Selected B physics results from D0: B** and $B_s \to \mu^+\mu^-$

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Outline

- Introduction to B physics
- D0 detector
- Recent Results
- Conclusions

650 collaborators:
110 graduate students
85 post-docs

80 institutions, 18 countries

Approx. half the collaboration is non-US

Why B physics?

- Understanding structure of flavour dynamics is crucial
  3 families, handedness, mixing angles, masses, …
  any unified theory will have to account for it
- Weak decays, especially Mixing, CP violating and rare decays provide an insight into short-distance physics
- Short distance phenomena are sensitive to beyond-SM effects
- CKM matrix determines the charged weak decays of quarks, tree level diagrams, one-loop transitions…
- In most beyond-SM extensions, role is same

Need to precisely determine the CKM matrix

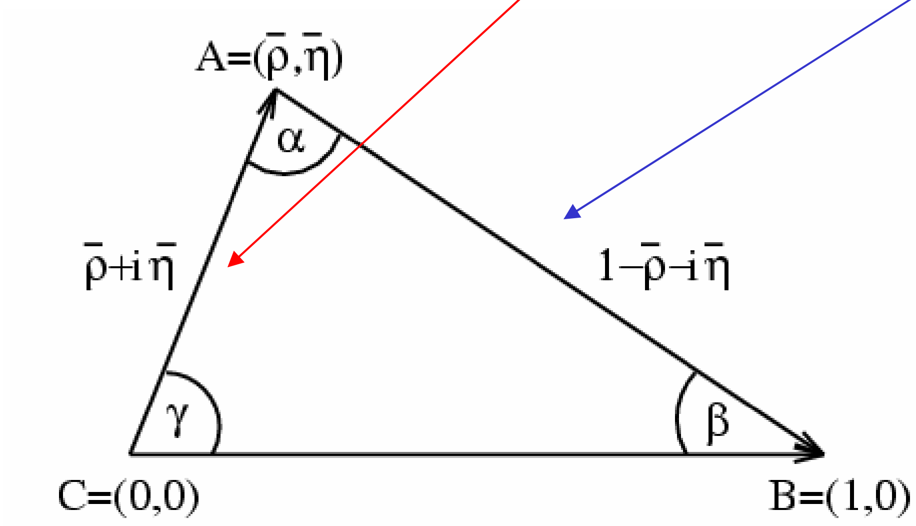
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv \hat{V}_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Elements of the CKM matrix can be written as:
  - λ – Cabbibo angle (~0.22), A (~0.85),

    $\overline{\rho}, \overline{\eta} \quad (\overline{\rho} = \rho(1 - \lambda^2 / 2))$

- Magnitude of CP violation is given by η

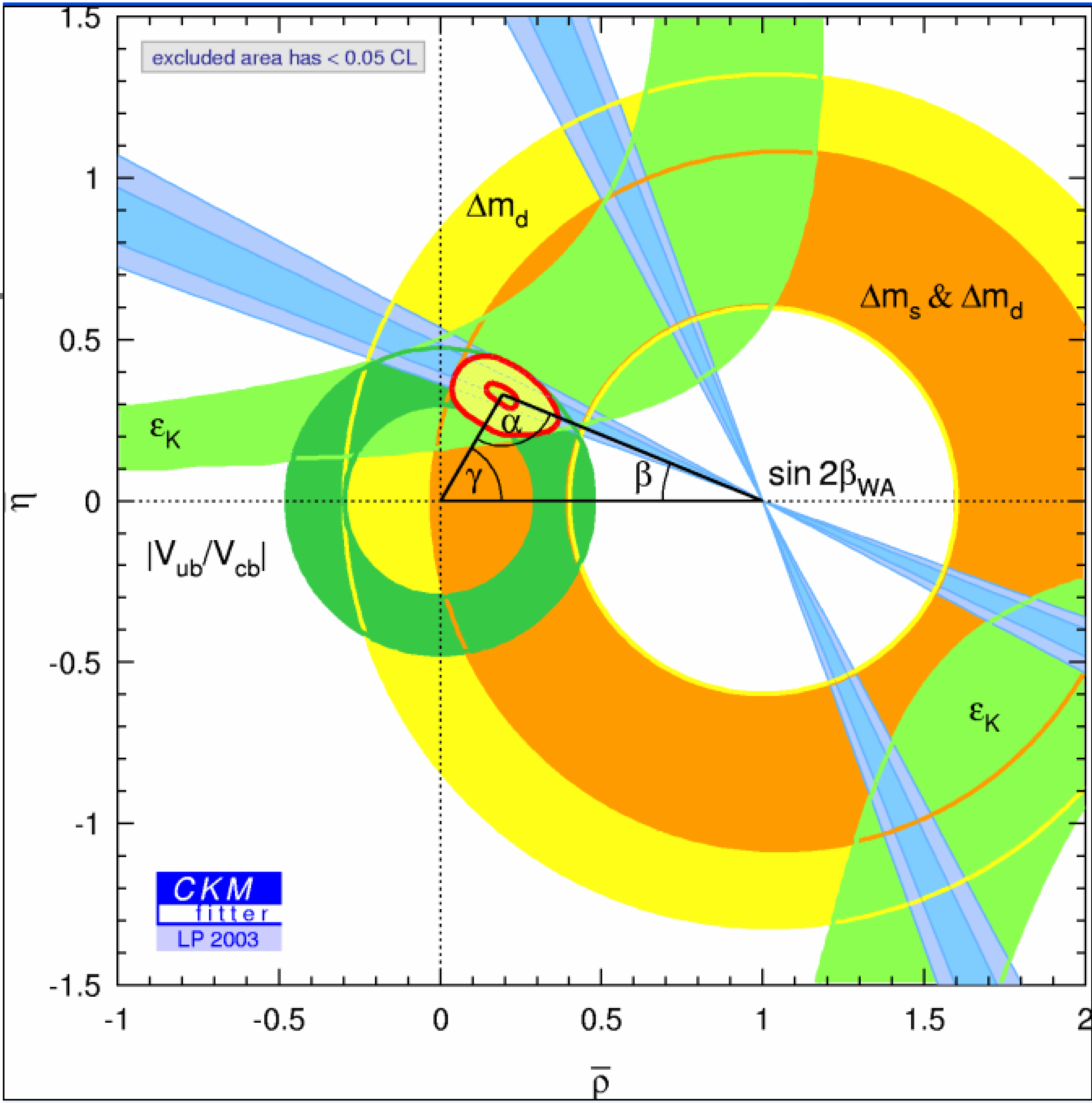
- Unitarity of the CKM matrix leads to relationship between various terms
- One such relation: $V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$



- Study of B hadrons yields $|V_{cb}|, |V_{ub}/V_{cb}|, V_{td}, V_{ts}, \eta$
  - B mixing: V_{td}, V_{ts}
  - η can be inferred from CP violation
  - Within the SM, CP conserving decays sensitive to $|V_{cb}|, |V_{ub}/V_{cb}|, |V_{td}|$ can tell if η is non-zero
- $\bar{\rho} > 0$ can be inferred from limit on Bs mixing
- Complementary meas. of η, $|V_{td}|$ from $K \to \pi\nu\bar{\nu}$
- New phenomena might affect K and B differently

Winter 2004 HFAG avg.

(fit does not include results on Sin(2β))



B physics & beyond Standard Model

- As mentioned earlier, one can probe beyond SM physics -
  - $b \to s\gamma$ - In the SM goes via EW penguin (W boson and top/charm quark)

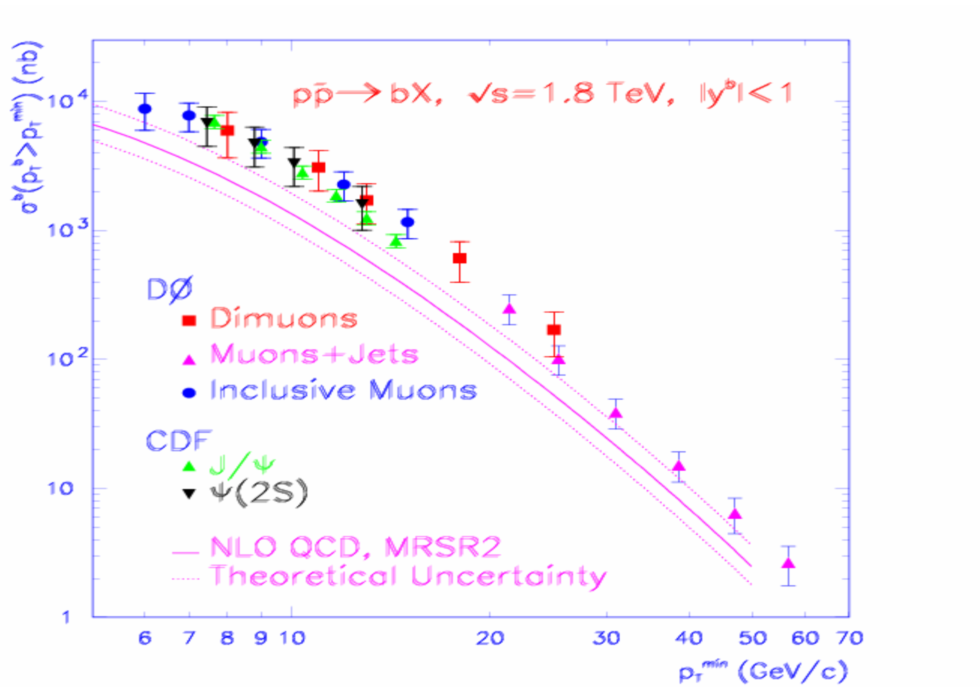
    Results can be used to constrain models -

    Anomalous top couplings, 2HDM, Leptoquarks, SUSY…
  - $B_s \to \mu^+ \mu^-$

B physics and QCD

- B hadrons are a good laboratory for QCD studies, especially non-perturbative
  - Difference in lifetime between various B hadrons probes spectator quark effects. Calculations based on QCD (Heavy Quark Expansion) have been quite successful – expansion in terms of 1/M_b, inputs from lattice QCD
  - B semi-leptonic decays give information on form factors
  - B spectroscopy (B**) is useful for Quark Models.

B physics at the Tevatron



- At Ecm = 2 TeV

  $\sigma(p\bar{p} \to b\bar{b}) \approx 150\,\mu b$

- At Z pole

  $\sigma(e^+e^- \to b\bar{b}) \approx 7\,nb$

- At Υ(4S)

  $\sigma(e^+e^- \to b\bar{b}) \approx 1\,nb$

- All species produced,B** $B_c, B_s, \Lambda_b \ldots$

Environment not as clean as at electron machines
Low trigger efficiencies

B Physics Program at D0

- Unique opportunity to do B physics during the current run
- Complementary to program at B-factories (KEK, SLAC)

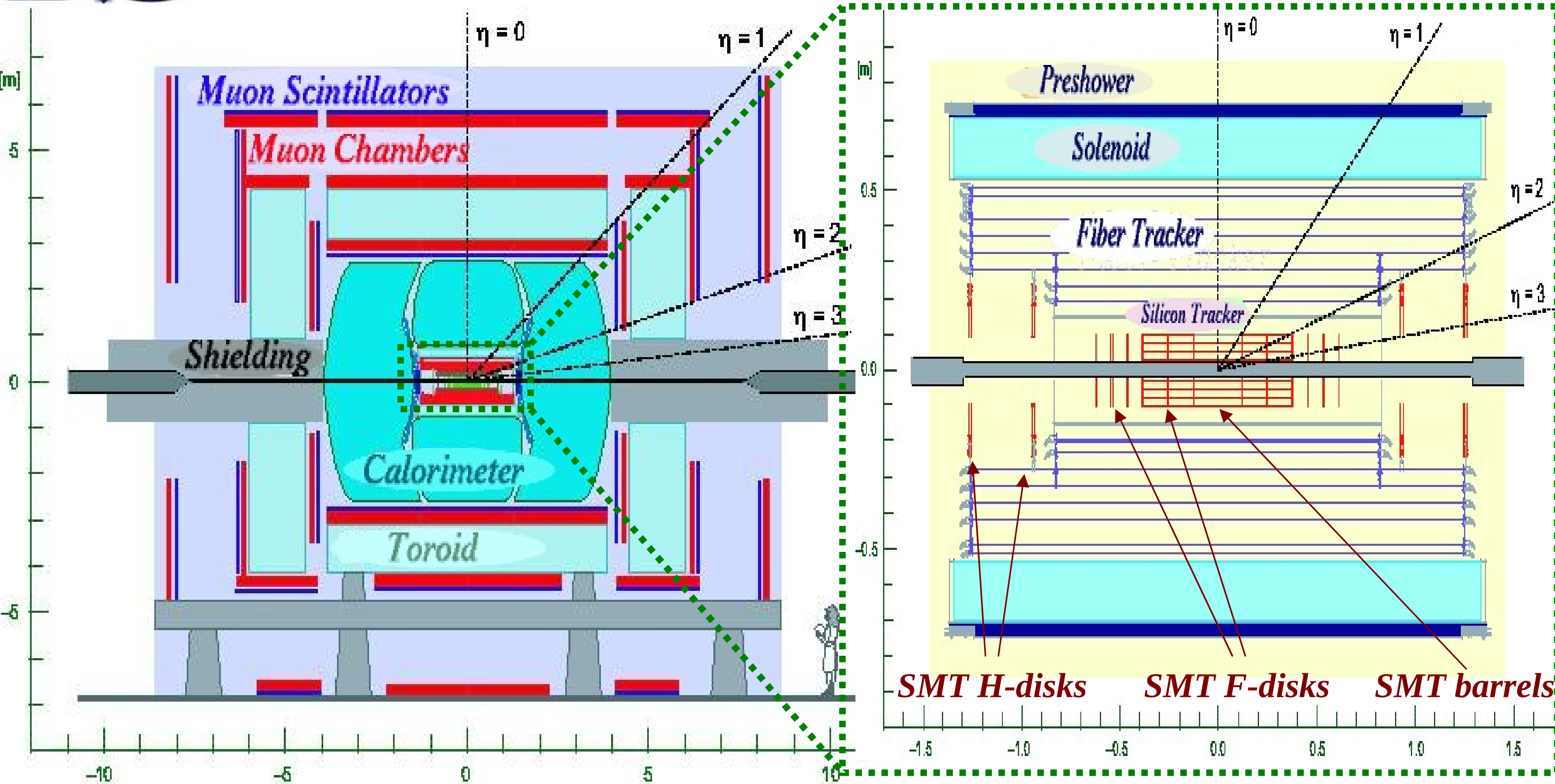
- B_S mixing, $\Delta\Gamma_s / \Gamma_s$
- Rare decays: $B_S \to \mu^+ \mu^-$

- Beauty Baryons, Λ_b lifetime, Ξ_b …
  - $\tau(\Lambda_b)/\tau(B_d^0)$ expt: 0.80±0.06 (SL modes), theory ~ 0.95

- B_C, B^{**}, B lifetimes, B semi-leptonic, CP violation studies

- Quarkonia - $J/\psi, \Upsilon$ production, polarization. b-prod x-section

DZero Detector

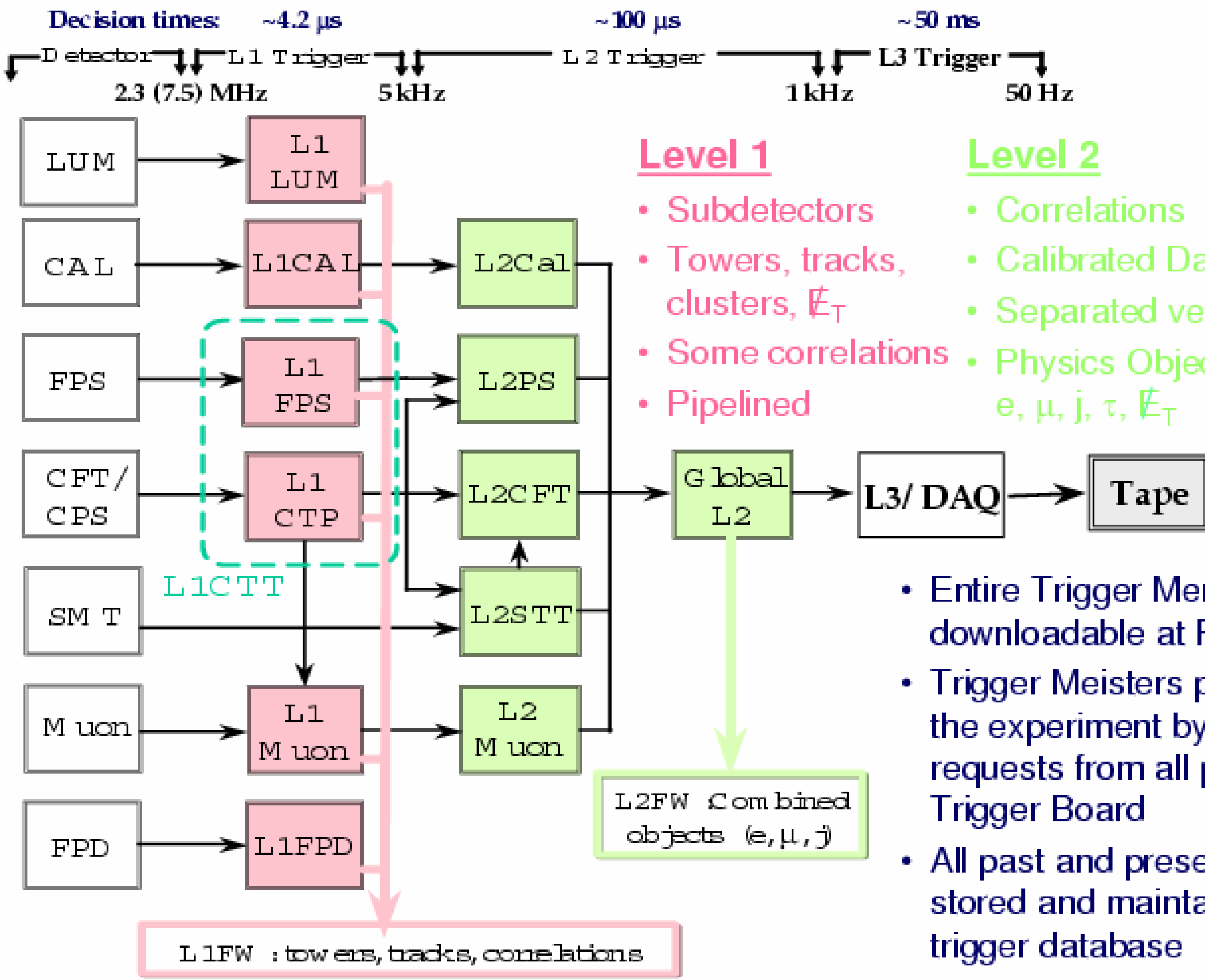


- Muon system with coverage |η|<2 and good shielding

❑ **Trackers**
  - ➢ **Silicon Tracker: |η|<3**
  - ➢ **Fiber Tracker: |η|<2**

❑ **Magnetic field 2T**

DØ Trigger System



Level 1
- Subdetectors
- Towers, tracks, clusters, $\not{E}_T$
- Some correlations
- Pipelined

Level 2
- Correlations
- Calibrated Data
- Separated vertex
- Physics Objects e, μ, j, τ, $\not{E}_T$

Level 3
- Simple Reconstruction
- Physics Algorithms

- Entire Trigger Menu configurable and downloadable at Run start
- Trigger Meisters provide trigger lists for the experiment by collecting trigger requests from all physics groups in the Trigger Board
- All past and present trigger lists are stored and maintained in the dedicated trigger database

All trigger components have simulation software

Triggers for B physics

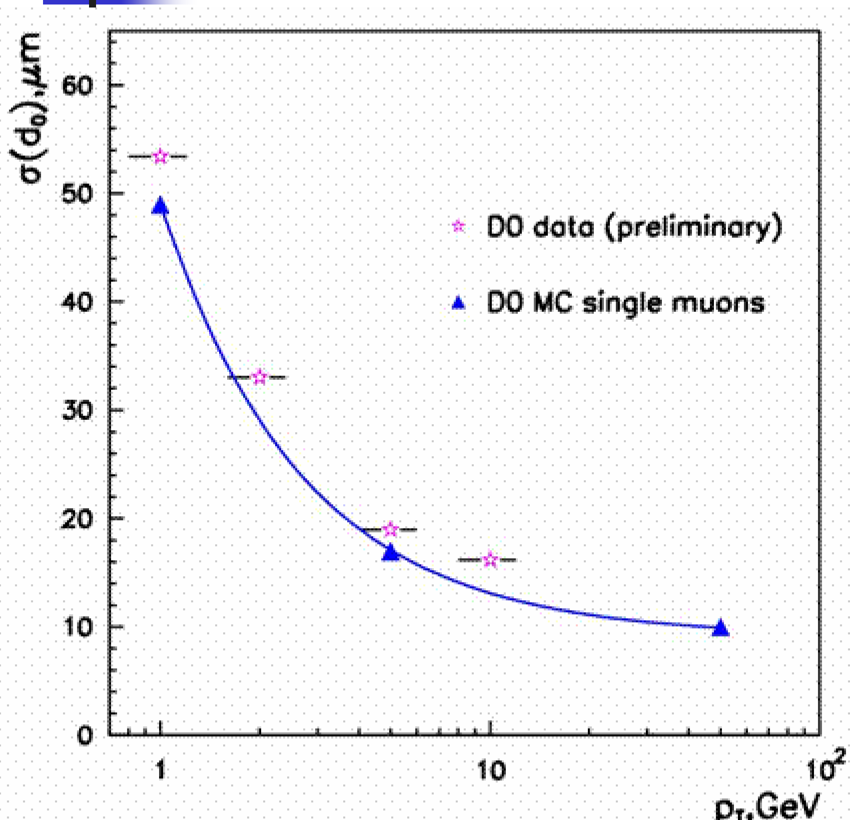
- Robust and quiet di-muon and single-muon triggers
  - Large coverage $|\eta|<2$, p>1.5-5 GeV – depends on Luminosity and trigger
  - Variety of triggers based on
    - **L1 Muon & L1 CTT (Fiber Tracker)**
    - **L2 & L3 filters**
- Typical total rates at medium luminosity (40 10^{30} $s^{-1}cm^{-2}$)
  - Di-muons : 50 Hz / 15 Hz / 4 Hz @ L1/L2/L3
  - Single muons : 120 Hz / 100 Hz / 50 Hz @ L1/L2/L3 (prescaled)
    - **Muon purity @ L1: 90% - all physics!**
  - Current total trigger bandwidth

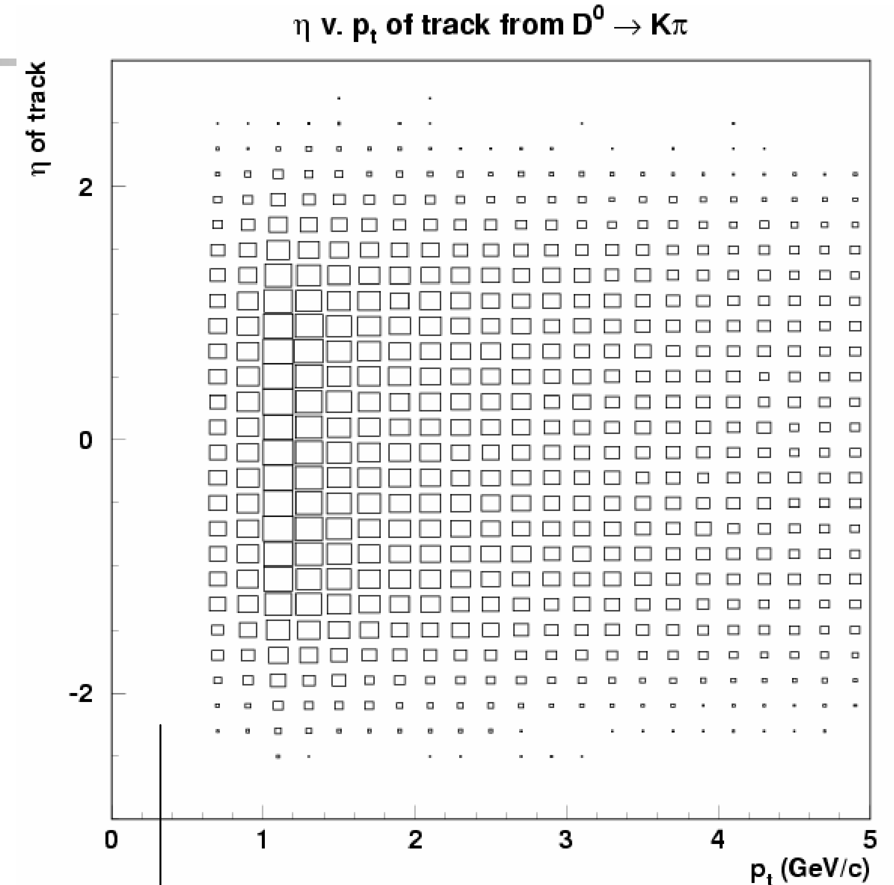
    1600 Hz / 800 Hz / 60 Hz @ L1/L2/L3

$B \rightarrow D^0 \mu X, \quad D^0 \rightarrow K^- \pi^+$

$p_T(\mu) > 2\ \mathrm{GeV}, \quad |\eta(\mu)| < 2.2$

All tracks





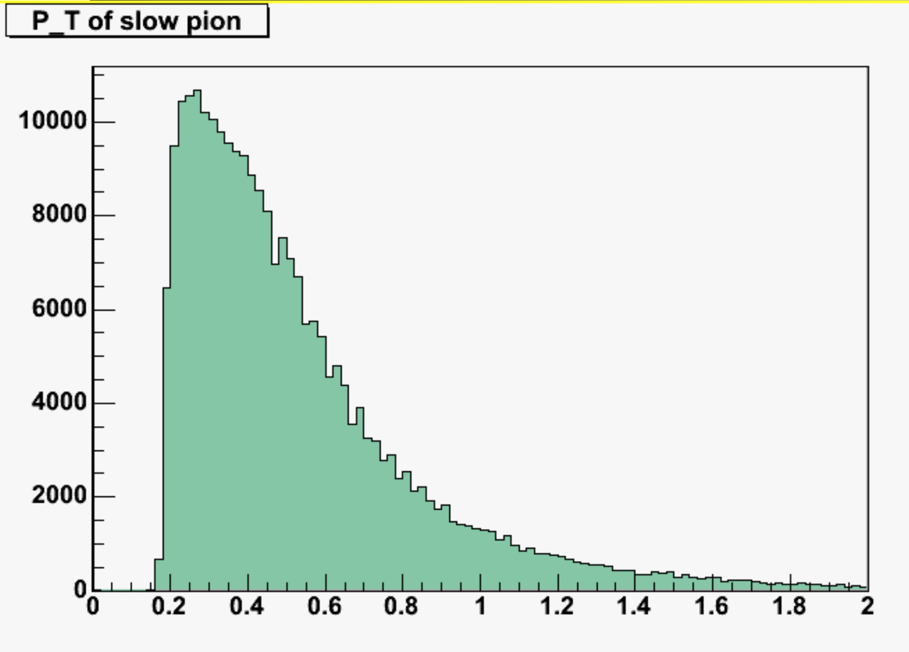
σ(DCA)≈50μm @ P_t=1GeV

Better than 20 μm for P_t > 5 GeV

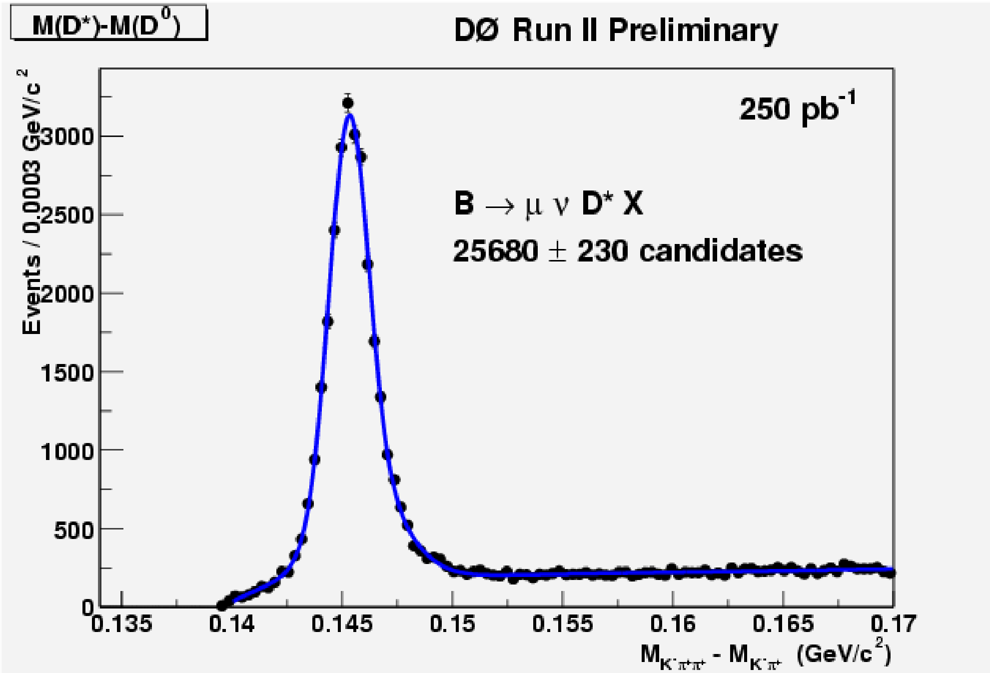
Analysis cuts – pT>0.7 GeV

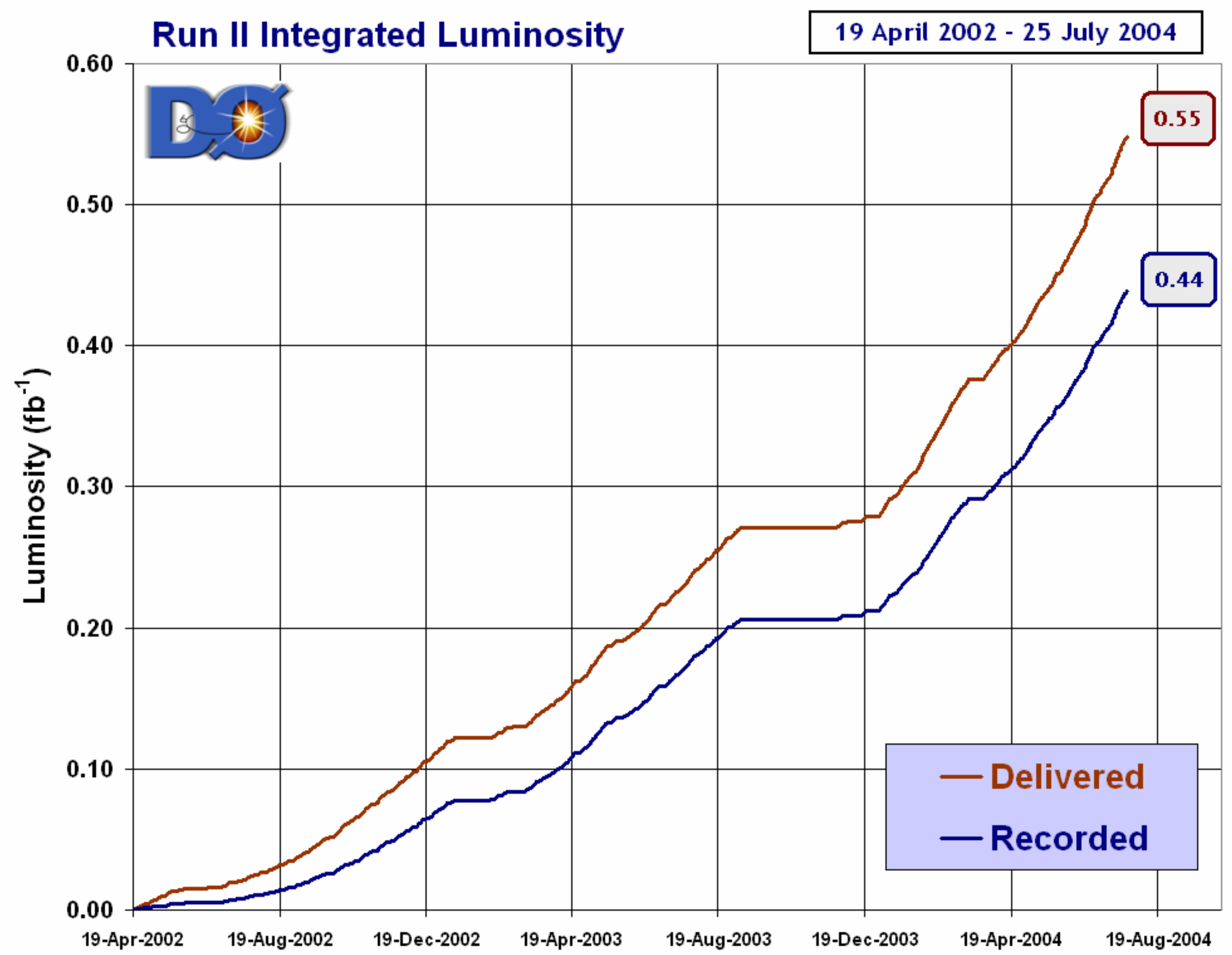
data

p_T spectrum of soft pion candidate in $D^{*+} \rightarrow D^0\pi^+$



~100 events/pb^{-1}





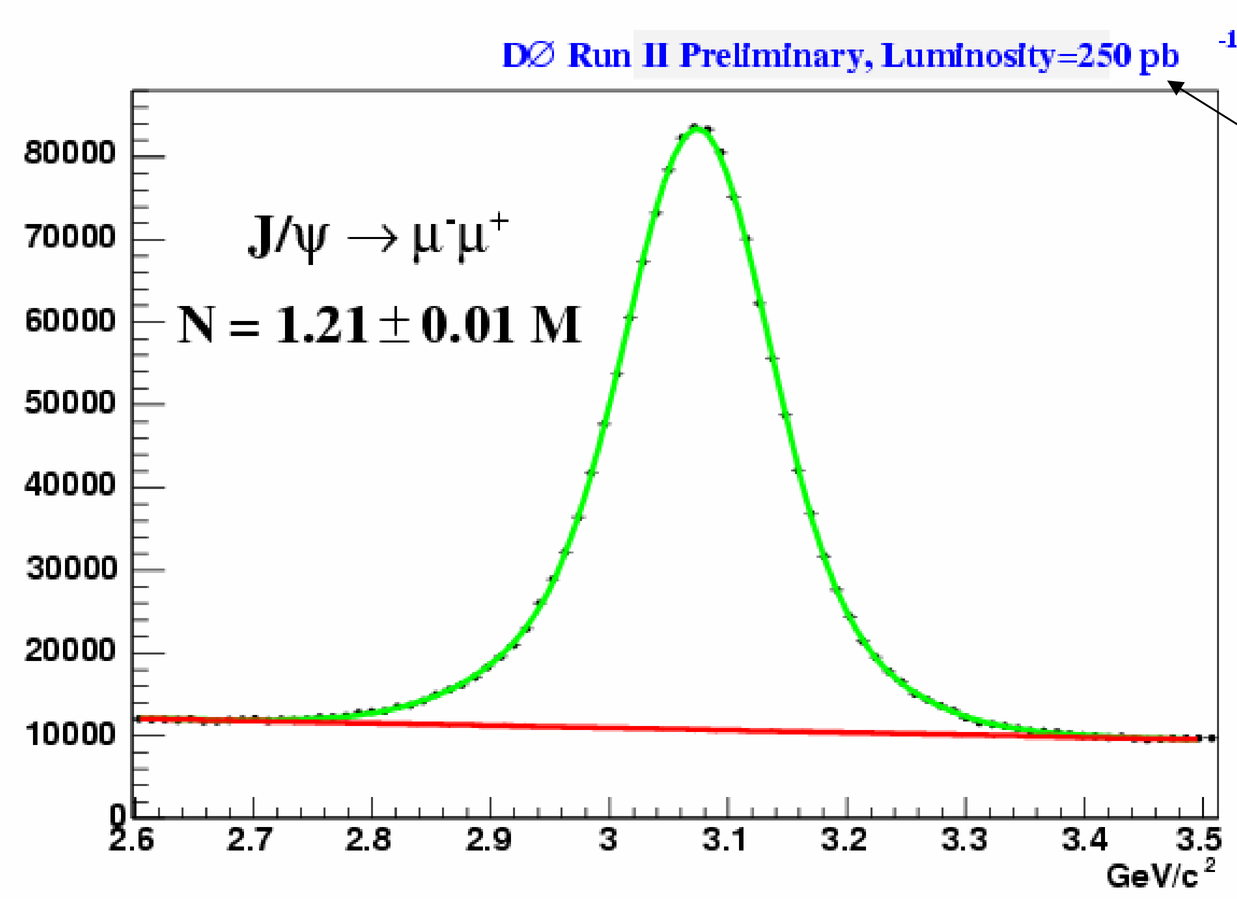
Results are based on smaller datasets

Recent results

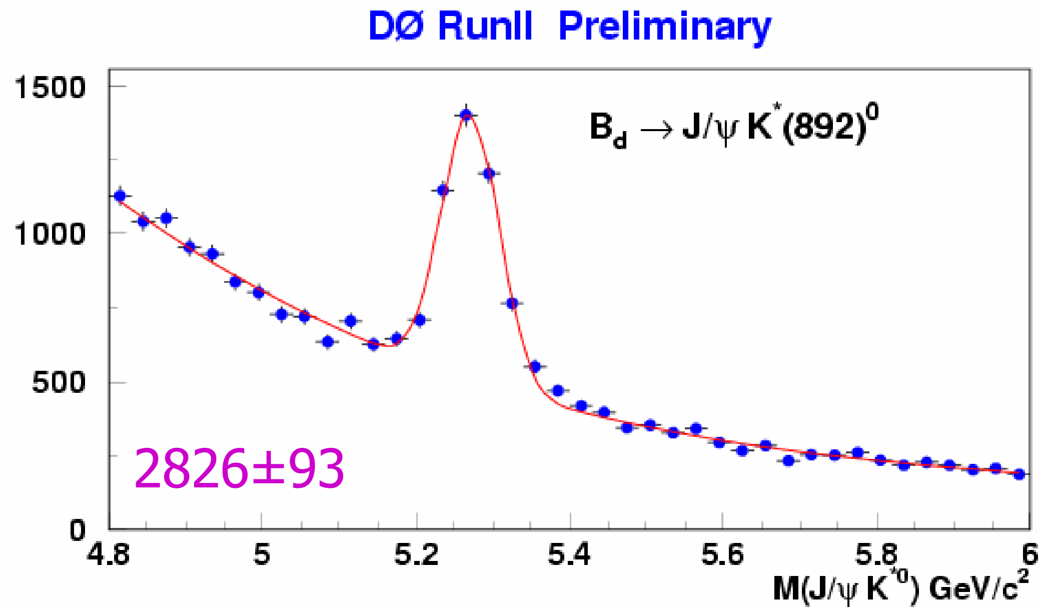
- B** - Dataset was 350 pb^{-1}

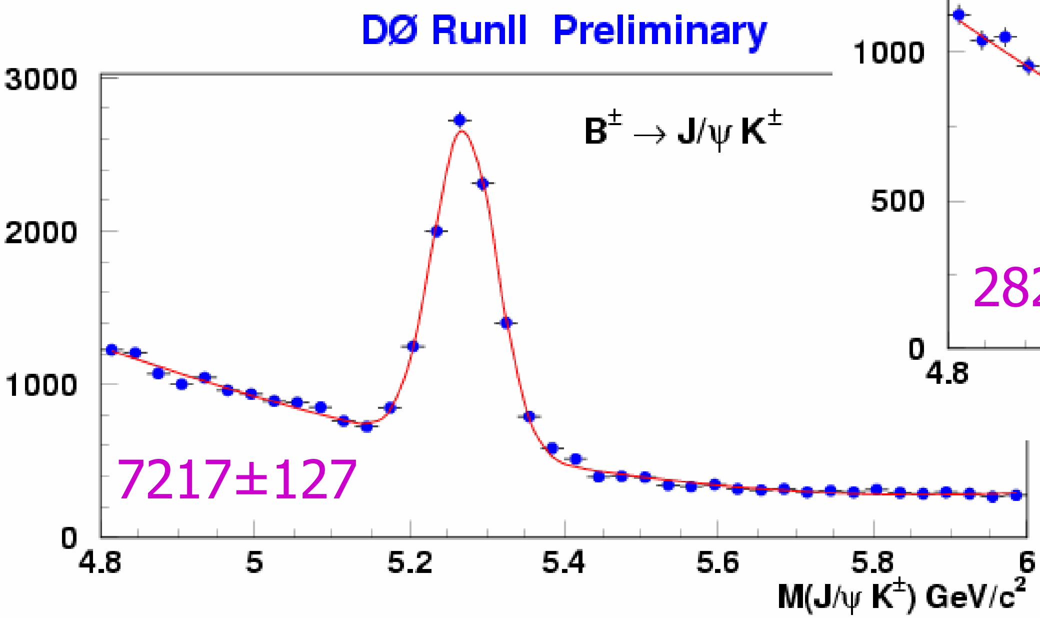
- $B_s \rightarrow \mu^+ \mu^-$ 240 pb^{-1}

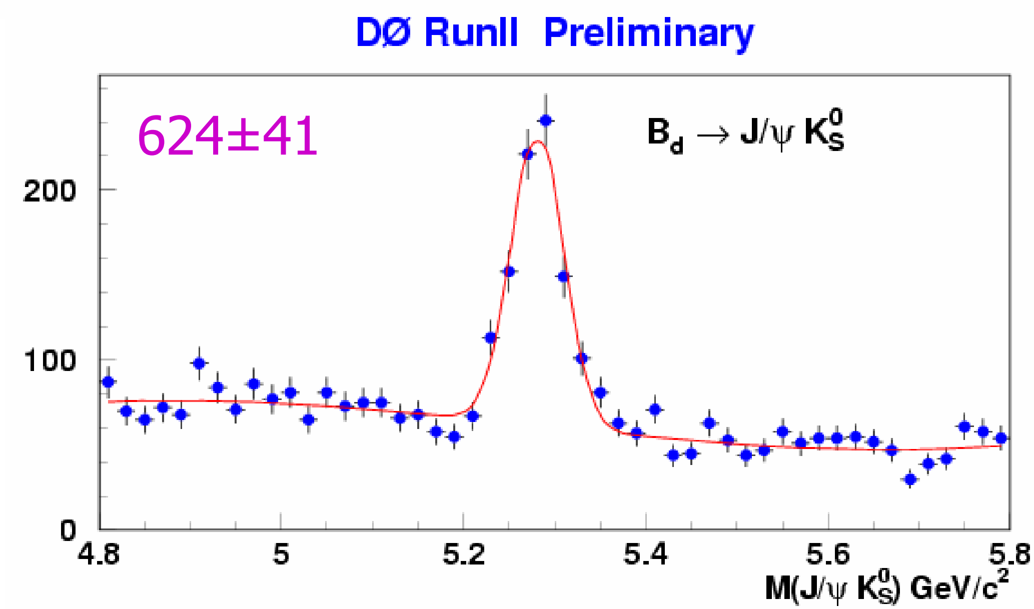
Basic particles



Plot is for illustrative purpose







~ 350 pb^{-1}

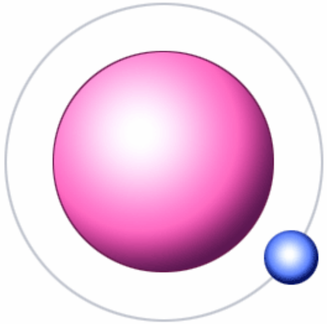
Large exclusive samples

Impact parameter cuts

July 30, 2004

B spectroscopy – B**

- For Hadrons with one heavy quark, QCD has additional symmetries as $m_Q >> \Lambda_{QCD}$ (Heavy Quark Symmetry)



- The spin of the heavy quark decouples and meson properties are given by the light degrees of freedom – light quark, gluons (aka "brown muck")

- Such hadrons are the closest analog of hydrogen atoms (of QED) for strongly interacting systems

- $\vec{S}_Q$ and $\vec{j}_q = \vec{s}_q + L$ are the Angular momentum of the heavy quark and light d.o.f

- In heavy quark limit, each energy level in the spectrum of such mesons has a pair of degenerate states given by $j_q, \quad \vec{J} = \vec{j}_q + \vec{s}_Q$

- For L=0, two states with $j_q = \frac{1}{2}, \quad J = 0, 1$

B,B*

- For L=1, get two pairs of degenerate doublets,

j_q=1/2, J=0, 1 - B_0^*, B'

j_q=3/2, J=1, 2 - B_1, B_2^*

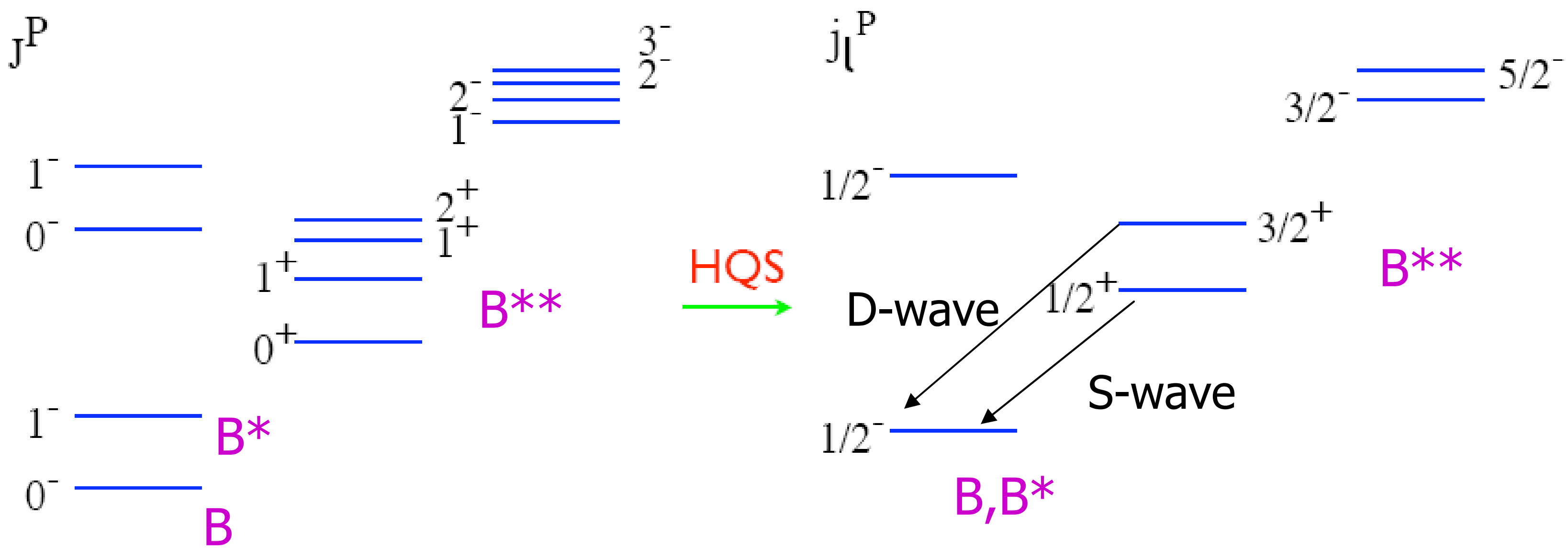
These four L=1 states are collectively known as B** or B_J

- HQS also constrains the strong decays of these states

- j_q = 1/2 decay via S-wave, hence expected to be wide
- j_q = 3/2 decay via D-wave, hence narrow

Strong decays

Heavy-Light Spectrum



Eichten, BEACH conference: June 27-July 3, 2004

- Since mass of charm, bottom quarks is not infinite degeneracy is broken – corrections appear as $1/m_Q$

- Prediction of masses/widths of such hadrons needs models which include QCD (non-perturbative) dynamics

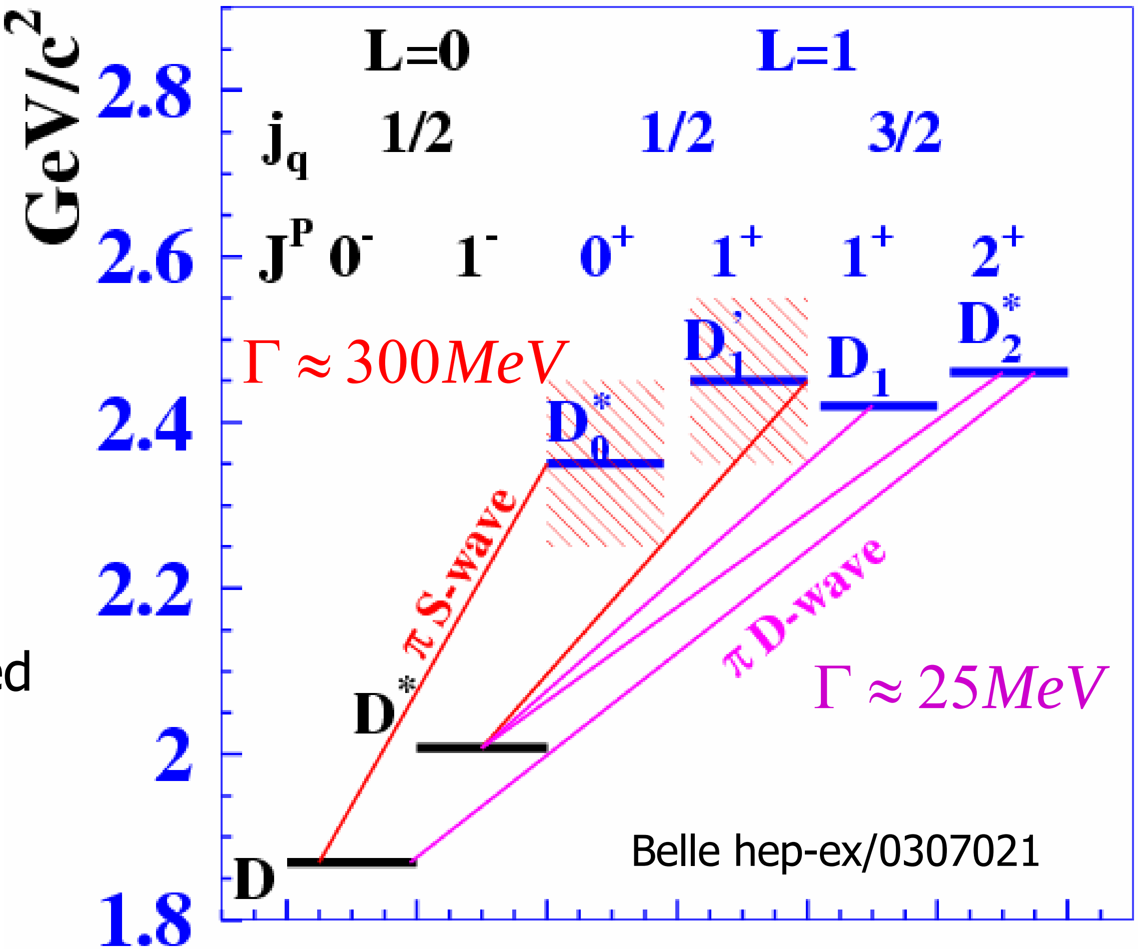
- Relativistic quark models, potential models are some examples.

Lessons from charm (I)

For non-strange
L=1 Charm mesons
j_q = 1/2, 3/2 have
been seen

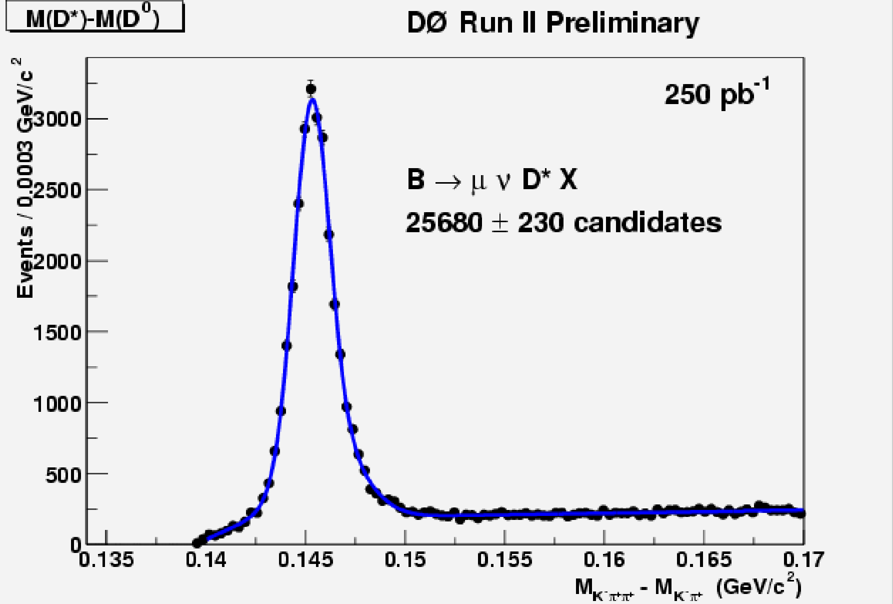
The wide states were observed via Dalitz plot analysis in

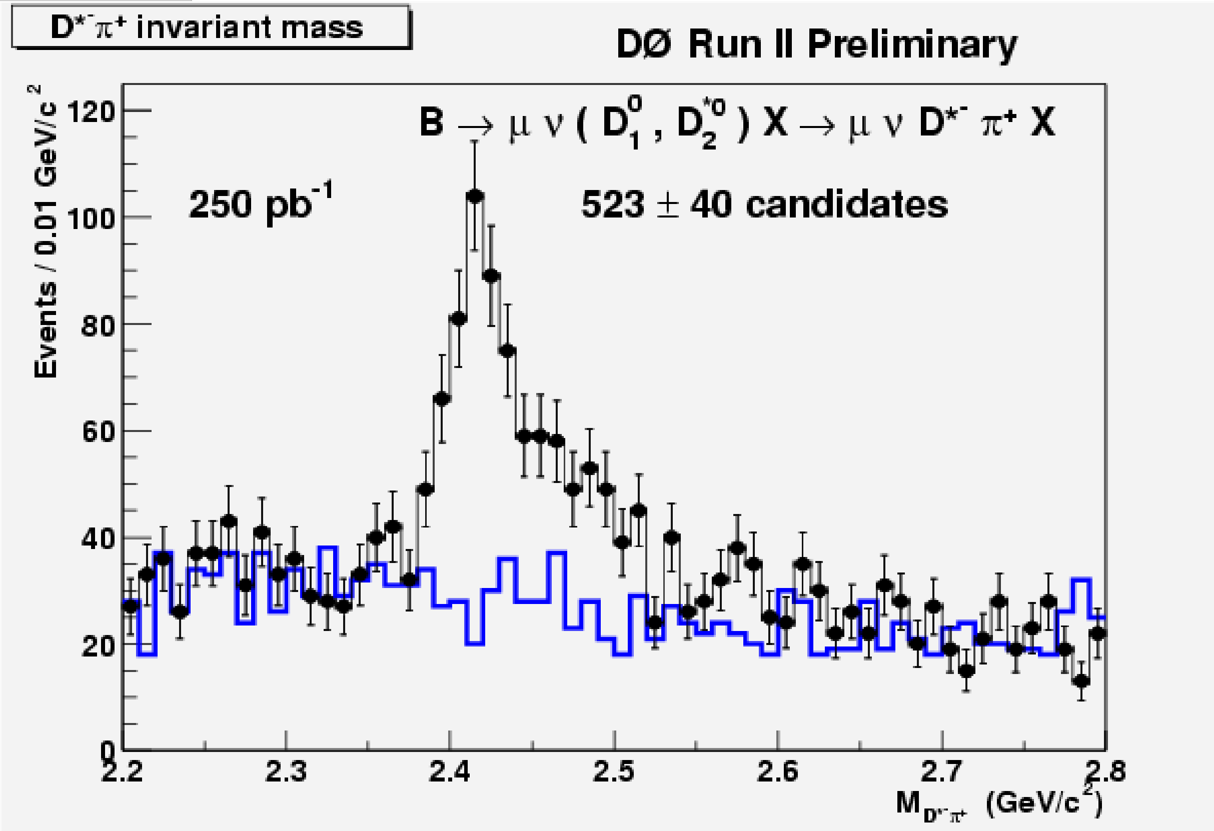
$$B \to D^{(*)}\pi\pi$$



D** at D0

Observed in B semi-leptonic decays





Lessons from charm (II) – Ds**

For L=1 D_s mesons,

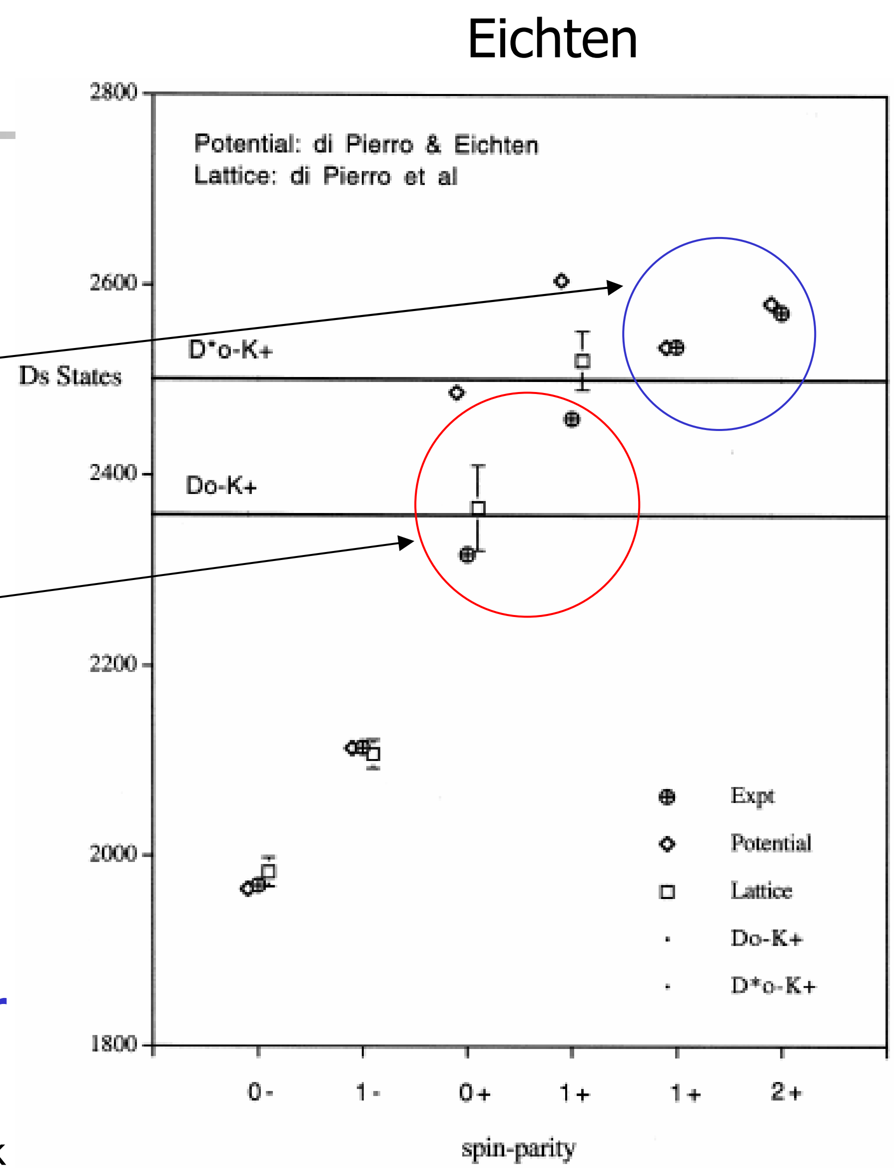
preferred decay mode:DK

j_q = 3/2 -> DK, D*K

j_q = 1/2 below DK threshold, decay to $D_s^{(*)}\pi^0 / D_s^{(*)}\gamma$

Mass/widths unexpected!

Maybe Bs** have similar behaviour



Lessons from Charm (III)

- For charm mesons, M(D*)-M(D) ~ 140-145 MeV
- For bottom, M(B*)-M(B) ~ 46 MeV

Theory: Splitting within a doublet has 1/m_Q corrections

- For non-strange charm, M(D**)-M(D) ~550-600 MeV
- Would expect similar behaviour for B mesons

- M(D_2^*)-M(D_1) ~ 32-37 MeV (j_q=3/2 doublet)
- Could expect this to be ~ 10-15 MeV for M(B_2^*)-M(B_1)

Previous results on B**

Probably not the natural width of these states

- Previous experiments did not resolve the four states:
  <PDG mass> = 5698±8 MeV

Experiment	B reconstruction	B_J mass (MeV)	B_J width
ALEPH	exclusive	5695±18	53±16
CDF	(μD)+π	5710±20	-----
DELPHI	inclusive B + π	5732±21	145±28
OPAL	inclusive B + π	5681±11	116±24

- Theoretical estimates for $M(B_1) \sim 5700 - 5755$ and for $M(B_2^*) \sim 5715$ to 5767. Width ~ 20 MeV

Signal reconstruction (I)

- Search for narrow B** - Use B hadrons in the foll. modes and add $\pi^{\pm}$ coming from the Primary Vertex
  - $B^{\pm} \to J/\psi K^{\pm}$ 7217±127 events
  - $B_d^0 \to J/\psi K^{*0}, K^{*0} \to K^+\pi^-$ 2826± 93 events
  - $B_d^0 \to J/\psi K^0, K^0 \to \pi^+\pi^-$ 624± 41 events

- Since ΔM between B^{**+} and B^{**0} is expected to be small compared to resolution, we combine all channels (e.g., ΔM for B^+/B^0 = 0.33±0.28 MeV)

Signal Reconstruction (II)

- Dominant decays modes of B_1, B_2^*
  - $B_1 \to B^* \pi, \ B^* \to B\gamma$ ($B\pi$ forbidden by J,P conserv.)
  - $B_2^* \to B^* \pi, \ B^* \to B\gamma$
  - $B_2^* \to B\pi$ (ratio of the two modes expected to be 1:1)

- To improve resolution, we measure mass difference between B_1, B_2^* and B, ΔM

Signal reconstruction (III)

- Now, ΔM(B* - B) = 45.78±0.35 MeV – small

$$\Delta M(B_2^* - B^*) = M(B\pi\gamma) - M(B\gamma) \approx M(B\pi) - M(B)$$

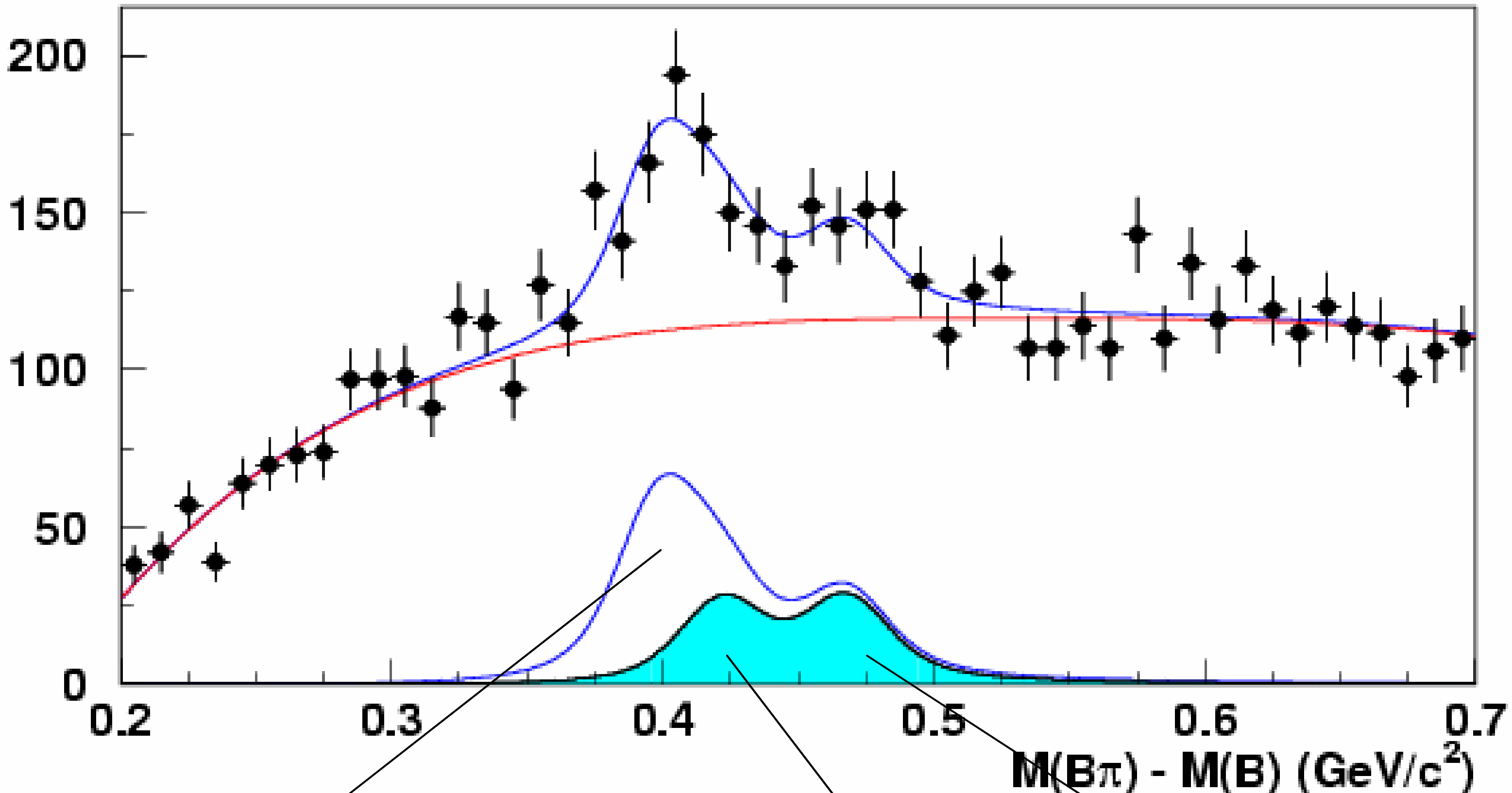
- Thus, if we ignore γ , ΔM shifts down by ~ 46 MeV, e.g.,

$$\Delta M(B_2^* - B) = M(B_2^*) - M(B^*) - 46MeV$$

Signal Reconstruction (IV)

- We get three peaks:
  - Δ_1 = M(B_1) – M(B*) – 46 MeV
  - Δ_2 = M(B_2^*) – M(B*) – 46 MeV
  - Δ_3 = M(B_2^*) – M(B) - in correct place
- In addition to these two narrow states, also have the two wide states (j_q = 1/2 doublet). Cannot be distinguished from non-resonant bkgd.

First observation of the separated states DØ RunII Preliminary



$B_1 \rightarrow B^* \pi, \ B^* \rightarrow B\gamma$

Interpreting the peaks as

$B_2^* \rightarrow B\pi$

$B_2^* \rightarrow B^* \pi, \ B^* \rightarrow B\gamma$

Signal Reconstruction (V)

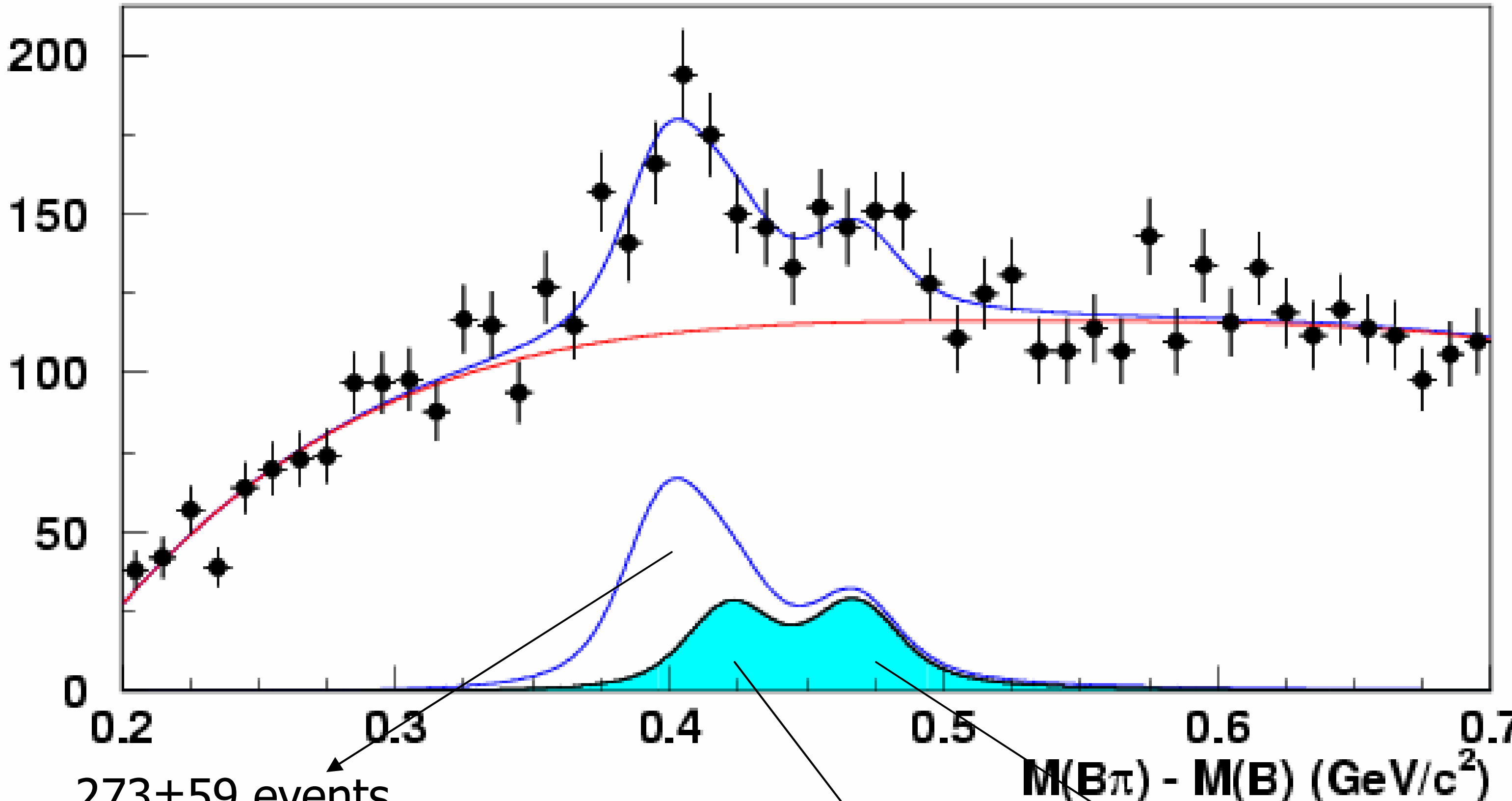
- We fit the ΔM signal with 3 relativistic Breit-Wigner functions convoluted with Gaussians

$$N.(f_1 * G(\Delta_1,\Gamma_1) + (1-f_1)(f_2 * G(\Delta_2,\Gamma_2) + (1-f_2) * G(\Delta_3,\Gamma_2)))$$

  - N: Number of events in the three peaks
  - f_1 : Fraction of B_1 in all events
  - f_2 : Branching fraction of $B_2^* \rightarrow B^* \pi$
  - From theory fix $\Gamma_1 = \Gamma_2$ and $f_2 = 0.5$
  - From MC fix resolution of ΔM=10.5 MeV

First observation of the separated states

DØ RunII Preliminary



From fit:

N = All B**

536±114 events

~7σ signif.

273±59 events

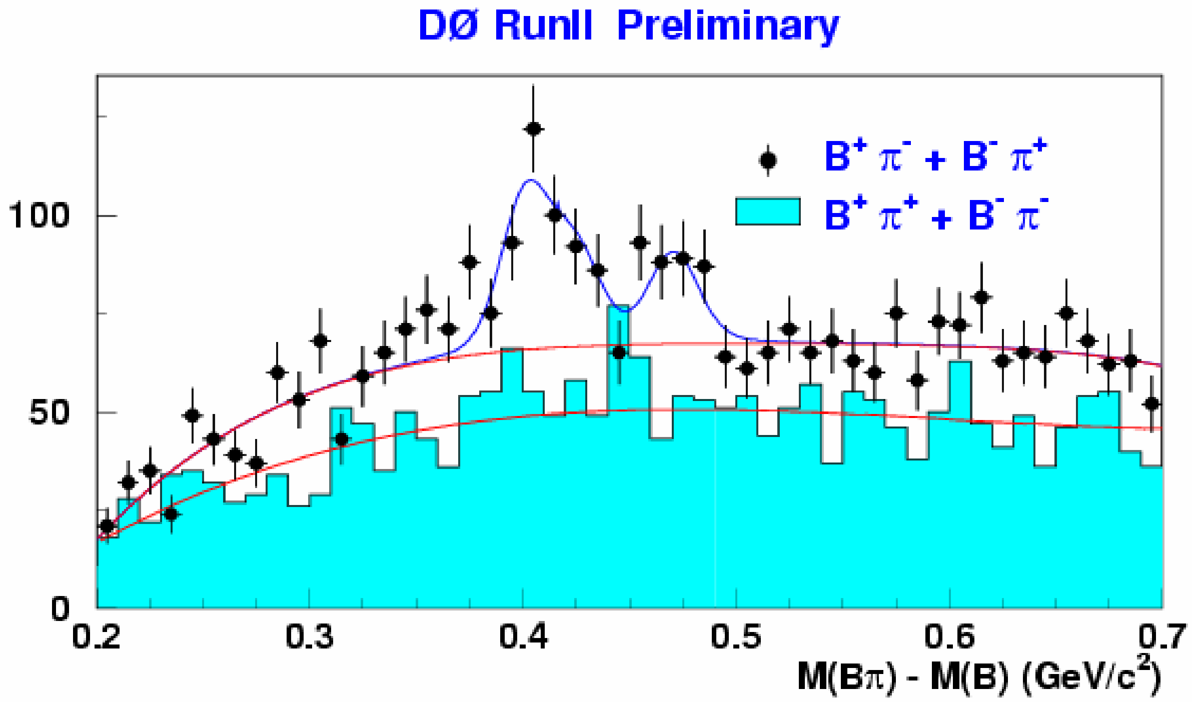
$B_1 \to B^* \pi,\ B^* \to B\gamma$

Interpreting the peaks as

$B_2^* \to B\pi$

131±30 events

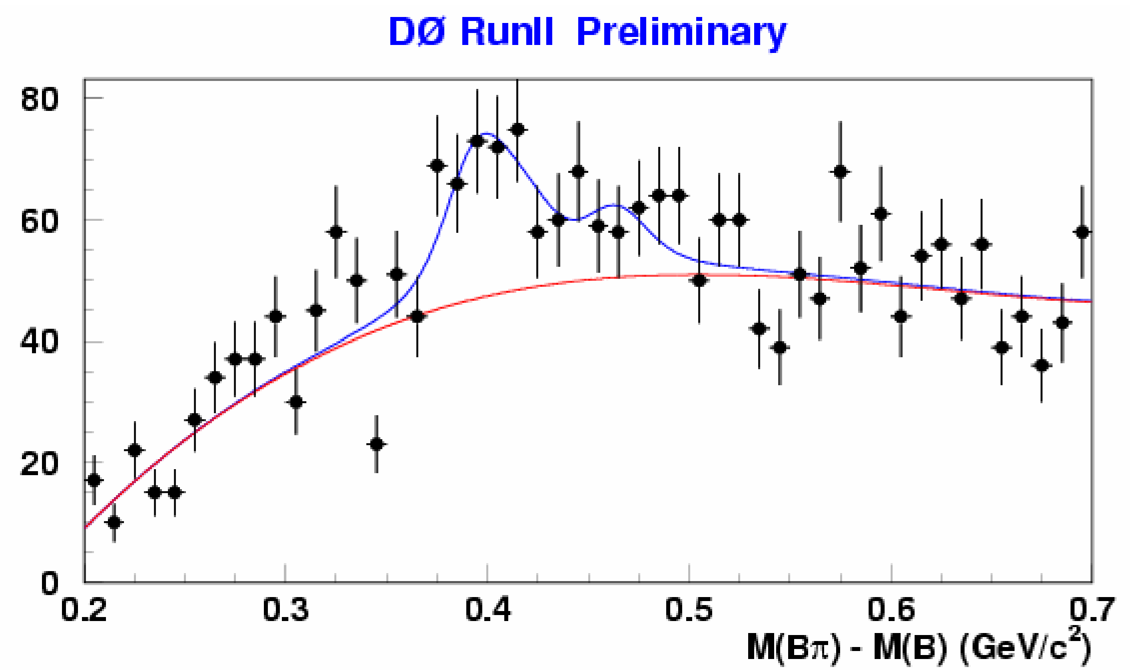
$B_2^* \to B^* \pi,\ B^* \to B\gamma$



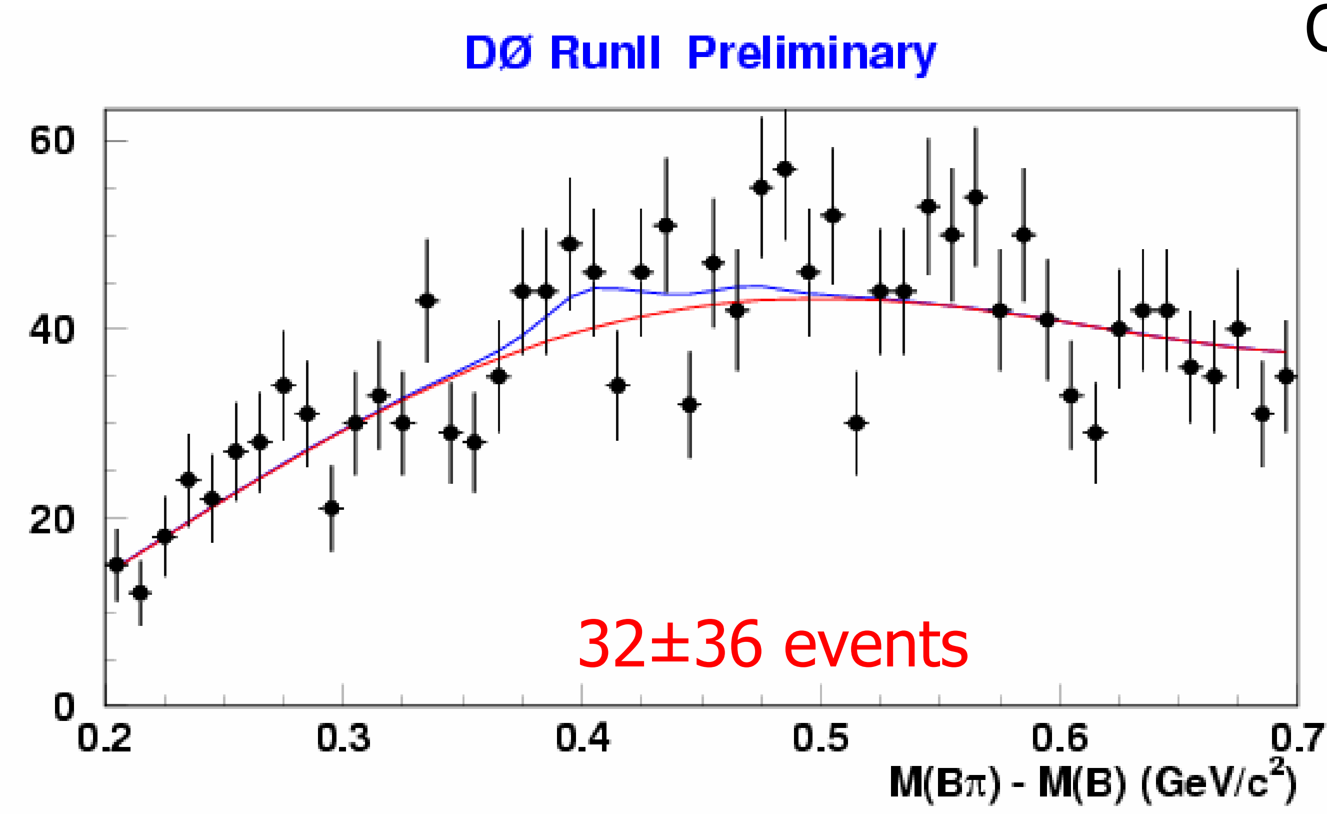
Neutral B**

Consistency checks:

Charged B**
(from B^0 mesons)



Consistency checks:



$\pi^{\pm}$ required to have large Impact parameter significance relative to Primary vertex – No Signal (as expected)

Vary relative fraction of the two B_2^* decay modes

Systematic errors (preliminary)

Source	$M(B_1)$ MeV	$M(B_2^*)$-$M(B_1)$ MeV	Width of B_1/B_2^* MeV	Fraction of $B_1 - f_1$
Bkgd Fit:	2	2.2	4.5	0.03
f_2:[0,0.7]	6	3.1	6.2	0.21
Γ_2 free in fit	0	0.5	1.4	0.02
Res. Of ΔM	2	0.6	7.1	0.03
Mom. scale	1	0.1	0	0
Total	6.7 MeV	3.9 MeV	9.3 MeV	0.21

Results of fit - Preliminary

$$M(B_1) = 5724 \pm 4(stat) \pm 7(syst) \;\; MeV/c^2$$

$$M(B_2^*) - M(B_1) = 23.6 \pm 7.7(stat) \pm 3.9(syst) \;\; MeV/c^2$$

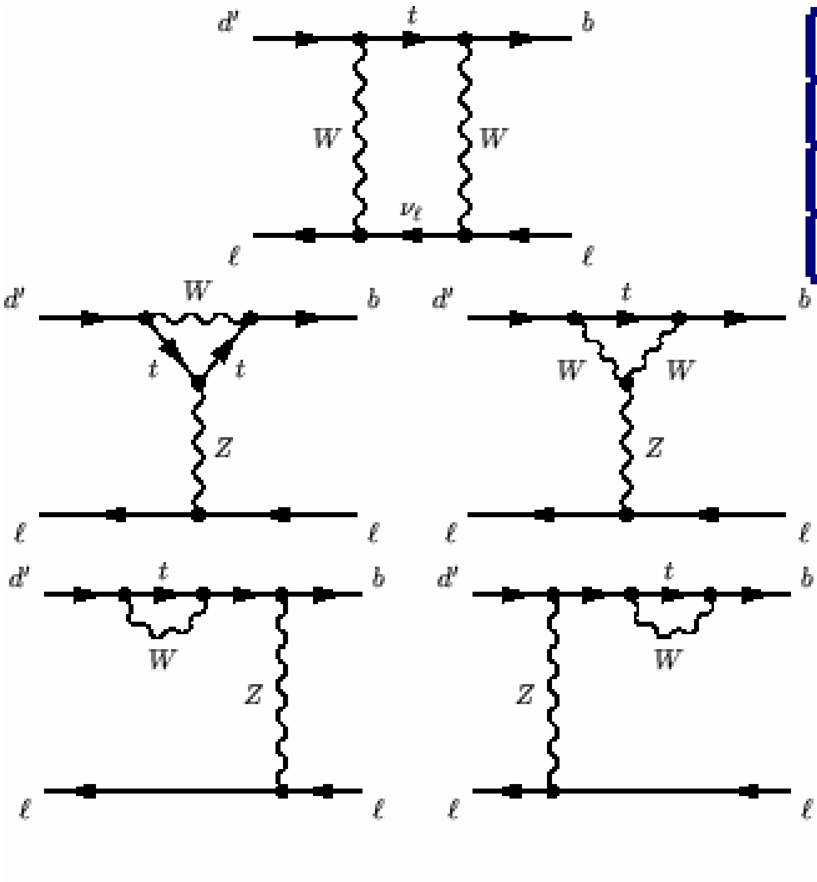
$$\Gamma_1 = \Gamma_2 = 23 \pm 12(stat) \pm 9(syst) \;\; MeV/c^2$$

$$f_1 = 0.51 \pm 0.11(stat) \pm 0.21(syst)$$

To do list:

- Add more data and separately fit charged and neutral B**
- Measure rates relative to L=0 B hadrons
- Get the Spin/Parity of these states
- Can we improve some of the systematic errors, e.g., variation in f_2 has large effect?
- Search for Bs**
- …

$B_s \to \mu^+ \mu^-$



Standard Model predictions

	$BR(B_d \to l^+l^-)$	$BR(B_s \to l^+l^-)$
$l = e$	$(3.4 \pm 2.3) \cdot 10^{-15}$	$(8.0 \pm 3.5) \cdot 10^{-14}$
$l = \mu$	$(1.5 \pm 0.9) \cdot 10^{-10}$	$(3.4 \pm 0.5) \cdot 10^{-9}$
$l = \tau$	$(3.1 \pm 1.9) \cdot 10^{-8}$	$(7.4 \pm 1.9) \cdot 10^{-7}$

Exptl. Results 90% (95%) CL

	$BR(B_d \to l^+l^-)$	$BR(B_s \to l^+l^-)$
$l = e$	$< 5.9 \cdot 10^{-6}$	$< 5.4 \cdot 10^{-5}$
$l = \mu$	$< 1.5(1.9) \cdot 10^{-7}$	$< 5.8(7.5) \cdot 10^{-7}$
$l = \tau$	$< 2.5\%$	$< 5.0\%$

Beyond Standard Model

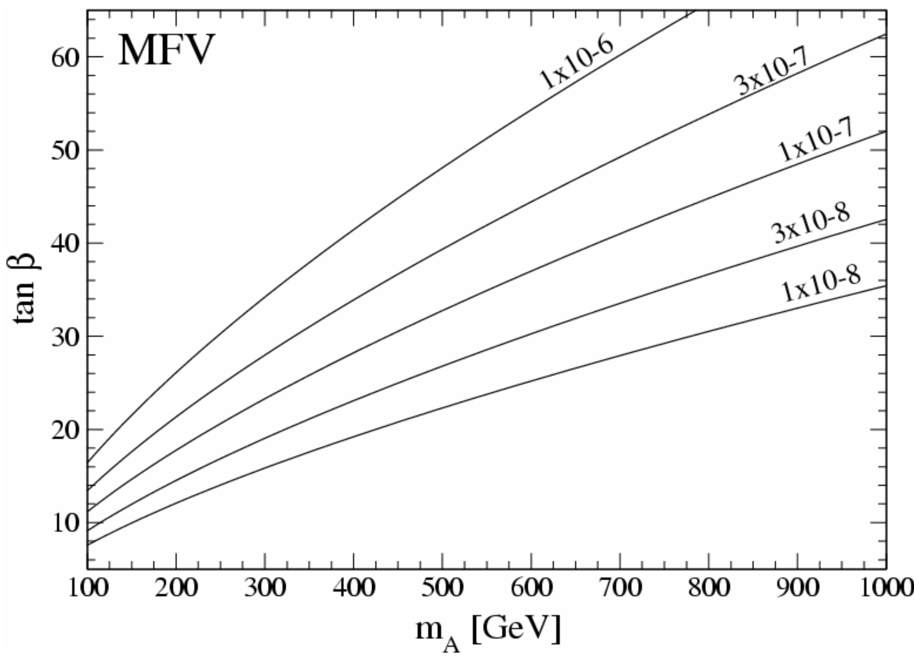
- First proposed by Babu/Kolda as a probe of SUSY (hep-ph 9909476)

- Branching fraction depends on tan(β) and charged Higgs mass

- Branching fraction increases as $\tan^4 \beta \ (\tan^6 \beta)$ in 2HDM (MSSM)

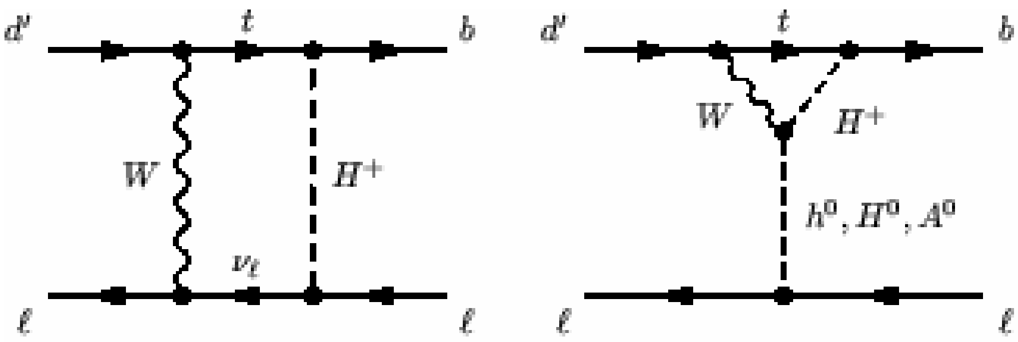
Complementary to

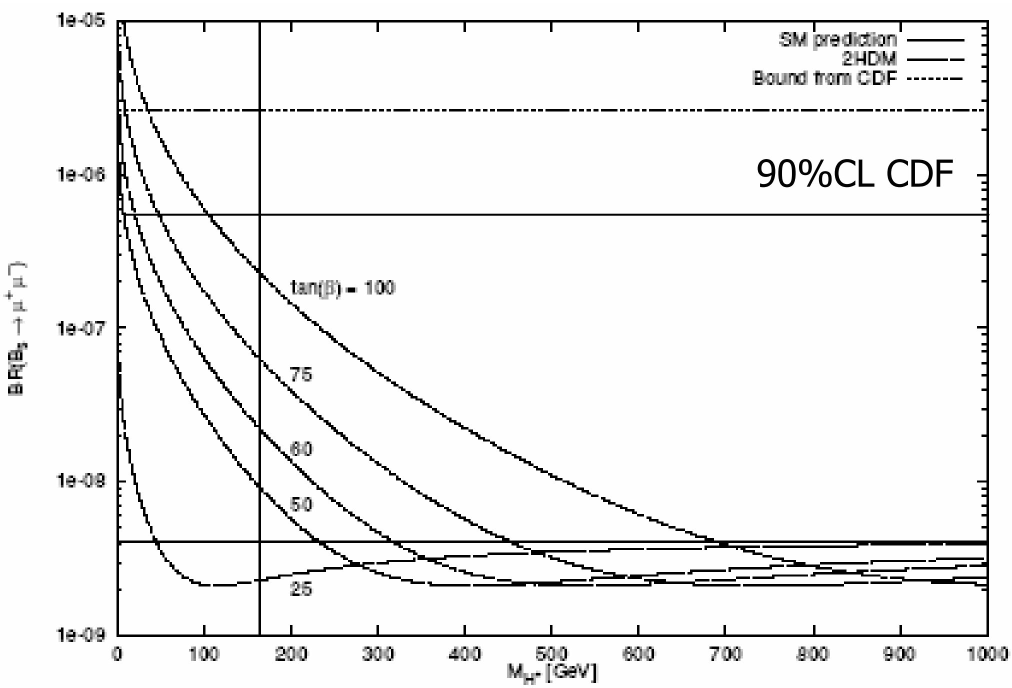
$b \rightarrow s\gamma$

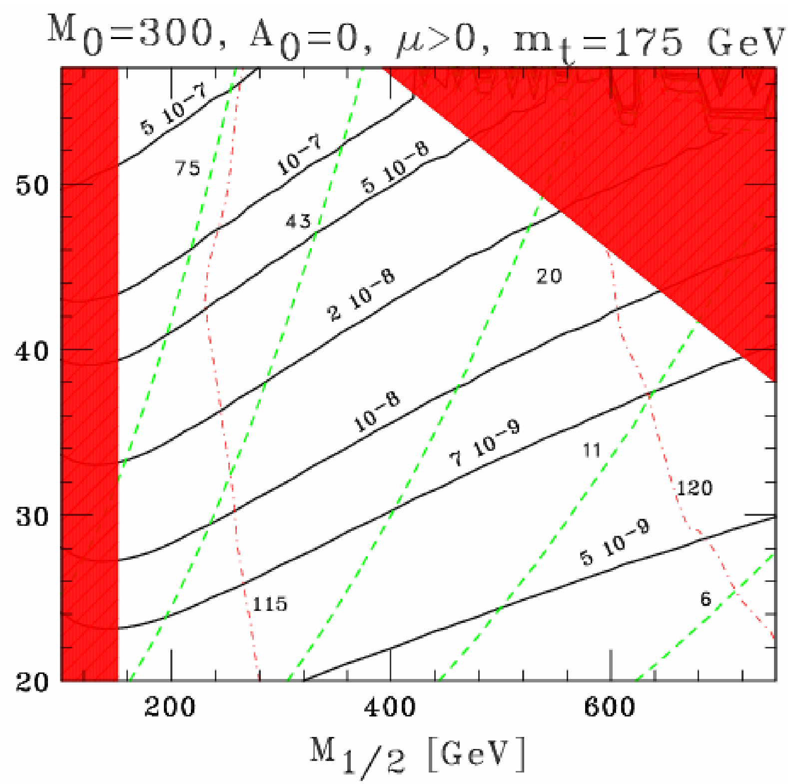


Kane/Kolda/Lennon – hep-ph 0310042
MSSM

Other models



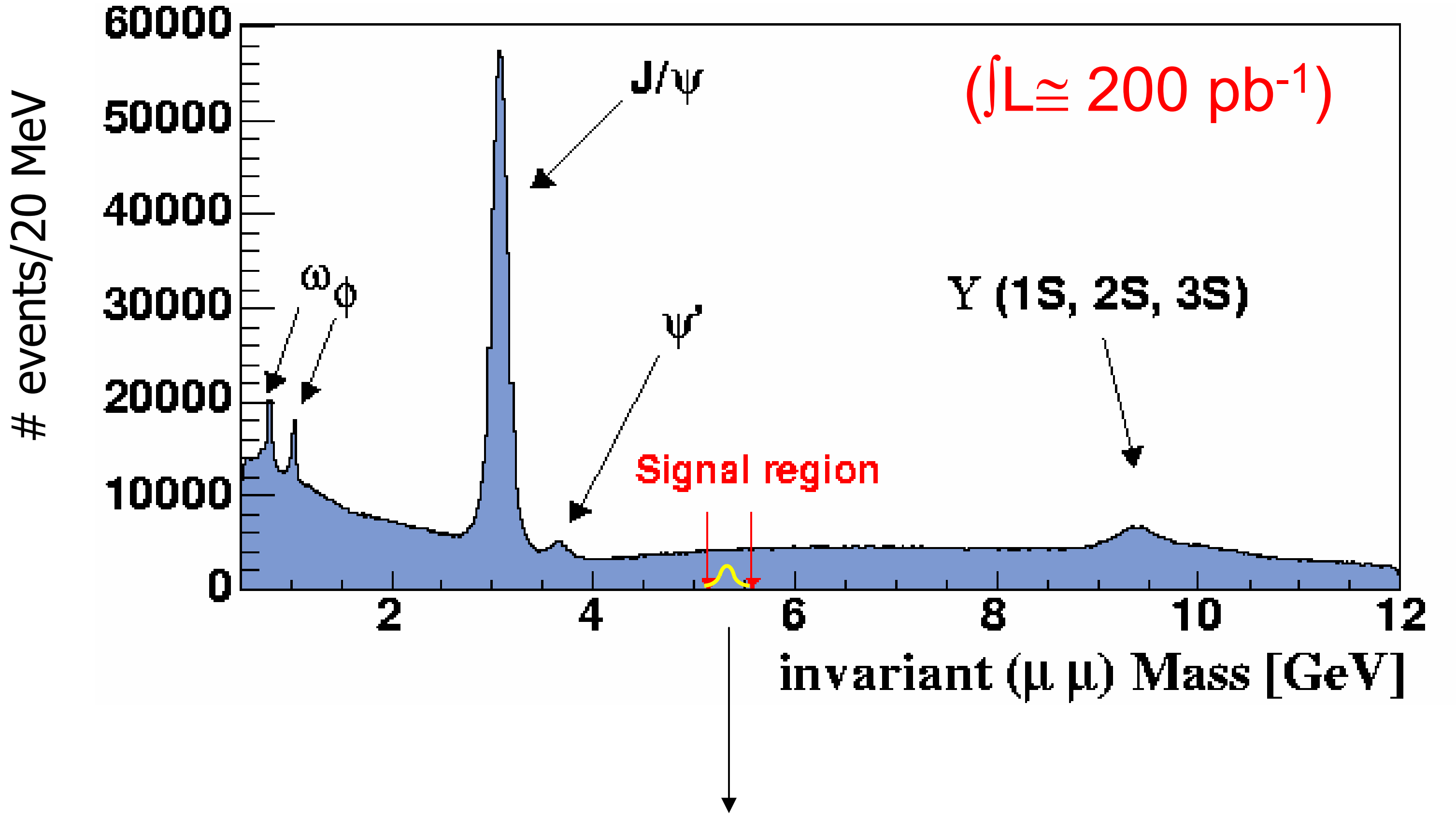




2HDM

Dedes, Nierste hep-ph 0108037
mSUGRA

Experimental Challenge



Expected SM signal*10^6 - from MC

Preselection cuts:

		# of candidates
Mass window (GeV)	$4.5 < M_{\mu\mu} < 7.0$	405,307
Good muon ID		234,792
Vertex cut	<10/dof	146,982
Muon p_T (GeV)	>2.5	129,558
Muon $\lvert\eta\rvert$	<2.0	125,679
Tracking hits	CFT>3, SMT>2	92,678
δL_{xy} (mm)	<0.15	90,935
B cand. pT (GeV)	>5.0	38,167

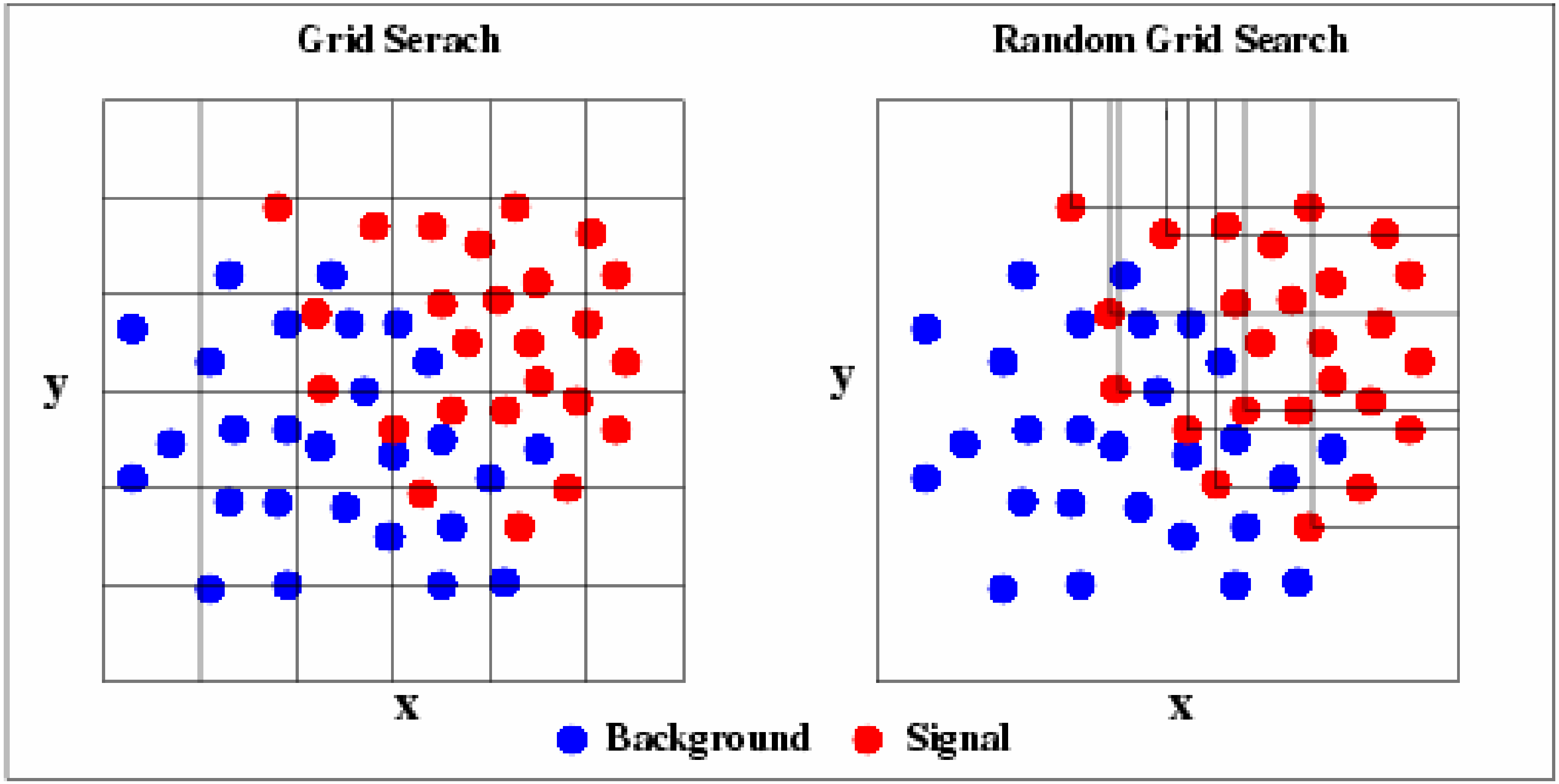
Optimization Procedure (I)

- ~ 80 pb^{-1} of data was used to optimize cuts
- Three additional variables were used to discriminate bkgd. from signal -
- Isolation : Since most of b-quark's mom. is carried by the B-hadron, track population around it is low
  - $I = |p(\mu\mu)| / (|p(\mu\mu)| + \sum_{i \neq B} p_i(\Delta R < 1))$
- Decay Length significance: $L_{xy}/\delta L_{xy}$ – remove combinatoric background, e.g., fake muons
- Pointing angle: Angle, α, between B_s decay vector and B_s momentum vector

Optimization Procedure (II)

- Perform Random Grid Search of these variables –
- Signal MC: ($M\_Bs \pm 3\sigma$) ($\sigma \sim 90$ MeV/c^2) – processed through trigger simulator

- Data (mass regions shifted down by 30 MeV)
  - Signal region is hidden – ($\pm 3\sigma$): 5.07 – 5.61 GeV
  - Sideband regions: (-9σ to -3σ and 3σ to 9σ)
    4.53-5.07 and 5.61-6.15 GeV
- For final limit, use a signal region of $\pm 2\sigma$


Grid Serach
Random Grid Search
y
x
y
x
Background
Signal

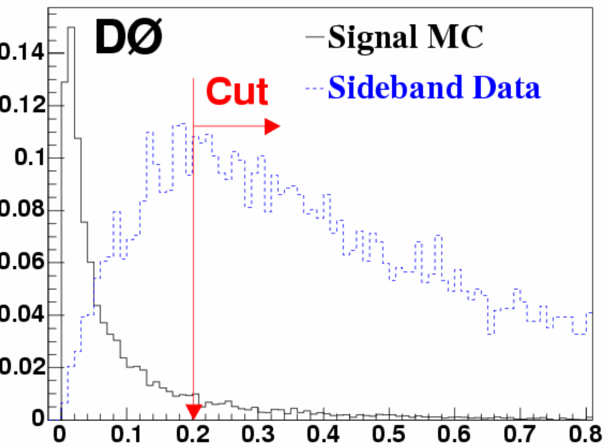
Optimization Procedure (III)

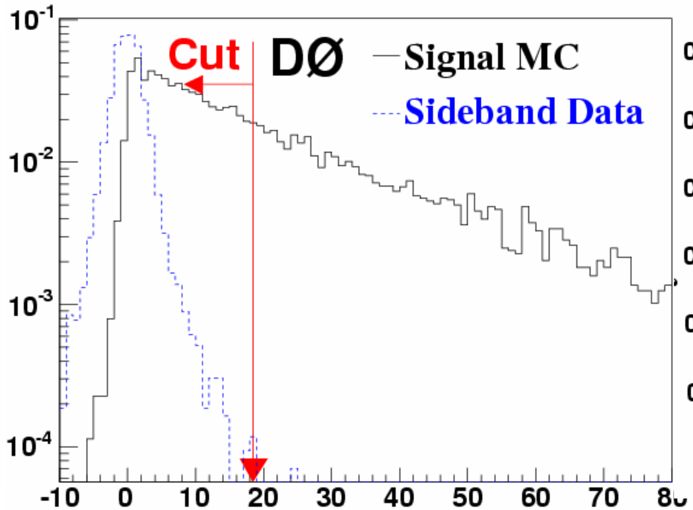
- To maximize sensitivity to new searches, use method proposed by Punzi (physics/0308063)
- Maximize

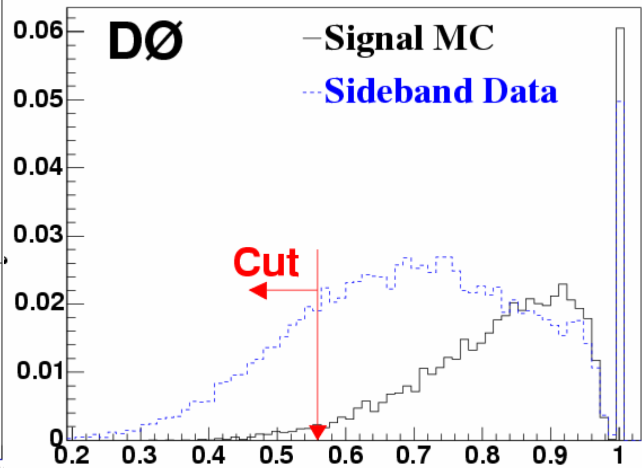
$$P = \frac{\varepsilon_{\mu\mu}^{Bs}}{(a/2+\sqrt{N_{back}})}$$

  - (MC) ε for signal reco. after pre-selection cuts
  - a is the number of sigmas corresponding to the confidence level at which the signal hypothesis is tested (a =2 ~ 95% C.L.) - set beforehand
  - N_{back} : # of bkgd. extrapolated from sidebands

Result of optimization







Pointing angle < 0.203 (rad)

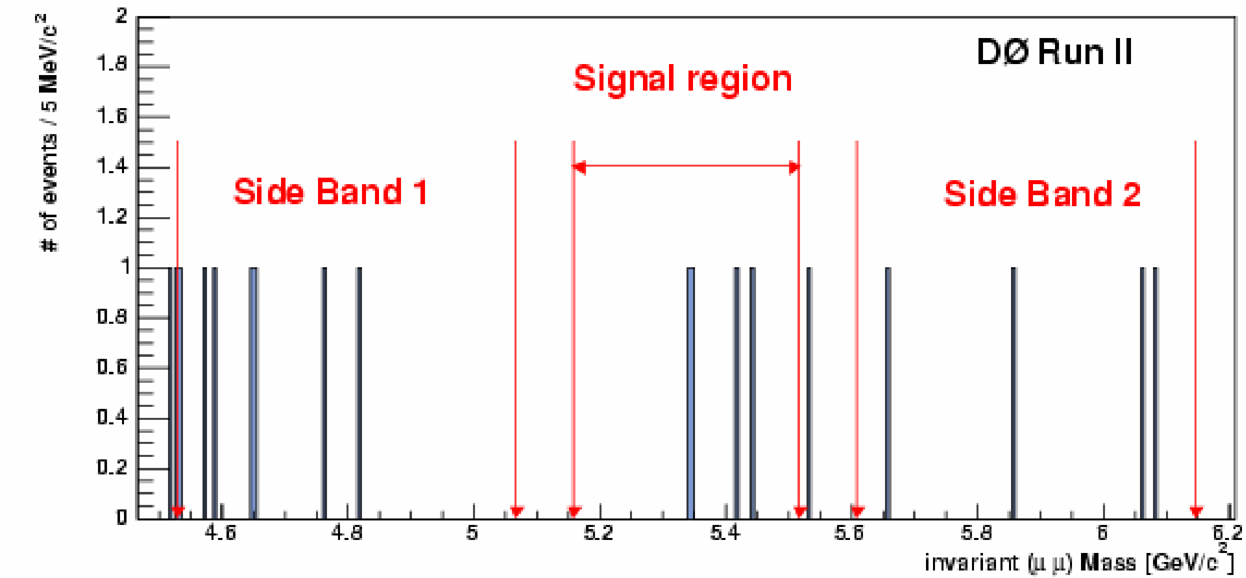
$\delta L_{xy} / \delta L > 18.47$

Isolation > 0.56

Reco Eff. of Signal to survive cuts (rel. to pre-selection) = (38.6±0.7)%

Background prediction from sidebands in ($M_B \pm 2\sigma$) = 3.7 ± 1.1 events

Opened the box (July 8' 04)



Preliminary

Nothing remarkable about the four events – look like background!

Some checks on these events

Cut	Predicted Bkgd from sidebands	# events in box
Pointing Angle	573±14	580
Decay length sig.	4.3±1.2	5
Isolation	3.7±1.1	4

Calculate upper limit (I)

- To calculate limit on branching fraction, normalize to $B^+ \rightarrow J/\psi K^+$

Feldman-Cousins → N_{ul}; PDG → $B_1(B^\pm).B_2(J/\psi)$

$$\mathrm{Br}(B_s) \leq \frac{N_{ul}}{N_{B^\pm}} \cdot \frac{\varepsilon^{B\pm}_{\mu\mu K}}{\varepsilon^{Bs}_{\mu\mu}} \cdot \frac{\mathrm{B}_1(B^\pm).\mathrm{B}_2(J/\psi)}{(f_{b\rightarrow Bs}/f_{b\rightarrow Bu,d}) + R.\frac{\varepsilon^{Bd}_{\mu\mu}}{\varepsilon^{Bs}_{\mu\mu}}}$$

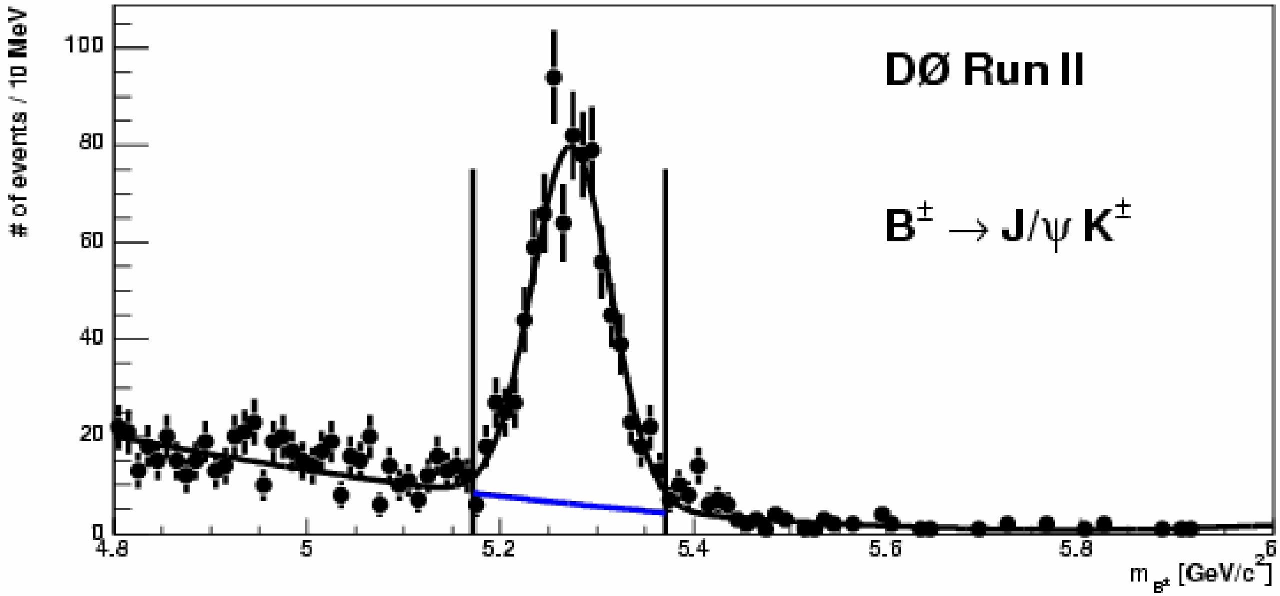
MC: 0.229±0.016 → $\varepsilon^{Bs}_{\mu\mu}$

0.270±0.034 (PDG) → $f_{b\rightarrow Bs}/f_{b\rightarrow Bu,d}$

MC → $\varepsilon^{Bd}_{\mu\mu}/\varepsilon^{Bs}_{\mu\mu}$

Since our signal region overlaps B_d, can have contamination
R: theoretical expectation for ratio of Br. frac. of B_d /B_s - set R=0
If $R \neq 0$ limit will be better

Normalization Channel



Preliminary

741±38 events

Use cuts similar to $B_s \to \mu^+ \mu^-$

B p_T in MC have been matched to data

Uncertainties included in upper limit

Source	Relative Uncertainty (%)
Ratio of eff. – B^+/B_s	6.9
# of B^+ events	5.1
Br. Fraction for B^+	4.0
Br. Fraction for J/ψ	1.7
Error from fragmentation	12.7

Calculation of upper limit (II)

- Include all statistical and systematic errors into the limit calculation by integrating over PDF parametrizing the uncertainties
  - Used a prescription (Conrad et al) where we construct a frequentist confidence interval with the Feldman-Cousins ordering scheme for MC integration
  - All PDFs assumed to be Gaussians
- Also used a Bayesian approach – flat prior and Gaussian smeared uncertainties

Upper Limit - Preliminary

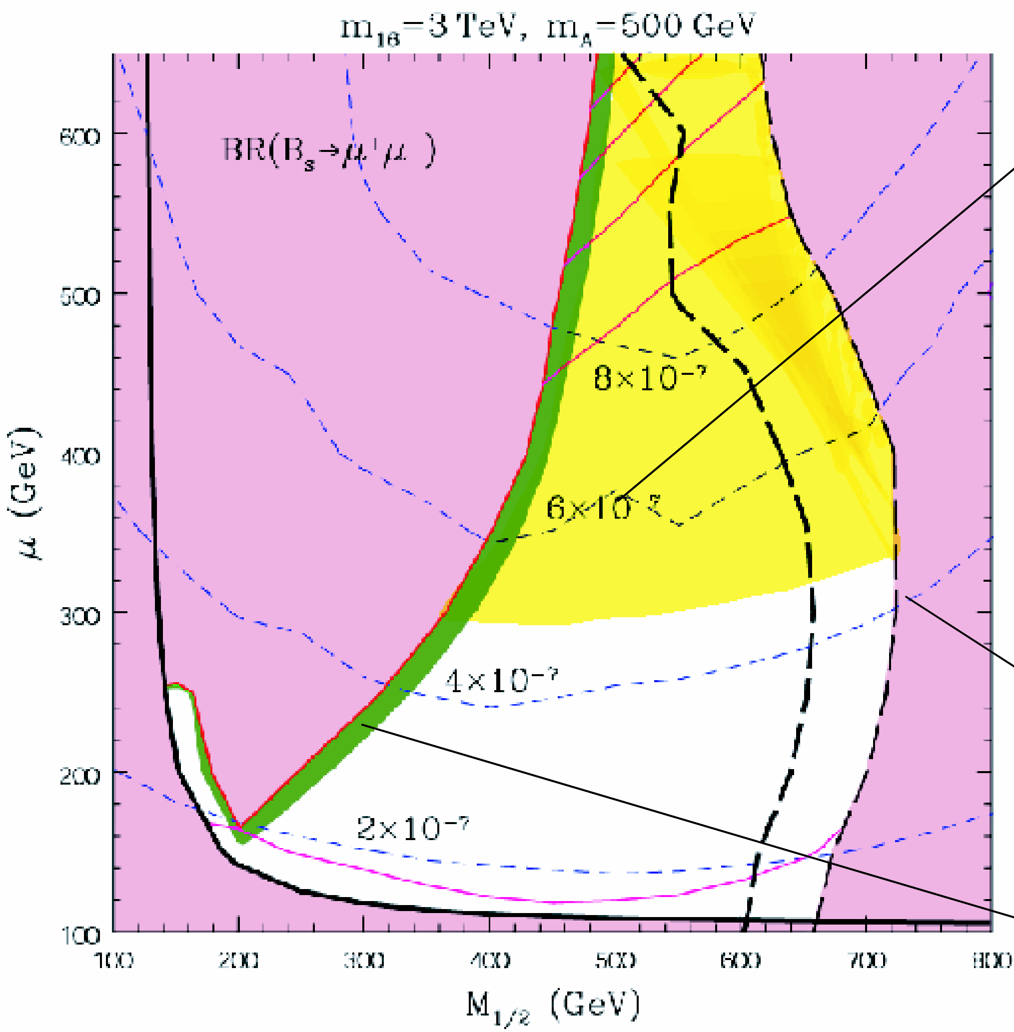
The 95% (90%) C.L. upper limit:

$$\mathrm{Br}(B_s \to \mu^+\mu^-) < 4.6\cdot 10^{-7} \quad (3.8\cdot 10^{-7})$$

Currently, the most stringent limit on this decay channel

If we use Bayesian approach, we get 4.7 (3.8)

Implications of this result



Excluded by
D0 Run II 240 pb^{-1}
4.6E-7 (95%CL)

Dermisek et al
Hep-ph 0304101

Dark Matter and $B_s \to \mu^+\mu^-$
Minimal SO_{10} with soft SUSY breaking

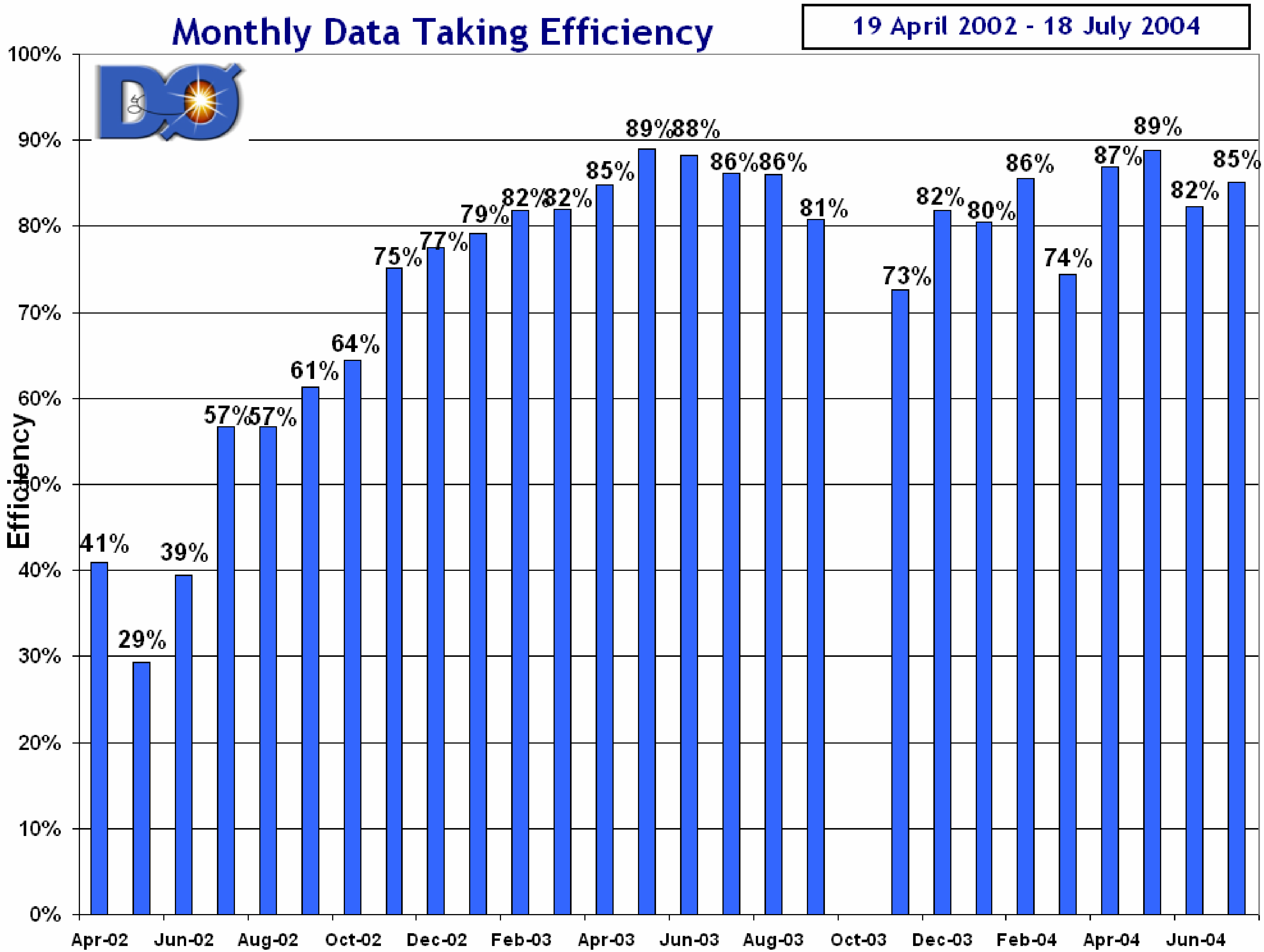
Contours of constant
Br$(B_s \to \mu^+\mu^-)$

Allowed by Dark Matter constraints

Conclusions

- First observation of the separated states for the j=3/2 doublet in the B system
- Currently, the most stringent limit on $B_s \to \mu^+ \mu^-$
- More data on tape!
- Lots of exciting results to be released in the coming weeks
- Improved triggers online
- Thanks to Fermilab for all this data!

Backup slides


Monthly Data Taking Efficiency
19 April 2002 - 18 July 2004
Efficiency
100%
90%
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