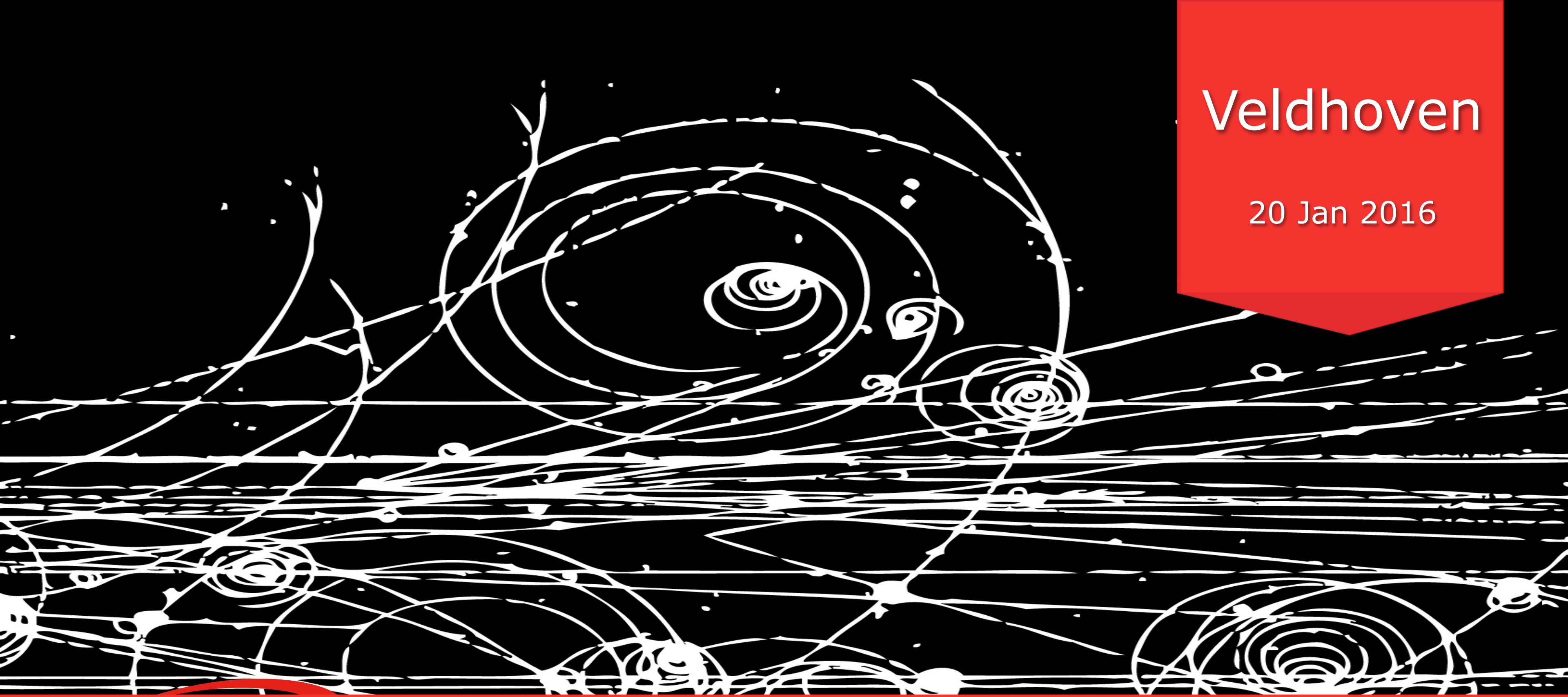


Veldhoven

20 Jan 2016

Exploring the high-precision frontier

with the LHCb detector

Niels Tuning

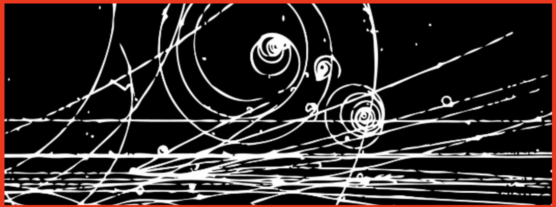
Nikhef

High-precision measurements

- Standard Model and Feynman Diagrams

- Historical perspective

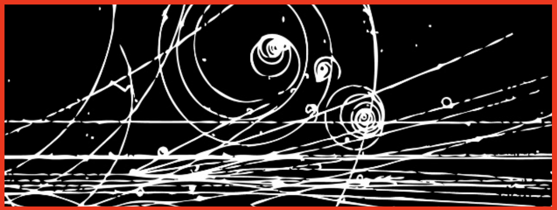
- Recent highlights from CERN



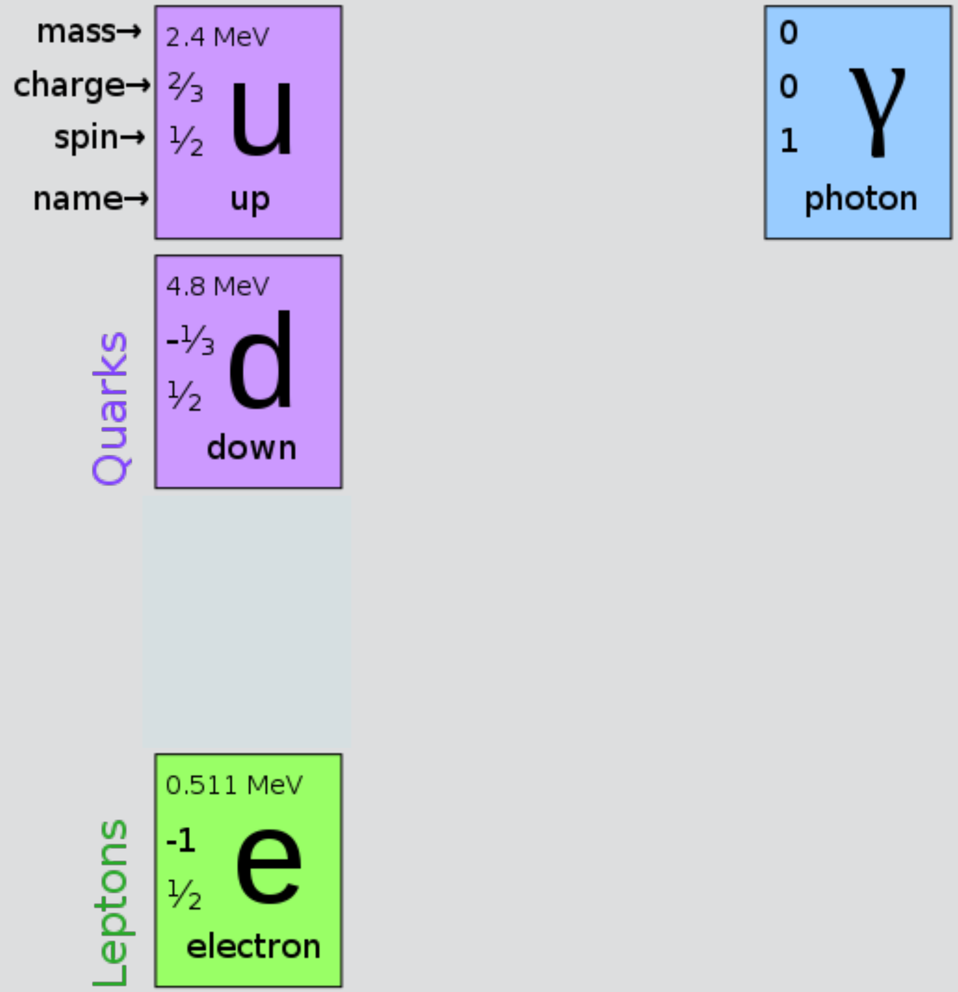
High-precision measurements

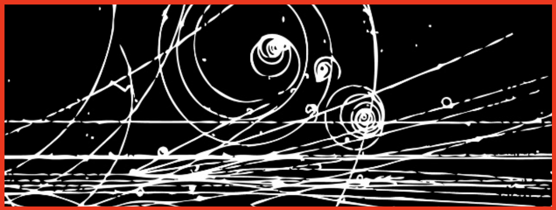
- Standard Model and Feynman Diagrams

- Historical perspective
  - **W**
  - **neutrino**
  - **charm**
  - **bottom**
  - **top**
  - **Z**
  - **Higgs**
- Recent highlights from the LHCb experiment
  - **CP violation in** $B^0_s \rightarrow J/\psi\varphi$ *and* $B^0_s \rightarrow D_s^- \mu^+ \nu$
  - **Observation of** $B^0_s \rightarrow \mu^+\mu^-$
  - **Precision measurements on** $B^0 \rightarrow K^* \mu^+\mu^-$
  - **Lepton flavour violation?**
    - $B^+ \rightarrow K^+ \mu^+\mu^-$
    - $B \rightarrow D \mu^+ \nu$

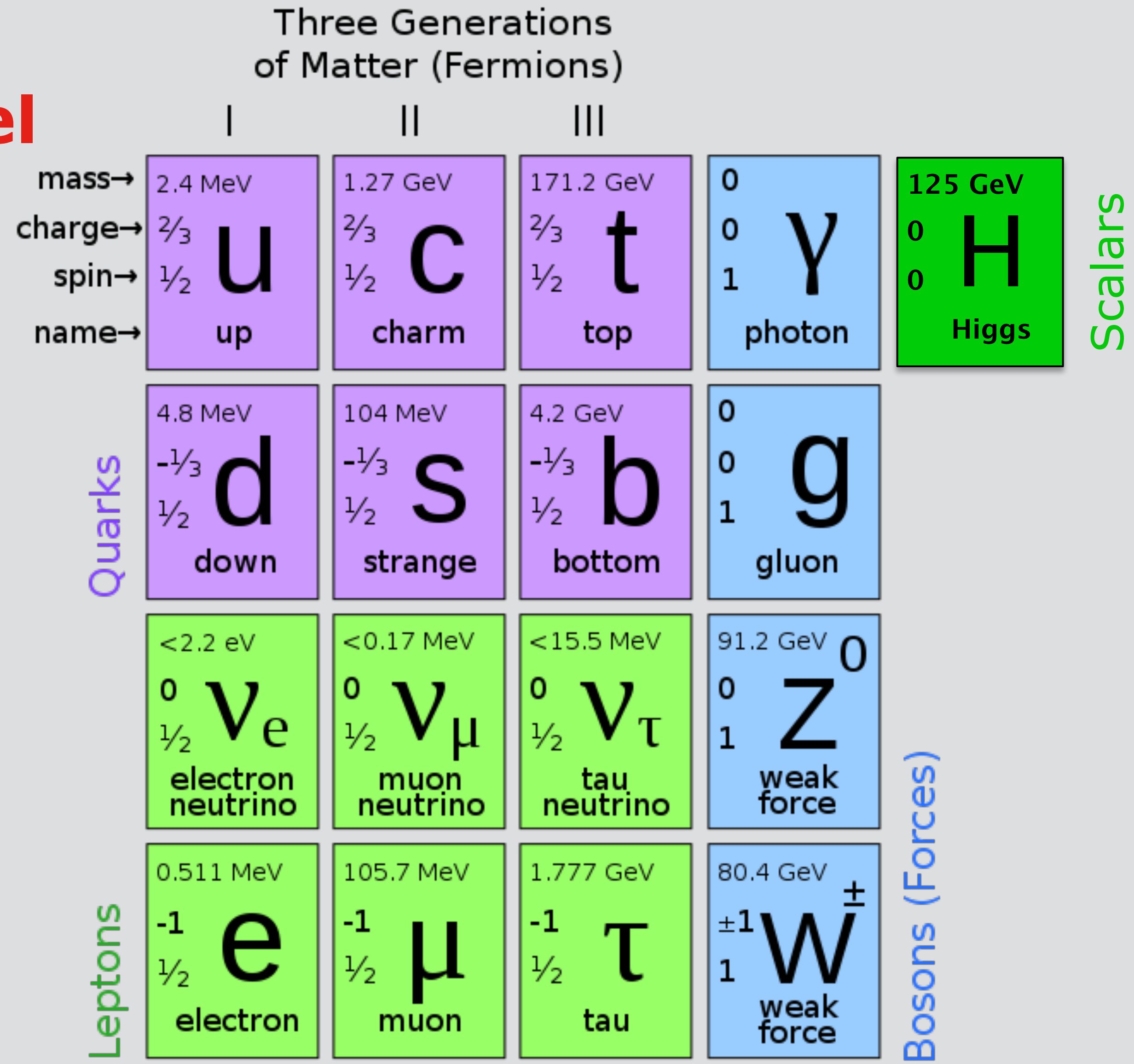


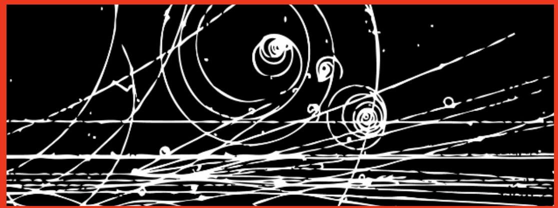
Standard Model



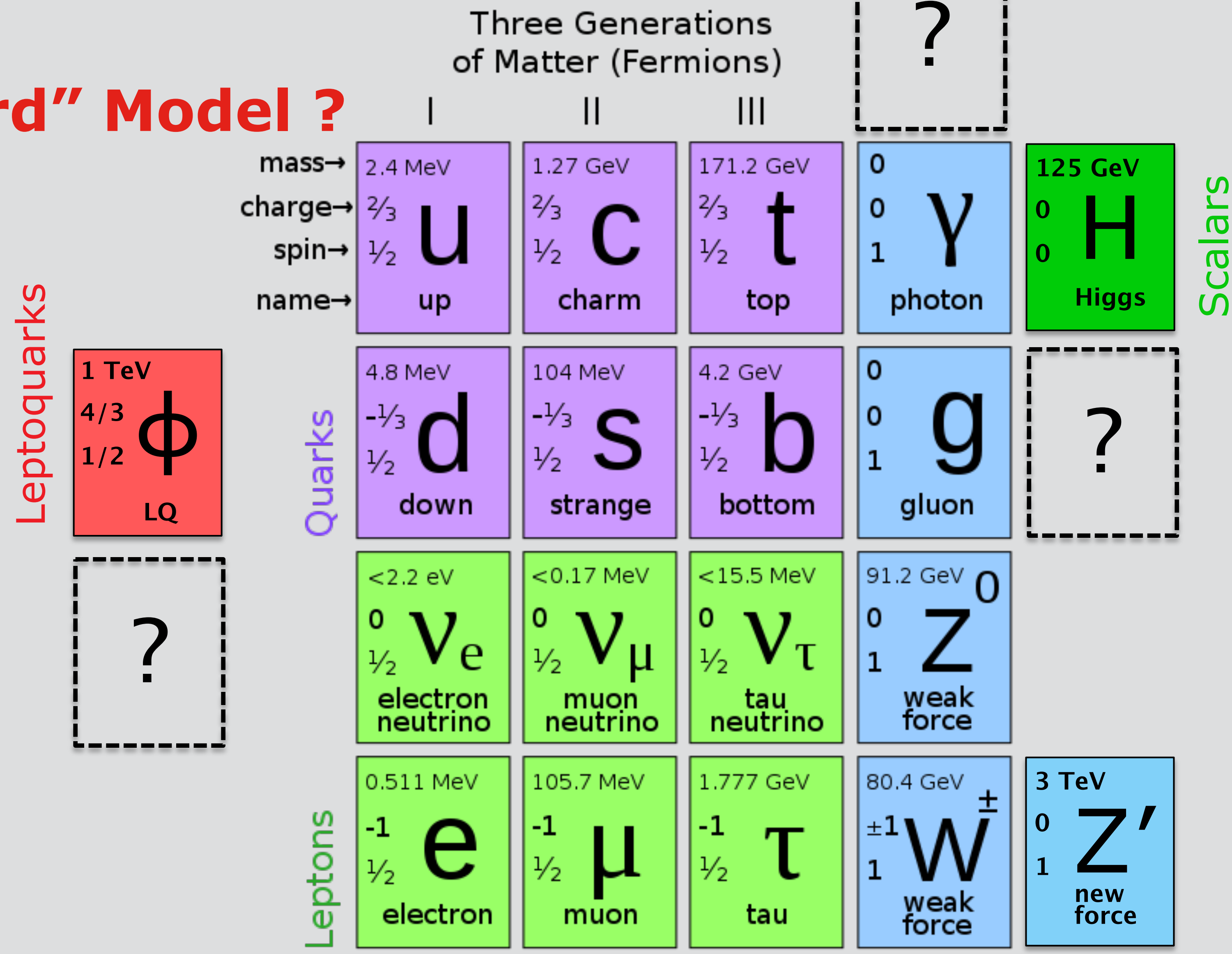


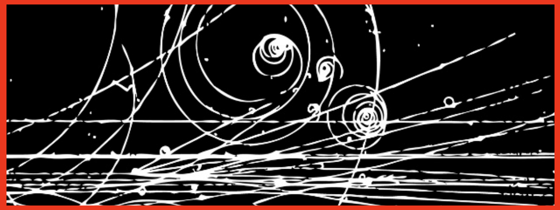
Standard Model





"Standard" Model ?





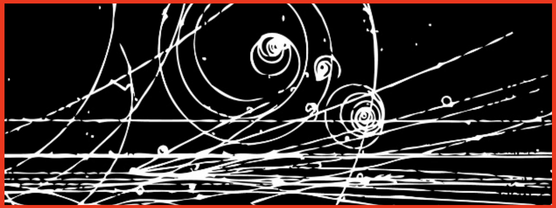
“Standard” Model ?

- Enough unanswered questions that justify search for new phenomena…
  - What is dark matter?
  - What caused the matter – antimatter imbalance?
  - Why does the strong interaction preserve CP symmetry?
  - Why is the neutrino mass so small?
  - Is lepton number conserved?
  - …?

?

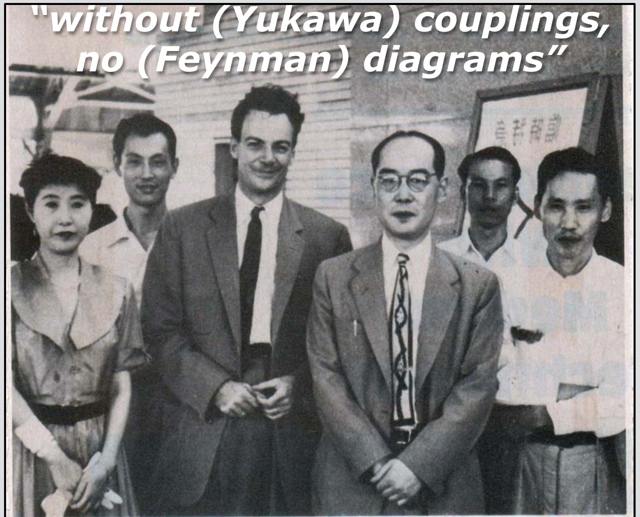
?

?



Feynman diagram

R.Feynman, Phys.Rev. 76 (1949) 769



Hideki Yukawa and Richard Feynman during Feynman's visit to Kyoto, Japan, in the summer of 1954. Left to right: Mrs. Yukawa, Satio Hayakawa, Feynman, Yukawa, unknown, Minoru Kobayasi. (Courtesy of Satio Hayakawa.)

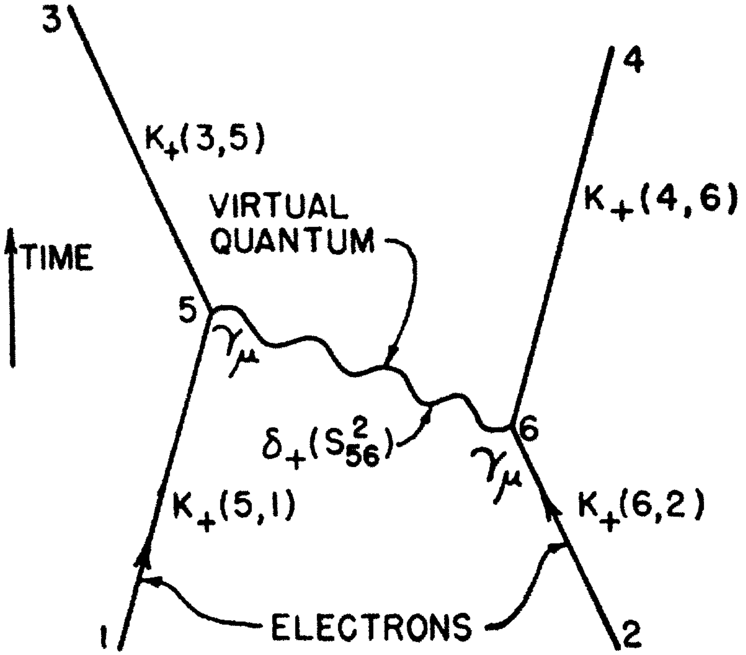
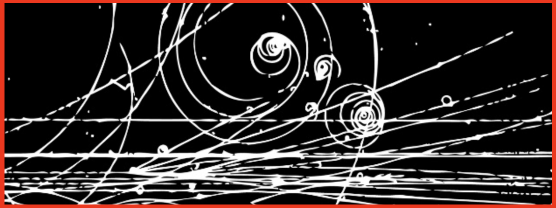


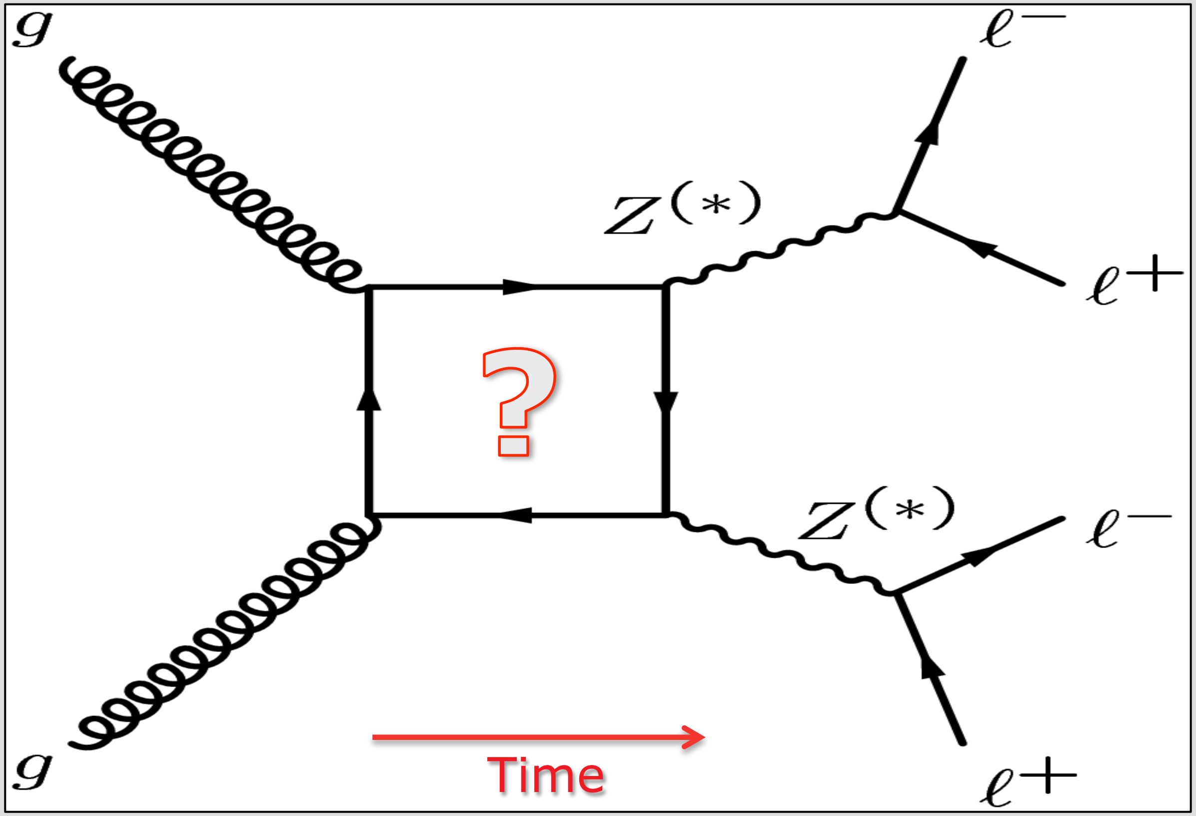
FIG. 1. The fundamental interaction Eq. (4). Exchange of one quantum between two electrons.

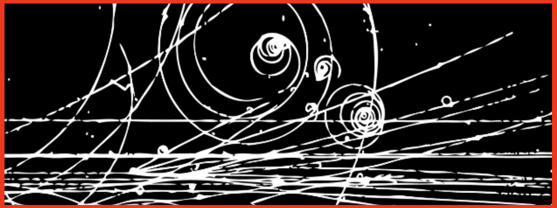
In addition to their value as a mathematical tool, Feynman diagrams provide deep physical insight into the nature of particle interactions. Particles interact in every way available; in fact, intermediate virtual particles are allowed to propagate faster than light.



Feynman diagram

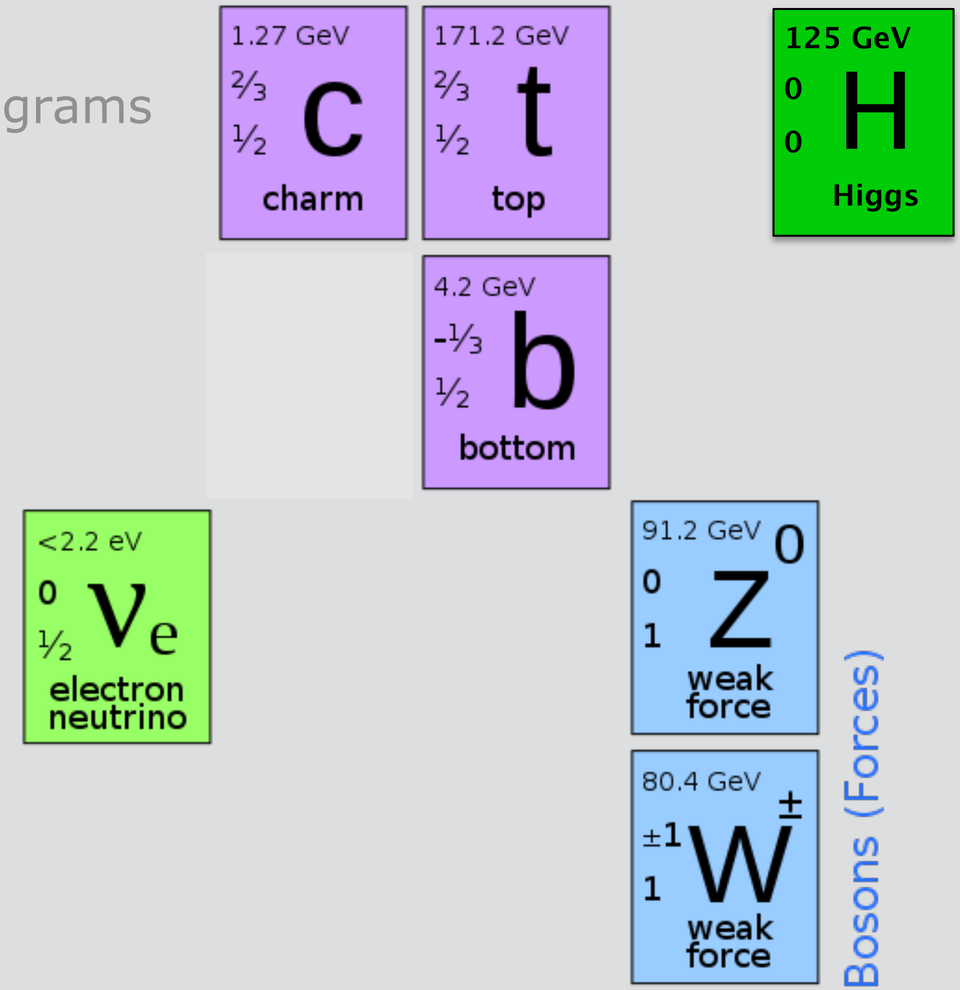
- Higher order diagram
- “Virtual” particles

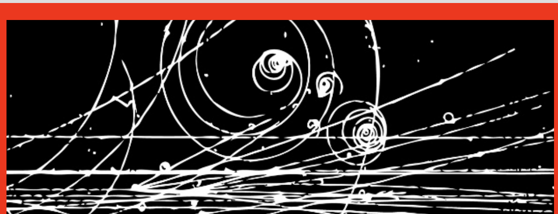




High-precision measurements

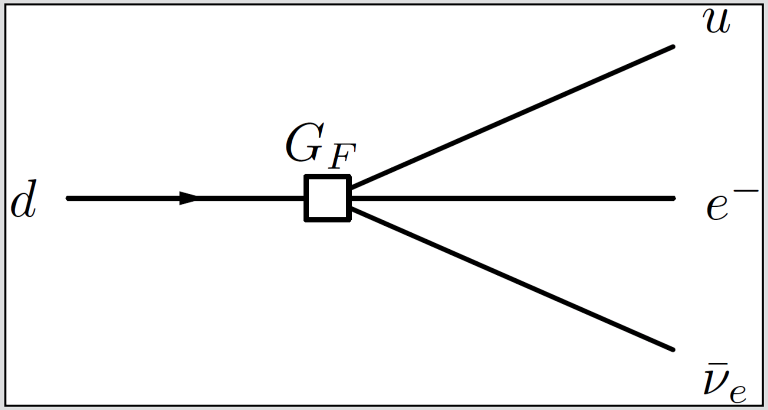
- Standard Model and Feynman Diagrams
- Historical perspective
  - W
  - neutrino
  - charm
  - bottom
  - top
  - Z
  - Higgs
- Recent highlights from CERN

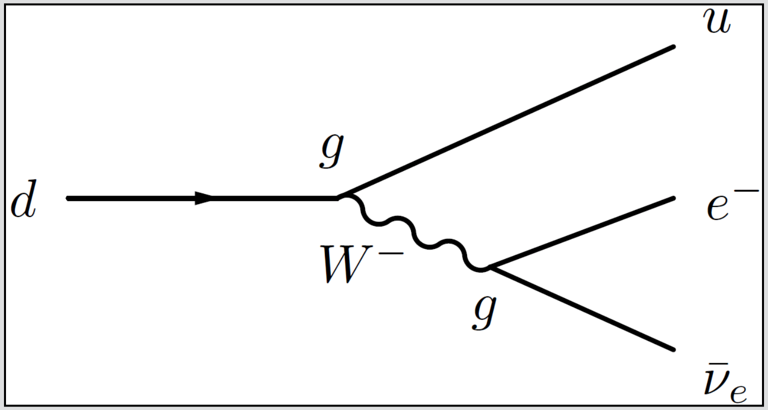




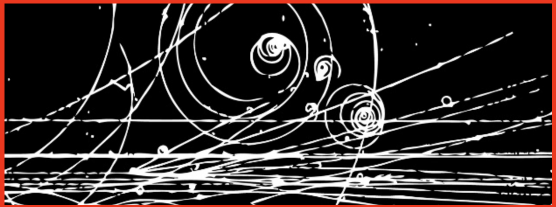
Historical perspective: W

- Radioactive decay was “discovery” of weak interaction?





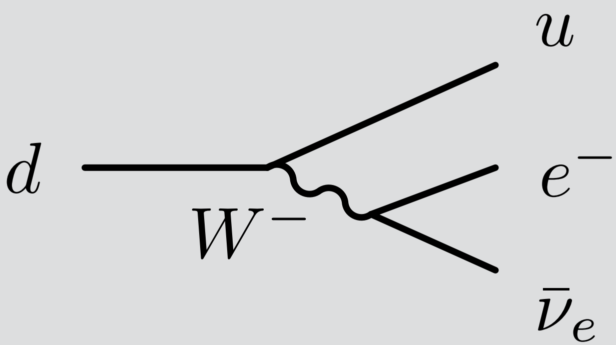
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

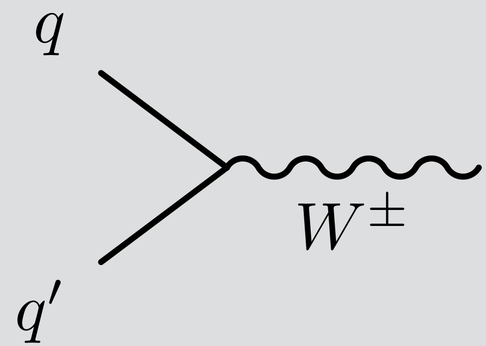


Historical perspective: W

- Radioactive decay was “discovery” of weak interaction?

Indirect





Direct

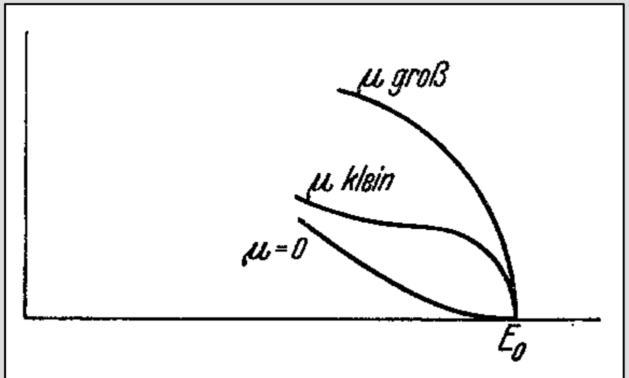
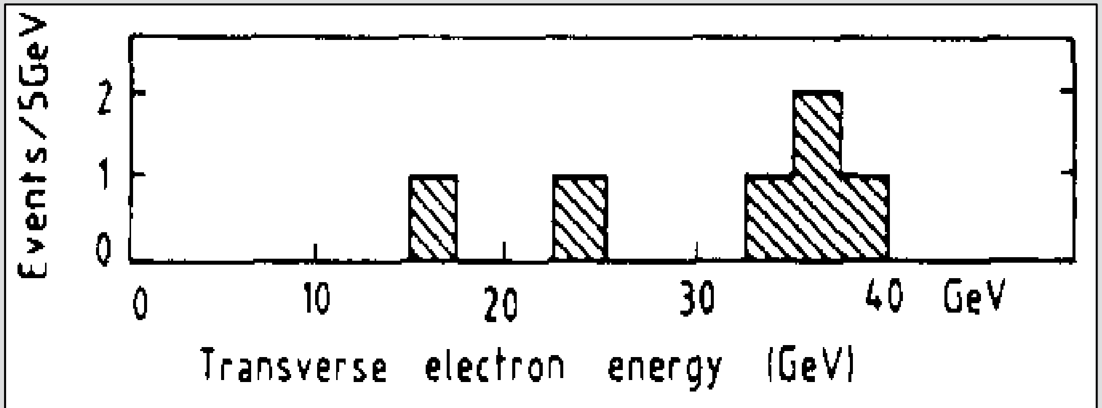
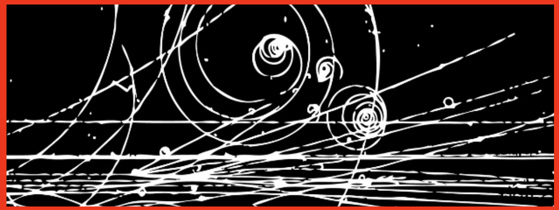


Fig. 1.



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

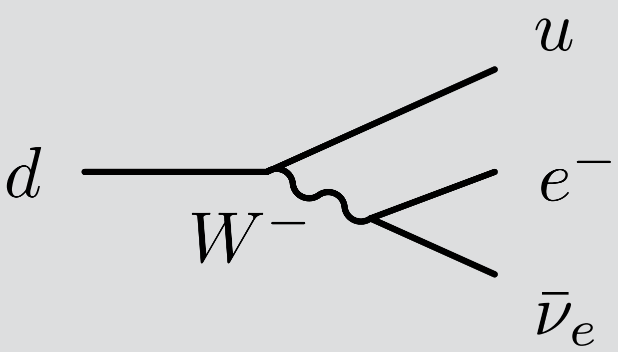
UA1 Coll., Phys.Lett. B122 (1983) 103



Historical perspective: ν

- Radioactive decay was “discovery” of neutrino?

Indirect



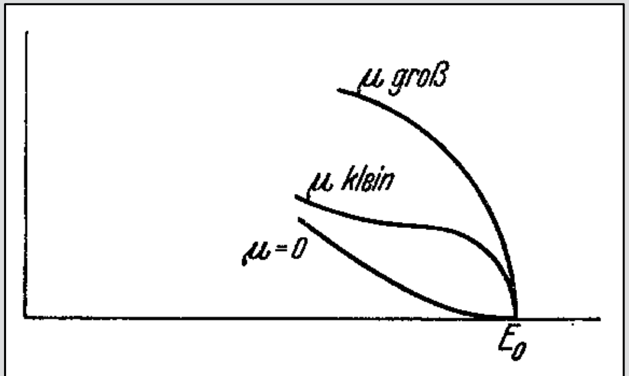
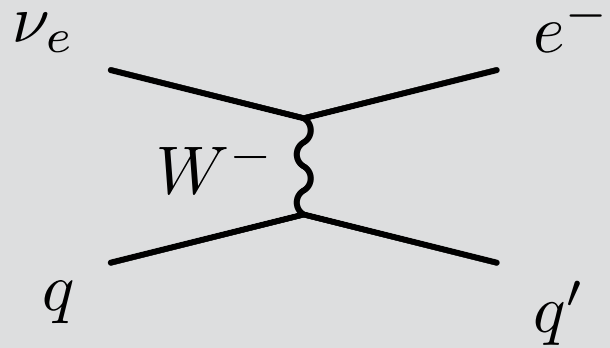
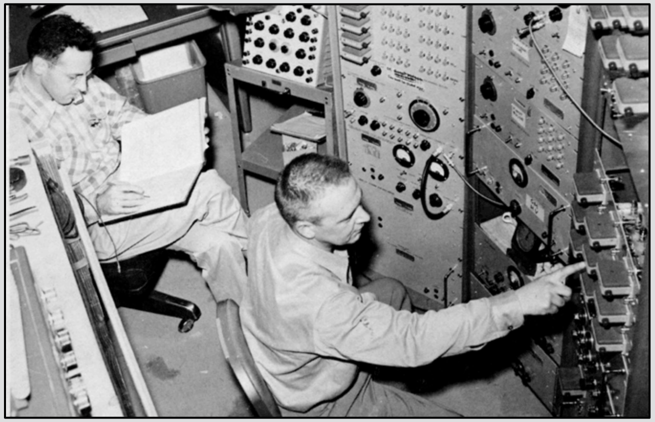


Fig. 1.

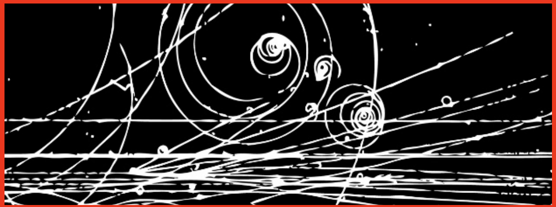
E.Fermi, Z.Phys. 88 (1934) 161

Direct





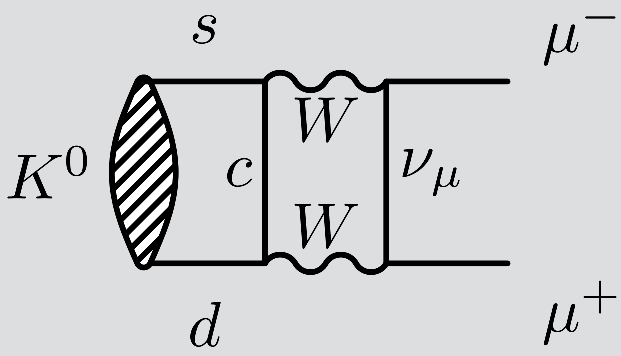
Cowan, Reines, et al., Science 124 (1956) 103-104

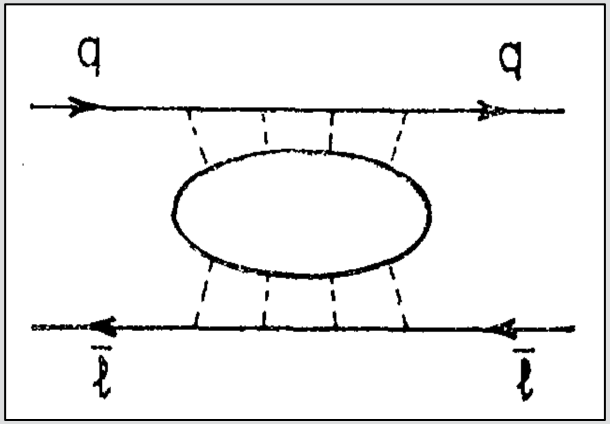


Historical perspective: charm

- Kaon decay was “discovery” of charm quark?

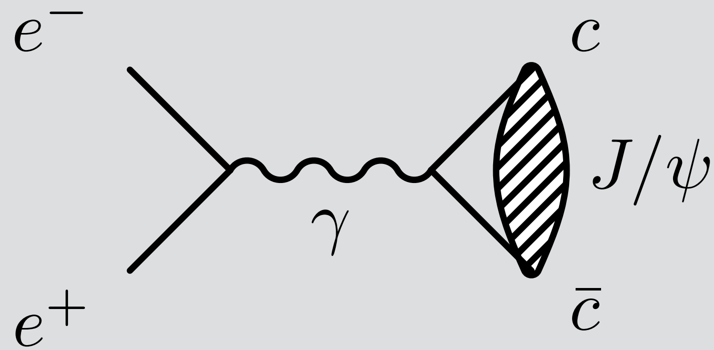
Indirect

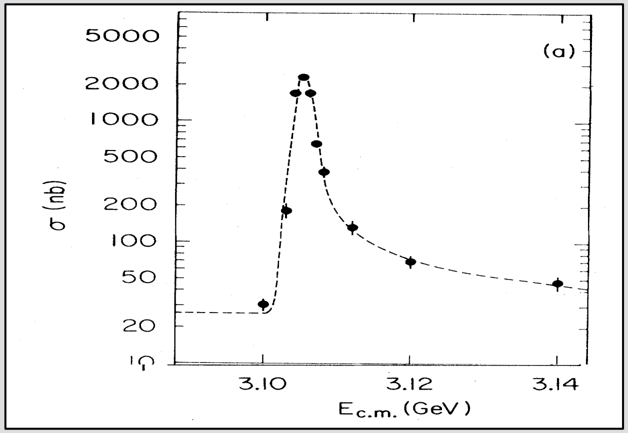




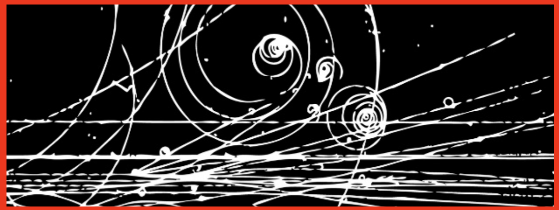
GIM, Phys.Rev. D2 (1970) 1285

Direct





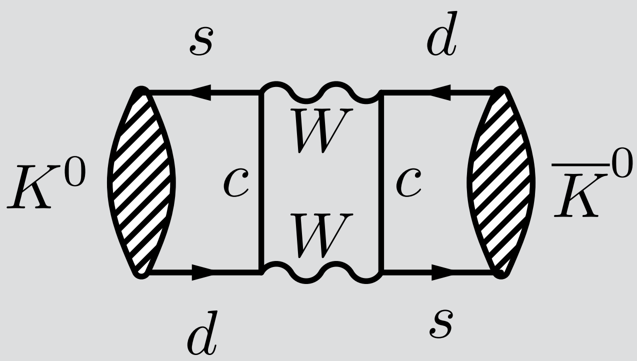
B.Richter et al, Phys.Rev.Lett. 33 (1974) 1406

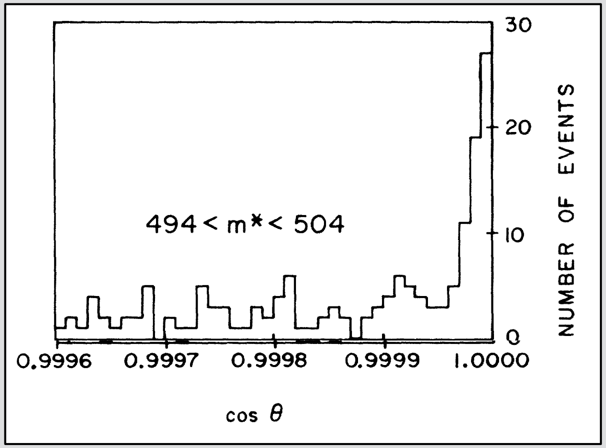


Historical perspective: bottom

- CP violation was "discovery" of 3rd generation?

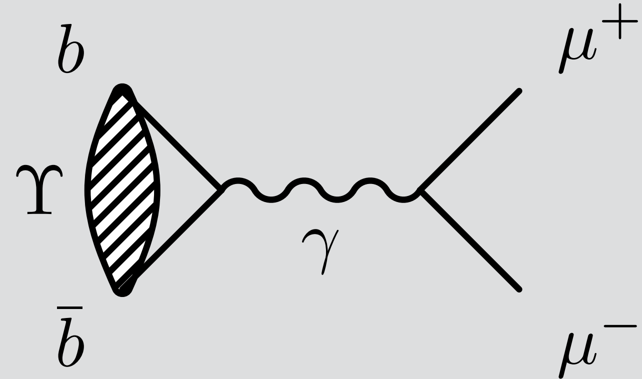
Indirect

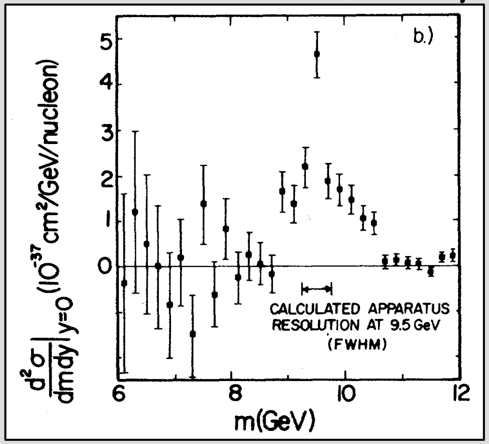




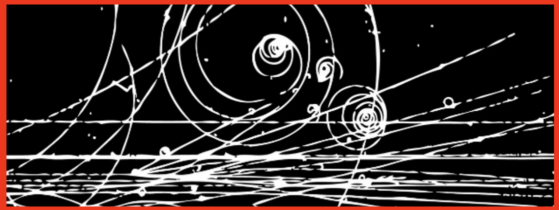
Cronin and Fitch, Phys.Rev.Lett. 13 (1964) 138

Direct





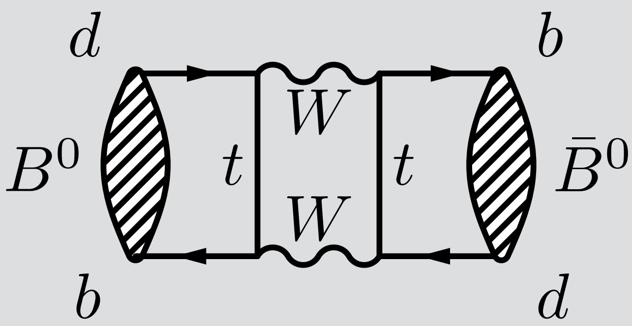
L.Lederman et al., Phys.Rev.Lett. 39 (1977) 252



Historical perspective: top

- Bottom mixing was “discovery” of top quark?

Indirect



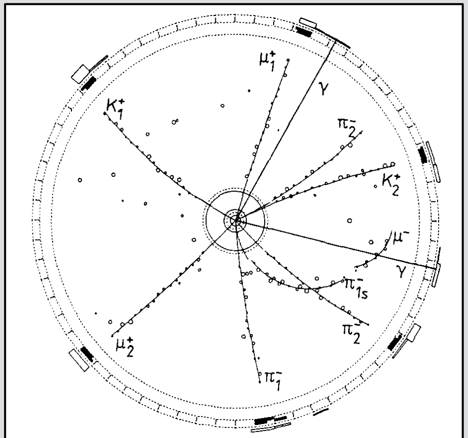
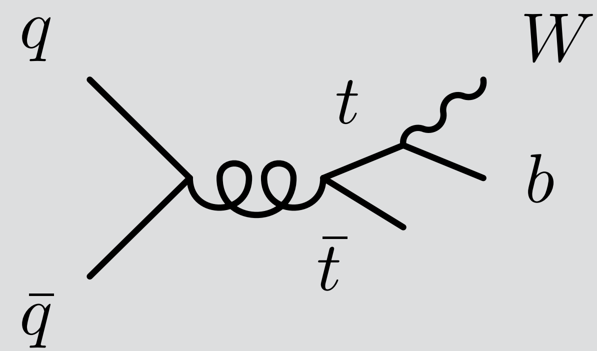
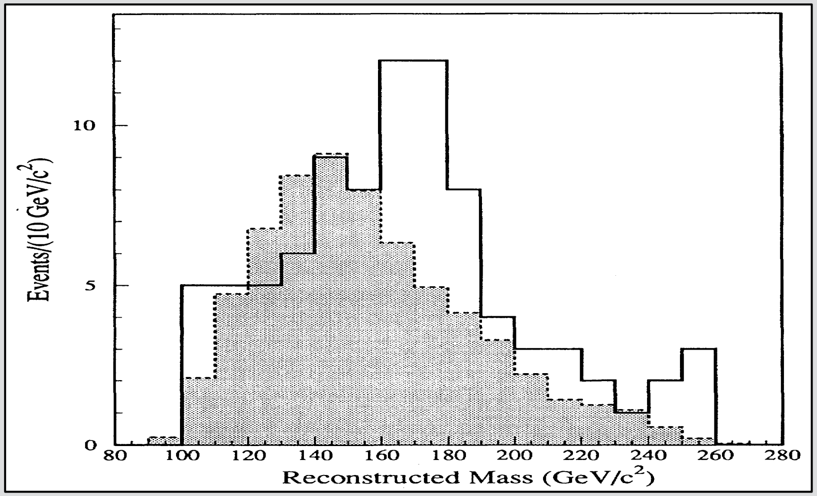


Fig. 2. Completely reconstructed event consisting of the decay Υ (4S)$\to B^0 B^0$.

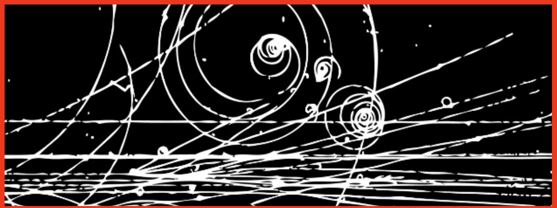
ARGUS, Phys.Lett. B192 (1987) 245

Direct





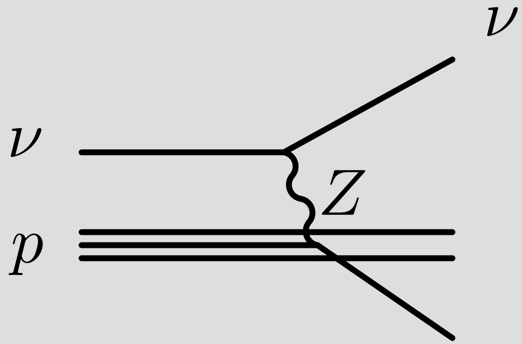
CDF Coll., Phys.Rev.Lett. 74 (1995) 2626

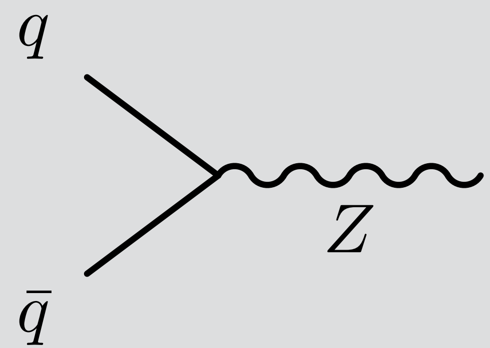


Historical perspective: Z

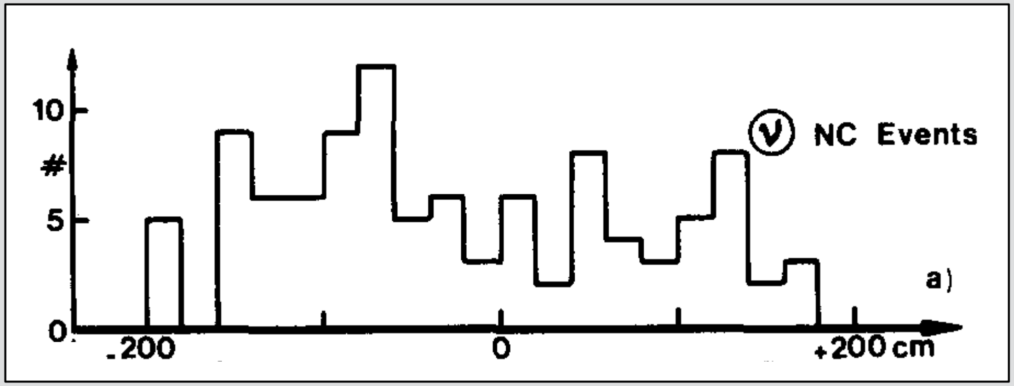
- Neutral current interaction was “discovery” of Z?

Indirect

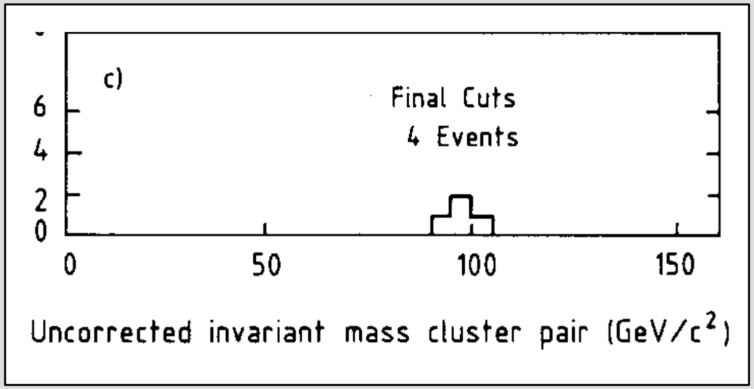




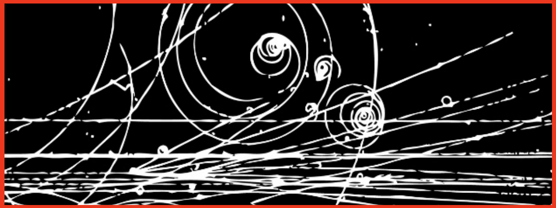
Direct



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



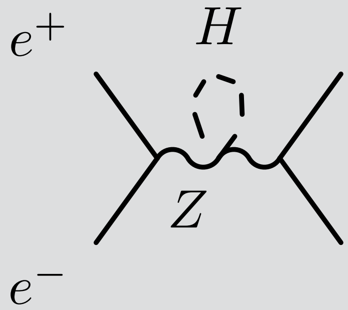
UA1 Coll., Phys.Lett. B126 (1983) 398

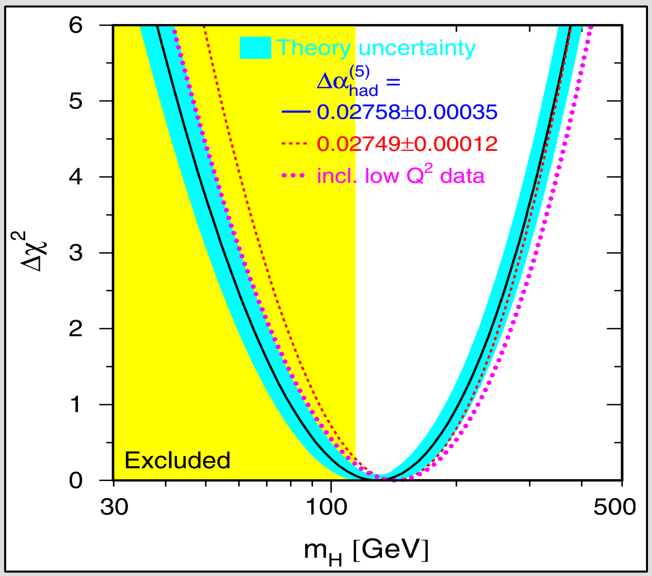


Historical perspective: Higgs

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

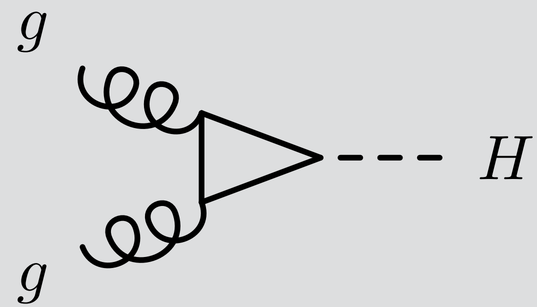
Indirect

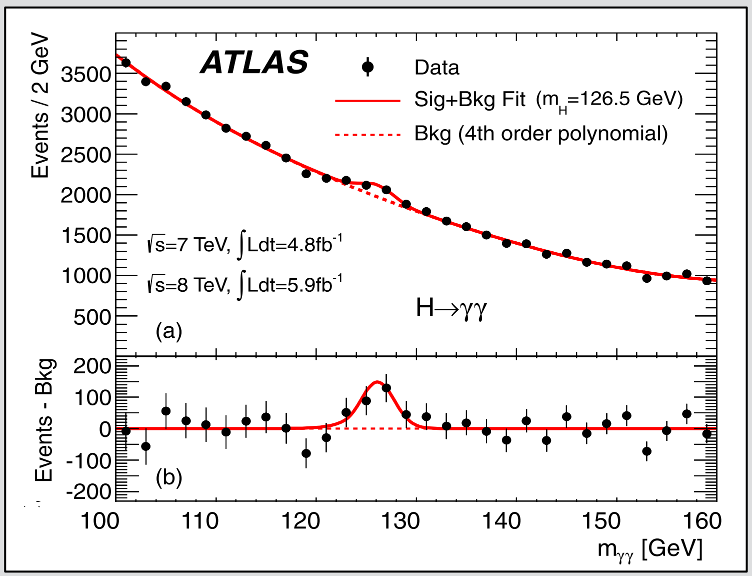




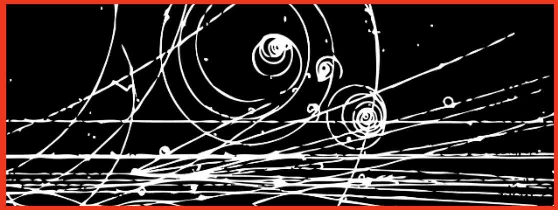
LEP, Phys.Rept. 427 (2006) 257

Direct



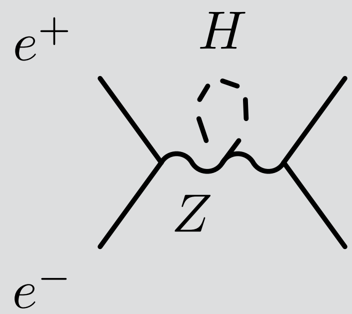


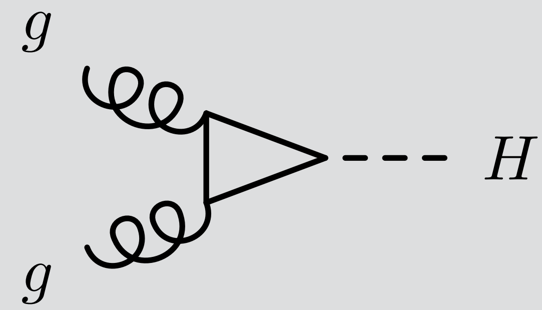
ATLAS Coll., Phys.Lett. B716 (2012) 1



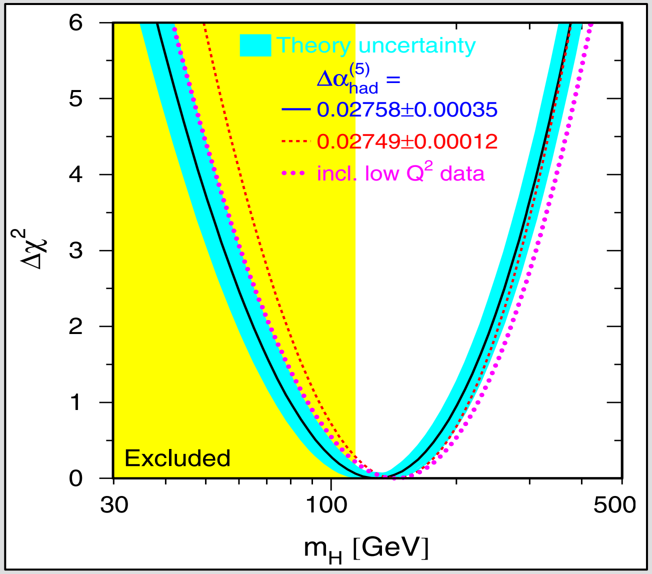
Historical perspective: Higgs

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



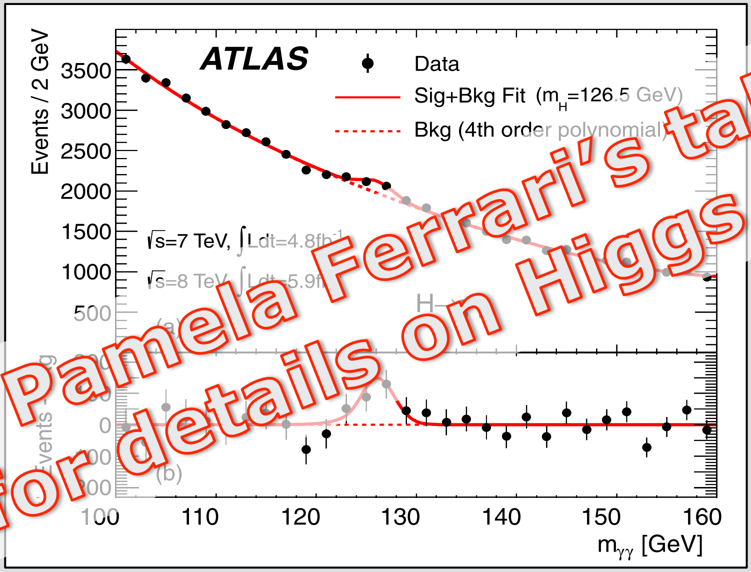


Indirect



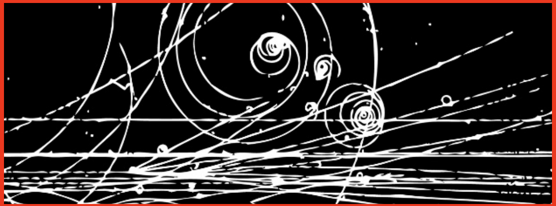
LEP, Phys.Rept. 427 (2006) 257

Direct

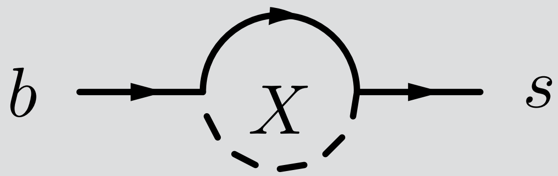


ATLAS Coll., Phys.Lett. B716 (2012) 1

See Pamela Ferrari's talk for details on Higgs



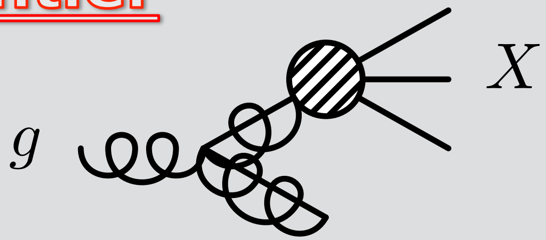
Precision measurements point to new phenomena

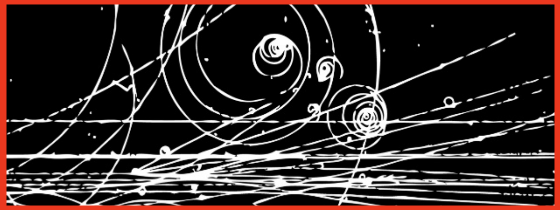


Quantum fluctuations at precision frontier

complement

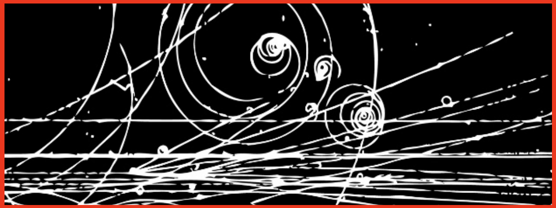
direct production at energy frontier





High-precision measurements

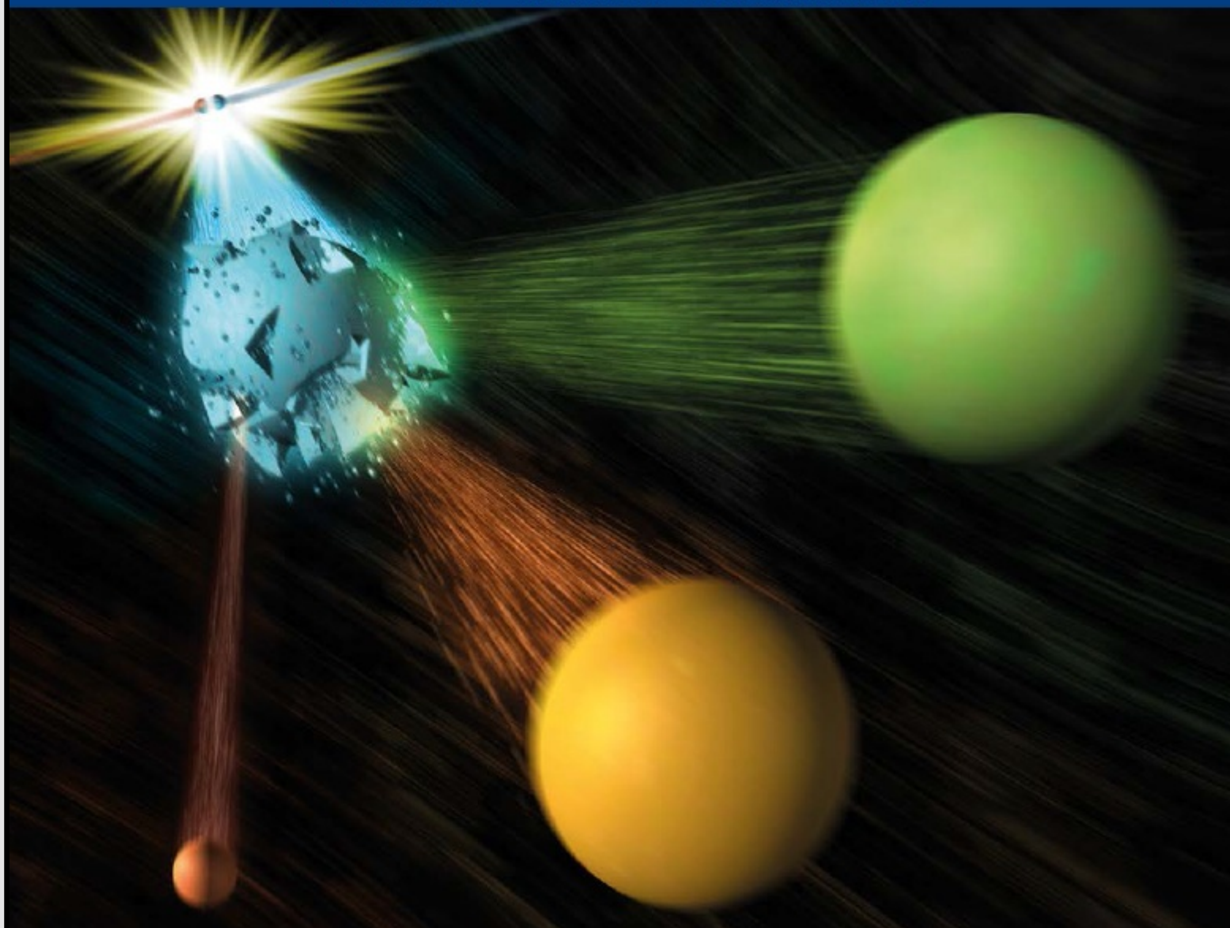
- Standard Model and Feynman Diagrams
- Historical perspective
- Recent highlights from LHCb
  - **CP violation in $B^0_s \rightarrow J/\psi\varphi$ and $B^0_s \rightarrow D_s^- \mu^+ \nu$**
  - **Observation of $B^0_s \rightarrow \mu^+\mu^-$**
  - **Precision measurements on $B^0 \rightarrow K^* \mu^+\mu^-$**
  - **Lepton flavour violation?**
    - $B^+ \rightarrow K^+ \mu^+\mu^-$
    - $B \rightarrow D\mu^+\nu$



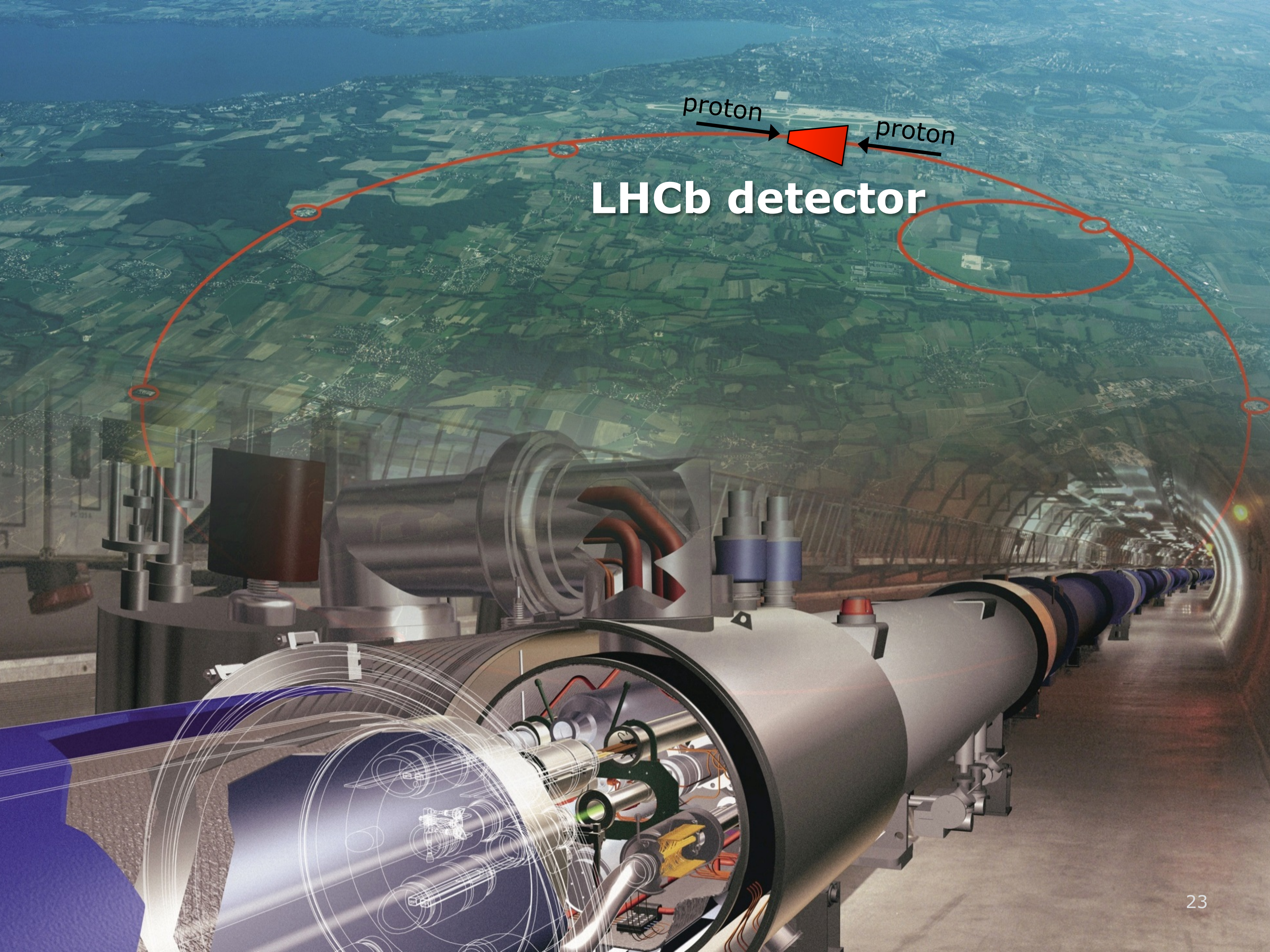
INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERNCOURIER

VOLUME 55 NUMBER 9 NOVEMBER 2015

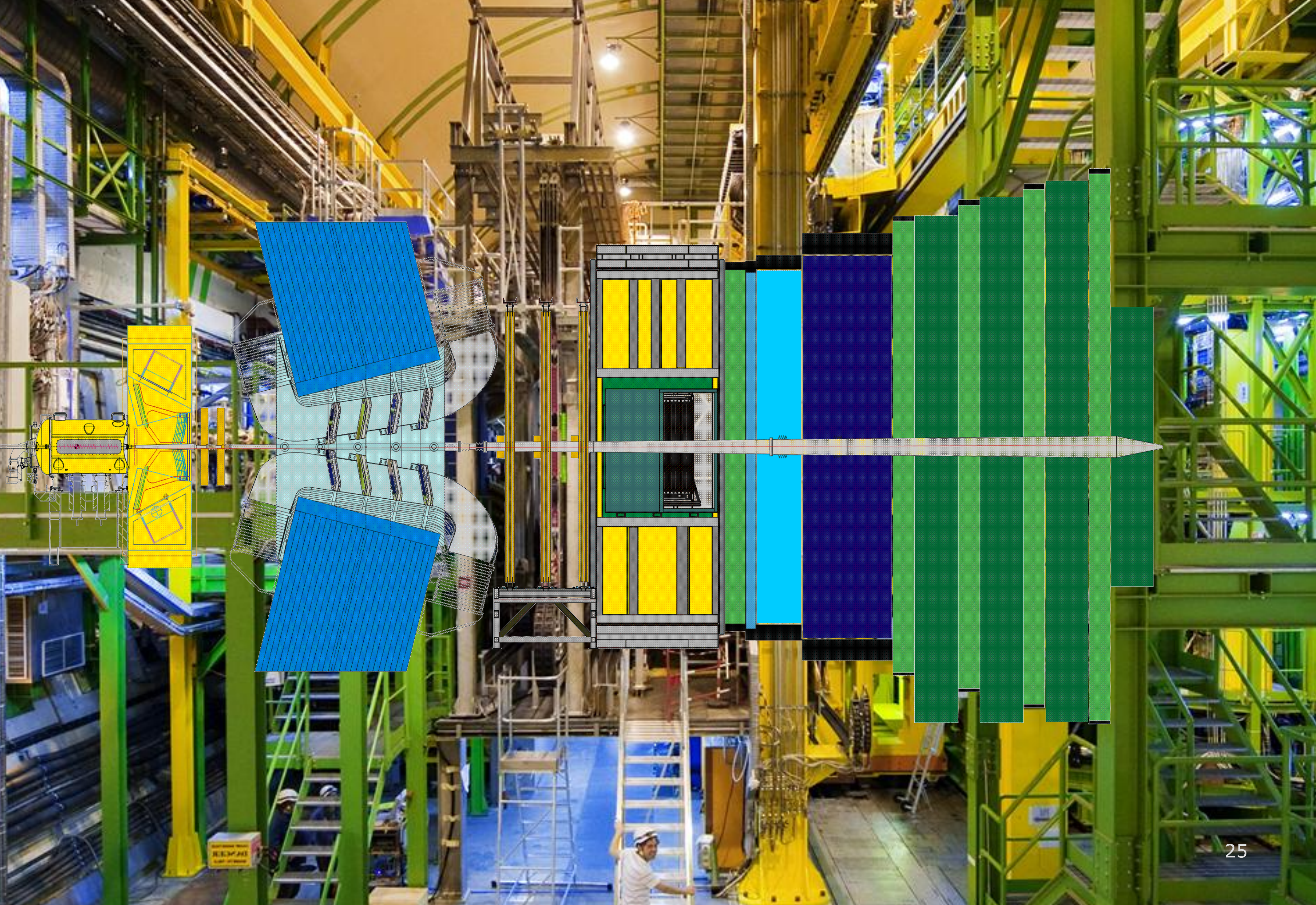


Tensions in the Standard Model

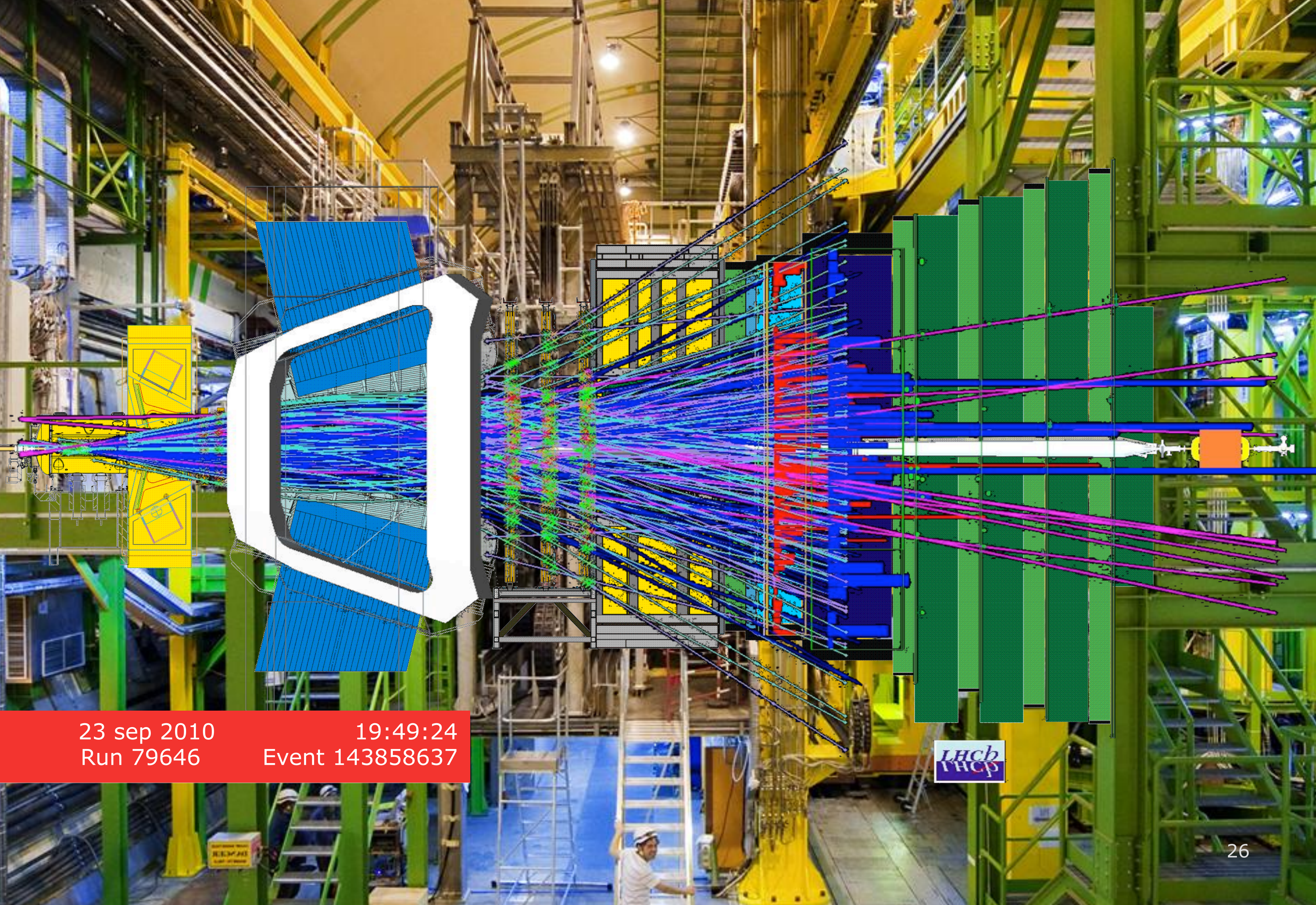

proton
proton
LHCb detector

The LHCb Detector

The LHCb Detector

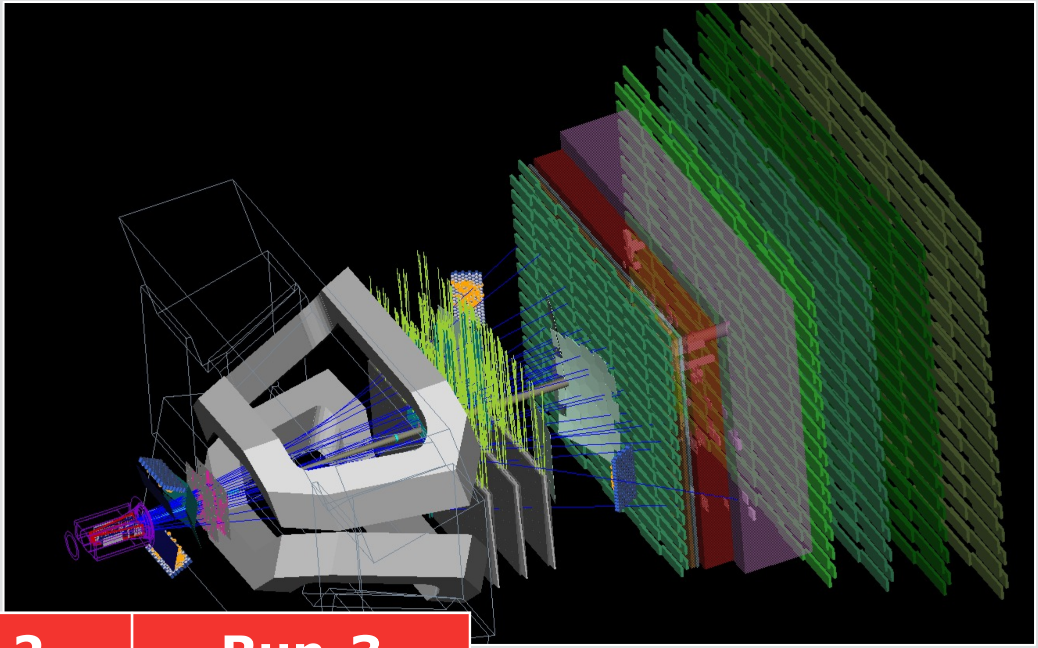


The LHCb Detector



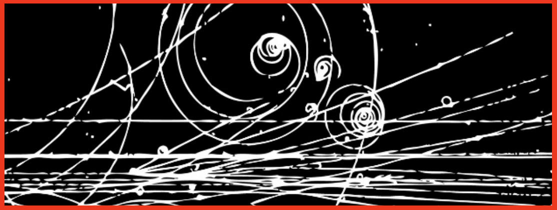
LHC and LHCb

- First LHC run: big success

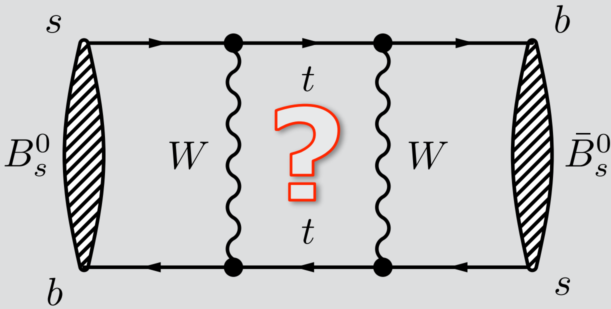


	Run-1	Run-2	Run-3
Year	2010 - 2012	2015 - 2018	2020 - 2030
Energy	7-8 TeV	13 TeV	13 TeV
Lumi	3 fb^{-1}	5 fb^{-1}	50 fb^{-1}
Nr(B)	10^{12}	$5x10^{12}$	$5x10^{13}$

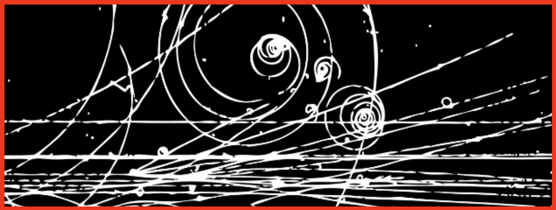
1,000,000,000,000 B-mesons produced



$B_s^0 \rightarrow J/\psi\varphi$ and $B_s^0 \rightarrow D_s^- \mu^+ \nu$

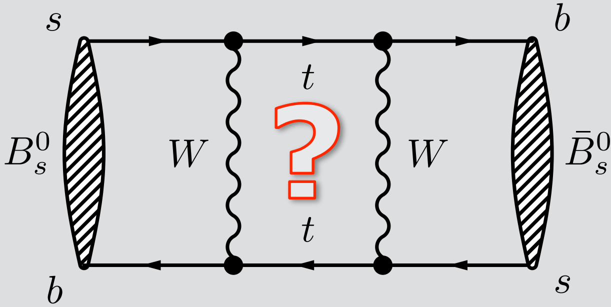


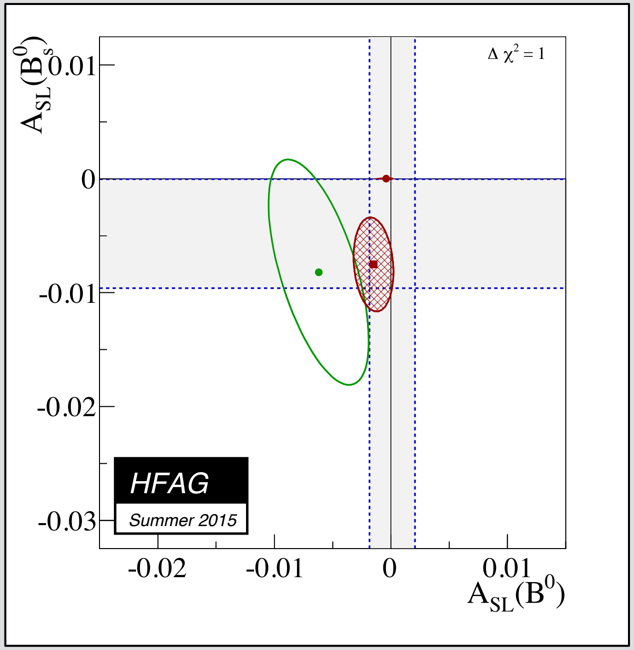
- Search for new matter – antimatter differences
- Do new particles contribute to the asymmetry?
  - *Is there more CP violation in the "box" ?*

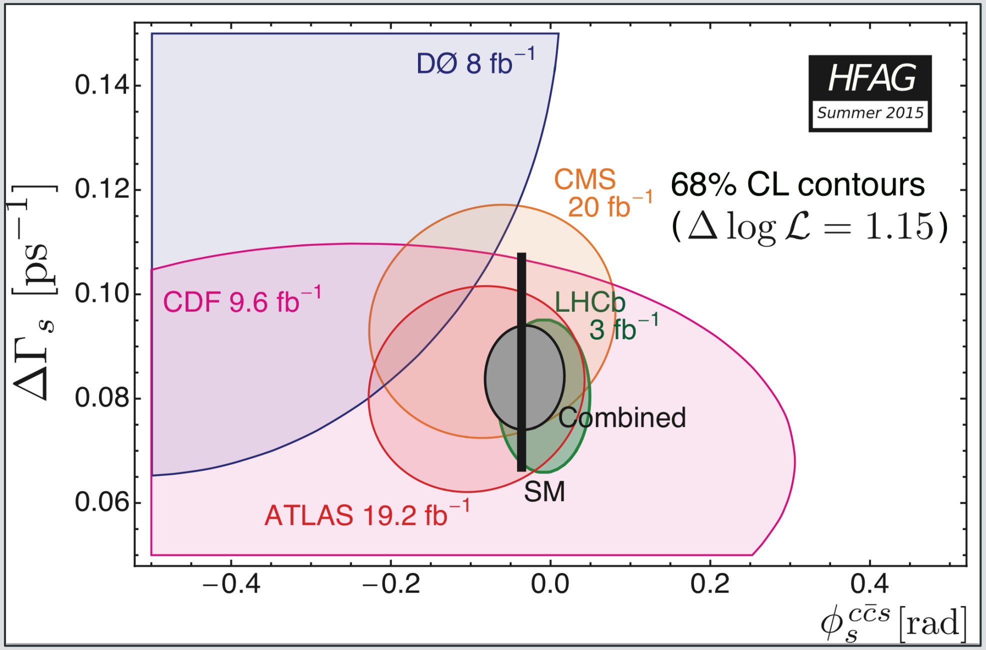


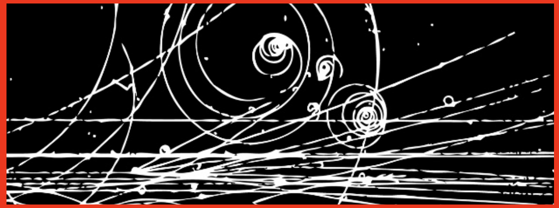
$B_s^0 \rightarrow J/\psi\varphi$ and $B_s^0 \rightarrow D_s^- \mu^+ \nu$

- Search for new matter – antimatter differences
- Do new particles contribute to the asymmetry?
  - *Is there more CP violation in the "box" ?*

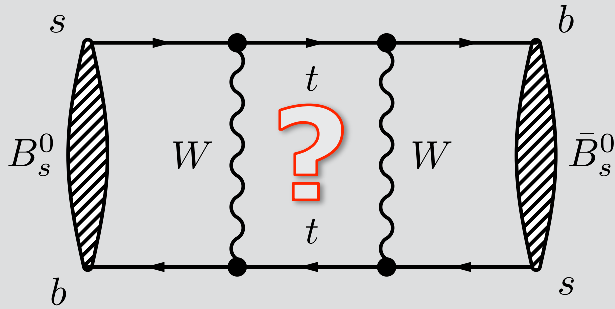




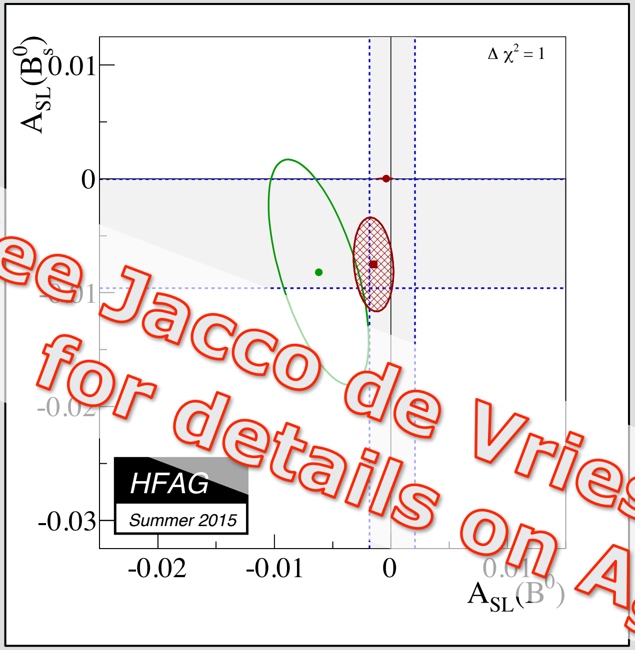


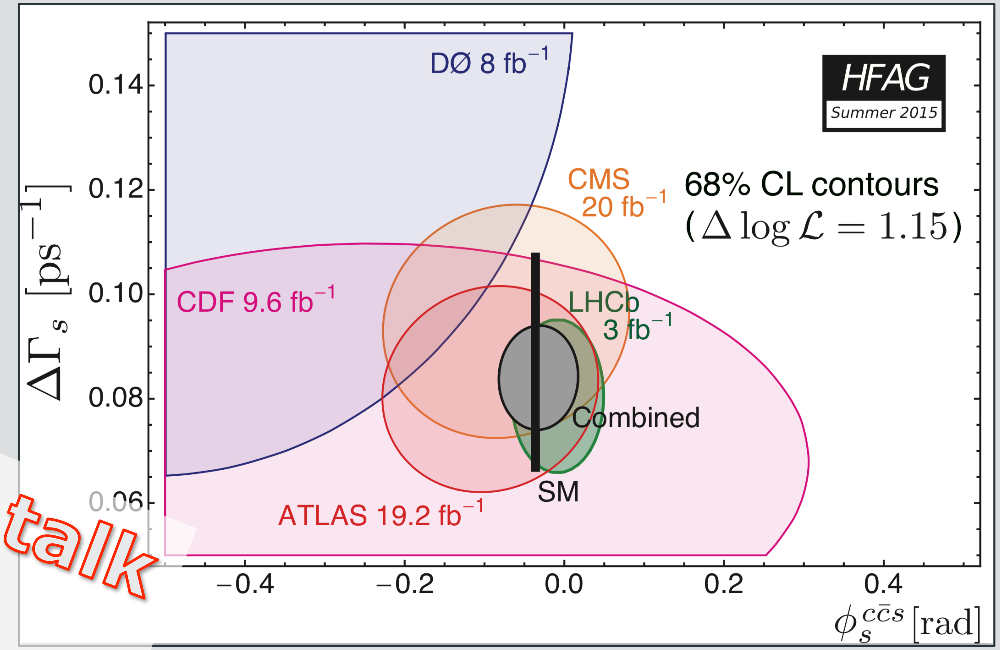


$B_s^0 \to J/\psi\varphi$ and $B_s^0 \to D_s^- \mu^+ \nu$

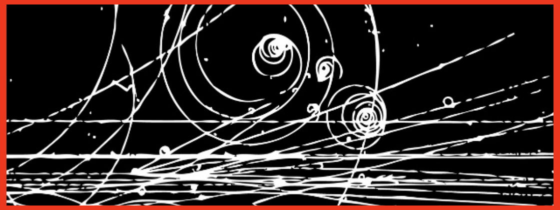


- Search for new matter – antimatter differences
- Do new particles contribute to the asymmetry?
  - *Is there more CP violation in the "box" ?*

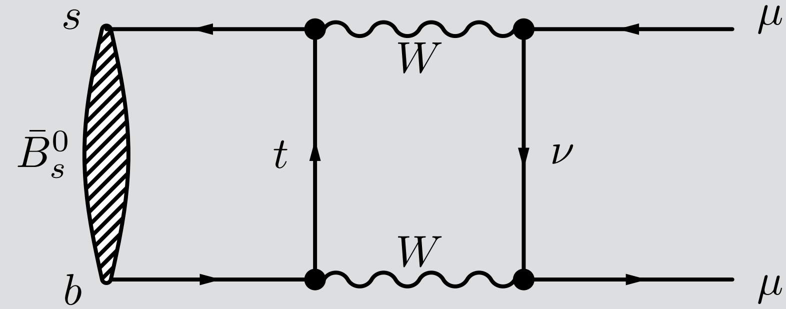




See Jacco de Vries' talk for details on A_{SL}

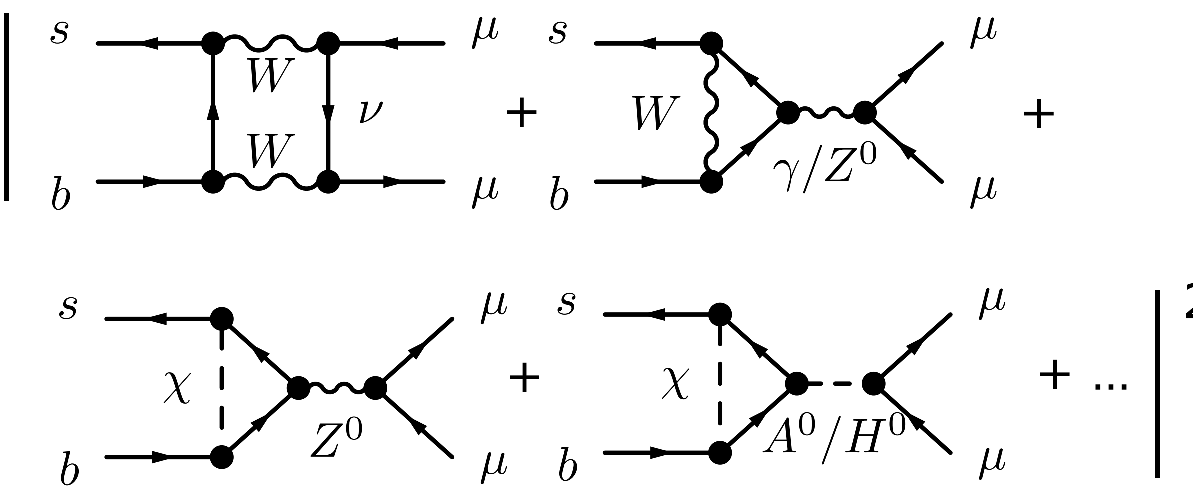


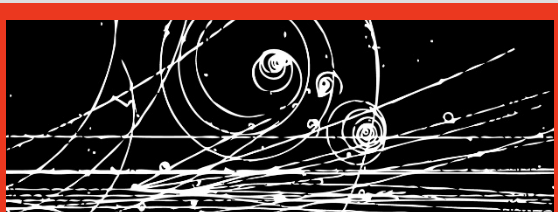
$B_s^0 \rightarrow \mu^+\mu^-$



- Similar rare decay as $K^0 \rightarrow \mu^+\mu^-$
- Very, very rare in the SM
- Sensitive to small effects beyond the SM

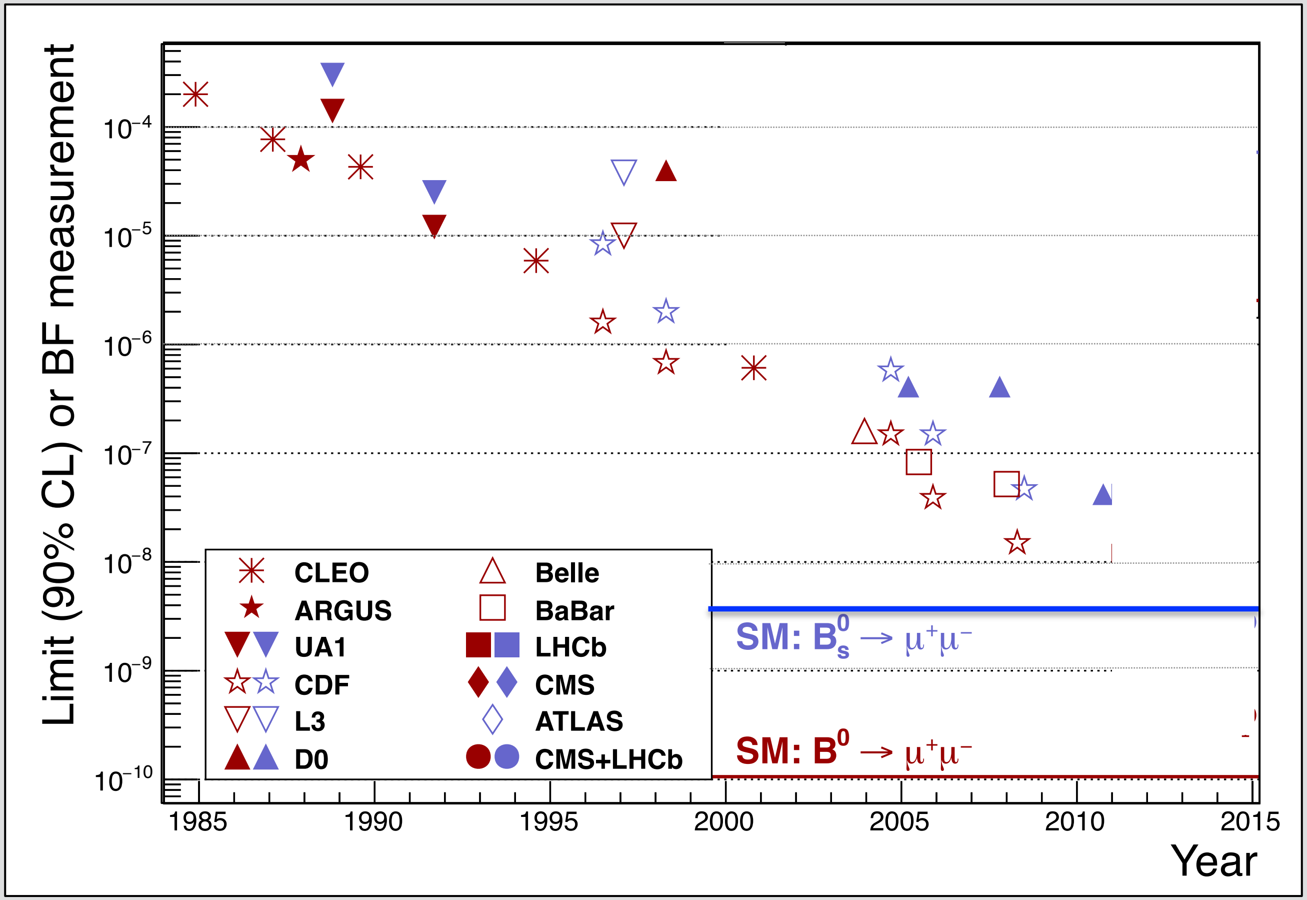
$$N(B_s^0 \rightarrow \mu^+\mu^-) = C \left| \ldots \right|^2$$

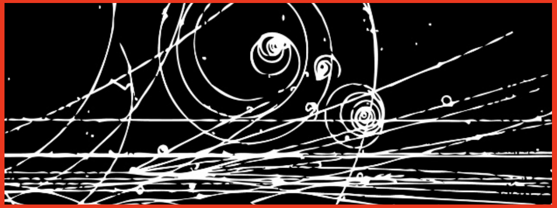




$B_s^0 \to \mu^+\mu^-$

- Historical endeavour!

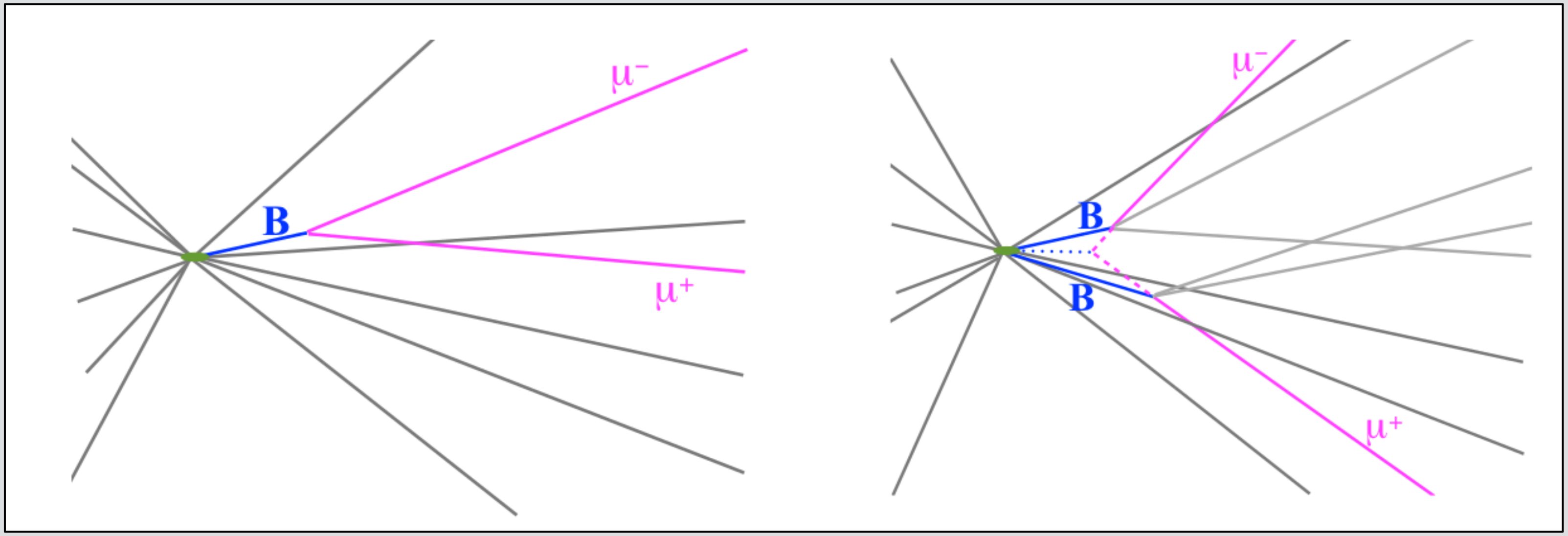




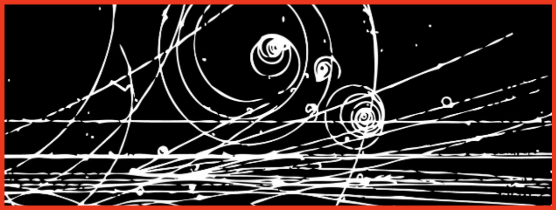
$B_s^0 \to \mu^+\mu^-$

- 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}
- 10^{12} B produced; probability of $\mu\mu$ decay 10^{-9}; eff ~5%
  - Expect ~50 events

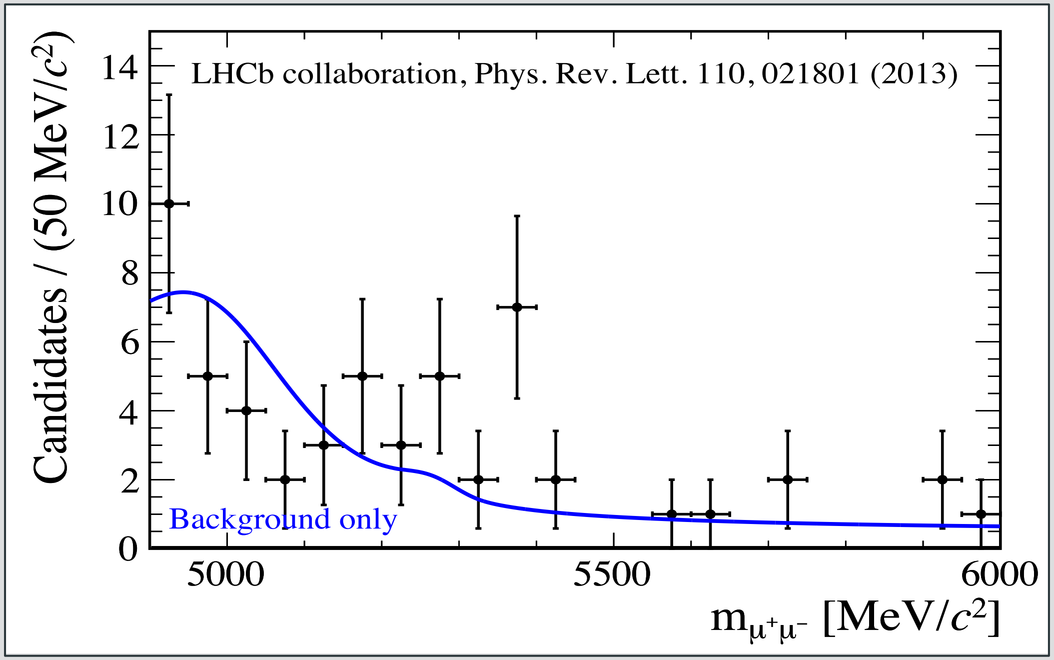
Thesis S.Oggero (2013)



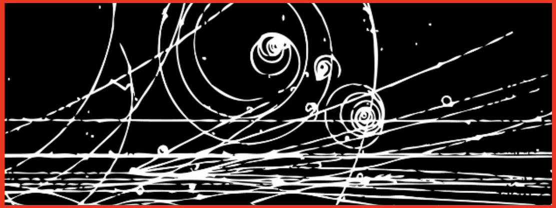
Signal 1 : 10^7 Background



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

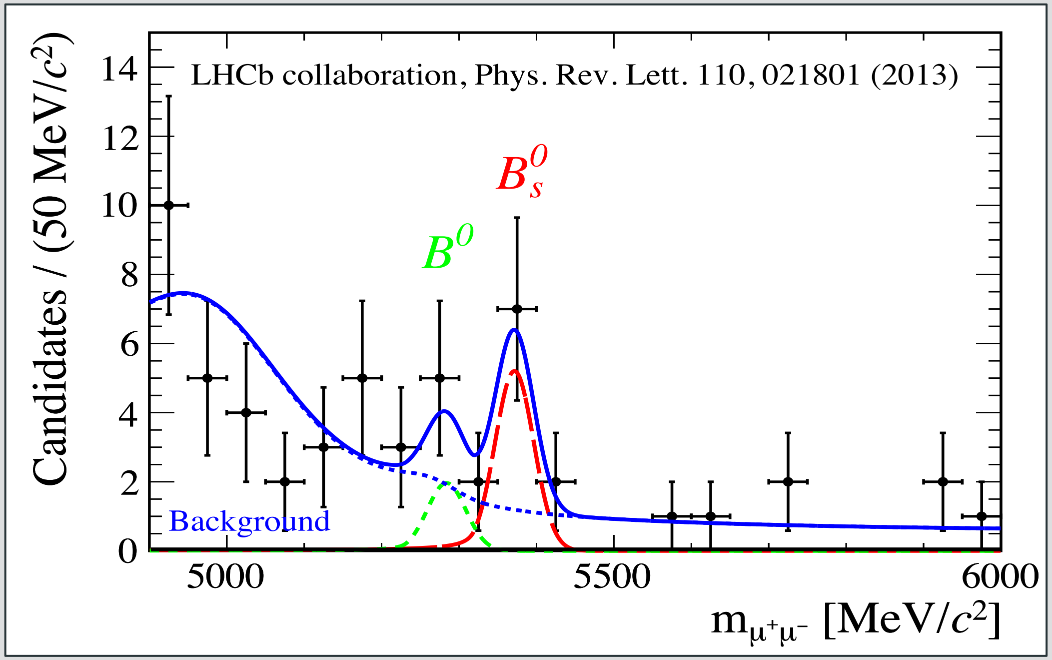


LHCb Coll. Phys.Rev.Lett. 110, 021801 (2013)

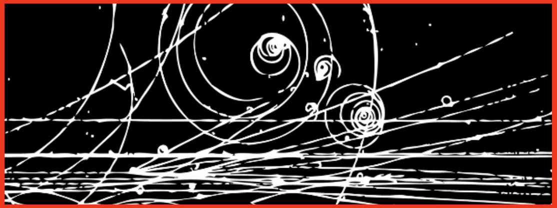


$B_s^0 \rightarrow \mu^+\mu^-$

- First evidence, 3.5σ

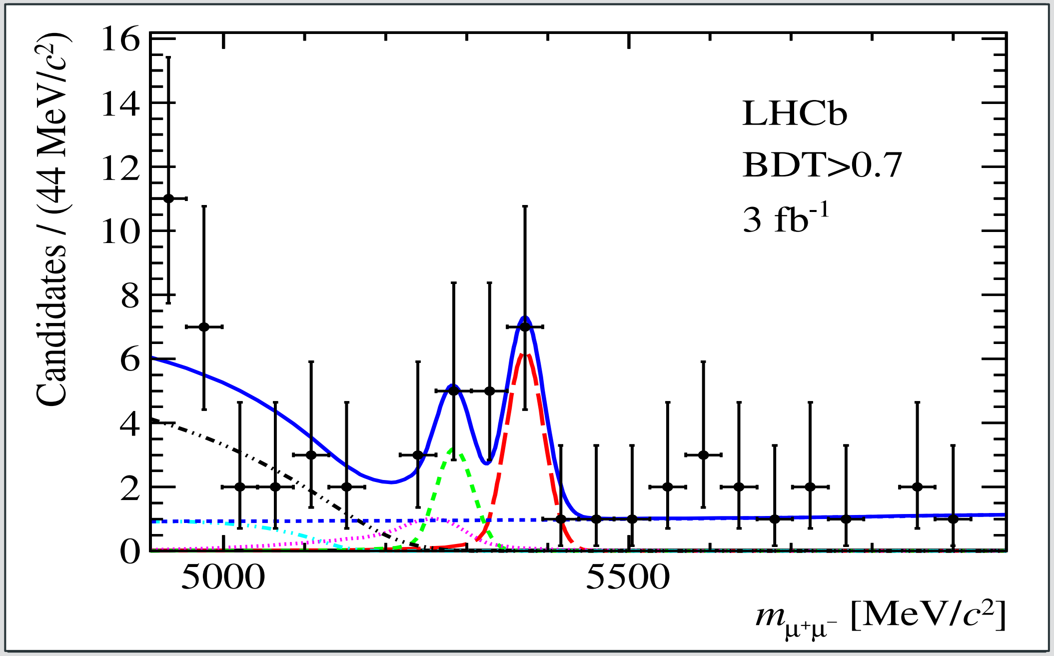


LHCb Coll. Phys.Rev.Lett. 110, 021801 (2013)

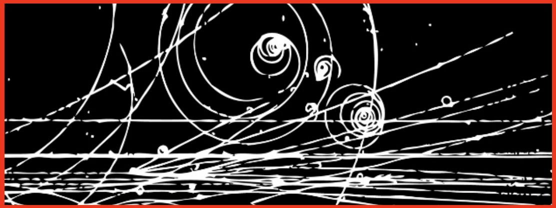


$B_s^0 \rightarrow \mu^+\mu^-$

- 4σ

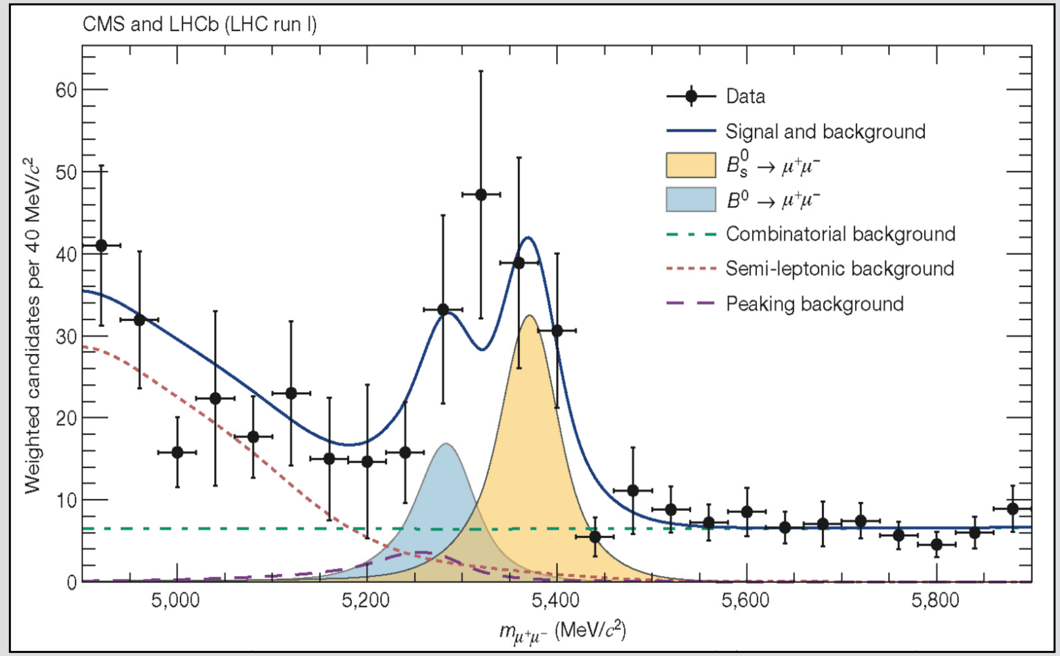


LHCb Coll. Phys.Rev.Lett. 111, 101805 (2013)



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

- First observation, 6.2σ

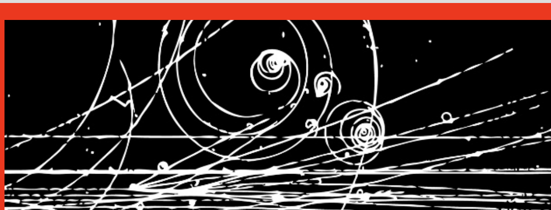


Nature 522, 68–72 (2015)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10}$$

$B_d^0 \rightarrow \mu^+\mu^-$?

- First evidence at 3.0σ

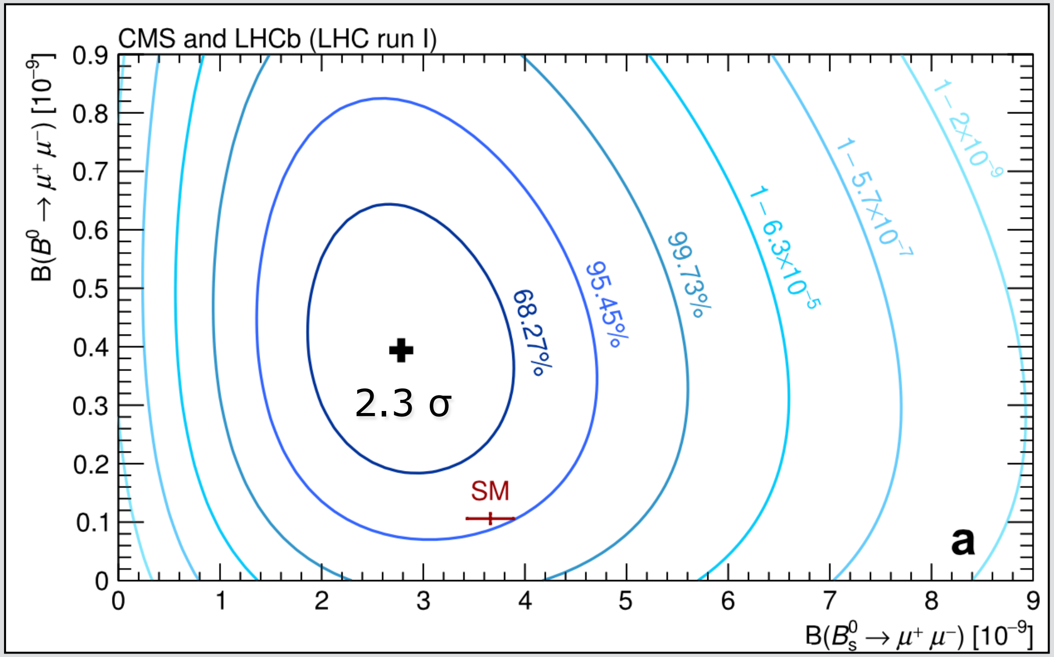


$B_s^0 \rightarrow \mu^+\mu^-$

- First observation, 6.2σ

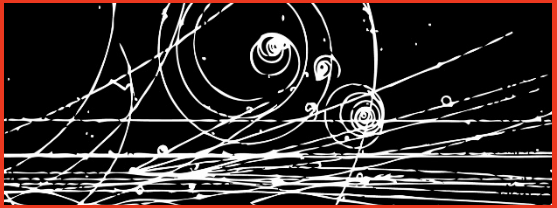
$B_d^0 \rightarrow \mu^+\mu^-$?

- First evidence at 3.0σ
- 2.3σ above SM prediction
- R_{SM}=0.030±0.003



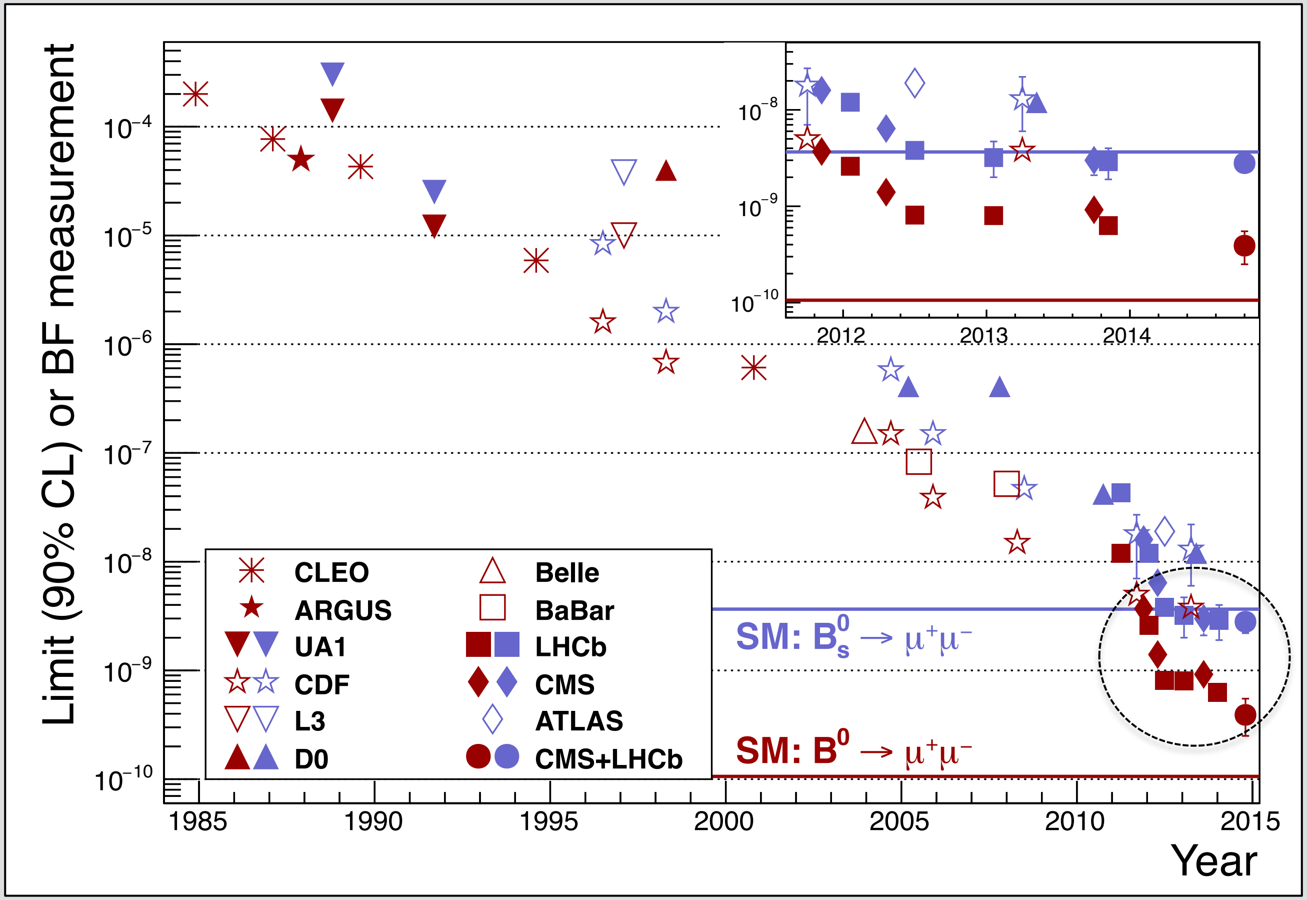
Nature 522, 68–72 (2015)

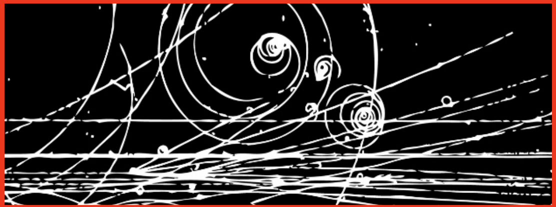
$$R = \frac{\mathcal{B}(B^0 \rightarrow \mu\mu)}{\mathcal{B}(B_s^0 \rightarrow \mu\mu)} = 0.14^{+0.08}_{-0.06}$$



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

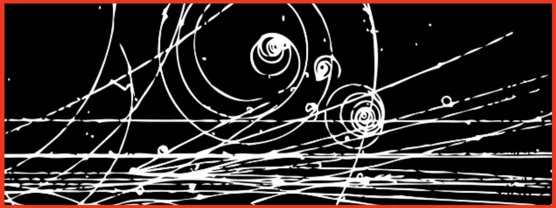
- Historical endeavour!



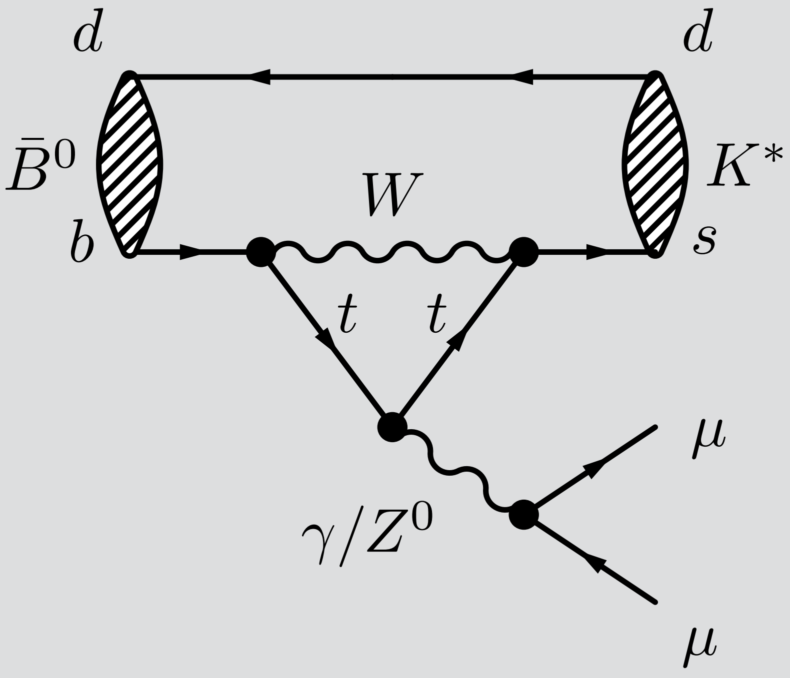


High-precision measurements

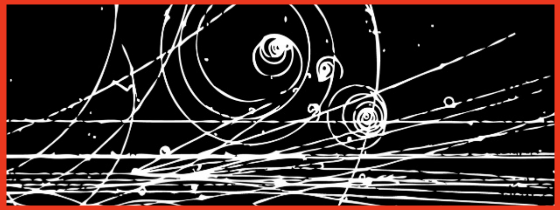
- Standard Model and Feynman Diagrams
- Historical perspective
- Recent highlights from LHCb
  - **CP violation in *$B^0_s \rightarrow J/\psi\varphi$* and *$B^0_s \rightarrow D_s^- \mu^+ \nu$***
  - **Observation of *$B^0_s \rightarrow \mu^+\mu^-$***
  - **Precision measurements on *$B^0 \rightarrow K^*\mu^+\mu^-$***
  - **Lepton flavour violation?**
    - ***$B^+ \rightarrow K^+\mu^+\mu^-$***
    - ***$B \rightarrow D\mu^+\nu$***



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

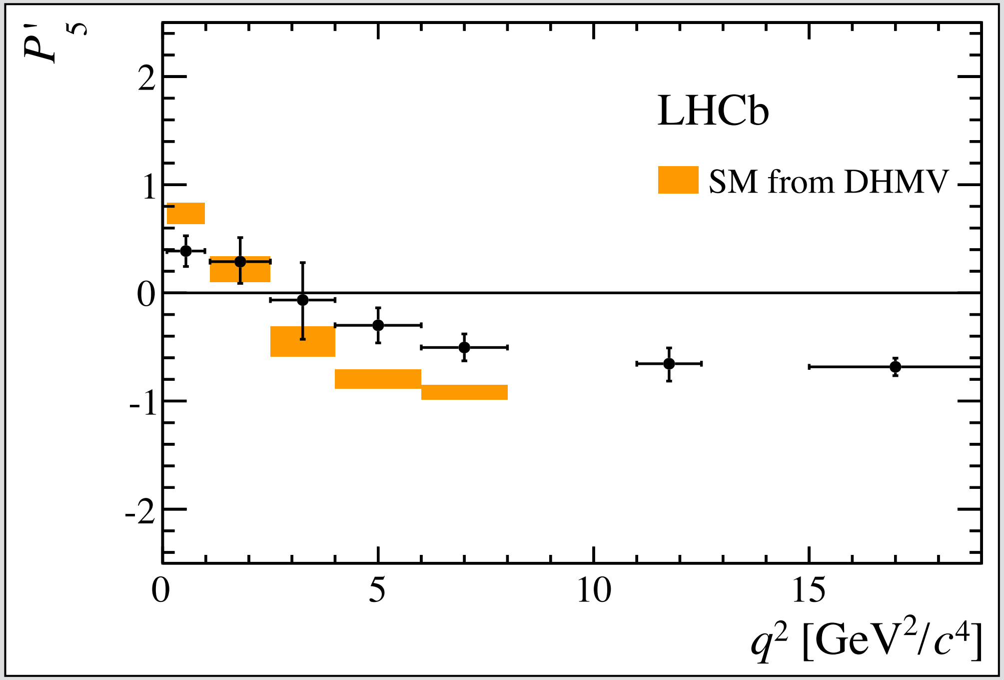


- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of K and μ

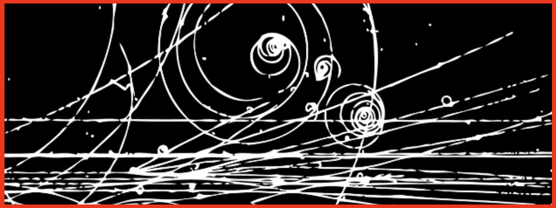


$B_d^0 \rightarrow K^0{}^*\mu^+\mu^-$

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

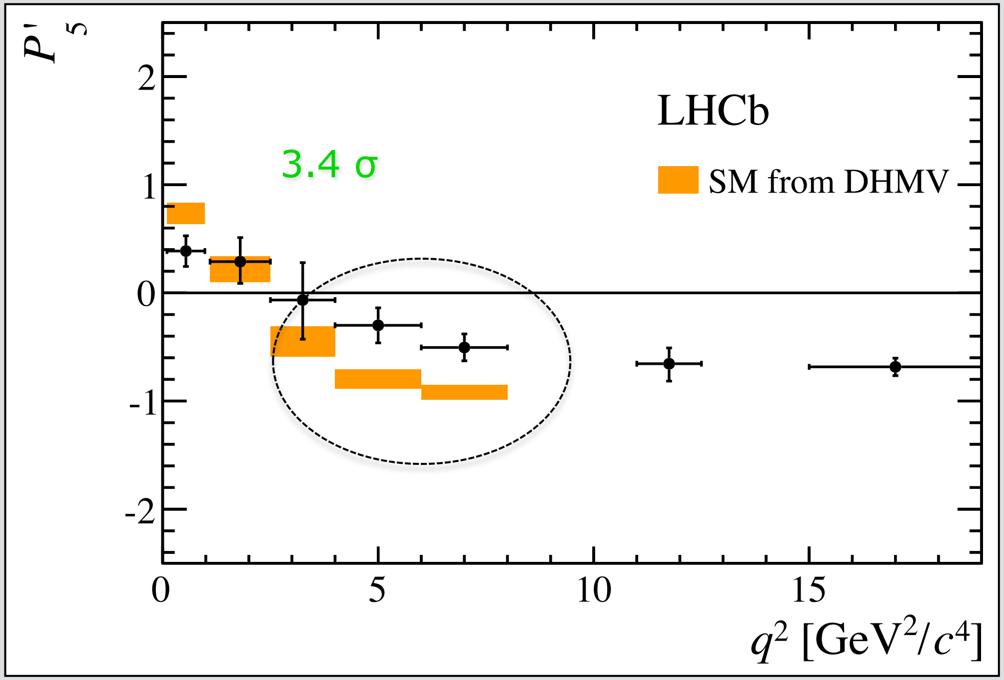


LHCb, arXiv:1512.04442

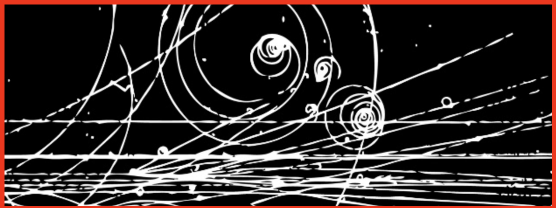


$B_d^0 \rightarrow K^{0*}\mu^+\mu^-$

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

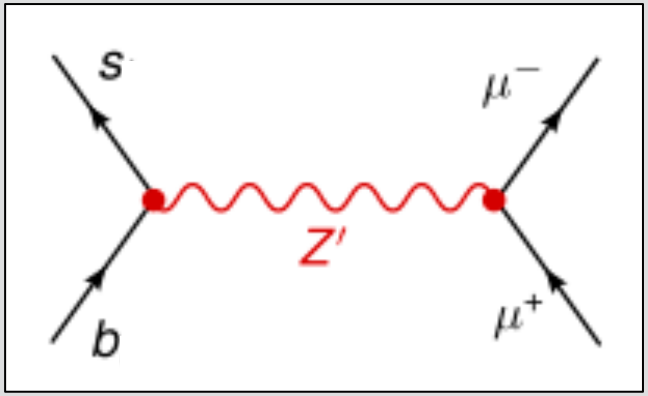


LHCb, arXiv:1512.04442

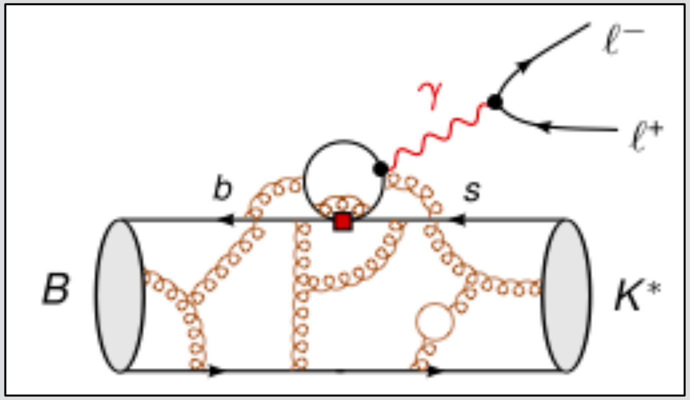


$B_d^0 \rightarrow K^{0*}\mu^+\mu^-$

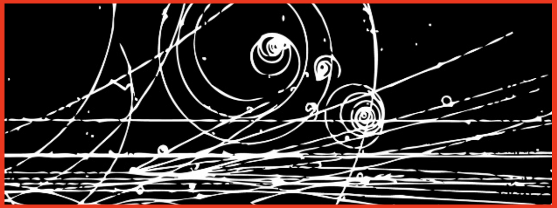
- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of K and μ
- Debate on SM calculation
  - Non-perturbative "charm loop" effects?



or



?

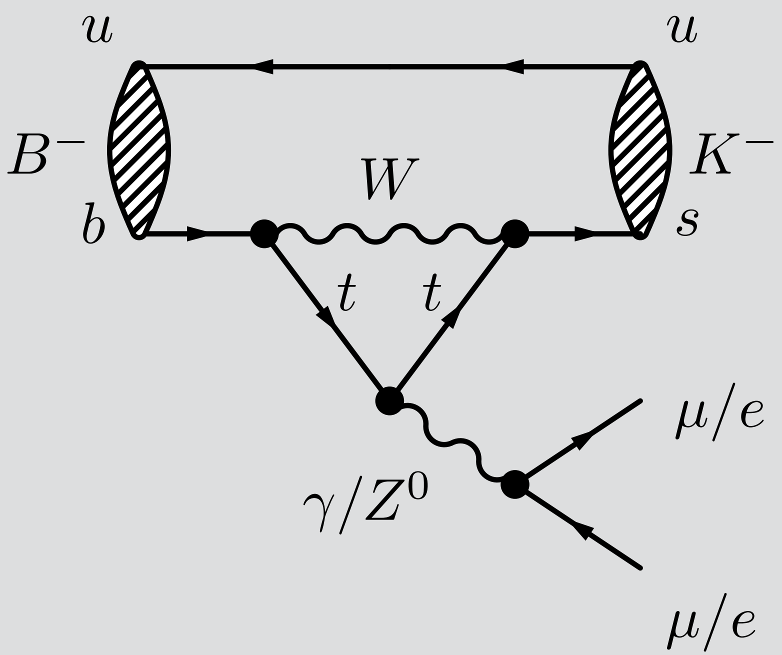


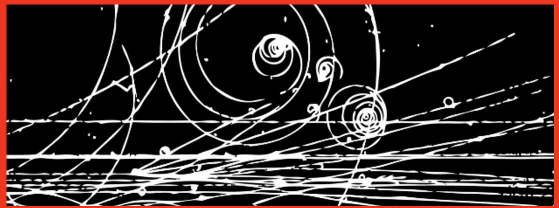
$B^+ \rightarrow K^+ \mu^+ \mu^-$

- Similar loop diagram!

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

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



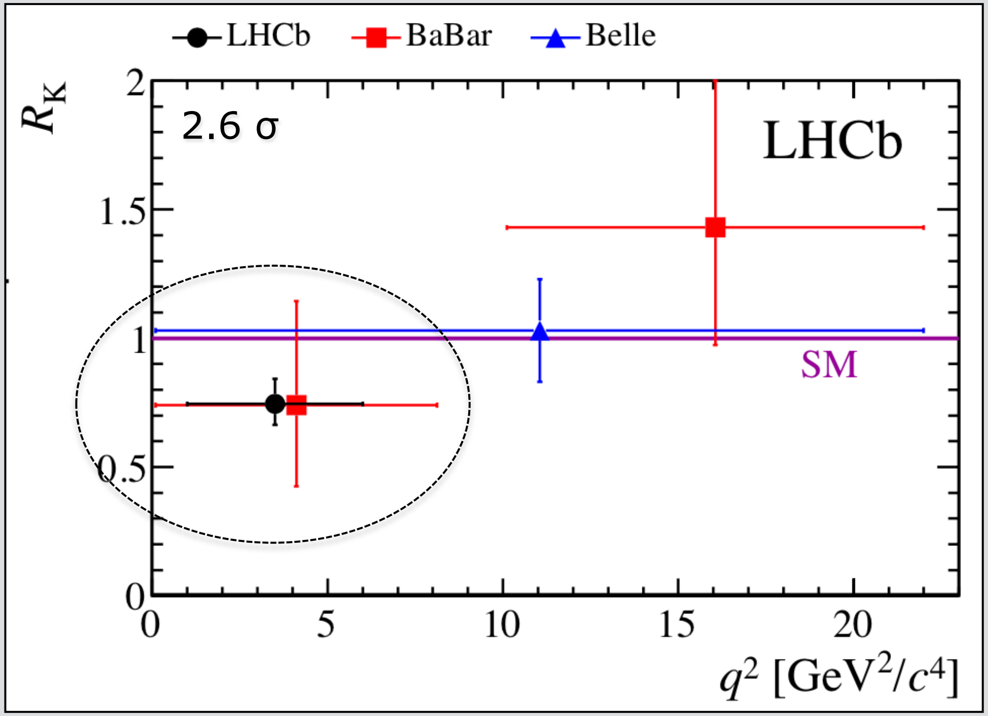


$B^+ \rightarrow K^+\mu^+\mu^-$

- Similar loop diagram!

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

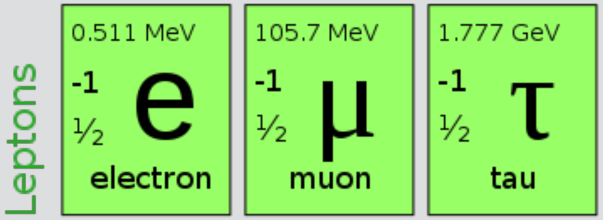
$$R_K = \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)}$$

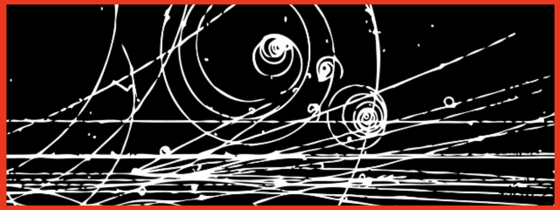


LHCb Coll.,Phys.Rev.Lett. 113 (2014) 151601

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

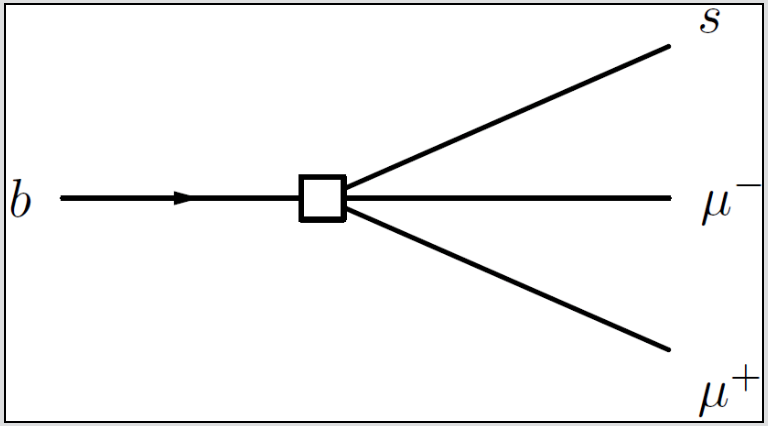
- **Lepton flavour "non-universal" ?**

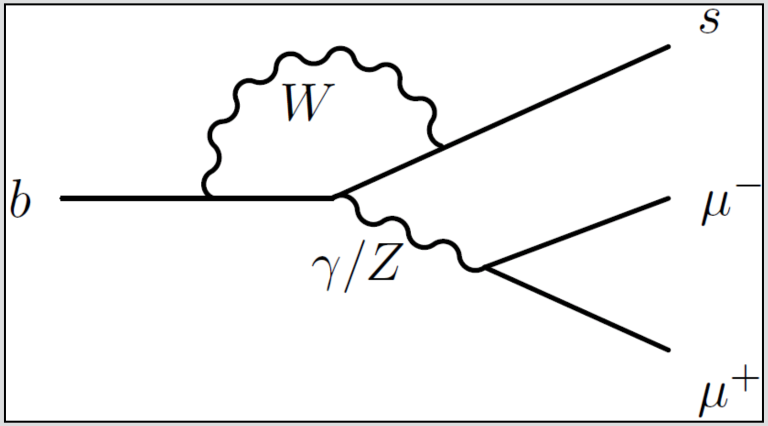


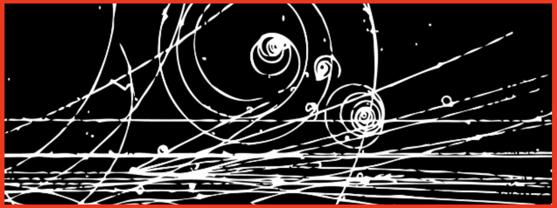


Intermezzo:

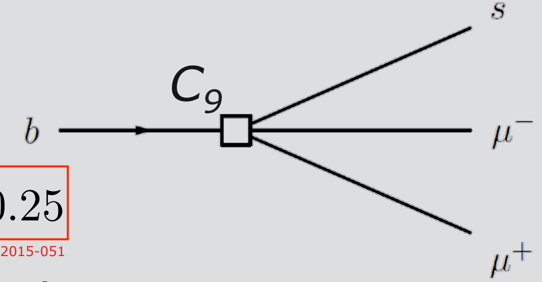
- Effective coupling can be of various “kinds”
  - Vector coupling: C_9
  - Axial coupling: C_{10}
  - Left-handed coupling (V-A): C_9-C_{10}
  - Right-handed (to quarks): C_9', C_{10}', …
  - …







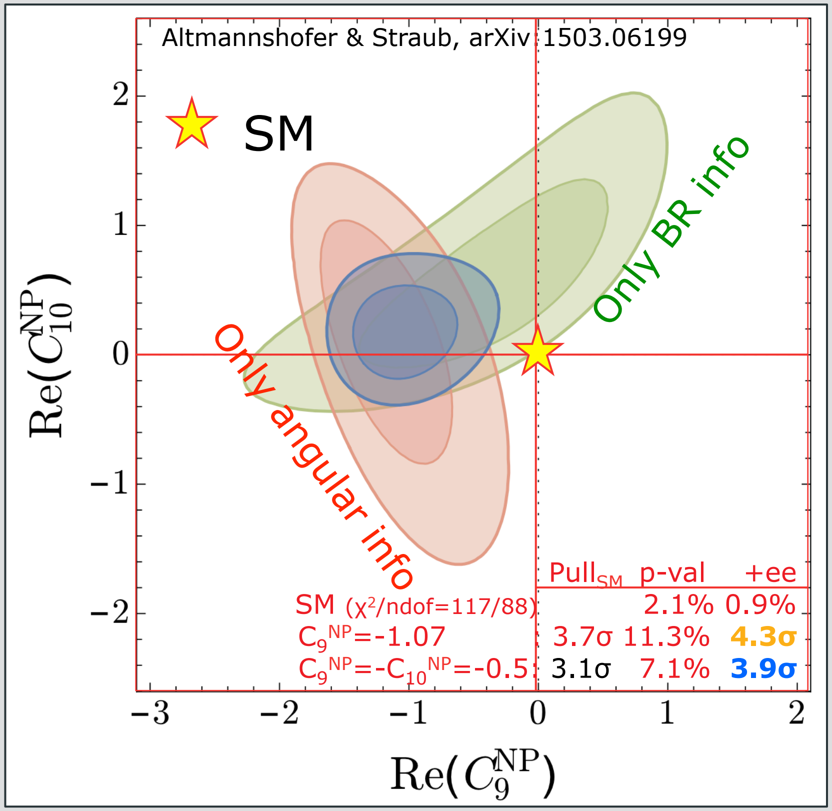
Theory: Model independent fits

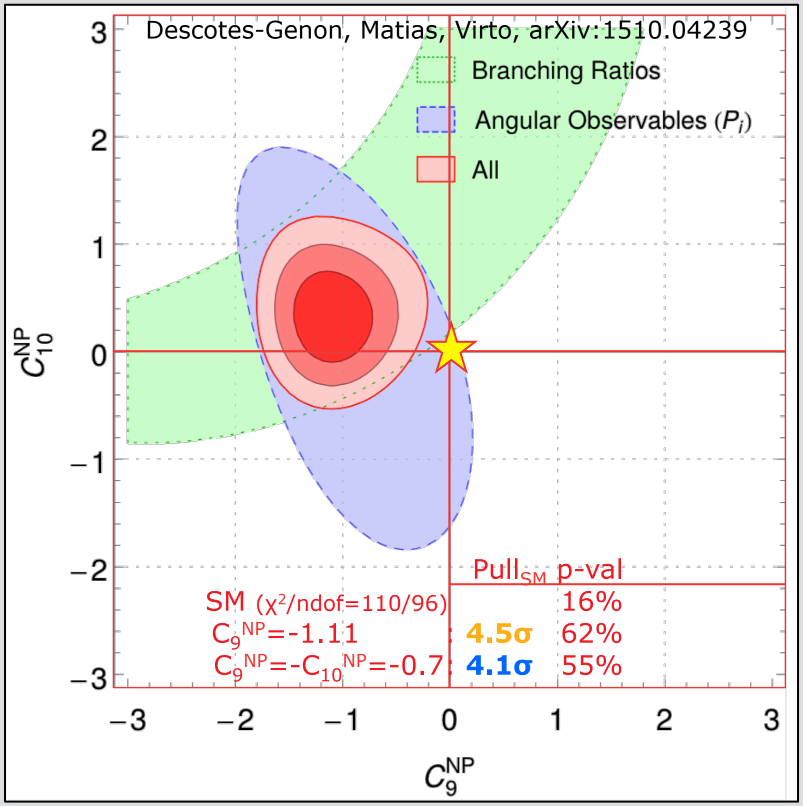


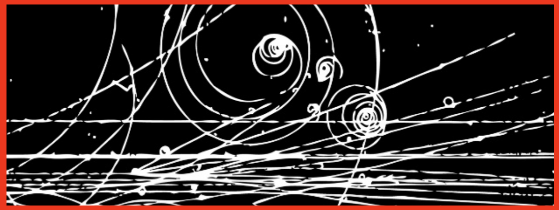
$$\Delta\mathrm{Re}(\mathcal{C}_9) = -1.04 \pm 0.25$$

LHCb-PAPER-2015-051

- C_9^{NP} deviates from 0 by >4σ
- Caveat: debate on non-pertirbative charm-loop effects





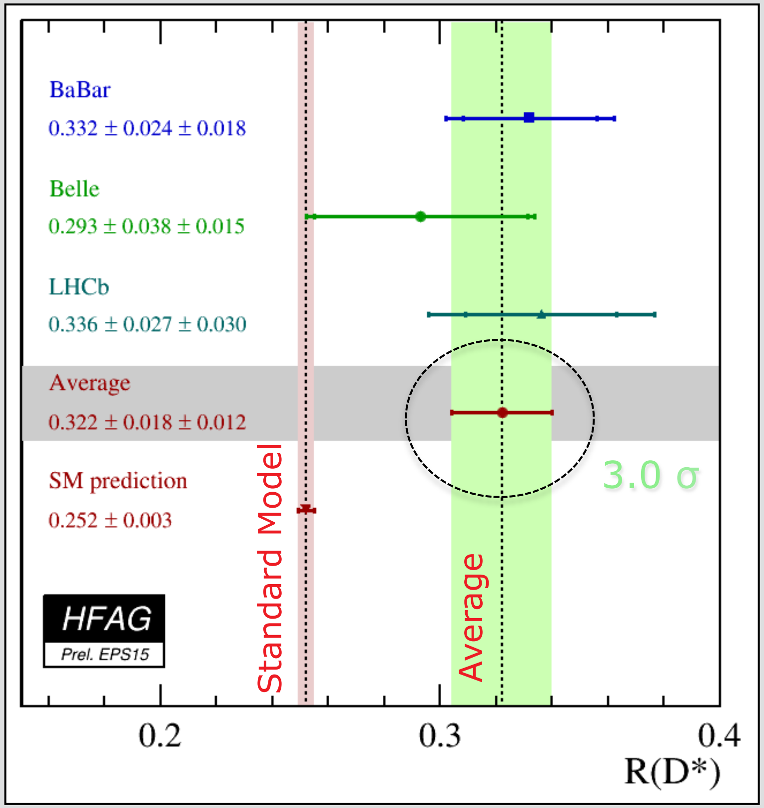


$B \to D^* \mu^+ \nu$

- Measure ratio τ/μ :
- SM expectation: R(D*)=0.252±0.003

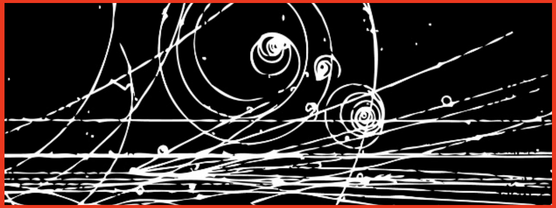
$$\mathcal{R}(D^*) \equiv \mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$$

$$R(D^*) = 0.322 \pm 0.018\,(\text{stat}) \pm 0.012\,(\text{sys})$$



LHCb Coll., Phys.Rev.Lett. 115 (2015) 11, 111803

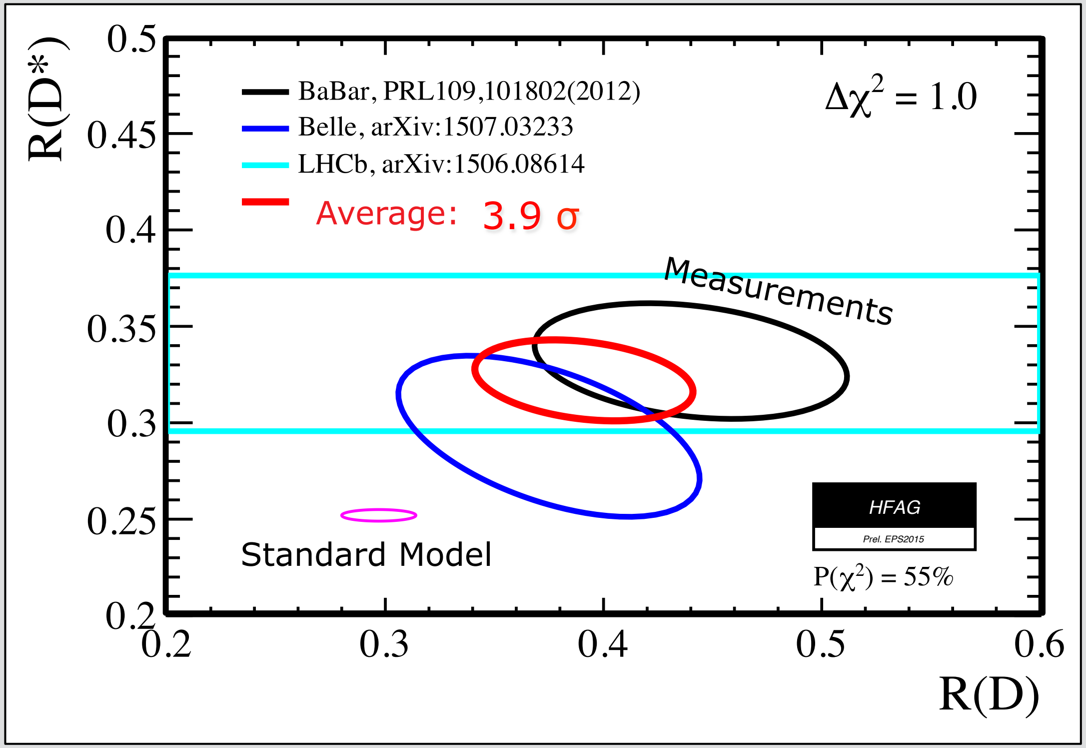
- **Lepton flavour “non-universal” ?**



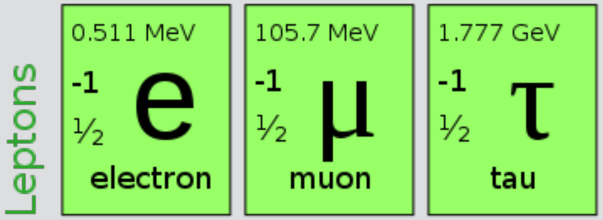
$B \rightarrow D^{(*)}\mu^{+}\nu$

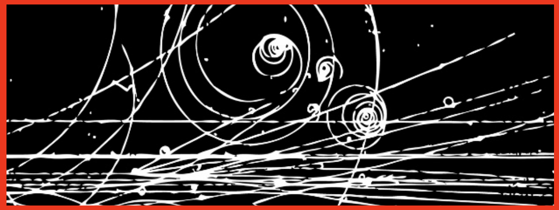
- Measure ratio τ/μ
- R(D) also deviates…

- Combined: 3.9σ

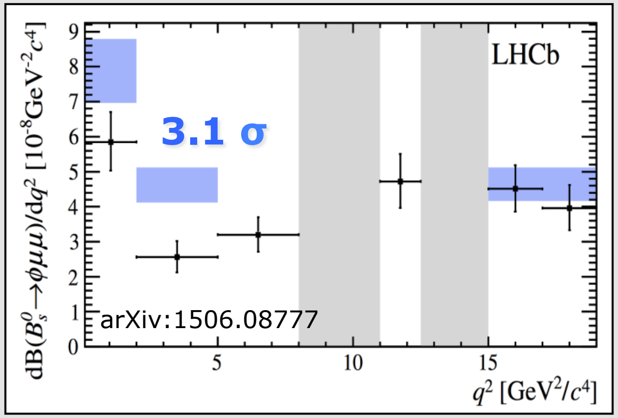


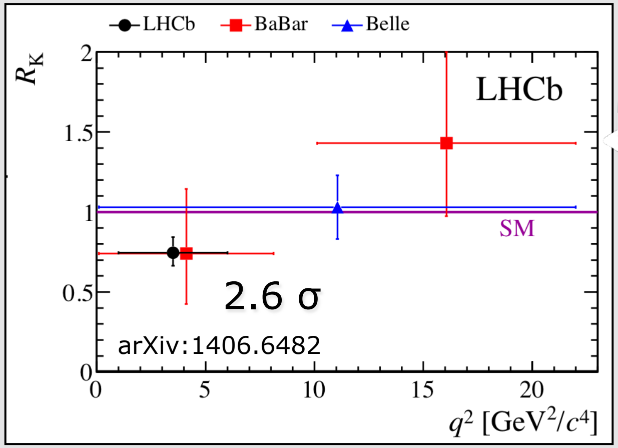
- **Lepton flavour "non-universal" ??**

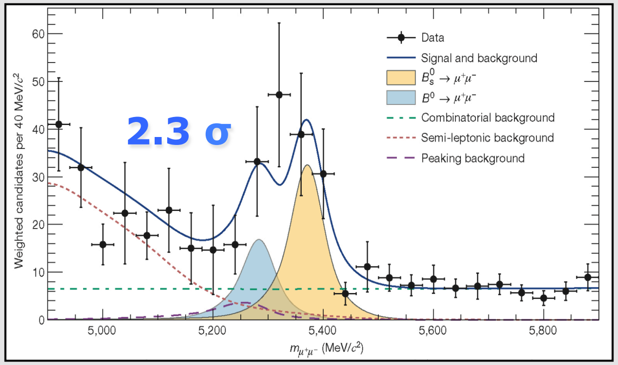


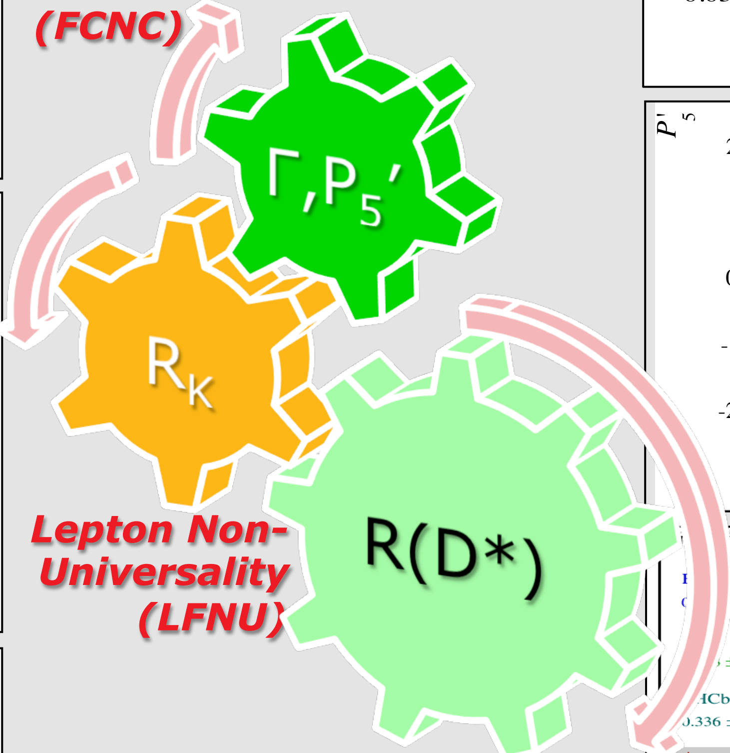


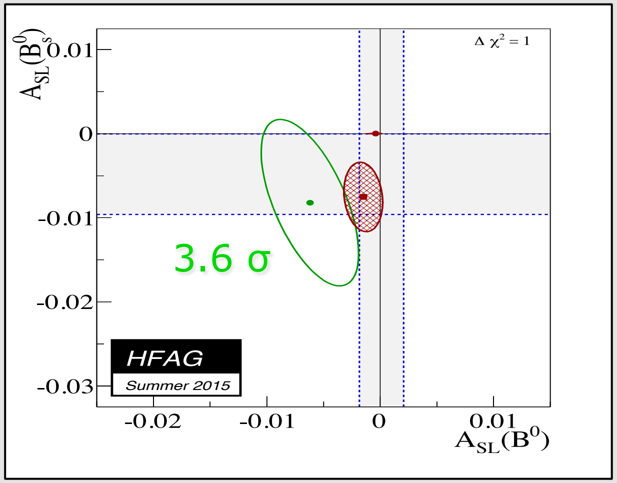
Tensions...?

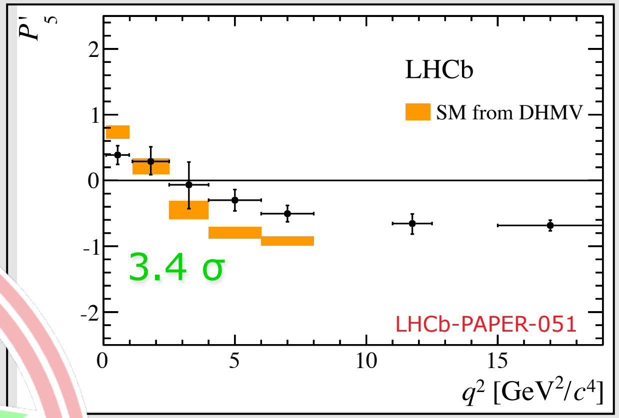

LHCb
3.1 σ
arXiv:1506.08777
$dB(B_s^0 \to \phi\mu\mu)/dq^2$ [10^{-8}GeV$^{-2}c^4$]
q^2 [GeV$^2/c^4$]

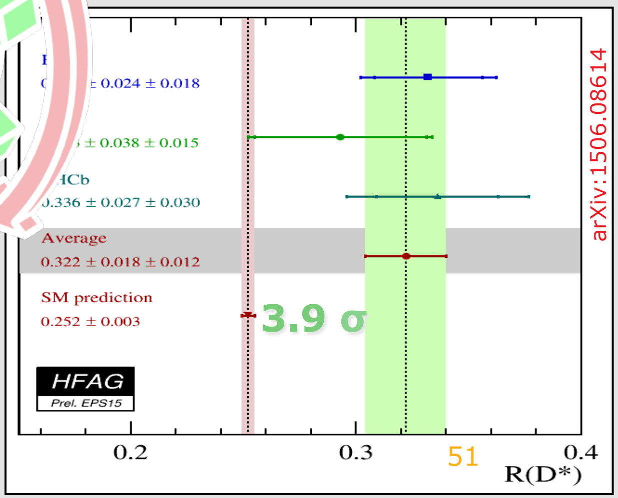

LHCb
BaBar
Belle
R_K
LHCb
SM
2.6 σ
arXiv:1406.6482
q^2 [GeV$^2/c^4$]


2.3 σ
Data
Signal and background
$B_s^0 \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
Combinatorial background
Semi-leptonic background
Peaking background
Weighted candidates per 40 MeV/c^2
$m_{\mu^+\mu^-}$ (MeV/c^2)


Flavour Changing Neutral Current (FCNC)
Γ,P5′
R_K
R(D*)
Lepton Non-Universality (LFNU)

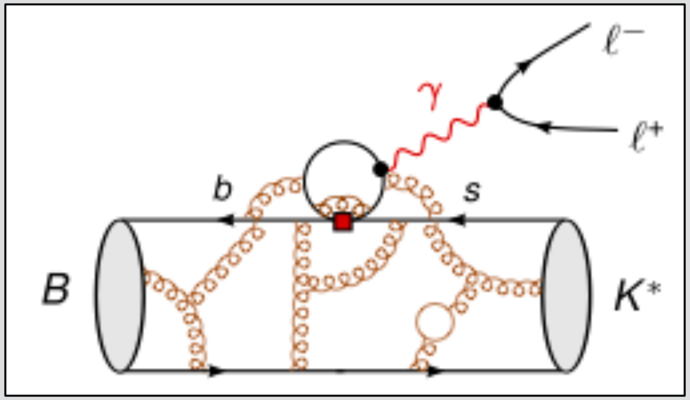

$A_{SL}(B_s^0)$
$\Delta\chi^2 = 1$
3.6 σ
HFAG
Summer 2015
$A_{SL}(B^0)$

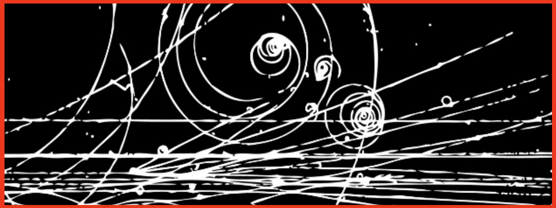

P'_5
LHCb
SM from DHMV
3.4 σ
LHCb-PAPER-051
q^2 [GeV$^2/c^4$]


± 0.024 ± 0.018
± 0.038 ± 0.015
LHCb
0.336 ± 0.027 ± 0.030
Average
0.322 ± 0.018 ± 0.012
SM prediction
0.252 ± 0.003
3.9 σ
HFAG
Prel. EPS15
R(D*)
arXiv:1506.08614

New physics?

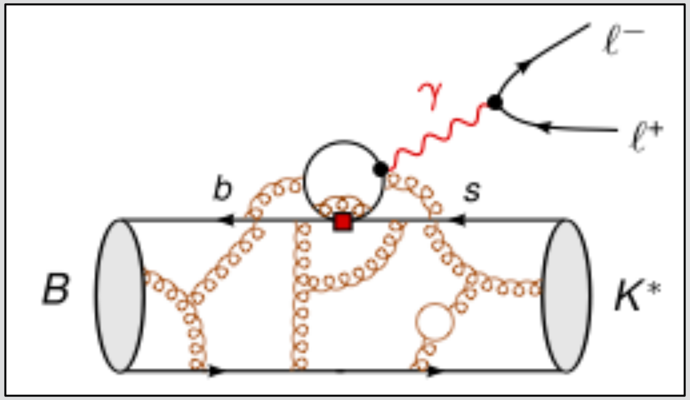
- More involved Standard Model calculation?

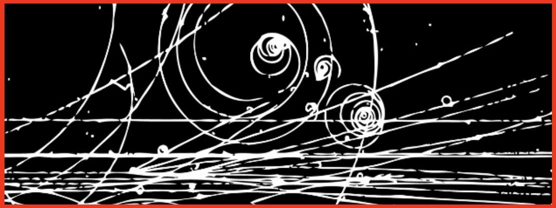




New physics?

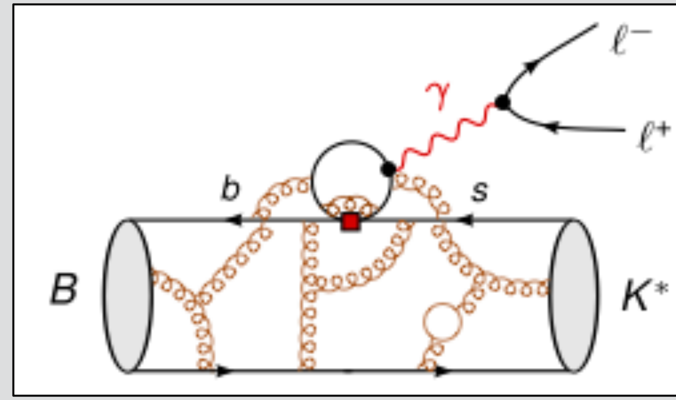
- More involved Standard Model calculation?
- Statistical fluctuations?





New physics?

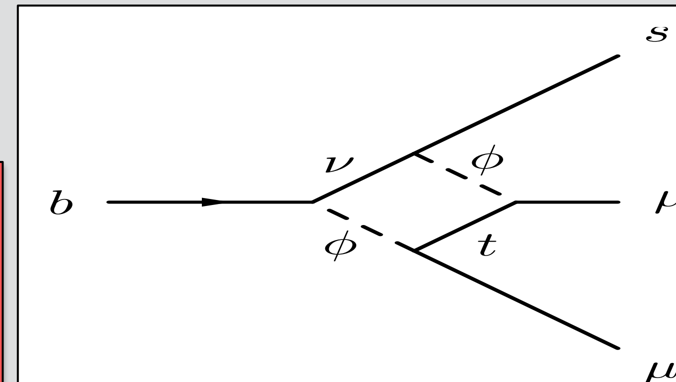
- More involved Standard Model calculation?



- Statistical fluctuations?

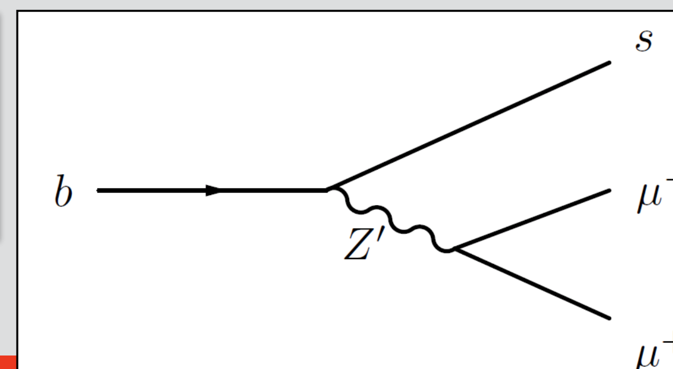
- Or first hints for new particles??
  - Leptoquark ?
  - – Couples to quark ánd leptons
  - – Explaining many open questions
    - g-2, *B→Kμμ, B→D*μν*, diphoton

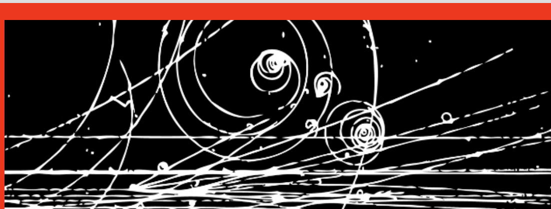
1 TeV
4/3
1/2
ϕ
LQ



  - Z′ ?
  - – New symmetry, new boson (force)
  - – Explaining many open questions
    - *B→Kμμ, B→D*μν*

3 TeV
0
1
Z′
new force





Outlook

- Run-2 just started
- Expect x5 more B-decays by 2018
- Preparations for Run-3 in 2020 are ongoing