The
Large Hadron Collider beauty experiment

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20th October 2014

YEARS / ANS CERN

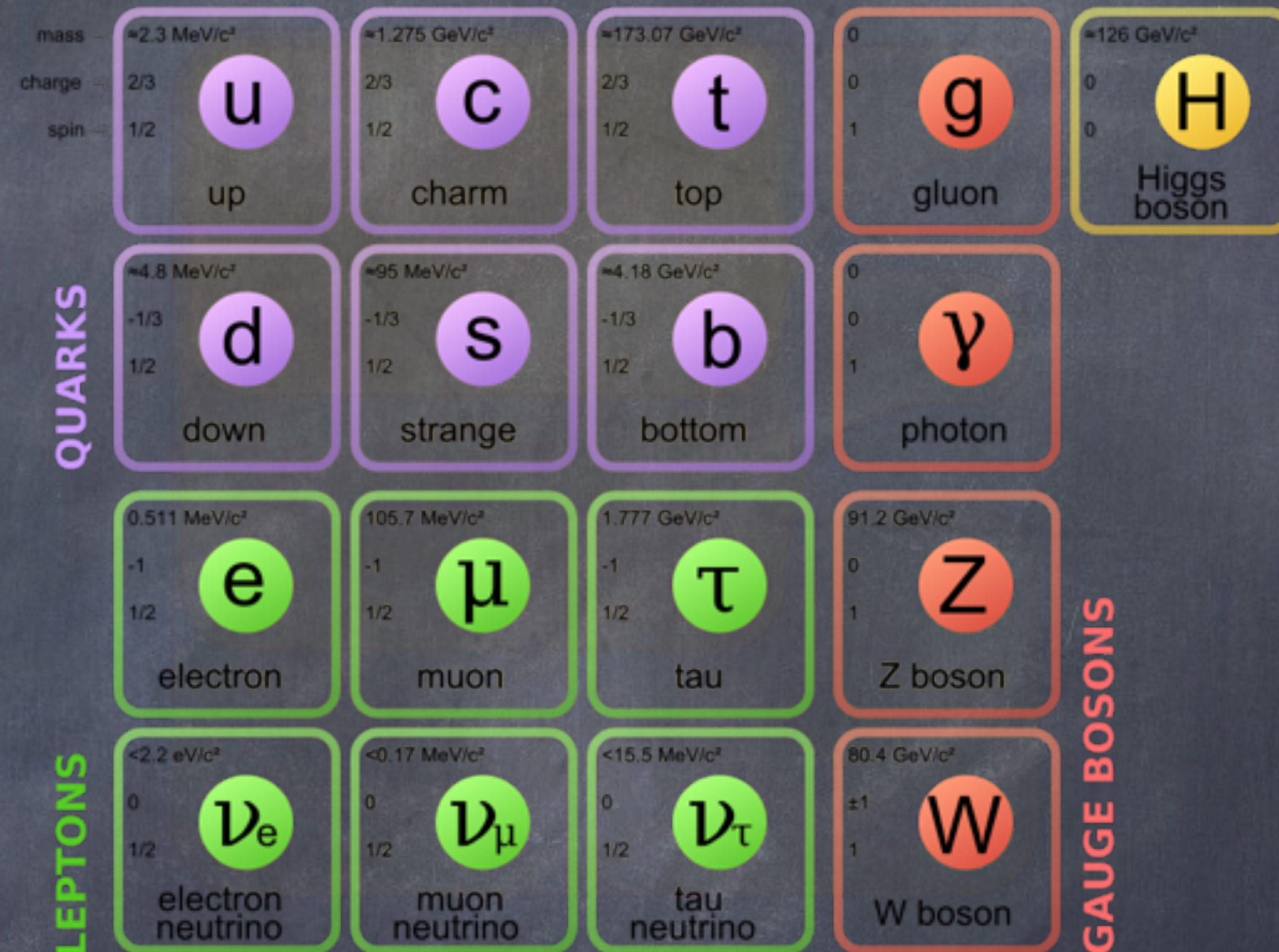
1. The big questions
2. Some headline results
3. My research

1. The big questions
2. Some headline results
3. My research

The Standard Model

(Staggeringly) successful…

- Elegant simplicity
- electroweak unification
- quantum chromodynamics
- Predictive: $W^{\pm}$,Z^{0}, g, t, c…



… but broken

- Failure to incorporate gravity
- Large number of external parameters
- Constituent particle mass hierarchy problem
- ***No dark matter candidate***
- ***Unable to explain matter/antimatter asymmetry***

The Standard Model

Standard Model Lagrangian (including neutrino mass terms)
From *An Introduction to the Standard Model of Particle Physics, 2nd Edition*,
W. N. Cottingham and D. A. Greenwood, Cambridge University Press, Cambridge, 2007,
Extracted by J.A. Shifflett, updated from Particle Data Group tables at pdg.lbl.gov, 25 Aug 2013.

$$\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)}\\
& +(\bar\nu_L,\bar e_L)\,\tilde\sigma^\mu iD_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar e_R\sigma^\mu iD_\mu e_R + \bar\nu_R\sigma^\mu iD_\mu\nu_R + \text{(h.c.)} && \text{(lepton dynamical term)}\\
& -\frac{\sqrt2}{v}\left[(\bar\nu_L,\bar e_L)\,\phi M^e e_R + \bar e_R\bar M^e\bar\phi\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] && \text{(electron, muon, tauon mass term)}\\
& -\frac{\sqrt2}{v}\left[(-\bar e_L,\bar\nu_L)\,\phi^* M^\nu\nu_R + \bar\nu_R\bar M^\nu\phi^T\begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right] && \text{(neutrino mass term)}\\
& +(\bar u_L,\bar d_L)\,\tilde\sigma^\mu iD_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar u_R\sigma^\mu iD_\mu u_R + \bar d_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)}\\
& -\frac{\sqrt2}{v}\left[(\bar u_L,\bar d_L)\,\phi M^d d_R + \bar d_R\bar M^d\bar\phi\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] && \text{(down, strange, bottom mass term)}\\
& -\frac{\sqrt2}{v}\left[(-\bar d_L,\bar u_L)\,\phi^* M^u u_R + \bar u_R\bar M^u\phi^T\begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right] && \text{(up, charmed, top mass term)}\\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar\phi\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \quad (1)
\end{aligned}$$

where (h.c.) means Hermitian conjugate of preceeding terms, $\bar\psi = \text{(h.c.)}\psi = \psi^\dagger = \psi^{*T}$, and the derivative operators are

$$D_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} = \left[\partial_\mu - \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}, \quad D_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix} = \left[\partial_\mu + \frac{ig_1}{6}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu + ig\mathbf{G}_\mu\right]\begin{pmatrix}u_L\\ d_L\end{pmatrix}, \quad (2)$$

$$D_\mu\nu_R = \partial_\mu\nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1B_\mu]\,e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R, \quad (3)$$

$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi. \quad (4)$$

ϕ is a 2-component complex Higgs field. Since $\mathcal{L}$ is $SU(2)$ gauge invariant, a gauge can be chosen so ϕ has the form

$$\phi^T = (0, v+h)/\sqrt2, \qquad <\phi>_0^T = \text{(expectation value of } \phi) = (0,v)/\sqrt2, \quad (5)$$

where v is a real constant such that $\mathcal{L}_\phi = \overline{(\partial_\mu\phi)}\partial^\mu\phi - m_h^2[\bar\phi\phi - v^2/2]^2/2v^2$ is minimized, and h is a residual Higgs field. B_μ, $\mathbf{W}_\mu$ and $\mathbf{G}_\mu$ are the gauge boson vector potentials, and $\mathbf{W}_\mu$ and $\mathbf{G}_\mu$ are composed of 2×2 and 3×3 traceless Hermitian matrices. Their associated field tensors are

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu\mathbf{G}_\nu - \partial_\nu\mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu - \mathbf{G}_\nu\mathbf{G}_\mu). \quad (6)$$

The non-matrix $A_\mu, Z_\mu, W_\mu^\pm$ bosons are mixtures of $\mathbf{W}_\mu$ and B_μ components, according to the weak mixing angle θ_w,

$$A_\mu = W_{11\mu}sin\theta_w + B_\mu cos\theta_w, \qquad Z_\mu = W_{11\mu}cos\theta_w - B_\mu sin\theta_w, \qquad W_\mu^+ = W_\mu^{-*} = W_{12\mu}/\sqrt2, \quad (7)$$

$$B_\mu = A_\mu cos\theta_w - Z_\mu sin\theta_w, \quad W_{11\mu} = -W_{22\mu} = A_\mu sin\theta_w + Z_\mu cos\theta_w, \quad W_{12\mu} = W_{21\mu}^* = \sqrt2\,W_\mu^+, \quad sin^2\theta_w = .2315(4). \quad (8)$$

The fermions include the leptons e_R, e_L, ν_R, ν_L and quarks u_R, u_L, d_R, d_L. They all have implicit 3-component generation indices, $e_i = (e,\mu,\tau)$, $\nu_i = (\nu_e,\nu_\mu,\nu_\tau)$, $u_i = (u,c,t)$, $d_i = (d,s,b)$, which contract into the fermion mass matrices $M_{ij}^e, M_{ij}^\nu, M_{ij}^u, M_{ij}^d$, and implicit 2-component indices which contract into the Pauli matrices,

$$\sigma^\mu = \left[\begin{pmatrix}1&0\\0&1\end{pmatrix},\begin{pmatrix}0&1\\1&0\end{pmatrix},\begin{pmatrix}0&-i\\i&0\end{pmatrix},\begin{pmatrix}1&0\\0&-1\end{pmatrix}\right], \quad \tilde\sigma^\mu = [\sigma^0,-\sigma^1,-\sigma^2,-\sigma^3], \quad tr(\sigma^i) = 0, \quad \sigma^{\mu\dagger} = \sigma^\mu, \quad tr(\sigma^\mu\sigma^\nu) = 2\delta^{\mu\nu}. \quad (9)$$

The quarks also have implicit 3-component color indices which contract into $\mathbf{G}_\mu$. So $\mathcal{L}$ really has implicit sums over 3-component generation indices, 2-component Pauli indices, 3-component color indices in the quark terms, and 2-component $SU(2)$ indices in $(\bar\nu_L,\bar e_L)$, $(\bar u_L,\bar d_L)$, $(-\bar e_L,\bar\nu_L)$, $(-\bar d_L,\bar u_L)$, $\bar\phi$, $\mathbf{W}_\mu$, $\binom{\nu_L}{e_L}$, $\binom{u_L}{d_L}$, $\binom{-e_L}{\nu_L}$, $\binom{-d_L}{u_L}$, ϕ.

The electroweak and strong coupling constants, Higgs vacuum expectation value (VEV), and Higgs mass are,

$$g_1 = e/cos\theta_w, \quad g_2 = e/sin\theta_w, \quad g > 6.5e = g(m_\tau^2), \quad v = 246GeV(PDG) \approx \sqrt2\cdot180\,GeV(CG), \quad m_h = 125-127GeV \quad (10)$$

where $e = \sqrt{4\pi\alpha\hbar c} = \sqrt{4\pi/137}$ in natural units. Using (4,5) and rewriting some things gives the mass of $A_\mu, Z_\mu, W_\mu^\pm$,

$$-\frac14 B_{\mu\nu}B^{\mu\nu} - \frac18 tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) = -\frac14 A_{\mu\nu}A^{\mu\nu} - \frac14 Z_{\mu\nu}Z^{\mu\nu} - \frac12\mathcal{W}_{\mu\nu}^-\mathcal{W}^{+\mu\nu} + \begin{pmatrix}\text{higher}\\ \text{order terms}\end{pmatrix}, \quad (11)$$

$$A_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu, \quad \mathcal{W}_{\mu\nu}^\pm = D_\mu W_\nu^\pm - D_\nu W_\mu^\pm, \quad D_\mu W_\nu^\pm = [\partial_\mu \pm ieA_\mu]W_\nu^\pm, \quad (12)$$

$$D_\mu <\phi>_0 = \frac{iv}{\sqrt2}\begin{pmatrix}g_2W_{12\mu}/2\\ g_1B_\mu/2 + g_2W_{22\mu}/2\end{pmatrix} = \frac{ig_2v}{2}\begin{pmatrix}W_{12\mu}/\sqrt2\\ (B_\mu sin\theta_w/cos\theta_w + W_{22\mu})/\sqrt2\end{pmatrix} = \frac{ig_2v}{2}\begin{pmatrix}W_\mu^+\\ -Z_\mu/\sqrt2\,cos\theta_w\end{pmatrix}, \quad (13)$$

$$\Rightarrow \quad m_A = 0, \qquad m_{W^\pm} = g_2v/2 = 80.425(38)GeV, \qquad m_Z = g_2v/2cos\theta_w = 91.1876(21)GeV. \quad (14)$$

Ordinary 4-component Dirac fermions are composed of the left and right handed 2-component fields,

$$e = \begin{pmatrix}e_{L1}\\ e_{R1}\end{pmatrix}, \ \nu_e = \begin{pmatrix}\nu_{L1}\\ \nu_{R1}\end{pmatrix}, \ u = \begin{pmatrix}u_{L1}\\ u_{R1}\end{pmatrix}, \ d = \begin{pmatrix}d_{L1}\\ d_{R1}\end{pmatrix}, \quad \text{(electron, electron neutrino, up and down quark)} \quad (15)$$

$$\mu = \begin{pmatrix}e_{L2}\\ e_{R2}\end{pmatrix}, \ \nu_\mu = \begin{pmatrix}\nu_{L2}\\ \nu_{R2}\end{pmatrix}, \ c = \begin{pmatrix}u_{L2}\\ u_{R2}\end{pmatrix}, \ s = \begin{pmatrix}d_{L2}\\ d_{R2}\end{pmatrix}, \quad \text{(muon, muon neutrino, charmed and strange quark)} \quad (16)$$

$$\tau = \begin{pmatrix}e_{L3}\\ e_{R3}\end{pmatrix}, \ \nu_\tau = \begin{pmatrix}\nu_{L3}\\ \nu_{R3}\end{pmatrix}, \ t = \begin{pmatrix}u_{L3}\\ u_{R3}\end{pmatrix}, \ b = \begin{pmatrix}d_{L3}\\ d_{R3}\end{pmatrix}, \quad \text{(tauon, tauon neutrino, top and bottom quark)} \quad (17)$$

$$\gamma^\mu = \begin{pmatrix}0&\sigma^\mu\\ \tilde\sigma^\mu&0\end{pmatrix} \qquad \text{where } \gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2Ig^{\mu\nu}. \quad \text{(Dirac gamma matrices in chiral representation)} \quad (18)$$

The corresponding antiparticles are related to the particles according to $\psi^c = -i\gamma^2\psi^*$ or $\psi_L^c = -i\sigma^2\psi_R^*$, $\psi_R^c = i\sigma^2\psi_L^*$. The fermion charges are the coefficients of A_μ when (8,10) are substituted into either the left or right handed derivative operators (2-4). The fermion masses are the singular values of the 3×3 fermion mass matrices M^ν, M^e, M^u, M^d,

$$M^e = \mathbf{U}_L^{e\dagger}\begin{pmatrix}m_e&0&0\\0&m_\mu&0\\0&0&m_\tau\end{pmatrix}\mathbf{U}_R^e, \quad M^\nu = \mathbf{U}_L^{\nu\dagger}\begin{pmatrix}m_{\nu_e}&0&0\\0&m_{\nu_\mu}&0\\0&0&m_{\nu_\tau}\end{pmatrix}\mathbf{U}_R^\nu, \quad M^u = \mathbf{U}_L^{u\dagger}\begin{pmatrix}m_u&0&0\\0&m_c&0\\0&0&m_t\end{pmatrix}\mathbf{U}_R^u, \quad M^d = \mathbf{U}_L^{d\dagger}\begin{pmatrix}m_d&0&0\\0&m_s&0\\0&0&m_b\end{pmatrix}\mathbf{U}_R^d, \quad (19)$$

$$m_e = .510998910(13)MeV, \quad m_{\nu_e} \sim .001 - .23eV, \qquad m_u = 1.7 - 3.1MeV, \quad m_d = 4.1 - 5.7MeV, \quad (20)$$

$$m_\mu = 105.658367(4)MeV, \quad m_{\nu_\mu} \sim .001 - .23eV, \qquad m_c = 1.18 - 1.34GeV, \quad m_s = 80 - 130MeV, \quad (21)$$

$$m_\tau = 1776.84(17)MeV, \quad m_{\nu_\tau} \sim .001 - .23eV, \qquad m_t = 171.4 - 174.4GeV, \quad m_b = 4.13 - 4.37GeV, \quad (22)$$

where the $\mathbf{U}$s are 3×3 unitary matrices ($\mathbf{U}^{-1} = \mathbf{U}^\dagger$). Consequently the “true fermions” with definite masses are actually linear combinations of those in $\mathcal{L}$, or conversely the fermions in $\mathcal{L}$ are linear combinations of the true fermions,

$$e_L' = \mathbf{U}_L^e e_L, \quad e_R' = \mathbf{U}_R^e e_R, \quad \nu_L' = \mathbf{U}_L^\nu\nu_L, \quad \nu_R' = \mathbf{U}_R^\nu\nu_R, \quad u_L' = \mathbf{U}_L^u u_L, \quad u_R' = \mathbf{U}_R^u u_R, \quad d_L' = \mathbf{U}_L^d d_L, \quad d_R' = \mathbf{U}_R^d d_R, \quad (23)$$

$$e_L = \mathbf{U}_L^{e\dagger}e_L', \quad e_R = \mathbf{U}_R^{e\dagger}e_R', \quad \nu_L = \mathbf{U}_L^{\nu\dagger}\nu_L', \quad \nu_R = \mathbf{U}_R^{\nu\dagger}\nu_R', \quad u_L = \mathbf{U}_L^{u\dagger}u_L', \quad u_R = \mathbf{U}_R^{u\dagger}u_R', \quad d_L = \mathbf{U}_L^{d\dagger}d_L', \quad d_R = \mathbf{U}_R^{d\dagger}d_R'. \quad (24)$$

When $\mathcal{L}$ is written in terms of the true fermions, the $\mathbf{U}$s fall out except in $\bar u_L'\mathbf{U}_L^u\tilde\sigma^\mu W_\mu^\pm\mathbf{U}_L^{d\dagger}d_L'$ and $\bar\nu_L'\mathbf{U}_L^\nu\tilde\sigma^\mu W_\mu^\pm\mathbf{U}_L^{e\dagger}e_L'$. Because of this, and some absorption of constants into the fermion fields, all the parameters in the $\mathbf{U}$s are contained in only four components of the Cabibbo-Kobayashi-Maskawa matrix $\mathbf{V}^q = \mathbf{U}_L^u\mathbf{U}_L^{d\dagger}$ and four components of the Pontecorvo-Maki-Nakagawa-Sakata matrix $\mathbf{V}^l = \mathbf{U}_L^\nu\mathbf{U}_L^{e\dagger}$. The unitary matrices $\mathbf{V}^q$ and $\mathbf{V}^l$ are often parameterized as

$$\mathbf{V} = \begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}e^{-i\delta/2}&0&0\\0&1&0\\0&0&e^{i\delta/2}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}\\0&1&0\\-s_{13}&0&c_{13}\end{pmatrix}\begin{pmatrix}e^{i\delta/2}&0&0\\0&1&0\\0&0&e^{-i\delta/2}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}, \quad c_j = \sqrt{1-s_j^2}, \quad (25)$$

$$\delta^q = 69(4)\,\text{deg}, \quad s_{12}^q = 0.2253(7), \quad s_{23}^q = 0.041(1), \quad s_{13}^q = 0.0035(2), \quad (26)$$

$$\delta^l = ?, \quad s_{12}^l = 0.558(16), \quad s_{23}^l = 0.7(1), \quad s_{13}^l = 0.151(17). \quad (27)$$

$\mathcal{L}$ is invariant under a $U(1)\otimes SU(2)$ gauge transformation with $U^{-1} = U^\dagger$, $detU = 1$, θ real,

$$\mathbf{W}_\mu \to U\mathbf{W}_\mu U^\dagger - (2i/g_2)U\partial_\mu U^\dagger, \quad \mathbf{W}_{\mu\nu} \to U\mathbf{W}_{\mu\nu}U^\dagger, \quad B_\mu \to B_\mu + (2/g_1)\partial_\mu\theta, \quad B_{\mu\nu} \to B_{\mu\nu}, \quad \phi \to e^{-i\theta}U\phi, \quad (28)$$

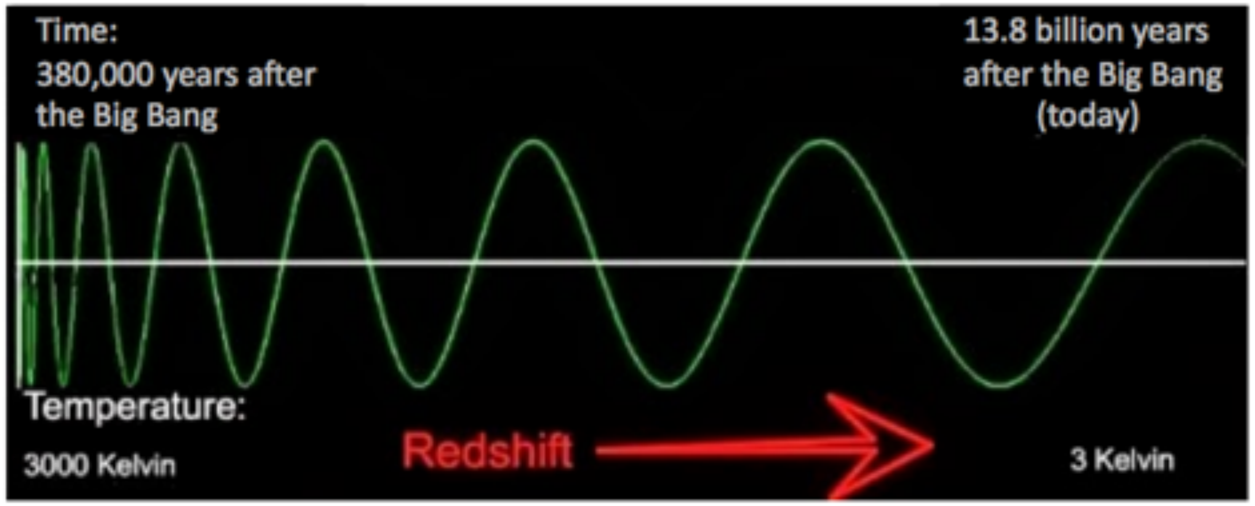
$$\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} \to e^{i\theta}U\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}, \quad \begin{pmatrix}u_L\\ d_L\end{pmatrix} \to e^{-i\theta/3}U\begin{pmatrix}u_L\\ d_L\end{pmatrix}, \quad \begin{matrix}\nu_R \to \nu_R, & u_R \to e^{-4i\theta/3}u_R,\\ e_R \to e^{2i\theta}e_R, & d_R \to e^{2i\theta/3}d_R,\end{matrix} \quad (29)$$

and under an $SU(3)$ gauge transformation with $V^{-1} = V^\dagger$, $detV = 1$,

$$\mathbf{G}_\mu \to V\mathbf{G}_\mu V^\dagger - (i/g)V\partial_\mu V^\dagger, \quad \mathbf{G}_{\mu\nu} \to V\mathbf{G}_{\mu\nu}V^\dagger, \quad u_L \to Vu_L, \quad d_L \to Vd_L, \quad u_R \to Vu_R, \quad d_R \to Vd_R. \quad (30)$$

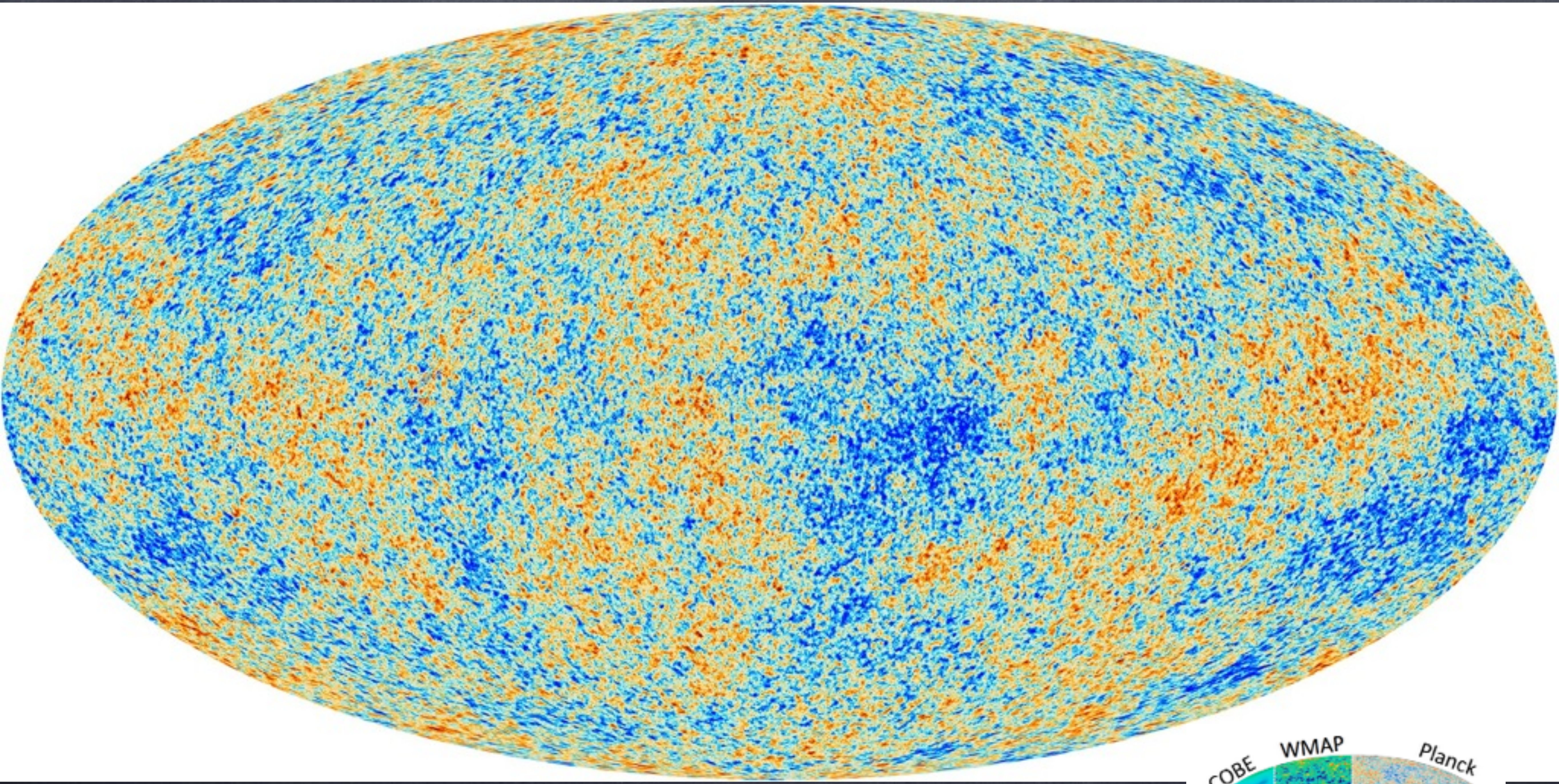
Case study 1: Dark matter

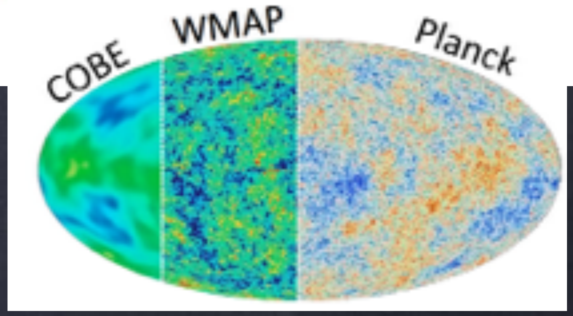
If you had microwave eyes



- Looking at the sky in the microwave range, uniform background radiation in every direction at about T=2.7255 K
  - This is the remnant of the radiation emitted at T≈3000 K at recombination time
  - Since then, red-shifted to present temperature by the expansion of the Universe
  - This is the afterglow of the Big Bang

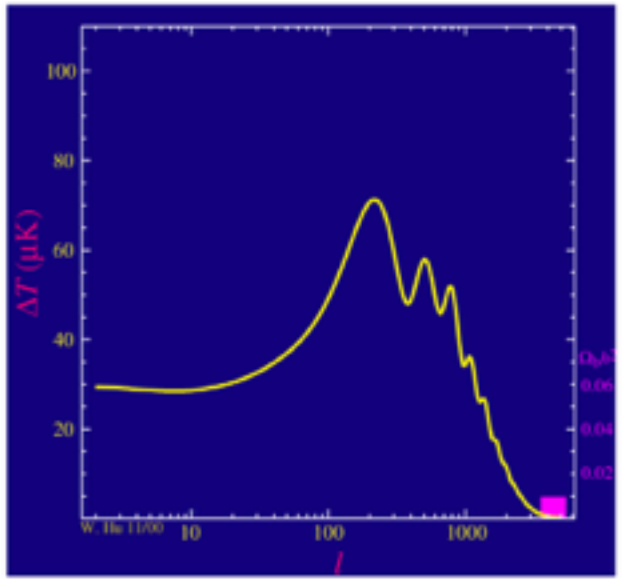
Case study 1: Dark matter





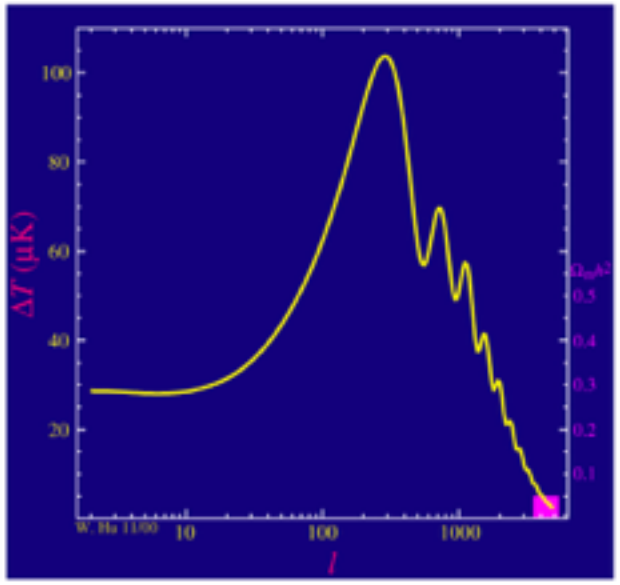
Case study 1: Dark matter

Ordinary matter



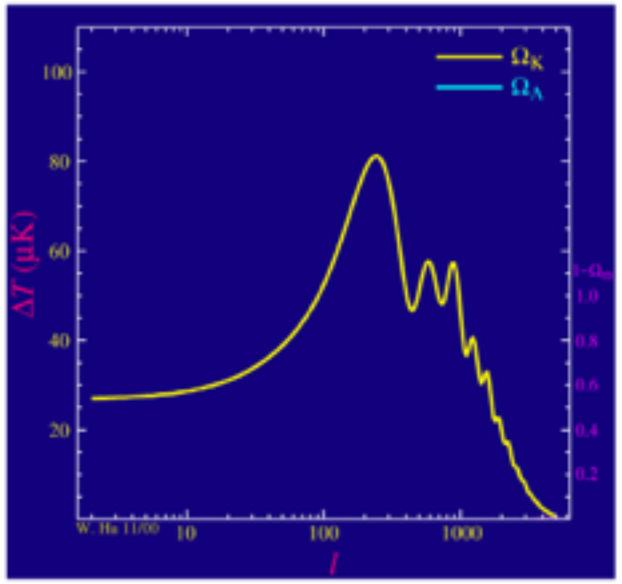
Increasing ordinary matter density, the odd numbered peaks are enhanced over the even numbered peaks

Dark matter



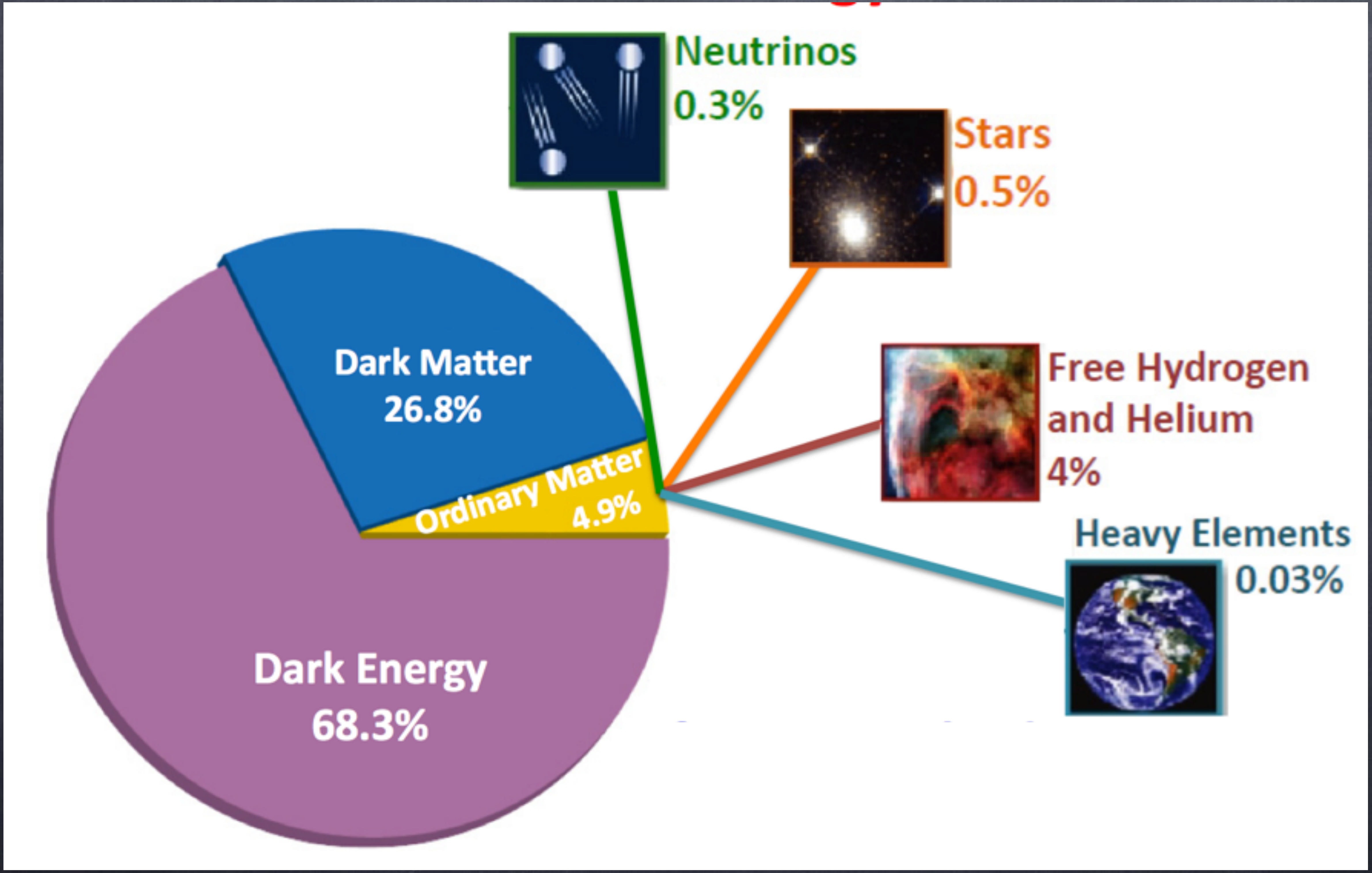
As the dark matter increases the overall amplitude of the peaks decrease

Dark energy



Spatial curvature and dark energy both shift the angular location of the peaks left and right

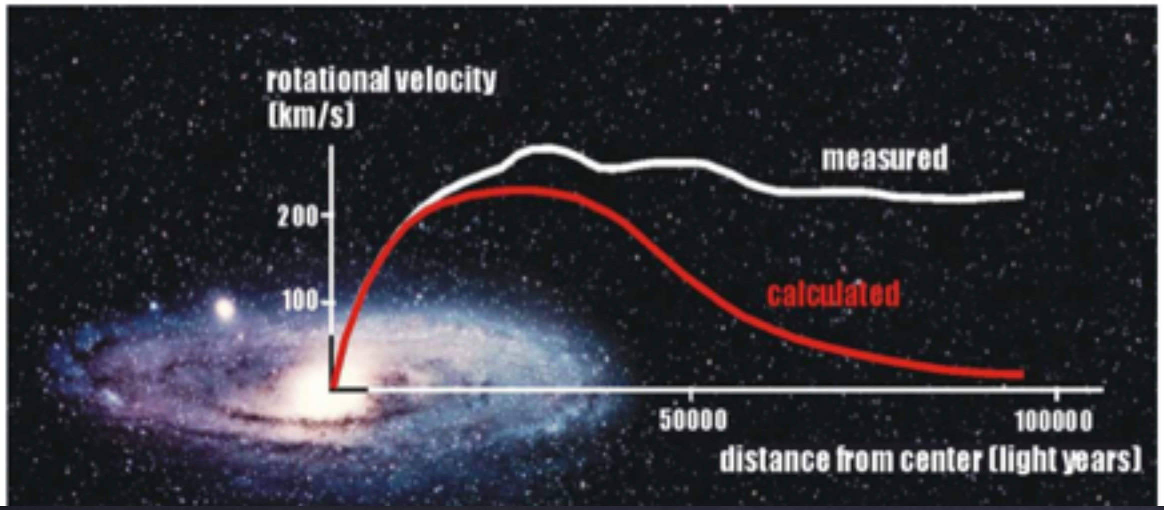
Case study 1: Dark matter



Case study 1: Dark matter

Gravitational lensing

Galaxy rotation curves



- Several independent observations (not only those shown here) are in very good agreement
- Note that the existence of invisible matter in the Universe was already conjectured in the 1930's by measuring the relative velocities of galaxies inside the Coma cluster, to estimate the mass of the cluster itself
  - The mass resulted to be much larger than that inferred from visible stars
- **Dark Matter is nowadays a solid experimental matter of fact**

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Case study 1: Dark matter

What is Dark Matter made of?

- The attempts to explain the totality of Dark Matter with astronomical objects that do not emit light have failed
  - unless contrived cosmological models are taken seriously
- Dark Matter properties are starting to be quite well-constrained
  - **Gravitationally interacting**
  - **Stable (on cosmological time scales)**
  - **Cold (slow-moving)**
  - **Not made of baryons and (very) weakly interacting**

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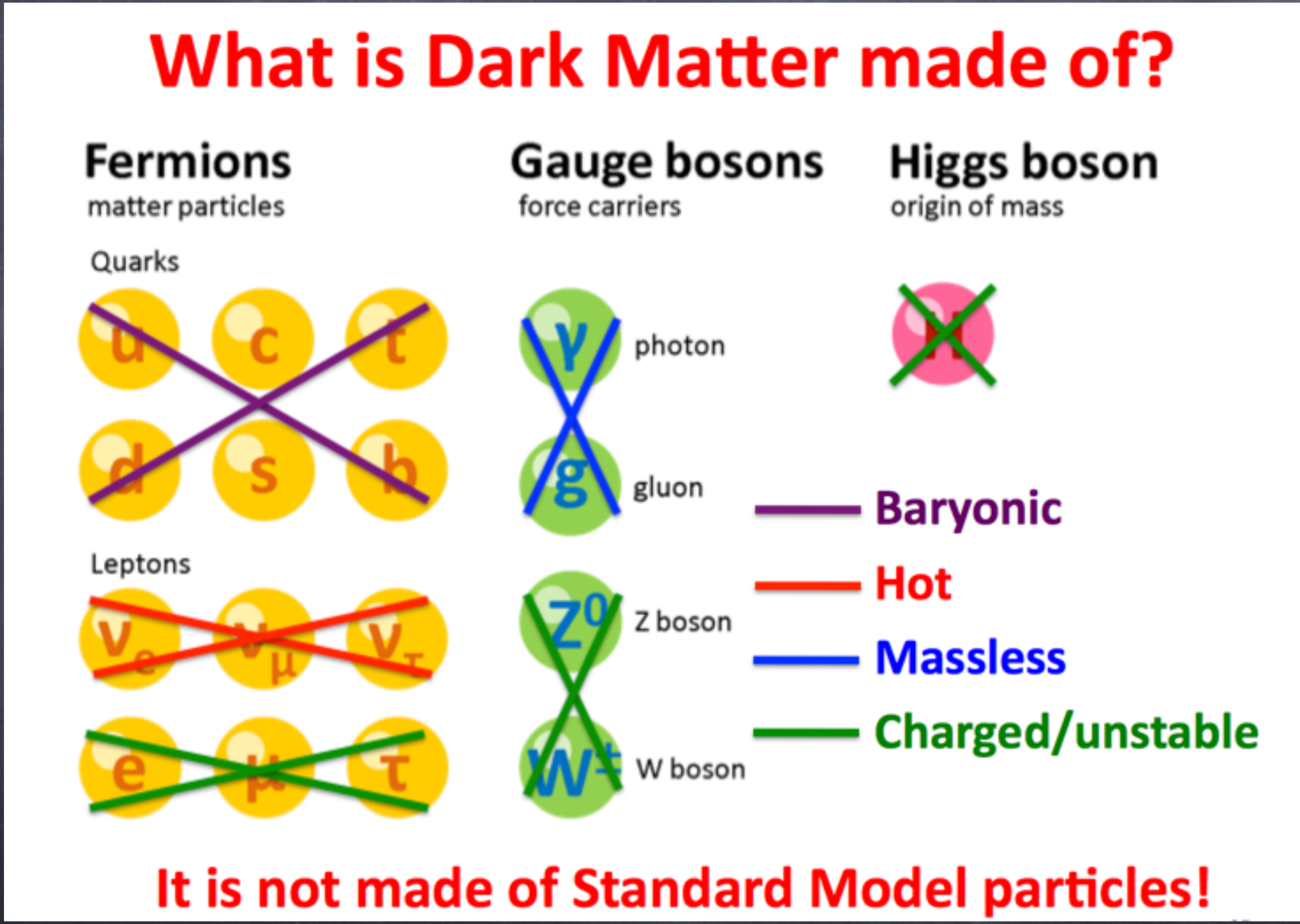
Case study 1: Dark matter



Case study 1: Dark matter

- More reasonable candidates include
  - Axion
    - Hypothetical particle to explain absence of *CP* violation in strong interactions
  - Sterile Neutrino
    - Most likely there are some fans today here
  - WIMPs
    - Supersymmetry: Lightest SUSY Particle (LSP)
    - Extra dimensions: Lightest Kaluza-Klein particle (LKP)

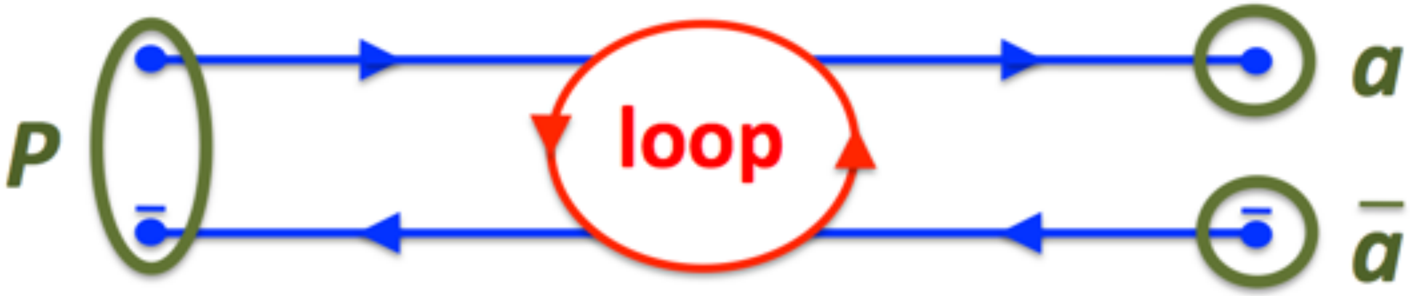
Case study 1: Dark matter

How to study the nature of Dark Matter?

- Basically four ways
  - Detect interactions of relic Dark Matter with dedicated massive detectors on Earth
    - e.g. experiments in underground laboratories
  - Detect remote signals of Dark Matter annihilation or decays
    - Either with ground- or satellite-based experiments
  - Produce brand new Dark Matter particles in highly energetic collisions and detect their existence directly
    - This is e.g. what ATLAS and CMS are looking at
  - Study low energy processes with high precision in order to unveil quantum effects of virtual particles, whose real incarnations are living at higher energy scales
    - **This is the realm of LHCb!**

Case study 1: Dark matter

Quantum effects



- Say a particle *P* is a bound state of one quark and one anti-quark and it decays through a loop of different particles to two daughters
- The relevant fact here is that quantum mechanics allows the particles circulating in the loop to have larger masses than that of the initial particle *P*, although they can only exist for a tiny amount of time
  - These are so-called virtual particles
  - Measuring the properties of the process, it is possible to infer the presence of such virtual particles, and understand some of their properties
- Even if some particles could never be created as real at the LHC, as maybe they are too heavy, their existence can affect the behaviour of lighter particles, and so we can pinpoint them!

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Case study 2: Matter and antimatter

Where has antimatter gone?

- Antimatter annihilated with matter particles, but a **tiny** difference must have been at work
  - For about every 10 billion particles and antiparticles which annihilated, a few matter particles were left
    - Photons produced in this initial annihilation process are nowadays detectable as CMB radiation
- **Where does this tiny difference come from?**

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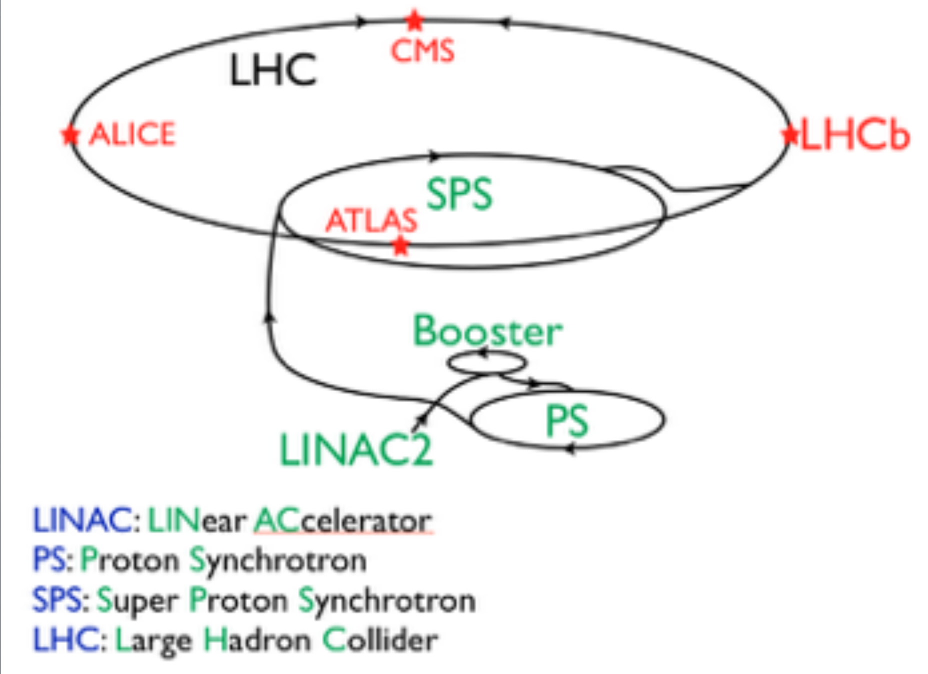
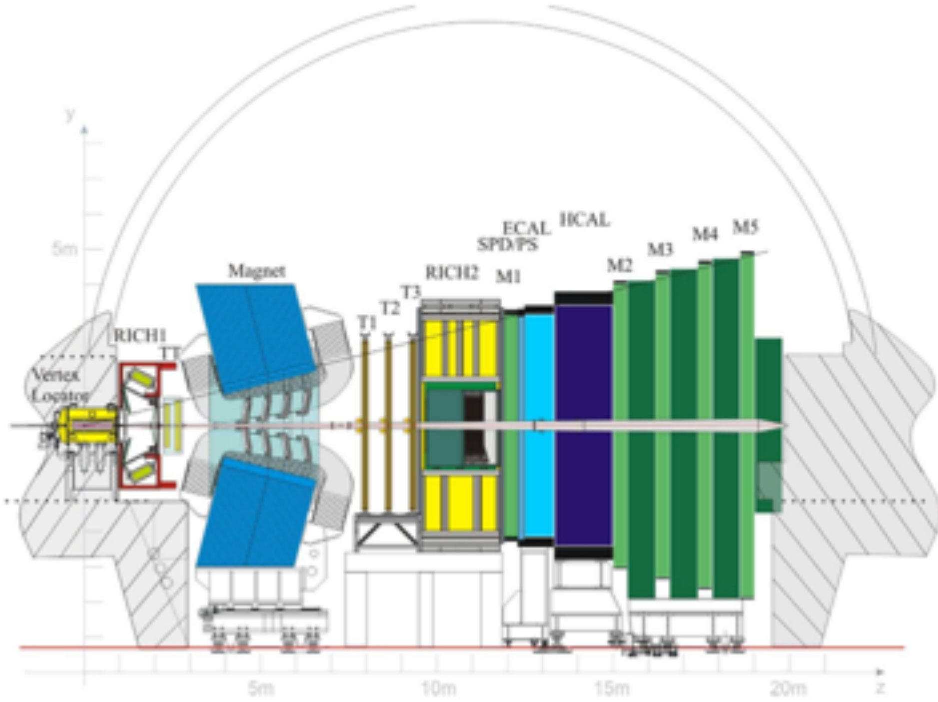
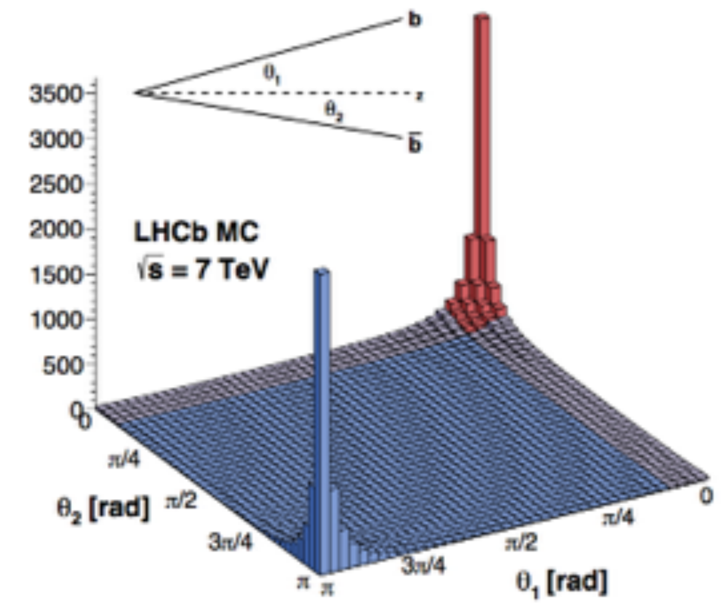
1. The big questions
2. Some headline results
3. My research

LHCb: designed to study B mesons



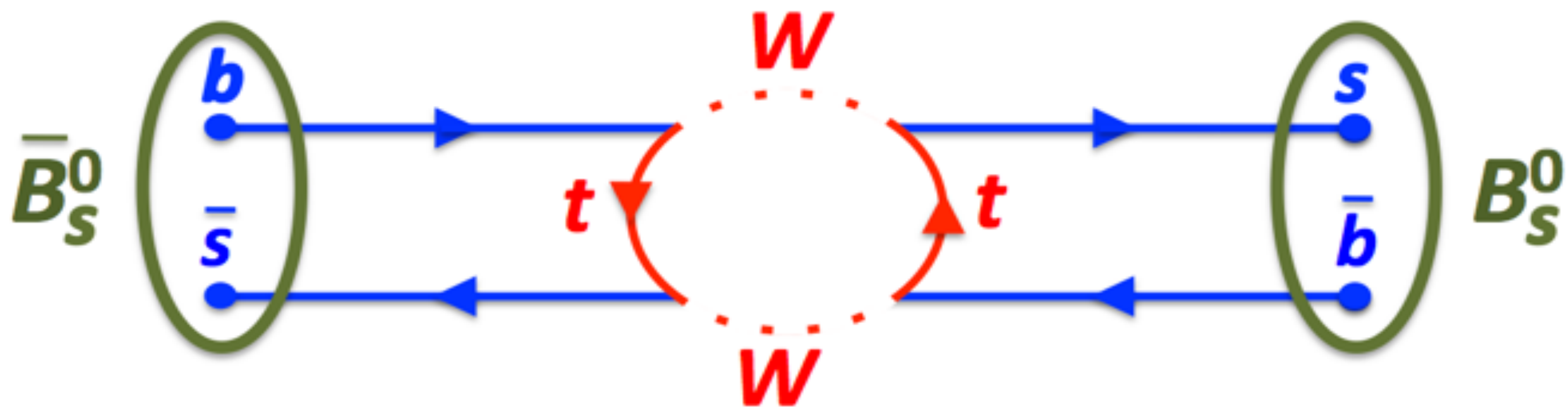




- Study B meson decays involving loops: sensitive to exotic particles
- Study $B/\bar{B}$ decays to investigate particle/anti-particle asymmetry
- (Many studies are sensitive to both!)

B/B oscillations

Cool example of quantum effects

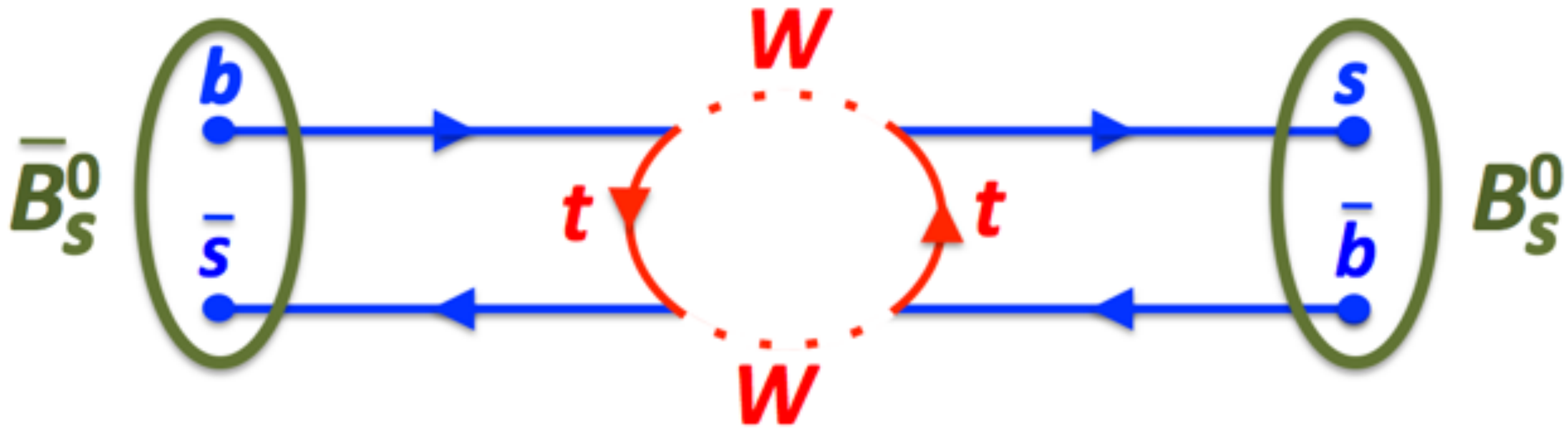


- These mesons are continuously transformed into each other by *weak interactions*

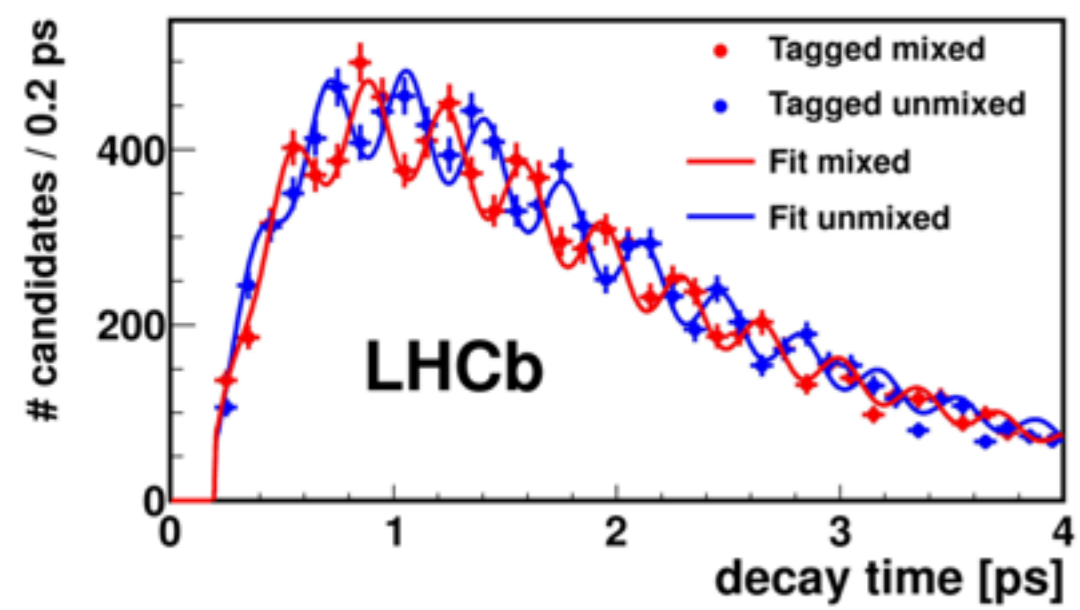
- At the same time they decay to several different possible final states with a lifetime of about 1.5 ps

Result 1: B/B oscillation frequency

Cool example of quantum effects



- We can measure this quantum dance very precisely!
- LHCb has performed the world's best measurement detecting the oscillations of the B_s^0 mesons by means of a large number of $B_s^0 \rightarrow D_s^- \pi^+$ decays



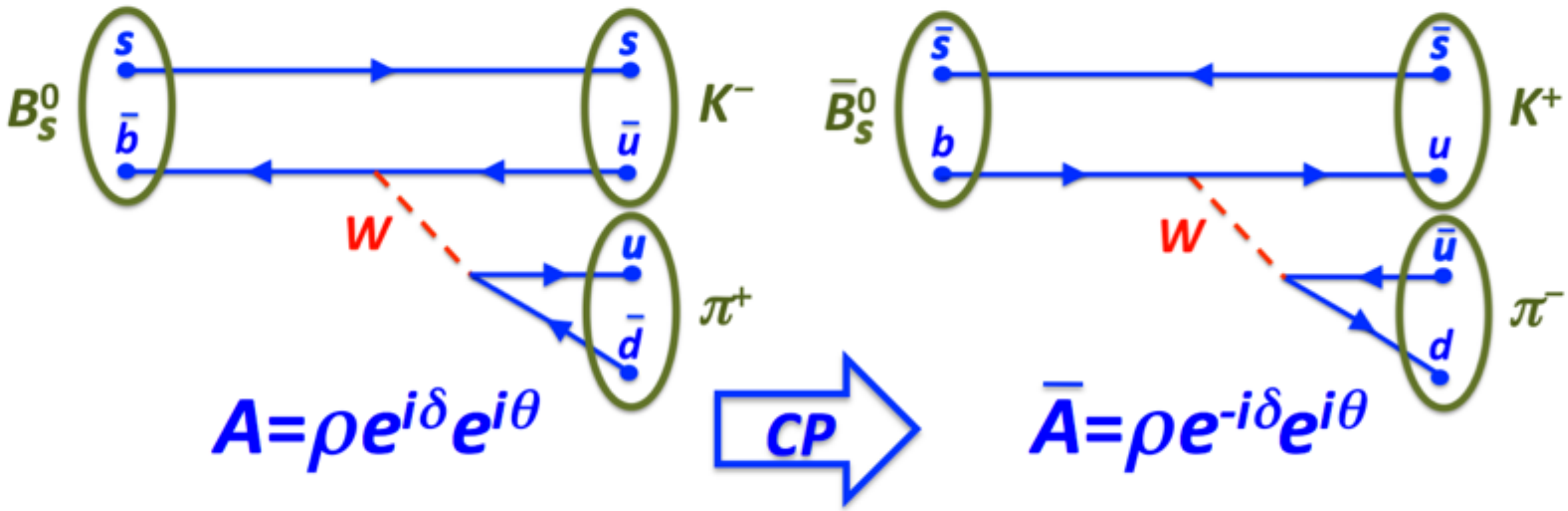
- The frequency of the oscillation is measured to be

$$\nu = 2.8279 \pm 0.0038 \text{ THz}$$

http://arxiv.org/pdf/1304.4741v1.pdf

Result 2: Asymmetry in B_s^0 decays

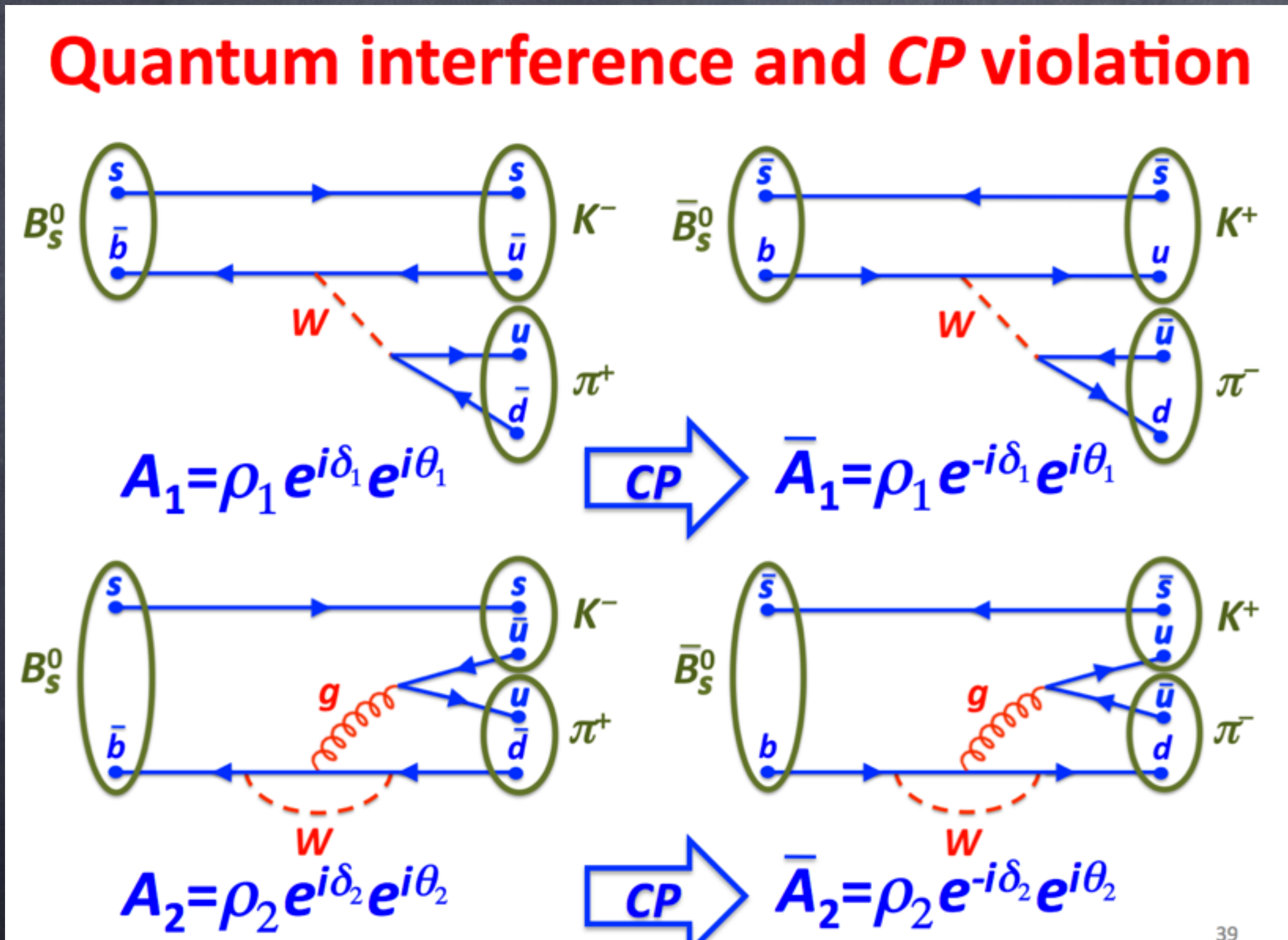
Quantum interference and *CP* violation



- In the quantum mechanical framework of the Standard Model, a *CP* transformation has the effect of changing the sign of the phase related to weak interactions in the decay amplitude
- But $|\bar{A}|^2 - |A|^2 = 0$, which unfortunately means that the number of decays to $K^+\pi^-$ and that to $K^-\pi^+$ are identical, **no *CP* asymmetry is observable!**

http://arxiv.org/pdf/1202.6251v2.pdf

Result 2: Asymmetry in B_s^0 decays



http://arxiv.org/pdf/1202.6251v2.pdf

Result 2: Asymmetry in B_s^0 decays

Quantum interference and *CP* violation

- Now the situation looks different

$$|\bar{A}_1+\bar{A}_2|^2 - |A_1+A_2|^2 = 4\rho_1\rho_2 \sin(\delta_1 - \delta_2)\sin(\theta_1 - \theta_2)$$

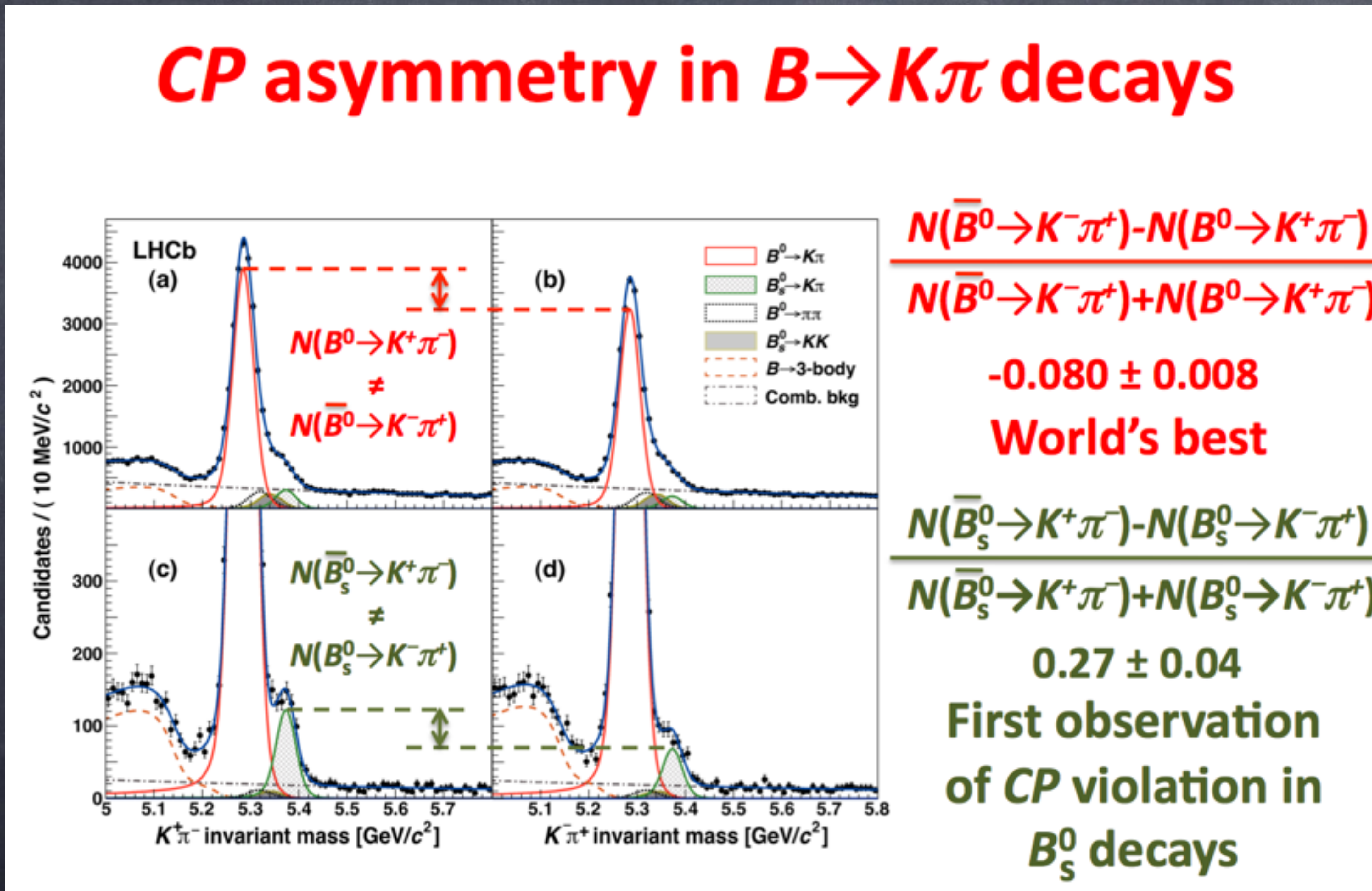
which differs from zero if $\delta_1 \neq \delta_2$ and $\theta_1 \neq \theta_2$

***CP* asymmetry can be observed!**

- This is the typical interference effect that occurs in quantum mechanics
  - two different paths with different phases
  - it is impossible to understand which of the two paths the state has been following to reach the point where the actual observation is carried out

http://arxiv.org/pdf/1202.6251v2.pdf

Result 2: Asymmetry in B_s^0 decays



http://arxiv.org/pdf/1202.6251v2.pdf

Result 3: (VERY!) rare B_s^0 decays

The power of the rarity: $B_s^0 \rightarrow \mu^+\mu^-$

- No *CP*-violating effect studied (so far), but its observation is one of the most important LHCb measurements to date, why?
- **Because, it is rare!**
  - The Standard Model **precisely** predicts that for every billion B_s^0 mesons created, only about 4 of them undergo this type of decay → New Physics may alter this

http://arxiv.org/pdf/1202.6251v2.pdf

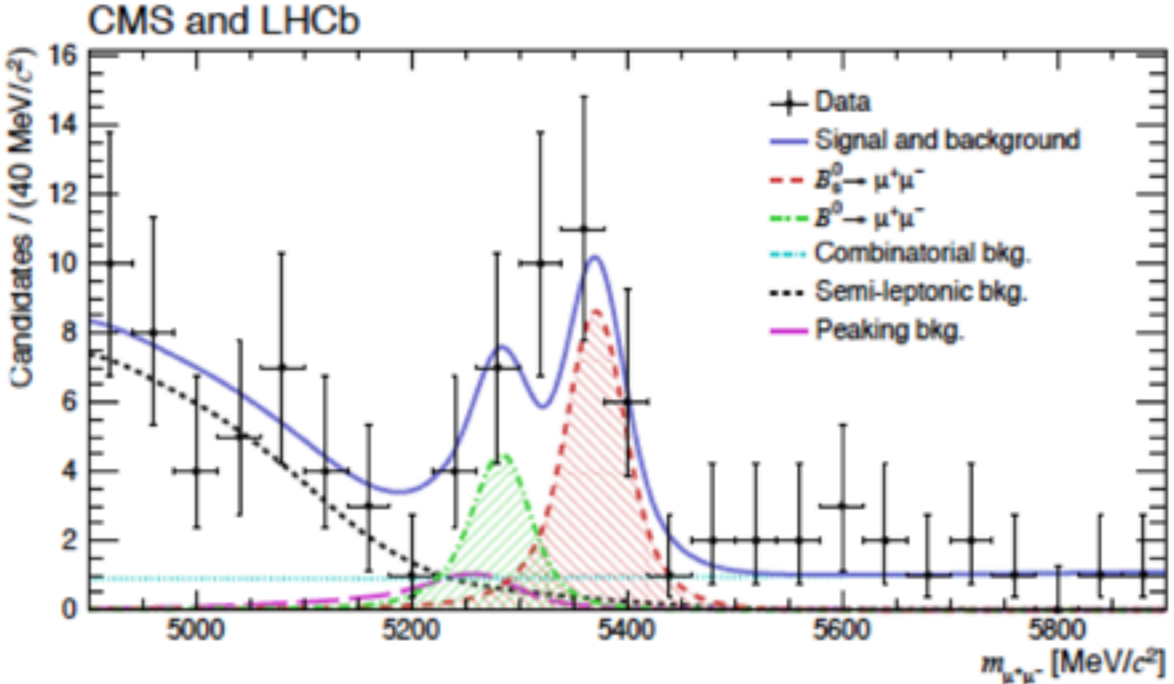
Result 3: (VERY!) rare B_s^0 decays

The power of the rarity: $B_s^0 \rightarrow \mu^+\mu^-$

Probability that the decay happens is measured to be

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$



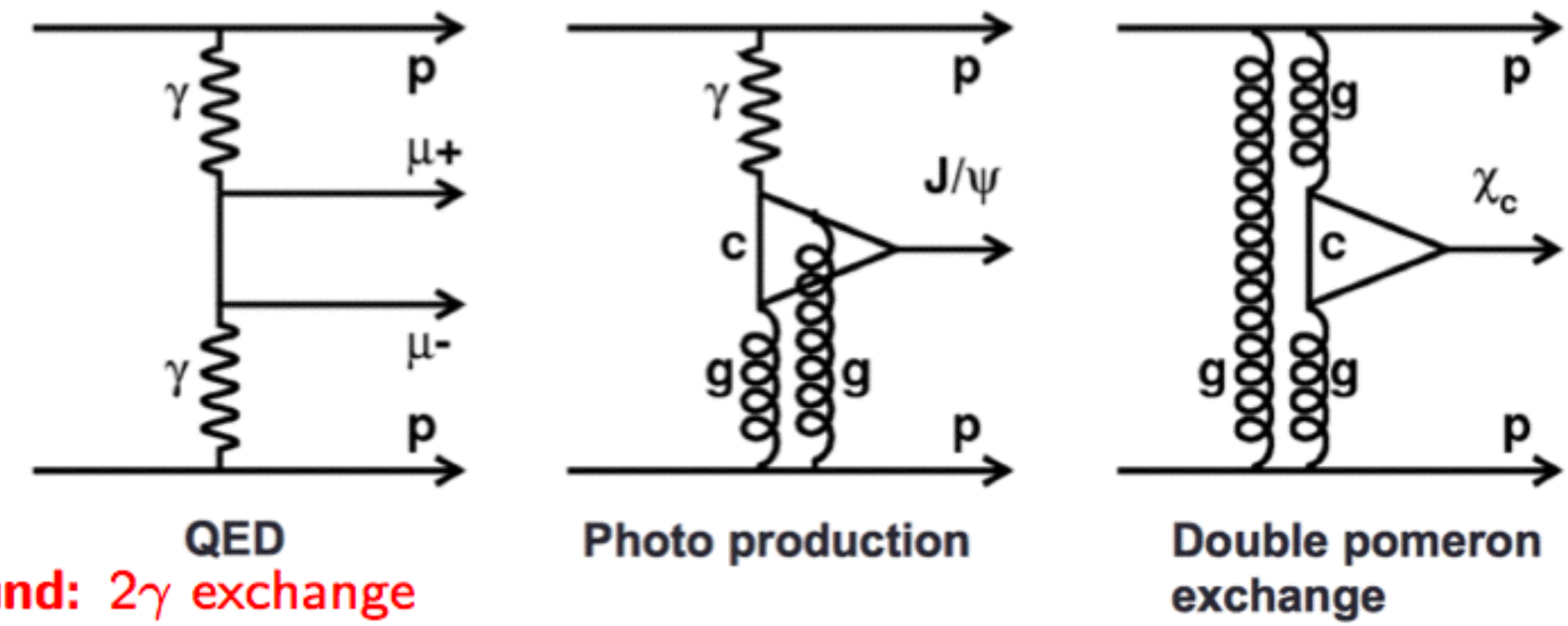
- Still a large uncertainty, but it is there for sure
  - Sadly Standard Model like, with the current precision, but **first unambiguous observation of the $B_s^0 \rightarrow \mu^+\mu^-$ decay!**
  - Also note that at the same time we are looking for the even more rare twin $B^0 \rightarrow \mu^+\mu^-$

http://arxiv.org/pdf/1202.6251v2.pdf

1. The big questions
2. Some headline results
3. My research

Exclusive Production

Interactions of the form $pp \to pEp$



QED background: 2γ exchange

- QED process with small proton form-factor corrections

Pomeron exchange:

- Pomeron is, at leading order, a pair of gluons in $++$ state

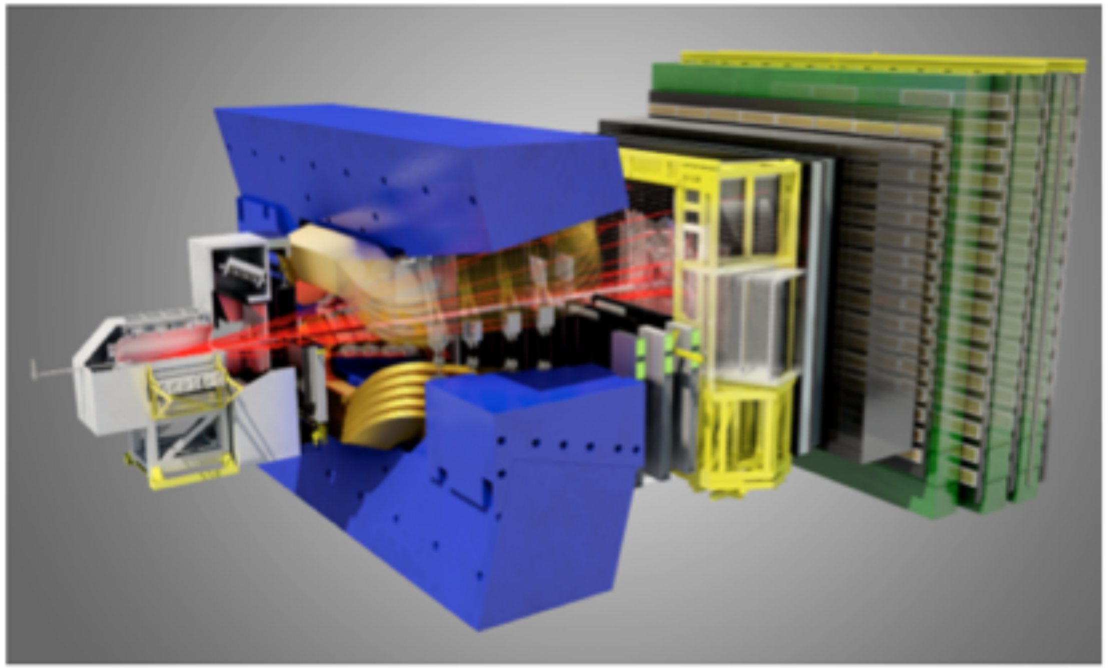
Exclusive Production

Experimental signature:

- 'Exclusive' candidate (e.g. $J/\psi \to \mu^+\mu^-$) large rapidity gaps with respect to beam

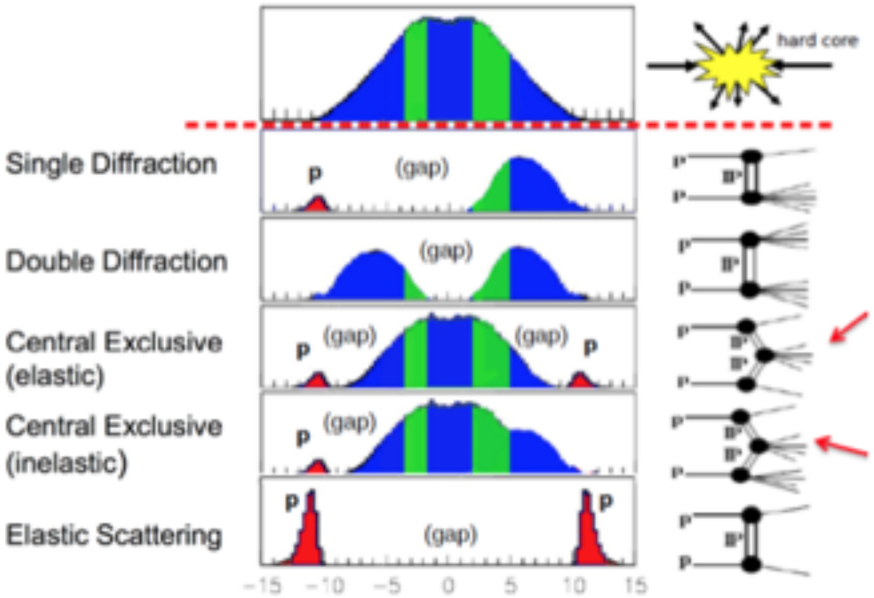
At LHCb:

- Low pile-up
- Detection in pseudorapidity range $2 \to 5$
- Fully reconstruct and identify tracks from exclusive candidate
- Require no other detector activity
  - Implicitly require only one *pp* interaction
  - Run 1 effective $\mathcal{L}_{\text{int}}$: $\sim$600 pb^{-1}



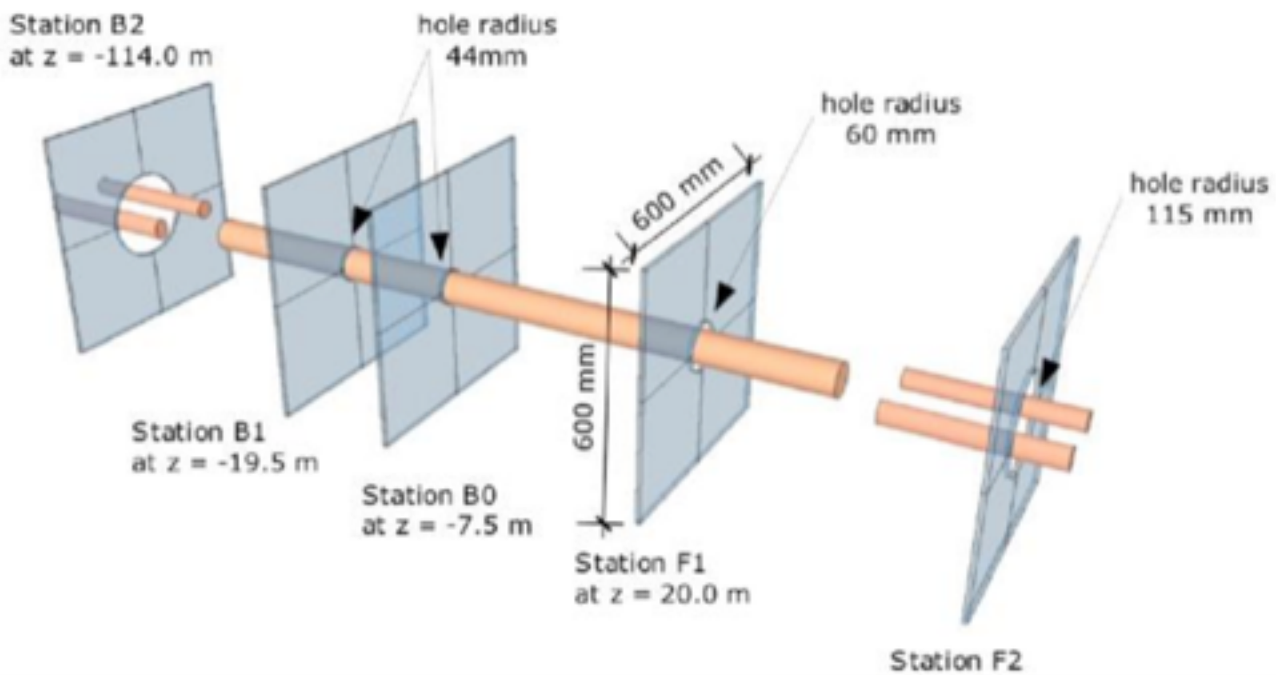
Exclusive Production

- Biggest challenge currently is to establish the rapidity gap
- High proportion (50% for $J\psi J\psi$ CEP) of 'empty-detector' signal where proton dissociation escapes down the beampipe
- LHCb hopes for $\sim 5\text{fb}^{-1}$ during run II at low pile-up

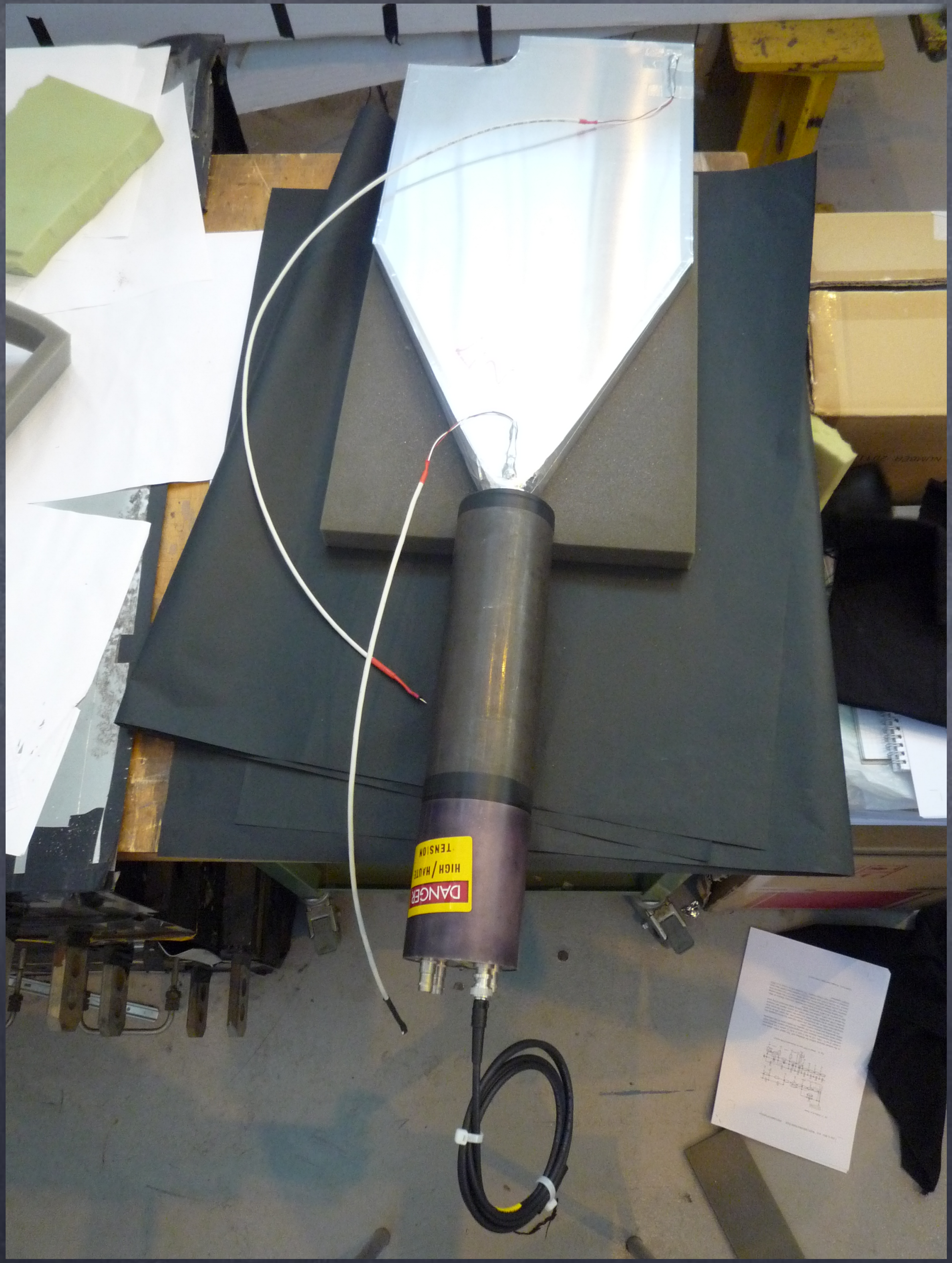


Install scintillators either side of LHCb

- Detect showers from high rapidity particles interacting with the beam-pipe elements



Exclusive Production



Exclusive Production

Exclusive Production