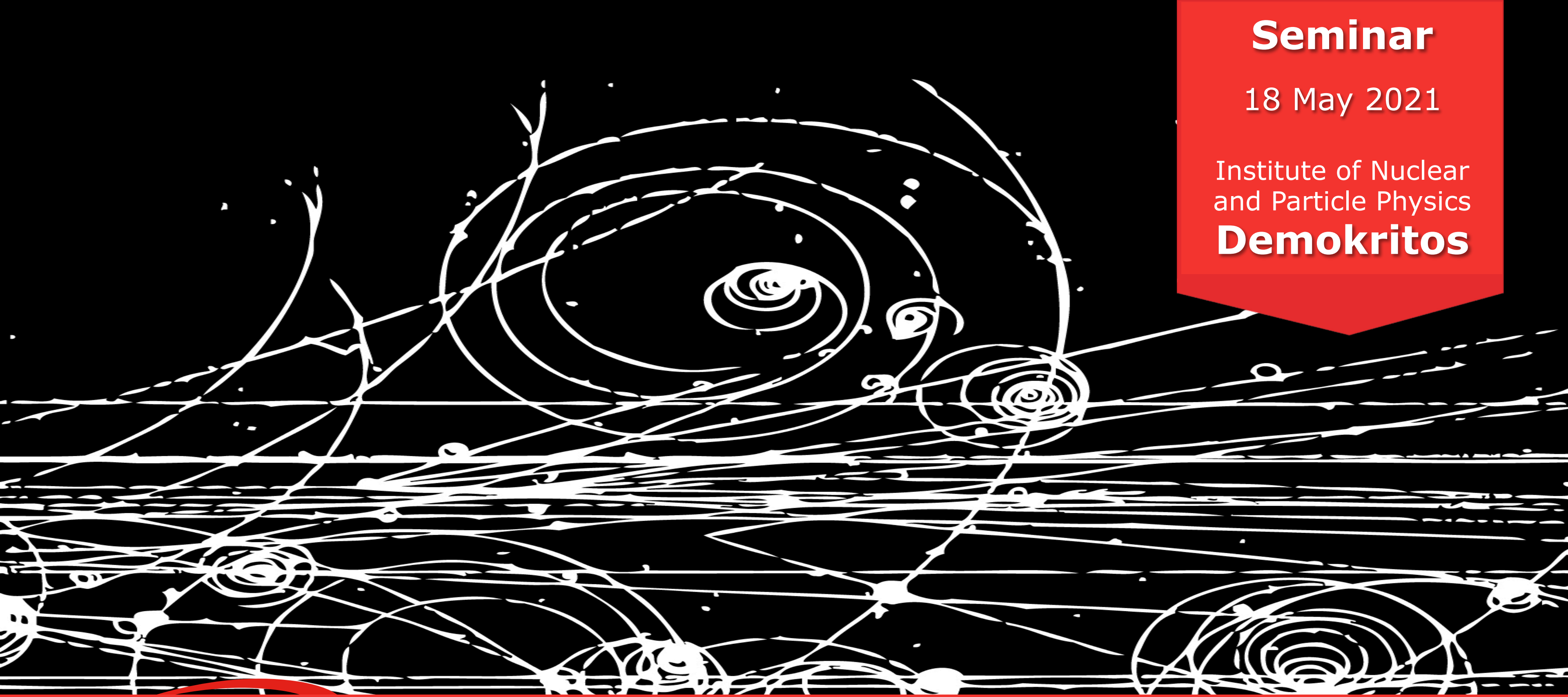


Seminar

18 May 2021

Institute of Nuclear and Particle Physics
Demokritos

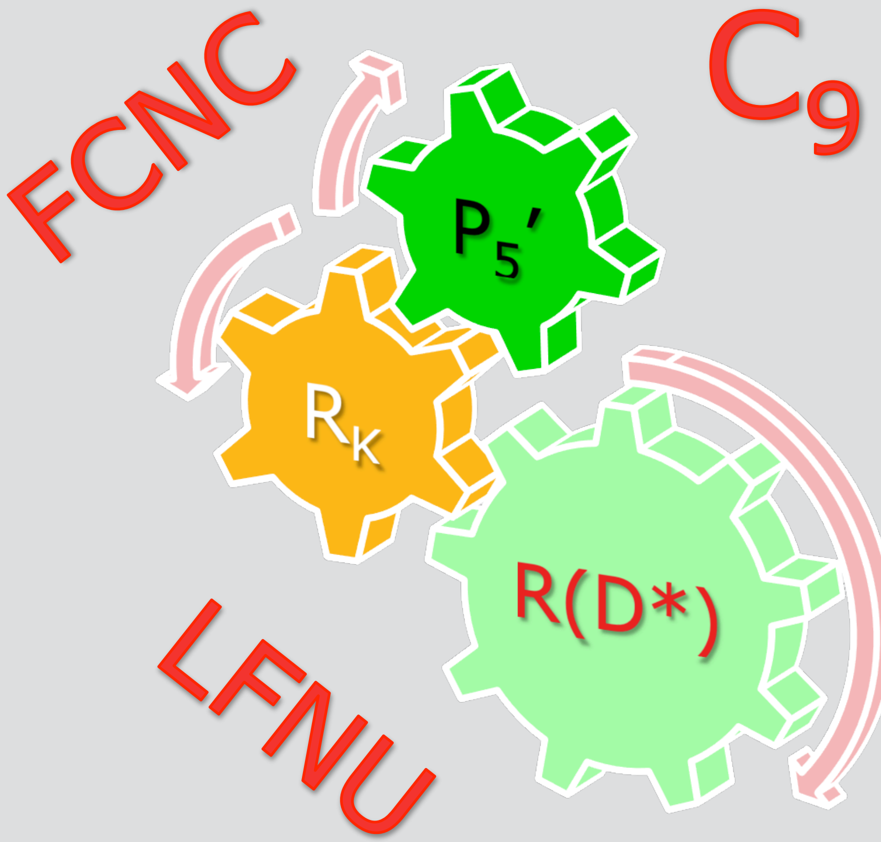
Pattern of Flavour Anomalies

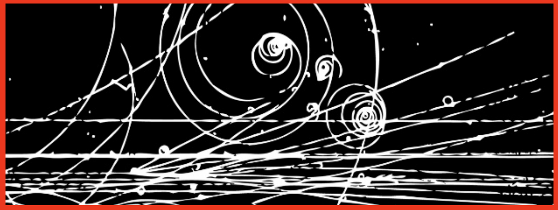
(in light of recent results from LHCb)

Niels Tuning

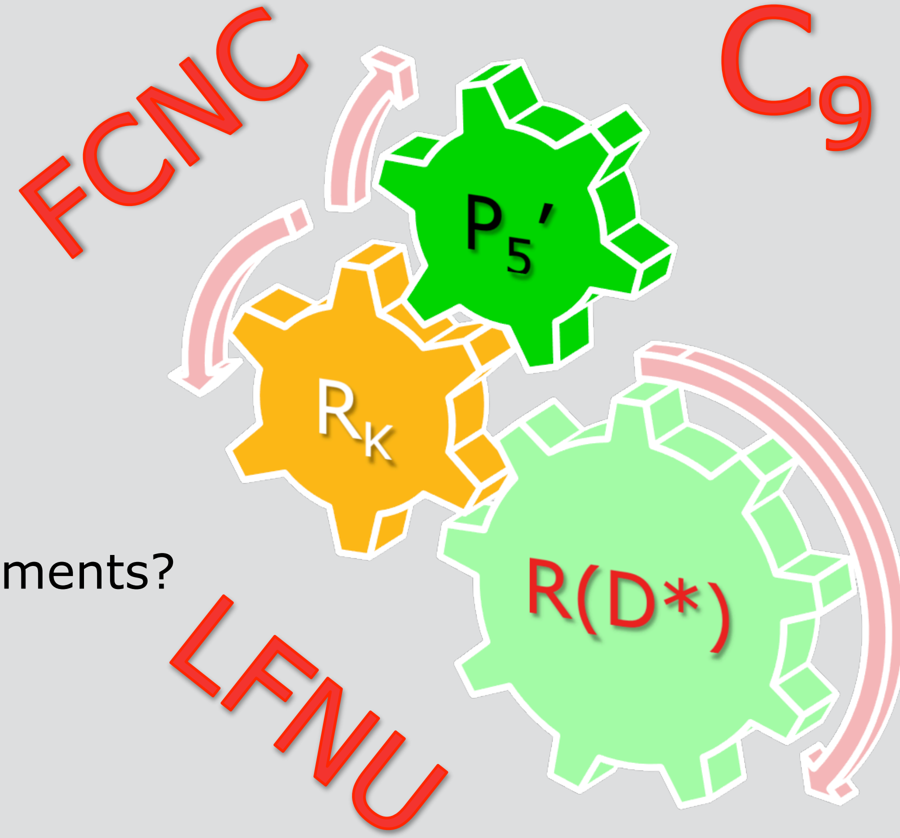

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
CERNCOURIER
VOLUME 55 NUMBER 9 NOVEMBER 2015
Tensions in the Standard Model

Outline: the jargon

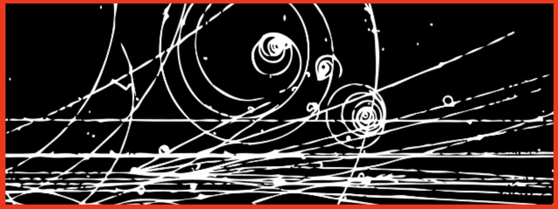




Outline



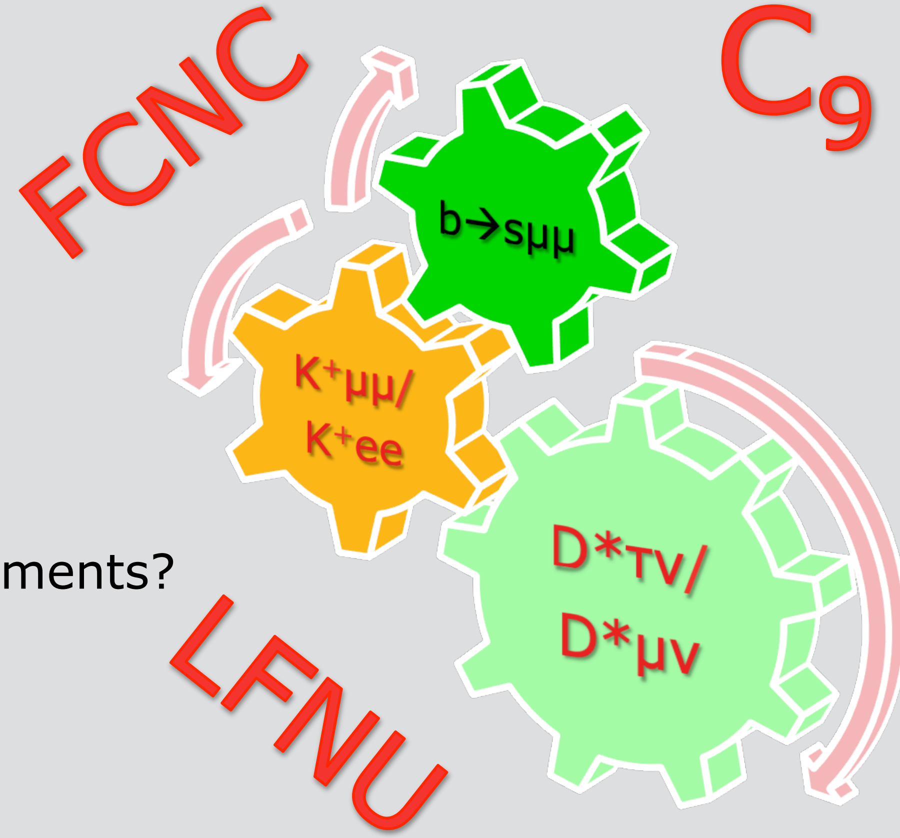
- Indirect measurements
- What are the (anomalous) measurements?
  - FCNC: b→sll
  - LFNU: b→sll and b→clν
- What are the interpretations?

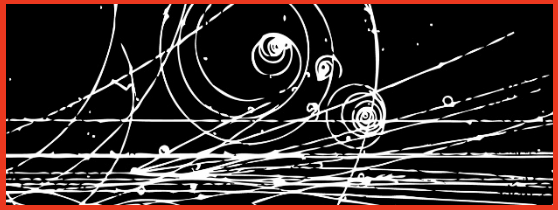


New results

Outline

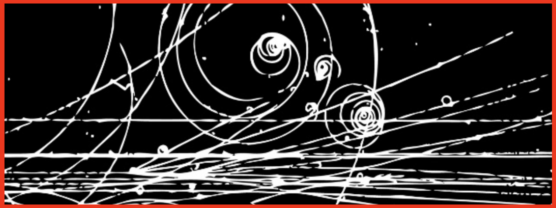
- Indirect measurements
- What are the (anomalous) measurements?
  - FCNC: b→sll
  - LFNU: b→sll and b→clv
- What are the interpretations?





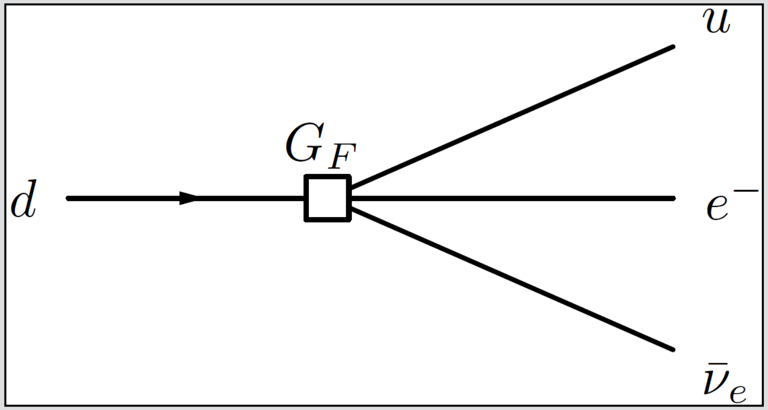
Historical perspective

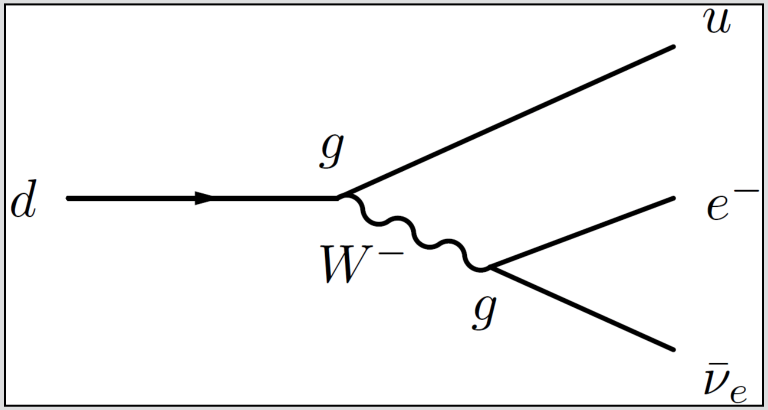
- The power of indirect measurements



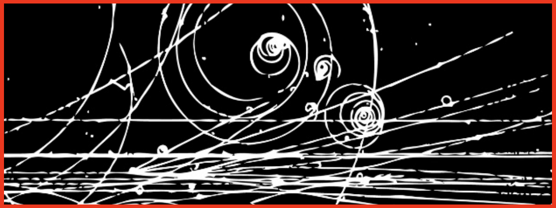
Historical perspective: W

- Radioactive decay was "discovery" of weak interaction?





$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$



Historical perspective: W

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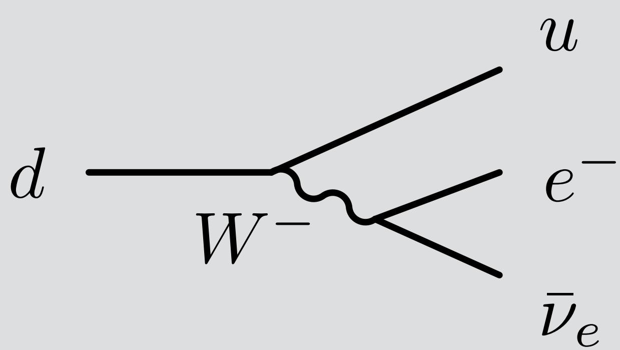
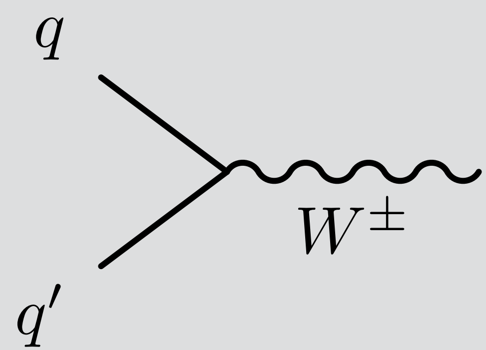




Direct

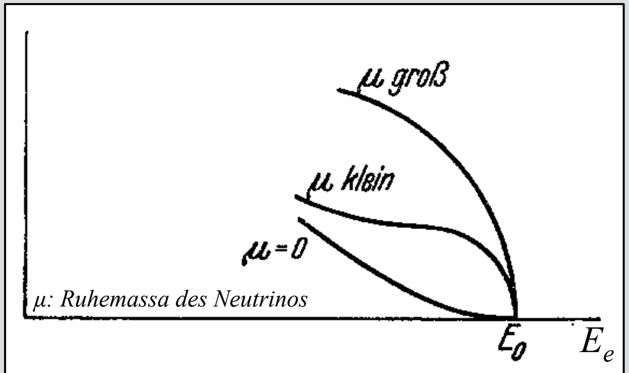
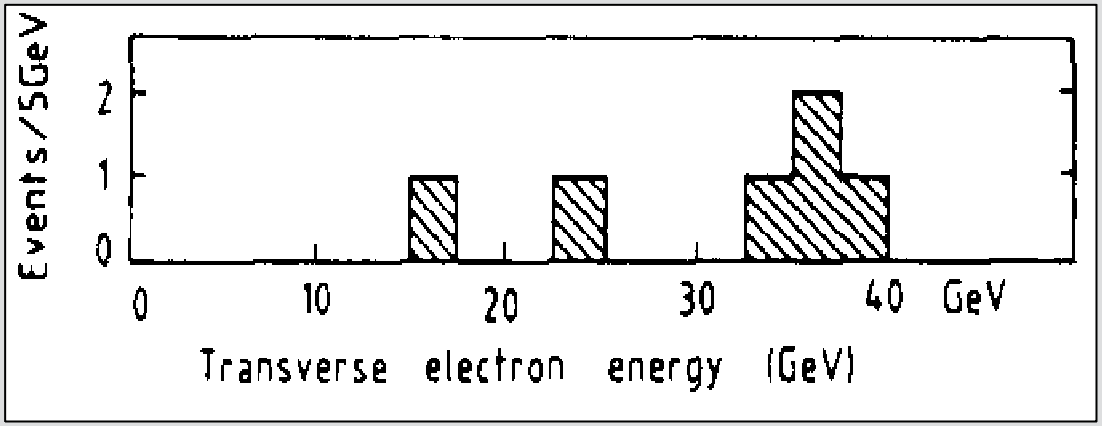
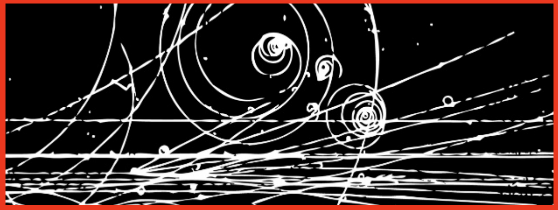


Fig. 1.

E.Fermi, Z.Phys. 88 (1934) 161



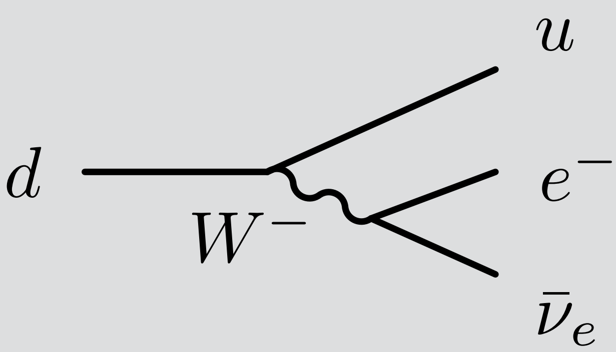
UA1 Coll., Phys.Lett. B122 (1983) 103



Historical perspective: ν

- Radioactive decay was "discovery" of neutrino?

Indirect



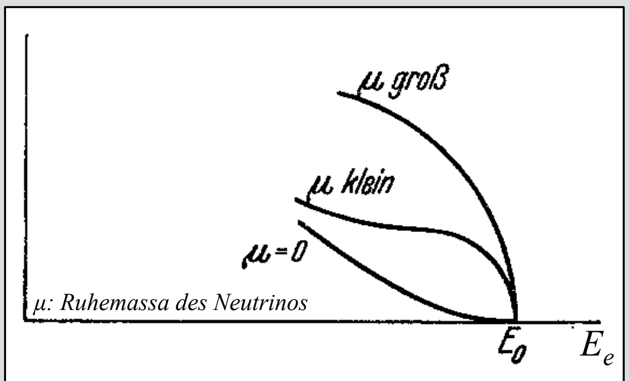
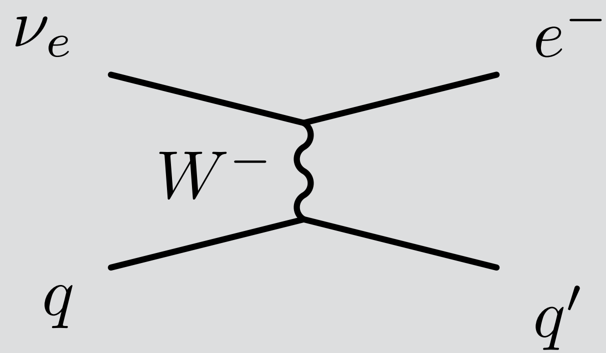
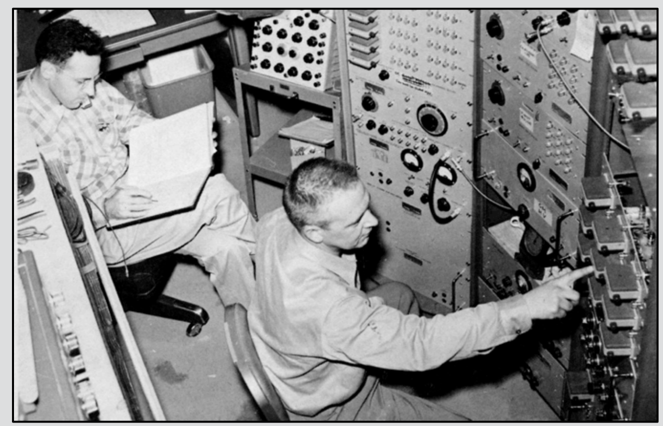


Fig. 1.

E.Fermi, Z.Phys. 88 (1934) 161

Direct



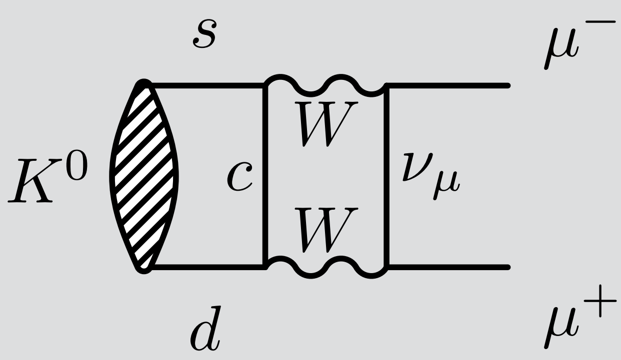


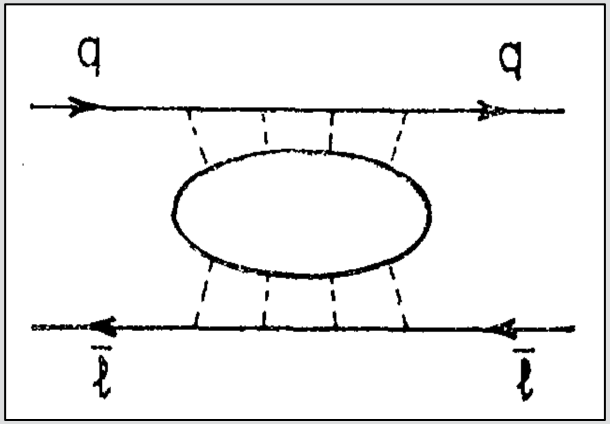
Cowan, Reines, et al., Science 124 (1956) 103-104

Historical perspective: charm

- Kaon decay was "discovery" of charm quark?

Indirect





GIM, Phys.Rev. D2 (1970) 1285

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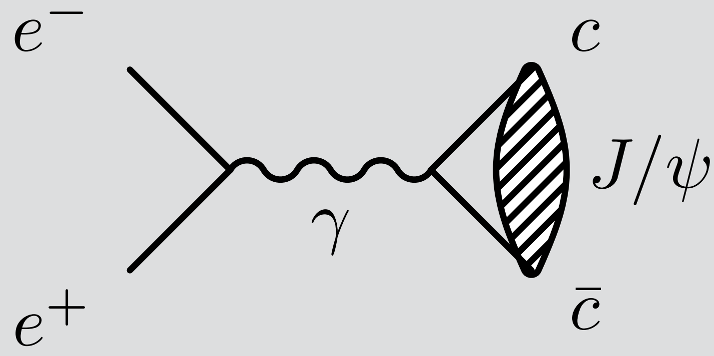
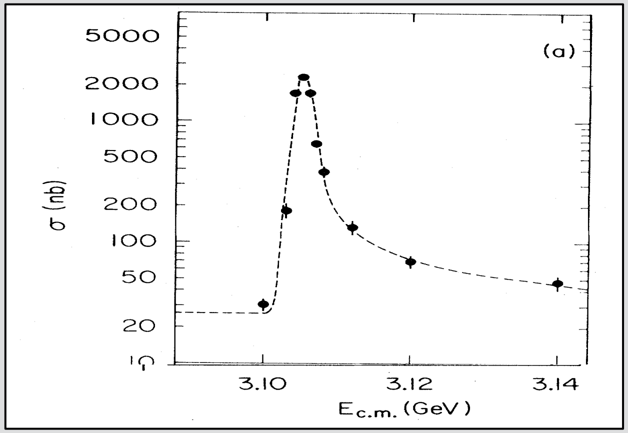
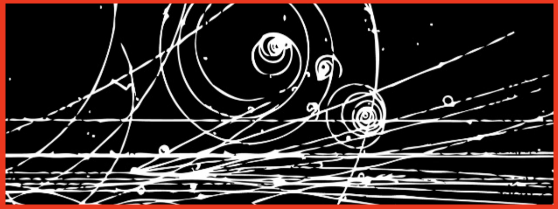




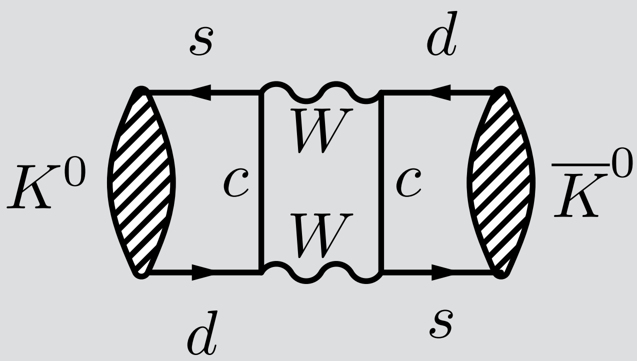
B.Richter et al, Phys.Rev.Lett. 33 (1974) 1406

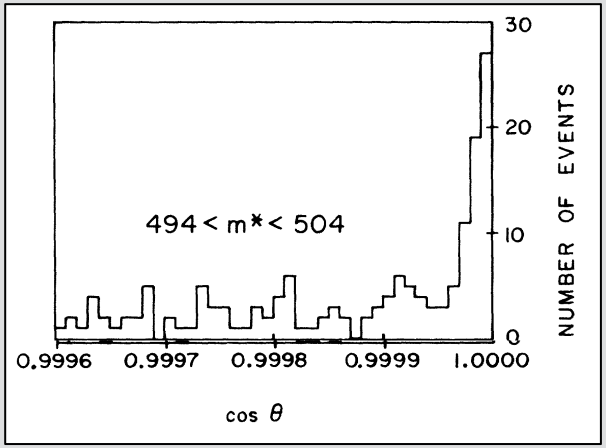


Historical perspective: bottom

- CP violation was “discovery” of 3rd generation?

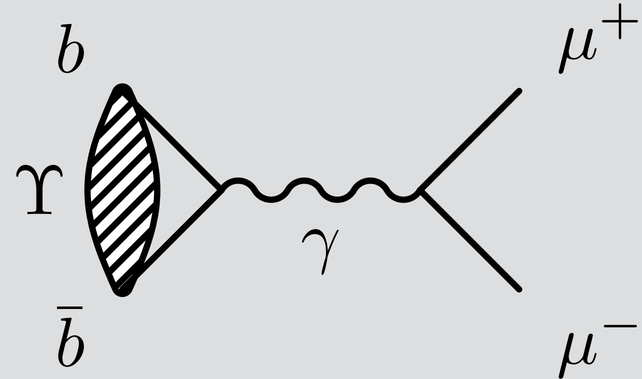
Indirect

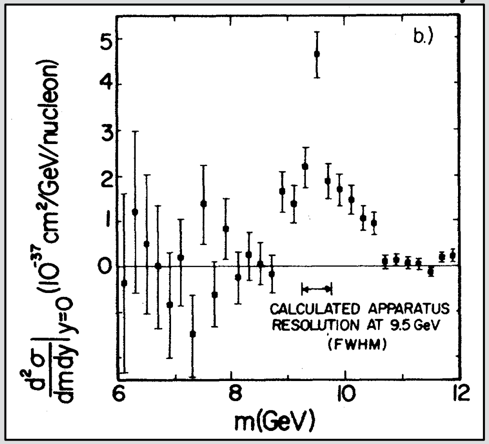




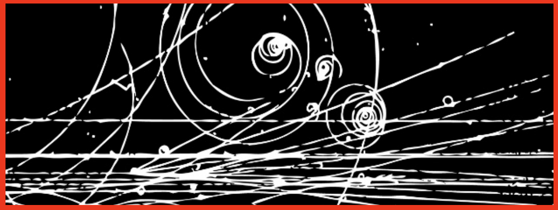
Cronin and Fitch, Phys.Rev.Lett. 13 (1964) 138

Direct





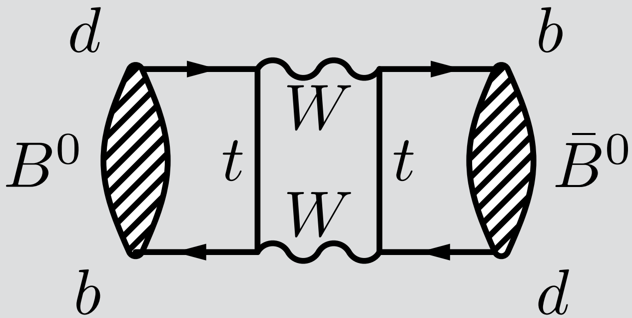
L.Lederman et al., Phys.Rev.Lett. 39 (1977) 252



Historical perspective: top

- Bottom mixing was “discovery” of top quark?

Indirect



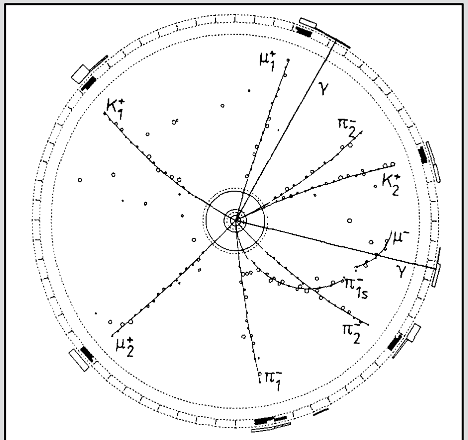
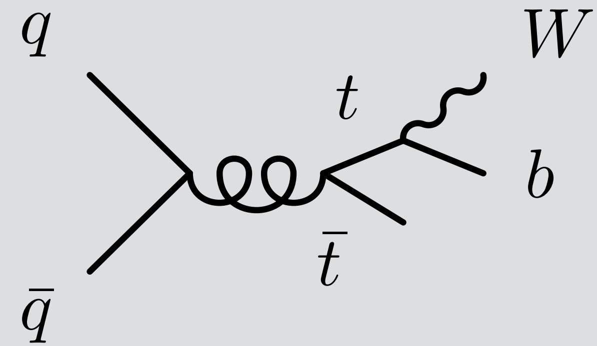
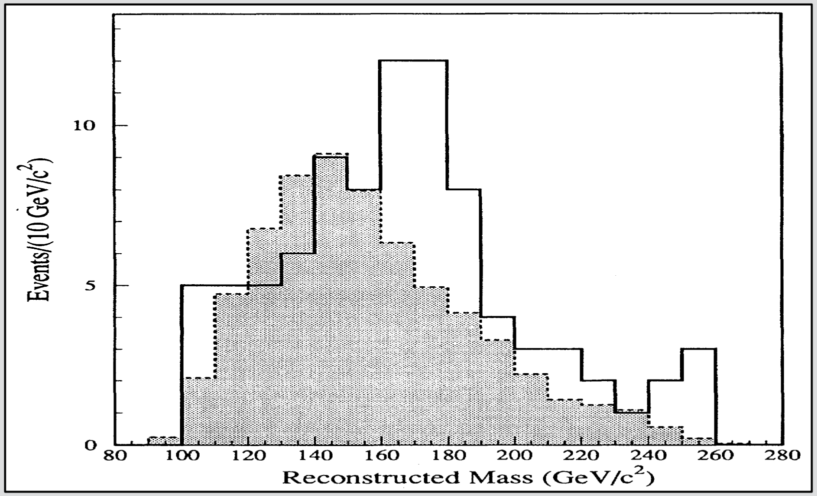


Fig. 2. Completely reconstructed event consisting of the decay Υ (4S)→B⁰B̄⁰.

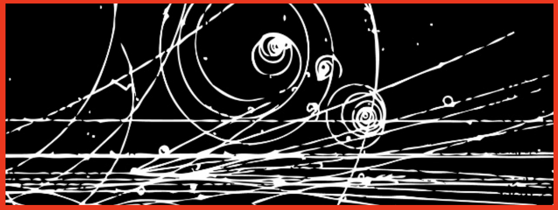
ARGUS, Phys.Lett. B192 (1987) 245

Direct





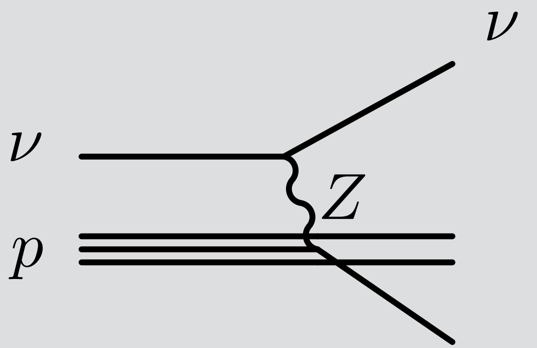
CDF Coll., Phys.Rev.Lett. 74 (1995) 2626

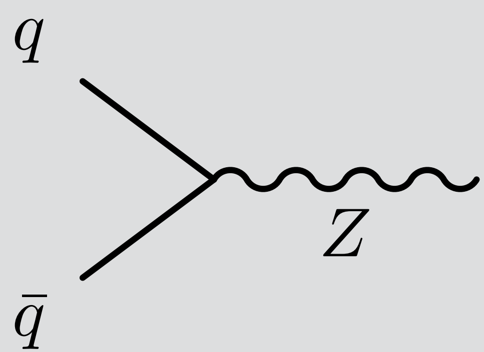


Historical perspective: Z

- Neutral current interaction was “discovery” of Z?

Indirect





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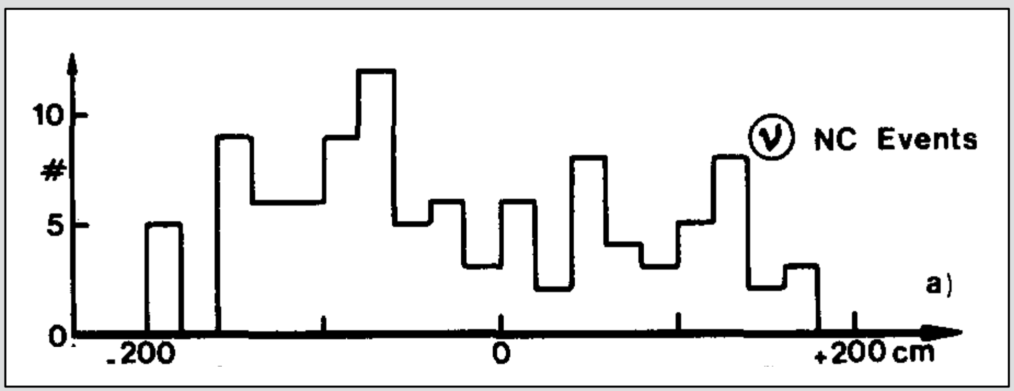
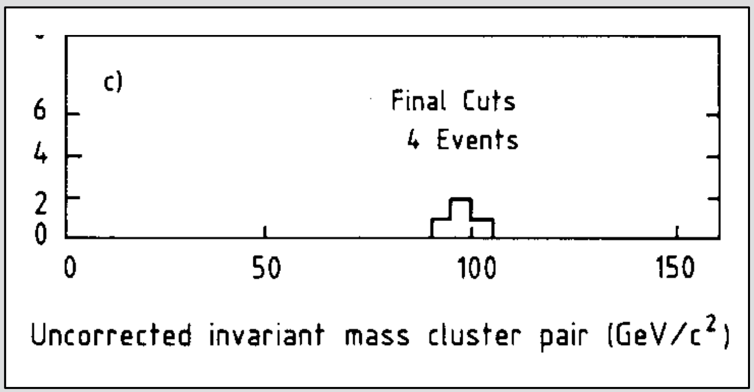
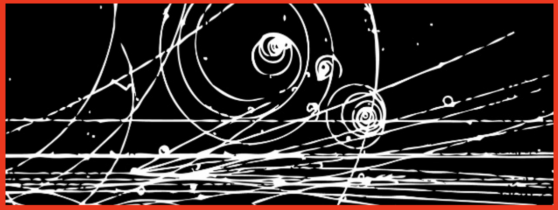


Gargamelle Coll., Phys.Lett. B46 (1973) 138



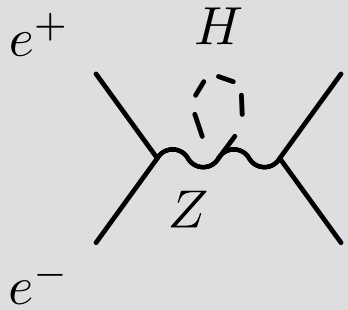
UA1 Coll., Phys.Lett. B126 (1983) 398

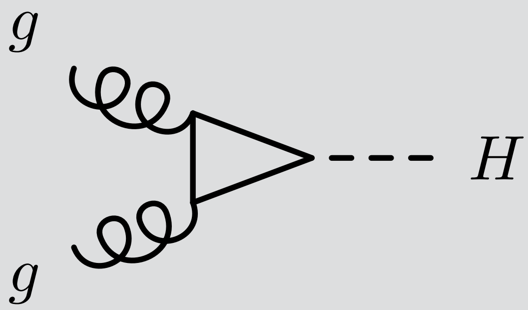


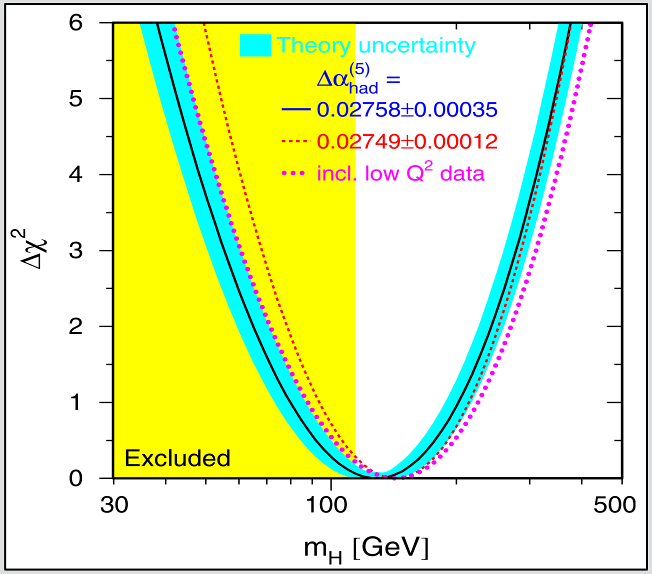
Historical perspective: Higgs

- Precision measurements at LEP were "discovery" of Higgs?

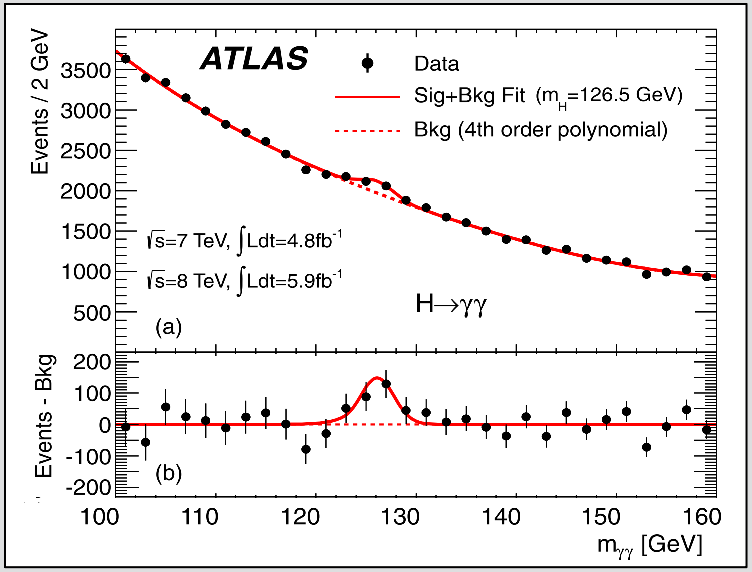
Indirect





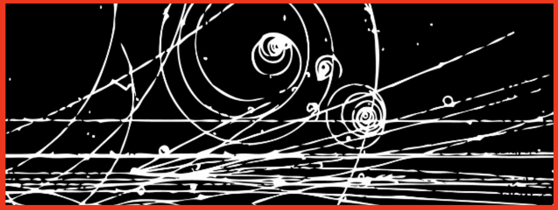


LEP, Phys.Rept. 427 (2006) 257



ATLAS Coll., Phys.Lett. B716 (2012) 1

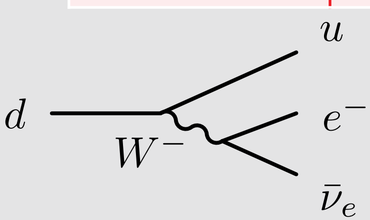
Direct

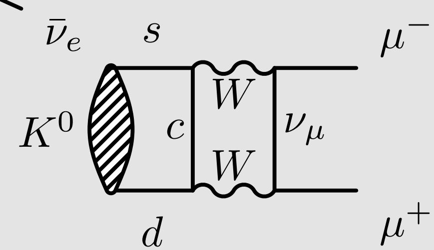


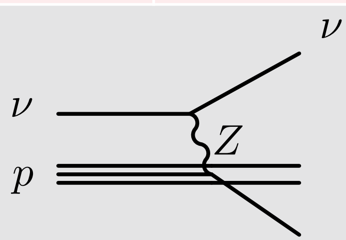
Heavy Flavour = Precision search for NP

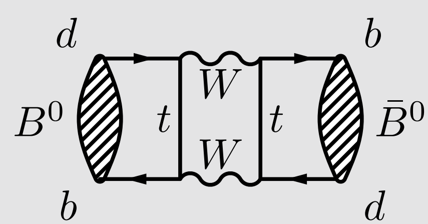
- Historical record of indirect discoveries:

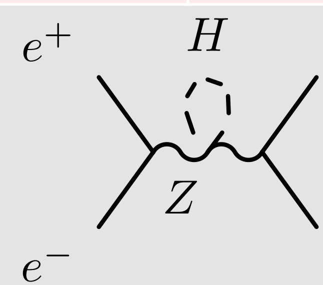
Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \rightarrow e\nu$	UA1, UA2	1983
c	$K^0 \rightarrow \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \rightarrow \pi\pi$	CKM, 3rd gen	1964/72	Y	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \rightarrow e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \rightarrow Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \rightarrow 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?











Heavy Flavour = Precision search for NP

- Direct discoveries rightfully higher valued:

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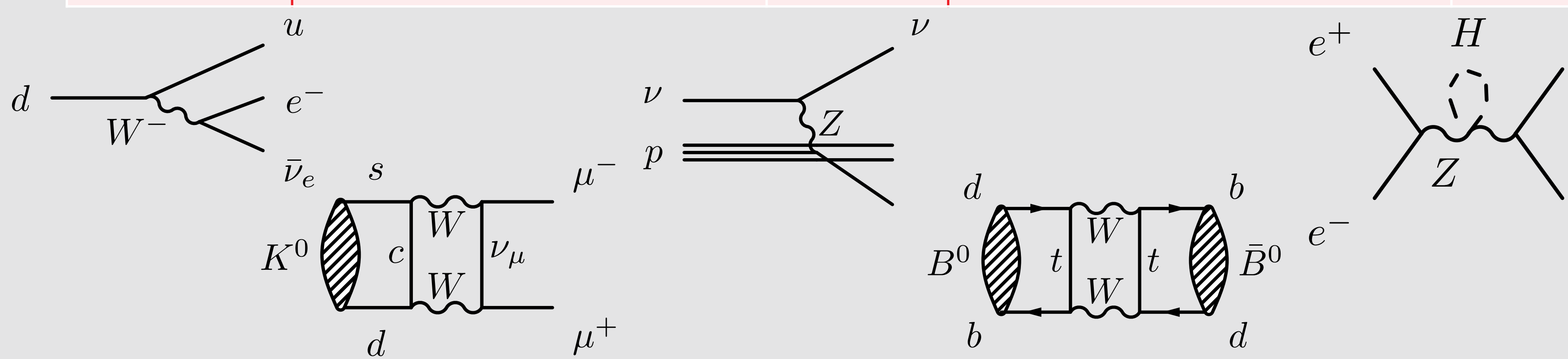
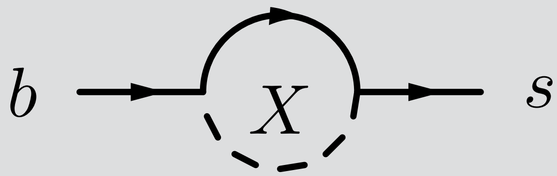


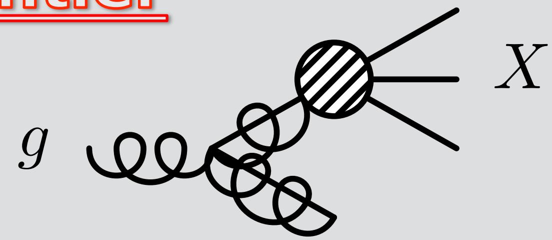
Precision measurements point to new phenomena

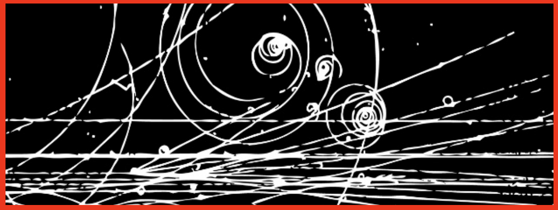


Quantum fluctuations at precision frontier

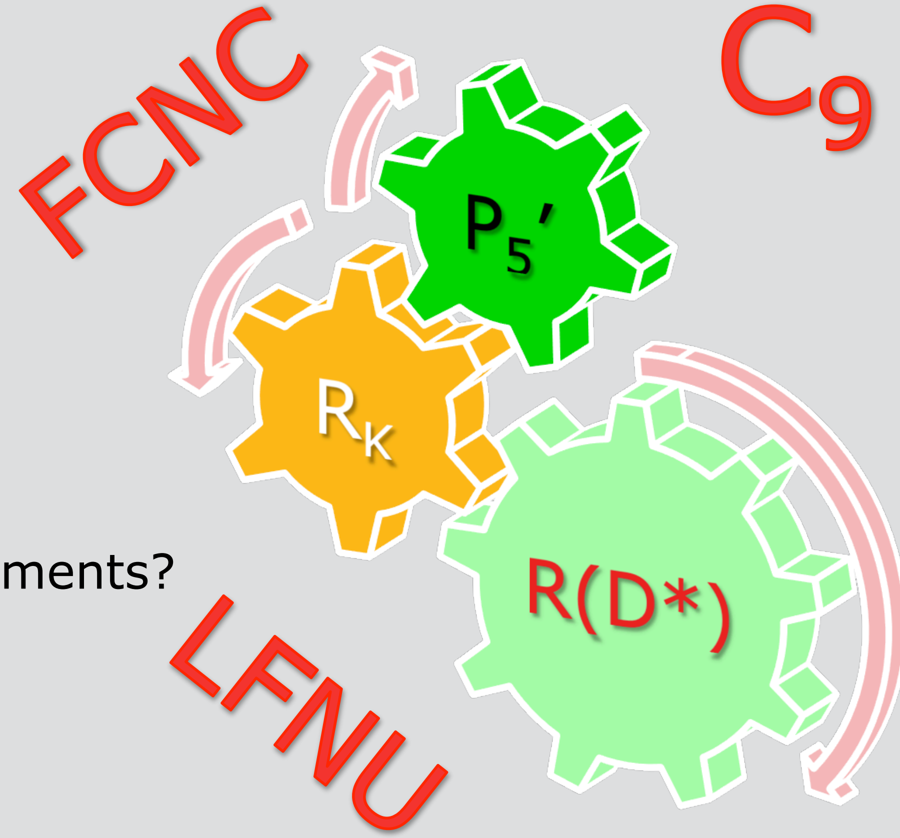
complement

direct production at energy frontier





Outline



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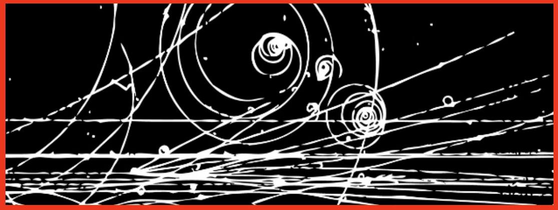
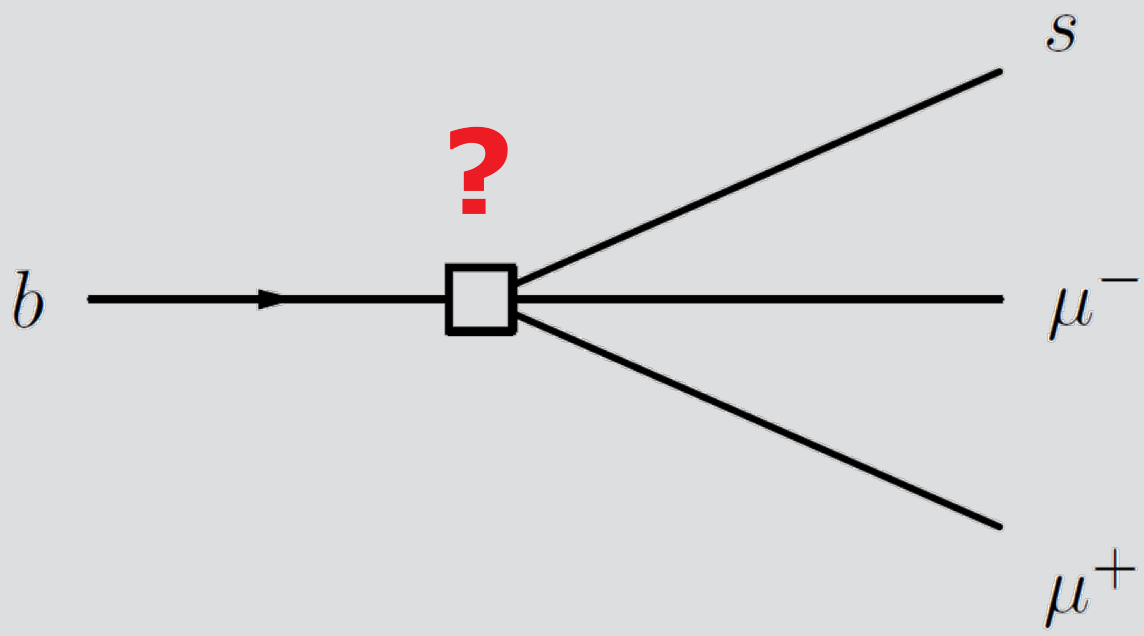
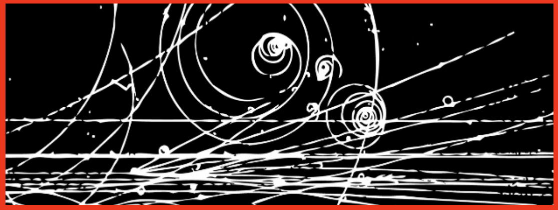


FCNC: *b→sll*

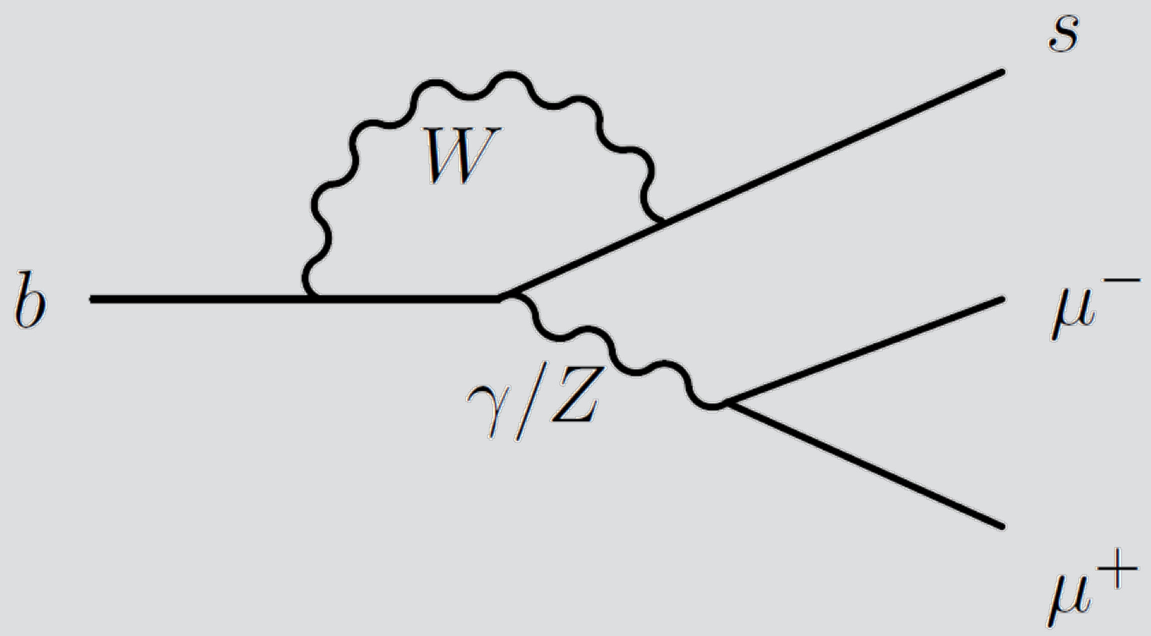
- b→s transition forbidden at tree level in SM

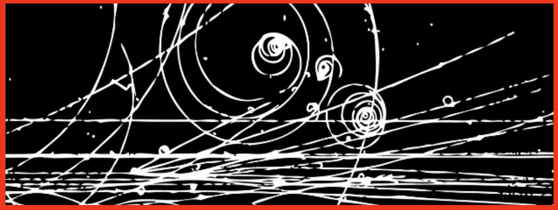




FCNC: *b→sll*

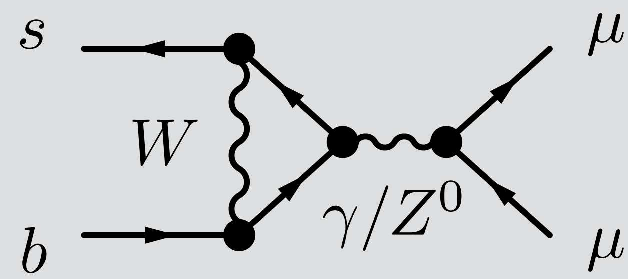
- b→s transition occurs at loop level
  - Suppressed in SM
  - NP can compete with SM



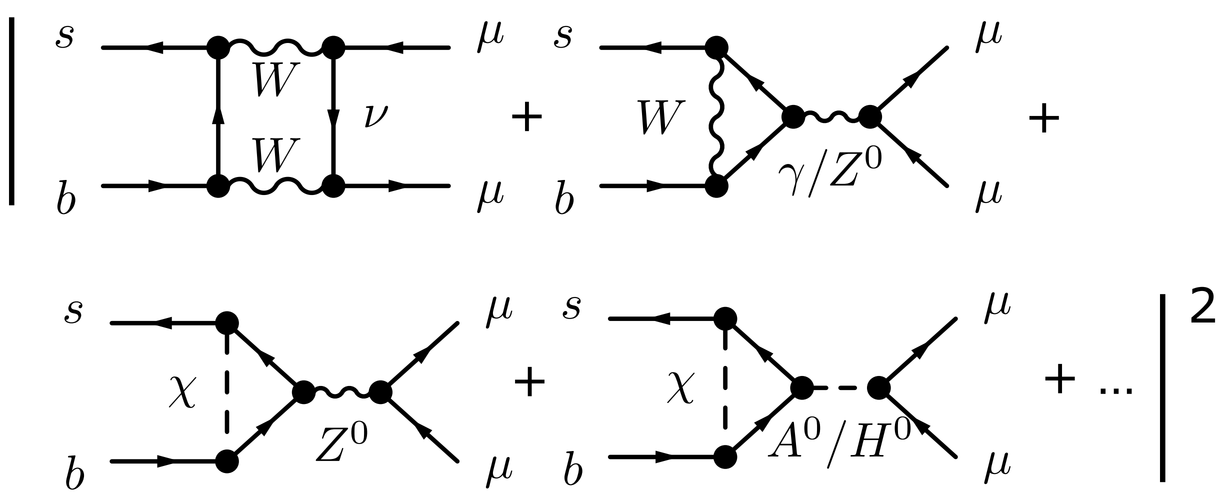


$B_s^0 \rightarrow \mu^+\mu^-$

- Famous example of b→sll process
- Very, very rare in the SM
- Sensitive to small effects beyond the SM

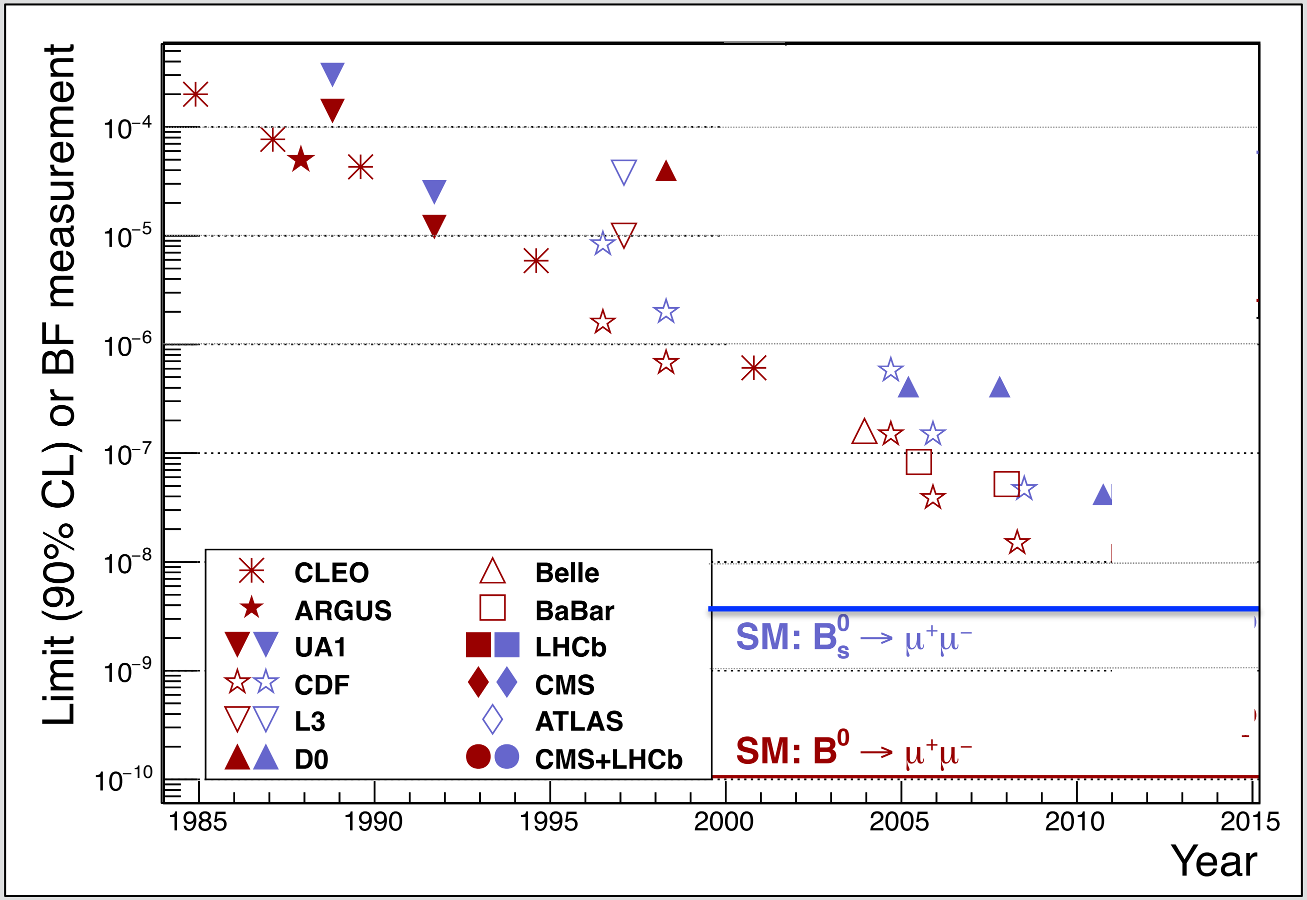


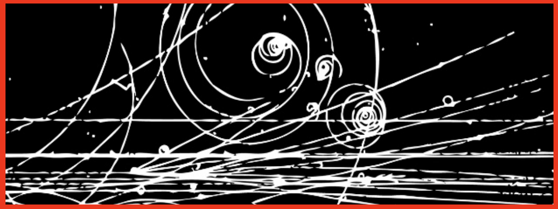
$$N(B_s^0 \rightarrow \mu^+\mu^-) = C$$



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

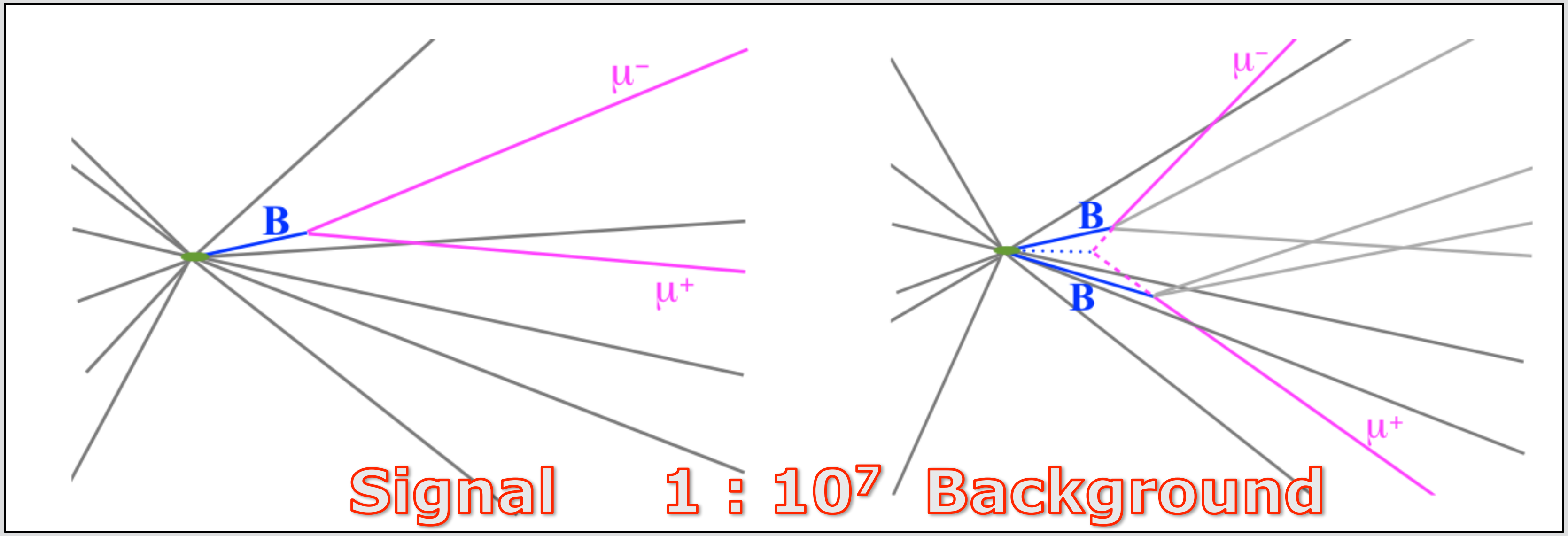
- Historical endeavour!

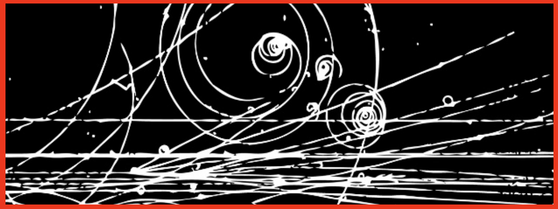




$B_s^0 \rightarrow \mu^+\mu^-$

- Challenge: huge amount of events with two muons!
  - Background: $BR(B \rightarrow X\mu^+) = 10^{-1}$
  - Signal: $BR(B_s^0 \rightarrow \mu^+\mu^-) < 10^{-8}$
- 10^{12} B produced; probability of $\mu\mu$ decay 10^{-9}; eff ~5%
  - Expect ~50 events

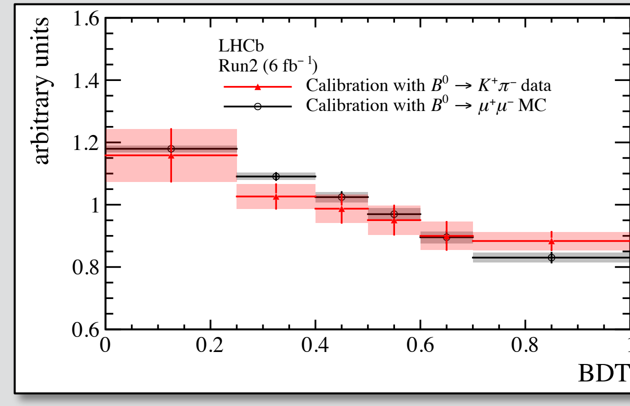


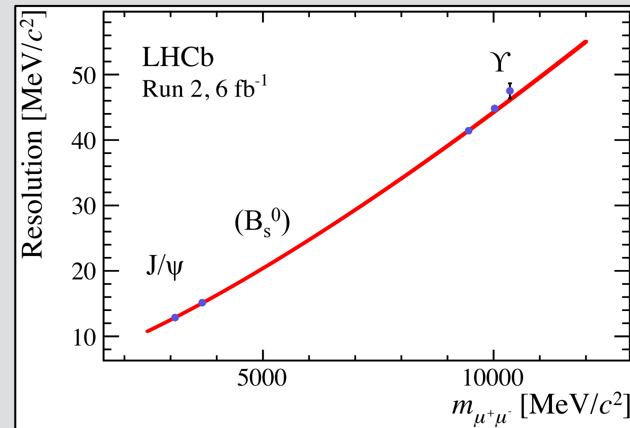


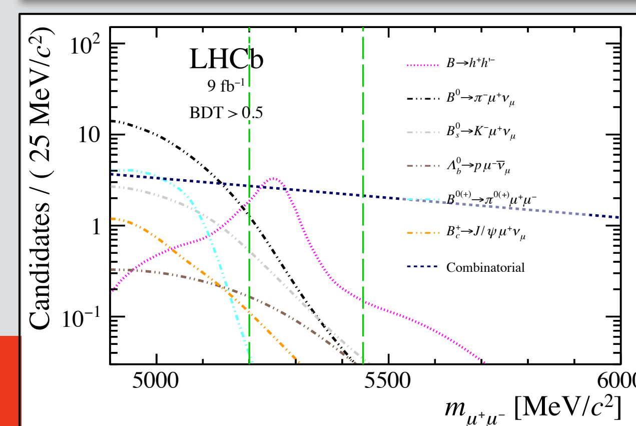
$B_s^0 \to \mu^+\mu^-$

- Challenge: huge amount of events with two muons!
  - Background: BR($B \to X\mu^+$) = 10^{-1}
  - Signal: BR($B_s^0 \to \mu^+\mu^-$) < 10^{-8}
- Analysis:
  - BDT event selection
    - Mainly lifetime
    - Calibrate efficiency on data with $B \to \pi\pi$ decays
  - Mass resolution
    - Interpolate between $J/\psi \to \mu\mu$ and $\Upsilon \to \mu\mu$
  - Backgrounds
    - $b \to \mu$ + $b \to \mu$
    - Semileptonic B^0, B_s^0, B_c^+ and Λ_b^0 decays
    - Misidentified $B \to \pi\pi$
- Largest systematic uncertainty:
  - Relative production of B_s^0 wrt B^0 mesons, f_s/f_d

LHCb coll., arXiv:2103.06810

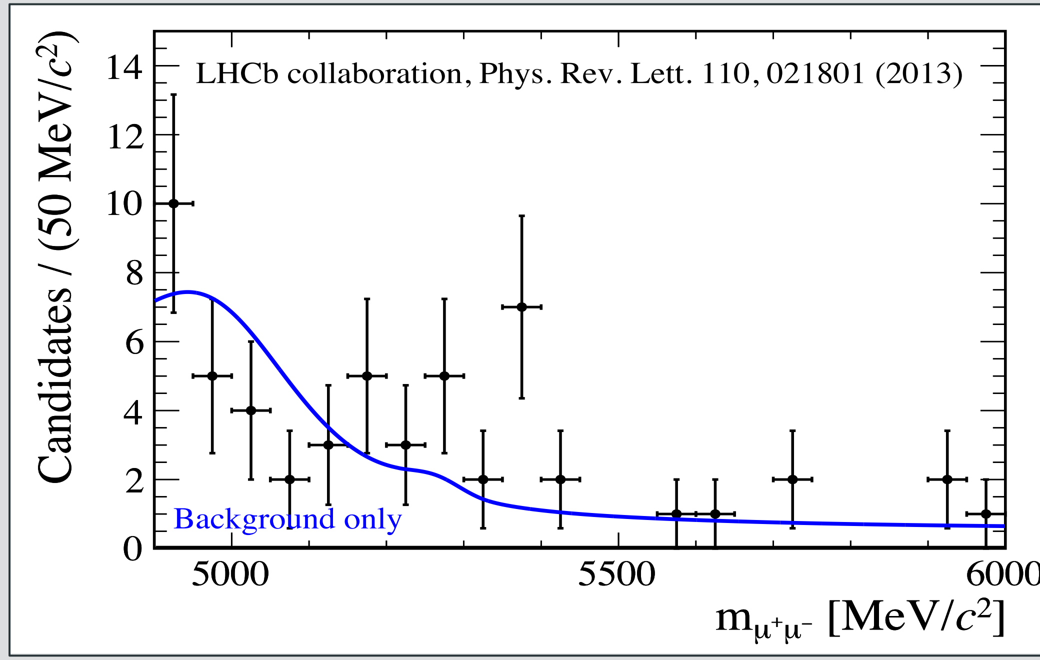






LHCb coll., PAPER-2021-007

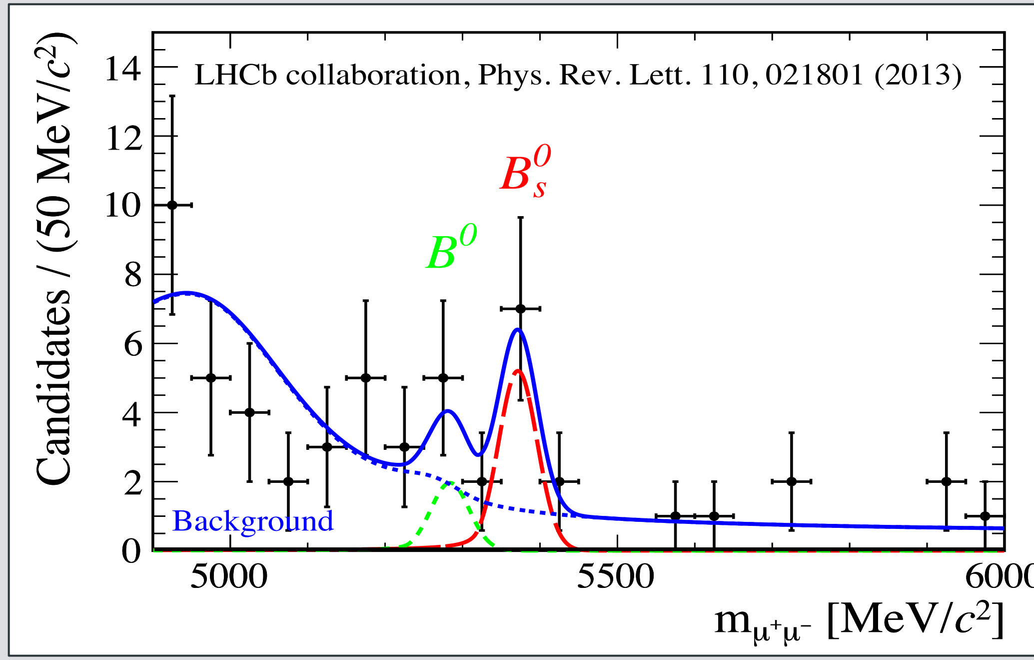
$B_s^0 \rightarrow \mu^+\mu^-$



LHCb Coll. Phys.Rev.Lett. 110, 021801 (2013)

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

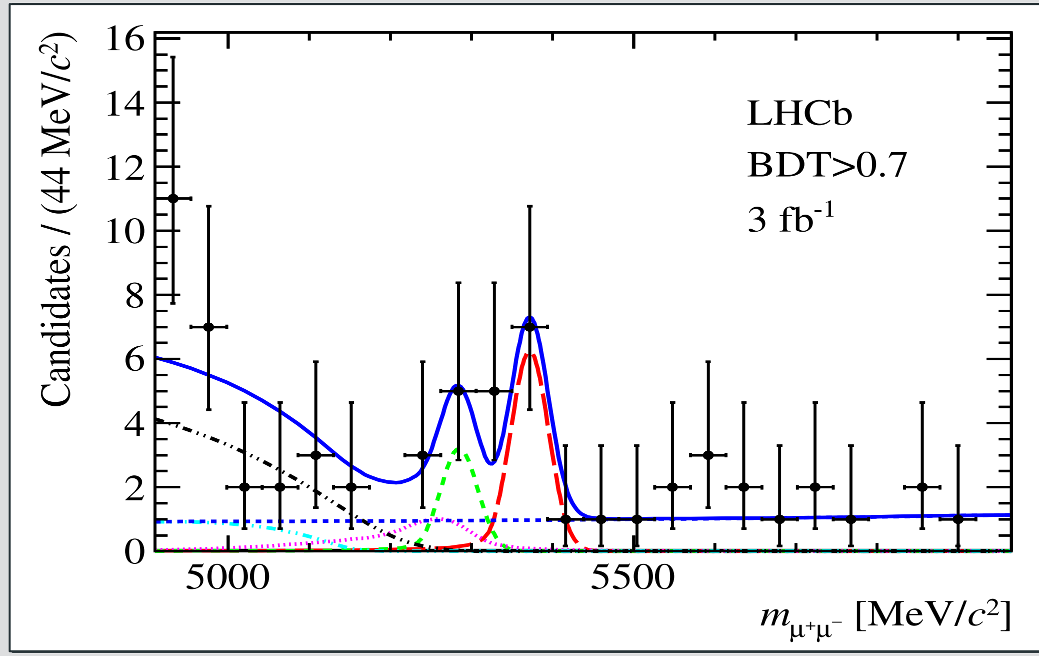
- First evidence, 3.5σ
  - ’11, part ’12
  - 2.1 fb^{-1}



LHCb Coll. Phys.Rev.Lett. 110, 021801 (2013)

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

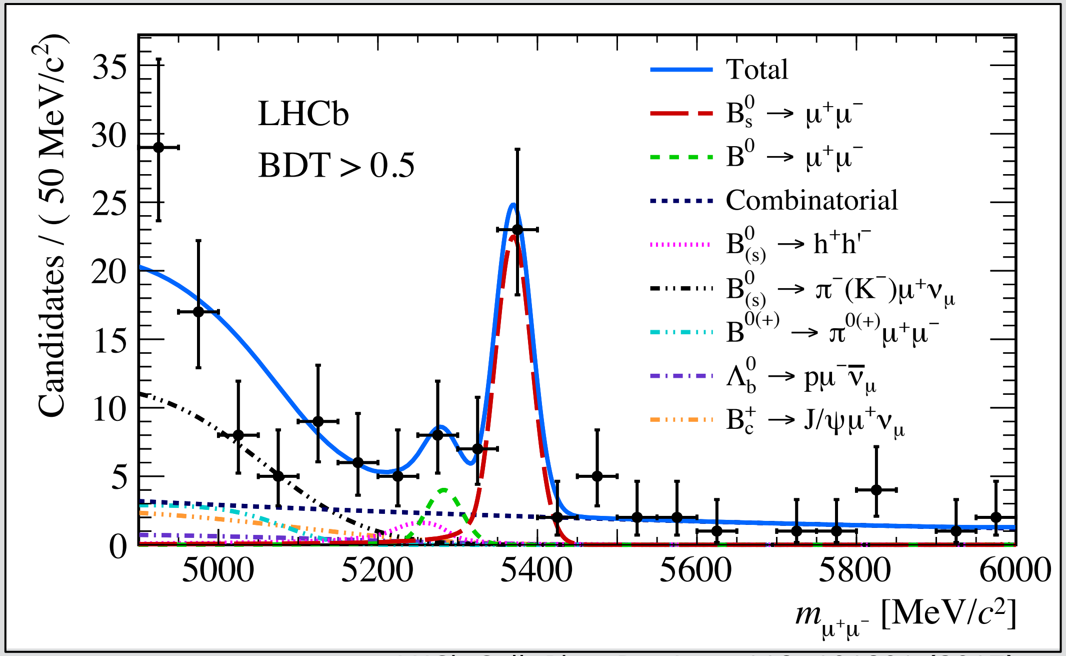
- 4.0σ
  - ’11 and ’12
  - 3.0 fb^{-1}



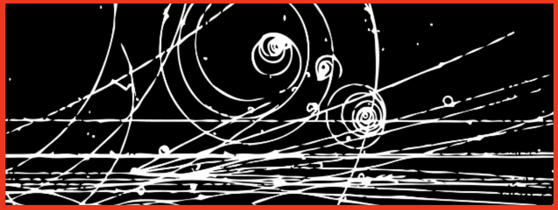
LHCb Coll. Phys.Rev.Lett. 111, 101805 (2013)

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

- 7.8σ
  - ’11, ’12, ’15, part ‘16
  - 4.4 fb^{-1}

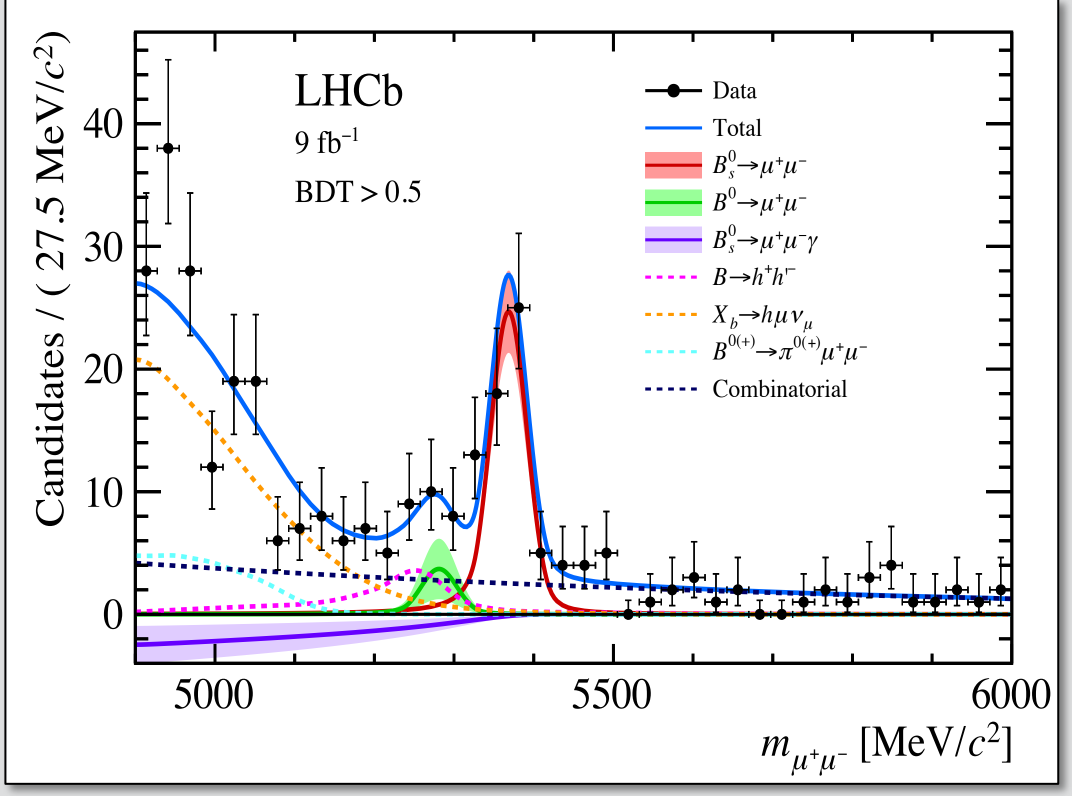


LHCb Coll. Phys.Rev.Lett. 118, 191801 (2017)



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

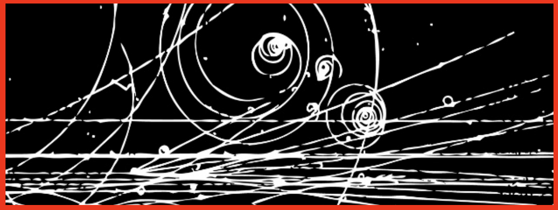
- 10 σ
  - Full data set
  - 9 fb^{-1}



LHCb Coll. PAPER-2021-007

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$

New result



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

- 10 σ
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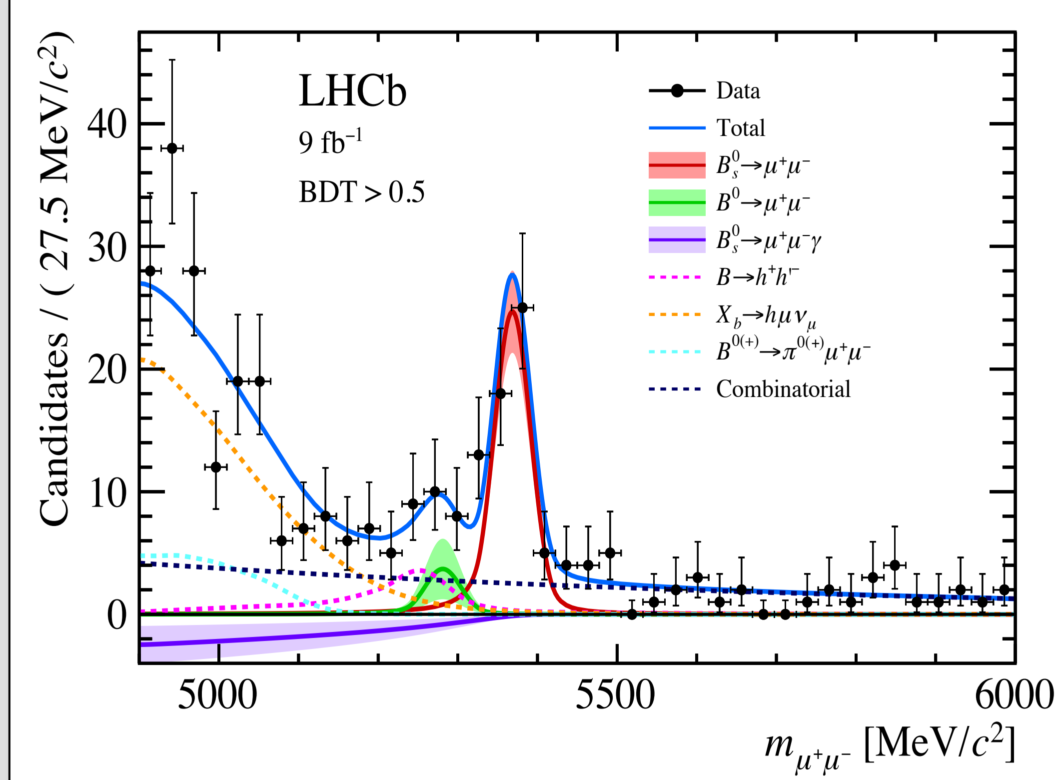
  - 9 fb^{-1}



LHCb Coll. PAPER-2021-007

$B^0 \to \mu^+\mu^-$?

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

Theory :

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

$$B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

Beneke, Bobeth, Szafron, arXiv:1908.07011

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$

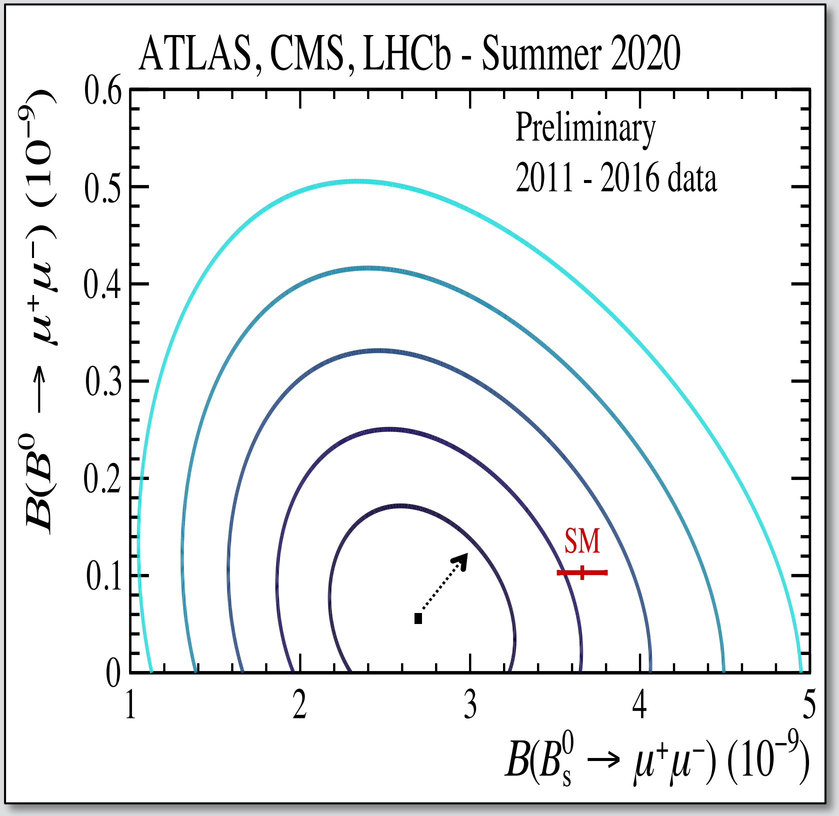
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$$

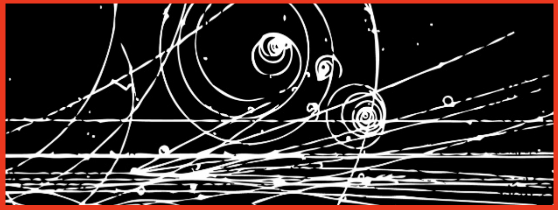
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu} > 4.9\,\mathrm{GeV}/c^2} < 2.0 \times 10^{-9}$$

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

- 10 σ
  - Full data set
  - 9 fb^{-1}

$B^0 \rightarrow \mu^+\mu^-$

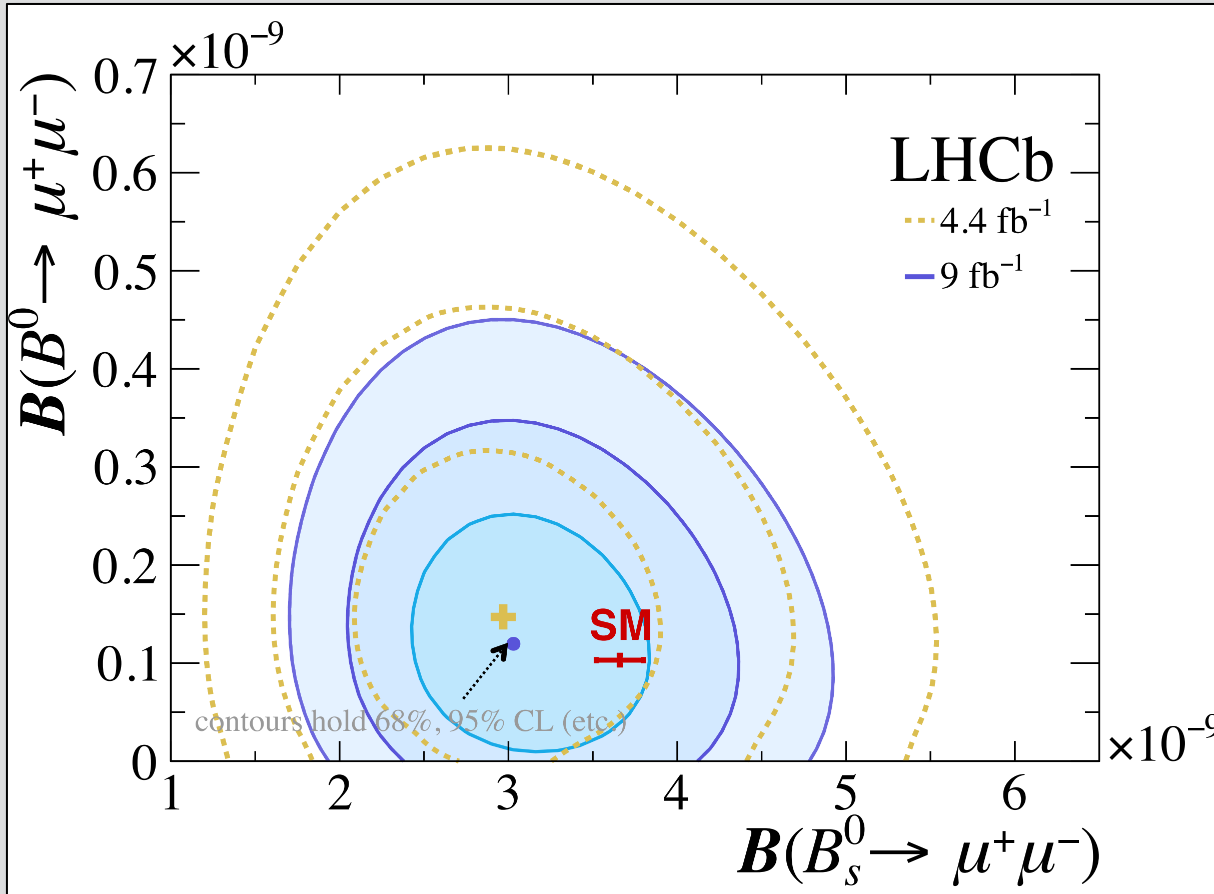




$B_s^0 \to \mu^+\mu^-$

- 10 σ
  - Full data set
  - 9 fb^{-1}

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



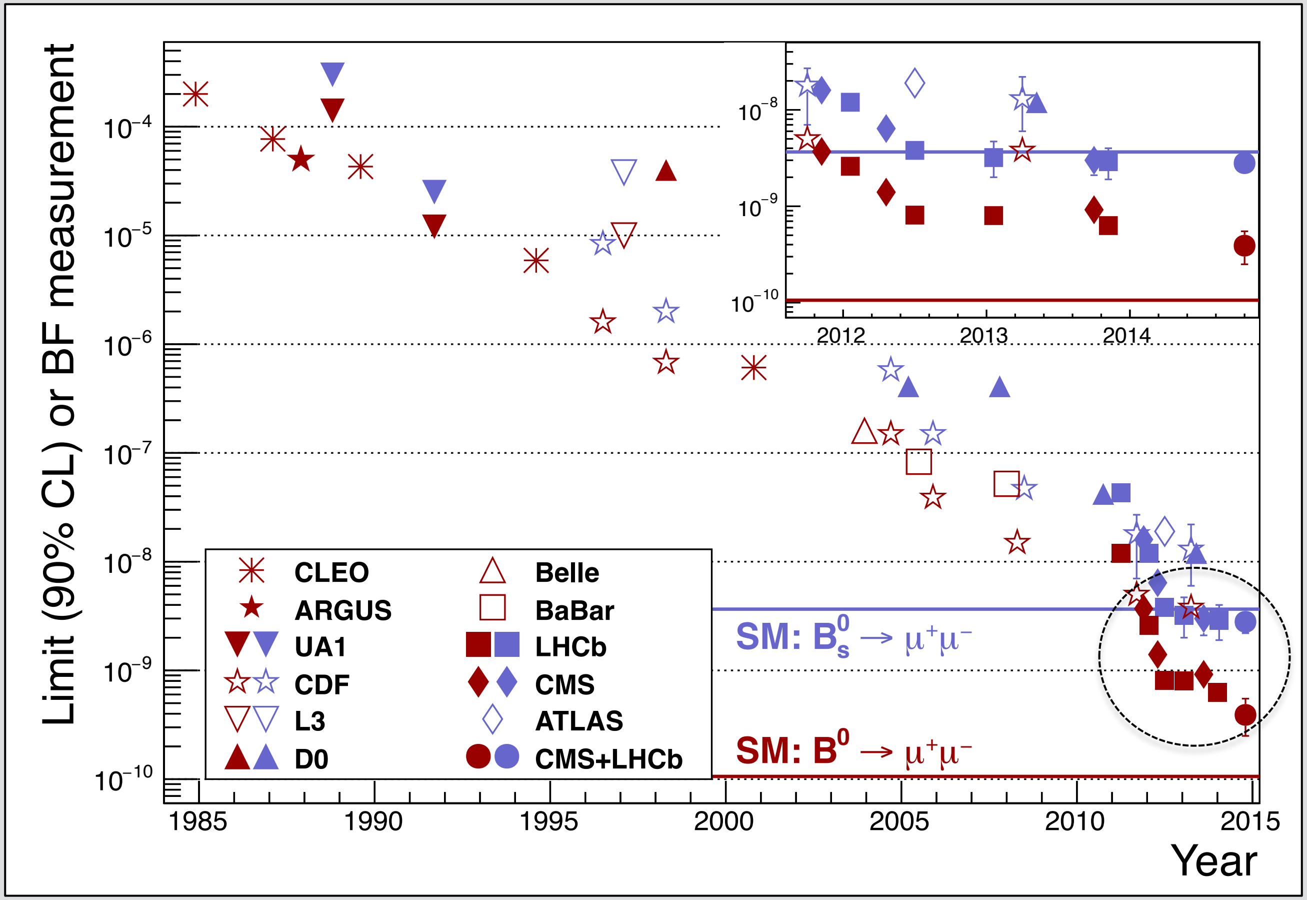
- Relative production of B_s^0 wrt B^0 mesons, f_s/f_d :
  - *updated average recently!*

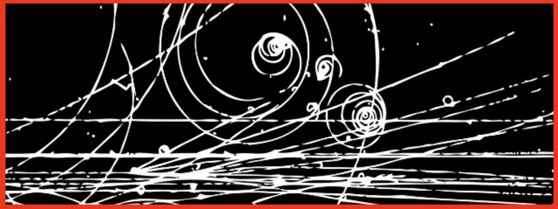
$$f_s/f_d\,(7\,\text{TeV}) = 0.2390 \pm 0.0076$$
$$f_s/f_d\,(8\,\text{TeV}) = 0.2385 \pm 0.0075$$
$$f_s/f_d\,(13\,\text{TeV}) = 0.2539 \pm 0.0079$$

LHCb coll., arXiv:2103.06810

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

- Historical endeavour!

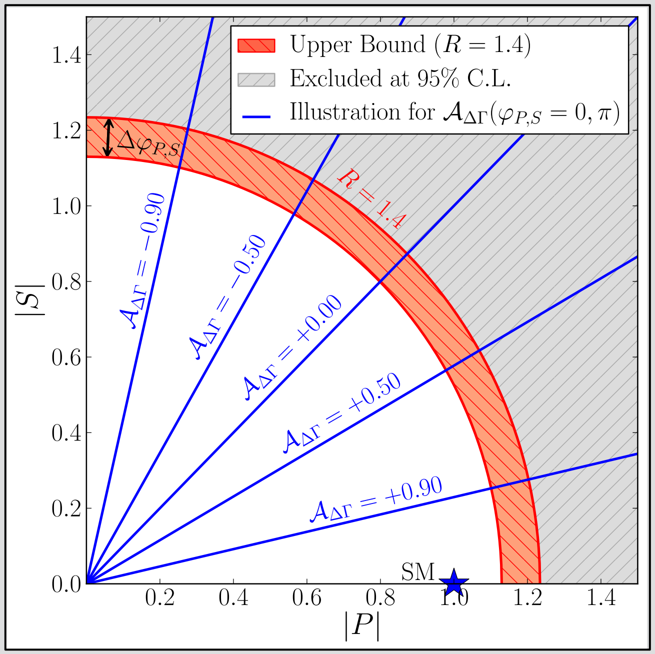




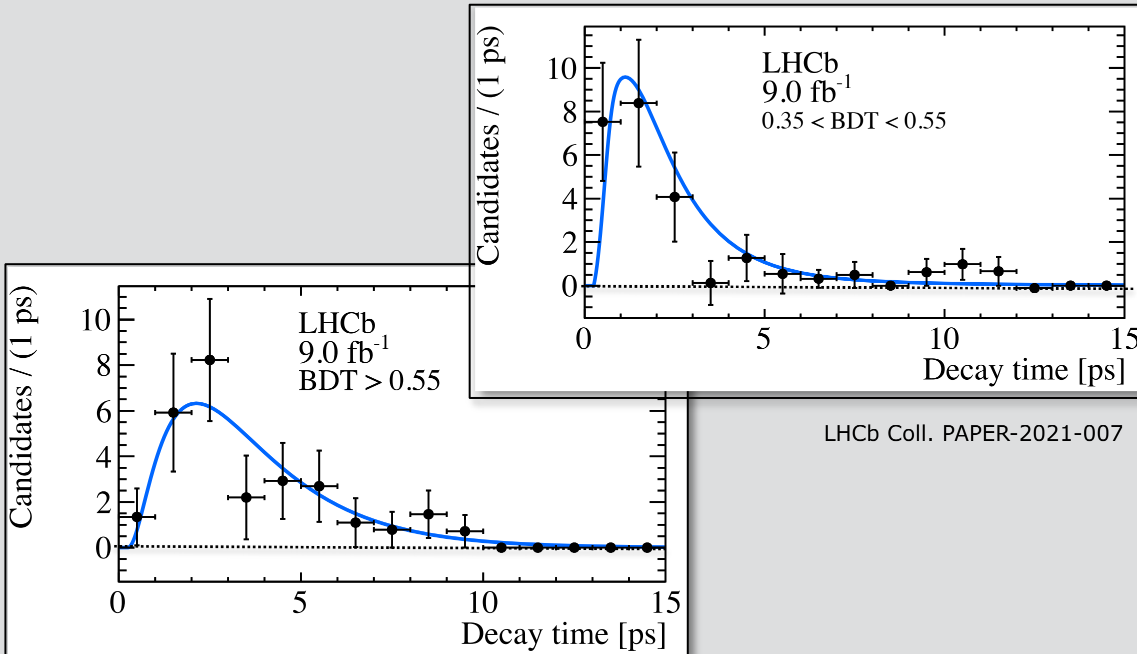
$B_s^0 \to \mu^+\mu^-$

New result

- More observables accessible
- New Physics can lead to different CP structure of final state
  - Affects the mix of long and short-living B_s^0 mesons



De Bruyn, Fleischer, NT, et al., PRL109 (2012) 041801

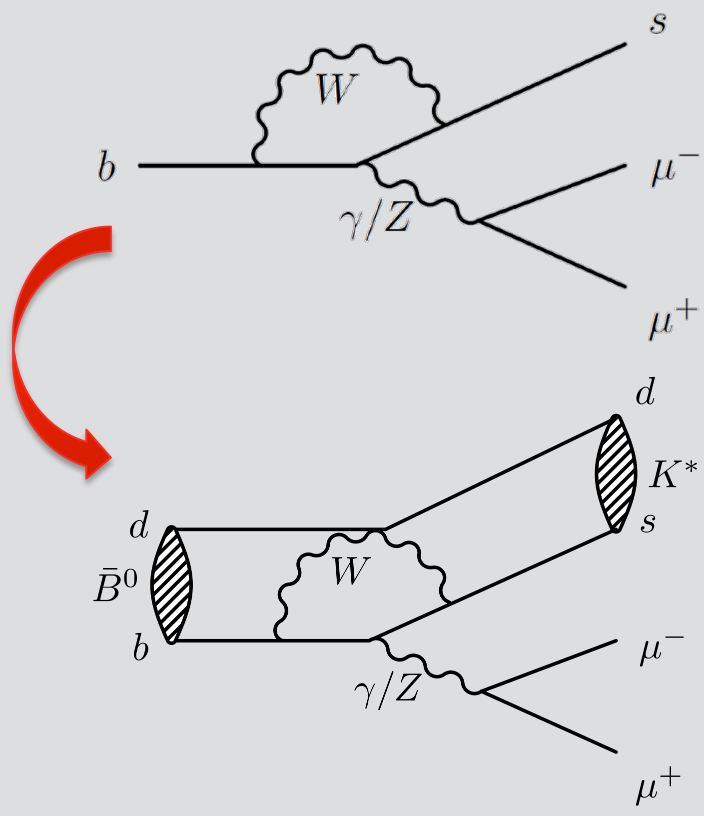


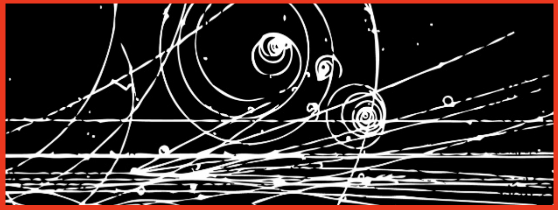
LHCb Coll. PAPER-2021-007

$$\tau(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03\,\text{ps}$$

FCNC: $B^0 \to K^{*0}\mu\mu$

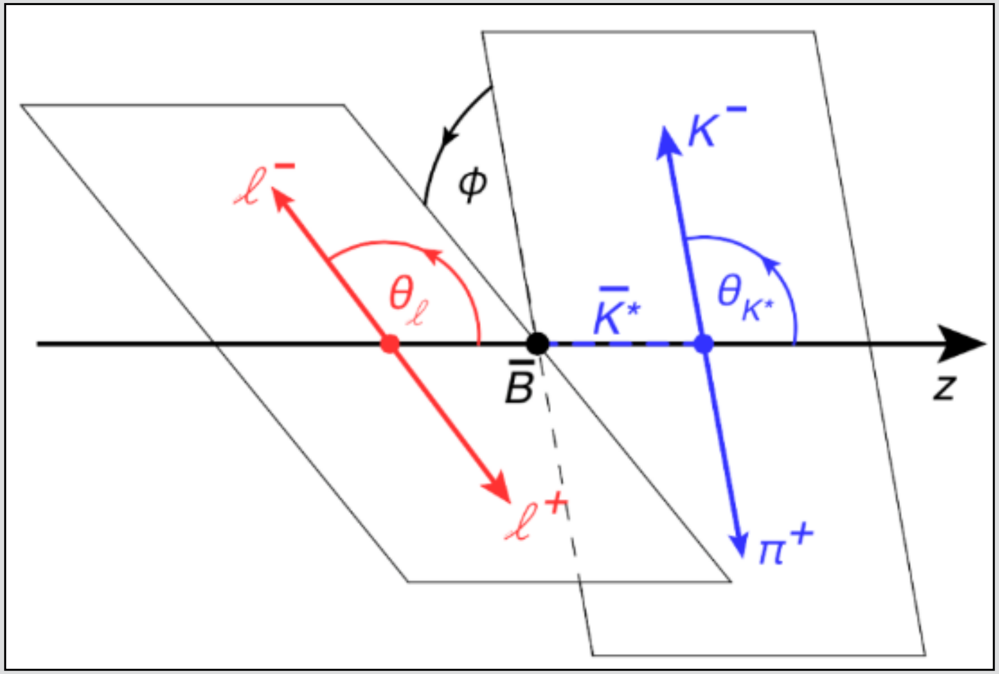
- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*

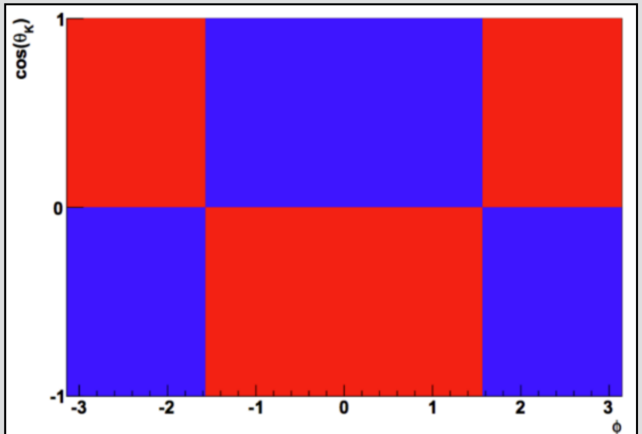




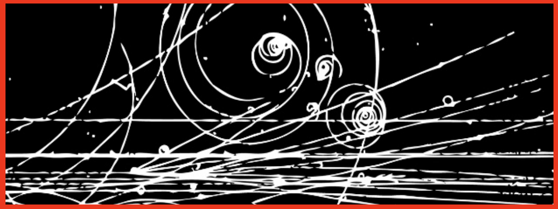
$B^0 \rightarrow K^{*0}\mu^+\mu^-$

- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*
- For example,
  - asymmetry of red and blue:



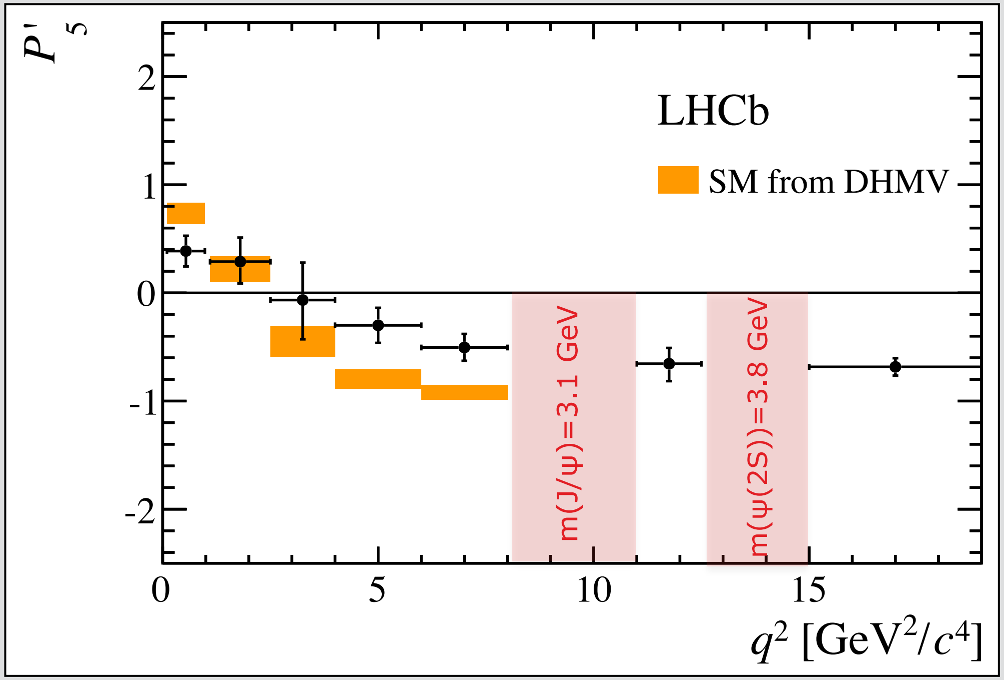


Counting S_5: blue minus red

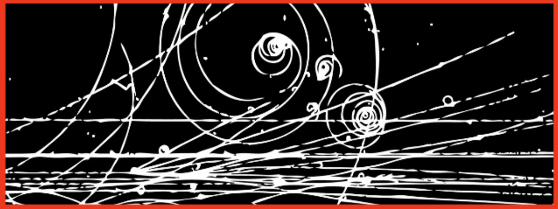


$B^0 \to K^{*0}\mu^+\mu^-$

- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*

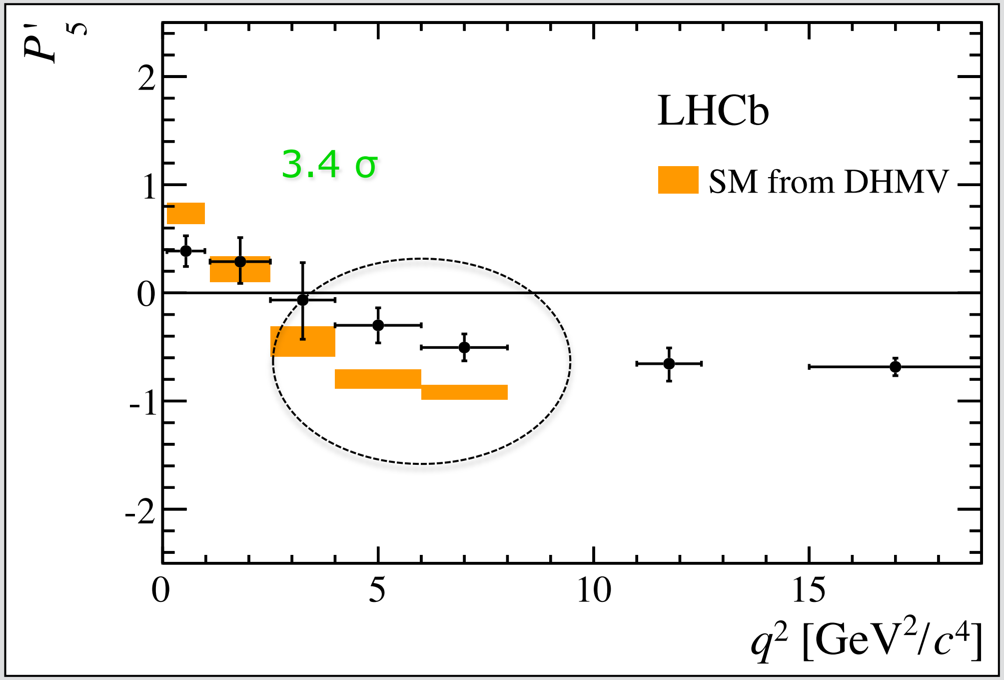


LHCb, arXiv:1512.04442

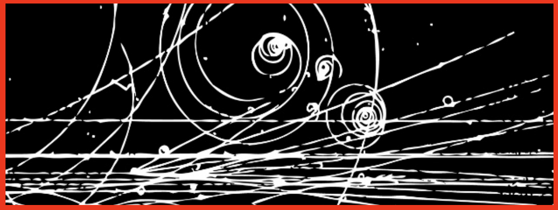


$B^0 \rightarrow K^{*0}\mu^+\mu^-$

- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*
- Debate on SM calculation
  - Non-perturbative "charm loop" effects?



LHCb, arXiv:1512.04442



$B^0 \to K^{*0}\mu^+\mu^-$

- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*
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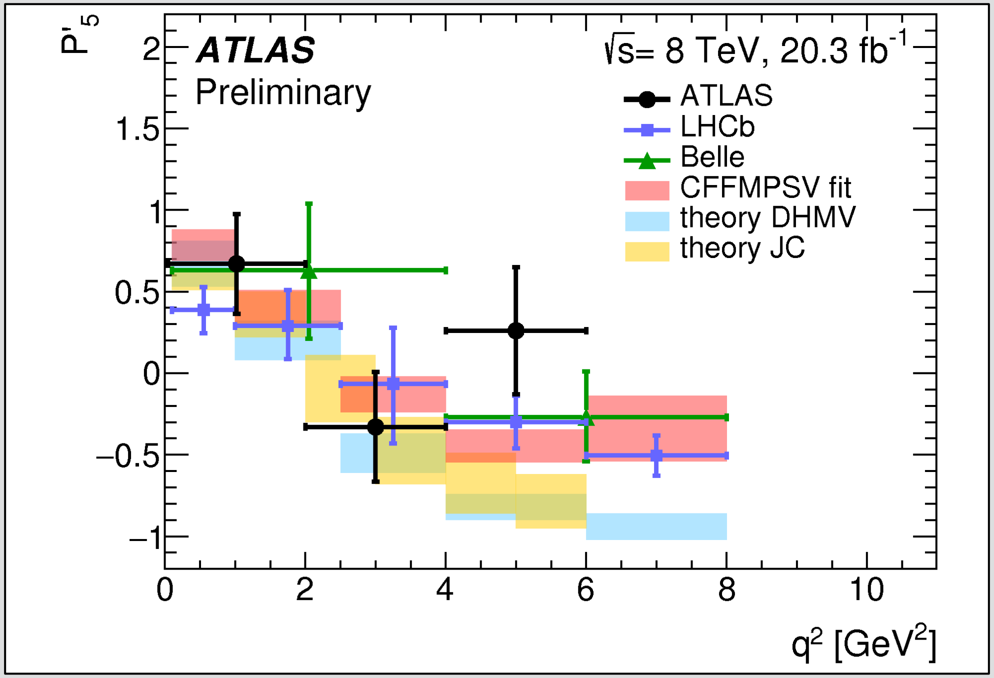
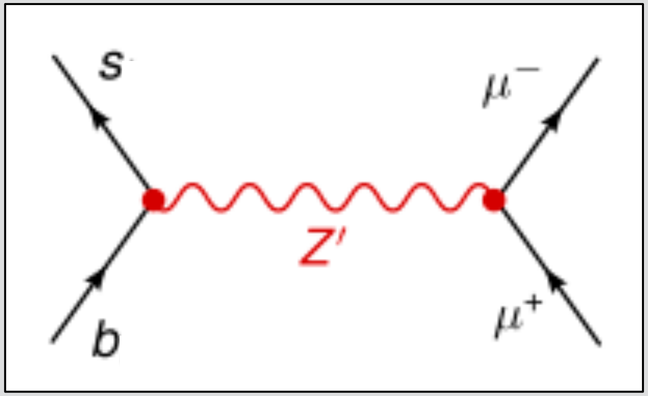
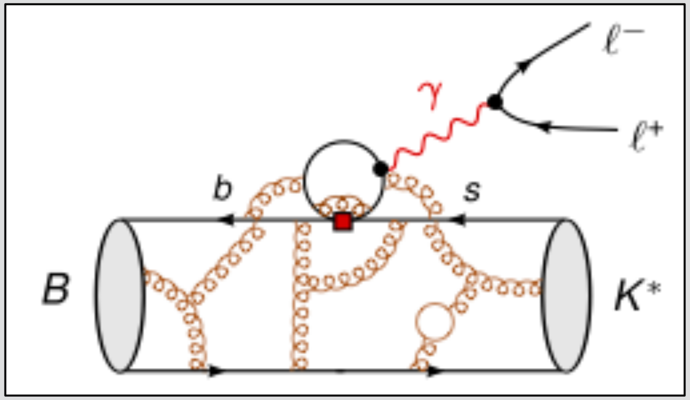


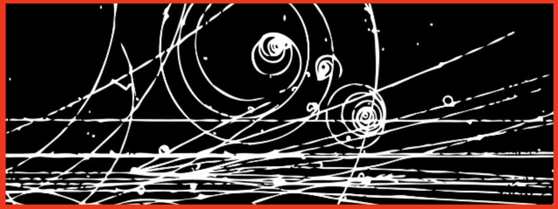
ATLAS-CONF-2017-023



or



?

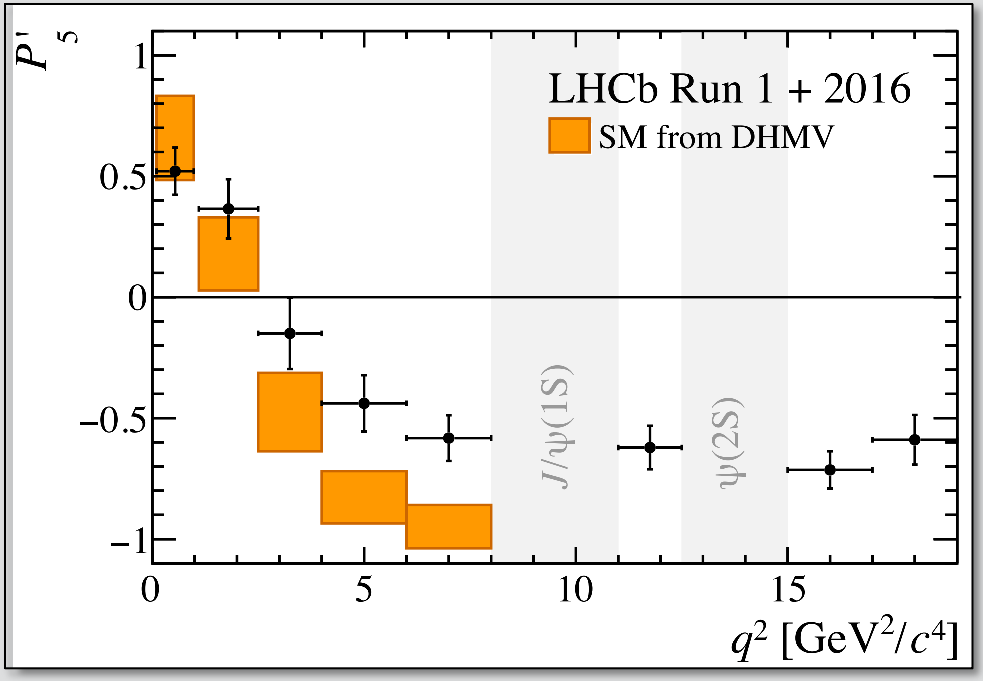


$B^0 \rightarrow K^{*0}\mu^+\mu^-$

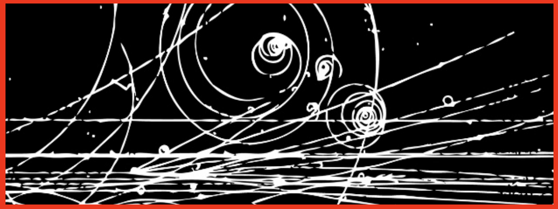
- Similar loop diagram!

- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*

- Debate on SM calculation
  - Non-perturbative “charm loop” effects?

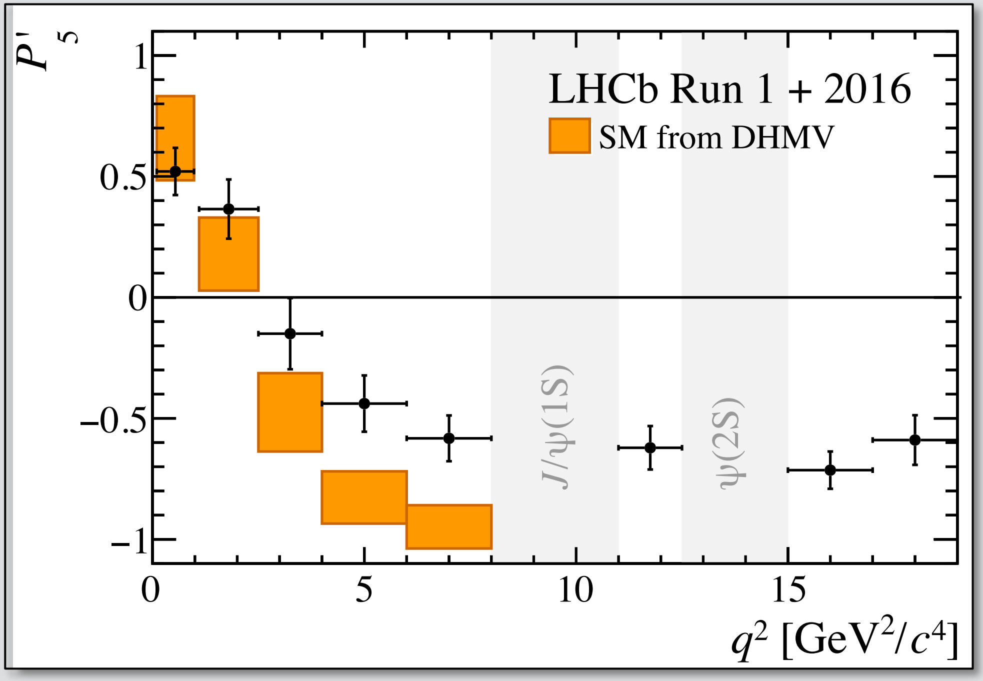


LHCb coll., arXiv:2003.04831



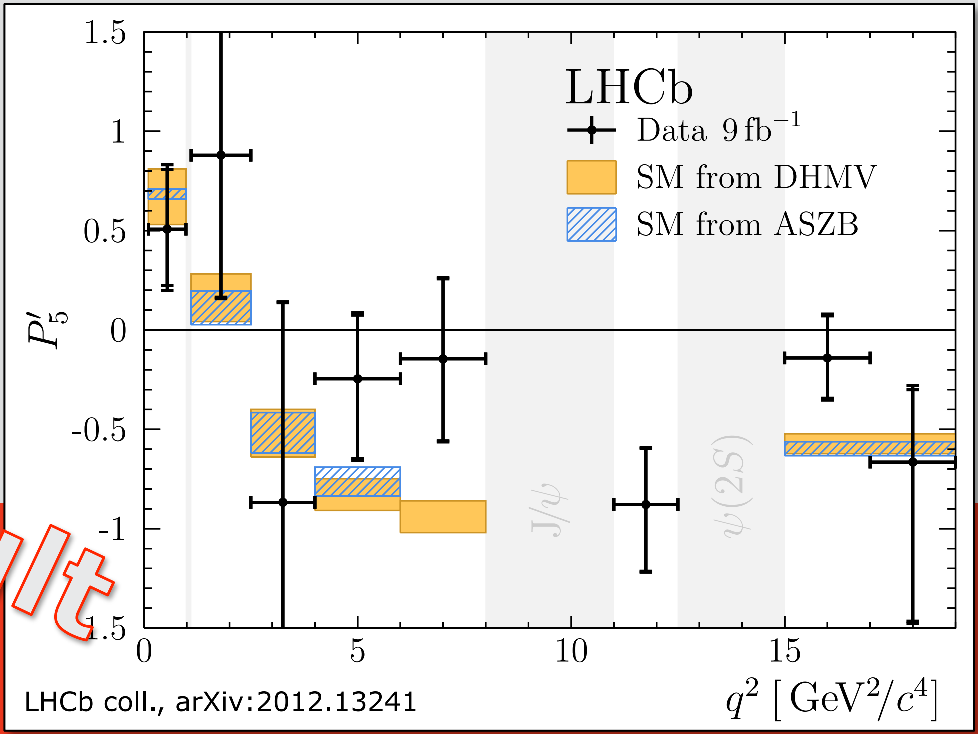
$B^+ \to K^{*+}\mu^+\mu^-$

- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*

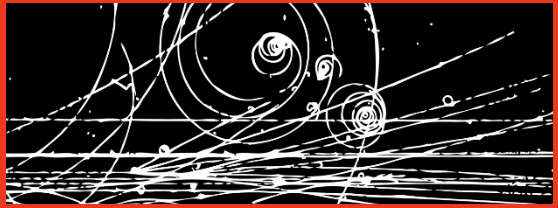


- Recently, the charged B^+ confirmed the same trend:

New result

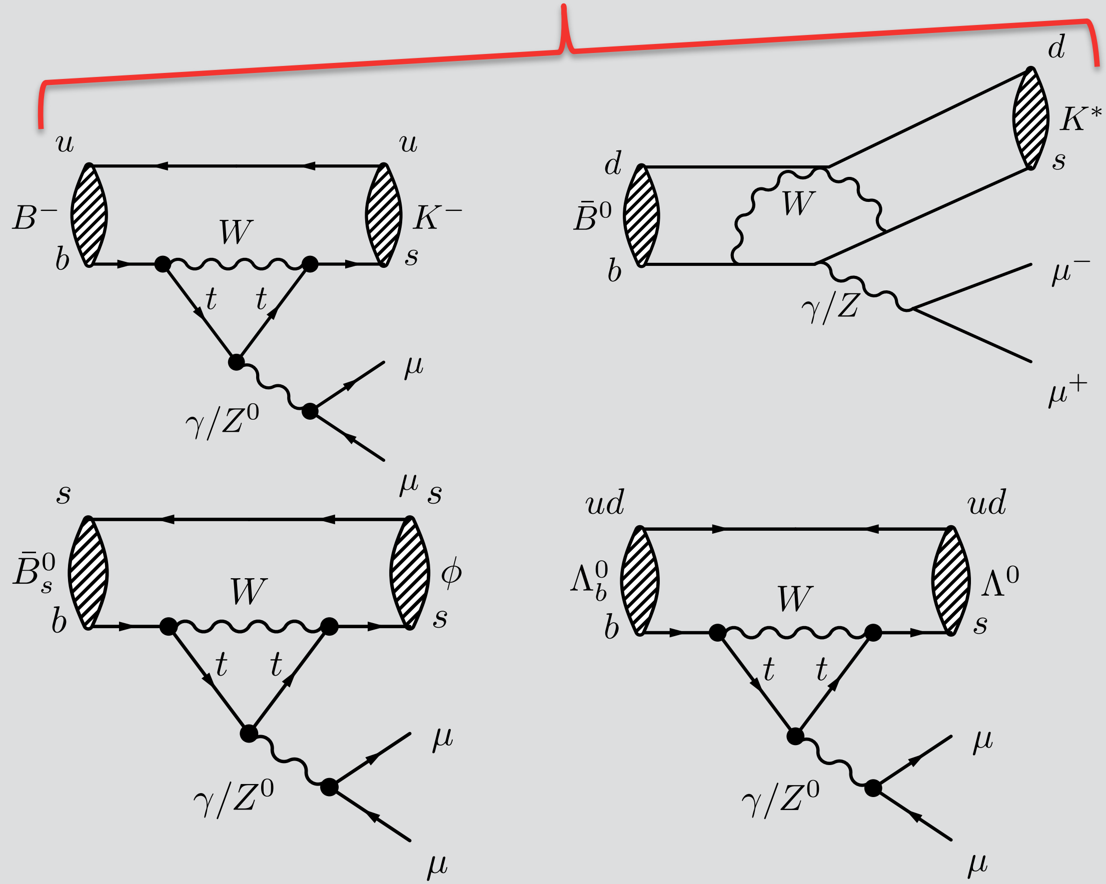


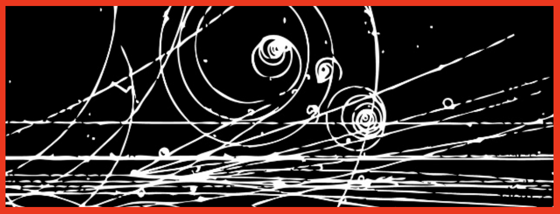
LHCb coll., arXiv:2012.13241



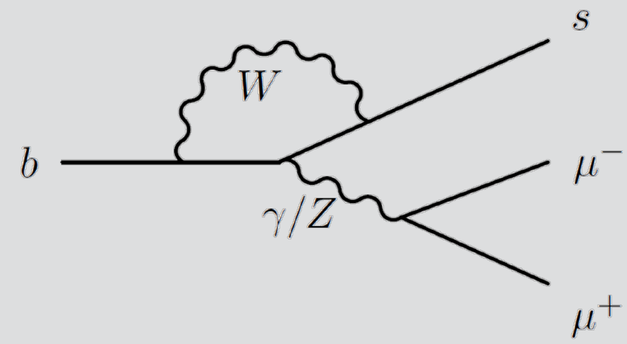
Decay rates: *b→sll*

- Study same process with different hadrons:

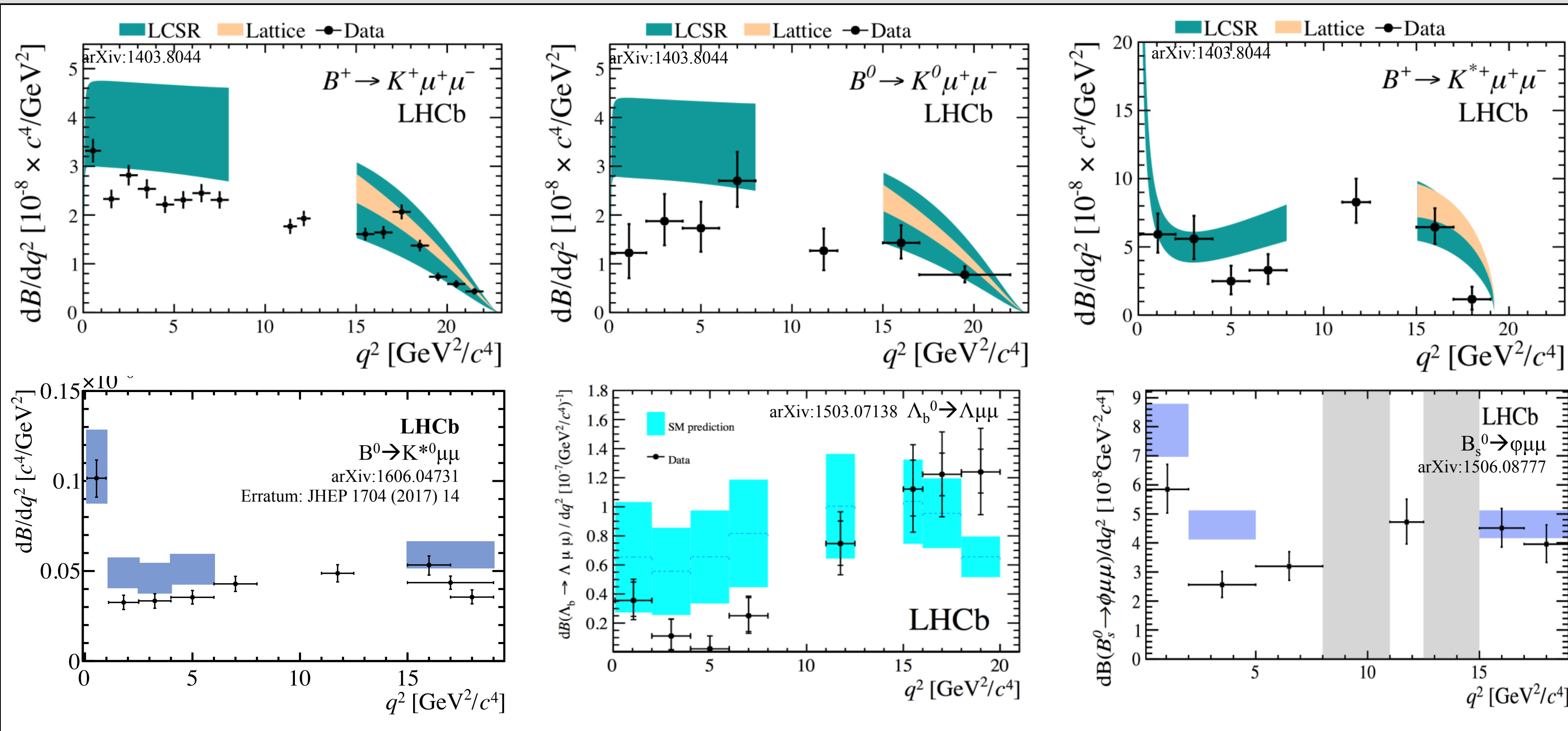


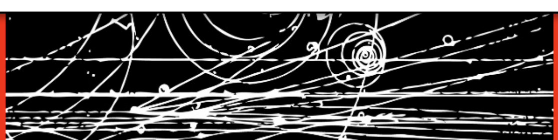


Decay rates: *b→sll*

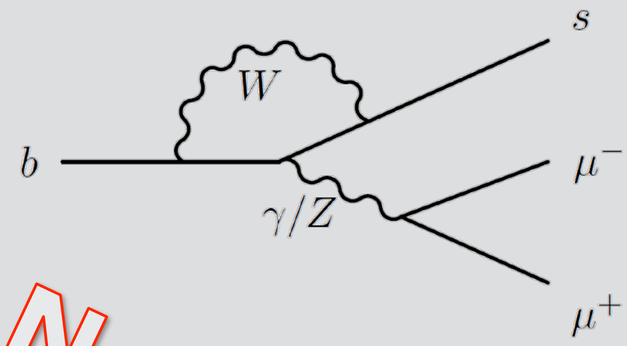


- Decay rate is consistently low:



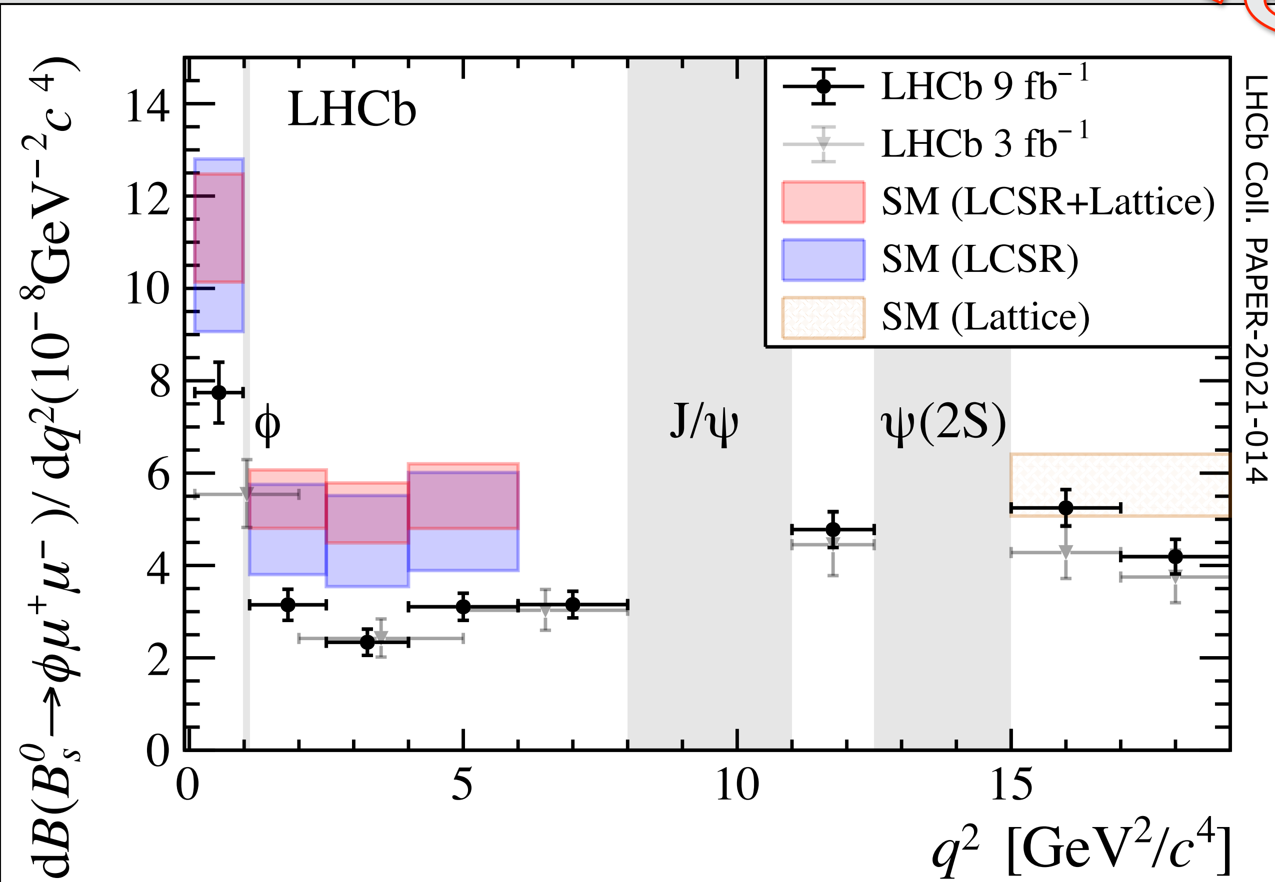


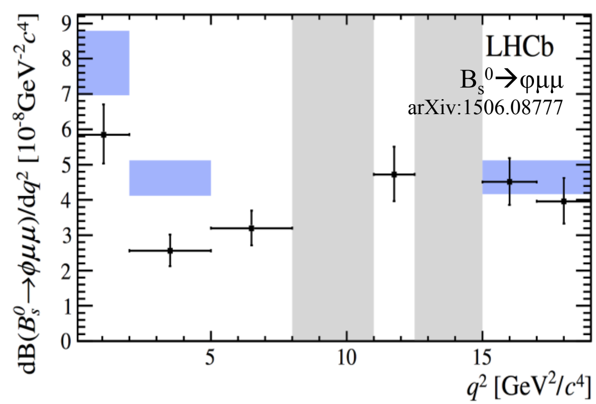
Decay rates: *b→sll*

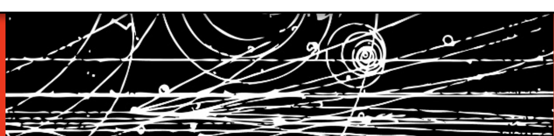


- Decay rate is consistently low:
  - 3.6 (1.8) σ below LCSR+Lattice (LCSR)

New result

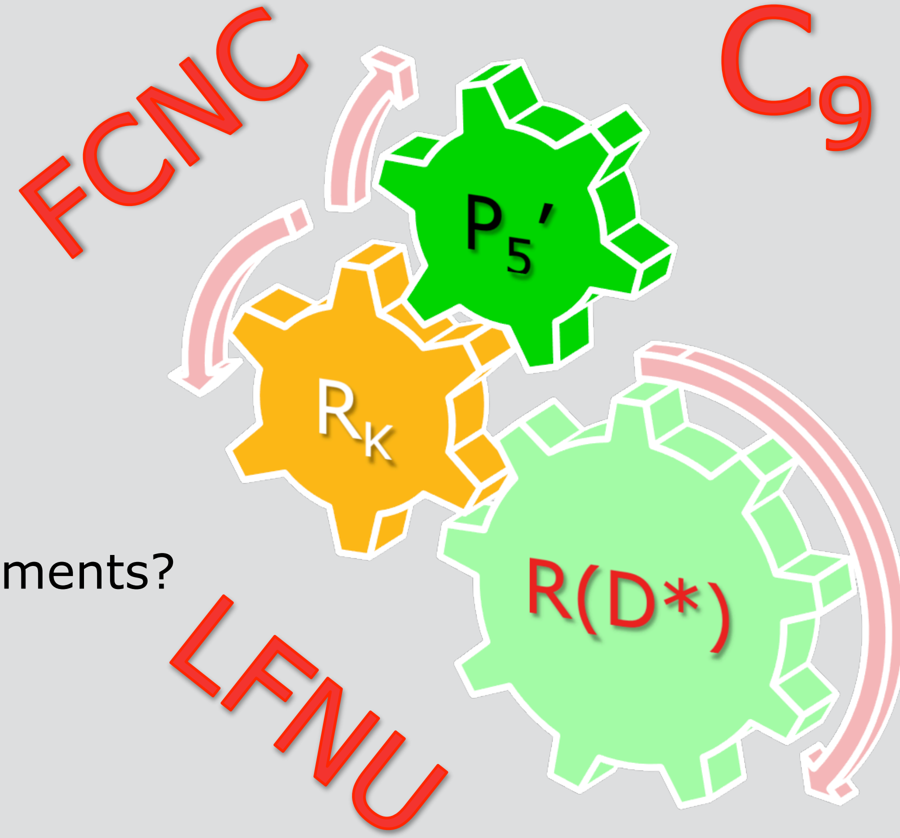


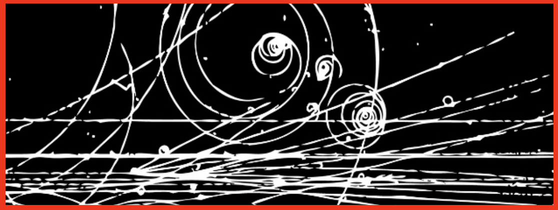




Outline

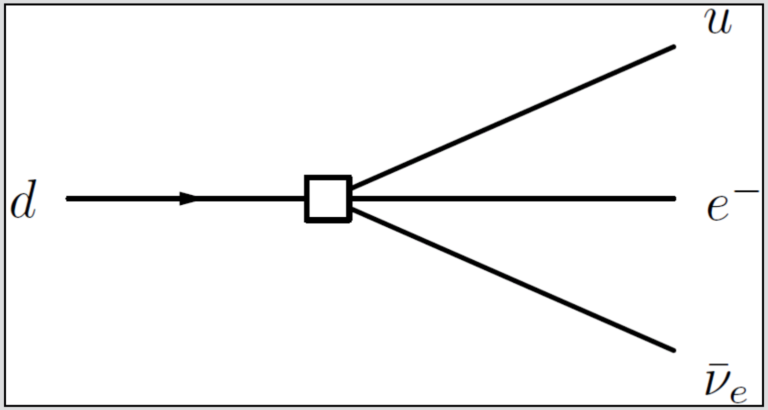
- Indirect measurements
- What are the (anomalous) measurements?
  - FCNC: b→sll
  - LFNU: b→sll and b→clν
- What are the interpretations?

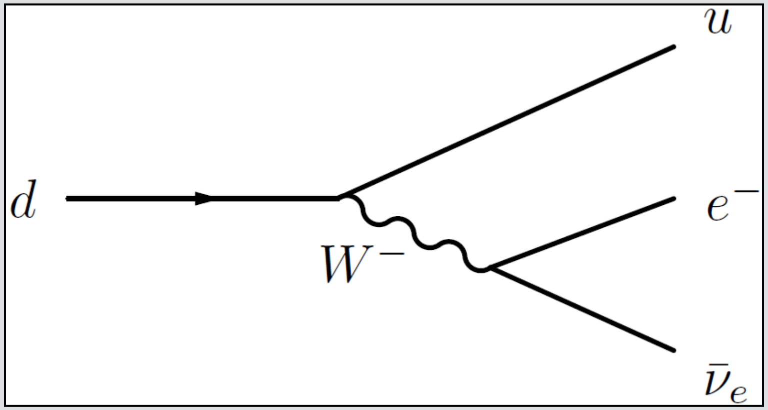




Effective couplings

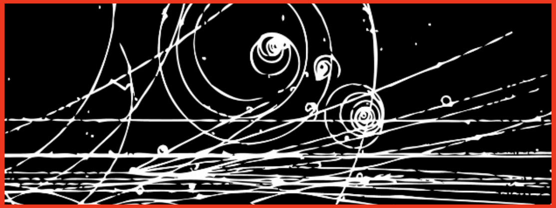
- Historical example





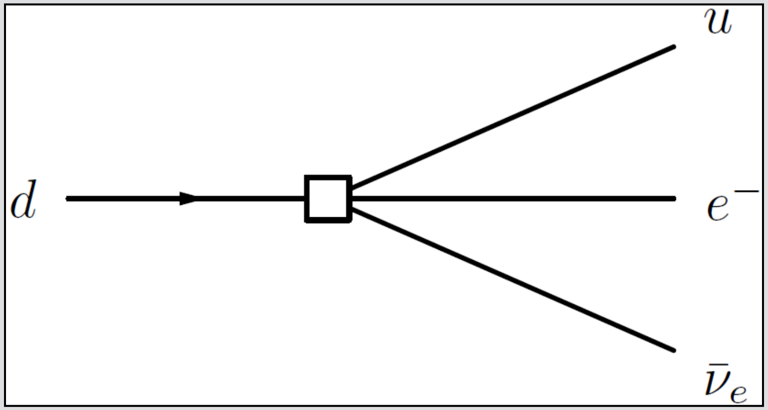
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

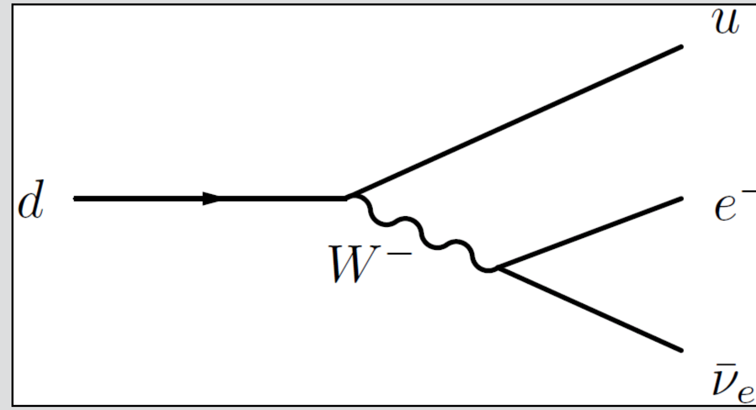
- Both are correct, depending on the energy scale you consider



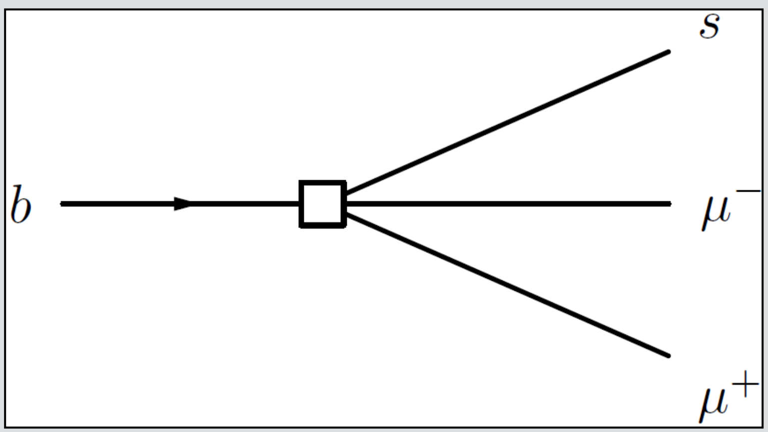
Effective couplings

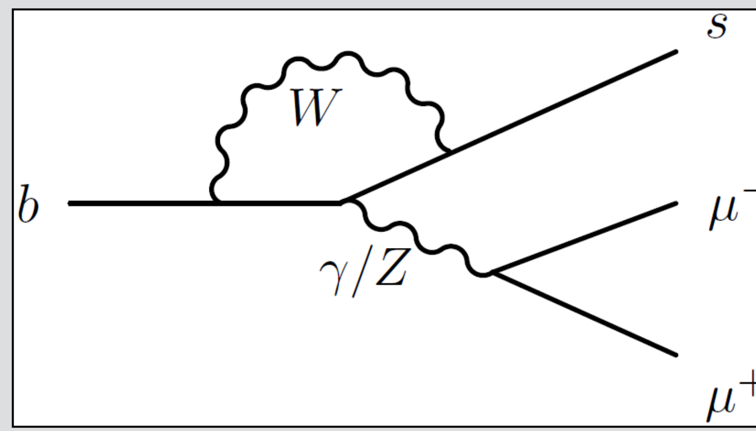
- Historical example





- Analog: Flavour-changing neutral current

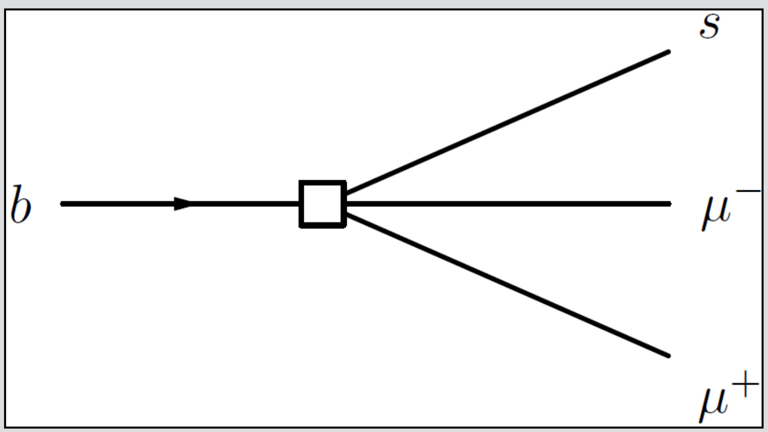


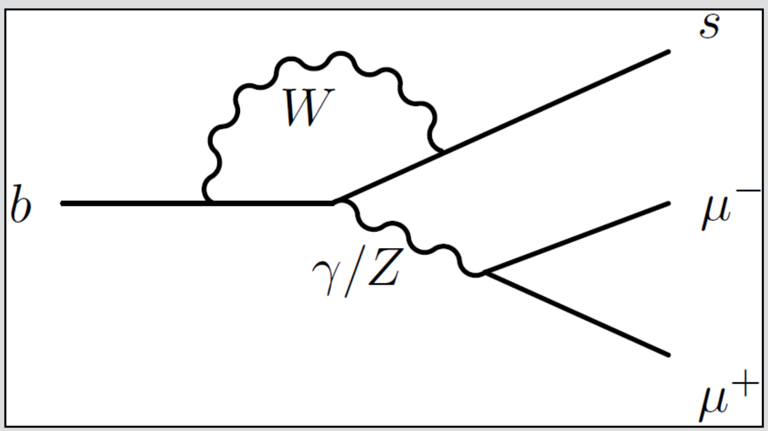


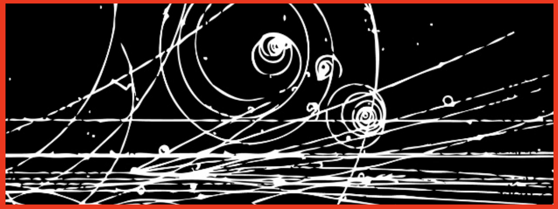
Effective couplings

- Effective coupling can be of various “kinds”
  - Vector coupling
  - Axial coupling
  - Left-handed coupling (V-A)
  - Right-handed (to quarks)
  - …

$$\mathcal{H}_{\text{eff}} = \frac{G_{\text{F}}}{\sqrt{2}} V_{\text{CKM}} \sum_i C_i(\mu) Q_i$$







Effective couplings

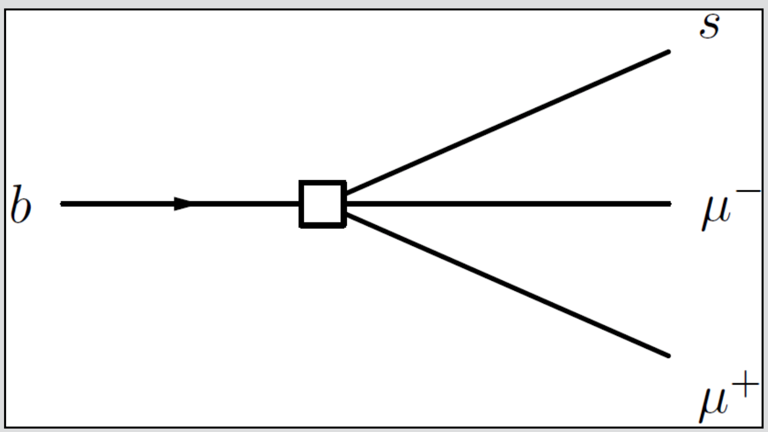
- Effective coupling can be of various "kinds"
  - Vector coupling: C_9
  - Axial coupling: C_{10}
  - Left-handed coupling (V-A): C_9-C_{10}
  - Right-handed (to quarks): C_9', C_{10}', …
  - …

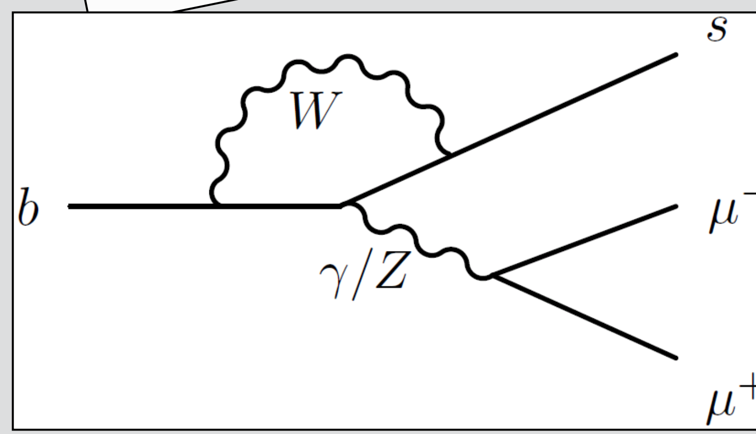
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{\text{CKM}} \sum_i C_i(\mu) Q_i$$

See e.g. Buras & Fleischer, hep-ph/9704376

Semi–Leptonic Operators (fig. 11f):

$$Q_{9V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V \qquad Q_{10A} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$





At this stage it should be mentioned that the usual Feynman diagram drawings of the type shown in fig. 11 containing full W-propagators, Z^0–propagators and top-quark propagators represent really the happening at scales $\mathcal{O}(M_W)$ whereas the true picture of a decaying hadron is more correctly described by the local operators in question. Thus, whereas at scales $\mathcal{O}(M_W)$ we have to deal with the full six-quark theory containing the photon, weak gauge bosons and gluons, at scales $\mathcal{O}(1\,\text{GeV})$ the relevant effective theory contains only three light quarks u, d and s, gluons and the photon. At intermediate energy scales $\mu = \mathcal{O}(m_b)$ and $\mu = \mathcal{O}(m_c)$ relevant for beauty and charm decays, effective five-quark and effective four-quark theories have to be considered, respectively.

From Buras & Fleischer, hep-ph/9704376

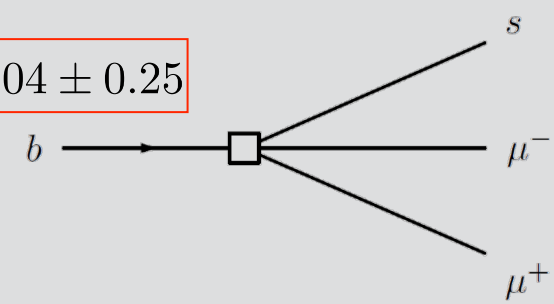
"the true picture of a decaying hadron is more correctly described by the local operators"

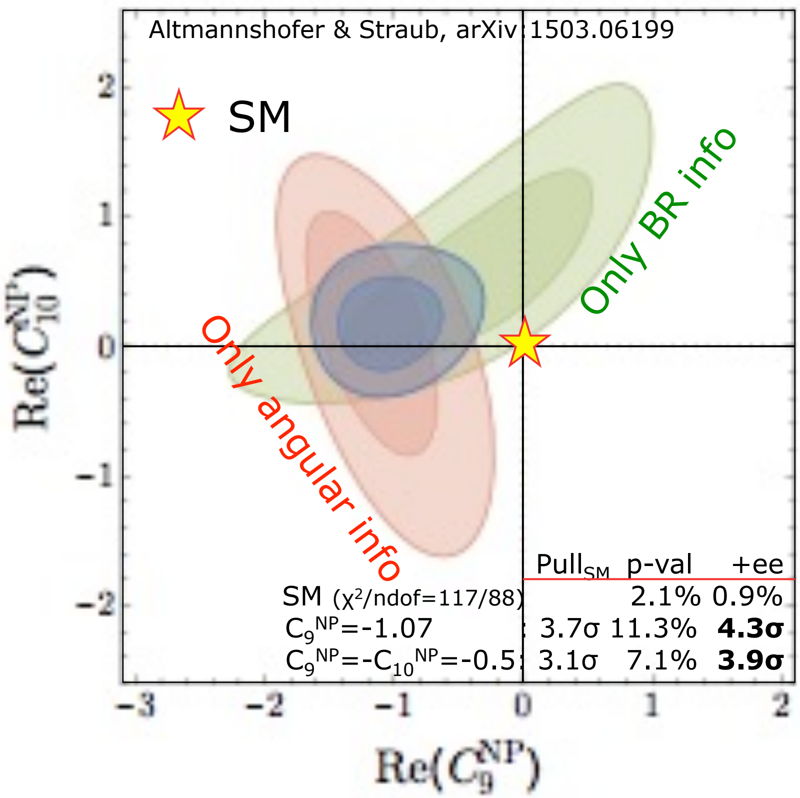
Model independent fits to b→sll processes

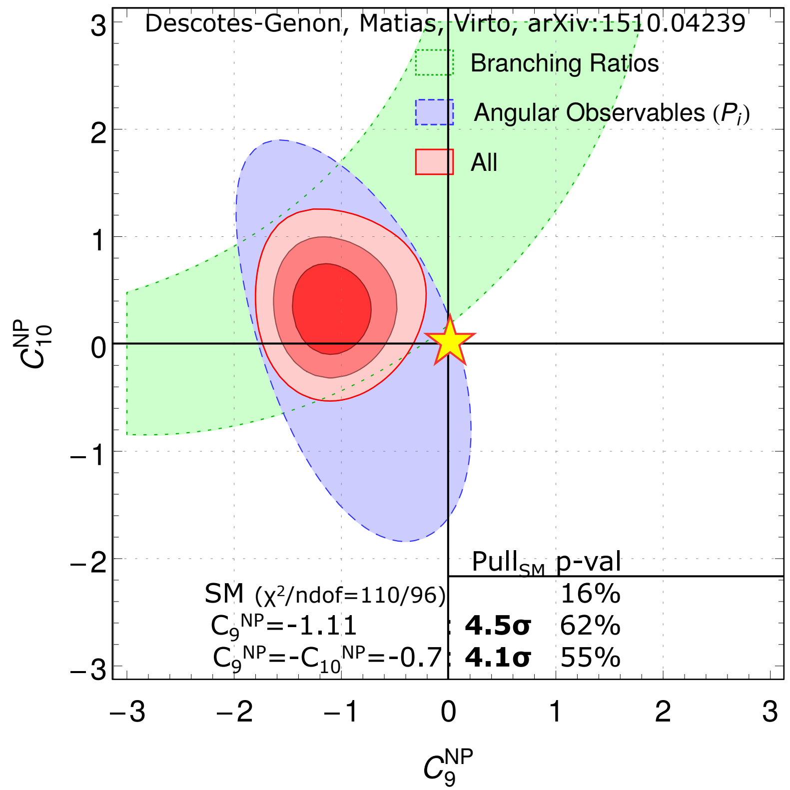
- C_9^{NP} deviates from 0 by >4σ
- Independent fits by more groups
  - C_9^{NP}=-1 or
  - $C_9^{NP}=-C_{10}^{NP}$
- Caveat: debate on charm-loop effects…

LHCb-PAPER-2015-051

$$\Delta\mathrm{Re}(\mathcal{C}_9) = -1.04 \pm 0.25$$

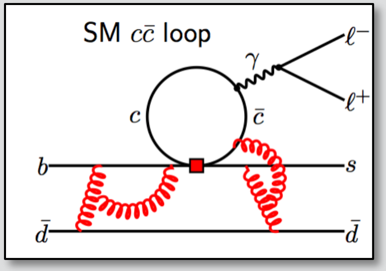


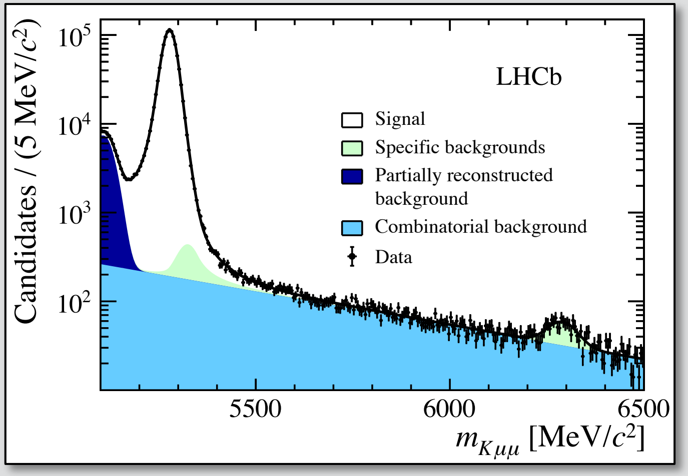




$B^+ \to K^+\mu^+\mu^-$ in detail

LHCb Coll., EPJ C77 (2017) 161

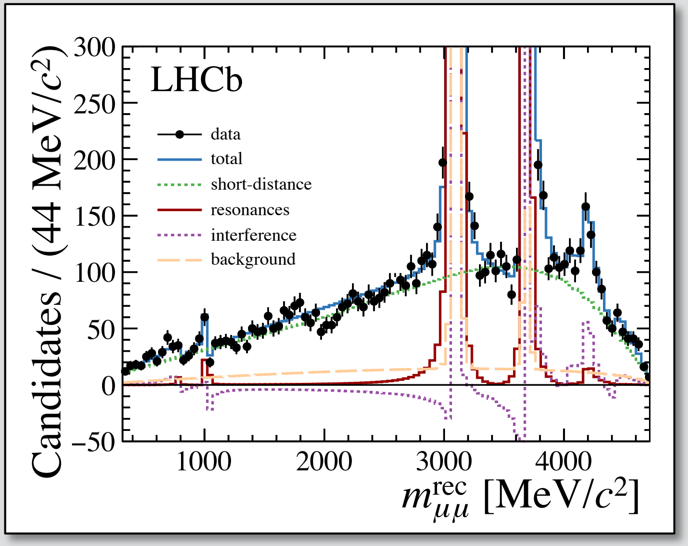


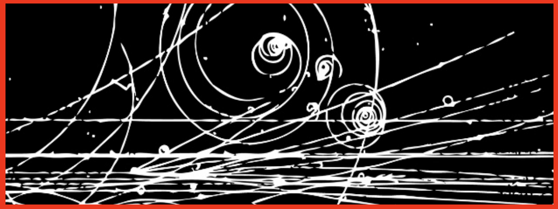


- Contributions from b→sll
  - $B^+ \to K^+\mu^+\mu^-$
- Contributions from b→scc
  - e.g. $B^+ \to K^+\varphi$, $B^+ \to K^+J/\psi$, $B^+ \to K^+\psi(2S)$, …
- Understand interference
  - Positive or negative?
  - More general: phase difference?
  - ➢ $\pm 90^0$
  - ➢ Small interference

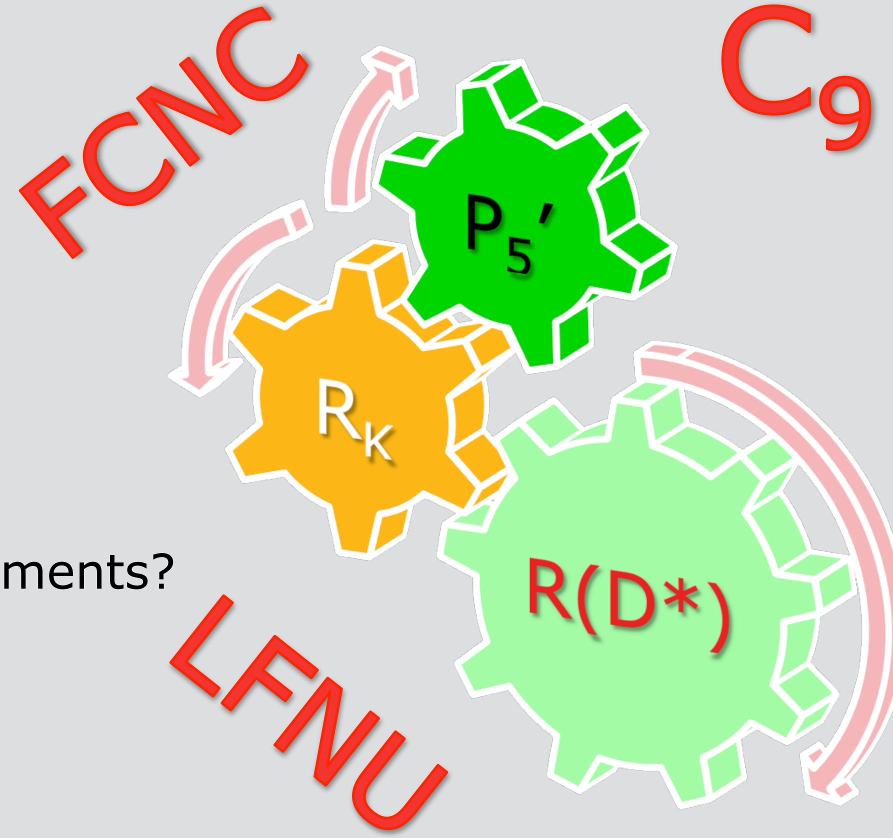
Resonance	Phase [rad]
J/ψ	-1.66 ± 0.05
$\psi(2S)$	-1.93 ± 0.10

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15\,(\text{stat}) \pm 0.23\,(\text{syst})) \times 10^{-7}$$

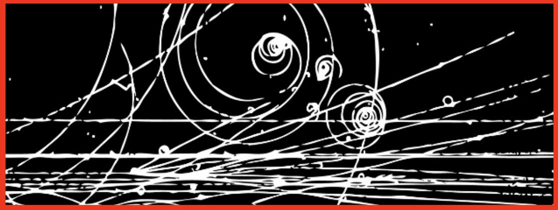




Outline



- Indirect measurements
- What are the (anomalous) measurements?
  - FCNC: b→sll
  - LFNU: b→sll and b→clν
- What are the interpretations?

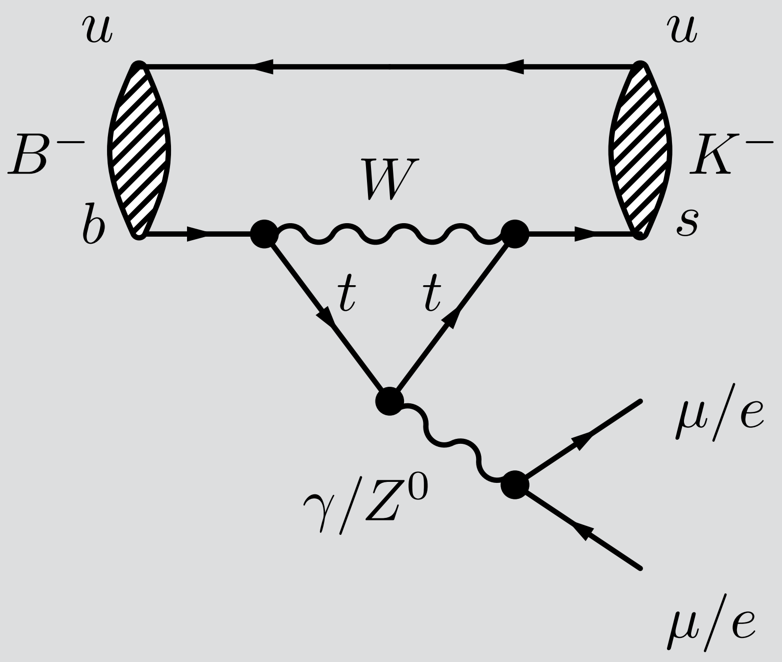


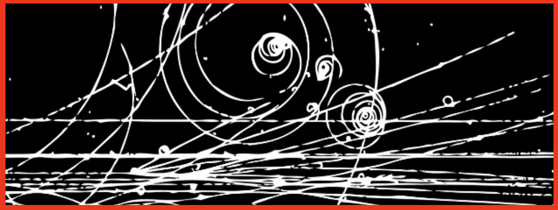
$B \rightarrow K\mu^+\mu^-$

- Similar loop diagram!

- Measure ratio μ/e
- SM expectation: $R_K=1$

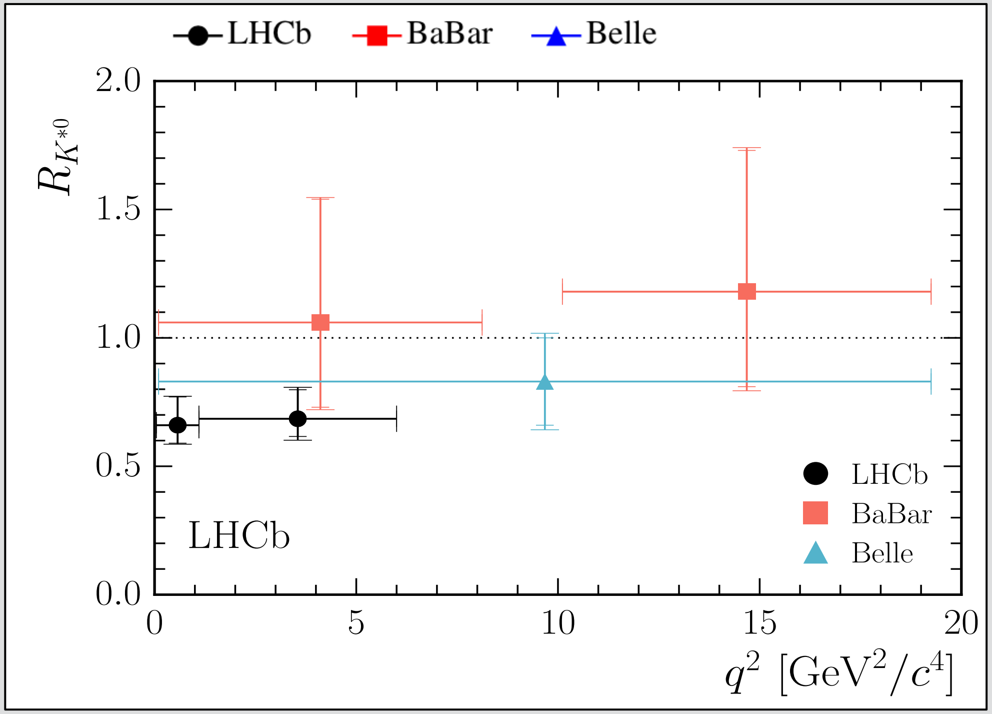
$$R_K = \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)}$$





$B^0 \to K^{0*}\mu^+\mu^-$

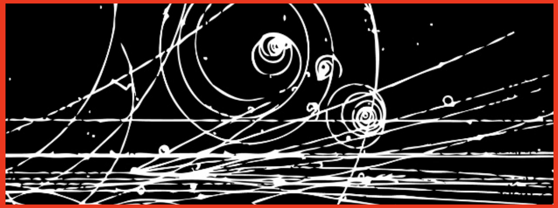
- Similar loop diagram!
- Measure ratio μ/e
- SM expectation: $R_{K*}=1$
- Extra bin at low q^2…
  - $q^2 \sim 0$ not helicity suppressed



LHCb Coll., JHEP 1708 (2017) 055

$$R_{K^{*0}} = \begin{cases} 0.66\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4 \\ 0.69\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0\ \text{GeV}^2/c^4 \end{cases}$$

- **Lepton flavour "non-universal" ?**



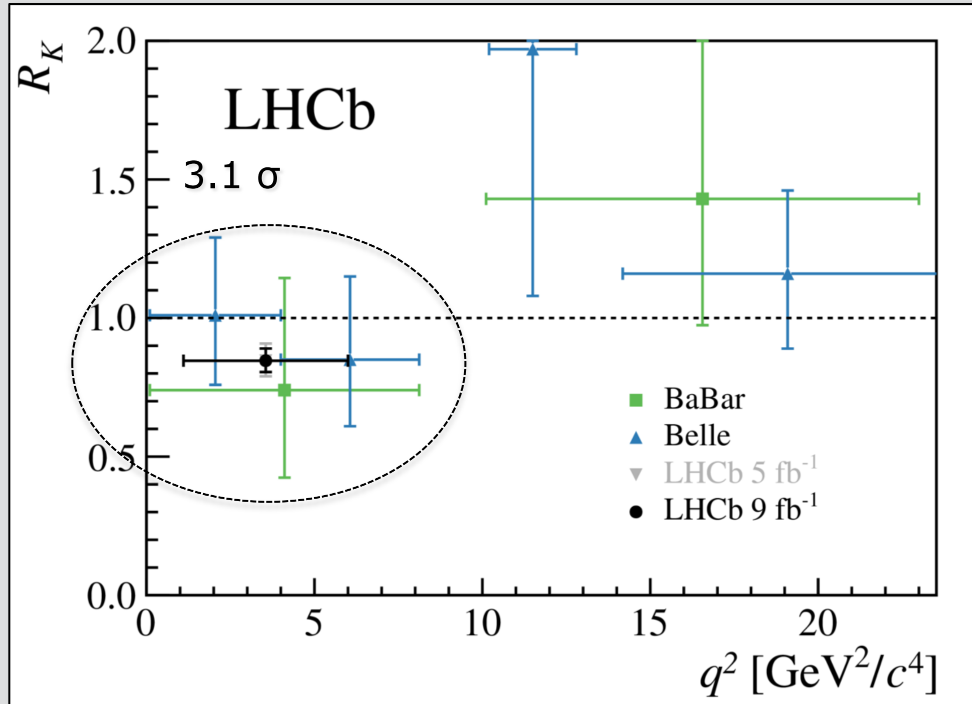
$B^+ \to K^+ \mu^+ \mu^-$

- Similar loop diagram!

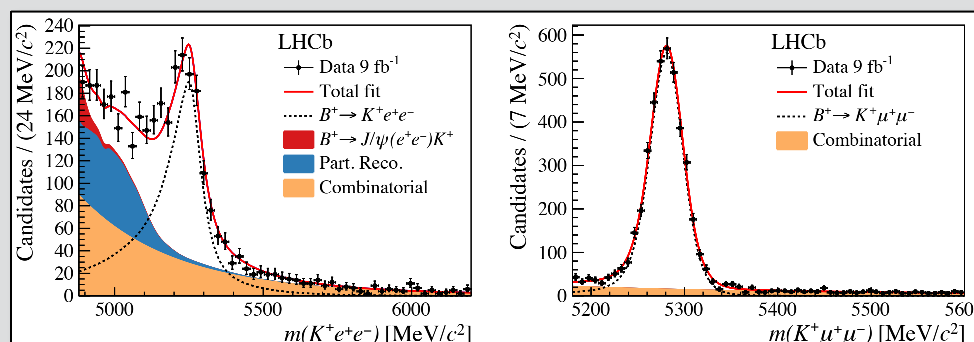
- Measure ratio μ/e
- SM expectation: $R_K = 1$

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

$$R_K = 0.846 \begin{array}{l} +0.044 \\ -0.041 \end{array}$$



LHCb Coll.,arXiv:2103.11769



- **Lepton flavour "non-universal" ?**

New result

R_K - Analysis

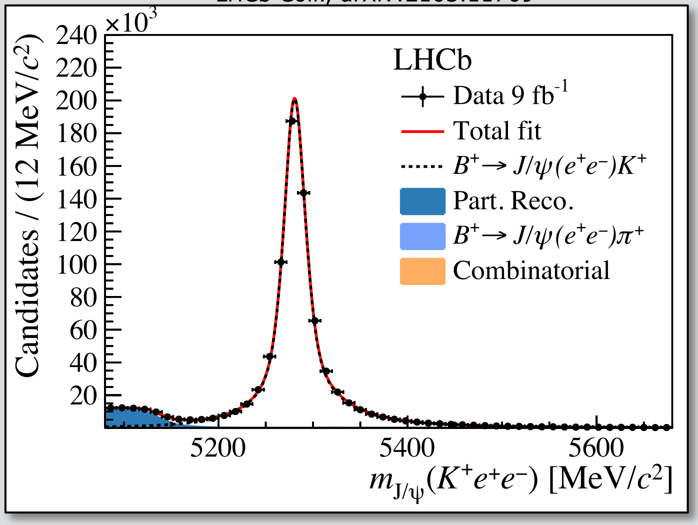
- Double ratio:

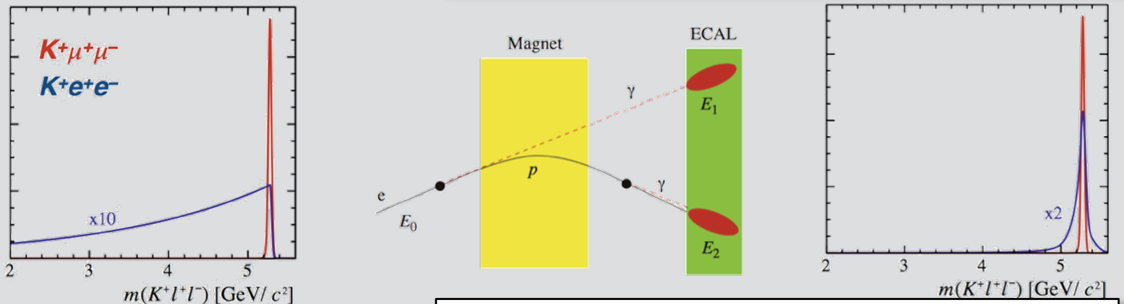
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

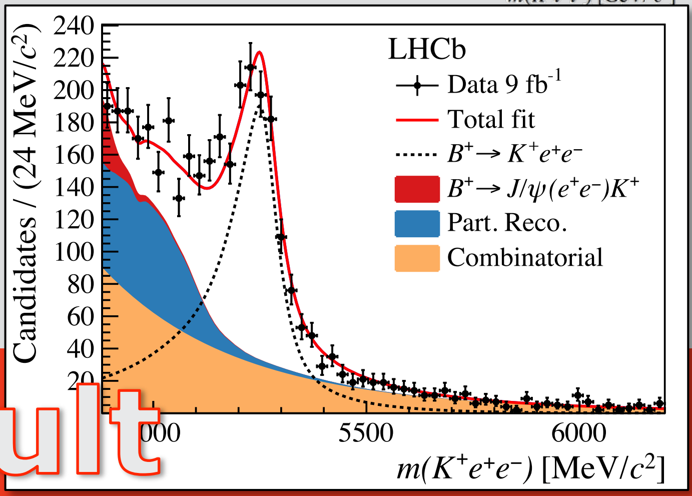
- Bremstrahlung correction

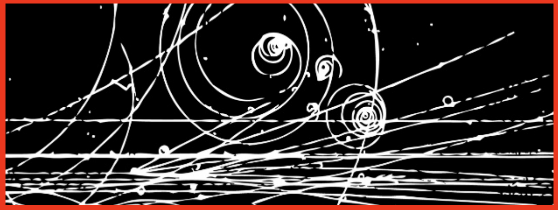
- Statistically dominated by $B^+ \to K^+ ee$

LHCb Coll., arXiv:2103.11769









New result

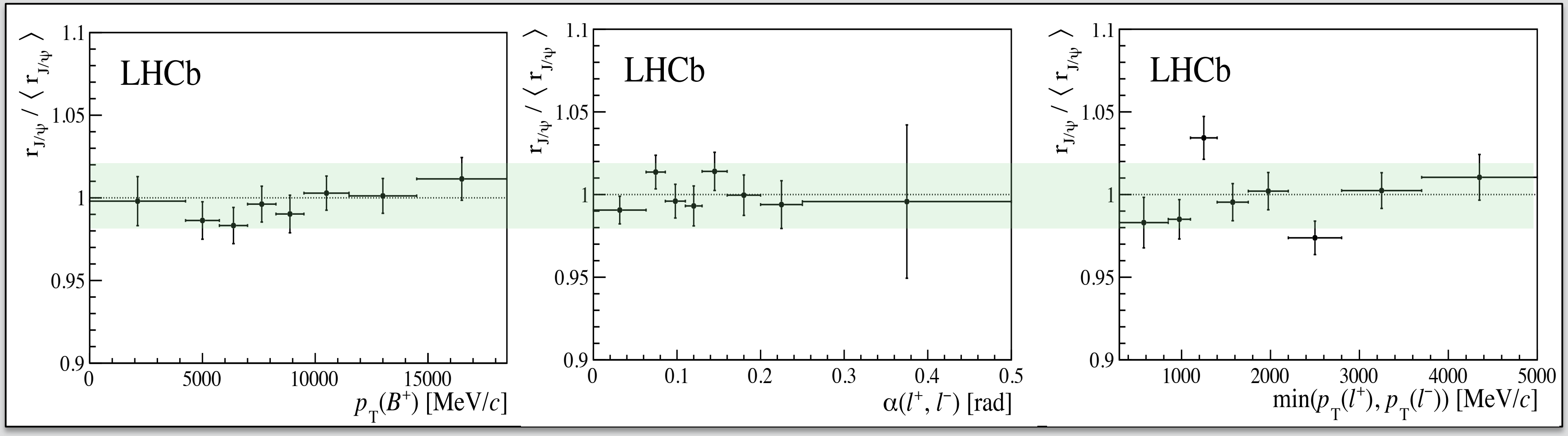
R_K - Analysis

- Event yields:

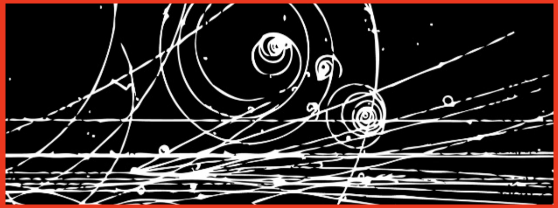
Decay mode	Yield
$B^+ \to K^+ e^+ e^-$	$1\,640 \pm 70$
$B^+ \to K^+ \mu^+ \mu^-$	$3\,850 \pm 70$
$B^+ \to J/\psi\,(\to e^+e^-)K^+$	$743\,300 \pm 900$
$B^+ \to J/\psi\,(\to \mu^+\mu^-)K^+$	$2\,288\,500 \pm 1\,500$

- $r_{J/\psi}$: control across phase space! $\langle r_{J/\psi} \rangle = 0.981 \pm 0.020$

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



- $R_{\psi(2S)}$: $$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi\,(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi\,(\to e^+e^-)K^+)} = 0.997 \pm 0.011$$



New result

R_{K^*} - Cross checks

- Check with J/ψ
  - Unity with 4.5% at 1σ

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006(\text{stat}) \pm 0.045(\text{syst})$$

- Check with ψ(2S)
  - Unity within 2% at 1σ

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

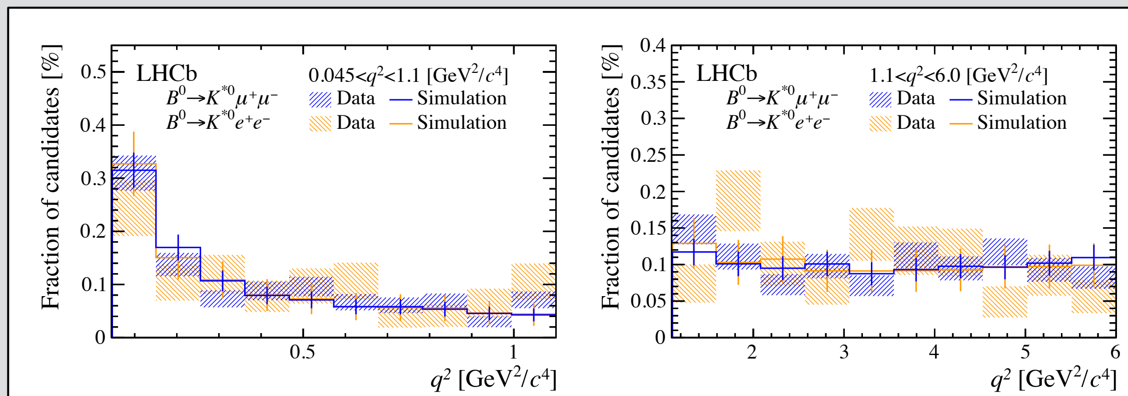
- Check BR($B^0 \to K^*\gamma(\to ee)$)
  - Agrees within 15% at 2σ

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

- Cross checked with earlier $d\Gamma/dq^2(B^0 \to K^*\mu\mu)$
  - Consistent

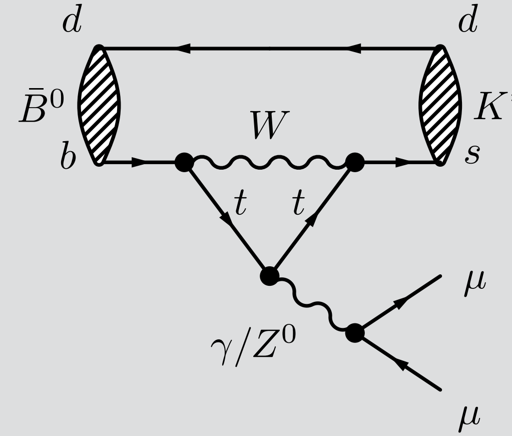
LHCb Coll., JHEP 1611 (2016) 47
Erratum: JHEP 1704 (2017) 14

- Data vs simulation:

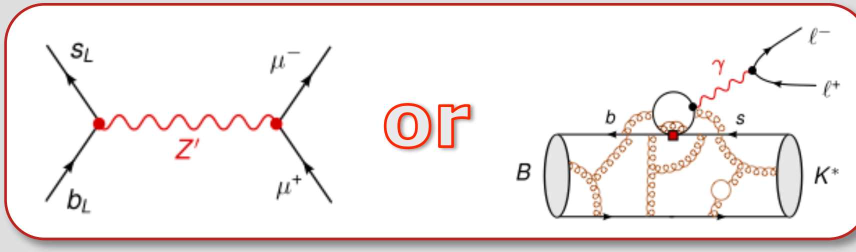


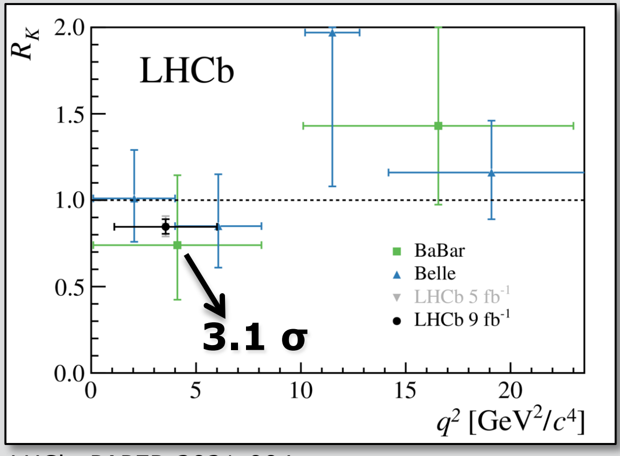
Summary $b \to sll$

- FCNC: EW penguin

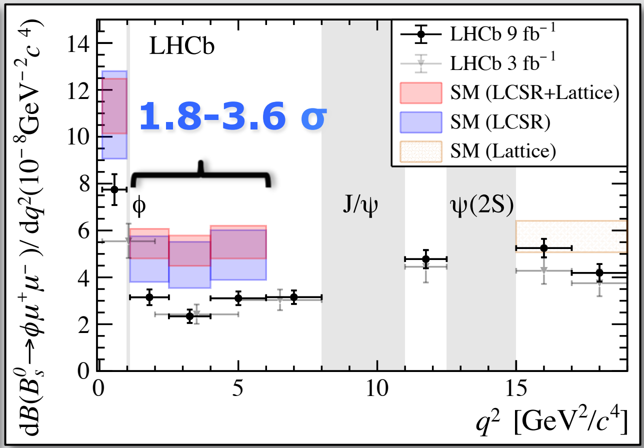


- Curious tensions:
  - Lepton flavour universality
  - Decay rates
  - Angular distributions, P_5'

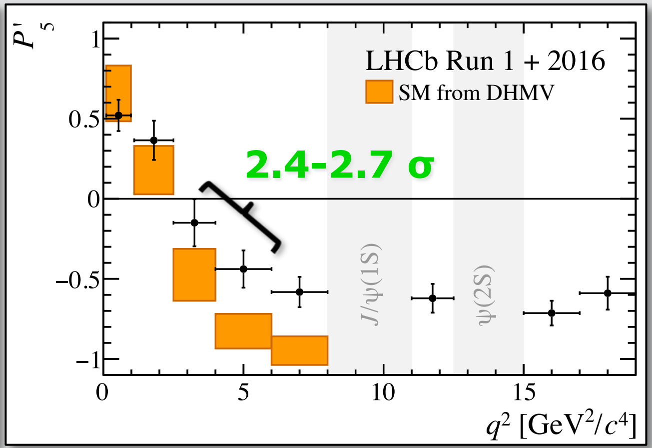




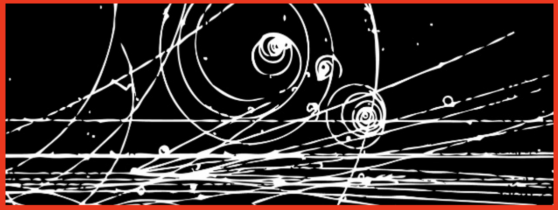
LHCb, PAPER-2021-004



LHCb, PAPER-2021-014

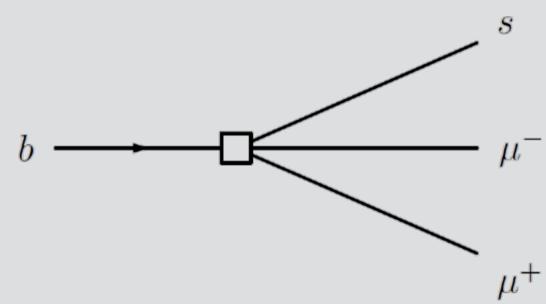


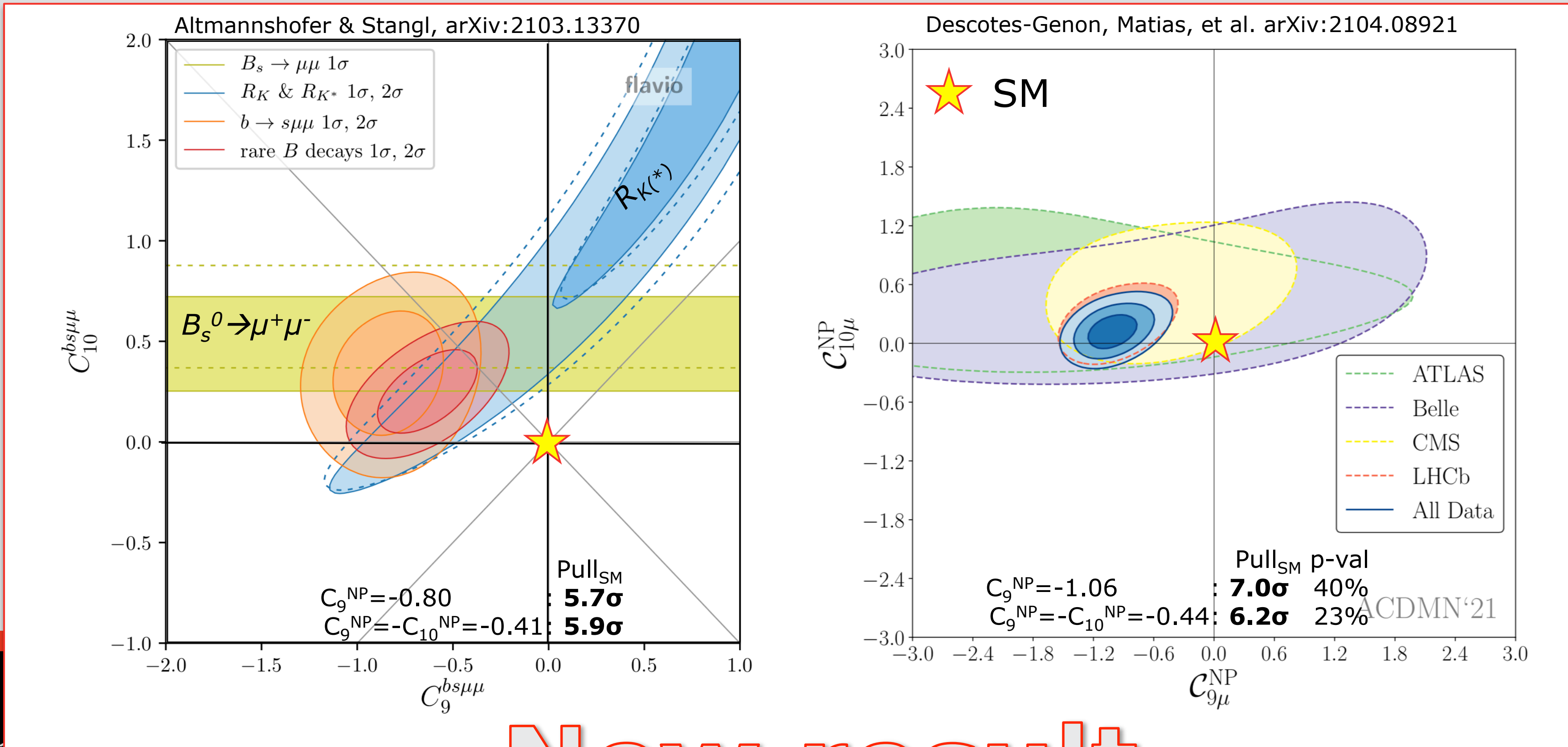
LHCb, arXiv:2003.04831



Model independent fits to b→sll processes

- C_9^{NP} deviates from 0 by >4σ
- Independent fits by more groups
  - 1D: $C_9^{NP}=-1$ or $C_9^{NP}=-C_{10}^{NP}$??
  - NB: Many possibilities (2D, RH, …) !
- Caveat: debate on charm-loop effects…

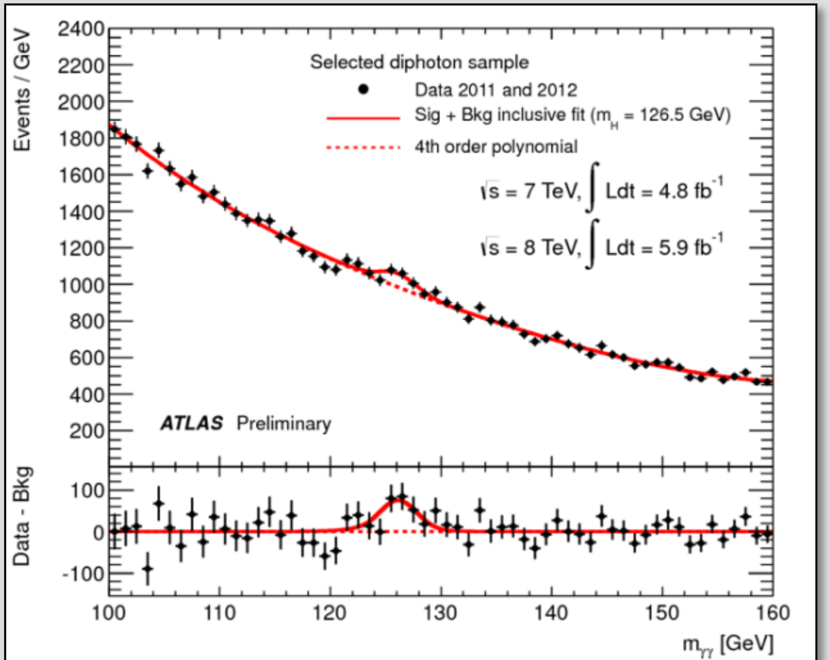


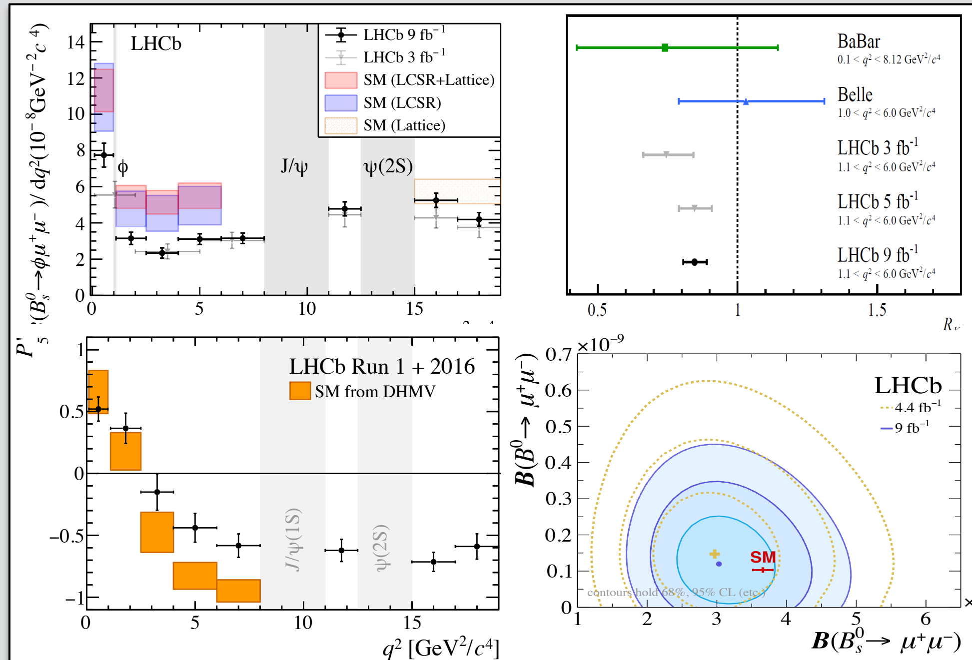


New result

Quantifying significance ?

Higgs vs $b \rightarrow sl^+l^-$





χ^2 of null hypothesis?

Good | Good

$\Delta\chi^2$ wrt discovery hypothesis *(coherent pattern)* ?

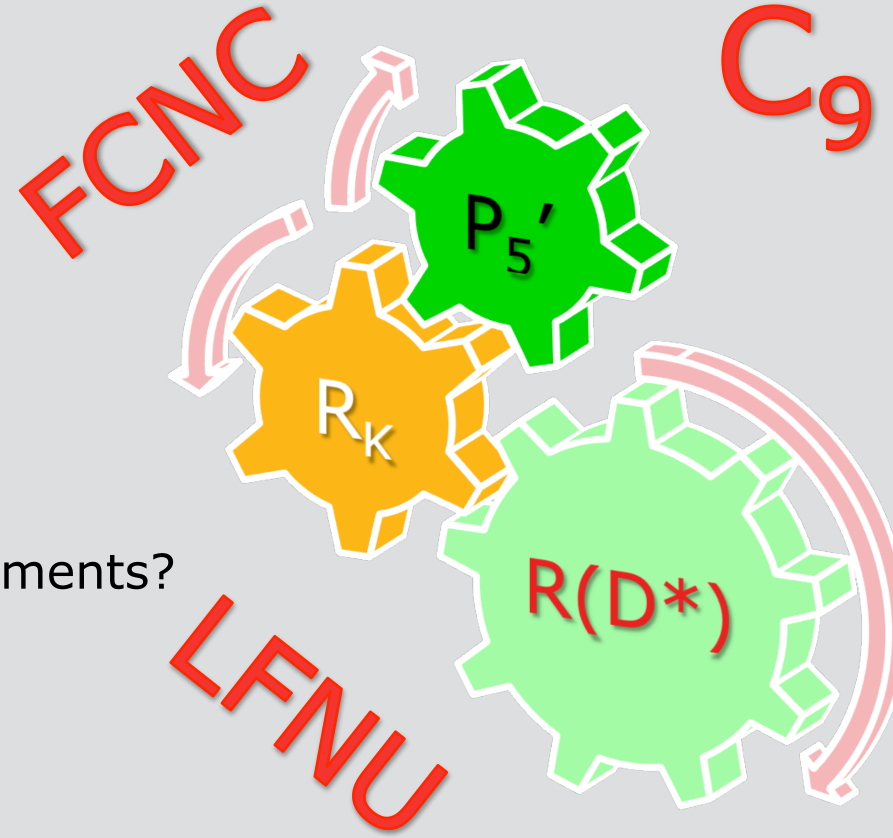
Favour Gauss | Favour $(C_9, C_{10})^{NP}$

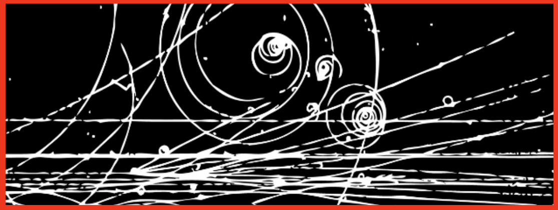
Look-elsewhere effect *(eg. arXiv:2104.05631)* ?

1-dim Mass range | n-dim Wilson space

Outline

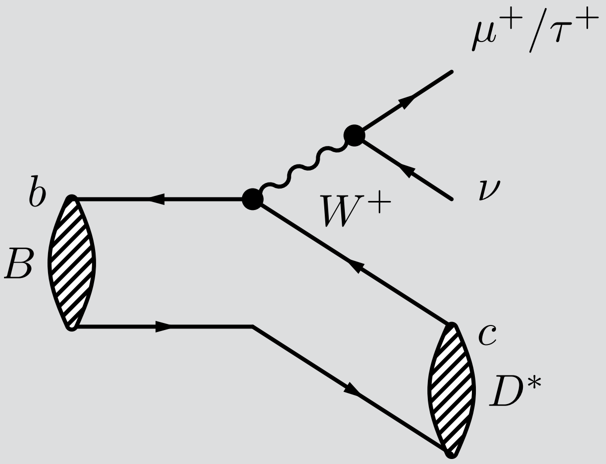
- Indirect measurements
- What are the (anomalous) measurements?
  - FCNC: b→sll
  - LFNU: b→sll and b→clν
- What are the interpretations?

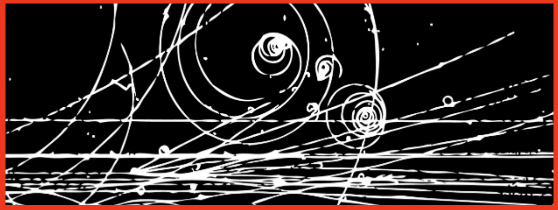




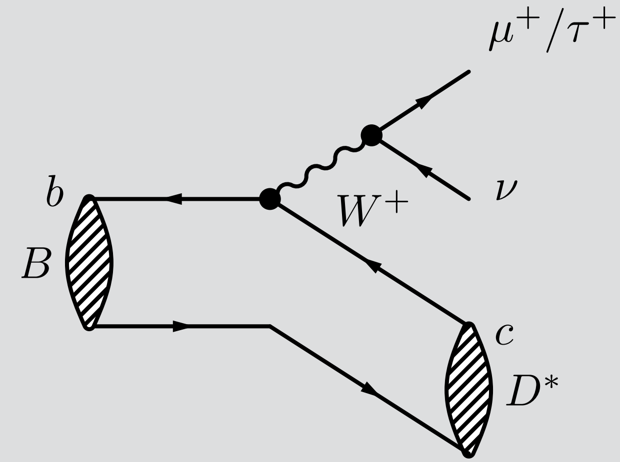
More LFNU ?!

- Surprises possible in tree-level decays?

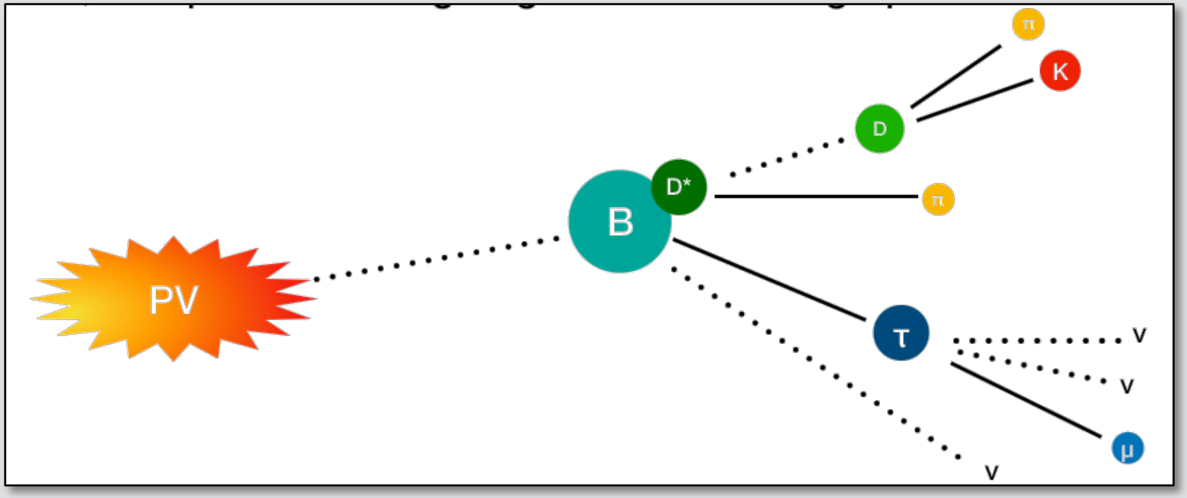


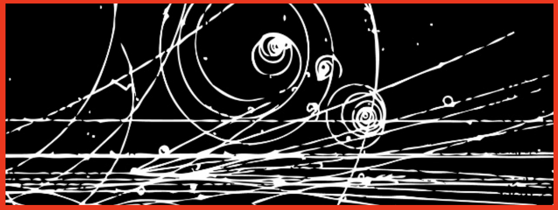


More LFNU: *b→clν*



- Surprises possible in tree-level decays?
- Challenging analysis:
  - Missing neutrino
  - Background from $B \to D^{**}\mu$
- Compare $B \to D^*\mu\nu$ with $B \to D^*\tau(\to\mu\nu\nu)\nu$: similar final state!



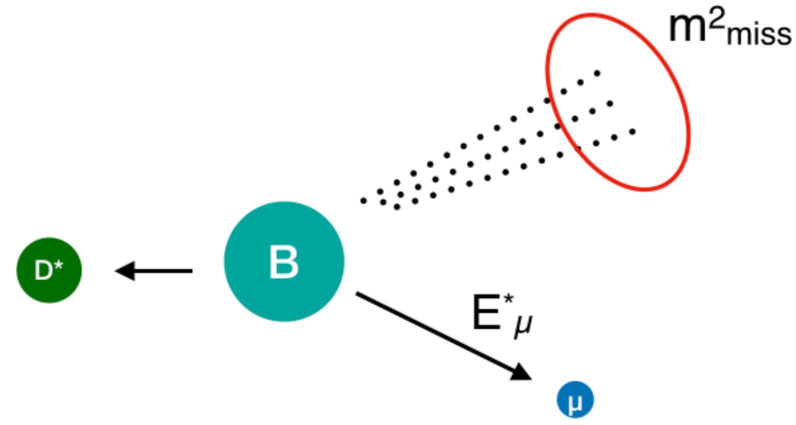


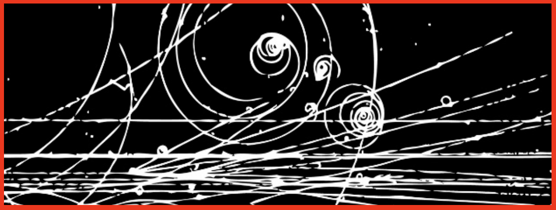
Semileptonic *B→D*νμ(τ)* decays: *b→clν*

Discriminating variables:

- m^2_{miss}: Missing mass (neutrino + ?)
- E^*_μ: Energy of muon in *B* rest frame
- q^2: Invariant mass of lepton-pair

$B^0 \to D^{*+}\tau^-\nu$	$B^0 \to D^{*+}\mu^-\nu$
$m^2_{miss} > 0$	$m^2_{miss} = 0$
E^*_ℓ spectrum is soft	E^*_ℓ spectrum is hard
$m^2_\tau \le q^2 \le 10.6\ \mathrm{GeV}^2$	$0 \le q^2 \le 10.6\ \mathrm{GeV}^2$





Semileptonic *B→D*νμ(τ)* decays: *b→clν*

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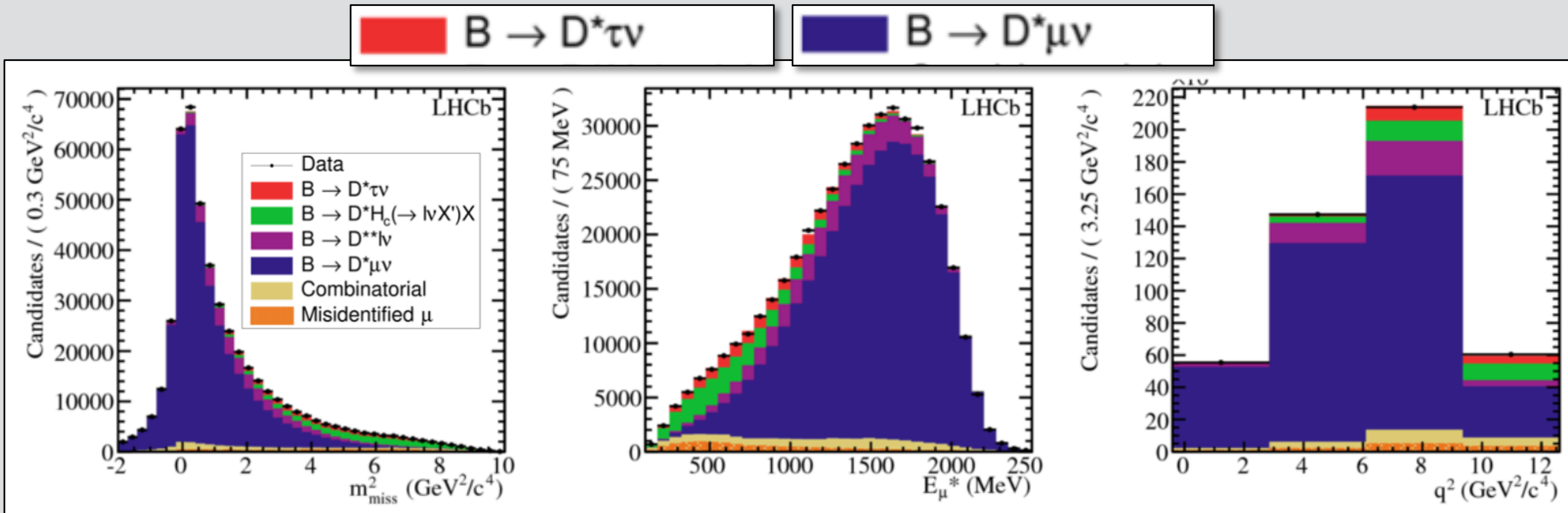
- E^*_μ: Energy of muon in *B* rest frame
- q^2: Invariant mass of lepton-pair

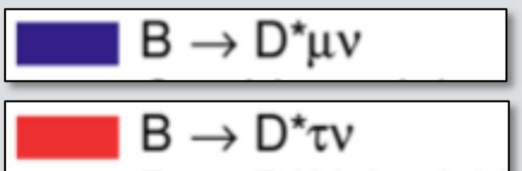


LHCb Coll., Phys. Rev. Lett. 115 (2015) 159901

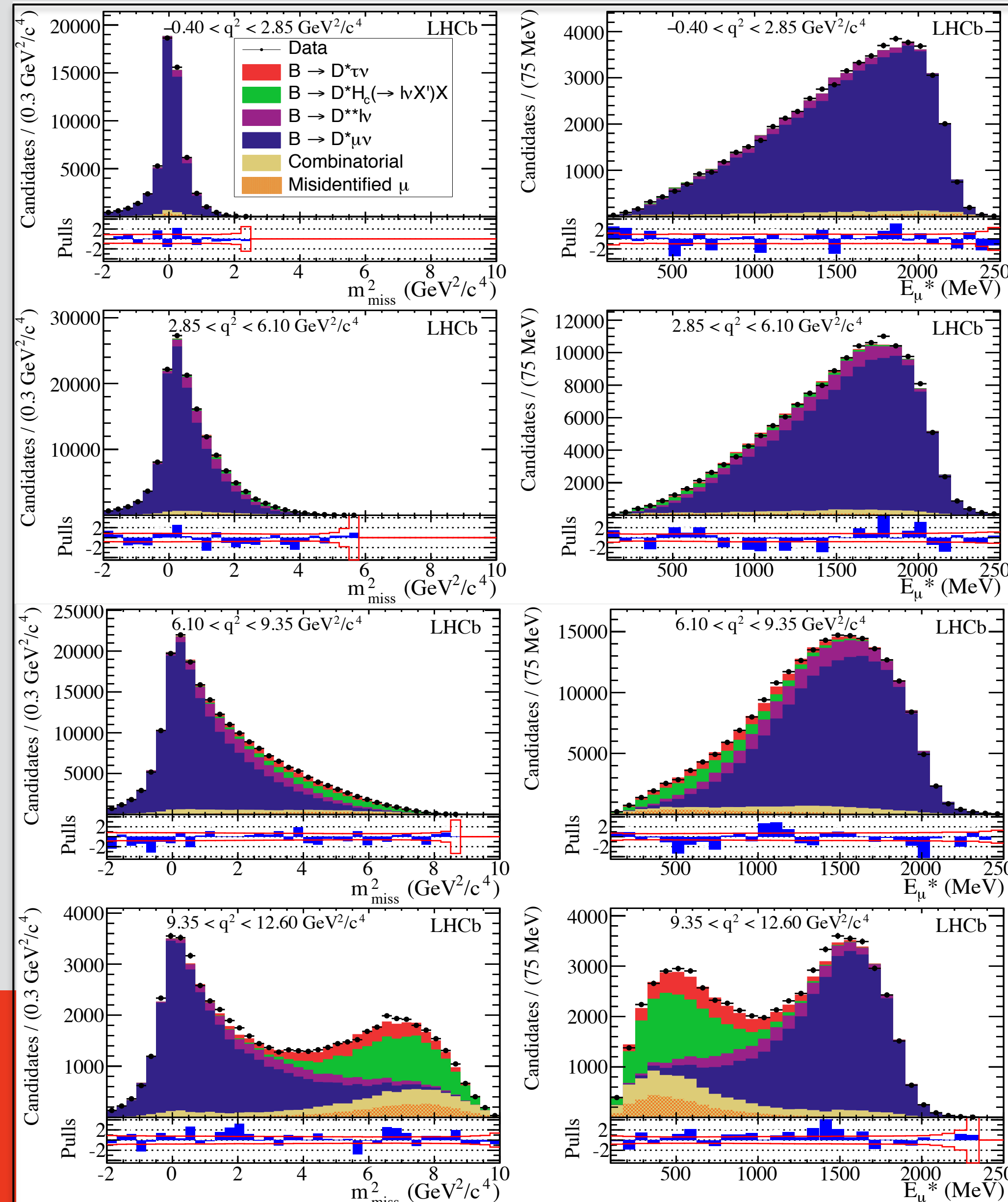
Semileptonic $B \to D^*\nu\mu(\tau)$ decays: $b \to cl\nu$

Discriminating variables:

- m^2_{miss}
- E^*_μ
- in bins of q^2:



q^2



LHCb Coll., PRL115 (2015) 111803

Semileptonic $B \to D^* \nu \mu(\tau)$ decays: $b \to c l \nu$

- Surprises possible in tree-level decays?

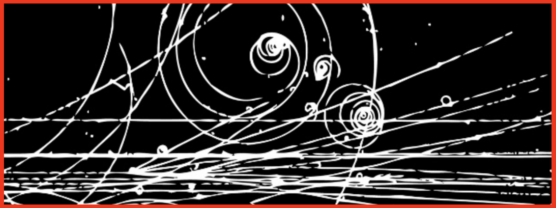
$$\mathcal{R}(D^*) \equiv \mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$$

- $B^0 \to D^* l \nu$
  - Measured ratio τ/μ :

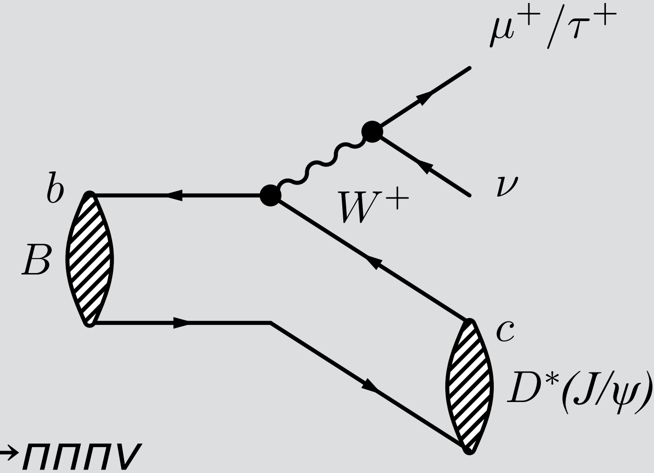
$$\mathcal{R}(D^*) = 0.336 \pm 0.027\,(\mathrm{stat}) \pm 0.030\,(\mathrm{syst})$$

  - SM: $R(D^*) = 0.252 \pm 0.003$
    - Different from unity due to smaller phase space for tau decays

      Fajfer, Kamenik, Nisandzic PRD 85, 094025 (2012)



More measurements!



- R(D*) from Babar and Belle
- R(D) from Babar and Belle

- R(D*) from LHCb with hadronic tau decays, $\tau \to \pi\pi\pi\nu$

$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+) = 1.93 \pm 0.13 \pm 0.18$$

$$\mathcal{R}(D^{*-}) = 0.286 \pm 0.019 \pm 0.025 \pm 0.021$$

$$\mathcal{B}(B^0 \to D^{*-}3\pi) = (7.23 \pm 0.51) \times 10^{-3}$$

$$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu) = (4.88 \pm 0.10) \times 10^{-2}$$

LHCb Coll. arXiv:1711.02505

- R(J/ψ) from LHCb (< 2σ)

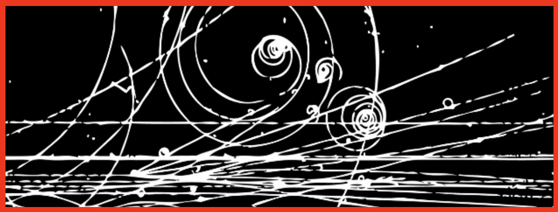
$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$$

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

LHCb Coll. arXiv:1711.05623

- R(Λ_c), R(D), R(D_s) being analyzed

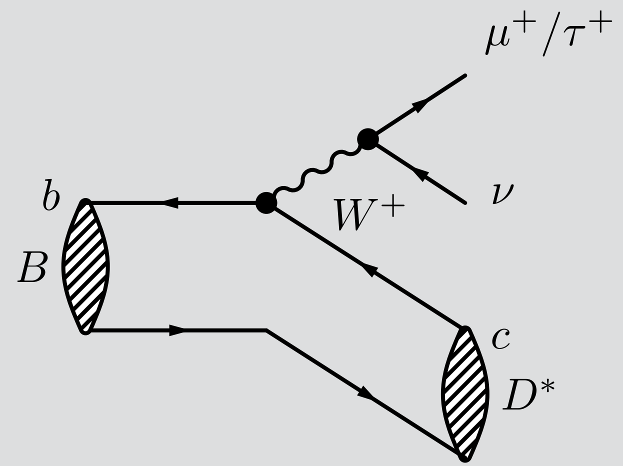
- Run-2 data on the shelves!

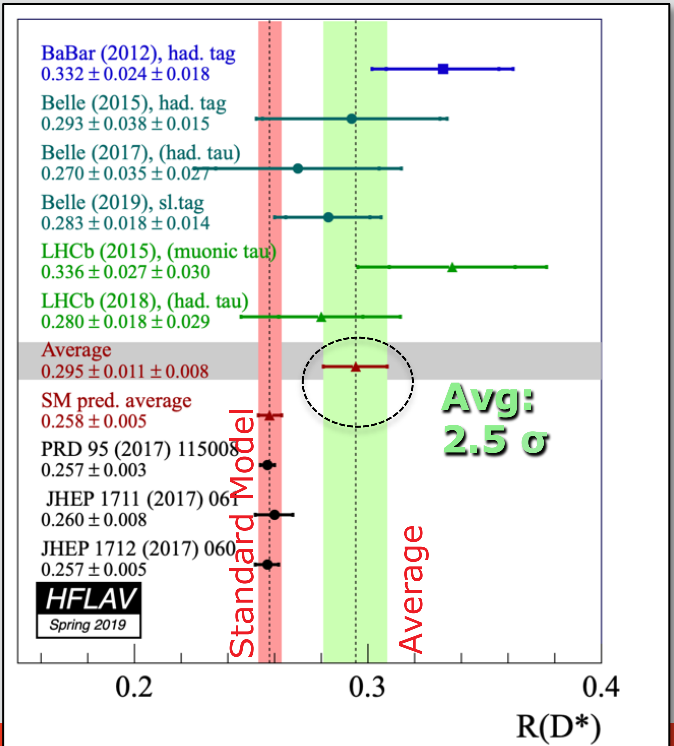


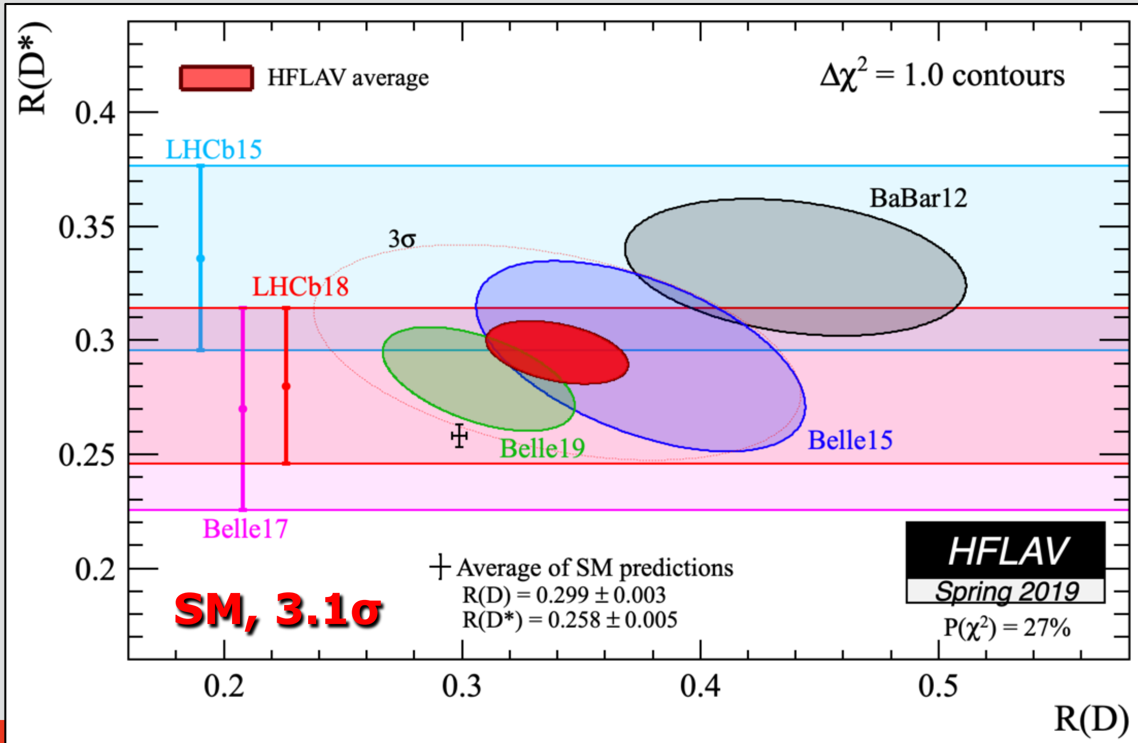
More LFNU

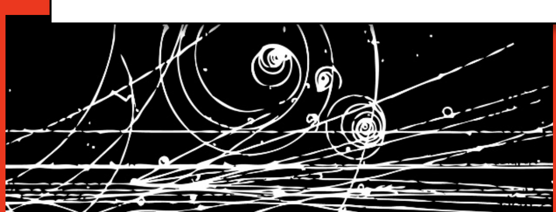
- Surprises possible in tree-level decays

- $B \to D^{(*)} l \nu$
  - R(D) and R(D*) combined: 3.1 σ



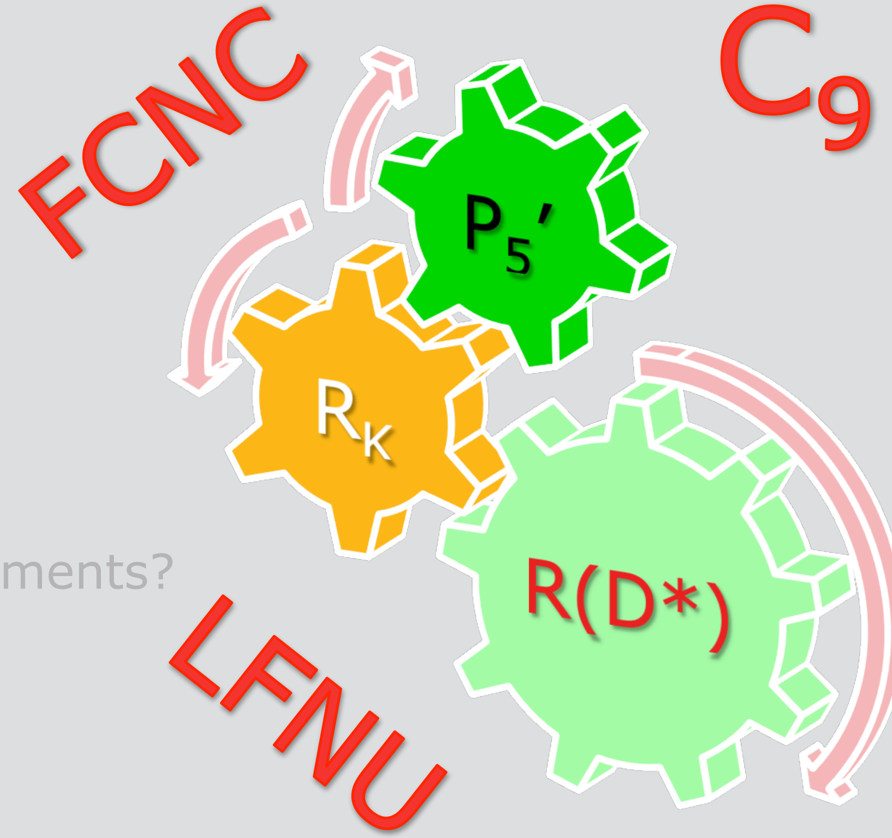


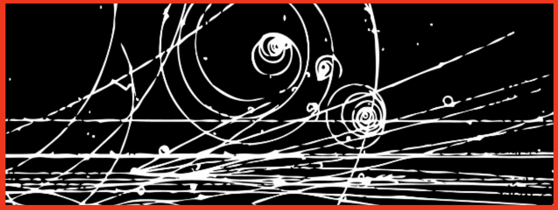




Outline

- Indirect measurements
- What are the (anomalous) measurements?
  - FCNC: b→sll
  - LFNU: b→sll and b→clν
- What are the interpretations?





What NP could it be?

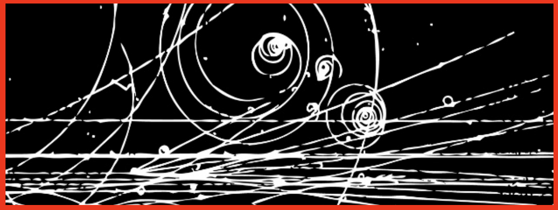
- If interpreted as NP signals, both set of anomalies are not in contradiction among themselves & with existing low- & high-energy data.
Taken together, they point out to NP coupled mainly to 3rd generation, with a flavor structure connected to that appearing in the SM Yukawa couplings

G. Isidori, *Implications workshop*, CERN, 10 Nov 2017
https://indico.cern.ch/event/646856/timetable/

- Indirect measurements

- What are the (anomalous) measurements?
  - FCNC: b→sll
  - LFNU: b→sll and b→clν

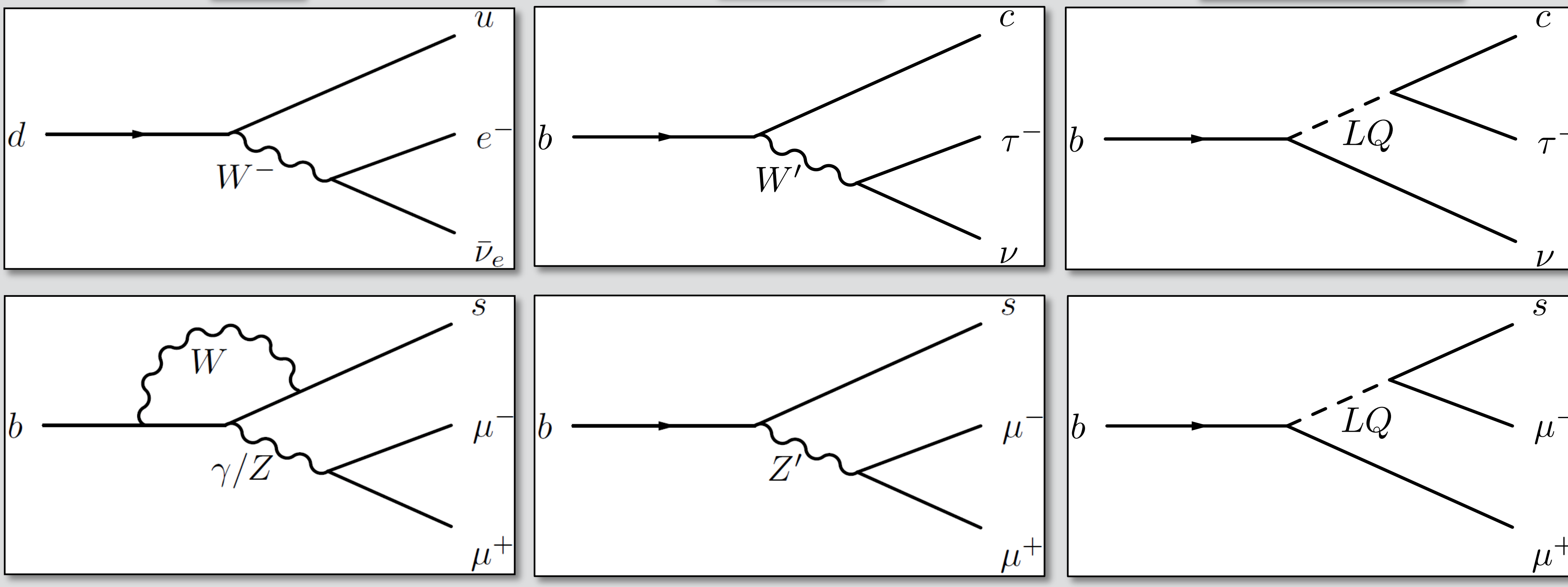
- What are the interpretations?

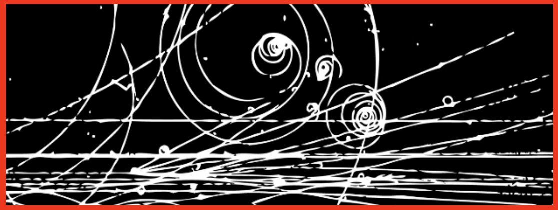


Model building

- Most popular models: Z′ or Leptoquark

SM | SU(2)′ | Leptoquark

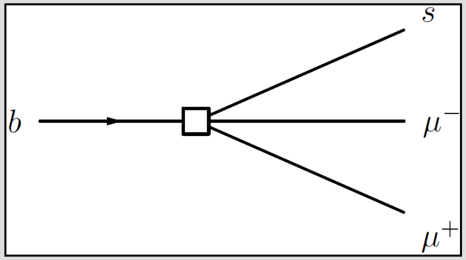




Buttazzo, Greljo, Isidori, Marzocca,
B-physics anomalies: a guide to combined explanations
JHEP 1711 (2017) 044

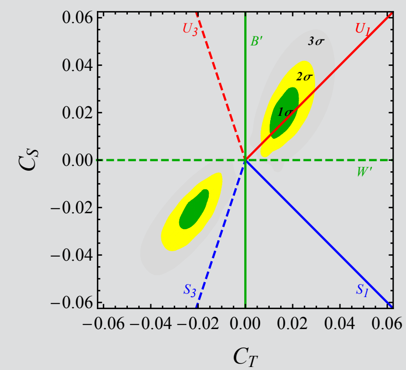
Model building

- Step 1: Effective theory

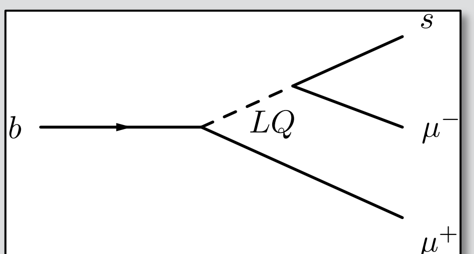


$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

Observable	Experimental bound	Linearised expression
$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1-\lambda^q_{sb}V^*_{tb}/V^*_{ts})(1-\lambda^\ell_{\mu\mu}/2)$
$\Delta C^\mu_9 = -\Delta C^\mu_{10}$	-0.61 ± 0.12 [36]	$-\frac{\pi}{\alpha_{\text{em}}V_{tb}V^*_{ts}}\lambda^\ell_{\mu\mu}\lambda^q_{sb}(C_T + C_S)$
$R^{\mu e}_{b\to c} - 1$	0.00 ± 0.02	$2C_T(1-\lambda^q_{sb}V^*_{tb}/V^*_{ts})\lambda^\ell_{\mu\mu}$
$B_{K^{(*)}\nu\bar{\nu}}$	0.0 ± 2.6	$1 + \frac{2}{3}\frac{\pi}{\alpha_{\text{em}}V_{tb}V^*_{ts}C^{\text{SM}}_\nu}(C_T - C_S)\lambda^q_{sb}(1+\lambda^\ell_{\mu\mu})$
$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033C_T - 0.043C_S$
$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033C_T - 0.043C_S$
$\lvert g^W_\tau / g^W_\ell \rvert$	1.00097 ± 0.00098	$1 - 0.084C_T$
$\mathcal{B}(\tau \to 3\mu)$	$(0.0 \pm 0.6) \times 10^{-8}$	$2.5 \times 10^{-4}(C_S - C_T)^2(\lambda^\ell_{\tau\mu})^2$



- Step 2: Simplified models

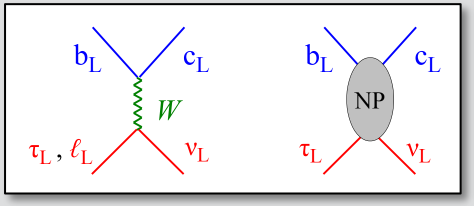


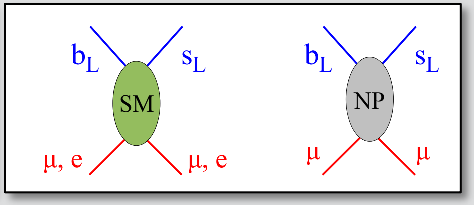
$SU(2)_L$-singlet vector leptoquark, $U^\mu_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$

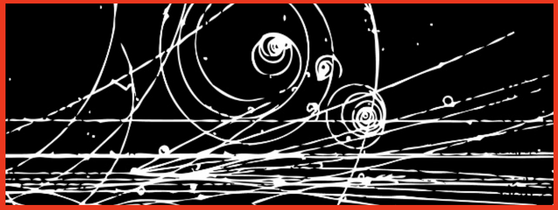
$$\mathcal{L}_U = -\frac{1}{2}U^\dagger_{1,\mu\nu}U^{1,\mu\nu} + M^2_U U^\dagger_{1,\mu}U^\mu_1 + g_U(J^\mu_U U_{1,\mu} + \text{h.c.})$$
$$J^\mu_U \equiv \beta_{i\alpha}\ \bar{Q}_i\gamma^\mu L_\alpha\ .$$

Model building

- Ingredients
  - NP: large coupling $b \rightarrow c\tau\nu$
    - Large coupling to 3rd gen leptons
    - Left-handed coupling (no RH neutrino)
  - NP: small (non-vanishing) coupling $b \rightarrow s\mu\mu$
    - Small coupling to 2nd gen leptons
    - Left-handed coupling (from C_9)







Model building

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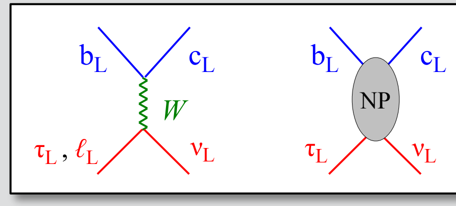
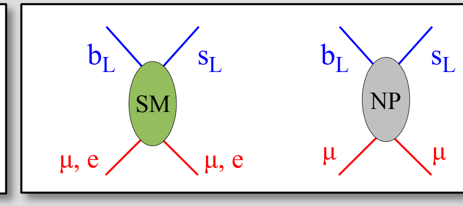
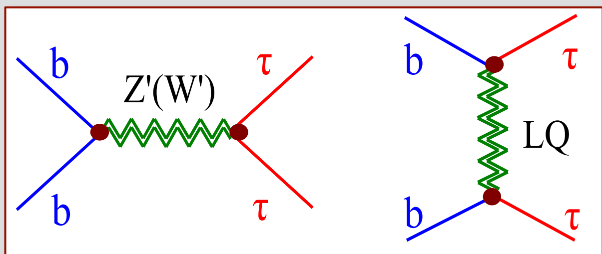
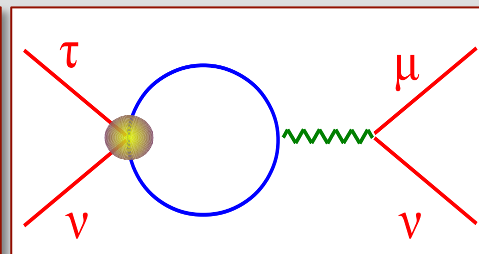
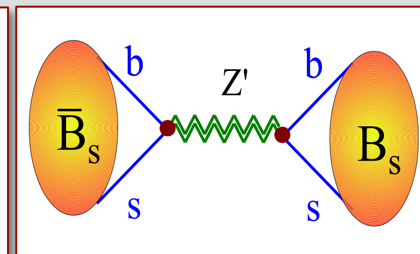
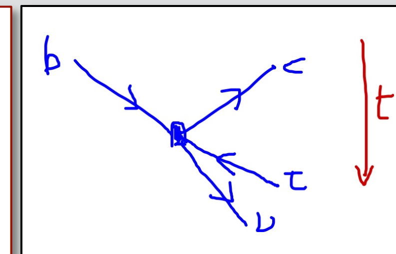












G.Isidori J.M.Camalich

- Experimental constraints
  - High p_T searches (No $\tau\tau$ resonance: no s-channel Z′)
  - Radiative constr. $\tau \to \mu\nu\nu$
  - B_s^0 mixing (No tree level NP: small bs implies large $\tau\nu$)
  - B_c^+ lifetime (Scalar LQ increases BR($B_c^+ \to \tau^+\nu$))

Vector LQ favoured over Scalar LQ or Z′

Model building

> $SU(2)_L$-singlet vector leptoquark
> emerges as a particularly simple and successful framework.

Buttazzo, Greljo, Isidori, Marzocca, B-physics anomalies: a guide to combined explanations, JHEP 1711 (2017) 044

- Many more experimental handles; predictions can be checked!
- Universal for all b→cτν:
  - Accurate R(D*), R(J/ψ), …

$$\frac{R_D}{(R_D)_{SM}} = \frac{\Gamma(B\to D^*\tau\nu)/\Gamma_{SM}}{\Gamma(B\to D^*\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(B_c\to\psi\tau\nu)/\Gamma_{SM}}{\Gamma(B_c\to\psi\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(\Lambda_b\to\Lambda_c\tau\nu)/\Gamma_{SM}}{\Gamma(\Lambda_b\to\Lambda_c\mu\nu)/\Gamma_{SM}} = \ldots$$

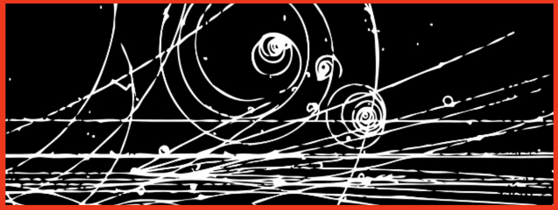
- Strong coupling to *tau's:*
  - Measure e.g. *$B^0\to K^*\tau\tau$*
- LFNU linked with LFV:
  - Look for e.g. *$B^0\to K^*\tau\mu$*
  - *$BR(\tau\to\mu\mu\mu)\sim10^{-9}$*

	μμ (ee)	ττ	νν	τμ	μe
$b\to s$	R_K, R_{K^*} O(20%)	$B\to K^{(*)}\tau\tau$ → 100×SM	$B\to K^{(*)}\nu\nu$ O(1)	$B\to K\tau\mu$ $\to\sim10^{-6}$	$B\to K\mu e$???
$b\to d$	$B_d\to\mu\mu$ $B\to\pi\mu\mu$ $B_s\to K^{(*)}\mu\mu$ O(20%) $[R_K=R_\pi]$	$B\to\pi\tau\tau$ → 100×SM	$B\to\pi\nu\nu$ O(1)	$B\to\pi\tau\mu$ $\to\sim10^{-7}$	$B\to\pi\mu e$???

- c, u symmetry:
  - Study suppressed semileptonic

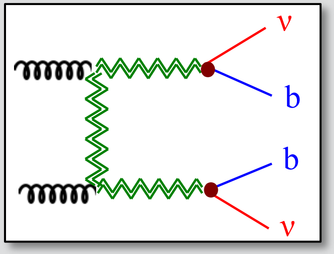
$$\frac{\Gamma(B\to\pi\,\tau\nu)/\Gamma_{SM}}{\Gamma(B\to\pi\,\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(\Lambda_b\to p\,\tau\nu)/\Gamma_{SM}}{\Gamma(\Lambda_b\to p\,\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(B_s\to K^*\tau\nu)/\Gamma_{SM}}{\Gamma(B_s\to K^*\mu\nu)/\Gamma_{SM}} = \ldots = \frac{R_D}{(R_D)_{SM}}$$

- B_s mixing
  - O(1-10%) effect on Δm_s



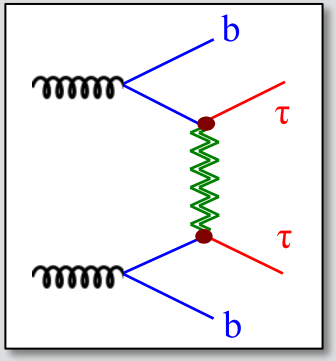
Model building

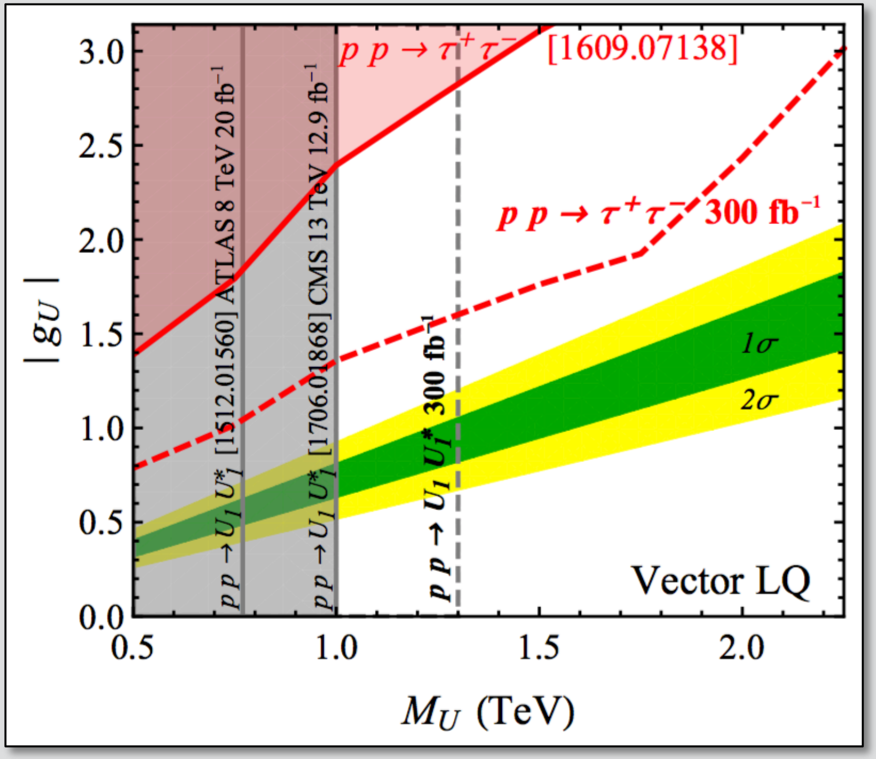
- Many more experimental handles; predictions can be checked!
- High p_T signatures?
  - LQ pairs



  - LQ t-channel in *bb→ττ*

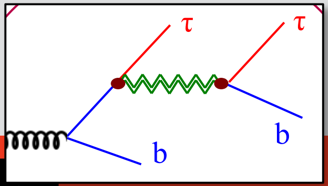
Reachable during HL-LHC

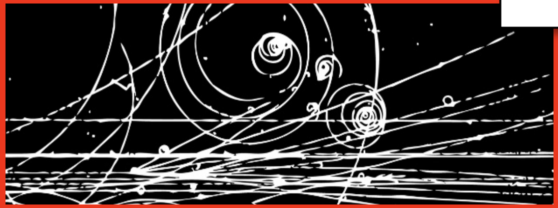




Buttazzo, Greljo, Isidori, Marzocca, B-physics anomalies: a guide to combined explanations JHEP 1711 (2017) 044

  - Single production channel (dominant?)





Outlook

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	203+
				Run III						Run IV				Run V	
	LS2						LS3					LS4			
LHCb 40 MHz **UPGRADE I**				$L = 2 \times 10^{33}$		**LHCb Consolidate: UPGRADE Ib**				$L = 2 \times 10^{33}$ $50\ fb^{-1}$		**LHCb UPGRADE II**		$L = 1\text{-}2 \times 10^{34}$ $300\ fb^{-1}$	
ATLAS Phase I Upgr				$L = 2 \times 10^{34}$		**ATLAS Phase II UPGRADE**				**HL-LHC** $L = 5 \times 10^{34}$				**HL-LHC** $L = 5 \times 10^{34}$	
CMS Phase I Upgr				$300\ fb^{-1}$		**CMS Phase II UPGRADE**								$3000\ fb^{-1}$	
Belle II					$5\ ab^{-1}$		$L = 6 \times 10^{35}$				$50\ ab^{-1}$				

LHC schedule:
https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

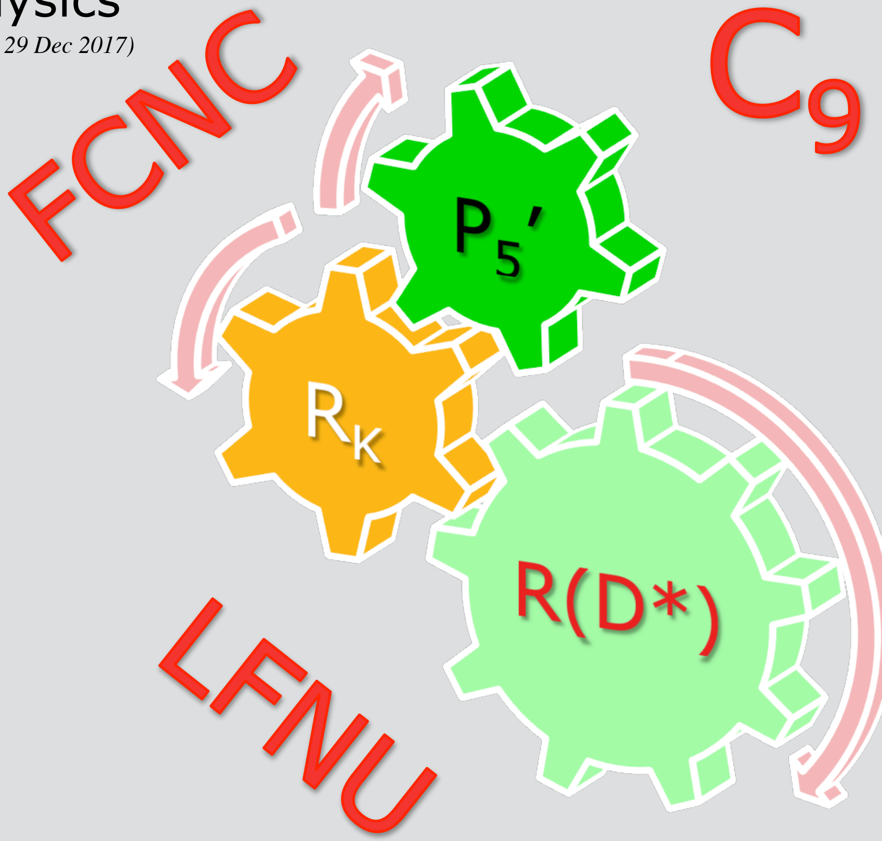
- LHCb Upgrade
  - Upgrade to 40 MHz readout
  - New VELO: strips → pixel
  - New SciFi tracker
- LHCb Upgrade II
  - Add timing for 4D tracking

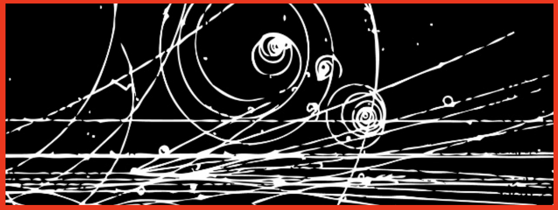
Summary

- Many "unresolved issues in flavor physics"
  (F. Gianotti, Jot Down Magazine, 29 Dec 2017)

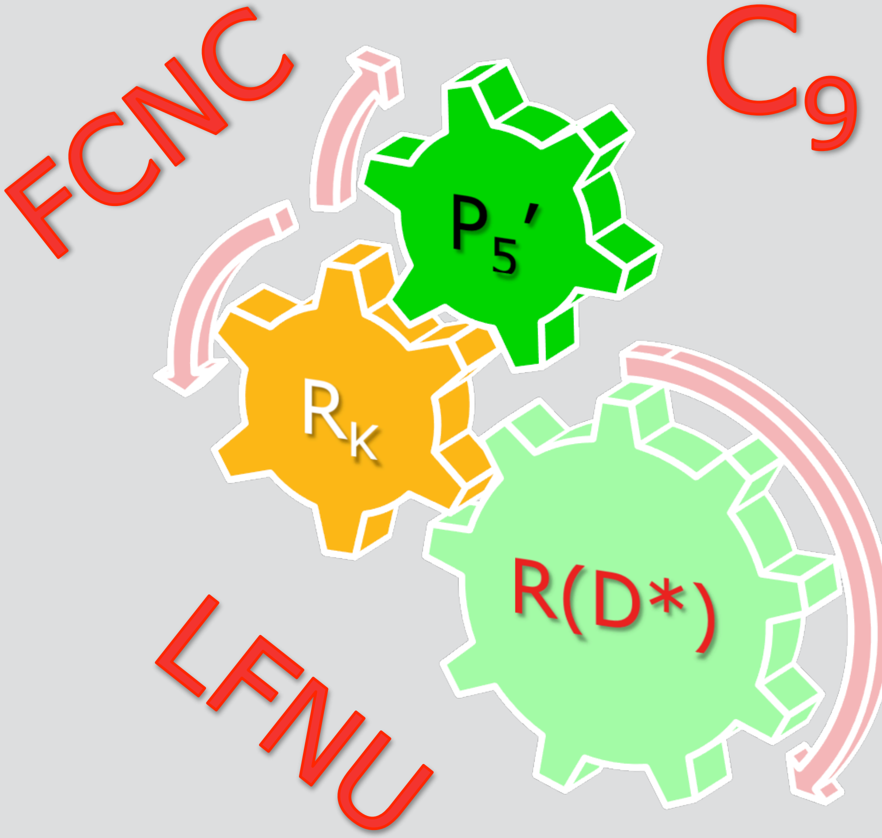
- Individually not so exciting…
  … but combined they are!

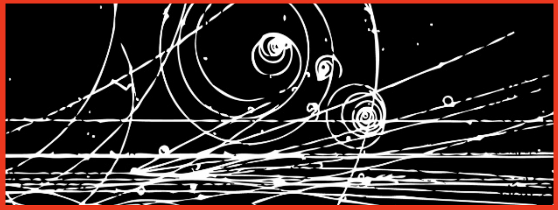
Stay tuned!





Thanks!



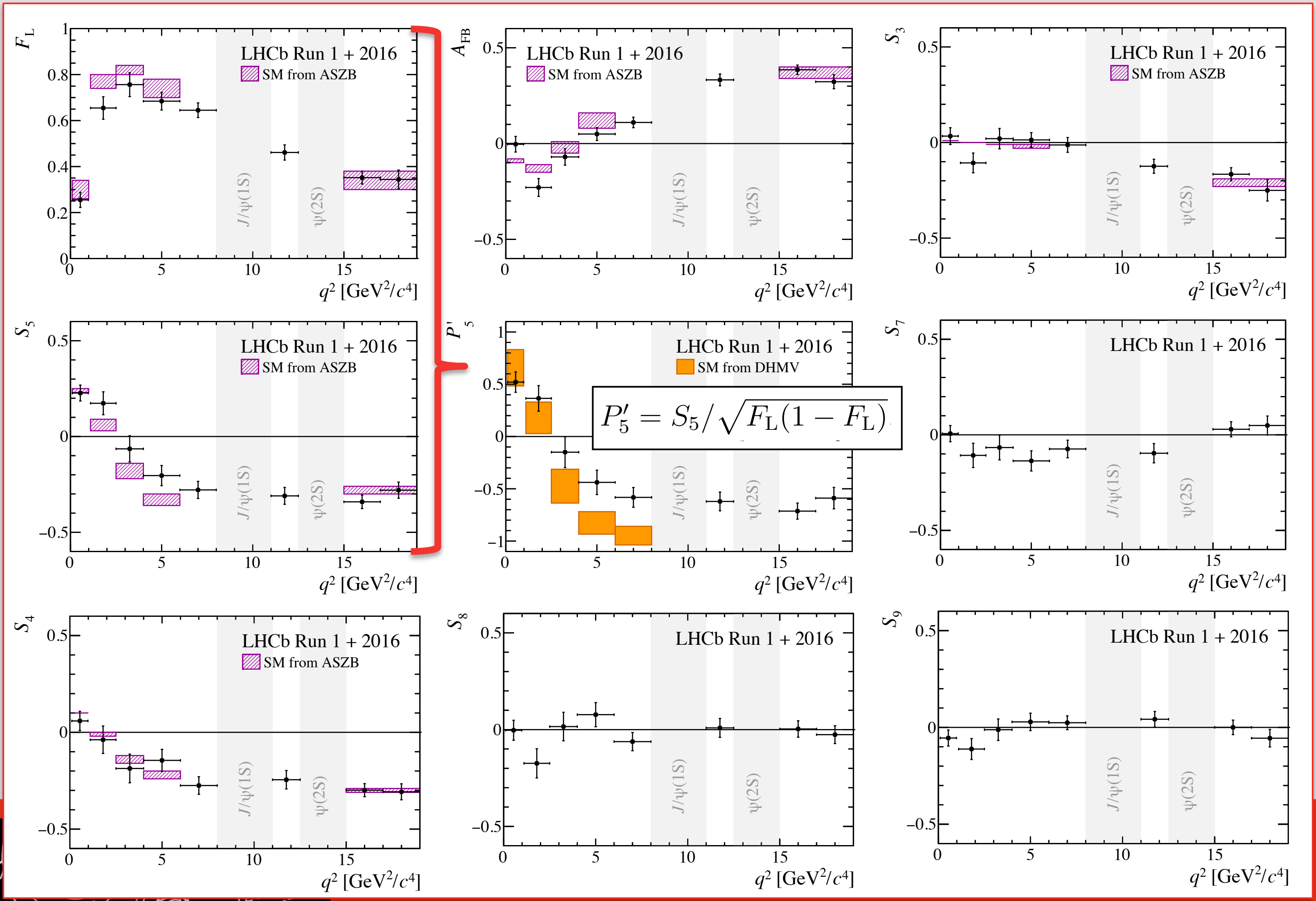


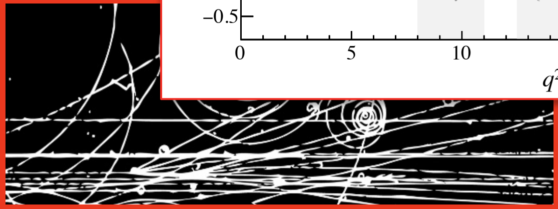
Backup slides

$B^0 \to K^{0*}\mu^+\mu^-$: more than just P_5'

- Many measurements:

LHCb coll., arXiv:2003.04831





Many variables; all sensitive to effective couplings:

- C_7 (photon), C_9 (vector) and C_{10} (axial) couplings hide everywhere:

$$A_\perp^{L,R} \propto (C_9^{eff} + C_9^{eff\prime}) \mp (C_{10}^{eff} + C_{10}^{eff\prime}) \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{eff} + C_7^{eff\prime}) T_1(q^2)]$$

$$A_\parallel^{L,R} \propto [(C_9^{eff} - C_9^{eff\prime}) \mp (C_{10}^{eff} - C_{10}^{eff\prime}) \frac{A_1(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{eff} - C_7^{eff\prime}) T_2(q^2)]$$

$$A_0^{L,R} \propto [(C_9^{eff} - C_9^{eff\prime}) \mp (C_{10}^{eff} - C_{10}^{eff\prime})] \times [(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*} A_1(q^2) - \lambda \frac{A_2(q^2)}{m_B + m_{K^*}})] + 2m_b(C_7^{eff} - C_7^{eff\prime})[(m_B^2 + 3m_{K^*}^2 - q^2) T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2 T_3(q^2)}]$$

$$F_L = \frac{A_0^2}{A_\parallel^2 + A_\perp^2 + A_0^2}$$

$$S_3 = \frac{A_\perp^{L2} - A_\parallel^{L2}}{A_\perp^{L2} + A_\parallel^{L2} + A_0^{L2}} + L \to R$$

$$S_4 = \frac{\Re(A_0^{L*} A_\parallel^L)}{|A_0^L|^2 |A_\parallel^L|^2 + |A_0^L|^2} + L \to R$$

$$S_5 = \frac{\Re(A_0^{L*} A_\perp^L)}{|A_0^L|^2 + A_\perp^L|^2 + |A_0^L|^2} - L \to R$$

$$S_6 = \frac{\Re(A_\perp^{L*} A_\parallel^L)}{|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} - L \to R = \frac{4}{3} A_{FB}$$

$$S_7 = \frac{\Im(A_0^{L*} A_\parallel^L)}{|A_0^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} + L \to R$$

$$S_8 = \frac{\Im(A_0^{L*} A_\perp^L)}{|A_0^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} + L \to R$$

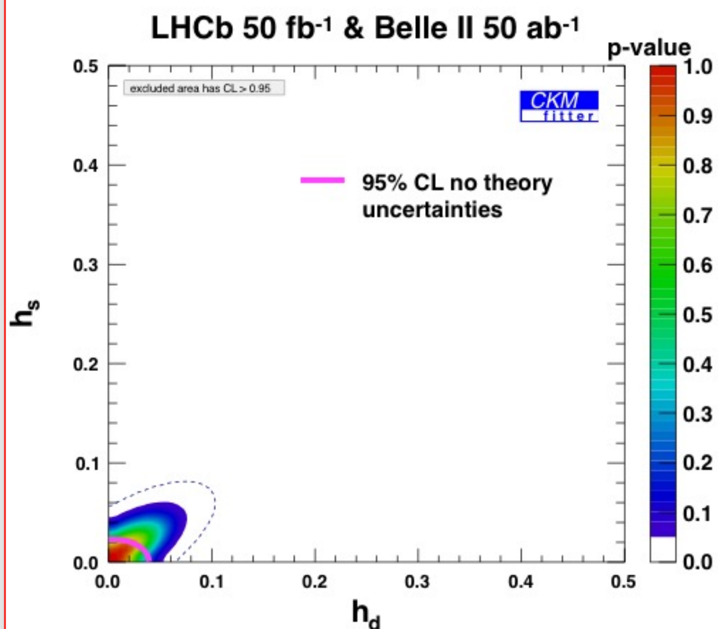
$$S_9 = \frac{\Im(A_\perp^{L*} A_\parallel^L)}{|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} - L \to R$$

$$\frac{1}{\Gamma} \frac{d^3(\Gamma + \bar{\Gamma})}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi} = \frac{9}{32\pi} \Big[\frac{3}{4}(1 - F_L)\sin^2\theta_K + F_L \cos^2\theta_K + \frac{1}{4}(1 - F_L)\sin^2\theta_K \cos 2\theta_\ell$$
$$- F_L \cos^2\theta_K \cos 2\theta_\ell +$$
$$S_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi +$$
$$S_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + S_6^s \sin^2\theta_K \cos\theta_\ell +$$
$$S_7 \sin 2\theta_K \sin\theta_\ell \sin\phi +$$
$$S_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + S_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big]$$

Heavy Flavour = Precision search for NP

- Depending on your model, sensitive to multi-TeV scales, eg:

[Charles et al., 1309.2293]



$$M_{12}^q = (M_{12}^q)_{\mathrm{SM}} \left(1 + h_q e^{2i\sigma_q}\right)$$

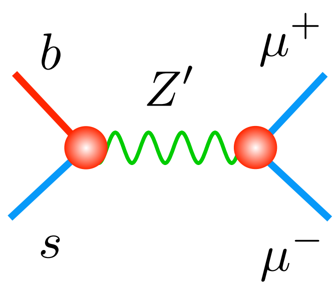
h_q parametrizes magnitude of NP in B_q mixing

$$h_d \lesssim 5\% \quad \Rightarrow \quad \Lambda \gtrsim \begin{cases} 2 \cdot 10^3\,\mathrm{TeV}, & \text{anarchic tree} \\ 1.4\,\mathrm{TeV}, & \text{MFV loop} \end{cases}$$

From Uli Haisch, 31 Aug 2016

Heavy Flavour = Precision search for NP

- Depending on your model, sensitive to multi-TeV scales, eg:



$$\mu_{B_s\to\mu^+\mu^-} \simeq 1 \pm \frac{4\pi}{g^2\,|V_{tb}^* V_{ts}|^2}\,\frac{v^2}{\Lambda^2}$$

$\mu_{B\to\mu\mu}$ is ratio BR^{exp}/BR^{SM}

$$\Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \dfrac{\sqrt{4\pi}}{g\,|V_{tb}^* V_{ts}|} \\ 1 \end{cases} \simeq \begin{cases} 50\,\text{TeV}\,, & \text{anarchic tree} \\ 0.6\,\text{TeV}\,, & \text{MFV loop} \end{cases}$$

From Uli Haisch, 31 Aug 2016

$B^0{}_{(s)} \rightarrow \mu\mu$: projections

- Statistics

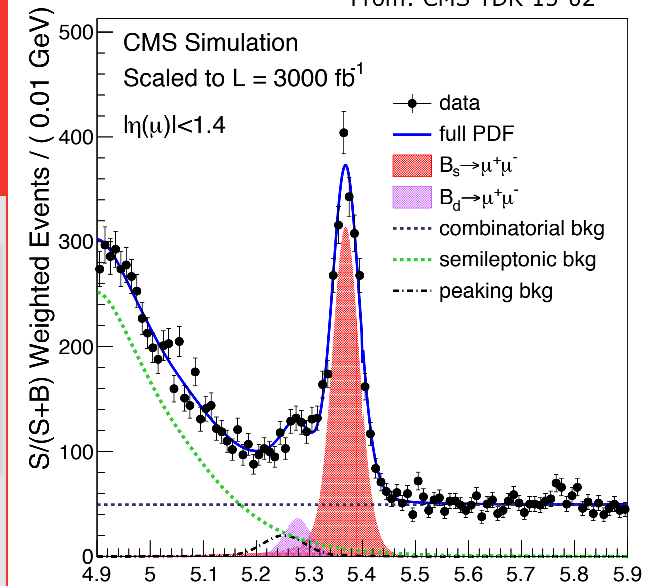
(3 ab^{-1})

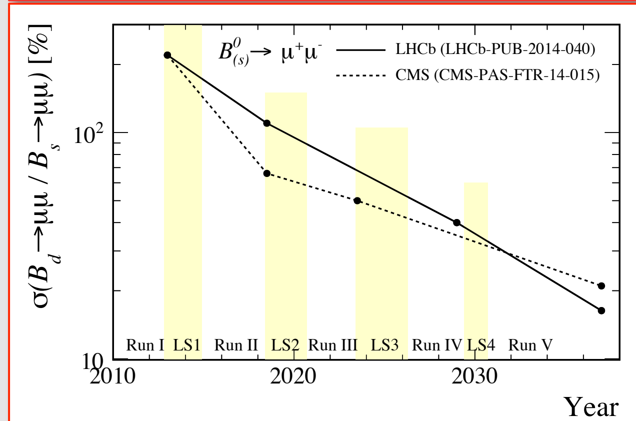
	CMS	LHCb (50fb-1)	LHCb (300fb-1)
$N(B_d)$	271	40	240
$N(B_s)$	2250	400	2400

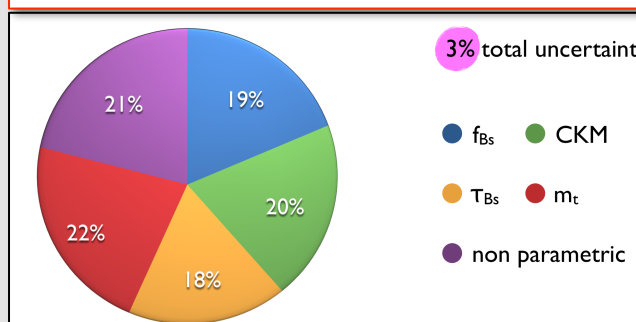
From: CMS-PAS-FTR-14-015

- Systematics
  - ATLAS+CMS: improved mass resolution
  - Limiting: f_s/f_d
- Theoretical prediction BR($B^0{}_{(s)} \rightarrow \mu\mu$)
  - CKM elements, B decay constants
    - Accuracy expected to increase with improved lattice
    - Future unc. might reach ~3% : →
  - Exp. uncertainty will probably not decrease to theoretical uncertainty

From: CMS-TDR-15-02







From: U.Haisch and USQCD Coll. http://www.usqcd.org/documents/13flavor.pdf

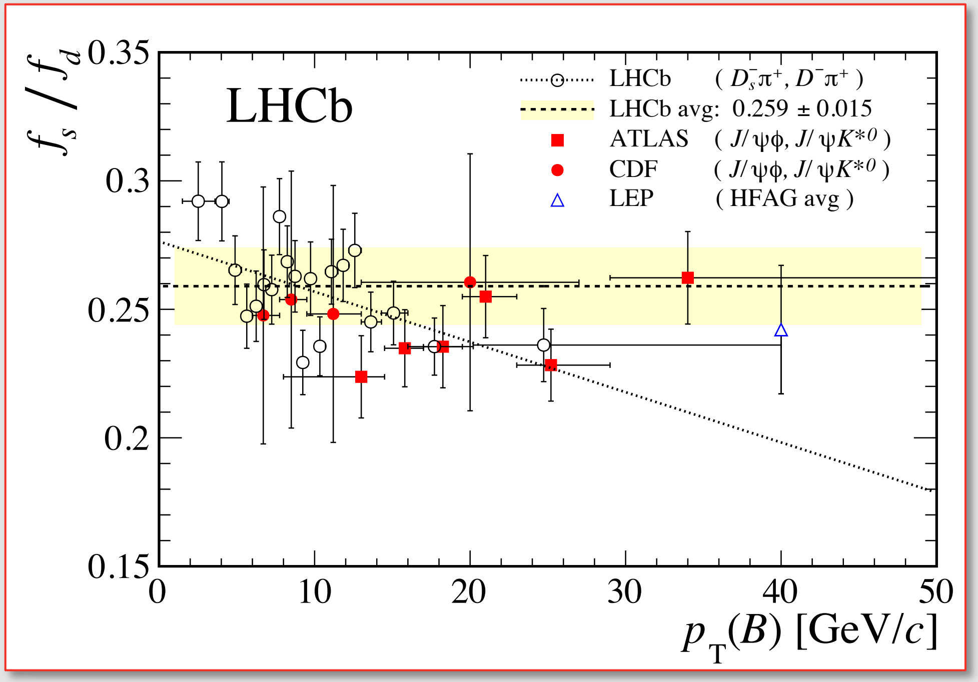
$B^0_{(s)} \to \mu\mu$: dominant systematic : f_s/f_d

- Dominant systematic uncertainty for BR($B_s^0 \to \mu\mu$)
- Relies on theoretical knowledge of ratio of BRs:
  - Semileptonic: $\Gamma(B_s^0 \to \mu X) = \Gamma(B \to \mu X)$
  - Hadronic: $$\frac{\mathrm{BR}(\bar{B}^0_s \to D_s^+\pi^-)}{\mathrm{BR}(\bar{B}^0_d \to D^+K^-)} = \frac{\Phi(D_s\pi)}{\Phi(DK)}\frac{\tau_{B_s}}{\tau_{B_d}}\left|\frac{V_{ud}}{V_{us}}\right|^2\left(\frac{f_\pi}{f_K}\right)^2\left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2\left|\frac{a_1(D_s\pi)}{a_1(D_dK)}\right|^2 = 14.2 \pm 1.3(\mathrm{FF})$$

Fleischer, Serra, NT, PRD82 (2010) 034038

  - B→J/ψX: $$R^{\mathrm{th.}}_{s/d} \equiv \frac{\mathrm{BR}(B_s \to J/\psi\phi)}{\mathrm{BR}(B_d \to J/\psi K^{*0})} \approx 0.83^{+0.03}_{-0.02}(\omega_B)^{+0.01}_{-0.00}(f_M)^{+0.01}_{-0.02}(a_i)^{+0.01}_{-0.02}(m_c)[0.83^{+0.03}_{-0.03}]$$

Liu, Wang, Xie, PRD89 (2014) 094010



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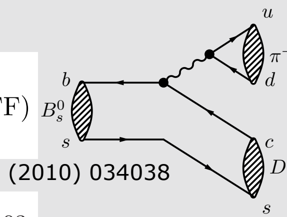
$$\left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right] = 1.046 \pm 0.044(\mathrm{stat}) \pm 0.015(\mathrm{sys})$$

Bailey et al, PRD.85(2012)114502



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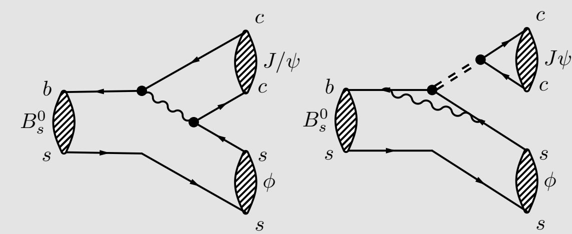
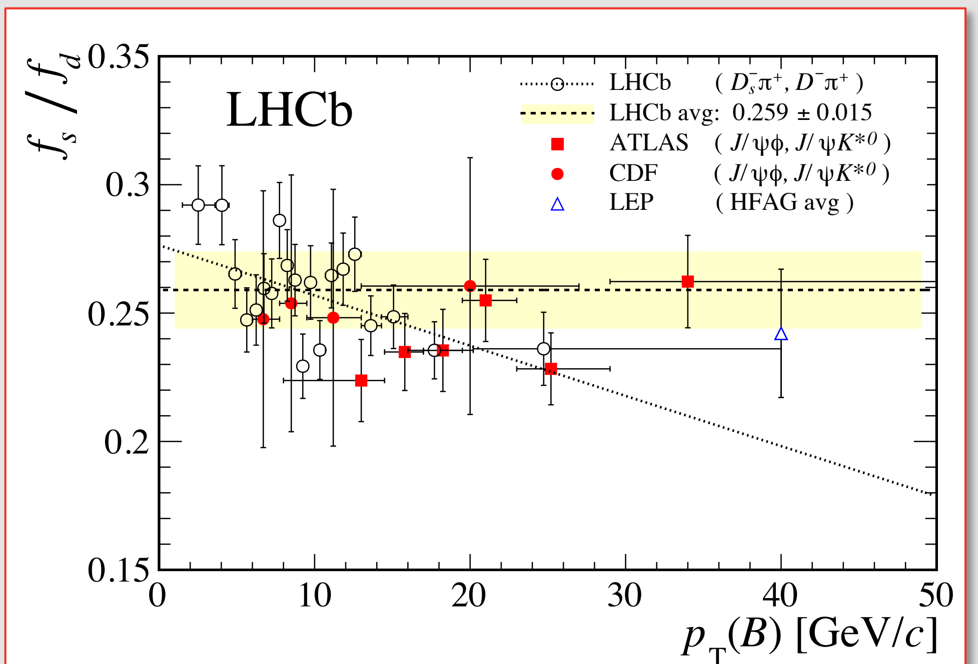
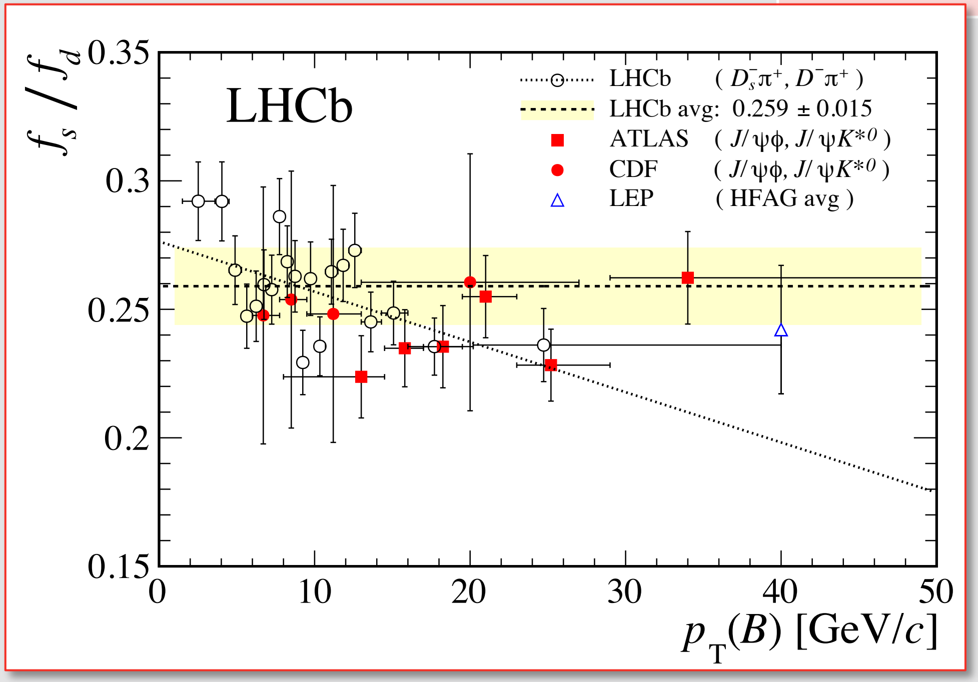




$B^0_{(s)} \to \mu\mu$: dominant systematic : f_s/f_d

- Dominant systematic uncertainty for BR($B_s^0 \to \mu\mu$)
- Measurements:

	Normalization	Dependence
LHCb	Semileptonic Phys. Rev. D 85 (2012) 032008 *B→Dh* Phys. Rev. Lett. 107 (2011) 211801 LHCb-CONF-2013-011	*B→Dh* JHEP 04 (2013) 001
CDF	Semileptonic Phys. Rev. D 77, 072003 (2008).	*B→J/ψX* Public Note 10795
ATLAS	*B→J/ψX*	*B→J/ψX* Phys.Rev.Lett. 115 (2015) 262001



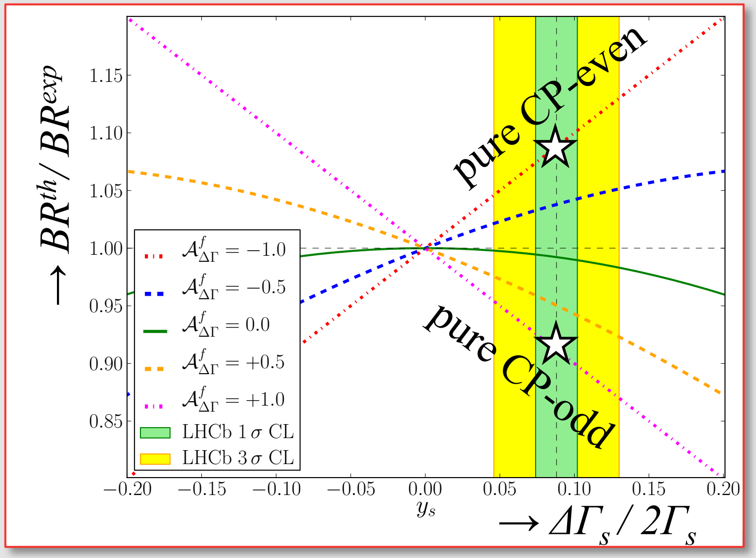
- Possible improvements:
  - $B_{(s)} \to D_{(s)}$ form factors: Lattice
  - $B_s \to D_s$ form factors: LHCb
  - BR($B \to DX\mu\nu$): BelleII
  - BR($D_{(s)}$): BESIII

$B^0{}_{(s)} \to \mu\mu$: effective lifetime

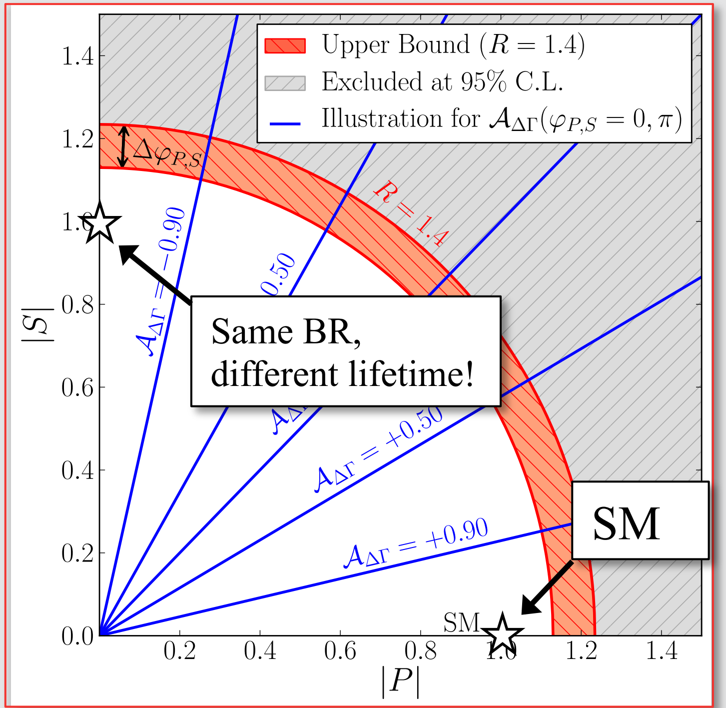
- Lifetime difference $B_s{}^0{}_H$ (CP-) and $B_s{}^0{}_L$ (CP+):

- SM: P-amplitude dominates, selecting CP-odd
- Different CP admixture affects effective lifetime
  - possibly not affecting the BR, when |S| and $A_{\Delta\Gamma}$ compensate…

➢ Could be due to scalar amplitude |S| from NP



De Bruyn, Fleischer, NT, et al. Phys.Rev. D86 (2012) 014027



De Bruyn, Fleischer, NT, et al. Phys. Rev. Lett. 109, 041801 (2012)

$$R \equiv \frac{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}}}{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} = \left[\frac{1 + \mathcal{A}_{\Delta\Gamma} y_s}{1 - y_s^2}\right] \left(|P|^2 + |S|^2\right)$$

$B^0 \rightarrow K^*\mu\mu$: Projections

- Statistics for $B^0 \rightarrow K^*\mu\mu$:

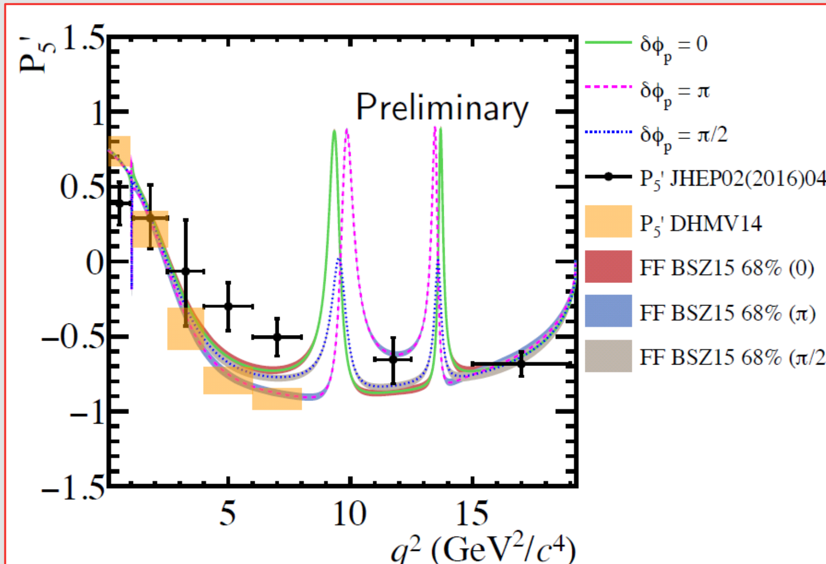
	Run 1	Run 1-3(4)	Run 1-5
LHCb JHEP 02 (2016) 104	600	20,000	120,000*
CMS Phys. Lett. B 753 (2016) 424	300	10,000	100,000
		(naïve scaling with lumi)	

From: P.Owen, 31 Aug 2016

- Understand theory:
  - Measure q^2 dependence
    - To disentangle charm loop effects!
  - Factorisable power corrections
  - Form factors

For P_5' in [4, 6] GeV^2 bin:

$$-0.82^{+0.01}_{-0.01}{}^{+0.02}_{-0.02}{}^{+0.03}_{-0.06}{}^{+0.06}_{-0.06}{}^{+0.07}_{-0.08}$$



Pomery, Egede, Owen, Petrides, Blake

b→sll : Projections

- Statistics for $B^0 \to K^*\mu\mu$:

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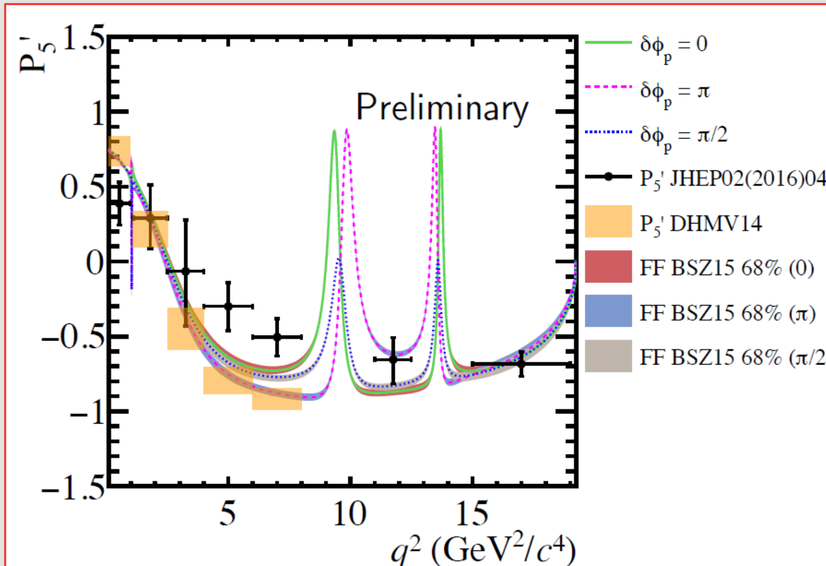


Pomery, Egede, Owen, Petrides, Blake

- Many more observables!
  - Lepton-flavour universality, R_{K*}
  - Lepton-flavour violation searches
  - BR's
  - A_{FB}(S6), A9, ...
  - $B^0 \to K^*ee$
  - ...

	Decay	Run 1	Run 2	50 fb^{-1}	300 fb^{-1}
R_K	$B^+ \to K^+\mu^+\mu^-$	11%	5%	2%	1%
R_{K^*}	$B^0 \to K^{*0}\mu^+\mu^-$	18%	8%	3%	1%
R_Φ	$B^0_s \to \phi\mu^+\mu^-$	36%	15%	8%	3%

From: P.Owen, 31 Aug 2016

Experiment vs Theory

- For very long, flavour observables will stay statistically limited!

	LHCb up to LS2		LHCb upgrade		Theory
	Run 1	Run 2	Run 3	Run 4	Theory uncertainty
Integrated lumi	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	
$\frac{Br(B_d\to\mu\mu)}{Br(B_s\to\mu\mu)}$	-	110 %	60%	40% ⟷	5%
$q_0^2 A_{FB}(B_d \to K^{*0}\mu\mu)$	10%	5%	2.8%	1.9%	7%
$\phi_s(B_s \to J/\psi\phi, B_s \to J/\psi\pi\pi)$	0.05	0.025	0.013	0.009 ⟷	0.003
$\phi_s(B_s \to \phi\phi)$	0.18	0.12	0.04	0.026	0.02
γ	7°	4°	1.7°	1.1° ⟷	negl.
$A_\Gamma(D^0 \to KK)$	3.4 10^{-4}	2.2 10^{-4}	0.9 10^{-4}	0.5 10^{-4}	-

LHCb-PUB-2014-040

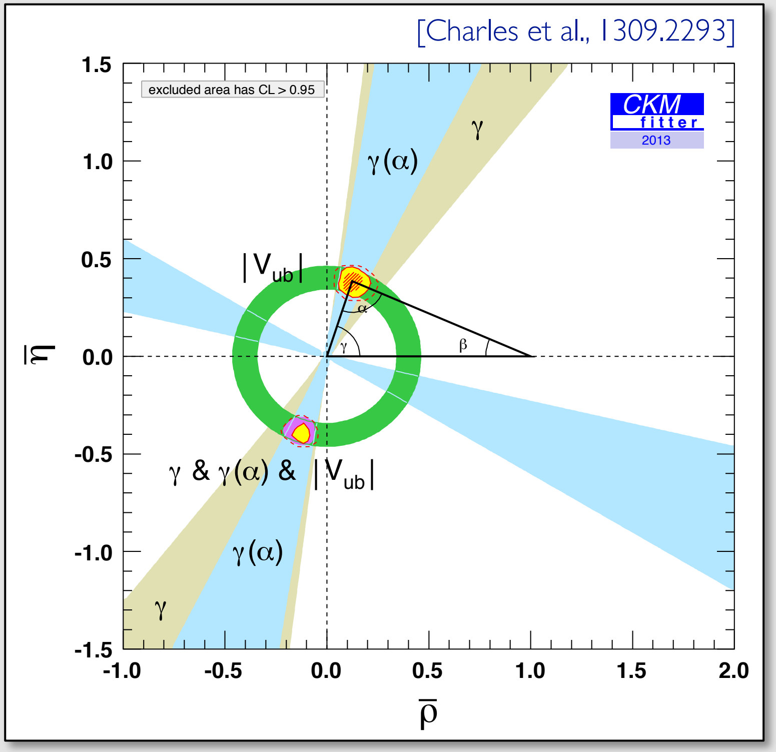
$\delta\gamma$	$\mathcal{O}(10^{-7})$	[Brod & Zupan, 1308.5663]
$\delta\beta$	$\mathcal{O}(1\%)$	[Ciuchini et al., hep-ph/0507290]
δR_{D^*}	$\mathcal{O}(1\%)$	[Fajfer et al., 1203.2654]
$\delta R_K, \delta R_{K^*}, \ldots$	$\mathcal{O}(1\%)$	[Bordone et al., 1605.07633]

From Uli Haisch, 31 Aug 2016

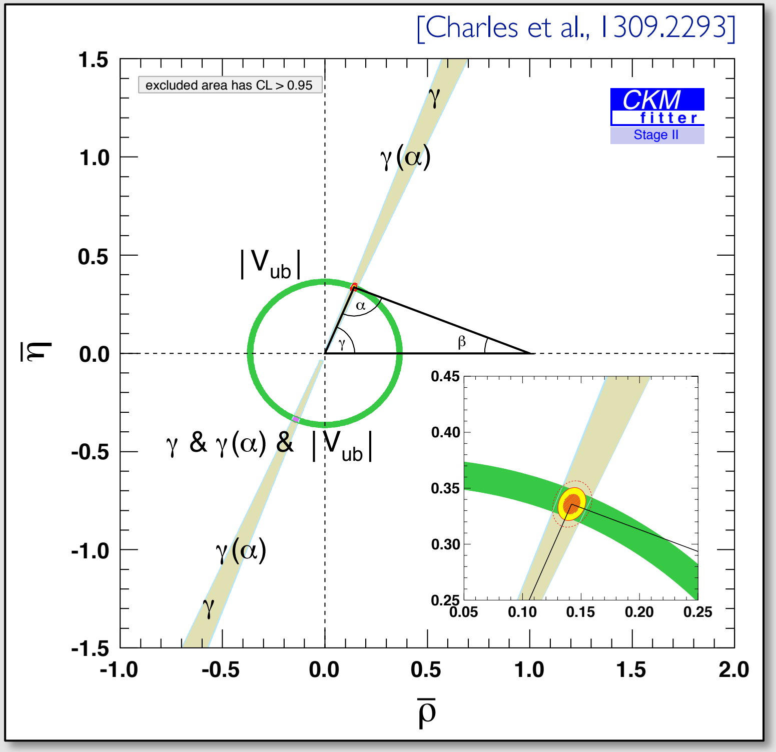
CKM unitarity triangle: test consistency

- Precision measurements to scrutinize the Standard Model
- Precision measurements only way to reach very high mass scales
- Precision measurements are not yet precise enough

2013



2030



The need for more precision

Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed”

– A.Soni

- “A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky.”

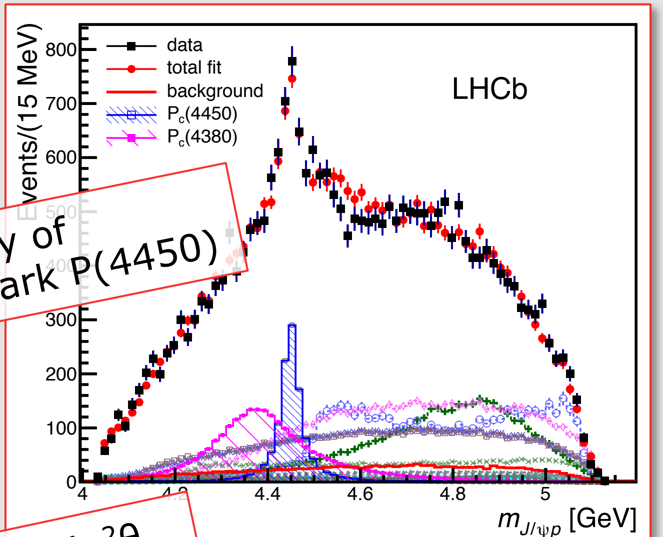
– L.Okun

(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

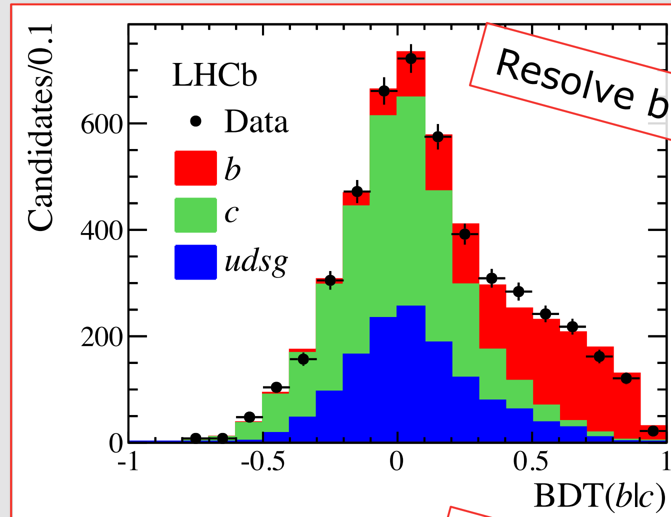
LHCb = more than flavour

pdfs, jets, heavy-ion, EW, exotic states…

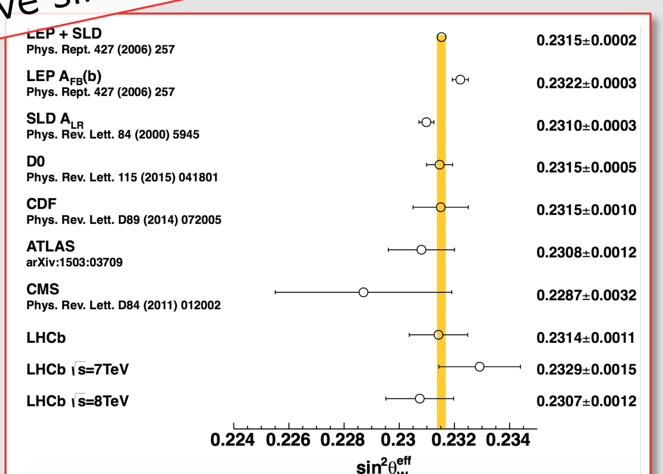
Discovery of pentaquark P(4450)



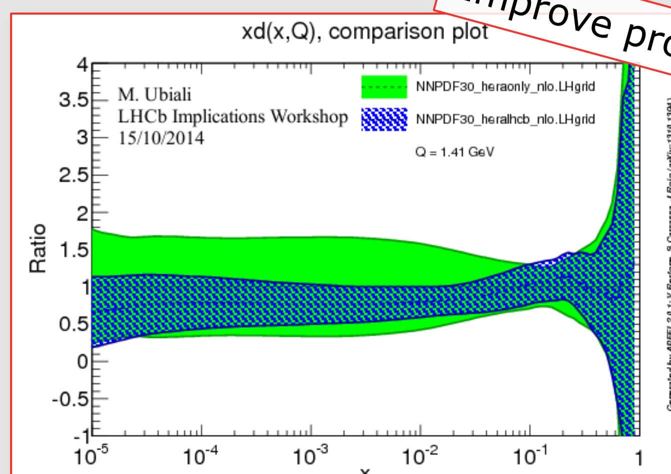
Resolve b and c jets



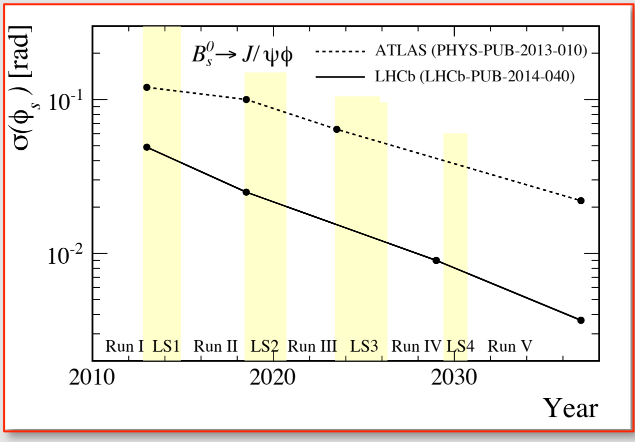
Impressive $\sin^2\theta_W$

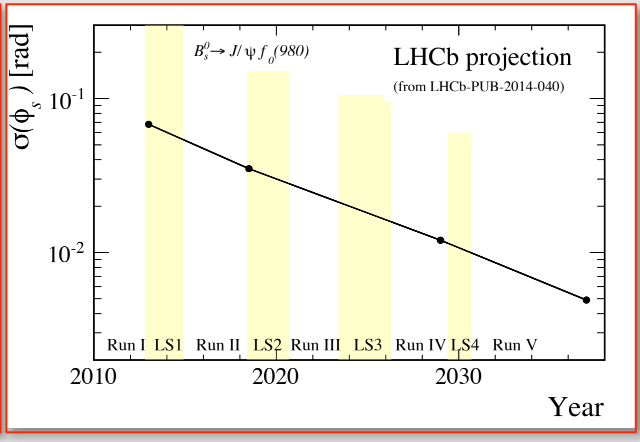


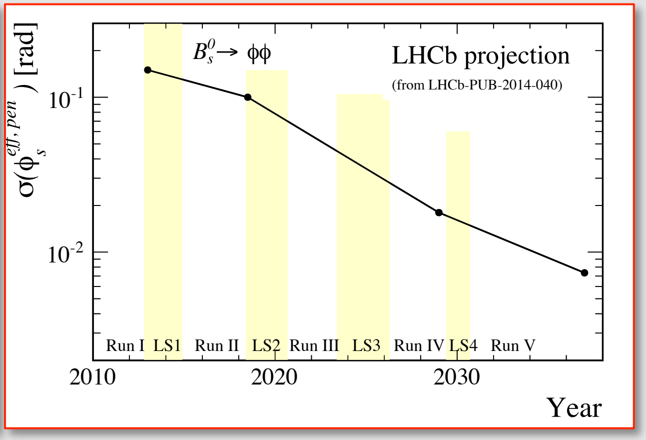
Improve proton pdf's

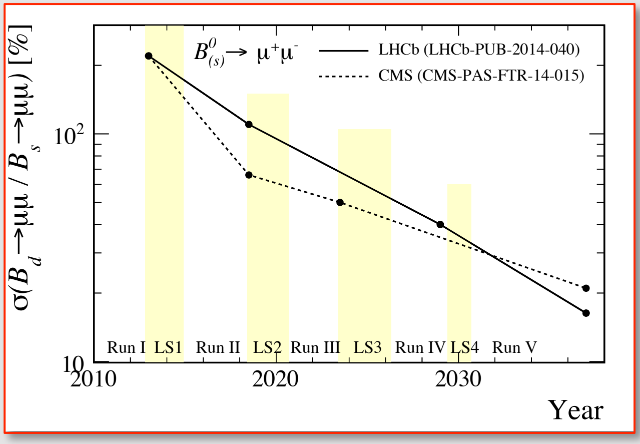


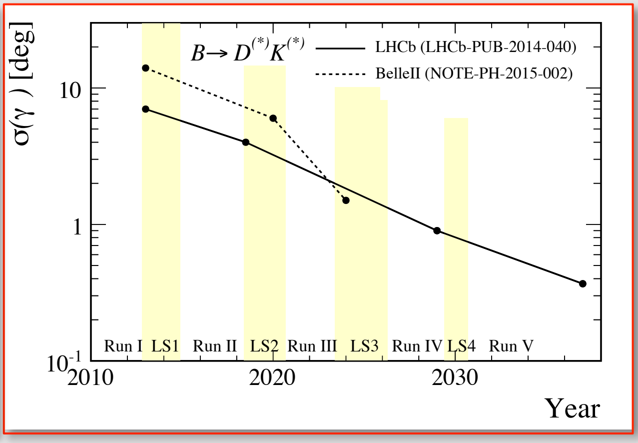
Projected sensitivities

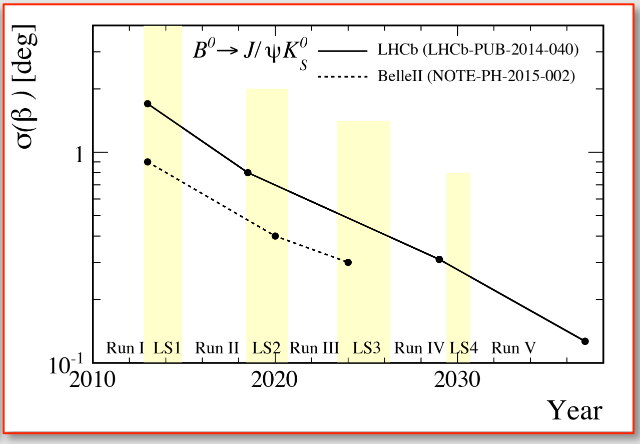






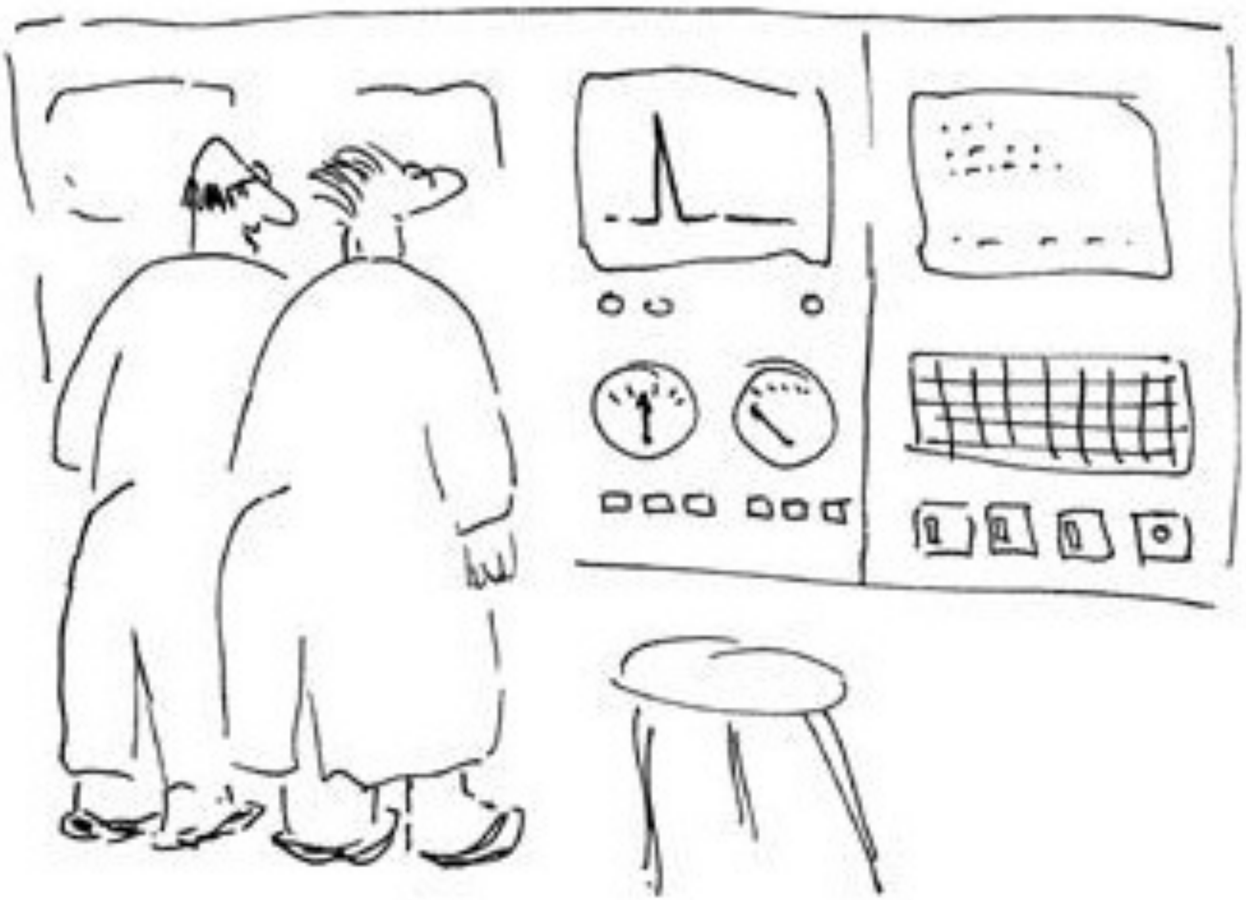






ATL-PHYS-PUB-2013-010
CMS-PAS-FTR-14-015

BELLE2-NOTE-PH-2015-002
LHCB-PUB-2014-040



WELL, EITHER WE'VE FOUND A LEPTOQUARK, OR GEORGIOS'S JUST PUT THE KETTLE ON