Charm Physics

Recent Measurements & Future Prospects at BelleII

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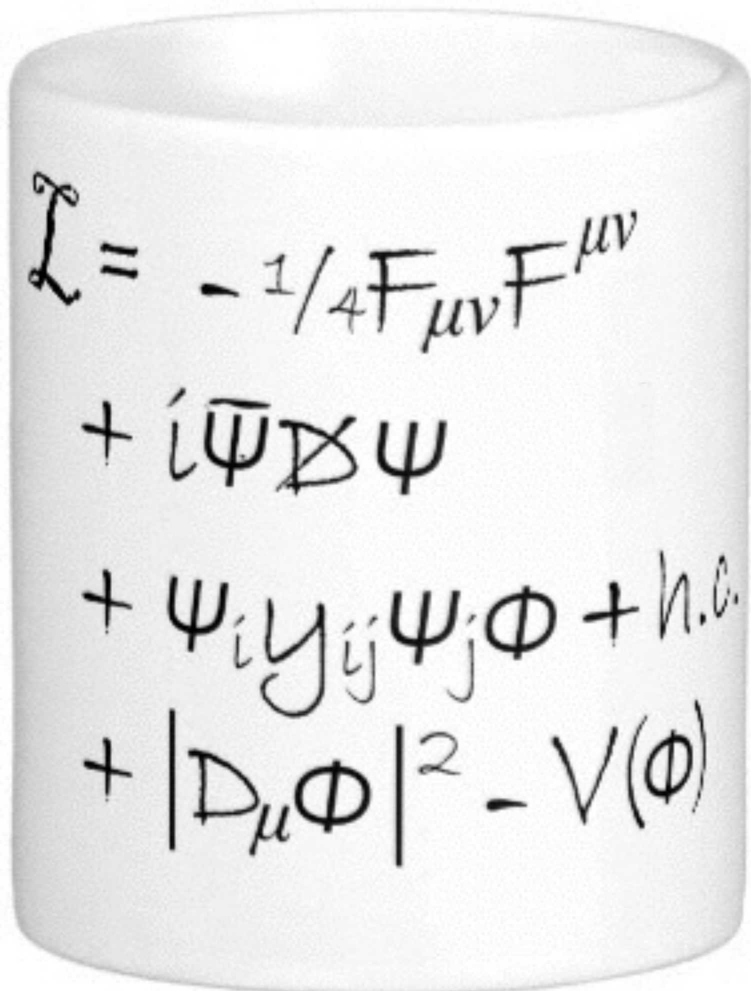
Outline

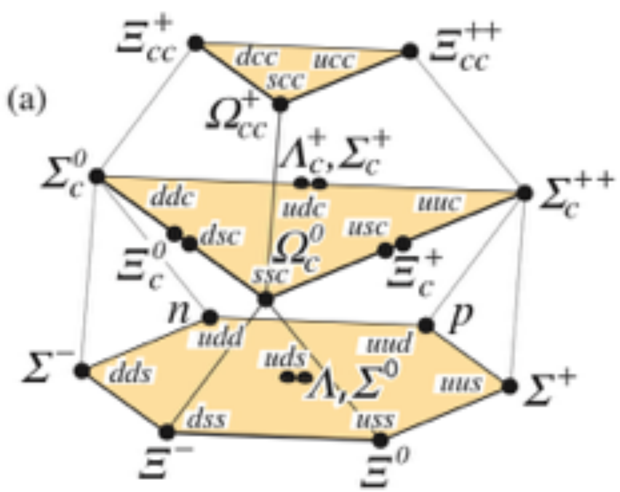
- ☑ *Introduction: Charm in the Standard Model*
- ☑ *A Snapshot of Charm Physics*
  - *Theory & Standard Model predictions*
  - *Selected Recent Measurements*
- ☑ *The Belle II Experiment: detector & innovative reconstruction techniques*
- ☑ *Charm Prospects at Belle II*

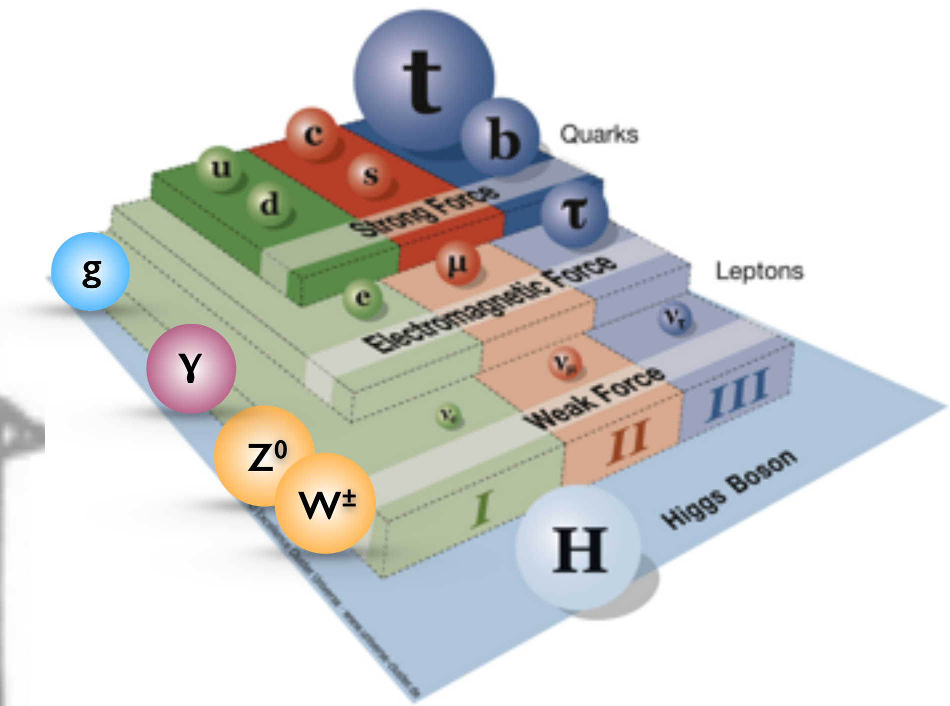


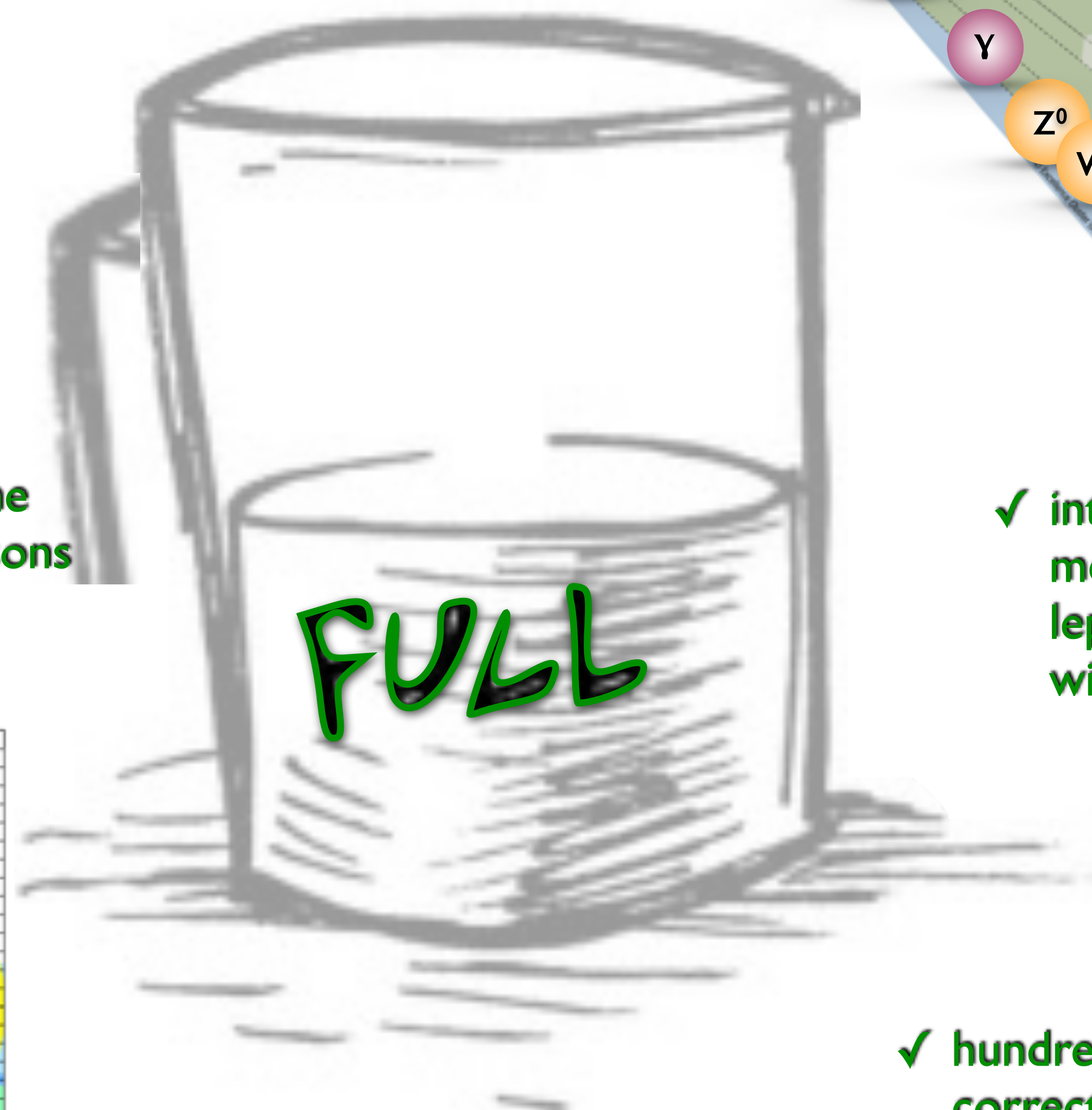
is the
Standard Model
mug
half empty
or
half full?

Introduction

The SM Mug is Half Full …

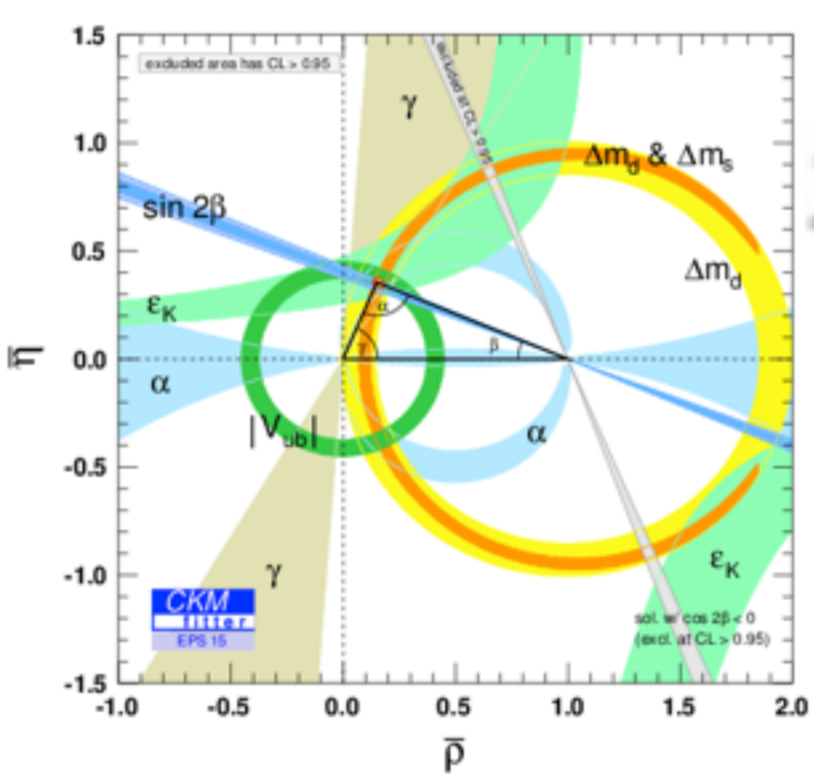






✓ the quark model predicts the observed bound states, mesons and baryons

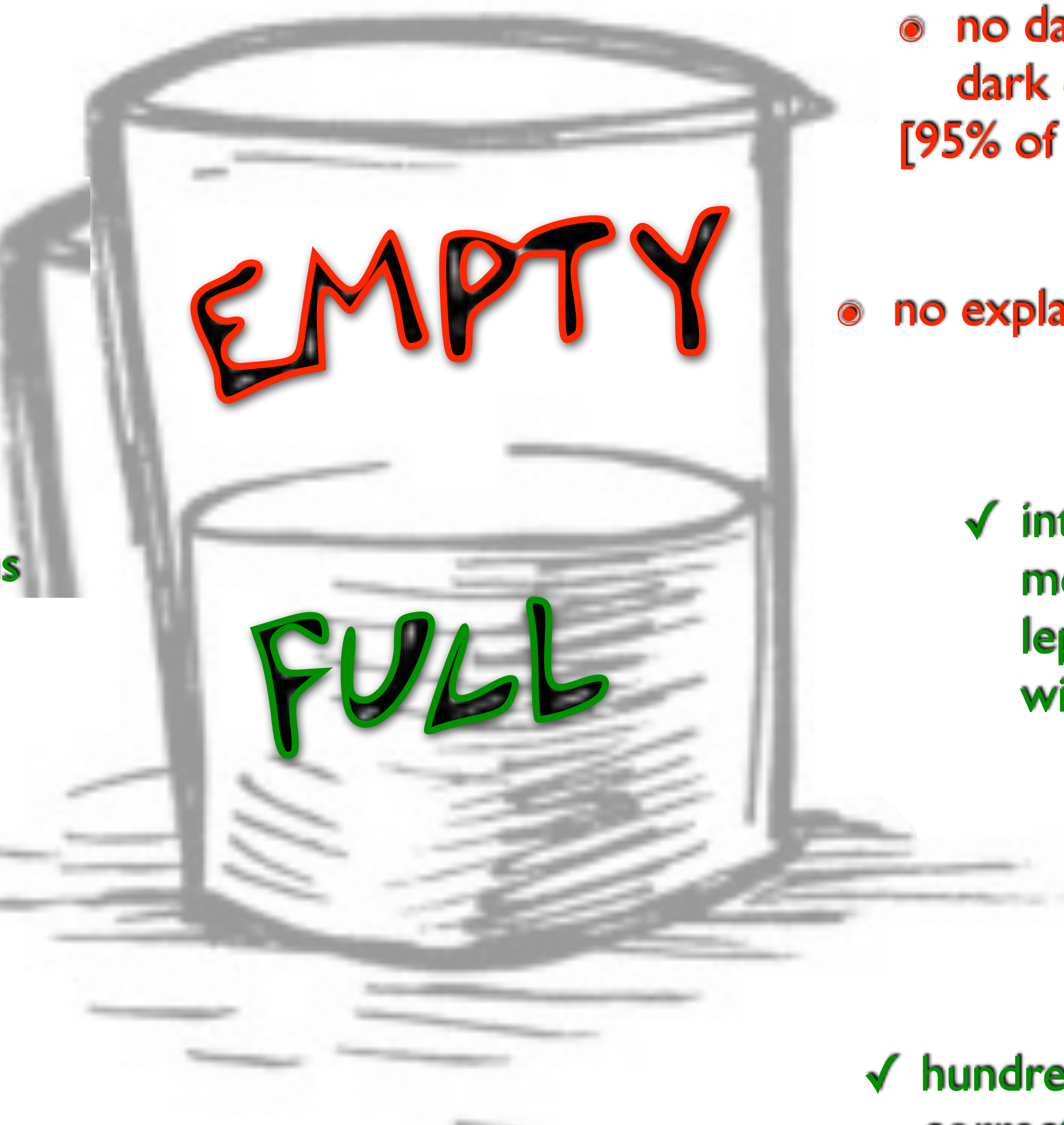
✓ interactions between mesons, baryons and leptons are predicted with a precision of o(1%)



✓ hundreds of observables are correctly predicted within the theoretical and the experimental errors

The SM Mug is Half Full and Half Empty

- no explanation of the observed matter-antimatter asymmetry [effect o(100%)]
- no dark matter candidate nor dark energy explanation [95% of the universe is unknown]
- no explanation of masses hierarchy



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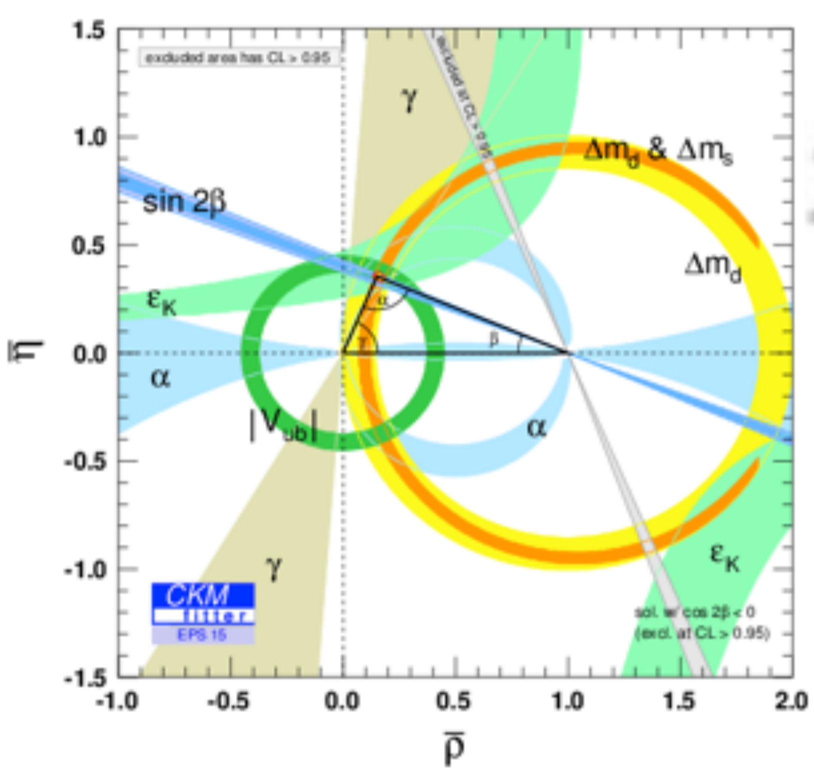


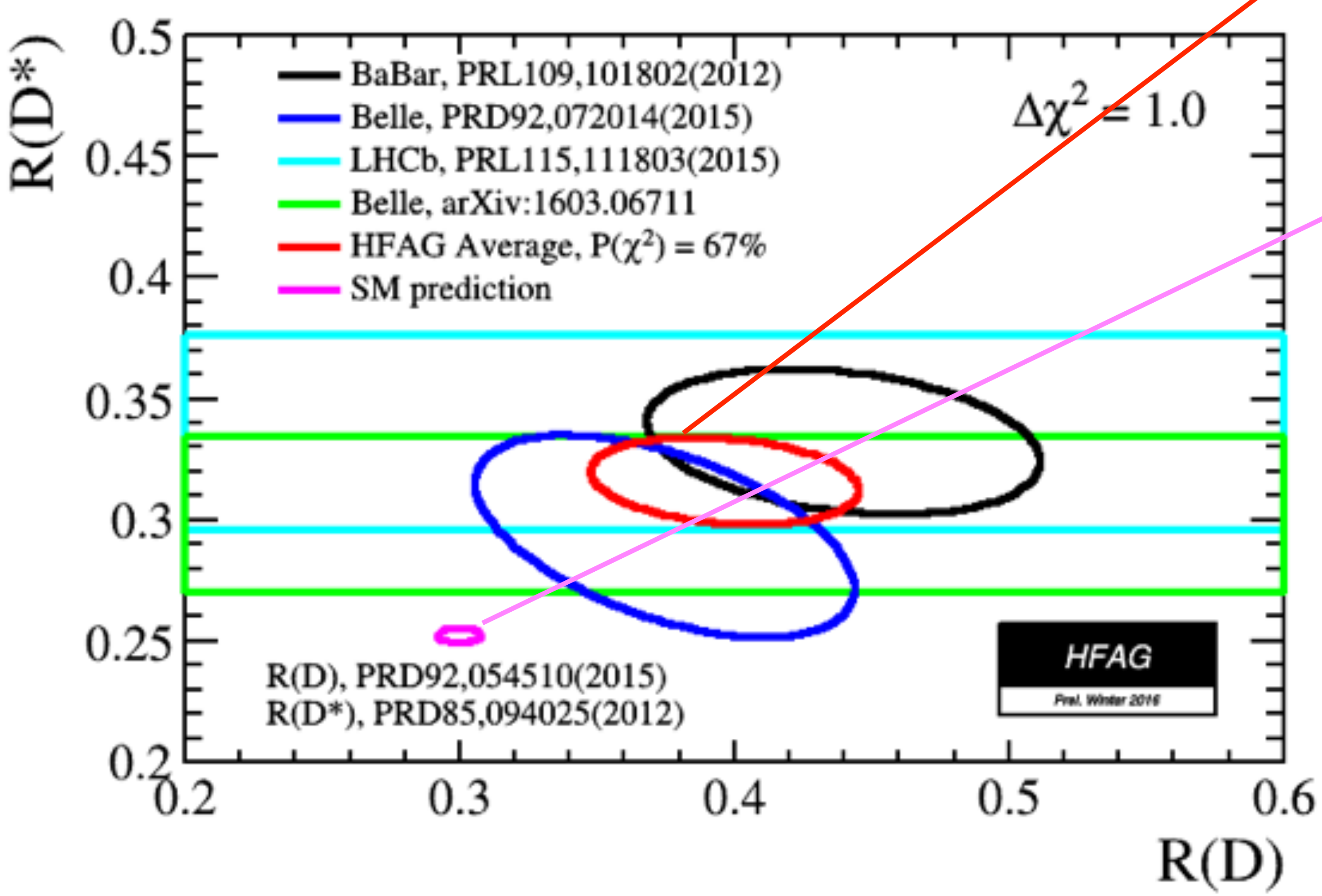
✓ hundreds of observables are correctly predicted within the theoretical and the experimental errors

… *and* Maybe Cracked Somewhere?

- There are some effects that can be compatible with statistical fluctuations, as well as hints of physics beyond the Standard Model

- e.g.: **B → D$^{(*)}$ τ ν**

$$\mathcal{R}(D^*) = \frac{\Gamma(B \to D^* \tau \nu_\tau)}{\Gamma(B \to D^* \ell \nu_\ell)}_{\ell = e, \mu}$$

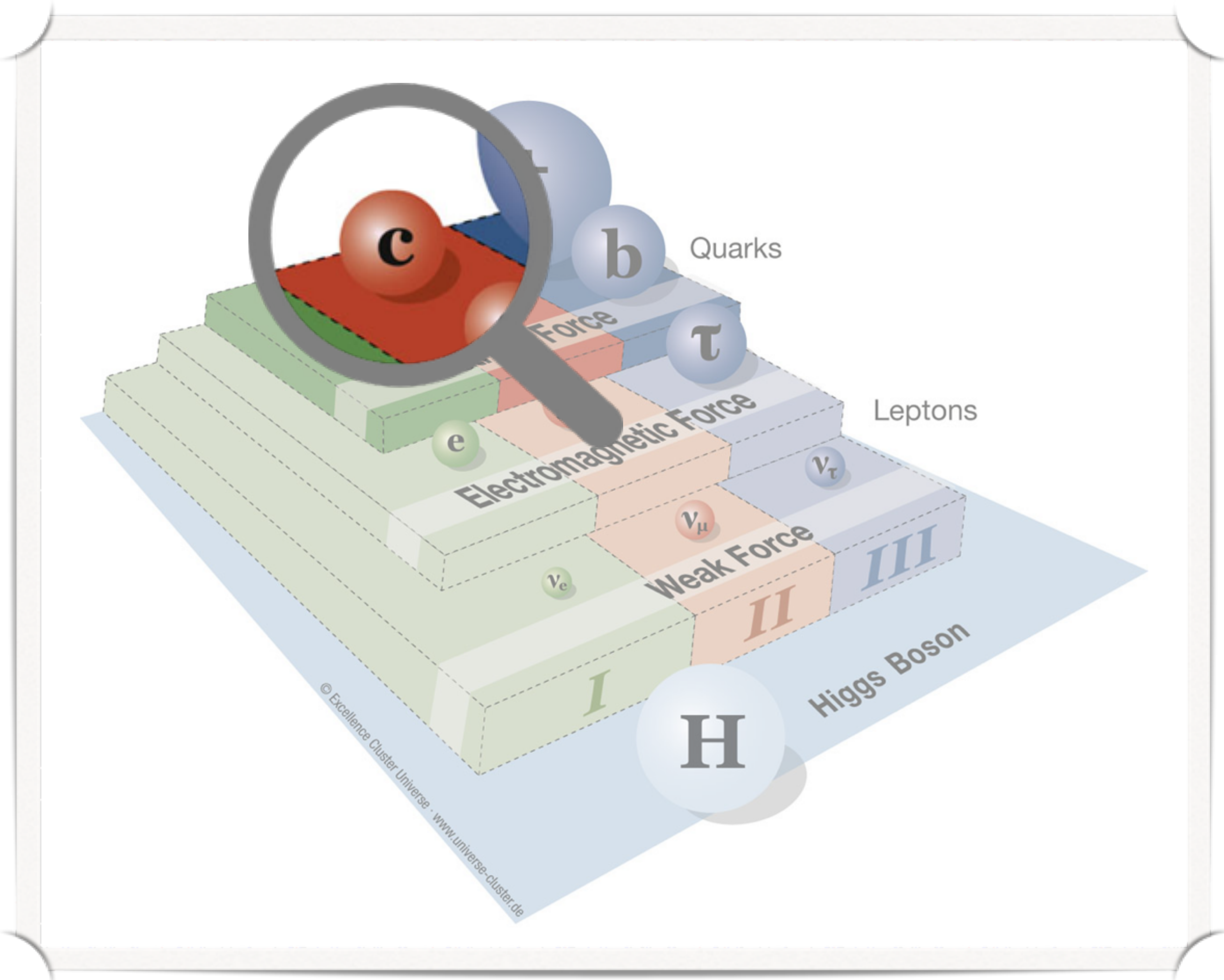


R(D*) = 0.316 ±0 .016 ± 0.010
R(D) = 0.397 ± 0.040 ± 0.028

VS

R(D*) = 0.300 ± 0.008
R(D) = 0.252 ± 0.003

the world average is inconsistent with the SM at 4 σ

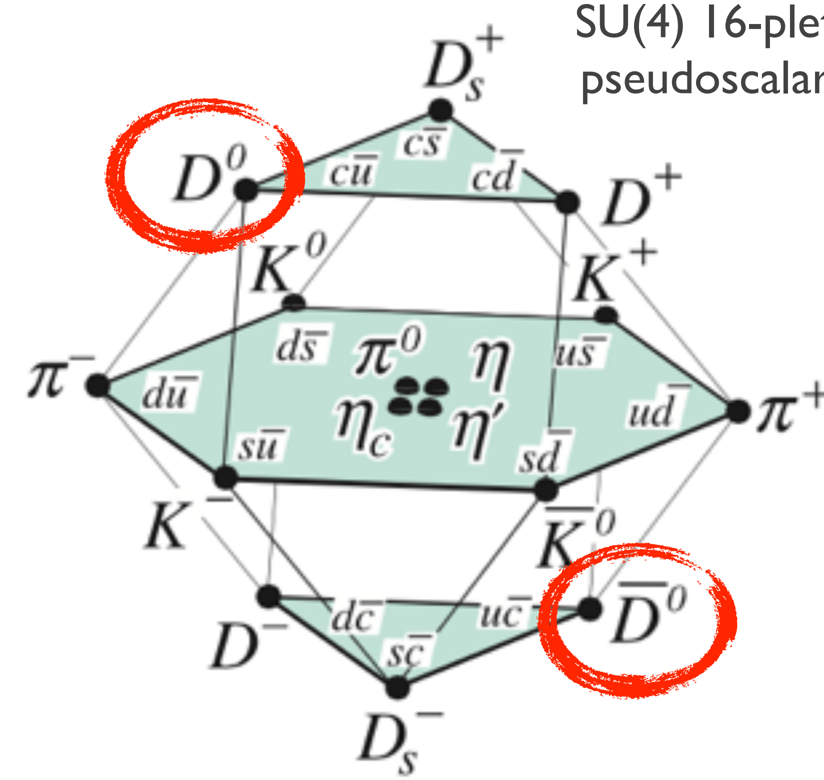


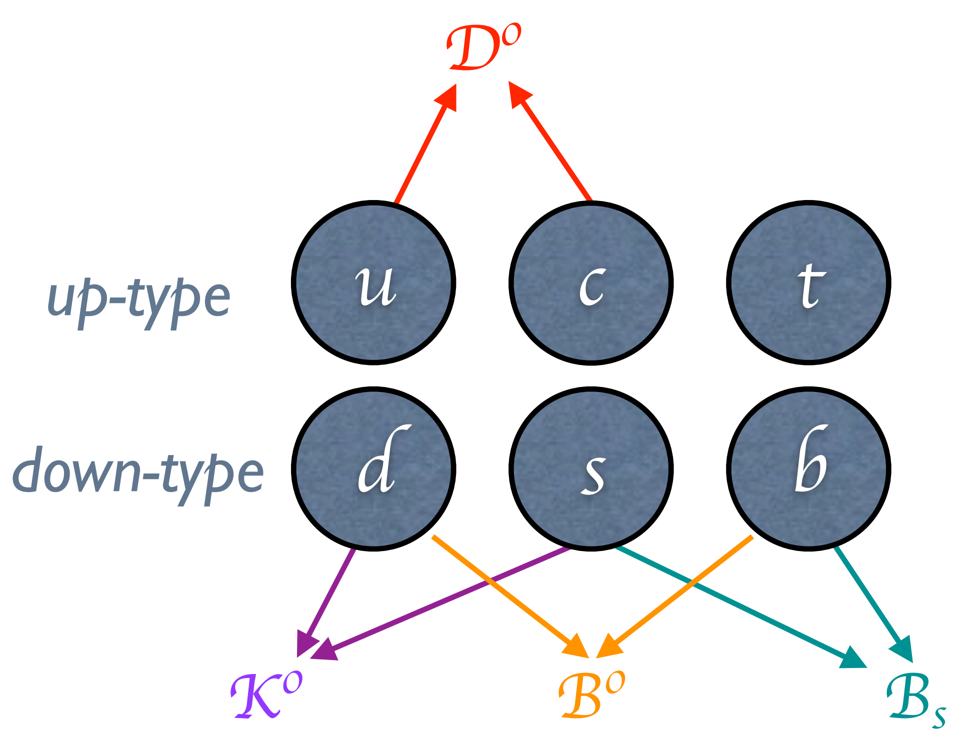
Zooming on Charm

Charm in the Standard Model

- ➡ *charm* is an up-type quark, of mass ~ 1.25 GeV/c^2
  - not heavy (m(b) ~ 4.2 GeV/c^2) nor light (m(s) ~ 100MeV/c^2)
- ➡ it forms charged and neutral mesons and baryons
- ➡ in particular the neutral meson D^0 *is the only mixing meson made of up-type quarks:*
  - the top quark decays before forming bound states
  - π^0 coincides with its own antiparticle

SU(4) 16-plets pseudoscalars





charm flavour physics

- ➡ complementary informations provided w.r.t. K and B mixing and CPV
- ➡ eventual NP contributions must couple to the up-type sector
- ➡ constraints NP models probing a different parameters space

Mixing and CP Violation T-evolution

- prediction of K^0 mixing (*theta-tau puzzle*)
- **1955** — observation of K^0 mixing
- **1956** — observation of P violation
- **1964** — observation of CP violation in the K^0 system
- **1967** — Sakharov Conditions for Baryogenesis
- **1973** — proposal of CKM mechanism
- **1987** — observation of B^0 mixing
- **1999** — observation of direct CP violation in K^0 decays
- **2001** — observation of CP violation in the B^0 system
- **2006** — observation of B_s mixing
- **2008** — evidence of D^0 mixing
- **2011** — evidence CPV in the D^0 system
- **2012** — **observation of D^0 mixing**; observation of direct CP violation in B_s decays
- **2013** — **evidence CPV in the D^0 system experimentally disappeared**
- **2016** — search of CPV in the charm sector reaches the sub ‰ precisions

charm mixing and CPV

- ➡ only in the last few years experiments have become sensitive to D^0 mixing
- ➡ no clear observation of CP Violation yet
- ➡ the charm mixing system is the *less known* among the four SM mixing systems

Neutral Meson Mixing

- Mixing occurs when the mass eigenstates differ from the flavour eigenstates:

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

with $|p|^2 + |q|^2 = 1$
and assuming CPT conservation

- The time evolution of the flavour eigenstates is described by the **mixing parameters**:

$$x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

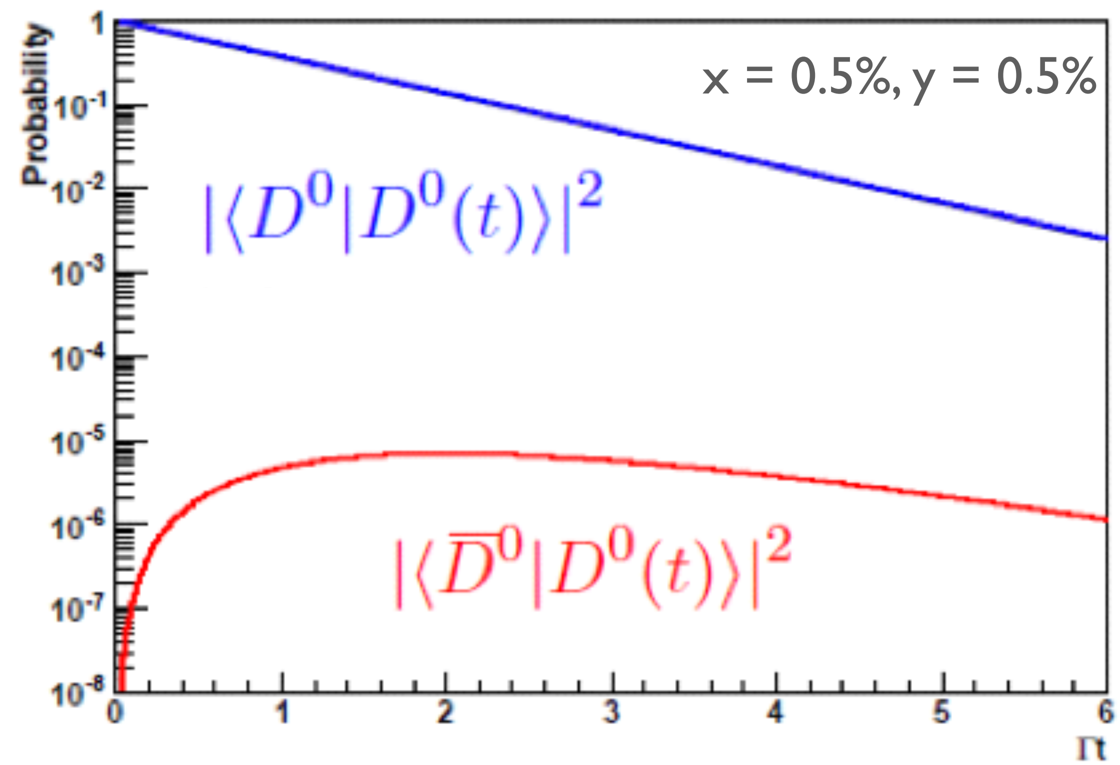
with $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$

- Let's consider the state of a neutral charmed meson that was a D^0 at t = 0:
  - The probability that the flavour is changed at time t is:

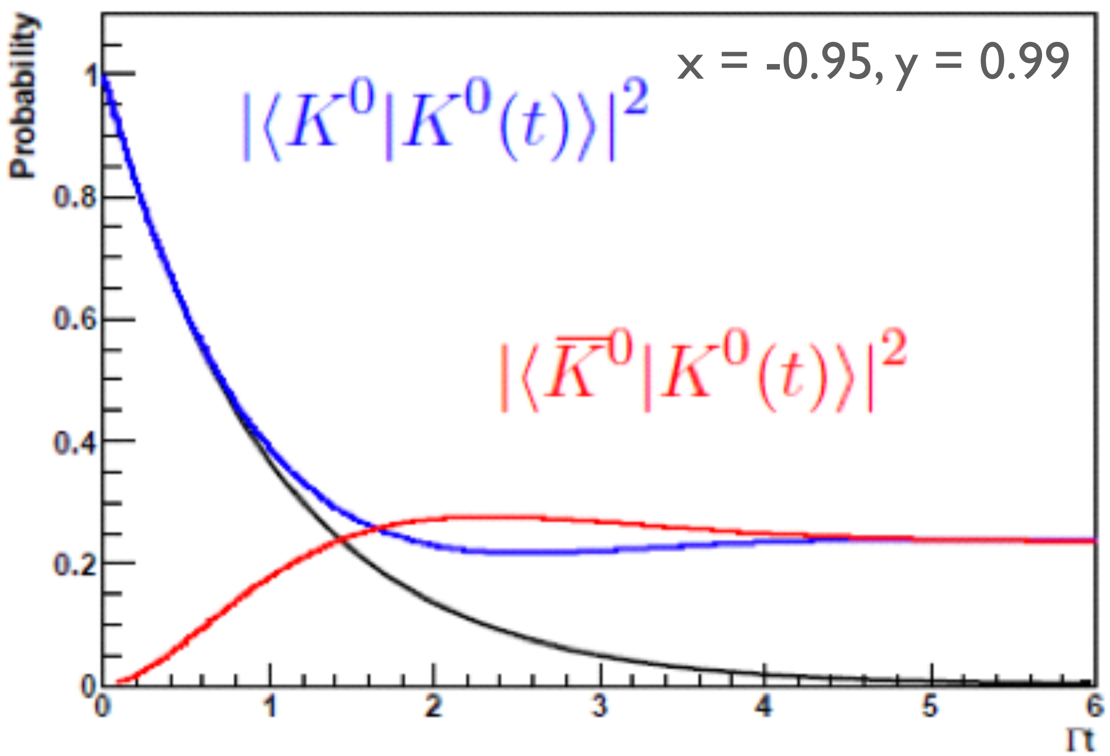
$$|\langle \overline{D}^0 | D^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

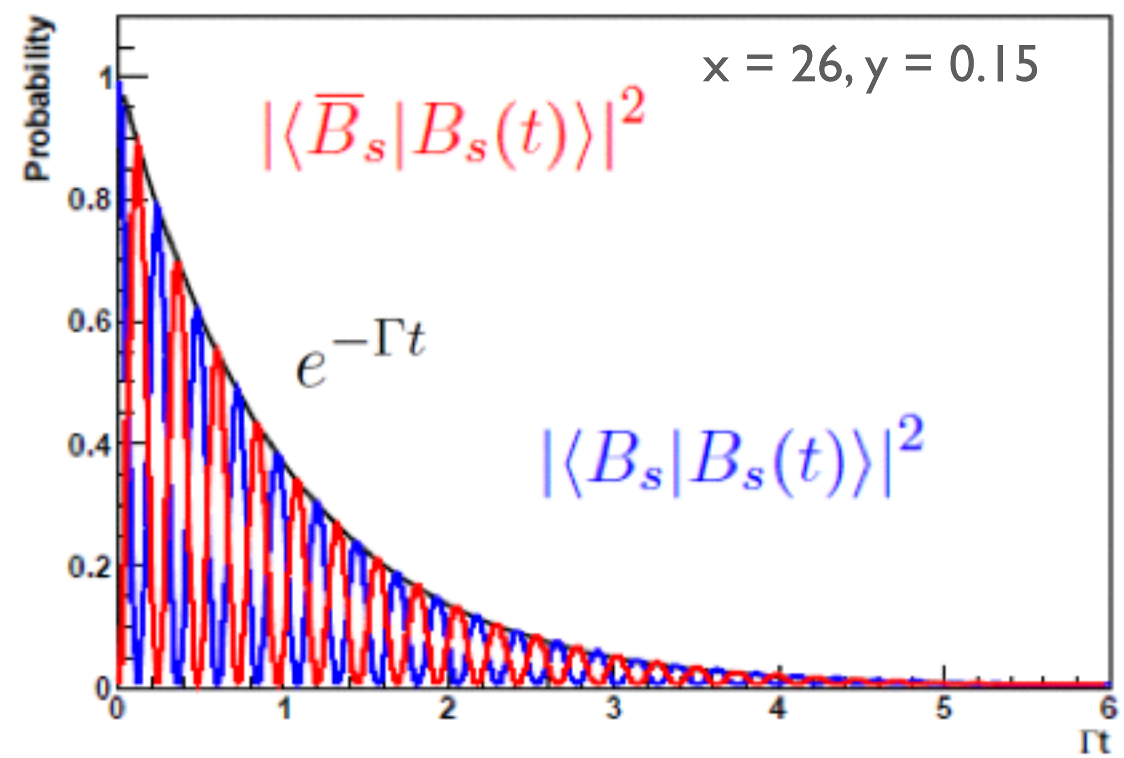
  - The probability that the flavour is not changed at time t is:

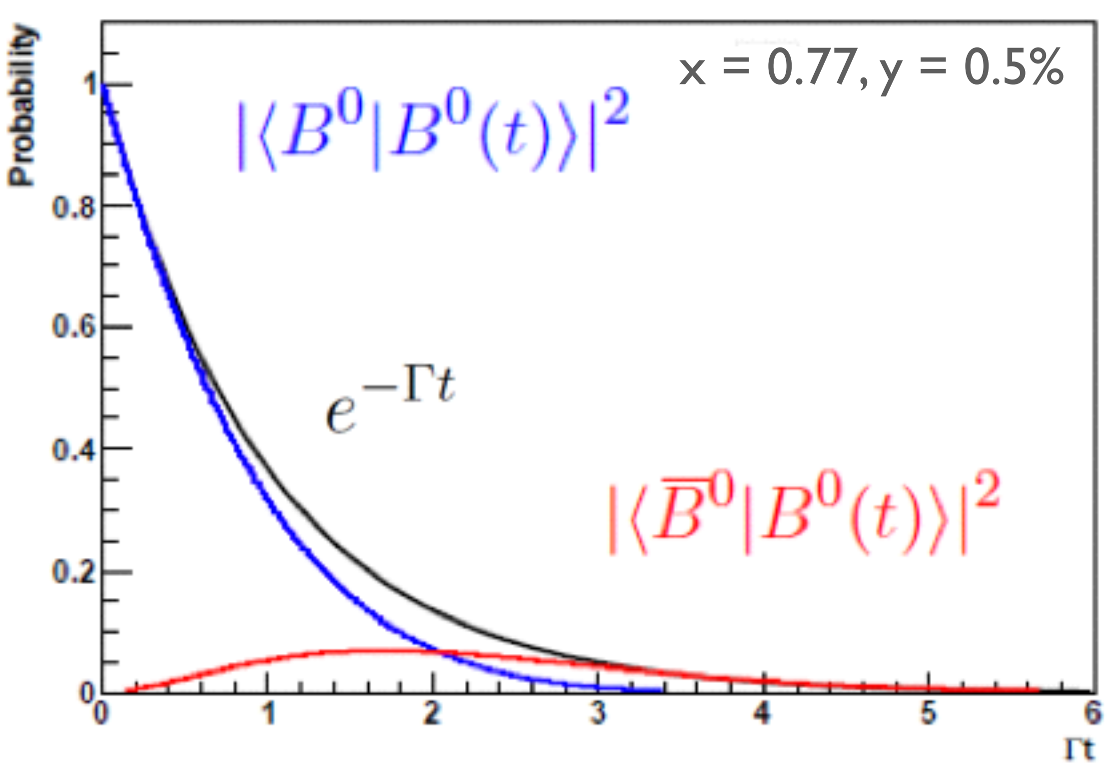
$$|\langle D^0 | D^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$$

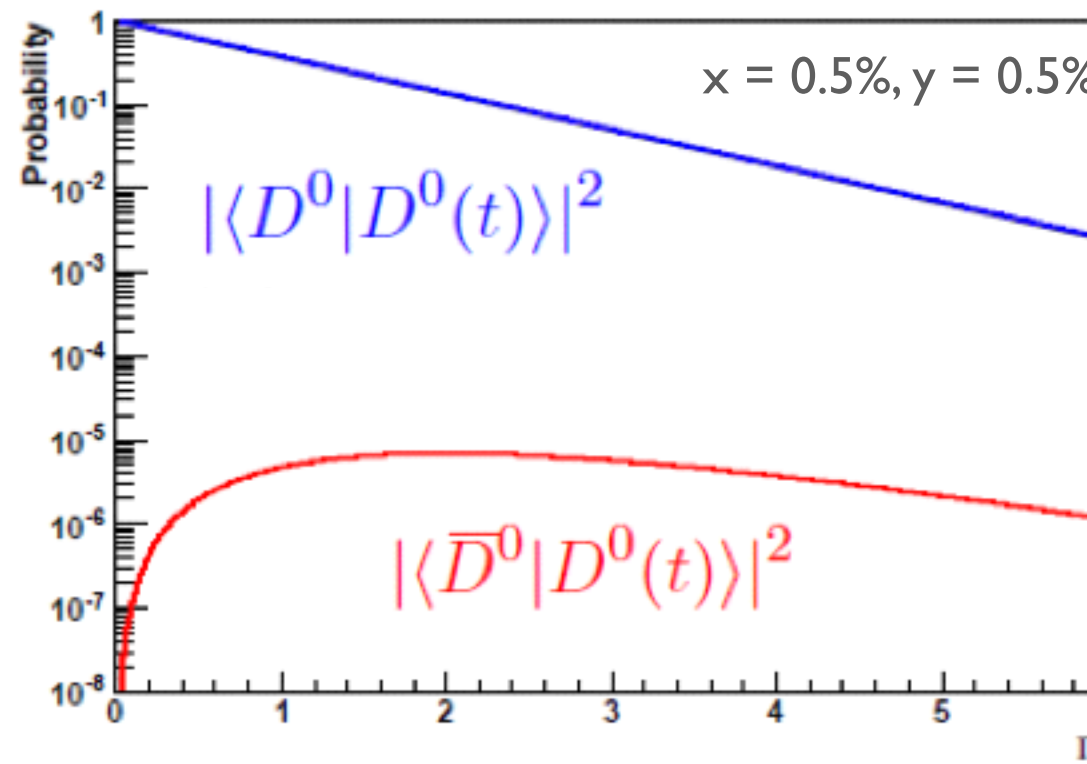


The 4 Standard Model Mixing Systems









What About CP Violation?

- CP Violation (CPV) is naturally introduced in the SM by the unitary CKM matrix, through its irreducible complex phase:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} \overset{u}{1-\lambda^2/2} & \overset{c}{\lambda} & \overset{t}{A\lambda^3(\rho - i\eta)} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfeinstein parameterization up to λ^3

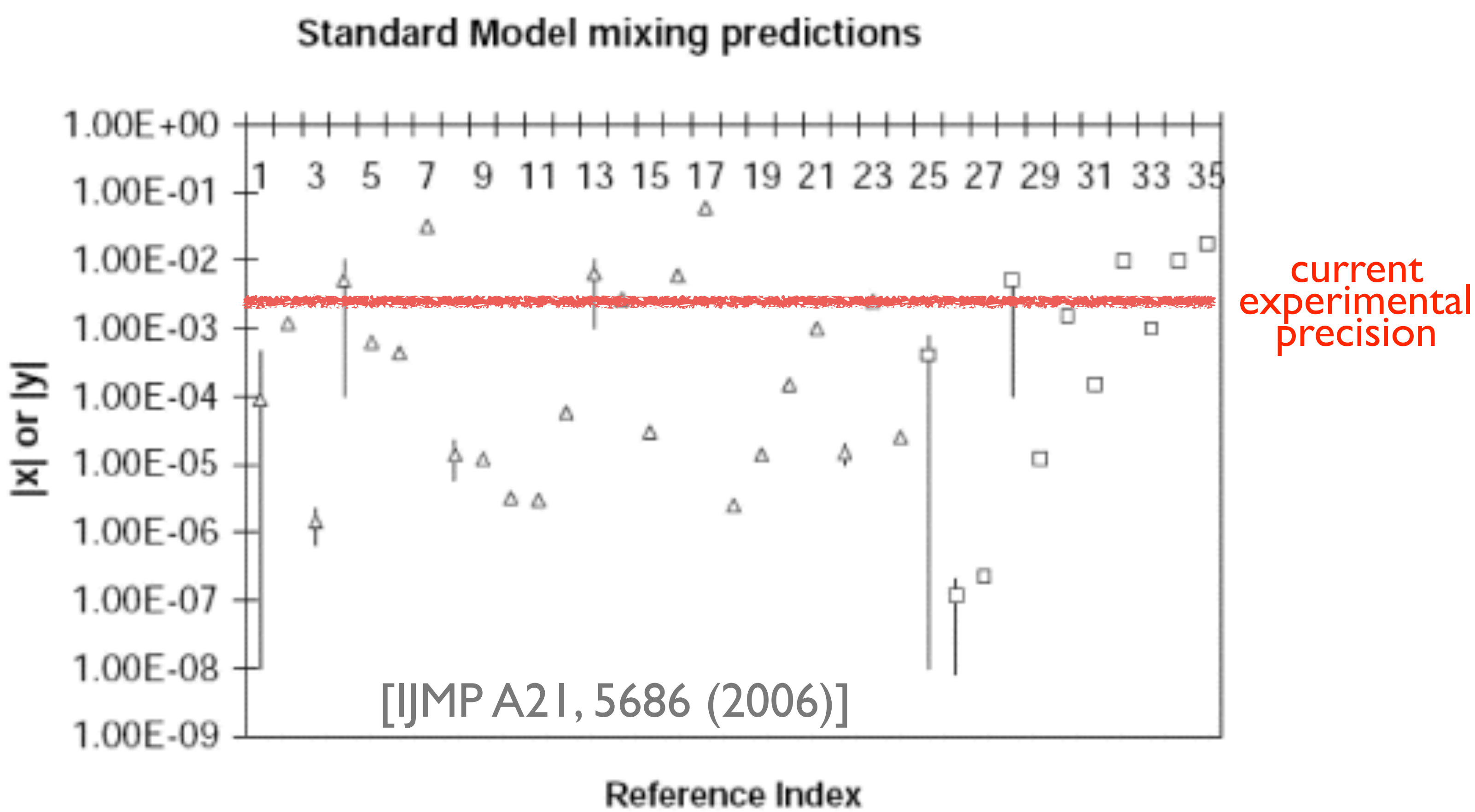
- Charm decays involve primarily the first two generations → naively no CPV expected in the Standard Model

- Real life is more complicated:
  - due to the difficulties in the diagrams computation, it is hard to predict a precise value (or upper limit) for the CPV that we can expect from the SM
  - with the increase of the experimental precision theorists have revised their conclusions

~~*"measuring CPV with the current experimental sensitivity is a clear sign of NP"*~~

Standard Model Predictions

- The Standard Model predictions on mixing and CP Violation parameters are affected by large uncertainties due to the difficulties in the computation of the dominant long-distance contributions:
  - computation of D-mixing diagrams is non perturbative (approximations holding in the B and K cases do not apply for charm)
  - the available computational power is not enough for lattice QCD



[IJMP A21, 5686 (2006)]

Current Theoretical Approaches

1. D^0 mixing and indirect CP Violation
    - employ a *parameterization* that is appropriate for the level of precision expected in the *BelleII*/LHCb-upgrade era
2. Flavour SU(3) analysis of direct CPV and rates in $D \to PP$ and $D \to VP$ decays
    - infer the presence of NP in direct CPV measurements using SM SU(3) relations
    - quantifying SU(3) violation in $D \to PP, VP$ decays with increasing experimental precision can improve upper bound estimates of SM mixing CP Violation
3. Relatively clean opportunities for NP in leptonic and semileptonic decays
    - lattice QCD input needed (bonus: feedbacks to the lattice theory community)

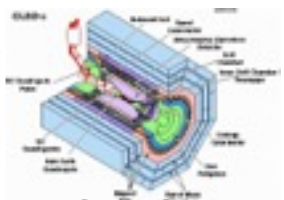
> *need of experimental inputs*
>
> *theory needs experimental inputs not only to check the final predictions but also to check the model hypothesis!*

Recent Charm Results

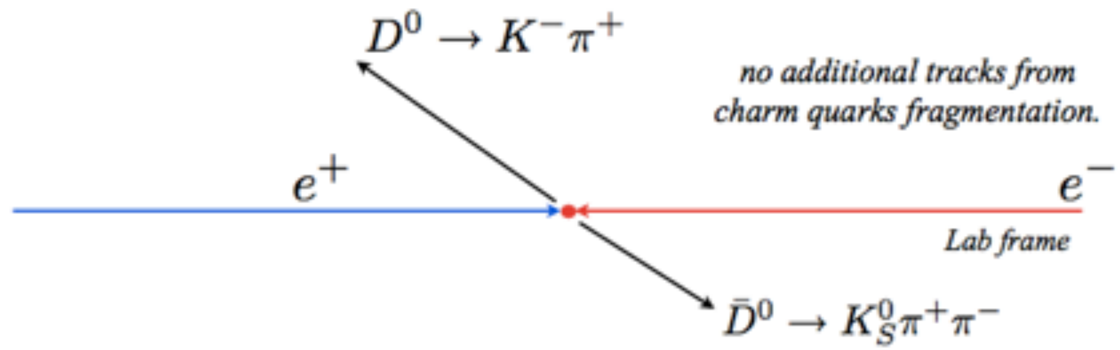
A Selection of Charm Experiments

threshold production

BESIII



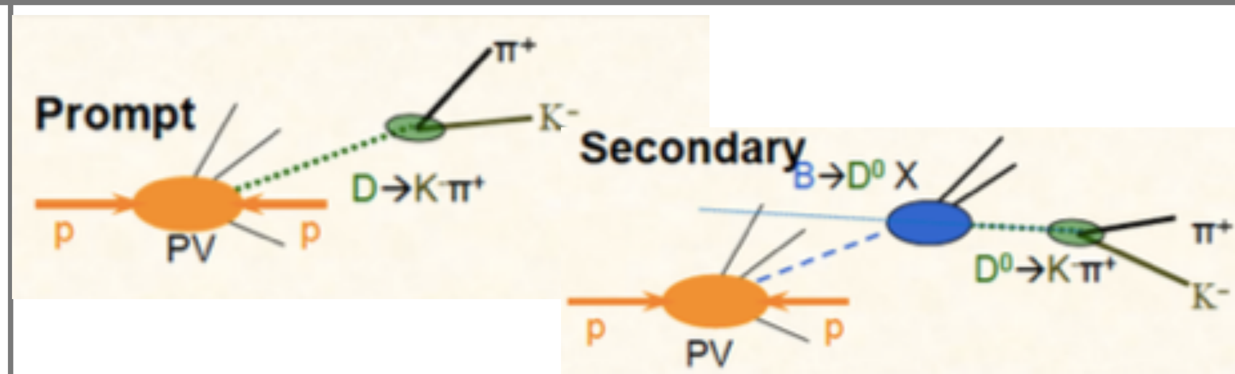
CLEO-c



- ✓ extremely clean environment
- ✓ pure D-beam, almost no bkg
- ✓ quantum coherence
- ◉ no CM boost, no T-dep analyses

hadron colliders

CDF II, LHCb, DØ



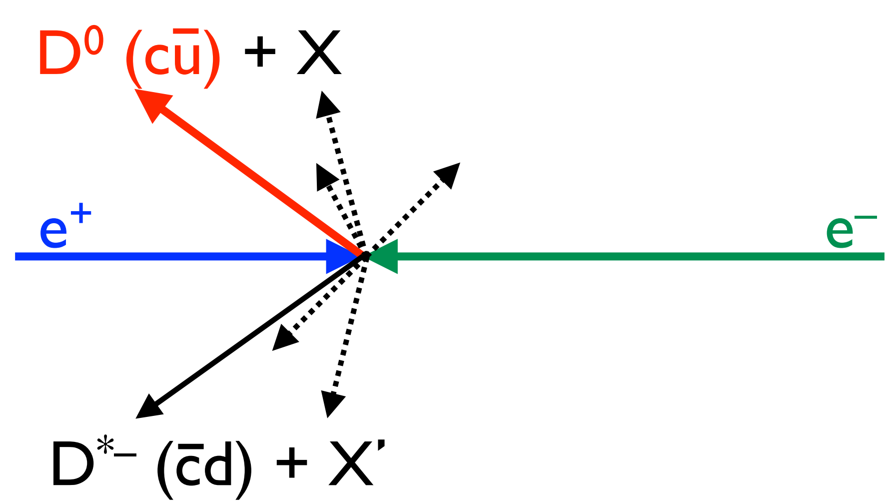
- ✓ large production cross-section
- ✓ large boost: excellent time res
- ◉ dedicated trigger required
- ◉ hard to do neutrals and neutrinos

B-Factories

BELLE, BaBar

high-luminosity B-Factory

Belle II



- ✓ clean event environment
- ✓ high trigger efficiency
- ✓ high-efficiency detection of neutrals
- ✓ many high-statistics control samples
- ✓ time-dependent analysis
- ◉ smaller cross-section than hadron colliders

A Selection of Charm Observables

CP Violation

time-integrated A_{CP}, ΔA_{CP} and T-odd asymmetries

- $D^0 \to K_S\pi^0, \pi^0\pi^0, K^+K^-, \pi^+\pi^-$
- $D^0 \to K^+K^-\pi^+\pi^-, \pi^+\pi^-\pi^0, K_SK_S$
- $D^+ \to K_S\pi^+, K_SK^+, \pi^+\pi^0$
- $D_s^+ \to K_S\pi^+, K_SK^+$ …

mixing & indirect CPV

x, y, $|q/p|$, $A_\Gamma/\Delta Y$, $\arg(q/p)$, R_M

- $D^0 \to K_S\pi^+\pi^-$
- $D^0 \to K^+K^-, \pi^+\pi^-, K^+\pi^-$
- $D^0 \to \pi^+\pi^-\pi^0$ …

rare/forbidden decays

cross sections

- $D^0 \to$ invisible (γ)
- $D^0 \to e^\pm\mu^\mp$
- $D^0 \to \mu^+\mu^-, e^+e^-$ …

(semi)leptonic & radiative decays

branching ratios, f_D

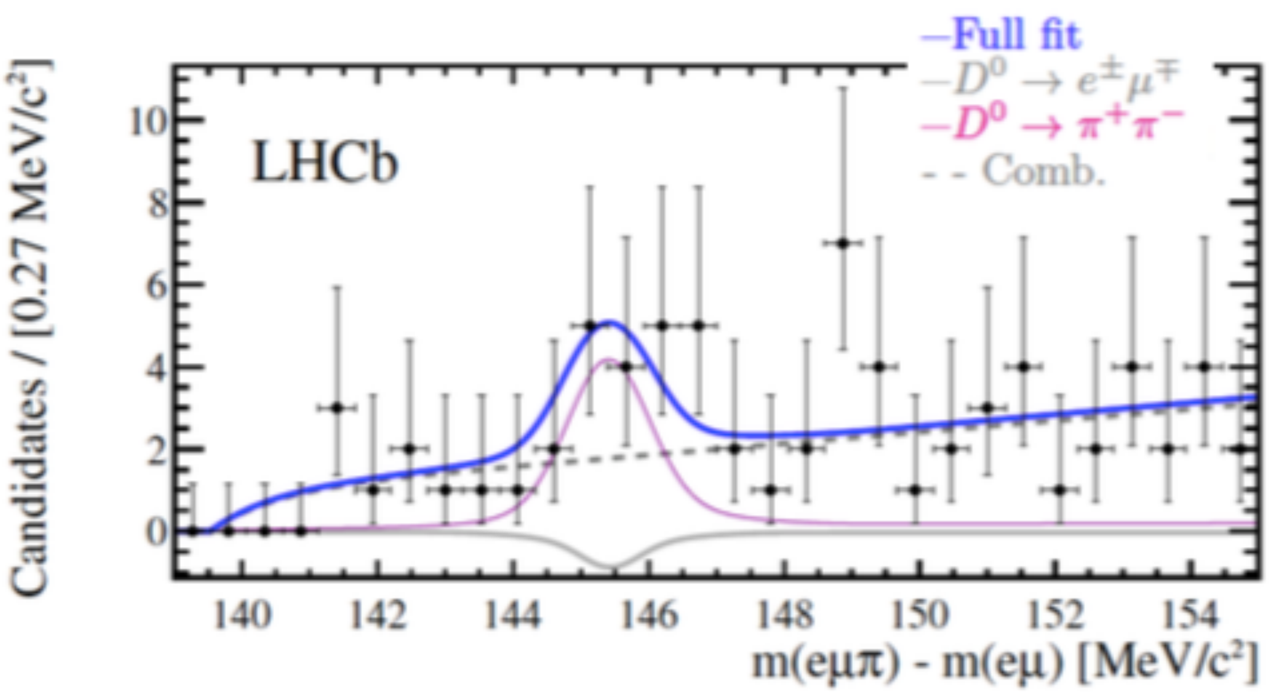
- $D^+ \to \pi\ell\nu, K\ell\nu, K^*\ell\nu$
- $D_s^+ \to \pi\ell\nu, K\ell\nu, K^*\ell\nu$
- $D^0 \to \omega\gamma, \rho\gamma, \gamma\gamma$ …

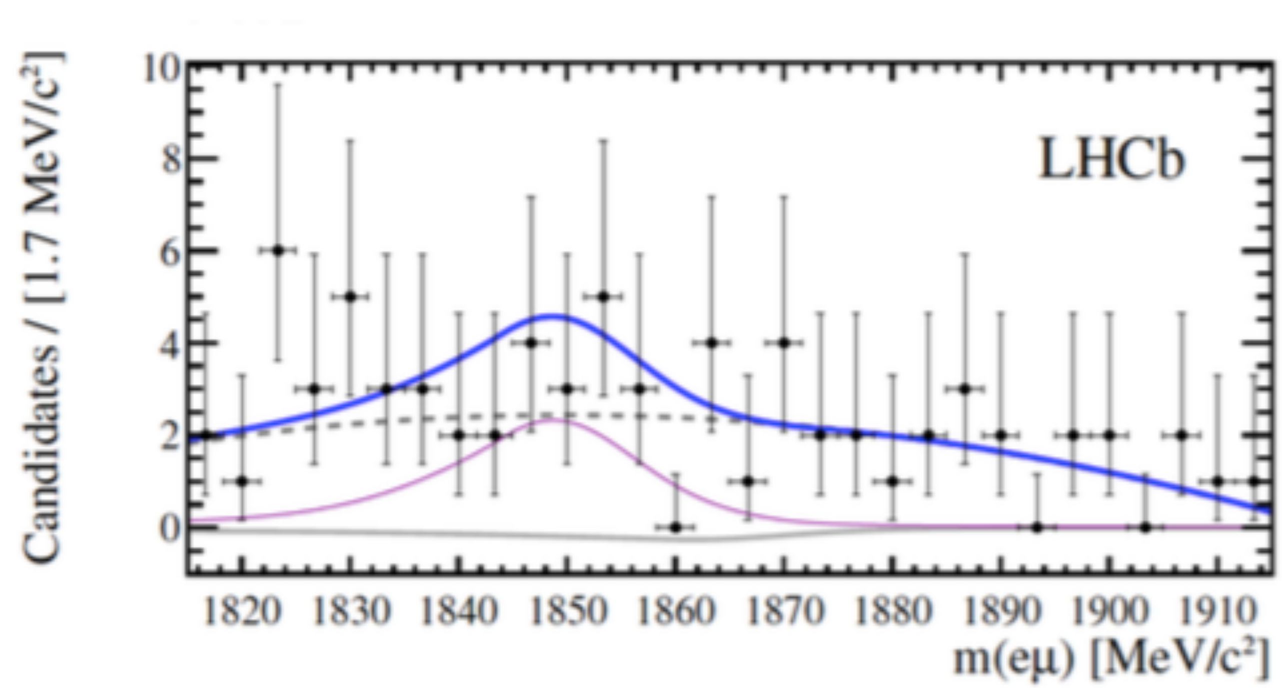
NOTE: the displayed list of channels is only a selection

Search for $D^0 \to e^\pm \mu^\mp$

LHCB-PAPER-2015-048
1+2 fb^{-1} @ 7,8 TeV

- ➡ The decay is forbidden: lepton flavour is not conserved
- ➡ Several models beyond-SM predict it with a BR of the order of 10^{-6}
- ➡ Use D^*-tagged D^0 mesons and normalize to the $D^0 \to K\pi$ channel





- ➡ Set the world best limit and constrains the parameter space in some leptoquark models.

$$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 1.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

CP Violation Observables

direct CPV (final state dep.) + indirect CPV (for D^0 only)

➡ CP Violation in the decay if $|A_f| \neq |\bar{A}_{\bar{f}}|$

- need at least 2 amplitudes with different strong and weak phases, the observables are in form of asymmetries:

$$A_{CP}(f) = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} \quad \text{or} \quad A_D^f = \frac{|A_f/\bar{A}_f|^2 - |\bar{A}_{\bar{f}}/A_{\bar{f}}|^2}{|A_f/\bar{A}_f|^2 + |\bar{A}_{\bar{f}}/A_{\bar{f}}|^2}$$

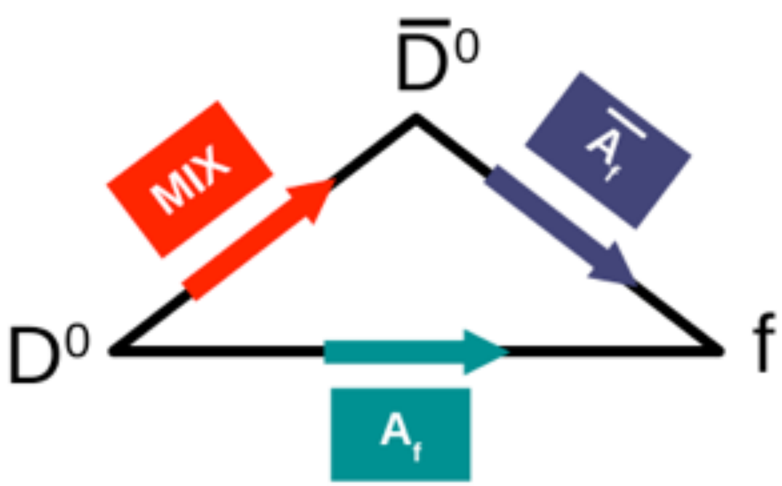
indirect CPV

➡ CP Violation in the mixing if $R_M = \left|\frac{q}{p}\right| \neq 1$ or $A_M = \frac{R_M^2 - R_M^{-2}}{R_M^2 + R_M^{-2}}$

- probability of $D^0 \rightarrow \bar{D}^0$ is different than the CP-conjugate $D^0 \rightarrow \bar{D}^0$

direct CPV + indirect CPV

➡ CP Violation in the interference between decays with and without mixing:



if $\phi_f \neq 0$ where $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = \left|\frac{q}{p}\frac{\bar{A}_f}{A_f}\right| \exp\left[i(\delta_f + \phi_f)\right]$

strong + weak phase

$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

➡ The combination of A_{CP} enhances the sensitivity to CPV

➡ First LHCb measurement used $D^{*+} \to D^0 \pi^+$ to tag of the D^0 flavour: PRL108, 111602 (2012)

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})]\%$$ ★ 3.5σ evidence of CPV

➡ Second measurement done with with muon tagged D^0: $B \to D^0 \mu^- X$ Phys.Lett.B723 33 (2013)

- $1\,\text{fb}^{-1}$ @7TeV, different trigger wrt D^{*+} tagged analysis

$$\Delta A_{CP} = (0.49 \pm 0.30\,(\text{stat}) \pm 0.14\,(\text{syst}))\%$$ ★ no evidence of CPV

➡ Update of the muon tagged analysis, also the single asymmetries are provided

- $1\,\text{fb}^{-1}$ @7TeV + $2\,\text{fb}^{-1}$ @8TeV LHCb-PAPER-2014-013

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

$$A_{CP}(\pi^-\pi^+) = (-0.20 \pm 0.19\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

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

977/fb

$$A_{CP}^{KK} = (-0.32 \pm 0.21 \pm 0.09)\%$$
$$A_{CP}^{\pi\pi} = (+0.55 \pm 0.36 \pm 0.09)\%$$
$$\Delta A_{CP} = (-0.87 \pm 0.41 \pm 0.06)\%$$

BELLE

➡ Last update of the D^{*+} tagged analysis

- $1\,\text{fb}^{-1}$ @7TeV + $2\,\text{fb}^{-1}$ @8TeV PRL 116, 1191601 (2016)

$$\Delta A_{CP} = [-0.10 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})]\%$$

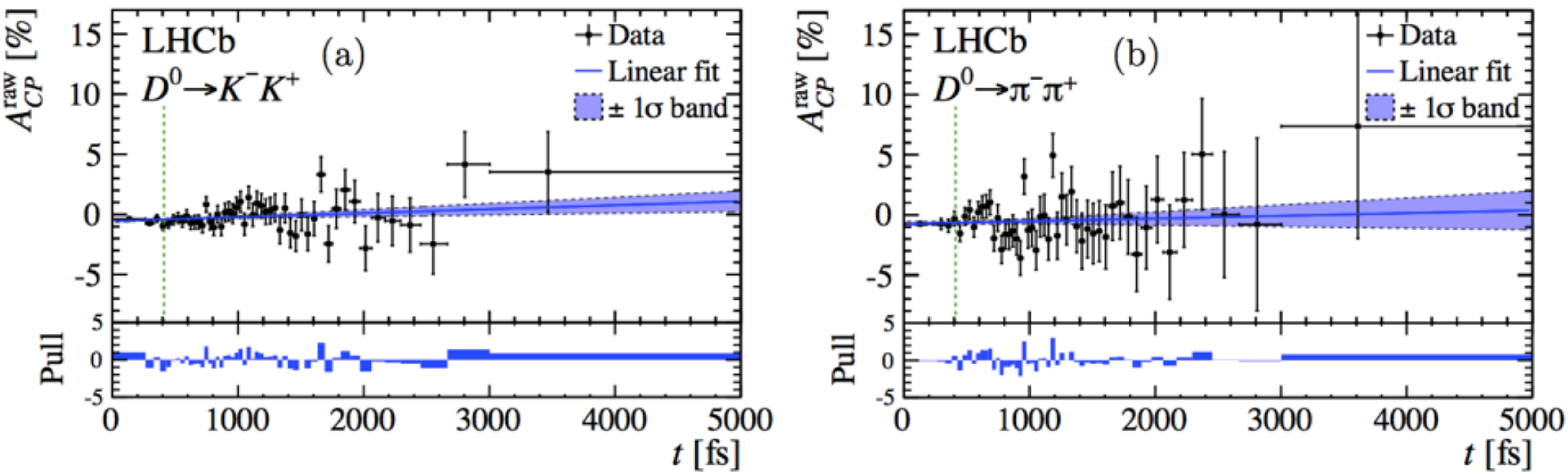
most precise measurement of a time-integrated CP asymmetry in the charm sector from a single experiment

Indirect CPV in $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$

PRL 116 (2016) 191601
$3\ fb^{-1}$ @ 7,8 TeV

- Determine D^0 flavour using $B \to D^0 \mu^- X$ decays
- Simultaneous fit to D^0 and $\bar{D}^0$ mass distributions in each of the 50 bins of the decay time. Evaluation of the raw A_{CP} in each bin.
- Determine A_Γ by a χ^2 fit to the time dependent asymmetry: $A_{CP}(t) \approx A_{CP}^{dir} - A_\Gamma \frac{t}{\tau}$

2.34×10^6 events | 0.79×10^6 events



$$A_\Gamma(K^-K^+) = (-0.134 \pm 0.077\ ^{+0.026}_{-0.034})\%$$
$$A_\Gamma(\pi^-\pi^+) = (-0.092 \pm 0.145\ ^{+0.025}_{-0.033})\%$$

no evidence of indirect CPV
precision reaching the sub-‰ level

$$A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0} - \hat{\Gamma}_{\bar{D}^0}}{\hat{\Gamma}_{D^0} + \hat{\Gamma}_{\bar{D}^0}}$$

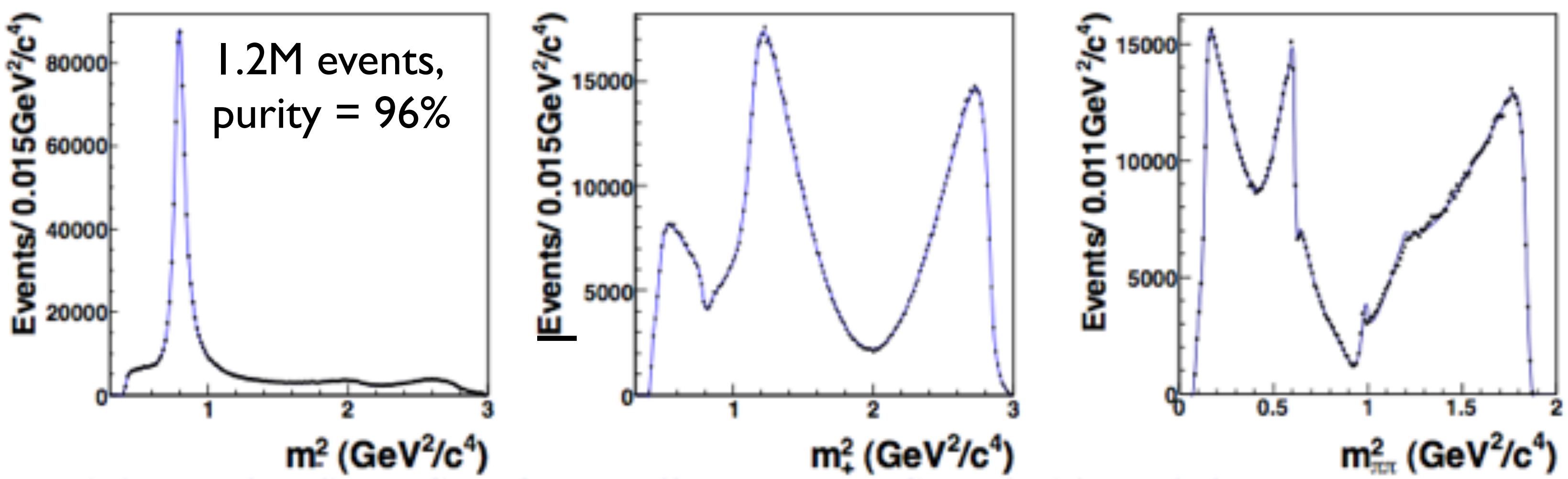
Time-Dependent Dalitz Plot $D^0 \to K_S \pi^+ \pi^-$

PRD 89, 09110(R) (2014)
921 fb^{-1}

- directly sensitive to the mixing and the CPV parameters: x, y, $|\lambda_f|$ and $\arg(\lambda_f)$ (assuming no direct CPV). Tag the D^0 flavour with $D^{*+} \to D^0\pi^+$ decays.
- Mixing and CPV modify the decay time distribution over the Dalitz Plot:

$$|\mathcal{A}|^2 \propto |A_f|^2 e^{-\Gamma t}\left[\frac{1+|\lambda_f|^2}{2}\cosh(y_D\Gamma t) + \frac{1-|\lambda_f|^2}{2}\cos(x_D\Gamma t) - Re\lambda_f \sinh(y_D\Gamma t) + Im\lambda_f \sin(x_D\Gamma t)\right]$$

- Use a *model* $A_f(m^2_+, m^2_-)$ to describe the interference of resonances over the Dalitz Plot:



Dalitz Plot fit projections
13 resonances taken into account, extract magnitude and phases for each of them

- A time-dependent fit to the Dalitz Plot distribution allows to extract:
  - an additional systematic error is associated to the particular choice of the DP model

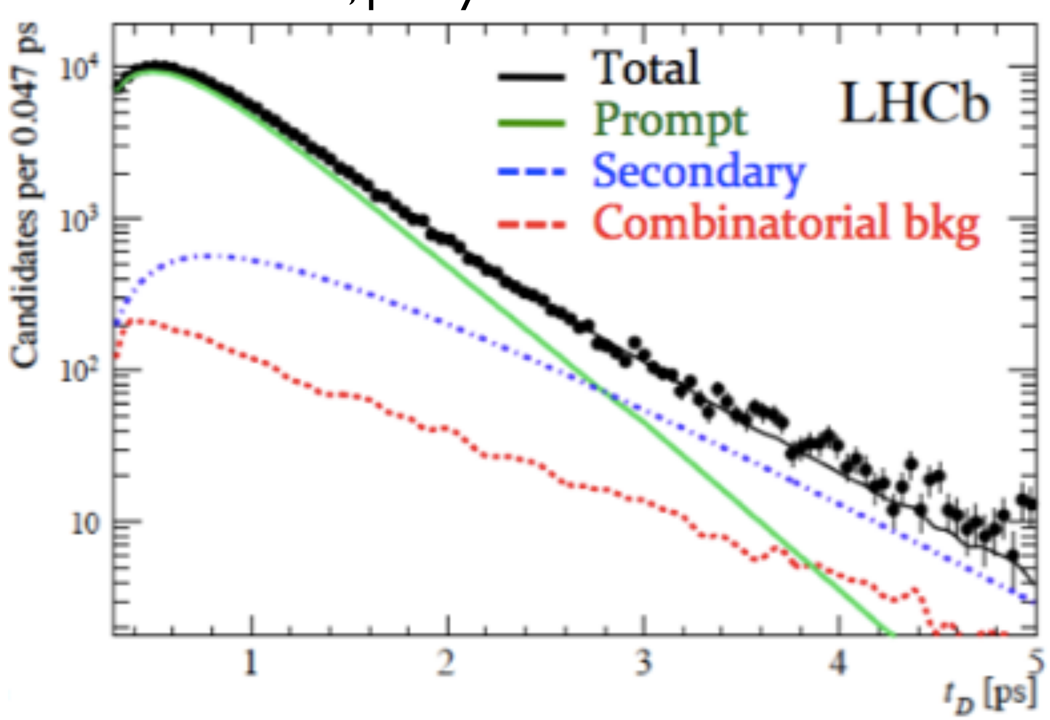
Fit type	Parameter	Fit result
No *CPV*	$x(\%)$	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$
CPV	$x(\%)$	$0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07}$
	$\lvert q/p \rvert$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
	$\arg(q/p)(°)$	$-6 \pm 11 \pm 3^{+3}_{-4}$

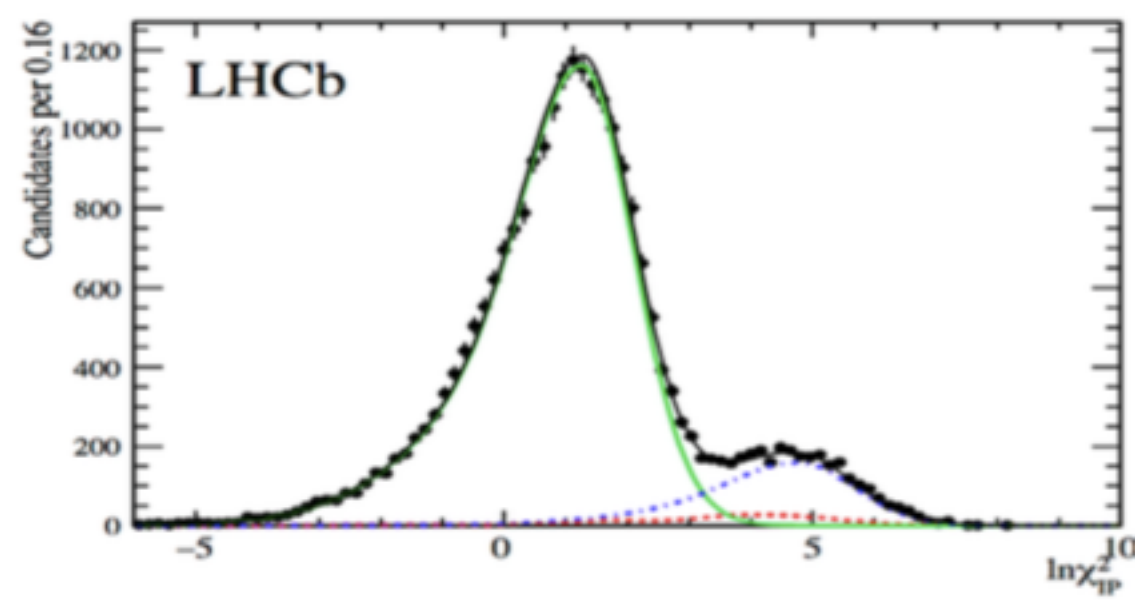
Time-Dependent Dalitz Plot $D^0 \to K_S \pi^+ \pi^-$

JHEP 04 (2016) 033
1 fb^{-1} @ 7 TeV

- Use a *model-independent* approach
  - DP divided in 16 bins with constant strong phase difference
  - constrain hadronic parameters (T_i, c_i, s_i) to values measured by CLEO [PRD 82 (2010) 112006]
  - Time-Dependent decay rate (assuming no CPV): $\mathcal{P}_{D^0} = e^{-\Gamma t}\left[T_i - \Gamma t\sqrt{T_i T_{-i}}\left(y c_i + x s_i\right)\right]$
- use $D^{*+} \to D^0 \pi^+$ decays and simultaneously fit DP bins (Δm, m_D) to separate signal from background and in (t_D, $\ln(\chi^2_{(IP)})$) to distinguish prompt D from D from B decays

178k events, purity = 97.4%

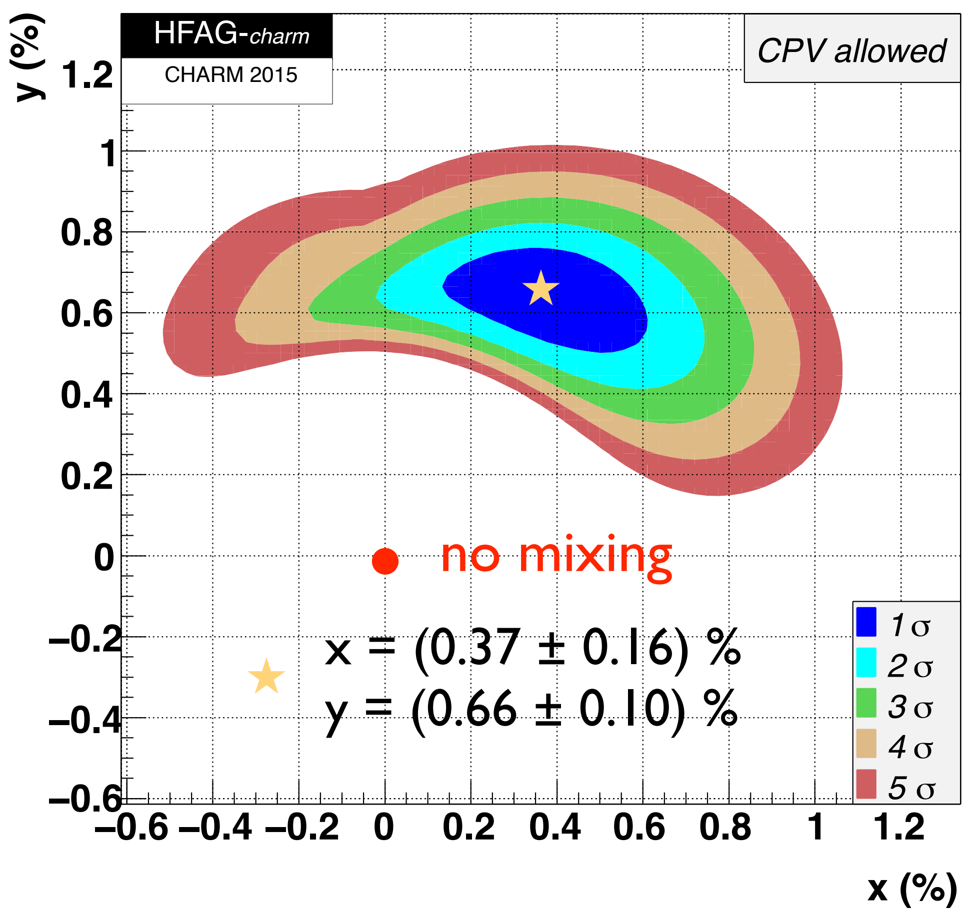




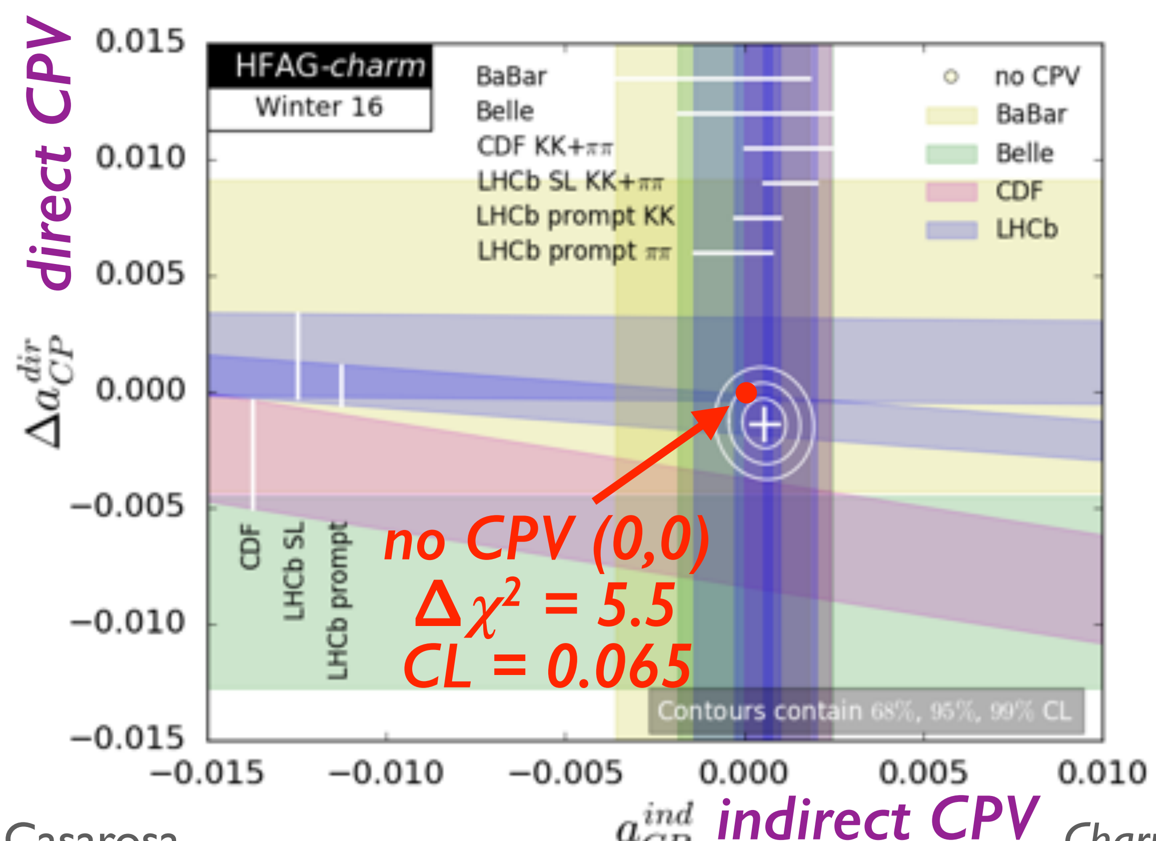
this is the *first* model-independent measurement of the mixing parameters (assuming no CPV)

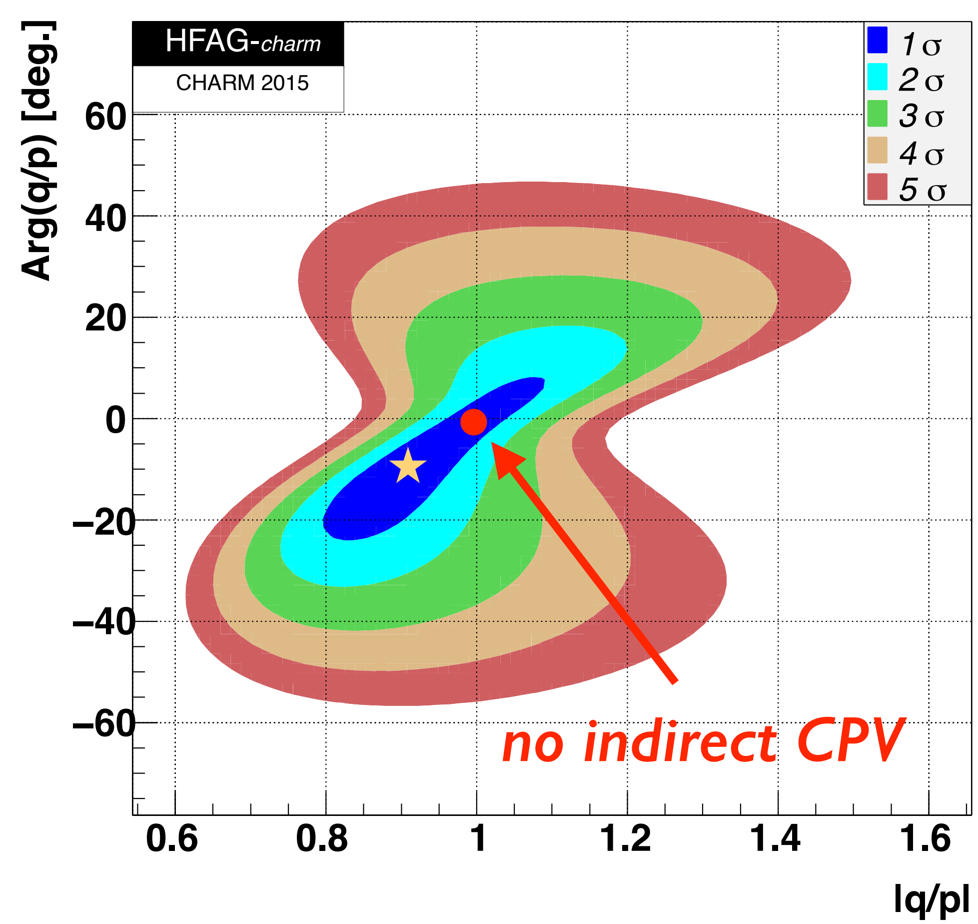
$x = (0.86 \pm 0.53 \pm 0.17)\%$
$y = (0.03 \pm 0.46 \pm 0.13)\%$

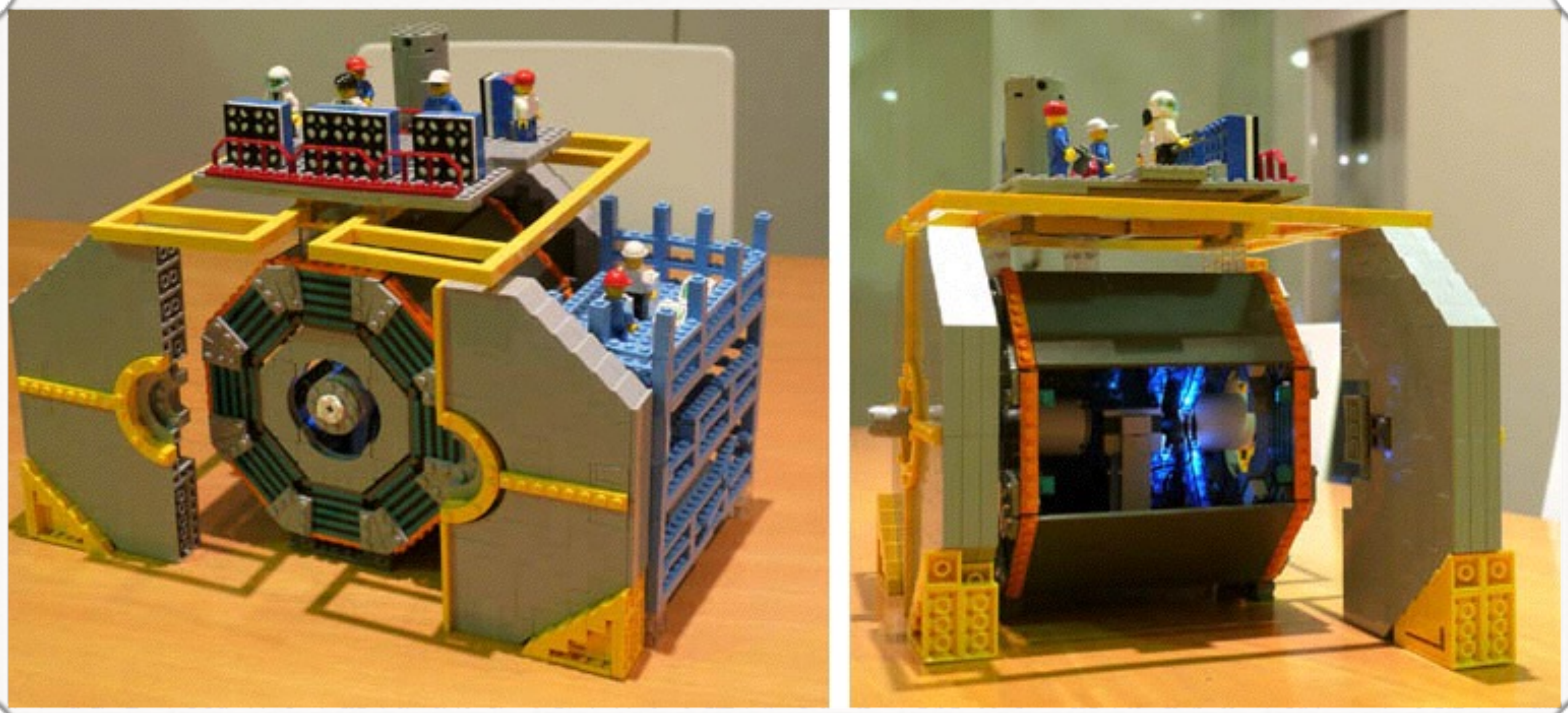
Experimental World Averages



- Mixing have been experimentally established, the mixing parameter *x* is the less known
- No clear evidence of direct CPV
- No hints of indirect CPV







Belle II

High-Luminosity Asymmetric B Factory

- Target luminosity is $\mathscr{L} = 8\times10^{35}\ \mathrm{cm^{-2}s^{-1}}$ (x40 w.r.t. BELLE)
- Achievable in the *nano-beam scheme* (P. Raimondi for SuperB)
  - double beam currents
  - squeeze beams @ IP by 1/20

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

- Lorentz factor
- beam current
- beam-beam parameter
- geometrical reduction factors
- beam aspect ratio at the IP
- vertical beta-function at the IP

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
beam energy	E_b	3.5	8	4	7	GeV
CM boost	$\beta\gamma$	0.425		0.28		
half crossing angle	φ	11		41.5		mrad
horizontal emittance	ε_x	18	24	3.2	4.6	nm
emittance ratio	κ	0.88	0.66	0.37	0.40	%
beta-function at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam parameter	ξ_y	129	90	0.0881	0.0807	
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		μm
Luminosity	$\mathscr{L}$	2.1×10^{34}		8×10^{35}		$\mathrm{cm^{-2}s^{-1}}$

High-Luminosity Asymmetric B Factory

- ➡ Target luminosity is $\mathscr{L} = 8\times10^{35}\ \mathrm{cm^{-2}s^{-1}}$ (x40 w.r.t. BELLE)
- ➡ Achievable in the *nano-beam scheme* (P. Raimondi for SuperB)
  - double beam currents
  - squeeze beams @I[illegible]

Lorentz factor

beam

beam-beam

$L = \frac{\gamma}{2e r_e} \ldots$ [illegible]

beam aspect [illegible] at the IP

vertical beta-function at the IP

reduced CM boost

- reduced vertex separation, Δt resolution
- increased detector hermeticity

squeezed beams @ IP

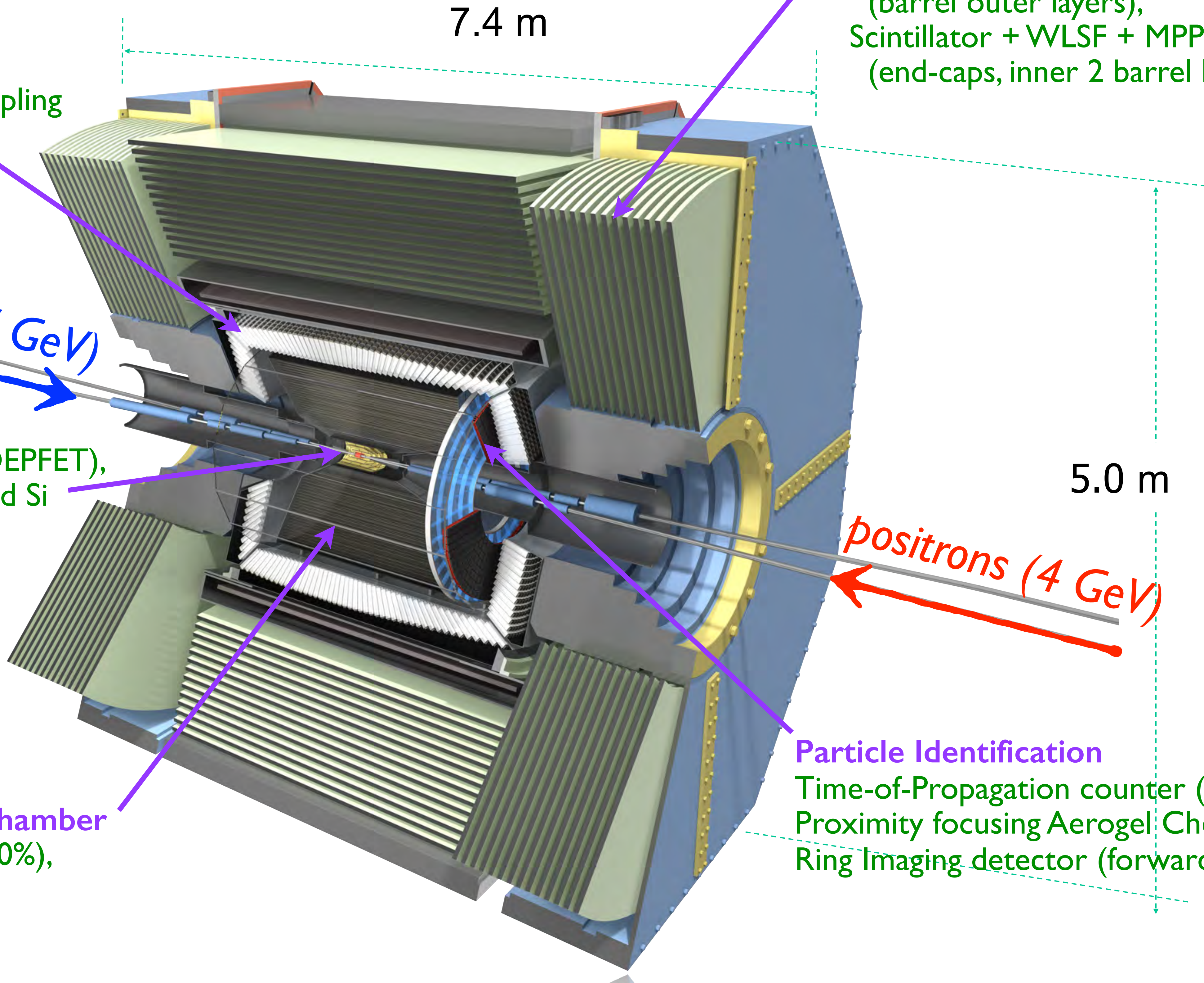
- greatly improved constraint for decay chain vertex fitting

parameters		KEKB LER	KEKB HER	SuperKEKB LER	SuperKEKB HER	units
beam energy		3.5	8	4	7	GeV
CM boost		0.425		0.28		
h[illegible]		[illegible]	[illegible]	41.5		mrad
ho[illegible]		[illegible]	24	3.2	4.6	nm
[illegible]		[illegible]	0.66	[illegible]37	0.40	%
b[illegible]		[illegible]	5.9	32/0.27	25/0.30	mm
[illegible]		[illegible]	1.19	3.6	2.6	A
bea[illegible]		[illegible]	90	0.0881	0.0807	
[illegible]		[illegible]	2	10/0.059		μm
[illegible]		[illegible]	[illegible]0^{34}	8×10^{35}		$\mathrm{cm^{-2}s^{-1}}$

x40 luminosity

- higher background rates (~10-20x)
  - detectors occupancy, radiation damage, fake hits, pile-up noise in the calorimeter
- higher event rate
  - higher trigger rate, DAQ, computing
- x40 produced signal events

The *BelleII* Detector



K_L & μ Detector
Resistive Plate Counter (barrel outer layers),
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM calorimeter
CsI(Tl), waveform sampling electronics

Vertex Detector
PXD: 2 layers Si pixels (DEPFET),
SVD: 4 layers double sided Si strips (DSSD)

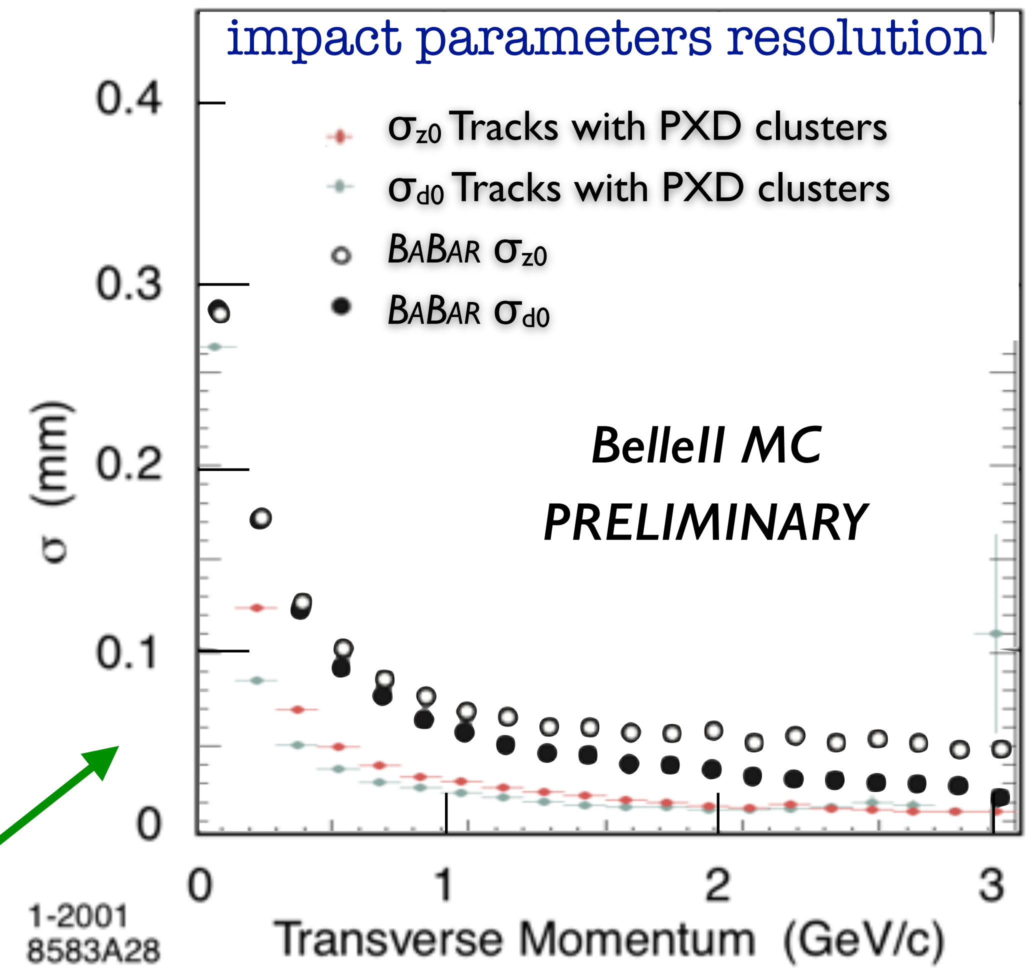
Particle Identification
Time-of-Propagation counter (barrel),
Proximity focusing Aerogel Cherenkov Ring Imaging detector (forward)

Central Drift Chamber
He(50%):C_2H_6(50%),
smaller cell size,
long lever arm,
fast electronics

Belle II Perfomance Improvements

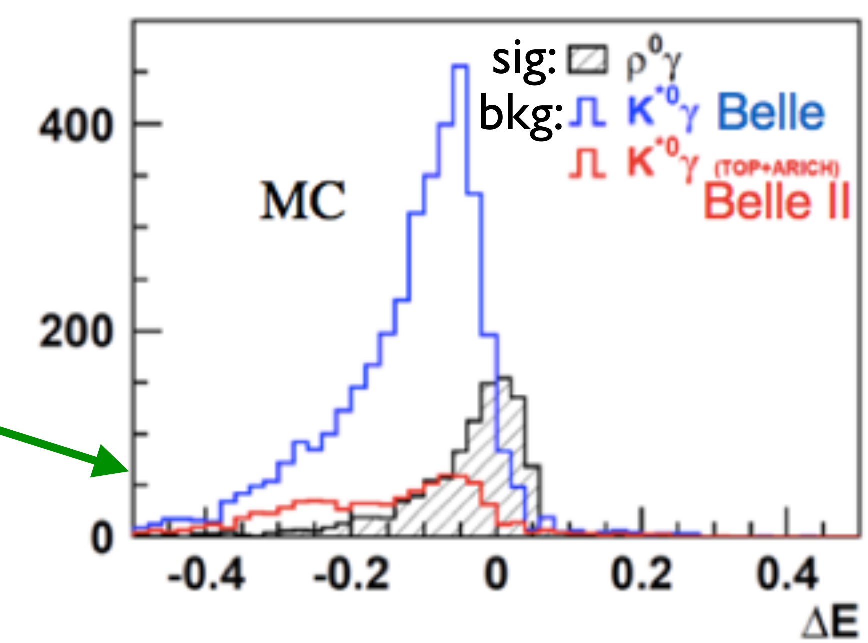
➡ B-Factory advantages over hadron collider detectors:

- clean event environment
- high trigger efficiency
- high-efficiency detection of neutrals (γ, π^0, η, η', …)
- many control samples to study systematics
- good kinematic resolution (Dalitz plots analysis)
- missing energy and missing mass analysis are straightforward (for B physics)



IMPROVEMENTS wrt Belle

- IP and secondary vertex resolution
- K_S and π^0 reconstruction
- K/π separation
- PID and μ ID in the end caps



Estimation of Expected Sensitivities

➡ The projections on the expected sensitivities are extrapolated from Belle measurements

$$\sigma_{BelleII} = \sqrt{(\sigma^2_{stat} + \sigma^2_{sys})\frac{\mathcal{L}_{Belle}}{50\ \mathrm{ab}^{-1}} + \sigma^2_{\mathrm{ired}}}$$

M. Staric, KEK FFW14

➡ we assume that most of the systematics scale with statistics

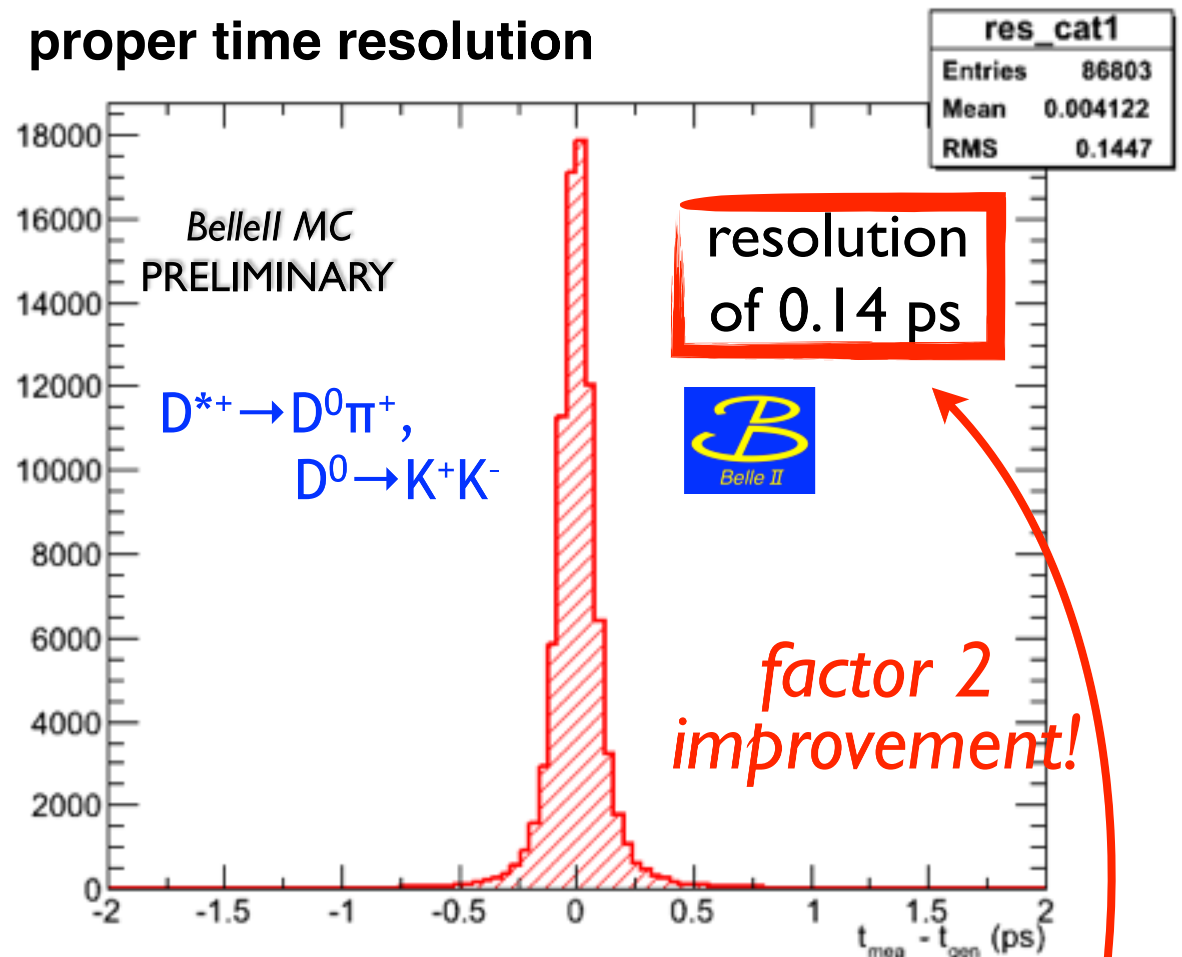
➡ There maybe (other) sources of systematic errors that do not scale with statistics, that show up only in very high statistics samples

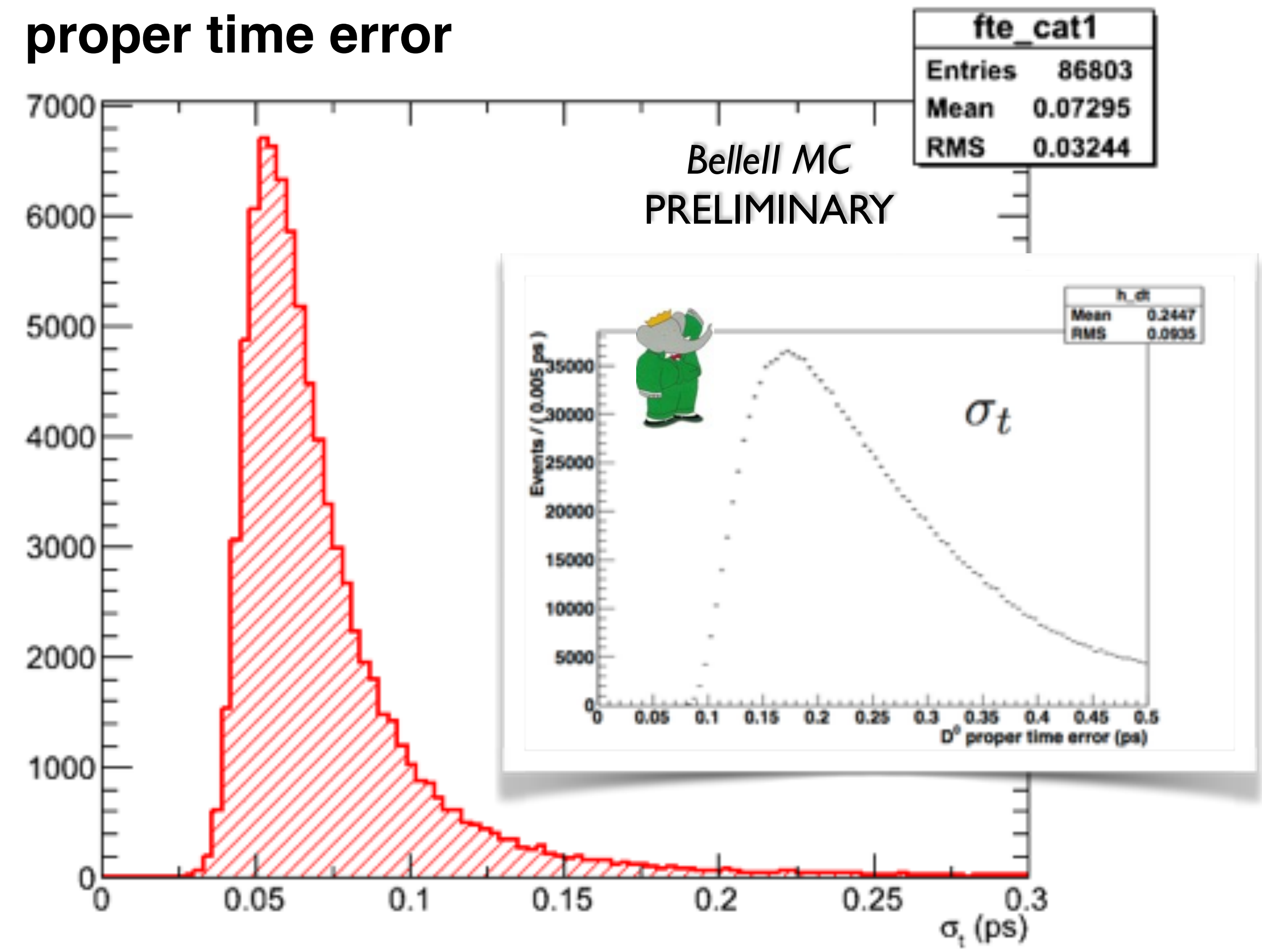
- *Belle II* will have high statistics control samples to keep them under control

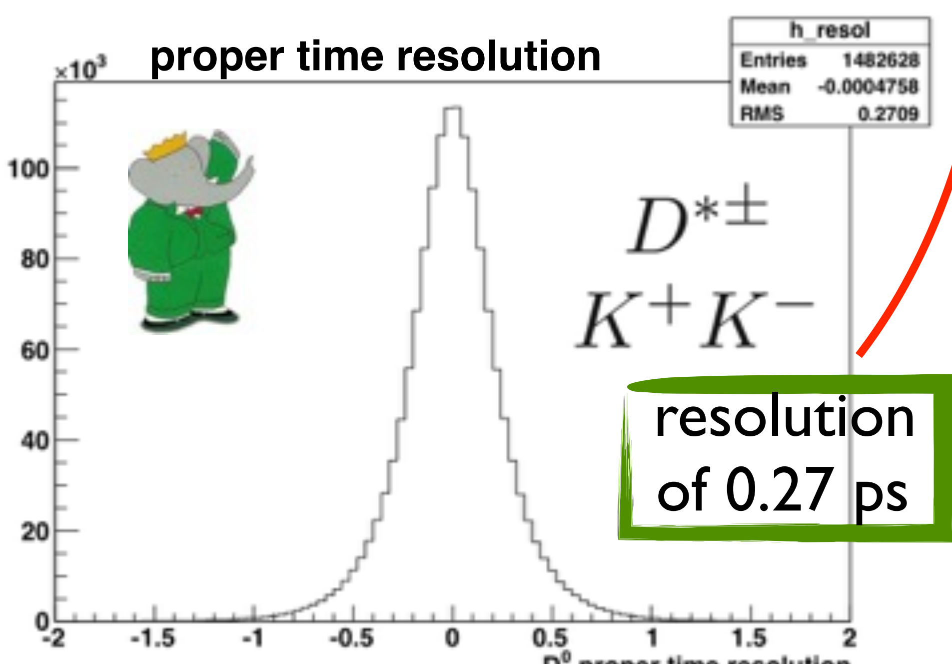
➡ The *detector improvements* w.r.t. Belle will be helpful, but their effect is *not included* in these extrapolations, unless otherwise stated

- increase hermiticity
- *increase K_S efficiency*
- *improve IP and secondary vertex resolution*
- improve K/π separation
- *improve π^0 reconstruction*
- add PID and μ ID in end caps

D^0 Proper Time: Resolution and Error







- ➡ **factor 2 improvement in the proper time resolution**
- ➡ factor 3.5 improvement in the estimation of σ_t
  - average σ_t = 0.07 ps VS 0.25 ps for *BaBar*
  - RMS σ_t = 0.03 ps VS 0.09 ps for *BaBar*
- ➡ factor 3 improvement in the D^0 proper time significance
  - average t/σ_t = 6 VS 2 for *BaBar*

results confirmed in $D^{*+} \to D^0\pi^+, D^0 \to \pi^+\pi^-$

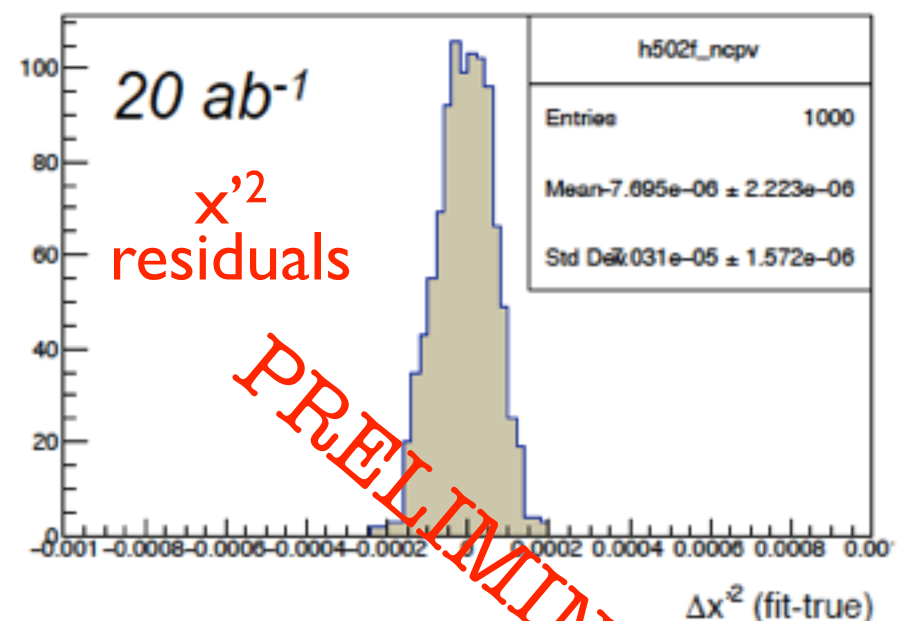
Estimation of Mixing and CPV Parameters

- Use the (almost) systematic-free measurement of Mixing and CPV in the WS $D^0 \to K^+\pi^-$ channel
  - generate $D^0 \to K^+\pi^-$ decays with mixing
  - smear decay times according to resolution (σ = 0.14 ps)
  - generate ensembles of 1000 experiments (438630 D^0 each - 50 ab^{-1})

$x' = x\cos\delta + y\sin\delta, \quad y' = y\cos\delta - x\sin\delta$

- ToyMC study #1: no CPV
  - fit decay time distribution for mixing parameters R_D, x'^2, y'
  - use same PDF for D^0 and $\overline{D}^0$ (convolved with a Gaussian resolution function)

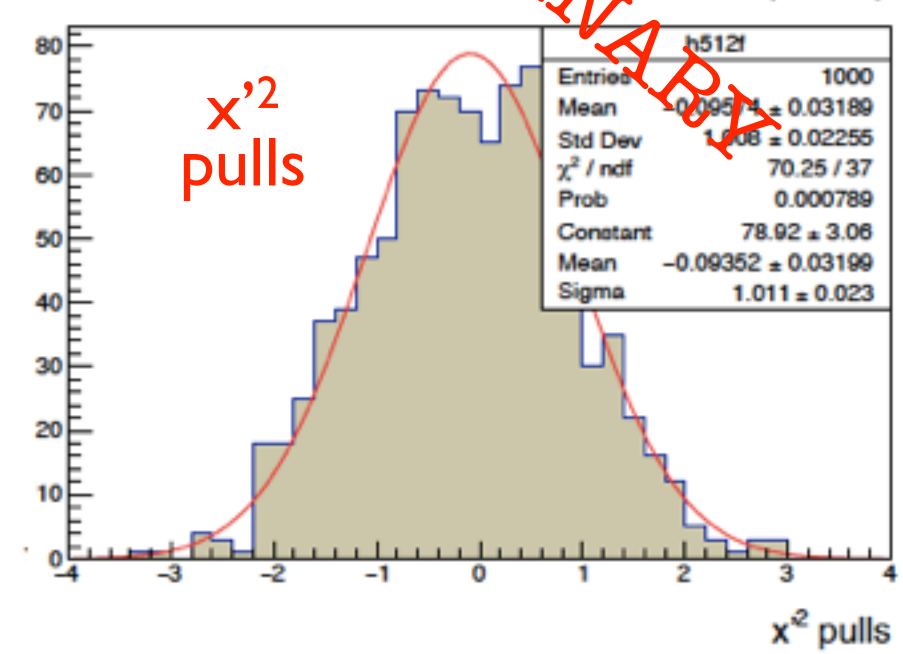
$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\bar{\Gamma} t}\left\{R_D + \sqrt{R_D}\, y'(\bar{\Gamma} t) + \frac{(x'^2 + y'^2)}{4}(\bar{\Gamma} t)^2\right\}$$



- ToyMC study #2: fitting for CPV
  - fit decay time distribution for mixing and CPV parameters R_D, x', y', $|q/p|$, ϕ (*sensitive to the sign of x'!*)
  - use different PDFs for D^0 and $\overline{D}^0$ (both convolved with a Gaussian resolution function)

$$D^0(t) = : e^{-\bar{\Gamma} t}\left\{R_D + \left|\frac{q}{p}\right|\sqrt{R_D}(y'\cos\phi - x'\sin\phi)(\bar{\Gamma} t) + \left|\frac{q}{p}\right|^2 \frac{(x'^2 + y'^2)}{4}(\bar{\Gamma} t)^2\right\}$$

$$\overline{D}^0(t) = : e^{-\bar{\Gamma} t}\left\{R_D + \left|\frac{p}{q}\right|\sqrt{R_D}(y'\cos\phi + x'\sin\phi)(\bar{\Gamma} t) + \left|\frac{p}{q}\right|^2 \frac{(x'^2 + y'^2)}{4}(\bar{\Gamma} t)^2\right\}$$



Impact on Mixing & CPV Observables

$$\sigma_{BelleII} = \sqrt{(\sigma^2_{stat} + \sigma^2_{sys})\frac{\mathcal{L}_{Belle}}{50\ \mathrm{ab}^{-1}} + \sigma^2_{\mathrm{ired}}}$$

estimated error on	current	Belle + BaBar	scaled	Toy MC with improved σ_t PRELIMINARY	
	HFAG	1.5/ab	50/ab	50/ab, no CPV	50/ab, CPV
x' (%)	–	(*) 0.98	(*) 0.45	(*) 0.22	0.15
x'^2 (%)	–	0.0195	0.009	0.0044	–
y' (%)	–	0.321	0.16	0.047	0.10
|q/p|	0.1	–	–	–	0.051
Φ (deg)	10	–	–	–	5.7

- ➡ *factor 3 improvement on x' and more than 50% improvement on y' with respect to the crude scaling with luminosity*
- ➡ *factor 2 improvement with respect to the current world-average on the CPV parameters, competitive with LHCb-upgrade*

(*) measurements are NOT sensitive to x', the error is computed from the error on x'^2, as $\sigma(x') = 2\sigma(x'^2)/x' = 50\ \sigma(x'^2)$

Prospects for $D^0 \to K_S\pi^+\pi^-$

Belle II NOTE: improvements in the proper ime resolution are not included!!

	Observable	Statistical	Systematic red.	Systematic irred.	Total
x	$x^{K_S\pi^+\pi^-}$ $[10^{-2}]$				
	976 fb^{-1}	0.19	0.06	0.11	0.20
	50 ab^{-1}	0.03	0.01	0.11	0.11
|q/p|	$\|q/p\|^{K_S\pi^+\pi^-}$ $[10^{-2}]$				
	976 fb^{-1}	15.5	5.2-5.6	7.0-6.7	17.8
	50 ab^{-1}	2.2	0.7-0.8	7.0-6.7	7.0-7.4
y	$y^{K_S\pi^+\pi^-}$ $[10^{-2}]$				
	976 fb^{-1}	0.15	0.06	0.04	0.16
	50 ab^{-1}	0.02	0.01	0.04	0.05
ϕ	$\phi^{K_S\pi^+\pi^-}$ [°]				
	976 fb^{-1}	10.7	4.4-4.5	3.8-3.7	12.2
	50 ab^{-1}	1.5	0.6	3.8-3.7	4.0-4.2

$$\sigma_{BelleII} = \sqrt{(\sigma^2_{stat} + \sigma^2_{sys})\frac{\mathcal{L}_{Belle}}{50\ \text{ab}^{-1}} + \sigma^2_{\text{ired}}}$$

- ➡ precision limited by the irreducible systematics related to the Dalitz Plot model
- ➡ final precision can be improved using a model-independent approach

LHCb upgrade arXiv:1208.3355

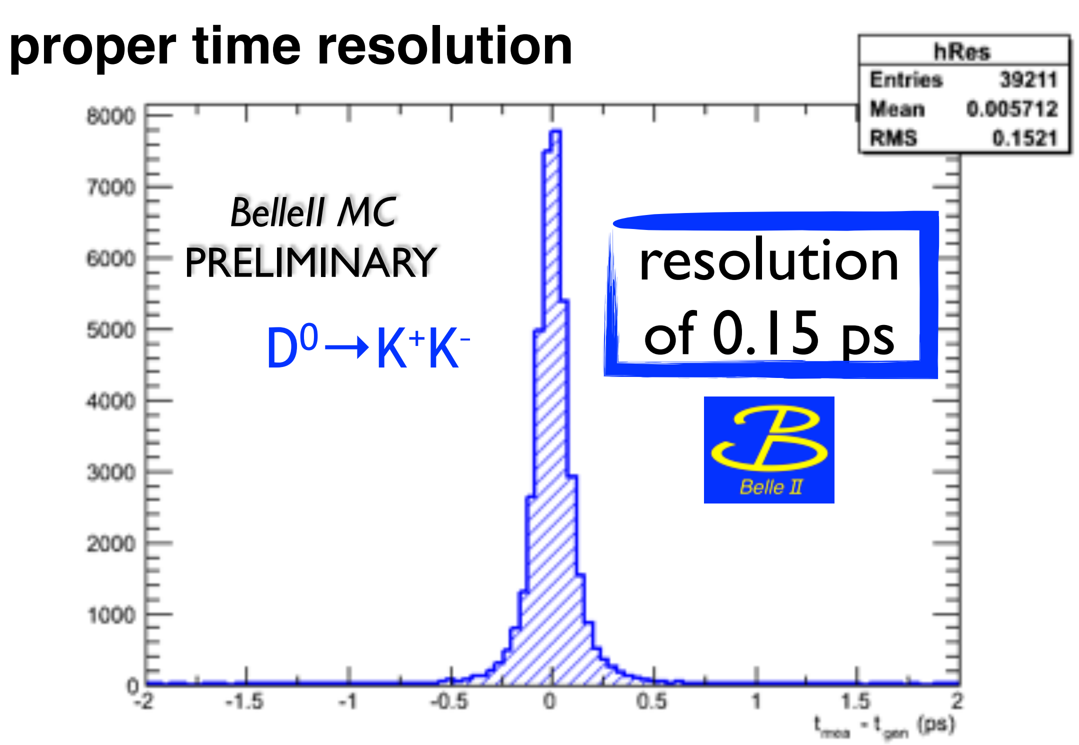
Parameter	Precision ($3\,fb^{-1}$)	Precision ($50\,fb^{-1}$)
x	2×10^{-3}	4×10^{-4}
y	2×10^{-3}	4×10^{-5}
$\|q/p\|$	0.2	0.04
ϕ	15°	3°

- *BelleII and LHCb expected precisions on ϕ are comparable*
- *statistical precision on |q/p| and x is comparable with LHCb predictions, systematics need to be reduced*

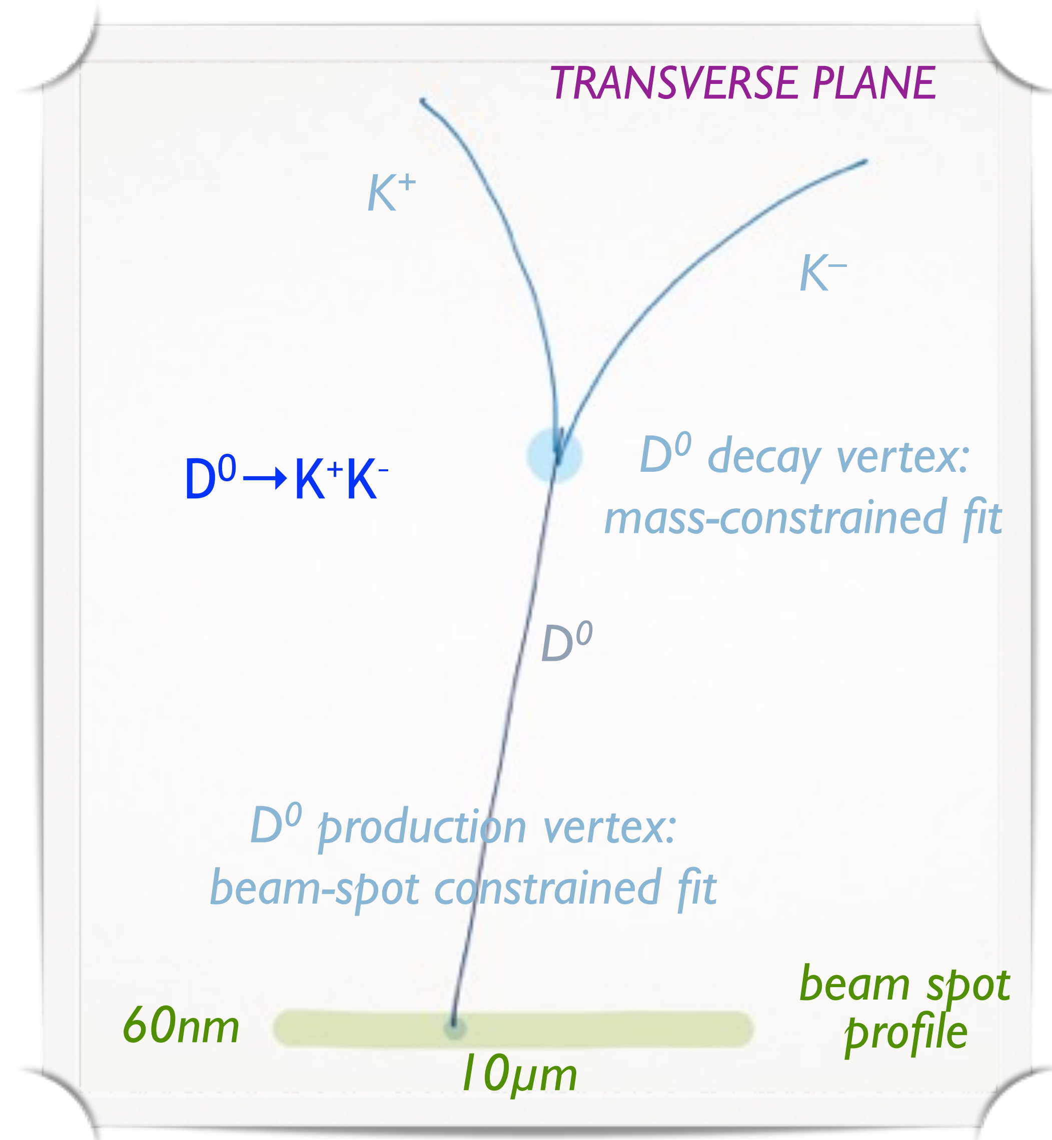
Proper Time Resolution for $e^+e^- \to D X$

➡ We can measure the proper time of D^0 coming directly from the hadronization of the charm quark with comparable precision.

➡ The flavour of the D^0 at production cannot be tagged in the standard way ($D^* \to D^0\pi$)



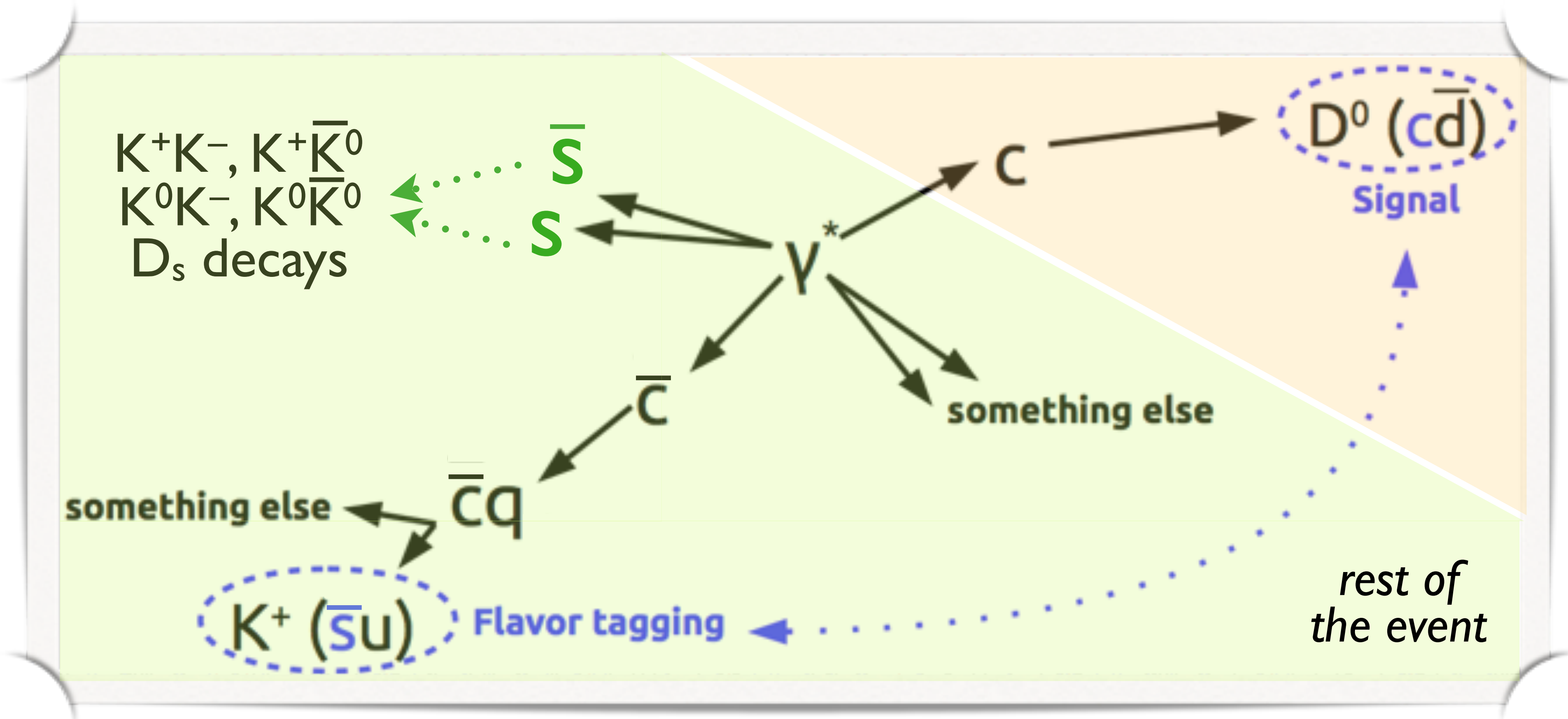
Is there a way to determine the flavour of the prompt D^0, i.e. not coming from a charged D^* decay?



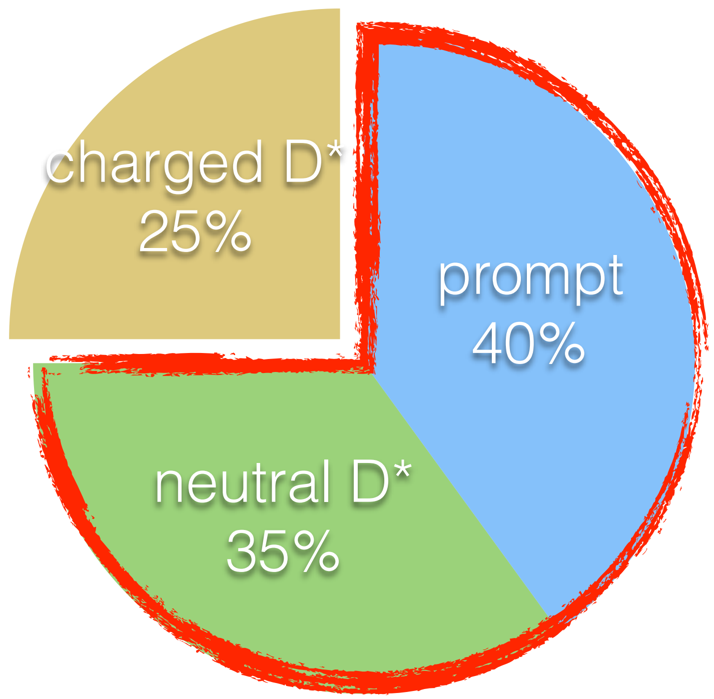
NOTE: the cartoon is not to scale

Prompt D^0 Flavour Tagging

- ➡ Can we recover at least a fraction of the 75% produced D^0 not coming from a charged D^* decay?
  - reconstruct the D^0 in the signal channel and define the rest of the event (ROE) as all the reconstructed particles that are not coming from the signal D^0 decay
  - select events with one single K in the ROE



D^0 mothers in $c\bar{c}$ events



Typical Correctly Tagging Events

$cc \to D^0 D^- X$, $D^0 \to$ signal ch

$D^- \to K^{*0} e^- \nu$; $K^{*0} \to K^+ \pi^-$

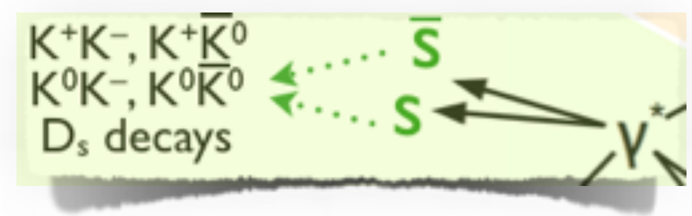
$cc \to D^0 \Lambda_c^- X$, $D^0 \to$ signal ch

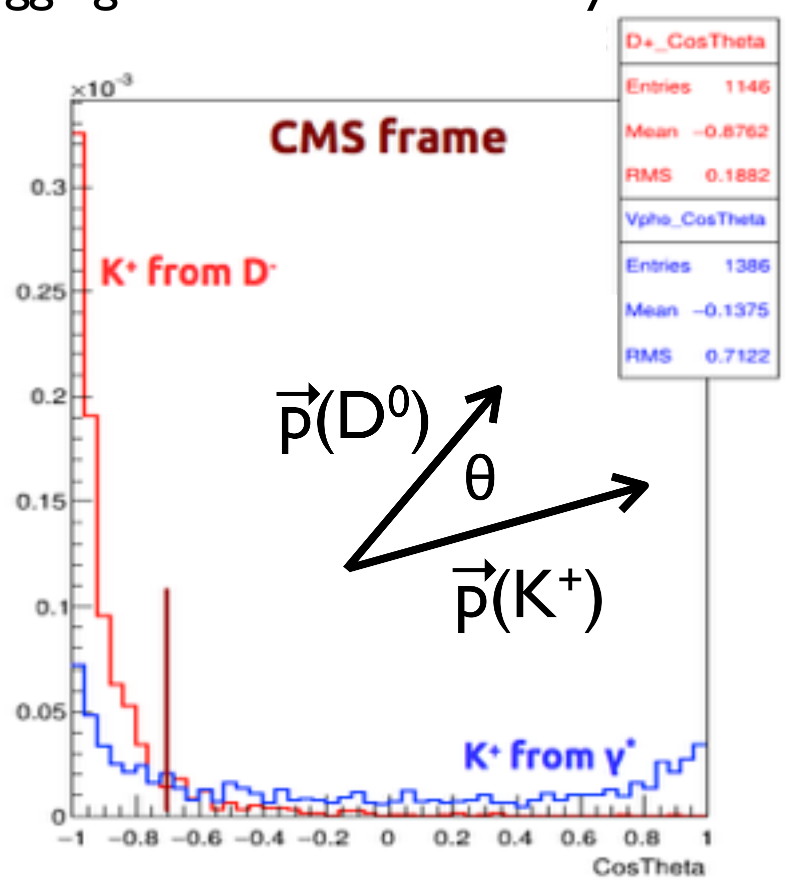
$\Lambda_c^- \to \Delta^{--} K^{*+}$; $K^{*+} \to K^+ \pi^0$

- ➡ flavour mis-tagging due to $c\bar{c}s\bar{s}$ when a K escapes reconstruction: these events introduce un-correlated charged kaons into the rest of the event
- ➡ irreducible mistag due to DCS decays of the rest of the event charmed meson or baryon

Selection and Results

- The non-trivial part of this reconstruction technique is the **selection of the tagging charged kaon**
  - too tight requirements would result in a miscount of K^+ in the ROE, too loose would result in a higher fraction of misidentified kaons, in both cases increasing the mistake levels.
  - **winning strategy** is to use a **two-step selection based on a BDT** with a first loose cut to reject most of the background and count the number of charged kaons, and a second tighter cut to reject fake kaons
- A considerable faction of the background is represented by tagging kaons from the direct hadronization of a strange quark coming from the fragmentation
  - tagging kaons are most likely back to back to the signal D^0





a cut at $\cos\theta<0.7$ rejects 66% of the mis-tagging K and 10% of the signal

Results obtained with BelleII full simulation(*)
- *tagging efficiency = 15%*
- *mistag probability = 5%*
- *expected D^0 sample = 60% of the one obtained with the D^* tagging reconstruction technique with an overlap of 3%*

a completely new tagging method has been developed:
- *increase of statistics with an additional D^0 sample,*
- *very useful to independently evaluate systematics*

(*) MC veto on K_S and K_L have been applied

Impact on the Statistical Error on A_{CP}

- Let's evaluate the statistical error on A_{CP} using the prompt D^0 with respect to what obtained using the D^* tagging technique

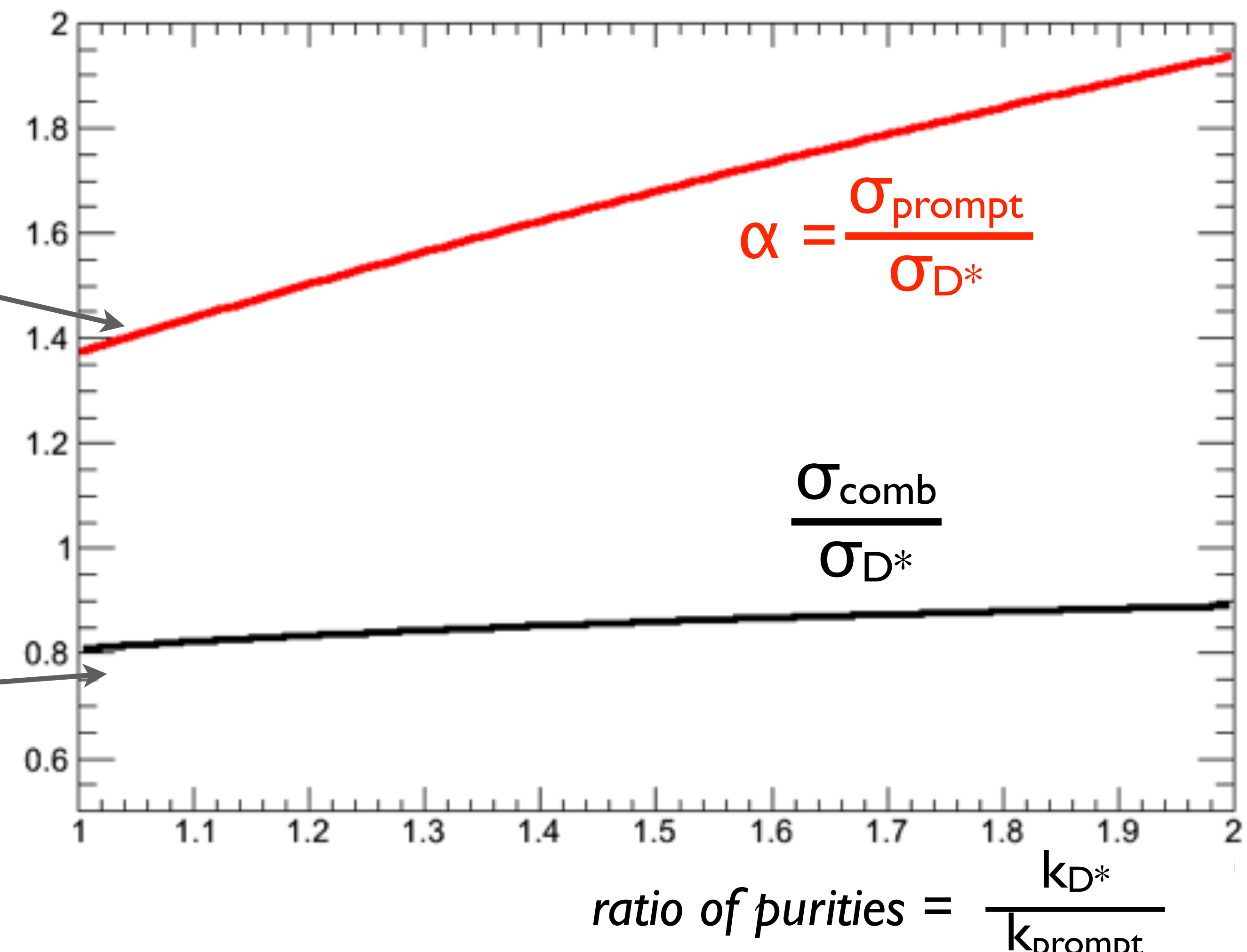
tagging method	tagging efficiency	mistag probability	available Ds	effective tagging efficiency	purity	A_{CP} statistical error
	ε_{tag}	ω	N	$Q = \varepsilon_{tag}(1-2\omega)^2$	channel dep.	σ_{stat}
D^*	80%	0,5%	x1	68%	k_{D^*}	σ_{D^*}
prompt	15%	5%	x3	12%	k_{prompt}	σ_{prompt}

- assuming the same D^0 reconstruction efficiency for both tagging methods:

$$\sigma_{prompt} = \sigma_{D^*}\sqrt{\frac{N_{D^*}}{N_{prompt}}\frac{k_{D^*}}{k_{prompt}}\frac{Q_{D^*}}{Q_{prompt}}}$$

- combining the statistical errors from the two measurements, under the assumption that the two D^0 samples are independent:

$$\sigma_{comb} = \sigma_{D^*}\frac{\alpha}{\sqrt{1+\alpha^2}}$$



reduction of 80% to 90% on the σ_{stat} on A_{CP} corresponding to 3 to 6 months of data taking at design luminosity

Prospects for CP Asymmetries

Belle II M. Staric @ KEK Flavour Factory Workshop 2014

mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 50 ab^{-1}	
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03	LHCb
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05	LHCb
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09	
$D^0 \to K_s^0\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.03	
$D^0 \to K_s^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07	
$D^0 \to K_s^0\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09	
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04	LHCb
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14	
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14	
$D^+ \to K_s^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03	
$D^+ \to K_s^0K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05	LHCb
$D_s^+ \to K_s^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29	LHCb
$D_s^+ \to K_s^0K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05	

- ➡ *Only the D^* tagging method is considered*
- ➡ A_{CP} precision will reach o(10^{-4}), better than the current theoretical predictions
- ➡ Other interesting channels not included: $D^+ \to \pi^+\pi^0$, $D^0 \to K_S K_S$, 3-body final states (DP analysis)

LHCb upgrade arXiv:1208.3355

Measurement	Current Precision	Precision (50 fb^{-1})
$D^0 \to K^+ K^-$	0.15% (3 fb^{-1}- SL)	0.03%
$D^0 \to \pi^+ \pi^-$	0.19% (3 fb^{-1}- SL)	0.03%
$D^+ \to \phi\pi^+$	0.14% (1 fb^{-1})	0.01%
$D^+ \to K_S^0 K^+$	0.14% (3 fb^{-1})	0.03%
$D_s^+ \to K_S^0 \pi^+$	0.17% (3 fb^{-1})	0.03%

(*) K_S efficiency may be lower in LHCb upgrade

- *BelleII can do lot's of channels, important for SU(3) analysis*
- *Belle II is favourited on measurements with neutrals in the final state, but will be competitive with LHCb anyway also on some channels with charged tracks in the final state*

Charm from B Decays

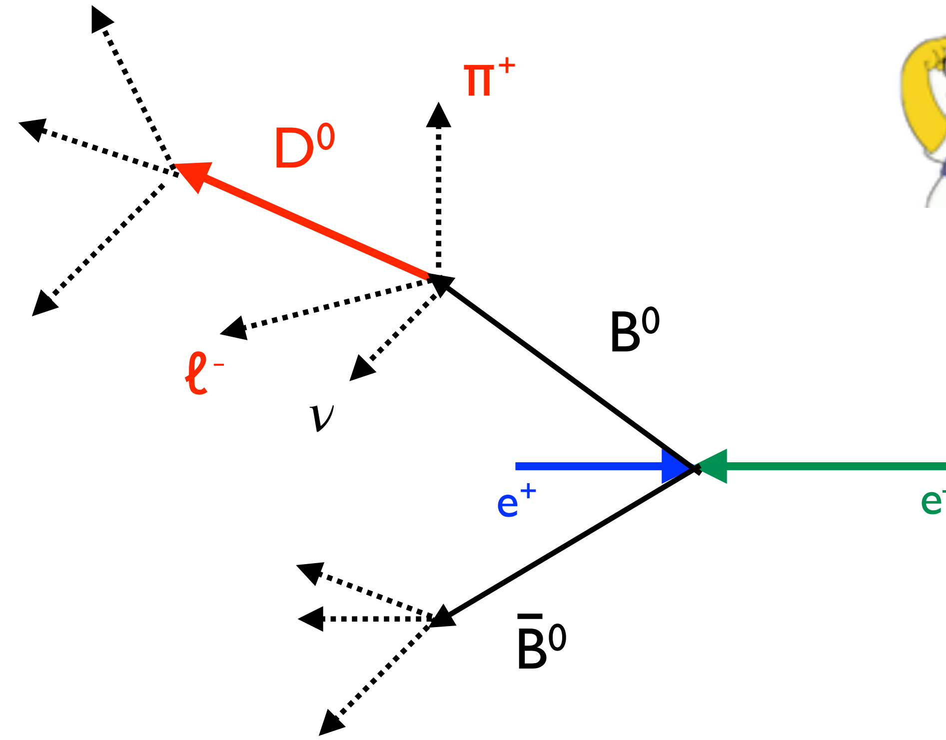
technique pioneered by BaBar

$B^0 \to D^{*+} \ell^- \nu;\ D^{*+} \to D^0 \pi^+$

Partial Reconstruction of the B assuming…

- ➡ B^0 is at rest in the center-of-mass of the $\Upsilon(4S)$ (p=380MeV/c)
- ➡ D^0 produced at rest in the center-of-mass of the D^{*+}, therefore:
  - $p(D^{*+}) = \alpha + \beta\, p(\pi_s)$
  - D^{*+} and π_s have the same direction

…allows to compute the M_ν^2 peaking at 0 for signal.



Estimate from *BaBar* (200fb^{-1}onPeak + 22 fb^{-1} offPeak):
[M.Rotondo, F.Simonetto]

tag	# signal	purity
e	2150	52%
μ	1740	55%

→

1 ab^{-1}
6M
4.8M

= 10M/ab tagged D^0

VS

~ 80M/ab from D^{*+} tagging
(depends on the final state)

- *different reconstruction technique allows to have a tagged sample of D^0 that can be reconstructed a posteriori!*
- *can exploit full reconstruction of the "other" B, e.g. for D → invisible searches*

Conclusions

- ➡ Charm Physics will contribute significantly to Flavour Physics in the process of understanding Nature in the next decades
    - efforts on both the theory and the experimental sides are required in order to significantly improve the knowledge on charm
- ➡ *Belle II* has a rich charm physics program. Innovative reconstruction techniques are being developed in order to maximally exploit the features of the improved detector
- ➡ *Belle II* and LHCb will provide one-order-of magnitude more precise measurements of charm observables in the next decade, improving our knowledge of charm physics and searching for physics beyond the Standard Model

The Belle II Collaboration:

July 2016