Electroweak Physics with p̄anda

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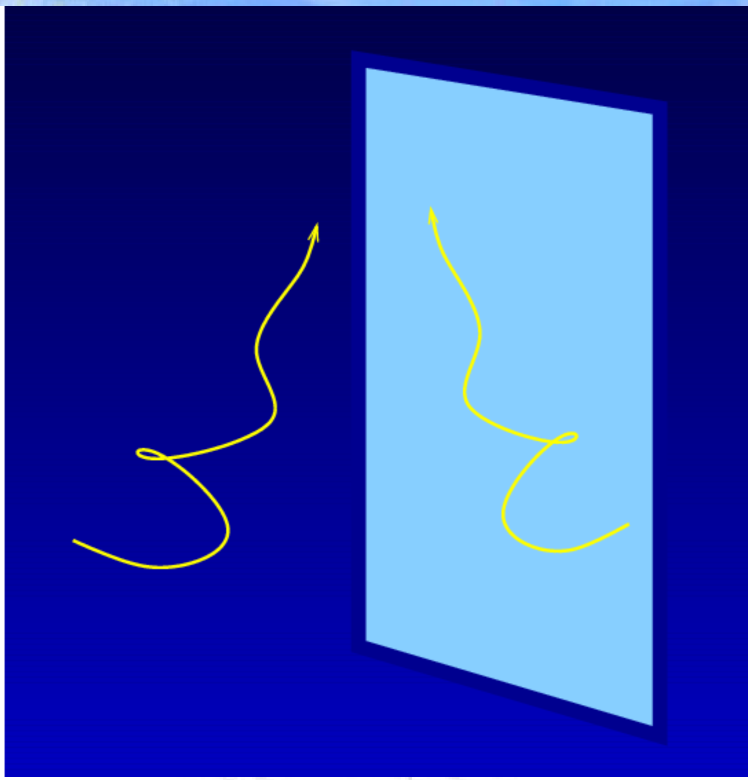
- Introduction to the Physics
- Status of CPV in Charm
- Rates and Prospects
- Conclusions

Symmetries: C, P and T



Fundamental Symmetries

- P : Parity, mirror
- C : Charge conjugation
- T : Time reversal
- CPT conserved in all QFTs

What is CP Violation?

- Particle physics and cosmology: difference matter / anti-matter
- Weak interaction: Parity violation
- CP symmetry should be conserved
- Phase in CKM matrix causes CPV

Brief History of CP Violation

- 1964: CPV in $K \leftrightarrow \bar{K}$ mixing
  (small effect: $\varepsilon \approx 1.6 \times 10^{-3}$)
- 1973: Kobayashi & Maskawa: 3 families
- 1999: Direct CPV in $K \rightarrow \pi\pi$ decay
  (small effect: $\varepsilon'/\varepsilon \approx 1.7 \times 10^{-3}$)
- 2001: CPV in $B, \bar{B} \rightarrow J/\psi K_s$ decay
  (large effect: $\sin 2\beta = 0.74 \pm 0.07$)

SM explains CPV pattern in mixing & decay

Flavour Mixing and CP Violation

CP Violation in Standard Model:

- Interference of 2 amplitudes
- CKM elements with phase difference
- CP asymmetry: $\alpha_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2}$

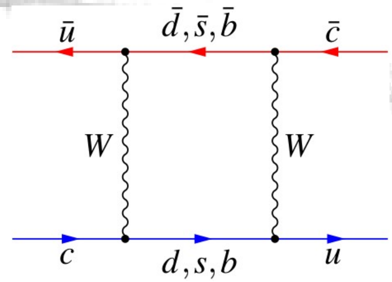
Indirect CP Violation: ΔF=2

- Mixing induced:
  D^0 oscillates to $\bar{D}^0$
- Mass difference, lifetime difference
- 2 States: $|D_{H/L}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$

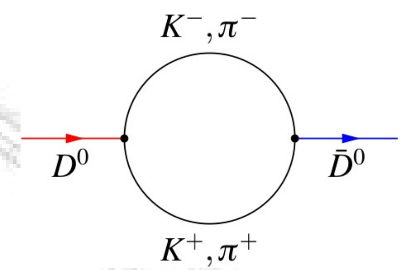
Direct CP Violation: ΔF=1

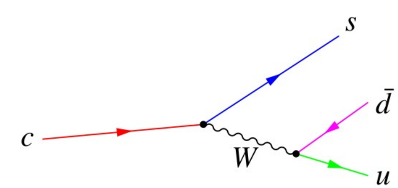
- CP violating phases in decay
  $A(D \rightarrow f) \neq A(\bar{D} \rightarrow \bar{f})$
- CKM elements

Short range:
Box graph

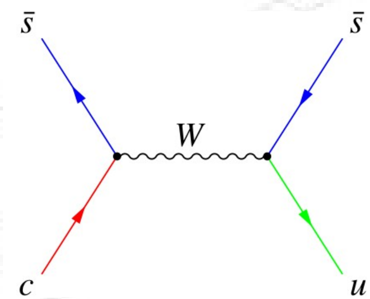


Long range:
Final state mixing

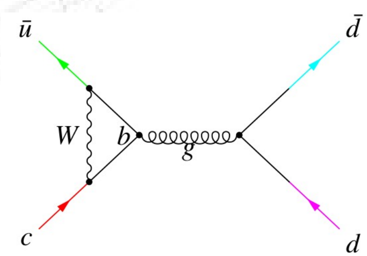




Free decay
(SCS)



Annihilation



Penguin

Direct CP Violation

Direct CP Violation in SM:

- Two interfering amplitudes needed
- Singly Cabibbo suppressed (SCS):

Channel	BR (%)	$\alpha_{CP}(10^{-3})$
$D^+ \to \pi^+\eta'$	0.75	0.77
$D^+ \to K^+\bar{K}^0$	0.72	0.52
$D^+ \to \rho^+\pi^0$	0.45 (th)	0.89
$D_s^+ \to K^+\pi^0$	0.15 (th)	1.1
$D_s^+ \to K^+\eta'$	0.5 (th)	0.64
$D^0 \to \pi^\pm\rho^\mp$	0.5 - 0.7 (th)	0.4

- Typical BR ~ 0.2-1%
  need 10^8 rec. charm for $\alpha_{CP} \approx 10^{-3}$
- Large α_{CP} could be due to new physics (NP) or strong phase
- CF or DCS : $\alpha_{CP} = 0 \to$ search NP

Comparison of B and D

- Decay amplitudes:

	tree	penguin
B-mesons	small CKM	large CKM
D-mesons	large CKM	small CKM

- $\alpha_{CP} \sim 10^{-3}$ for D-mesons
- α_{CP} ~ several % for B-mesons

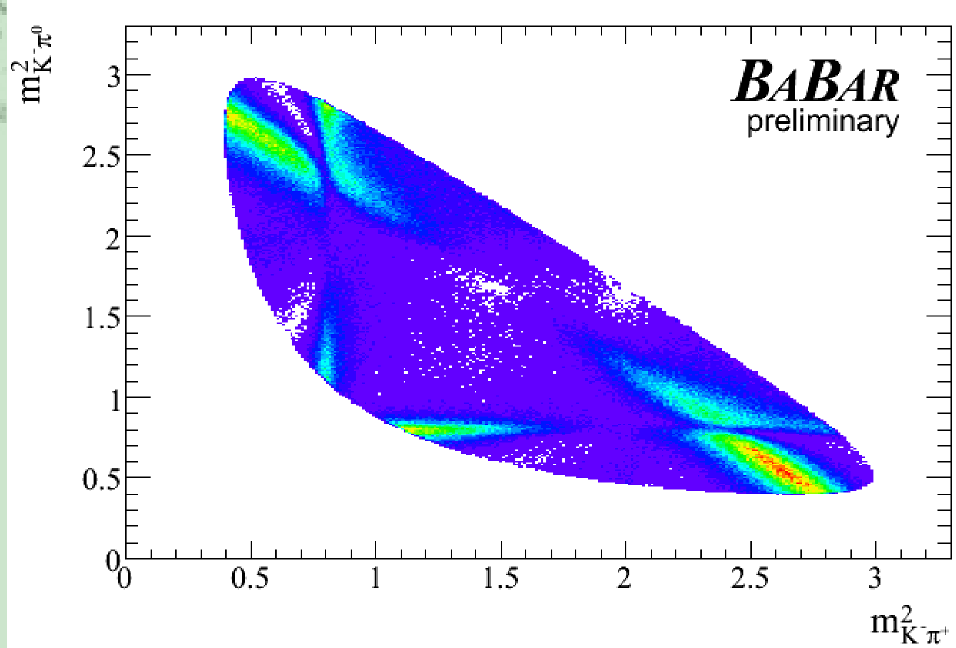
➔ Search for NP in D decays

New Methods for CP Violation Searches

Phase space analysis:

Measure phase differences

- **Dalitz plot analysis**
- → Multiple channels
- → Get strong phase & amplitude, mixing and CPV parameters
- **Partial Wave Analysis**
- → Get CP-odd and CP-even states, DCS modes
- → Depends on decay model



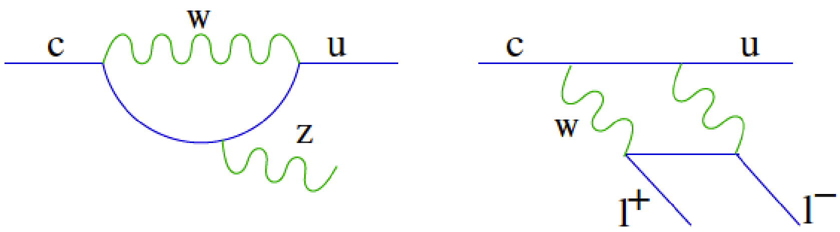
Polarisation

- Hyperon decays
- η-decays

Other Electroweak Topics

FCNC decays:

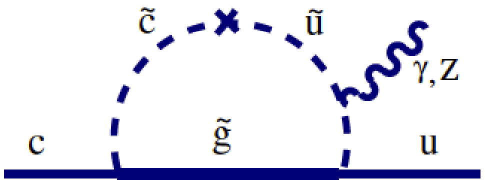
- In SM: BR ~ 10^{-8}
- Beware of resonances in $D \rightarrow X l^+ l^-$:
  e.g. $D^+ \rightarrow \pi^+ \phi \rightarrow \pi^+ \mu^+ \mu^-$
- SUSY channels often bigger than SM



SM FCNC

Dilepton decays:

- E.g. $D^0 \rightarrow \mu^+ \mu^-$, BR ~$10^{-9}$–$10^{-12}$
- $D^0 \rightarrow \mu e$ in SM = 0
- ➔ BG-free tests for new physics



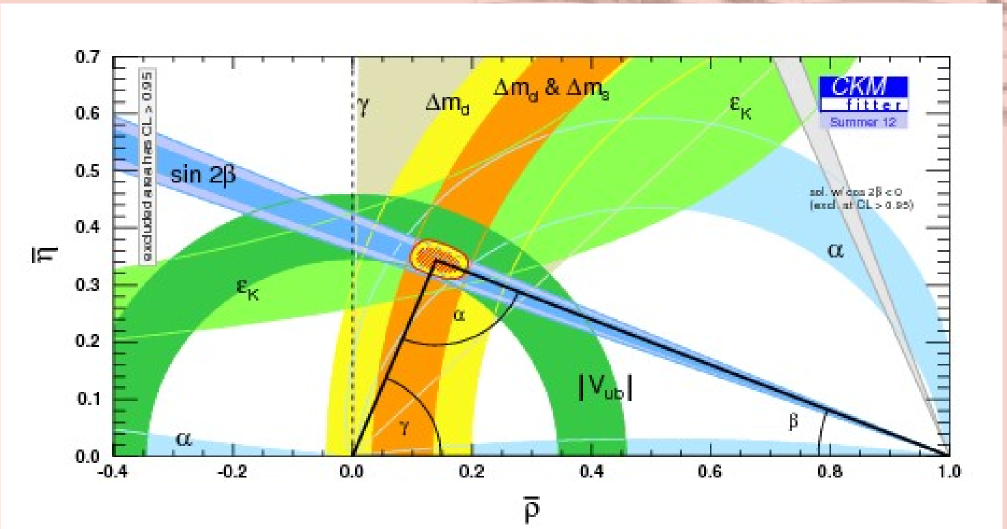
MSSM radiative decay

Charm vs. Beauty:

- Intermediate d-type quarks
- SM contribution small due to V_{ub}
- rate ~ f (m_s)− f (m_d) (=0 in SU(3) limit)
- ➔ Sensitive to new physics

Probing the Standard Model

Status of Unitarity Triangle



- CP violation in B decays well measured
- K system as well
- Further channels and constraints all fit the SM
  - → Impressive agreement with SM
  - → No hints for NP

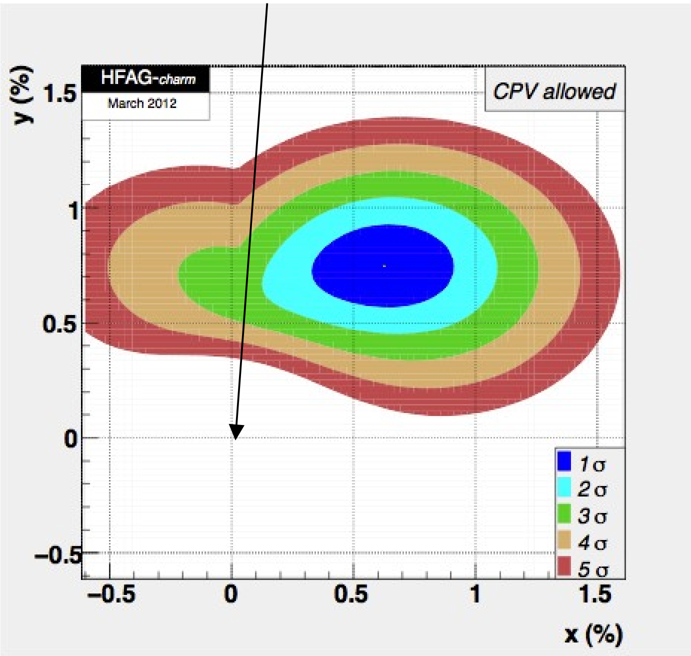
Alternative channels for NP

- D-mesons
  - → Same methods as for B
  - → SM CPV small
  - → Small deviations can hint for NP
- Hyperons
  - → CPV in decay polarisation
- η-mesons

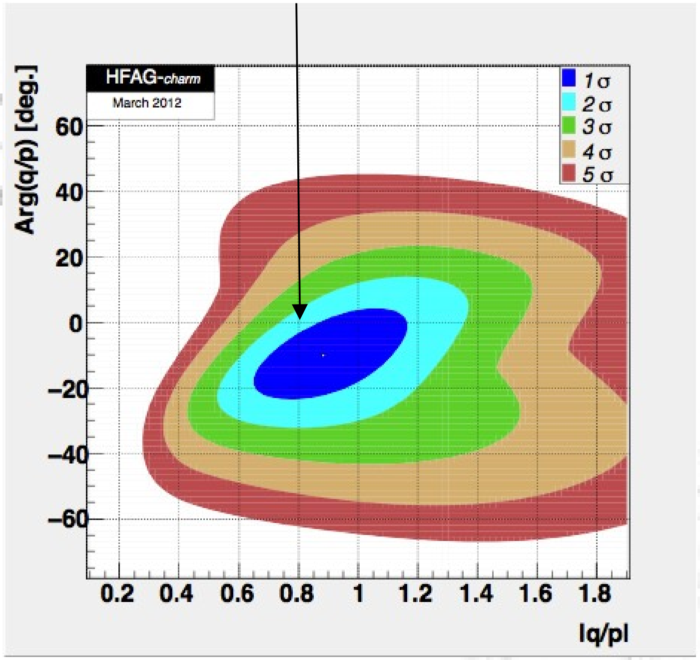
  $\eta \rightarrow \pi^+\pi^-e^+e^-$
  - → CP violating Bremsstrahlung

Status of Charm Mixing

No-mixing point excluded at 10σ



No-CPV point still allowed at 1.5σ

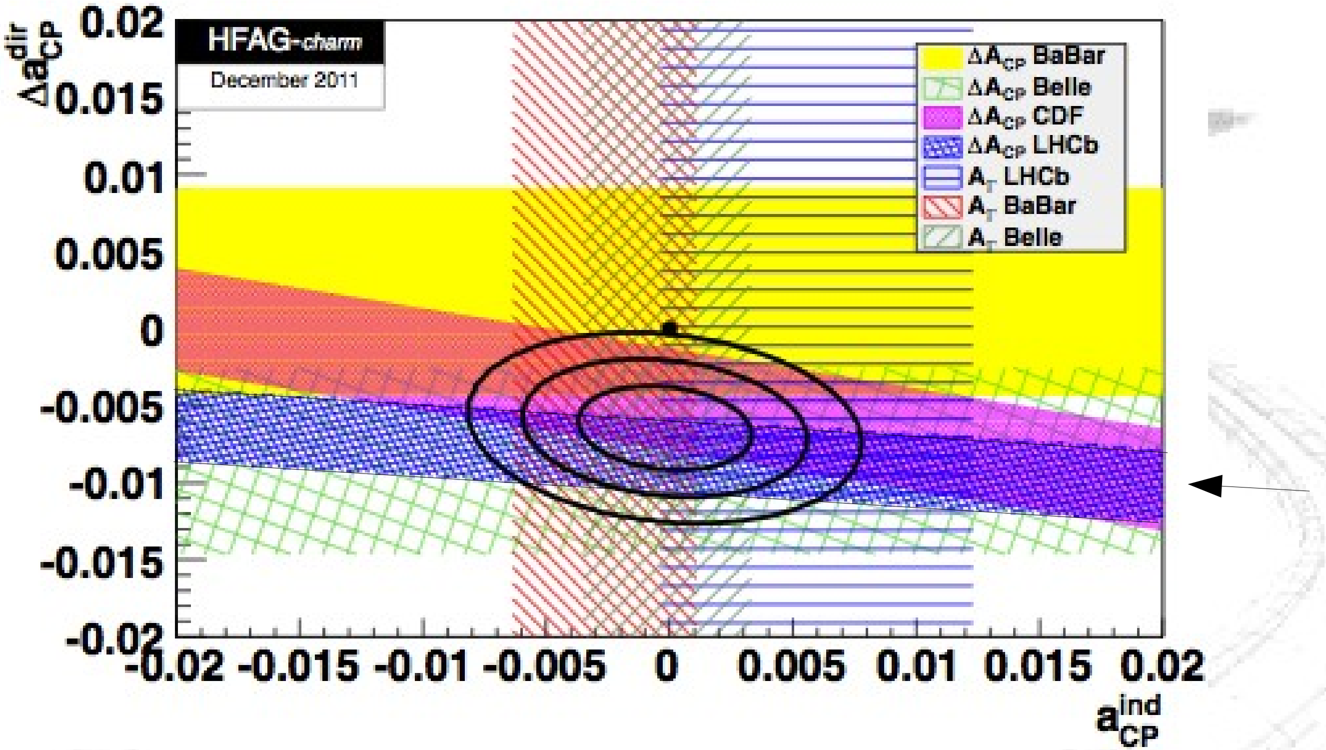


$$x = \frac{\Delta m}{\Gamma} = \left(0.81 \pm 0.30^{+0.13}_{-0.17}\right) \quad y = \frac{\Delta \Gamma}{2\Gamma} = \left(0.37 \pm 0.25^{+0.10}_{-0.15}\right)$$

Theoretical estimates:

- x,y ~ 10^{-3}
- SU(3) breaking (phase space, decay constants, FSI): O(1%) ok
- With x ~ y little room for new physics
- CPV very small, not measured

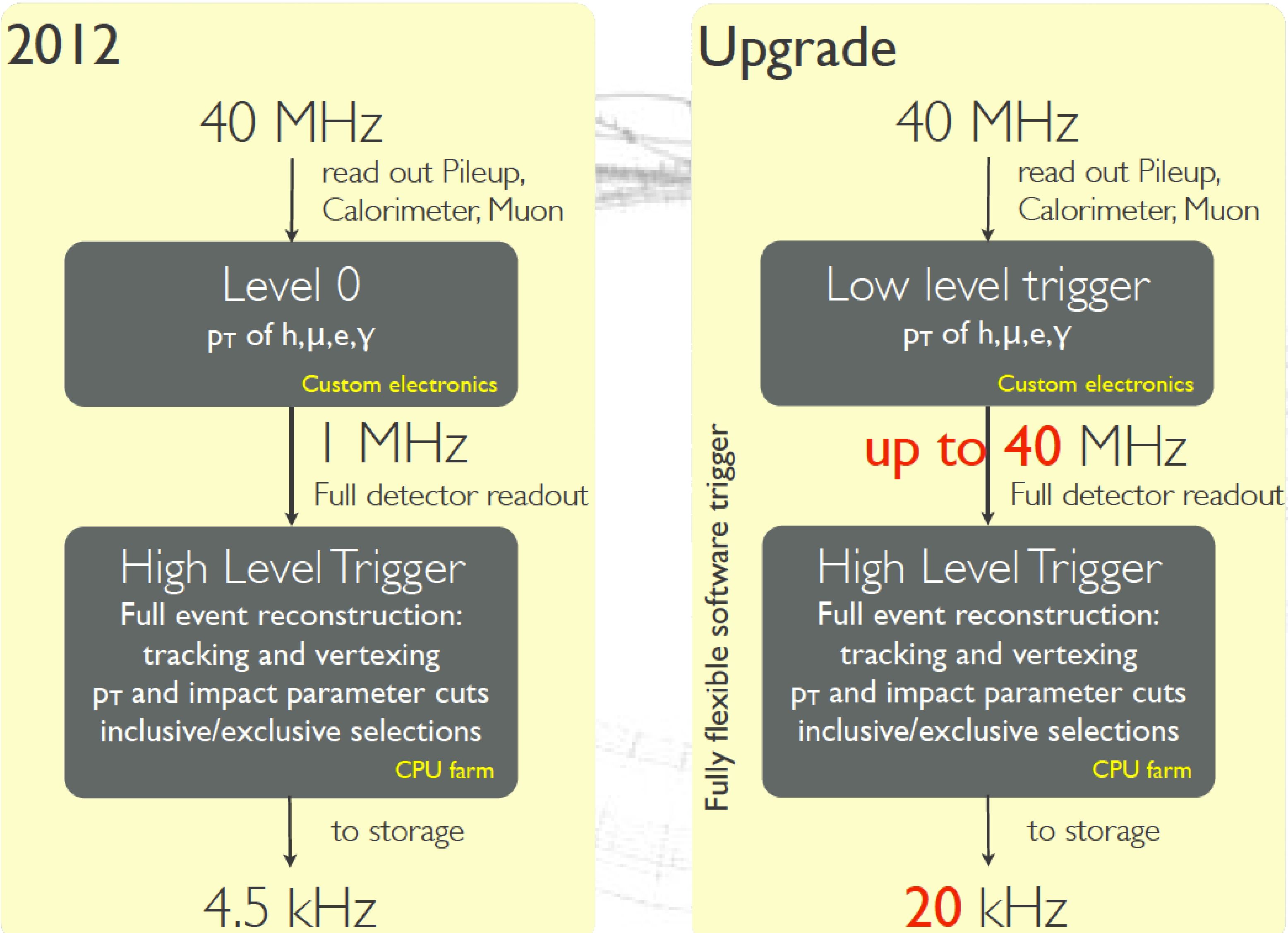
Status of Charm CPV



LHCb measurement of direct CPV in $D^0 \rightarrow h^+h^-$ from 2×10^6 decays ($0.6\ fb^{-1}$)

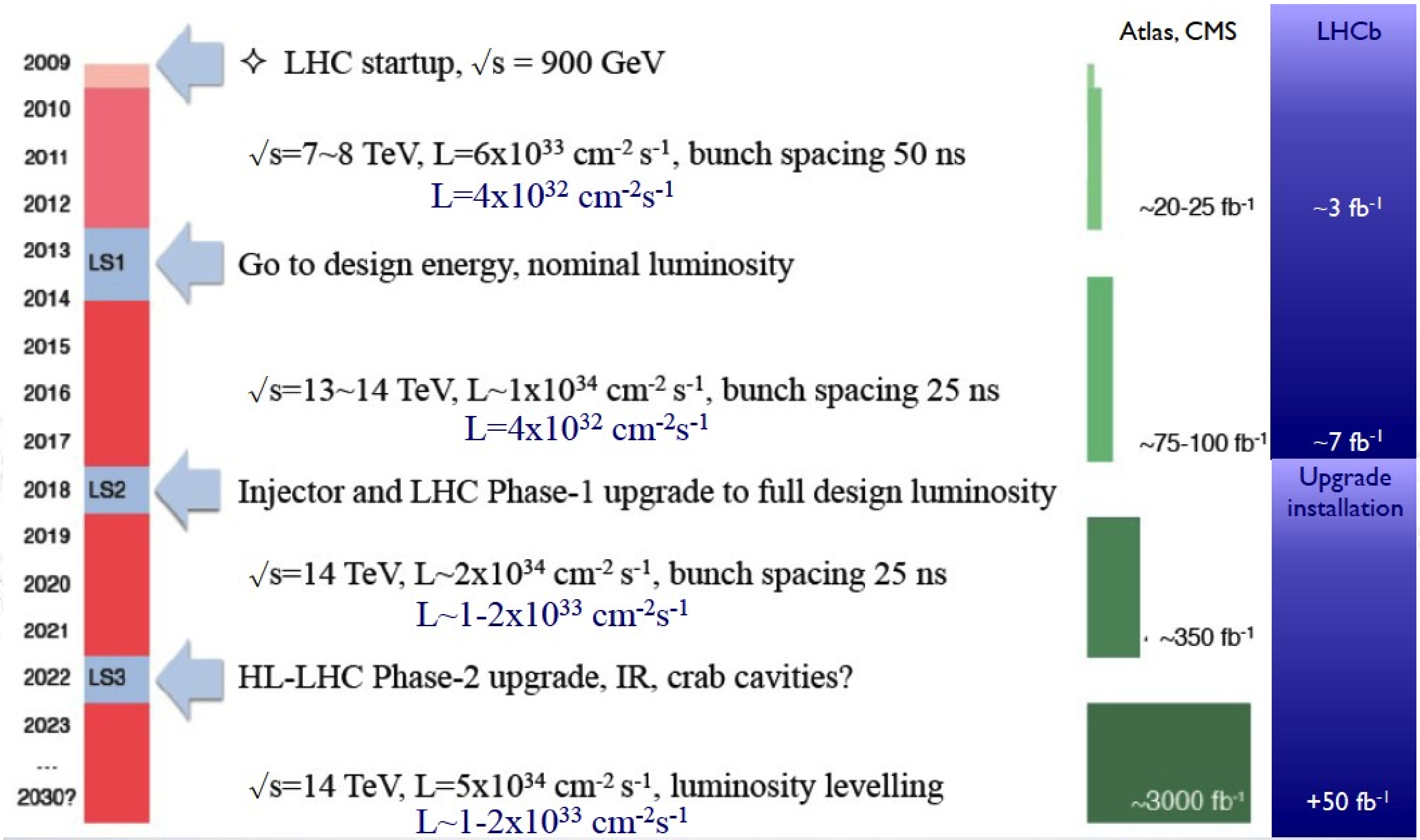
- ΔA_{CP} = (−0.82 ±0.21 (stat.) ±0.11 (syst.))%
- CPV evidence at 3.5σ
- First hint for new physics in charm decays
- Theoretical interpretations and more data needed

Future Developments at LHCb



M. Gersabeck, CERN

LHC Luminosity Prospects



With 50 fb^{-1} expect ~4×10^{10} offline selected $D^0\to K\pi$ decays or more than 10^{11} DX

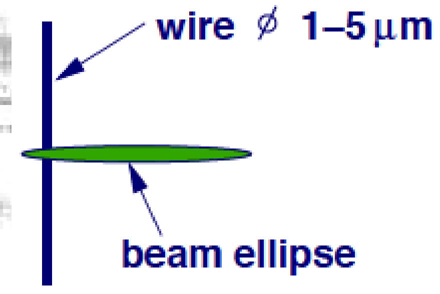
Possible Rates at PANDA

Cross section estimates:

- 100 – 200 nb $D\bar{D}$ optimistic, 10-20 nb pessimistic

Charm yields in one year, based on:

- Total $p\bar{p}$ cross section: s ~ 70 mb
- Average interaction rate R = 20 MHz
- $L_{max} = R/\sigma = 2\times10^{32}\ cm^{-2}s^{-1}$



Channel	Yield (opt.)	Yield (pess.)	Physics	Beam (GeV/c)
D^+D^- excl.	$3x10^8$	$3x10^7$	$D\rightarrow\mu\nu$	6.5
DX	$2x10^9$	$2x10^8$	Mixing, CPV, rare decays	> 7
$D_s\bar{D}_s$	$3x10^7$	$3x10^6$	$D_s\rightarrow\mu\nu$	7.5

Comparison to LHCb: $5x10^9$ DX at 3 fb^{-1} in 2013, 10^{11} at 25-30 fb^{-1} in 2023

Conclusions

Present outlook:

- Main uncertainty on physics reach of $\overline{\text{P}}$ANDA in electroweak D-channels is the $D\overline{D}$ production cross section
  - Full range of predictions from few nb to ~1 μb
  - How to achieve optimal luminosity for D-production?
- In any case LHCb is now where we would be in 2020 ff

Conclusions for us:

- Selection strategy similar to D-spectroscopy,
  i.e. no special efforts to tune for electroweak D-channels
- Measure $p\overline{p} \to D\overline{D}$ as soon as possible
- Keep an eye on the field and see what is left for us