B-Physics & Trigger at the DØ experiment
- operational experience

Daniela Bauer

Imperial College London

Motivation

- Can the experience gained at Fermilab help prepare for (*b*-physics at) the LHC ?

  - Yes.
  - No. Nothing can prepare you for the LHC.
  - Maybe, but we'd like to make our own mistakes, thank you.

Making the transition from an e^+e^- to a hadron collider can be an interesting experience →

b-physics at an e^+e^- collider
(simplified view)

b-physics at a hadron collider
(simplified view)

Background

- Talks given at Beauty2006 (Oxford) and IOP "Tevatron for LHC" meetings.

b-physics at hadron colliders ↔ *b*-physics at e^+e^- machines:
- No fixed centre of mass energy.
- Triggers ! Triggers ! Triggers !
- The mess we refer to as underlying event/additional interactions.

Additionally at DØ:
- No particle ID.
- Competition with high p_T programme.

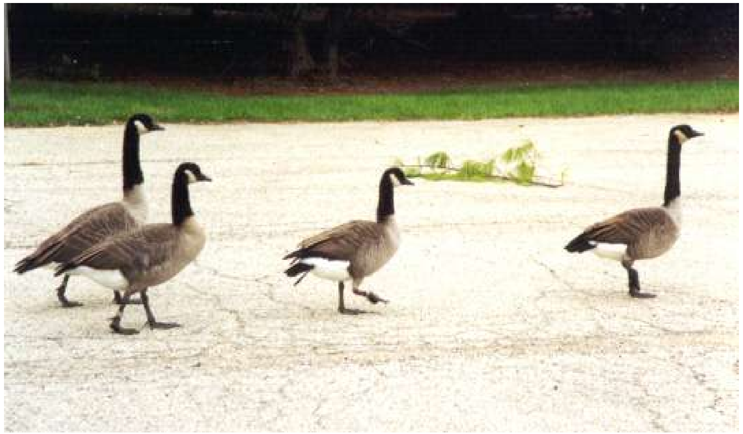
Overview

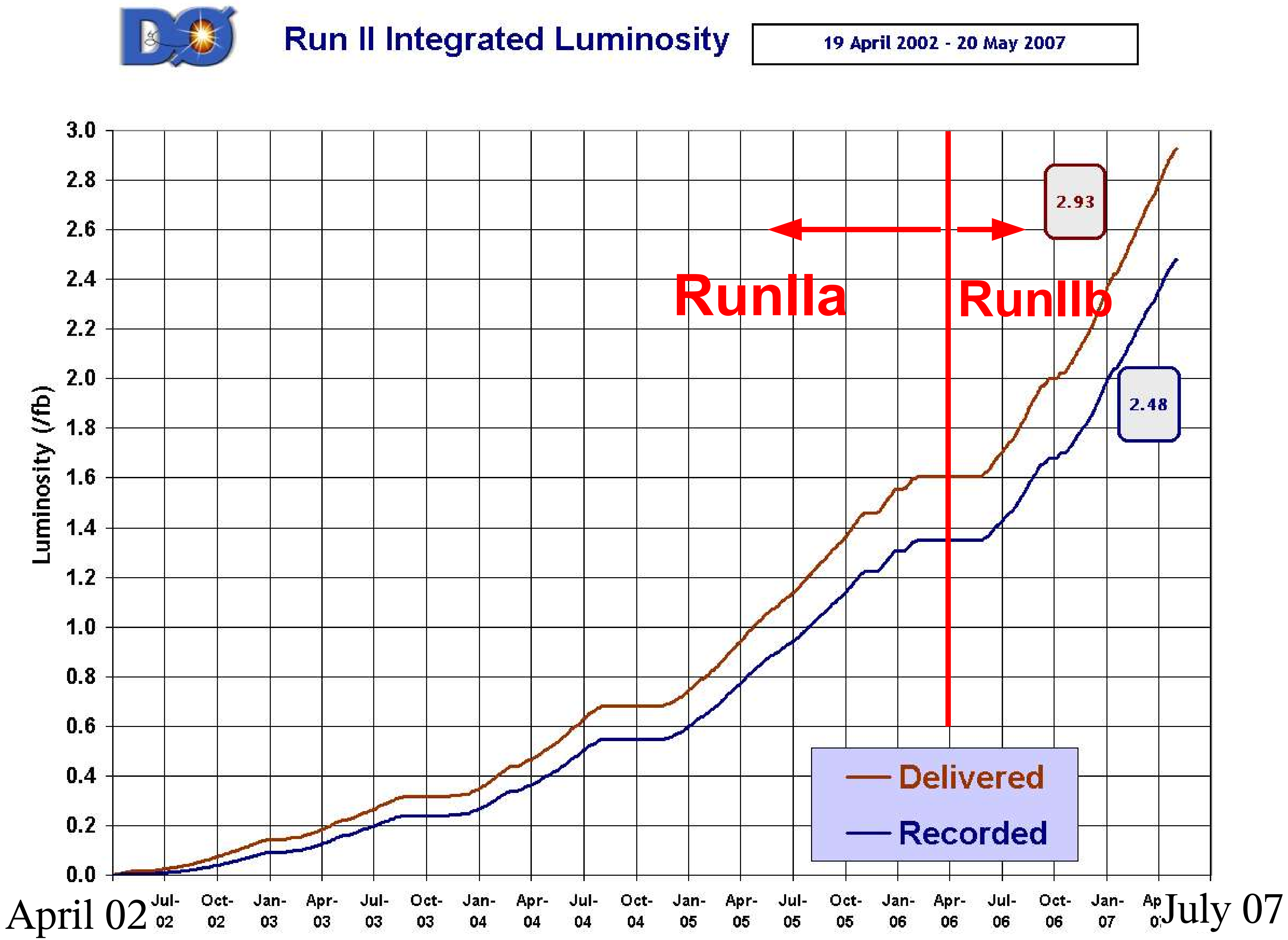
- The DØ Detector at Fermilab
- *B*-physics Highlights
- Trigger/High Luminosity Challenges
  - Trigger system
  - Doing *b*-physics at a multi purpose detector
  - *b*-physics triggers
- Conclusions

Fermilab

Run I 1992-1995
E_{CM} = 1.8 TeV
125 pb^{-1}

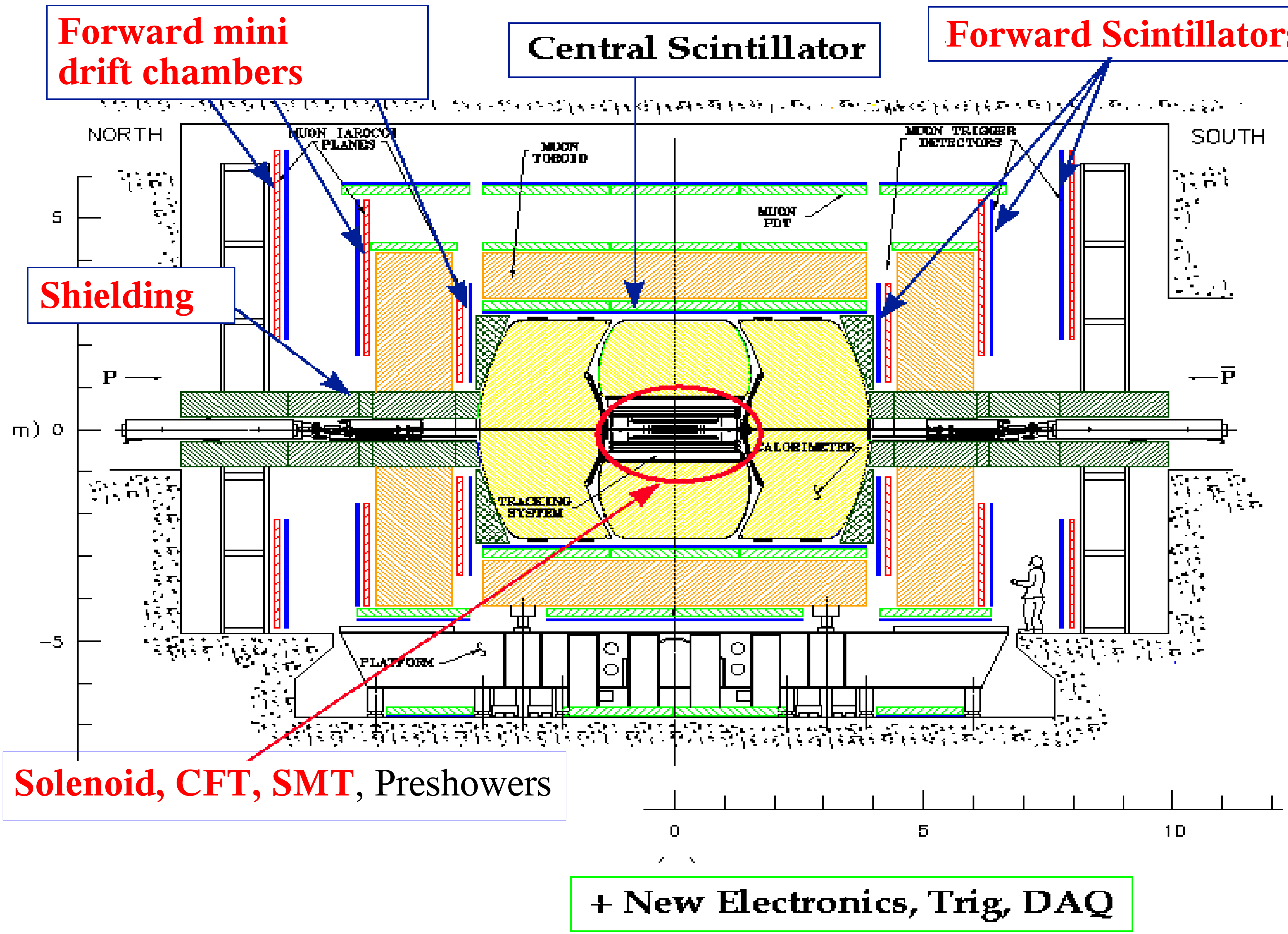
Run II
E_{CM}= 1.96 TeV
2.5 fb^{-1}





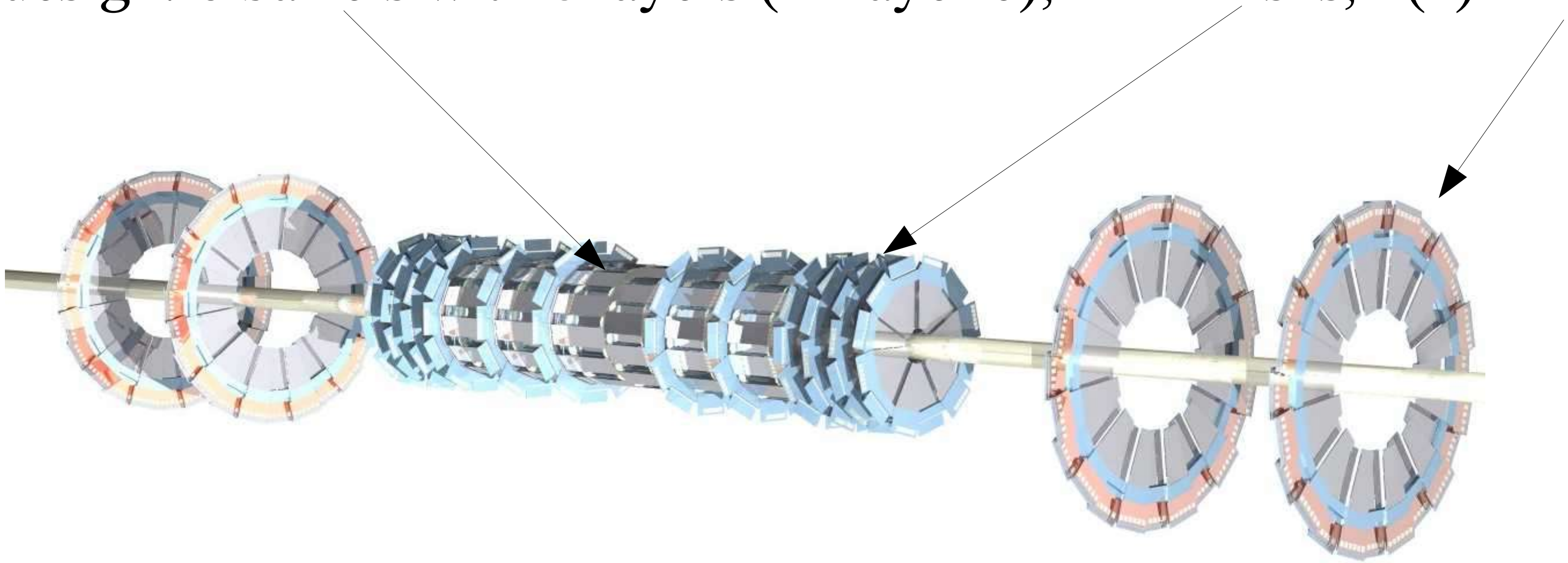
Run II Integrated Luminosity
19 April 2002 - 20 May 2007
Luminosity (/fb)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Jul-02
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
Apr-06
Jul-06
Oct-06
Jan-07
RunIIa
RunIIb
2.93
2.48
Delivered
Recorded
April 02
July 07

The upgraded DØ Detector



Silicon Microstrip Tracker (SMT)

Hybrid design: 6 barrels with 8 layers (+ Layer 0), 12 F-Disks, 4(2) H-Disks



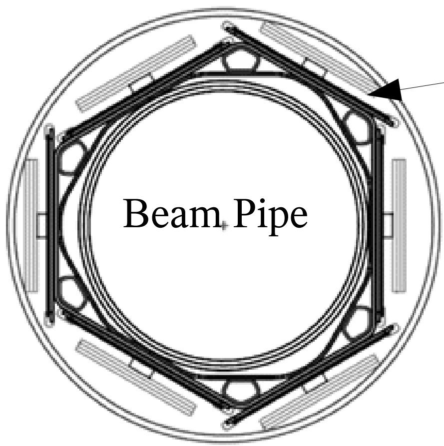
Essential for *b*-physics trigger *and* analysis:

Tracking, primary and secondary vertex reconstruction, impact parameter.

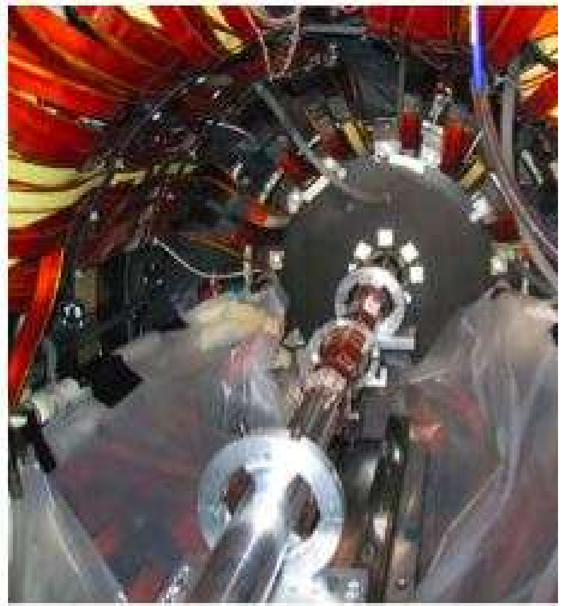
Design provides tracking up to $|\eta| < 3.0$, but

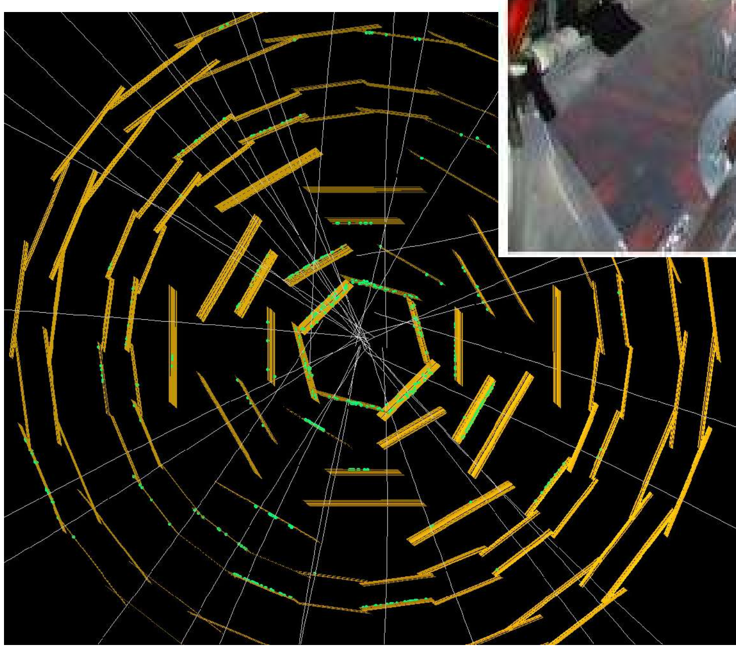
- Most analyses also require tracks to have hits in the CFT.
- H-disks had high rate of failure, most forward disks have now been decommissioned to make room for Layer 0 readout cables.

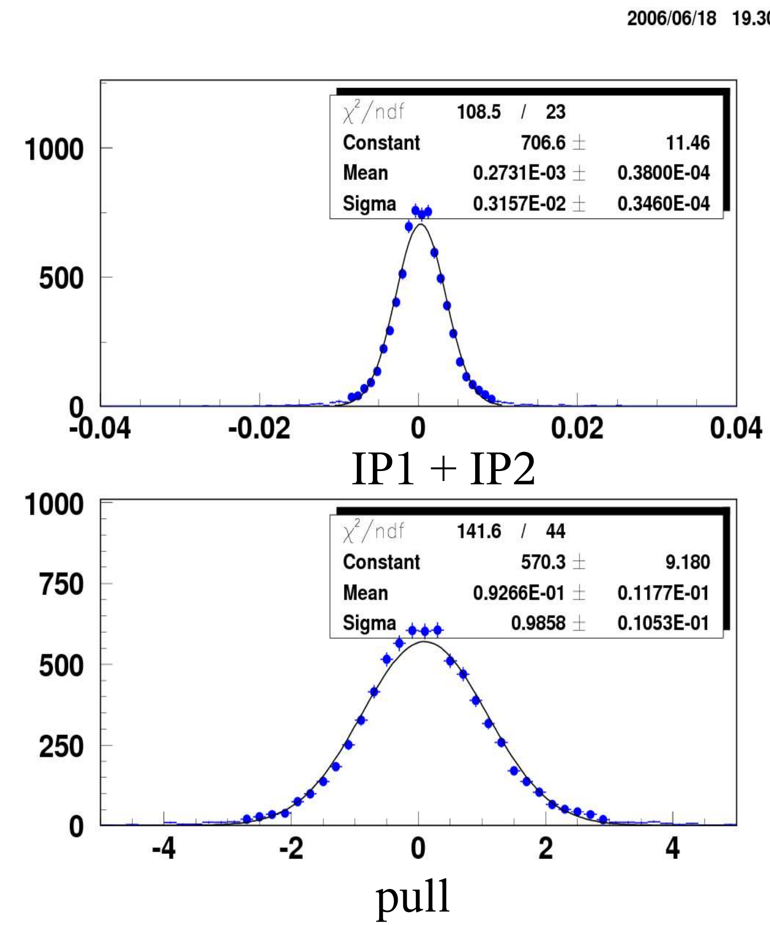
Silicon Microstrip Tracker Layer 0



30% improvement in impact parameter resolution vs RunIIa → great news for *b*-physics







Impact parameter resolution from cosmics: 21 μm

Commissioned and up and running.

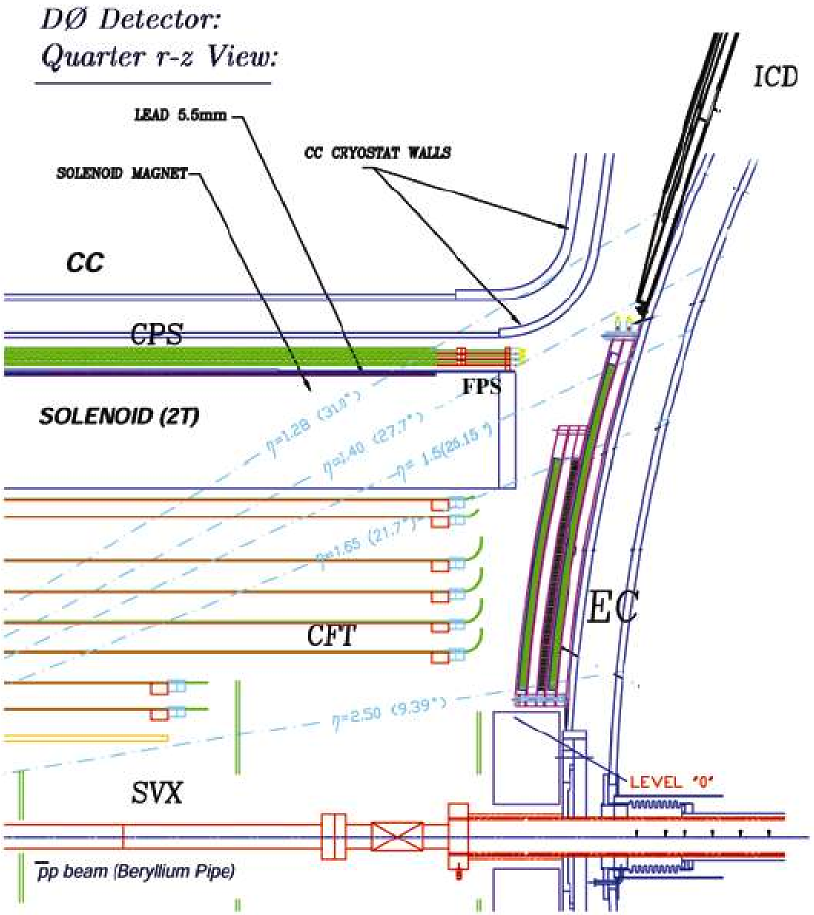
Central Fibre Tracker (CFT)

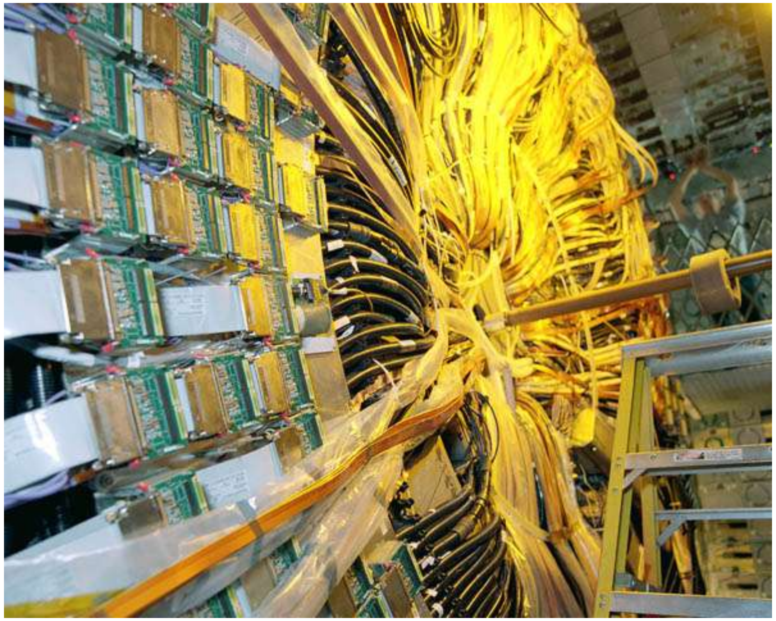
16 doublet layers of scintillating fibres, arranged in 8 superlayers

Radius 20 – 52 cm

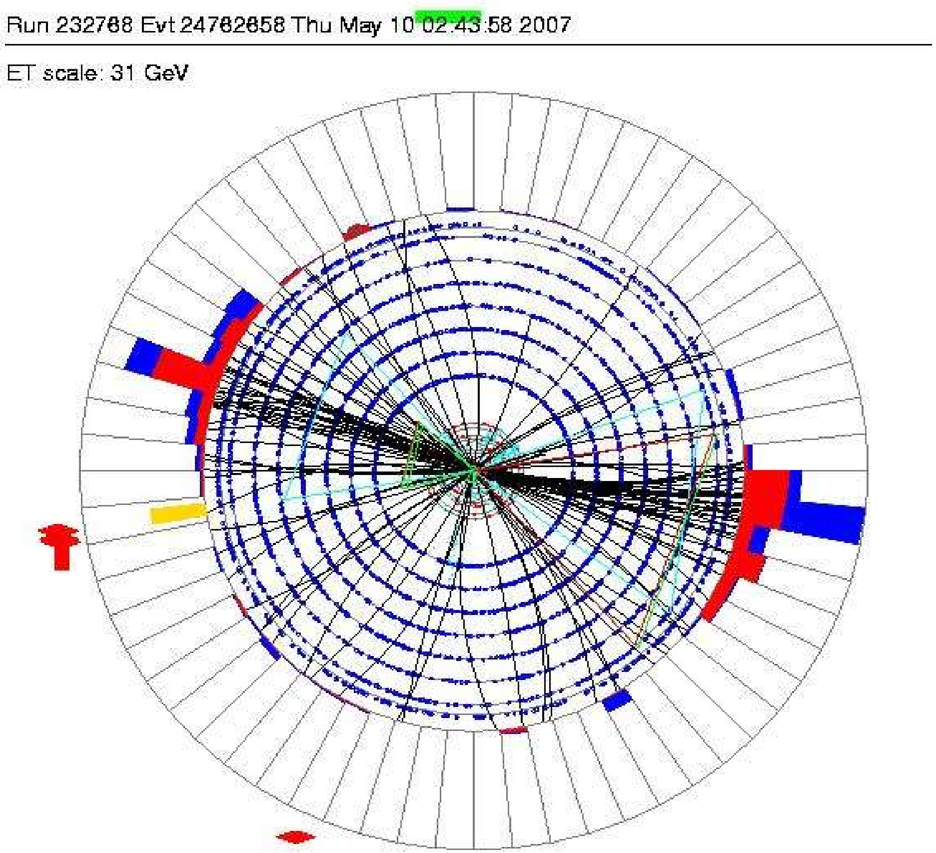
Track reconstruction up to $|\eta| < 2.0$

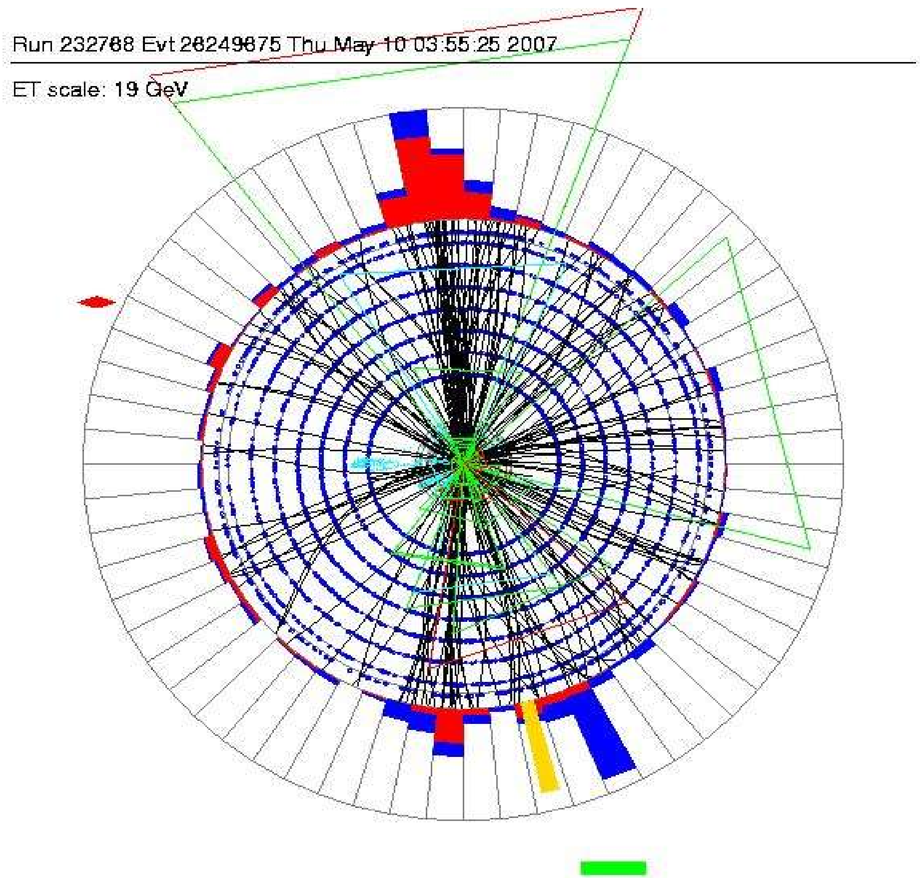
CFT standalone used for triggering at lowest trigger level.



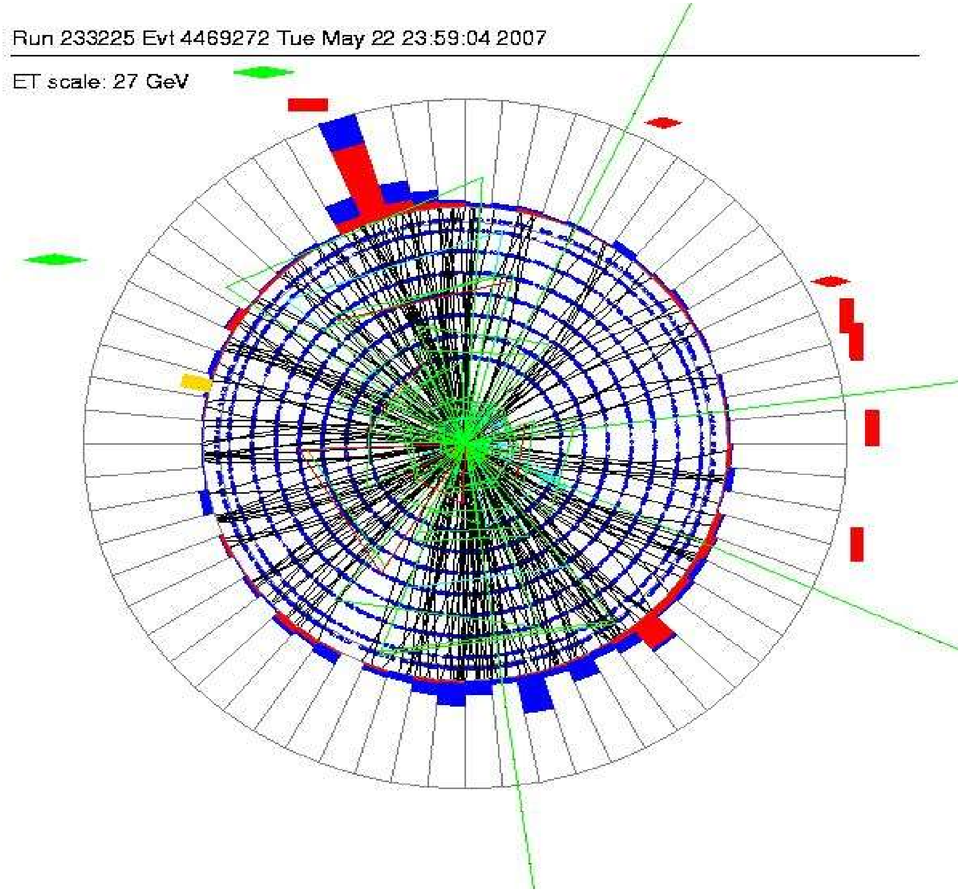


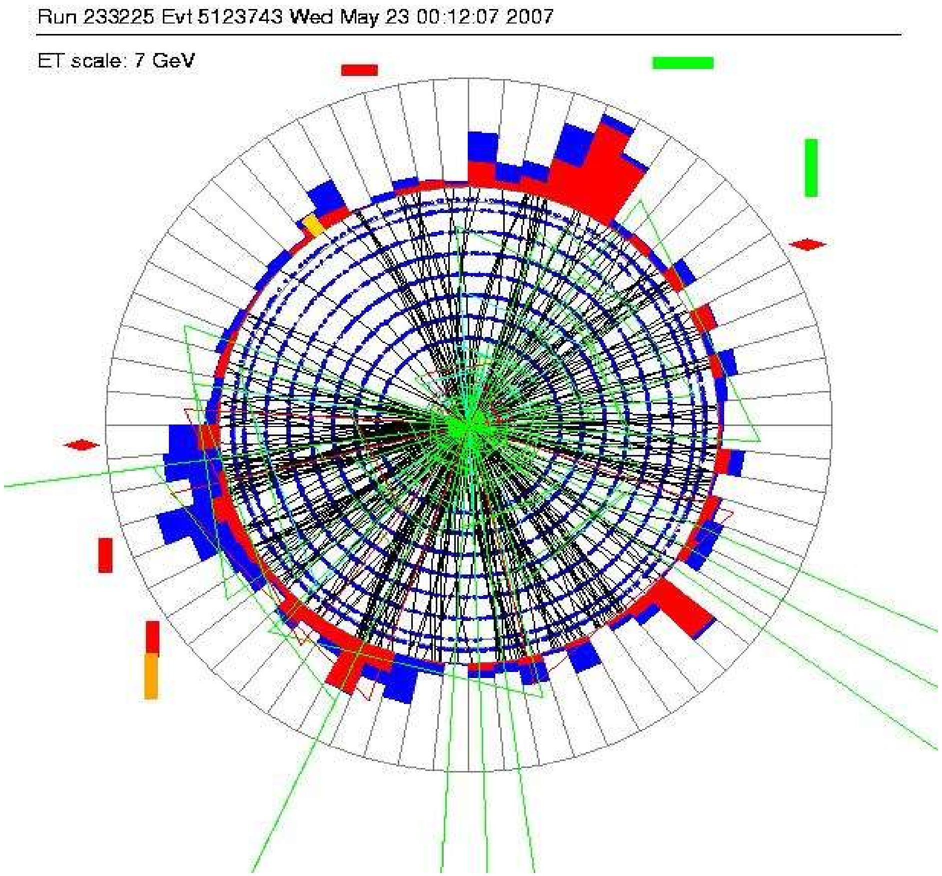
Tracker Event Displays at 70e^{30} cm^{-2} s^{-1}





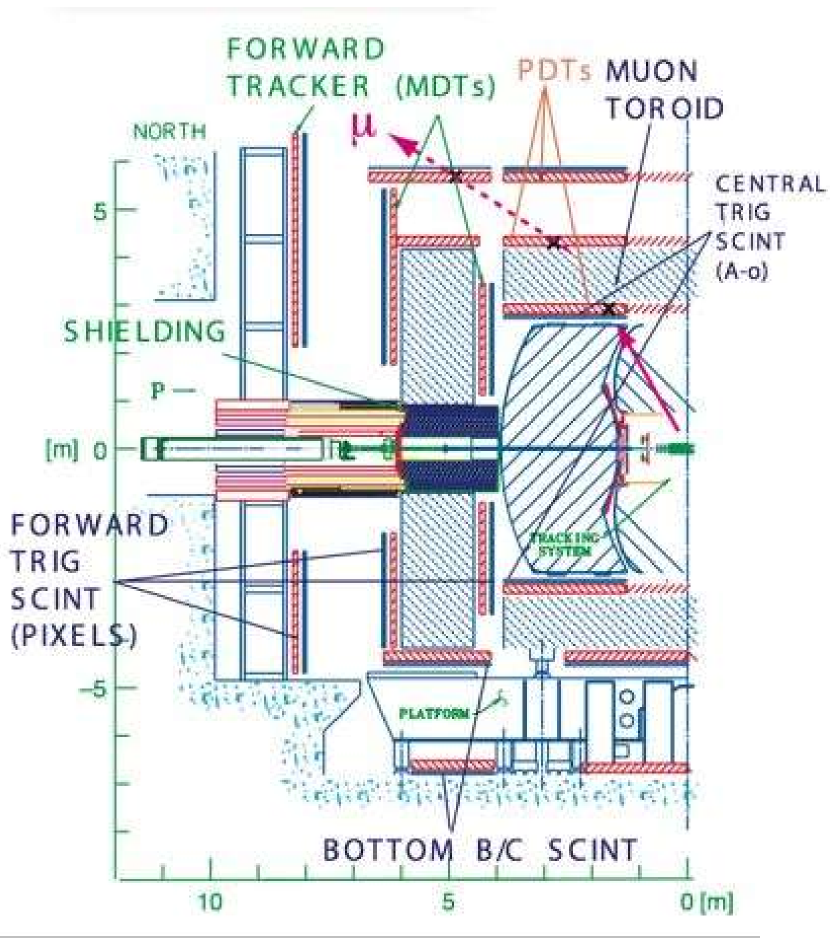
Tracker Event displays at 140e^{30} cm^{-2} s^{-1}

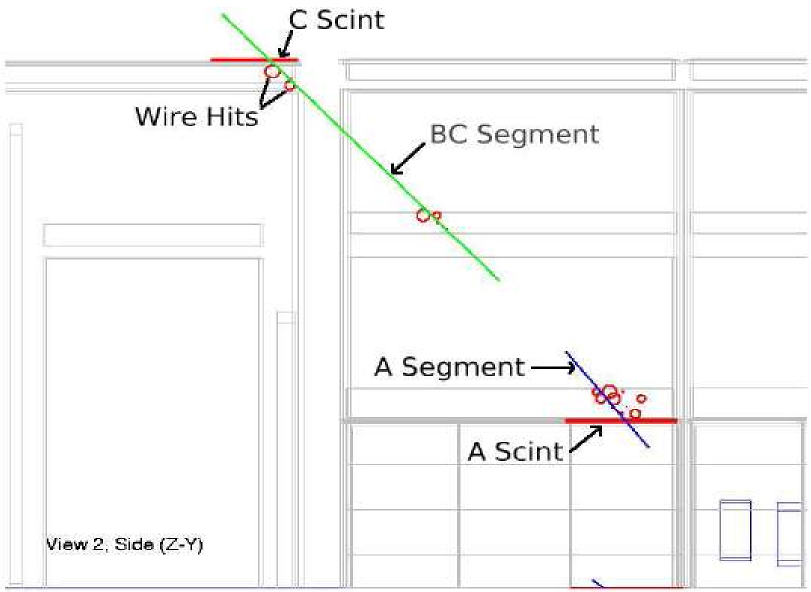




If this was the LHC you probably wouldn't see the detector underneath all the tracks.

Muon system



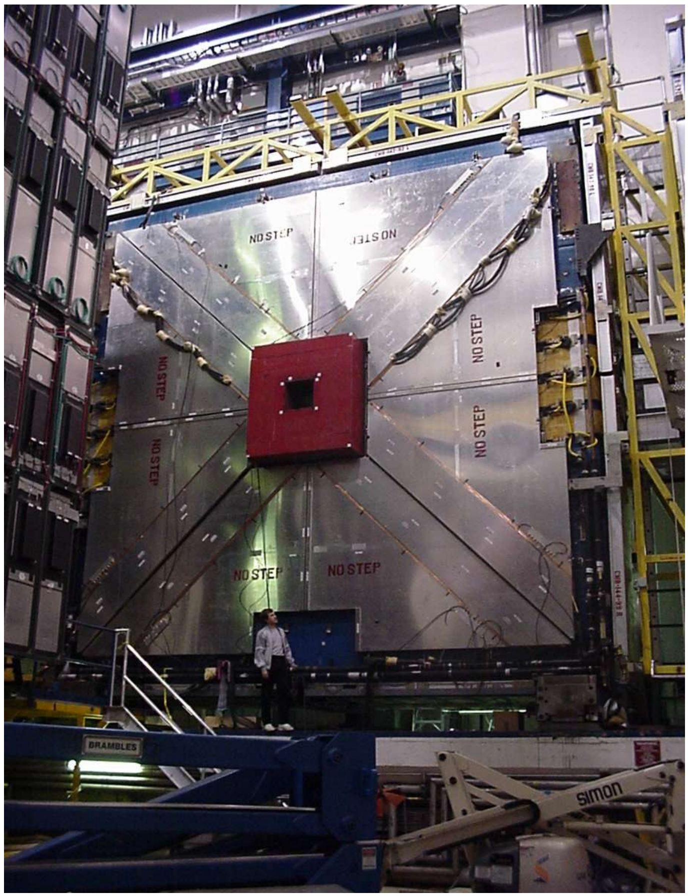


Main features:

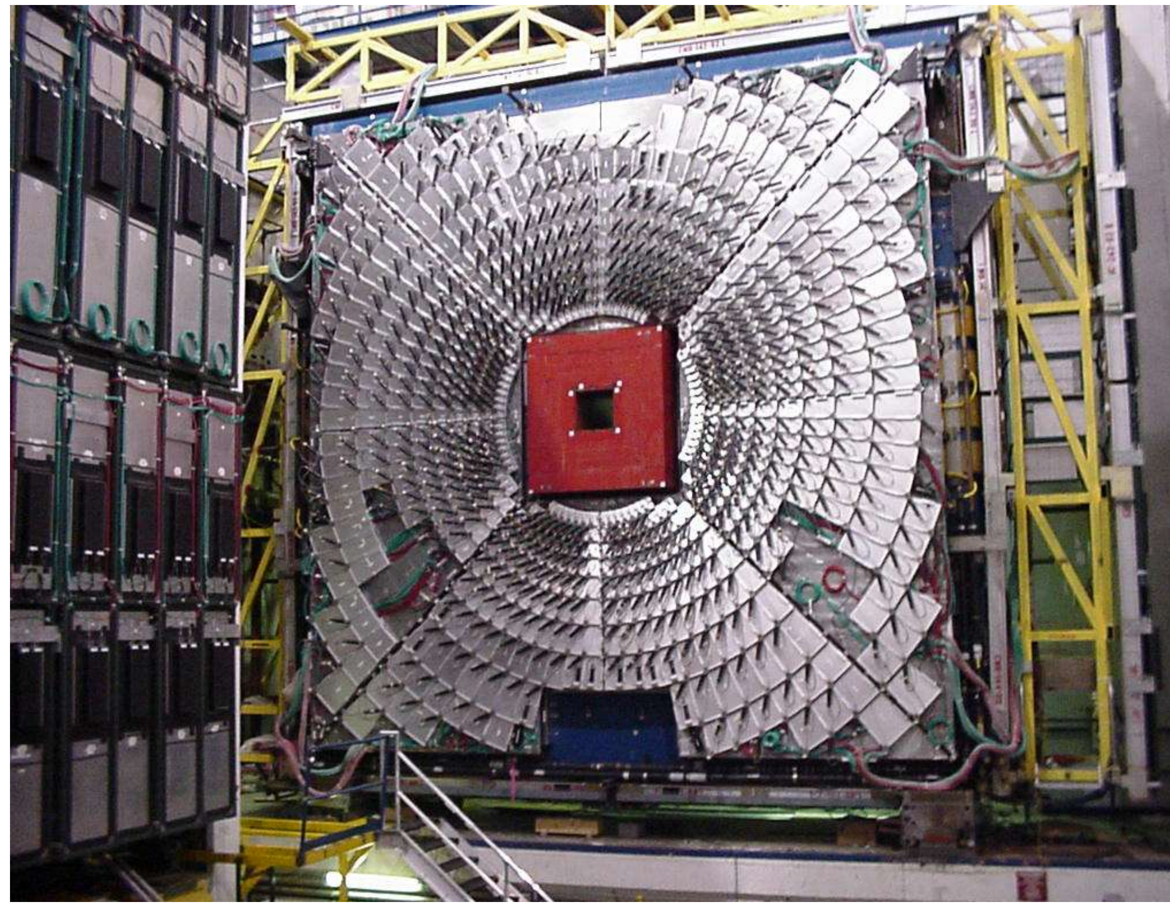
- 3 layers of drift tubes.
- 3 layers of scintillators: triggering, improved resolution in wire direction, rejection of cosmics
- Toroid magnet (1.8 T) after the first layer: local p_T measurement (trigger).
- Toroid and solenoid polarities reversed on regular basis.
- Track matched muons up to $|\eta| < 2.2$

Muon System

Mini Drift Tube plane

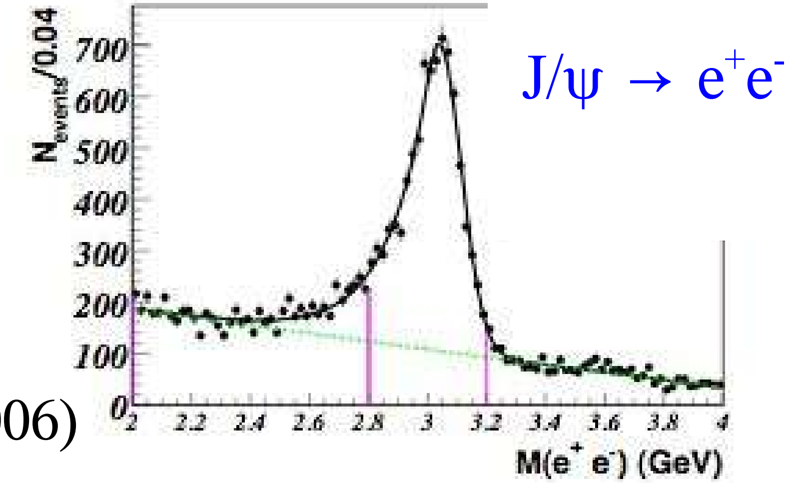


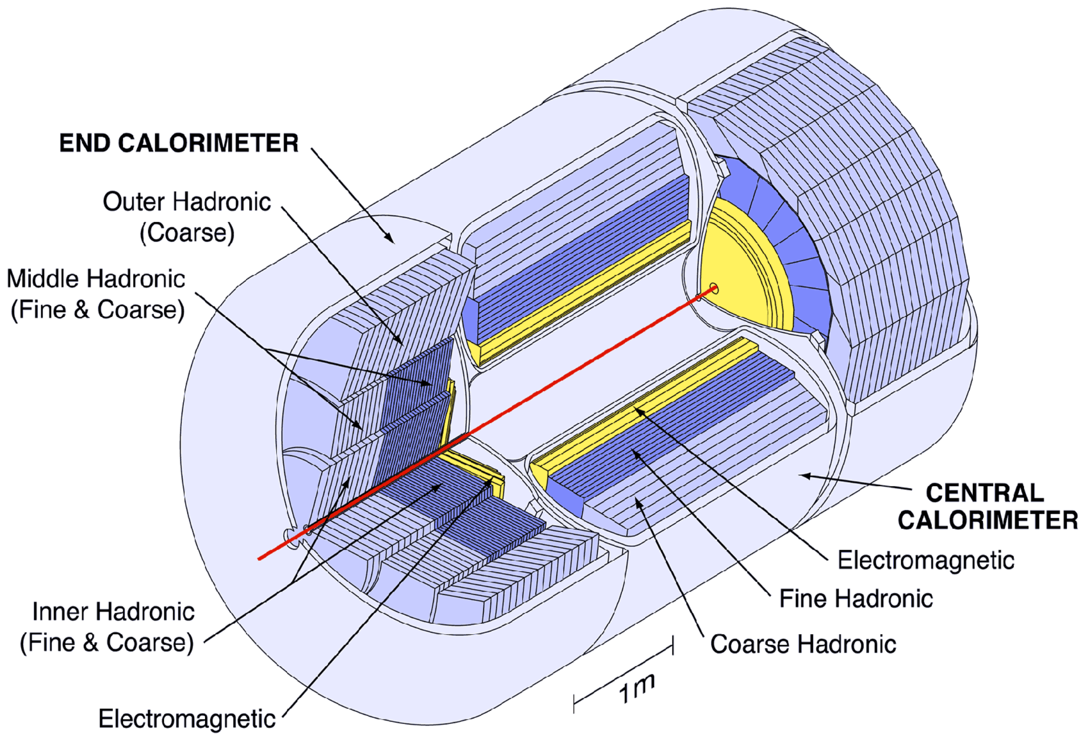
Scintillator plane



Calorimeter

Designed for high p_T physics, but
low p_T electrons can be used for *b*-tagging:
E.g. Measurement of B_d mixing using
opposite-side flavour tagging, PRD 74, 112002(2006)



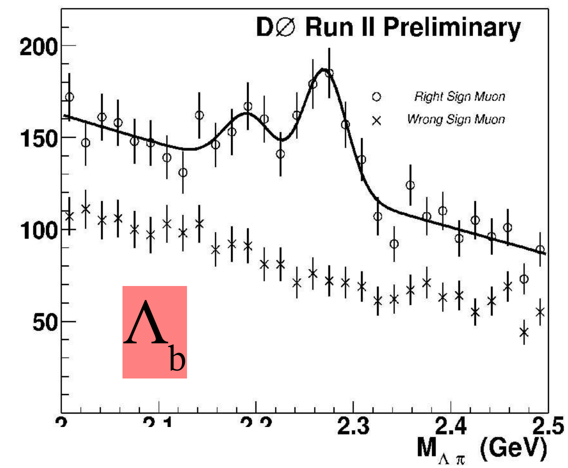


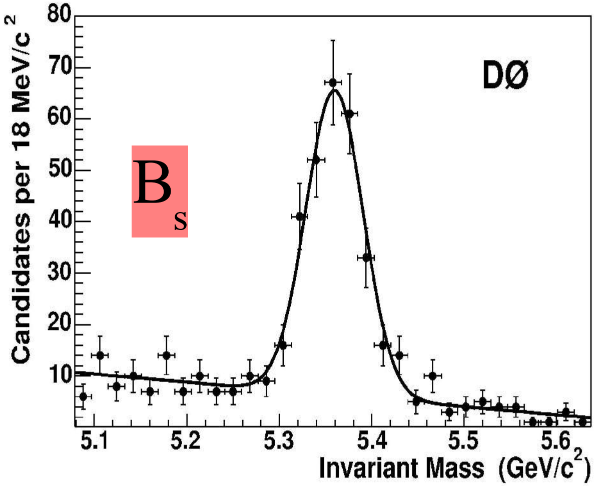
Tagging efficiency $\varepsilon = N_{tag}/N_{tot}$
Dilution $D = (N_R - N_W)/(N_R + N_W)$
Tagging power$=\varepsilon D^2$

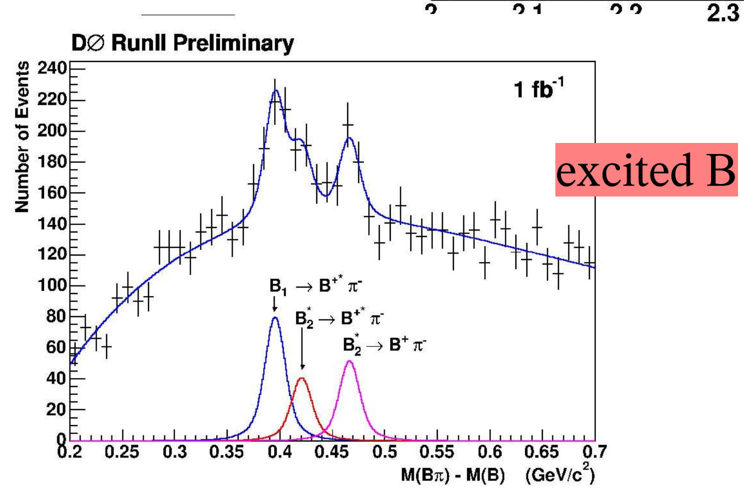
$\varepsilon D^2(\mu) = 1.48\%$
$\varepsilon D^2(e^-) = 0.21\%$

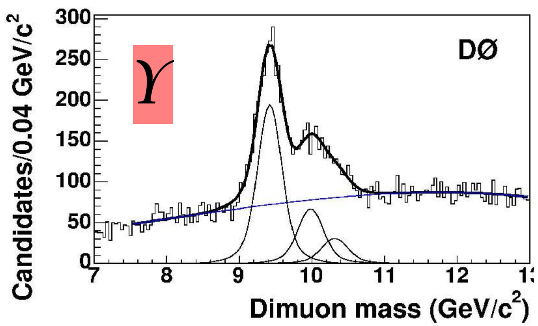
Results

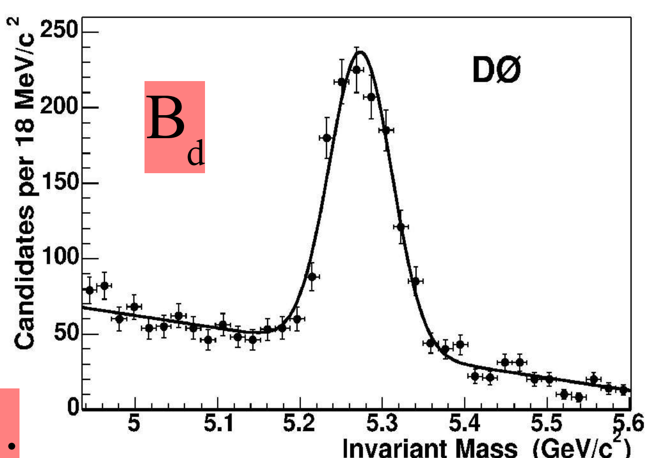
With this detector we have seen all sorts of *b*.....

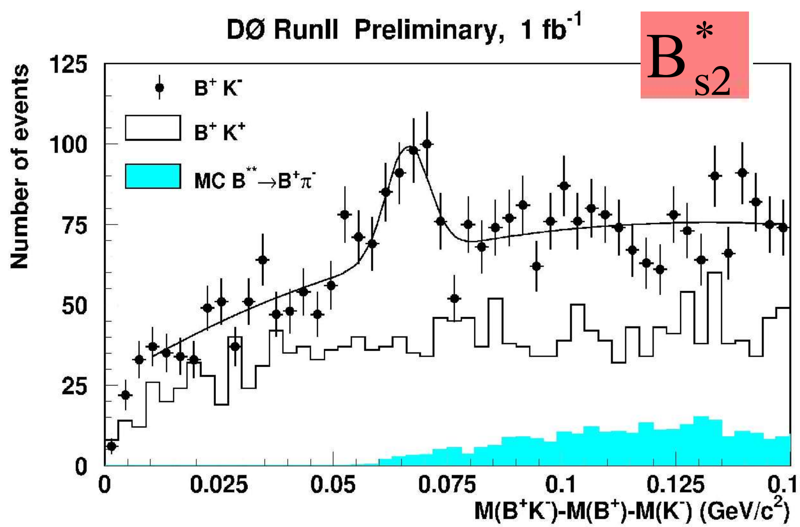










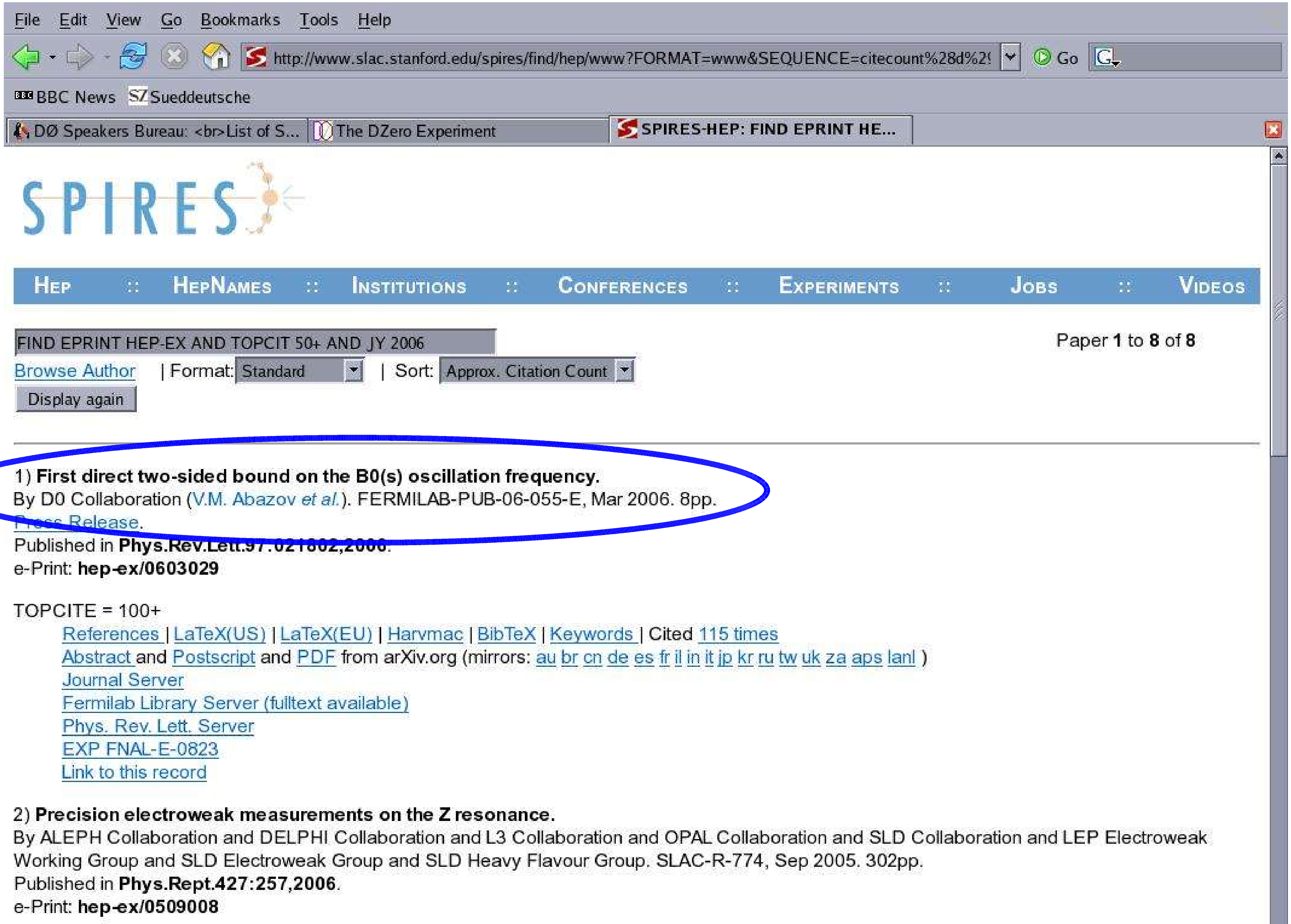


$+ B^+, B_c, X(3872), \ldots$

DØ *b*-physics publications

- Measurement of the charge asymmetry in semileptonic B_s decays, PRL 98, 151801 (2007)
- Lifetime difference and CP violating phase in the B_s system, PRL 98, 121801 (2007)
- Measurement of B^0 mixing using opposite-side flavor tagging, PRD 74, 112002 (2006)
- Measurement of the B_s lifetime in Semileptonic Decays PRL 97, 241801 (2006)
- Measurement of the CP-violation parameter of B^0 mixing and decay with ppbar → mumuX data PRD 74, 092001 (2006)
- Search for the Rare Decay $B_s \to \Phi\mu^+\mu^-$ with the DØ Detector, PRD 74, 031107 (2006)
- Direct Limits on the B_s Oscillation Frequency, PRL 97, 021802 (2006)
- Measurement of the Upsilon differential cross section..., PRL 94, 232001 (2005)
- Measurement of the ratio of B^+ and B^0 meson lifetimes, PRL 94, 182001 (2005)
- Measurement of the Λ_b lifetime in the decay $J/\psi\ \Lambda$ decays..., PRL 94, 102001 (2005)
- A search for the flavour-changing neutral current decay $B_s \to \mu^+\mu^-$, PRL 94, 071802 (2005)
- Measurement of the B_s lifetime in the exclusive decay channel $B_s \to J/\psi\ \Phi$, PRL, 94, 042001 (2005)
- Measurement of the lifetime difference in the B_s system, PRL 95, 171801 (2005)
- Measurement of semileptonic branching fractions of B mesons to narrow D** states, PRL 95, 171803 (2005)
- Observation and Properties of the X(3872) Decaying to $J/\psi\ \pi^+\pi^-$..., PRL 93, 162002 (2004)

The most talked about paper in 2006



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Paper **1** to **8** of **8**

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1) **First direct two-sided bound on the B0(s) oscillation frequency.**
By D0 Collaboration (V.M. Abazov *et al.*). FERMILAB-PUB-06-055-E, Mar 2006. 8pp.
Press Release.
Published in **Phys.Rev.Lett.97:021802,2006**.
e-Print: **hep-ex/0603029**

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EXP FNAL-E-0823
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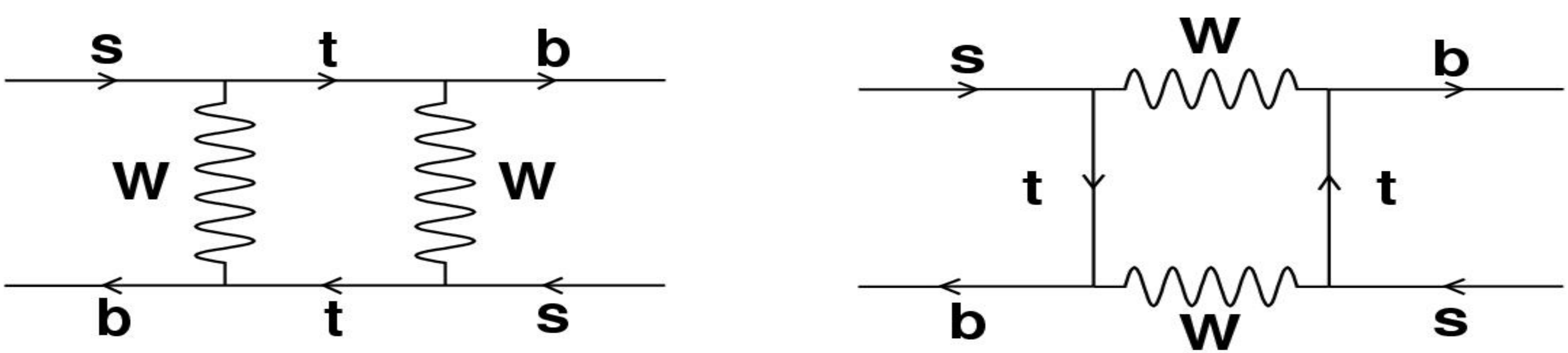
2) **Precision electroweak measurements on the Z resonance.**
By ALEPH Collaboration and DELPHI Collaboration and L3 Collaboration and OPAL Collaboration and SLD Collaboration and LEP Electroweak Working Group and SLD Electroweak Group and SLD Heavy Flavour Group. SLAC-R-774, Sep 2005. 302pp.
Published in **Phys.Rept.427:257,2006**.
e-Print: **hep-ex/0509008**

B_s Mixing

- B_s (~$\bar{b}s$), $\bar{B}_s$(~bs) are produced in one of the two possible flavour states.
- This initial state evolves into a time-dependent superposition of the two states according to:

$$i\frac{\partial}{\partial t}\begin{pmatrix} |B_q^0(t)\rangle \\ |\overline{B}_q^0(t)\rangle \end{pmatrix} = \left(\mathbf{M} - i\frac{\Gamma}{2}\right)\begin{pmatrix} |B_q^0(t)\rangle \\ |\overline{B}_q^0(t)\rangle \end{pmatrix}$$

M = mass matrix
Γ = decay matrix



B_s mixing via the dominant top-quark process

Observables in B_s Mixing

$$\Delta m = m_H - m_L = 2|m_{12}|$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\phi$$

$$\phi = \arg\left(-\frac{m_{12}}{\Gamma_{12}}\right)$$

$$\overline{\Gamma} = \frac{1}{\overline{\tau}} = \frac{1}{2}(\Gamma_L + \Gamma_H)$$

$$\Delta\Gamma_{CP} = \Gamma_{even} - \Gamma_{odd} = 2|\Gamma_{12}|$$

→ extract V_{ts}

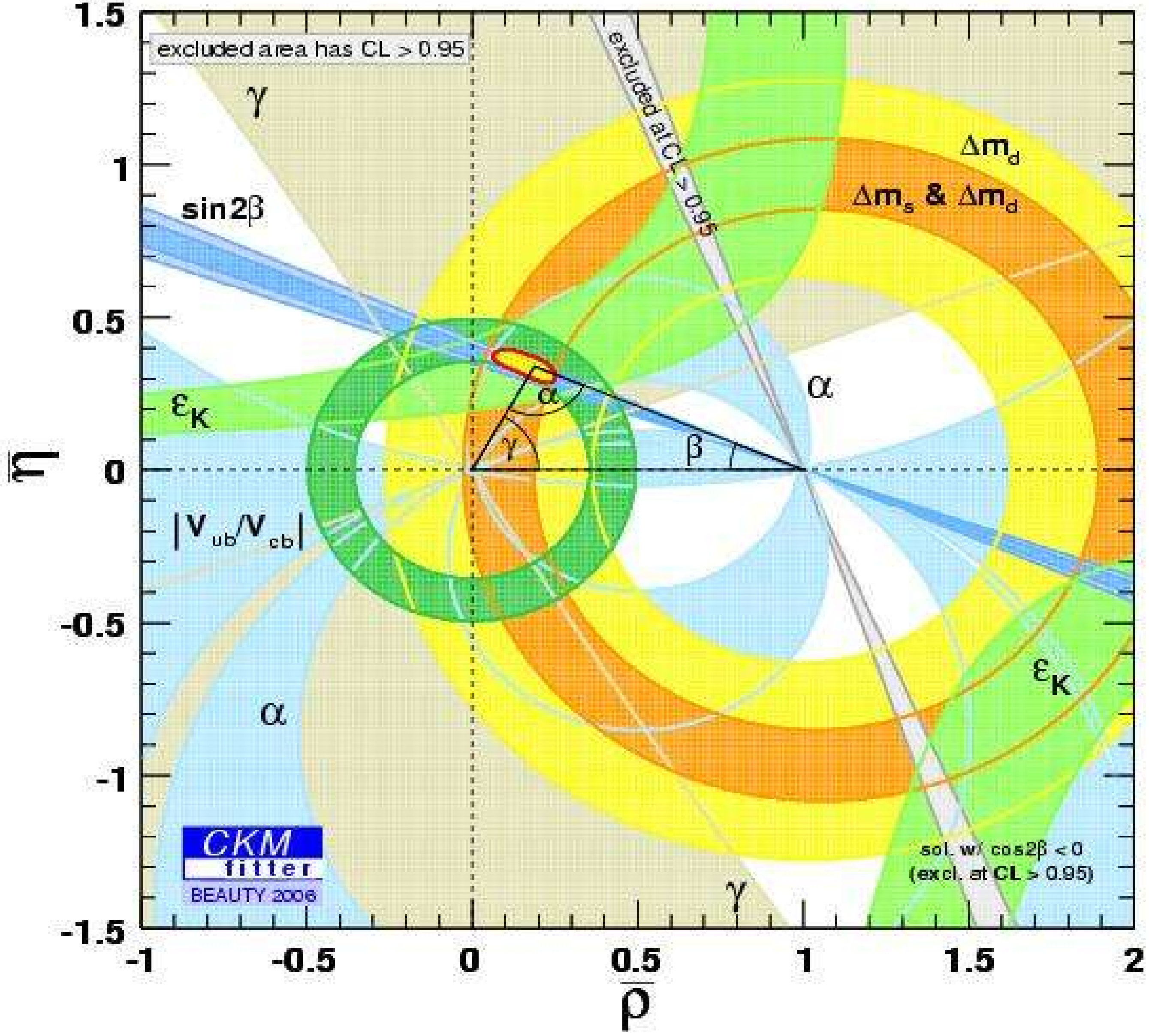
large values could indicate physics beyond the SM

CP violating phase: The level of CP violation in the Standard Model is too small to produce the observed baryon number density

→ looking at all sources of CP violation

→ CP violation in SM is expected to be small

The Big Picture



Measuring Δm_s at DØ

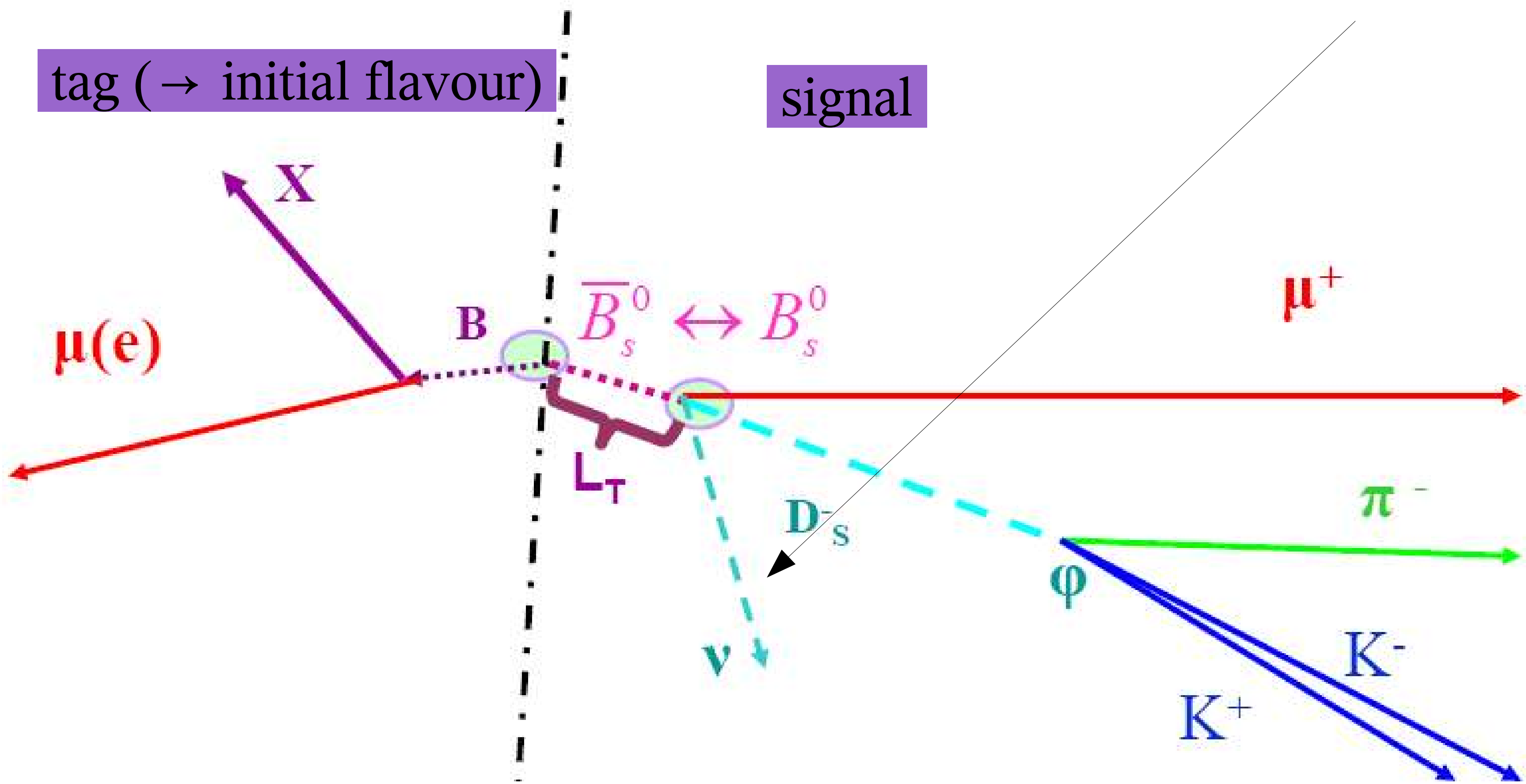
$B_s \rightarrow \mu^+ D_s^- X$

$D_s^- \rightarrow \Phi \pi^-$

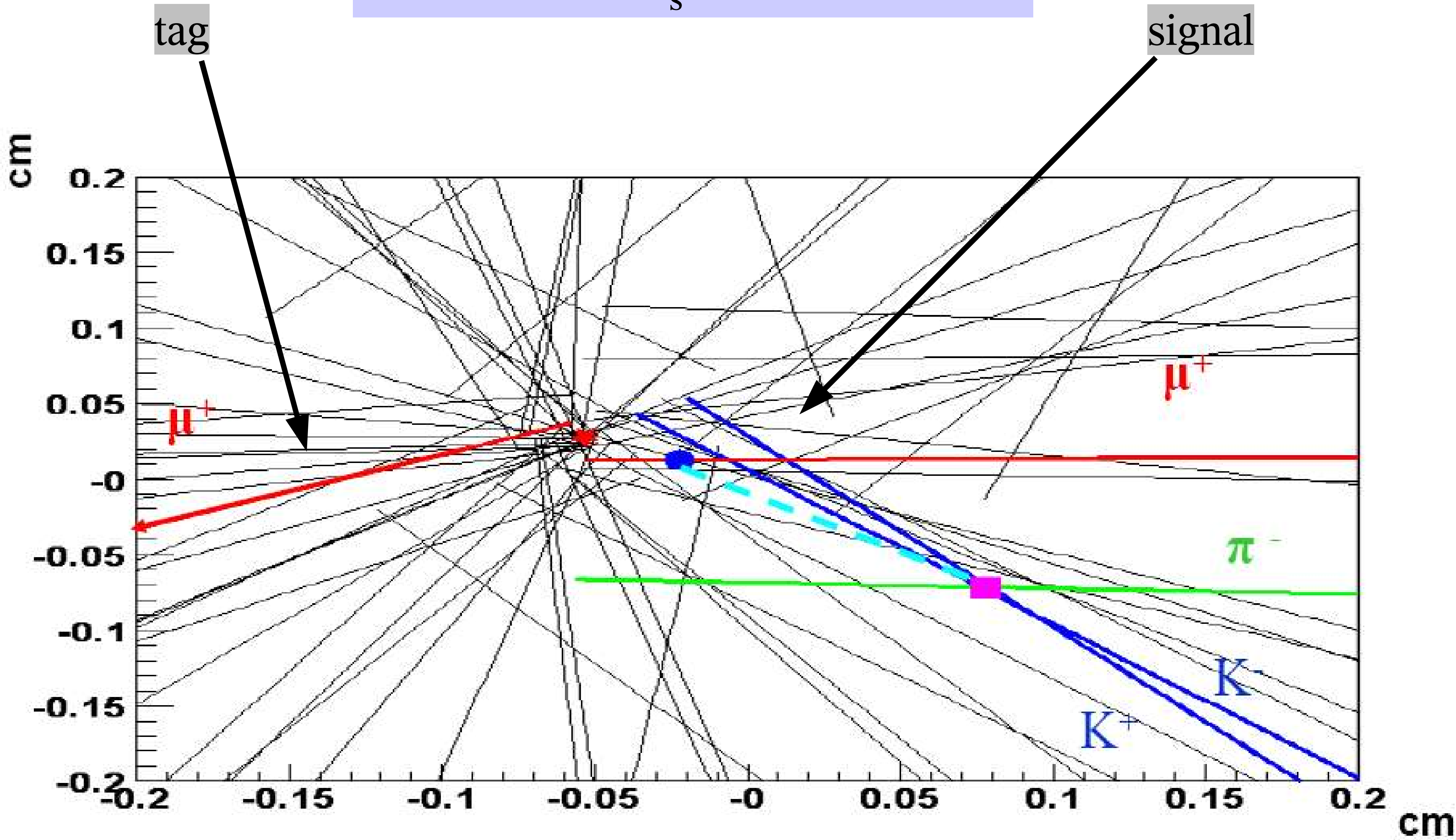
$\Phi \rightarrow K^+ K^-$

Problem.

$\rightarrow$ limited reach in Δm_s



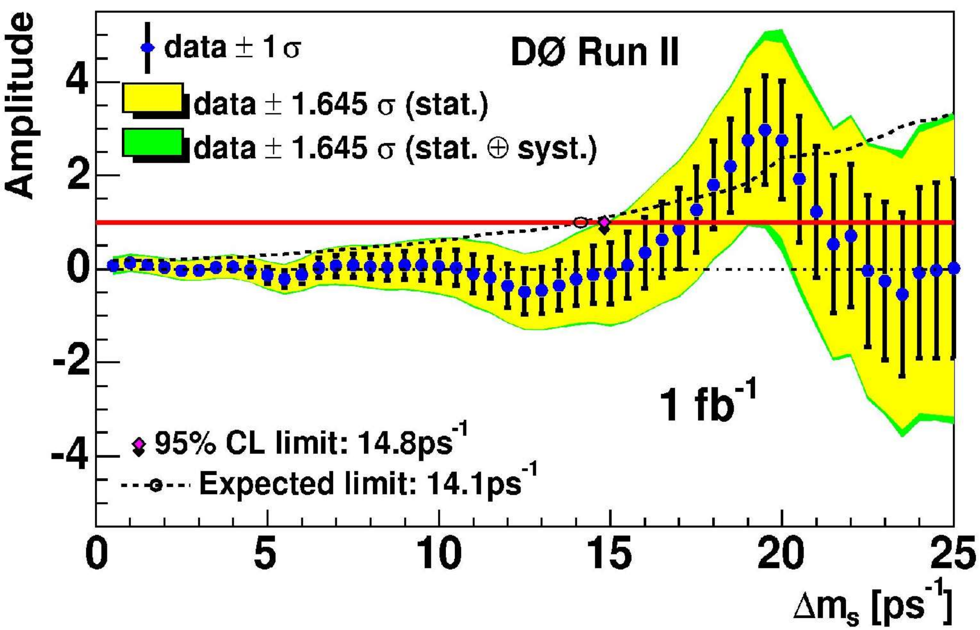
Measuring B_s mixing at DØ



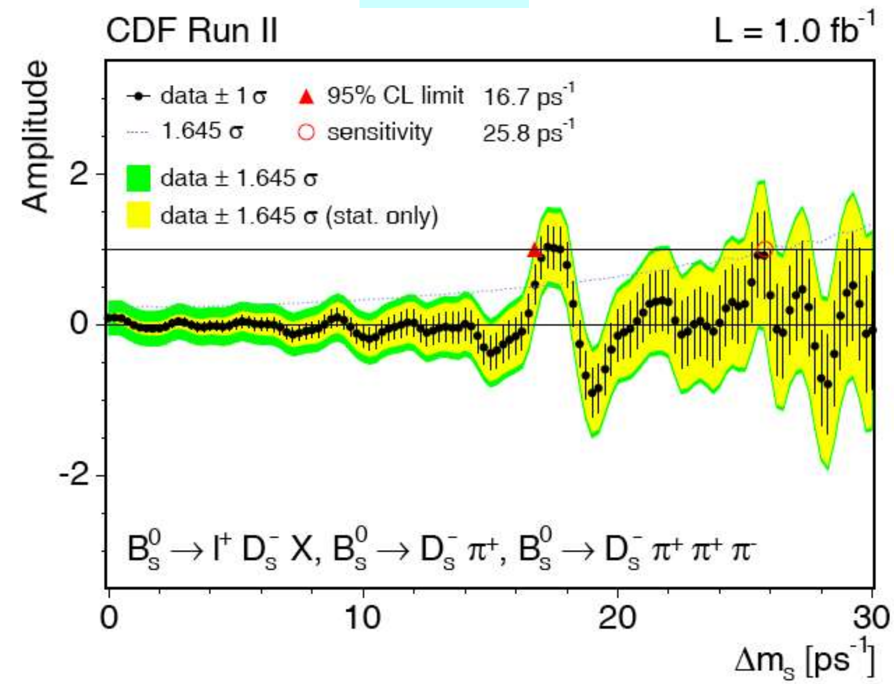
Limited reach in Δm_s, but ....

Results (DØ and CDF)

First !!



Best !!



$17 < \Delta m_s < 21\ ps^{-1}$
at 90 % confidence level

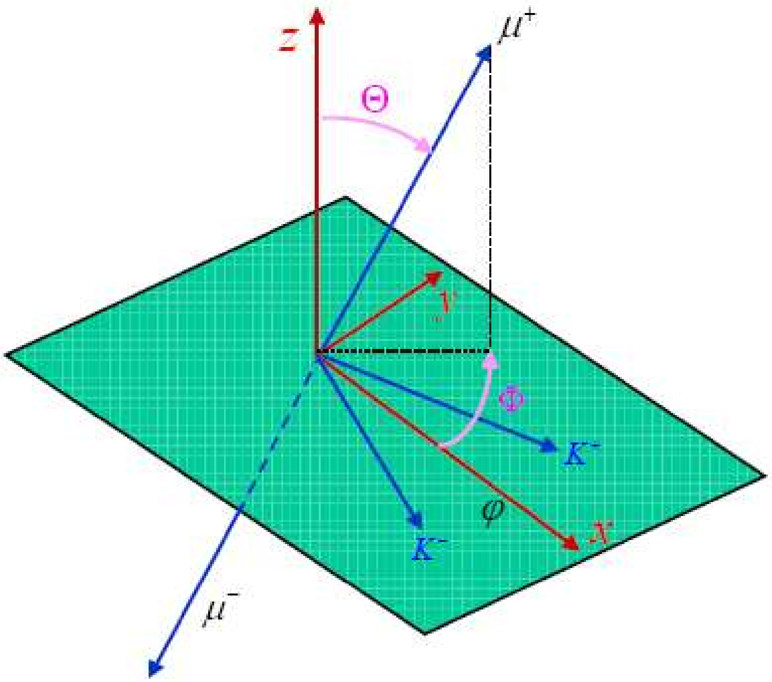
semileptonic decays only

$\Delta m_s = 17.77 \pm 0.10\ (stat) \pm 0.07\ (syst)\ ps^{-1}$

semileptonic + hadronic decays

$\rightarrow |V_{td}/V_{ts}| = 0.26060 \pm 0.0007\ (exp) \pm^{0.0081}_{0.0060}\ (theory)$

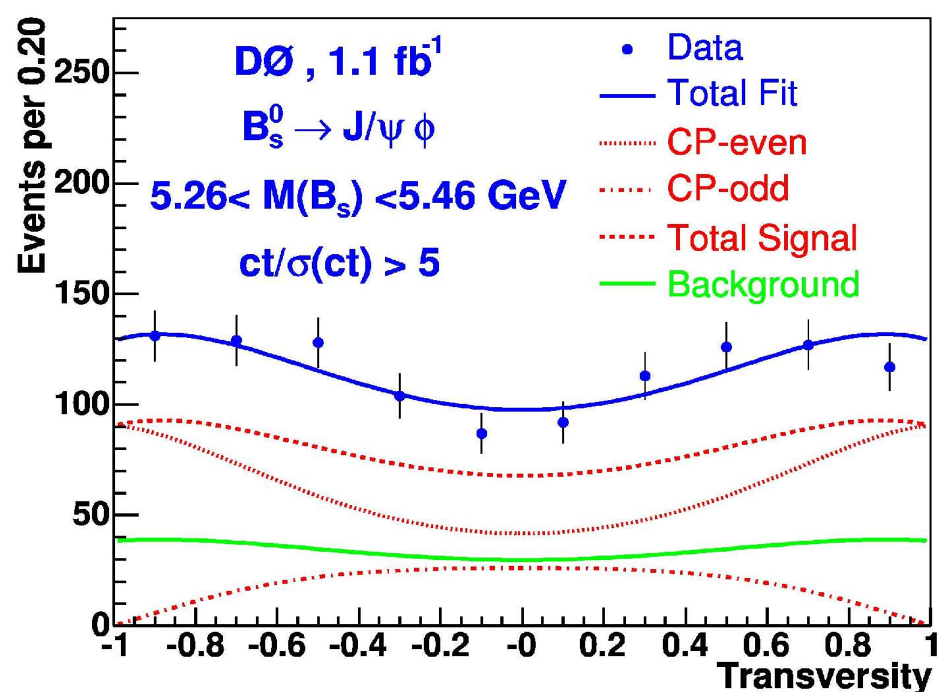
$\Delta\Gamma_s$ and ϕ_s from $B_s \rightarrow J/\psi\ \phi$



$$B_s^H = \frac{1}{\sqrt{2}}(|B_s\rangle + |\bar{B}_s\rangle) = CP-odd$$
$$B_s^L = \frac{1}{\sqrt{2}}(|B_s\rangle - |\bar{B}_s\rangle) = CP-even$$

scalar → VV decay
➔ 3 amplitudes
L = 0 (even),1 (odd), 2 (even)
described in ***transversity*** basis

In J/Ψ restframe:
K^+K^- plane defines (*x,y*) plane
K^+ defines +y direction
Θ, Ψ polar and azimuthal angles of μ^+
φ in Φ restframe: angle(K^+, -J/Ψ)



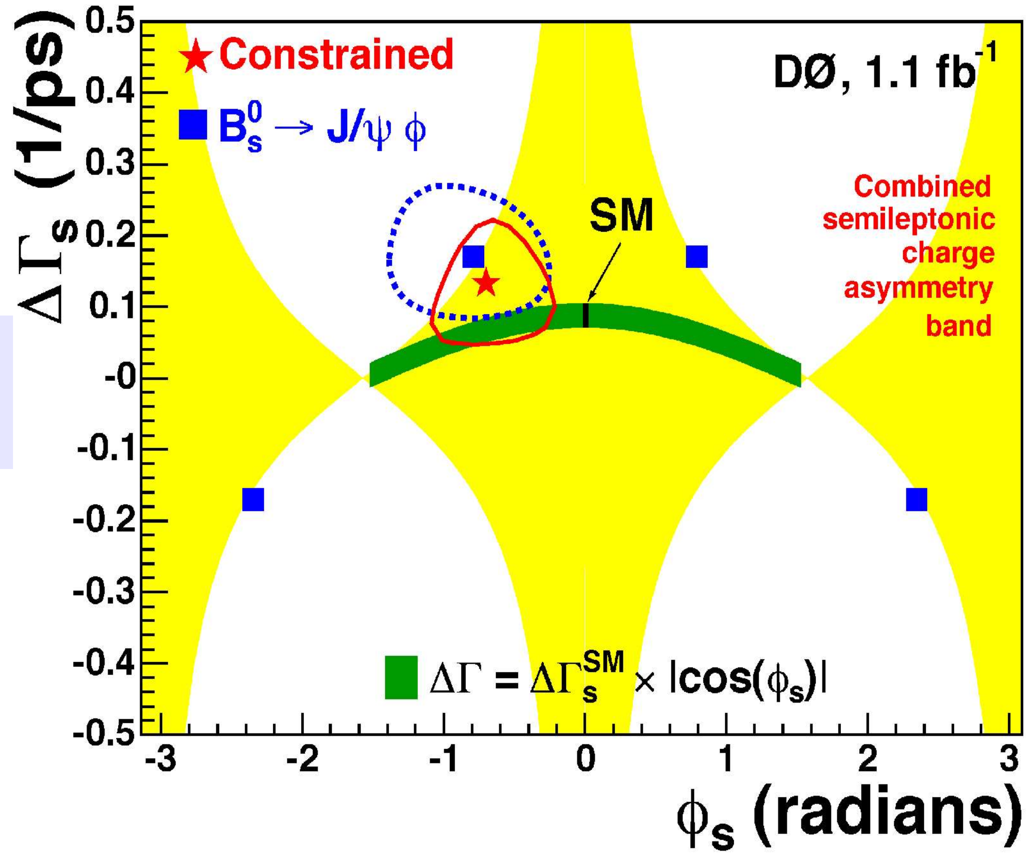
$\Delta\Gamma$ and Φ_s

- $B_s \rightarrow \mu X$ asymmetry
  Dimuon Asymmetry
  World Average: τ_{fs}

$\Delta\Gamma_s = 0.13 \pm 0.09\ ps^{-1}$
SM prediction*: $0.088 \pm 0.017\ ps^{-1}$

$\Phi_s = -0.70 \pm^{0.47}_{0.39}$
SM prediction*: $(4.2 \pm 1.4) \times 10^{-3}$

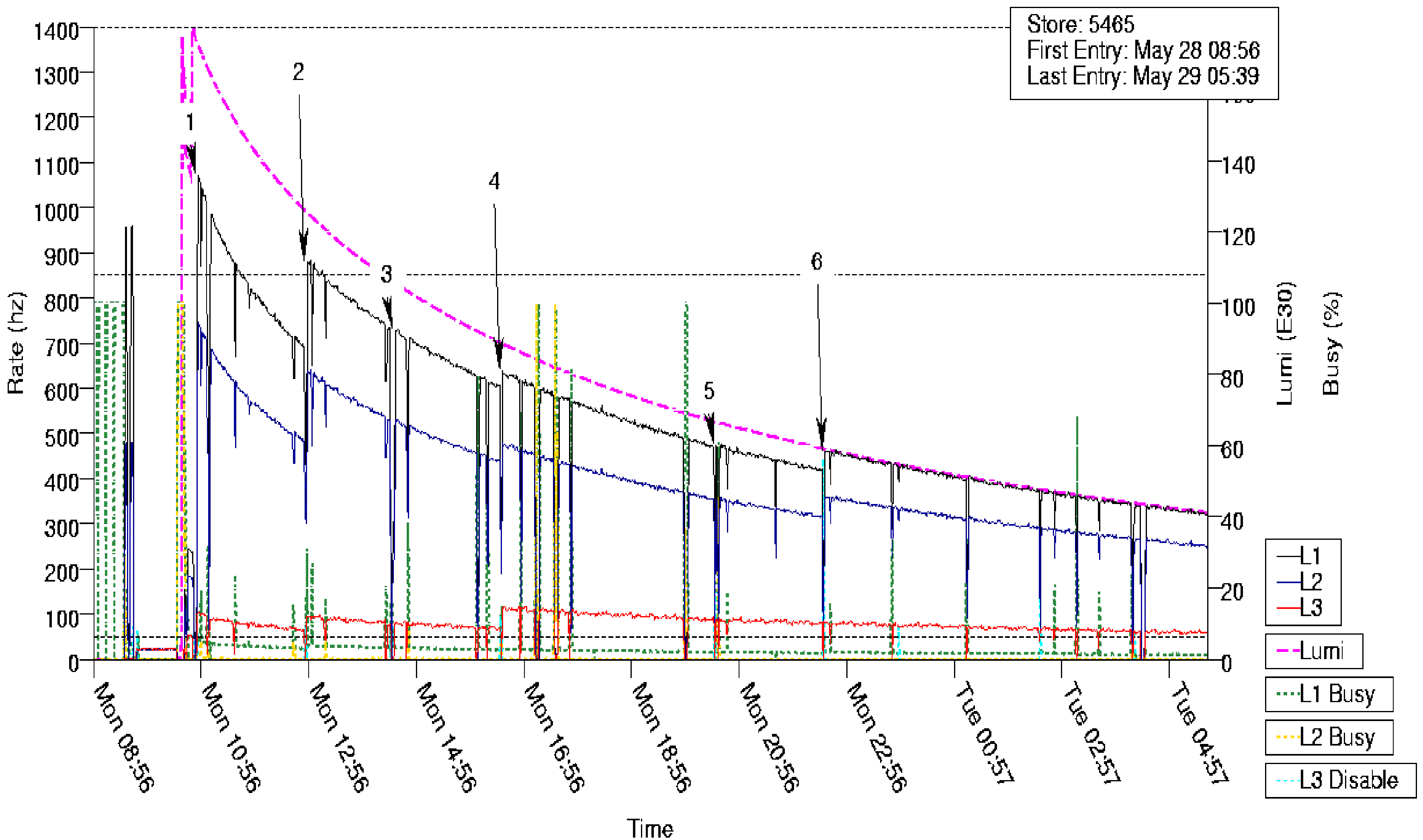
*Lenz,Nierste hep-ph/0612167



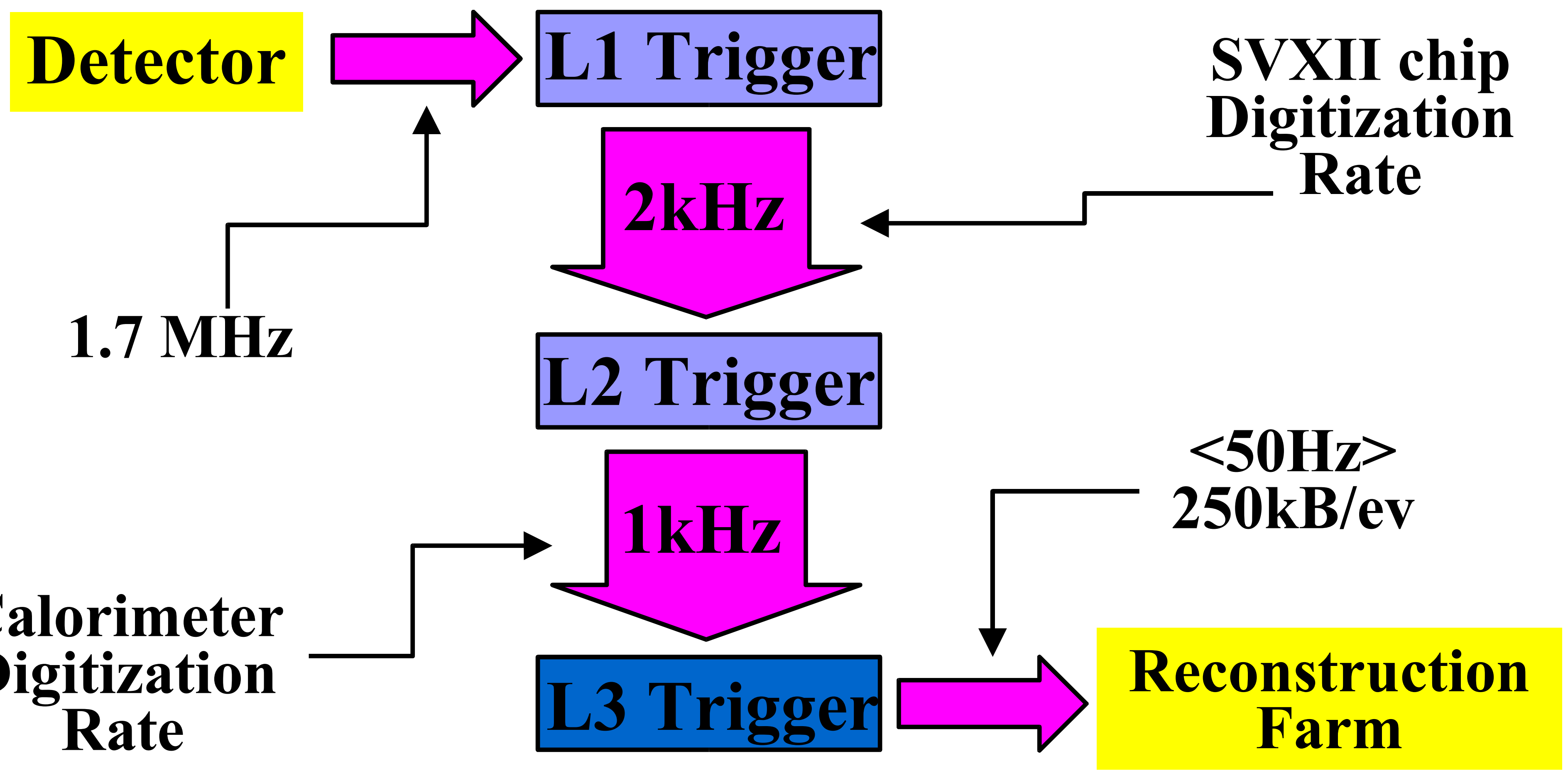
Triggers

Go ahead, make my data !!!!!

Data taking rates



The DØ trigger system



Trigger System: Level 1 & Level 2

Level 1 triggers

Calorimeter: 0.2x0.2 η-φ triggers towers (+E_T)

Central Track Trigger (CTT): uses axial layers of the CFT to find tracks
4 p_T bins
Tracks can be confirmed by muon hits.

Muon: Looks for hits (wire & scintillator) consistent with muons.

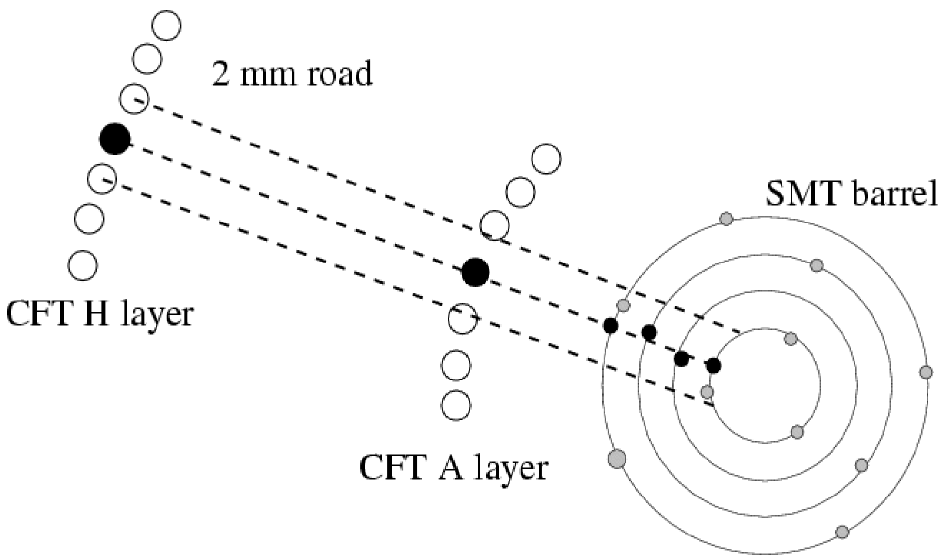
Level 2 triggers

- Refine L1 trigger terms using added event information (e.g. wire and scintillator times for muons).
- Results are combined in a global L2 term.
- Silicon Track Trigger for displaced vertices, improved momentum measurement.

Silicon Track Trigger

- L1 CTT tracks are used to define roads into the SMT.
- SMT hits are clustered in these roads.
- Track is refit within the road.

→ Improved p_T measurement wrt L1.
→ Impact parameter measurement.



Under-used by *b*-physics in RunIIa:

- Impact parameter bias difficult to model/analyze.
- (Planned) late commissioning: Triggers already well established with sufficient rate reduction.
- No displaced track only trigger due to L1 bandwidth limitations.

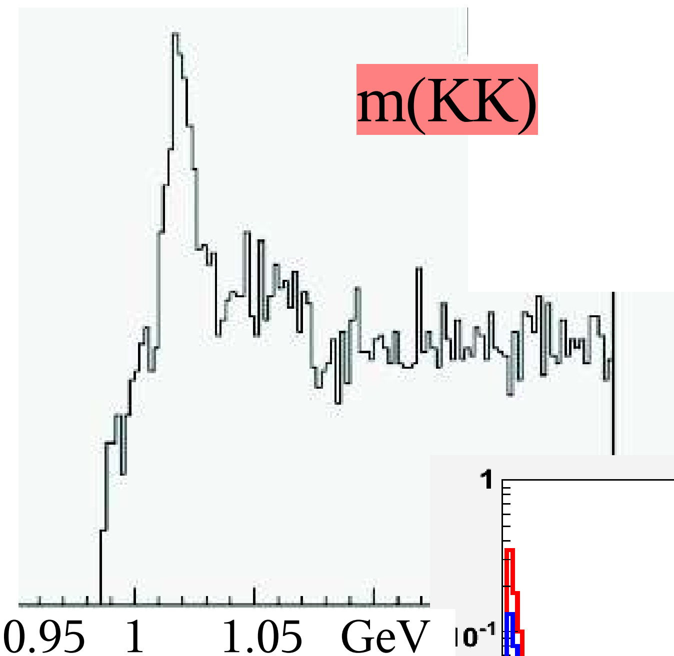
RunIIb: *b*-physics and Higgs group are the main users of the STT.

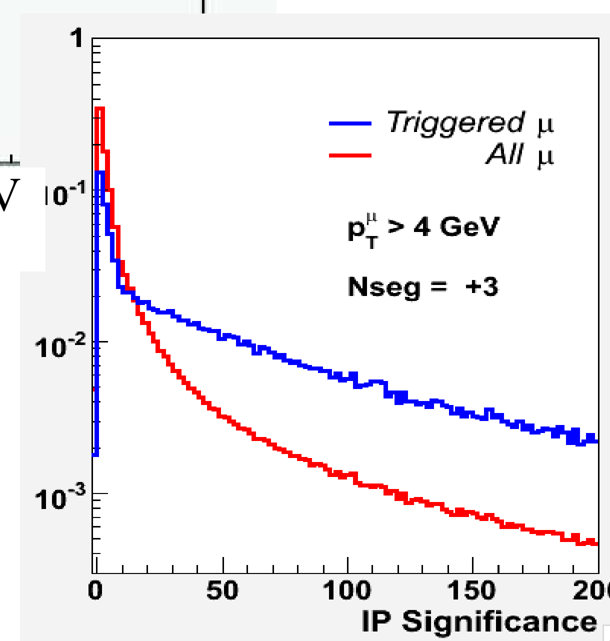
Trigger System: Level 3

- Software based.
- Goal: To perform a (partial) reconstruction of the event.

Tools of the trade:

- muons
- electrons
- tracking
- taus
- jets
- missing E_T
- primary & secondary vertexing
- isolation (muons, electrons)
- impact parameter (tracks, muons)
- invariant mass





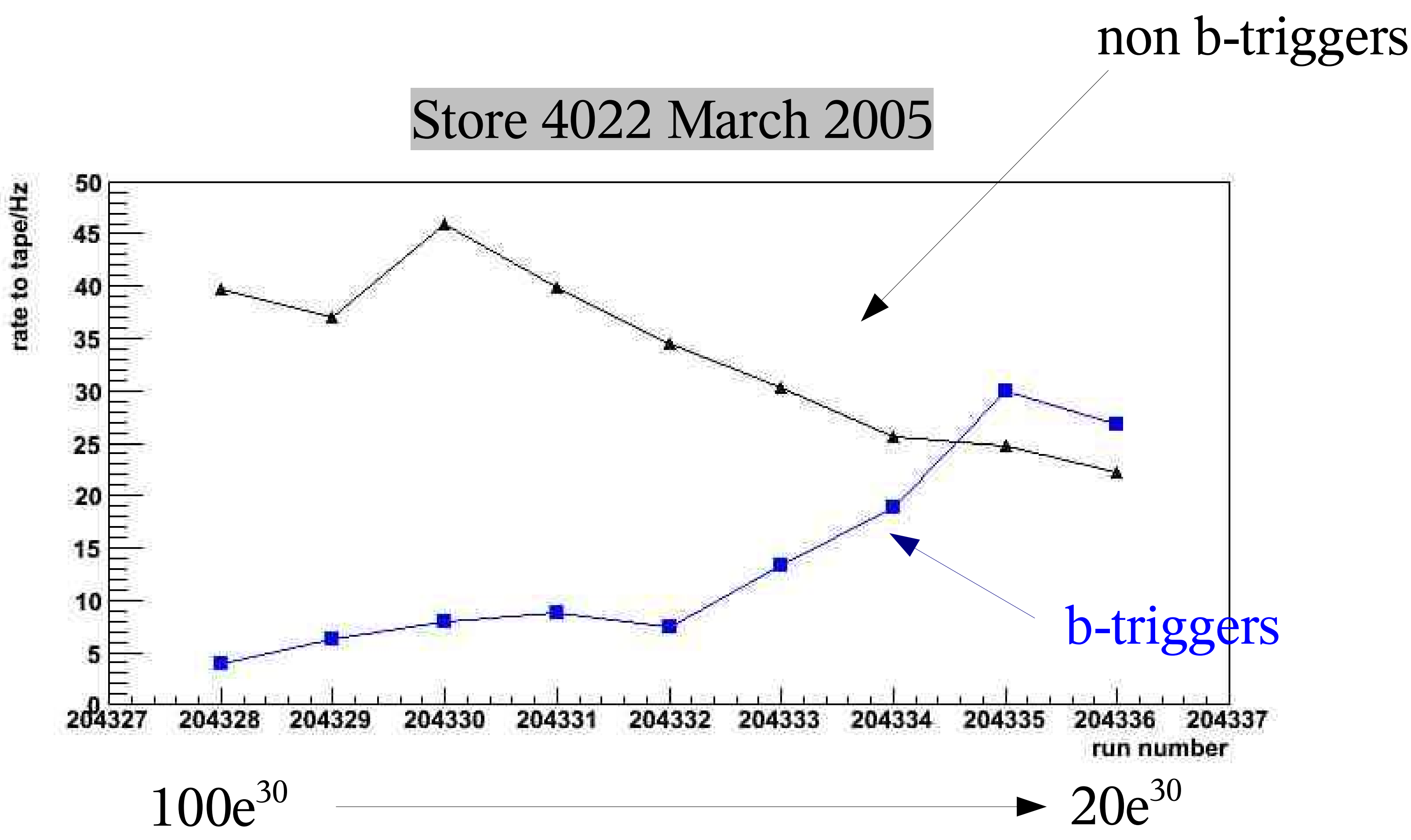
... and almost any combination thereof

Doing *b*-physics at a multi-purpose experiment

Trigger strategy:

- The trigger menu needs to accommodate all physics groups.
- Most physics aiming for maximum *luminosity* on a given trigger.
- Most *b*-physics needs the maximum of *b-events*.

Store 4022 March 2005



b-physics triggers at DØ

- At the end of RunIIa there were 56 *b*-triggers (out of ~ 300 triggers total).
- The number of triggers was limited by the number of L1/L2 bits (128).
- Only L1/L2 bits could be prescaled individually.

300 triggers should be enough for everybody, right ?

Apparently not:

RunIIb has seen L2 oring/splitting and a doubling of the number of triggers:

- Needs increasingly sophisticated tools (and databases) to administer this list.
- Difficulties in identifying problematic triggers during run time.
- Automated performance monitoring helps, but you still need a brain to analyse it.
- Only 10% (or so) of all triggers are actually used for analysis.
- Manpower ~ $triggers^2$
- Yes, I am bitter.

b-physics triggers at DØ

In RunIIa there were 3 major groups of *b*-physics triggers:

- single muons, impact parameter unbiased ('low' lumi)
- single muons with impact parameter requirement (all luminosities)
- di-muons (all luminosities)

additionally

- tri-lepton
- electron-muon
- muon+jets

Apart from requiring one or more muons, the *b*-physics triggers also use the following trigger requirements:

- track match for muons: tracks required to have SMT hits
- tracks (number of tracks, p_t)
- impact parameters (for muons and/or tracks)
- invariant mass filters: Φ, J/ψ, Υ
- charge (opposite sign)
- primary vertex: ± 35 cm

Anatomy of three 'best-of' (late) RunIIa triggers

unbiased single muon trigger (up to $55e^{30}$, $100e^{30}$ RunIIb)

- semileptonic decays, mixing
- L1: tight scintillator, loose wire, pT > 3 GeV (from CTT), primary vertex
- L2: one medium muon (RunIIb: track match requirement)
- L3: track matched, 3-layer muon with pT > 3,4,5 GeV,
  $|z$ (primary vertex)$| < 35$ cm

single muon trigger with impact parameter (all luminosities)

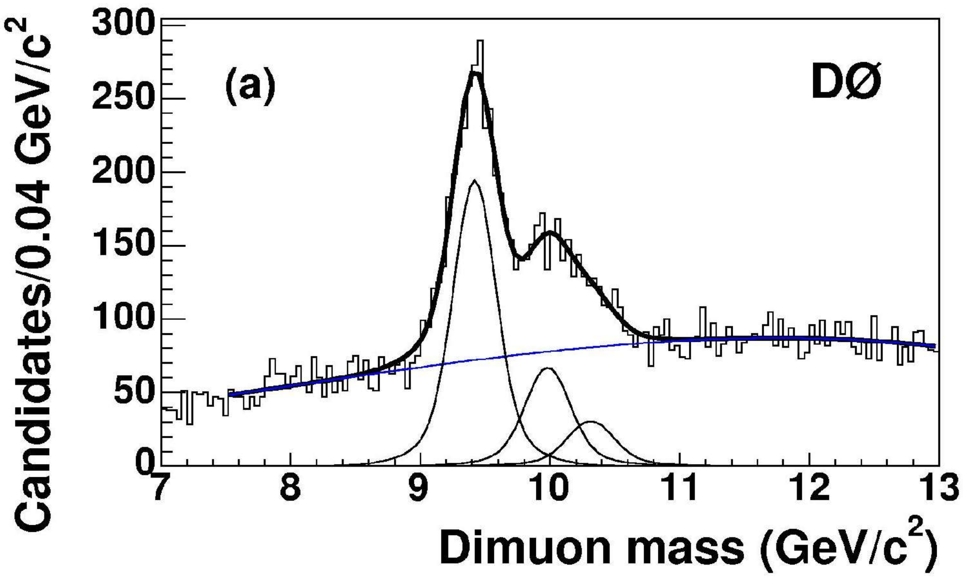
- use muon for tagging to avoid IP bias in the signal (hadronic decays)
- L1: tight scintillator, loose wire, pT > 5 GeV (from CTT), primary vertex
- L2: one medium muon (RunIIb: track match requirement)
- L3: track matched 3-layer muons with IP significance > 3 and pT > 5 GeV
  $|z$ (primary vertex)$| < 35$ cm

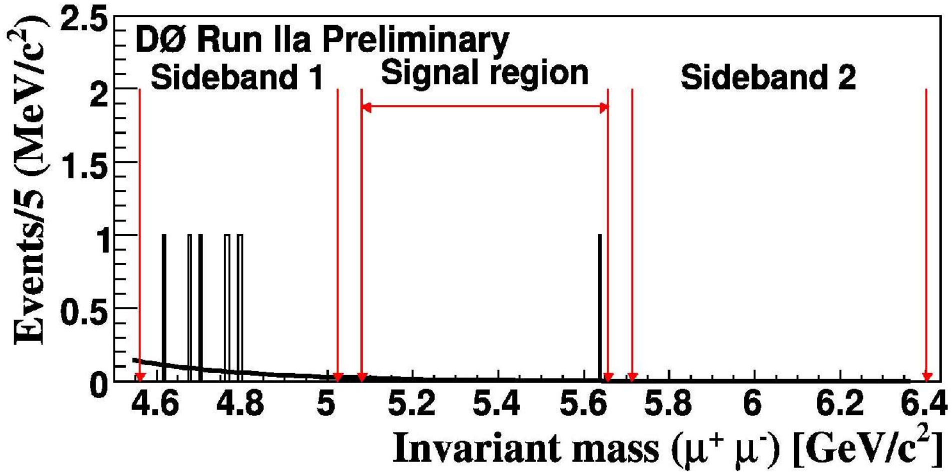
Beloved by trigger people, hated by analysers ➡ data goes unused.

Anatomy of three 'best-of' (late) RunIIa triggers (cont)

di-muon trigger (all luminosities)

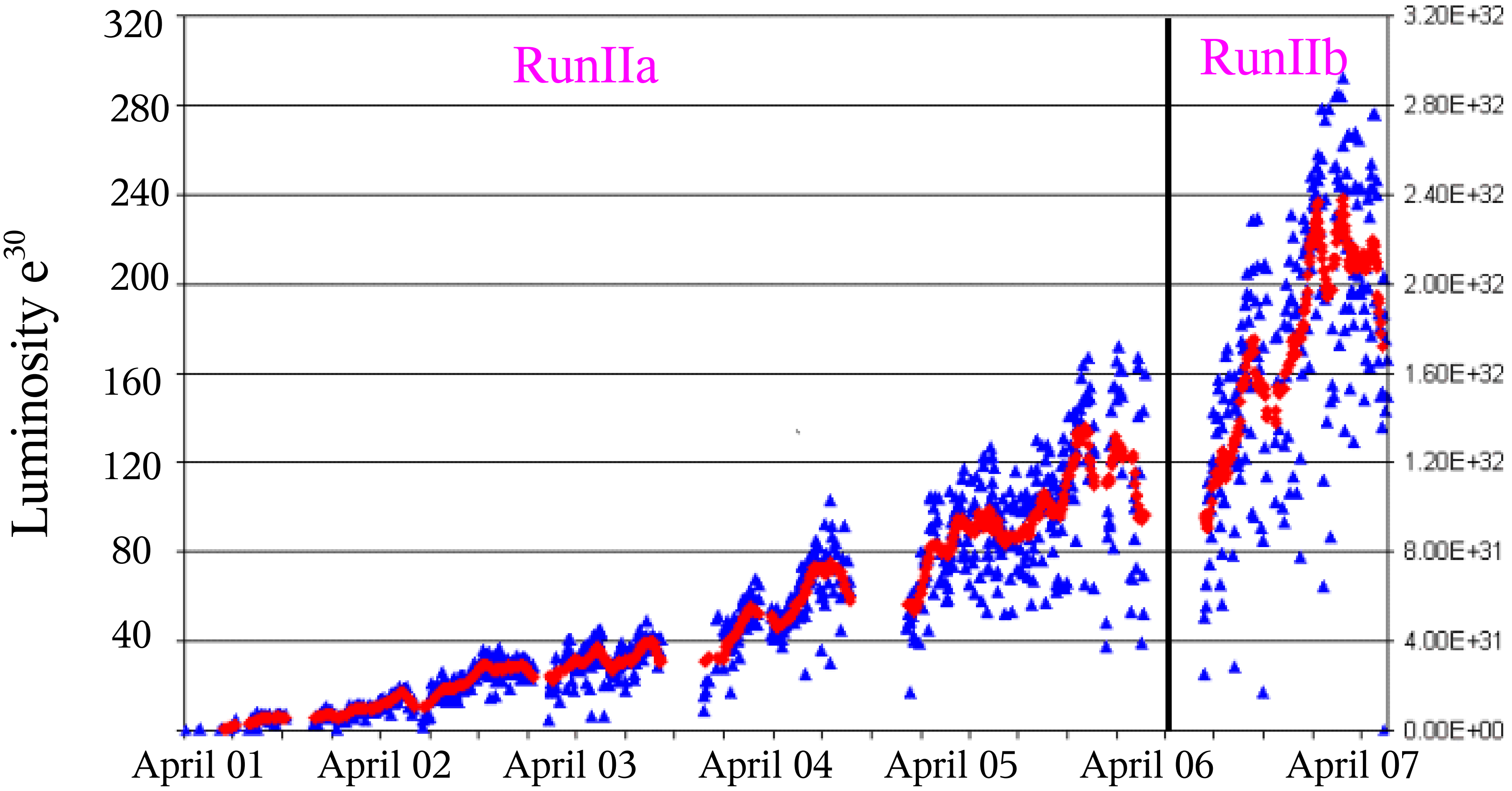
- J/ψ (e.g. ΔΓ/Γ), ϒ , $B_s \rightarrow \mu\mu$
- L1: 2 muons, no pT cut, (RunIIb: one match to a CTT track required)
- L2: one or two muons, depending on luminosity
- L3: 2 muon system only muons, pT > 2 GeV, one or two muons must have hits in all 3 layers.





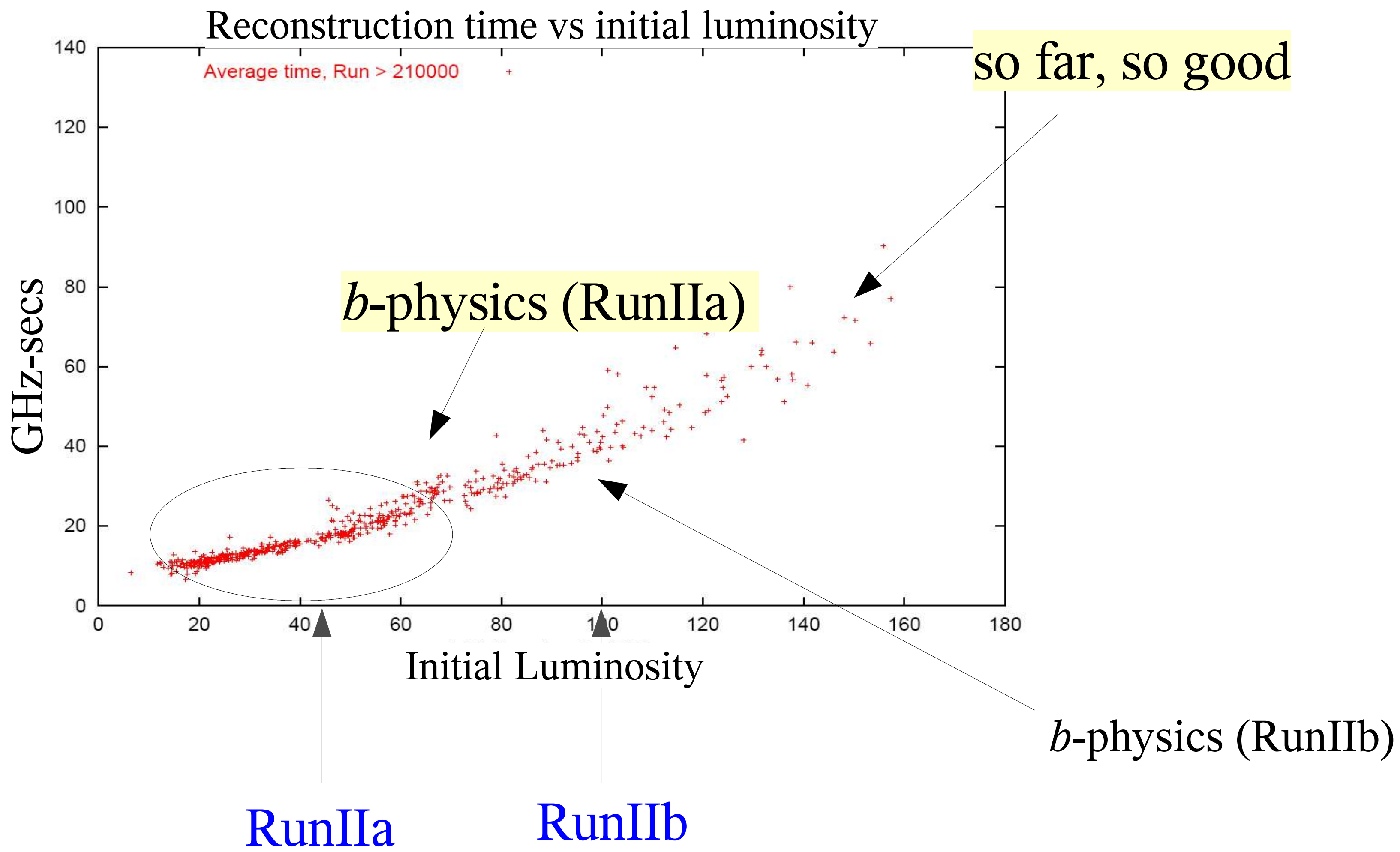
Challenges ahead: Increasing instantaneous luminosity

Peak Luminosities RunII



Challenges ahead: Increasing instantaneous luminosity

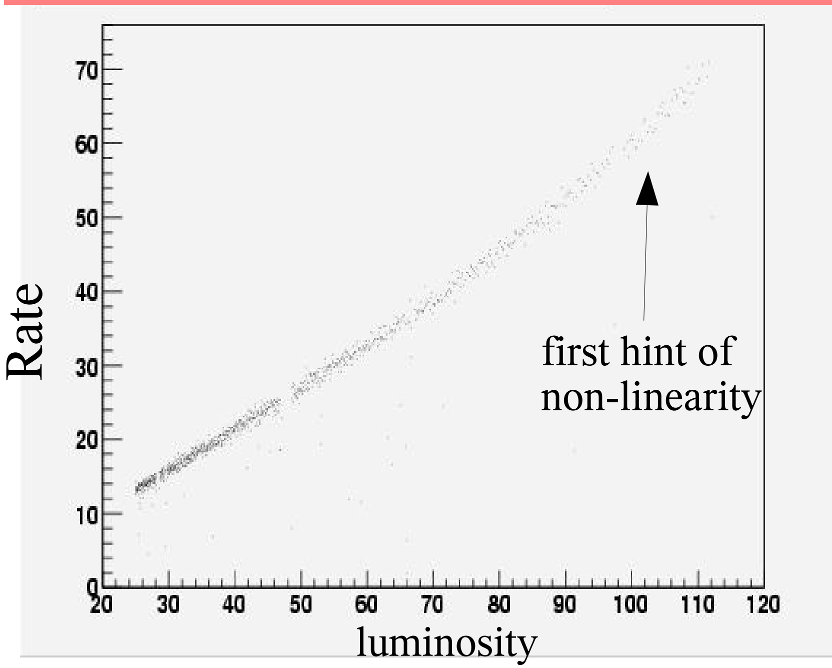
- Reconstruction of the events dominated by track finding.
- The same tracking algorithm has to run at all luminosities !



unbiased single muon triggers prescaled

Triggers – timing is (almost) everything

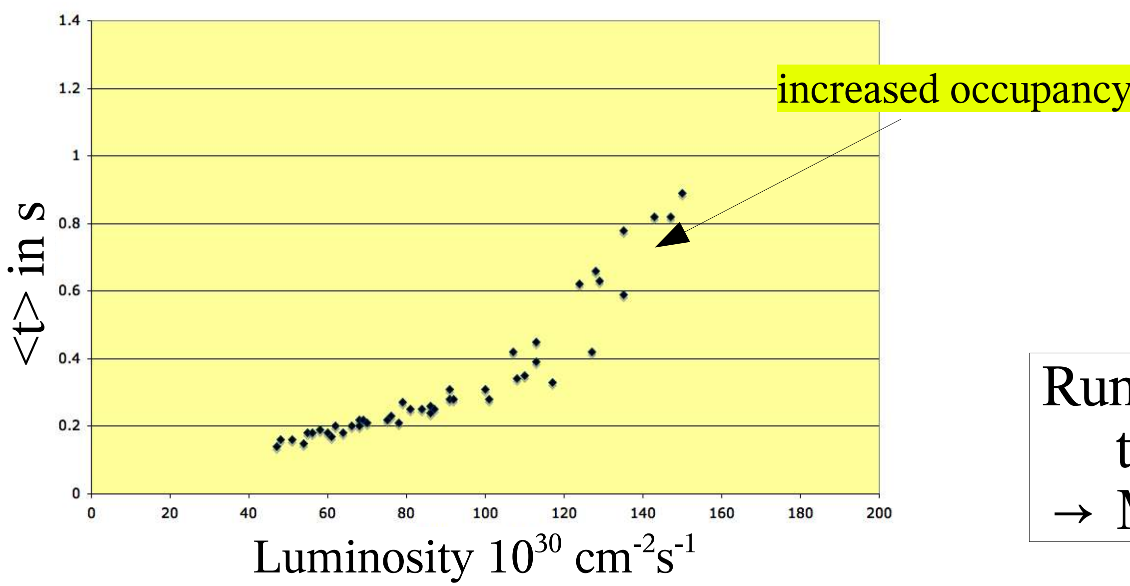
L1 track matched muon



b-physics triggers often require low p_T tracks → triggers are intrinsically slow:

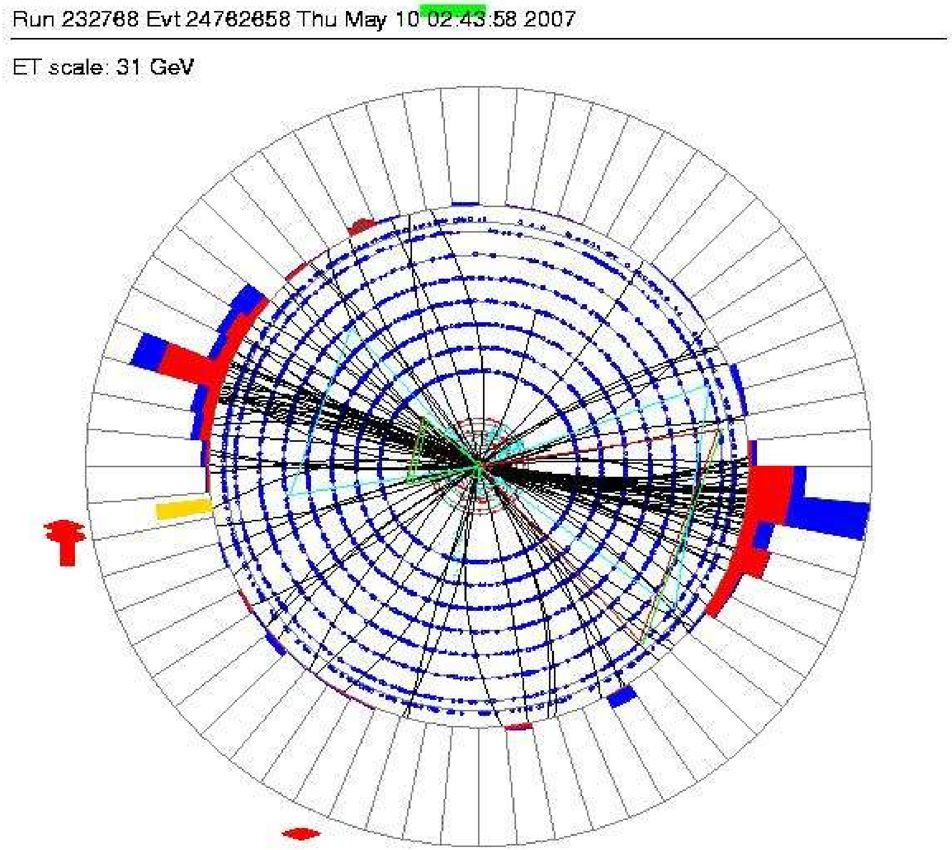
- optimize trigger ordering
- move rate reduction from L3 to L1/L2 (e.g. STT)

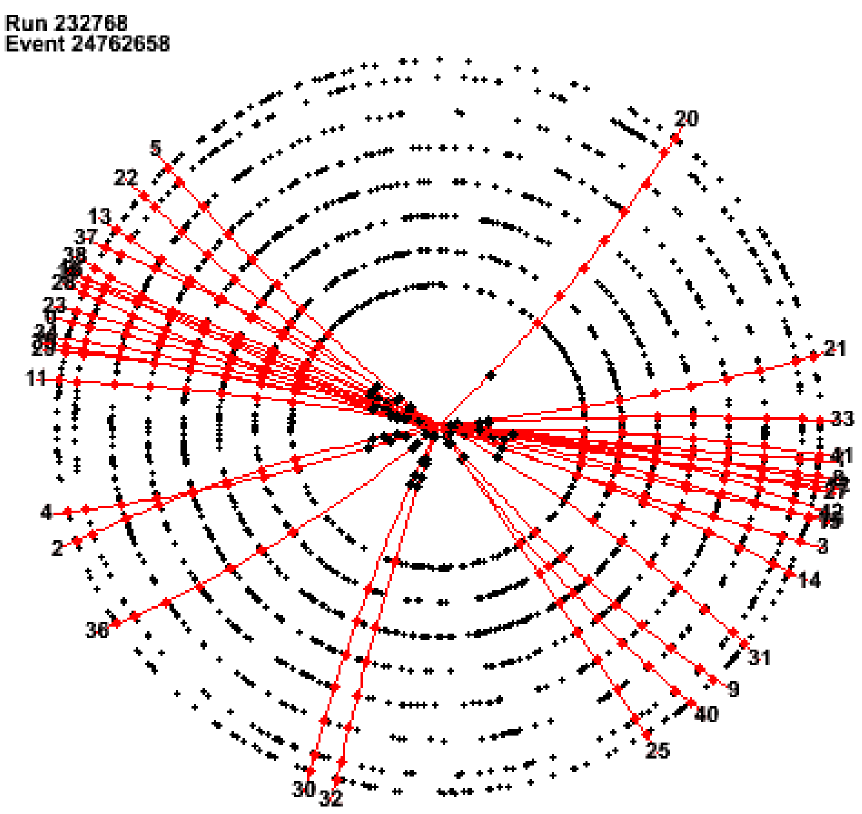
L3 Track CPU consumption vs lumi



RunIIb tracker 3 x faster than RunIIa tracking, but still not fast enough:
→ More CPUs.

Remember the event display from the beginning of the talk ?





Level 3

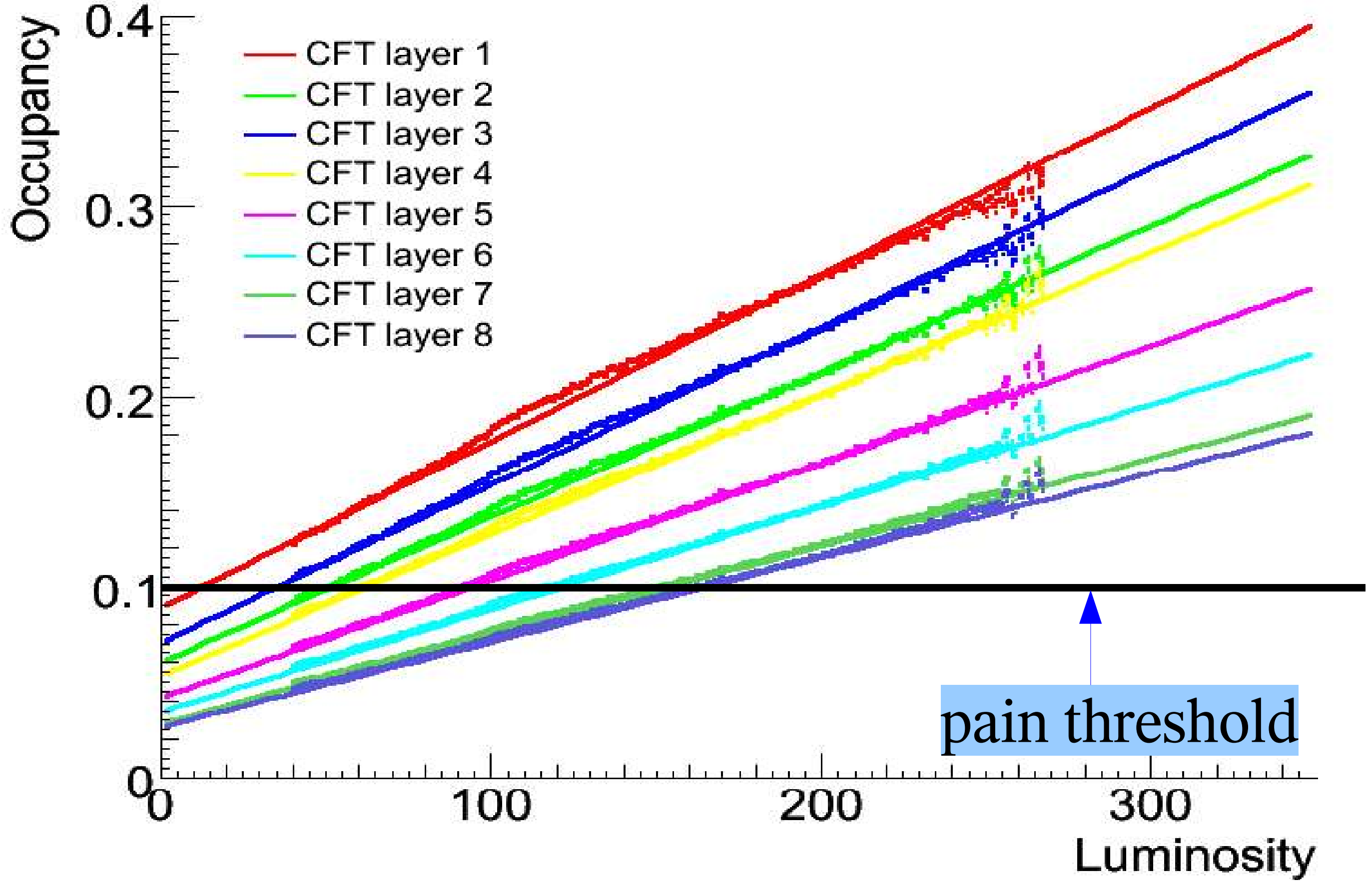
Offline reconstruction

We can't do everything.

seconds

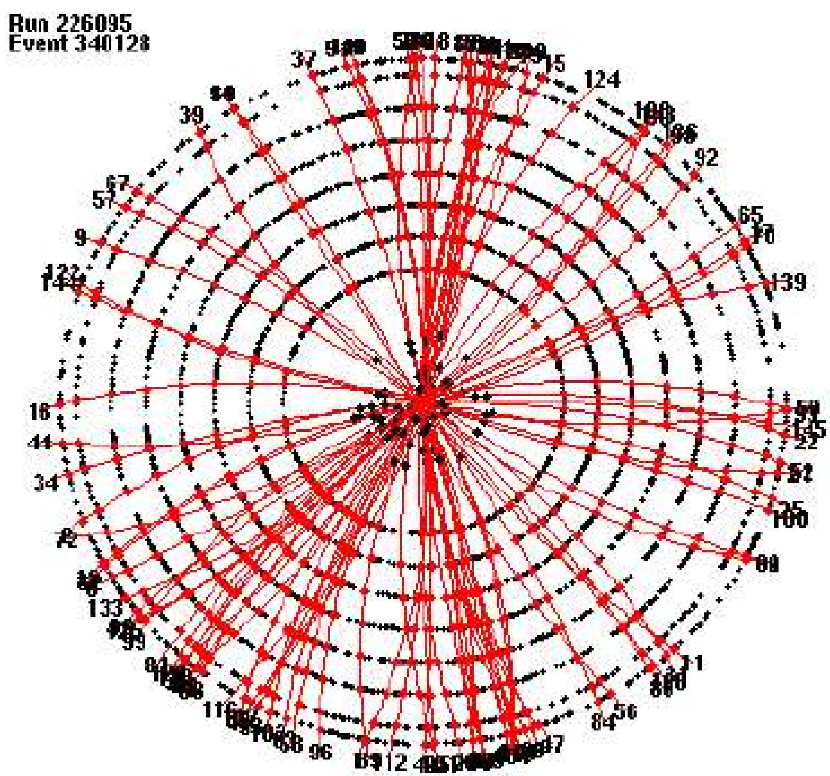
milliseconds

High occupancy will kill your trigger.

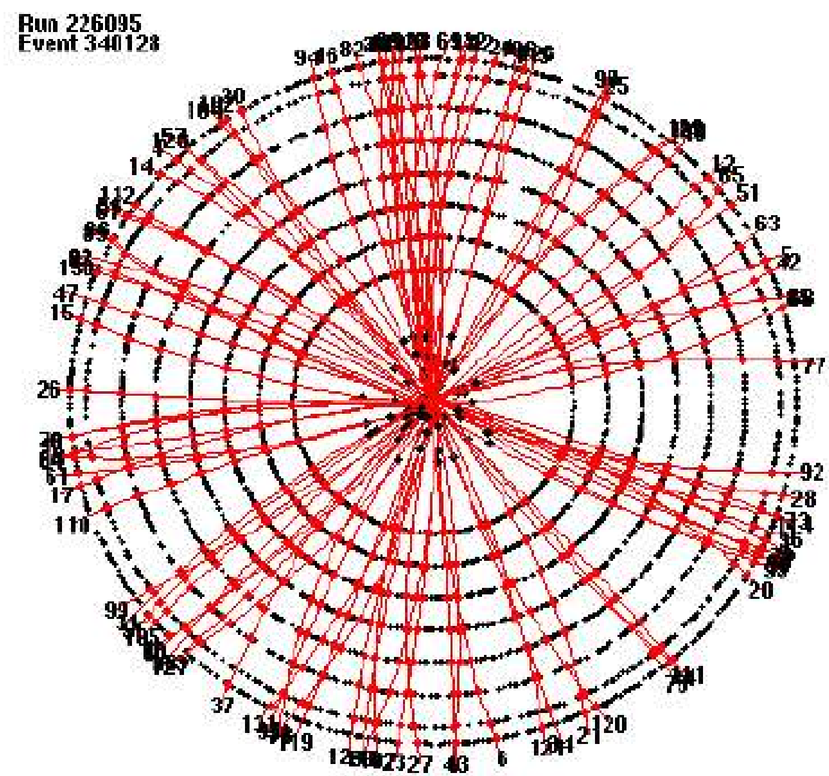


Coincidence makes great tracks.

original



random*

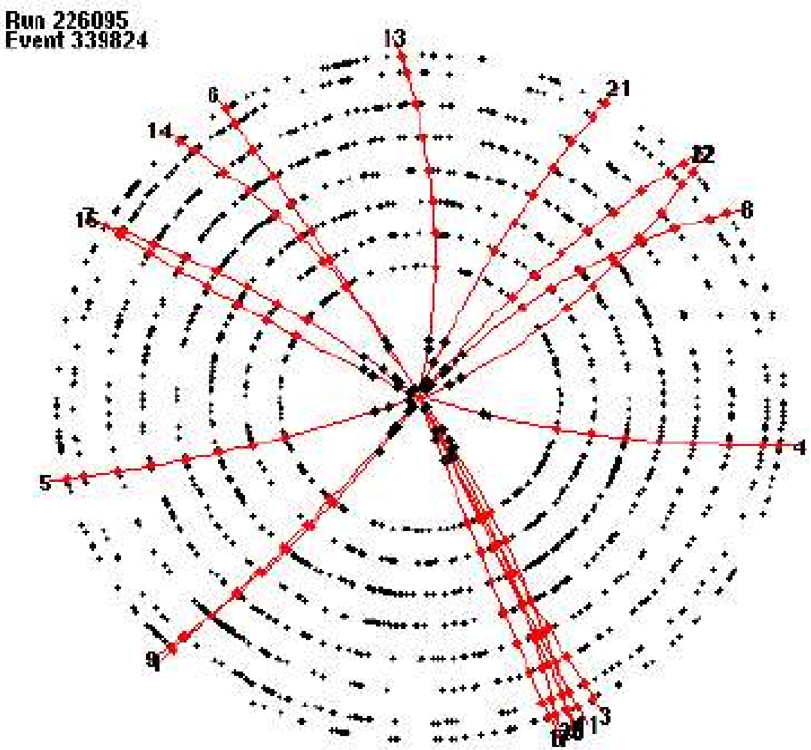


* same number of clusters per CFT layer
as before, randomly distributed

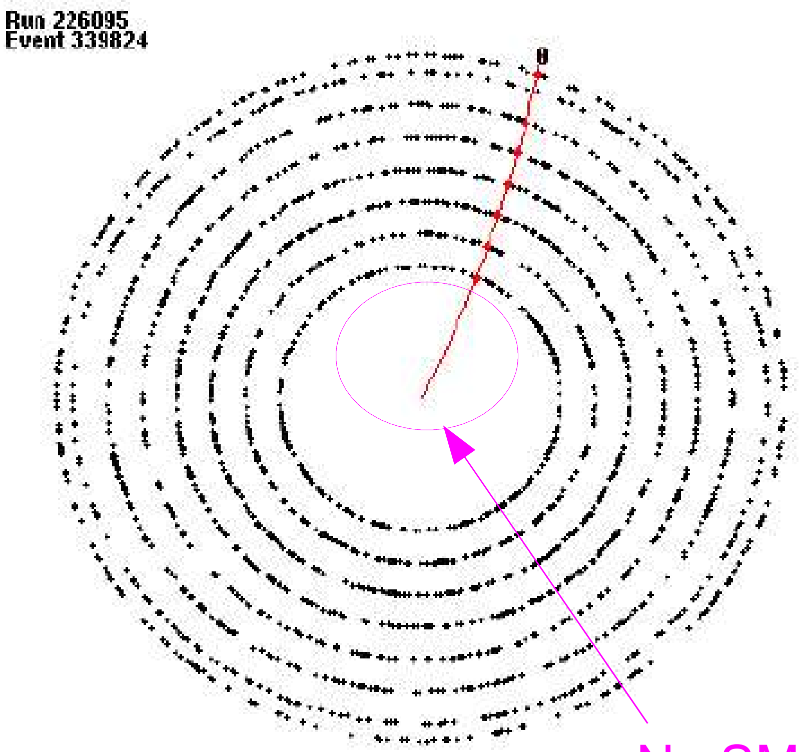
Special thanks to R. Beuselinck for making these plots.

What do we do now ?

original



random



- More layers: Singlet equations at L1, SMT requirement at L3
- Less noise (new AFE boards)
- Luminosity levelling ?
- So far everything is under control .....

The RunIIa *b*-physics programme has been a great success !

By playing to our strengths, i.e. making optimal use of our wide muon coverage and upgraded tracking system, DØ

- published 15 *b*-physics papers (4 more are submitted, plus 13 preliminary results)
- Results are also available on the web: http://www-d0.fnal.gov/Run2Physics/WWW/results/b.htm

- Increasing luminosity is a challenge and an opportunity.
- Layer 0 working as expected.
- High expectations for RunIIb.

CKM Matrix

Quarks: Weak Eigenstates ≠ Mass Eigenstates

$\Rightarrow$ CKM Mixing Matrix

- 3 angles
- 1 complex phase $\Rightarrow$ CP-violation

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

weak — mass

Wolfenstein parametrization:
$\lambda = |V_{us}|$

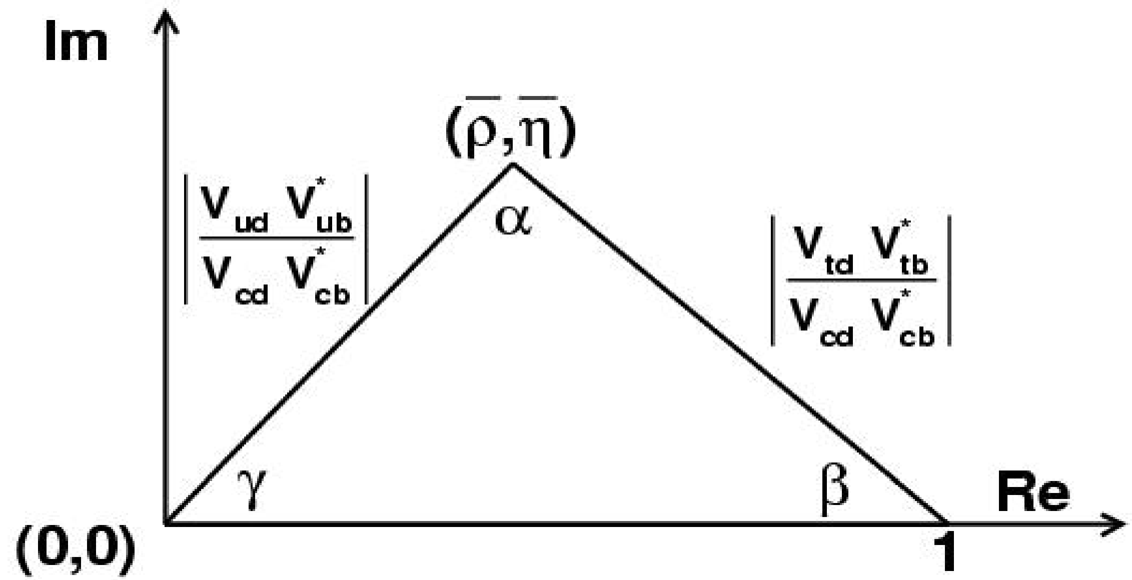
$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

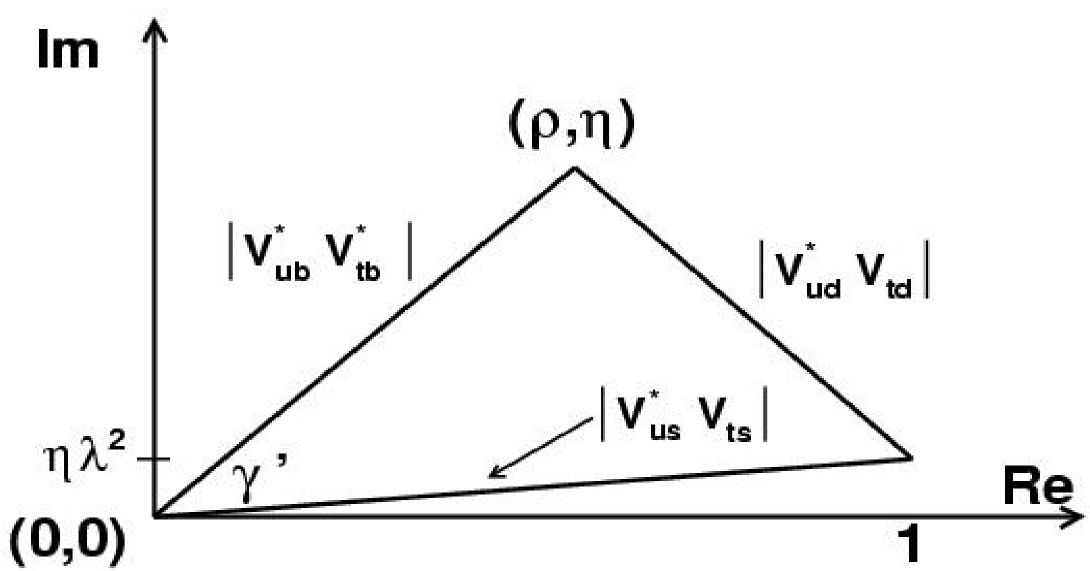
CP violation

(higher orders)

CKM triangle(s)

$\bar{\rho} = (1-\lambda^2/2)\rho$
$\bar{\eta} = (1-\lambda^2/2)\eta$
Wolfenstein parametrization:
$\lambda = |V_{us}|$
η: CP violation





Triangles identical up to λ^3

$\Delta m_s \rightarrow |V_{ts}/V_{td}|$

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \frac{f_{Bs}^2 B_{Bs}}{f_{Bd}^2 B_{Bd}} \frac{|V_{ts}|^2}{|V_{td}|^2} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

Inputs:

- $m(B^0)/m(B_s) = 0.9830$ (PDG 2006)
- $\xi = 1.21^{+0.047}_{-0.035}$ (M. Okamoto, hep-lat/0510113)
- $\Delta m_d = 0.507 \pm 0.005$ (PDG 2006)