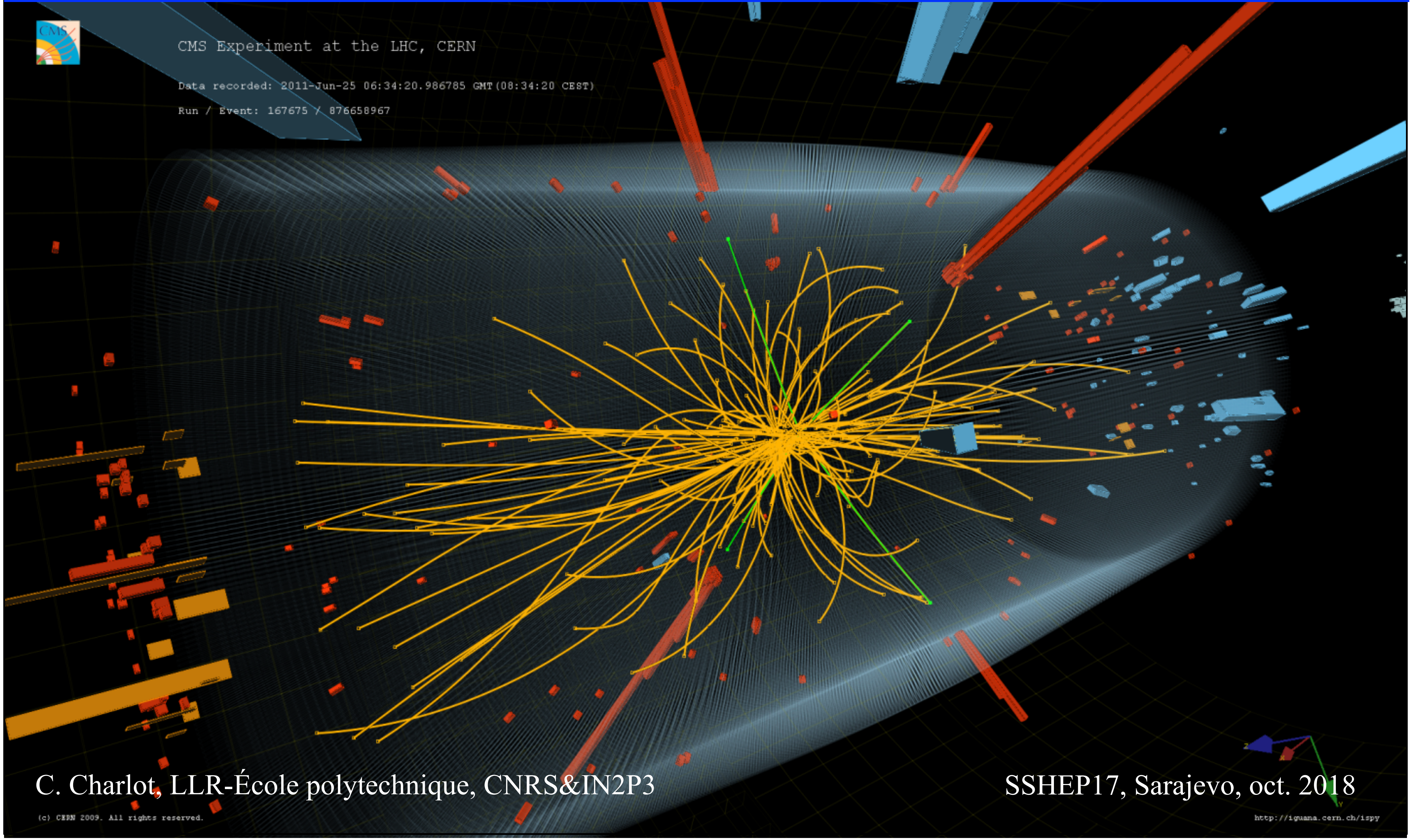
LHC Physics



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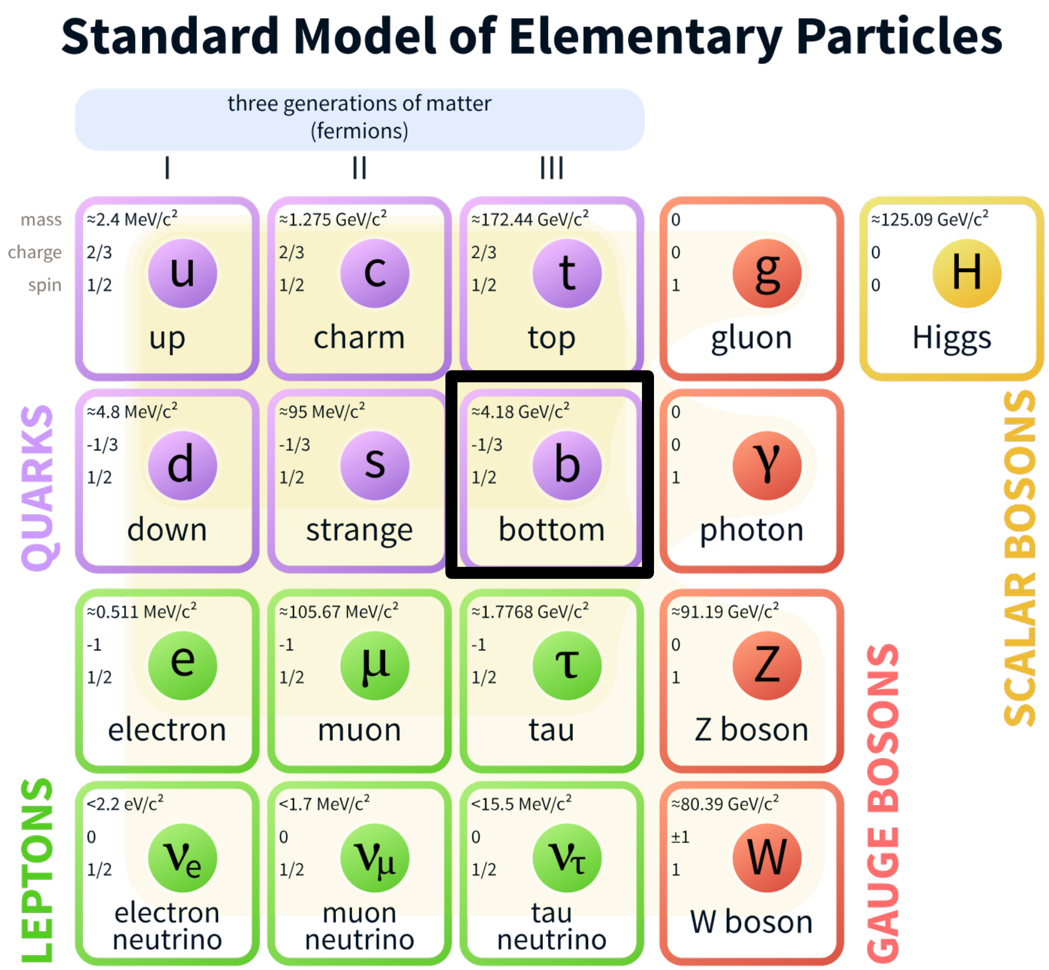
- **Part 4: B Physics**
- **Part 5: Beyond Standard Model Physics**

Part 4: B physics

Why B physics?

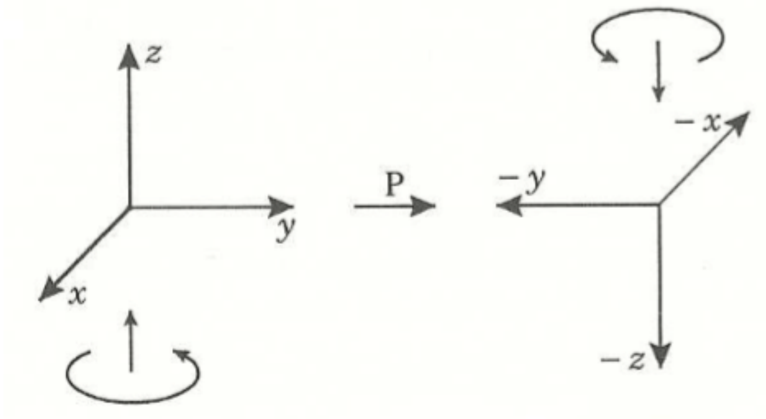
- ❑ Flavor and families physics

- ❑ <u>In this lecture:</u>
  - ❑ Flavor structure of SM: mixing, CKM matrix and the unitarity triangle
  - ❑ **CP violation**
  - ❑ Indirect search for **new physics**



Remind: parity transformation

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



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

Another transformation: charge conjugation

- Charge conjugation transformation C
- Change particle → anti-particle (choice is just convention)

$$e^- \rightarrow e^+$$

$$\gamma \rightarrow \gamma$$

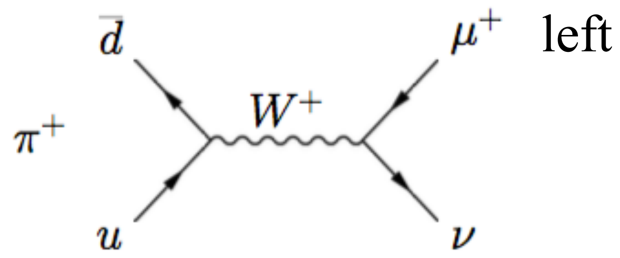
- π^0 decay
  - $\pi^0 \rightarrow \gamma\gamma$ decay is observed experimentally
  - γ has C-parity -1, therefore π^0 has C-parity $(-1)^2 = +1$
  - $\pi^0 \rightarrow 3\gamma$, that would violate C-conservation, is not observed

→ Charge conjugation is conserved in electromagnetic interactions. It is also the conserved in the strong interactions (QCD)

Parity and charge conjugation: CP

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

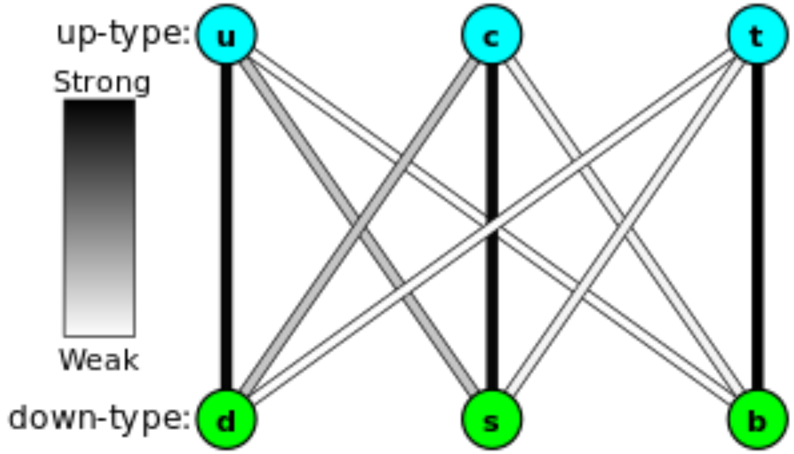
- In this interaction the μ^+ always has its spin anti // to the momentum (left handed)
- For the charge conjugate reaction: $\pi^- \rightarrow \mu^- +$ anti-ν, the μ^- always has its spin // to the momentum (right handed)



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

Quark mixing, Cabibo angle

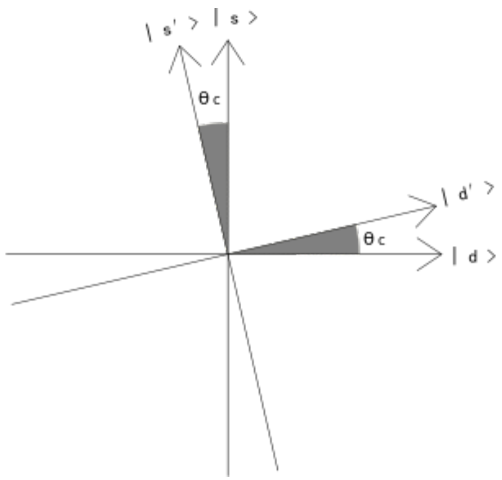
- Weak charged interaction allows for transitions between quark of different families
  - Not just u $\rightarrow$ d + W^+ (and similarly for the two other families)



- 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, Cabibbo angle

- Let’s assume 2 families, we can identify u → d weak coupling in the quark sector and to the e → ν_e in the lepton sector, provided that the transition u → d occurs towards a rotated state



Weak Int flavor state

Flavor mass eigenstates

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

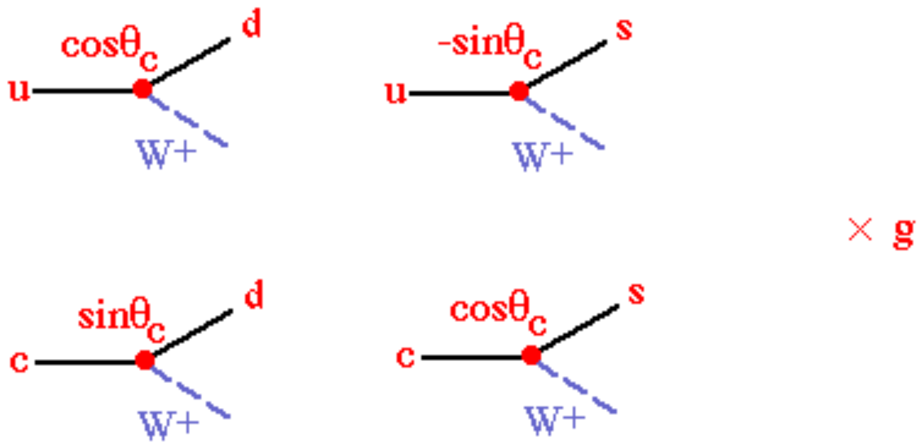
Unitarity: $|\alpha|^2 + |\beta|^2 = 1$ $\quad \alpha = \cos\theta_c; \quad \beta = \sin\theta_c$

θ_c="Cabibbo angle"

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

Quark mixing, Cabibbo angle

- Weak charged transitions between quarks will get $\cos\theta_C$ or $\sin\theta_C$ factor in front of the weak coupling constant



- 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 3 families => 3-dimensional rotation => 3 2D rotations/angles

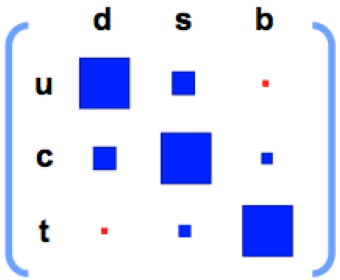
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$=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

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 ($V_{12}=V_{us}$, $V_{13}=V_{ub}$, 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_{CKM} in Nature is hierarchical: $\theta_{13} \ll \theta_{23} \ll \theta_{12} \ll 1$
- ❑ Wolfenstein parameterization: expansion in $\lambda = \sin\theta_C$, A, ρ, η ~ O(1)

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

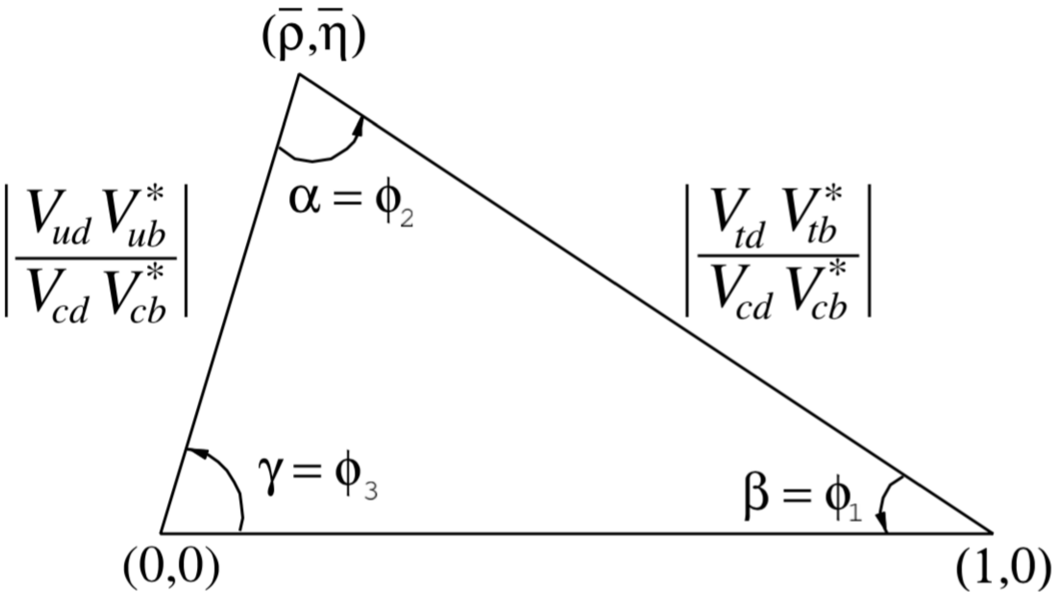
fits: $\lambda = 0.225, \quad A = 0.81, \quad \bar{\rho} = 0.14, \quad \bar{\eta} = 0.34$

- ❑ Beyond lowest order: $\bar{\rho} = \rho(1-\lambda^2/2)$ and $\bar{\eta} = \eta(1-\lambda^2/2)$

→ η different from 0 features CP violation

Unitarity triangle

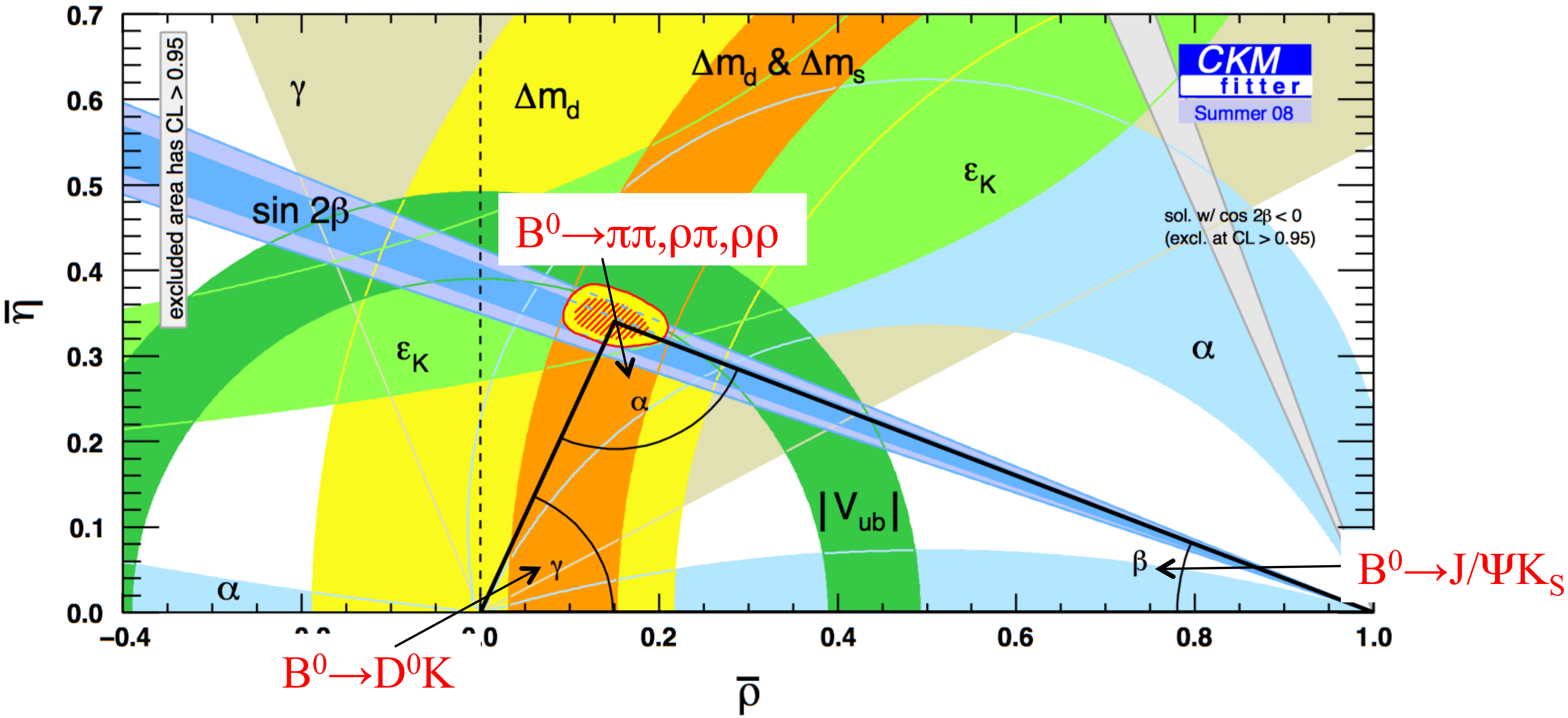
- CKM matrix being unitary: $\sum_j V_{ij}V_{kj}^* = \delta_{ik}$ $\sum_i V_{ij}V_{ik}^* = \delta_{jk}$
  - 6 vanishing contributions => 6 triangles
- Most relevant one: $V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$
- Normalized sides: $|V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}|$, 1, $|V_{td}V_{tb}^{*}/V_{td}V_{tb}^{*}|$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



If there is CP violation => the triangle is not flat

Unitarity triangle: status

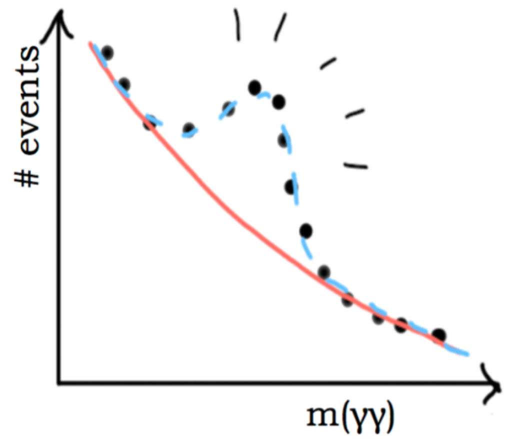
- Measurements constrain the triangle parameters in the complex $\bar{\rho}, \bar{\eta}$ plane

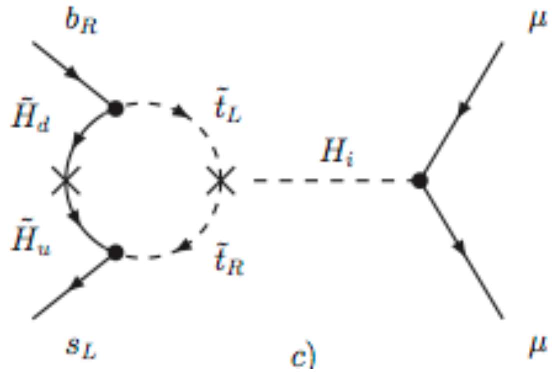


→ Consistent evidence for CP violation from many different measurements

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

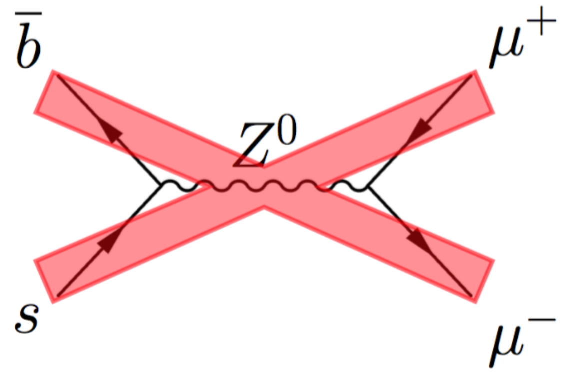


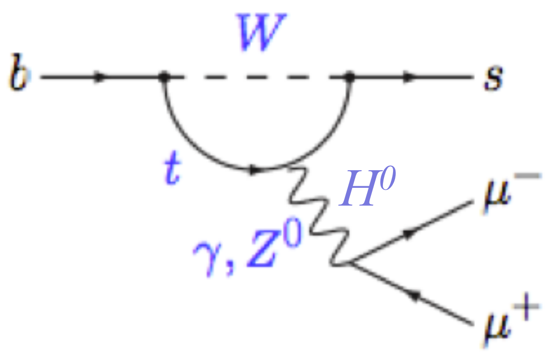


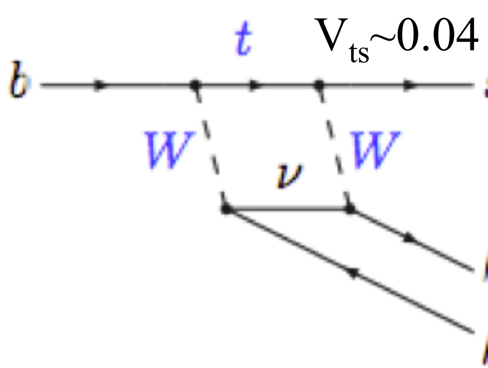
$B_s \to \mu\mu$

- Very interesting potential to constrain physics beyond standard model
- SM prediction: $(3.35 \pm 0.32)\ 10^{-9}$ => **extremely rare** process

  => 3 decays in $\mu\mu$ every billions of B_s decays
- Dominating contribution in the SM: **Higgs** (γ/Z) (pinguin) diagram (box diagram suppressed + CKM suppressed +helicity suppressed)
- Therefore extremely **sensitive to extended scalar sector** (SUSY)

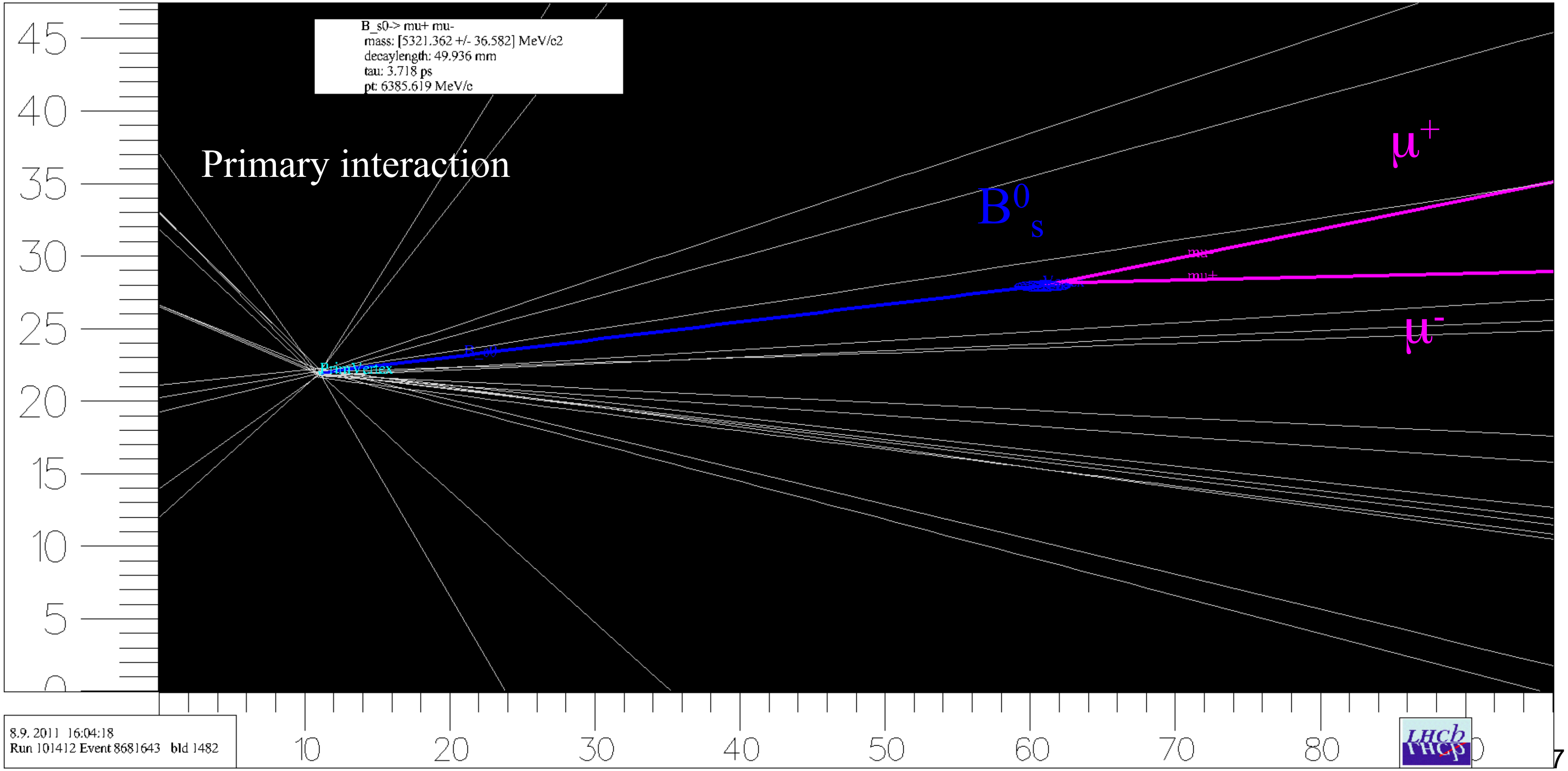






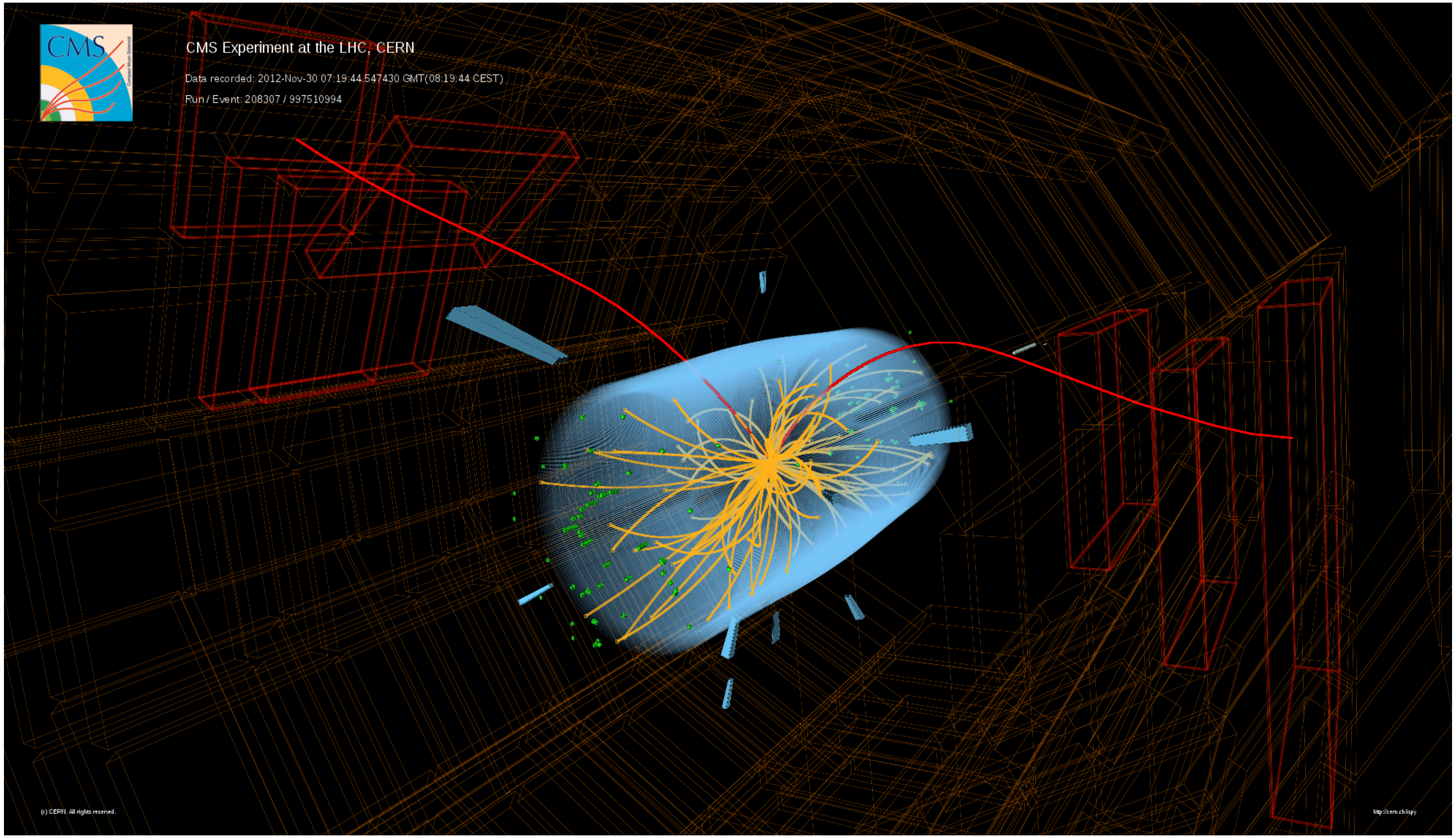
$B_s \rightarrow \mu\mu$ at LHCb

- LHCb is the dedicated experiment at LHC to study B mesons (contain b quark)



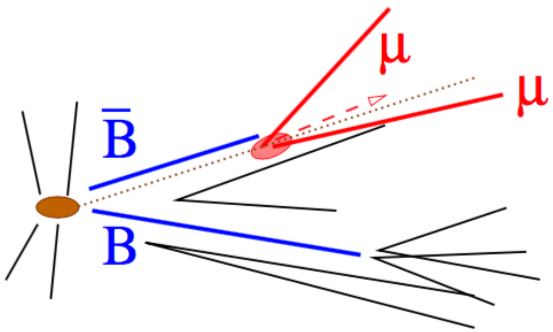
$B_s \rightarrow \mu\mu$ at CMS

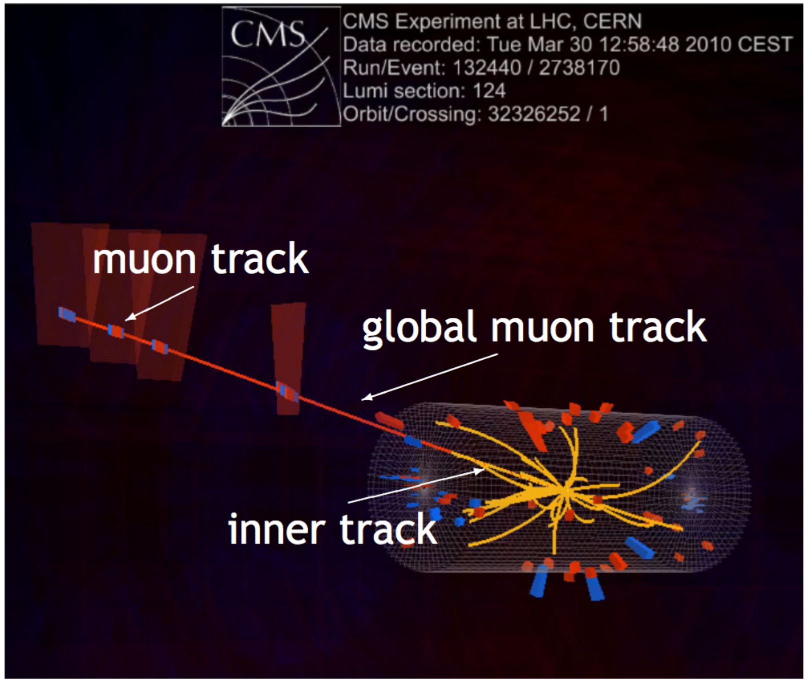
- General-purpose experiments as CMS can also be used to study B mesons



$B_s \to \mu\mu$ at CMS

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

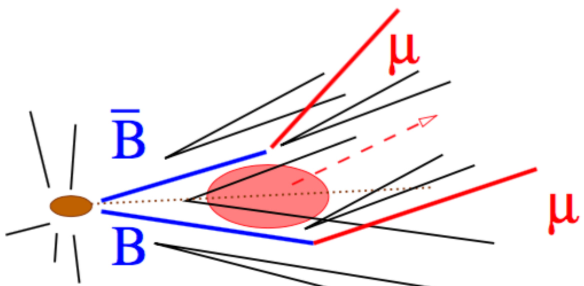


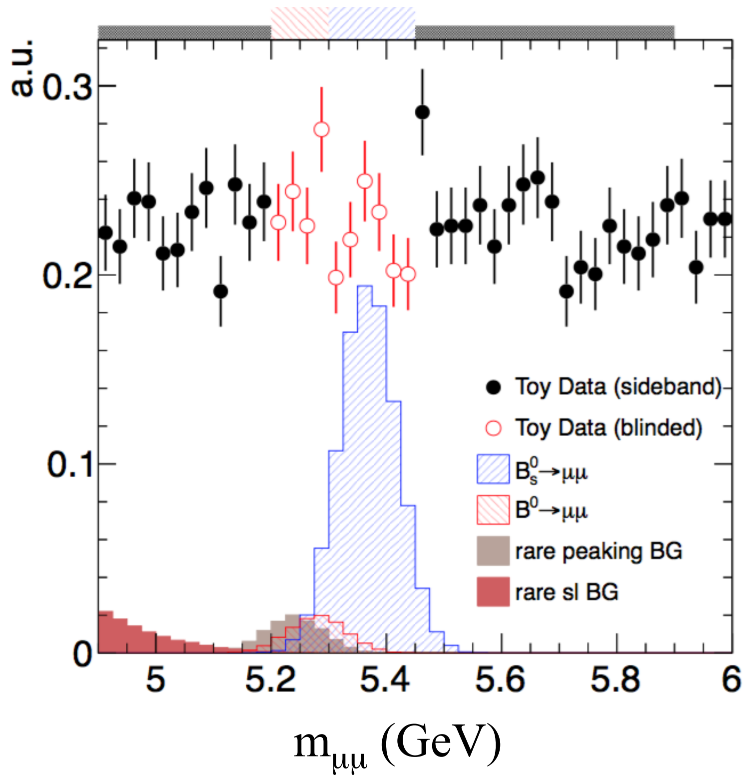


→ Needs excellent muon identification capability

$B_s \rightarrow \mu\mu$ 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: $B^0_s \rightarrow K^- \mu^+ \nu$, $B^0_s \rightarrow K^+ K^-$ (peaking)

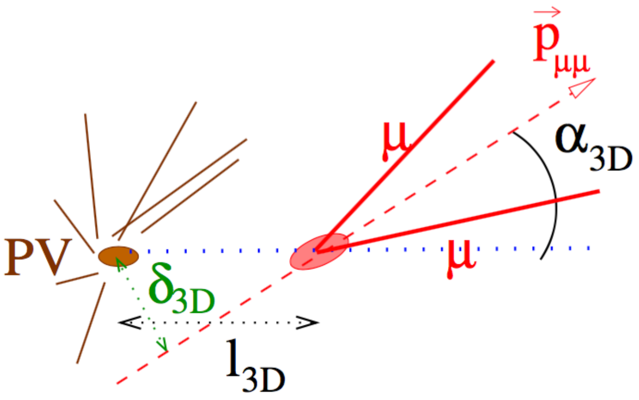


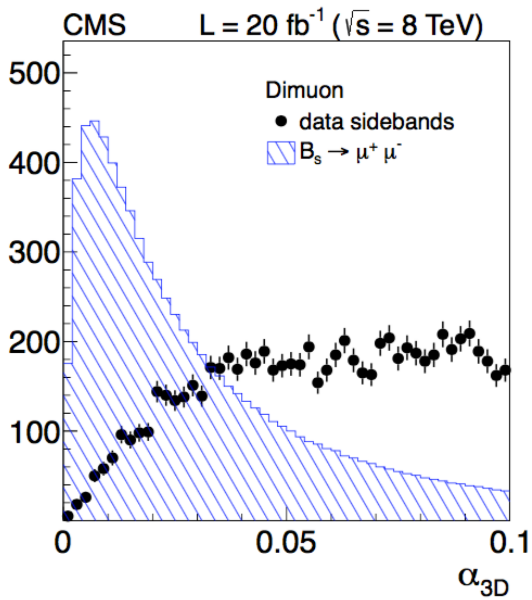


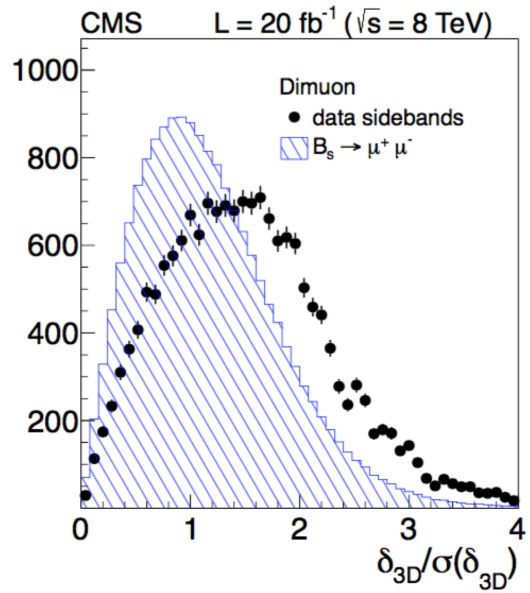
$B_s \rightarrow \mu\mu$ at CMS

- 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
    - $B^0_s \rightarrow J/\Psi \phi$: B^0_s signal simulation (p_T and isolation)

- Discriminating variables

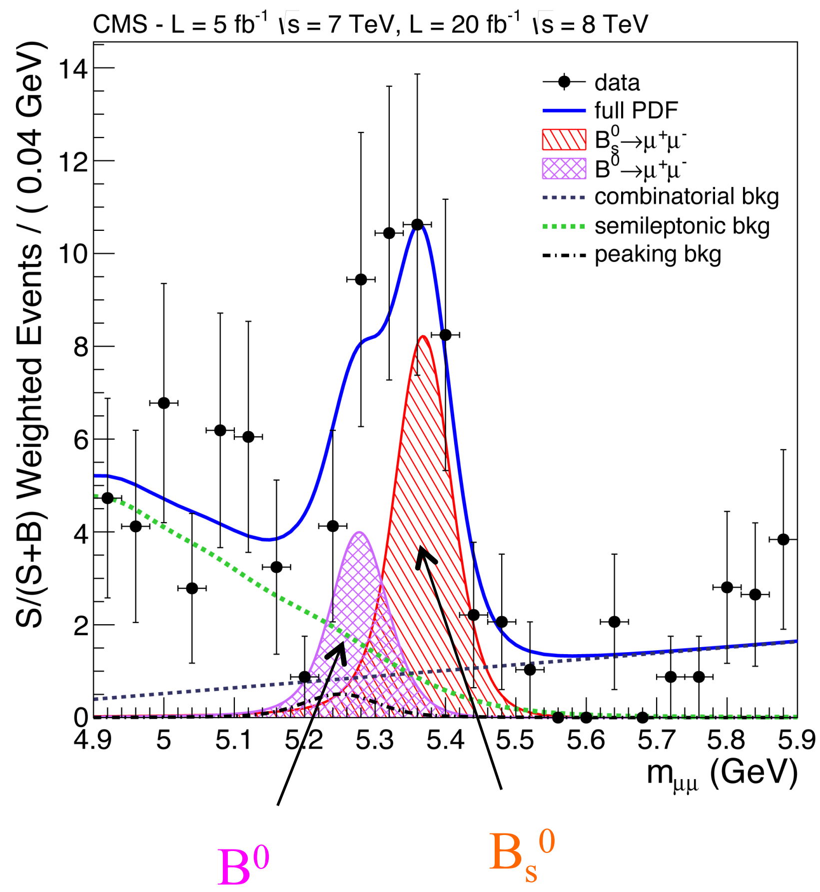




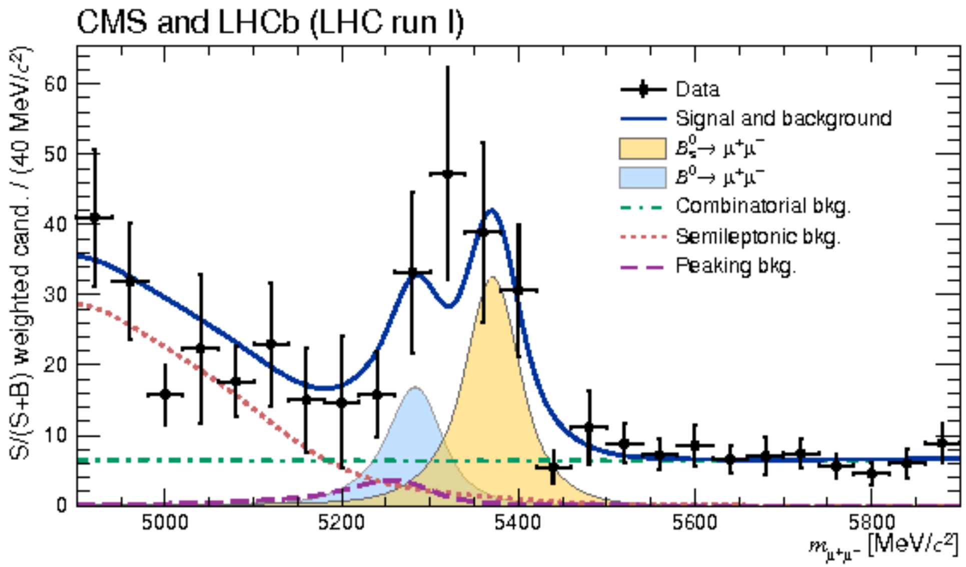


$B_s \to \mu\mu$ at CMS

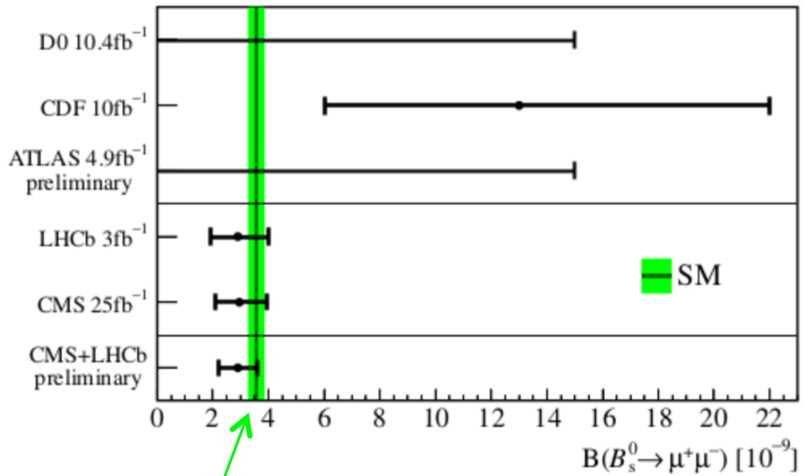
- Fit B_s^0 and B^0 simultaneously
- Peaking background
  - Normalized to measured B^+ yield
  - Yield cross-checked on independent dataset
- Semi-leptonic background
  - Fixed shape
  - Free normalization within uncertainties
- Combinatorial background
  - No constraint on slope
  - Varied functional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



$B_s \to \mu\mu$ CMS+LHCb



Combined CMS + LHCb results



Measured fraction of decay to μμ

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

Theory prediction

→ Agrees with SM prediction

→ Stringent constraints on BSM physics

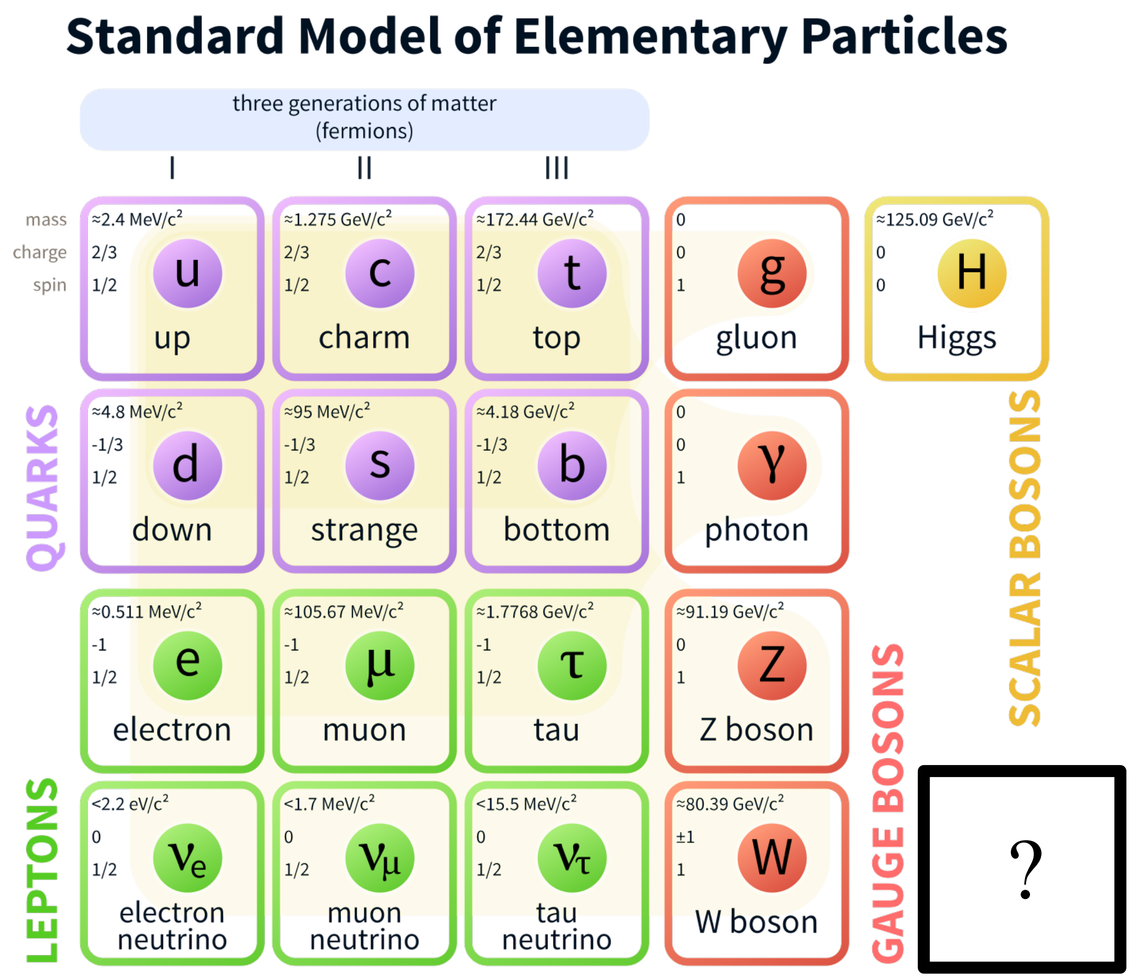
B Physics summary

- 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

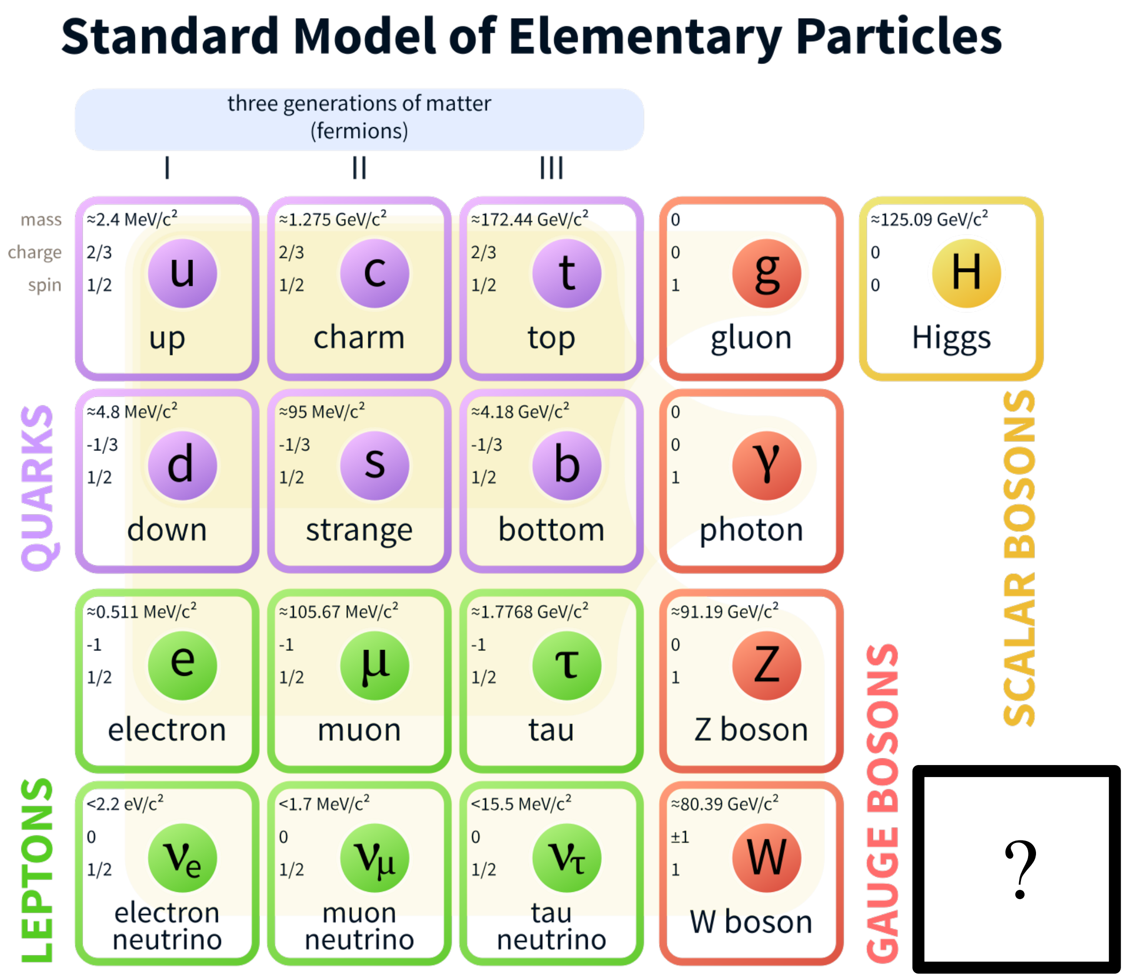
Beyond standard model

- ❑ 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 beleive that the SM is not a complete theory



Why BSM physics?

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

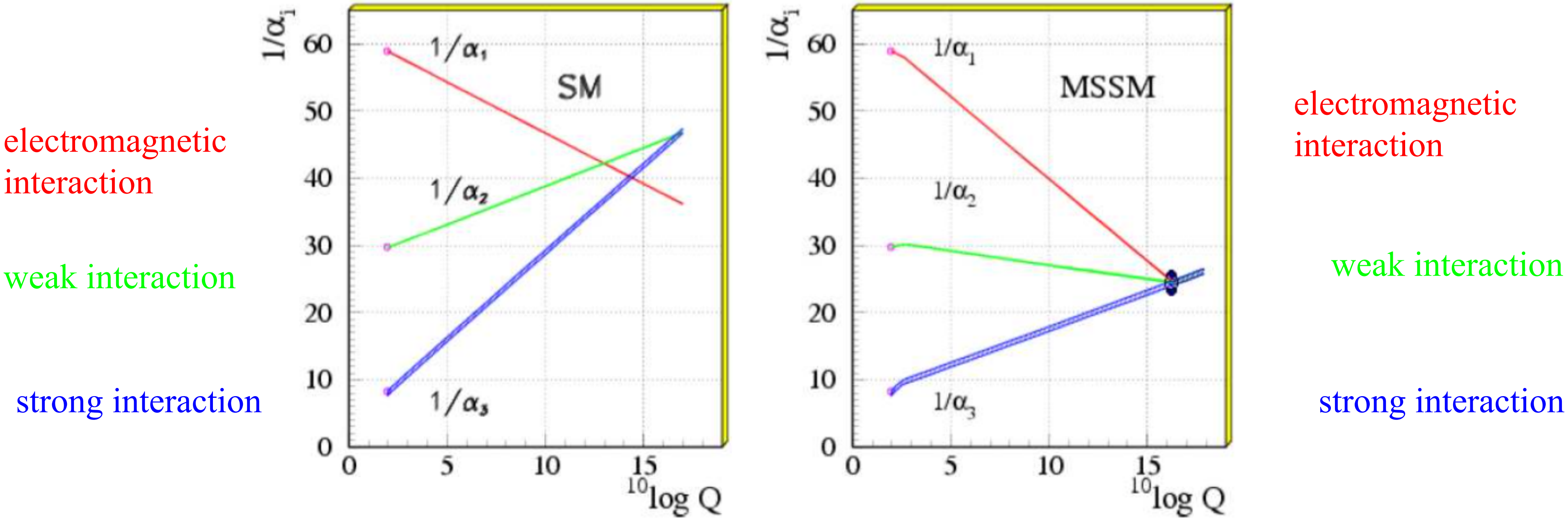


Why is the standard model incomplete?

- The standard model does not explain the following:
  - The relationship between the different interactions (electroweak, strong and gravity)
  - The hierarchy of masses for quarks and leptons
  - 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)

Grand unification

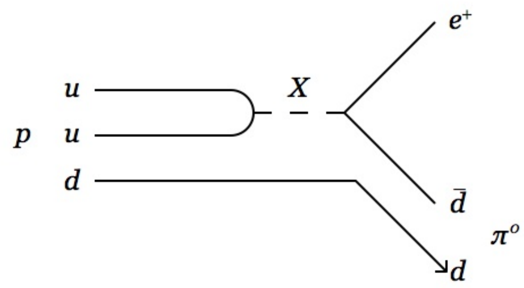
- The strong, electromagnetic and weak couplings (α_s, e and g) depend on the energy scale, can they be unified at an energy scale Q~10^{15} GeV?



- We also woud like to include gravity at the Plank scale Q ~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, 1980s)
- Introduces 12 new gauge bosons at $m_X \sim 10^{15}$ GeV
- These are known as leptoquarks, they induce 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 ~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 an the γ are orthogonal states

→ The sum of loop diagrams over all fermion pairs must be zero

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

- 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 $\sin^2\theta_W$ close to the measured value

Proton decay

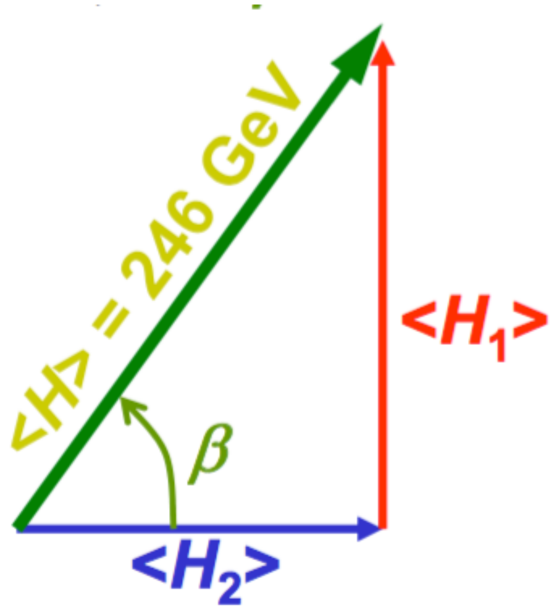
- The leptoquarks couplings in GUT do not conserve baryon and lepton numbers, only the combination B-L

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

- This is >> age of the universe, not a problem for our existence
- Large underground experiments (Kamiokande, …) have searched for proton decays, none seen => $\tau_p > 2.10^{32}$ years
- Minimal SU(5) GUT ruled out by the absence of proton decay signal
- Non-minimal SO(10) GUT not ruled out
  - Predicts different decay modes, eg $p \to K^+ + \text{anti-}\nu$

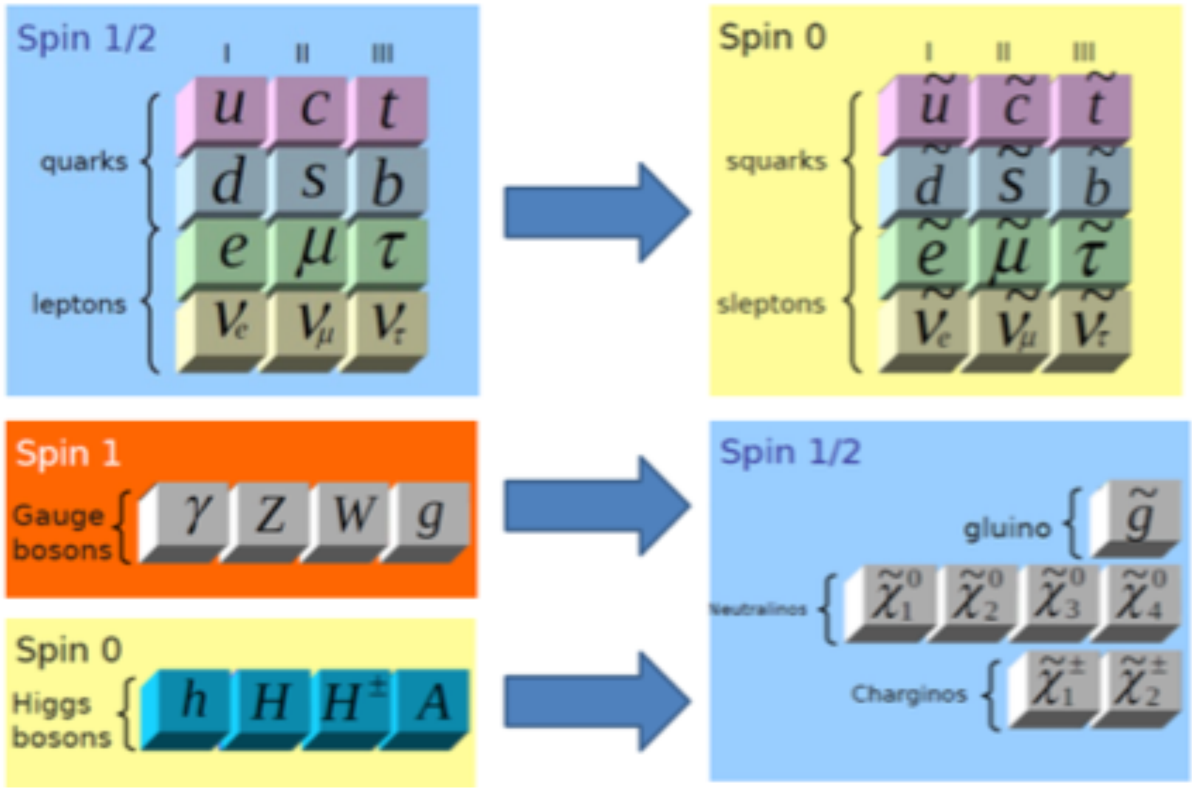
Multiple Higgs doublets

- 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, 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 $v_1^2 + v_2^2 = v_2^2$ 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

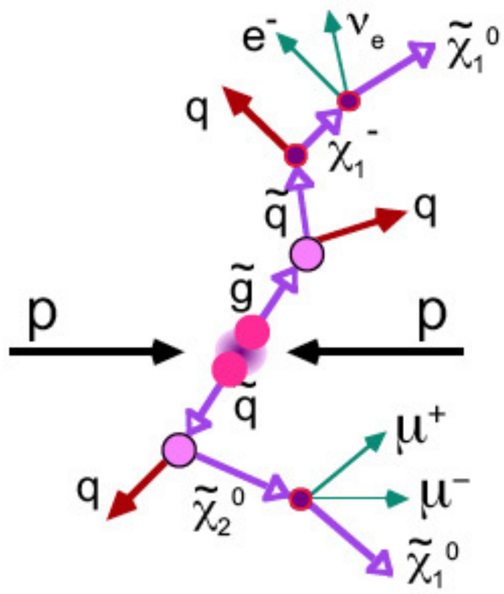
- Gives an explanation to the mass hierarchy problem (GUT>> EWK scale)
- Higgs and fermion loop contributions cancel precisely with SUSY partners at all mass scales between 10^2 and 10^{14} GeV
- In R-parity conserved models, the lightest supersymmetric particle (LSP) is stable and a candidate for dark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

BUT

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

Direct searches at LHC

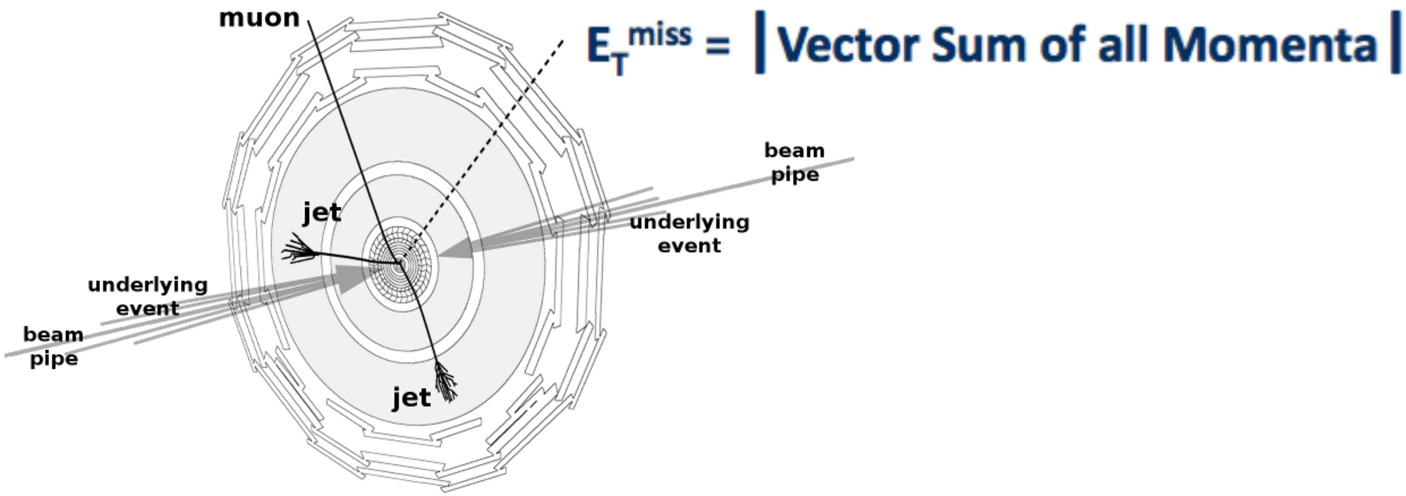
- Squark and gluinos copiously produced at LHC (if SUSY)
- Desintegration of SUSY partners into standard model particles gives rise to **cascade decays**
- In the MSSM the neutralino is the **lightest supersymetric particle** and is **stable**



- High E_T jets: from squarks and guinos
- Multiple leptons: from cascade decays of charginos/neutralinos
- Mutliple τ-jet or b-jet: abundant production from 3rd generation sparticles
- E_T^{miss}: from LSP escaping detection

Missing transverse energy

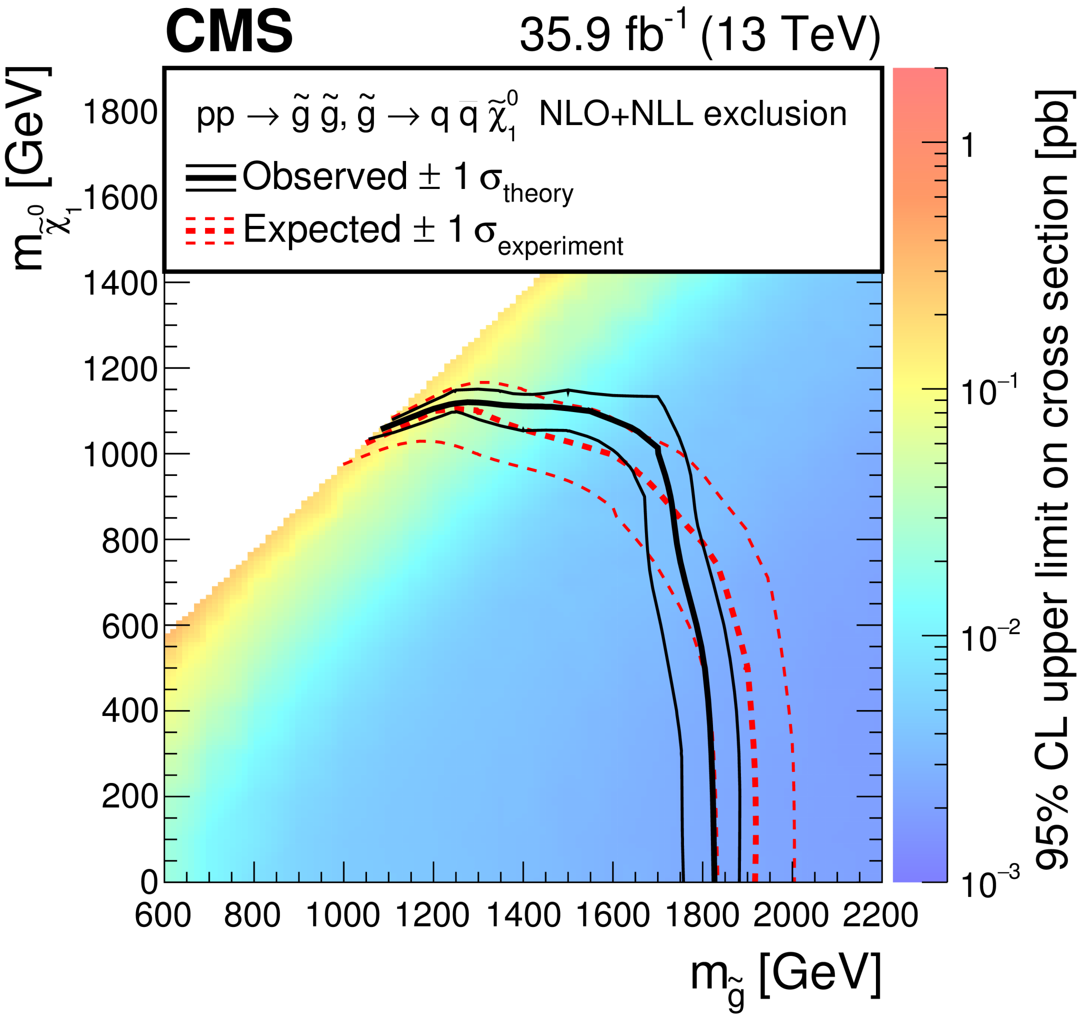
- Undetected particle is a generic feature of SUSY (LSP) and dark matter searches
- We expect also undetected energy in SM processes due to:
  - Undetectable neutrinos
  - Mismeasurement of visible objects
  - Other instrumental sources (such as cosmic muons overlayed on collision data)
- Due to the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



Gluino searches

- No observation of gluino production up to now
- Limits are set on gluino mass

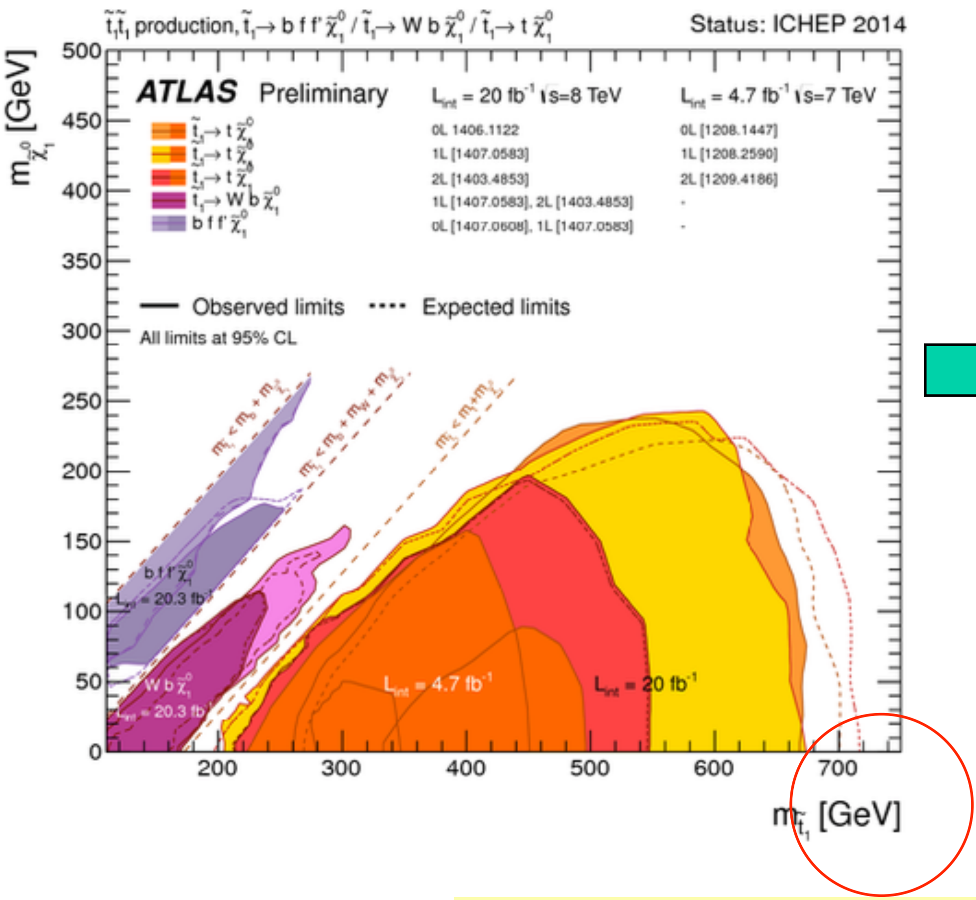
m_g>1800 GeV or $m_{\chi 0}$>1100 GeV

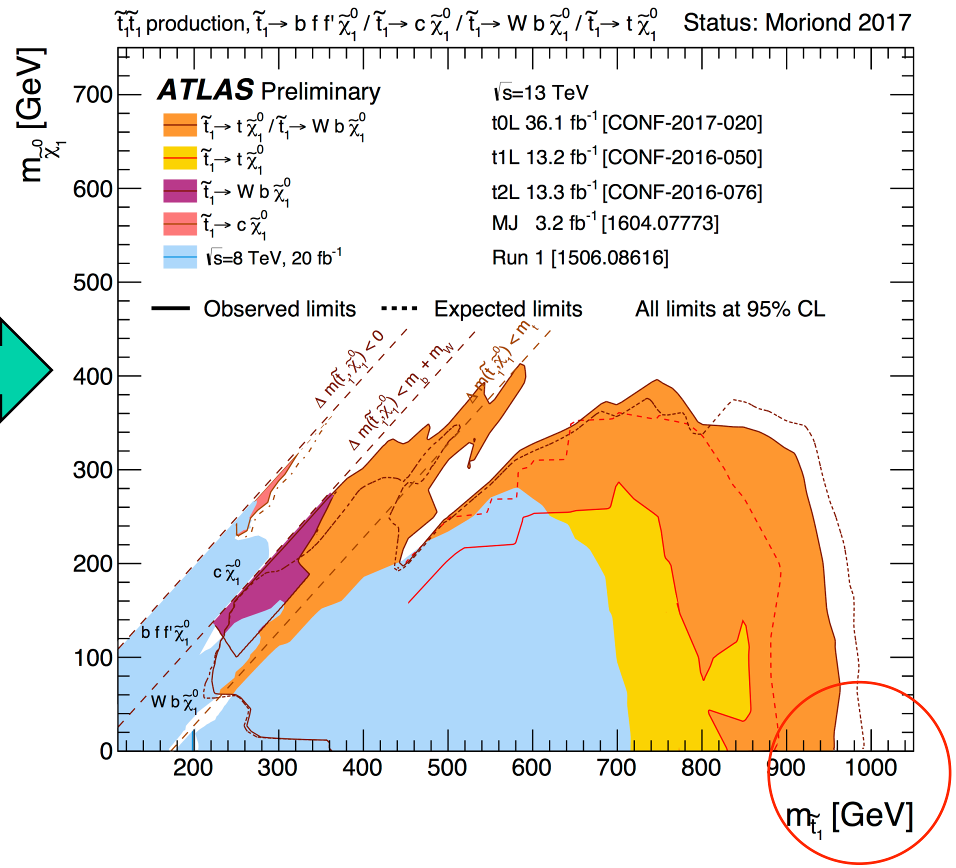


Stop searches

7 TeV

13 TeV

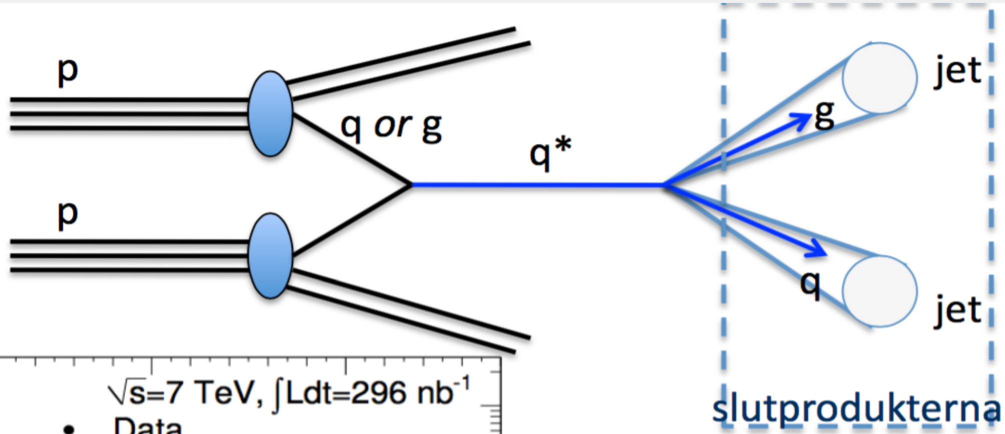


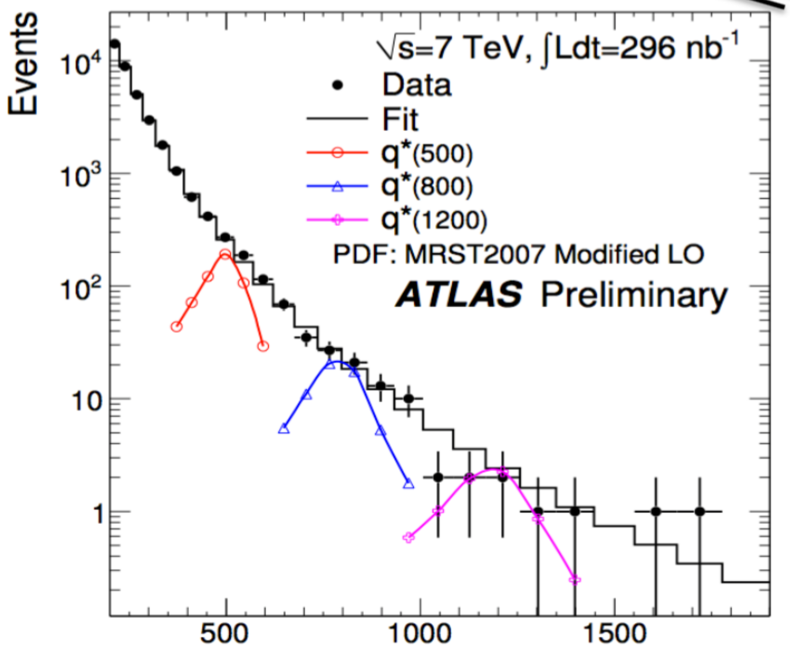


Higher beam energy → sensitivity to higher masses

Quark compositeness

- Quark compositness can be searched for by looking for resonance(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
$400 < m_{q*} < 1290$ GeV (~14 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) => unification of general relativity and U(1) requires 5 dimensions
  - Realistic superstring theories: only consistent in 10D, extradimension have size ~ Planck length
  - Since 1998: possibility of large extra-dimension, developpment of popular models inspired from string theory

→ 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 gravity cannot be neglected

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

h: quantum nechanics
c: relativity
G: gravity

$\sim 10^{19}$ GeV

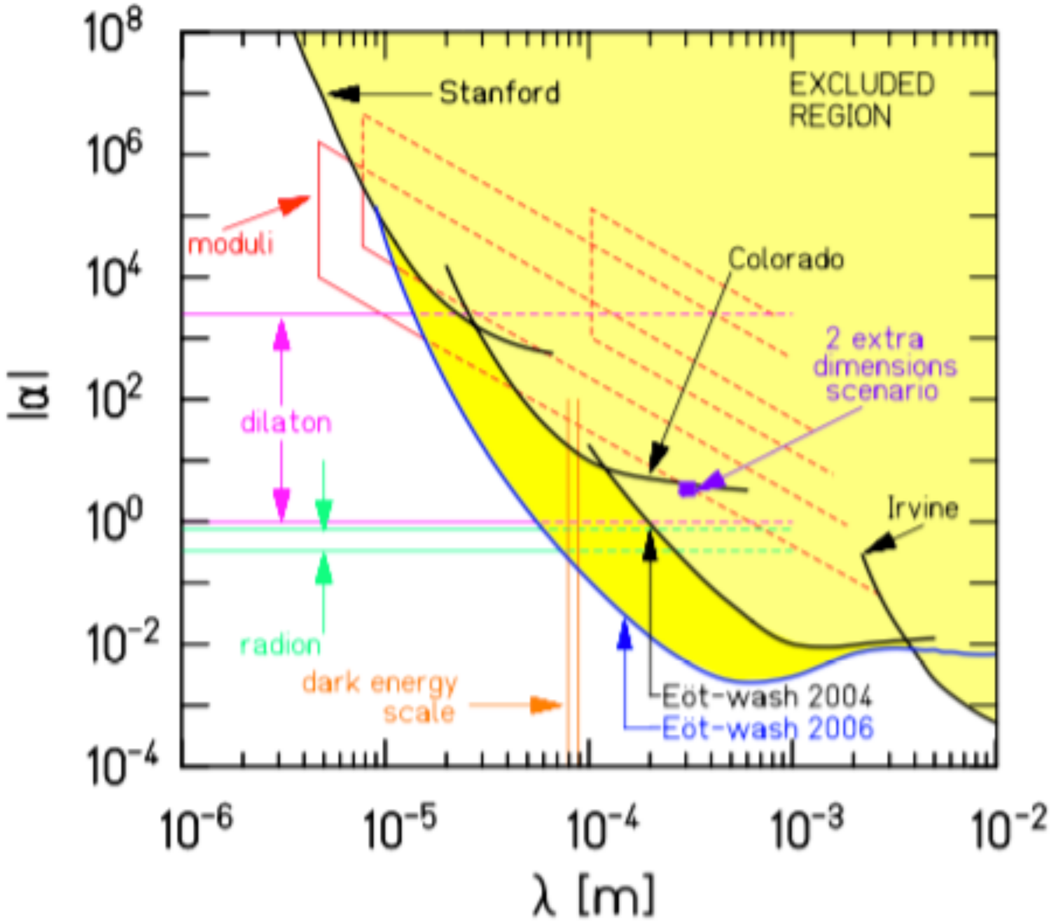
- Plank mass in 4+n dimensions (n extra spatial dimensions)

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

- Increasing the number of extra dimensions and/or increasing their lengths decreases the Planck mass in 4+n dimensions
- Assume Plank scale in 4+n dimension = 1 TeV
  - n=1 (5D): L~2.3 10^{28} / GeV^{-1} = 10^{14}m => excluded
  - n=2 (6D): L~3.1 10^{11} GeV^{-1} = 1.5mm => interesting, gravity not tested on short distance scales (sub-mm) up to recent years

Limits on extra-dimension radius from gravity measurements

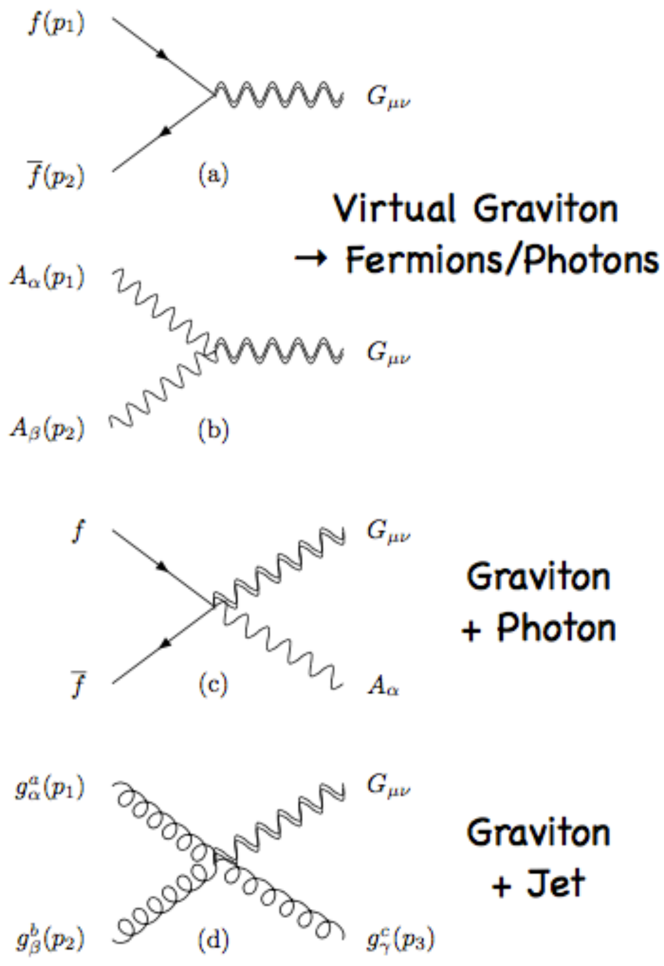
$$V(r) = -\frac{G m_1 m_2}{r}[1 + \alpha \exp(-r/\lambda)]$$



[D. Kapner et al., Phys. Rev. Lett. 98 (2007) 021101]

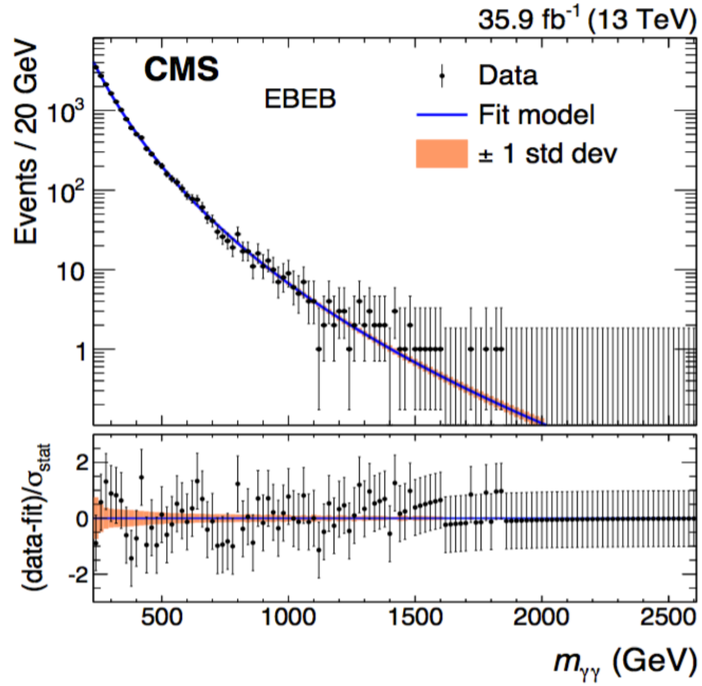
Extra-dimension phenomenology

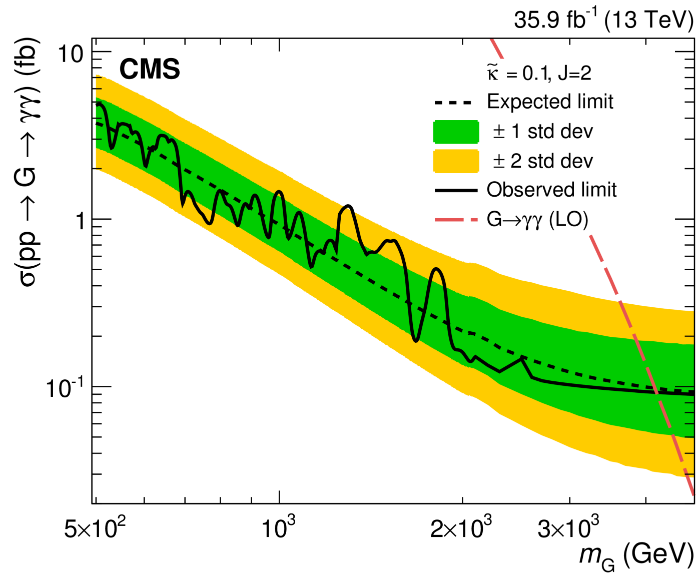
- KK states are observable consequences in 4D of the presence of compactified extra-dimensions
- Scalar fields with mass related to the size of the extra-dimensions, as visible consequence in 4D of the momentum components in the extra-dimensions
- ADD phenomenology but also many other models (WED, UED,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



Example of search @ LHC

- Search for Randal-Sundrum graviton decaying into a photon pair
- No resonance is observed
- Results interpreted as limits on the production cross section for the graviton as a function of the graviton mass



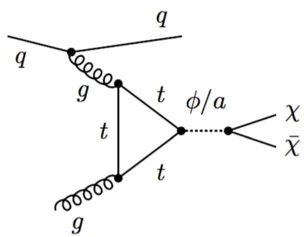


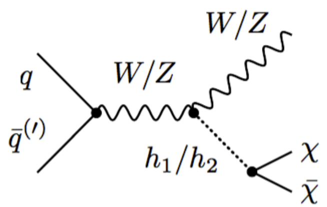
→ Graviton mass below ~4 TeV excluded (for this model and with the specified model parameters ..)

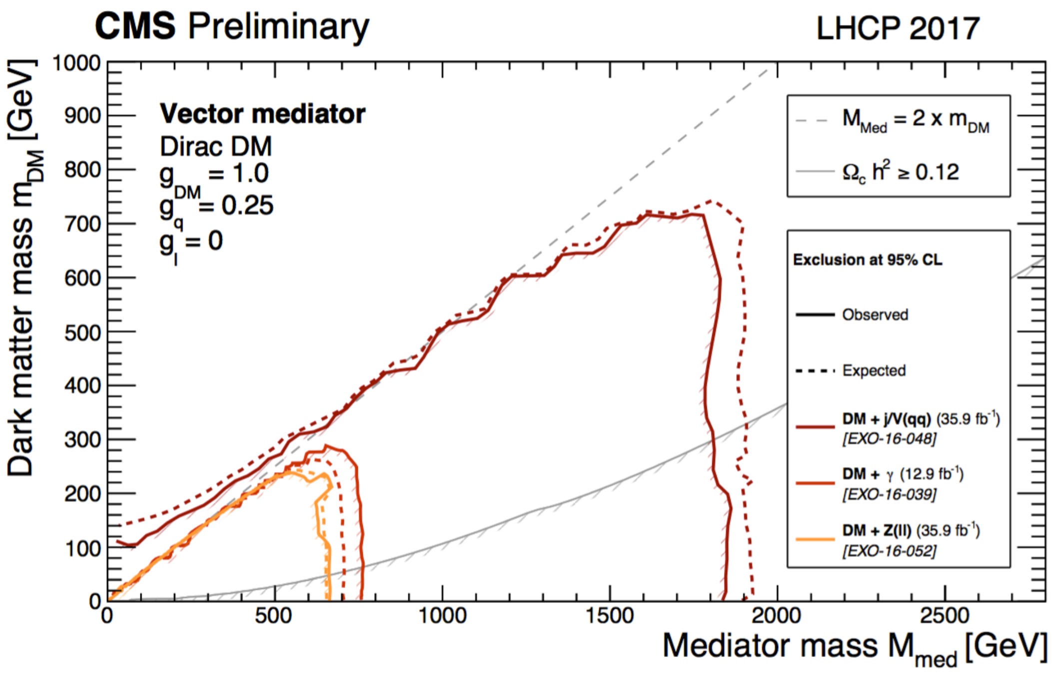
DM searches

- Generic searches for dark matter based on simplified models assuming spin-0 and spin-1 mediators, also Higgs portal scenarios

- Final states: j + E_T^{miss}, γ + E_T^{miss}, Z + E_T^{miss}
- Example of results for vector mediator (LHCP 2017)

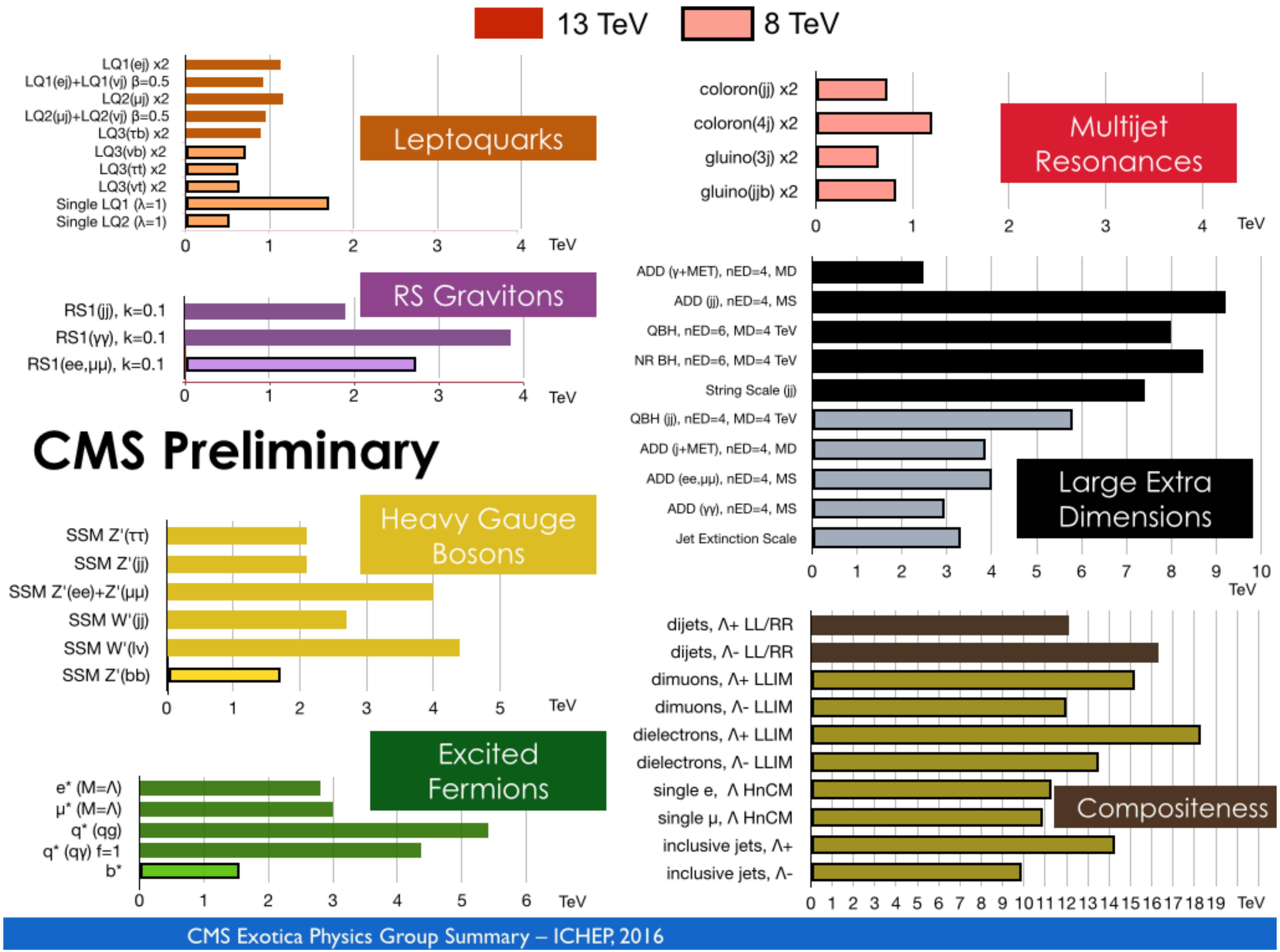






→ DM mass up to ~700 GeV excluded, depending on mediator mass (very sensitive to chosen model and parameters ..)

CMS BSM searches



Beyond Standard Model summary

- There are **many theoretical reasons** to beleive that SM is incomplete
  - The relationship between the different interactions (electroweak, strong and gravity)
  - The hierarchy of masses for quarks and leptons
  - The existence of three families of quarks and leptons
  - The conservation of lepton and baryon numbers
  - The pattern of weak quarks couplings (CKM matrix)
- On the experimental side **we know we need matter-antimatter asymmetry, dark matter, neutrino masses**
- The **new scalar sector may also be the door towards new physics**

B mesons & decays

- Weak interaction responsible for mesons decays, eg $\pi^+ \rightarrow \mu^+ \nu$
- The B^+ meson is similar to the $\pi^{+,}$ 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)
  - Prefered decay to second generation' quarks, eg charm
- The neutral B^0_s meson is similar to the B^+ except that the u quark is replaced by the second generation s quark (q=-1/3)