Flavour Physics

Starting a new era at LHC
Learned a few lessons from Tevatron ?

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Overview

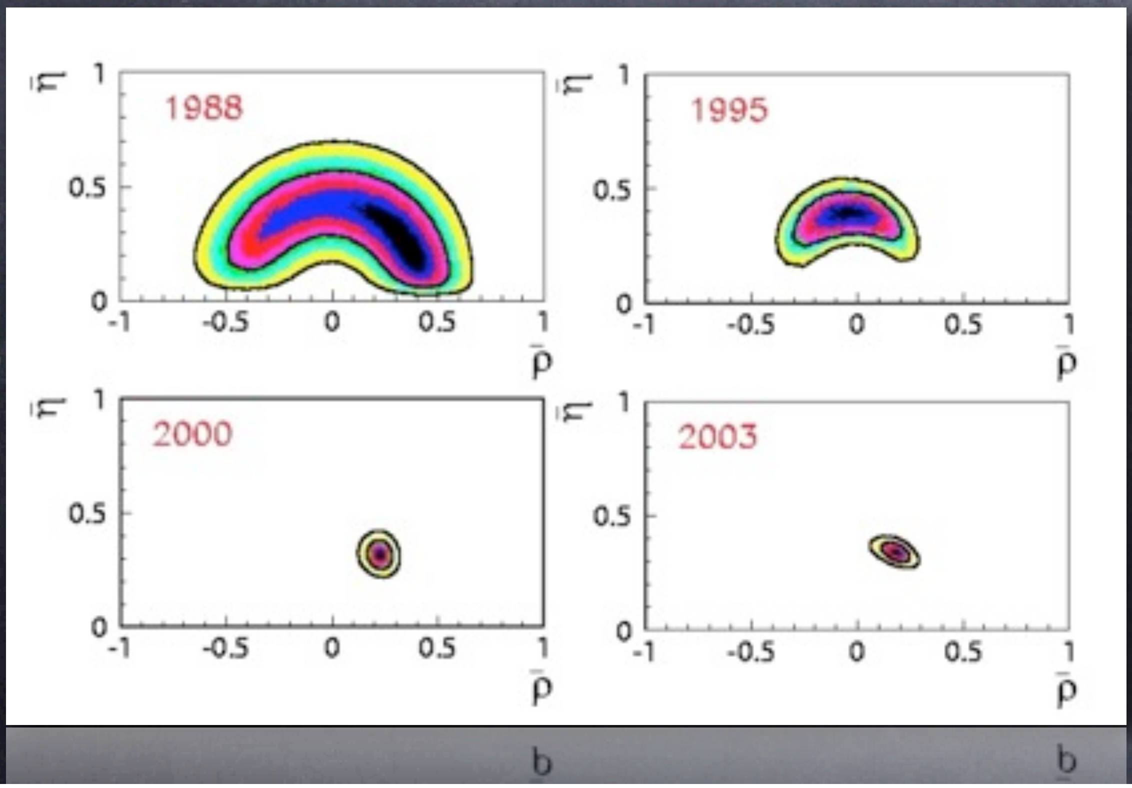
- The name of the game
- The players at CERN
- The other team at FNAL
  - B_s mixing at CDF - precision measurements at a hadron machine
  - Early physics
- Think Trigger !
- Will not cover B-factories
  - Extremely successful
  - Many significant contributions to Flavour Physics
  - Cannot access B_s system from $\Upsilon(4S)$ resonance
    (but remember Belle 'engineering run')

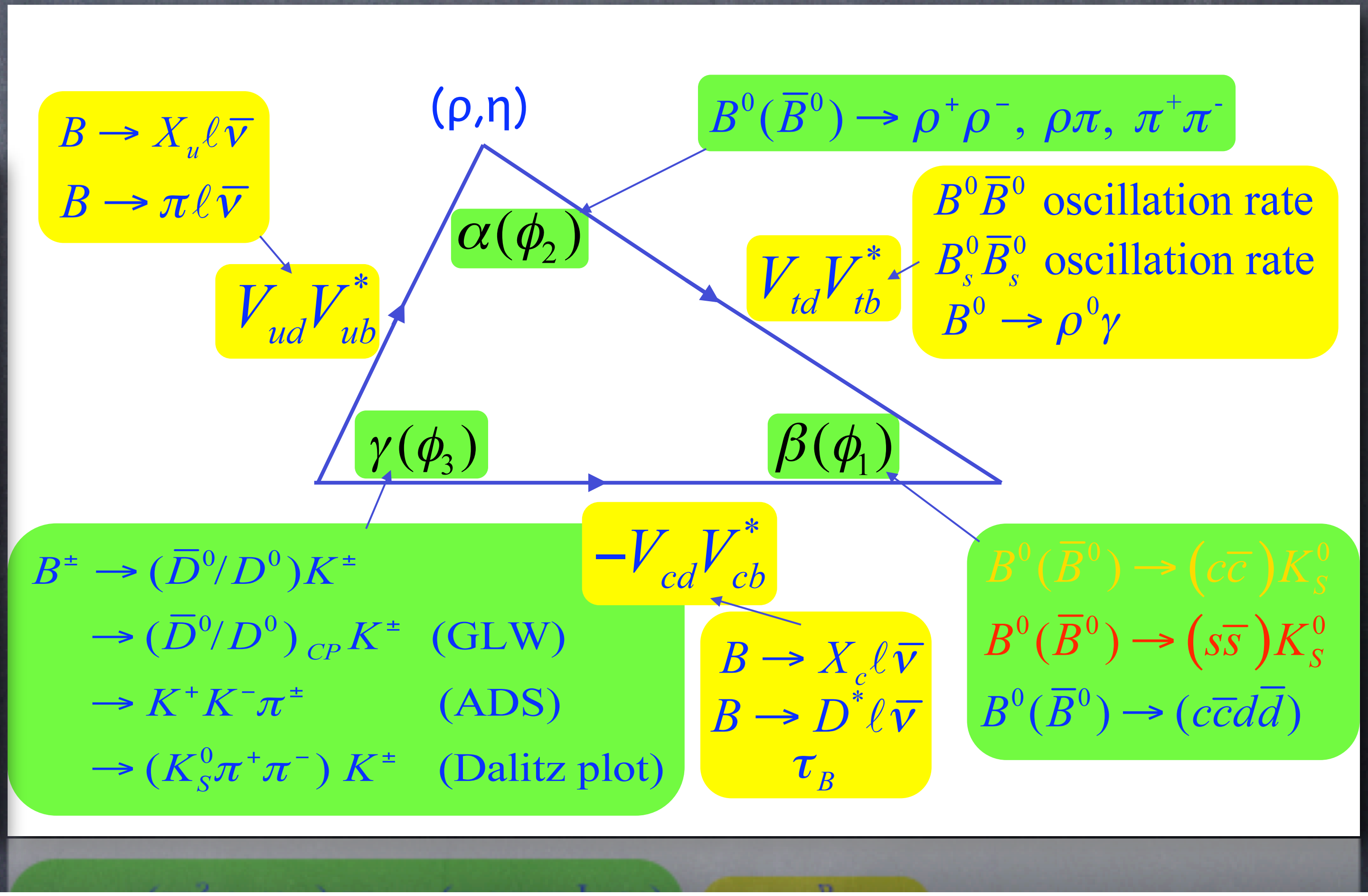
Flavour Physics

Weak Eigenstates are non-trivial superposition of flavour Eigenstates
→ CKM matrix

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

- Phases in some of the V_{xy}
  - ➥ CP violation: matter treated differently from anti-matter
- Popular parametrisation: Wolfenstein → ρ,η, λ, A
  - triangle in complex ρ,η plane
- Precision tests of CP violation:
  - Over-constrain triangle
  - Ongoing effort !





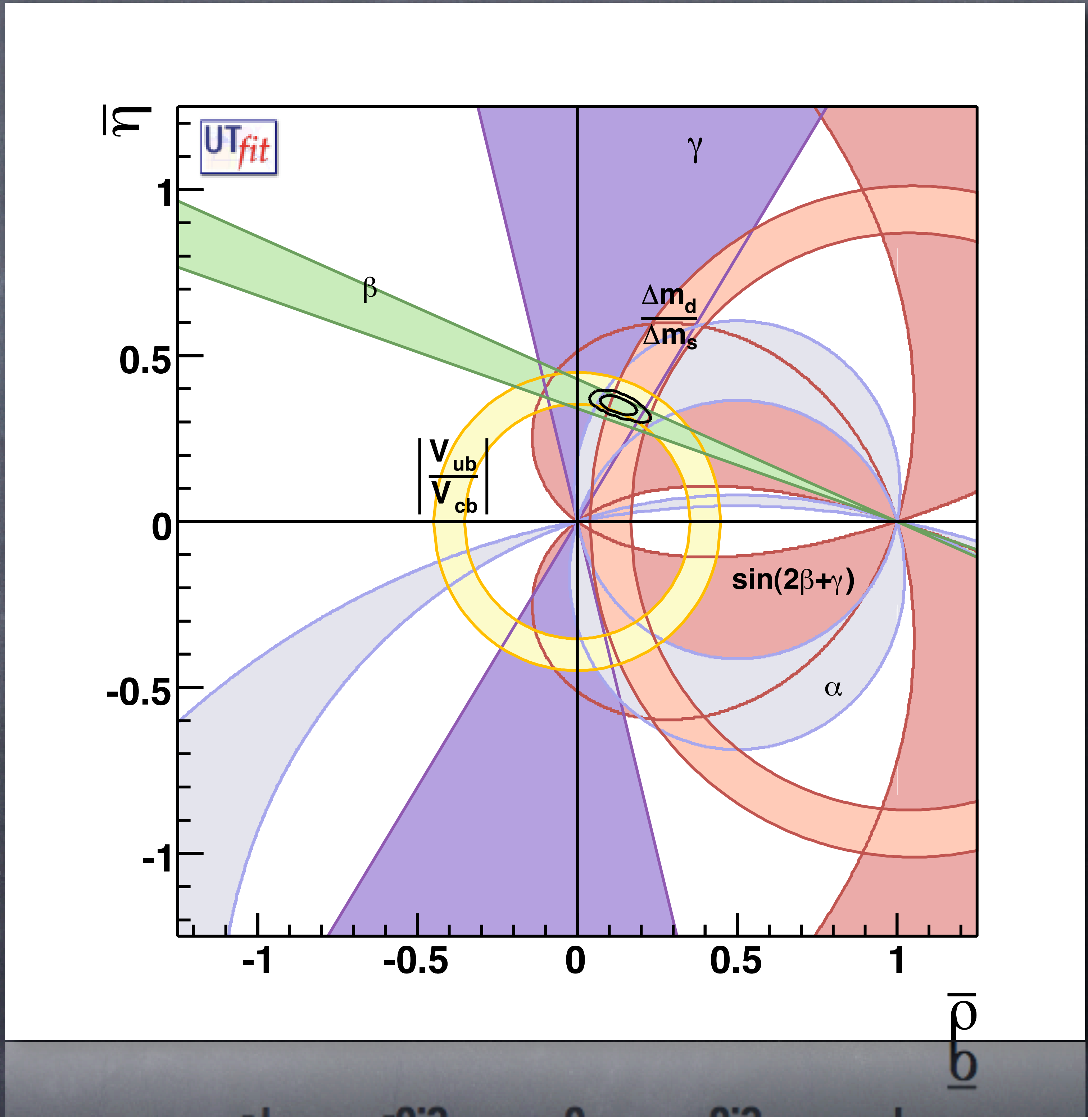
C. Matteuzzi, Moriond 2009

Flavour Physics

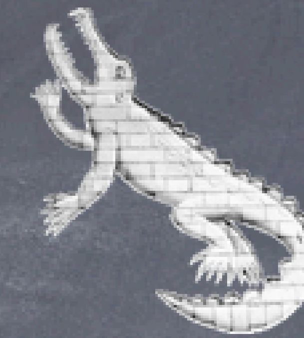
- Current averages / summary from the UTFit collaboration

ρ = 0.1454 ± 0.022
η = 0.342 ± 0.014
α = 92.0 ± 3.2 °
β = 22.0 ± 0.8 °
γ = 65.6 ± 3.3 °
....

(many more ... worth a summary talk on its own...)



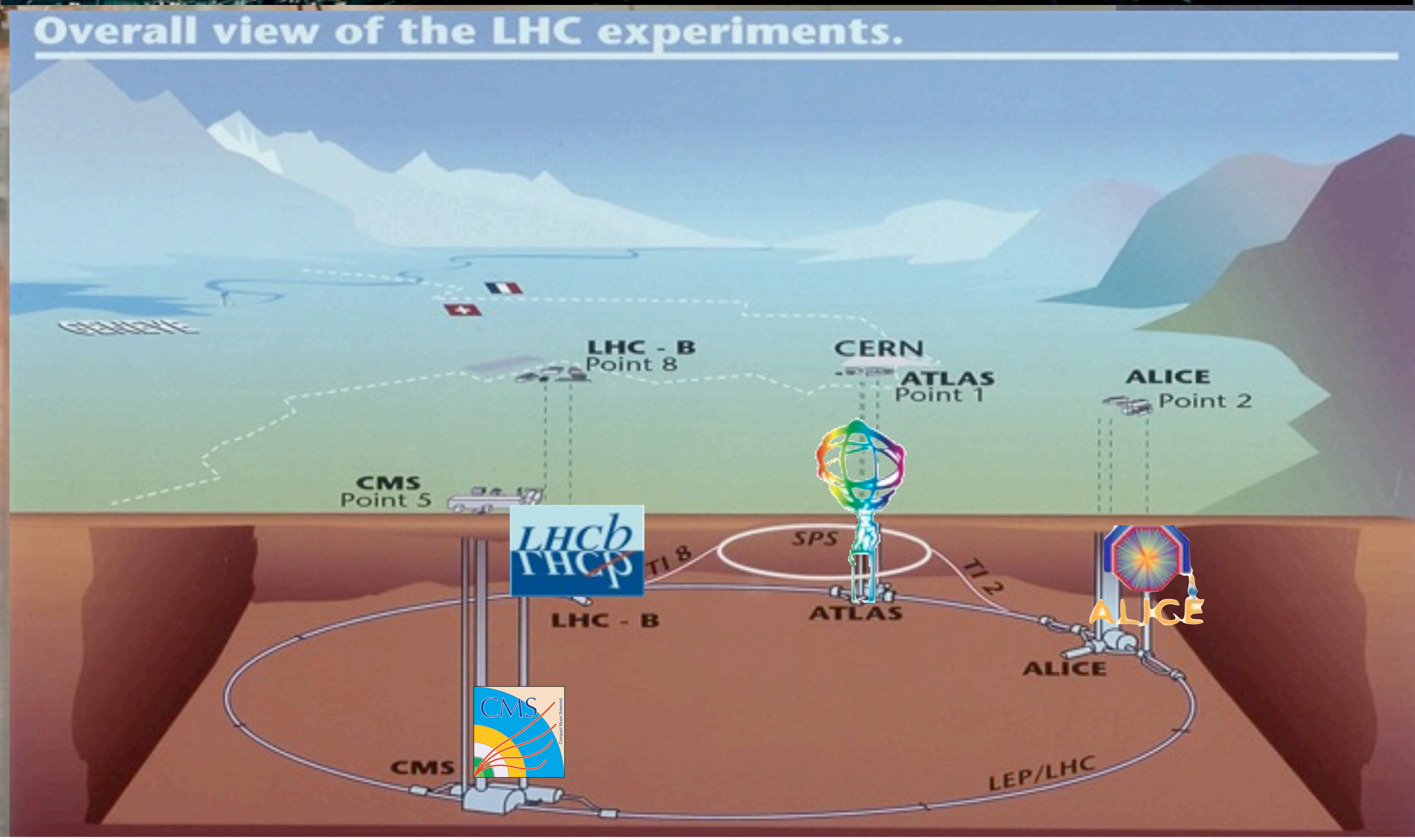
The Road ahead...



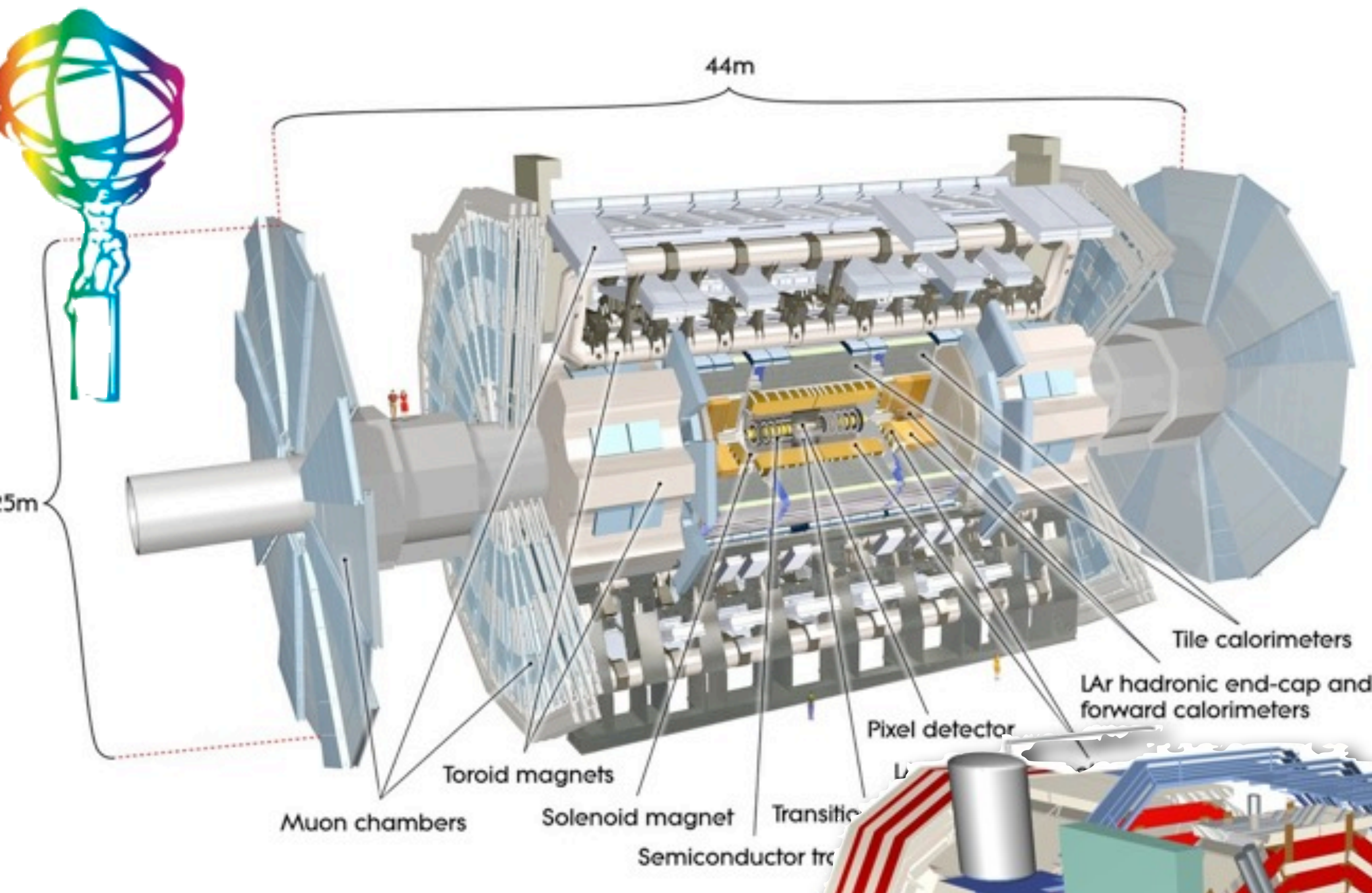
- All measurements fit into the Standard Model / CKM picture
  - Over-constrained tests OK to theoretical uncertainties
  - CKM phase consistent with source of CP violation
  ➥ need further sources to explain cosmic abundance of matter
- Searching for New Physics
  - Direct searches: Expect NP at TeV scale
  - Indirect searches
    - Complement direct searches
    - Measure properties, flavour structure of NP
    - E.g.
      - Enhancing rare decay branching ratios
      - Precision measurements - theoretical expectations

LHC at CERN

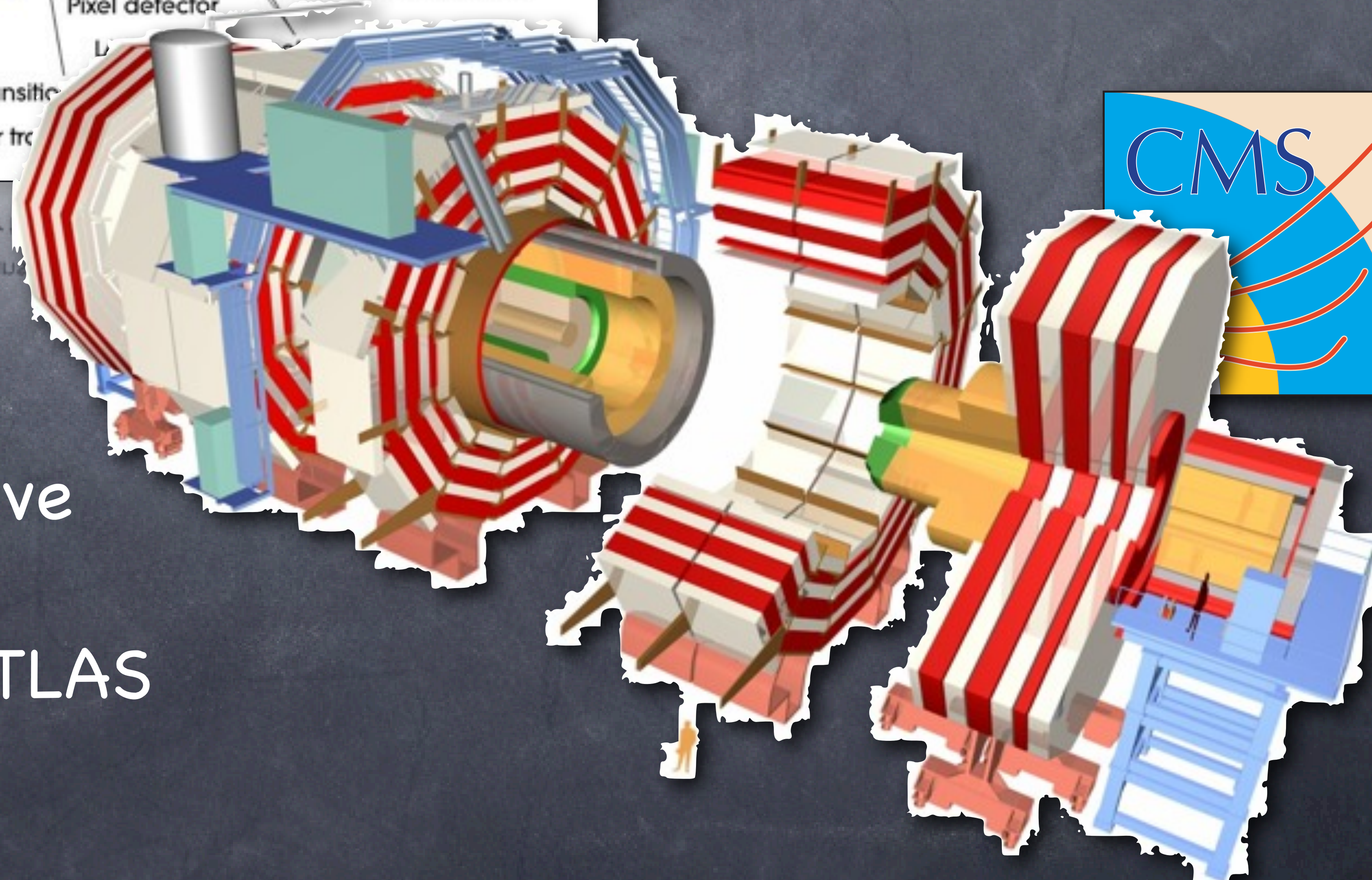

LHCb
CMS
ALICE


Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
LHCb
TI 8
SPS
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

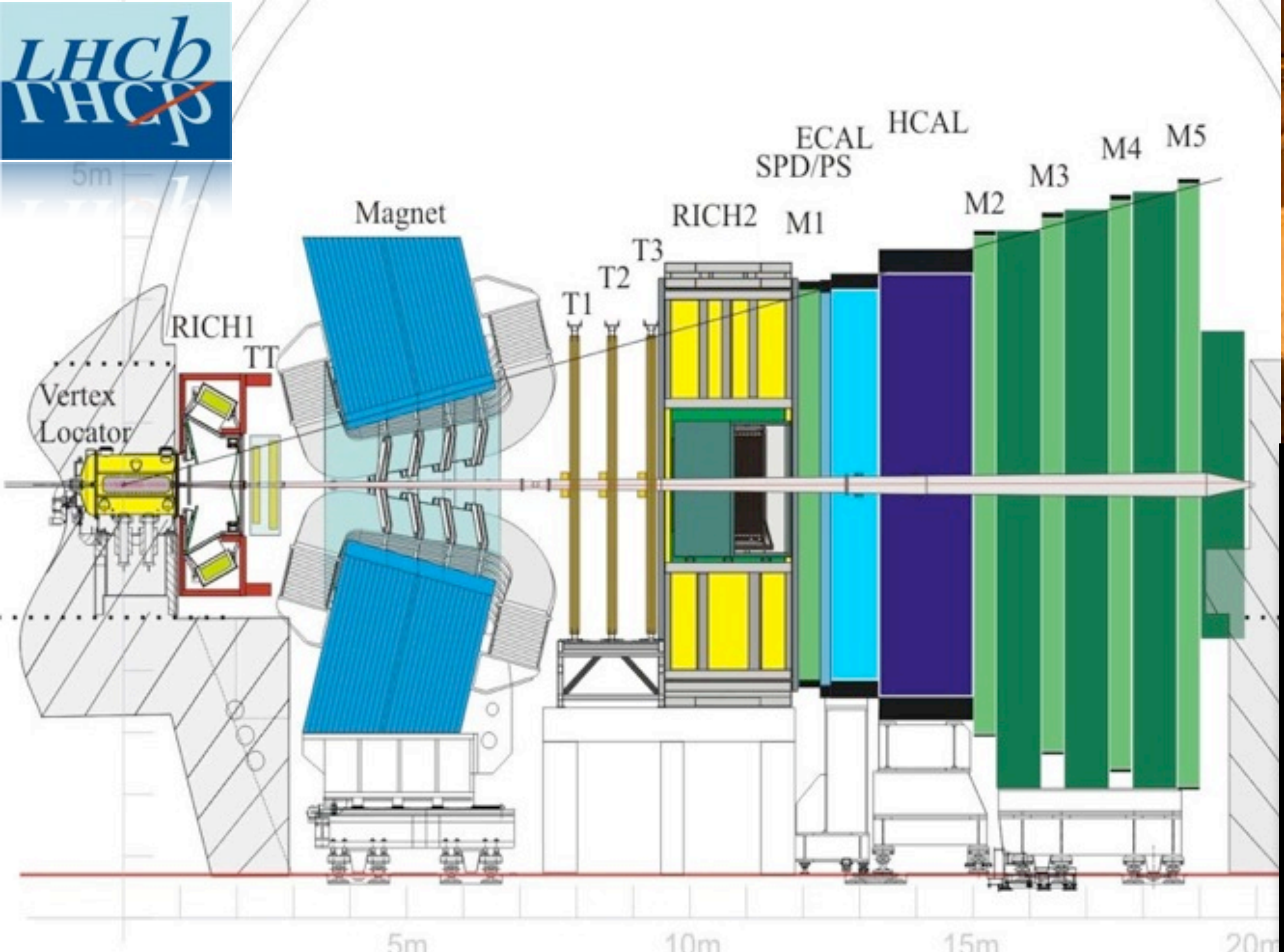
ATLAS & CMS

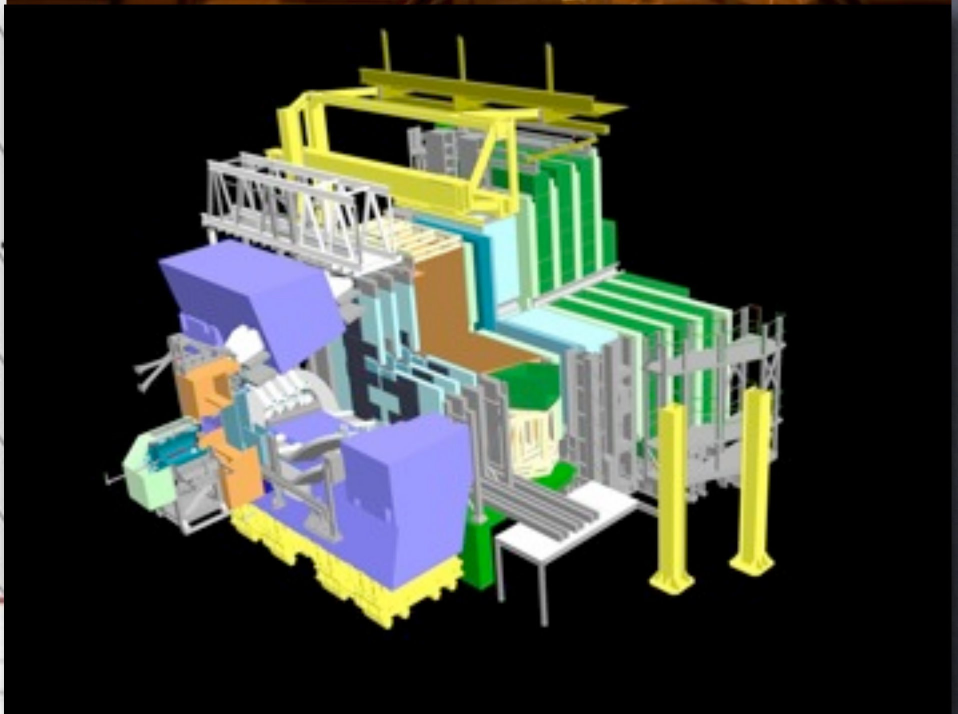


- General purpose detector
- “Hermetic” design
➥ missing energy



- Mainly Higgs, direct searches, QCD, ...
- Both ATLAS & CMS have flavour programme
➥more extensive at ATLAS

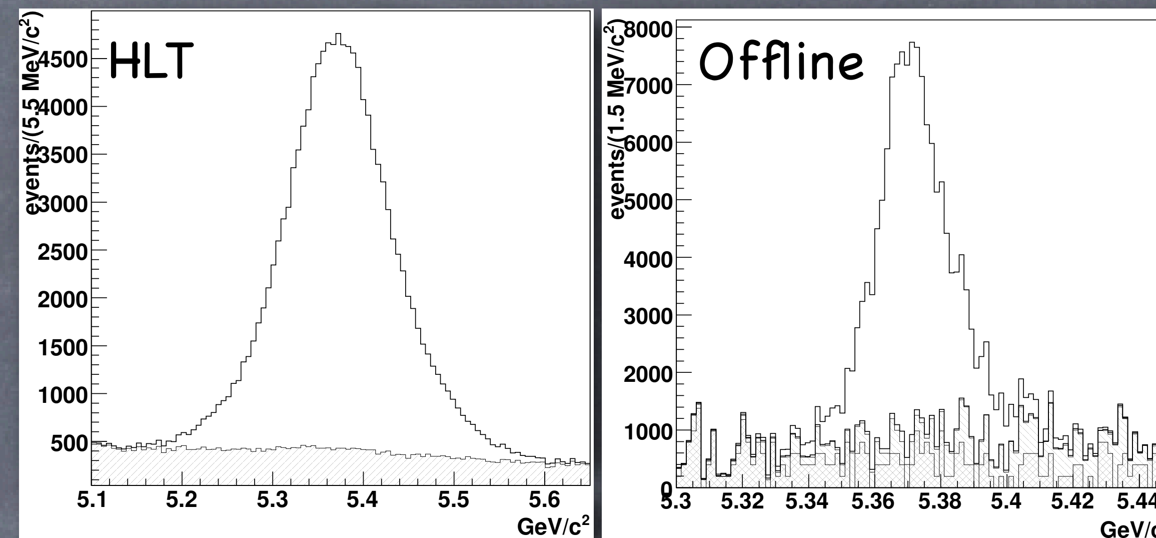




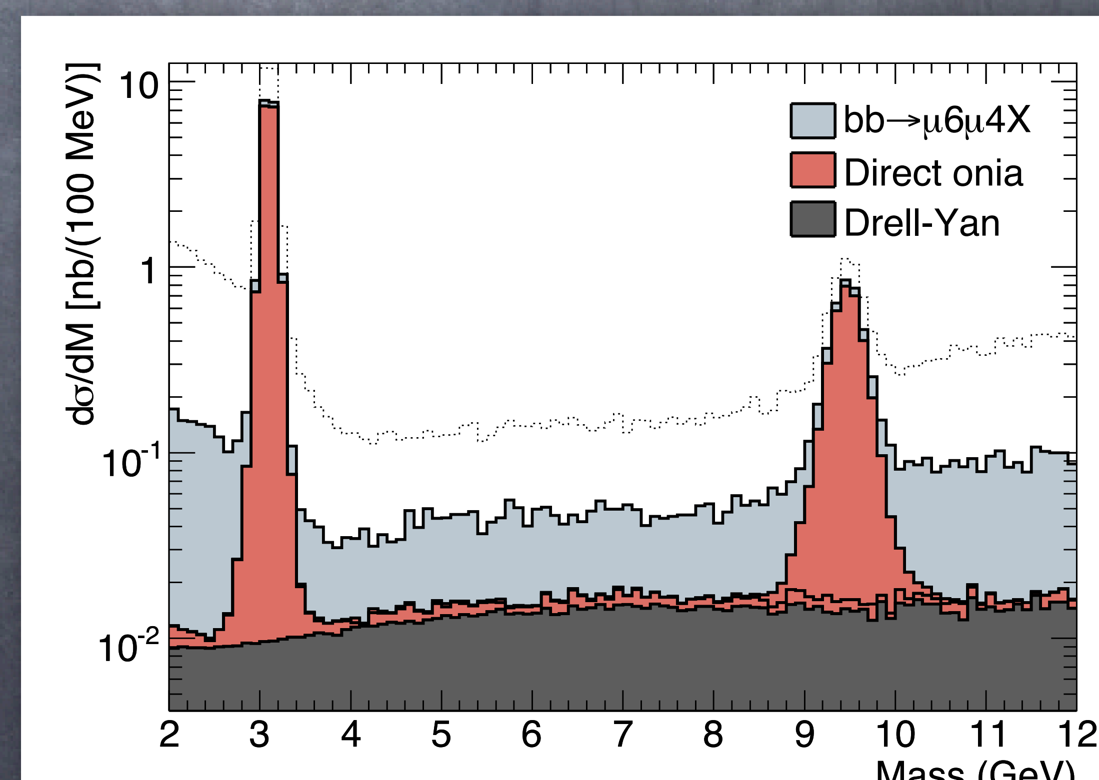
- Detector optimised towards Flavour Physics
  ➥ both b quarks produced in forward direction
- Only look in a cone - no measurements with missing energy
- High-precision vertex detector (inside beam-pipe) and RICH detectors for particle ID

CMS / ATLAS

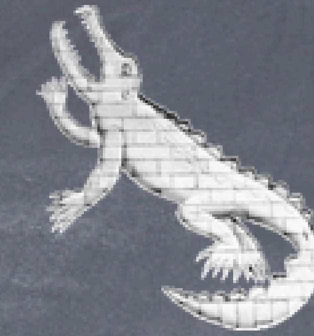
- **CMS:**
  - Flavour physics not in centre of physics effort
    ➥ b tagging mainly part of Higgs
  - $B_s \to J/\psi\ \phi$
    (resolution: 51 MeV for J/ψ, 65 MeV for B)
  - $\sigma(J/\psi \to \mu\mu)$ for "first physics"



- **ATLAS:**
  - Much more extensive flavour programme
  - B mass resolution ~40MeV
  - Centered on $b \to J/\psi\ X$
    - B_s oscillation, $\sin(2\beta)$, $\Delta\Gamma/\Gamma$ (including $B_s \to D_s\pi$, $D_s a_1$)
    - cross sections, e.g. $B^\pm \to J/\psi\ K^\pm$
    - Rare decays, e.g. $B_s \to \mu\mu$
    - Spin properties, e.g. $\Lambda_b \to J/\psi\Lambda$
    - Quarkonia, e.g. $\chi_b \to J/\psi\ J/\psi$
    - $\sigma(J/\psi, \Upsilon \to \mu\mu)$ for "first physics"



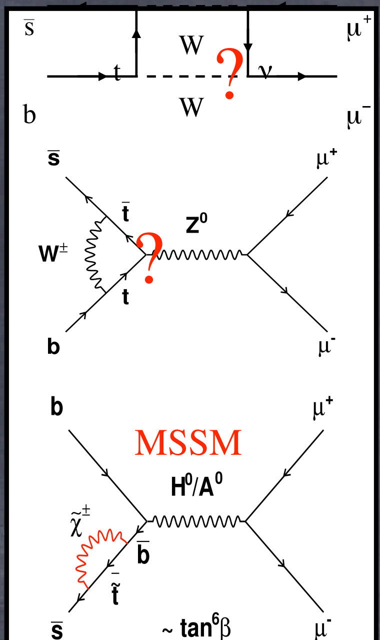
LHCb physics

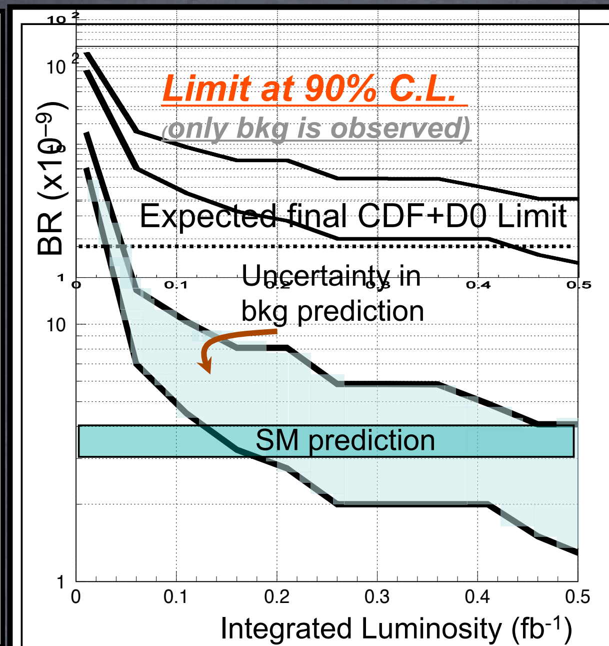


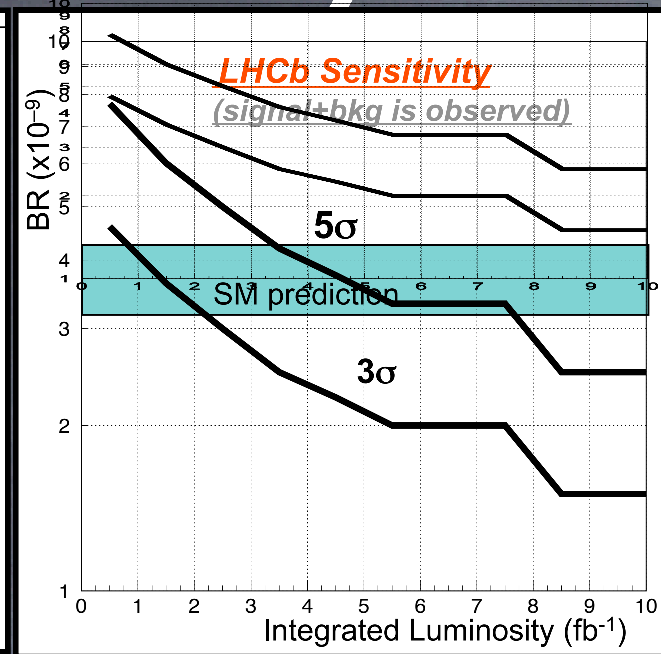
- Dedicated B physics experiment
- Covering all aspects of Charm and Bottom physics
  - Cross-section, rare decays, lifetimes, spectroscopy, ...
- Higher cross-section than FNAL, better detector, trigger
  ➥ more B (D) per fb^{-1}

Channel	1 fb^{-1} at LHCb = ... fb^{-1} at Tevatron	
$D^0 \to K\pi$	20	50M / 2fb^{-1} at LHCb 0.5M / 0.35fb^{-1} at CDF
$B \to hh$	30	200k / 2fb^{-1} at LHCb 6.5k / 1fb^{-1} at CDF
$B^+ \to J/\psi K^+$	60	1.7M / 2fb^{-1} at LHCb 3.4k / 0.25fb^{-1} at CDF
$B_s \to D_s \pi$	10	120k / 2fb^{-1} at LHCb 5.6k / 1fb^{-1} at CDF

LHCb - Key Analyses



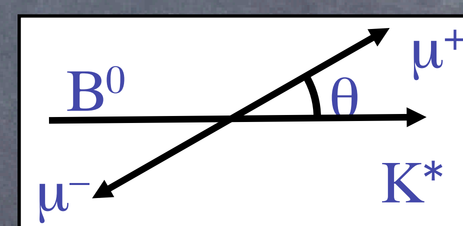




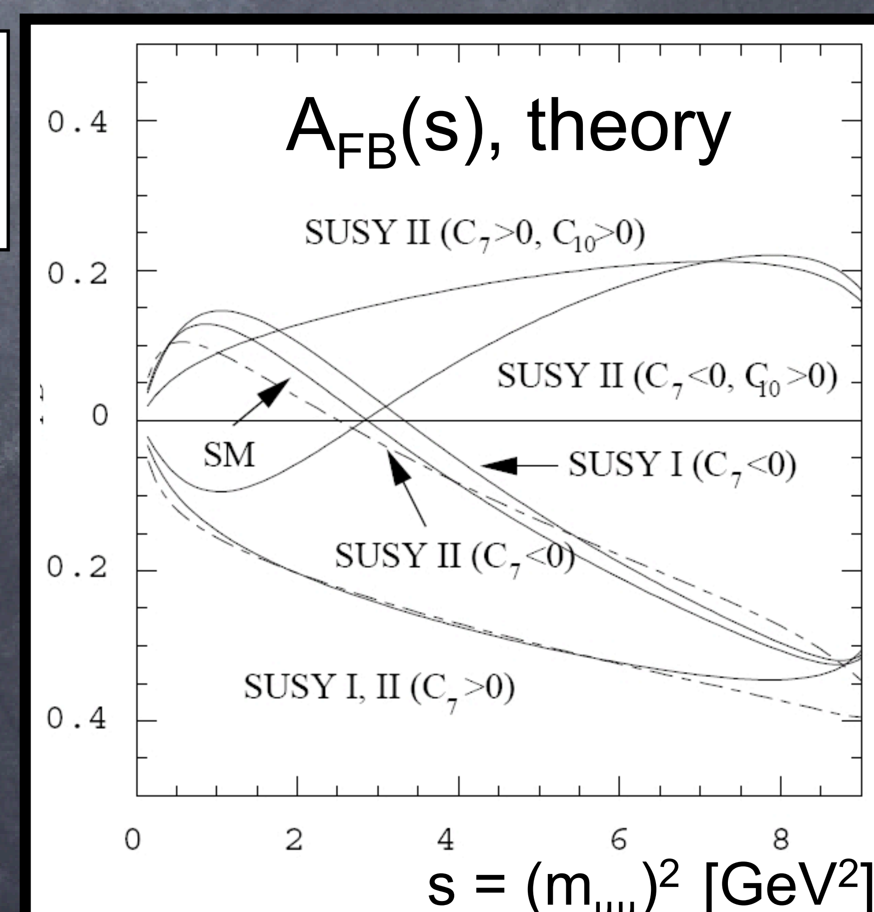
$B_s \to \mu\mu$

- Very rare decay
- Strongly enhanced in some SUSY models

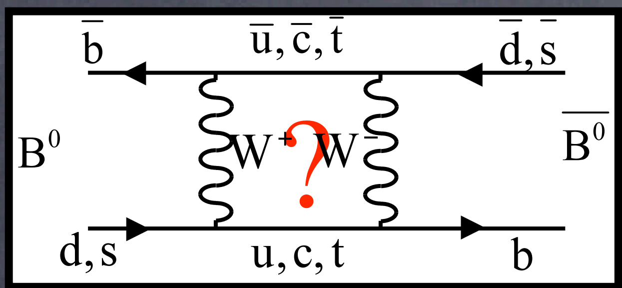
A_{FB} in $B^0 \to K^* \mu\mu$



- Suppressed loop decay
- $A_{FB}(s)$ in μμ rest-frame probe of NP
  - Shape of distribution
  - Zero crossing
- Determine ratio of Wilson coefficients C_7/C_9 with 13% stat. uncertainty



LHCb - Key Analyses

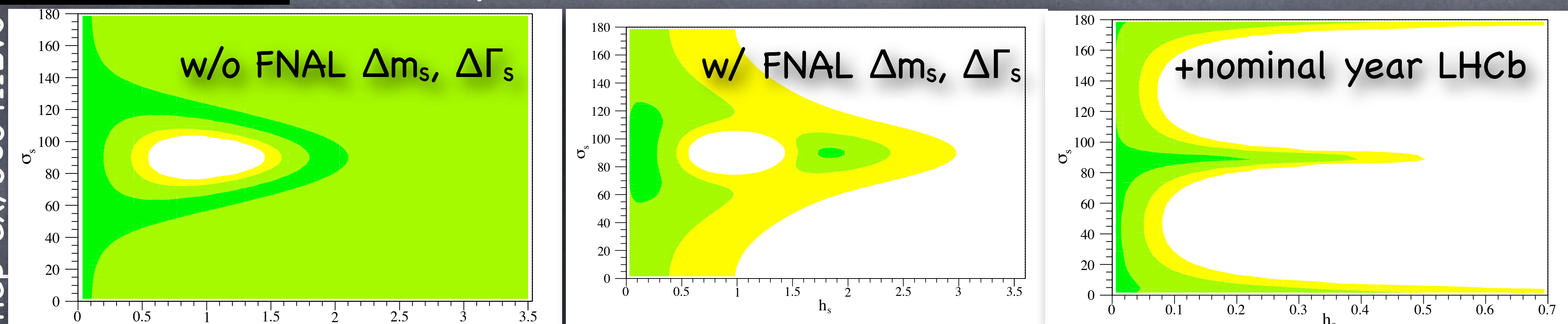


<u>Bs mixing phase ϕ_s</u> very small in SM

➥ potentially large contributions from NP

Analyses: $B_s \to J/\psi\phi$, $J/\psi\eta$, D_sD_s || $c\tau(B) \to \Delta\Gamma$ ...

hep-ex/0604112v3



<u>CKM angle γ</u>

<u>Tree Level:</u>

$B_s \to D_sK$

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

$B^\pm$, $B_d \to D^{(*)}K^{(*)}$, with D^0 decaying to:

2 bodies: πK, KK, ππ

3 bodies: KS ππ, KS KK, KS Kπ

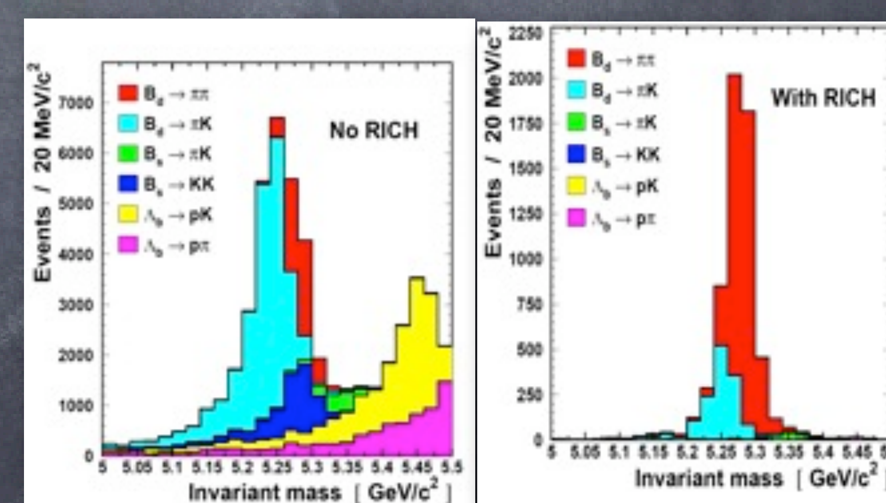
4 bodies: Kπππ, KKππ

<u>Penguin Level:</u>

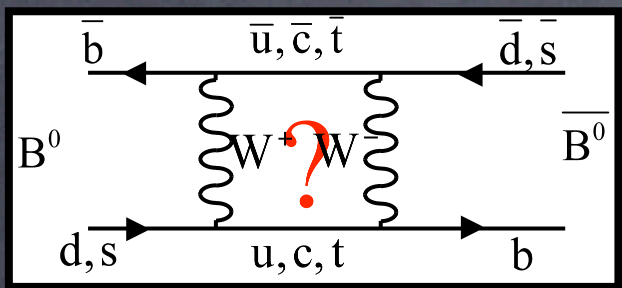
$B_s \to KK$, $B_d \to \pi\pi$

➥ PID paramount

U spin approach



LHCb - Key Analyses



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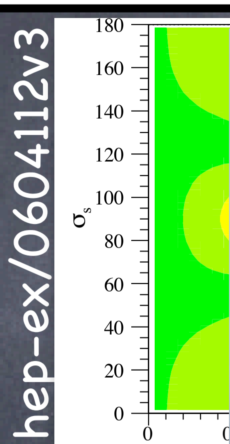

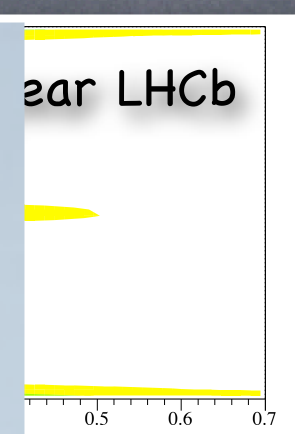

CKM ang

Tree Level:

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$B^{\pm}$, $B_d \to D^{(*)}K^{(*)}$, with D^0 decaying to:

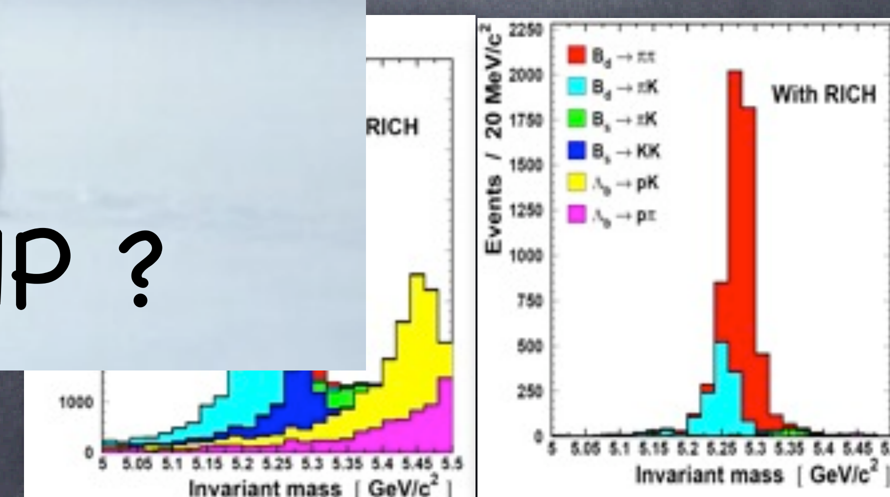
2 bodies: πK, KK, $\pi\pi$

3 bodies: $K_S\ \pi\pi$, $K_S\ KK$, $K_S\ K\pi$

4 bodies: $K\pi\pi\pi$, $KK\pi\pi$

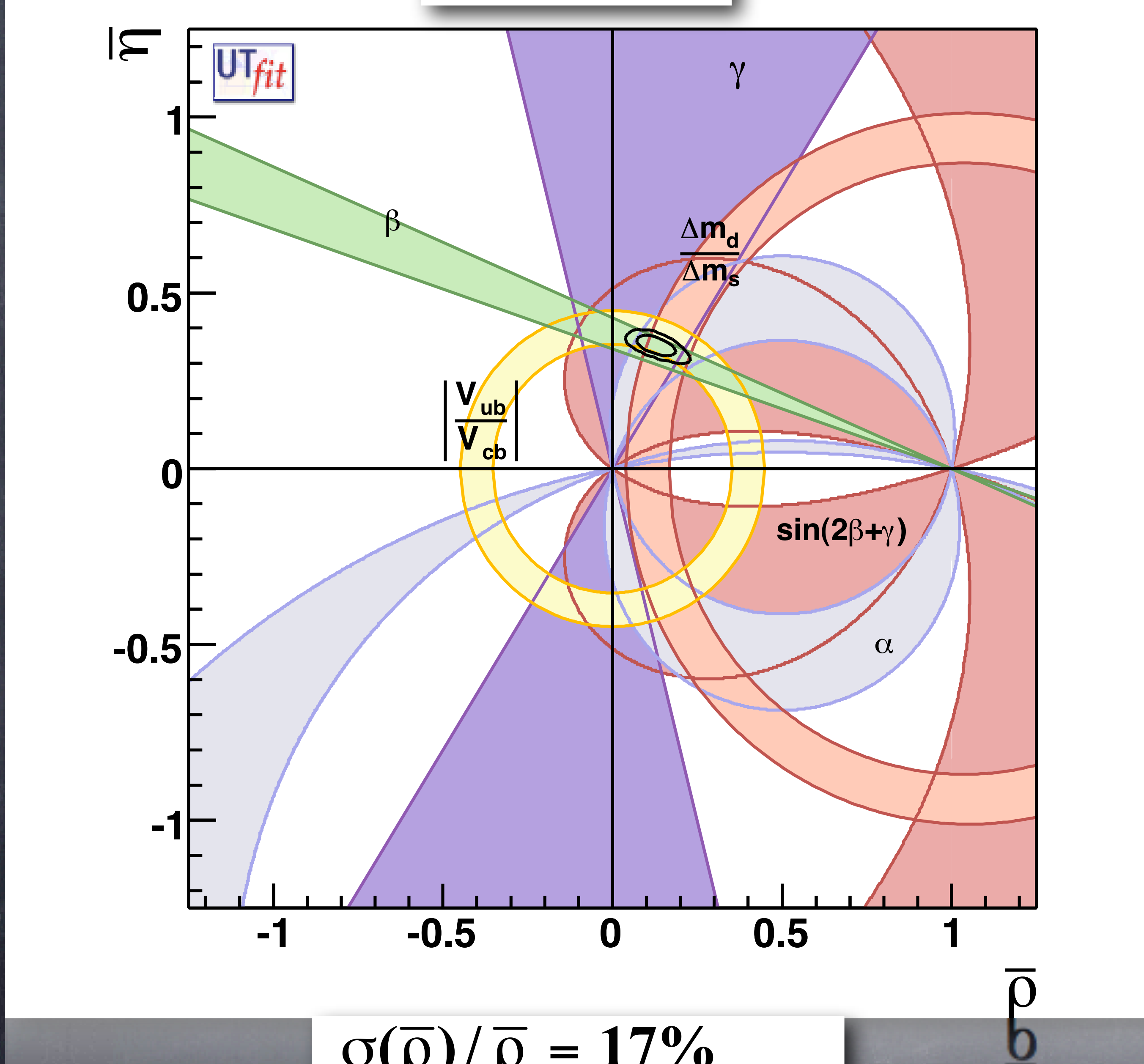
➥ PID paramount

U spin approach



5+ years later ?

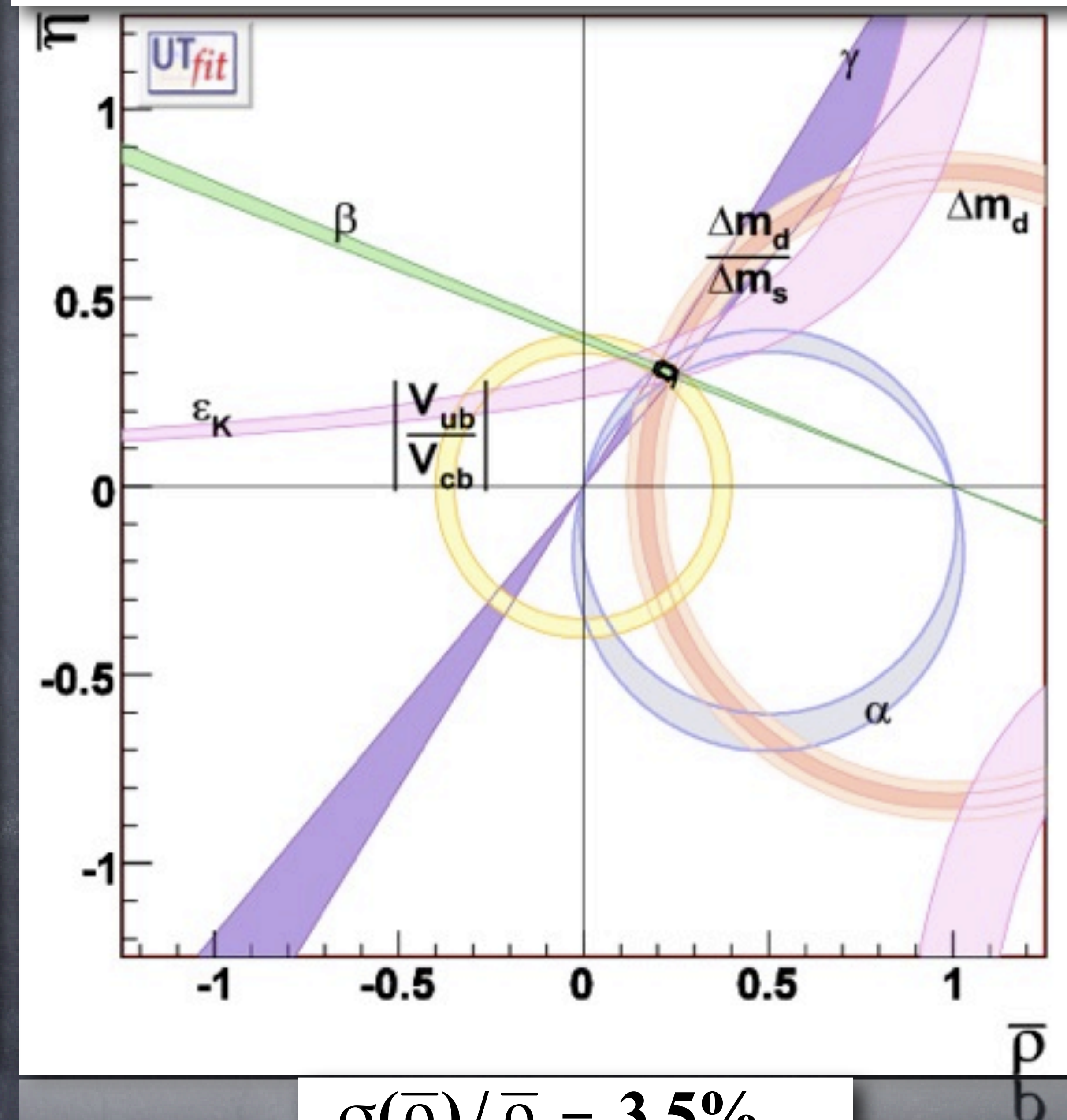
Now ...



$\sigma(\bar{\rho})/\bar{\rho}$ = **17%**

$\sigma(\bar{\eta})/\bar{\eta}$ = **4.7%**

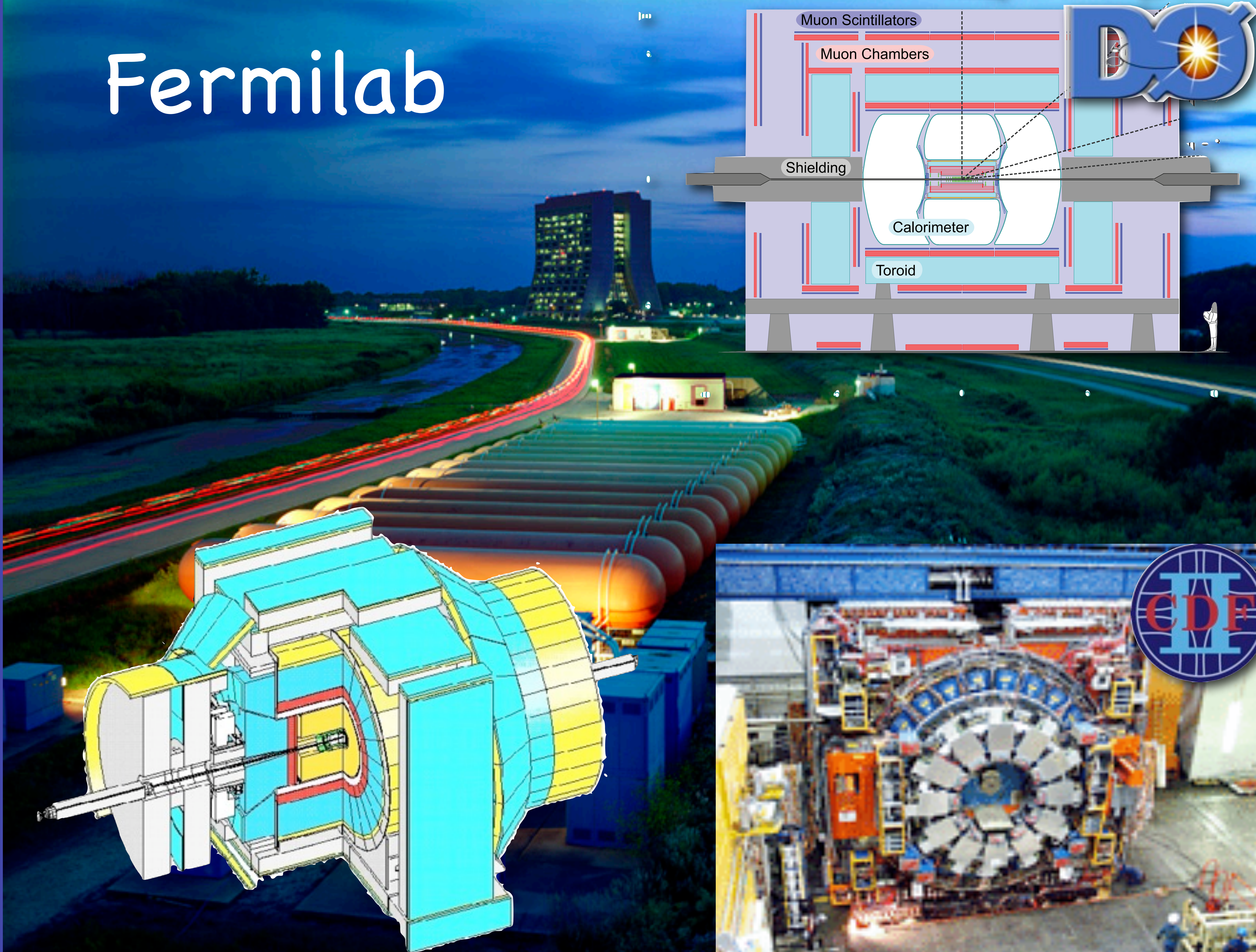
LHCb projection (10 fb^{-1})



$\sigma(\bar{\rho})/\bar{\rho}$ = **3.5%**

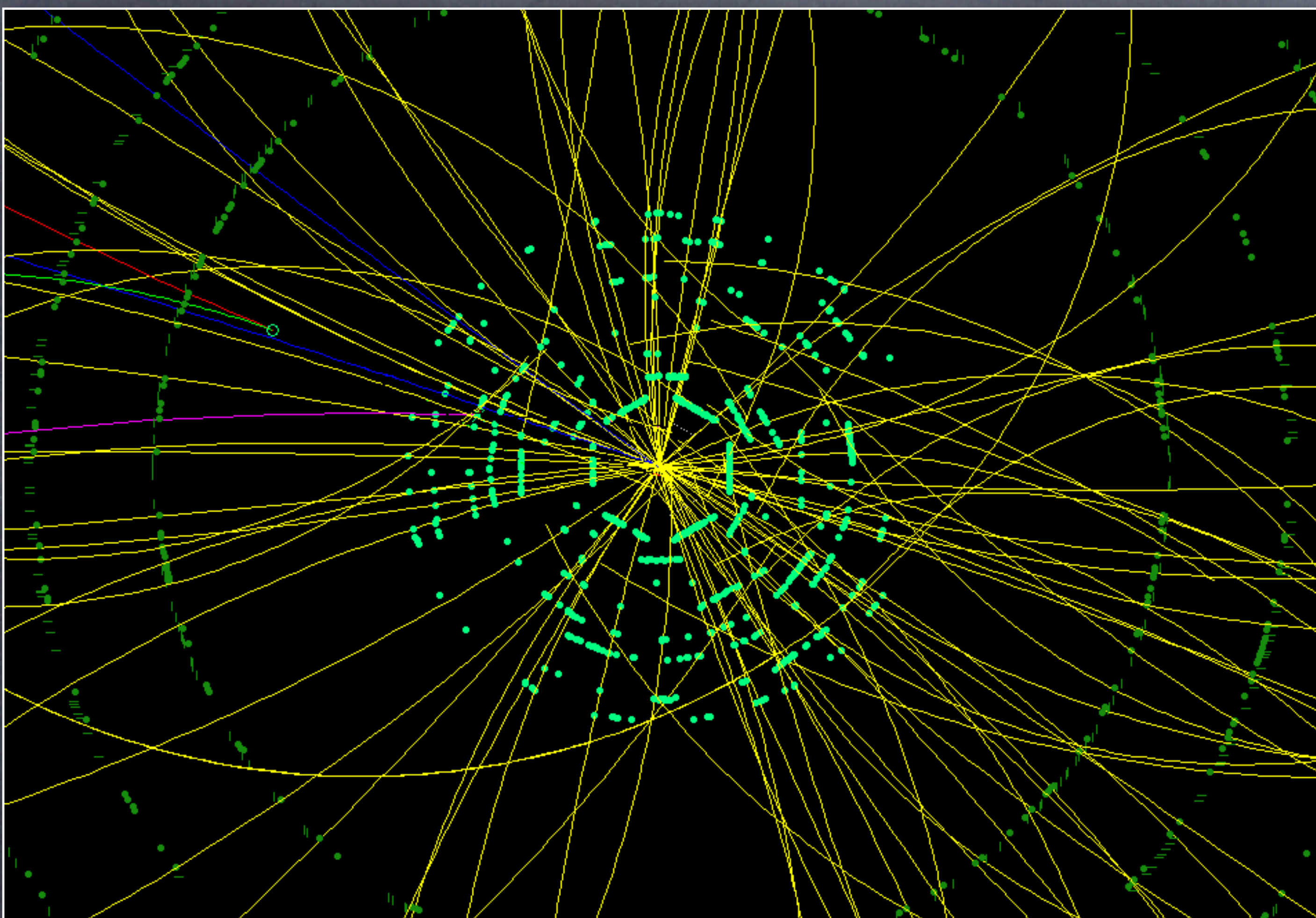
$\sigma(\bar{\eta})/\bar{\eta}$ = **1.7%**

Fermilab



Muon Scintillators
Muon Chambers
Shielding
Calorimeter
Toroid

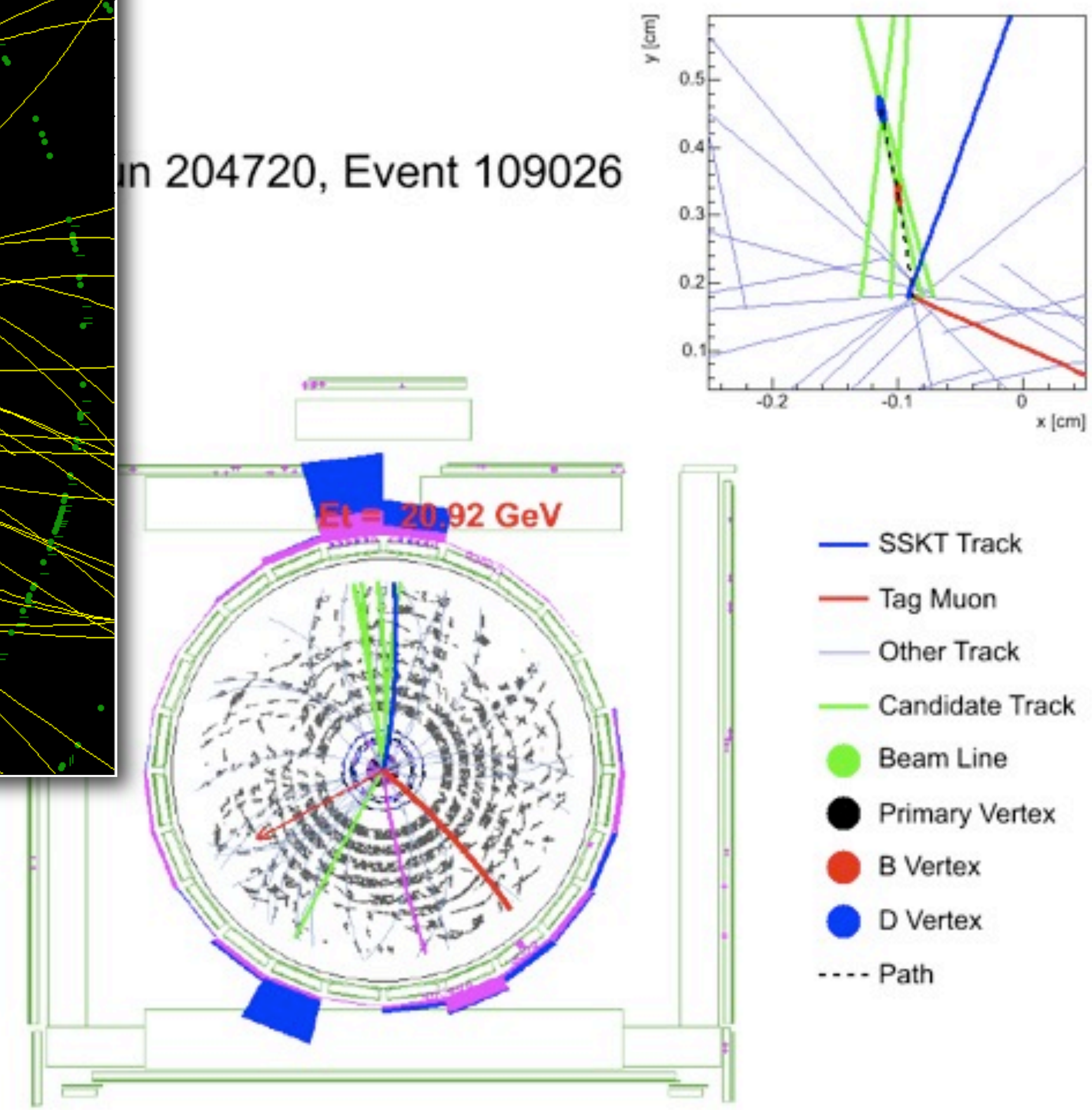
Typical Events at FNAL



D0: Ω_b

PRL 101,232002 (2008)

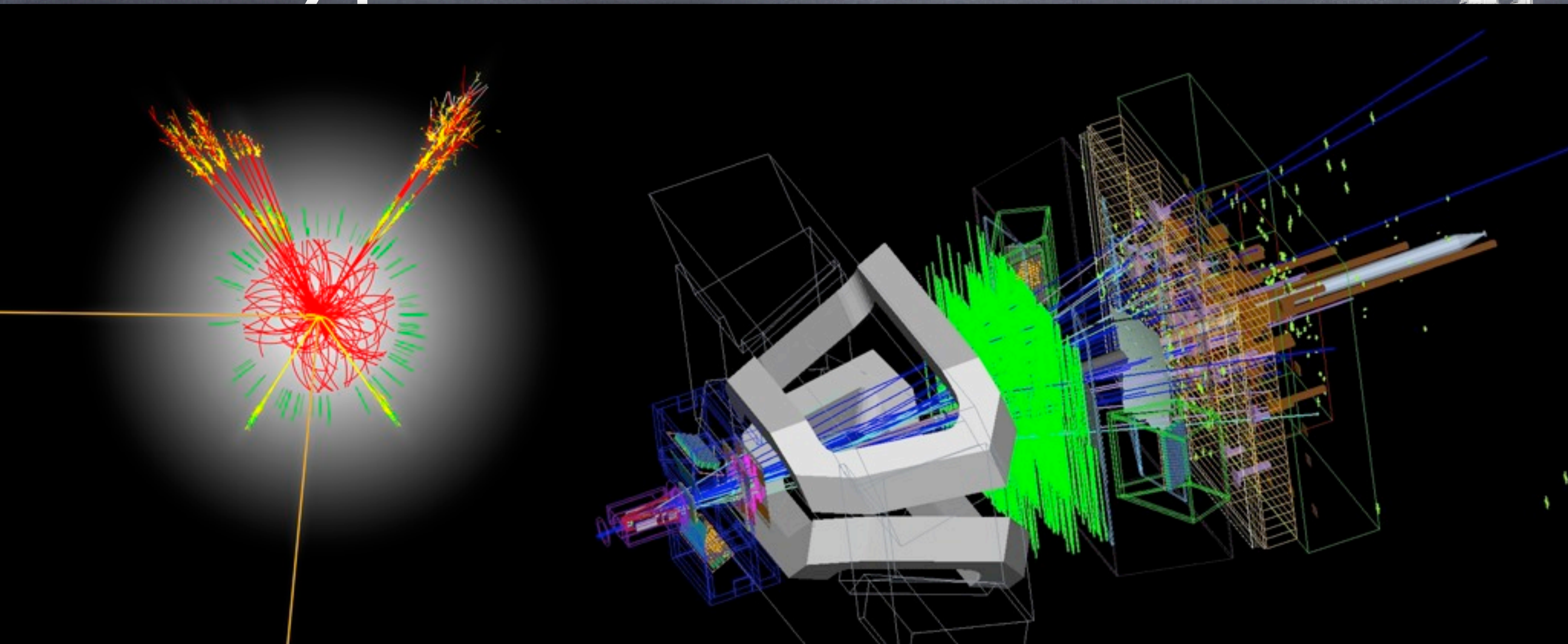
B physics "soft"
➥ no nice jets



CDF: B_s oscillations

PRL 97, 062003 (2006)

Typical Events at LHC

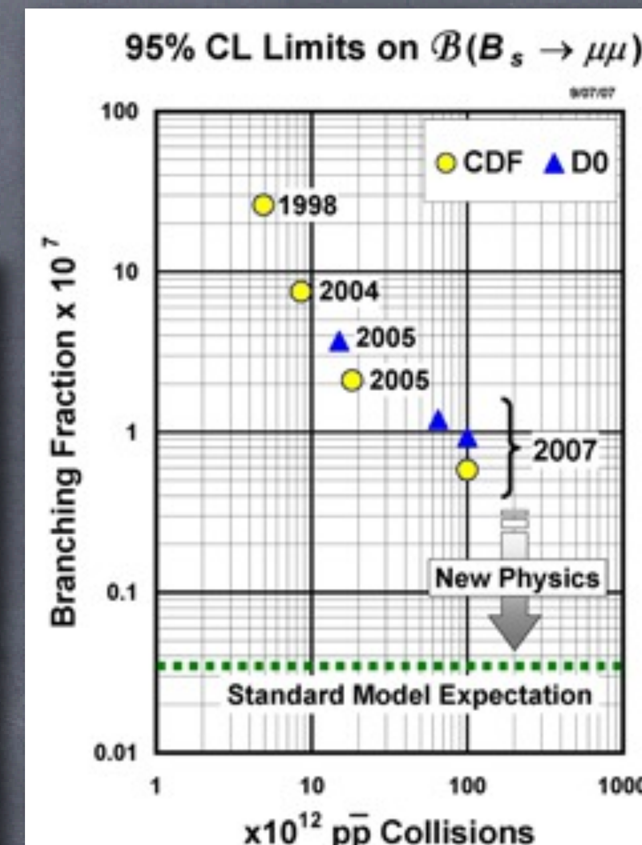


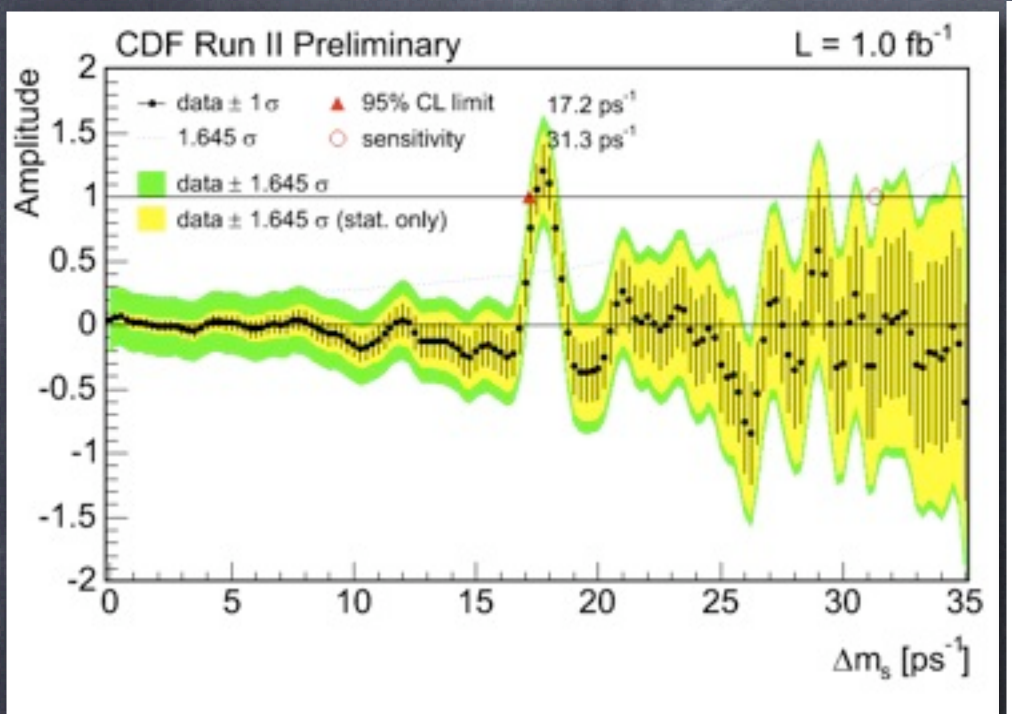
ATLAS: Higgs LHCb: $B_s \rightarrow J/\psi\ \phi$

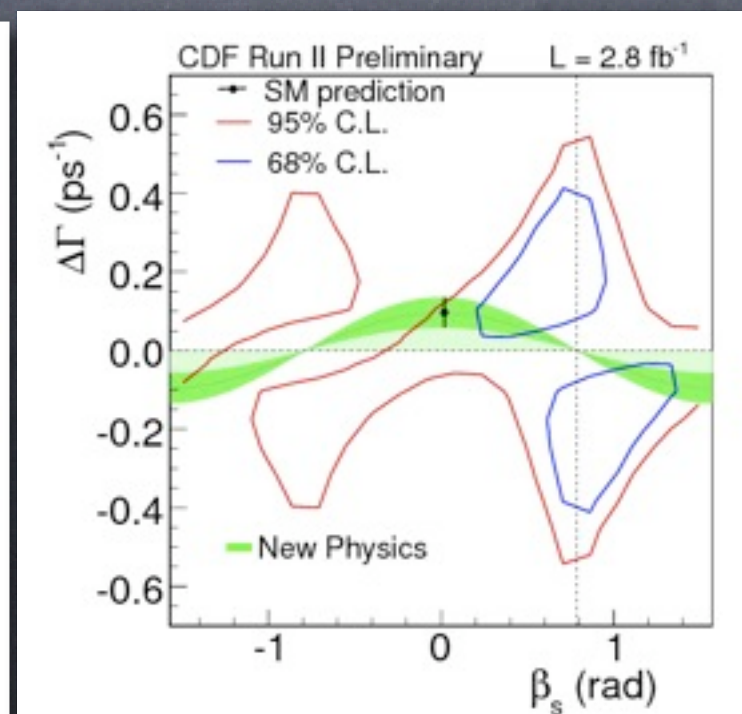
- Much busier events (again)
- Pile-up, multiple events, ….
- Again requires (steep) learning curve:
  - ➥ LEP → FNAL → LHC

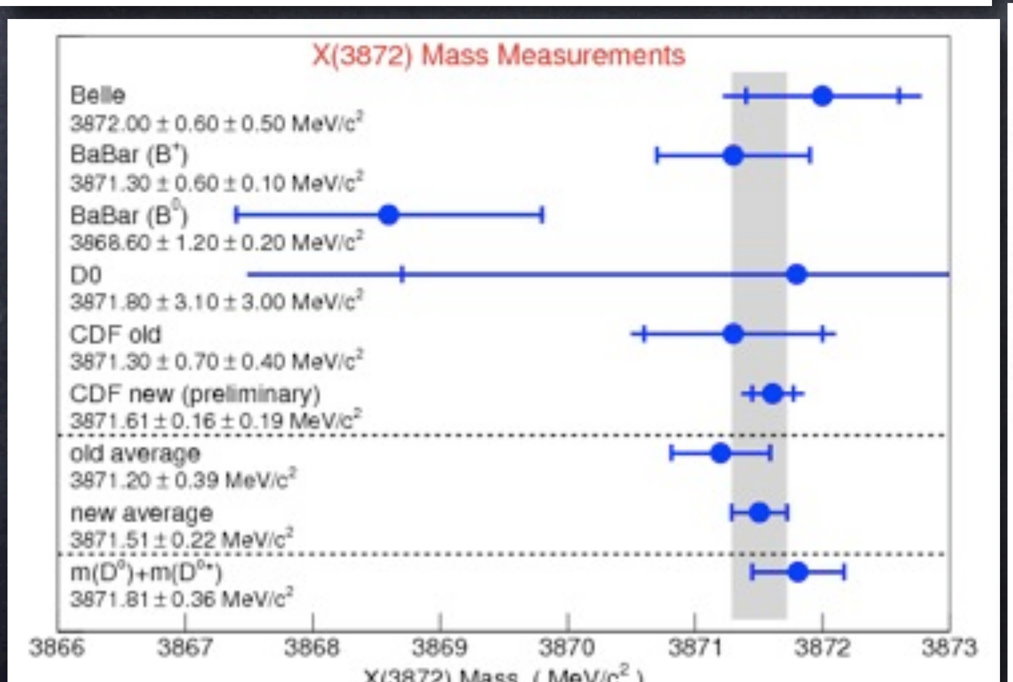
Precision measurements

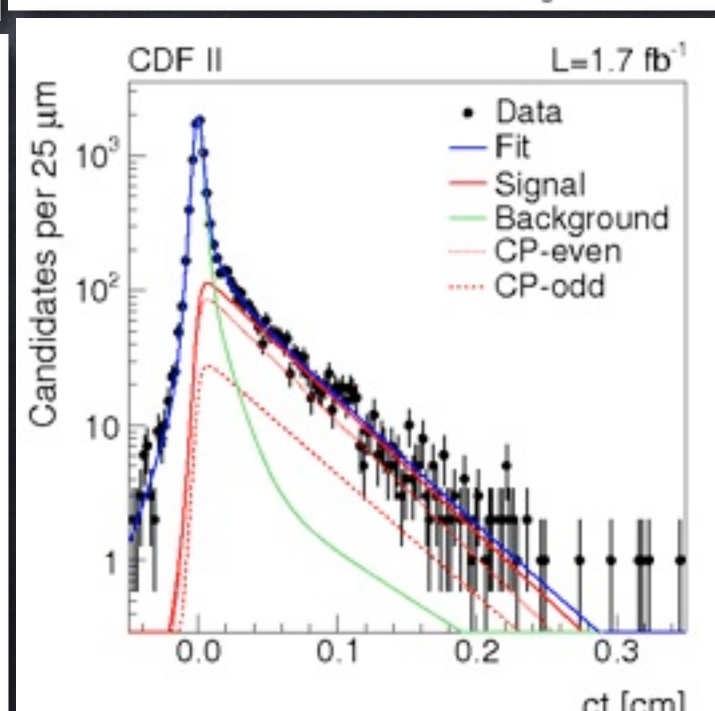
- Tevatron can perform precision flavour measurements !

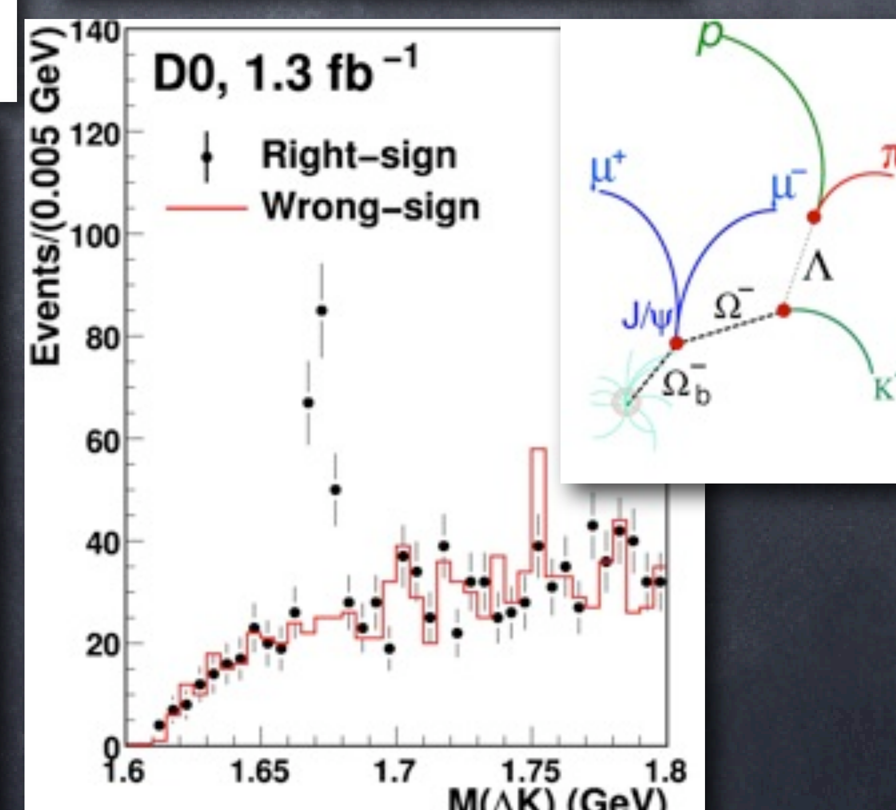






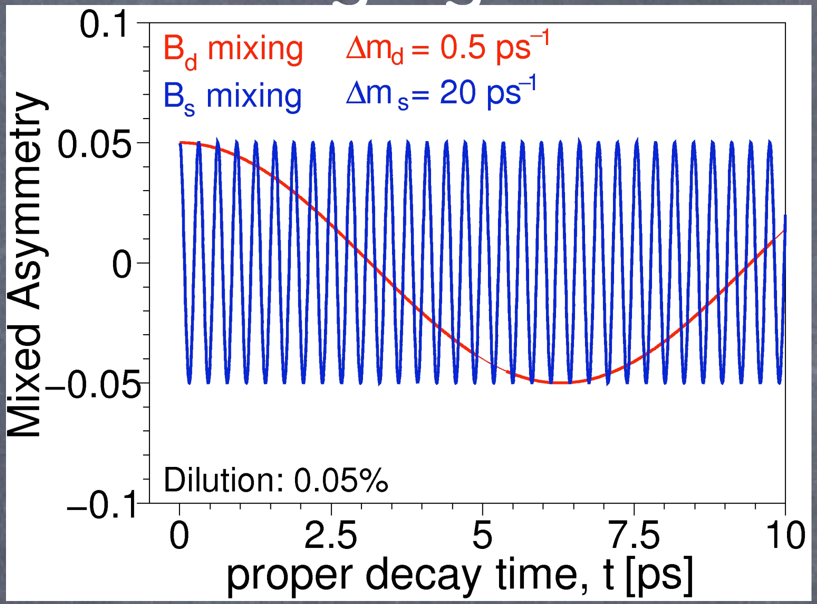






B_s mixing at FNAL

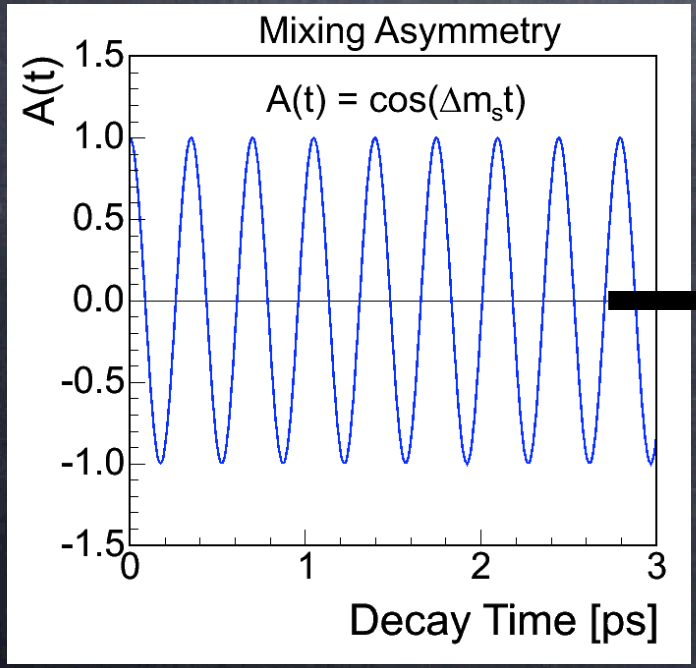
- One of the key analyses at FNAL
- Many FTE and PhD theses to make this measurement possible
- Experimentally very challenging

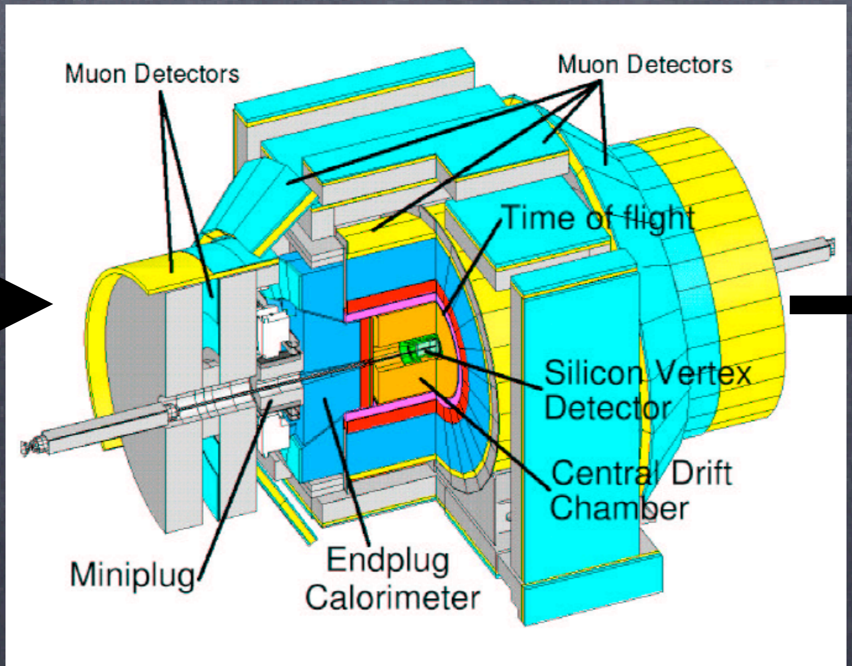


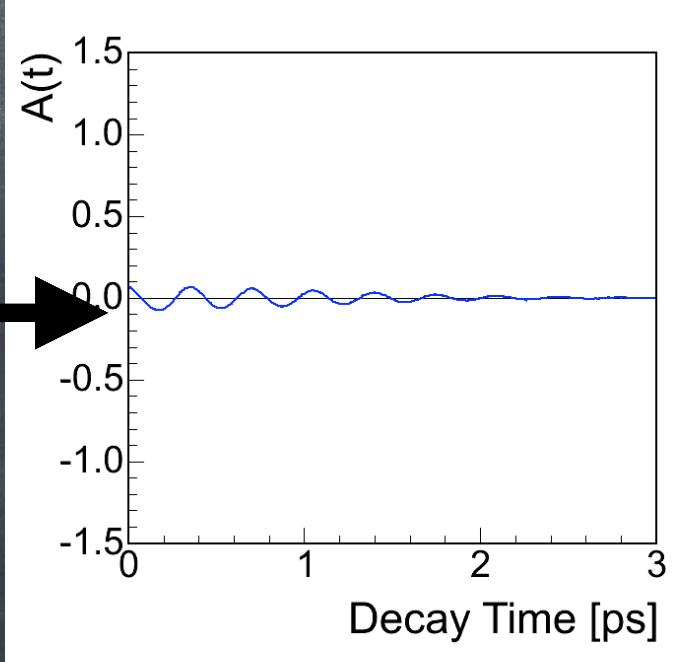
B_s oscillations much faster than B_d

➥ large statistics

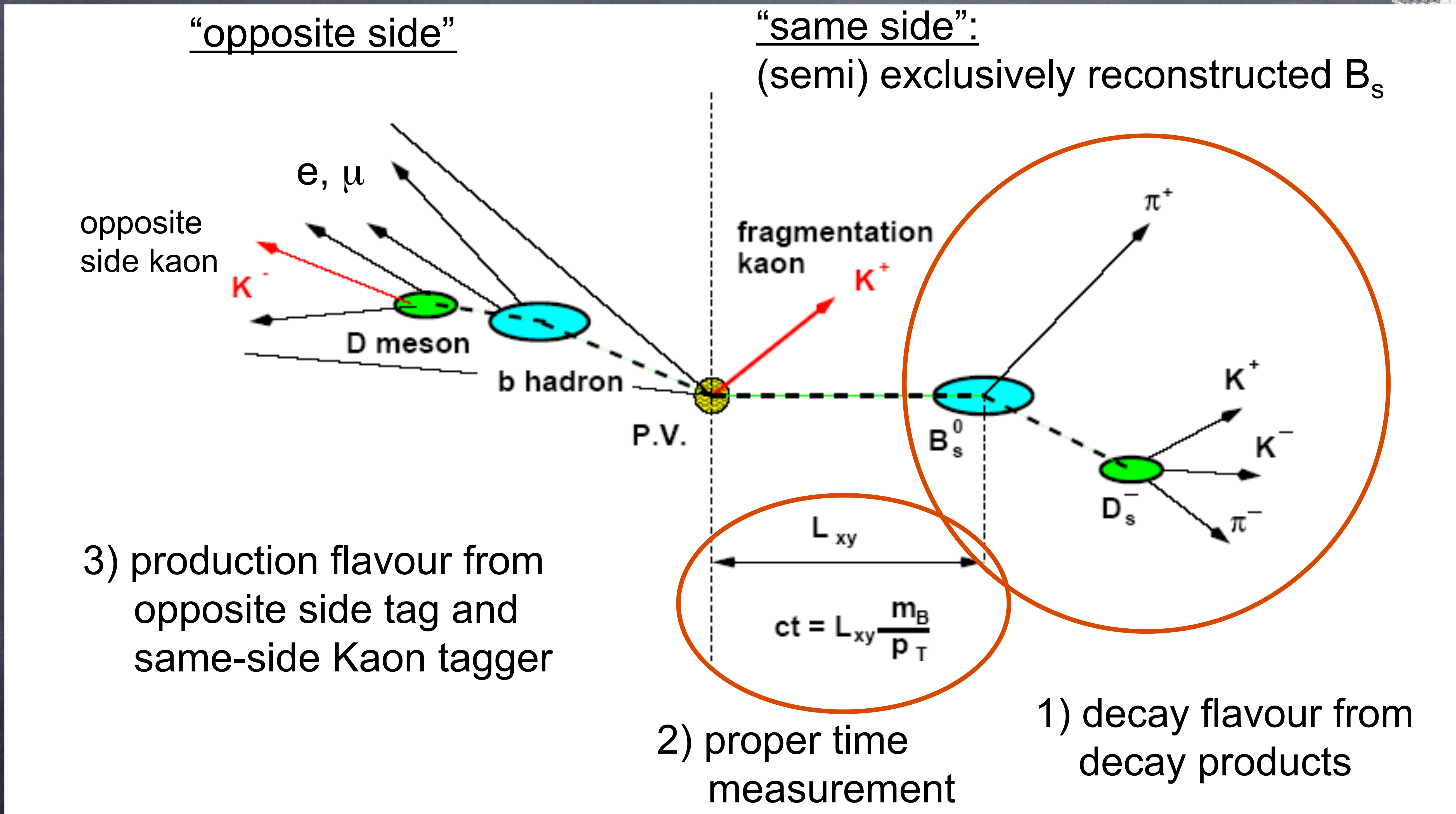
➥ high resolution



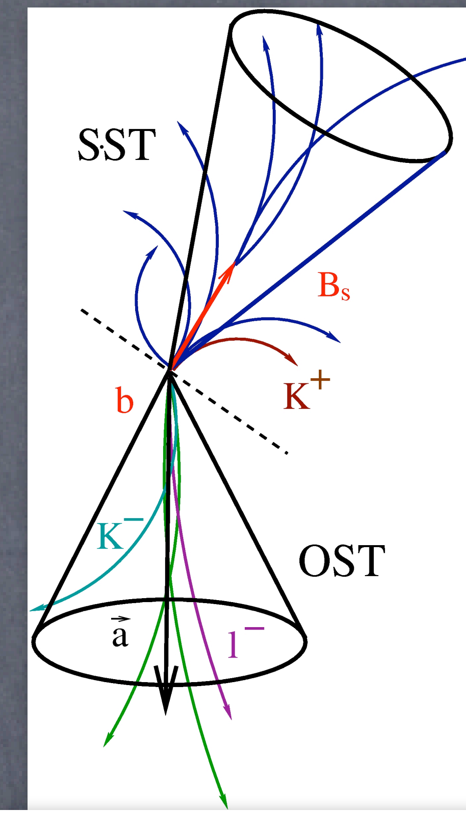




B_s mixing at FNAL



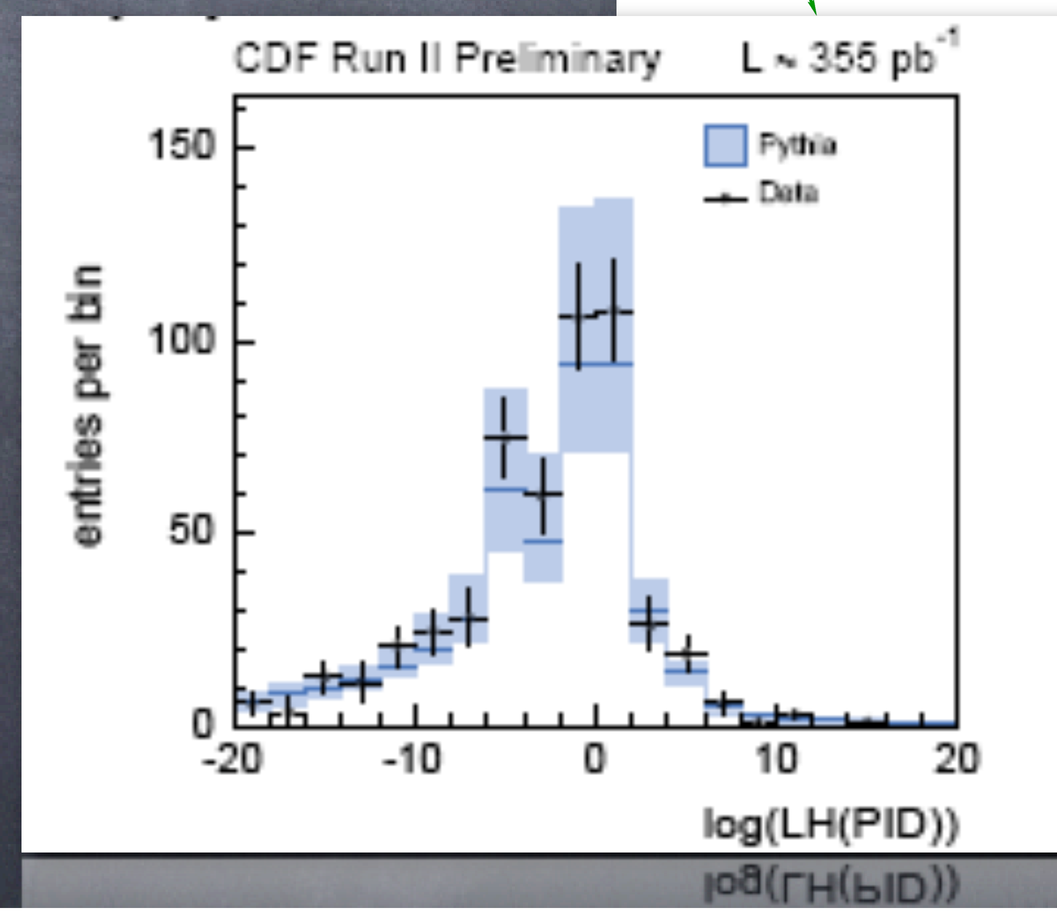
B_s mixing at FNAL



Tagger:

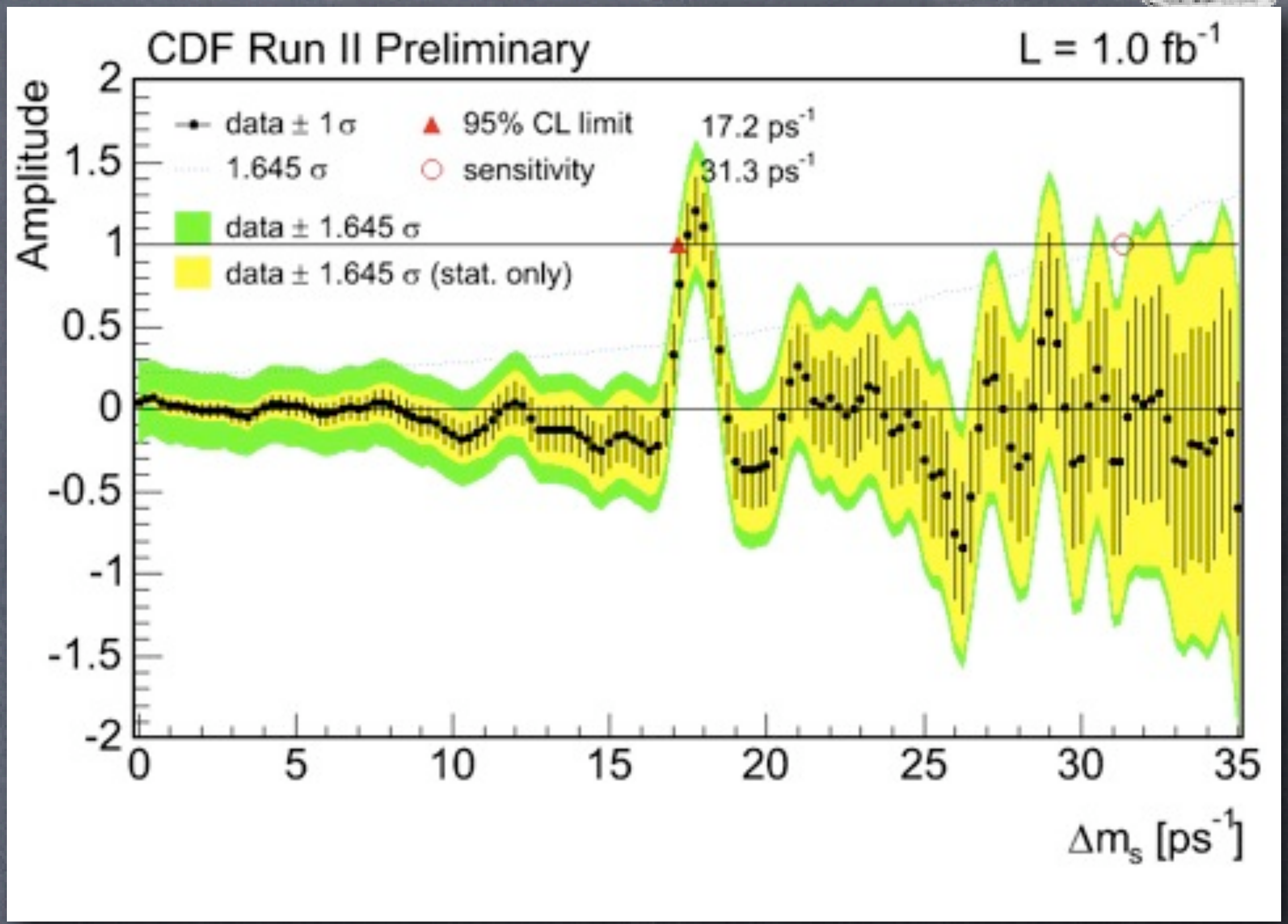
- Same Side Tagger (SST) $Q_{jet} = \frac{\sum_i w_i Q_i}{\sum_i w_i}$
  - Jet Charge
  - Soft lepton ID
    - Flavour from semi-lep. B decay
    - Diluted by oscillation and cascade
  - Calibrated on data

- Opposite Side Tagger (OST)
    - $K^{\pm}$ leading fragmentation partner
    - Very powerful tagger
    - Checked using $B_s \to D_s \pi$ data
    - Calibration / Performance via MC
      - ➥ many FTE data/MC agreement
      - ➥ extensive checks to verify MC



B_s mixing at FNAL

- "Pushing" on all fronts...
- Neural Networks:
  - Identify tracks from B decays
  - Identify B jets
  - Identify leptons from B
  - Jet Charge Tagger
  - B candidate selection

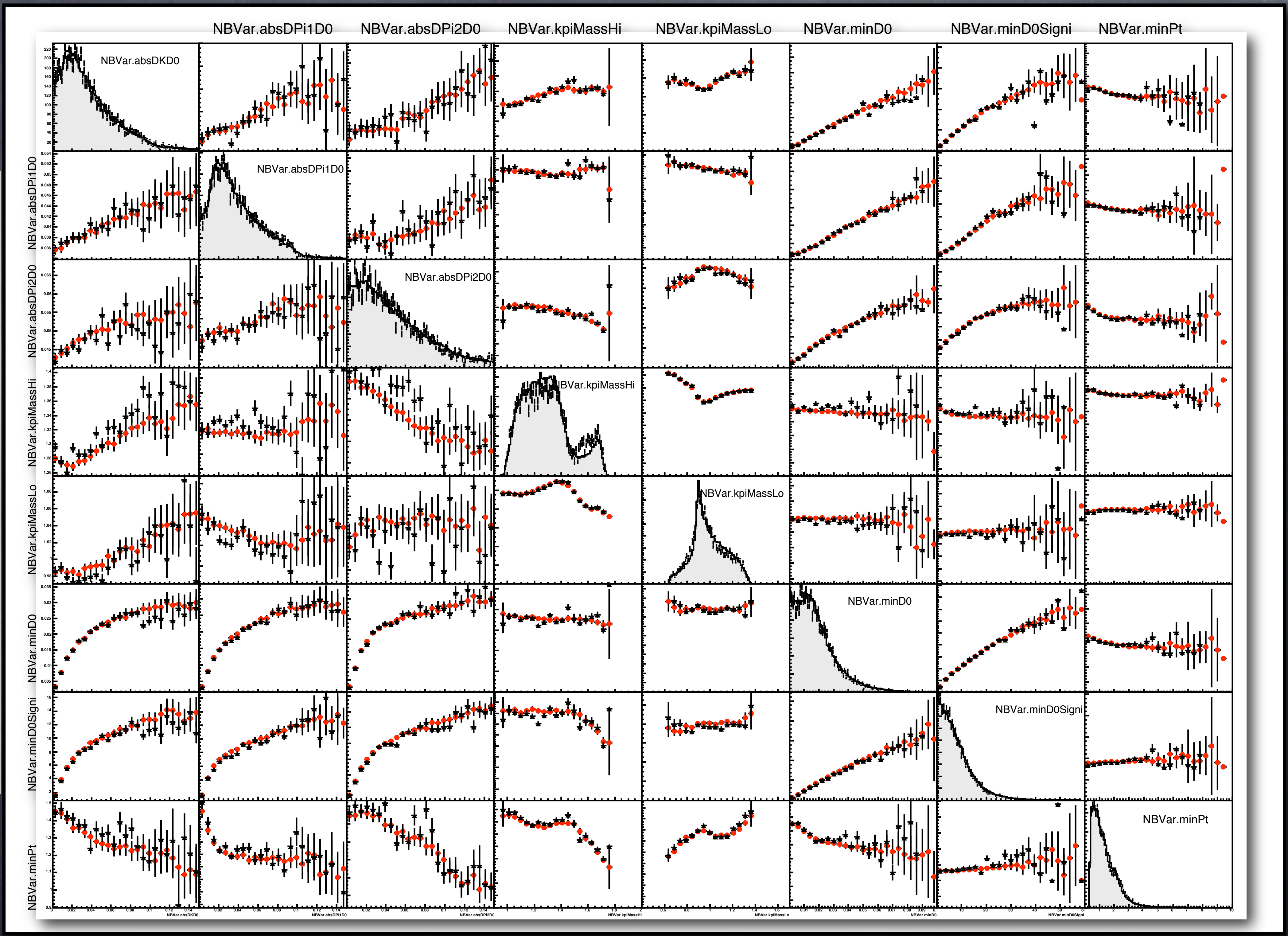


→ significant improvements w.r.t. "conventional" approaches

- Requires detailed understanding of simulation, including correlations
- Rigorous tuning ...
- ... and still not good enough for all tasks
  - ➥ signal events modeled reasonably well
  - ➥ have to take background from data
- Many iterations until cut-based, etc. analyses could be replaced

⇨ Has to be done all over again at LHC !

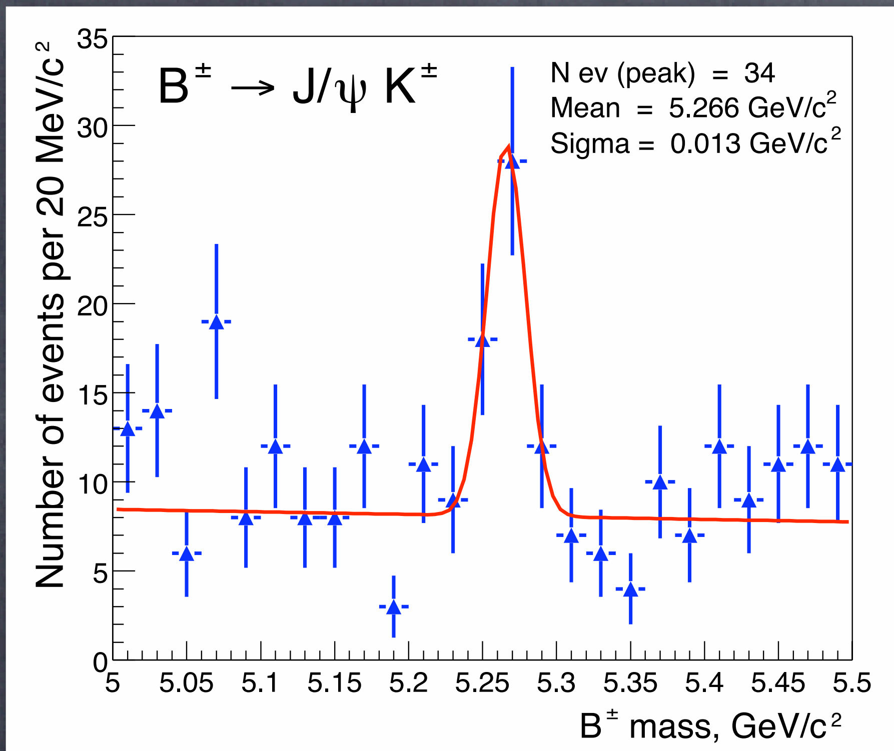
Data vs MC: CDF Example

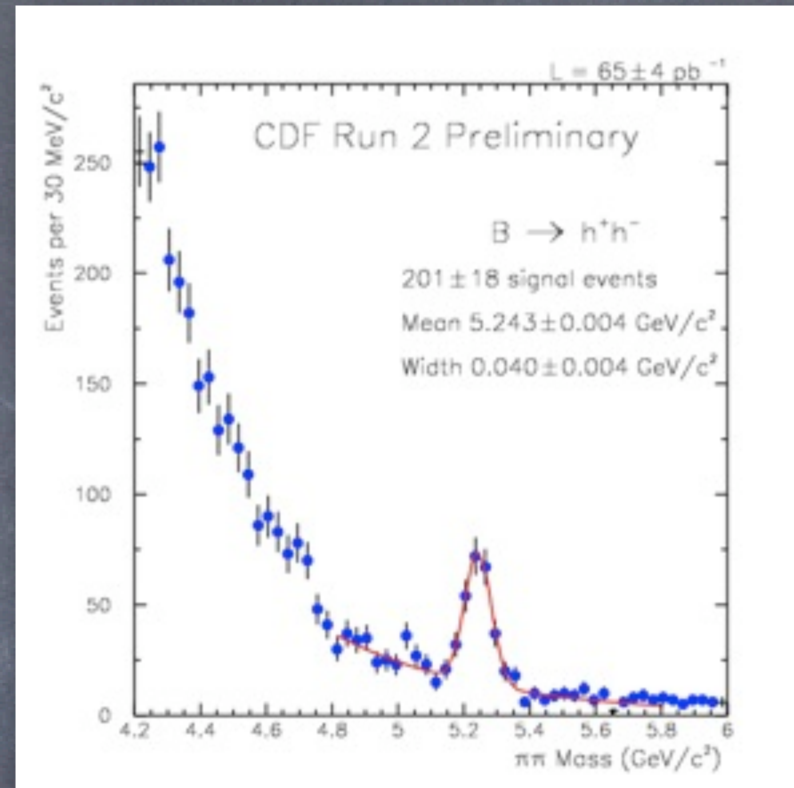


PhD Thesis, Ch. Dörr IEKP-KA/2006-6

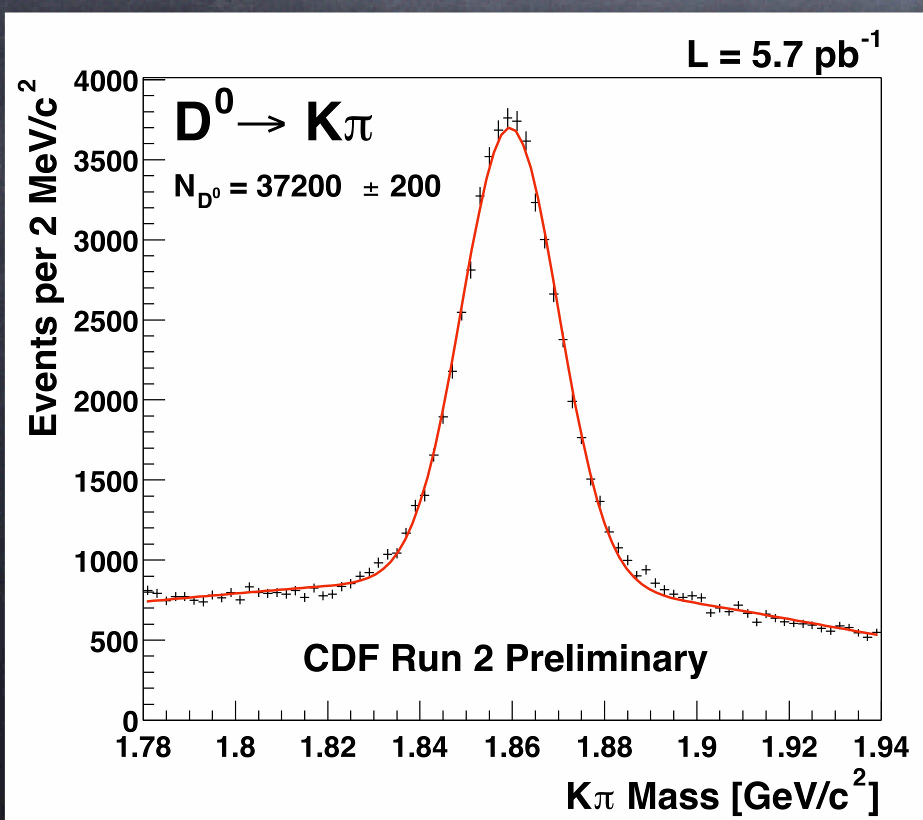
- Check not only each variable - but also all correlations!

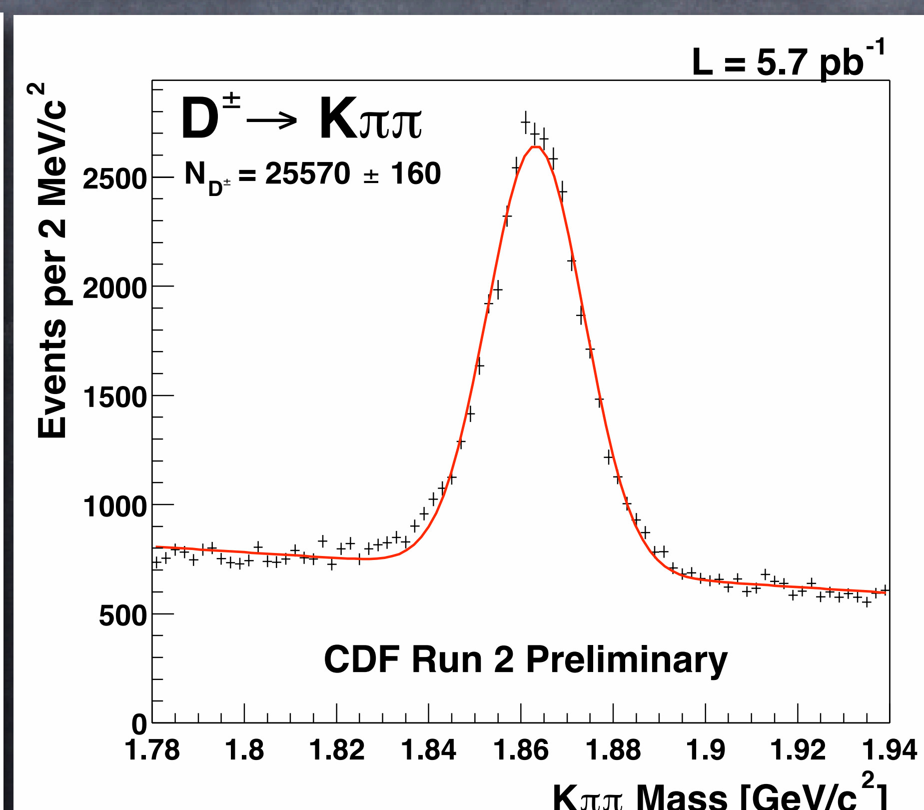
Early Physics

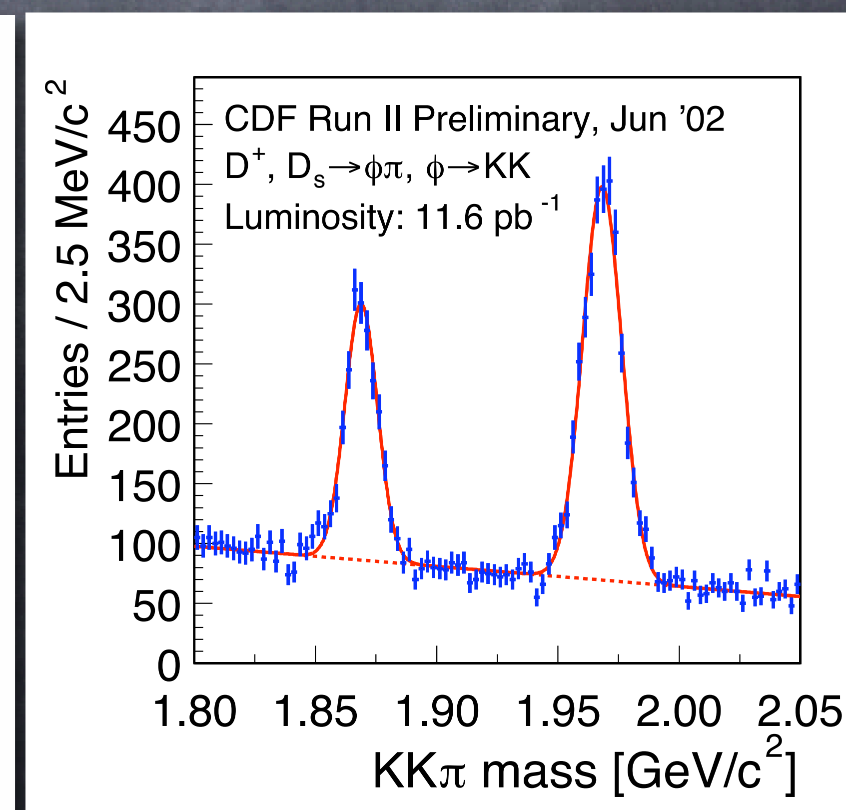




- … but it's been a long way to go…
- Indeed not too much B-physics - but Charm!





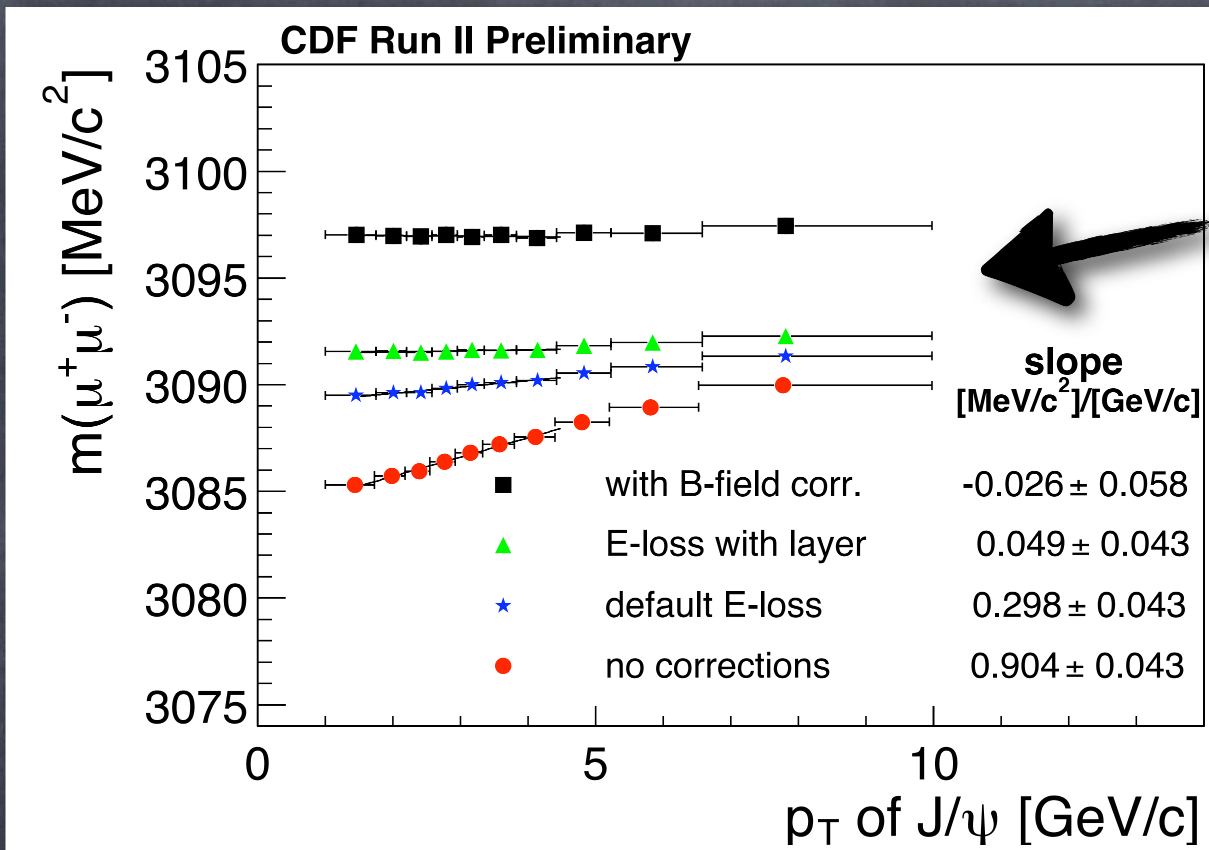


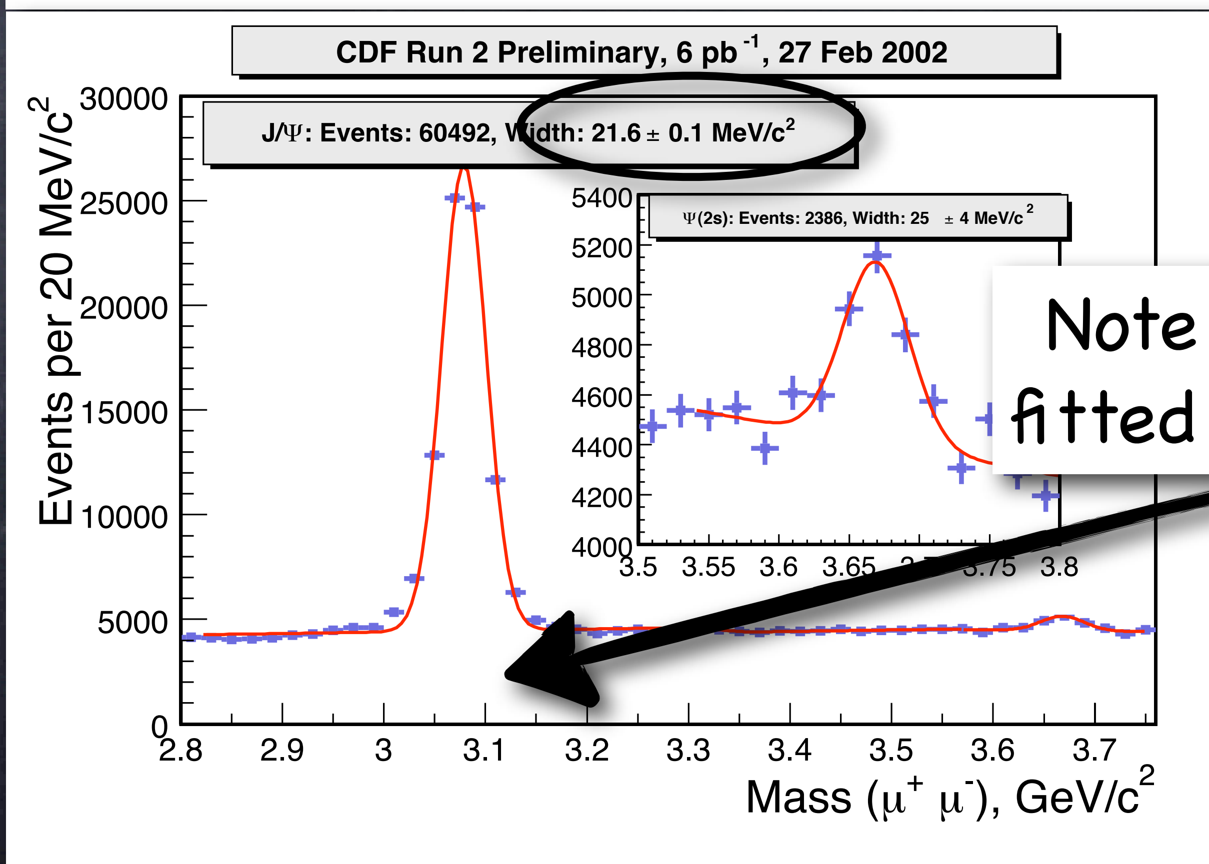
Understanding the Detector

Use known resonances to calibrate detector

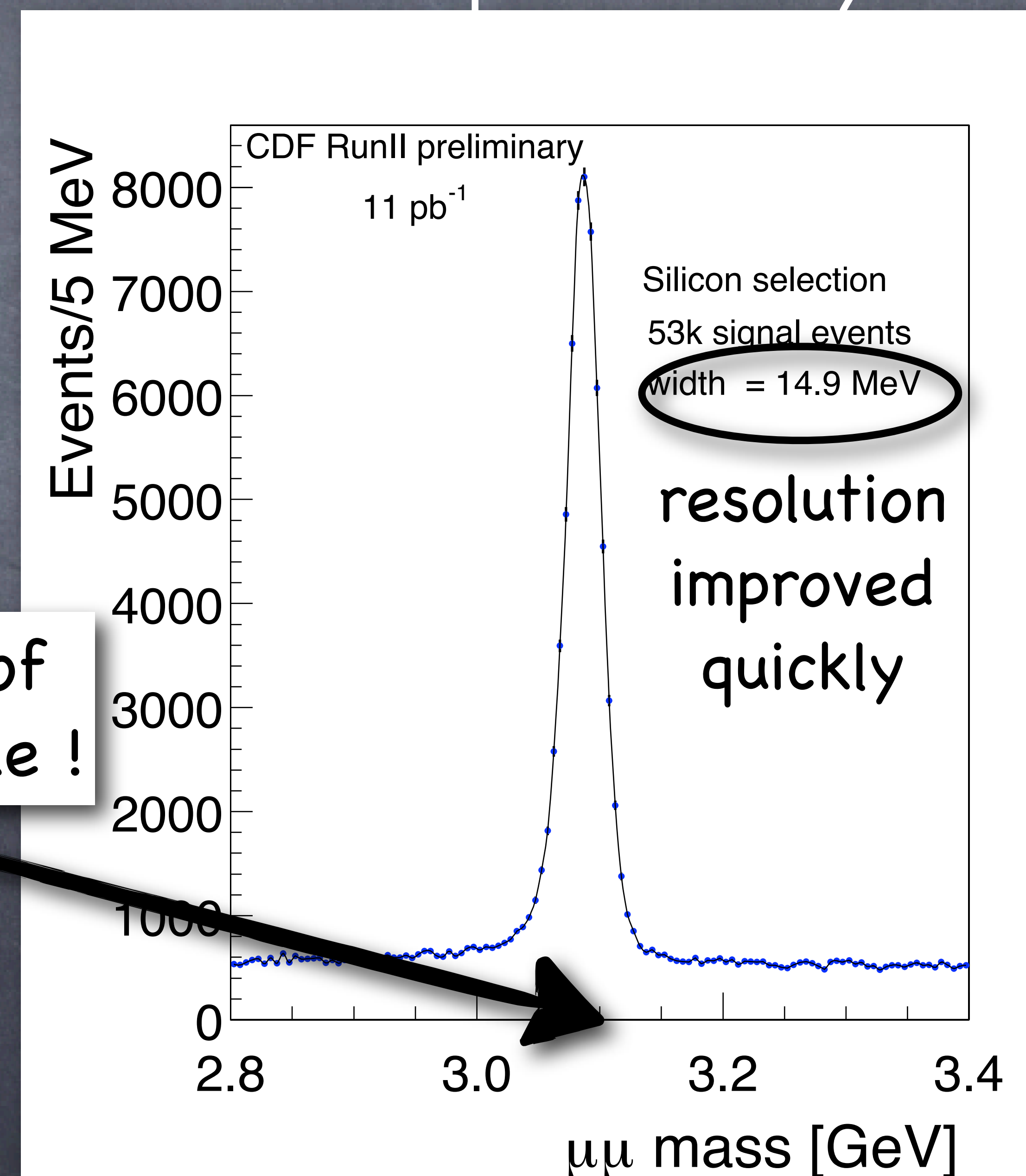
➥ missing material

➥ introduce several "phantom layers"





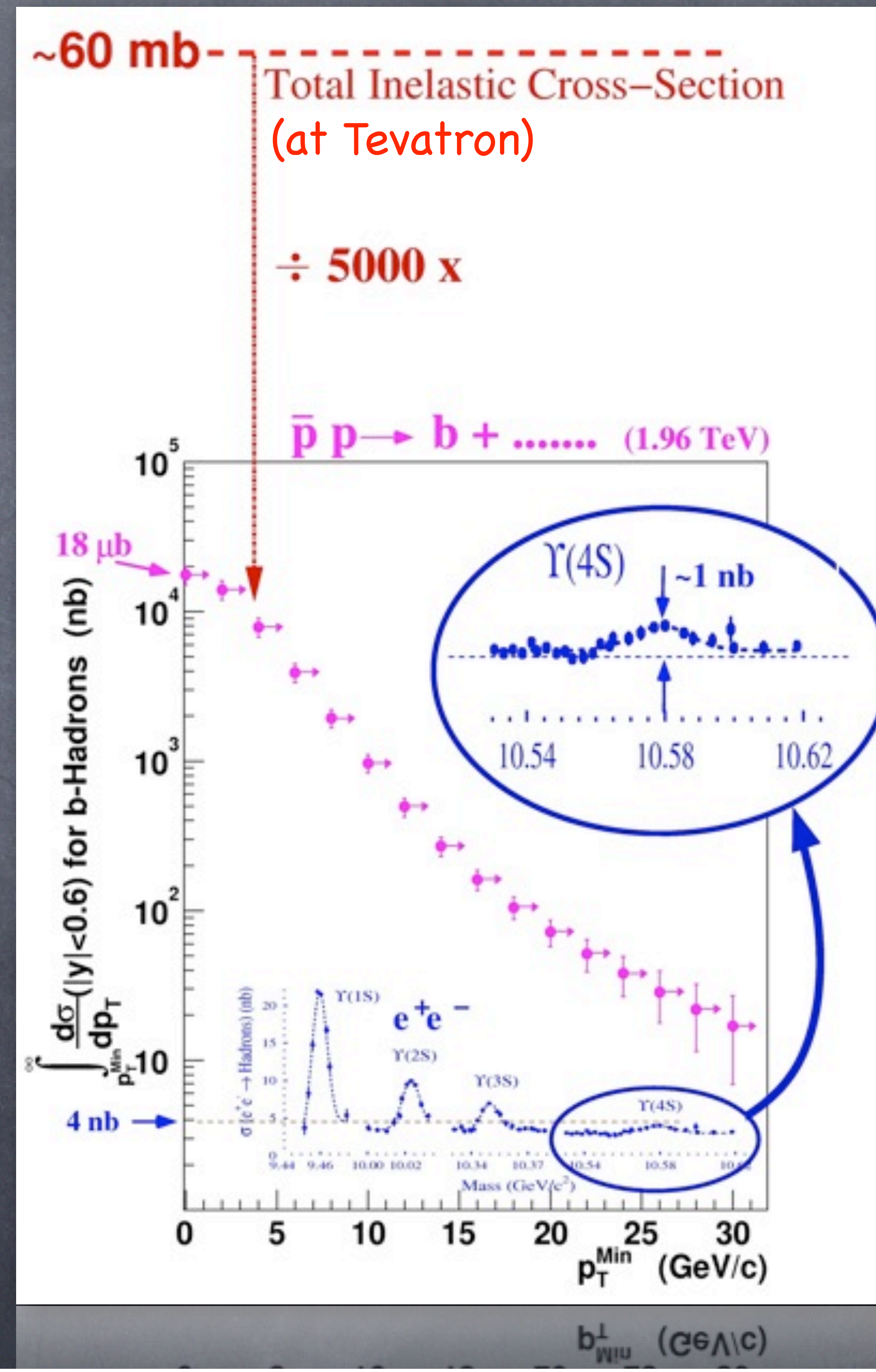
Note absence of fitted mass value !



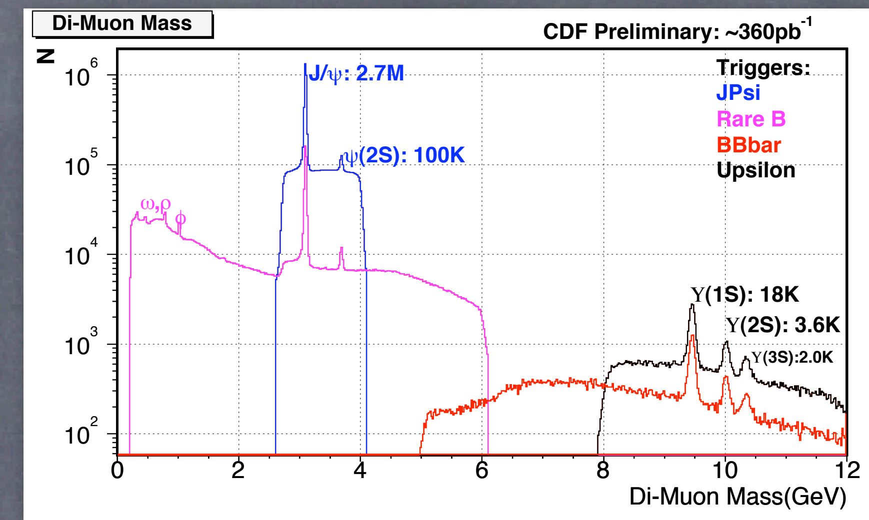
resolution improved quickly

Trigger

- Hadronic environment very challenging for Flavour Physics.
- Interesting signal "buried" under large hadronic background.
- Triggers are essential
- Much more challenging than
  - B-factories "event shape"
  - LEP(1): Z^0 event



Trigger



- Trigger approaches:
  - **First level:**
    - Di-muon (J/ψ): "easy" trigger, clean signal
    - Single lepton : Semi-leptonic B decays
      - Combine with displaced track (CDF)
    - Hadronic B : ~80% of B decays
      - Require several displaced tracks at trigger level
      - Needs precision tracking at trigger level
      - Biases lifetimes, etc.
      - Challenging for first physics...
    - PID based at LHCb ?
  - **High Level Trigger (HLT)**
    - Fully reconstructed decays
- Need to adapt to changing luminosity - maximise recorded data
  - Set of fixed pre-scales
  - Dynamic pre-scaling
  - "Uber-prescaling"
  - Need to keep track of recorded luminosity ....

LHC Start-Up

- The "big adventure" is about to begin … again …

BACKUP

- Further material