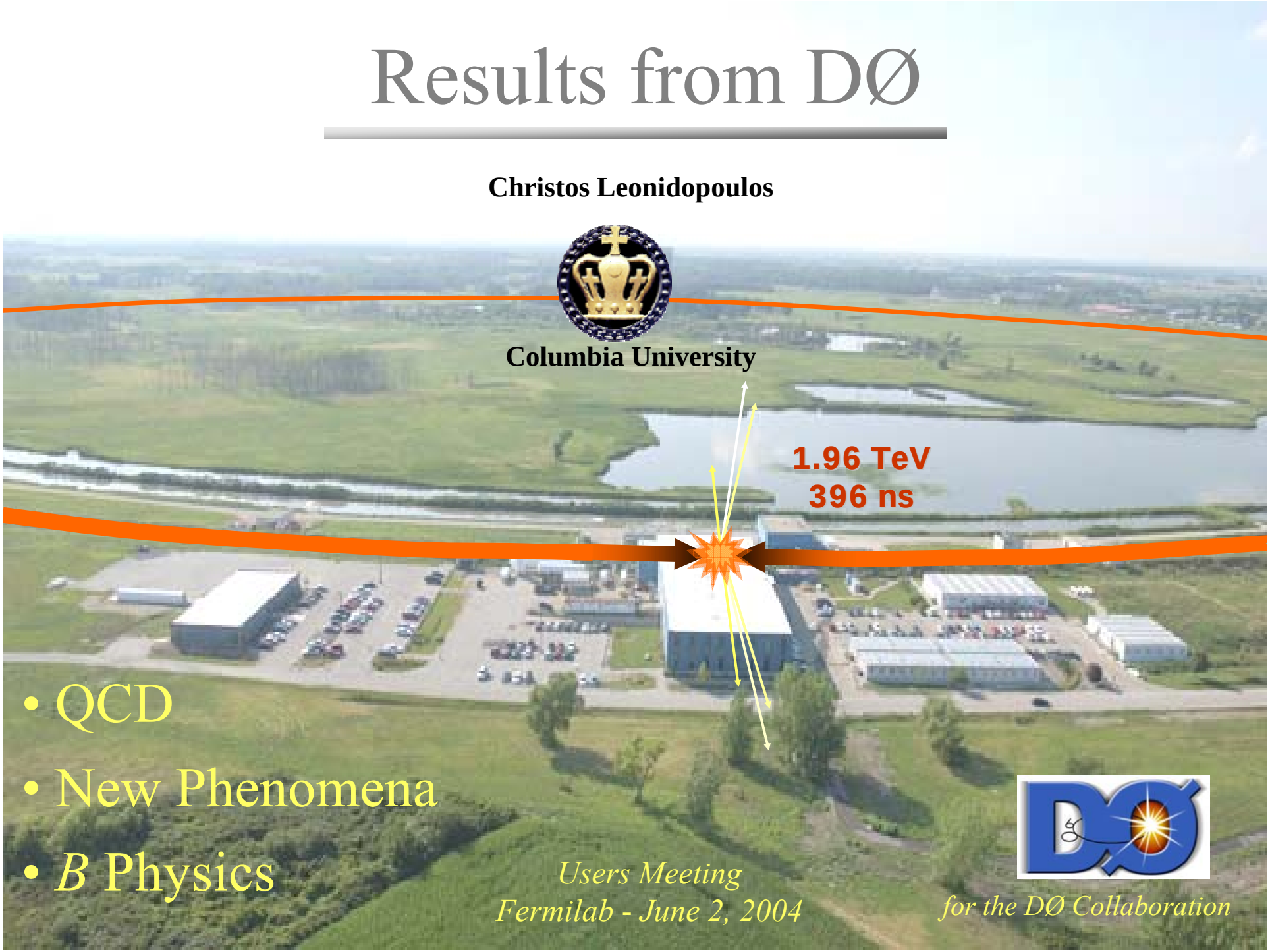
Results from DØ

Christos Leonidopoulos

Columbia University



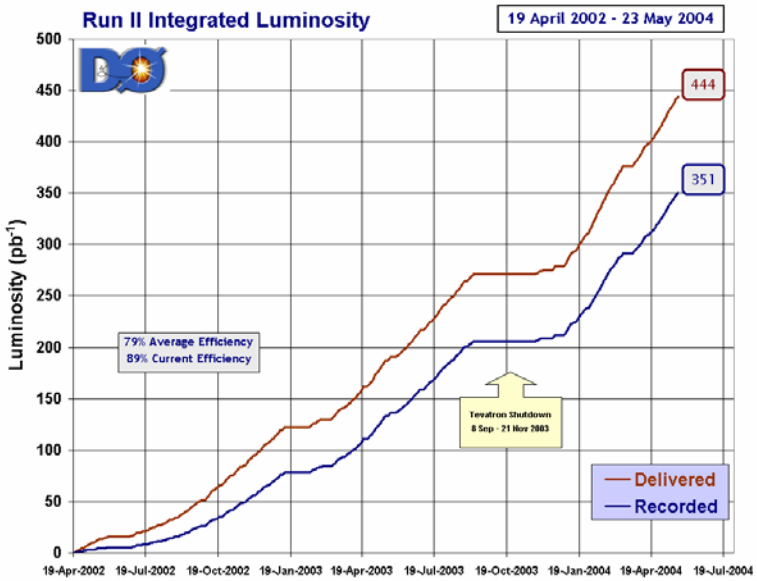
- QCD
- New Phenomena
- *B* Physics

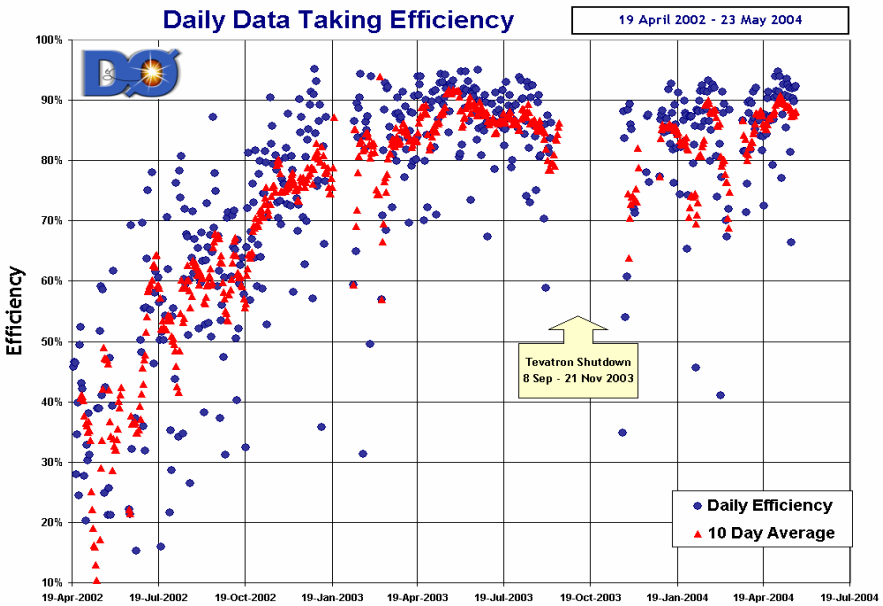
Users Meeting
Fermilab - June 2, 2004

for the DØ Collaboration

Operations Overview

- DØ operating well and recording physics quality data with high (> 90%) efficiency
- Data reconstructed on the Fermilab farm within days
- > 350 pb^{-1} of data on tape.
- 150-250 pb^{-1} used in today's results
- *Compare with ~ 110 pb^{-1} in Run-I*





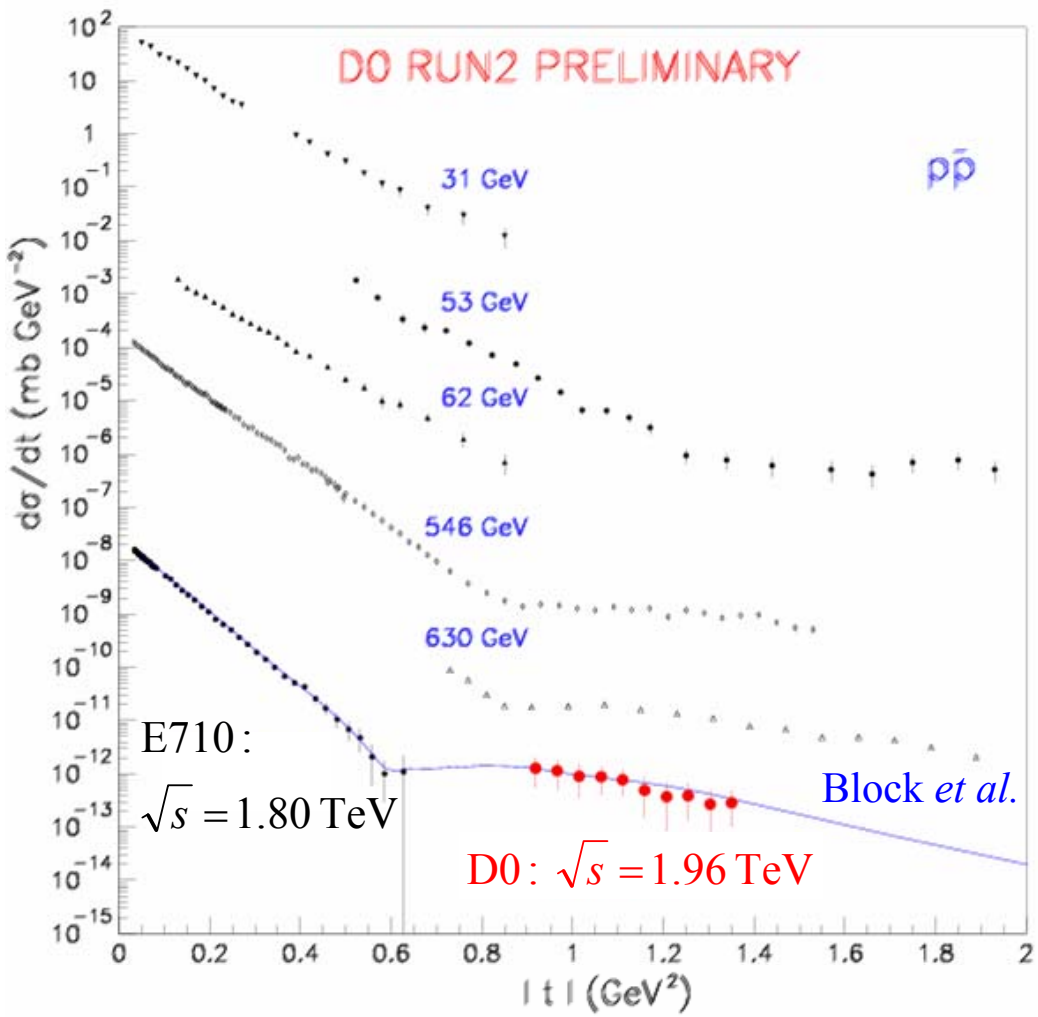
We have entered a new era in hadron collider physics!

- QCD
- New Phenomena
- *B* Physics

- Elastic $p\bar{p}$ scattering
- Inclusive jet p_T cross section
- Di-jet mass cross section
- Studies on $\Delta\varphi$ between jets

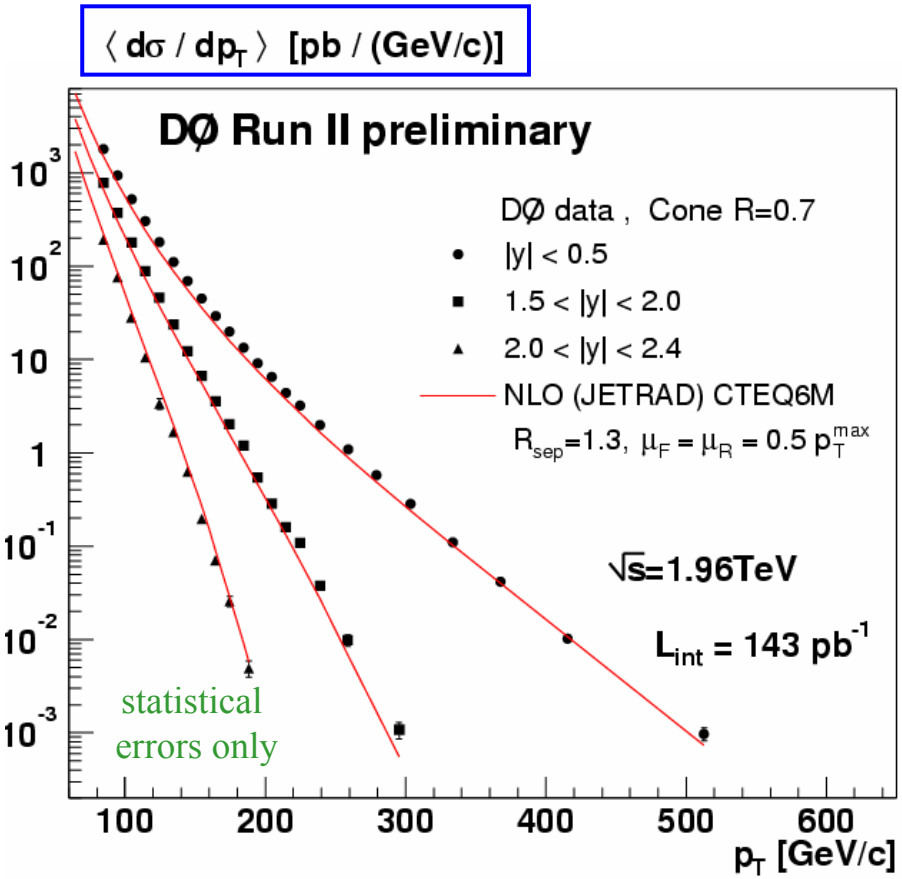
– Verify accuracy of parton-level NLO calculations
– Search for compositeness of elementary particles
– Look for new physics

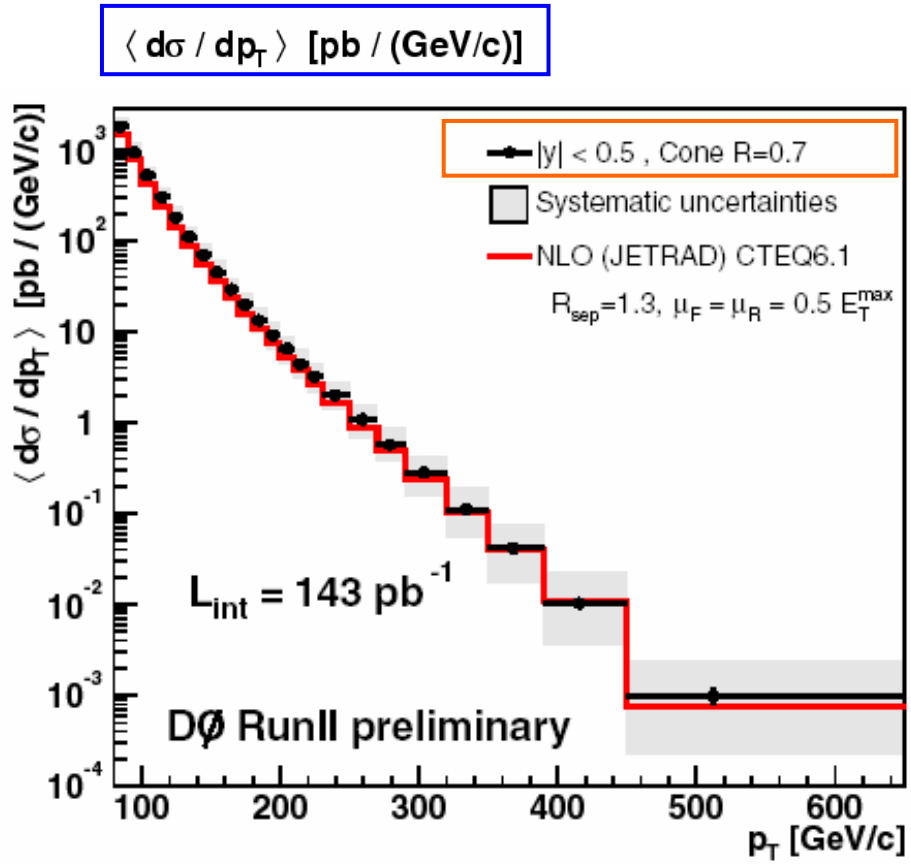
dN/dt spectrum (elastic $p\bar{p}$)



- DØ points normalized to E710 data
- First measurement performed in this *t* region & energy!
- Using standalone data from Forward Proton Detector (Roman pots at $z = \pm$ 23, 33, 57, 59m cover $2.5 < |\eta| < 6$ region)

Inclusive jet p_T cross section



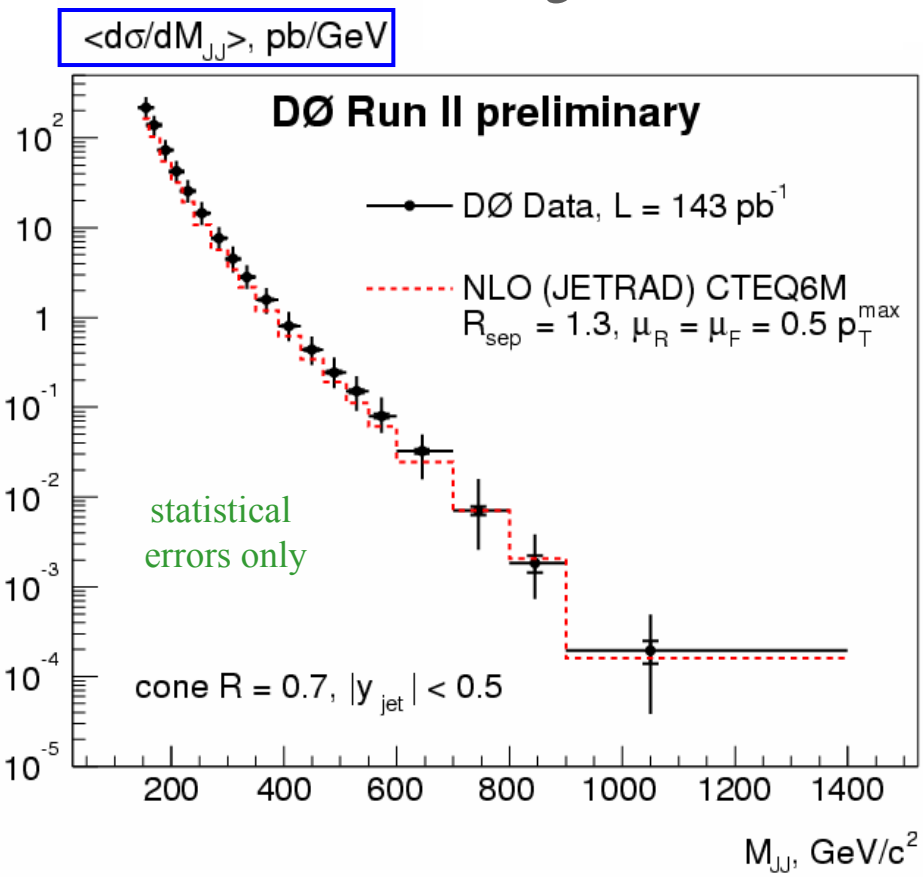


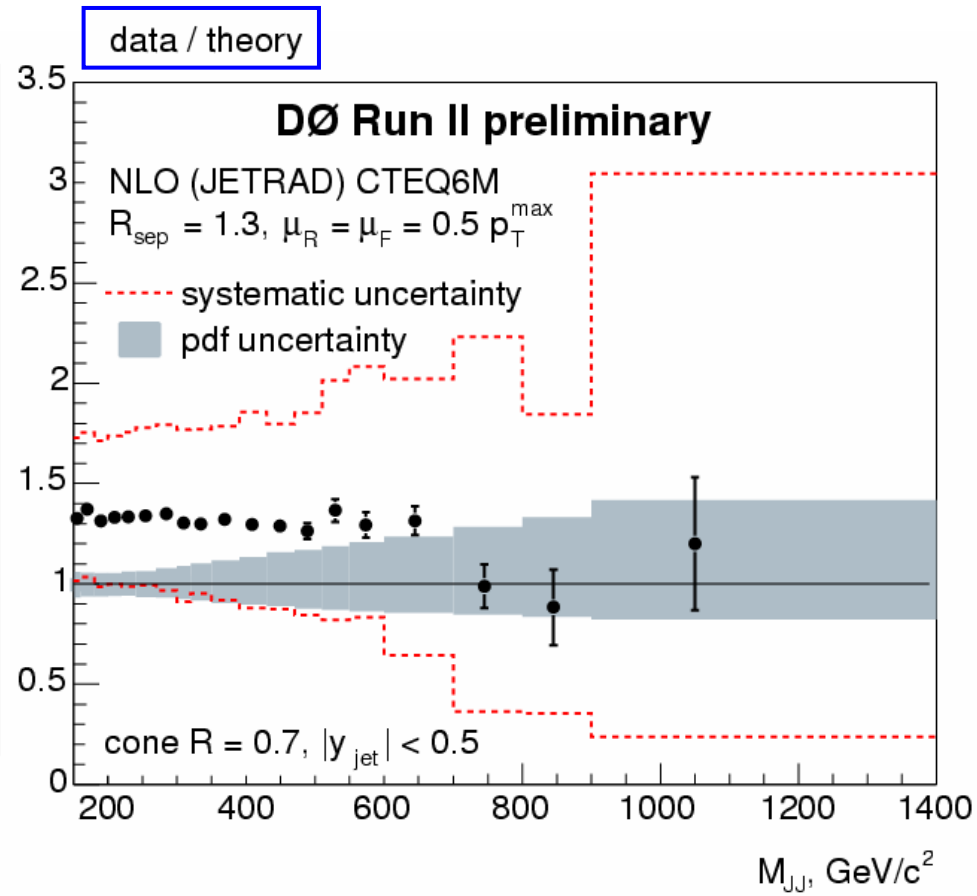
Are quarks composite?
Look for excess at high p_T!

- First measurements for large rapidity region!
- Aim: constrain gluon at high x (poorly known)
- Good agreement between data & NLO

- Agreement with theory within systematic uncertainties (mainly jet-energy scale correction)
- Systematic errors reduced by end of summer

Di-jet mass cross section





Look for "bumps" (new particles) at di-jet spectrum

- Measurements in central region ($|y_{jet}|<0.5$)
- Good agreement between data & NLO pQCD

- Agreement with theory within (large) systematic uncertainties (mainly jet-energy scale correction)
- Systematic errors reduced by end of summer

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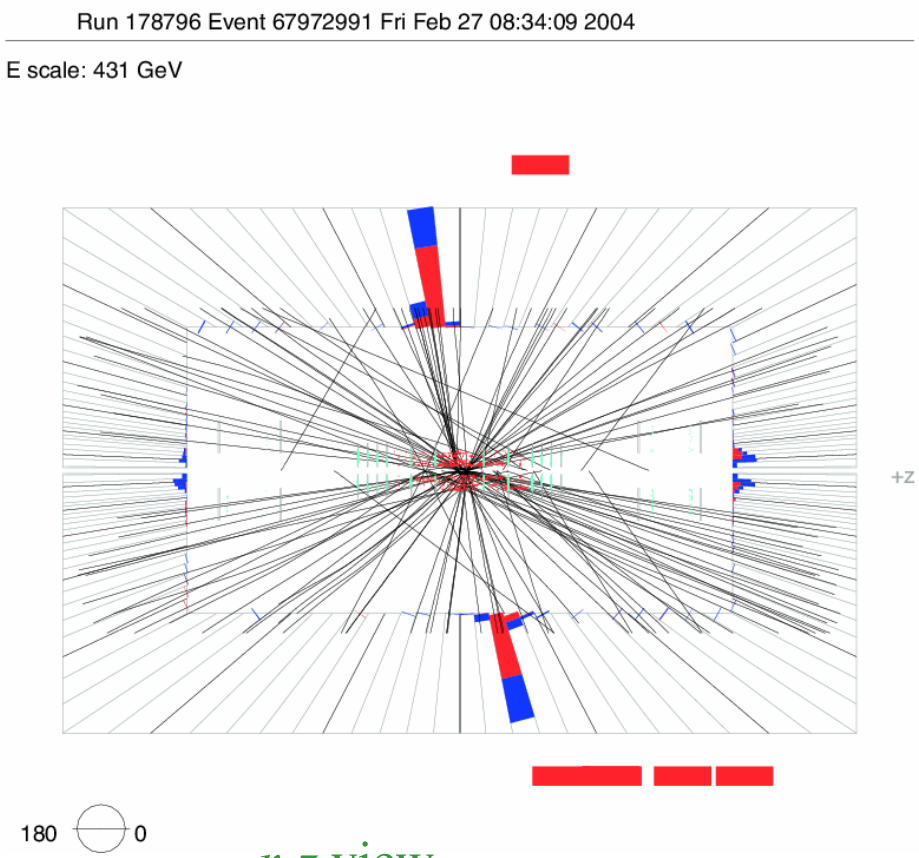
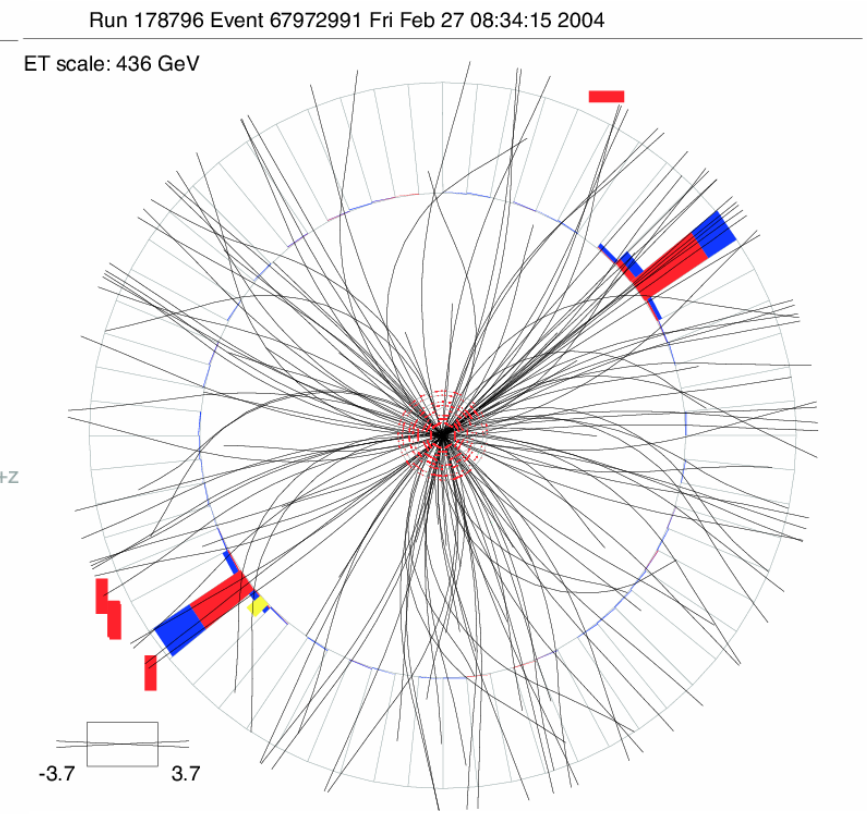
Highest di-jet mass event



r-z view



x-y view

- Jet #1: p_T = 616 GeV/c, y = -0.19, φ = 0.65 rad
- Jet #2: p_T = 557 GeV/c, y = 0.25, φ = 3.78 rad
- M_{JJ} = 1206 GeV/c^2

Enough energy to create 1200 hydrogen atoms!

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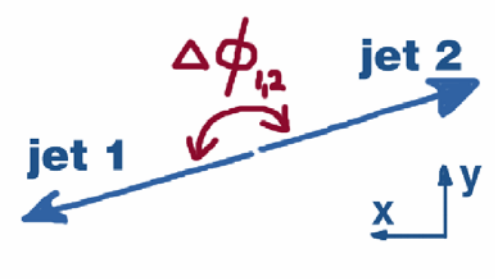
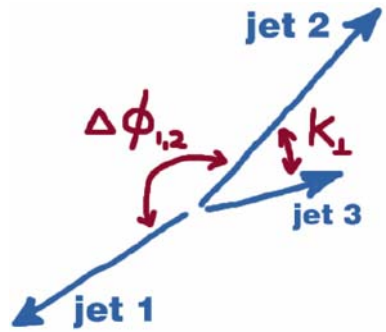
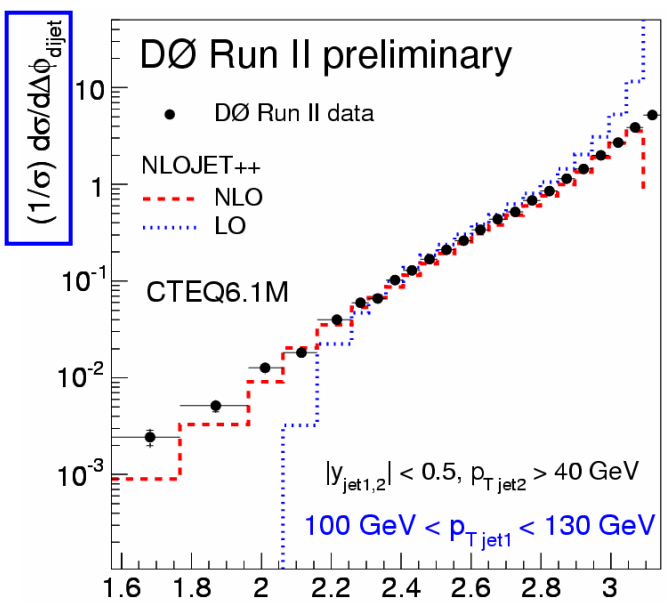
Studies on Δφ between jets

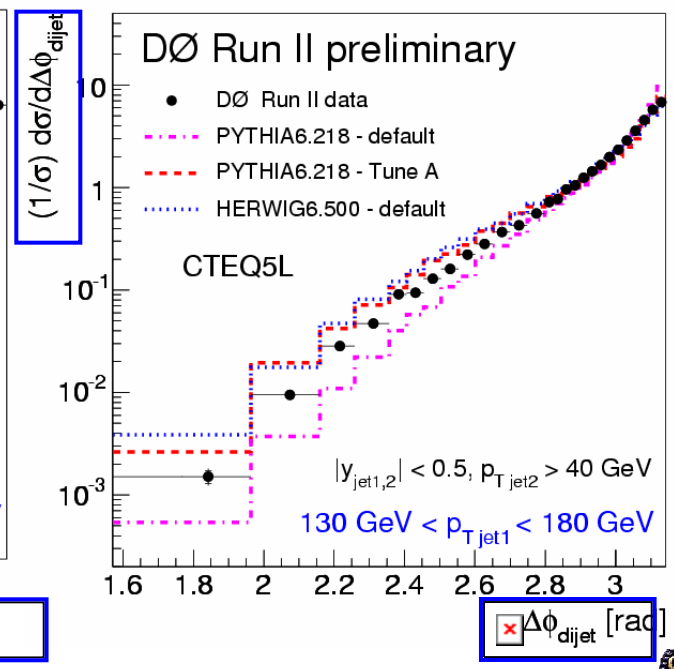


pQCD, leading order:
jets produced back-to-back



Higher order effects:
additional jets ("radiation")





- Good agreement between data & NLO QCD for medium Δφ values
- Disagreement for low (hard radiation) and large Δφ (soft radation)
- Agreement with parton shower MC generators (PYTHIA and HERWIG)

- QCD
- New Phenomena
- *B* Physics

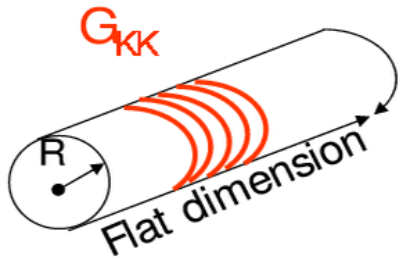
- Search for extra dimensions in $ee/\gamma\gamma$ and mono-jet channels
- Search for 1st generation Leptoquarks
- Search for squarks/gluinos
- Search for trileptons
- Search for GMSB SUSY

The Tevatron is the highest-energy accelerator in the world!
− Look for signs of SUSY at the TeV scale
− Discover new particles
− Constrain (or rule out!) theoretical models for Physics beyond SM

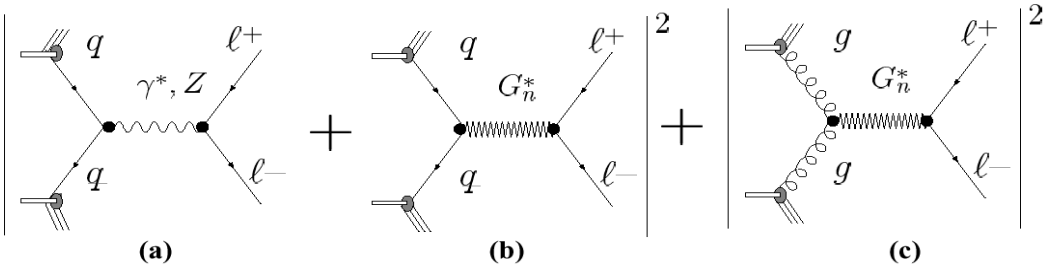
The Search for Extra Dimensions

- Hierarchy problem: why is gravity so weak?
  - Electroweak scale: $M_W \sim 100\,\mathrm{GeV}/c^2$
  - Gravity scale: $M_{\mathrm{Planck}} = \sqrt{\hbar c / G_{\mathrm{Newton}}} \sim 10^{19}\ \mathrm{GeV}/c^2$

- String theory solution: extra dimensions
- SM forces live in "usual" 3 spatial dimensions
  - Gravity "leaks" into extra dimensions: 3 →3+n
  - "True" gravity: $M_S \equiv M_{\mathrm{Planck}}(3+n) \sim O(\mathrm{TeV}/c^2)$



- Signs to look for:
  - Excess in di-lepton & di-photon channels (via virtual gravitons)



  - Or mono-jet & missing E_T (real graviton escapes into extra dimensions!)

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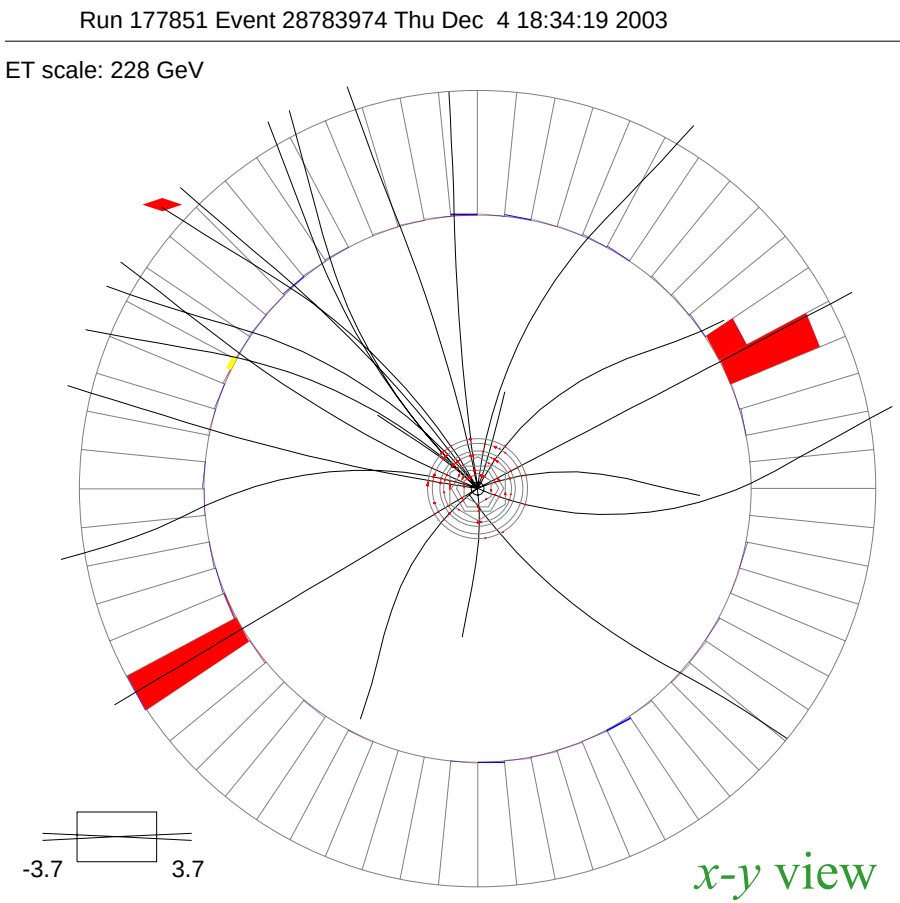
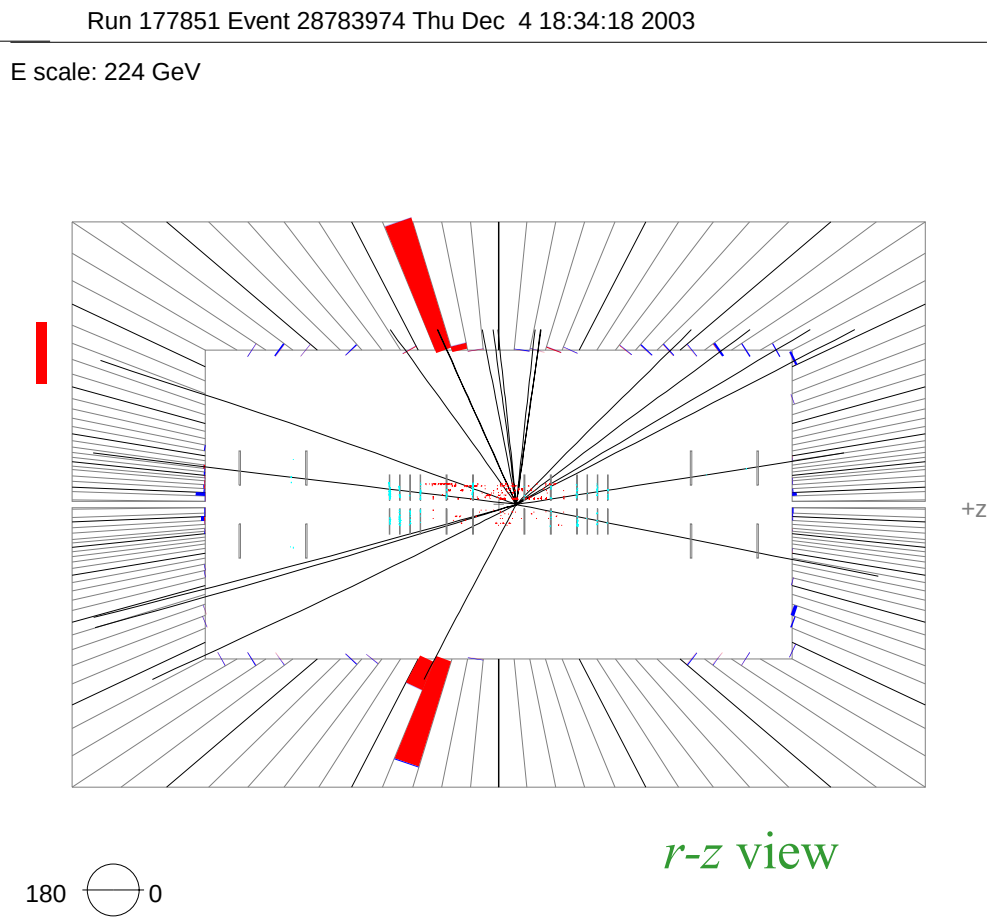
Highest mass Drell-Yan event

$$M_{ee} = 475\,\mathrm{GeV}/c^2 \qquad \cos\theta^* = 0.01$$





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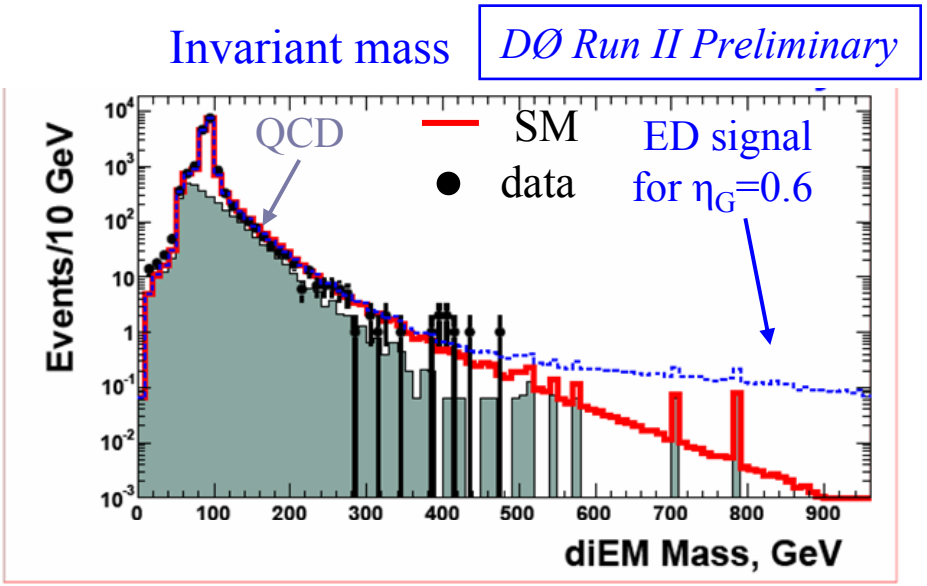
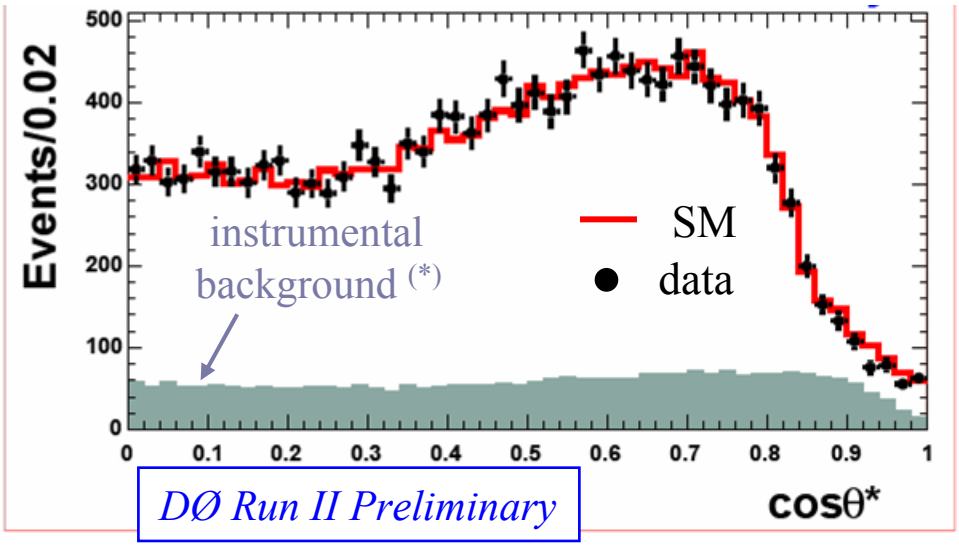
Large Extra Dimensions

Invariant mass



Scattering angle at rest frame



Distributions for e^+e^-, $\gamma\gamma$ (200 pb^{-1})

- Background: Drell-Yan & direct $\gamma\gamma$ production (normalized to low end of invariant mass spectrum)
- (*) "Instrumental background": jets misidentified as electrons or photons
- Determine extra-dimension contribution from fits to spectra

$$\frac{d^2\sigma}{d\mathrm{M}\, d\cos\theta^*} = f_{SM} + f_{\mathrm{int}}\eta_G + f_{KK}\eta_G^2, \quad \eta_G = \frac{F}{M_S^4}$$

Large Extra Dimensions: results

Measure η_G; extract lower limit on M_S (for different F models)

$$\eta_G = \frac{F}{M_S^4}$$

- GRW: $F=1$
- HLZ: $F=\log(M_s^2/M^2)$, $n=2$
  $F=2/(n-2)$, $n>2$
- Hewett: $F=2\lambda/\pi$, $\lambda=\pm1$

200 pb^{-1}

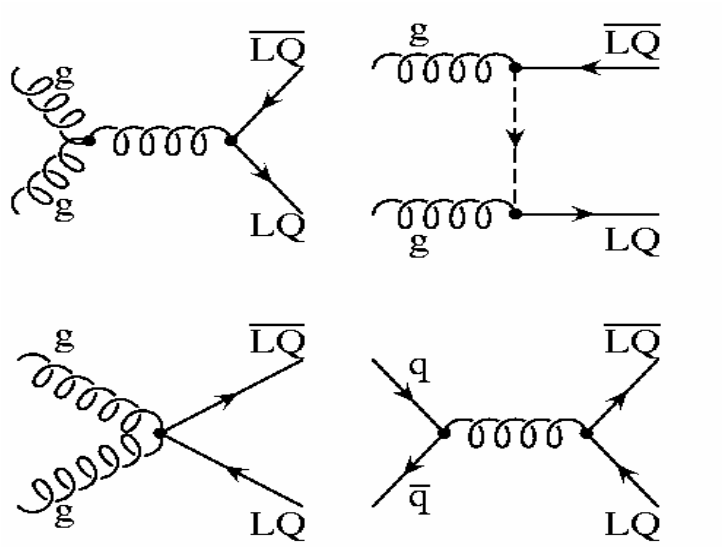
Model	GRW	HLZ						Hewett	
		n=2	*n=3*	*n=4*	*n=5*	*n=6*	*n=7*	*λ=+1*	*λ=−1*
Run-II limits (95% C.L.)									
M_S (TeV)	1.36	1.56	1.61	1.36	1.23	1.14	1.08	1.22	1.10
Run-I & Run-II limits combined (95% C.L.)									
M_S (TeV)	1.43	1.67	1.70	1.43	1.29	1.20	1.14	1.28	N/A

World's best sensitivity!

Mono-jet analysis currently limited by systematic uncertainties

The Search for Leptoquarks

- Unification of lepton-quark sectors at high-energy scales
- LQ: Fractionally charged particles; carry both color & lepton numbers
- Common element in many Grand-Unified models



- "1st generation LQ": coupling to *e* (*ν*) and *u*, *d* quarks
- <u>Experimental signature</u>: look for final states with two jets + *ee* (or *eν*)

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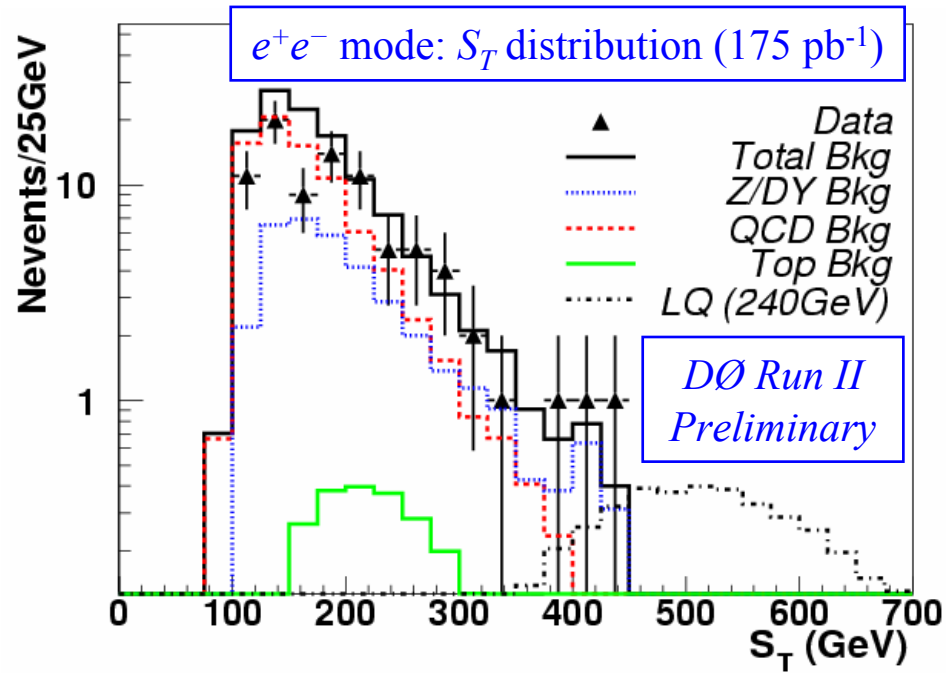
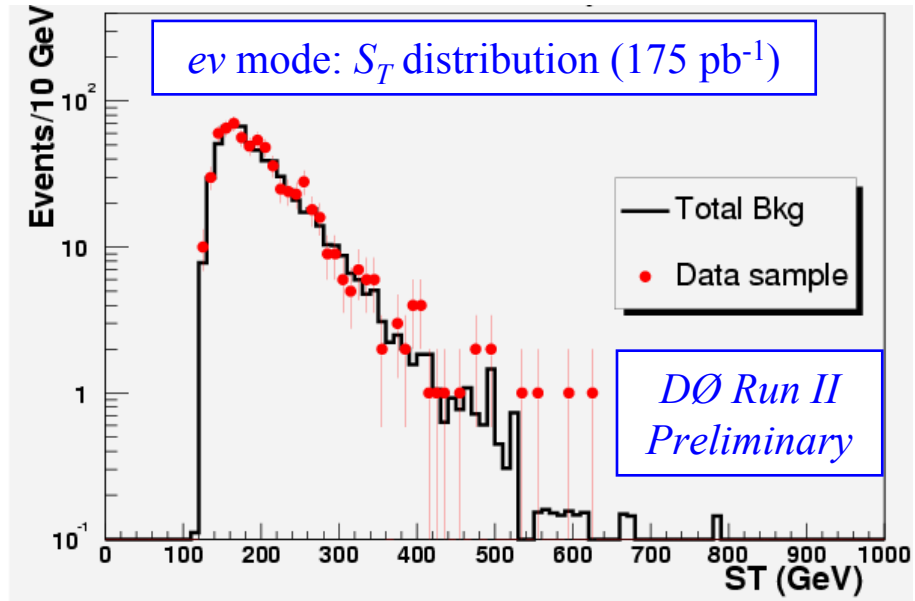
…The Search for Leptoquarks





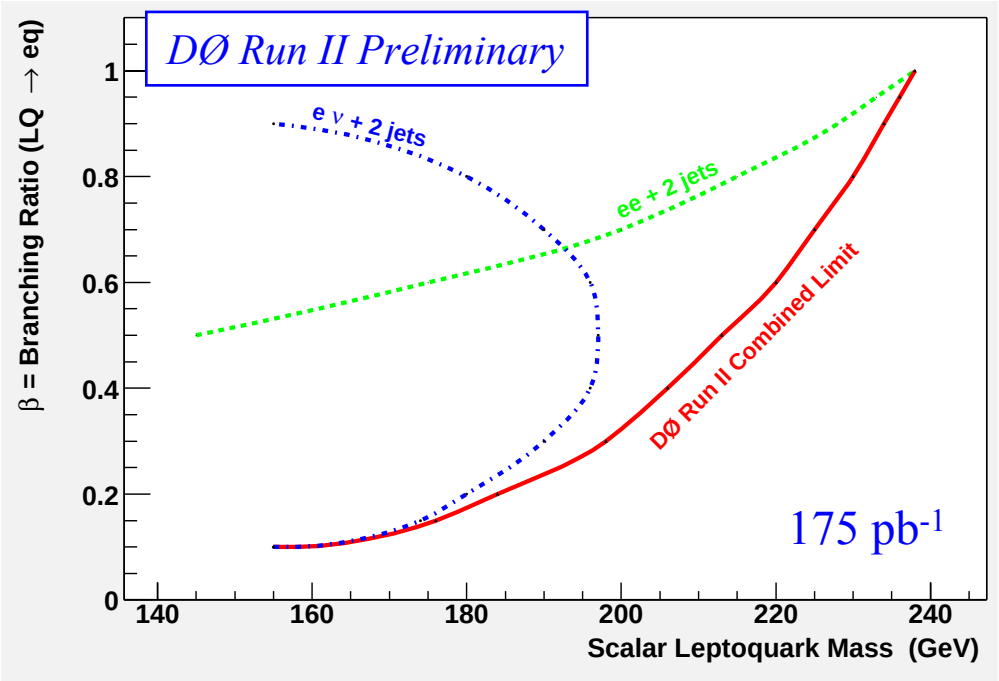
Main background:

- Drell-Yan or Z & jets
- QCD (w/ fake e^+e^-)
- top-quark pair

- W & jets
- QCD (w/ fake e or γ)
- top-quark pair

$$S_T = \sum_{eejj} E_T$$

Search for Leptoquarks: results



- Combine two channels, extend reach
- Very competitive limit on leptoquark mass:
  $M_{LQ} > 238$ GeV/c^2 , if $BR(LQ \rightarrow eq)$=100%
- Analysis on 2nd generation LQ search in progress

Search for squarks and gluinos

Squarks & gluinos: supersymmetric partners of quarks & gluons

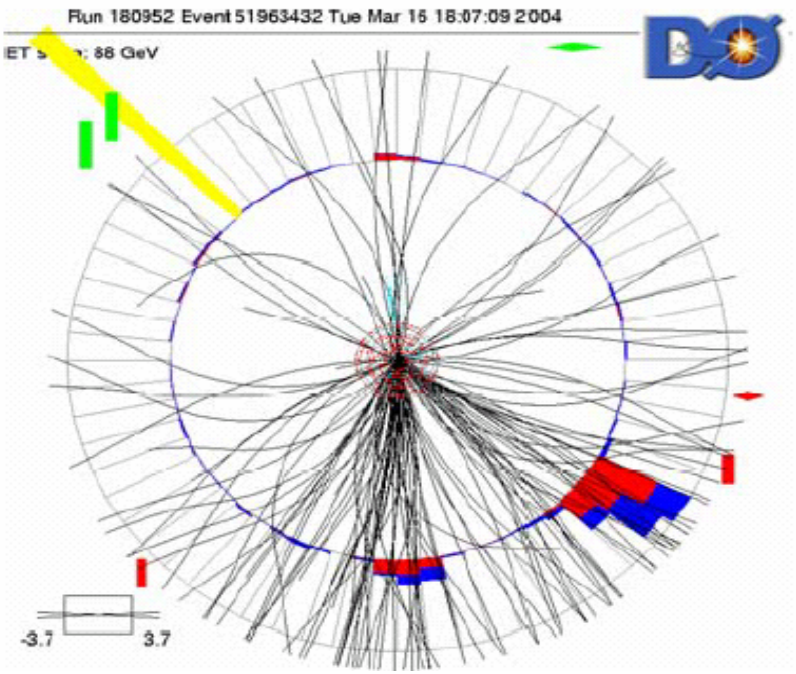
- If squarks are lighter than gluinos: $\tilde{q} \rightarrow q\chi_1^0$
- If gluinos are lighter than squarks: $\tilde{g} \rightarrow q\bar{q}\chi_1^0$

(Stable) Lightest Supersymmetric Particle (LSP):
A great candidate for explaining the (unaccounted) dark matter

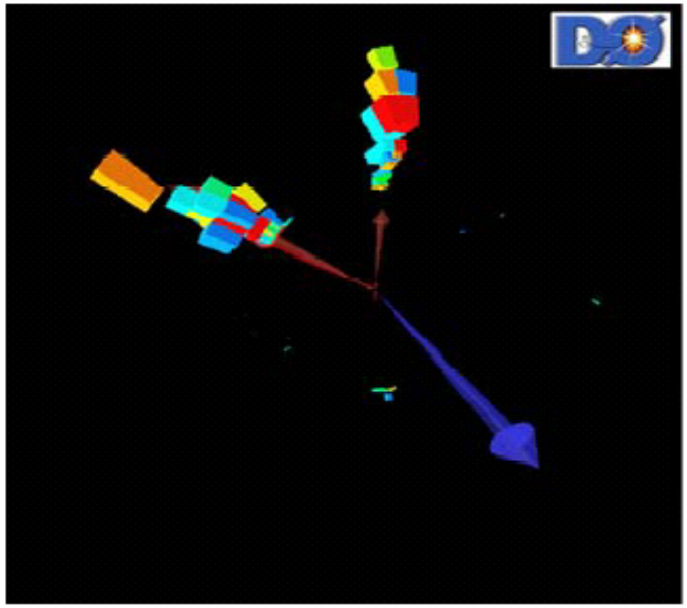
- Results here are interpreted in the minimal supersymmetric gravity (mSUGRA) framework (simplest & robust SUSY model)
- High cross-section: about 800 squarks/gluinos produced for 200 pb^{-1}

<u>Experimental signature:</u> look for final states with jets & $\not{E}_T$

SUSY candidate



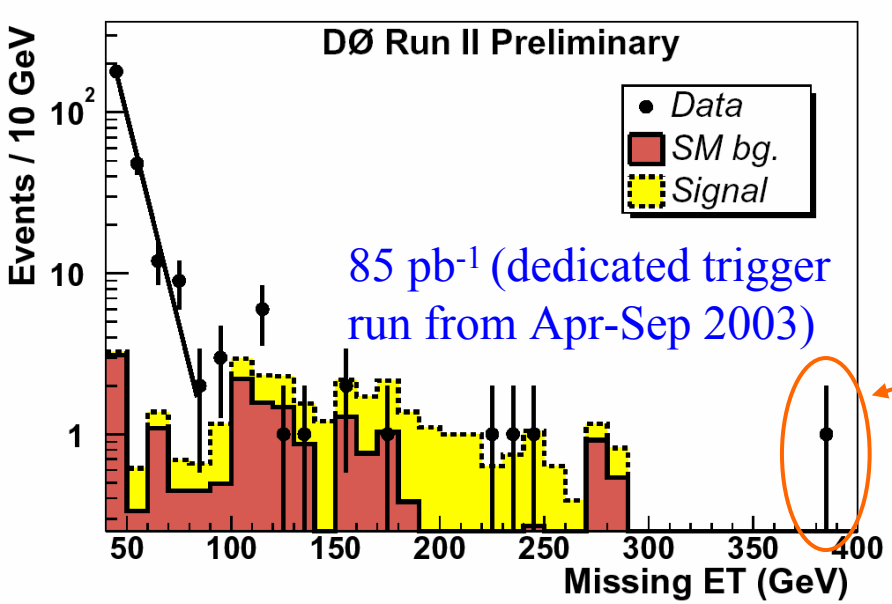
x-y view



3d view

- Jet #1: $p_T = 289$ GeV/c
- Jet #2: $p_T = 117$ GeV/c
- $\not{E}_T = 385$ GeV/c^2

Squarks and gluinos: results

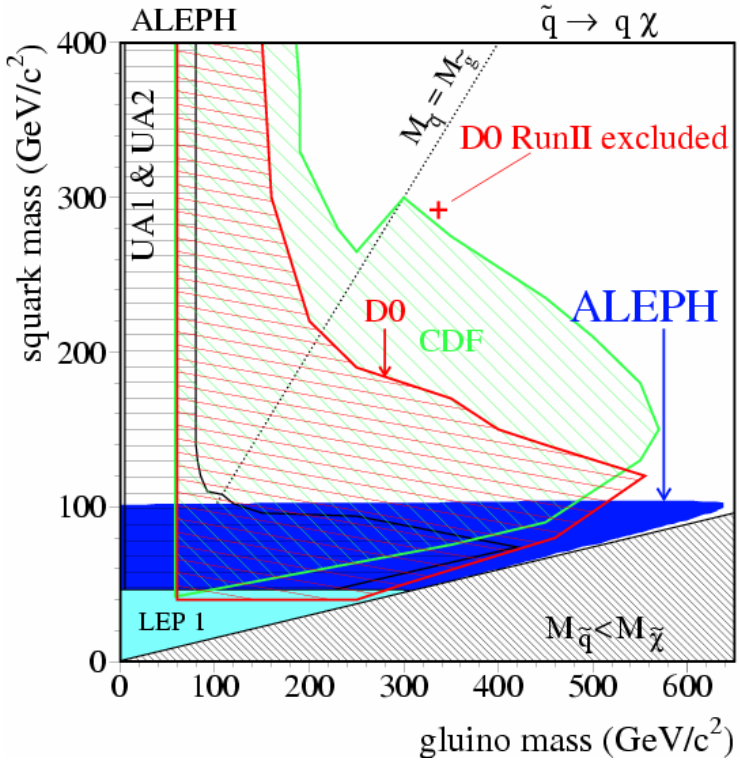


$M_0 = 25\,\text{GeV},\ A_0 = 0,\ \tan\beta = 3,\ \mu < 0$

(scan over $m_{1/2}$)

- 4 events observed
- 2.7 SM events expected (Z/W production)

Exciting event!



$M_{\tilde{g}} > 333\,\text{GeV}/c^2$

(310 GeV/c^2 in Run - I)

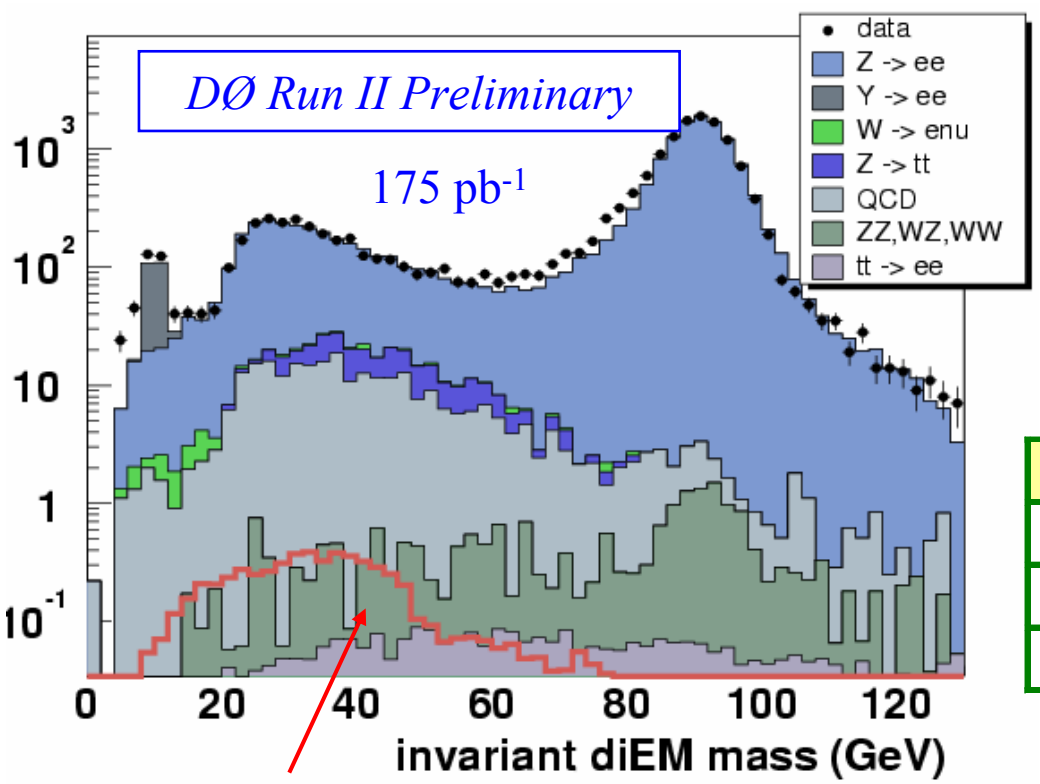
$M_{\tilde{q}} > 292\,\text{GeV}/c^2$

More SUSY searches: trileptons

- Chargino-neutralino production: $q\,\overline{q'} \rightarrow \chi_1^{\pm}\ \chi_2^0$

$$\chi_1^{\pm} \rightarrow \chi_1^0\ \ell^{\pm}\ \nu, \quad \chi_2^0 \rightarrow \chi_1^0\ \ell^+\ \ell^-$$

- <u>Experimental signature</u>: $\ell+\ell+\ell$+missing E_T: *one of the cleanest for SUSY*



Expected signal distribution

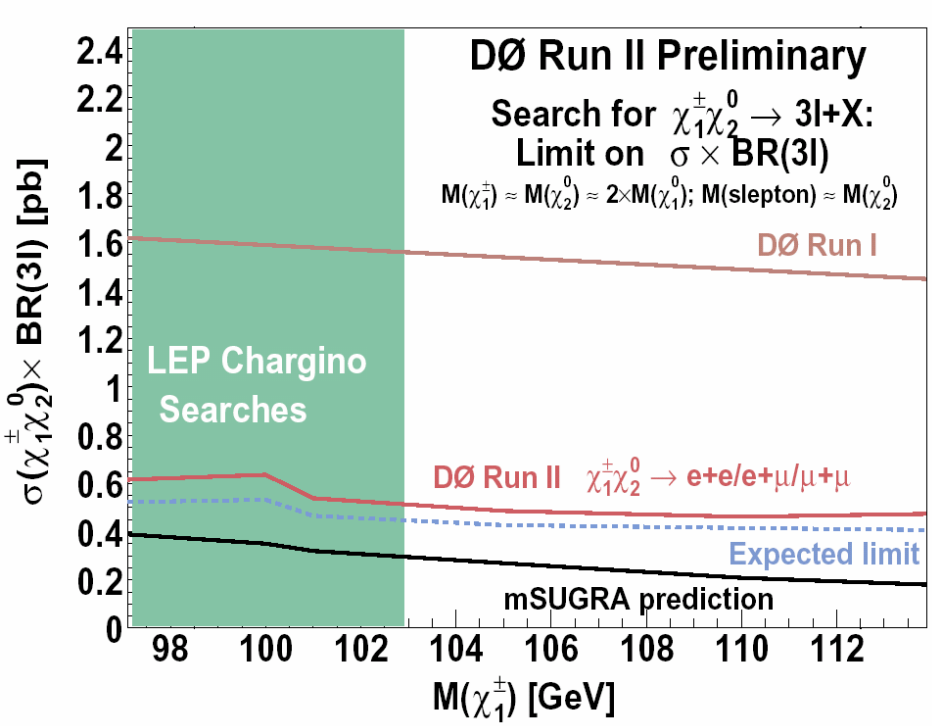
- Have to battle many sources of background

- After final cuts:

Channel	Data	SM background
$ee\ell$	1	0.27±0.42±0.02
$e\mu\ell$	0	0.54±0.24±0.04
$\mu^{\pm}\mu^{\pm}$	1	0.13±0.04

Trilepton searches: results

- Combination of trilepton searches



175 pb^{-1}

- Significant improvement over Run-I cross section limit
- mSUGRA prediction within reach by end of year (with additional channels and for the best scenario)

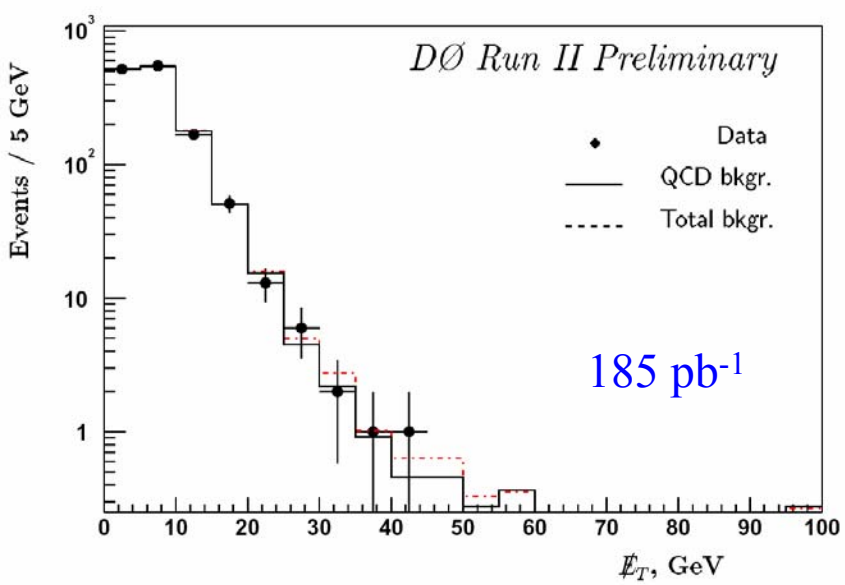
Even more SUSY: GMSB

- Gauge Mediated Symmetry Breaking (GMSB) at scale Λ:
  Light Gravitino (<< eV) is LSP, NLSP can be neutralino or slepton
- If NLSP is neutralino:

$$\tilde{\chi}_1^0 \rightarrow \gamma\, \tilde{G}$$

All standard SUSY signatures complemented by two photons

<u>Experimental signature:</u> inclusive $\gamma\gamma\, \not{E}_T$ final states



- 1 events observed
- 2.5 SM events expected

$$\Lambda > 78.7\ \mathrm{TeV}/c^2$$
$$m(\chi_1^0) > 105\ \mathrm{GeV}/c^2$$
$$m(\chi_1^+) > 180\ \mathrm{GeV}/c^2$$

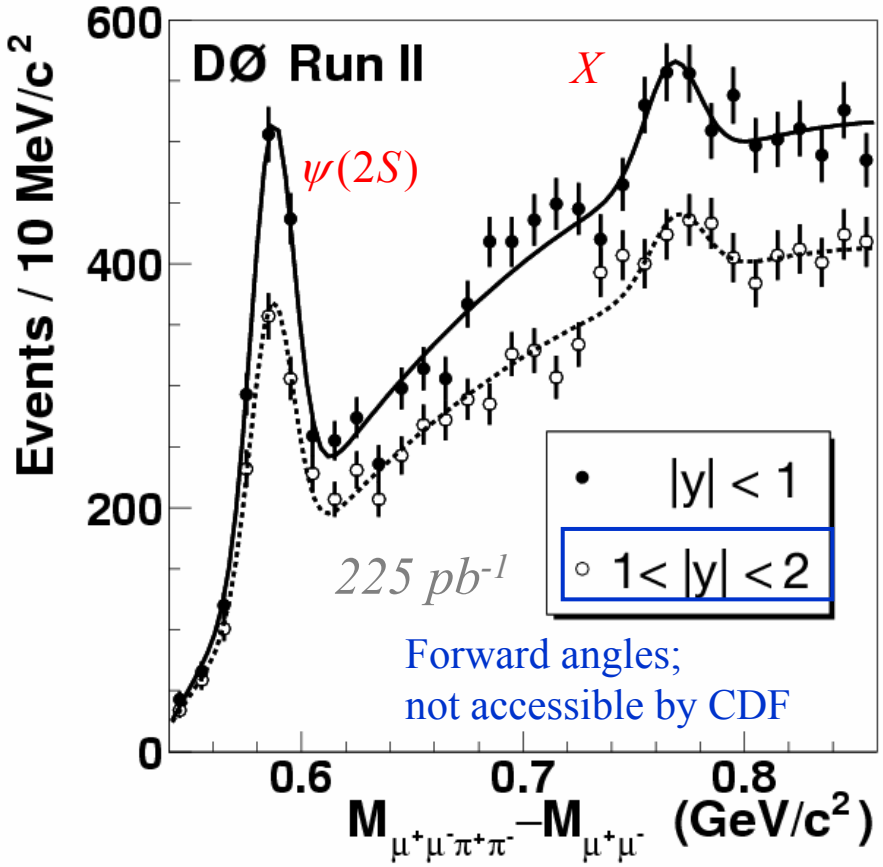
Improves LEP limit for this model

- QCD
- New Phenomena
- *B* Physics

- Confirmation of *X(3872)* state
- Search for $B_s \rightarrow \mu^+\mu^-$ rare decay
- Precise $\tau(B^{\pm})/\tau(B^0)$ measurement
- B_d mixing measurements
- Prospects for B_s mixing

– Look for rare/exotic decays
– Challenge SM with precision *b*-quark measurements unique at Tevatron
– Discover new particles

Observation of new particle: *X(3872)*



- New particle "*X(3872)*" observed by Belle(*) last summer in the decay mode: $B^{\pm} \to X\, K^{\pm}$ where

$$X \to J/\psi\, \pi^{+}\pi^{-}$$

(*) Confirmed by CDF

- DØ observed X(3872) using

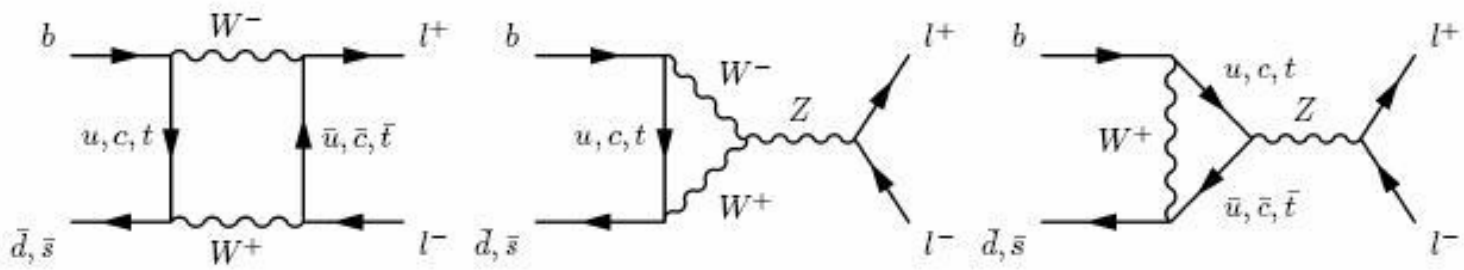
$$X \to J/\psi(\mu^{+}\mu^{-})\, \pi^{+}\pi^{-}$$

$$M_X - M_{J/\psi} = 774.9 \pm 3.1\,(\text{stat}) \pm 3.0\,(\text{syst})\ \text{GeV}/c^2$$

$$N_X = 522 \pm 100$$

X(3872) has similar behavior to that of the charmonium state ψ(2S)

Rare decays: $B_S \to \mu^+\mu^-$



- SM: forbidden at tree level:

$$BR(B_S \to \mu^+\mu^-) = (3.4 \pm 0.5) \times 10^{-9}$$ Buras, Phys. Lett. **B**566 (2003) 115

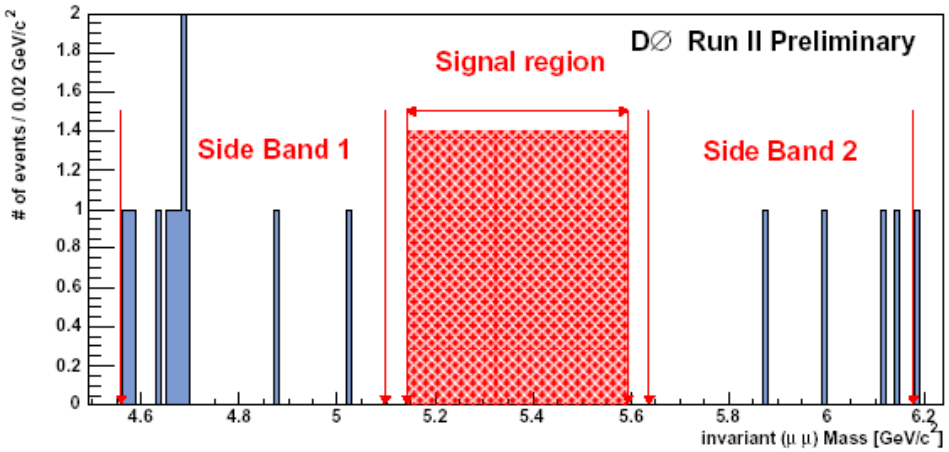
B_d decay additionally suppressed: $|V_{td}/V_{ts}| = (4.0 \pm 0.8) \times 10^{-2}$

- But: significantly enhanced in some extensions to SM:
  - Two Higgs Doublet Model: $BR(B_S \to \mu^+\mu^-) \propto \tan^4 \beta$
  - Minimal Supersymmetric SM: $BR(B_S \to \mu^+\mu^-) \propto \tan^6 \beta$

    or $BR_{\mathrm{MSSM}} \approx 10^3 \times BR_{\mathrm{SM}}$

…Rare decays: $B_S \rightarrow \mu^+\mu^-$

B_S mass distribution



Blind analysis: signal box will open at end of 2004
(expected bgd: 2.9±1.7 evts)

Assuming no signal events

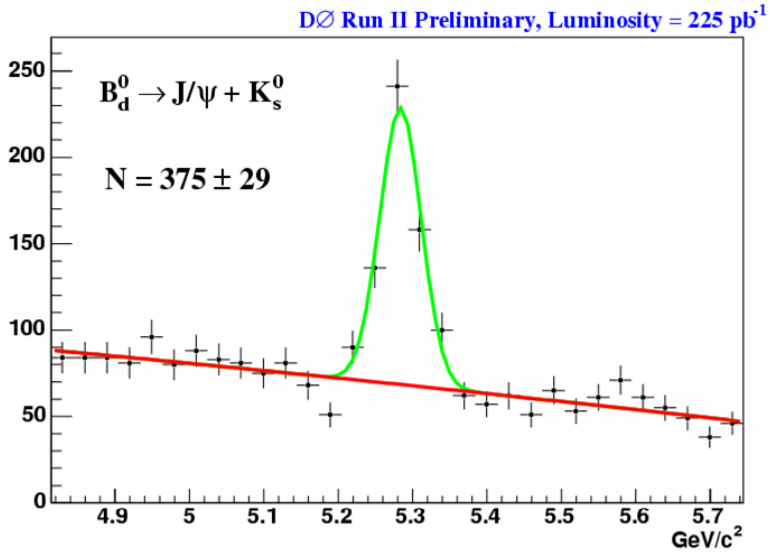
Normalized to $BR(J/\psi \rightarrow \mu\mu)$

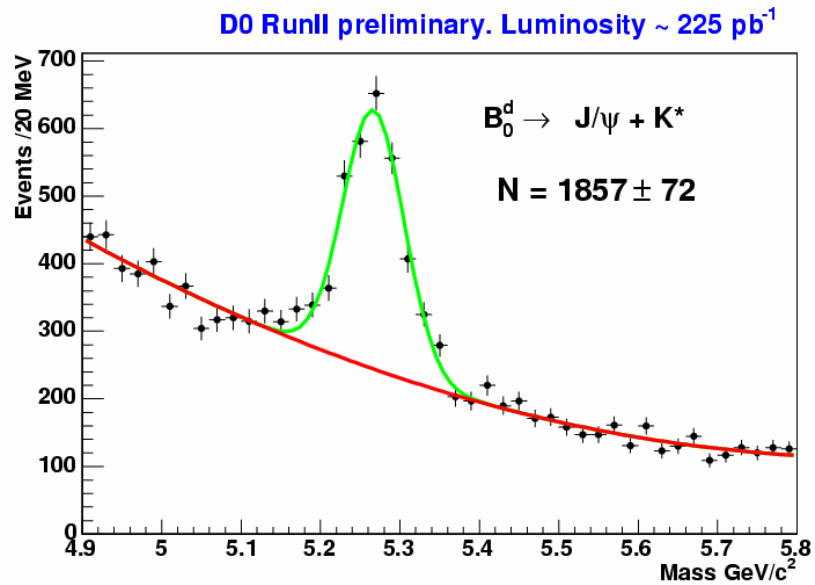
$$BR(B_S \rightarrow \mu^+\mu^-) < 1.0 \times 10^{-6} \text{ @95\% C.L. } (165\,\text{pb}^{-1})$$ à la Feldman & Cousins

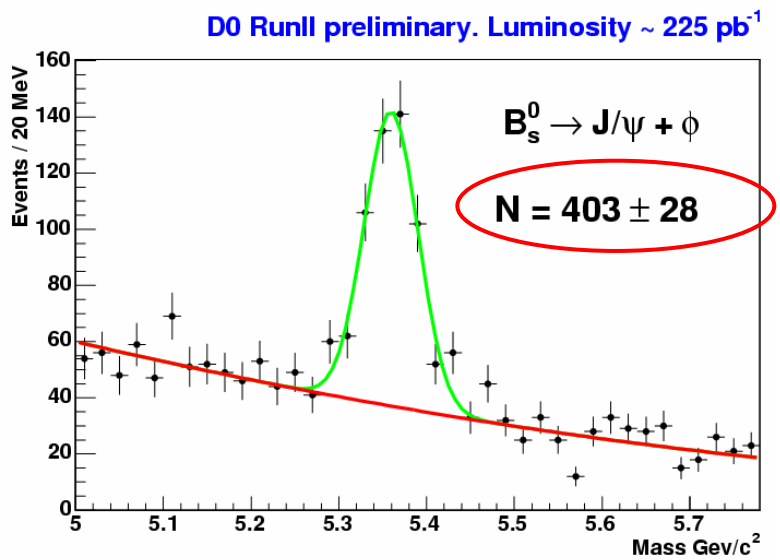
(statistical & systematic uncertainties included)

Working on improving acceptance, suppressing background

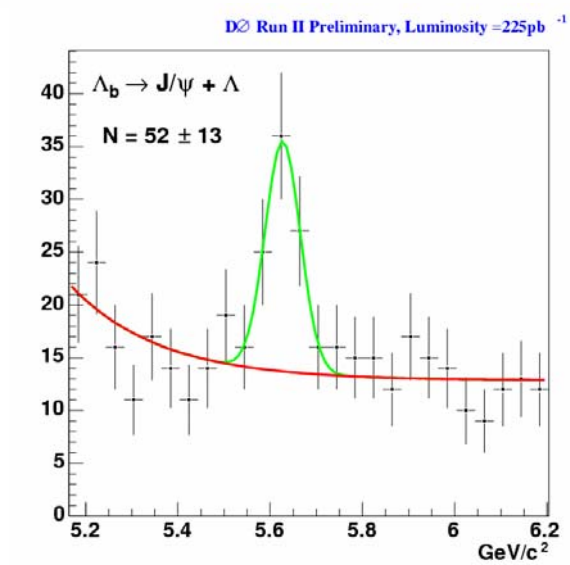
Exclusive B_d, B_s, Λ_b decays





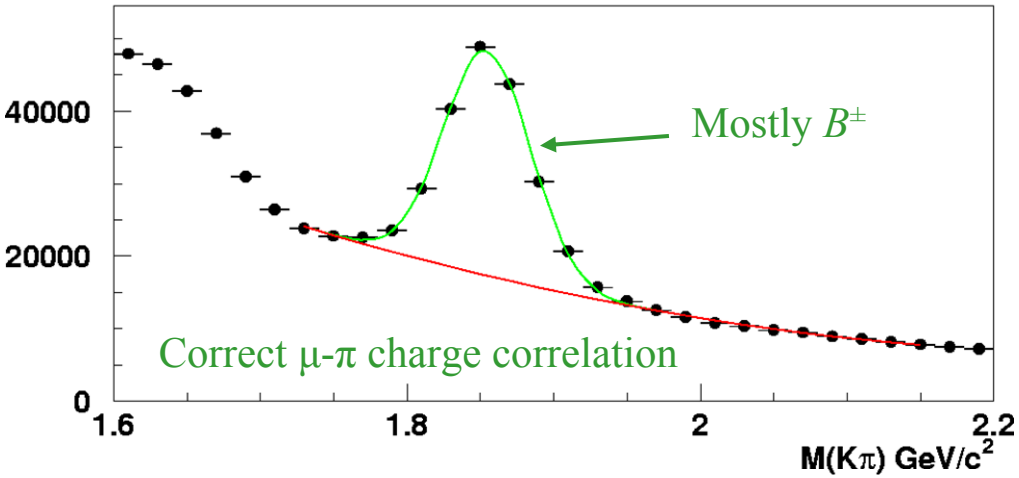


World record!

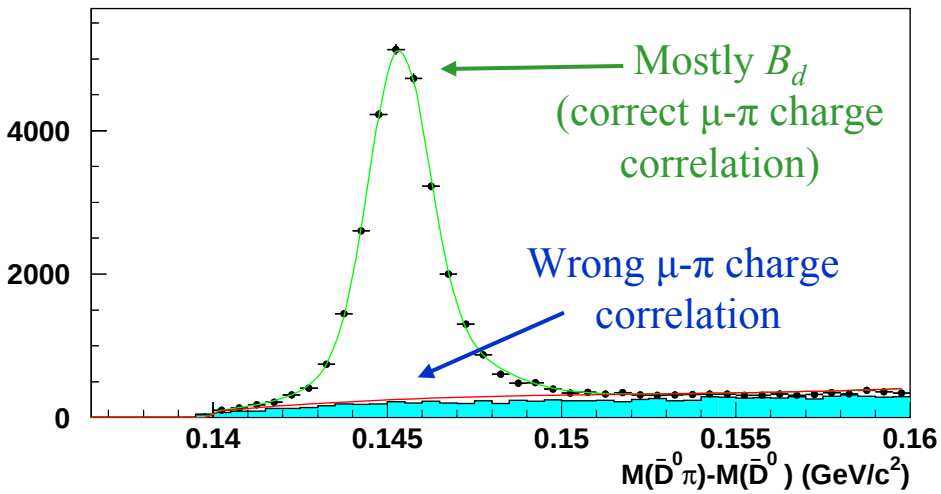


B semileptonic mass peaks

D^0 mass distribution (250 pb^{-1})



$M(D^*)$-$M(D^0)$ mass difference (250 pb^{-1})



- No particle-id on π, K
- Loose id on muon

$$B \rightarrow \mu^{\mp} D^0 \nu X$$
$$D^0 \rightarrow K^{\mp}\pi^{\pm}$$

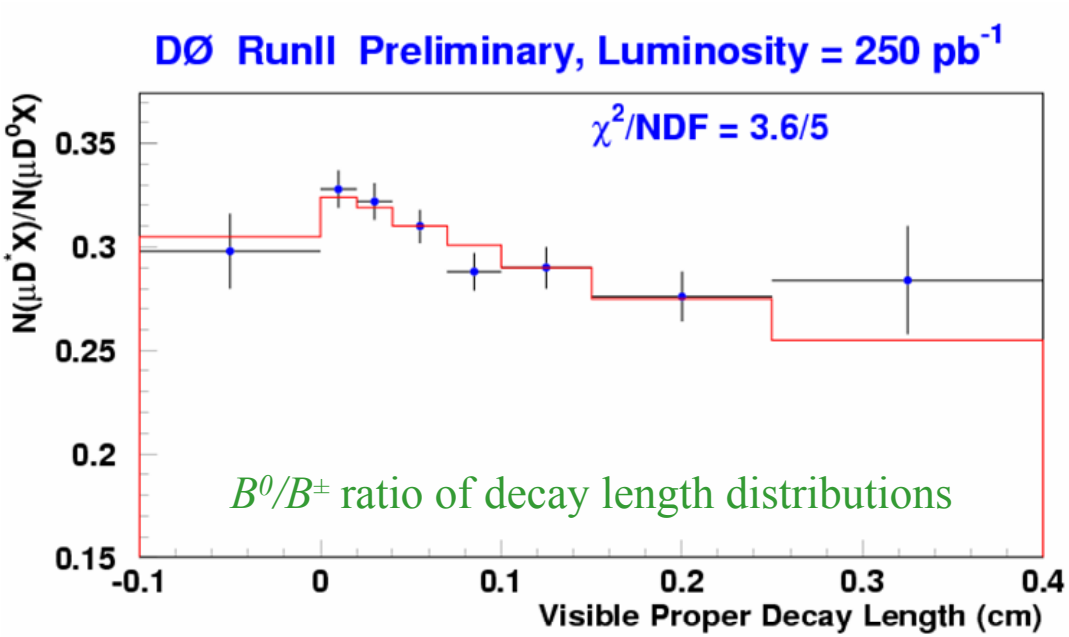
of D^0+μ events: ~110k (250 pb^{-1})

$$B \rightarrow \mu^{\pm} D^{*\mp} \nu X$$
$$D^{*\mp} \rightarrow D^0 \pi^{\mp}$$

of D^*+μ events: > 25k (250 pb^{-1})
(or >100 semil. B events/pb^{-1})

- Very good tracking & muon coverage (|η|<2):
- Robust muon trigger
- *Very large statistics*

B Lifetimes: $\tau(B^{\pm})/\tau(B^{0})$



$$\lambda_B = L_{xy}\frac{M_B}{p_T^D}$$

- Analysis exploits large statistics in B semileptonic channel
- Novel technique: measure directly lifetime ratio in different time bins (extract event yields from D^0 mass spectrum for both $B^{\pm}$, B^0 samples): many systematic errors cancel out
- Eff(soft π): flat [$p_T(D^0)$>5 GeV/c]

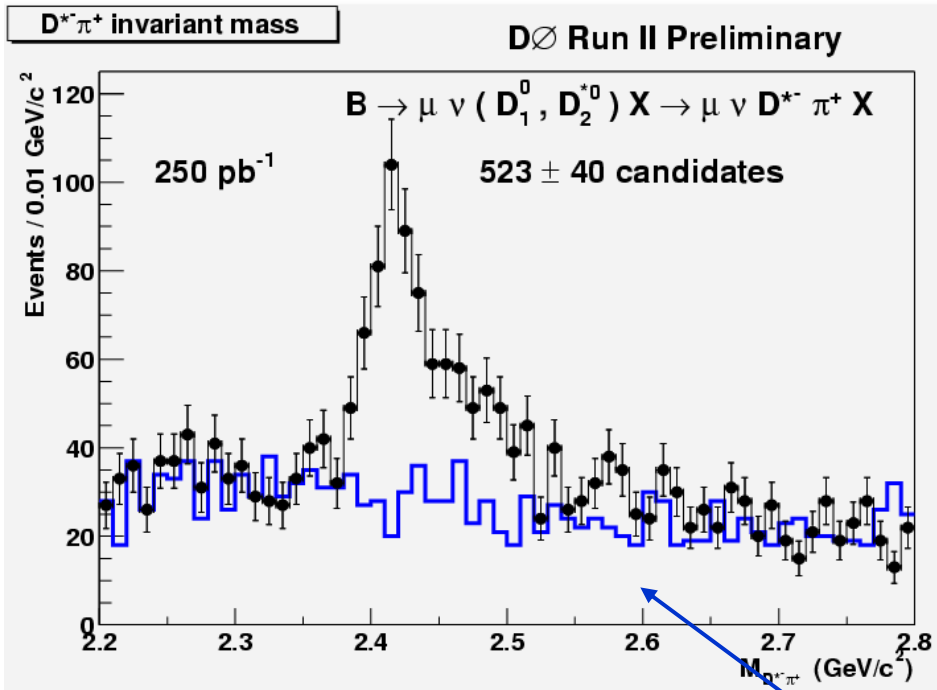
$$\frac{\tau^{\pm}}{\tau^{0}} - 1 = 0.053 \pm 0.016 \pm 0.017$$

Quenched lattice (NLO) QCD
Nierste, hep-ph/0209008

$$\boxed{\frac{\tau^{\pm}}{\tau^{0}} - 1 = 0.093 \pm 0.021 \pm 0.022}$$

$$\frac{\tau^{\pm}}{\tau^{0}} - 1 = 0.086 \pm 0.017$$ PDG2004

More *B* semileptonic decays



Wrong μ-π
charge correlation

Combine D^* candidate with $\pi^{\pm}$

$$B \to \mu\, D_1^0(2420) / D_2^{*0}(2460)\, \nu\, X$$

$$D_1^0(2420) / D_2^{*0}(2460) \to D^{*\mp}\pi^{\pm}$$

of $D^{**}+\mu$ events:
523 ± 40 (250 pb^{-1})

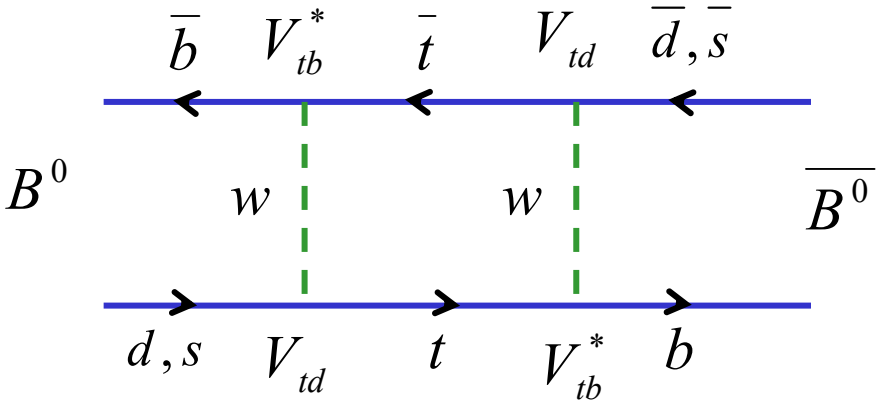
- Clear contribution from two states
- Interference between D_1^0, D_2^{*0} ?

$$BR(B \to \mu\, \nu\, D^{*\pm}\pi^{\mp} X) = (0.48 \pm 0.10)\%$$ LEP (PDG 2002)

$$BR(B \to \mu\, \nu\, D^{*\pm}\pi^{\mp} X) = (0.241 \pm 0.018 \pm 0.072)\%$$
via $D_1^0(2420) / D_2^{*0}(2460)$

First time measurement!

B_s mixing: why do we care?



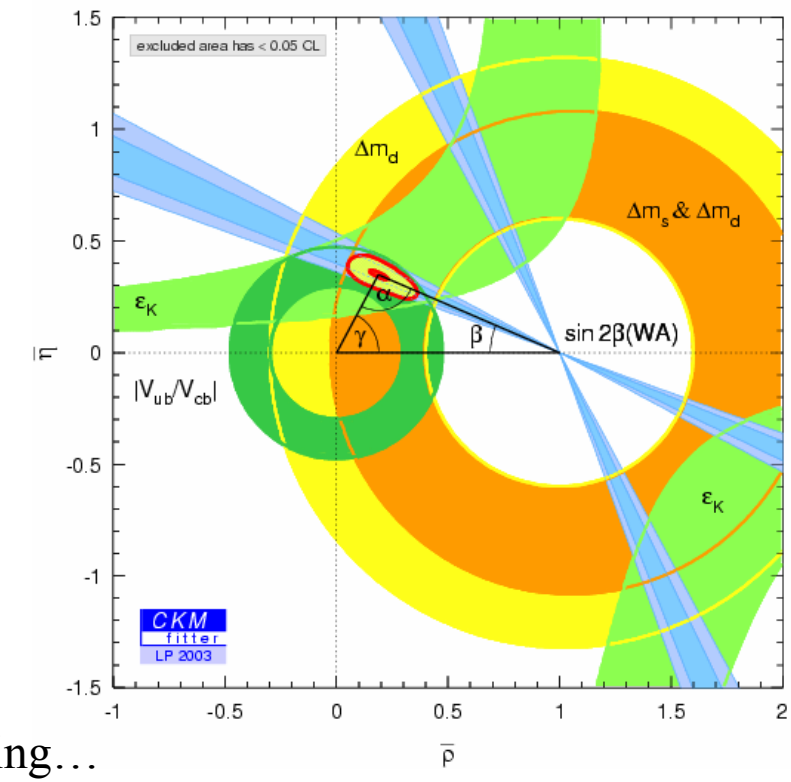
We *think* we understand the mixing of B's.
A deviation from this simple diagram is a deviation from SM.

$$\frac{\Delta m_s}{\Delta m_d} = \frac{M_{B_s}}{M_{B_d}} \cdot \frac{\hat{B}_{B_s} f_{B_s}^2}{\hat{B}_{B_d} f_{B_d}^2} \cdot \left| \frac{V_{ts}}{V_{td}} \right|^2$$

Measure!

Lattice QCD

Consistent with CKM?



A B_s mixing measurement will be precise!

Before B_s mixing comes B_d mixing…

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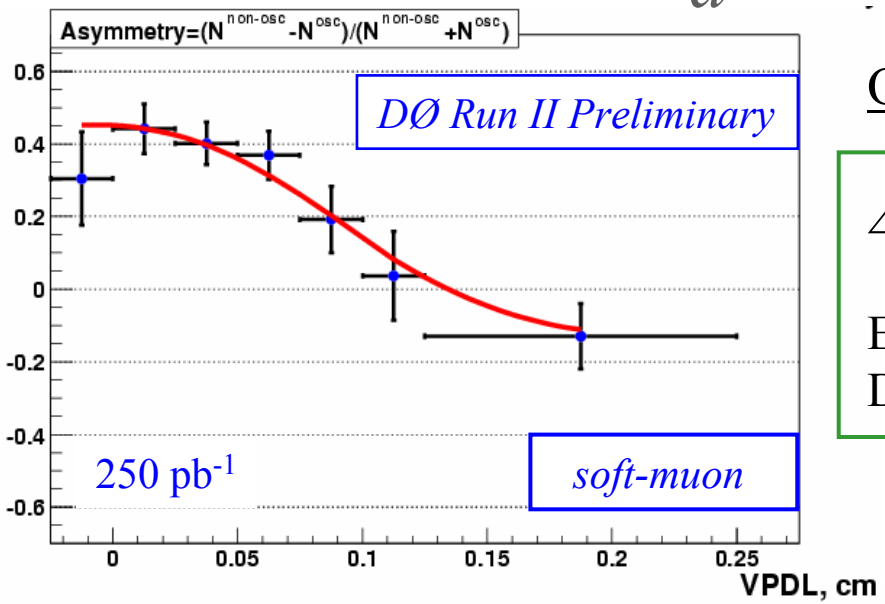
B_d oscillations



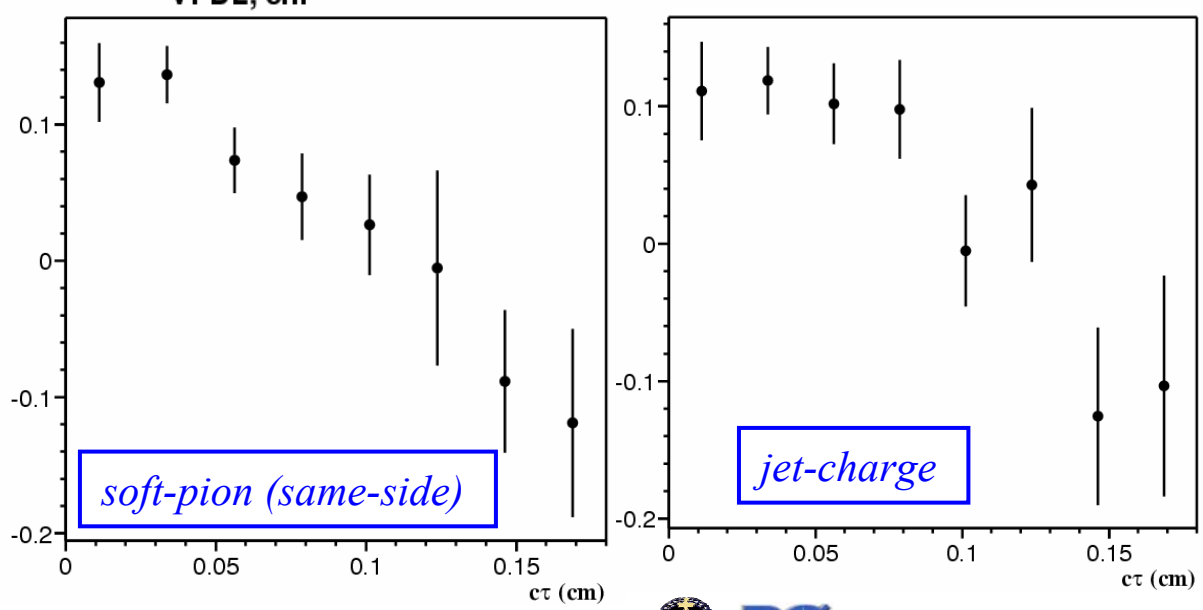
Oscillations with soft-muon tagging:

$\Delta m_d = 0.506 \pm 0.055(\text{stat}) \pm 0.049(\text{syst})\ \text{ps}^{-1}$

Efficiency $\varepsilon = (4.8 \pm 0.2)$ %
Dilution $D = (46.0 \pm 4.2)$ %

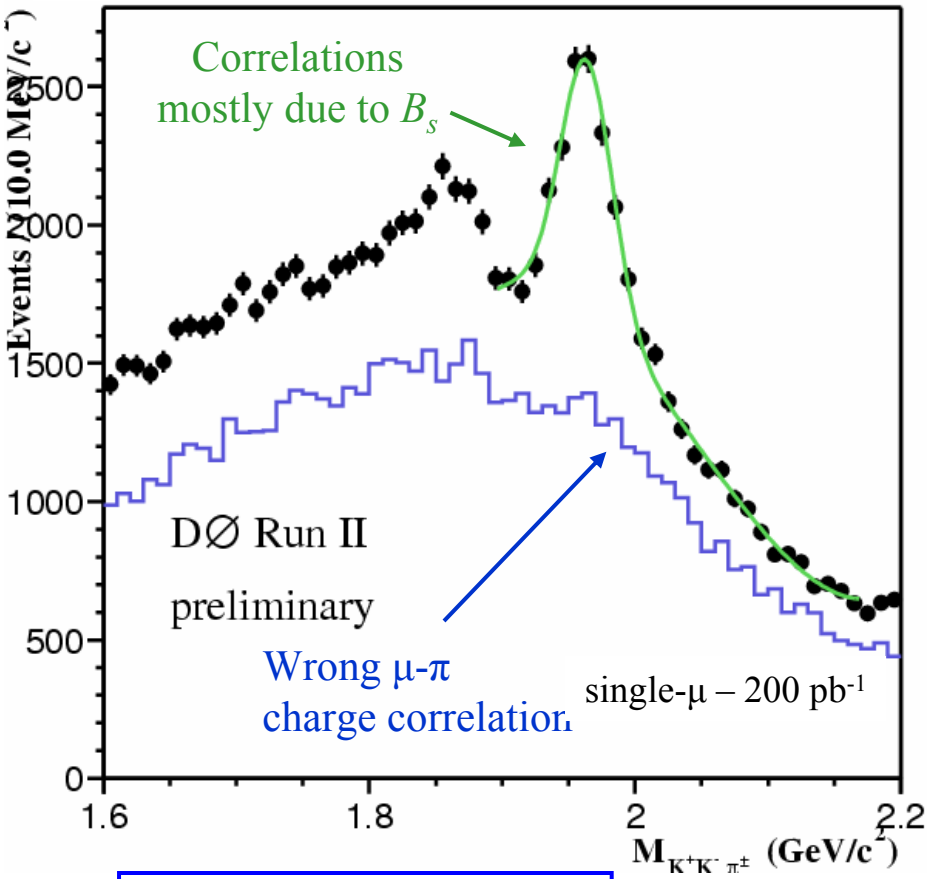
First B_d oscillations seen at DØ!

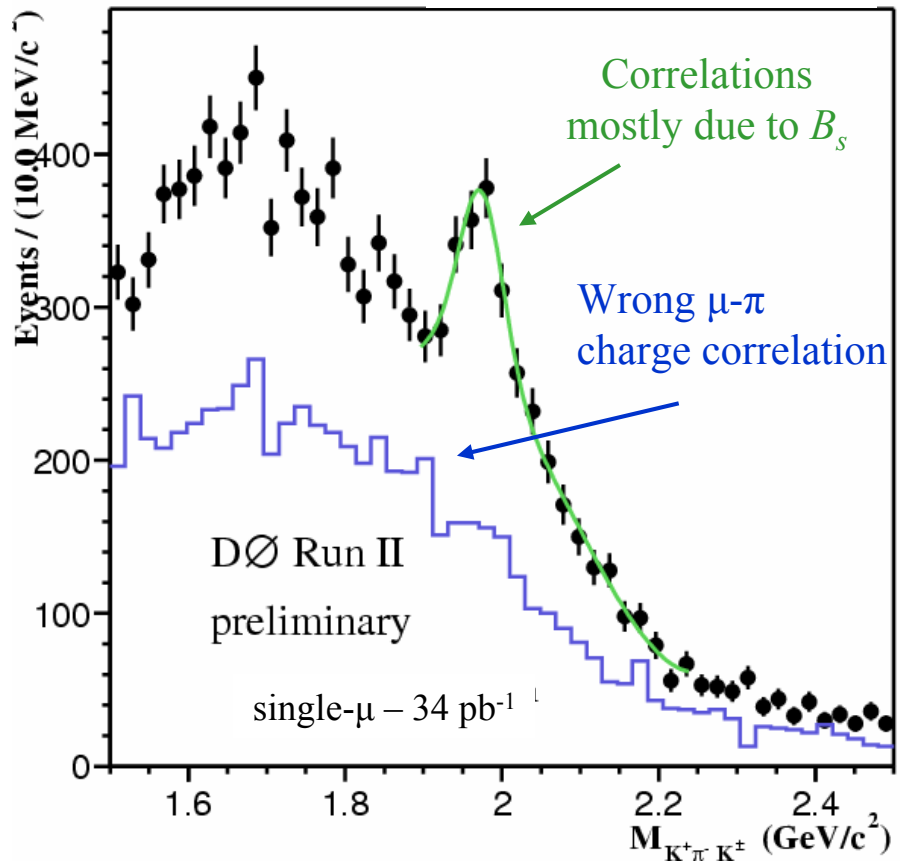
In the works:
Additional measurements with two more taggers!



B_s semileptonic decays: $B_S \to \mu^{\mp} D_S^{\pm} \nu X$

$D_S^{\pm} \to \phi(K^+K^-)\,\pi^{\pm}$ D_s mass distributions $D_S^{-} \to K^*(K^+\pi^-)\,K^-$





of D_S+μ events:
4458 ± 342 (200 pb^{-1})
(or ~22 B_S events/pb^{-1})

- *Large event yields*!
- Pushing for limit on B_s oscillations by end of summer

of D_S+μ events:
796 ± 256 (34 pb^{-1})
(or ~23 B_S events/pb^{-1})

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Summary

Latest Run-II results from DØ presented

Analyses: twice the statistics of Run-I

- QCD:
  - Studying the proton structure
- New Phenomena:
  - Exploring new territory
  - Going after spacetime & dark matter mystery
- *B* Physics:
  - Already producing world-class measurements
  - Gearing up for B_s mixing

Lots of Physics ahead: Stay tuned!

Today at 16.00:
Arnulf Quadt on
"Top, E/W & Higgs results from DØ"

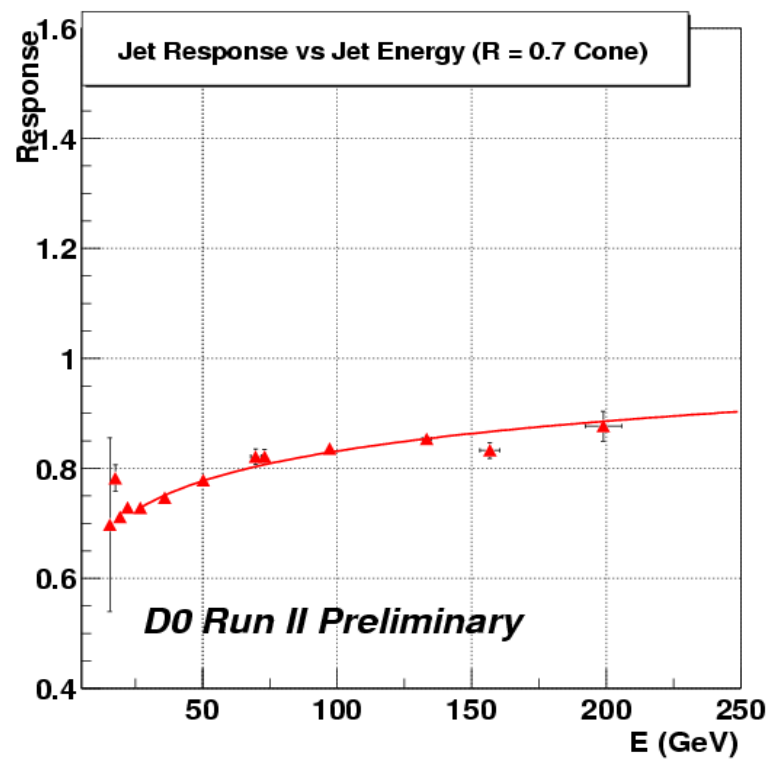
Backup slides

Jet Energy Scale correction

Methodology for correcting the jet energy:

$$E_{corr} = \frac{E_{meas} - E_O}{R_{jet} S_{cone}}$$

- E_0 (offset): electronic noise, uranium noise, underlying event
  Use zero bias & minimum bias events (data)
- S_{cone}: out of code showering
  Measure energy density in ring around the jet axis (data)
- R_{jet} (response): ratio of measured to deposited energy
  Determine imbalance in energy in γ + jet events (data)



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Leptoquarks: selection cuts

two jets + ee

- Electrons: $E_T > 25$ GeV/c^2
- Jets: $E_T > 20$ GeV/c^2 , $|\eta| < 2.4$
- Z veto
- $S_T > 450$ GeV/c^2

Signal efficiency: 12−33%

two jets + $e\nu$

- Electron: $E_T > 35$ GeV/c^2
- Jets: $E_T > 25$ GeV/c^2 , $|\eta| < 2.5$
- $\not{E}_T > 30$ GeV/c^2
- $M_T\,(e\nu) > 130$ GeV/c^2
- $S_T > 330$ GeV/c^2

Signal efficiency: 13−25%

Trilepton searches: selection cuts

- 2 electrons:
  - E/M cluster matched to track
  - $P_T > 12$ (8) GeV/c
  - $|\eta| < 1.1$ (3.0)
- Z suppressant:
  - $15 < M_{ee} < 60$ GeV/c^2
  - $\Delta\varphi_{ee} < 2.8$ rad
- W ($e\nu$) + γ suppressant: silicon hit requirement or better e quality
- top suppressant:
  - Jet transverse energy $E_T > 80$ GeV/c^2
- Drell-Yan suppressant:
  - $\not{E}_T > 20$ GeV/c^2
  - $\Delta\varphi(e, \not{E}_T) > 0.4$ rad
- 3rd electron:
  - isolated track
  - $P_T > 3$ GeV/c

Squarks and gluinos: selection cuts

- Jets:
  - $E_T > 60\ (50)$ GeV/c^2
  - E/M fraction < 0.95
- $\not{E}_T > 175$ GeV/c^2
- $30° < \Delta\varphi(\text{jet}, \not{E}_T) < 165°$
- $\Sigma_{\text{jets}}(p_T) > 275$ GeV/c

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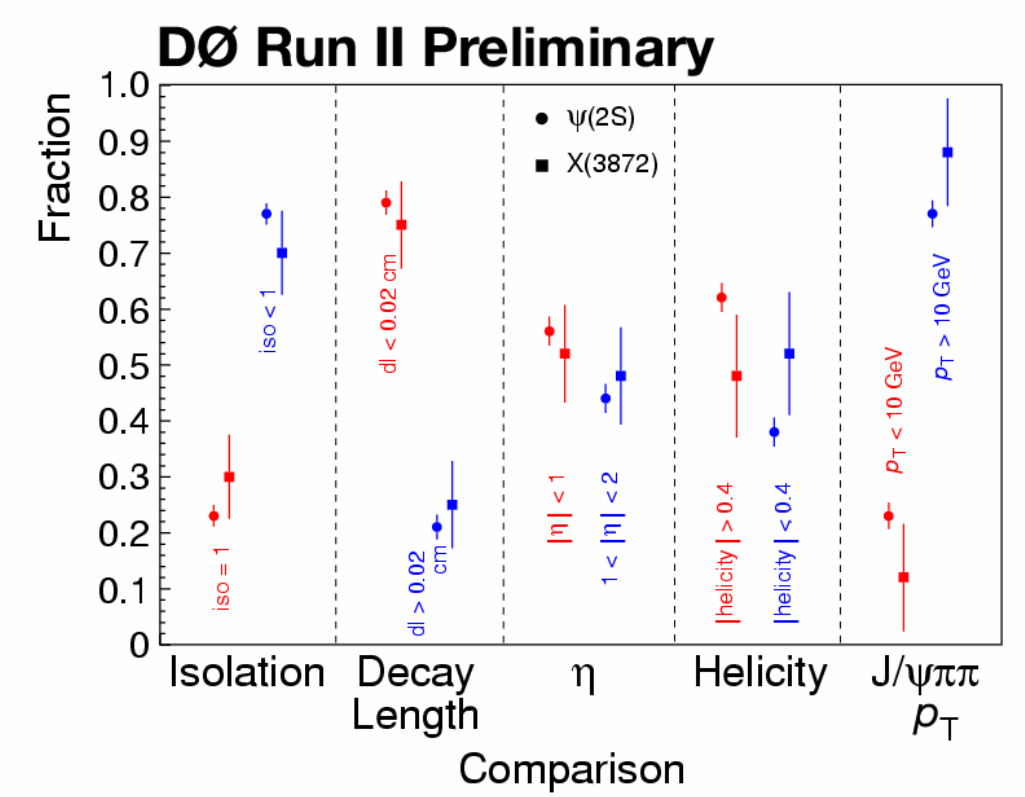
Comparing *X(3872)* to *ψ(2S)*



Examine X(3872) properties; compare event fractions to those of ψ(2S) for different cuts

- Isolation

$$\frac{p_T(X)}{p_T(\text{all trks})_{\Delta R<0.5}} < 1$$

- Decay length: $d\ell > 0.02\ \text{cm}$
- Central vs. forward production
- Helicity (angles at $\pi\pi/\mu\mu$ rest frame)

$$\cos(\pi/\mu, X) < 0.4$$

- Transverse momentum

$$p_T(X) > 5\ \text{GeV}/c$$

X(3872) has similar behavior to that of the charmonium state ψ(2S)

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$B_S \to \mu^+\mu^-$: systematic errors

Source	Error (%)
$BR(B^\pm \to J/\psi\, K^\pm)$	4
$BR(J/\psi \to \mu^+\mu^-)$	2
$b \to B_S, b \to B^\pm$	15
MC stat for $B^\pm \to J/\psi\, K^\pm$	4
$N(B^\pm \to J/\psi\, K^\pm)$	7
trigger efficiency = f($M_{\mu\mu}$)	?

B_s mixing reach: The Über Formula

Average statistical significance:

Moser & Roussarie NIM A 384 (1997)

$$S(\Delta m, \sigma_t) = \sqrt{\frac{\varepsilon D^2 N}{2}} \sqrt{\frac{S}{S+B}} \times e^{-(\Delta m \sigma_t)^2/2}$$

Flavor tagging

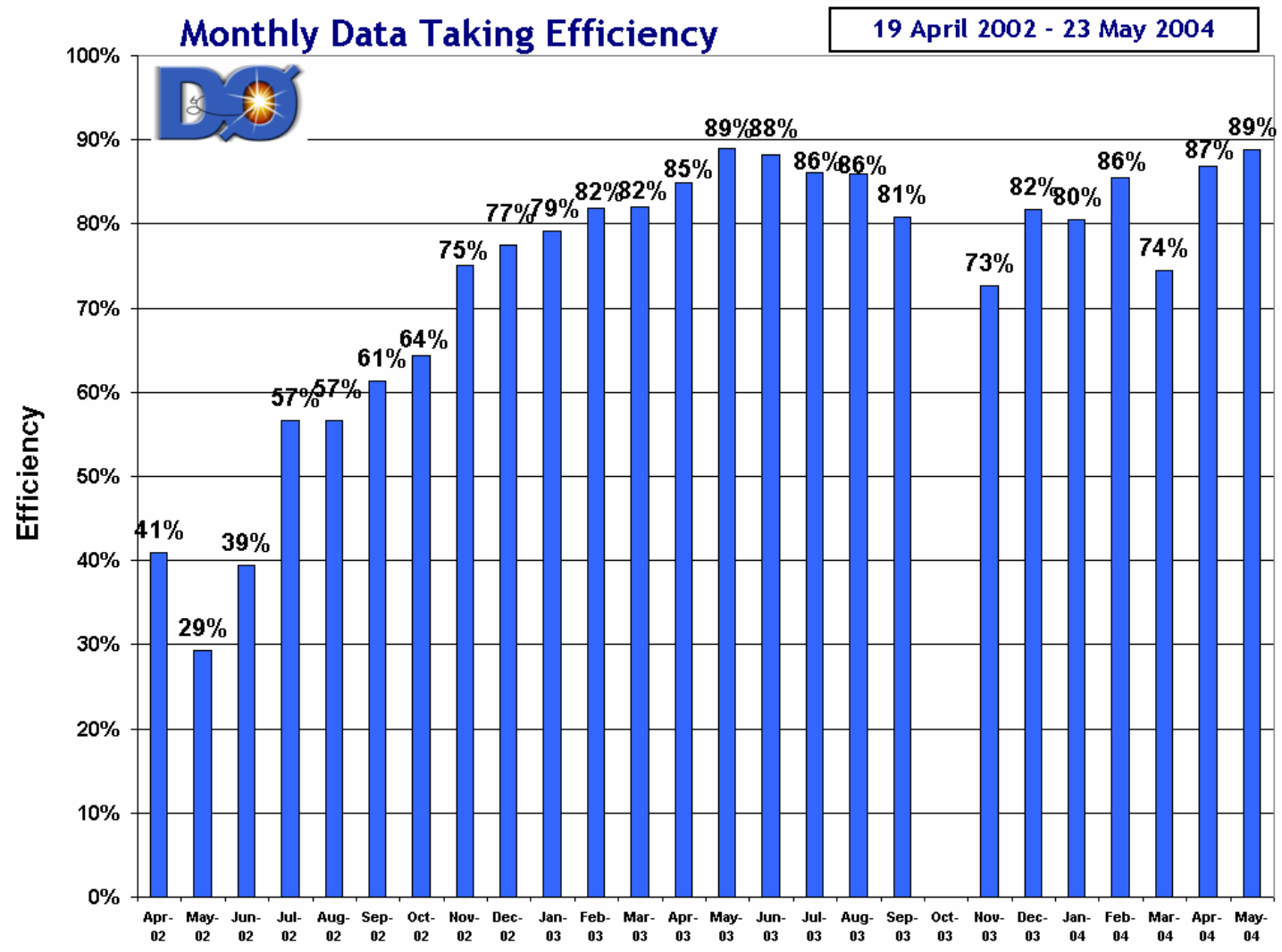
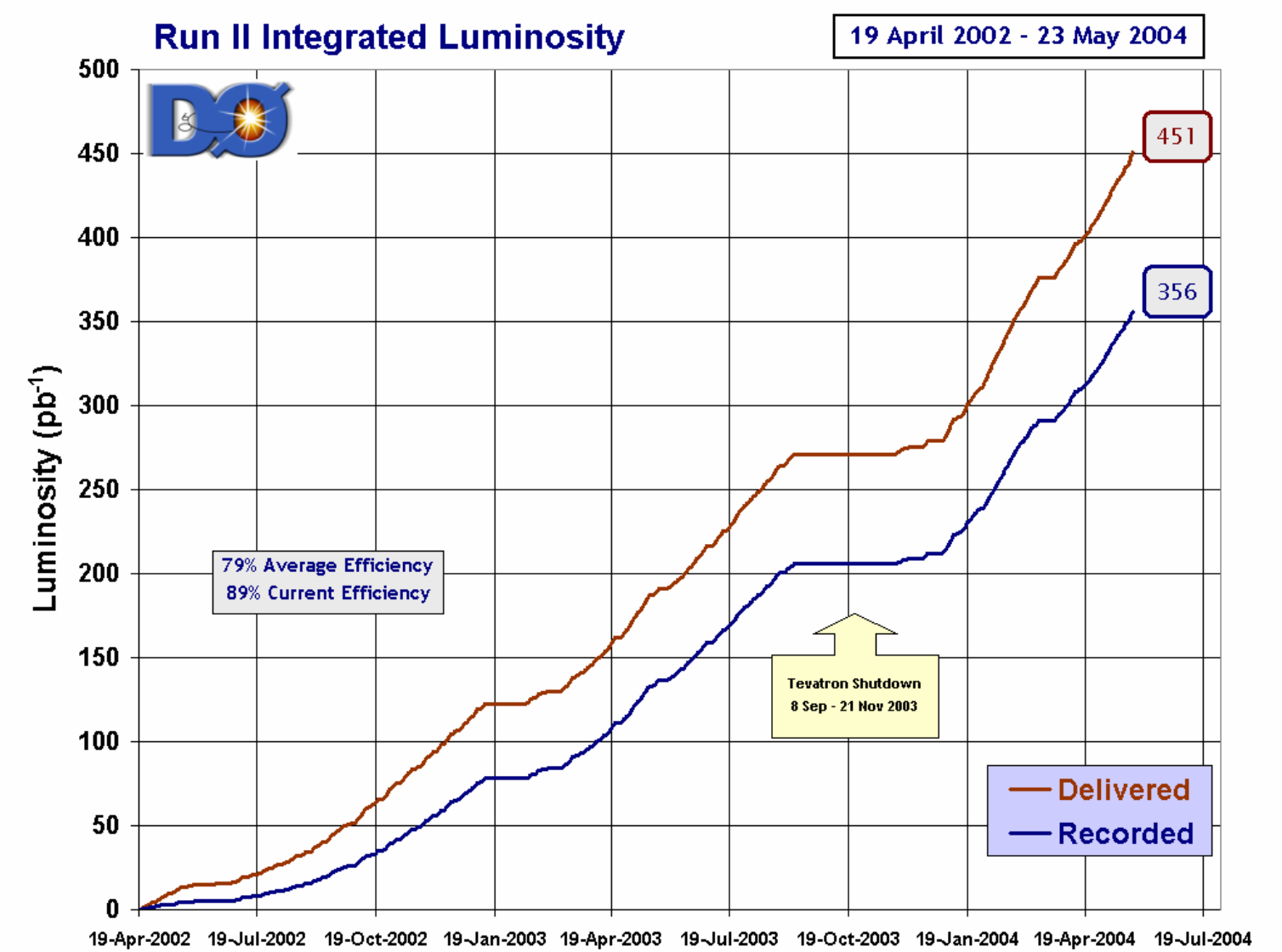
# of reconstructed events

Signal purity

Proper time resolution

Having a good understanding of all the above factors means that we are confident about the Δm_S reach of DØ

DØ: data-taking efficiency



DØ: Integrated Luminosity