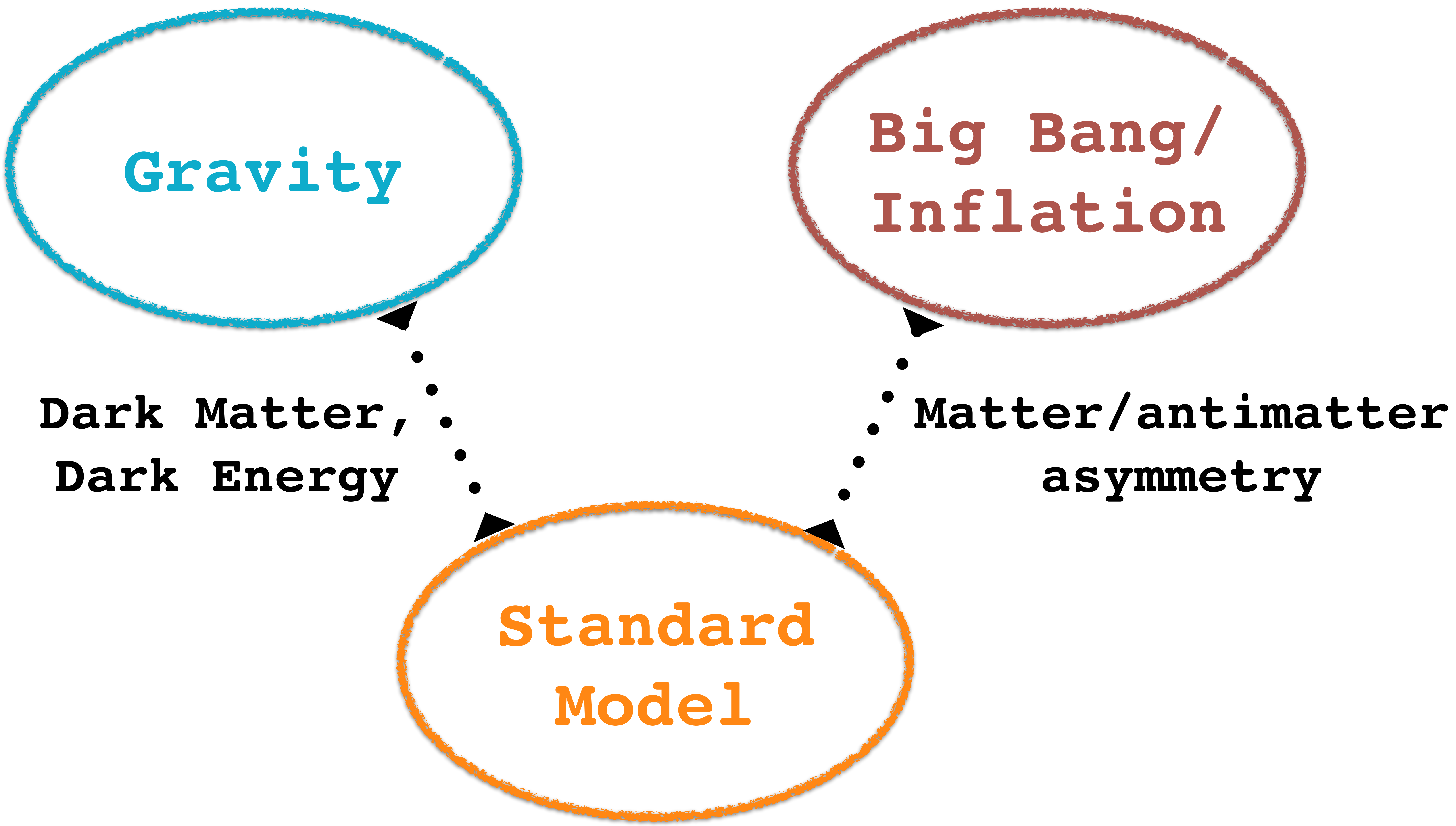
Real-time precision searches for New Physics

Vladimir V. Gligorov

TIFR, December 3rd 2016

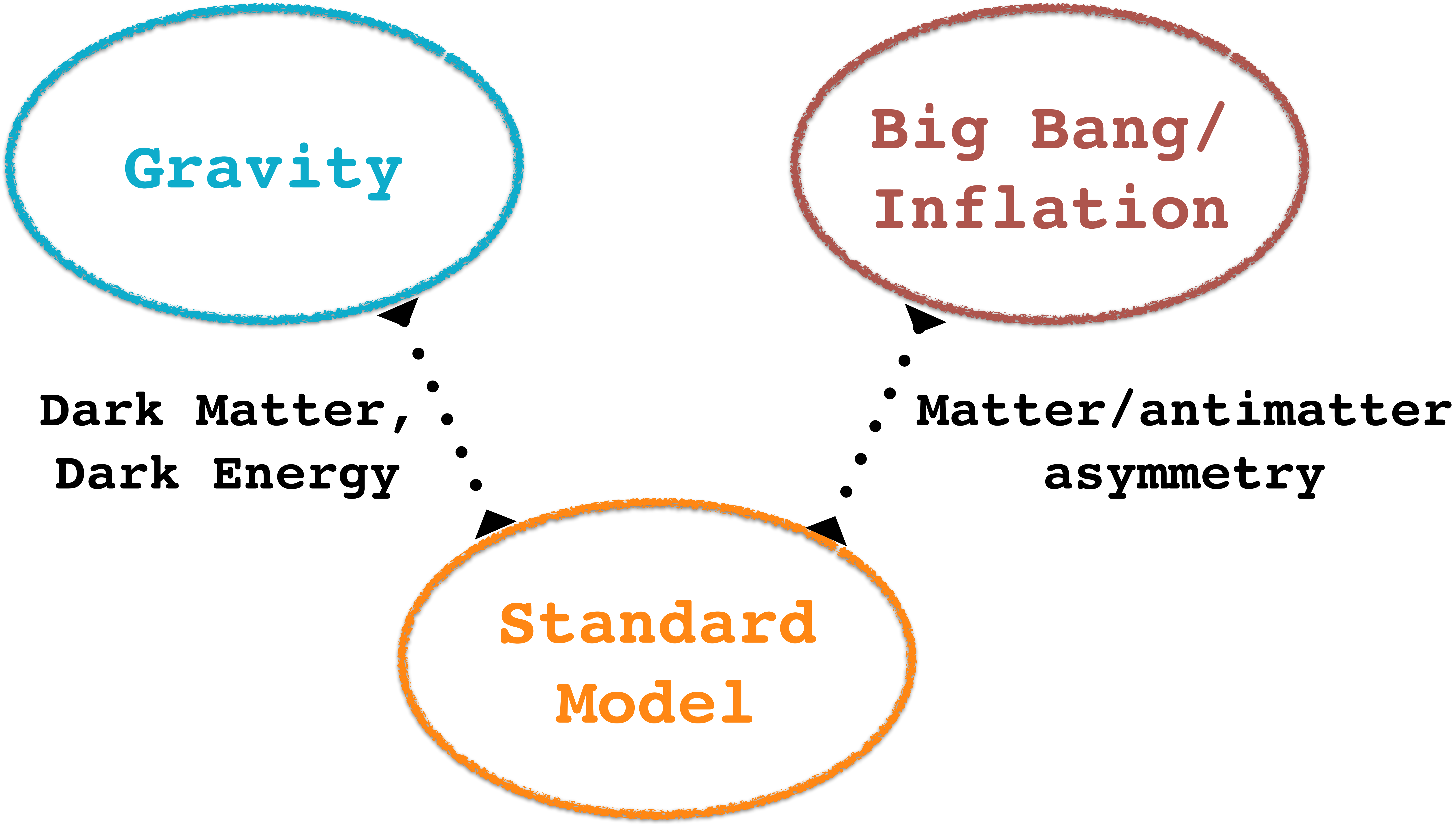
Why are we here?



Our theories of nature are inconsistent with each other => something has to give

Why are we here?

And the really big bad ghoul… nonlocality. But let’s not go there.



Our theories of nature are inconsistent with each other => something has to give

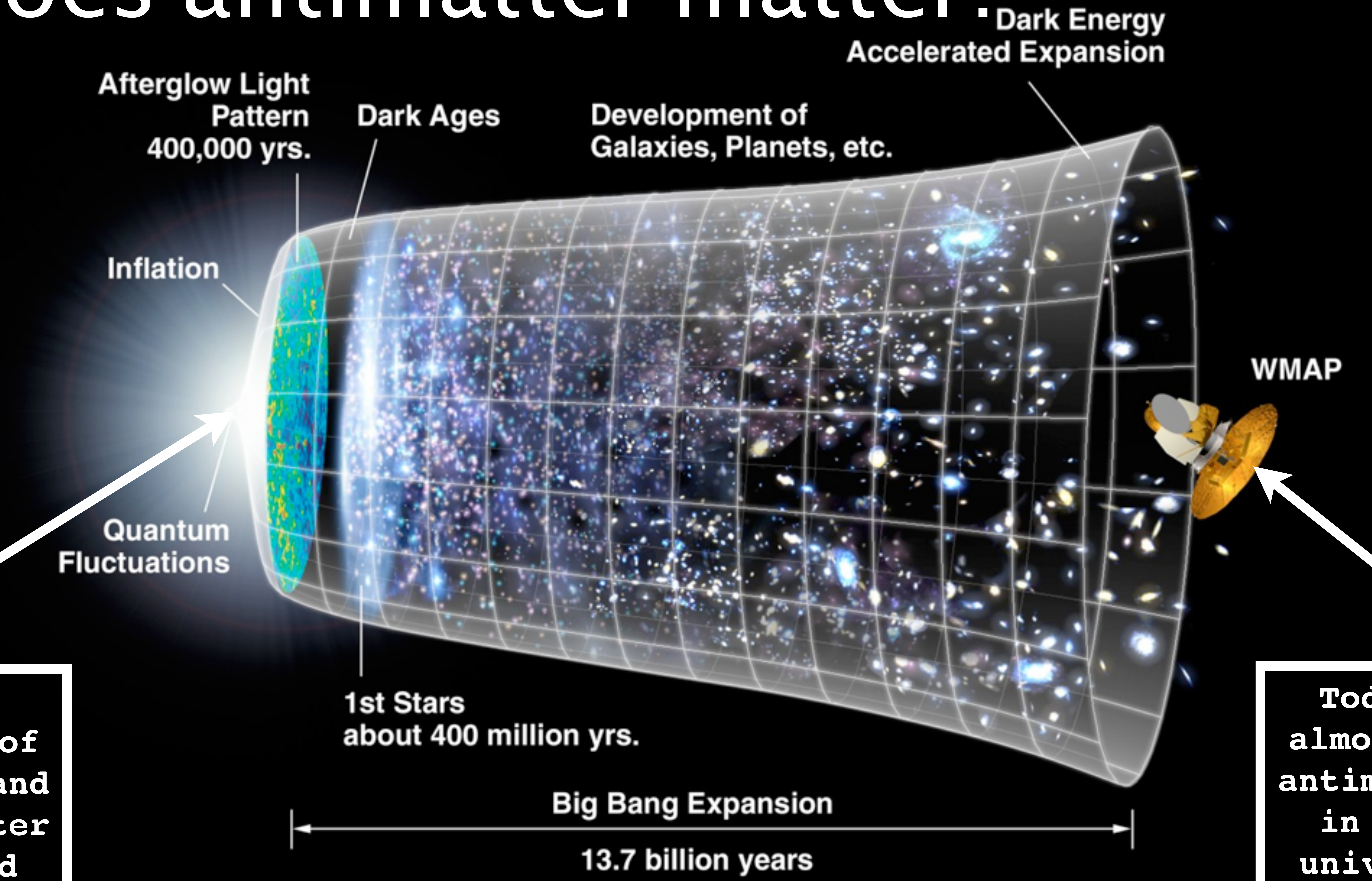
Quark mixing in the Standard Model

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

$$\mathbf{V_{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \sum_{n=4}^{N} O(\lambda^n)$$

Imaginary component gives rise to matter-antimatter asymmetry (CP violation)

Why does antimatter matter?



Equal amount of matter and antimatter created

Today: almost no antimatter in the universe

So where did all the antimatter go?

Other reasons exist

Hierachy, naturaleness, etc.

Inconsistency between SM picture of CPV and Big Bang comes directly from the quark masses and cannot be explained away though.

If Big Bang picture is correct, there must be sources of CPV outside the SM!

Potential NP is constrained by flavour

Hierachy, naturaleness, etc.

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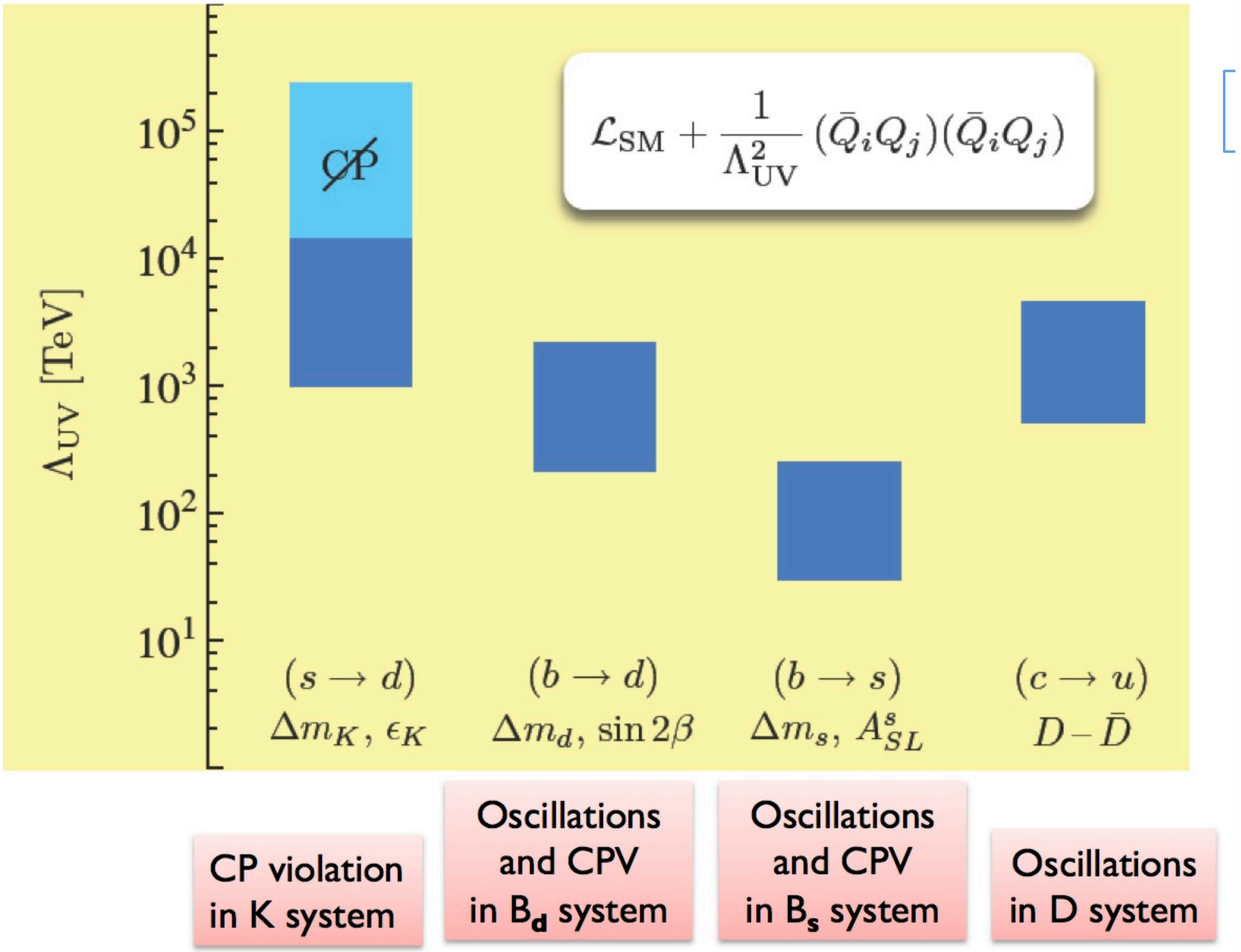
Existing quark-mixing measurements constrain generic BSM models at the TeV scale, competitive with direct searches.



(Fig. Neubert, EPS-HEP'11)

Isidori, Nir, Perez, Ann. Rev. Nucl. Part. Sci. 60 (2010) 355 [arXiv:1002.0900],
Isidori, arXiv:1302.0661

Potential NP is constrained by flavour

Hierachy, naturaleness, etc.

Inconsistency between SM picture of CPV and Big Bang comes directly from the quark masses and cannot be explained away though.

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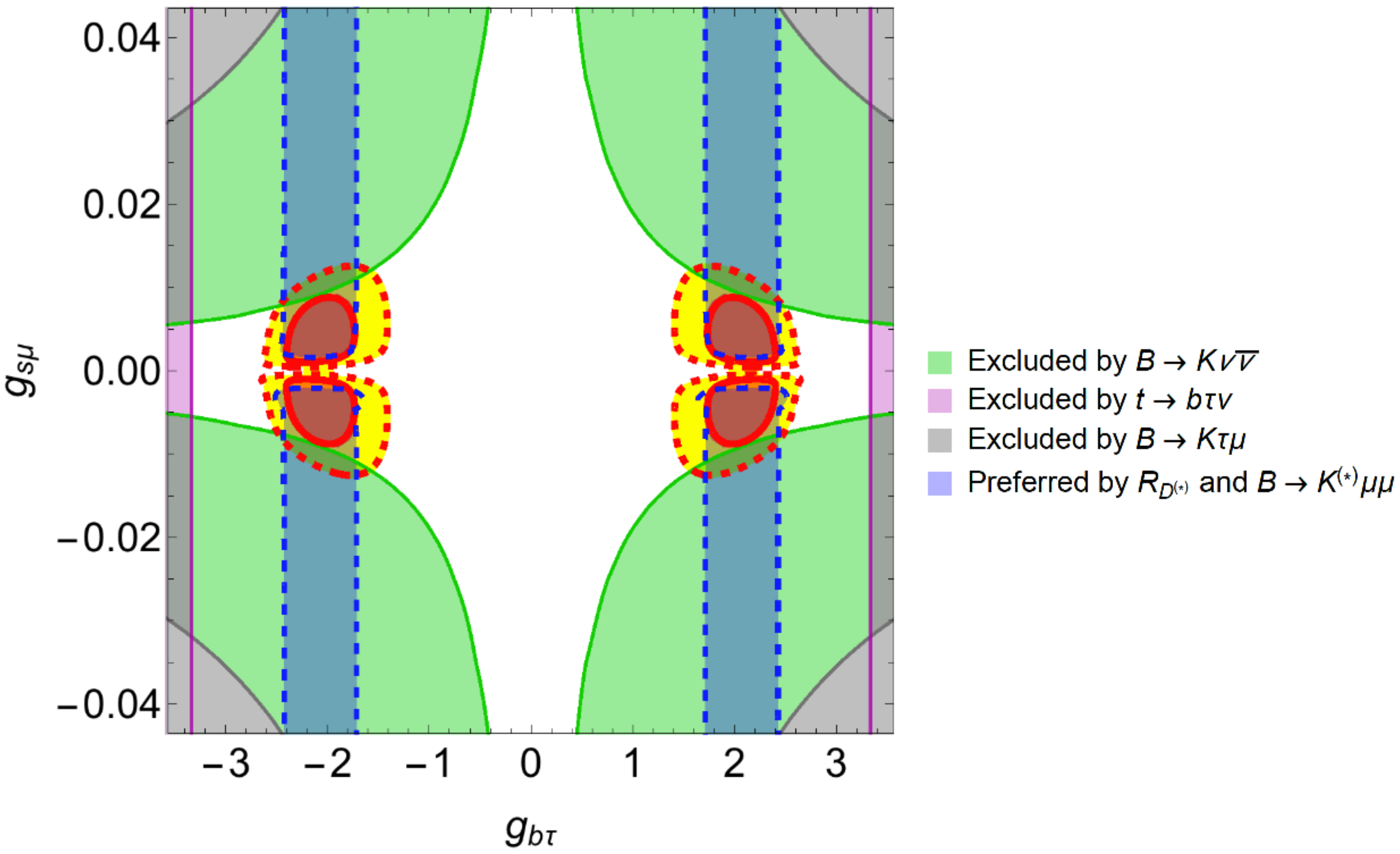
Also, measurements of LFU/LFV in decays of heavy flavour are powerful probes of BSM physics.



Taken from Fajfer & Košnik
http://arxiv.org/abs/1511.06024v4

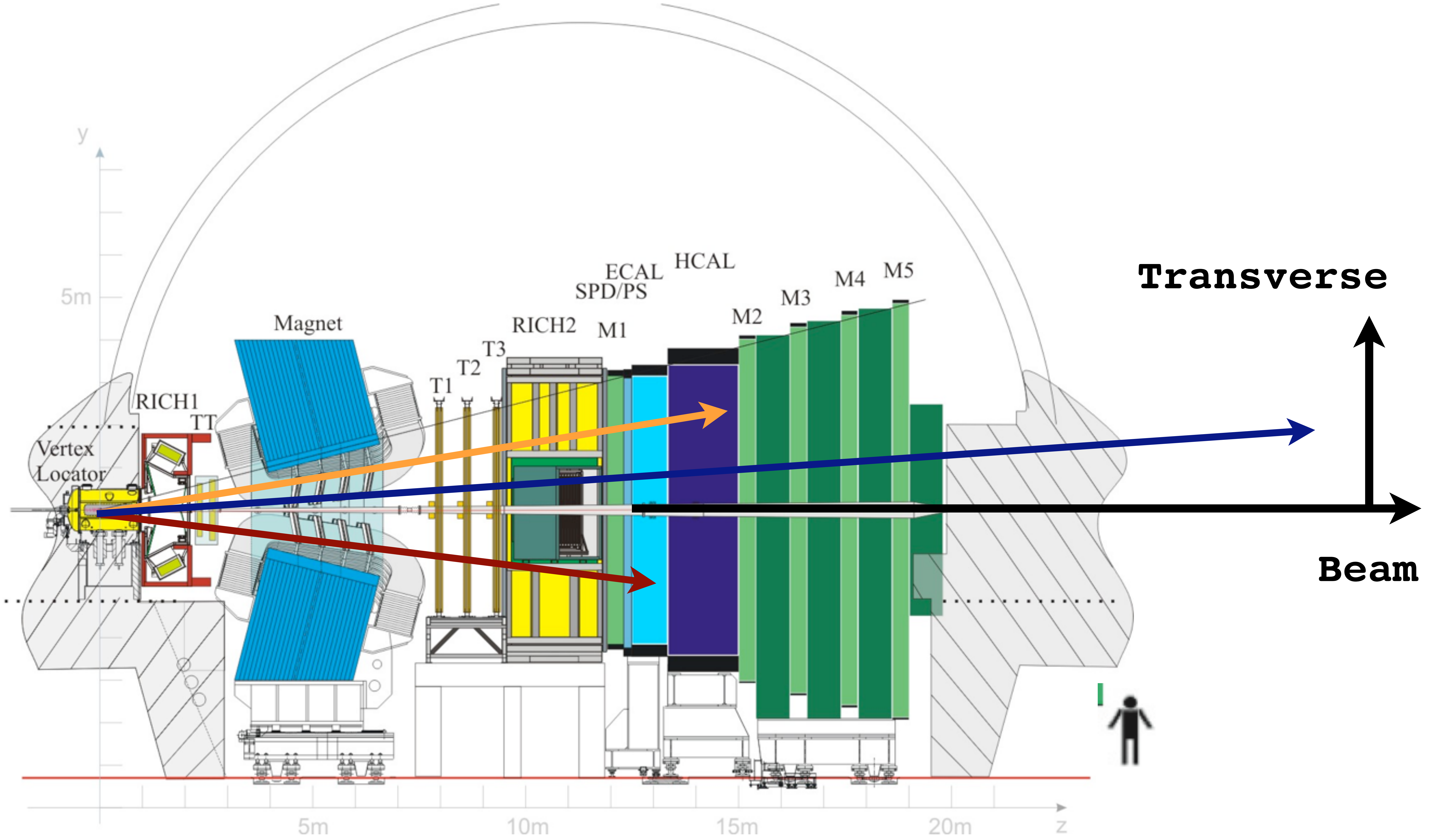
So this will be my own biased view of…

1. Precision (flavour) tests today
2. Precision (flavour) tests in 2030
3. How does real-time analysis get us there?

I work on LHCb, which may be obvious from what follows…

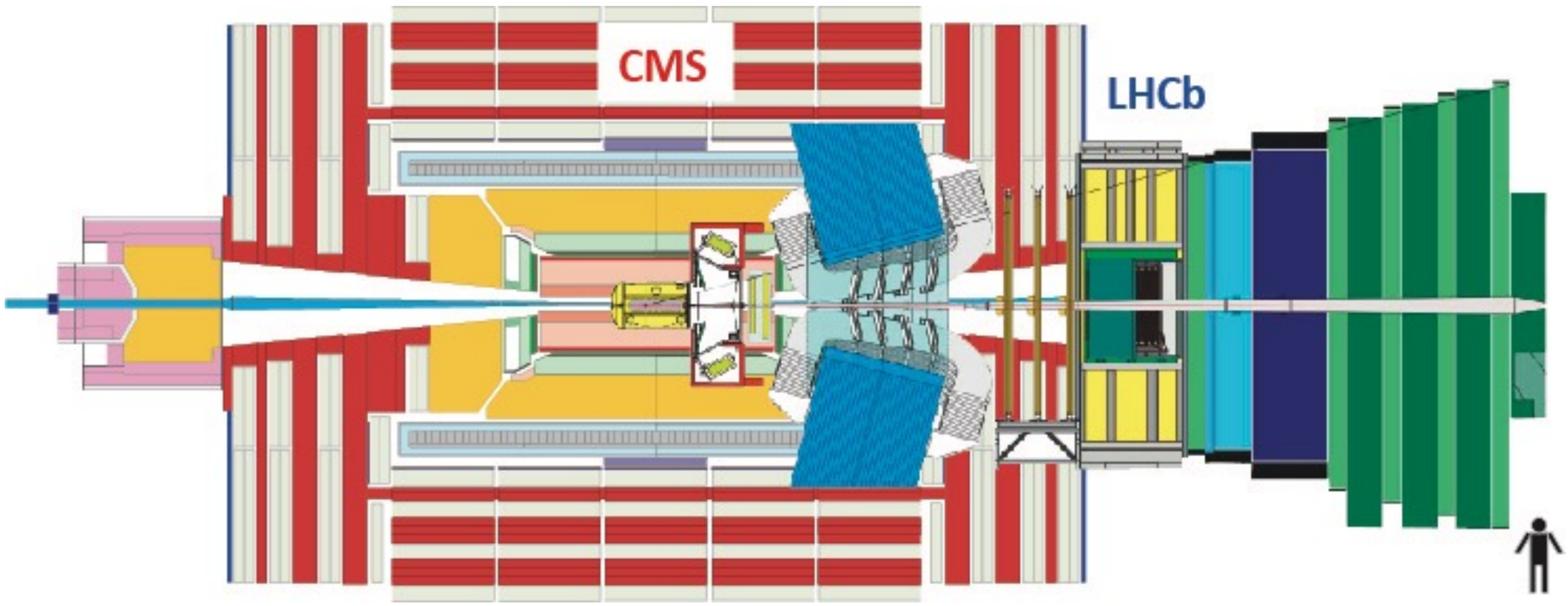
The LHCb detector

- ELECTRONS
- PHOTONS
- HADRONS
- MUONS



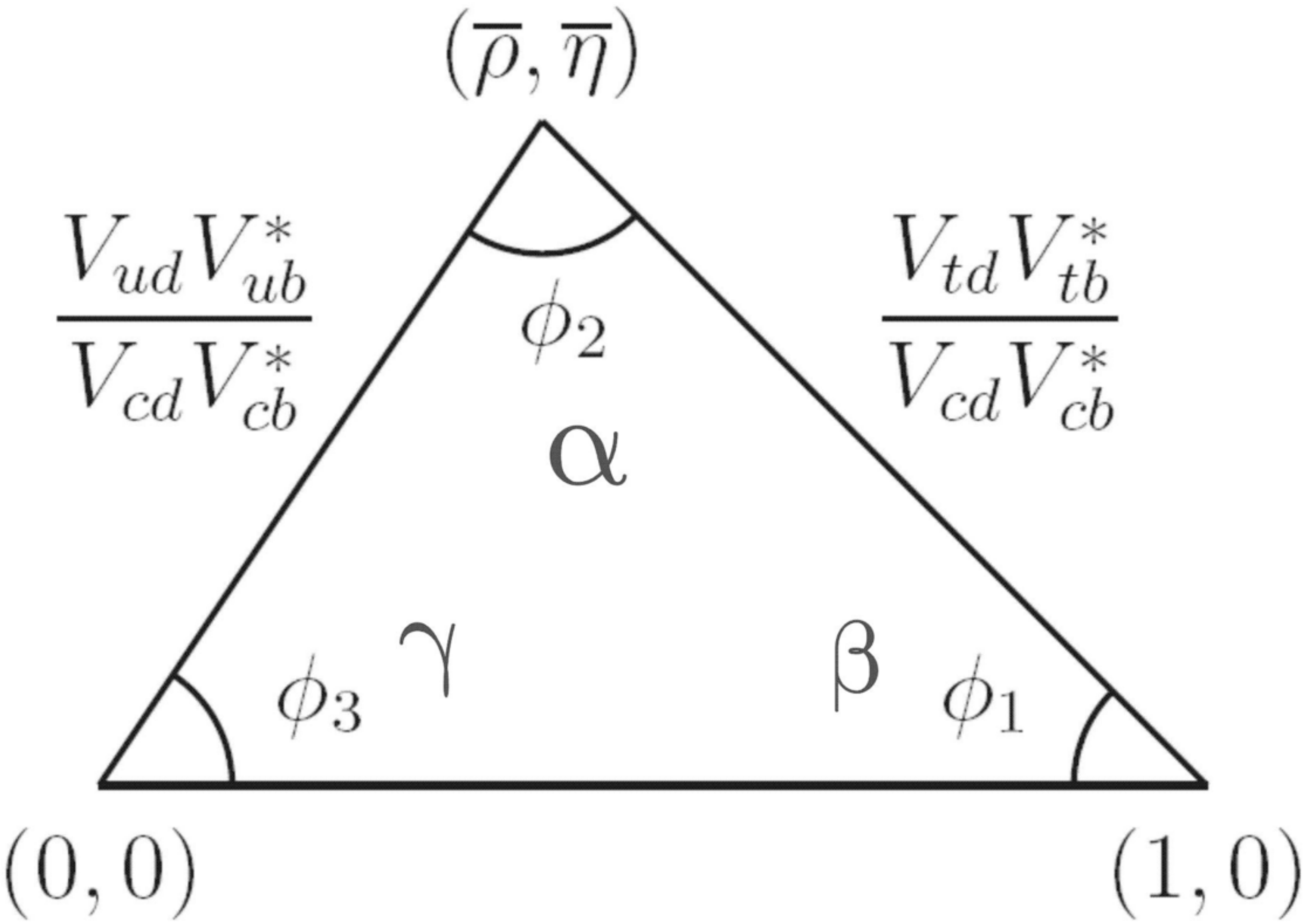
p_T = Transverse momentum
E_T = Transverse energy

Compared to a central detector




Here & Now

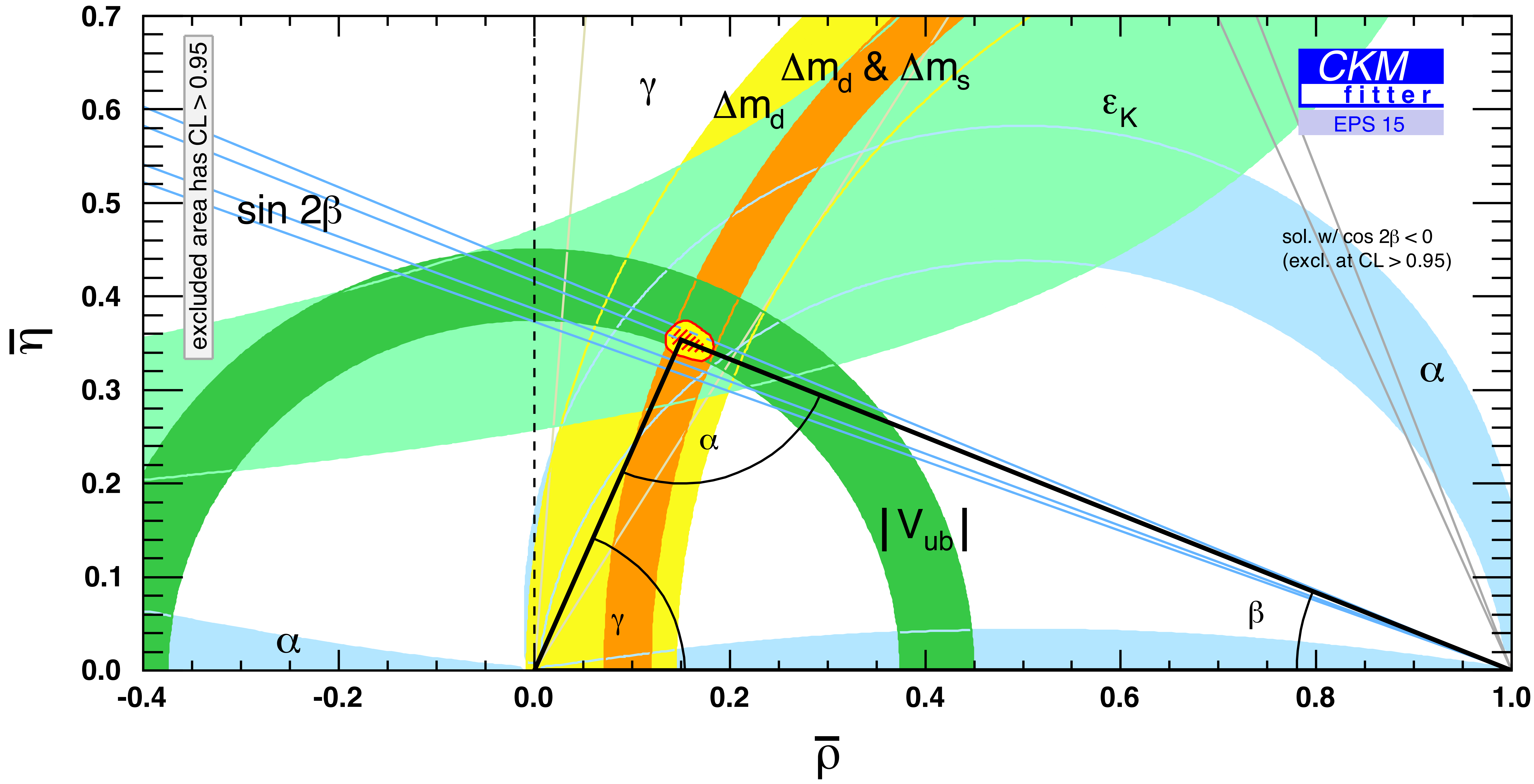
The unitarity triangle



Unitary matrix => 6 triangles in imaginary plane, one experimentally convenient

The apex of the triangle

http://ckmfitter.in2p3.fr
Similar plots with Bayesian treatment available at www.utfit.org



Overconstraining the apex tests the consistency of the SM picture of CP Violation

The apex of the triangle

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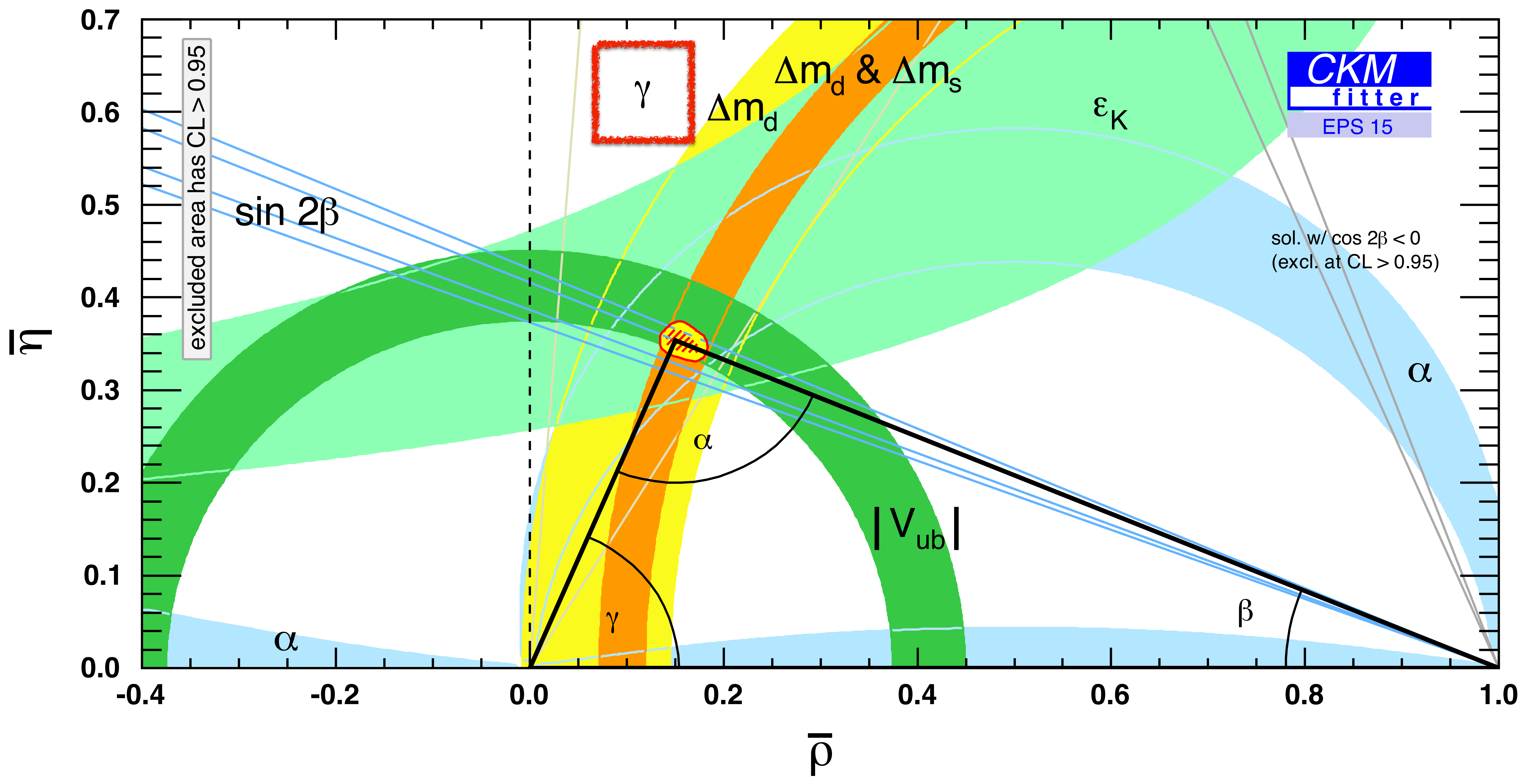
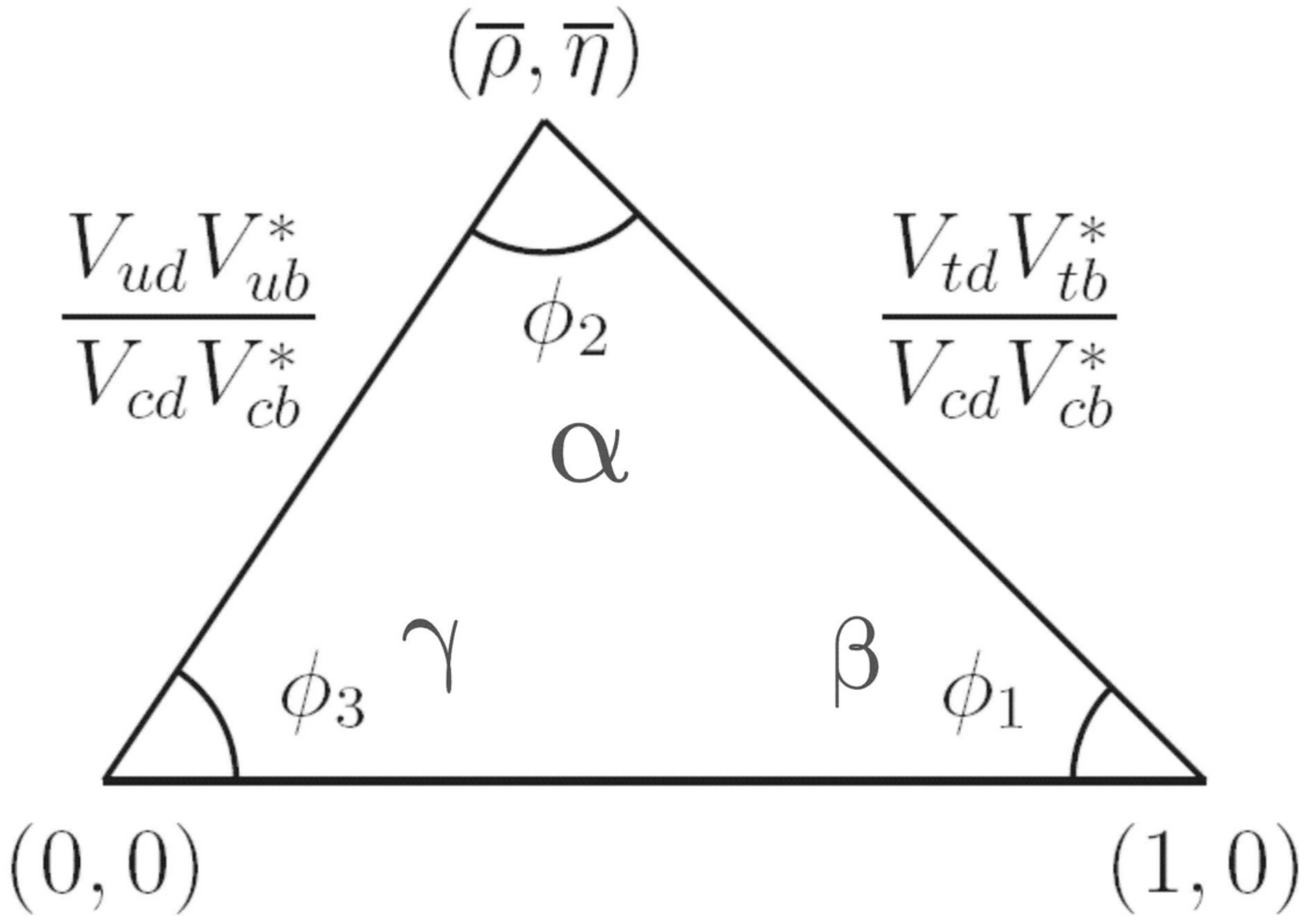


Let's start with measuring the angle γ

γ comes from b→u,c interference



V_{ub} imaginary, get γ by measuring CPV

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

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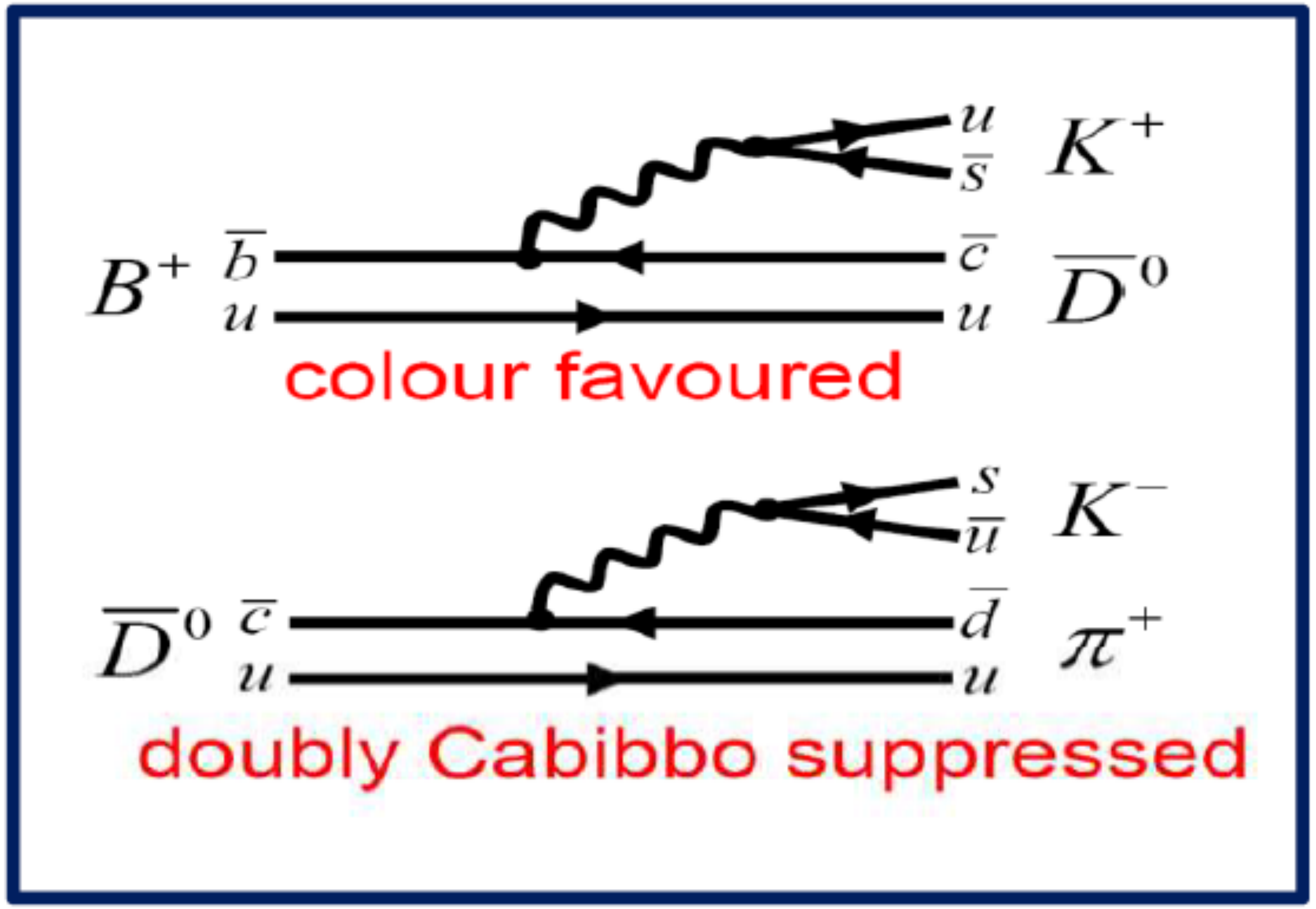
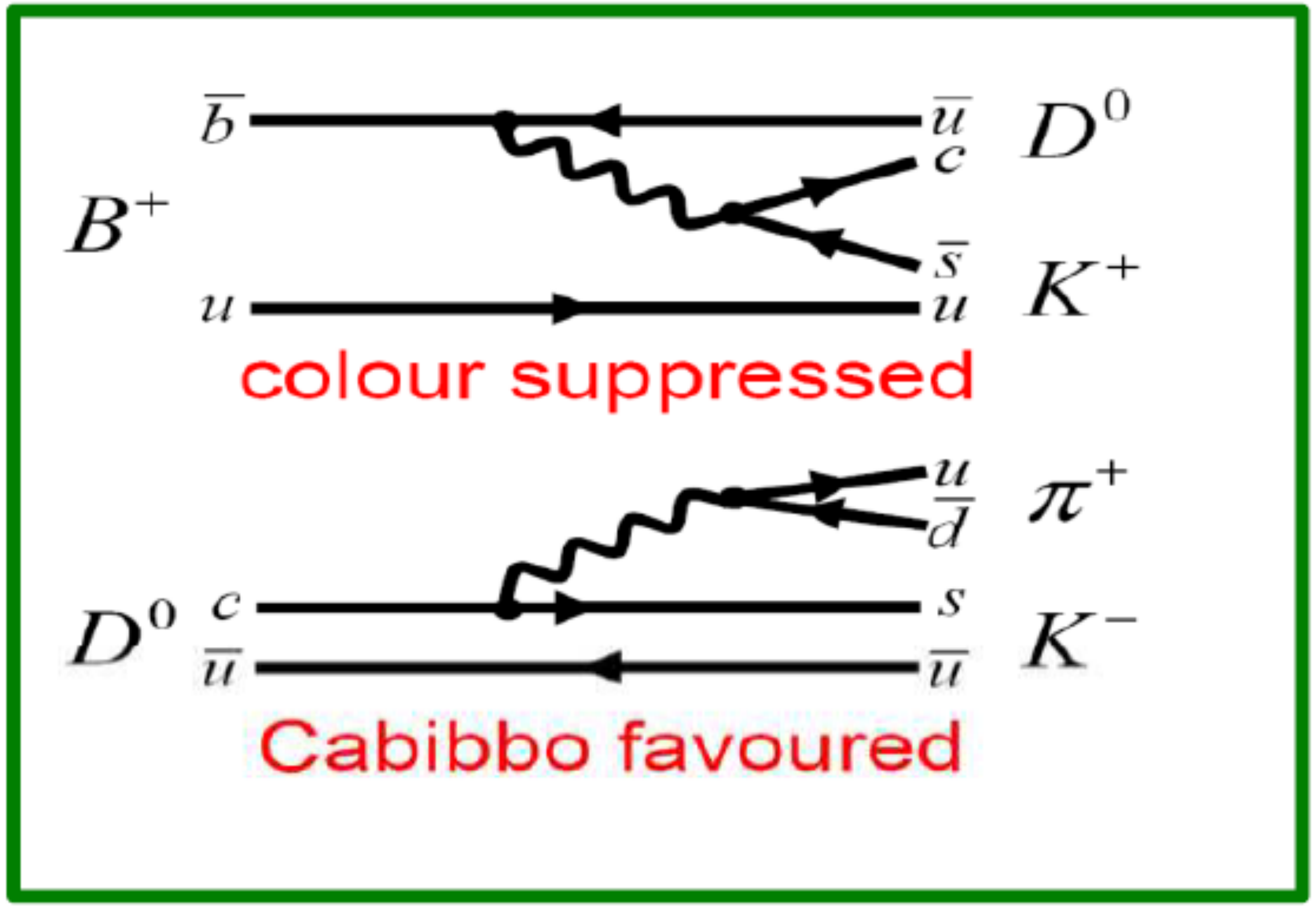
How do we measure γ?





Interfering V_{ub} and V_{cb} decays to the same final state. Sensitivity to γ proportional to ratio of interfering amplitudes => written as r_X for a given set of decays X

What scales does γ probe?

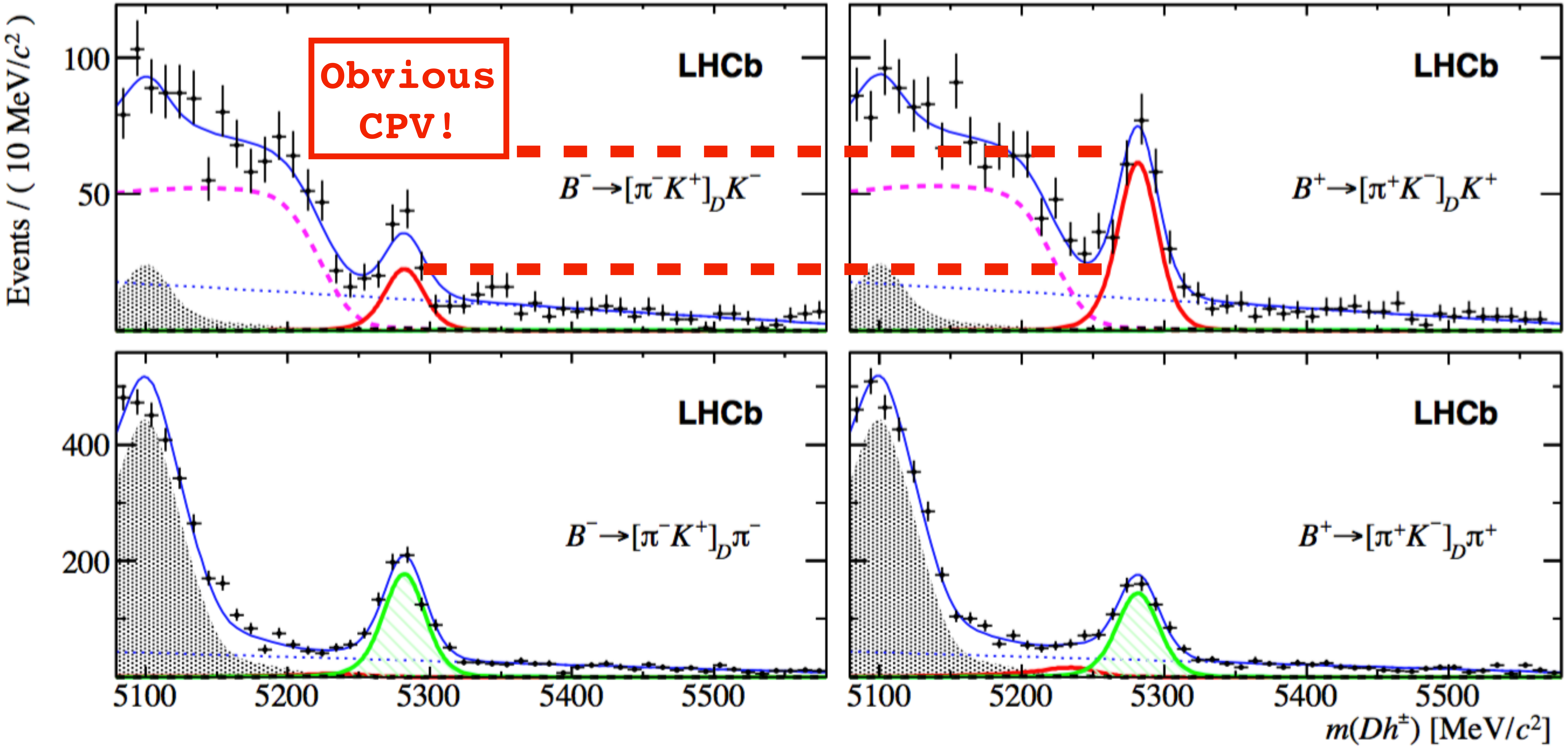
$$|\delta\gamma| \lesssim \mathcal{O}(10^{-7})$$

Probe	Λ_{NP} for (N)MFV NP	Λ_{NP} for gen. FV NP	$B\overline{B}$ pairs
γ from $B \to DK$[1]	$\Lambda \sim \mathcal{O}(10^2\ \mathrm{TeV})$	$\Lambda \sim \mathcal{O}(10^3\ \mathrm{TeV})$	$\sim 10^{18}$
$B \to \tau\nu$[2]	$\Lambda \sim \mathcal{O}(\ \mathrm{TeV})$	$\Lambda \sim \mathcal{O}(30\ \mathrm{TeV})$	$\sim 10^{13}$
$b \to ss\bar{d}$[3]	$\Lambda \sim \mathcal{O}(\ \mathrm{TeV})$	$\Lambda \sim \mathcal{O}(10^3\ \mathrm{TeV})$	$\sim 10^{13}$
β from $B \to J/\psi K_S$[4]	$\Lambda \sim \mathcal{O}(50\ \mathrm{TeV})$	$\Lambda \sim \mathcal{O}(200\ \mathrm{TeV})$	$\sim 10^{12}$
$K - \overline{K}$ mixing[5]	$\Lambda > 0.4$ TeV (6 TeV)	$\Lambda > 10^{3(4)}$ TeV	now

Zupan&Brod
http://arxiv.org/pdf/1308.5663.pdf

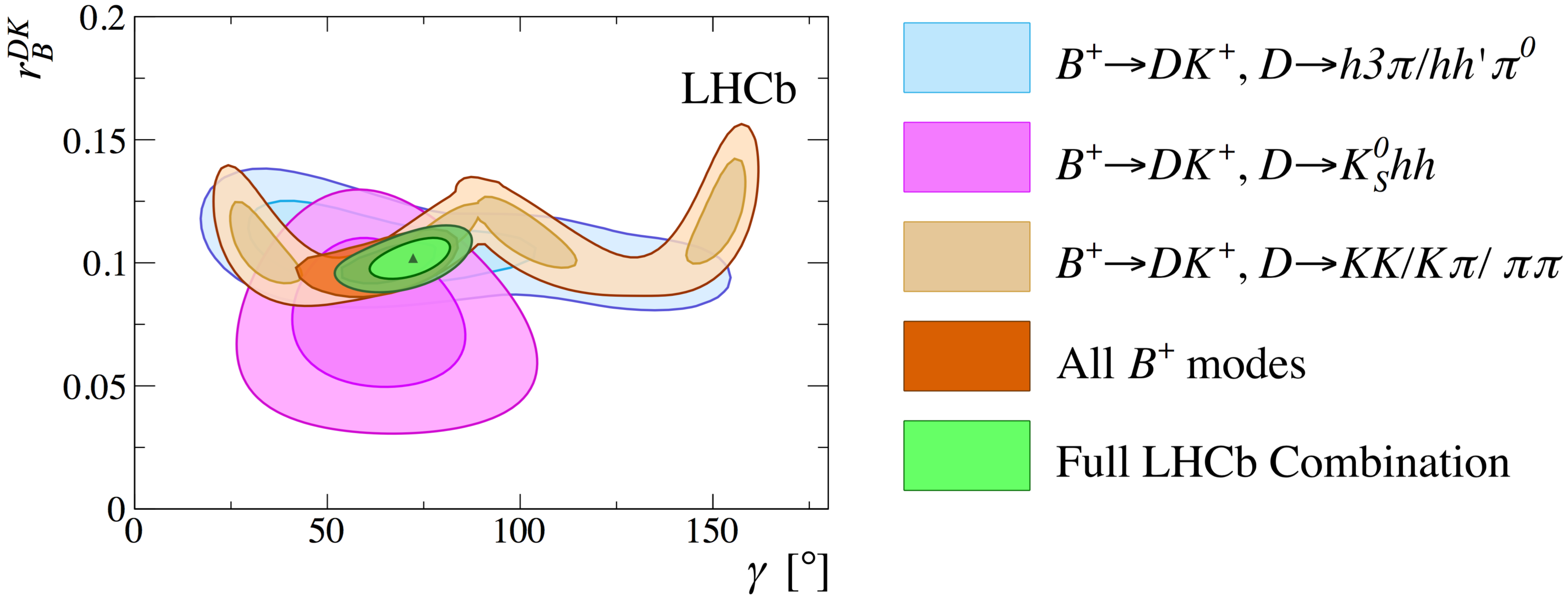
γ in the LHC era

The "ADS" B→DK decay mode, total branching fraction O(10^{-7})



LHCb-PAPER-2016-003

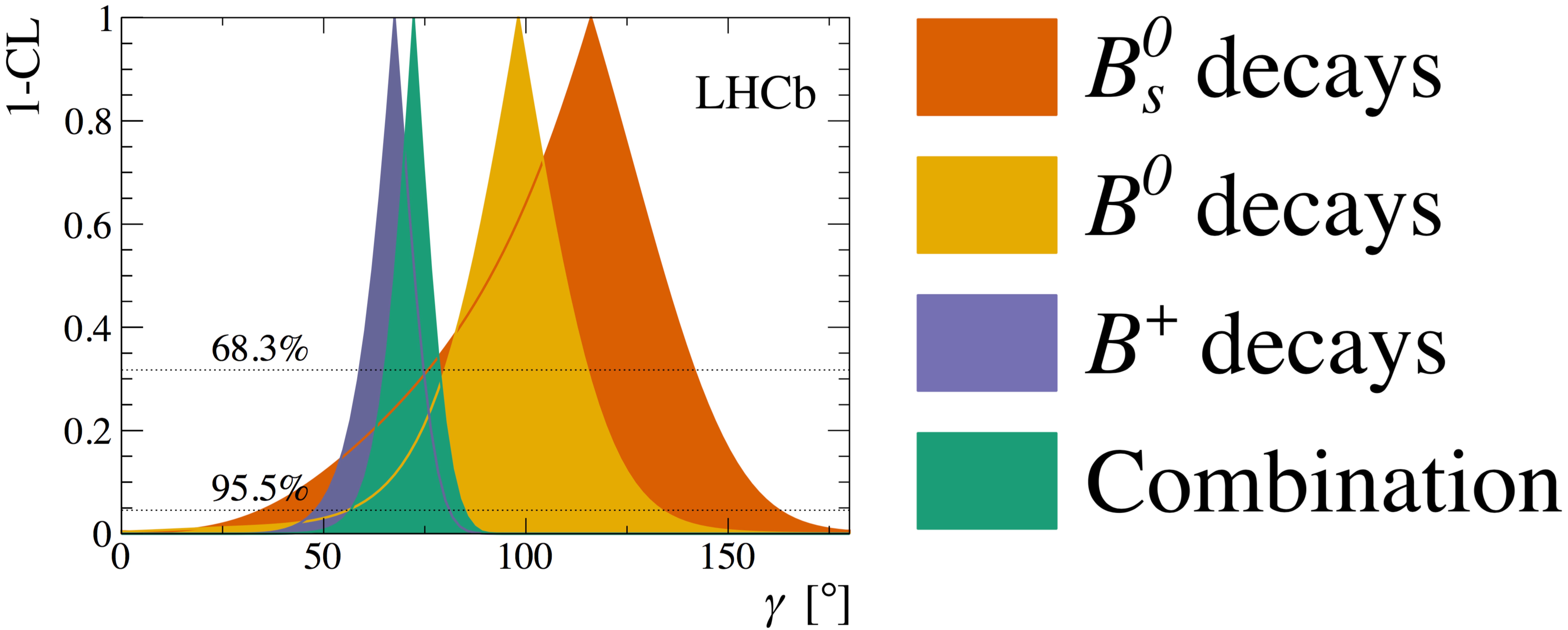
Merging the roads to γ



LHCb-PAPER-2016-032

Merging the roads to γ

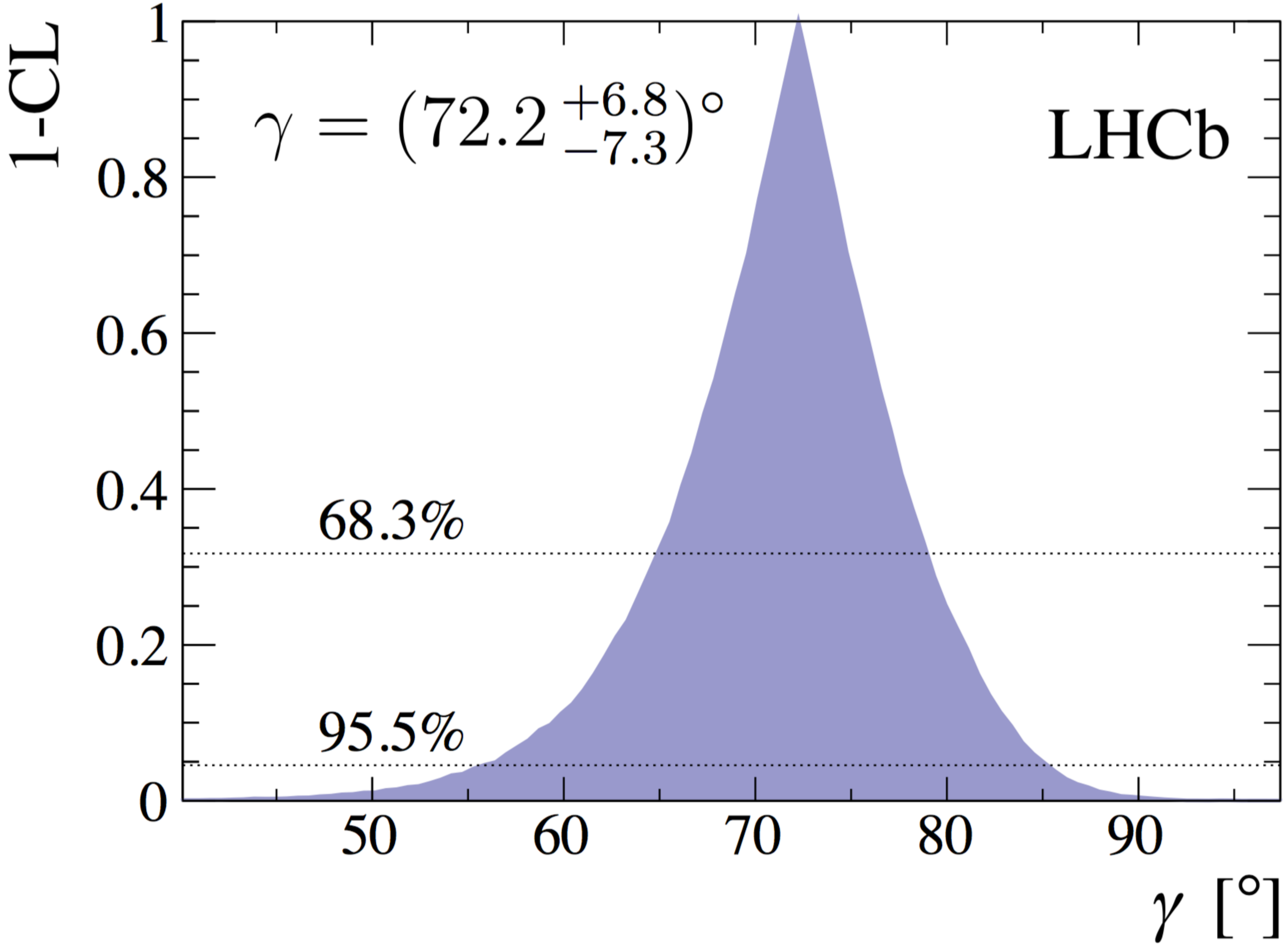
Will eventually include b-baryon and B_c decays, certainly with the upgrade!



LHCb-PAPER-2016-032

Merging the roads to γ

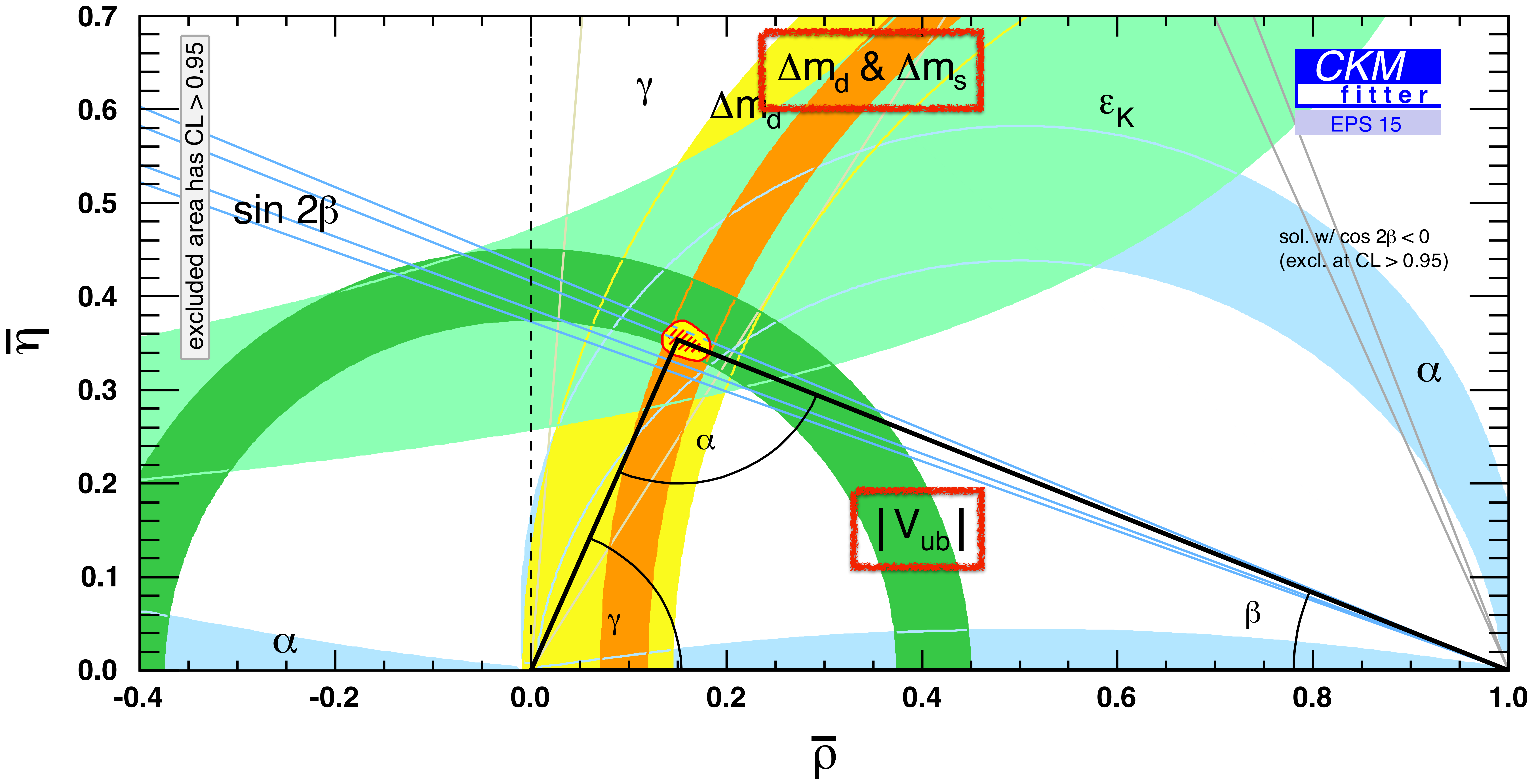
CKM angle γ now known to ~10% relative uncertainty with LHCb data alone, and we are almost in the Gaussian regime for the uncertainties.



LHCb-PAPER-2016-032

The apex of the triangle

http://ckmfitter.in2p3.fr
Similar plots with Bayesian treatment available at www.utfit.org



So we know γ to 10%, what about V_{ub} and $\Delta m_{d,s}$?

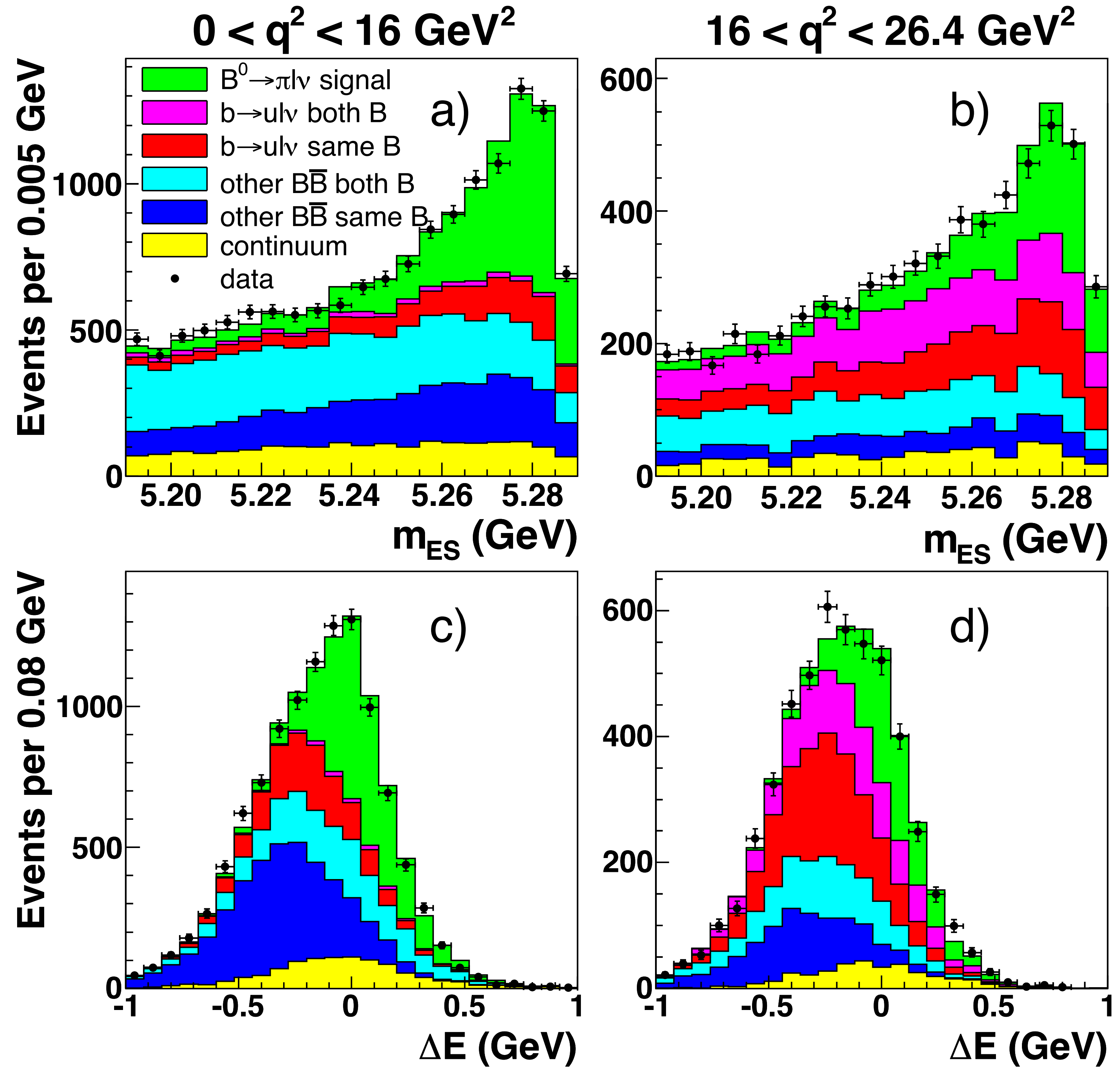
V_{ub} : inclusive, exclusive

References, left to right :

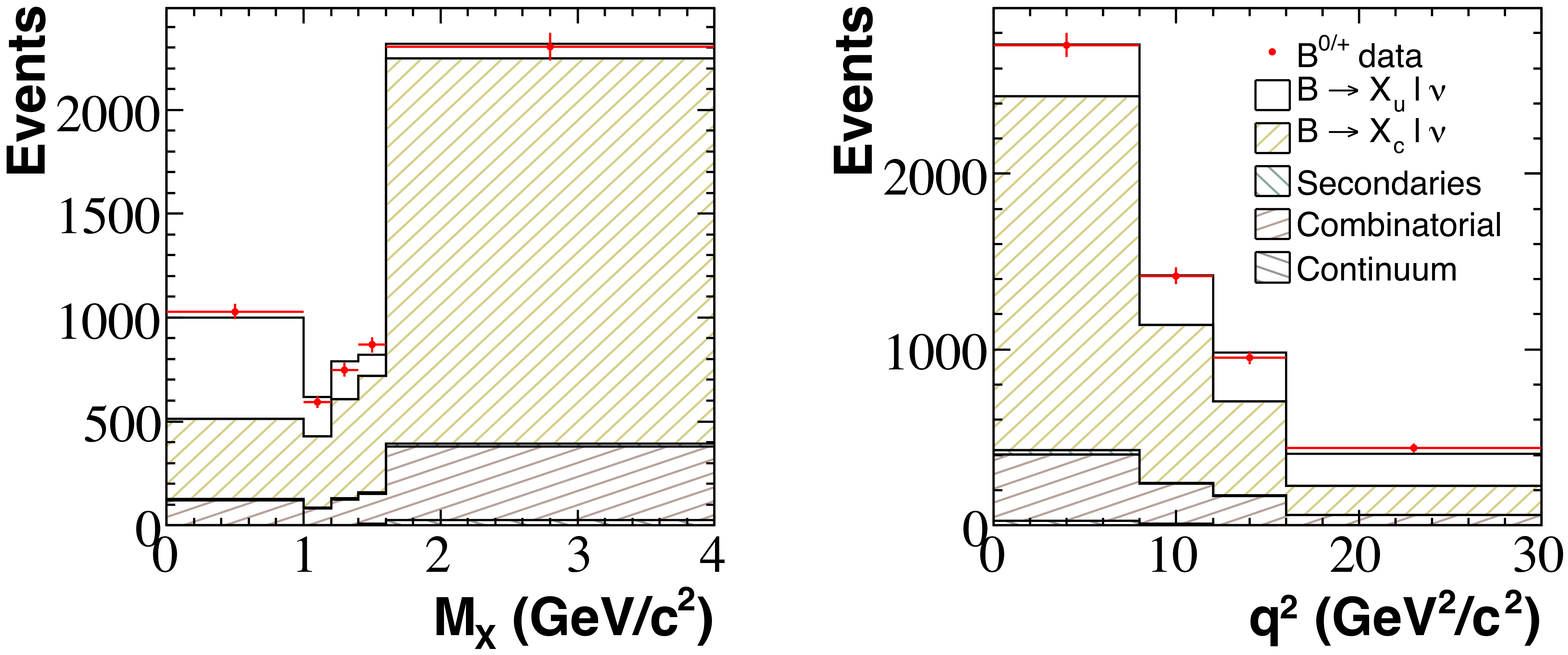
http://arxiv.org/pdf/1208.1253v2.pdf

http://arxiv.org/pdf/0907.0379v2.pdf

BABAR Exclusive



BELLE Inclusive



$$|V_{ub}| = (4.41 \pm 0.15 \, {}^{+\,0.15}_{-\,0.17}) \times 10^{-3} \quad \text{(inclusive)},$$

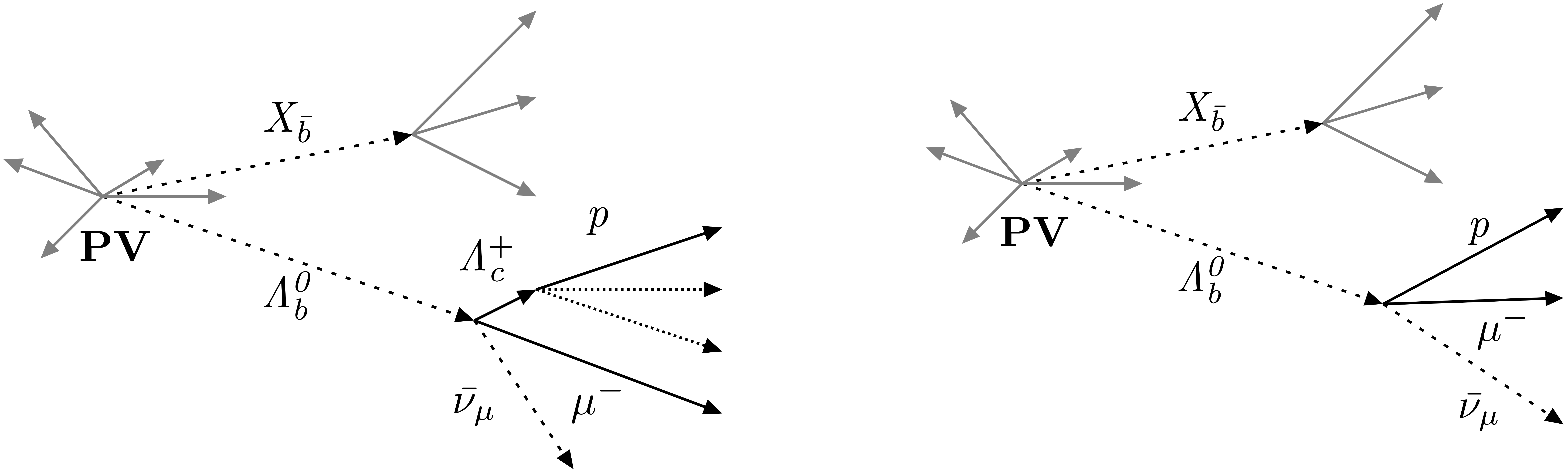
$$|V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \quad \text{(exclusive)}.$$

Exclusive : needs lattice input for form factors

Inclusive : large backgrounds, HQE uncertainties

V_{ub} : LHCb enters the picture

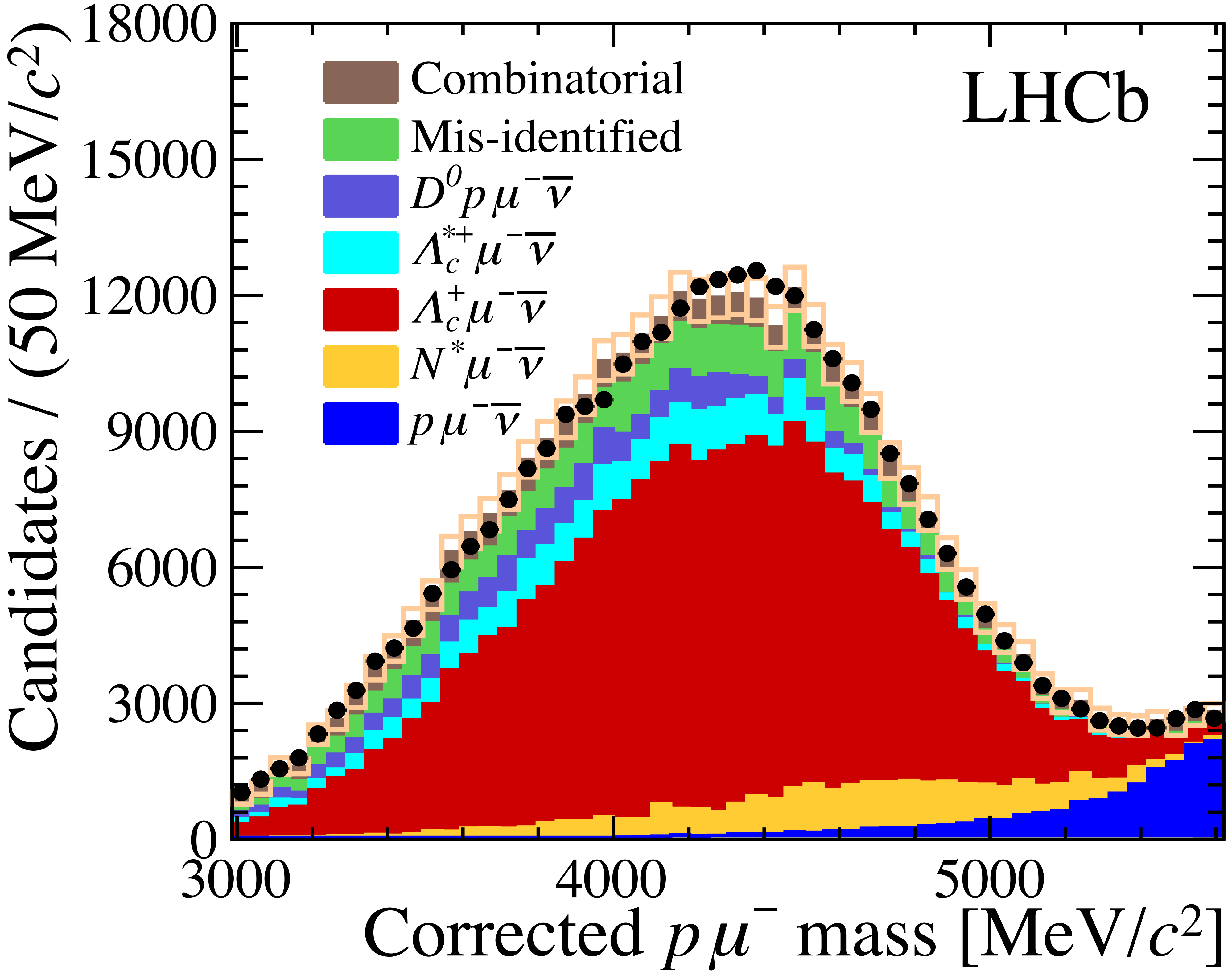
LHCb-PAPER-2015-013

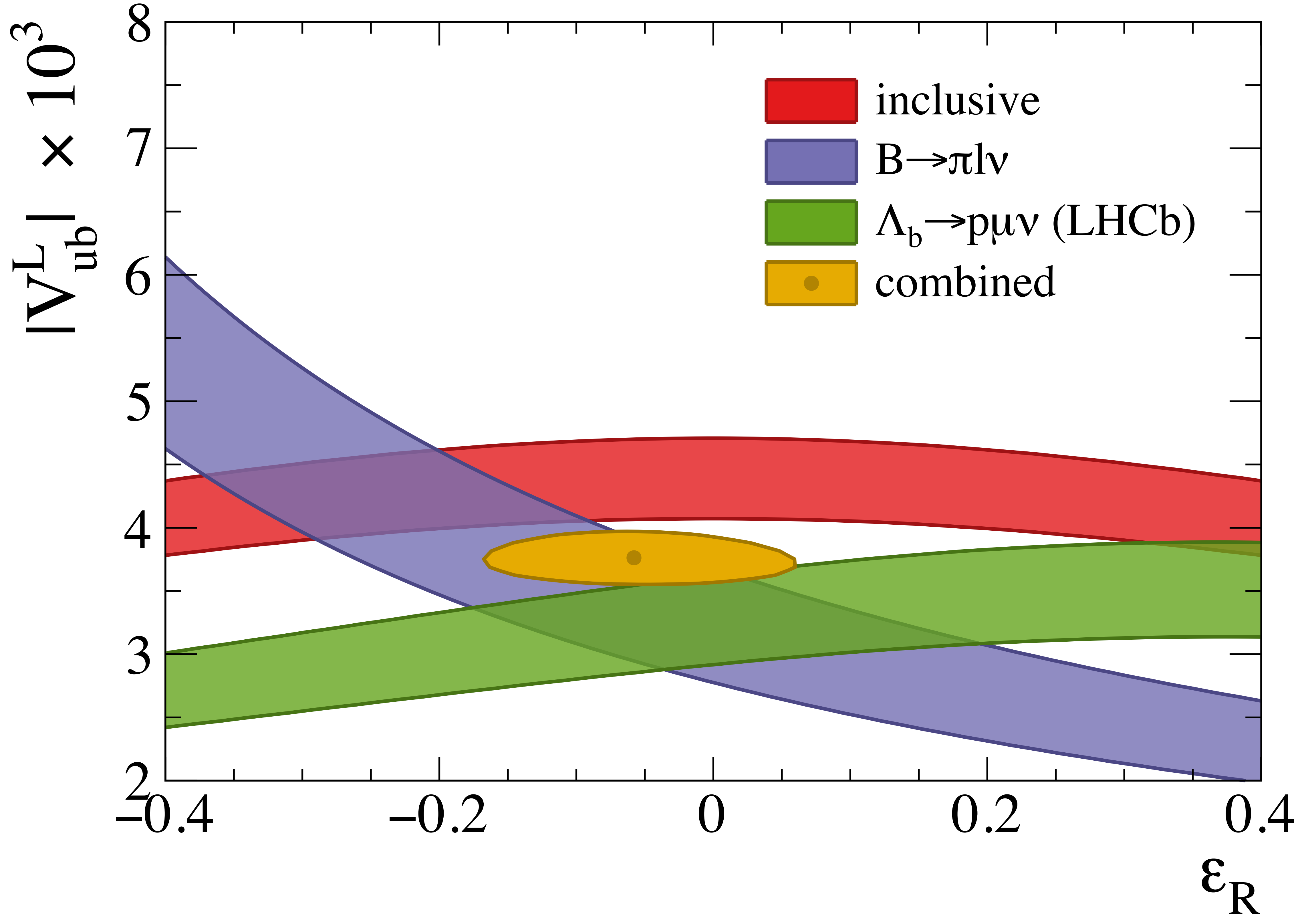


LHCb is able to make this measurement with b-baryon decays, using (thanks to our vertex detector) isolation criteria to reject the dominant background from charmed decays

V_{ub} : LHCb enters the picture

LHCb-PAPER-2015-013





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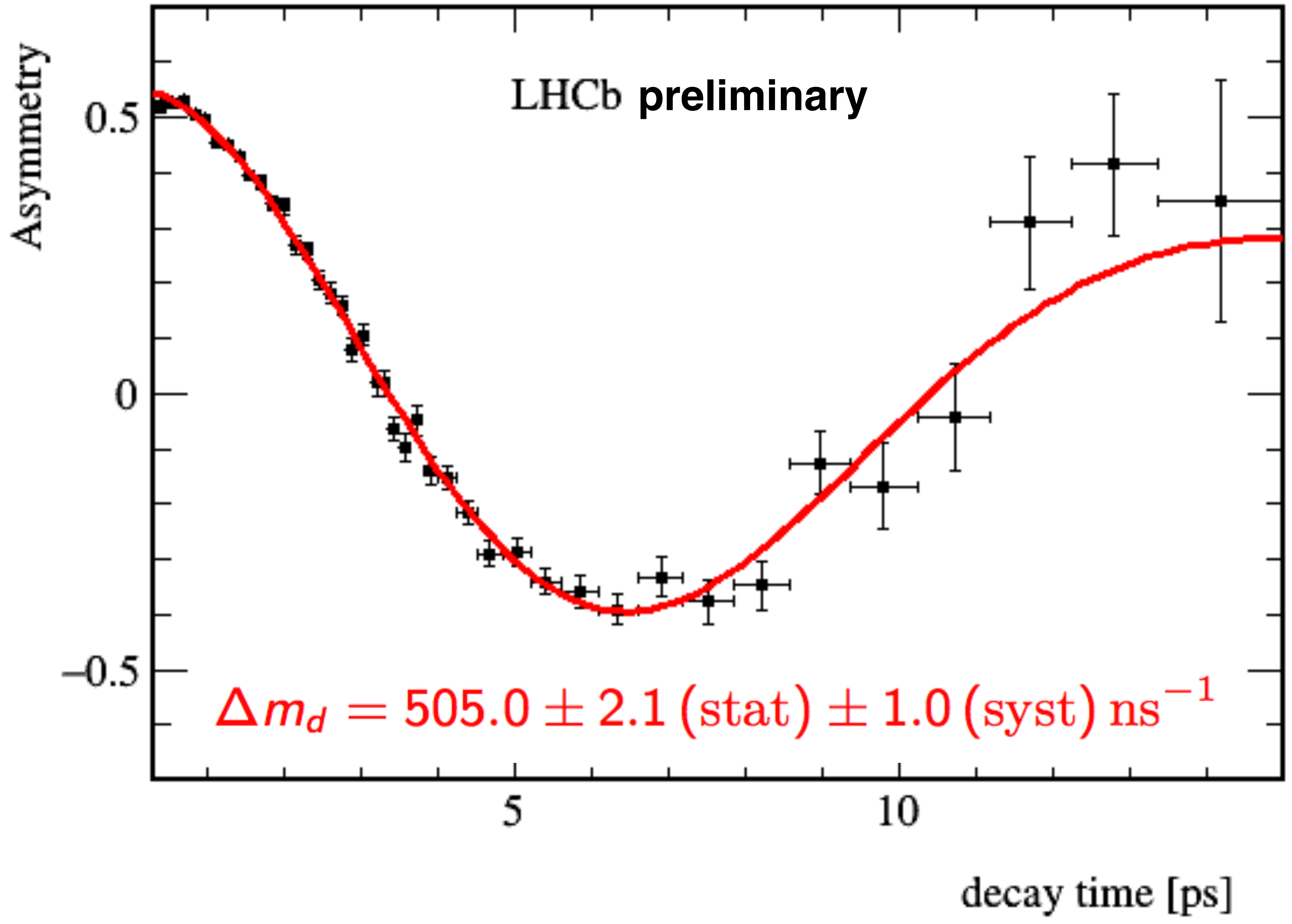
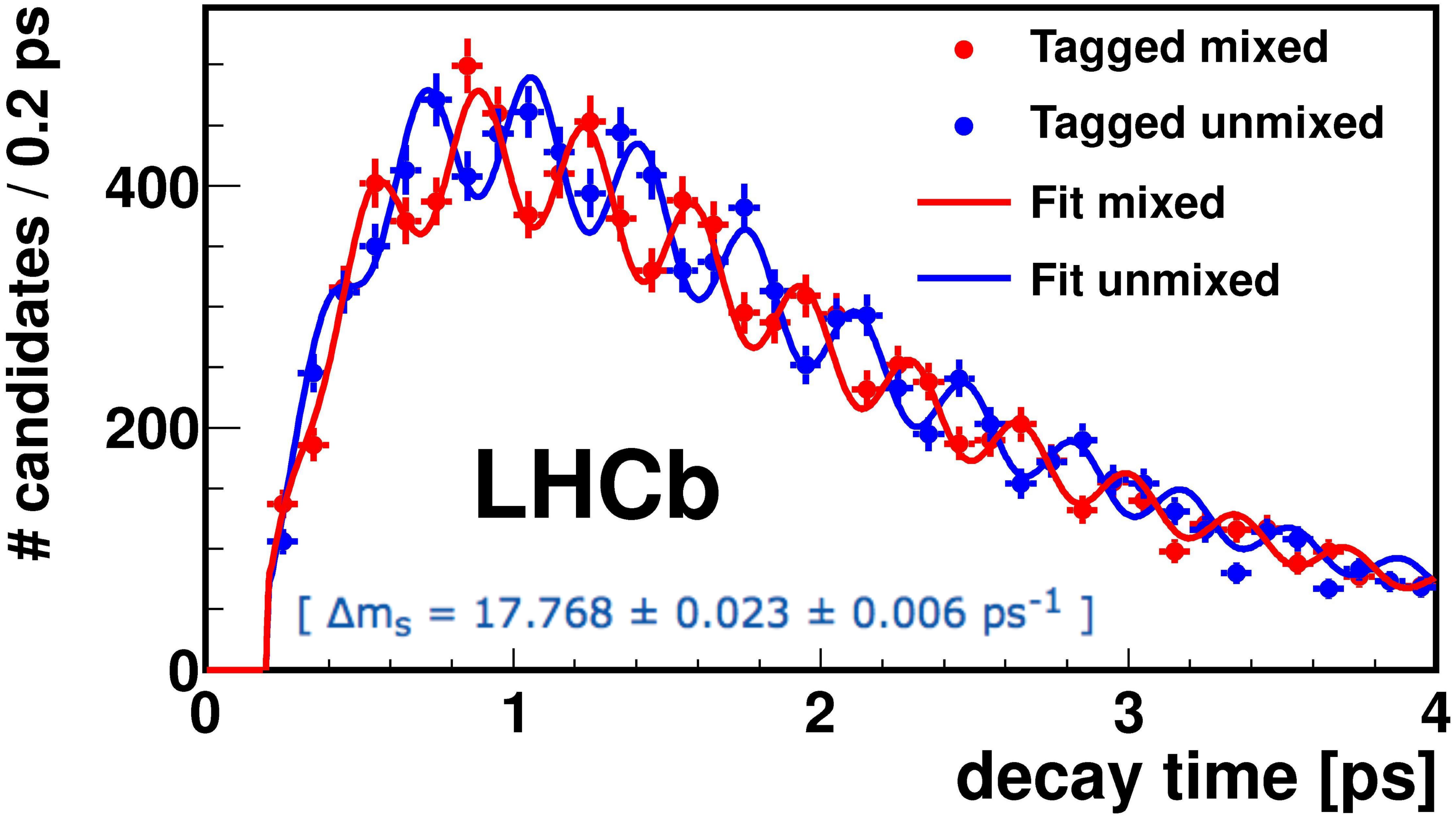
$\Delta m_{d,s}$ and recent MILC results

LHCb-PAPER-2015-031
LHCb-PAPER-2013-006



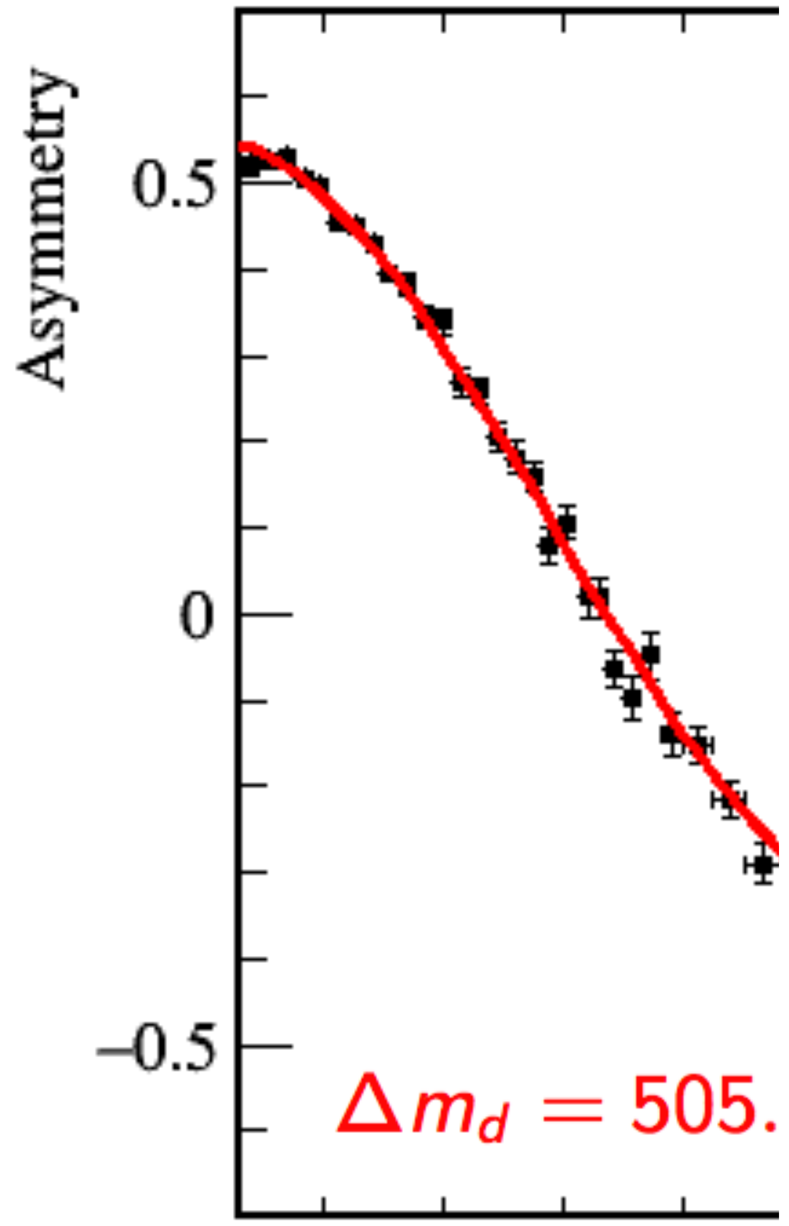


LHCb recently measured Δm_d using semileptonic B decays, world-best precision. Have also measured Δm_s using $B_s \to D_s \pi$ decays before, also a world-best measurement

$\Delta m_{d,s}$ and recent MILC results

LHCb-PAPER-2015-031
LHCb-PAPER-2013-006

$$\Delta m_d = \frac{G_F^2 m_W^2 M_{B^0}}{6\pi^2} S_0(x_t)\eta_{2B} |V_{td}^* V_{tb}|^2 f_{B^0}^2 B_{B^0}$$



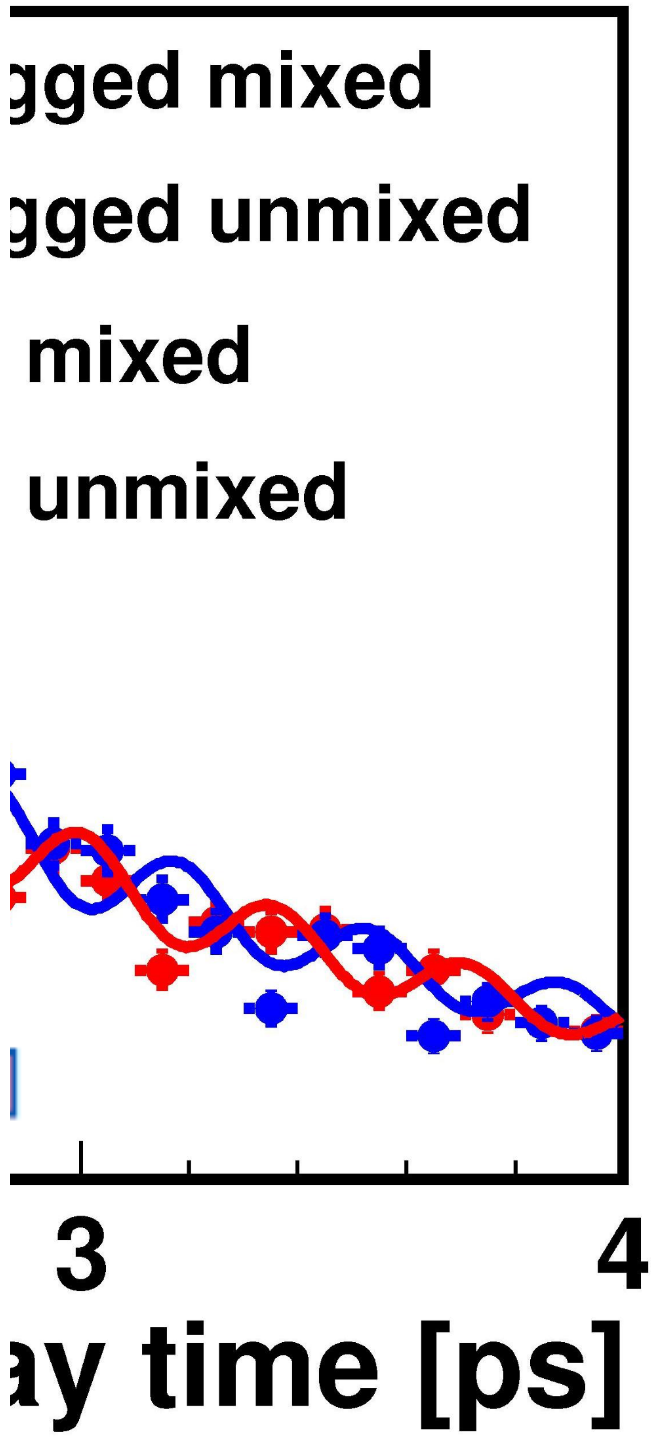
- arXiv:1602.03560: Fermilab Lattice and MILC Collaborations
- Improvements on uncertainties related to hadronic matrix elements:

$$f_{B^0}^2 B_{B^0} = 0.0526 \pm 0.0042\,\mathrm{GeV}/c^2$$

$$\Delta m_d(\text{Theory}) = 0.639(50)(36)(5)(13)\,\mathrm{ps}^{-1}$$

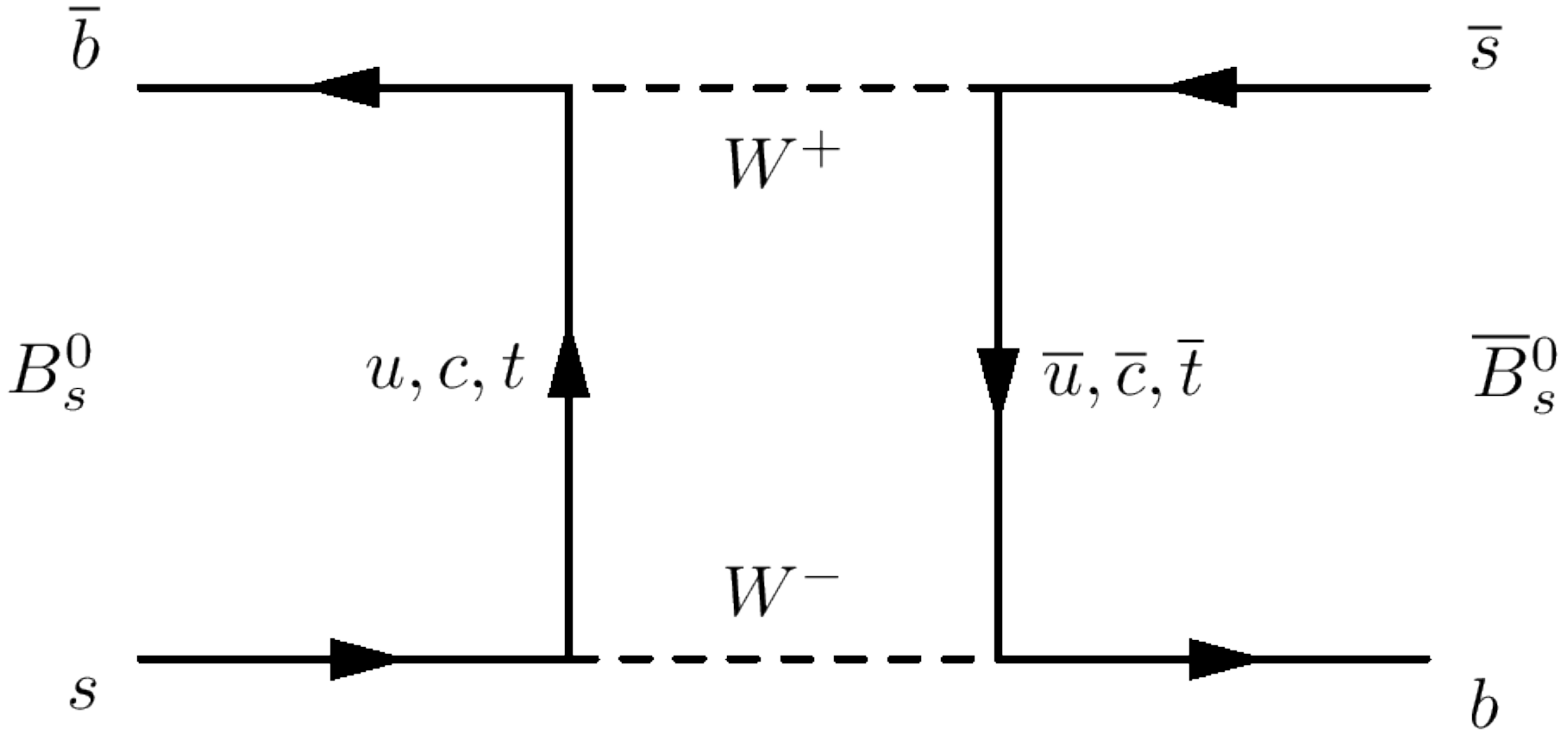
$$\Delta m_d/\Delta m_s(\text{Theory}) = 0.0323(9)(9)(0)(3)$$

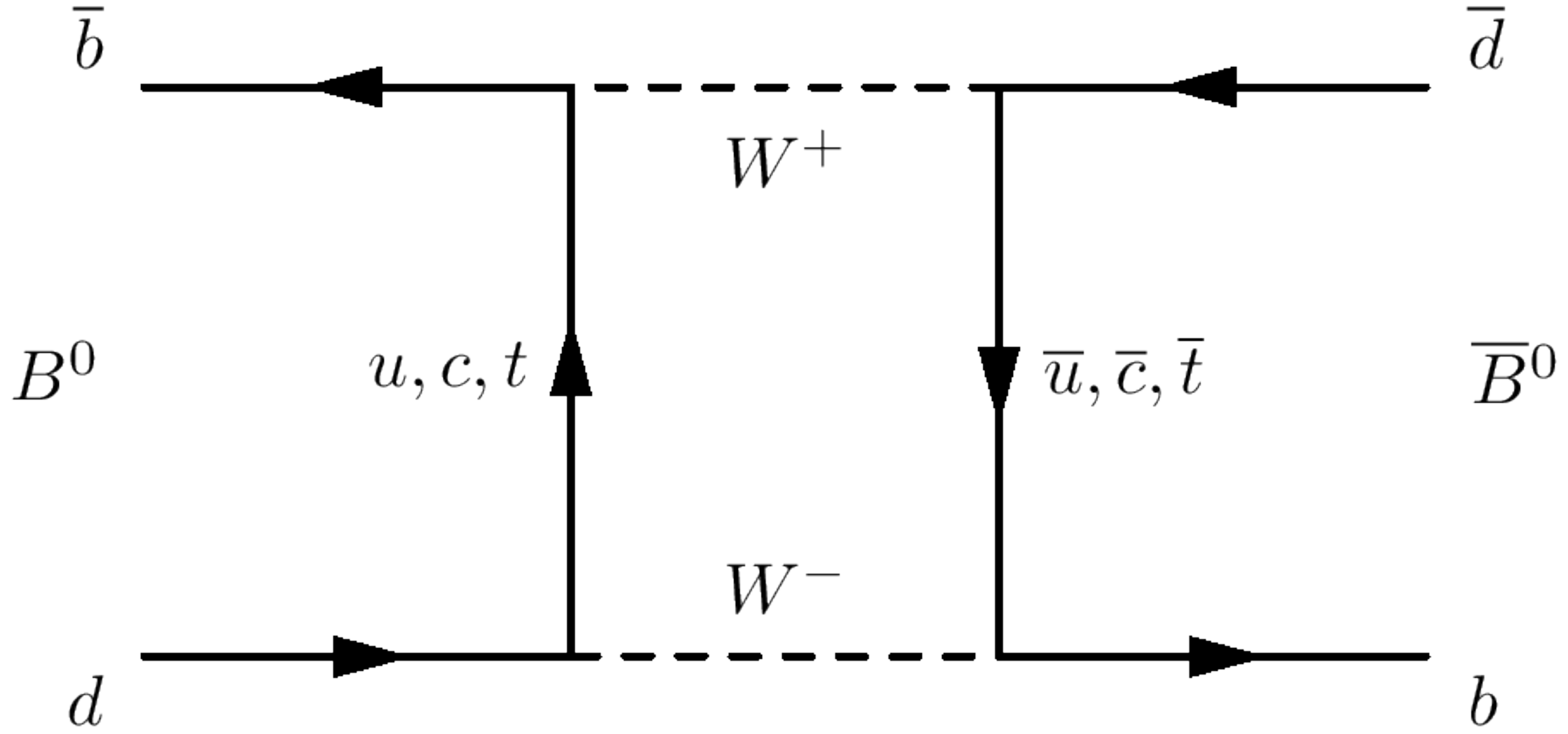
- PDG 2015: $\Delta m_d = (0.510 \pm 0.003)\,\mathrm{ps}^{-1}$, $\Delta m_s = (17.757 \pm 0.021)\,\mathrm{ps}^{-1}$
- Theory prediction for: Δm_d, $\Delta m_d/\Delta m_s$ are 2.1, 2.9σ away from experiment



Recent update from Fermilab lattice and MILC collaborations improves the theory uncertainties, and there is now a growing tension between $\Delta m_d/\Delta m_s$ from theory/exp

Another way of looking at mixing





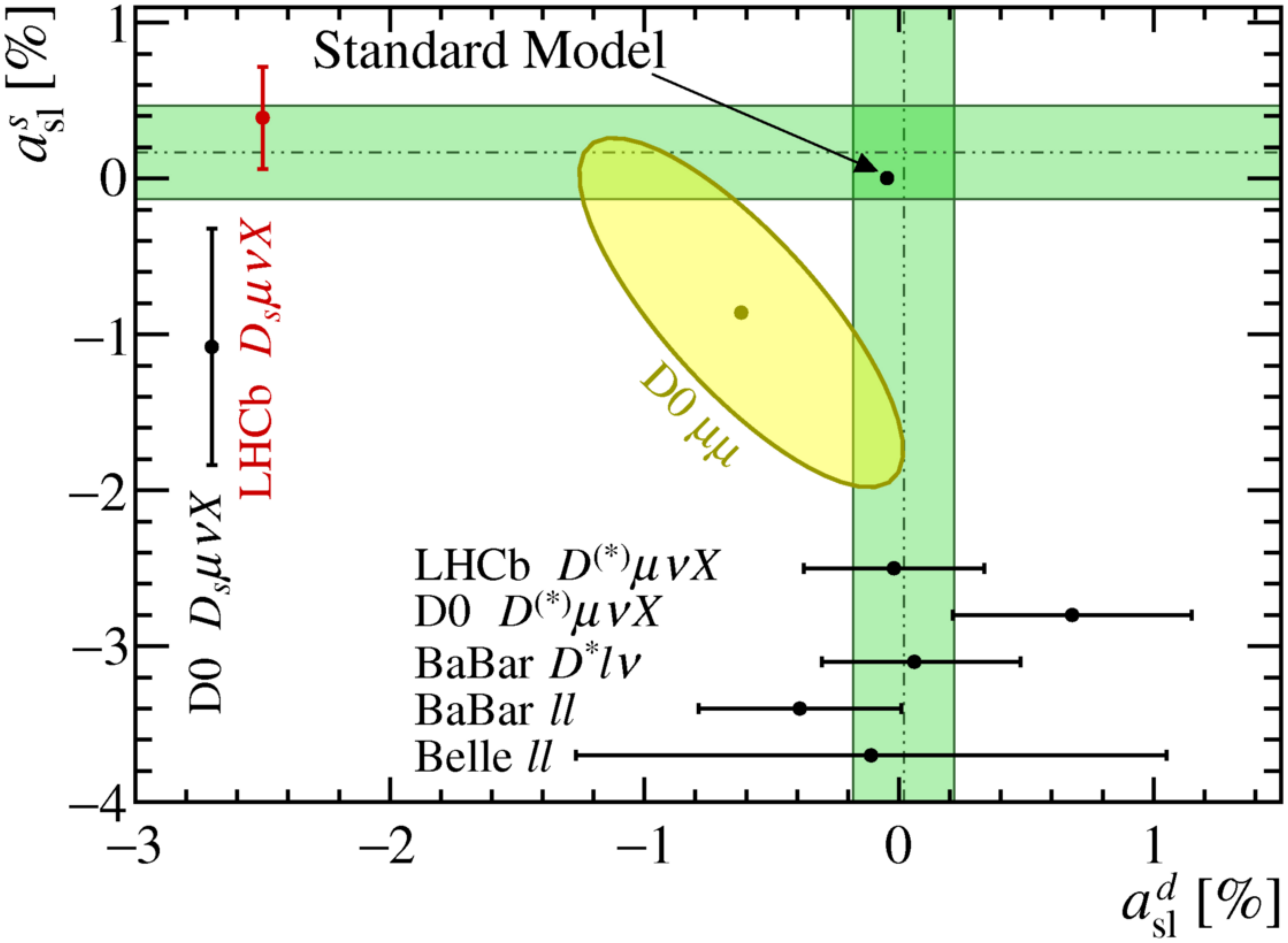
CPV in mixing essentially 0 in SM

=> Measure using B→DμX decays

=> Another excellent null test

Current status

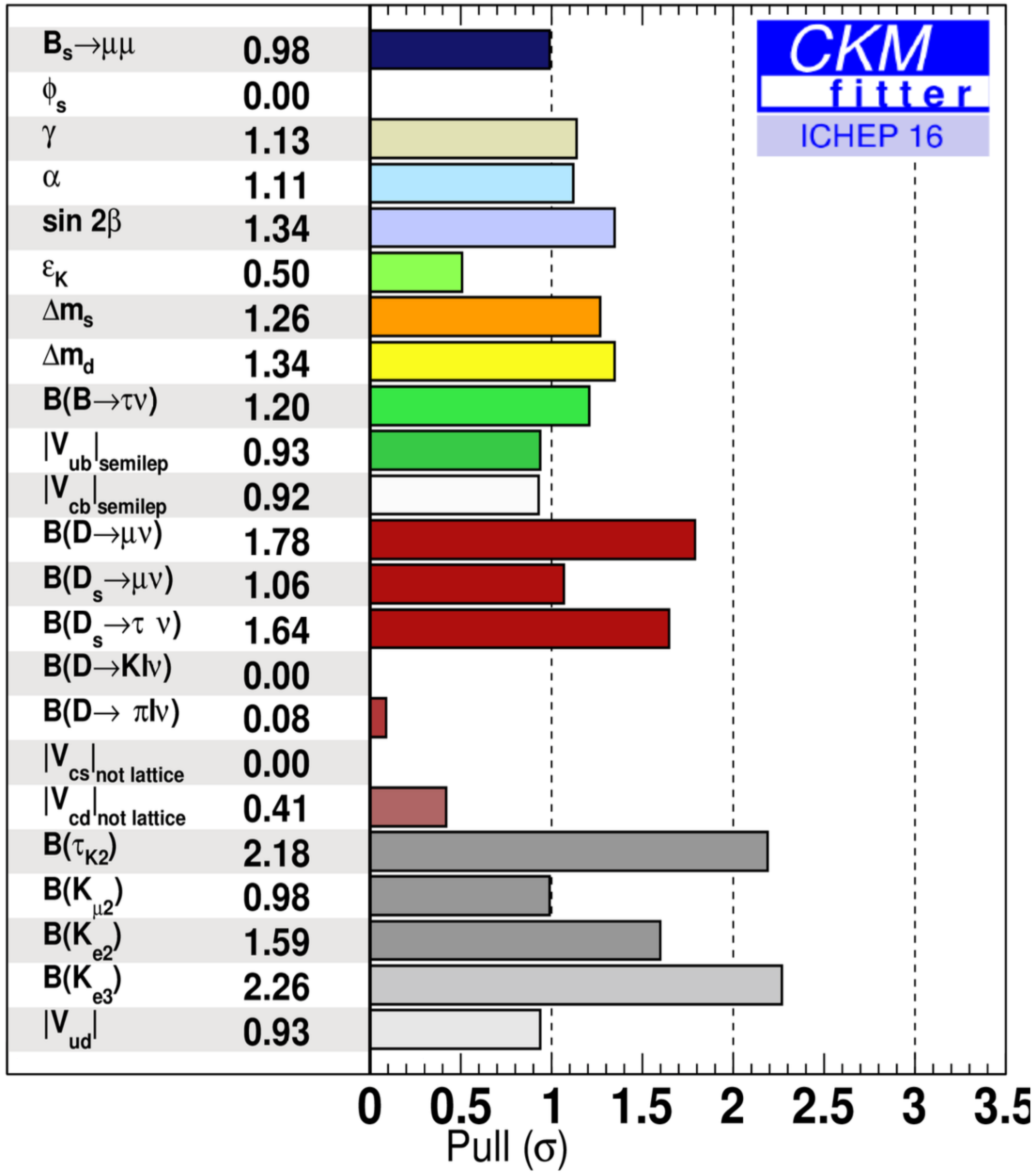
LHCb-PAPER-2016-013



We see a good global agreement with the Standard Model expectations despite earlier tension driven by D0 result

Back to the apex

http://ckmfitter.in2p3.fr
Summer 2015 update so doesn't include many of the show LHCb results

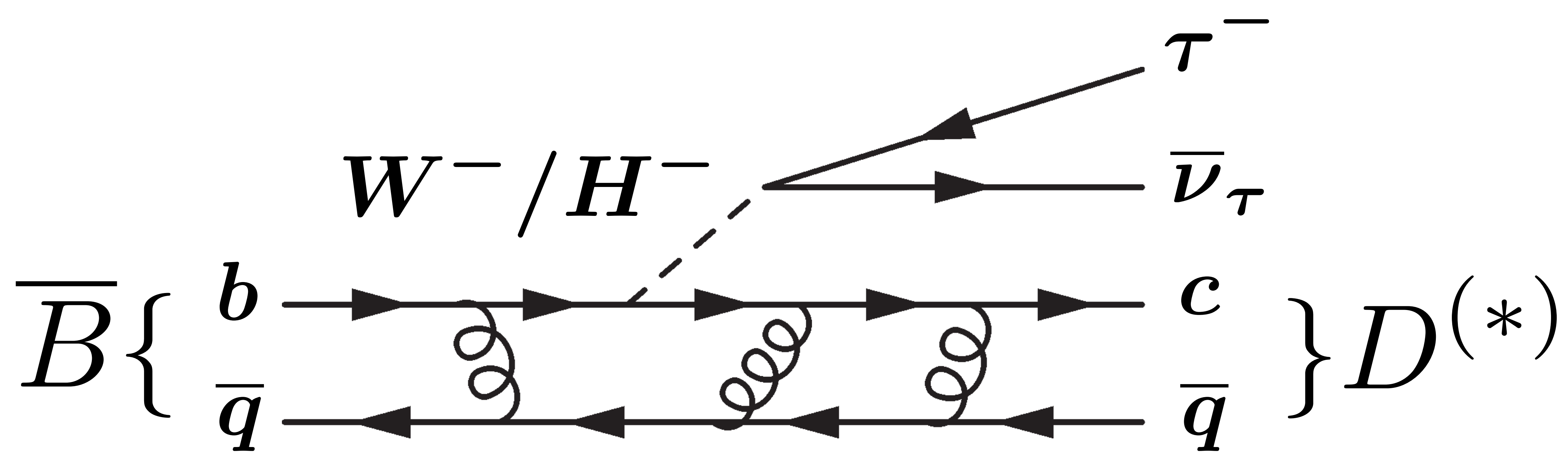


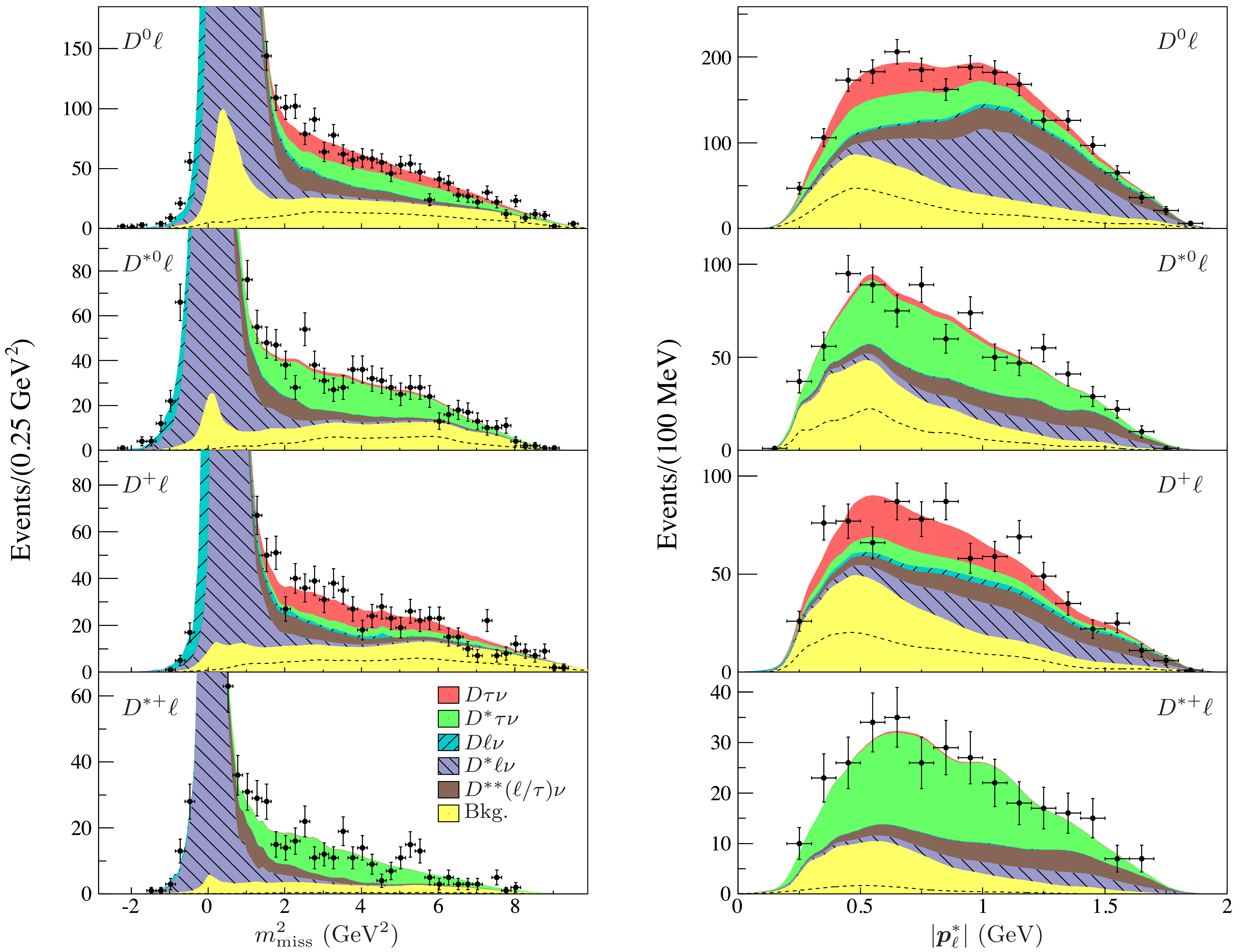
Continue to improve precision on all measurements to overconstrain the apex.
Progress in theory/lattice calculations critical to exploit experimental data.


Lepton Universality
All leptons are equal,
but some leptons…

In tree-level decays

http://arxiv.org/pdf/1303.0571v1.pdf

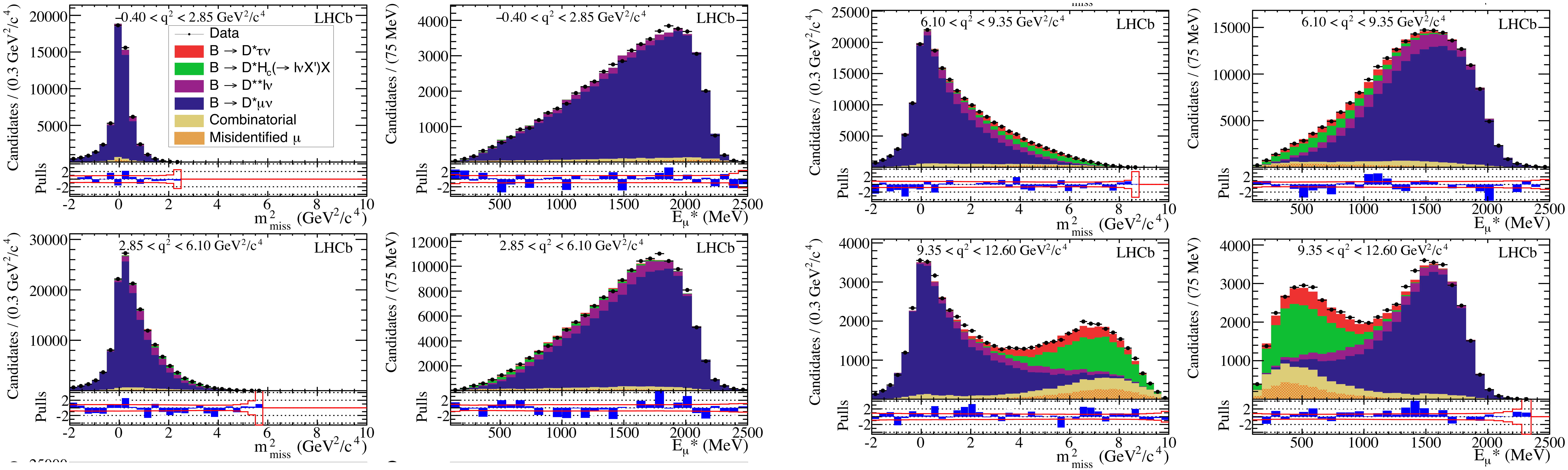




Challenging analysis, significant backgrounds even at B-factories

In tree-level decays

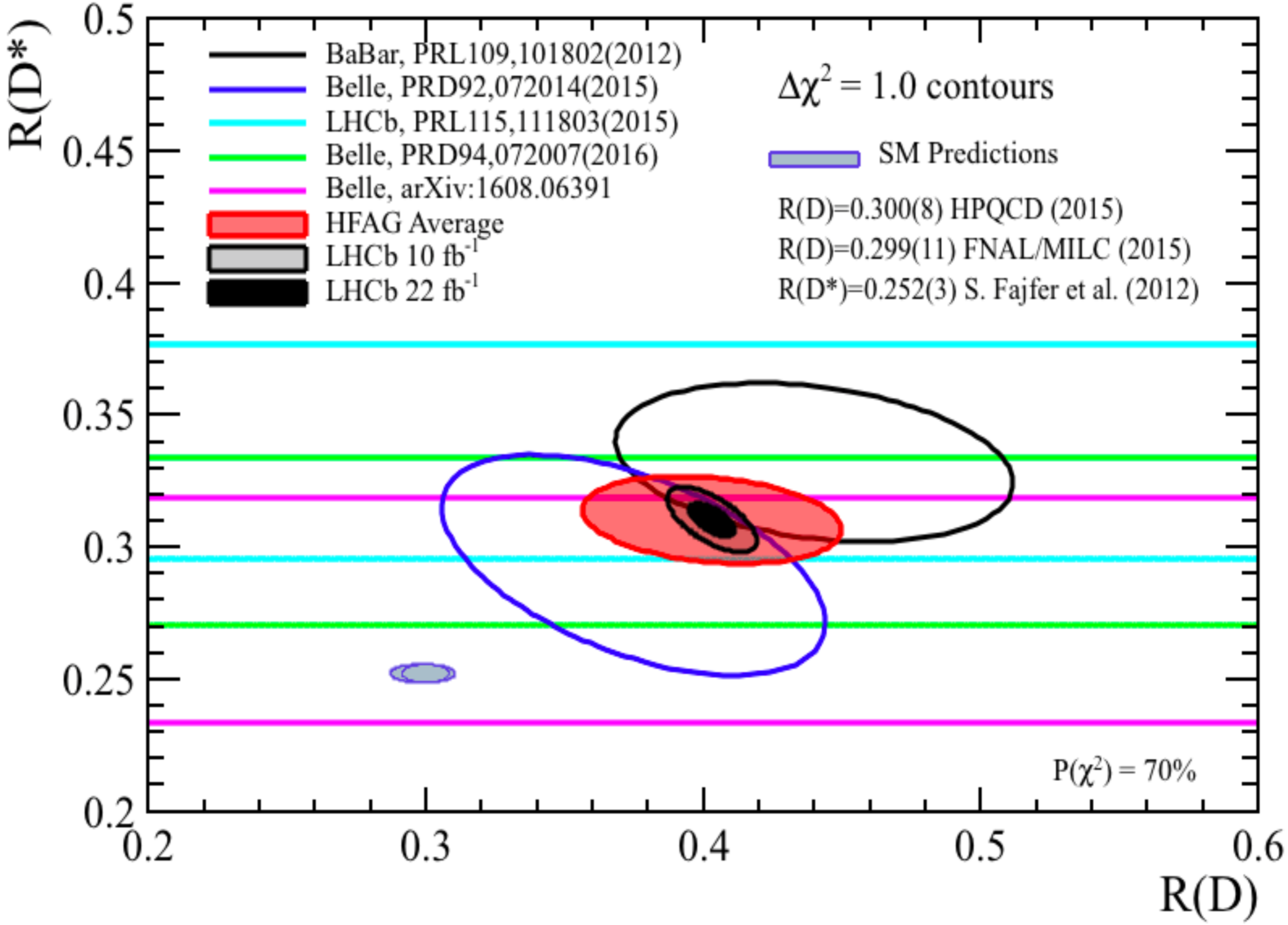
LHCB-PAPER-2015-025



Another area where LHCb has performed despite expectations…

In tree-level decays

©M. Rotondo

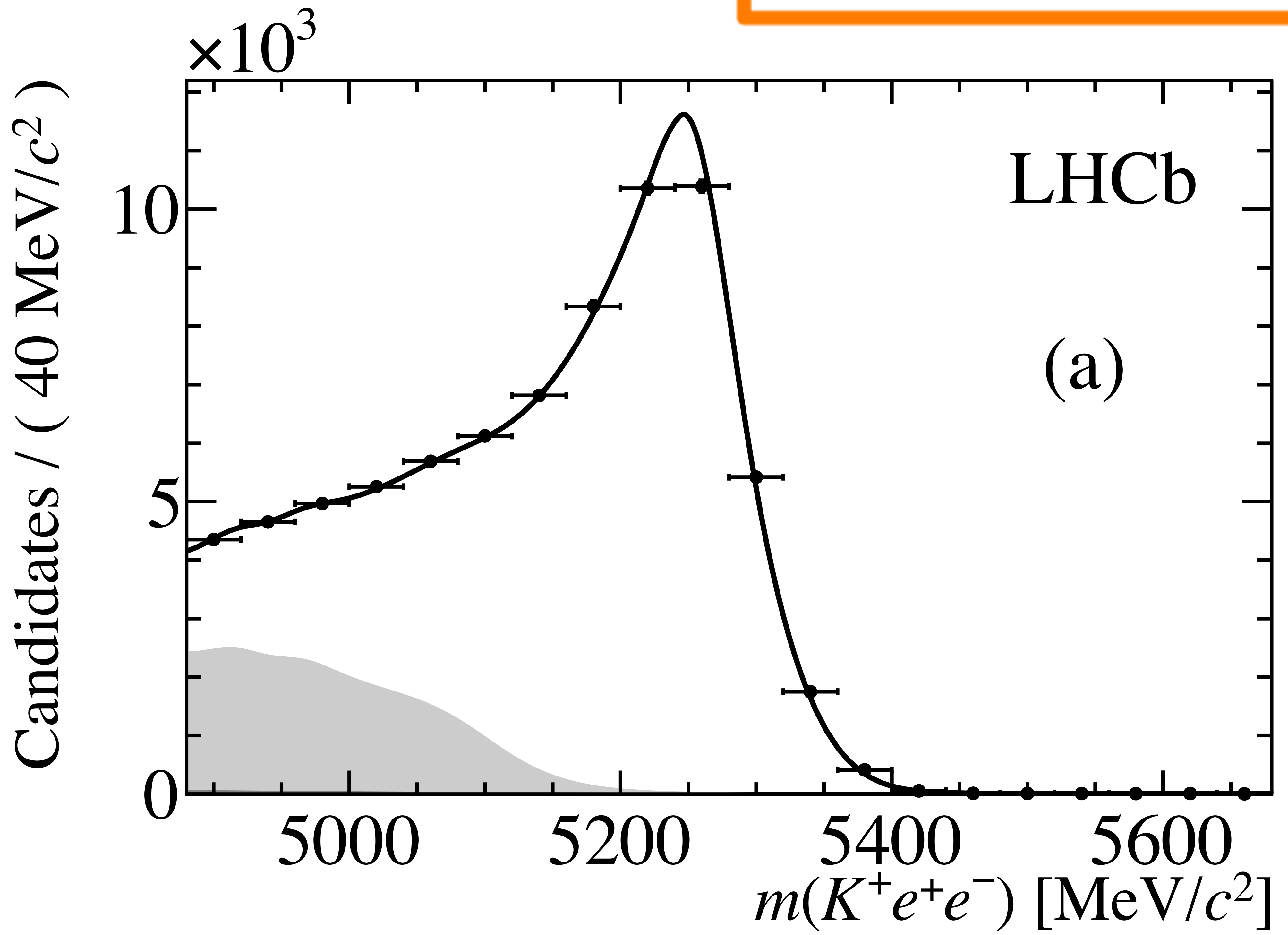


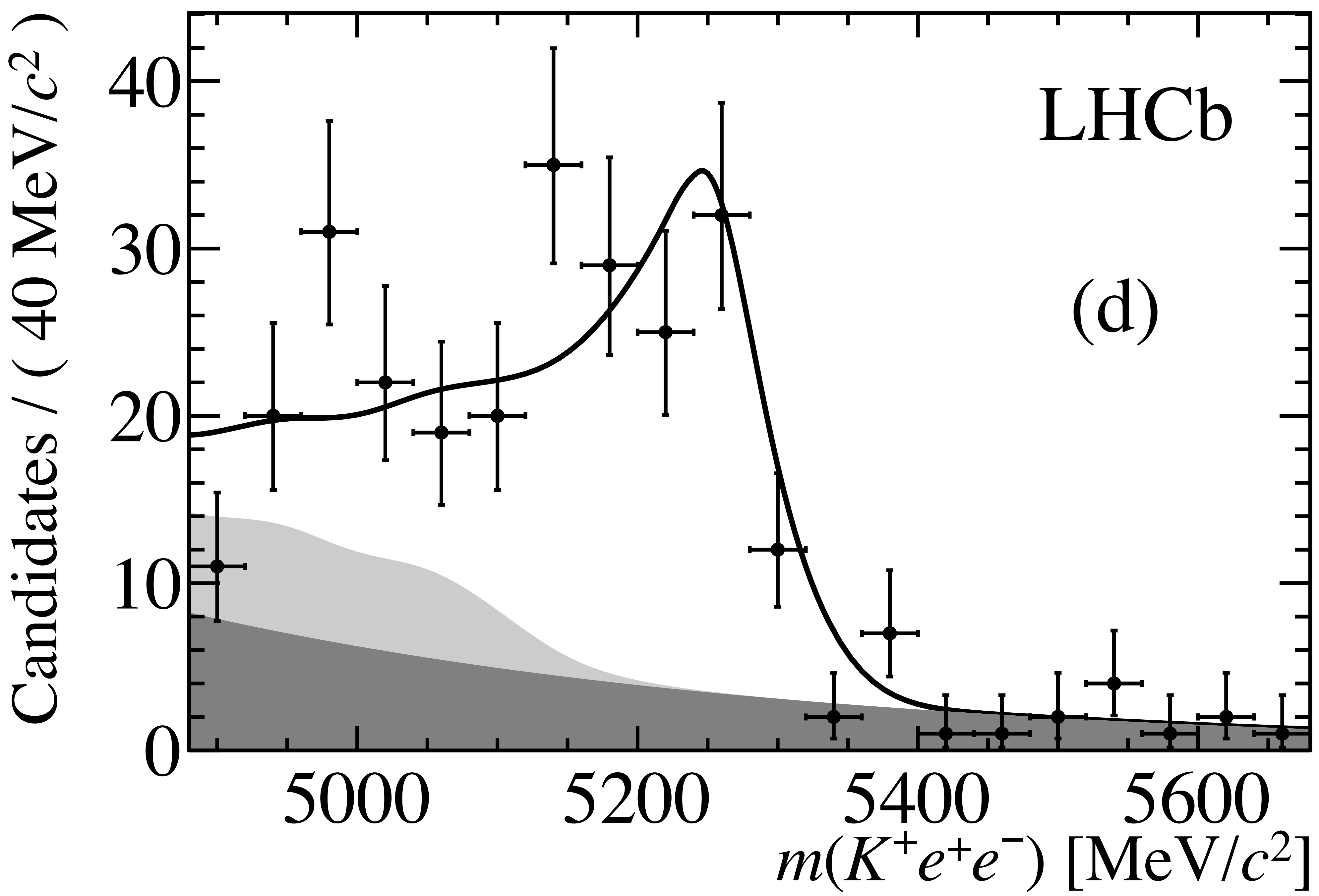
Latest summary of results shown at CKM 2016

In loop-level decays

LHCb-PAPER-2014-024

$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)}$$



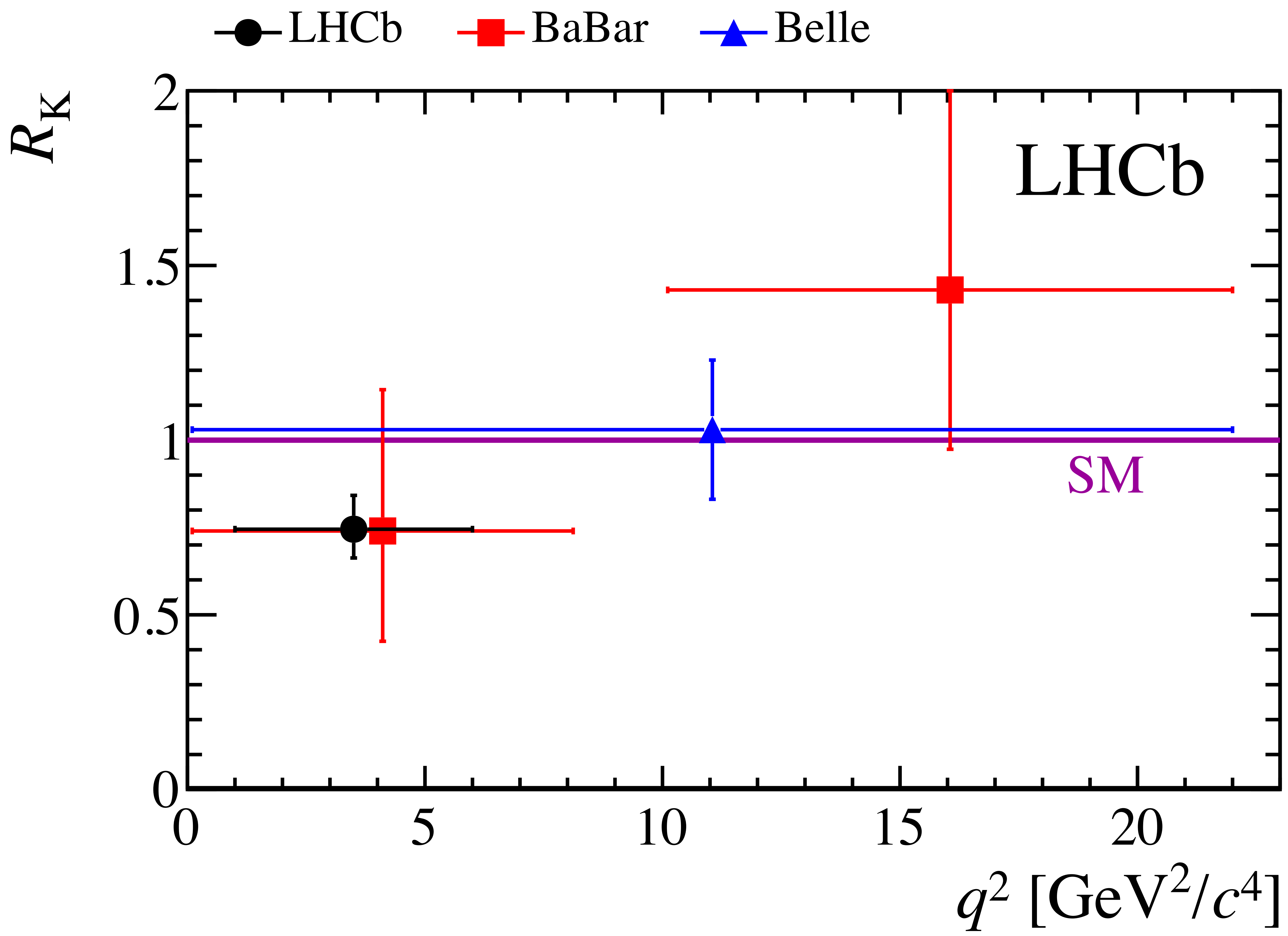


Analysis uses double ratio between resonant/non-resonant modes to help keep the systematics minimal

In loop-level decays

LHCb-PAPER-2014-024

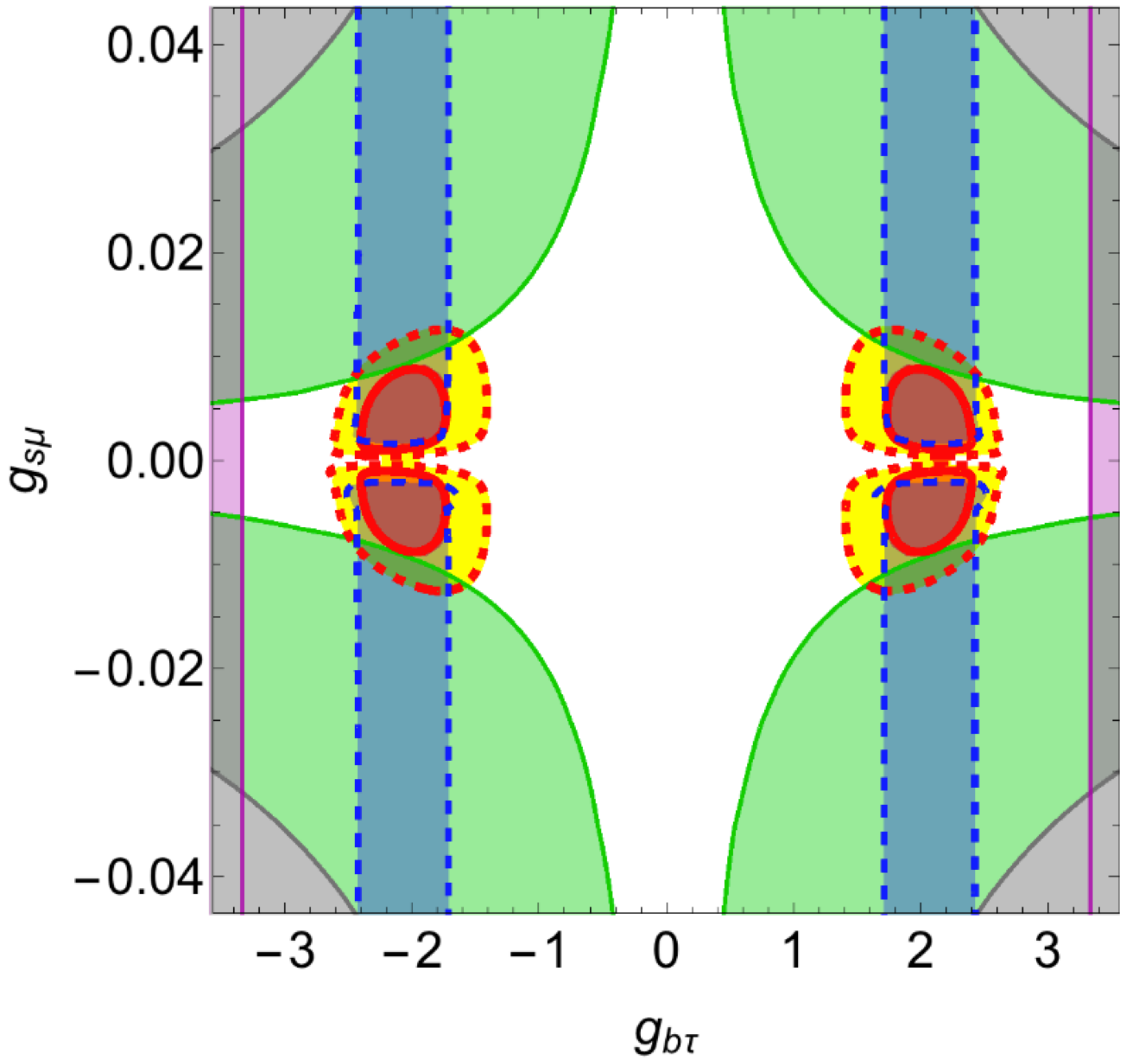
$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} = 0.745 \begin{array}{l} +0.090 \\ -0.074 \end{array} (stat) \pm 0.036 (syst)$$

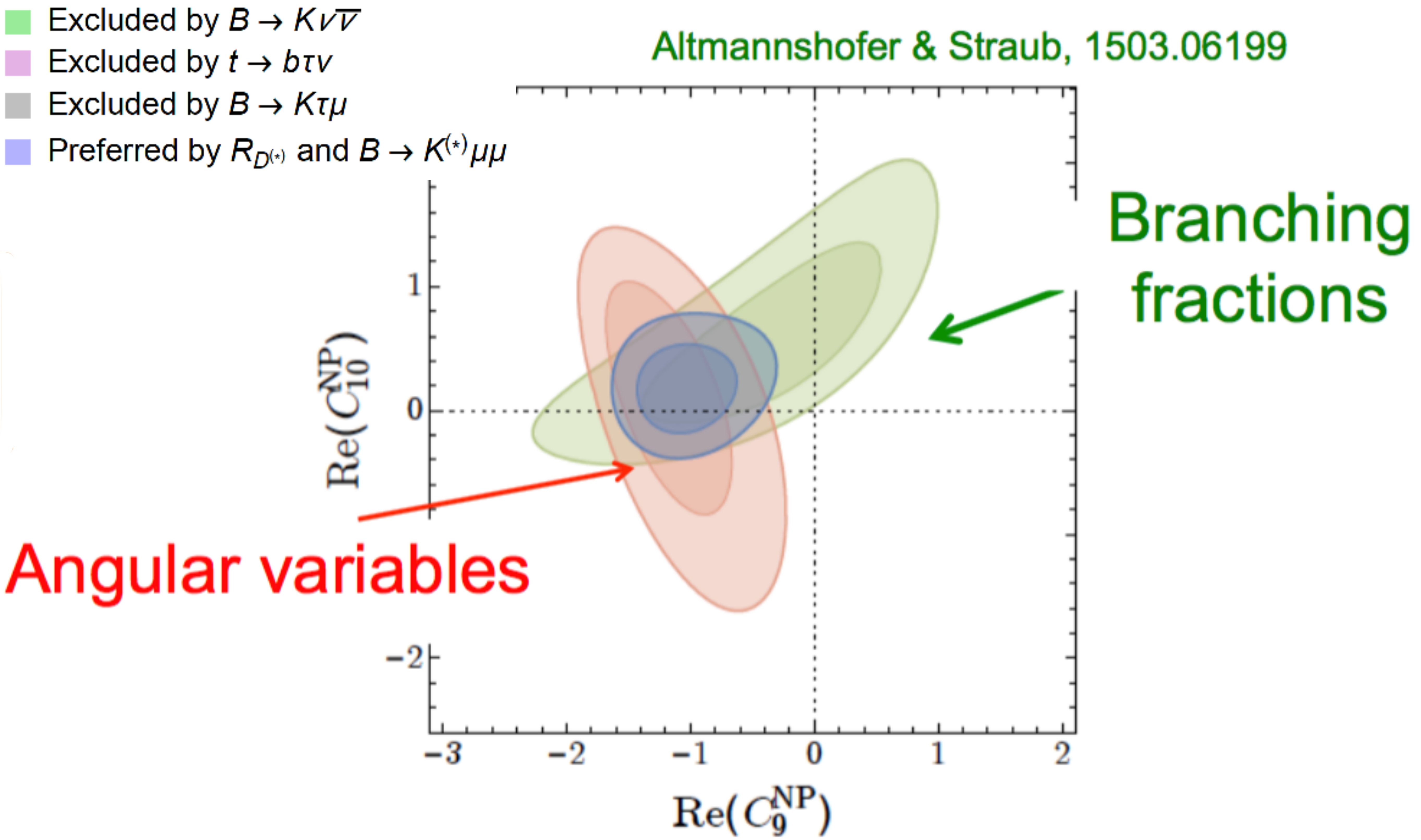


A 2.6σ tension when looked at on its own…

Global picture shows tension with SM

Fajfer & Košnik 1511.06024v4





I am stealing again from Albrecht's talk at Moriond EW 2016


WHAT DO WE WANT?
More precise measurements
WHEN DO WE WANT IT?
Now!


The Future Is Now!

Latest crystal ball projections

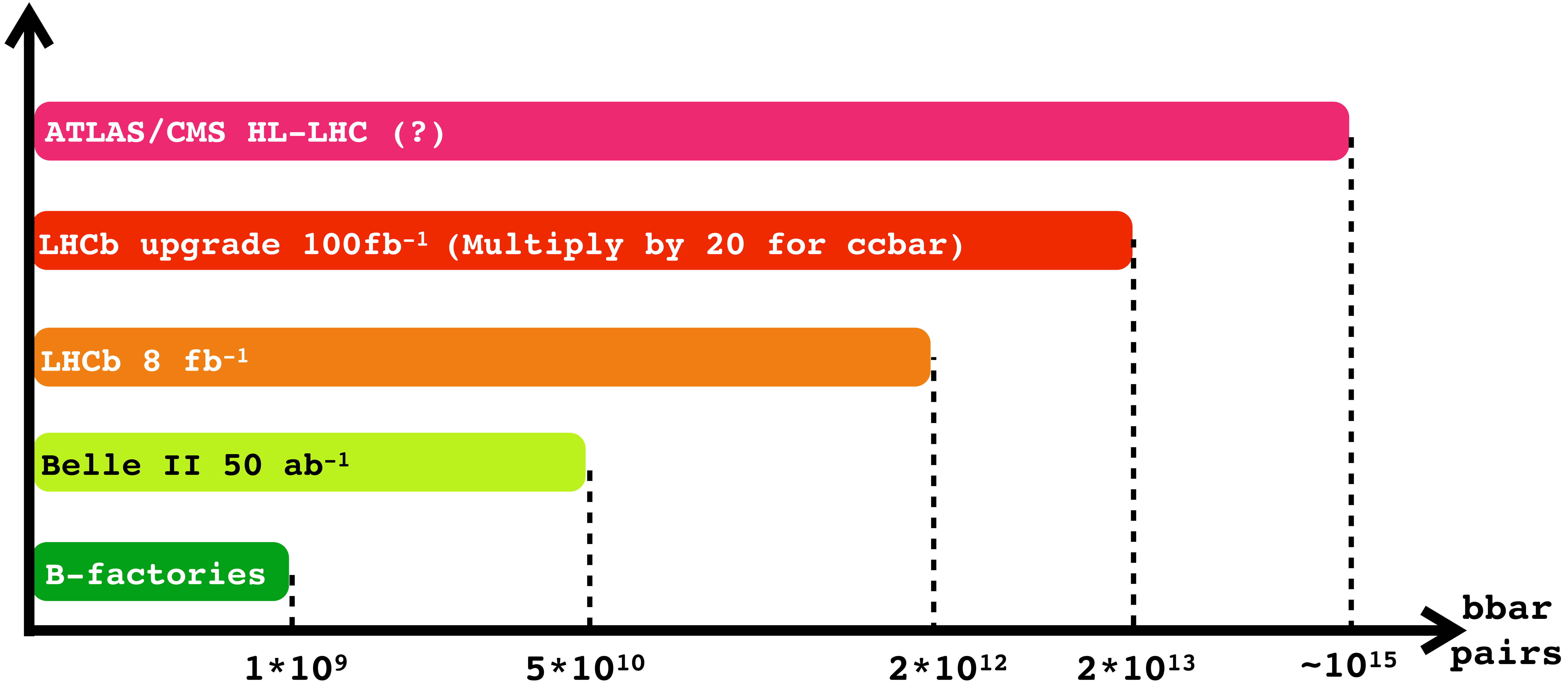
	LHC era			HL-LHC era	
	Run 1 (2010–12)	Run 2 (2015–17)	Run 3 (2019–21)	Run 4 (2024–26)	Run 5+ (2028–30+)
ATLAS & CMS	$25\,\text{fb}^{-1}$	$100\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$	$\longrightarrow$	$3000\,\text{fb}^{-1}$
LHCb	$3\,\text{fb}^{-1}$	$8\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$46\,\text{fb}^{-1}$	$100\,\text{fb}^{-1}$
Belle II	—	$0.5\,\text{ab}^{-1}$	$25\,\text{ab}^{-1}$	$50\,\text{ab}^{-1}$	—

+NA62, 10% on BR($K^+\to\pi^+\nu\nu$) roughly by start of Run III

+KOTO observes $K^0\to\pi^0\nu\nu$ by the end of Run XX?

https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

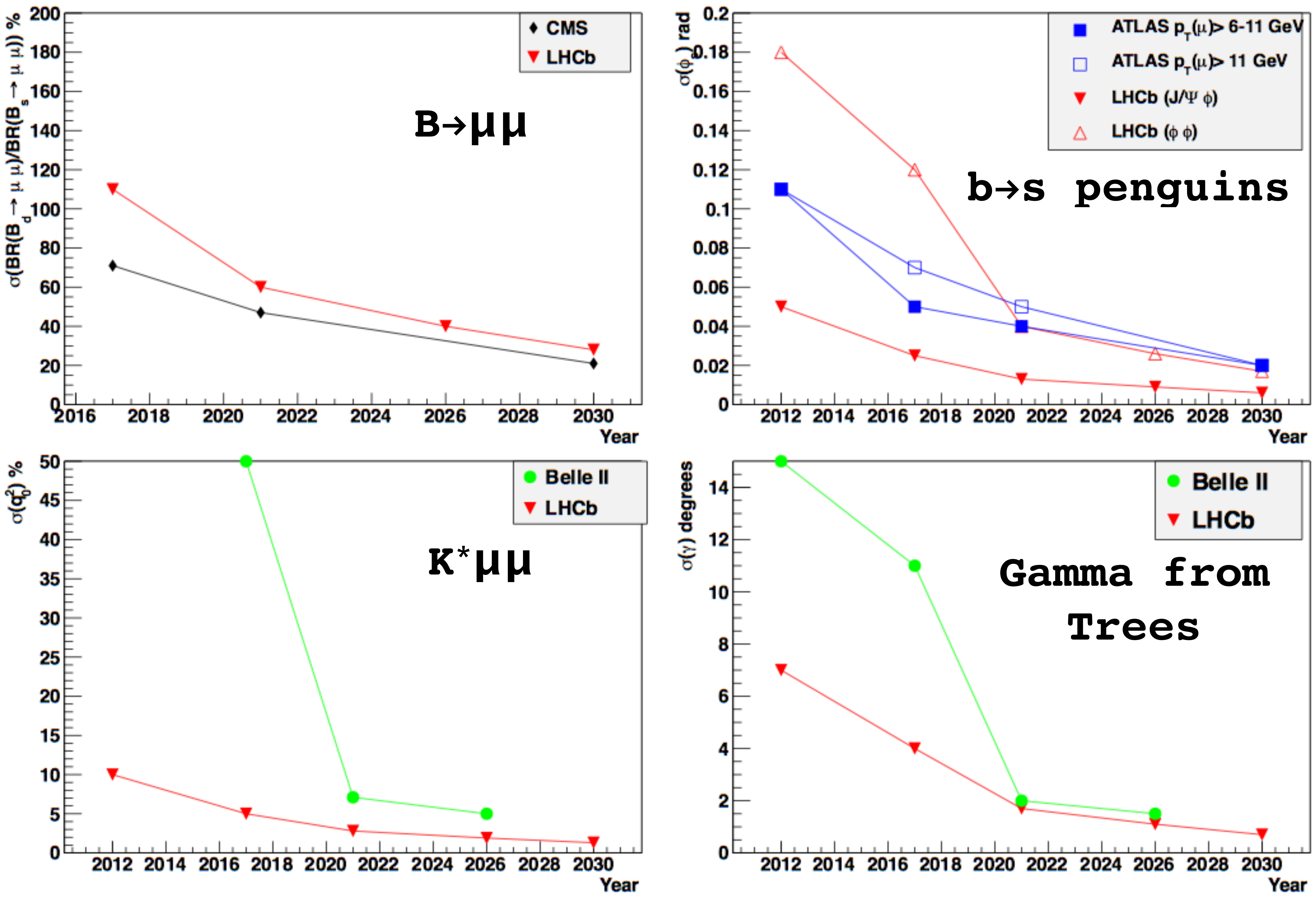
Some example signal rates



B-factories/Belle II should be scaled by ~10 compared to LHCb to account for efficiencies, hermetic detectors, and a cleaner environment.

Effective size of ATLAS/CMS sample depends on their trigger evolution.

A few key observables



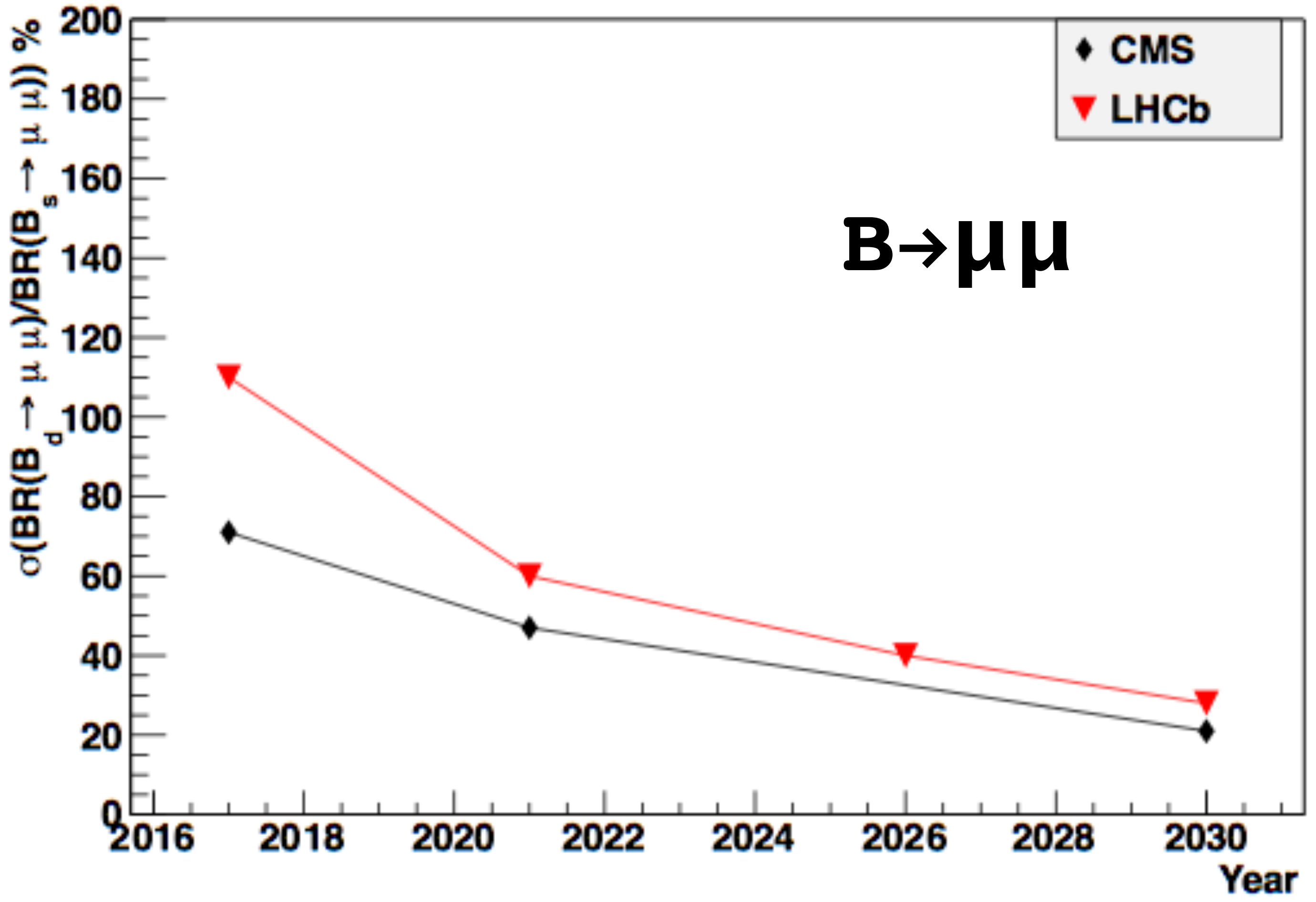
https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

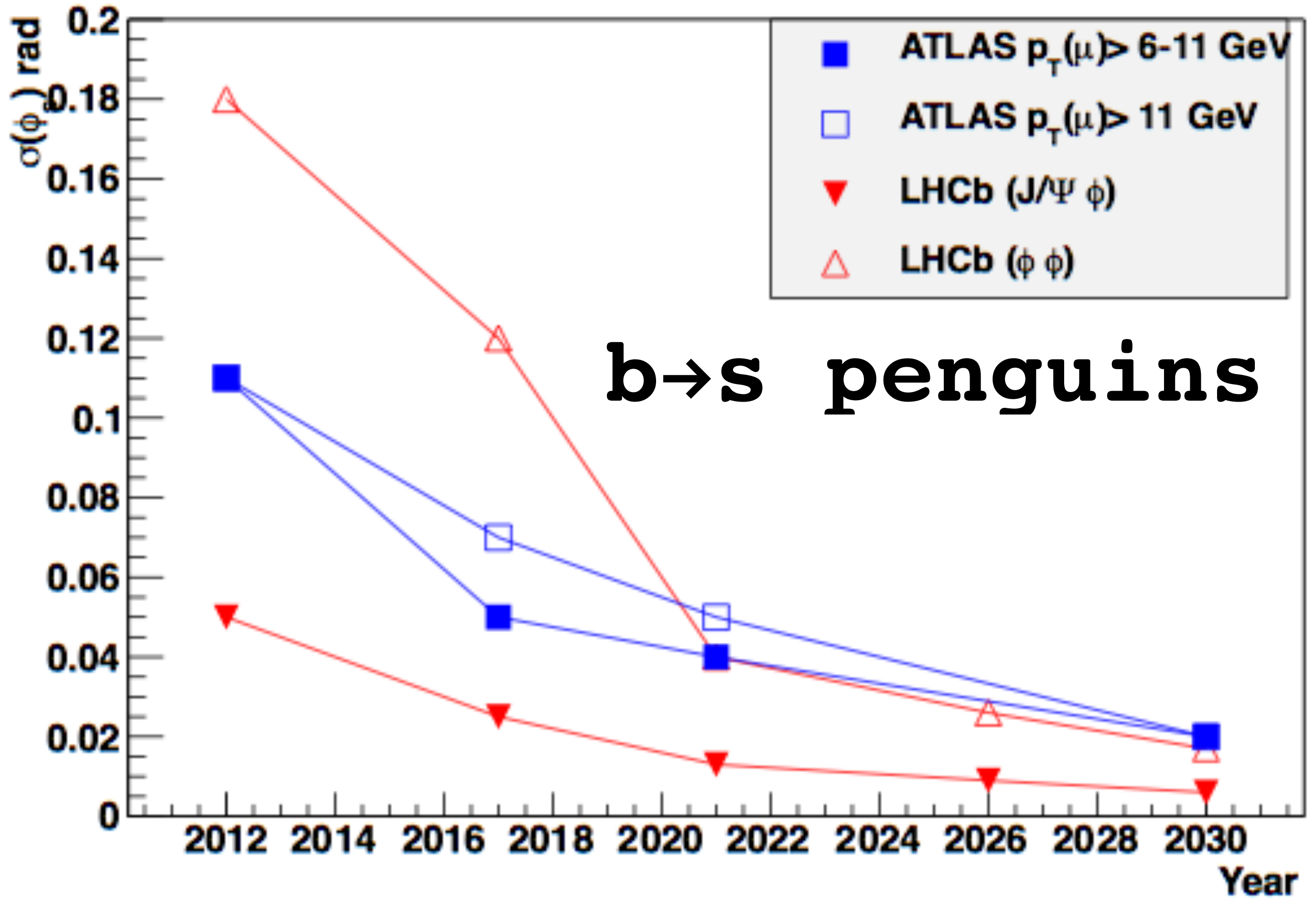
Personal aside on complementarity

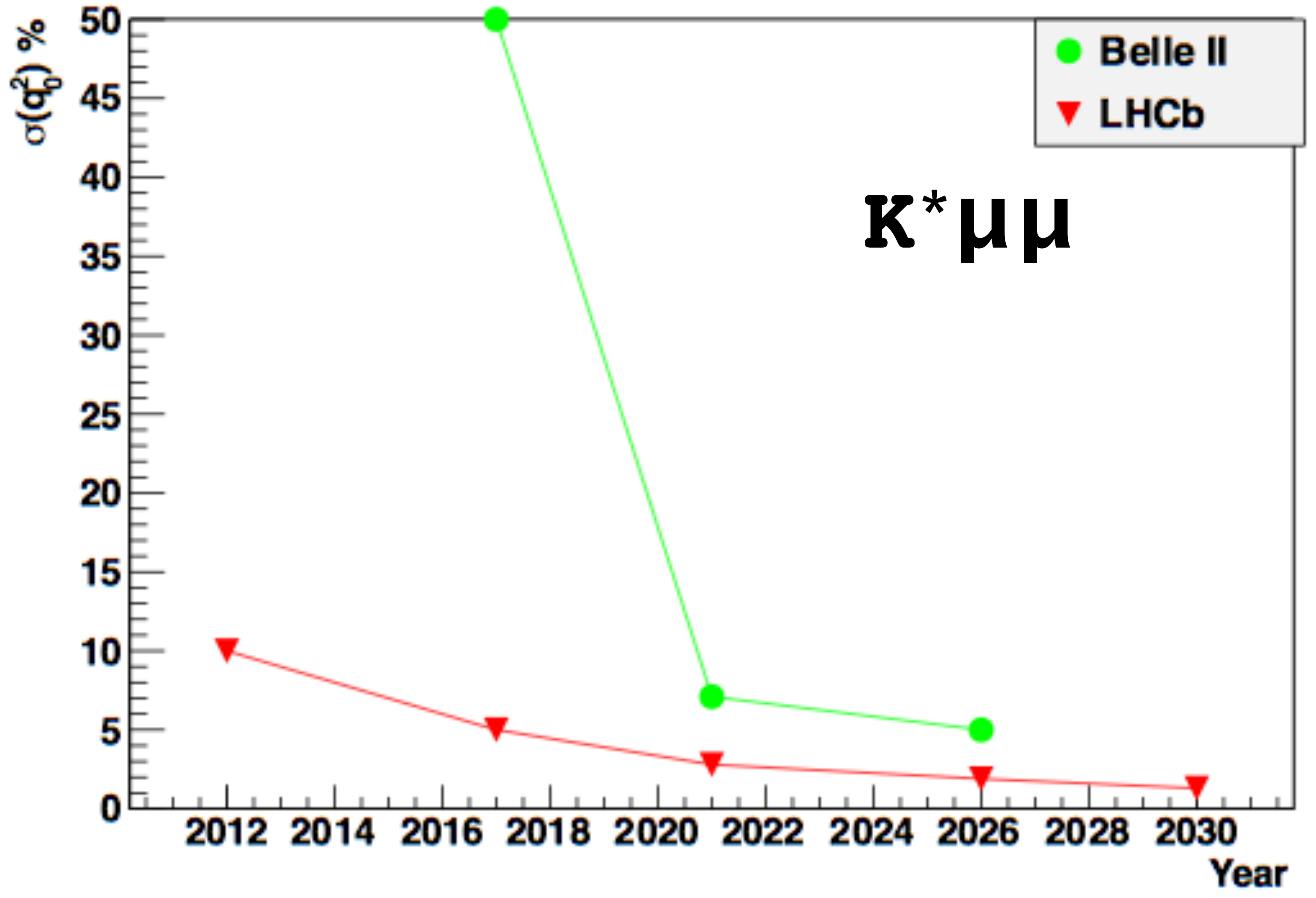
	LHCb upgrade	Belle II	ATLAS/CMS
Rare B decays	*****	***	****
B_s mixing	*****		**
B_d mixing	**	*****	
Incl. processes ($X_s\gamma$, $X_s ll$, etc.)		*****	
b-baryon and B_c physics	*****		**
Charm, charged final states	*****	**	?
Charm, neutral final states	**	*****	
LFV ($\tau \to \mu\gamma, \mu\mu\mu$)	**	*****	?

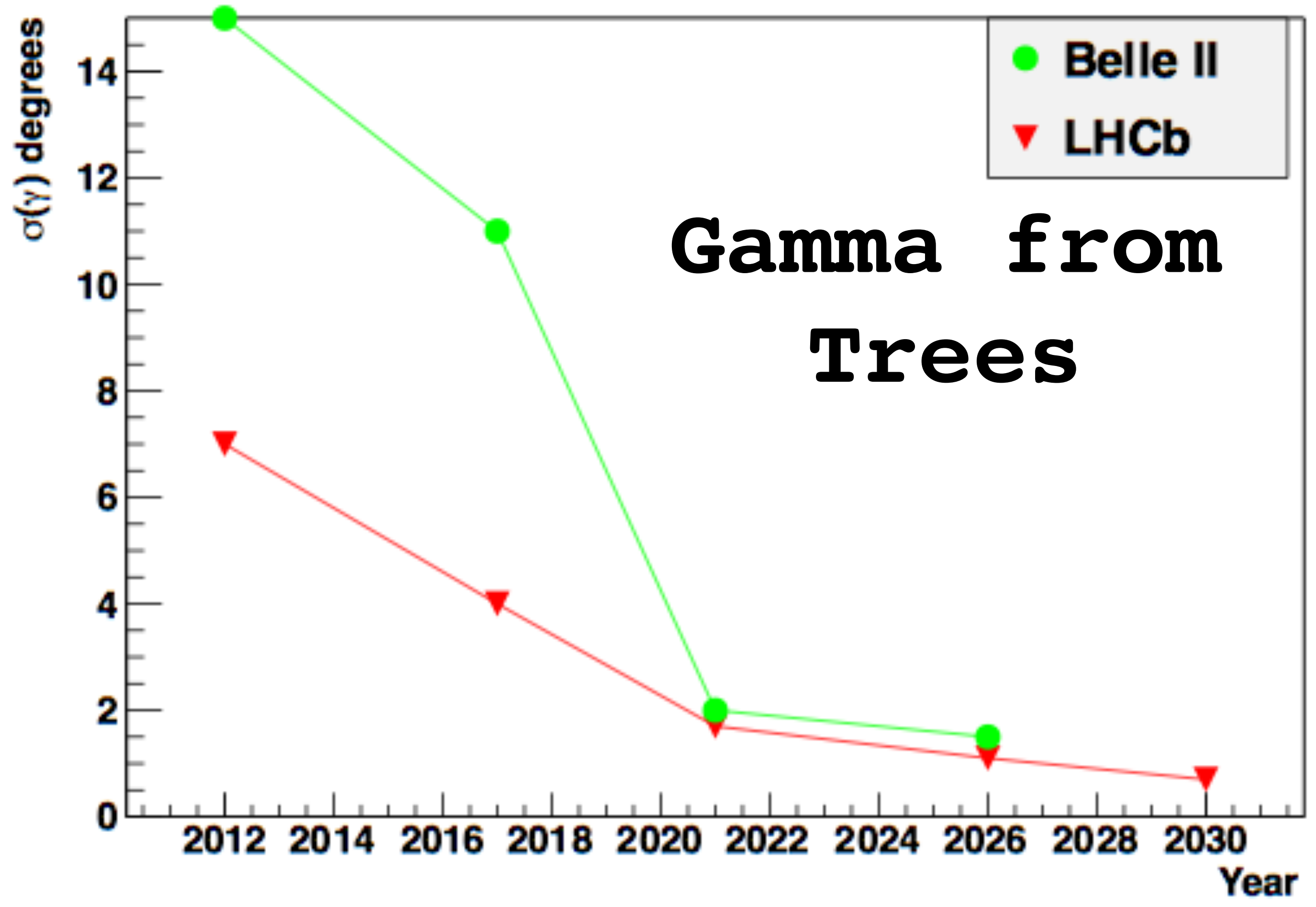
Publicity plots are made with observables which are by definition common to all experiments, therefore they hide the complementarity of the programme.

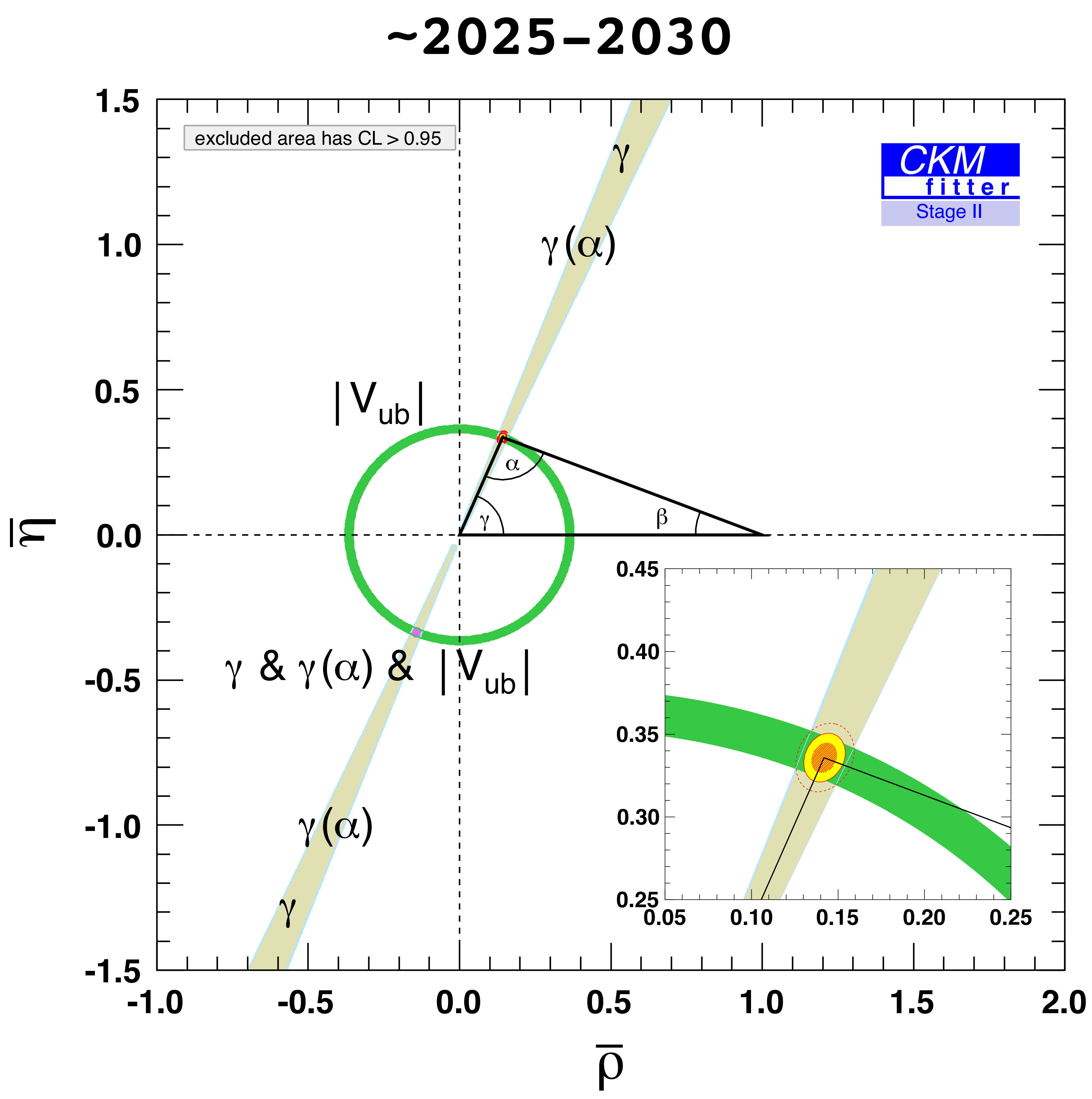
The impact on the UT, 2030







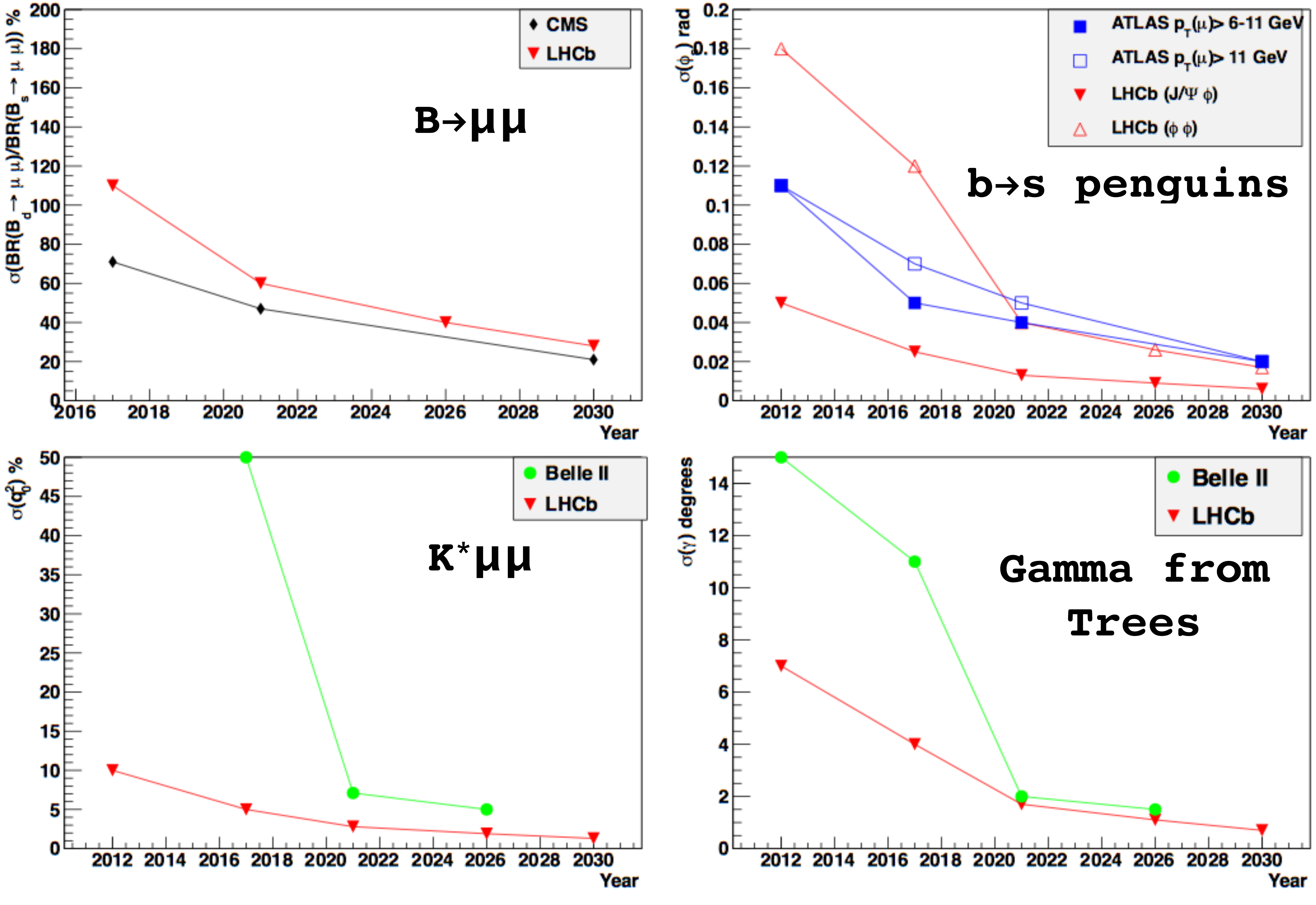


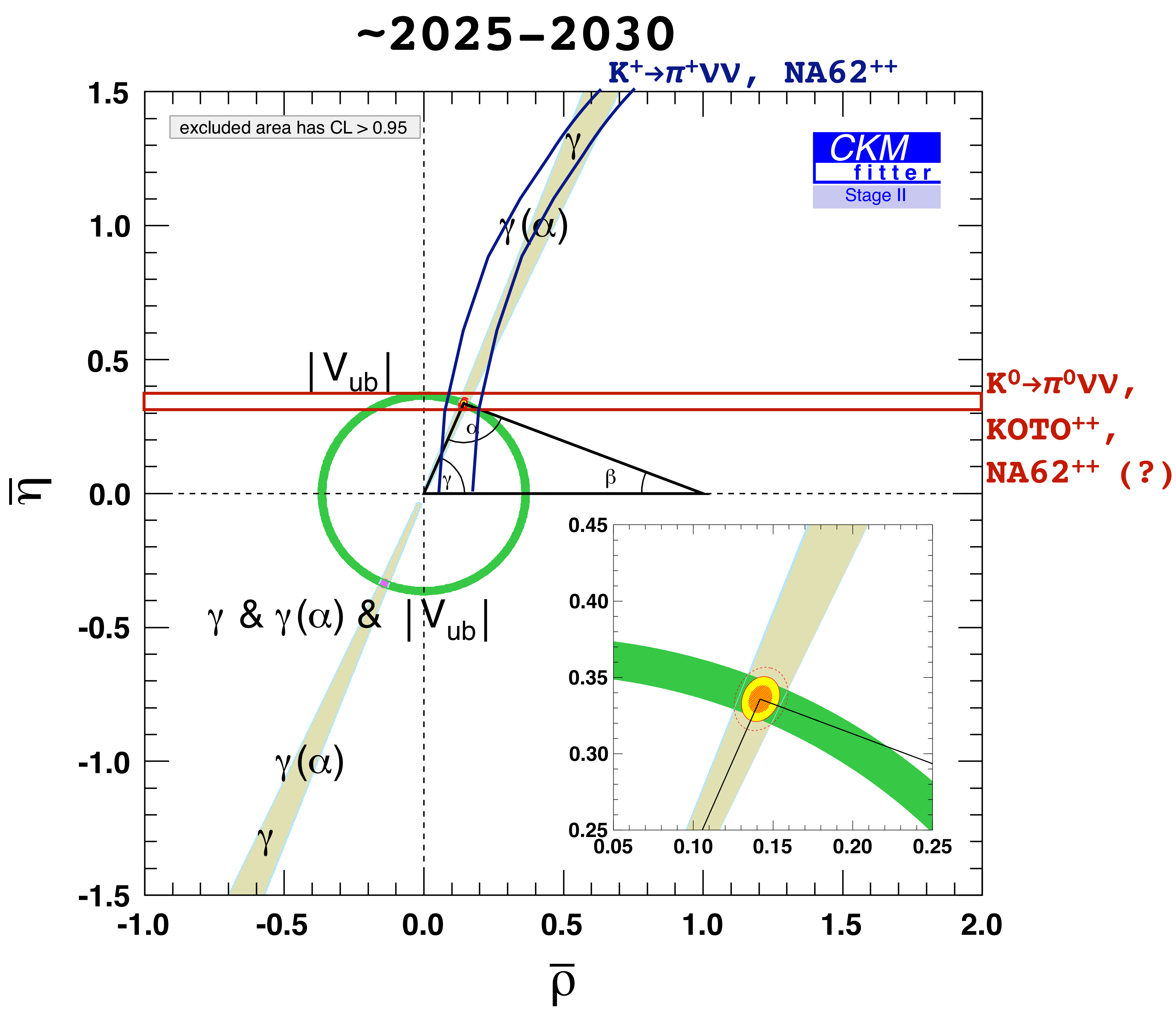


https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

J. Charles et al. http://arxiv.org/abs/1309.2293

Let’s add a bit of wishful thinking





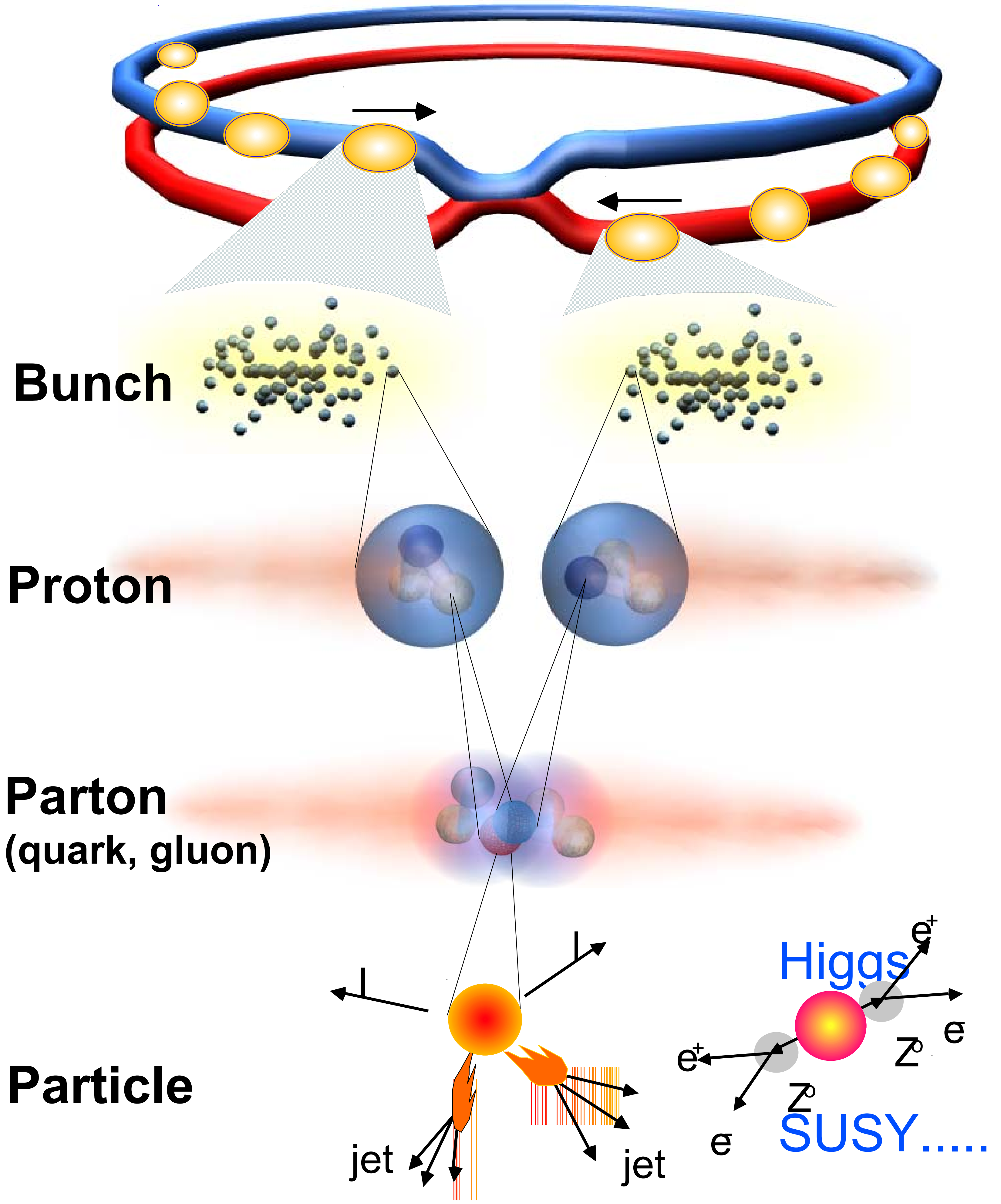
https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

J. Charles et al. http://arxiv.org/abs/1309.2293

Let’s talk about practicalities

The traditional view of data processing

Collisions at the LHC: summary



Proton - Proton	2804 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	$10^{34} cm^{-2} s^{-1}$
Crossing rate	40 MHz
Collision rate ≈	10^7-10^9

New physics rate ≈ .00001 Hz

Event selection:
1 in 10,000,000,000,000

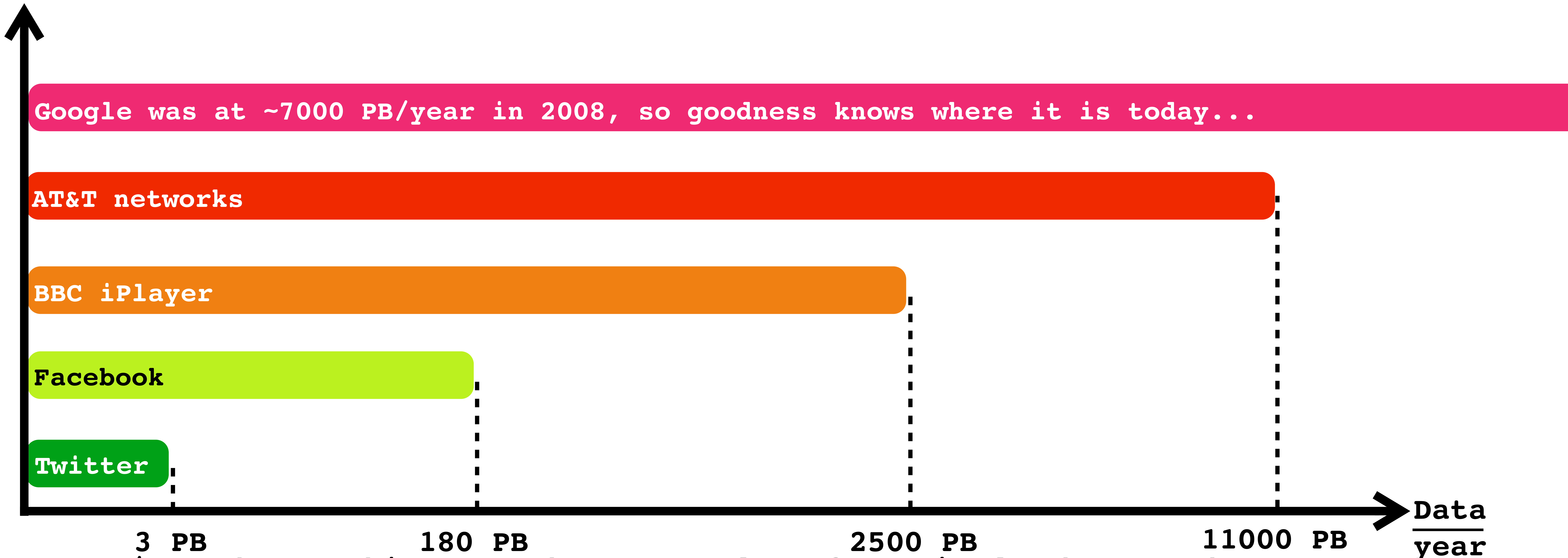
Analysis today

How much data do we process?

Input data rate of the LHCb experiment in 2020 = 5 TB/second

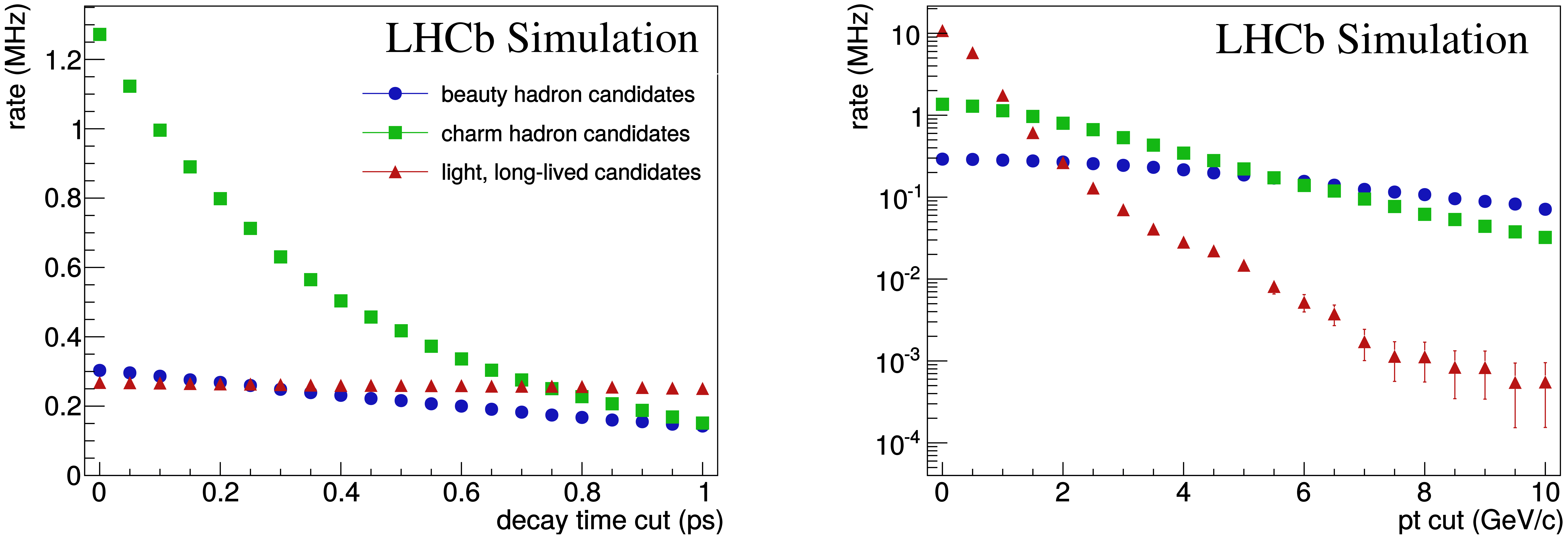
→

This means about 20000 PB of data every year



NB : ATLAS/CMS about a bit more than one order of magnitude above LHCb

Enter the MHz signal era



In the HL-LHC era there is no such thing as an uninteresting *pp* interaction!

Fitzpatrick&Gligorov http://cds.cern.ch/record/1670985?ln=en

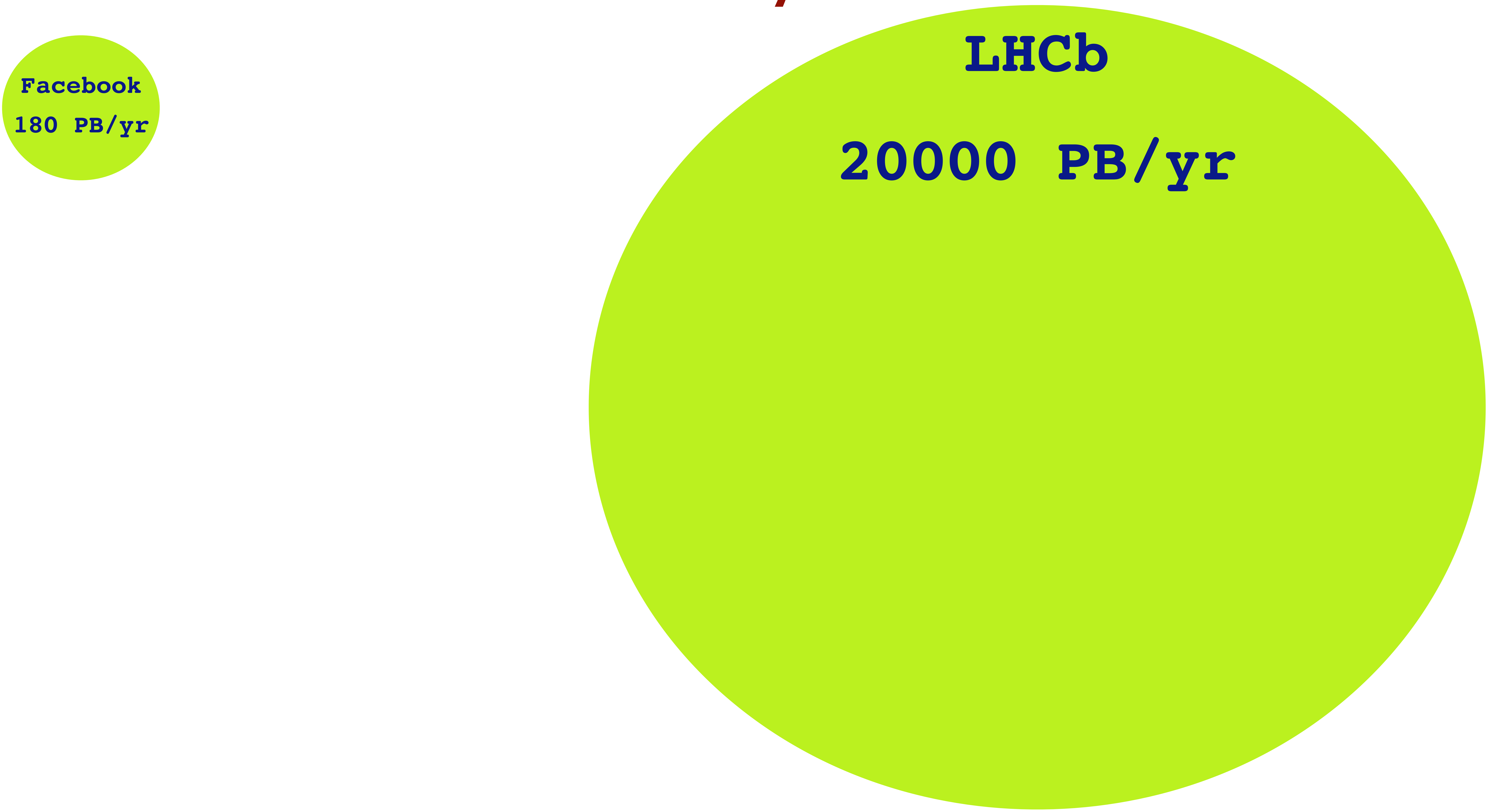
Analysis today

Analysis in the future

It’s all about the money

Facebook
180 PB/yr

It’s all about the money



It’s all about the money

It's all about the money

Facebook

180 PB/yr

LHCb

20000 PB/yr

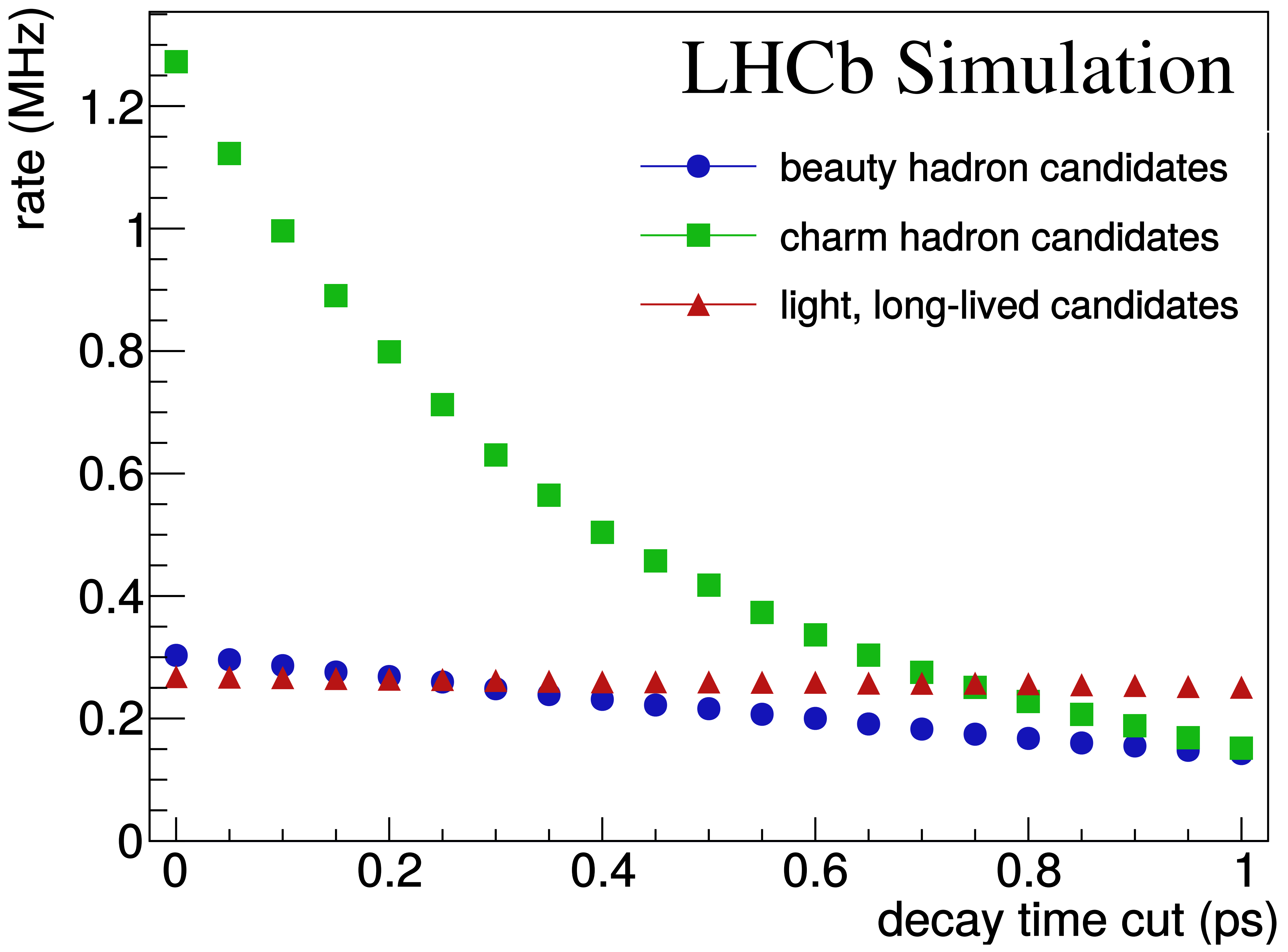
Storing and distributing data costs more than processing => real time analysis!

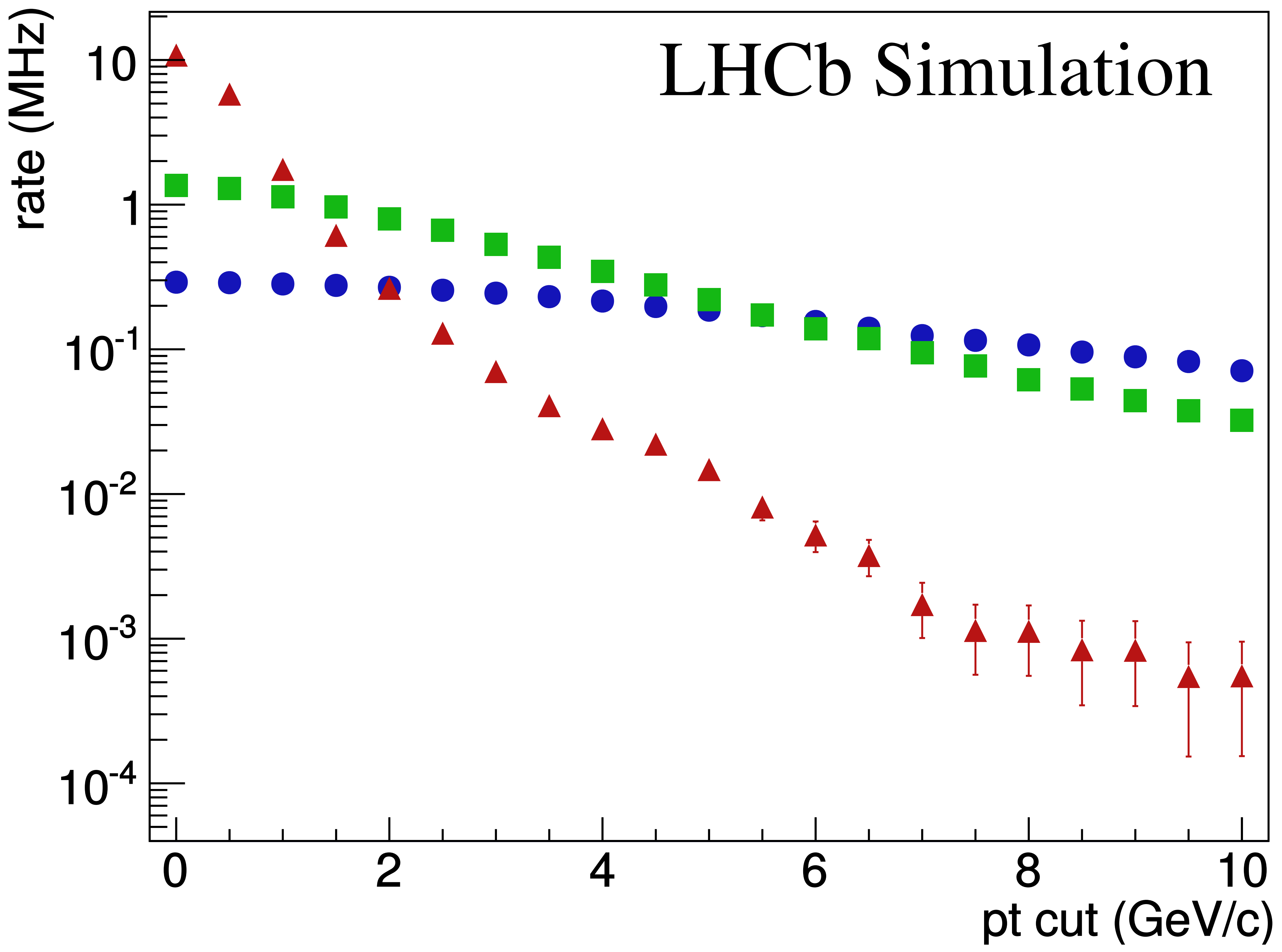
Must reduce data rate by O(10^{-3}) for affordable long-term processing.

LHCb Computing

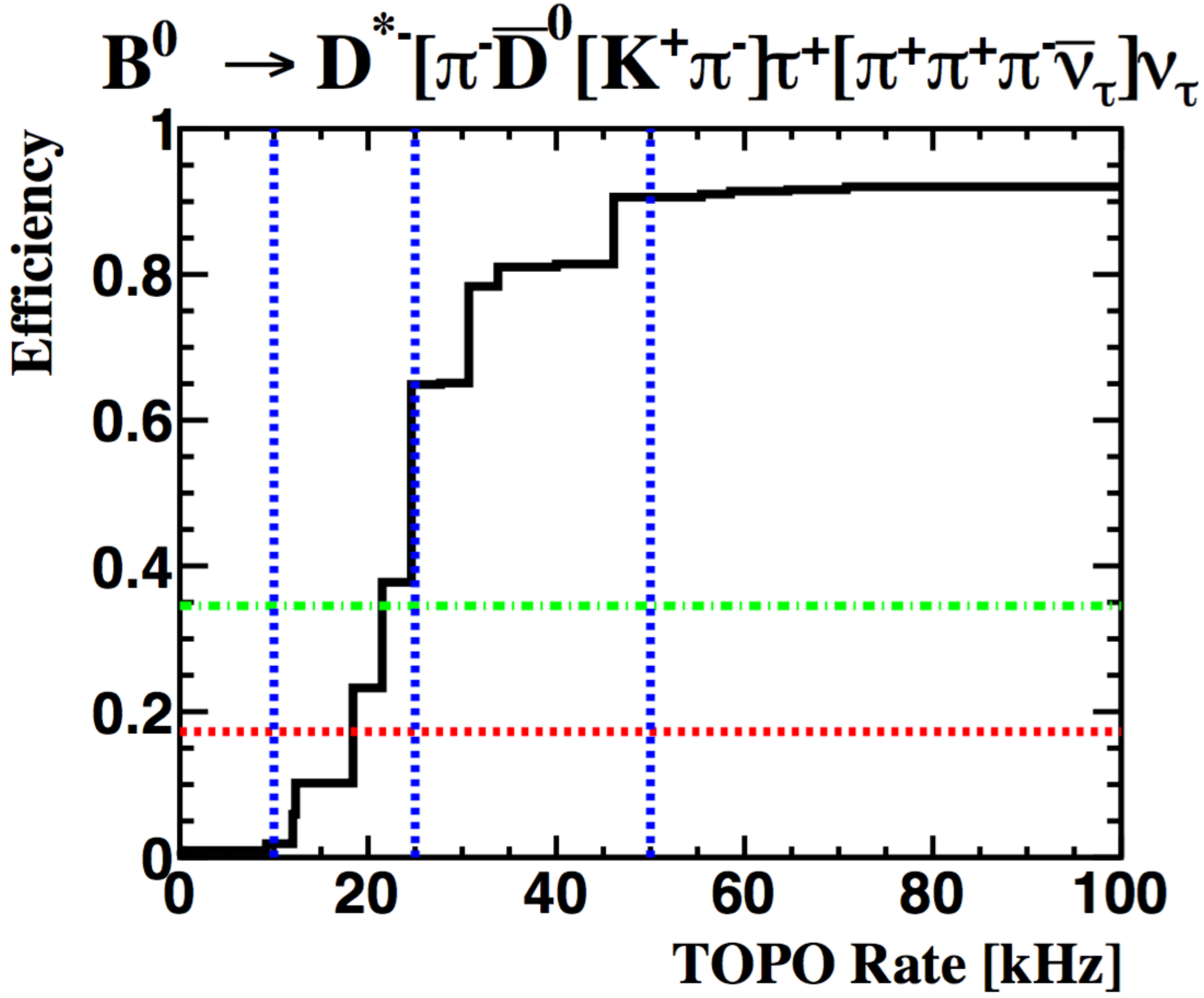
O(10) M$/yr

But does this matter for B-physics?





Yes, it does



To reach the efficiency plateau for complex B-decays using a purely inclusive, "topological" trigger, would require saturating the entire trigger bandwidth.

Answer => Keep some inclusive B-physics triggers, but move the majority of complicated signatures to exclusive selections. Real-time analysis is mandatory.

So you want real-time analysis...

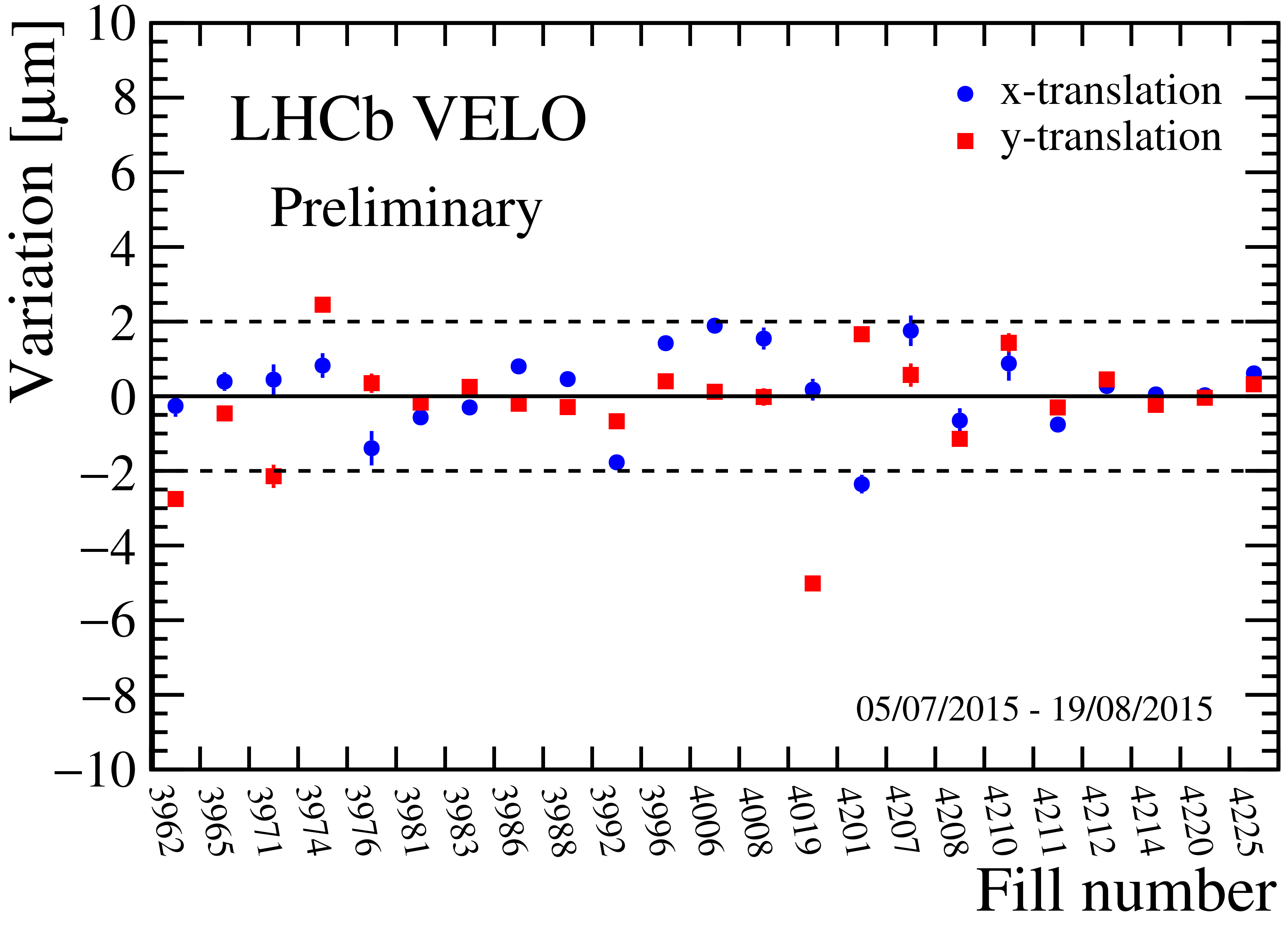
If we want precise real-time analysis, we must have a detector which is continuously aligned and calibrated in real-time

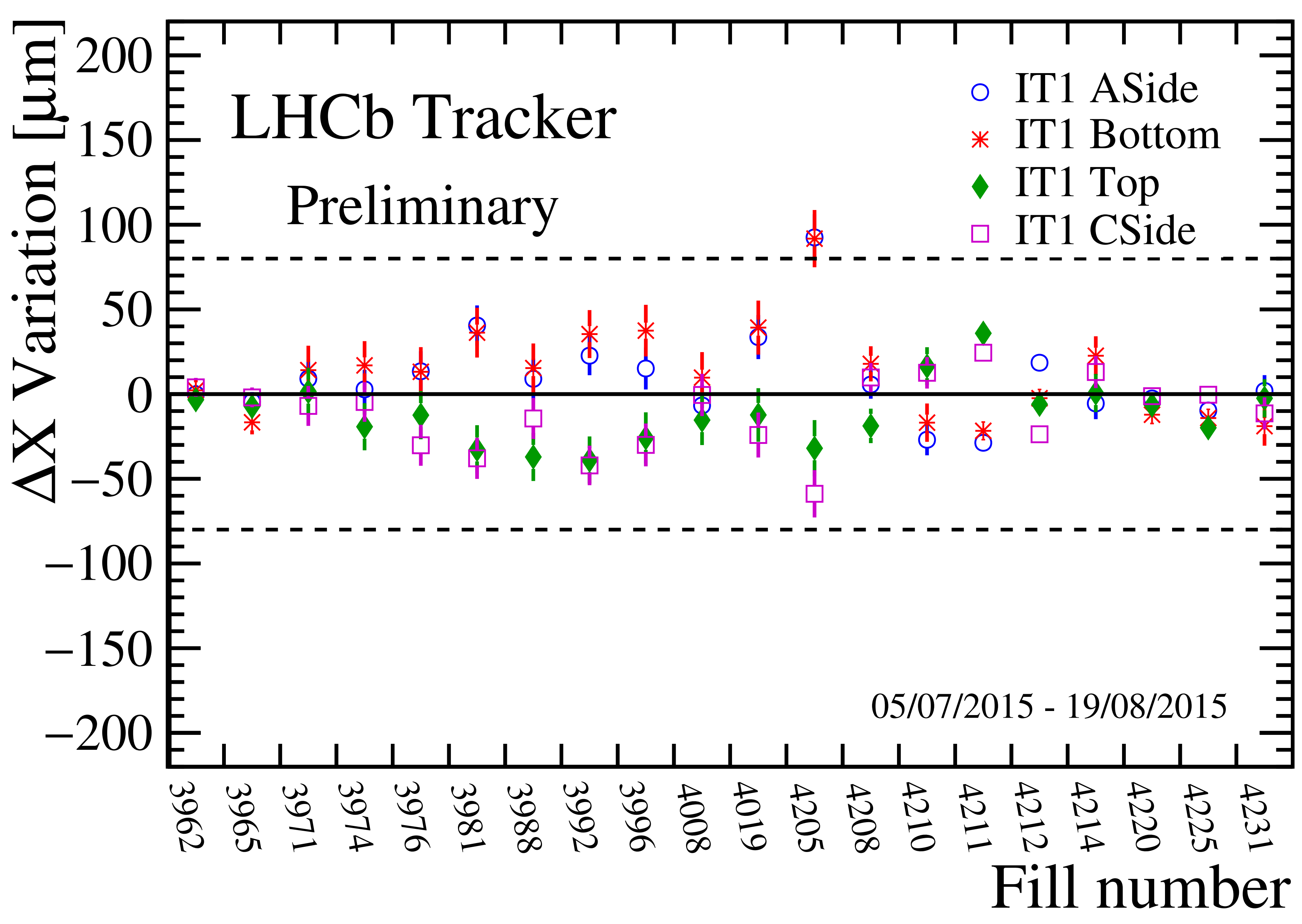
We must also define and select relevant control samples for all efficiency corrections already in the trigger

In 2015 LHCb did this for the first time

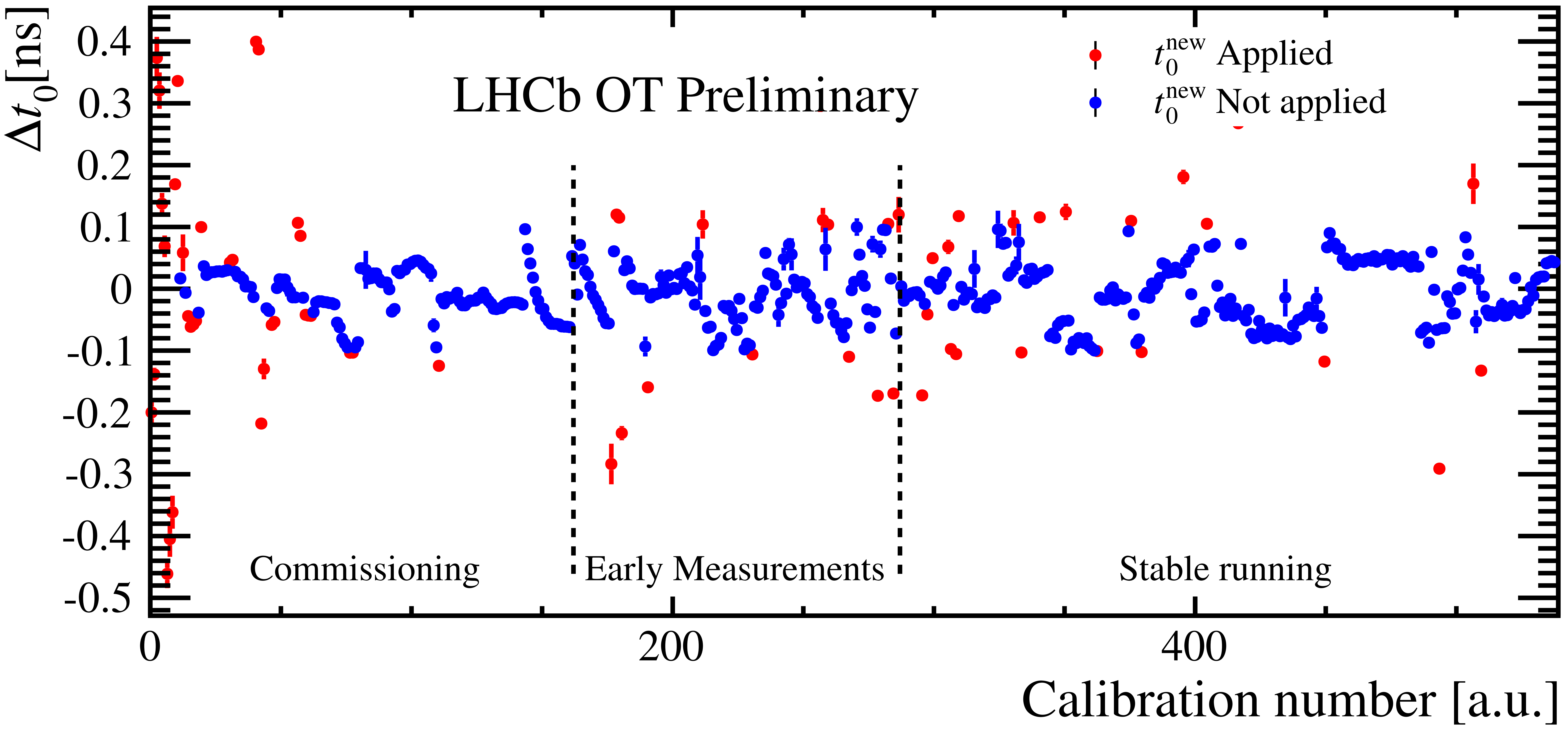
Real time alignment and calibration

- update alignment constants only when above threshold (dashed lines)
  - VELO opens and closes each fill (protect sensors during injection): expect updates every few fills
  - tracking system (TT, IT, OT): expect updates every few weeks





Calibrating the straw-tube tracker

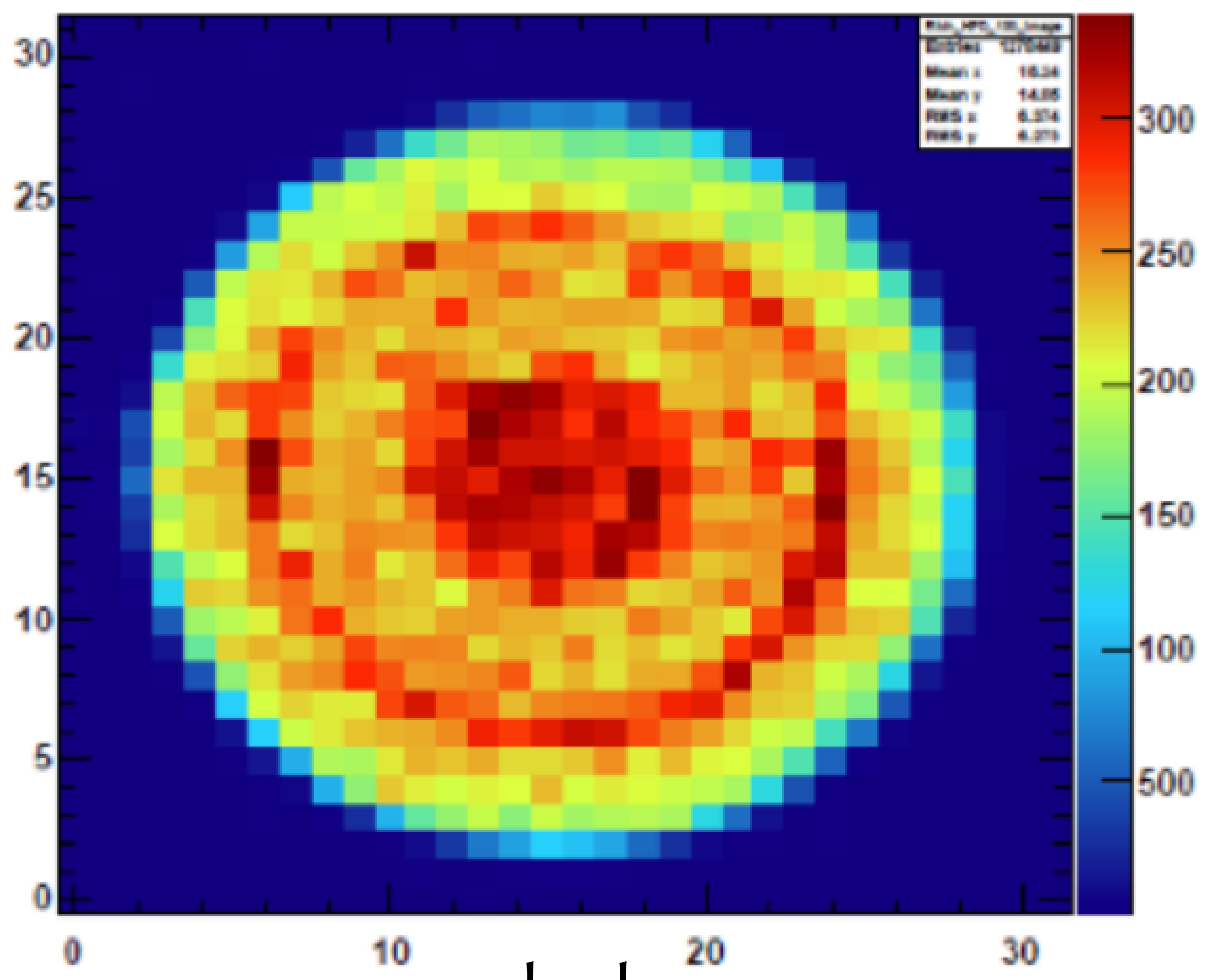


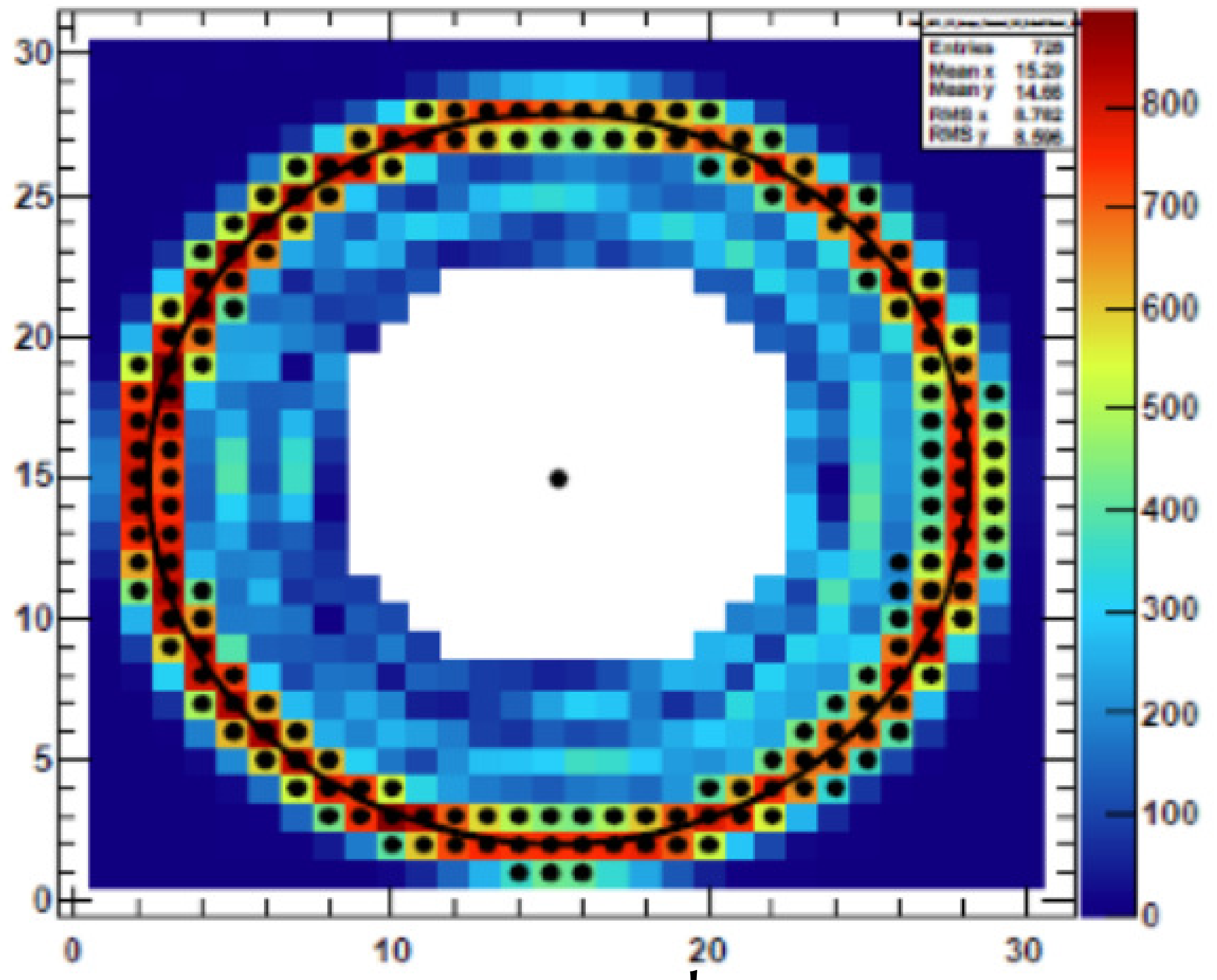
Calibrating the RICH

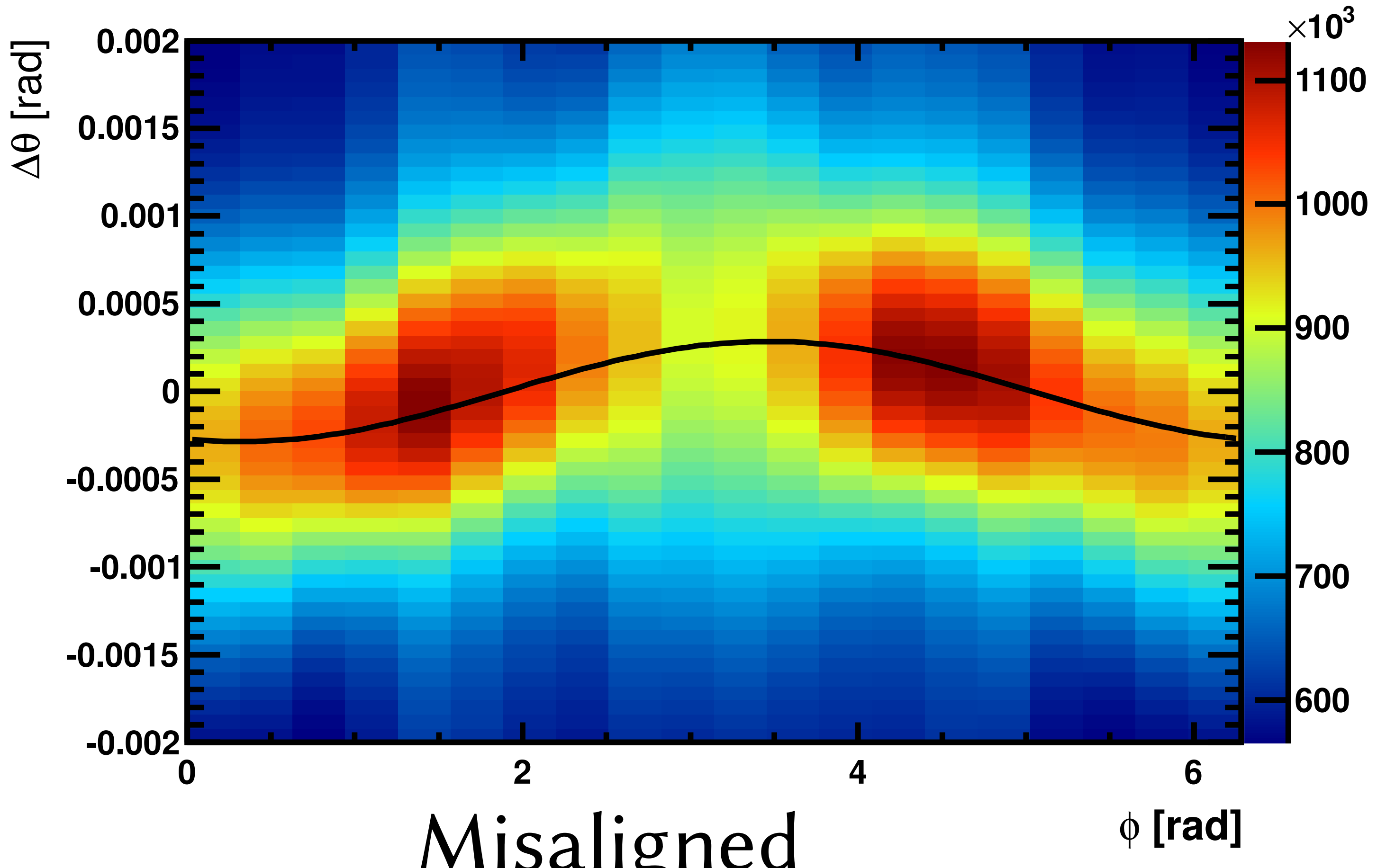
For optimal physics must calibrate and align the gaseous Ring-Imaging Cherenkov Detectors in real time.

Monitor & adjust mirror alignment, image distortion, and refractive index of the gas.

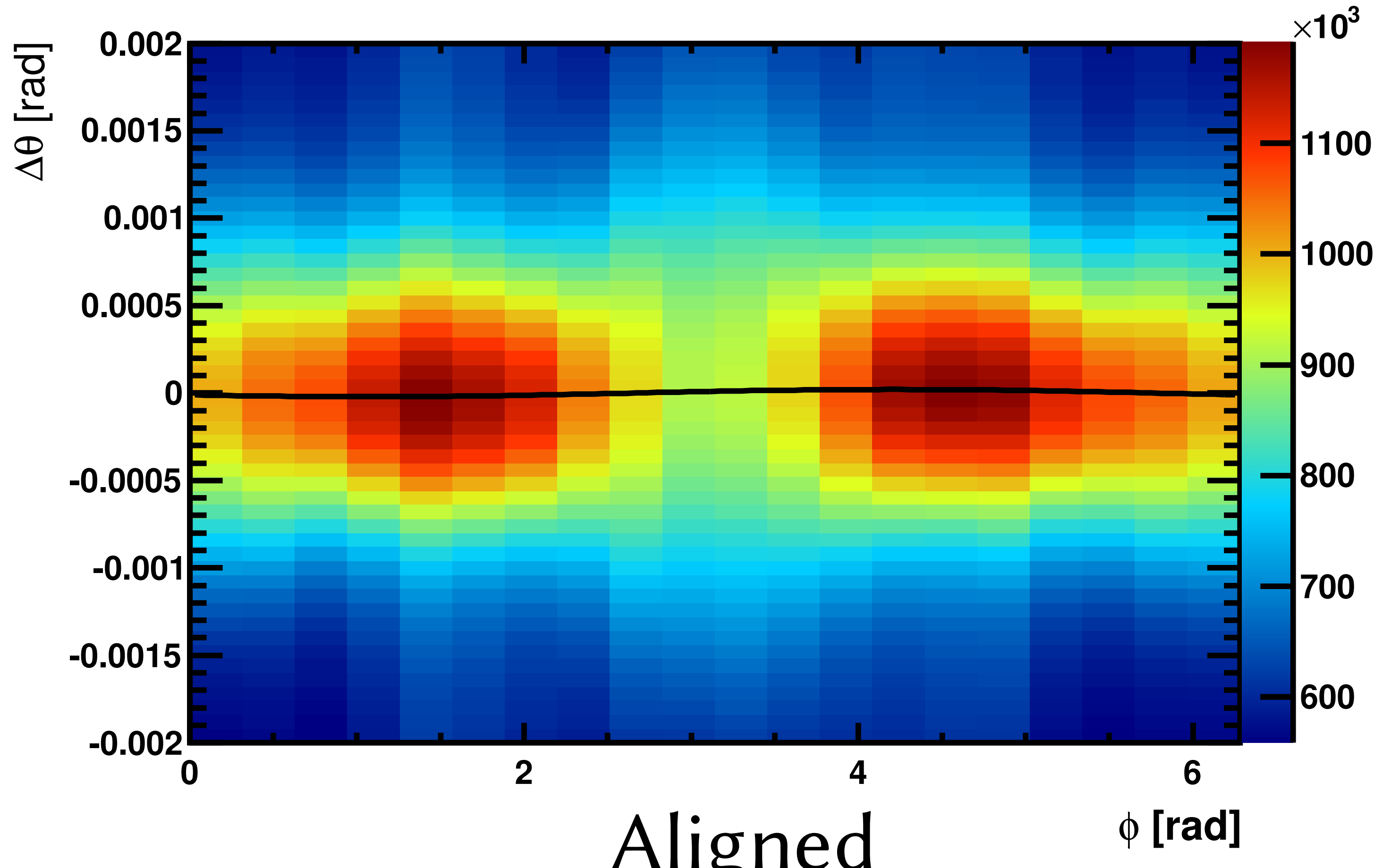
System is automated, can update image and refractive index parameters within less than a minute if needed. Alignment takes longer but also changes much less frequently (1-2 times per year).


bad


good

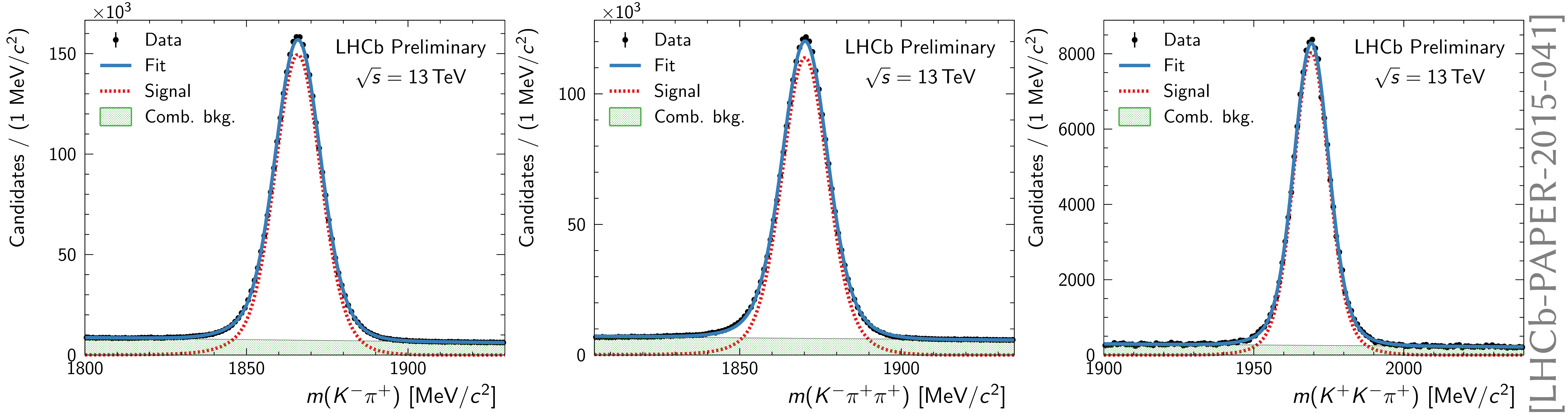


Misaligned



Aligned

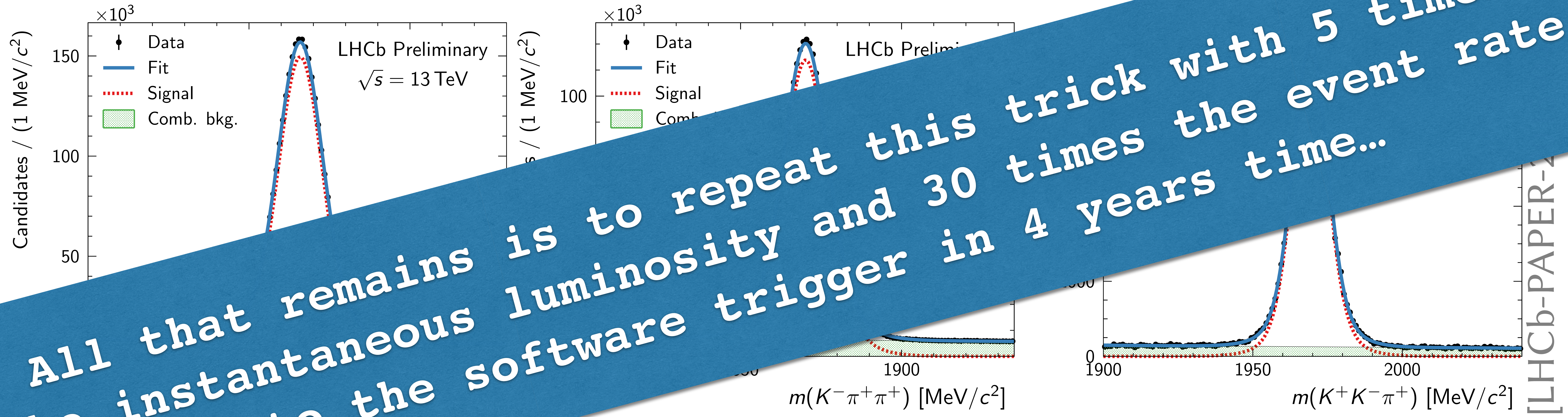
Real time signals in 2015



$D^0 \to K^- \pi^+$ $D^+ \to K^- \pi^+ \pi^+$ $D_s^+ \to K^+ K^- \pi^+$

Trigger level signal purities and resolutions for charged particles identical to the best possible offline ones. Published first papers 2 weeks after data taken!

Real time signals in 2015



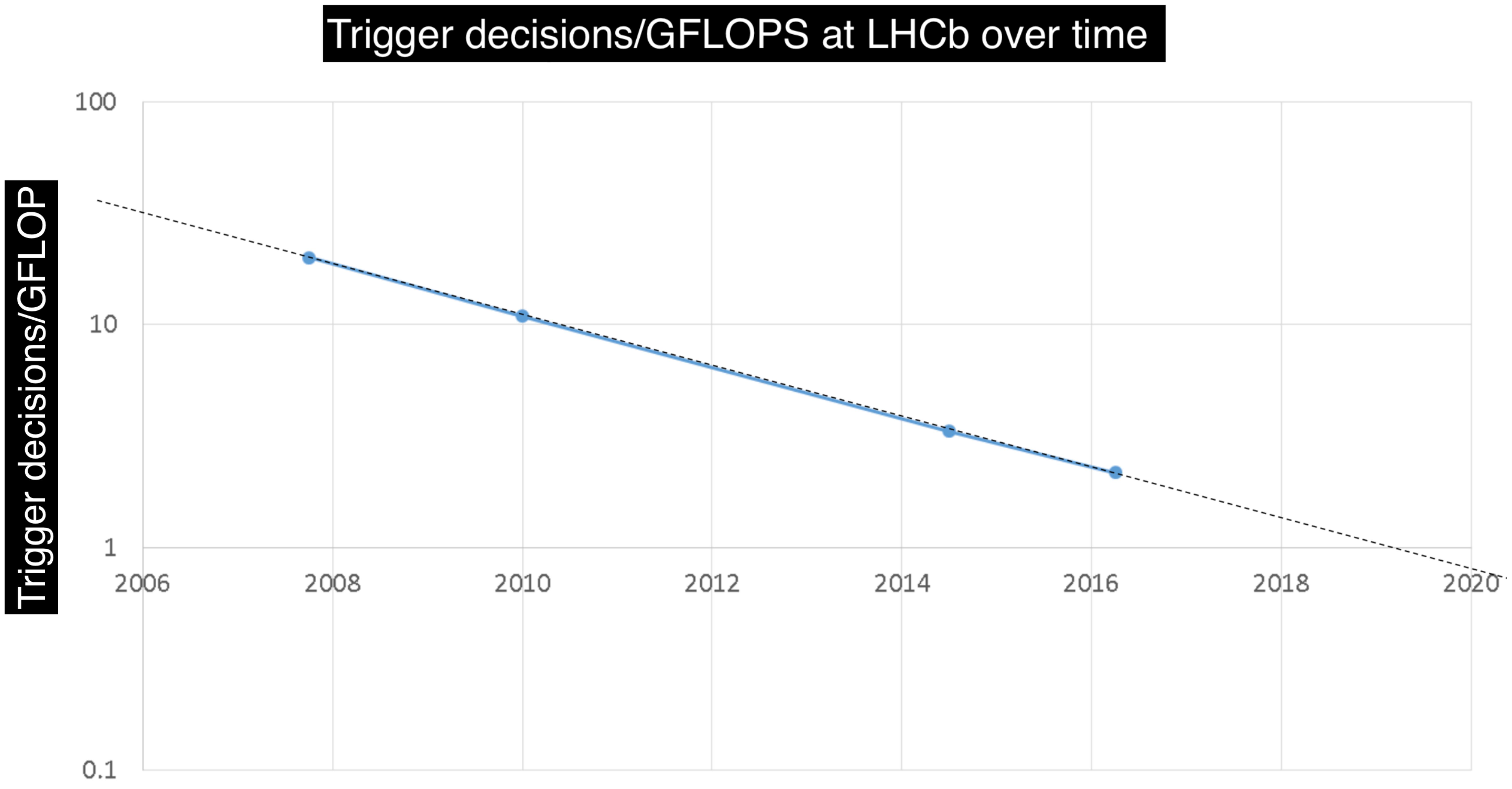
$D^+ \to K^-\pi^+\pi^+$

$D_s^+ \to K^+K^-\pi^+$

All that remains is to repeat this trick with 5 times the instantaneous luminosity and 30 times the event rate into the software trigger in 4 years time…

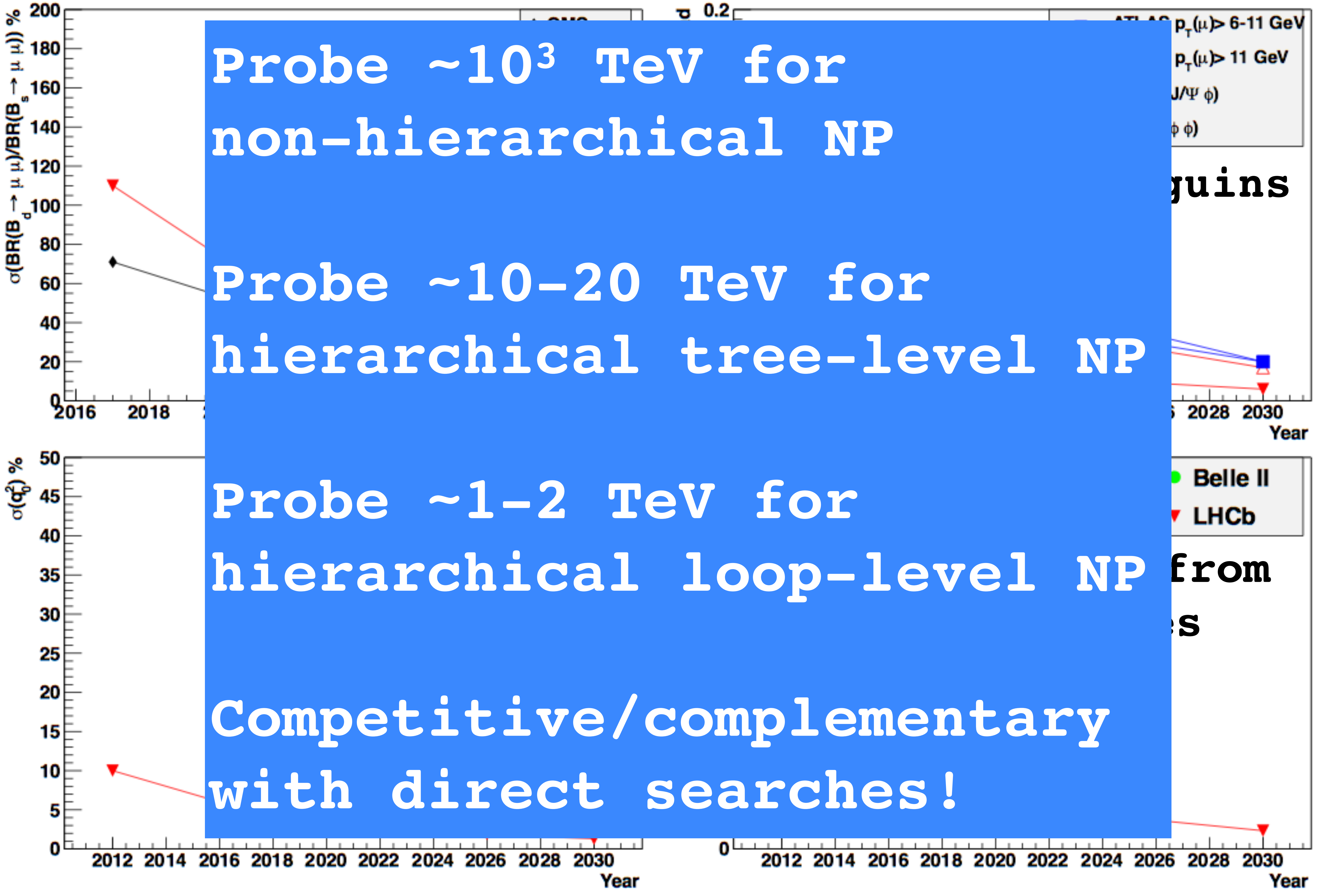
Trigger level signal purities and resolutions for charged particles identical to the best possible offline ones. Published first papers 2 weeks after data taken!

Which is quite a challenge by the way



Modern computing architectures are highly parallel, but HEP code is not. Must rewrite our entire software framework over the next 4 years to fully exploit upgrade!

But if we succeed, the rewards are great

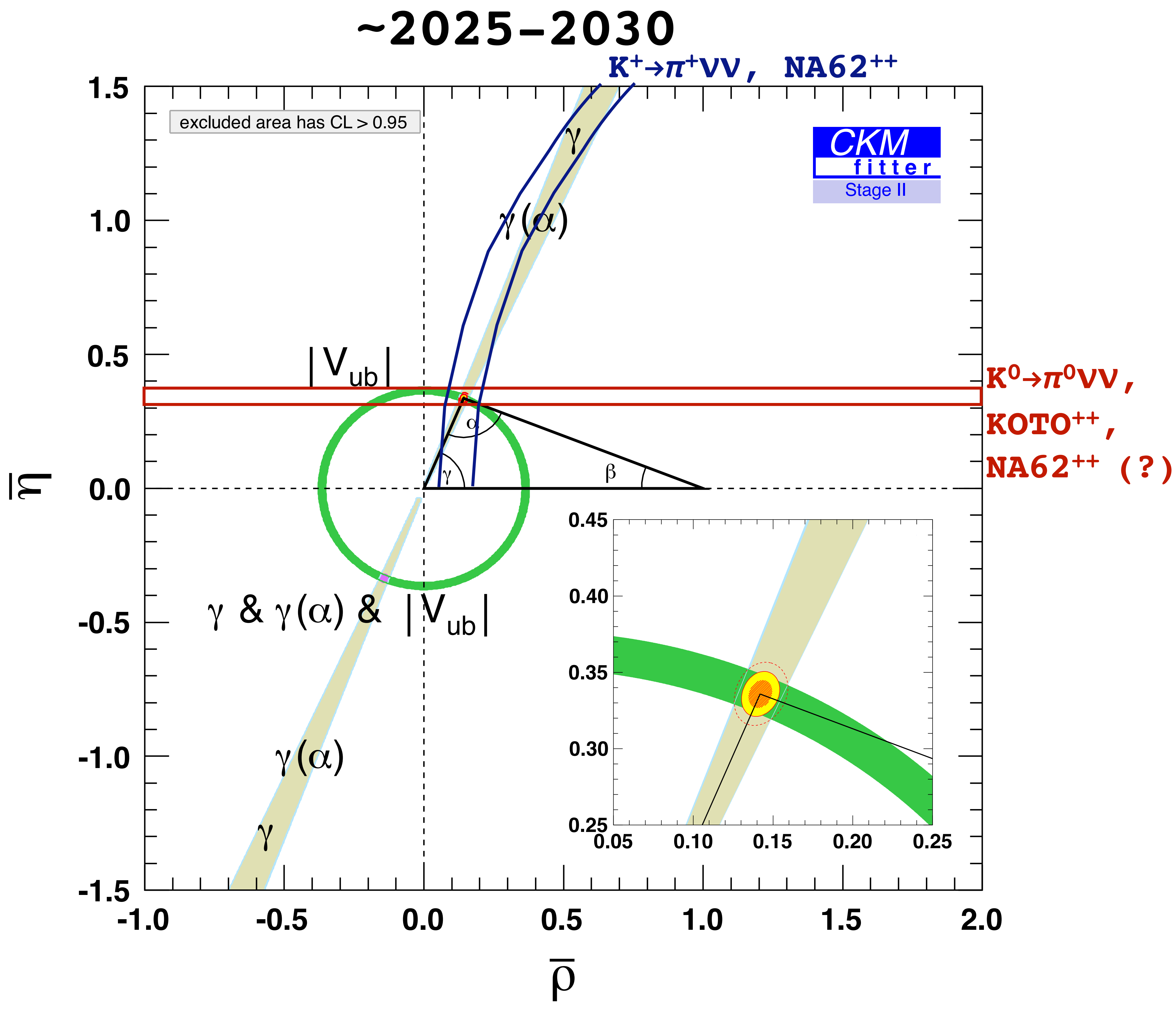


Probe ~10^3 TeV for non-hierarchical NP

Probe ~10-20 TeV for hierarchical tree-level NP

Probe ~1-2 TeV for hierarchical loop-level NP

Competitive/complementary with direct searches!



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