0002 \pm 0.00002$
1000	0	$0.0002 \pm 0.0002 \pm 0.00003$



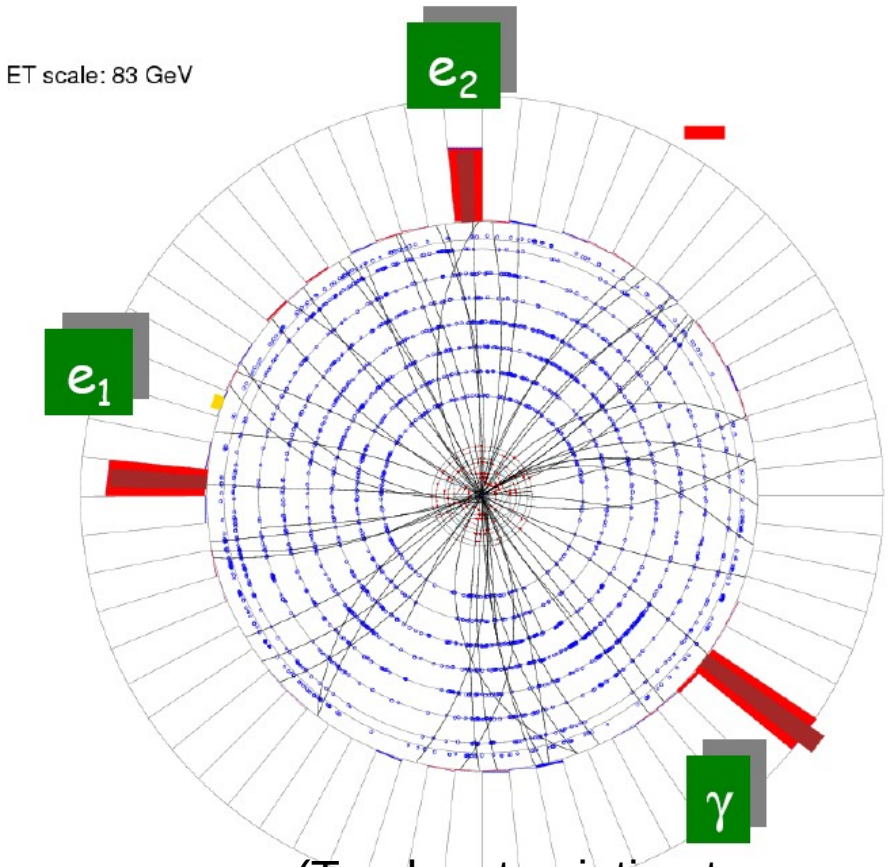
Excited Fermions: e* – Results

- Limit: **m(e*) > 756 GeV for compositeness scale Λ = 1 TeV**
- For comparison: m(e*) > 946 GeV when neglecting CI decays and for Λ = m(e*)
  - CDF Run II: m(e*) > 879 GeV
- Corresponding exclusion in Λ vs. m(e*) plane



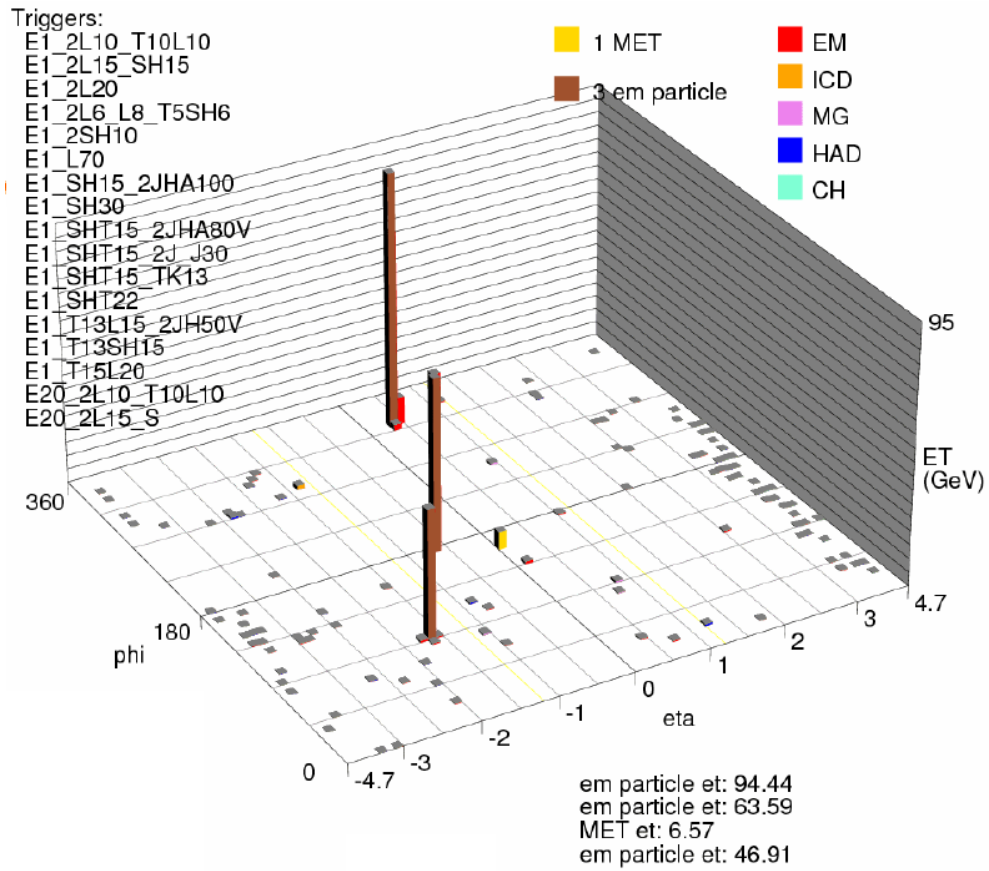


e* Candidate Event



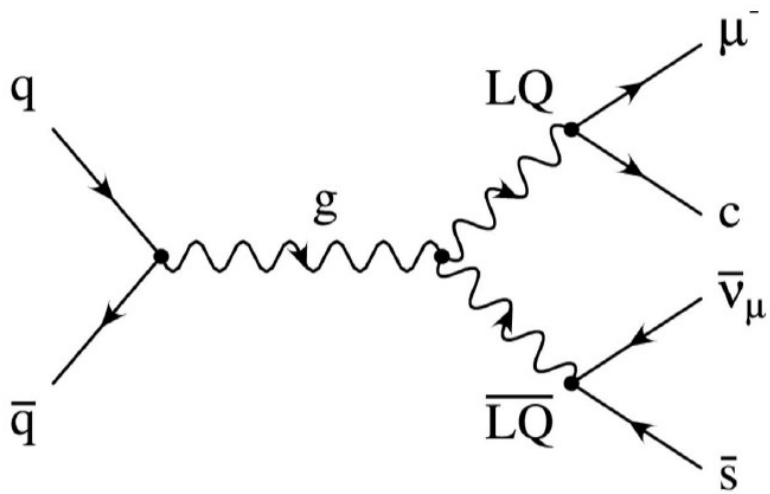
(Track not pointing to EM cluster)

$M(e_2, \gamma) = 195$ GeV



Leptoquarks: 2nd Generation

- Leptoquark = Boson with third-integer charge, carrying lepton and quark quantum numbers
- Three generations, each coupling to one fermion generation only (lepton number violation, FCNC)
- Searched for pair production of all three generations and different decays, with 200 – 400 pb^{-1}
- Mass limits range from 117 GeV to > 300 GeV
- Pair production: no dependence on coupling of LQ to lepton and quark

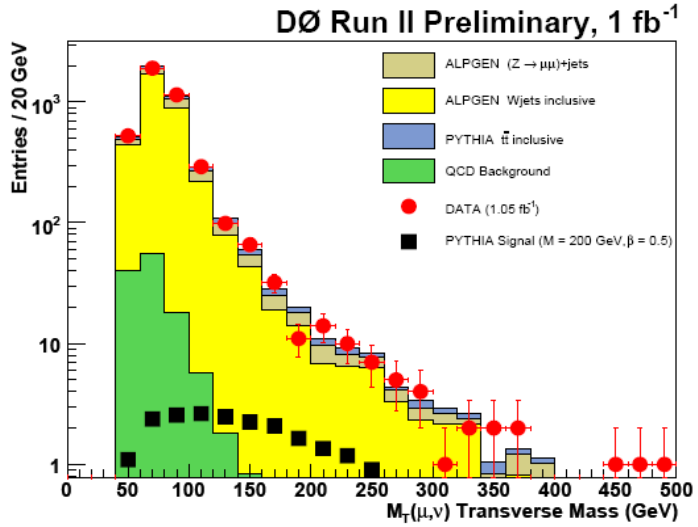


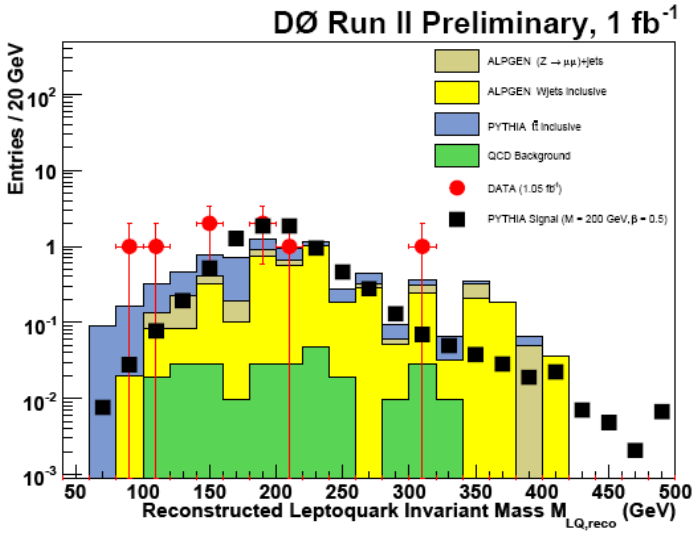
β = BF(LQ $\rightarrow \mu$ q)

<u>New:</u> search for $\mu + \nu$ + 2 jets
$\rightarrow$ maximal for β = 0.5

Leptoquarks: 2nd Generation – Selection

- Basic selection:
  - Exactly one muon with p_T>20 GeV, at least 2 jets with p_T>25 GeV, MET > 25 GeV
  - MET not aligned with muon to minimize mis-measured MET
  - $M_T(\mu, \nu)$ > 50 GeV to reject QCD background



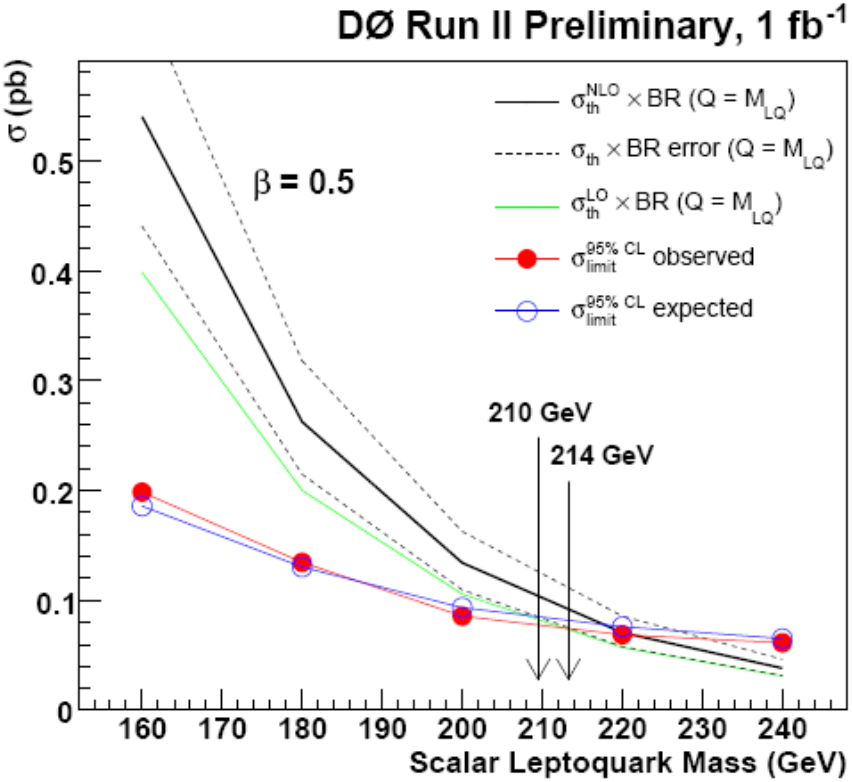


- Optimize for m(LQ) = 200 GeV:
  - $M_T(\mu, \nu)$ > 160 GeV – remove background from W production
  - Scalar transverse energy $S_T = p_T(\mu) + p_T(\text{jet1}) + p_T(\text{jet2}) + \text{MET} > 350$ GeV
  - $M_T(\nu, \text{jet1})$ > 150 GeV – correlated with LQ mass
  - |M(LQ)_rec – M(LQ)_gen| < 100 GeV for the μ-jet combination closest to searched LQ

Leptoquarks: 2nd Generation – Results

Samples	$\frac{M_T(\mu\nu)}{GeV} > 160$	$\frac{S_T}{GeV} > 350$	$\frac{M_T(\nu jet_1)}{GeV} > 150$	$\frac{\lvert M_{LQ,reco} - M_{LQ,gen}\rvert}{GeV} < 100$
$W(+jets) \to l\nu + jets$	$67 \pm 3 \pm 14$	$35 \pm 2 \pm 7$	$4.0 \pm 0.7 \pm 0.8$	$3.2 \pm 0.6 \pm 0.7$
$Z/\gamma^*(+jets) \to \mu\mu + jets$	$20 \pm 1 \pm 3$	$10 \pm 1 \pm 1$	$0.92 \pm 0.24 \pm 0.12$	$0.68 \pm 0.19 \pm 0.09$
$t\bar{t}$ (inclusive)	$10.0 \pm 0.4 \pm 2.2$	$7.2 \pm 0.4 \pm 1.5$	$2.6 \pm 0.2 \pm 0.6$	$2.3 \pm 0.2 \pm 0.5$
QCD	$0.79 \pm 0.09 \pm 0.16$	$0.52 \pm 0.07 \pm 0.10$	$0.26 \pm 0.05 \pm 0.05$	$0.22 \pm 0.05 \pm 0.04$
Total Background	$98 \pm 3 \pm 14$	$53 \pm 2 \pm 7$	$7.8 \pm 0.8 \pm 0.1$	$6.4 \pm 0.7 \pm 0.8$
Data	94	48	8	6
$\varepsilon_{\mathbf{signal}}$	$0.130 \pm 0.002 \pm 0.011$	$0.110 \pm 0.002 \pm 0.010$	$0.082 \pm 0.001 \pm 0.007$	$0.079 \pm 0.001 \pm 0.007$

(m(LQ) = 200 GeV, others similar)

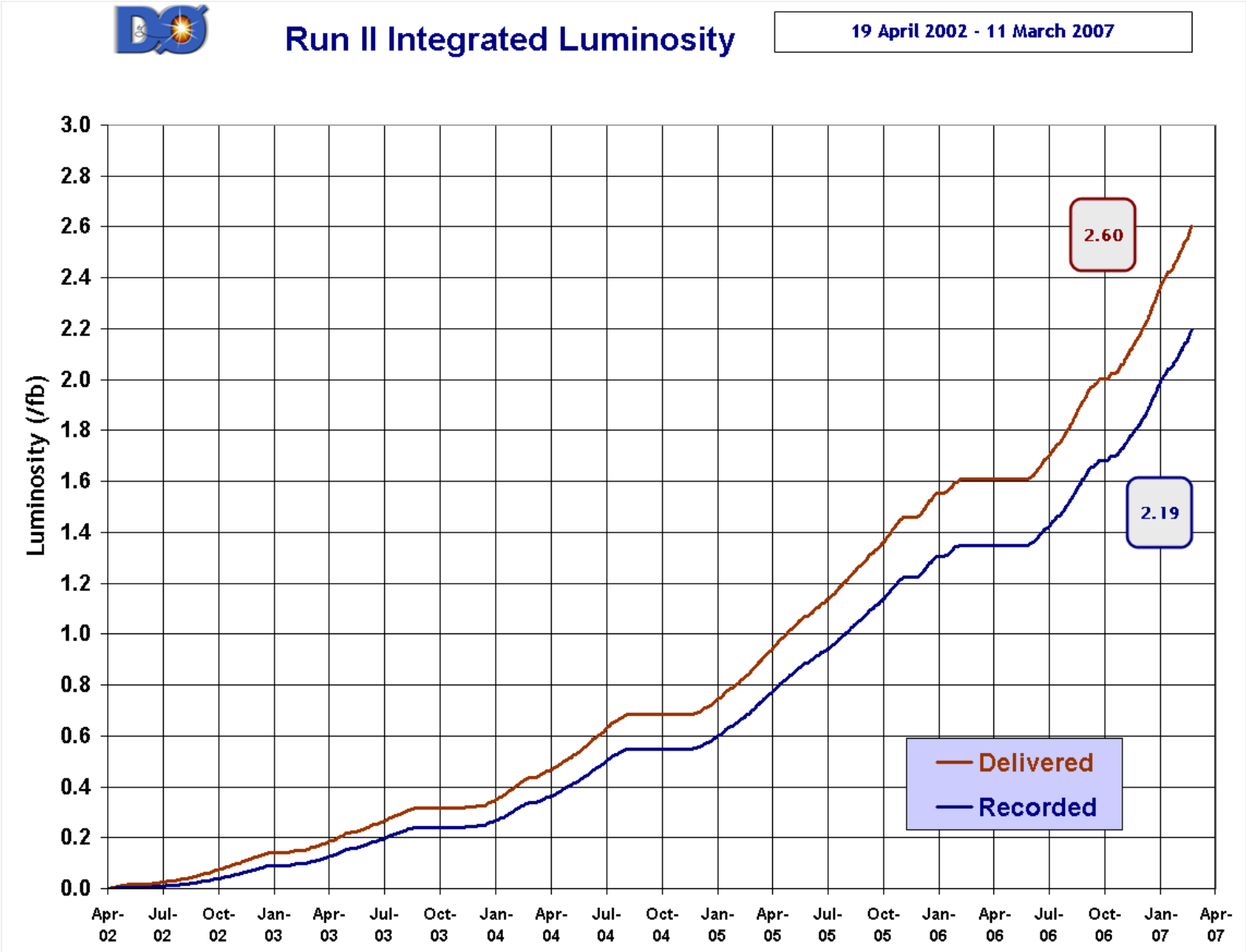


m(LQ) > 214 GeV for β = 0.5

Compare:

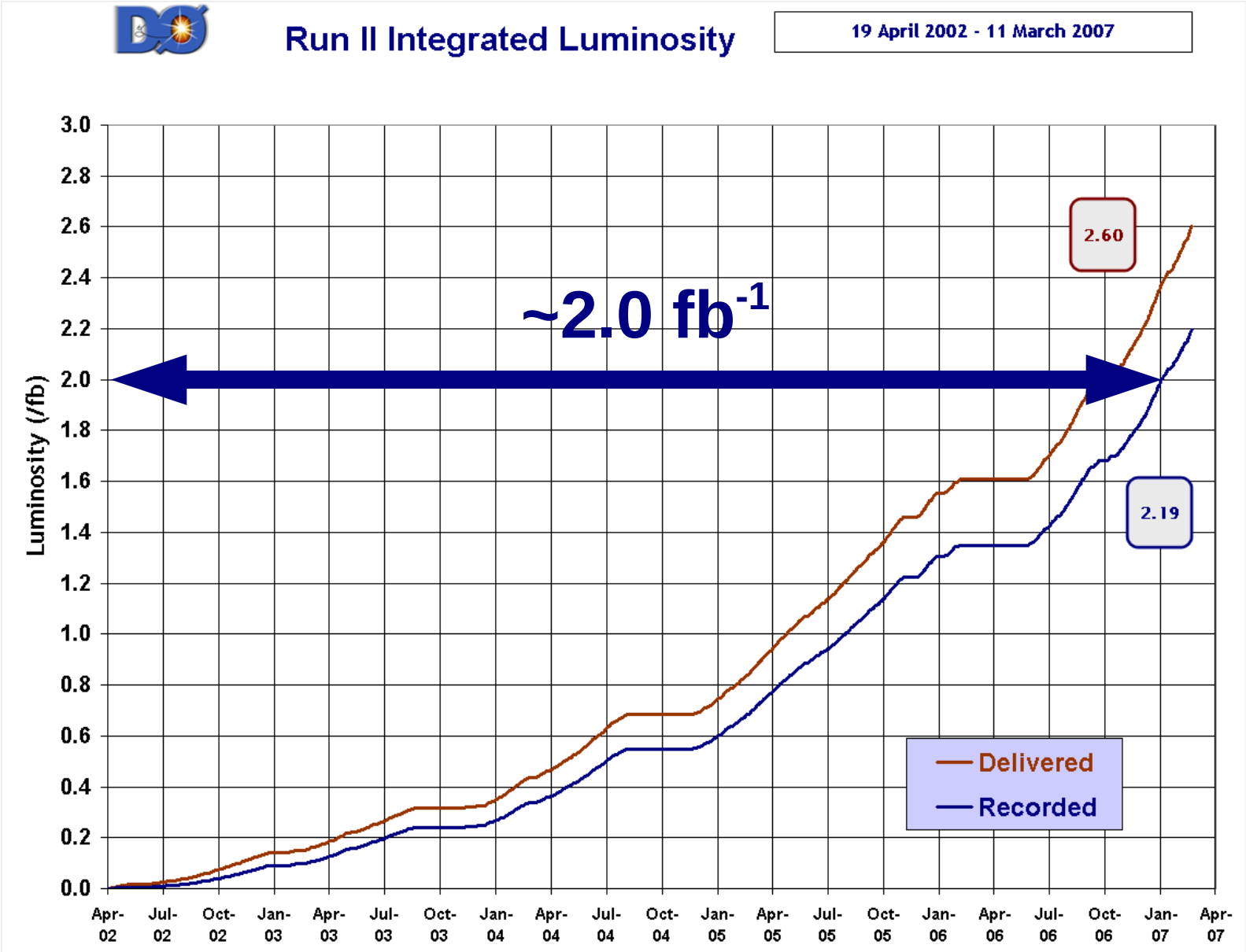
170 GeV	**CDF Run II (μν jj)**
160 GeV	**DØ Run I (μν jj)**
208 GeV	CDF comb. channels
204 GeV	DØ comb. Channels (μμ jj, μν jj, νν jj)

Perspective



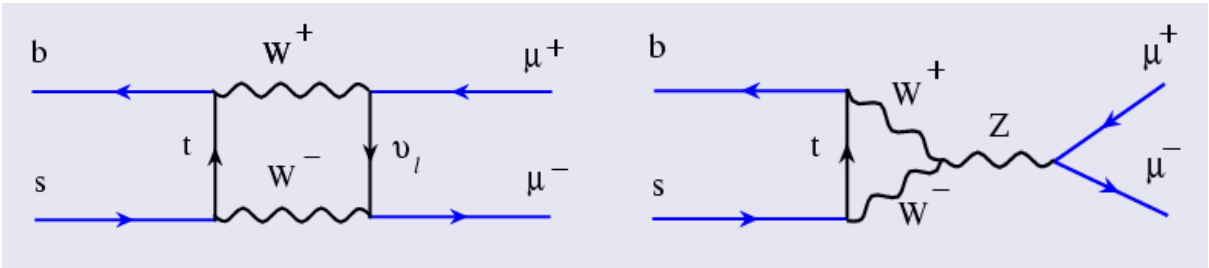
- Plus Layer 0, trigger upgrades, ...

Perspective



- Plus Layer 0, trigger upgrades, ...

The First "2 fb^{-1}" Result: $B_s \to \mu\mu$

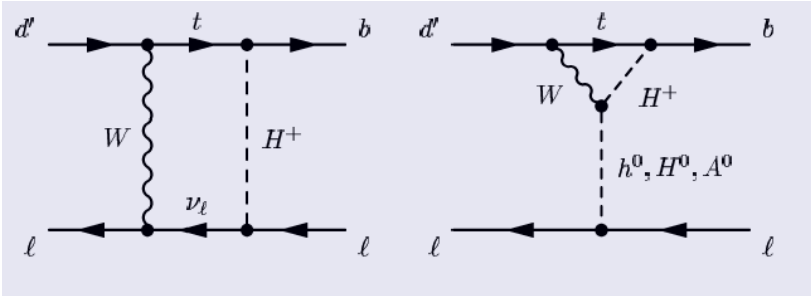


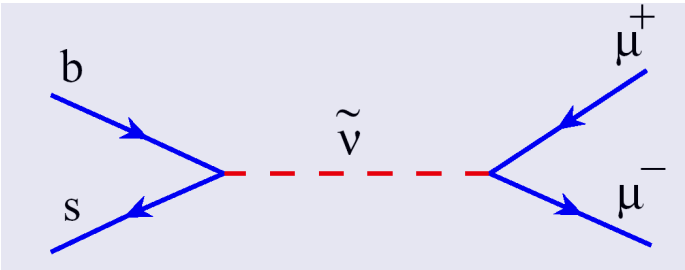
Standard model:

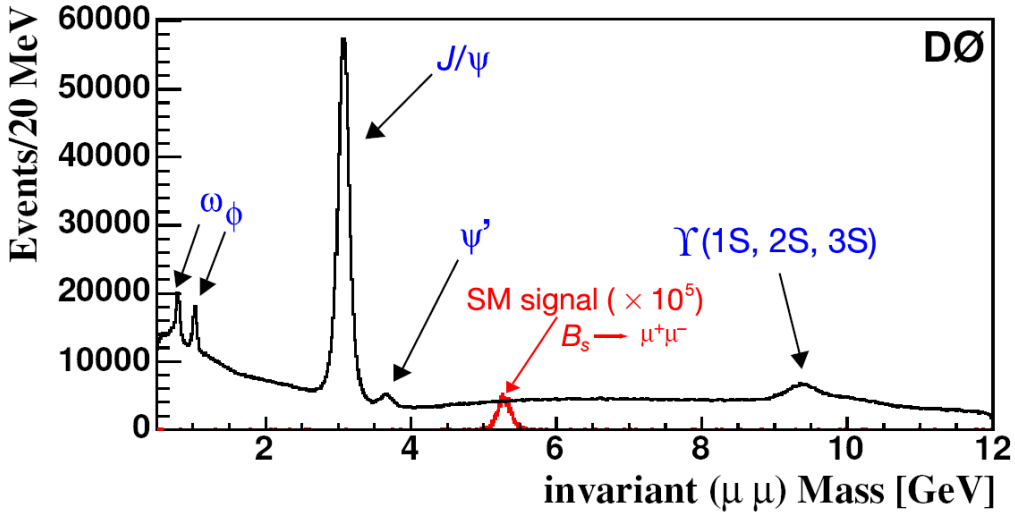
BF ($B_s \to \mu\mu$) $\simeq 3 - 4 \cdot 10^{-9}$

Sensitive to new physics, e.g.:

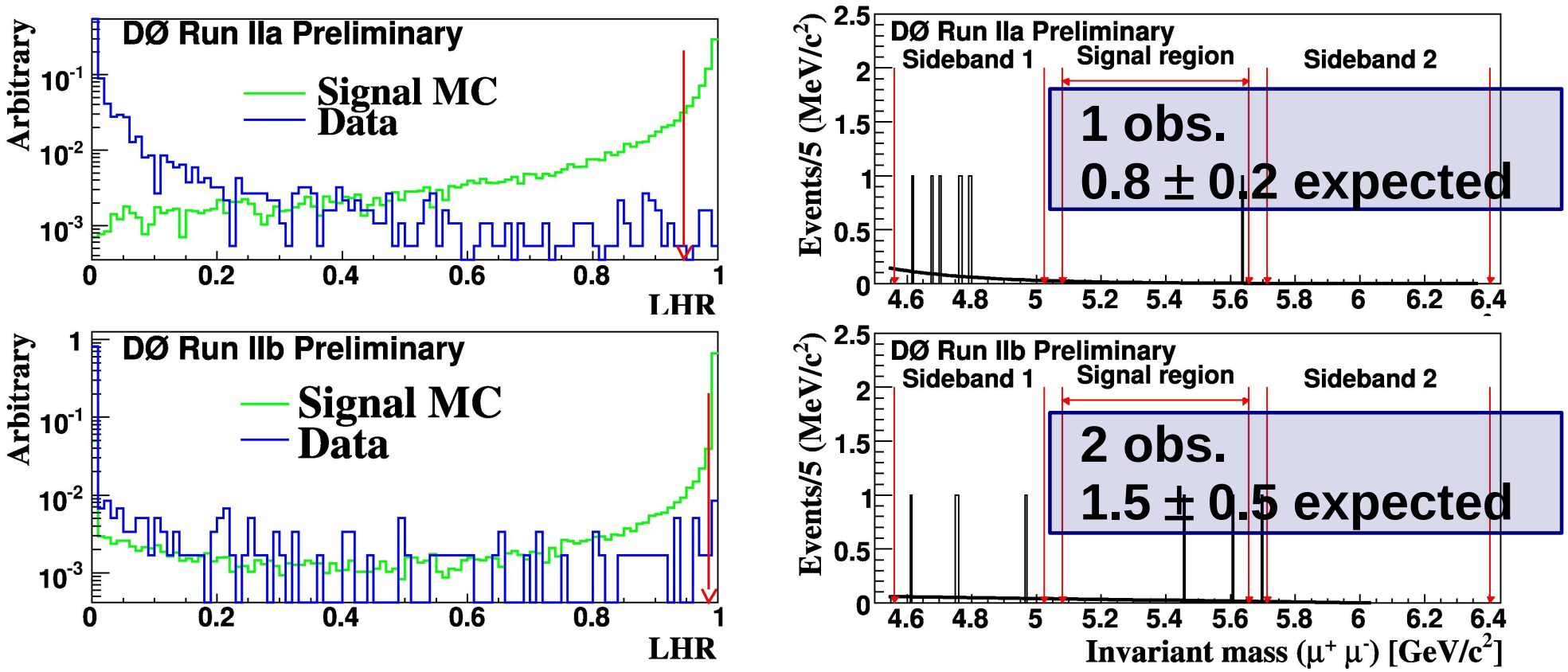
- Models with extended higgs sector (2HDM)
- e.g. MSSM: BF ~ $\tan^6\beta$
- minimal SO(10) GUT
- R-parity violation







Search for $B_s \to \mu\mu$ with 2 fb^{-1}



$BF(B_s \to \mu^+ \mu^-) < 9.3 \times 10^{-8}$ (95% C.L.) **current best limit**

Expect improvements from final calibrations (Run IIb upgrade!)

"Only" factor 30 above SM expectation, already very sensitive for BSM

Conclusions

- New and unsuccessful searches in (almost) all areas of searches for new phenomena
  - Not probing every conceivable model, but most final states
- Little time left before LHC starts up
  - ... Really? No LHC collisions at 14 TeV before mid 2008, date for “first physics” has considerable uncertainties
- For sure we don't want to miss anything exciting, or make it too easy for LHC
- Discoveries can come late
  - Top: seven years after turning on Tevatron
  - Evidence for single top after 18 years, same for B_s mixing and WZ production