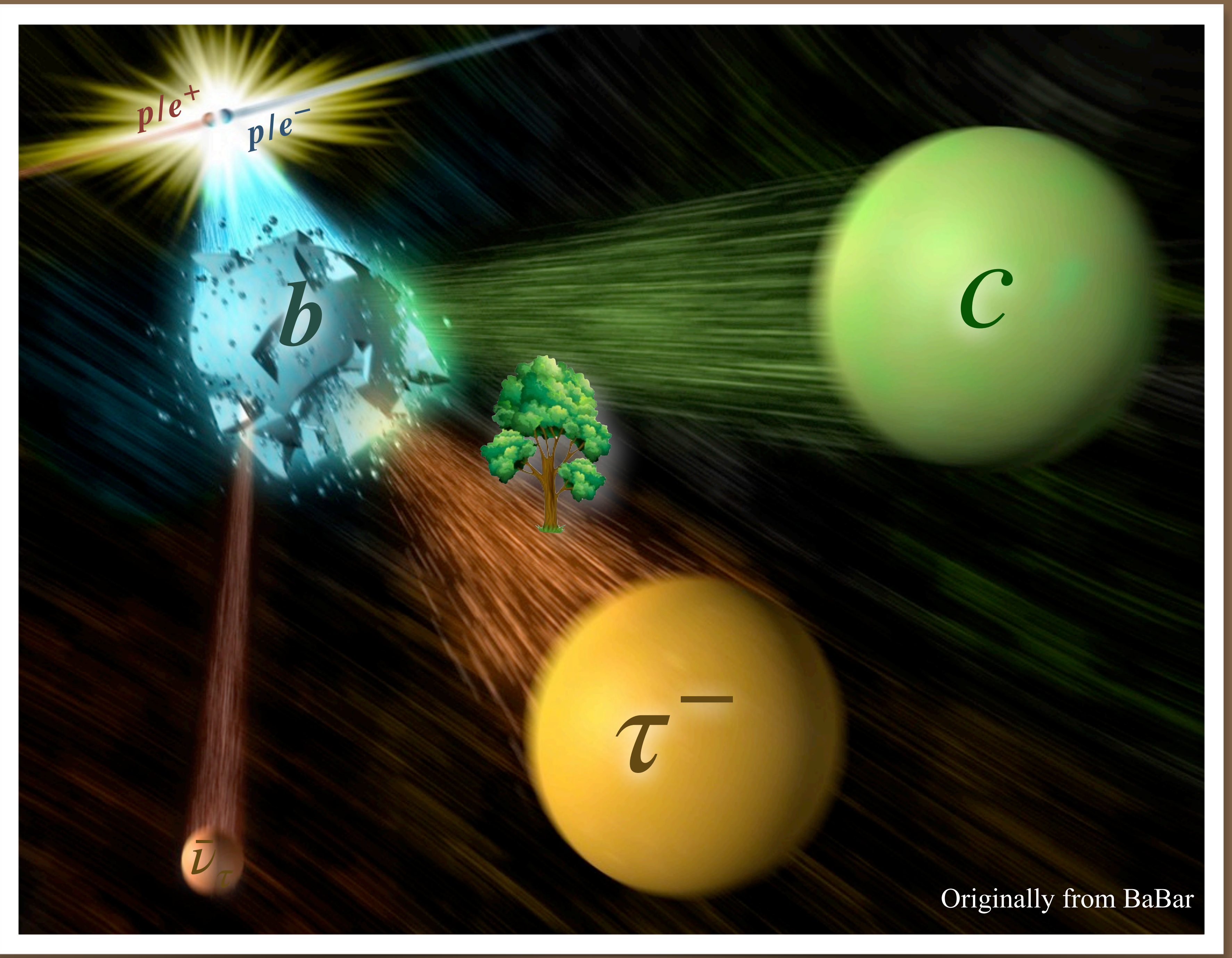
New physics in B decays? Challenges to Lepton Flavor Universality from LHCb and the B factories

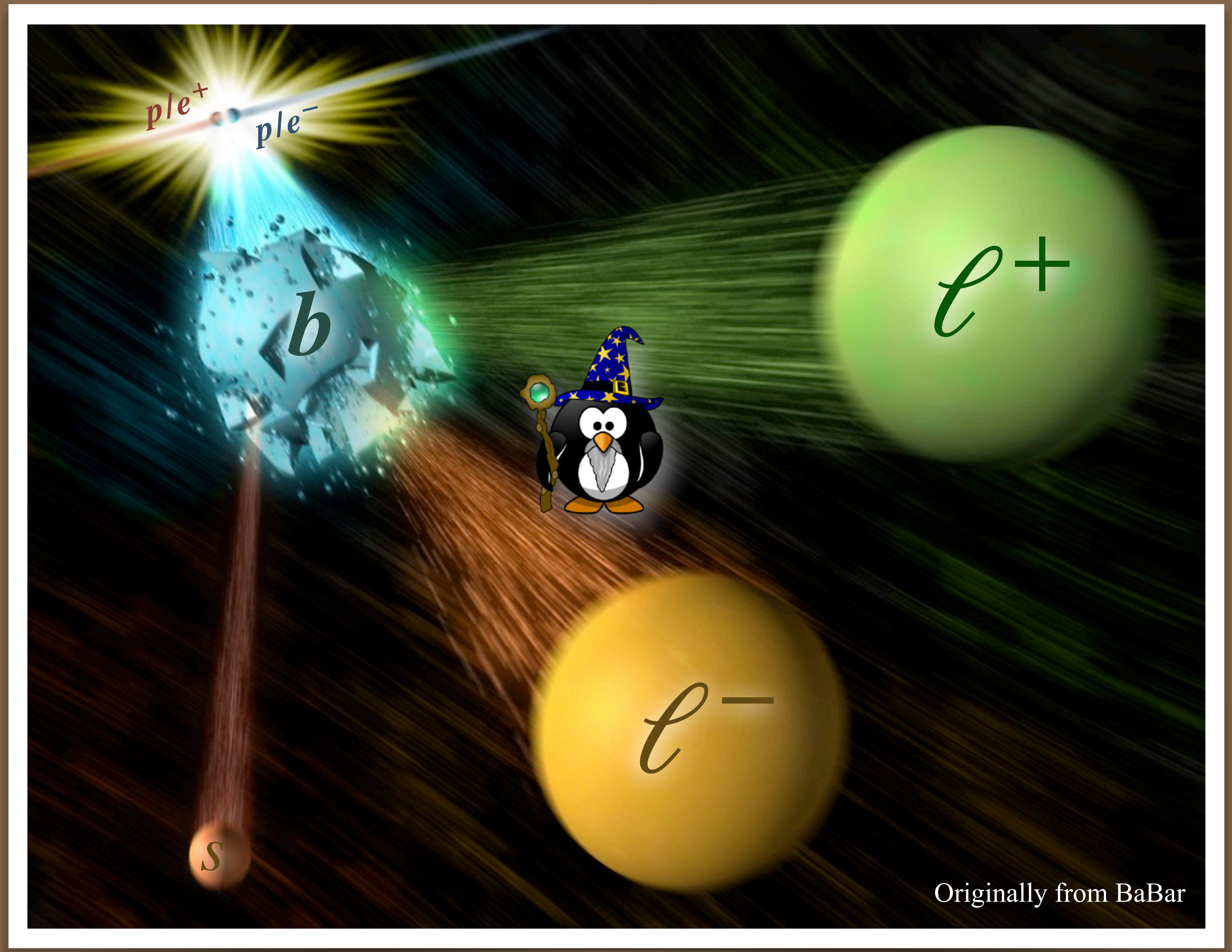
Manuel Franco Sevilla

University of Maryland



7th September 2021

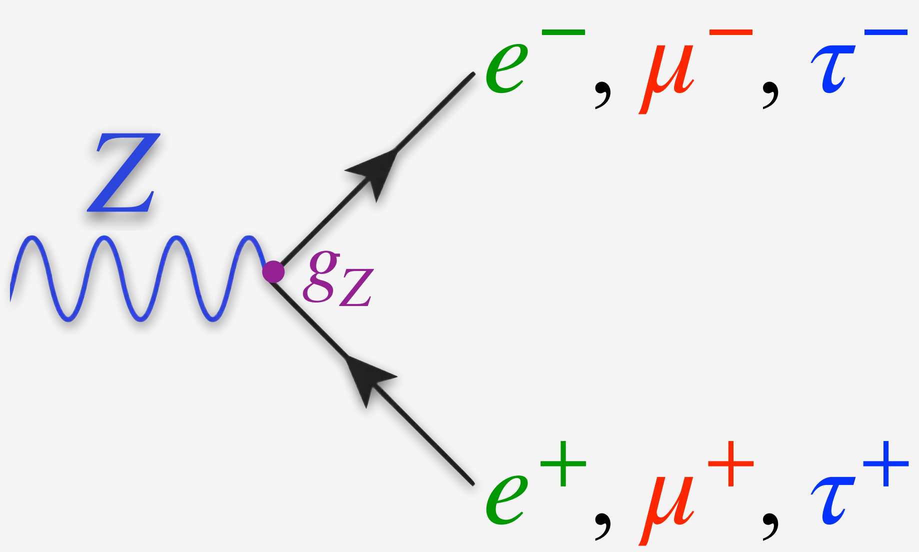
UMD colloquium



Penguin from Jeff Brassard

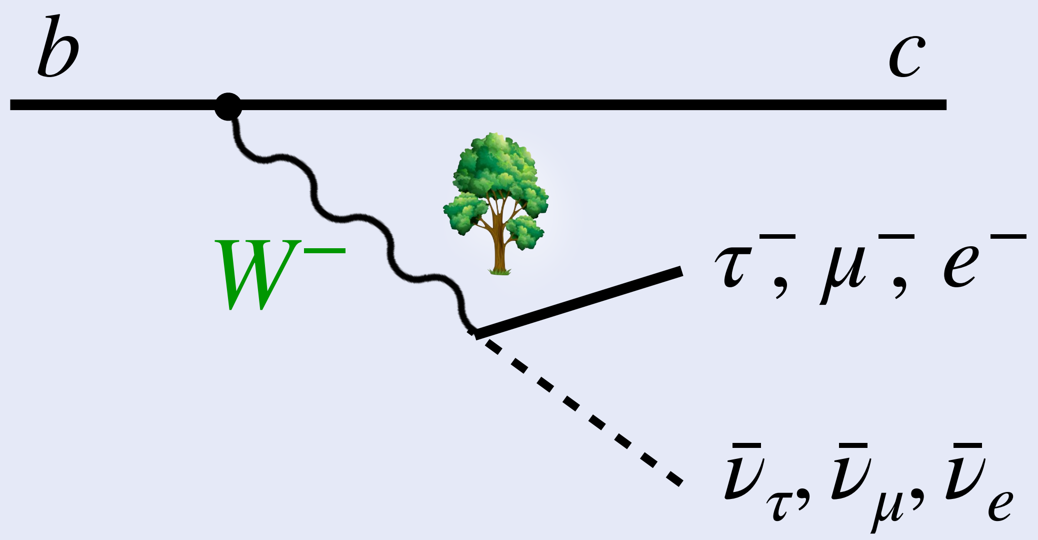
Outline

1. What is LFU and why we care

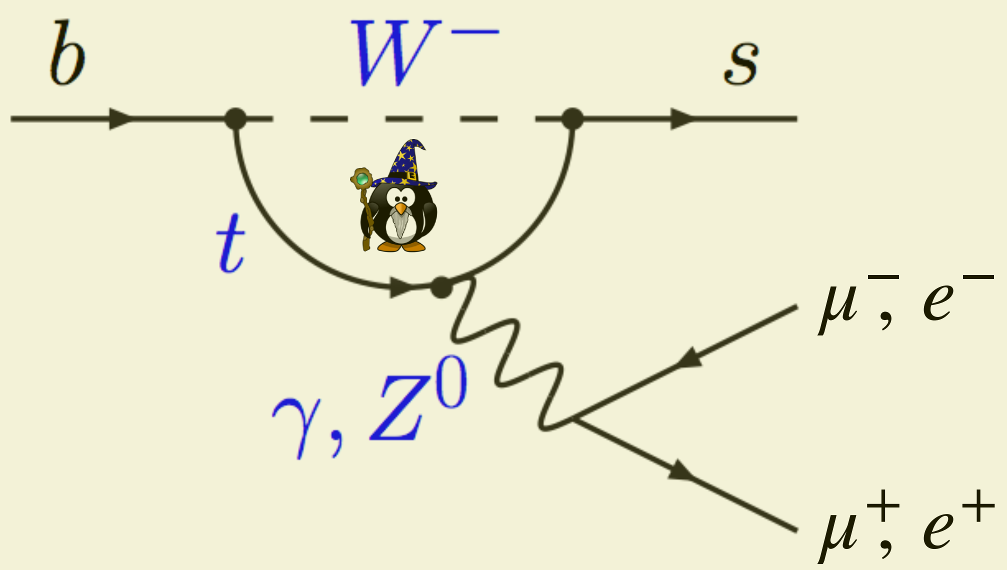


2. The machines

3. Charged LFU results

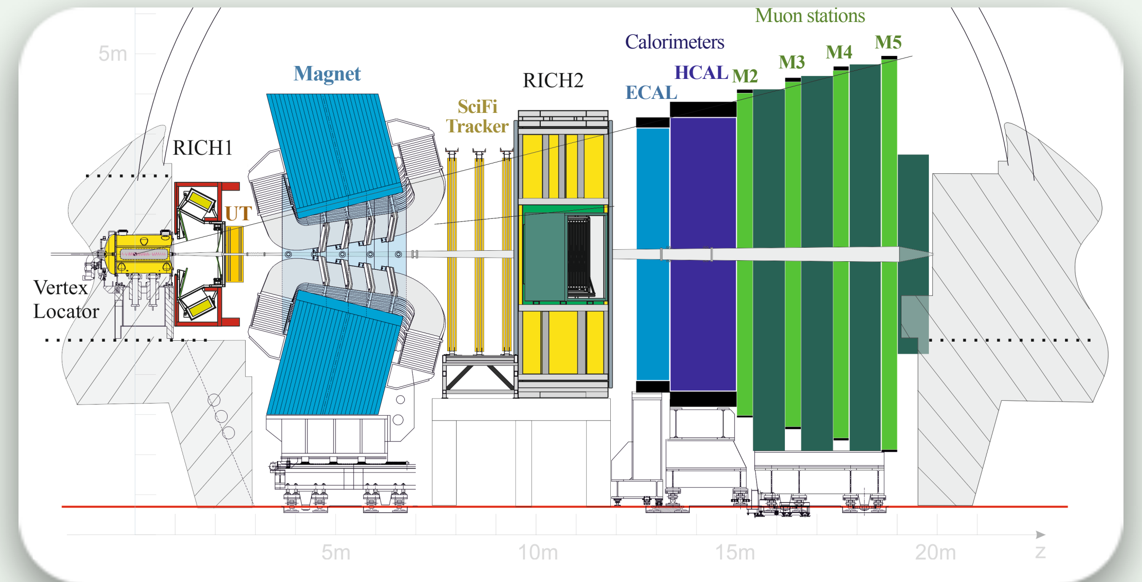


4. Neutral LFU results



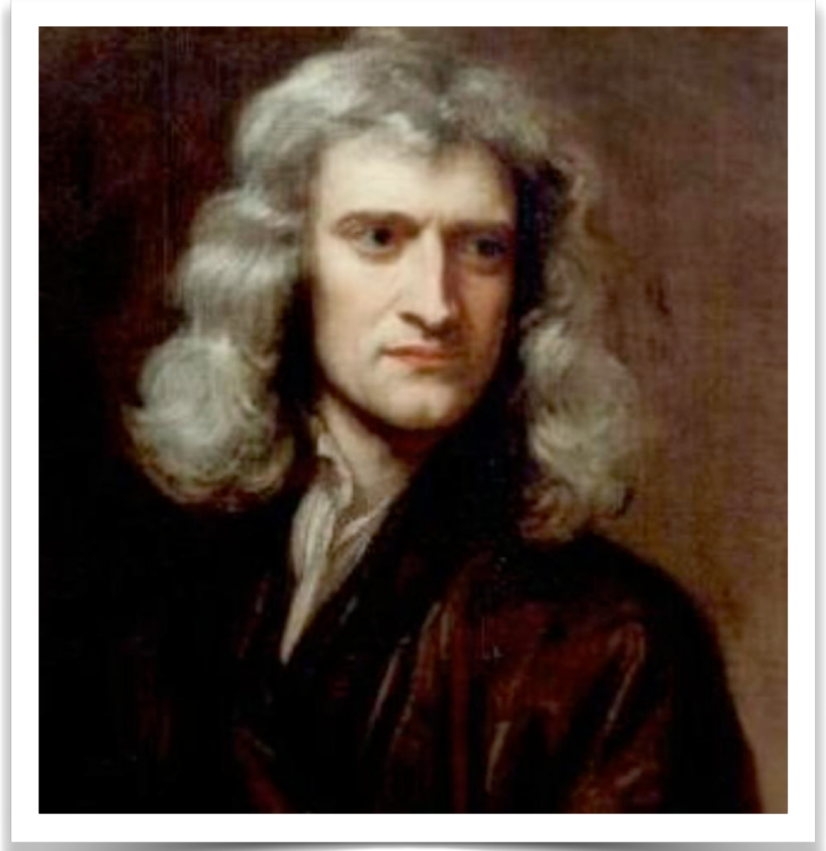
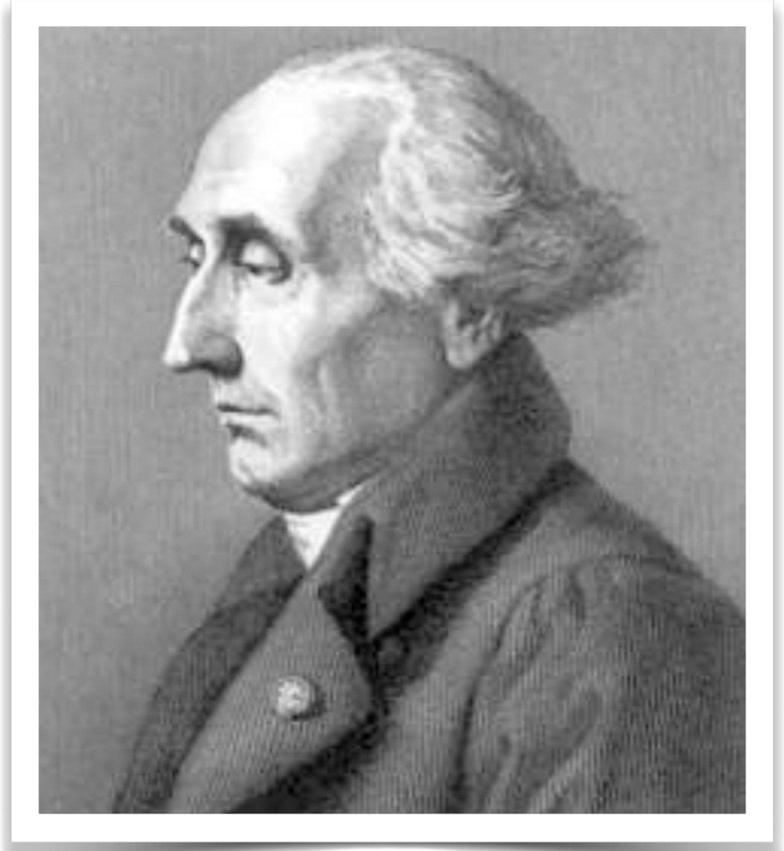
5. Leptoquarks?

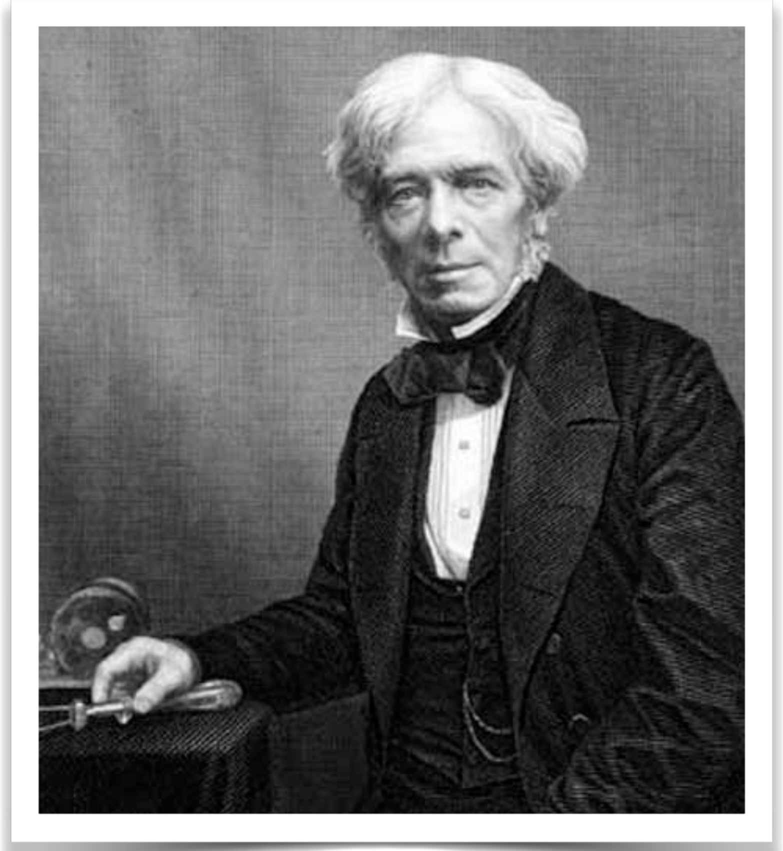
6. Going forward

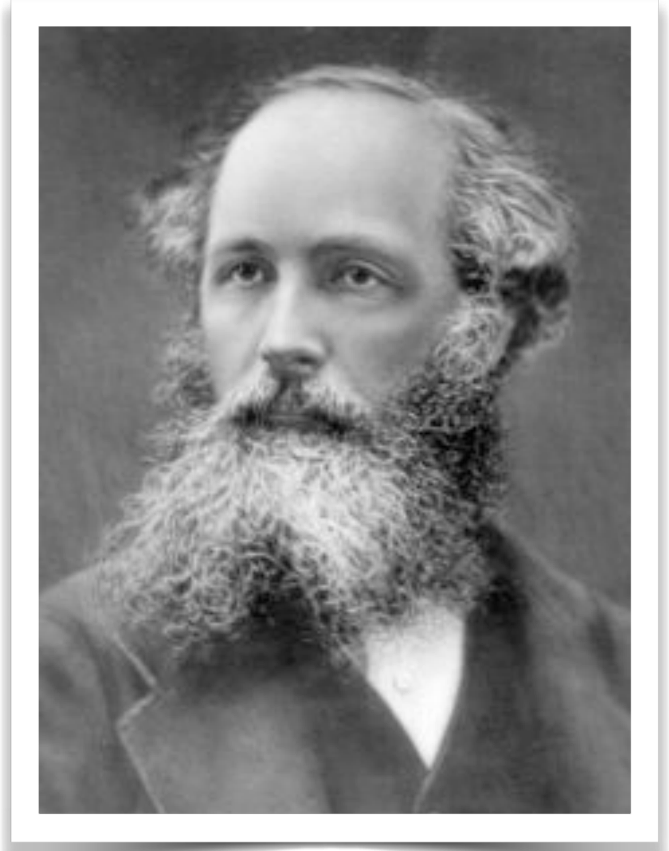


Physics complete in the XIX century?

- From the **XVII to the XIX centuries, extraordinary progress** in our fundamental understanding of the universe





$$F = G\frac{Mm}{R^2}$$

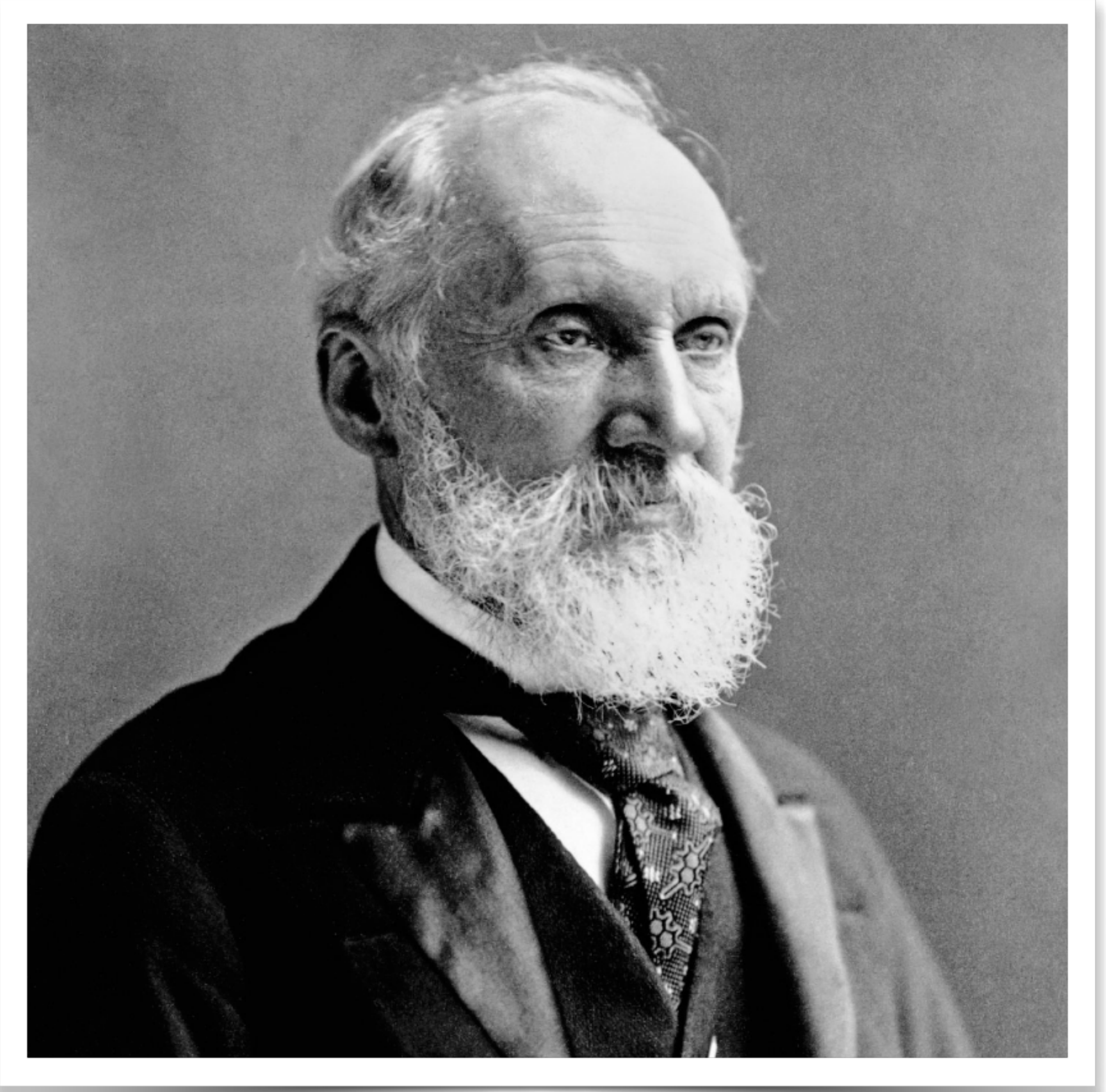
$$\boldsymbol{\nabla} \cdot \boldsymbol{E} = \frac{\rho}{\epsilon_0} \qquad \boldsymbol{\nabla} \cdot \boldsymbol{B} = 0 \qquad \boldsymbol{\nabla} \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \qquad \boldsymbol{\nabla} \times \boldsymbol{B} = \mu_0 \left(\boldsymbol{J} + \frac{\partial \boldsymbol{E}}{\partial t}\right)$$

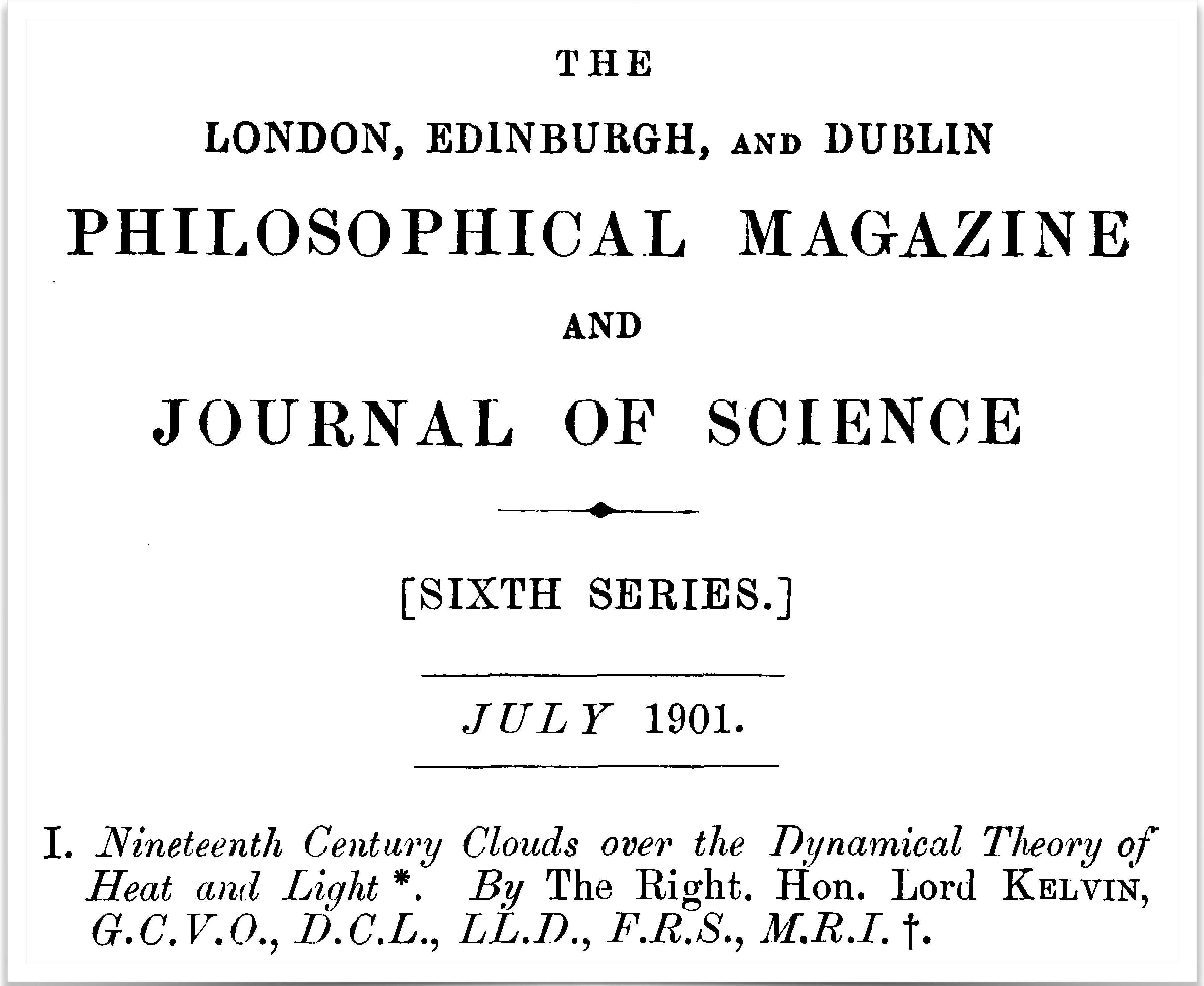
Michelson in 1894

> *"It seems probable that most of the **grand underlying principles have been firmly established**... An eminent physicist remarked that the future truths of physical science are to be looked for in the **sixth place of decimals**"*

Lord Kelvin's clouds

"The beauty and clearness of the dynamical theory, which asserts heat and light to be modes of motion, is at present obscured by two clouds"





THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

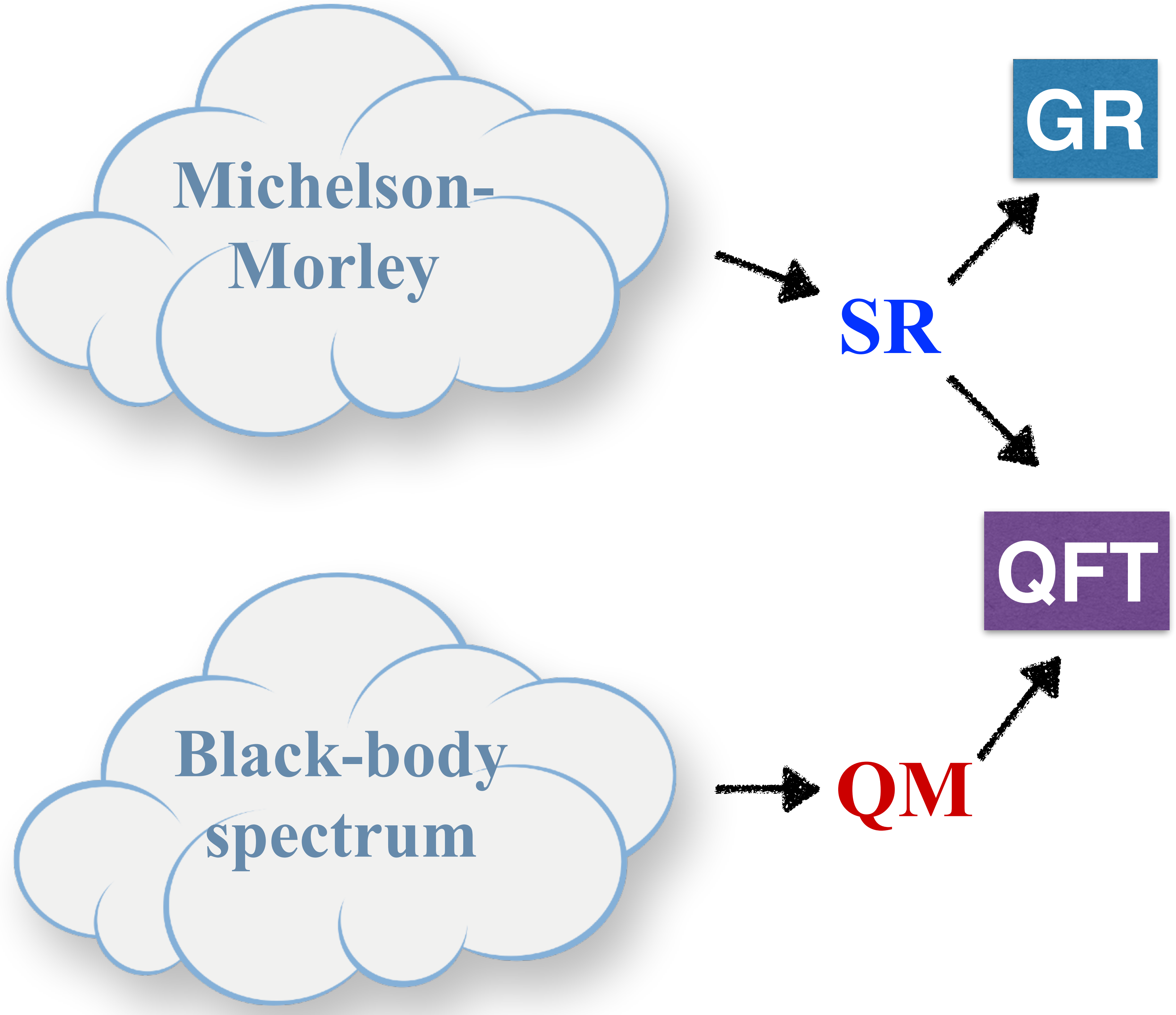
AND

JOURNAL OF SCIENCE

[SIXTH SERIES.]

JULY 1901.

I. *Nineteenth Century Clouds over the Dynamical Theory of Heat and Light* *. *By* The Right. Hon. Lord KELVIN, *G.C.V.O., D.C.L., LL.D., F.R.S., M.R.I.* †.



The Standard Model of particle physics

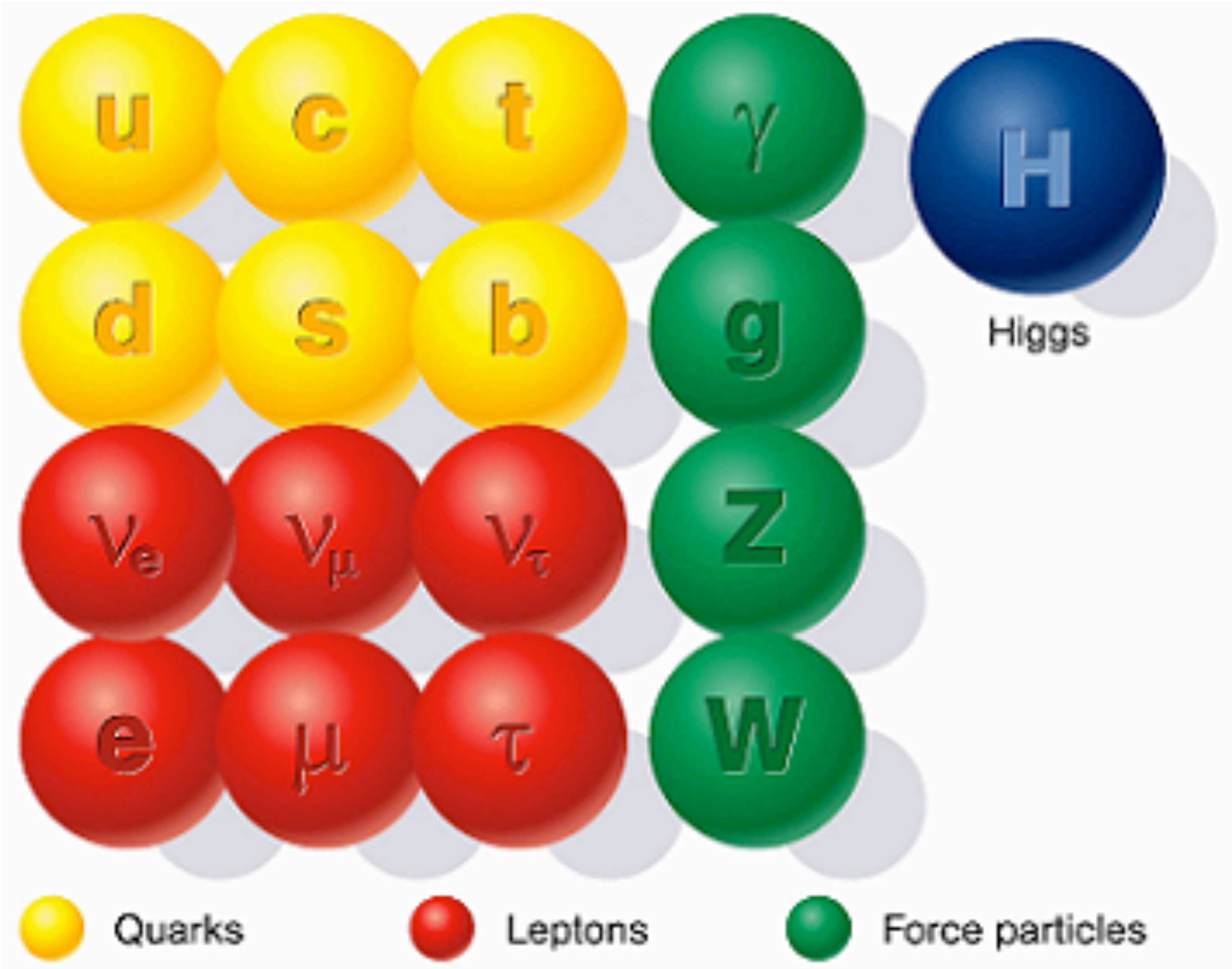
Quantum Field Theory

+

$SU(3) \times SU(2)_L \times U(1)$

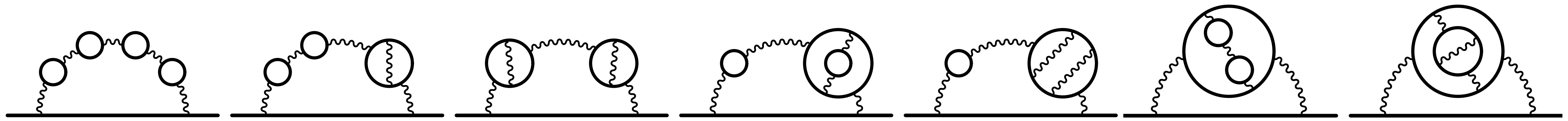
symmetry

+



Most precise and **comprehensive theory** in the **history of mankind**

Electron's anomalous magnetic dipole moment



12,672 diagrams of 10th order

$$\left.\frac{g_e - 2}{2}\right|_{\mathrm{SM}} = 0.001\ 159\ 652\ 181\ 606\,(230)$$

Atoms 7, 28 (2019)

$$\left.\frac{g_e - 2}{2}\right|_{\mathrm{exp}} = 0.001\ 159\ 652\ 180\ 73\,(28)$$

Phys. Rev. Lett. 100, 120801 (2008)

The Standard Model of particle physics

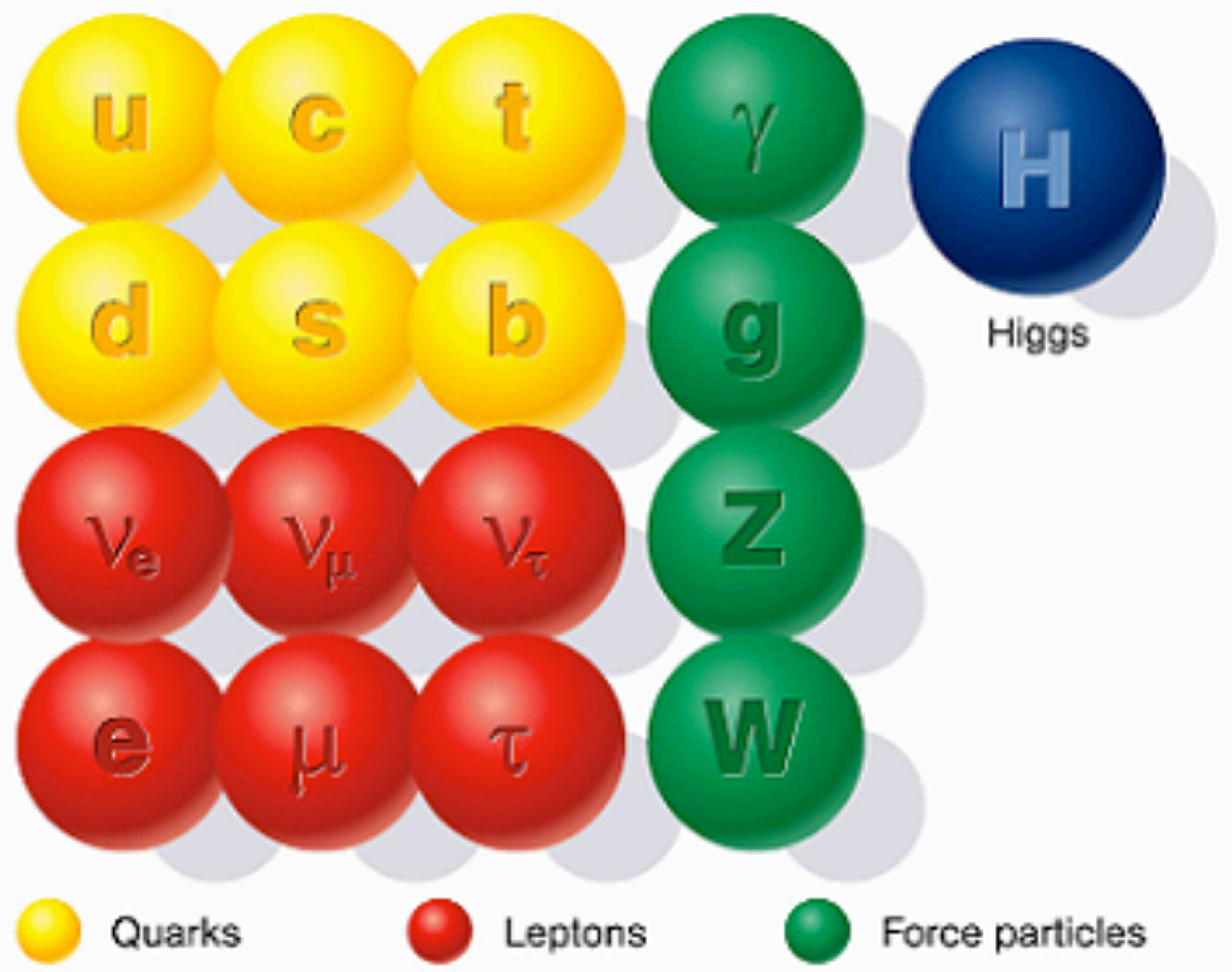
Quantum Field Theory

+

$$SU(3) \times SU(2)_L \times U(1)$$

symmetry

+

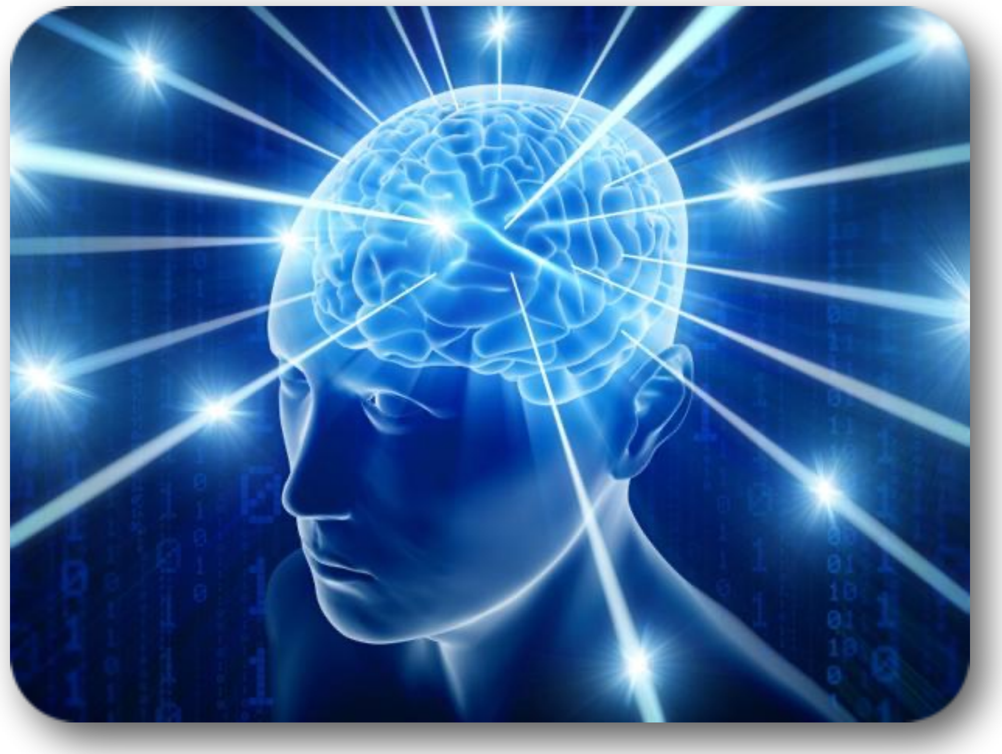


Most precise and **comprehensive theory** in the **history of mankind**

cokada / Getty Images/iStockphoto

Duke

englandlogistics



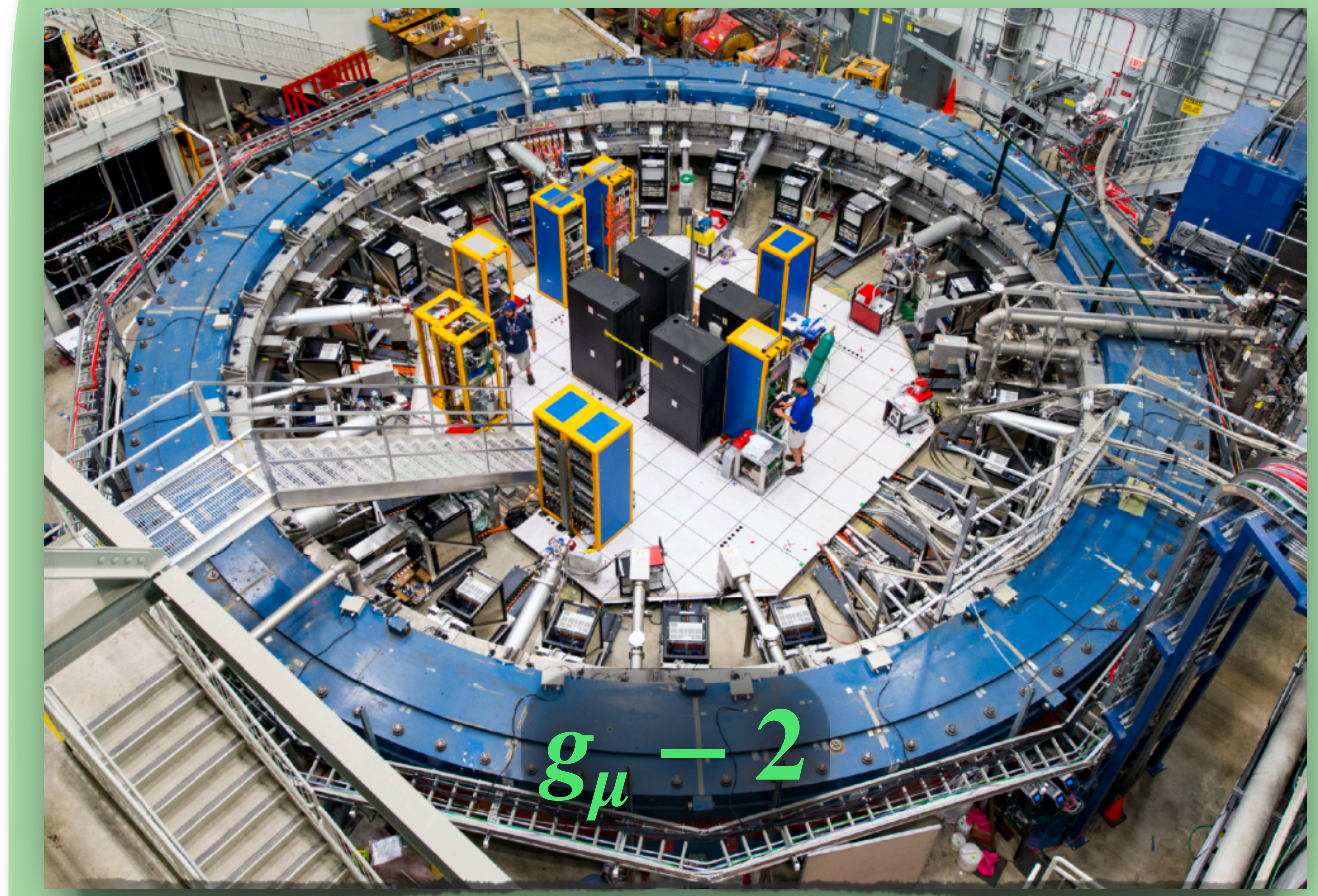
VMU

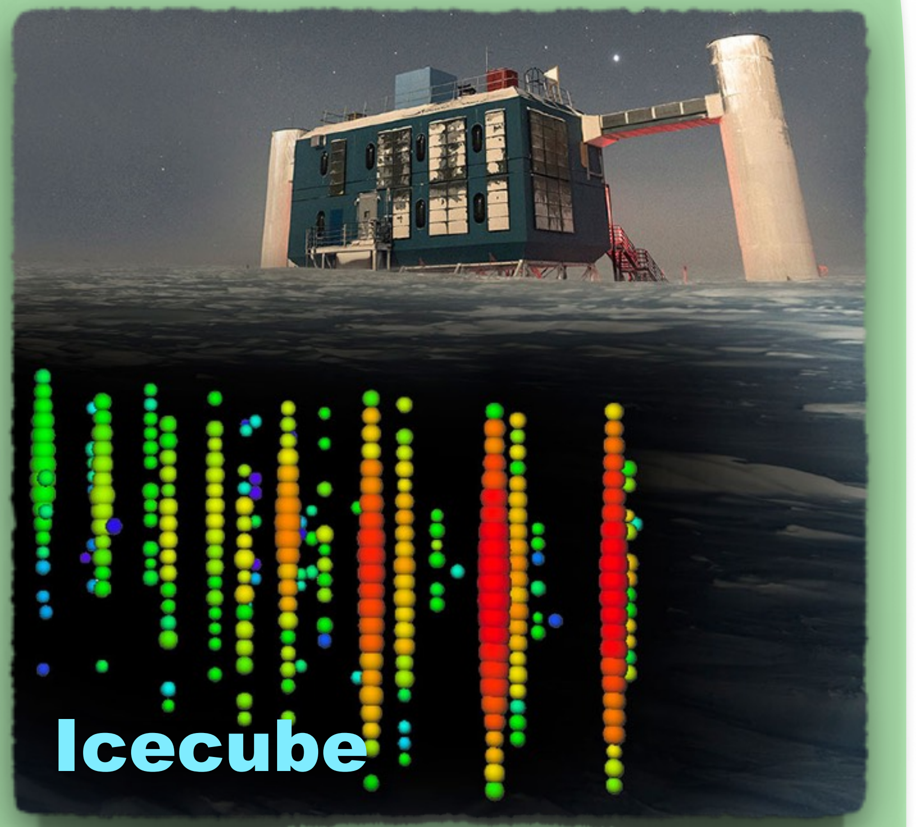
Anything left to discover?

Beyond the SM (BSM)

Sill, many questions left

Looking in many directions



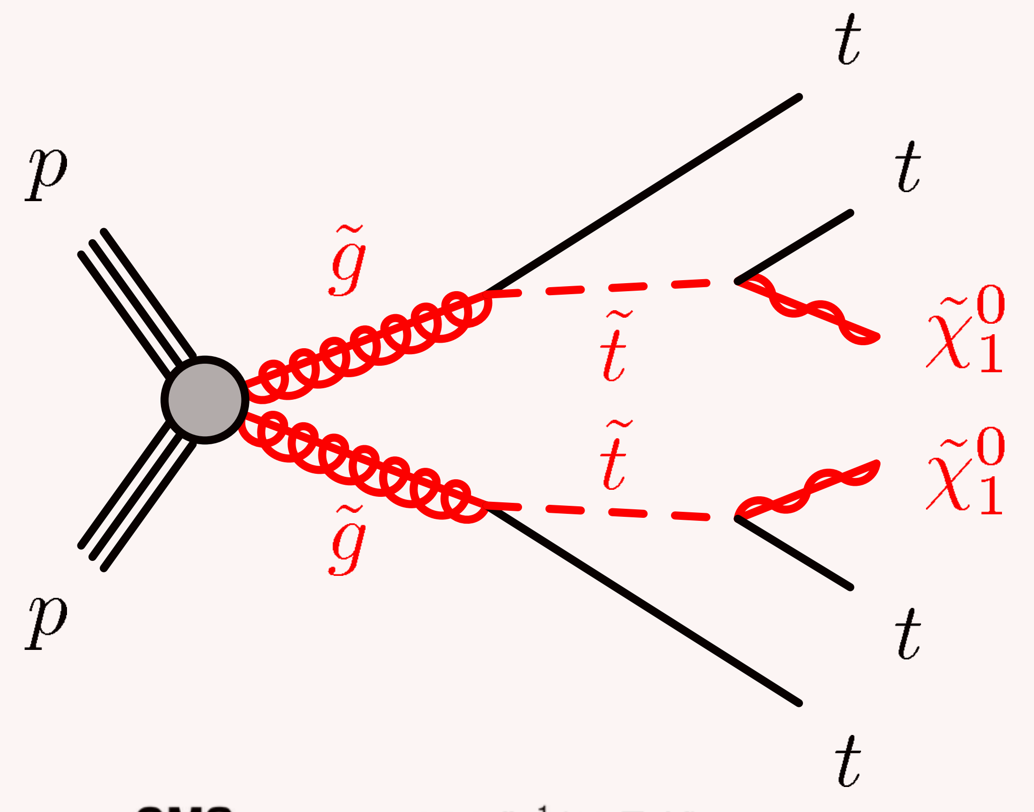


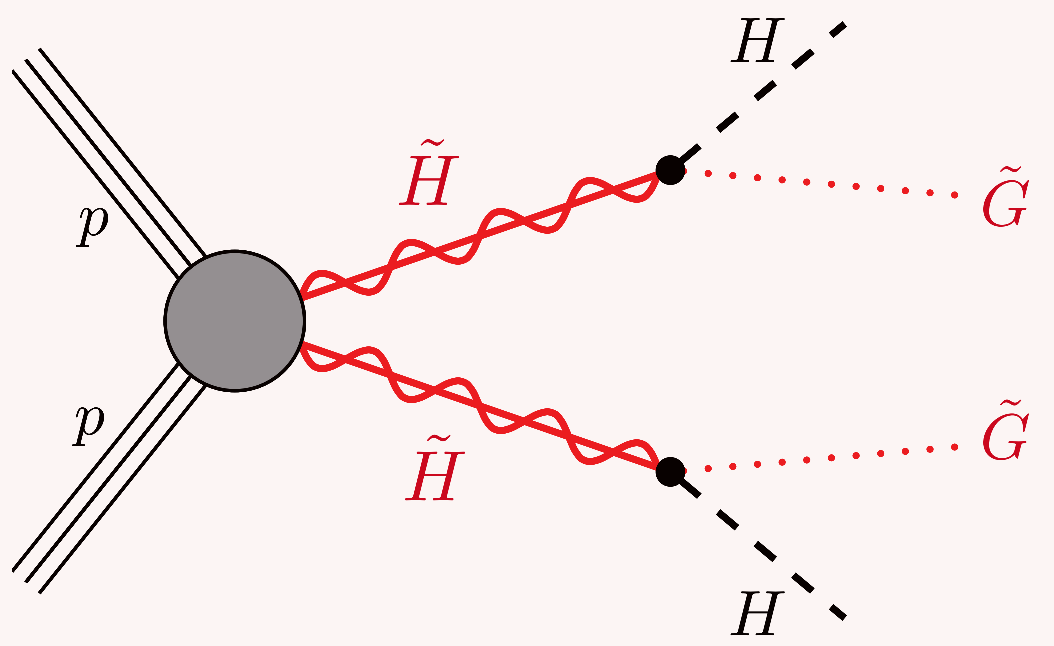
BSM searches

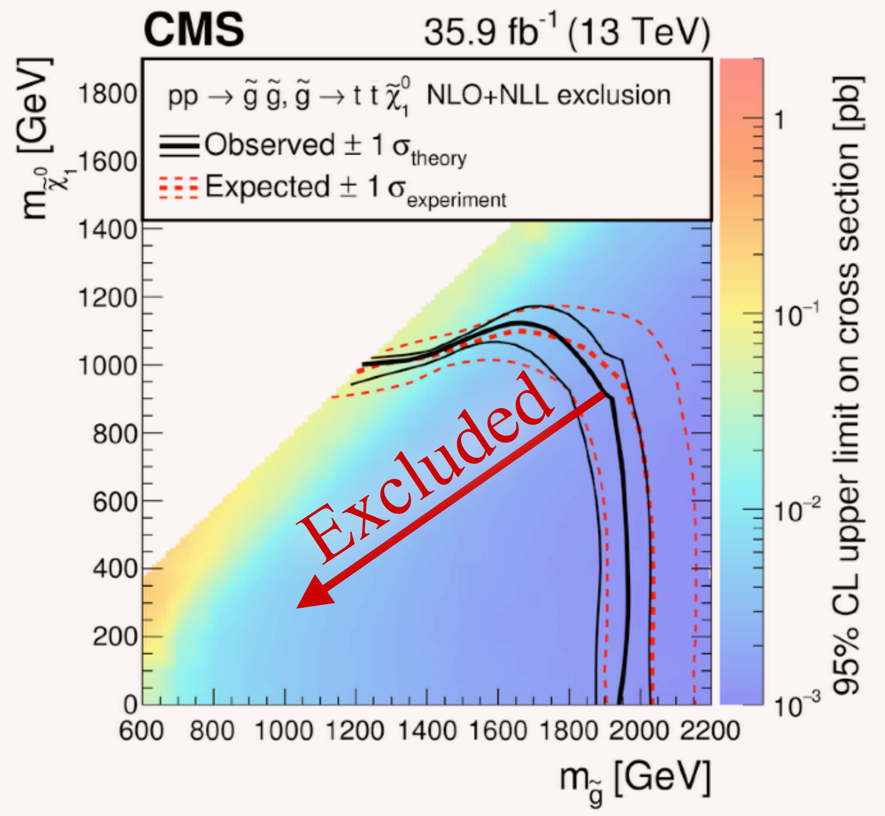
Direct searches

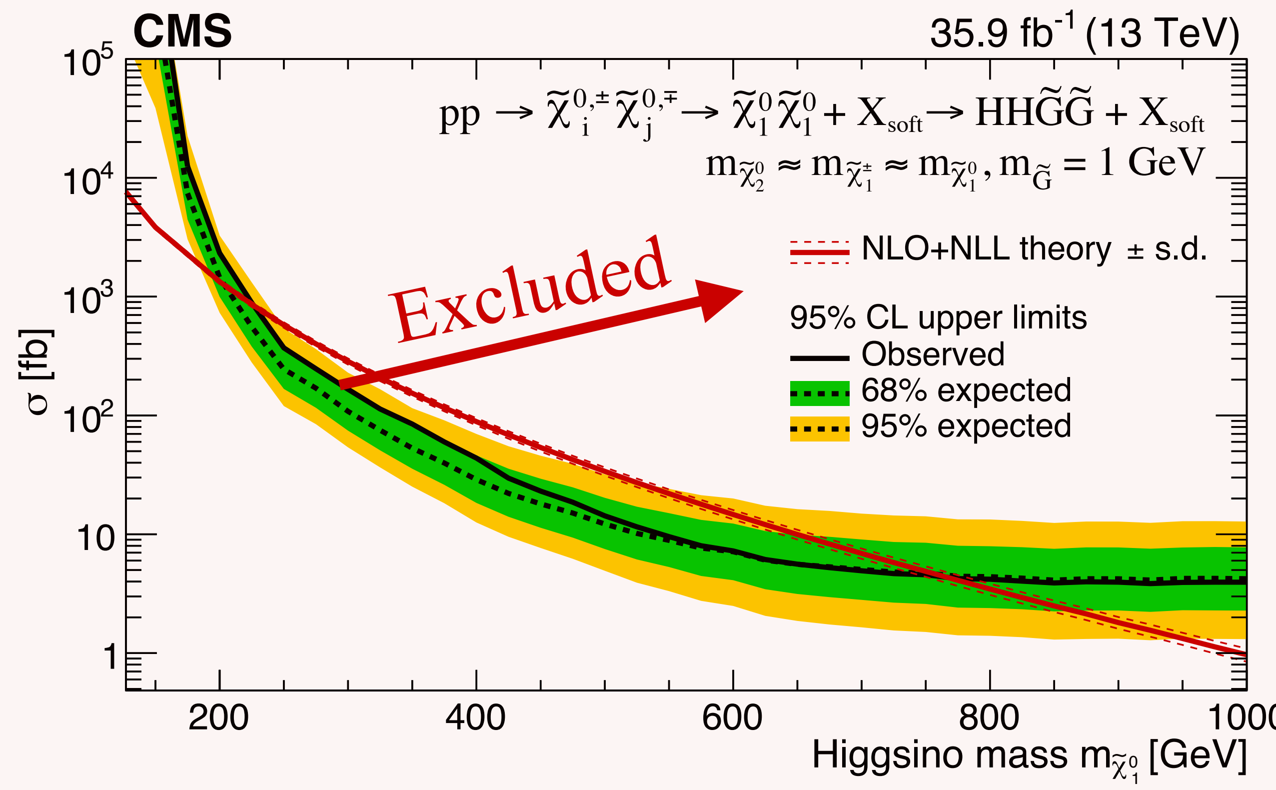
Produce and *detect* BSM physics

Example: Tevatron's 2 TeV → LHC's 14 TeV allowed for searches for **multi-TeV supersymmetric particles**









Indirect searches

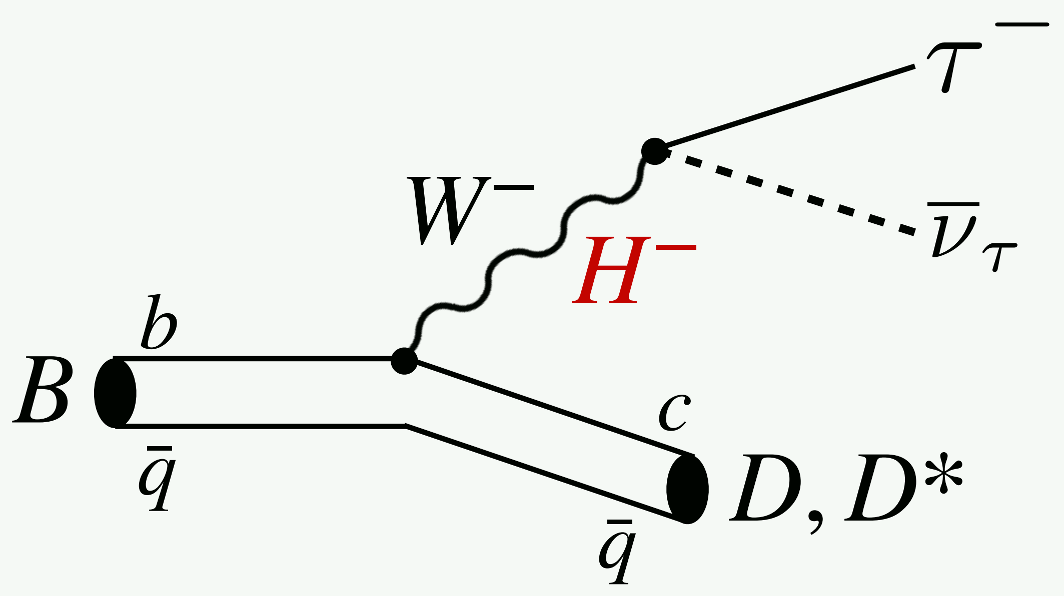
Compare *precision measurements* to SM predictions looking for *virtual BSM contributions*

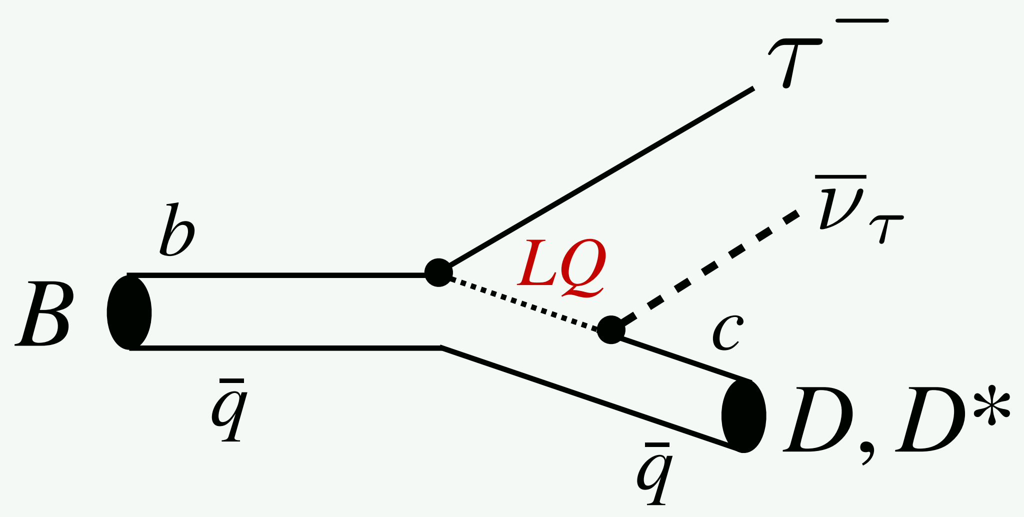
Guided us to discoveries in the past

- Absence of $K_L \to \mu\mu \Rightarrow$ charm quark (Glashow, Iliopoulos, Maiani, 1970)
- $\epsilon_K \Rightarrow$ 3rd generation (t, b quarks) (Kobayashi & Maskawa, 1972)
- $\Delta m_K \Rightarrow m_c \sim 1.5\,\text{GeV}$ (Gaillard & Lee; Vainshtein & Khriplovich, 1974)
- $\Delta m_B \Rightarrow m_t \gtrsim 100\,\text{GeV}$ (bound in 1987: $23\,\text{GeV}$) $\Rightarrow$ large CP violation & FCNC

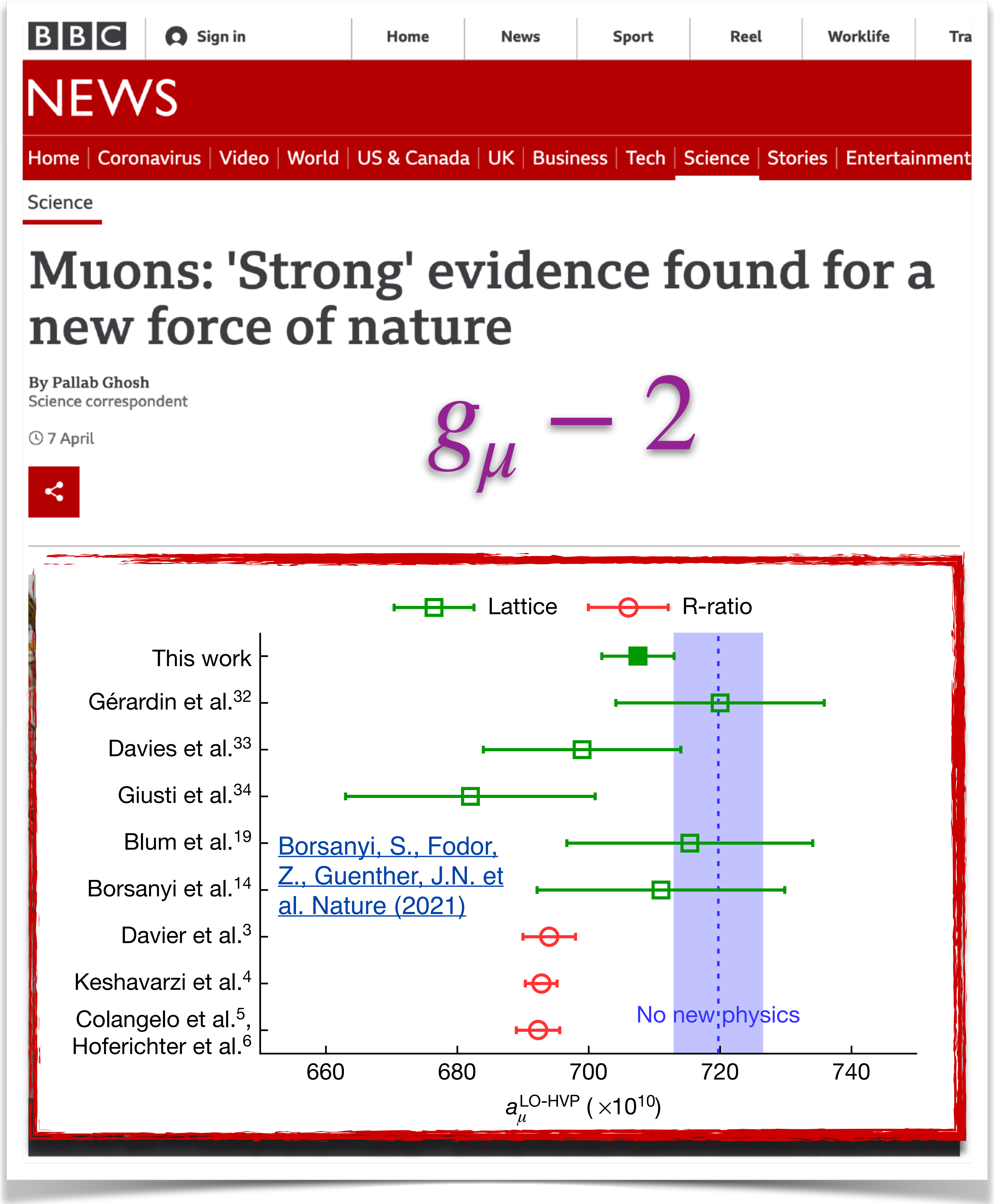
Z. Ligeti

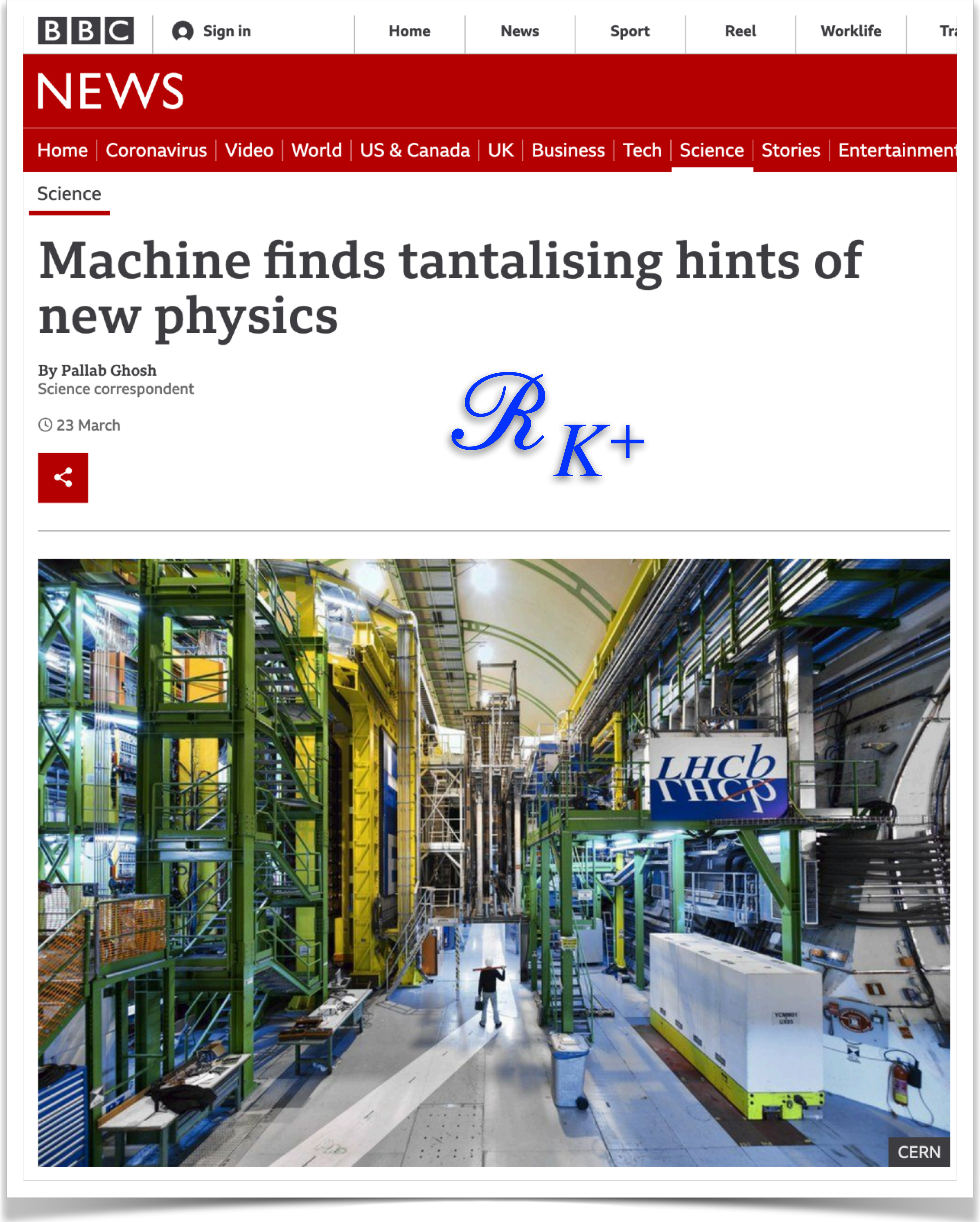
Measurements of B decays give us **access to mass scales beyond the reach** of **current particle accelerators**



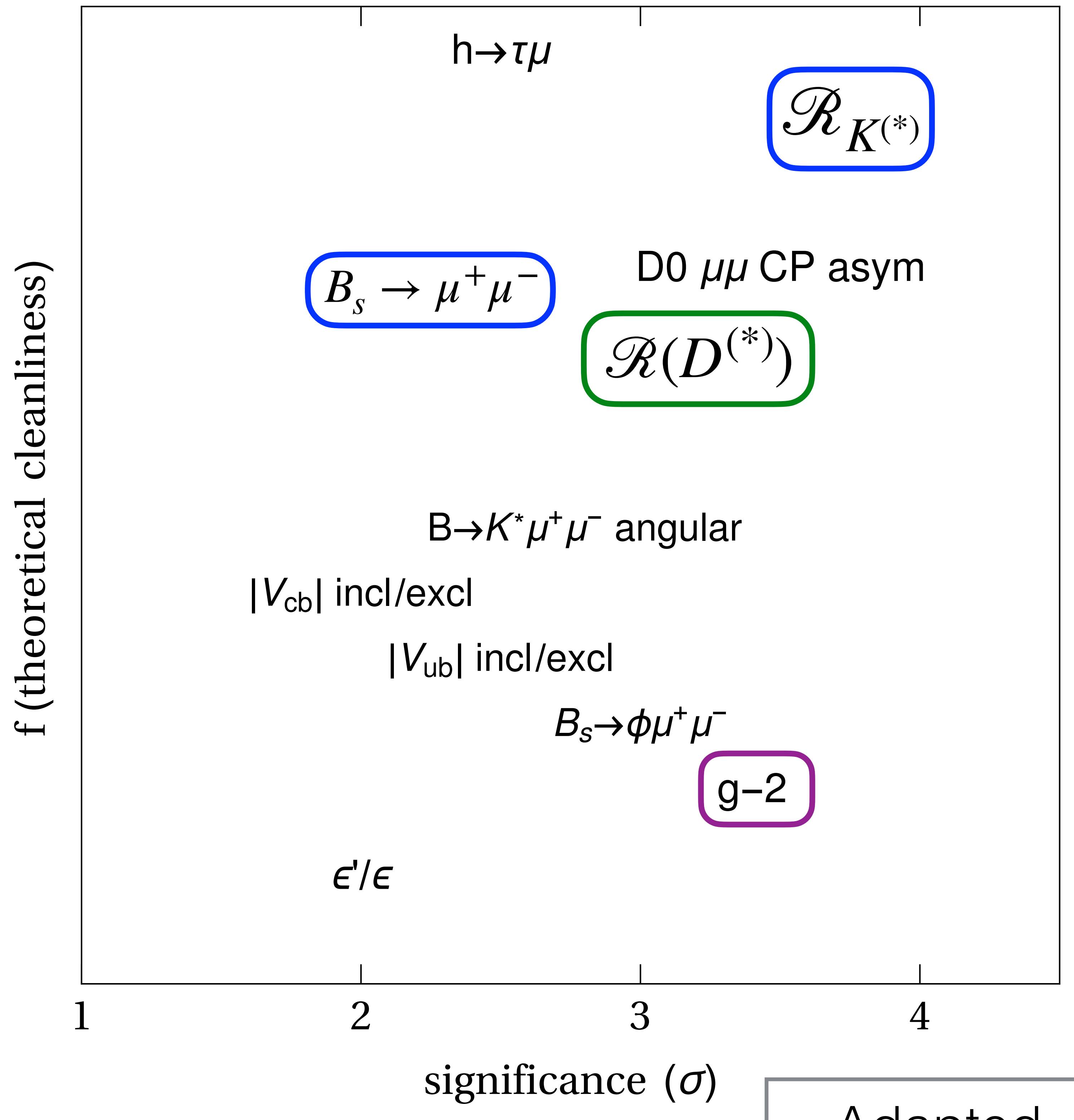


Indirect searches in the news



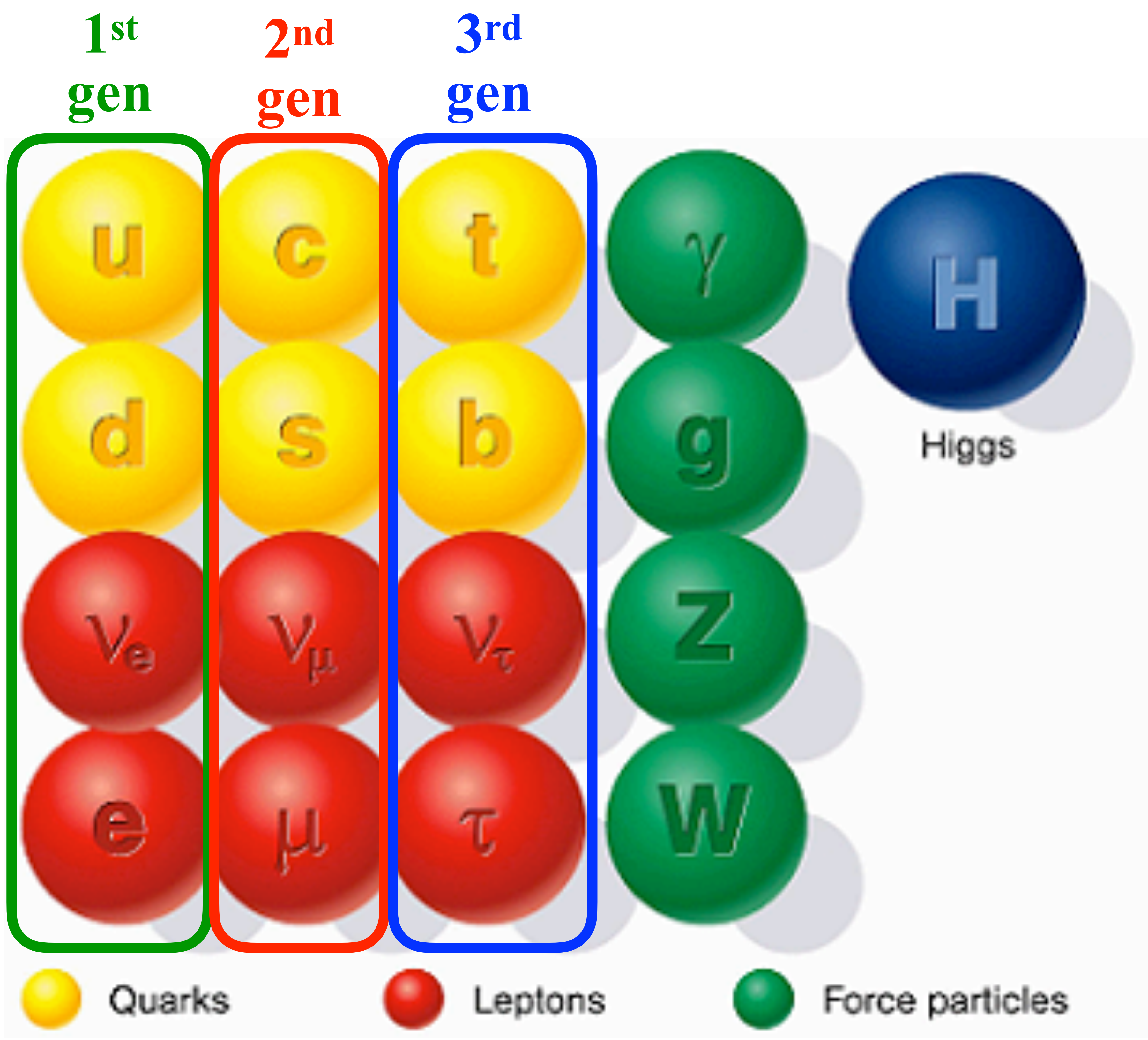


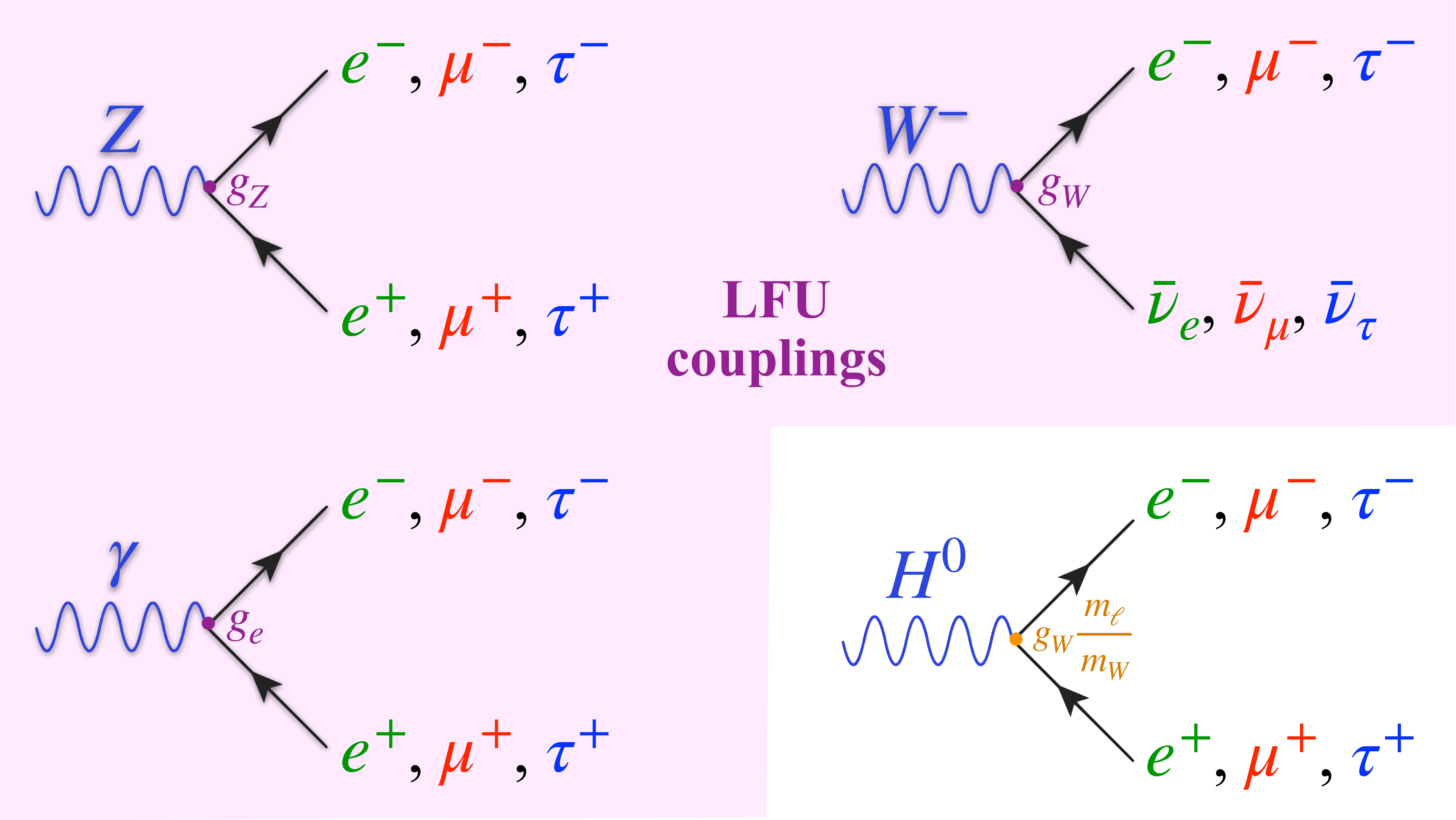
Important to have a clean SM prediction

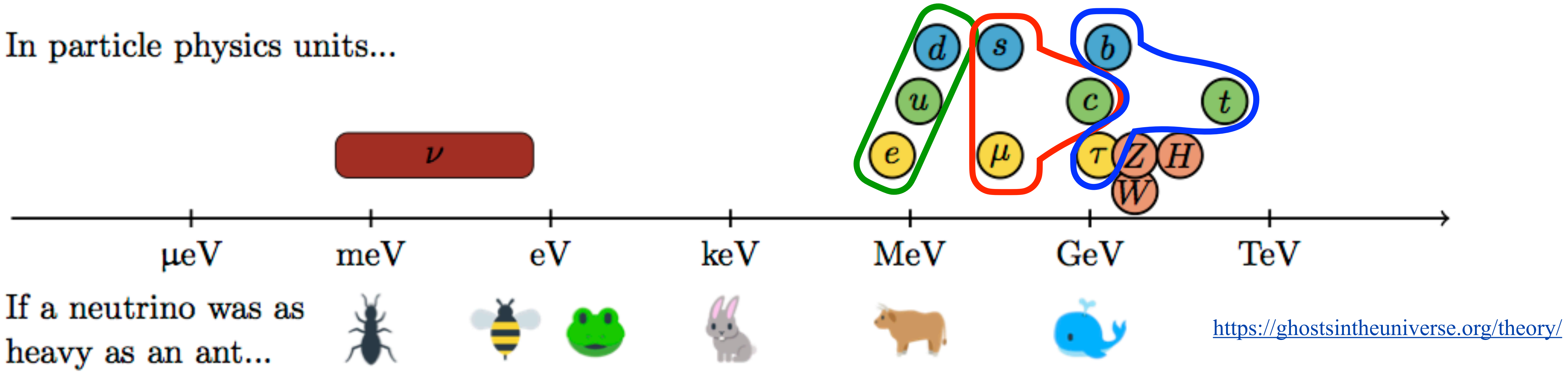


Adapted from Z. Ligeti

- It is assumed that electroweak gauge **couplings** to **3 fermion generations** are **identical**







https://ghostsintheuniverse.org/theory/

LFU tested to great precision

LFU tests with e/μ (1st/2nd gen.)

To **0.28%** in Z decays
$$\frac{\Gamma_{Z\to\mu\mu}}{\Gamma_{Z\to ee}} = 1.0009 \pm 0.0028$$
LEP, Phys. Rept. 427 (2006) 257

To **0.8%** in W decays
$$\frac{\mathcal{B}(W\to e\nu)}{\mathcal{B}(W\to\mu\nu)} = 1.004 \pm 0.008$$
CDF + LHC, JPG: NPP, 46, 2 (2019)

To **0.31%** in meson decays
$$\frac{\Gamma_{J/\psi\to\mu\mu}}{\Gamma_{J/\psi\to ee}} = 1.0016 \pm 0.0031$$
PDG (BESIII), RPP, Chin. Phys. C40 (2016) 100001
$$\frac{\Gamma_{K\to e\nu}}{\Gamma_{K\to\mu\nu}} = (2.488 \pm 0.009)\times 10^{-5}$$
PDG (NA62), RPP, Chin. Phys. C40 (2016) 100001
$$\frac{\Gamma_{\pi\to e\nu}}{\Gamma_{\pi\to\mu\nu}} = (1.230 \pm 0.004)\times 10^{-4}$$
PiENu, Phys. Rev. Lett. 115, 071801 (2015)

To **0.14%** in $\tau\to\ell\nu\nu$
$$g_\mu/g_e = 1.0018 \pm 0.0014$$
PDG, A. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

LFU tests with τ (3rd gen.)

To **0.32%** in Z decays
$$\frac{\Gamma_{Z\to\tau\tau}}{\Gamma_{Z\to ee}} = 1.0019 \pm 0.0032$$
LEP, Phys. Rept. 427 (2006) 257

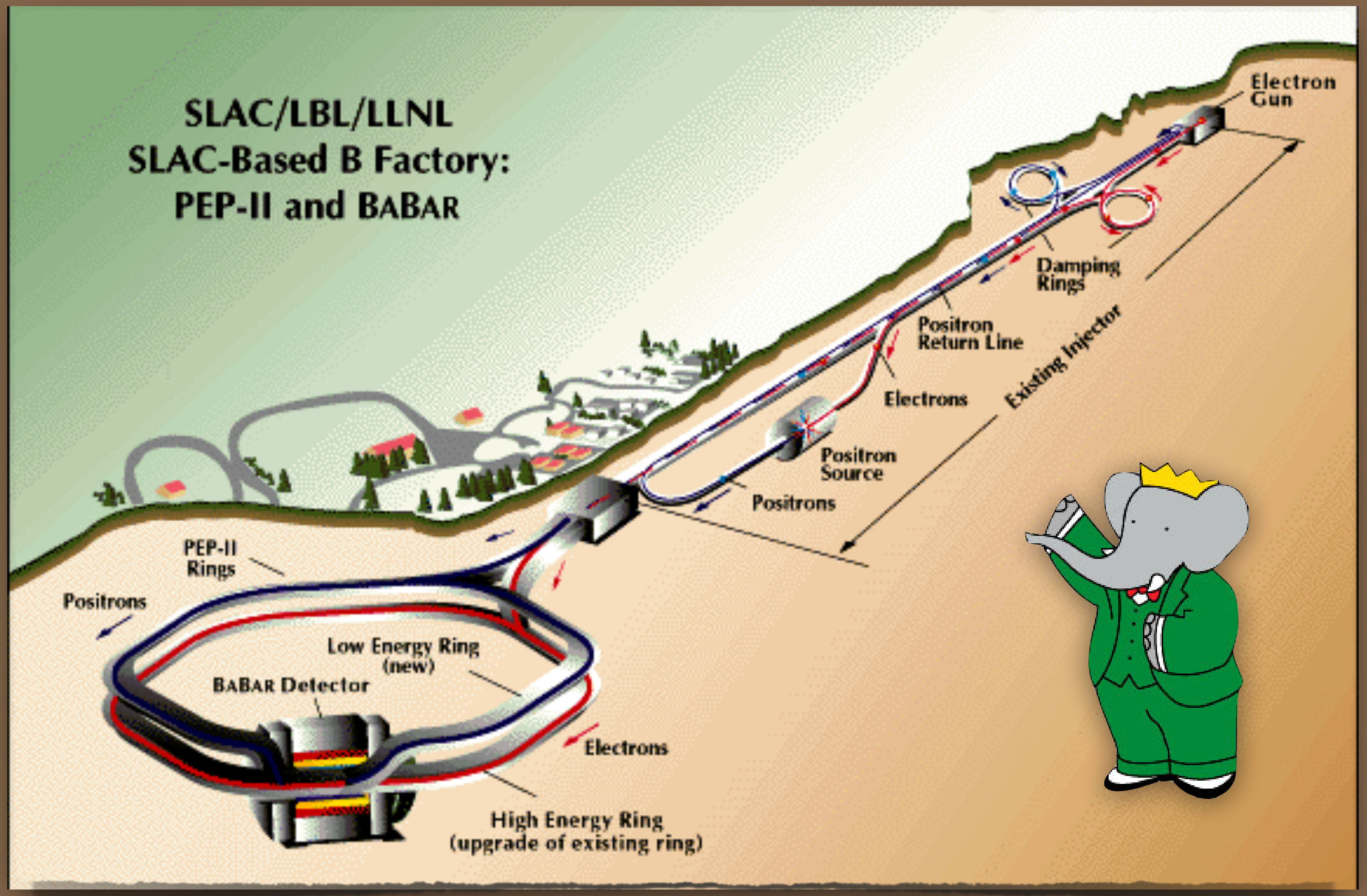
2.6σ tension in W decays
$$\frac{\Gamma_{W\to\tau\nu}}{\Gamma_{W\to\mu\nu}} = 1.070 \pm 0.026$$
LEP, Phys. Rept. 532 (2013) 119,

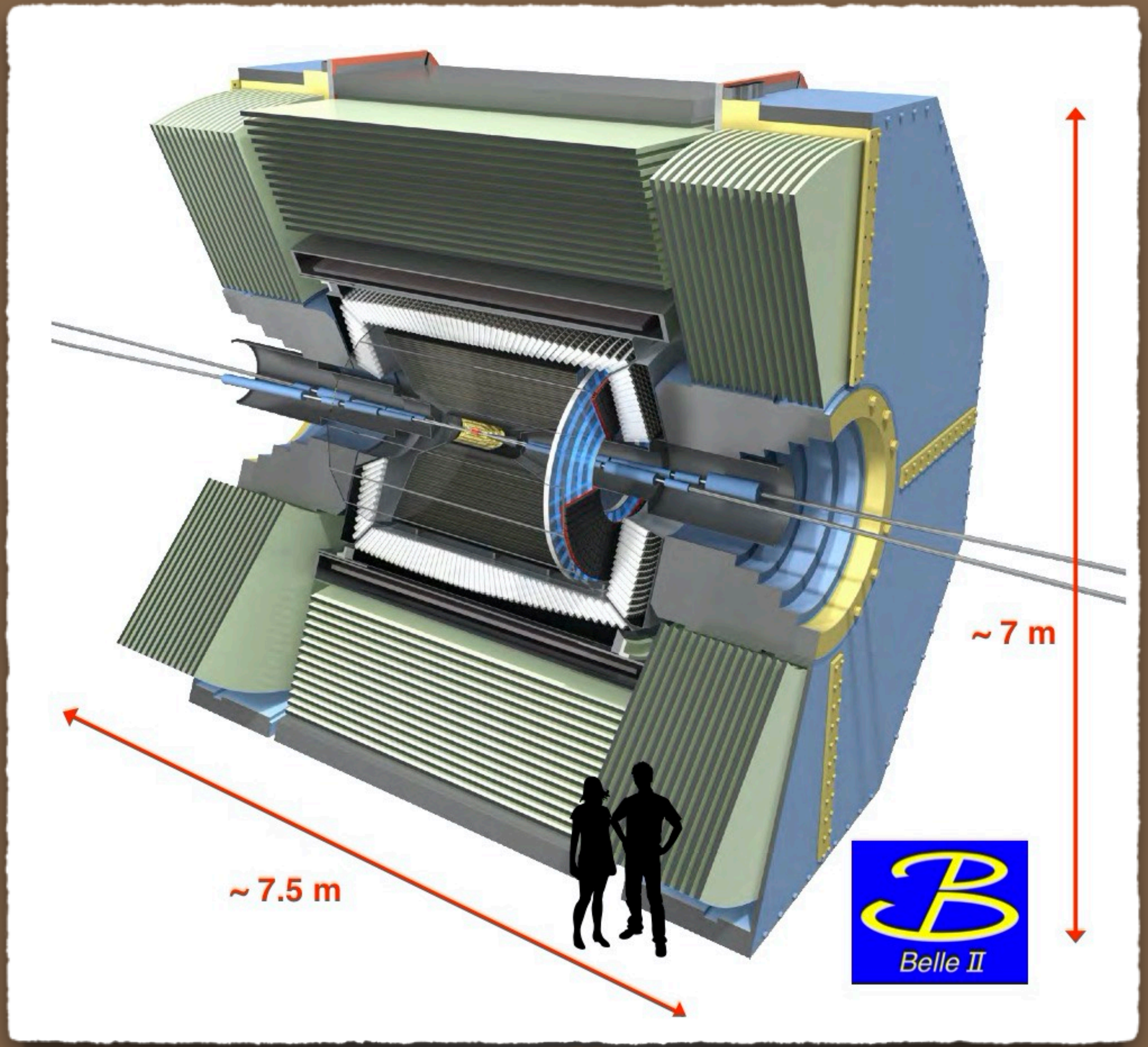
To **1.3%** in W decays
$$\frac{\Gamma_{W\to\tau\nu}}{\Gamma_{W\to\mu\nu}} = 0.992 \pm 0.013$$
ATLAS, arXiv:2007.14040

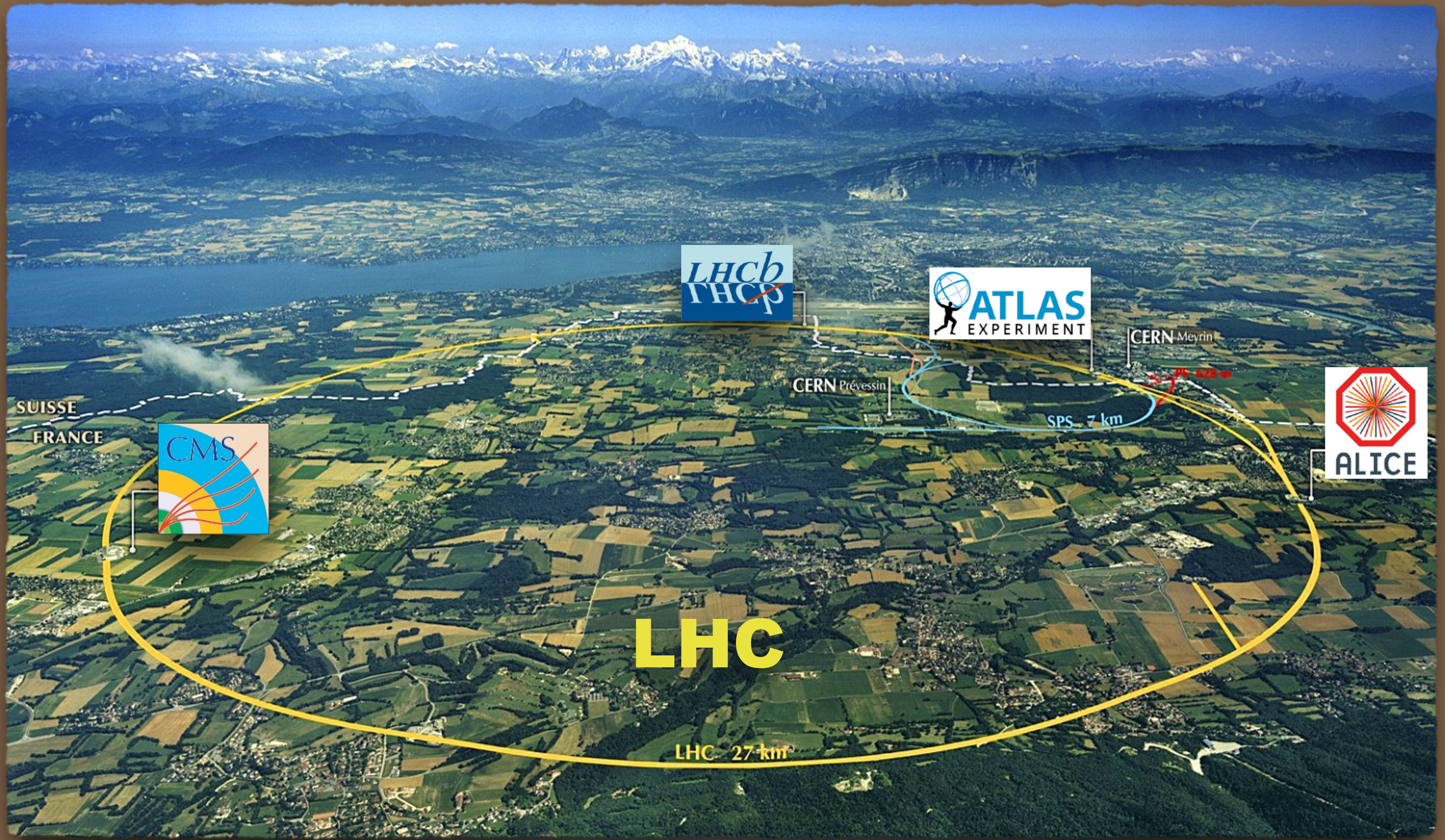
To **6.1%** in D_s decays
$$\frac{\Gamma_{D_s\to\tau\nu}}{\Gamma_{D_s\to\mu\nu}} = 9.95 \pm 0.61$$
HFLAV, Eur. Phys. J. C77 (2017) 895

To **0.15%** in $\tau\to\ell\nu\nu$ (with τ_τ)
$$g_\tau/g_\mu = 1.0030 \pm 0.0015$$
PDG, S. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

2. The machines







B factories

	Accelerator	Lab	Country	From	To
BaBar	PEP-II	SLAC	USA	1999	2008
Belle	KEKB	KEK	Japan	1999	2010
Belle II	KEKB	KEK	Japan	2018	~2031

Optimized for **clean** $e^+e^- \to B\bar{B}$ production

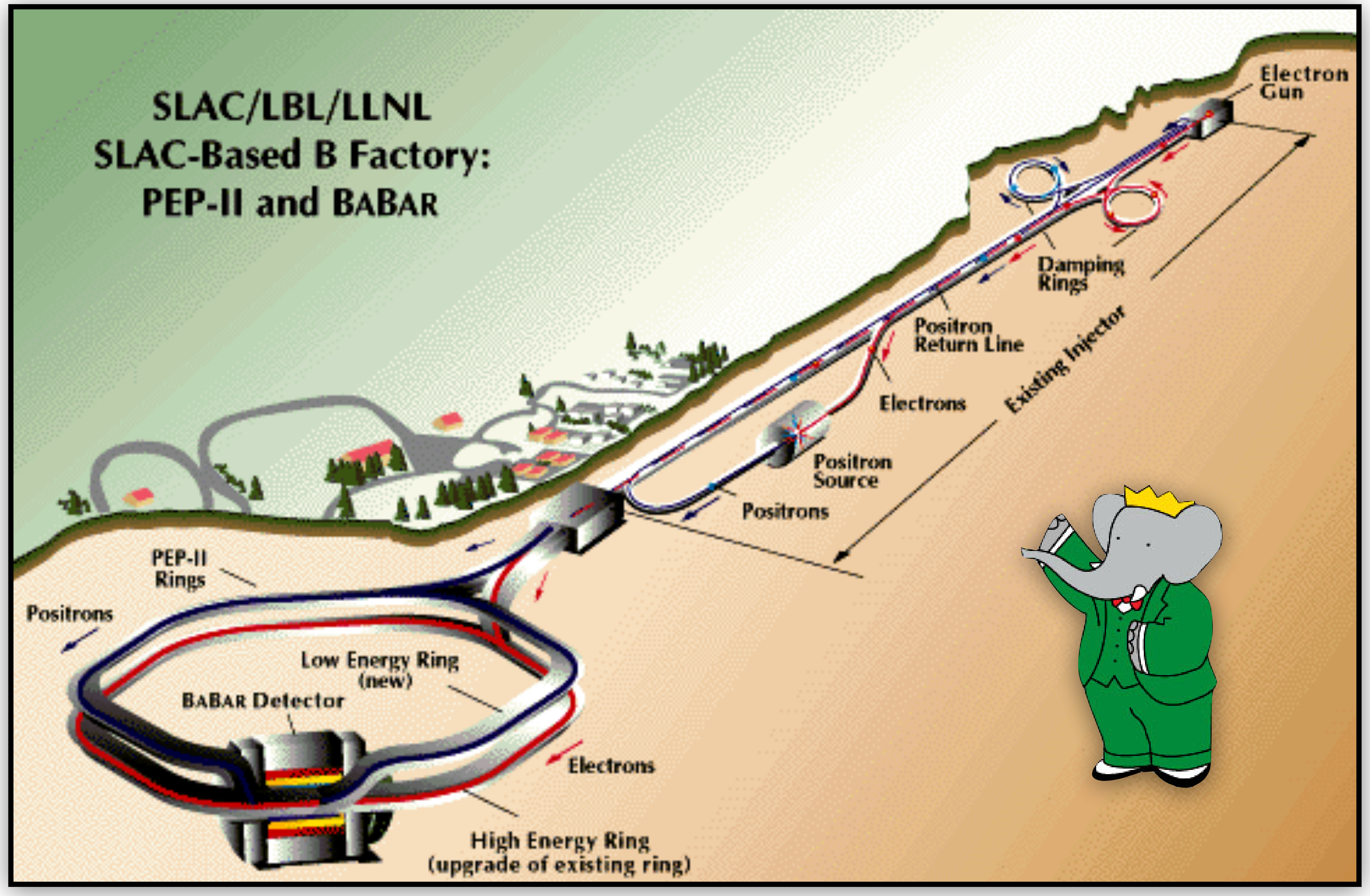
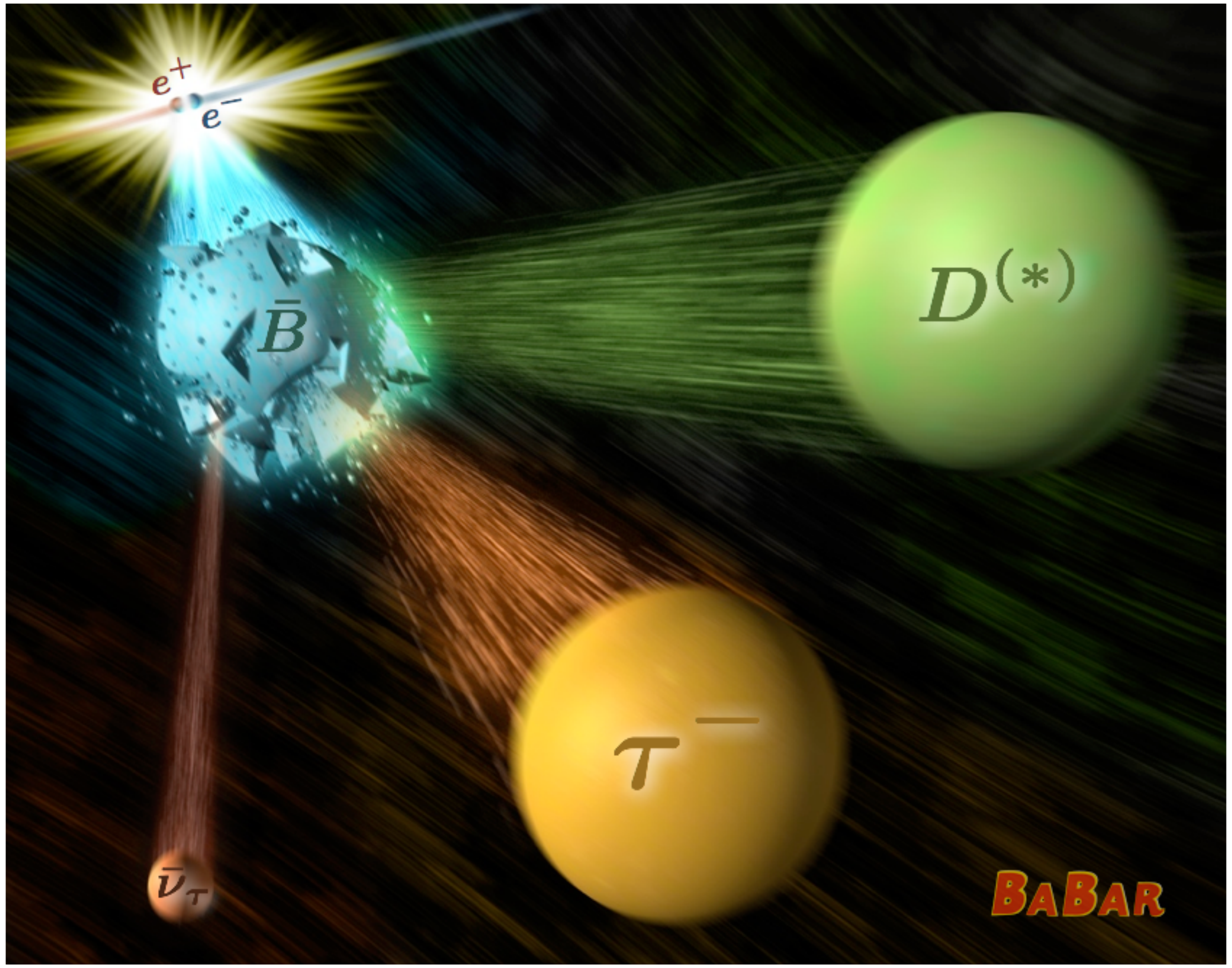


Photo of a $B \to D^{(*)}\tau\nu_\tau$ event!



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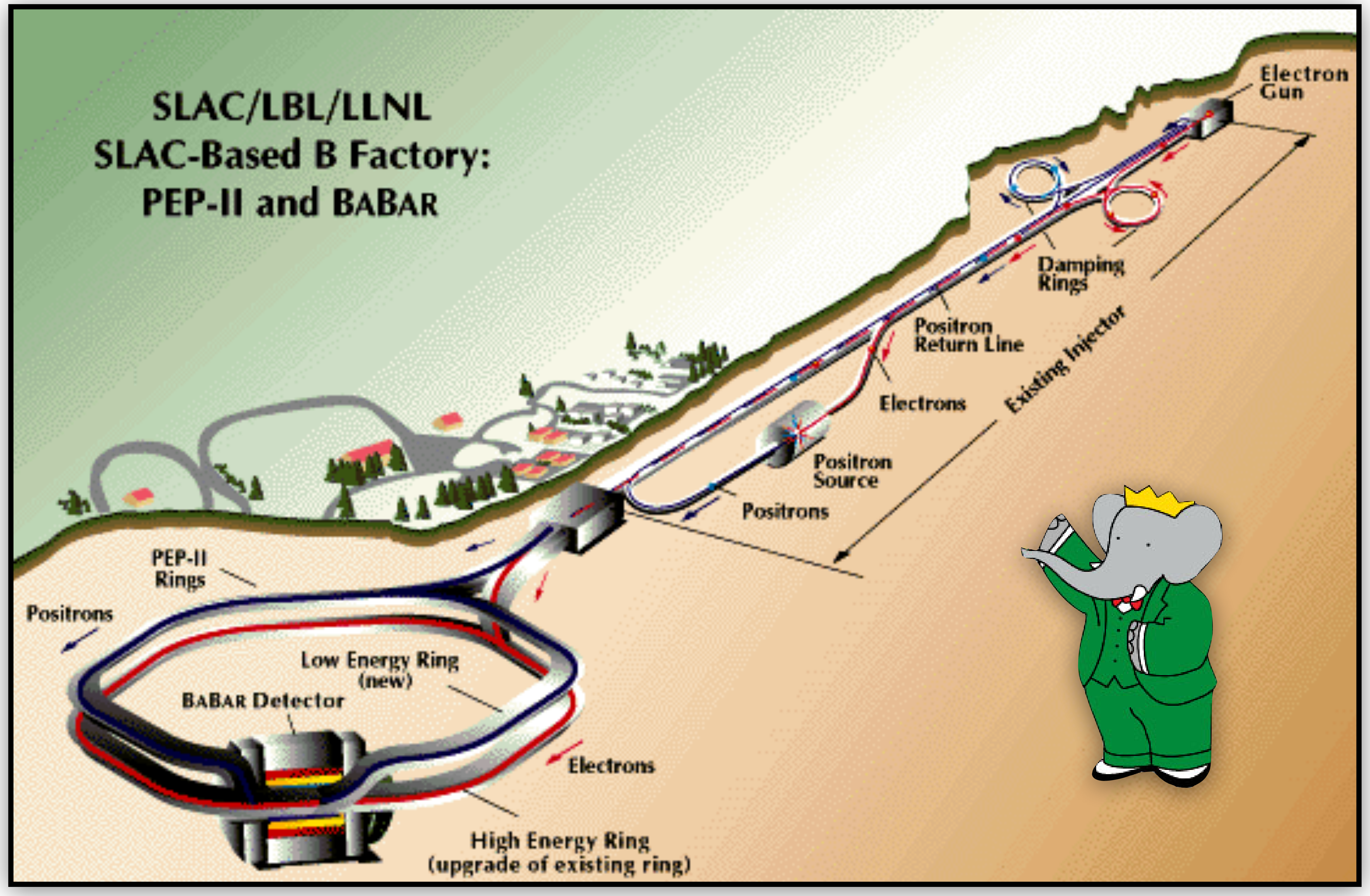
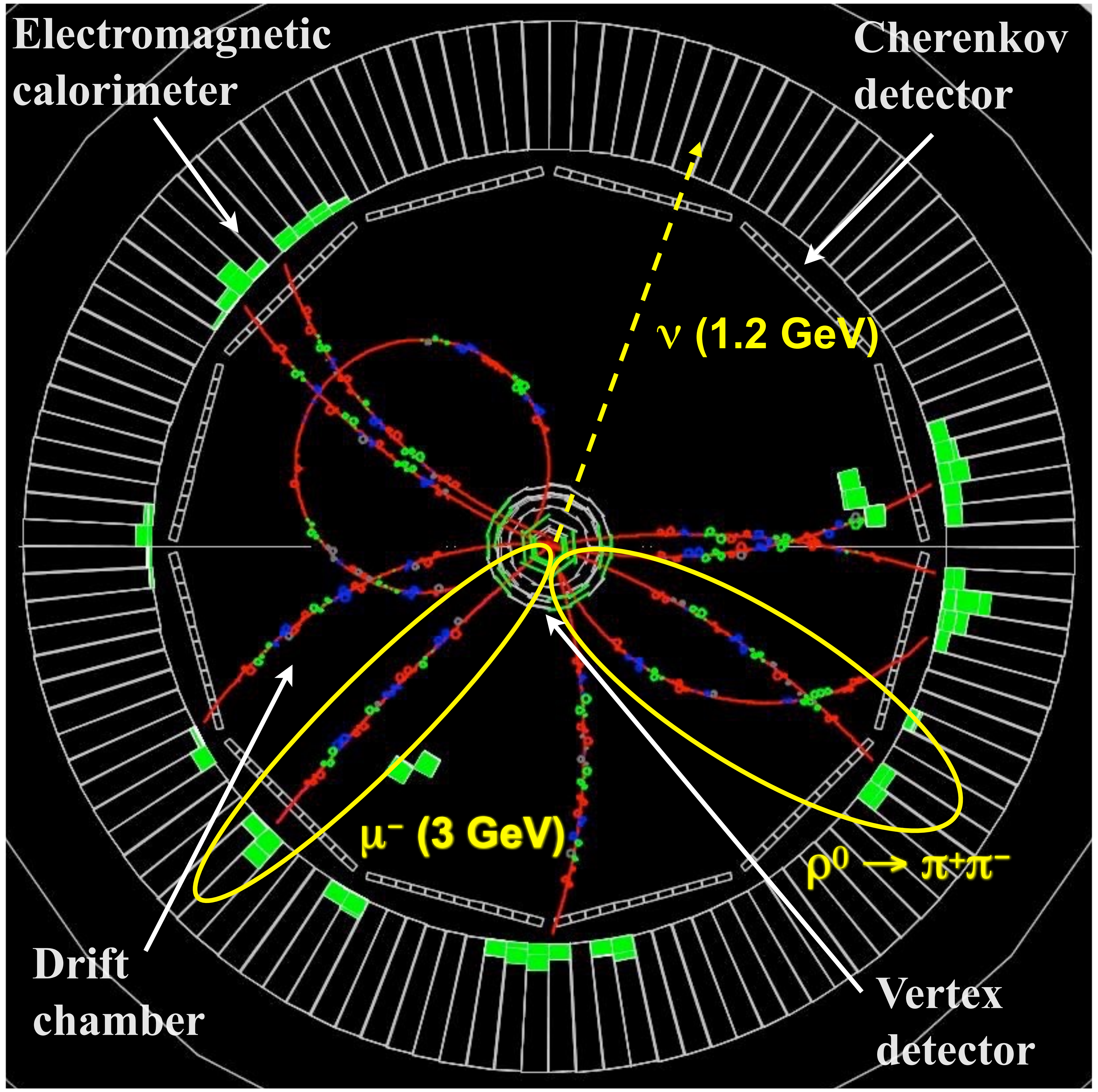


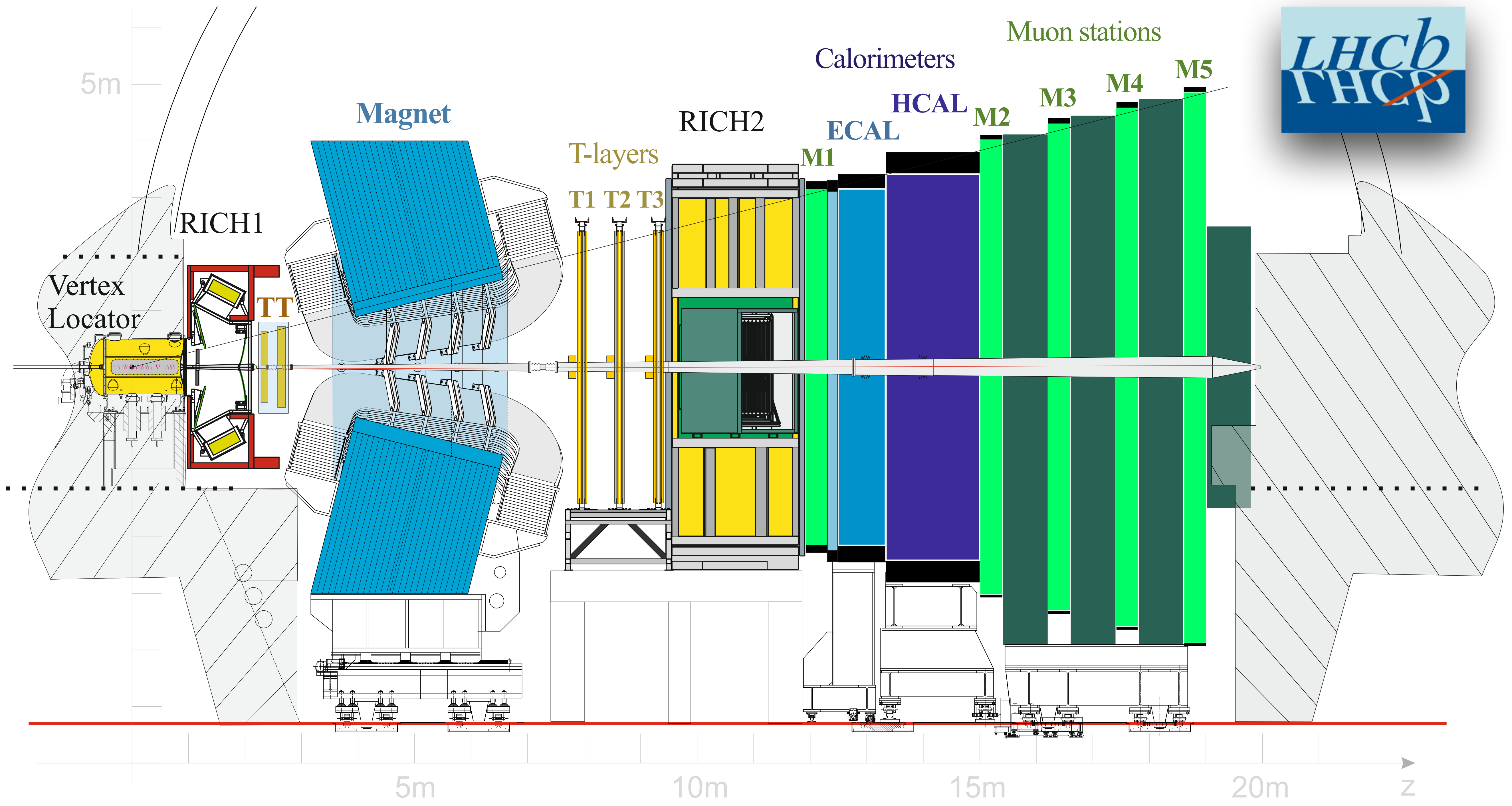
Since **100%** of e^+e^- **collision energy** goes **to** $B\bar{B}$, can **reconstruct** ν **4-momentum**

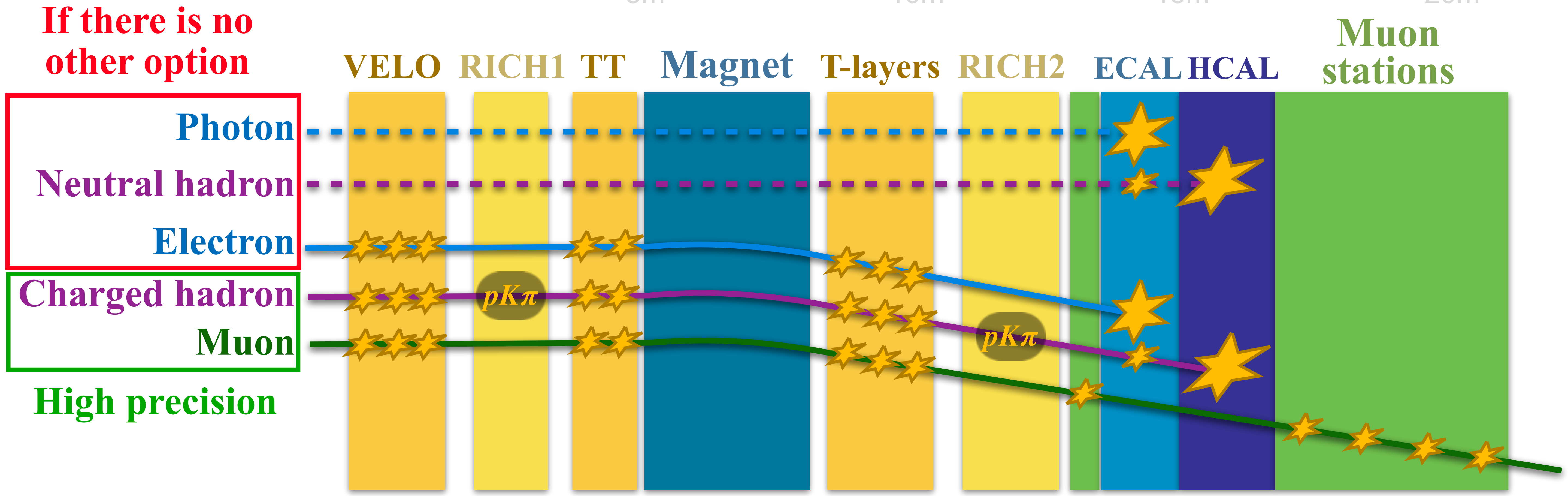


The LHC experiments

Accelerator	Lab	Country	From	To
LHC	CERN	Switzerland/ France	2008	~2041

- LHC pp collisions at 14 TeV
  - $pp \to b\bar{b} \to H_b\bar{H}_b$ with $H_b = B, B_s, \Lambda_b, B_c$
  - **Cross section 10^5 higher** than **B factories**
  - **Messy environment** and **protons not elementary**
- Detectors
  - **LHCb** tailored for **B physics**
  - **ATLAS**, **CMS general purpose**, but higher stats



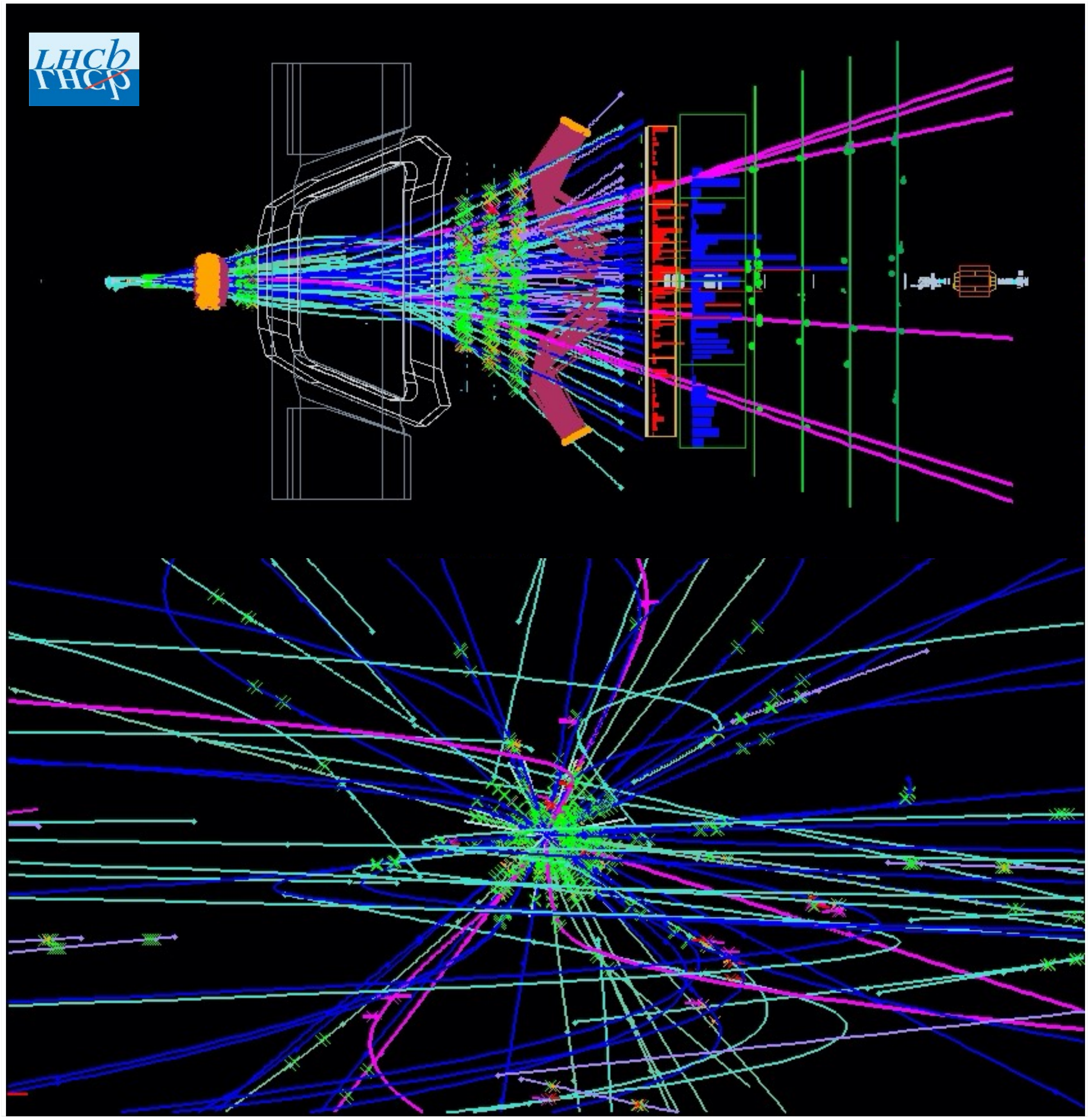


$pp \to X_b B_s^0 X$

$B_s^0 \to \mu^+\mu^-$

$e^+e^- \to B^+_{\mathrm{tag}} B^-_{\mathrm{sig}}$

$B^- \to \rho^0 \mu^- \nu_\mu$

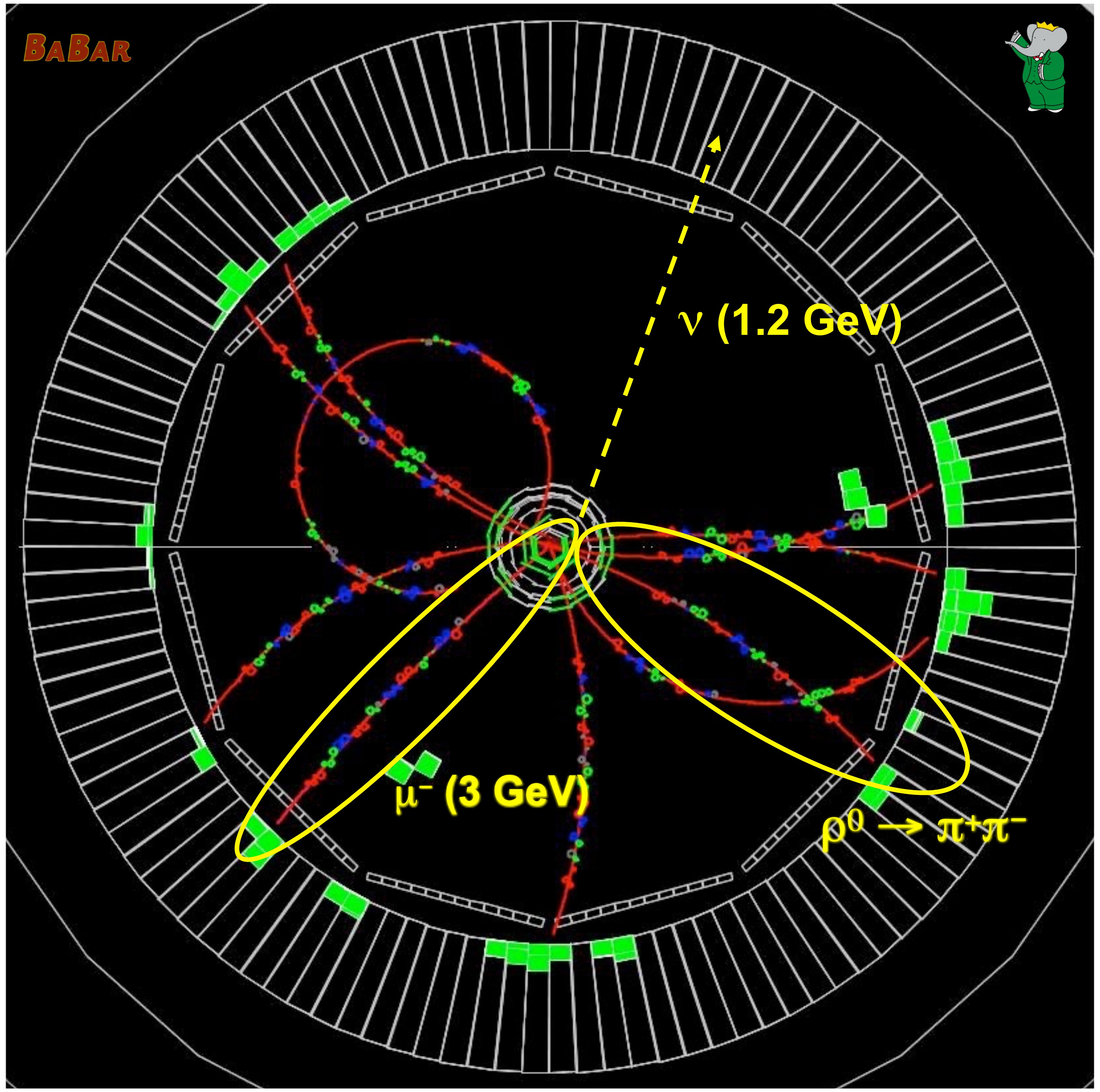


LHC

pp collisions have background from $b\bar{b}$ hadronization, underlying event, and pileup

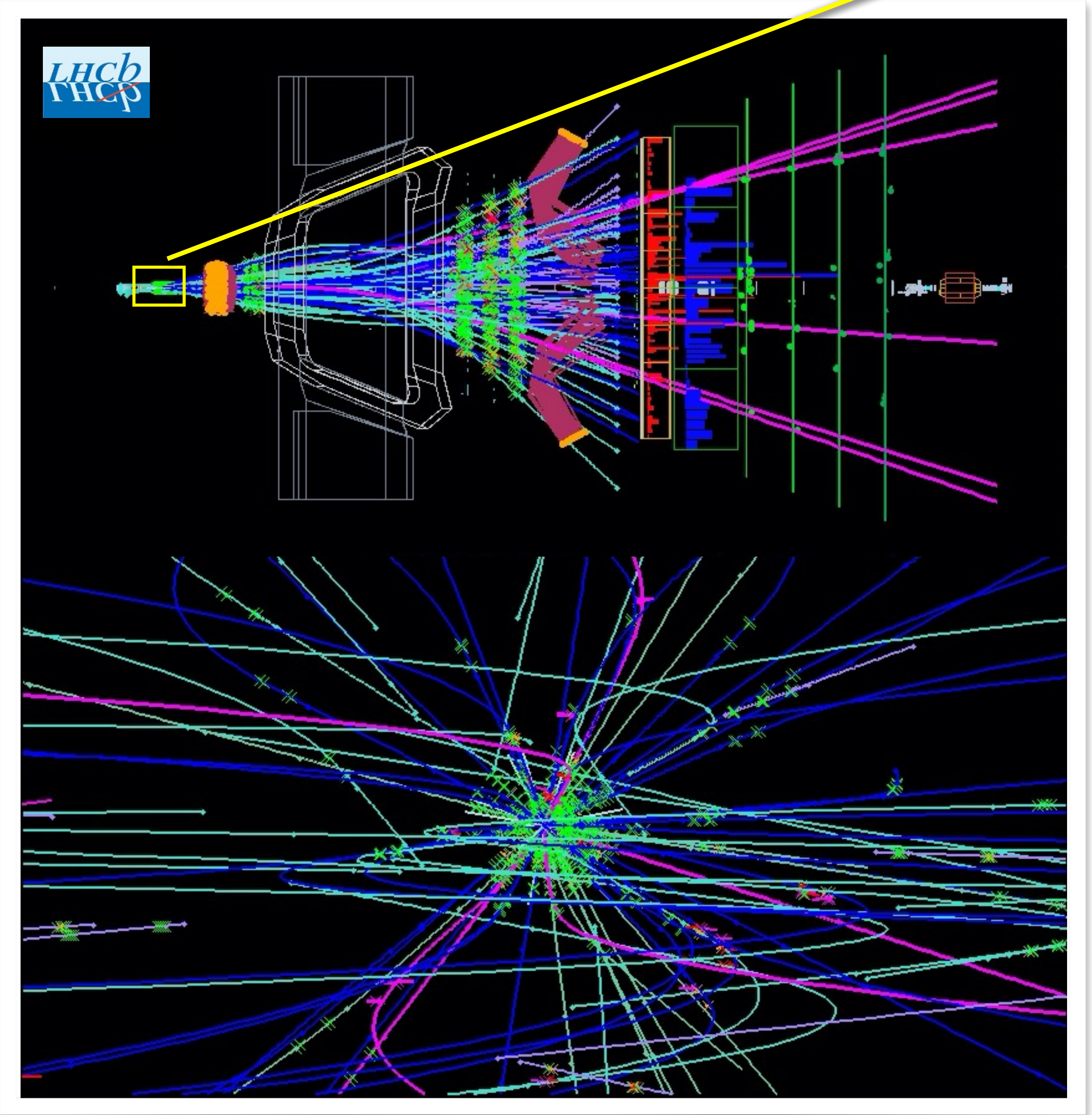
B-factories

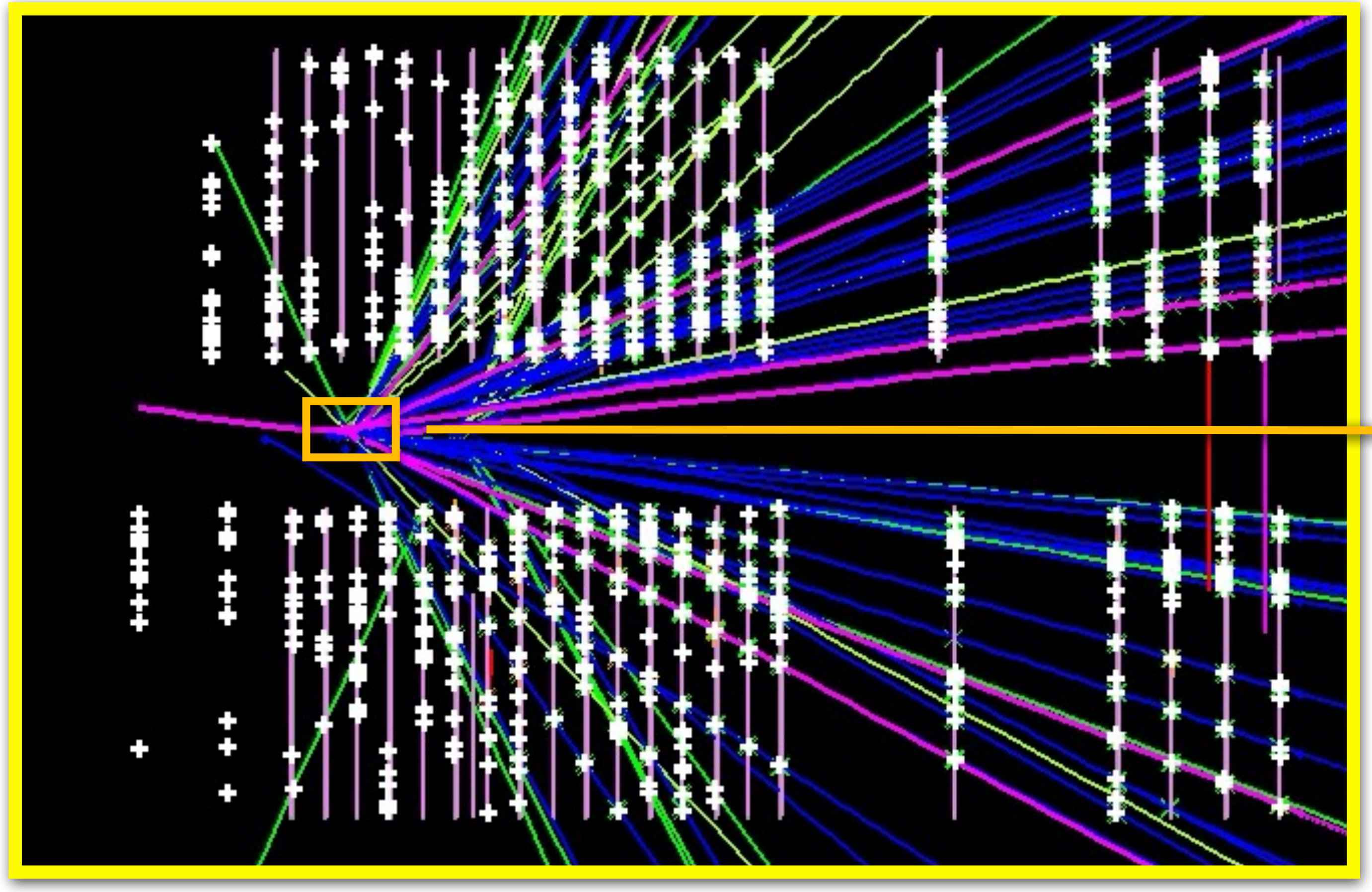
Clean e^+e^- collisions only produce two B mesons (for the most part)

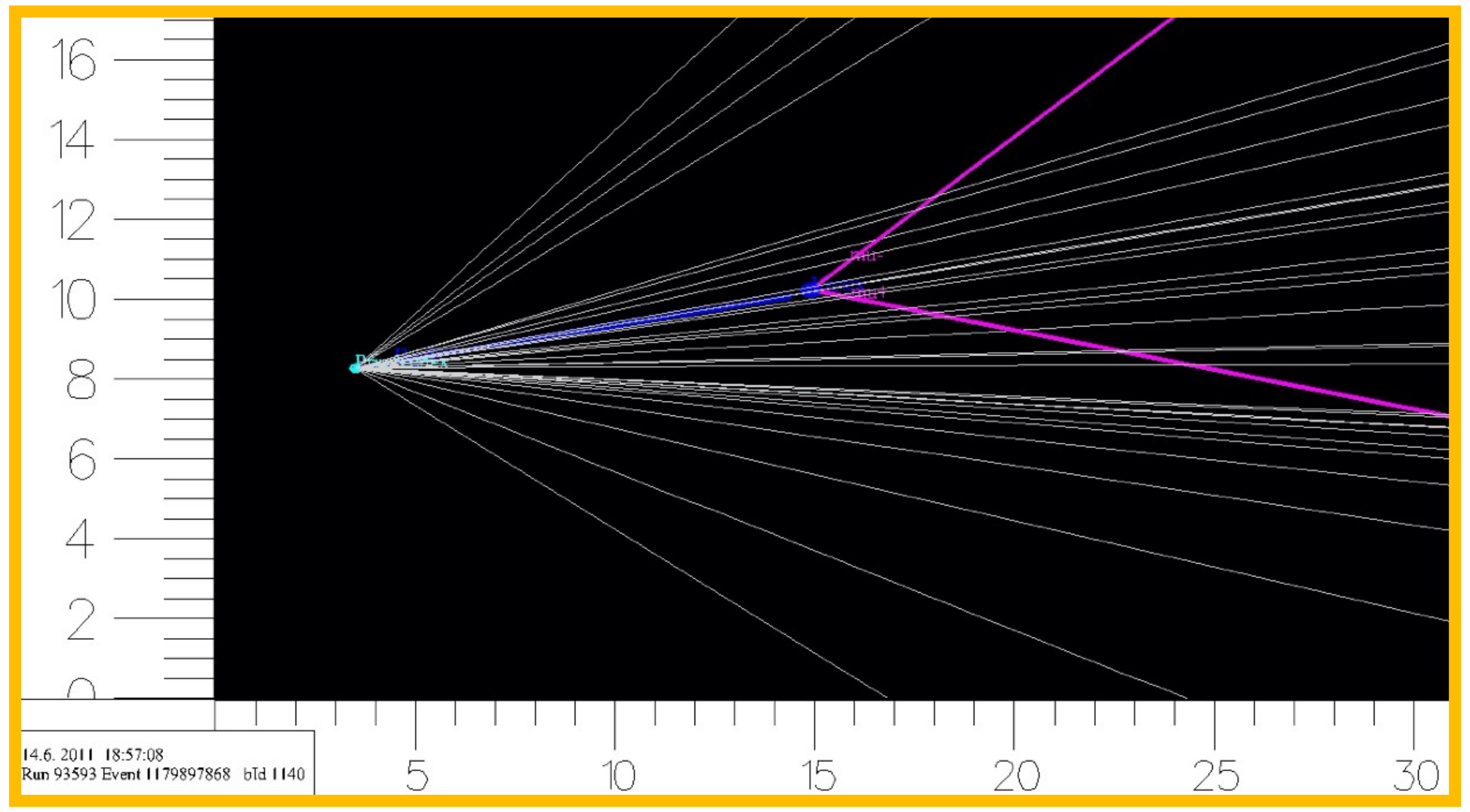


$$pp \to X_b B_s^0 X$$

$$B_s^0 \to \mu^+\mu^-$$







- **B mesons can fly ~cm** thanks to large boost
- **Excellent trackers** in **CMS** and **ATLAS**
- **Superb vertexing** by VELO in **LHCb**
  - Only 8.2 mm from IP, reduced to 5.1 in upgrade
- Multivariate algorithms ensure **tracks isolated**
  - Based on track impact parameter, other variables

B factories vs LHC summary

B-factories

BaBar, Belle

$\mathcal{O}\left(10^{9}\right)$ $B^{0/+}$ **mesons**

Low uncertainty on absolute rates, 100% ε(trigger), PID, **low e-brem, knowledge of collision momentum**

Belle II

With $\mathcal{O}\left(10^{8}\right)$ $B^{0/+}$ mesons already competitive search for $B \to K\nu\bar{\nu}$!

LHC

LHCb

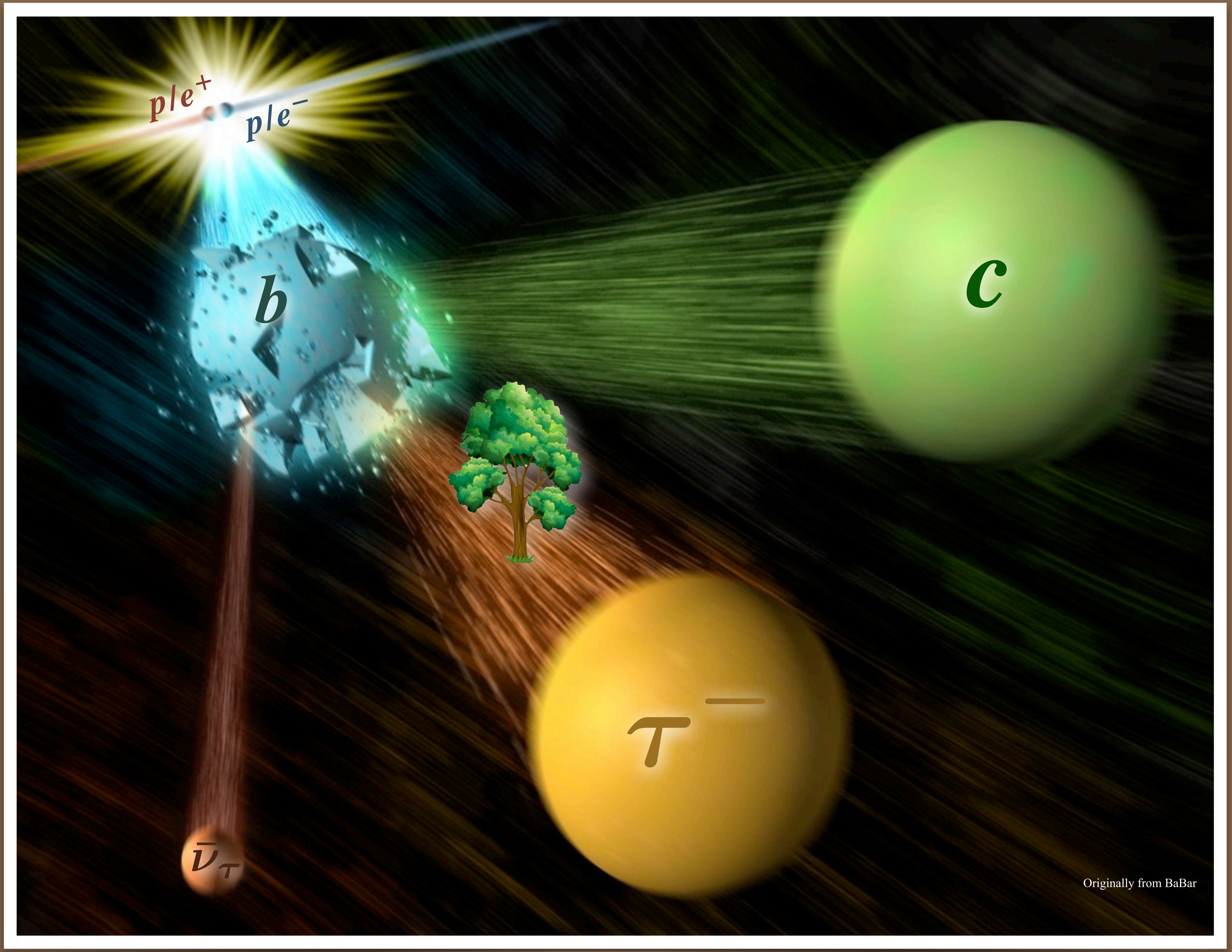
$\mathcal{O}\left(10^{11}\right)$ $B^{0/+}_{(s)}$ **mesons**

Triggers primarily for flavor, PID, VELO, **all b-hadron species**

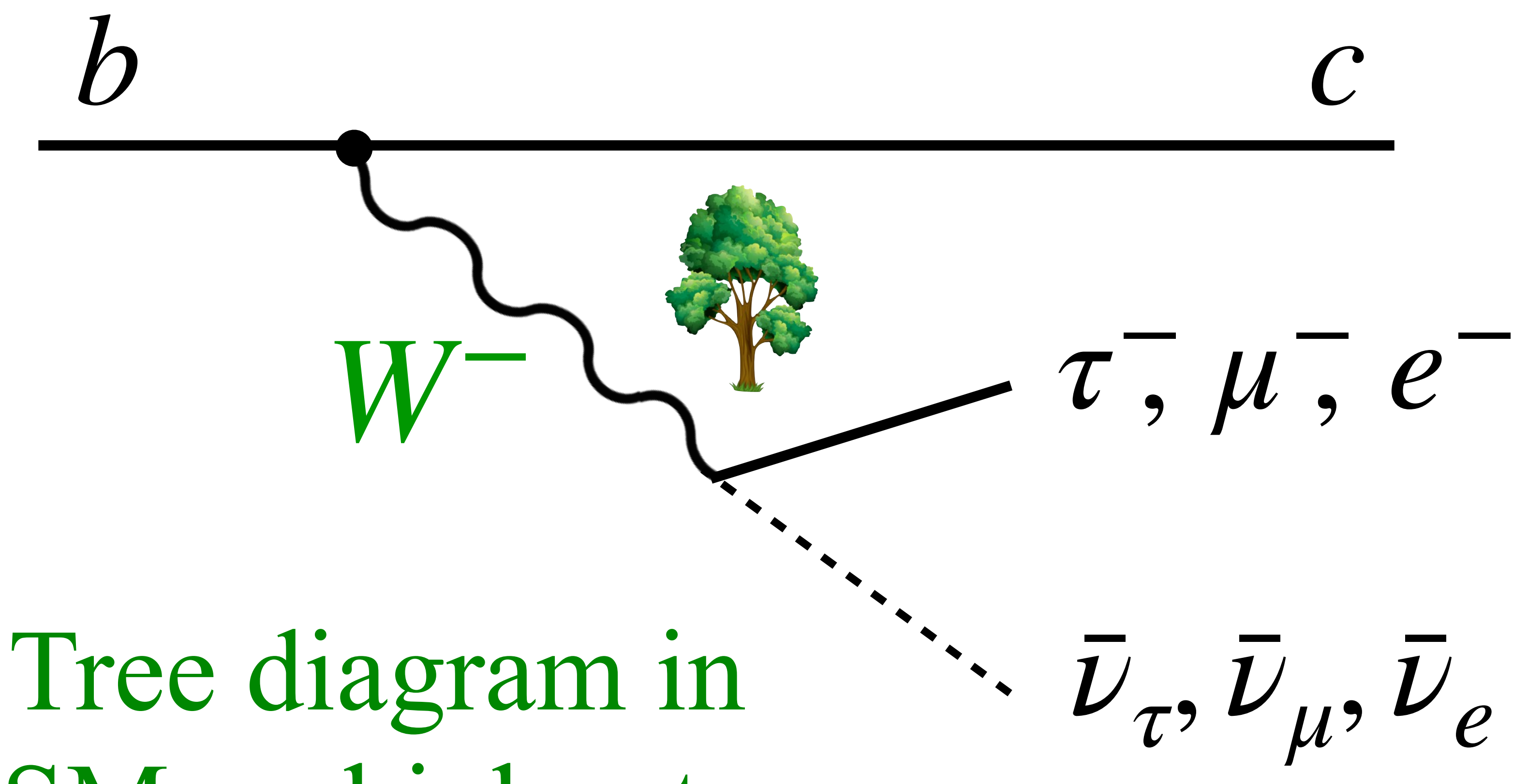
ATLAS EXPERIMENT, CMS

$\mathcal{O}\left(10^{12}\right)$ $B^{0/+}_{(s)}$ **mesons**

All b-hadron species



3. Charged LFU results with $b \to c\tau\nu$ transitions



Tree diagram in SM $\rightarrow$ high rate

Ratios of branching fractions to cancel out uncertainties

$$\mathcal{R}\left(D^{(*)}\right) = \frac{\mathcal{B}\left(\bar{B} \to D^{(*)}\tau\nu_\tau\right)}{\mathcal{B}\left(\bar{B} \to D^{(*)}\ell\nu_\ell\right)}$$

with $\ell = \mu, e$

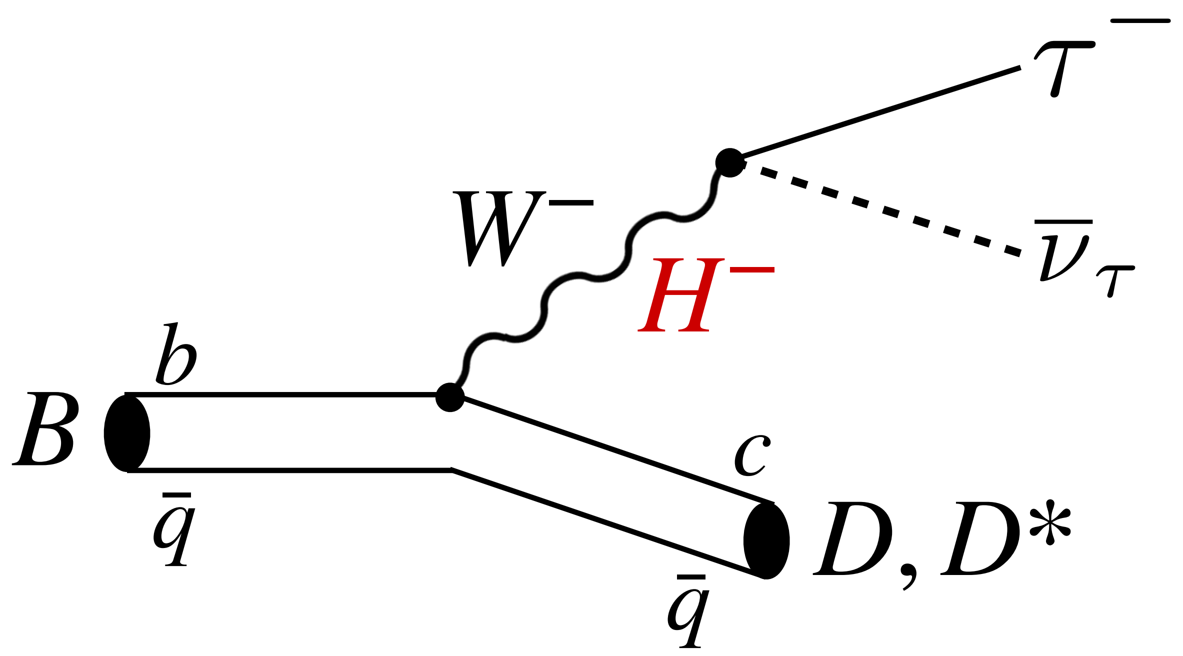
$\mathcal{R}\left(D^{(*)}\right) \equiv \mathcal{R}(D)$ or $\mathcal{R}(D^*)$

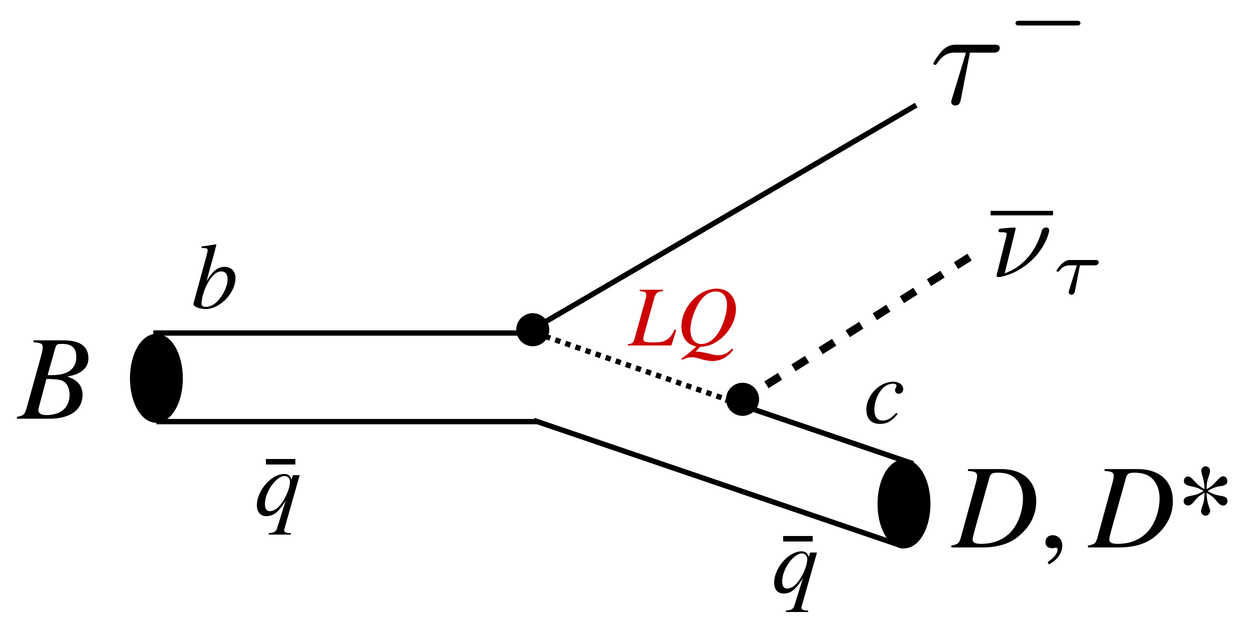
Very solid SM predictions with **just 1-2% uncertainty**

$$\mathcal{R}(D)^{SM} = 0.299 \pm 0.003$$

$$\mathcal{R}\left(D^*\right)^{SM} = 0.258 \pm 0.005$$

Any established **deviations** would be clear indications of **BSM physics**

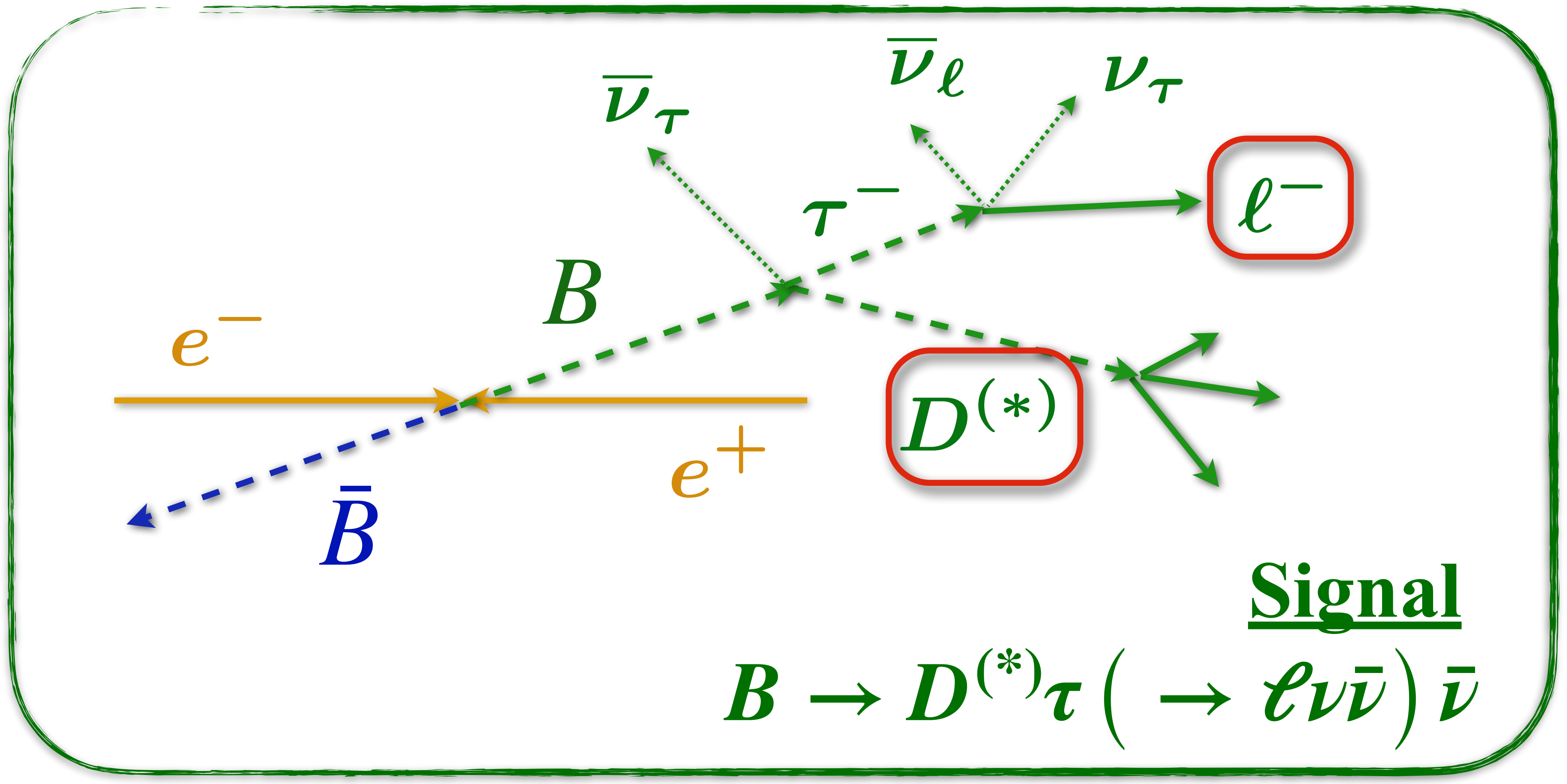


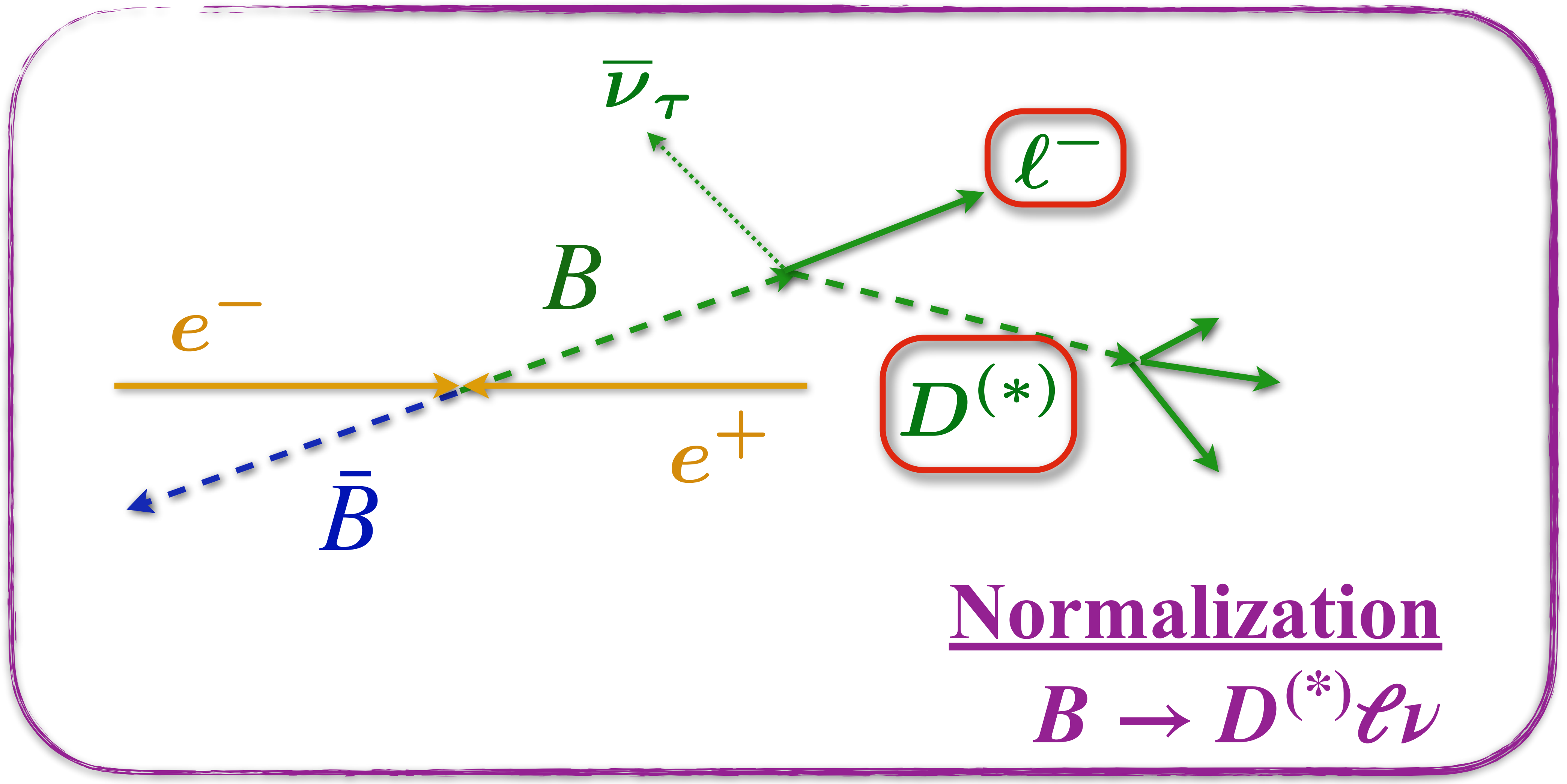


Signal τ reconstructed as $\tau^- \to \ell^- \nu_\tau \bar{\nu}_\ell$, leads to **same reco particles** as **normalization**

$$\mathscr{R}\left(D^{(*)}\right) = \frac{\mathscr{B}\left(\bar{B} \to D^{(*)} \tau \nu_\tau\right)}{\mathscr{B}\left(\bar{B} \to D^{(*)} \ell \nu_\ell\right)}$$

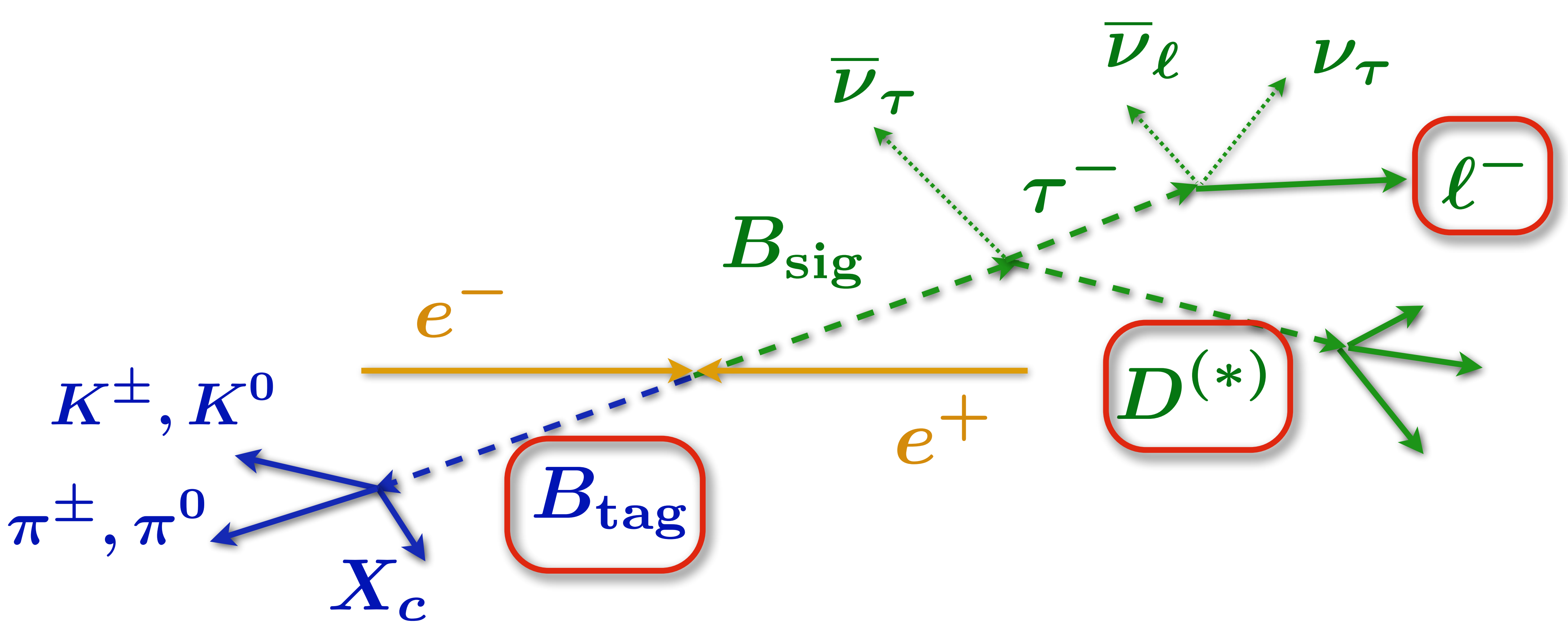
Many experimental uncertainties cancel on $\mathscr{R}\left(D^{(*)}\right)$





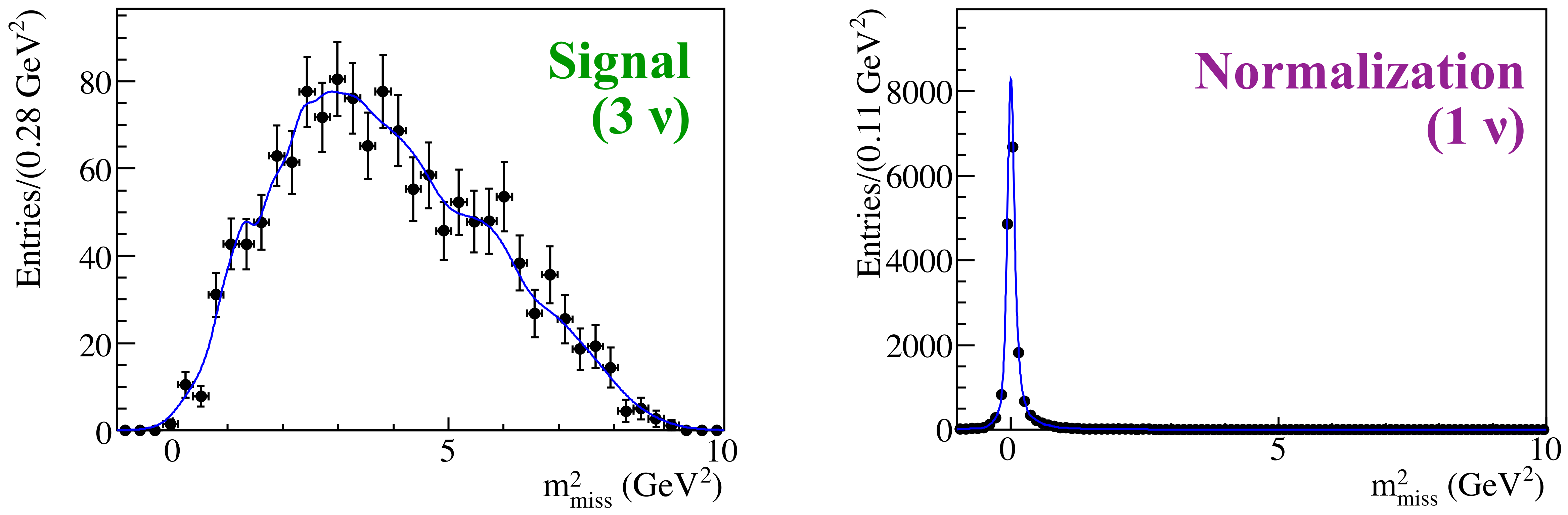
Missing mass at the B factories

Reconstruct B_{tag} and take advantage that **100%** of e^+e^- **collision energy** goes **to** $B\bar{B}$ to **measure 4-momenta of neutrinos**

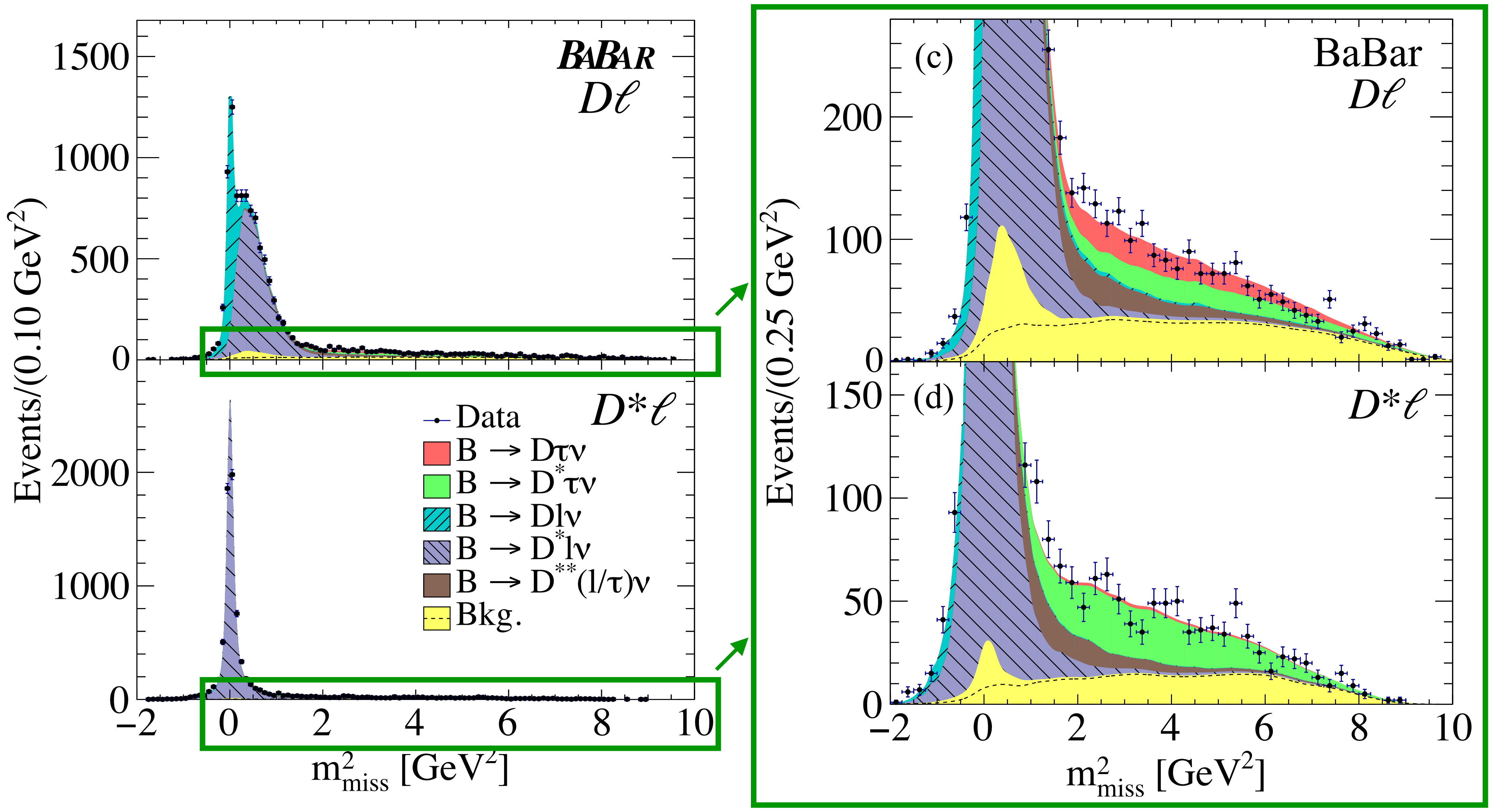


$$m^2_{miss} = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^{(*)}} - p_\ell\right)^2$$

$B \to D^*\tau(\to \ell\nu\bar{\nu})\bar{\nu}$ $\qquad$ $B \to D^*\ell\nu$

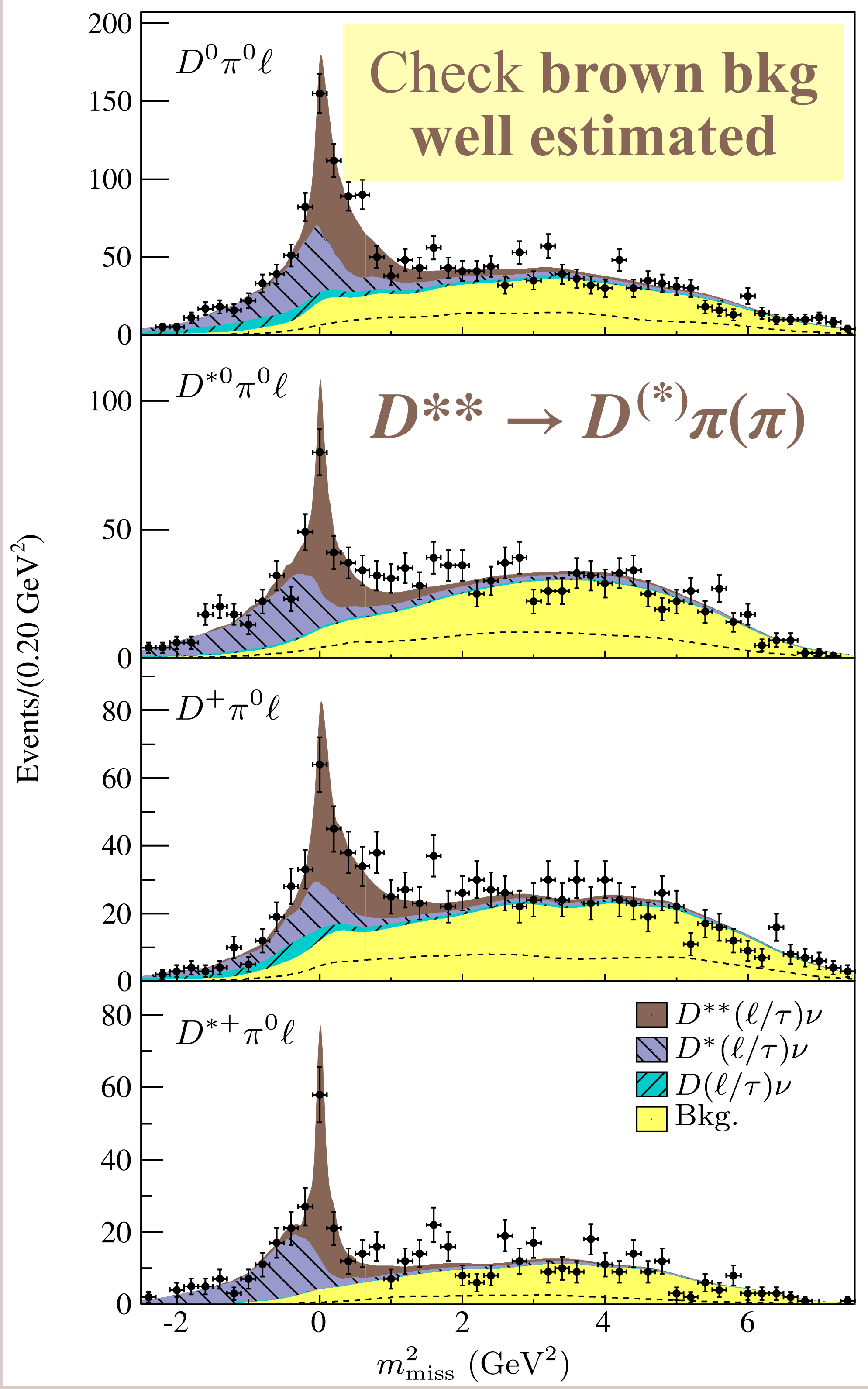


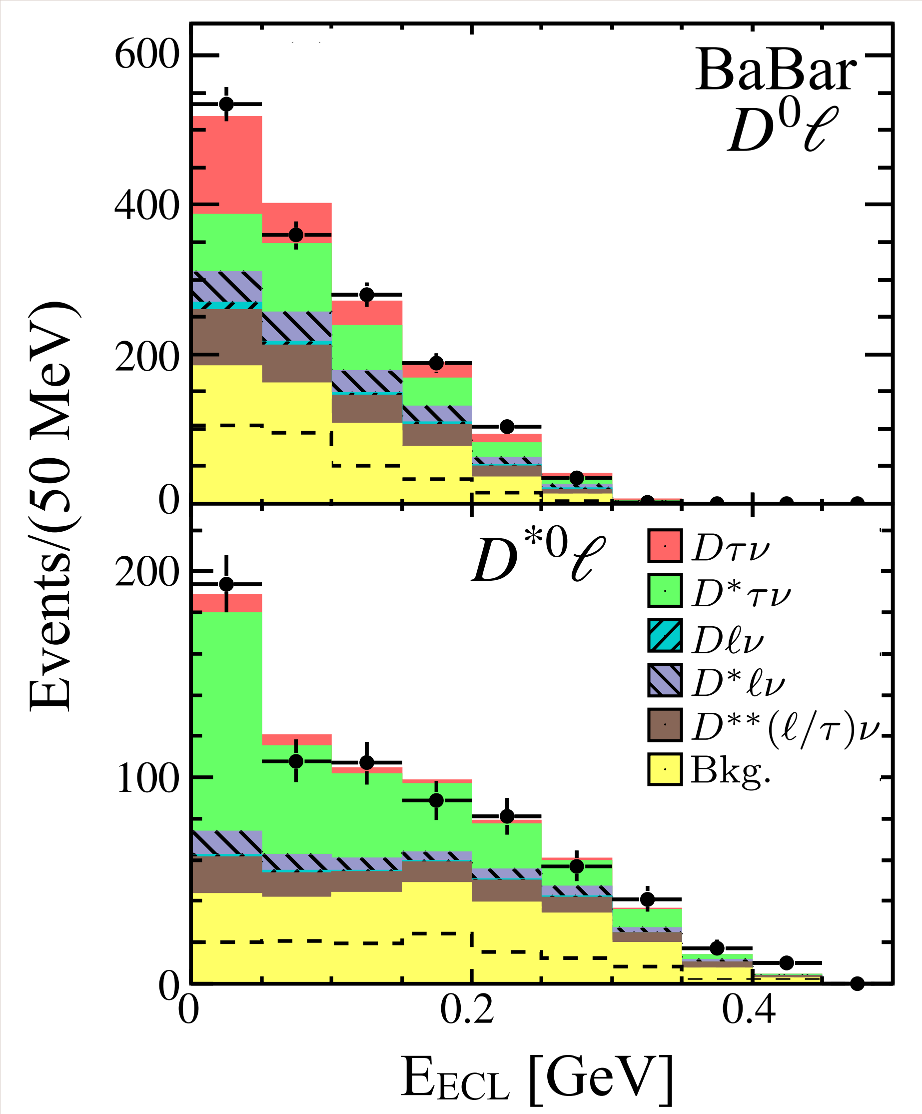
Phys. Rev. Lett. **109**, 101802 (2012)



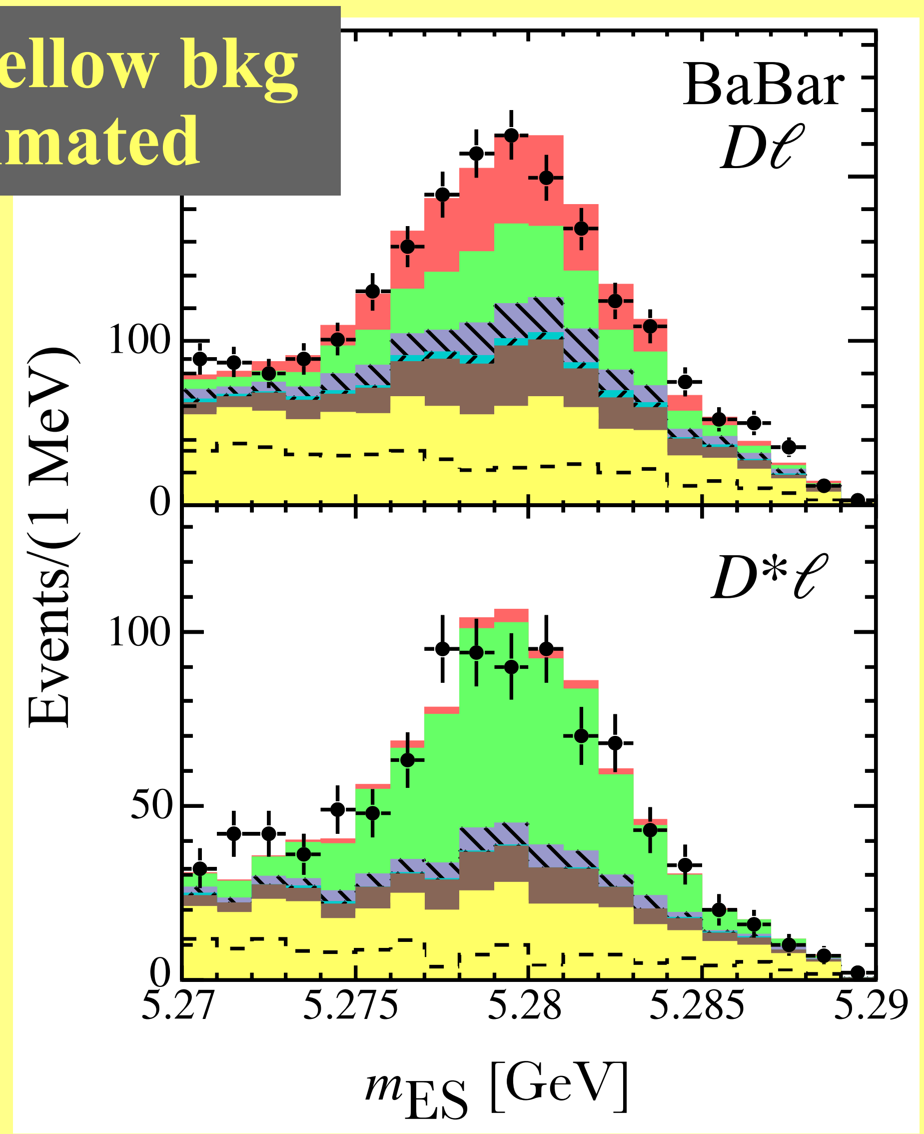
Check **brown bkg** well estimated

$D^{**} \to D^{(*)}\pi(\pi)$

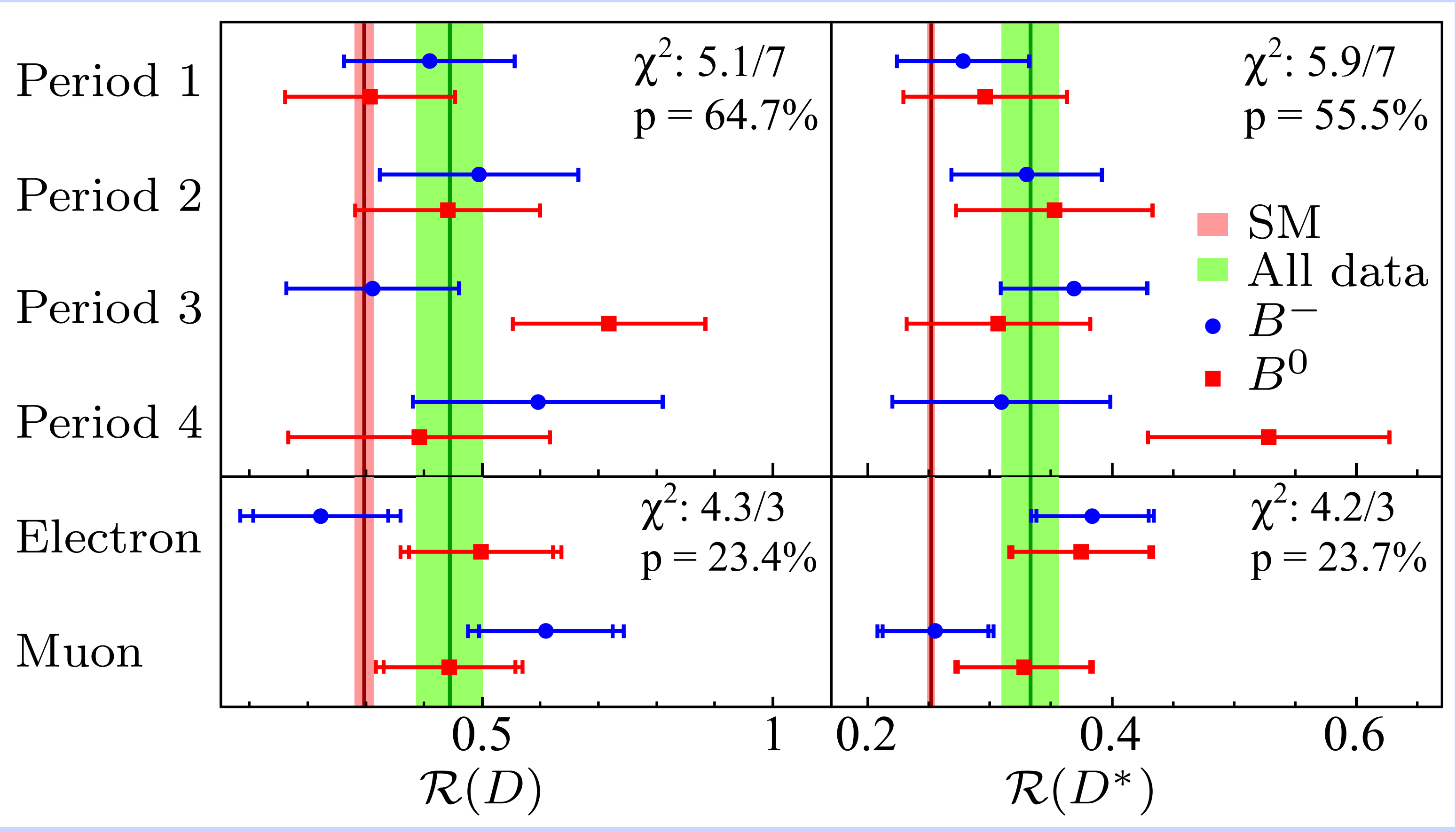




Check **yellow bkg** **well estimated**



Check **result stable** as a function of **lepton flavor**, **run period**, and **purity**

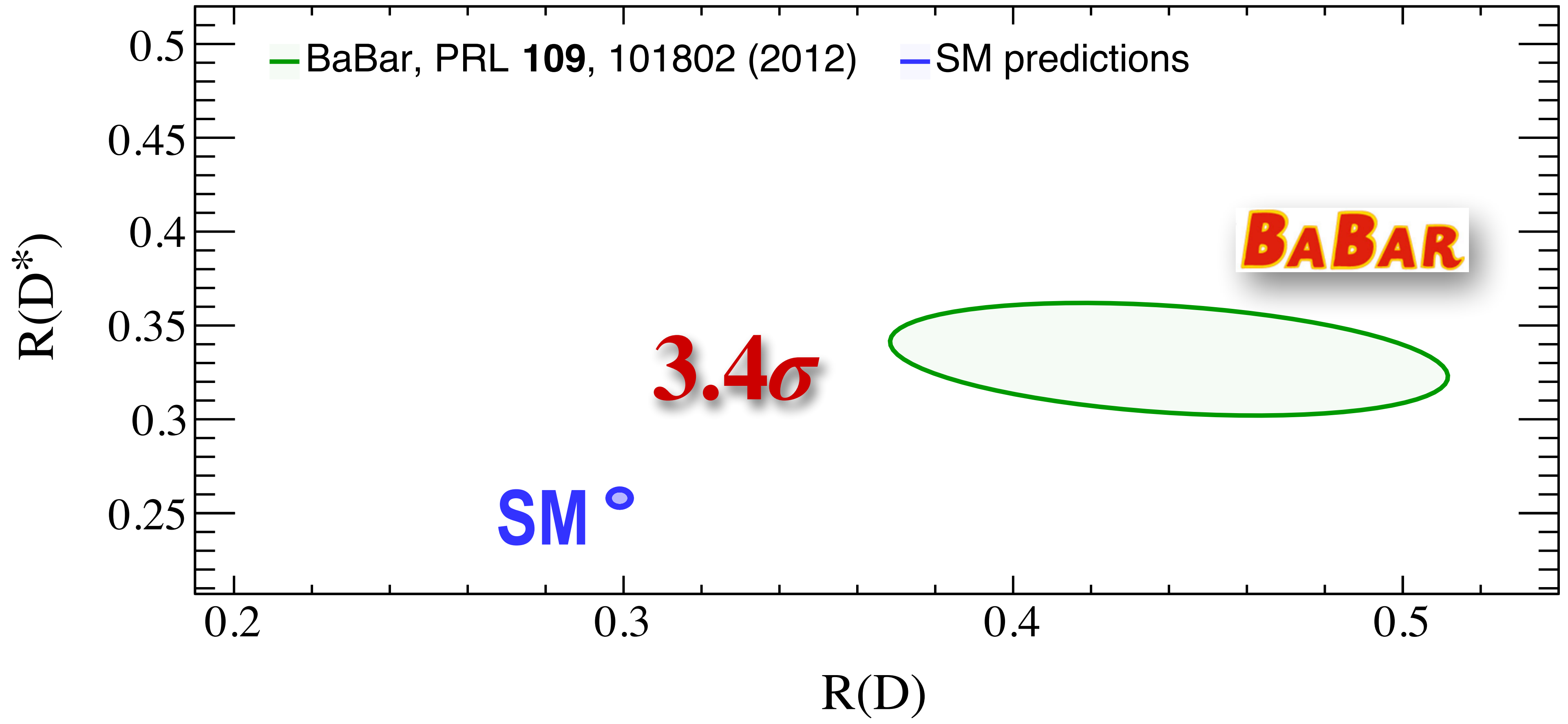


Phys. Rev. Lett. **109**, 101802 (2012)

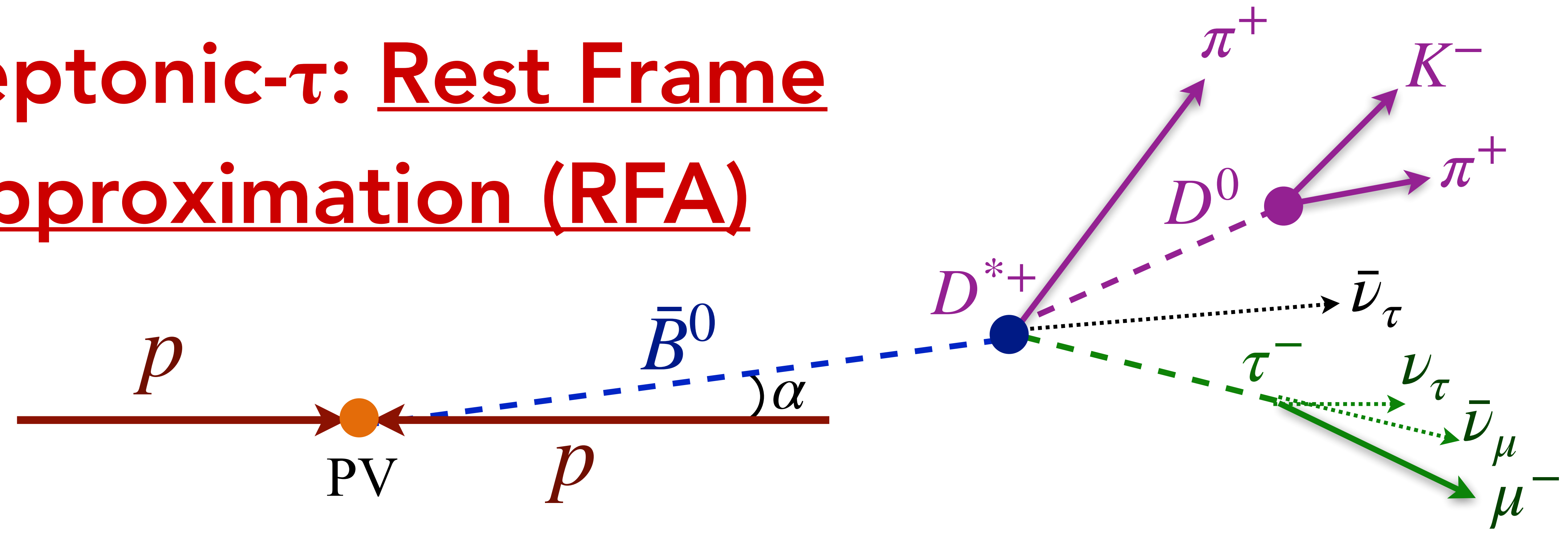
Phys. Rev. D **88**, 072012 (2013)

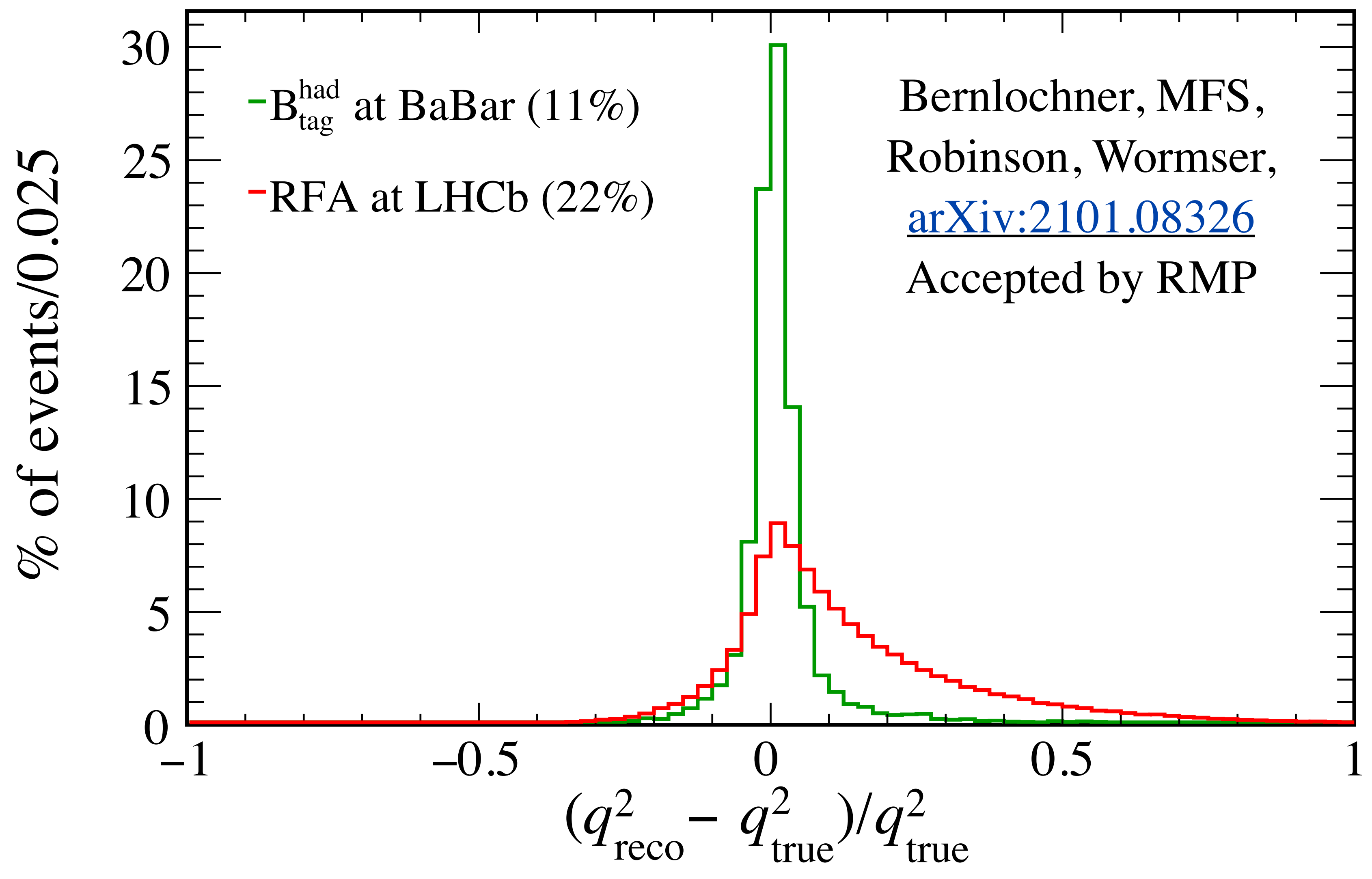
$$R(D) = \left\{\begin{array}{ll} 0.440 \pm 0.072 & \text{BABAR} \\ 0.300 \pm 0.008 & \text{SM} \end{array}\right\} \quad \mathbf{2.0\sigma}$$

$$R(D^*) = \left\{\begin{array}{ll} 0.332 \pm 0.030 & \text{BABAR} \\ 0.252 \pm 0.003 & \text{SM} \end{array}\right\} \quad \mathbf{2.7\sigma}$$



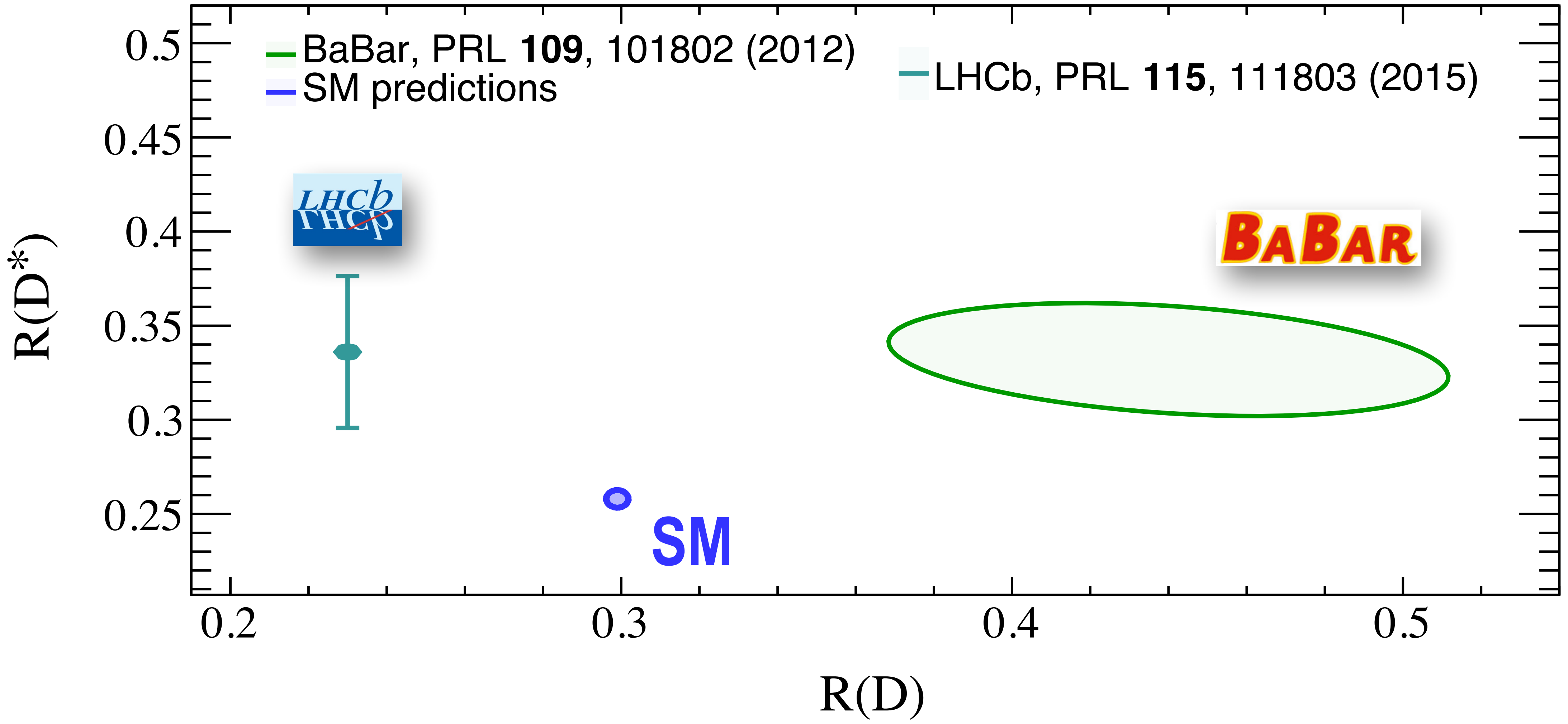
Leptonic-τ: Rest Frame Approximation (RFA)

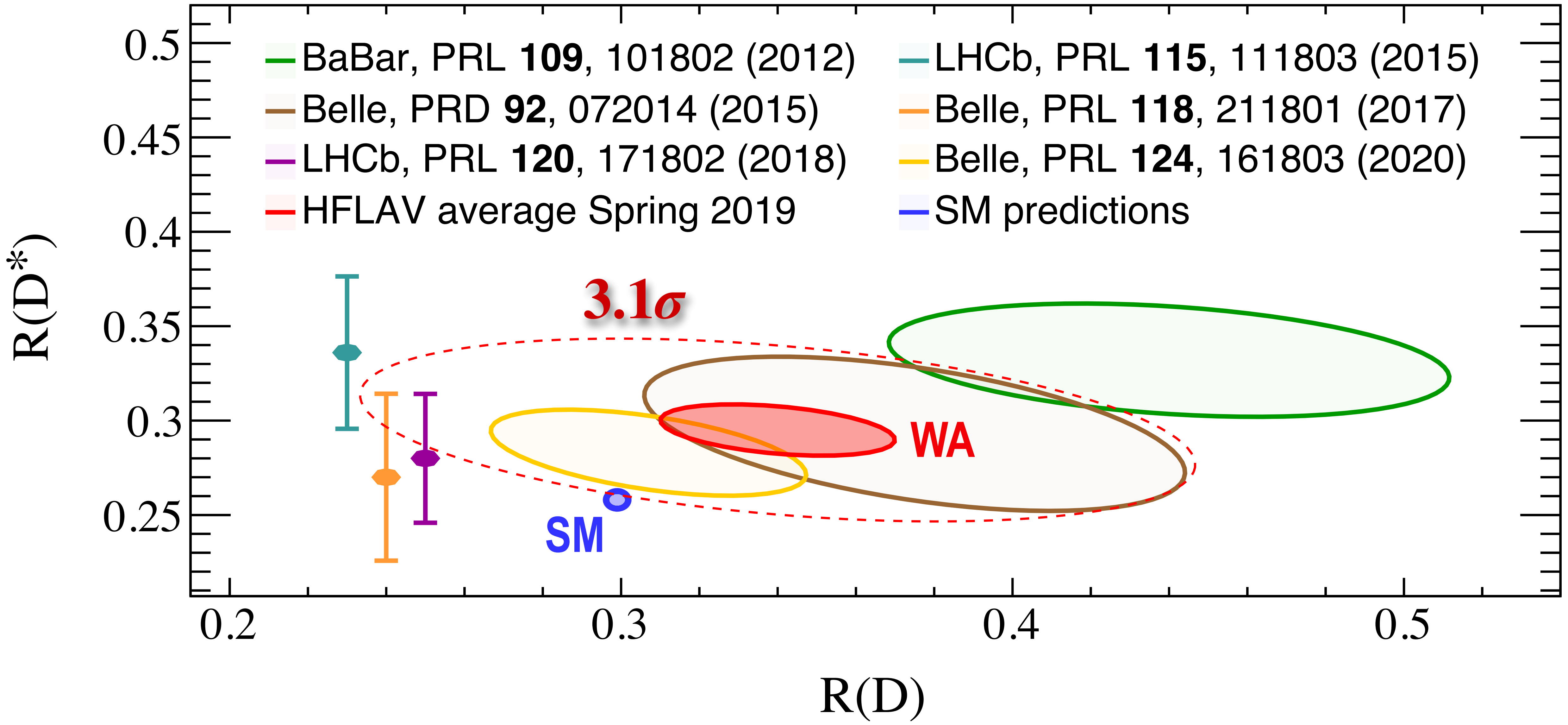




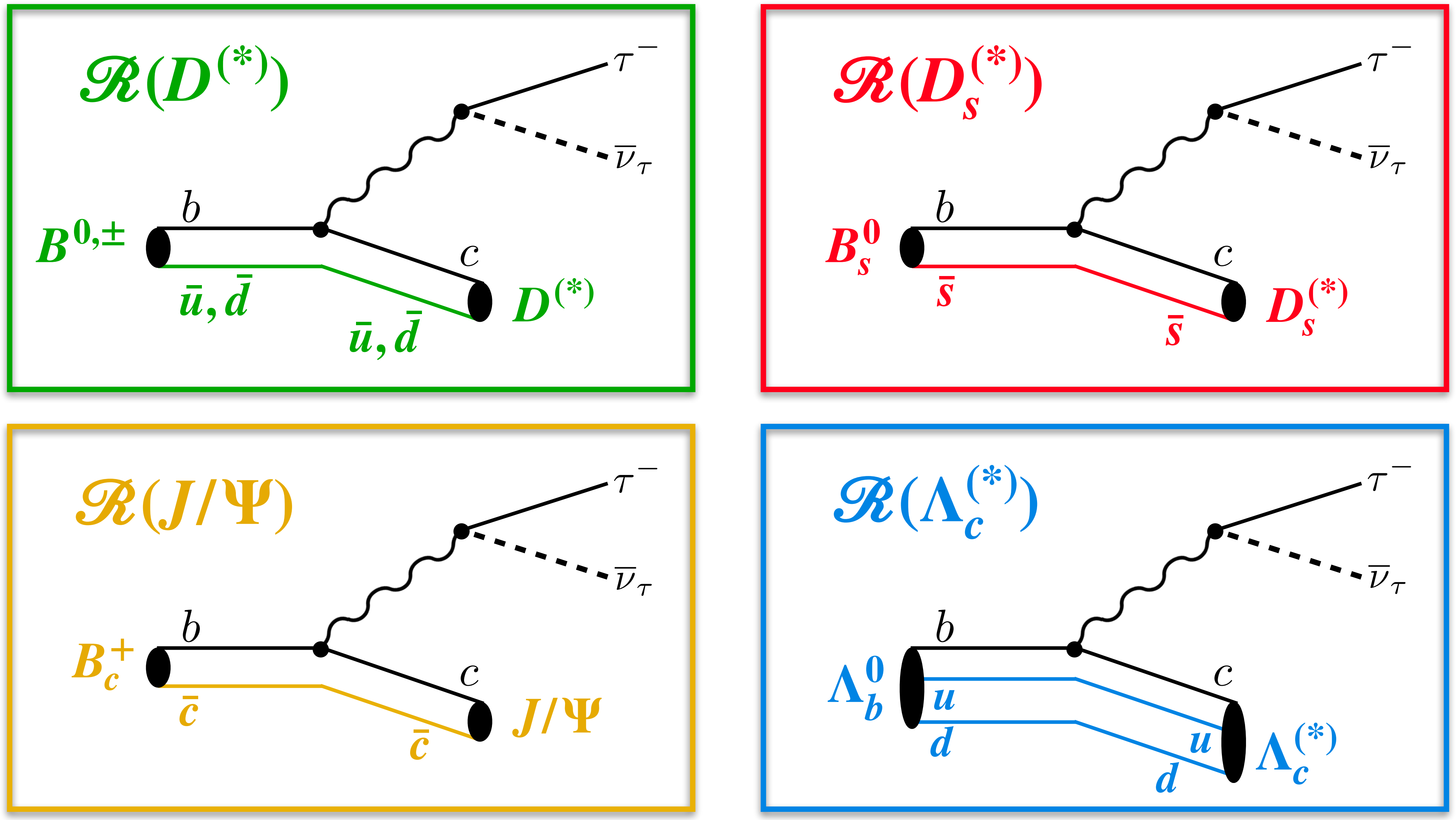
Estimate B momentum based on B vertex and assumption proper velocity of B and reco particles ($\mu\, D^*$) along z is the same

$$\mathscr{R}(D^*) = \begin{cases} 0.332 \pm 0.030 & \text{BaBar} \\ 0.336 \pm 0.040 & \text{LHCb} \end{cases}$$





LHCb has a unique ability to study $b \to c\tau\nu$ transitions because $b\bar{b}$ production at the LHC hadronizes into all species of b-hadrons



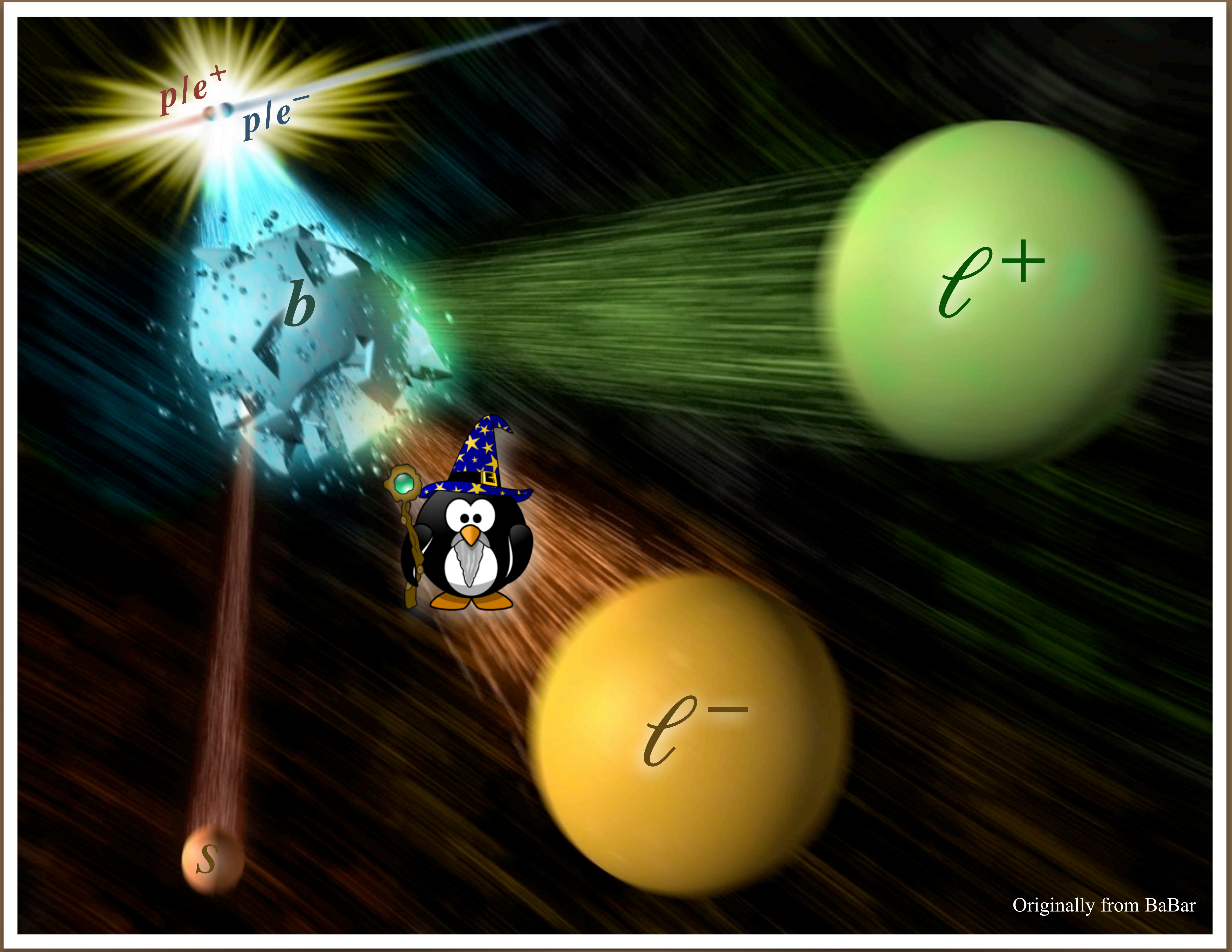
- Even a **5σ** on $\mathcal{R}(D^{(*)})$ **would not be sufficient** to **convince** ourselves of **NP**
  - ➡ **Indirect measurement** with **broad signal distributions** due to multiple ν in final state

LHCb already published first non-$\mathcal{R}(D^{(*)})$ measurement

$\mathcal{R}(J/\Psi) = 0.71 \pm 0.17 \pm 0.18$,

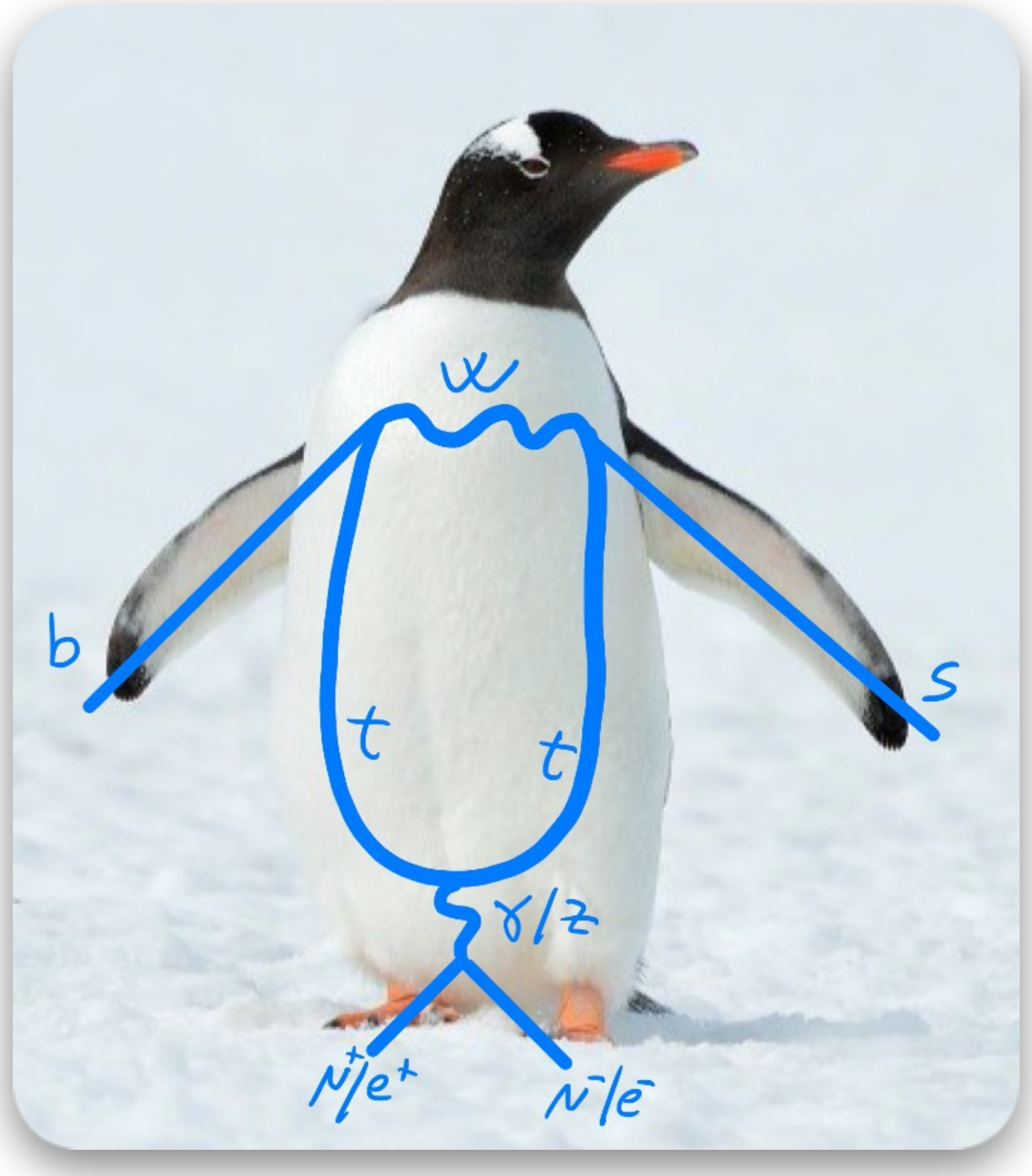
1.8σ above SM

Phys. Rev. Lett. **120**, 121801 (2018)

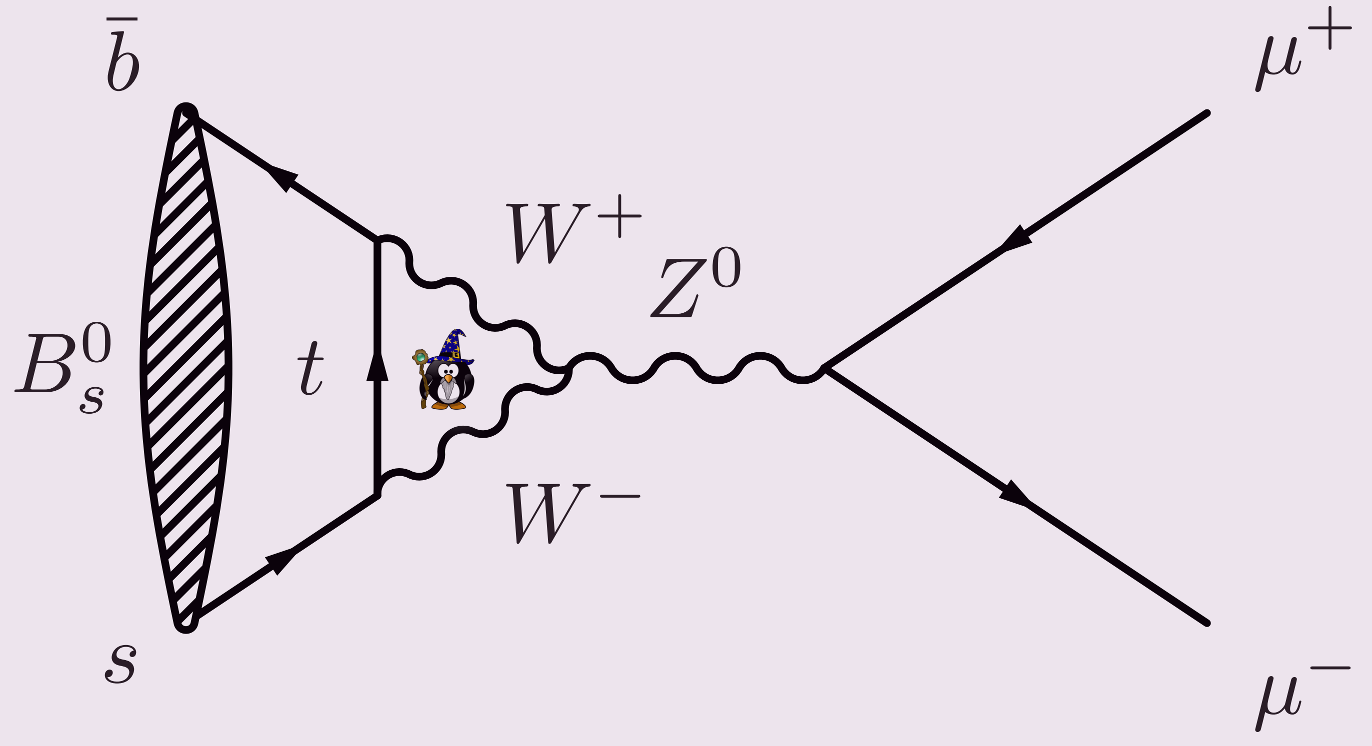


Penguin from Jeff Brassard

4. Neutral LFU results with $b \to s\ell\ell$ transitions

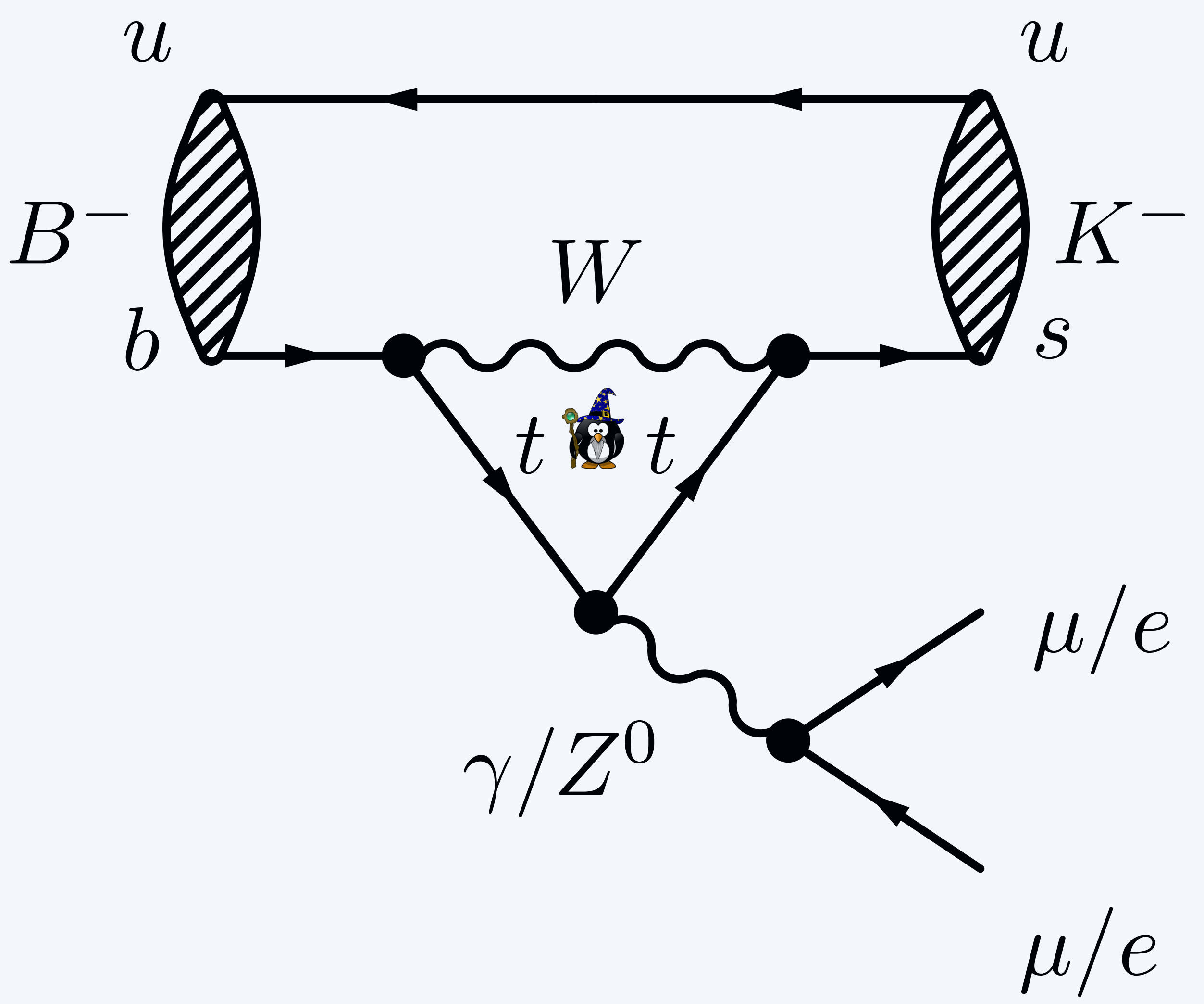


- **Loop suppresses SM contribution**
  - Very rare $\mathcal{B} < 10^{-7}$
- Easier to detect possible BSM physics



SM prediction with 5% precision

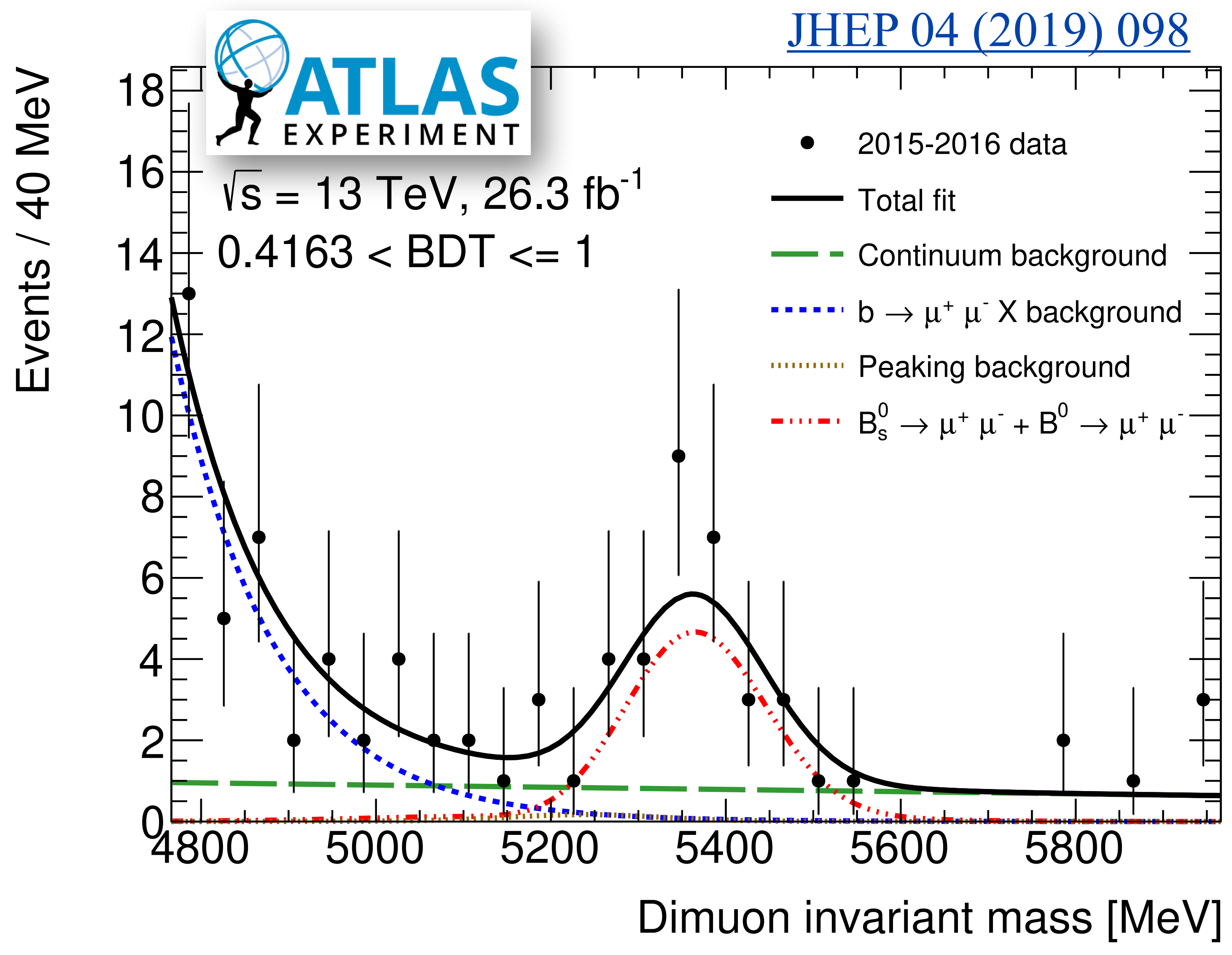
$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right) = \left(3.66 \pm 0.14\right) \times 10^{-9}$$

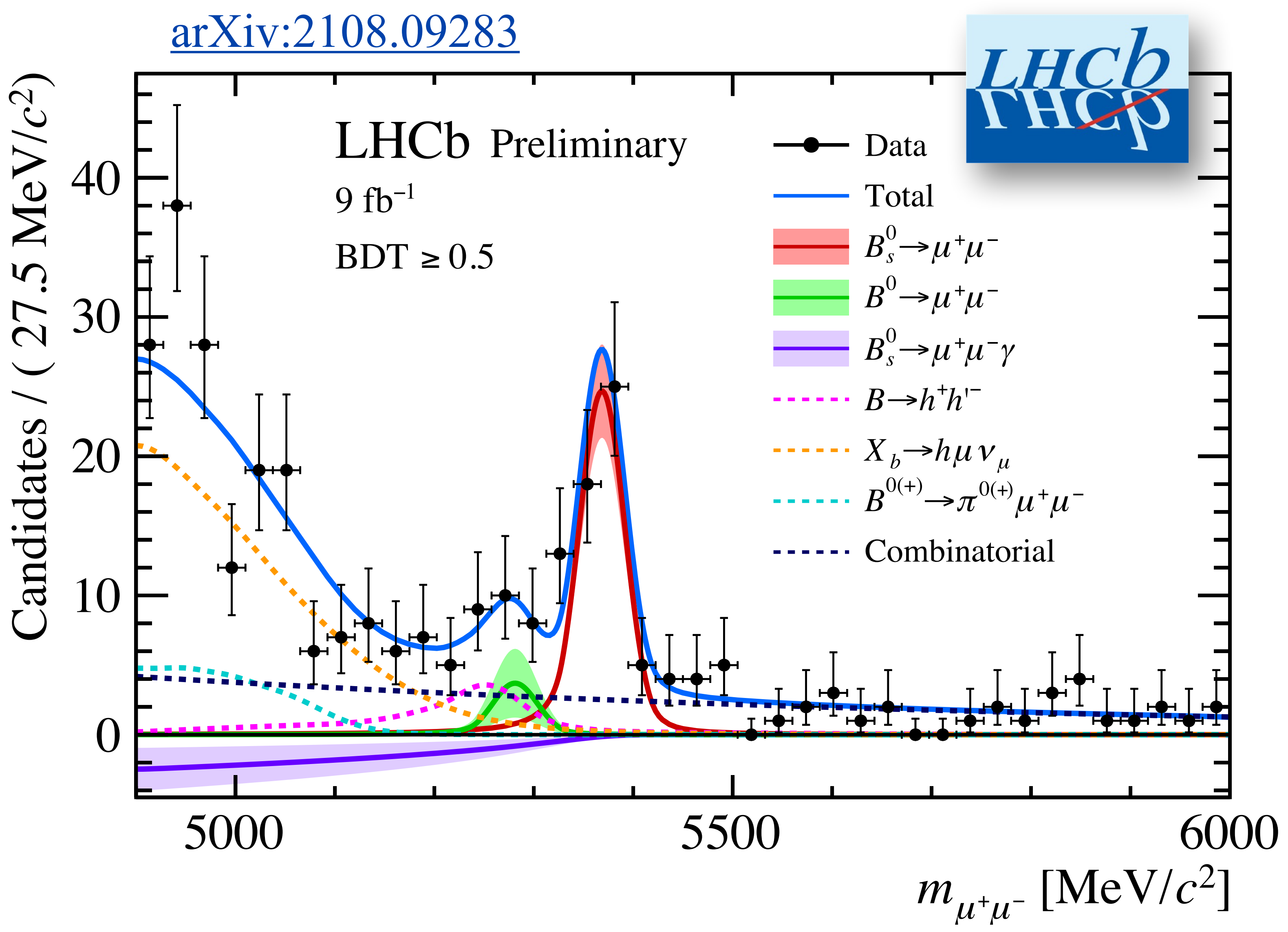


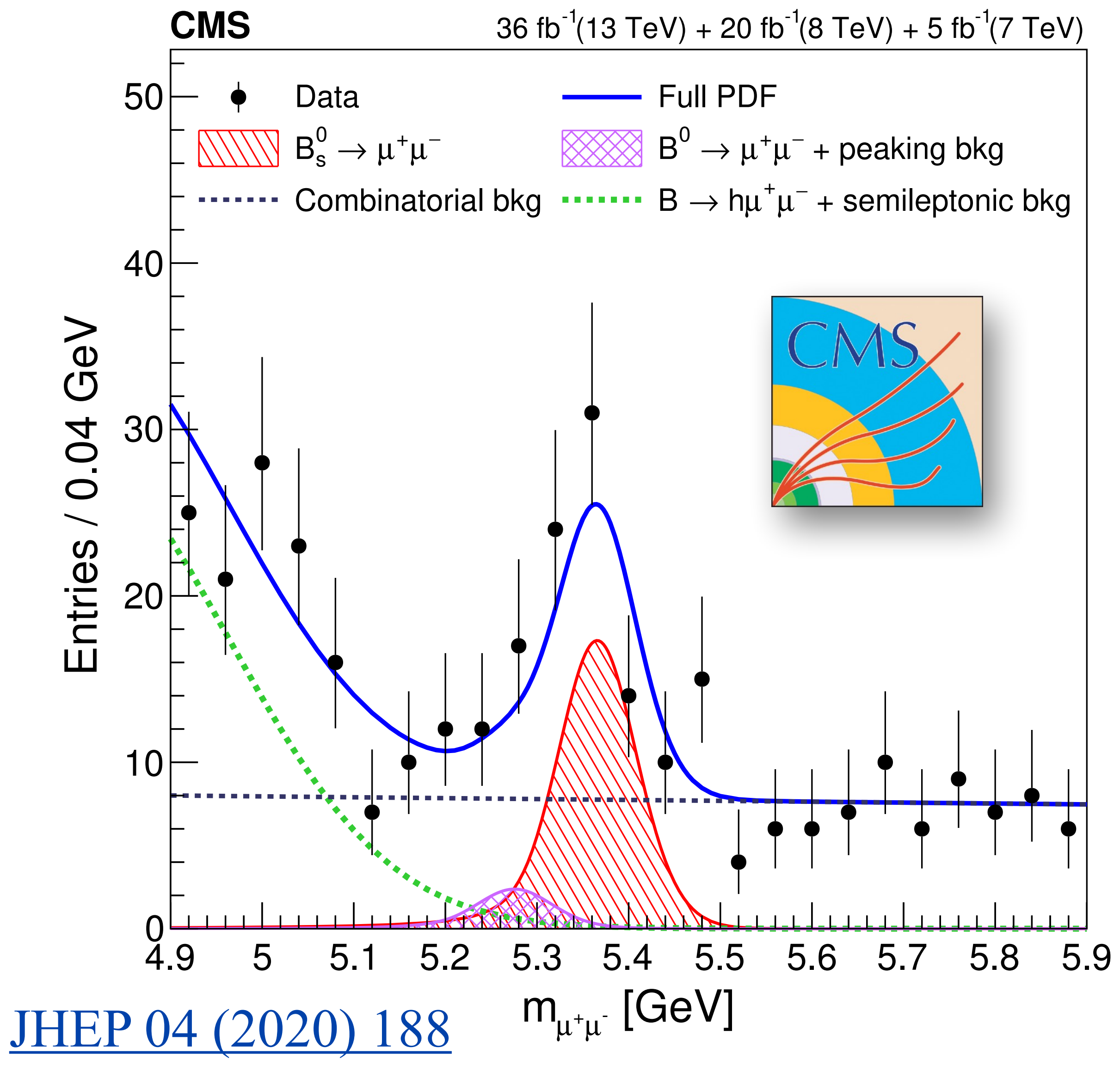
Very robust SM prediction with **better than 1% precision**

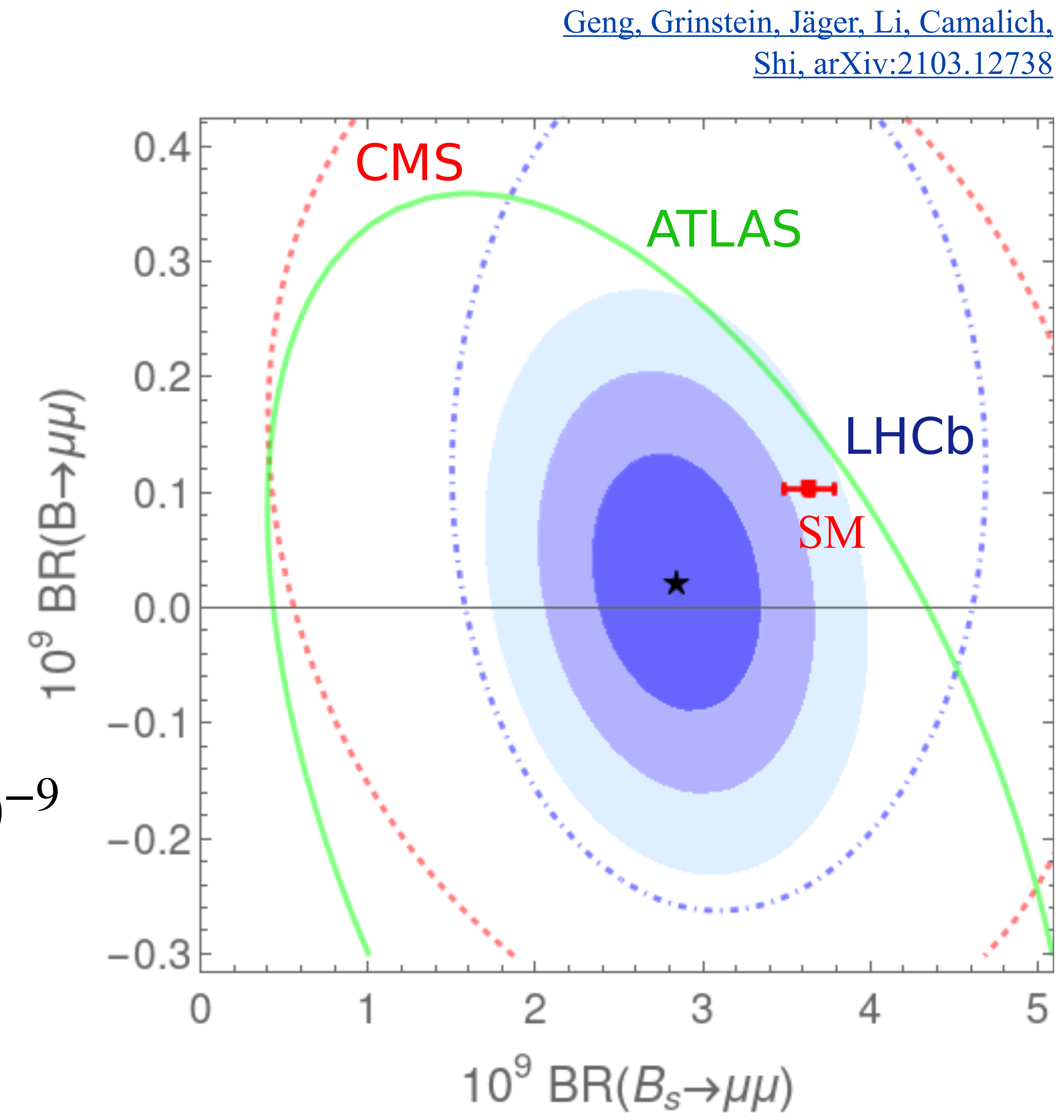
$$\mathcal{R}_{K^{(*)}} = \frac{\mathcal{B}\left(\bar{B} \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(\bar{B} \to K^{(*)}e^+e^-\right)}$$

$$\mathcal{R}_K^{SM} \approx \mathcal{R}_{K^*}^{SM} \approx 1.00 \pm 0.01$$









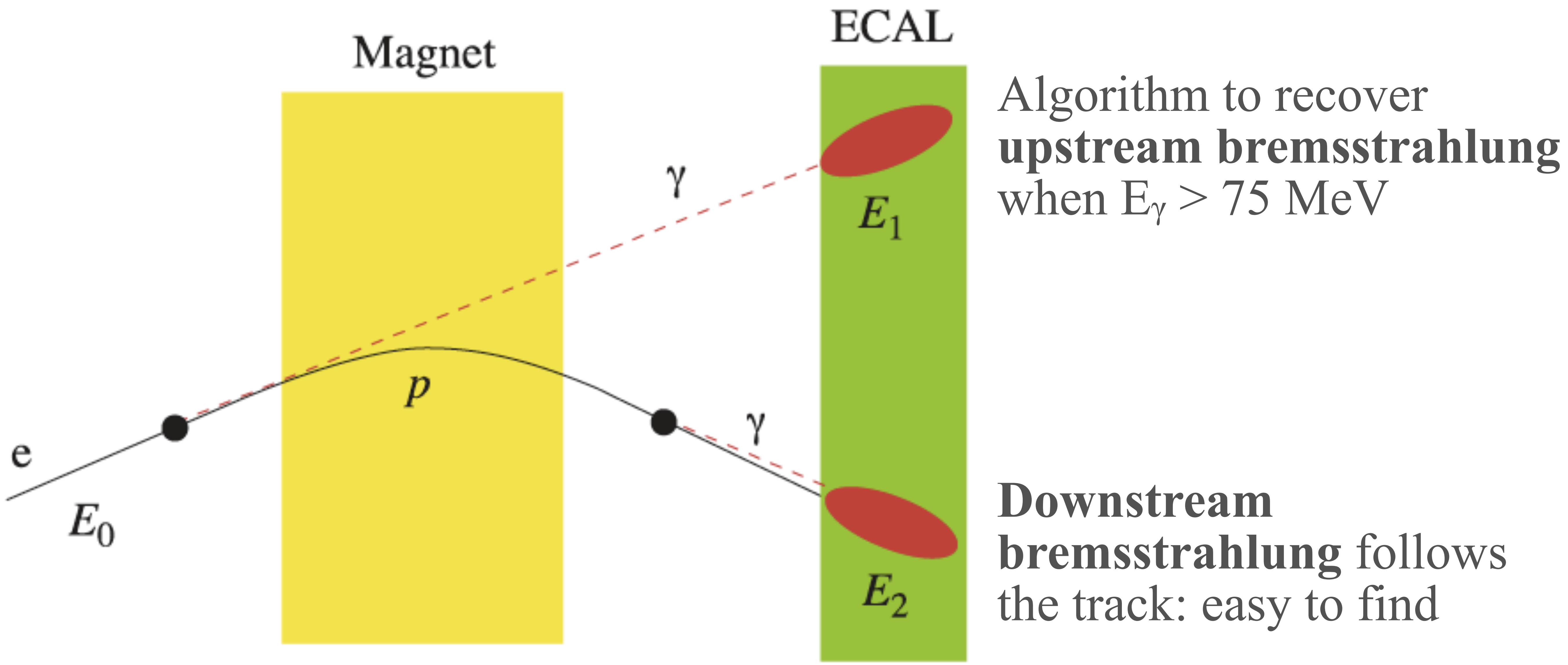
- Combination of ATLAS/CMS/LHCb is

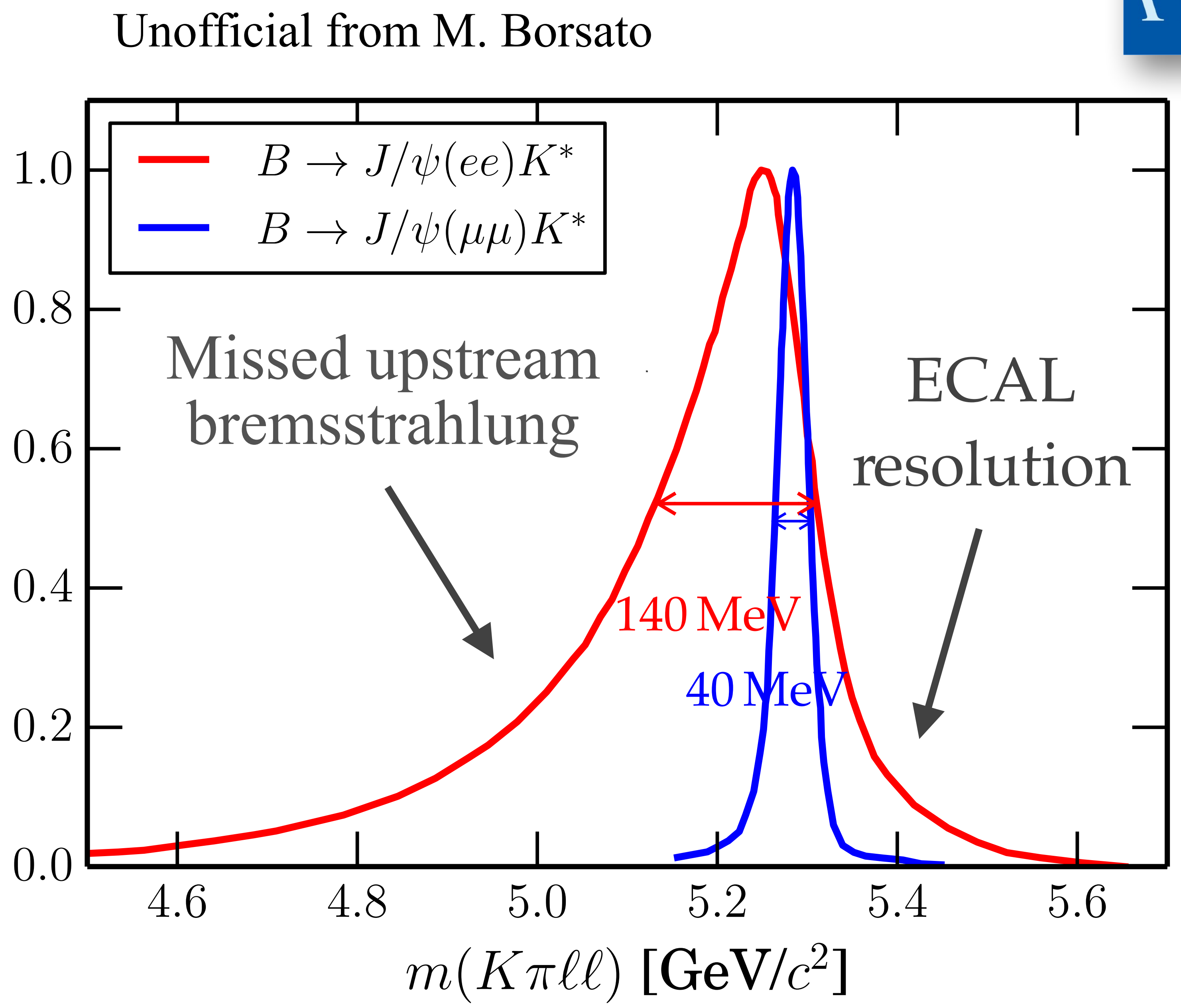
$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right)_{WA} = (2.84 \pm 0.33) \times 10^{-9}$$

➡ **22% below SM prediction**

$\sim 2.3\sigma$ tension with SM

- At LHCb, **electrons** are **major challenge**





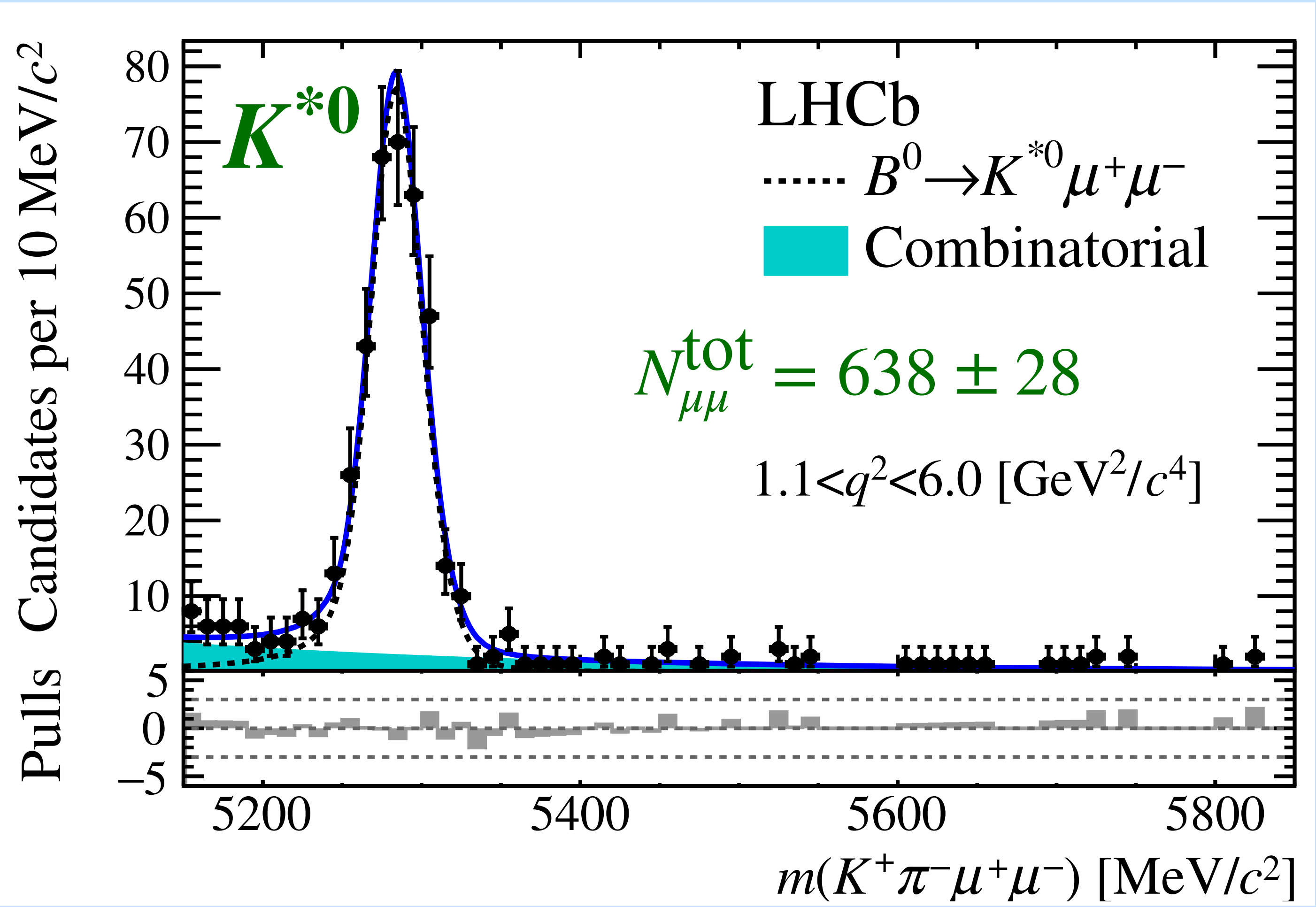
Electrons have **worse mass resolution** and are **more difficult to trigger on**

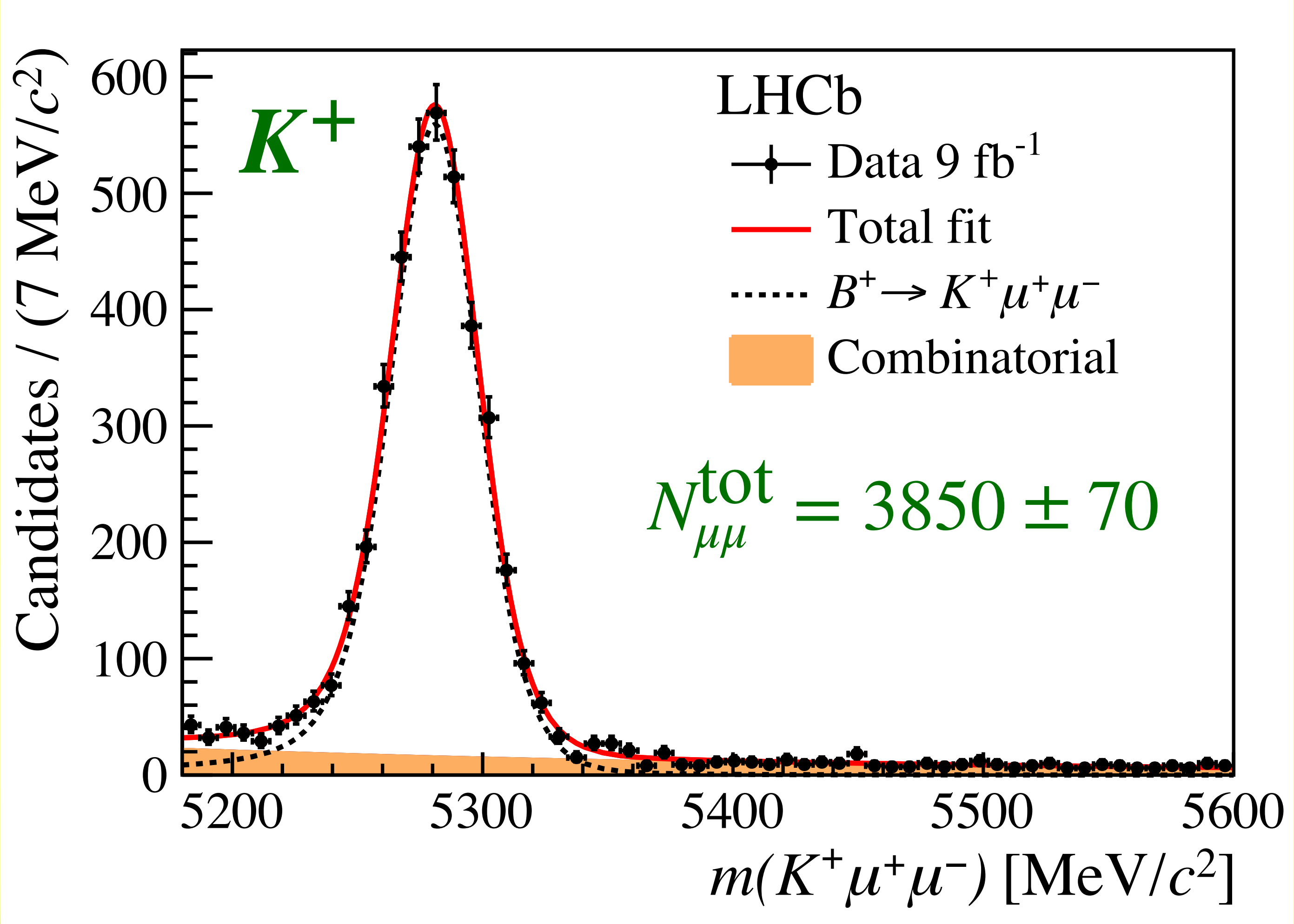
- Use **double ratio** with $B \to K^{(*)} J/\psi(\to \ell\ell)$

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

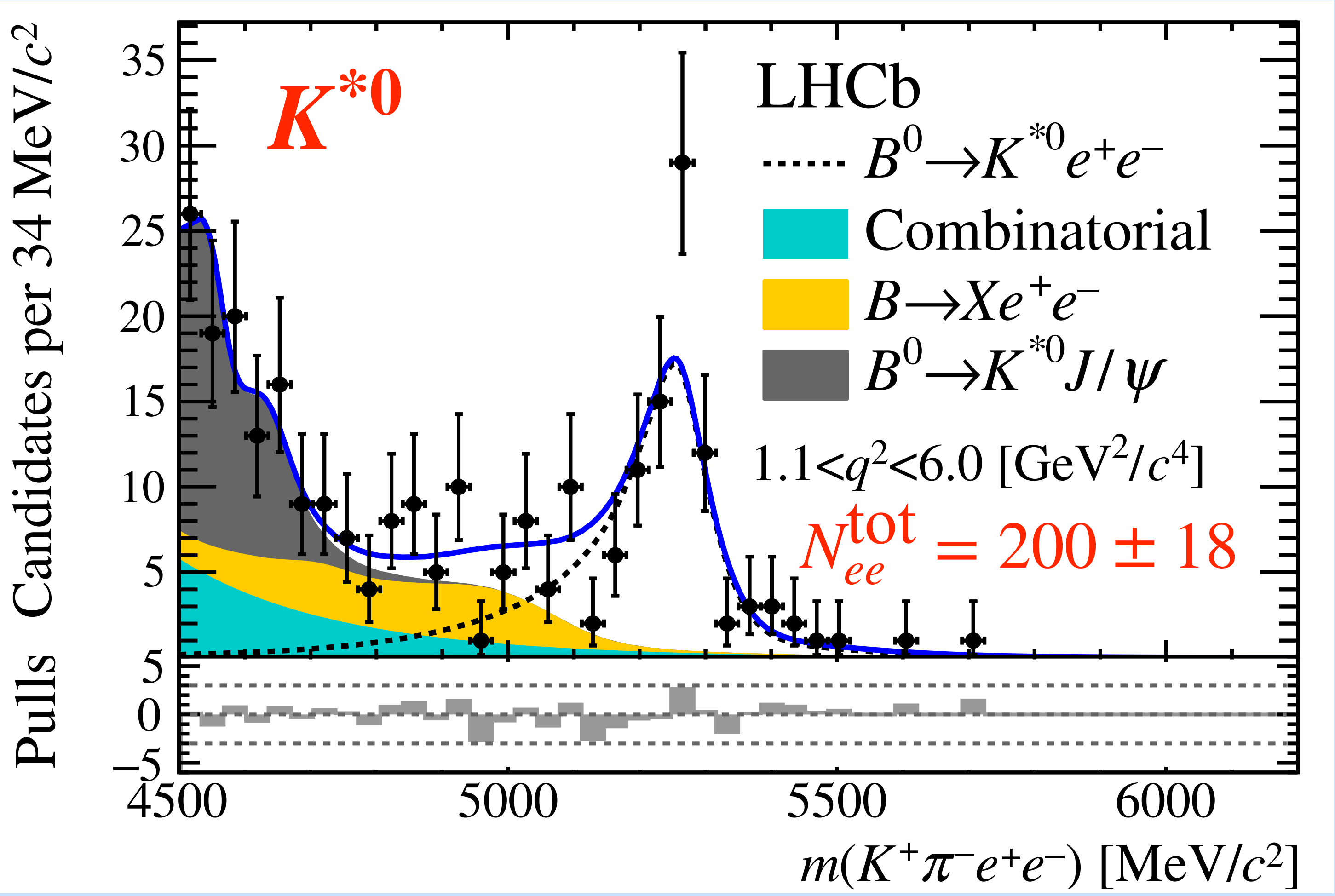
LFU $\mathscr{R}_{K^{(*)}}$ at LHCb: results

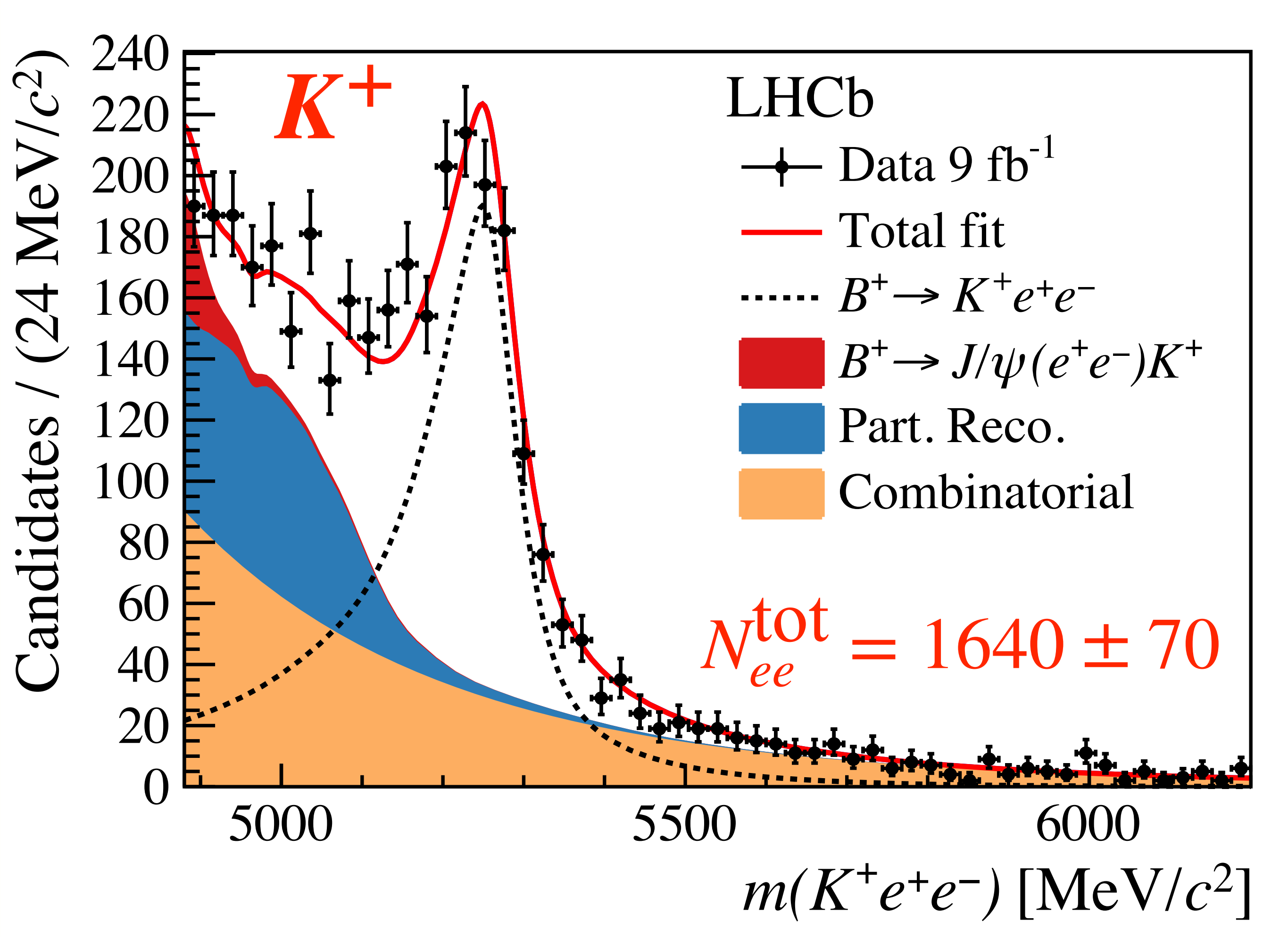
$B \to K^{(*)}\mu^+\mu^-$





$B \to K^{(*)}e^+e^-$





$\mathscr{R}_{K^{*0}}$ with 25% of Run 1+2

$$\mathscr{R}^{[0.045,\,1.1]}_{K^{*0}} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

2.1σ below SM

JHEP 08, 055 (2017)

$$\mathscr{R}^{[1.1,\,6]}_{K^{*0}} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

2.4σ below SM

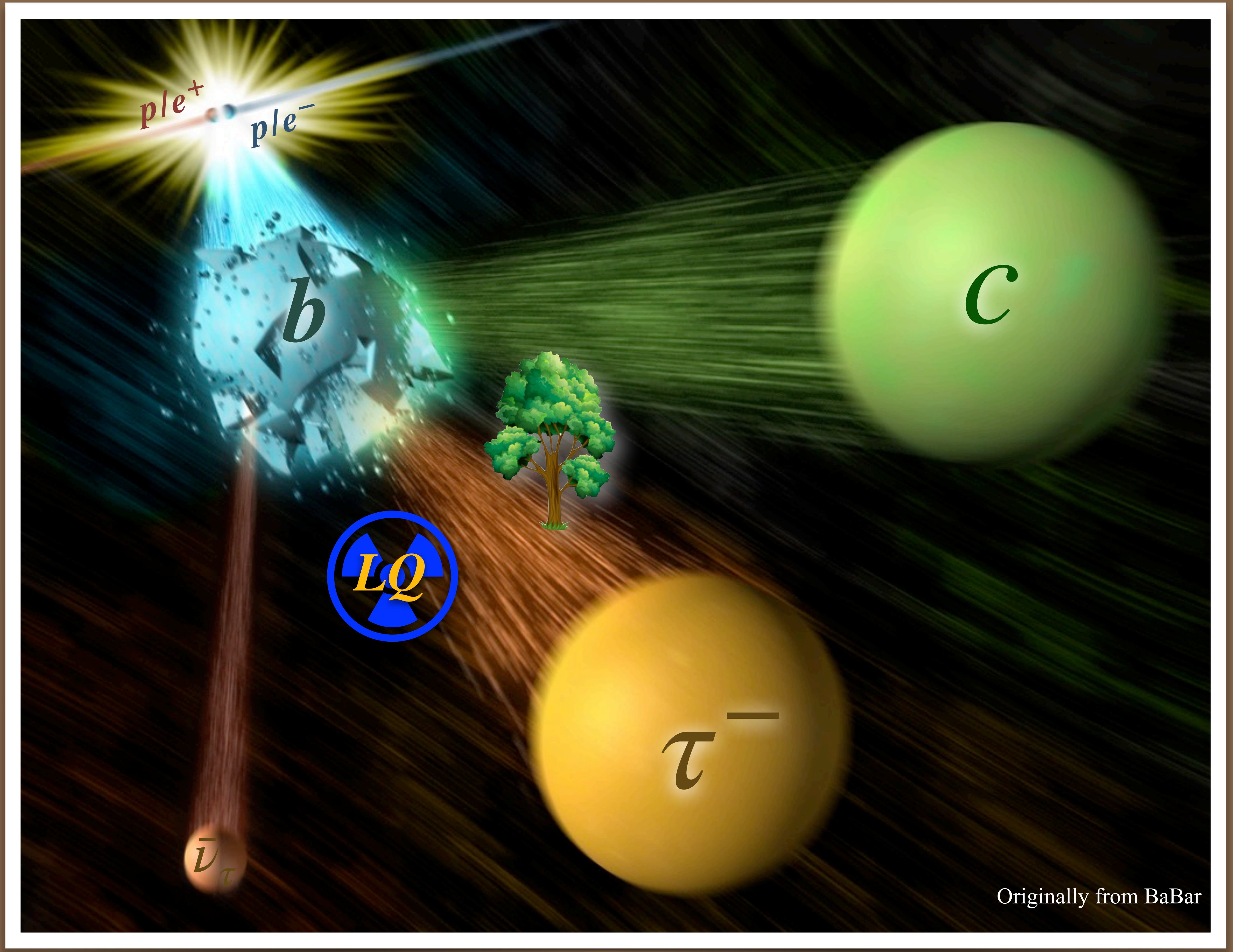
$\mathscr{R}_{K^+}$ with 100% of Run 1+2

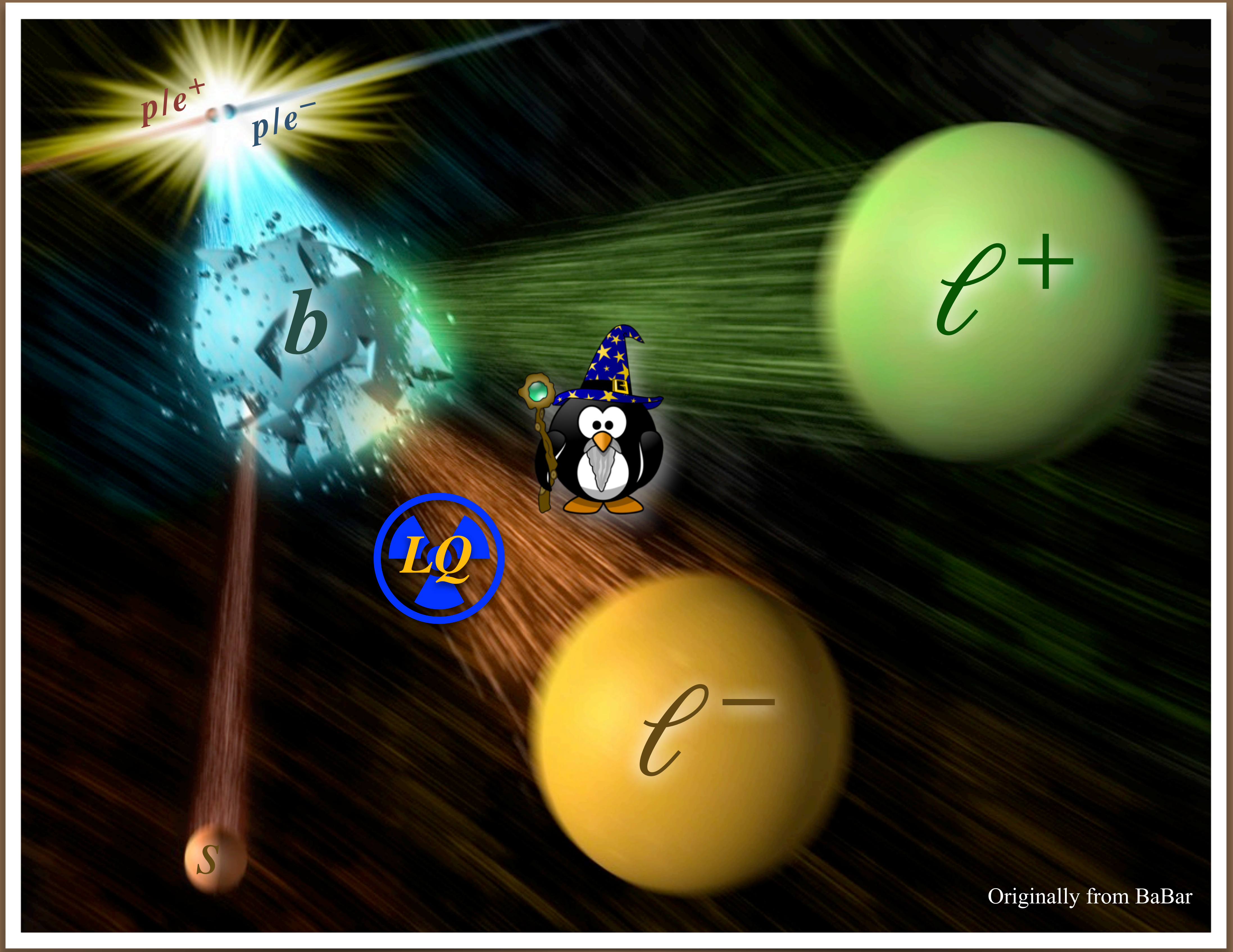
$$\mathscr{R}^{[1.1,\,6]}_{K^+} = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

3.1σ below SM

arXiv 2103.11769

5. One elegant interpretation





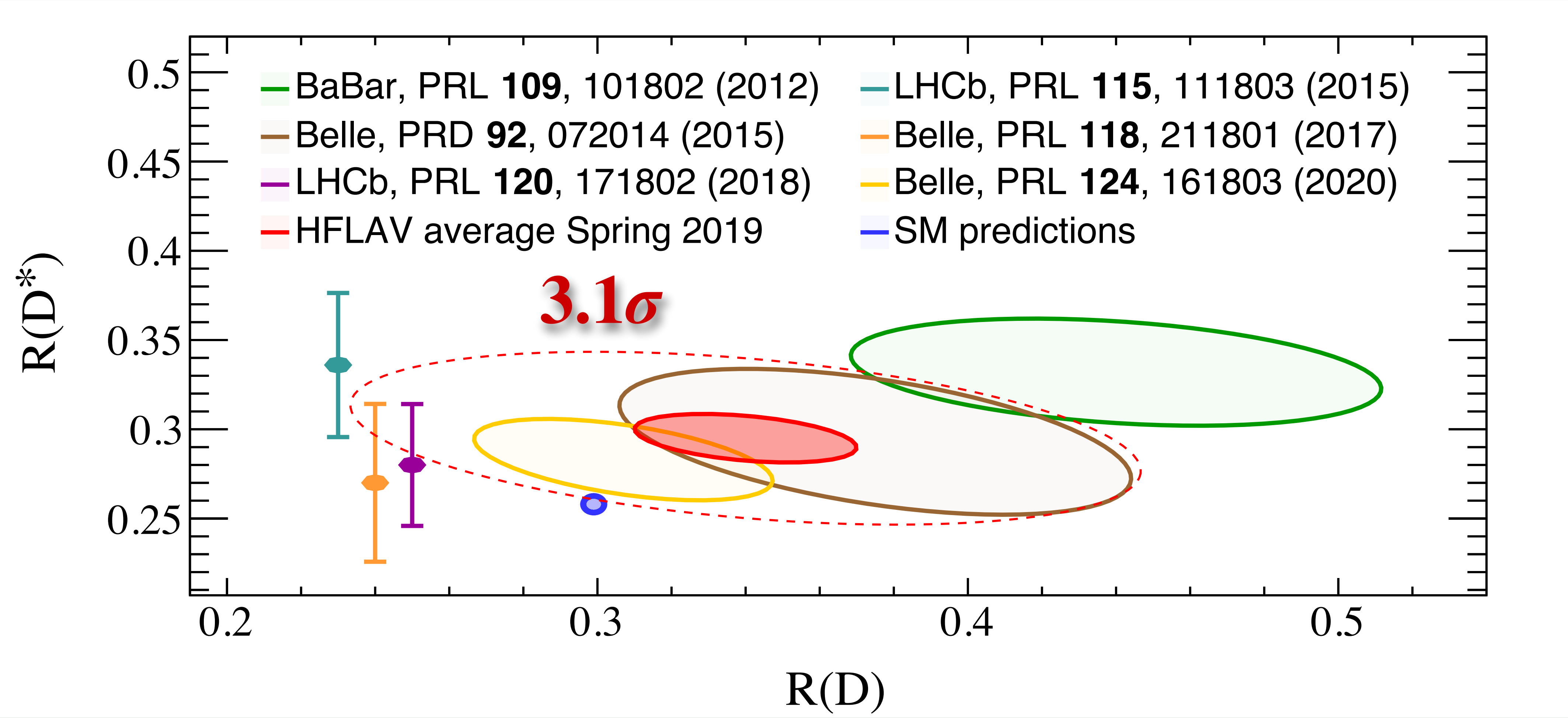
Penguin from Jeff Brassard

Based on *Isidori at APS April 2021* and *Cornella, Faroughy, Fuentes-Martín, Isidori, Neubert - arXiv:2103.16558*

Anomalies recap

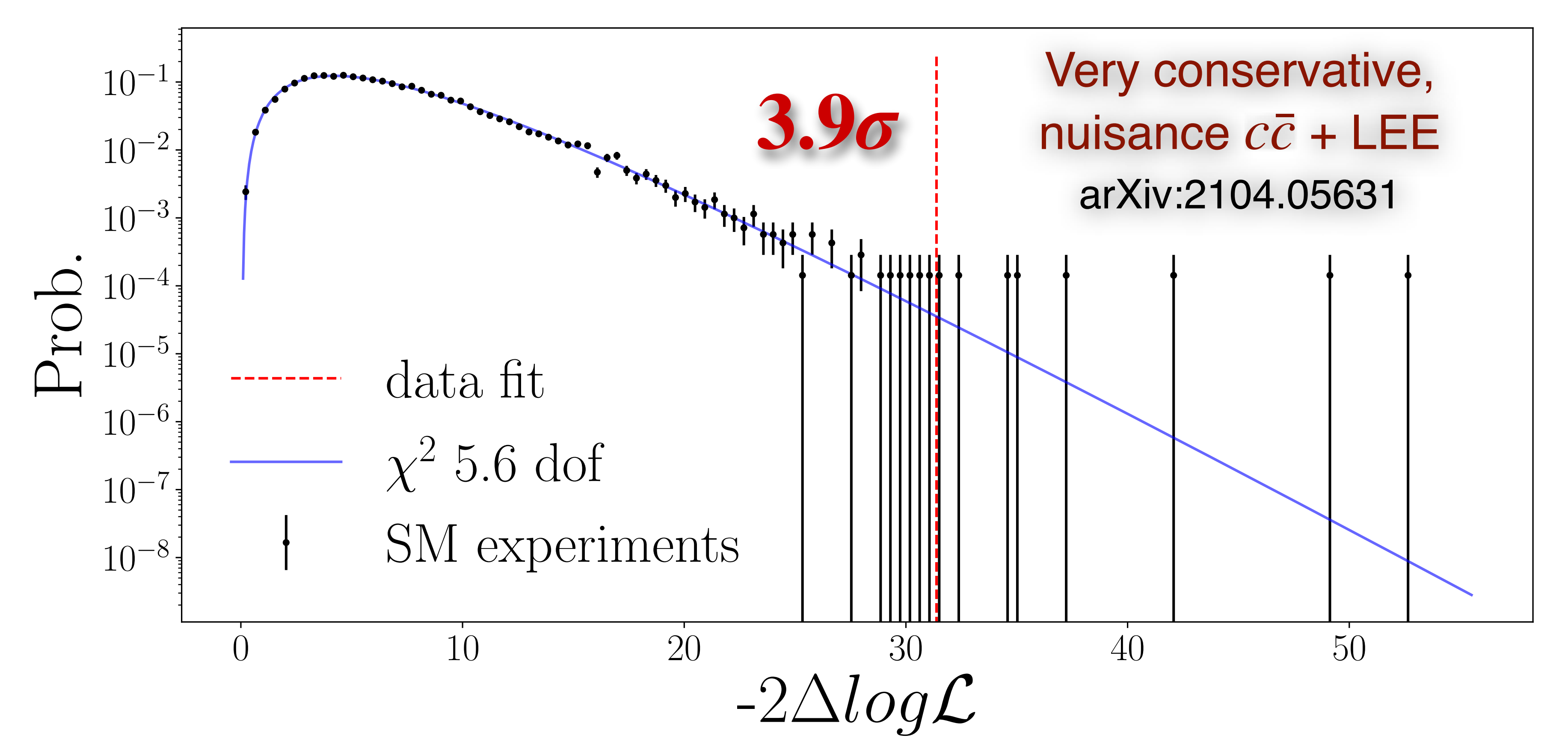
LFU results with $b \to c\tau\nu$

- 1.8σ **excess** in $\mathscr{R}(J/\Psi)$
- 14% **excess** in $\mathscr{R}(D)$
- 14% **excess** in $\mathscr{R}(D^*)$



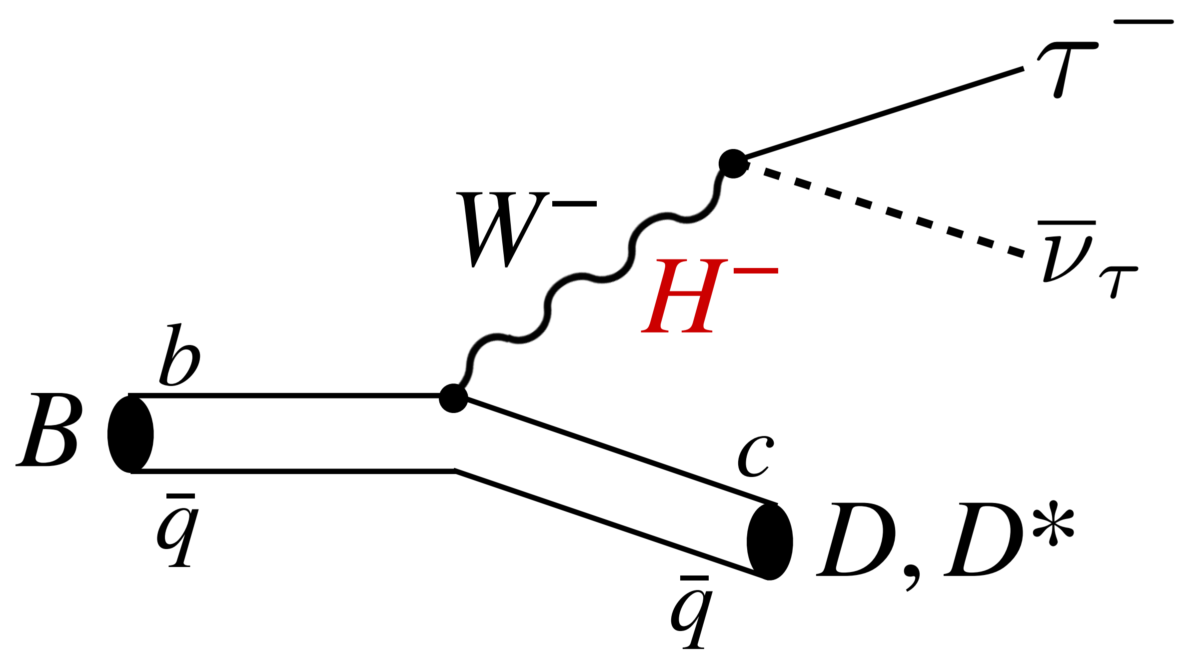
LFU results with $b \to s\ell\ell$

- 22% **deficit** in $B^0_{(s)} \to \mu^+\mu^-$
- 15% **deficit** in $\mathscr{R}_K$
- ~30% **deficit** in $\mathscr{R}_{K^*}$
- Disagreement in $B \to K^*\ell\ell$ angular P_5'

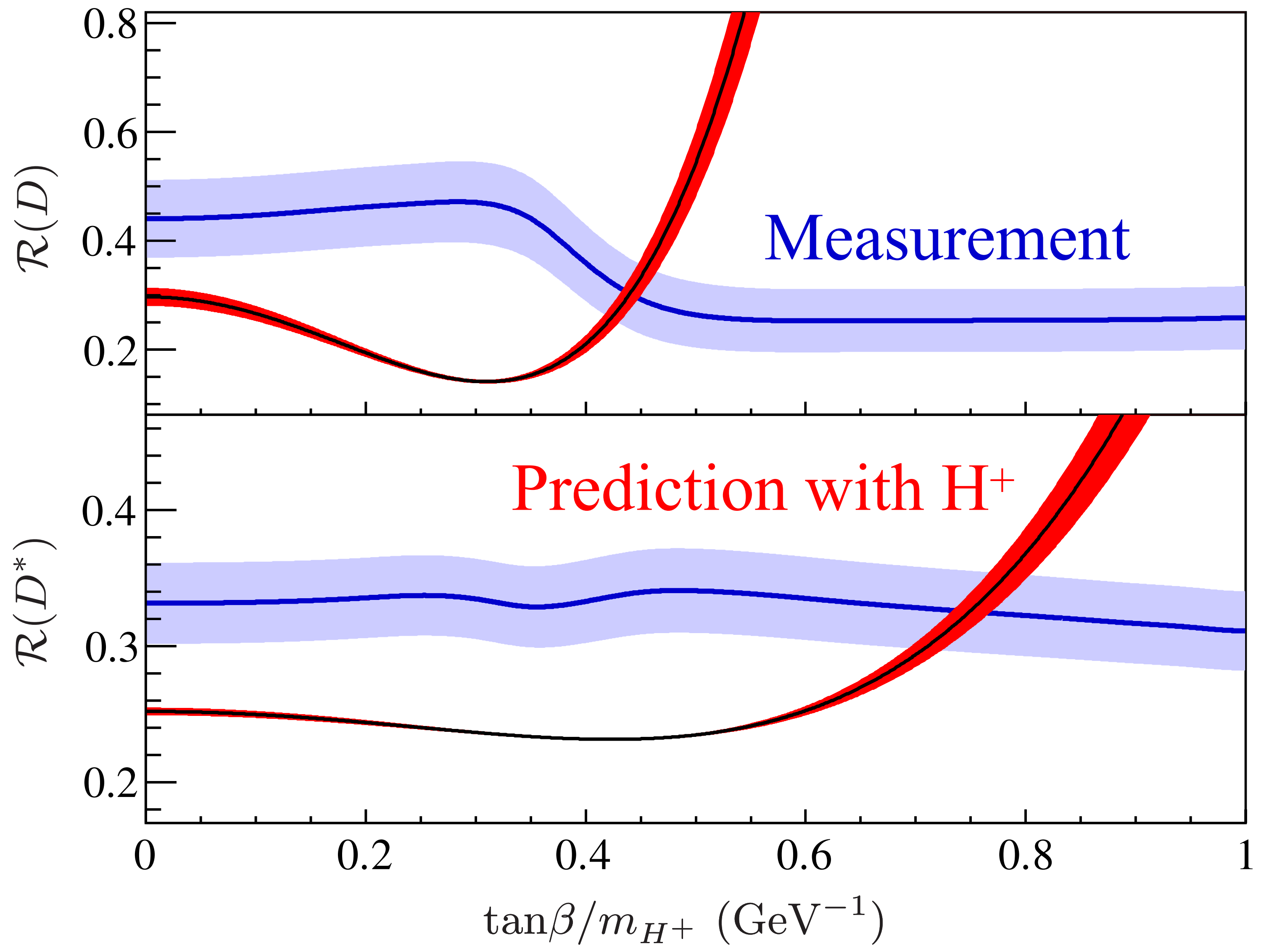


Charged Higgs (H^+)

- **Initial excitement** because **H^+ in Supersymmetry** can lead to **larger $\mathscr{R}(D^{(*)})$**
  - However, **not simultaneously compatible with both measurements**



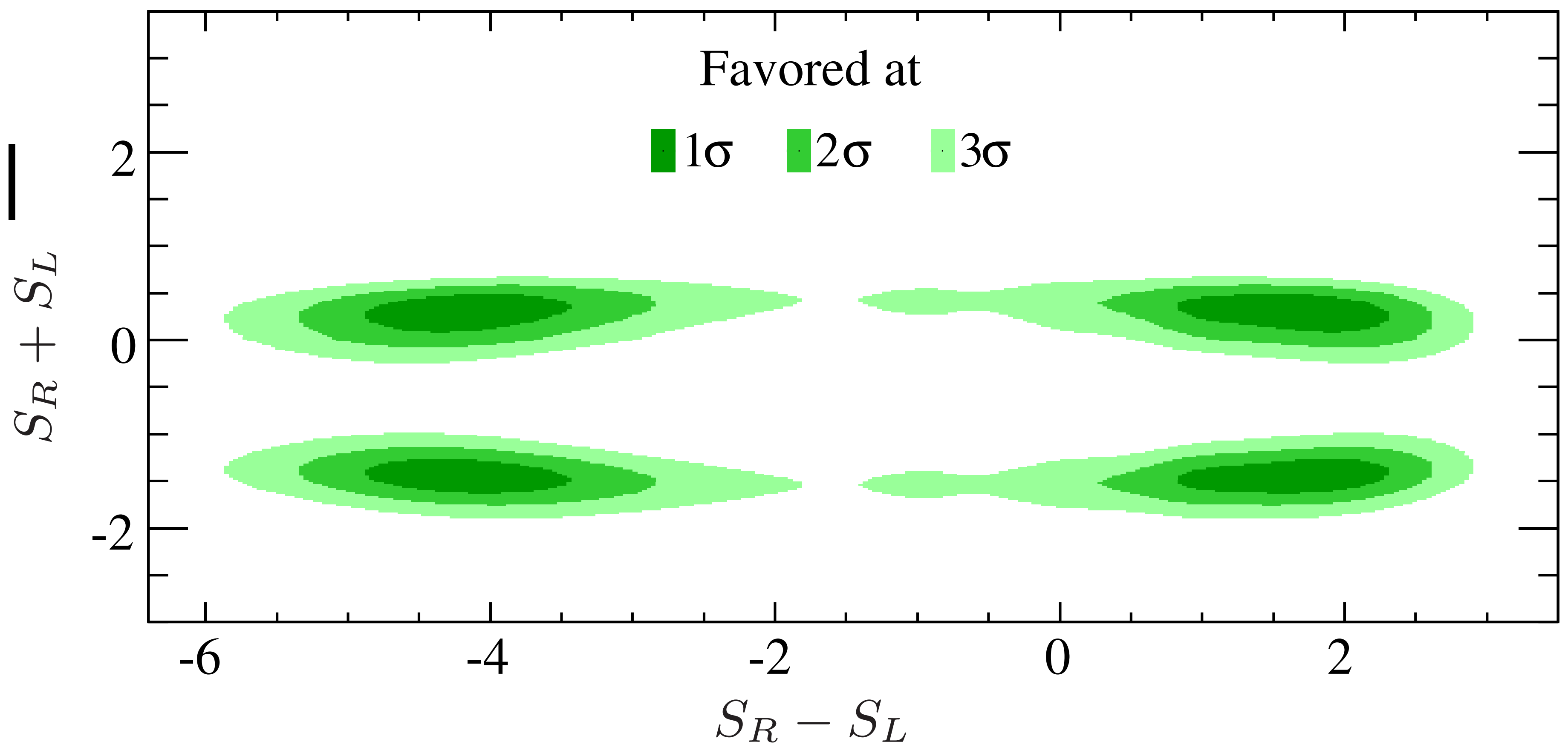
- **H^+** in **less constrained** model can explain **both excesses**
  - However, **not compatible with measured q^2**

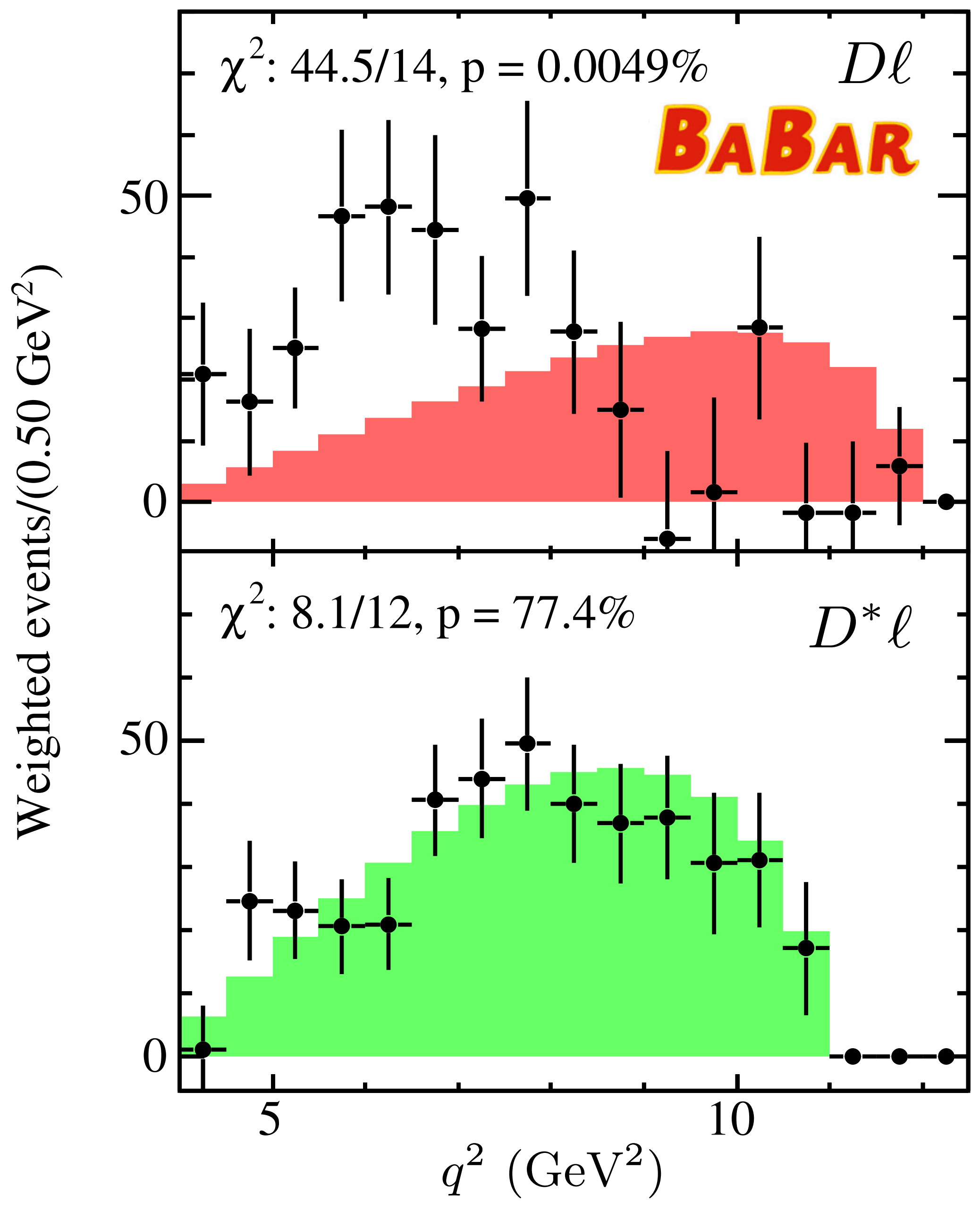


Phys. Rev. D **88**, 072012 (2013)

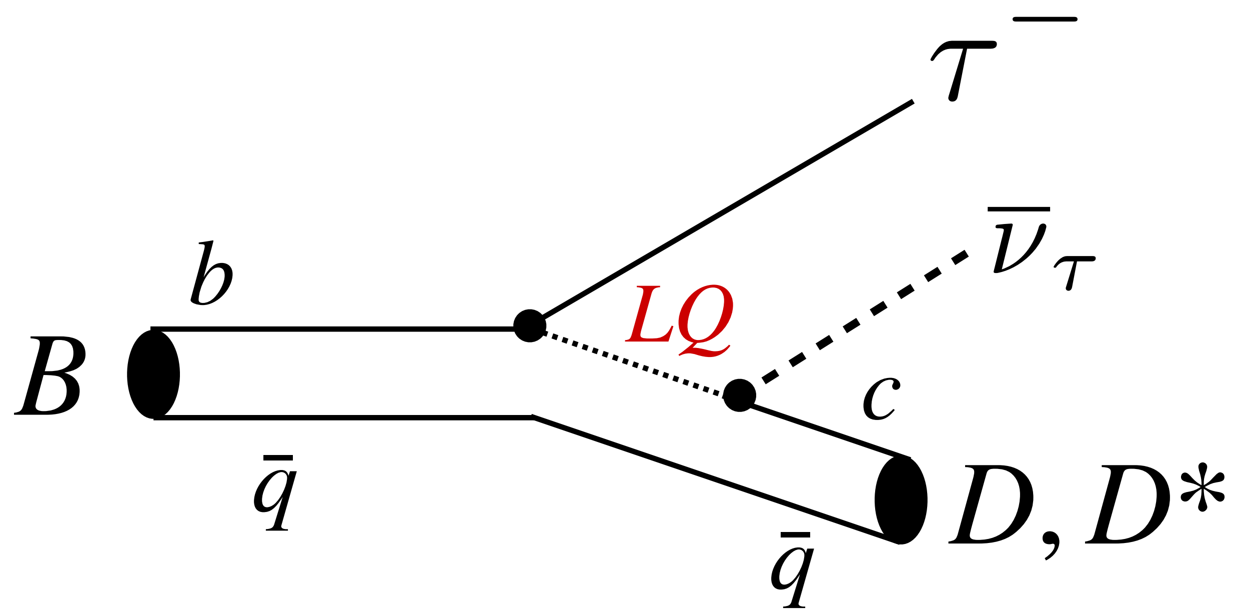
$\tan\beta/m_H = 0.45\ \mathrm{GeV}^{-1}$

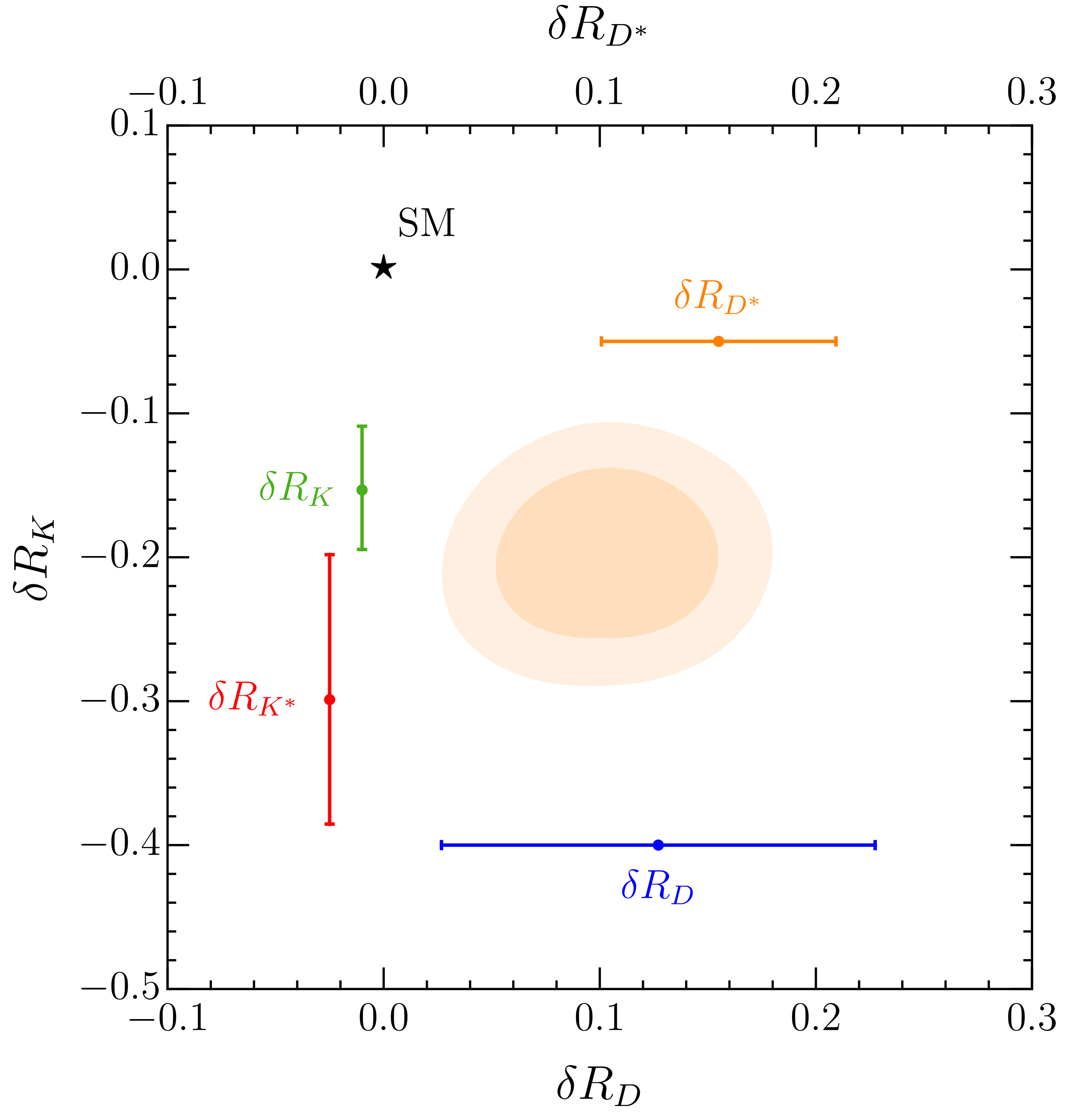
Not compatible with full spin 0 mediator





U_1 leptoquark fits all low-energy data





Isidori at APS April 2021, arXiv:2103.16558

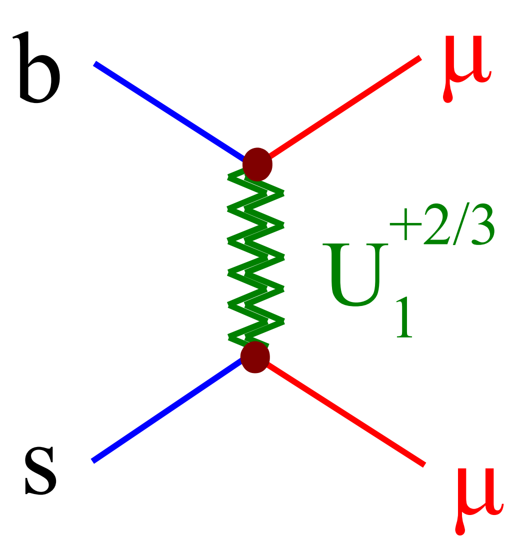
"Renaissance" of LQ models (*to explain the anomalies, but not only...*):

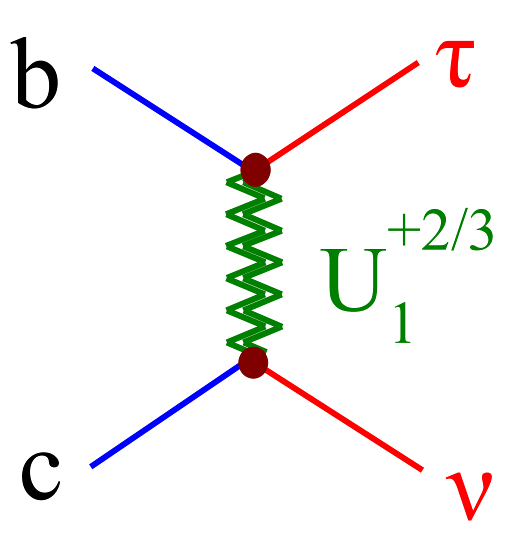
- Scalar LQ as PNG
  Gripaios, '10
  Gripaios, Nardecchia, Renner, '14
  Marzocca '18
- Scalar LQ from GUTs & ~~R~~ SUSY
  Hiller & Schmaltz, '14; Becirevic *et al.* '16, Fajfer *et al.* '15-'17; Dorsner *et al.* '17; Crivellin *et al.* '17; Altmannshofer *et al.* '17 Trifinopoulos '18, Becirevic *et al.* '18 + ...
- Vector LQ in GUT gauge models
  Assad *et al.* '17
  Di Luzio *et al.* '17
  Bordone et *al.* '17
  Heeck & Teresi '18
  + ...
- Vector LQ as techni-fermion resonances
  Barbieri *et al.* '15; Buttazzo *et al.* '16, Barbieri, Murphy, Senia, '17
- LQ as Kaluza-Klein excit.
  Megias, Quiros, Salas '17
  Megias, Panico, Pujolas, Quiros '17
  Blanke, Crivellin, '18

Which LQ explains which anomaly?

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3}, \mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3}, \mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3}, \mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3}, \mathbf{3})_{-1/3}$	✓	✗	✗
Vector	$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3}, \mathbf{3})_{2/3}$	✓	✗	✗

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

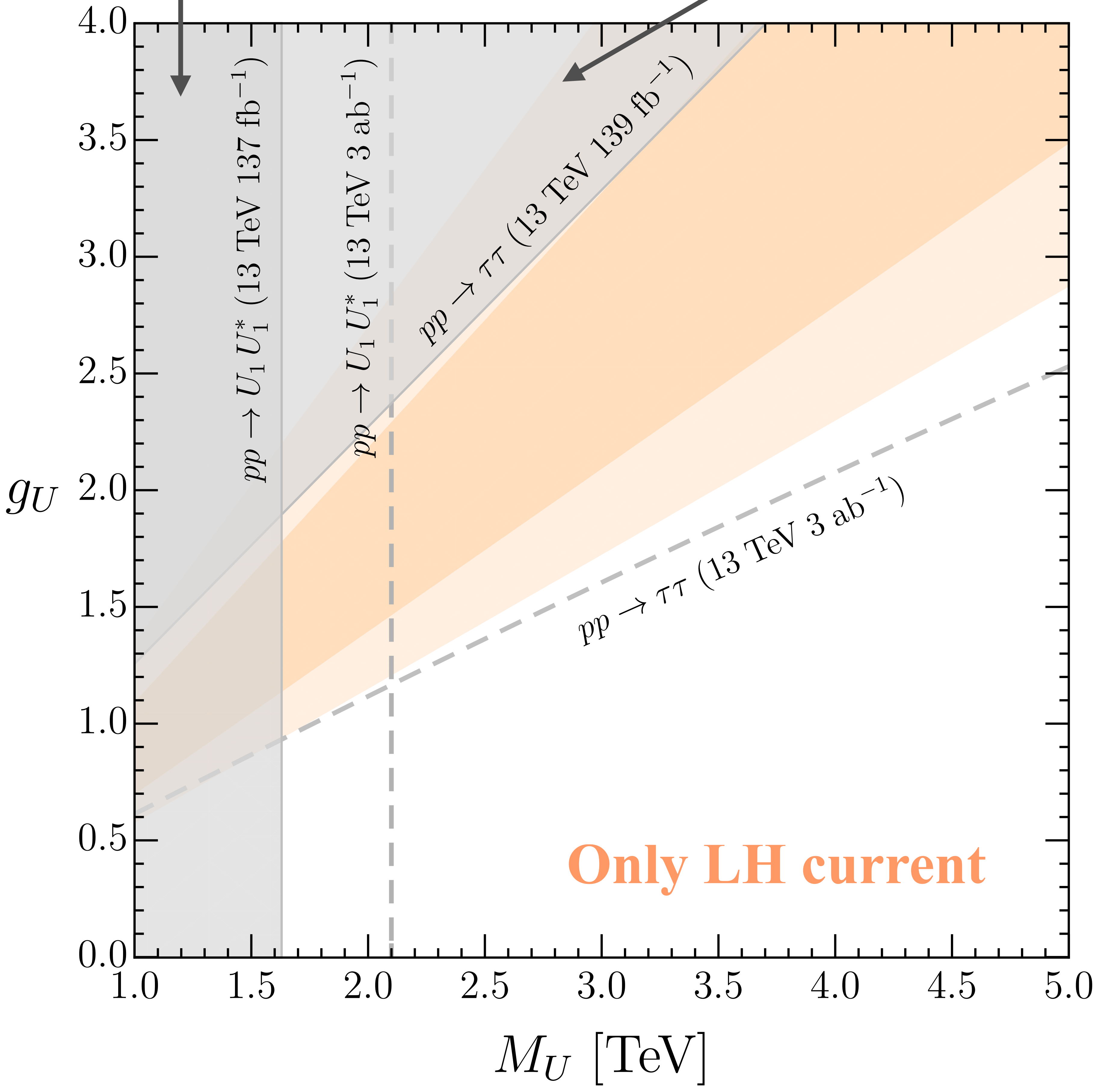


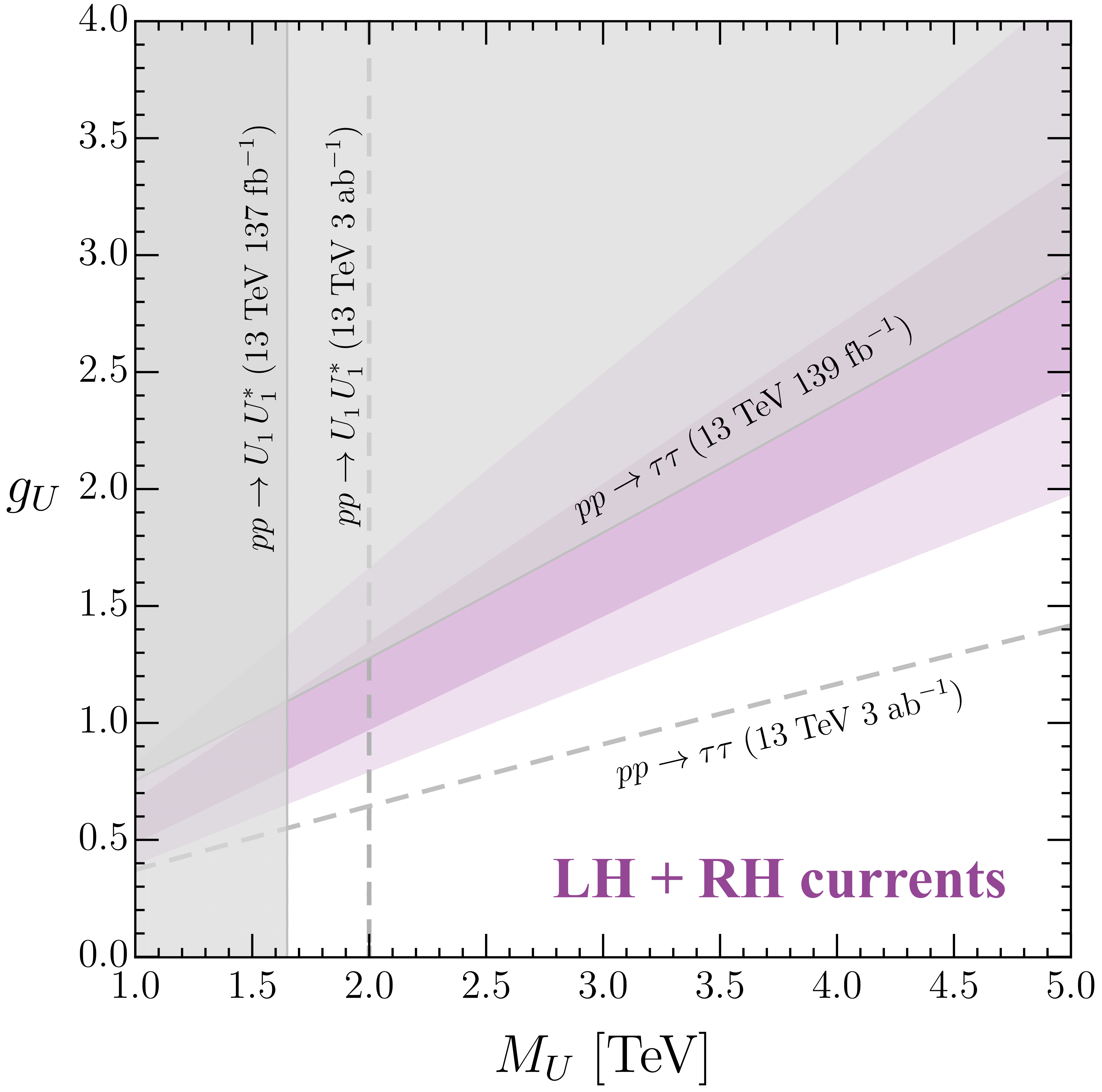


LQ of the Pati-Salam gauge group:
$SU(4) \times SU(2)_L \times SU(2)_R$

Direct LQ search from CMS, arXiv:2012.04178

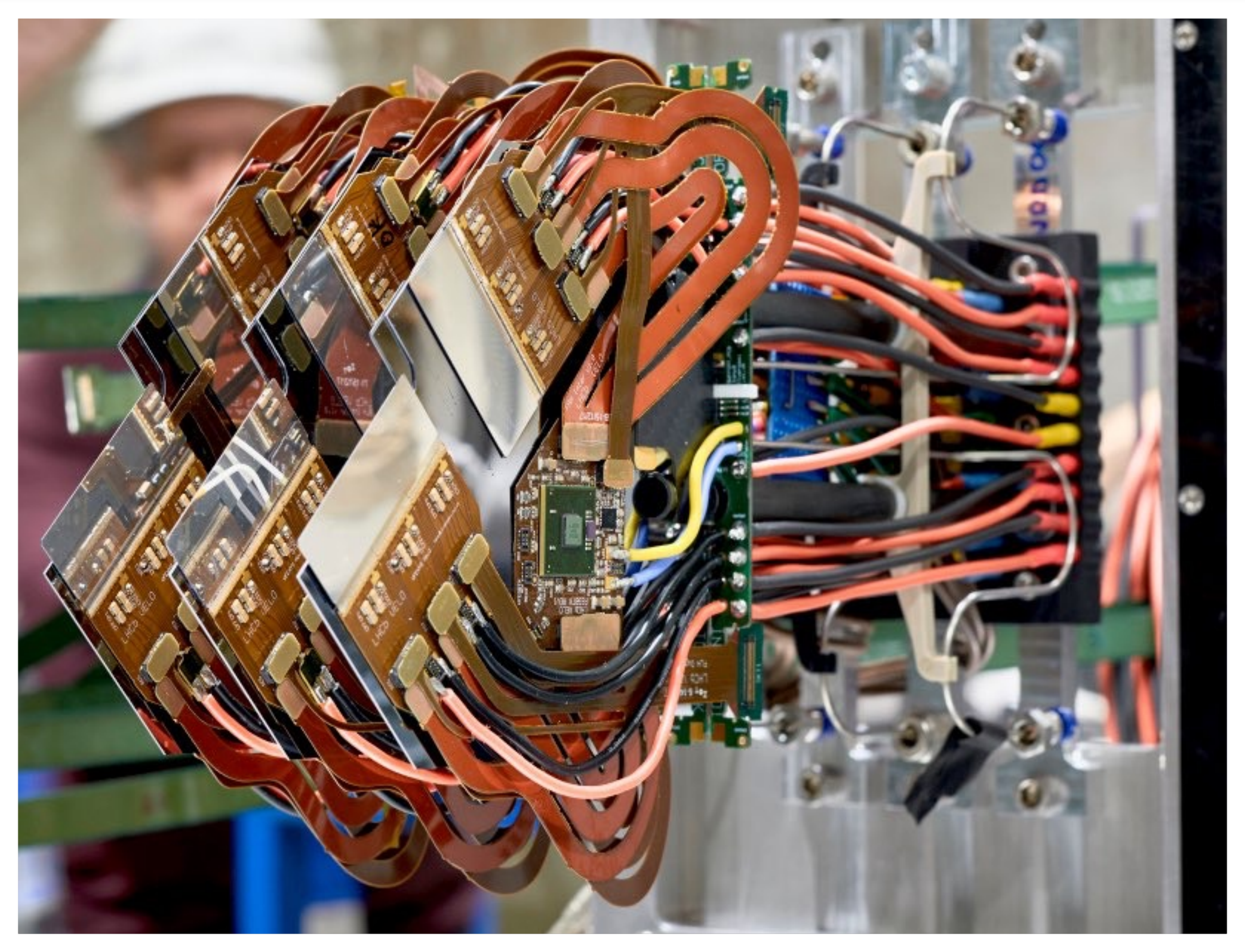
Study of high p_t tails in $\tau\tau$ events from ATLAS, PRL 125, 051801 (2020)



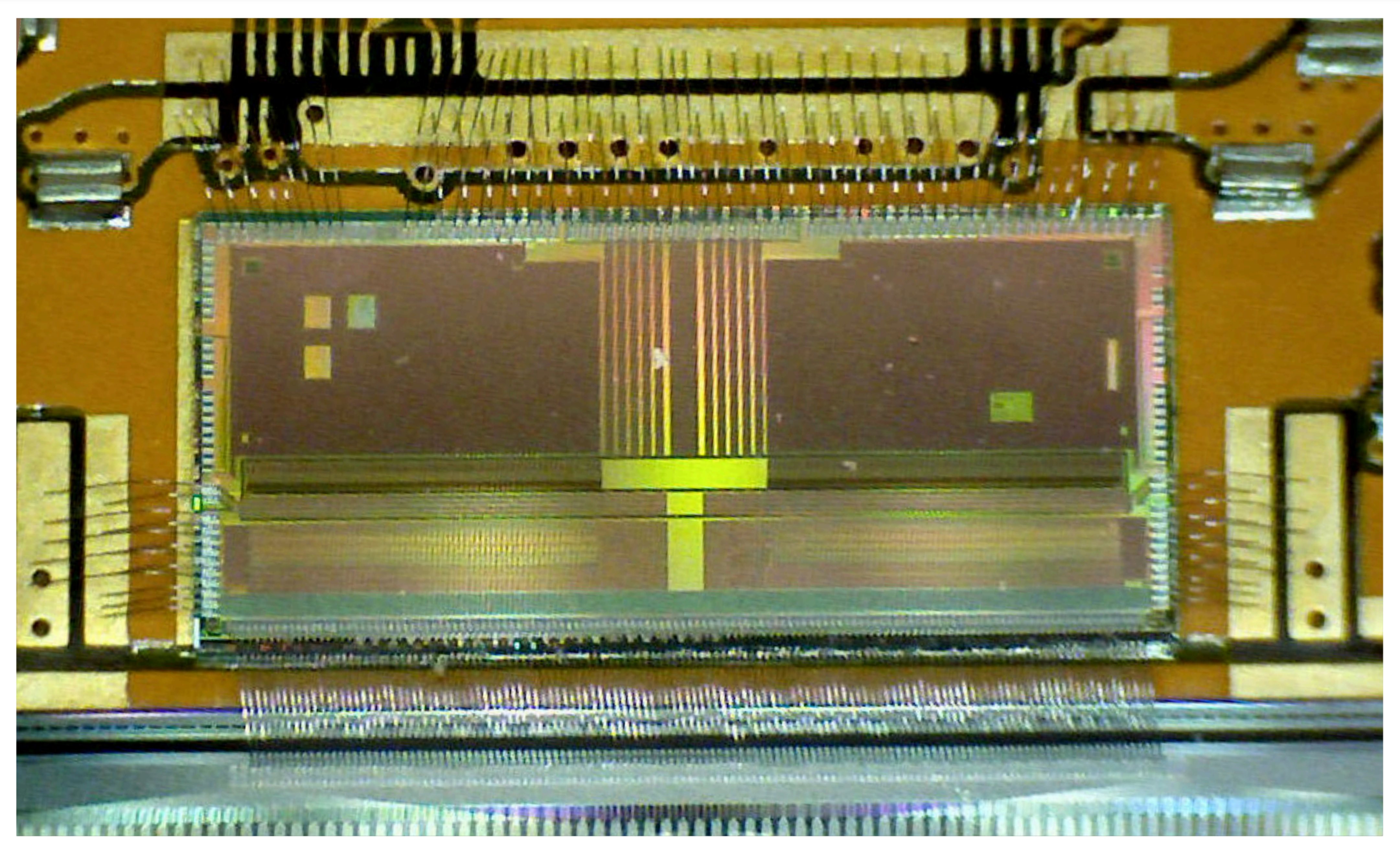


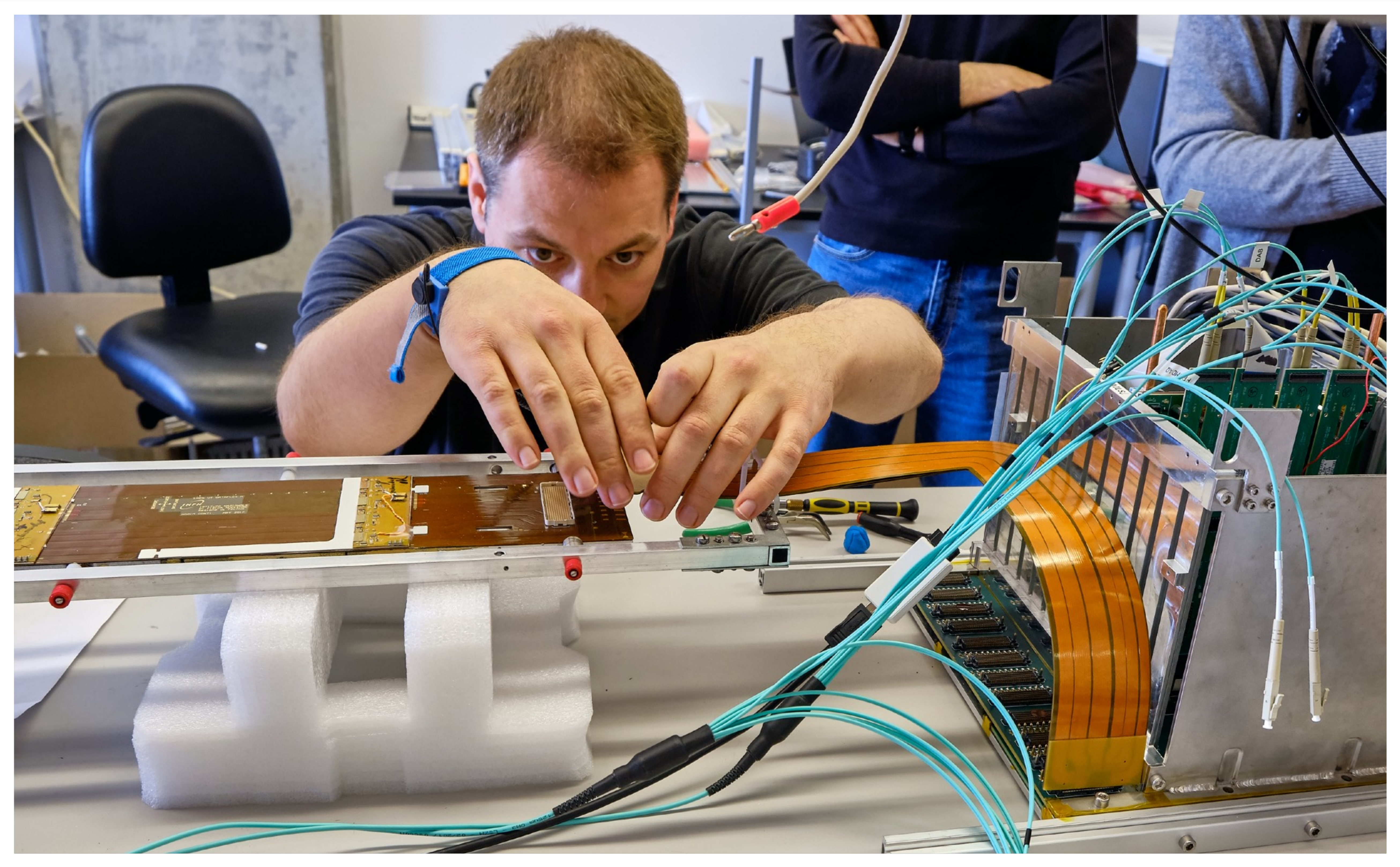
Direct LQ searches at LHC have limited mass reach, but **high p_T tails** in $\tau\tau$ events would have **sensitivity at HL-LHC**

Isidori at APS April 2021, arXiv:2103.16558



6. Going forward





Upgrading LHCb

9 fb^{-1} | Upgrade I | Goal: 50 fb^{-1}

Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4
2010 2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022 2023 2024	2025 2026 2027	2028 2029 2030

Runs 1 and 2

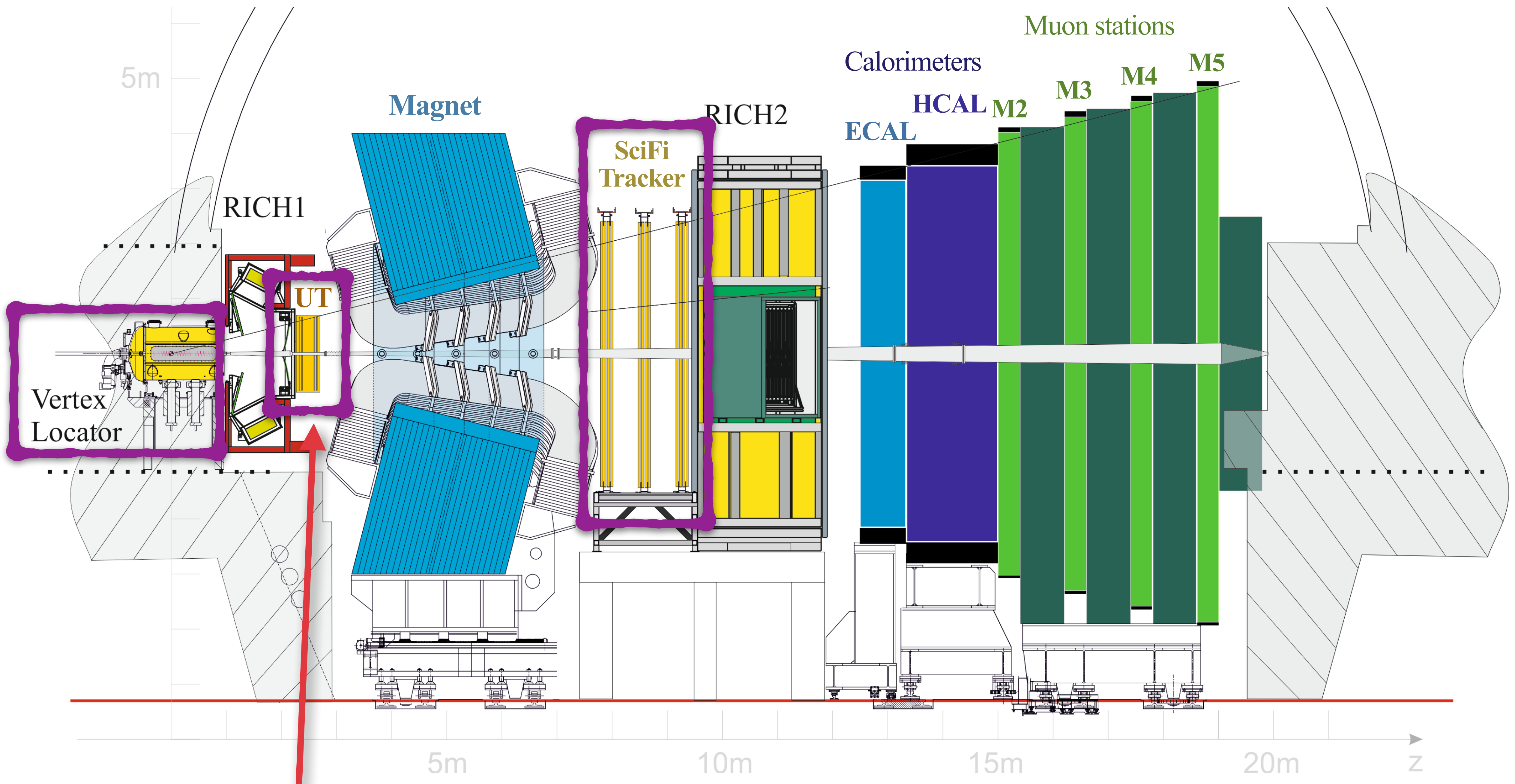
40 MHz (pp collisions) → **L0** Hardware → **1.1 MHz** (Detector readout) → **HLT** Software → **12.5 kHz (0.6 GB/s)** Events on disk

Upgrade I (being installed)

40 MHz (pp collisions) → Detector readout → **HLT** Software → **100 kHz (2-5 GB/s)** Events on disk

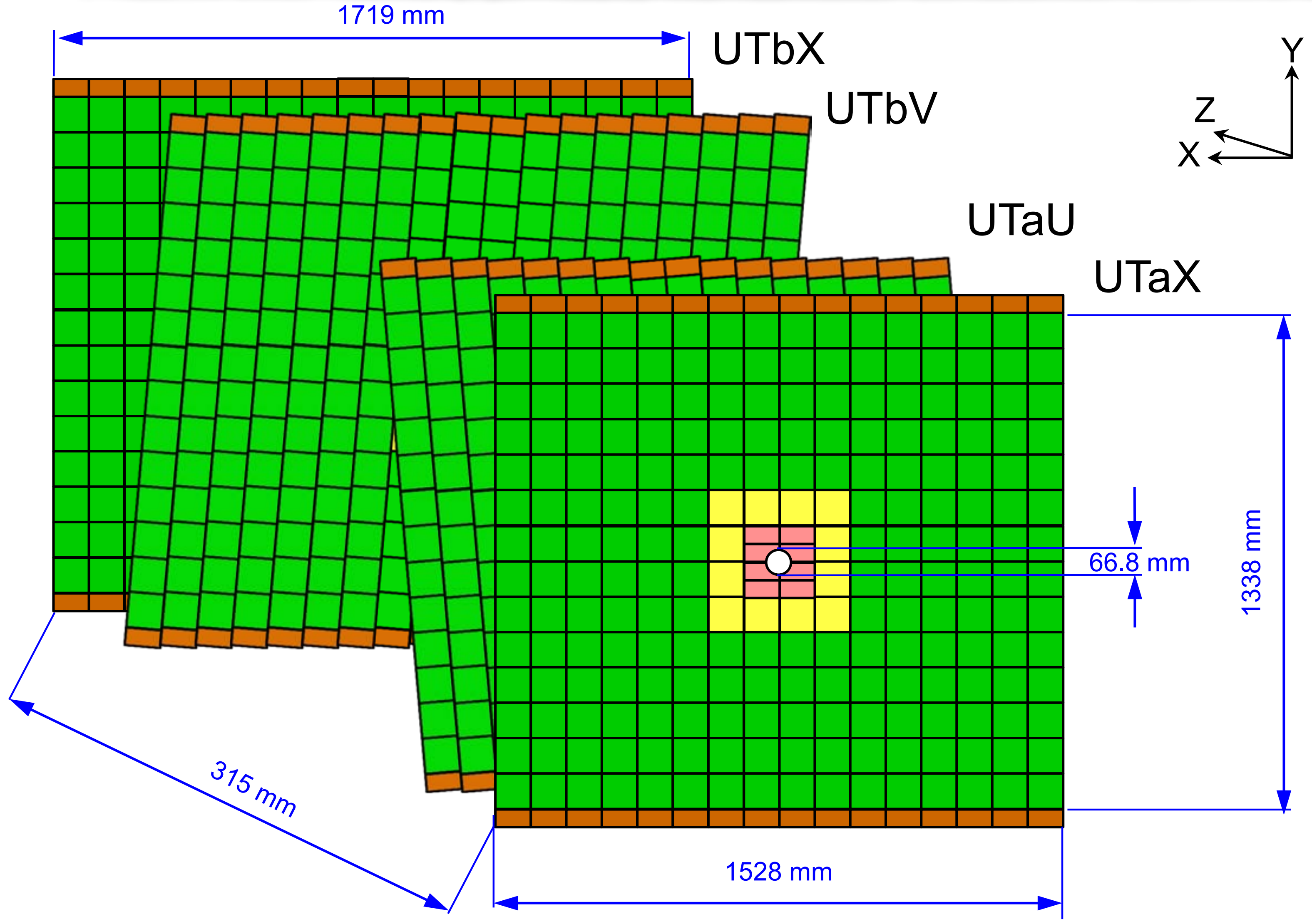
All electronics upgraded to send every hit to **flexible software trigger**

Increase granularity and longevity of **3 new trackers**

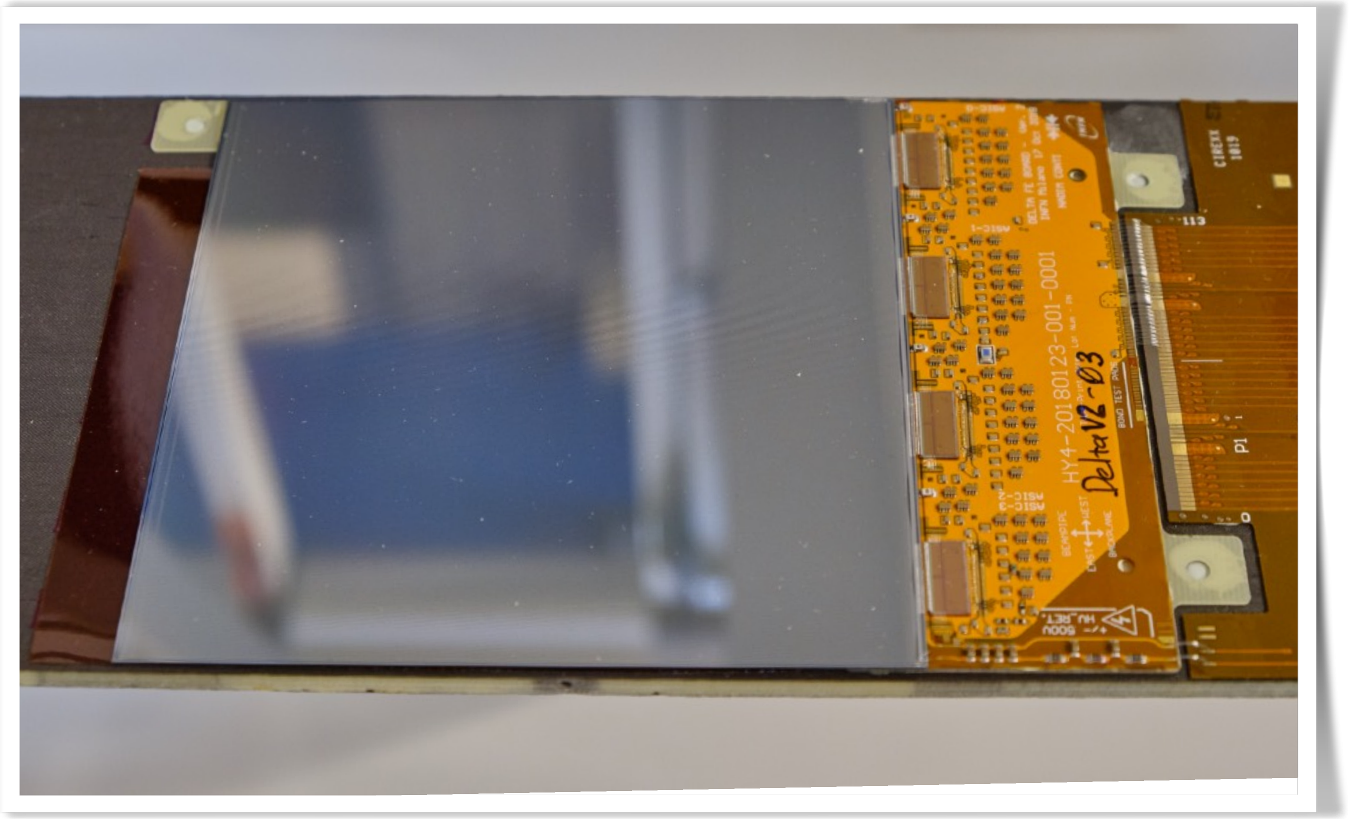


Upstream Tracker (UT)

Upstream Tracker (UT)

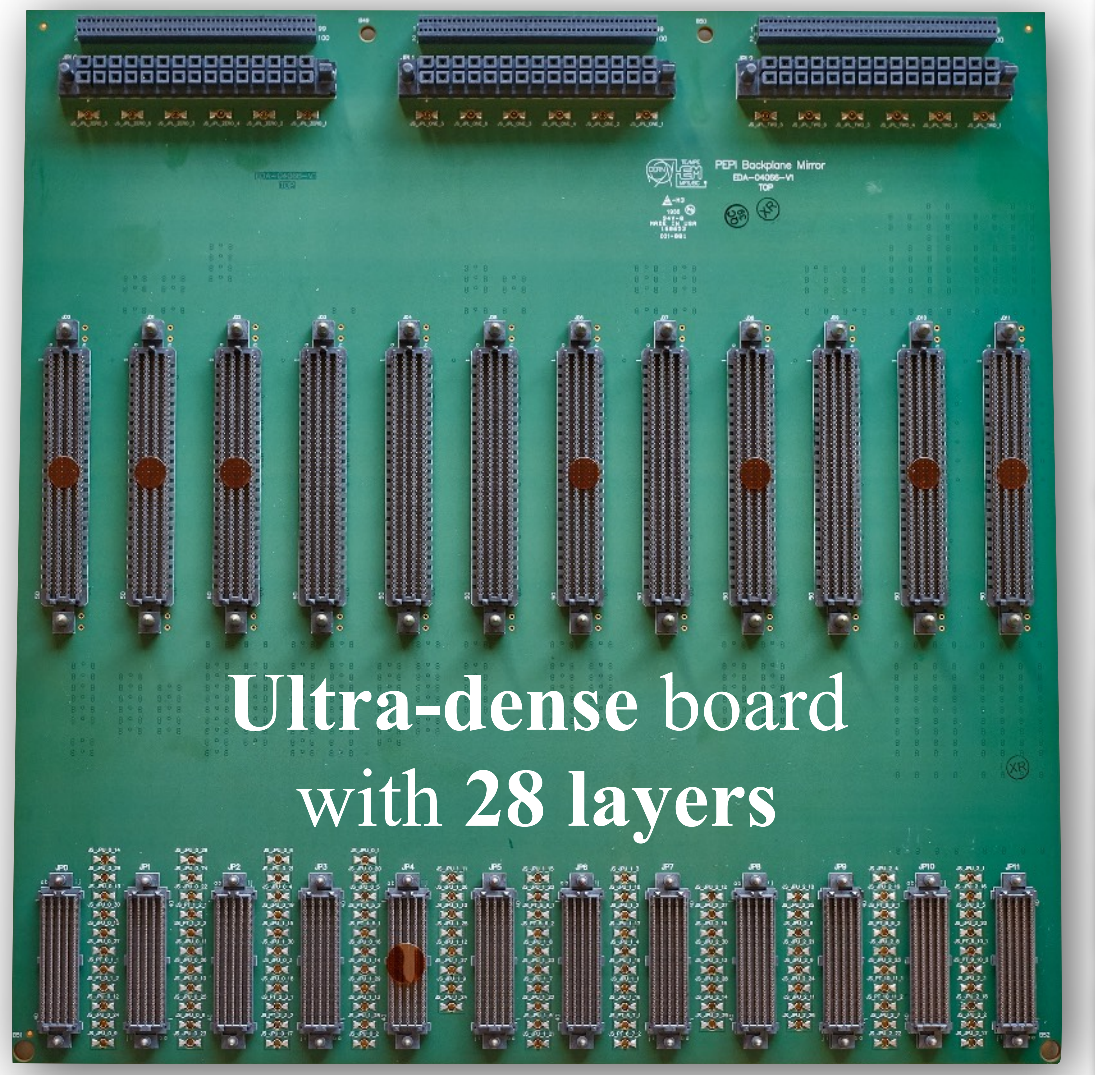


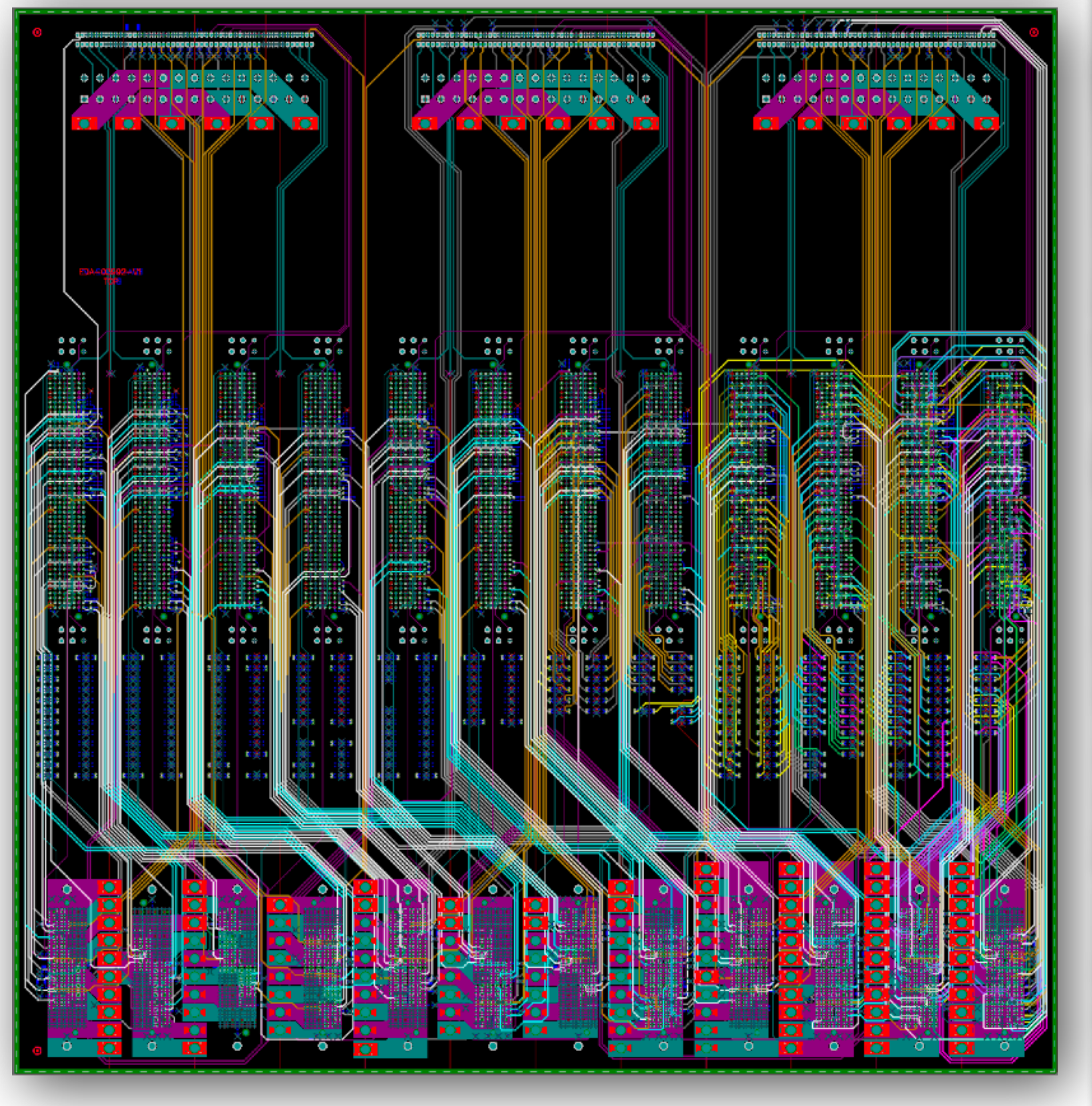
- Tracker with **4 layers of silicon strips**
  - ➡ **First major US contribution to LHCb**



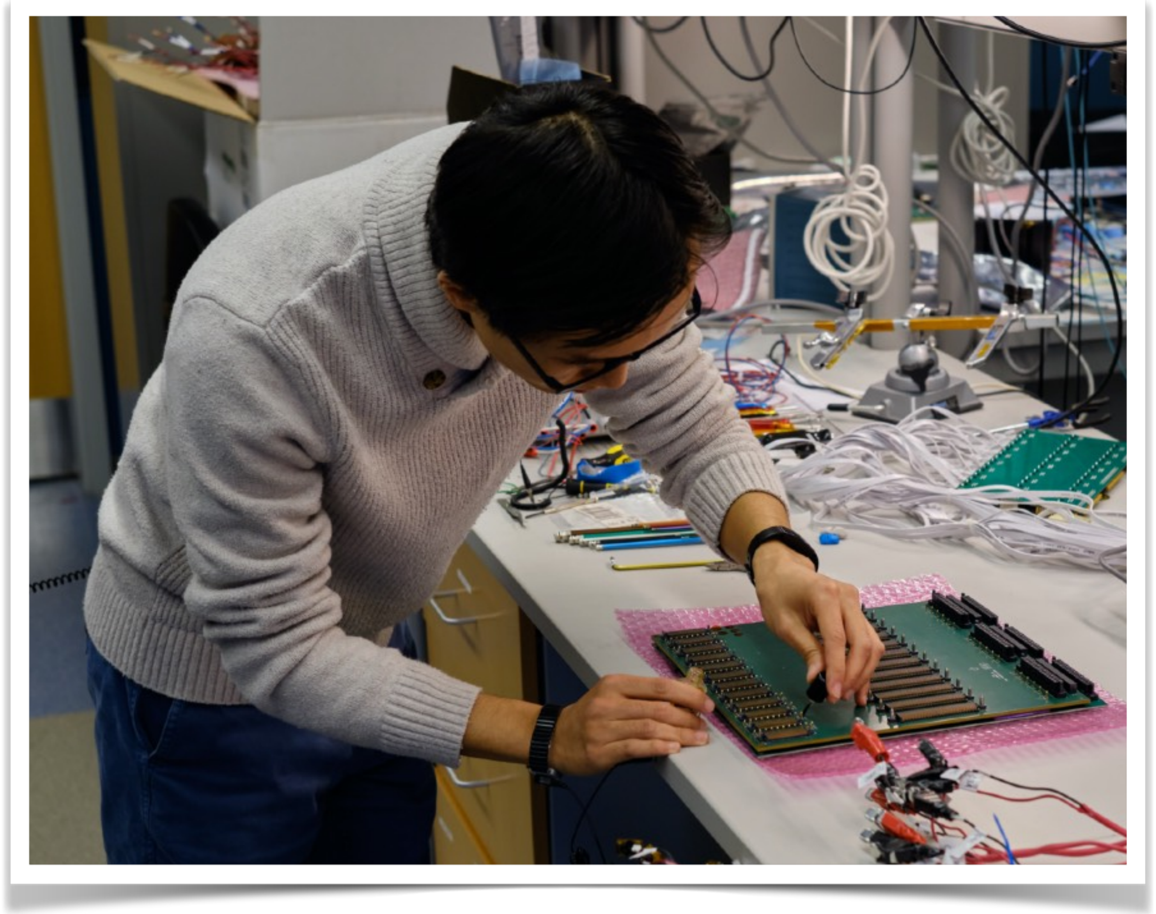
- **UMD** in charge of **readout electronics**
  - ➡ **595 main boards** (3 designs) and **3000+ ancillary boards**

Data readout at 40 MHz with radiation-hard optical components





Thanks to a great team



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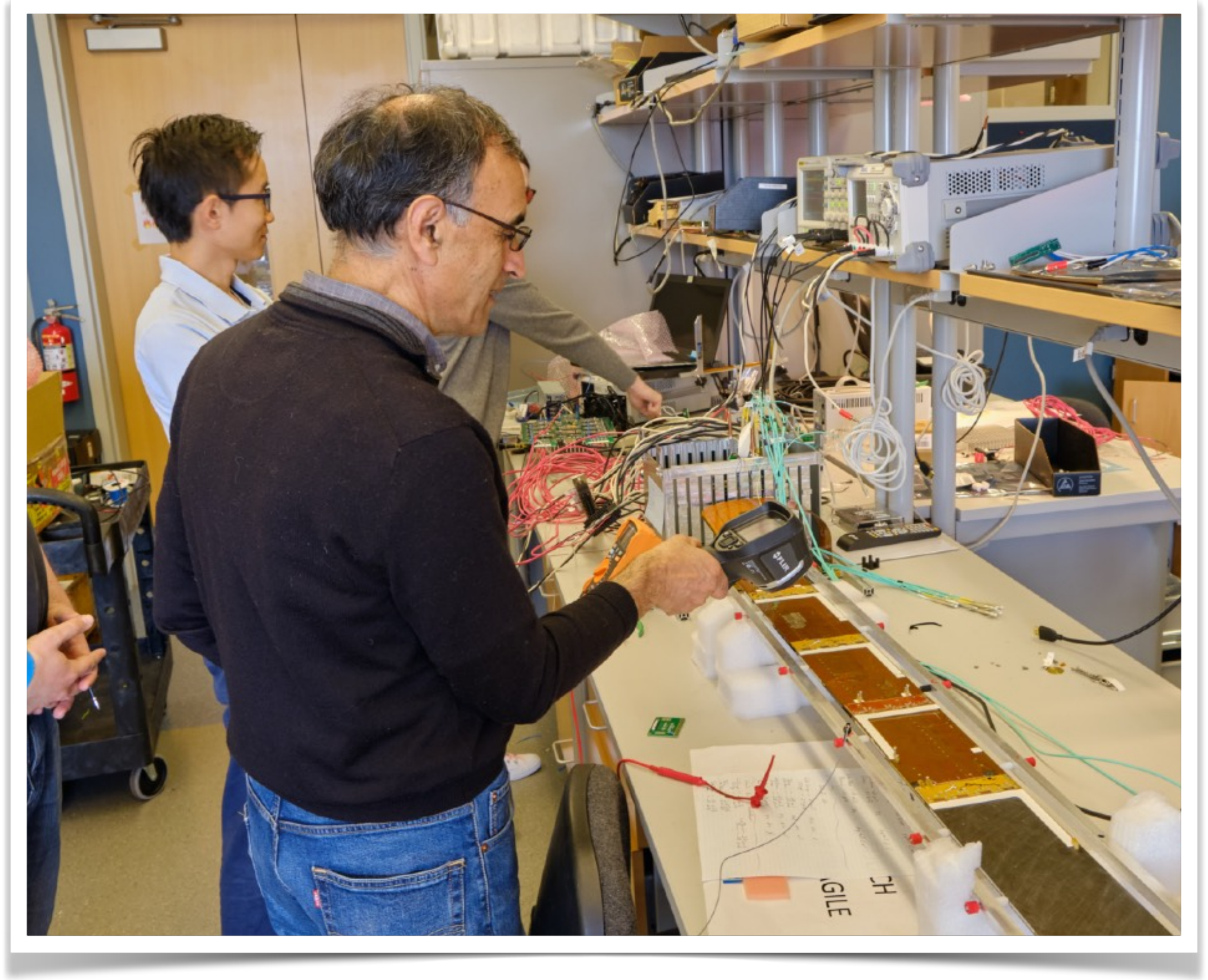
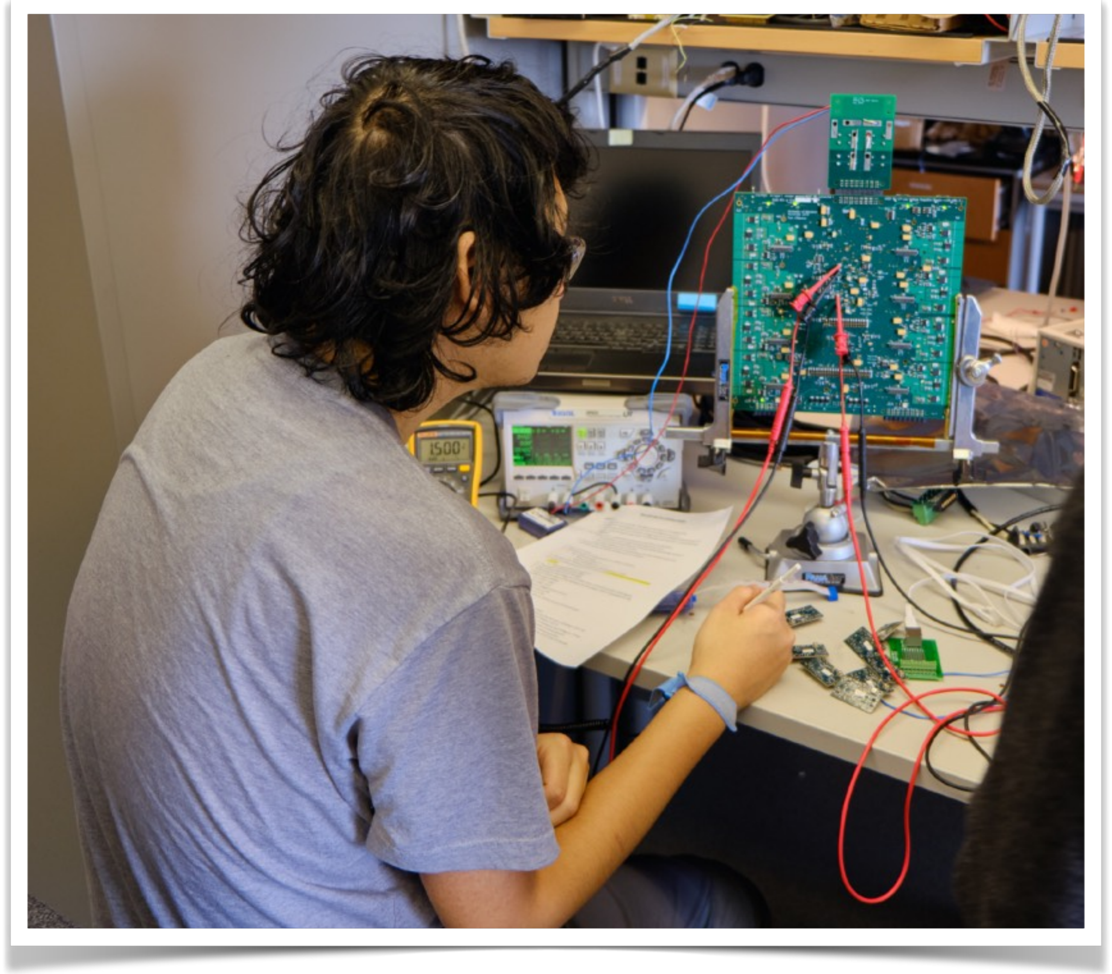
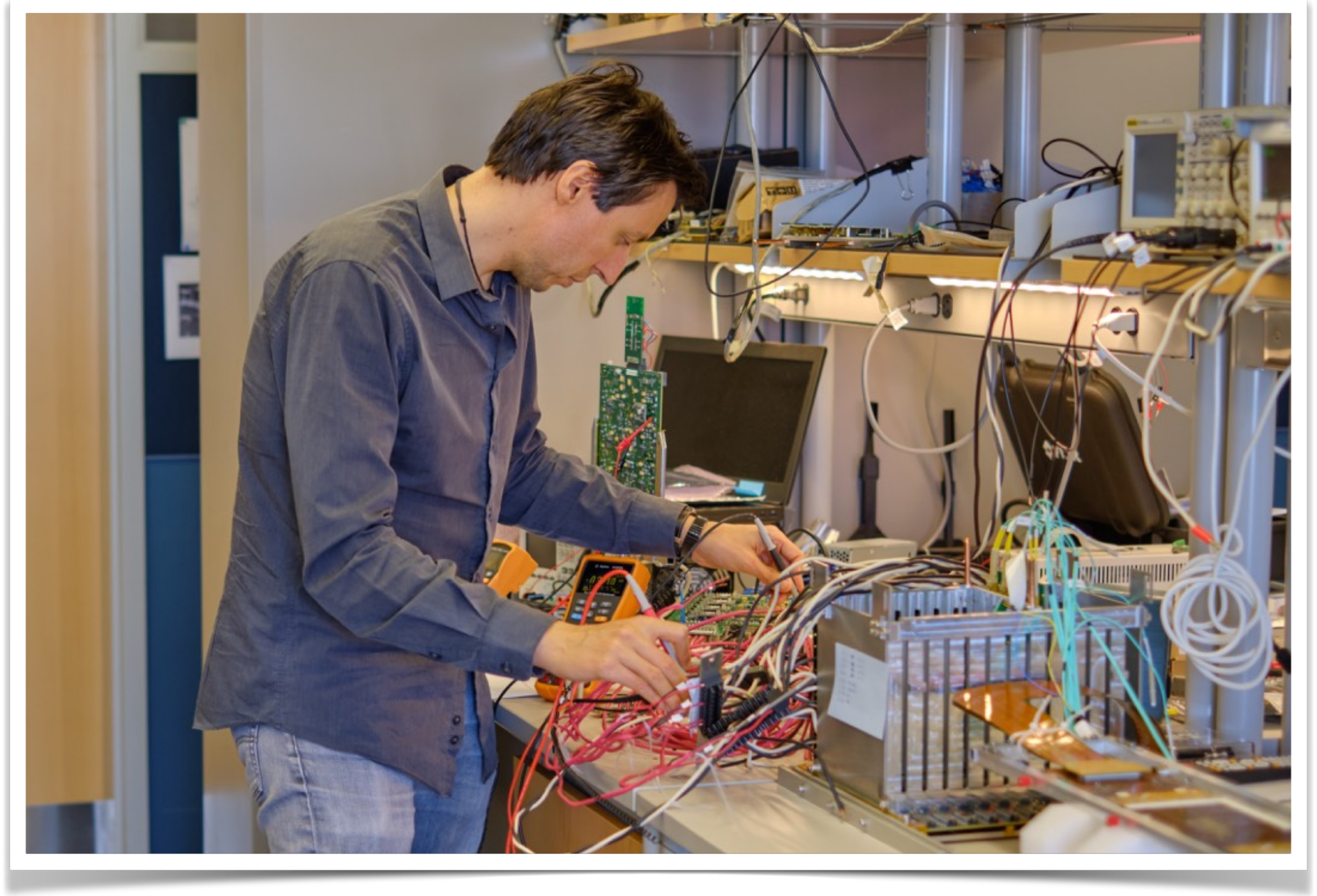
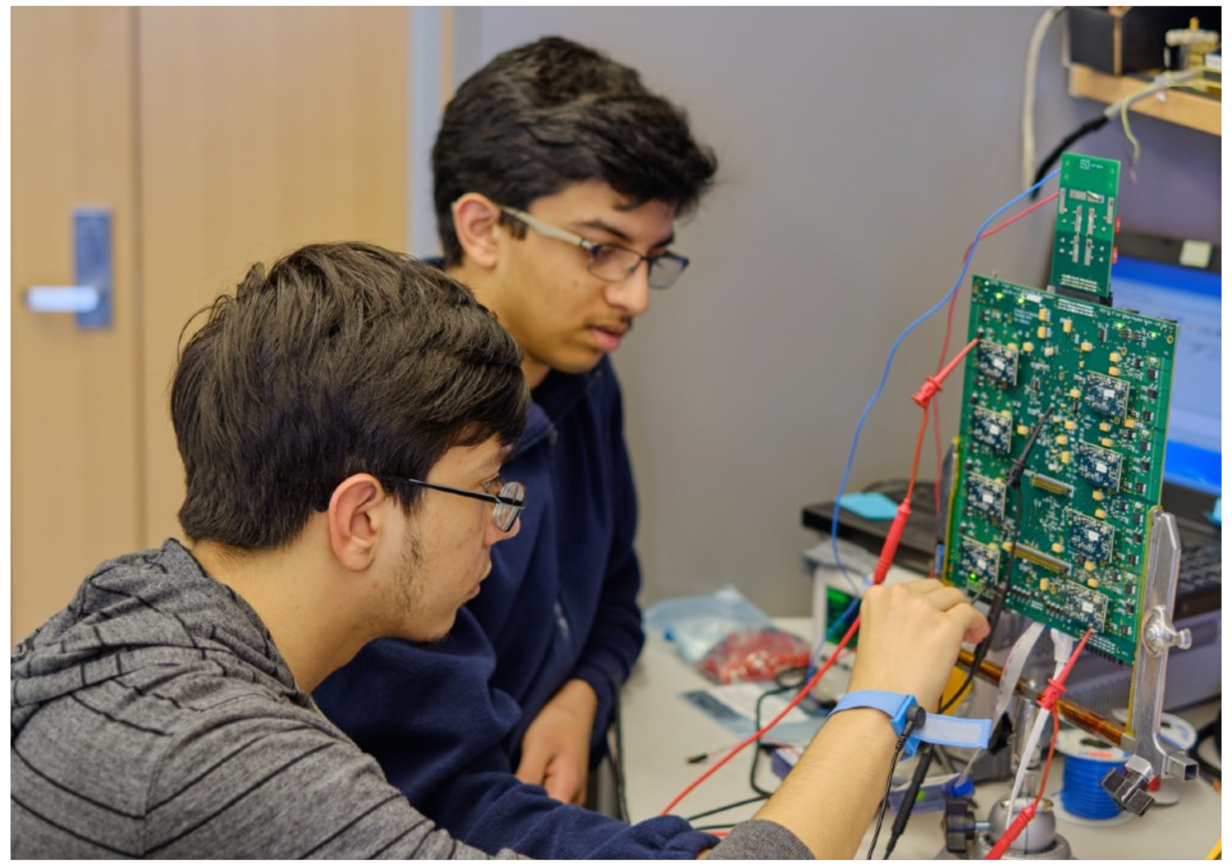
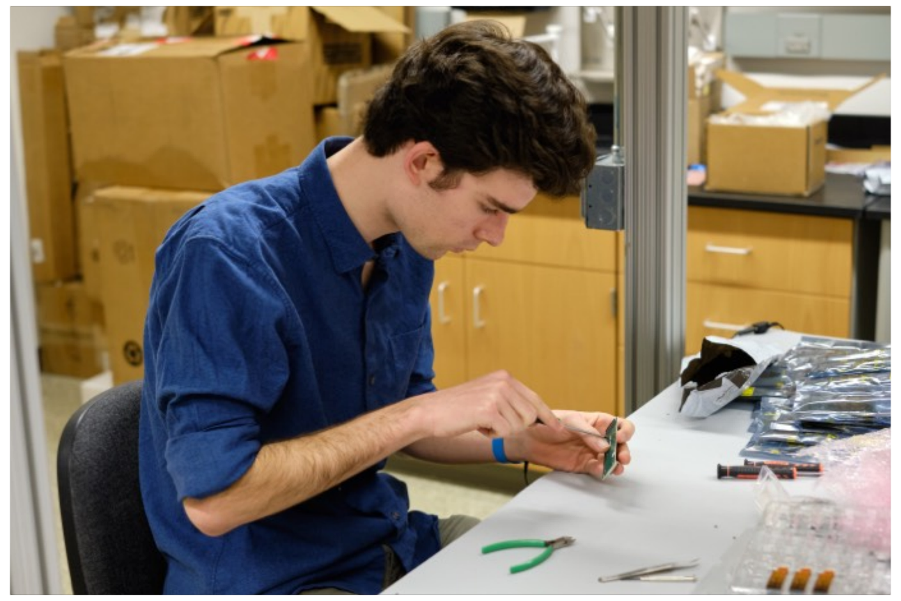






Thanks to great students





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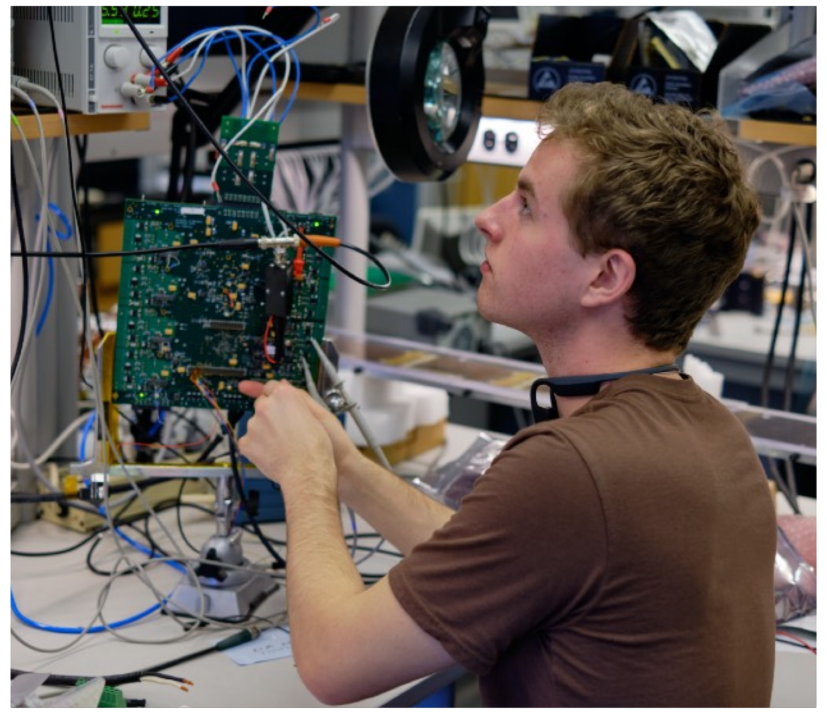


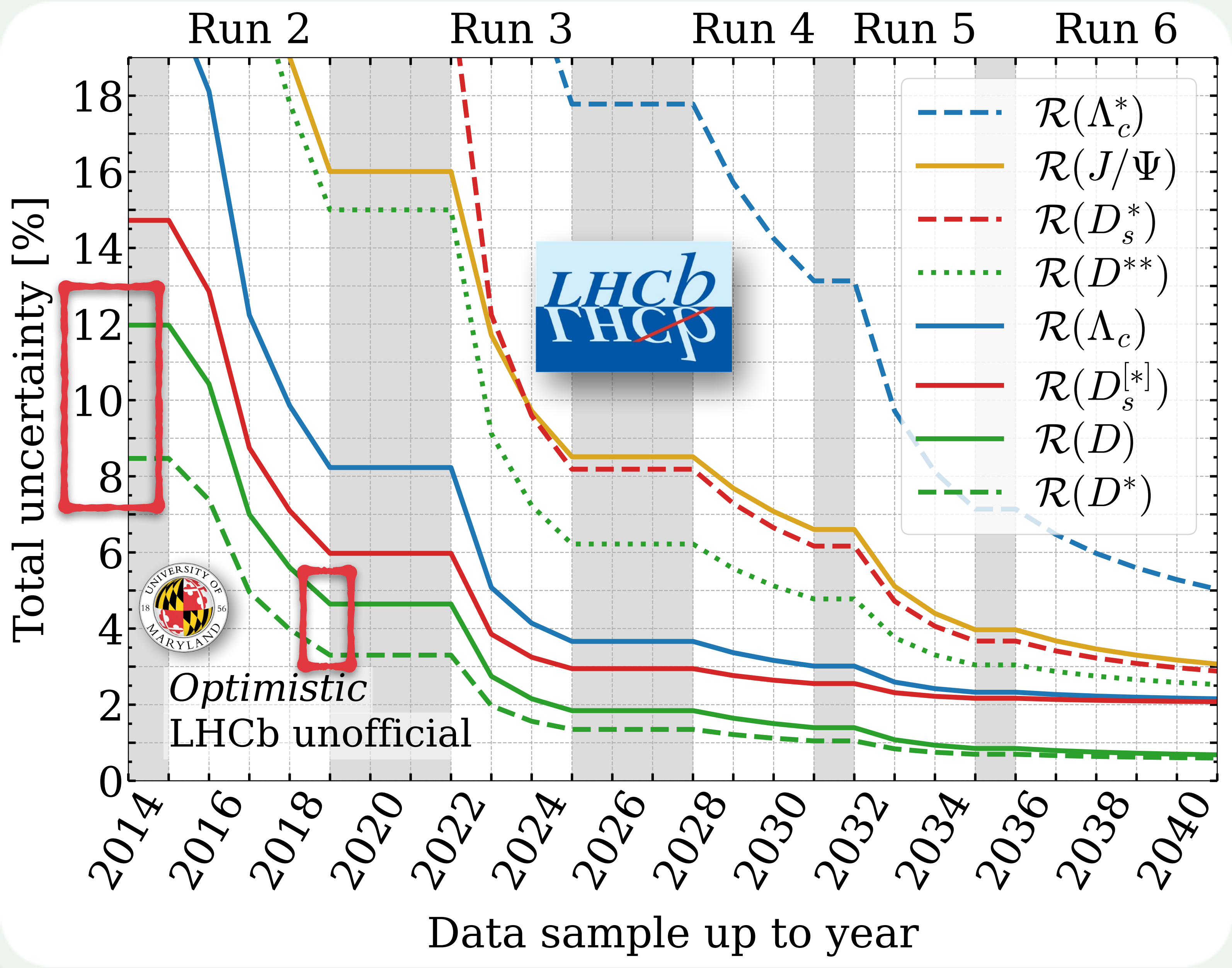
Prospects

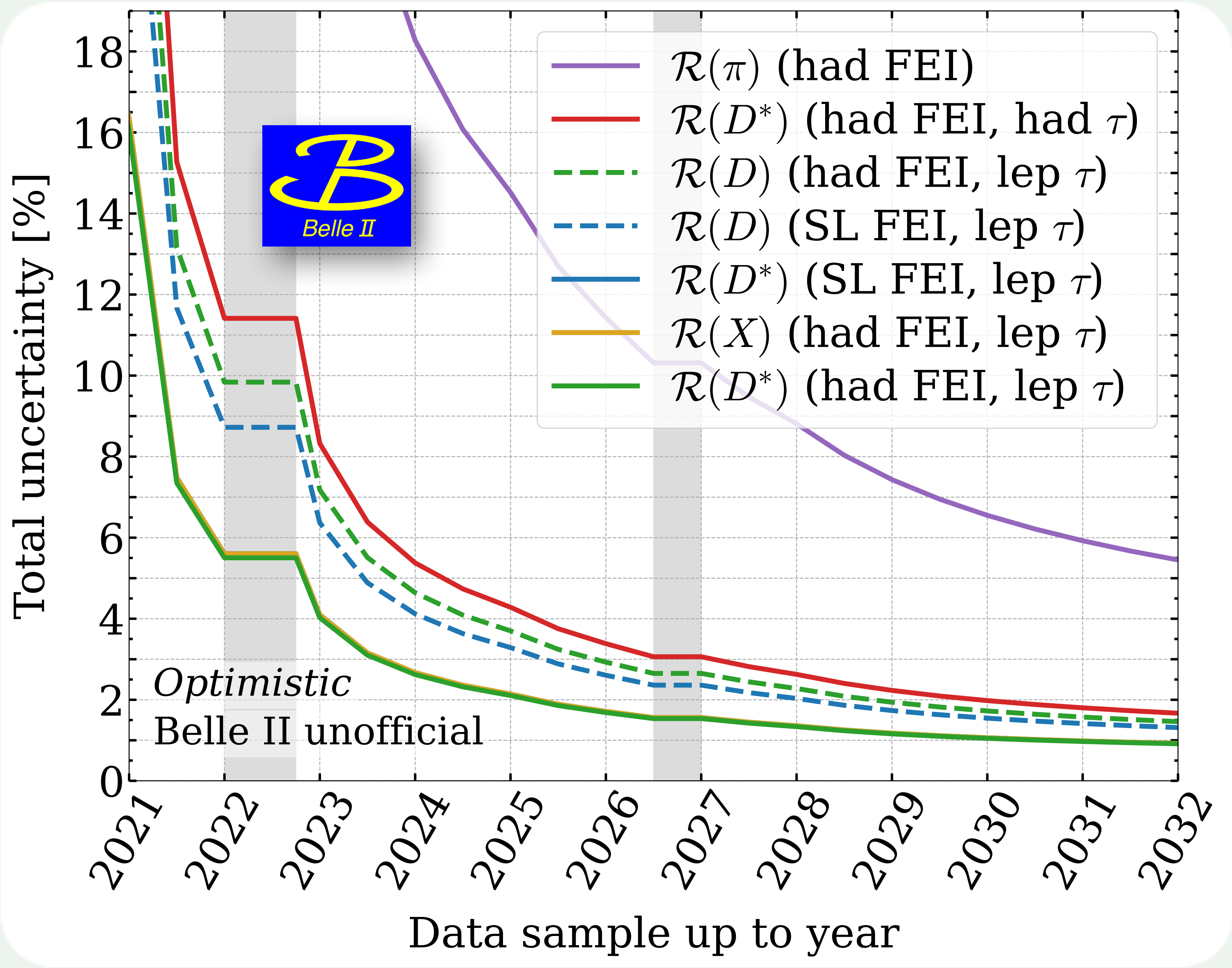
~ **Delivered UT electronics to CERN**, racing to complete UT installation

➡ **LHC expected to restart in 2022**

$b \to c\tau\nu$

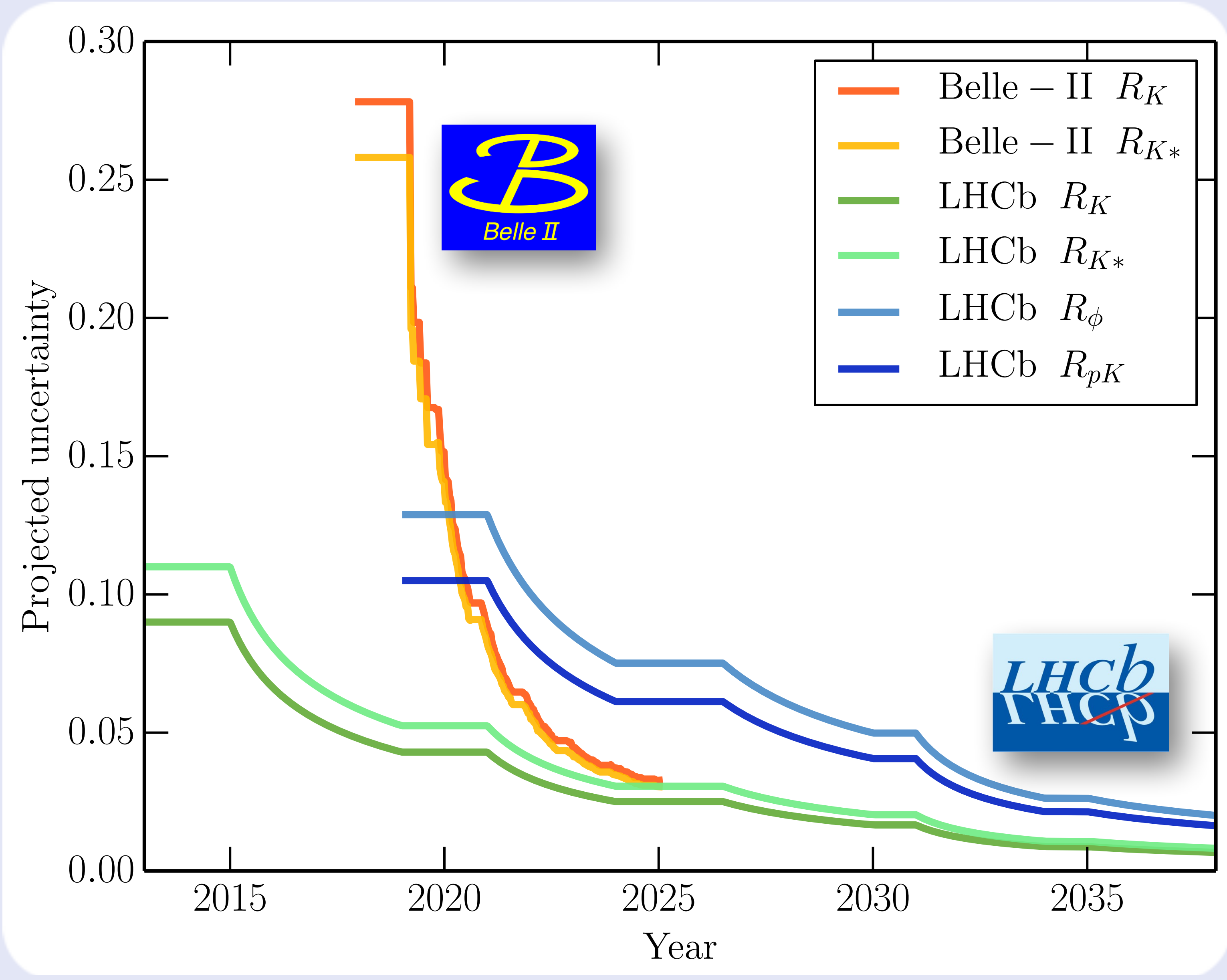
Bernlochner, MFS, Robinson, Wormser,
arXiv:2101.08326 (2021), accepted by RMP





$b \to s\ell\ell$

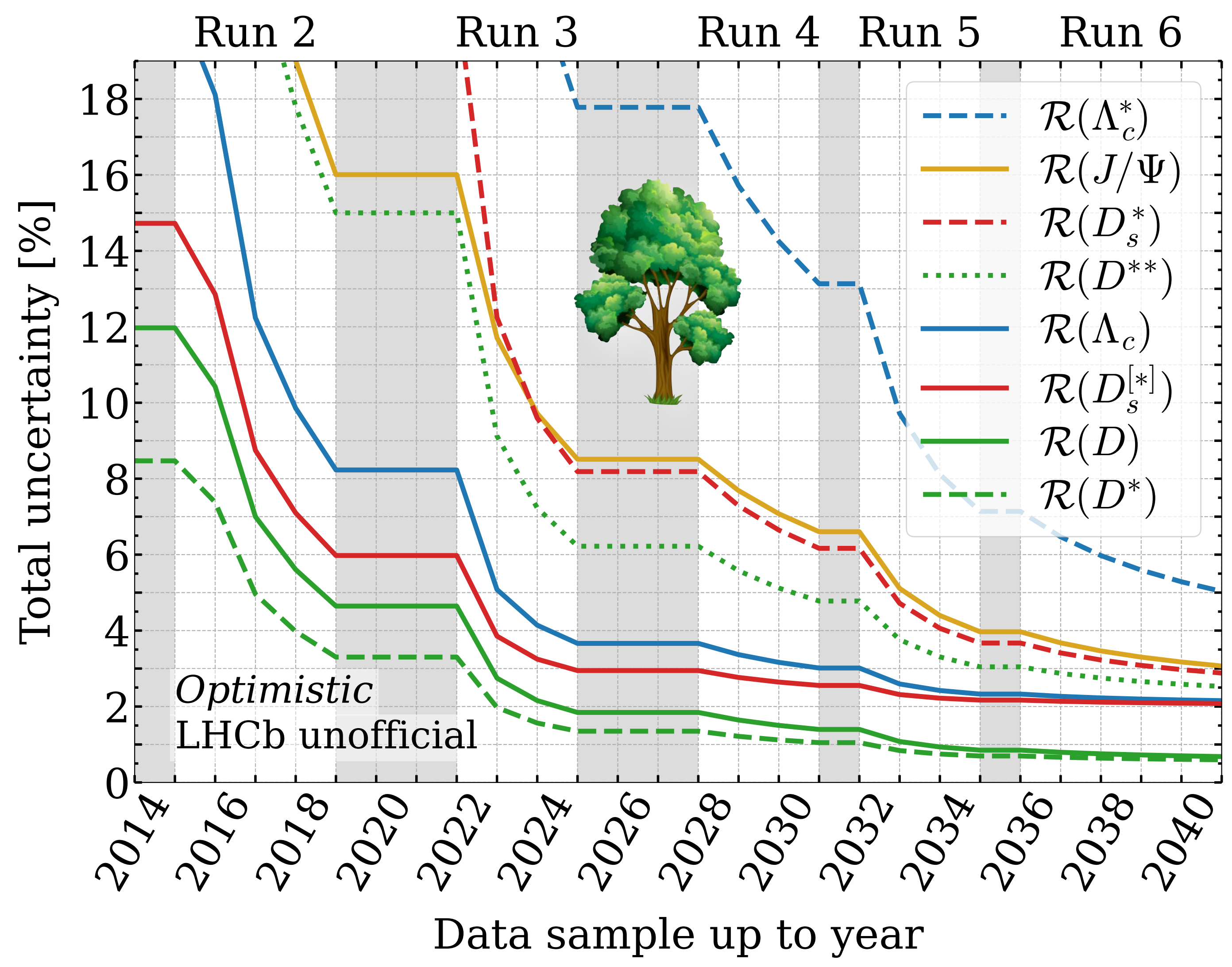
Bifani, Descotes-Genon, Romero Vidal, Schune
J. Phys. G: Nucl. Part. Phys. 46, 023001 (2018)

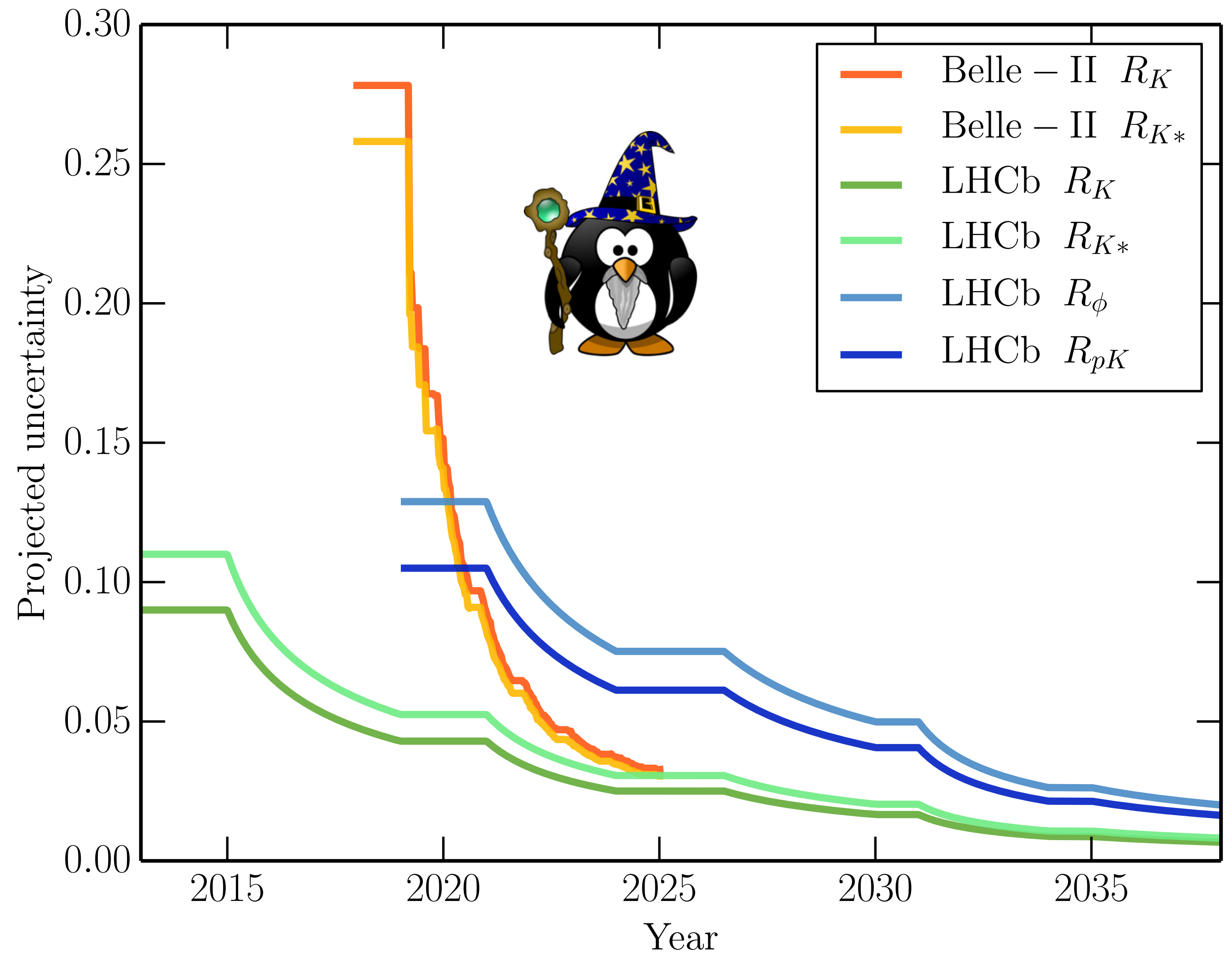


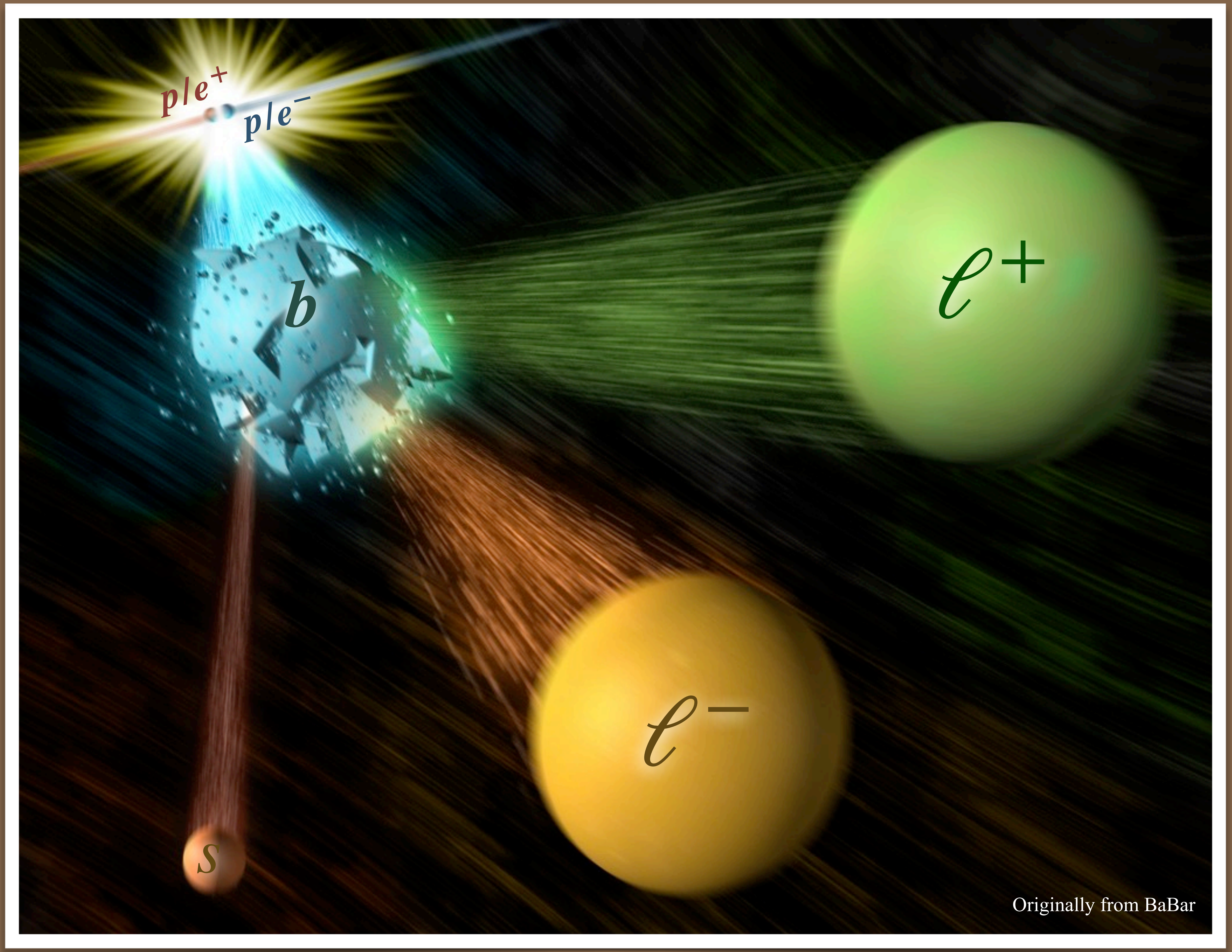
Since discrepancies are 15-30%, **precision better than 3%** will **resolve the anomalies one way or the other**

Conclusions

- **Excesses** in decays involving $b \to c\tau\nu$ transitions
  - 3.1σ significance
- **Deficits** in decays involving $b \to s\mu\mu$ transitions
  - At least 3.9σ significant
- **U_1 leptoquark** could explain both
  - Within reach at HL-LHC
- Exciting times ahead
  - **LHC** still **analyzing Runs 1+2 data**
  - **Run 3** to start next year with **5x inst. lumi at LHCb**
  - **Belle II** will increase **B-factories dataset** by **50x**
  - to play a **key role in the years to come**







Backup

Penguin from Jeff Brassard

LHCb upgrades I and II

9 fb^{-1} — Goal: 50 fb^{-1} — Goal: 250 fb^{-1}

Upgrade I — Upgrade Ib — Upgrade II

Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022 2023 2024	2025 2026 2027	2028 2029 2030	2031	2032 2033 2034	2035	2036 2037

Runs 1 and 2

40 MHz pp collisions → **L0** Hardware → 1.1 MHz Detector readout → **HLT** Software → 12.5 kHz (0.6 GB/s) Events on disk

Upgrade I (being installed)

40 MHz pp collisions Detector readout → **HLT** Software → 100 kHz (2-5 GB/s) Events on disk

Flexible software trigger and 3 new/better trackers

Upgrades Ib and II (proposed)

Even better granularity, improved calorimeter, and fast timing