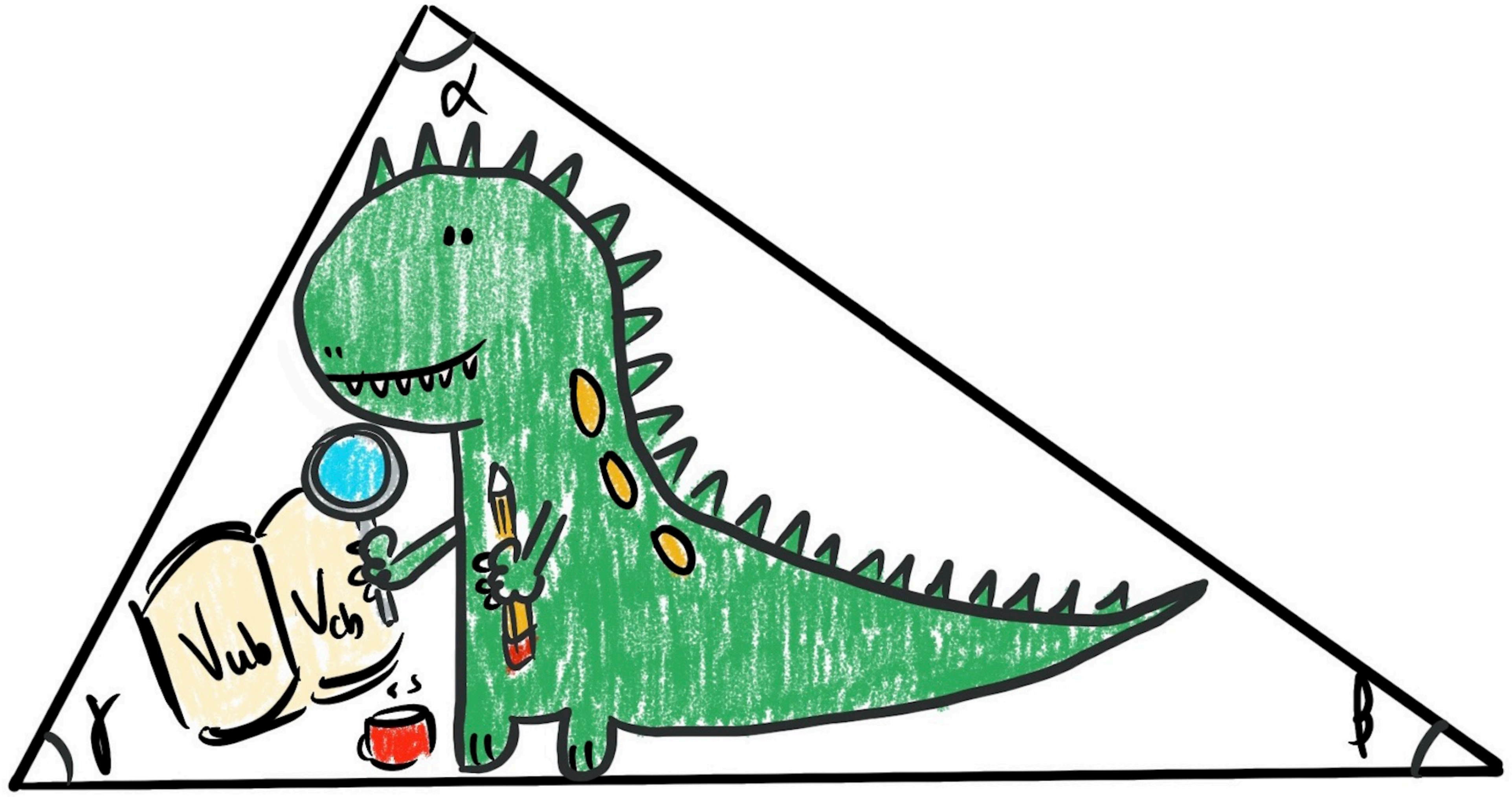
Flavour Physics - Chapter III

Yasmine Amhis
CERN Summer School

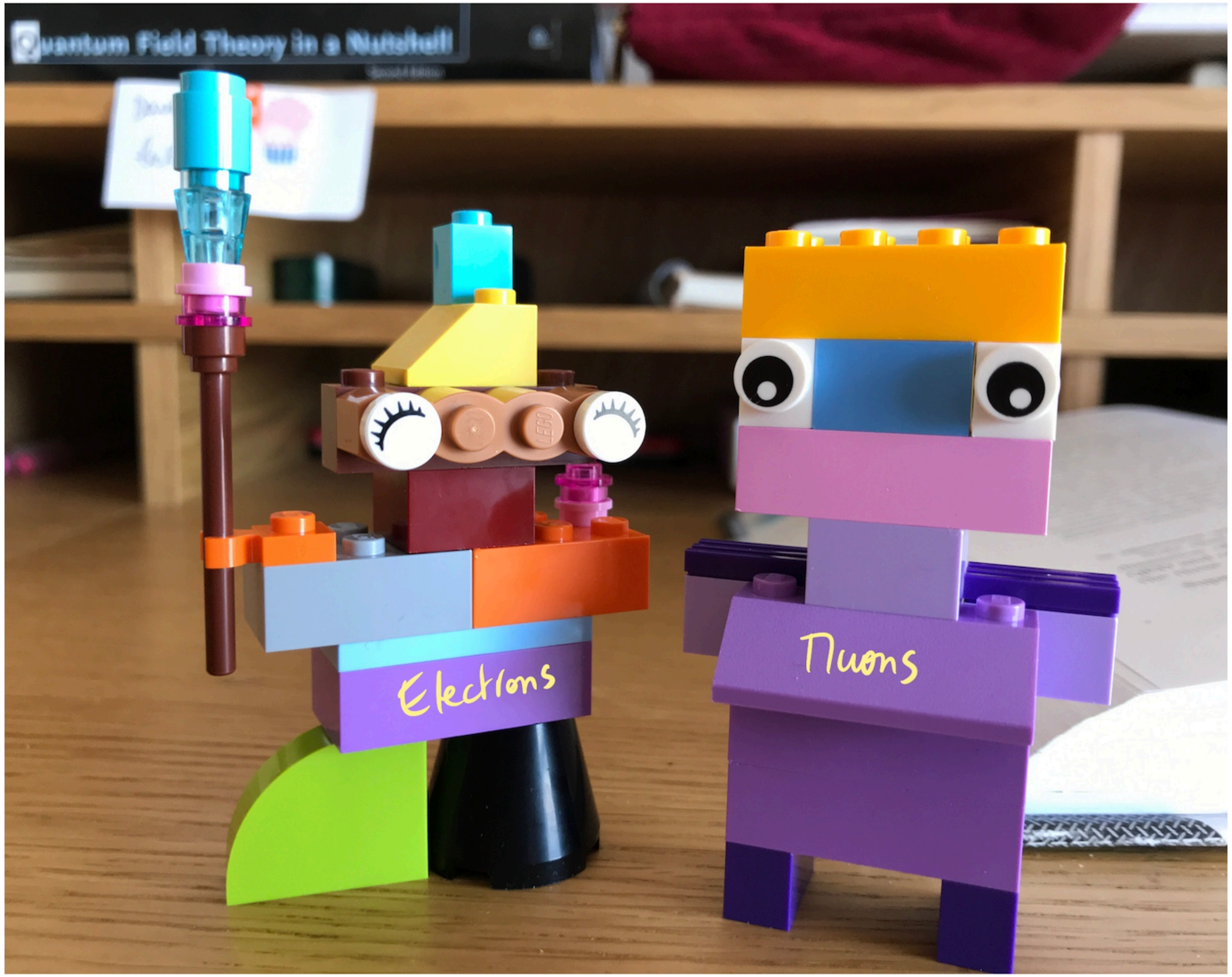


July/August 2024

In this lecture

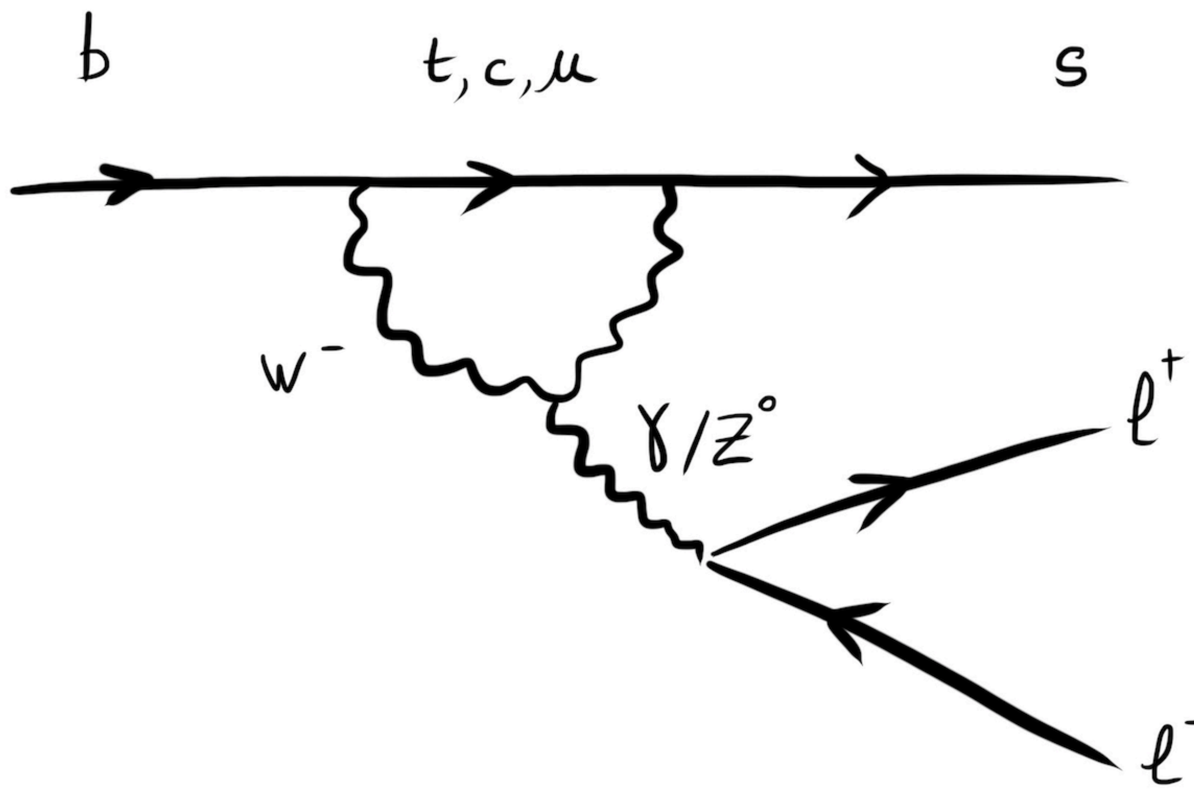
Angular Analyses

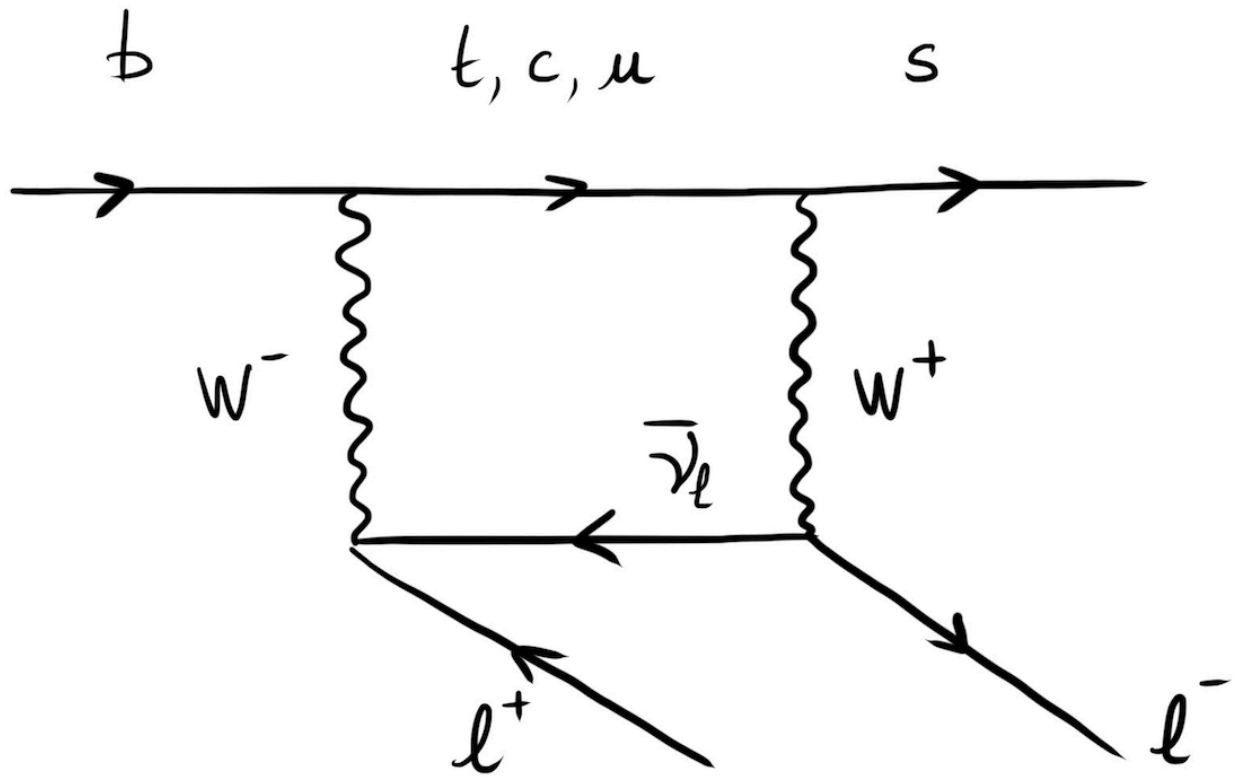
Lepton Universality tests



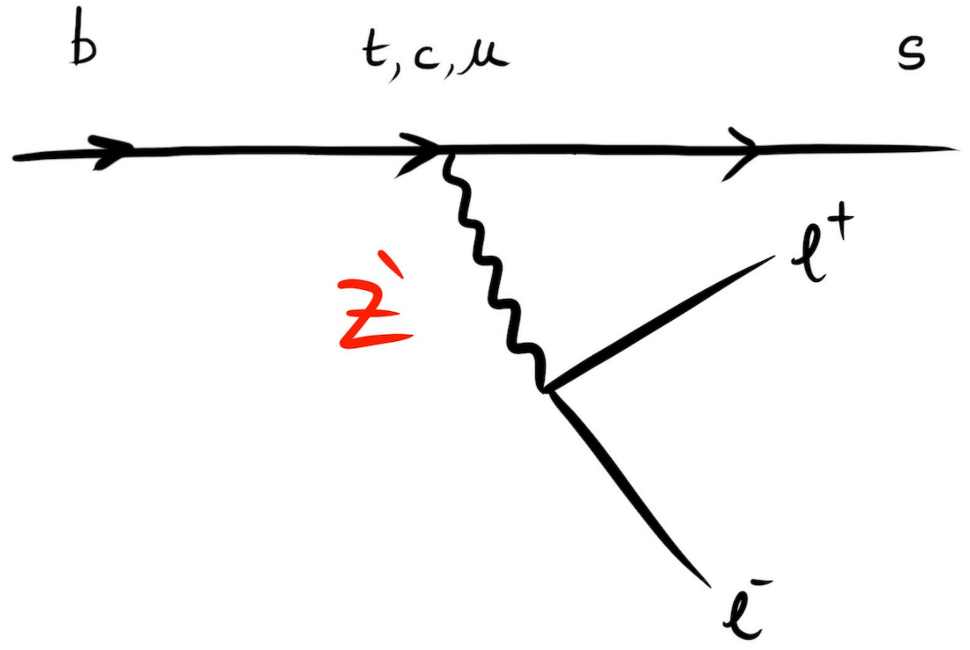
Are we the same?

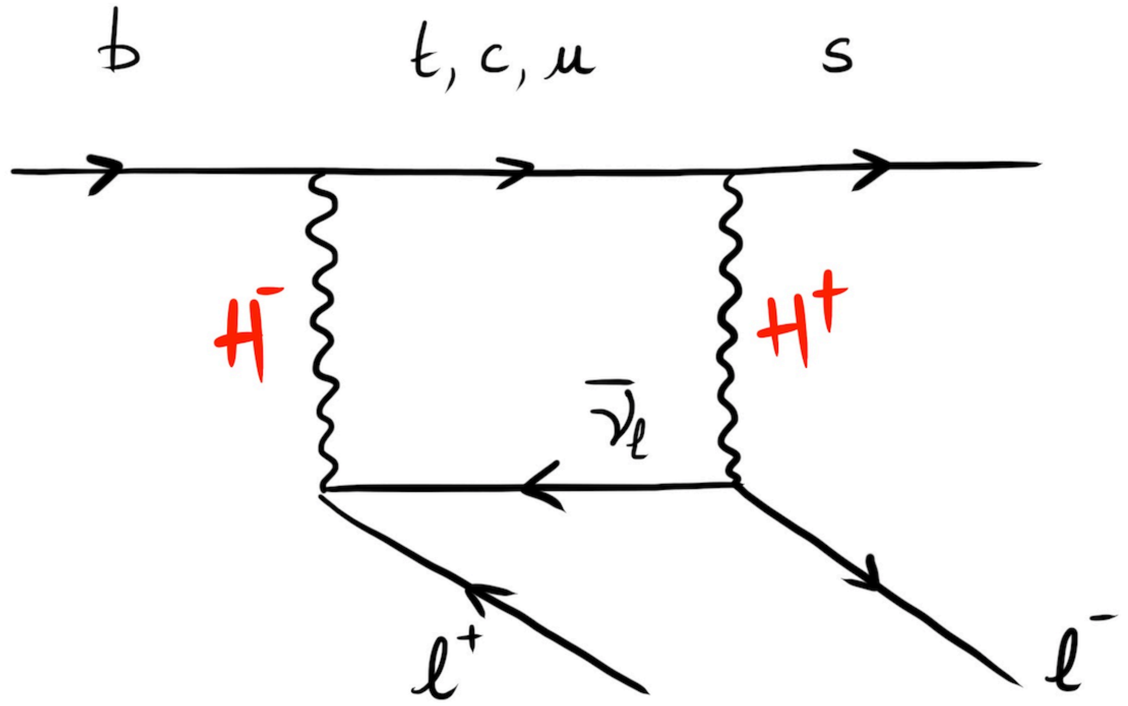
Standard Model





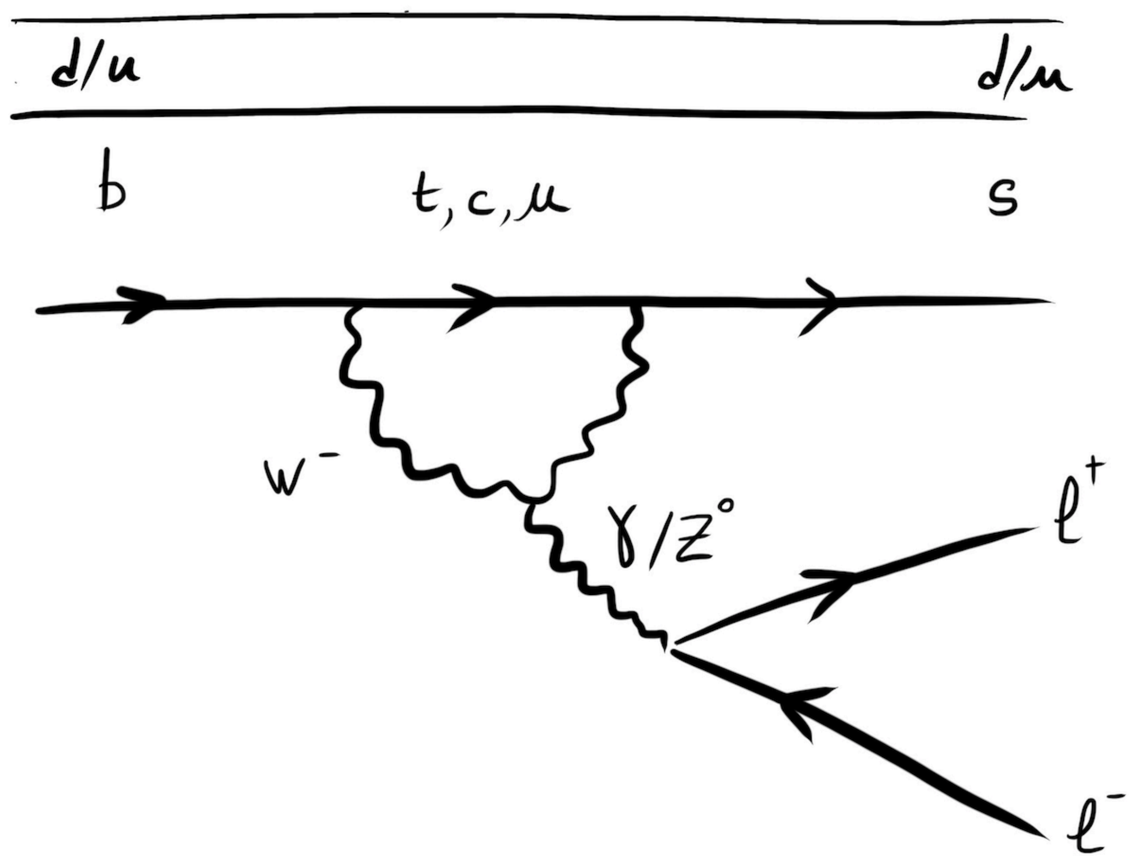
New Physics





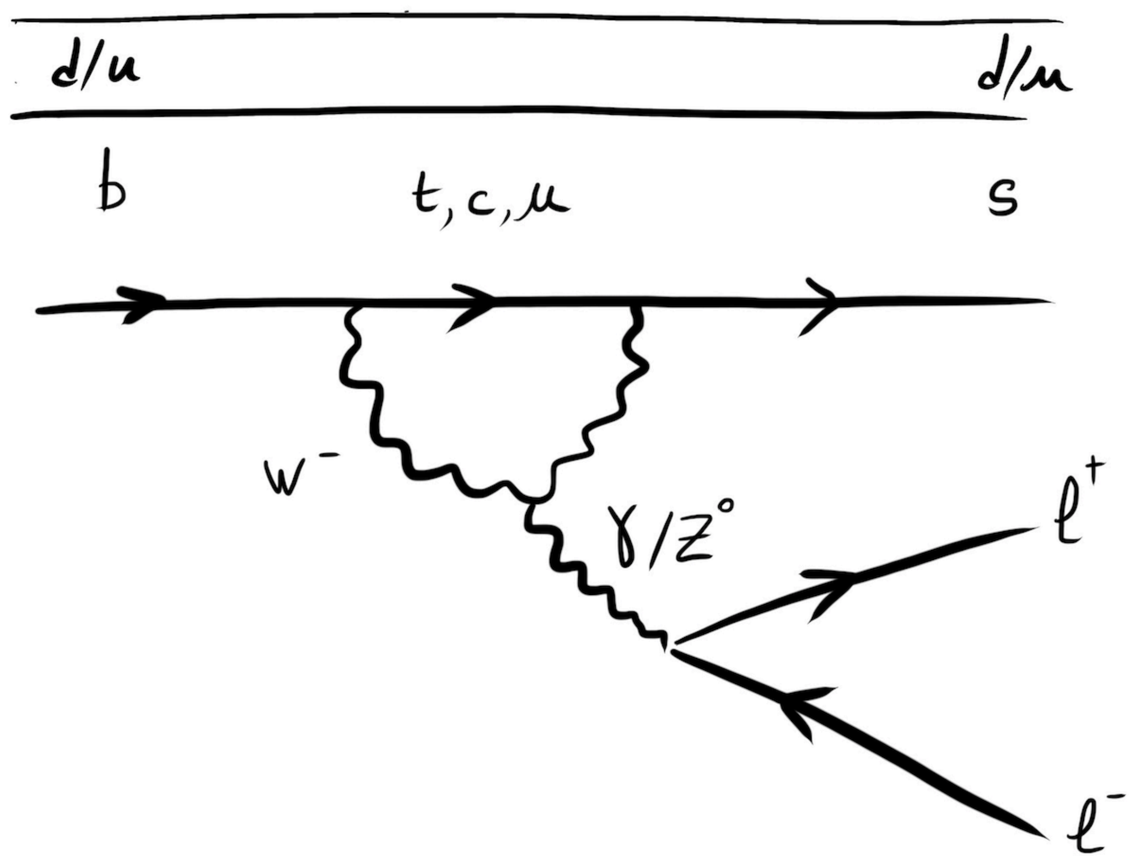
Note to self next time add LQs

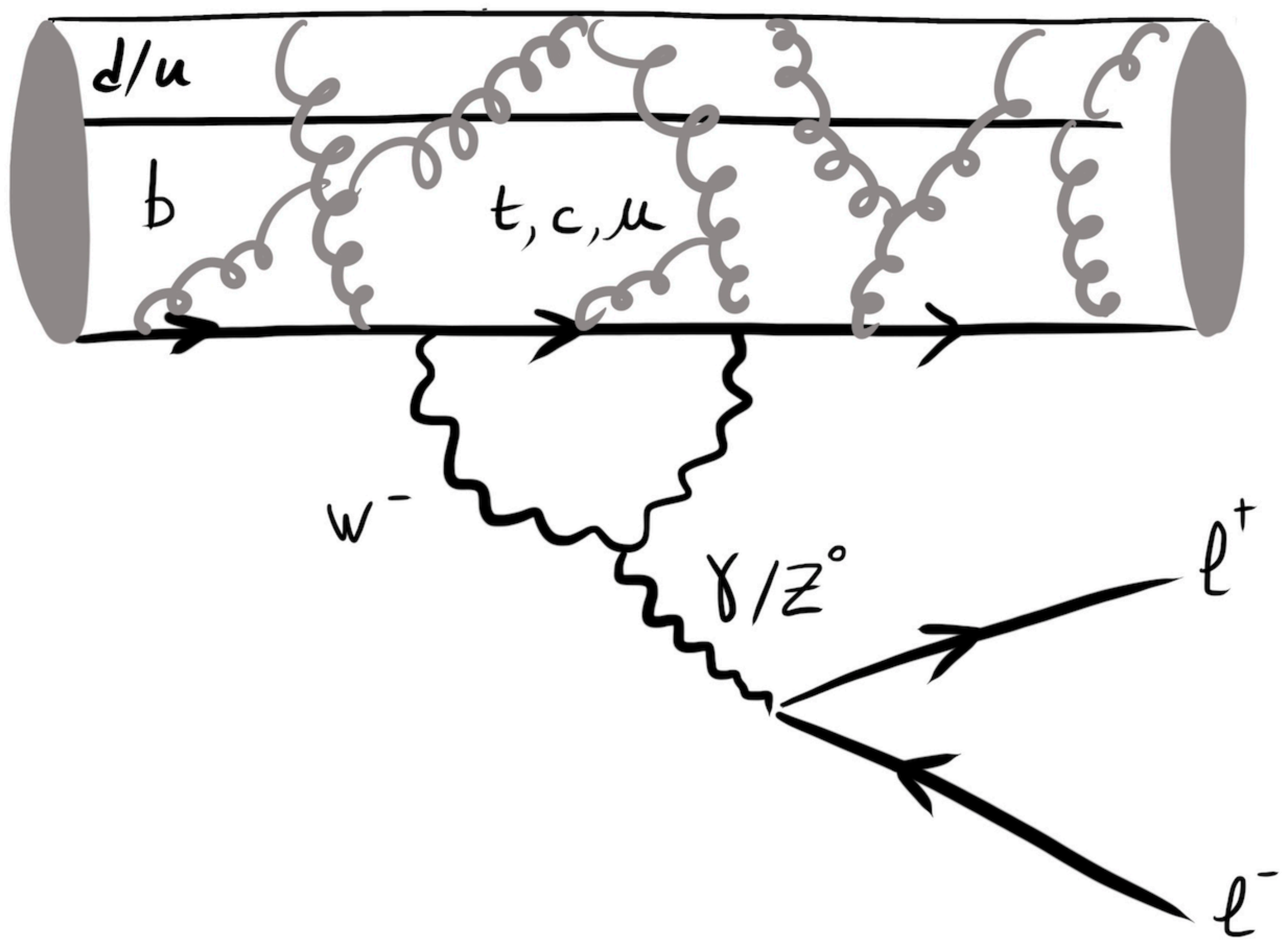
Effective Field Theory



hep-ph/9806303

Effective Field Theory





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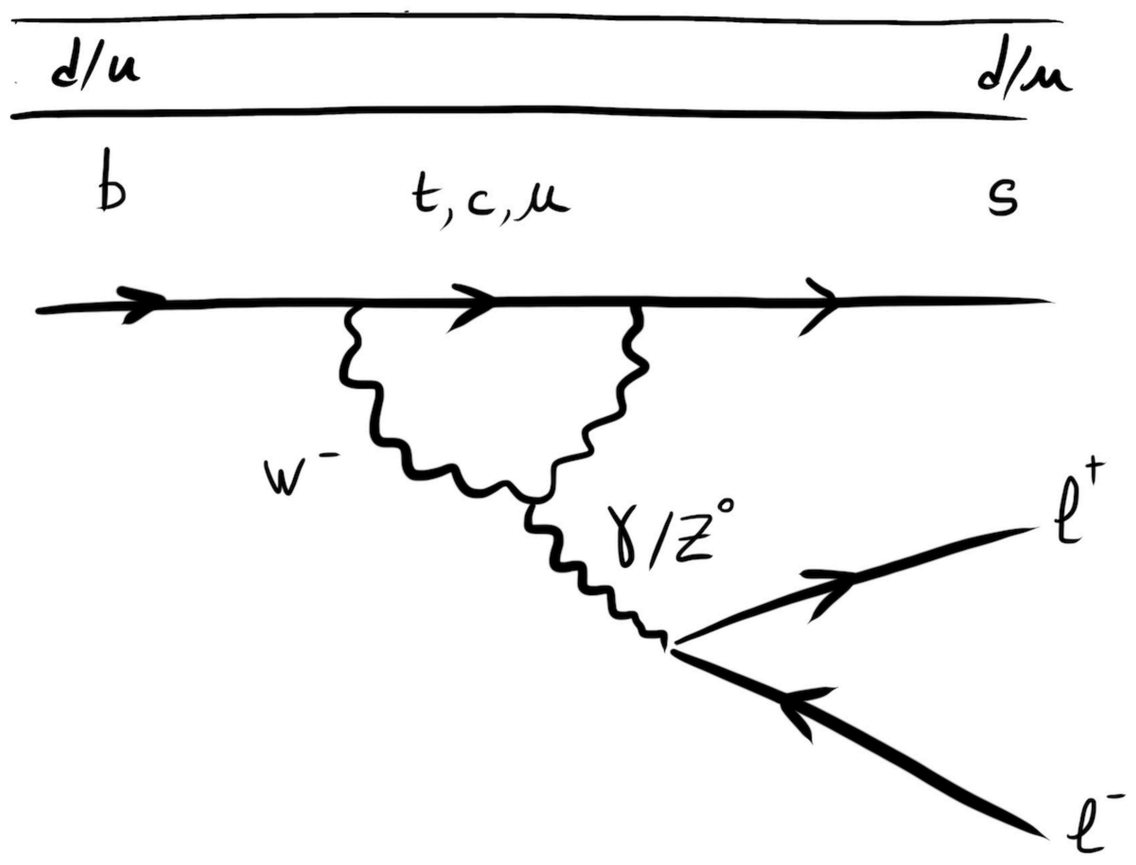
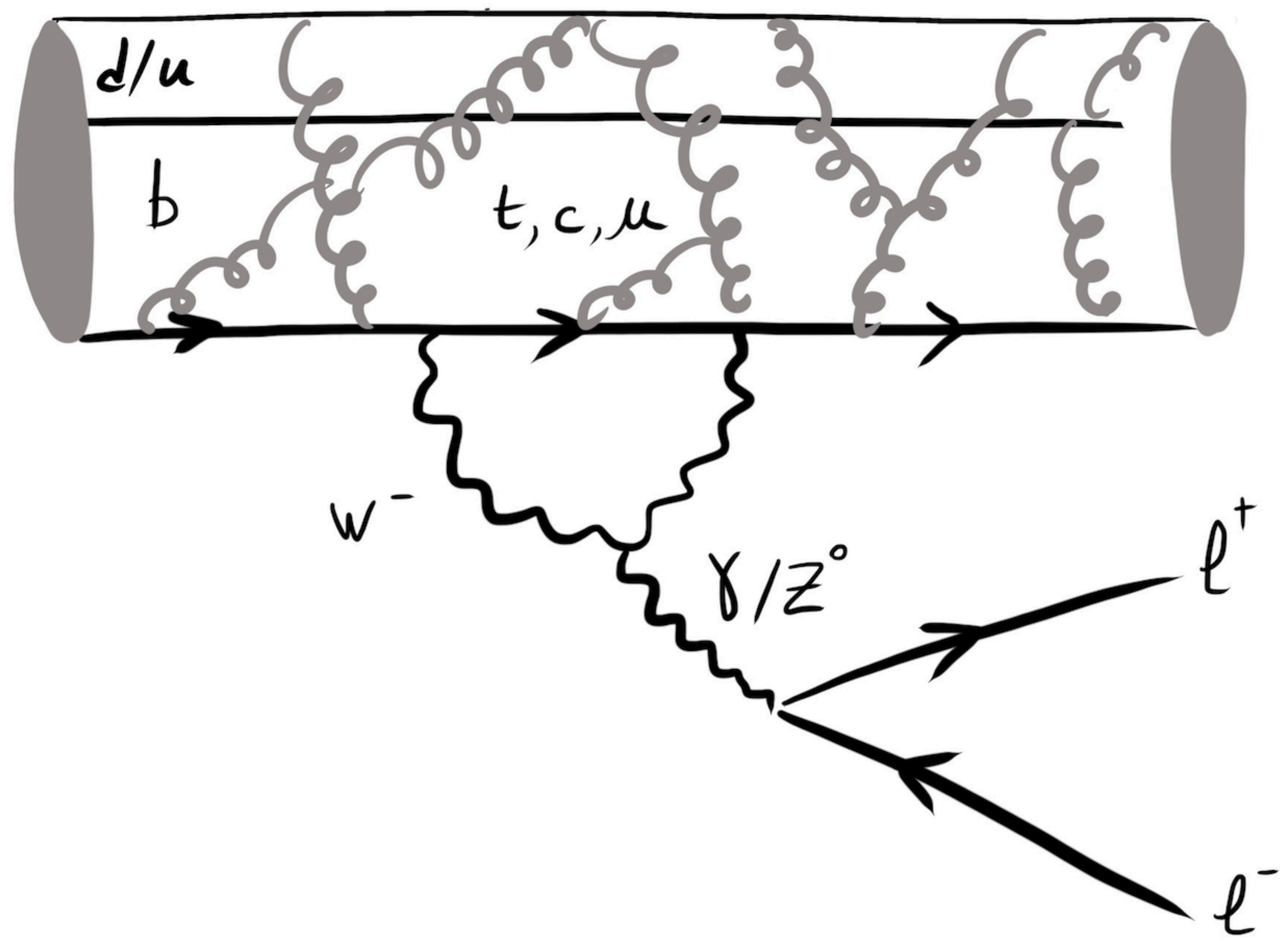
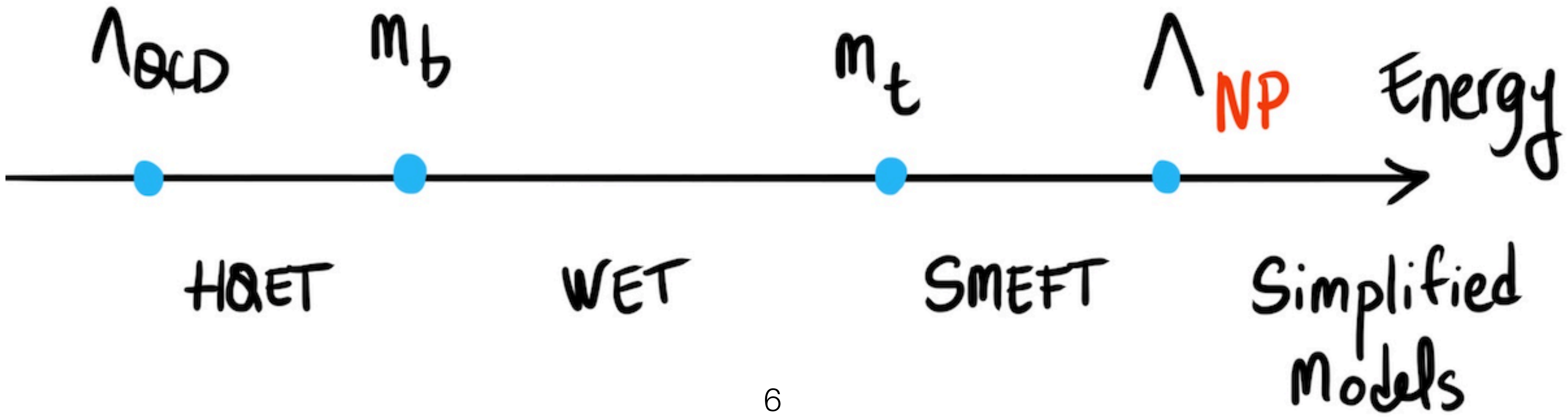
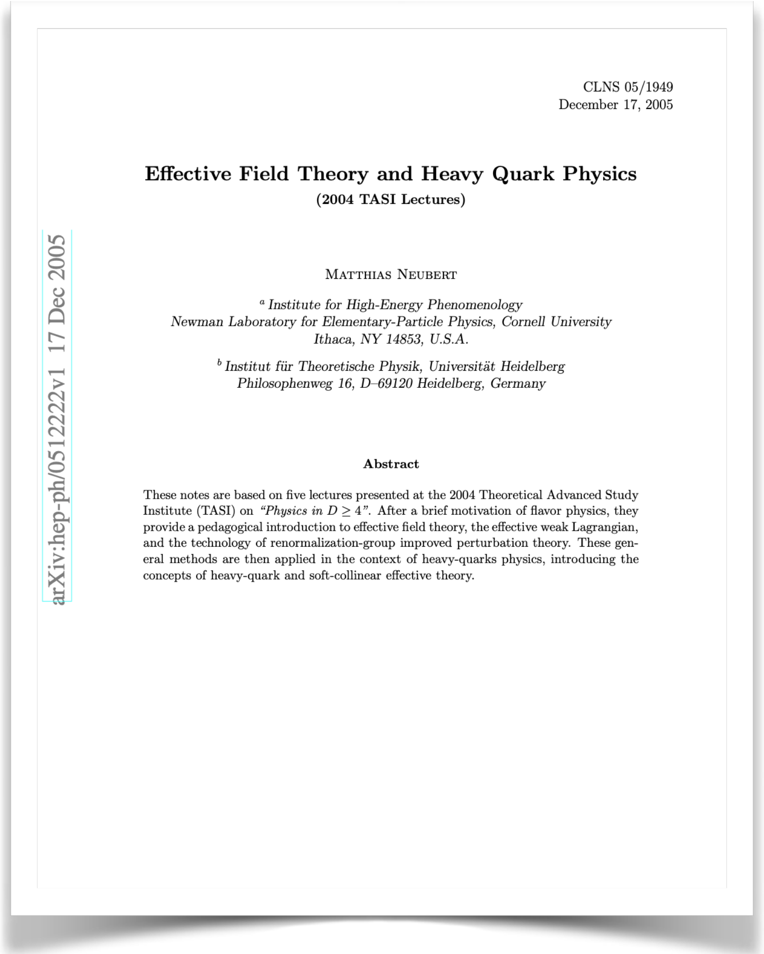






Effective Field Theory


arXiv:hep-ph/0512222v1 17 Dec 2005

CLNS 05/1949
December 17, 2005

Effective Field Theory and Heavy Quark Physics
(2004 TASI Lectures)

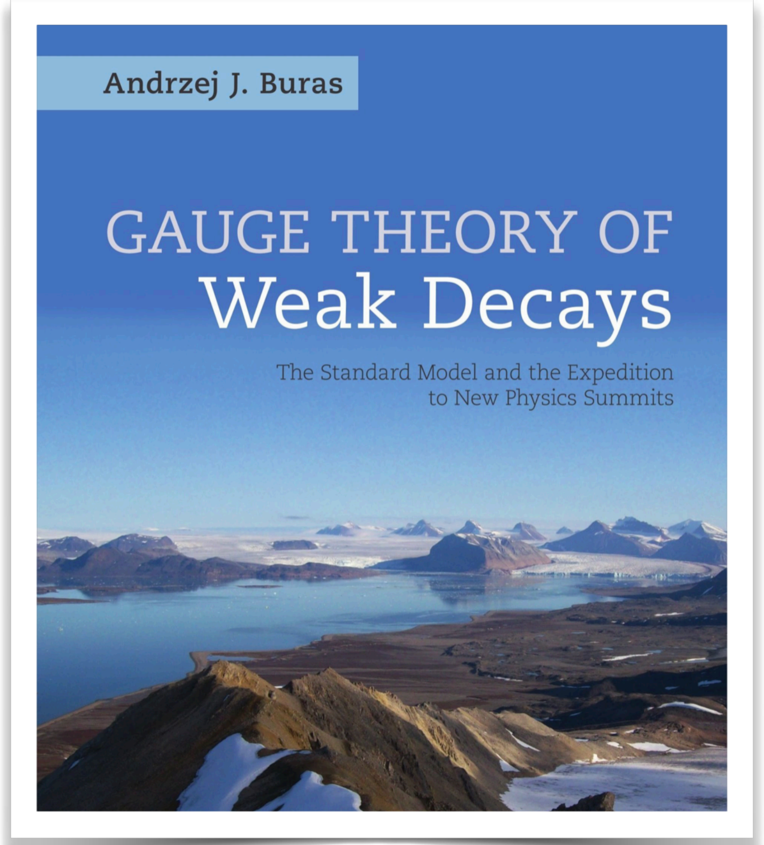
Matthias Neubert

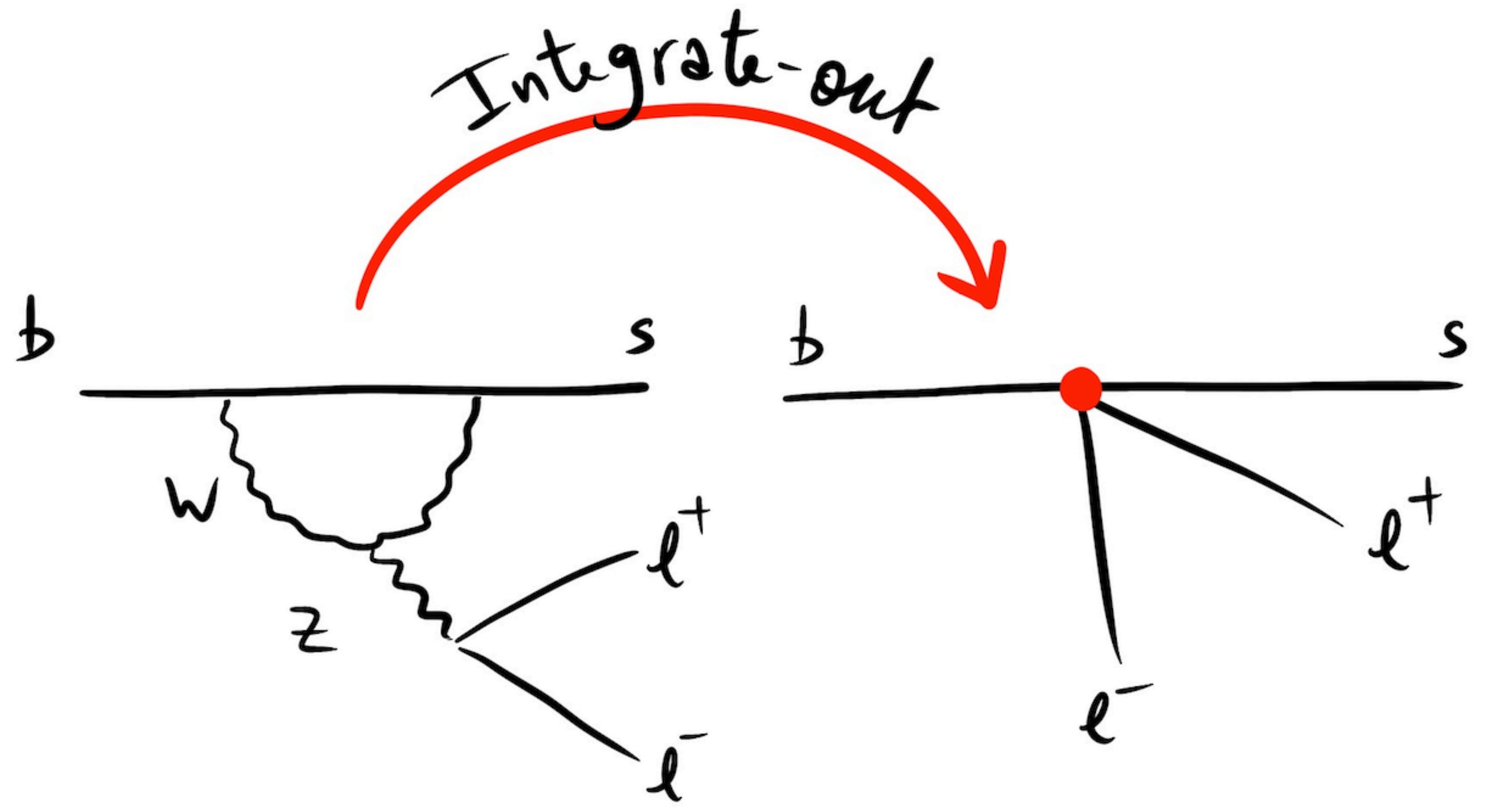
[a] Institute for High-Energy Phenomenology
Newman Laboratory for Elementary-Particle Physics, Cornell University
Ithaca, NY 14853, U.S.A.

[b] Institut für Theoretische Physik, Universität Heidelberg
Philosophenweg 16, D-69120 Heidelberg, Germany

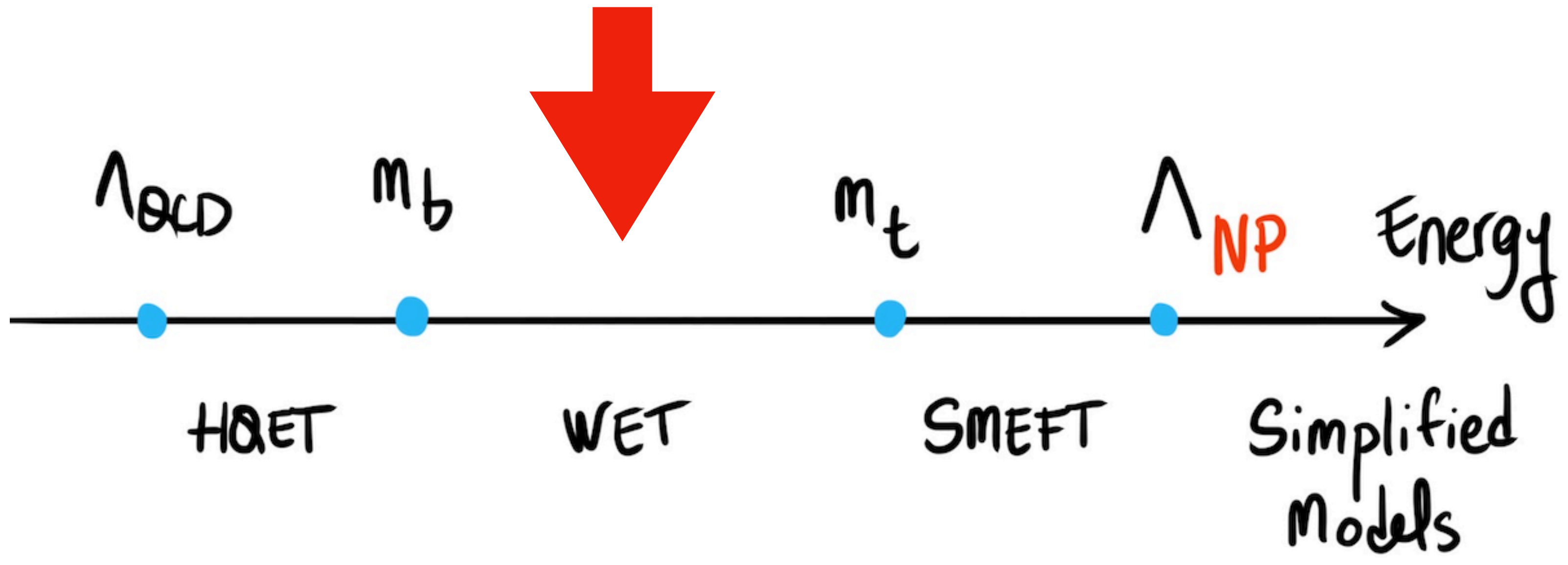
Abstract

These notes are based on five lectures presented at the 2004 Theoretical Advanced Study Institute (TASI) on "Physics in $D \geq 4$". After a brief motivation of flavor physics, they provide a pedagogical introduction to effective field theory, the effective weak Lagrangian, and the technology of renormalization-group improved perturbation theory. These general methods are then applied in the context of heavy-quark physics, introducing the concepts of heavy-quark and soft-collinear effective theory.





$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \lambda^{\rm CKM} \sum_i C_i \mathcal{O}_i + h.c,$$



Effective Field Theory

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i \mathcal{O}_i + h.c,$$

SD: Wilson coefficients + perturbative

LD: Local operators + non perturbative
(LCSR, Lattice, etc.)

Effective Field Theory

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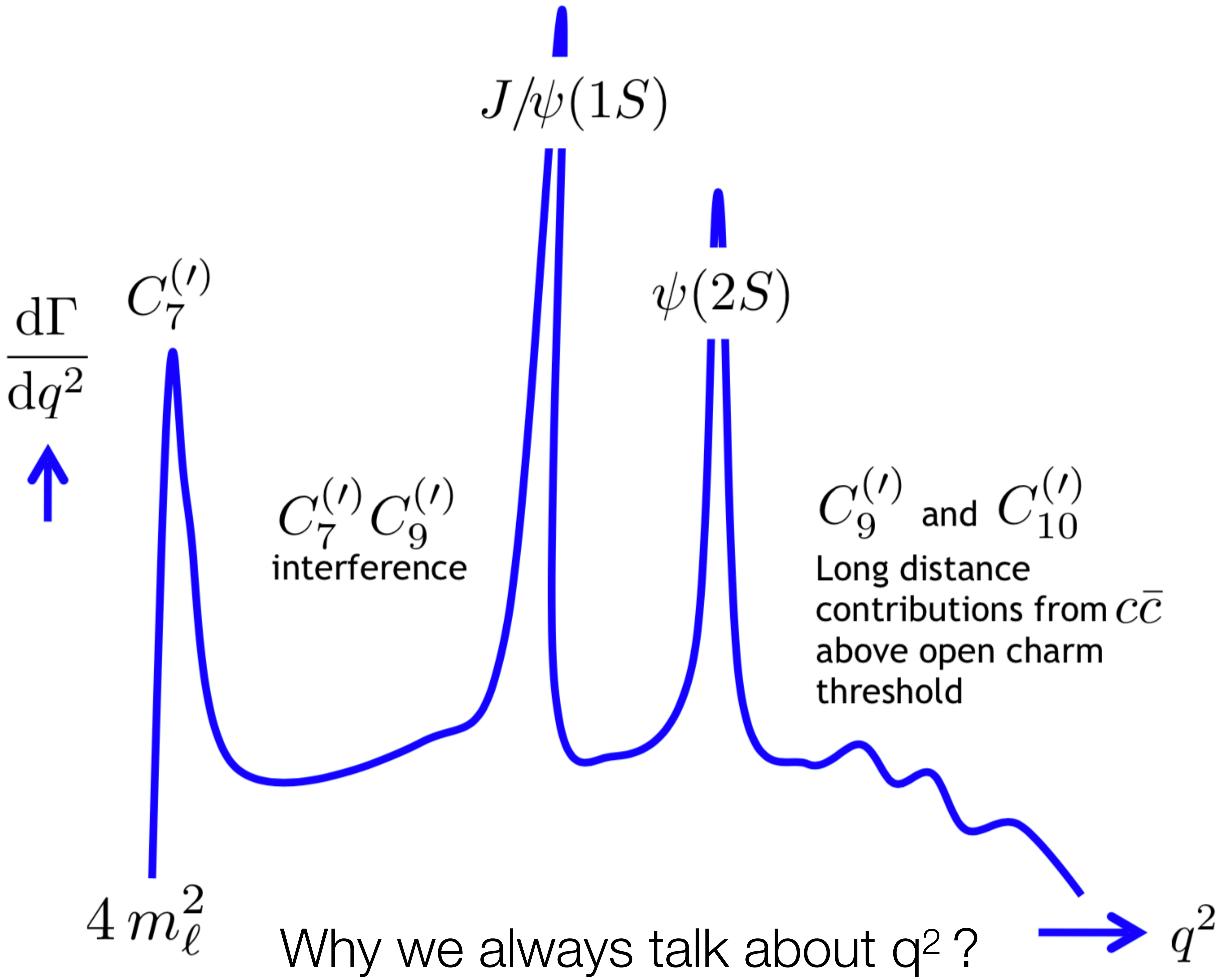
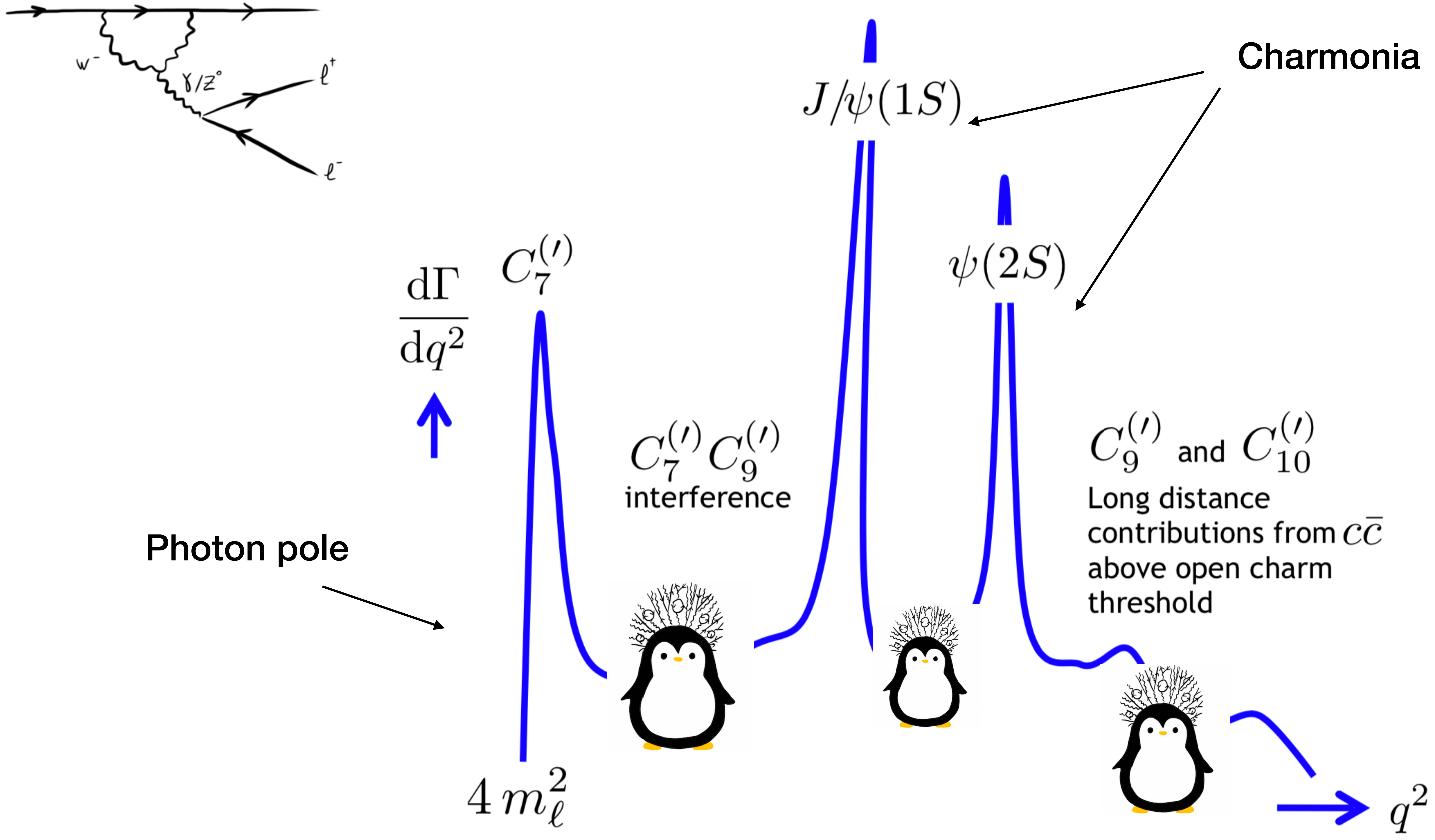


Why we always talk about q^2 ?

$$\mathcal{H}_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}}\lambda^{\mathrm{CKM}}\sum_i C_i\mathcal{O}_i + h.c,$$



To summarize, the resulting Standard Model operator basis for FCNC processes (without leptons, for simplicity) contains the "current-current operators" (with $p = u, c$)

$$Q_1^{(p)} = (\bar{s}_i p_i)_{V-A} (\bar{p}_j b_j)_{V-A} ,$$
$$Q_2^{(p)} = (\bar{s}_i p_j)_{V-A} (\bar{p}_j b_i)_{V-A} , \qquad (32)$$

the "QCD penguin operators"

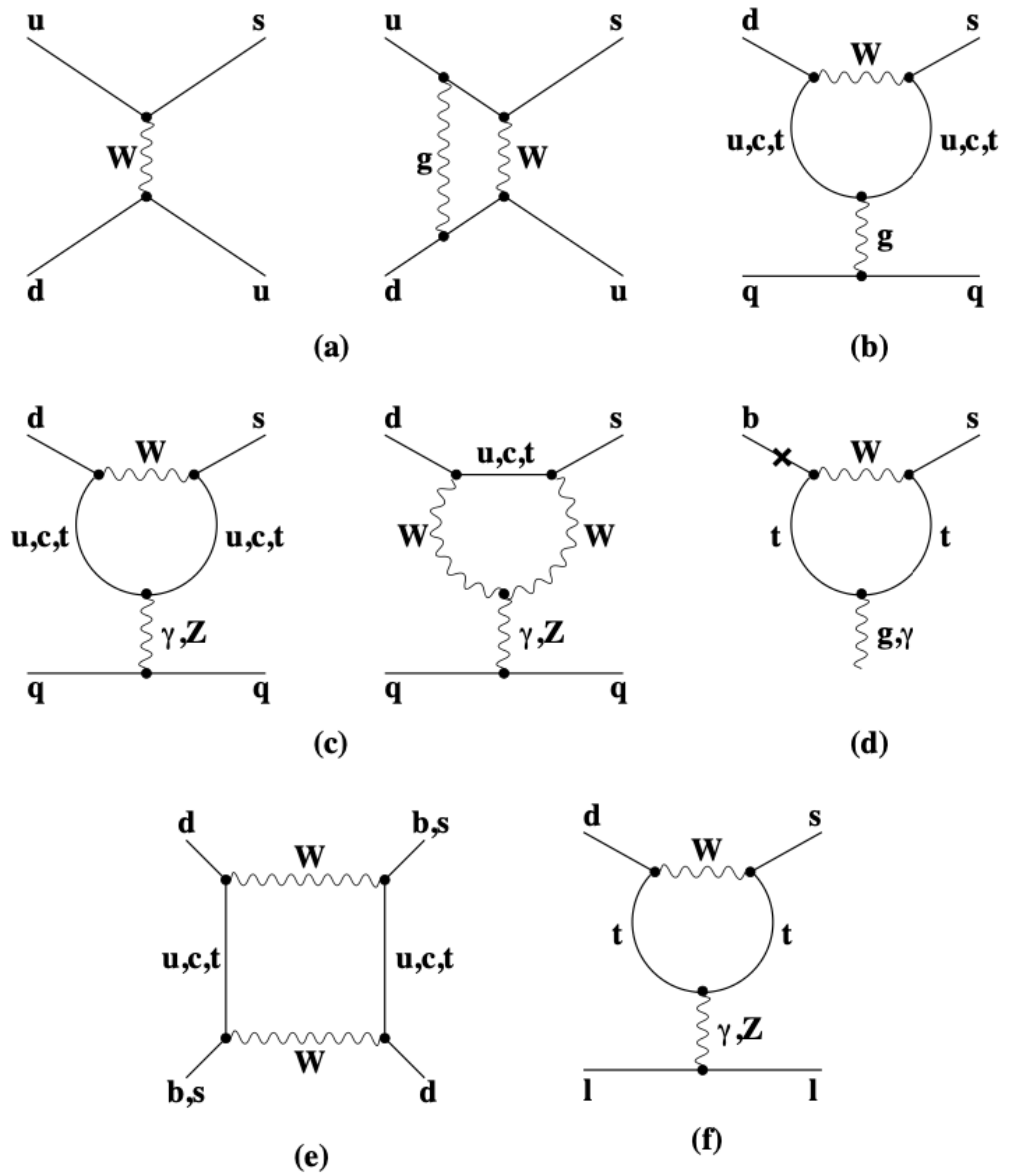
$$Q_3 = (\bar{s}_i b_i)_{V-A} \sum_{q=u,d,s,c,b} (\bar{q}_j q_j)_{V-A} ,$$
$$Q_4 = (\bar{s}_i b_j)_{V-A} \sum_{q=u,d,s,c,b} (\bar{q}_j q_i)_{V-A} ,$$
$$Q_5 = (\bar{s}_i b_i)_{V-A} \sum_{q=u,d,s,c,b} (\bar{q}_j q_j)_{V+A} ,$$
$$Q_6 = (\bar{s}_i b_j)_{V-A} \sum_{q=u,d,s,c,b} (\bar{q}_j q_i)_{V+A} , \qquad (33)$$

the "electroweak penguin operators" (with e_q the electric changes of the quarks in units of $|e|$)

$$Q_7 = (\bar{s}_i b_i)_{V-A} \sum_{q=u,d,s,c,b} \frac{3}{2} e_q (\bar{q}_j q_j)_{V+A} ,$$
$$Q_8 = (\bar{s}_i b_j)_{V-A} \sum_{q=u,d,s,c,b} \frac{3}{2} e_q (\bar{q}_j q_i)_{V+A} ,$$
$$Q_9 = (\bar{s}_i b_i)_{V-A} \sum_{q=u,d,s,c,b} \frac{3}{2} e_q (\bar{q}_j q_j)_{V-A} ,$$
$$Q_{10} = (\bar{s}_i b_j)_{V-A} \sum_{q=u,d,s,c,b} \frac{3}{2} e_q (\bar{q}_j q_i)_{V-A} , \qquad (34)$$

and the electromagnetic and chromo-magnetic dipole operators

$$Q_{7\gamma} = -\frac{e m_b}{8\pi^2} \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R ,$$
$$Q_{8g} = -\frac{g_s m_b}{8\pi^2} \bar{s}_L \sigma_{\mu\nu} G_a^{\mu\nu} t_a b_R . \qquad (35)$$



https://arxiv.org/pdf/hep-ph/0512222

The unitarity of the CKM matrix implies $\lambda_u + \lambda_c + \lambda_t = 0$, where $\lambda_p \equiv V_{pb} V_{ps}^*$. We will use this relation to eliminate CKM factors involving couplings of the top quark. Note also that in the limit $m_u = m_c = 0$ (which is justified at dimension-6 order) the penguin graphs always involve $\lambda_t = -(\lambda_u + \lambda_c)$. The final result for the effective weak Lagrangian reads

$$\mathcal{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \left[\sum_{p=u,c} \lambda_p \left(C_1 Q_1^{(p)} + C_2 Q_2^{(p)} \right) + \sum_{i=3,\ldots,10,7\gamma,8g} (\lambda_u + \lambda_c)\, C_i Q_i \right]. \tag{36}$$

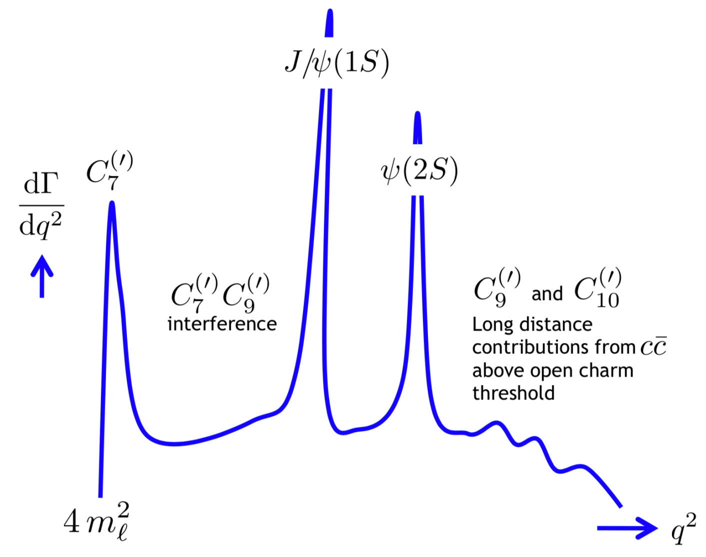
16

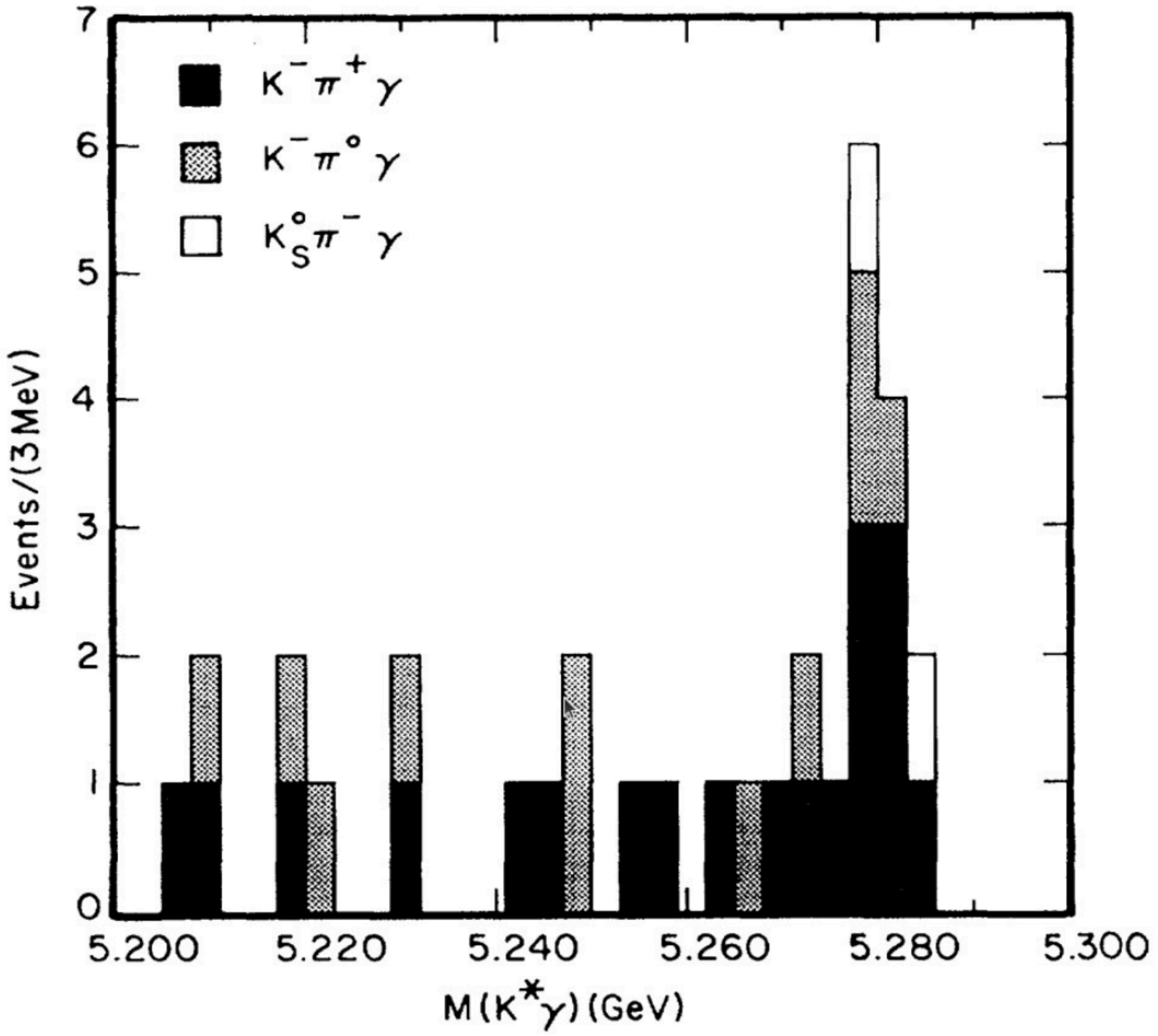
Note that

$$\frac{\lambda_u}{\lambda_c} = \frac{V_{ub} V_{us}^*}{V_{cb} V_{cs}^*} \sim e^{-i\gamma} \tag{37}$$

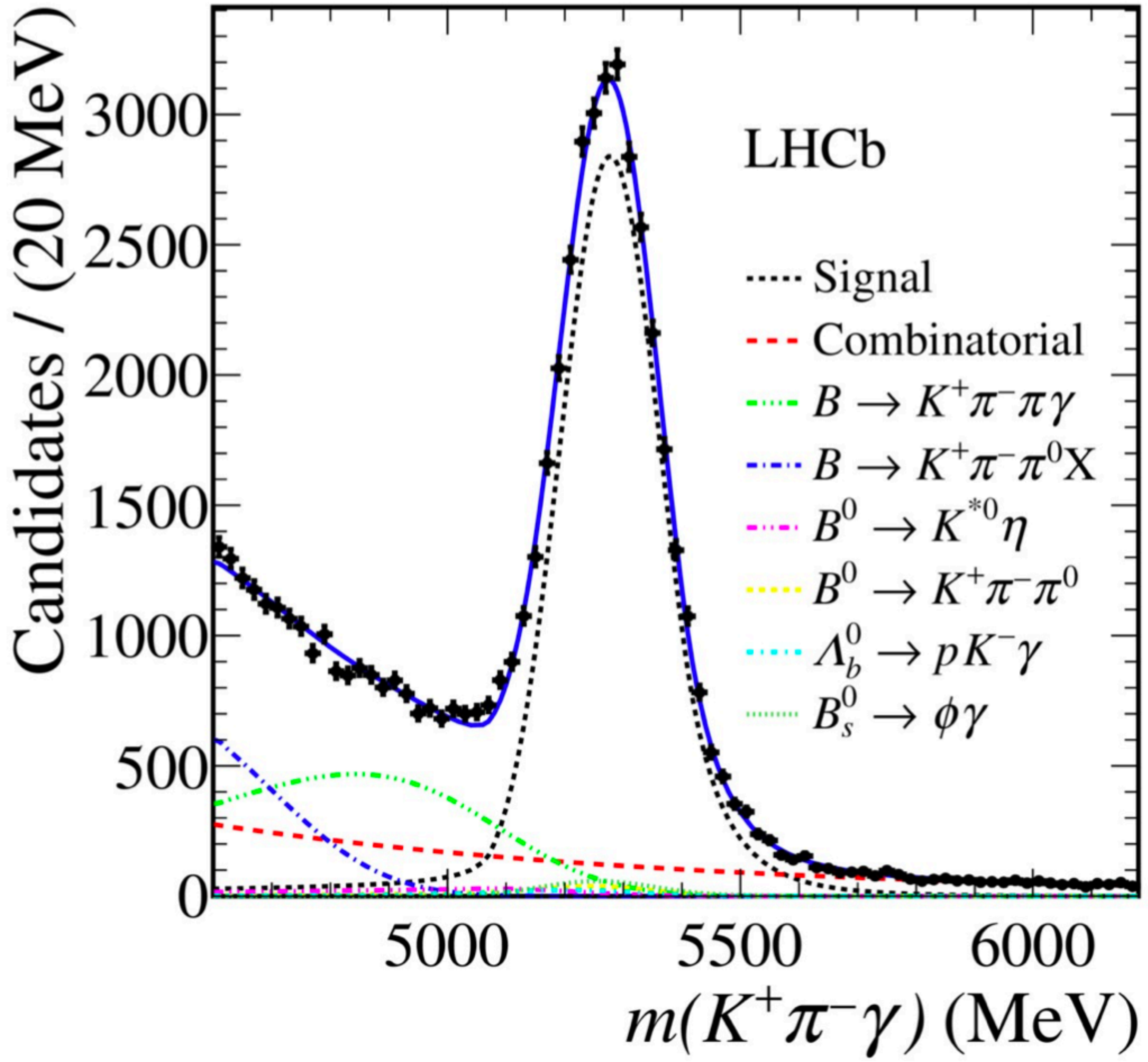
has a non-zero, relative CP-violating phase. This allows for the phenomenon of CP violation from amplitude interference in FCNC processes – a phenomenon that is currently being studied extensively at the B-factories (see, e.g., [1]).

Photon pole - family of radiative decays





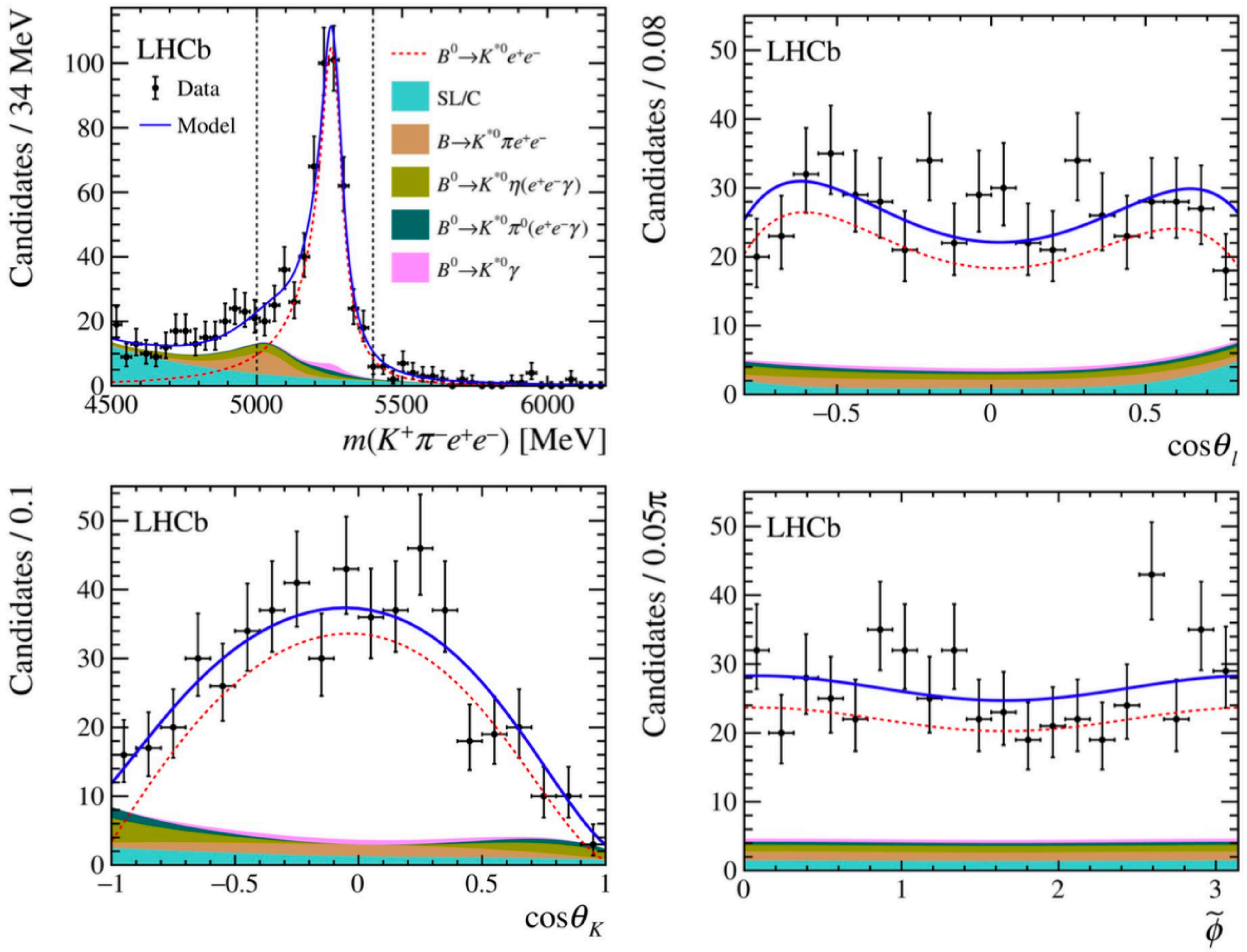
CLEO, PRL 71 (1993) 674

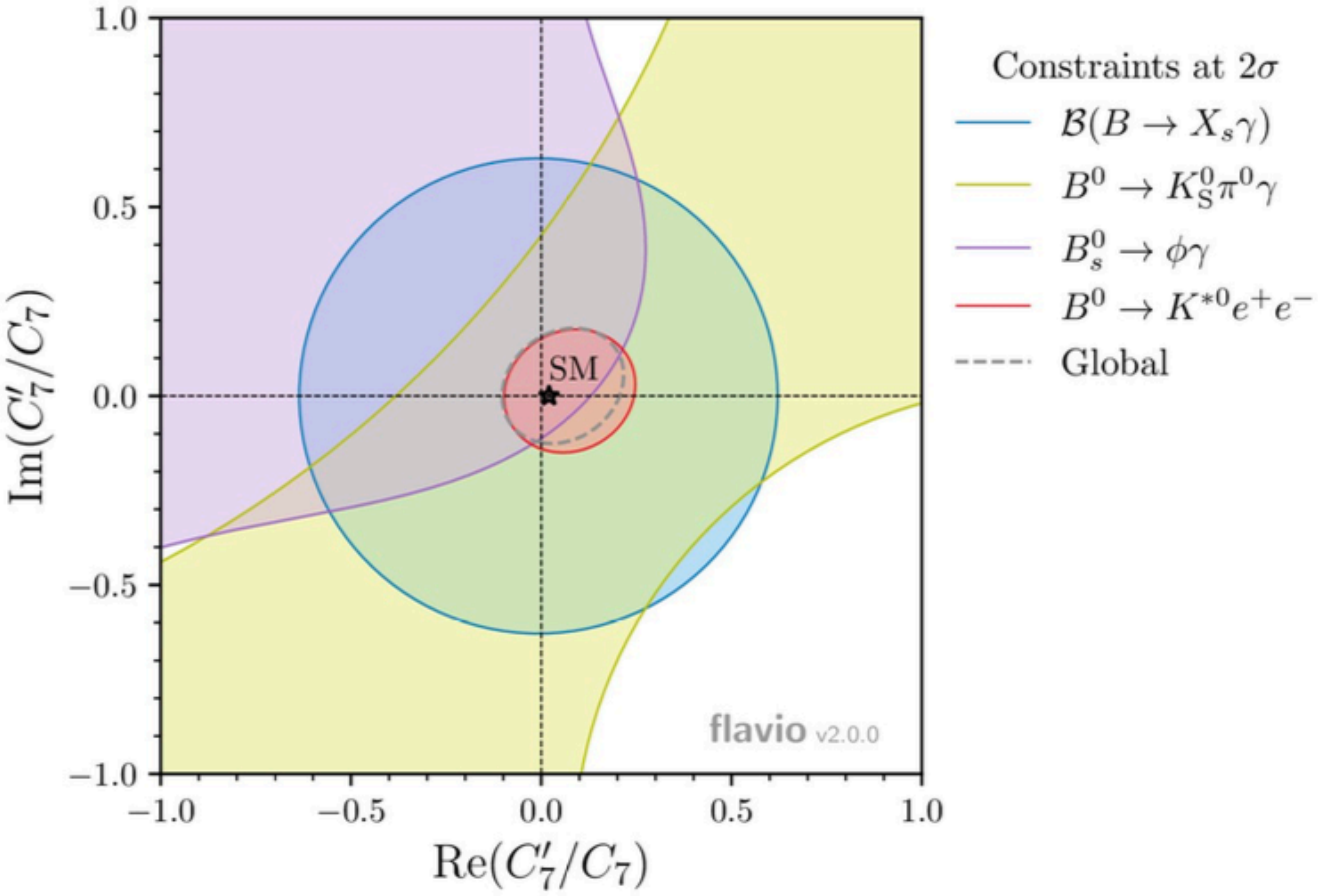


LHCb, PRL 123 (2019) 031801

A glimpse of what goes on here

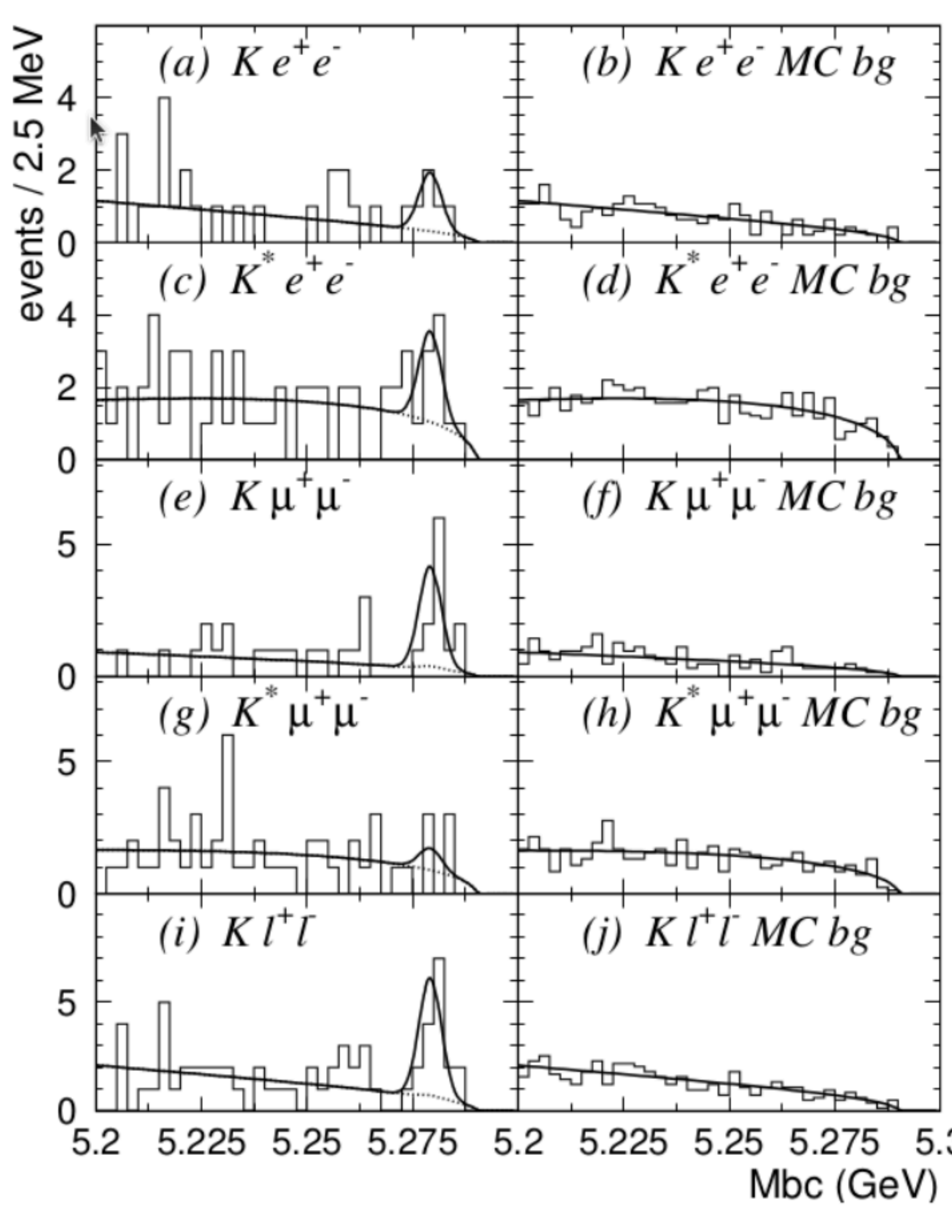
$B^0 \to K^{*0} e^+ e^-$
Very low q^2



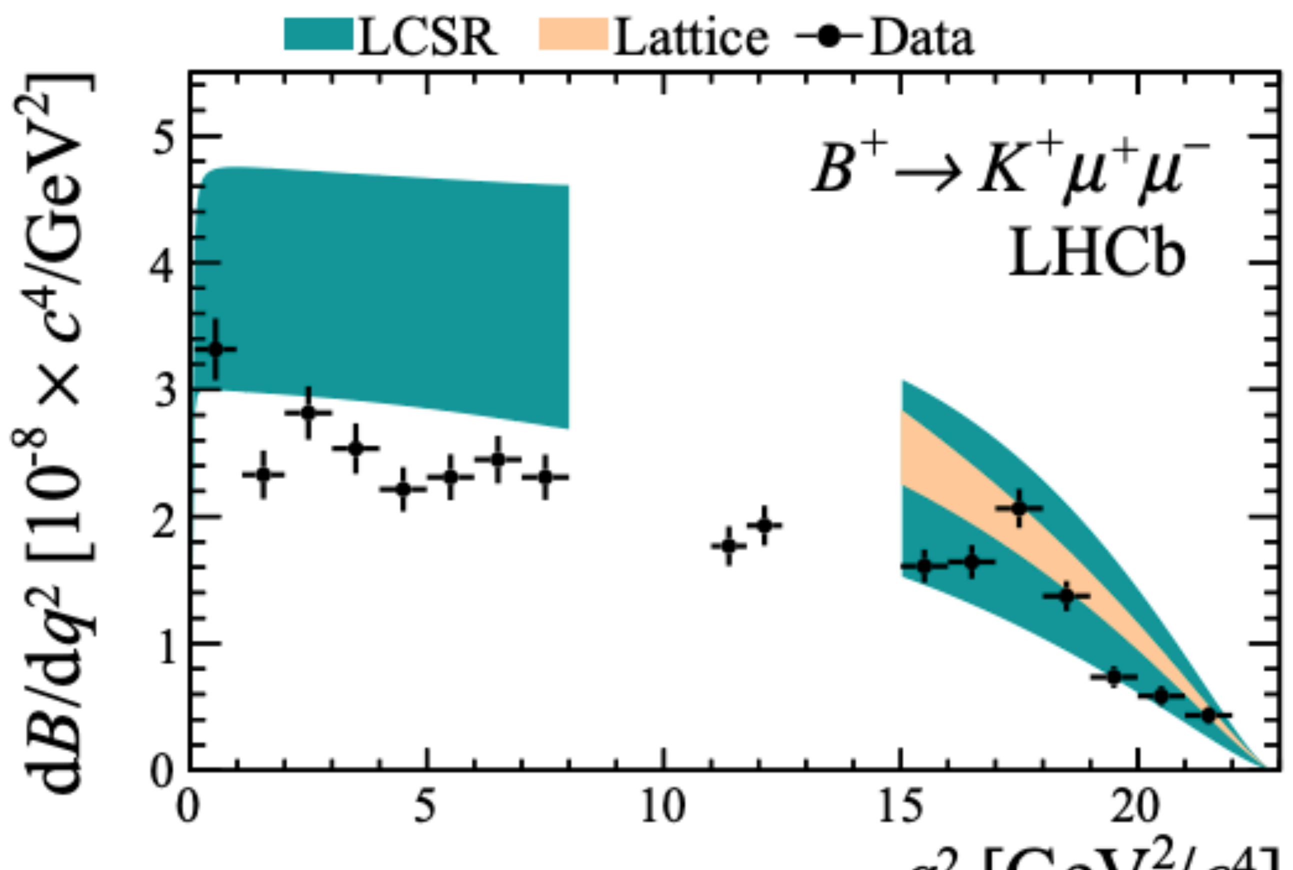


JHEP 12 (2020) 081

A collection of tensions



Belle, PRL 88 (2002) 021801



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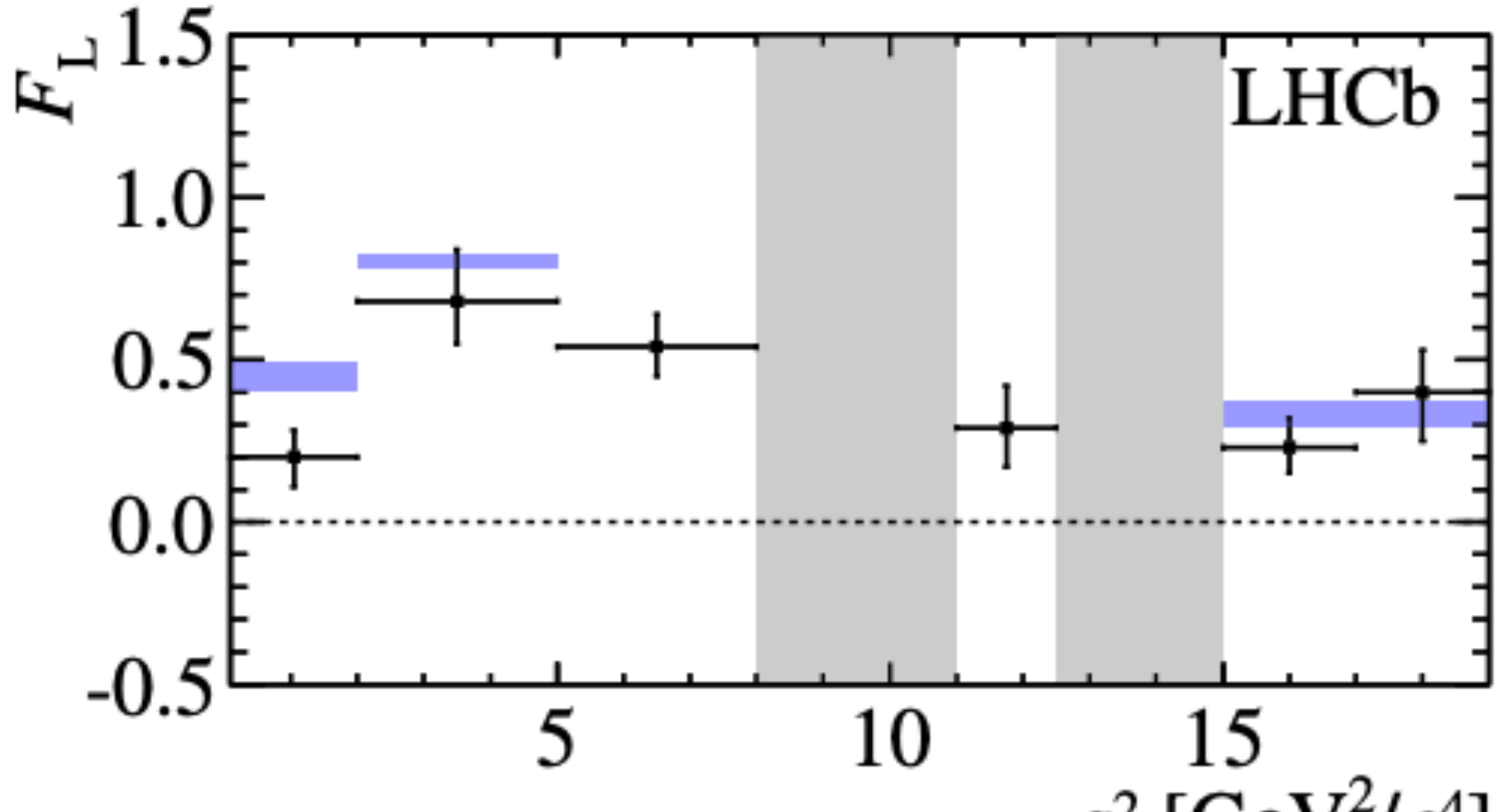

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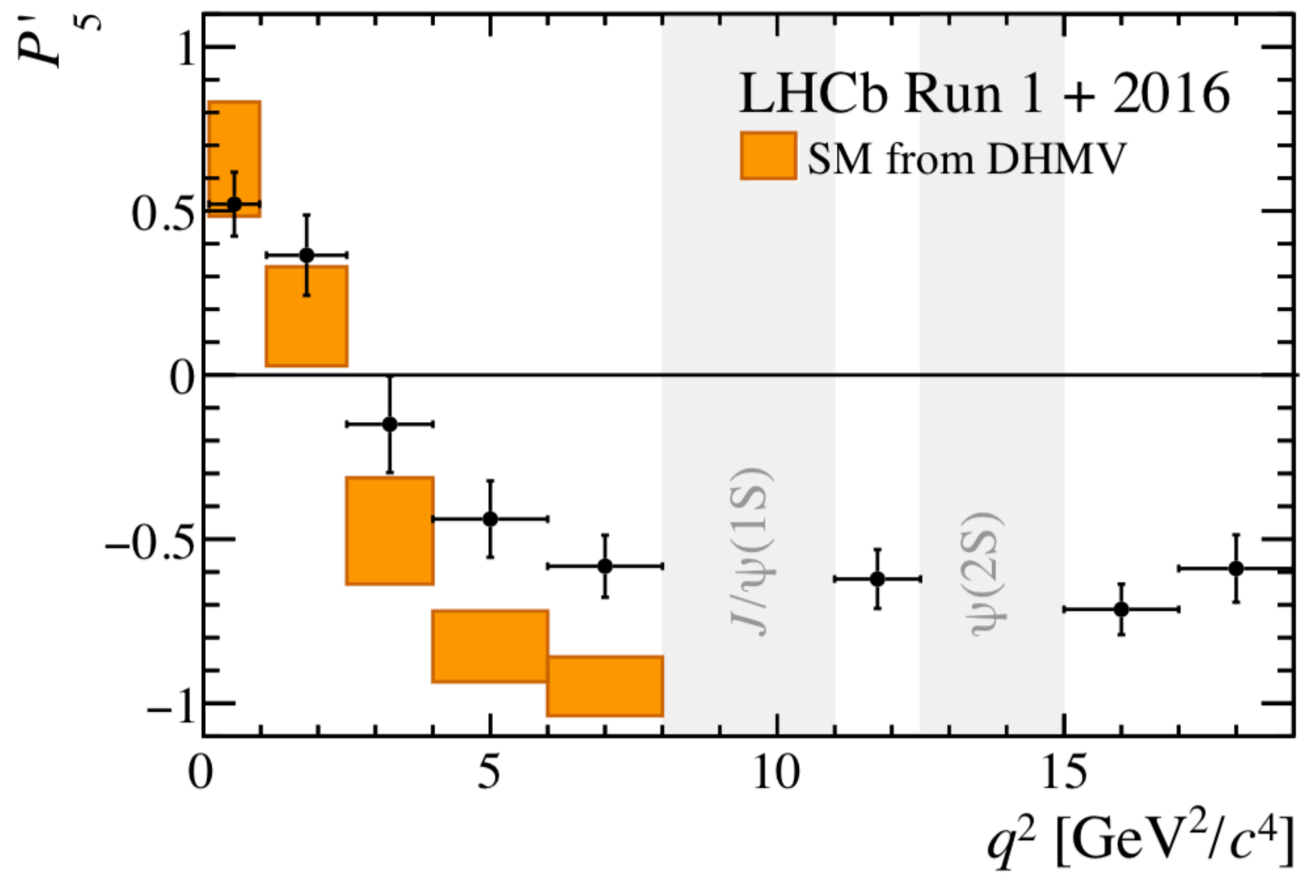

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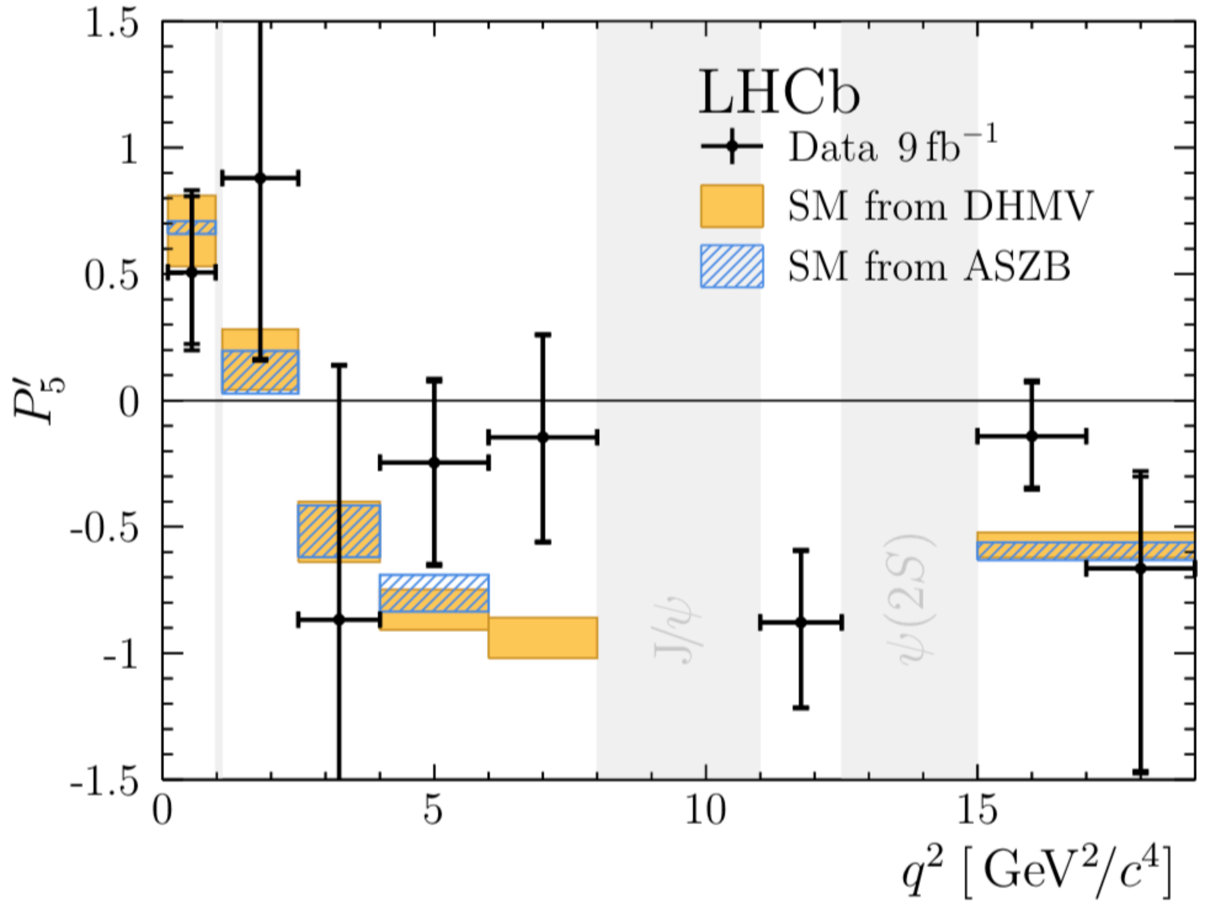
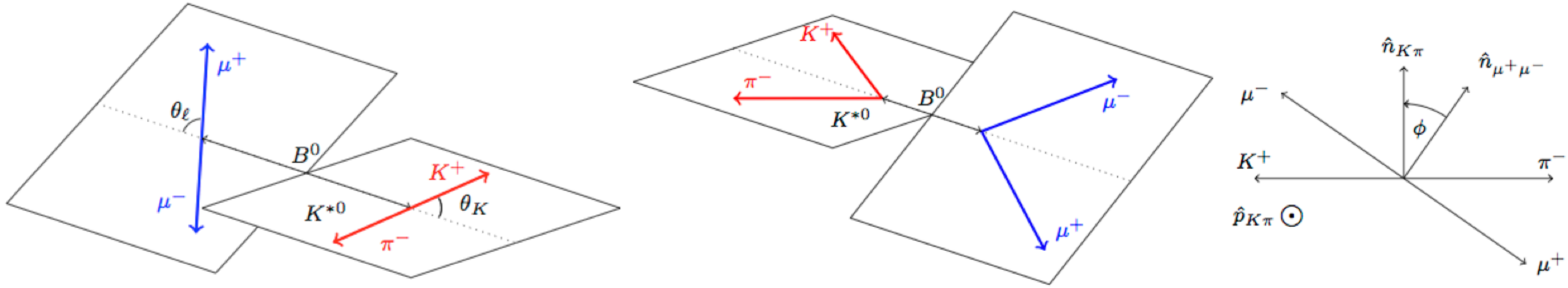


2012.13241

$d\Gamma/dq^2, F_L, P'_5, \ldots$

Large effort to develop optimised variables to cancel hadronic uncertainties from LD.

K*μμ the cool kid on the block



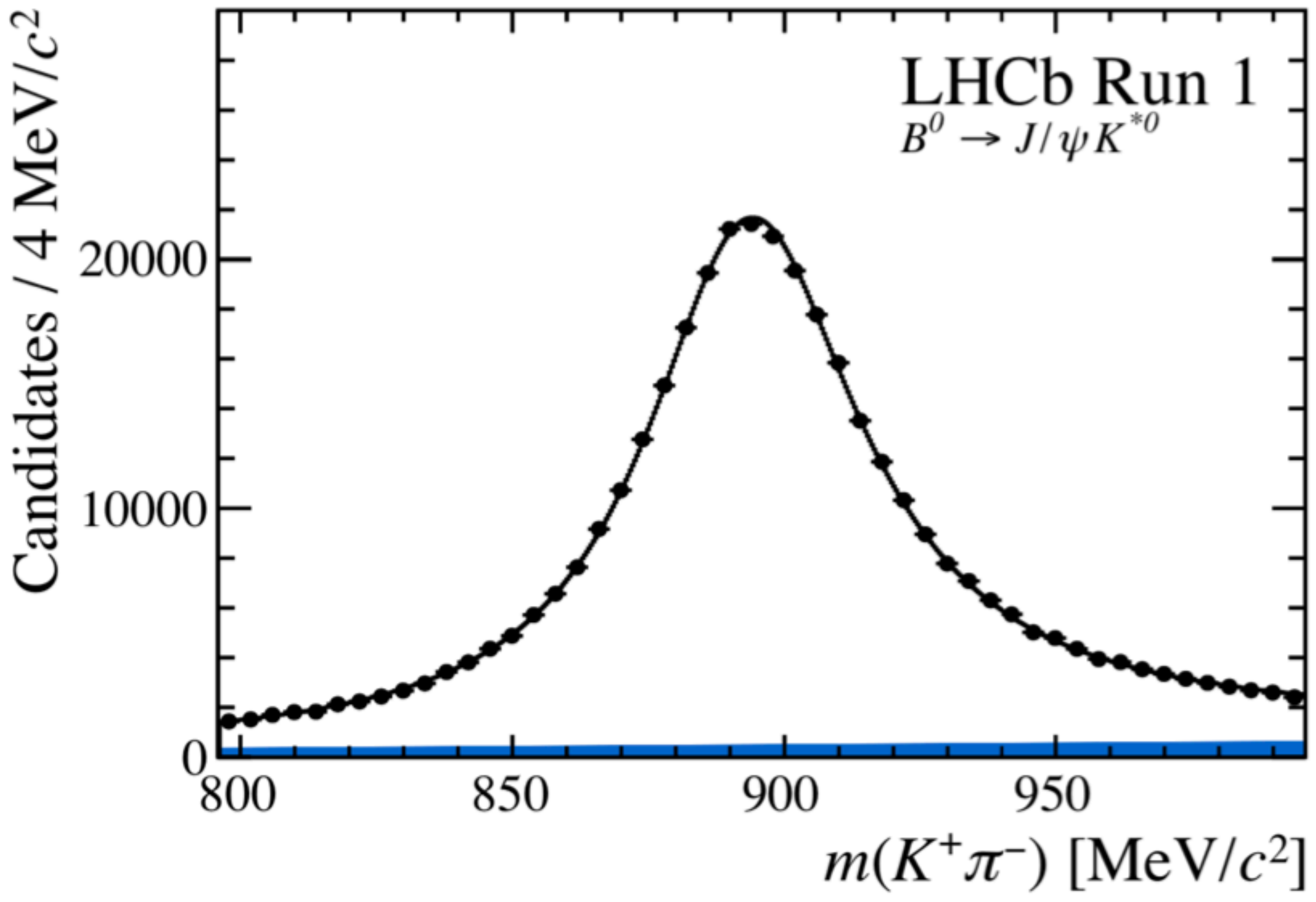
(a) θ_K and θ_ℓ definitions for the B^0 decay

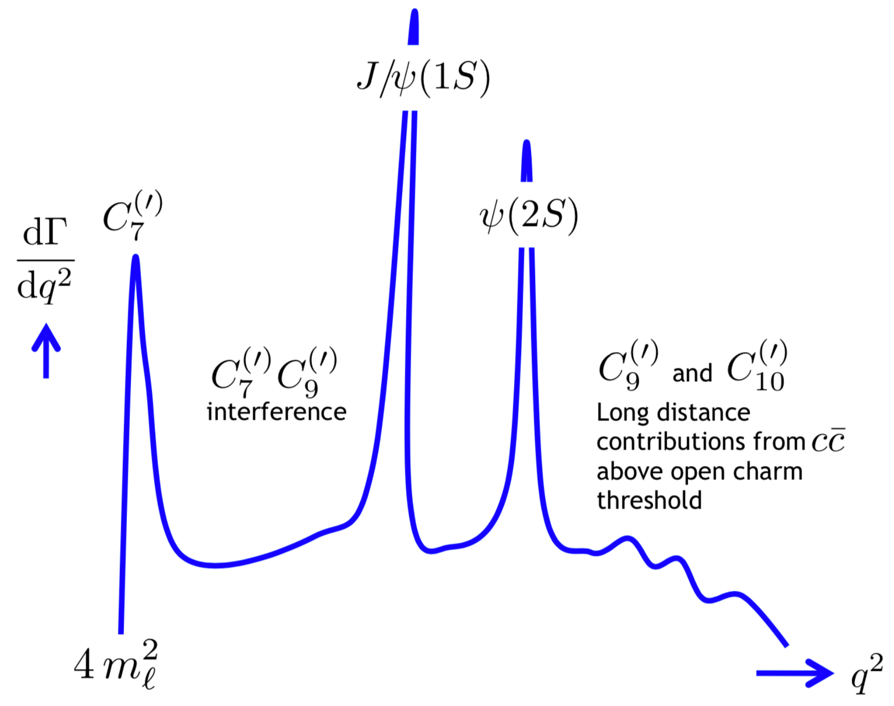
(b) ϕ definition for the B^0 decay

The helicity basis

The K* meson is a vector with spin 1: 3 polarisations

This allows for a rich angular structure





Narrow bins

Wide bins

Bin	q^2 range $[\mathrm{GeV}^2/c^4]$
1	$[0.1, 0.98]$
2	$[1.1, 2.5]$
3	$[2.5, 4.0]$
4	$[4.0, 6.0]$
5	$[6.0, 8.0]$
6	$[11.0, 12.5]$
7	$[15.0, 17.0]$
8	$[17.0, 19.0]$
9	$[1.1, 6.0]$
10	$[15.0, 19.0]$

$B^0 \to K^{*0}\phi(1020)(\to \mu^+\mu^-)$

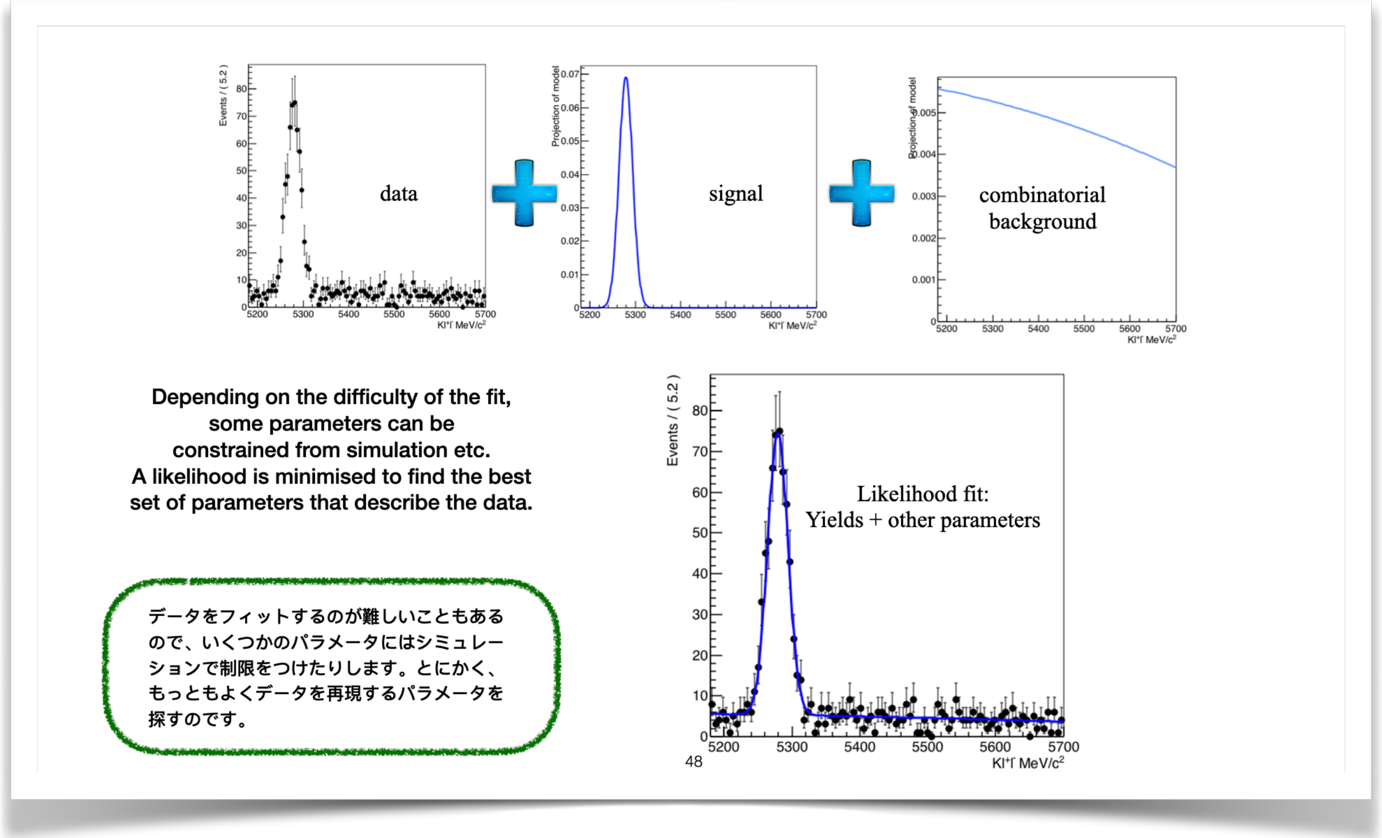
Control channel

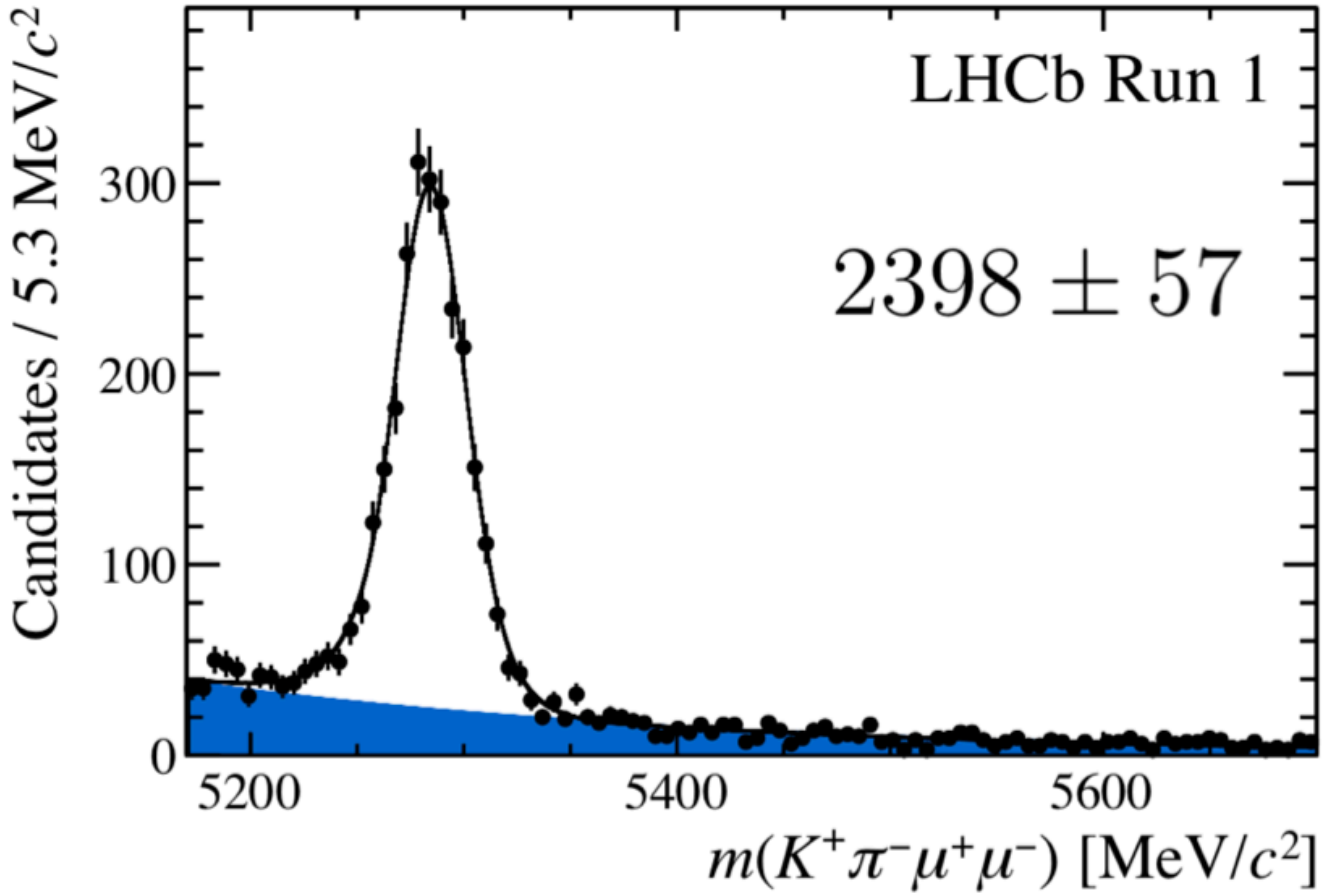
$[8.0, 11.0]$ GeV^2/c^4

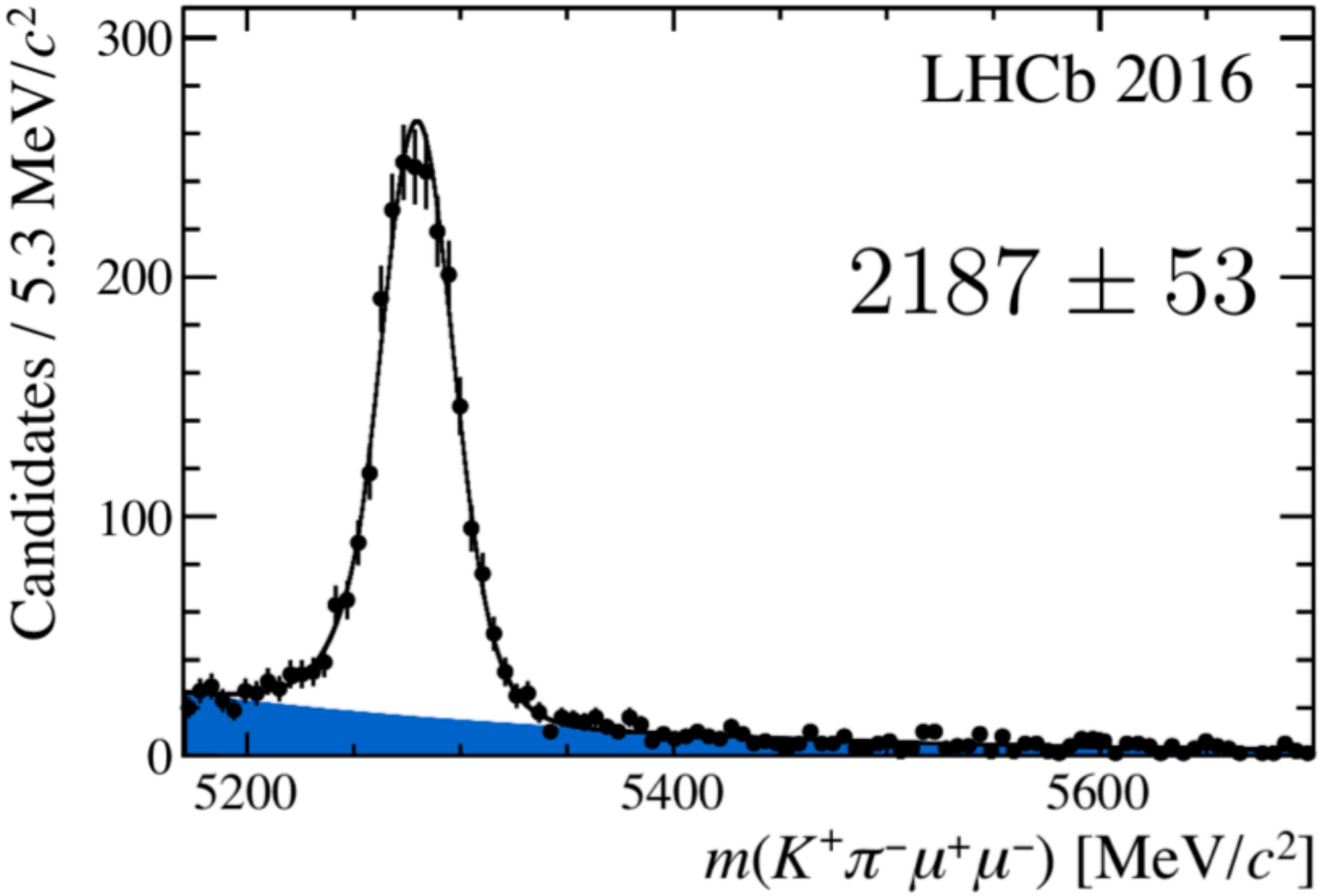
$B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-)$

$B^0 \to K^{*0}\psi(2S)(\to \mu^+\mu^-)$

The signal - it’s a very rare decay yes, but this is very clean.







$$\frac{d^4\Gamma[\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

angular coefficients angular functions

- Angular coefficients are combinations of the different K^{*0} amplitudes

i	$I_i(q^2)$	$f_i(\vec{\Omega})$
1s	$\frac{3}{4}\left[\lvert\mathcal{A}_\parallel^L\rvert^2 + \lvert\mathcal{A}_\perp^L\rvert^2 + \lvert\mathcal{A}_\parallel^R\rvert^2 + \lvert\mathcal{A}_\perp^R\rvert^2\right]$	$\sin^2\theta_K$
1c	$\lvert\mathcal{A}_0^L\rvert^2 + \lvert\mathcal{A}_0^R\rvert^2$	$\cos^2\theta_K$
2s	$\frac{1}{4}\left[\lvert\mathcal{A}_\parallel^L\rvert^2 + \lvert\mathcal{A}_\perp^L\rvert^2 + \lvert\mathcal{A}_\parallel^R\rvert^2 + \lvert\mathcal{A}_\perp^R\rvert^2\right]$	$\sin^2\theta_K \cos 2\theta_l$
2c	$-\lvert\mathcal{A}_0^L\rvert^2 - \lvert\mathcal{A}_0^R\rvert^2$	$\cos^2\theta_K \cos 2\theta_l$
3	$\frac{1}{2}\left[\lvert\mathcal{A}_\perp^L\rvert^2 - \lvert\mathcal{A}_\parallel^L\rvert^2 + \lvert\mathcal{A}_\perp^R\rvert^2 - \lvert\mathcal{A}_\parallel^R\rvert^2\right]$	$\sin^2\theta_K \sin^2\theta_l \cos 2\phi$

The number of amplitudes will depend on the spin structure

- The K^{*0} **amplitudes** are in turn dependent on **Wilson coefficients** and **form factors (non-perturbative QCD)**

$$\mathcal{A}_{\perp}^{\mathrm{L(R)}} = \mathcal{N}\sqrt{2}\lambda\left\{\left[(C_9^{\mathrm{eff}} + C_9^{\prime\mathrm{eff}}) \mp (C_{10}^{\mathrm{eff}} + C_{10}^{\prime\mathrm{eff}})\right]\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\mathrm{eff}} + C_7^{\prime\mathrm{eff}})T_1(q^2)\right\}$$

$$\mathcal{A}_{\parallel}^{\mathrm{L(R)}} = -\mathcal{N}\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(C_9^{\mathrm{eff}} - C_9^{\prime\mathrm{eff}}) \mp (C_{10}^{\mathrm{eff}} - C_{10}^{\prime\mathrm{eff}})\right]\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\mathrm{eff}} - C_7^{\prime\mathrm{eff}})T_2(q^2)\right\}$$

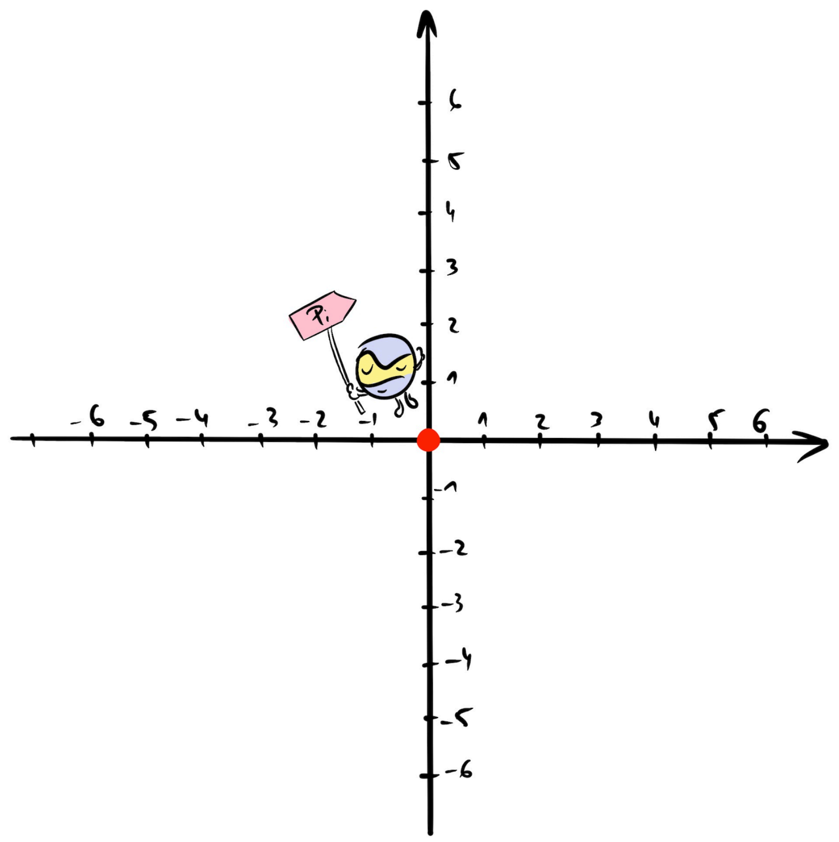
$$\mathcal{A}_{0}^{\mathrm{L(R)}} = -\frac{\mathcal{N}}{2m_{K^*}\sqrt{q^2}}\left\{\left[(C_9^{\mathrm{eff}} - C_9^{\prime\mathrm{eff}}) \mp (C_{10}^{\mathrm{eff}} - C_{10}^{\prime\mathrm{eff}})\right] \times \left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})A_1(q^2) - \lambda\frac{A_2(q^2)}{m_B + m_{K^*}}\right] + 2m_b(C_7^{\mathrm{eff}} - C_7^{\prime\mathrm{eff}})\left[(m_B^2 + 3m_{K^*} - q^2)T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2}T_3(q^2)\right]\right\}$$

JHEP 0901:019,2009

We meet again our favorite Wilson coefficients and form factors

But how do we relate the amplitude with what we fit in the data ?

First we have to pick a basis



For this decay we encounter often two the S_i basis and the P_i basis.

For the curious there a number of pheno packages where the amplitudes are already coded if you want to play with them Flavio, EOS, et al.

S_i **basis** *8 CP-averaged observables are extracted from the fit*

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{dcos}\theta_l\,\mathrm{dcos}\theta_K\,\mathrm{d}\phi}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K + \boxed{F_{\mathrm{L}}}\cos^2\theta_K + \tfrac{1}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K\cos 2\theta_l - \boxed{F_{\mathrm{L}}}\cos^2\theta_K\cos 2\theta_l + \boxed{S_3}\sin^2\theta_K\sin^2\theta_l\cos 2\phi + \boxed{S_4}\sin 2\theta_K\sin 2\theta_l\cos\phi + \boxed{S_5}\sin 2\theta_K\sin\theta_l\cos\phi + \tfrac{4}{3}\boxed{A_{\mathrm{FB}}}\sin^2\theta_K\cos\theta_l + \boxed{S_7}\sin 2\theta_K\sin\theta_l\sin\phi + \boxed{S_8}\sin 2\theta_K\sin 2\theta_l\sin\phi + \boxed{S_9}\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]. \quad (29)$$

F_L :fraction of longitudinal polarisation of the K^{*0}

A_{FB} :forward-backward asymmetry of dimuon system

$P_i^{(\prime)}$ **basis**

Reparameterise the fit to obtain optimised observables:

form factor uncertainties cancel at first order

JHEP 12 (2014) 125, JHEP 09 (2010) 089

7 CP-averaged observables are extracted from the fit (+F_L)

Extracted by reparametrising the fit PDF in this basis

$$\frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$$

$$P_1 = \frac{2\,S_3}{(1-F_{\rm L})} = A_{\rm T}^{(2)}$$

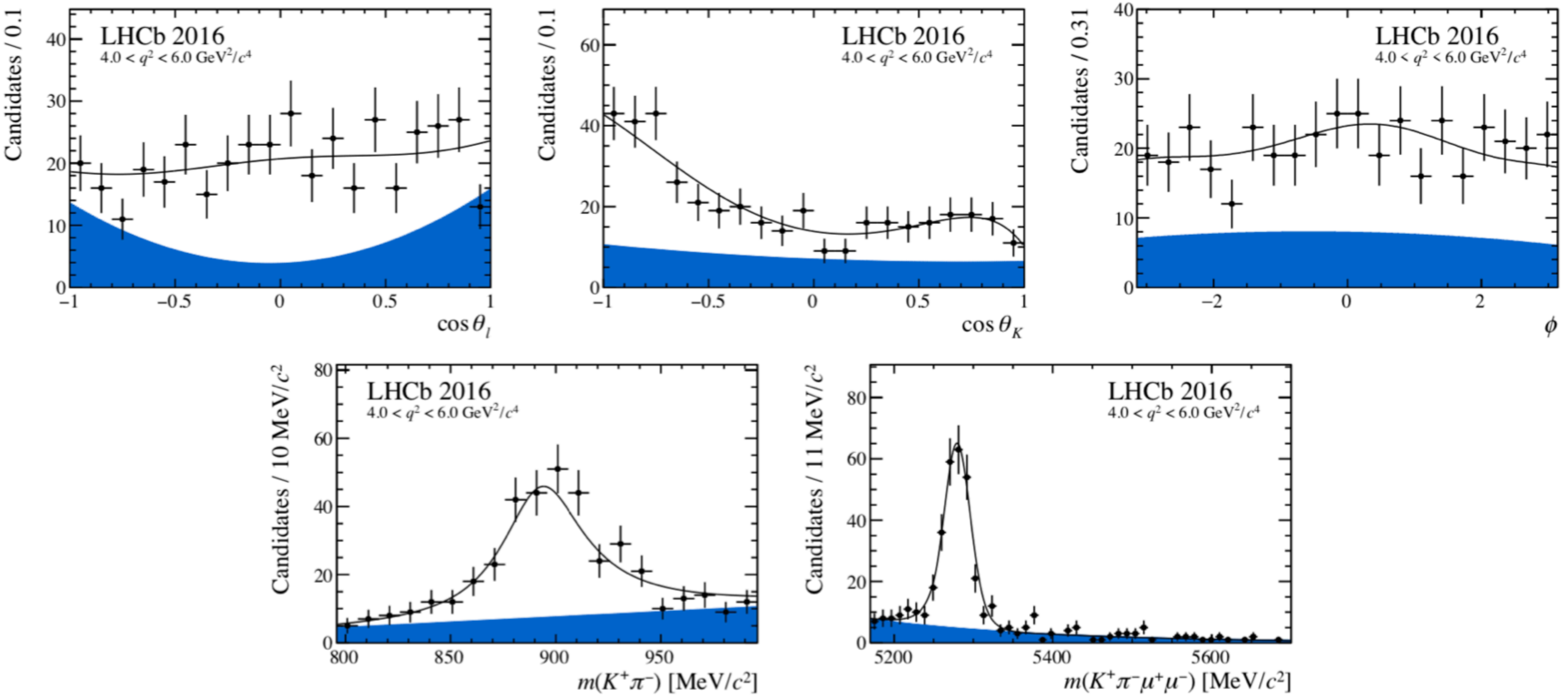
$$P_2 = \frac{2}{3}\frac{A_{\rm FB}}{(1-F_{\rm L})},$$

$$P_3 = \frac{-S_9}{(1-F_{\rm L})},$$

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}},$$

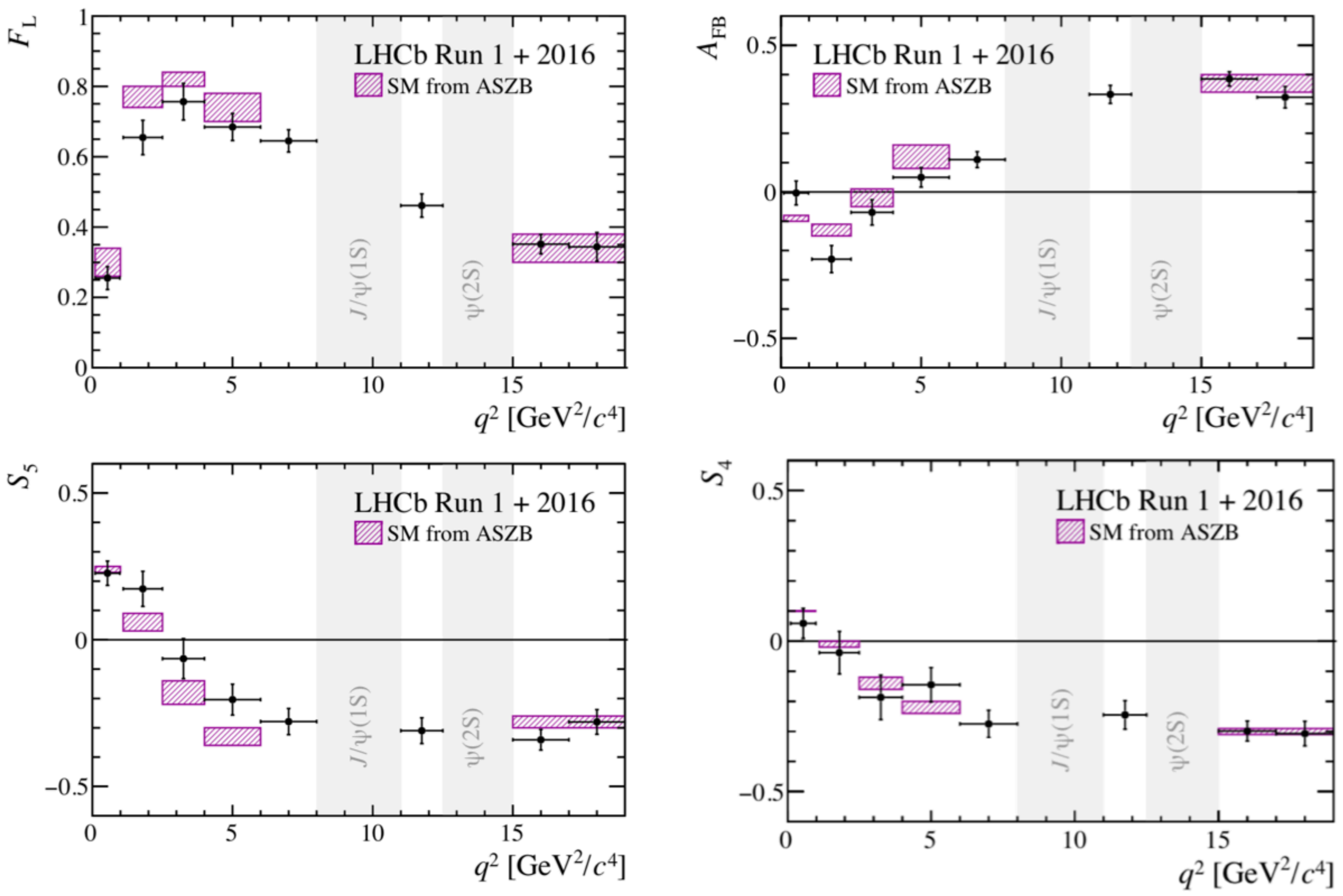
$$P'_6 = \frac{S_7}{\sqrt{F_{\rm L}(1-F_{\rm L})}}.$$

Fast forward to the results skipping all the lovely details about angular acceptance, simulation reweighing, systematic uncertainties, statistical coverage etc.



Fit projections for the bin $4.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$ for 2016 data

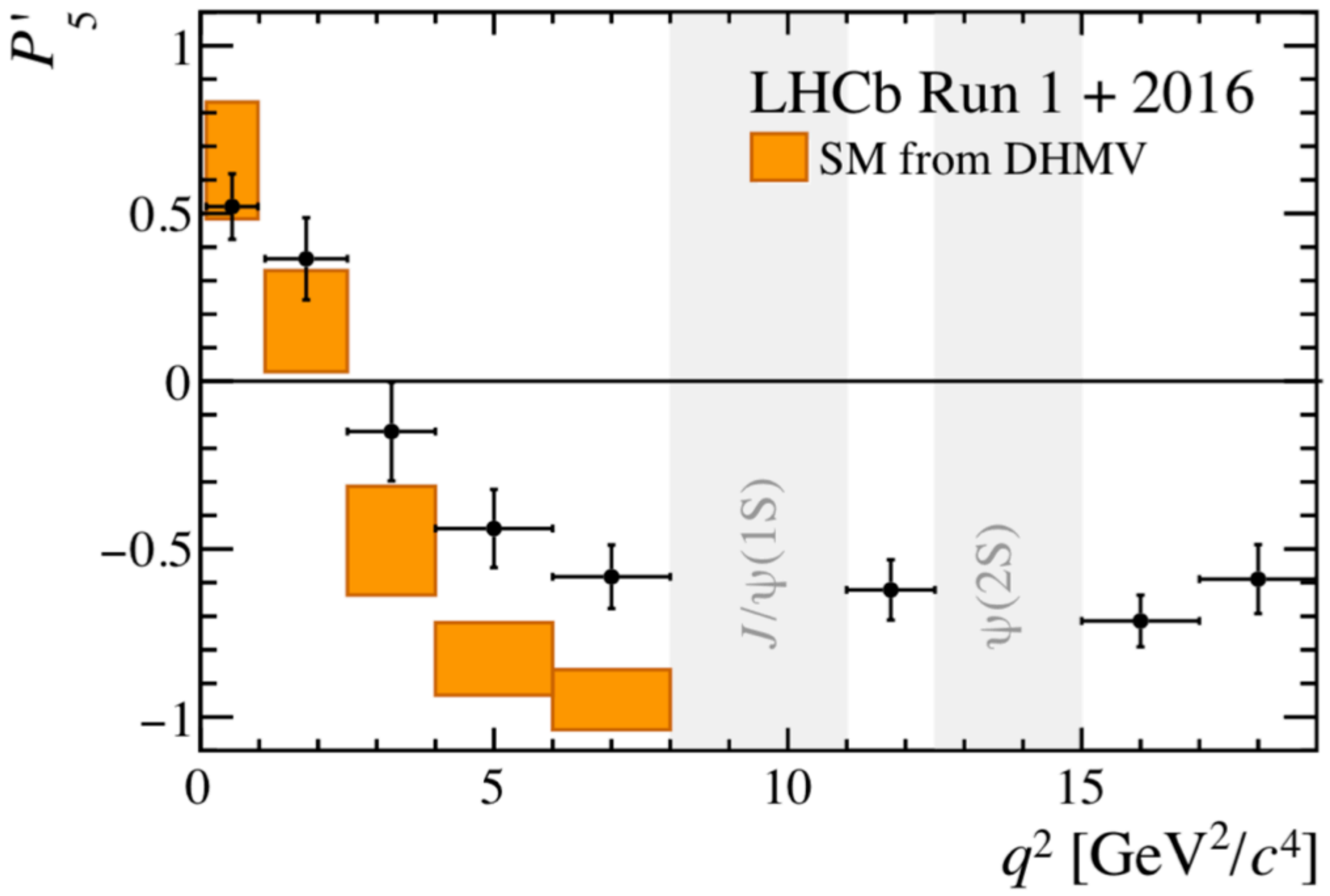
Some example of the results



Theory predictions from JHEP 08 (2016) 098 , Eur. Phys. J. C75 (2015) 382

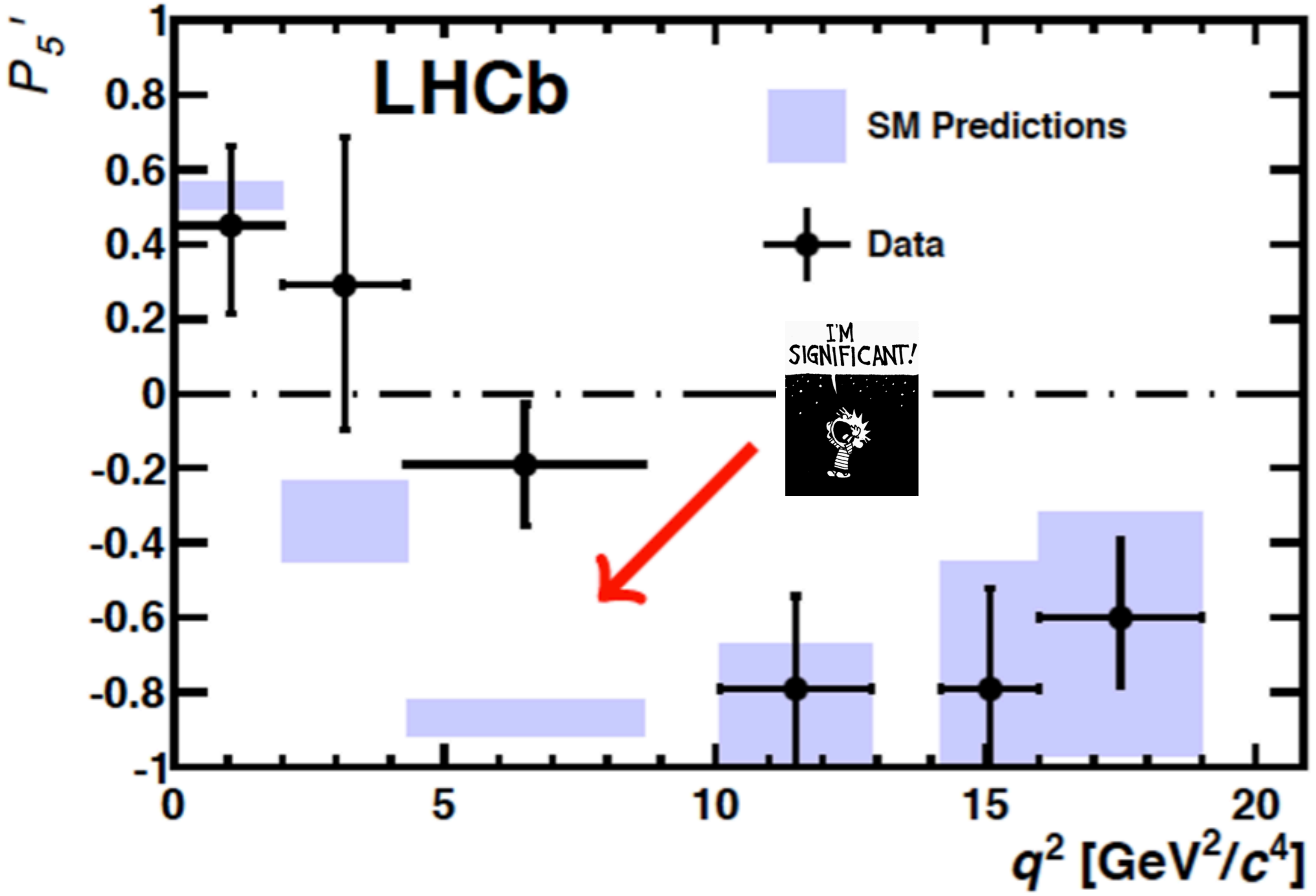
,

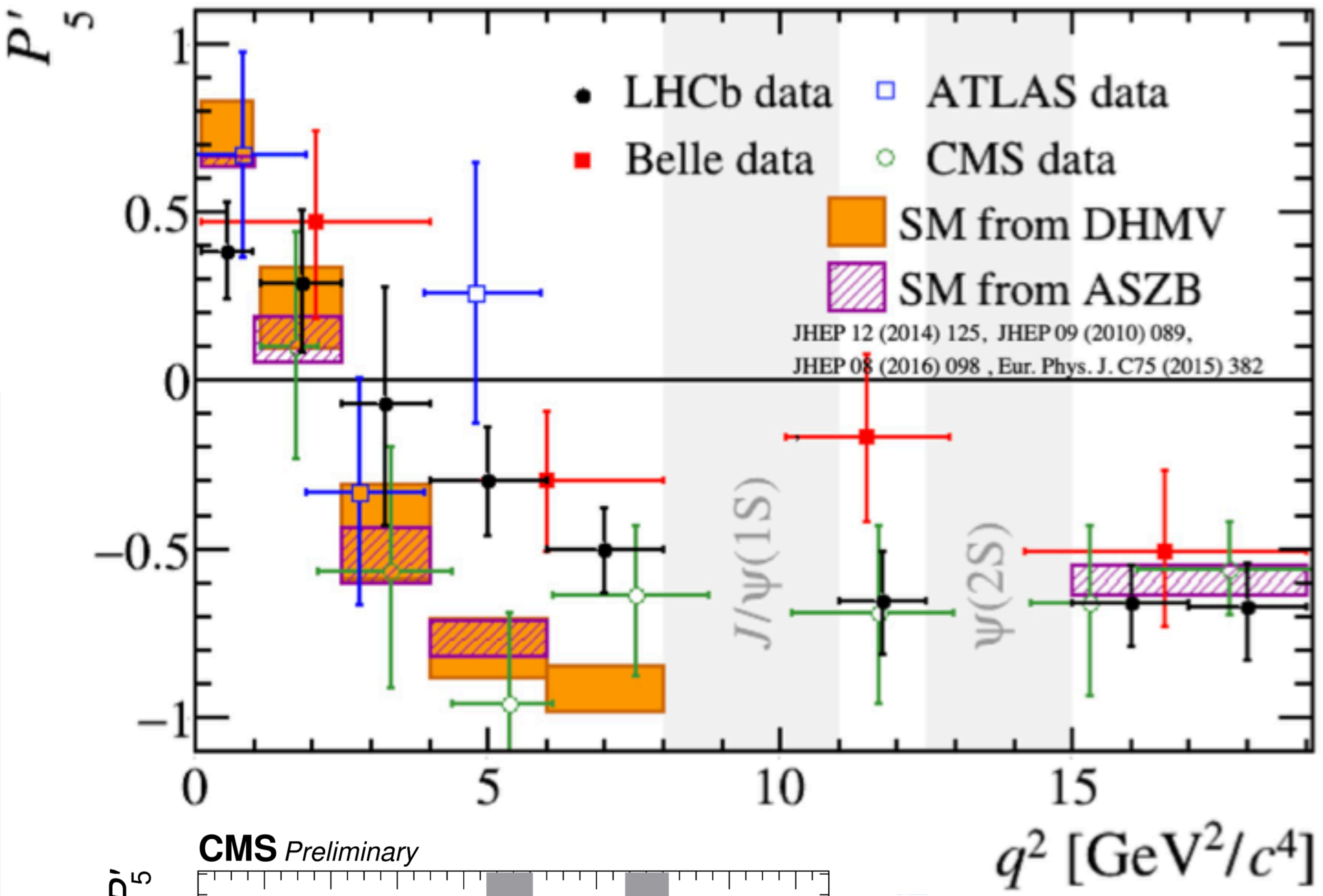
One the guiltiest plots in the B anomalies saga

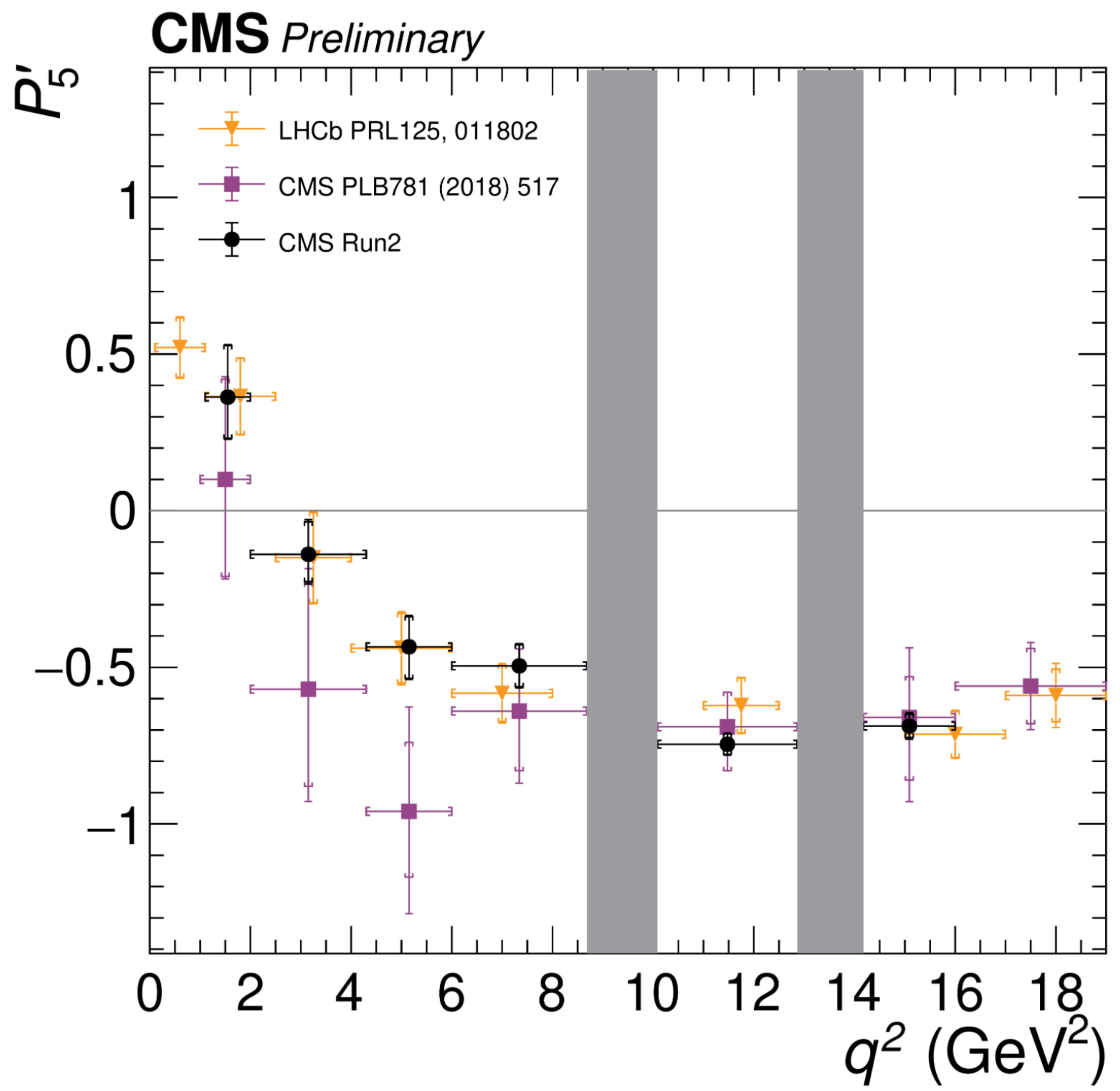


Often many discussion about the predictions, you may have heard of the words Non factorable charm loops

Patience often required…

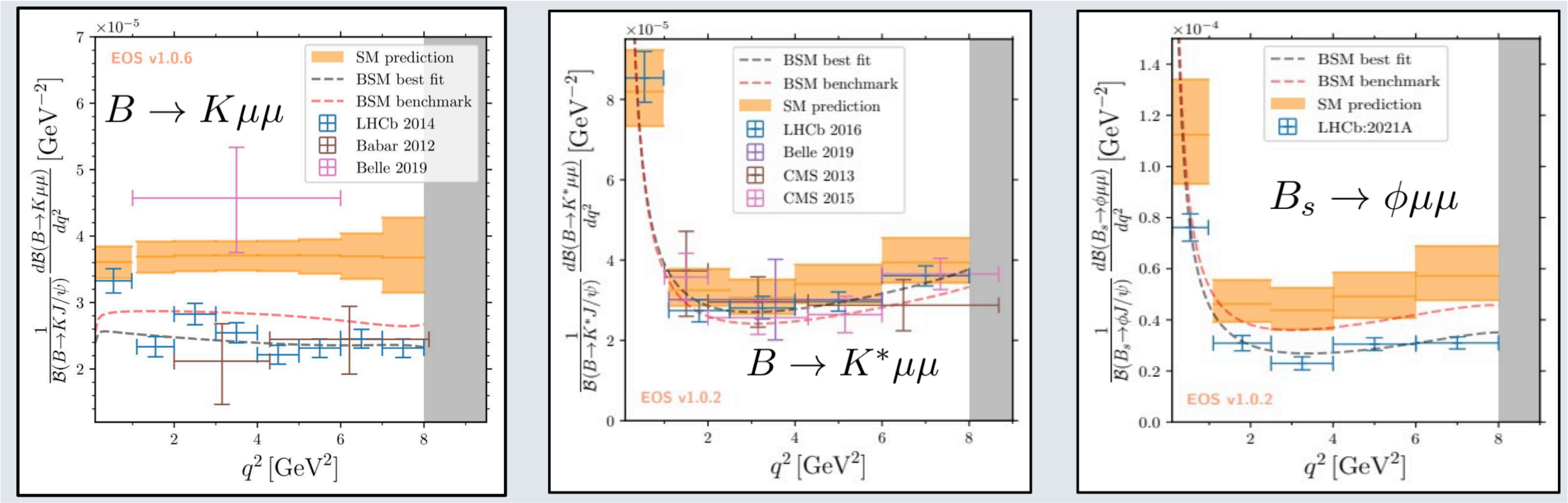






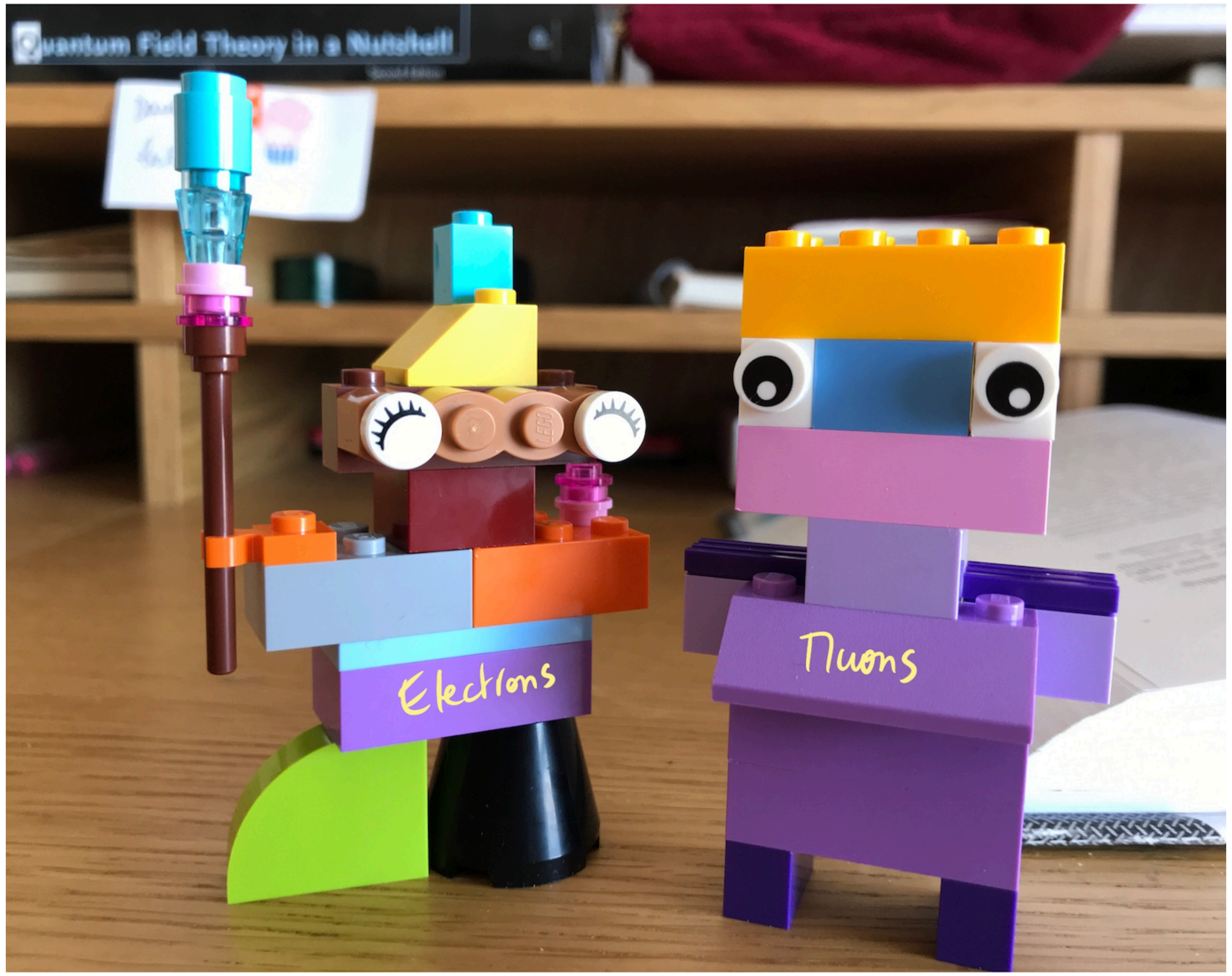
A couple of words

- Explore also other B systems.
- Continue the work on the theory predictions.
- One things which would be interesting is to measure this also with electrons.



Méril's talk

The idea behind a lepton universality test



Are we the same?

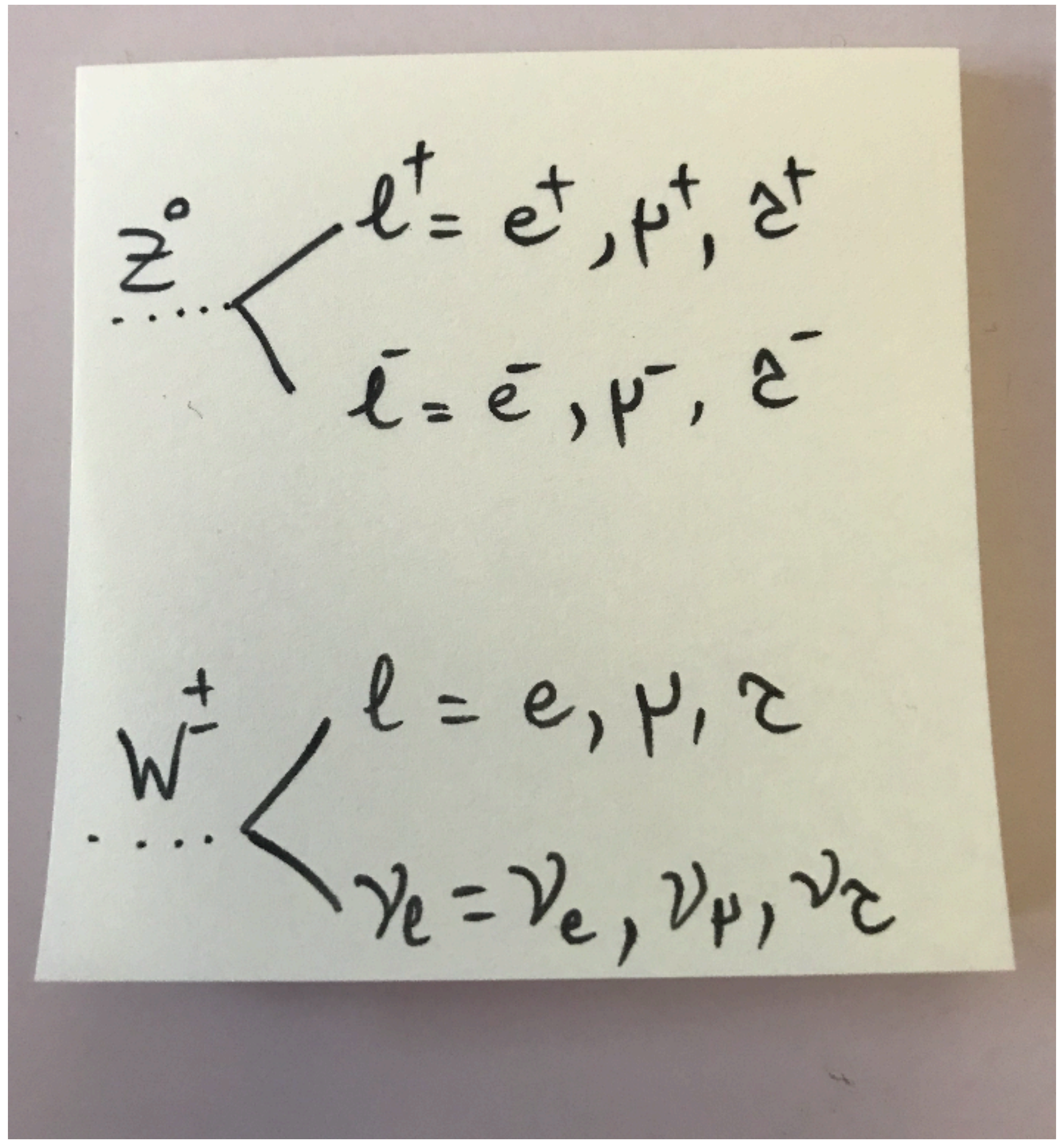
It's very simple
we expect the coupling to the leptons
to be the same

これはシンプル。

レプトンとの結合はどれも同じだと期待できます。
それをテストしてみようというわけです。

Lepton Universality tests

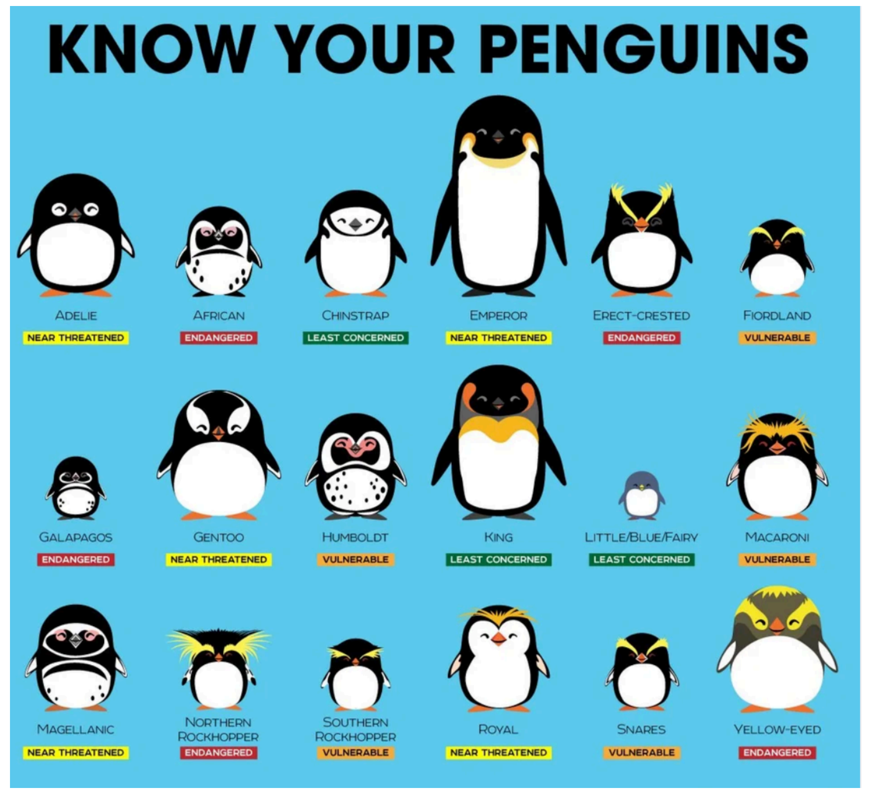
レプトン普遍性のテスト

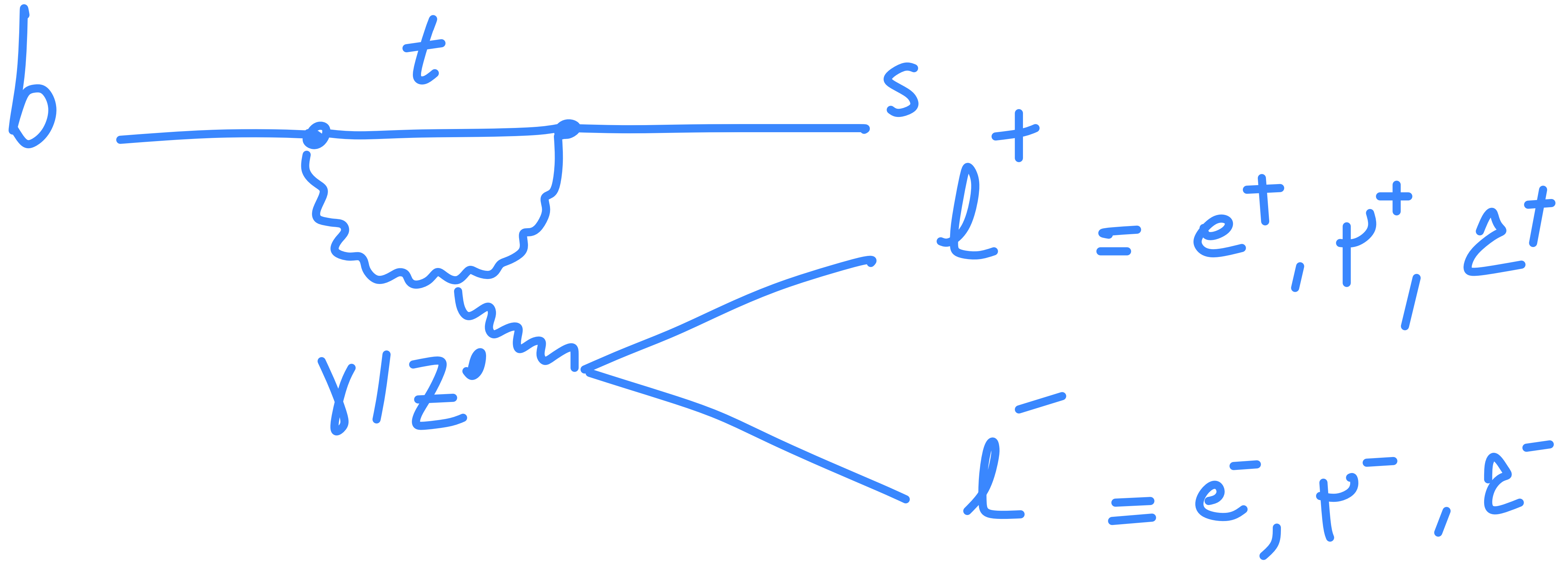


From the PDG or equivalent :

$$\frac{\Gamma_{Z\to\mu^+\mu^-}}{\Gamma_{Z\to e^+e^-}} = 1.0009 \pm 0.0028\,,$$

$$\frac{\Gamma_{Z\to\tau^+\tau^-}}{\Gamma_{Z\to e^+e^-}} = 1.0019 \pm 0.0032\,.$$





$$R = \frac{\#\,\text{muons}}{\#\,\text{electrons}}$$

“The” observable

$$R_H \equiv \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2},$$

A powerful probe to look for NP in an indirect way.

Today, we discuss three papers: 1705.05802, 1903.09252, 2103.11769

The "Simplicity" of Lepton Universality test

Loop induced

$$R_H \equiv \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2}\, dq^2},$$

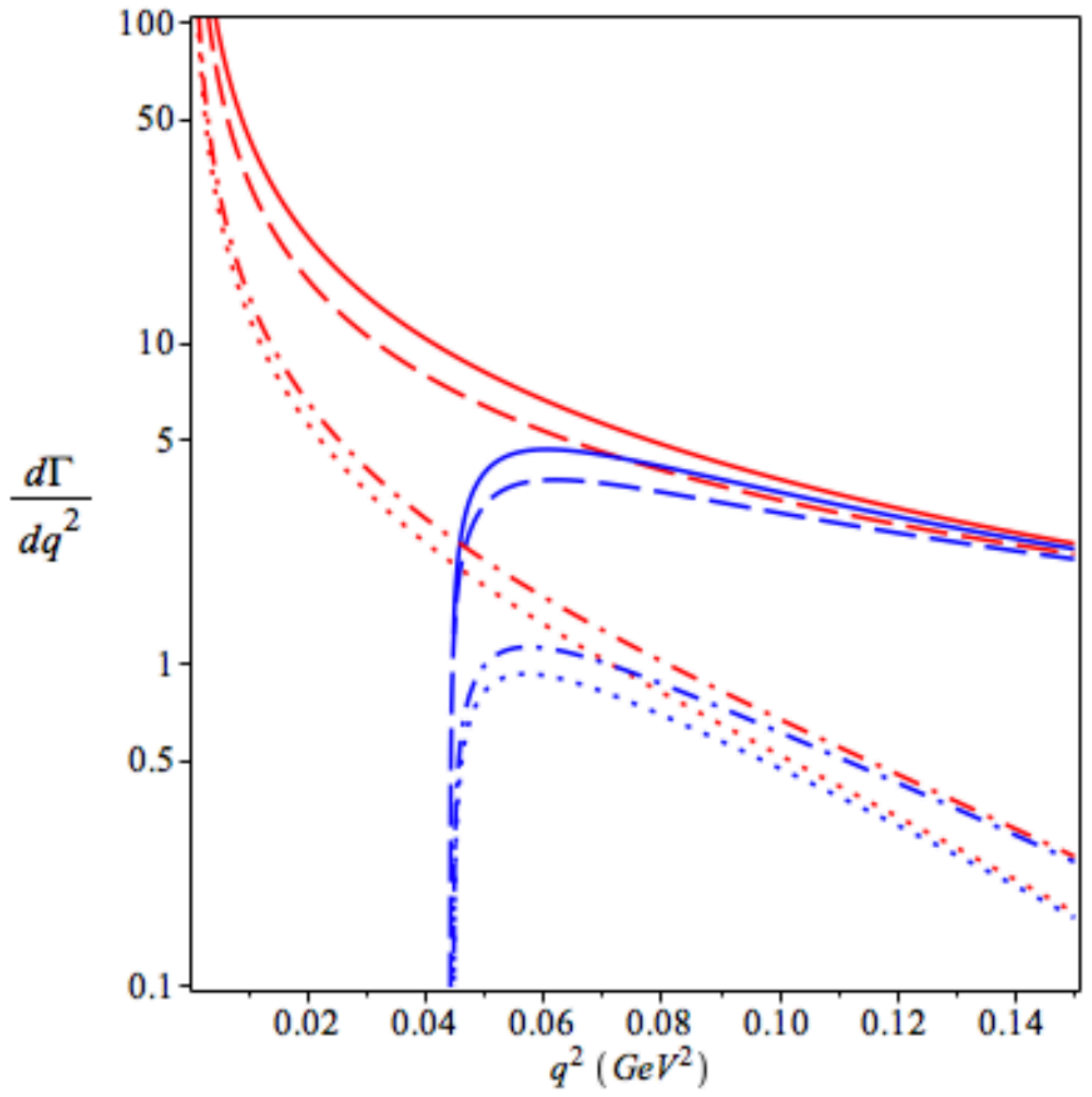
Similar observables in charged currents

$$R_{D^*}^{(\tau/\mu)}[q^2_{\rm min}] = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^*\tau\bar{\nu})}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^*\mu\bar{\nu})}$$

Tree level

What can we expect in the SM

1605.07633



$$R_{K^*}[1.1,\ 6.0]^{\mathrm{SM}} = 1.00 \pm 0.01_{\mathrm{QED}}$$

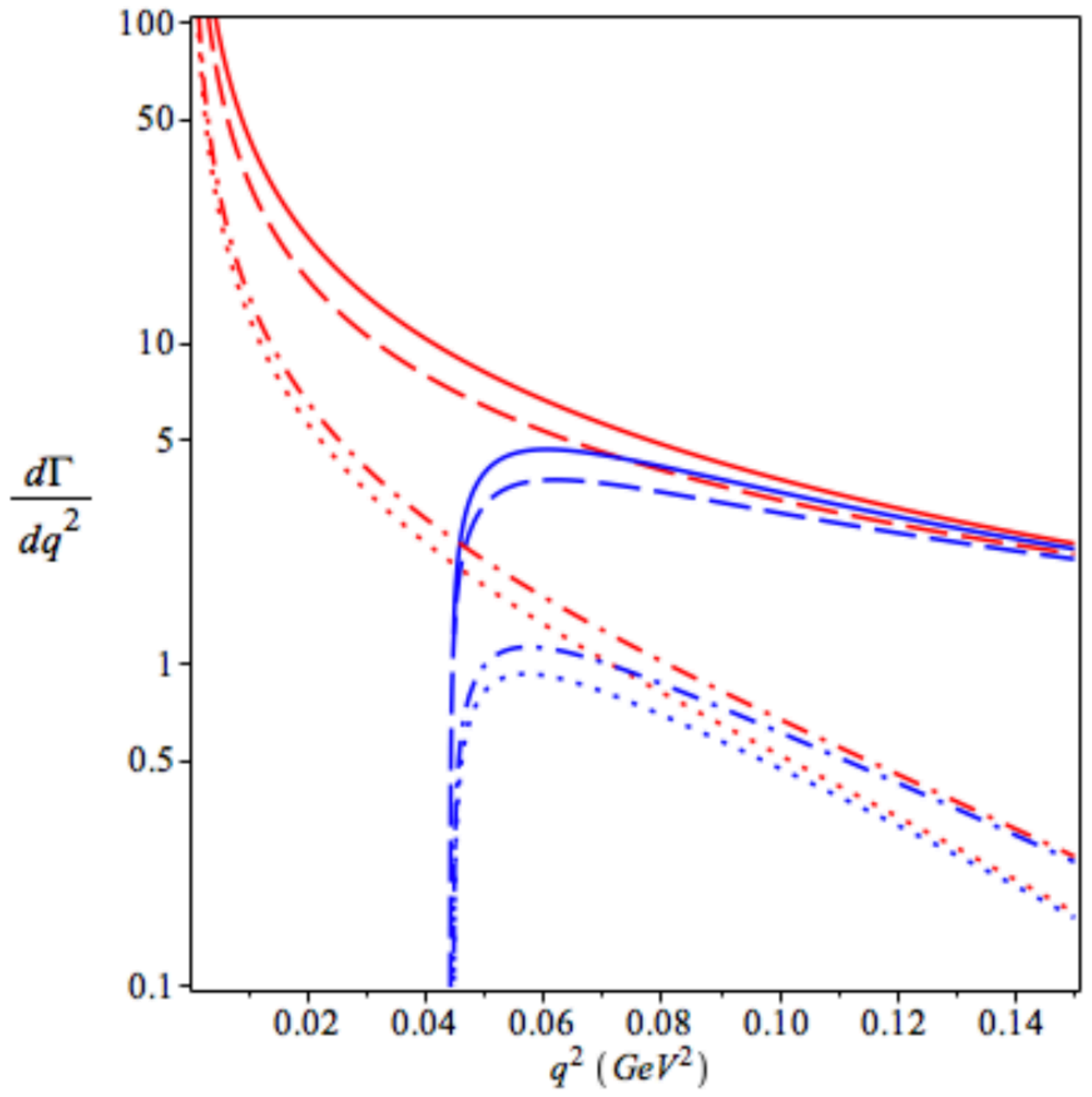
$$R_{K^+}[1.0,\ 6.0]^{\mathrm{SM}} = 1.00 \pm 0.01_{\mathrm{QED}}$$

Assuming V-A currents

$$R_\phi(B_s) \approx R_{\pi K}(B) \approx R(\Lambda_b)_\Lambda \approx R(\Lambda_b)_{pK} \approx \ldots \approx R_K$$

1909.02519

What can we expect in the SM



$$R_{K^*}[1.1,\ 6.0]^{\mathrm{SM}} = 1.00 \pm 0.01_{\mathrm{QED}}$$

$$R_{K^+}[1.0,\ 6.0]^{\mathrm{SM}} = 1.00 \pm 0.01_{\mathrm{QED}}$$

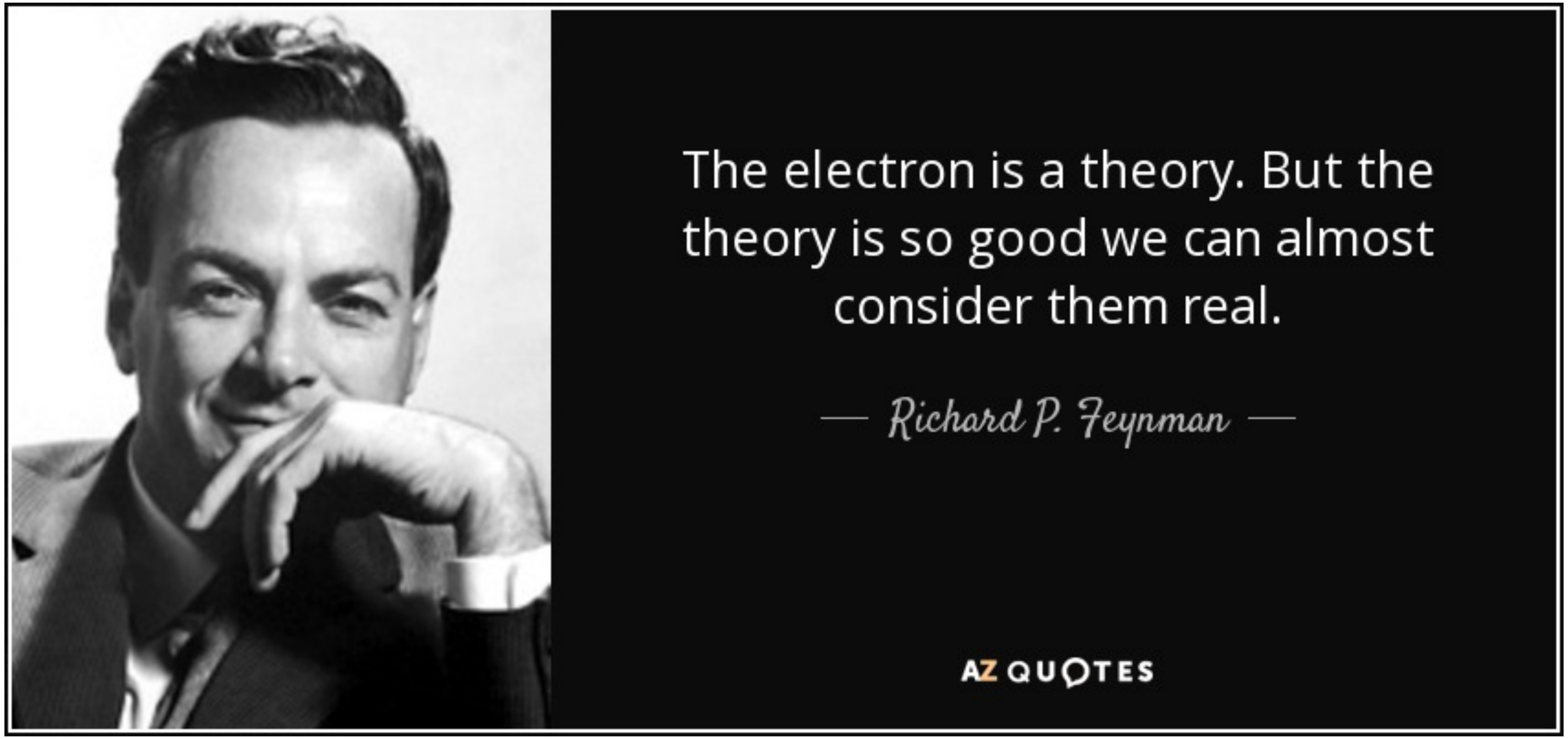
$$R_\phi(B_s) \approx R_{\pi K}(B) \approx R(\Lambda_b)_\Lambda \approx R(\Lambda_b)_{pK} \approx \ldots \approx R_K$$

1605.07633

1909.02519

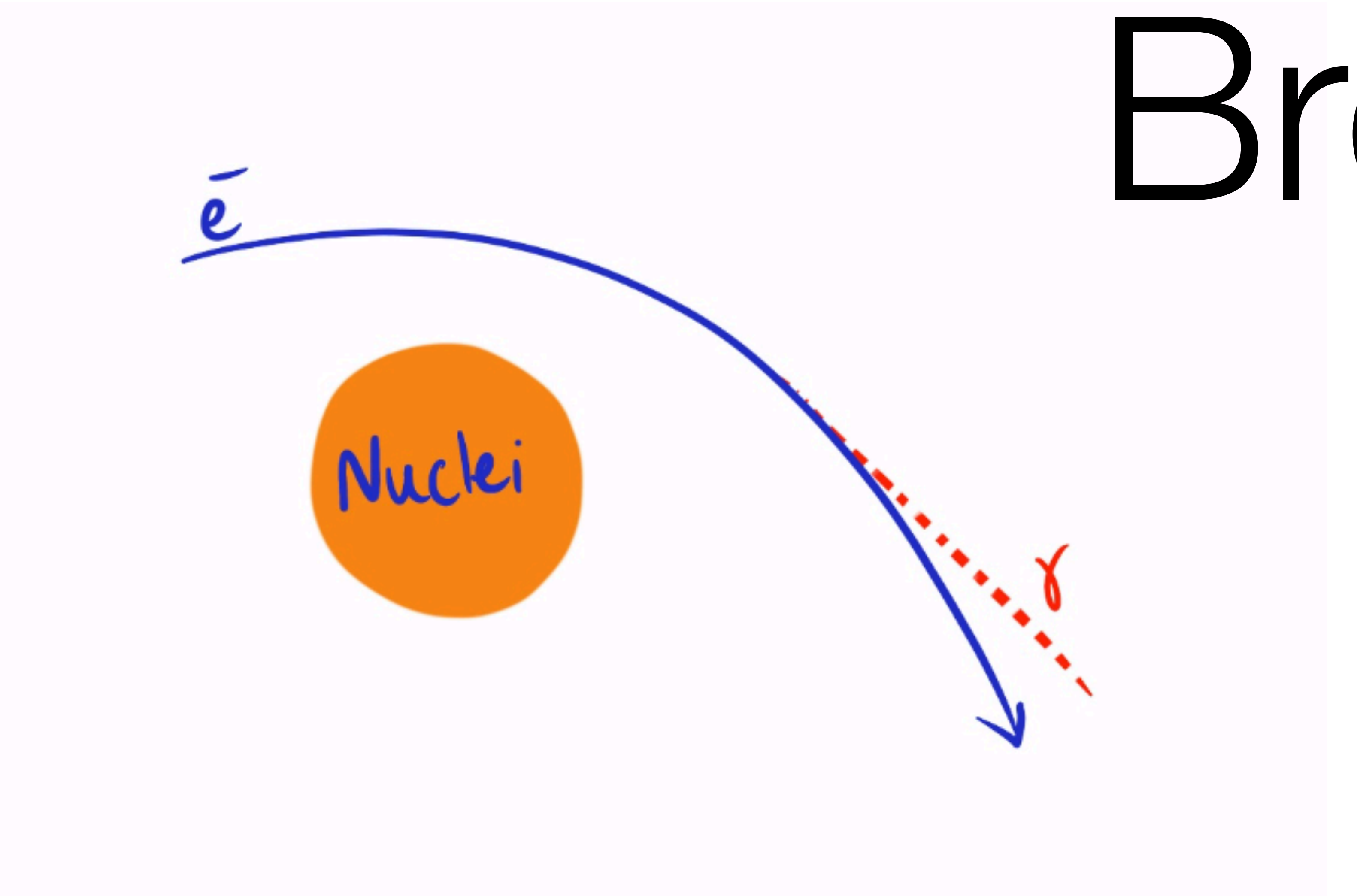
https://indico.in2p3.fr/event/18845/

Why are electrons difficult ?



I am not sure this is the answer we are looking for

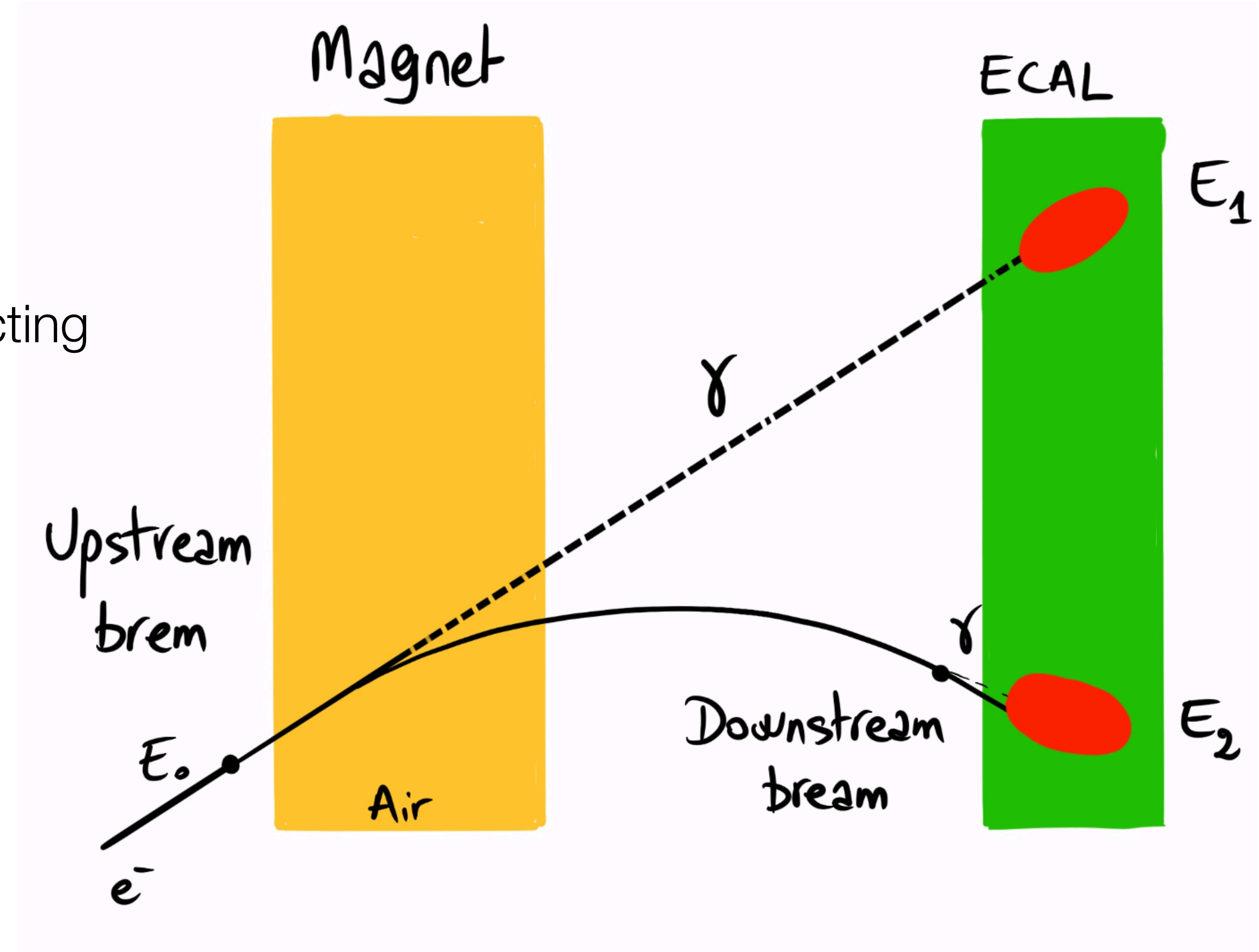
Bremsstrahlung



$\sigma \propto 1/m_l^2$
Energy loss $\propto$ E_e
Energy loss $\propto$ material

Match electron tracks to photon clusters in the ECAL
Correct electron momenta by “attaching” photons.

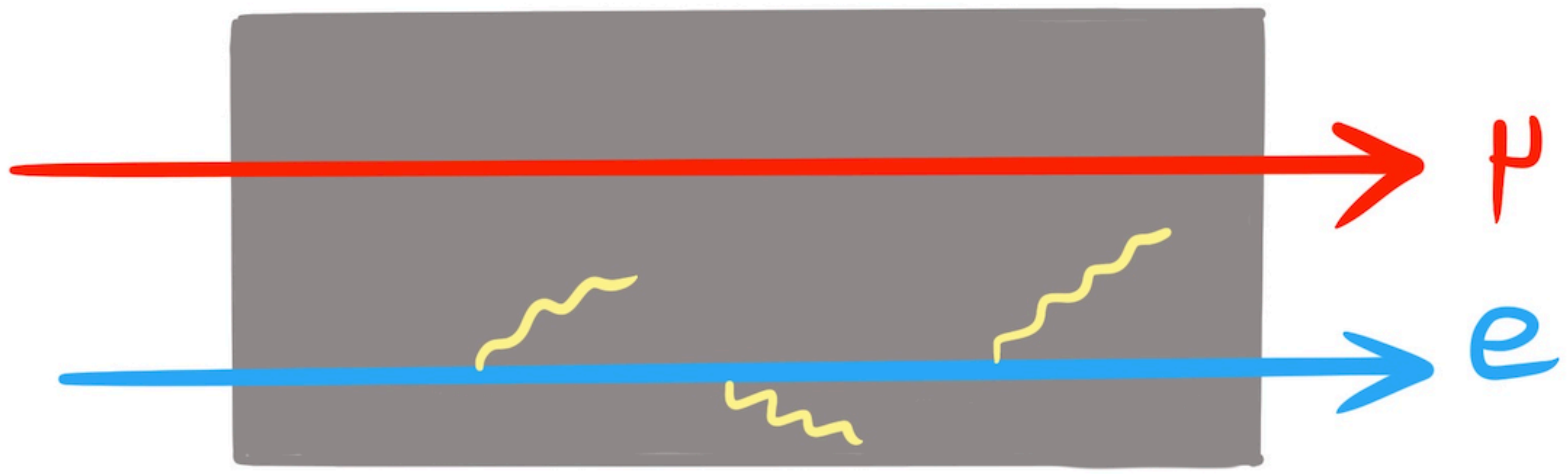
Three categories of events: 0, 1, > 1 photons
Different invariant mass shapes due to under- or over-correcting
ECAL resolution is worse than tracker.
Bin migration included in systematics.



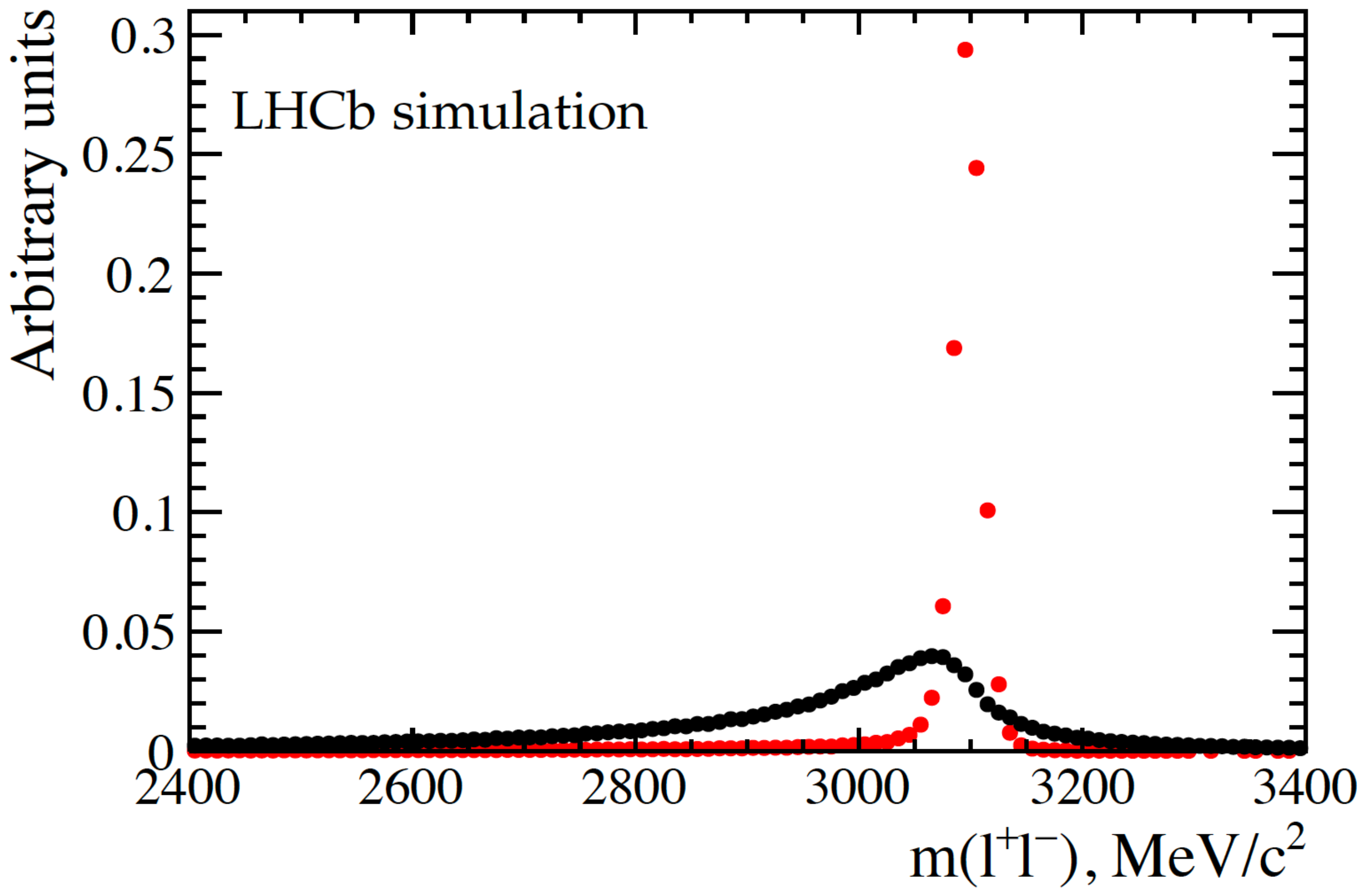
Electrons vs muons

Even after Bremsstrahlung recovery, electrons still have degraded momentum, mass, q^2 resolution.

Particle ID and track reconstruction efficiencies also larger for muons than for electrons.

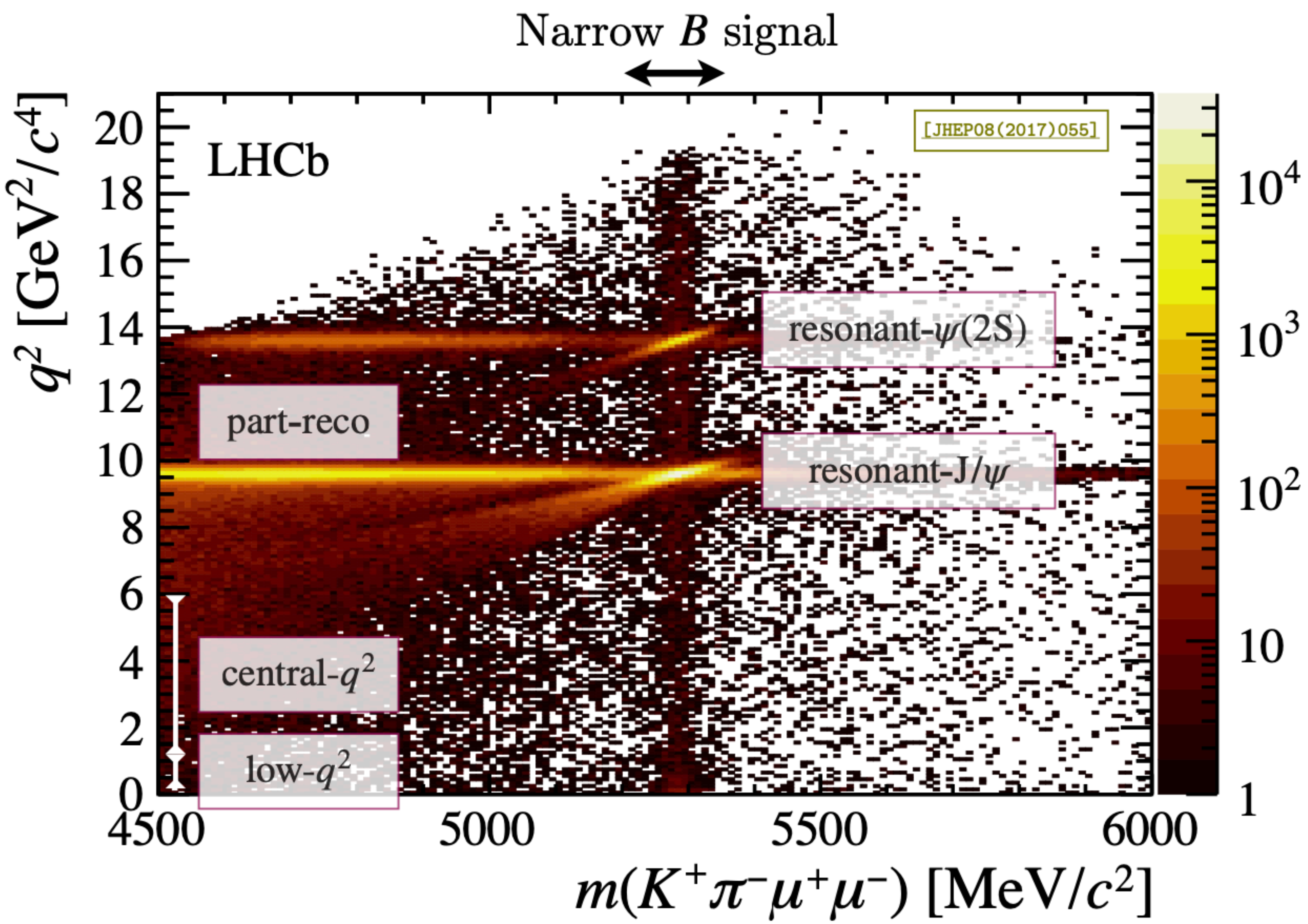


Get the differences between electron and muon efficiencies fully under control



From Vitalii Lisovskyi my former PhD student

What does the data look like?



What is actually measured is

$$R_{K,K^*}(q_a^2, q_b^2) = \frac{\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2} \times \frac{\Gamma(J/\psi \to e^+e^-)}{\Gamma(J/\psi \to \mu^+\mu^-)}$$

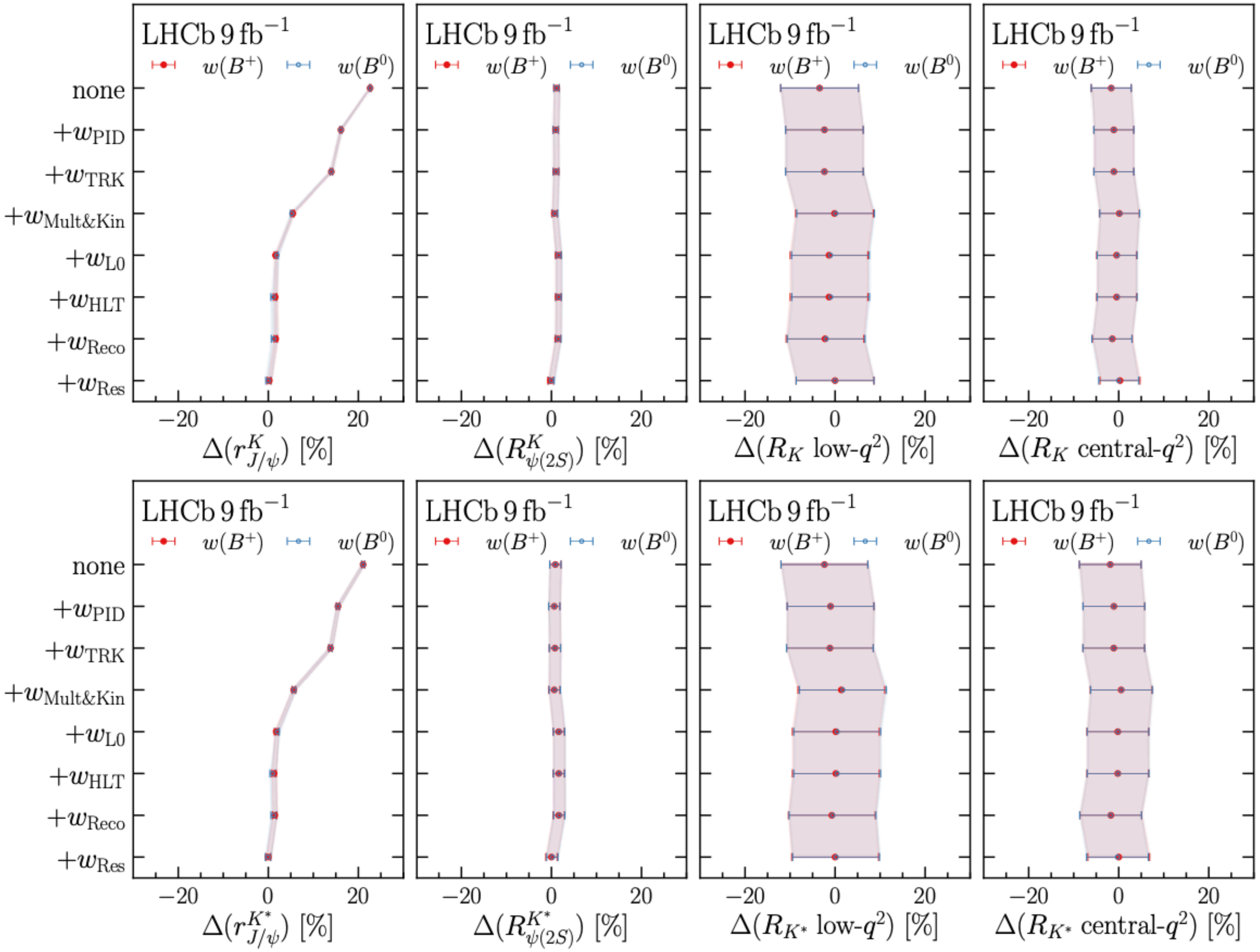
Measured to be 1 Phys. Lett. B731, 227 (2014)

$$r_{J/\psi}^{-1} = 1$$

$$R_{(K,K^*)} = \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)} \times \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(e^+e^-))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\mu^+\mu^-))}$$

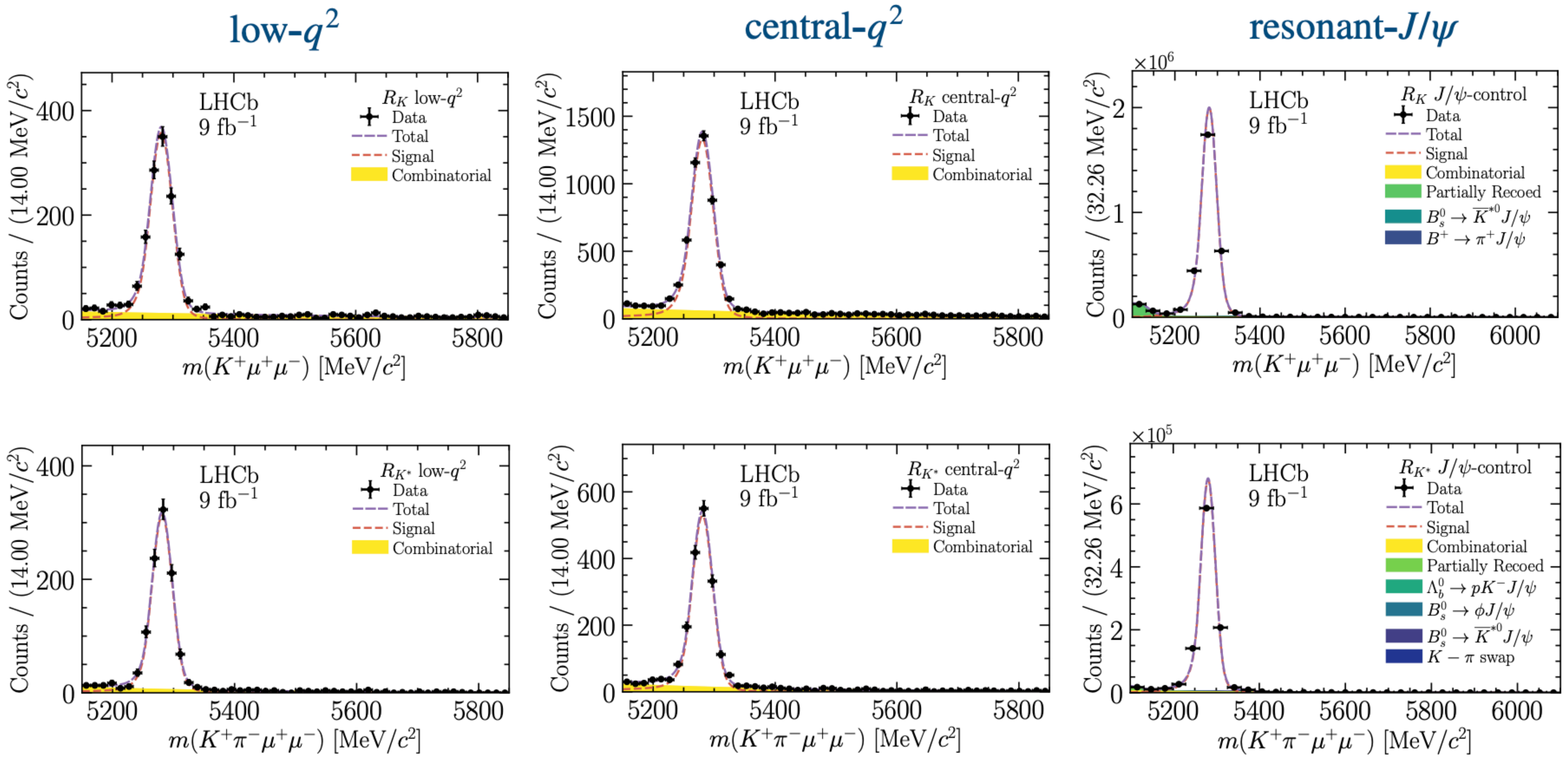
Try to calibrate as much as possible from data

Getting the single/double ratios correct is very painful but it pays off

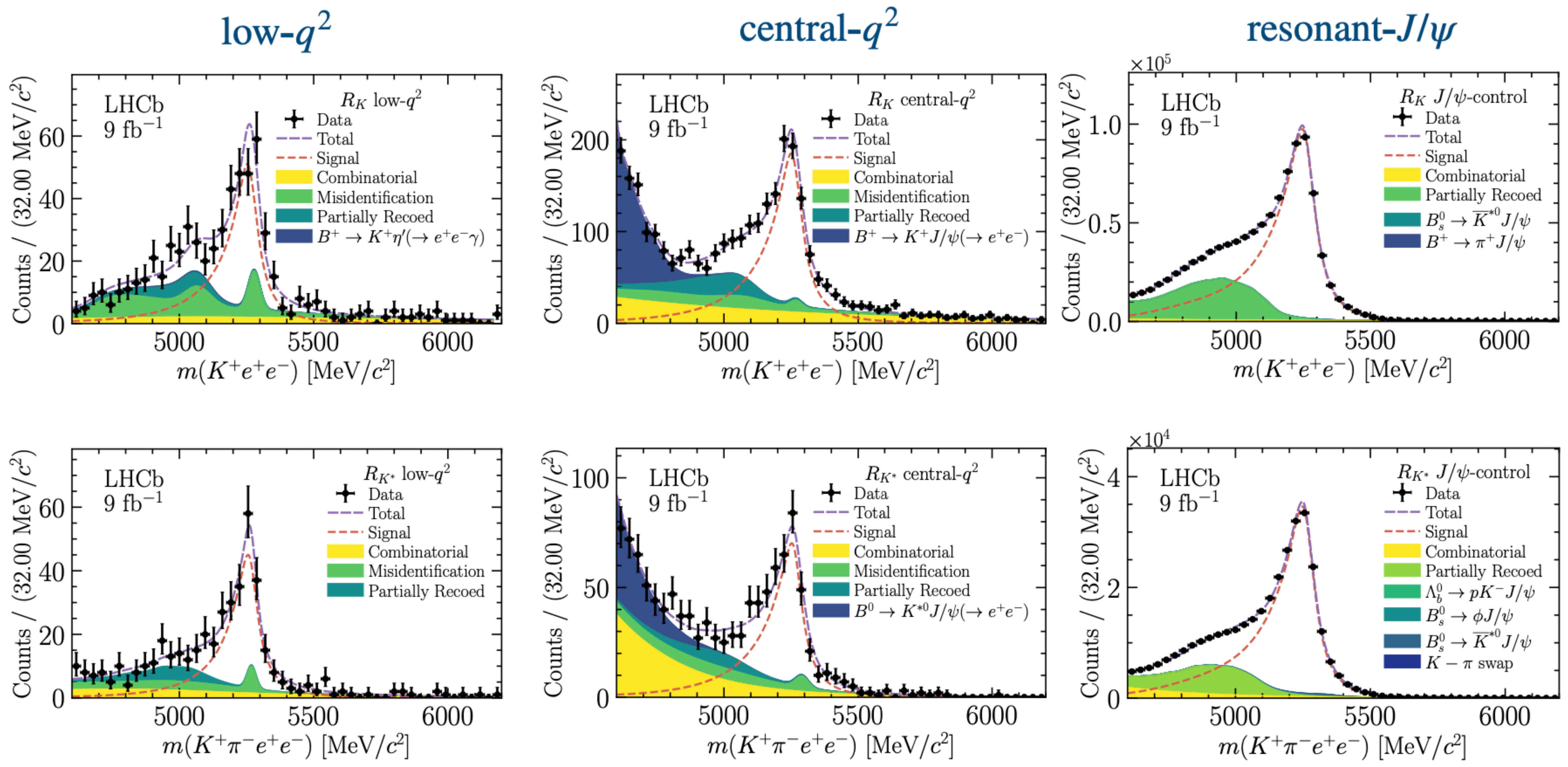


Checked also in various bins of kinematic etc.

Now we look at the data



Once again the muons are a day at the beach

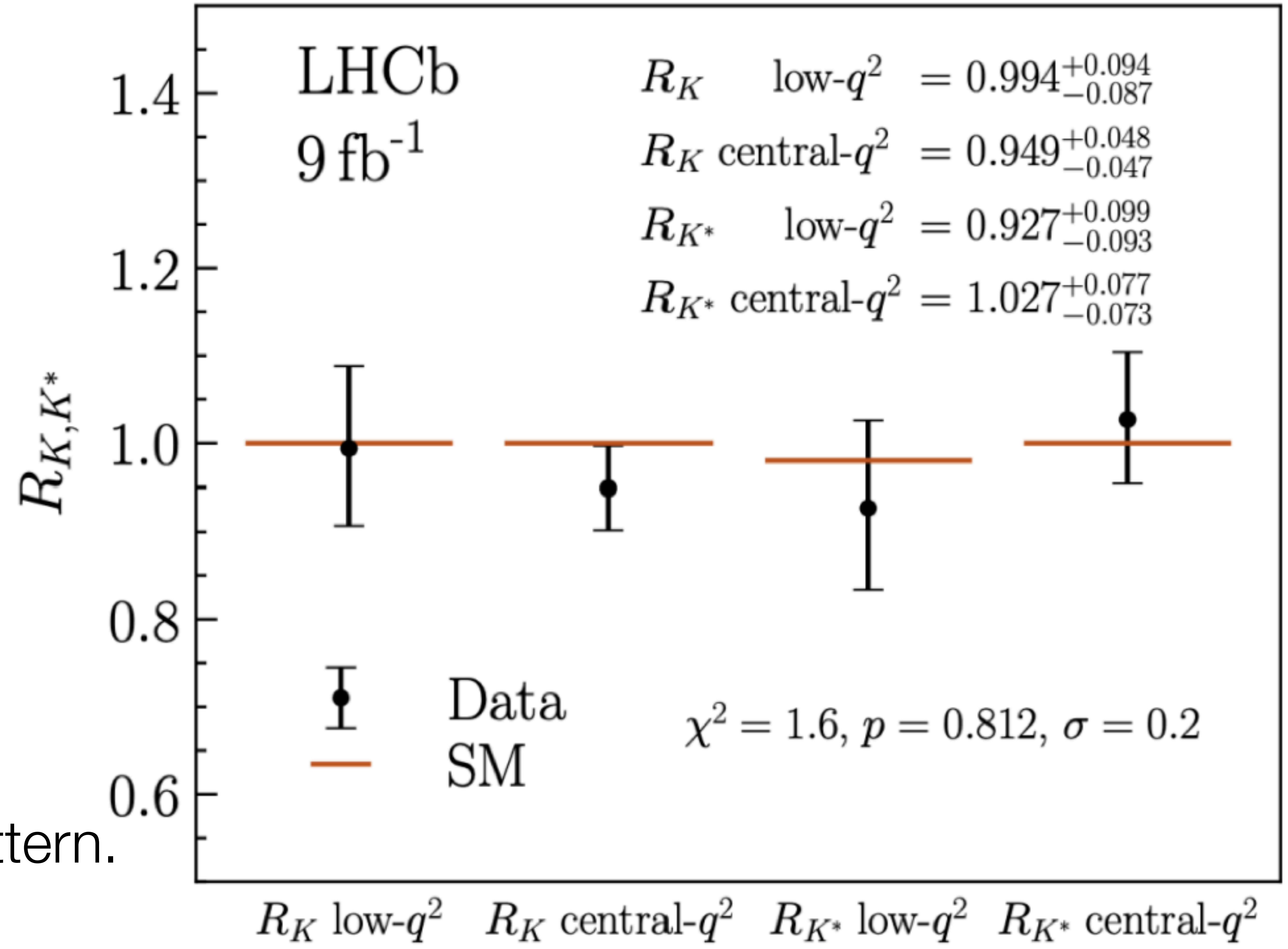


The electrons less so

The cold shower

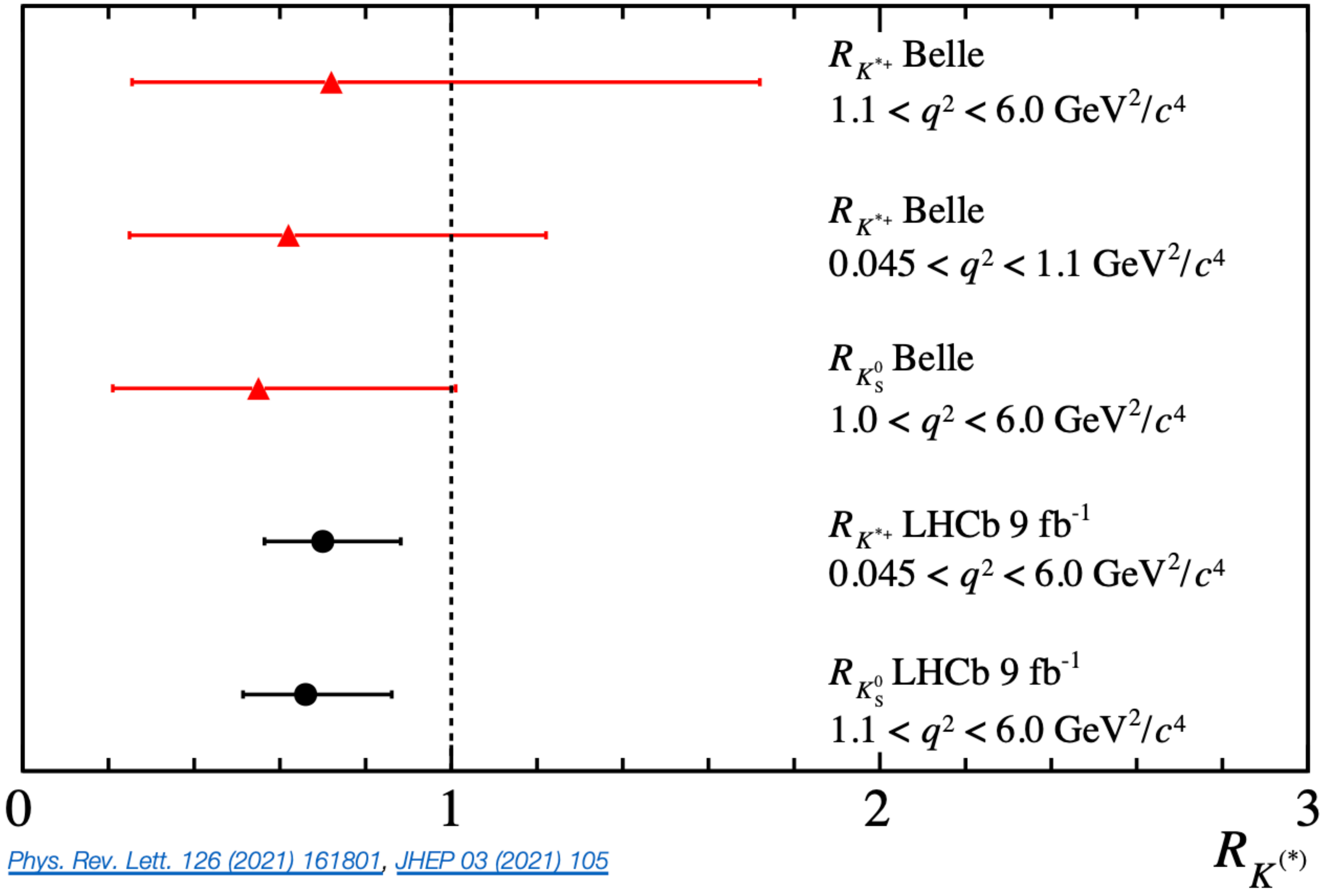
Taking a cold shower is good for your health, here's why

It's widely known that a hit of cold water can do wonders for your body. Swedish bathhouses are among an age-old Nordic healing tradition, the world's happiest people go ice swimming, and Brits swear by a jolt of cold water for a mood-boost. But when all is said and freezing, what good does a cold shower actually do? We break down four reasons why

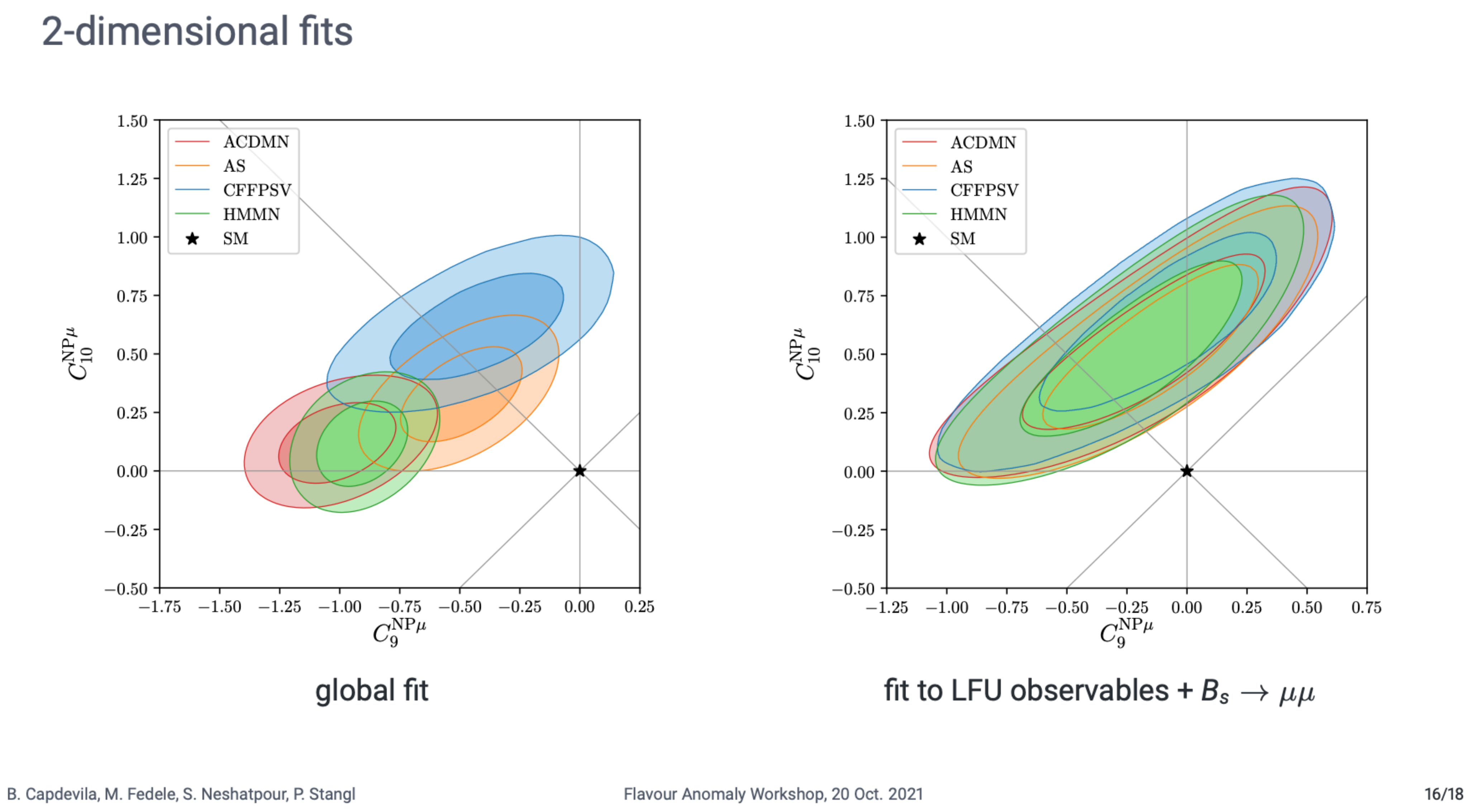


Why a cold shower?
The result before that indicated a consistent pattern.
But !
These results are still statistically limited…

Just for reference - the pre-cold shower picture

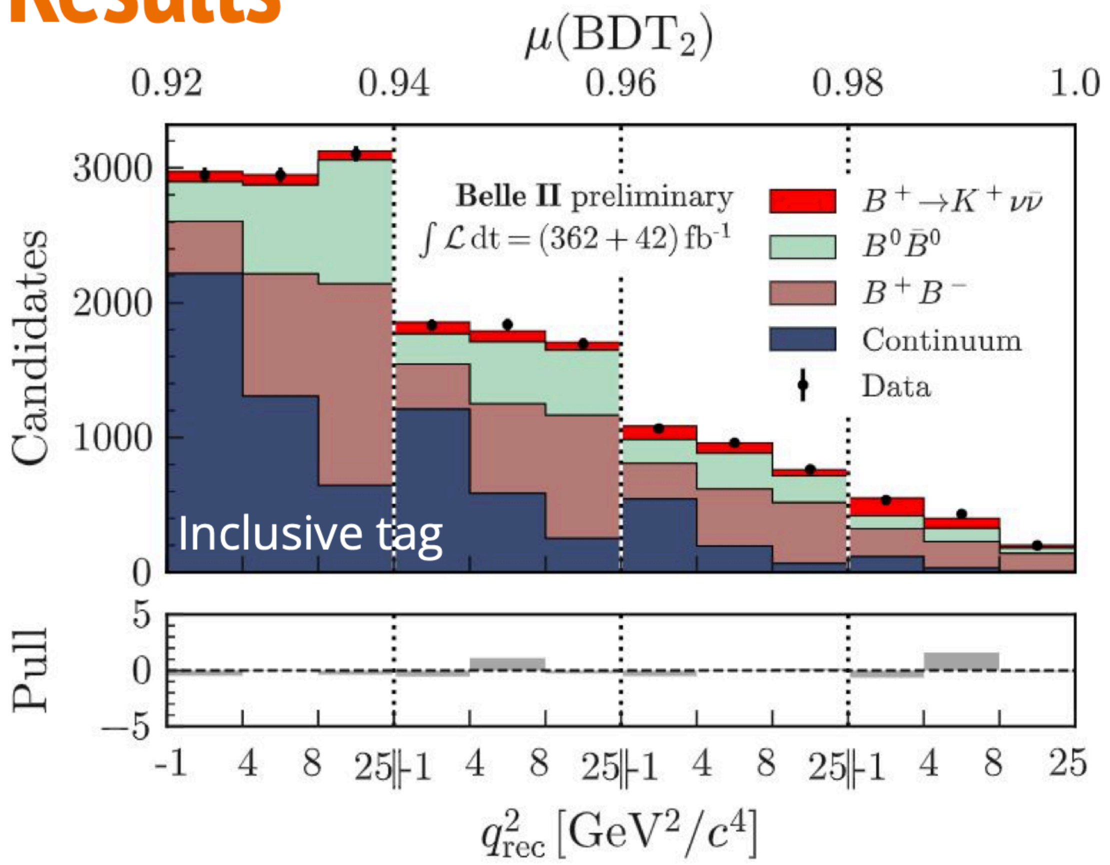


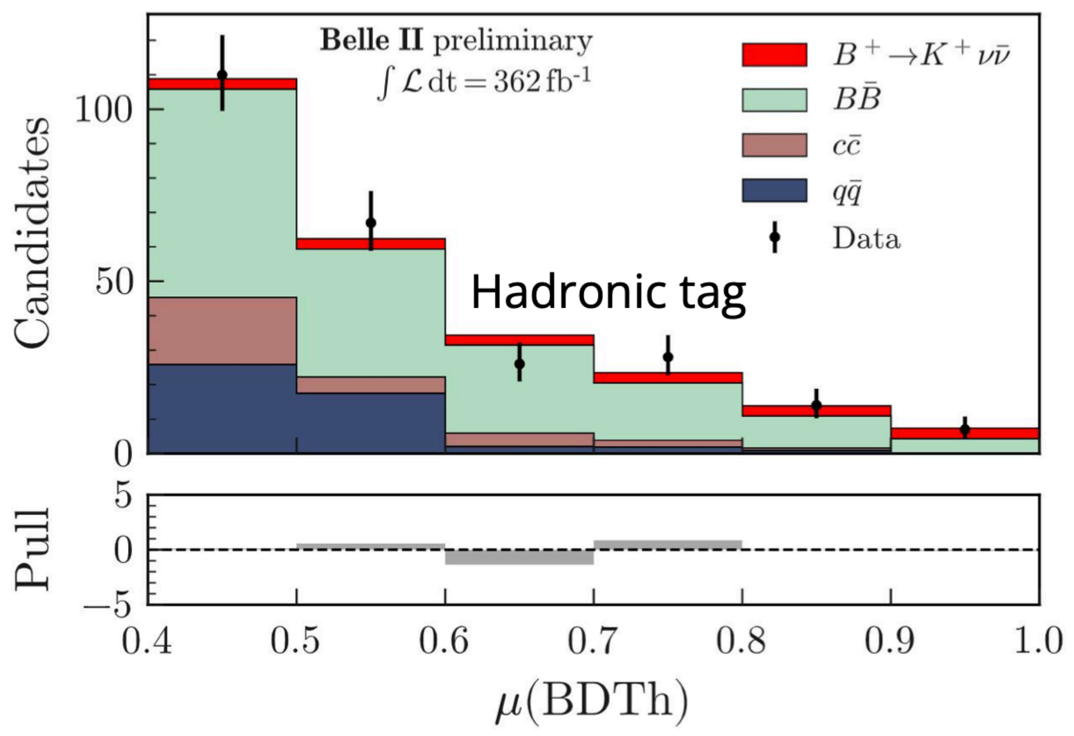
Phys. Rev. Lett. 126 (2021) 161801, JHEP 03 (2021) 105



Observation of B→Kνν on the side of the world

Results





- Maximum likelihood fit to data using signal and background templates
- Branching fractions: $B_{incl.}$=(2.8±0.5(stat)±0.5(stat)) x 10^{-5} , $B_{had.}$=($1.1^{+0.9}_{-0.8}$(stat)$^{+0.8}_{-0.5}$(syst)) x 10^{-5}
- For inclusive analysis, **evidence for B→Kνν̄** at 3.6σ, branching fraction within 3.0σ of standard model (both considering total uncertainty)
- For hadronic tag, the result is consistent with null hypothesis and SM at 1.1σ and 0.6σ

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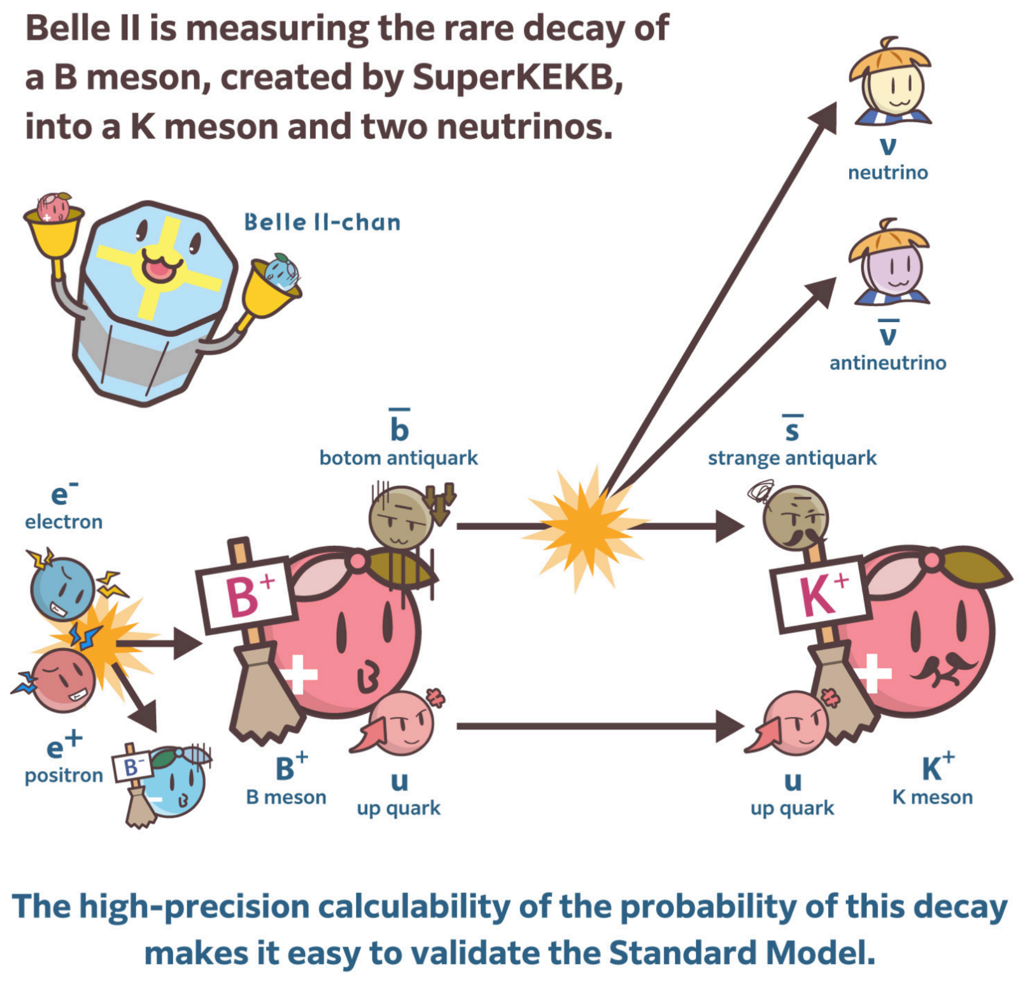
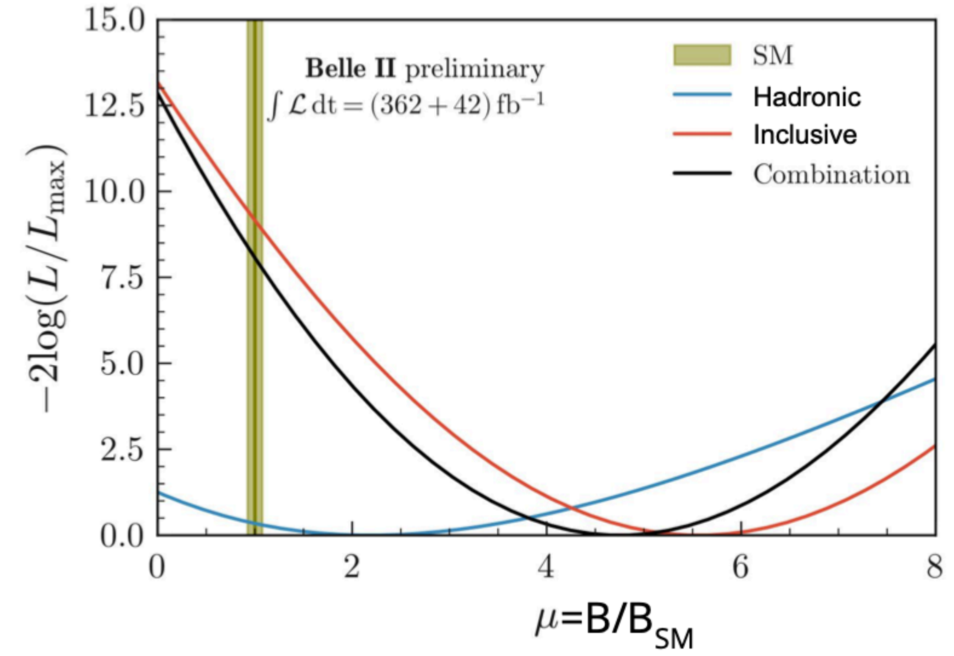
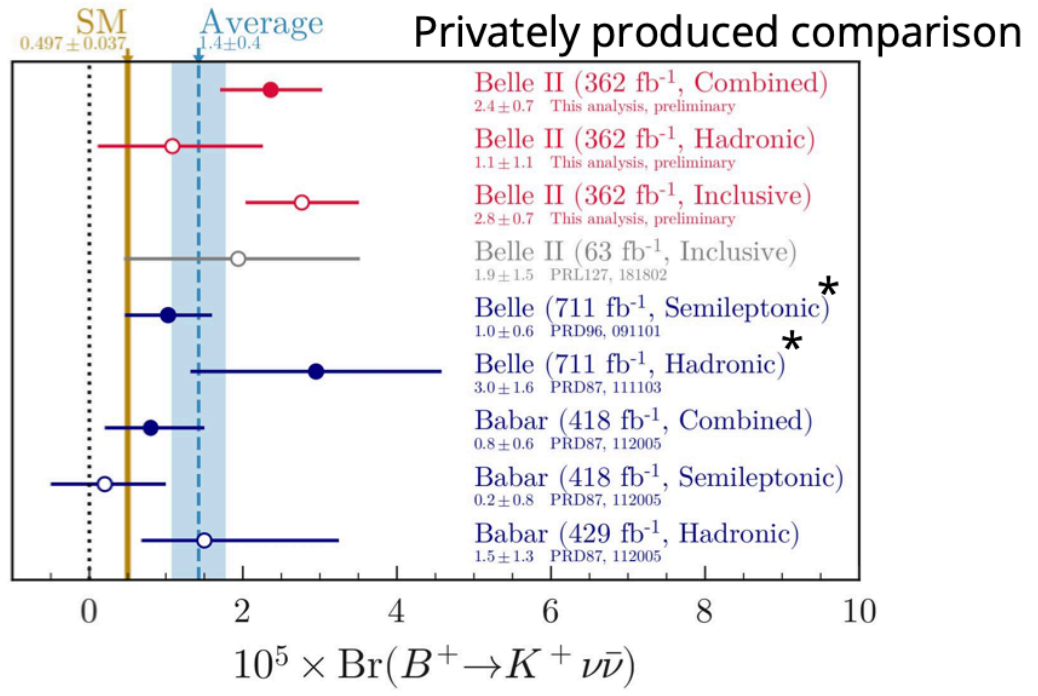
Very interesting result !
Looking forward to seeing impact on phenomenology work



Combination and comparison with other measurements





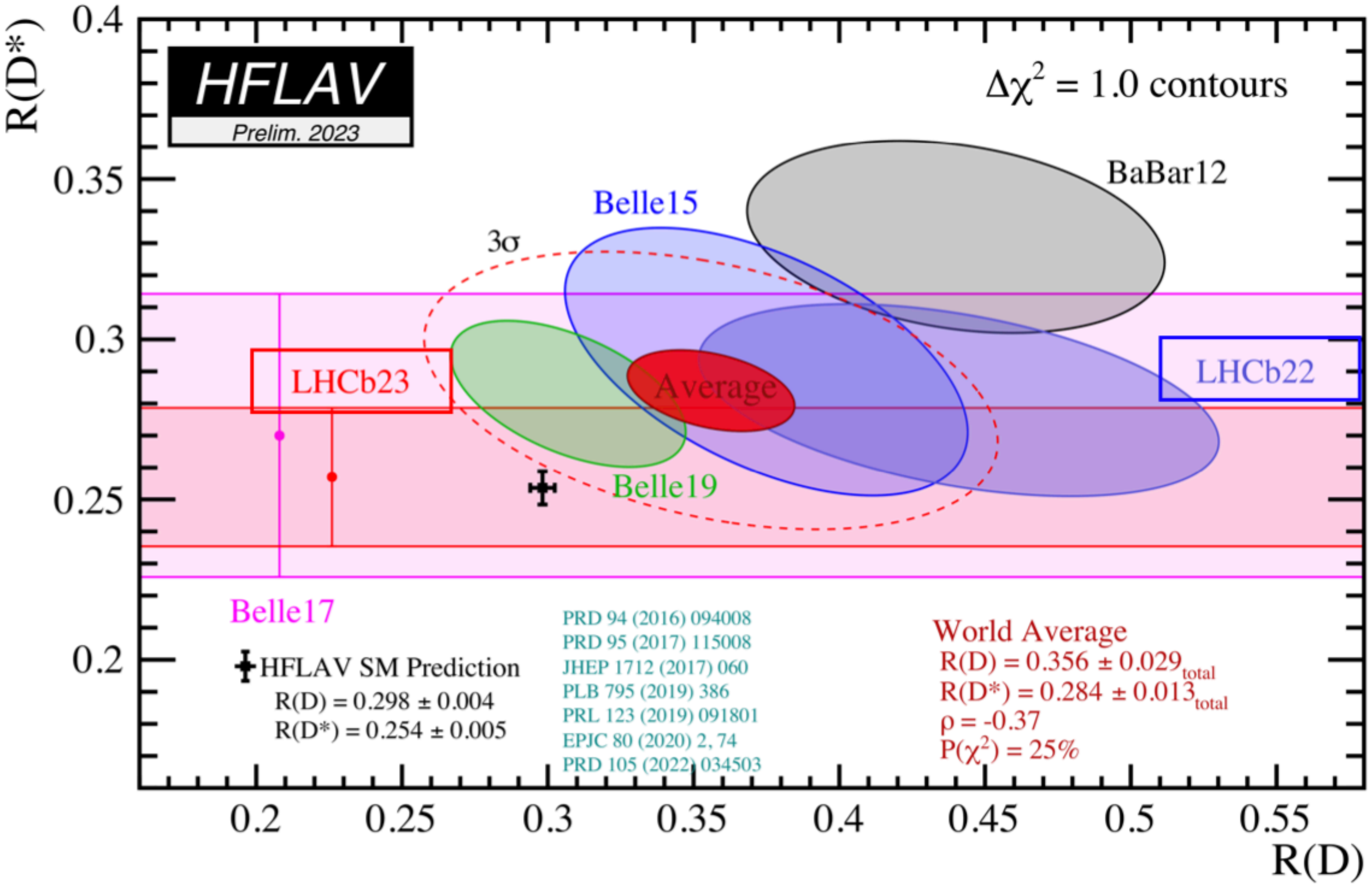
- Inclusive and hadronic measurements are combined, taking into account common correlated uncertainties. The resulting branching fraction is **B_{comb}($B^+ \to K^+ \nu\nu$) = (2.4 ± 0.7) x 10^{-5} =[2.4 ± 0.5(stat)$^{+0.5}_{-0.4}$(syst)]x10^{-5}** significance of observation is **3.6σ** the result is within **2.8σ** vs standard model
- Some tensions between inclusive and semileptonic results for Belle and BaBar, however overall compatibility of the results is good with χ^2/dof = 4.3/4

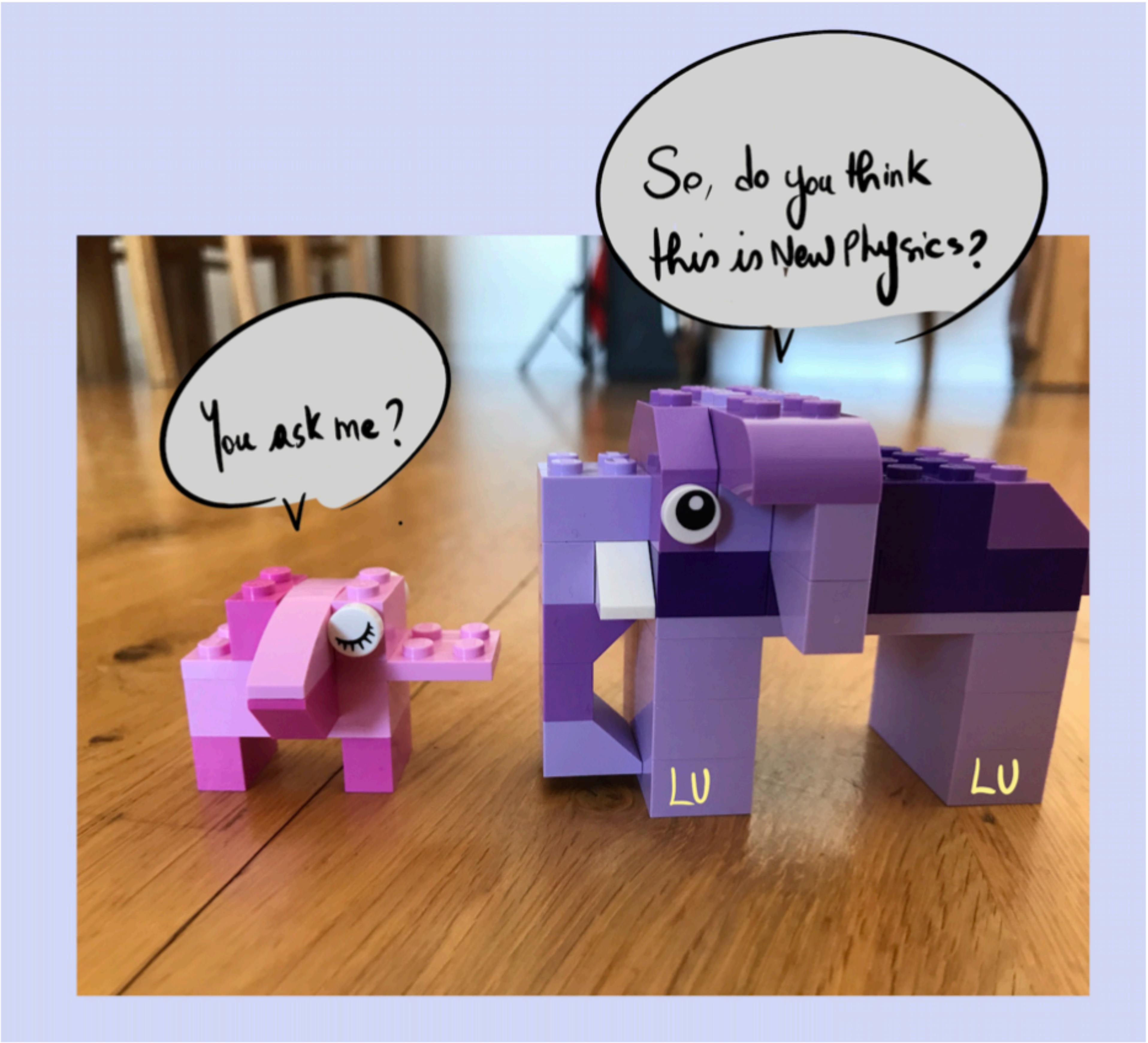
23

*Belle reports upper limits only; branching fractions are estimated using published number of events and efficiency

More information

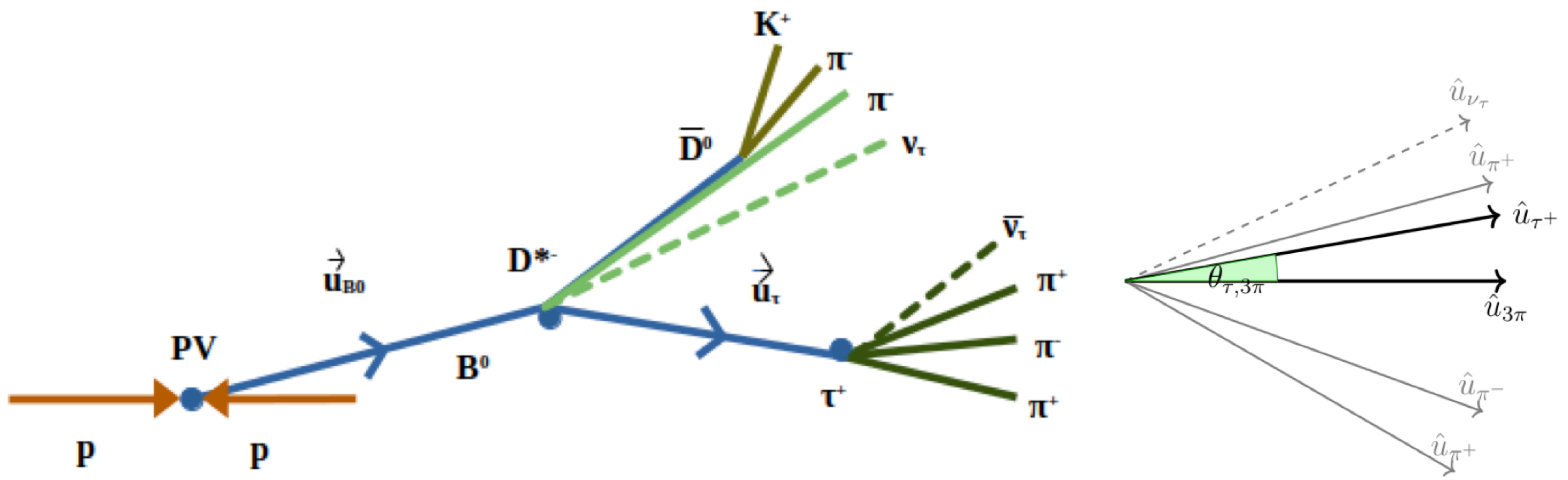
Let's continue… charged currents





Why are decays with τ in the final state difficult ?

The first discussion we had with G. Isidori to prepare the lectures was in June…
Obviously I finished this lectures a way hours ago.



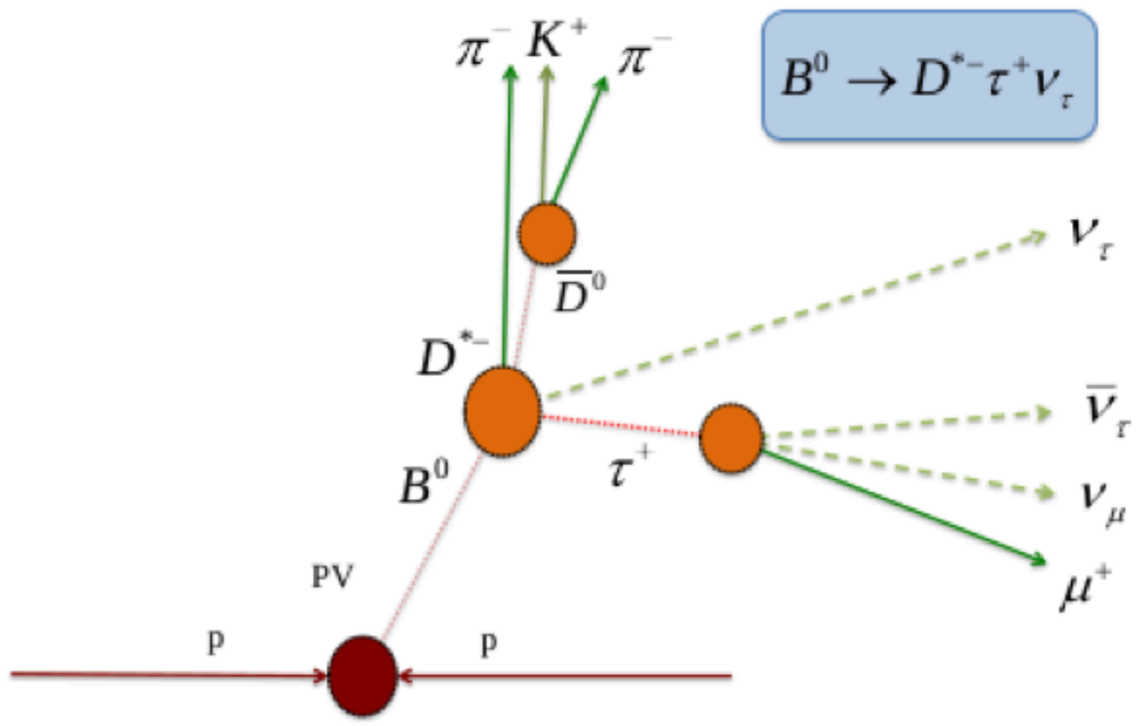
Thank you class of 2023 CERN Fermilab

Why are tau leptons difficult ?

Tau leptons, also known as tau particles or tauons, are not inherently difficult in the sense that they are inherently complicated or hard to understand. However, there are certain characteristics and properties of tau leptons that can make them challenging to study and detect in certain experimental contexts. Here are a few reasons why tau leptons might be considered "difficult":

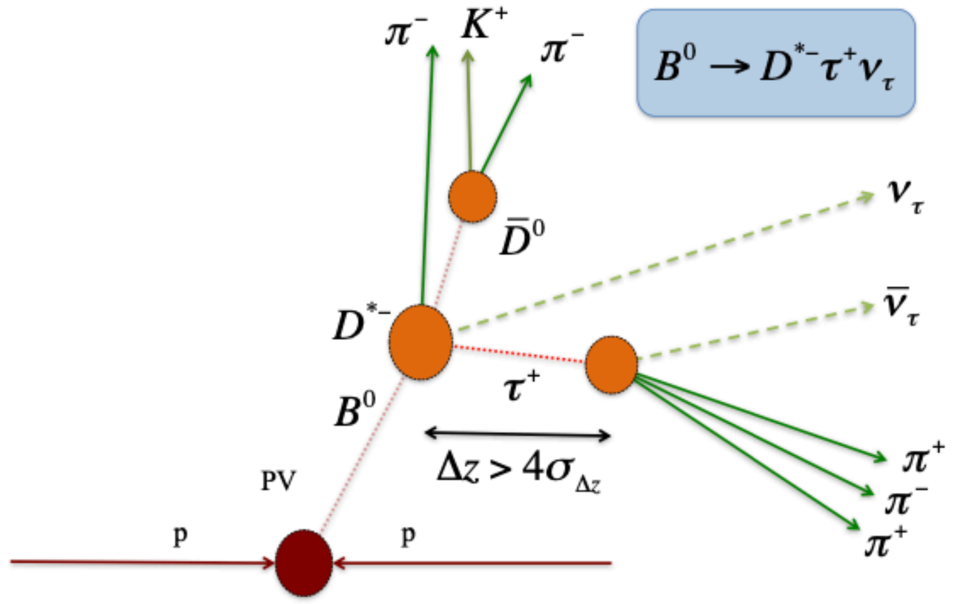
1. **Short Lifetime**: Tau leptons have a relatively short lifetime of about 2.9 × 10^-13 seconds. This means that they decay into other particles very quickly after being produced in particle collisions. Detecting and studying these decay products accurately requires sophisticated experimental setups and techniques.
2. **Heavy Mass**: Tau leptons are much more massive than their lighter counterparts, the electron and the muon. Their larger mass affects the kinematics of their interactions and decays, making their behavior more complex to model and understand.
3. **Rare Processes**: In many particle physics experiments, tau leptons are not as commonly produced as other particles, like electrons or muons. This rarity can make it challenging to collect a sufficient number of tau events for detailed studies.
4. **Neutrinos**: Tau leptons often decay into other particles, including neutrinos. Neutrinos are extremely difficult to detect because they interact very weakly with matter. As a result, a significant portion of the energy and momentum of the tau's decay products might b Regenerate carried away by neutrinos, making it challenging to accurately reconstruct the initial tau's

$\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$



- Direct measurement of $R(X_c)$
- High statistics
- Backgrounds from D^+ must be controlled well
- Sensitive to $D^{**}\mu^-\nu_\mu$

$\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$



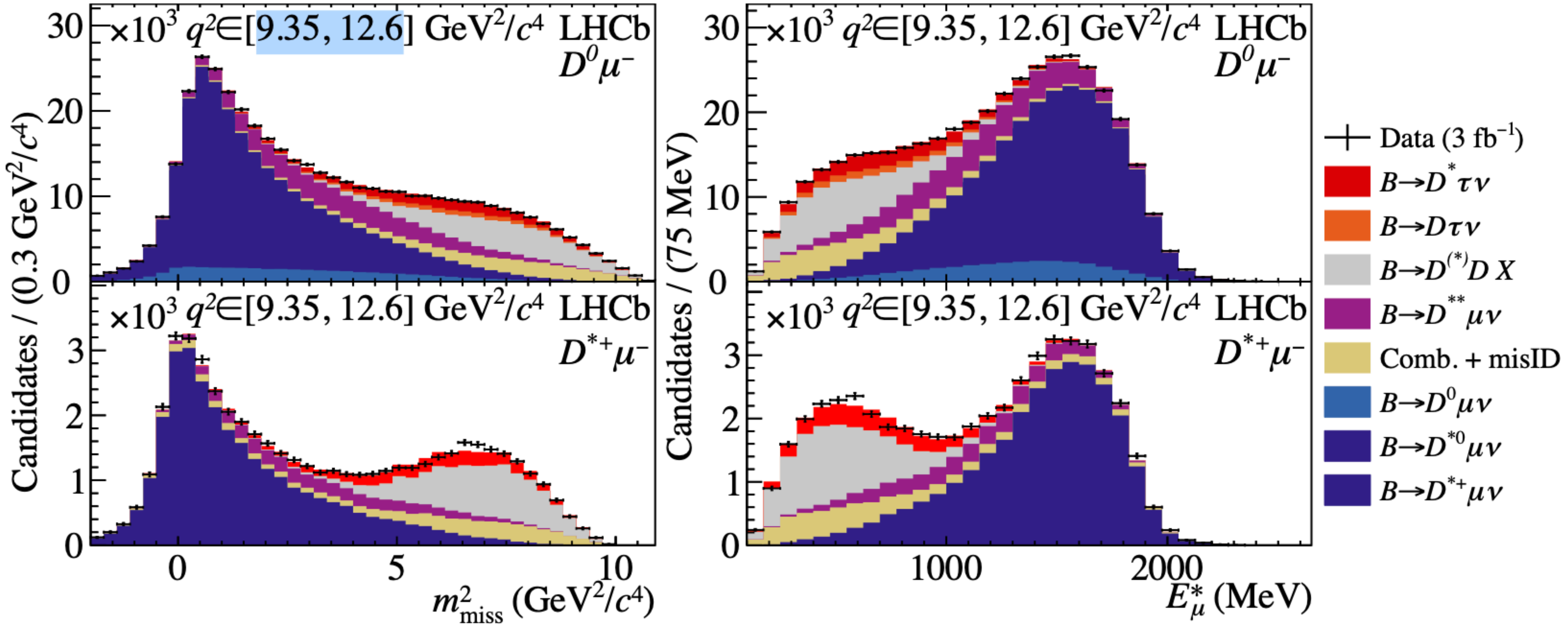
- Measuring τ^+ decay position key to reject dominant backgrounds
- High purity sample
- $\tau^+ \to 3\pi^\pm$ dynamics is very specific $\Rightarrow$ more control over backgrounds
- $R(X_c)$ requires external inputs
- Lower statistics

Missing energy much easier at GDP & B-factories

Welcome to the world of template fits

3D template fit to

- $q^2 \equiv (p_B - p_{D^{(*)}})^2$
- $m^2_{\text{miss}} \equiv (p_B - p_{D^{(*)}} - p_\mu)^2$
- E^*_μ energy of μ

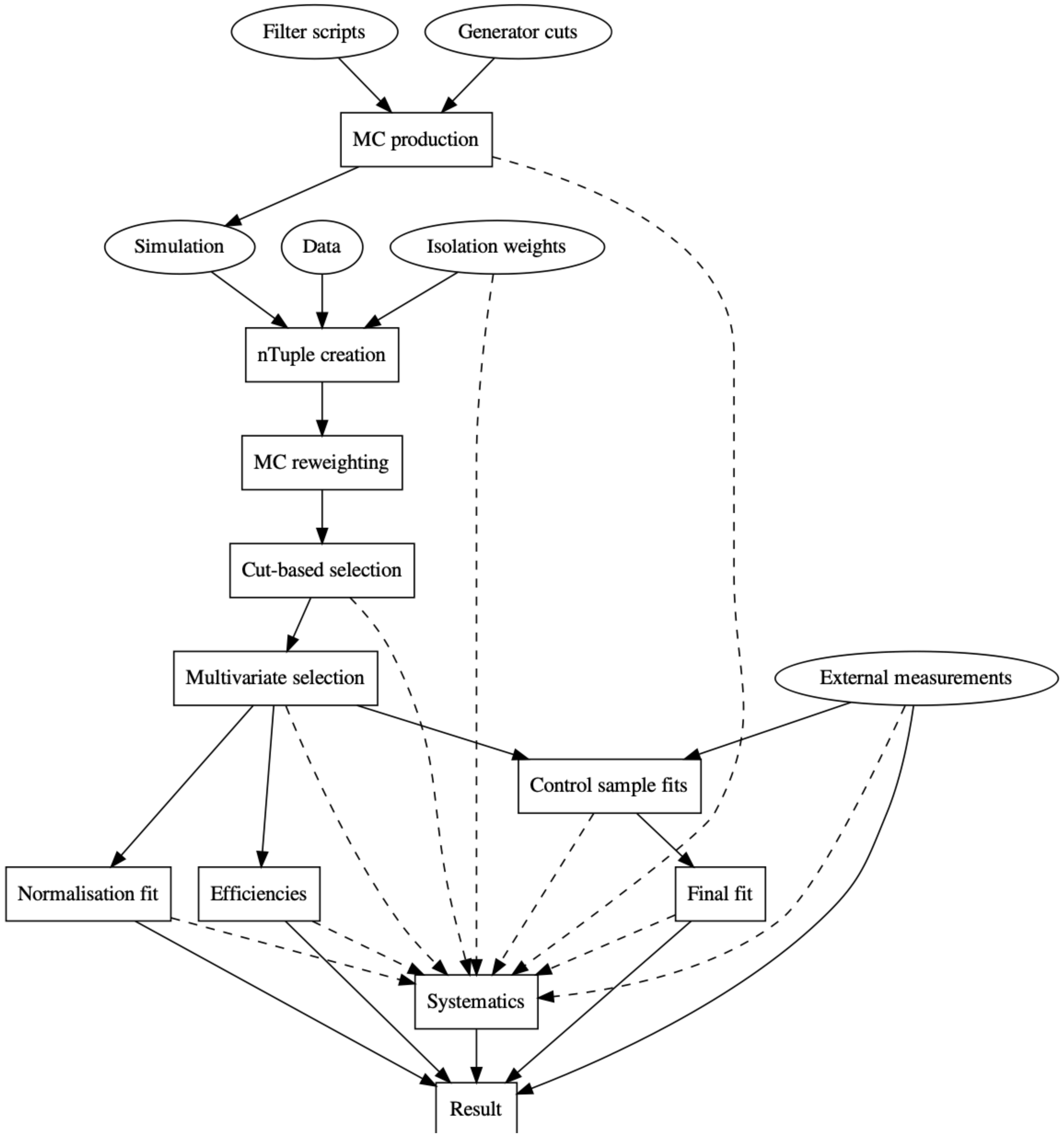


$$R(D) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst})$$
$$R(D^*) = 0.281 \pm 0.018(\text{stat}) \pm 0.023(\text{syst})$$

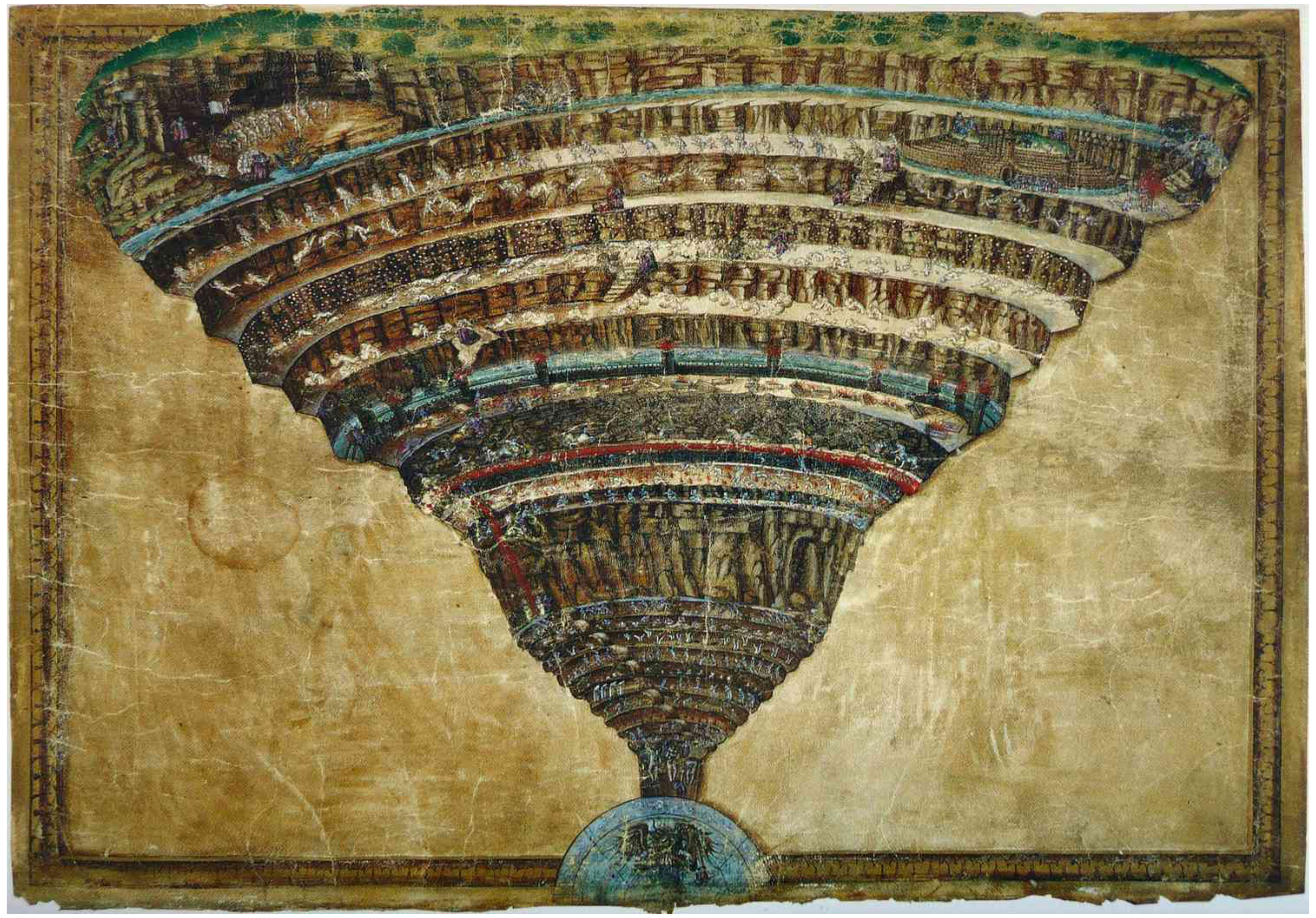
Agreement with SM at 1.9σ

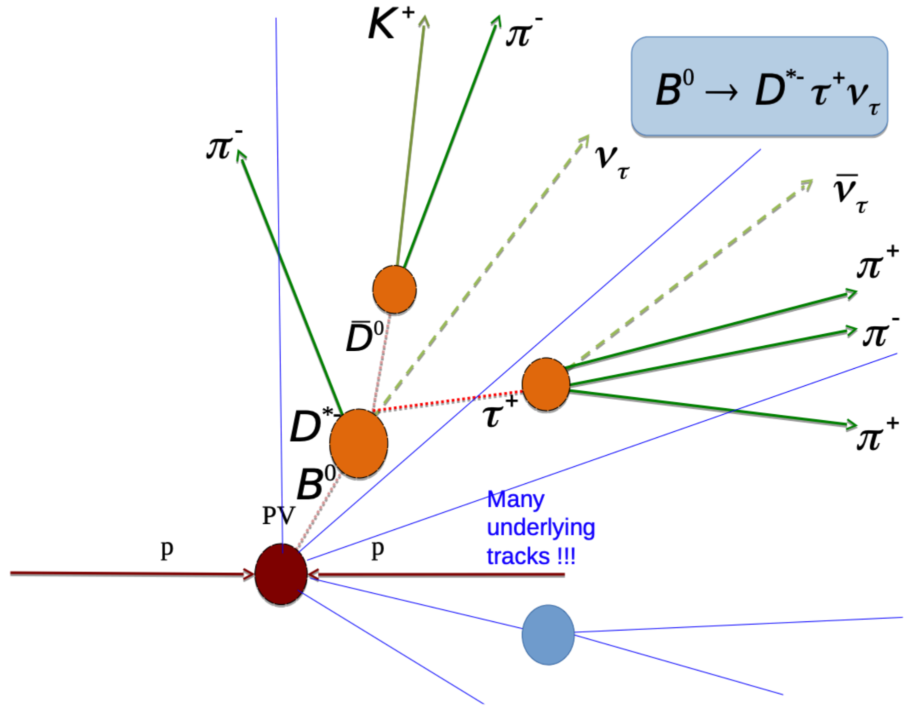
It's just a Tuesday for my colleagues from ATLAS and CMS

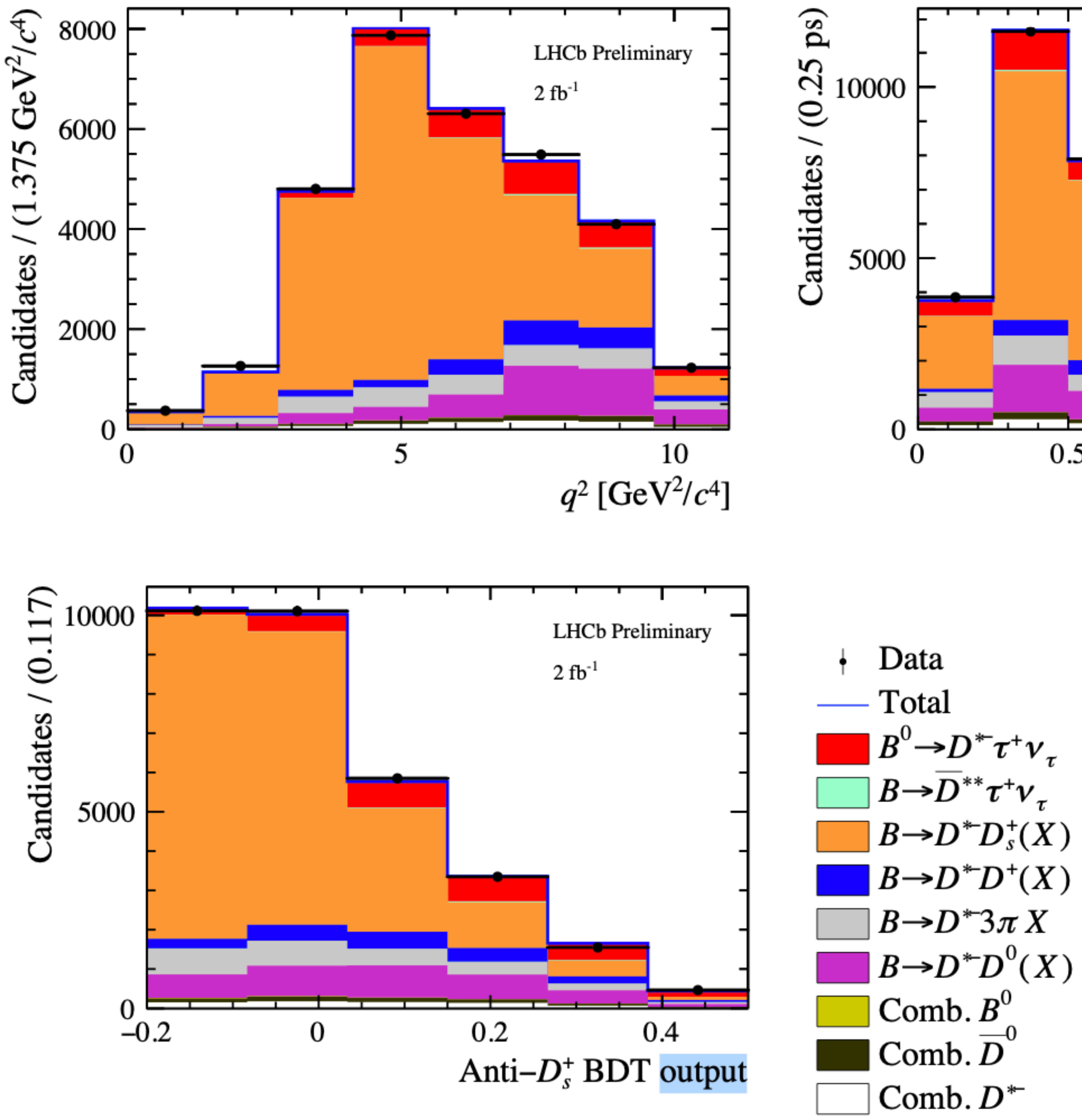
Why does it take so long ?

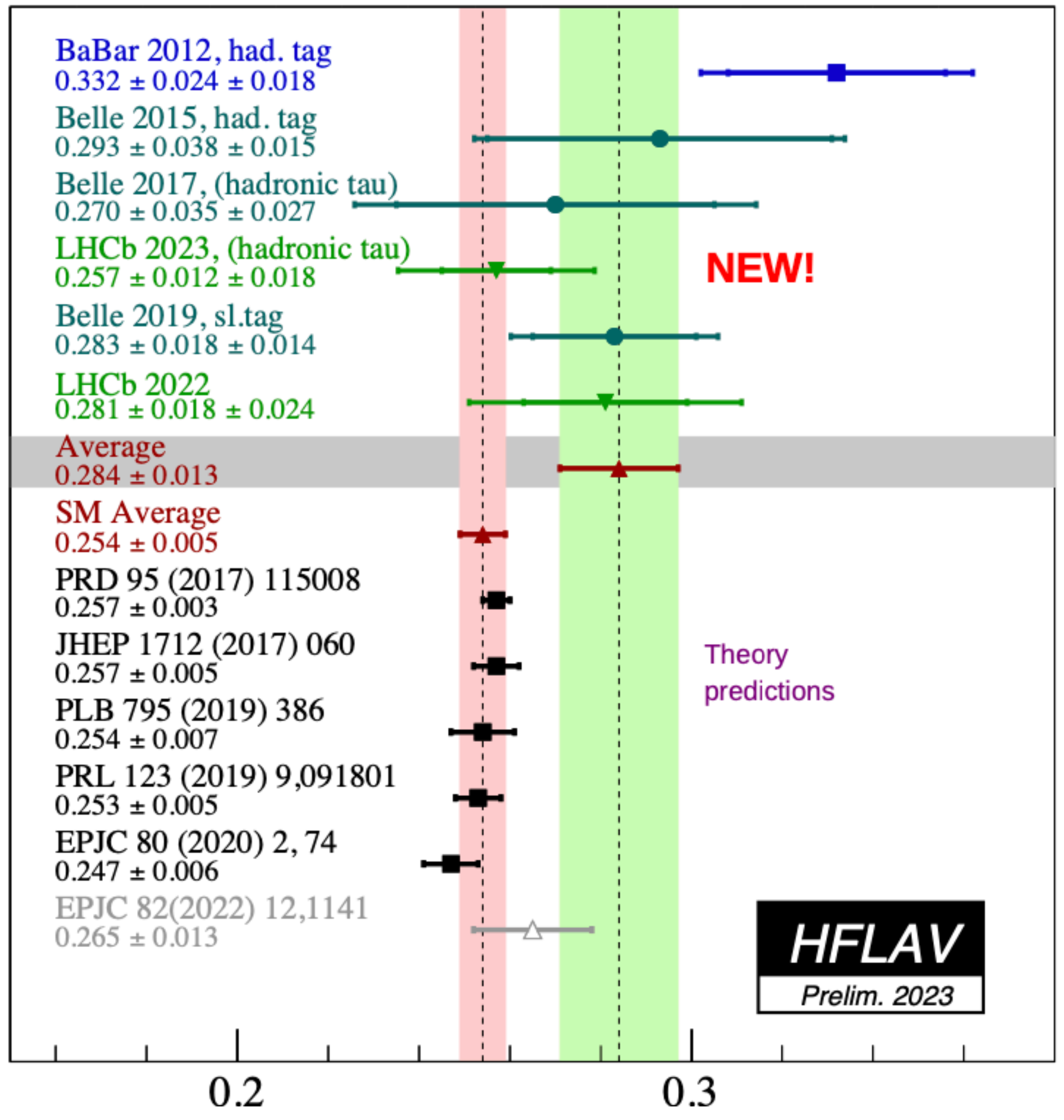


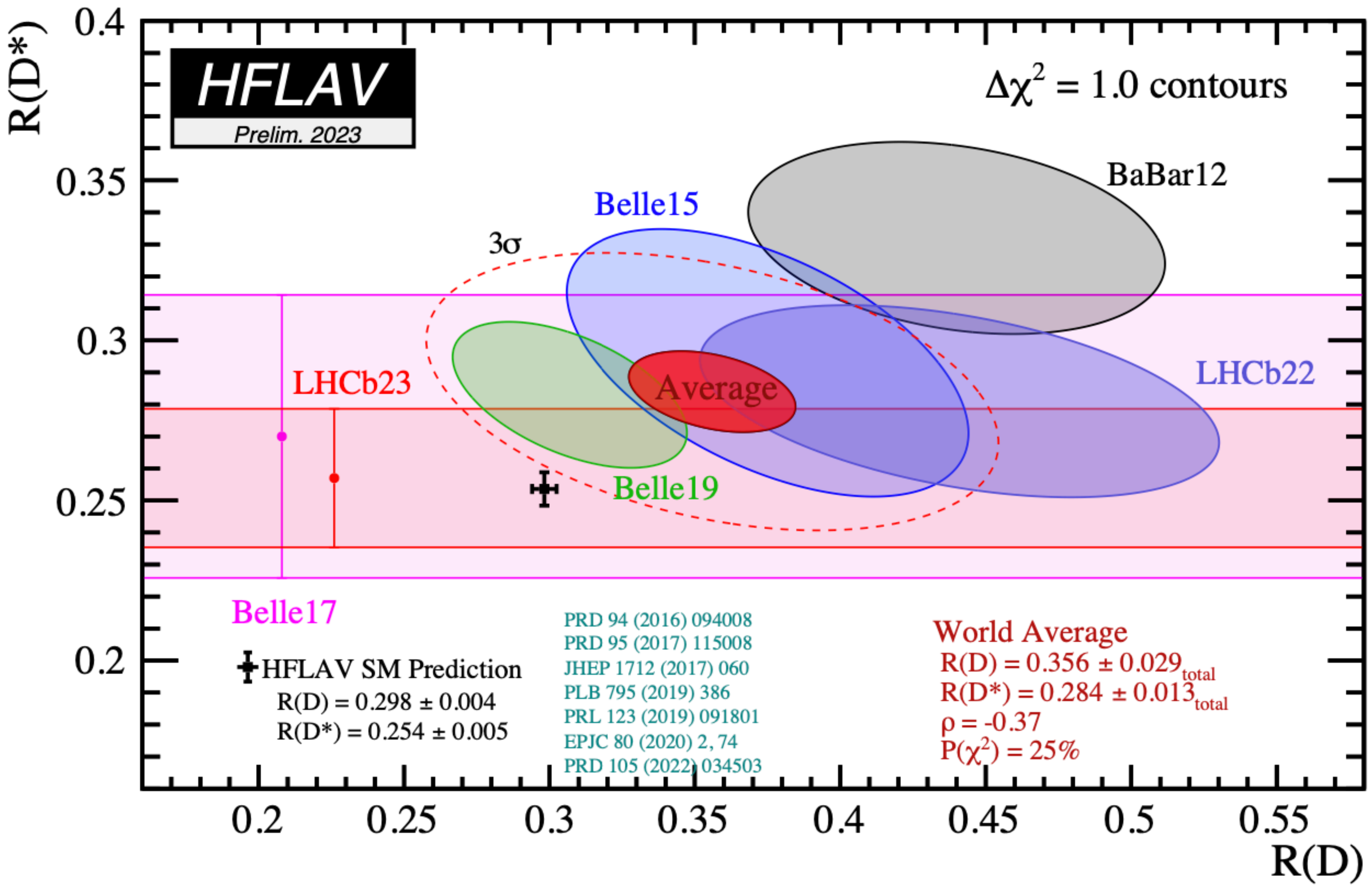
Dante 9 circles of Hell






LHCb Preliminary
2 fb-1
Candidates / (1.375 GeV2/c4)
q2 [GeV2/c4]
Candidates / (0.25 ps)
tτ [ps]
Candidates / (0.117)
Anti−D+s BDT output
Data
Total
B0→D*−τ+ντ
B→D**τ+ντ
B→D*D+s(X)
B→D*D+(X)
B→D*3π X
B→D*D0(X)
Comb. B0
Comb. D0
Comb. D*−

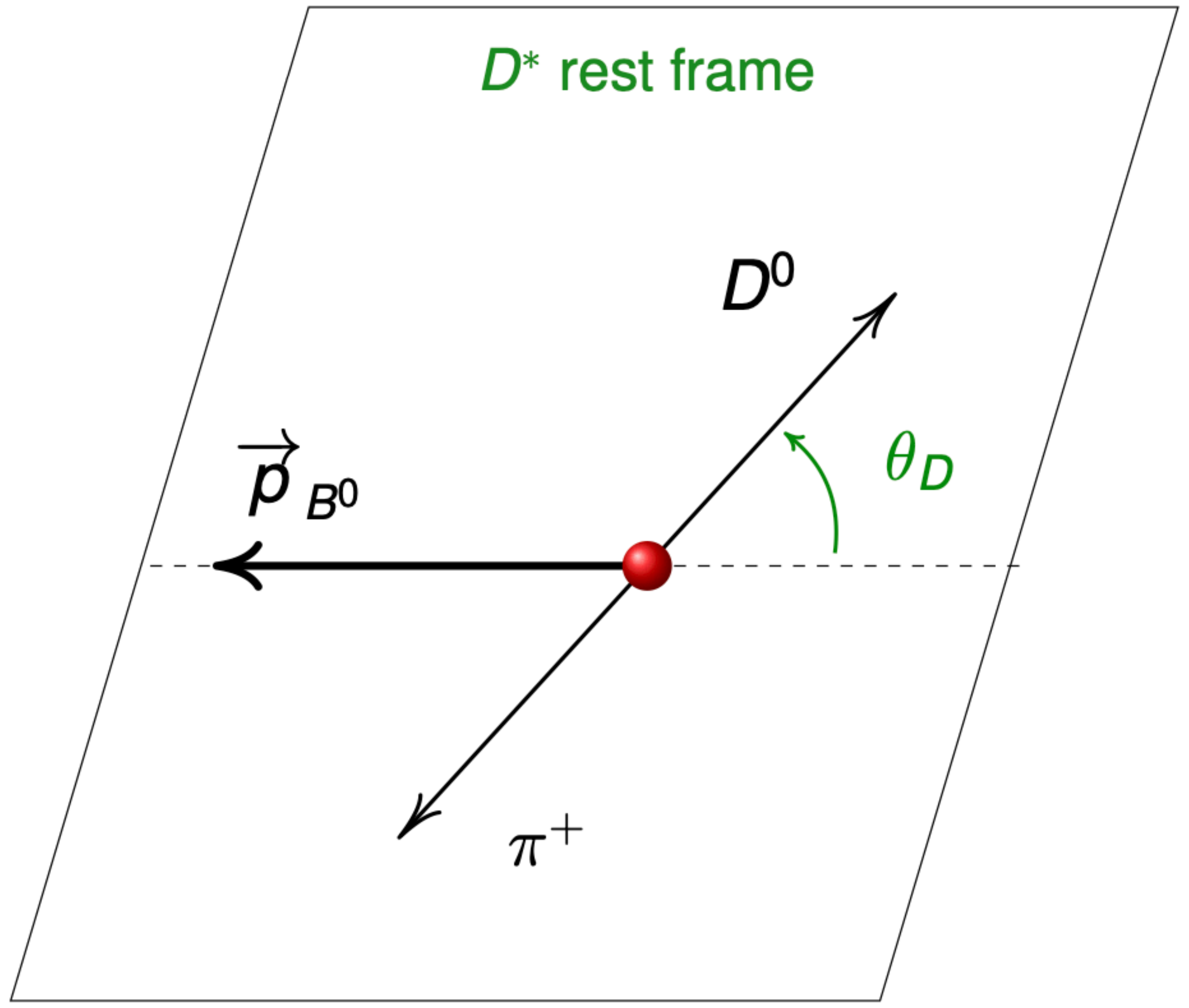

BaBar 2012, had. tag
0.332 ± 0.024 ± 0.018
Belle 2015, had. tag
0.293 ± 0.038 ± 0.015
Belle 2017, (hadronic tau)
0.270 ± 0.035 ± 0.027
LHCb 2023, (hadronic tau)
0.257 ± 0.012 ± 0.018
NEW!
Belle 2019, sl.tag
0.283 ± 0.018 ± 0.014
LHCb 2022
0.281 ± 0.018 ± 0.024
Average
0.284 ± 0.013
SM Average
0.254 ± 0.005
PRD 95 (2017) 115008
0.257 ± 0.003
JHEP 1712 (2017) 060
0.257 ± 0.005
PLB 795 (2019) 386
0.254 ± 0.007
PRL 123 (2019) 9,091801
0.253 ± 0.005
EPJC 80 (2020) 2, 74
0.247 ± 0.006
EPJC 82(2022) 12,1141
0.265 ± 0.013
Theory predictions
HFLAV
Prelim. 2023
0.2
0.3

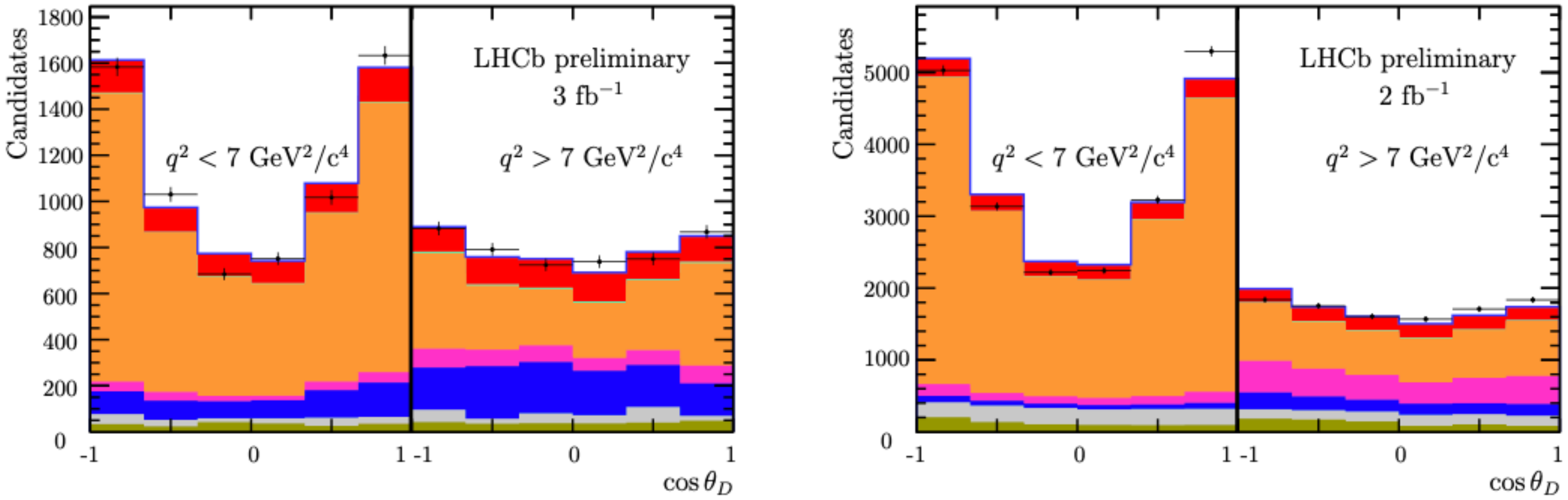


- Including this result, the world average becomes
  $R(D^*) = 0.284 \pm 0.013; \quad R(D) = 0.356 \pm 0.029$ [HFLAV]
- The deviation w.r.t. the SM is at **3.2σ** for the combination of $R(D)$-$R(D^*)$

Have a look back at G. Isidori's talk about the implications !

LHCb enters the game of semi-leptonic angular analyses

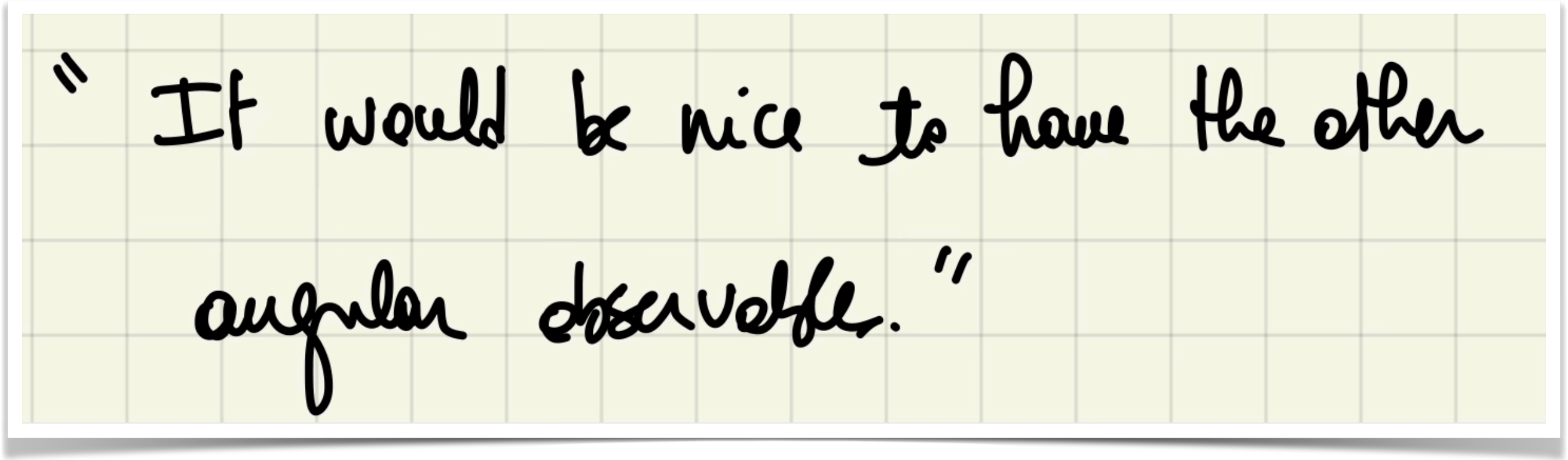




$F_L^{D^*}$ value extracted for the 3 q^2 region

$q^2 < 7\,\mathrm{GeV}^2/c^4$:	$0.51 \pm 0.07(stat) \pm 0.03(syst)$
$q^2 > 7\,\mathrm{GeV}^2/c^4$:	$0.35 \pm 0.08(stat) \pm 0.02(syst)$
q^2integrated :	$0.43 \pm 0.06(stat) \pm 0.03(syst)$

- All values are found to be compatible with the SM within 1σ



Test on forward-backward asymmetry:

$$\mathcal{A}_{\mathrm{FB}} = \frac{\int_0^1 \mathrm{d}\cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell - \int_{-1}^0 \mathrm{d}\cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell}{\int_0^1 \mathrm{d}\cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell + \int_{-1}^0 \mathrm{d}\cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell}$$

$$\Delta\mathcal{A}_{\mathrm{FB}} = \mathcal{A}_{\mathrm{FB}}^{\mu} - \mathcal{A}_{\mathrm{FB}}^{e}$$

Preliminary

$$\mathcal{A}_{\mathrm{FB}}^{e} = 0.219 \pm 0.011 \pm 0.020\,,$$

$$\mathcal{A}_{\mathrm{FB}}^{\mu} = 0.215 \pm 0.011 \pm 0.022\,,$$

$$\boxed{\Delta\mathcal{A}_{\mathrm{FB}} = (-4 \pm 16 \pm 18) \times 10^{-3}}$$

Test on D* longitudinal polarization fraction:

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_V} = \frac{3}{2}\left(F_L \cos^2\theta_V + \frac{1-F_L}{2}\sin^2\theta_V\right)$$

$$\Delta F_L = F_L^{\mu} - F_L^{e}$$

Preliminary

$$F_L^{e} = 0.521 \pm 0.005 \pm 0.007$$

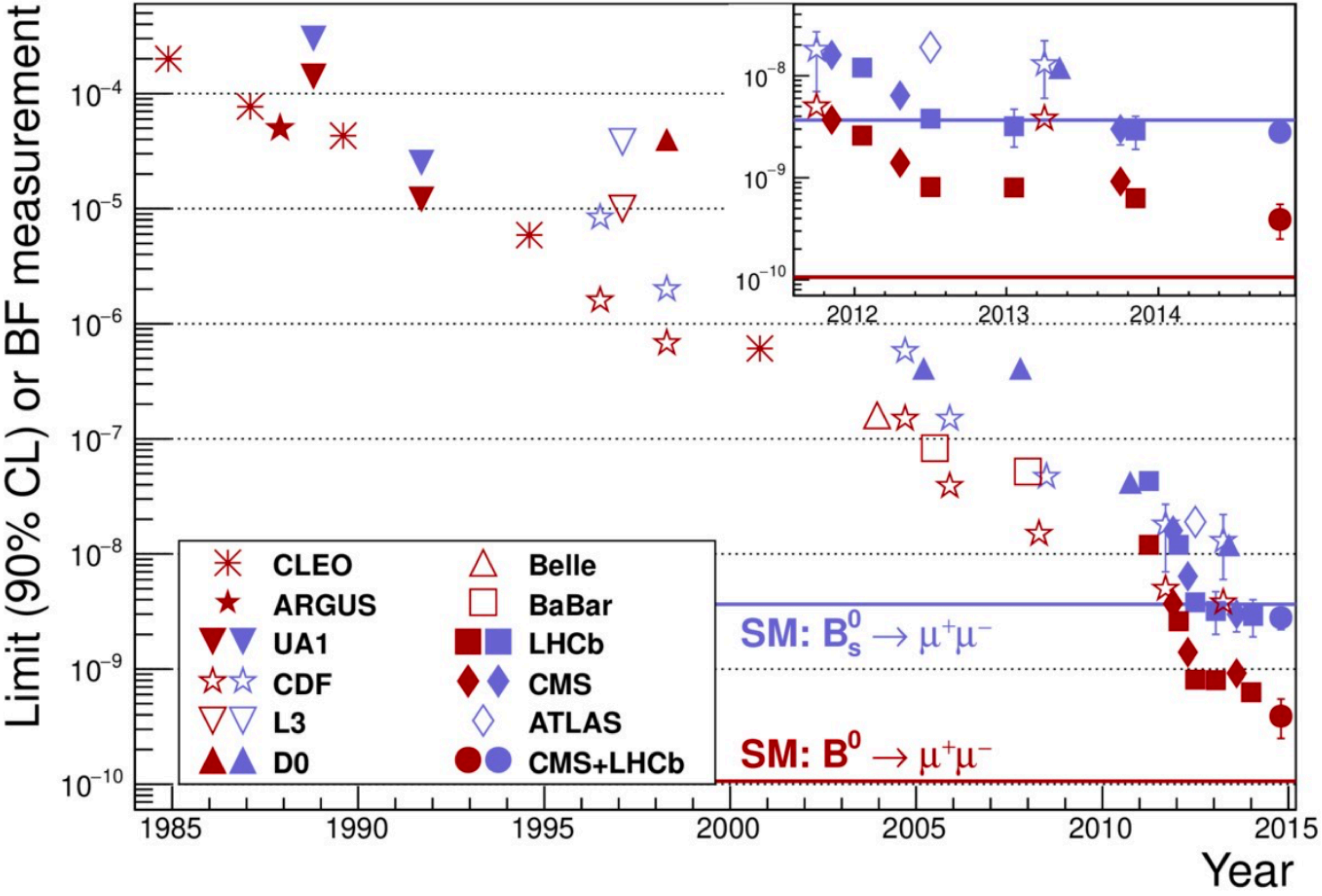
$$F_L^{\mu} = 0.534 \pm 0.005 \pm 0.006$$

$$\boxed{\Delta F_L = 0.013 \pm 0.007 \pm 0.007}$$

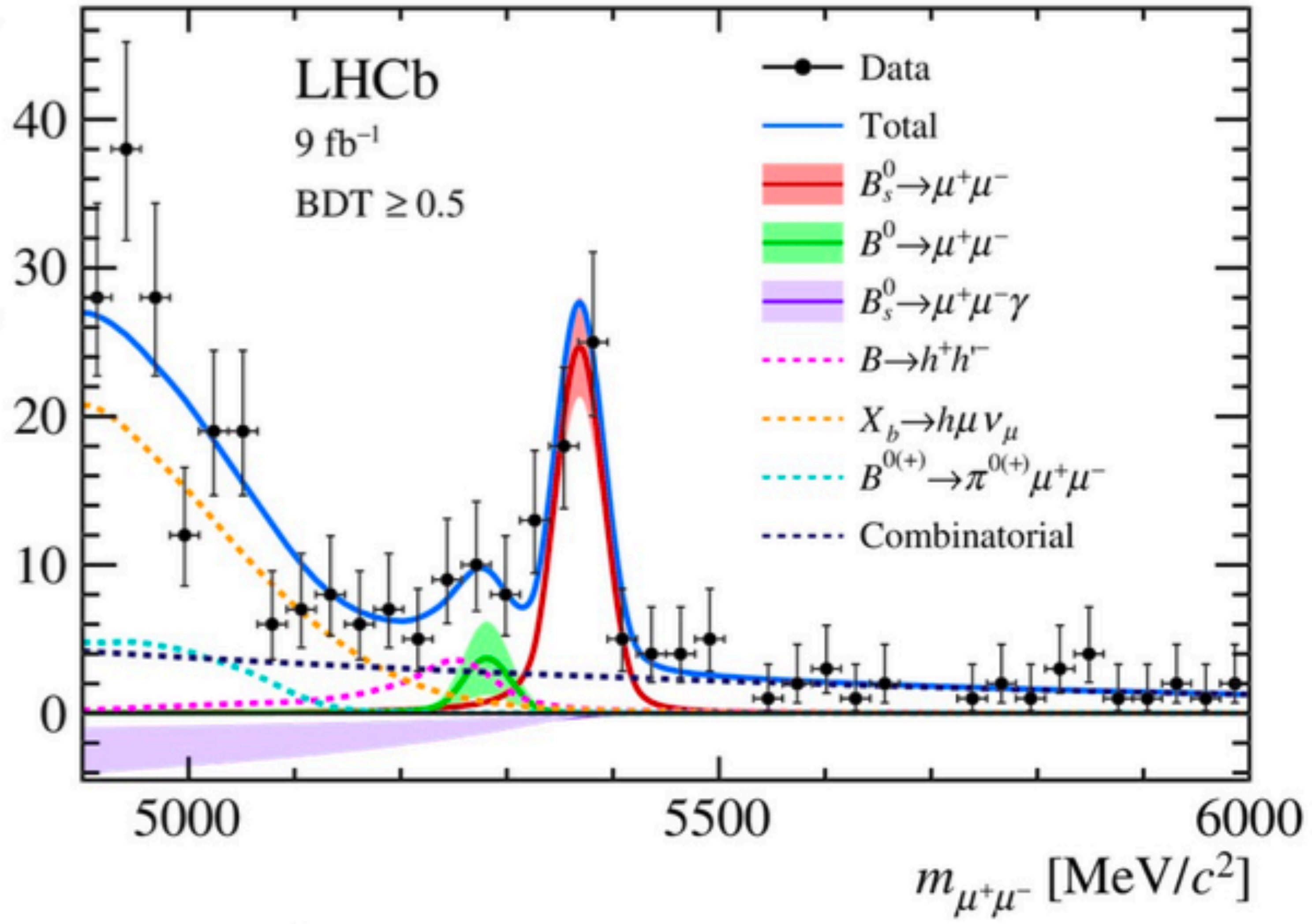
Belle 2

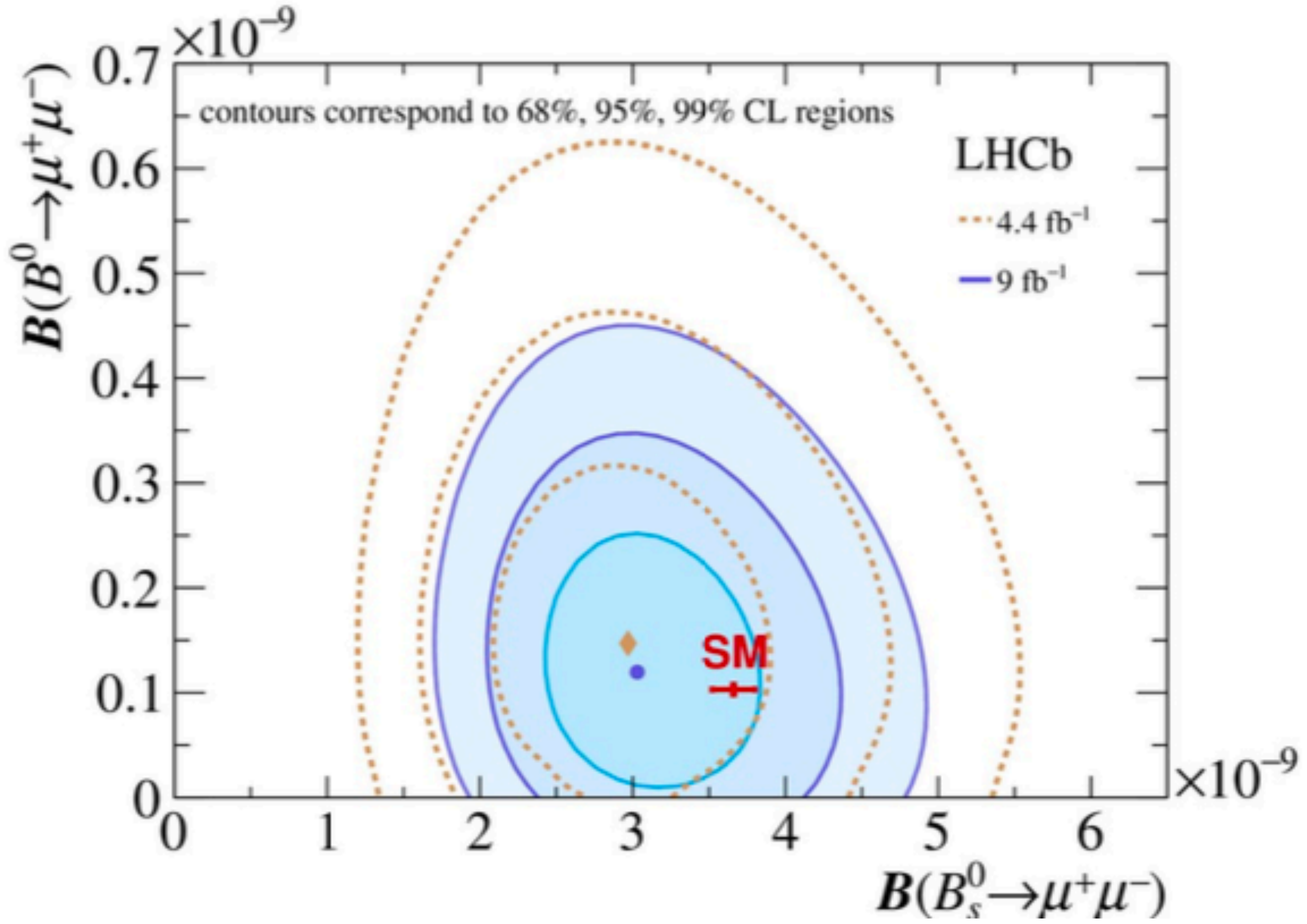
Very appealing to be able to do Lepton Universality tests from angular analysis

What else?

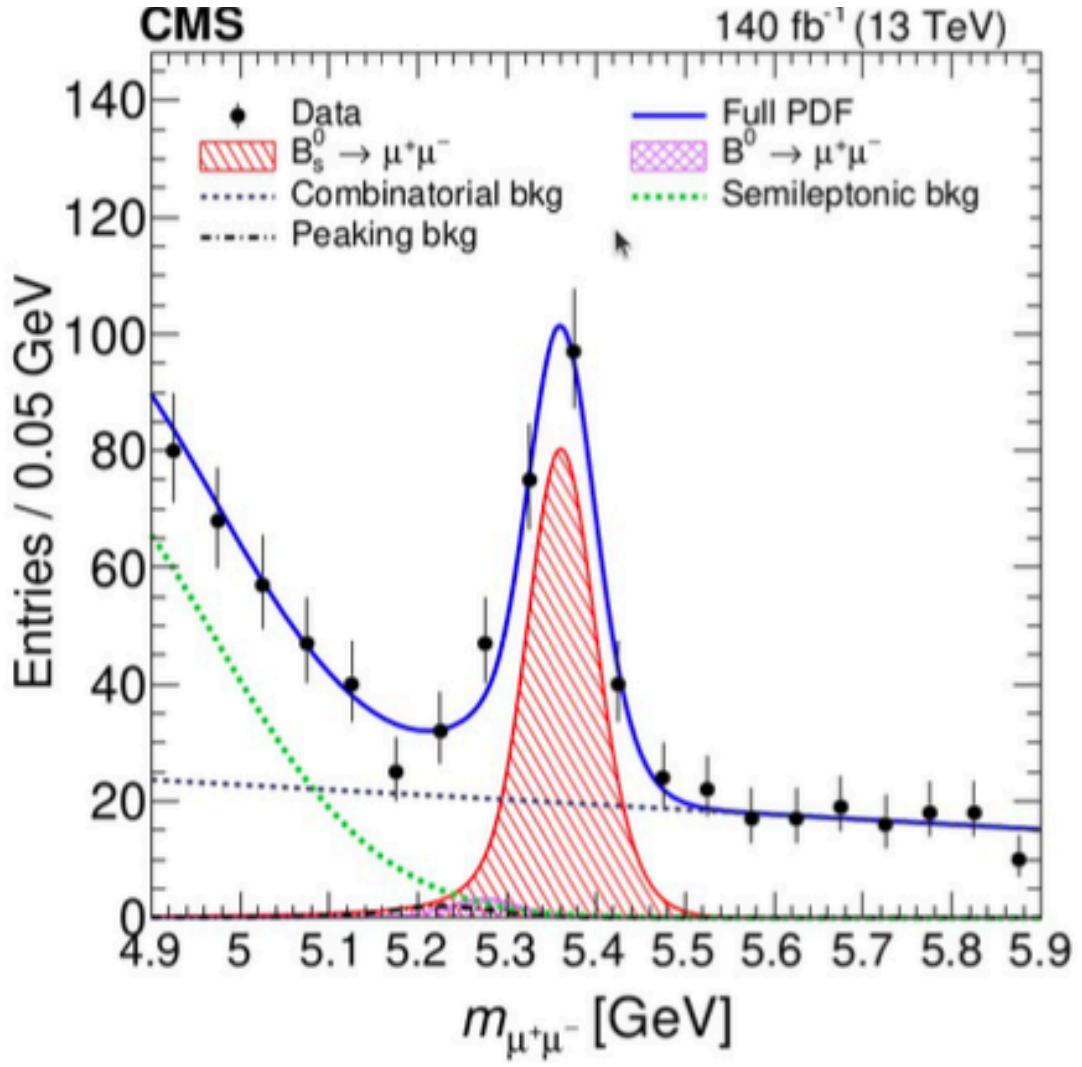


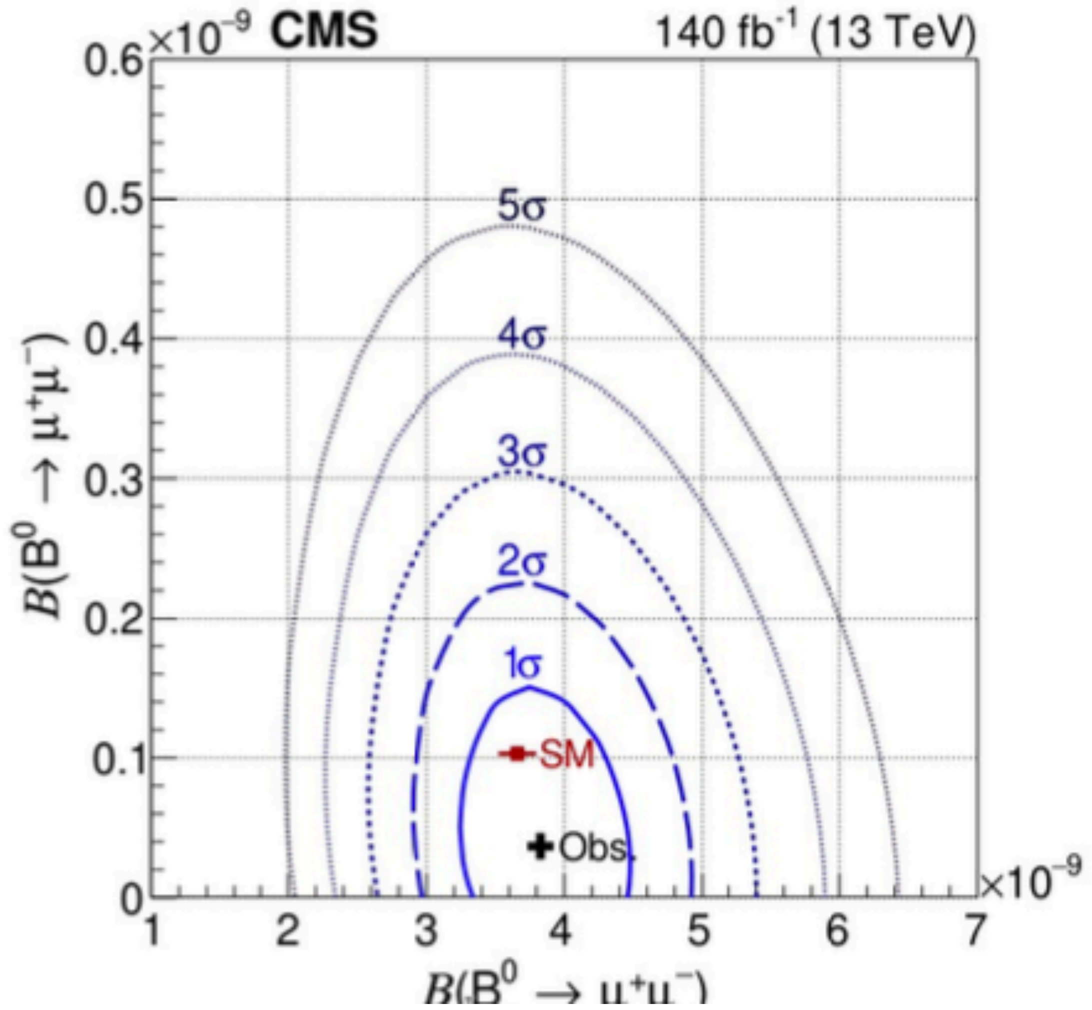
Limit (90% CL) or BF measurement
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
1985
1990
1995
2000
2005
2010
2015
Year
2012
2013
2014
CLEO
ARGUS
UA1
CDF
L3
D0
Belle
BaBar
LHCb
CMS
ATLAS
CMS+LHCb
SM: $B_s^0 \to \mu^+\mu^-$
SM: $B^0 \to \mu^+\mu^-$



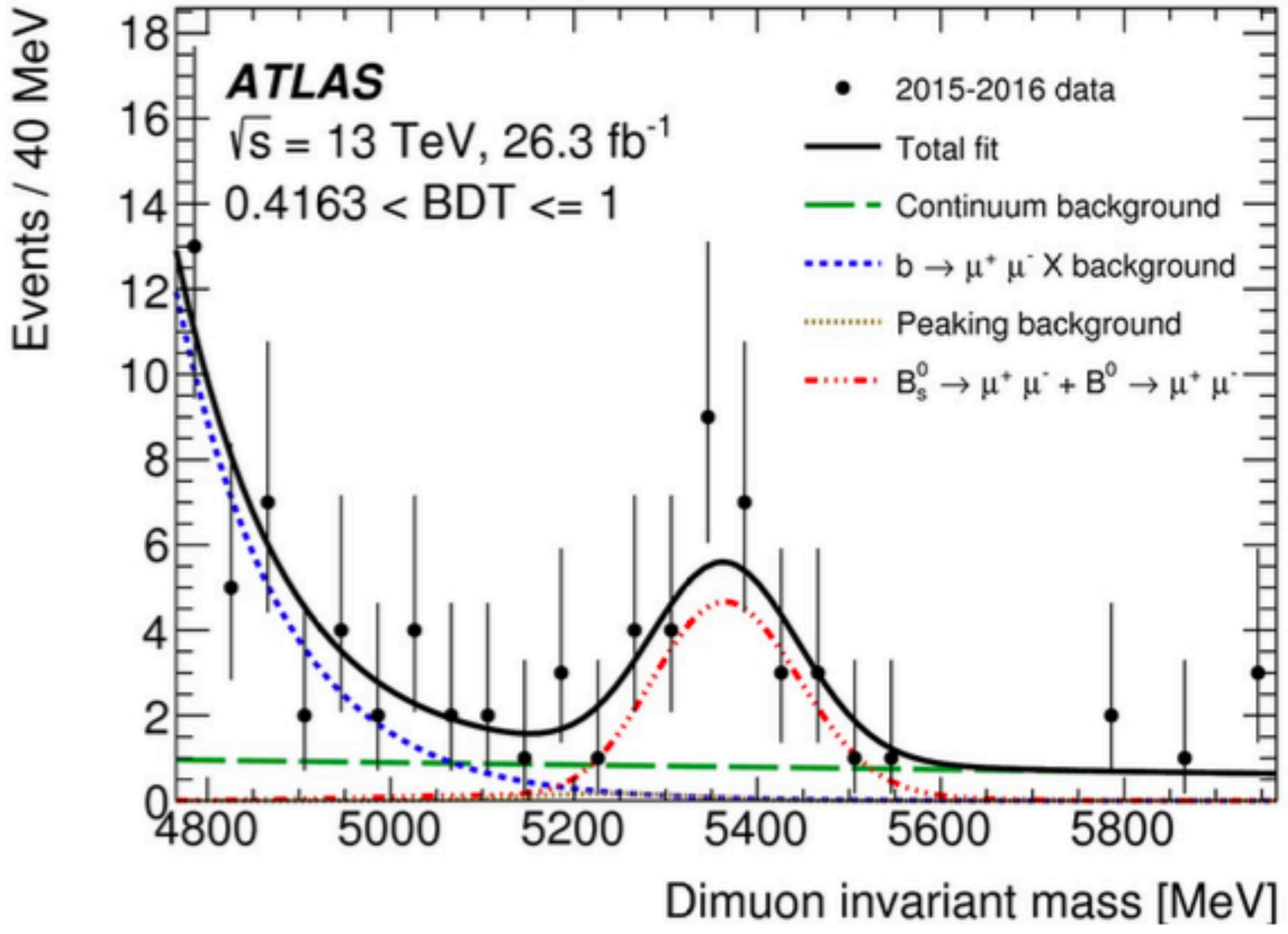


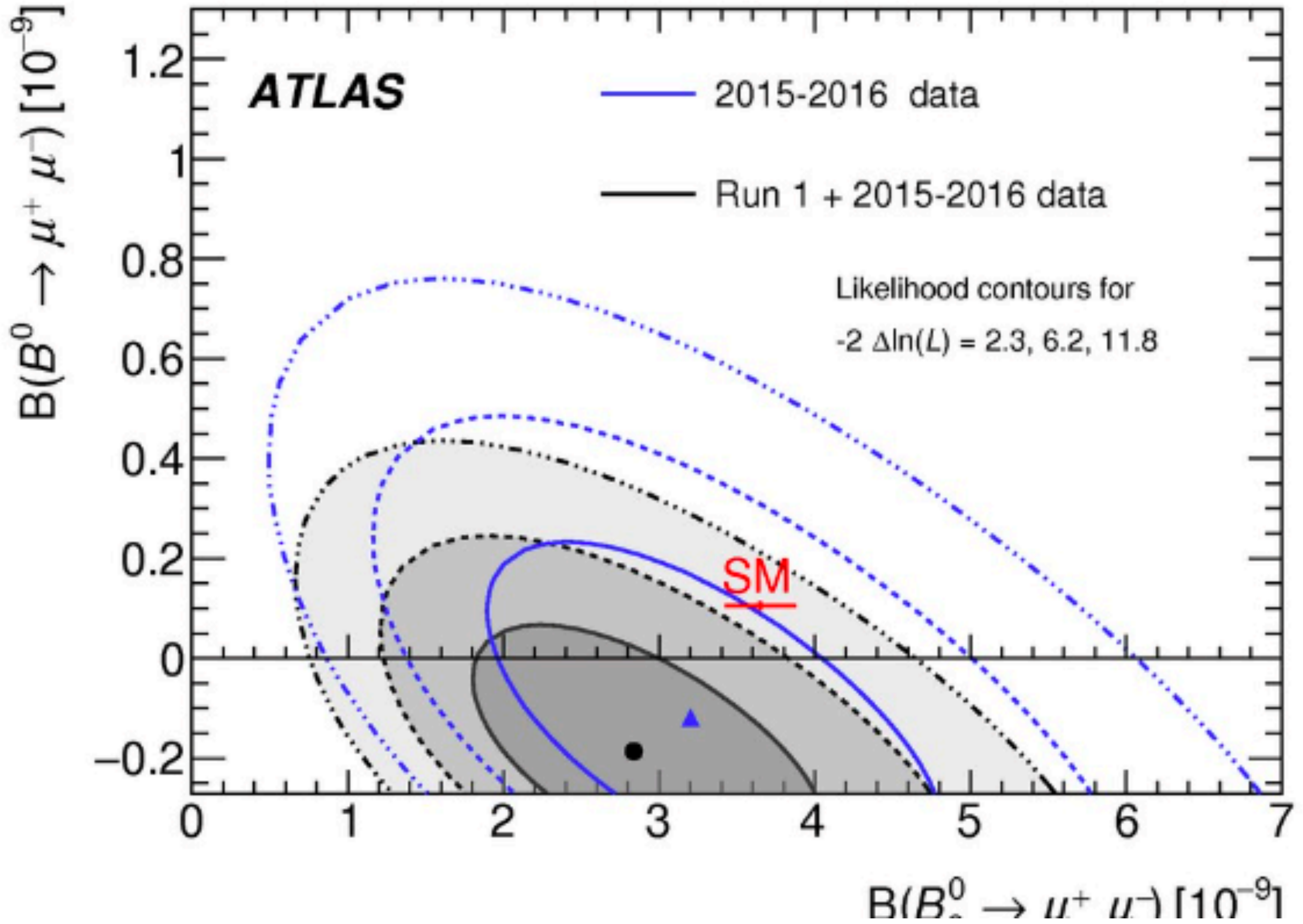
LHCb, PRL 128 (2022) 041801



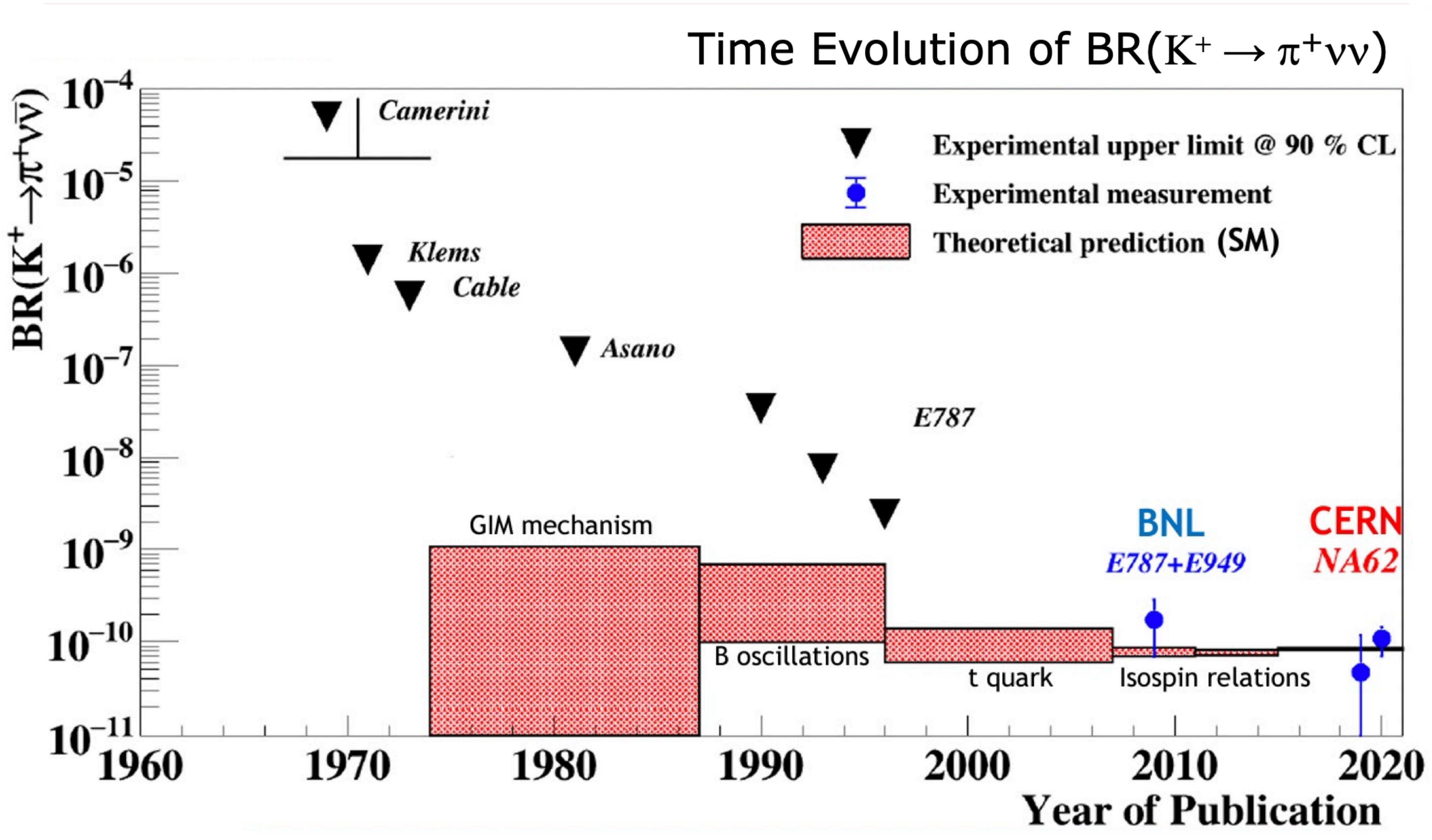


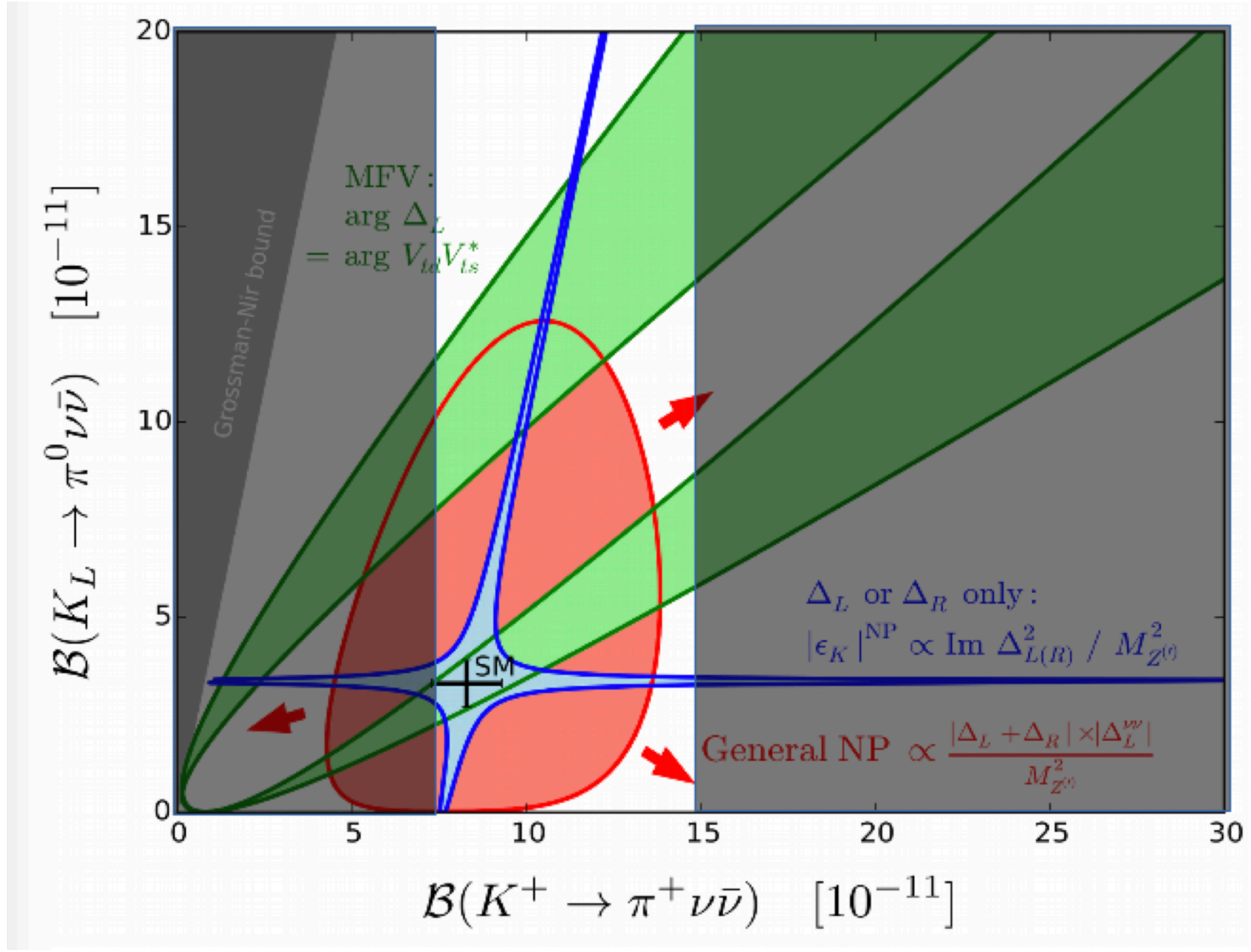
CMS, PL B842 (2023) 137955

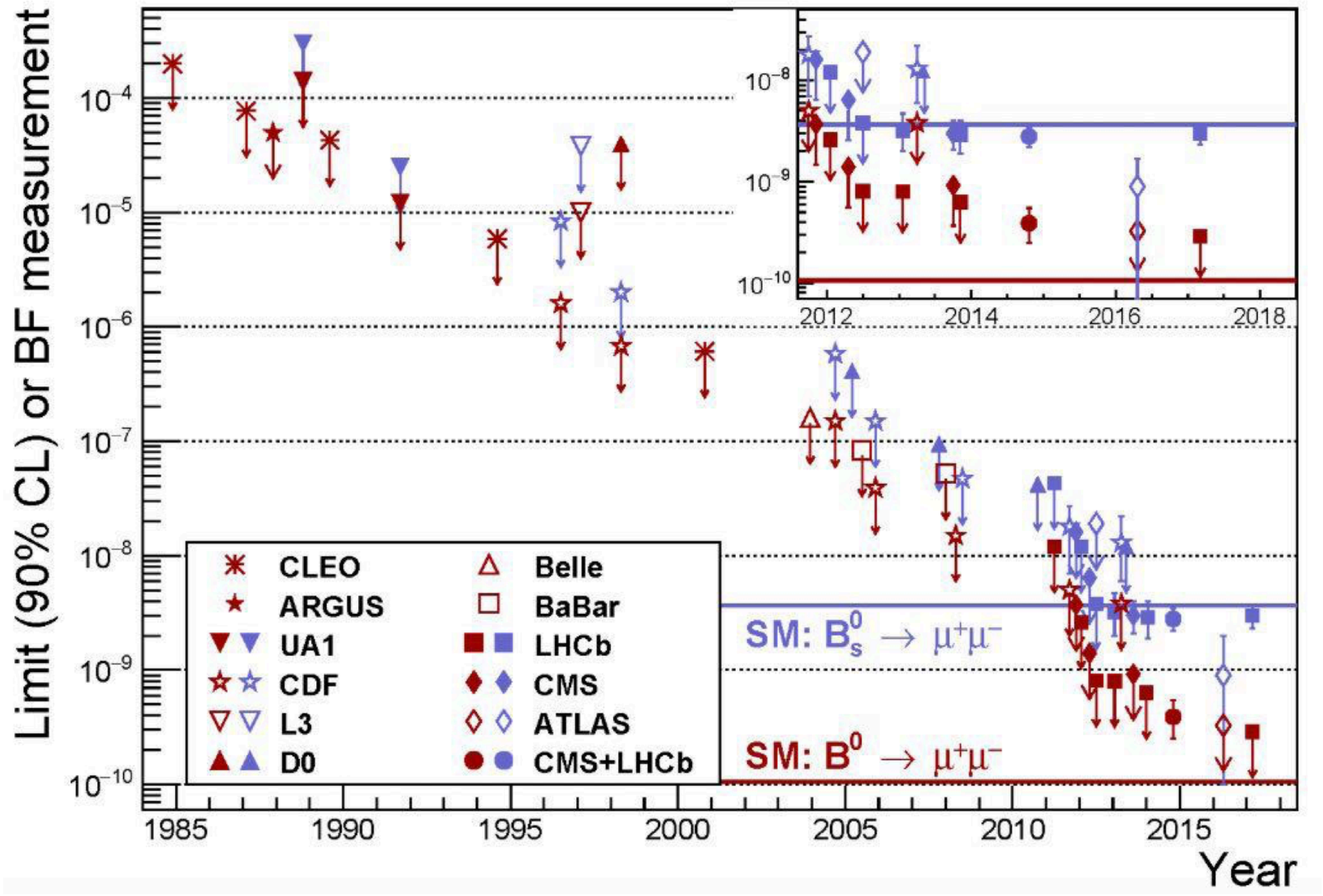


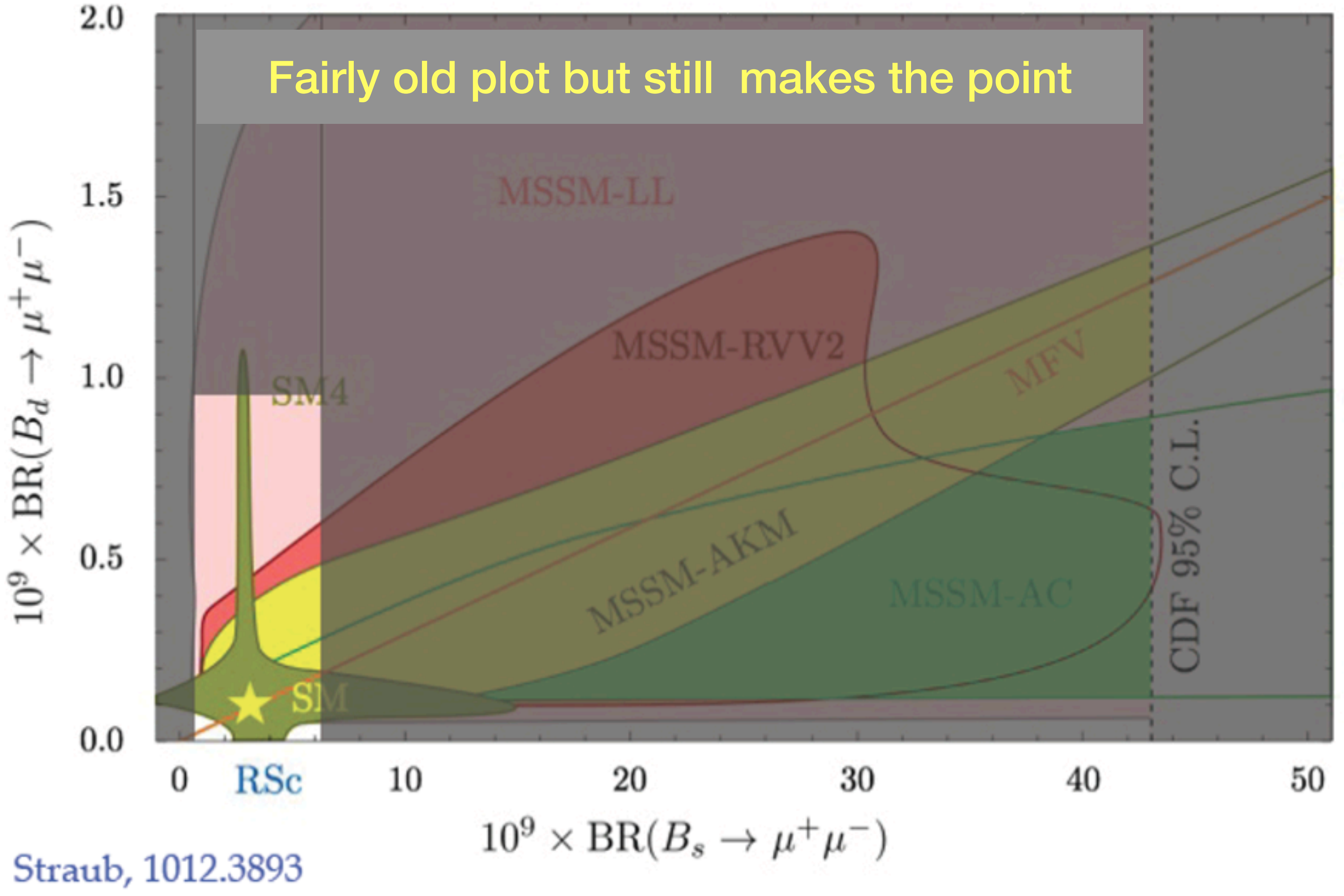


ATLAS, JHEP 04 (2019) 098







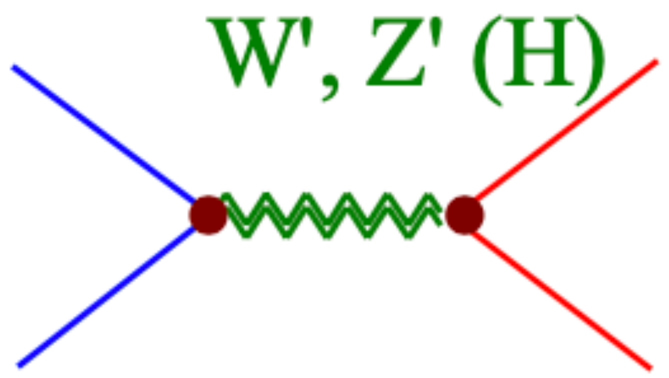


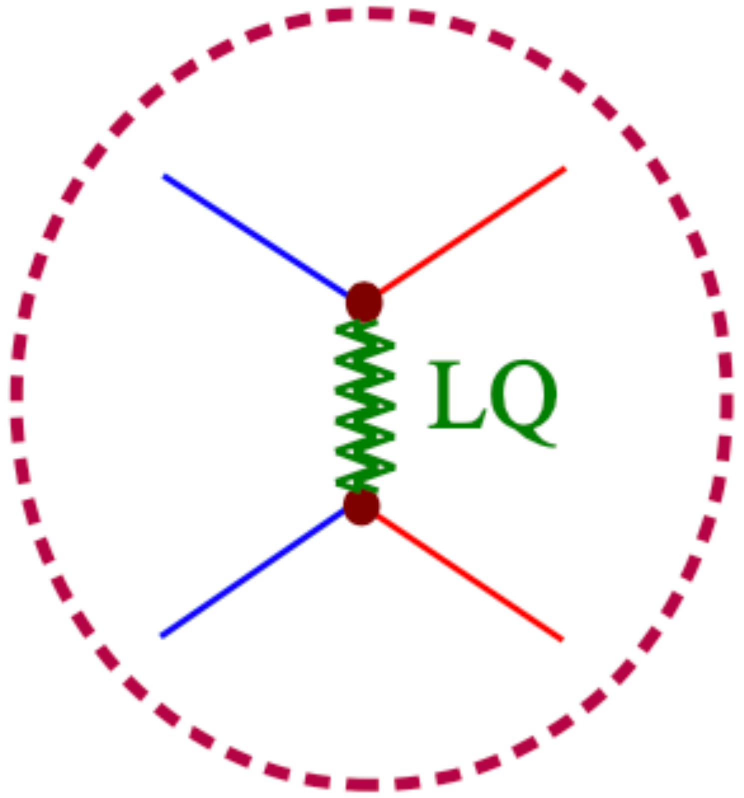
Always be grateful to D.Straub for inventing Flavio

Yes but what about New Physics?

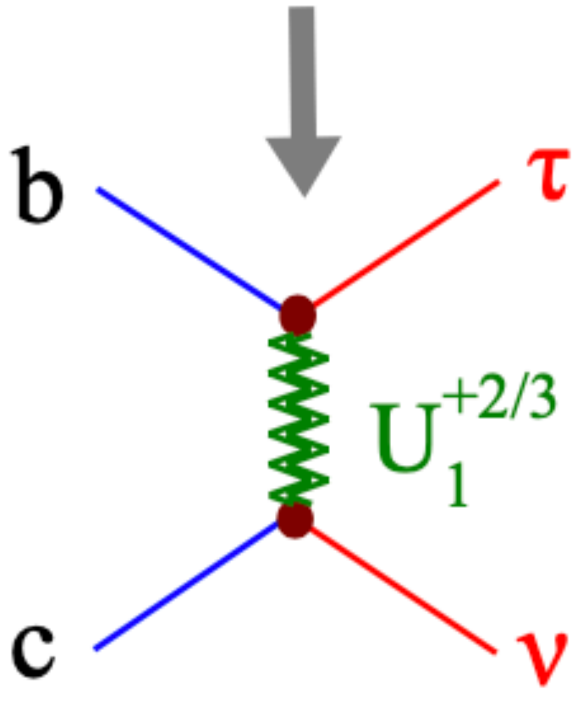
Speculations on present data: from EFT to the UV

Which mediators can generate the effective semileptonic operators required by EFT analysis? Not many possibilities...





Leptoquarks (both scalar and vectors) have a strong advantage: only semileptonic operators at the tree-level (*no four-quark operators → strong bounds from meson-antimeson mixing*)



Simplest option:

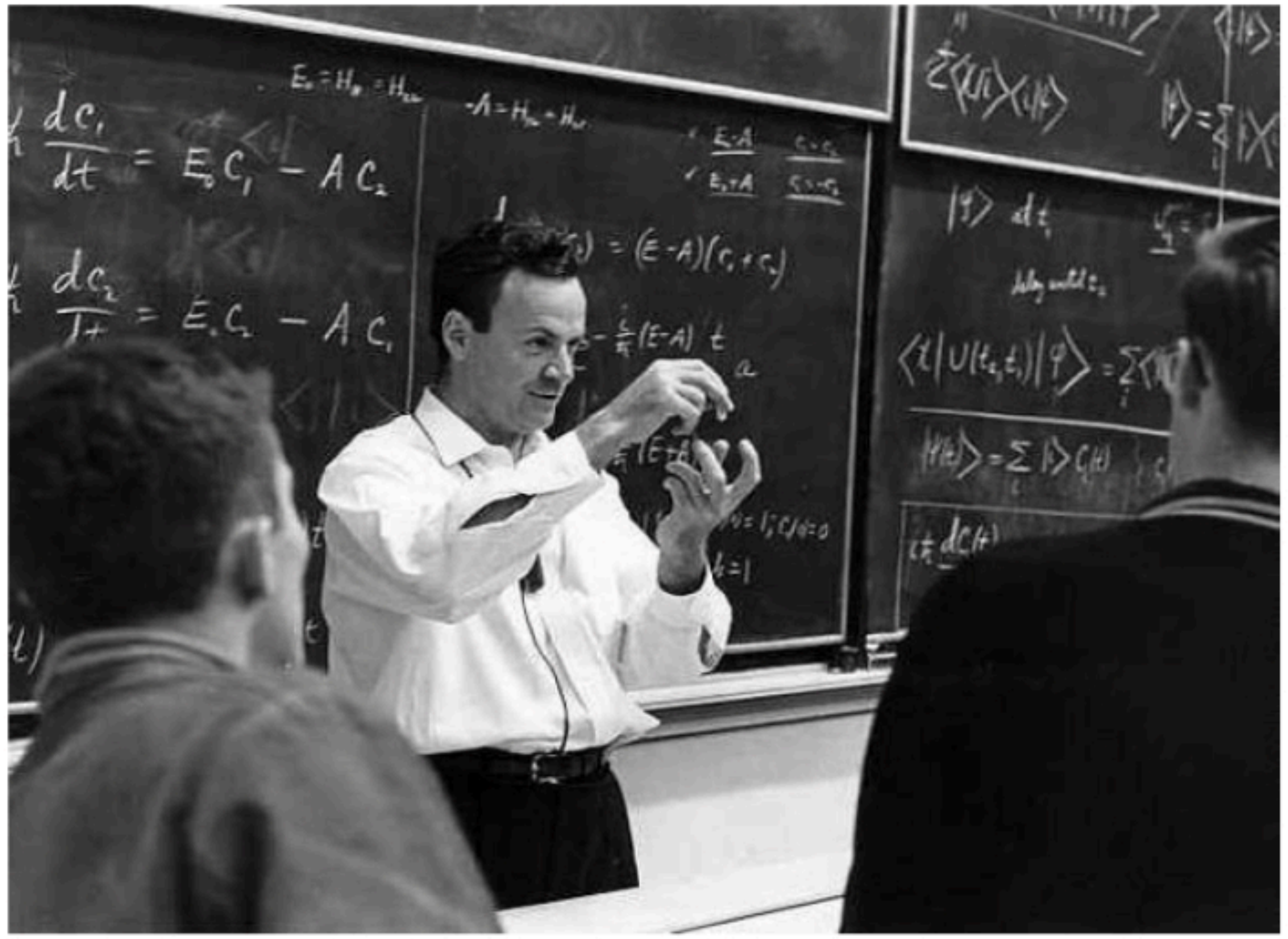
LQ of the Pati-Salam gauge group:

$SU(4) \times SU(2)_L \times SU(2)_R$

Fermions in SU(4): $\begin{bmatrix} Q^\alpha \\ Q^\beta \\ Q^\gamma \\ L \end{bmatrix}$

$$SU(4) \sim \left[\begin{array}{c|c} SU(3)_C & 0 \\ \hline 0 & 0 \end{array}\right] \left[\begin{array}{c|c} 0 & LQ \\ \hline LQ & \end{array}\right] \left[\begin{array}{c|c} \frac{1}{3} & 0 \\ \hline 0 & -1 \end{array}\right]$$

Implications & future prospects



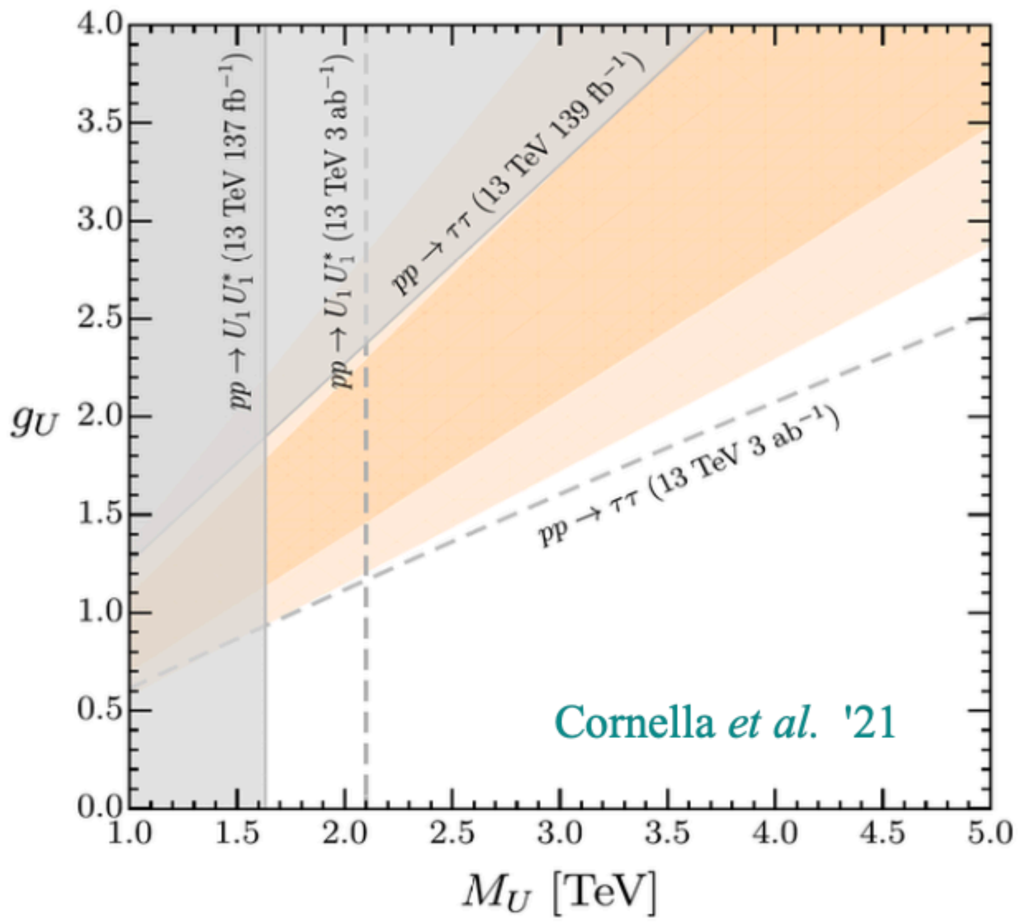
"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]

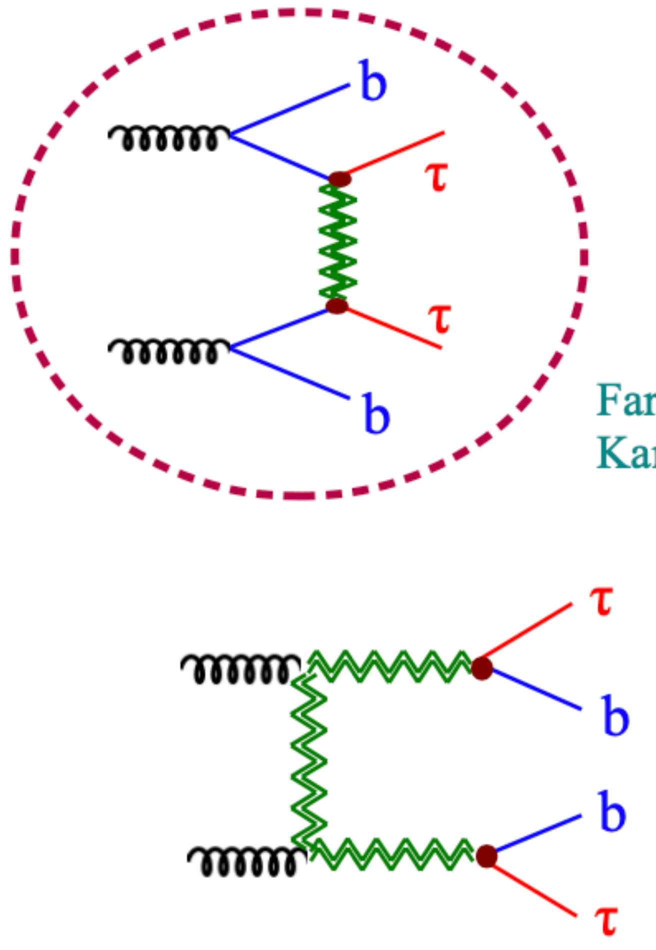
Implications & future prospects

If the ideas I sketched before are correct (*even only in part...*), we can expect several interesting new phenomena, at both low and high energies

I The U_1 exchange @ high-energies
[very general, directly connected to the EFT analysis]

$pp \to \tau\tau$

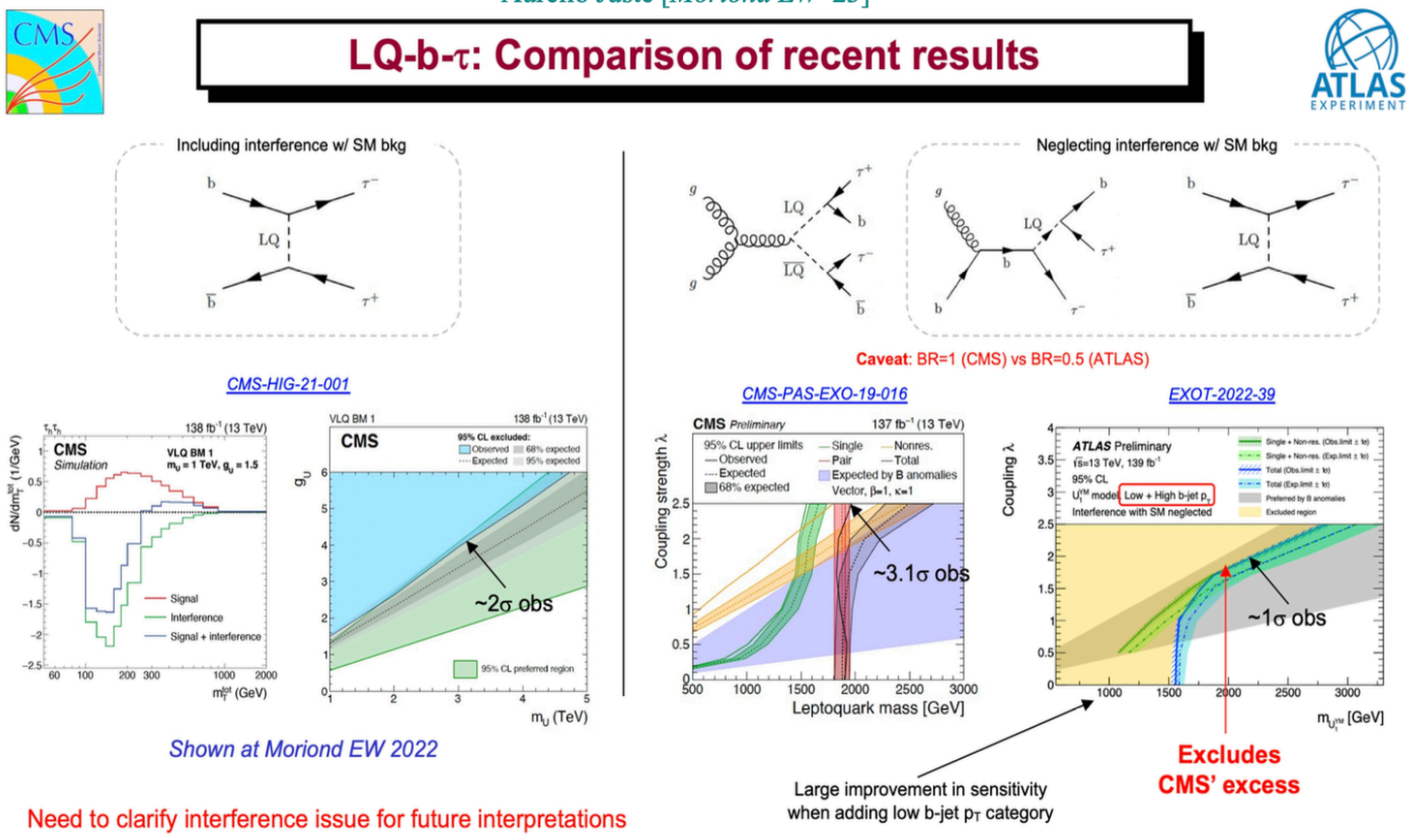




Faroughi, Greljo, Kamenik '16

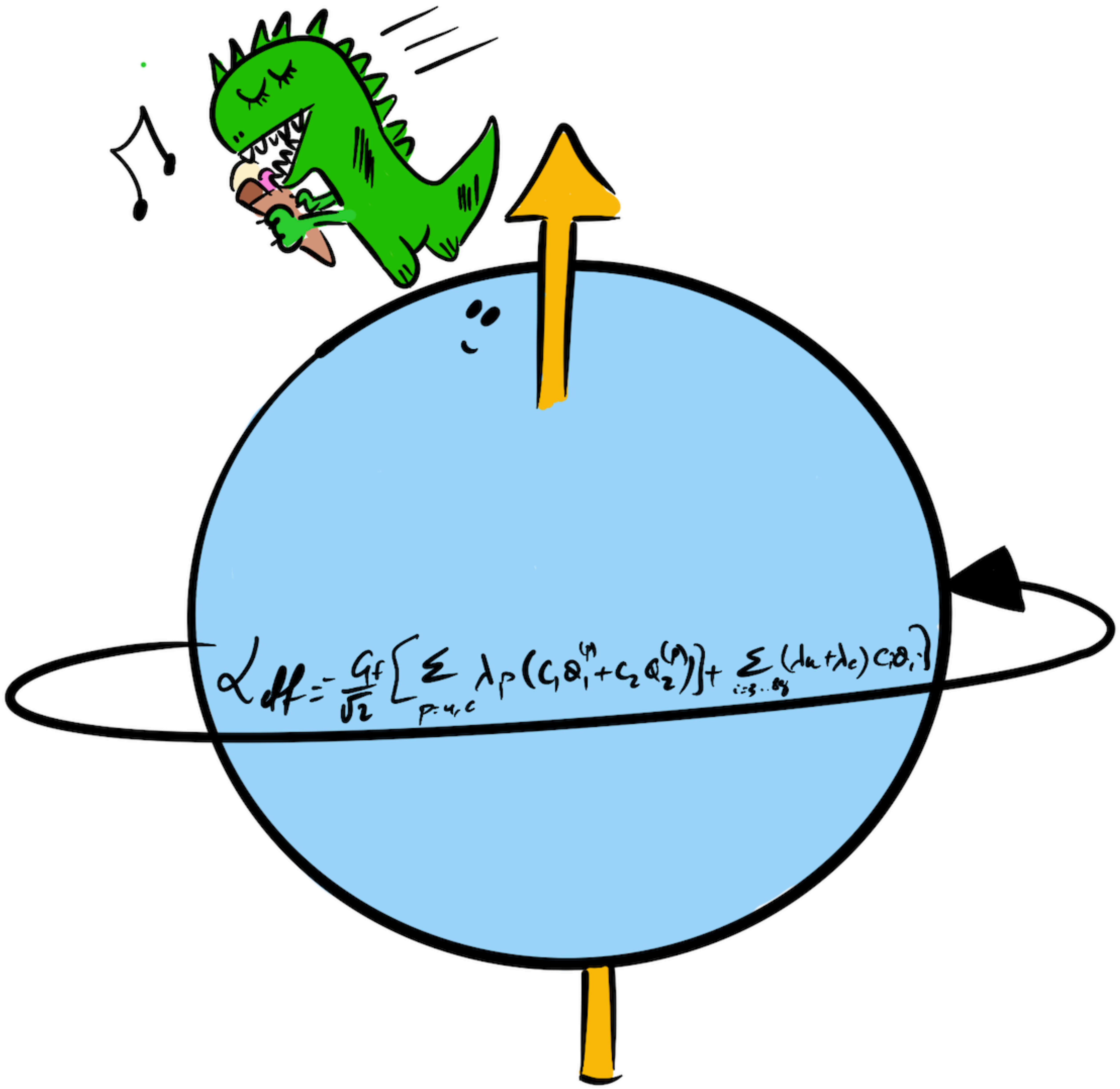
Implications & future prospects

Aurelio Juste [*Moriond EW* '23]



To almost conclude

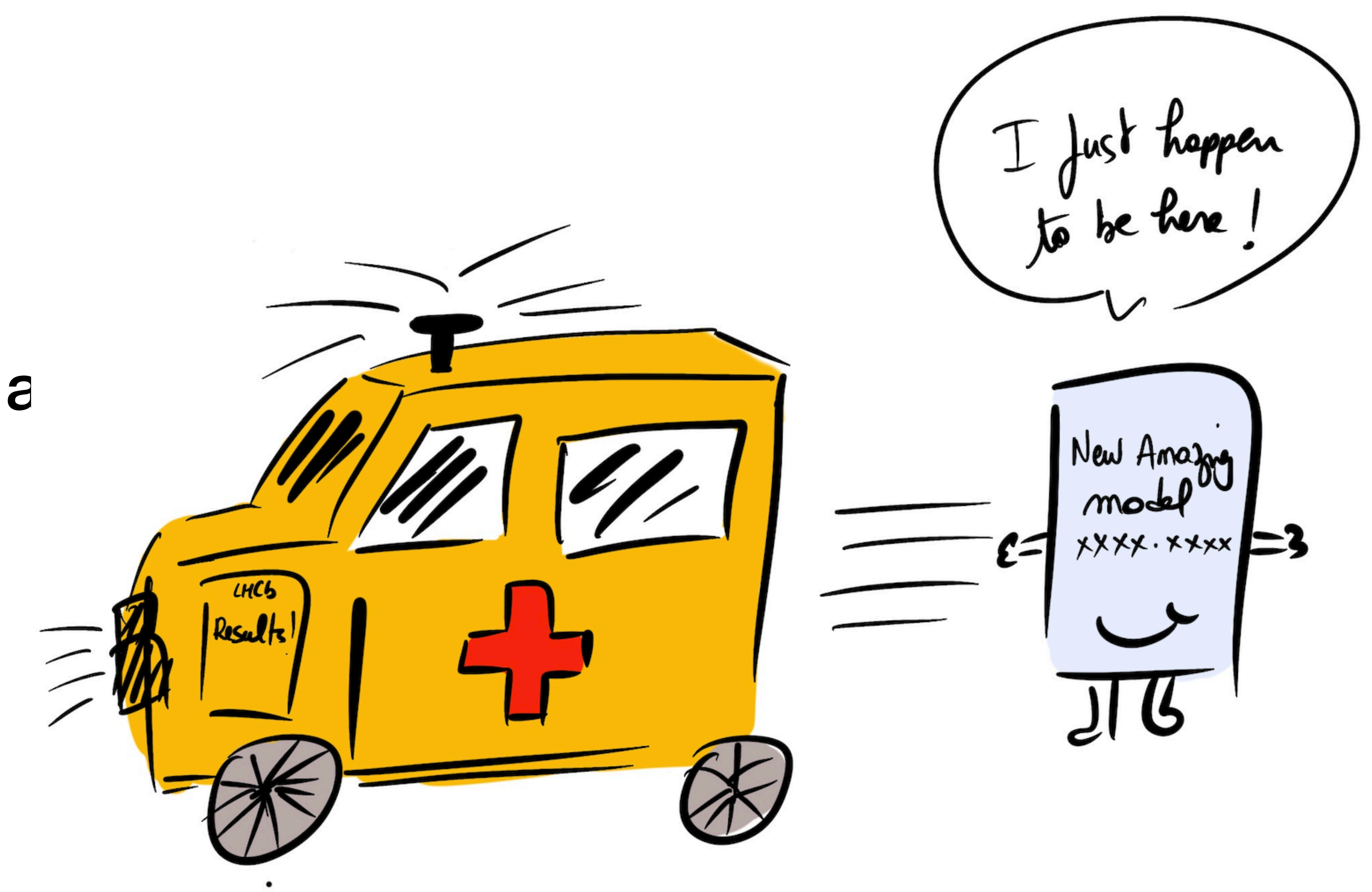
- We need New Physics !
- Flavour Physics is a super cool laboratory to search for it.
- So far the Standard Model seems to be putting up a good fight.
- We can only reply on the imagination of physicists to make the next breakthroughs.
- There are a number of experiments lined up to pursue this adventure !



Good practices for PhD students

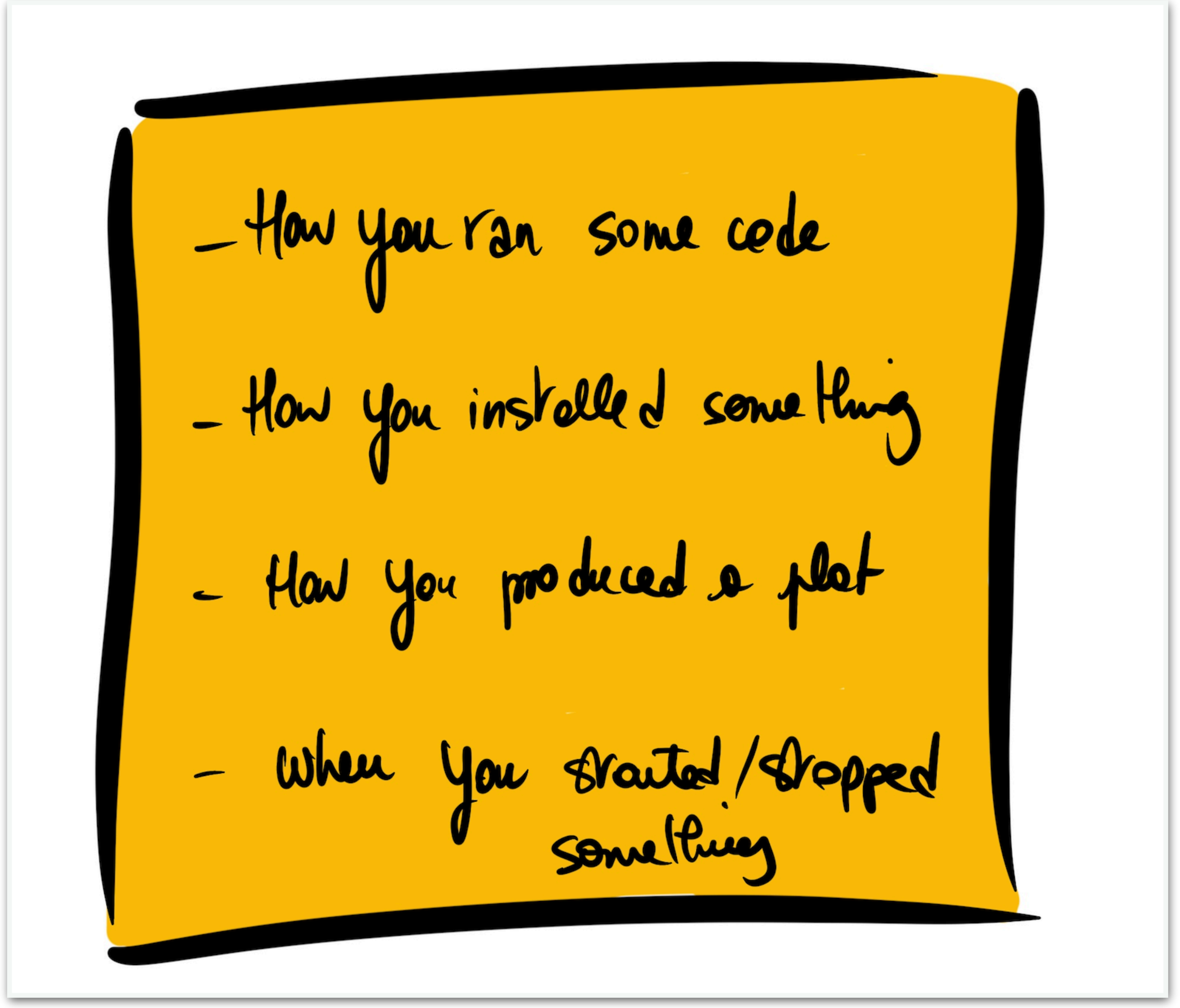
If one day you become a PhD student

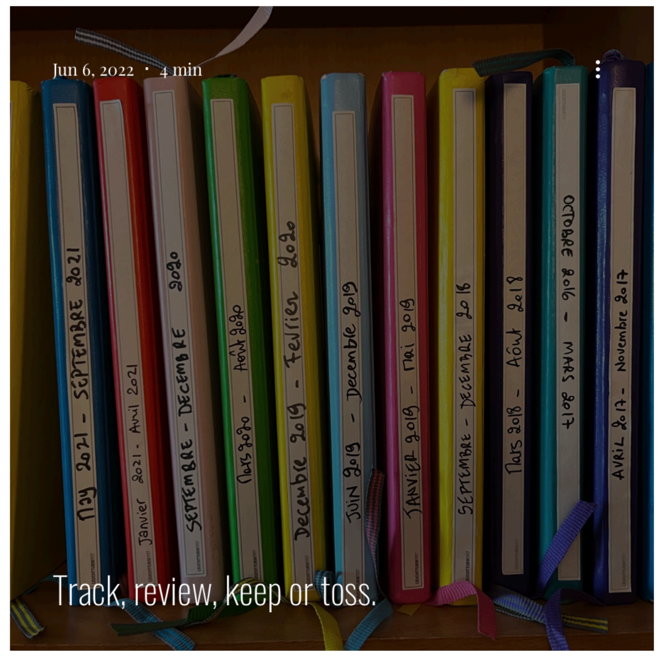
- Keep an eye on arXiv.
- Check the theory and experimental summeries talks at conferences a workshops
- Check the review articles.
- Check other submitted PhDs manuscripts.
- Don’t be shy and ask questions.



And please please please

- Log your work, it does not matter if you use notebooks, software, whatever.
- Keep track of everything you do, we forget details, we forget obvious things. We always think that we will remember.
- The amount of information to store only increases, so help your future you and write down things.



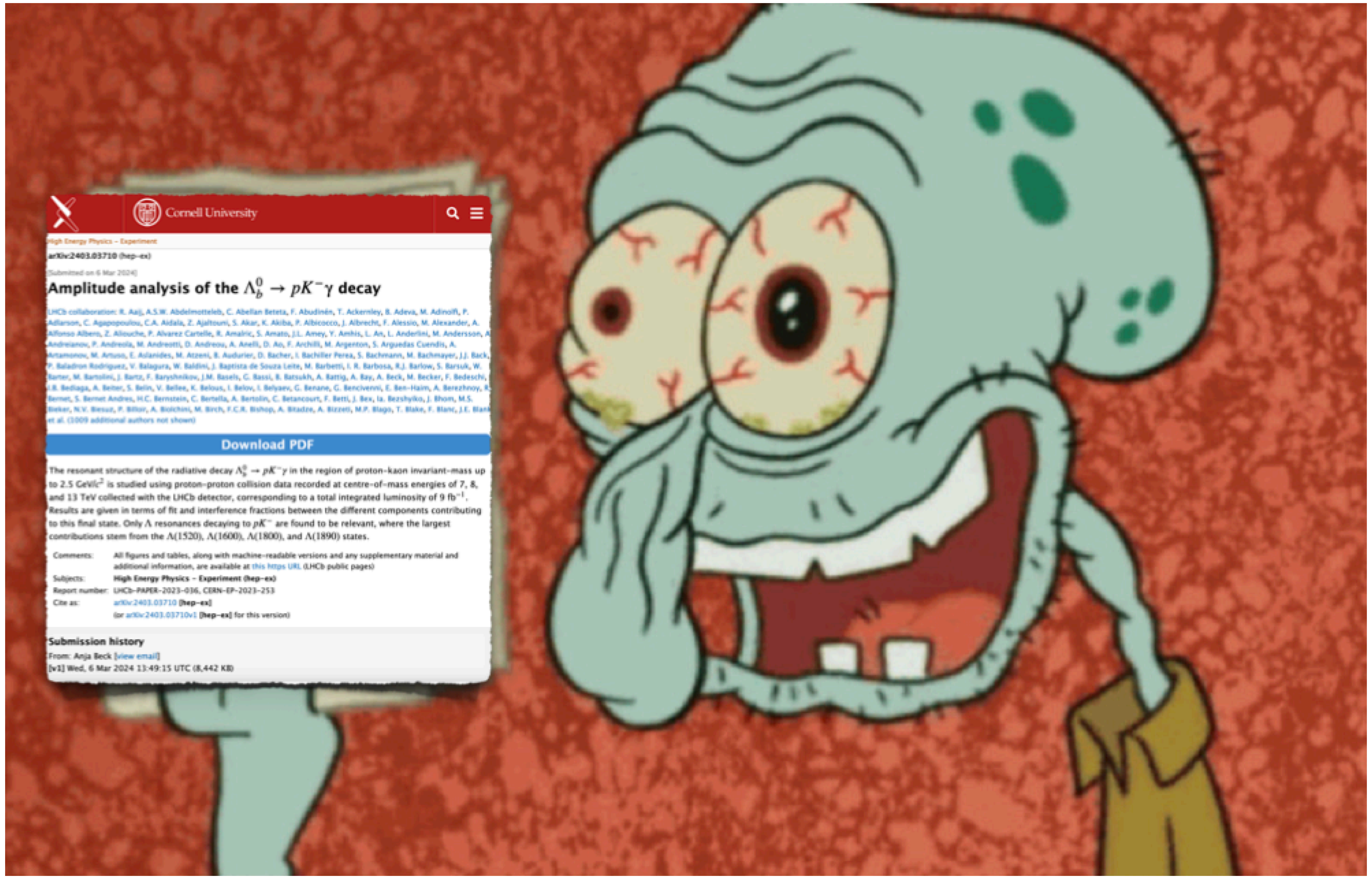


https://www.yasmineamhis.com/post/track-review-keep-or-toss

https://www.yasmineamhis.com/post/3-tips-for-new-phd-graduates

A colouring book for children will soon be available at the CERN Science Gateway

More information yasmineamhis.com



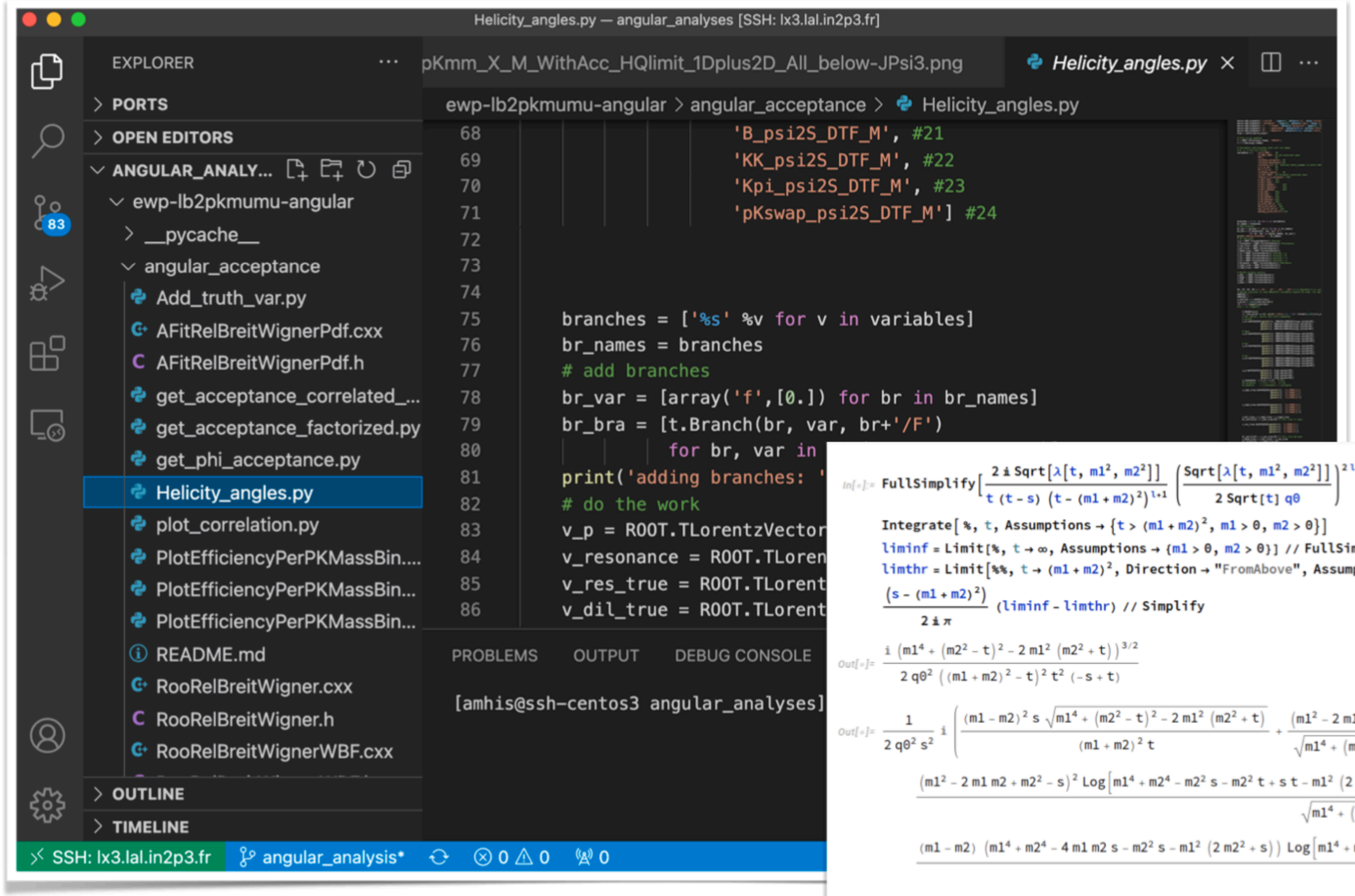
Credit to Anja Beck

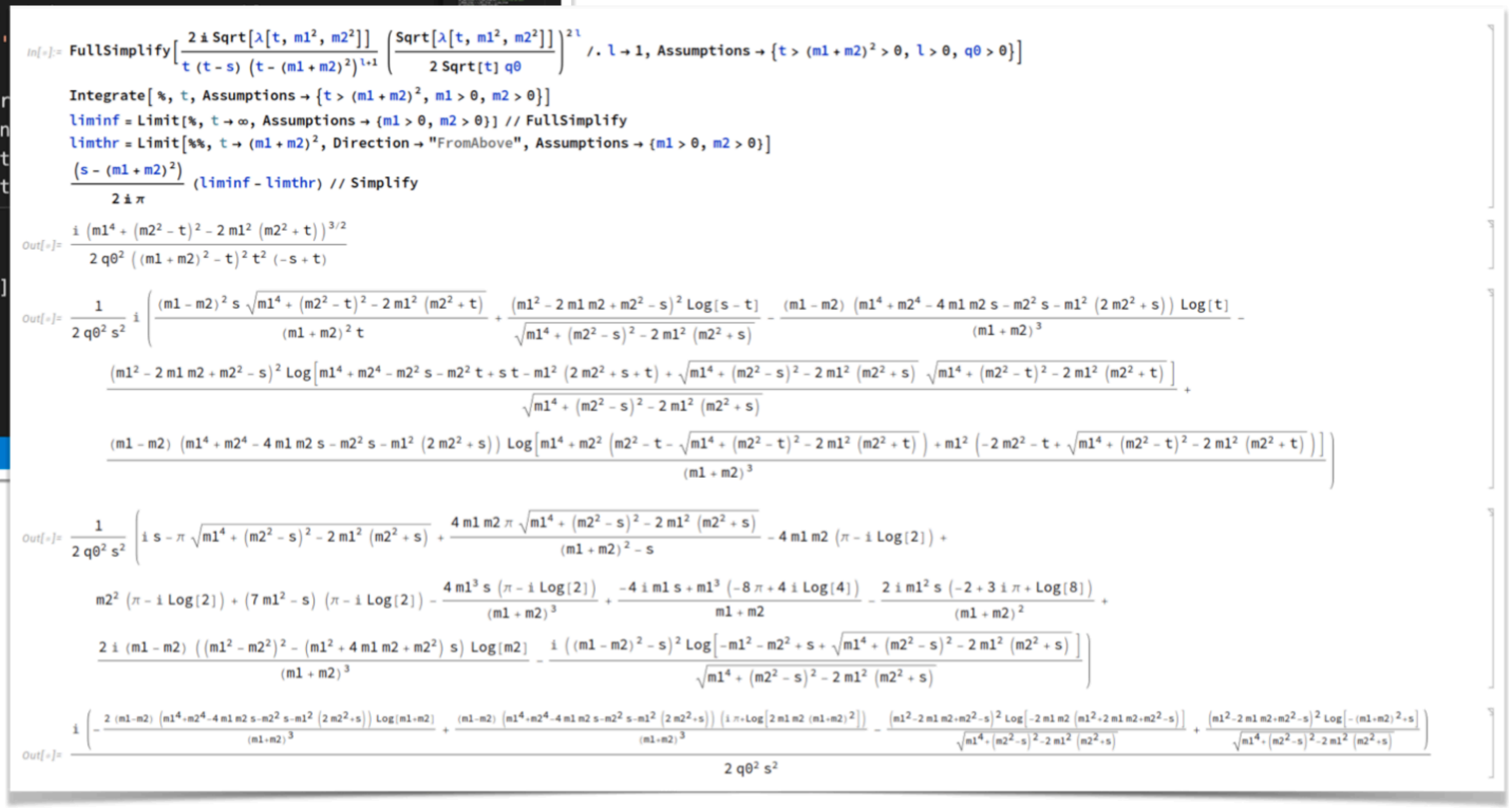
What are we doing here?

Understanding the origin of the universe

Searching for Physics Beyond the Standard Model

And how’s that working out for you?





Most probably …

Hang in there, it will get better (maybe)

It’s a chance to do things with your “hands”

Thank you for your attention

If you have questions yasmine.sara.amhis@cern.ch