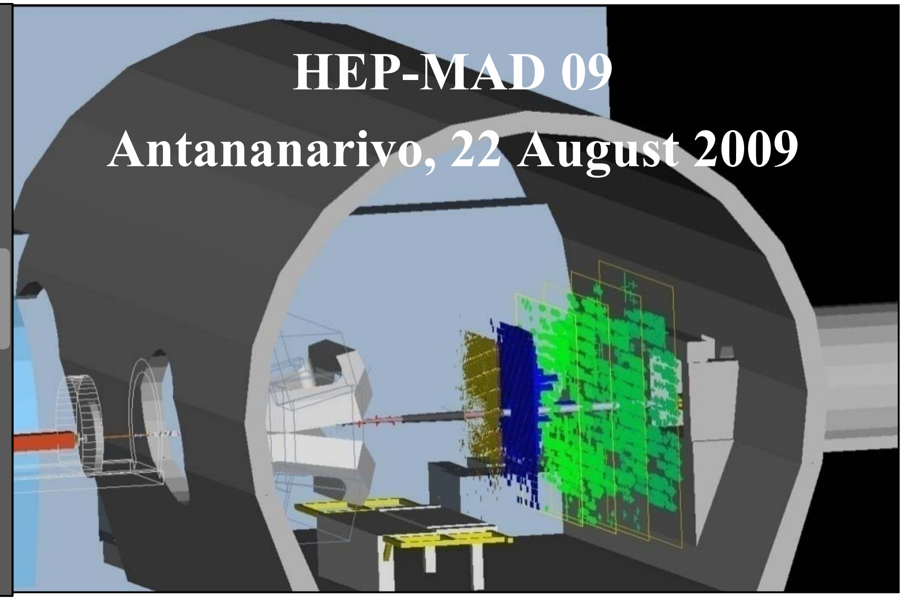
Status of LHCb and Physics Prospects



Beam induced “splash” in LHCb

- **Physics motivation**
- **Detector overview and performance**
- **Physics prospects**

presented by

Andreas Schopper (CERN)

on behalf of the LHCb Collaboration

B Physics as a probe for New Physics

Standard Model (SM) cannot be the ultimate theory !

- SM could be a low-energy effective theory of a ***more fundamental theory at a higher energy scale***, probably in the TeV region → accessible at LHC !

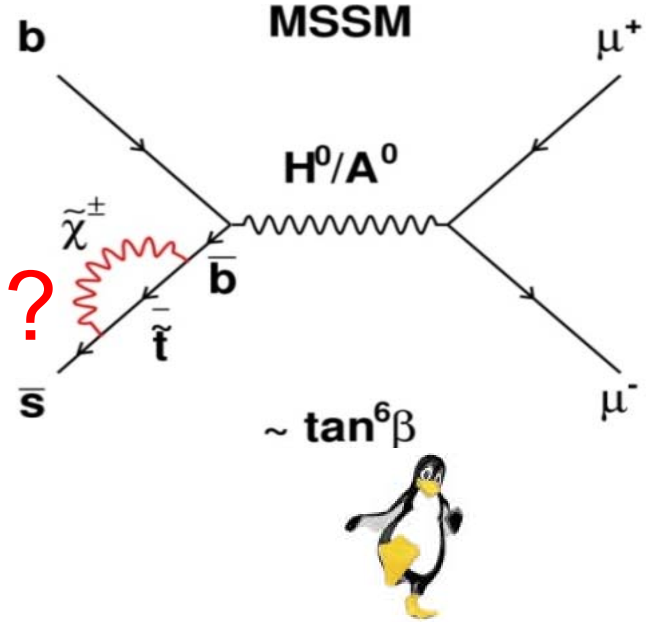
How can New Physics (NP) be discovered and studied ?

- NP models introduce ***new particles***, dynamics and/or symmetries at a higher energy scale, and these new particles could
  - ✓ be produced and observed ***as real particles*** at energy frontier machines like the LHC → detected by GPD (ATLAS & CMS)
  - ✓ appear ***as virtual particles*** in e.g. loop processes, leading to observable deviations from the pure SM expectations in flavour physics and CP violation → detected by LHCb in B decays

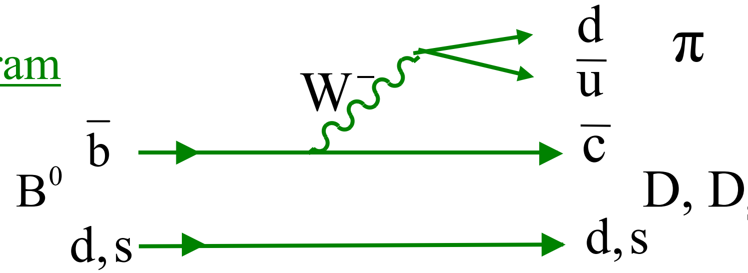
B decays in the Standard Model and beyond

virtual particles appear in loop mediated processes

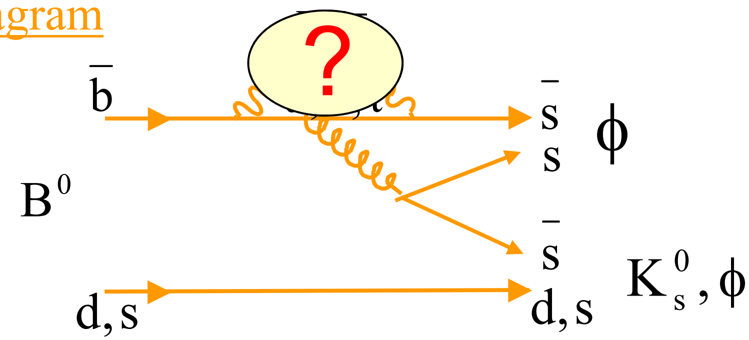
$B_s \rightarrow \mu^+\mu^-$ "s-channel penguin"



Tree diagram

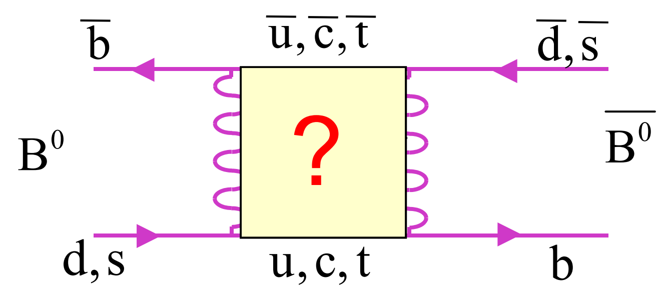


Penguin diagram



New Physics

Box diagram



- ✓ Dominant decay process: "tree" b→c transition
- ✓ Very suppressed "tree" b→u transition
- ✓ FCNC: "penguin" b→s,d transition
- ✓ Flavour oscillations (b→t "box" diagram)

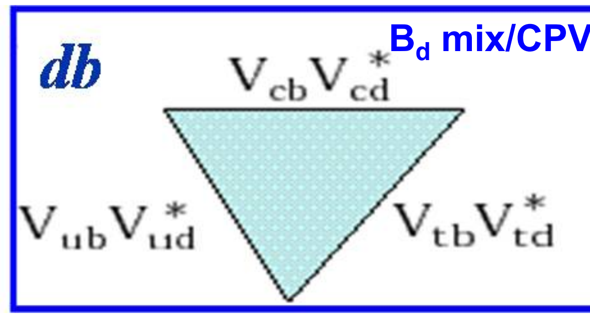
B decays in the Standard Model

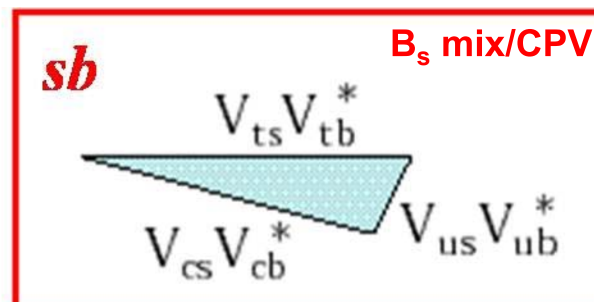
The B-meson provides a laboratory where theoretical predictions can be precisely compared with experimental results

- ✓ favourable experimental conditions due to relatively long lifetime of B mesons
- ✓ in many New Physics scenarios large effects are seen in third generation family
- ✓ B_d and B_s mesons are sensitive to CP violation via mixing and decays, allowing to detect deviations from the SM expectations

CKM matrix

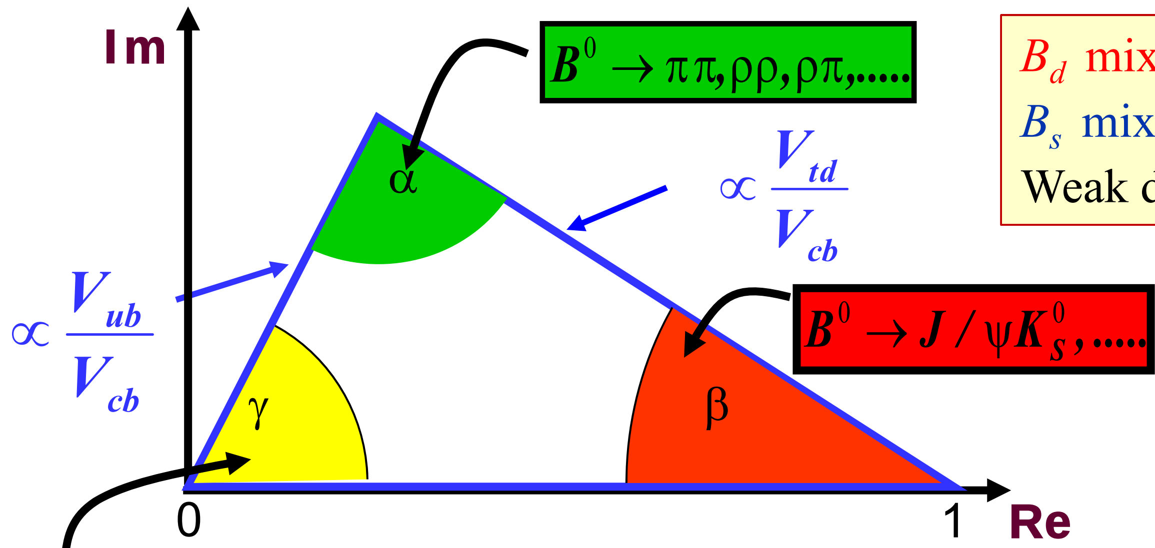
flavour states
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$
mass states





- ➢ the Cabibbo-Kobayashi-Maskawa matrix $\mathbf{V_{CKM}}$ describes rotation between the flavour eigenstates and quark mass eigenstates; it is complex and unitary
- ➢ unitarity gives relationship between rows and columns: $\Sigma\, V_{ij}\, V_{ik}^* = 0 \;\; (j \neq k)$ → triangles in complex plane
- ➢ area of CKM unitarity triangles = amount of CP violation

CKM Unitarity Triangles



B_d mixing phase: $\phi_d = 2\beta = -\arg(V_{td}^2)$

B_s mixing phase: $\phi_s = -2\beta_s = -\arg(V_{ts}^2)$

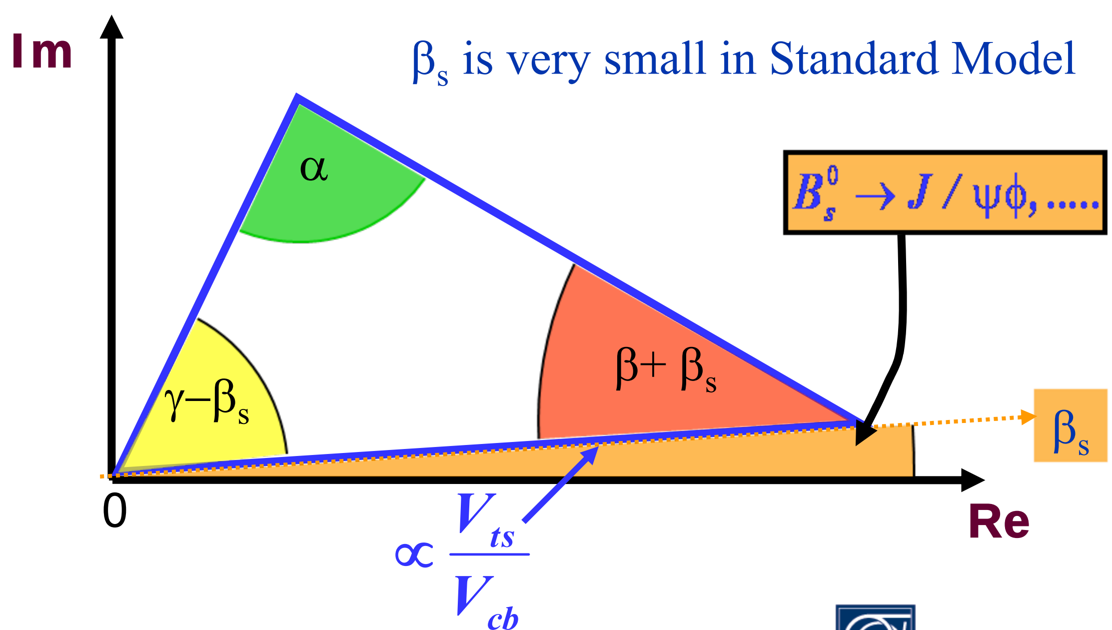
Weak decay phase: $\gamma = -\arg(V_{ub})$

$B_{d,u} \to DK, DK^*, K\pi, \ldots$

$B_d \to \pi^+\pi^-$ *and* $B^0 \to K^+K^-$

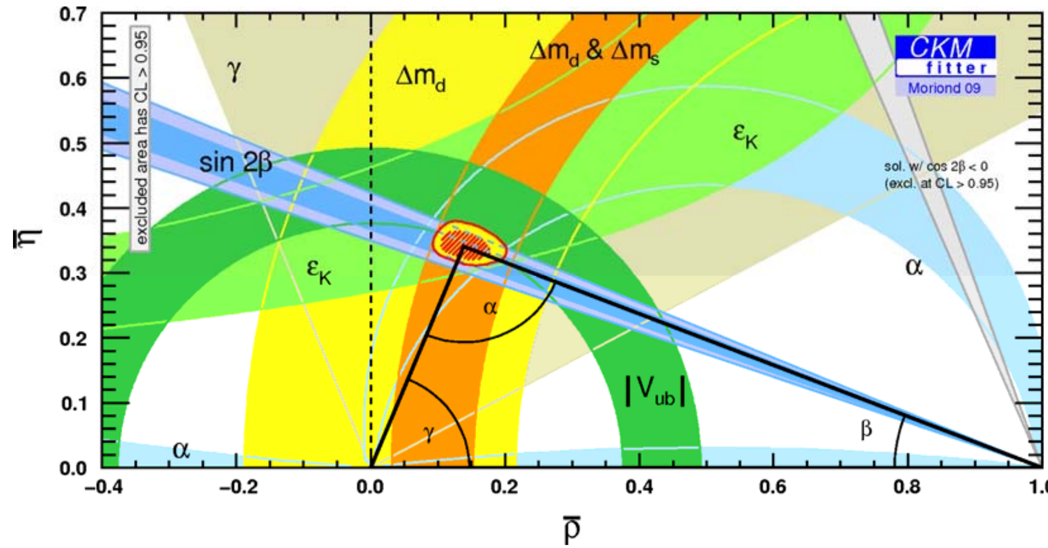
$B_s \to D_sK$ $(\gamma\text{-}2\beta_s)$

$B_d \to D^*\pi$ $(\gamma\text{-}2\beta)$



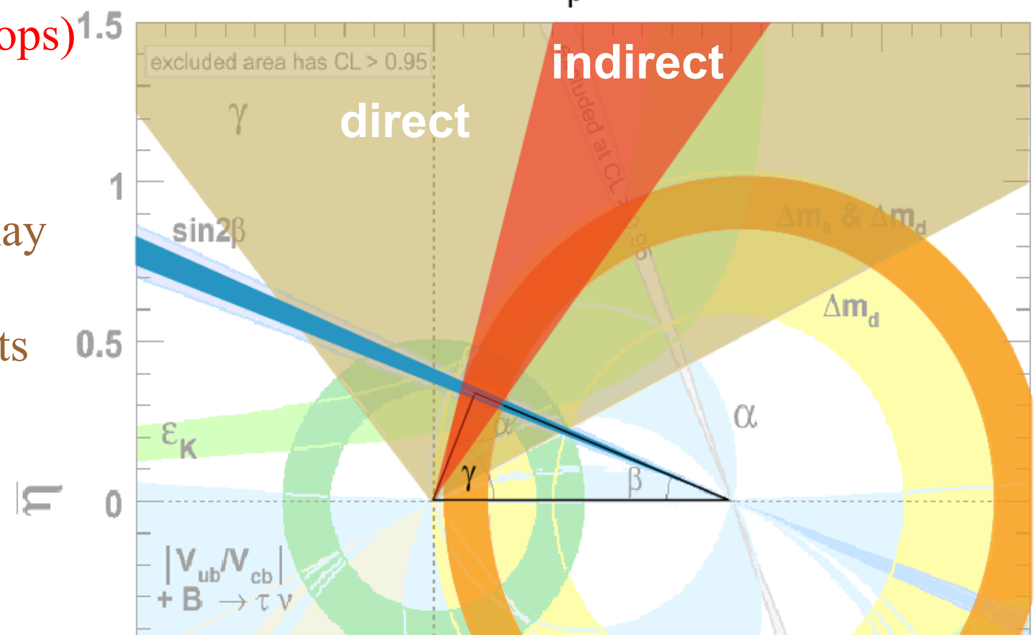
Status of CKM parameters

➢ Impressive experimental results from B-factories and Tevatron show a very consistent picture of the Standard Model

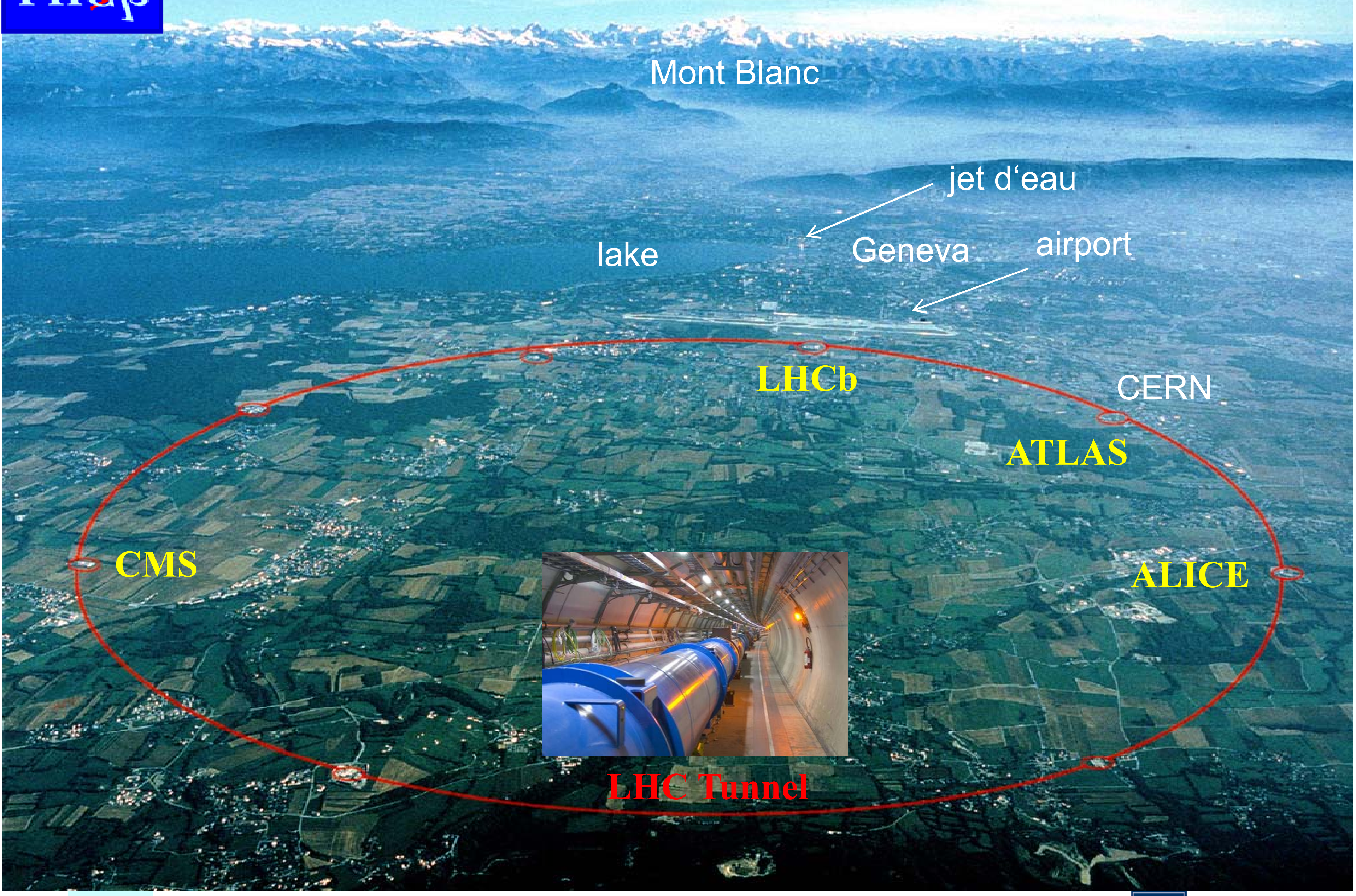


➢ All measurements together (trees & loops) determine "indirectly" the CKM angle $\gamma = (67 \quad 5)^o$

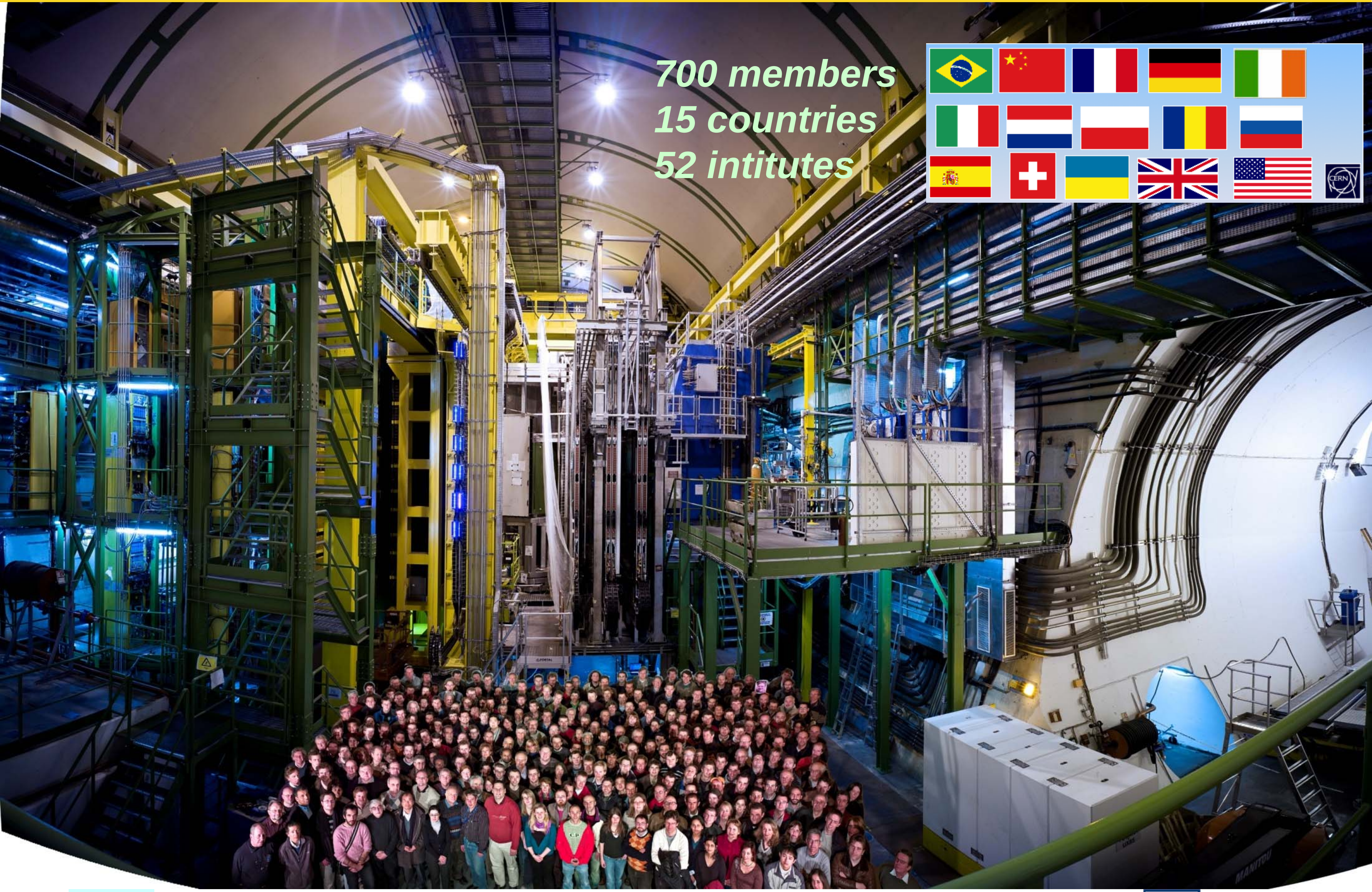
➢ However, processes involving loops may be affected by New Physics → should be compared with measurements of γ from tree processes only: B → DK, unaffected by new physics currently only poorly constrained: $\gamma = (70 \quad 28)^o$ (direct measurement)



a dedicated B-Physics Experiment at the LHC

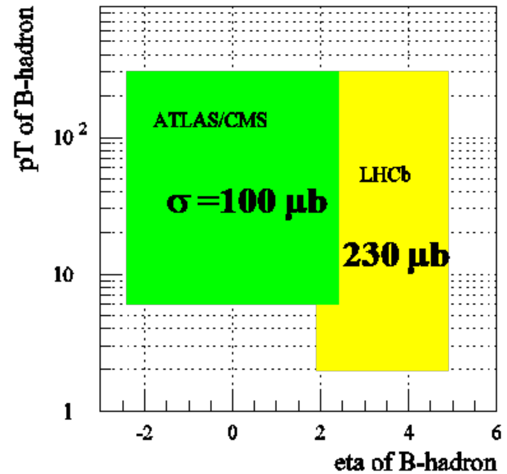


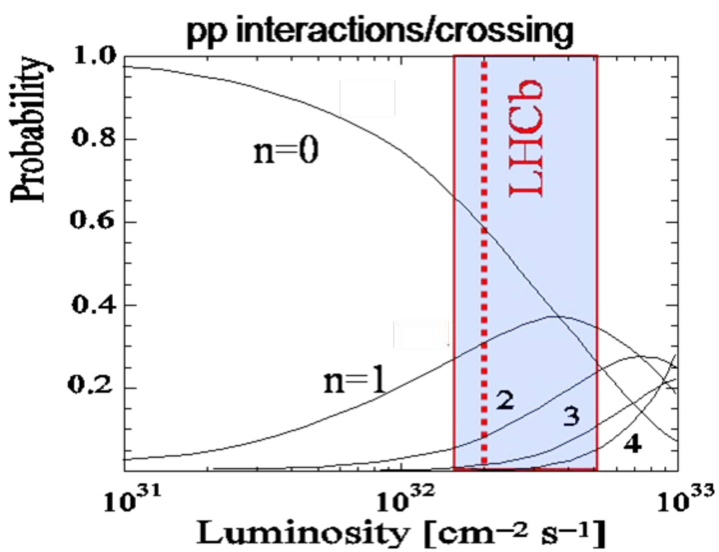
The LHCb Collaboration

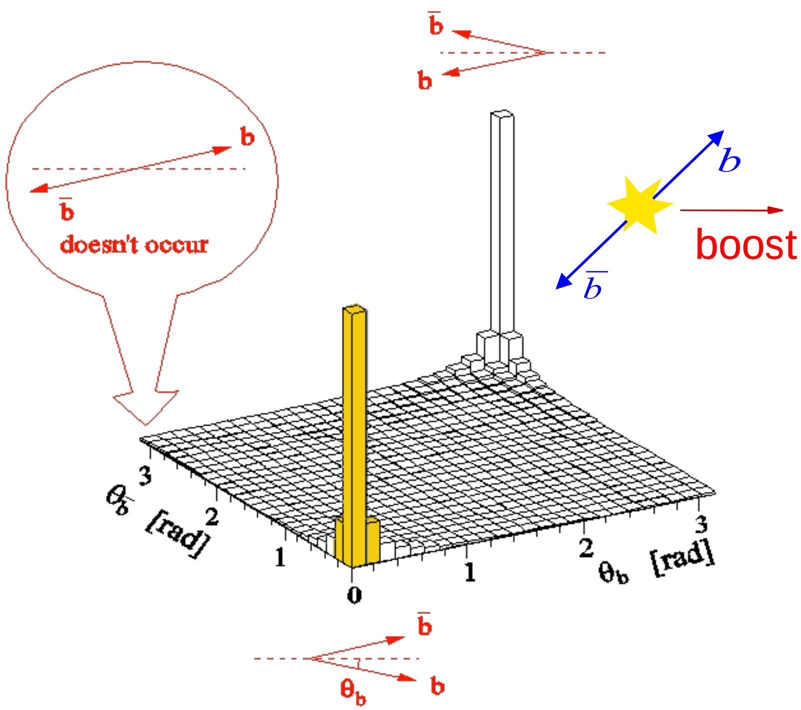


B production in LHCb

- ✓ $b\bar{b}$ pair production correlated and sharply peaked forward-backward
  - ➢ Single-arm forward spectrometer : θ~15-300 mrad (4.9>η>1.9)
  - ➢ Cross section of $b\bar{b}$ production in LHCb acceptance: $\sigma_{bb} \sim 230\ \mu b$
  - ➢ B^+ (40%), B^0 (40%), B_s (10%), b-baryons (10%), B_c (< 0.1%)
- ✓ LHCb limits luminosity to few $10^{32}\ cm^{-2}s^{-1}$ instead of $10^{34}\ cm^{-2}s^{-1}$ by not focusing the beam as much as ATLAS and CMS
  - ➢ maximizes probability of a single interaction per crossing
  - ➢ design luminosity soon after start-up

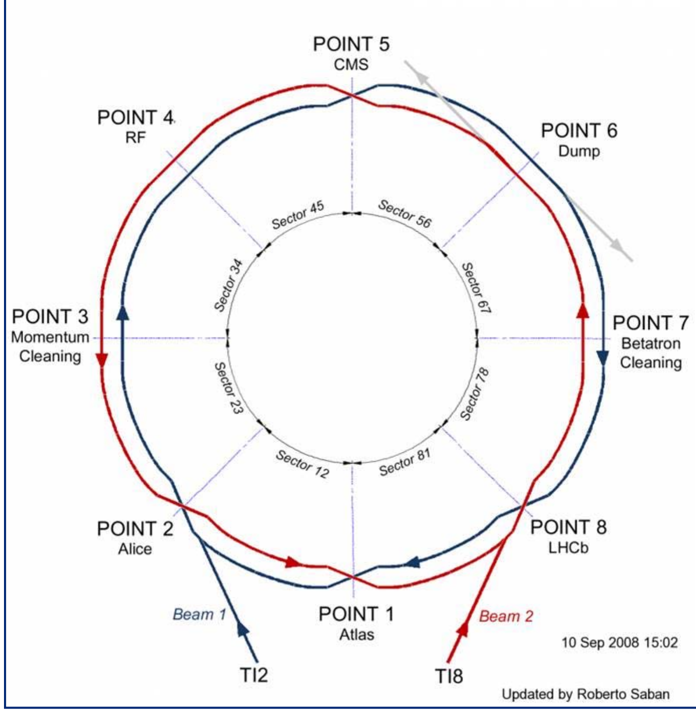






→ collect $2fb^{-1}$ per nominal year
→ ~ 10^{12} $b\bar{b}$ pairs produced per year

Status of the LHC accelerator



On 10 September 2008 (Media Day)

- 7 out of 8 sectors fully commissioned for 5 TeV operation and 1 sector (3-4) commissioned up to 4 TeV
- very impressive start-up with circulating beams

On 19 September very unfortunate failure of superconducting interconnect

- Major incident in sector 34 with subsequent repair and installation of new protection systems

Following substantial consolidation work, the machine will now start up in November 2009

- The LHC will run for the first part of the 2009-2010 run at 3.5 TeV per beam, with the energy rising later in the run (to max 5 TeV per beam)
- This allows the LHC operators to gain experience of running the machine safely while opening up a new discovery region for the experiments

➔ LHCb expects running in 2010 with L $\leq 10^{32}$ $cm^{-2}s^{-1}$ at 7-10 TeV CM energy, with the aim to accumulate ~$200 pb^{-1}$

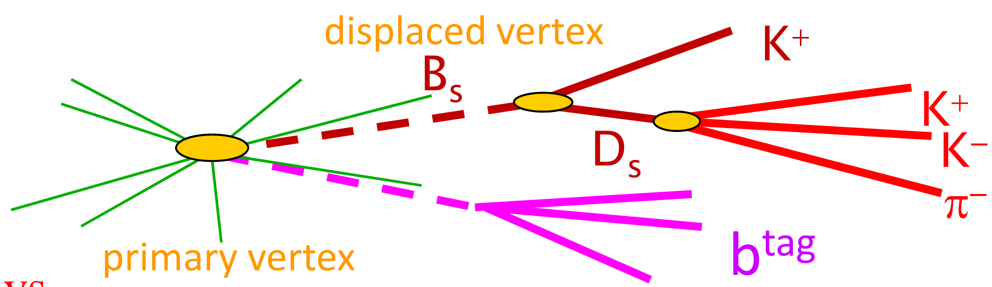
Requirements to detector performance

Triggering & selecting B's

- ✓ B's have a typical decay length of L~1cm in LHCb
- ✓ B decay products have large transverse momentum (because of their high mass)
- ➢ Select particles with high p_t that come from displaced vertex

Reconstructing B decays

- ✓ good mass resolution
- ✓ particle identification
- ➢ Efficient background reduction
- ✓ good decay time resolution
- ➢ Time resolved measurements for B_s decays



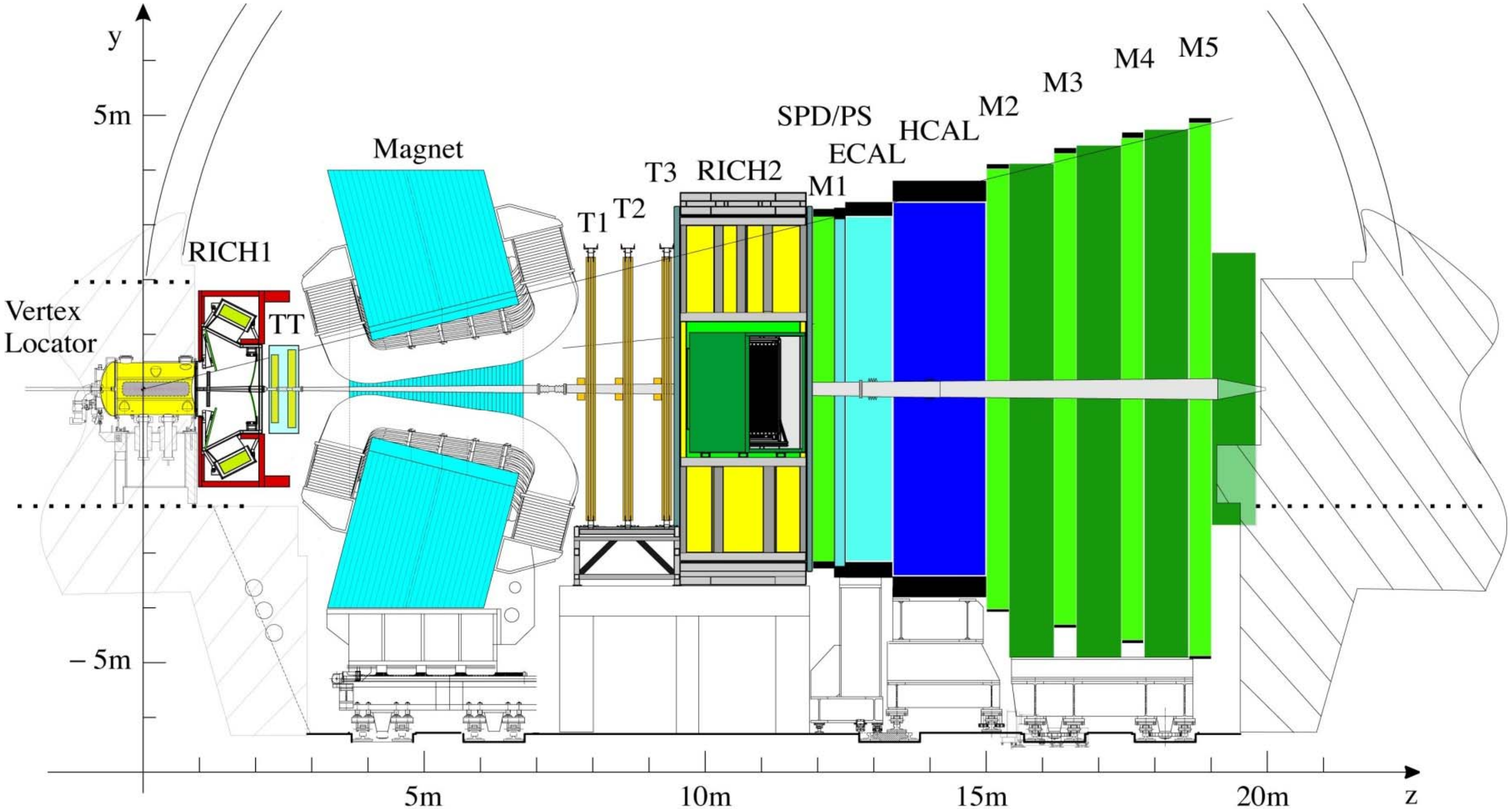
example: $B_s \rightarrow D_s K$ decay

Tagging flavour of the B at production

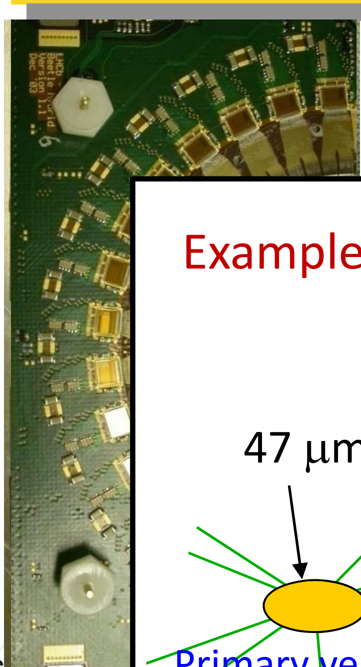
- ✓ Opposite side tagging of companion B (e.g. charge of the kaon in the b→ c→ s chain)
- ✓ Same side tagging (e.g. charge of the kaon accompanying the B_s)
- ➢ Tagging power: εD^2 = 4-5% for B^0_d and 7-9% for B^0_s

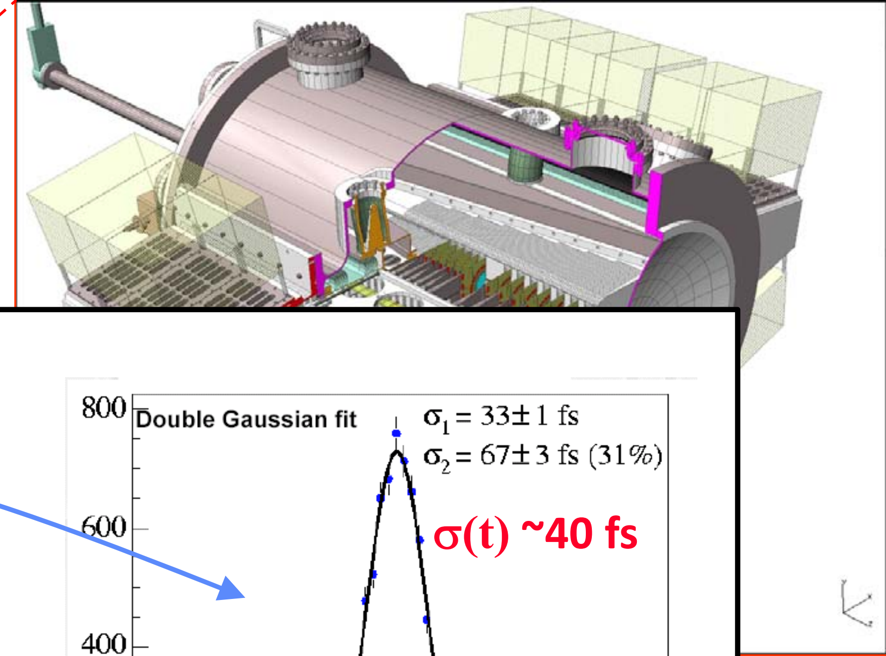
Detector overview and performance

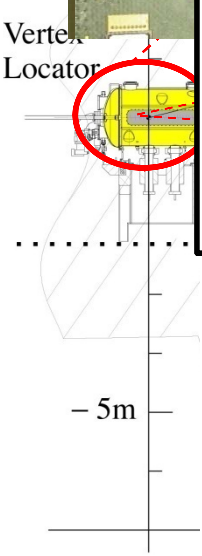
walk through the detector
with the example of a $B_s \rightarrow D_s K$ decay

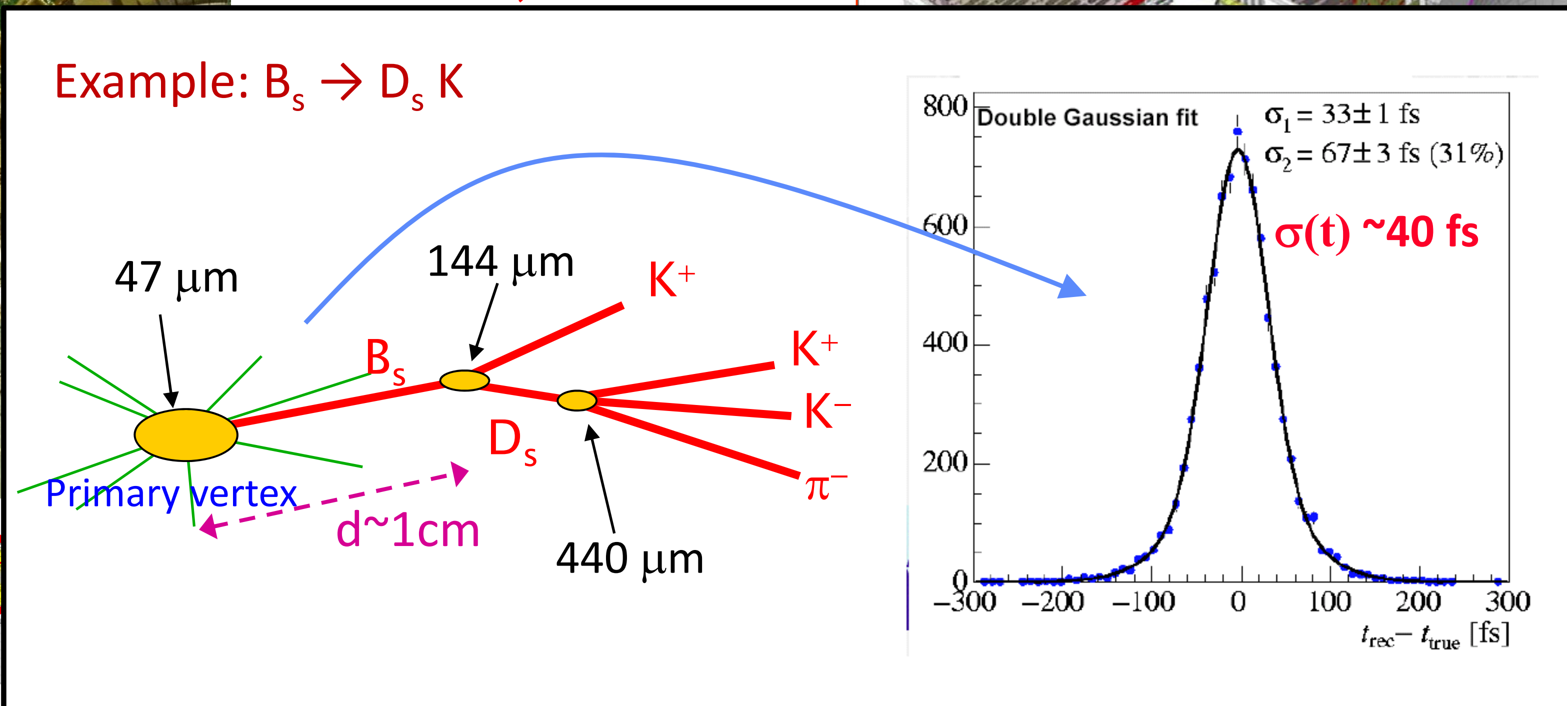


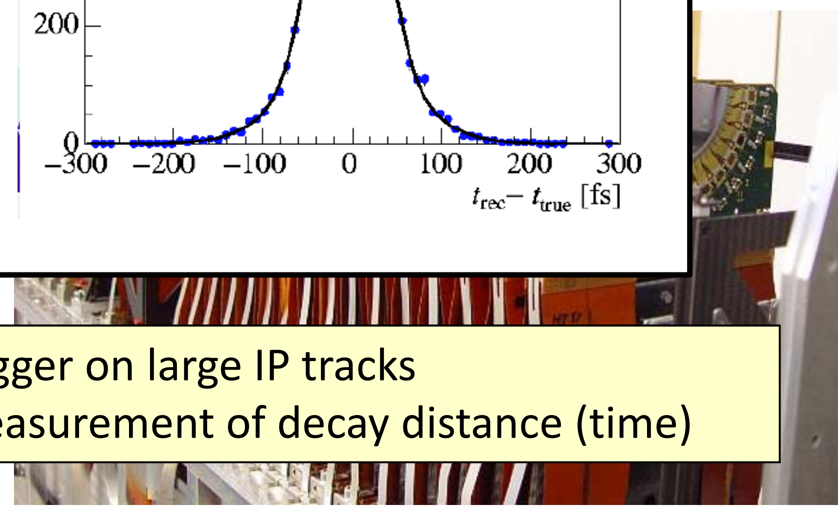
B-Vertex Measurement











Vertex Locator (Velo)

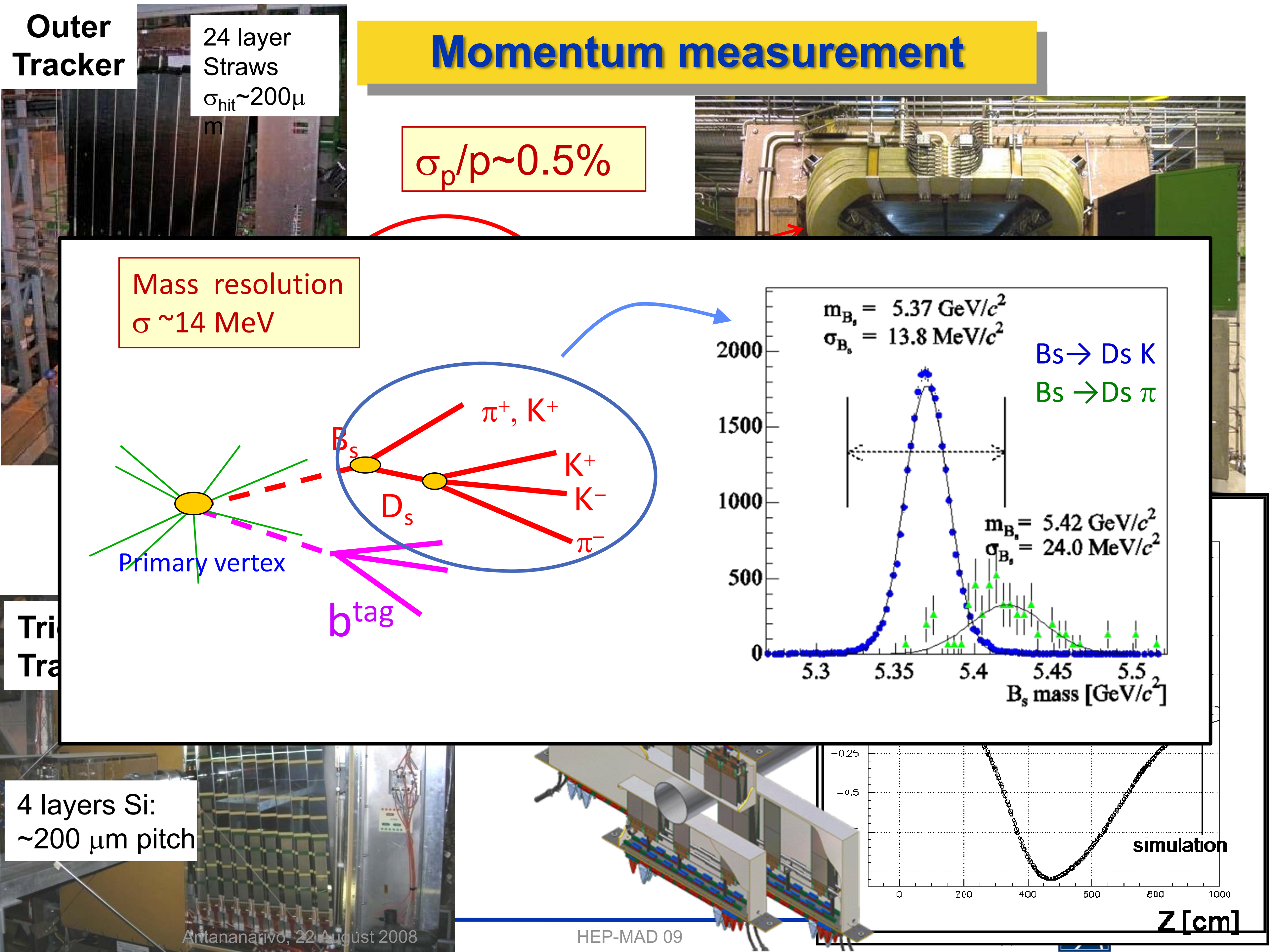
21 stations of silicon strip detectors (r-ϕ)

~ 8 μm hit resolution

~25 μm IP resolution

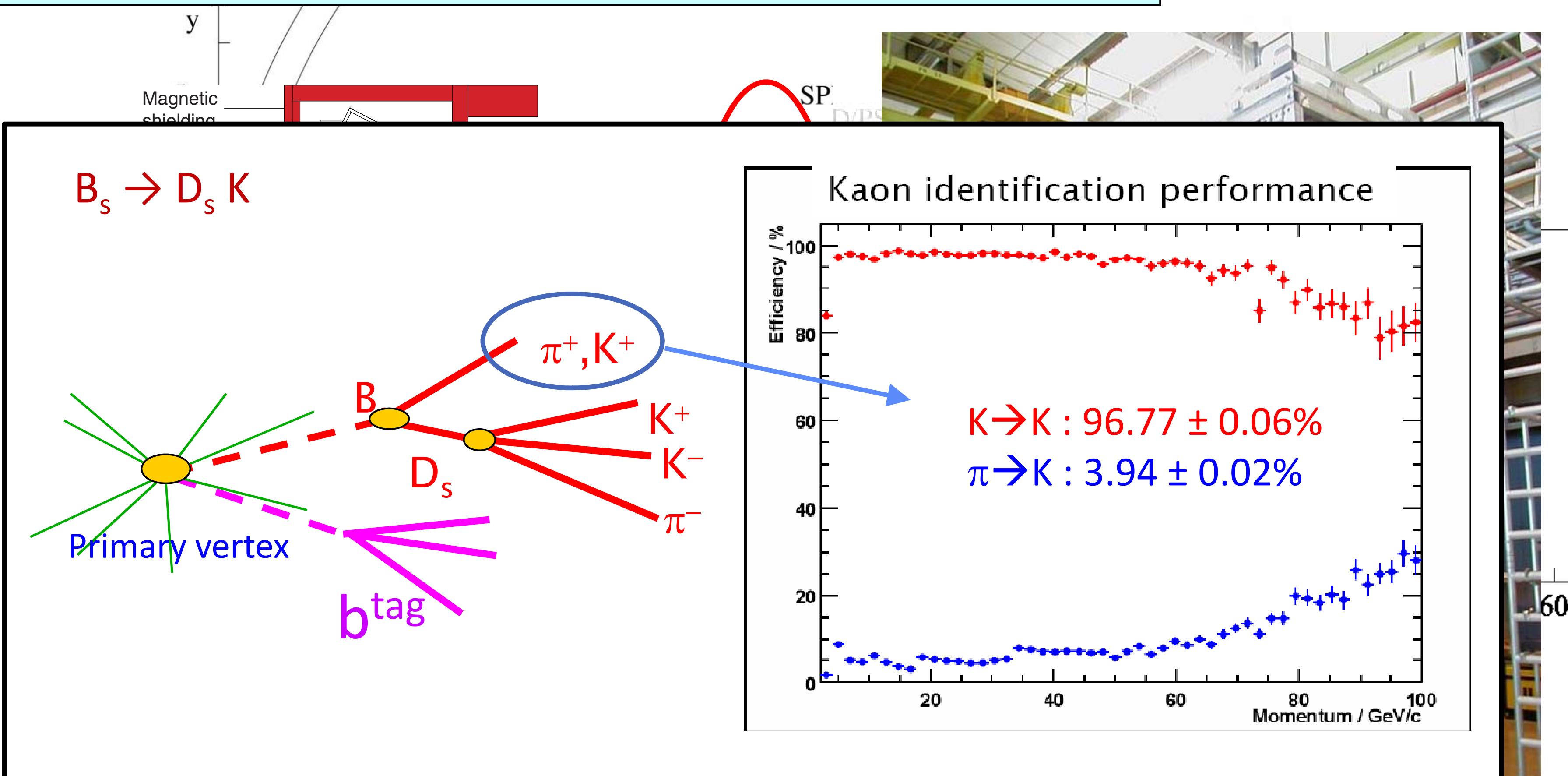
- Trigger on large IP tracks
- Measurement of decay distance (time)

Momentum measurement



Particle Identification

RICH: K/π identification using Cherenkov light emission angle

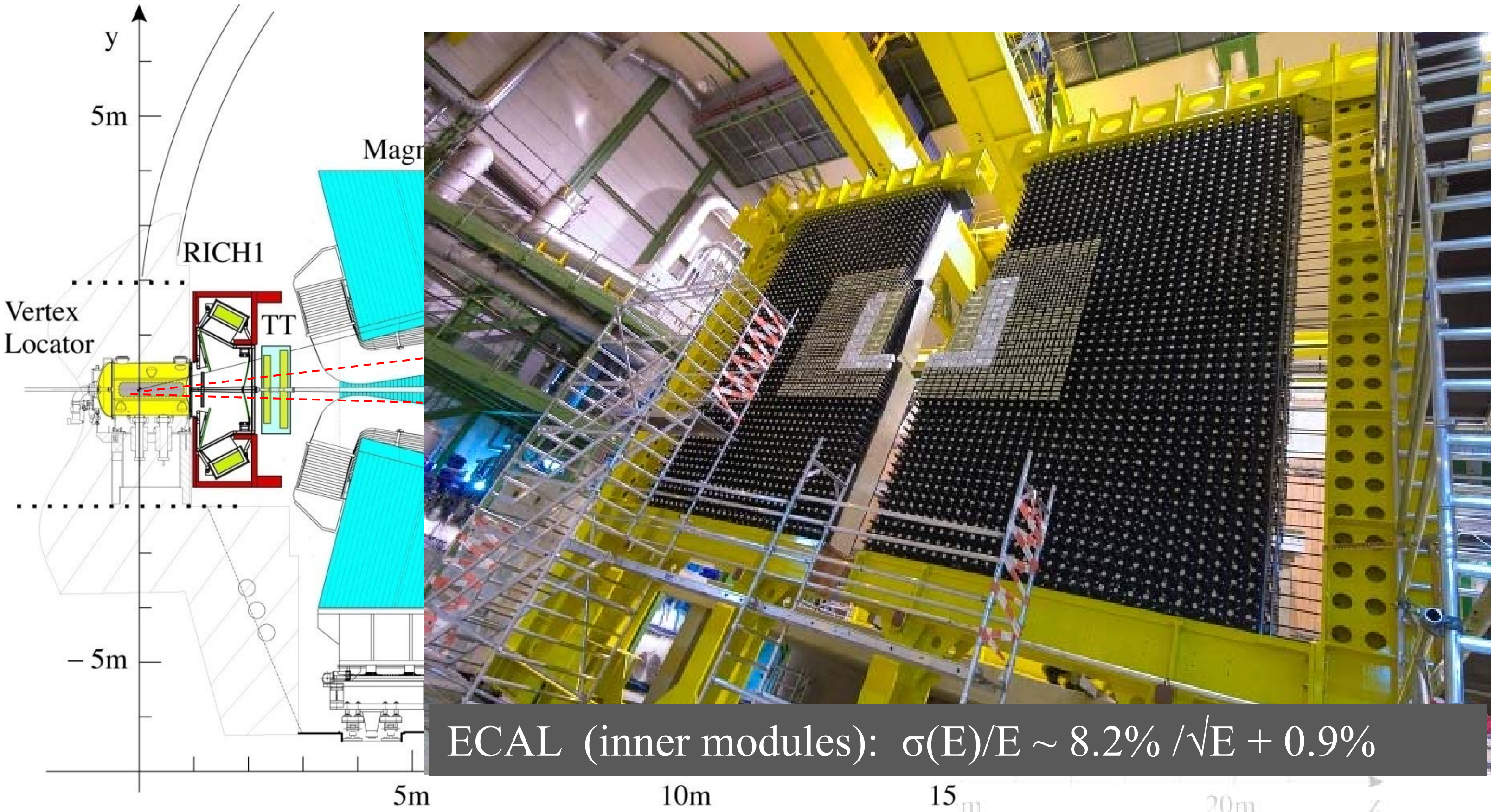


RICH1: 5 cm aerogel n=1.03

4 m^3 C_4F_{10} n=1.0014

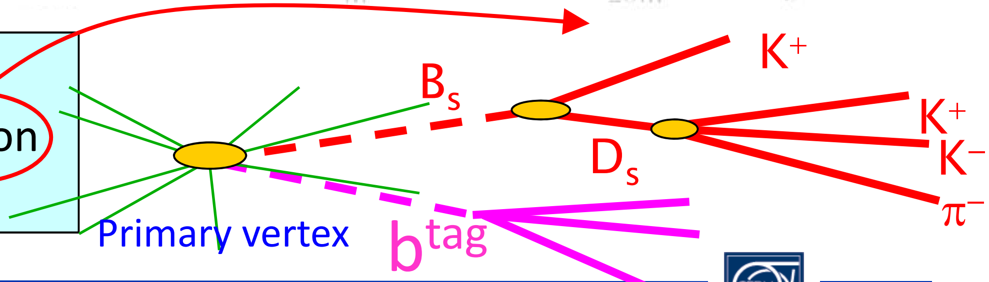
RICH2: 100 m^3 CF_4 n=1.0005

Particle identification and L0 trigger

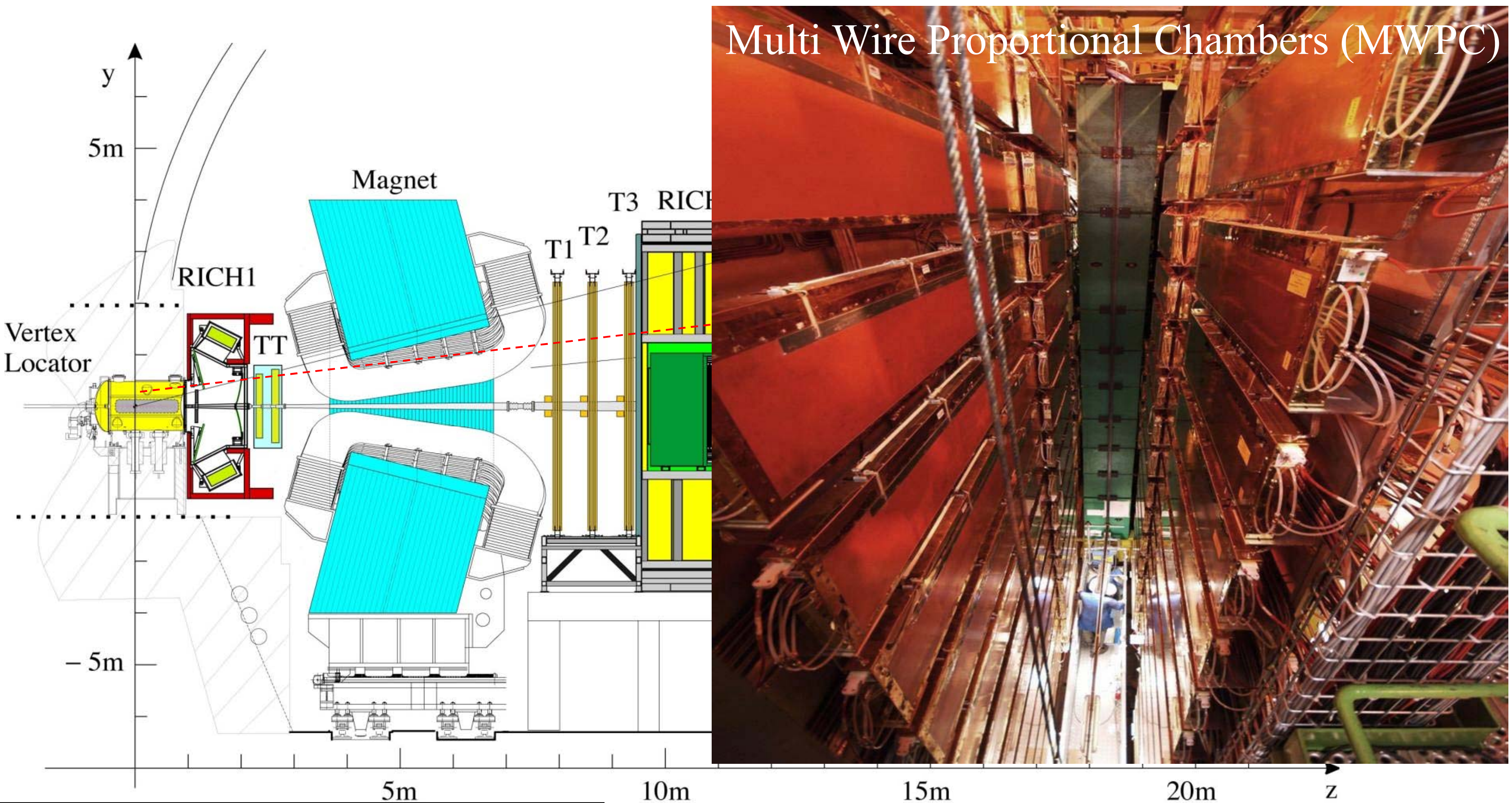


Calorimeter system :

- Level 0 trigger: high E_T electron and hadron
- Identify electrons, hadrons, π^0 ,γ

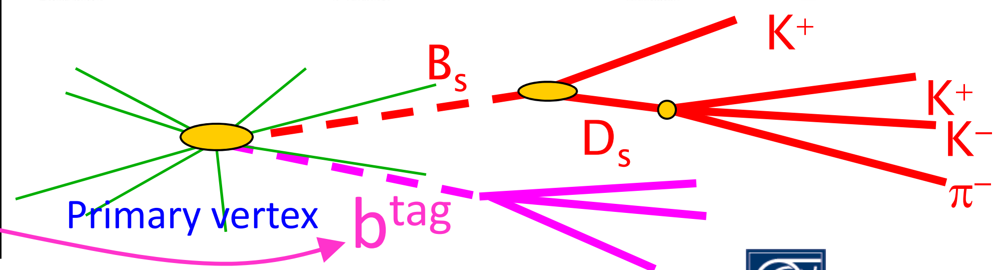


Particle identification and L0 trigger

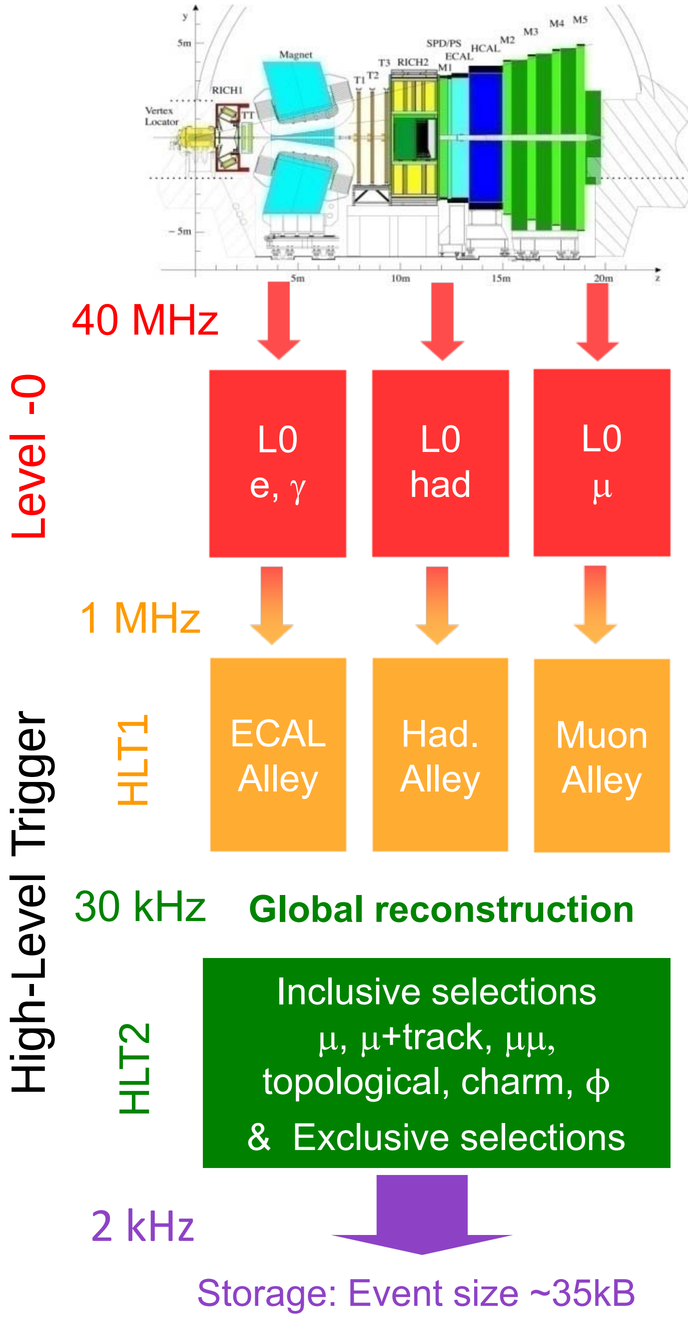


Muon system:

- Level 0 trigger: High P_t muons
- Identify muon
  (also important for flavour tagging)



LHCb trigger



Trigger is crucial:

- $\sigma_{b\bar{b}}$ is less than 1% of total inelastic cross section
- B decays of interest typically have BR < 10^{-5}

Hardware level (L0)

- Search for high-p_T μ, e, γ and hadron candidates

Software level (High Level Trigger, HLT)

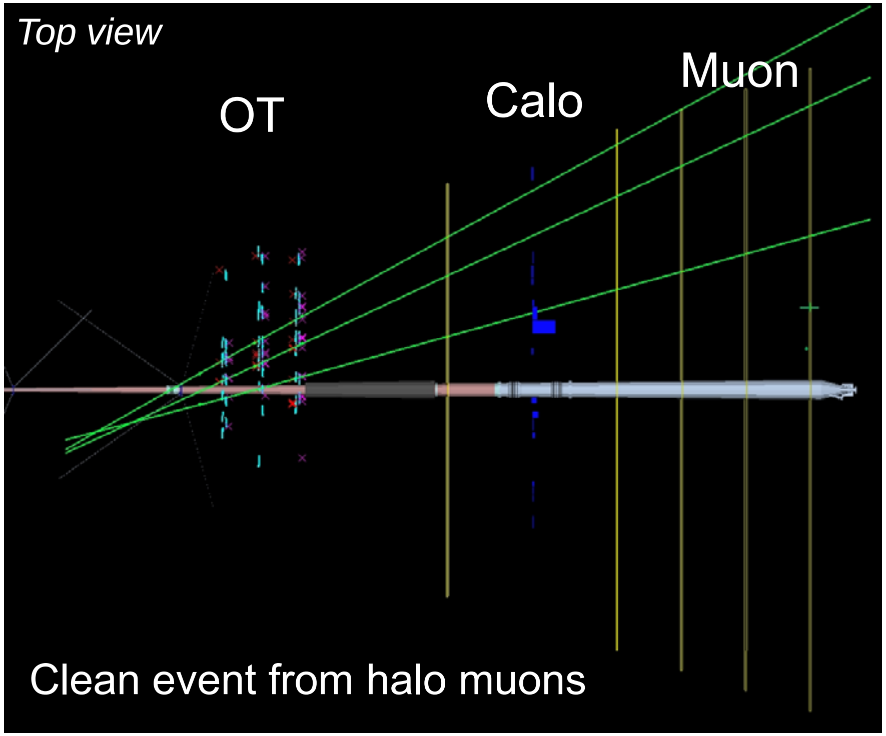
Farm with O(2000) multi-core processors

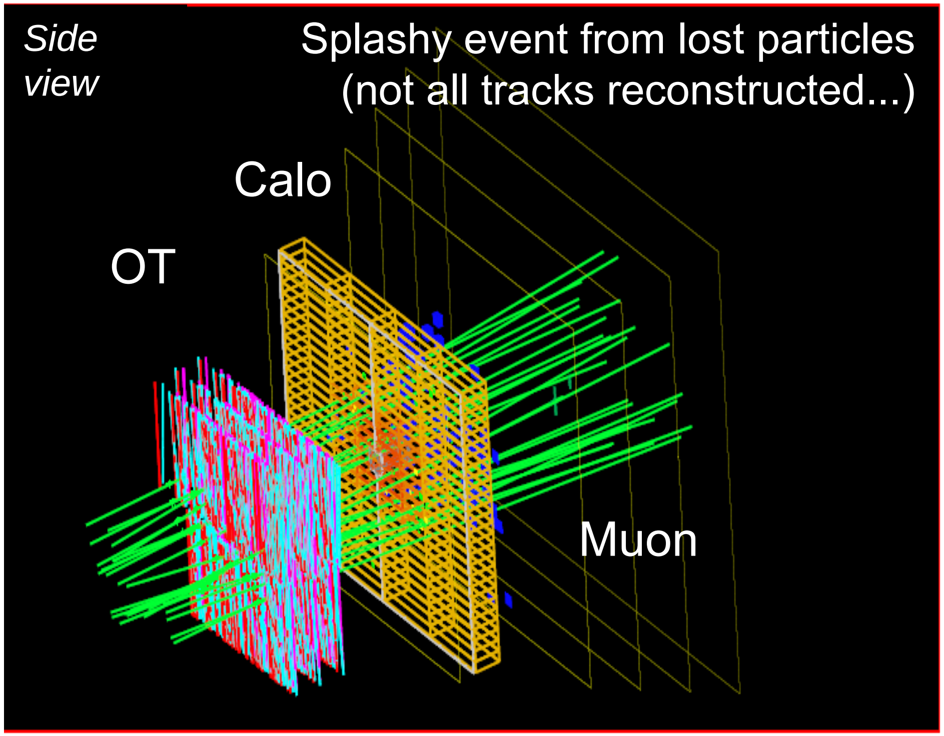
- HLT1: Confirm L0 candidate with more complete info, add impact parameter and lifetime cuts
- HLT2: B reconstruction + selections

Trigger efficiency	ε(L0)	ε(HLT1)	ε(HLT2)
Electromagnetic	70 %		
Hadronic	50 %	> ~80 %	> ~90 %
Muon	90 %		

Status of LHCb

- LHCb detector fully installed and commissioned, including L0 trigger
- Events registered at LHC start-up on 10 September 2008 (media day)

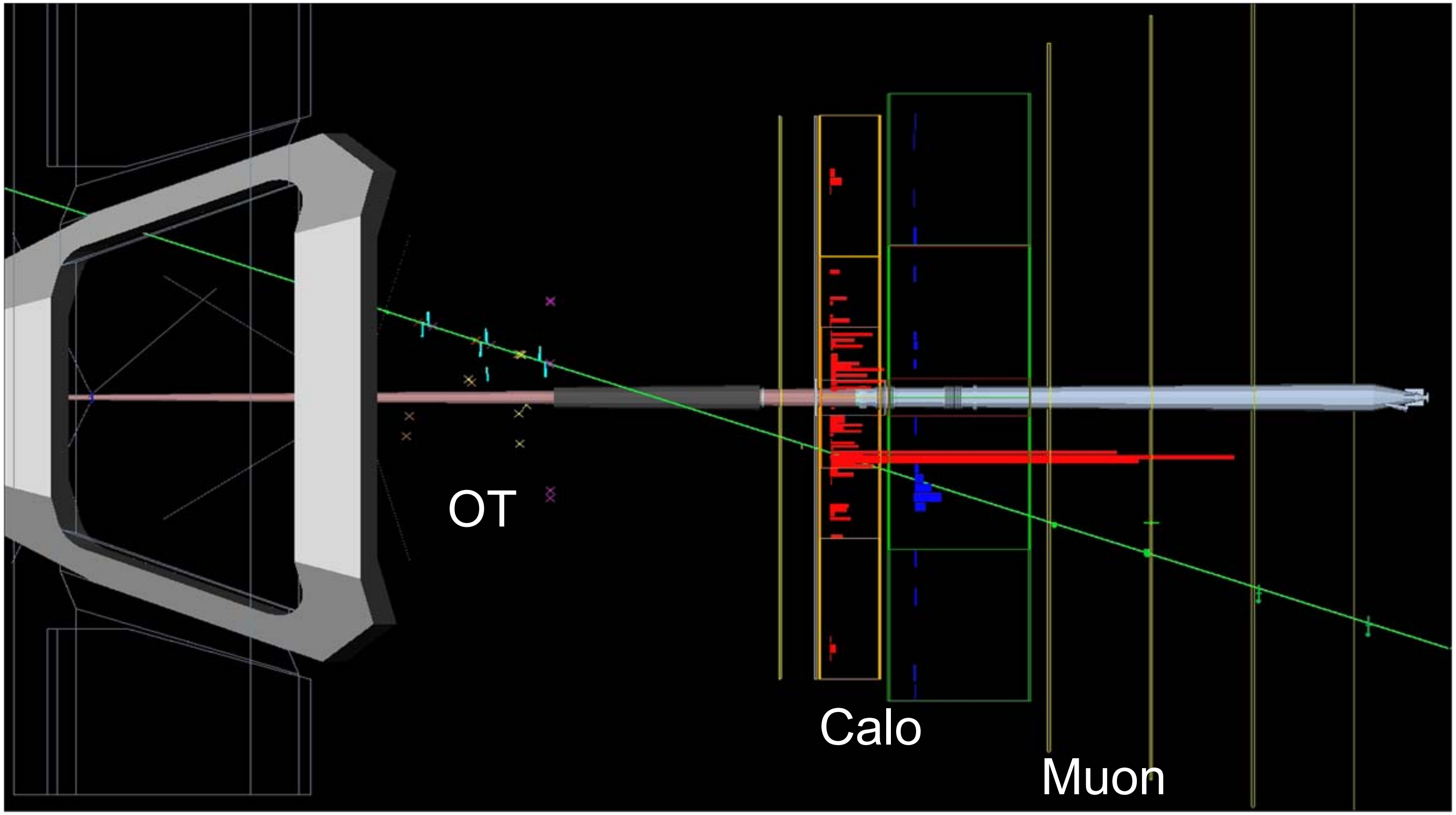




- All sub-detectors have undergone the first time and space alignment with cosmics & LHC beam-induced particles

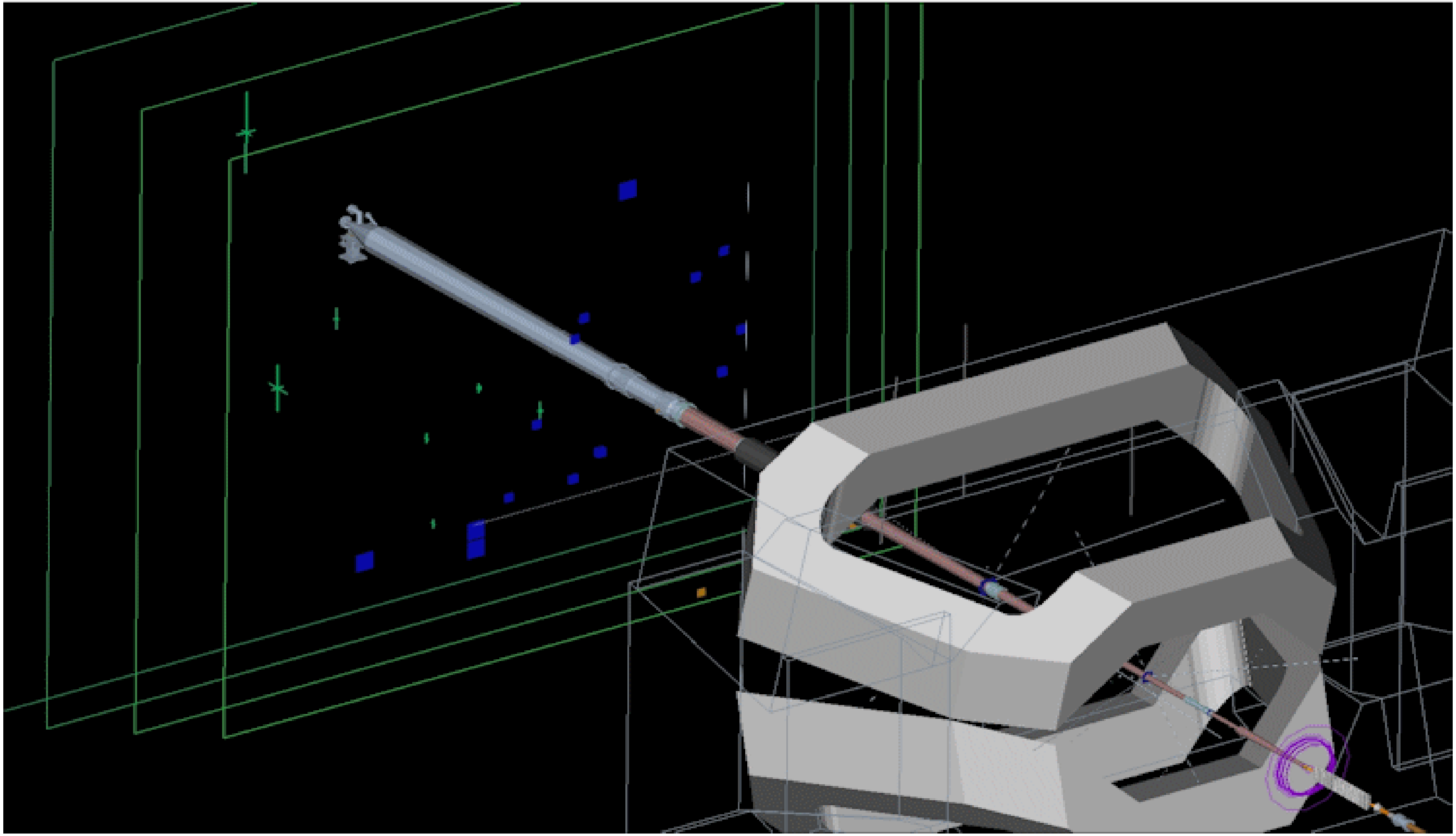
Commissioning with Cosmics

- ✓ LHCb geometry NOT well suited for cosmics… A challenge!
- ✓ Calorimeters used to trigger on useful 'horizontal' cosmics
  → Rate of 'horizontal' cosmics below 1 Hz, still very useful
- ✓ Collected a total of ~$1.1*10^6$ triggers to perform 1st time synchronization (~few ns) and space alignment (~1 mm) of large area detectors



Commissioning with Cosmics

10.9. 2008 11:25:26 -25ns

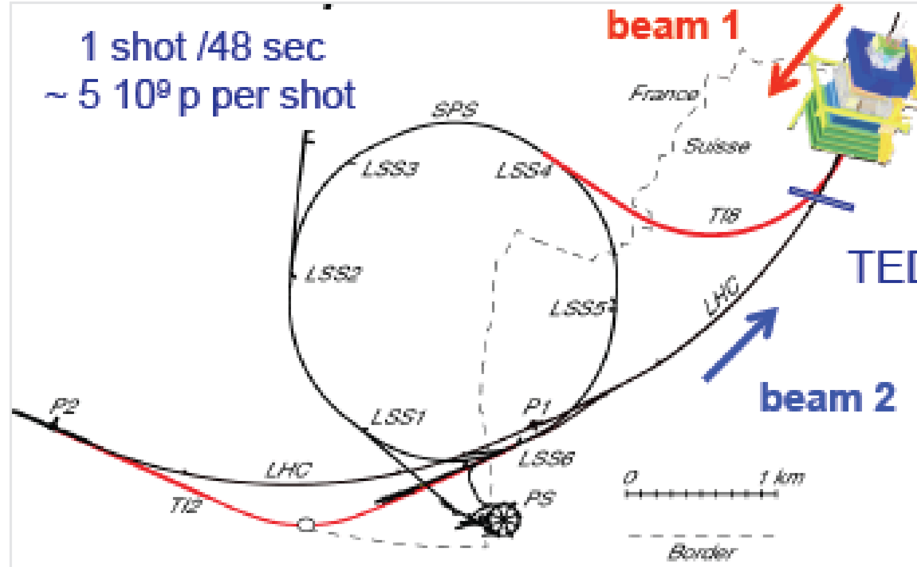


Readout of consecutive 25ns crossings for a single trigger

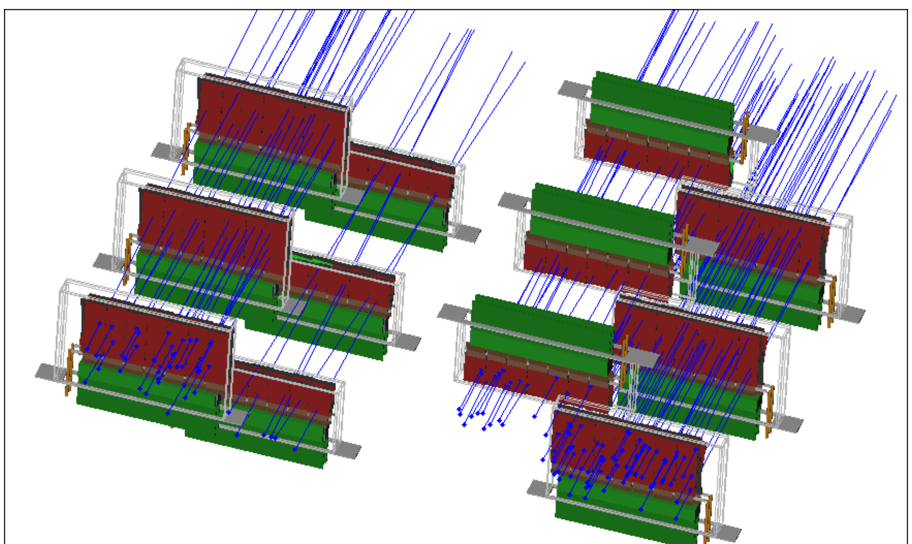
Commissioning with beam-induced particles

Beam 2 dumped on beam stopper (TED) in injection line:

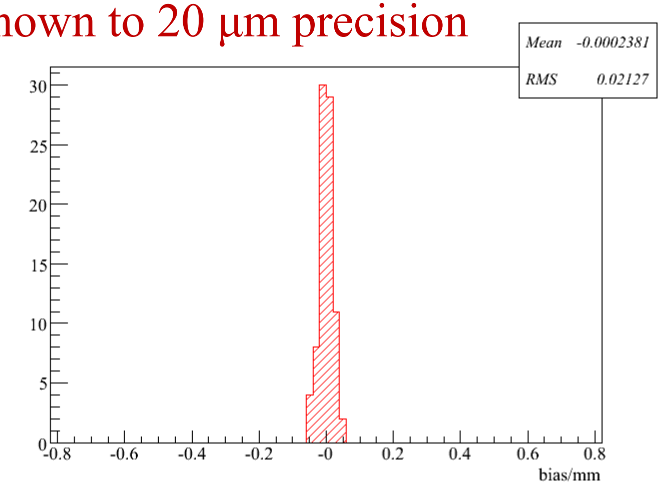
- TED located 340 m away from LHCb
- High flux O(10) particles / cm^2
- particles cross LHCb in a wrong direction
- ~40 k tracks collected and used to align high granular Vertex (VELO) and Inner Tracker (IT) detectors



Inner Tracker

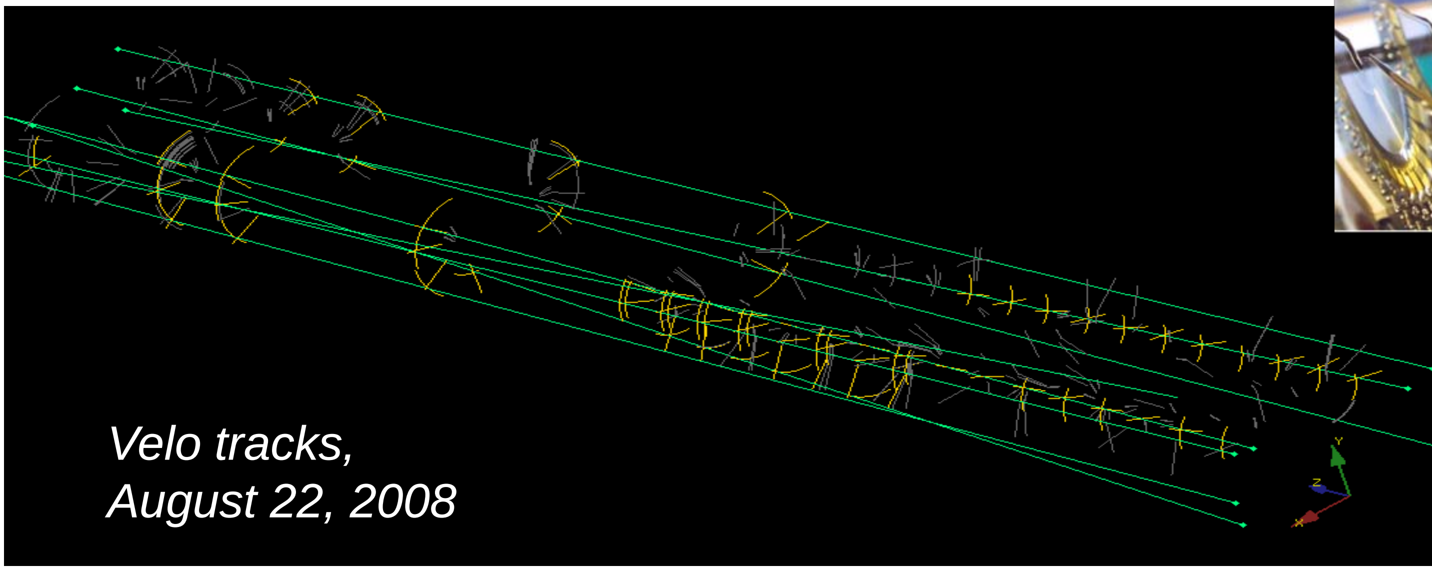


Ladder position in the Inner Tracker is known to 20 μm precision

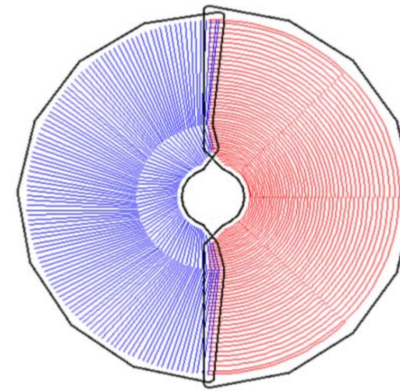


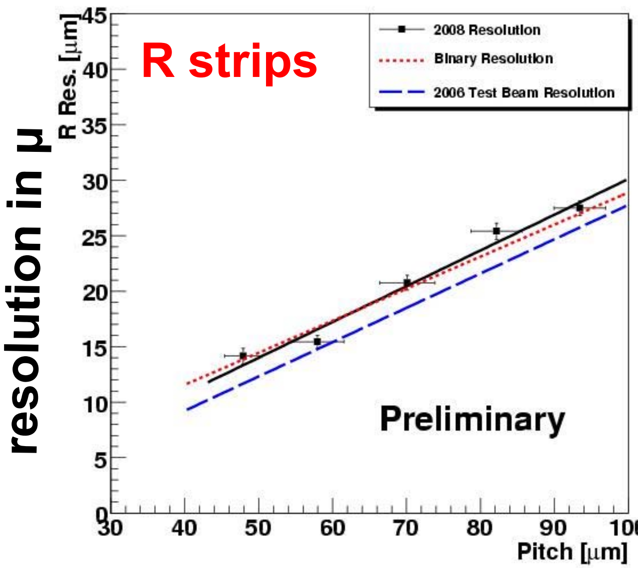
Commissioning with beam-induced particles

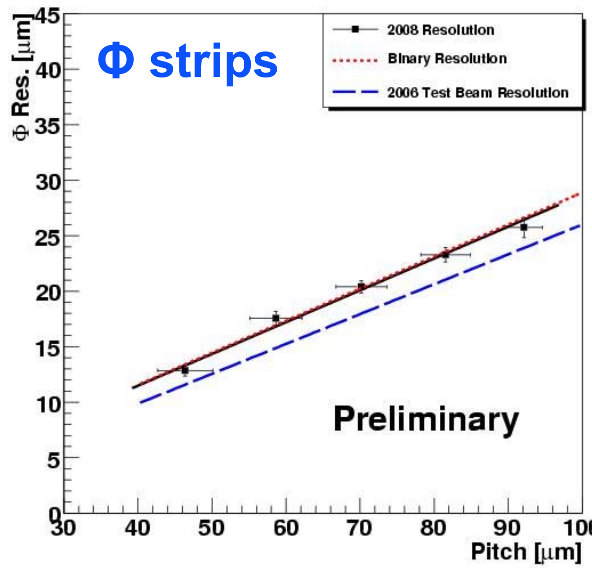
VELO alignment: TED tracks cross detector almost parallel to z-axis



21 stations of Si wafer pairs with R and Φ strip readout







Resolution estimated from VELO hit residuals, agrees well with expectations

Further improvement possible

Search for New Physics

Search for effects induced by New Physics in CP violation and Rare decays using the FCNC processes mediated by loop diagrams (box and penguin)

are New Physics already around the corner ?
(see EPS09 talk by Punzi)

LHCb key measurements

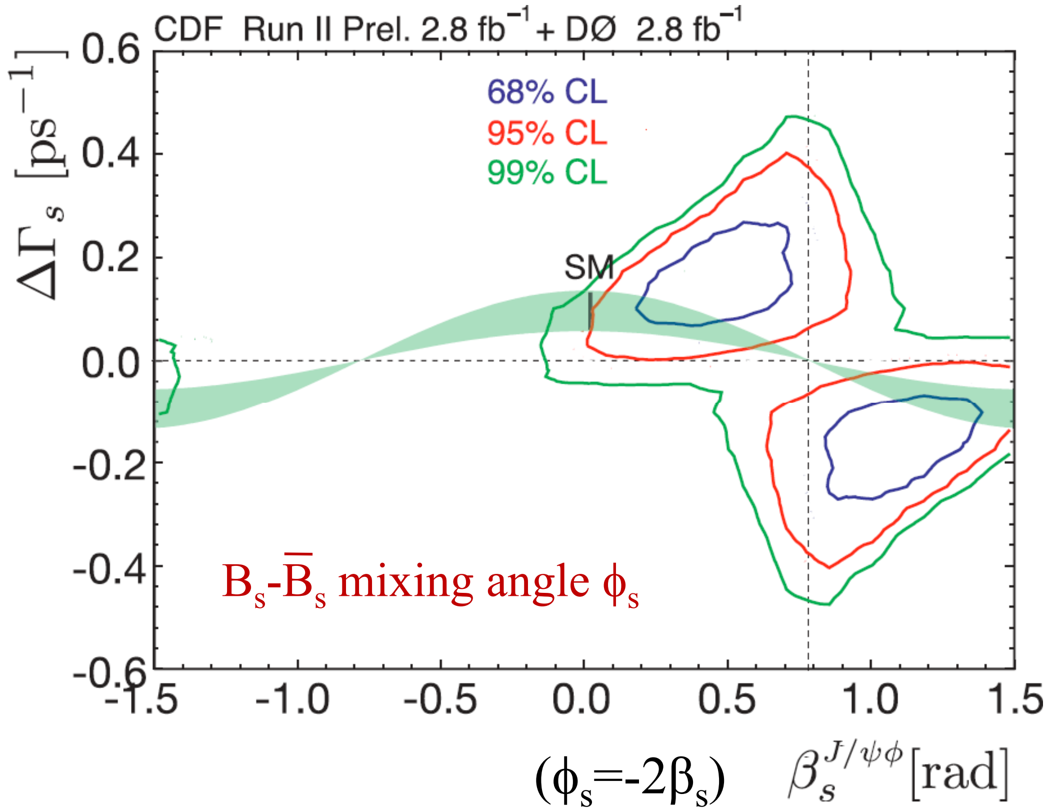
<u>in CP–violation</u>: → S. Poss

- B_s-$\bar{B}_s$ mixing angle ϕ_s
- weak phase γ in trees
- weak phase γ in loops

<u>in Rare Decays</u>: → V. Egorychev

- branching ratio of $B_s \to \mu\mu$
- forward-backward asymmetry in $B \to K^*\mu\mu$
- polarization of photon in radiative penguin decays

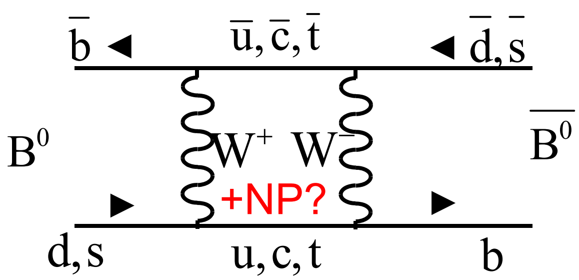
(early measurements in red)



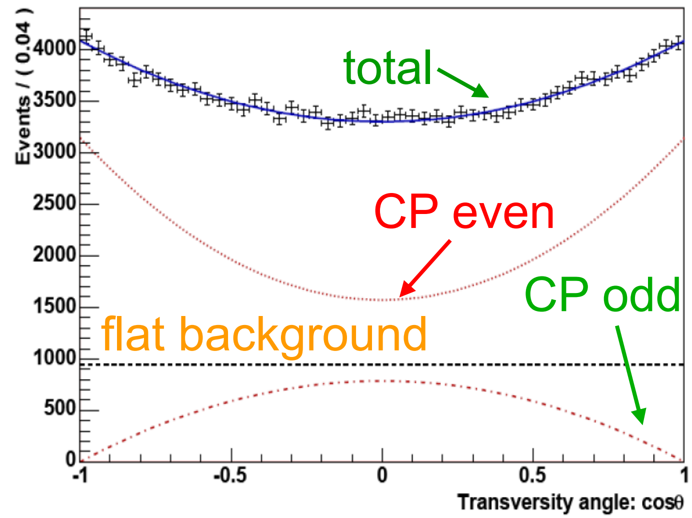
SM p-value = 0.034 (2.1σ)
(2.0 σ at nearest point)

B_s-$\bar{B}_s$ mixing phase ϕ_s in $B_s \to J/\psi(\mu\mu)\,\phi$

- ✓ Sensitive to New Physics effects in mixing
- ➢ $\phi_s = \phi_s(SM) + \phi_s(NP)$

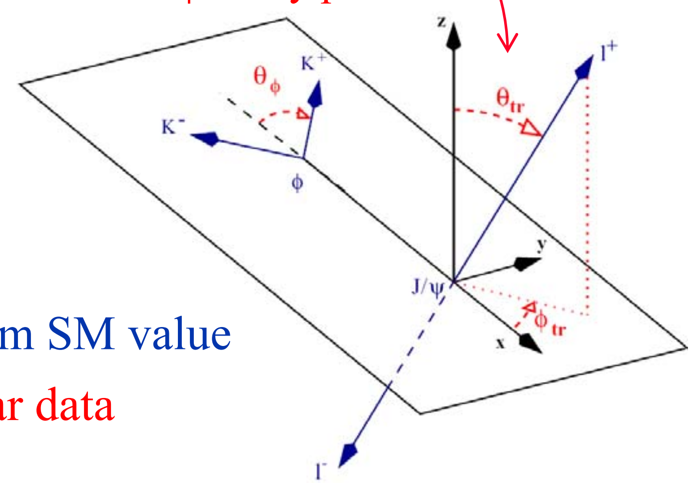


- ➢ in SM: $\phi_s = -2\beta_s = -\arg(V_{ts}^2) = -0.036\ \ 0.002$



- ✓ $J/\psi\phi$ is not a pure CP eigenstate (2 CP even, 1 CP odd amplitude)
- ➢ need to fit angular distributions of decay final states as function of proper time (requires very good proper-time resolution)

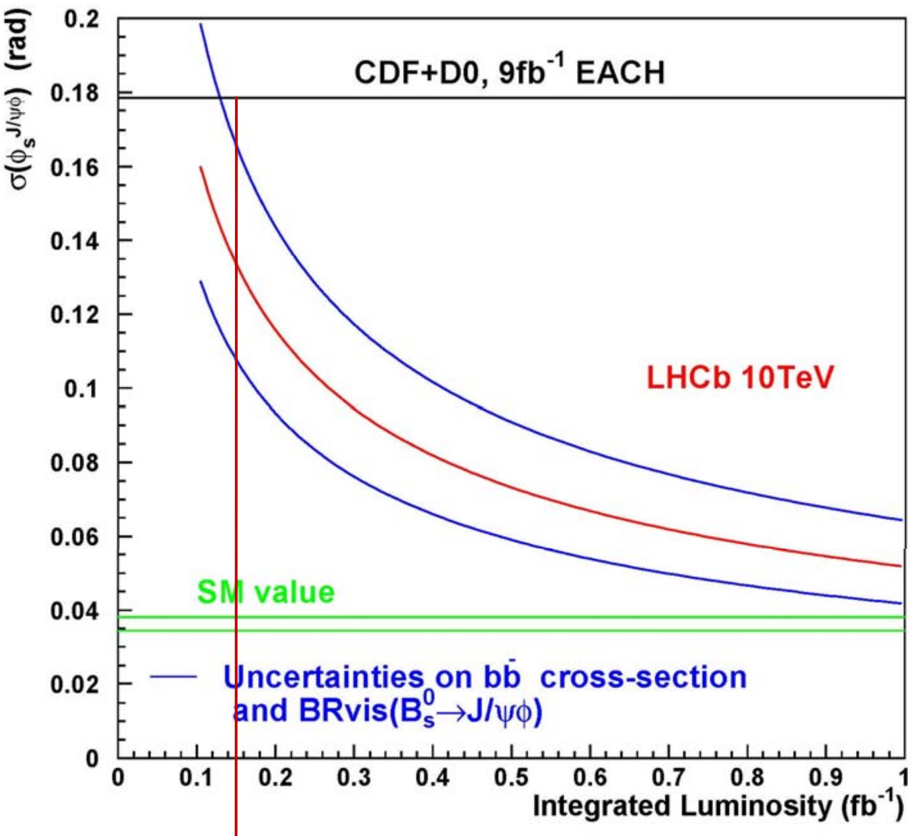
Θ_{tr}= angle between l^+ and normal to ϕ decay plane

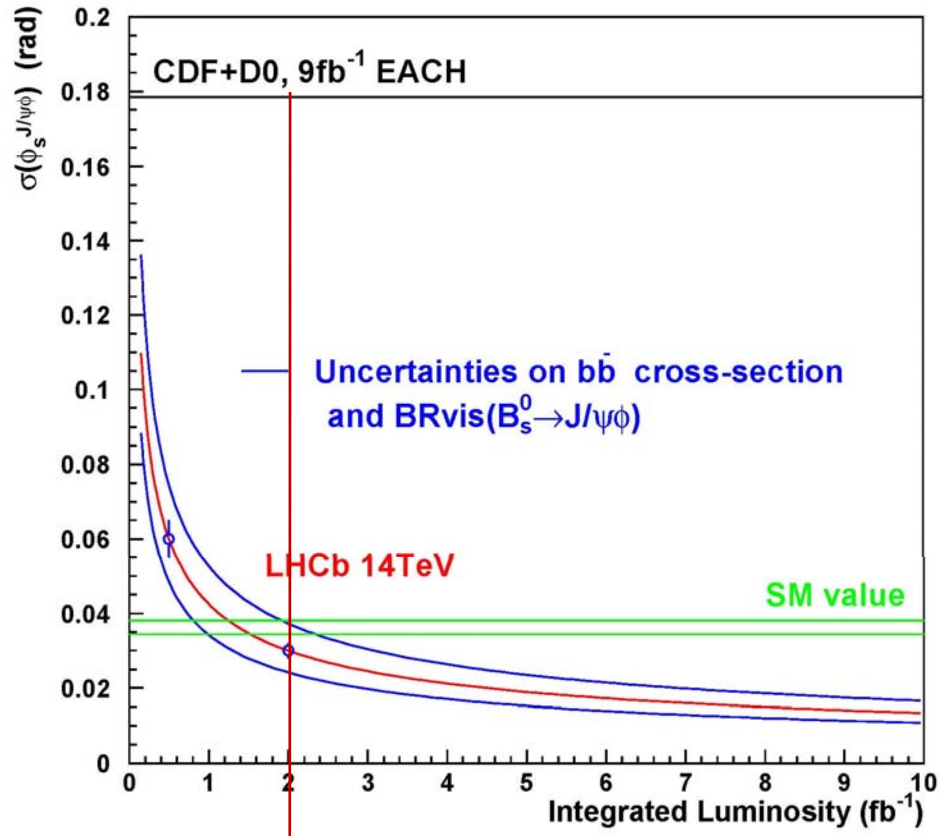


- ✓ with 2.8 fb^{-1} current Tevatron result ~2.1σ away from SM value
- ➢ Hope to improve significance with LHCb's first year data

B_s-$\bar{B}_s$ mixing phase ϕ_s in $B_s \to J/\psi(\mu\mu)\phi$

Physics reach for ϕ_s measurement as function of integrated luminosity



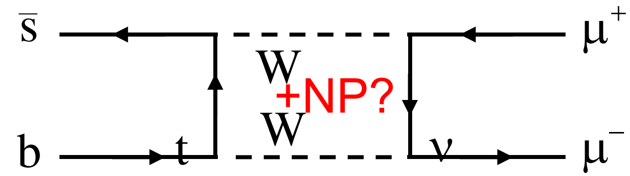


→ collect ~0.15 fb^{-1} to improve on expected Tevatron limit with 9 fb^{-1}

→ with ~2 fb^{-1} $\sigma(\phi_s)$ reaches SM value

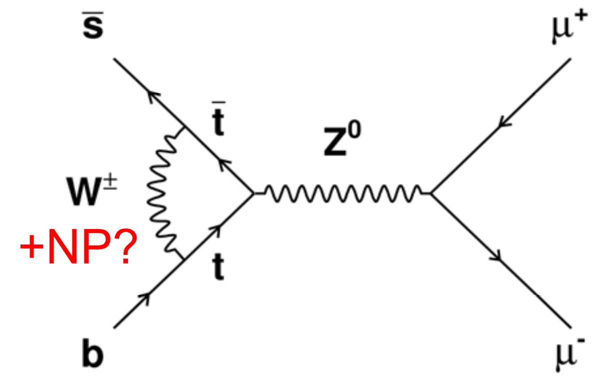
Branching Ratio of rare decay $B_s \rightarrow \mu^+\mu^-$

- ✓ Very rare loop decay, sensitive to New Physics
- ✓ BR ~ 3.35×10^{-9} in SM, can be strongly enhanced in SUSY with scalar Higgs exchange (scales like ~$\tan^6\beta$)

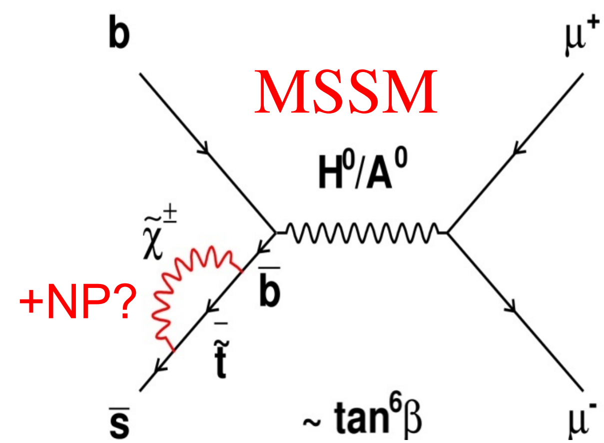


<u>Main issues are statistics and background rejection</u>:

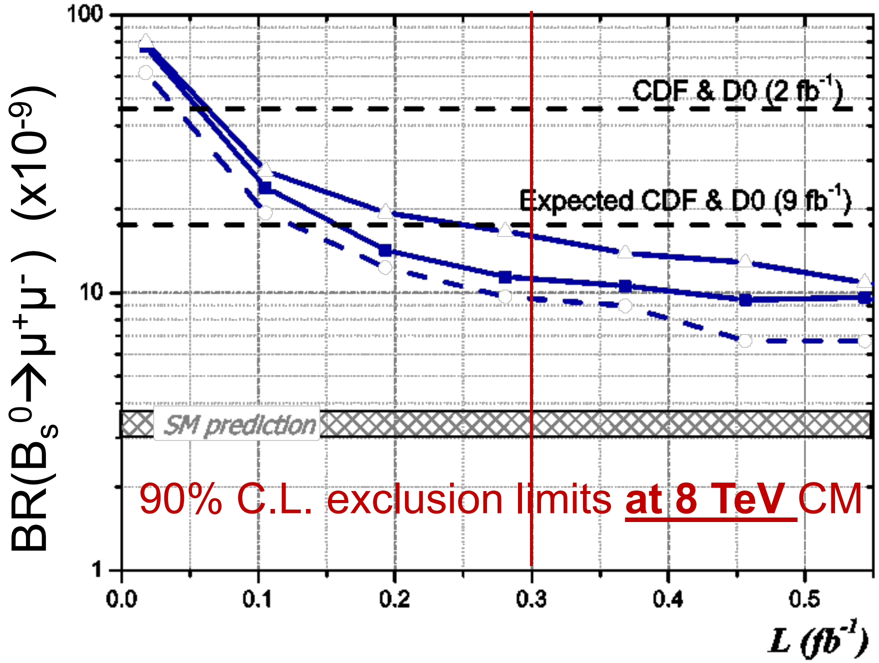
- ➢ very efficient trigger for signal
- ➢ background dominated by $B\rightarrow\mu^+X$, $\overline{B}\rightarrow\mu^-X$ decays
- ➢ good mass resolution (18 Mev/c^2), vertexing and PID essential
- ➢ to minimize dependence on MC simulation, various control channels will be used ($B^+\rightarrow J/\psi\ (\mu^+\mu^-)\ K^+$, $B\rightarrow J/\psi\ (\mu^+\mu^-)\ K^*\ (K^+\pi^-)$, $B_{(s)}\rightarrow h^+h^-$)



- ➢ current limit from CDF: < 43 10^{-9} (90% CL)
- ➢ with 9 fb^{-1} expect: < 20 10^{-9} (90% CL)
  ~5 times higher than SM prediction

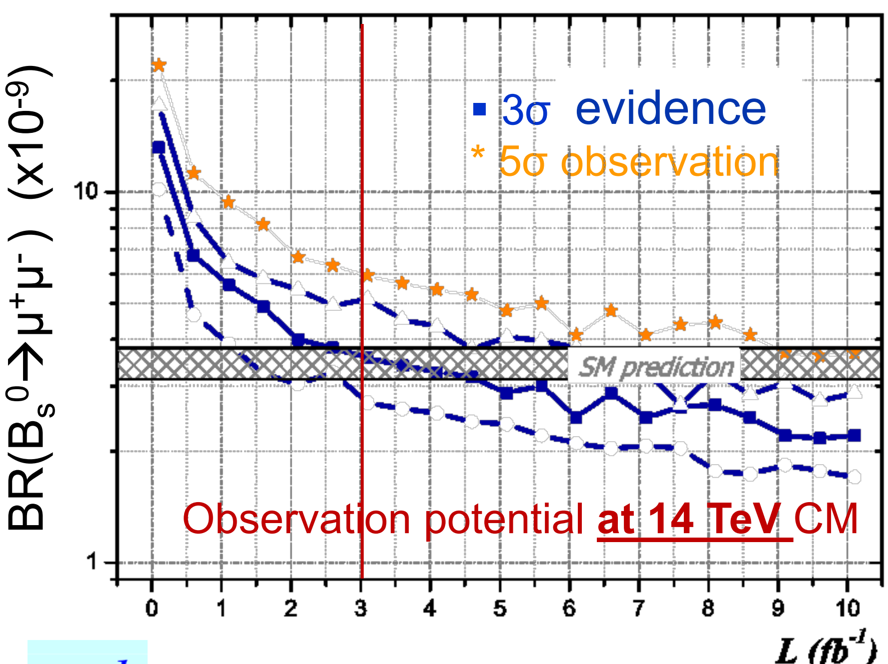


Branching Ratio of rare decay $B_s \to \mu^+\mu^-$



Physics reach for BR($B_s^0 \to \mu^+\mu^-$) measurement as function of integrated luminosity (and comparison with Tevatron)

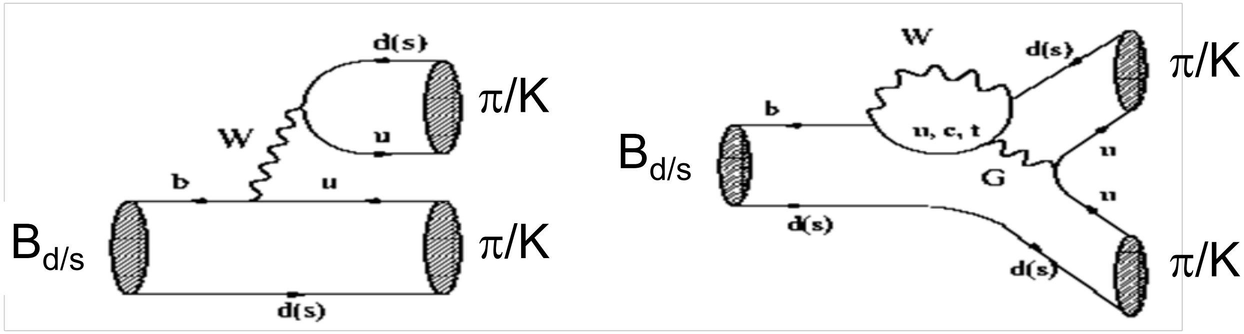
→ collect ~0.3 fb^{-1} to improve on expected Tevatron limit with 9 fb^{-1}



→ collect ~3 fb^{-1} for 3σ evidence and ~10 fb^{-1} for 5σ observation of SM value

γ in loops from $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$

- large penguin contributions in both decays → sensitive to New Physics



- measure <u>time-dependent CP asymmetry</u> for $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$
  - ✓ $A_{CP}(t) = A_{dir} \cos(\Delta mt) + A_{mix} \sin(\Delta mt)$
  - ✓ A_{dir} and A_{mix} depend on γ, mixing phases, and ratio of penguin to tree = $d\, e^{i\theta}$

- exploit "U-spin" symmetry (d↔s) *[R.Fleischer, Phys.Lett. B459, 306 (1999)]*
  - ✓ assume $d_{\pi\pi} \approx d_{KK}$ within 20% and $\theta_{\pi\pi} \approx \theta_{KK}$ within 20
  - ✓ 4 measurements and 3 unknowns, if mixing phase 2β taken from $B^0 \to J/\psi K_S$ and ϕ_s left free in the fit (to be compared to $B_s \to J/\psi\, \phi$ measurement)

<u>Expected sensitivity:</u>

- ✓ 59k $B^0 \to \pi^+\pi^-$ with B/S~0,5
- ✓ 72k $B_s \to K^+K^-$ with B/S~0.07

➔ $\sigma(\gamma) \sim 7$ in 1 year/$2fb^{-1}$ assuming U-spin symmetry at the level of 20%

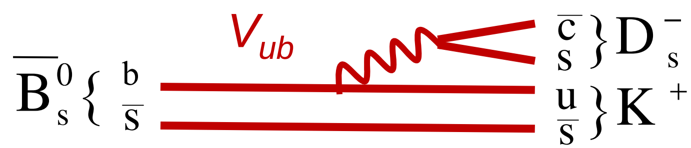
γ in trees from $B_s \to D_sK$

✓ 2 time dependent asymmetries from 4 decay rates:
B_s ($\overline{B}_s$) $\to D_s^- K^+$, $D_s^+ K^-$

✓ 2 tree decays *(b→c)* and *(b→u)* of same magnitude interfere via B_s mixing:

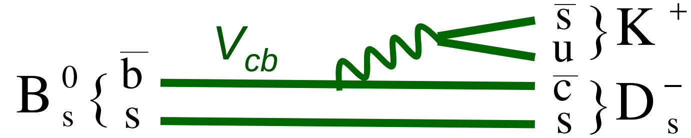
→ large interference effects expected

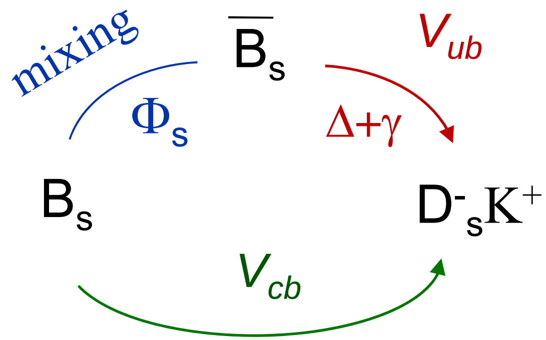
→ insensitive to new physics

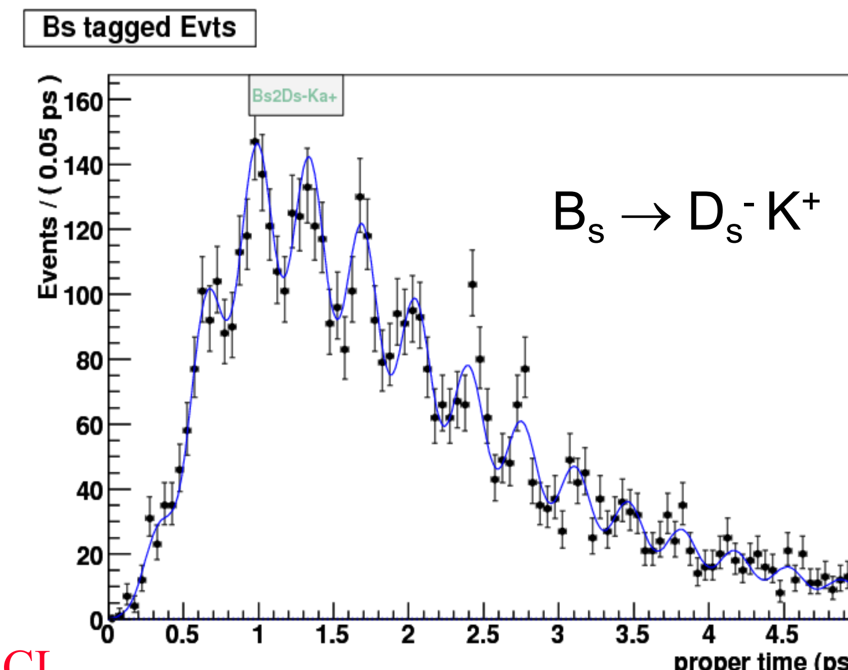


***b→u* transition, phase Δ+γ**

***b→c* transition, phase 0**







Fit the 4 tagged, time-dependent rates:

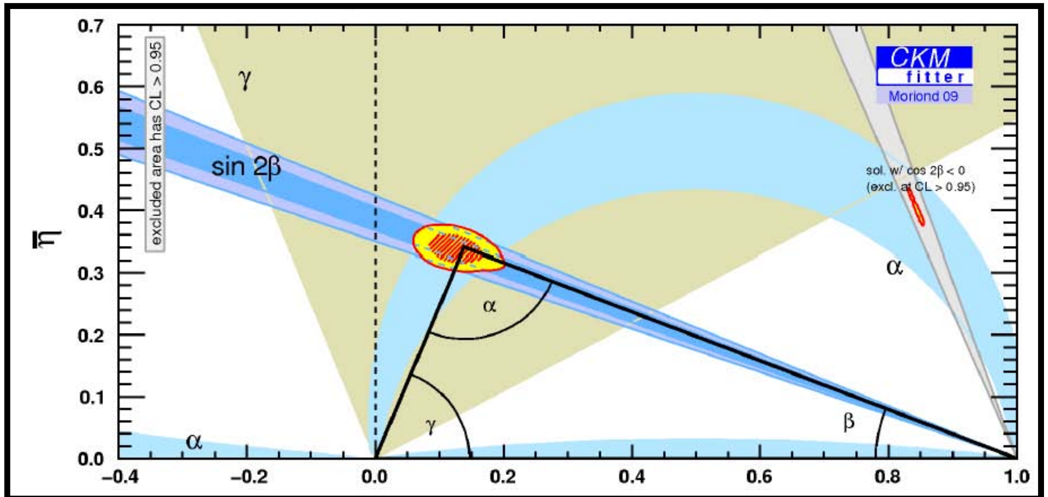
✓ phase of $D^-_s K^+ = \Delta + (\gamma + \phi_s)$

✓ phase of $D^+_s K^- = \Delta - (\gamma + \phi_s)$

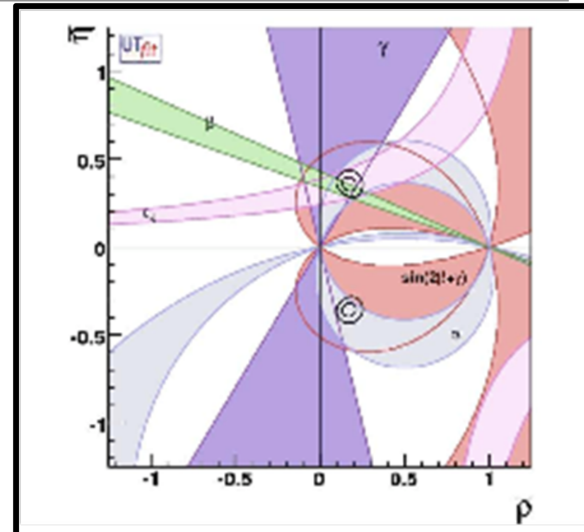
→ extract both Δ and $(\gamma + \phi_s)$
with ϕ_s being determined using $B_s \to J/\psi\ \phi$

Expect ~6200 signal events with B/S~0.7 at 90% CL
→ $\sigma(\gamma)$ ~ 9-12 in 1 year/$2fb^{-1}$

Determination of γ in loops and trees



$$\gamma = (70^{+27}_{-29})^\circ$$

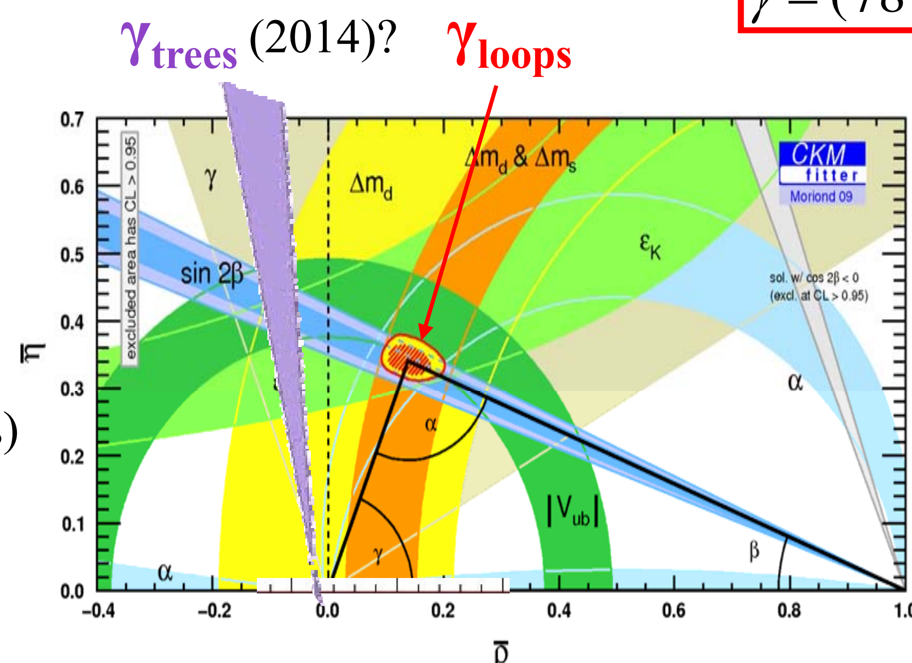


$$\gamma = (78 \pm 12)^\circ$$

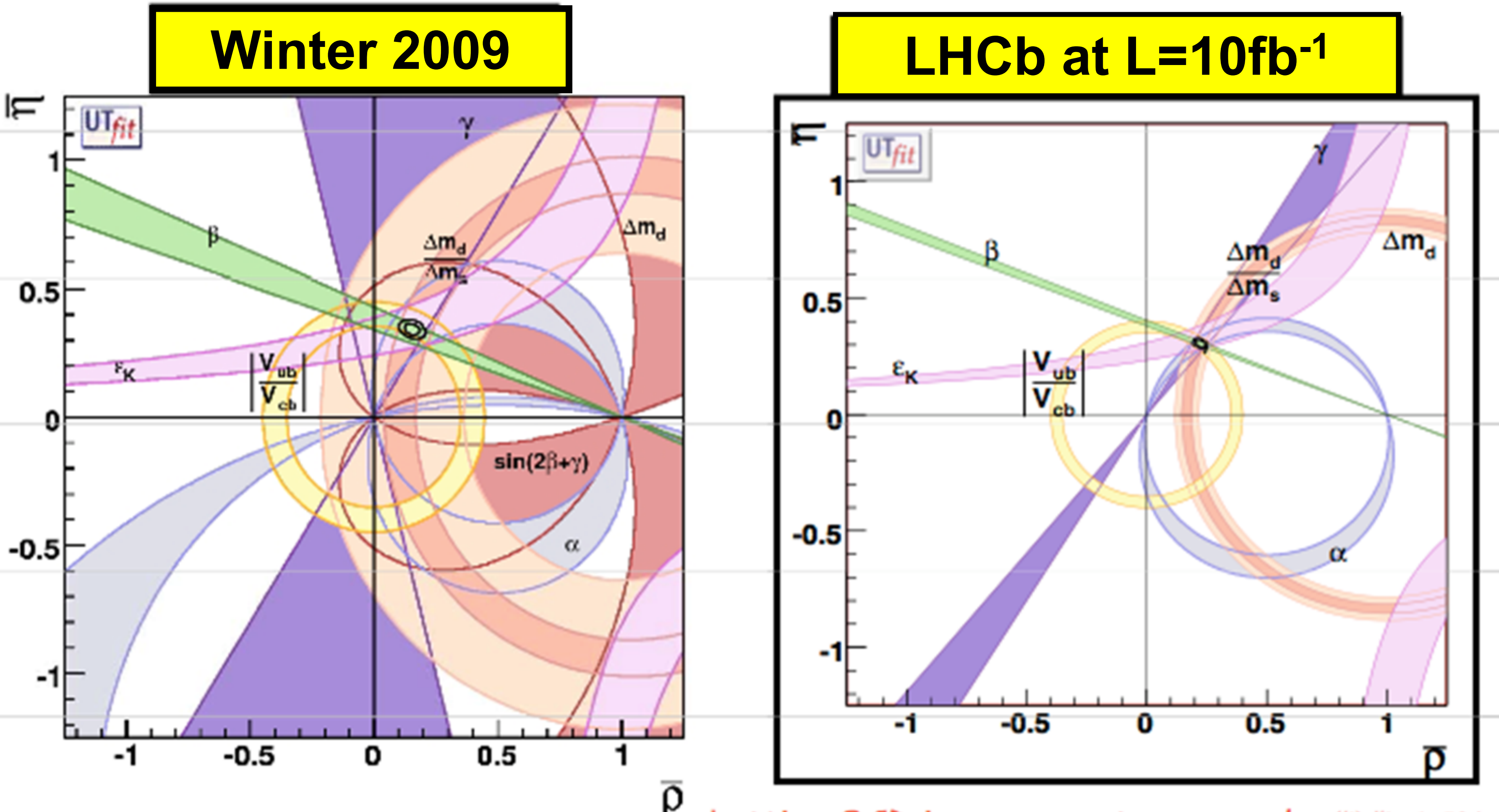
- ✓ γ is the least well-known angle of the Unitarity Triangle…
- ✓ CKMfitter (frequentist) and Utfit (Bayesian) groups barely agree…

<u>LHCb with 10 fb^{-1}</u> (~5 nominal years)

- ➢ **γ with loops ~ 5°**
- ➢ **γ in trees ~ 2° – 3°** (depending on r_B, δ_B)



Outlook to CKM picture in 2014



Lattice QCD improvements assumed: $\sigma(\xi)/\xi=1.5\%$

$\sigma(\sin(2\beta)) = 0.01$; $\sigma(\gamma) = 2.4^\circ$; $\sigma(\alpha) = 4.5^\circ$

Conclusion

- LHCb is a heavy flavour precision experiment searching for New Physics in CP-violation and rare decays
- The experiment is ready for data taking to start end of this year
- Cosmics and first LHC-induced tracks were very useful to commission the detector
- With fraction of a 1 years nominal data set LHCb can already perform important key measurments probing New Physics

…and many more details on 27th :

'Prospects for CP violation at LHCb' by Stephan Poss

'Search for new physics with rare decays at LHCb' by Victor Egorychev