Summary of Anomalies in the B-sector

Daniel Aloni

Searching for Physics Beyond the Standard Models Using Charged Leptons
COFI, San Juan, Puerto Rico, 24 May 2018

WEIZMANN INSTITUTE OF SCIENCE

~~Interpreting Hints for Lepton Flavor Universality Violation~~

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Summary of Anomalies in the B-sector from a theorist point of view

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Why is it interesting (1) ?

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$R(D)$

$B_s \to \mu\mu$

$R(K)$

V_{cb}

P_5'

$R(D^*)$

$\Lambda_b \to \Lambda\mu\mu$

$R(K^*)$

$B_s \to \phi\mu\mu$

$B \to K^*\mu\mu$

$R(J/\psi)$

$B \to K\mu\mu$

Why is it interesting (1) ?

$R(D)$ maybe σ $B_s \to \mu\mu$ $R(K)$

3.5σ

V_{cb}

4.1σ P'_5 $R(D^*)$ $\Lambda_b \to \Lambda\mu\mu$

$(1-3)\sigma$

$R(K^*)$

no σ $B_s \to \phi\mu\mu$

$B \to K^*\mu\mu$

2σish

0.8σ

$R(J/\psi)$

$B \to K\mu\mu$

Why is it interesting (2) ?

Why is it interesting - Belle2!

First collision @ April 26 2018

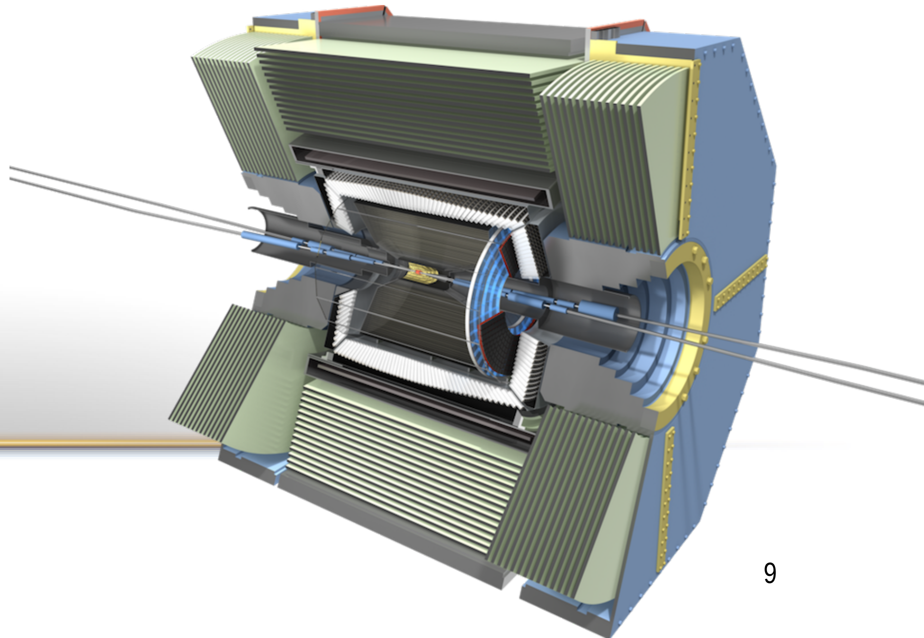
New machine

Webcasted with 460k people watching

$\mathcal{O}(\text{once})$ in a life

Belle 2 is coming

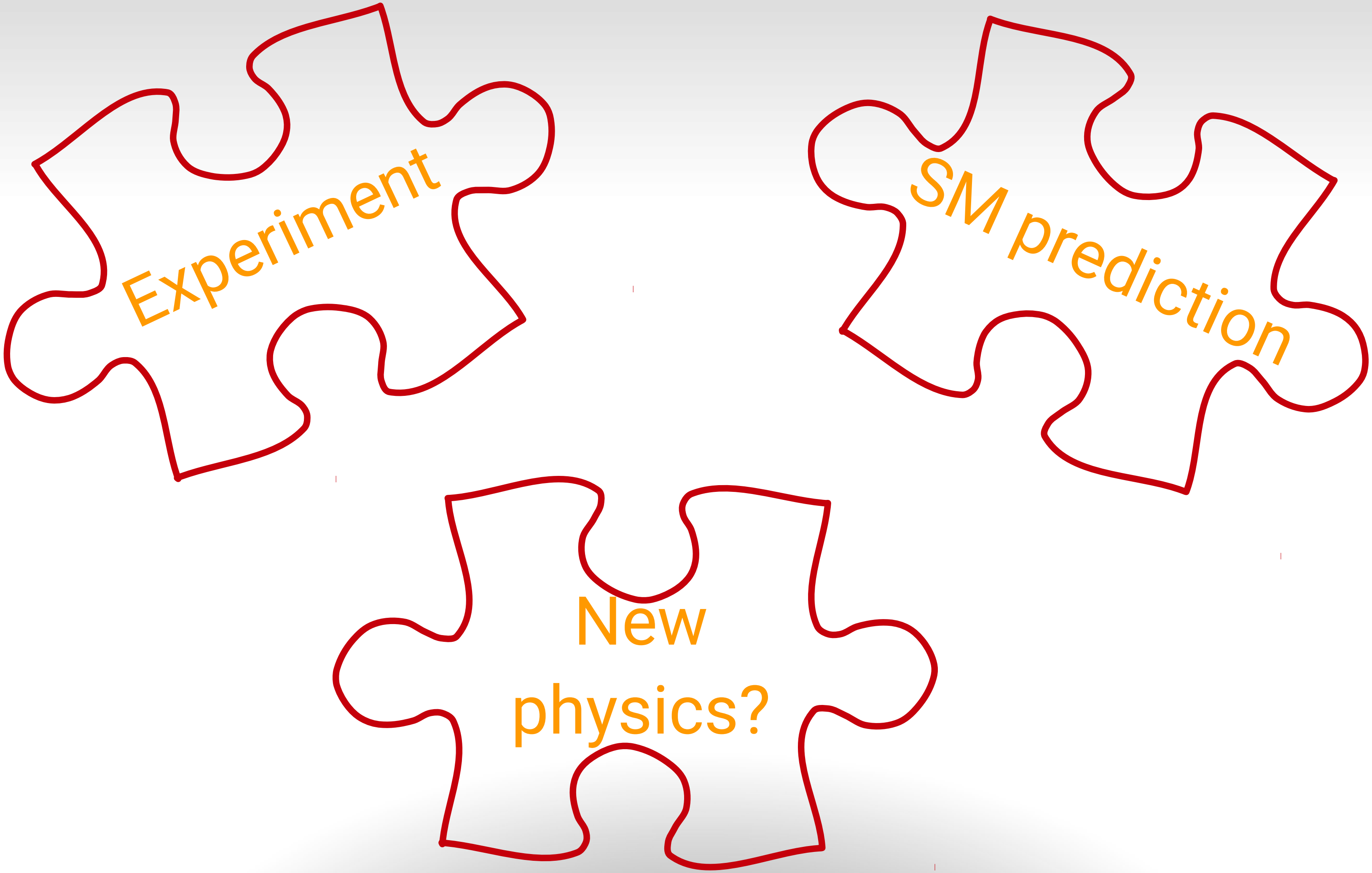
- New e^+e^- asymmetric collider in the market
- Operate mostly at $\sqrt{s} = m_{\Upsilon(4s)}$ (B-factory)
- High luminosity $\sim 1/ab$ per month
- Will study B-physics, flavor physics, CP violation, and more
- We must ask: what else?



Outline

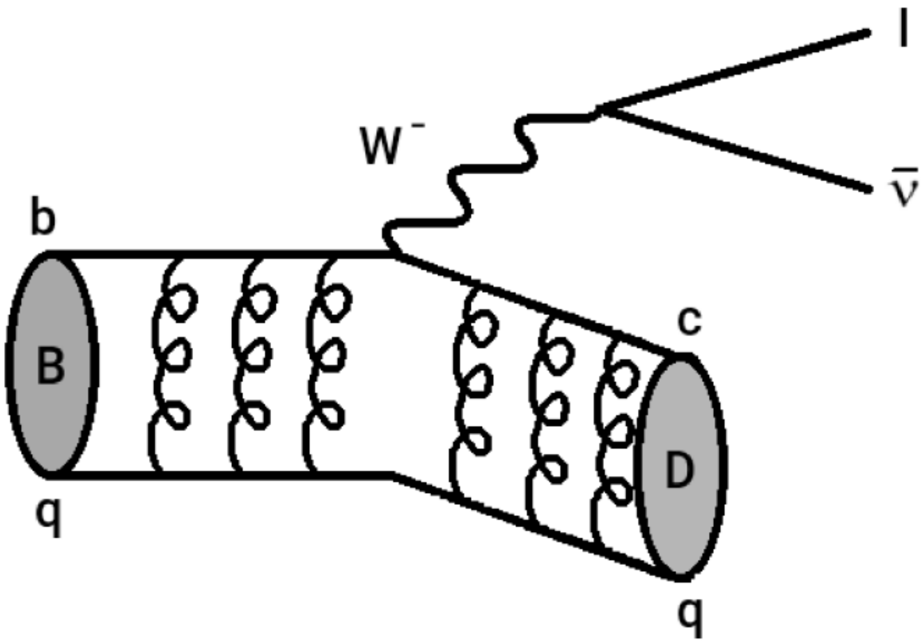
- $R(D^{(*)})$
- $R(K^{(*)})$
- Other anomalies in the B-sector
- Where else to look
- Summary

B mesons are puzzling



What is $R(D^{(*)})$?

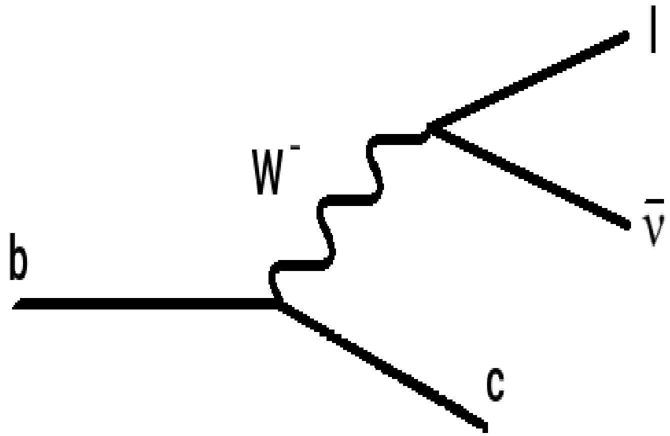
- $R(D^{(*)}) \equiv \dfrac{BR(B \to D^{(*)}\,\tau\,\bar{\nu})}{BR(B \to D^{(*)}\,\ell\,\bar{\nu})}$, $\ell = \mu, e$



What is $R(D^{(*)})$?

- $R(D^{(*)}) \equiv \dfrac{BR(B \to D^{(*)}\,\tau\,\bar{\nu})}{BR(B \to D^{(*)}\,\ell\,\bar{\nu})}\ , \quad \ell = \mu, e$

- At the quark level: $b \to c\tau(\ell)\bar{\nu}$



- SM: $b \to c\tau(\ell)\bar{\nu}$ transition is mediated by the W boson

The SM prediction

- Can we have any prediction?
- Yes we can!
  - Semileptonic
  - Unknown parameters cancel in the ratio
  - Can systematically expand in the heavy quark limit $m_b, m_c \to \infty$
  - Electroweak interactions are Lepton Flavor Universal
    - $m_\tau \to m_\ell$, R(D)=R(D*)=1
    - $m_\tau \to m_b$, R(D)=R(D*)=0
  - We also have partial Lattice QCD results

The SM prediction

$R(D^*)$

- Lattice results only at zero recoil (preliminary away from zero recoil)
- Bernlochner, Ligeti, Papucci, Robinson (1703.05330)
  - NLO at HQET and perturbative QCD
  - Lattice + QCDSR
  - $R^{SM}(D^*) = 0.257 \pm 0.003$
- Bigi, Gambino, Schacht (1707.09509)
  - Assign 15% uncertainty to unknown NNLO
  - $R^{SM}(D^*) = 0.260 \pm 0.008$

The SM prediction

$R(D)$

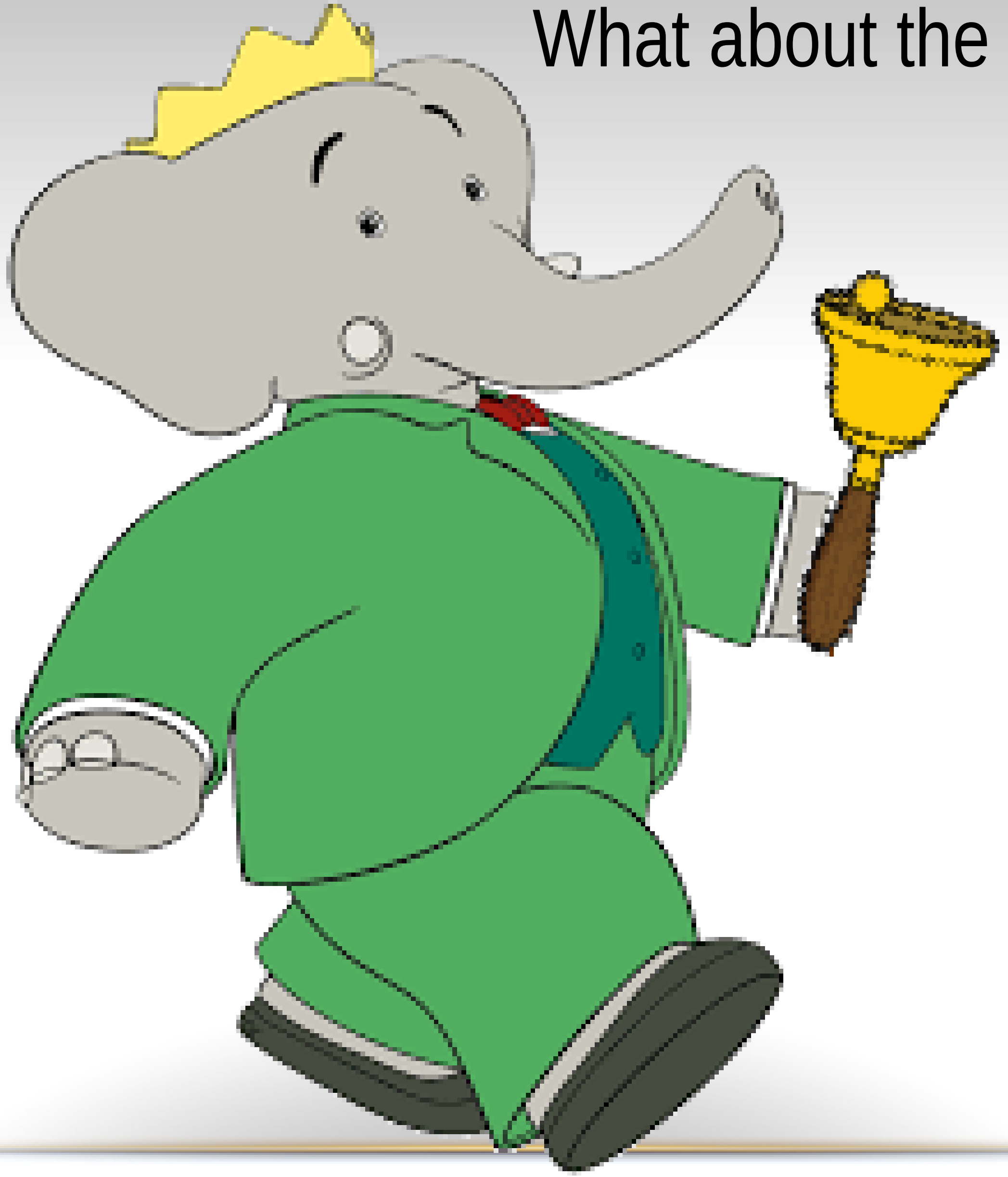
- Lattice results are available to all (SM) form factors
- Lattice results at few kinematical points
- FLAG combination of FNAL/MILC and HPQCD (1607.00299):

$$R^{SM}(D) = 0.300 \pm 0.008$$

- Bernlochner, Ligeti, Papucci, Robinson (1703.05330)

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

What about the experiments?



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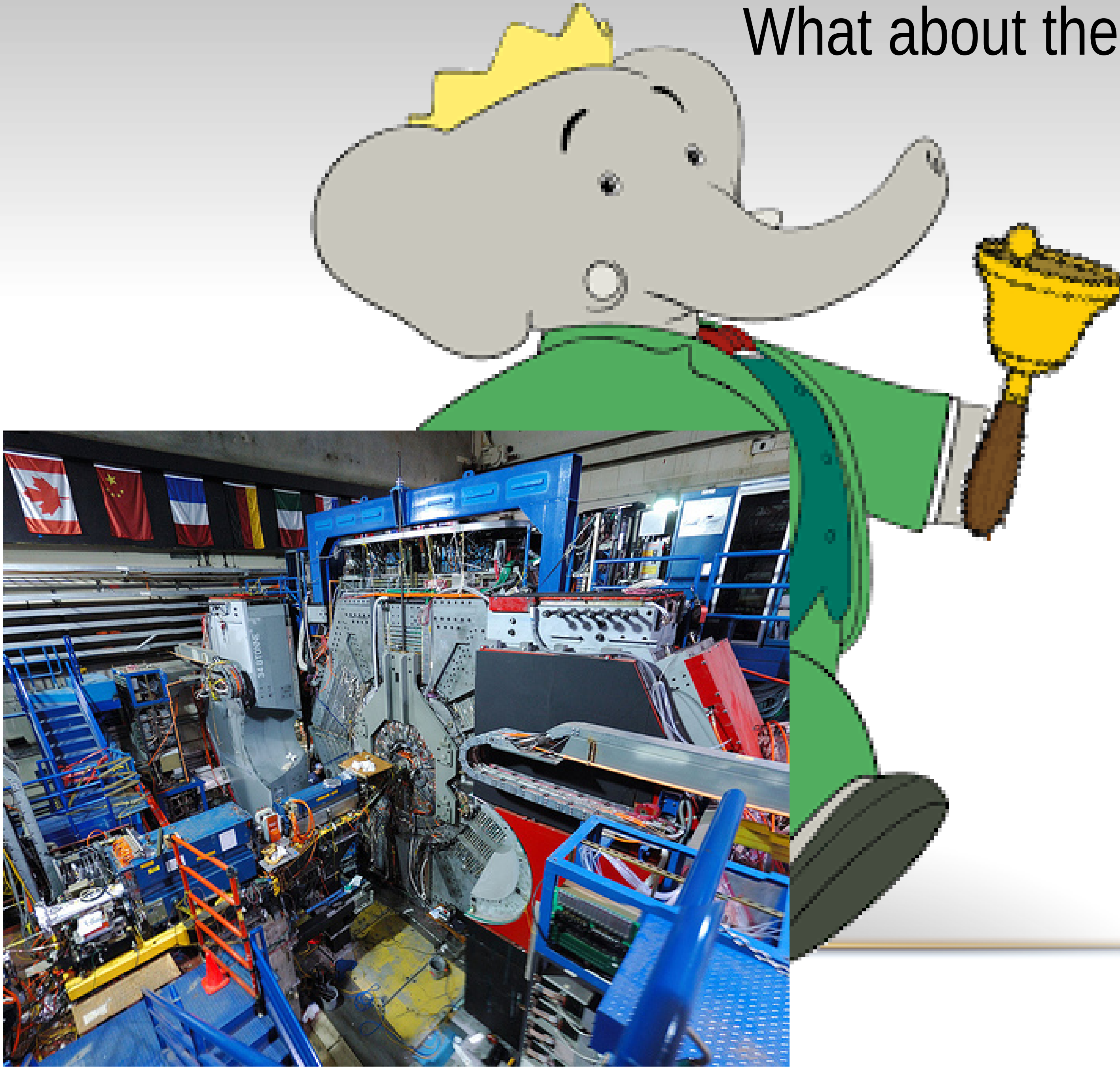
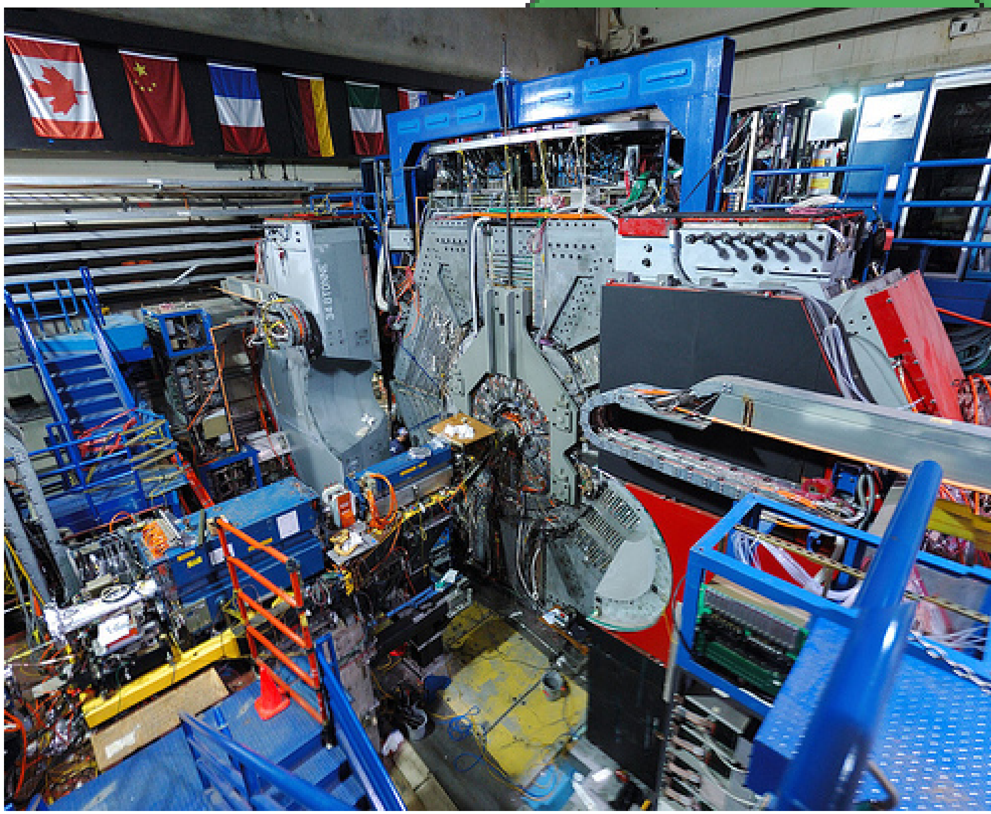
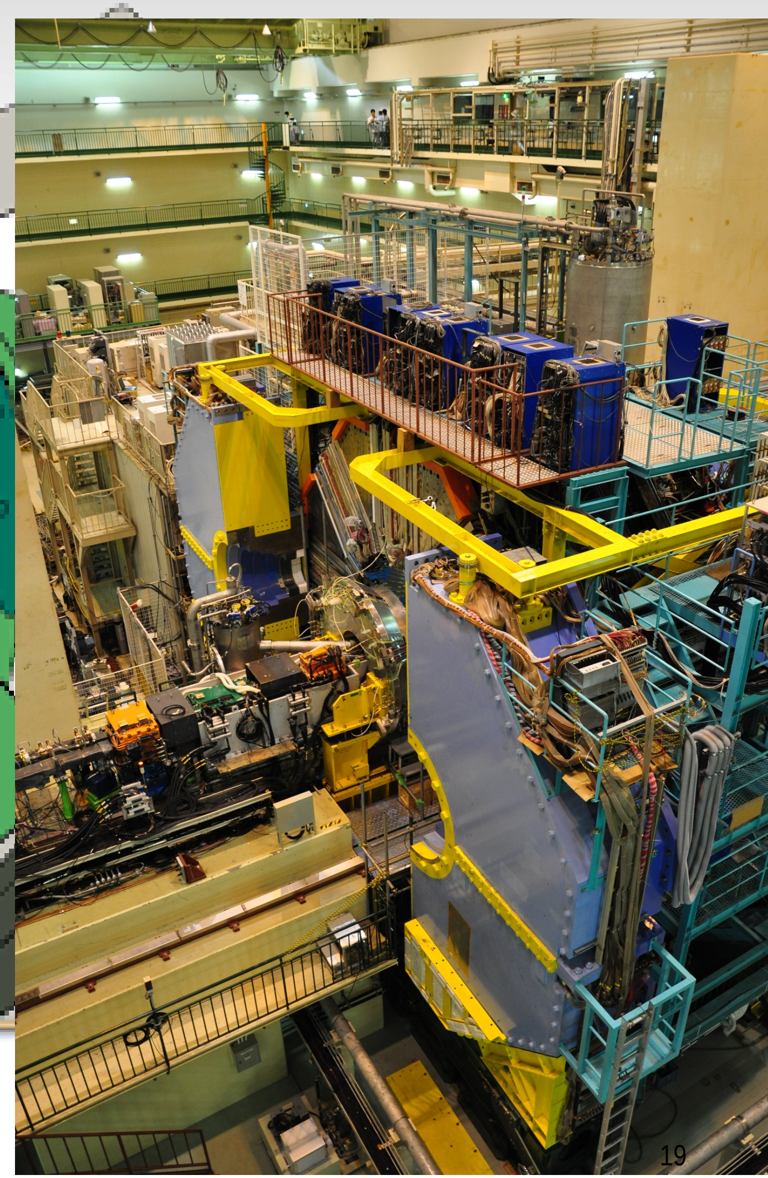


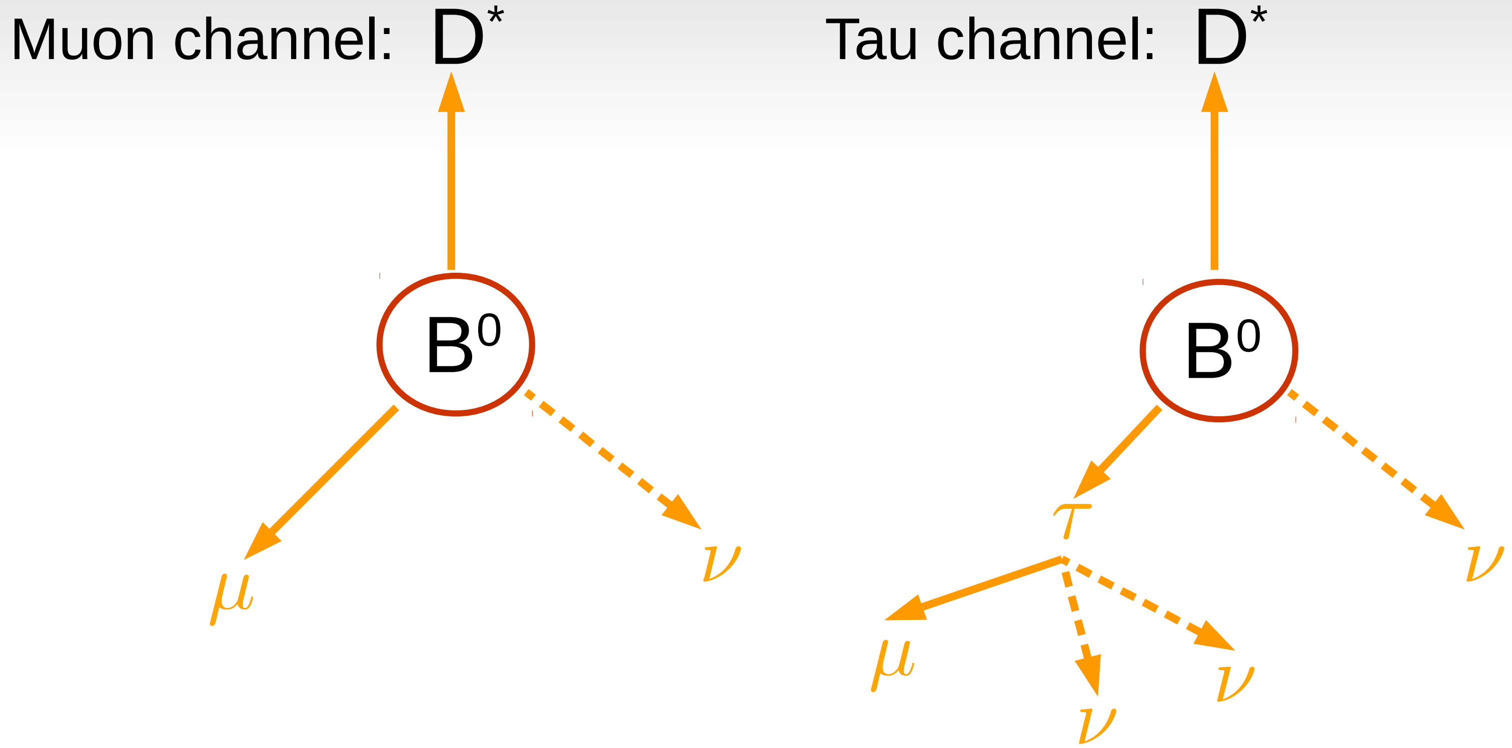
What about the experiments?





Also experimentalists like ratios!

- Most* of the experiments looked for muonic tau



- $$\mathrm{R}(\mathrm{D}^{(*)}) = \frac{N_\tau}{N_\mu} \frac{\varepsilon_\mu}{\varepsilon_\tau} \frac{1}{BR(\tau \to \mu\nu\nu)}$$

* Babar (1205.5442), Belle (1507.03233, 1607.07923), LHCb (1506.08614)

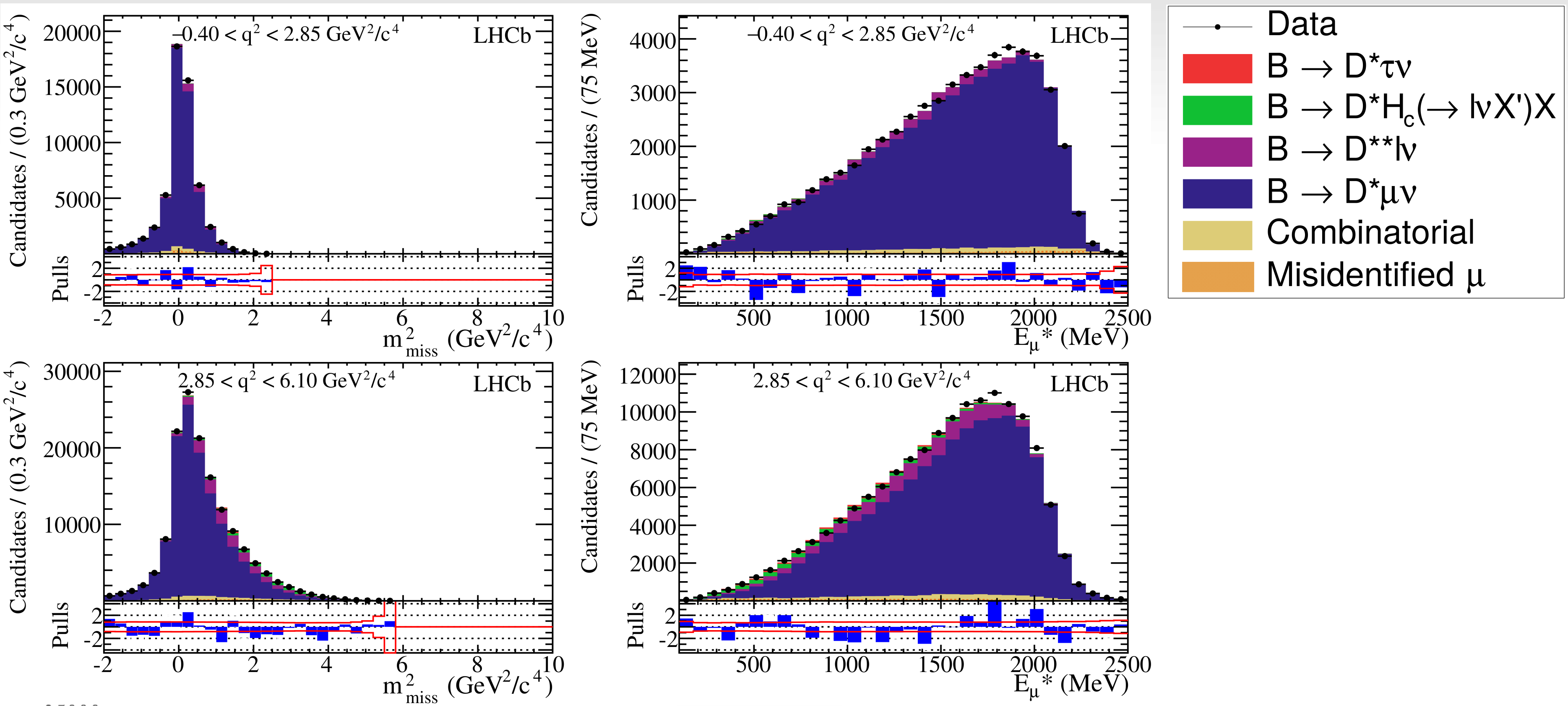
What is the experimental challenge?

- Tau and muon have same topology
- $N_\mu \sim 20 \cdot N_\tau$
- Need good discrimination between tau channel and muon channel
- *"The most discriminating kinematic variables … in the B rest Frame..." :*

$$E^*_\mu,\ m^2_{miss} = (p^\mu_B - p^\mu_{D*} - p^\mu_\mu)^2,\ q^2 = (p^\mu_B - p^\mu_{D*})^2$$

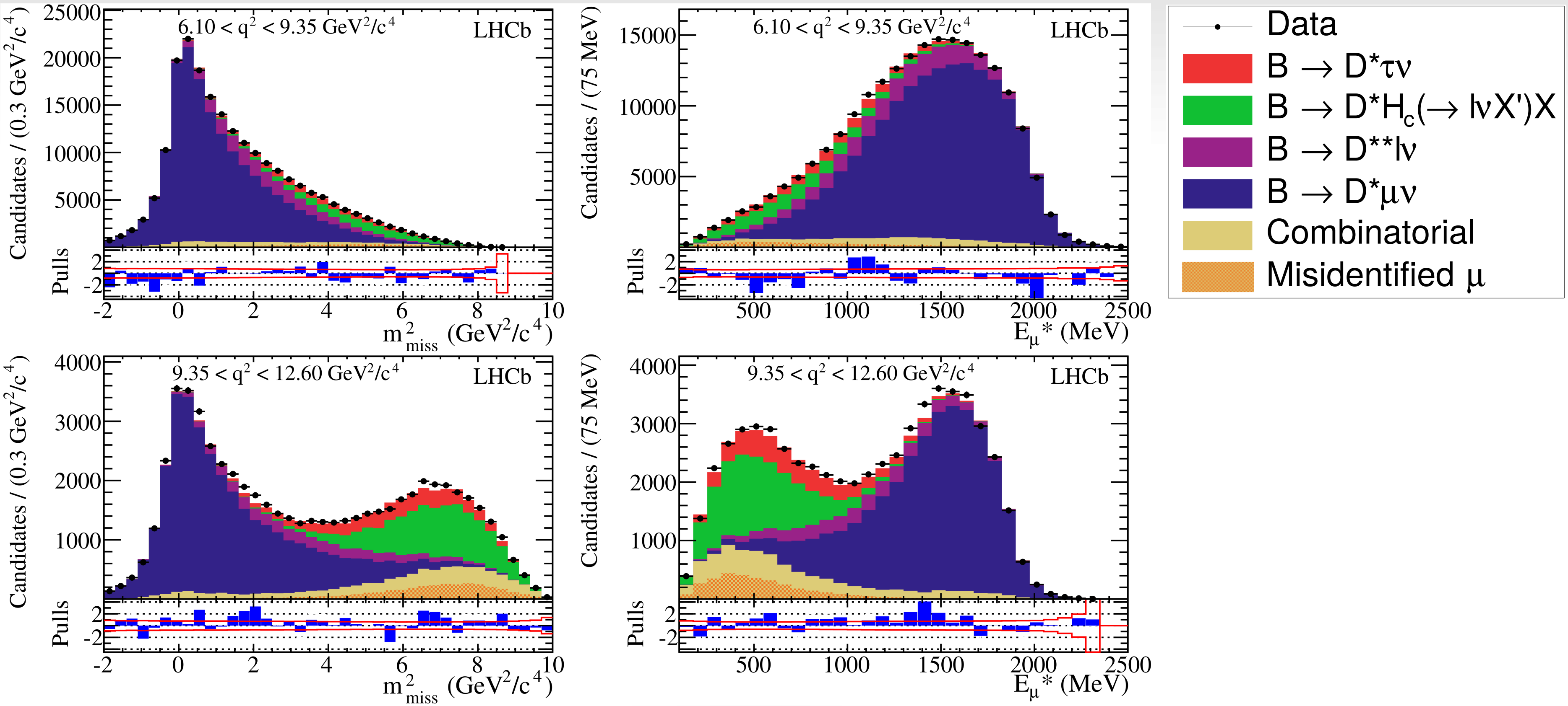
arXiv:1506.08614 [hep-ex]

“Below” threshold



arXiv:1506.08614 [hep-ex]

Above threshold



arXiv:1506.08614 [hep-ex]

$R(D^*)$ with hadronic modes

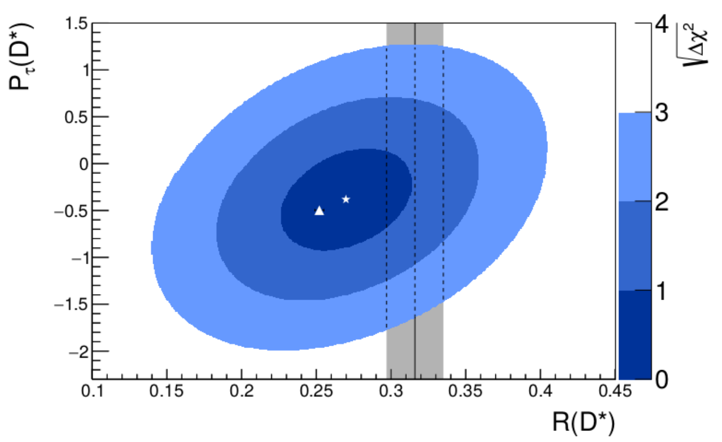
- Belle (1612.00529)
  - $\tau^- \to \pi^- \nu_\tau,\ \tau^- \to \rho^- \nu_\tau$
  - τ polarization asymmetry

$$P_\tau(D^*) = \frac{\Gamma(\lambda_\tau = 1/2) - \Gamma(\lambda_\tau = -1/2)}{\Gamma(\lambda_\tau = 1/2) + \Gamma(\lambda_\tau = -1/2)}$$

can be measured using angular distribution

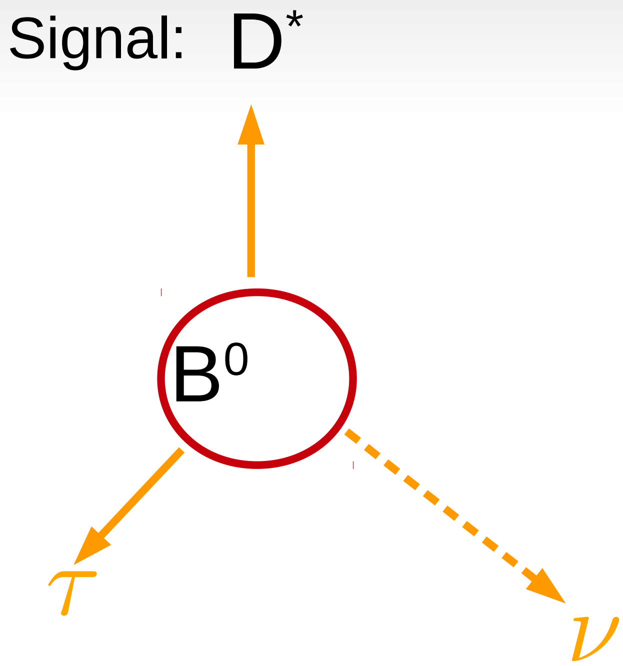
$$d\Gamma/d\cos\theta \propto 1 + \alpha P_\tau \cos\theta\ ,$$

$$(\alpha_\pi = 1, \alpha_\rho = 0.45)$$



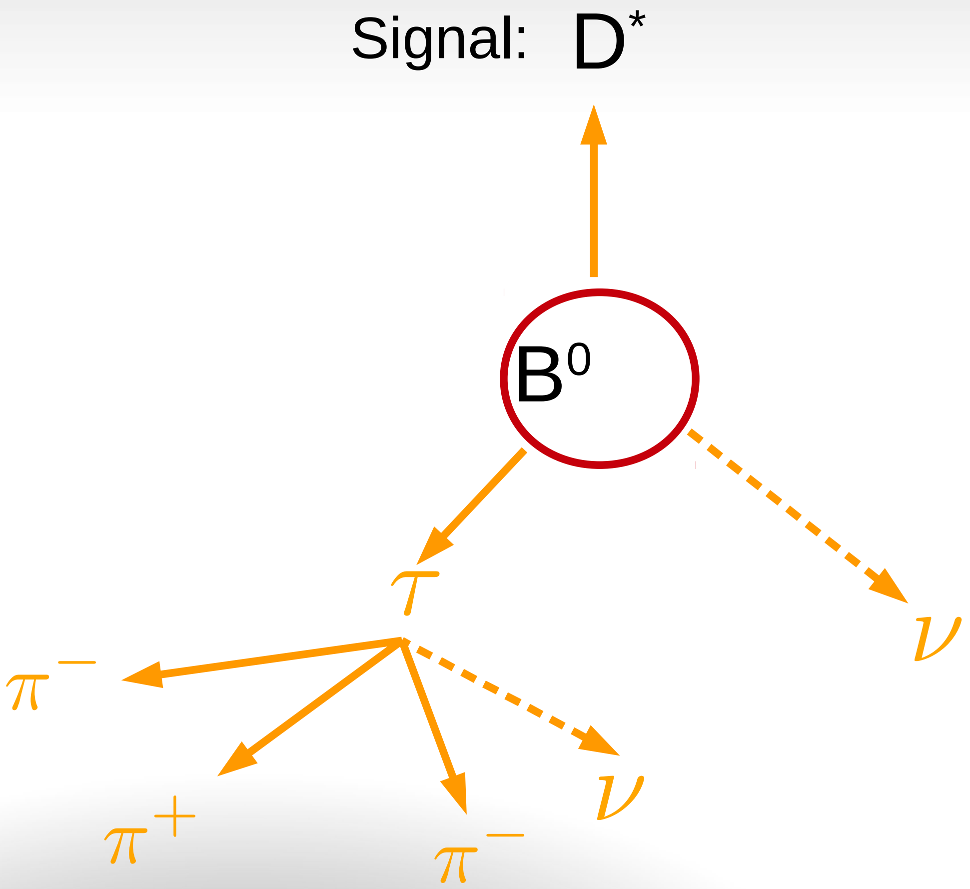
$R(D^*)$ with hadronic modes

- LHCb (1708.08856)



$R(D^*)$ with hadronic modes

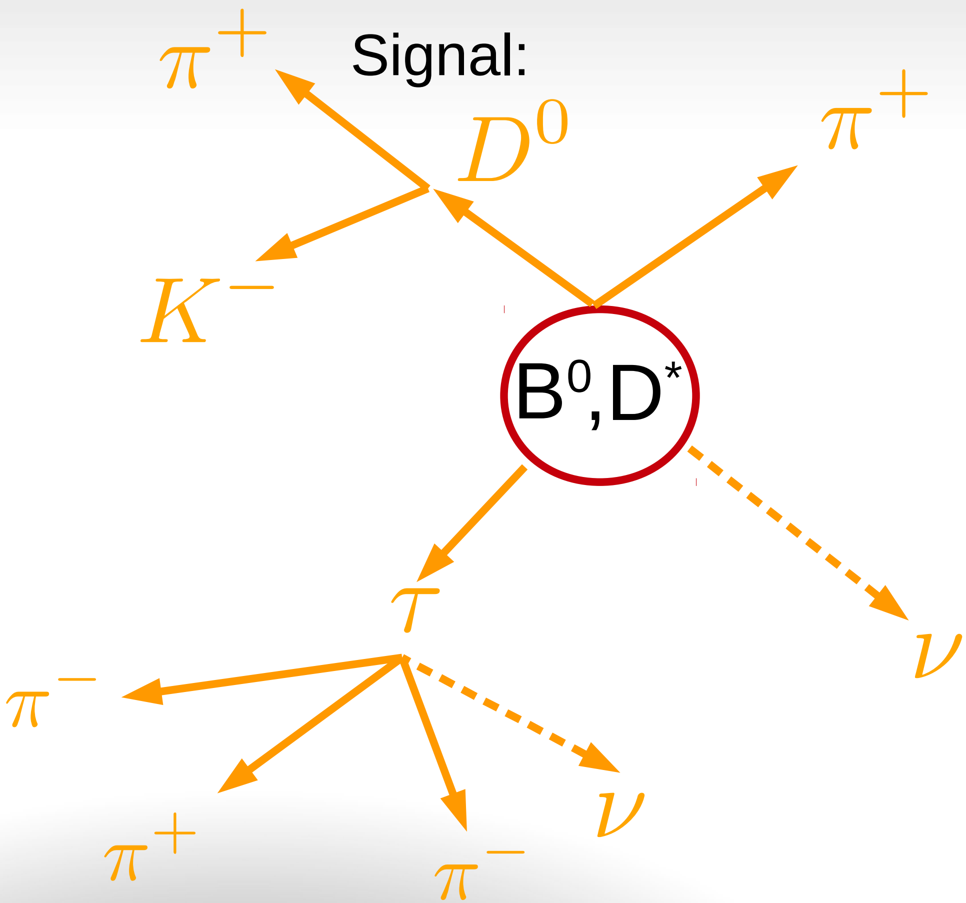
- LHCb (1708.08856)



(* Use also $\tau \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$)

$R(D^*)$ with hadronic modes

- LHCb (1708.08856)



(* Use also $\tau \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$)

Reducing the systematic uncertainties

Normalization:

$$\mathcal{K}(D^{*-}) \equiv \frac{BR(B^0 \to D^{*-}\tau^+\nu_\tau)}{BR(B^0 \to D^{*-}3\pi)}$$

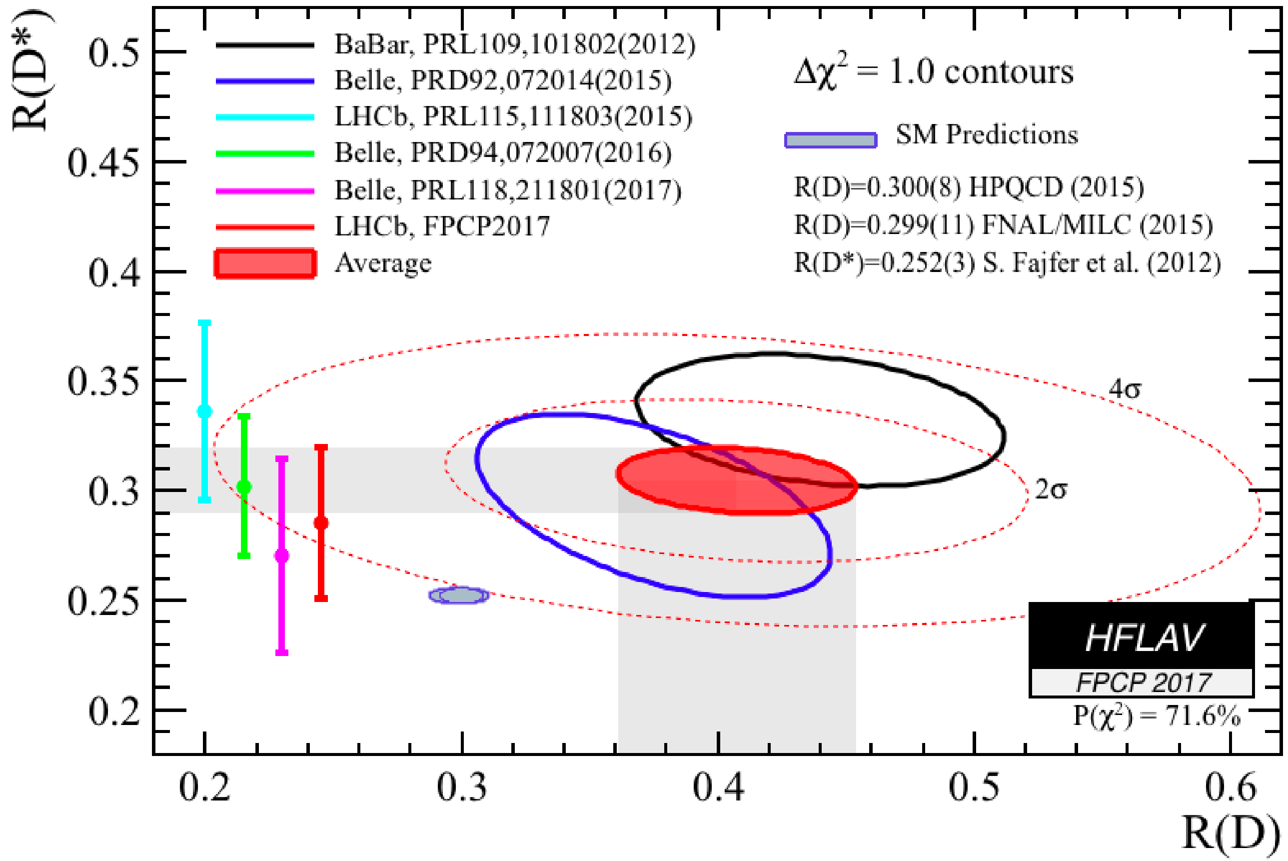
Problems:

- How to discriminate signal from normalization?
- How to discriminate signal from background?

Solution: Discriminate by using different $(D^*)\,3\pi$ kinematics

arXiv:1708.08856 [hep-ex]

Measurement



- $\sim 4\sigma$ compared to HFLAV (out of date) SM prediction prediction
- Updated theoretical results ease (mildly) the tension

*https://hflav.web.cern.ch/

A word on New physics

- If we just re-scale the SM operator the effective Hamiltonian is

$$\mathcal{H} = \left(\frac{4G_F}{\sqrt{2}} V_{cb} + C_{NP} \right) \mathcal{O}_{V_L}$$

- Interfere with SM: 30% enhancement in the rate means $C_{NP} \sim 15\% \, C_{SM}$

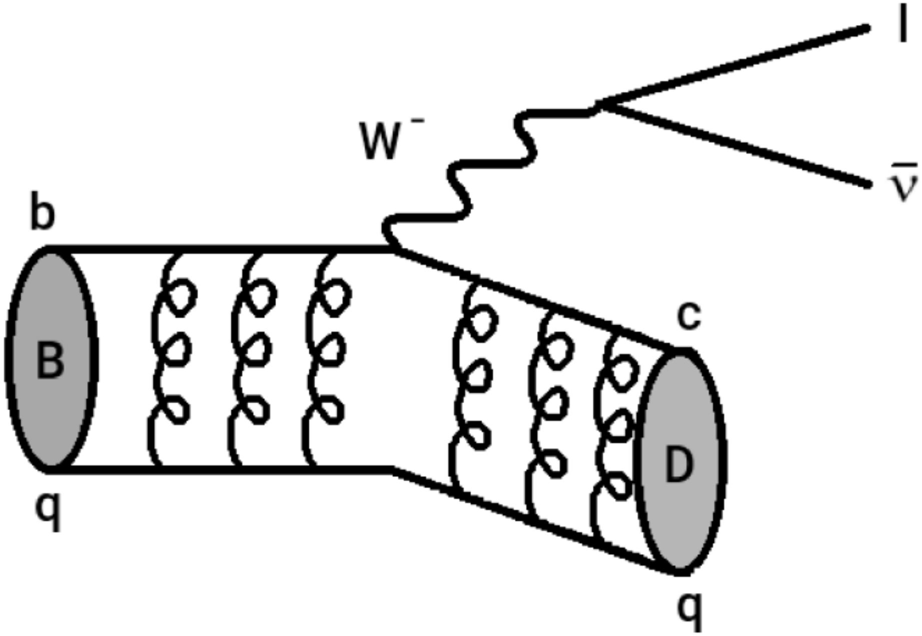
- The scale of new physics

$$C_{NP} \sim 1/m_{NP}^2 \Rightarrow m_{NP} \sim 1 \, TeV$$

$R(D^{(*)})$ - Summary

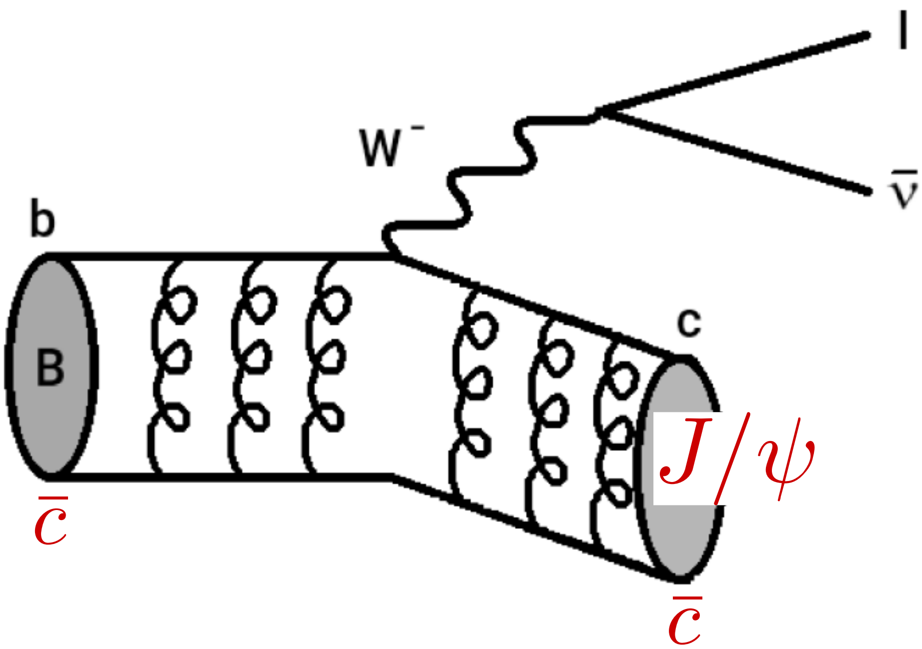
- $R(D^{(*)})$ is puzzling and shows $\sim 4\sigma$ deviation from SM prediction
- Updated SM predictions ease the tension but do not solve the puzzle
- LHCb with 13 TeV, and Belle 2 will shed light
- New physics (?) at the TeV scale

$$R(J/\psi) = \frac{BR(B_c \to J/\psi\,\tau\nu)}{BR(B_c \to J/\psi\,\mu\nu)}$$



ArXiv:1711.05623 [hep-ex]

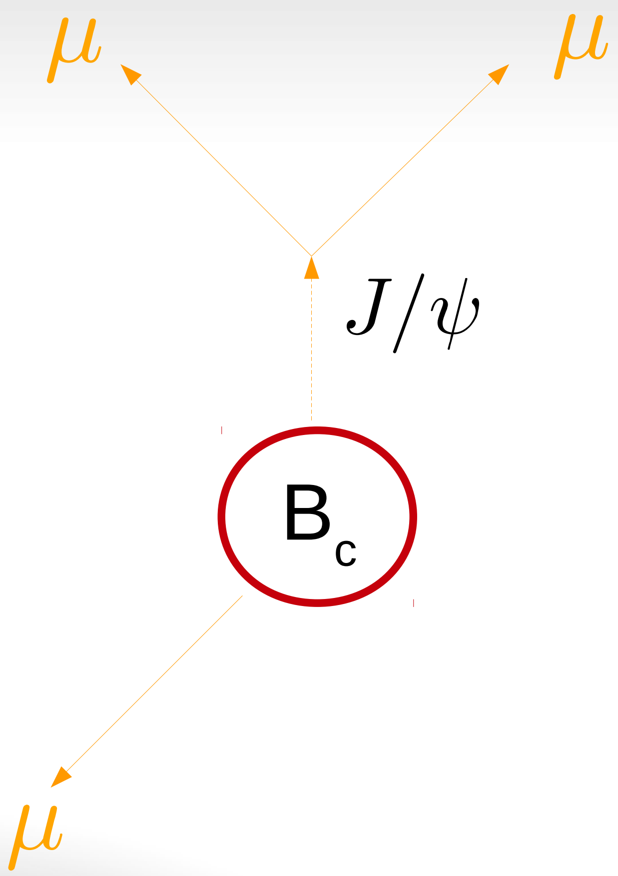
$$R(J/\psi) = \frac{BR(B_c \to J/\psi\, \tau\nu)}{BR(B_c \to J/\psi\, \mu\nu)}$$



ArXiv:1711.05623 [hep-ex]

The experimental signature

- By using muonic τ the analysis is very similar to $\mathcal{R}(D^*)$ with muonic τ



ArXiv:1711.05623 [hep-ex]

Result and summary

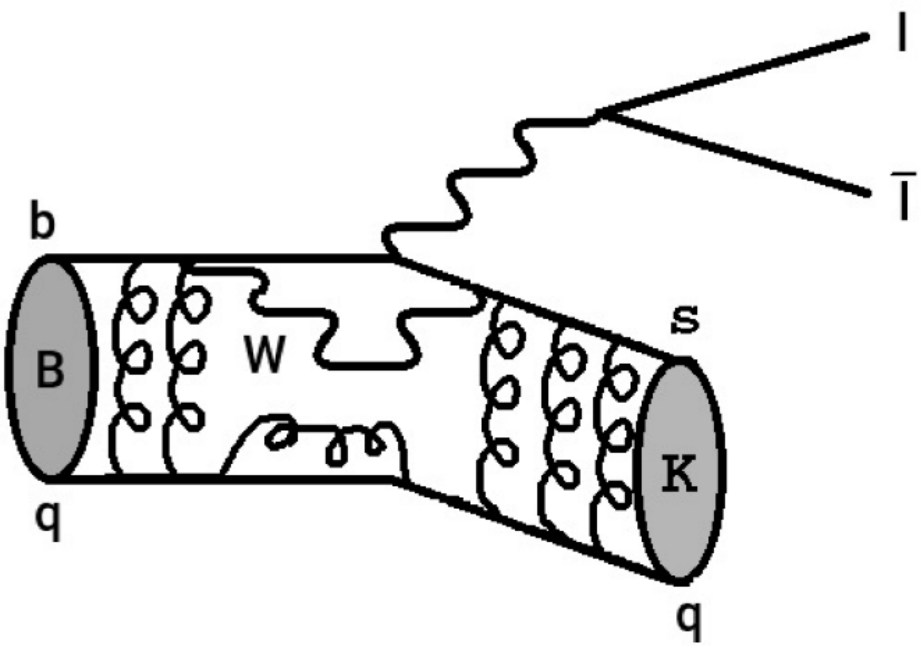
$$\mathcal{R}(J/\psi) = 0.71 \pm 0.17(\mathrm{stat}) \pm 0.18(\mathrm{syst})$$

- LHCb quote $R_{SM}(J/\psi) = 0.25 - 0.28$ which is 2σ below measurement
- ~100% disagreement on SM prediction in literature
- Interesting but not clear – keep your eyes open
- First evidence ($> 3\sigma$) for $B_c \to J/\psi\tau\nu$

ArXiv:1711.05623 [hep-ex]

What is $R(K^{(*)})$?

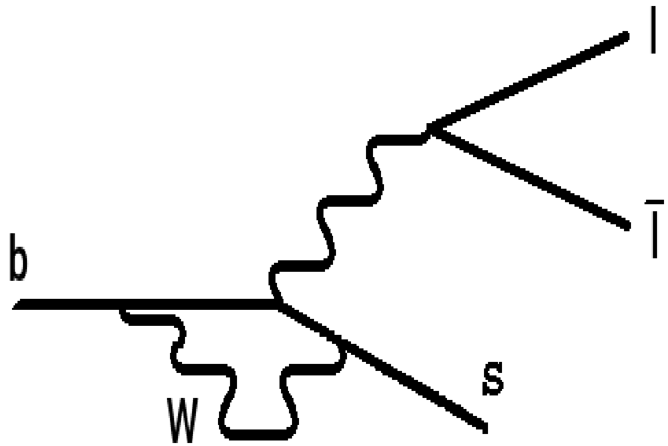
- $R(K^{(*)}) \equiv \frac{\text{"}BR(B \to K^{(*)}\mu^+\mu^-)\text{"}}{BR(B \to K^{(*)}e^+e^-)}$



What is $R(K^{(*)})$?

- $R(K^{(*)}) \equiv \frac{\text{"} BR(B \to K^{(*)} \mu^+\mu^-) \text{"}}{BR(B \to K^{(*)} e^+e^-)}$

- At the quark level: $b \to s\ell^+\ell^-$



- SM: One loop process (Flavor changing neutral current)

The SM prediction

- Correct definition includes kinematical range

$$R_{K^{(*)}}[q^2_{min}, q^2_{max}] \equiv \frac{\int_{q^2_{min}}^{q^2_{max}} dq^2\, d\Gamma(B \to K^{(*)}\, \mu^+\mu^-)/dq^2}{\int_{q^2_{min}}^{q^2_{max}} dq^2\, d\Gamma(B \to K^{(*)}\, e^+e^-)/dq^2}$$

- For $q^2_{min} \gg m^2_\ell$ we expect

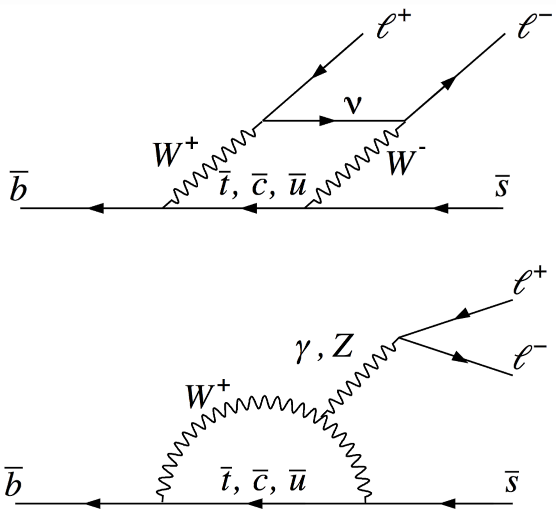
$$R_K = R_{K^*} = 1$$

Anatomy of $R(K^{(*)})$

- Integrate out heavy d.o.f. - Effective Hamiltonian

  - Penguins and Boxes:

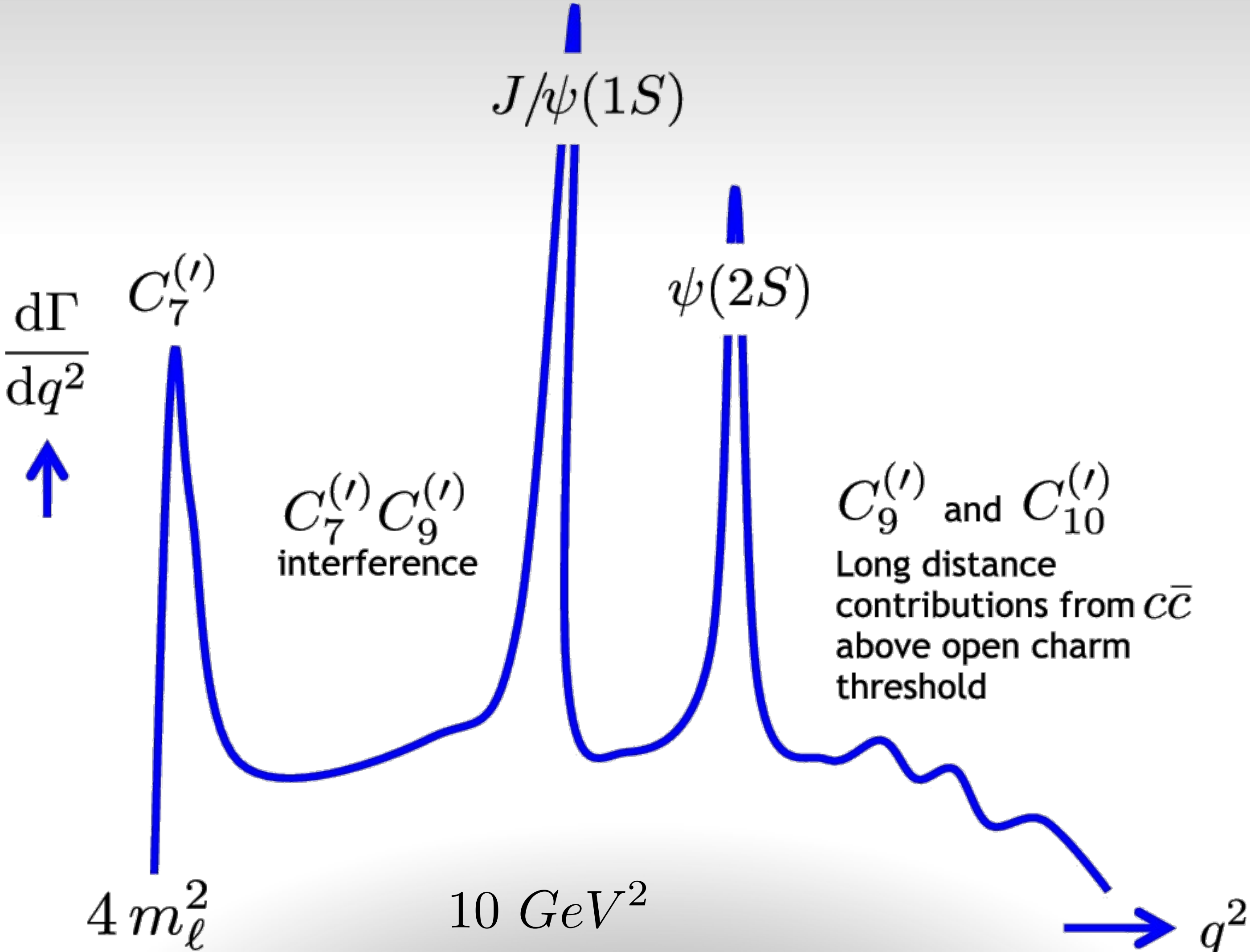
    $$\mathcal{O}_9^\ell \propto (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell)$$
    $$\mathcal{O}_{10}{}^\ell \propto (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$



  - Dipole operator

    $$\mathcal{O}_7 \propto (\bar{s}\sigma^{\mu\nu} b) F_{\mu\nu}$$

Anatomy of $R(K^*)$



Anatomy of $R(K^{(*)})$

- Within the SM at the scale m_b accidentally $C_9^{SM} \simeq -C_{10}^{SM}$

$$\mathcal{O}_{SM} \sim (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \ell)$$

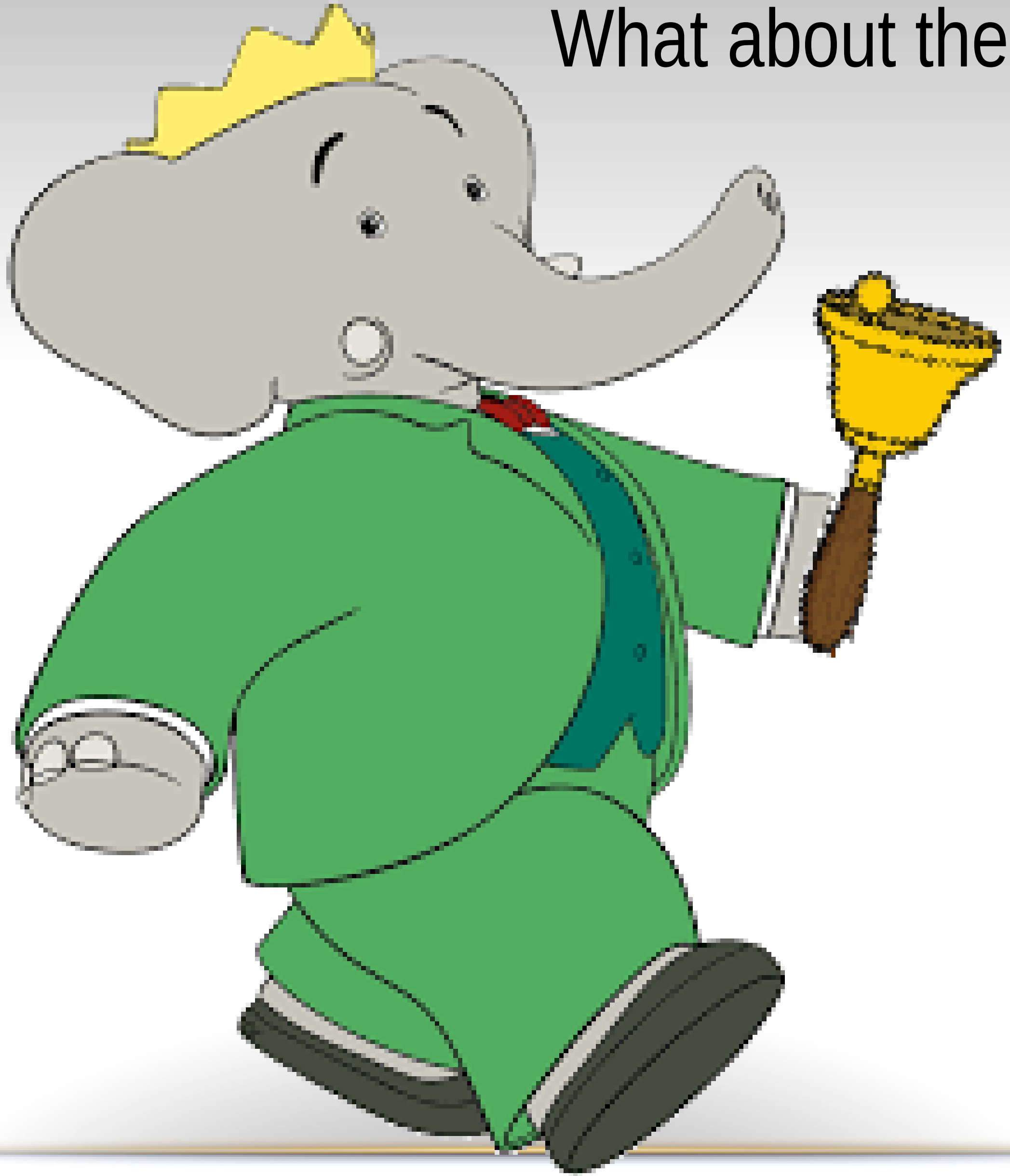
- At low q^2
  - $R(K^*)$ - Dominated by the photon pole
  - $R(K)$ - No photon pole
- At high q^2 dominated by the J/ψ resonance
- In between $R_K^{SM} = R_{K^*}^{SM} = 1$

Uncertainties

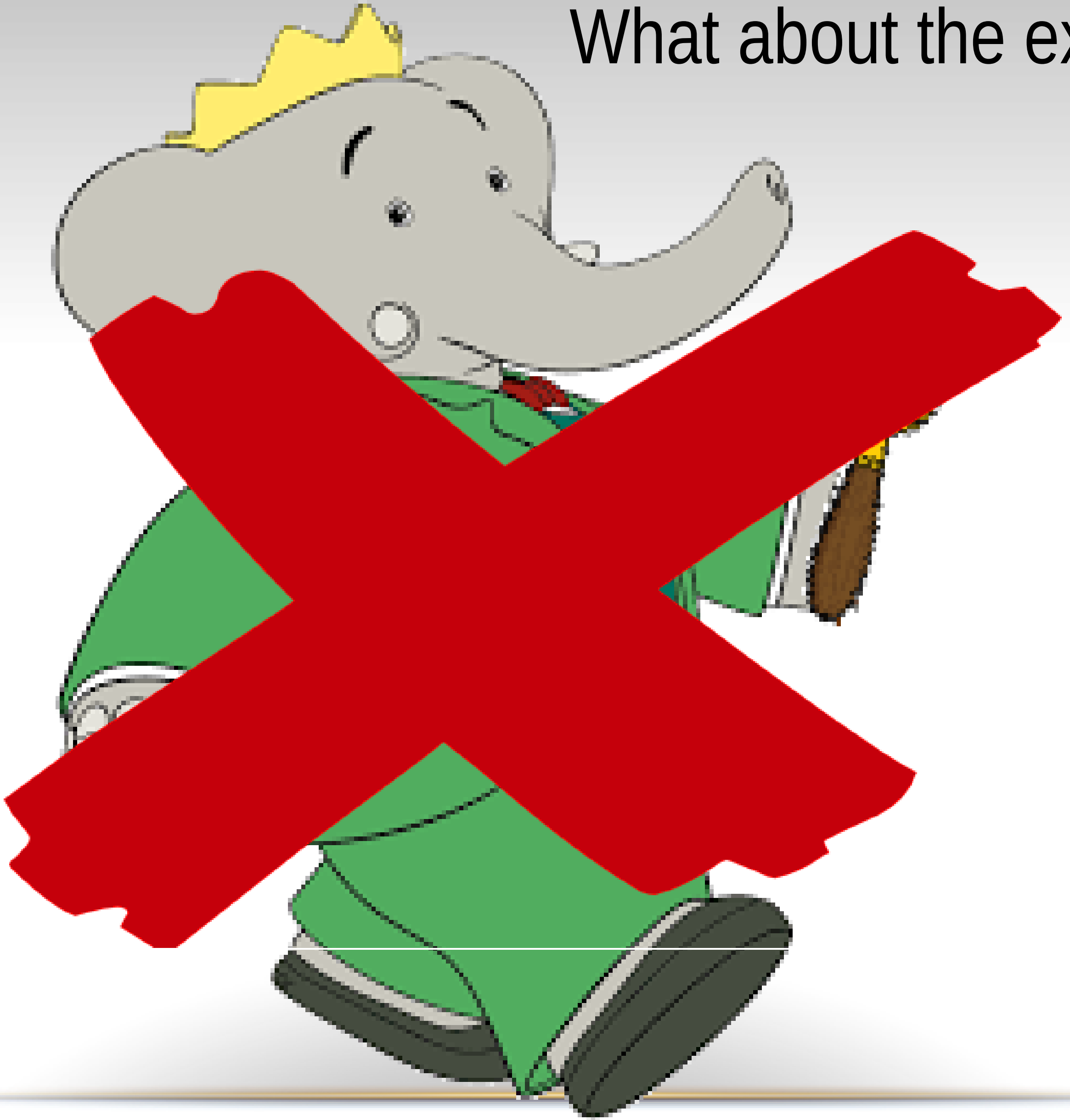
- Bordone, Isidori, Pattori (1605.07633)
  - Perturbative and non-perturbative QCD cancel in the ratio
  - Leading QED corrections are $(\alpha/\pi) log^2 (m_B/m_\ell)$
  - High q^2 but below J/ψ

    $$\mathrm{R}^{SM}(K) = R^{SM}(K^*) = 1 \pm 0.01_{QED}$$
  - Low q^2
    - No perfect cancellation ⇨ Form-factors uncertainties
    - Larger and subtle QED uncertainties

What about the experiment?



What about the experiment?



Experimentalists **really** like ratios!

- Only measured by LHCb

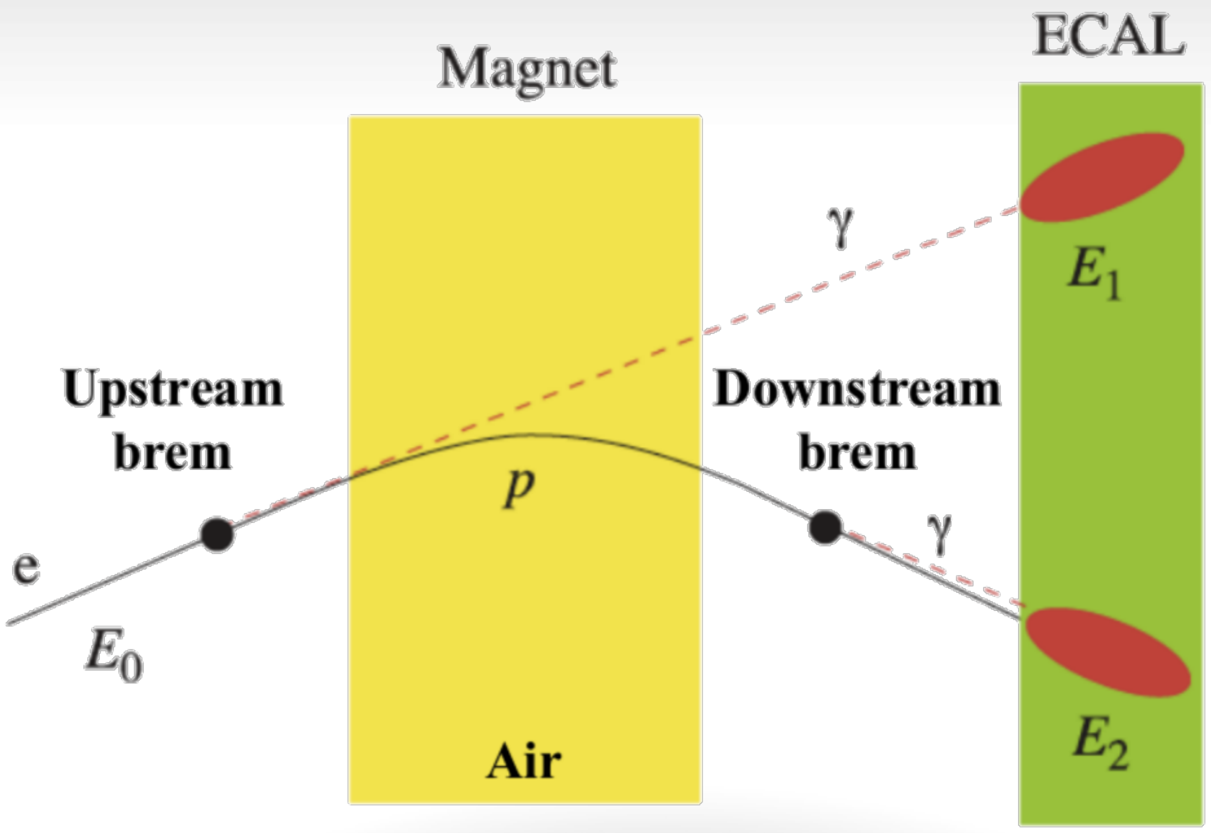
- Electrons and muons do not look the same

- Electrons are difficult for LHCb

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}J/\psi(\to \mu\mu))} \Big/ \frac{BR(B \to K^{(*)}ee)}{BR(B \to K^{(*)}J/\psi(\to ee))}$$

- J/ψ is known to be lepton flavor universal to the relevant accuracy

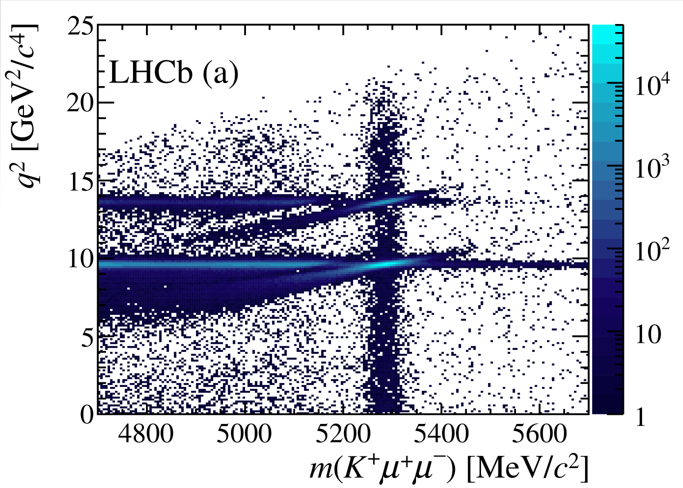
Electrons and Bremsstrahlung

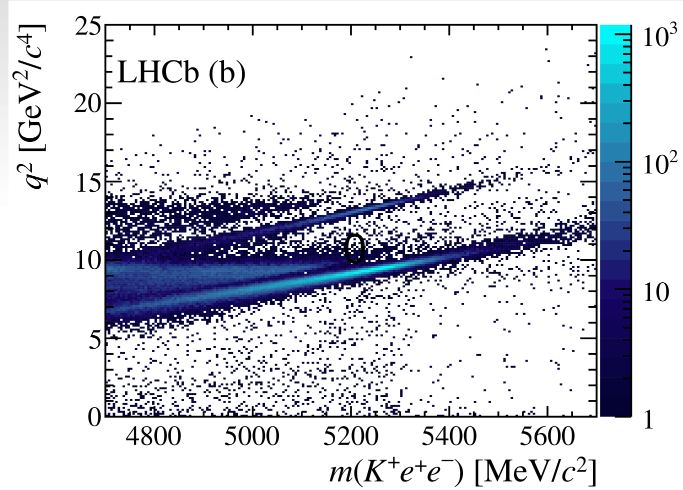


Simone Bifani, Cern seminar (18.04.17)

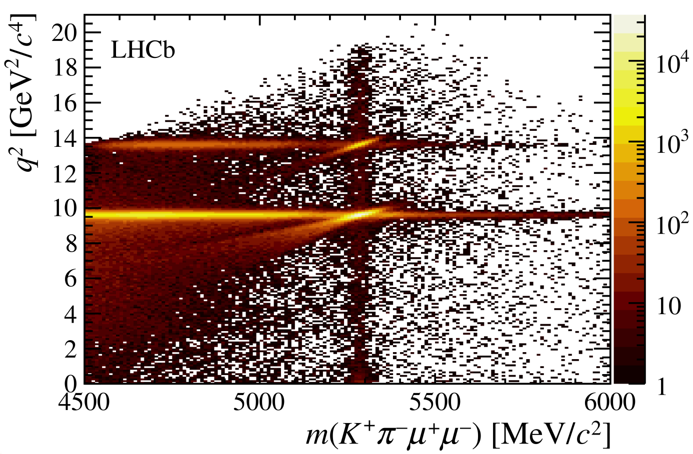
The data samples

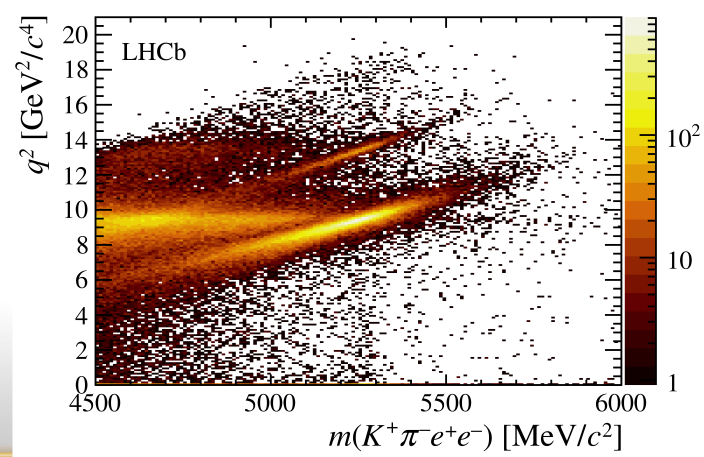
- 1406.6482





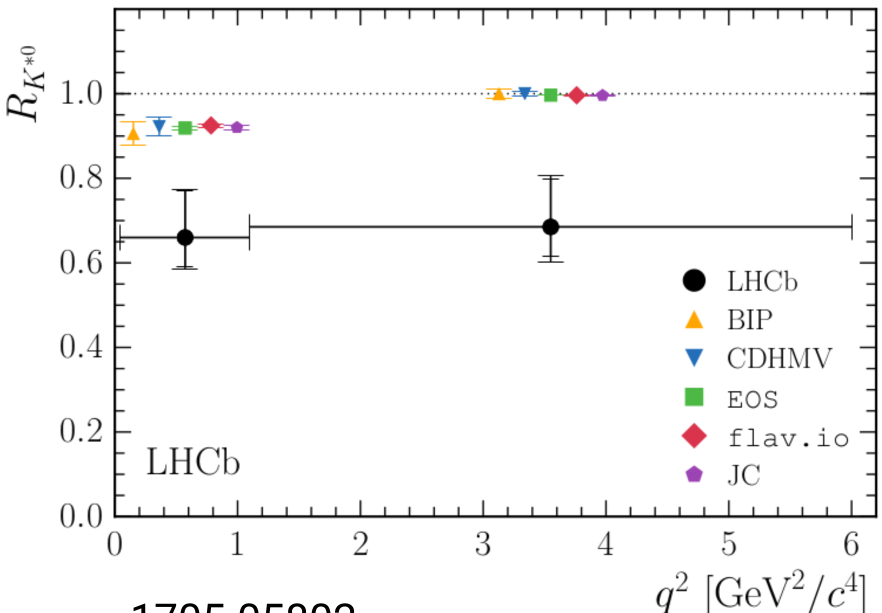
- 1705.05802



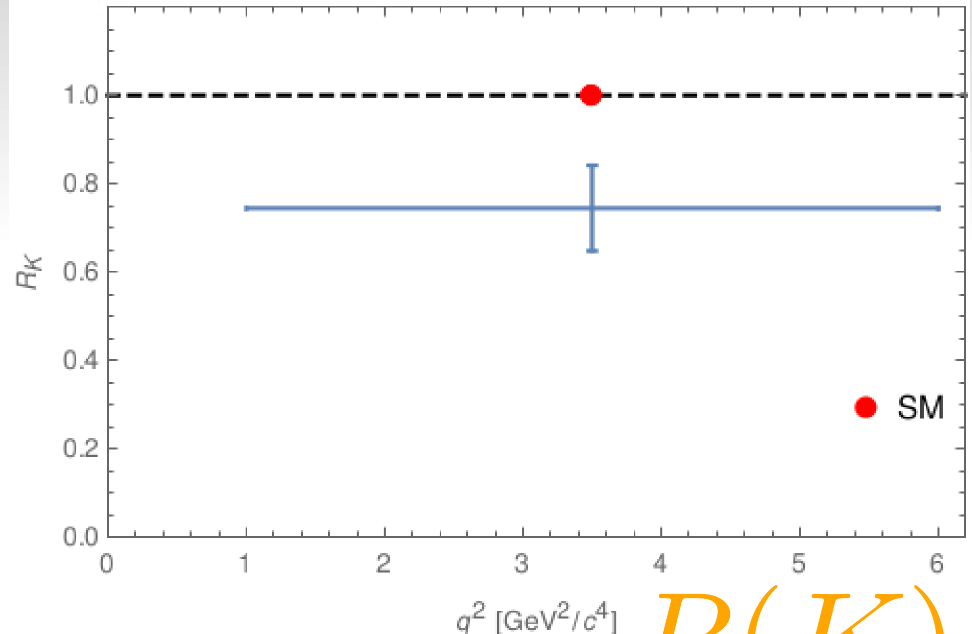


Results !

$R(K^*)$



1705.05802



$R(K)$

My plot for 1406.6482 result

Results

- $R_K[1\,GeV^2, 6\,GeV^2] = 0.75 \pm 0.10$

  $R_{K^*}[1.1\,GeV^2, 6\,GeV^2] = 0.69 \pm 0.12$

  $R_{K^*}[0.045\,GeV^2, 1.1\,GeV^2] = 0.66 \pm 0.11$
- SM prediction for the low bin $R^{SM}_{K^*,low} \simeq 0.91$
- Each measurement deviates by $\sim 2.1 - 2.6\sigma$ from SM prediction
- Low bin is confusing $(4m_\mu^2 \sim 0.045\,GeV^2)$. Hard to violate the photon universality
- Threshold effects are challenging both theoretically and experimentally

A word on New physics

- If we just re-scale the SM operator the effective Hamiltonian is

$$\mathcal{H} = \left(\frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} V_{tb} V_{ts}^* + C_{NP} \right) \mathcal{O}_{LL}$$

- Interfere with SM: 30% reduction means $C_{NP} \sim 15\% \, C_{SM}$

- The scale of (tree level) new physics

$$C_{NP} \sim 1/m_{NP}^2 \Rightarrow m_{NP} \sim 30 \, TeV$$

$R(K^{(*)})$ - Summary

- $R(K^{(*)})$ is puzzling and shows $\sim 2.5\sigma$ deviation from SM prediction for each measurement
- $R(K^{*})$ at low q^2 is even more puzzling. It is preferred to measure away from threshold, *e.g.* from 0.1 GeV^2
- LHCb with 13 TeV, and Belle 2 will shed light from the experiment side
- New physics at the 30 TeV scale

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

- LHCb observed with 7.8σ significance (1703.05747)

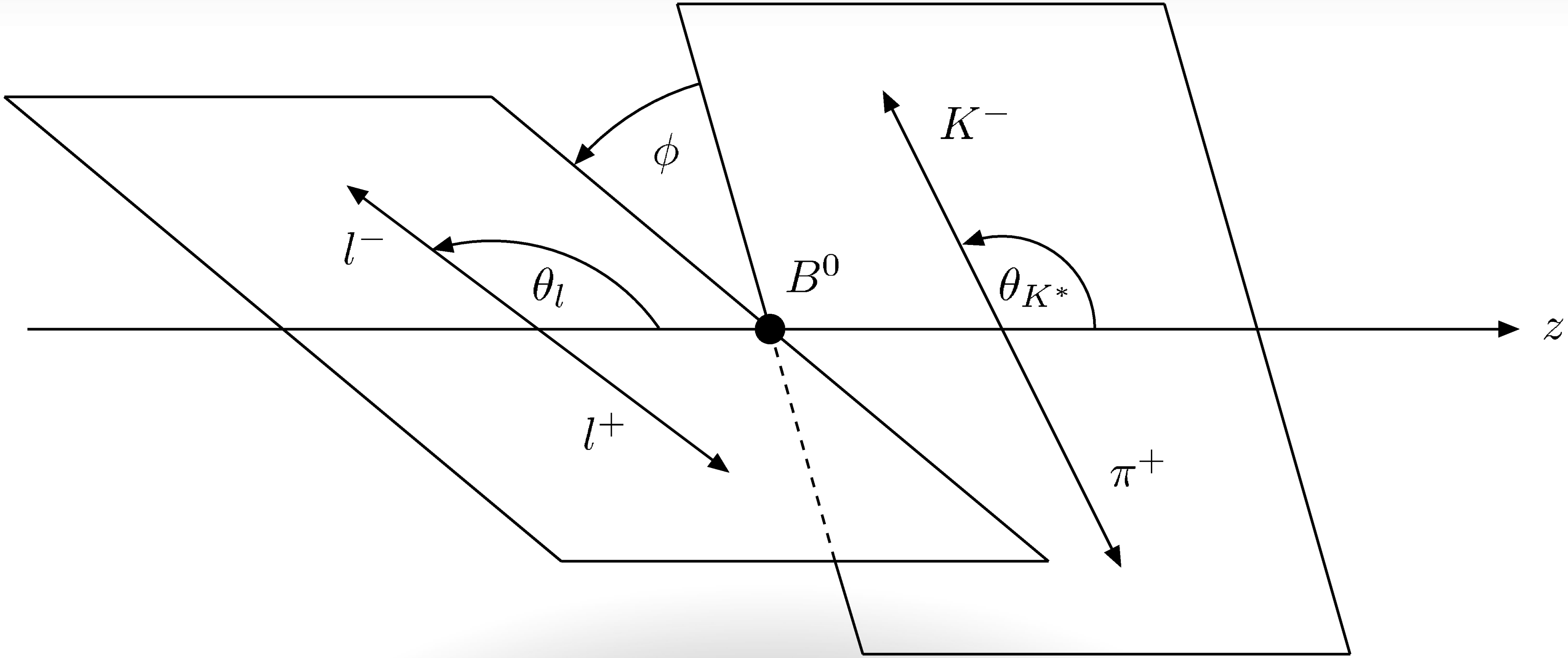
$$BR(B_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

- Fleischer, Jaarsma, Tetlalmatzi-Xolocotzi (1703.10160) updated

  Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser (1311.0903)

$$BR_{SM}(B_s \to \mu^+\mu^-) = (3.57 \pm 0.16) \times 10^{-9}$$

$B \to K^*(\to K\pi)\mu\mu$ angular distribution



Kruger, Matias (hep-ph/0502060)

$B \to K^*(\to K\pi)\mu\mu$ angular distribution

$$\frac{d^{(4)}\Gamma(B \to K^*(\to K\pi)\mu\mu)}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\,\pi}$$

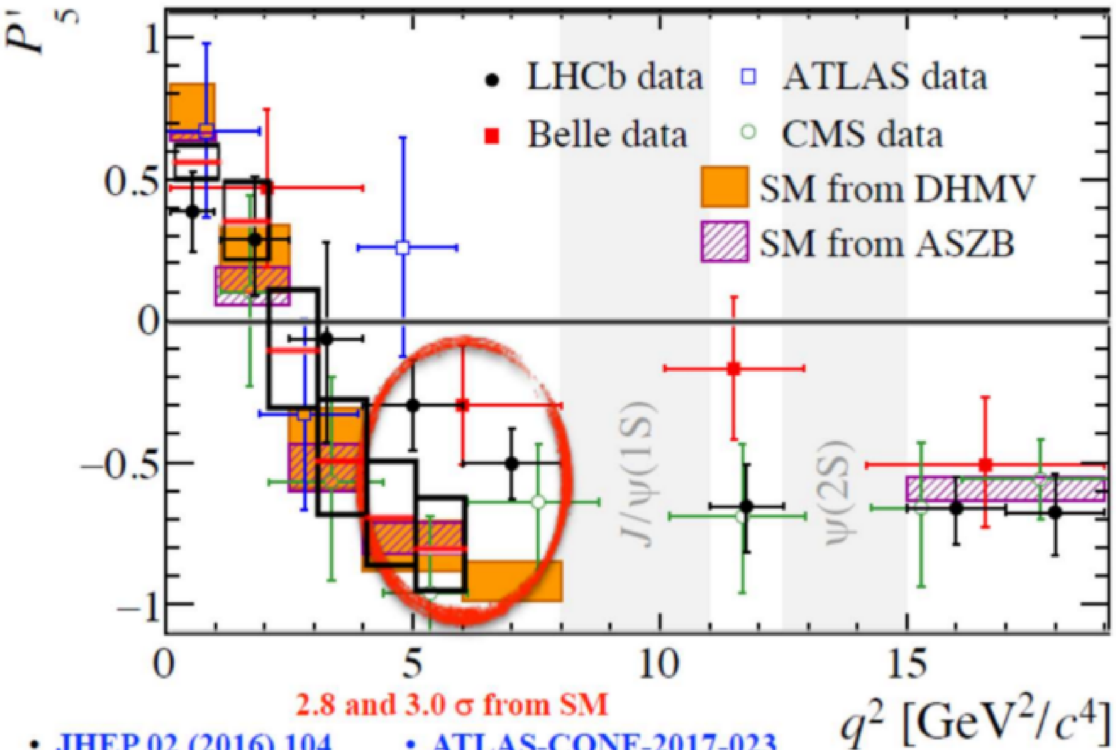
$$\times \quad \Big(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k + (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l$$
$$+ I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi$$
$$+ I_5 \sin 2\theta_k \sin\theta_l \cos\phi + (I_6^s \sin^2\theta_k + I_6^c \cos^2\theta_K)\cos\theta_l$$
$$+ I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi$$
$$+ I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi \Big).$$

Jager, Camalich, (1212.2263)

$B \to K^*(\to K\pi)\mu\mu$ angular distribution

- The I_i are functions of q^2 only
- $I_6 \propto$ forward-backward (FB) asymmetry
- @ $\mathrm{I}_6(q_0^2) = 0\,,\ \ I_6$ is considered clean
- $I_5(q_0^2) \sim I_6(q_0^2) + \text{HQET suppressed} + \text{1-term}$
- $P_5' \sim \dfrac{I_5}{\sqrt{-I_2^s I_2^c}}$ some debate in the community about its cleanness

P5'



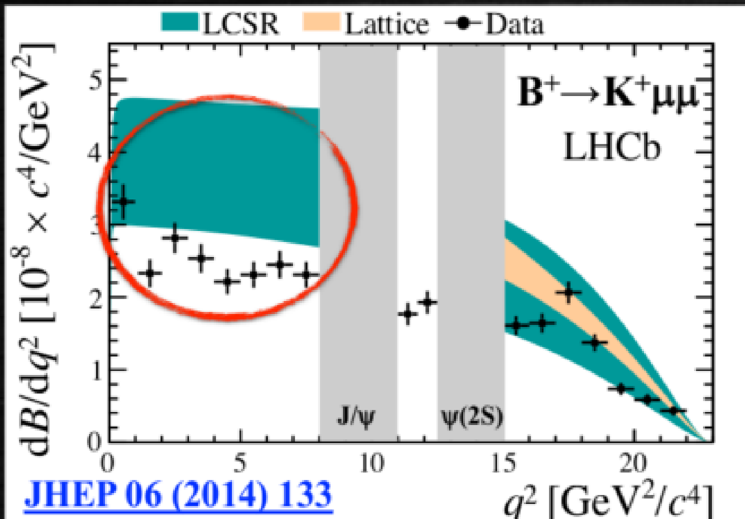
- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

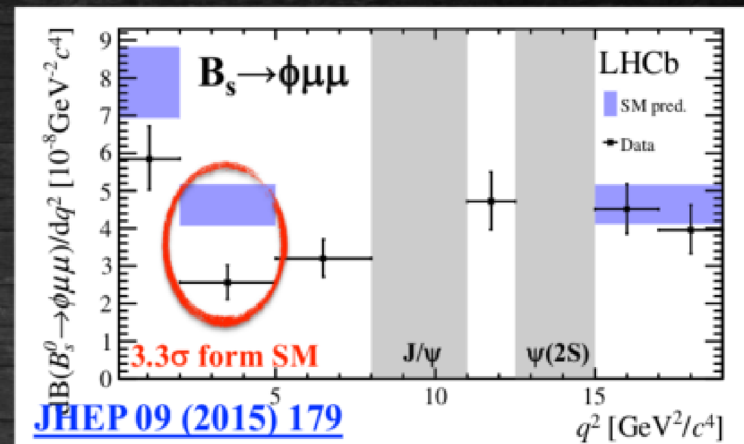
Simone Bifani, seminar at CERN (overlaid predictions from SJ&Martin Camalich 2014)

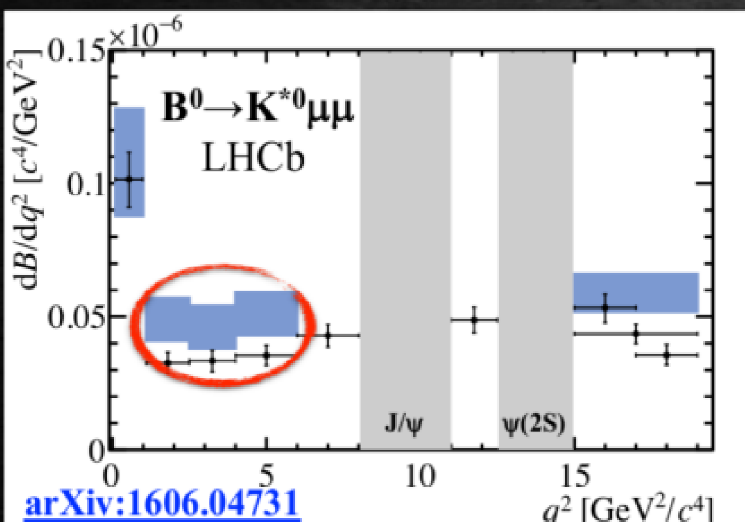
Modest discrepancy around 4-6 GeV, consistent with reduced C9

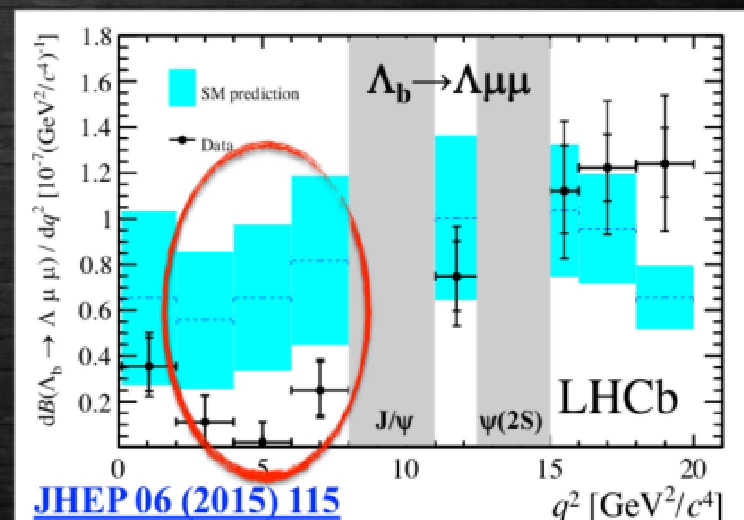
Differential Branching Fractions

› Results **consistently lower than SM predictions**









V_{cb} – inclusive or exclusive?

- Inclusive (PDG)

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$$

- Exclusive – two methods:

BGL (Boyd, Grinstein, Lebed)	CLN (Caprini, Lellouch, Neubert)
BGS (1703.06124) $|V_{cb}| = (41.7^{+2.0}_{-2.1}) \times 10^{-3}$	Belle (1702.01521) $|V_{cb}| = (38.2 \pm 1.5) \times 10^{-3}$
GK (1703.08170) $|V_{cb}| = (41.9^{+2.0}_{-1.9}) \times 10^{-3}$	BLPR (1703.05330) $|V_{cb}| = (38.5 \pm 1.1) \times 10^{-3}$

- See also BLPR (1708.07134)

B mesons are PUZZLING

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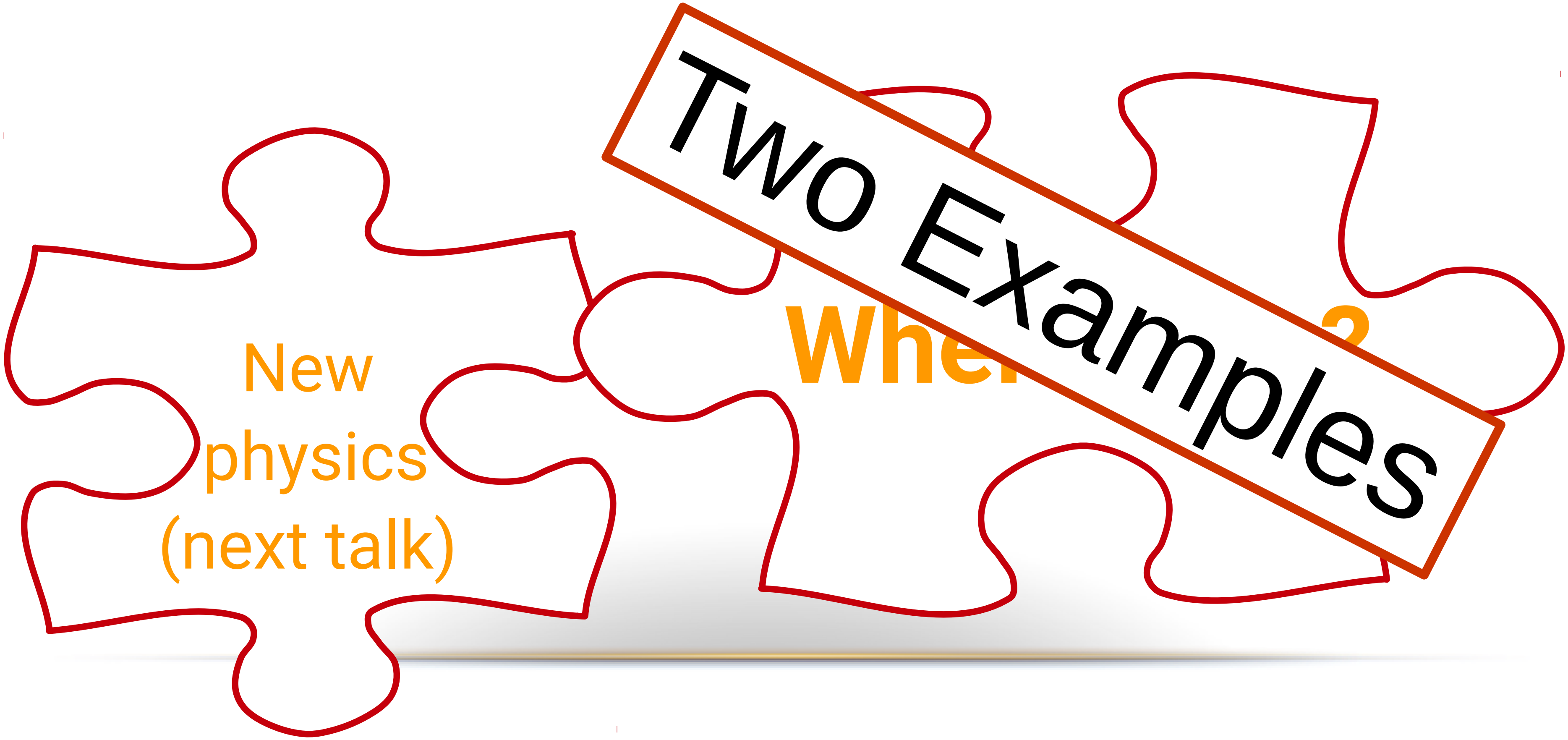


Two things to do

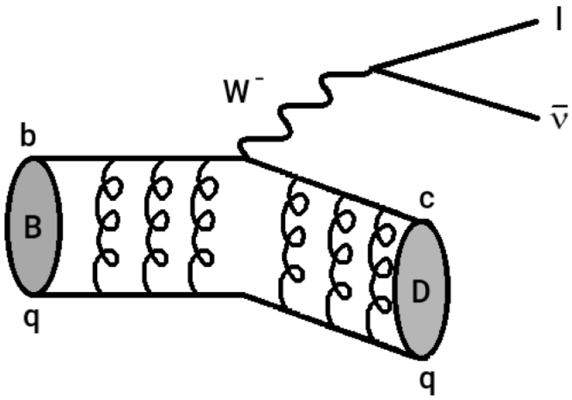
with Belle two

Υ and ψ decays as probes of solutions to the $R(D^{(*)})$ puzzle

DA, Aielet Efrati (WIS), Yuval Grossman (Cornell), Yossi Nir (WIS)

JHEP 1706 (2017) 019, Arxiv: 1702.07356

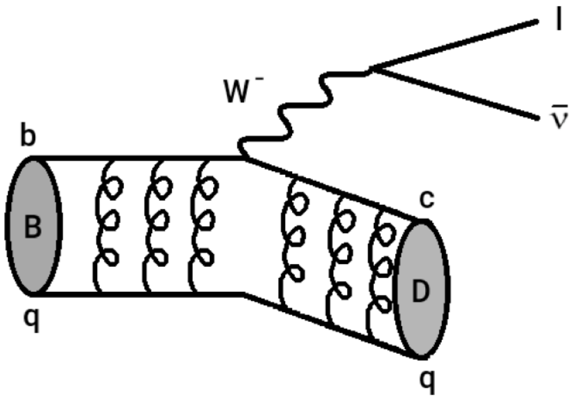
Υ and ψ decays as probes of solutions to the $R(D^{(*)})$ puzzle



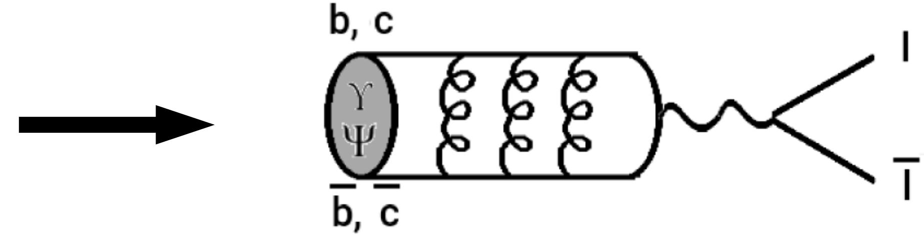
Charge current (CC)

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

Υ and ψ decays as probes of solutions to the $R(D^{(*)})$ puzzle



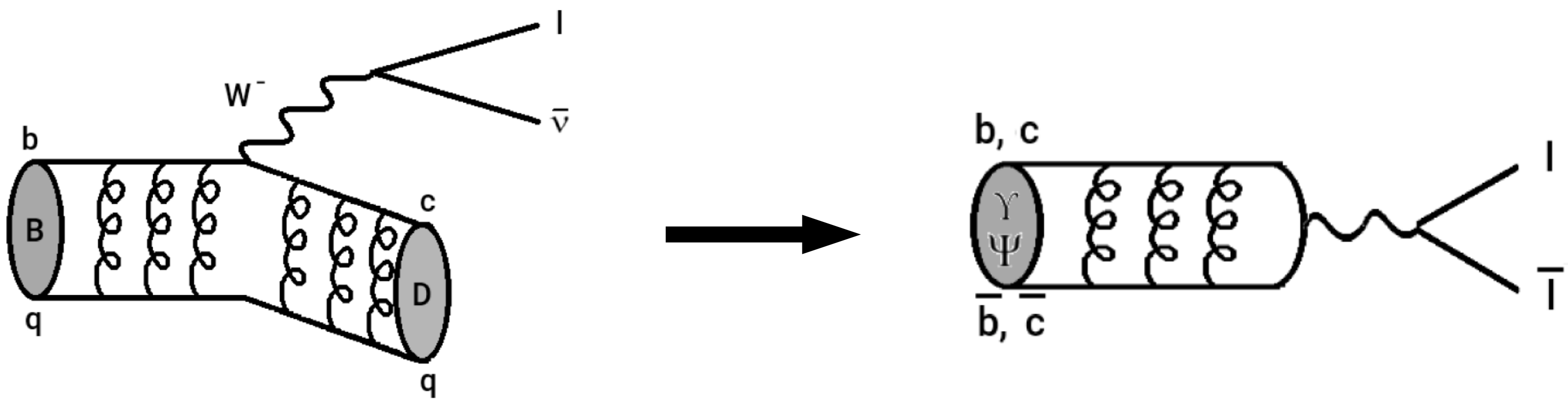
Charge current (CC)



Neutral current (NC)

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

Υ and ψ decays as probes of solutions to the $R(D^{(*)})$ puzzle



Charge current (CC) — Neutral current (NC)

ν is part of a doublet → if we have ν we have τ

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

New observables - $R(\Upsilon)$ & $R(\psi)$

- We suggest to look for lepton non universality of Υ and ψ decays

$$R^V_{\tau/\ell} \equiv \frac{\Gamma(V \to \tau^+\tau^-)}{\Gamma(V \to \ell^+\ell^-)}, \qquad (V = \Upsilon, \psi(2s);\ \ell = e, \mu)$$

- ✗ $\Upsilon = b\bar{b}$ bound state
- ✗ $\psi = c\bar{c}$ bound state

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

These observables are extremely clean!

$R^V_{\tau/\ell}$:

$V(nS)$	SM prediction	Exp. value $\pm\sigma_{\rm stat} \pm \sigma_{\rm syst}$
$\Upsilon(1S)$	$0.9924 \pm \mathcal{O}(10^{-5})$	$1.005 \pm 0.013 \pm 0.022$
$\Upsilon(2S)$	$0.9940 \pm \mathcal{O}(10^{-5})$	$1.04 \pm 0.04 \pm 0.05$
$\Upsilon(3S)$	$0.9948 \pm \mathcal{O}(10^{-5})$	$1.05 \pm 0.08 \pm 0.05$
$\psi(2S)$	$0.390 \pm \mathcal{O}(10^{-4})$	0.39 ± 0.05

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

One things to do with Belle two

- Current error is $\sigma_{1S}^{BaBar} \sim 2\%$
- Running at $\Upsilon(3S)$ with $\mathcal{L} \sim 1/ab$ Belle II might reach $\sigma_{1S} \simeq 0.4\%$
- Cover most region of parameter space related to $R(D^{(*)})$
- LFU in Υ decays provide additional motivation to study $\Upsilon(3S)$ at Belle II
- Test the SM and Probe NP even if $R(D^{(*)})$ disappears

Measuring CP violation in $R(D^{(*)})$ by using D^{**}

DA, Yuval Grossman (Cornell), Abner Soffer (TAU)

Arxiv: 1805.?????

Why is it interesting to have a phase?

- $R(D^{(*)})$ is puzzling!

- NP breaks LFU at O(1)! Why shouldn't it break CP at O(1)?

- CP violation = NP. No CPV within the SM

Can we measure CP asymmetry directly?

- The most naive observable

$$\mathcal{A}_{CP} \propto |A(B \to \bar{D}^{(*)}\bar{\tau}\nu)|^2 - |A(\bar{B} \to D^{(*)}\tau\bar{\nu})|^2$$

- Checklist:
  - ➔ Two amplitudes
  - ➔ Weak phase
  - ➔ Strong phase

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- Checklist:
  - → Two amplitudes ✓
  - → Weak phase ✓
  - → Strong phase ✗

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- Checklist:
  - ➔ Two amplitudes ✔
  - ➔ Weak phase ✔
  - ➔ Strong phase ✘

How can we get a strong phase?

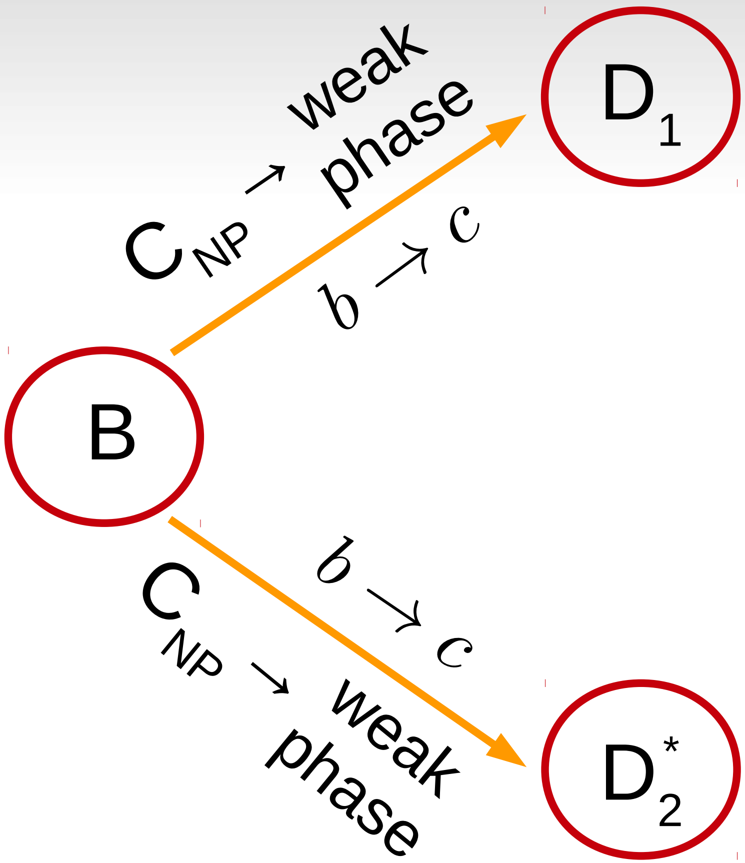
You get strong phase from

INTERFERENCE

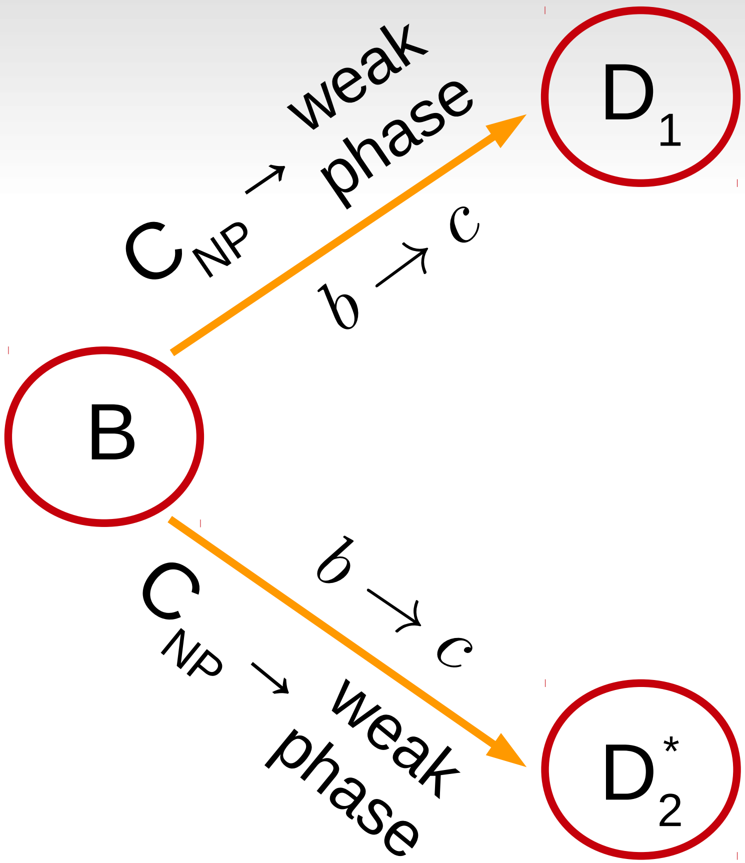
How does it work?

B

How does it work?



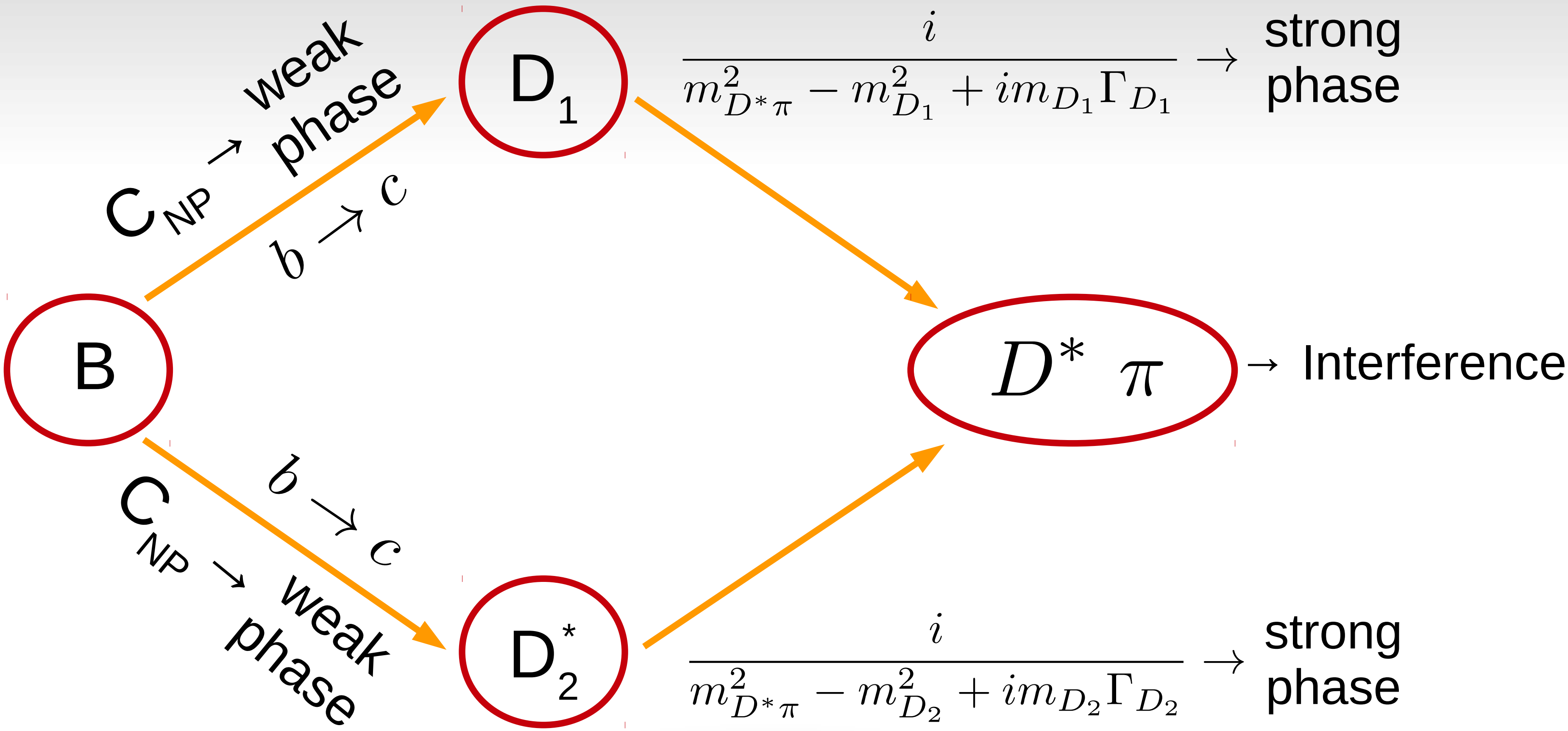
How does it work?



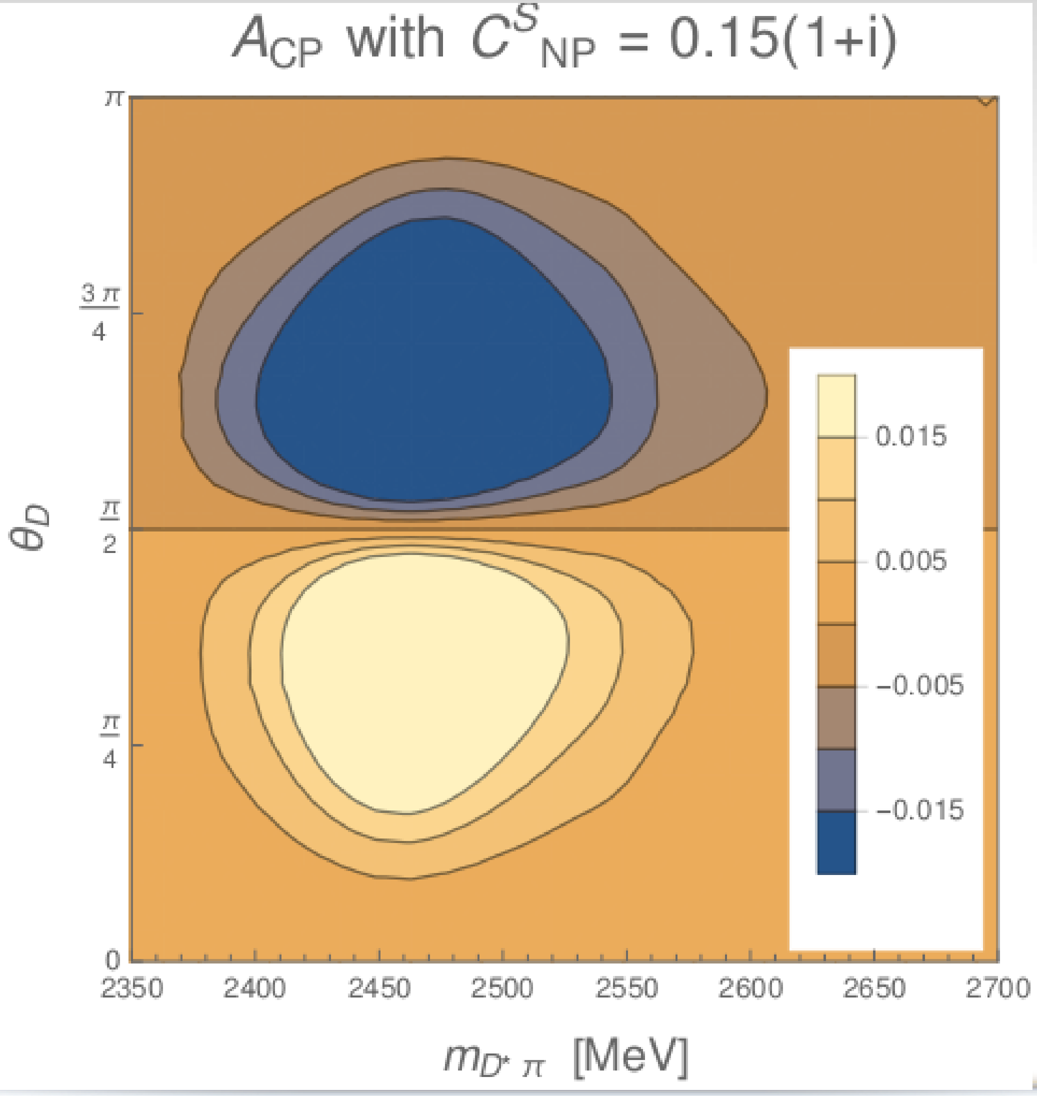
$$\frac{i}{m_{D^*\pi}^2 - m_{D_1}^2 + i m_{D_1}\Gamma_{D_1}} \rightarrow \text{strong phase}$$

$$\frac{i}{m_{D^*\pi}^2 - m_{D_2}^2 + i m_{D_2}\Gamma_{D_2}} \rightarrow \text{strong phase}$$

How does it work?



What do we get?



Summary

Summary

$R(D)$ $B_s \to \mu\mu$ $R(K)$

V_{cb}

P_5' $R(D^*)$ $\Lambda_b \to \Lambda\mu\mu$

$R(K^*)$

$B_s \to \phi\mu\mu$

$B \to K^*\mu\mu$

$R(J/\psi)$

$B \to K\mu\mu$

Summary

$R(D)$

no σ

$B_s \to \mu\mu$

$R(K)$

3.5σ

V_{cb}

4.1σ

P_5'

$R(D^*)$

$\Lambda_b \to \Lambda\mu\mu$

$(1-3)\sigma$

$R(K^*)$

maybe σ

$B_s \to \phi\mu\mu$

$B \to K^*\mu\mu$

2σish

0.8σ

$B \to K\mu\mu$

$R(J/\psi)$

Summary

no σ

$R(D)$

$B_s \to \mu\mu$

$R(K)$

Υ lepton non-universalities

P'_5

$(1-3)\sigma$

$R(D^*)$

$\Lambda_b \to \Lambda\mu\mu$

CPV with excited charm mesons

$B \to K^*\mu\mu$

0.8σ

$B \to K\mu\mu$

$R(J/\psi)$

2σish

Thank you!