

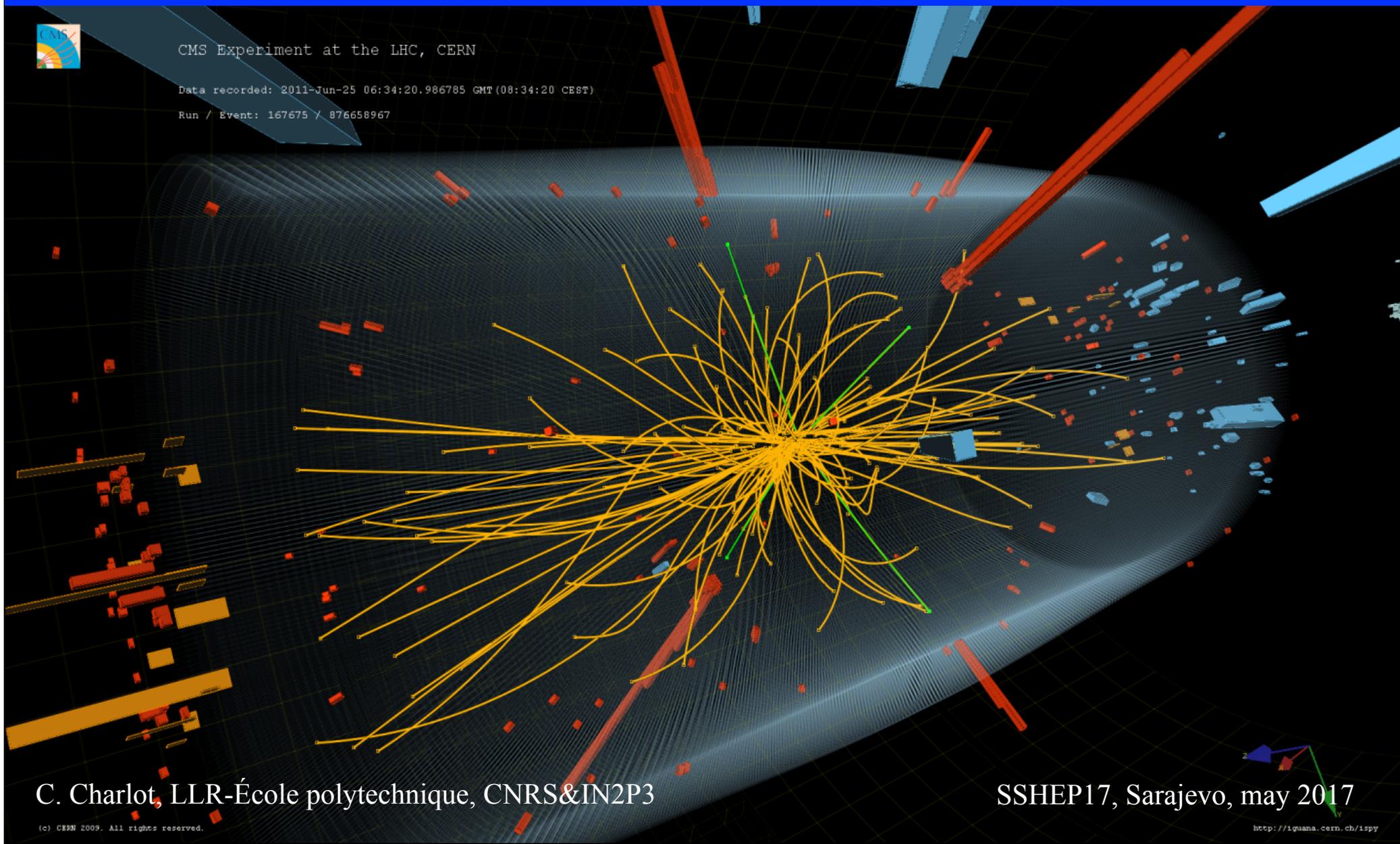
LHC Physics



CMS Experiment at the LHC, CERN

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Content

- ❑ Part 1: Introduction
- ❑ Part 2: QCD Physics
- ❑ Part 3: Electroweak Physics
- ❑ **Part 4: B Physics**
- ❑ **Part 5: Beyond Standard Model Physics**

- ❑ Not covered here:
 - ❑ Higgs Physics (dedicated lecture in this school)
 - ❑ Neutrinos Physics
 - ❑ Many other things

Part 4: B physics

Why B physics?

□ Flavor and families physics

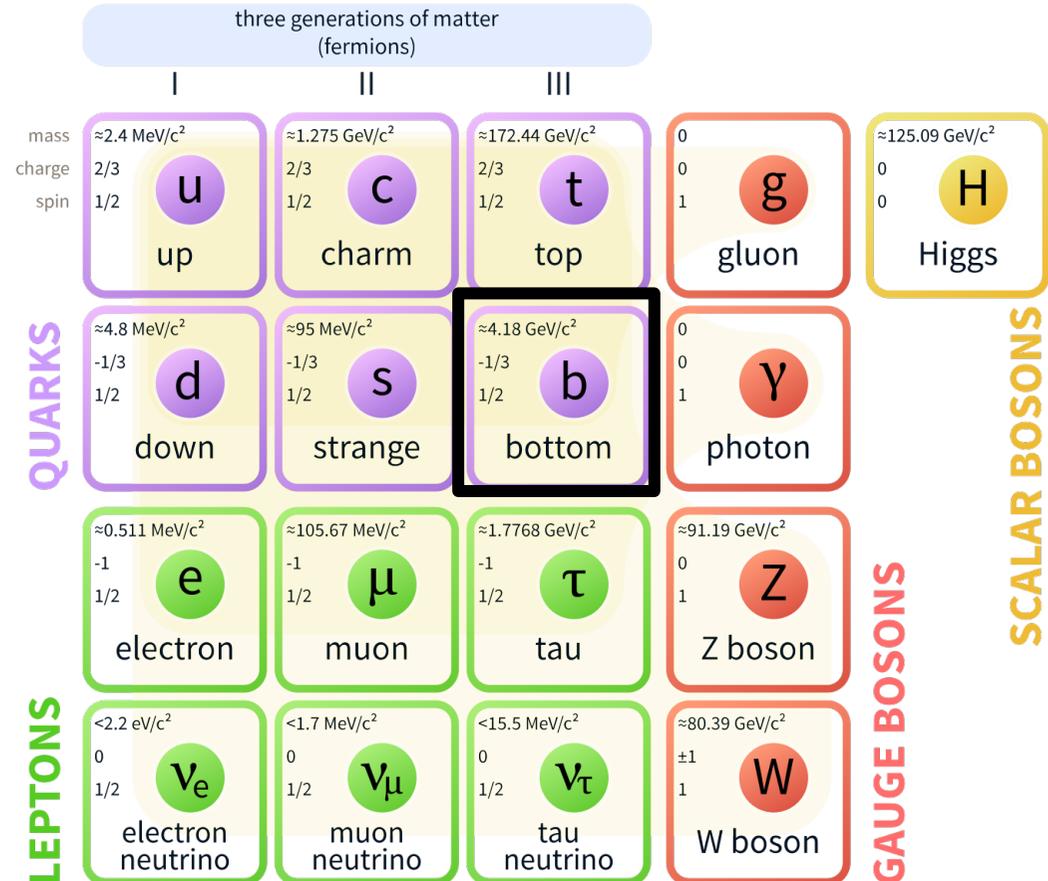
□ In this lecture:

□ Flavor structure of SM:
mixing, CKM matrix and
the unitarity triangle

□ **CP violation**

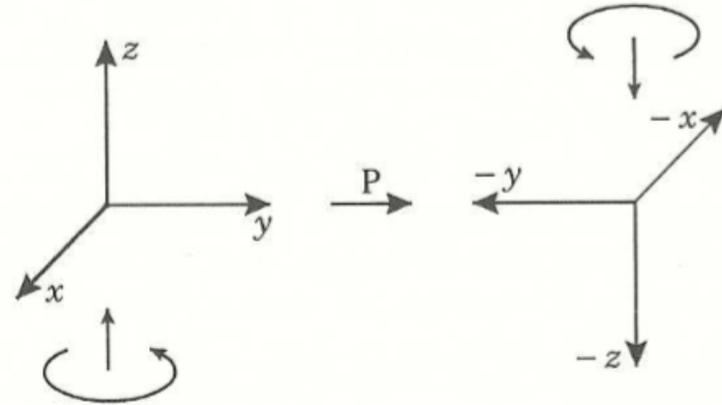
□ Search for **new physics**

Standard Model of Elementary Particles



Remind: parity transformation

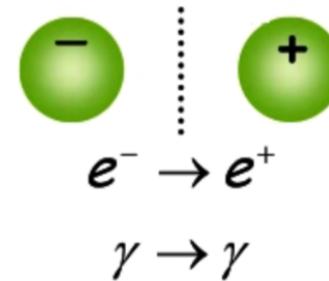
- ❑ Parity (unitary) transformation P
- ❑ Invert all coordinates $x \rightarrow -x$
- ❑ Left handed frame \rightarrow right handed frame



- ❑ How do common mathematical objects transform under P ?
 - ❑ Scalar (E): $E \rightarrow E$
 - ❑ Pseudo-scalar (h): $h \rightarrow -h$
 - ❑ Vector (p): $p \rightarrow -p$
 - ❑ Pseudo-vector (J): $J \rightarrow J$

Another transformation: charge conjugation

- ❑ Charge conjugation transformation C
- ❑ Change particle \rightarrow anti-particle
 - ❑ Choice is just convention



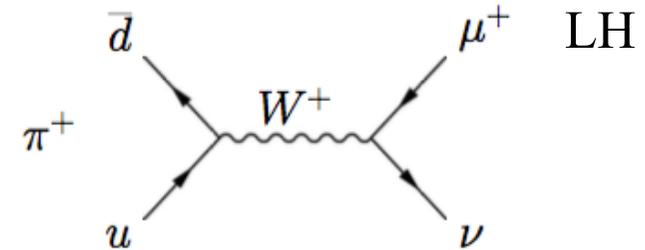
- ❑ π^0 decay
 - ❑ $\pi^0 \rightarrow \gamma\gamma$
 - ❑ γ has C-parity -1, therefore π^0 has C-parity $(-1)^2 = +1$
 - ❑ $\pi^0 \rightarrow 3\gamma$ that would violate C conservation, is not observed

\rightarrow Charge conjugation is conserved in electromagnetic interactions. It is also the case for the strong interactions (QCD)

Parity and charge conjugation: CP

- ❑ Hadron decays through weak interactions, consider weak decay of the charged pion through W charged weak current

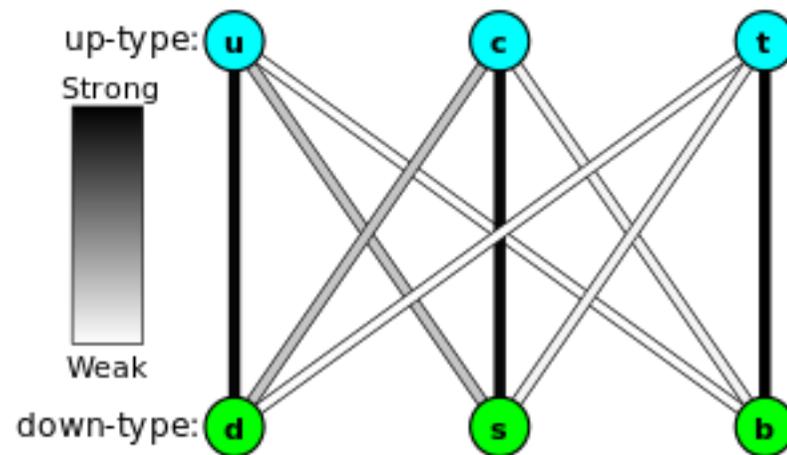
- ❑ In this interaction the μ^+ always has its spin anti // to the momentum (left handed)
- ❑ For the charge conjugate reaction: $\pi^- \rightarrow \mu^- + \text{anti-}\nu$, the μ^- always has its spin // to the momentum (right handed)



→ This means charge conjugation symmetry **C is not conserved by weak interactions**
→ However if we add P, then the spins are unchanged but the momentum $p \rightarrow -p$ and therefore **CP is conserved** in this process

Quark mixing, Cabibo angle

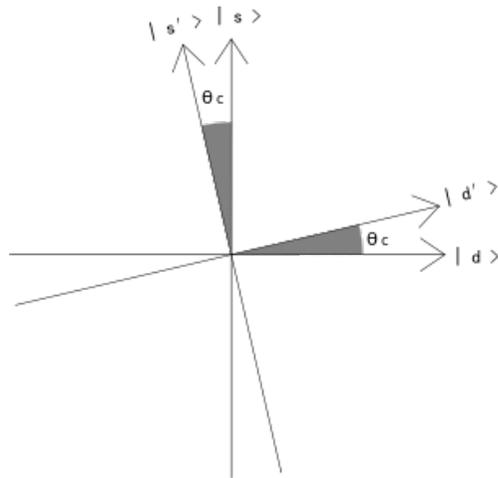
- Weak charged interaction allows for transitions between quark of different families
 - Not just $u \rightarrow d + W^+$ (and similarly for the two other families)



- There is an amount of coupling $u \rightarrow d + W^+$ but also $u \rightarrow s + W^+$ (assume crossing in all transitions when not kinematically available), and $u \rightarrow b + W^+$
- Sum of transition probabilities equals probability neutrino \rightarrow electron + W^-

Quark mixing, Cabibo angle

- Let's assume 2 families, we can identify $u \rightarrow d$ coupling in the quark sector and in the lepton sector, provided that the transition $u \rightarrow d$ occurs towards a rotated state



Weak Int
flavor state

Flavor mass
eigenstates

$$d' = \alpha d + \beta s$$

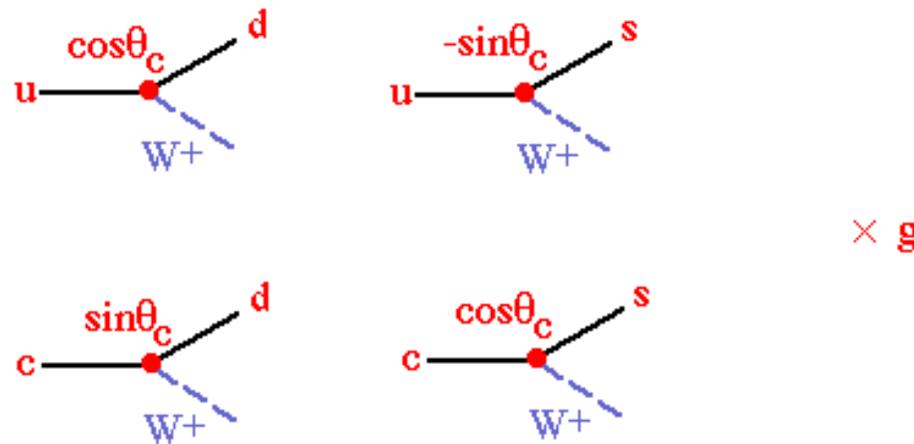
Unitarity: $|\alpha|^2 + |\beta|^2 = 1$ $\alpha = \cos \theta_c$; $\beta = \sin \theta_c$

$\theta_c =$ "Cabibbo angle"

→ weak interaction eigenstates are not identical to mass eigenstates, but rather a mixture of them

Quark mixing, Cabibo angle

- Weak charged interaction allows for transitions between quark of different families



- A similar mixing is present in the neutrino sector
- This is not the case for the coupling of quarks to the Z^0 (Zqq interactions are flavour diagonal)
- We don't know if its is also the case for the charged leptons ...

CKM matrix

- The mixing actually occurs between the three families => three-dimensional rotation
=> three 2D rotations/angles

$$\begin{aligned}
 & \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
 & = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}
 \end{aligned}$$

Fully general
parametrisation

- V_{ij} connects the left handed u-type quark of i-th family with the left-handed down-type quark of j-th family, rather use intuitive labeling ($V_{12}=V_{ub}$, $V_{13}=V_{us}$, etc..)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM matrix

- V in Nature is hierarchical: $\theta_{13} \ll \theta_{23} \ll \theta_{12} \ll 1$
- Wolfenstein parameterization: expansion in $\lambda = \sin\theta_C$, $A, \rho, \eta \sim O(1)$

$$\begin{pmatrix} & \text{d} & \text{s} & \text{b} \\ \text{u} & \blacksquare & \blacksquare & \cdot \\ \text{c} & \blacksquare & \blacksquare & \blacksquare \\ \text{t} & \cdot & \blacksquare & \blacksquare \end{pmatrix}$$

$$V = \begin{pmatrix} 1 - \lambda^2/2 & +\lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & +A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

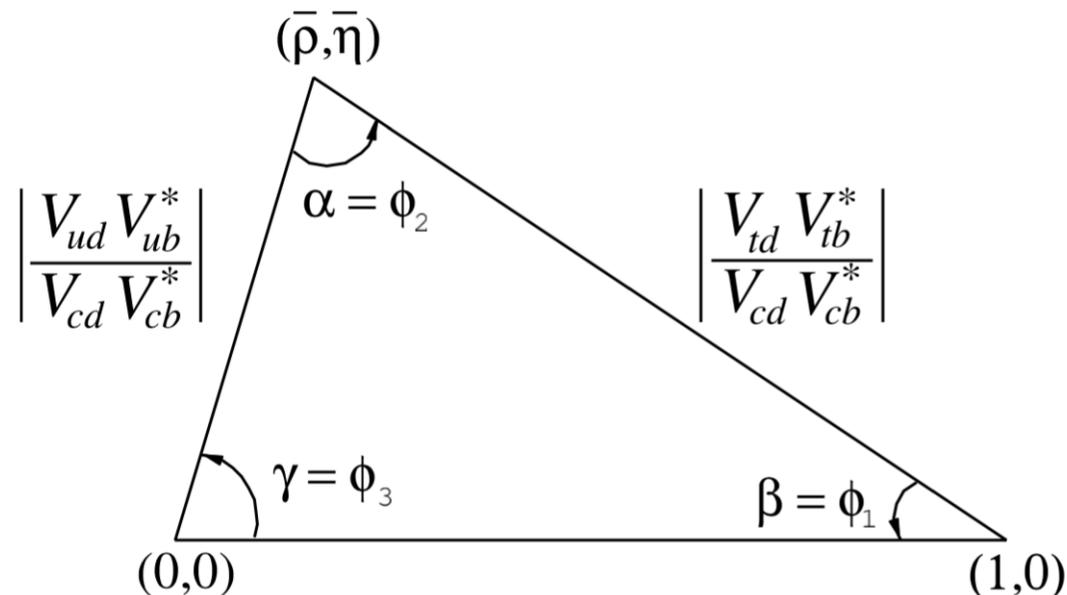
fits: $\lambda = 0.225$, $A = 0.81$, $\bar{\rho} = 0.14$, $\bar{\eta} = 0.34$

- Beyond lowest order: $\bar{\rho} = \rho(1 - \lambda^2/2)$ and $\bar{\eta} = \eta(1 - \lambda^2/2)$
- Fundamental point: **CP is violated in any theory that has complex coupling constants** in the Lagrangian (that cannot be removed by a redefinition of fields)

→ η different from 0 features CP violation

Unitarity triangle

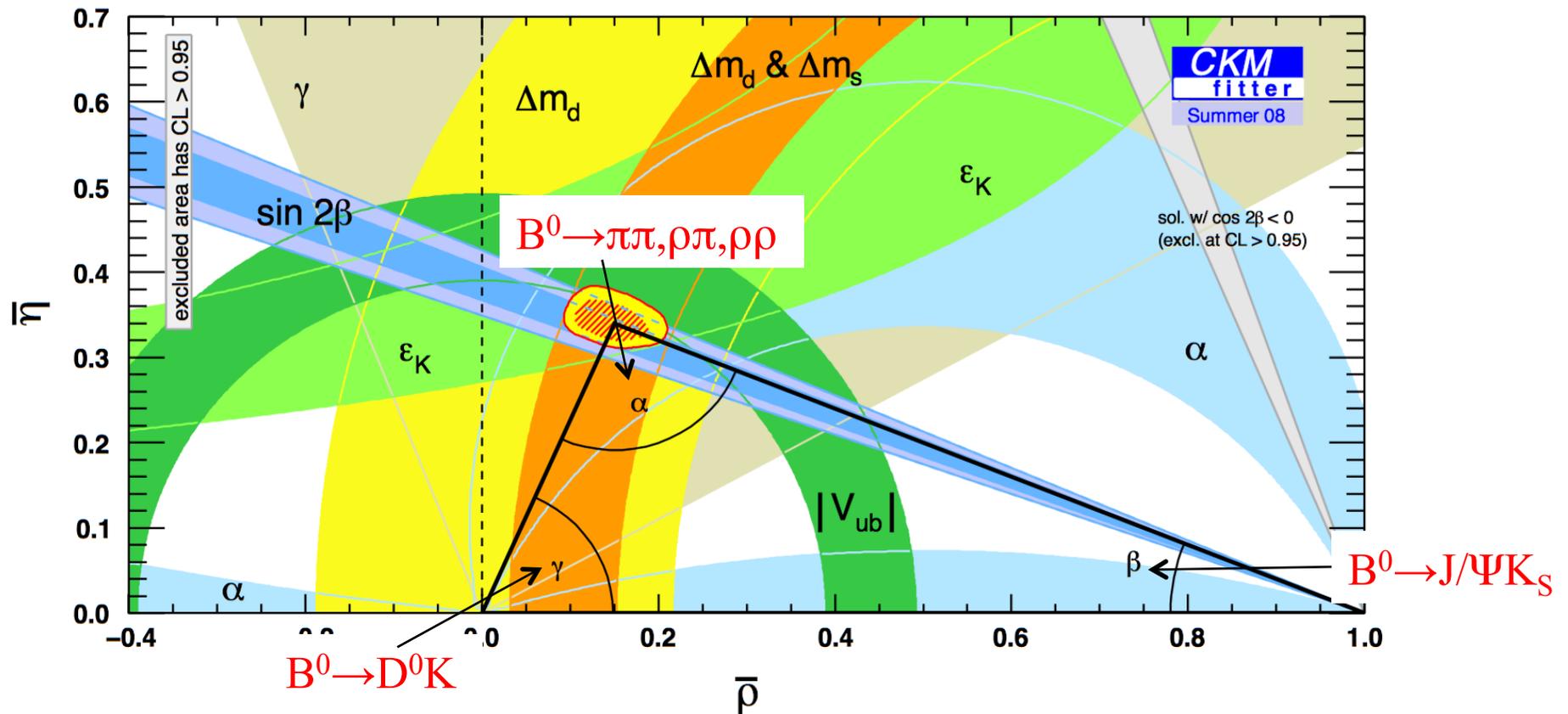
- CKM matrix being unitary: $\sum_j V_{ij}V_{kj}^* = \delta_{ik}$ $\sum_i V_{ij}V_{ik}^* = \delta_{jk}$
 - 6 vanishing contributions \Rightarrow 6 triangles
- Most relevant one: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
- Normalized sides: $|V_{ud}V_{ub}^*/V_{cd}V_{cb}^*|$, 1, $|V_{td}V_{tb}^*/V_{td}V_{tb}^*|$



If there is CP violation \Rightarrow the triangle is not flat

Unitarity triangle: status

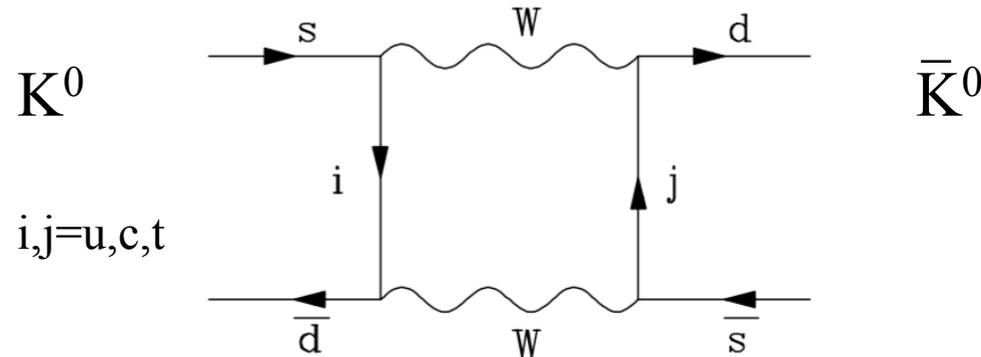
- Measurements to constrain the triangle parameters in the complex $\bar{\rho}$, $\bar{\eta}$ plane



→ Consistent evidence for CP violation from many different measurements

Quark mixing and oscillation

- Allow weak interaction to couple between different families/generation, then:



- Therefore K^0 transforms into \bar{K}^0 and vice-versa \Rightarrow **oscillations between matter and anti-matter** before the decay
- Oscillation probability at time t given by

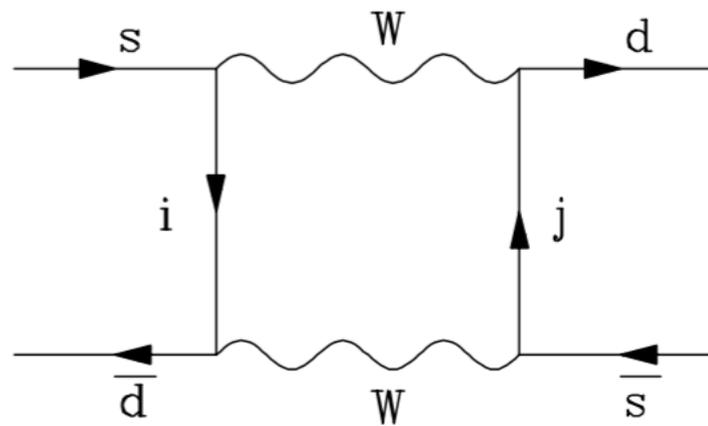
$$|\langle \bar{K}^0 | \exp(-iHt) K^0 \rangle|^2$$

- K^0 - \bar{K}^0 mixing/oscillation also happens for D^0 - \bar{D}^0 , B^0 - \bar{B}^0 , any neutral system where the antiparticle is distinct due to non zero quantum number that is not conserved by weak interaction

Neutral meson oscillations

- ❑ Neutral meson oscillation happens for K^0 (sd), D^0 (cu) and B^0 (bd or bs) systems
- ❑ M^0 and \bar{M}^0 are the flavor eigenstates (defined flavour), different from physics eigenstates (defined mass and width)
- ❑ If we consider only electromagnetic or strong interactions, these flavour eigenstates would correspond to the physics states
- ❑ However, due to the weak interaction, the physical eigenstates are different from the flavour ones, therefore they mix between each other
- ❑ $M = pM^0 + q\bar{M}^0$

$K^0 - \bar{K}^0$



Neutral meson oscillations

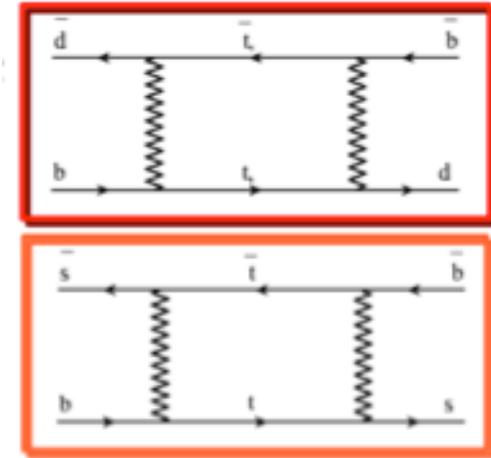
- M^0 and \bar{M}^0 are the flavor eigenstates (defined flavour), different from mass (physics) eigenstates (defined mass and width)
- Time-dependent Schrödinger equation describes the evolution of the system

$$i \frac{\partial}{\partial t} \begin{pmatrix} M^0 \\ \bar{M}^0 \end{pmatrix} = H \begin{pmatrix} M^0 \\ \bar{M}^0 \end{pmatrix} = \left(M - \frac{i}{2} \Gamma \right) \begin{pmatrix} M^0 \\ \bar{M}^0 \end{pmatrix}$$

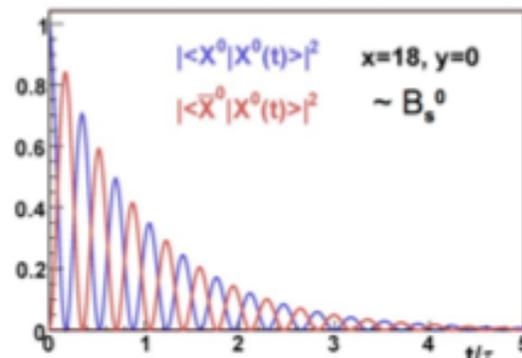
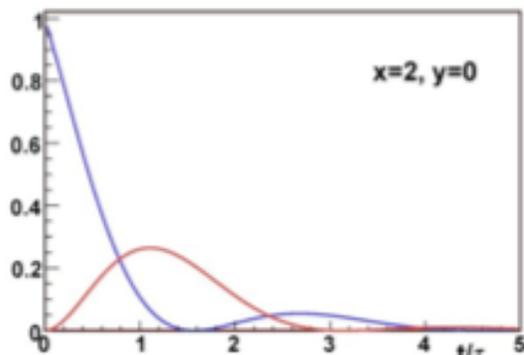
- H is hamiltonian, M and Γ are 2 hermitian matrices ($a_{ij} = \bar{a}_{ji}$)
 - $m_{11}=m_{22}$, $\Gamma_{11}=\Gamma_{22}$ (particles and anti-particles have equal mass and lifetime)
- Physical states: $M_{S,L}$ (or $M_{L,H}$) = $pM^0 \pm q\bar{M}^0$ ($|p|^2+|q|^2=1$)
- Label can be either S,L (short, long-lived) or L,H (light, heavy) depending on the values of δm and $\delta \Gamma$
- **δm and $\delta \Gamma$ can be derived by this formalism**

B oscillations

- $B^0-\bar{B}^0$ transition \rightarrow box diagram at quark level
- Same phenomenology also in the B_s^0 , except that the oscillation frequency is very different



$$x = (M_H - M_L) / \Gamma; \quad y = (\Gamma_L - \Gamma_H) / 2\Gamma$$

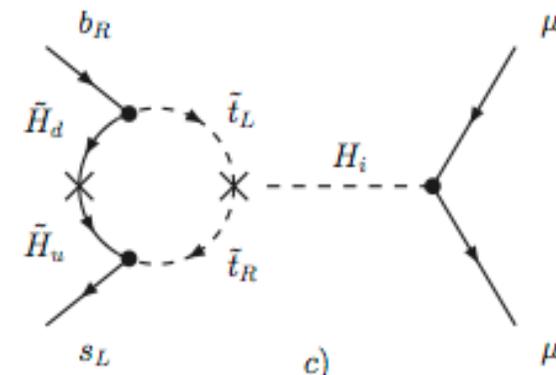
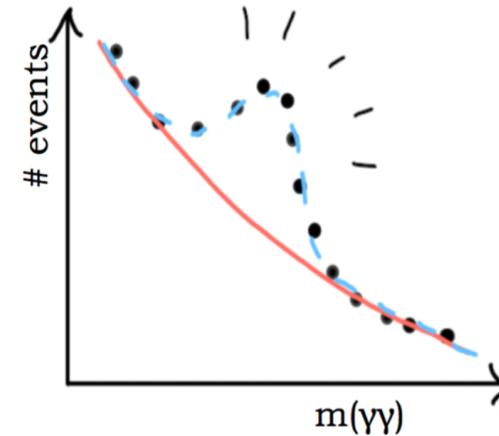


Probability to observe an initially produced B^0 as a B^0 after time t
 Probability to observe an initially produced B^0 as a \bar{B}^0 after time t

\rightarrow By measuring the oscillation frequency one can get information on δm and $\delta \Gamma$, and therefore on the sides and/or angles of the unitary triangle

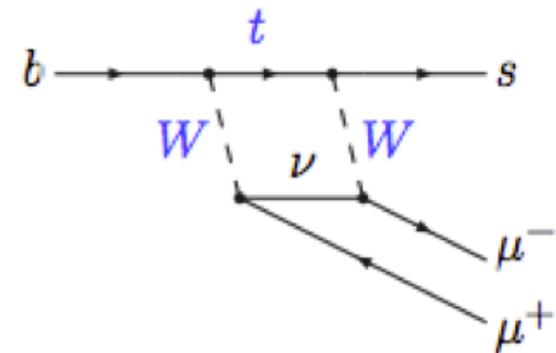
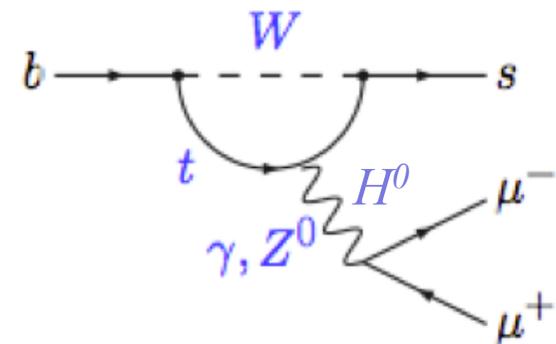
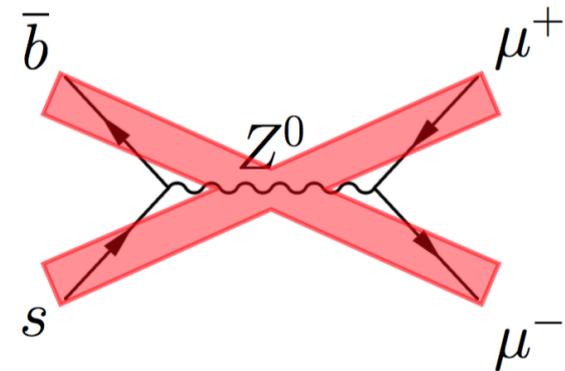
digression: direct and indirect measurements

- ❑ In the search for new physics, there are two main approaches:
- ❑ **Direct search**
 - ❑ Produce the new particle and measure its properties
 - ❑ E.g. recently discovered Higgs boson
- ❑ **Indirect search** can also be performed to get hint at new physics
 - ❑ New particles contributes to virtual correction in SM processes
 - ❑ eg LEP fit, but also many other measurements
 - ❑ This is also the area of B physics



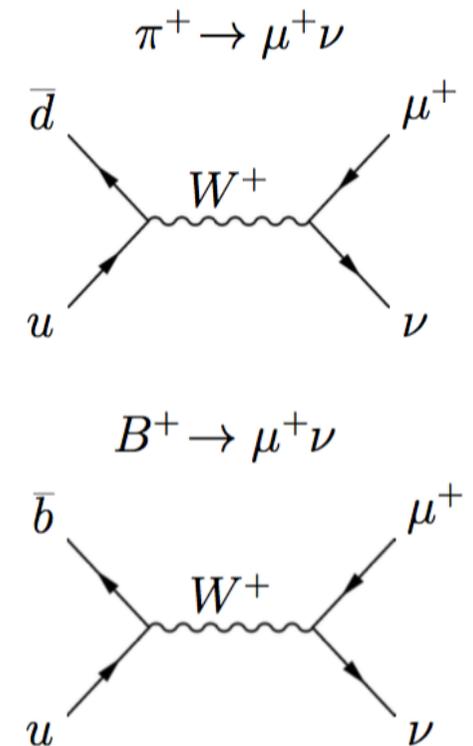
$B_s \rightarrow \mu\mu$

- ❑ Very interesting potential to constrain physics beyond standard model
- ❑ SM prediction: $(3.35 \pm 0.32) \cdot 10^{-9} \Rightarrow$ **extremely rare** process
 \Rightarrow 3 decays in $\mu\mu$ every billions of B_s decays
- ❑ Dominating contribution in the SM: **Higgs** (γ/Z) (penguin) diagram (box diagram suppressed + CKM suppressed + helicity suppressed)
- ❑ Therefore extremely **sensitive to extended scalar sector** (SUSY)
- ❑ Before the LHC starts, no evidence found to deviations from SM predictions



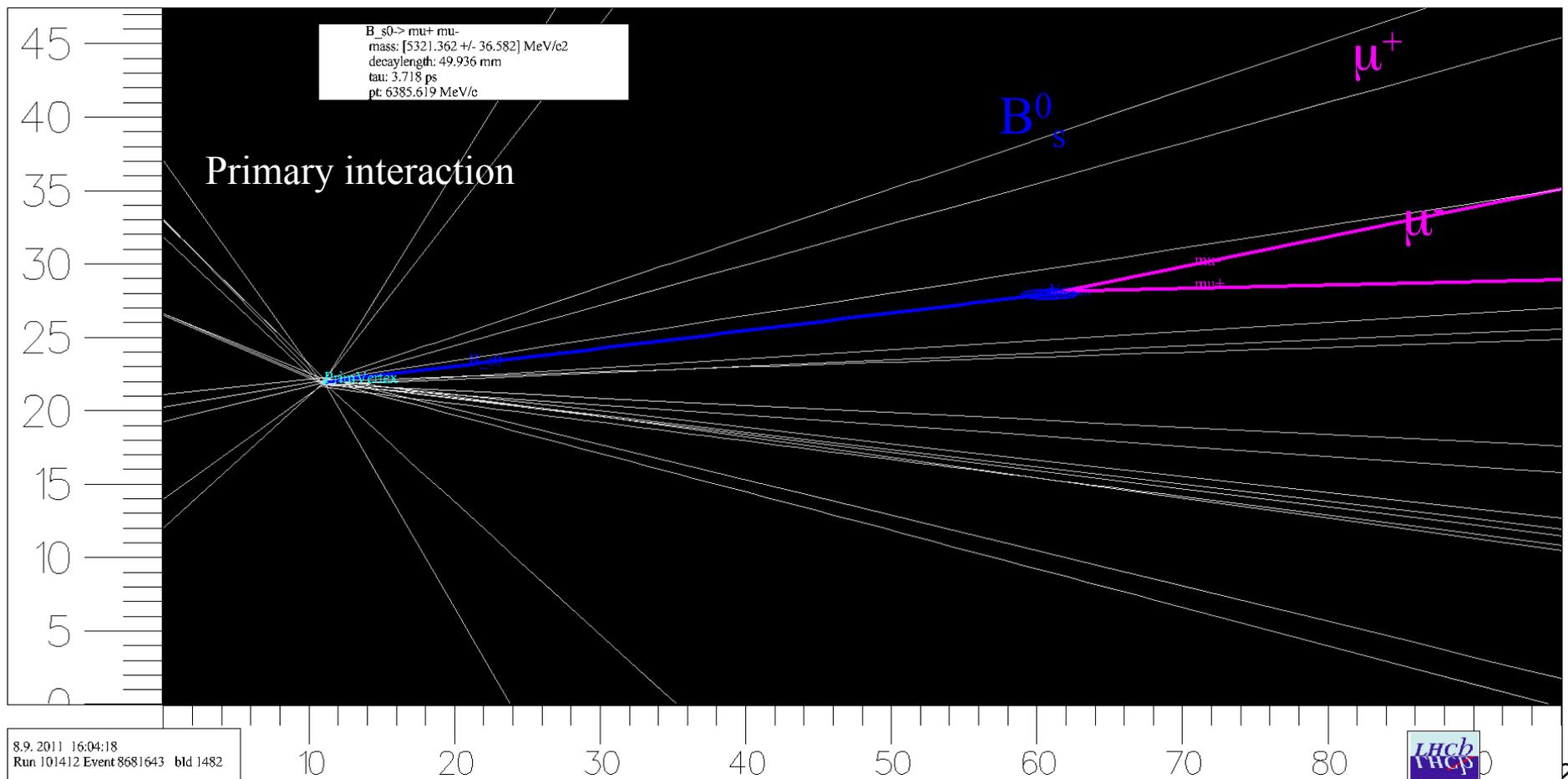
B mesons & decays

- ❑ Weak interaction responsible for mesons decays, eg $\pi^+ \rightarrow \mu^+ \nu$
- ❑ The B^+ meson is similar to the π^+ , with d antiquark is replaced by the third generation b antiquark
- ❑ B^+ decay heavily suppressed because of transition between 1st and 3rd generation (CKM suppression)
 - ❑ Preferred decay to second generation' quarks, eg charm
- ❑ The neutral B_s^0 meson is similar to the B^+ except that the u quark is replaced by the second generation s quark ($q=-1/3$)



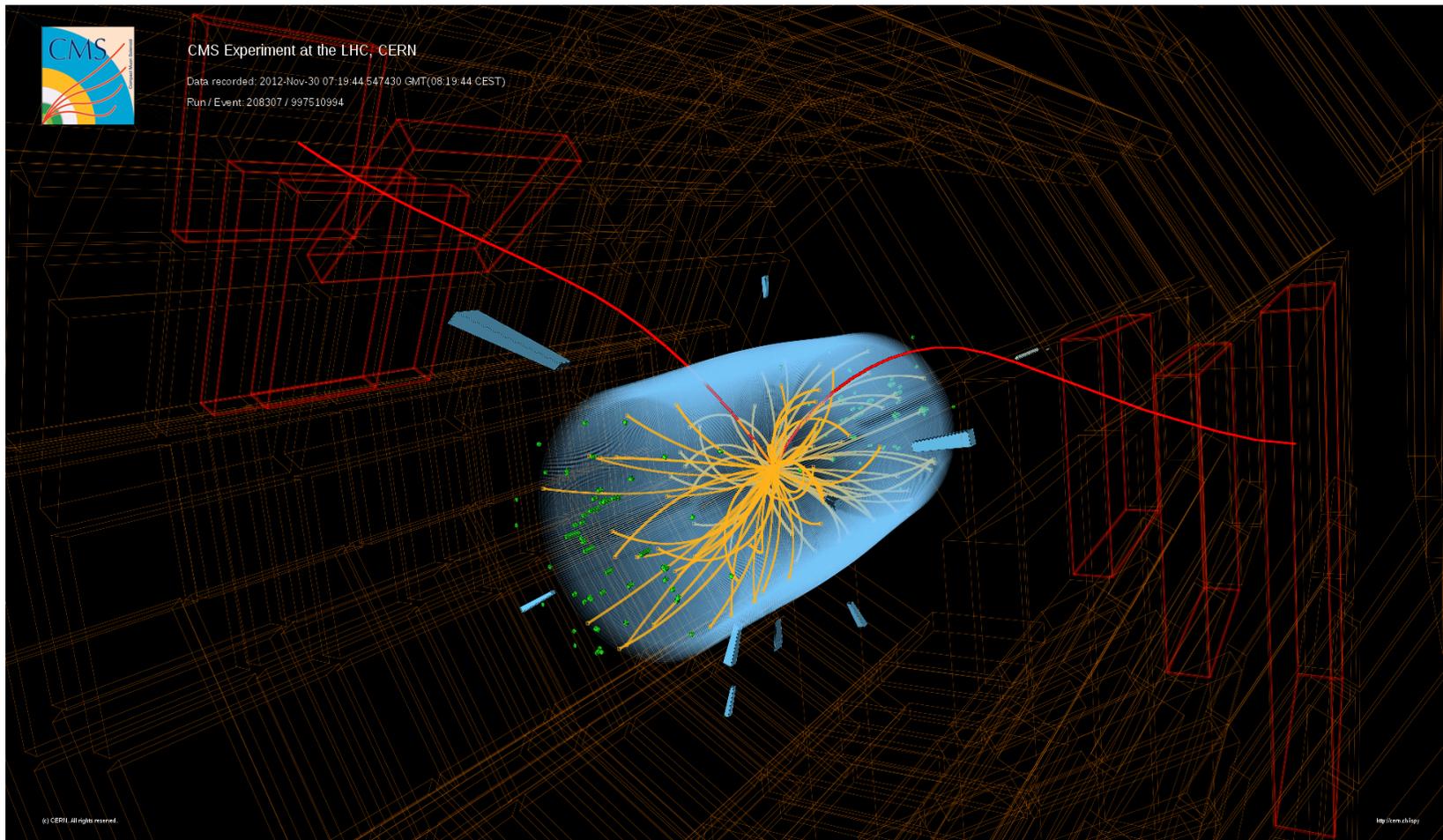
$B_s \rightarrow \mu\mu$ at LHCb

- LHCb is the dedicated experiment at LHC to study B mesons



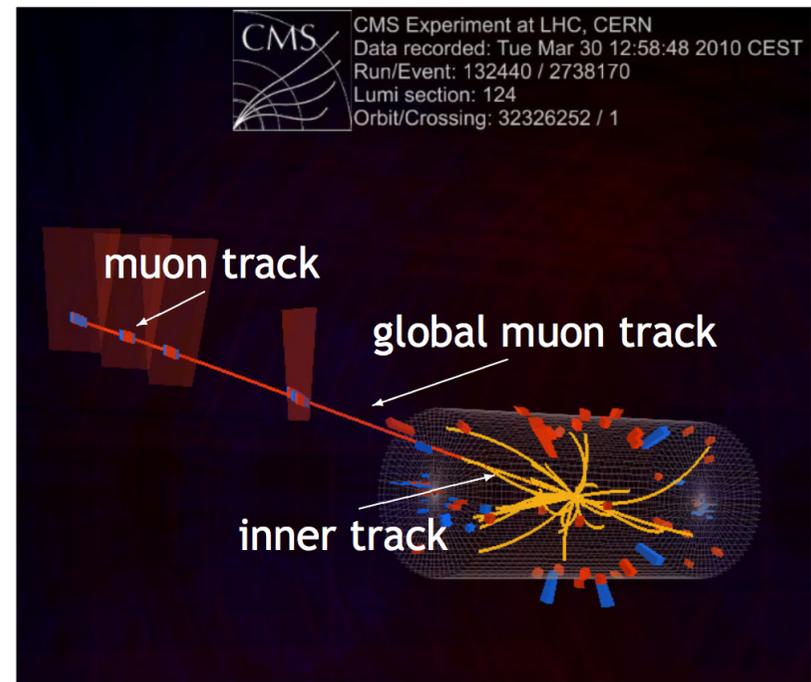
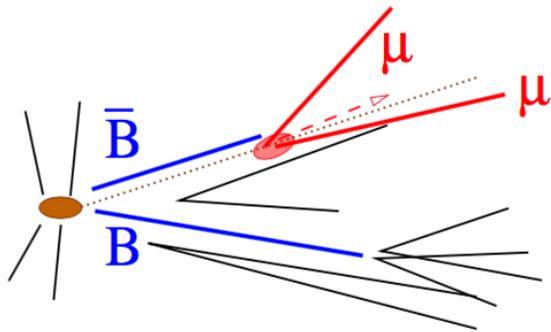
$B_s \rightarrow \mu\mu$ at CMS

- General-purpose experiments as CMS can also be used to study B mesons



$B_s \rightarrow \mu\mu$ at CMS

- Signal: $B_s \rightarrow \mu\mu$
 - Two muons from one decay vertex
 - Well reconstructed secondary vertex
 - Momentum aligned with flight direction
 - Mass around m_{B_s}

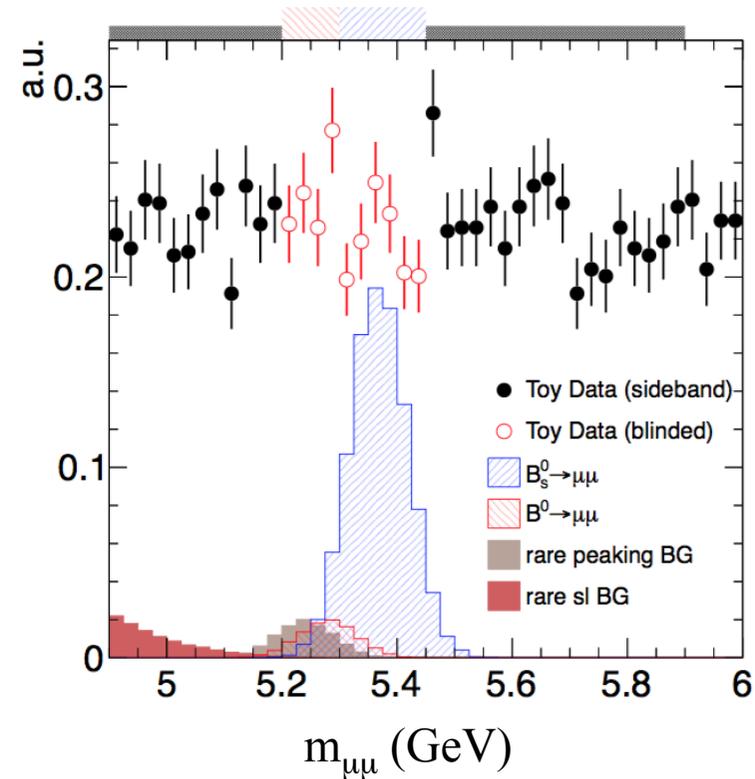
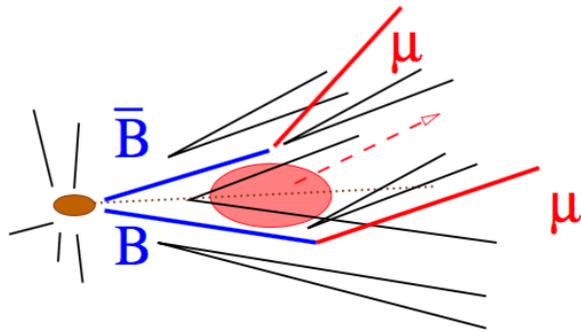


→ Needs excellent muon identification capability

$B_s \rightarrow \mu\mu$ at CMS

□ Backgrounds

- **Combinatorial** (from side-bands): two semi-leptonic B decays or one semi-leptonic B decay plus one misidentified hadron
- Rare single B-decay: $B_s^0 \rightarrow K^- \mu^+ \nu$, $B_s^0 \rightarrow K^+ K^-$ (peaking)

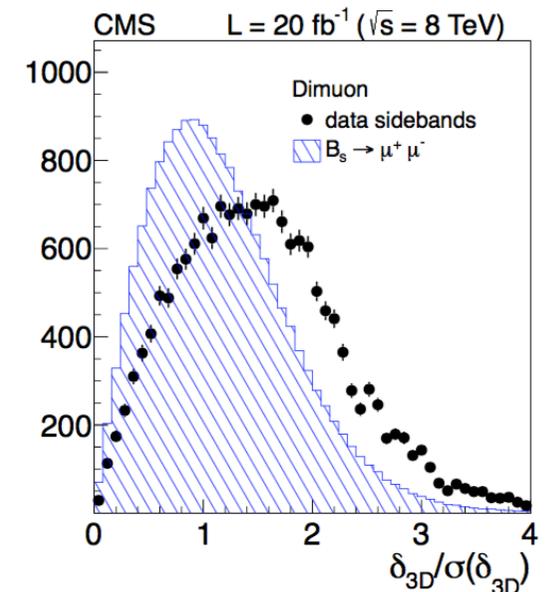
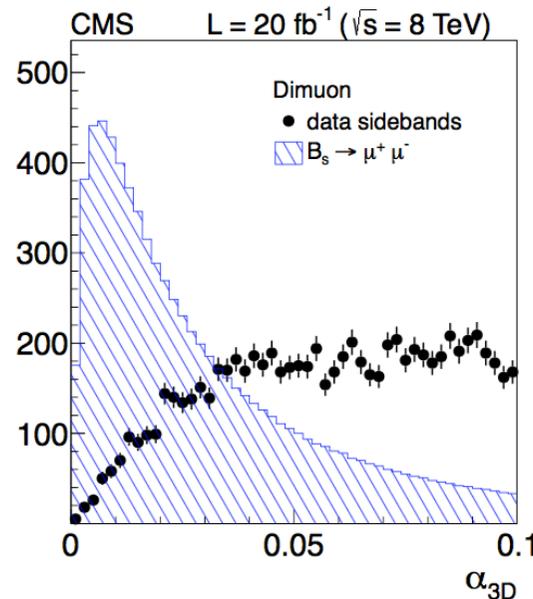
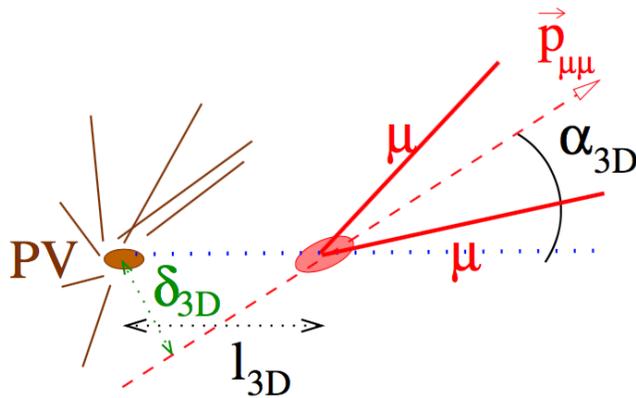


$B_s \rightarrow \mu\mu$ at CMS

Methodology

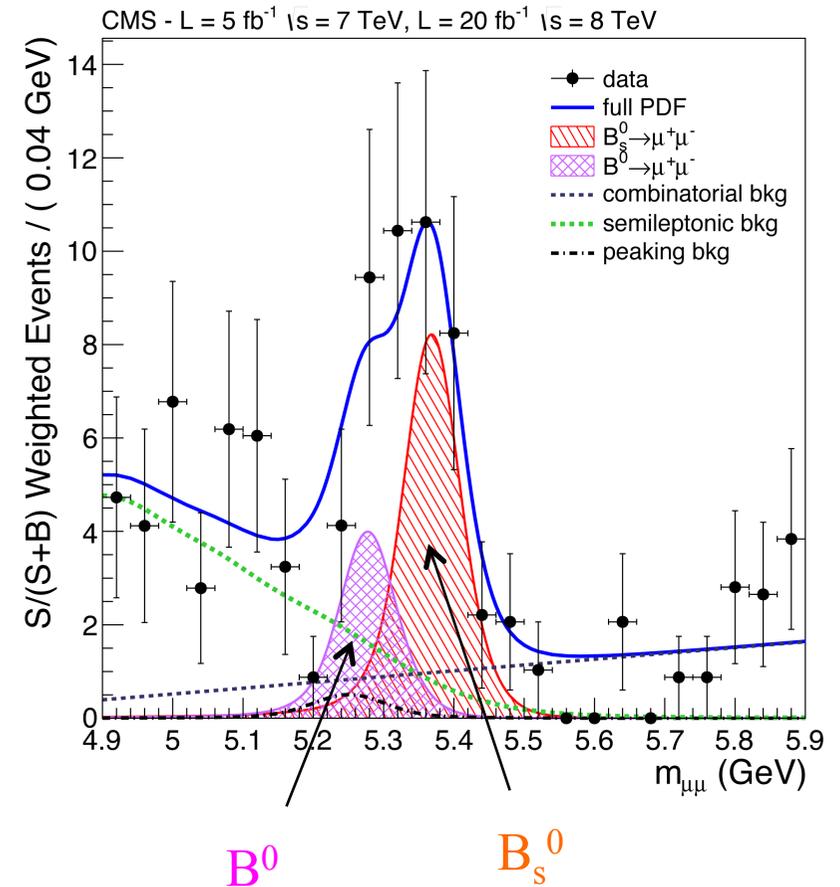
- Measurement of $B_s \rightarrow \mu\mu$ relative to a normalization channel
 - $B^\pm \rightarrow J/\Psi K^\pm$ with well-known fraction of decay
 - Nearly identical selection to reduce systematic uncertainties
- Calibration of simulation with reconstructed exclusive decays
 - $B^\pm \rightarrow J/\Psi K^\pm$: normalization with high statistics
 - $B_s^0 \rightarrow J/\Psi \phi$: B_s^0 signal simulation (p_T and isolation)

Discriminating variables

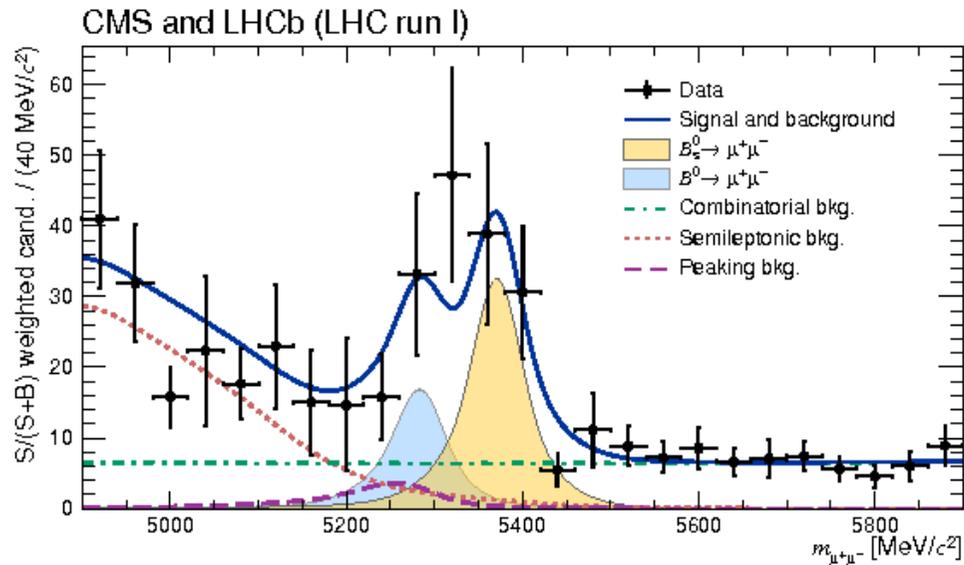


$B_s \rightarrow \mu\mu$ at CMS

- ❑ Fit B_s^0 and B^0 simultaneously
- ❑ Peaking background
 - ❑ Normalized to measured B^+ yield
 - ❑ Yield cross-checked on independent dataset
- ❑ Semi-leptonic background
 - ❑ Fixed shape
 - ❑ Free normalization within uncertainties
- ❑ Combinatorial background
 - ❑ No constraint on slope
 - ❑ Varied functional form
 - ❑ Validated on independent dataset



$B_s \rightarrow \mu\mu$ CMS+LHCb



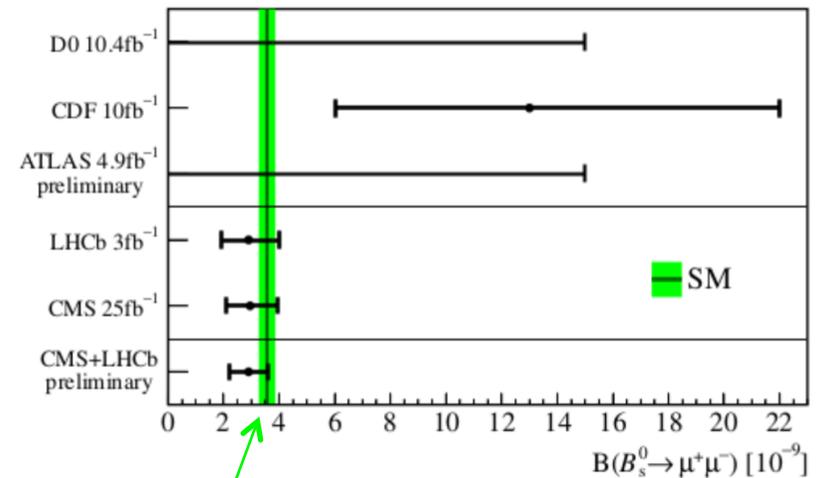
Measured fraction of decay to $\mu\mu$

$$\text{BR}(B_s \rightarrow \mu^+\mu^-) = 2.8 \pm 0.7 \times 10^{-9}$$

→ Agree with SM prediction

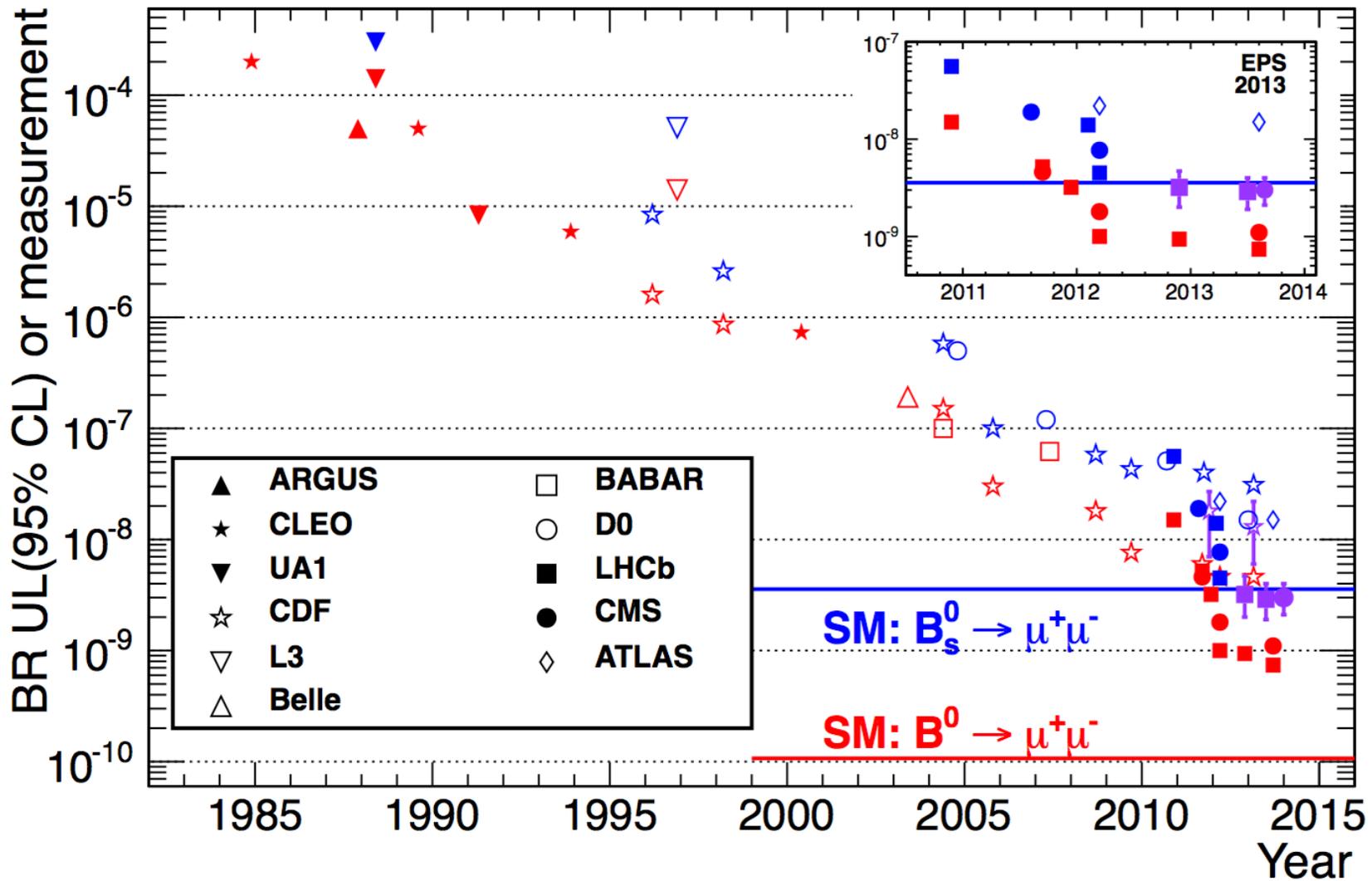
→ Stringent constraints on BSM physics

Combined CMS + LHCb results



Theory prediction

$B_s \rightarrow \mu\mu$, historical perspective



B Physics summary

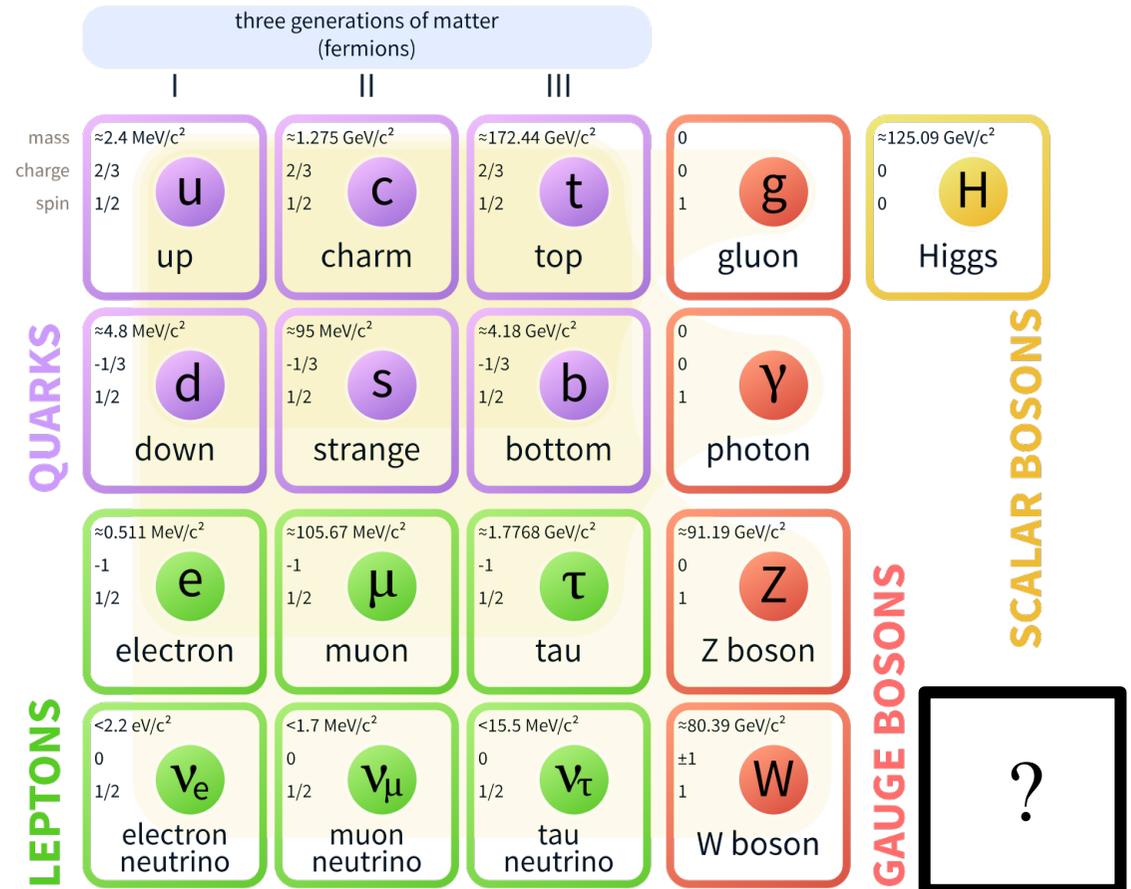
- ❑ Electromagnetic and strong interactions conserve C, P and CP but the **weak interaction does not**
- ❑ Weak interaction allows for transition between quarks of different families
- ❑ Neutral mesons physics states (mass and width eigenstates) are **mixed states** of the flavour eigenstates
- ❑ **CKM matrix** and unitarity triangle(s)
- ❑ CP violation by weak interaction → phase in CKM matrix
- ❑ In addition to quark mixing and CP violation, the measurement of rare B decays can also shed light on **new physics**
- ❑ These are difficult measurements that require extremely precise reconstruction and **identification of B decays**

Part 5: Beyond Standard Model Physics

Beyond standard model

- ❑ In addition to performing measurements to gain better understanding of the standard model, LHC is **the place to search for new physics**
- ❑ There are many reasons to believe that the SM is not a complete theory

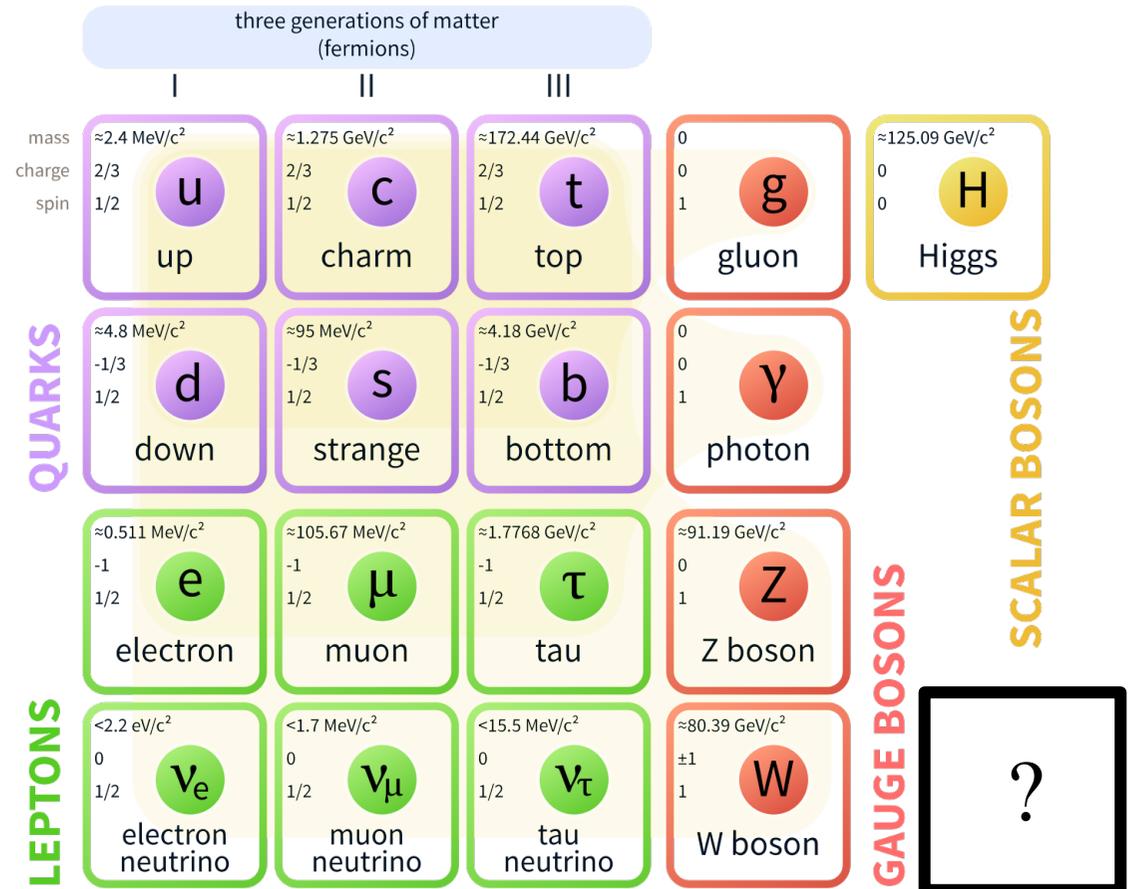
Standard Model of Elementary Particles



Why BSM physics?

- ❑ In this lecture:
 - ❑ Why is the standard model incomplete?
 - ❑ Grand unification
 - ❑ More Higgs bosons
 - ❑ Supersymmetry
 - ❑ Compositeness
 - ❑ Extra-dimensions

Standard Model of Elementary Particles

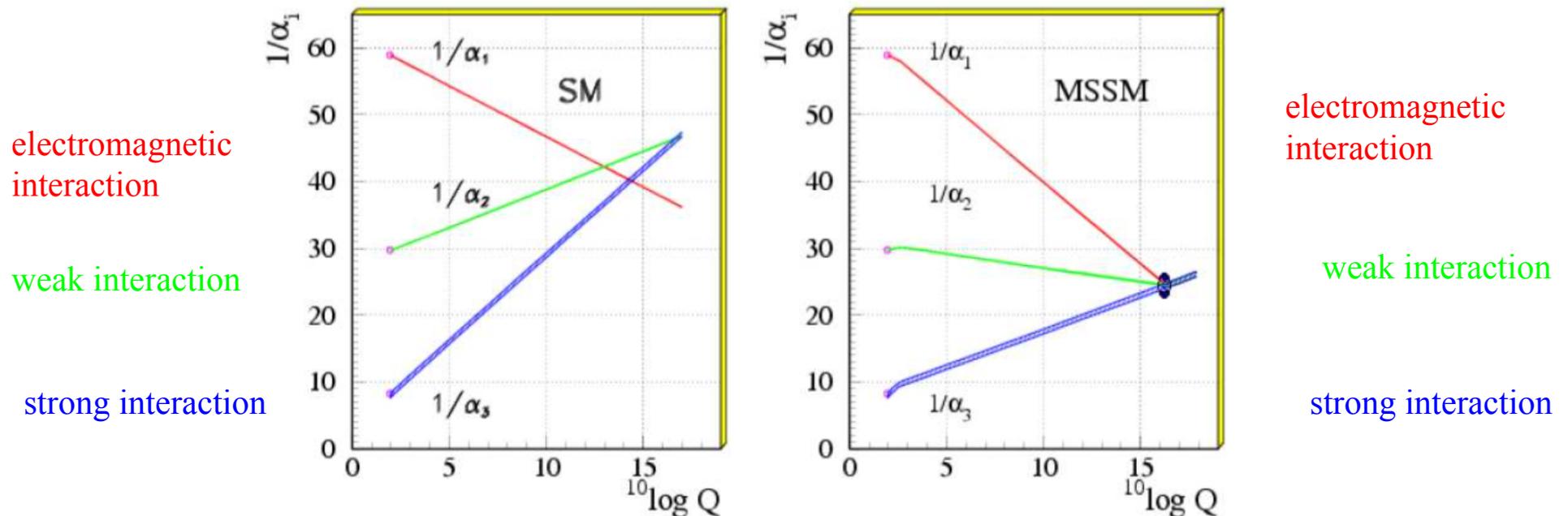


Why is the standard model incomplete?

- ❑ The standard model does not explain the following:
 - ❑ The relationship between the different interactions (electroweak, strong and gravity)
 - ❑ The nature of dark matter and dark energy
 - ❑ The matter-antimatter asymmetry of the universe
 - ❑ The existence of three families of quarks and leptons
 - ❑ The conservation of lepton and baryon numbers
 - ❑ The hierarchy of masses for quarks and leptons
 - ❑ Neutrino masses and mixing
 - ❑ The pattern of weak quarks couplings (CKM matrix)

Grand unification

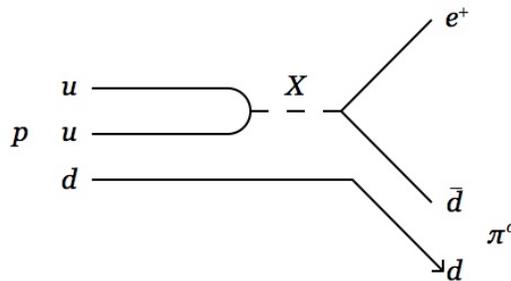
- The strong, electromagnetic and weak couplings (α_s , e and g) depend on the energy scale, can they be unified at an energy scale $Q \sim 10^{15}$ GeV?



- We also would like to include gravity at the Plank scale $Q \sim 10^{19}$ GeV. Is a string theory a candidate for this?

SU(5) Grand Unified Theory

- ❑ Simplest theory that unifies strong and electroweak interactions (Georgi & Glashow)
- ❑ Introduces 12 gauge bosons at $m \sim 10^{15}$ GeV
- ❑ These are known as leptoquarks, they make charged and neutral couplings between leptons and quarks
- ❑ Explains why $q_\nu - q_e = q_u - q_d$
- ❑ Existence of 3 colors related to the fractional charges of the quarks $\sim 1/3$
- ❑ Predicts proton decay $p \rightarrow \pi^0 + e^+$



Prediction of $\sin^2\theta_W$

- Loop diagram with $f\bar{f}$ pair couples a Z^0 boson to a photon (γ)
- In electroweak theory the Z^0 and the γ are orthogonal states
- The sum of loop diagrams over all fermion pairs must be zero

$$\sum Q(I_3 - Q \sin^2 \theta_W) = 0 \quad \sin^2 \theta_W = \frac{\sum Q I_3}{\sum Q^2}$$

- In a Grand Unified Theory (GUT) the sum is taken over a fermion supermultiplet (ν_e, e, d_r, d_g, d_b)
- This gives $\sin^2\theta_W = 0.375$ but GUT predicts the running of $\sin^2\theta_W$ from 0.375 at 10^{15} GeV to 0.215 at m_Z

→ GUT prediction for $\sin^2\theta_W$ very close to the measured value

Proton decay

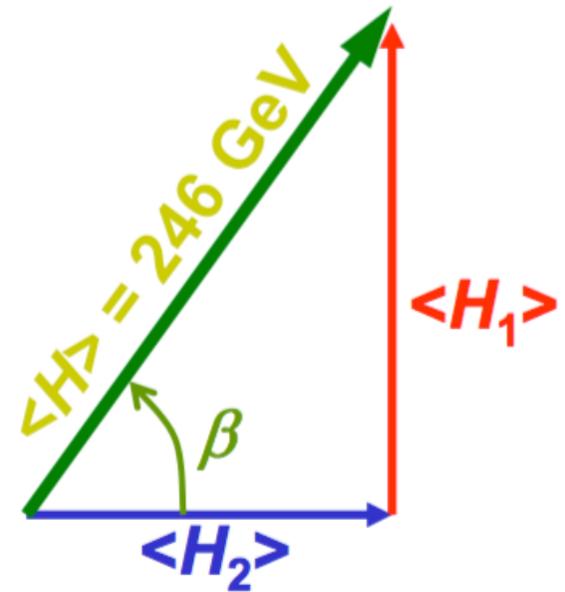
- ❑ The leptoquarks couplings in GUT do not conserve baryon and lepton numbers, only the combination B-L

$$\Gamma(p \rightarrow \pi^0 e^+) \neq 0 \quad \tau_p \propto \frac{M_X^4}{\alpha^2 m_p^5} \approx 10^{31} \text{ years}$$

- ❑ This is \gg age of the universe, not a problem for our existence
- ❑ Large underground experiments (Kamiokande, ...) have looked at proton decays. None seen $\Rightarrow \tau_p > 2 \cdot 10^{32}$ years
- ❑ Minimal SU(5) GUT ruled out by the absence of proton decay signal
- ❑ Non-minimal SO(10) GUT is not ruled out
 - ❑ Predicts different decay modes, eg $p \rightarrow K^+ + \text{anti-}\nu$

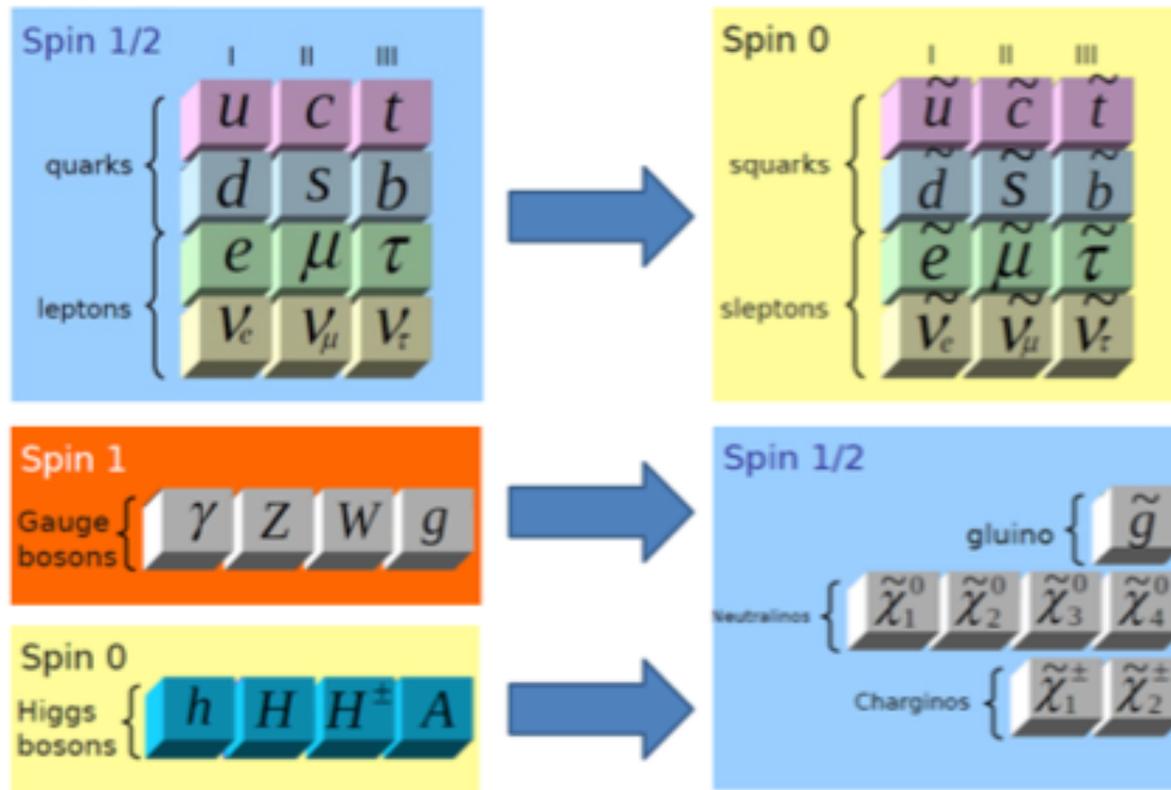
Multiple Higgs doublets

- ❑ The standard model only requires one Higgs doublet of scalar fields, after EWSB we are left with one physical Higgs boson
- ❑ It is possible to have more than one Higgs doublet, and introduce for instance:
 - ❑ A doublet that couples to u-quarks and charged leptons
 - ❑ A doublet that couples to d-quarks
- ❑ In a two-Higgs doublet model there are 8 degrees of freedom. After the EWSB there remains 5 physical Higgs bosons: H^+ , H^- , h^0 , H^0 , A^0
- ❑ There are two vacuum expectation values v_1 and v_2 with:
 - ❑ $\tan\beta = v_2/v_1$ and $v_1^2 + v_2^2 = v^2$ with $v = 246$ GeV



Supersymmetry (SUSY)

- Introduce a new symmetry that relates fermions and bosons
 - Every standard model particles gets a supersymmetric (SUSY) partner



Pros and cons for supersymmetry

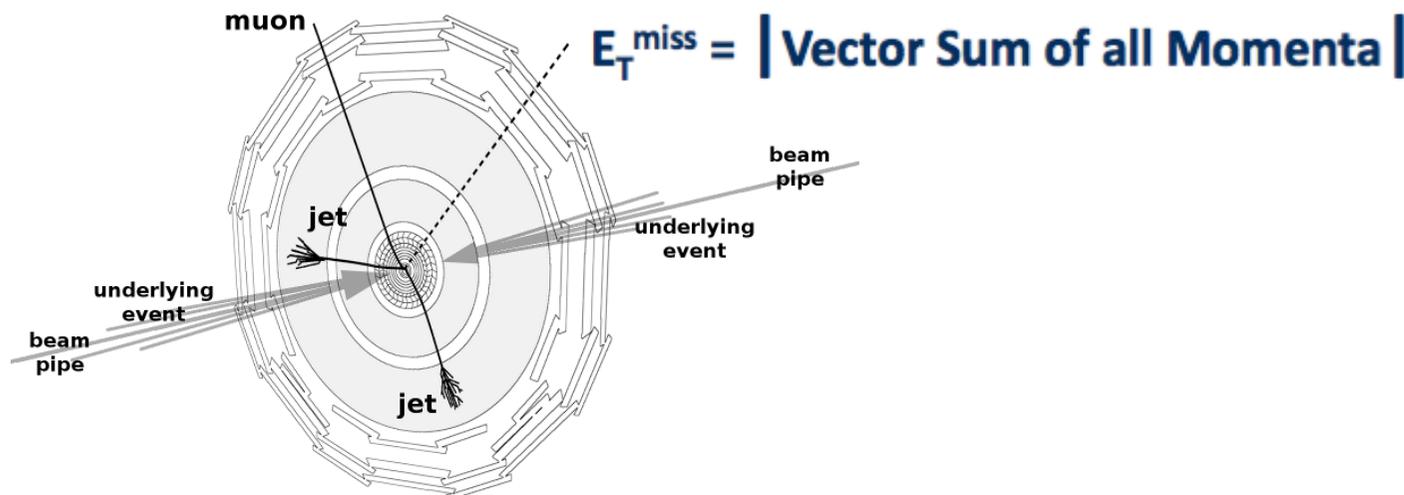
- ❑ Gives an explanation to the mass hierarchy problem (GUT \gg EWK scale)
- ❑ Higgs and fermion loop contributions cancel precisely with SUSY partners at all mass scales between 10^2 and 10^{14} GeV
- ❑ The lightest supersymmetric particle (LSP) is stable and a candidate for dark matter
- ❑ String theories that include gravity are naturally supersymmetric

BUT

- ❑ SUSY partners masses and mixing are unknown
- ❑ Many new parameters compared to Standard Model
- ❑ No experimental sign of SUSY partners up to now

Missing transverse energy

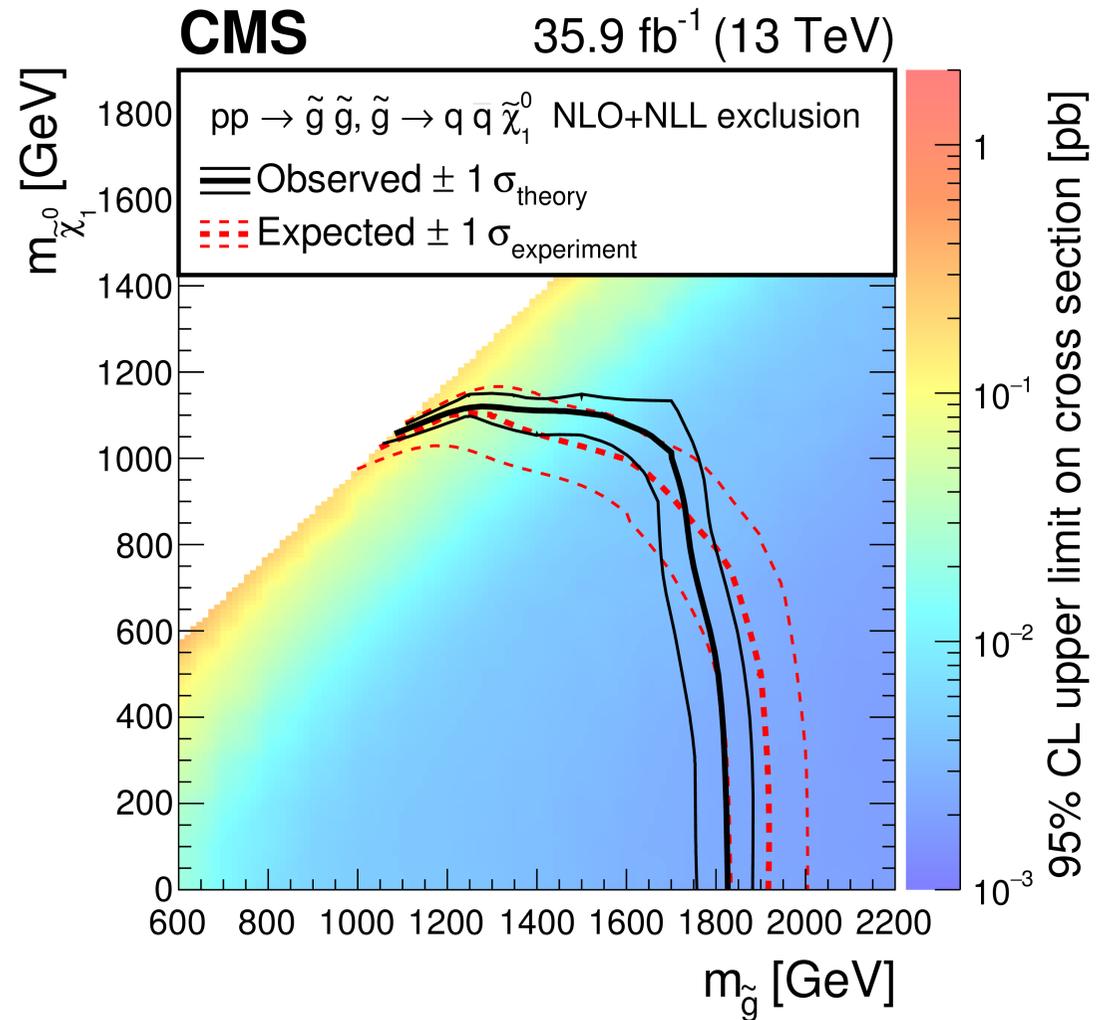
- ❑ We expect some undetected energy in SM processes due to
 - ❑ Undetectable neutrinos
 - ❑ Mismeasurement of visible objects
 - ❑ Other fake sources (such as cosmic muons overlaid on collision data)
- ❑ Undetected particle is also a generic feature of SUSY (LSP) and dark matter searches
- ❑ Due to the unknown initial p_L , only the transverse energy balance can give access to particle escaping detection



Glino searches

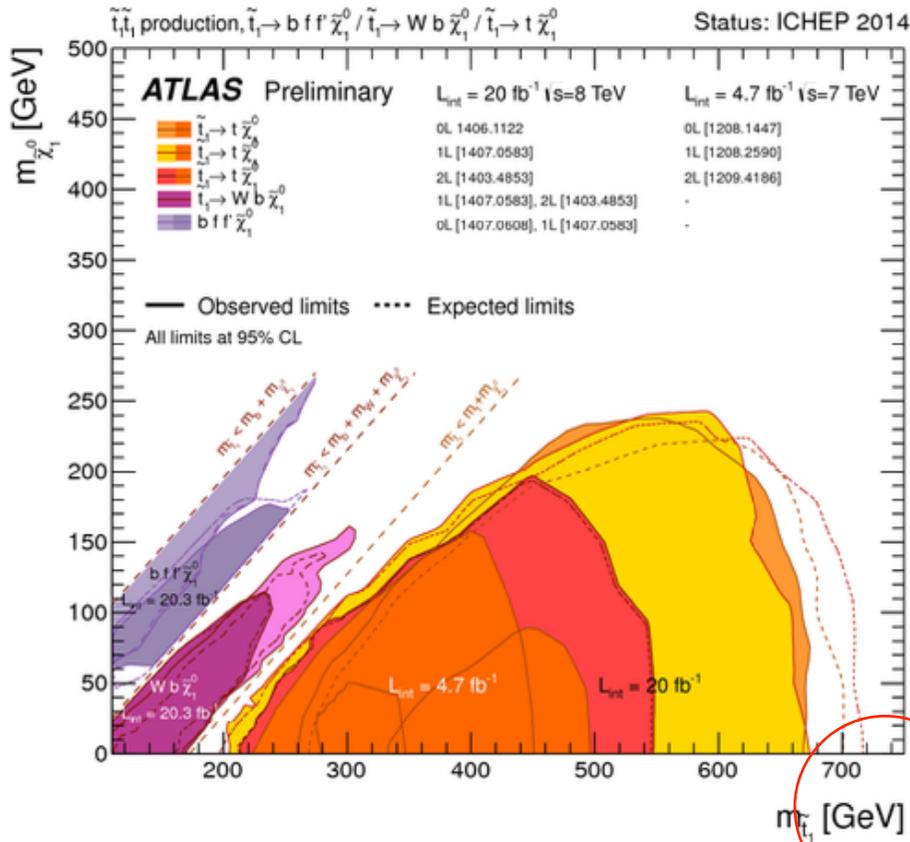
- ❑ No detection of gluino production up to now
- ❑ We put limits on gluino mass

$m_{\tilde{g}} > 1800 \text{ GeV}$ or $m_{\tilde{\chi}_1^0} > 1100 \text{ GeV}$

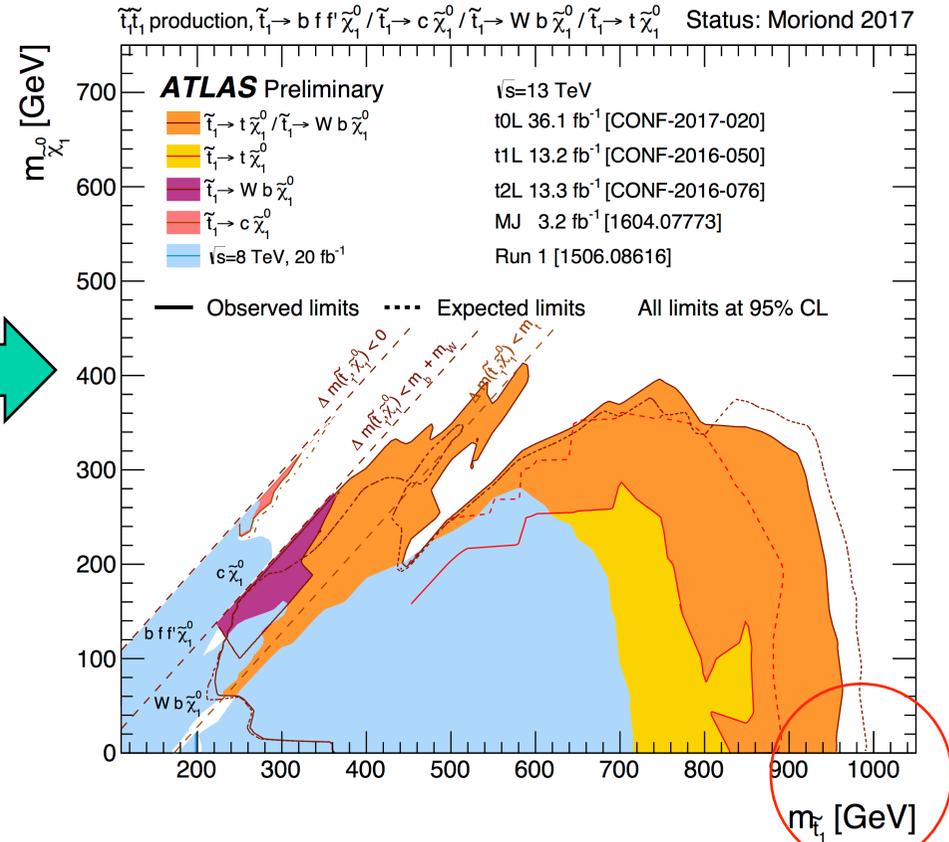


Stop searches

7 TeV



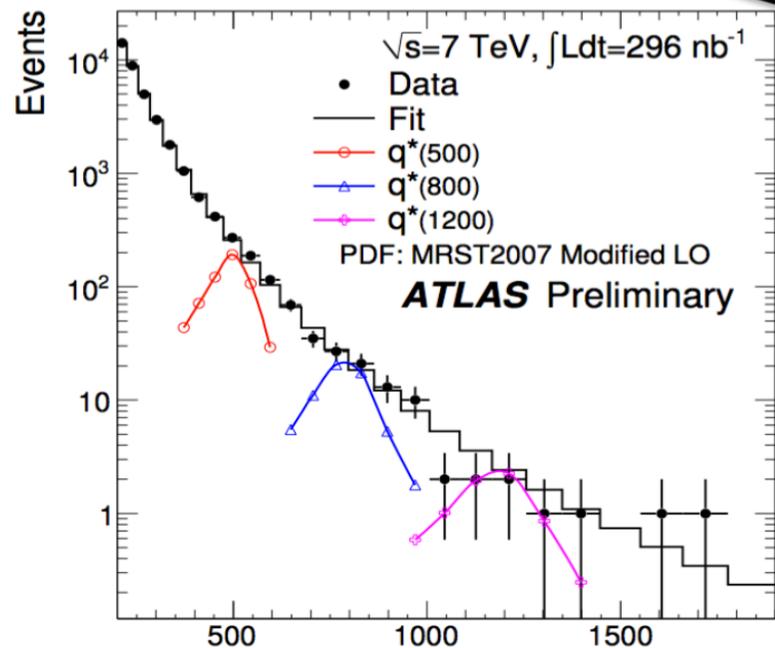
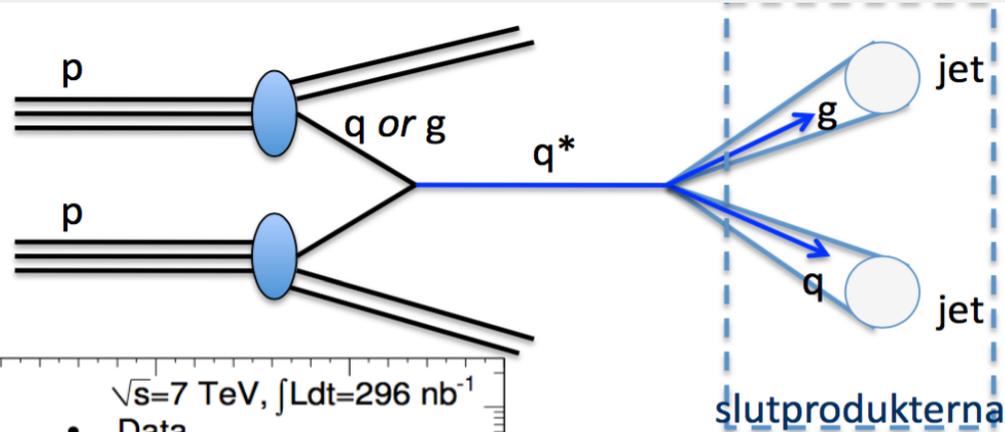
13 TeV



Higher beam energy \rightarrow sensitivity to higher masses

Quark compositeness

- Quark compositeness can be searched for by looking for deviation(s) in the dijet mass spectrum



Invariant mass of the 2 4-vectors P_1, P_2

$$m^2_{p1,p2} = (E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2$$

Preliminarily excluded region with ATLAS
 $400 < m_{q^*} < 1290 \text{ GeV}$ ($\sim 14 \cdot 10^{-20} m$)

Extra dimensions

- ❑ Mass hierarchy problem: why is the electroweak scale so much smaller than the Plank scale
 - ❑ Idea: Plank scale only « appears » much larger than EW scale in 4D while in >4 dimensions weak scale = « natural » scale
 - ❑ Initial ideas: Nordström (1914), Kaluza and Klein (1916-1926) \Rightarrow unification of general relativity and U(1) requires 5 dimensions
 - ❑ Realistic superstring theories: only consistent in 10D, extradimension have size \sim Planck length
 - ❑ Since 1998: possibility of large extra-dimension, developpment of popular models inspired from string theory

\rightarrow Gravity appears much weaker than the other interactions because it propagates in $N > 3$ spatial dimensions

$$V(r) \sim \frac{1}{r^{N-2}} \quad \text{at small distances } r < R$$

Extra dimensions

- Plank mass = mass (energy) scale at which quantum effect on gravity cannot be neglected

$$m_P = \sqrt{\frac{\hbar c}{G}}$$

h: quantum mechanics
c: relativity
G: gravity

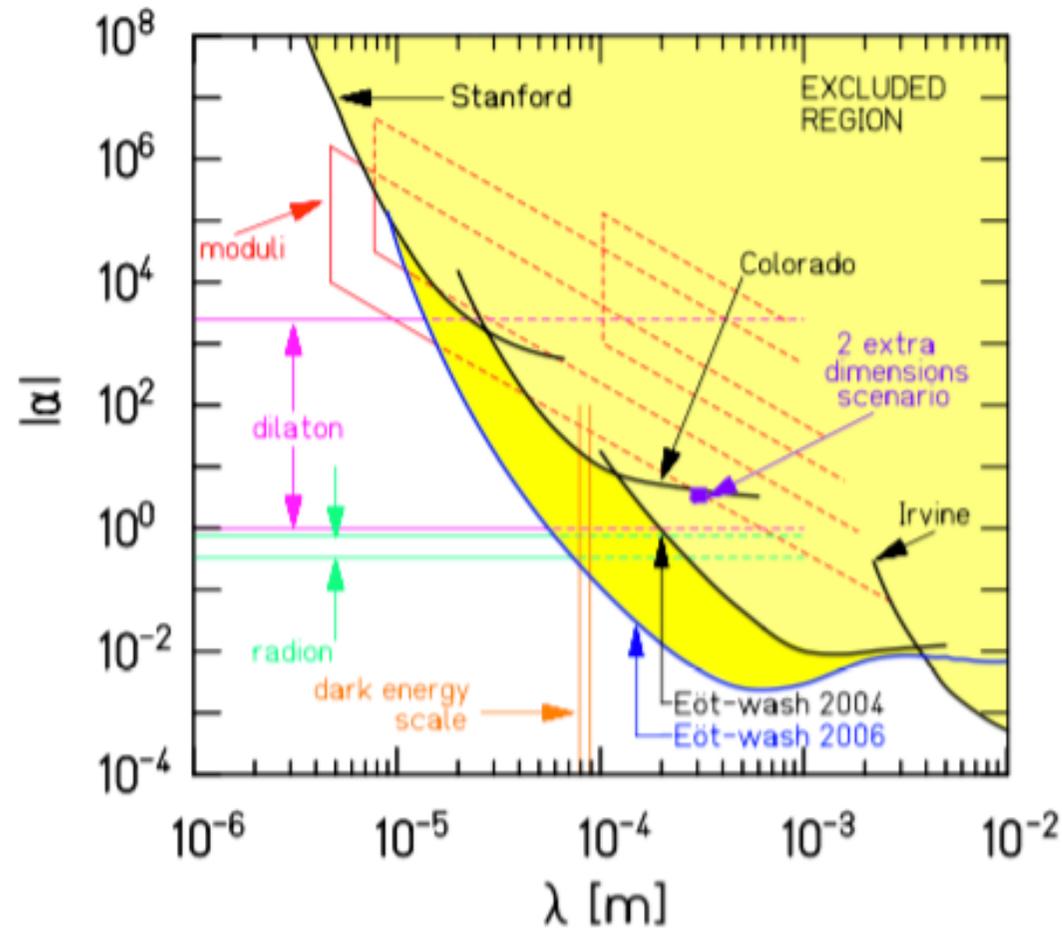
- Plank mass in 4+n dimensions (n extra spatial dimensions)

$$M_D^{2+n}[(4+n)D] \sim \frac{M_{Pl}^2[4D]}{(2\pi L)^n}$$

- Assume Plank scale in 4+n dimension = 1 TeV
 - n=1 (5D): $L \sim 2.3 \cdot 10^{28} / \text{GeV}^{-1} = 10^{14} \text{m} \Rightarrow$ excluded
 - n=2 (6D): $L \sim 3.1 \cdot 10^{11} \text{GeV}^{-1} = 1.5 \text{mm} \Rightarrow$ getting interesting!
- Experimentally: gravity on short distance scales (sub-mm) not well tested up to recent years

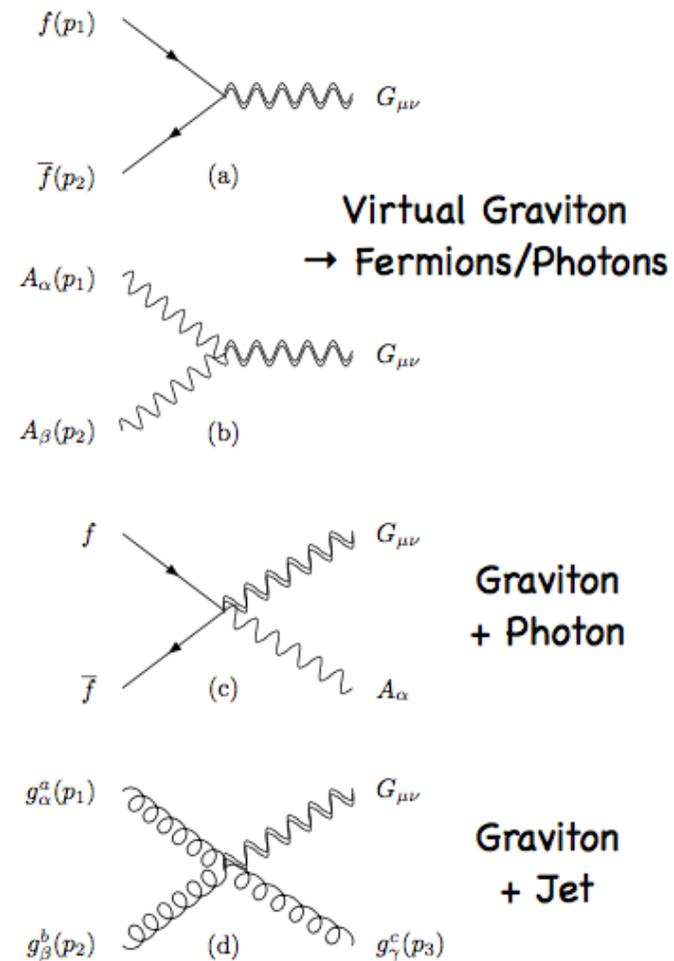
Limits on extra-dimension radius

$$V(r) = -\frac{G m_1 m_2}{r} [1 + \alpha \exp(-r/\lambda)]$$



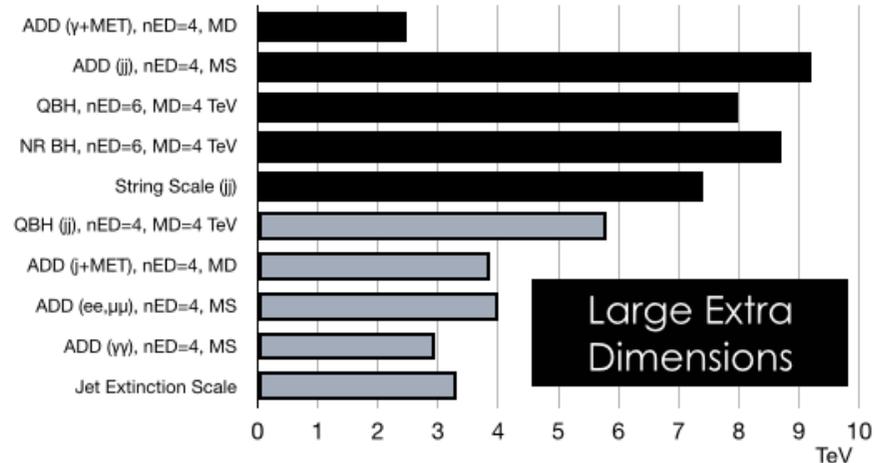
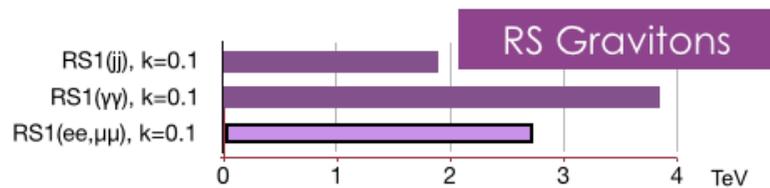
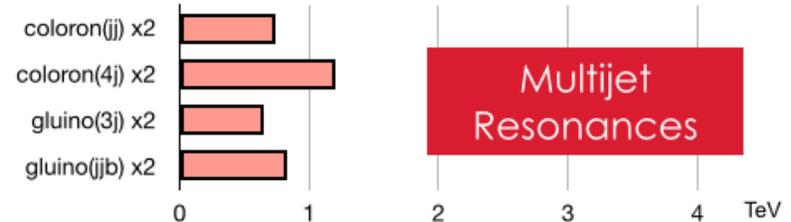
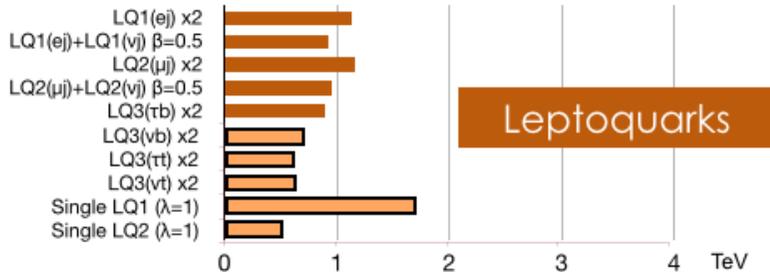
Extra-dimension phenomenology

- KK states are observable consequences in 4D of the presence of compactified extra-dimensions
- Scalar fields with mass related to the size of the extra-dimensions, as visible consequence in 4D of the momentum components in the extra-dimensions
- ADD phenomenology but also many other models (WED, UED, ..)

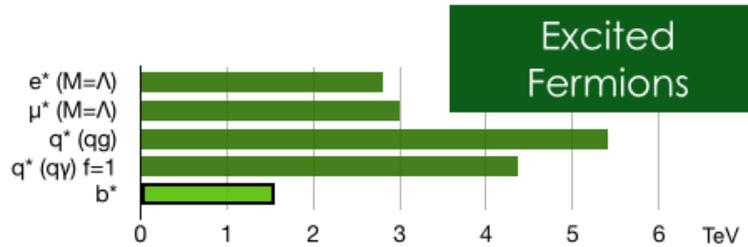
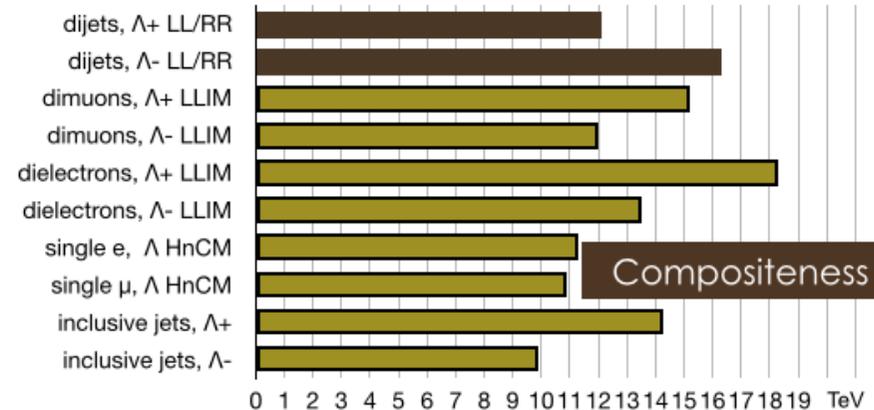
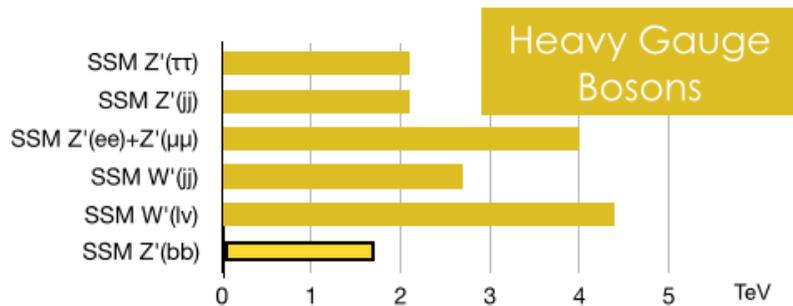


CMS BSM searches

13 TeV 8 TeV



CMS Preliminary



Beyond Standard Model summary

- ❑ There are **strong theoretical reasons** to believe that SM is incomplete
 - ❑ The relationship between the different interactions (electroweak, strong and gravity)
 - ❑ The nature of dark matter and dark energy
 - ❑ The matter-antimatter asymmetry of the universe
 - ❑ The existence of three families of quarks and leptons
 - ❑ The conservation of lepton and baryon numbers
 - ❑ Neutrino masses and mixing
 - ❑ The pattern of weak quarks couplings (CKM matrix)
 - ❑ The hierarchy of masses for quarks and leptons
- ❑ On the experimental side **we know we need dark matter, neutrino masses, and the new scalar sector is still to be studied**