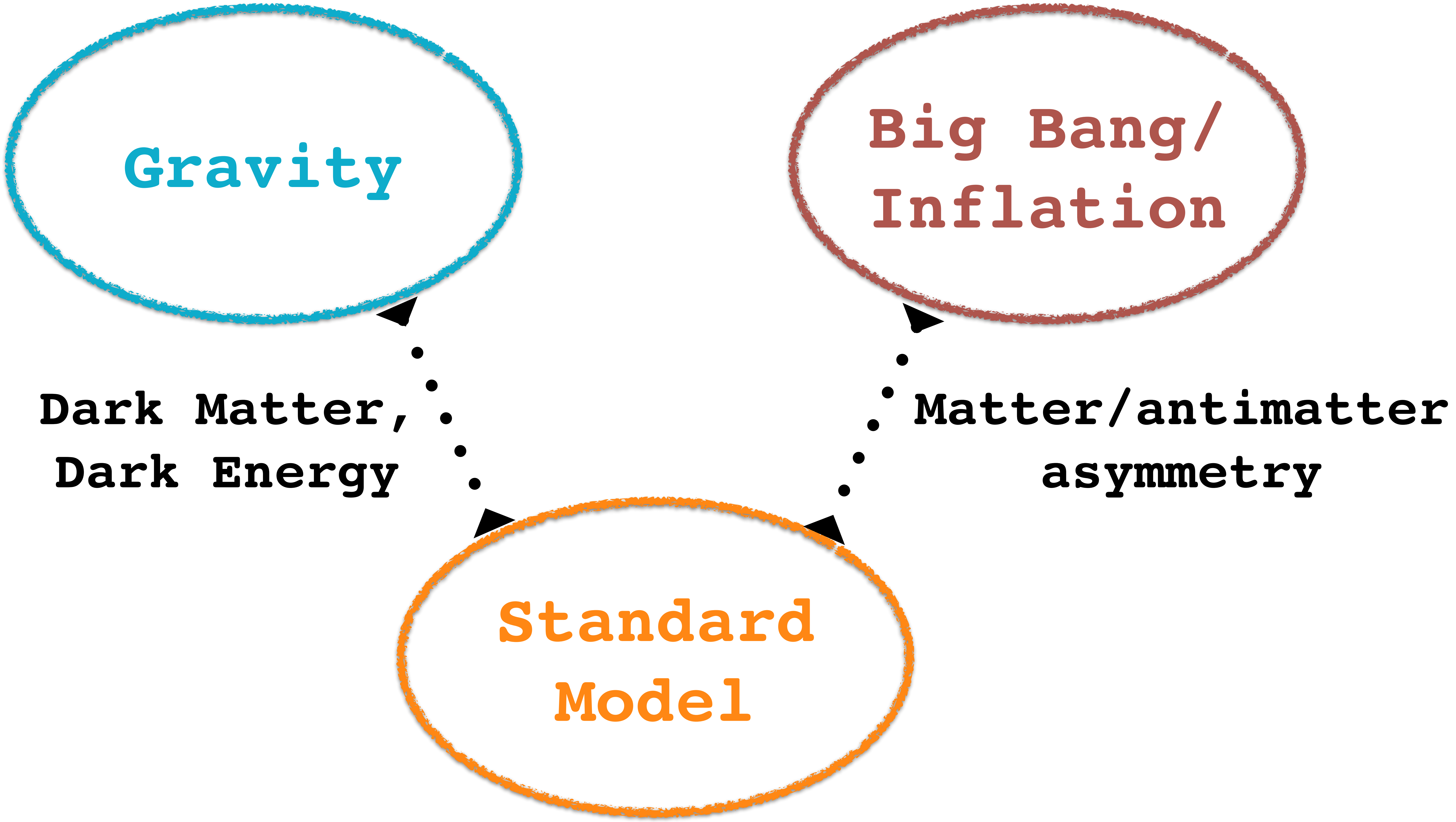
Horizons beyond the Standard Model @ LHC

Vladimir V. Gligorov
(speaking in a personal capacity)
LPNHE, April 20th 2017

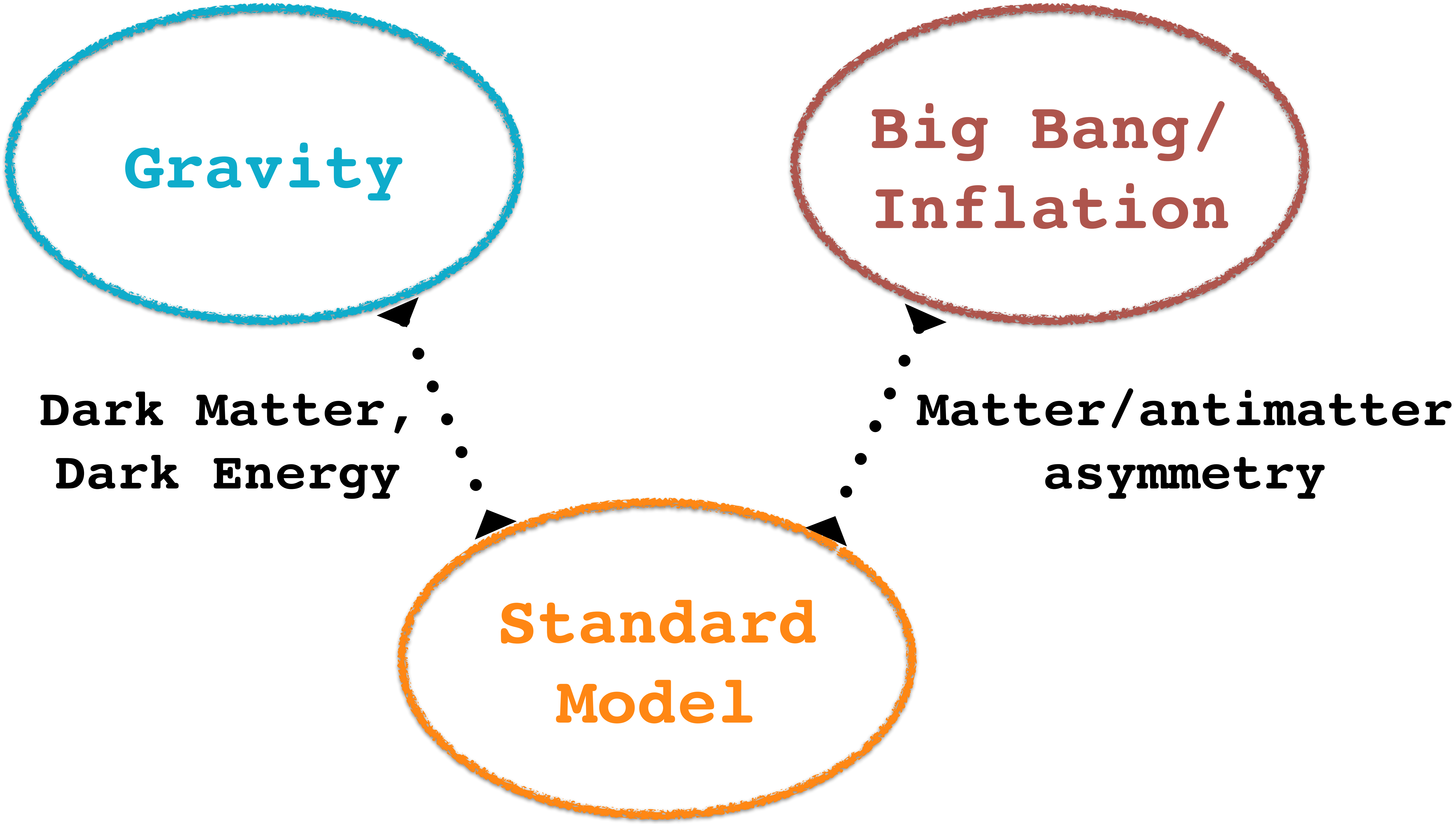
Why are we here?



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

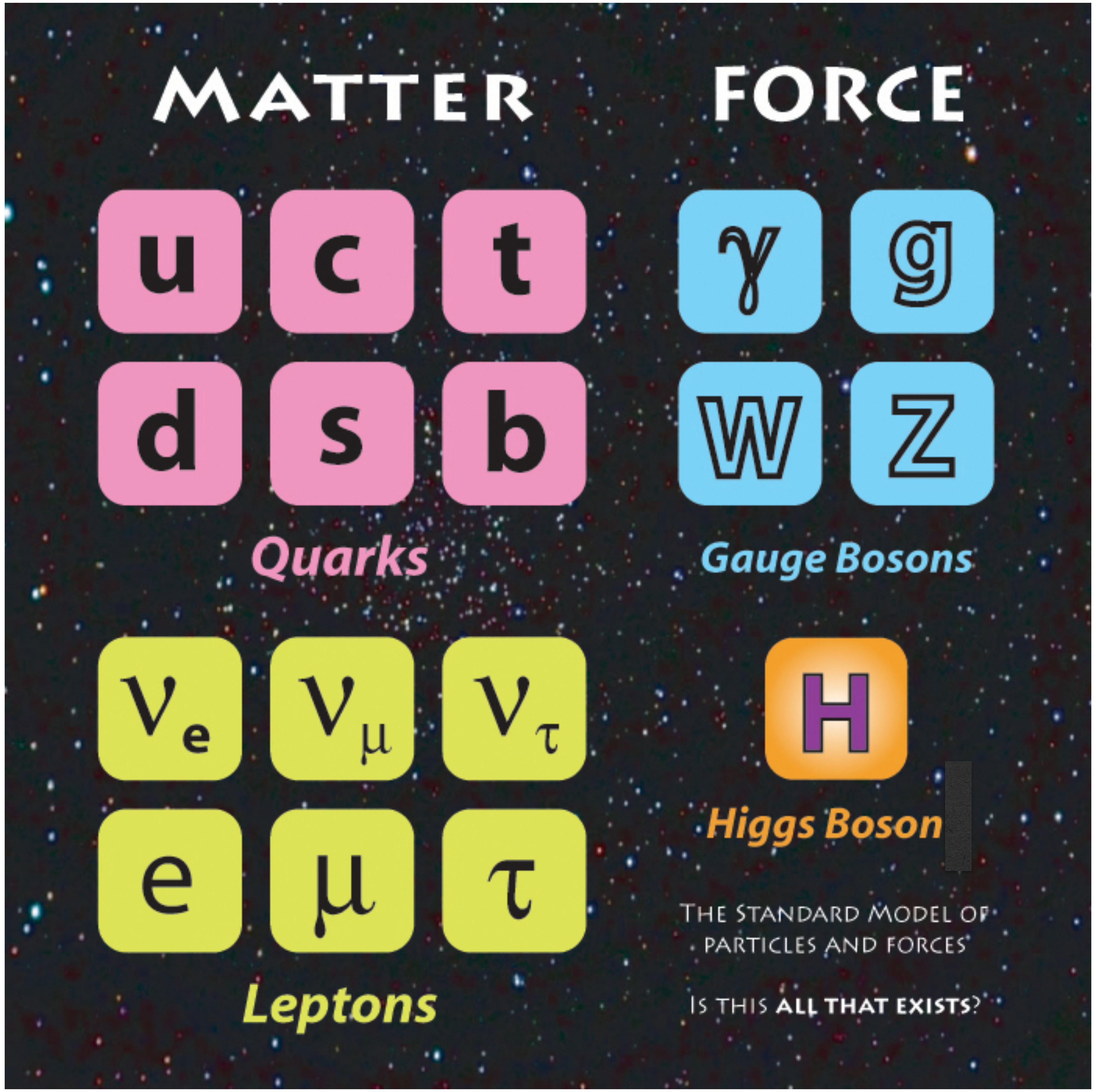
Why are we here?

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



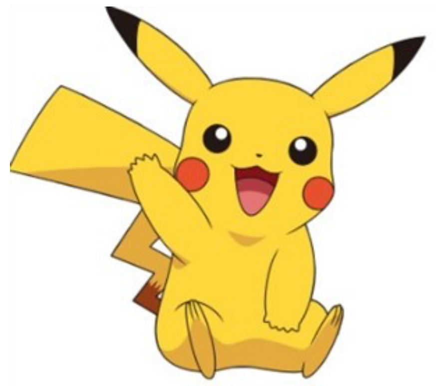
Our theories of nature are inconsistent with each other => something has to give

So what does beyond the SM mean?



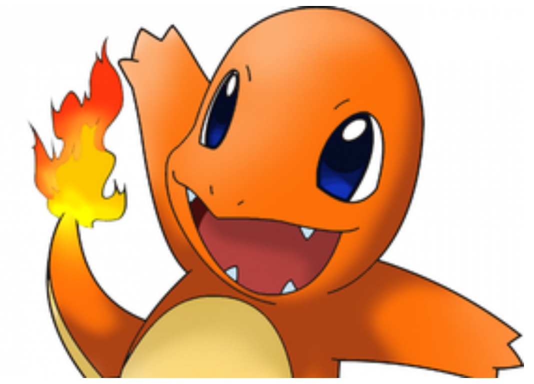
Beyond the Standard Model

neutralino



Z′

leptoquark



Theories which extend the SM do so through a variety of new particles and force carriers, and these in turn resolve the contradictions between the SM and theories of macroscopic reality (gravity/Big Bang…)

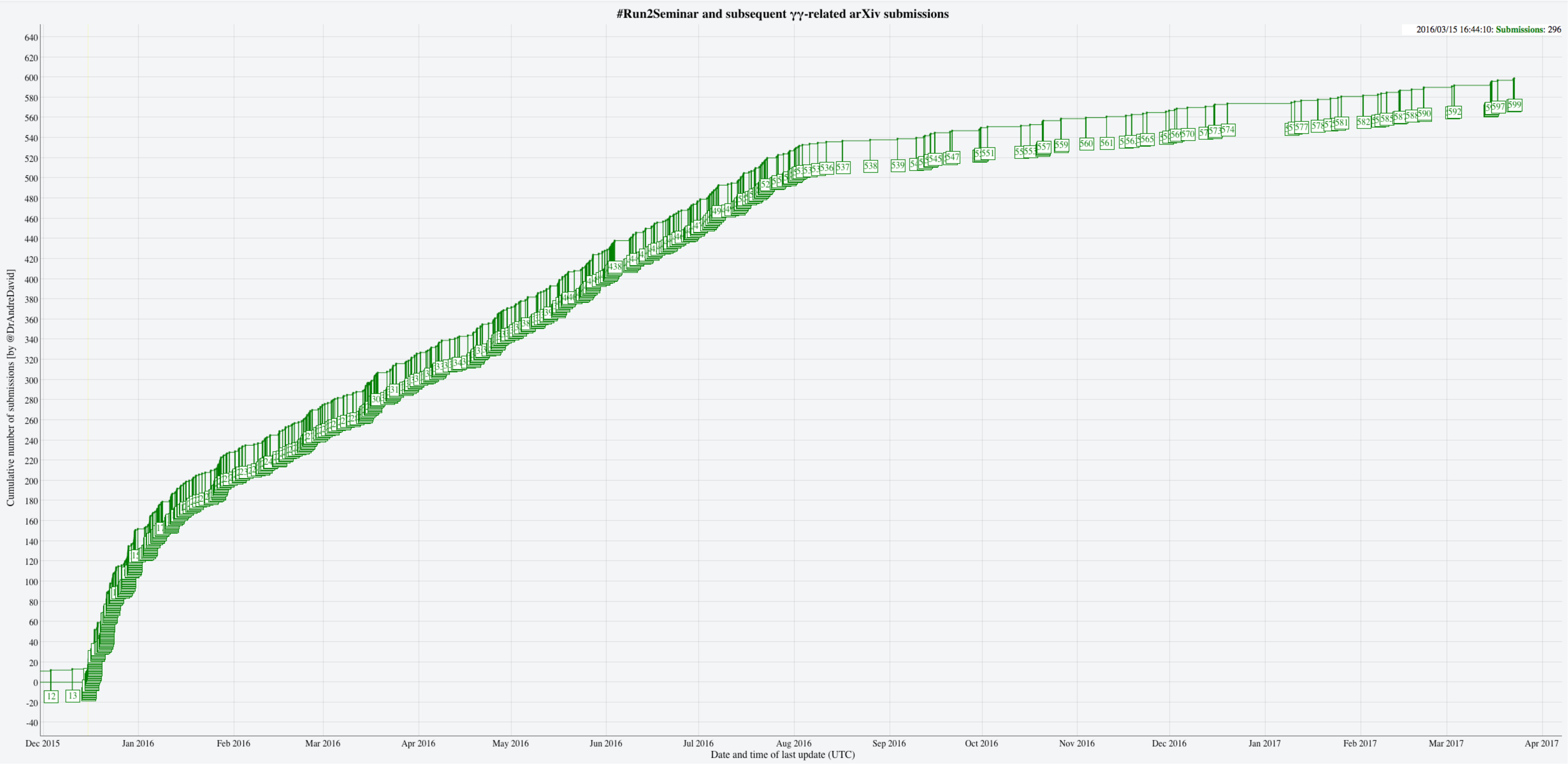
1-slide version of this talk

See talk by D. Zerwas
for the direct searches

All direct BSM searches have come up empty so far; most "motivated" models are in trouble

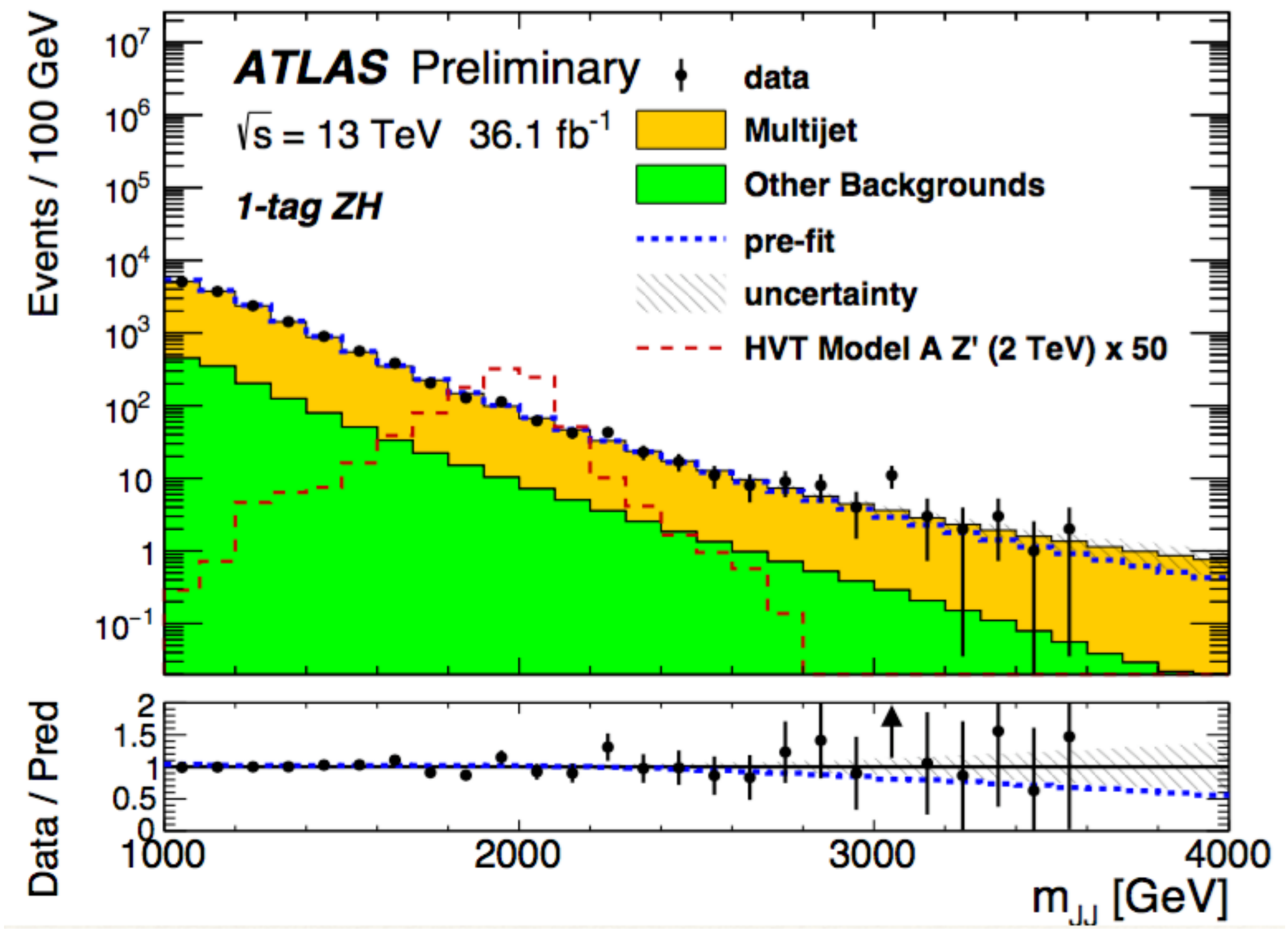
There are stronger and stronger indirect hints of BSM effects, but are they simply a mirage?

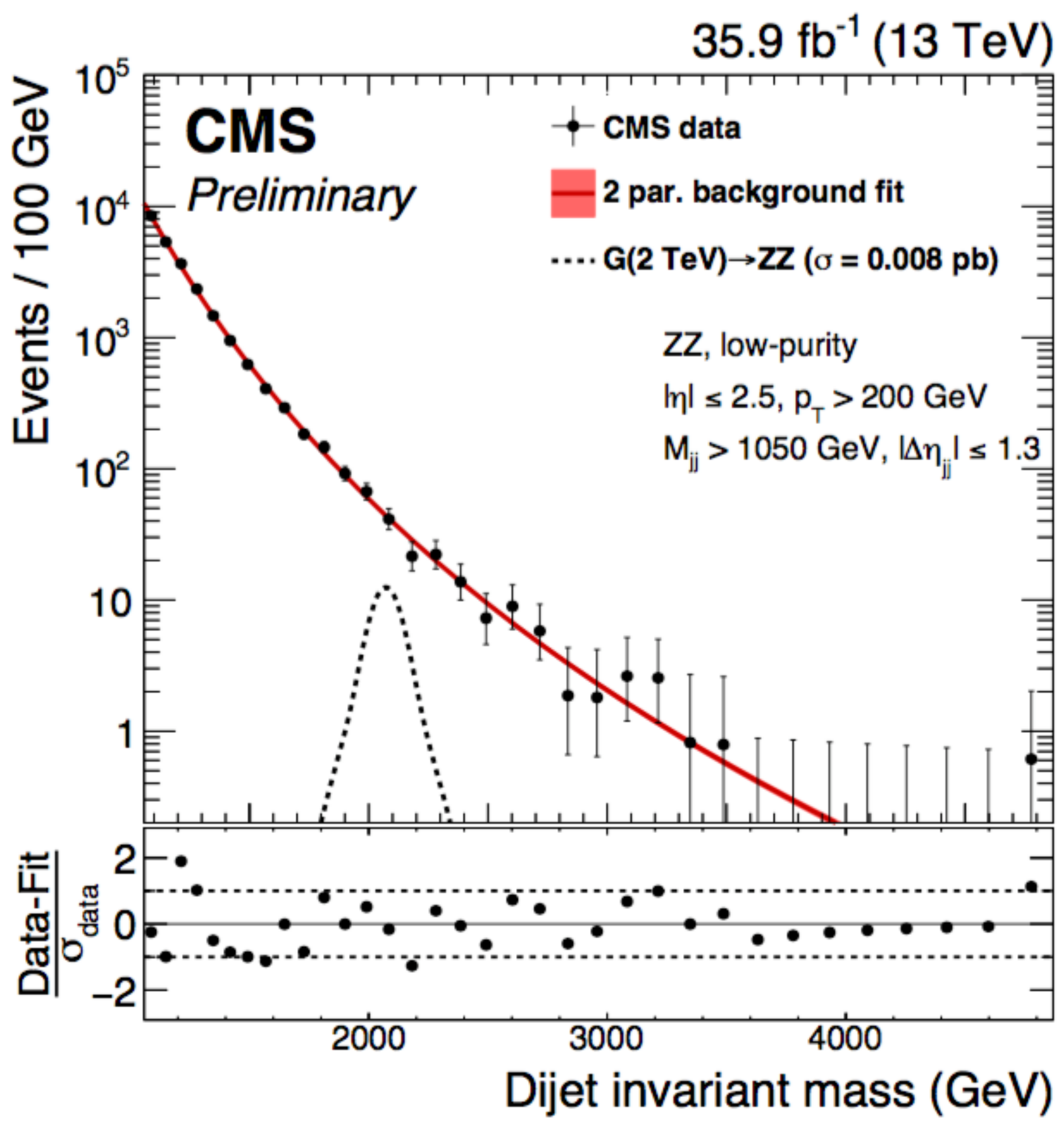
750 shades of model building…

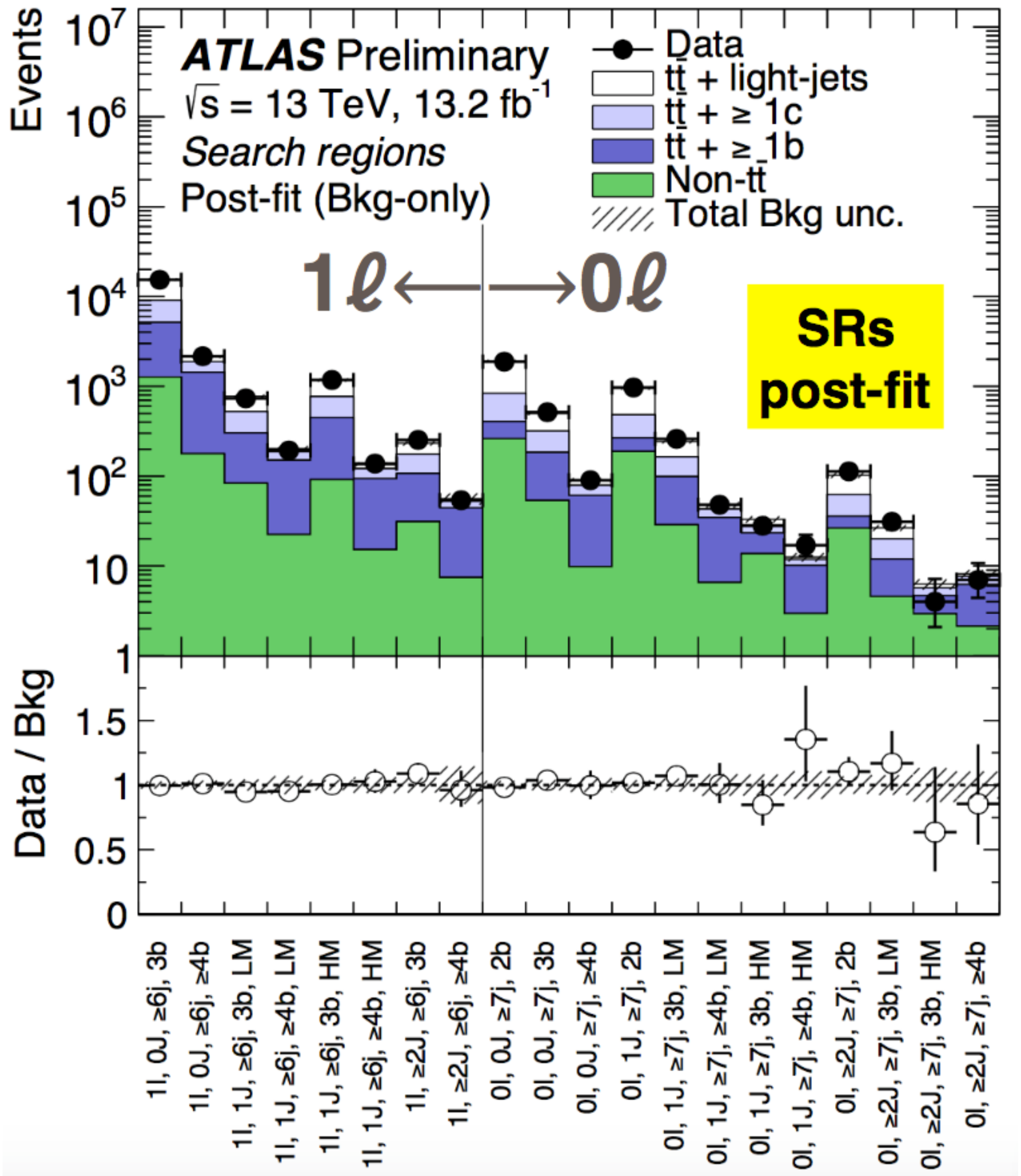


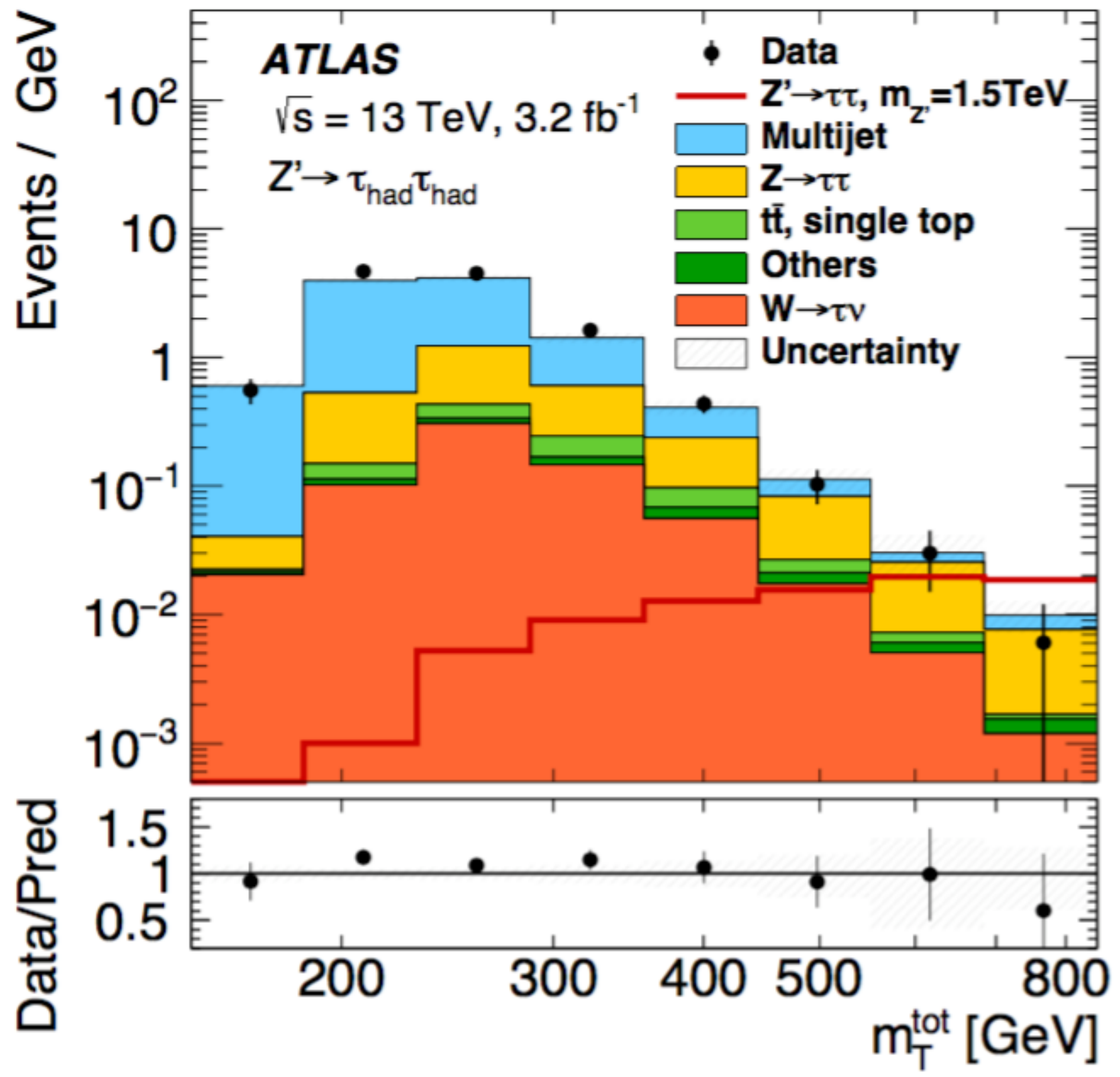
…confront the desert of the real

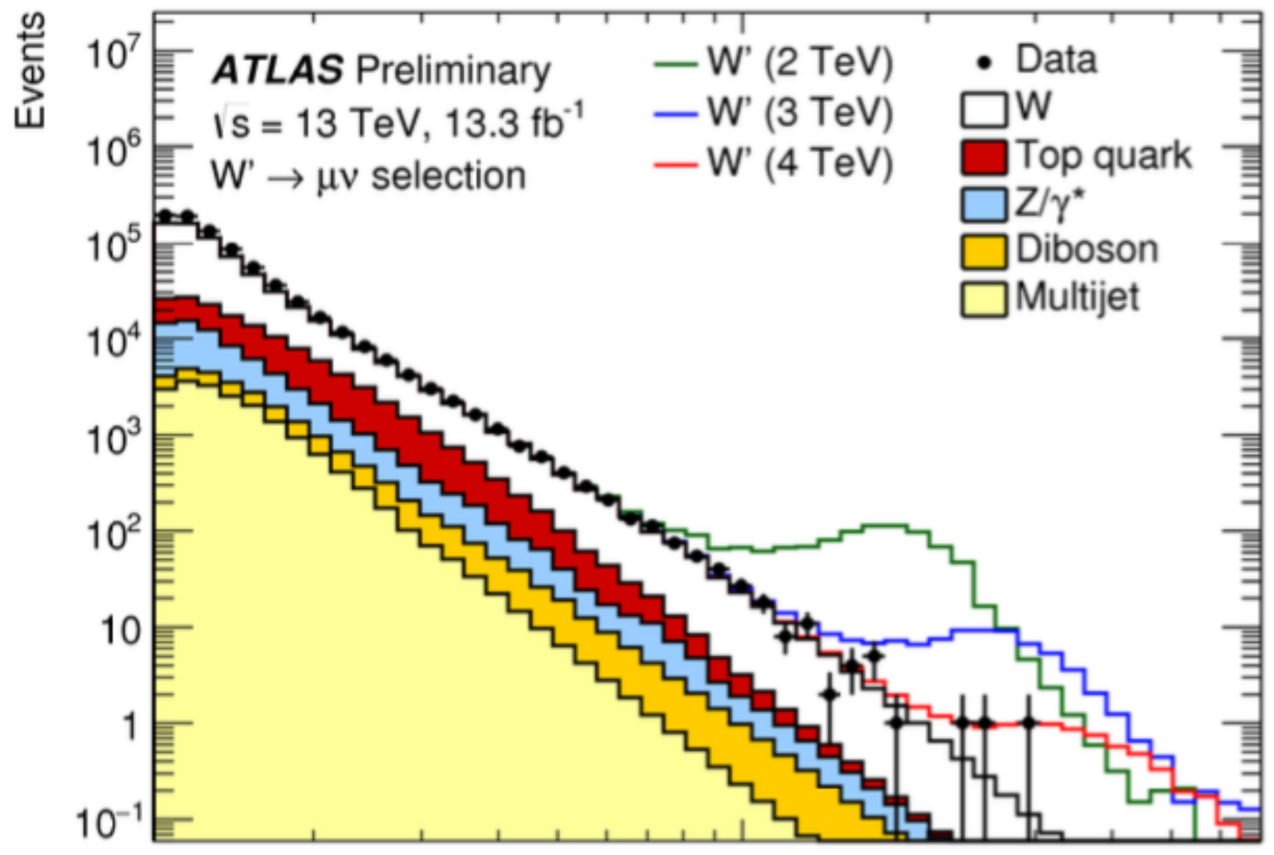
MEW 2017 BSM session talks









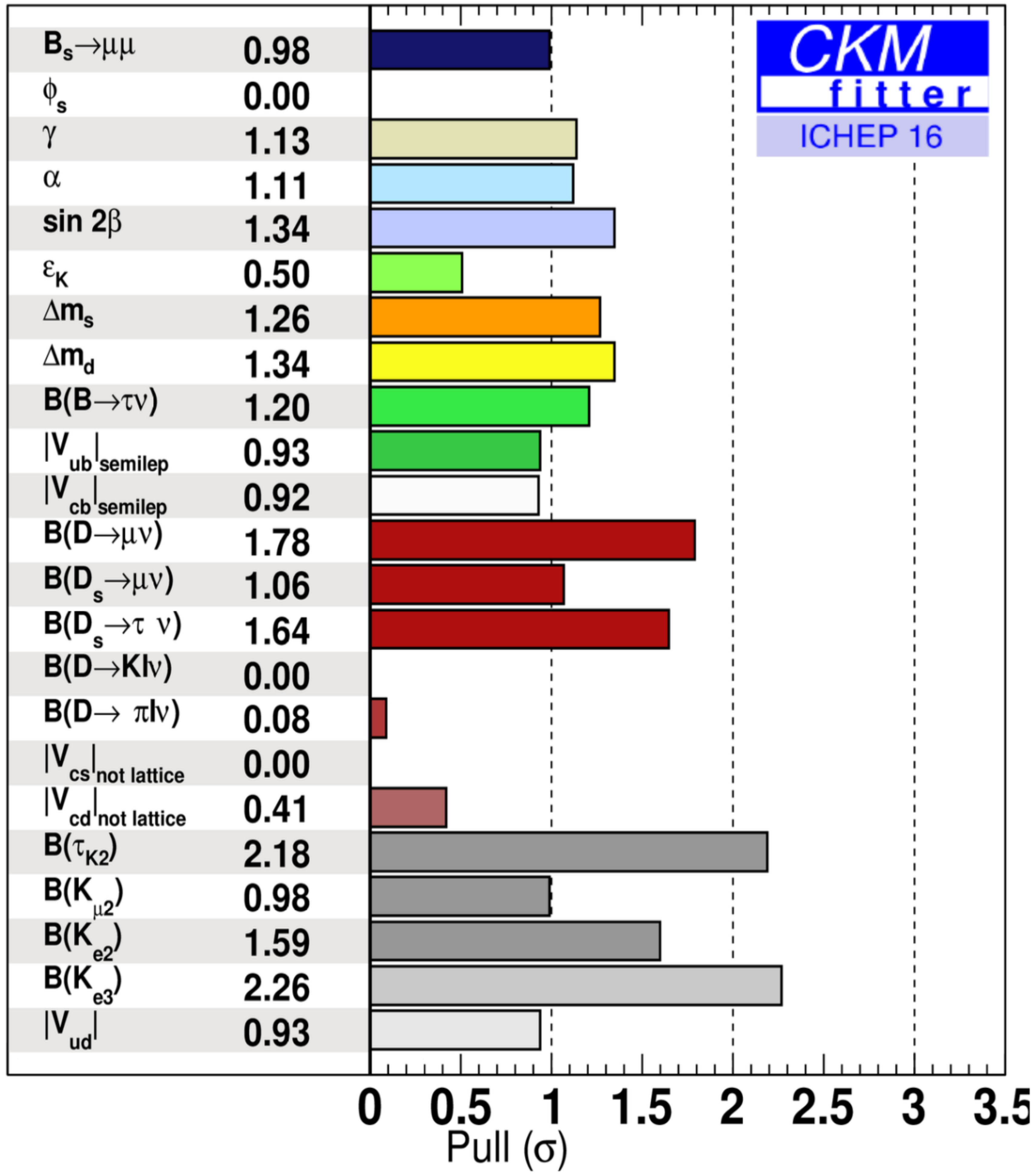


Moriond experimental summary

We do not have, and it is becoming increasingly likely that we will not have, another discovery that allows such a straightforward statement

Bear the wise words of Tim Gershon in mind for what follows

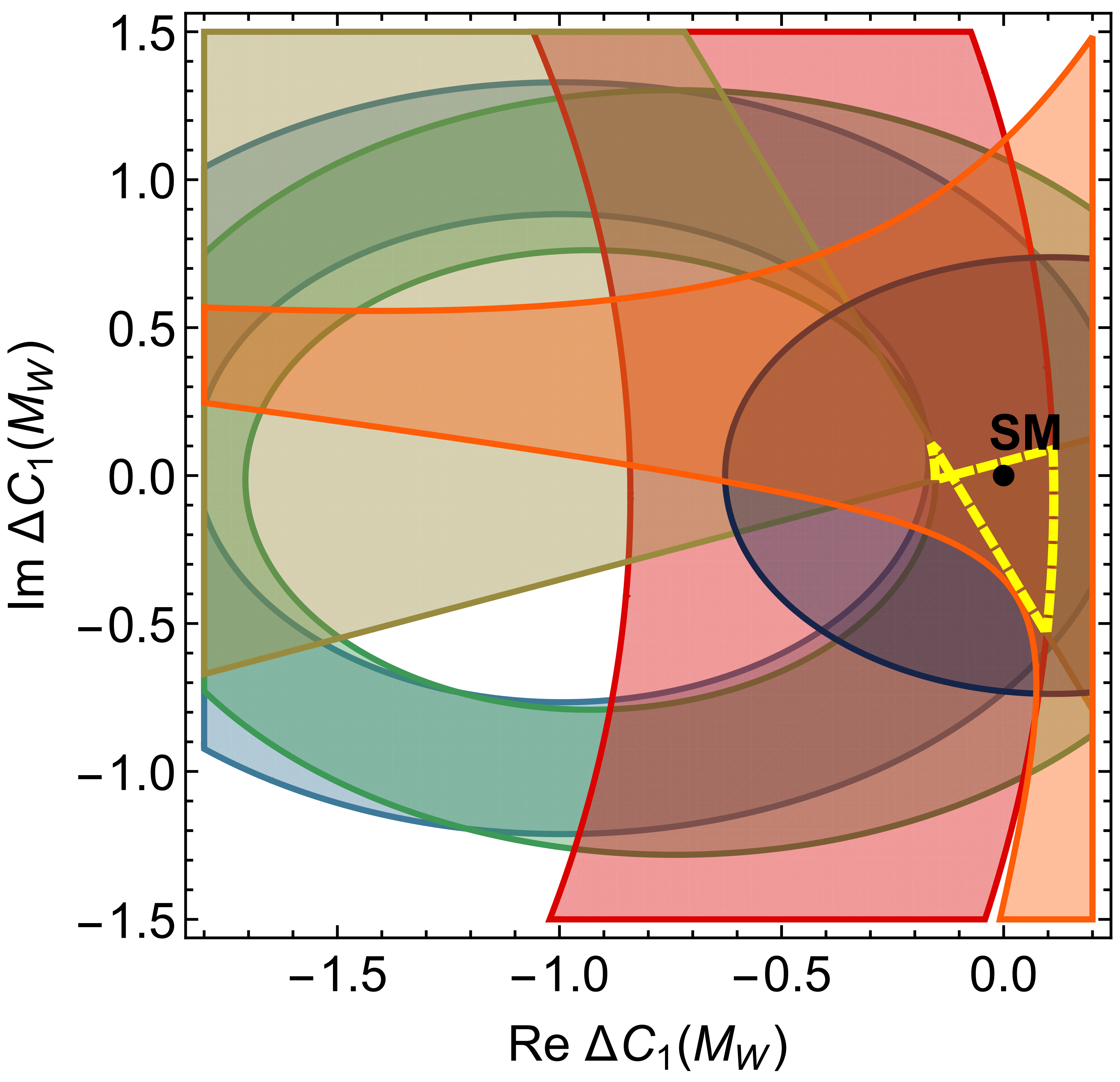
Hints of BSM in quark transitions?

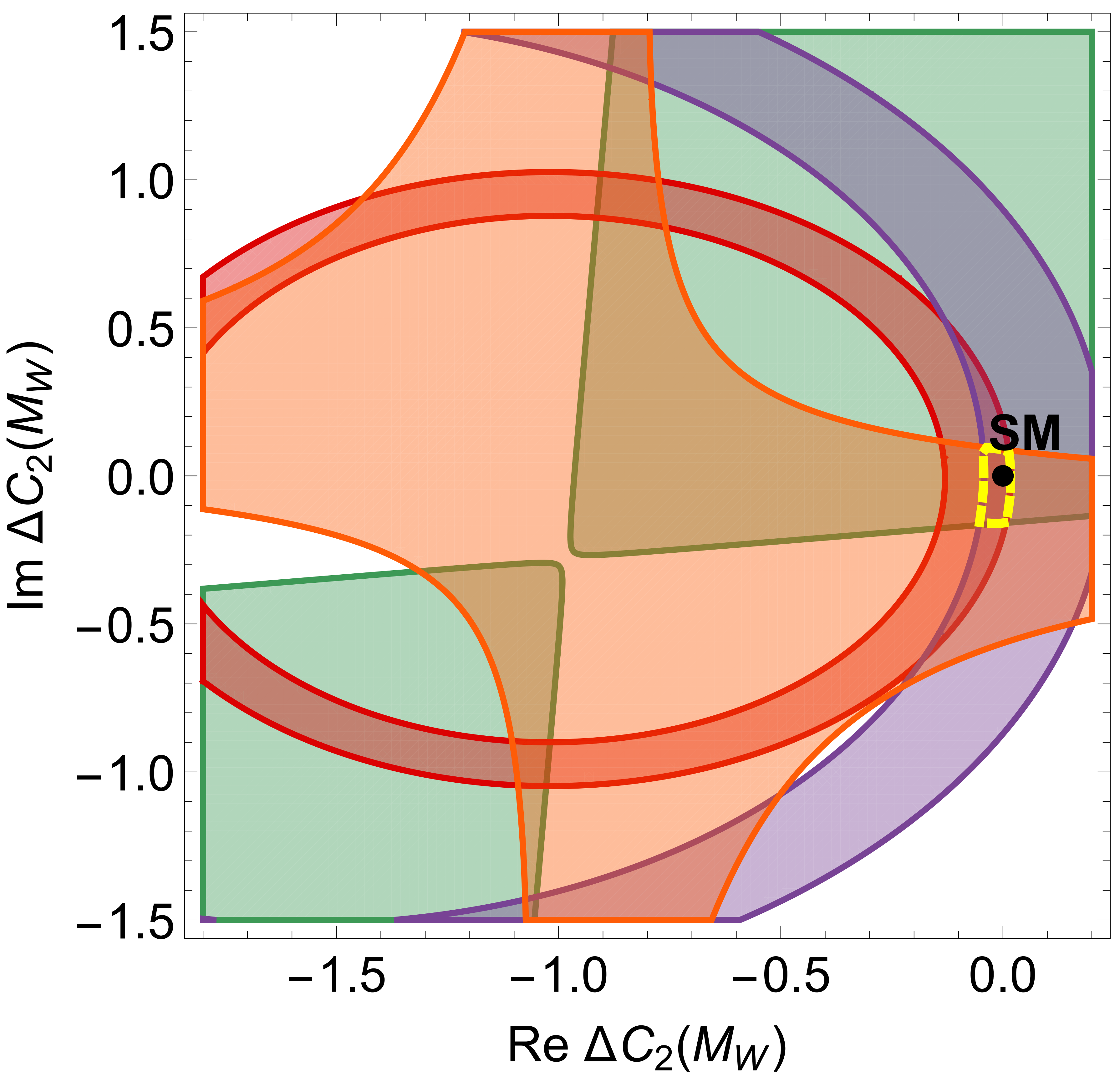


Over past decades flavour experiments have made enormous progress mapping out theoretically clean observables associated with quark transitions. SM has passed these tests with remarkable success.

But there is still room for BSM effects

J. Brod, A. Lenz et al.
arXiv:1412.1446

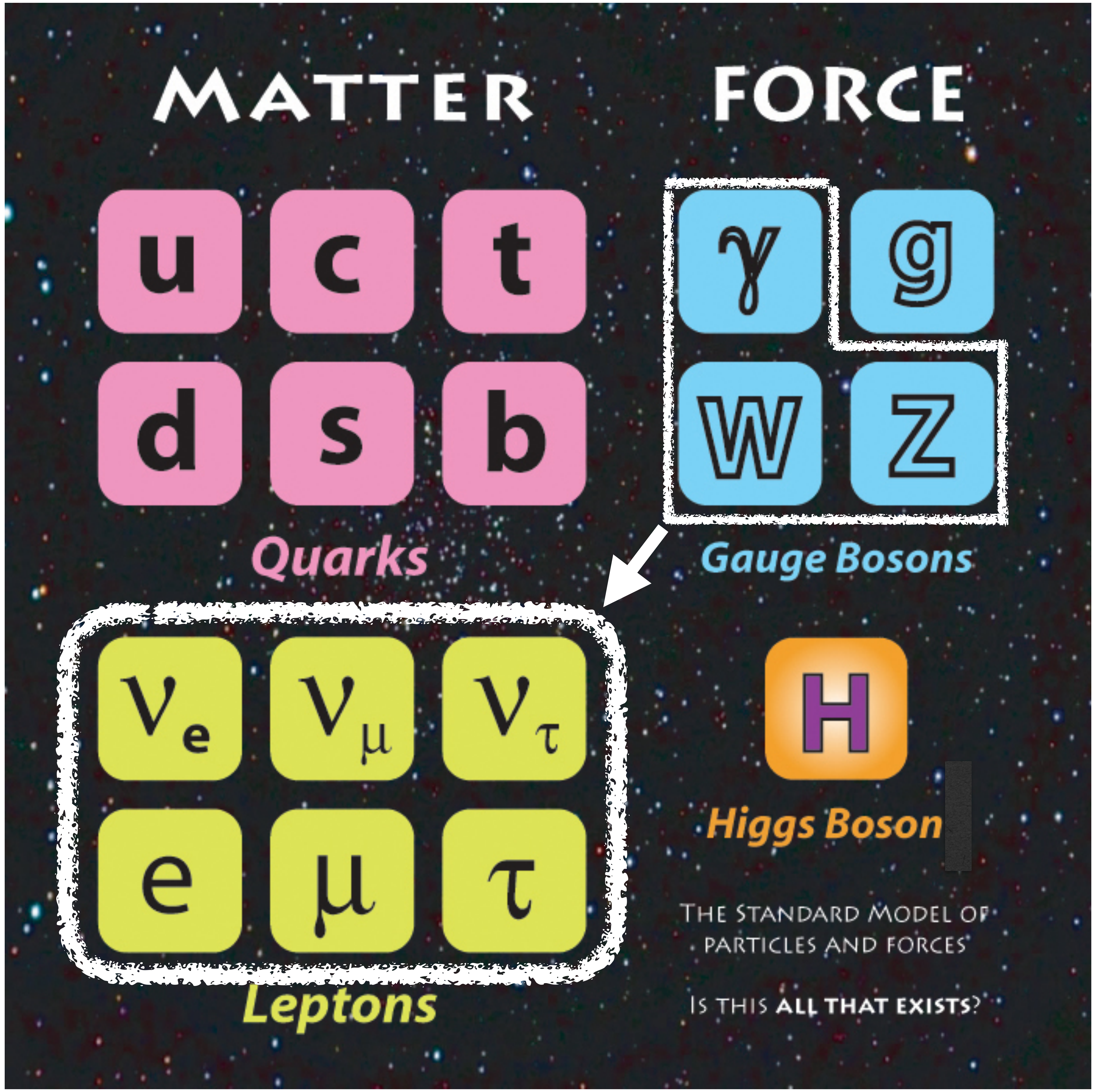




NP effects are actually allowed at 10% of SM, even in tree level in quark transitions! Constraints are not always what they seem


So the SM works?
Well all leptons are equal, but some leptons…

LU in the Standard Model



Decay Modes W

W^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i /Γ)
Γ_1	$\ell^+\nu$	$(10.86 \pm 0.09)\%$
Γ_2	$e^+\nu$	$(10.71 \pm 0.16)\%$
Γ_3	$\mu^+\nu$	$(10.63 \pm 0.15)\%$
Γ_4	$\tau^+\nu$	$(11.38 \pm 0.21)\%$

Decay Modes Z

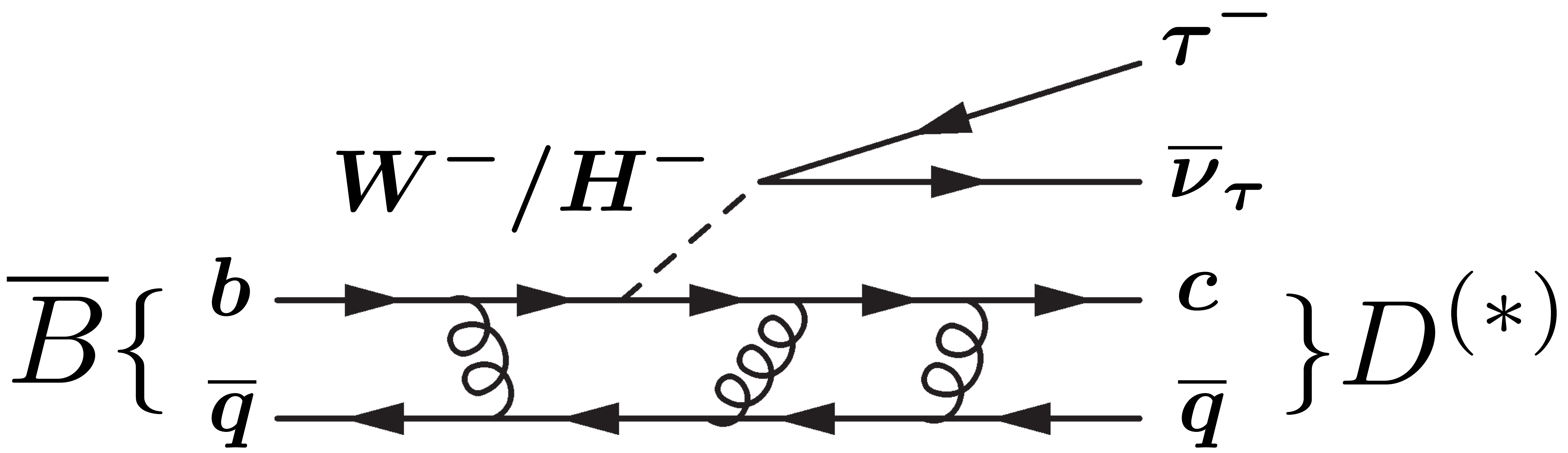
	Mode	Fraction (Γ_i /Γ)
Γ_1	e^+e^-	$(3.363 \pm 0.004)\%$
Γ_2	$\mu^+\mu^-$	$(3.366 \pm 0.007)\%$
Γ_3	$\tau^+\tau^-$	$(3.370 \pm 0.008)\%$

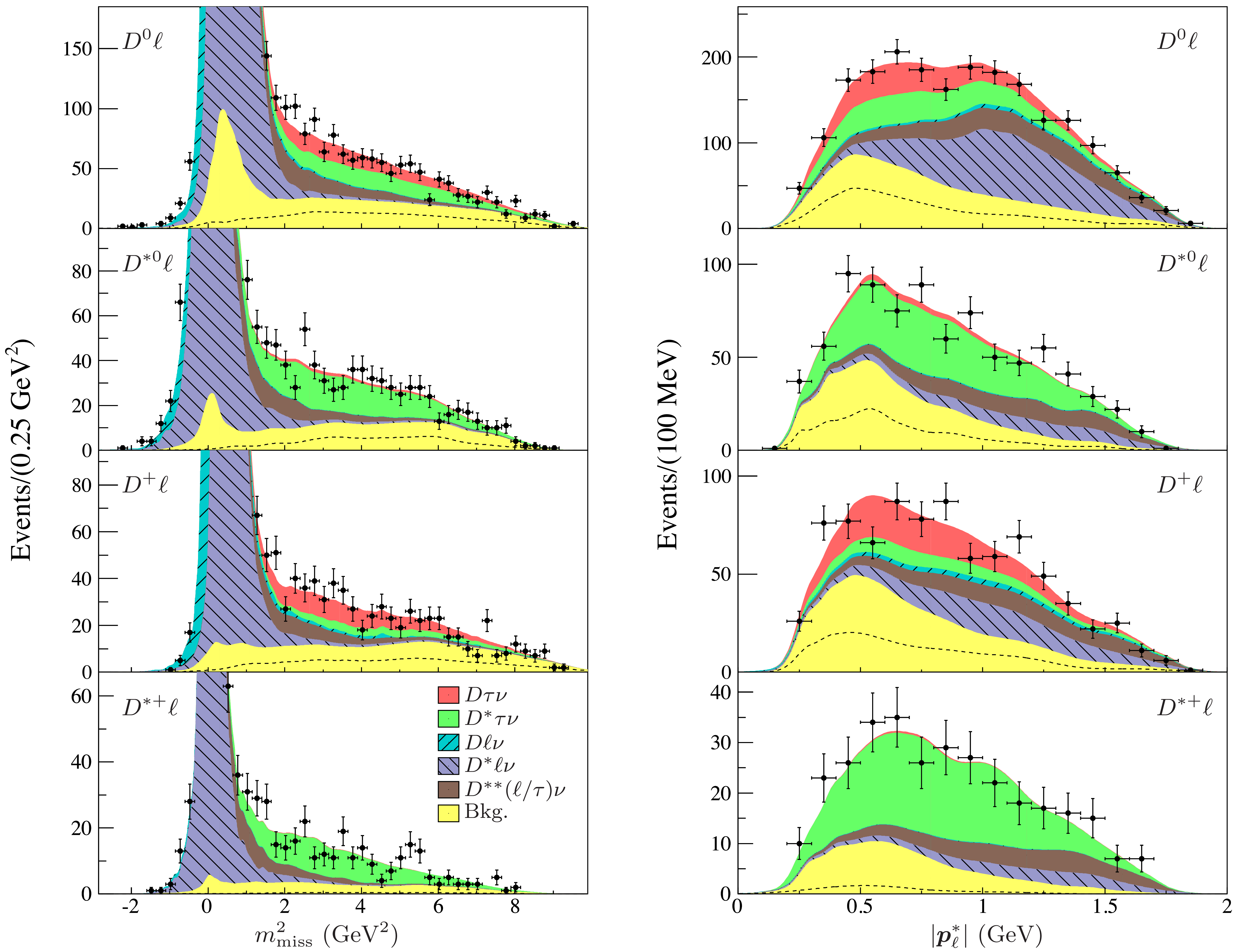
In SM the EW force-carriers are blind to lepton flavour, within stringent experimental limits.

When we discuss LU we are discussing new BSM force-carriers which can in principle have different couplings to different lepton flavours.

LU tests in b→clν

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

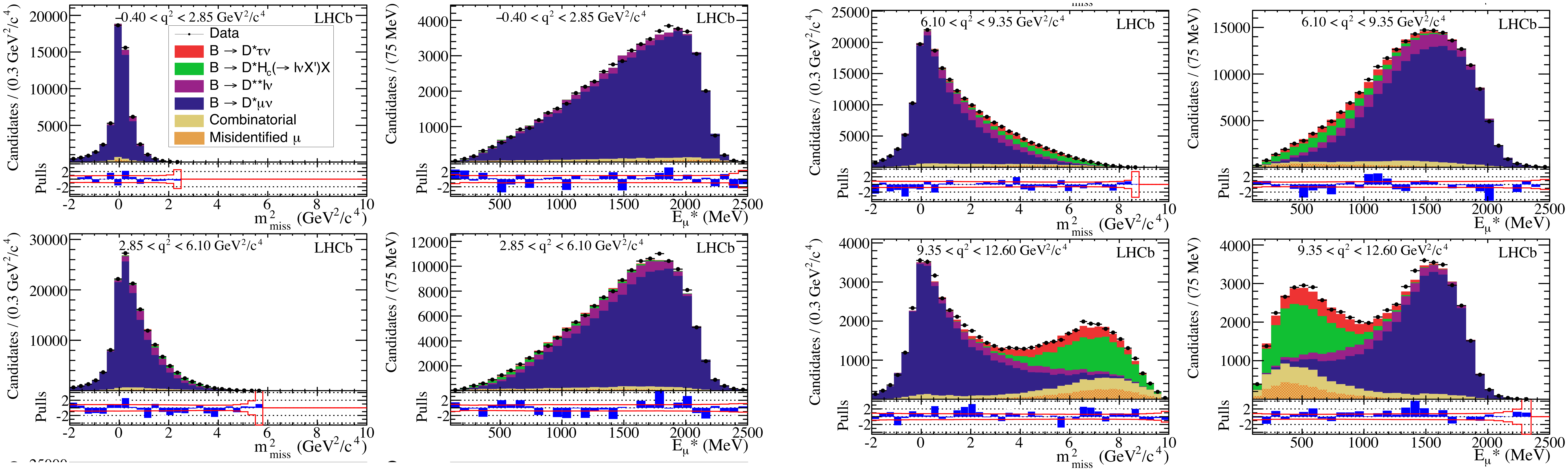




Challenging analysis, significant backgrounds even at B-factories
Thought for a long time to be impossible at a hadron collider

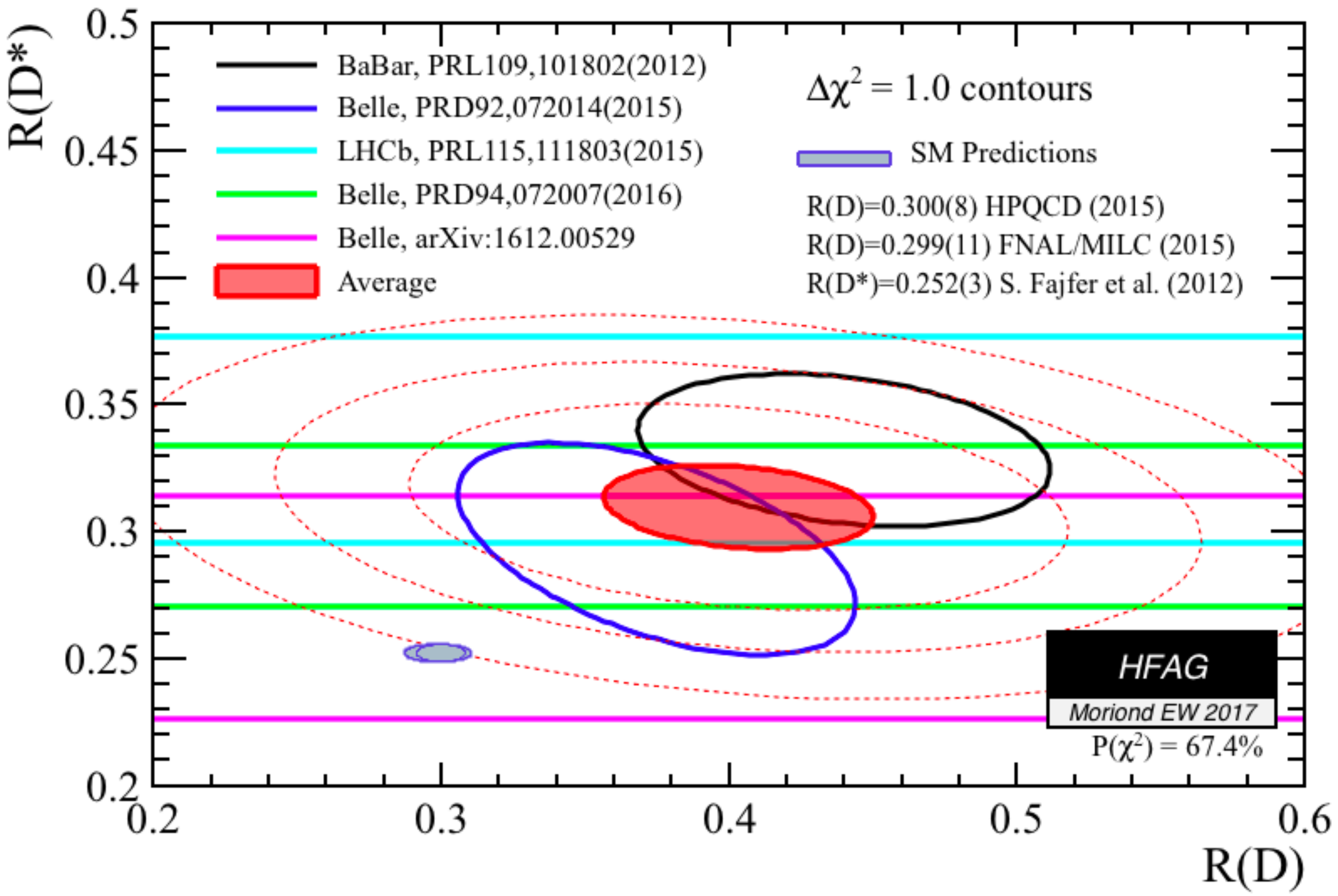
LHCb says yes we can

LHCB-PAPER-2015-025



Another area where LHCb has performed despite expectations…

Summary of b→clν results @ MEW 2017

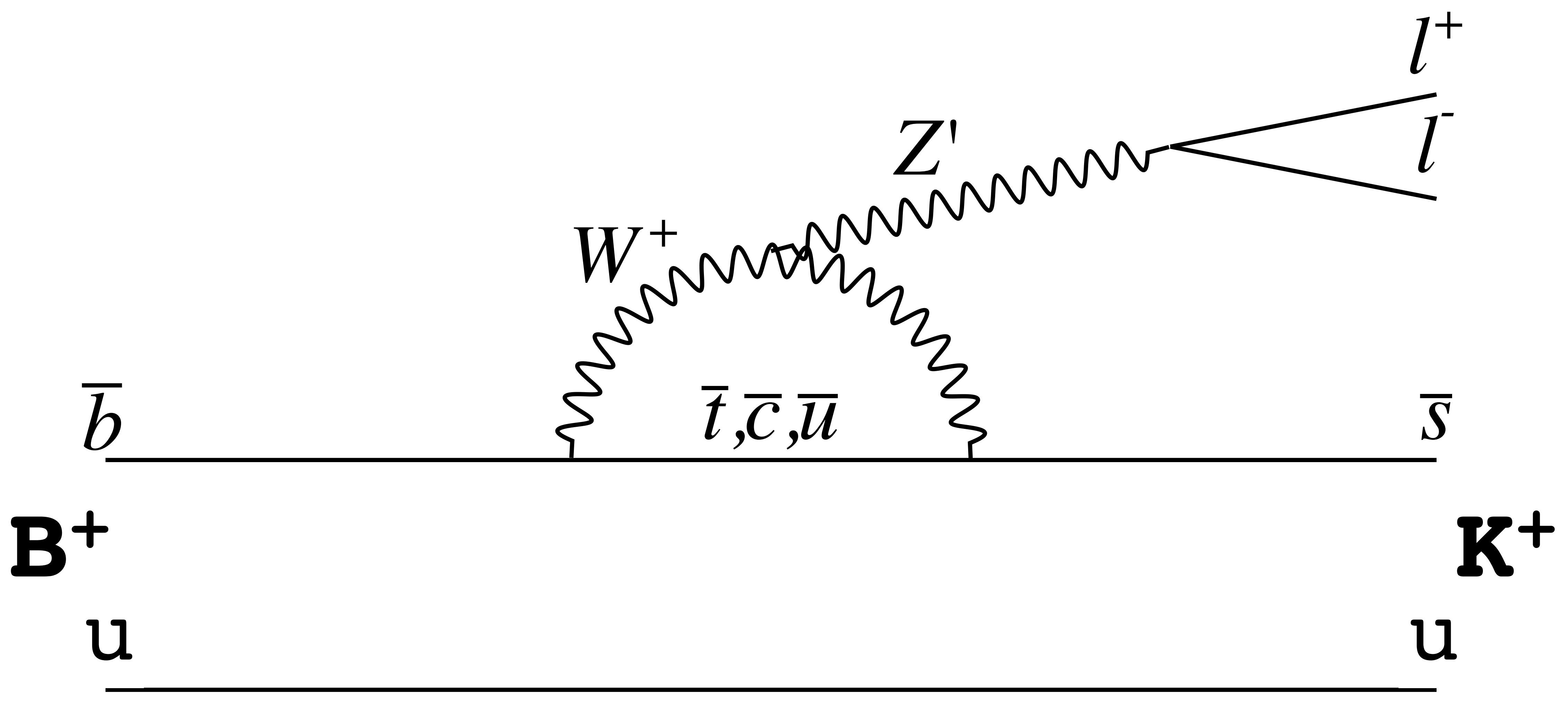


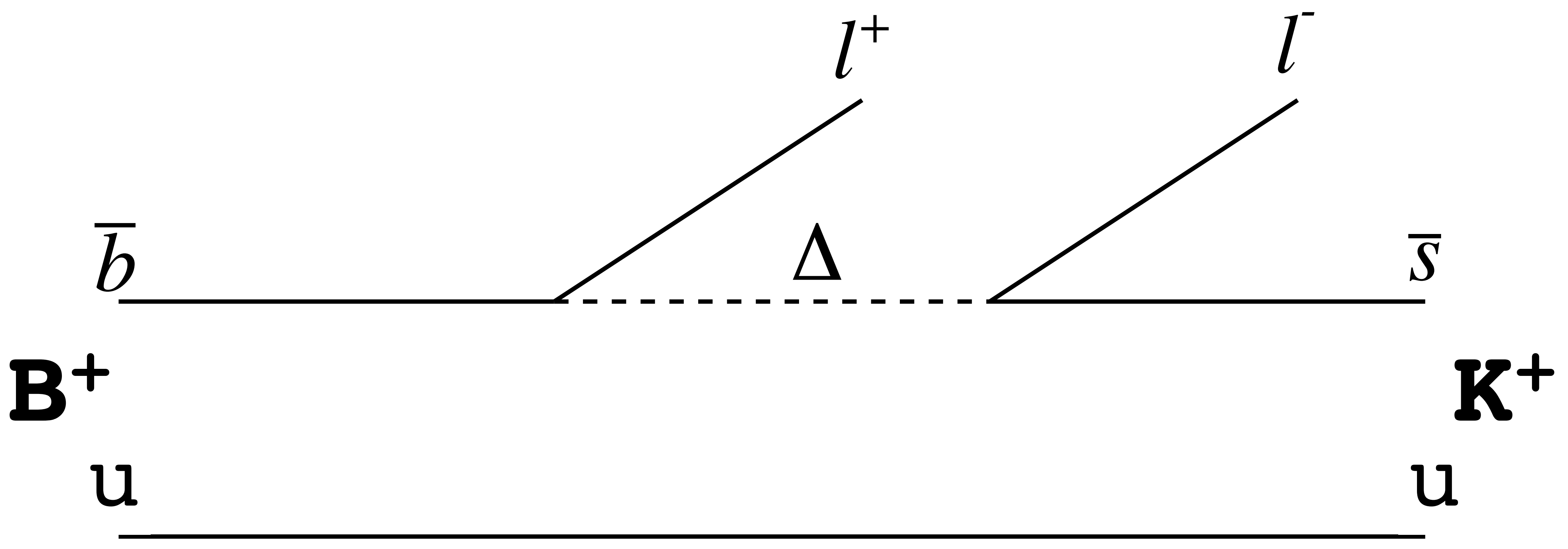
B factories starting to access angular observables, will be increasingly important for the interpretation in the future

LU tests in b→sll

LHCb-PAPER-2014-024

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

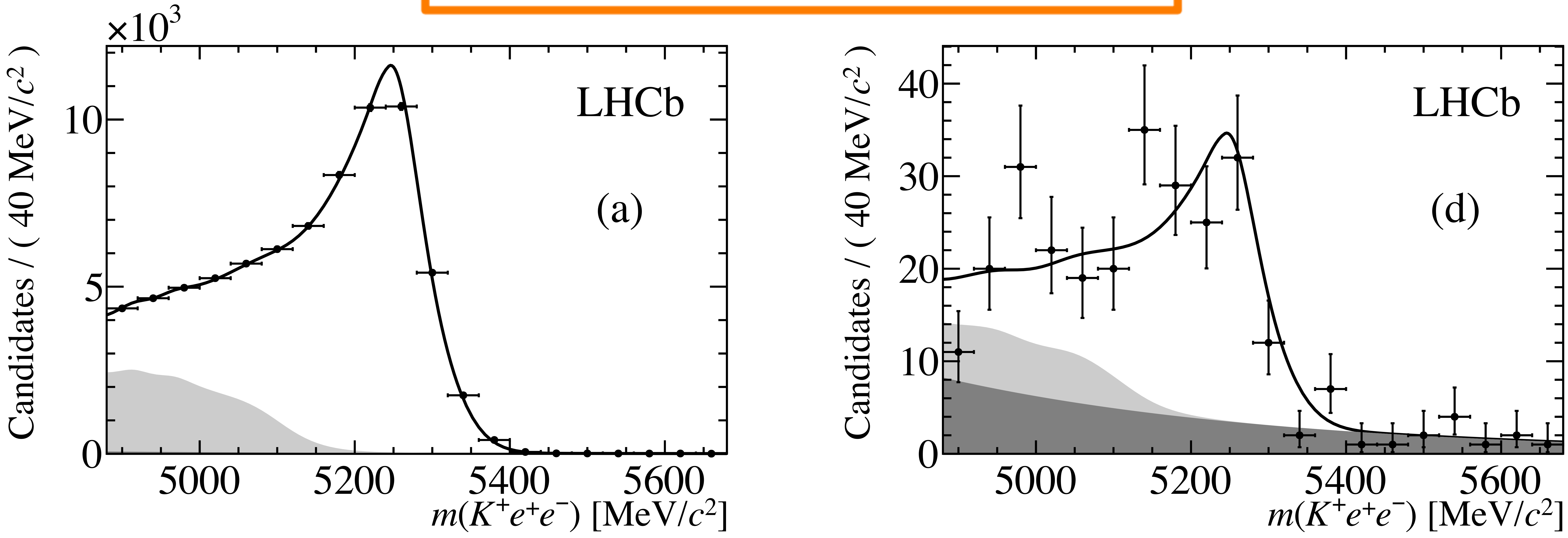




LHCb R_K analysis

LHCb-PAPER-2014-024

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

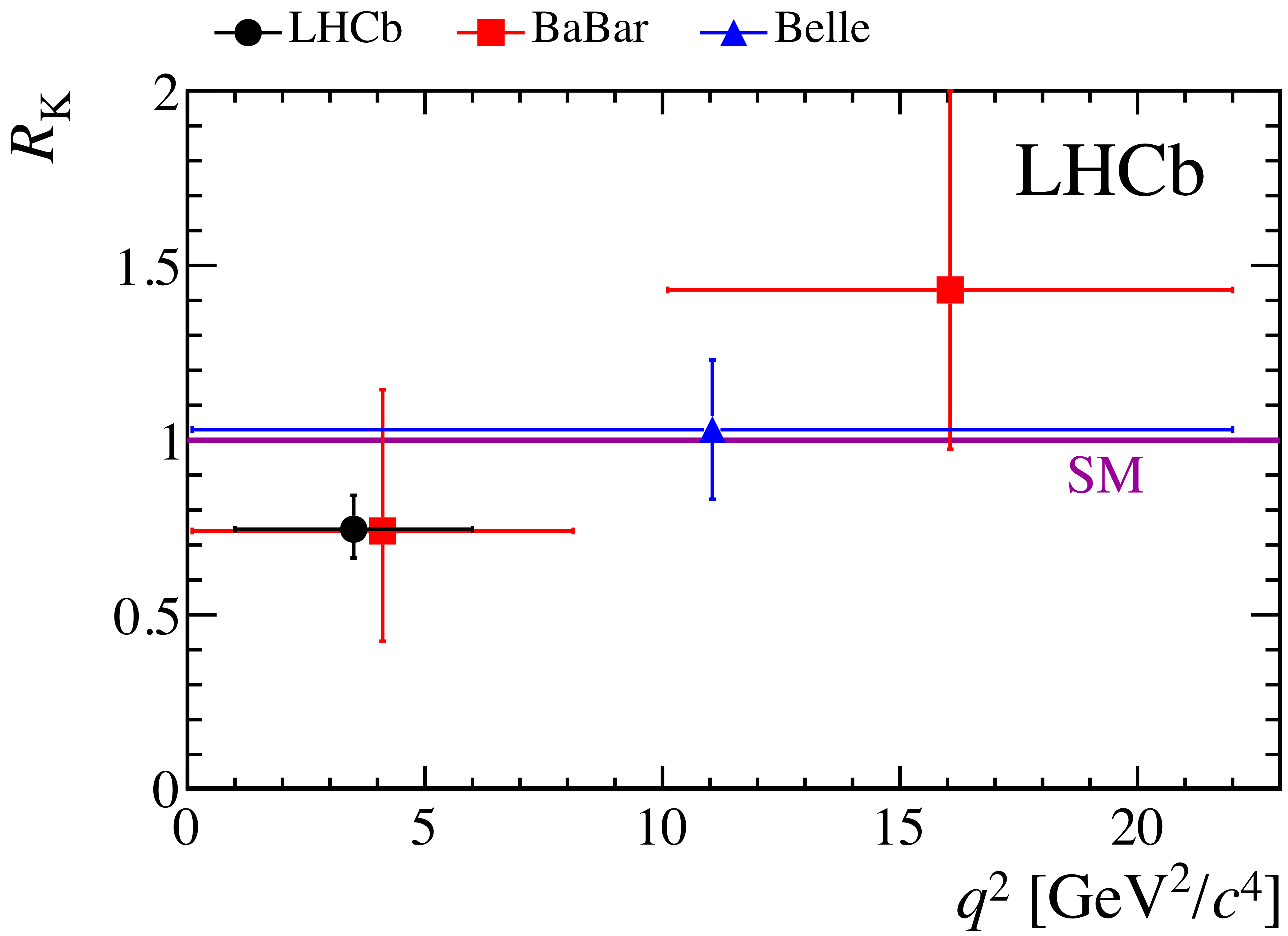


Analysis uses double ratio between resonant/non-resonant modes to help keep the systematics minimal

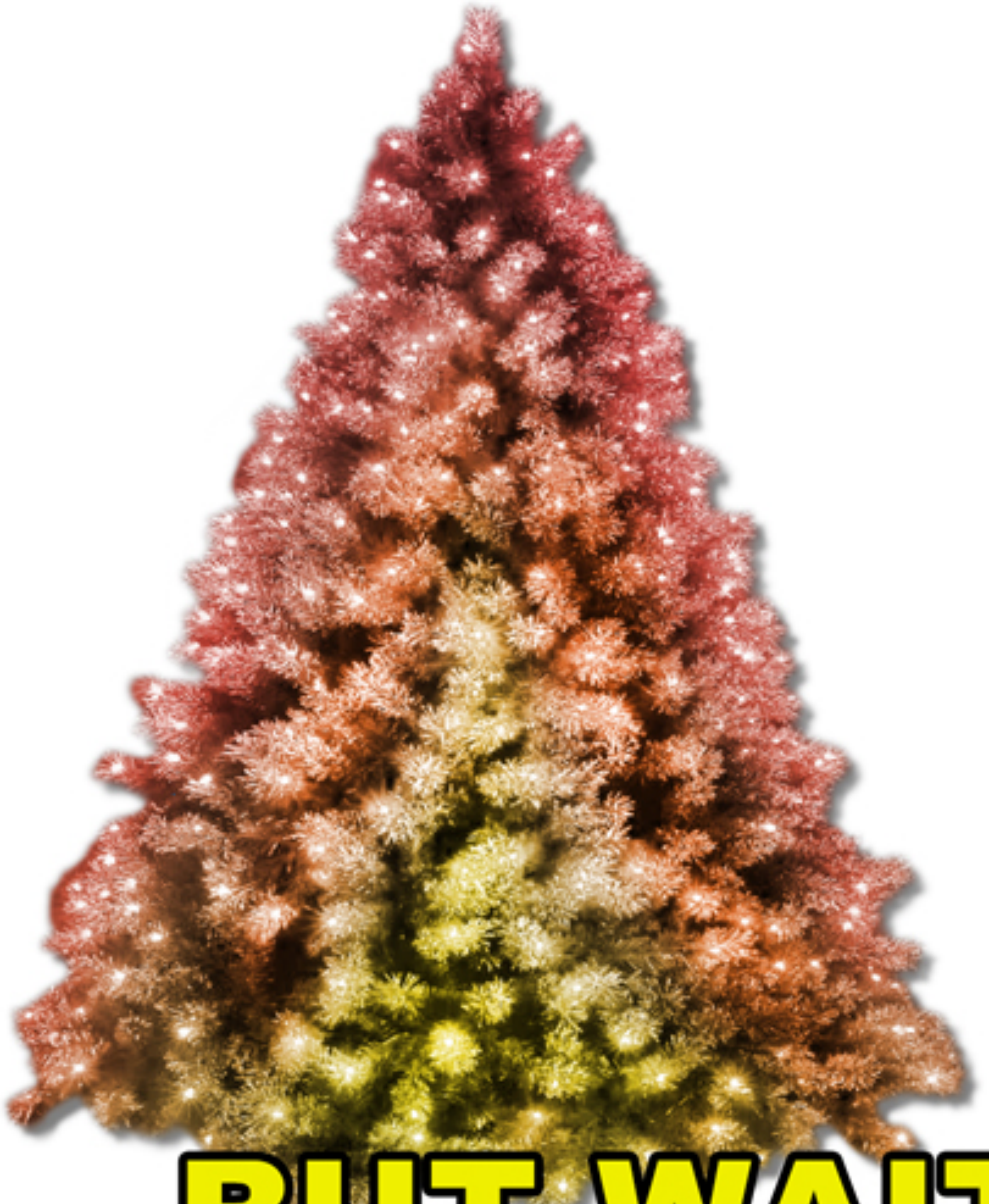
R_K global picture

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…



UNIVERSAL HOLIDAY TREE

3 EASY PAYMENTS OF

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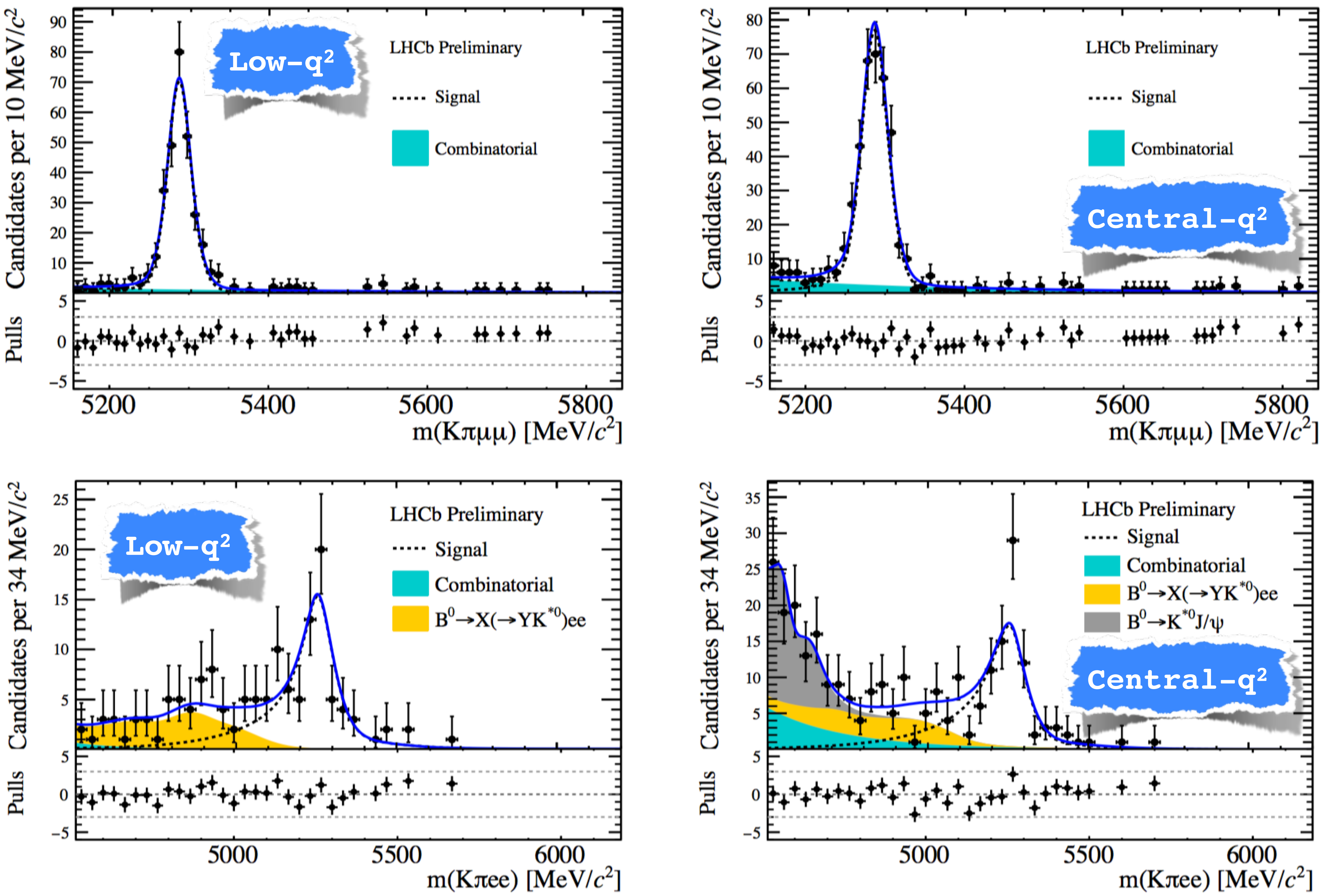
BUT WAIT, THERE'S MORE!

R_{K^*} is finally here

R_{K^*} signal yields

See CERN Seminar for details



Same double-ratio method as R_K, backed up by unbiased measurements of the electron/muon ratio in the J/ψ and ψ(2S) resonant modes

Control channel results

See CERN Seminar for details

› Control of the absolute scale of the efficiencies via the ratio

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

which is expected to be unity and measured to be

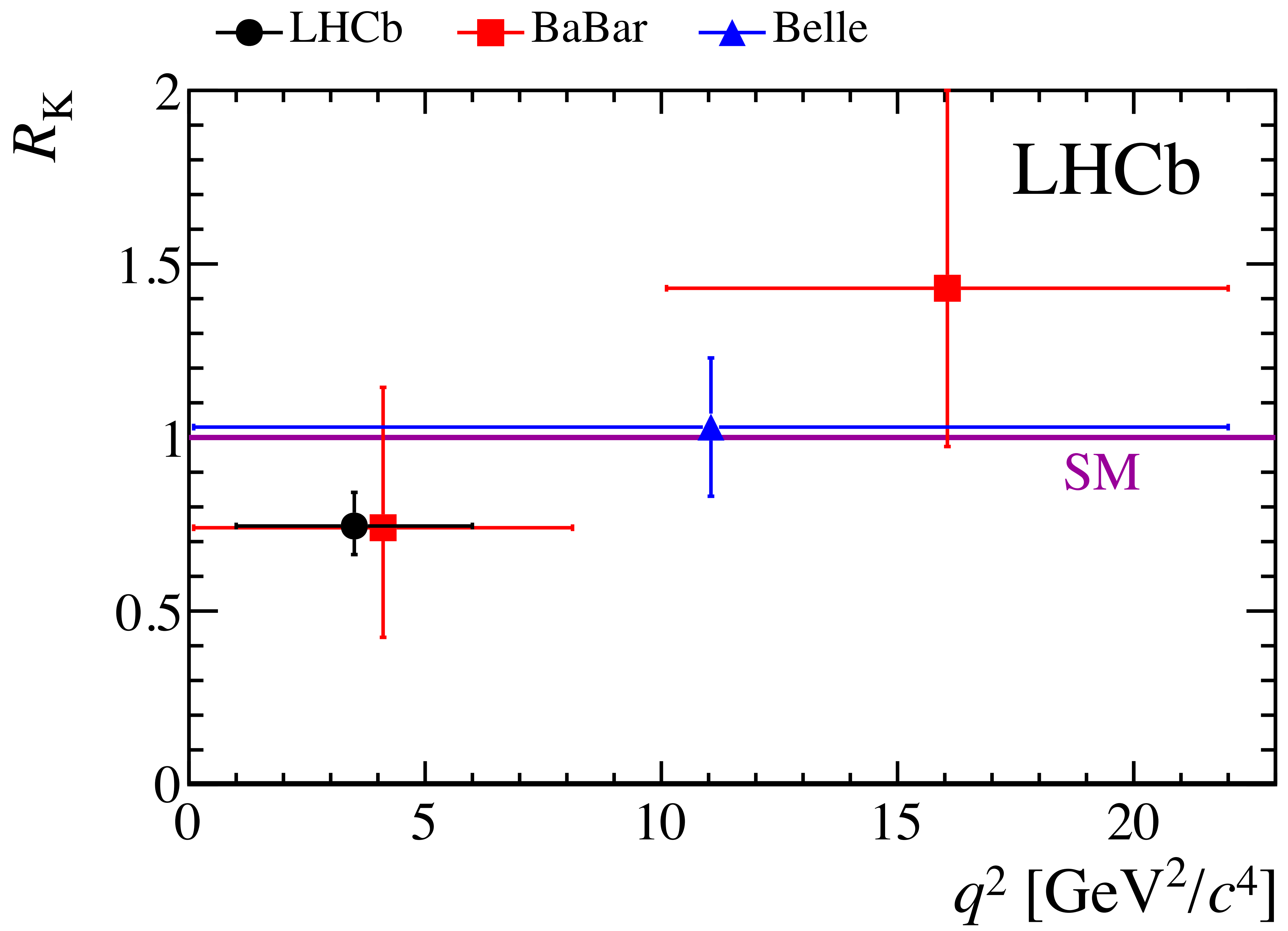
$$1.043 \pm 0.006\,(\text{stat}) \pm 0.045\,(\text{syst})$$

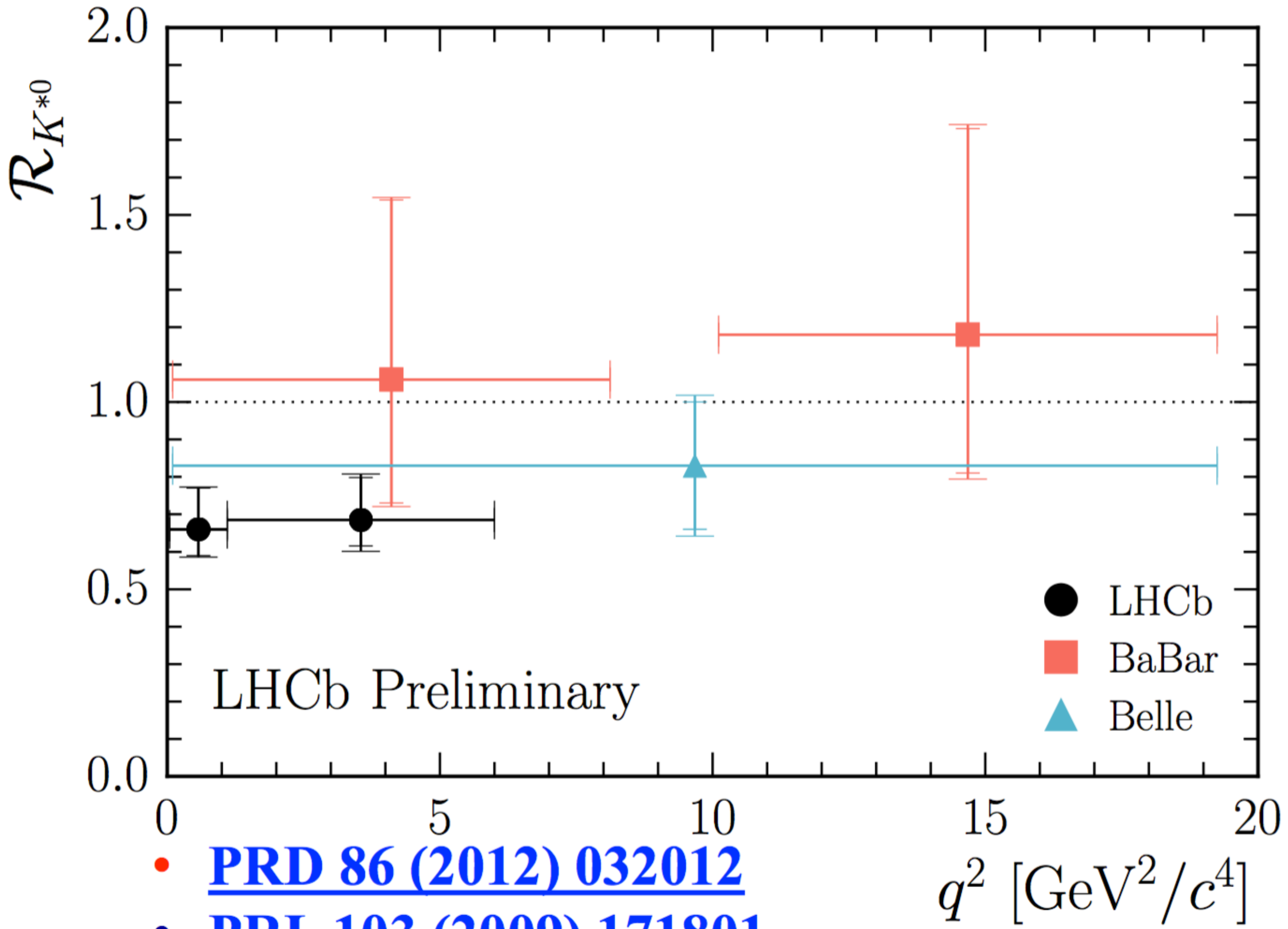
› Result observed to be reasonably flat as a function of the decay kinematics and event multiplicity

Same double-ratio method as R_K, backed up by unbiased measurements of the electron/muon ratio in the J/ψ and ψ(2S) resonant modes

R_{K^*} results compared to R_K

See CERN Seminar for details



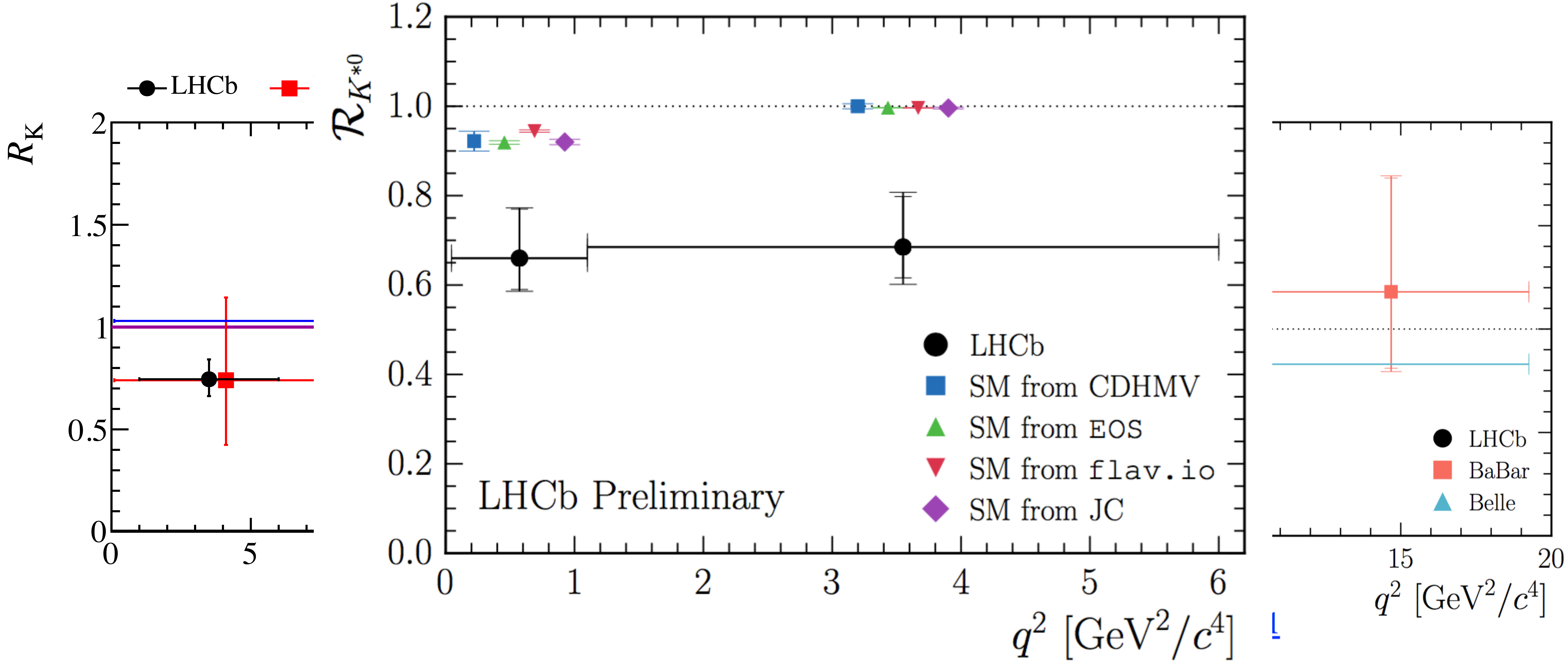


- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

Compatible with SM at 2.2-2.5σ in each q^2 region
Same pattern as R_K : can we get excited yet?

R_{K^*} vs. SM theory predictions

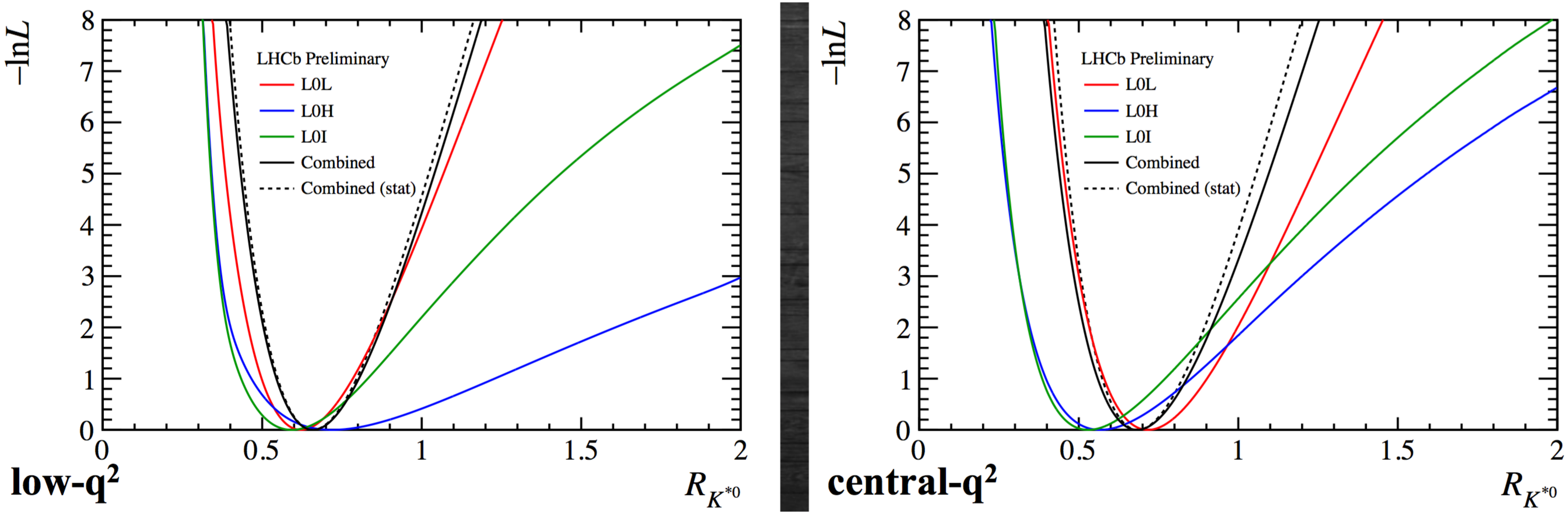
See CERN Seminar for details



I'll come back to why no combination in a moment, for now just notice that the spread of theory predictions at low-q^2, is significantly greater than their "theory uncertainties"

R_{K^*} likelihoods

See CERN Seminar for details

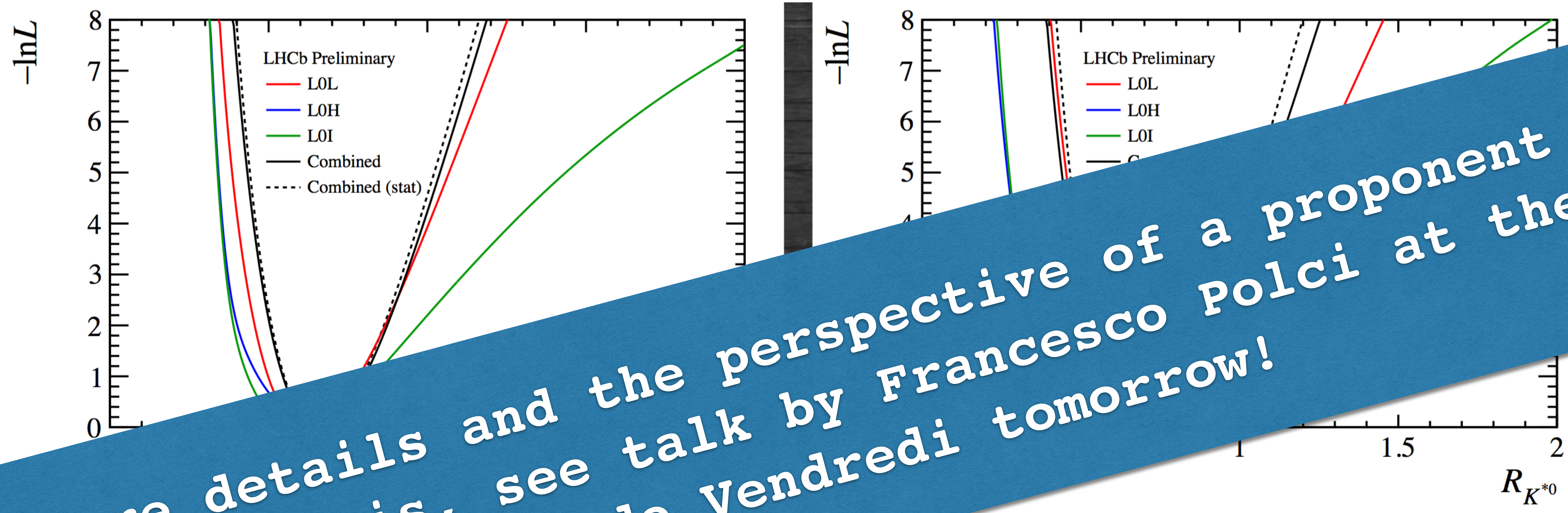


LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]

Excellent agreement in likelihoods between different trigger paths in each of the q^2 regions. Non-Gaussian likelihood regime.

R_{K^*} likelihoods

See CERN Seminar for details



For more details and the perspective of a proponent of this analysis, see talk by Francesco Polci at the reunion de Vendredi tomorrow!

	low-q^2	central-q^2
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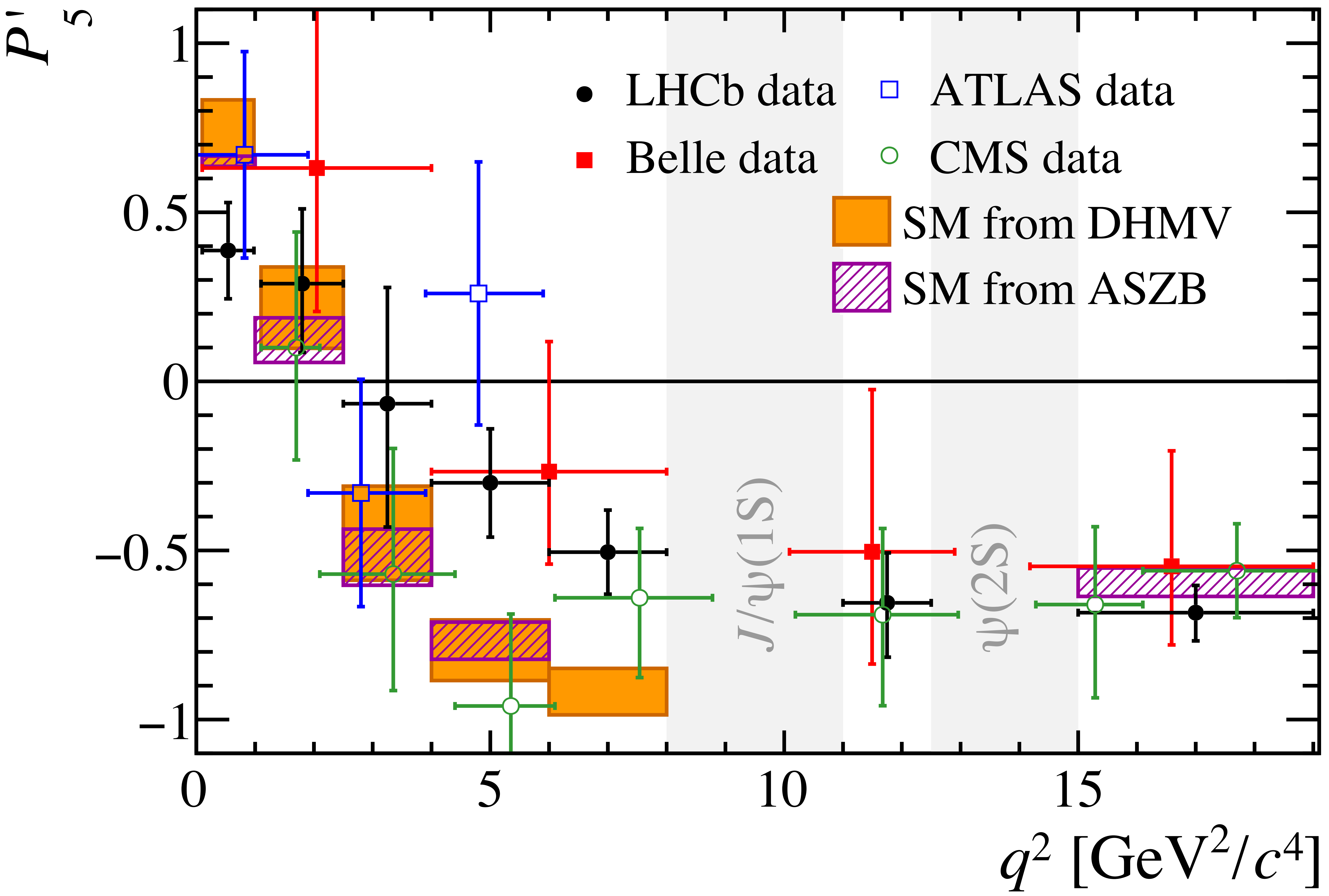
Discrepancies driven by μ/τ?

LHCb-PAPER-2015-051
ATLAS & CMS prelim

Thanks to Tom Blake for the plot!



New ATLAS/CMS $B \to K^{*0}\mu\mu$ results @ Moriond EW 2017 move P5′ central values a bit closer to the SM, but with smaller uncertainties

Discrepancies driven by μ/τ?

LHCb-PAPER-2015-051
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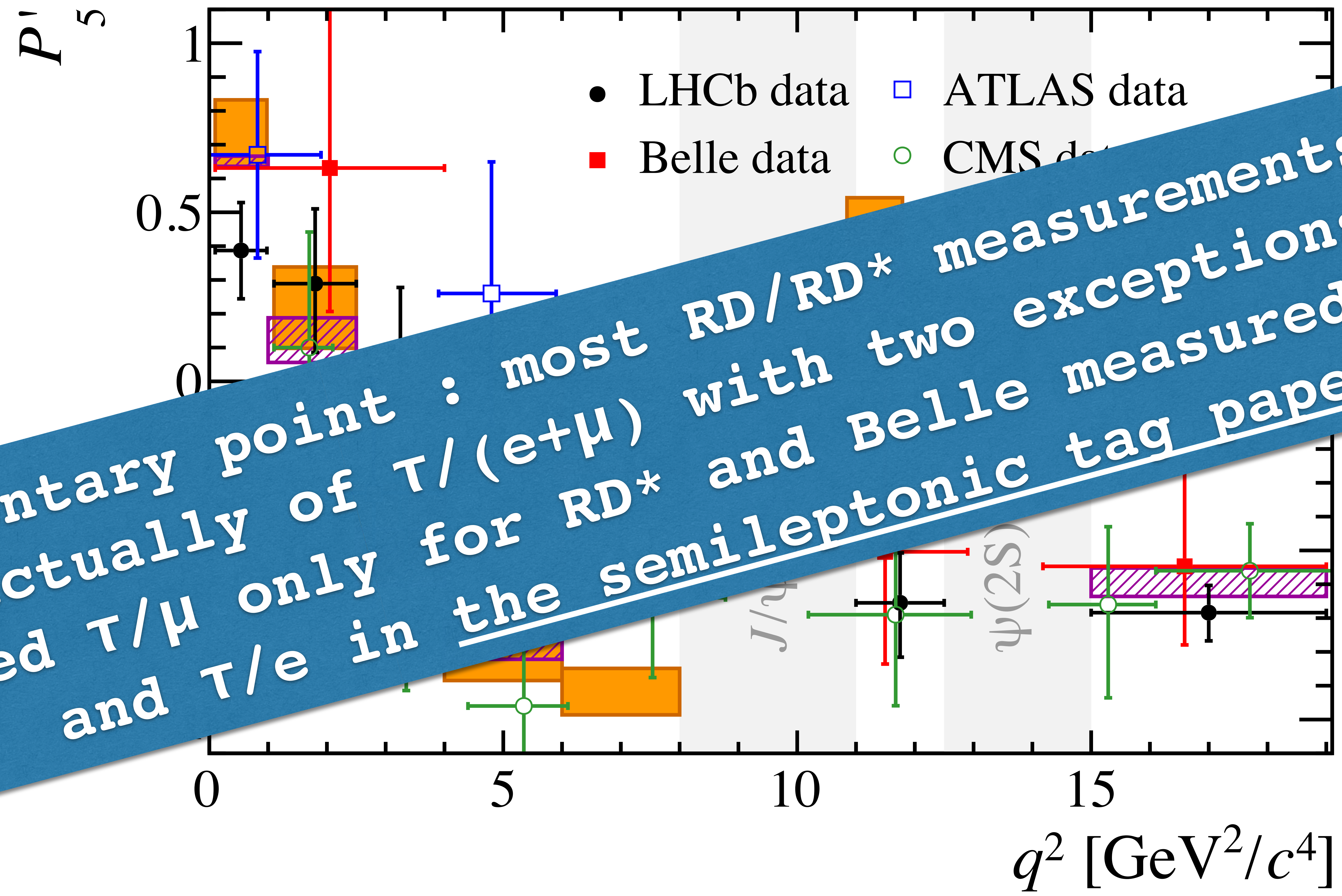
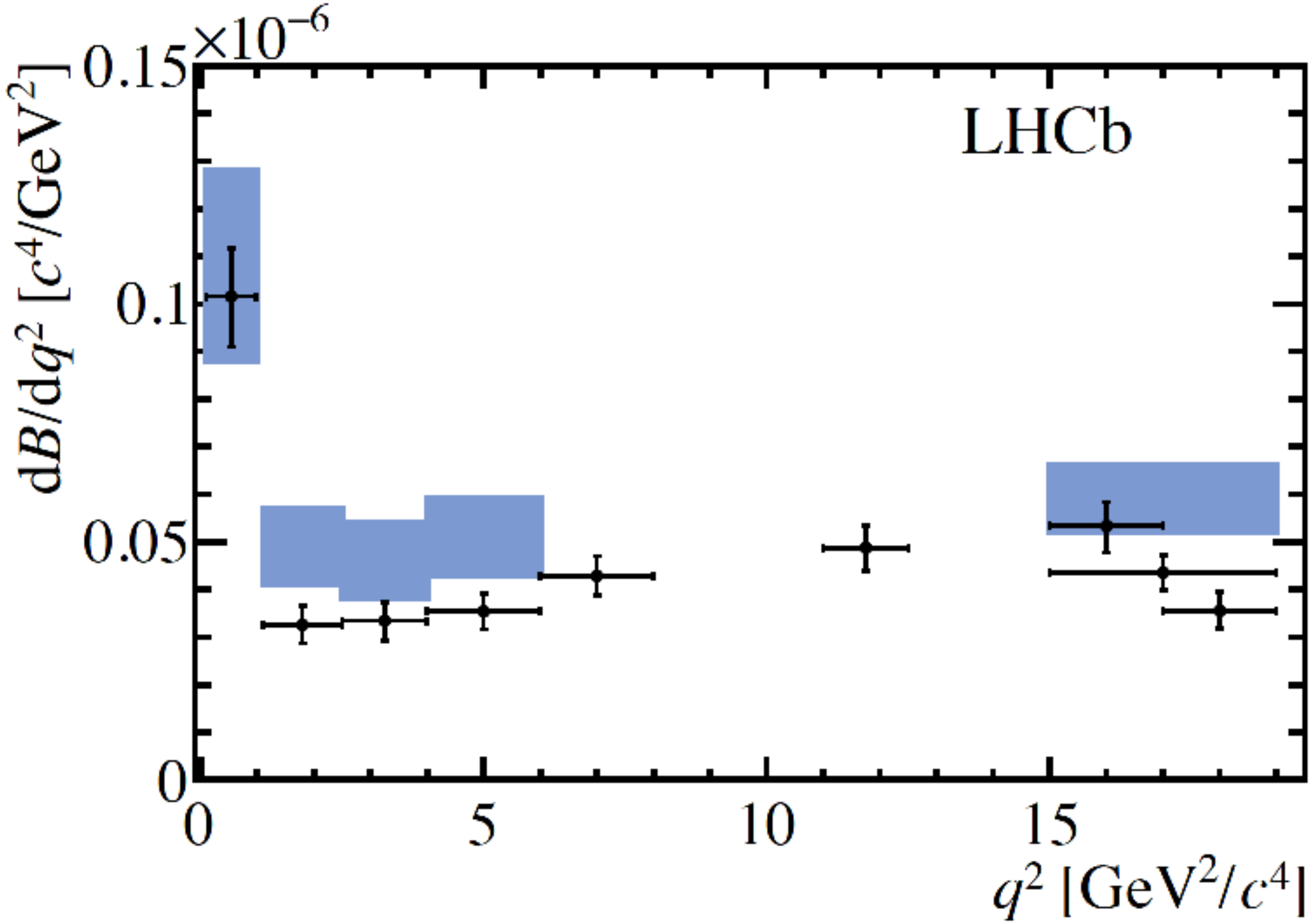


Supplementary point : most RD/RD* measurements to date are actually of τ/(e+μ) with two exceptions. LHCb measured τ/μ only for RD* and Belle measured both τ/μ and τ/e in the semileptonic tag paper.

New ATLAS/CMS B→K^{*0}μμ results @ Moriond EW 2017 move P5′ central values a bit closer to the SM, but with smaller uncertainties

Discrepancies driven by μ/e?

LHCb-PAPER-2016-012



Note : the RK* paper analyzes in a mass window around the K*, while the K*μμ BF analysis performed a proper extraction of the P-wave component. This is why we did not convert RK* into a measurement of the K*ee BF yet. Also the low-q^2 bin is different in the two cases, so not fully comparable. Still from the above plot effect seems driven by muons.

A rhetorical interlude

Already heard from many people in the field

"R_{K^*} is LHCb's 750 GeV moment"

My response : it is exactly nothing like that

The 750 GeV was a statistical fluctuation. We already know that what I've shown you is not a statistical fluctuation. It is either an experiment/theory oversight or BSM. That is both more exciting and more worrying.

B-physics anomalies:

Clean observables? Not having the SM "*breathing behind*"?

$R(K) = \mathrm{Br}(B \to K\mu^+\mu-)/\mathrm{Br}(B \to Ke^+e^-) \overset{\text{exp.}}{=} 0.75^{+0.09}_{-0.07} \pm 0.04$

2.6 sigma deviation from clean SM prediction $R(K) = 1$

Lars Hofer

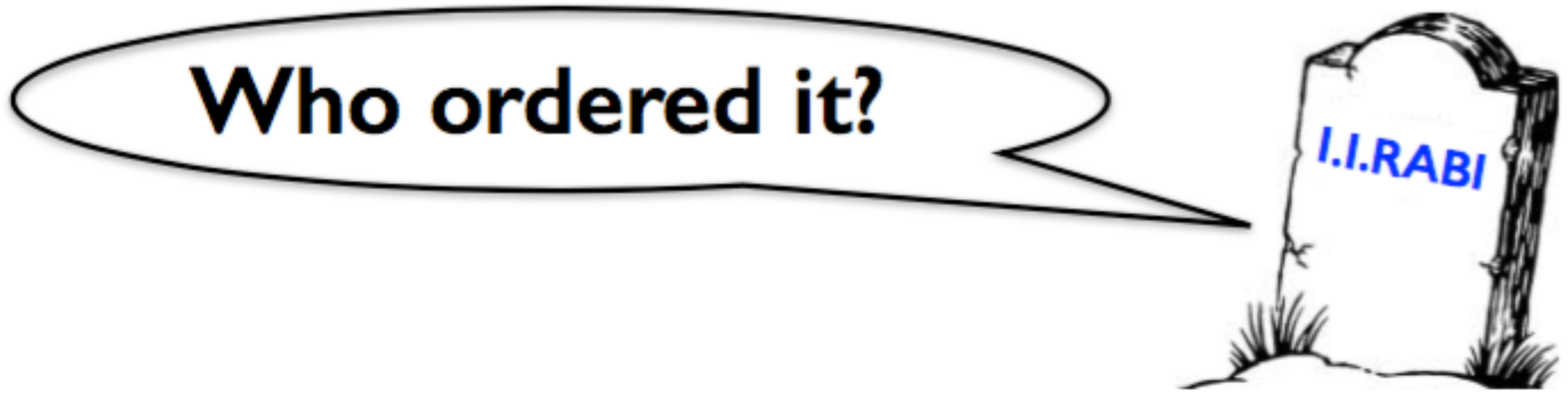
↳ Needs extra BSM contribution to quarks→leptons, so… leptoquarks!

- Z' or light leptoquarks naturally realize these operators

Nejc Kosnik

Z' models possible explanations

Martin Jung



No clear connection with any BSM explaining the EW scale !

A. Pomerol theory summary of MEW 2016 is still quite relevant here

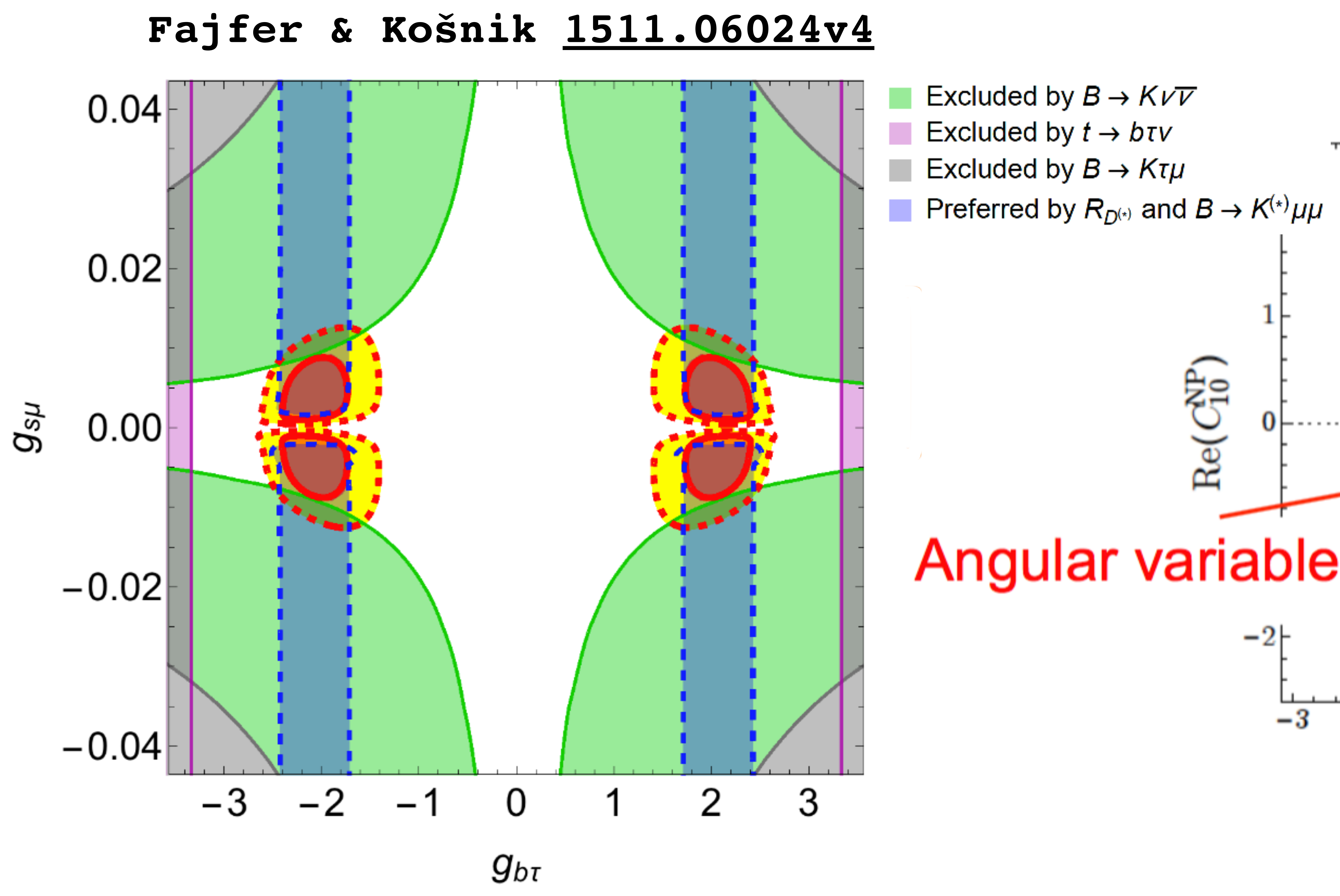
Indirect signs of BSM or wishful thinking?

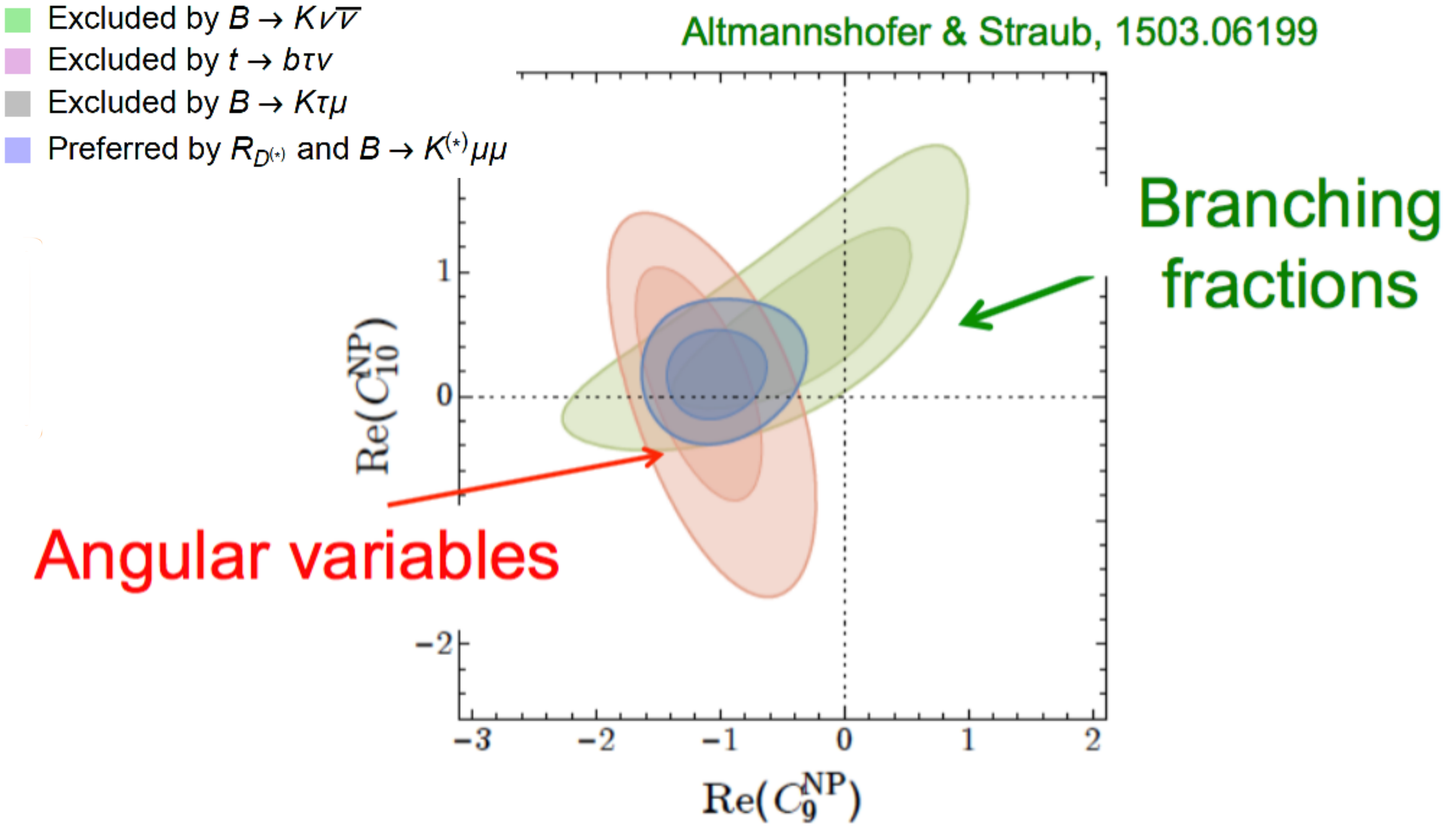
So why no combined significance from the SM? Because you don't need *me* to tell you the sum total of what you've seen is > 5σ from the SM.

But the recent history of flavour physics is littered by exciting deviations (though none this big) which have gone away due to either theoretical or experimental oversights.

The job now is therefore not to rush to claim a discovery, it is to think of how to shed more light on what we are seeing.

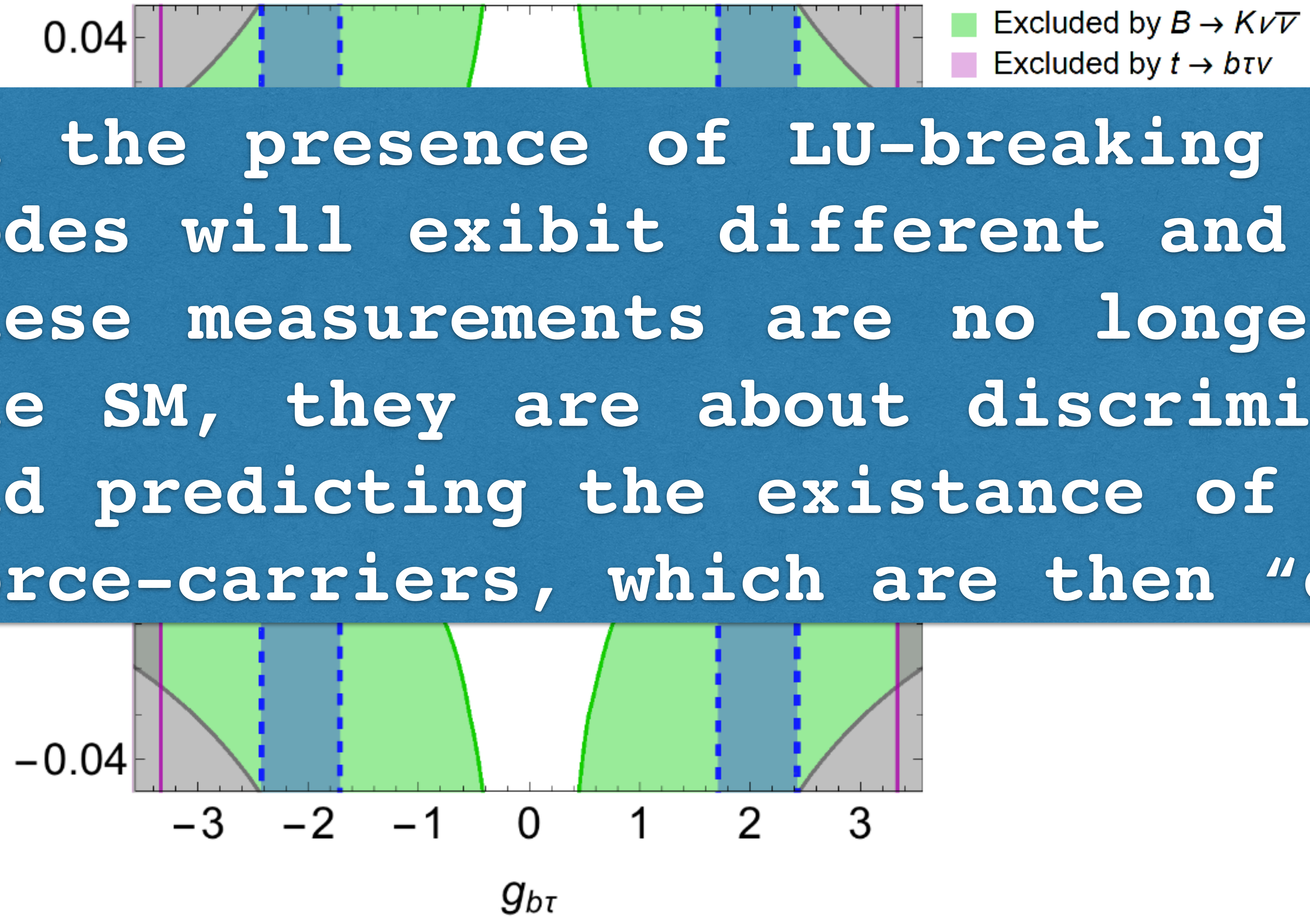
In any case the global picture is available



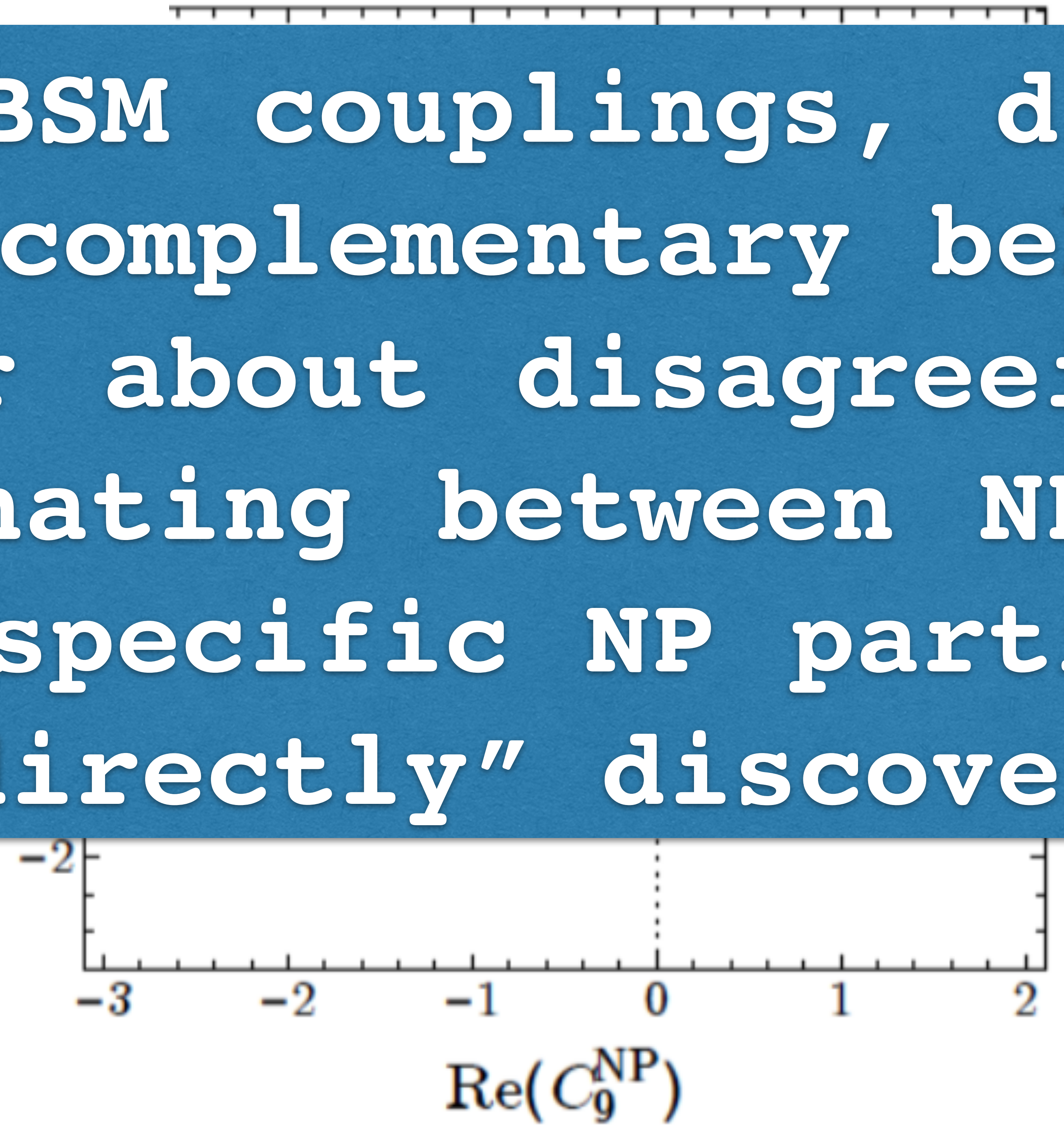


Global picture vs. the SM

Fajfer & Košnik 1511.06024v4



Altmannshofer & Straub, 1503.06199



In the presence of LU-breaking BSM couplings, different modes will exibit different and complementary behaviour. These measurements are no longer about disagreeing with the SM, they are about discriminating between NP models and predicting the existance of specific NP particles or force-carriers, which are then “directly” discovered.

Indirect probes vs. "direct" searches

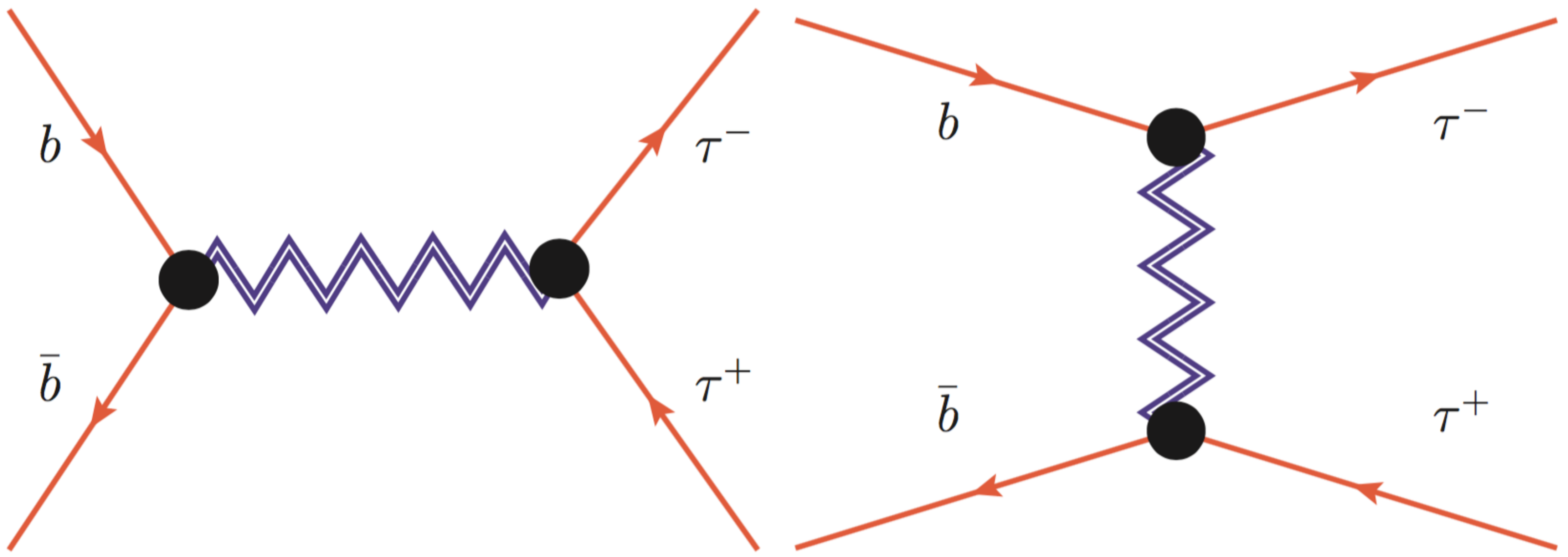
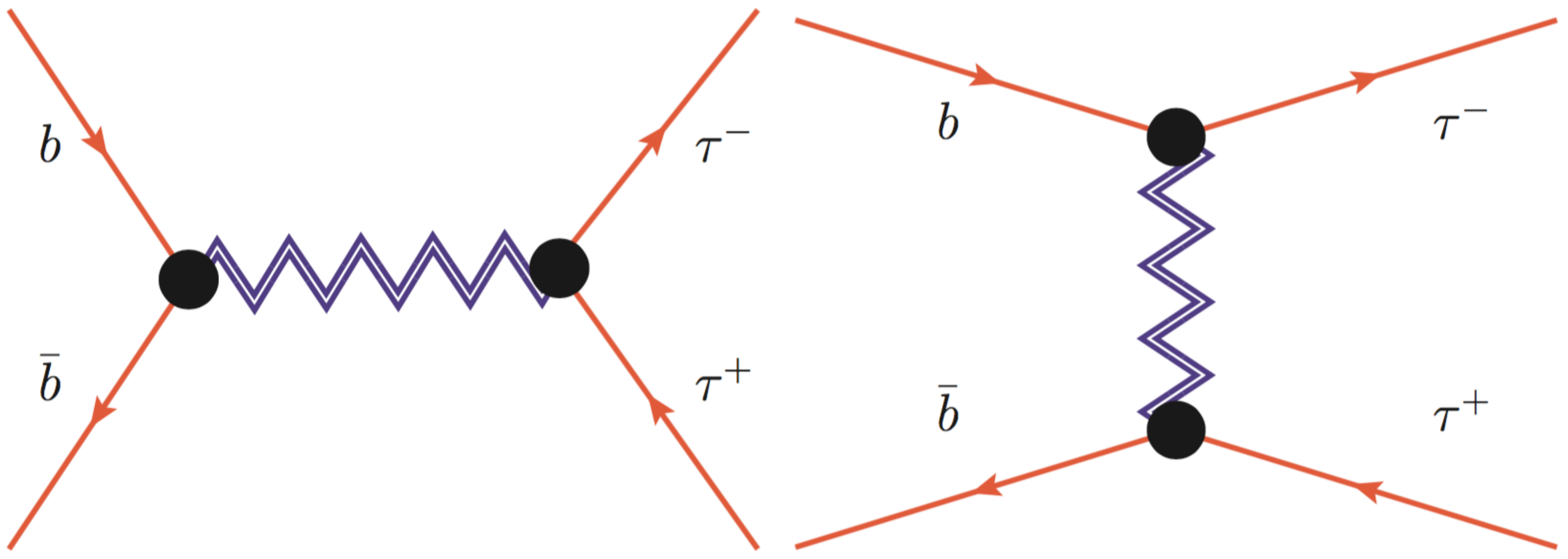


Figure 1: Diagramatic representation of $s-$channel (left-hand side) and $t-$channel (right-hand side) resonance exhange (drawn in blue double see-saw lines) contributions to $b\bar{b} \to \tau^+\tau^-$ process.

Faroughy, Greljo, Kamenik
arXiv:1609.07138

Indirect probes vs. “direct” searches



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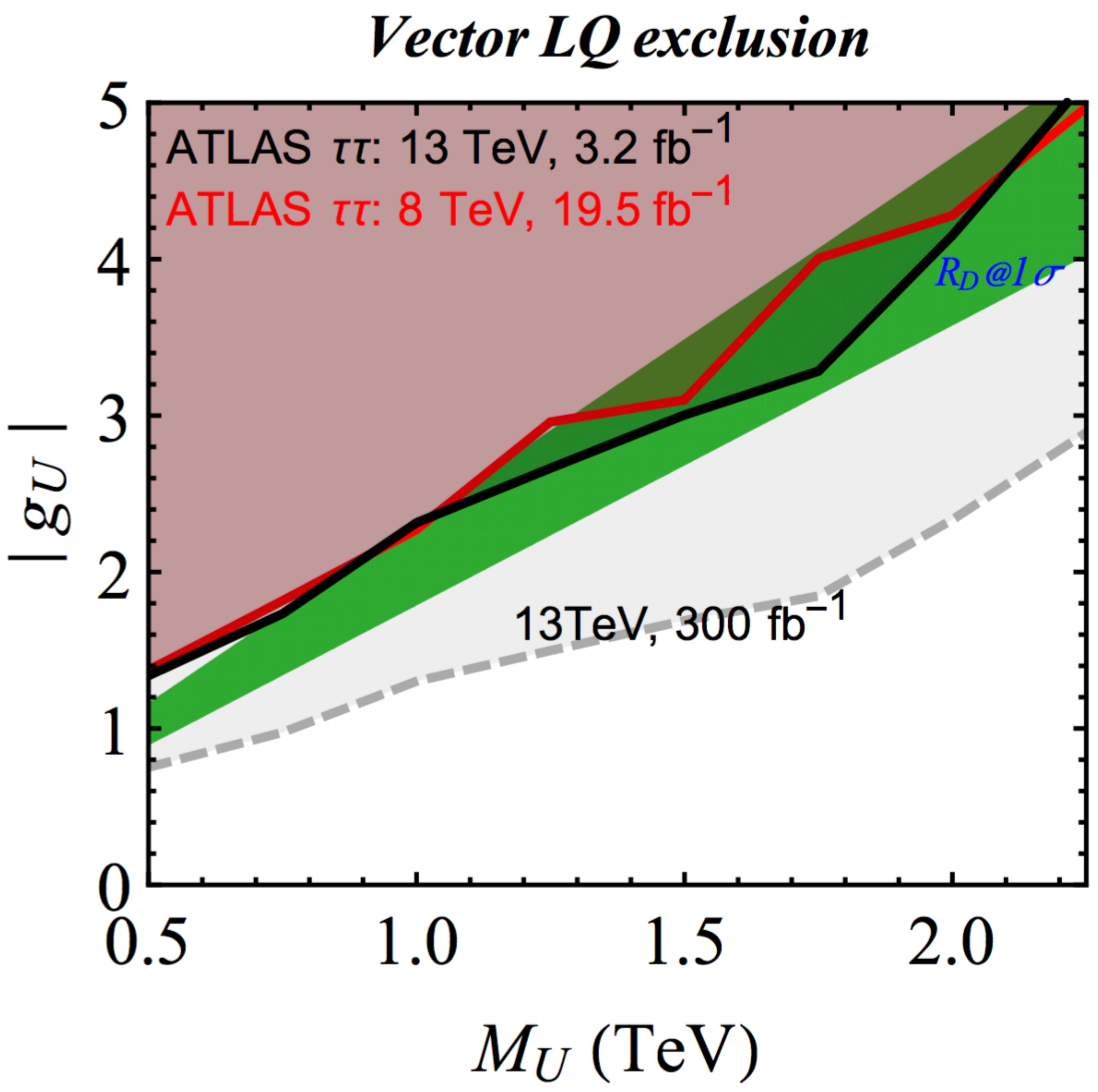


Faroughy, Greljo, Kamenik
arXiv:1609.07138

As Dirk will testify, the slides I have shown you were written before Wednesday. Since then…

Interpretations of RK* 1/8

	All					LFUV				
1D Hyp.	Best fit	1 σ	2 σ	Pull_{SM}	p-value	Best fit	1 σ	2 σ	Pull_{SM}	p-value
$\mathcal{C}_{9\mu}^{\text{NP}}$	-1.10	$[-1.27, -0.92]$	$[-1.43, -0.74]$	5.7	72	-1.76	$[-2.36, -1.23]$	$[-3.04, -0.76]$	3.9	69
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.61	$[-0.73, -0.48]$	$[-0.87, -0.36]$	5.2	61	-0.66	$[-0.84, -0.48]$	$[-1.04, -0.32]$	4.1	78
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}'_{9\mu}$	-1.01	$[-1.18, -0.84]$	$[-1.33, -0.65]$	5.4	66	-1.64	$[-2.12, -1.05]$	$[-2.52, -0.49]$	3.2	31
$\mathcal{C}_{9\mu}^{\text{NP}} = -3\mathcal{C}_{9e}^{\text{NP}}$	-1.06	[-1.23,-0.89]	[-1.39,-0.71]	5.8	74	-1.35	$[-1.82, -0.95]$	$[-2.38, -0.59]$	4.0	71

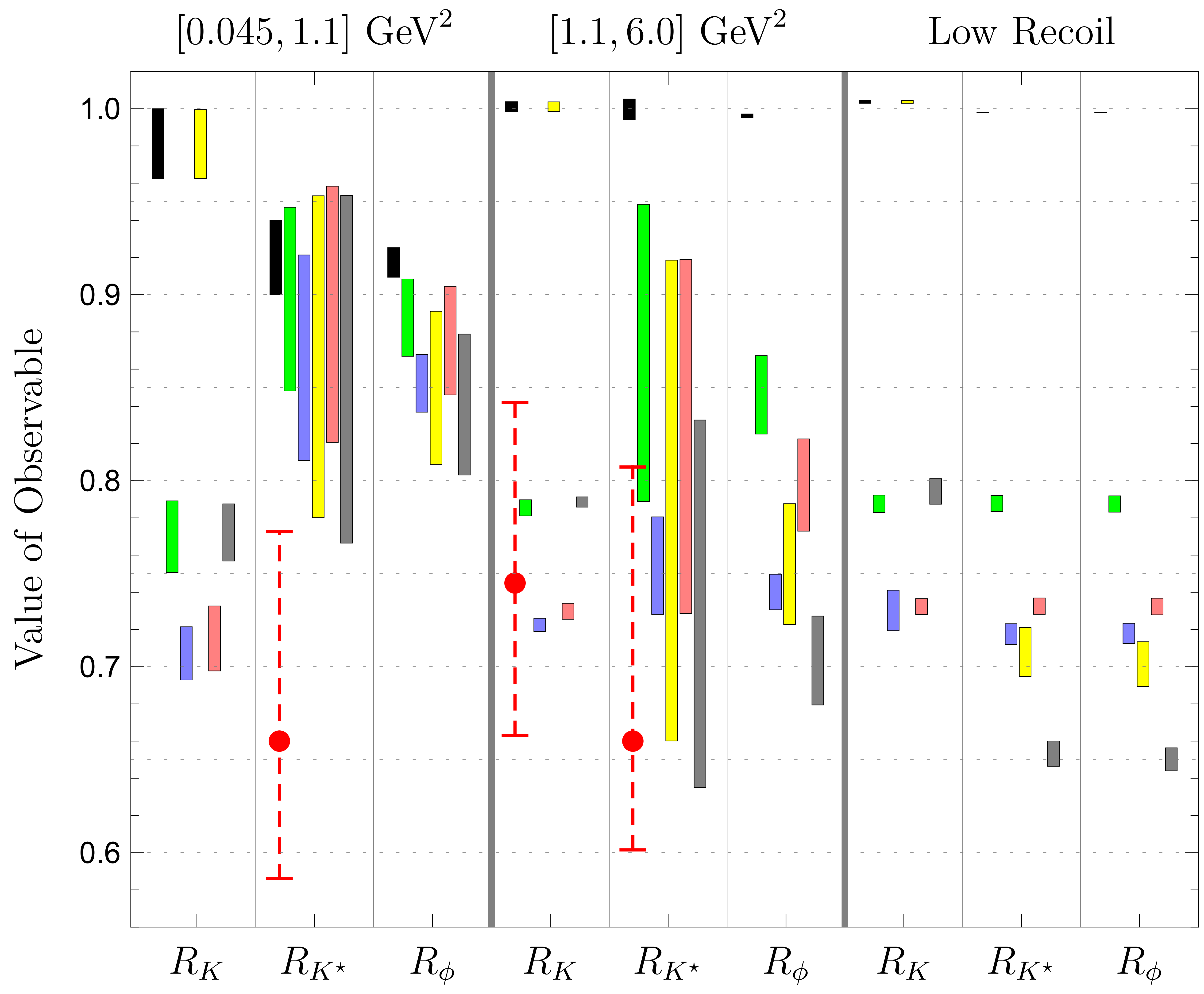
	All			LFUV		
2D Hyp.	Best fit	Pull_{SM}	p-value	Best fit	Pull_{SM}	p-value
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}})$	(-1.17,0.15)	5.5	74	(-1.13,0.40)	3.7	75
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}'_{7})$	(-1.05,0.02)	5.5	73	(-1.75,-0.04)	3.6	66
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu})$	(-1.09,0.45)	5.6	75	(-2.11,0.83)	3.7	73
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10'\mu})$	(-1.10,-0.19)	5.6	76	(-2.43,-0.54)	3.9	85
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9e}^{\text{NP}})$	(-0.97,0.50)	5.4	72	(-1.09,0.66)	3.5	65
Hyp. 1	(-1.08,0.33)	5.6	77	(-1.74,0.53)	3.8	77
Hyp. 2	(-1.00, 0.15)	4.9	61	(-1.89,0.27)	3.1	39
Hyp. 3	(-0.65,-0.13)	4.9	61	(0.58,2.53)	3.7	73
Hyp. 4	(-0.65,0.21)	4.8	59	(-0.68,0.28)	3.7	72

TABLE II: Most prominent patterns of New Physics in $b \to s\mu\mu$ with high significances. The last four rows corresponds to hypothesis 1: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\text{NP}} = \mathcal{C}_{10'\mu})$, 2: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\text{NP}} = -\mathcal{C}_{10'\mu})$, 3: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = \mathcal{C}_{10'\mu})$ and 4: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$. The "All" columns include all available data from LHCb, Belle, ATLAS and CMS, whereas the "LFUV" columns are restricted to R_K, R_{K^*} and $Q_{4,5}$ (see text for more detail). The p-values are quoted in % and Pull_{SM} in units of standard deviation.

Capdevilla et al.
arXiv:1704.05340v1

Interpretations of RK* 1/8

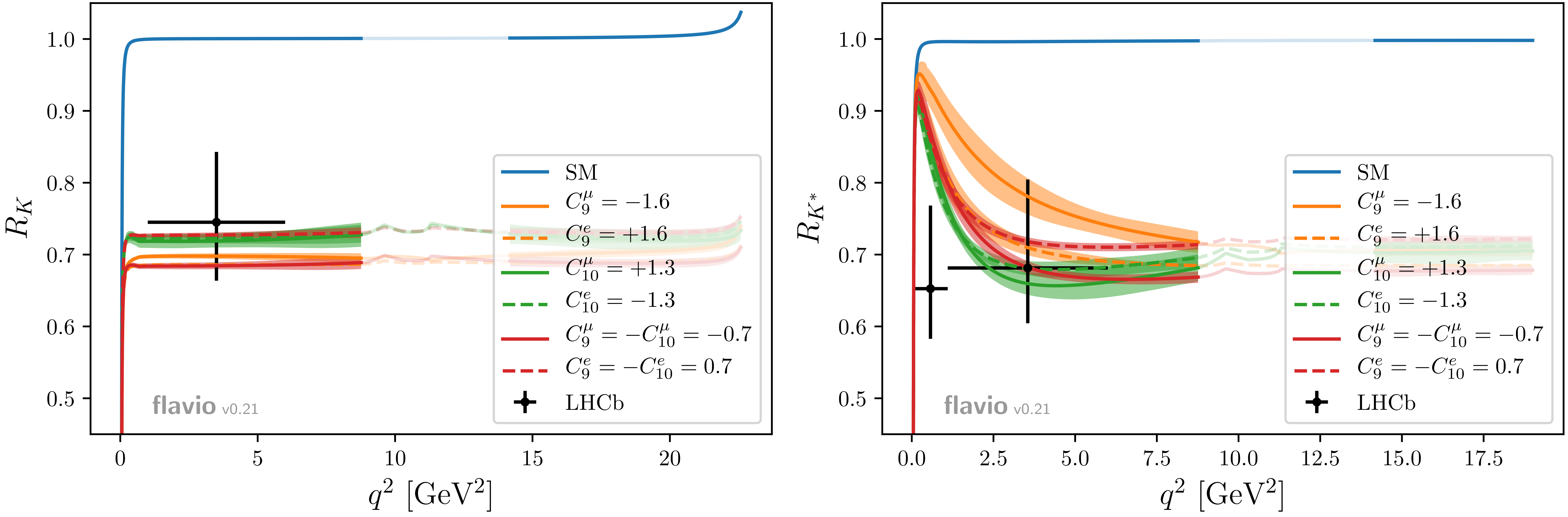
Capdevilla et al.
arXiv:1704.05340v1



Notice the large error bands for RK* at low-q2, this is because of the choice of the more conservative Khodjamirian et al. form factors

Interpretations of RK* 2/8

Almannshofer et al.
arXiv:1704.05435v1



Compared to previous slide, different choice of form factors. Statement in the paper that deviation from NP shapes at low-q^2 would imply new light degrees of freedom

Interpretations of RK* 3/8

D'Amico et al.
arXiv:1704.05438v1

We found that the new measurement of R_{K^*} together with R_K favours new physics in left-handed leptons. Furthermore, adding to the fit kinematical $b \to s\mu^+\mu^-$ distributions (plagued by controversial theoretical uncertainties), one finds that they favour the same of deviations from the SM in left-handed muons. However, even if the uncertainties on R_K, R_{K^*} will be reduced, a precise determination of the new-physics parameters will be prevented by the fact that these no longer are theoretically clean observables, if new physics really affects μ differently from electrons.

We next discussed possible theoretical interpretations of the anomaly. One can build ad-hoc models compatible with all other data:

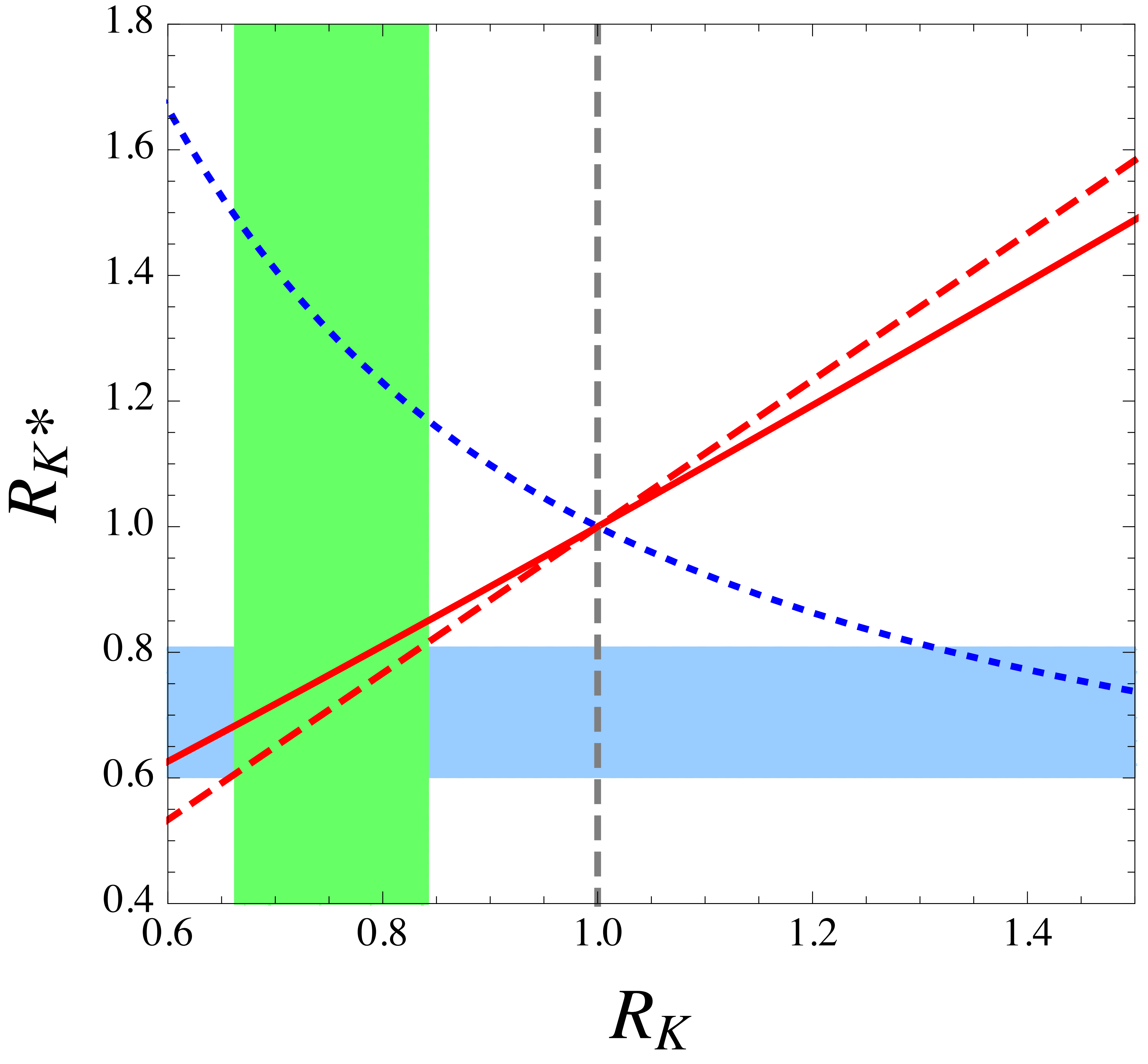
- One extra Z' vector can give extra new-physics operator that involve all chiralities of SM leptons: the simplest possibility motivated by anomaly cancellation is a vectorial coupling to leptons. However, unless the Z' is savagely coupled to $\bar{b}s$ quarks, a Z' coupled to $\bar{s}s$ and $\bar{b}b$ is disfavoured by $pp \to Z' \to \mu^+\mu^-$ searches at LHC and other contraints.

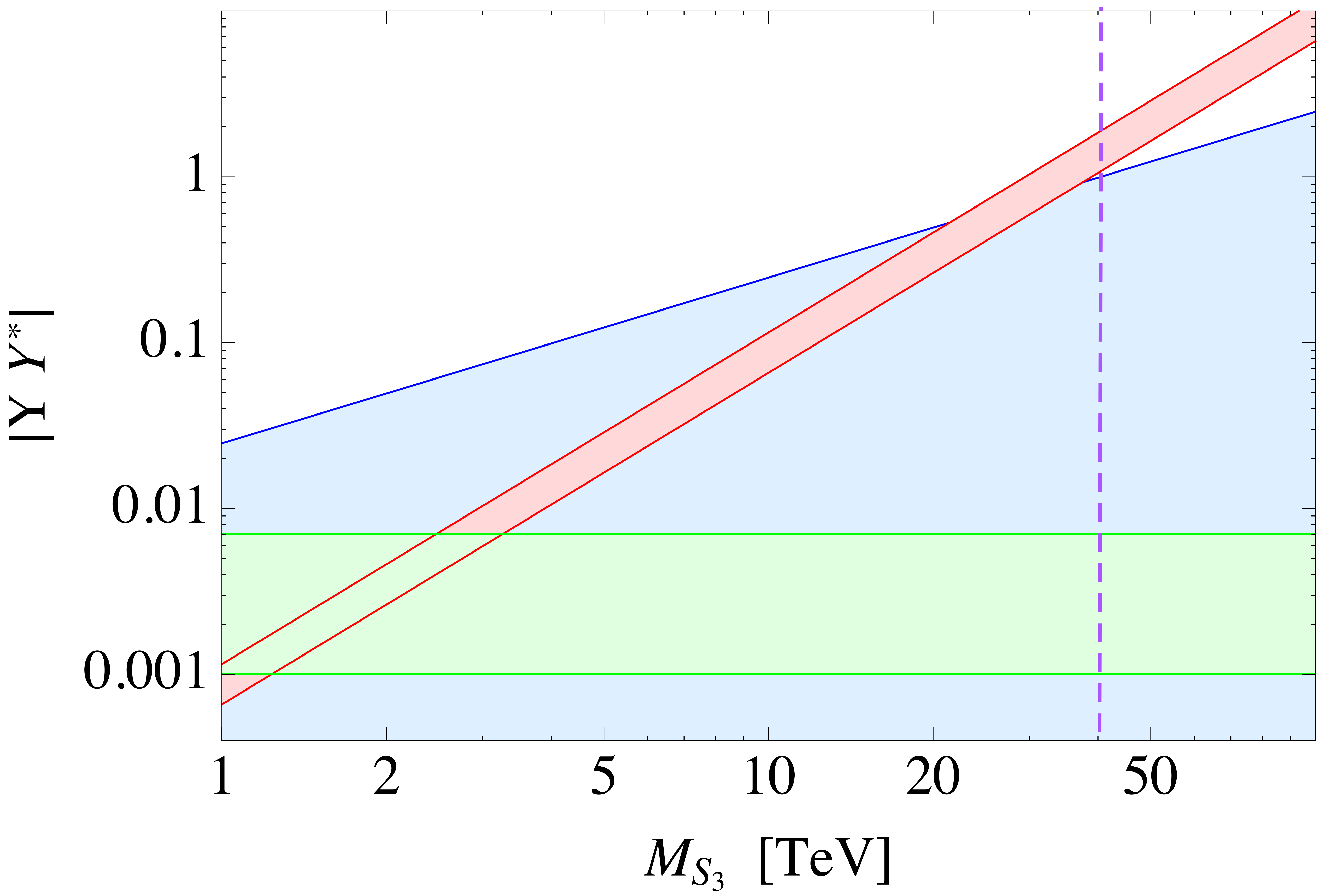
- One lepto-quark tends to give effects in muons or electron only (in order to avoid large flavour violations), and only in one chirality.

- One can add extra fermions and scalars such that they mediate, at one loop level, the desired new physics. Their Yukawa coupling to muons must be larger than unity.

Interpretations of RK* 4/8

Hiller & Nišandžić
arXiv:1704.05444v1

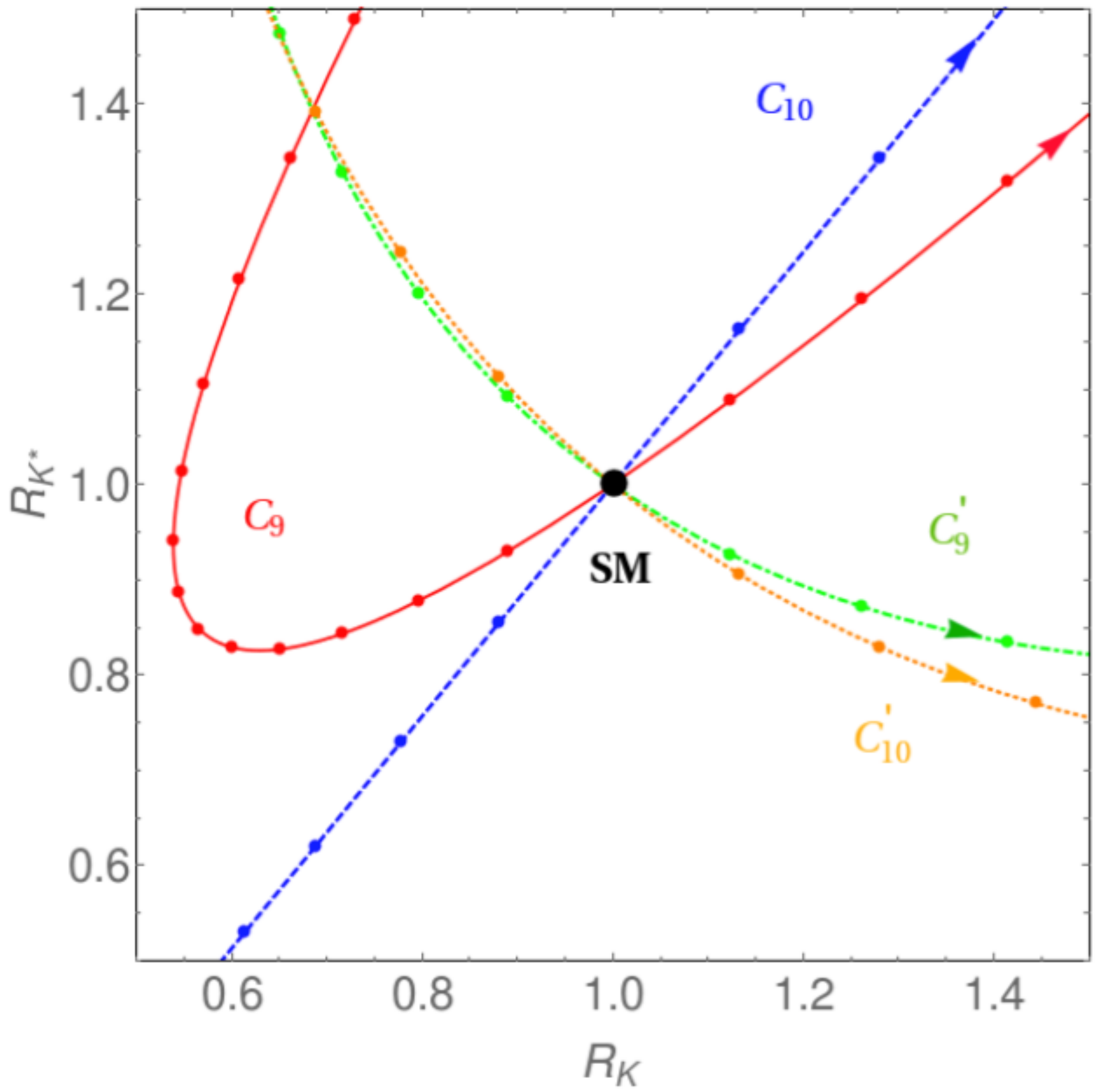


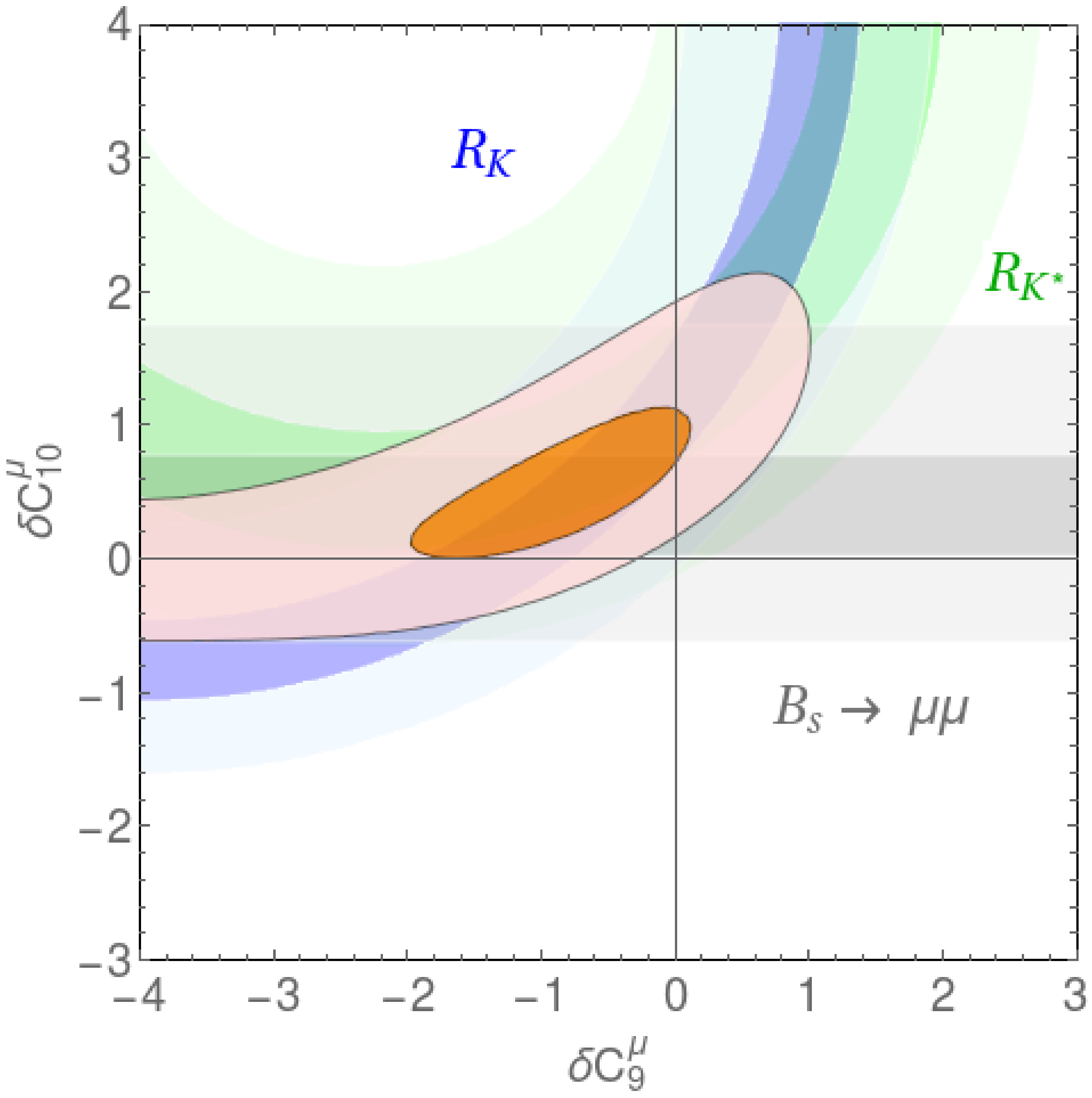


If leptoquark explanation, data prefers few-TeV to few-10s-TeV scale leptoquarks. Could be findable at LHC.

Interpretations of RK* 5/8

Geng et al.
arXiv:1704.05446v1





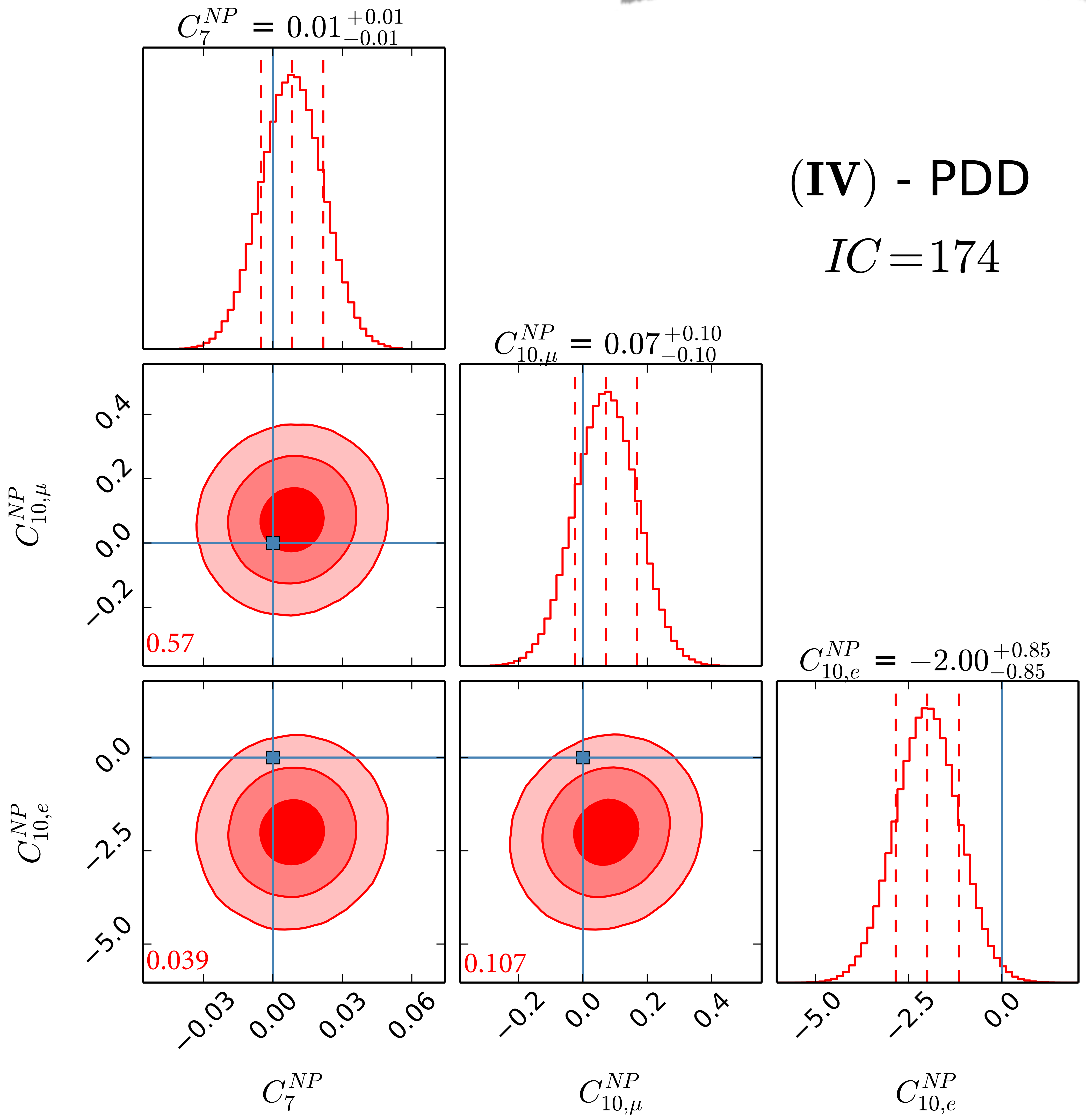
Proposes new measurement of LU in I_6 (or A_{FB}) in order to break correlation in RK/RK* measurements btw C10 and C9

Interpretations of RK* 6/8

Ciuchini et al.
arXiv:1704.05447v1

A $C^{NP}_{9,\mu}$ and $C^{NP}_{9,e}$ NP scenario is usually corroborated as the most satisfactory and minimal benchmark necessary to explain this set of anomalies. From Fig. 1 we find that a naive $\sim 7\sigma$ evidence in favour of $C^{NP}_{9,\mu} \neq 0$ boils down to only $\sim 3\sigma$ when a more conservative approach on hadronic effects is taken into account.

A C^{NP}_{7}, $C^{NP}_{10,\mu}$ and $C^{NP}_{10,e}$ NP scenario can be employed to explain the set of anomalies. To our knowledge, NP axial currents have been usually overlooked in the literature. However, this is actually an interesting case: on the one hand it displays the worst IC between all PMD fits, as shown in Fig. 4; on the other hand, when the more conservative approach of hadronic contribution in considered, we found that this scenario is equally capable of explaining the data, with an IC comparable to the one for the widely analyzed $C^{NP}_{9,\mu}$ and $C^{NP}_{9,e}$ NP scenario.



(IV) - PDD

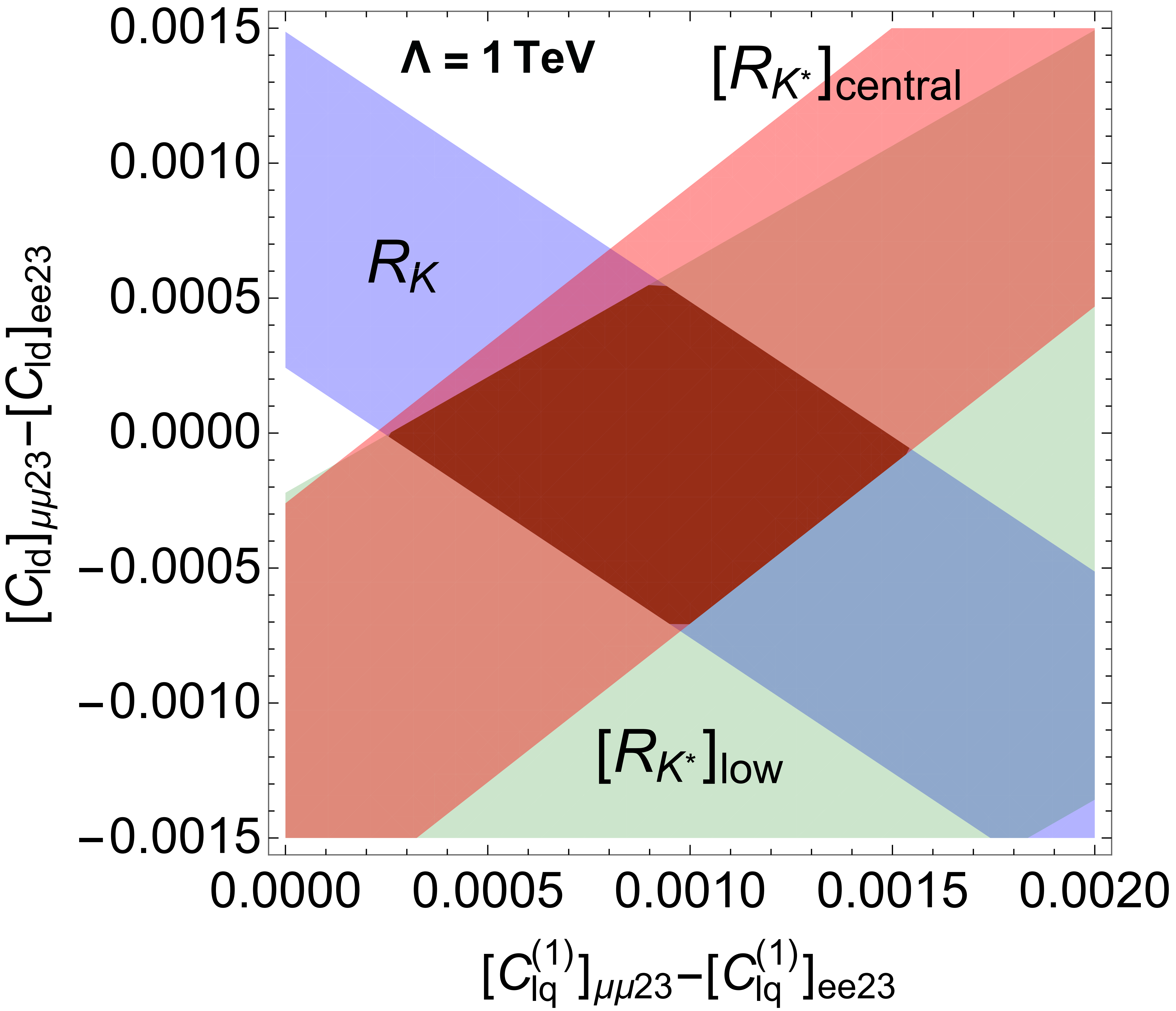
$IC = 174$

Scenario with C10 in electrons would naively be disfavoured by RK*/RK being driven by the muons? Not really sure how it fits.

Interpretations of RK* 7/8

Celis et al.
arXiv:1704.05672v1

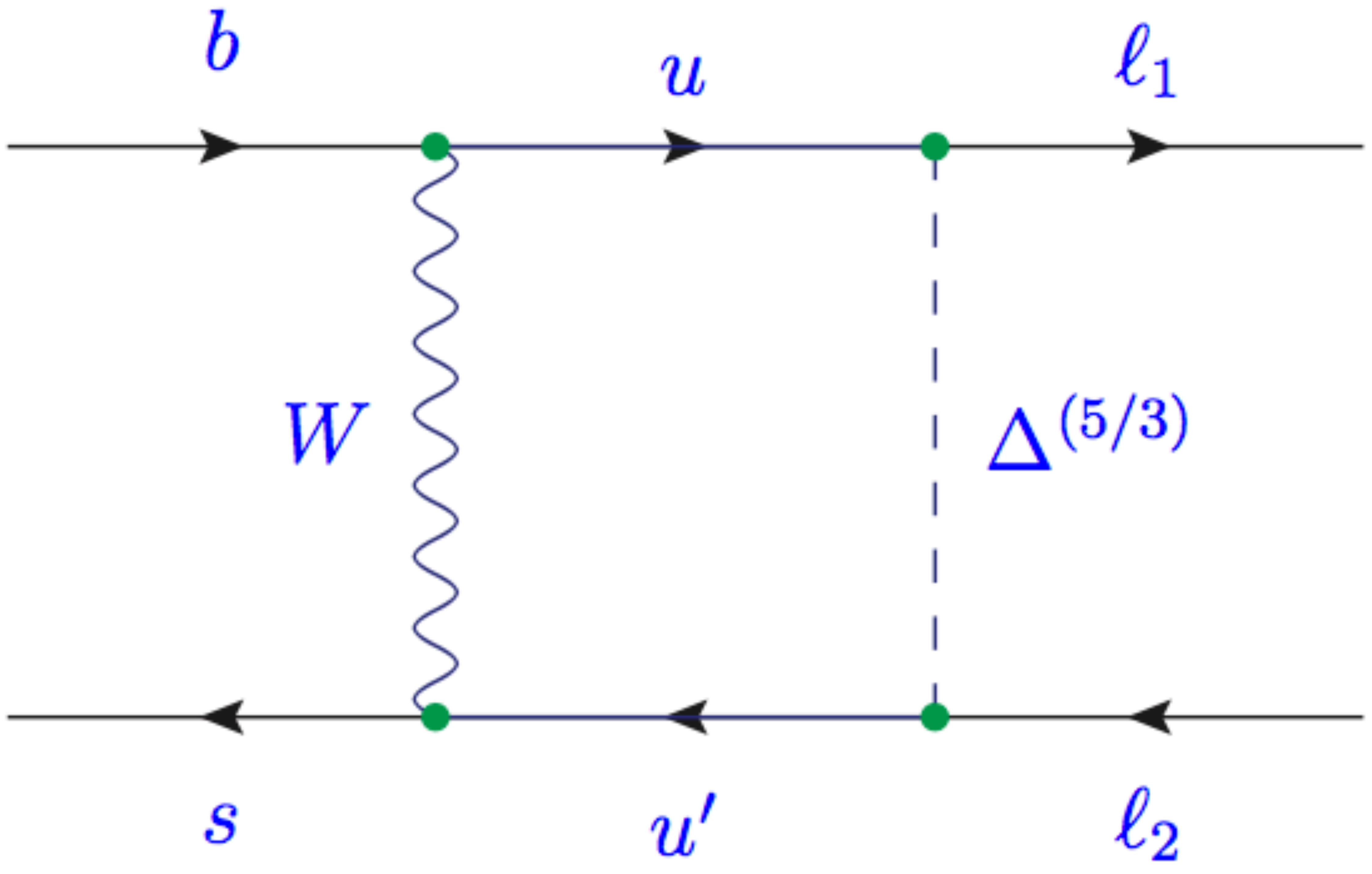
If confirmed, the violation of lepton flavour universality would have far-reaching consequences, implying the existence of new physics at energies relatively close to the TeV scale. In our analysis we have identified the cru-



Essentially agrees with general picture of C9/C10 contributions
Tree-level operators can sit at ~50 TeV but loop-level should be light, under a TeV. Directly searchable?

Interpretations of RK* 8/8

Becirevic & Sumensari
arXiv:1704.05835v1



A curious model : don't couple the leptoquark directly to the s, but rather through a loop. Has interesting implications for LFV searches, motivates direct searches in tμ/cτ/cμ final states

There is a growing list of flavour anomalies, mainly linked to lepton universality violation in quark transitions, which may be a manifestation of BSM particles or force-carriers

Examples of viable models are leptoquarks, Z′ models …

All that remains is to directly detect them! Over to you Dirk…

BACKUP

Looking towards the HL-LHC period

	LHC era			HL-LHC era	
	Run 1 (2010–12)	Run 2 (2015–18)	Run 3 2021-2023	Run 4 2026-2029	Run 5+ 2031 →
ATLAS & CMS	$25\,\text{fb}^{-1}$	$100\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$	$\longrightarrow$	$3000\,\text{fb}^{-1}$

LHCb detector timeline

	LHC Run	Period of data taking	Maximum $\mathcal{L}$ $[\text{cm}^{-2}\text{s}^{-1}]$		Cumulative $\int \mathcal{L}\,dt$ $[\text{fb}^{-1}]$	
Current detector	1 & 2	2010–2012, 2015–2018	4×10^{32}	x5	8	Exists
Phase-1 Upgrade	3 & 4	2021–2023, 2026–2029	2×10^{33}	x10	50	Approved
Phase-2 Upgrade	5 →	2031–2033, 2035 →	2×10^{34}		300	Proposed

Complementarity in flavour sector

	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 ($\tau \to \mu\gamma, \mu\mu\mu$)	**	*****	?

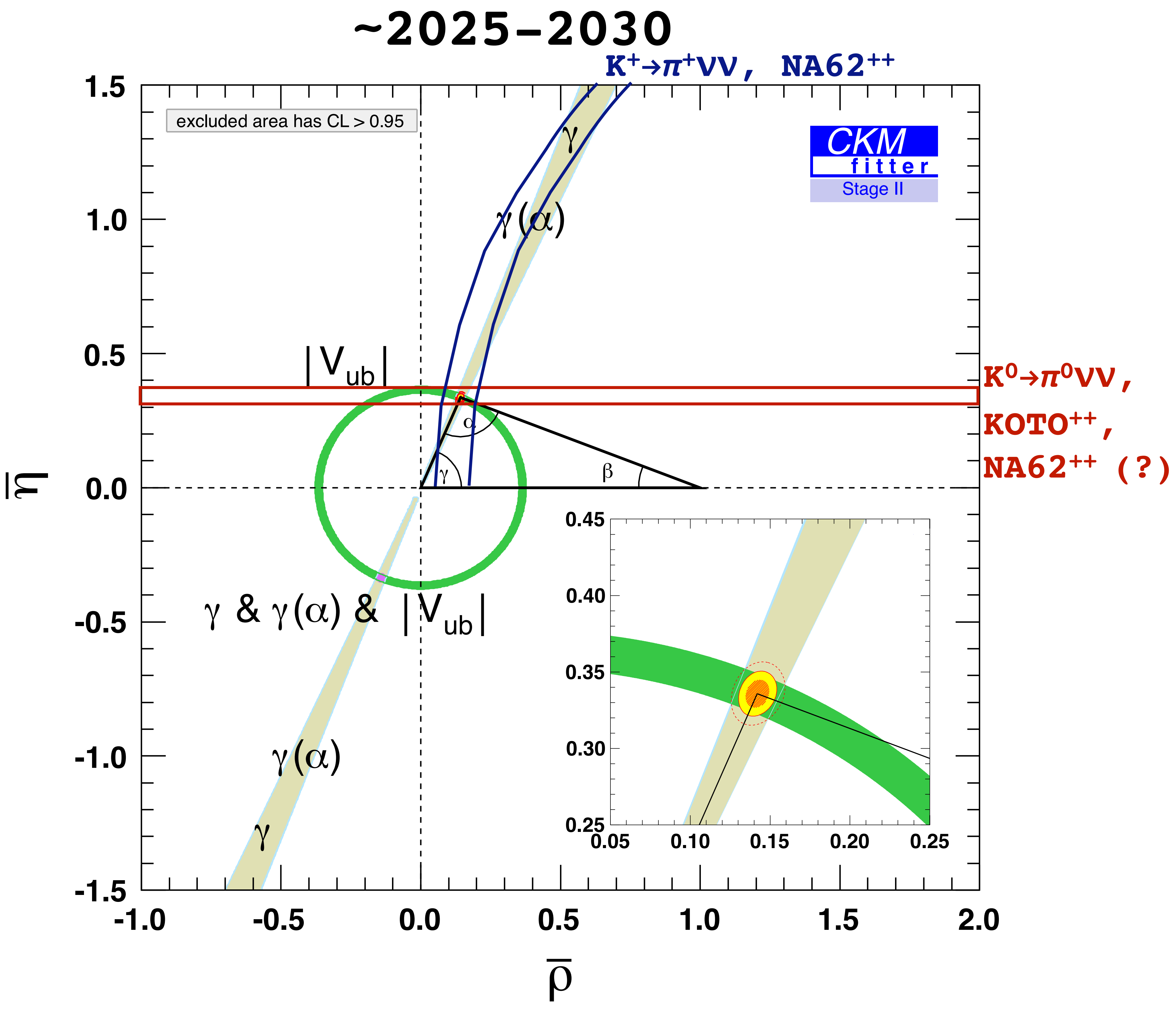
Potential reach of CKM measurements

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!



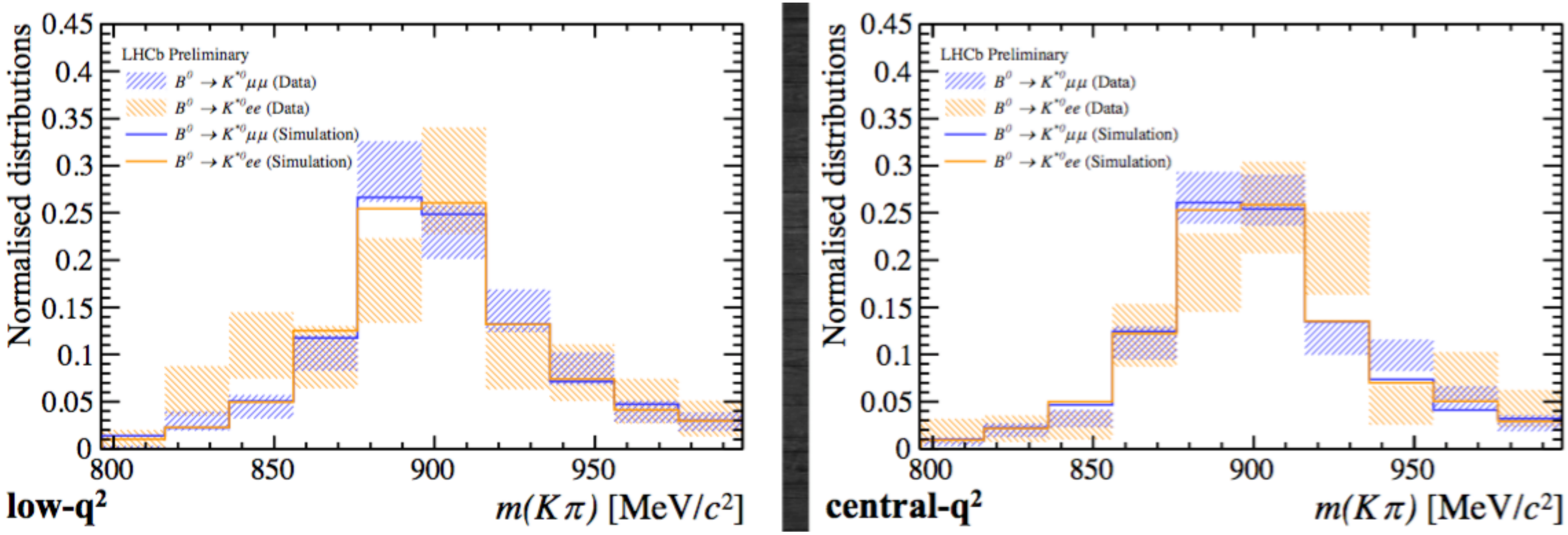
https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

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

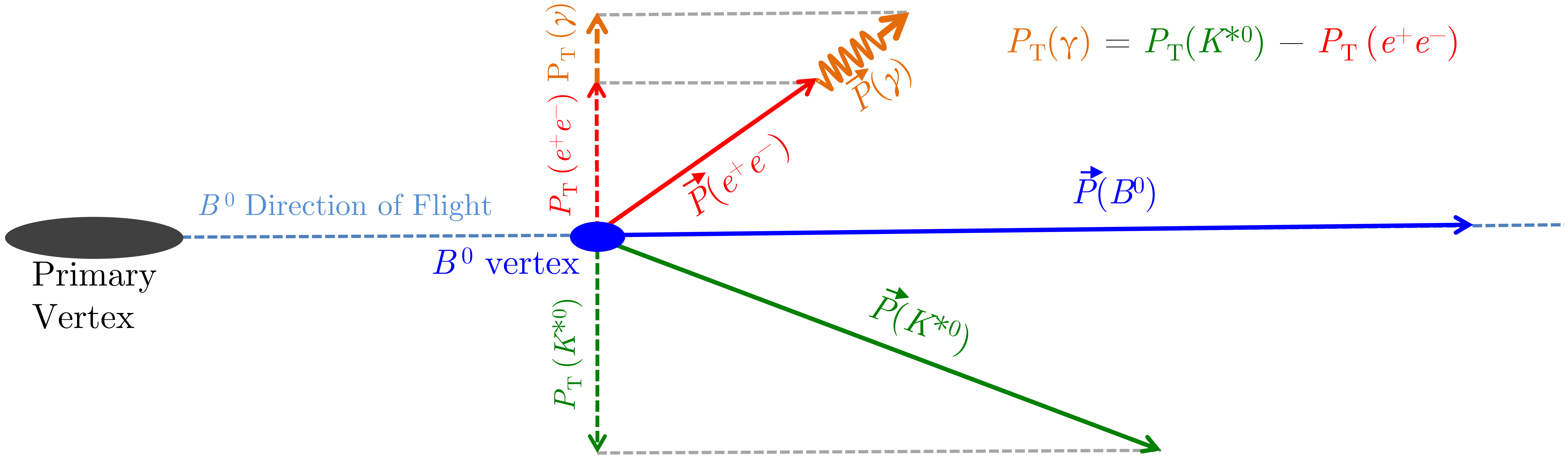
R_{K^*} systematics

	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ flatness	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

K* mass shape of signal in R_{K^*}

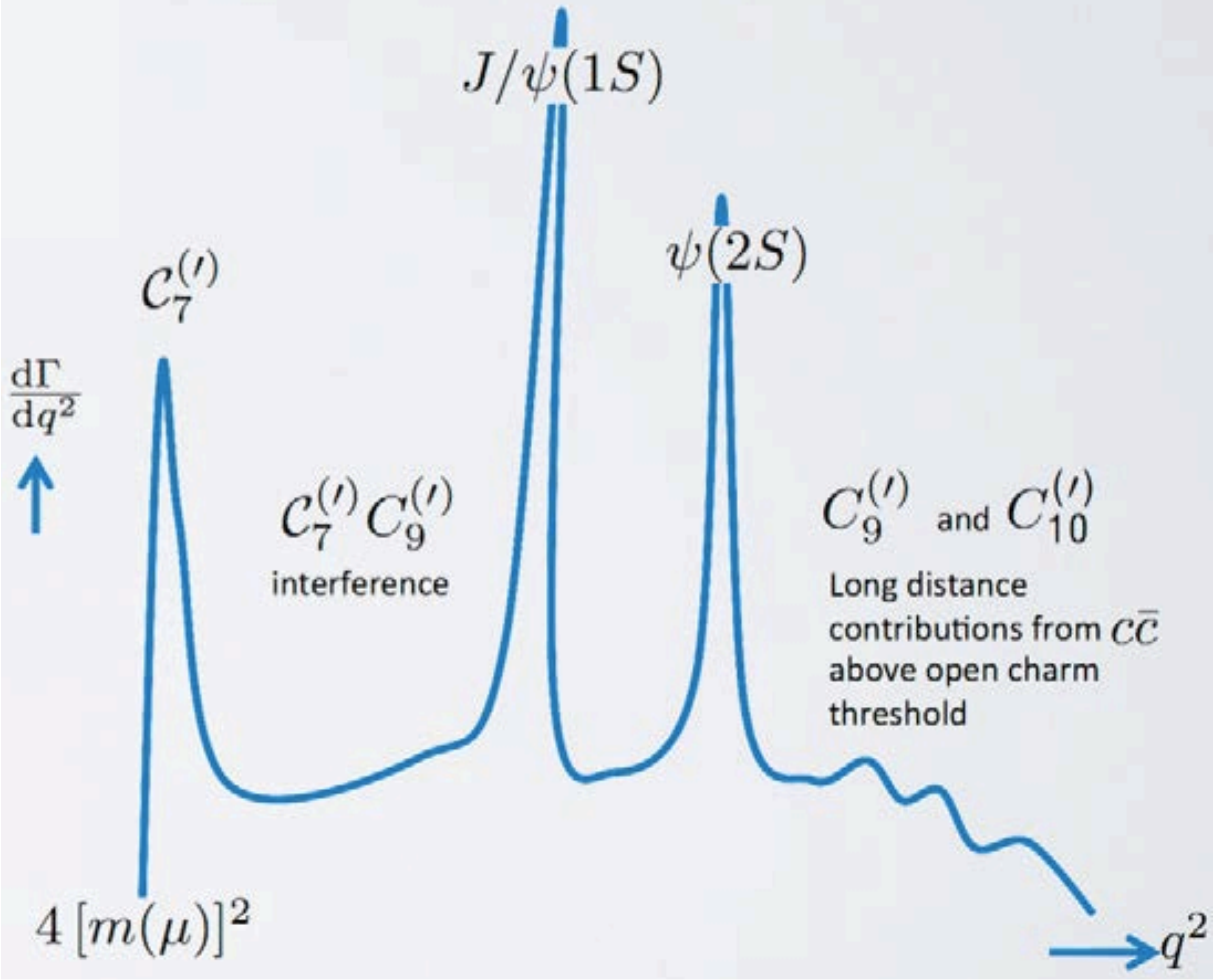


The HOP

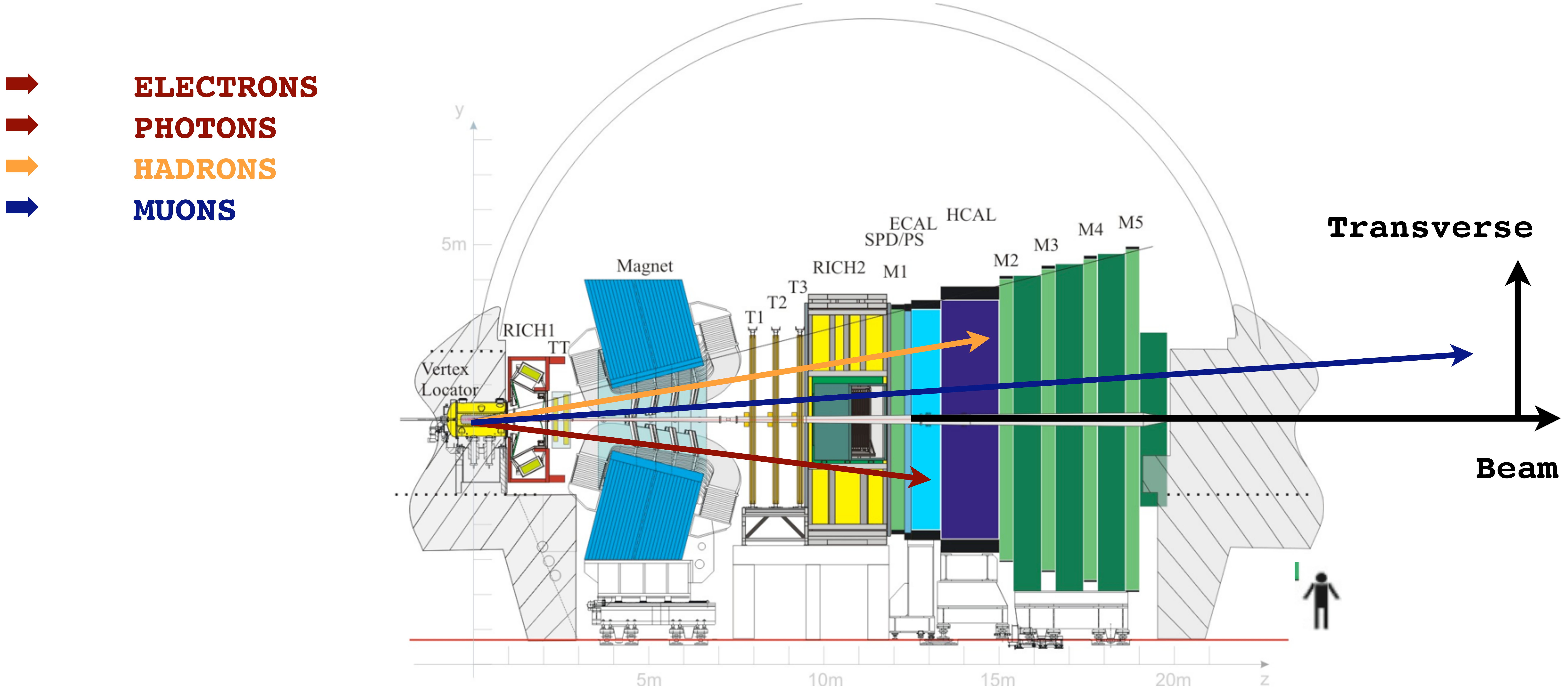


$P_T(\gamma) = P_T(K^{*0}) - P_T(e^+e^-)$
$P_T(\gamma)$
$P_T(e^+e^-)$
$\vec{P}(\gamma)$
$\vec{P}(e^+e^-)$
$\vec{P}(B^0)$
B^0 Direction of Flight
B^0 vertex
Primary Vertex
$\vec{P}(K^{*0})$
$P_T(K^{*0})$

Everyone loves a Wilson coefficient



The LHCb detector



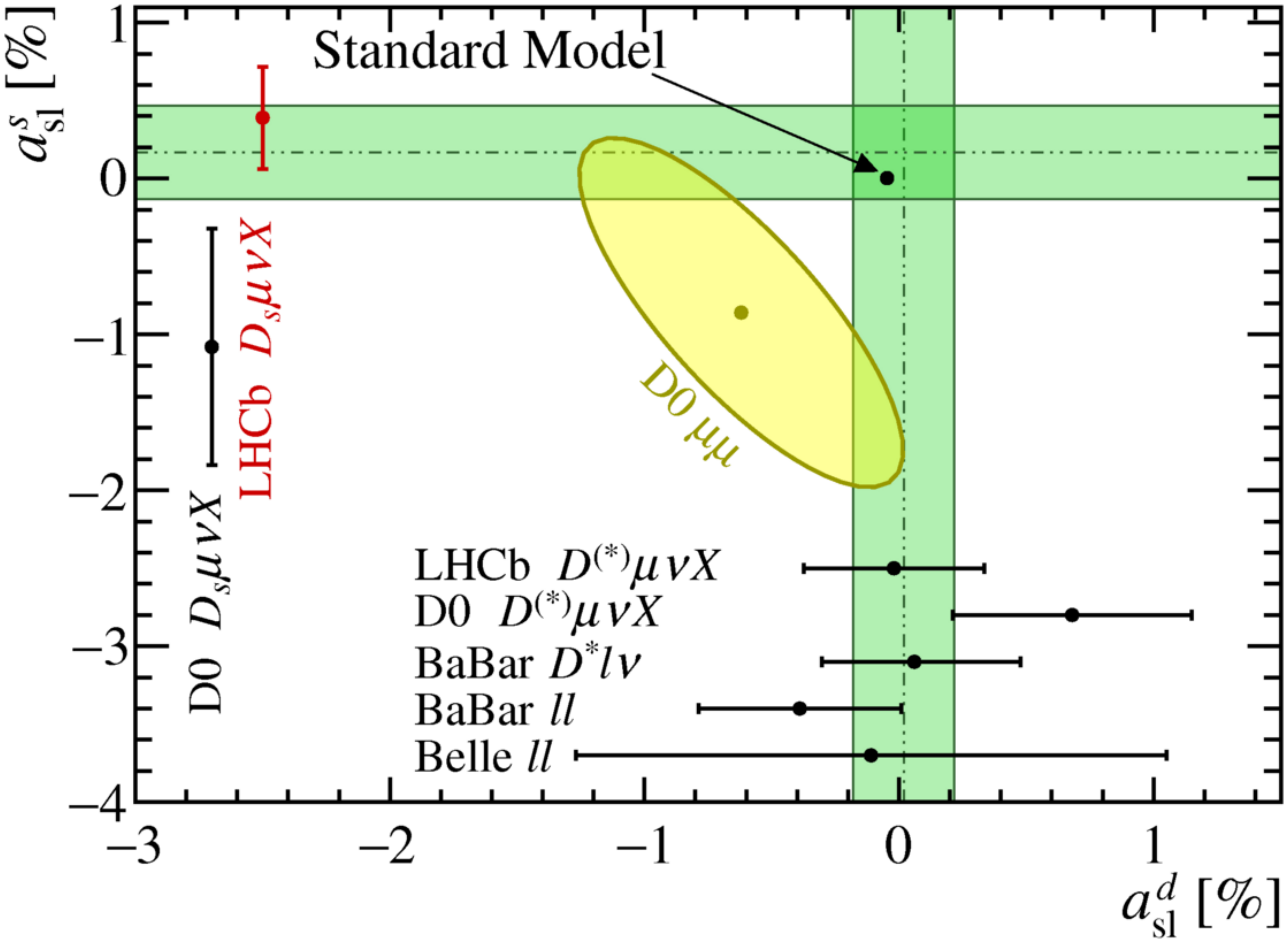
p_T = Transverse momentum

E_T = Transverse energy

LHCb : forward spectrometer for flavour physics at LHC

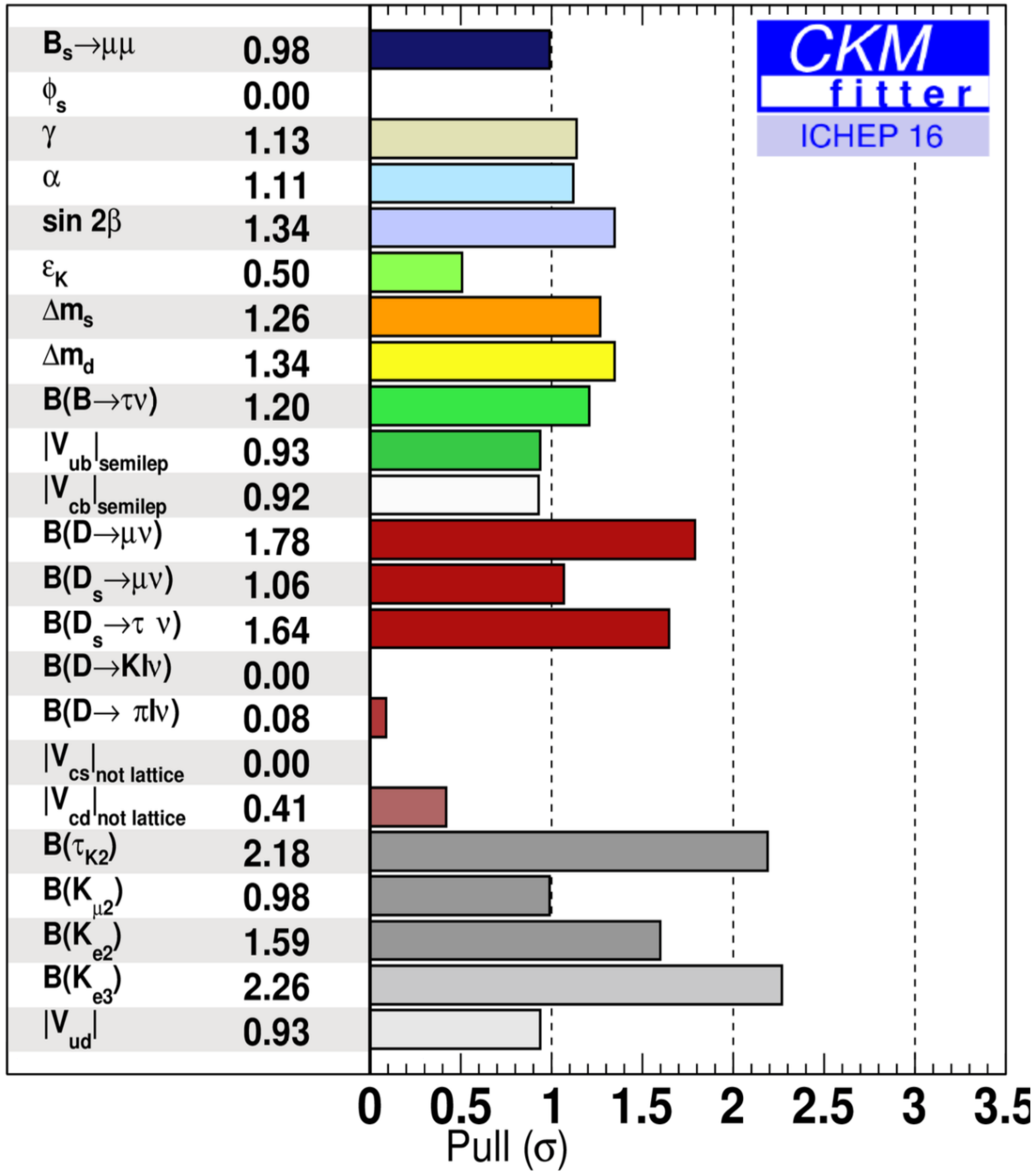
Current status

LHCb-PAPER-2016-013



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

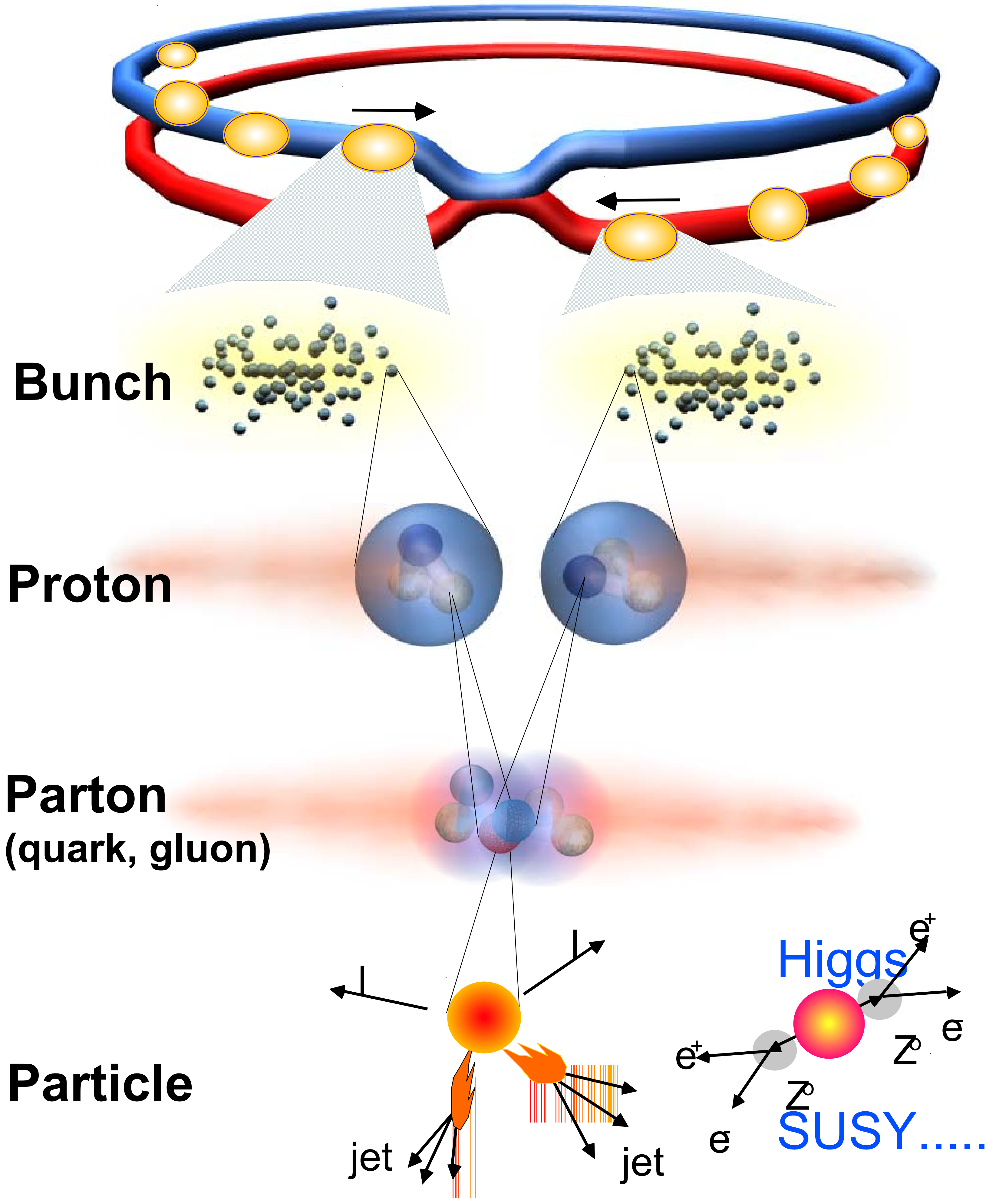
Back to the apex



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

The traditional view of data processing

Collisions at the LHC: summary



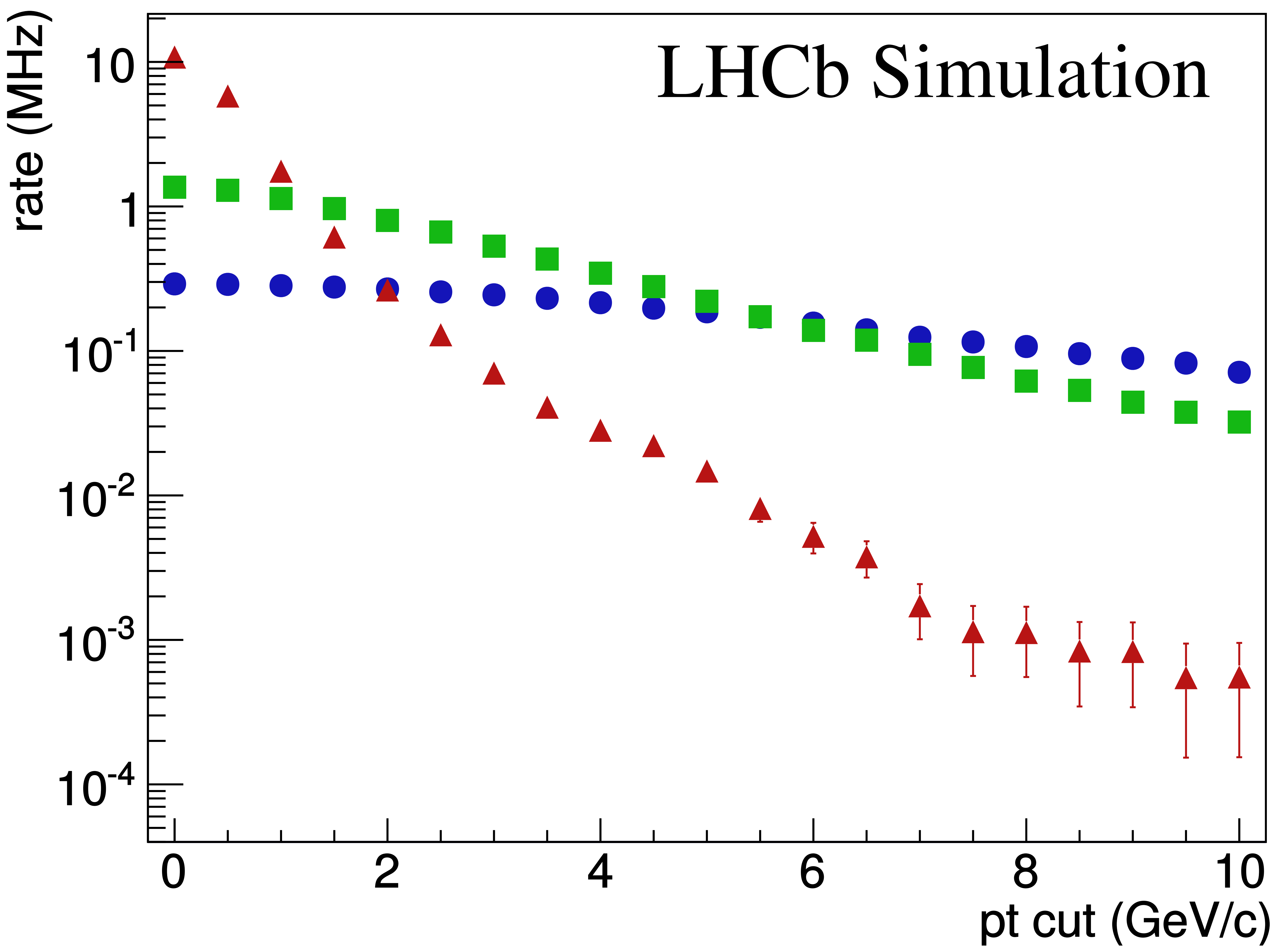
Proton - Proton	2804 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	$10^{34}cm^{-2}s^{-1}$
Crossing rate	40 MHz
Collision rate ≈	10^7-10^9

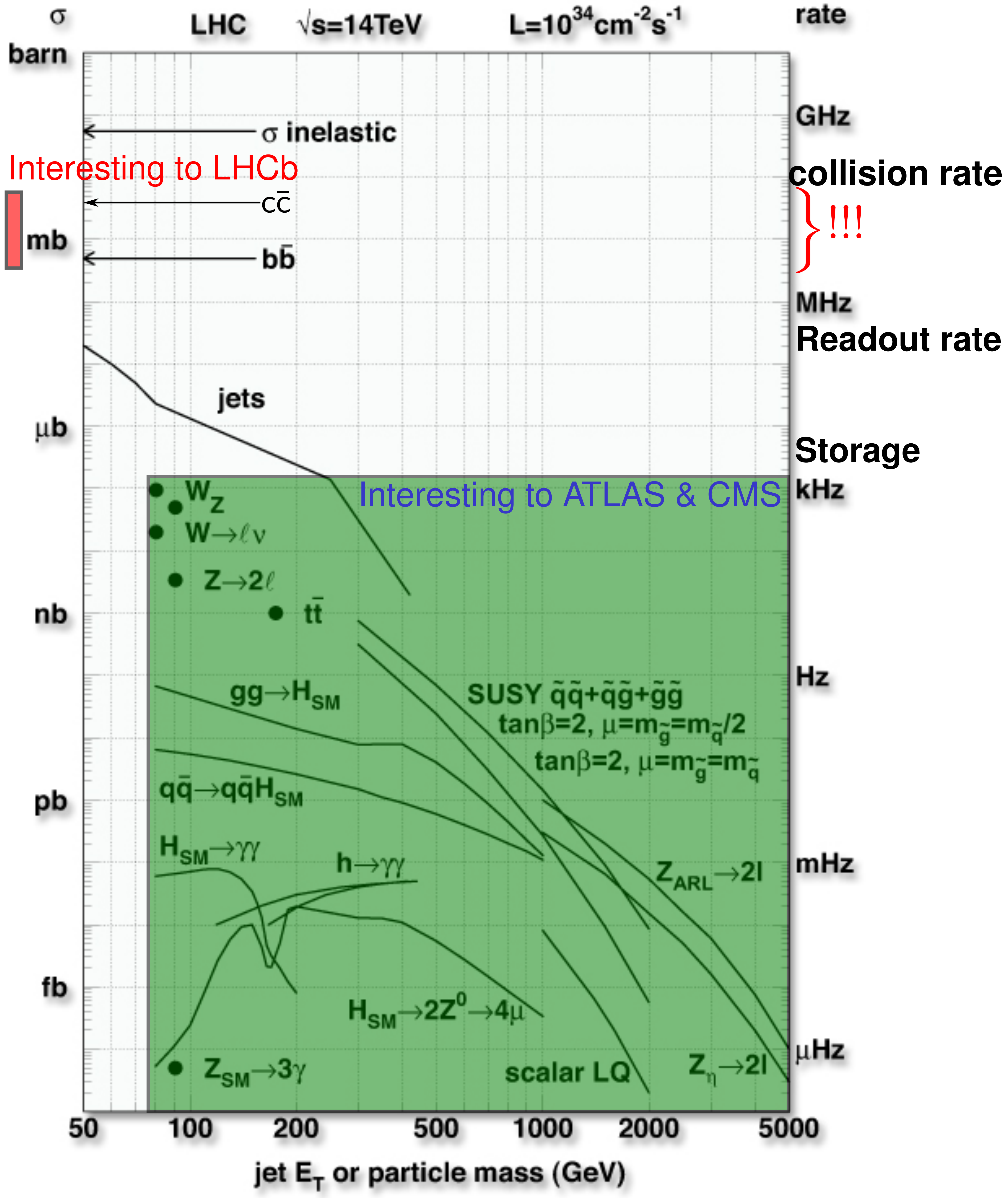
New physics rate ≈ .00001 Hz

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

Analysis today

Enter the MHz signal era





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

Analysis today

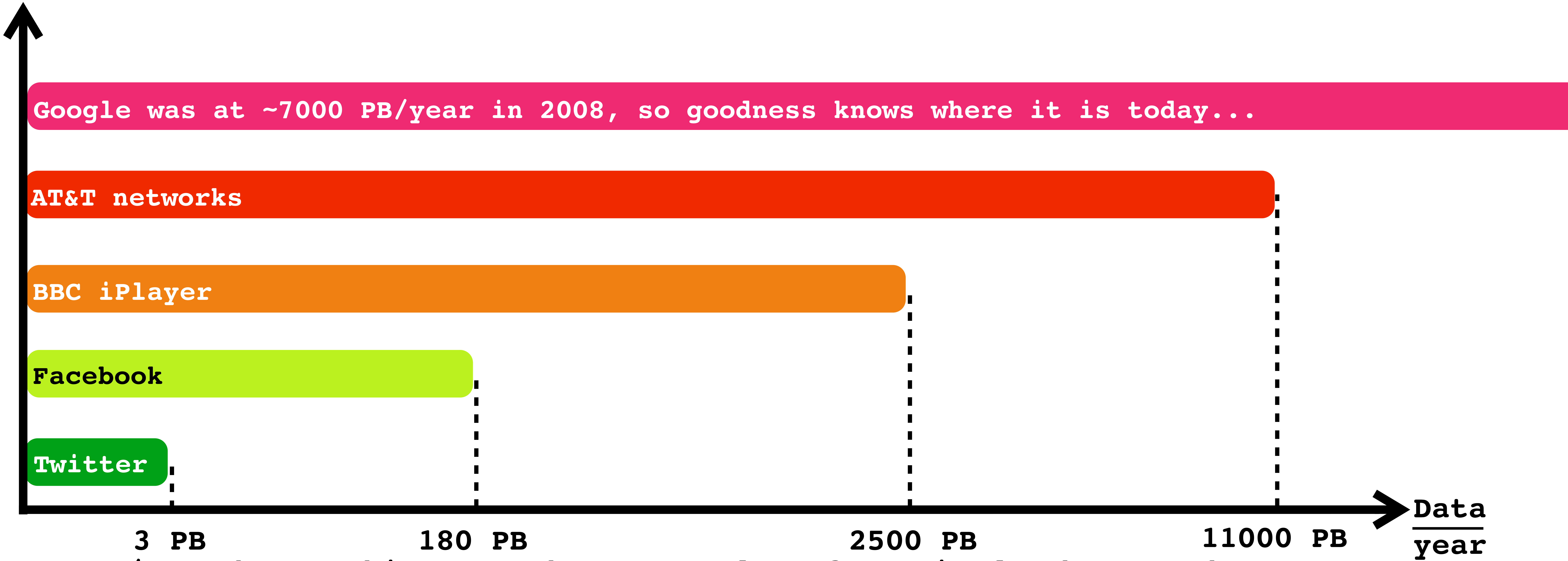
Analysis in the future

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

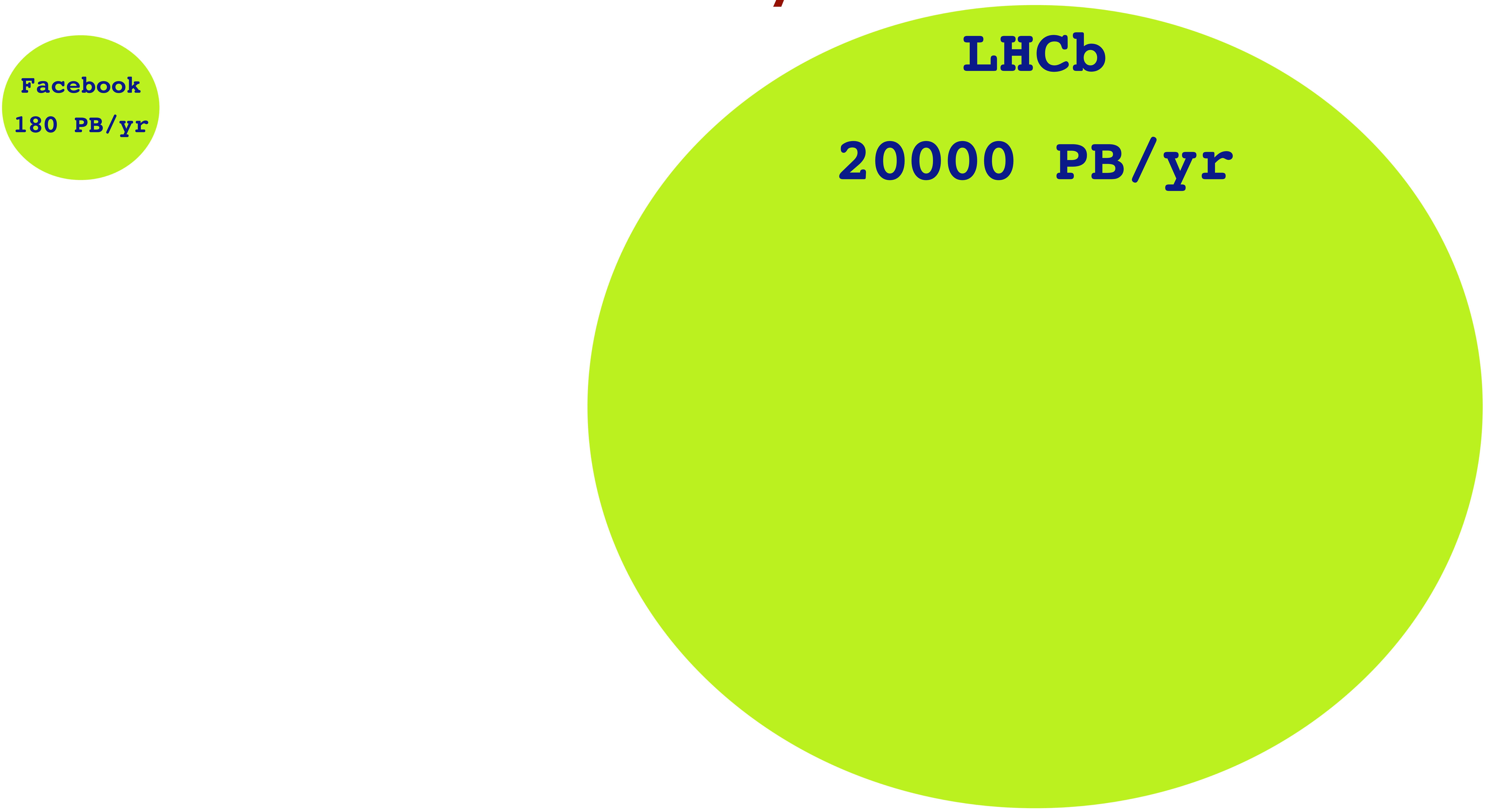


NB : ATLAS/CMS about a bit more than one order of magnitude above LHCb

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

Yes but what is analysis?

1. Align and calibrate your detector

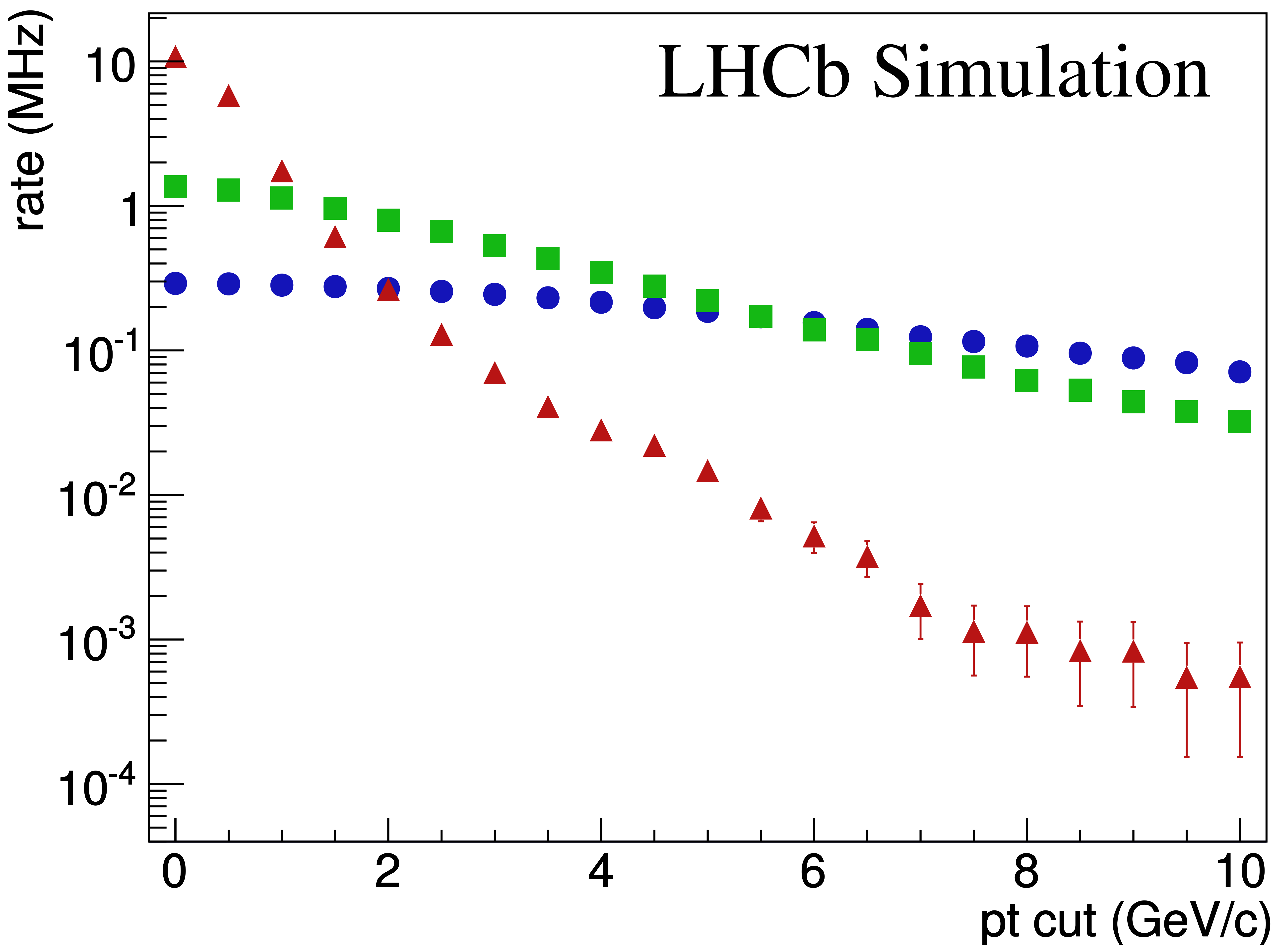
2. Reconstruct your detector using output of 1

3. Select your signal, background control modes, and additional fine detector calibration modes

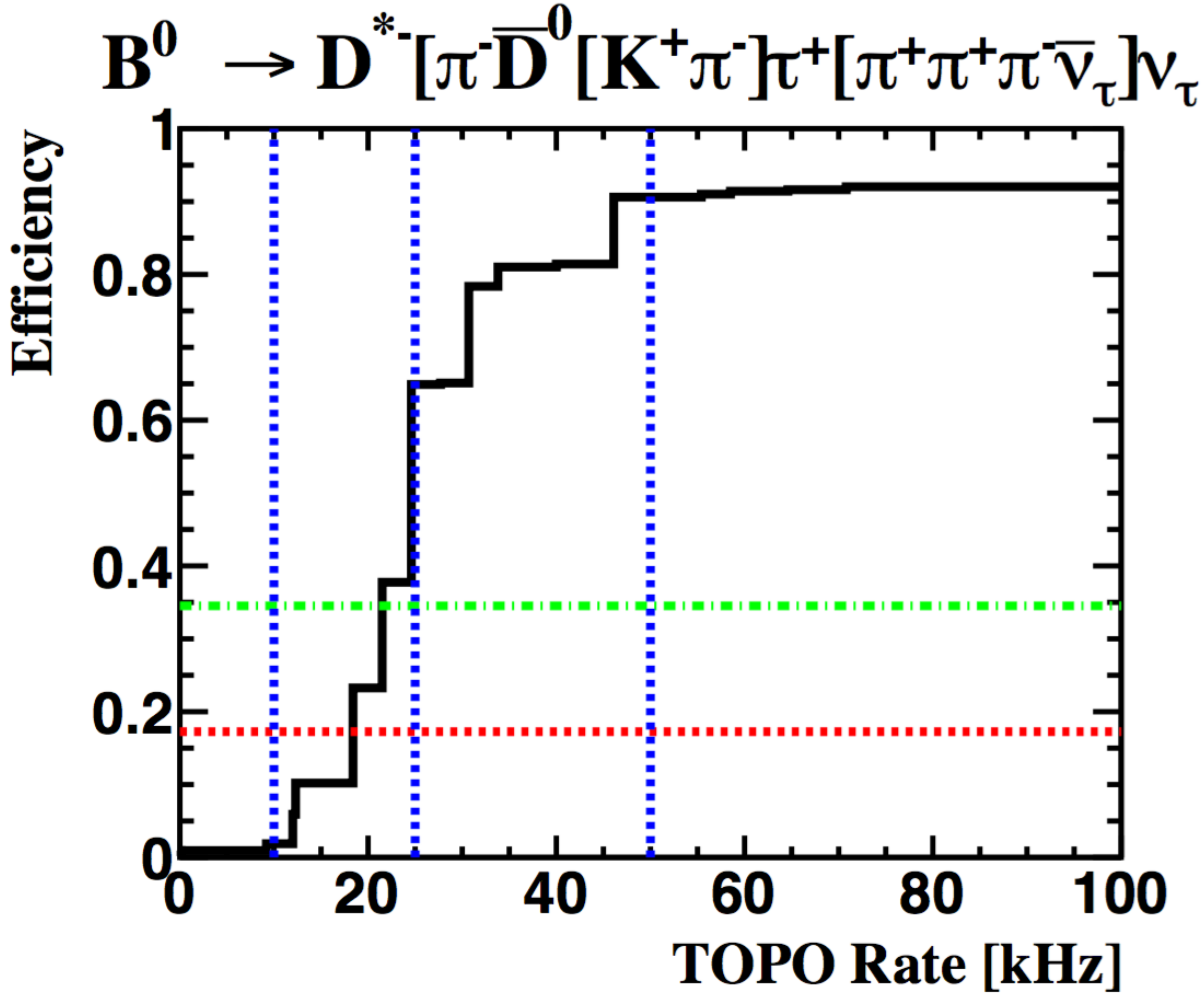
4. Fit to separate signal from background and extract the physical parameters of interest

The point is that part 4, which most people call "analysis" requires only a tiny fraction of data collected in each LHC bunch crossing. So we do 1-3 in real-time, and save 4 for later processing.

But does this matter for B-physics?



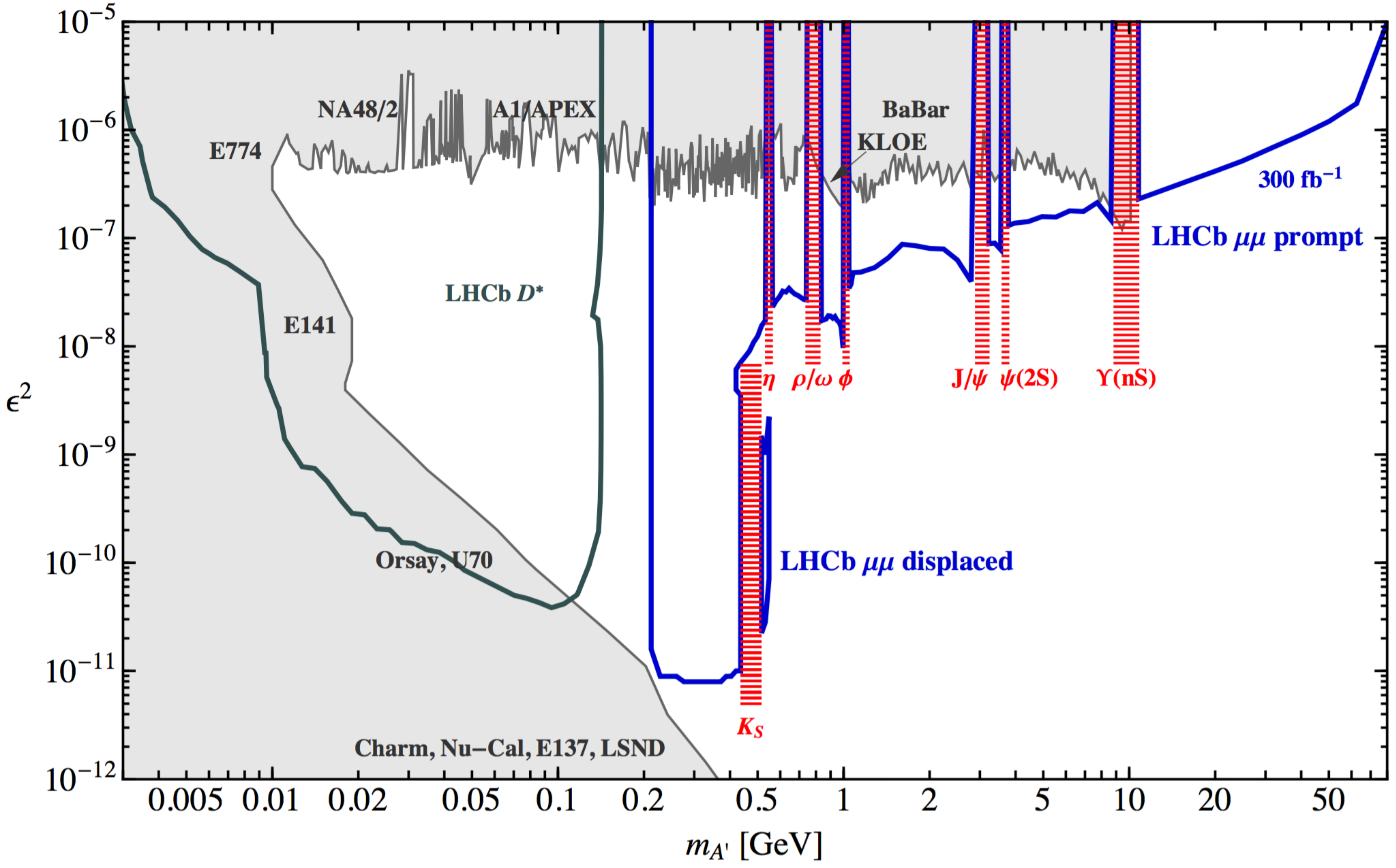
Yes, it does



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

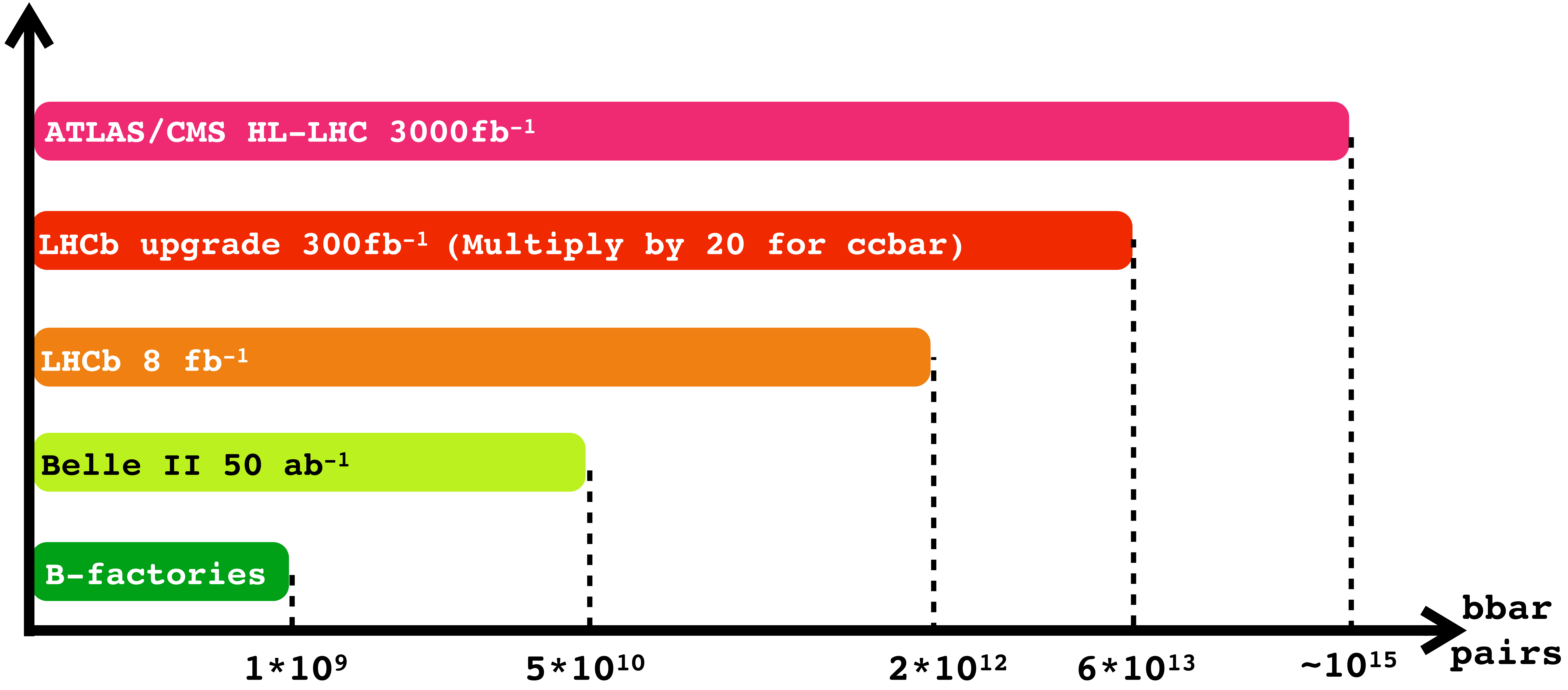
Answer => Keep some inclusive B-physics triggers, but move the majority of complicated signatures to exclusive selections. Real-time analysis is mandatory.

It also matters for dark matter searches



Real time analysis will allow LHCb to vastly expand its statistical power in dark photon searches in both the ee and μμ final states. Soft leptons make any “trigger” unfeasible.

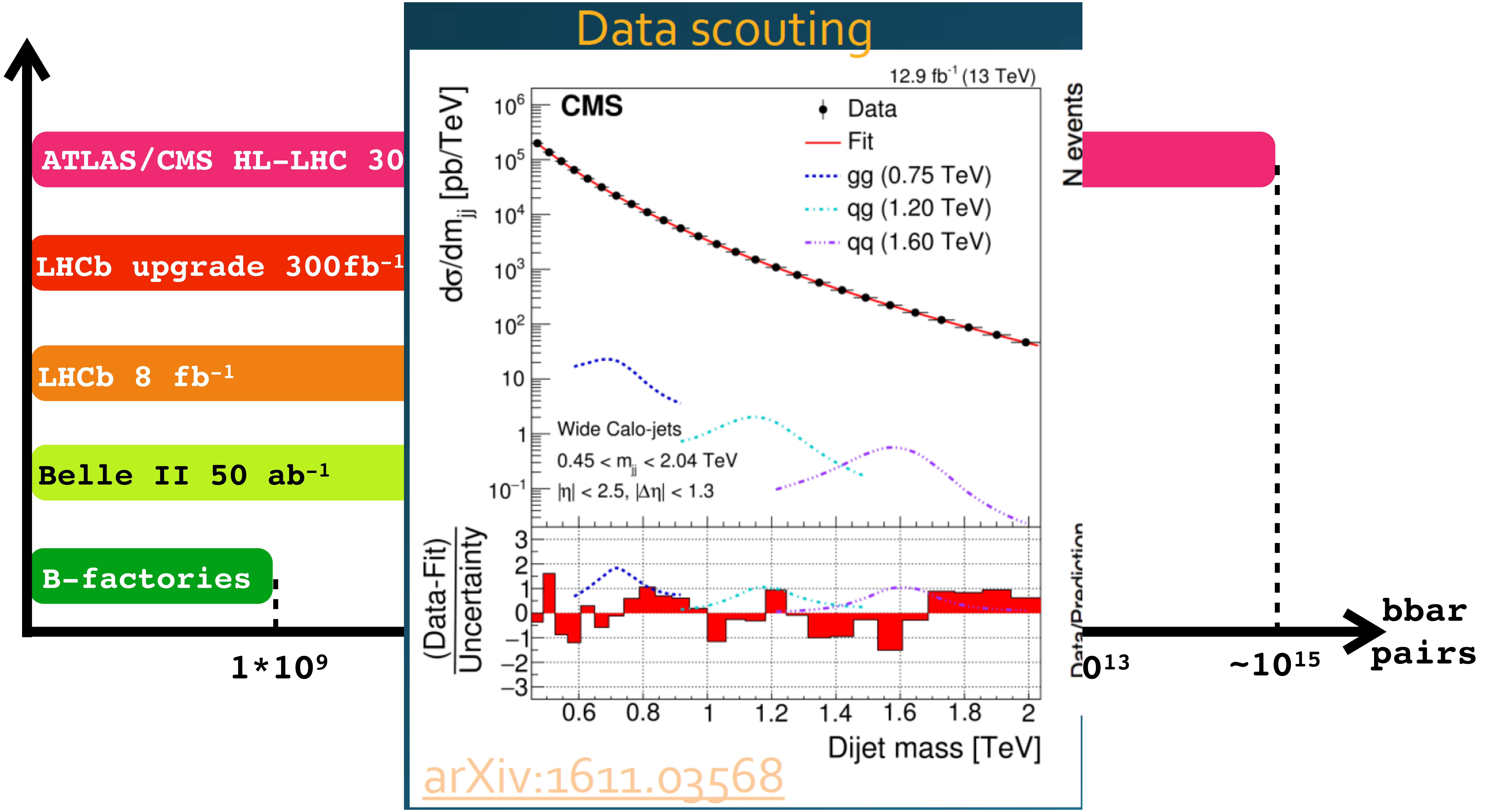
Could also matter for GPDs



B-factories/Belle II should be scaled by ~10/100/1000 depending on decay mode compared to LHCb to account for efficiencies, hermetic detectors, and a cleaner environment.

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

Could also matter for GPDs



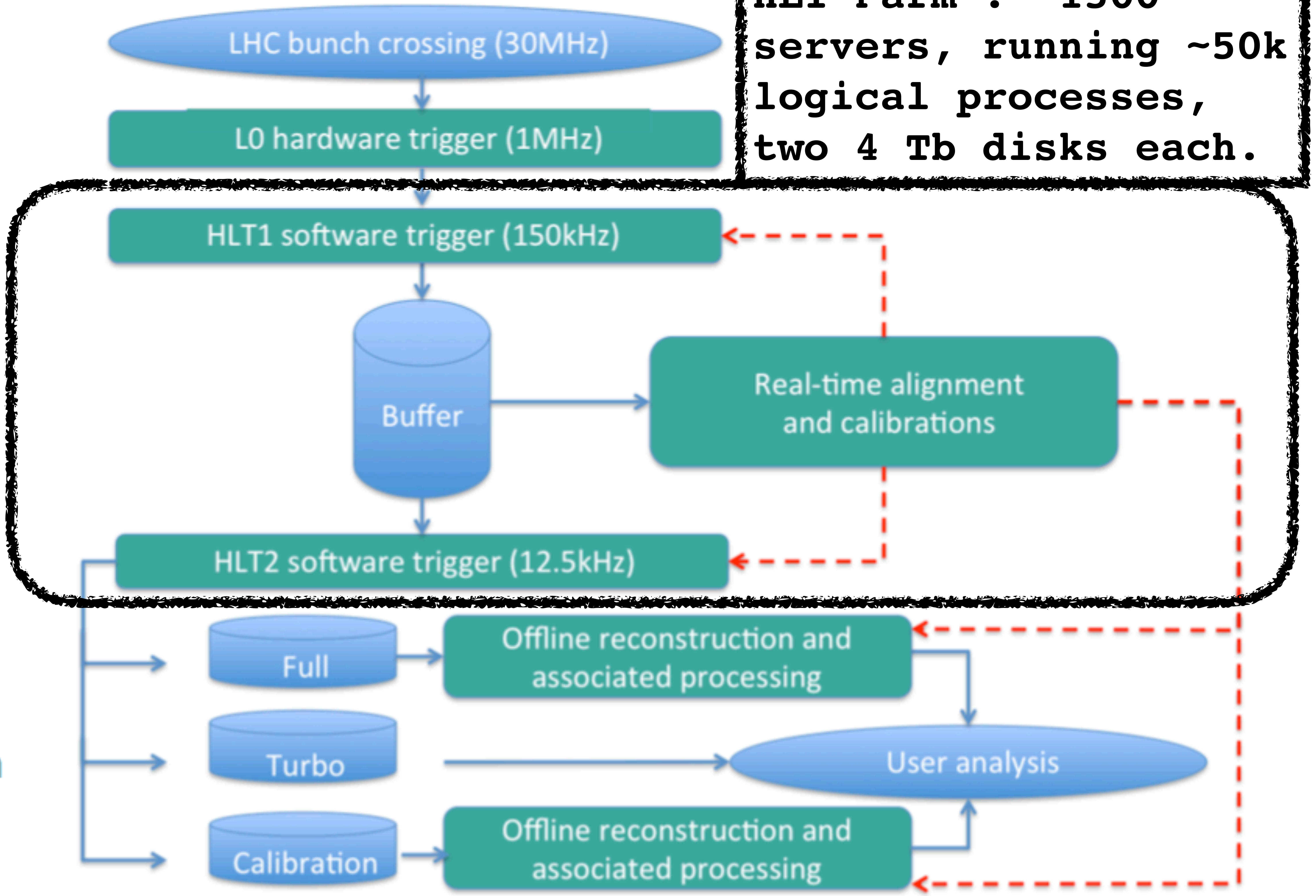
GPDs already use a kind of real-time analysis, in particular for dijet searches at very low masses. In the future this may expand to more such states, as well as B-physics

The scale of the problem

COMPLETE RUN2 DATA FLOW

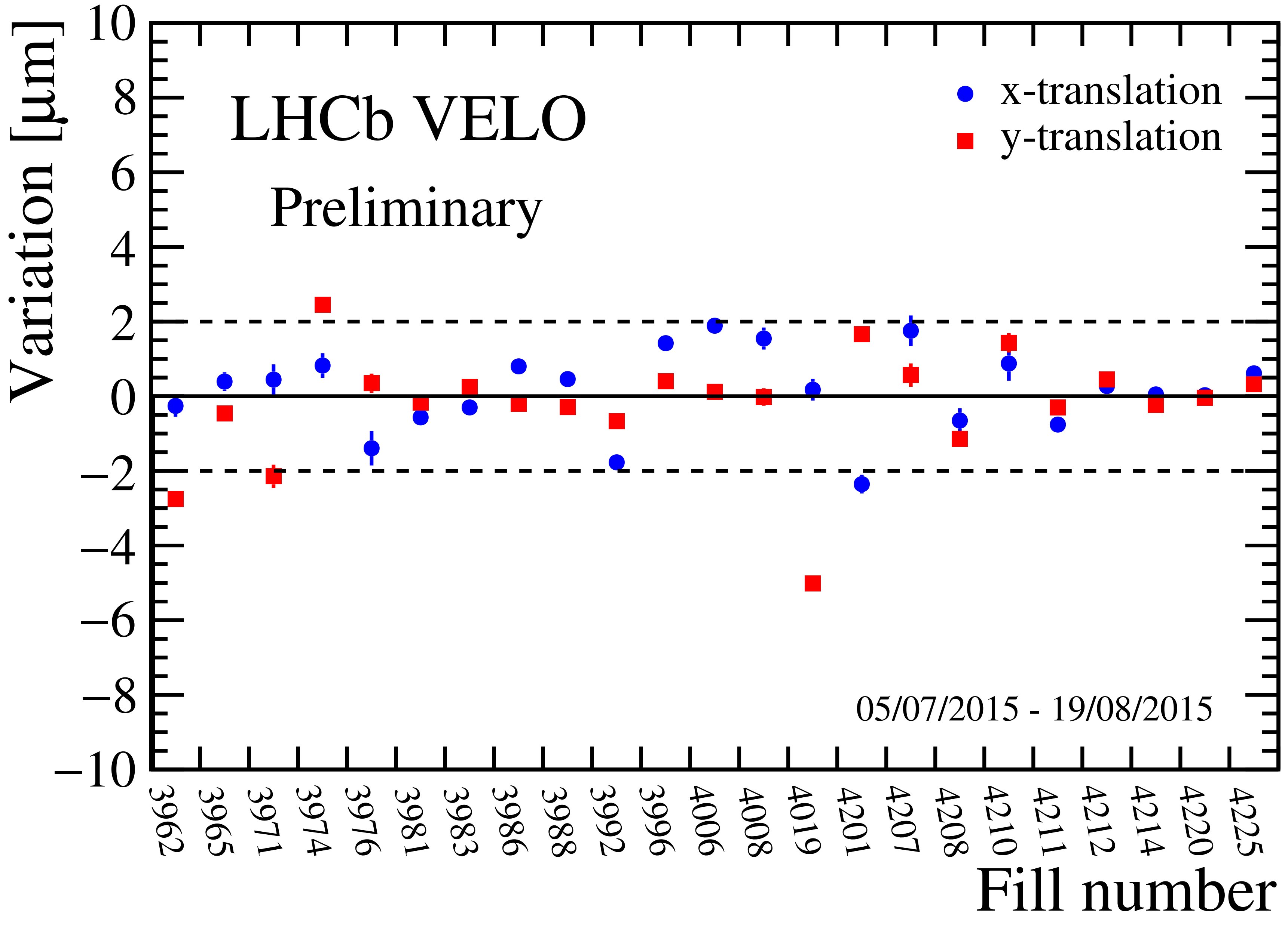
- Turbo:
  - *no* offline reconstruction
  - *only* candidate(s) explicitly reconstructed in trigger available for analysis
- in 2015, did not yet (!) remove the raw data from 'turbo' stream (but *not* available to analysis)

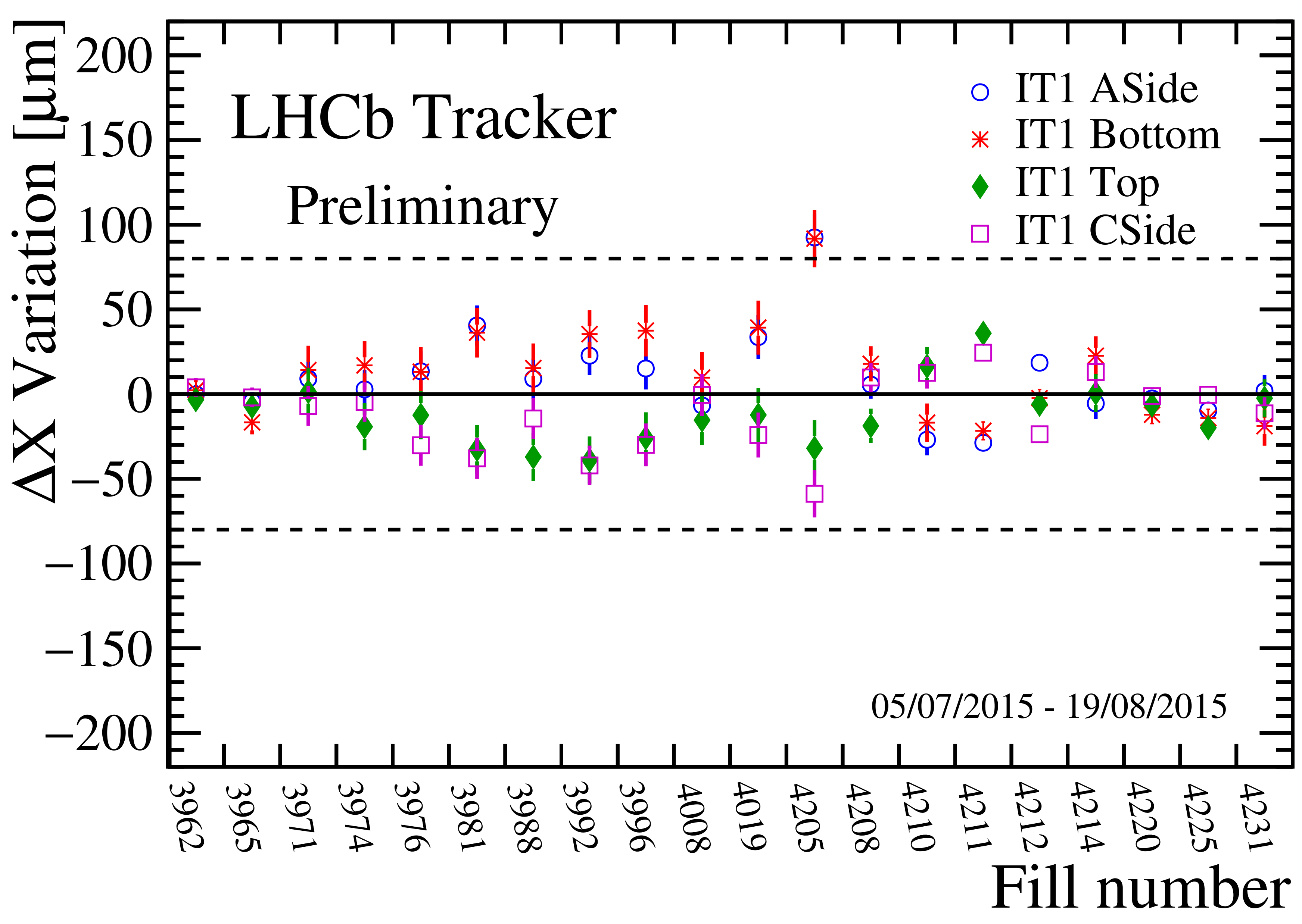
HLT Farm : ~1500 servers, running ~50k logical processes, two 4 Tb disks each.



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

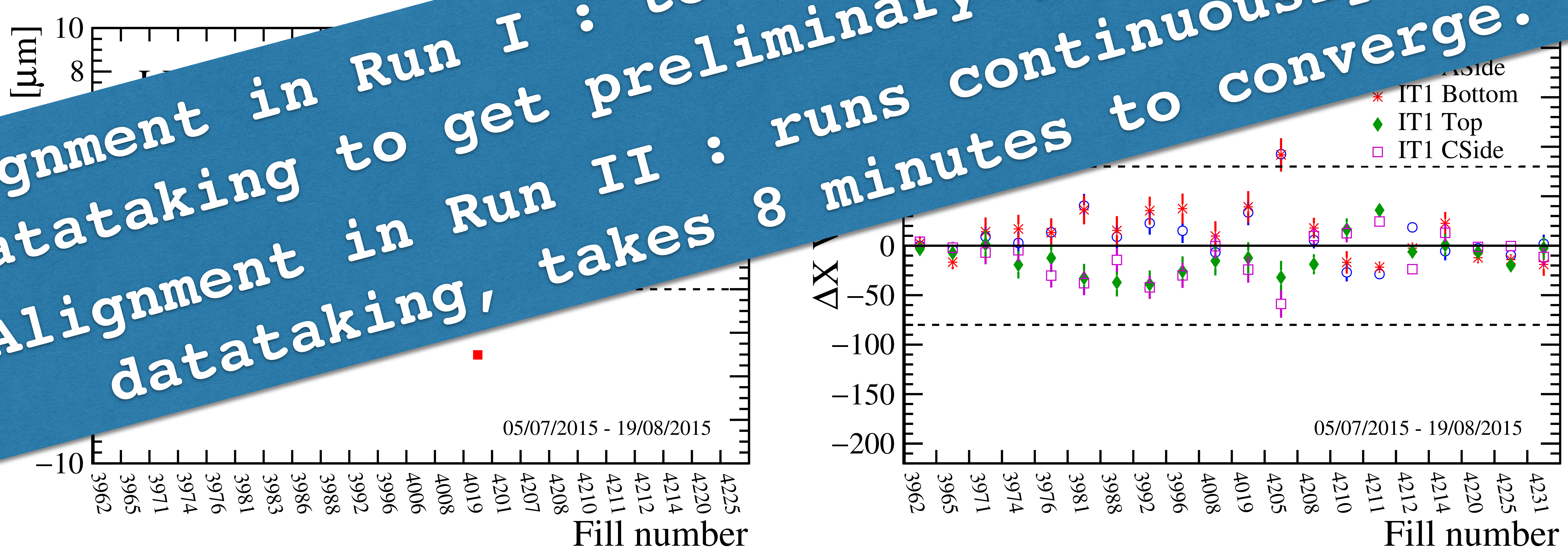




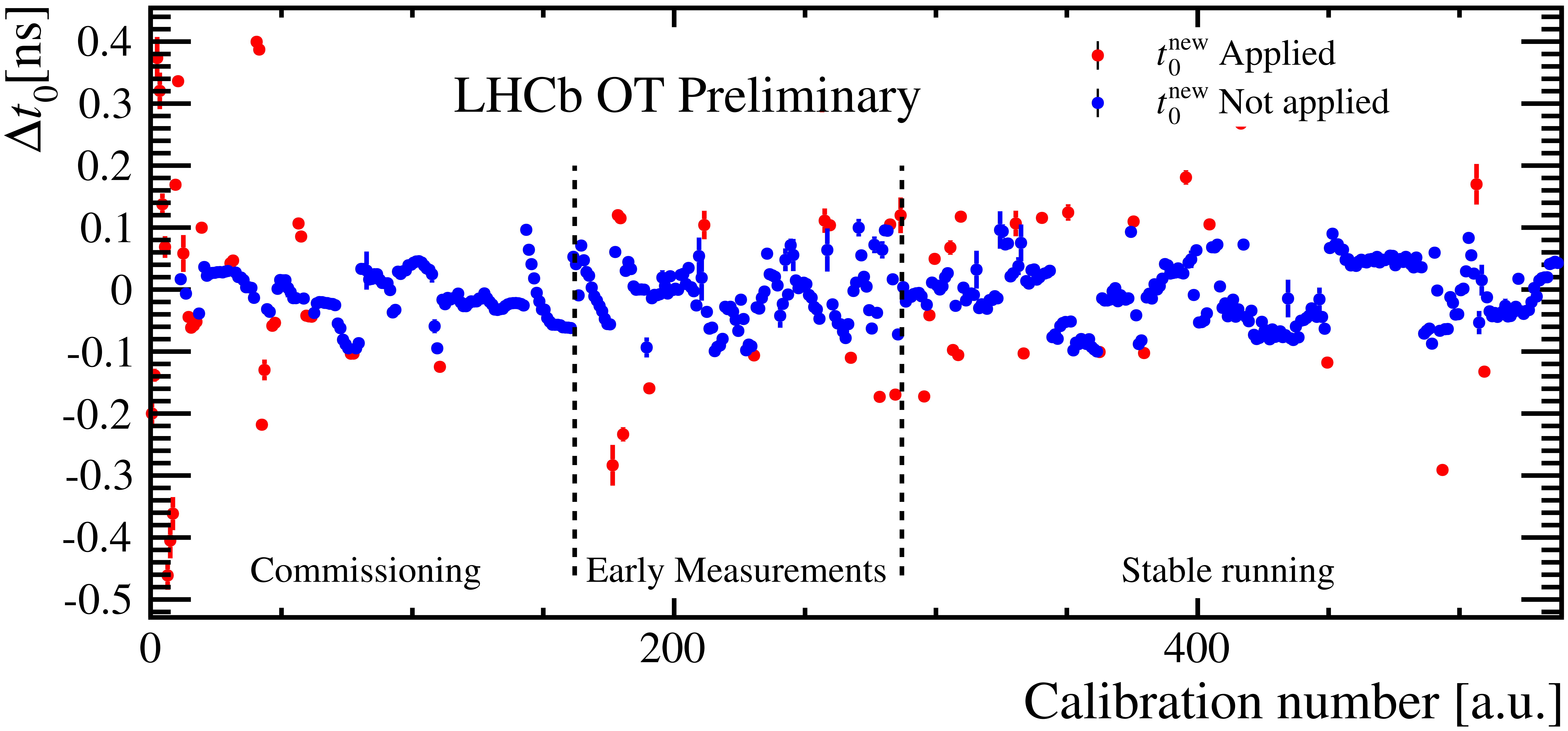
Real time alignment and calibration

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

Alignment in Run I : took a few weeks after first datataking to get preliminary quality alignment
Alignment in Run II : runs continuously during datataking, takes 8 minutes to converge.



Calibrating the straw-tube tracker

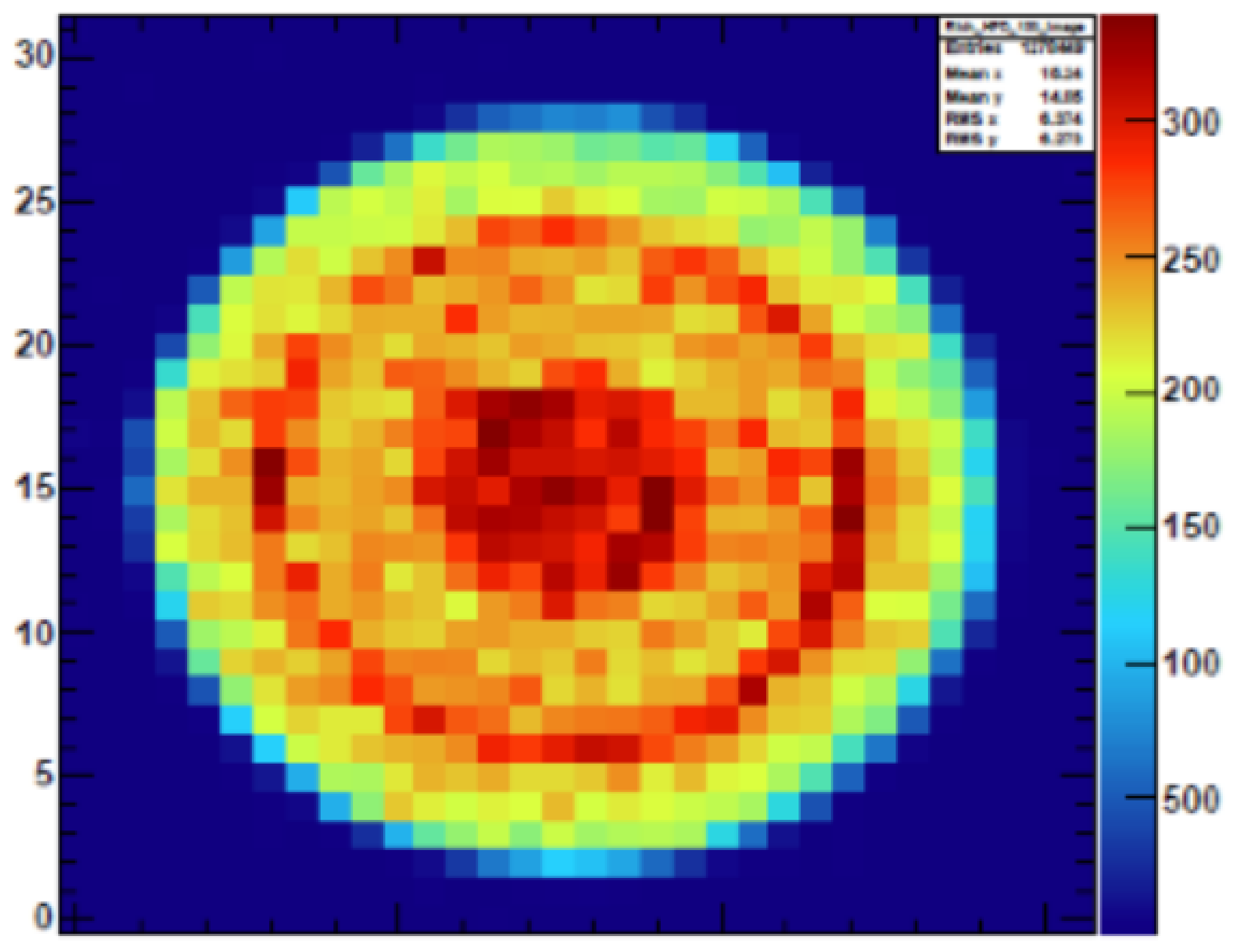


Calibrating the RICH

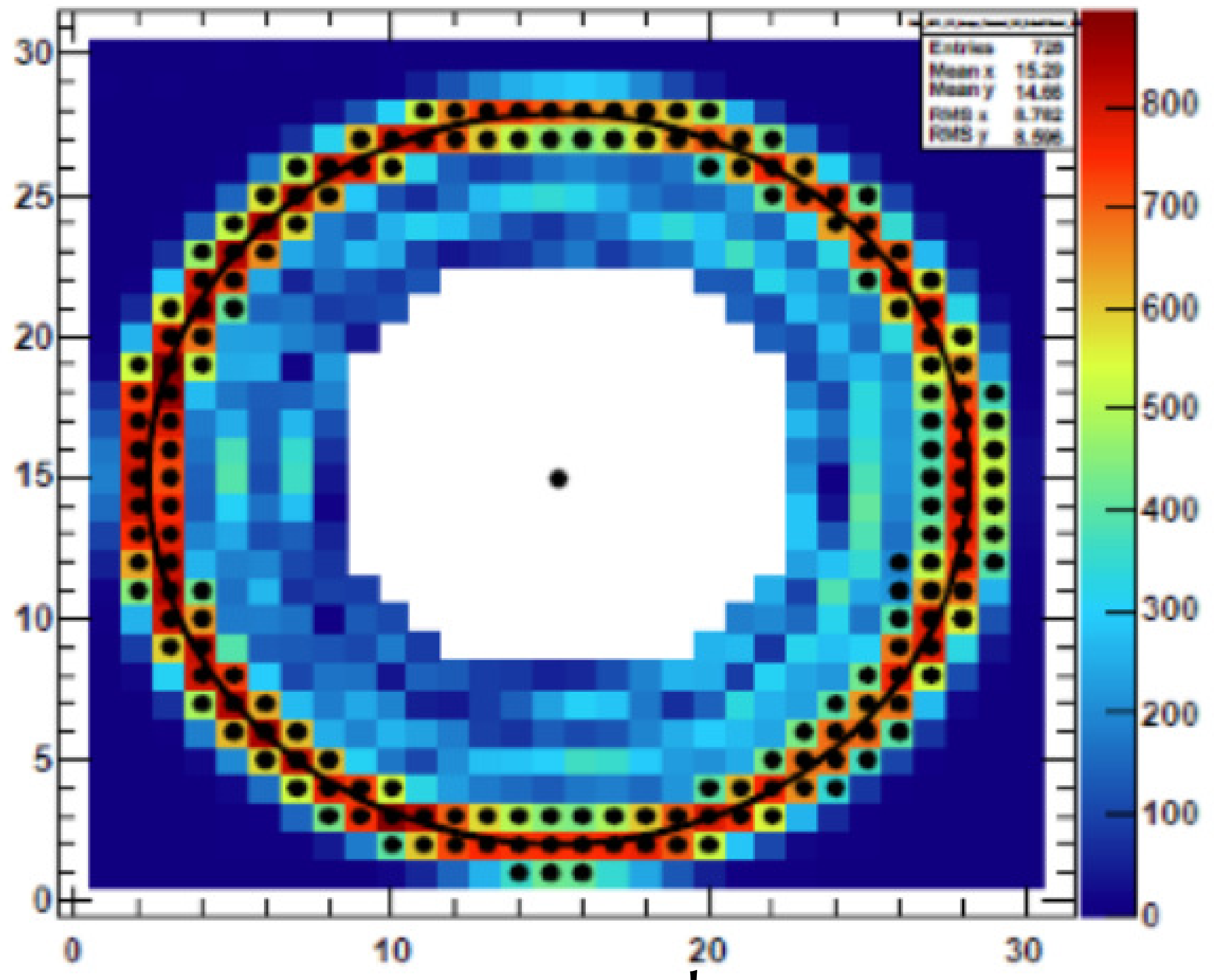
For optimal physics must calibrate and align the gaseous Ring-Imaging Cherenkov Detectors in real time.

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

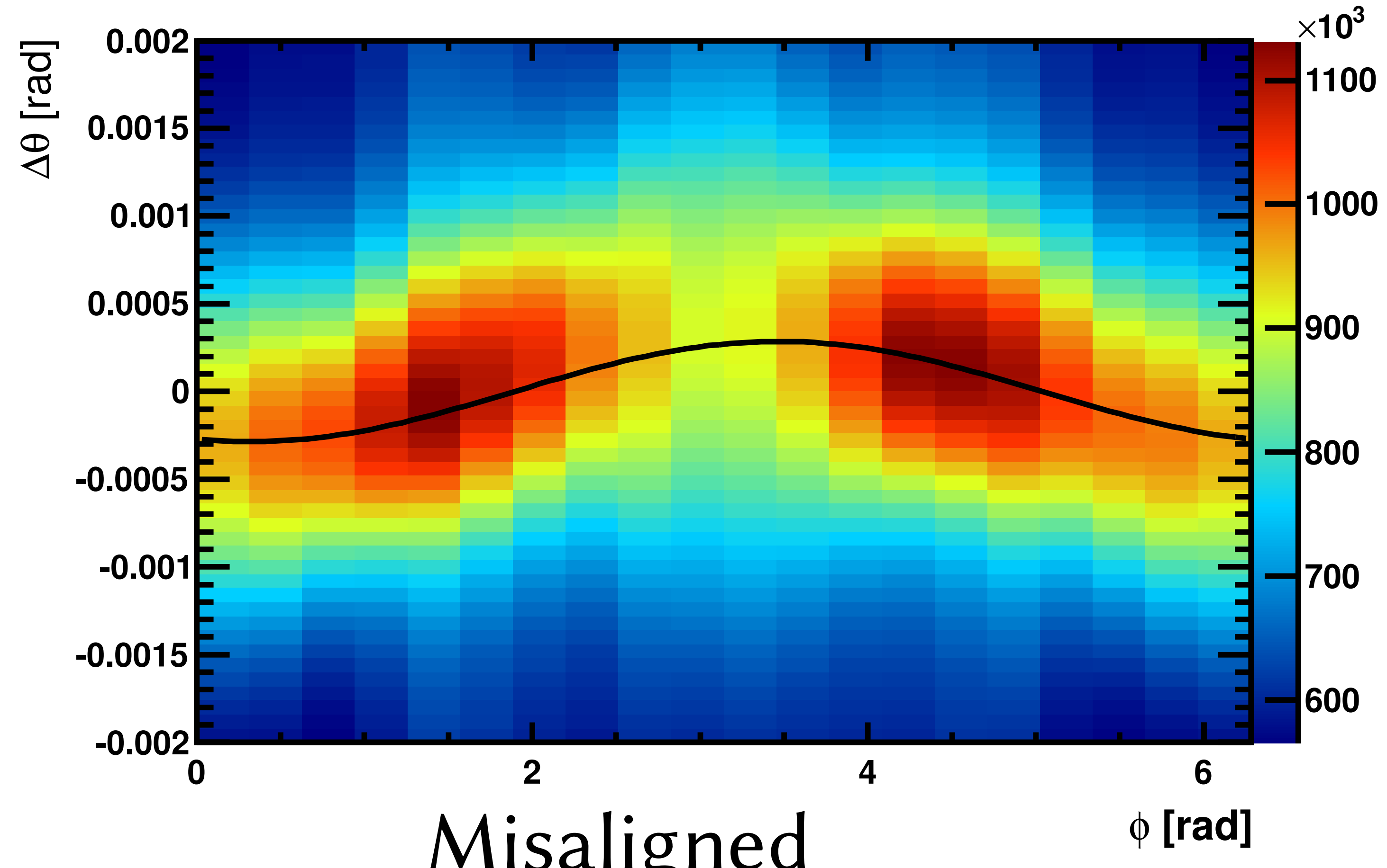
System is automated, can update image and refractive index parameters within less than a minute if needed. Alignment takes longer but also changes much less frequently (1-2 times per year).



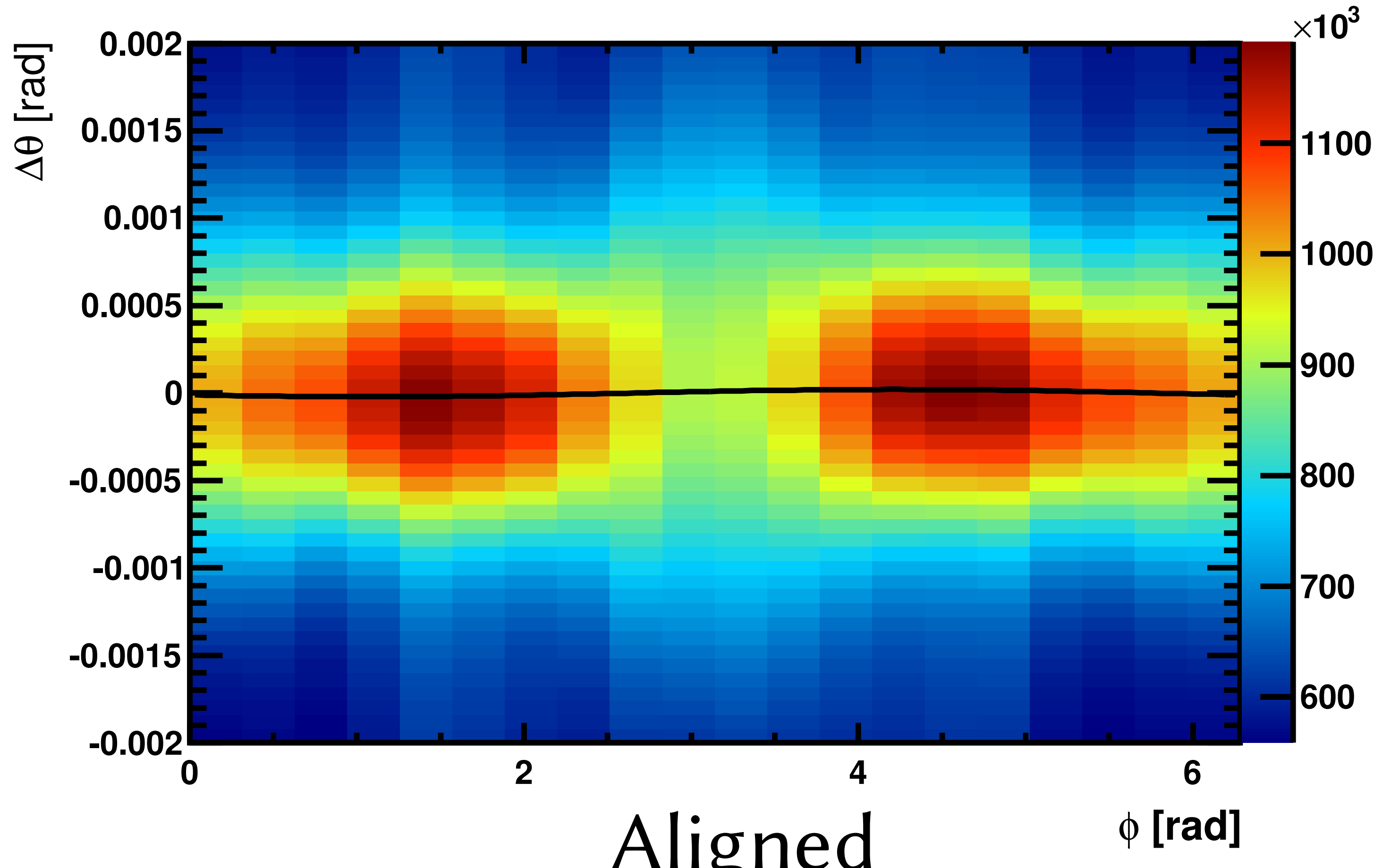
bad



good



Misaligned



Aligned

Aside on the buffer

COMPLETE RUN2 DATA FLOW

- Turbo:
  - *no* offline reconstruction
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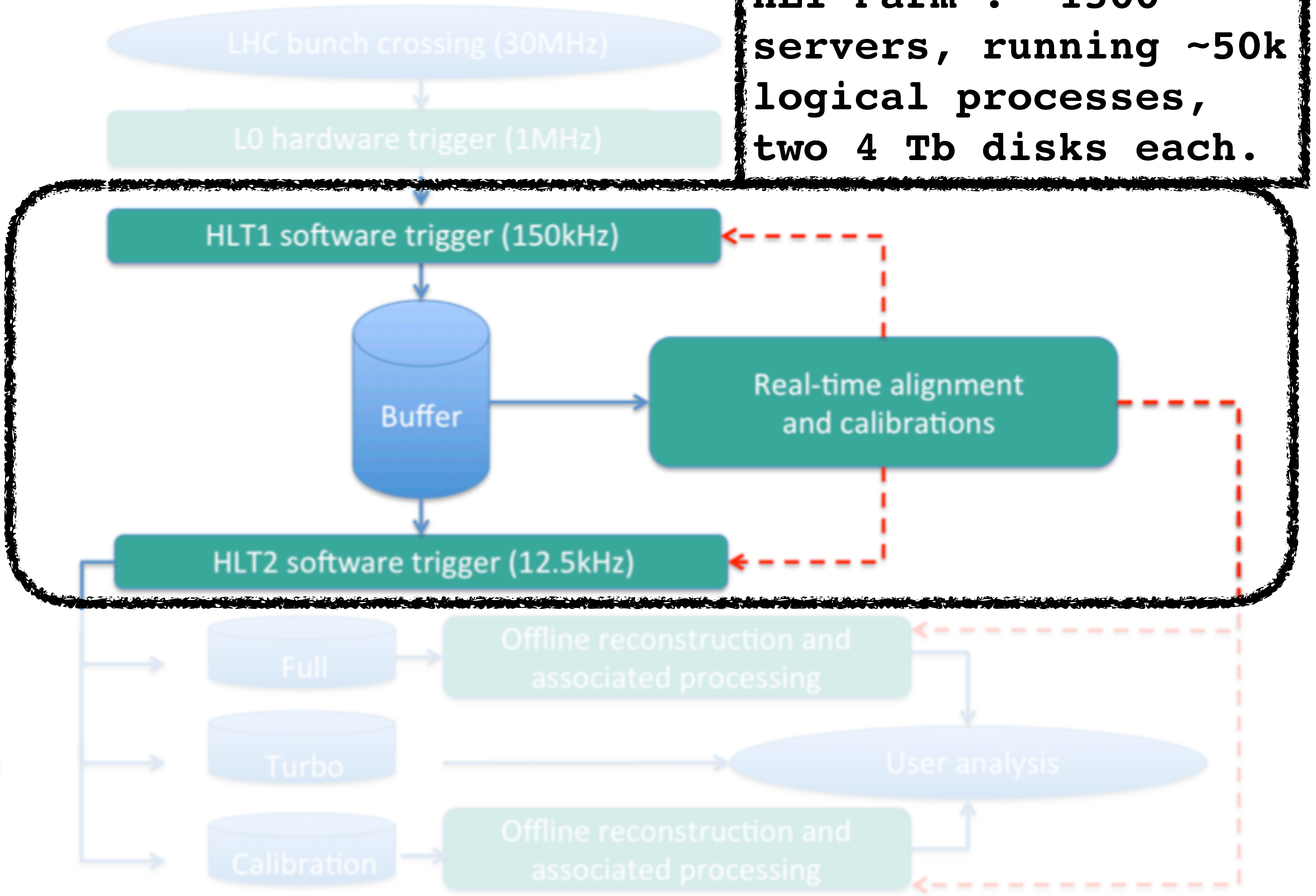
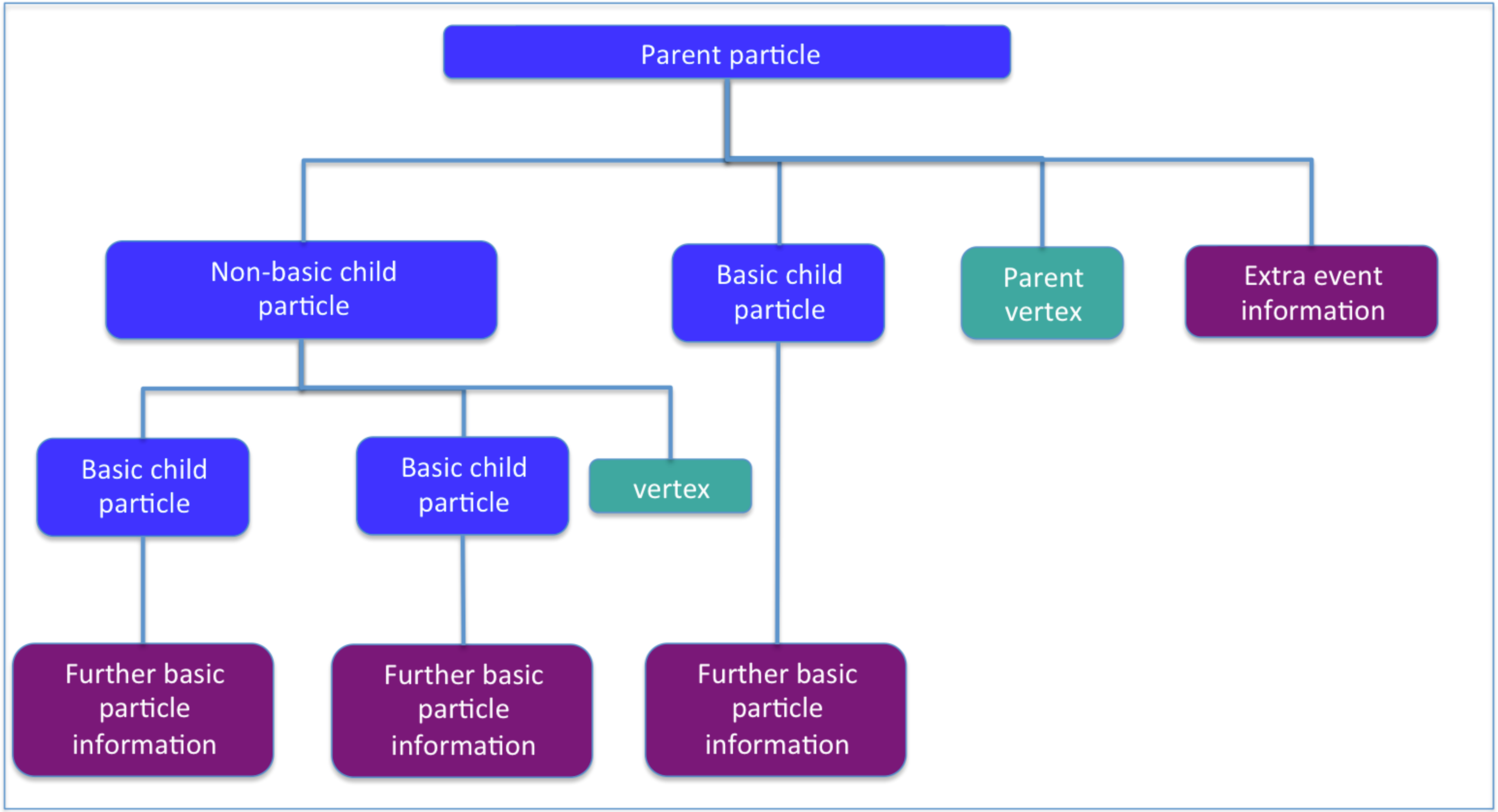


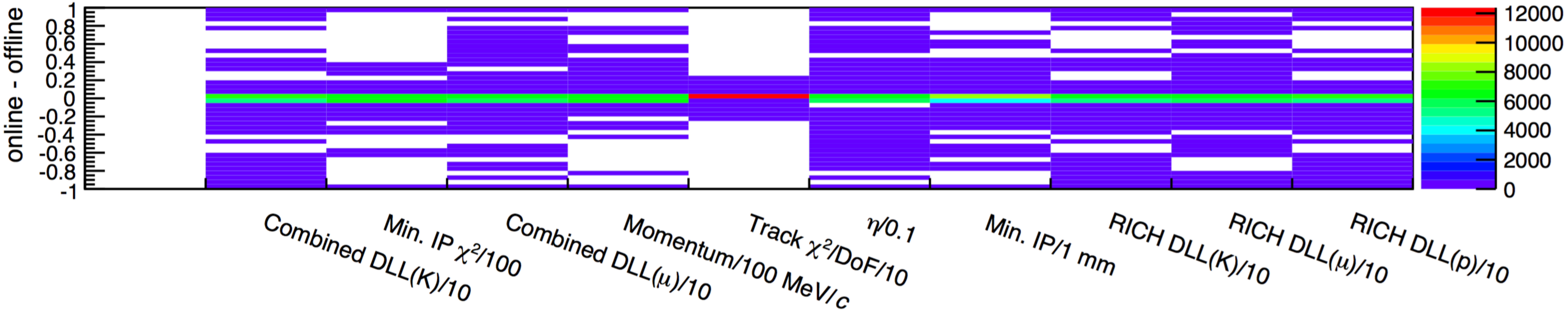
Data compression, aka TURBO stream

Data compression, aka TURBO stream

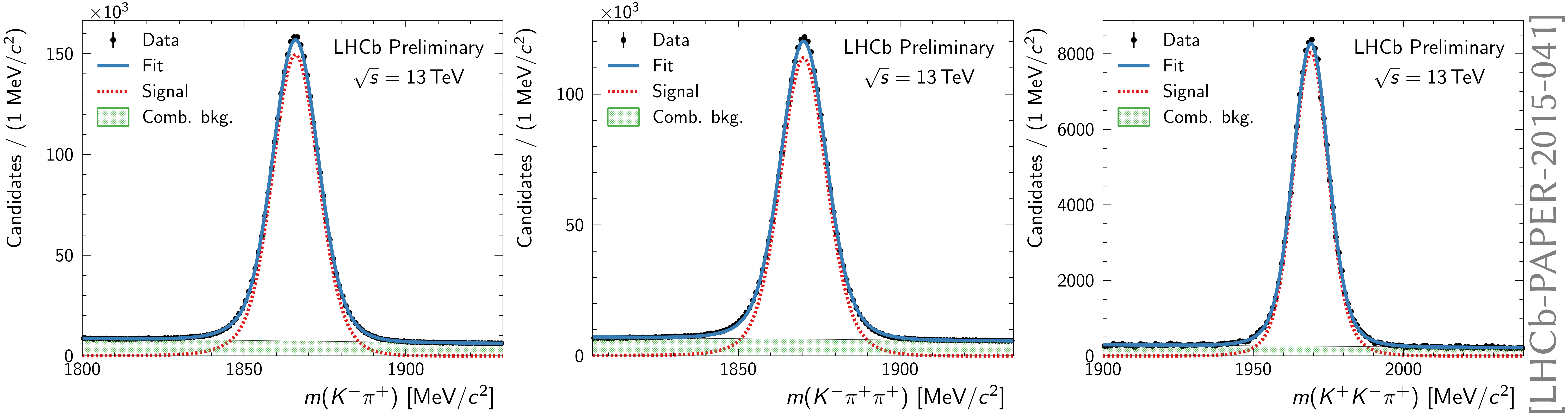
The devil is in the details



The devil is in the details



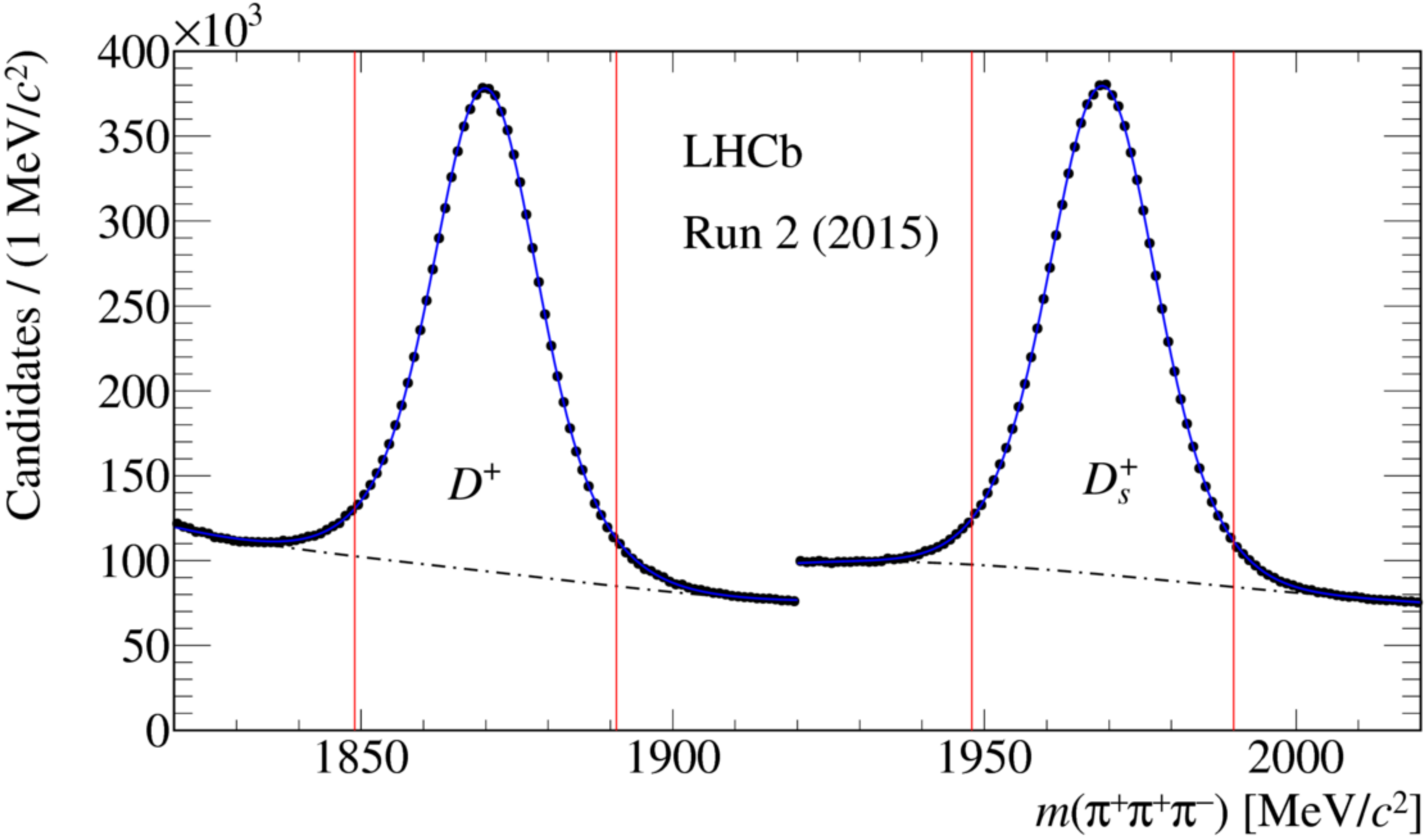
Real time signals in 2015



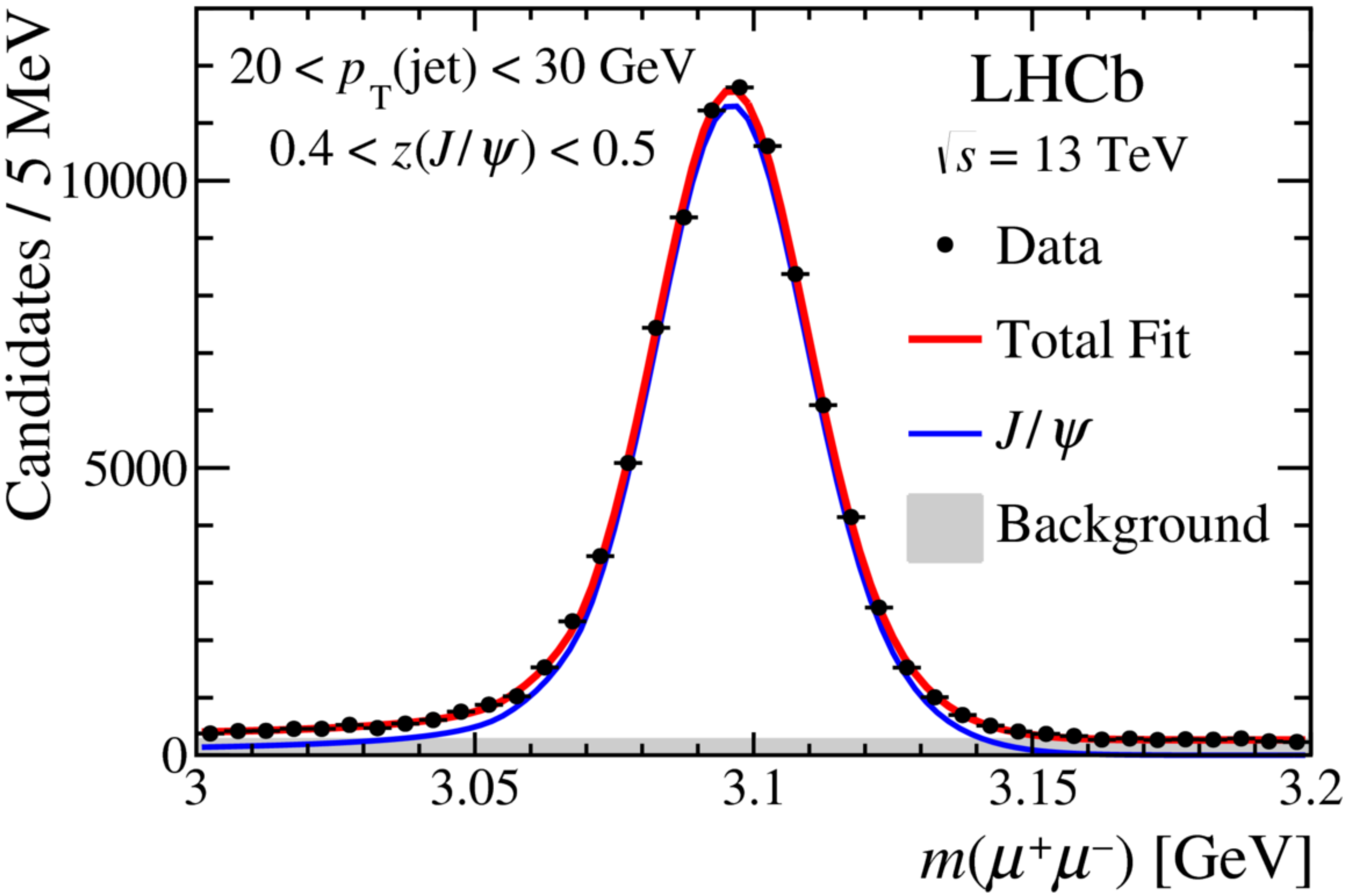
$D^0 \to K^- \pi^+$ $D^+ \to K^- \pi^+ \pi^+$ $D_s^+ \to K^+ K^- \pi^+$

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

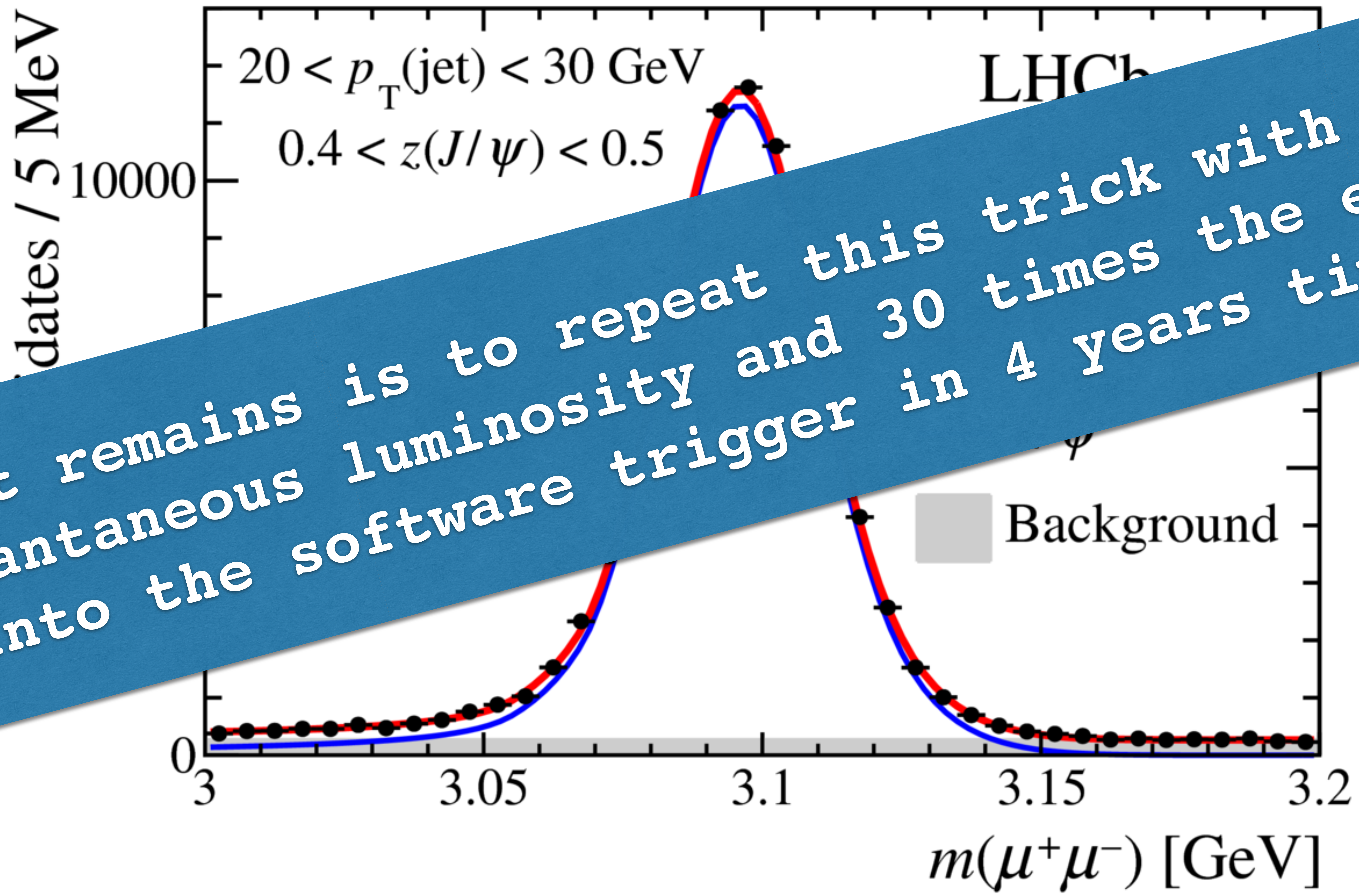
More real-time signals



Even more real-time signals

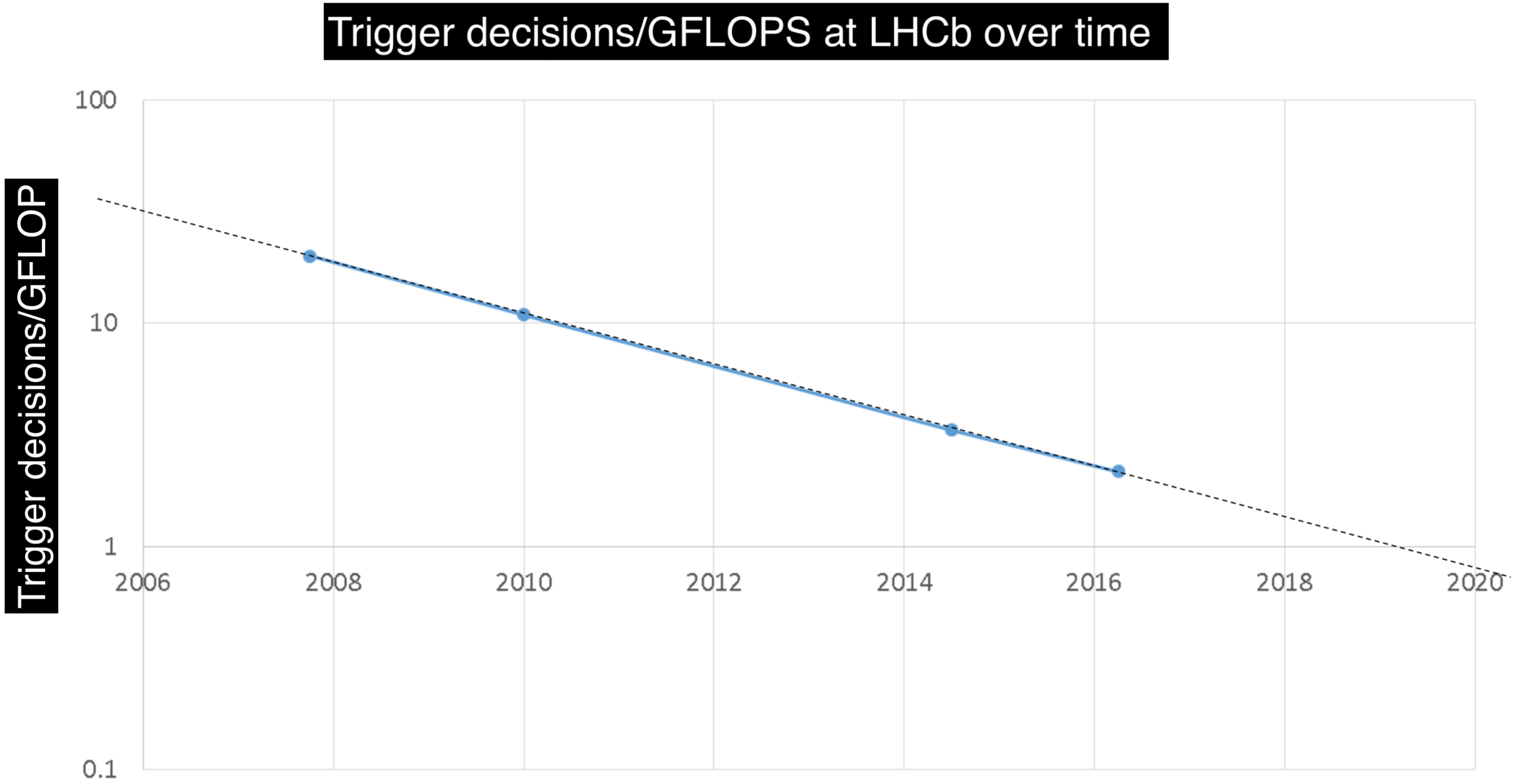


Even more real-time signals



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…

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!