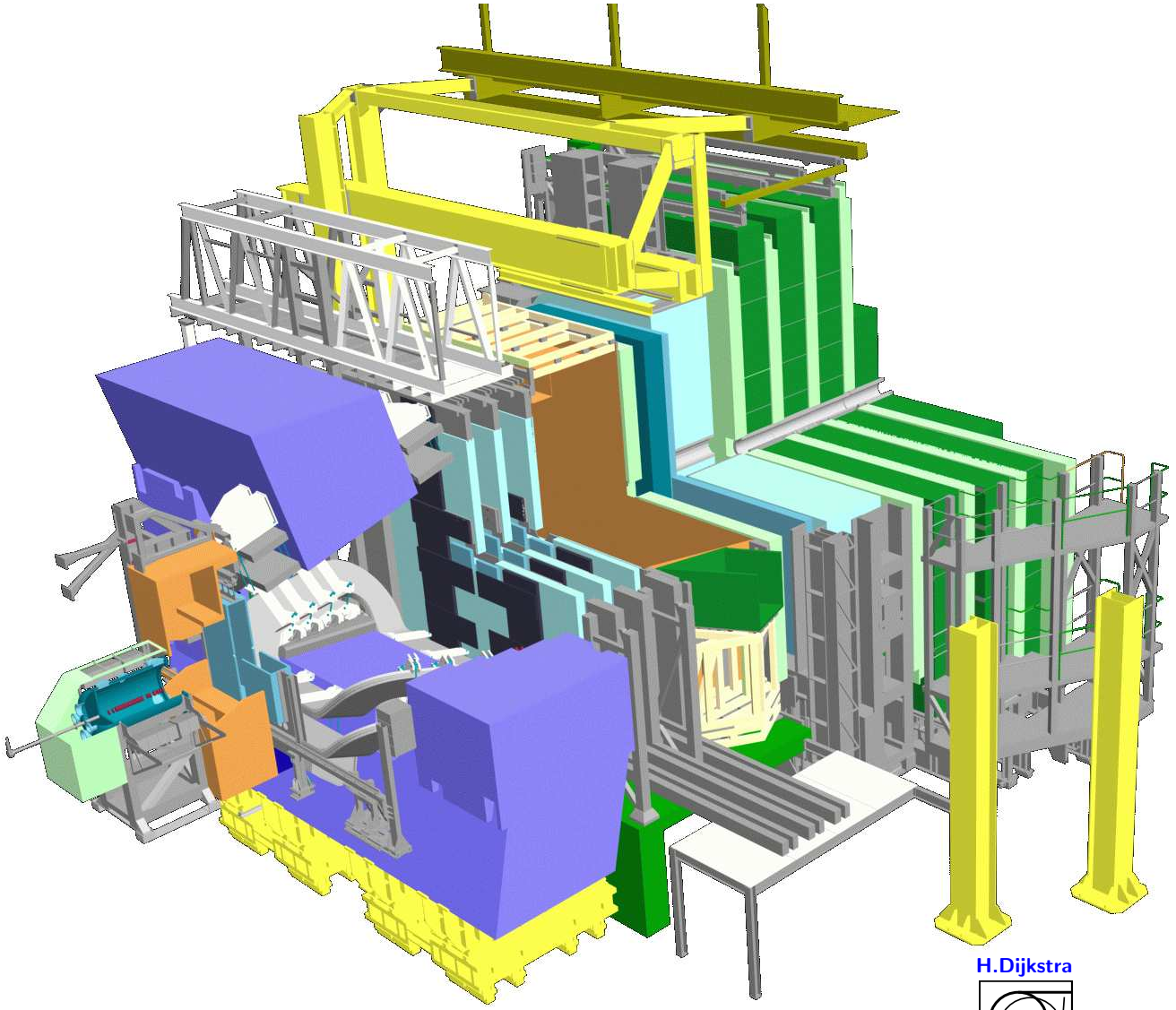
Highlights of LHCb

Hans Dijkstra
On behalf of the LHCb collaboration

- The LHCb Detector
- LHCb and Higgs?
- Selected (core) highlights
  - Rare decays
  - CKM parameters
  - Charm
- Conclusions



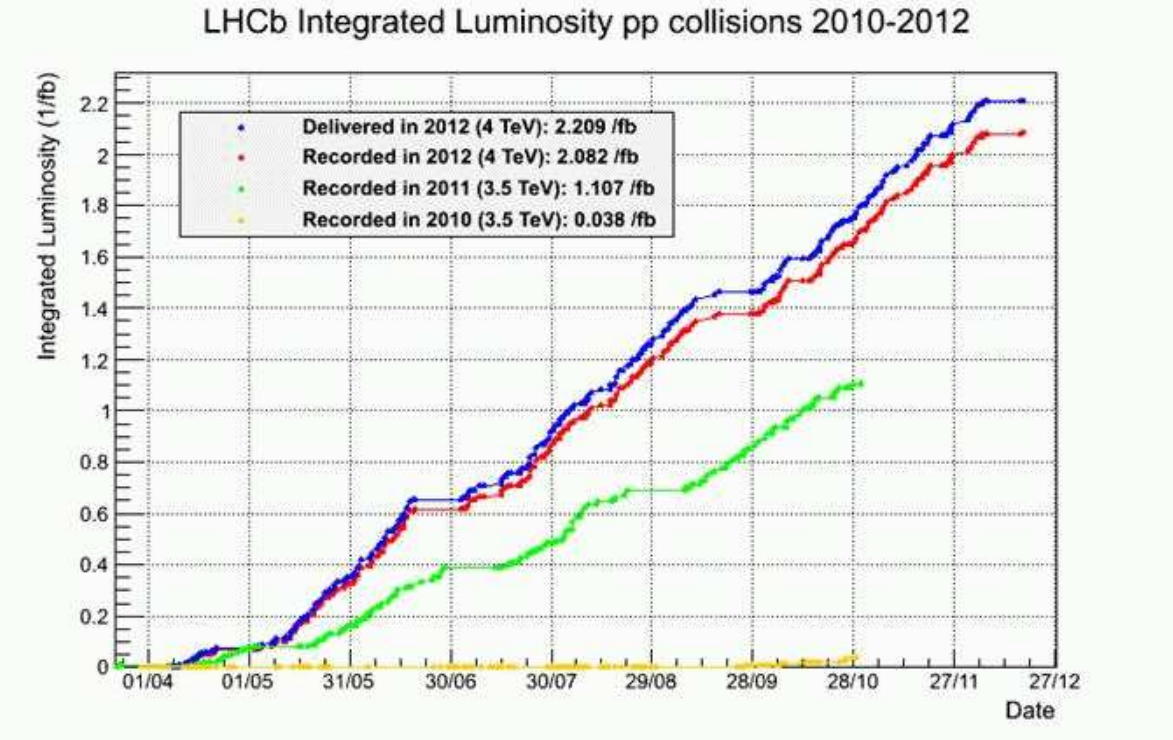
The LHCb Collaboration

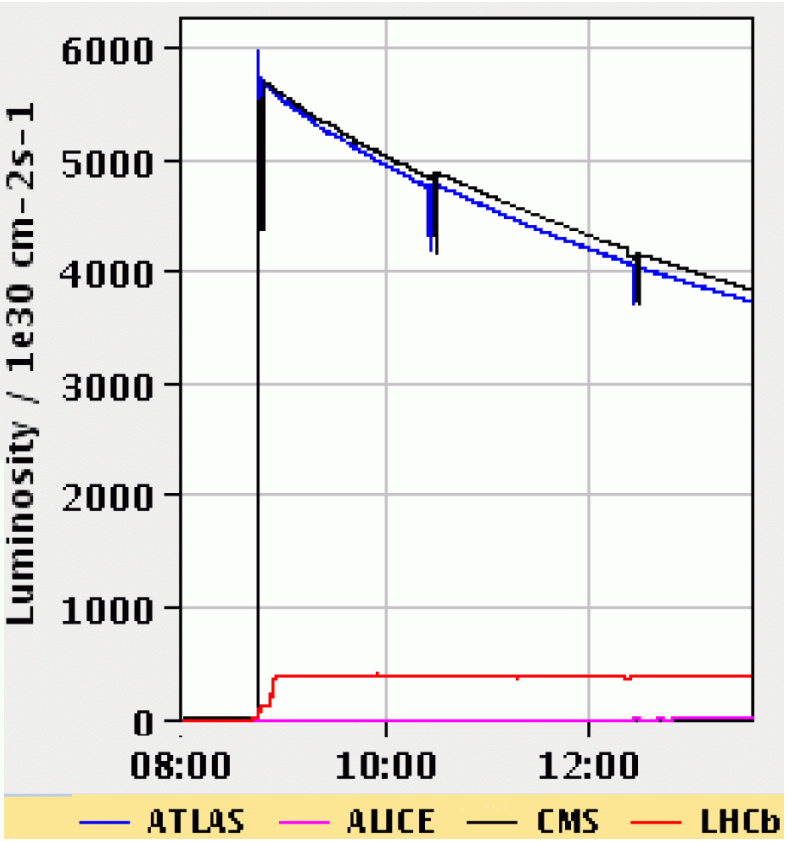
Collaborating institutes:

- Center for High Energy Physics, Tsinghua University, Beijing, China
- And another 59 institutes

LHCb and Luminosity

- Peak luminosity: $3 - 4 \times 10^{32}$ cm$^{-2}s^{-1}$
- Automatic luminosity leveling
- ~ 94 % recorded/delivered.
- $\int L = 0.035 + 1.1 + 2.$ fb^{-1}
  in 2010+2011+2012
- Published results mainly from 2011 data.

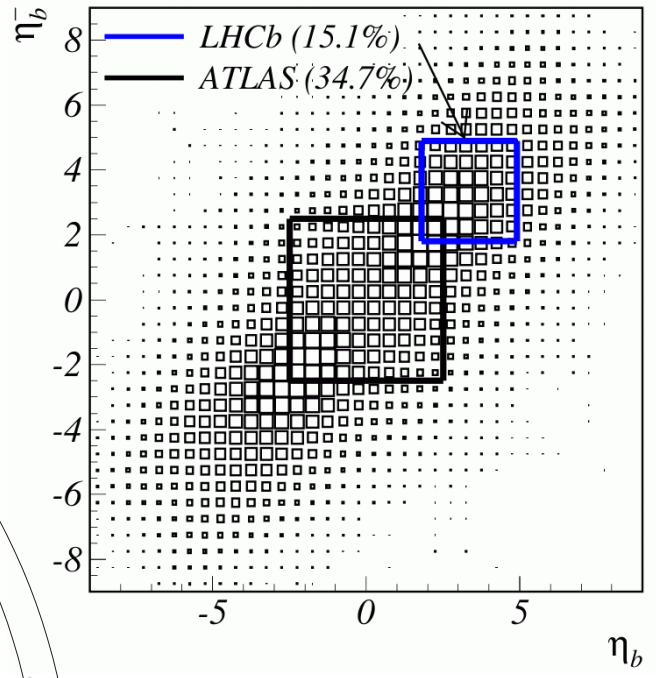


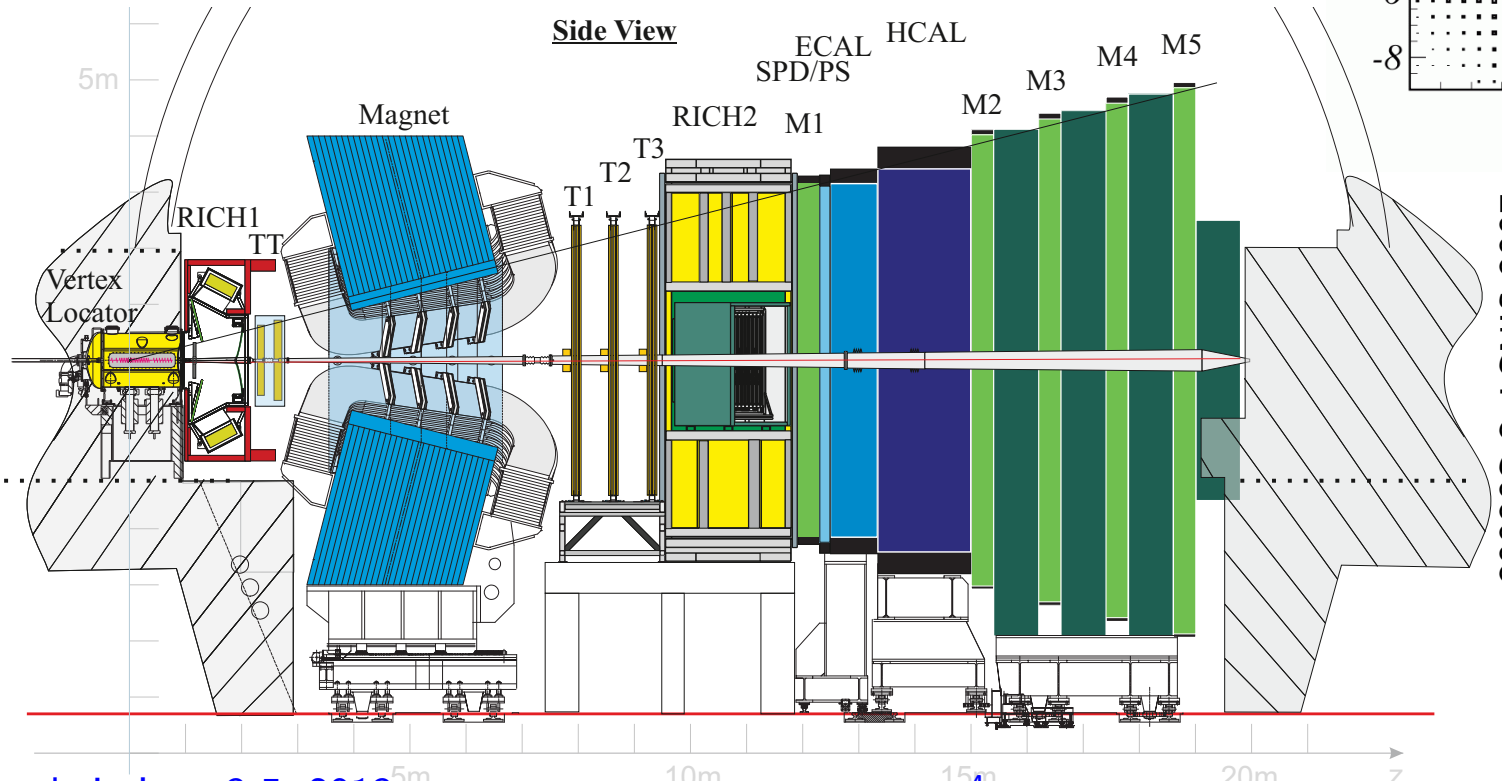


The LHCb Detector $2 < \eta < 5$

In LHCb acceptance, $\sqrt{s} = 7$ TeV:

- $\sigma(pp) = 59$ mb (J. Instrum. 7 (2012) P01010)
- $\sigma(pp) \to c\bar{c}X = 1.4$ mb (arXiv:1302.2864)
- $\sigma(pp) \to b\bar{b}X = 0.075$ mb (PLB 698 (2011))





2008 JINST 3 S08005

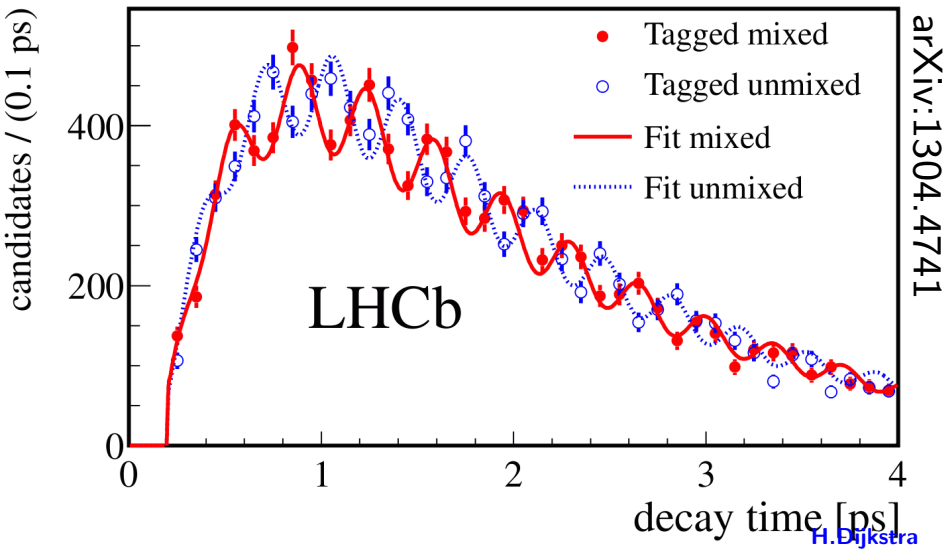
VELO Performance (arXiv:1302.5259)

VELO:

- 84 Si-sensors (semi CD size)
- 8 (30) mm from beam in closed (open) position)
- Radiation: 0.5×10^{14} 1 MeV n-equivalent per fb^{-1}
- $\sigma(\mathrm{IP}) = 20\ \mu\mathrm{m}$ (p_T few GeV/c tracks)

Δm_s with $B_s^0 \to D_s^- \pi^+$

- ~ 34000 events with $D_s^- \to$ $\phi\pi^-,\ K^*K^-,\ K^+K^-\pi^-,\ K^-\pi^+\pi^-,\ \pi^+\pi^-\pi^-$
- $\Delta m_s = 17.768 \pm 0.023(\mathrm{stat}) \pm 0.006(\mathrm{syst})\ \mathrm{ps}^{-1}$
- most precise measurement of Δm_s to date.



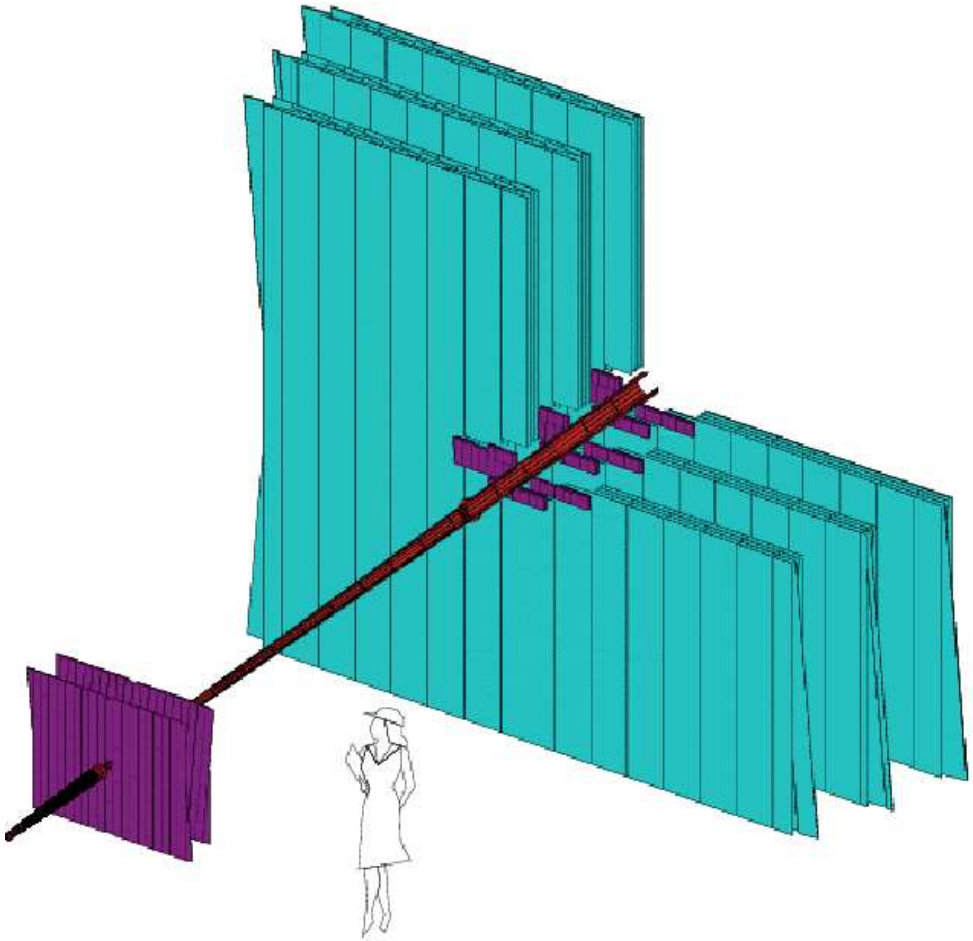
Tracking

TT 4 Si-planes: $\sigma - \text{hit} \sim 50\ \mu\text{m}$

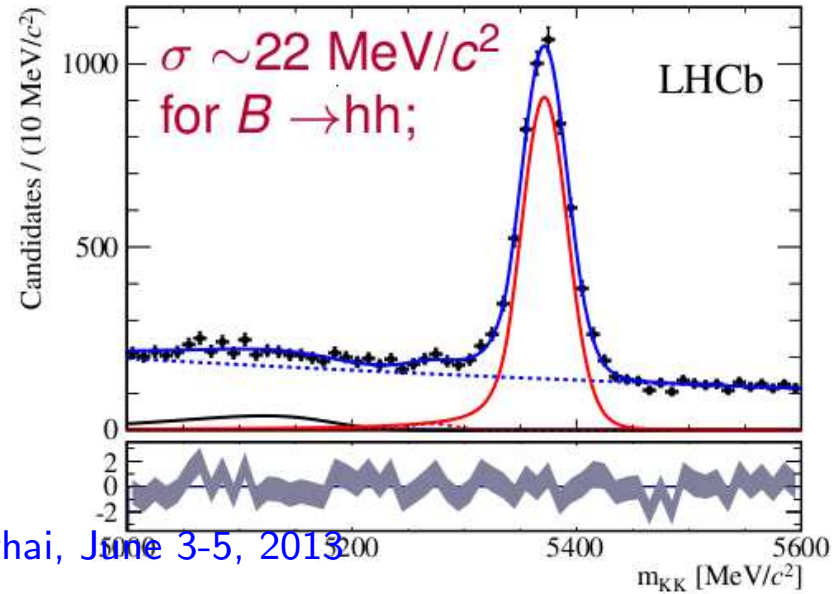
- 4 Tm dipole field

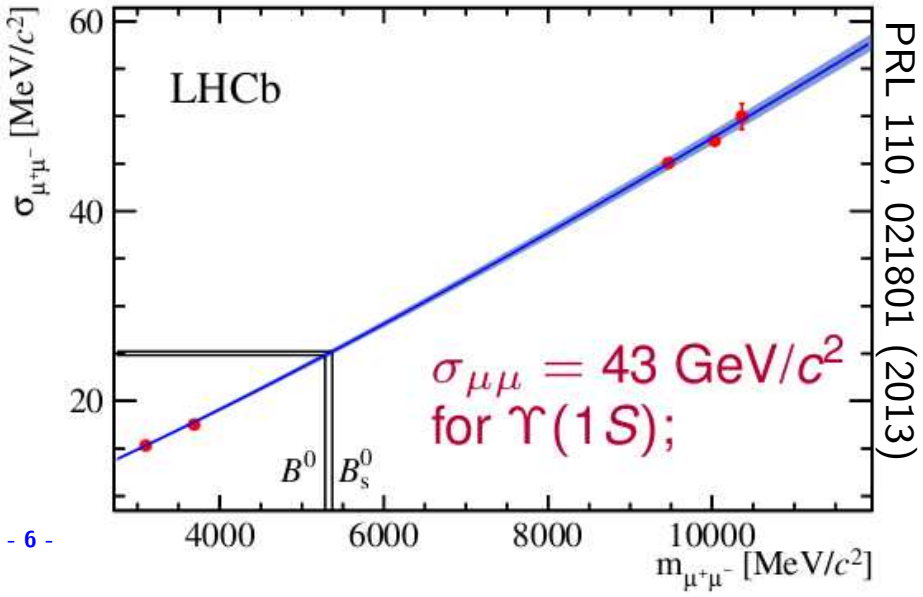
IT $3{\times}4$ Si-planes: $\sigma - \text{hit} \sim 50\ \mu\text{m}$

OT 3×8 straw-tube plane: $\sigma - \text{hit} \sim 200\ \mu\text{m}$



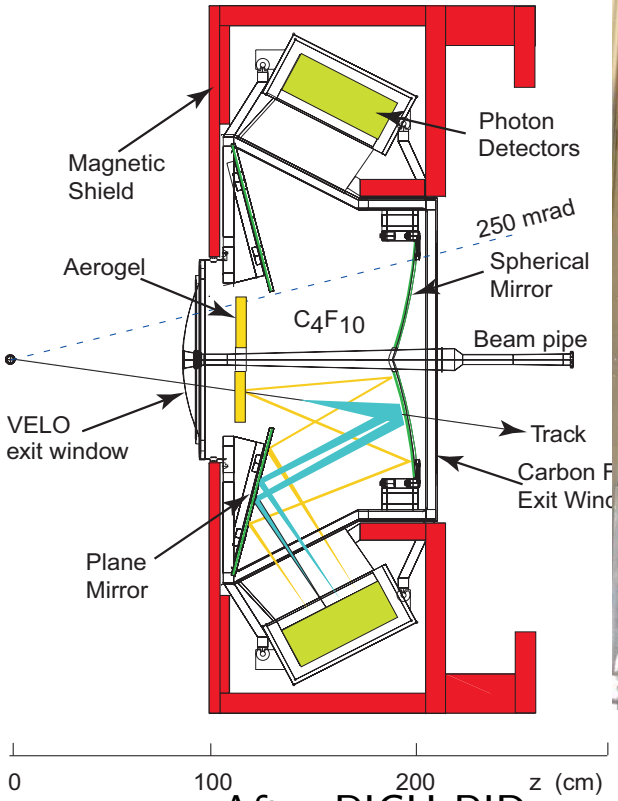
- Excellent invariant mass resolution!



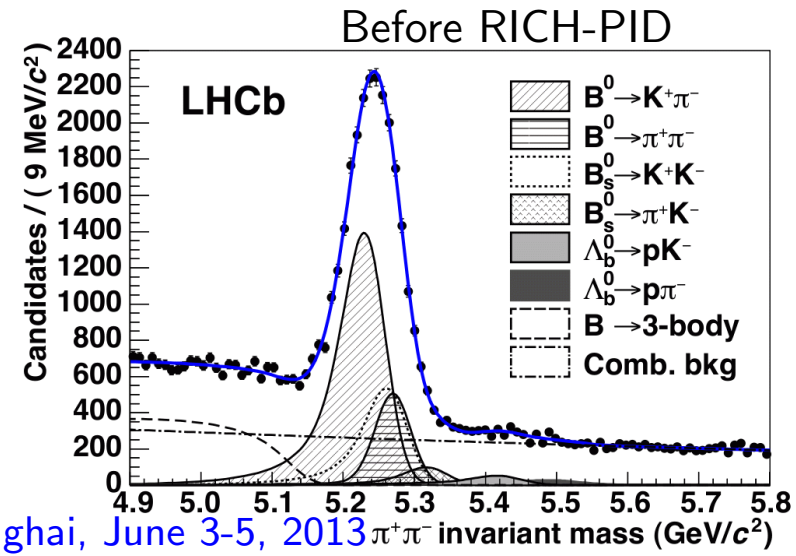


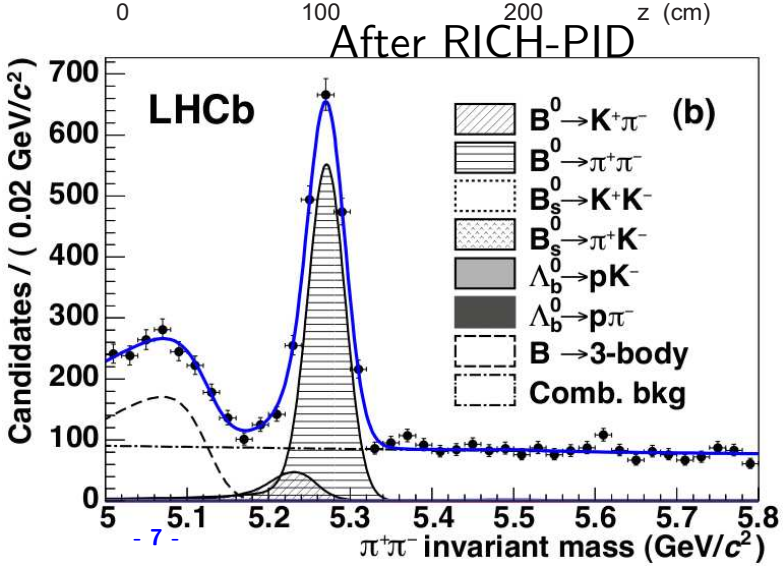
RICHes (arXiv:1211.6759)

- 484 HPDs outside LHCb acceptance.
- 1024 pixels 2.5×2.5 mm/HPD
- $\epsilon(\mathrm{K}^{\pm}) \sim 95\ \%$ for $\sim 5\ \%\ \pi \to K$ mis-id



- Without PID $B^0 \to \pi^+\pi^-$ completely dominated by $B^0 \to K^+\pi^-$

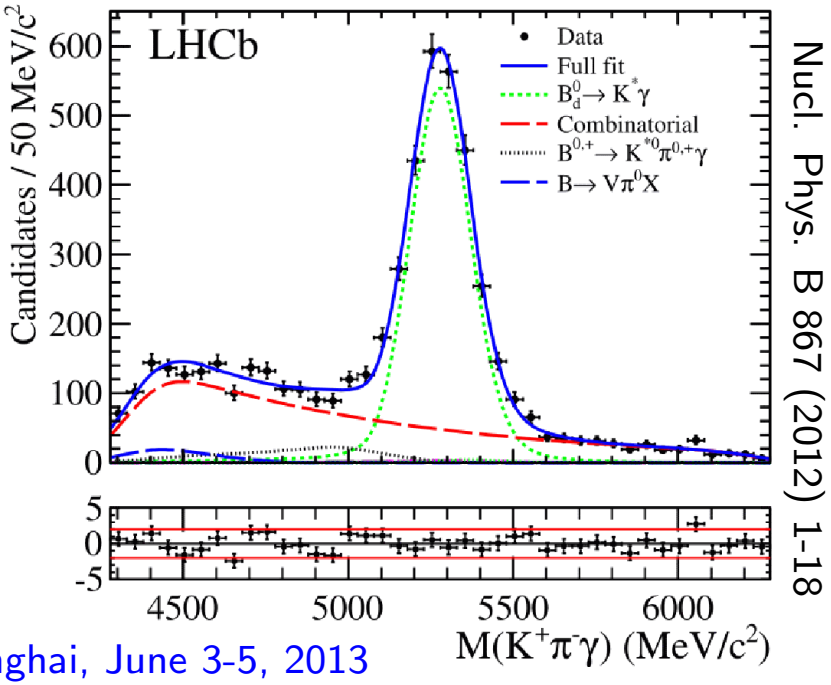


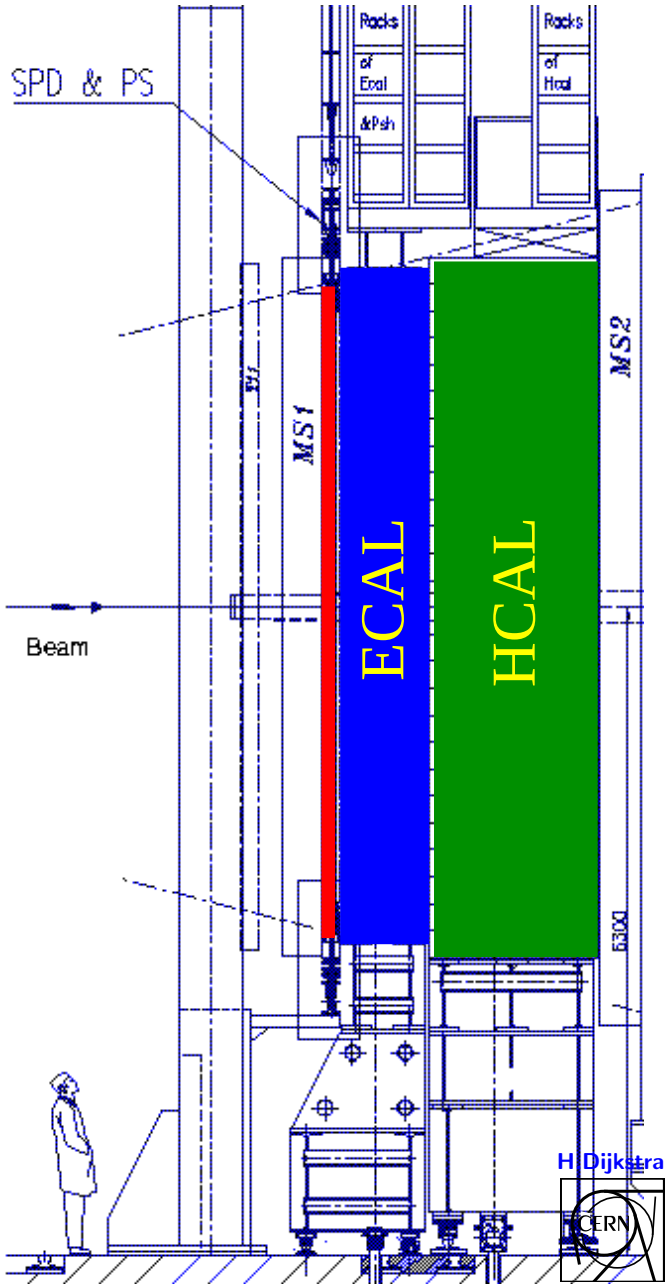


JHEP 10 (2012) 037

Calorimetry

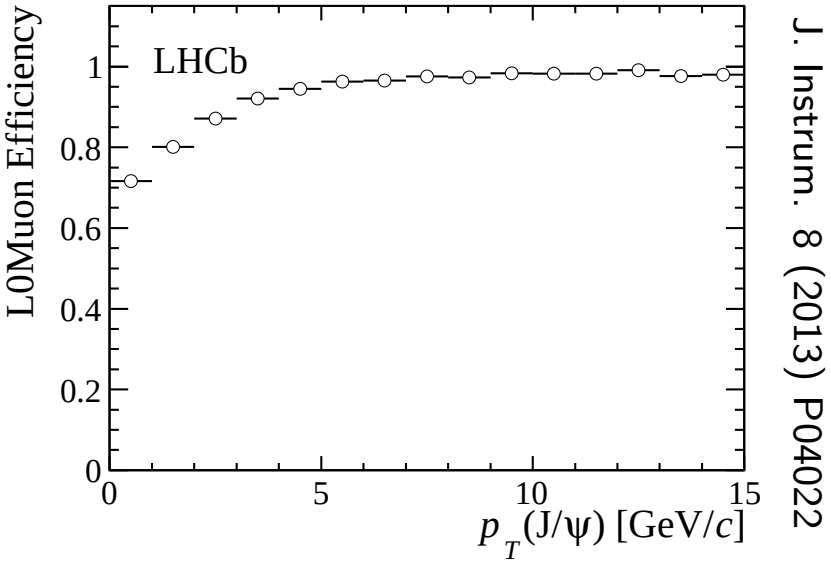
- Scintillating Pad Detector: 5984 cells
  Distinguish e/γ in Level-0 Trigger.
- Preshower: Pb/scintillator, 5984 cells, 2.5 X_0
- Electromagnetic-Cal.: Pb shashlik,
  5984 cells, 25 X_0, $\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 1\%$
- Hadron-Cal.: iron/scintillating tiles, 1468 cells, 5.6λ_I
  Level-0 hadron Trigger. $\frac{\sigma_E}{E} = \frac{80\%}{\sqrt{E}} \oplus 10\%$
- Cell-sizes: $4 \times 4 \rightarrow 26 \times 26$ cm^2

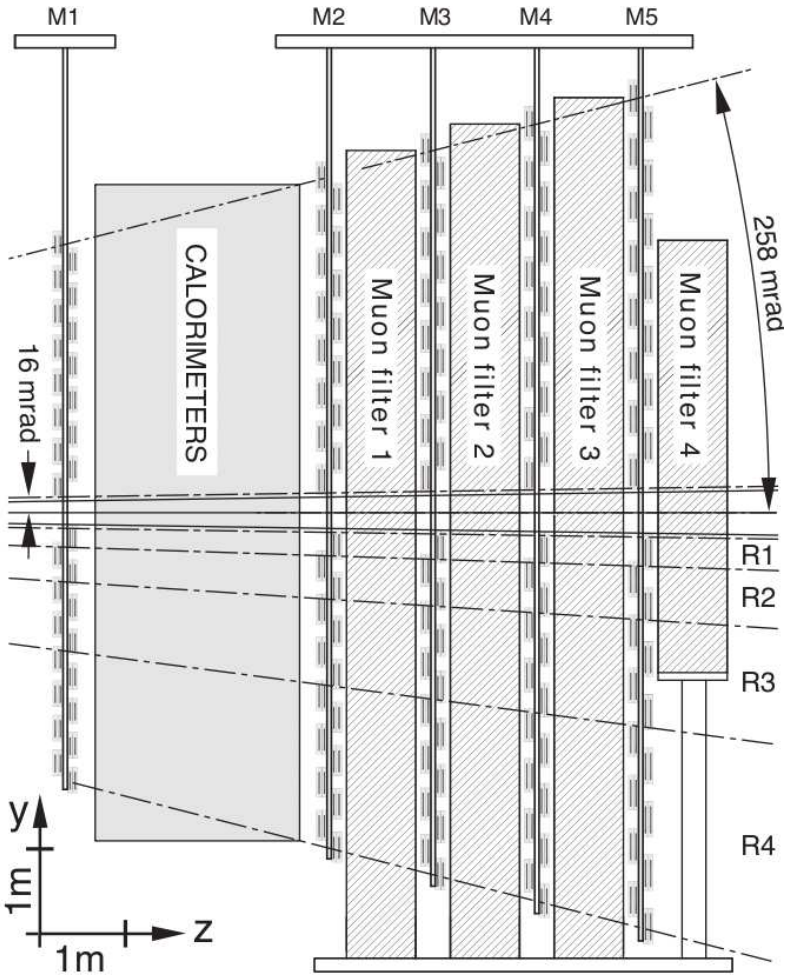




Muon System (arXiv:1211.1346)

- MWPC, projective in Y for L0-trigger.
- GEM in inner part M1
- 120k pads and strips.
- Eff$>99\%$ by .OR. 2 layers per station.
- Covers 435 m^2
- Pads: 1×2.5 cm^2 (M1-inner) to 16×20 cm^2 (M5-outer)
- Combine strips→ 26k pads for the trigger
- First Level trigger efficient down to low p_T





Trigger Overview

Level-0 (hardware):

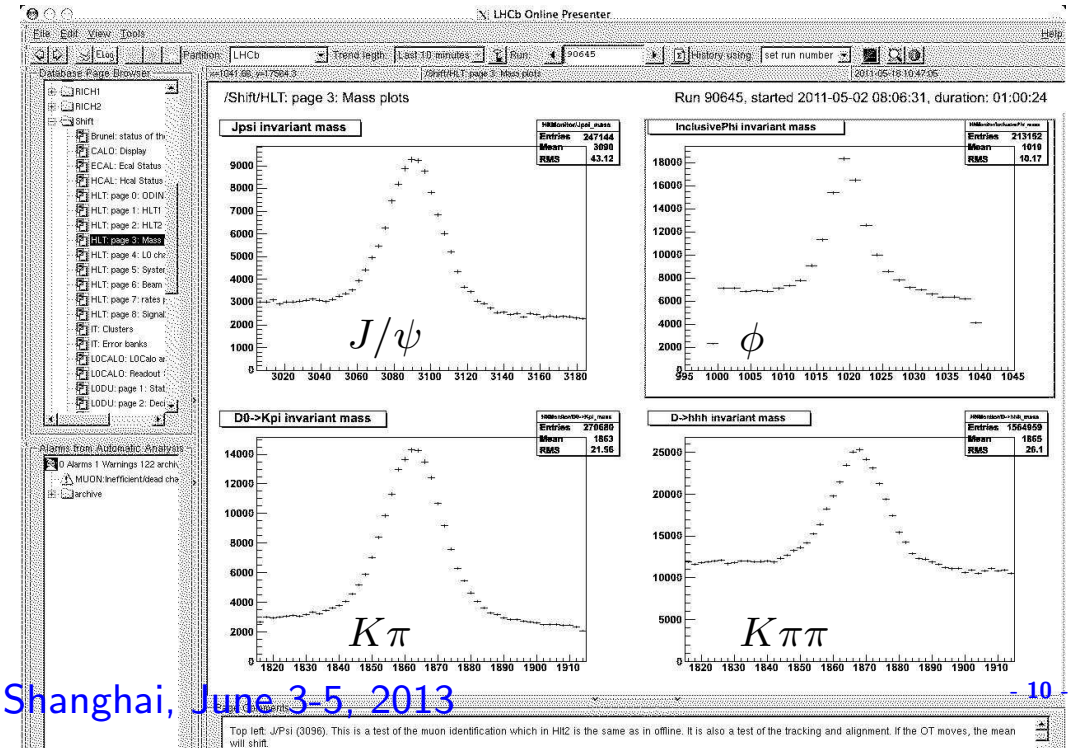
- Largest E_T hadron, e(γ) and μ.
  Typical thresholds: 3.5, 2.5, 1.5 GeV.
- Max accept rate 1 MHz.

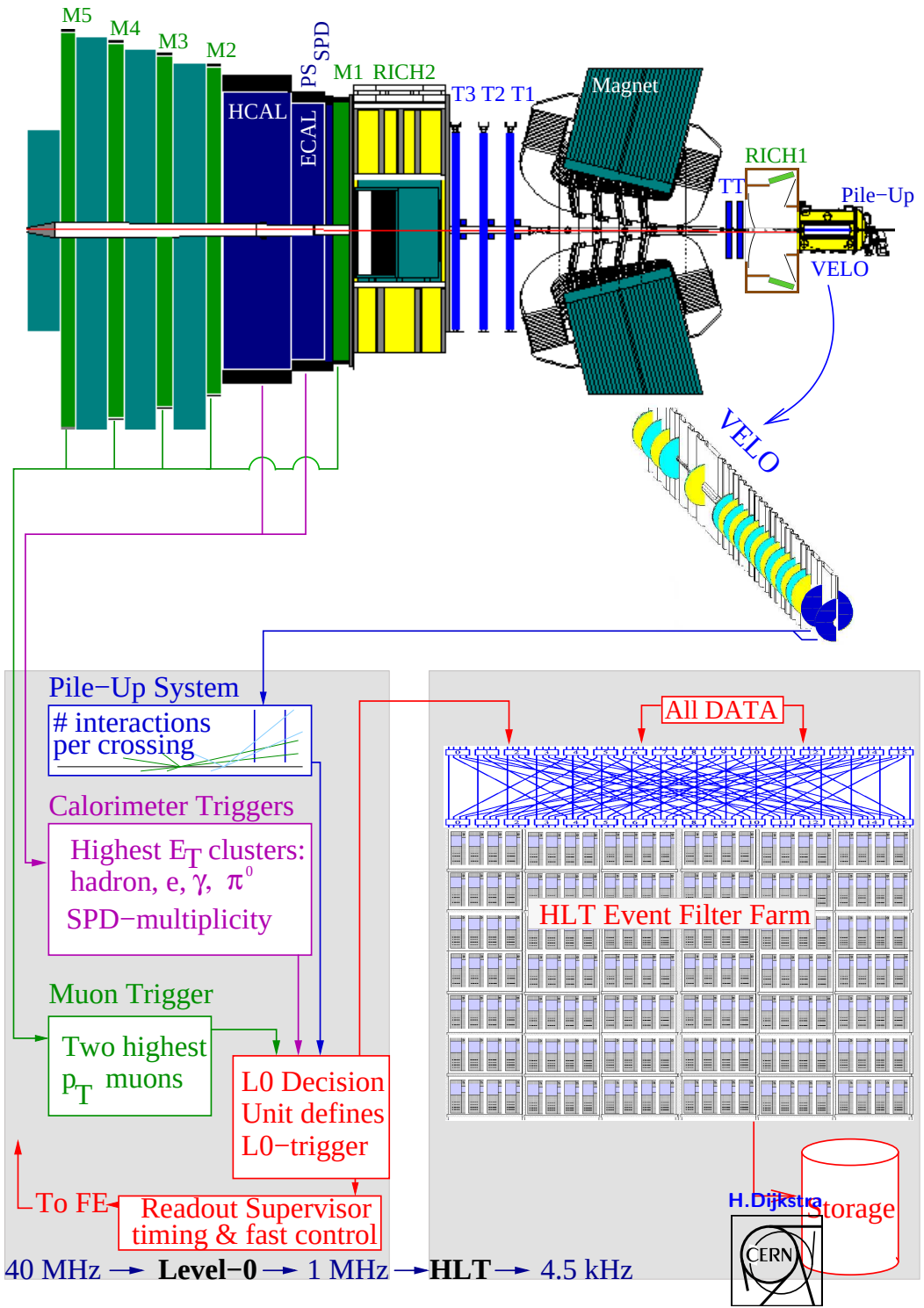
High Level Trigger (software):

- Access to all info in 29000 HLT jobs.
- First partial (large IP, muons) event reco.
- Then full reco, and mass cuts $\rightarrow 4.5$ kHz.

$\epsilon \sim 90(30)$ % for $B-$decays to $\mu\mu$X(hadrons)

J. Instrum. 8 (2013) P04022

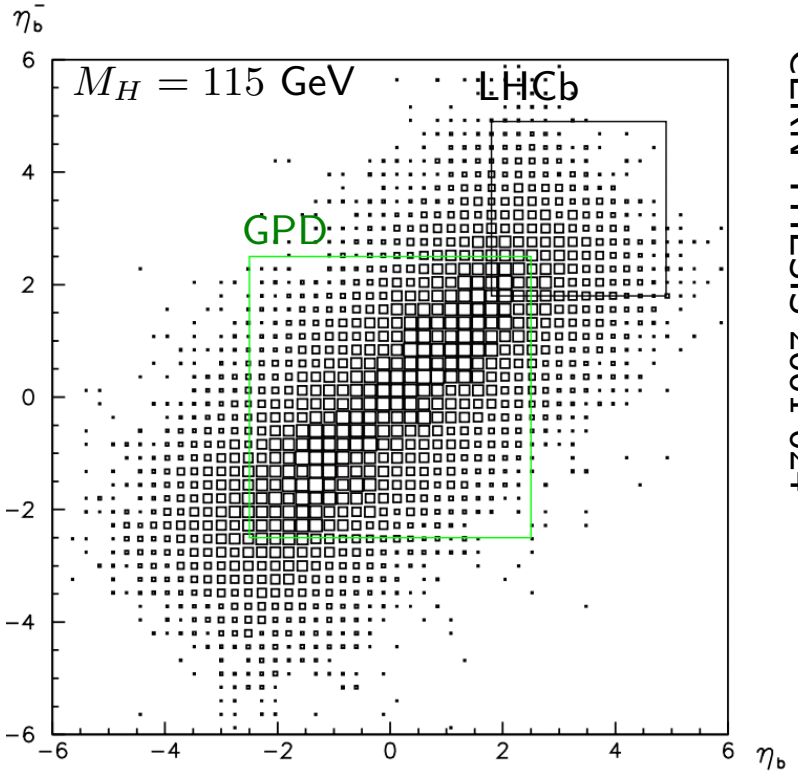




~5 min on-line screen-shot

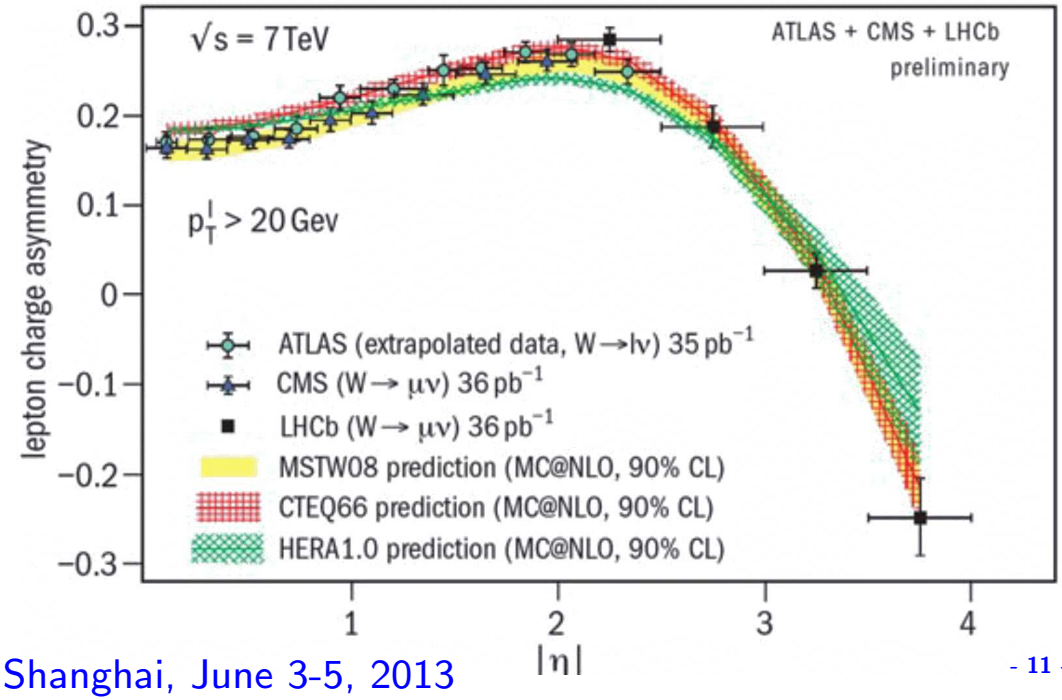
LHCb and Higgs (like)?

- LHCb covers forward region, complementary to GPDs.
- Acceptance $\sim 5(11)$ % at $\sqrt{s} = 7(14)$ TeV.
- Most promising channel: $H \to \tau^+\tau^-$



CERN-THESIS-2001-024

- Complementary at work:
  $A_W = \frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}}$



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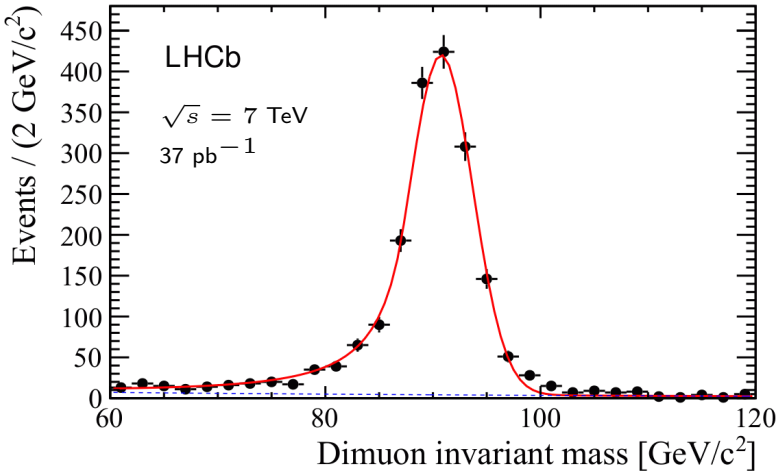
"Calibrating" τ-reconstruction using Z decays.

- $\sigma(Z)$ using both $\mu + \mu^-$ and $\tau^+\tau^-$ decays.
- Consider following τ-decays:
  $\tau_\mu\tau_\mu$, $\tau_\mu\tau_e$, $\tau_\mu\tau_h$, $\tau_e\tau_h$
- Most shapes and yields taken from data: side-bands, same-sign
- Find: $\frac{\sigma_{pp\to Z\to\tau\tau}}{\sigma_{pp\to Z\to\mu\mu}} = 0.93 \pm 0.09$
- Excellent agreement!



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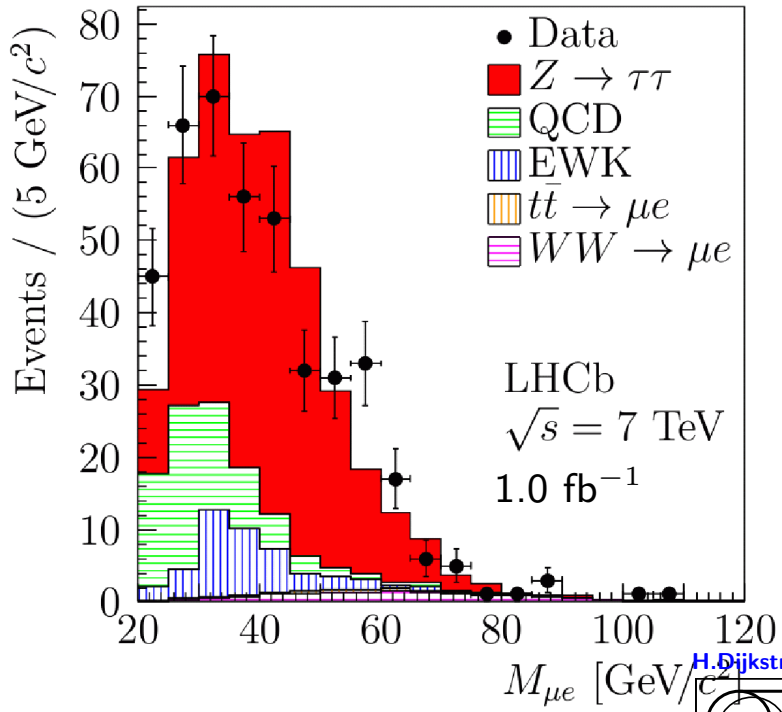


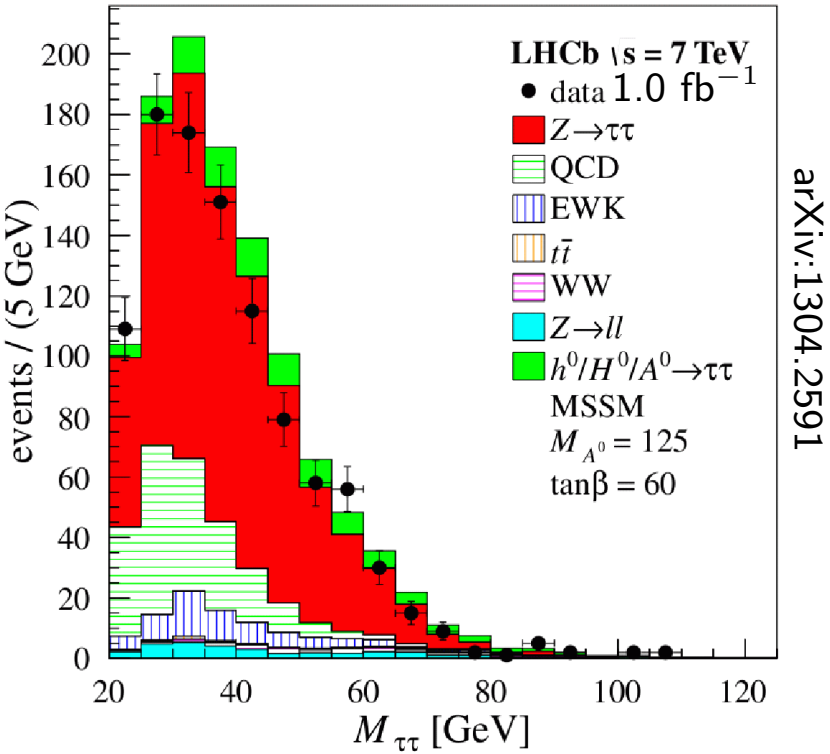
arXiv:1210.6289

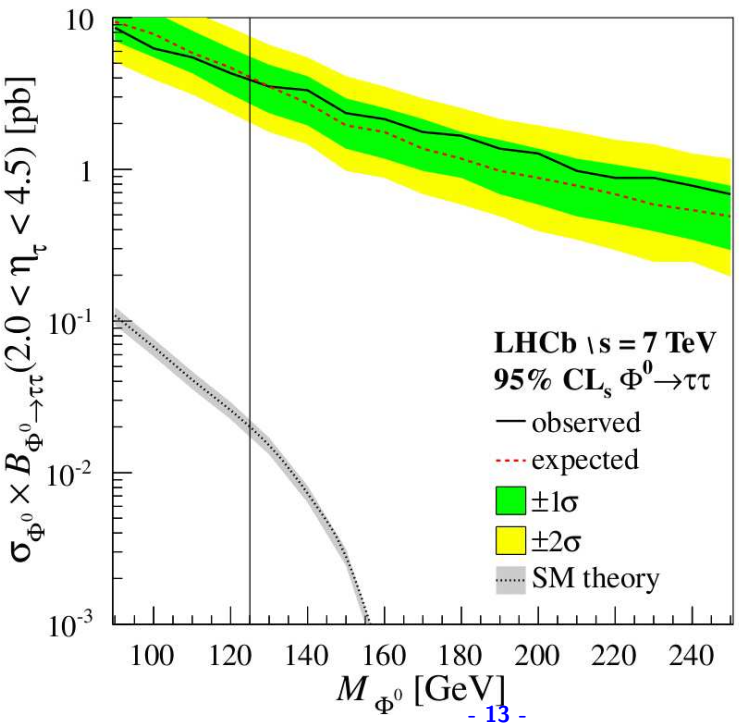
$H \to \tau^+\tau^-$

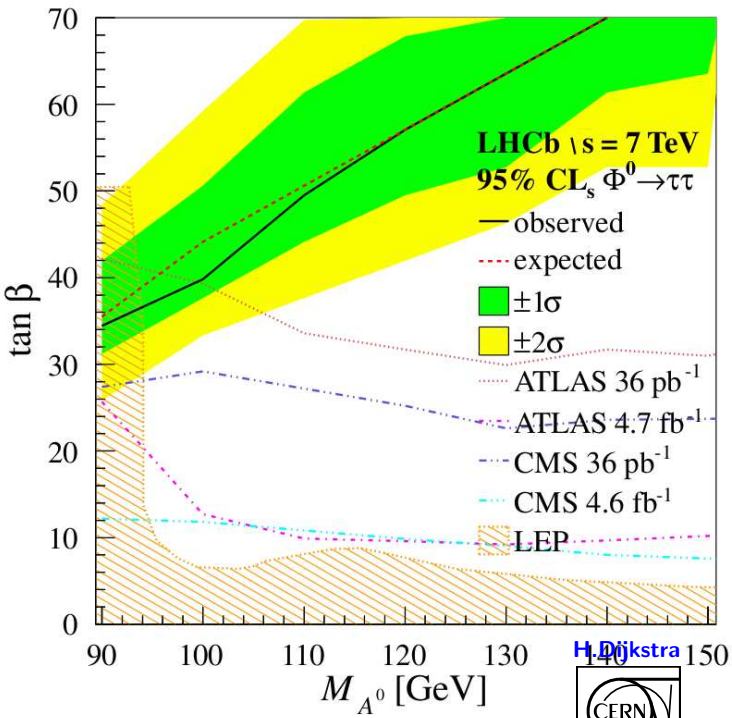
- Assume theoretical $\sigma(Z \to \tau^+\tau^-)$
- $\sigma(\mathrm{SM-Higgs}) \lesssim 3$ pb for $2 < \eta_\eta < 4.5$
- MSSM($M_{h^0}^{max}$ scenario):
  $\tan\beta > 32(70)$ for $M_{A^0} = 90(150)$ GeV/c^2

Outlook:

- $\sqrt{s} = 7 \to 14$ TeV: Acc$\times 2$, $\sigma \times 2$
- Increase $\int L$
- Upgrade: see later

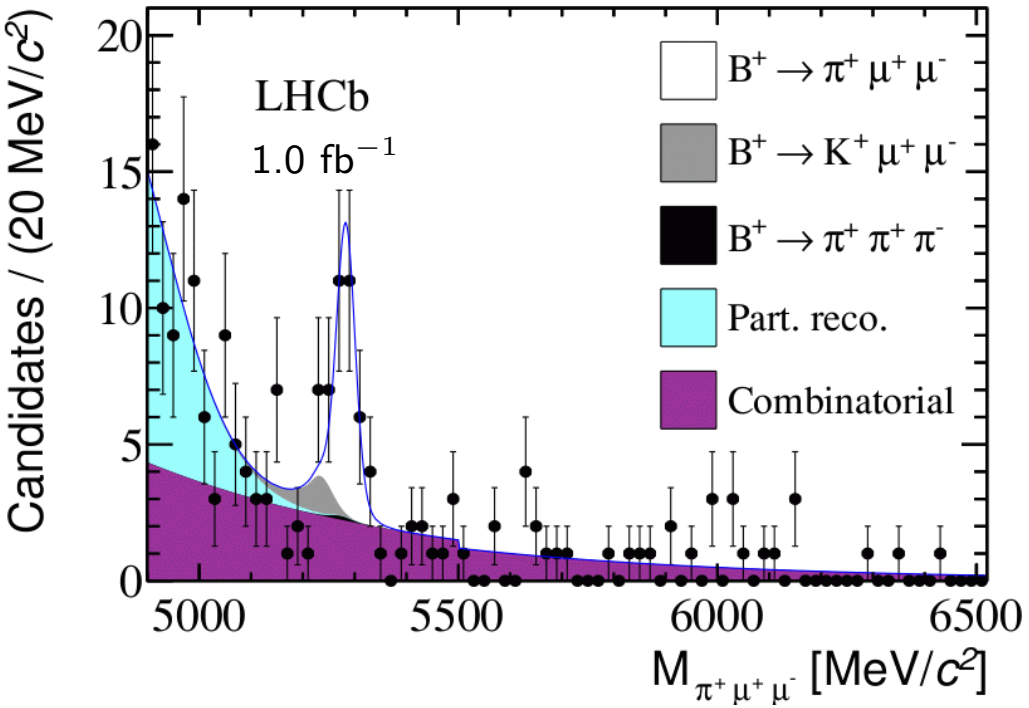






Highlights in Rare Decays

- Rarest B-decay observed:
- $B^+ \to \pi^+\mu^+\mu^-$: 5.2 σ significance
- $\mathcal{B} = (2.3 \pm 0.6\ (\text{stat.}) \pm 0.1\ (\text{syst.})) \times 10^{-8}$



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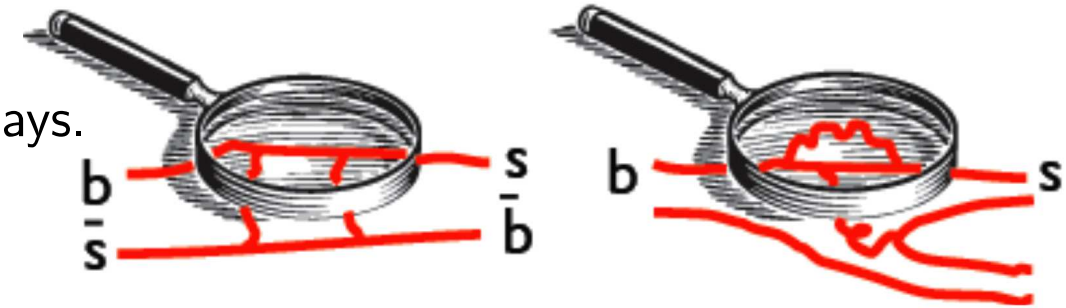
For NP discovery look for:

a) Decays with $\mathcal{B}$(NP$\sim$SM) $\to$ FCNC decays.

b) SM predictions "precise".

Selected decays:

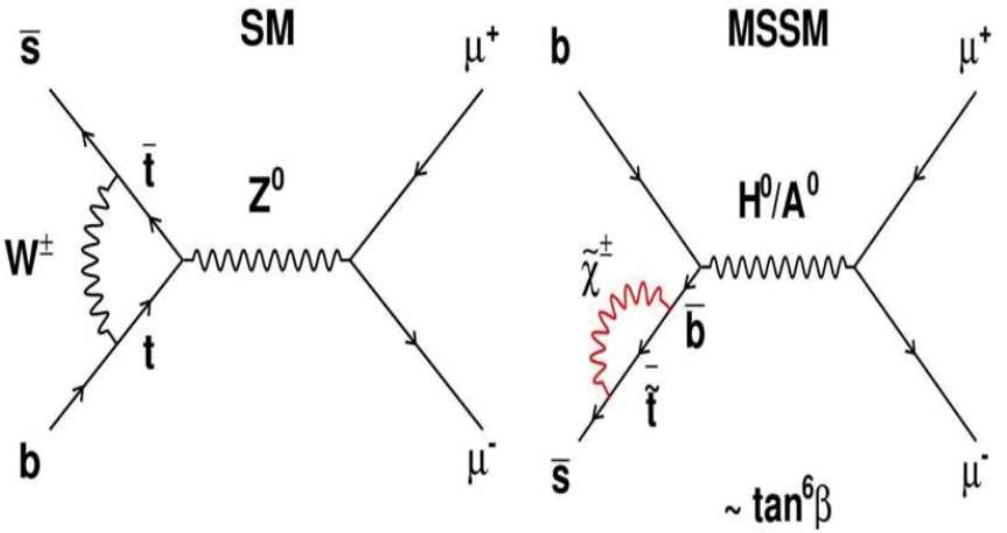
- $B_s \to \mu^+\mu^-$
- $B^0 \to K^*\mu^+\mu^-$



$B^0_{(s)} \to \mu^+\mu^-$

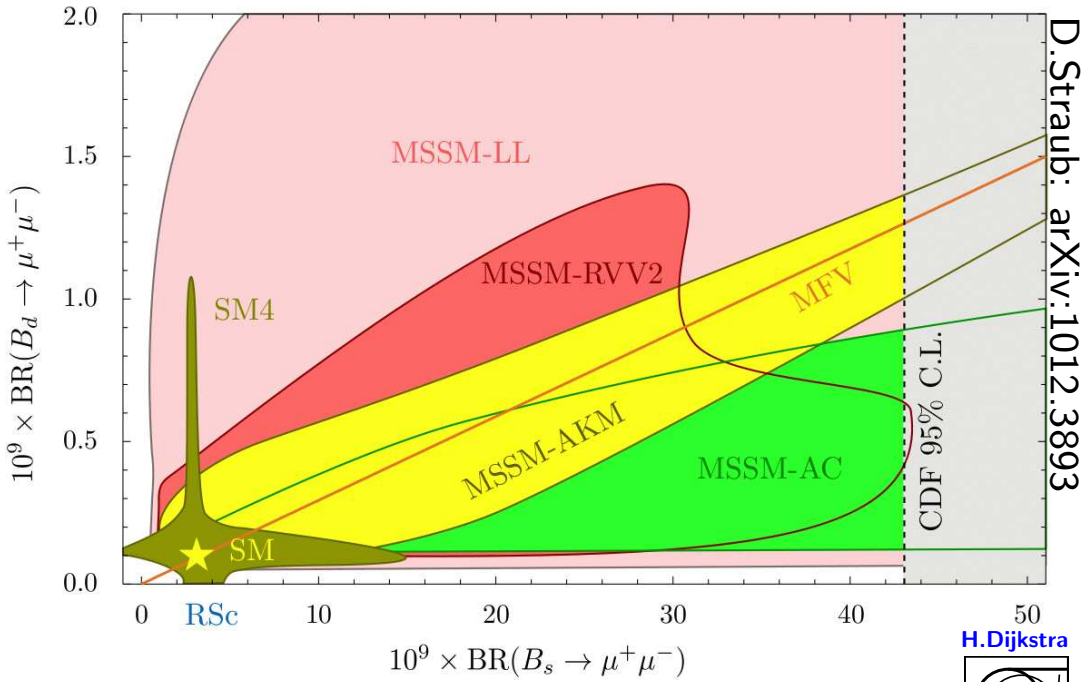
SM:

- No tree level decay
- Helicity suppressed
- Expected time integrated
  $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$
  (Phys. Rev. Lett. 109 (2012) 041801)



NP:

- MSSM: $\mathcal{B} \propto \tan^6\beta / \mathrm{M}^4_{\mathrm{A}^0}$
- Pre-LHC parameter space example:



D.Straub: arXiv:1012.3893

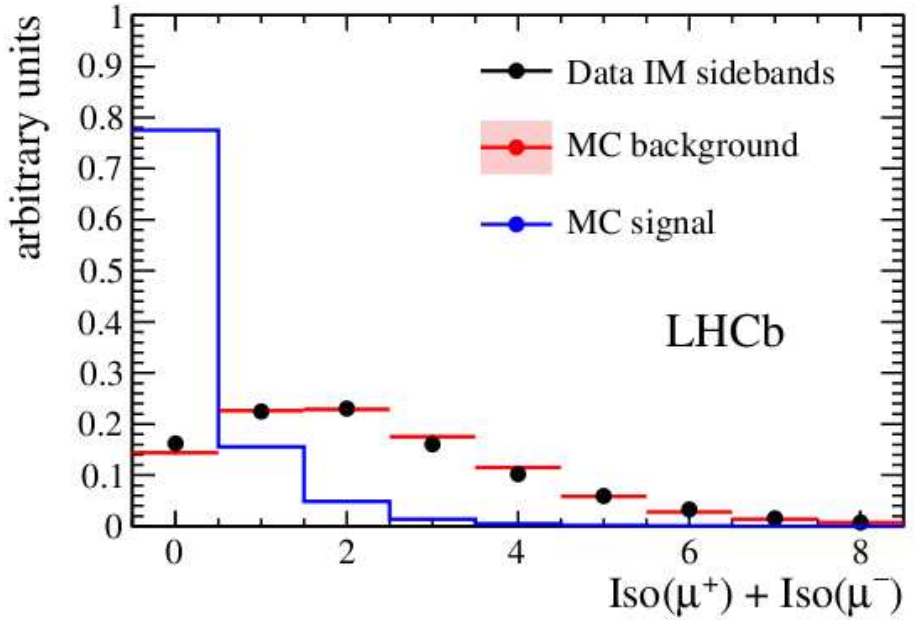
H.Dijkstra

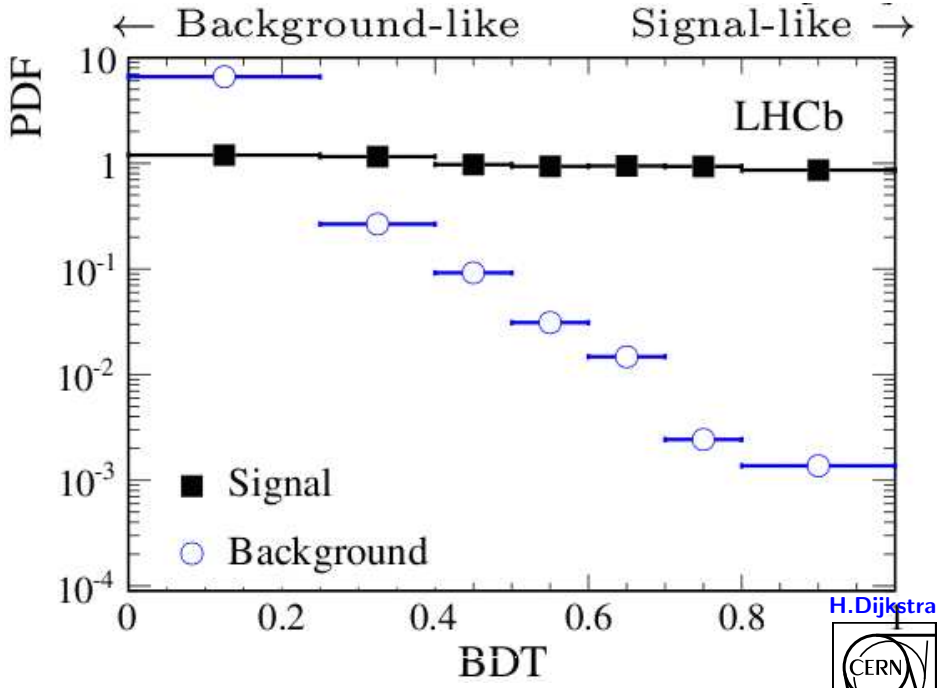
$B^0_{(s)} \to \mu^+\mu^-$ Experimentally

Trigger eff: $\sim 90\ \%$

Train BDT to distinguish background:

- both $B \to \mu X,\ B \to \pi(K)\mu\nu,\ \Lambda_b \to p\mu\nu,$ $B_c \to J/\psi\mu\nu,\ B_s \to D_s(\mu\nu)\mu\nu,\ B \to \pi\mu\mu$
- MC to train, data (side bands) to calibrate.
- Variables: IP(μ, B), p_T, τ, B-vertex, helicity angle and μ-isolation

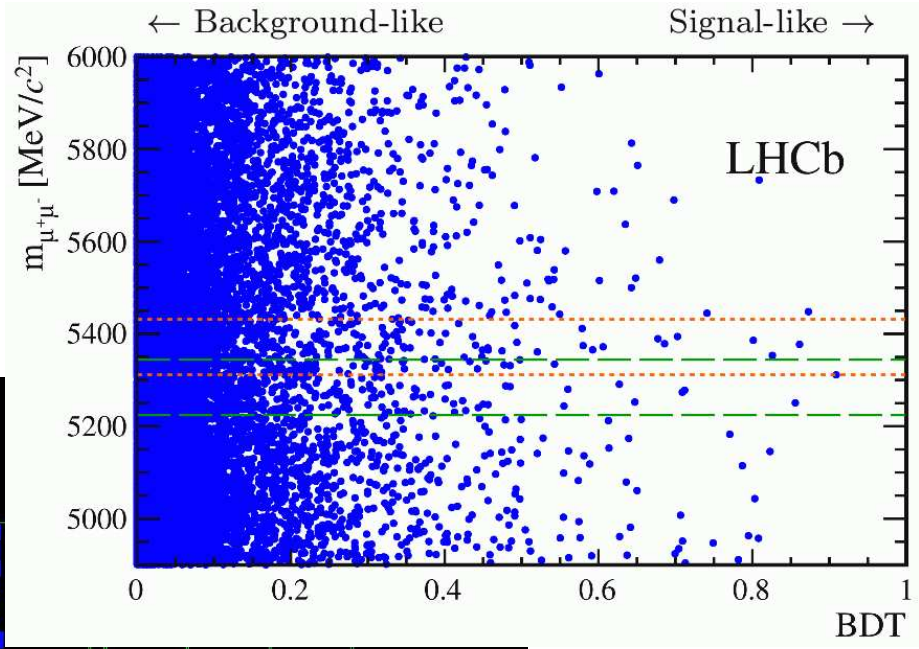


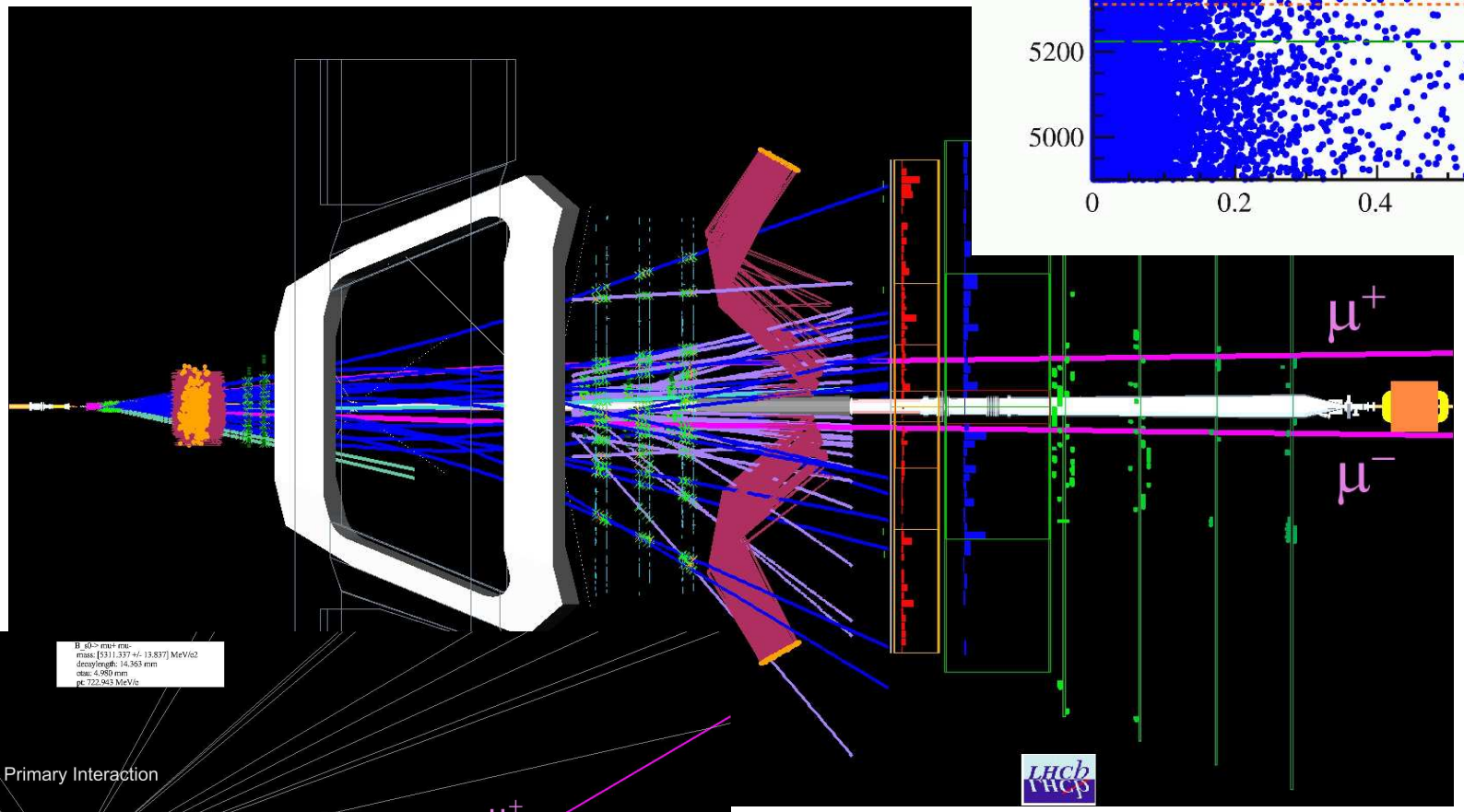


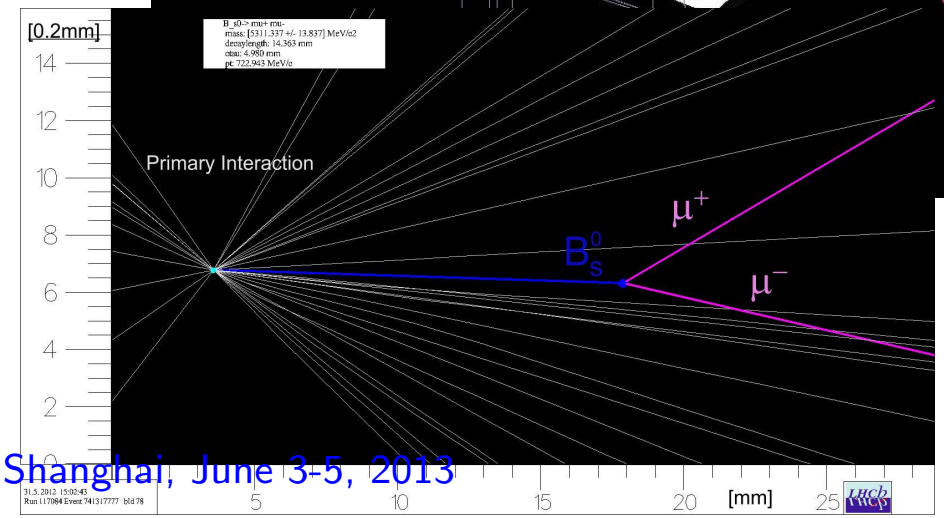
from signal:

- Excellent signal proxy: $B \to h^+h'^-$ triggered on other B.
- Blind analysis
- $\mathcal{B}$ normalisation:
  - $B^+ \to J/\psi K^+,\ B^0 \to K^-\pi^+$
  - $f_s/f_d = 0.256 \pm 0.020$ (hep-ph:1301.5286)

$B^0_{(s)} \to \mu^+\mu^-$

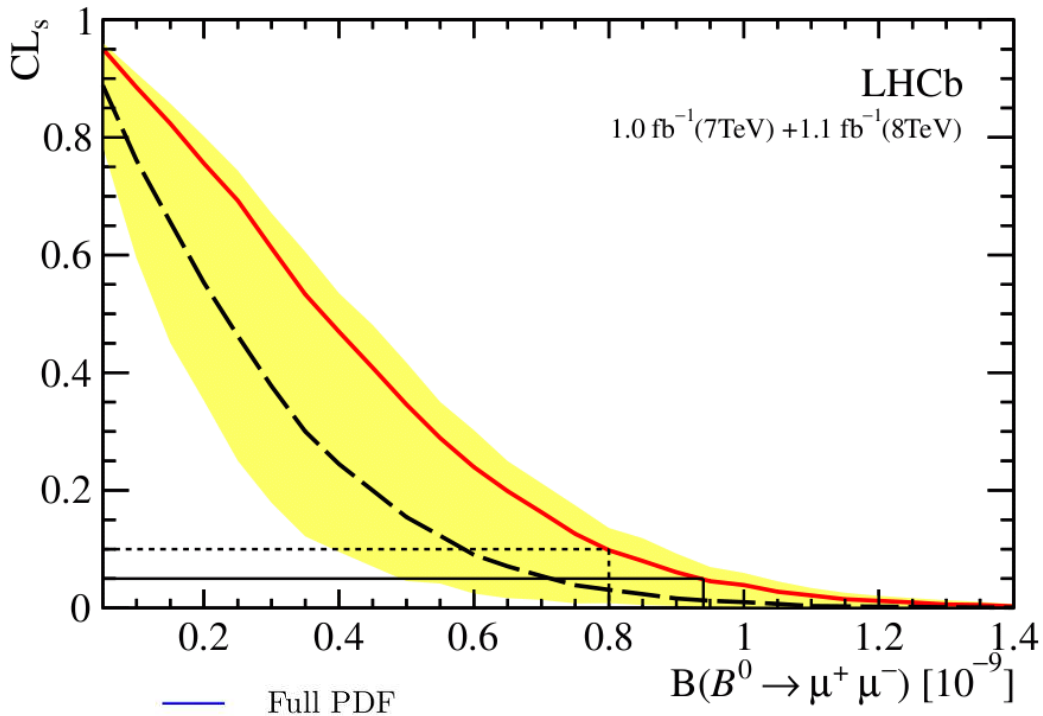

← Background-like
Signal-like →
$m_{\mu^+\mu^-}$ [MeV/c^2]
6000
5800
5600
5400
5200
5000
LHCb
B_s
B_d
0
0.2
0.4
0.6
0.8
1
BDT


μ^+
μ^-

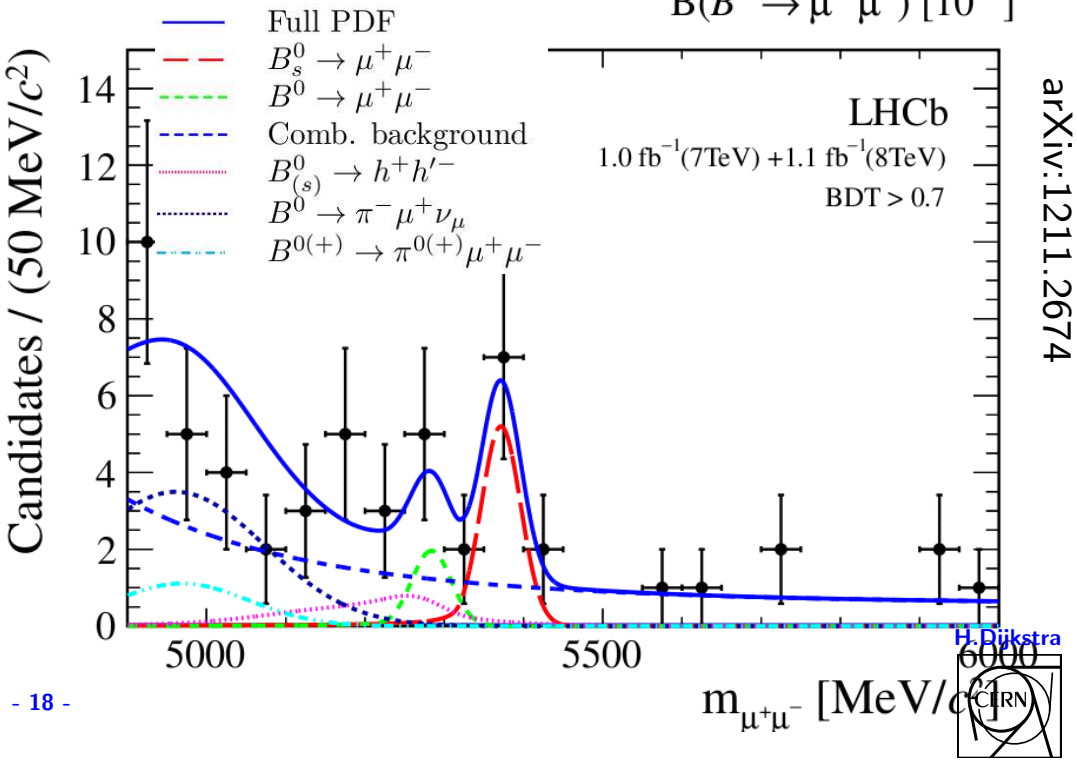

[0.2mm]
14
12
10
8
6
4
2
Primary Interaction
B^0_s
μ^+
μ^-
5
10
15
20
[mm]
25

$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)$

Upper limit:
$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$
at 95 % CL



Evidence:
$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$
with 3.5 σ

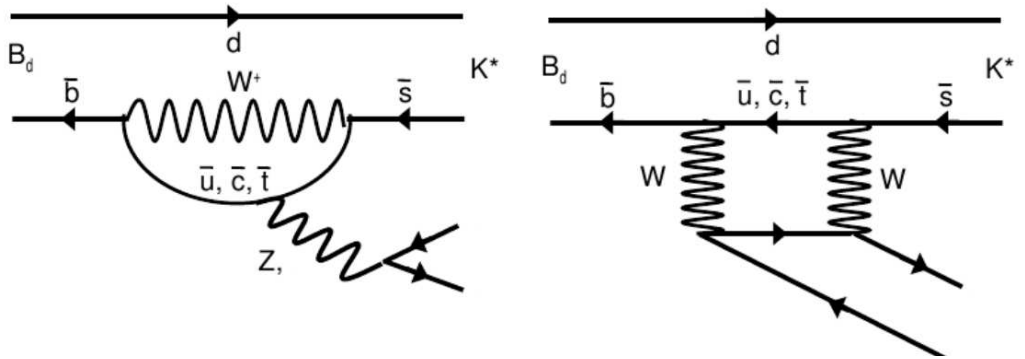


SM-reminder $(3.54 \pm 0.30) \times 10^{-9}$

$B^0_d \to K^* \mu^+ \mu^-$

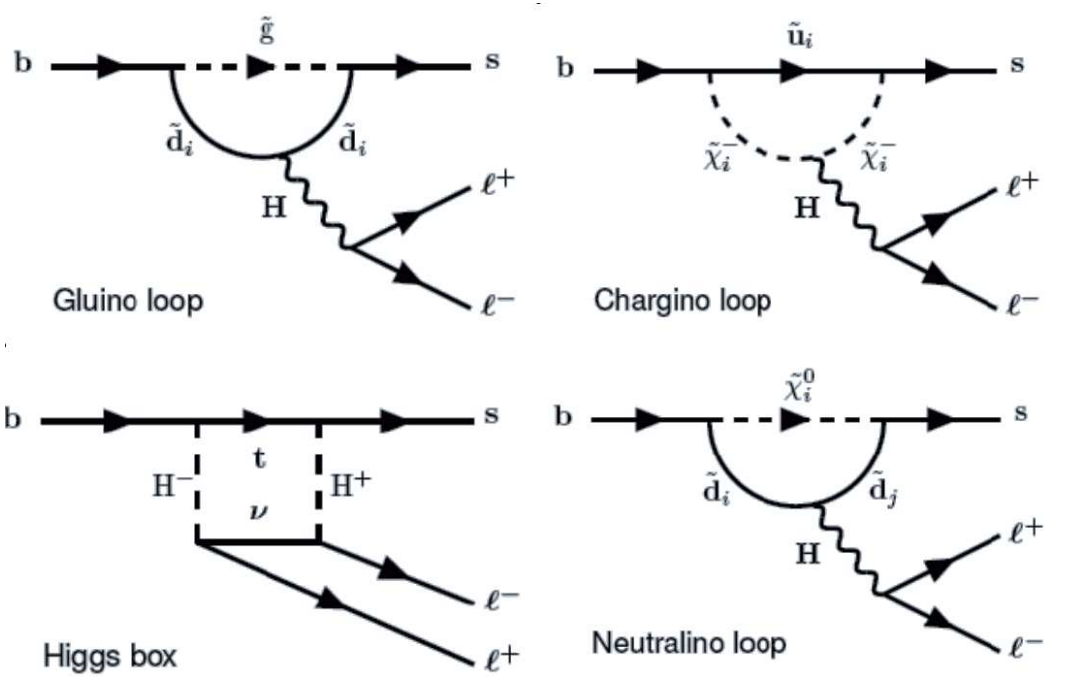
SM:

- $B \to sll$ FCNC decay.
- Rates, asymmetries and angular distributions have clean SM predictions.
- Experimentally clean



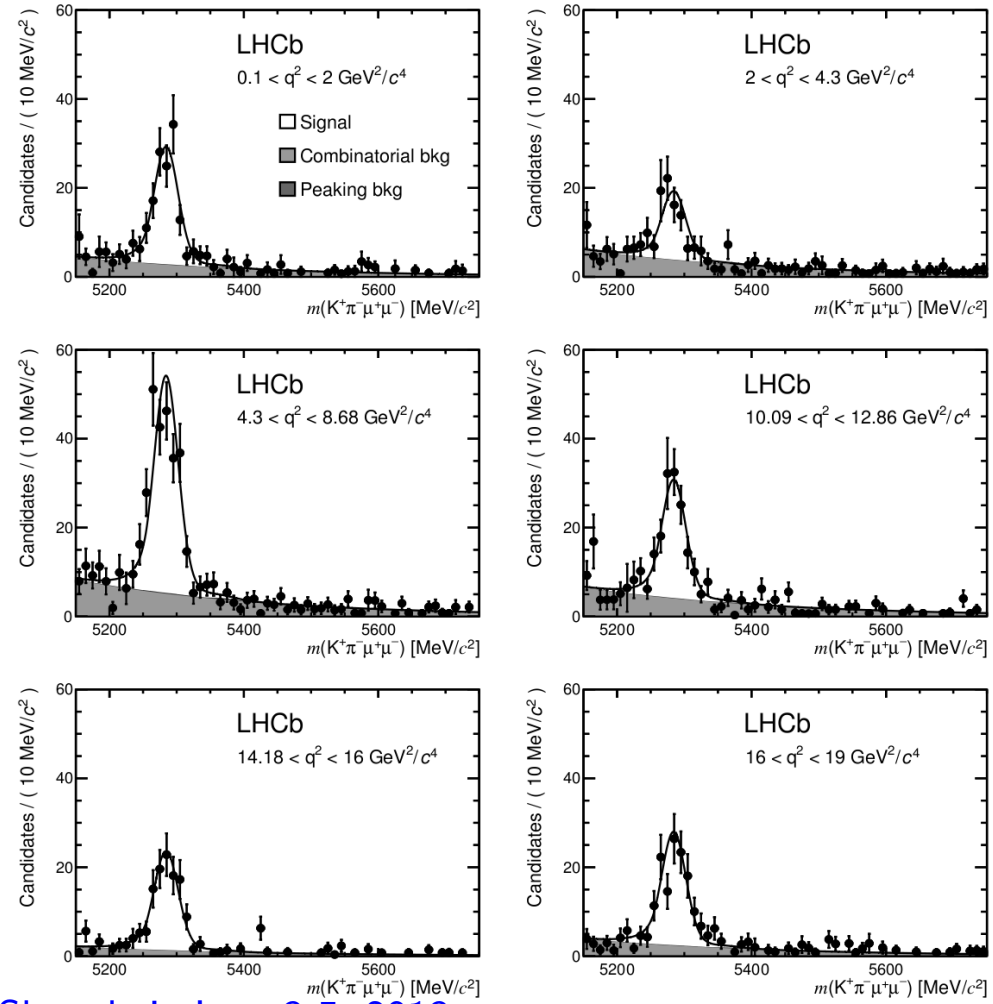
NP:

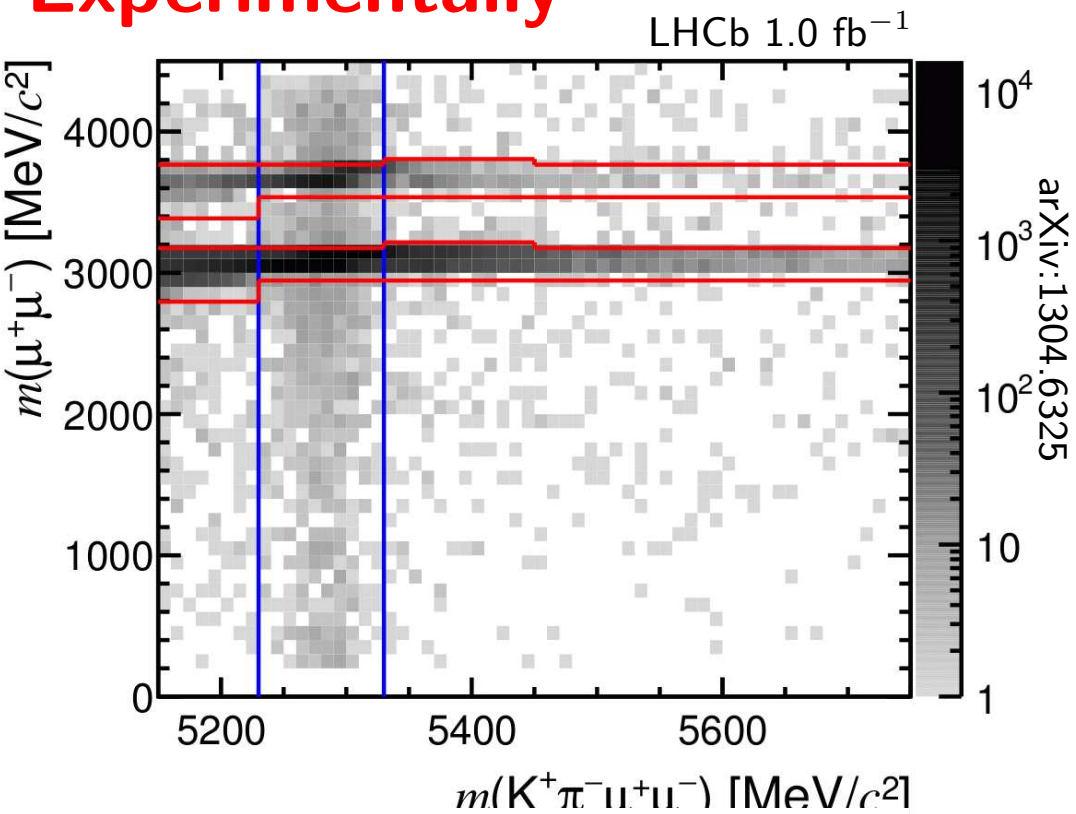
- Contributions also at low $tan\beta$, i.e. complementary to $B \to \mu\mu$
- Many variables to test NP models.

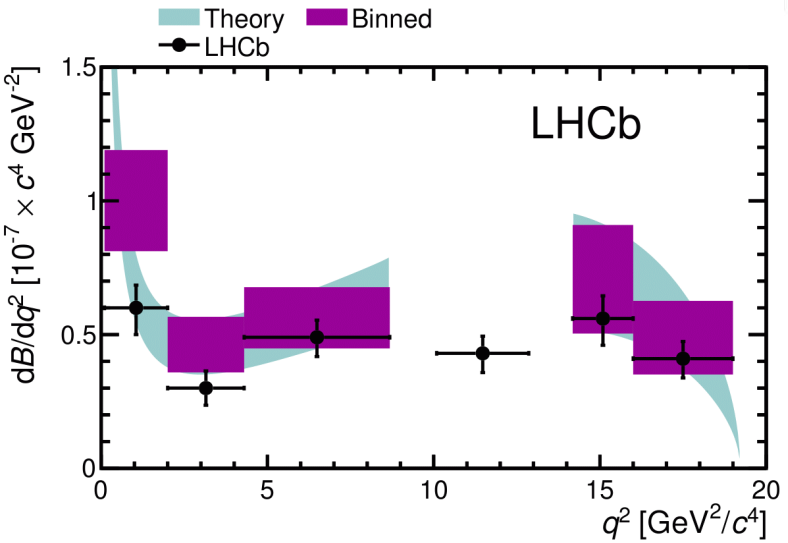


$B_d^0 \to K^*\mu^+\mu^-$ Experimentally

- Select K^* decay
- Bin in $q^2 = M_{\mu^+\mu^-}$ (exclude J/ψ, $\psi(2S)$)
- Fit yield/bin

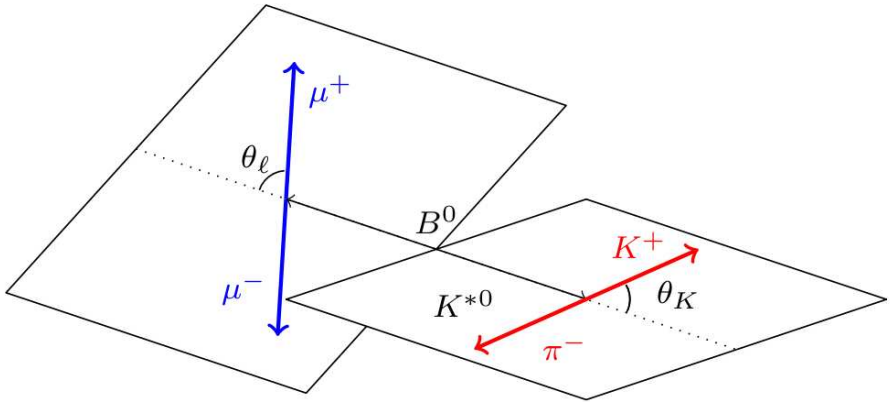


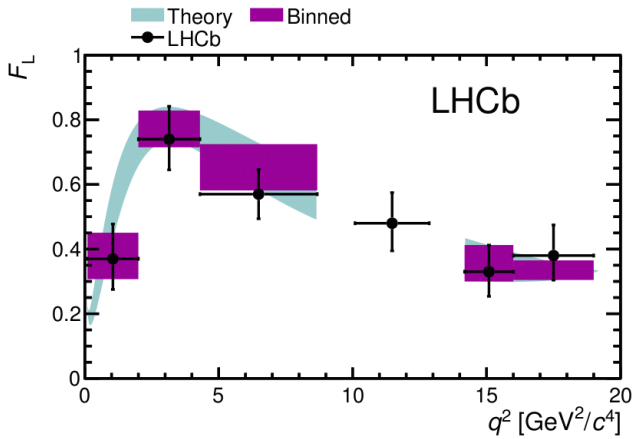


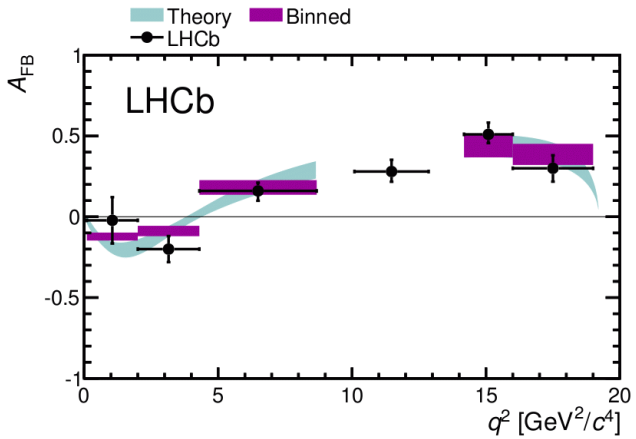


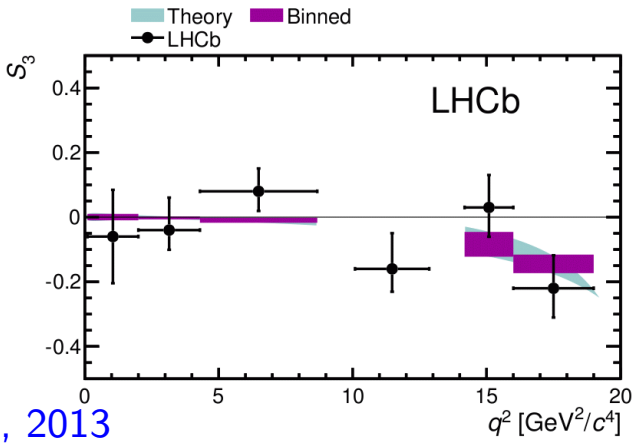
$B_d^0 \to K^*\mu^+\mu^-$ Angular Analysis

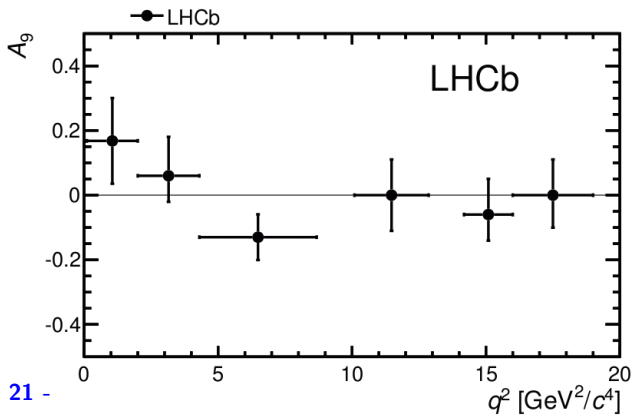
- Decay angular distribution: func(θ_K, θ_l, ϕ)
- Fit for amplitudes A_{FB}, F_L, S_3 and A_9
- SM: $A_{FB} = 0$ at $q^2 = 4.36^{+0.33}_{-0.31}$ GeV$^2/c^4$ (JHEP 01 (2012) 107)
- LHCb: $A_{FB} = 0$ at $q^2 = 4.9 \pm 0.9$ GeV$^2/c^4$





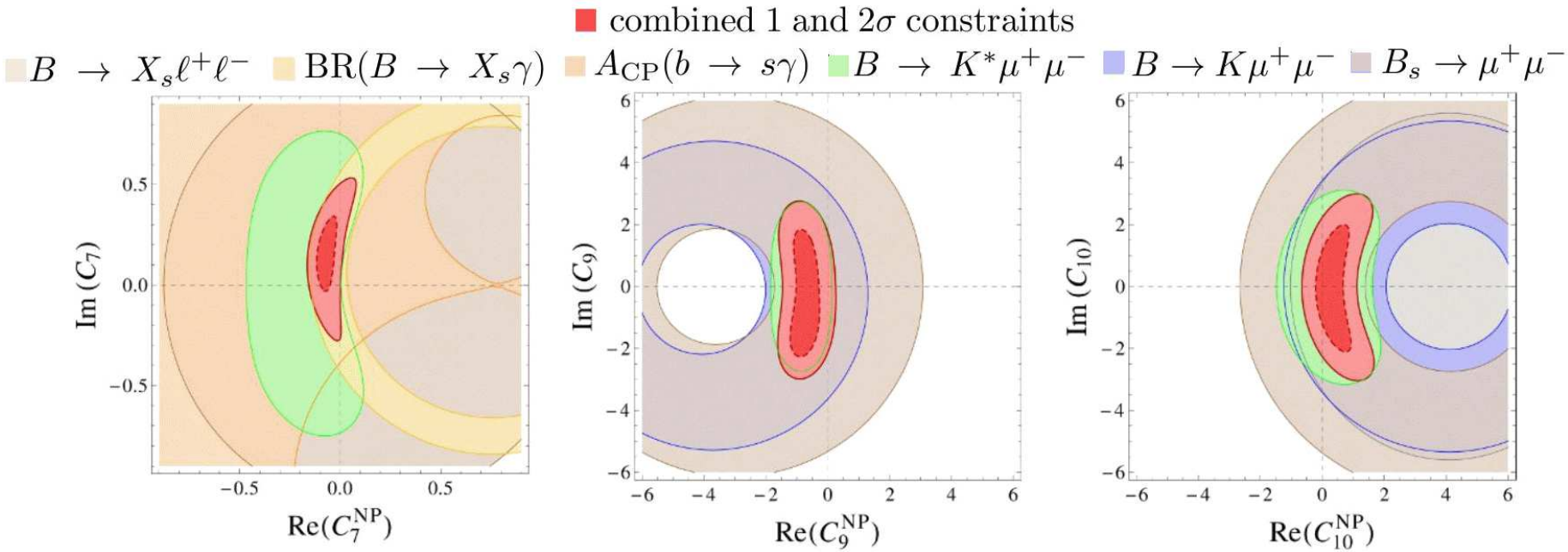






NP constraints from FCNC

Altmannshofer and Straub,
JHEP 08(2012)121



- NP in FCNC transition probed by modification to 9 Wilson operators in the Hamiltonian.
- Include data from CDF, D0, Belle, Babar, Atlas, CMS and LHCb.
- Angular analysis of $K^*\mu\mu$ imposes strongest constraints.
- $B_s \to \mu\mu$ (2011 data!) becomes competitive (for C_{10})

Conclusion: no deviations from SM (yet, check with more data...).

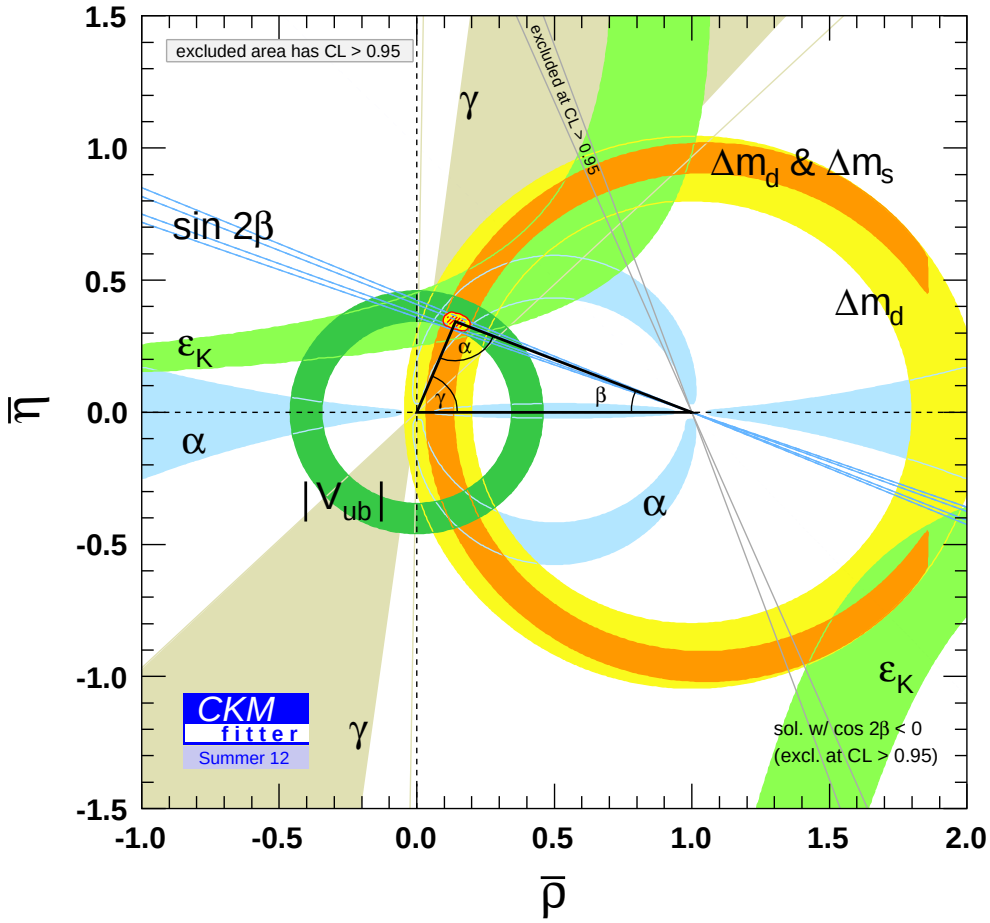
Selected CKM parameters

CKM-angle γ[a]

- Least well know:
  direct measurement $\gamma = (66 \pm 12)^o$
- Prediction from global CKM fit without direct measurements: $\gamma(\text{fit}) = (67.2^{+4.4}_{-4.6})^o$
- Hence: consistent, but very large error.
- Measure in tree decays: $B^{\pm} \to^{(} \bar{D}^{)0} K(\pi)^{\pm}$

B_s weak mixing phase ϕ_s

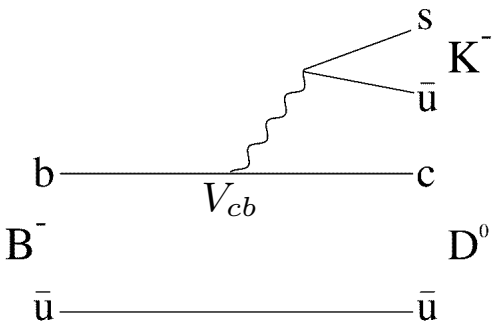
- Analogue of 2β of B^0-mixing.
- precisely predicted:
  $\phi_s = -0.036 \pm 0.002$ PRD84(2011)033005
- Measure in $B_s \to J/\psi K^+K^-(J/\phi\pi^+\pi^-)$

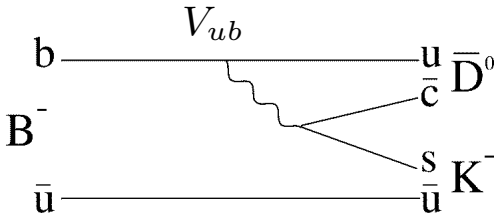


[a] plot/numbers from CKMFitter

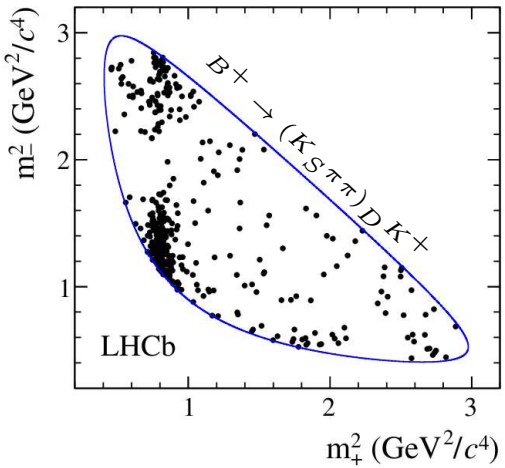
γ Measurements

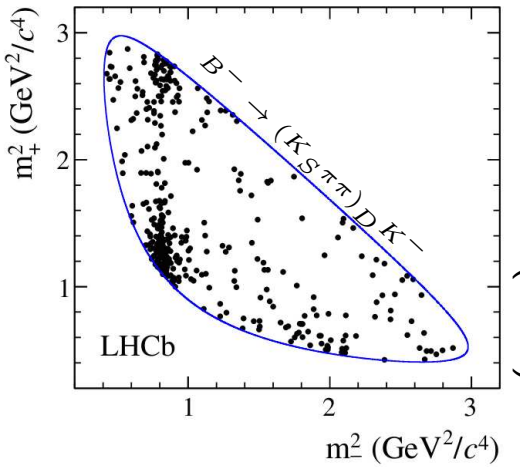
- phase between amplitudes $\propto \gamma$
- relative magnitude r_B





- Example: "GGSZ" mode: $D \to K_S h^+ h^-$
- Construct Dalitz distributions.





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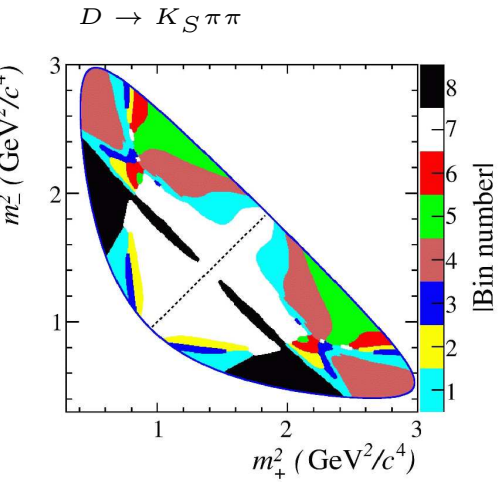
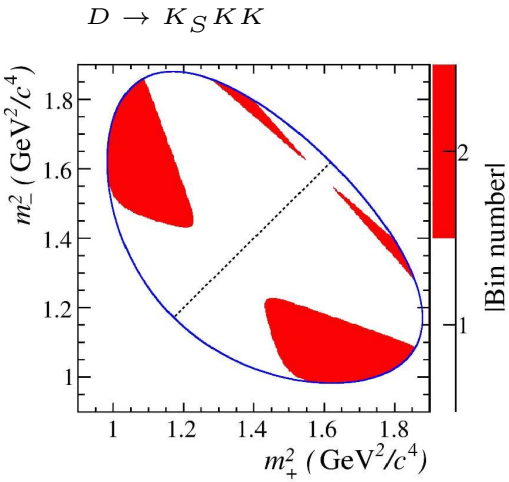
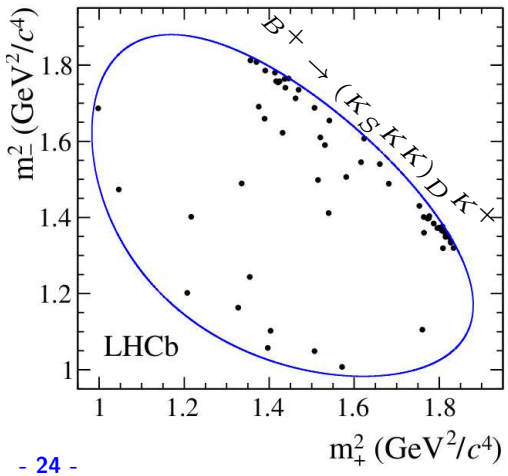
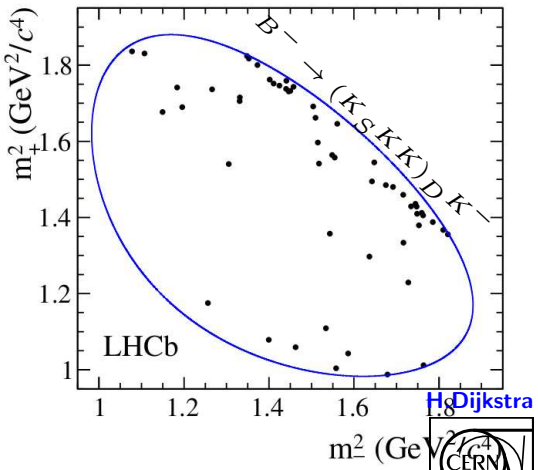
- Bin Dalitz (appropriately..)
- Fit for γ, r_B, etc..



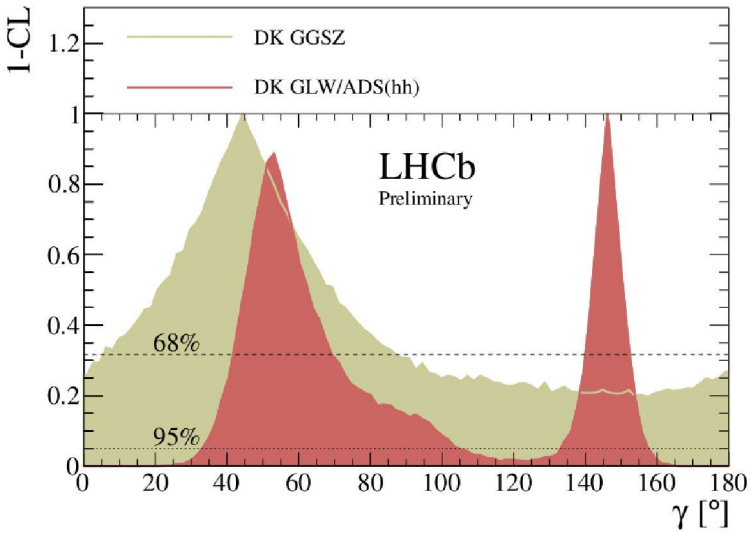


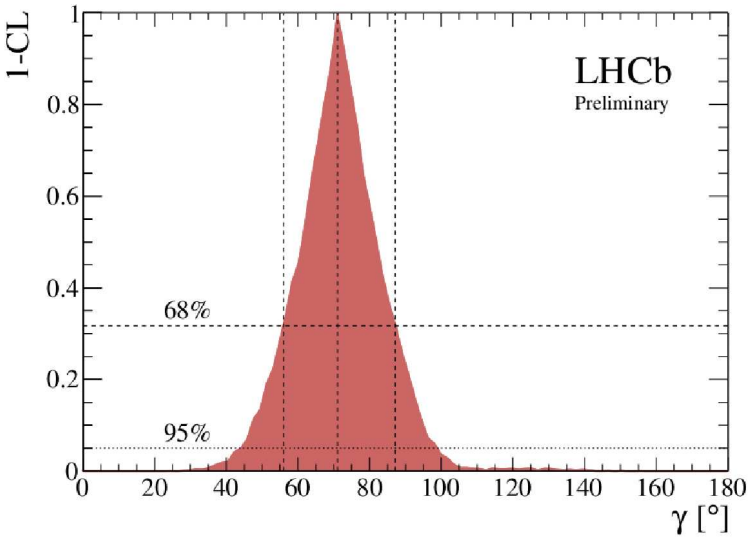




γ Measurement

- GGSZ[a] mode ($B^{\mp} \to DK^{\mp}$, $D \to K^0_S\pi^{\pm}\pi^{\mp}$ and $D \to K^0_S K^{\pm}K^{\mp}$) resolves γ ambiguity (only $|180^o|$ remains)
- GLW[b] mode: $D \to K^{\pm}K^{\mp}$ and $D \to \pi^{\pm}\pi^{\mp}$
- ADS[c] mode: $Dh^{\mp}$, $D \to \pi^{\pm}K^{\mp}$ and $D \to \pi^{\mp}K^{\pm}$





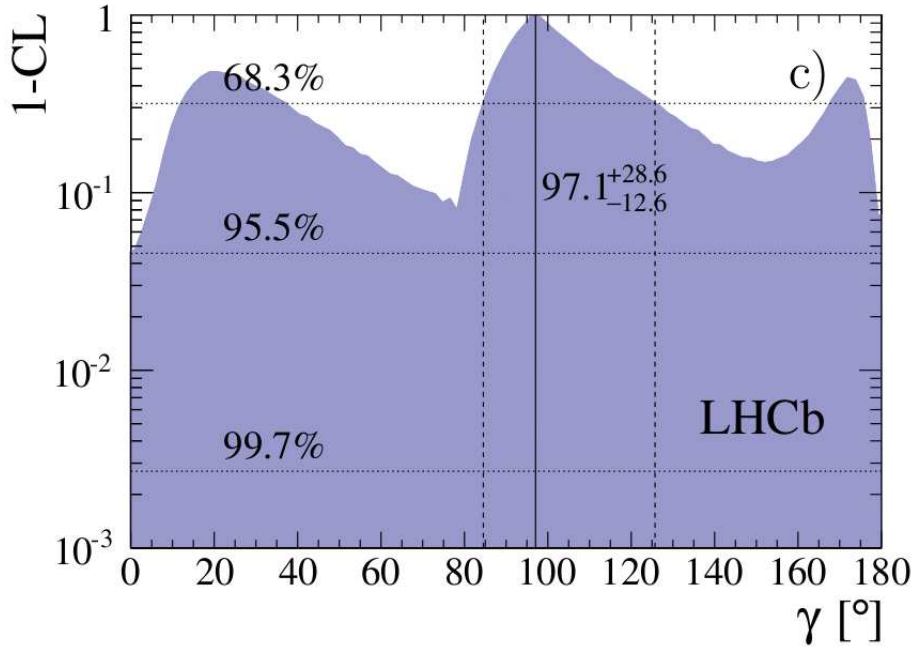
LHCb-CONF-2012-032

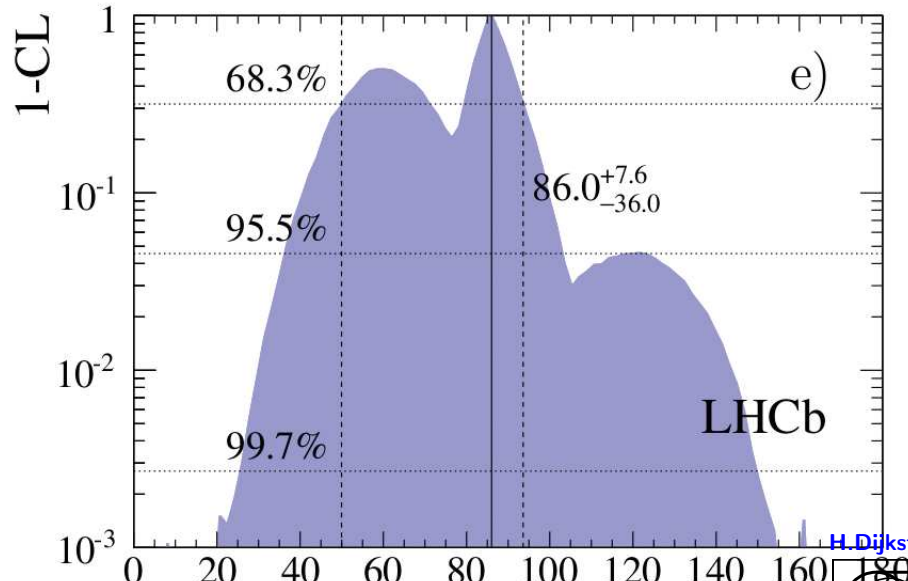
- Already compatible with beauty factories ($\sigma_\gamma = 12^o$) with 2011 (1.0 fb^{-1}) data.

[a] Giri, Grossman, Soffer, Zupan: PR. D66 (2003) 054018
[b] Gronau,London, Wyler: PL B253(1991)483, B265(1991)172
[c] Atwood, Dunietz, Soni: PR D63(2001)036005

γ Measurements

- What about $\to D\pi^{\pm}$ modes?





arXiv:1305.2050

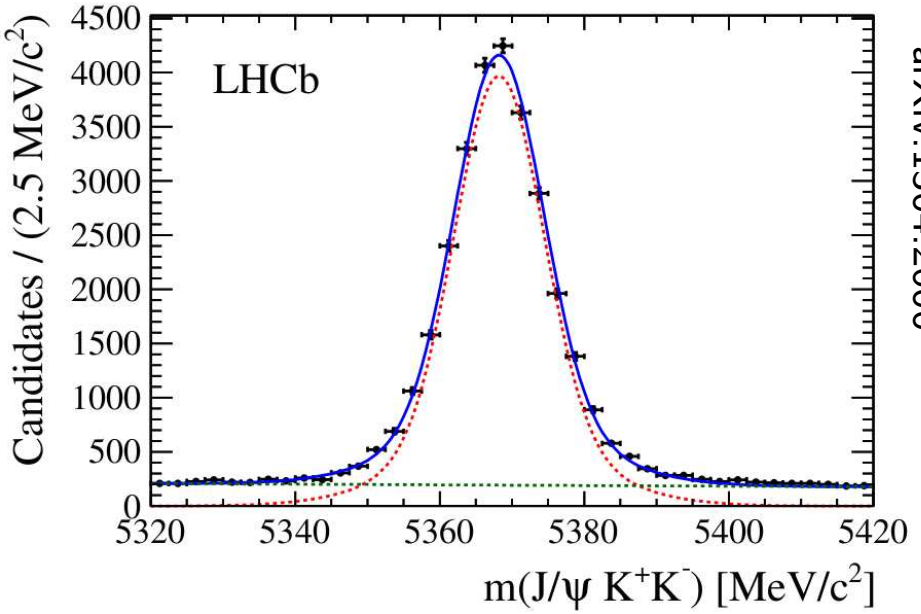
- Combine $\to D\pi^{\pm}$ and $\to DK^{\pm}$ for 2011 ($1.0\ \mathrm{fb}^{-1}$) data.
- $\gamma \in [54.9, 85.4]^o$ at 68% CL
- $\gamma \in [41.8, 98.1]^o$ at 95% CL

Improve accuracy with $3\times$ statistics already on tape.

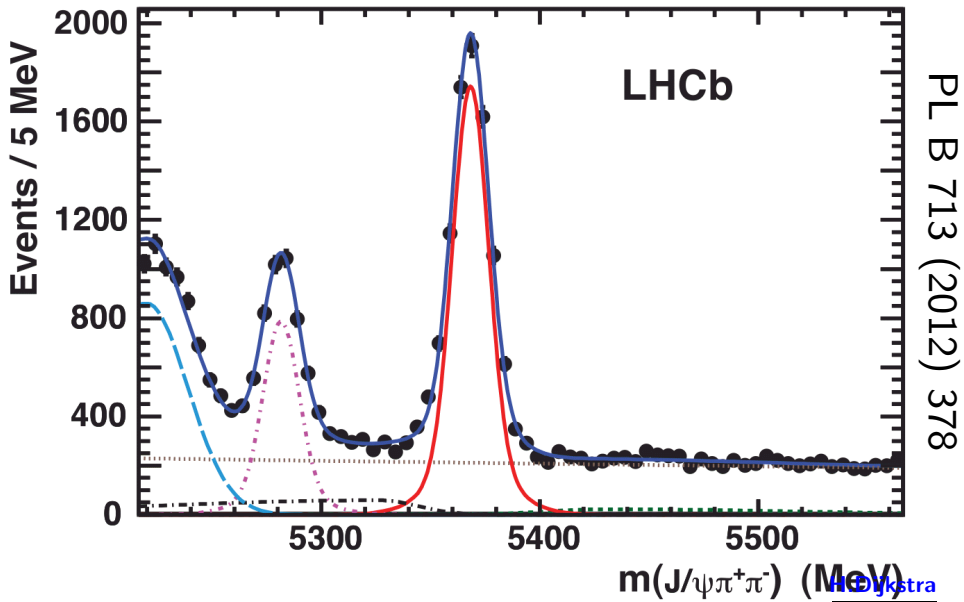
B_s weak mixing phase ϕ_s

$B_s \to J/\psi X$
to CP-eigenstates, interference of mixing-direct decay gives rise to CP -violating phase ϕ_s.
Global (indirect) fits to data gives in SM (ignoring sub-leading penguins) $\phi_s = -0.0364 \pm 0.0016$ rad[a]

- 2011: $\sim$ 28k $B_s \to J/\psi(\mu\mu)K^+K^-$ events
- $J/\psi\phi$ is a VV state, disentangle CP-even/odd with angular and time-dependent analysis.



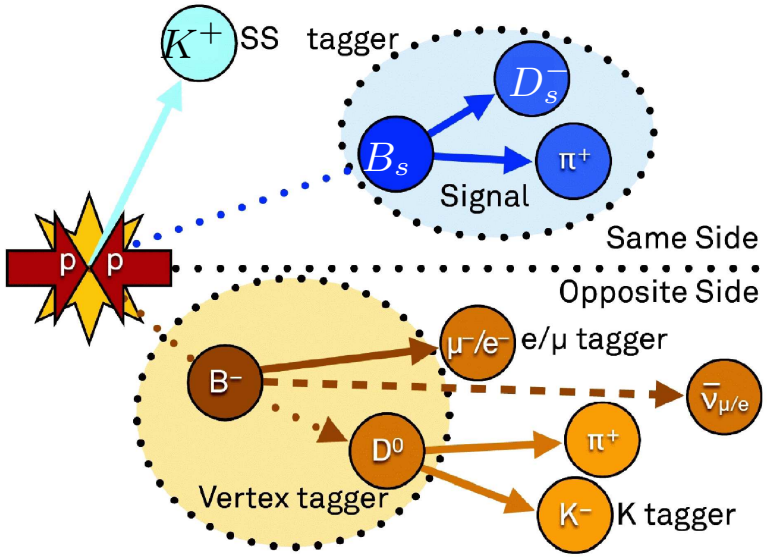
- 2011: $\sim$ 7k $B_s \to J/\psi(\mu\mu)f^0(\pi^+\pi^-)$ events
- Simpler analysis: f^0 single CP-state
- Combinatorial background:
  $B^- \to J/\psi K(\pi)^-$, $\bar{B}^0 \to J/\psi\pi\pi$, $\bar{B}_s \to J/\psi\eta'$, $\bar{B}_s \to J/\psi\phi(\pi^+\pi^-\pi^0)$ and $\bar{B}^0 \to J/\psi K^-\pi^+$



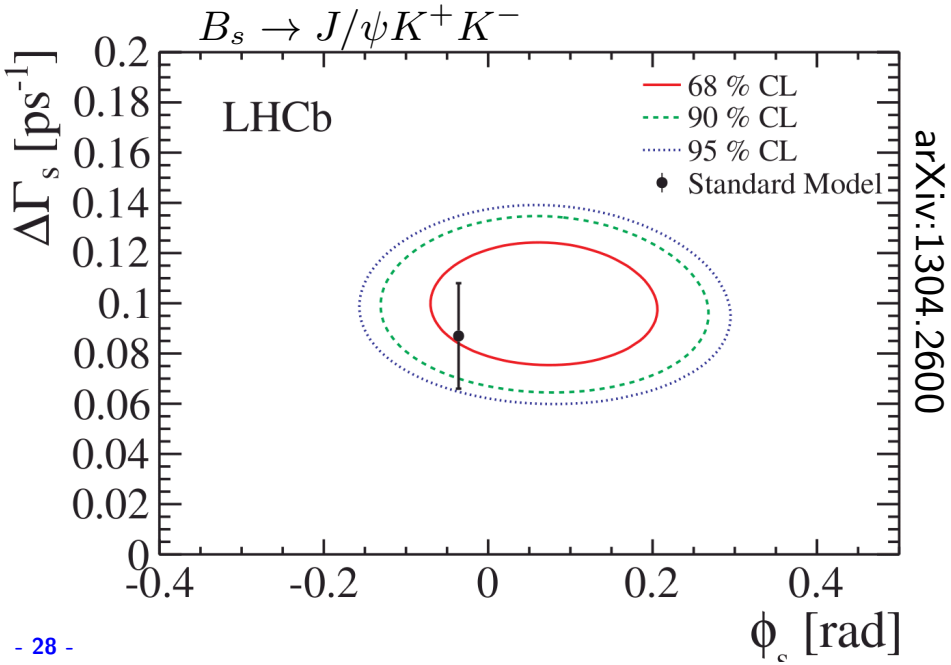
[a] PR D84 (2011) 033005, CKMFitter

B_s weak mixing phase ϕ_s

- Tag the flavour of B at origin with:
  - associated s with B_s (SST)
  - decay product other B (OST)
- Calibrate OST(SST) in data with: $B^+ \to J/\psi K^+$ ($B_s \to D_s^- \pi^+$)
- Effective tagging efficiency: $(3.13 \pm 0.12 \pm 0.20)\%$

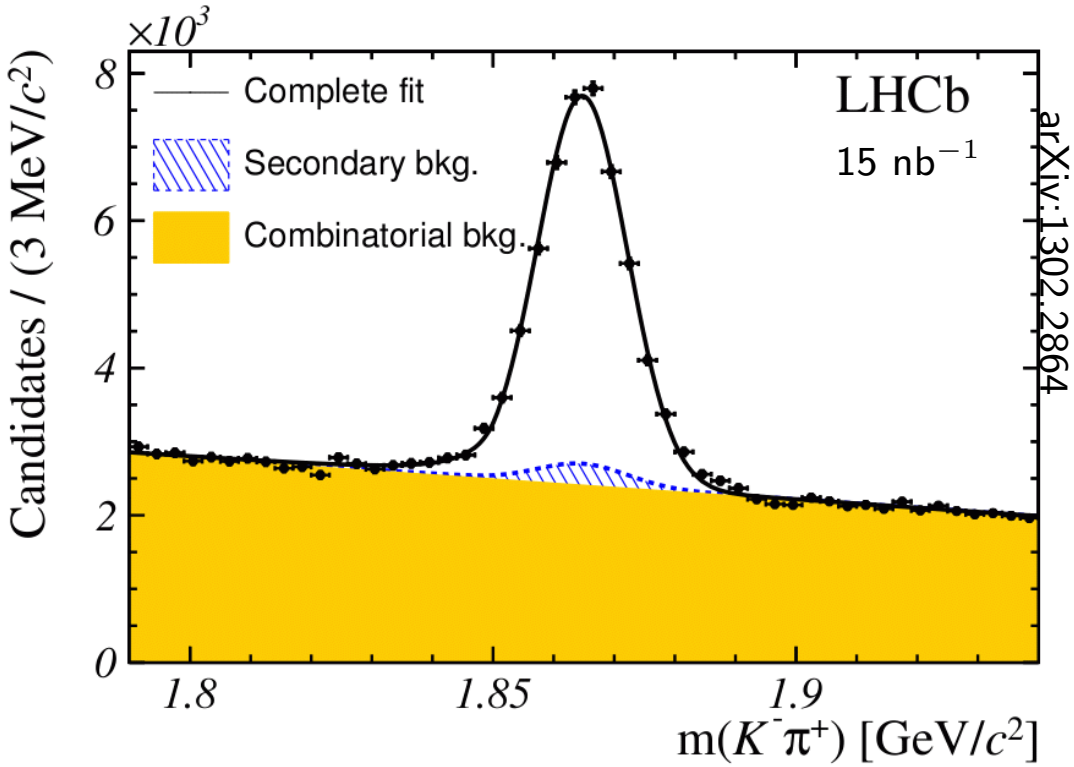


- Combined result:
- $\phi_s = 0.01 \pm 0.07(\text{stat}) \pm 0.01(\text{syst})$ rad
- Decay width difference: $\Delta\Gamma_s = 0.661 \pm 0.004(\text{stat}) \pm 0.006(\text{syst})$ ps^{-1}



Charm

- $\sigma(c\bar{c}) = 1419 \pm 12(\text{stat}) \pm 116(\text{syst}) \pm 65(\text{frag})\ \mu\text{b}$ at $\sqrt{(s)} = 7$ TeV in LHCb acceptance.
- visible $\sigma(pp) \sim 59 \pm 2$ mb at $\sqrt{(s)} = 7$ TeV (J. Instrum. 7 (2012) P01010)
- Plot: ∼min when running at full LHCb luminosity.



Hence: collect "huge" statistics:

- Charm mixing
- Charm CPV

Charm Mixing

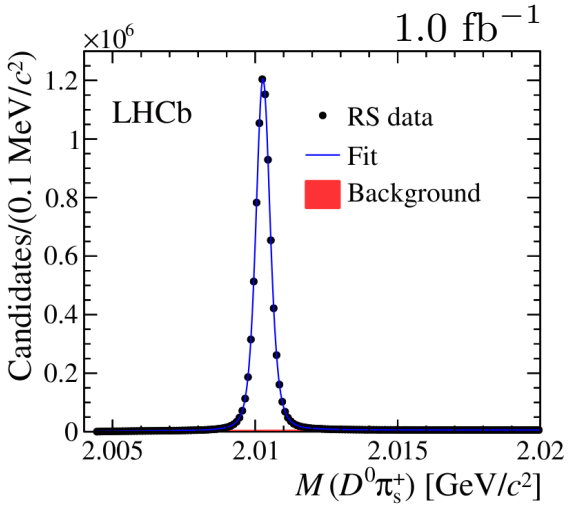
Right Sign (RS): $D^{*+} \to D^0(K^-\pi^+)\pi^+$

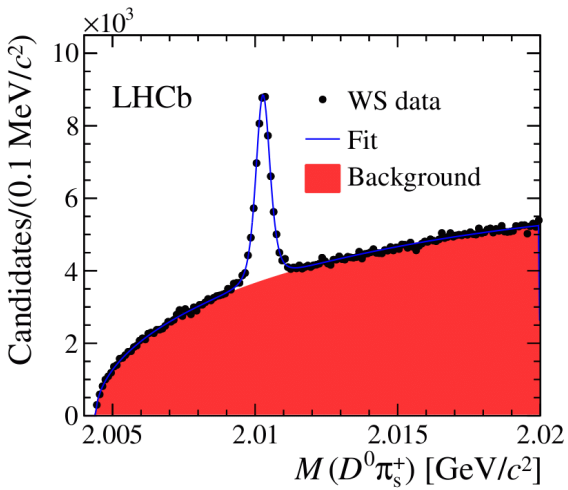
- Cabibbo favoured
- 8.4×10^6 events

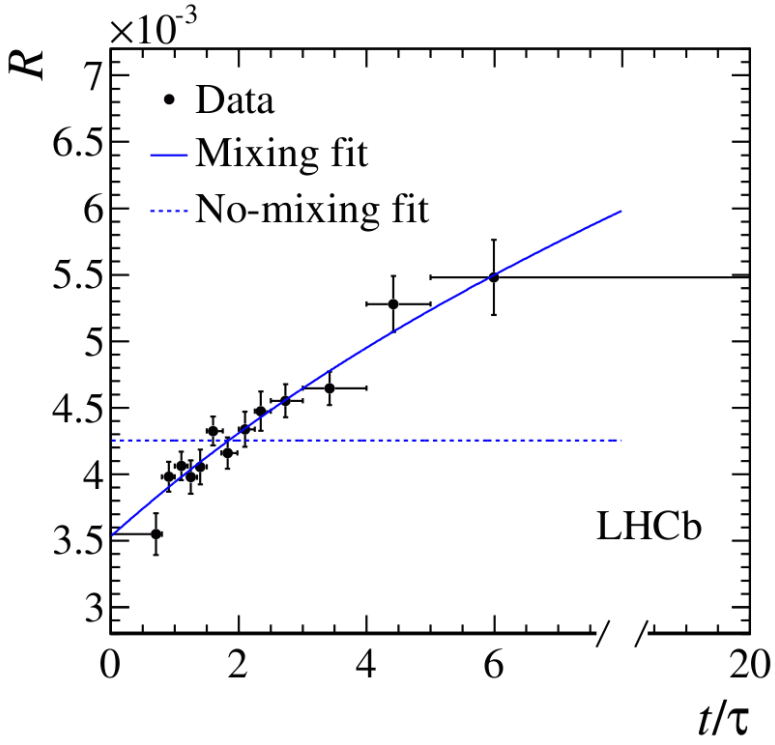
Wrong Sign (WS): $D^{*+} \to D^0(K^+\pi^-)\pi^+$

- Double Cabibbo suppressed and mixing
- 3.6×10^4 events

Ratio WS/RS: no mixing excluded at 9.1 σ.







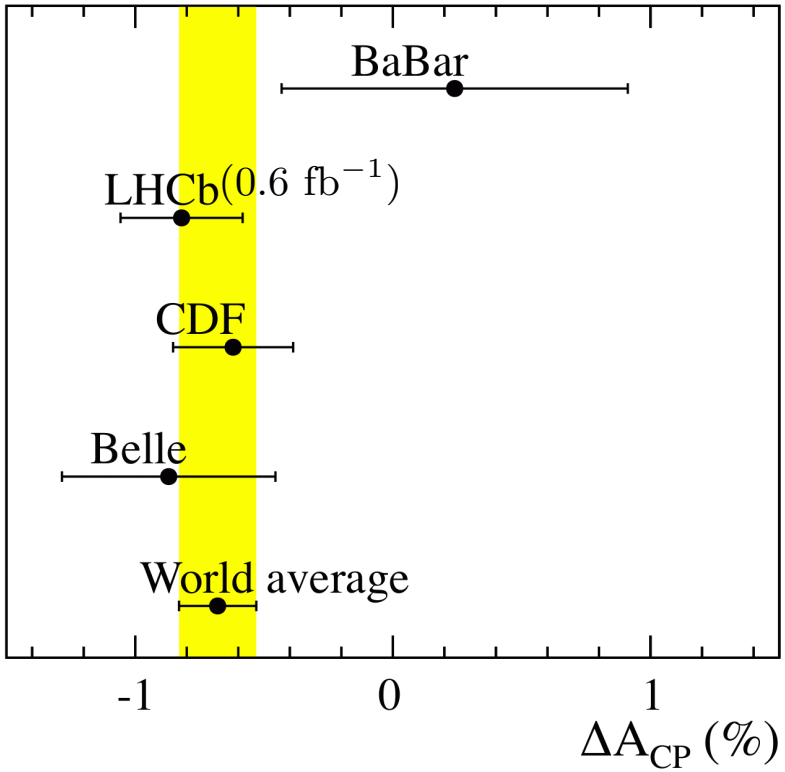
PRL 110, 101802 (2013)

Charm CPV

CPV well established in K, B-systems

CPV in charm (u-quark):

- Effectively 2-generation system
- $3^{\rm rd}$ enters through loops, hence
- expected to be very small: $< 0.1\%$
- Exp:
  $\Delta A_{\rm CP} = A_{\rm CP}(D \to KK) - A_{\rm CP}(D \to \pi\pi)$
- HFAG (ICHEP 2012):
  $\Delta a_{CP}^{\rm dir} = (-0.678 \pm 0.147)\%$



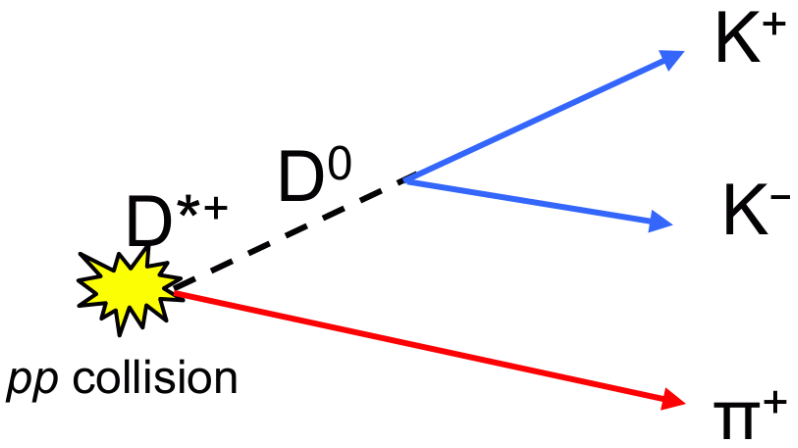
Charm CPV: Experimentally

$$A_{RAW} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)} \approx A_{CP} + A_{\text{Detection}} + A_{\text{Production}}$$

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \approx A_{\text{Raw}}(K^+K^-) - A_{\text{Raw}}(\pi^+\pi^-)$$

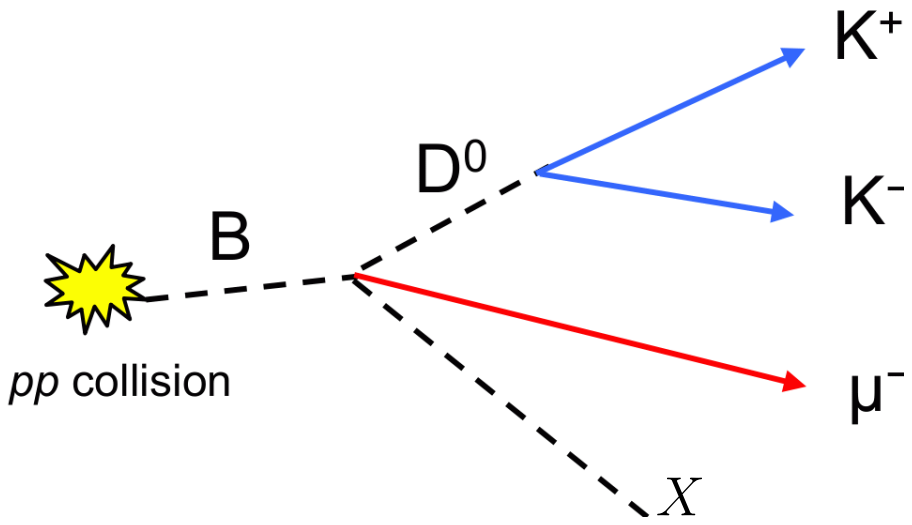
$D^{*+} \to D(hh')\pi^+_{\text{tag}}$:

- Update $0.6 \to 1.0$ fb^{-1}
- LHCb-CONF-2013-003
- Tag: (slow) π from D^*
- Use $\delta m = M(D^*) - M(D) - M(\pi)$



$B \to D(hh')\mu^+_{\text{tag}}X$:

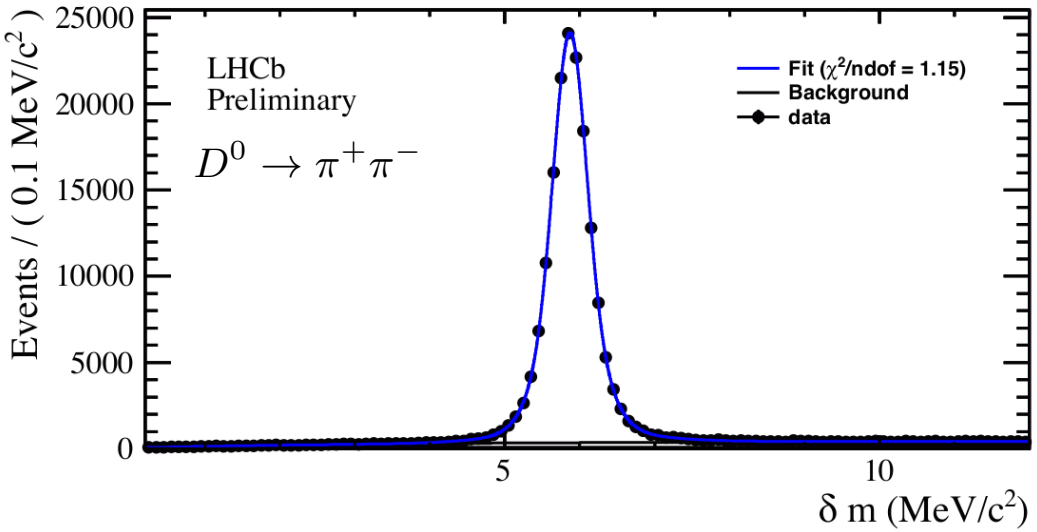
- 1.0 fb^{-1}
- New (complementary) measurement
- PLB 723 (2013)
- Tag (and trigger) with μ



Charm CPV

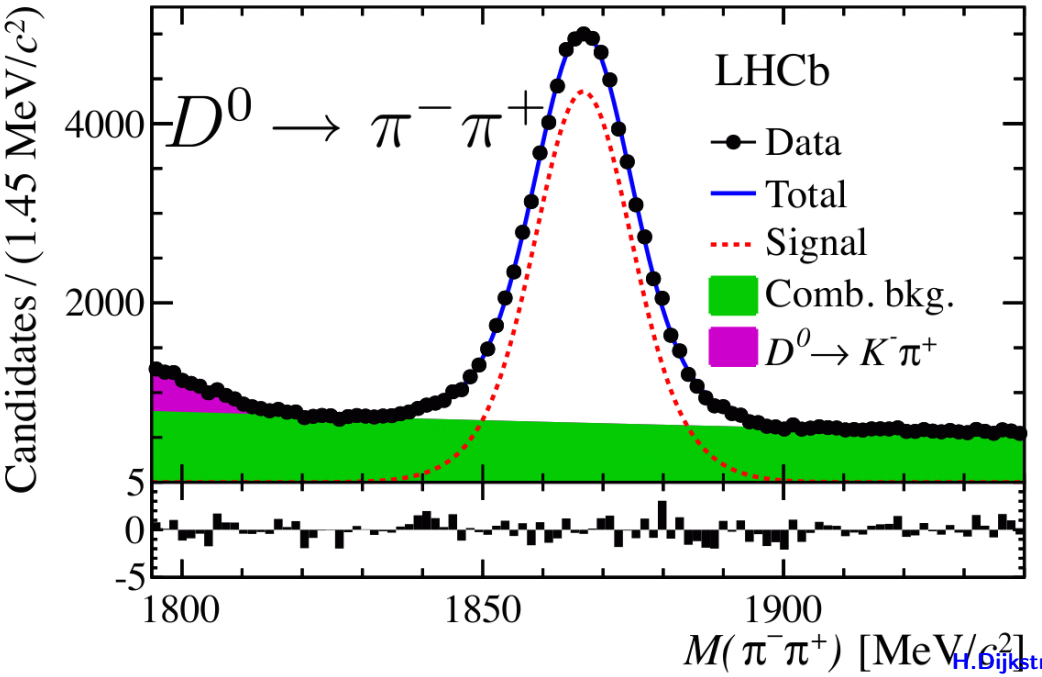
π-tagged

- Very clean signals!
- $D \to \pi\pi$: 0.69 M events.
- $D \to KK$: 2.24 M events.
- $\Delta A_{CP} = (-0.34 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}))\%$ [LHCb-CONF-2013-003]
- Supersedes: [PRL108.111602] $(-0.82 \pm 0.21 \pm 0.11)\%$



μ-tagged

- Clean signals
- $D \to \pi\pi$: 0.22 M events.
- $D \to KK$: 0.56 M events.
- $\Delta A_{CP} = (+0.49 \pm 0.30(\text{stat}) \pm 0.14(\text{syst}))\%$ [arXiv:1303.2614]

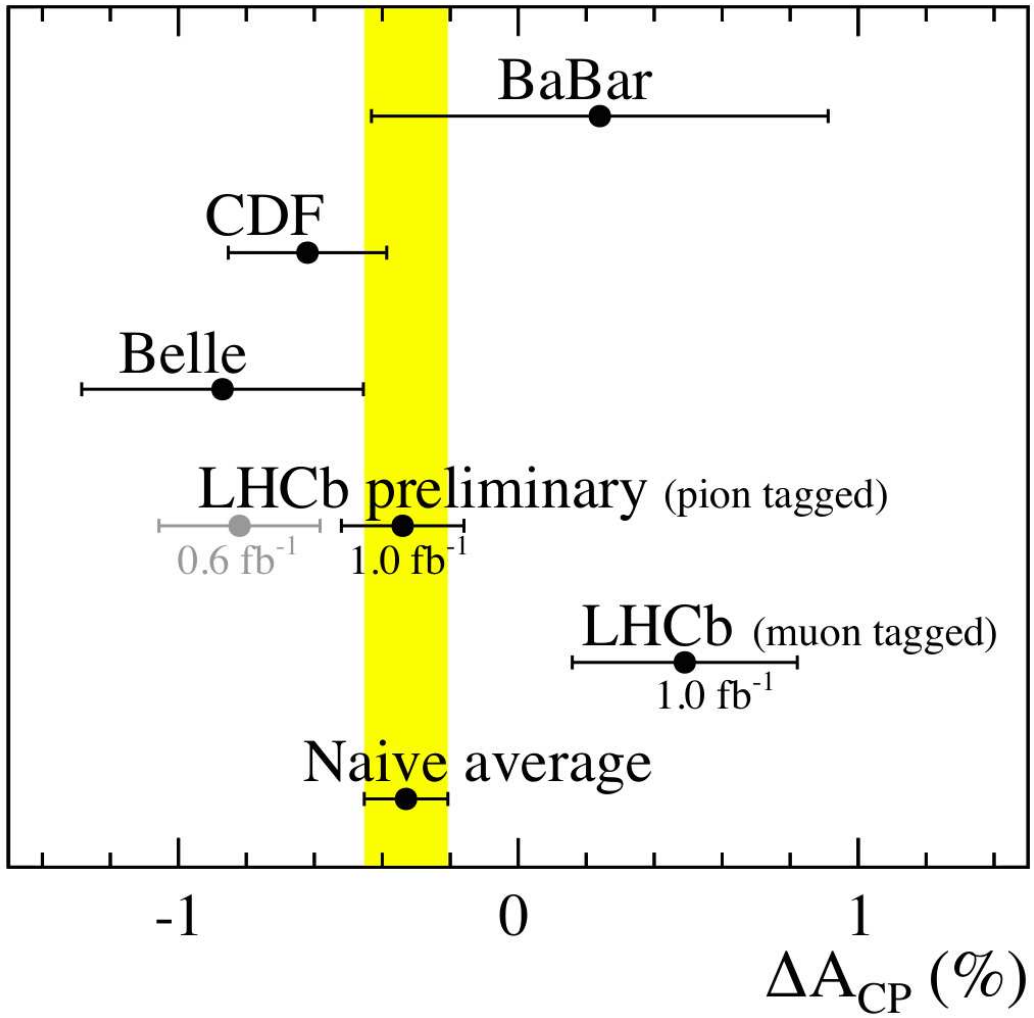


- $\pi - \mu$-tag samples independent, differ 2.2σ
- Many cross-checks: B-field, time, etc...

Charm CPV: Spring 2013

- Naïve average: $\Delta A_{CP} = (-0.33 \pm 0.12)\%$

- No "evidence" for CPV in charm anymore.
- $3\times$ more statistics on tape!



Conclusion and Outlook

- LHCb dominates many key measurements in heavy flavour physics with 2011 data alone.
- Adding 2012 data will triple statistics.

- SM does very well!
- Searches however (in many channels) still far from theoretical precision: much room for improvement.

- $\sigma(b\bar{b})$ will double after LS1
- LHCb upgrade planned for 2018. (CERN-LHCC-2012-007)
- Allows $5\times$ increase in luminosity.
- Full software trigger: will more than double (hadronic) efficiency.