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Science & Technology Facilities Council

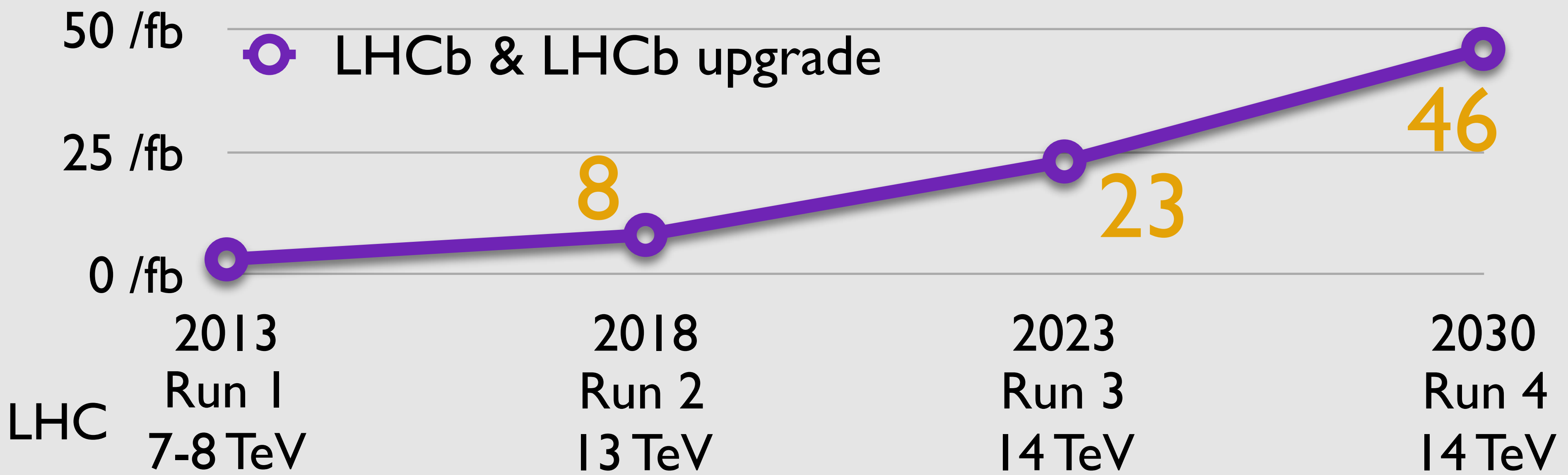
Charm physics at LHCb — Status and prospects

Marco Gersabeck (The University of Manchester)
on behalf of the LHCb collaboration

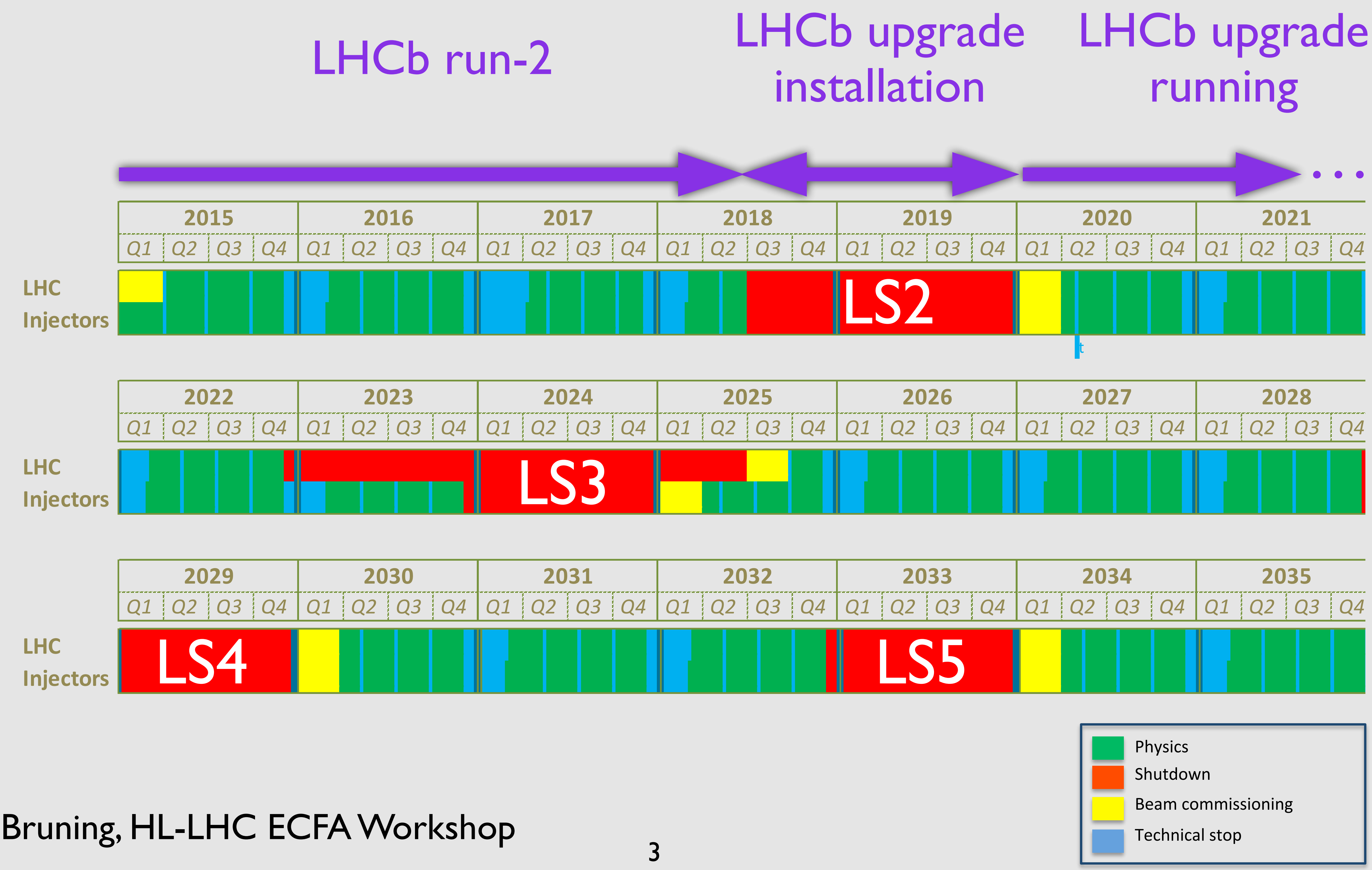
Flavor and top physics at 100 TeV workshop,
Beijing, 4-7 March 2015

LHCb timeline

- LHC run-1(2010-2012):
  - ➡ LHCb data taken
- LHC run-2 (2015-2018):
  - ➡ Enlarged computing cluster for event filter farm, added forward shower counters
- LHC run-3 (2020-2023):
  - ➡ LHCb upgrade
- LHC run-4+ (2025-):
  - ➡ LHCb upgrade+



LHCb and the LHC



O. Bruning, HL-LHC ECFA Workshop

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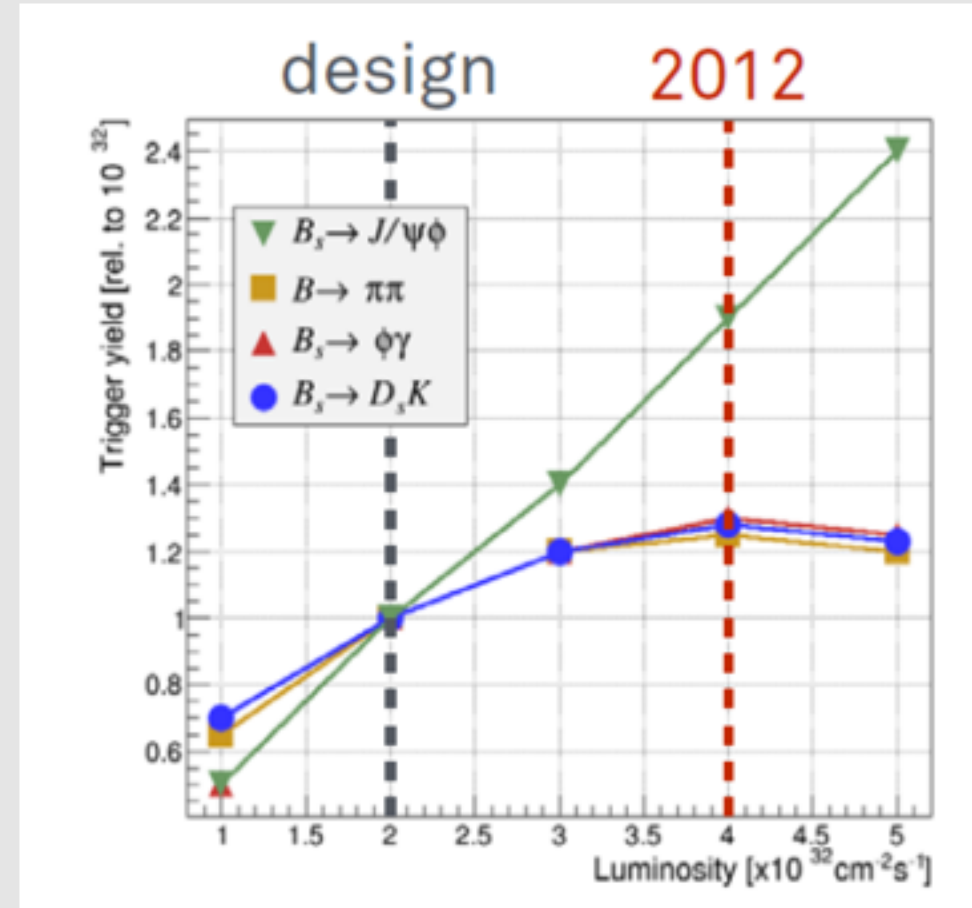
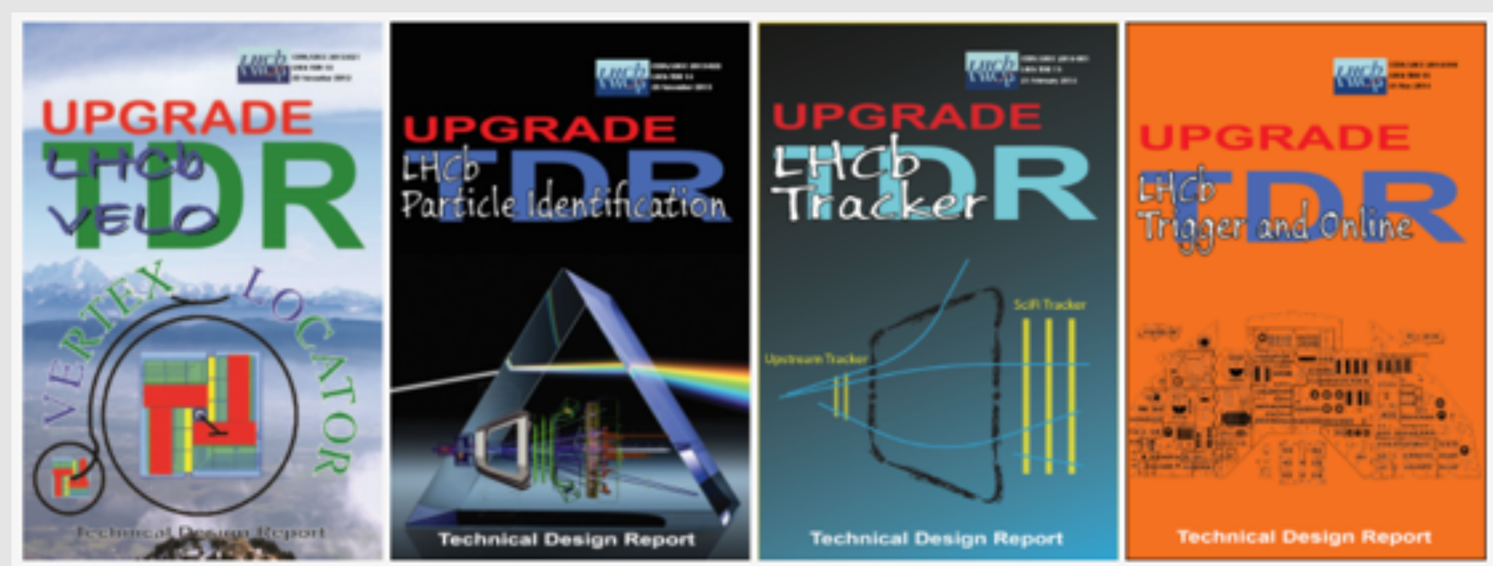
Why upgrade?*

- Want to go from ~2fb^{-1} per year to ~5fb^{-1} per year
- Need to increase instantaneous luminosity to 2×10^{33}cm^{-2}s^{-1}
- Hardware trigger saturating already for hadronic final states

➡ Higher luminosity requires tighter cuts

➡ No increase in signal yield possible



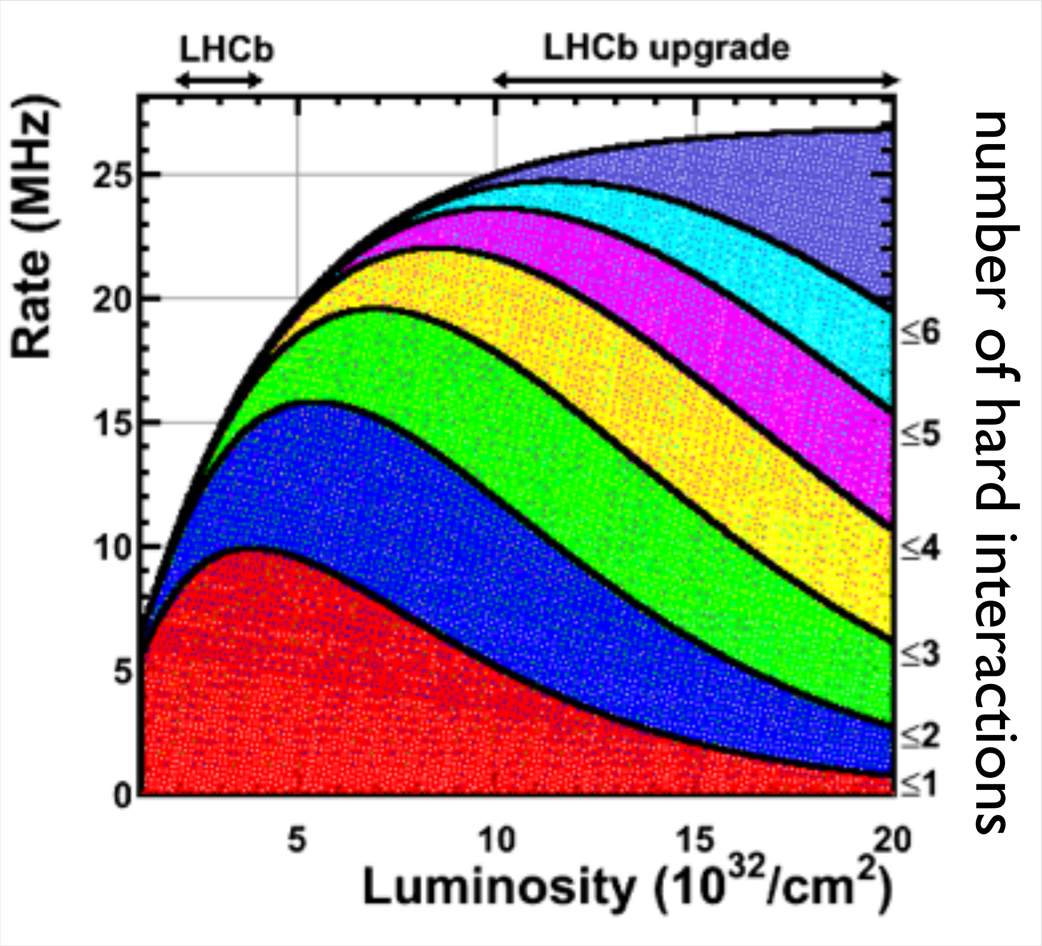


*Detailed physics motivation in talks by Vincenzo, Xabier, MG

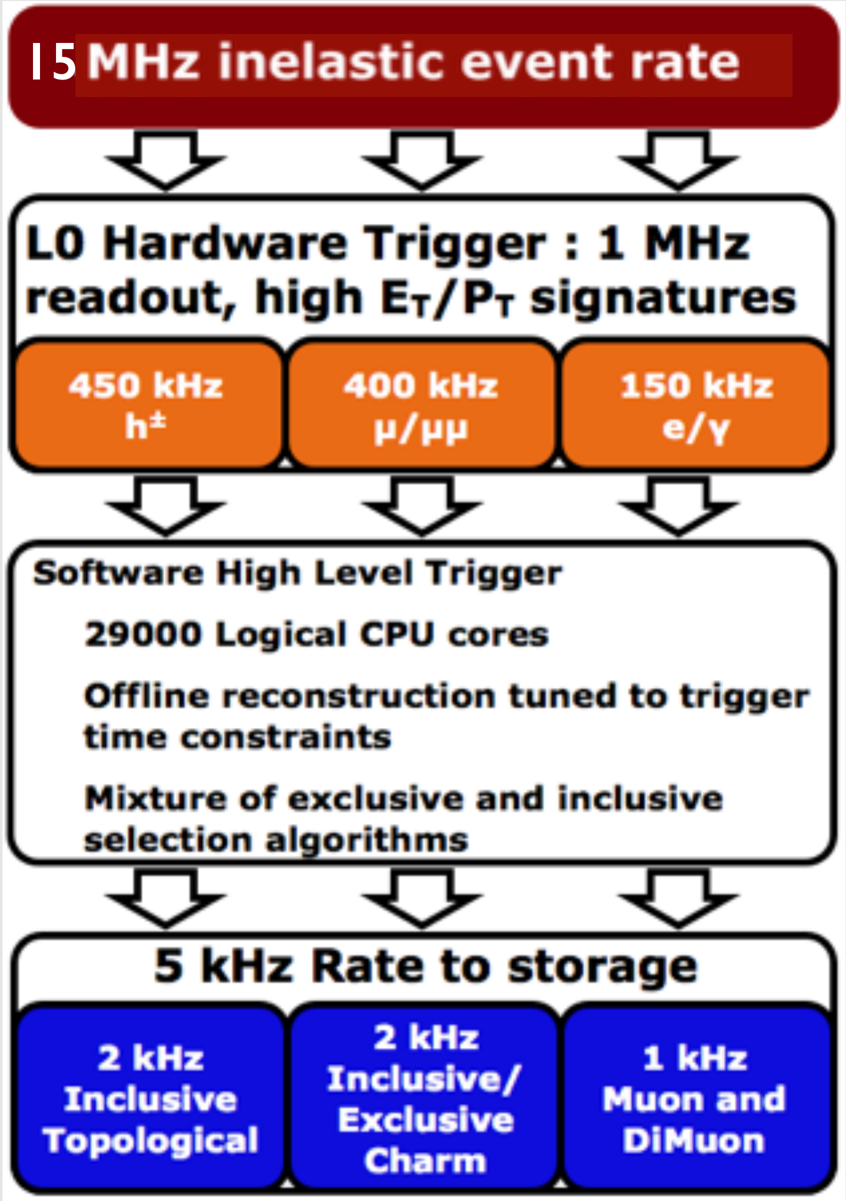
→ Framework TDR, CERN-LHCC-2012-007
→ Upgrade physics and trigger performance, LHCb-PUB-2014-040

How to upgrade?

- Remove hardware trigger as bottle-neck
- Read out full detector at 40 MHz
- Use full software trigger
- Maintain or improve current detector performance
  - ➡ Momentum resolution
  - ➡ Tracking efficiency
  - ➡ Ghost rate
  - ➡ Material budget

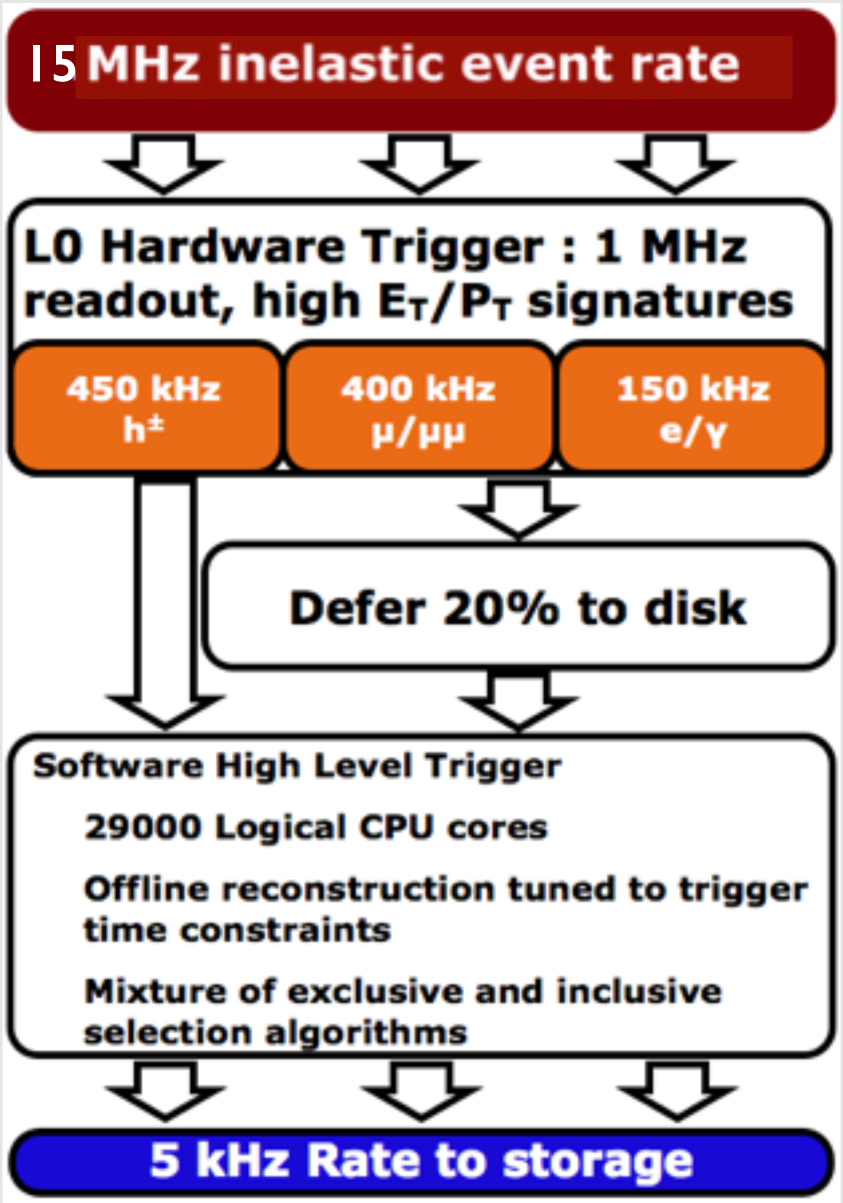


Trigger



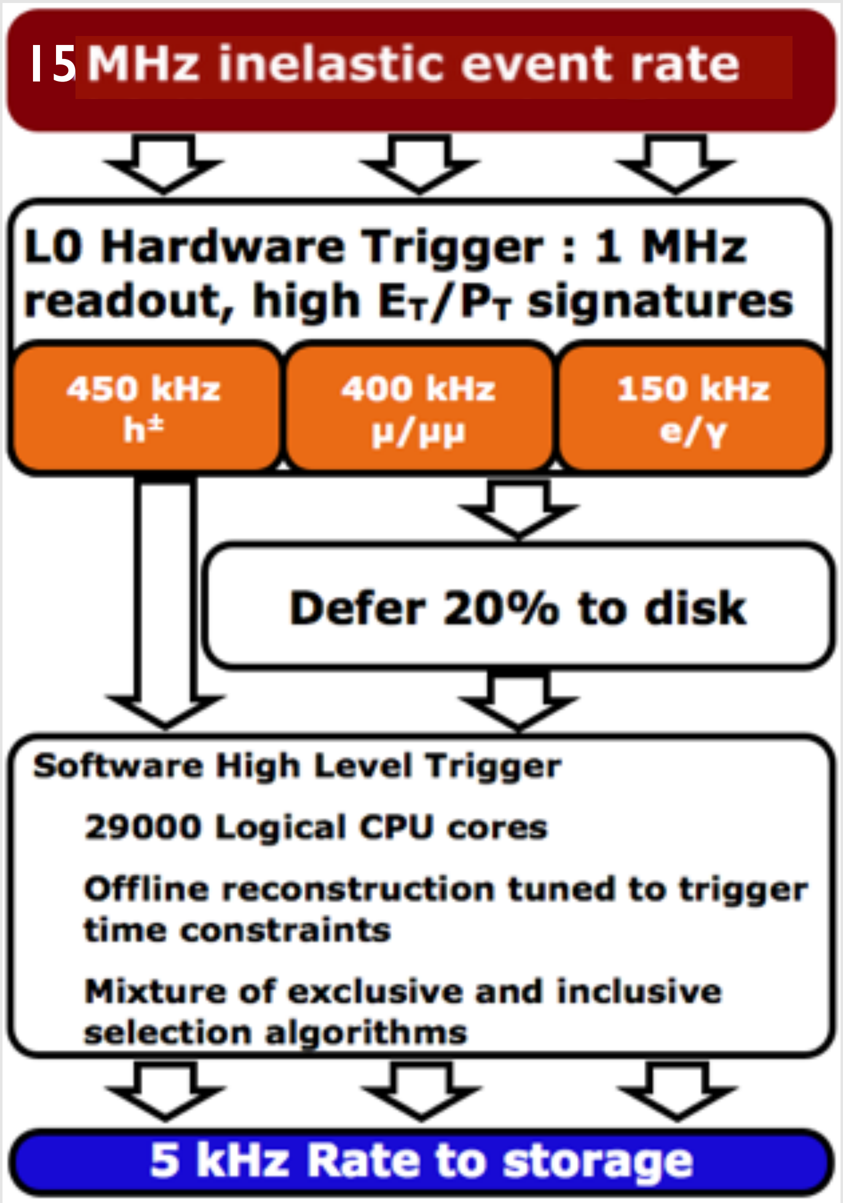
Run-I

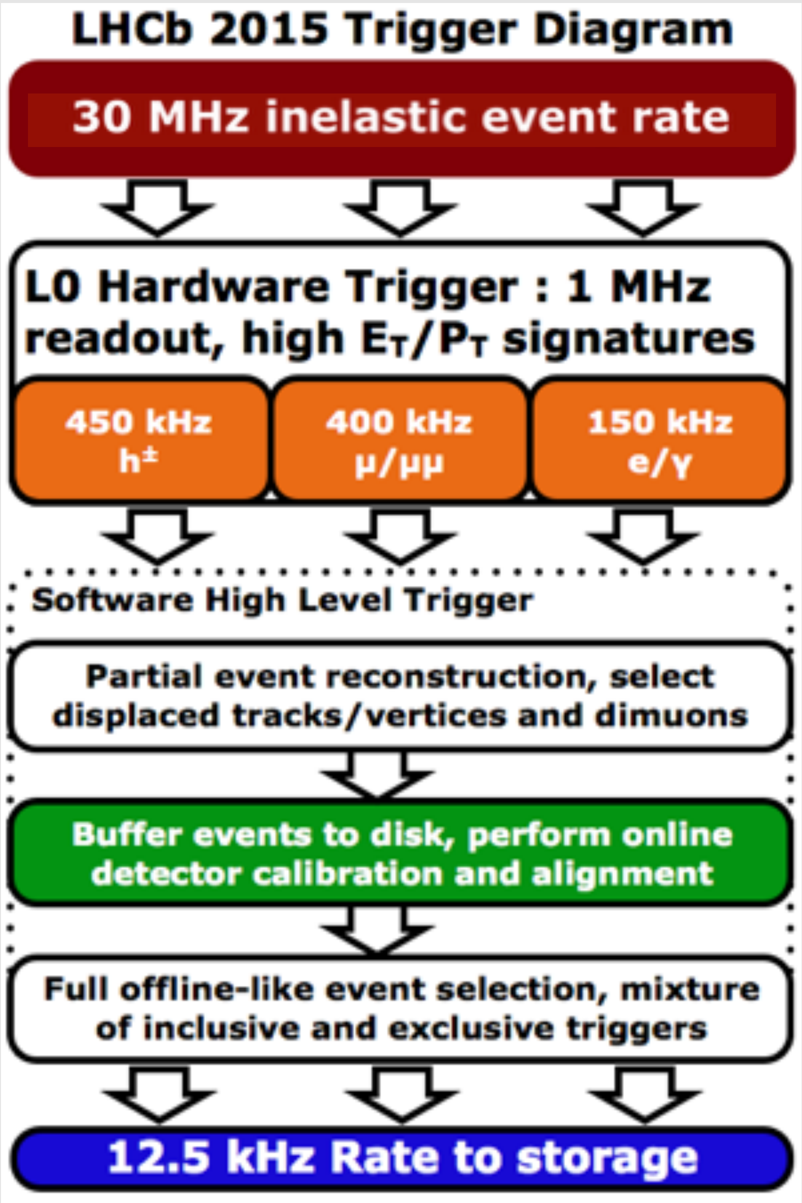
Trigger



Run-I

Trigger





Run-1

Run-2

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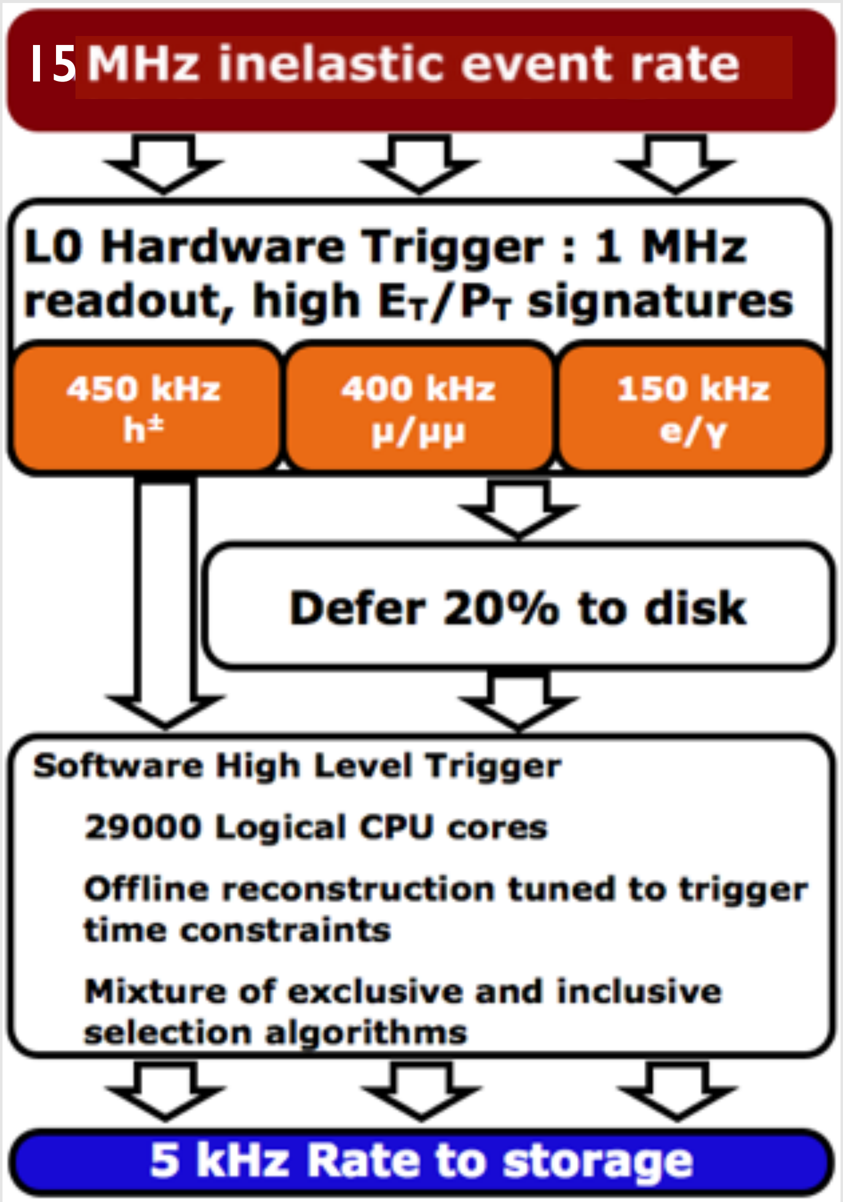
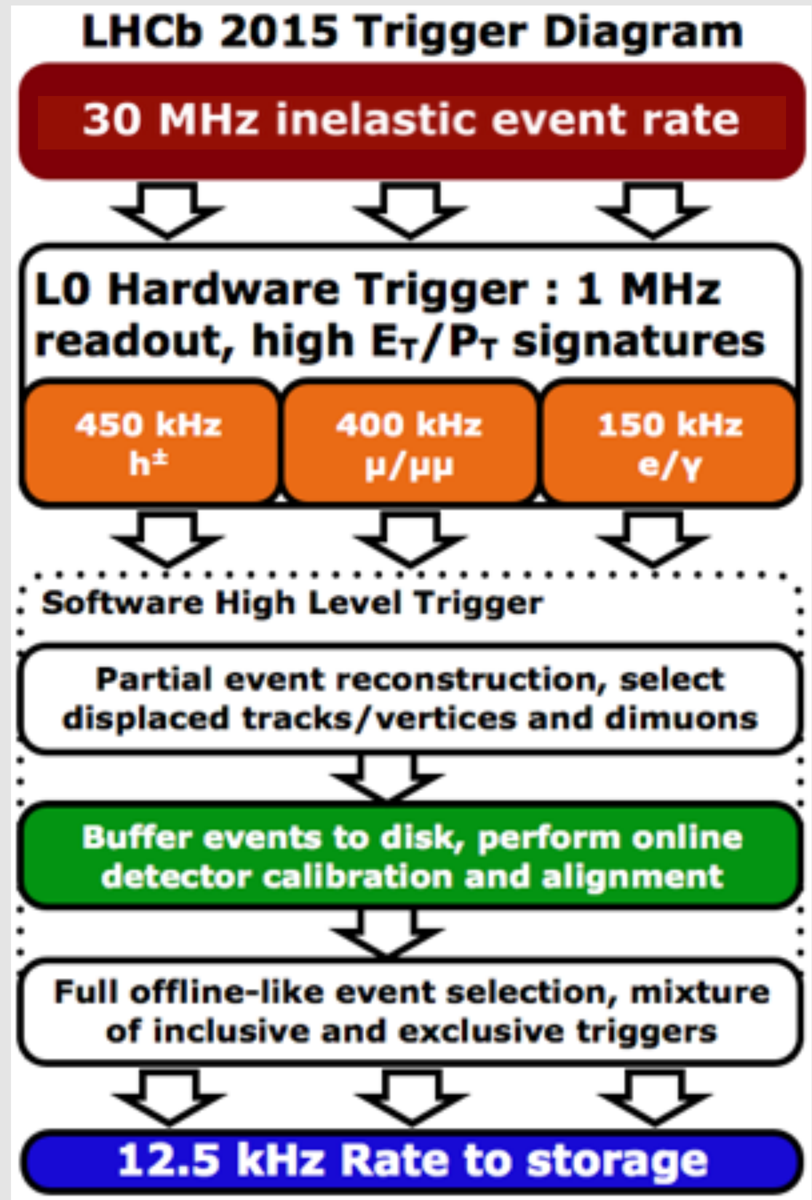
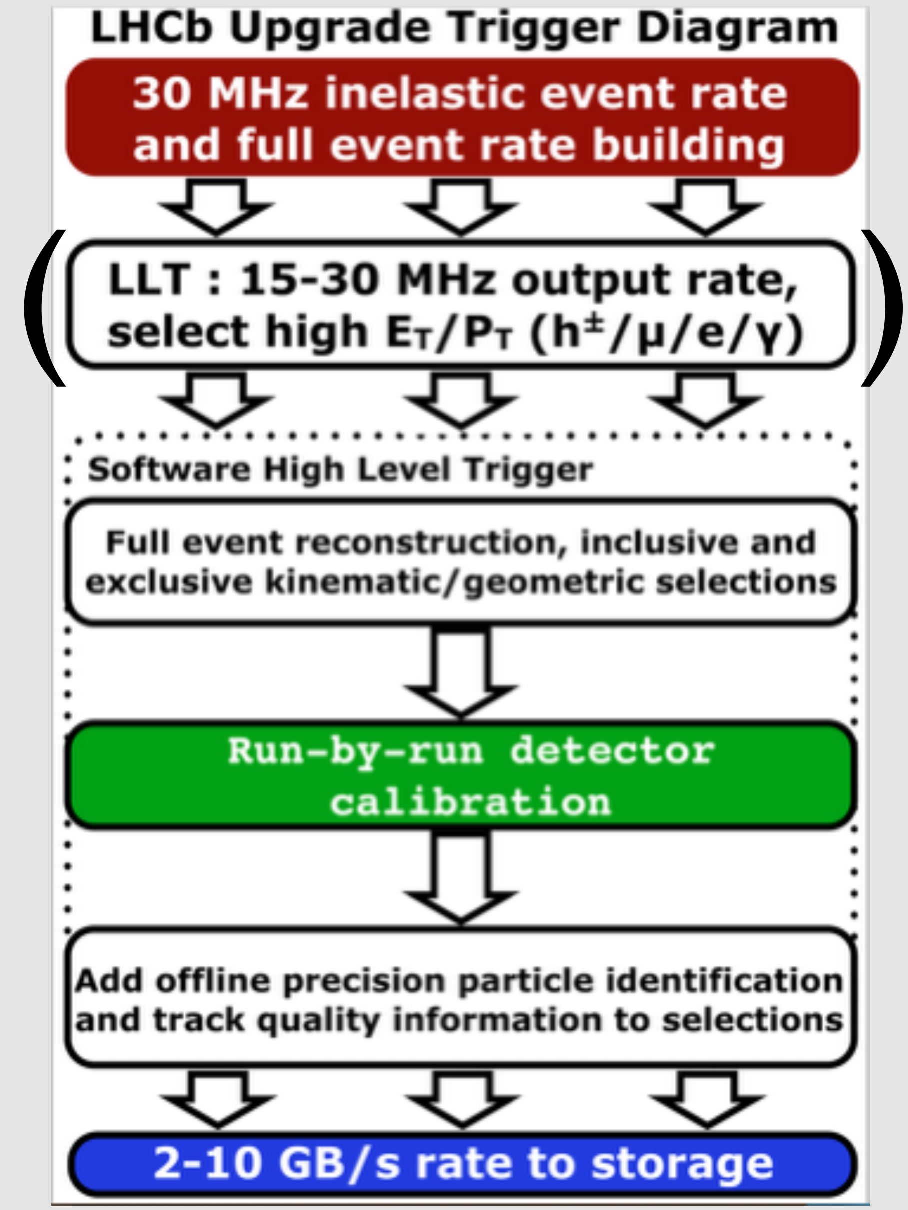
Trigger



Run-1

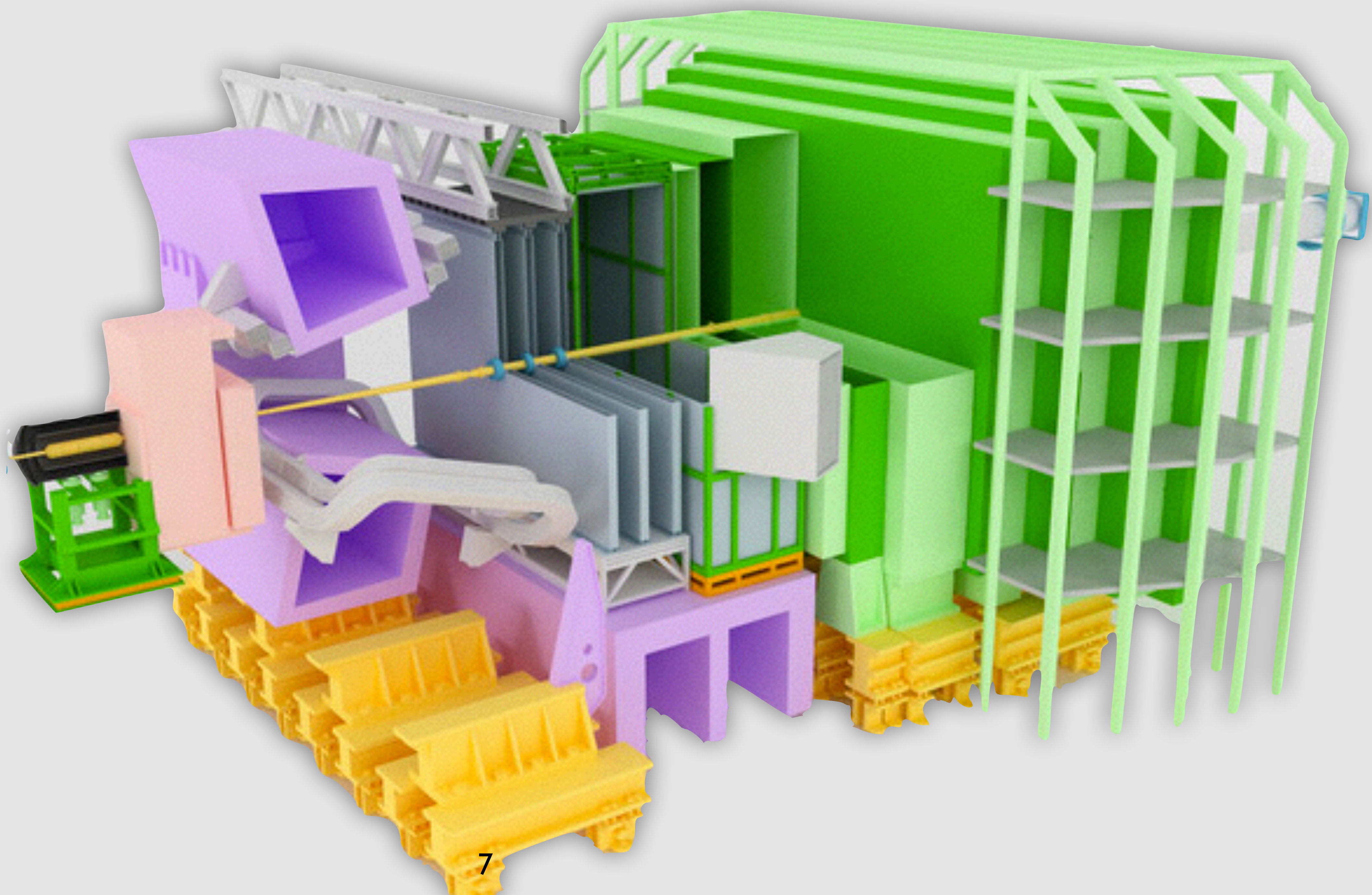


Run-2



Run-3+

Detector



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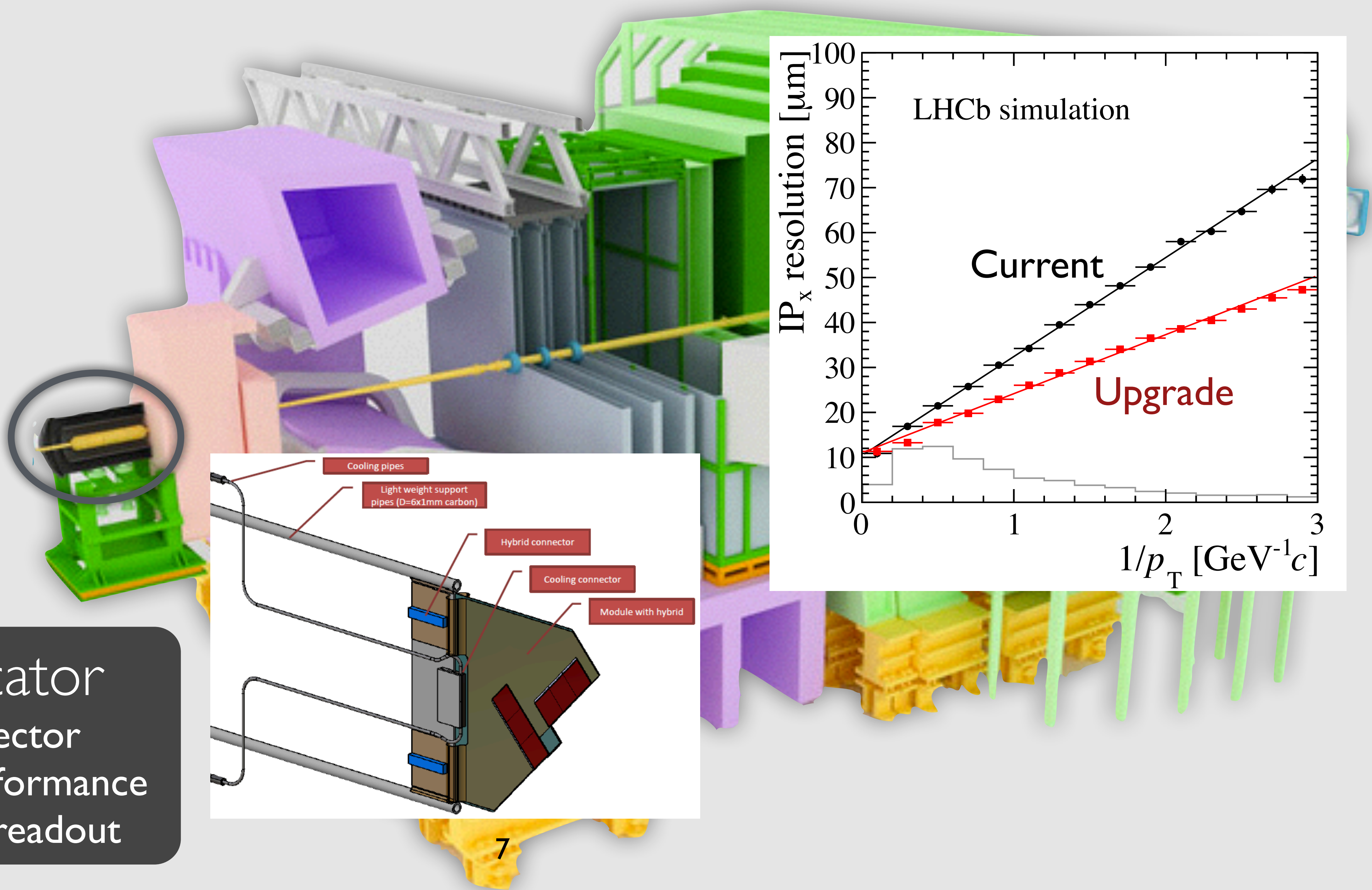
Detector



Vertex Locator

New pixel detector
Overall better performance with full 40MHz readout

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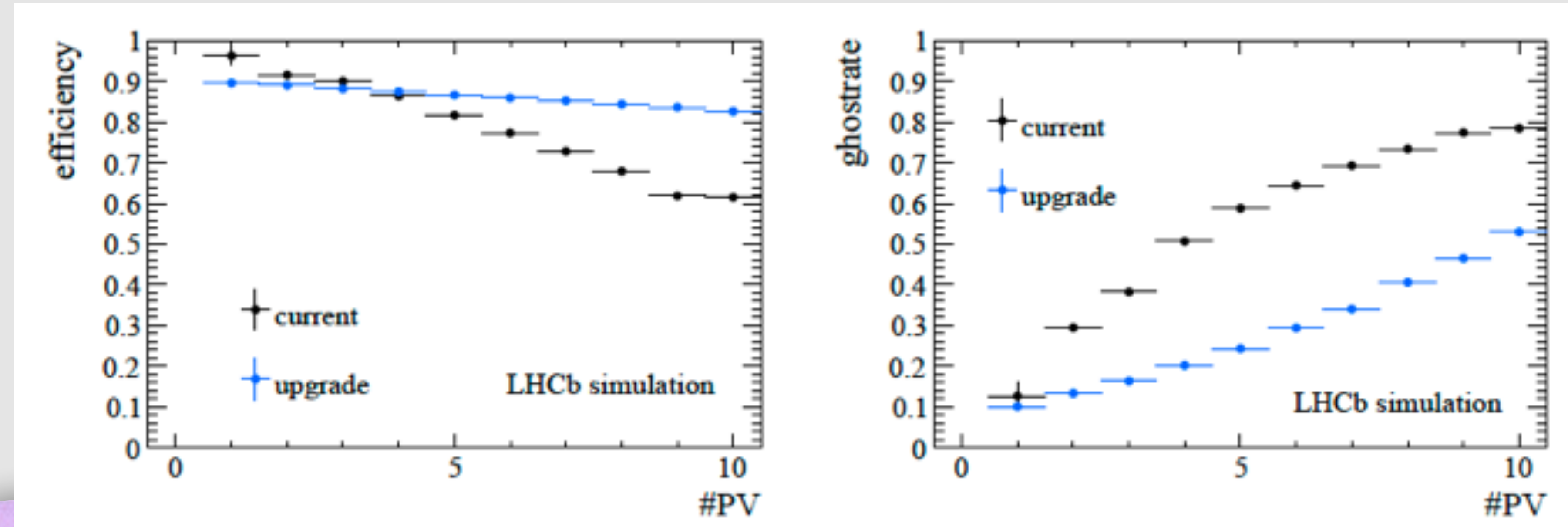
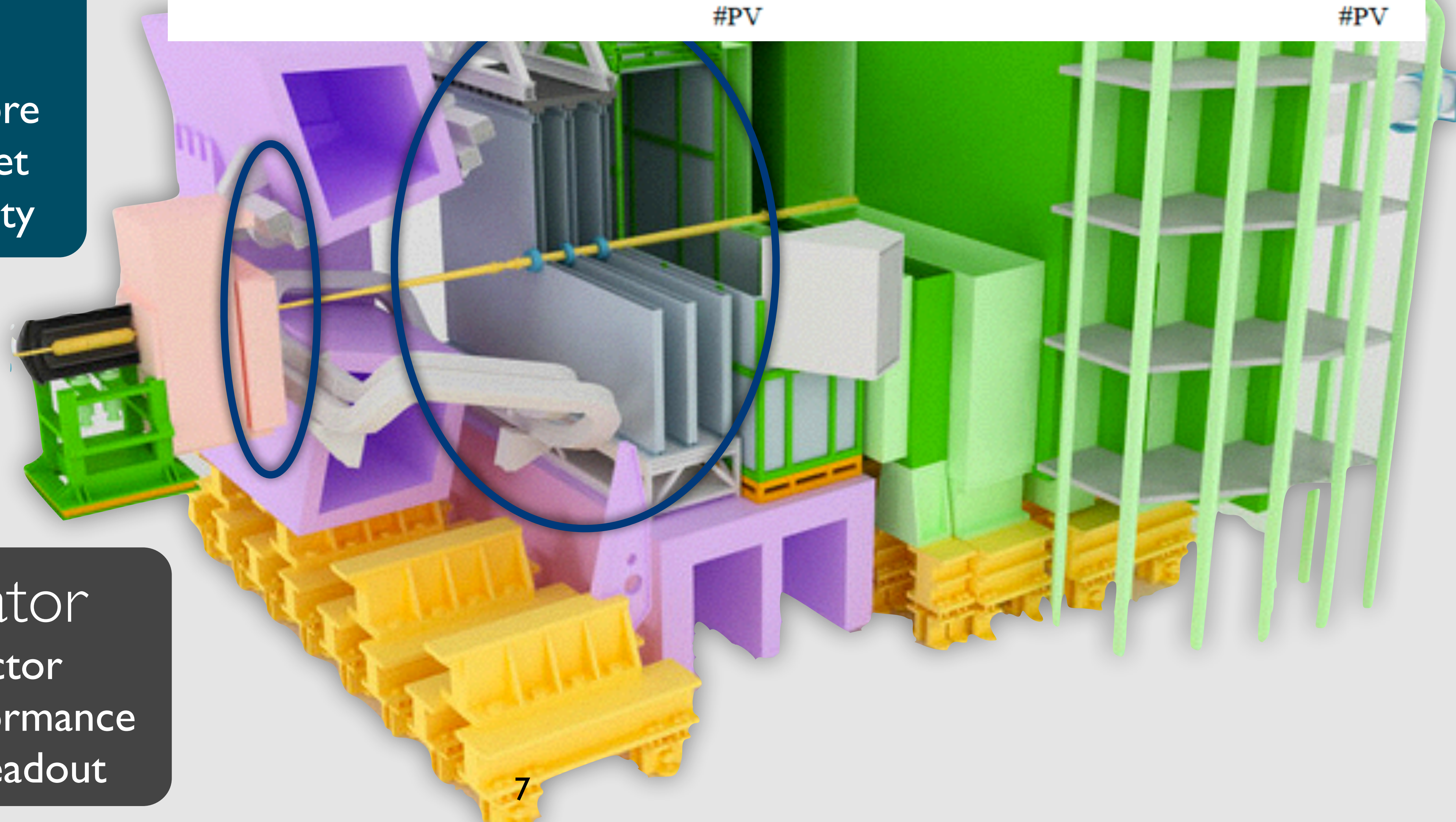
Detector





Tracking

New silicon strip tracker before magnet
→ Less material

New scintillating fibre tracker after magnet
→ Higher granularity

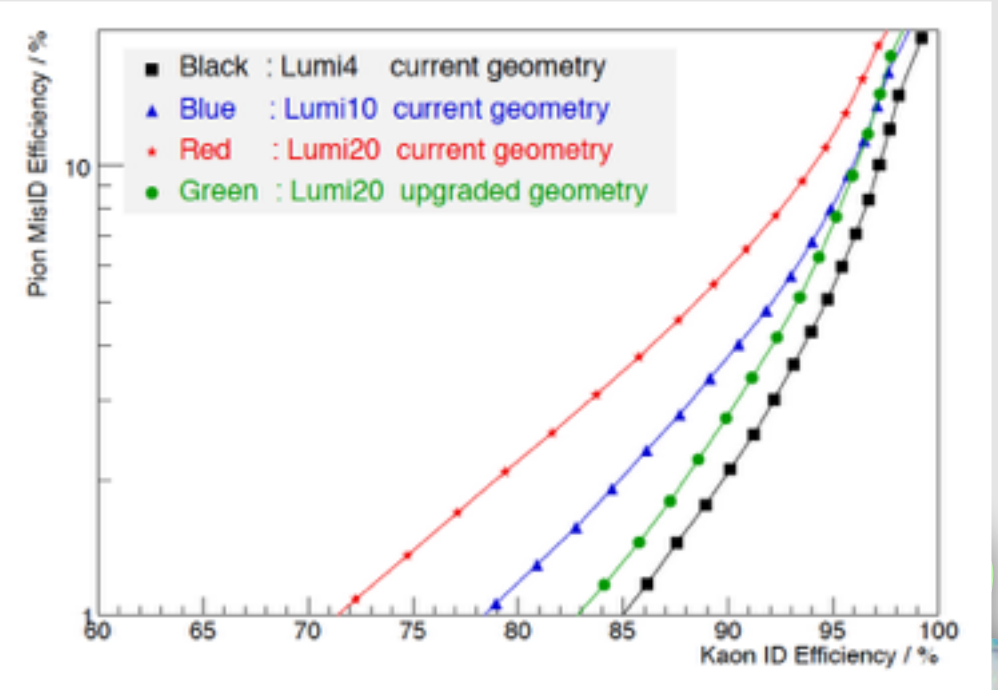
Vertex Locator

New pixel detector
Overall better performance with full 40MHz readout

Detector

RICH

New photon detectors
Improved mirror geometry



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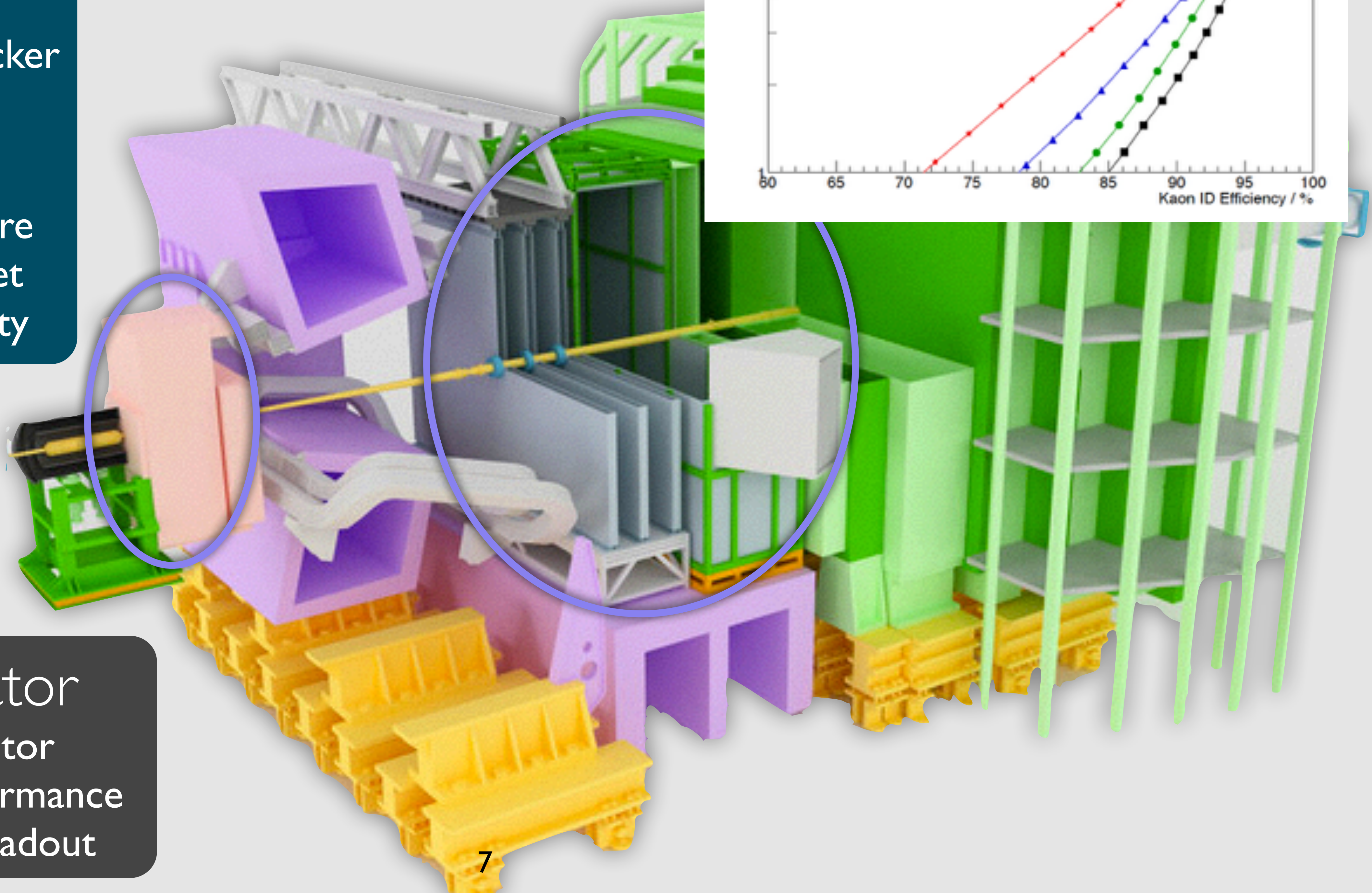

Vertex Locator

New pixel detector
Overall better performance with full 40MHz readout

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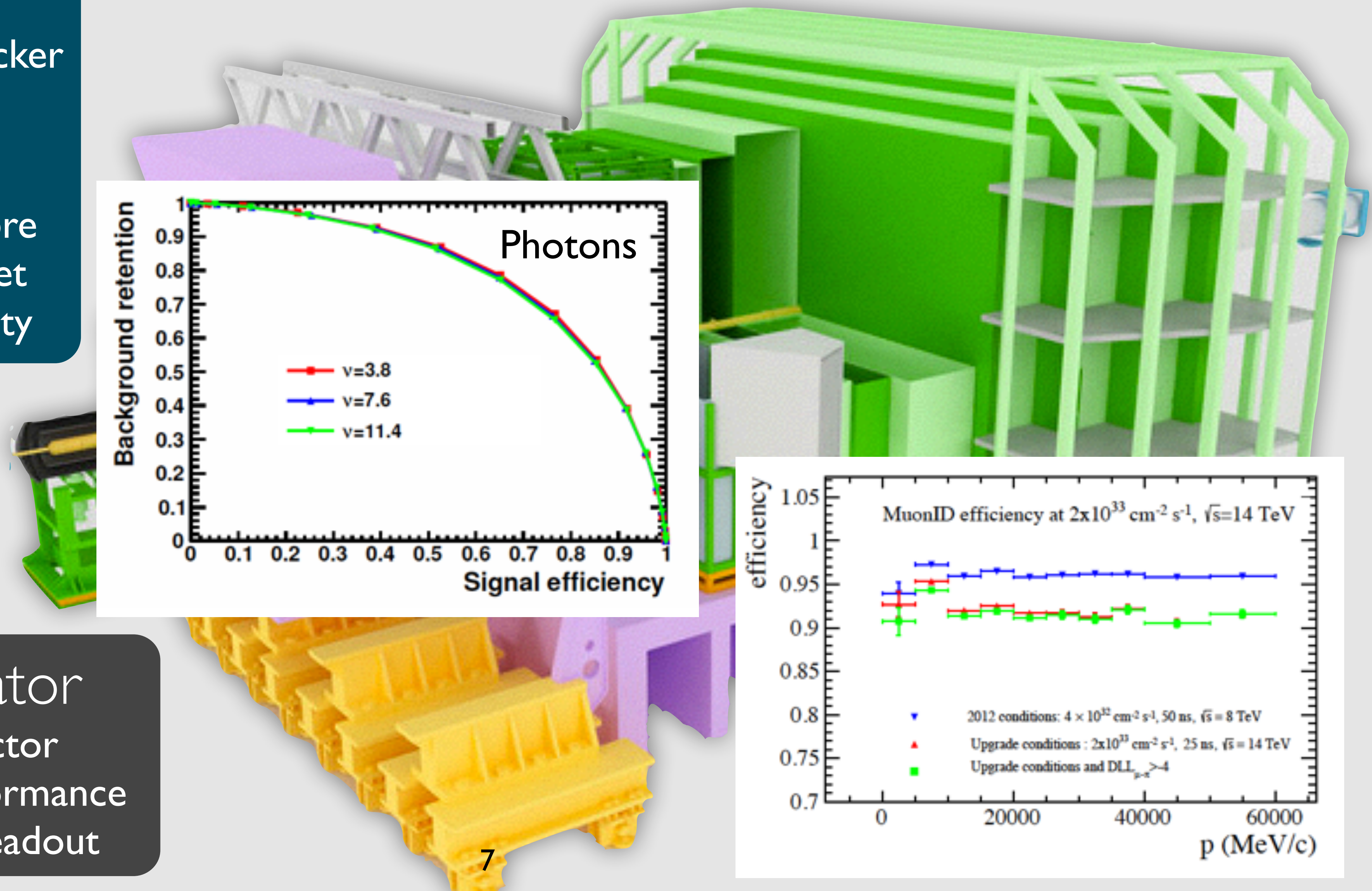
Detector

RICH
New photon detectors
Improved mirror geometry

Calorimeter+Muon
Remove M1, SPD, PS
New calorimeter FE electronics

Tracking
New silicon strip tracker before magnet
→ Less material

New scintillating fibre tracker after magnet
→ Higher granularity



Vertex Locator
New pixel detector
Overall better performance with full 40MHz readout

Physics performance: Assumptions

- Run-2
  - ➡ Cross-section increases linearly with $\sqrt{s}$
  - ➡ Non-muon trigger efficiency suffers from tighter thresholds and have a factor 2 lower efficiency
  - ➡ 2fb^{-1} per year, 5fb^{-1} in total for run-2
- Upgrade
  - ➡ Further cross-section increase for 14 TeV
  - ➡ Removal of hardware trigger brings factor 2 efficiency boost for non-muon triggered events
  - ➡ ~5fb^{-1} per year

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LHCb physics

Xabier

EW+top physics

Exotica searches

CPV & mixing in beauty hadrons

Vincenzo

$b \to s\gamma/sll$ decays FCNC and forbidden B decays

Heavy flavour spectroscopy

Central exclusive production

Rare and forbidden charm decays

CPV & mixing in charm hadrons

MG

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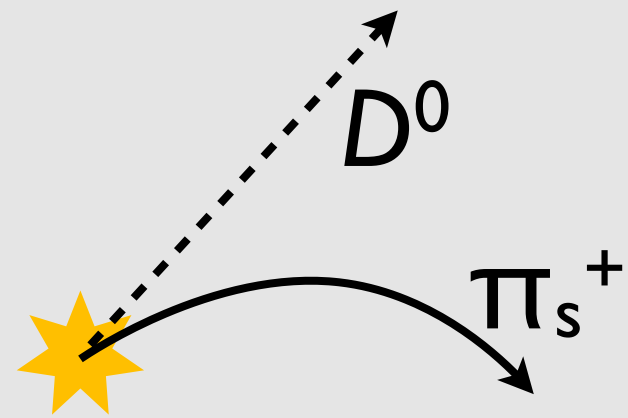
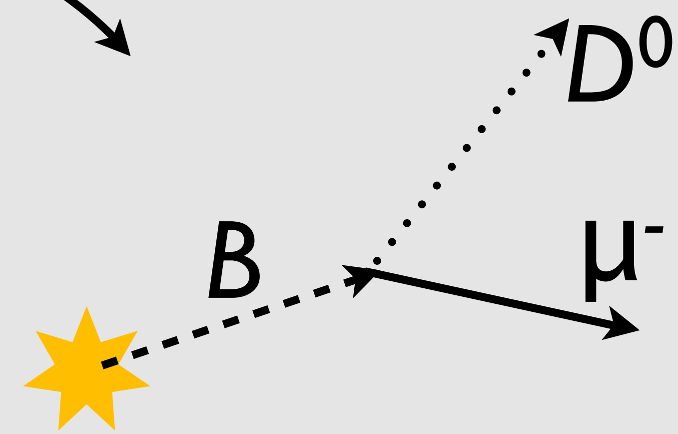
Charm physics

Charm

- Recent highlights
- What's expected for the future

Sources of charm





- Prompt charm
- Semileptonic b-hadron decays
- Hadronic B decays

➡ Not only useful to measure CKM γ

➡ Also revealed first spin-3 charm state

→ LHCb collaboration, Phys. Rev. Lett. 113 (2014) 162001

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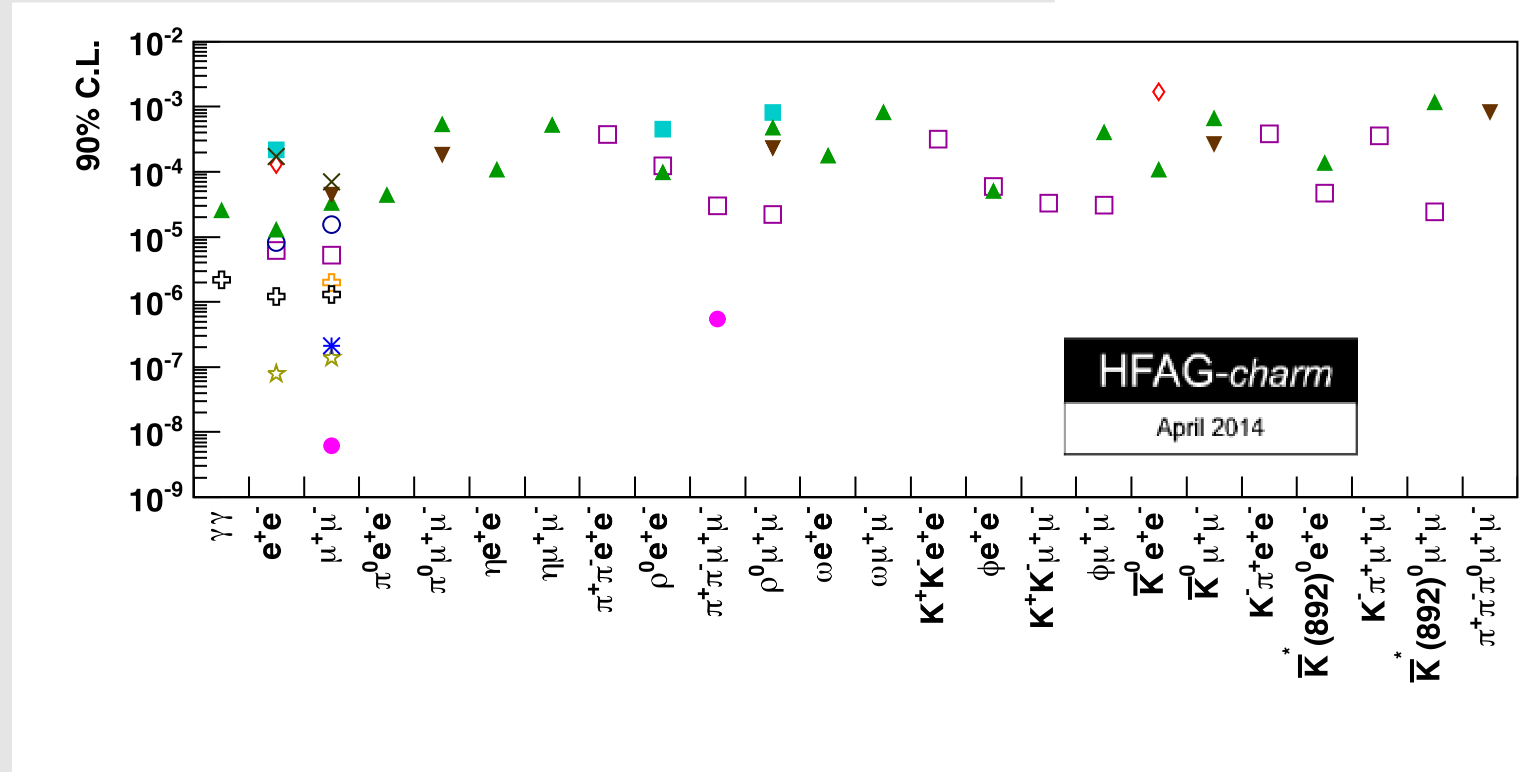
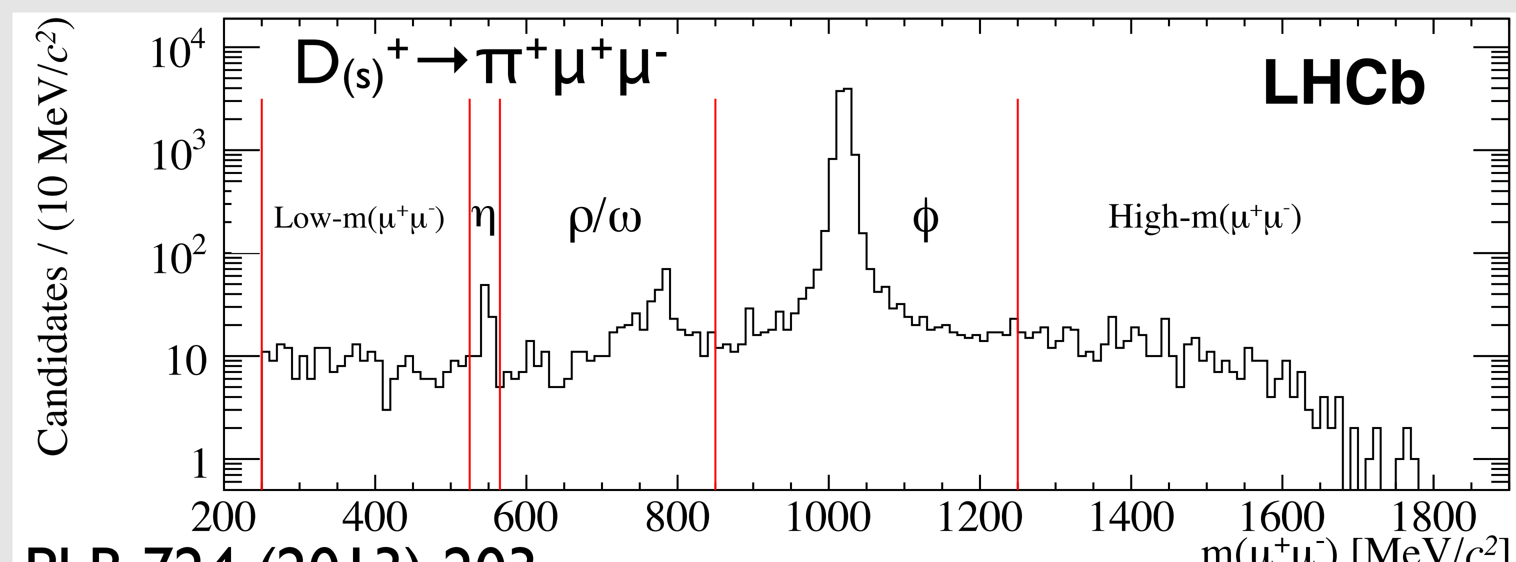
Rare charm



- World leading results for (semi-)muonic final states
- Work ongoing for states involving electrons
- Hunting for non-resonant contributions



PLB 724 (2013) 203

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Mixing and indirect CP violation

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

Mixing:

$x \equiv (m_2 - m_1)/\Gamma$

$y \equiv (\Gamma_2 - \Gamma_1)/2\Gamma$

CP violation:

$|q/p| \neq 0$

$\phi \equiv \arg(q/p) \neq 0, \pi$

Indirect CP violation:

$$a_{CP}^{ind} = -a_m\, y \cos\phi - x \sin\phi$$

with $a_m \approx \pm(|{}^q/_p|^2 - 1)$

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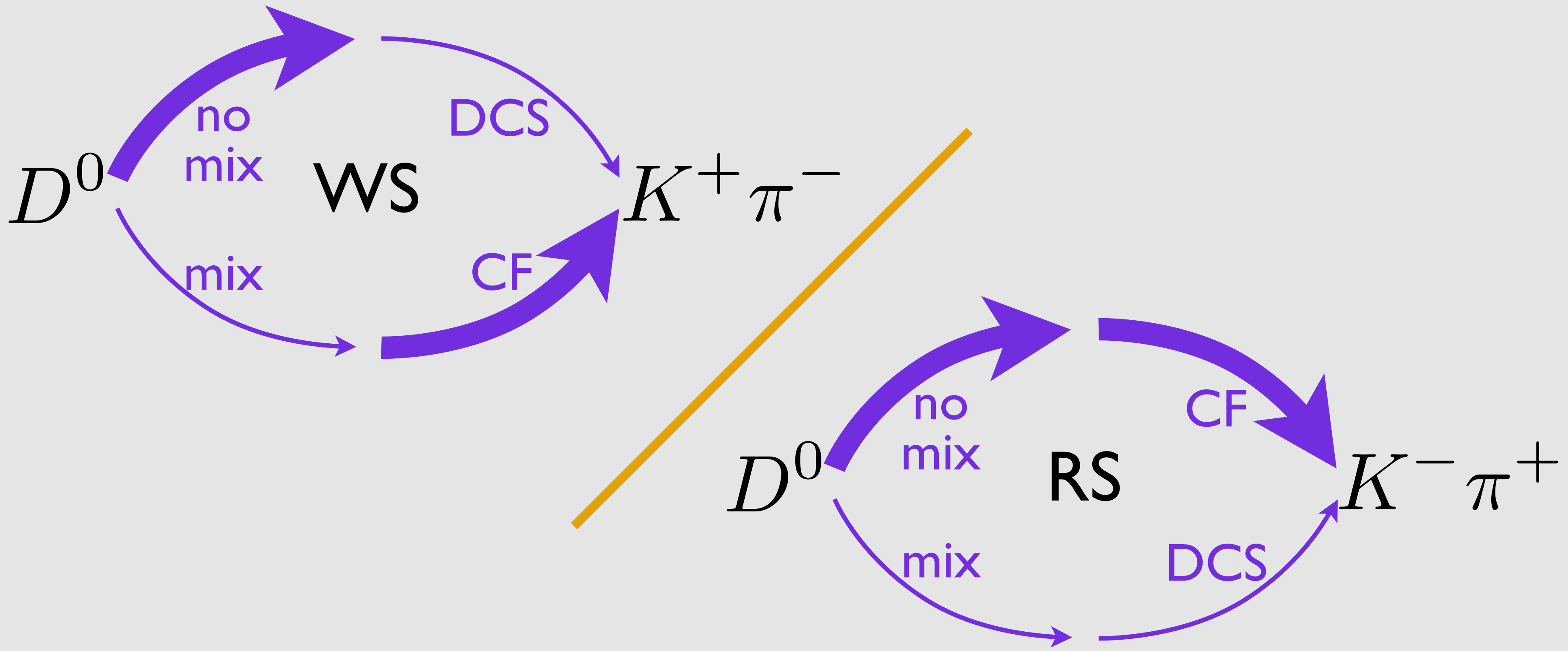
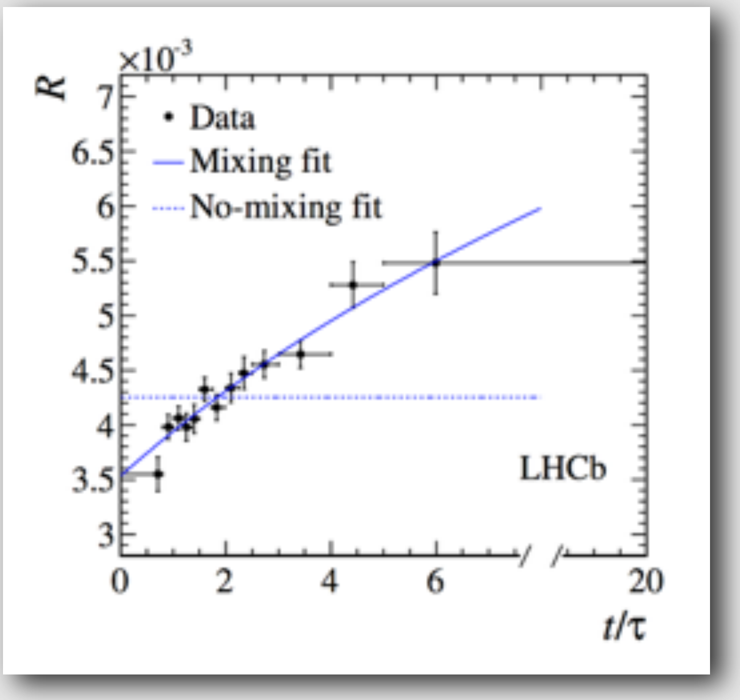
Mixing discovery



$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} (\frac{t}{\tau})^2$$

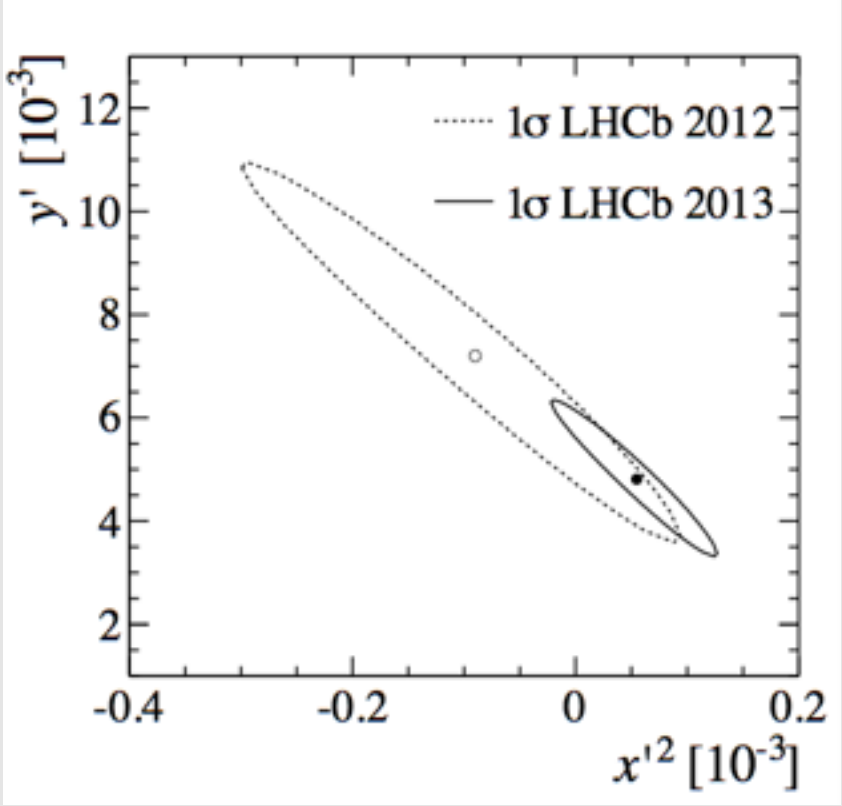


- First single-experiment measurement >5σ significance
- Rotation of mixing parameters by strong phase difference: x,y → x',y'

Phys. Rev. Lett. 110, 101802 (2013)

Mixing and CP violation

- Update with 3 fb^{-1}
- Split by flavour to search for CP violation
  - ➡ $x'^{\pm} = |q/p|^{\pm 1}(x' \cos\Phi \pm y' \sin\Phi)$
  - ➡ $y'^{\pm} = |q/p|^{\pm 1}(y' \cos\Phi \mp x' \sin\Phi)$
- No indication for CP violation

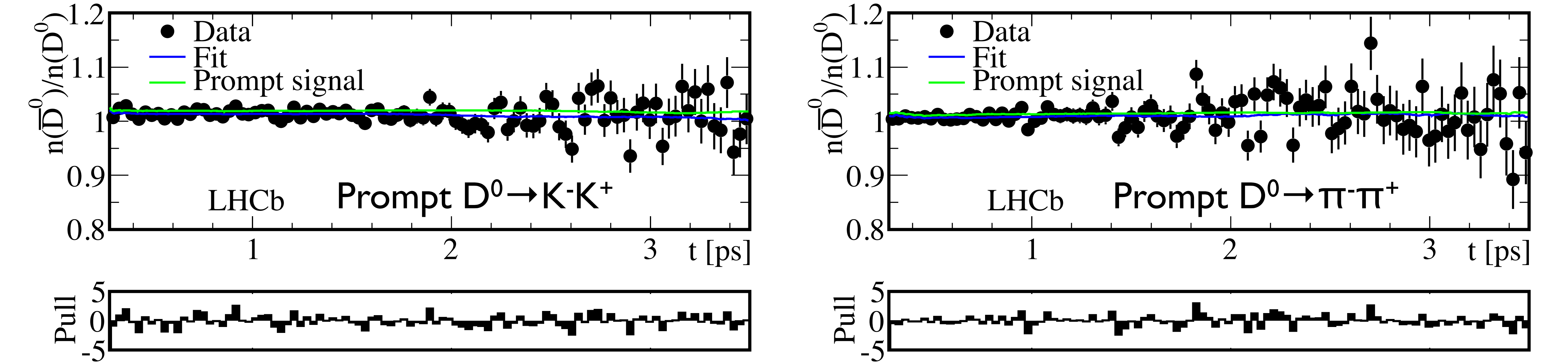


PRL 111 (2013) 251801

R_D^+	$[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
y'^+	$[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
x'^{2+}	$[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
R_D^-	$[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
y'^-	$[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
x'^{2-}	$[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$

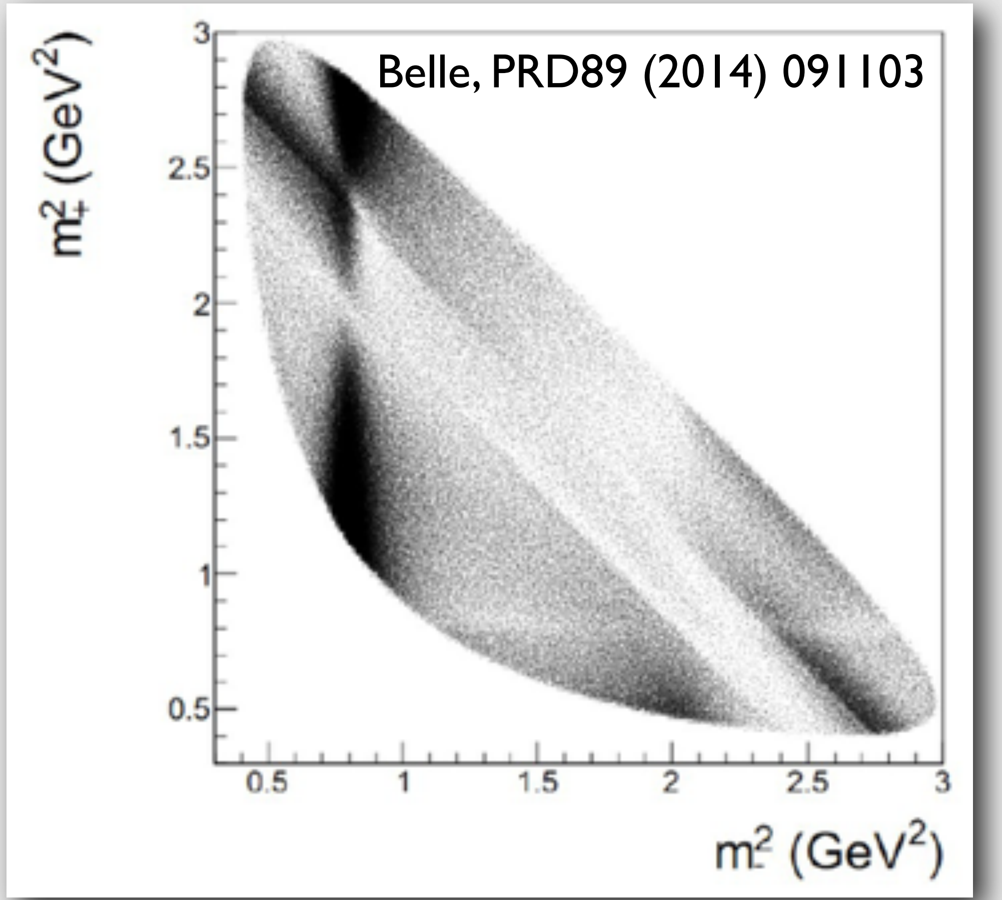
Indirect CP violation

- Measure asymmetries of effective lifetimes of decays to CP eigenstates:
  - ➡ $A_\Gamma \approx a_m\, y \cos\phi + x \sin\phi \equiv -a_{CP}^{ind}$
- Measures ability of both mass eigenstates to decay to CP eigenstate
- Measurements use $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays
- Prompt D^{*+}-tagged, 1fb^{-1} (PRL 112 (2014) 041801):
  - ➡ $A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$; $A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$
- D from semi-leptonic B decays, μ^+-tagged, 3 fb^{-1} (arXiv:1501.06777):
  - ➡ $A_\Gamma(KK) = (-1.34 \pm 0.77 \pm 0.30) \times 10^{-3}$; $A_\Gamma(\pi\pi) = (-0.92 \pm 1.45 \pm 0.29) \times 10^{-3}$



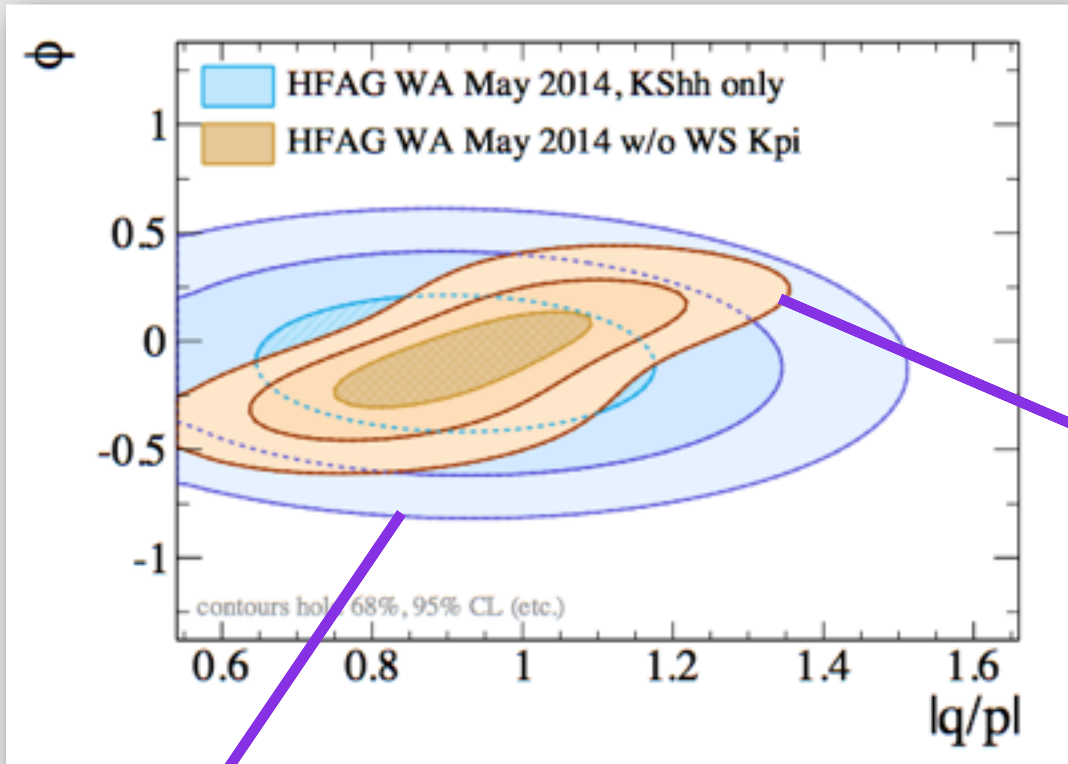
PRL 112 (2014) 041801

$D^0 \to K_S hh$



- $K_S K^- K^+$ and $K_S \pi^- \pi^+$
  - ➡ complex assembly of different resonances
  - ➡ including flavour and CP eigenstates
- Study decay-time dependence of resonances
  - ➡ Decay-time dependent Dalitz-plot analysis
- Access to individual mixing and CPV parameters
  - ➡ x, y, $|q/p|$, ϕ
- Results coming soon

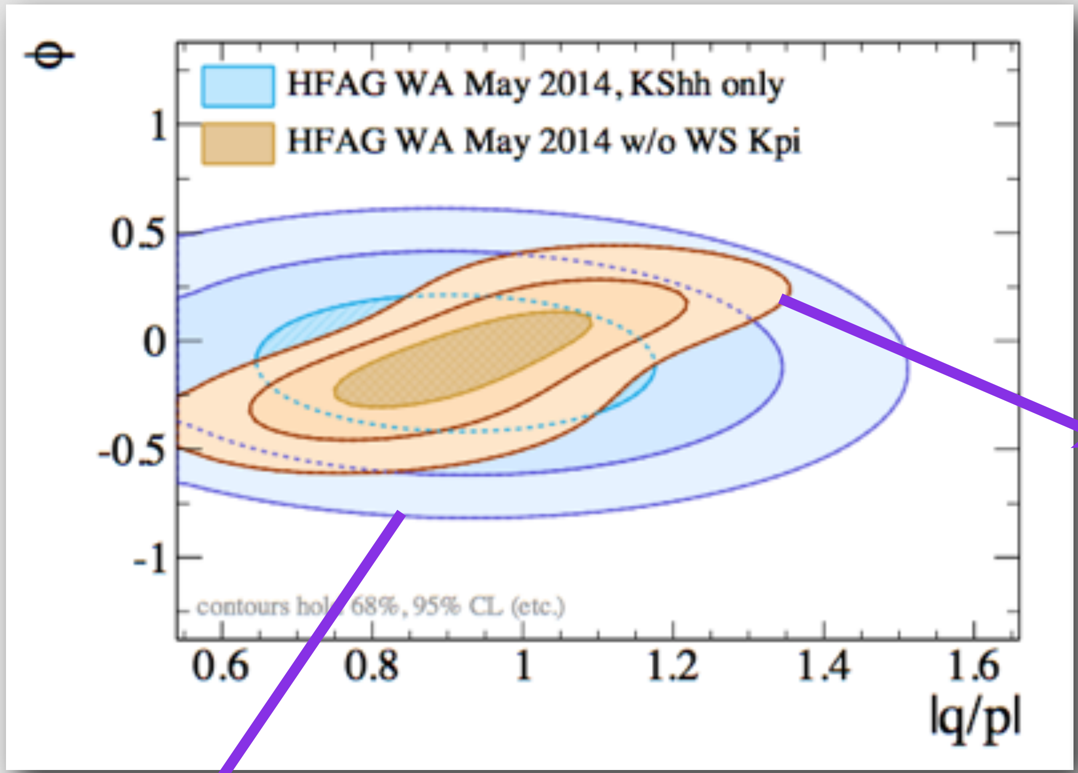
Contributions



Precise constraints if x and y provided, mostly from A_Γ

Direct access to |q/p| and φ from $K_S hh$

Contributions



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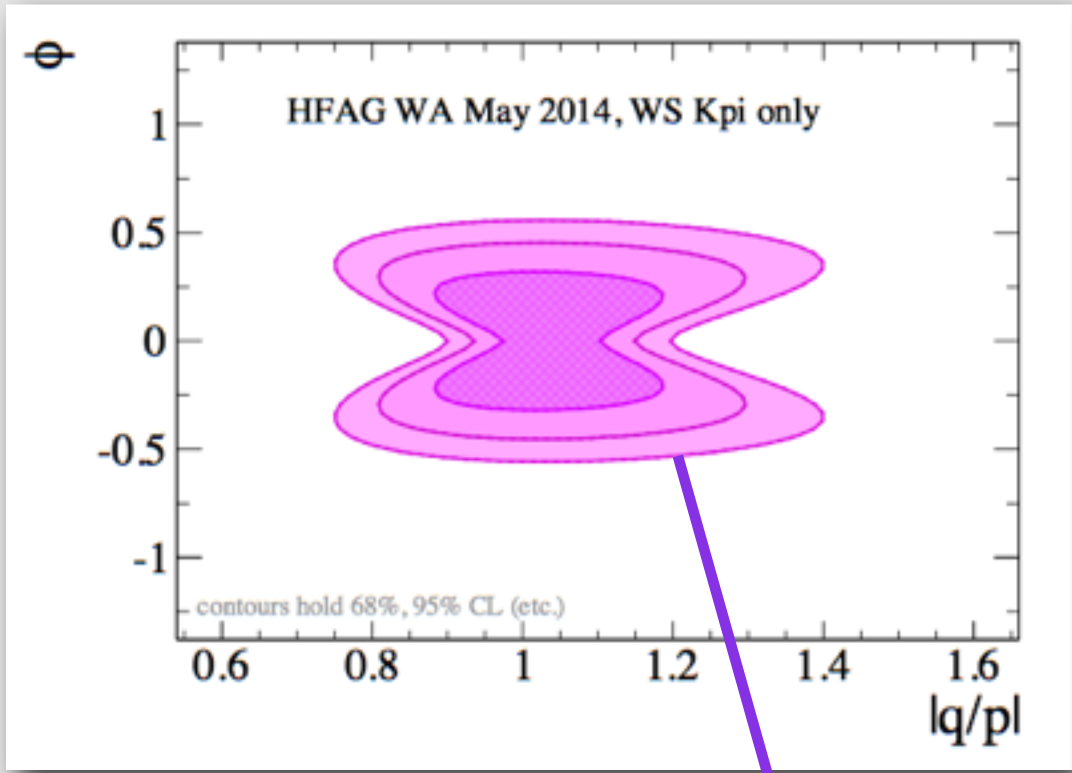
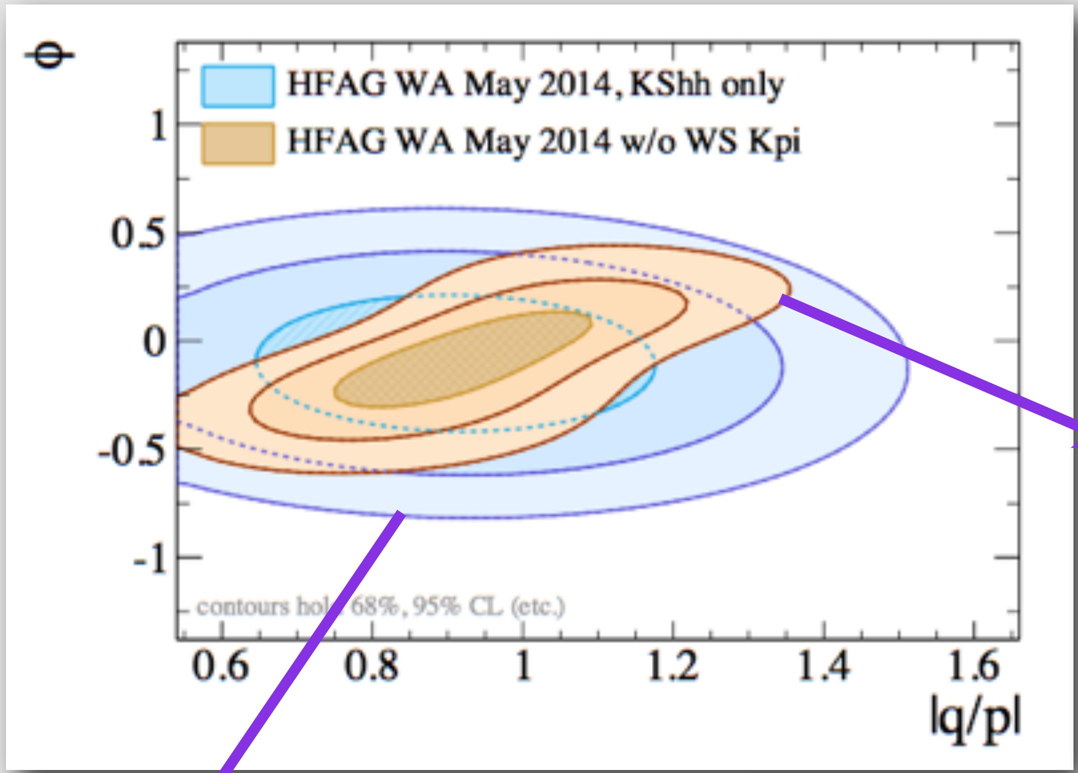
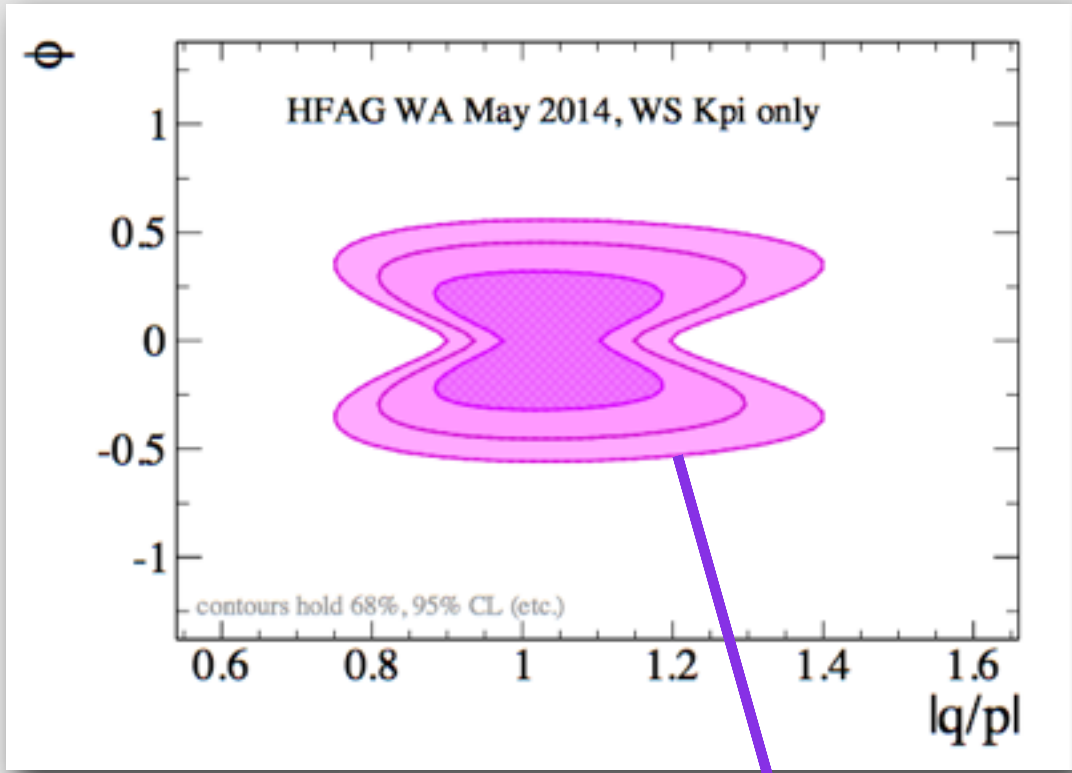


Direct access to |q/p| and φ from $K_S hh$

WS Kπ: symmetric in φ, good sensitivity to |q/p| for small φ

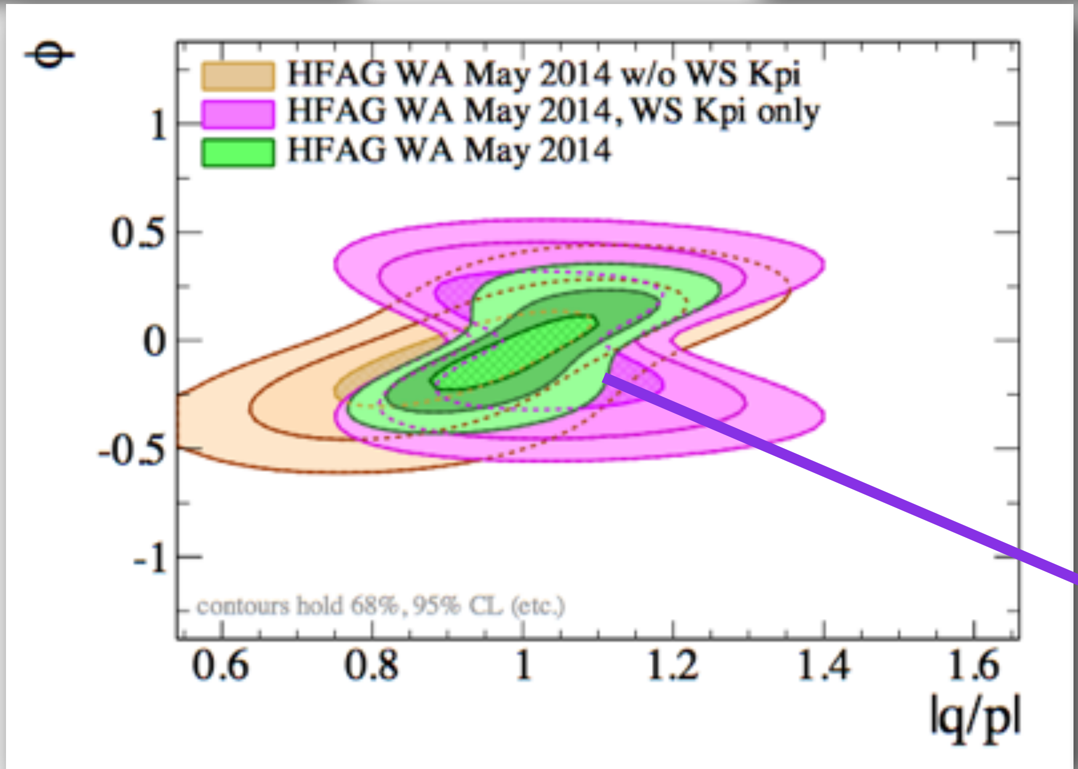
Contributions





Precise constraints if x and y provided, mostly from A_Γ

Direct access to |q/p| and φ from $K_S hh$



WS Kπ: symmetric in φ,

good sensitivity to |q/p| for small φ

Full average following intersection of contours

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Direct CP violation

Direct CP violation:

$$a_{CP}^{dir} \equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\overline{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\overline{D}^0 \rightarrow f)}$$

The Δa_{CP} saga

- What is Δa_{CP}?

$$\Delta a_{CP} \equiv a_{CP}(K^- K^+) - a_{CP}(\pi^- \pi^+) = a_{\mathrm{raw}}(K^- K^+) - a_{\mathrm{raw}}(\pi^- \pi^+).$$

- Interplay of direct and indirect CP violation

$$\Delta a_{CP} = \Delta a_{CP}^{\mathrm{dir}} \left(1 + y_{CP} \frac{\overline{\langle t \rangle}}{\tau}\right) + \overline{A}_{\Gamma} \frac{\Delta \langle t \rangle}{\tau},$$

- Individual asymmetries are expected to have opposite sign due to CKM structure

$$A(\overline{D}^0 \to \pi^+\pi^-, K^+K^-) = \mp\tfrac{1}{2}\left(V_{cs}V_{us}^* - V_{cd}V_{ud}^*\right)(T \pm \delta S) - V_{cb}V_{ub}^*\left(P \mp \tfrac{1}{2}\delta P\right),$$

EPJC 73 (2013) 2373

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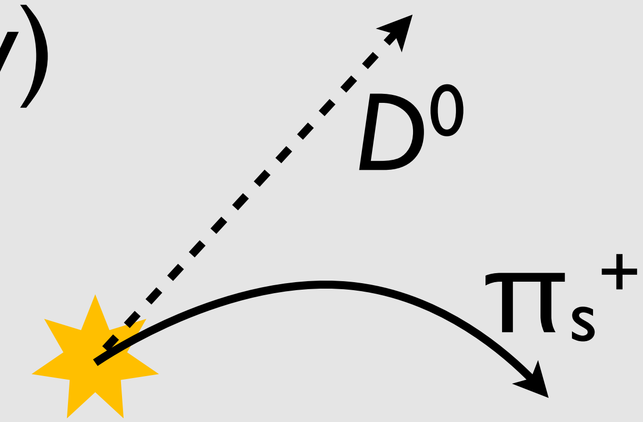
Latest results

- D*-tagged (2011 data, preliminary)

$$\Delta A_{CP} = (-0.34 \pm 0.15\,(\text{stat.}) \pm 0.10\,(\text{syst.}))\%\,.$$

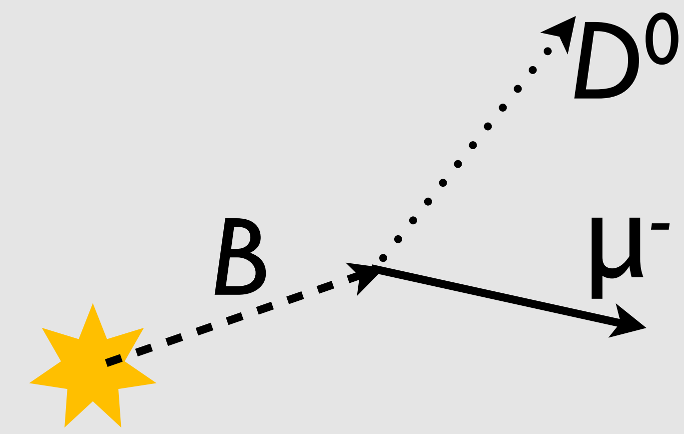
LHCb-CONF-2013-003



- muon-tagged (2011+12 data)

$$\Delta A_{CP} = (+0.14 \pm 0.16\,(\text{stat}) \pm 0.08\,(\text{syst}))\%\,,$$

JHEP 07 (2014) 014



Individual asymmetries

$a_{raw}(K^-K^+)$ $a_{CP}(K^-K^+)$ $a_P(B)$ $a_D(\mu^+)$

measure ← $a_{raw}(K^-K^+)$

want ← $a_{CP}(K^-K^+)$

Individual asymmetries

$a_{raw}(K^-K^+)$ $a_{CP}(K^-K^+)$ $a_P(B)$ $a_D(\mu^+)$

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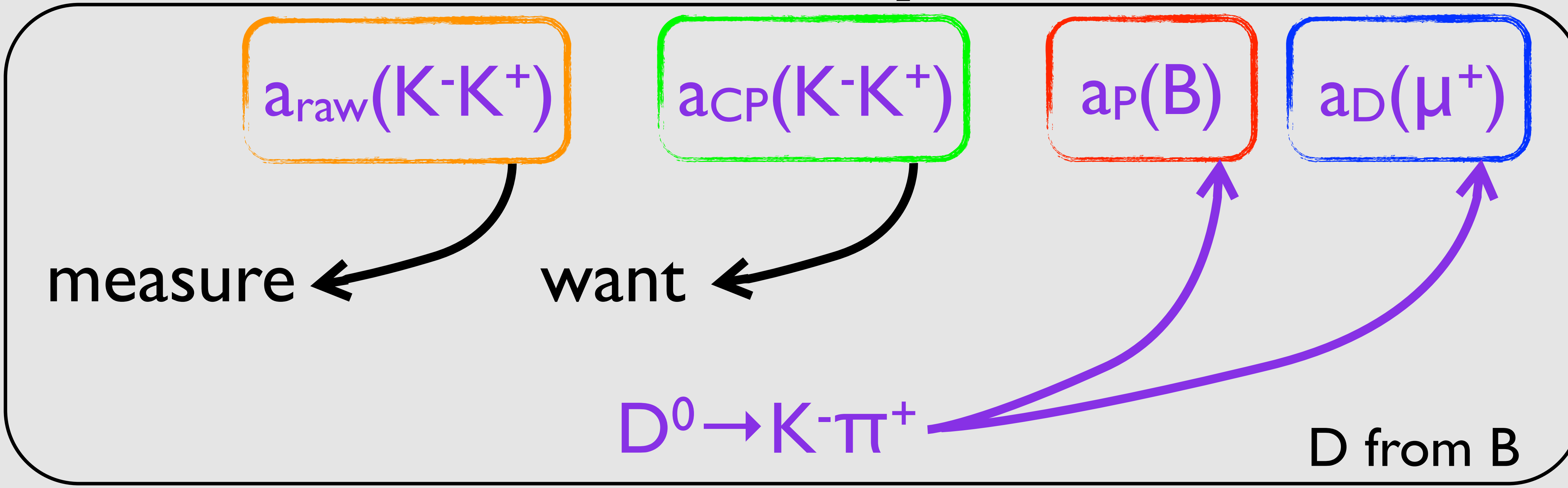
D from B

Individual asymmetries



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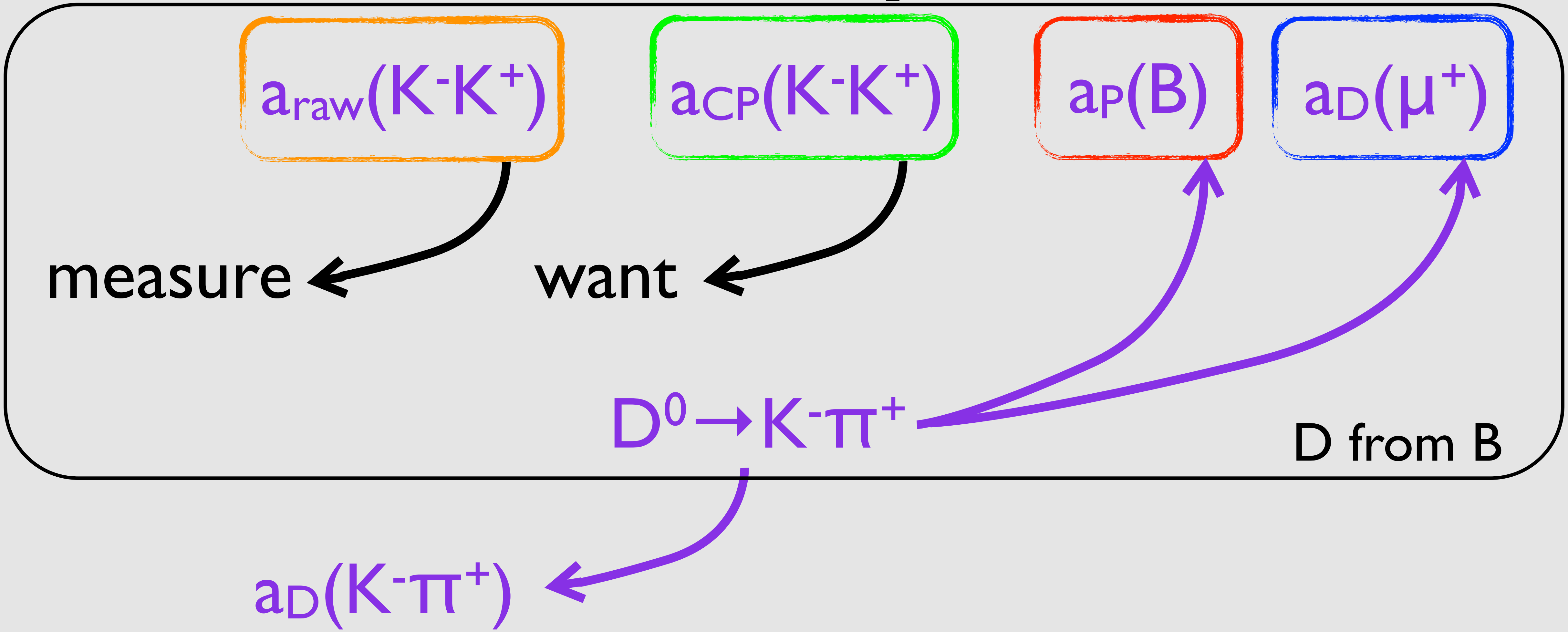
Individual asymmetries



Individual asymmetries

$a_{raw}(K^-K^+)$ → measure

$a_{CP}(K^-K^+)$ → want

$a_P(B)$

$a_D(\mu^+)$

$D^0 \rightarrow K^-\pi^+$

D from B

$a_D(K^-\pi^+)$

$D^+ \rightarrow K^-\pi^+\pi^+$

Prompt D

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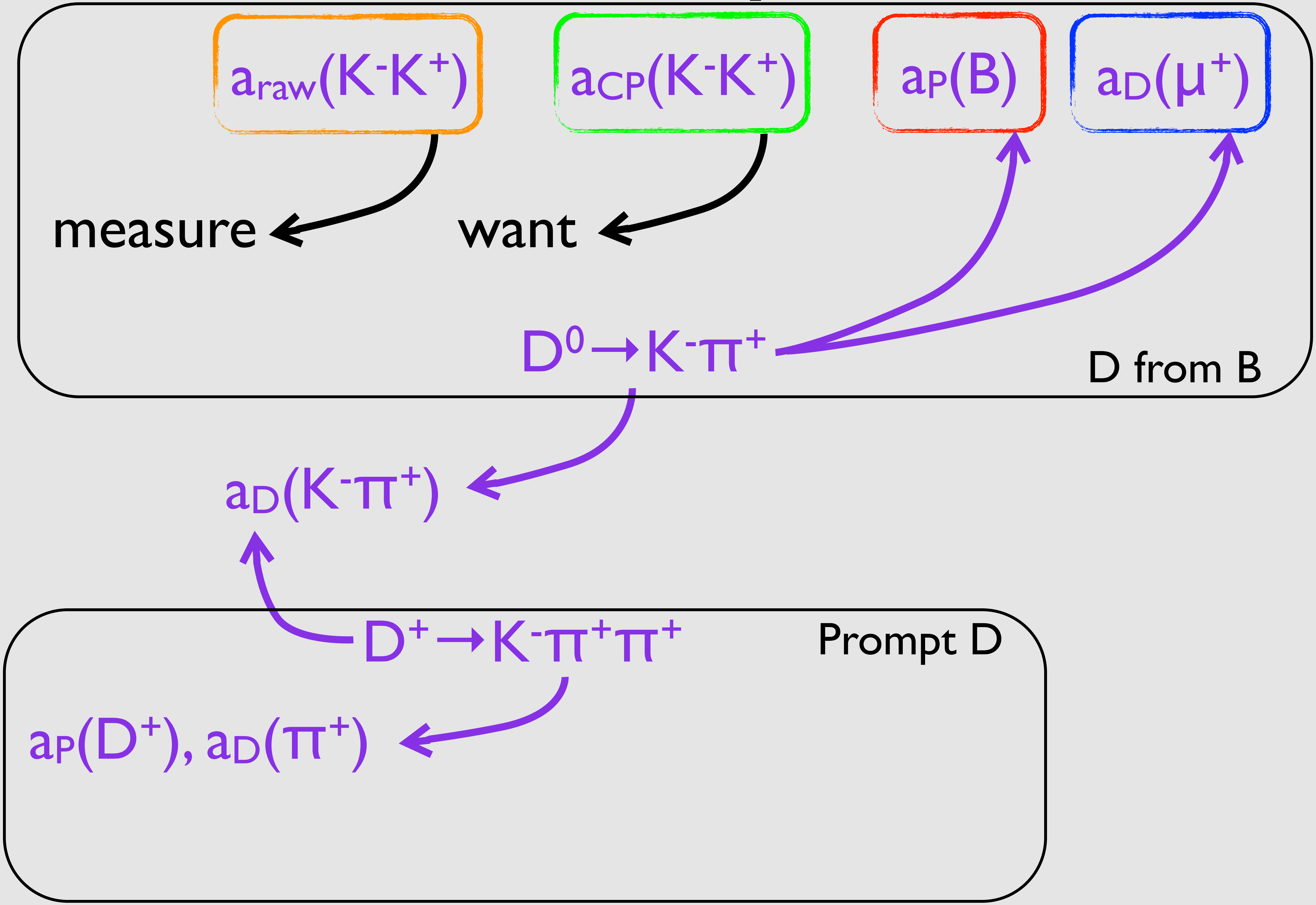
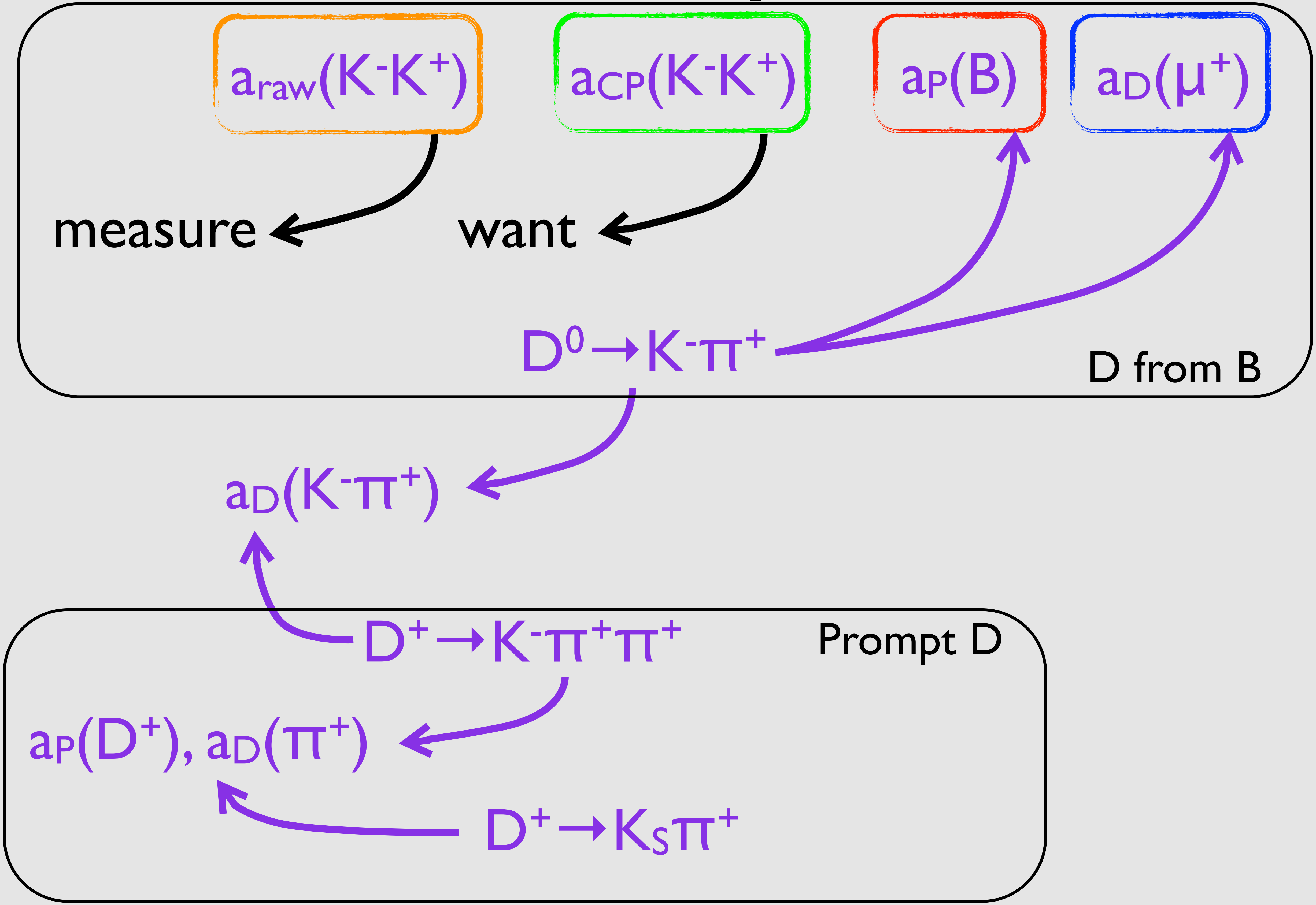
Individual asymmetries



Individual asymmetries



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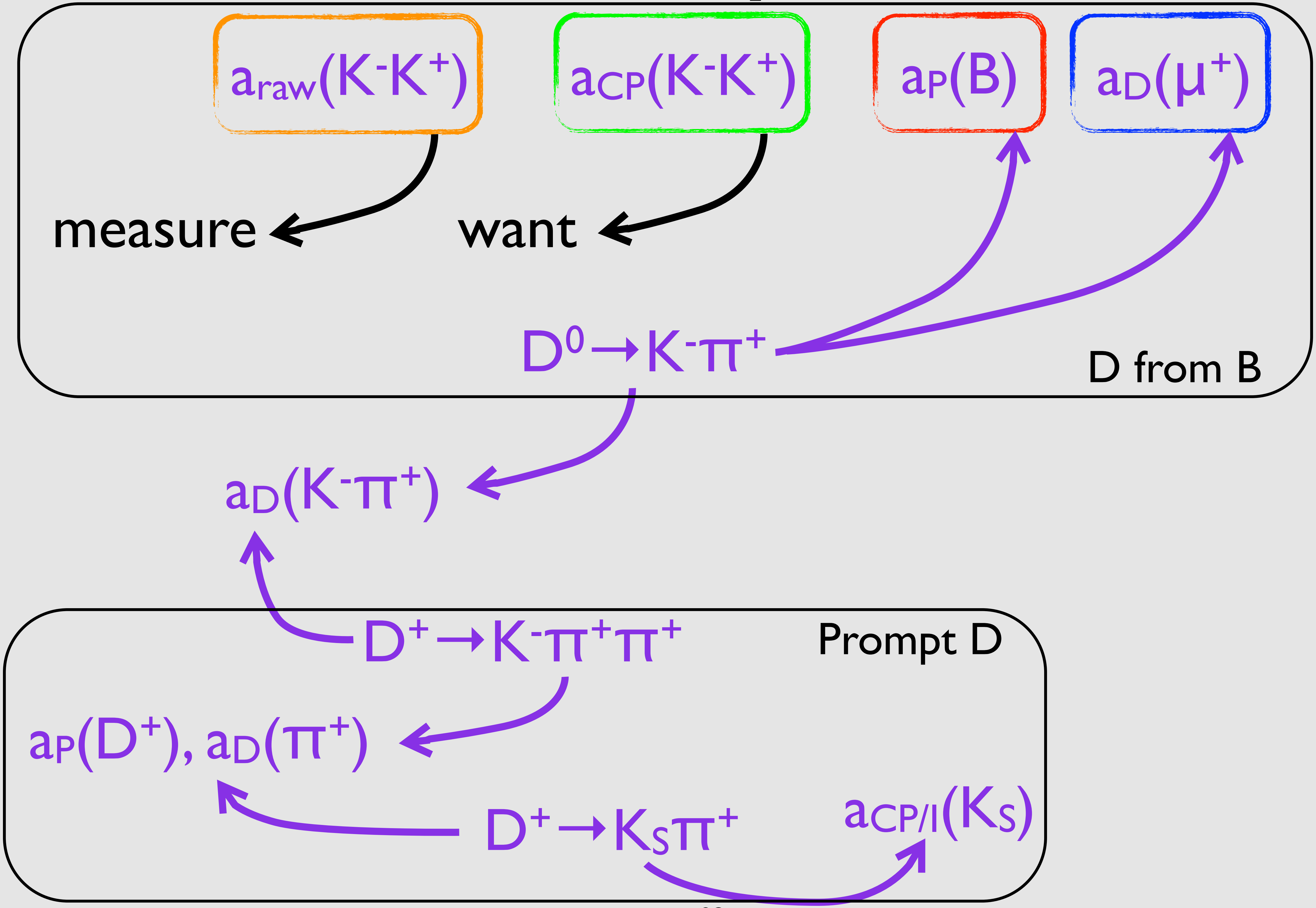
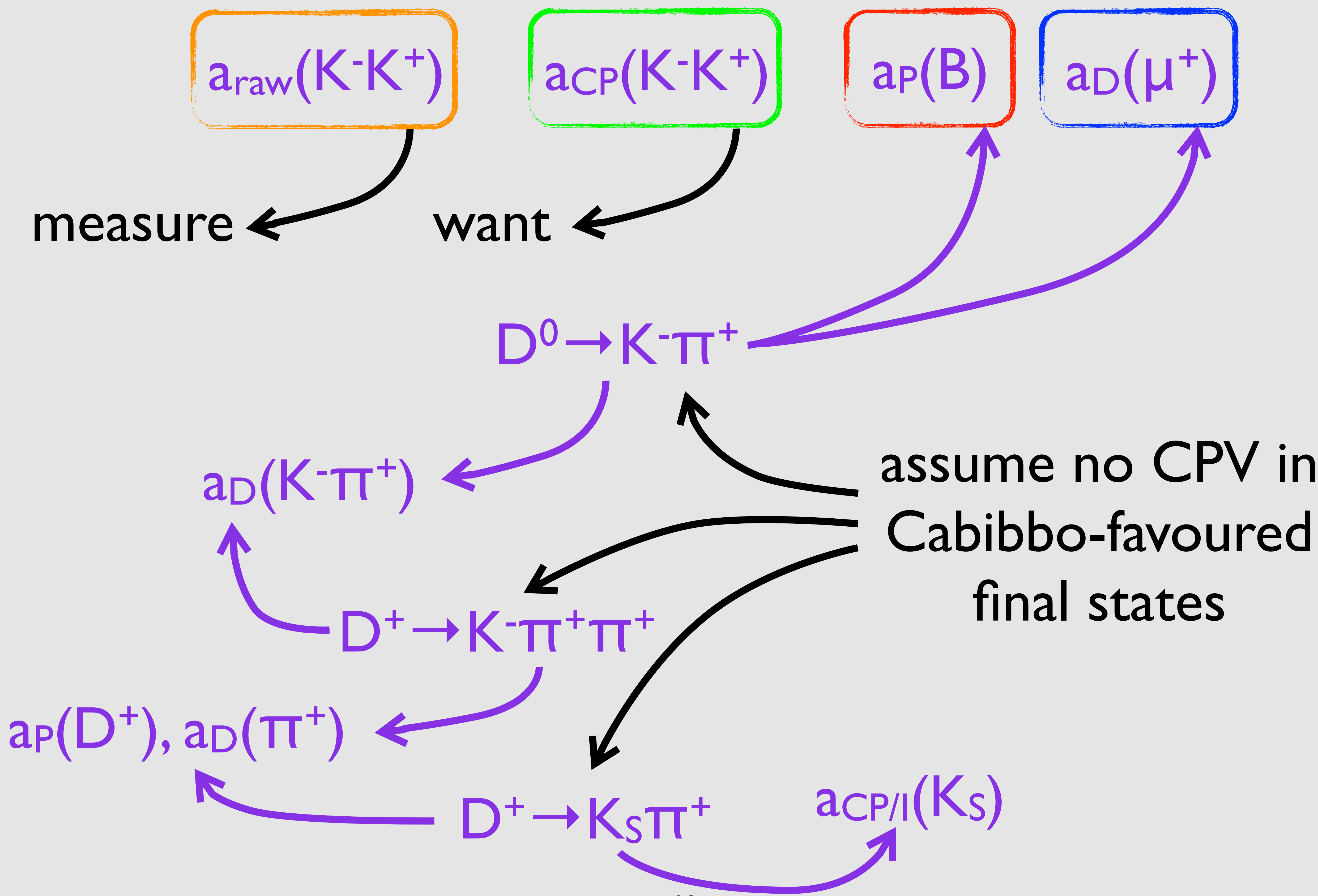
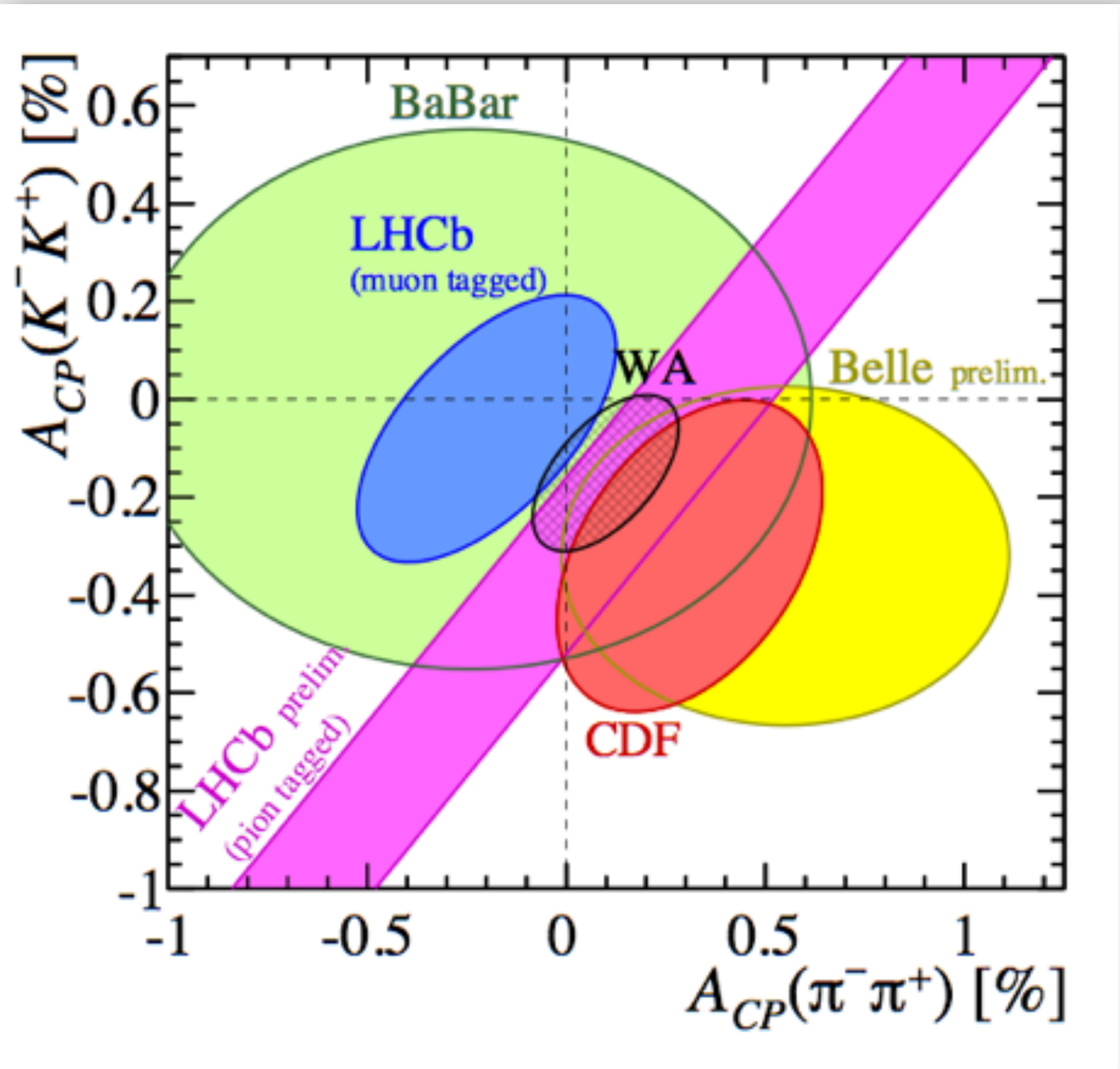


Individual asymmetries



(Δ)a_{CP} results

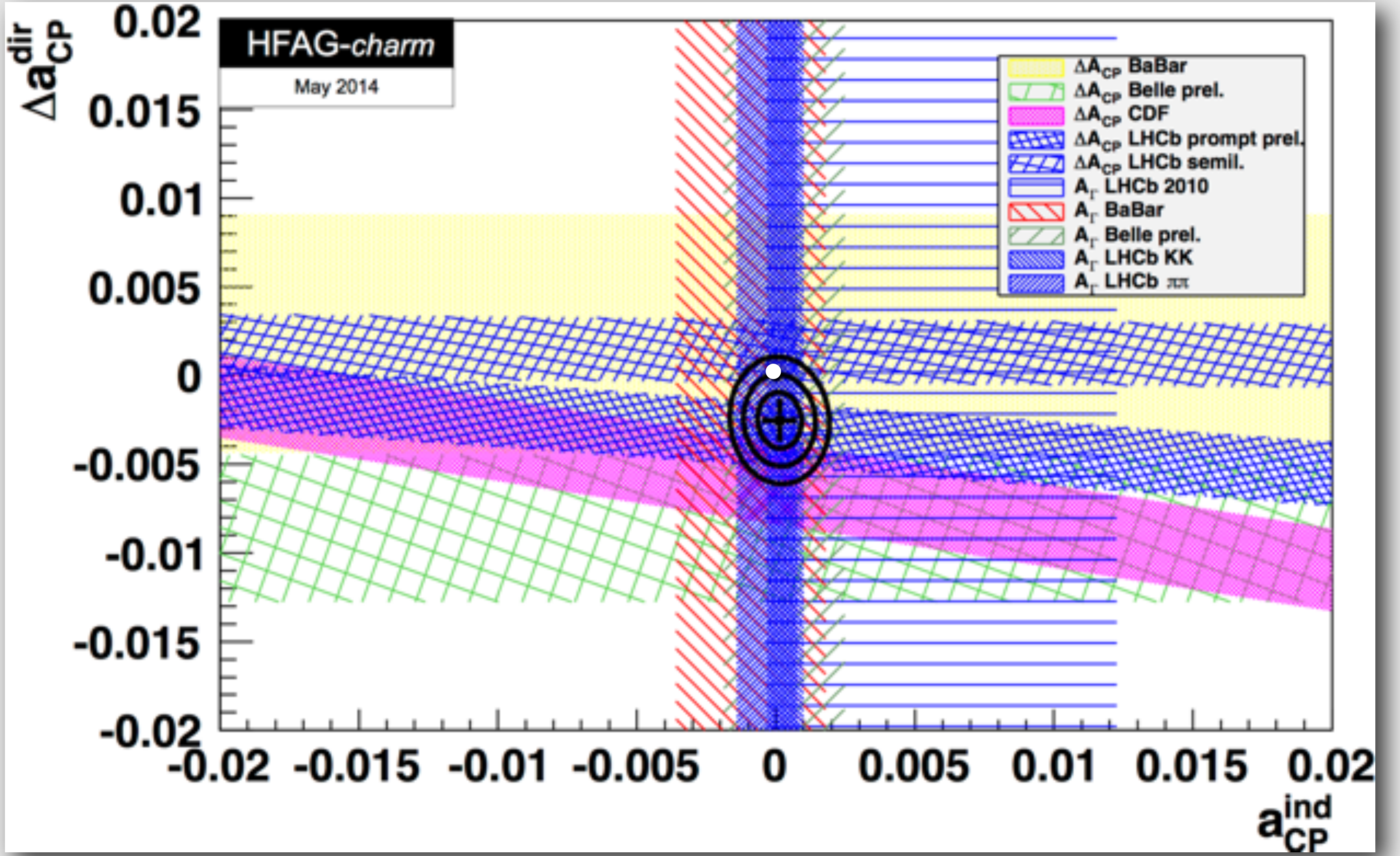
- Ignoring contribution from indirect CPV



$$A_{CP}(K^-K^+) = (-0.06 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%\,,$$

JHEP 07 (2014) 014

Direct vs indirect



- Results:
  - ➡ $a_{CP}{}^{ind}$ = (0.013 ± 0.052)%; $\Delta a_{CP}{}^{dir}$ = (−0.253 ± 0.104)%
  - ➡ no CPV $\Delta\chi^2$ = 5.9; corresponds to CL of 5.1×10^{-2}

Guessing the future

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Extrapolations

Run	√s in TeV	L in fb^{-1}	ε_{trig}	L_{eq}	ΣL_{eq}
1 (2011)	7	1	1	1	**1**
1 (2012)	8	2	1	2.3	**3.3**
2	13	5	0.5	4.6	**7.9**
3	14	15	2	60	**68**
4	14	25	2	100	**168**

- Calculate equivalent luminosities to 7 TeV
- Extrapolate signal yields accordingly
- Based on existing run-1 measurements where available

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Future charm measurements

- A_Γ, WS $K\pi$, ΔA_{CP}
  - ➡ Inherently robust against systematics due to cancellations
  - ➡ Not all at the same level, but no limiting uncertainty known
- $y_{CP} \equiv \tau_{K\pi}/\tau_{KK} - 1 \approx y$
  - ➡ Comparison of two different final states
  - ➡ Less robust but controllable if lifetime bias easier to account for
- $K_S\pi\pi$
  - ➡ Leading systematics are either model uncertainties or measurements of CP content at threshold
  - ➡ Relies on input from BESIII

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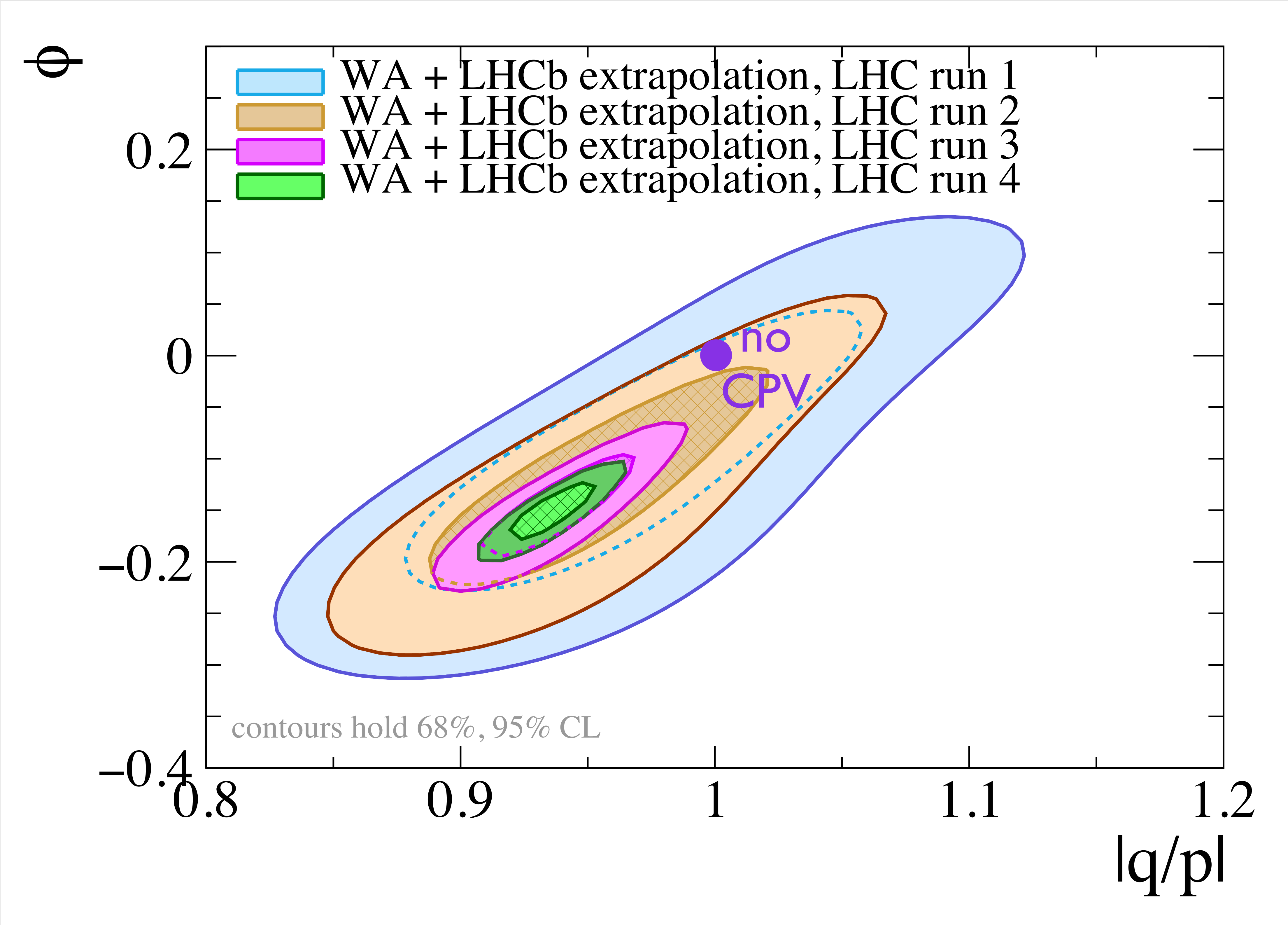
Future sensitivities

- Scaling sensitivities with $\sqrt{N}$
  - ➡ Assumes scaling of systematic uncertainties
  - ➡ Ignores potential improvements in selections and analyses
- Δa_{CP}: uncertainty 10^{-4} at 50 fb^{-1}
- Mixing and indirect CPV sensitivities of current world average + LHCb

Run	x [10^{-3}]	y [10^{-3}]	|q/p| [10^{-3}]	ϕ [mrad]
1	1.22	0.53	59	89
2	0.92	0.37	44	70
3	0.42	0.15	20	33
4	0.25	0.09	**12**	**20**

The need for the upgrade



Conclusions

- Huge potential of LHCb upgrade
  - ➡ Preparations for installation in 2018 on schedule
- LHCb is currently the main player in charm physics
  - ➡ Will probe SM level CP violation with LHCb upgrade
- The goal is not only to find CP violation in charm but also to identify its nature