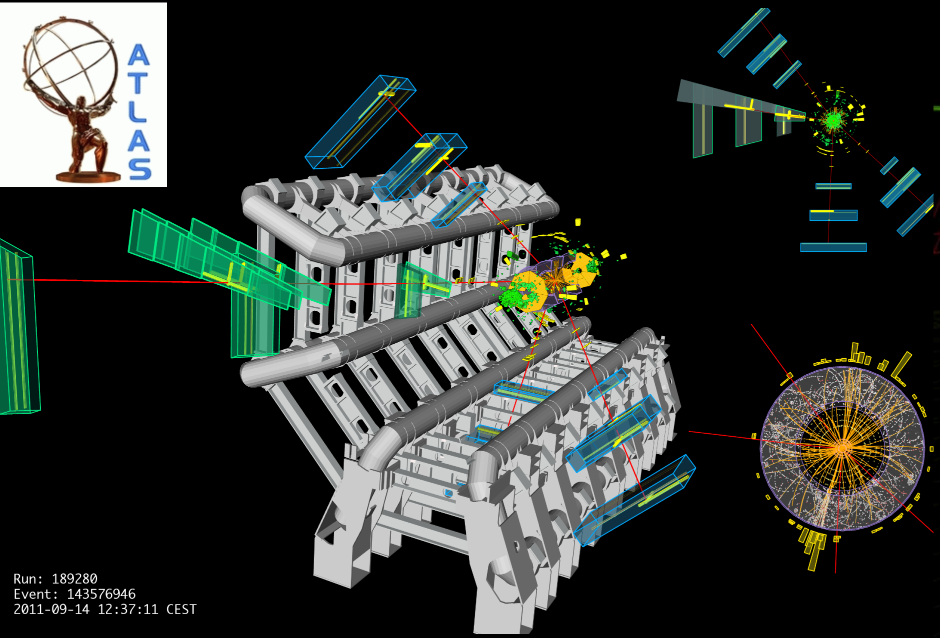
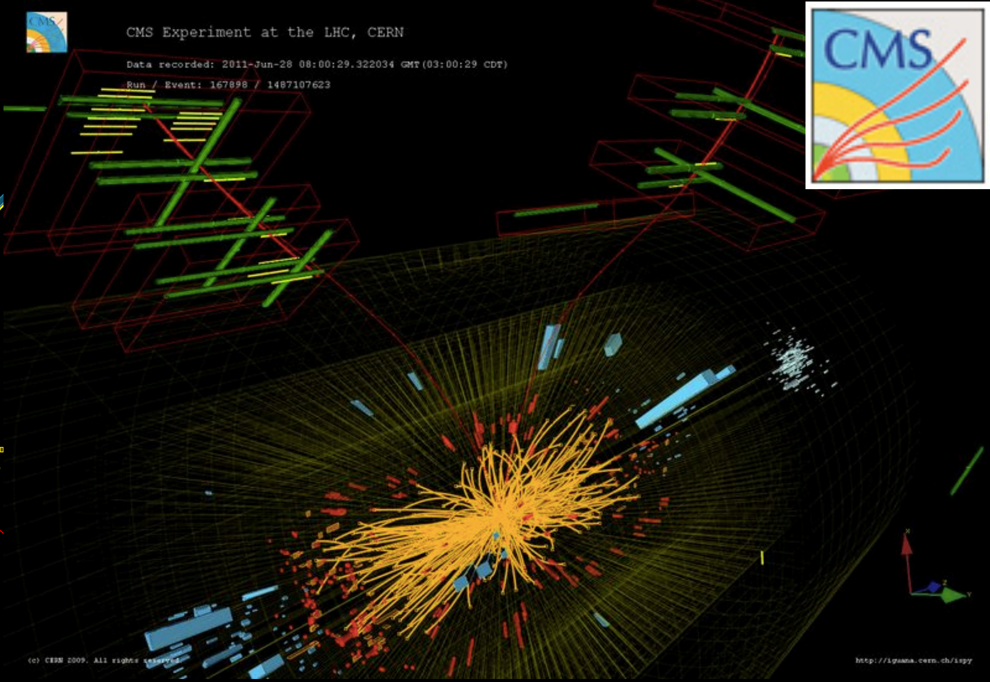
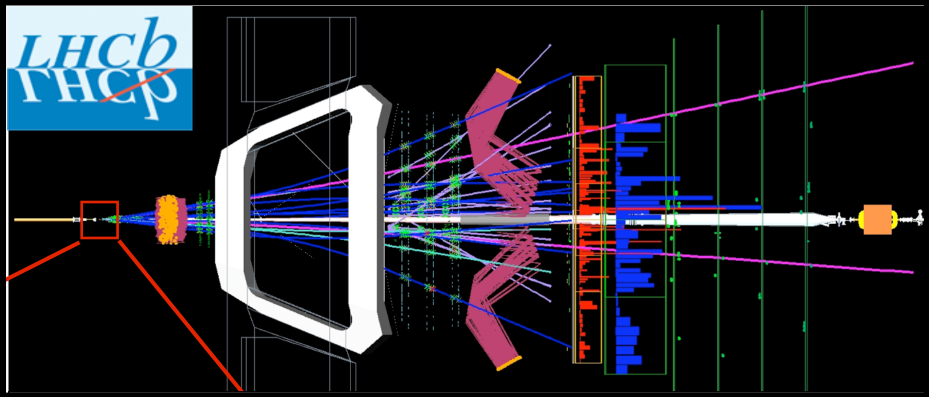
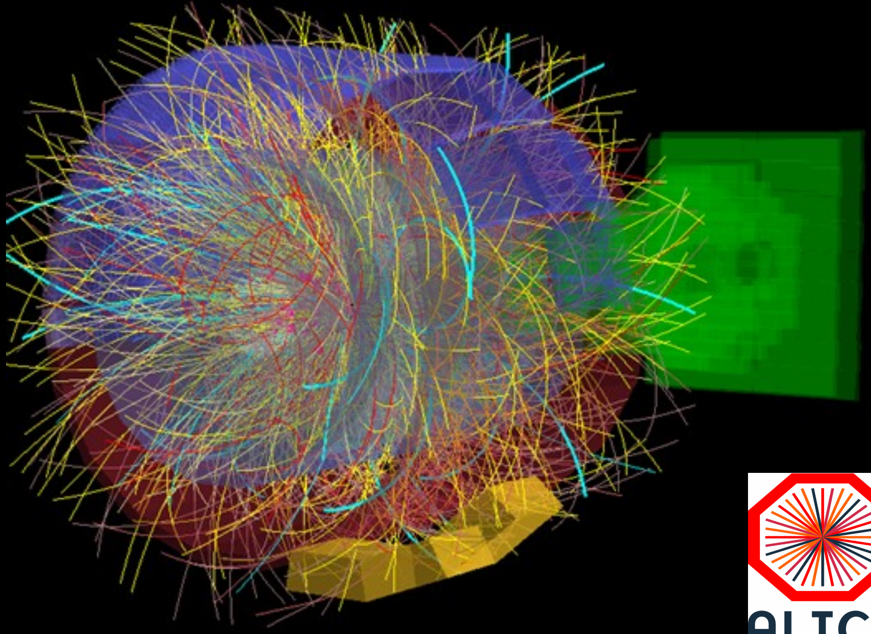




Flavor Physics at LHC





Flavor Physics at LHC

definition:
study of interactions in b- and c-hadrons produced in pp collisions at LHC (heavy quarks)

why:
search for new phenomena (= New Physics) beyond the Standard Model to explain the ORIGIN OF FLAVOR, one of the unsolved mysteries connected to the origin of fermion generations, the striking hierarchies in the fermion spectrum, the absence of CP violation in strong interactions and the matter antimatter asymmetry (the current level of CP violation being too small by ~ 10^{10})

how:
Heavy Flavor Physics probes large mass scales via virtual quantum "loops" of New Particles appearing as corrections to the dominant diagrams ("tree diagram")

where:
looking to very rare decays and searching for unexpected CP violation in b- and c-hadron decays, measuring CKM matrix elements in tree and loops diagrams

Heavy Flavor studies are also important in Pb-Pb collisions (as probes of QGP effects)

Direct vs. Indirect searches

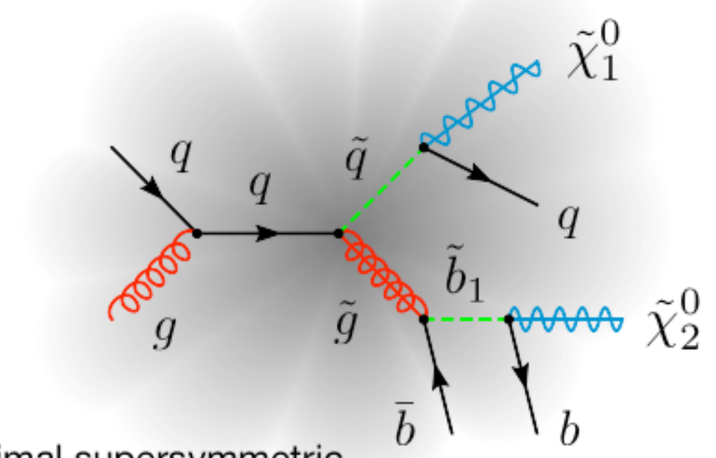
Production of new particles at LHC will probe directly the structure of matter and interactions

The goal is to give an answer to the HIERARCHY PROBLEM of Electroweak Symmetry Breaking (stability of SM Higgs under radiative corrections) and to find candidates for the DARK MATTER: the higher the energy available in the collision, the highest the reach in new mass scale (DIRECT SEARCHES)

But even in presence of discovery of new states, different New Physics scenarios can lead to similar signatures: difficult to disentangle the various theories

High statistics, high precision measurements on low energy rare process potentially affected by virtual quantum corrections, may offer indirect insights (INDIRECT SEARCHES)

This technique has been used since long time in Particle Physics, and it is an important part of LHC physics program



Minimal supersymmetric SM (MSSM)

A tiny effect with great consequences

PHYSICAL REVIEW VOLUME 72, NUMBER 3 AUGUST 1, 1947

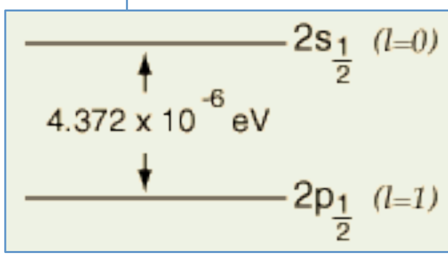
Fine Structure of the Hydrogen Atom by a Microwave Method* **

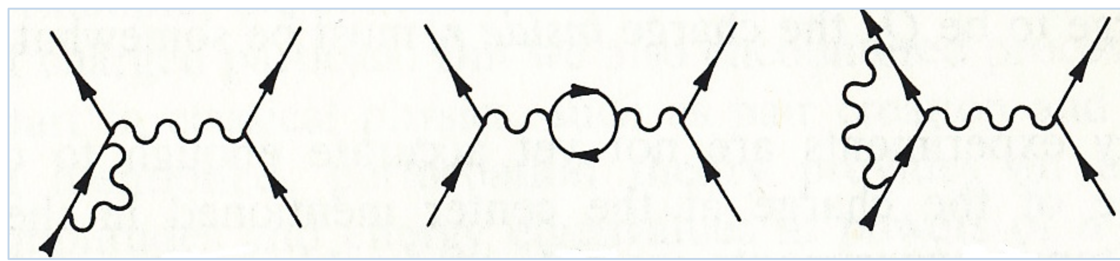
WILLIS E. LAMB, JR. AND ROBERT C. RETHERFORD
Columbia Radiation Laboratory, Department of Physics, Columbia University, New York, New York
(Received June 18, 1947)

PHYSICAL REVIEW VOLUME 72, NUMBER 4 AUGUST 15, 1947

The Electromagnetic Shift of Energy Levels

H. A. BETHE
Cornell University, Ithaca, New York
(Received June 27, 1947)



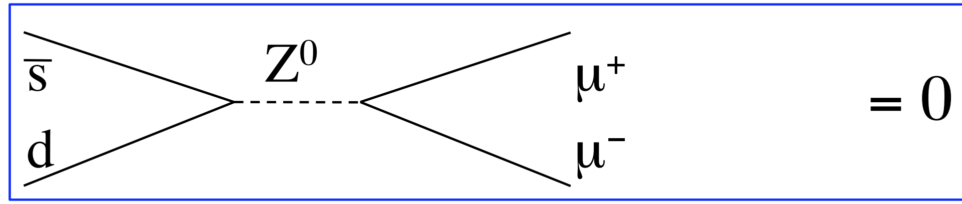


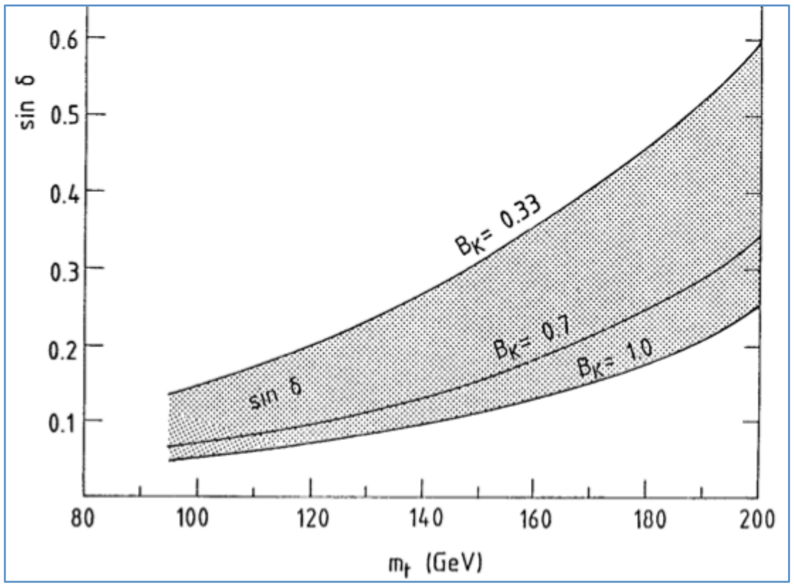
The experimental observation of a very small difference in the energy levels of $^2S_{1/2}$ and $^2P_{1/2}$ in H atoms ("Lamb shift") due to quantum virtual effects ("loops") has brought to the development of modern QED (Schwinger, Feynman, Tomonaga - Nobel prize in 1955)

New Physics from (ultra) low energy precise measurements !

Indirect searches: a bright recent past

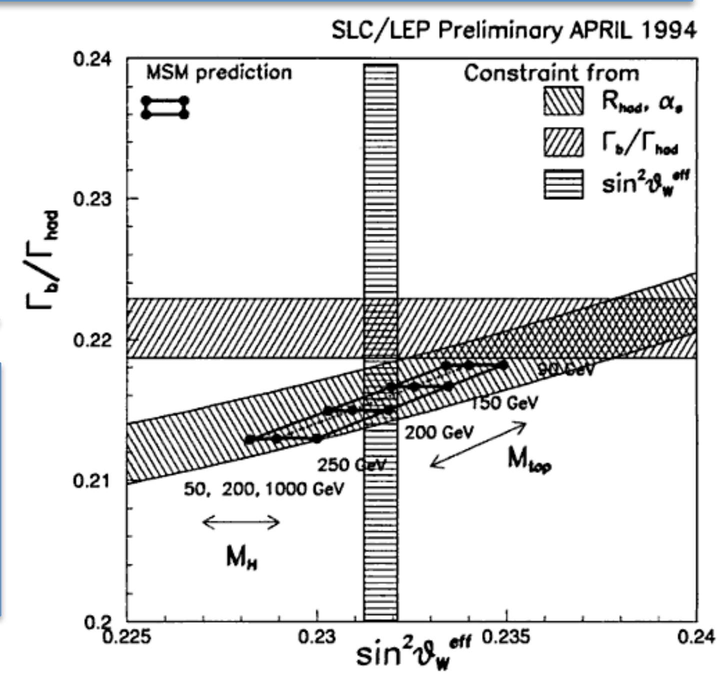
1970: GIM mechanism (hypothesis of c quark) to explain absence of $K_L \rightarrow \mu\mu$ decay. SU(2) quarks doublet





1987 ARGUS (DESY): the measurement of oscillations frequency of B^0 – anti B^0 system suggests a very high mass of top quark (at least > 50 GeV)

1994 LEP experiments (CERN): the fit to the Γ_b and sin θ_W electroweak parameters imposes strong constraints on M_{top} (found directly in 1995 at Fermilab)



Flavor as a portal to New Physics

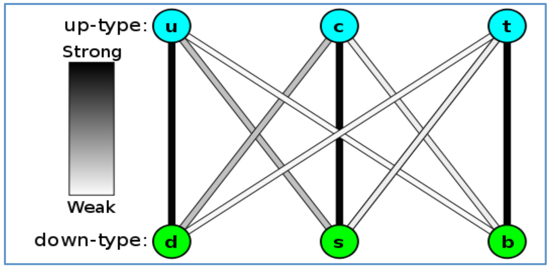
In the extensions of the Standard Model, additional flavor and CP violation can arise from exchange of new scalar (H+, squarks, …), fermionic (gluinos, t', …) or gauge (Z',W', …) degrees of freedom

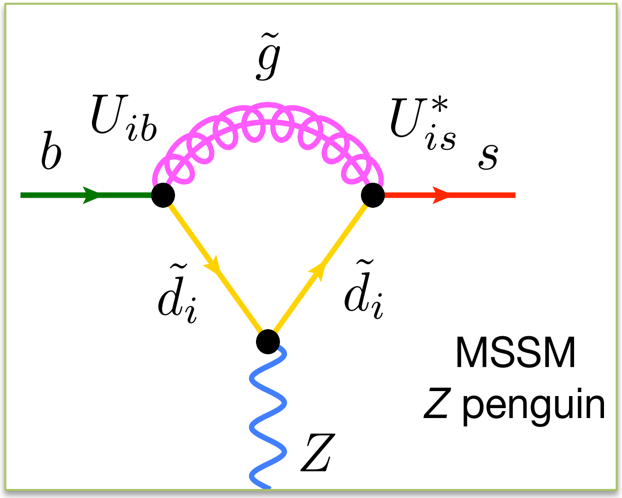
However new models must respect strong Flavor selection rules

In particular the absence of Flavor Changing Neutral Currents (no transitions between quarks of same charge) implies on New Models:

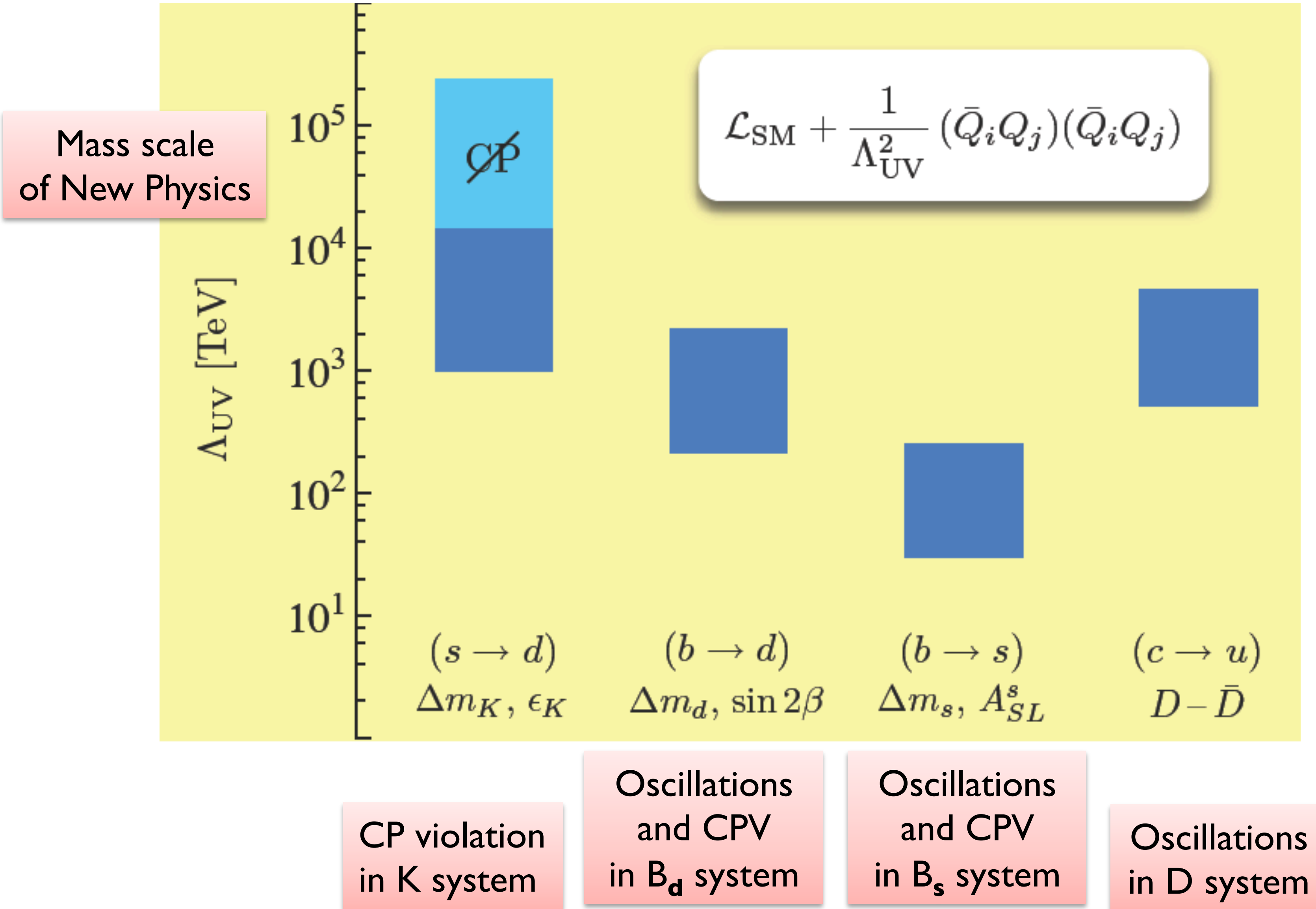
- new particles are heavy (M_x >> 1 TeV)
- their masses are degenerate ($\Delta m \sim 0$)
- or mixing angles are small

The absence of signals of New Physics in current measurements in Heavy Flavor, already now set strong constraints on the TeV-scale physics (higher than those found in direct searches so far, even at LHC)





Present constraints from Flavor Physics



The CKM Paradigm

Spectacular confirmation of the CKM model as the dominant source of flavor and CP violation in interactions among quarks
All flavor variables constrained in the SM CKM fit are in good agreement with experimental observations

Some variables still to be measured precisely (e.g. γ , now at 20%) and some discrepancy (~3σ) between some measurements (e.g. $V_{\mathbf{ub}}$): therefore a lot of room for surprises !

LHC is taking over the legacy from B factories and Flavor Physics at Fermilab

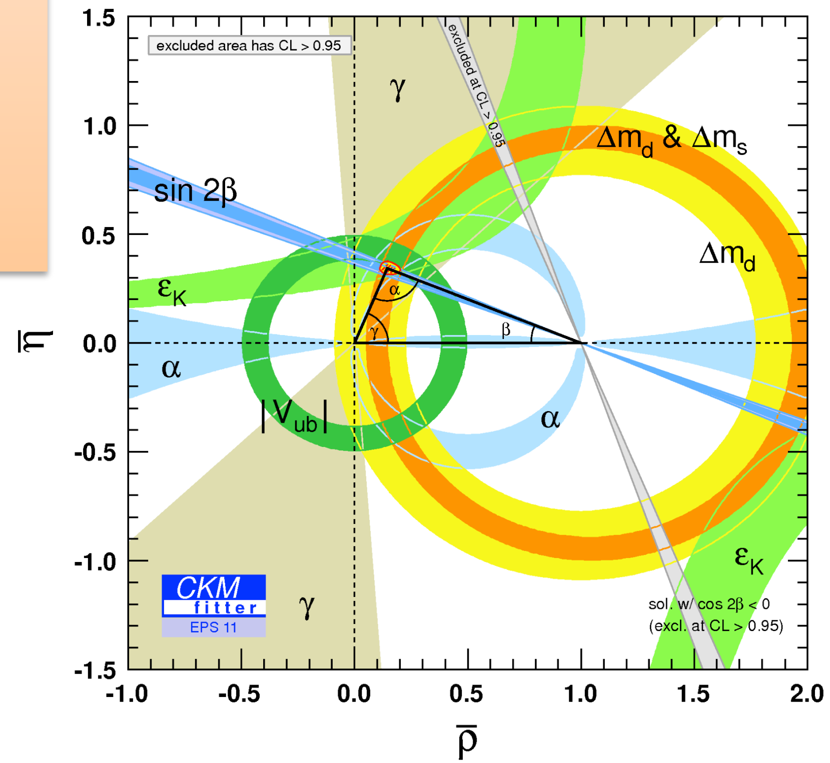
$$
\begin{array}{c} \\ V \approx \end{array}
\begin{array}{c} \quad d \qquad s \qquad b \\ \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \end{array}
\begin{array}{c} \\ u \\ c \\ t \end{array}
$$

$\lambda \approx 0.22$: Cabibbo angle

NOBEL in 2008

CKM

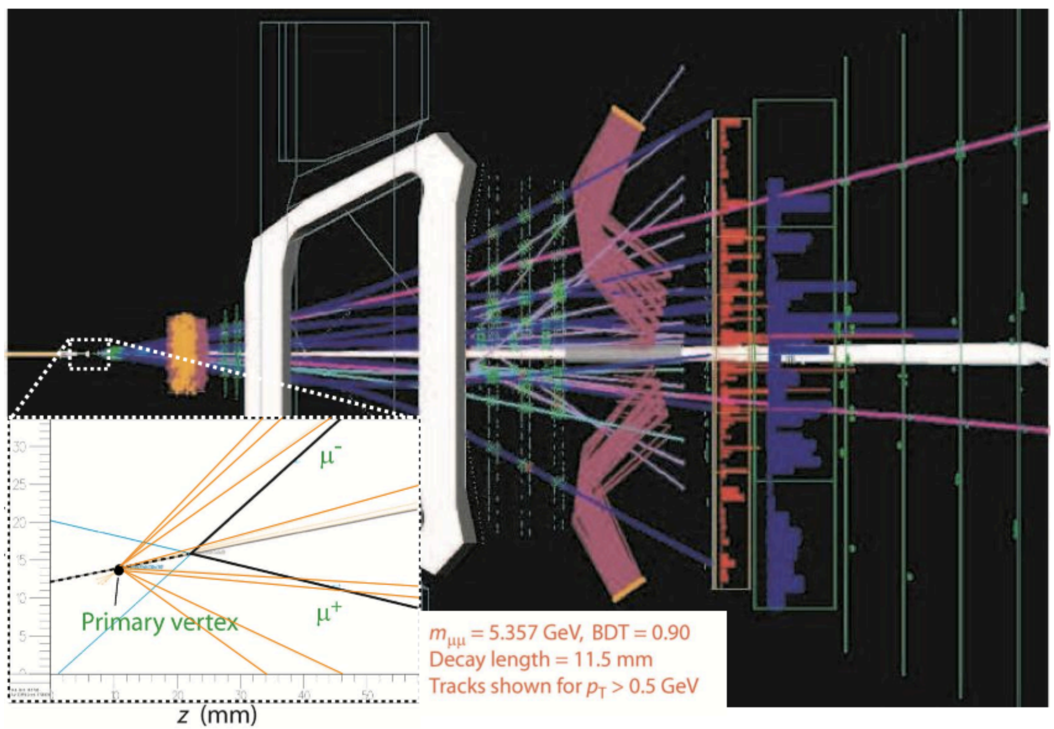
N. Cabibbo M. Kobayashi T. Maskawa



Why using B mesons ?

In most of the new physics scenarios, large effects are expected in decays of b-quarks (many times new physics effects couple to mass)

B_u , B_d , and B_s mesons are produced abundantly at LHC (together with b baryons)
Long lifetime of b hadrons allow for "easy" experimental detection of decays
Several techniques allow to tag the flavor of the b (b or anti-b)
Large mass of b quark gives phase space to many final states (and daughter particles have high momentum: easier to detect)

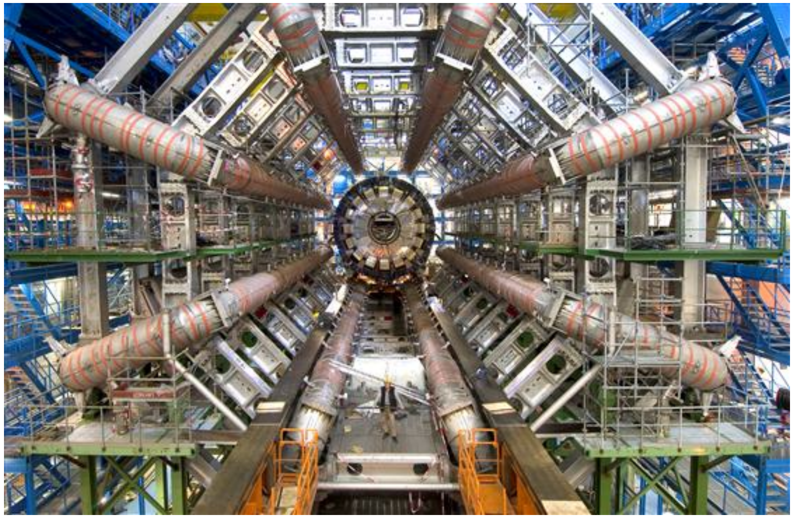


Theoretical predictions in b physics are often accurate (much easier than in lower mass quarks, e.g. charm) and can be compared with experimental observations

Wealth of data coming from B factories and Fermilab experiments, in a large variety of decay modes

Tools for studying the symmetries and the phases of the Universe

VLT spectrometer @ ESO

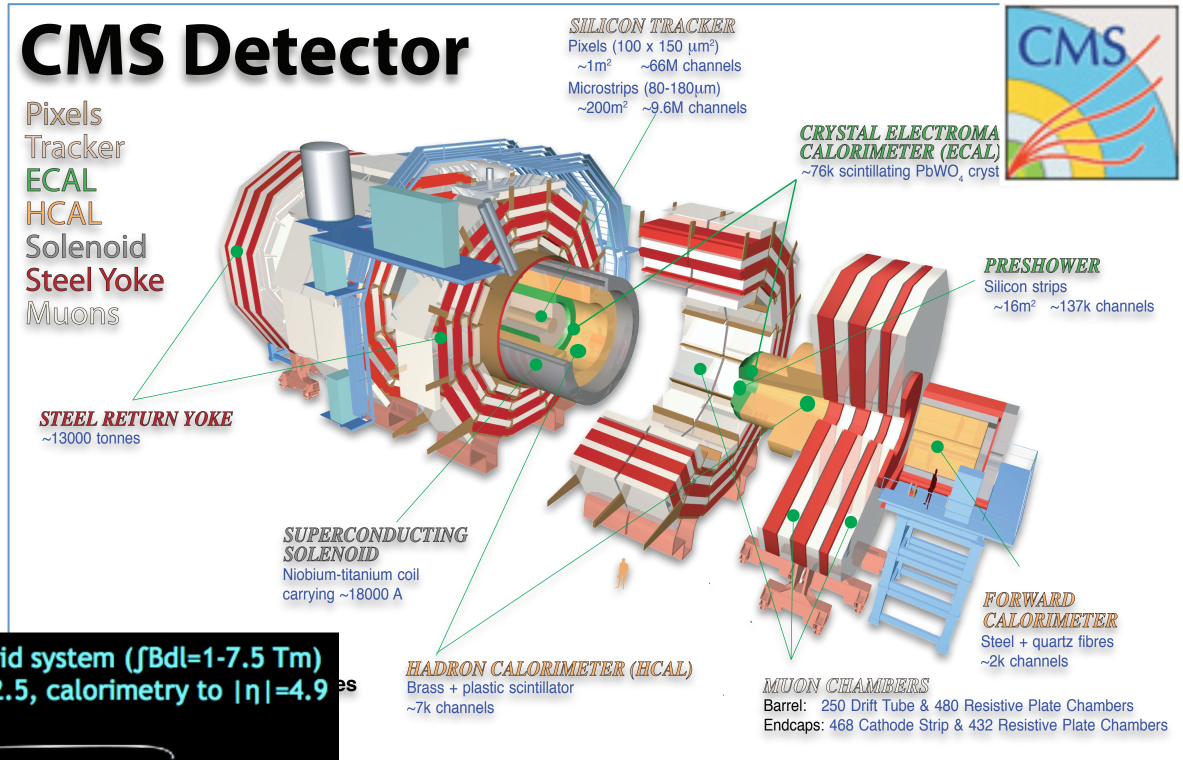


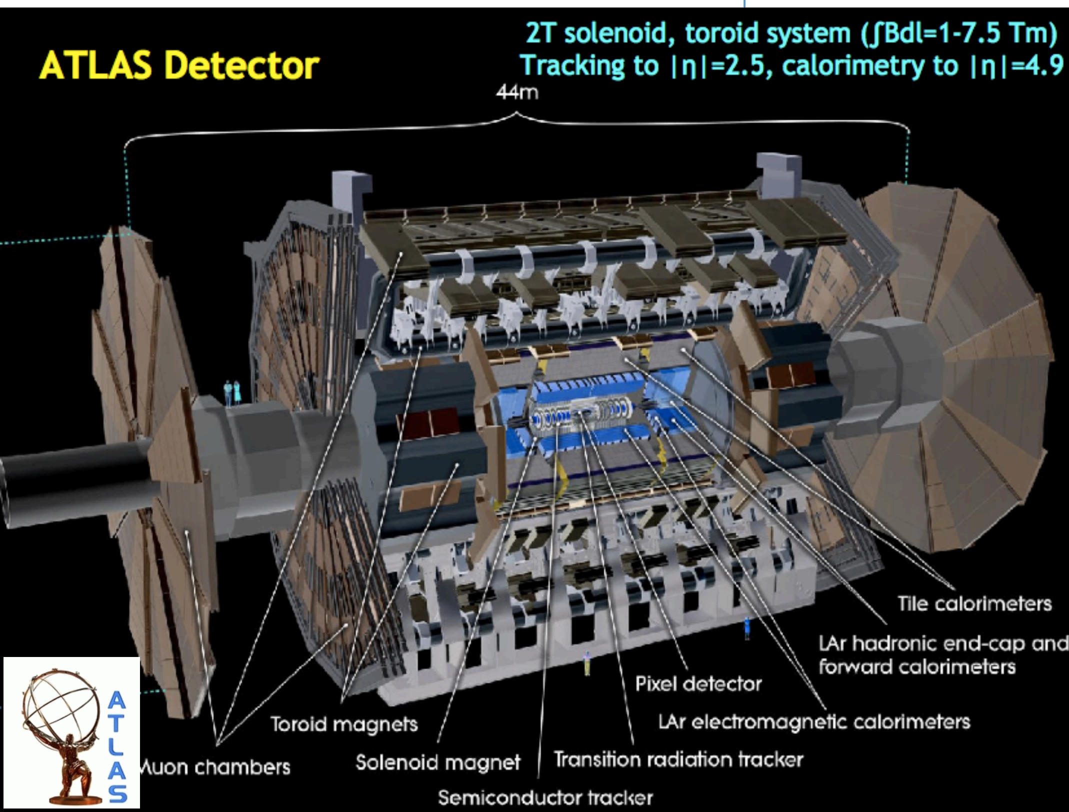
ATLAS spectrometer @ LHC

Atlas and CMS

Main focus on high p_T physics (Higgs and Supersymmetry) but large samples of B events available

Can stand to high luminosity from LHC ~ 3 10^{33} $cm^{-2}s^{-1}$ (now)
Up to ~ 5 10^{34} $cm^{-2}s^{-1}$ (in future)



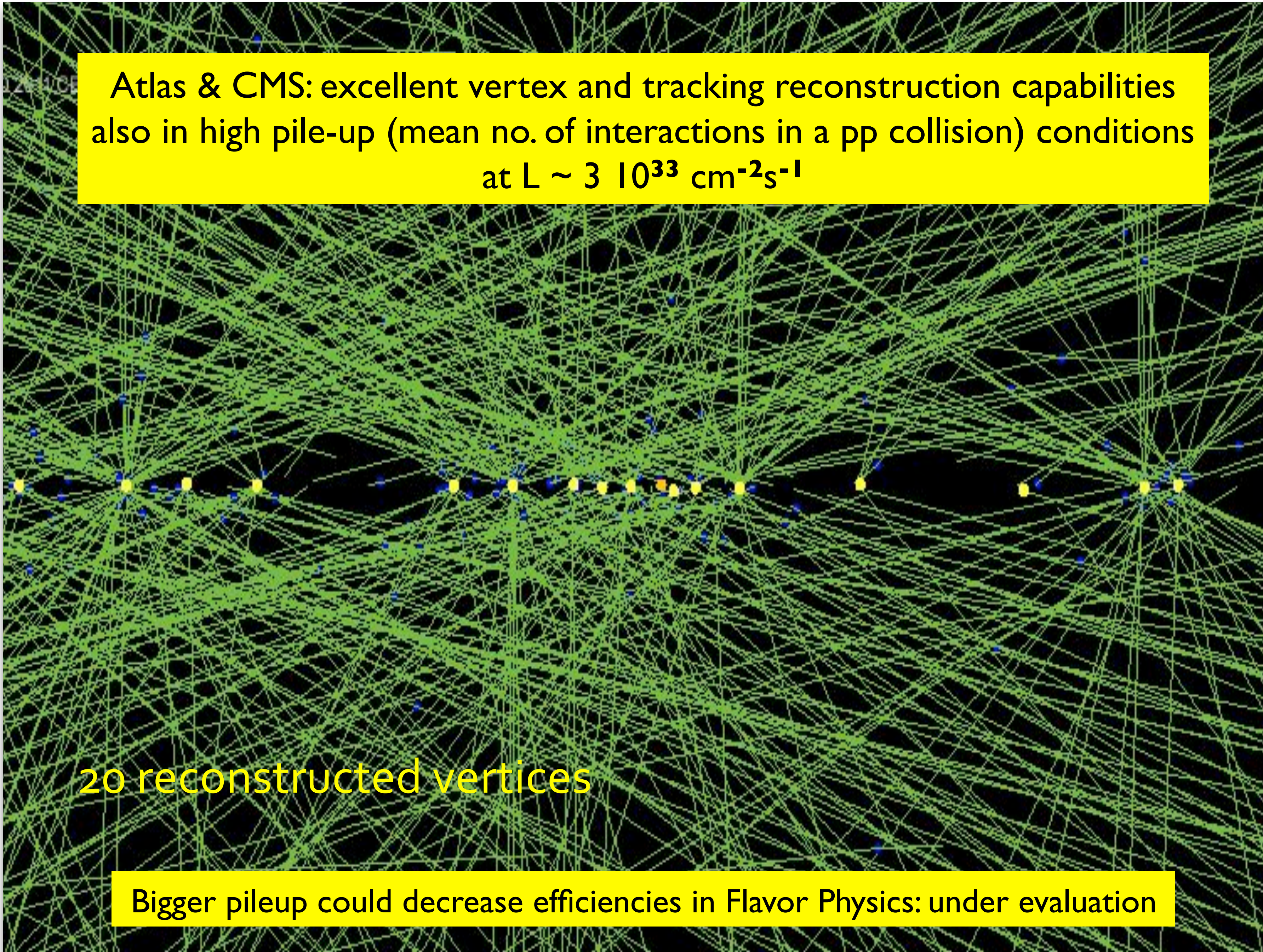


B-hadrons reconstruction mainly exploits excellent Vertex detectors (silicon strips and pixels) and Muon detectors for precise p measurements

Limited hadron identification, but excellent photon identification

Cuts on medium p_T (4-6 GeV) di-muon final states

Atlas & CMS: excellent vertex and tracking reconstruction capabilities also in high pile-up (mean no. of interactions in a pp collision) conditions at $L \sim 3\ 10^{33}\ cm^{-2}s^{-1}$



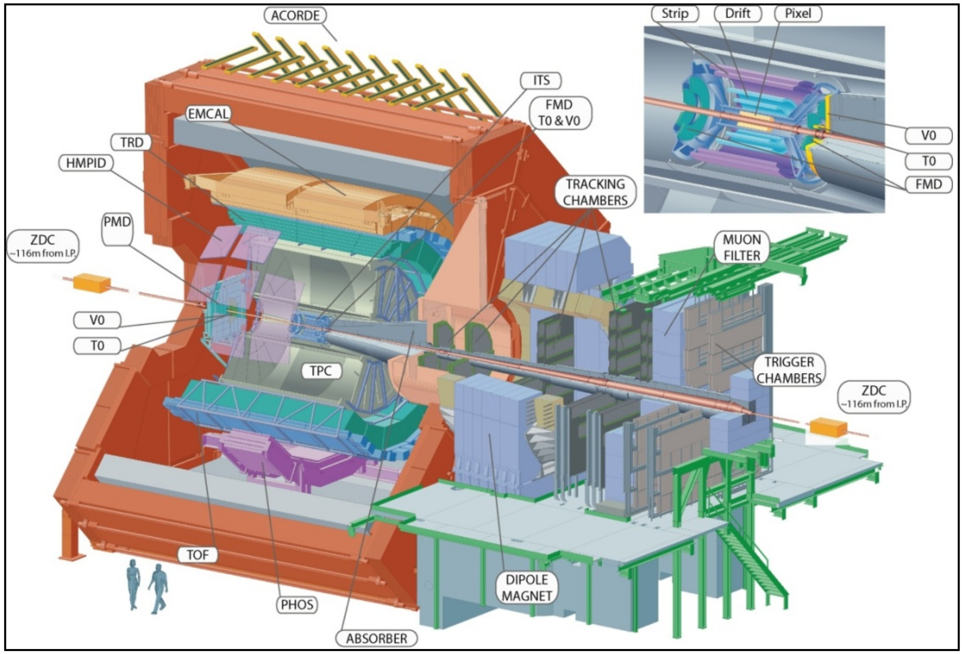
Bigger pileup could decrease efficiencies in Flavor Physics: under evaluation

ALICE (the Little Bang)

Study of QCD phase transition (QGP → hadrons) at $t_{Universe}$ ~10 μs

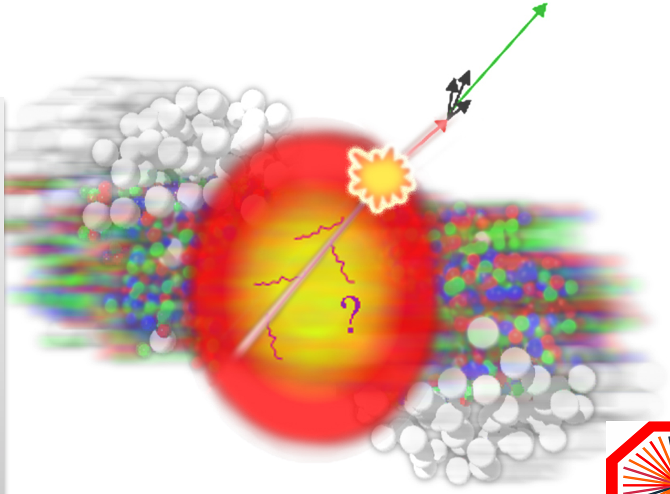
In high-energy Pb-Pb collisions, large energy densities are reached over large volumes (>> 100 fm^3)

Two main parts:
- barrel (|η|<0.9);
- forward μ-spectrometer (-4<η<-2.5)



Crucial for Heavy Flavor: vertexing, tracking, hadron and muon ID, performed in harsh conditions (very high particle multiplicities, several 10^3)

Flavor Physics as a probe to study behavior of strong interactions in the high density QCD medium of Pb-Pb collisions (e.g. charm production suppression)



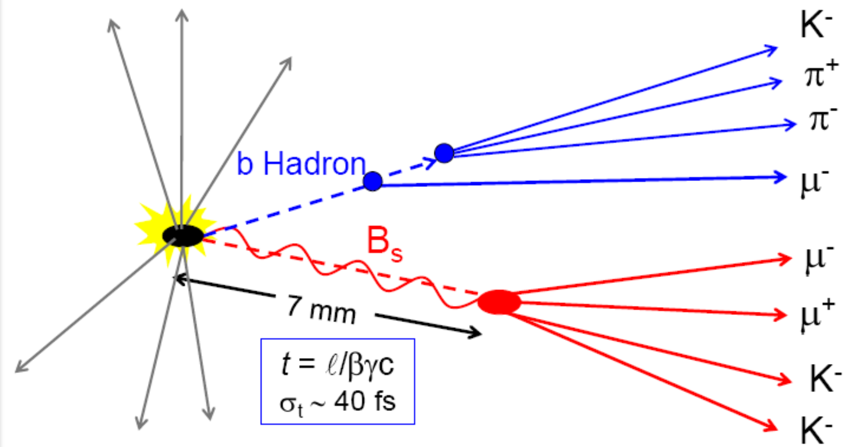
ALICE

LHCb (a dedicated Flavor Physics experiment)

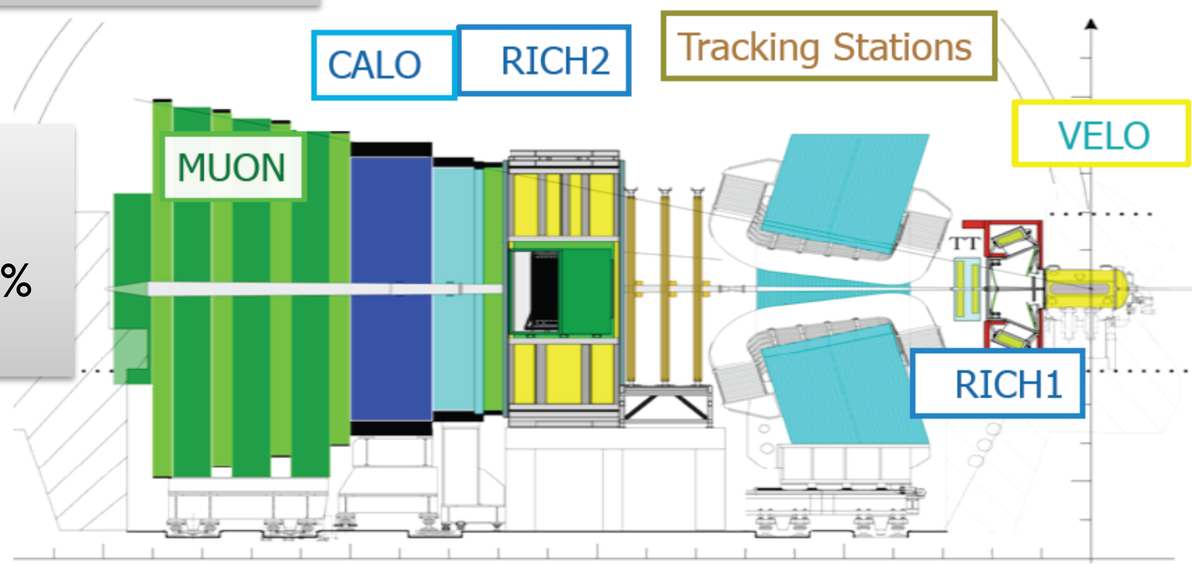
Excellent vertex resolution to resolve fast oscillation of B_s (~ 40 fs)

Background rejection (S/B=1/200 at production)
- Good particle ID (π, K, p, γ, μ)
- Precise momentum resolution (~0.5%)

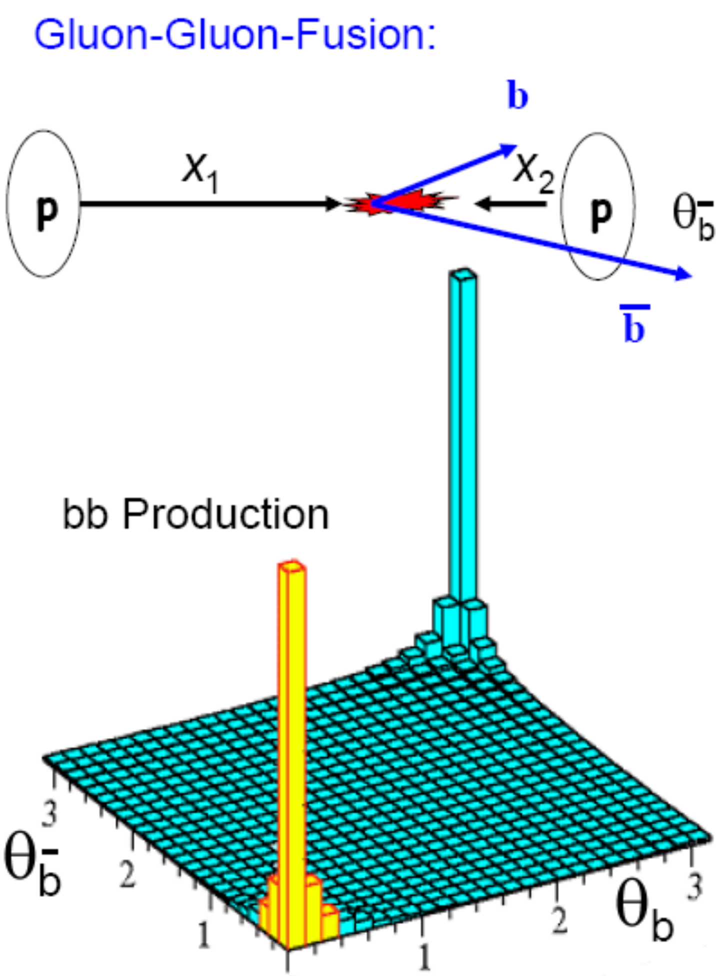
Trigger capability
- Efficient selection of hadronic and leptonic final states
- Low p_T single μ detection (>1.5 GeV)



Trigger efficiencies:
B decays with $\mu\mu$ $\varepsilon \sim$ 70-90 %
B decays with *hadrons* $\varepsilon \sim$ 20-45 %
Charm decays : $\varepsilon \sim$ 10-20 % (!)



b and c quark production in the LHCb environment

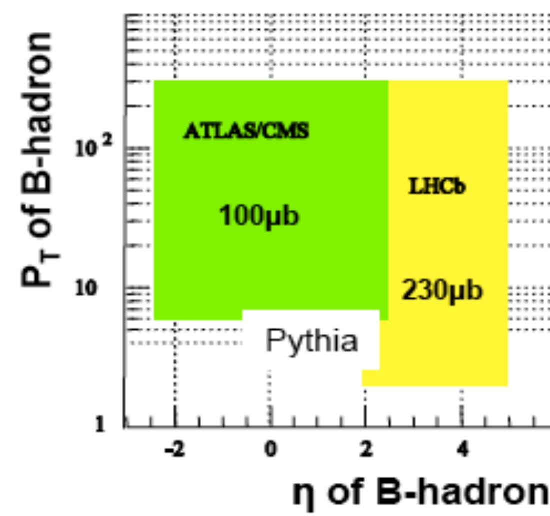


Both b quarks in the forward acceptance of LHCb

- inelastic pp collisions σ ~ 60 mb (7 TeV)
- c quark production σ ~ 6 mb (7 TeV)
- b quark production σ ~ 0.3 mb (7 TeV)

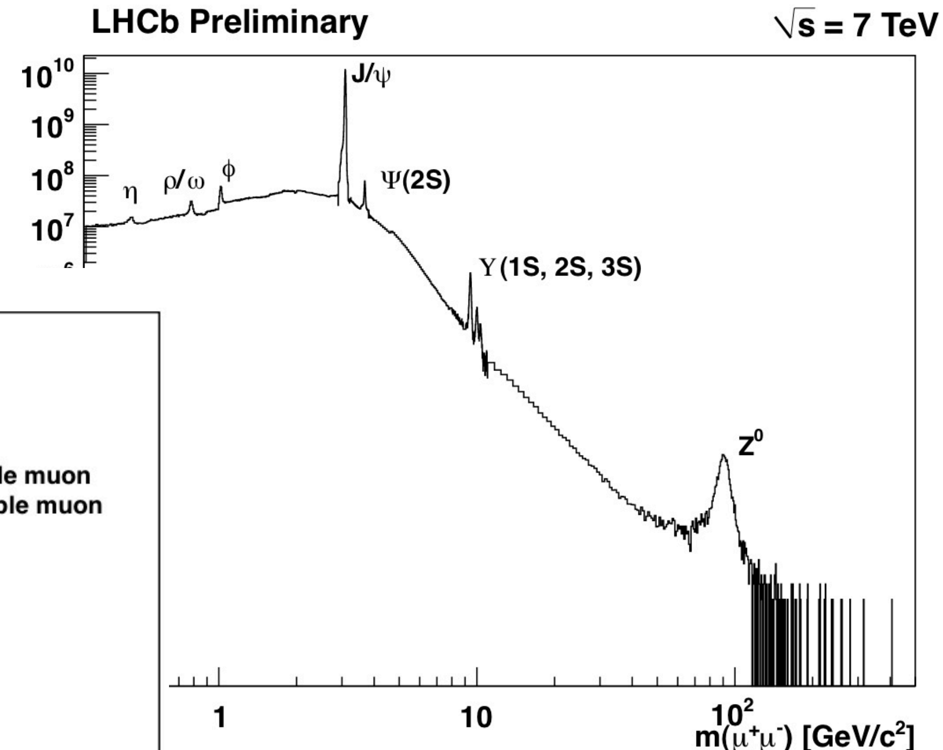
All c- and b- hadrons types produced

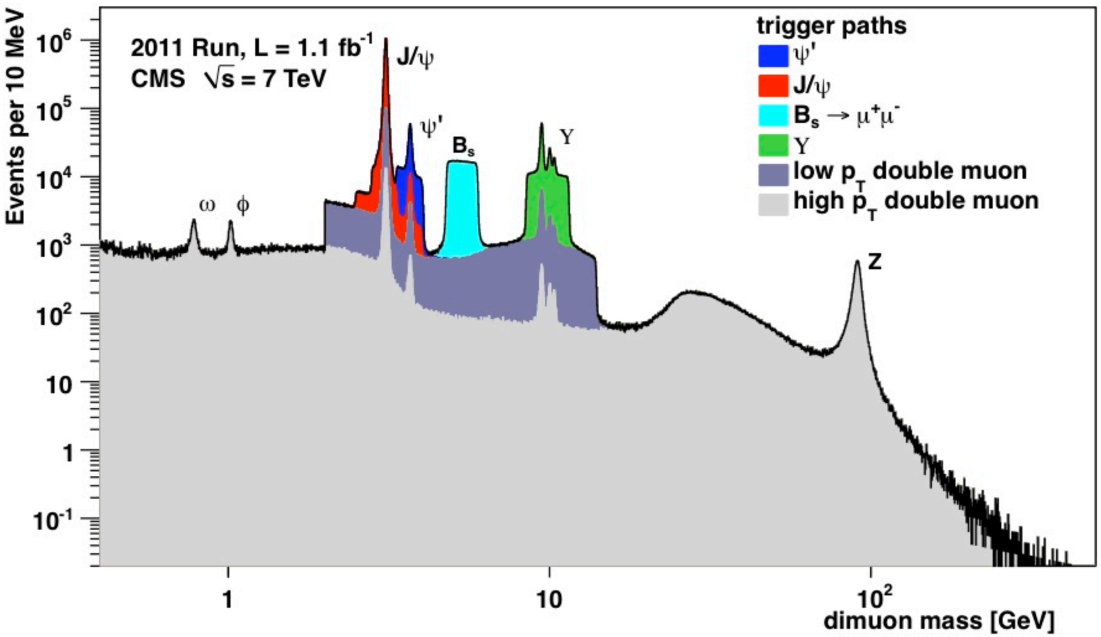
Typical running luminosity (LHCb)
~ 4 10^{32} $cm^{-2}s^{-1}$ (limited by occupancy)
~ 15 MHz of pp collisions (few 10 kHz bb)
~ 5 10^{11} b-anti b pairs /y

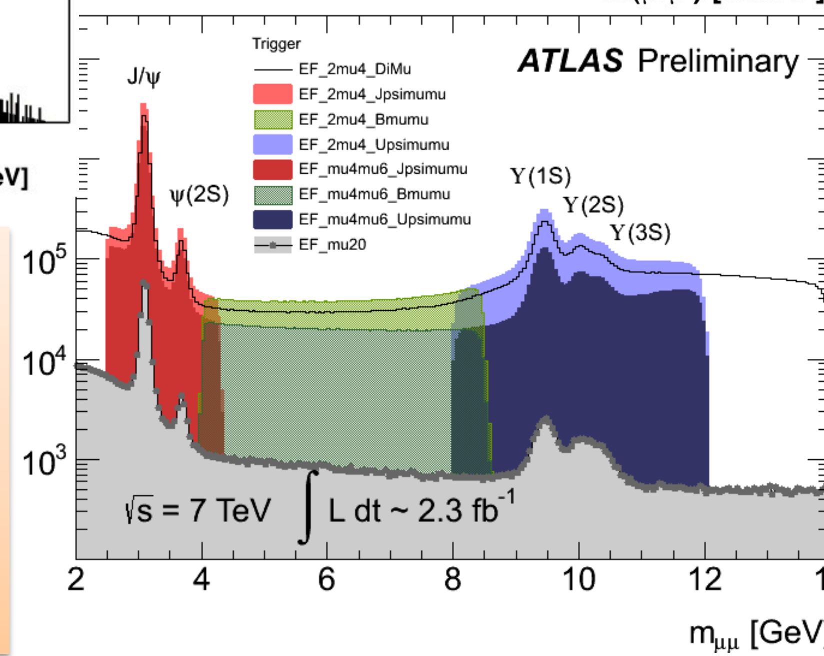


LHCb acceptance : 2 < η < 5 - ATLAS and CMS: |η| < 2.5
ALICE |η| < 0.9 and – 4< η < - 2.5

LHC detectors: precise spectrometers across energy decades





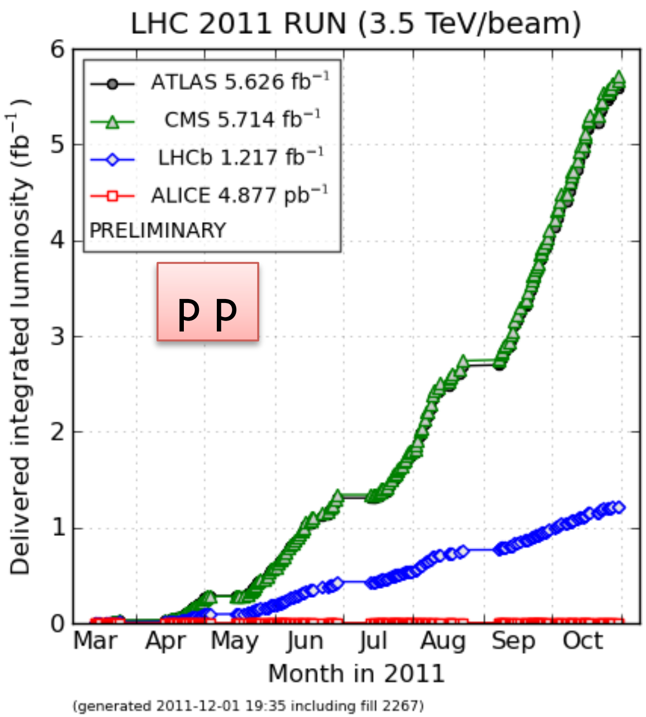


Muon identification plays a key role in reconstruction of heavy mesons with J/ψ in the final state:

- Good acceptance at low p_T
- Error on mass scale ~ 0.1 MeV

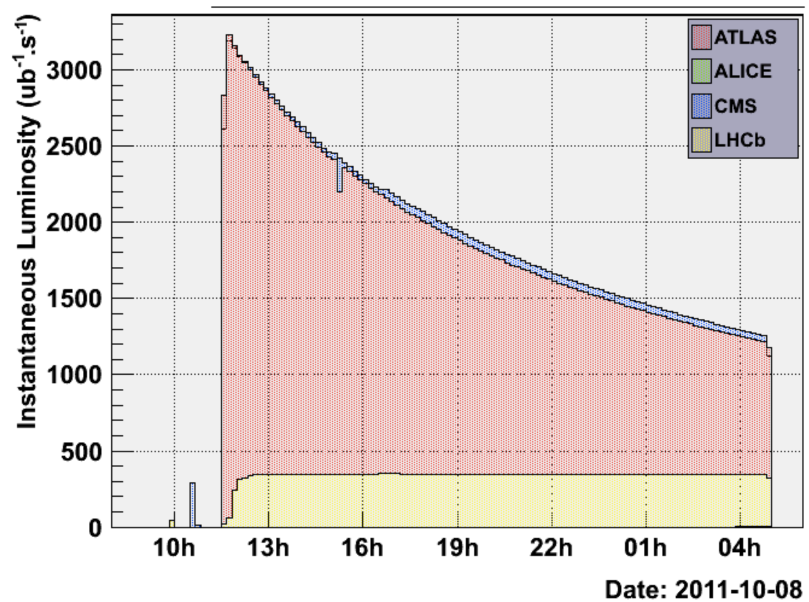
→ 30 years of Particle Physics in one plot (few months of data taking) !

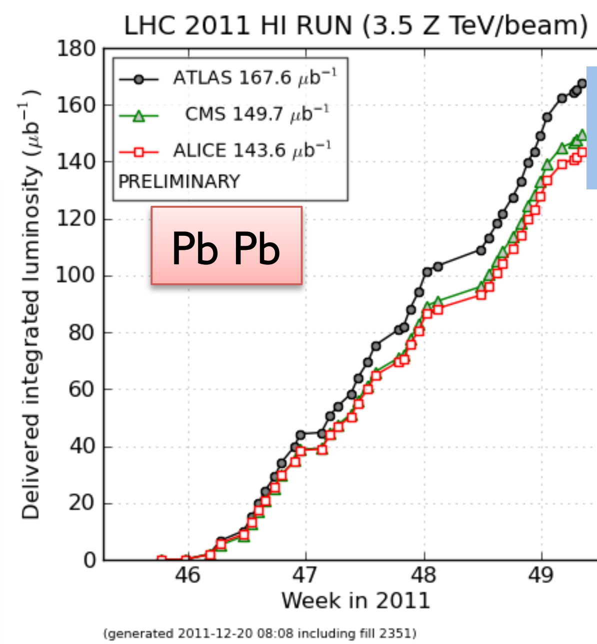
2011: a "luminous" year at LHC



> 5/fb
(Atlas, CMS)

> 1/fb
LHCb





>150/μb

Luminosity leveling guarantees adequate and stable running and trigger conditions for LHCb

Plans for 2012:

- $\sqrt{s}$ = 8 TeV (increased HF cross sections: +15%)
- 15/fb Atlas & CMS, 1.5/fb LHCb
- First run p-Pb for the four experiments

In 2015: $\sqrt{s}$ = 14 TeV – L > 10^{34} (Atlas & CMS)

Highlights of Heavy Flavor Physics at LHC

- Rare B decays (LHCb, Atlas and CMS)
- CP violation in B_s system (LHCb, Atlas and CMS)
- Search for CP violation in charm (LHCb)
- Heavy Flavor Production & Spectroscopy (All)
- Heavy Flavor as probe of QGP (Alice)

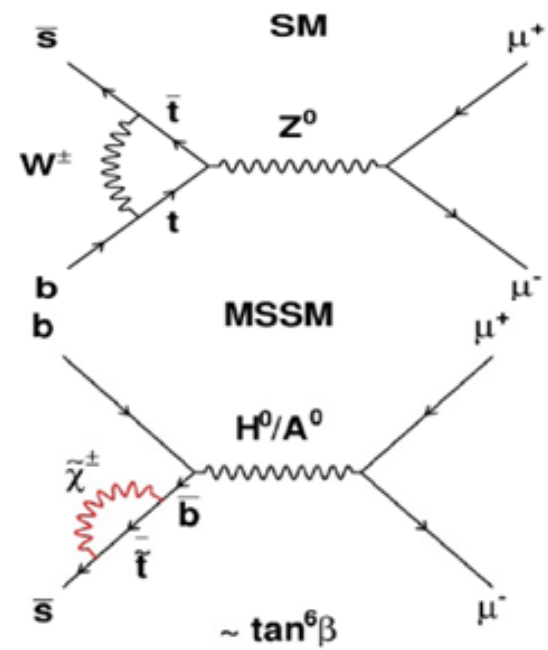
$B_s \to \mu\mu$

Predicted to be very rare in the SM due to GIM & helicity suppression:

- $Br_{SM}(B_s \to \mu\mu) = (3.2 \pm 0.2) \times 10^{-9}$

Large sensitivity to NP, eg SUSY:

- $$\mathrm{Br}_{\mathrm{MSSM}}(B_q \to \ell^+\ell^-) \propto \frac{M_b^2 M_\ell^2 \tan^6 \beta}{M_A^4}$$

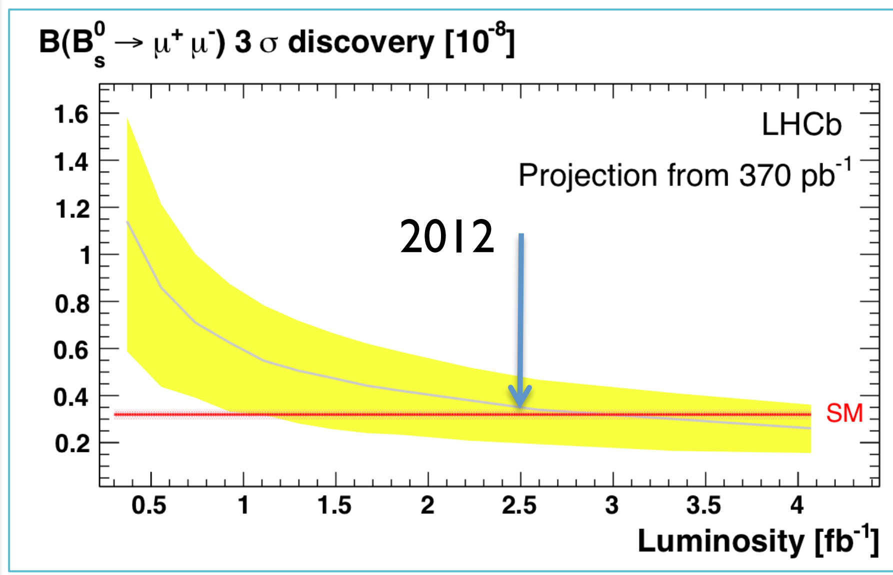


Last summer (EPS conf.) first results:

LHCb (0.4/fb) + CMS (1.3/fb) combination
BR ($B_s \to \mu\mu \leq 1.1 \times 10^{-8}$) (95% CL)

New round of measurements from ATLAS, CMS and LHCb soon available (at current winter conferences)

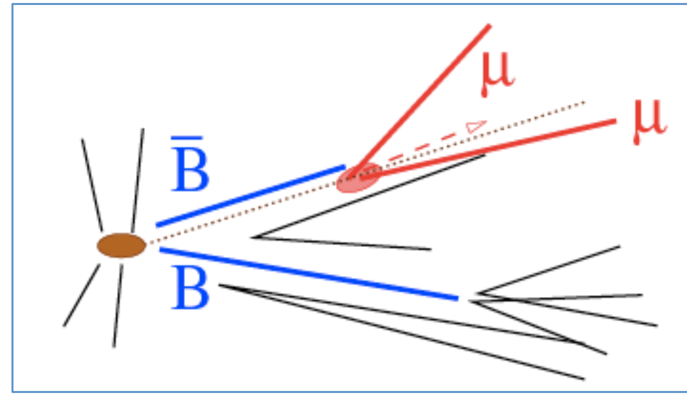
Prospects for 2012 (LHCb) → 3σ discovery (similar sensitivity for CMS)

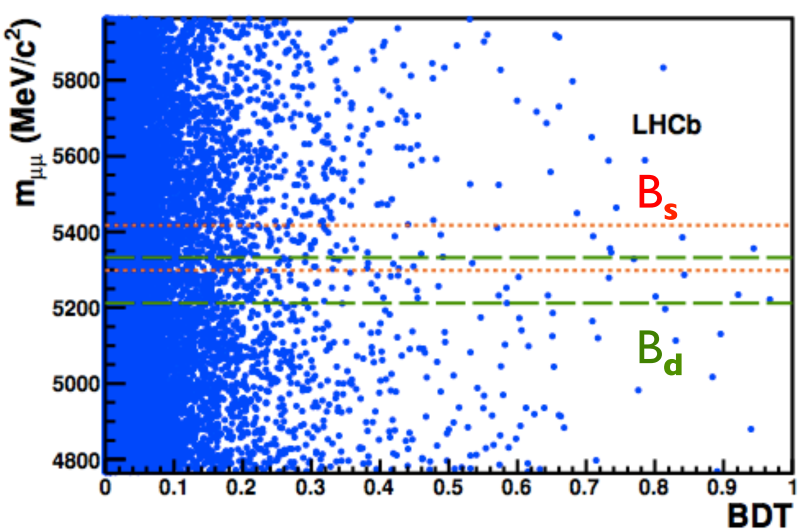


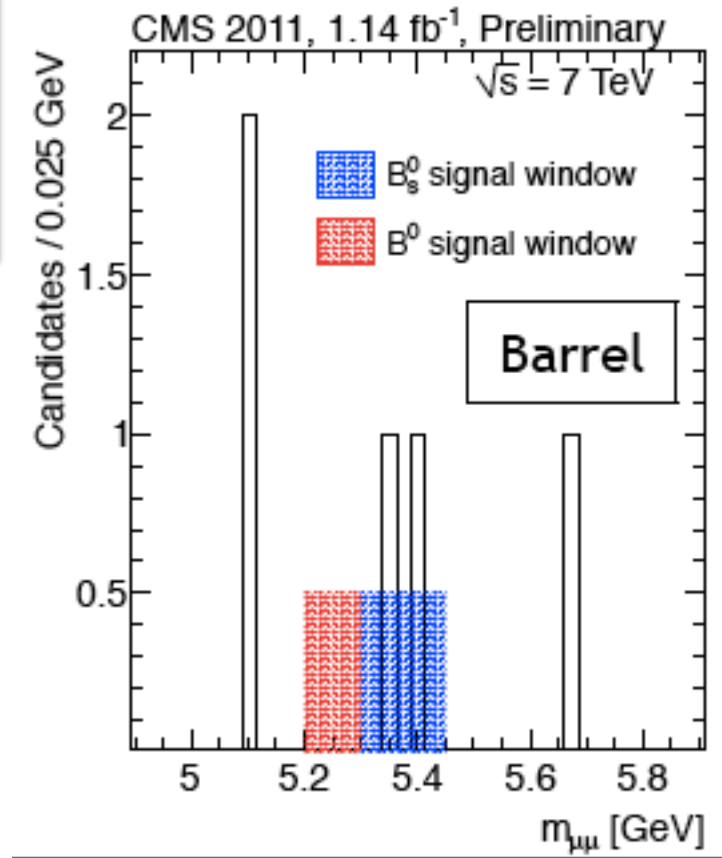
Particularly challenging measurement:
BR ~ few 10^{-9} against a strong peaking background (high efficiency/high discrimination required)

Background discriminated with B invariant mass and multivariate analysis variable (BDT) trained on data ($B \to \pi\pi$, $B \to KK$ are very similar to $B_s \to \mu\mu$)
"Standard candles" to obtain the BR:
$B^+ \to J/\psi\, K^+$, $B_s \to J/\psi\, \phi$, $B^0 \to K^+ \pi^-$

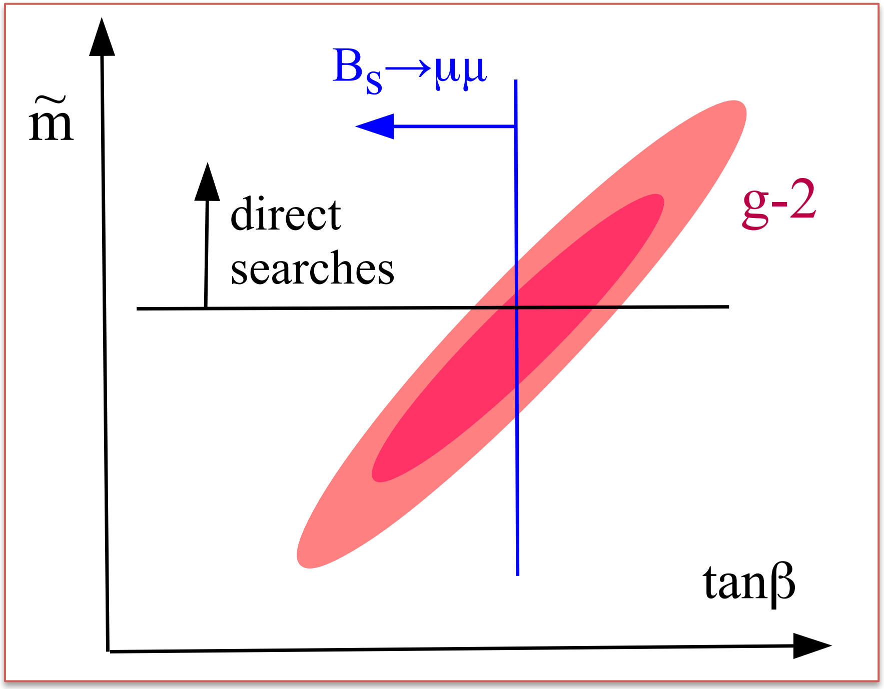
At the end of the analysis, few events are left (candidates $B_s \to \mu\mu$) with S/B<1 in the most sensitive kinematical region
Also very important $B_d \to \mu\mu$ (but BR~1/30 of B_s)



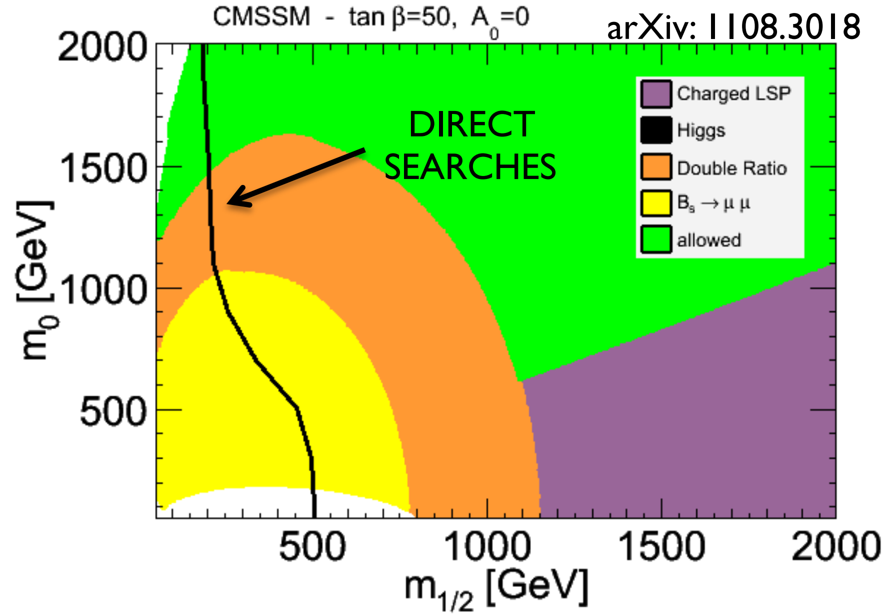


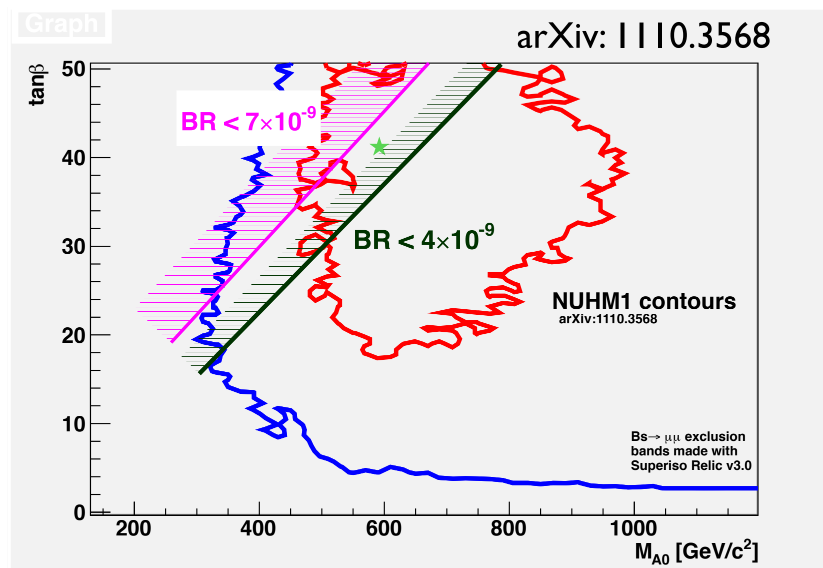


$B_s \to \mu\mu$ constraining Supersymmetry



G. Isidori, ICFA Seminar, 2011



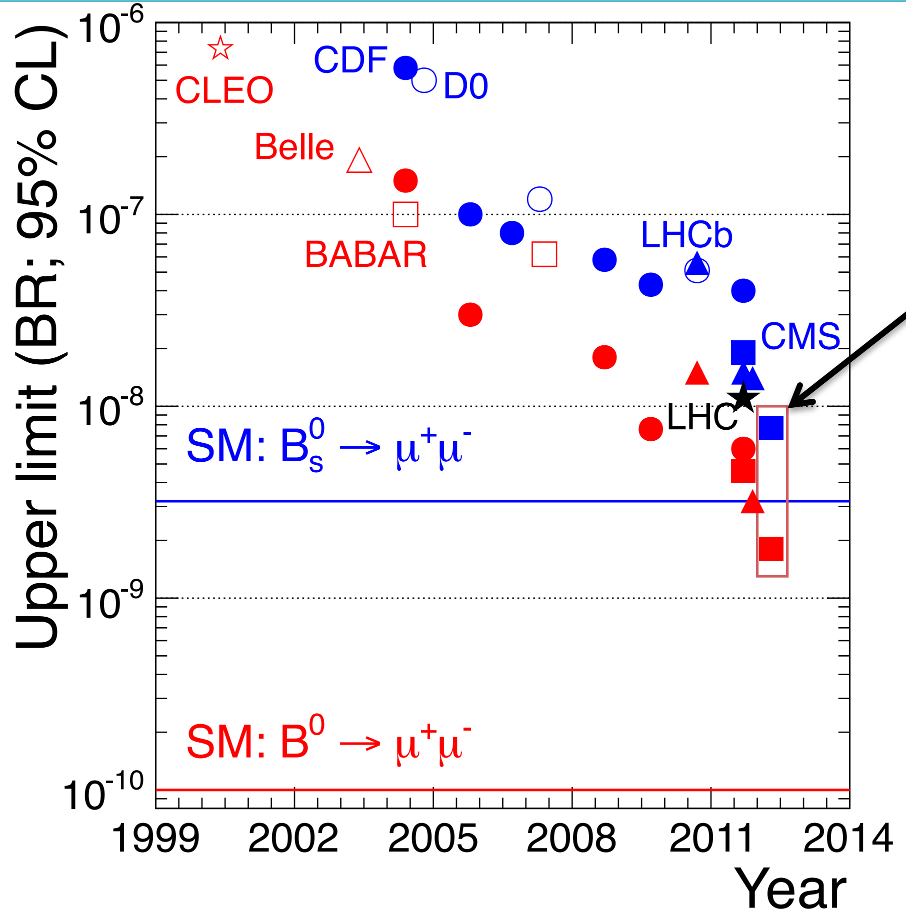


BR($B_s \to \mu\mu$) sets strong bounds on *tan β* at least in MSSM, complementary to direct searches and in tension with *g-2* result (presently the largest off-SM anomaly)

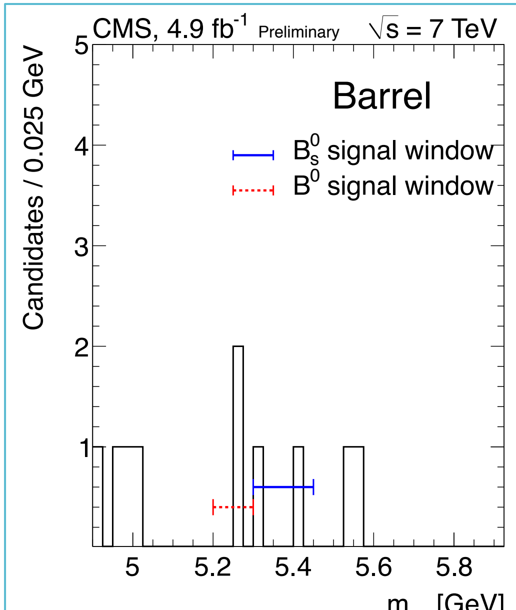
… breaking news … just few hours ago, CMS seminar at CERN with new limits on $B_s \to \mu\mu$ (5 times more statistics than in 2011)

Search for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ in 2011 dataset

upper limit (95%CL)	observed	expected
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	7.7×10^{-9}	8.4×10^{-9}
$\mathcal{B}(B^0 \to \mu^+\mu^-)$	1.8×10^{-9}	1.6×10^{-9}

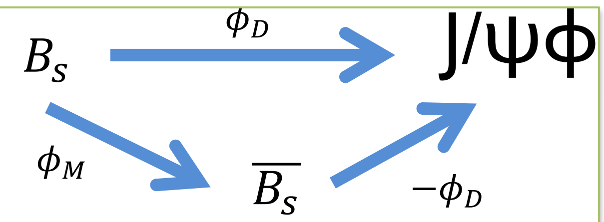


Significant improvement of the limit (~ 2.5 times the SM value)
More new results from LHCb and Atlas soon



CP violation & $B_s\overline{B}_s$ Mixing Phase

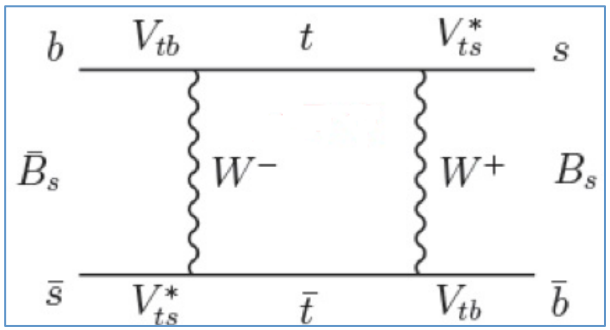
Interference between mixing and decay gives rise to CP violating phase $\phi_s = \phi_M - 2\,\phi_D$



$$\phi_s \overset{\text{SM}}{=} -2\beta_s \equiv -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

~ 0 in SM

Requires *time-dependent, flavour tagged, angular* analysis



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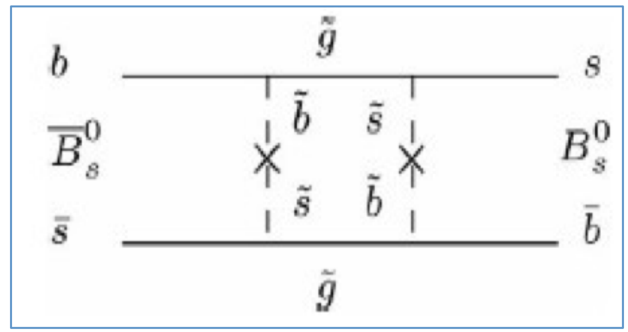


NP ?

Interference effects from New Physics could bring in the amplitude of the process a non zero phase with strong impact on the amount of CP violation

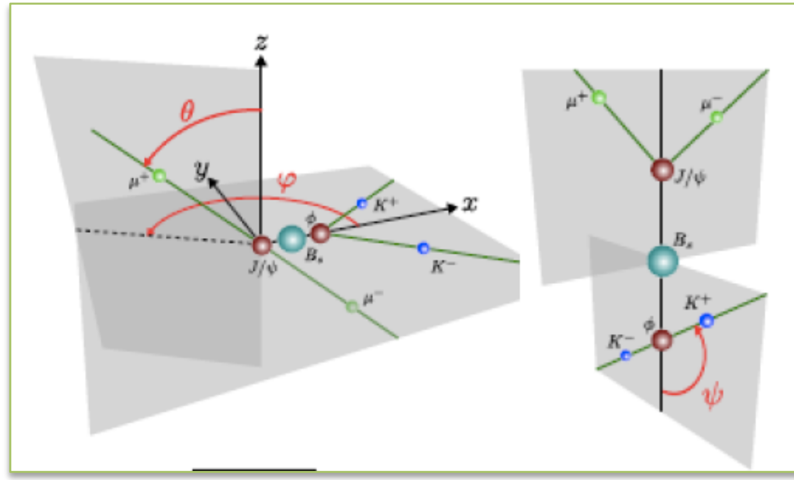
$$A_{CP}(t) \equiv \frac{N(\overline{B}\to f) - N(B\to f)}{N(\overline{B}\to f) + N(B\to f)} = S\,\sin(\Delta m_q t)$$

$S = \sin(\phi_M - 2\phi_D)$

Measuring ϕ_s

Particle ID, flavor ID, excellent mass and high time resolution needed (σ_t ~ 40 fs to follow the fast oscillations of B_s) as this is a time dependent measurement

Disentangling CP=1 and CP=-1 final states with angular analysis



Most precise measurement of ϕ_s

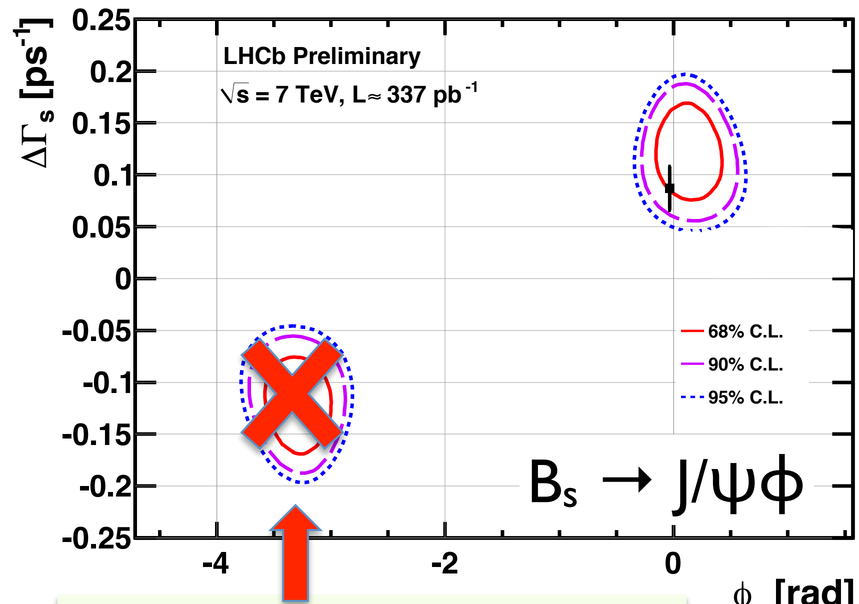
$$\phi_s = 0.15 \pm 0.18 \text{ (stat)} \pm 0.06 \text{ (syst) rad}$$

- Consistent with SM

4 σ Evidence for $\Delta\Gamma_s \neq 0$:

- $\Delta\Gamma s = 0.123 \pm 0.029 \text{ (stat)} \pm 0.008 \text{ (syst) ps}^{-1}$

Quantum effect: B_s mass eigenstates (B_{sH}, B_{sL}) have different lifetimes (like in the K_S,K_L system)

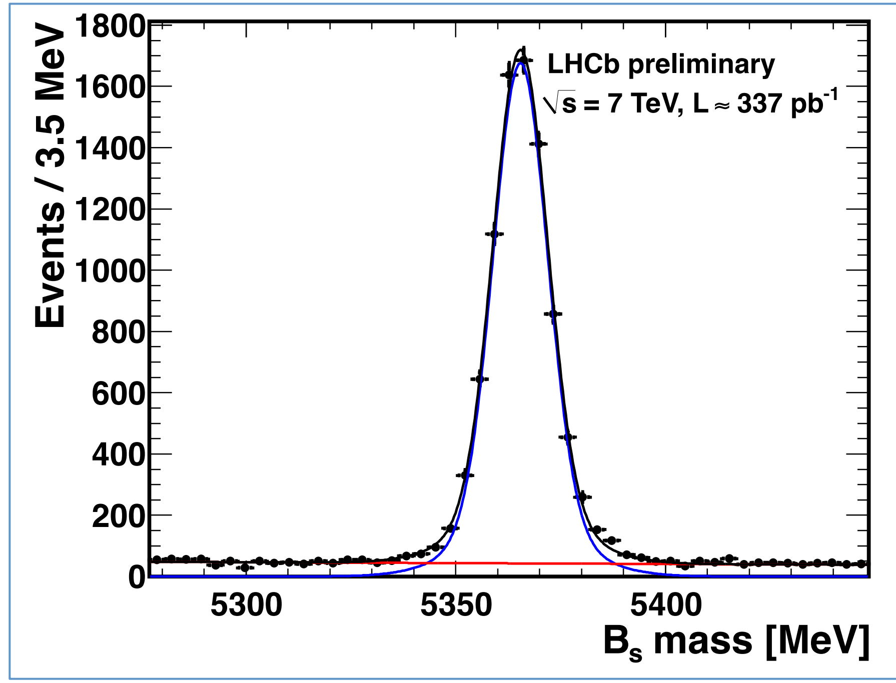


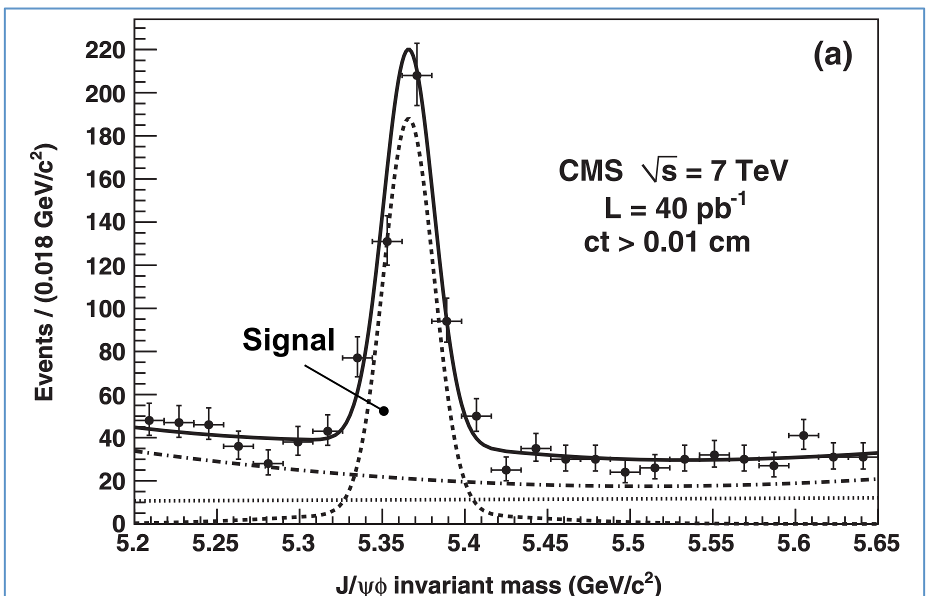
This unphysical solution removed with subsequent analysis

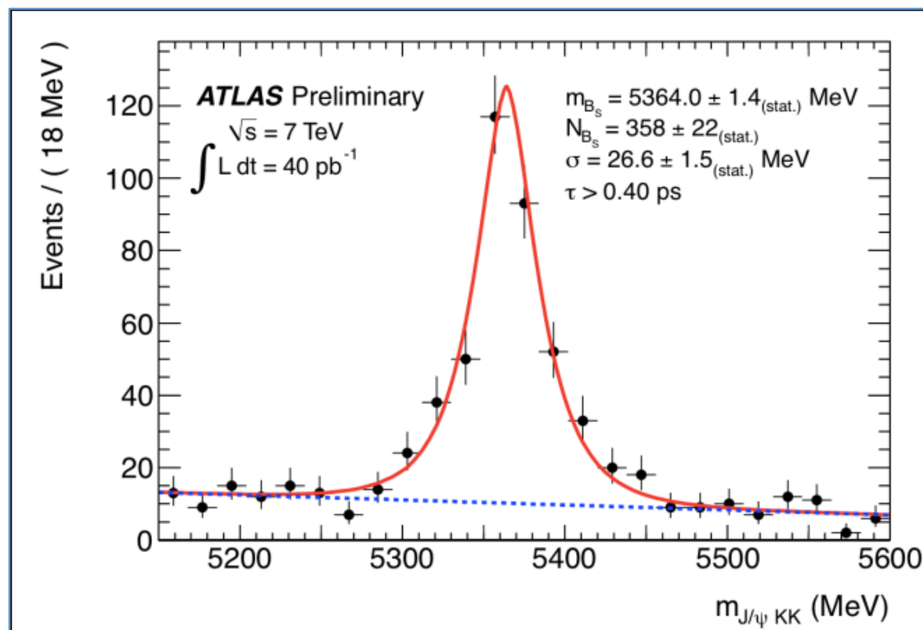
$B_s \to J/\psi\, \phi$

As of now, only LHCb ϕ_s measurement available

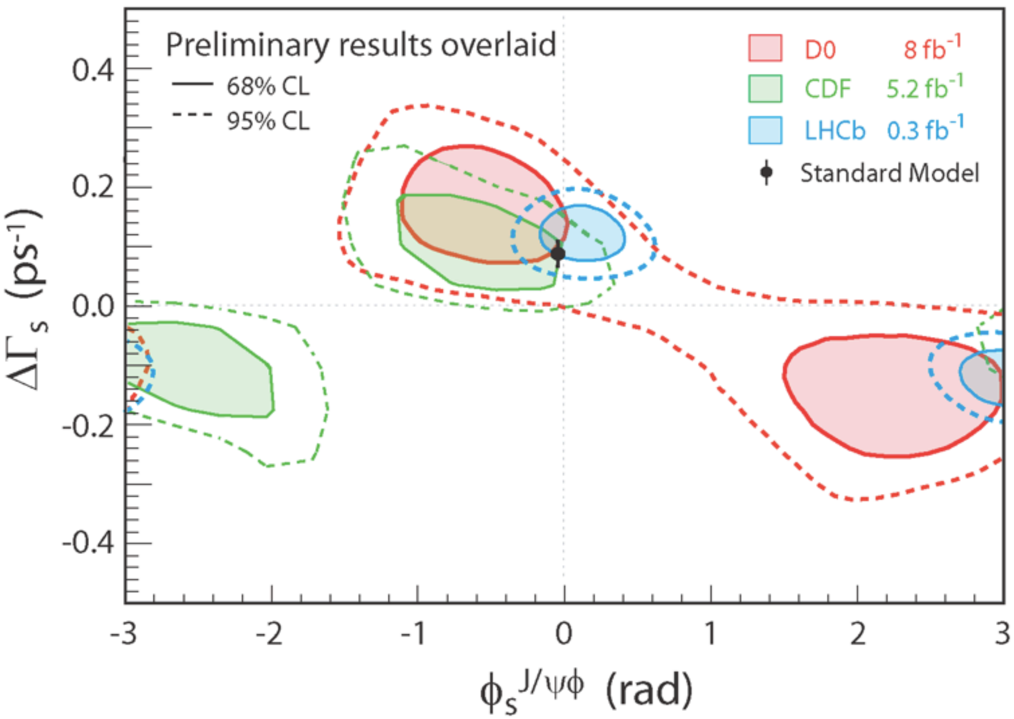
Atlas and CMS excellent detector performances even at high luminosities will allow for (future) new measurements of ϕ_s , in particular as their statistics will increase (competitive with O(>50/fb))

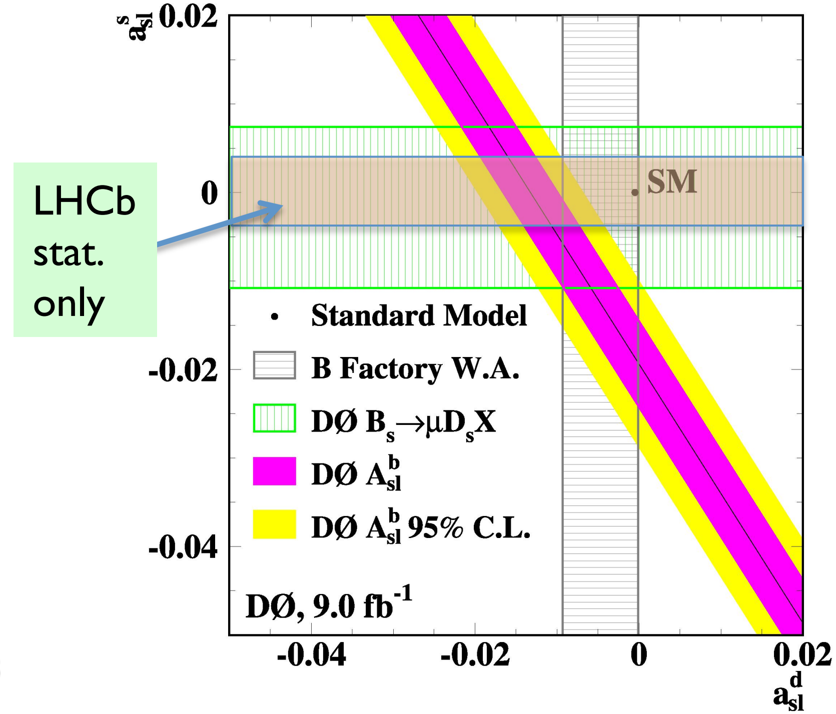






Status and perspectives of CPV measurements





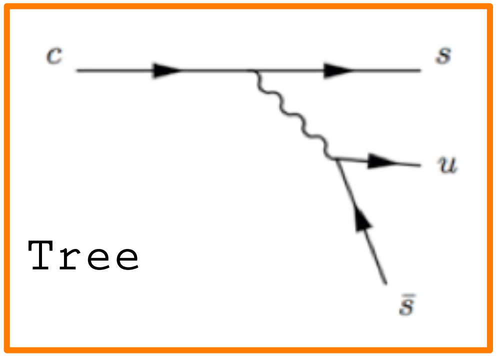
- Previous tensions with SM observed by CDF and D0 not confirmed
- A_{SL} (=asymmetry in semileptonic B decays) result from D0 (~4σ away from SM) to be tested soon by LHCb. This measurement planned also by CMS

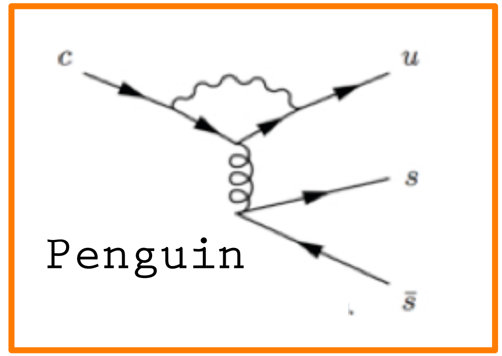
LHCb expects a precision of 0.1 rad with 1/fb data sample

A "charming" surprise

LHCb can profit of the huge charm production cross section at the LHC (~6 mb):
(non negligible trigger efficiency and huge sample of data)

B factories have observed tiny oscillations of D^0-anti D^0 system but not CP violation
Interference between tree and loop diagrams could generate direct CP violation





Measure CP violation in charmed mesons (e.g. in $D^0 \to hh$ decays) with unprecedented data samples

Particularly interesting as CPV in charm would be the only "up" quark type with this effect (top quark does not form hadrons)

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

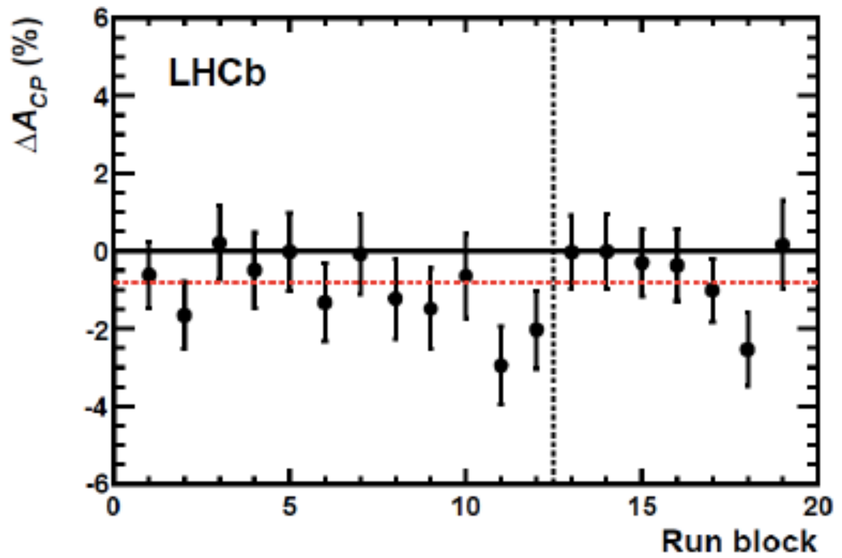
f = KK or $\pi\pi$

Theoretical expectations for A_{CP} are very small $10^{-3} \div 10^{-4}$ (but uncertainties up to 10^{-2})

LHCb has an evidence for CP violation in c quark at 3.5σ level (with 0.6/fb data sample): first "anomalous result" at LHC

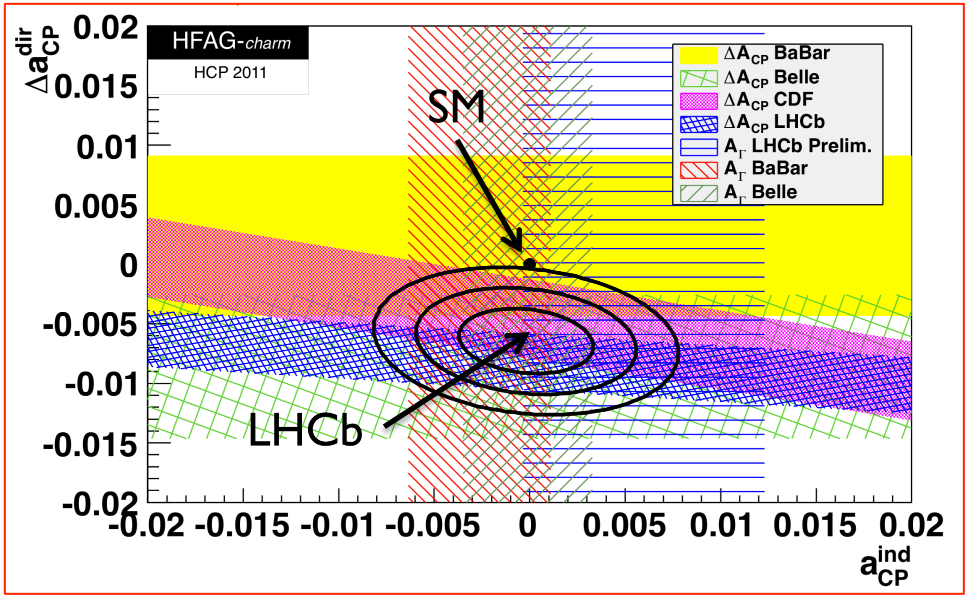
$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{sys.})]\,\%$$

Evidence to be confirmed with more statistics and with other independent cross checks



LHCb result generated a lot of theoretical interest
It has been suggested that the Standard Model could account for the measured value of CPV in charm (corrections to hadronic parts)

Only the observation of a similar result with other charm decays will solve the puzzle if it is NP or not

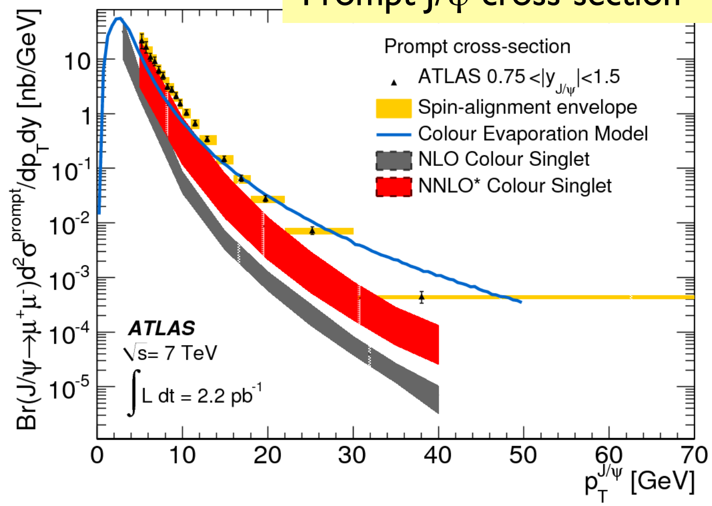


Quarkonia production

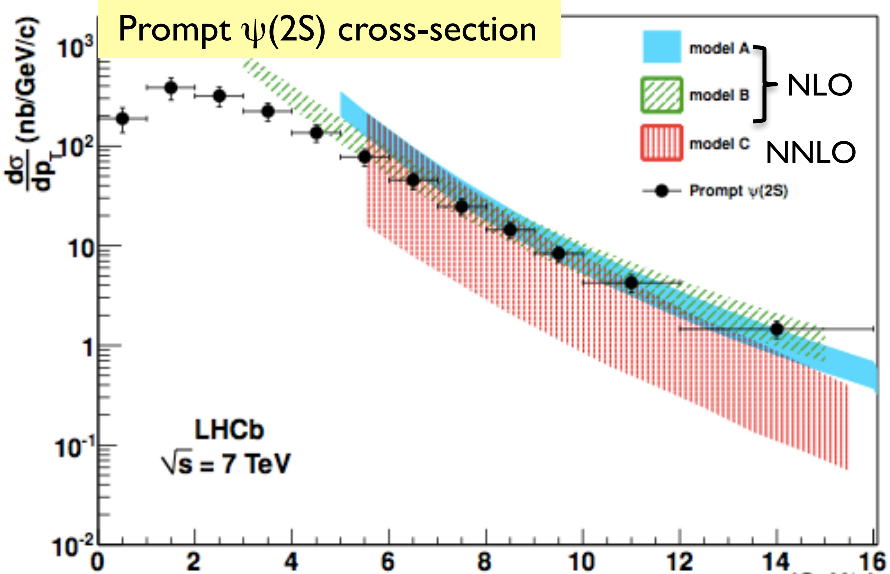
Test perturbative QCD at new energy regime, higher transverse momentum and wider rapidity range than previously (Atlas & CMS: high p_T, low η – LHCb: low p_T, high η)

Production mechanism for heavy quarkonium states (J/ψ, ψ(2S), Y and higher angular states) not fully understood.
Unprecedented level of test for the various fragmentation models

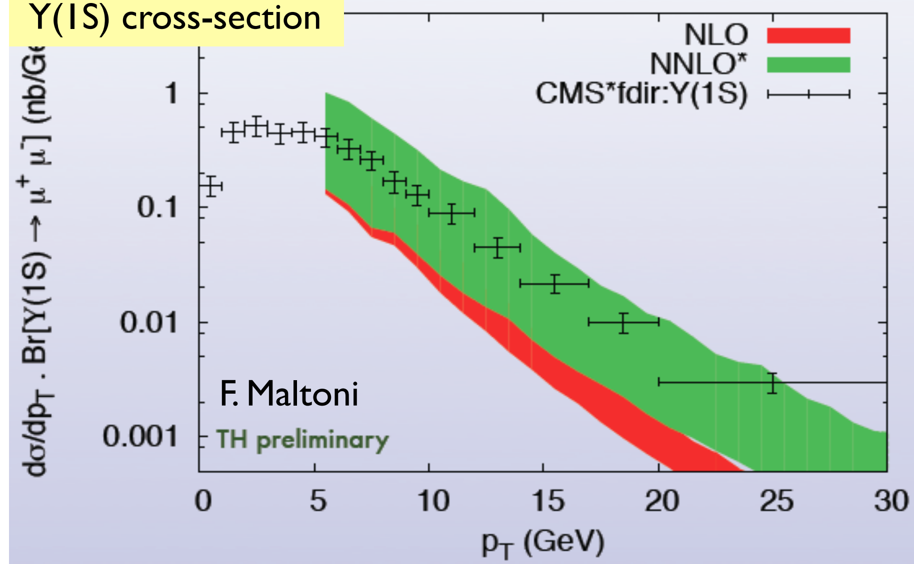
Prompt J/ψ cross-section



Prompt ψ(2S) cross-section



Y(1S) cross-section

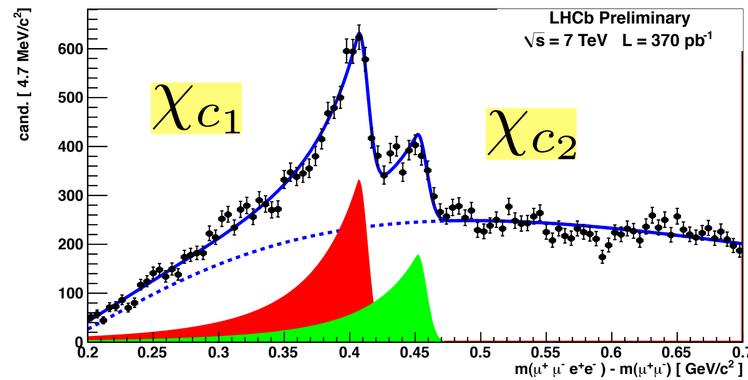


Next challenging measurements: obtain polarization values: strong test of models

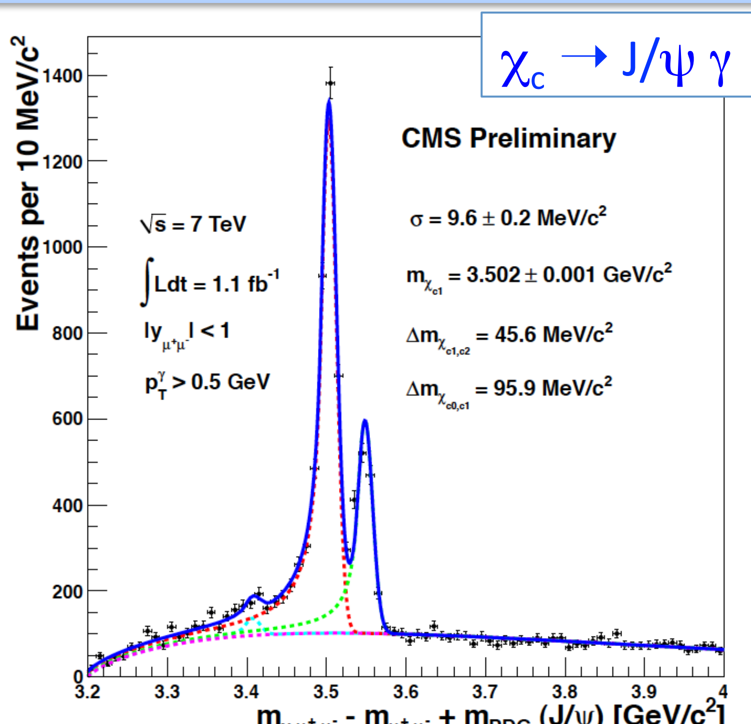
Study of radiative decays of cc and bb P wave resonances

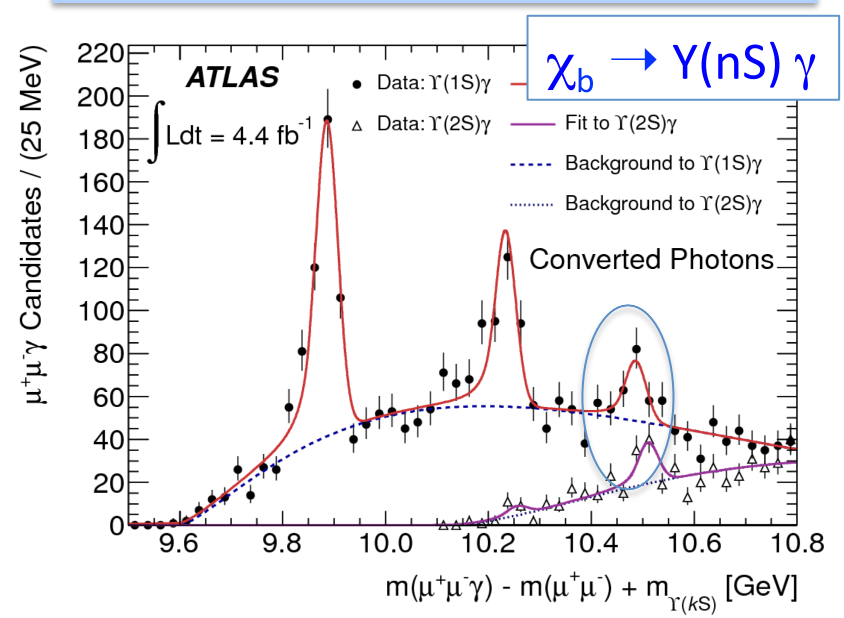
Clarify the mechanisms of hadron production in the fragmentation process
Present significant feed down states for J/ψ and Y (S wave states) inclusive production

Key role in identifying and measuring energy of photons in final states at LHC (first time at hadron colliders)

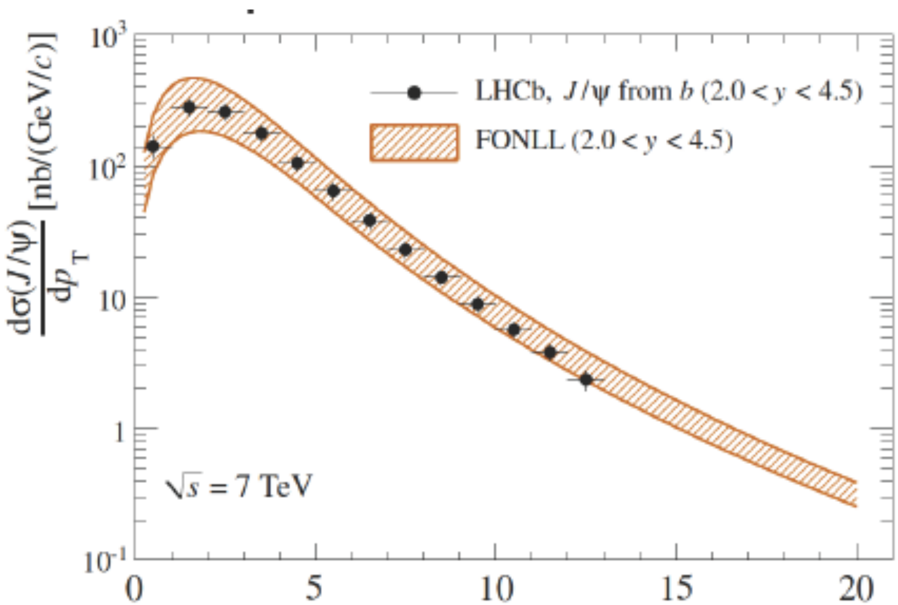


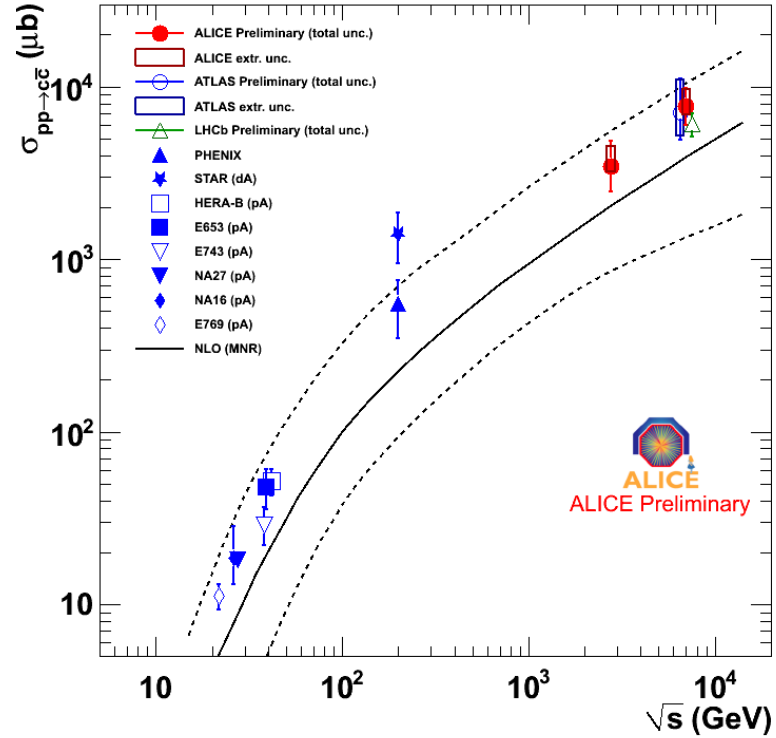
Mass (χ_b(3P)) = 10.530(9) GeV
First NEW observed particle at LHC
(… waiting for the Higgs …)



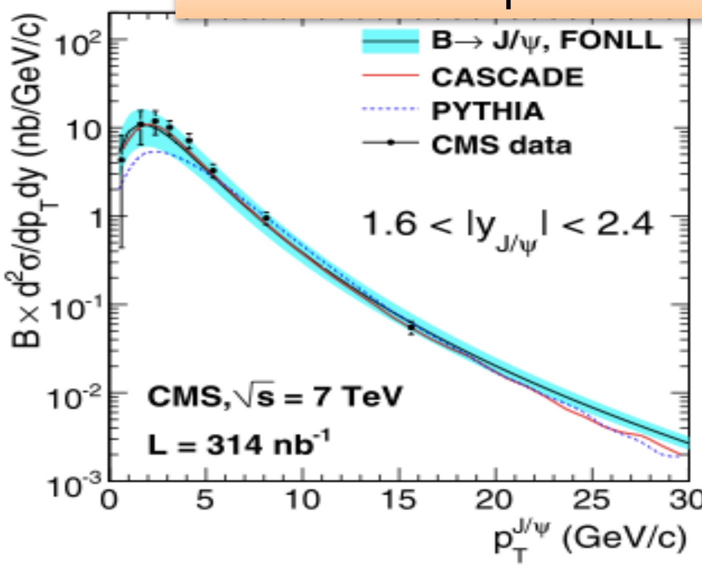


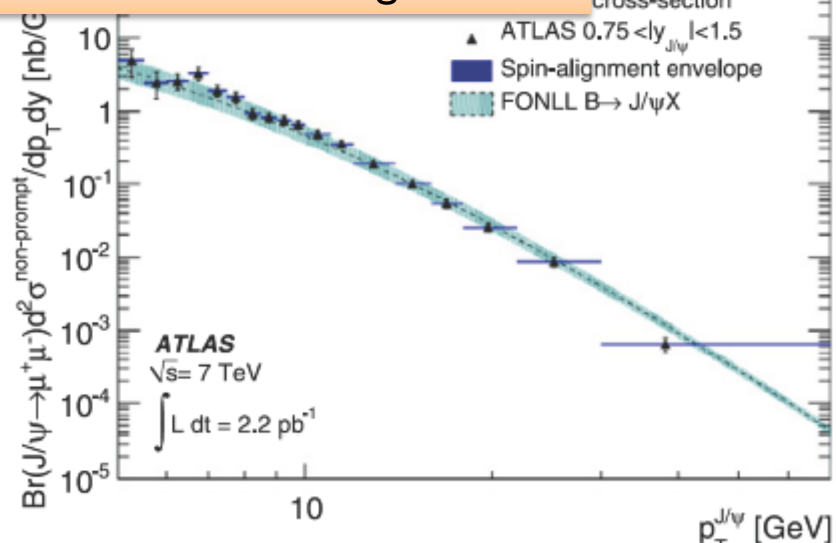
b and c production in pp collisions





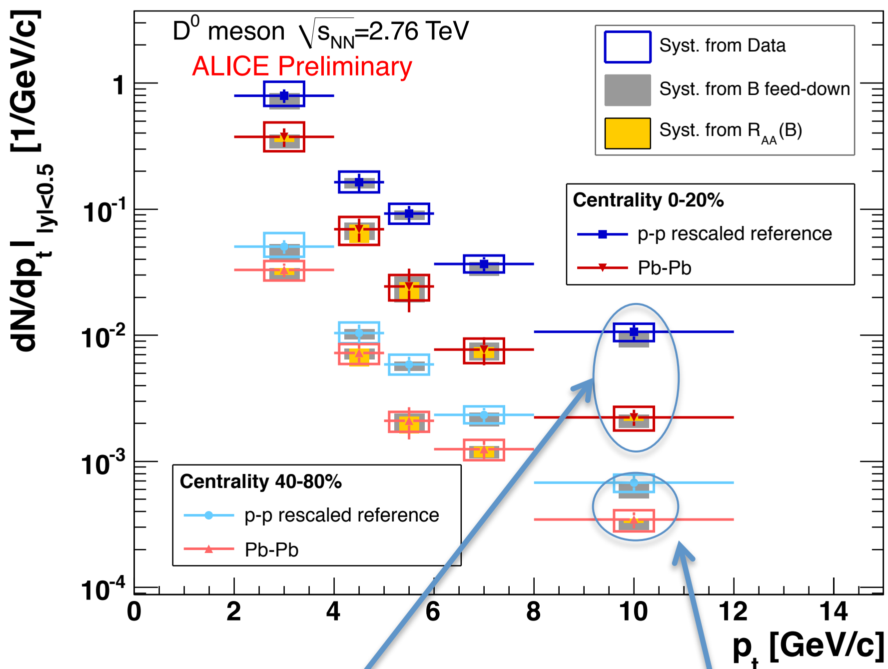
Consistent comparison with NLO over 3 orders of magnitude

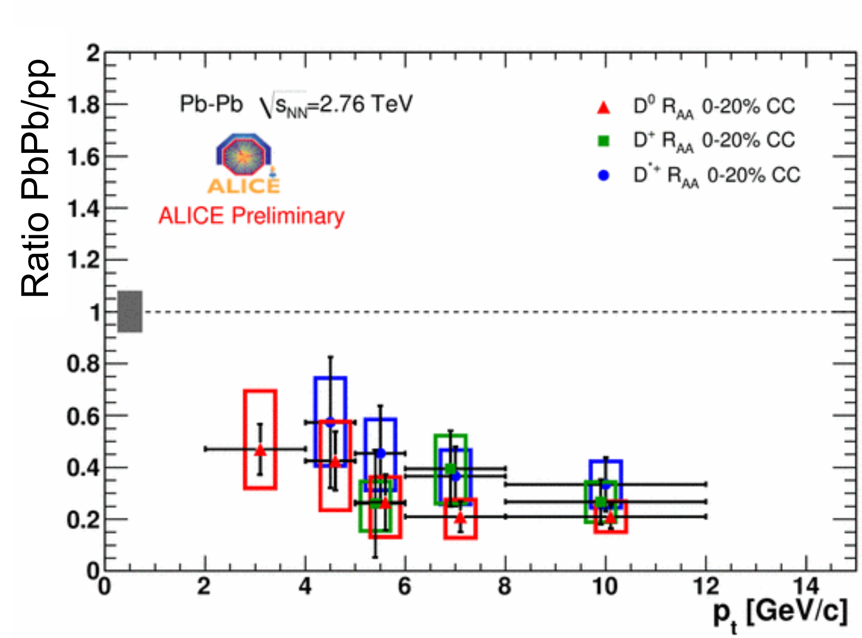




Charm production in dense matter (Alice)

"Centrality" (CC) gives an evaluation of density of matter probed by the heavy meson



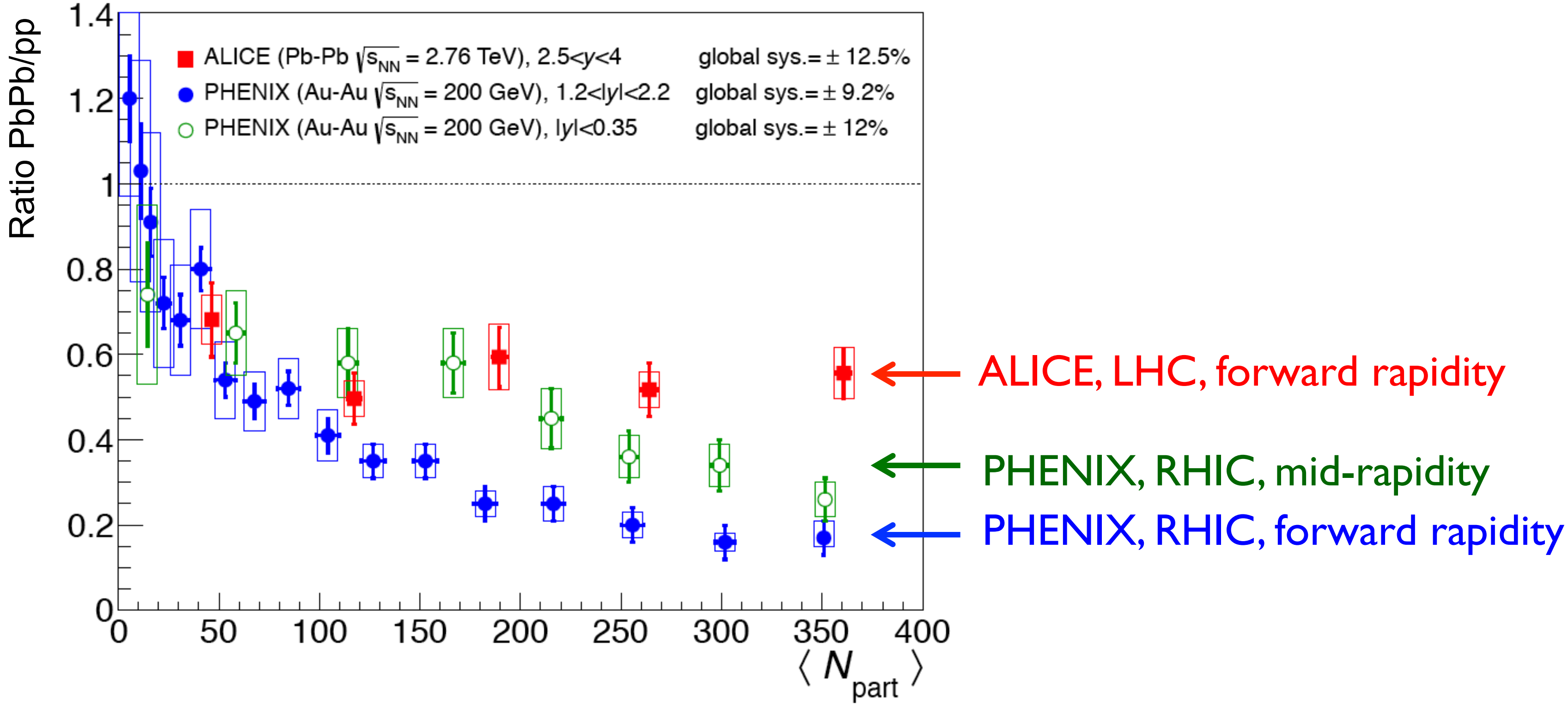


Strong suppression observed in central collisions (0-20%) wrt pp reference

Significant suppression also in semi-peripheral (40-80%) wrt pp reference

Suppression for charm is a factor 3-4 above p_T~5 GeV/c
Indicates strong energy loss of c quarks in the hot and dense QCD medium formed in these collisions

J/ψ in Pb-Pb: results and comparison with RHIC



R_{AA}(ALICE) > R_{AA} (PHENIX): smaller J/ψ suppression in spite of the factor 13 in $\sqrt{s}$

First indication for charm quark (re)combination in heavy-ion collisions

Similar studies possible also in Atlas & CMS

Perspectives: the long way to precision Heavy Flavor Physics

Type	Observable	Current precision (now)	LHCb (5 fb^{-1}) (~2017)	Upgrade (50 fb^{-1}) (~2025)	Theory uncertainty
Gluonic penguin	$S(B_s \to \phi\phi)$	-	0.08	0.02	0.02
	$S(B_s \to K^{*0}\bar{K}^{*0})$	-	0.07	0.02	< 0.02
	$S(B^0 \to \phi K_S^0)$	0.17	0.15	0.03	0.02
B_s mixing	$2\beta_s$ ($B_s \to J/\psi\phi$)	0.35	0.019	0.006	~ 0.003
Right-handed currents	$S(B_s \to \phi\gamma)$	-	0.07	0.02	< 0.01
	$\mathcal{A}^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	-	0.14	0.03	0.02
E/W penguin	$A_T^{(2)}(B^0 \to K^{*0}\mu^+\mu^-)$	-	0.14	0.04	0.05
	$s_0\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	-	4%	1%	7%
Higgs penguin	$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	30%	8%	$< 10\%$
	$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)}$	-	-	$\sim 35\%$	$\sim 5\%$
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	$\sim 20°$	$\sim 4°$	0.9°	negligible
	γ ($B_s \to D_s K$)	-	$\sim 7°$	1.5°	negligible
	β ($B^0 \to J/\psi\, K^0$)	1°	0.5°	0.2°	negligible
Charm CPV	A_Γ	2.5×10^{-3}	2×10^{-4}	4×10^{-5}	-
	$A_{CP}^{dir}(KK) - A_{CP}^{dir}(\pi\pi)$	4.3×10^{-3}	4×10^{-4}	8×10^{-5}	-

+ results from Atlas & CMS

Conclusions

Heavy Flavor is a portal to the discovery and the understanding the New Physics

The excellent performances of LHC and of the experiments has allowed to start producing exciting results in the Heavy Flavor Physics domain (LHCb in particular)

Standard Model still "un-cracked" but yet large room for unexpected phenomena: indirect searches are complementing direct searches for Supersymmetry

A lot of activities and very good perspectives for precise measurements in CP violation in b and c hadrons, CKM matrix, very rare decays, heavy flavor production in p-p and Pb-Pb collisions. LHC has produced already the best measurements in the field

Evidence (LHCb) of CP violation in charm could be an hint of New Physics (still to be verified with other measurements)

Looking forward to increase the statistics in 2012 (15/fb each ATLAS & CMS, 1.5 LHCb) and energy & statistics in 2015

Aiming to pin down theoretical expectations in Flavor Physics within the next decade !