The ATLAS beauty

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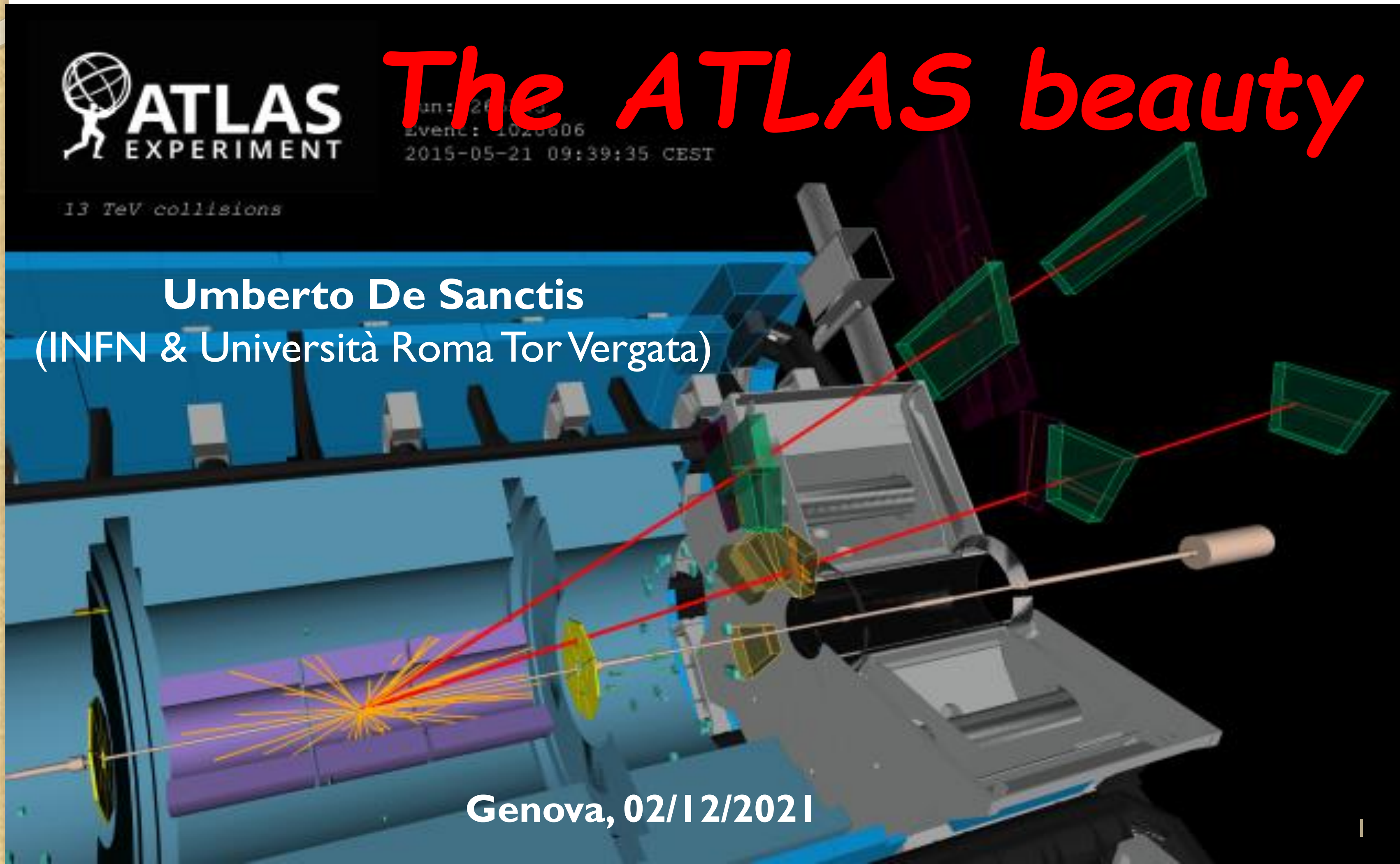


Genova, 02/12/2021

Outline

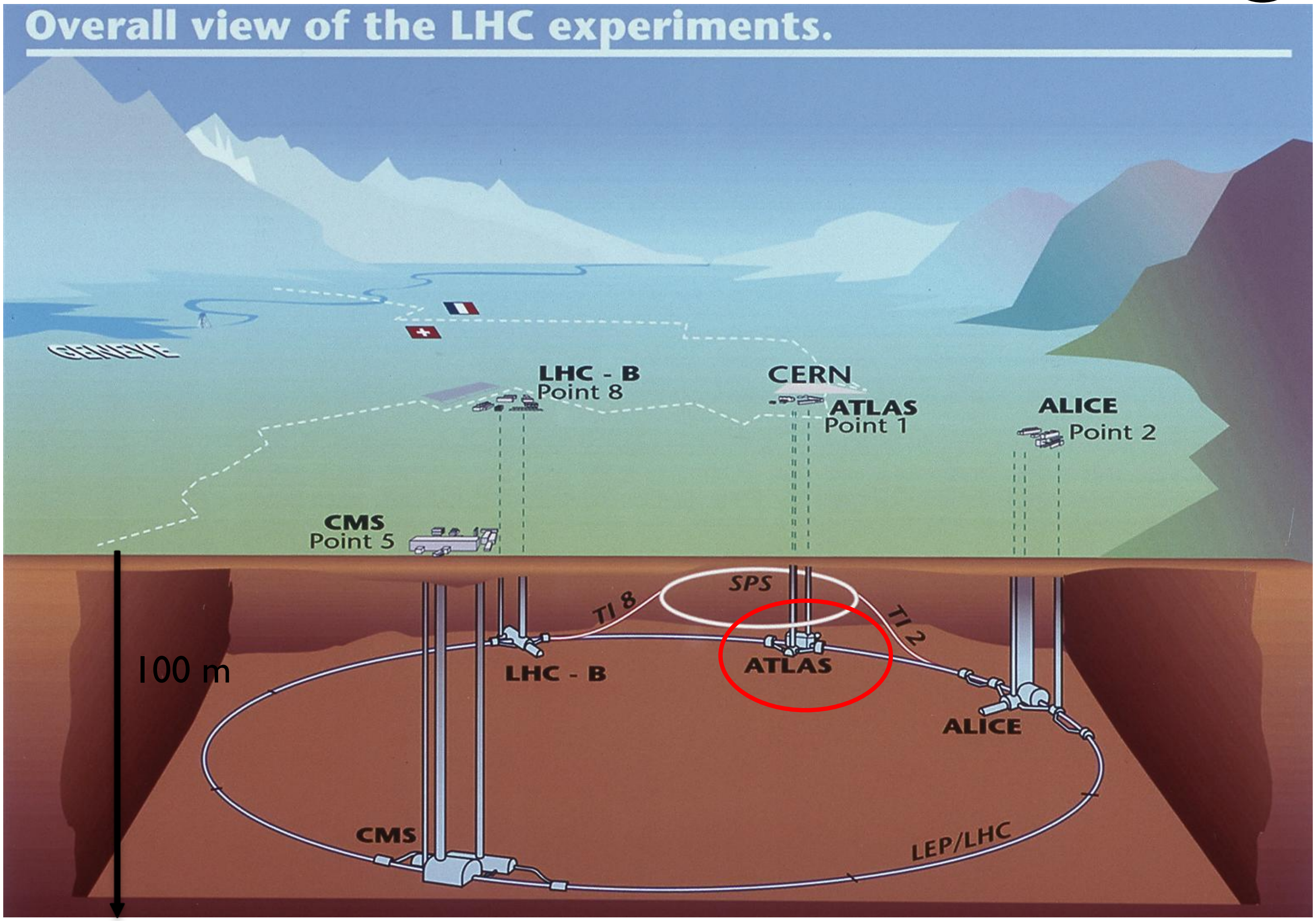
- LHC & the ATLAS Detector
- The ATLAS Trigger system
- (Some) ATLAS Highlights from LHC Run1 and Run 2
  - New particles
  - Exotic states
  - Quarkonium physics
  - B-mesons/hadrons properties
  - CP-violation measurements
  - Rare decays and New Physics contributions (e.g. B- anomalies)

CERN & LHC

- CERN (Centre Européen pour la Récherche Nucleaire)
  - Founded in 1954
  - The biggest laboratory for particle physics

- LHC (Large Hadron Collider)
  - The most powerful accelerator ever built
  - First pp collisions in 2010

CERN & LHC



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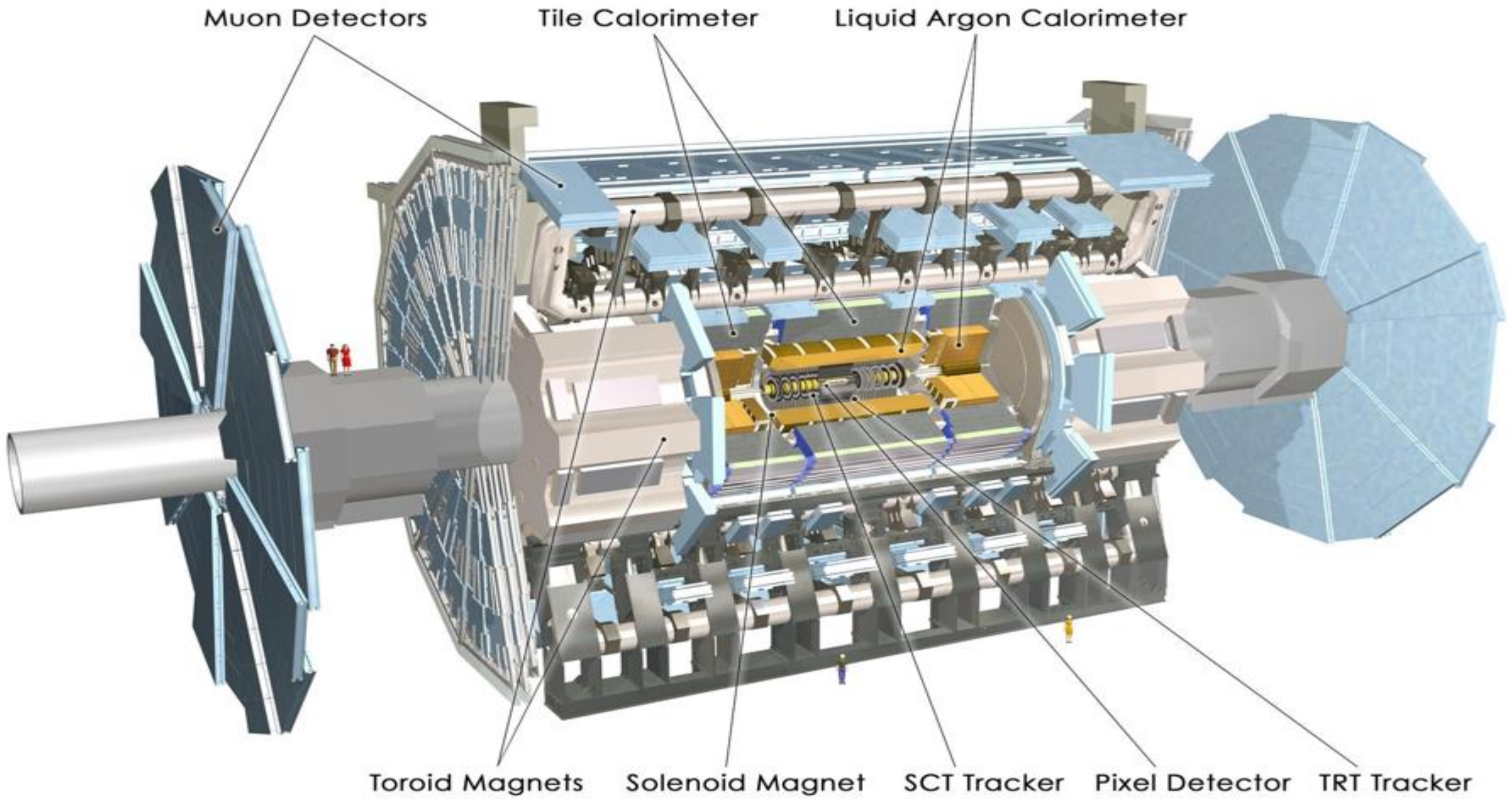
The ATLAS Experiment

- ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**)
  - "The Physics Giant"
  - 44x25 m, 7000 t
  - A multipurpose detector to find new particles and measure the properties of well-known particles



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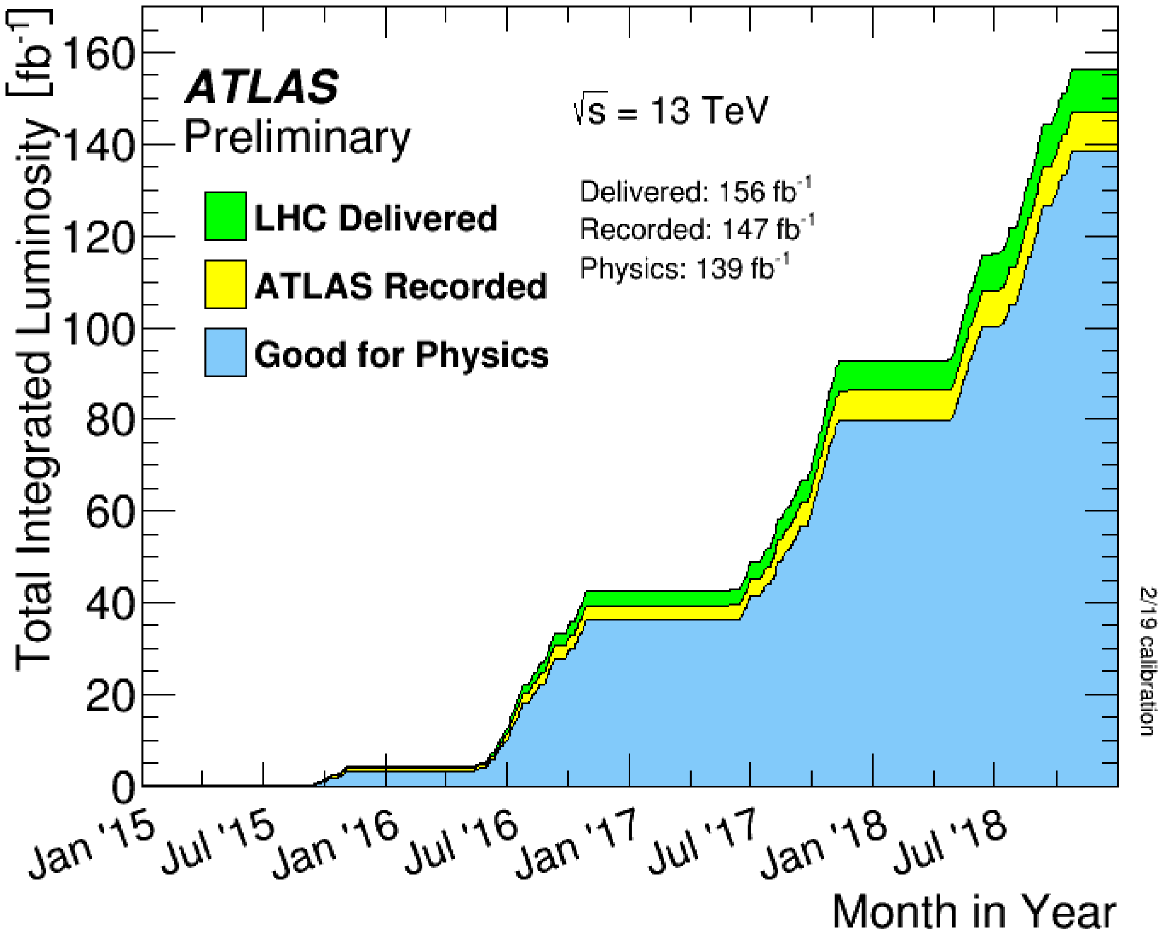
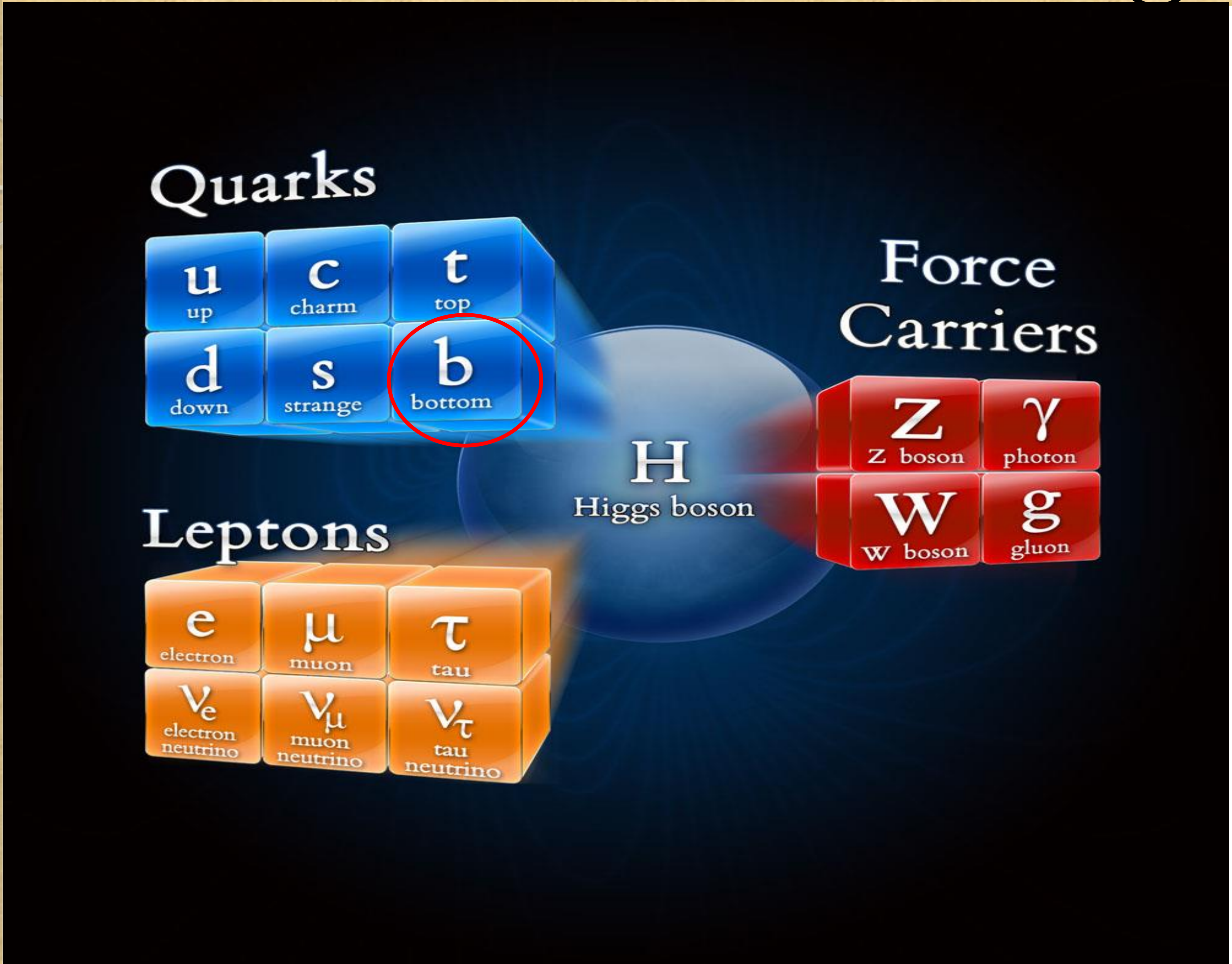
Integrated luminosities

- ATLAS collected data from 2010 to 2018 at a centre-of-mass energy $\sqrt{s}$ = 7, 8 and 13 TeV
  - Run 1 (2010-2013) → 4.9 fb^{-1} @ 7 TeV + 20.3 fb^{-1} @ 8 TeV
  - Run 2 (2015-2018) → 139 fb^{-1} @ 13 TeV



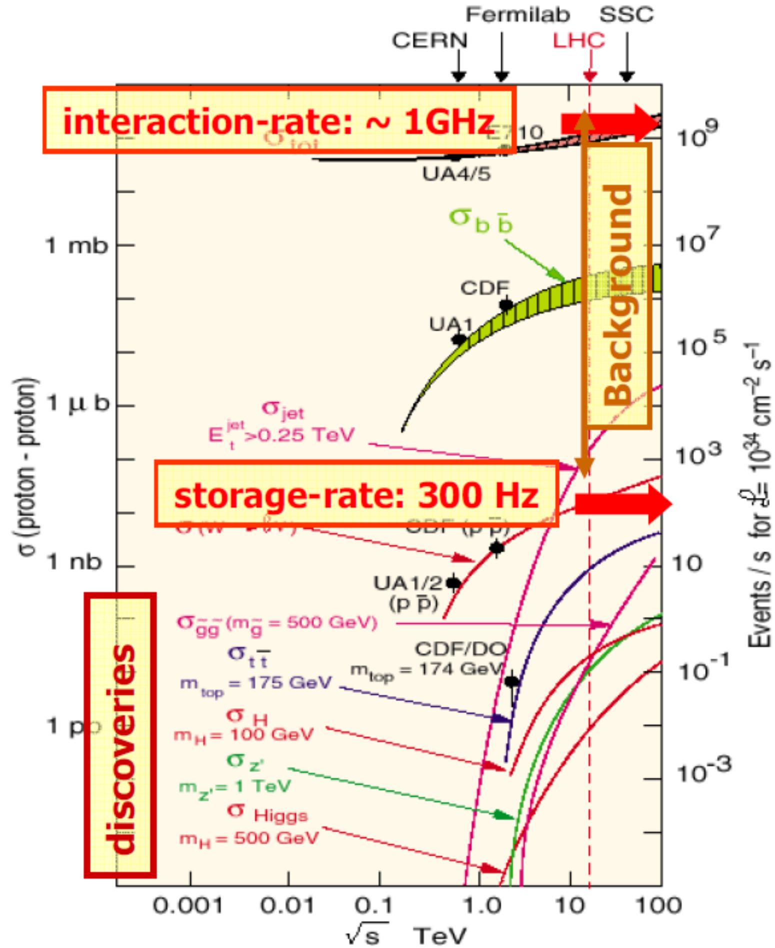
The Standard Model



Typical B-physics signatures

- B-physics signatures at hadron colliders are mainly made by:
  - Low transverse momentum (P_T) muons → Tracking system + muon system
  - Tracks in the Inner detector → Tracking system
  - Rarely photons/electrons → Electromagnetic calorimeter
- Trigger these events is complicated due to low thresholds in muon P_T → Incompatible with bandwidth constraints at high luminosity
- In addition ATLAS (and CMS) does not have specific detectors for particle identification → Kaons, pions, protons are all "just" tracks

Overview Trigger System



Selection of **rare events ($R \approx 10^{-5}$ Hz)** out of extremely **high background ($R = 10^9$ Hz)**

Realized in a **multi level trigger:**

Hardware

LVL1: muon and calorimeter signals used for "Regions of Interest"
stop data acquisition (75 kHz)

Software

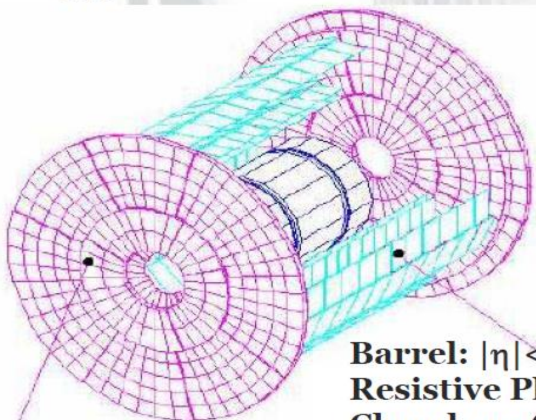
LVL2: LVL1 candidates used to find physics objects as **e**, **γ**, **μ**, **τ**, **jet**, **b-jet** or E_T^{miss} with reduced event information within Region of Interest
starts the read-out (2-3 kHz)

Software

EF: full event information, fast data analysis
storage after filtering (300 Hz)

Muon-trigger system in ATLAS

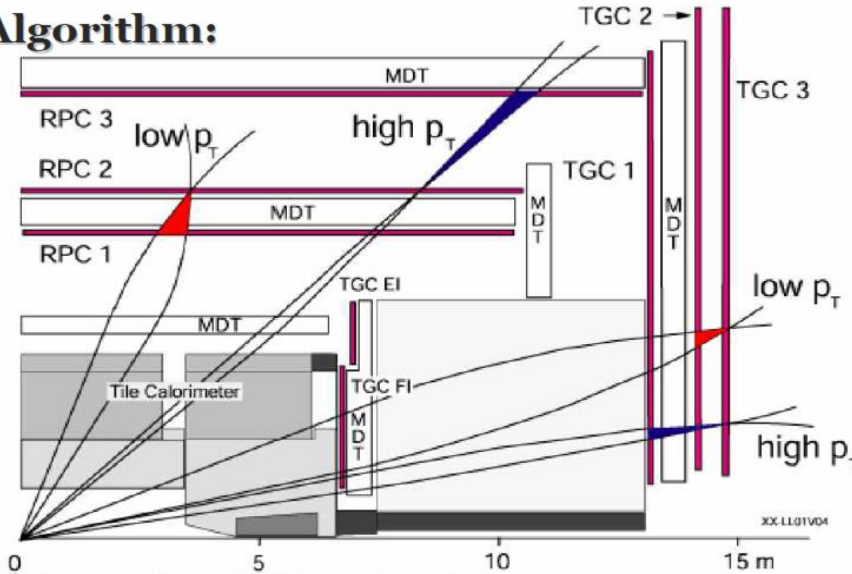
Trigger Chambers:



Barrel: |η|<1.0
Resistive Plate Chambers (RPCs)

End-caps: 1.0< |η|< 2.4
Thin Gap Chambers (TGCs)

Algorithm:



- **deflection** depends on muon p_T
- programmable width of **6 coincidence windows** determines the p_T threshold.
- MuCTPI collects information form RPC and TGC triggers does overlap removal. Sends results to the CTP for LVL1 event decision

Detector too big to be readout completely at L1 →Region of Interest (RoI) i.e. a region of the detector where something "interesting" happened

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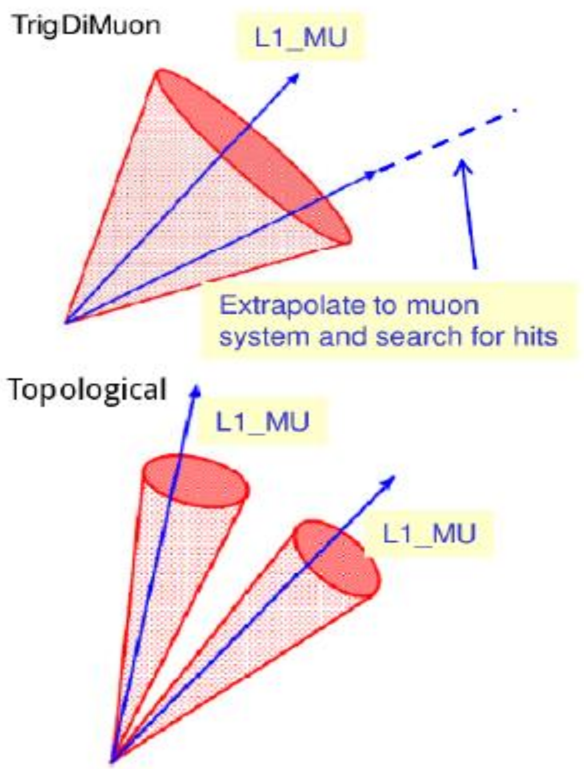
Triggering events in Run 1 …

- Two approaches based on instantaneous luminosity:
  - TrigDiMuon algorithm – low luminosity periods
    - Seeded by a single muon RoI
    - Look for Inner Detector track in the RoI and extrapolate to Muon Spectrometer
    - Efficient for low-P_T J/Ψ but high rate.
  - Topological algorithms
    - Seeded by two muon RoIs
    - Lower rate but less efficient for low-P_T
    - Primary trigger in most of Run1



Signatures looked at:

- Jpsimumu: 2.5–4.3 GeV
- Bmumu: 4–8.5 GeV
- Upsimumu: 8–12 GeV
- Dimu: 1.5–14 GeV, prescaled

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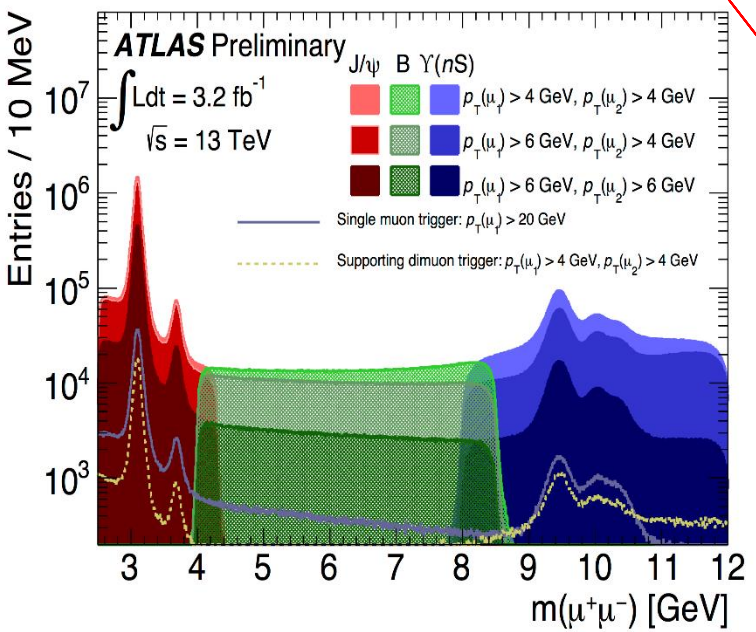
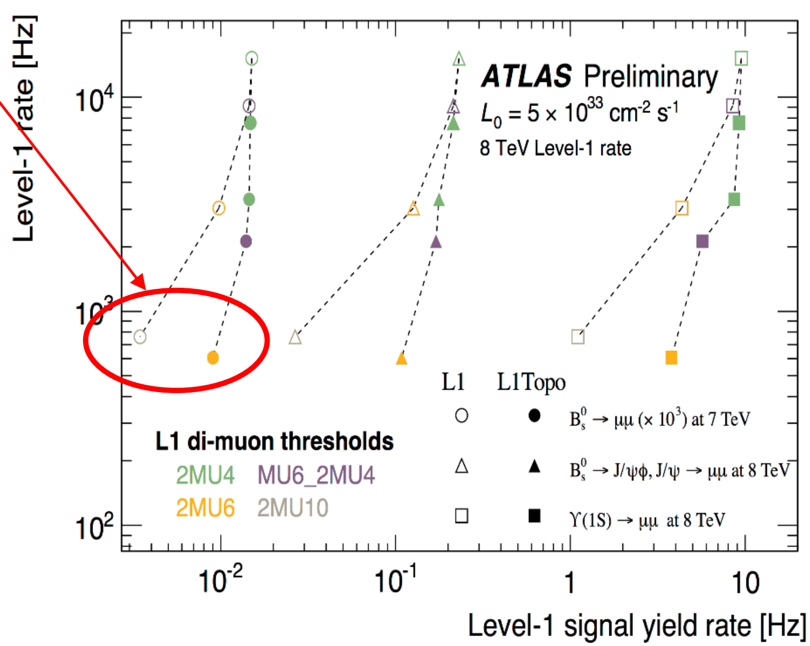
…and in Run2

- Topological trigger!
- Use info on PT, η and φ of the muon ROIs to build topological di-muon quantities (inv.mass or ΔR):
  - Efficient way to reduce bandwidth usage keeping the signal efficiency high
  - Gain up to a factor of 3 in di-muon background rejection!
  - Baseline for 2017 data (with MU4_MU6 and 2MU6 thresholds)

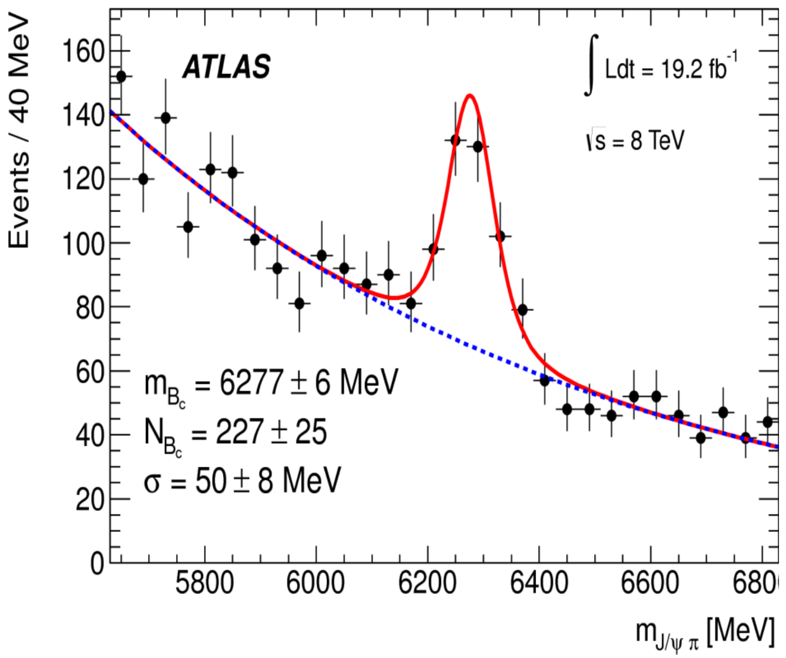


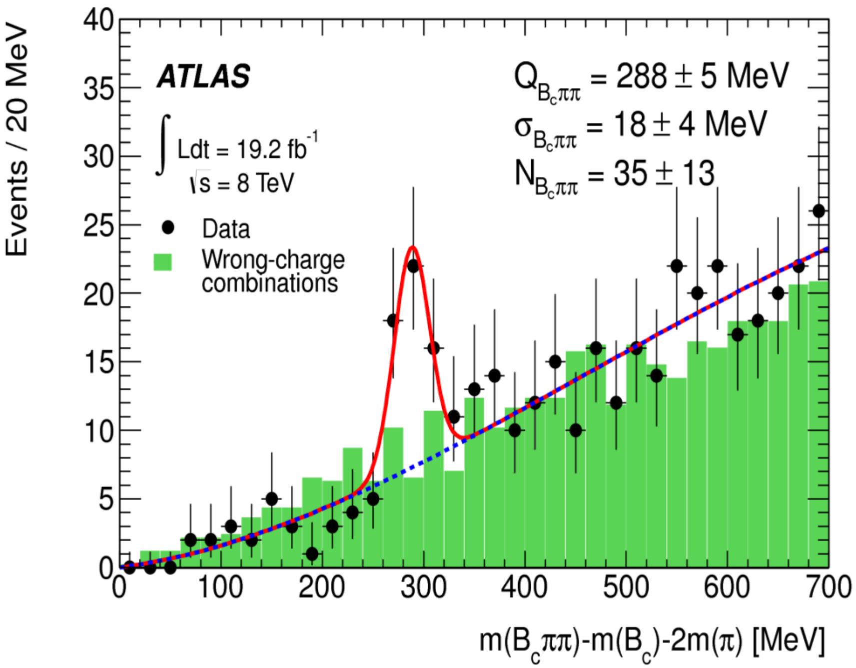


New Bc meson excited state

Phys. Rev. Lett. 113 (2014) 212004

- $B_c^{\pm}(2S) \rightarrow B_c^{\pm}\pi^{+}\pi^{-}$ $(B_c^{\pm} \rightarrow J/\psi(\rightarrow \mu\mu)\pi^{\pm})$
- Both 2011 and 2012 data with a combined significance 5.2 σ
- Consistent with second S-wave excitation of B_c

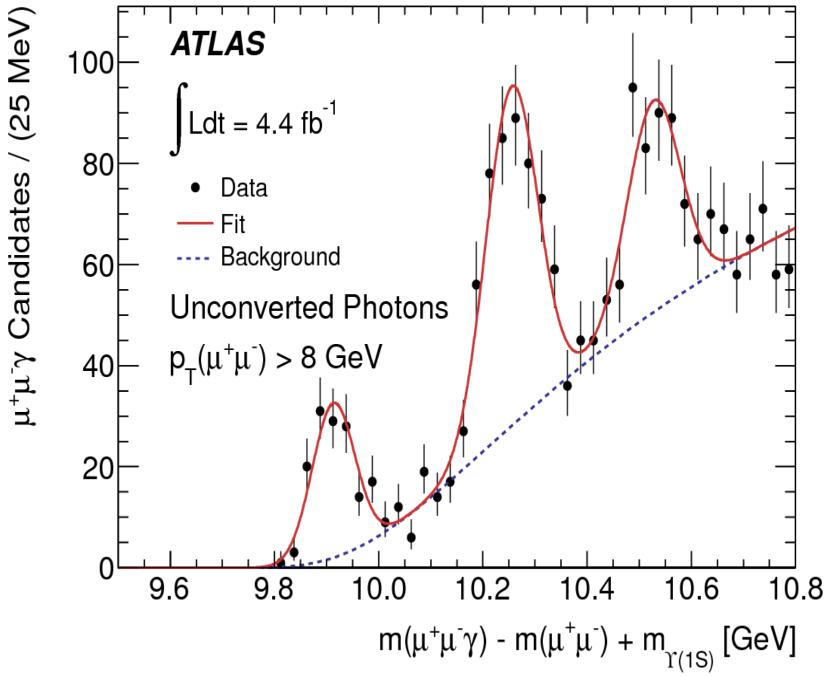


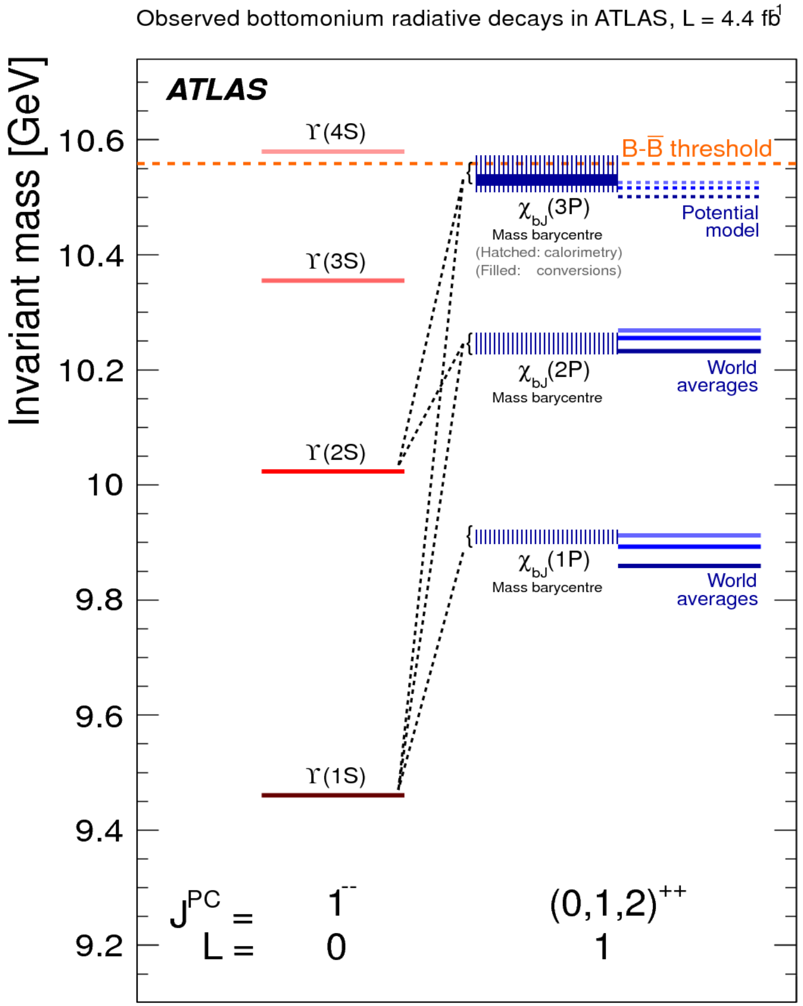


New particle!!!

- Observation of the new state $\chi_b(3P) \rightarrow \Upsilon(1S,2S)\gamma$
- First particle discovered in the LHC
- Confirmed by other experiments

Phys. Rev. Lett. 108 (2012) 152001





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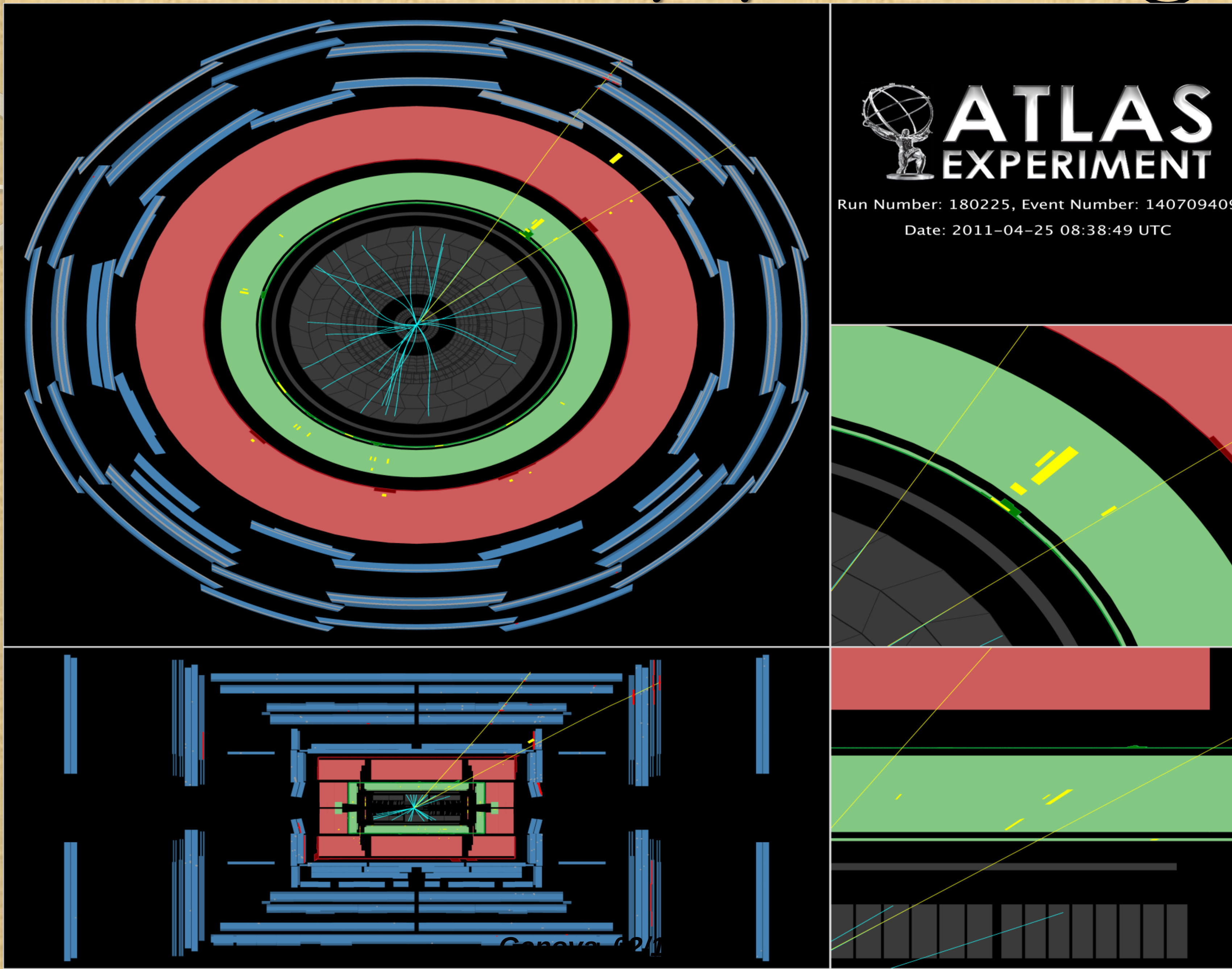
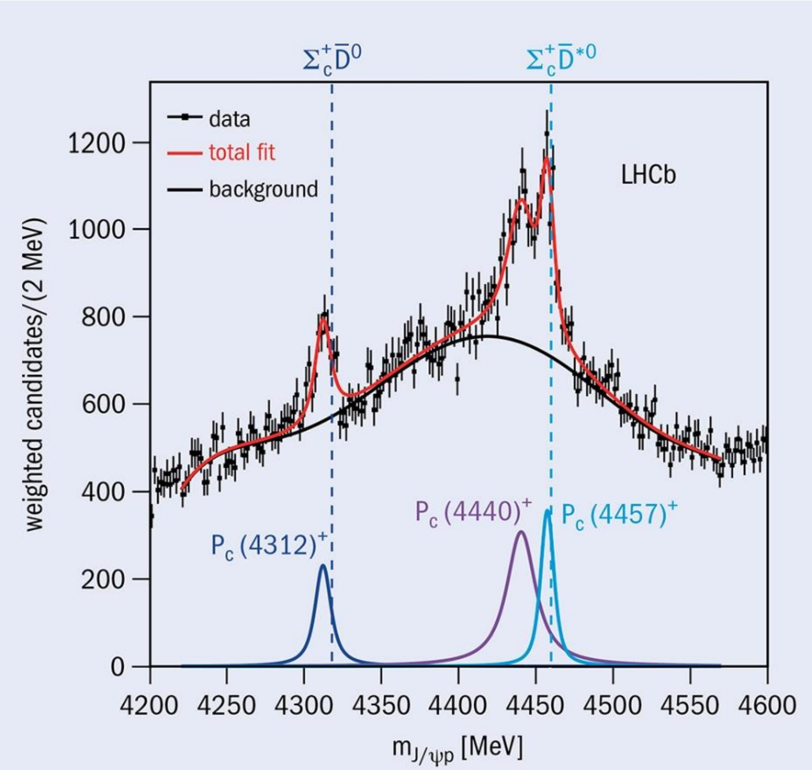
Event display



Exotic states: pentaquarks!

- Baryons and mesons are made of respectively by 3 quarks and a quark-antiquark pair $q\bar{q}$
  - Can baryons made of 5 quarks and mesons made of two $q\bar{q}$ pairs exist?
- In principle yes! They do not violate any symmetry….
- LHCb first and then ATLAS found evidence of the production of those strange particles..
- By looking at the Λ_b^0→J/ΨpK decays in 2015 LHCb claimed the presence of new states in the J/Ψp sub-system invariant mass
  - m(J/Ψp) not compatible with a 3-body decay
- The first firm evidence of a particle made of 5 quarks: the Pentaquark!
- Quark composition: $duuc\bar{c}$
- Spin-parity J^P: ½$^-$ for Pc(4312)



https://doi.org/10.1103/PhysRevLett.122.222001

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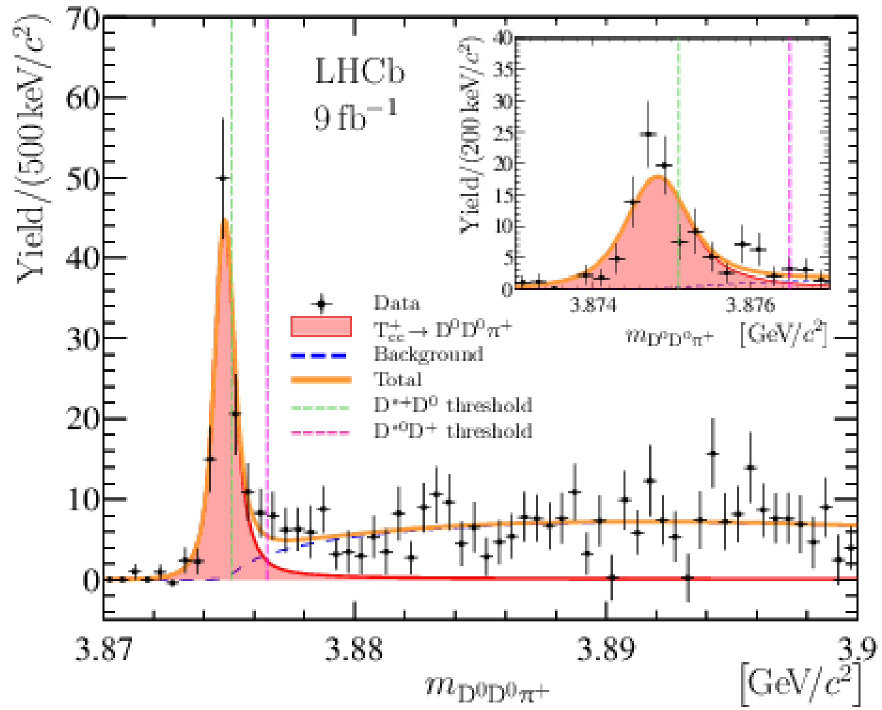
Exotic states: tetraquark!

- Baryons and mesons are made of respectively by 3 quarks and a quark-antiquark pair $q\bar{q}$
  - Can baryons made of 5 quarks and mesons made of two $q\bar{q}$ pairs exist?
- In principle yes! They do not violate any symmetry….
- LHCb first found evidence of the production of those strange particles..

- In 2021 LHCb claimed the presence of new states in the $D^0 D^0 \pi^+$ sub-system invariant mass
  - m($D^0 D^0 \pi^+$) not compatible with a $D^0 D^{0*}$ decay
- The first evidence of a particle made of 4 quarks: the Tetraquark!
- Quark composition: $cc\bar{u}\bar{d}$
- Spin-parity J^P: 1^+



http://arxiv.org/abs/2109.01038

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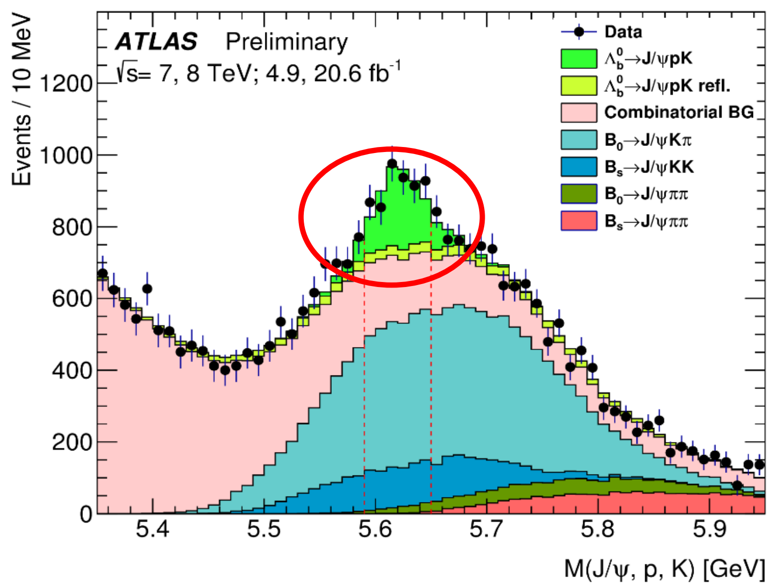
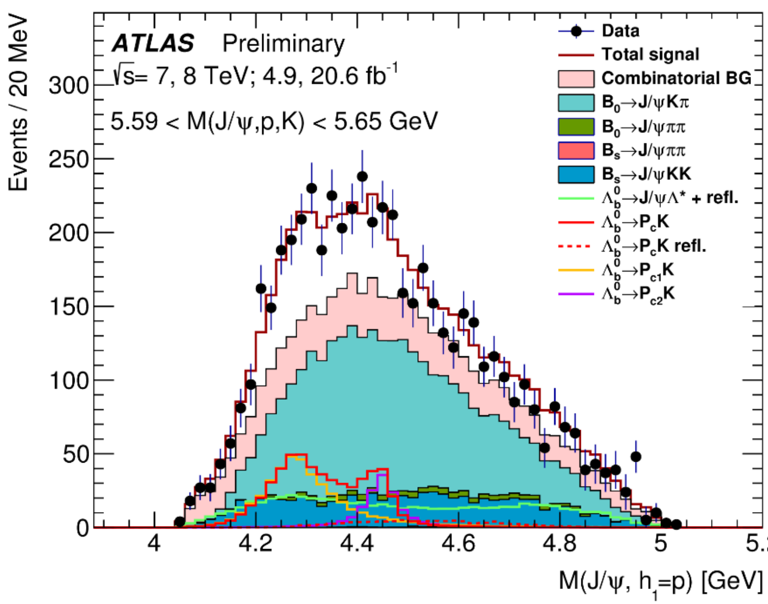
- ATLAS looked at the $\Lambda_b^0 \to J/\Psi pK$ decay as well to confirm/reject the LHCb evidence
- Reconstruction of both Λ_b^0 and $J/\Psi p$ invariant masses more complicated due to the missing particle identification → Combinatorial background difficult to treat!

ATLAS-CONF-2019-048





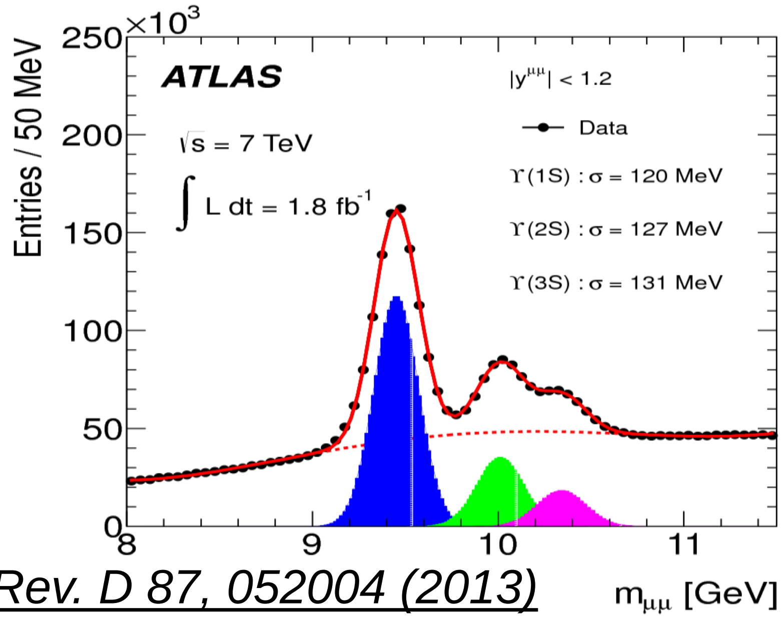
- The fits prefers the hypothesis of 2 pentaquarks with masses compatible with LHCb ones
  - No PQ hypothesis excluded with a p-value of 0.9%

Quarkonium physics

- Quarkonium is the generic definition of a bound state made of a quark-antiquark pair of the same flavour
    - Notable examples: J/Ψ (charmonium) and Υ (bottomonium)
    - Masses: 3.097 GeV and 9.46 GeV (ground-state)

- The J/Ψ can be produced at LHC in two ways:
    - Promptly (i.e. from the main partonic collision)
    - From the decay of B-hadrons (e.g. $B^{\pm} \rightarrow J/\Psi K^{\pm}$)

- The Υ can be produced only promptly (i.e. from the main partonic collision)
    - Present in several excitation (due to angular momentum)



Phys. Rev. D 87, 052004 (2013)

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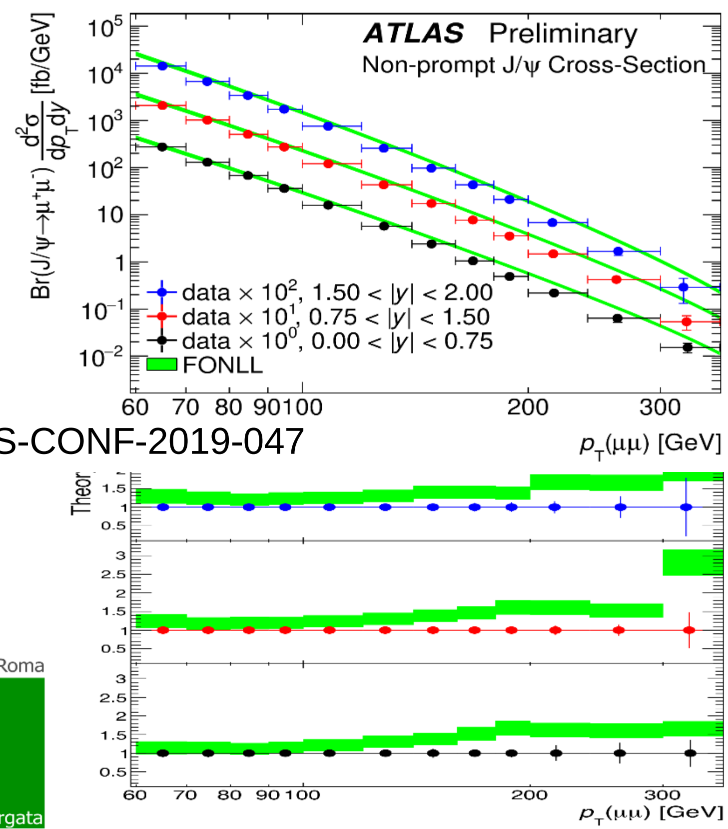
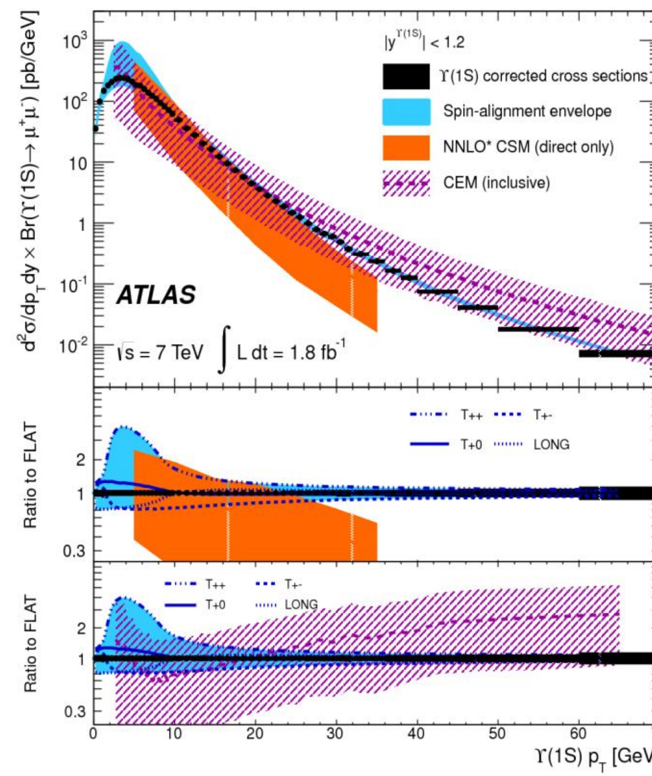
Quarkonium physics

- Both decays are reconstructed from the invariant mass of two muons
- Inclusive and differential cross-section (vs P_T and y)
  - Crucial to compare them with theory
- Both prompt and non-prompt (i.e. from B mesons decay mainly) components measured for J/Ψ



ATLAS-CONF-2019-047

Phys. Rev. D 87, 052004 (2013)



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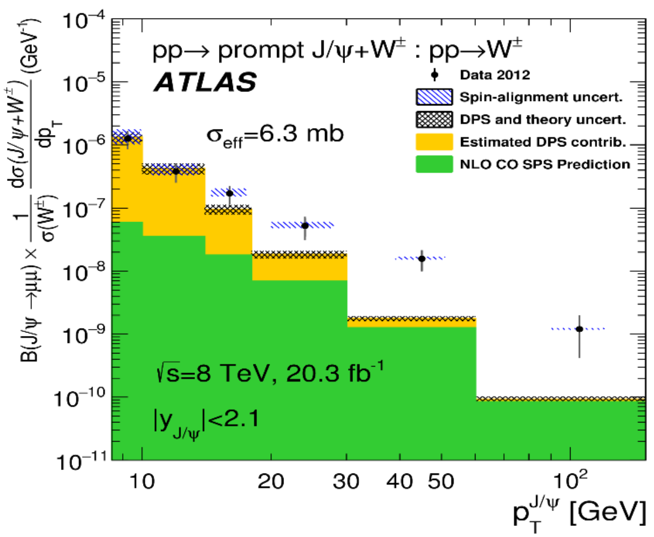
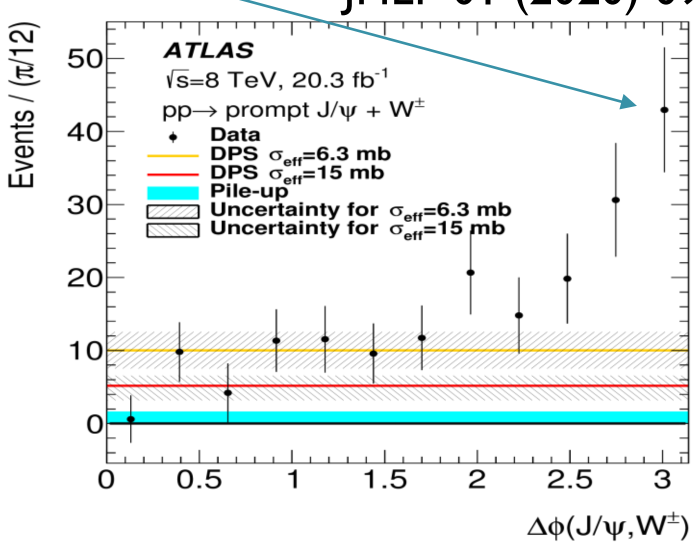
W+J/Ψ associated production

- Interesting to study the QCD at the border between perturbative and non-perturbative regimes.
- W+J/Ψ can be produced via two mechanisms:
  - SPS (Single Parton Scattering)
  - DPS (Double Parton Scattering)
- The J/Ψ is reconstructed in the di-muon decay while the W in its leptonic decay (electron/muon)
- SPS contribution extracted from data after subtracting the DPS (uncorrelated) component

JHEP 01 (2020) 095



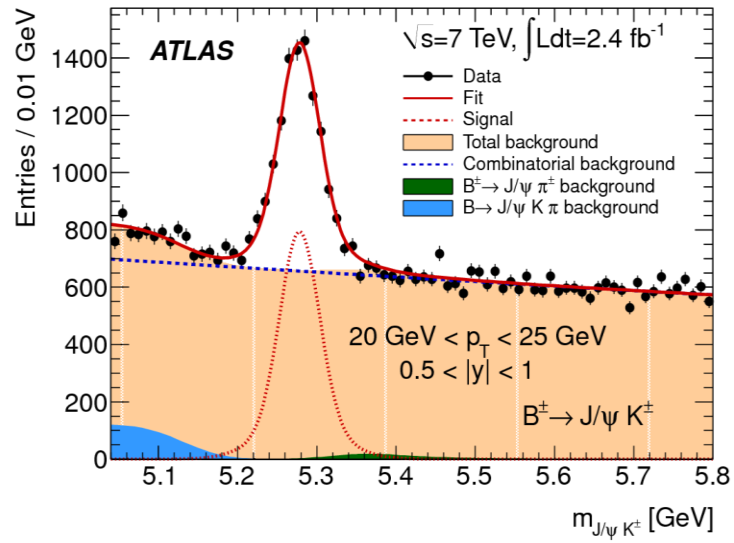


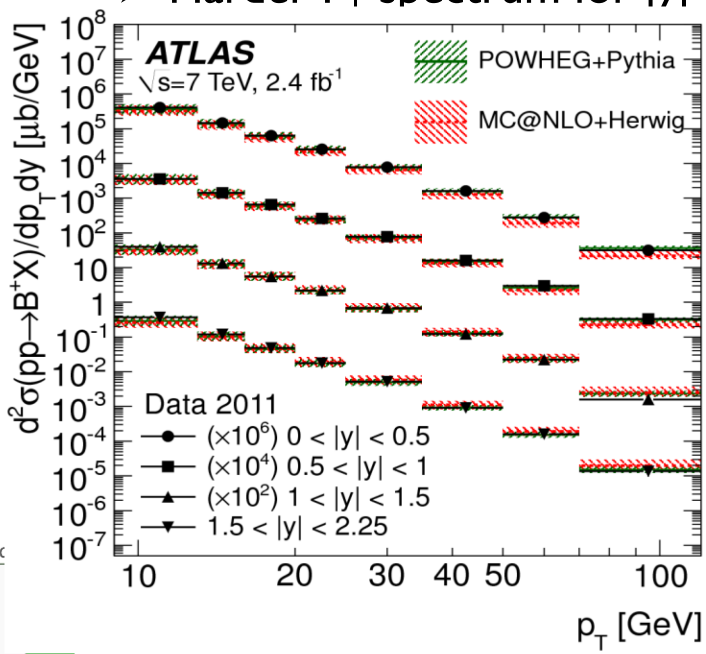
NLO CO model does not describe well data at high PT(J/Ψ)

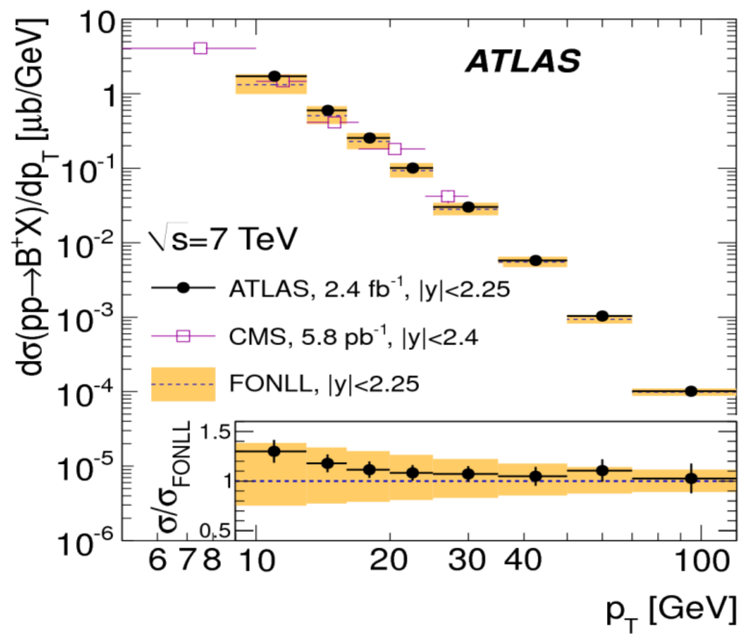
B+ production cross-section

JHEP 10 (2013) 042

- Look at $B^{\pm} \to J/\Psi K^{\pm} \to \mu\mu K^{\pm}$
- B+ cross-section up to P_T of 120 GeV
- Differential cross-section vs P_T and η
- Comparison with theoretical predictions:
  - POWHEG+Pythia agreement
  - FONLL good agreement
  - MC@NLO has:
    - Lower cross-section
    - Softer P_T spectrum for low |y|
    - Harder P_T spectrum for |y| > 1







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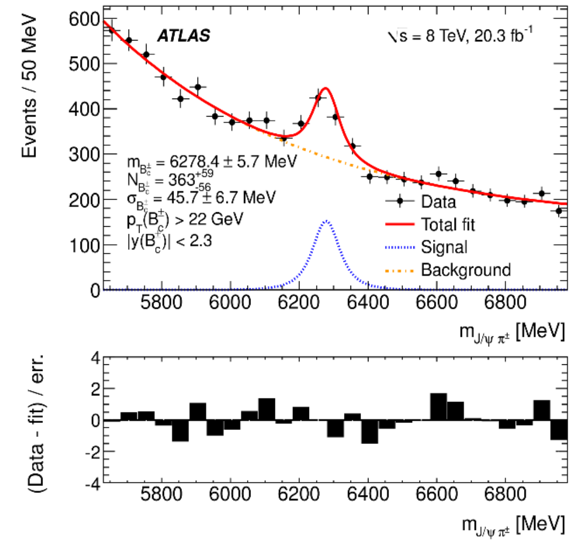
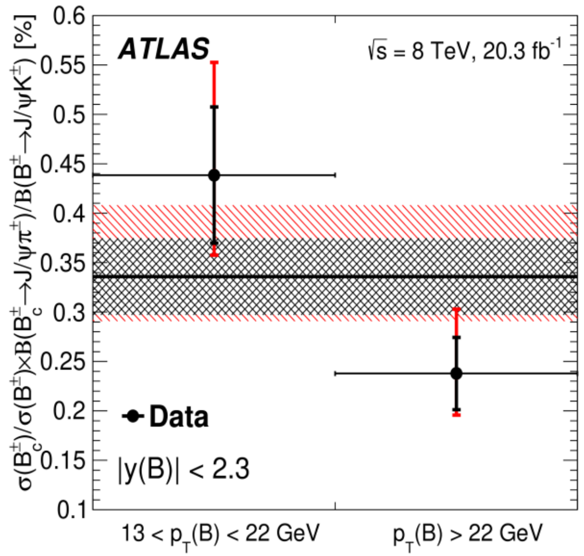
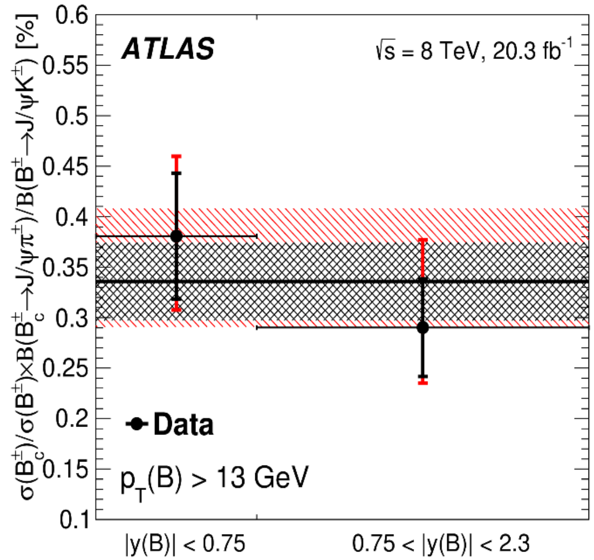
Bc/B+ production cross-section

- ➢Bc meson is the heaviest known meson
- ➢Its dynamics are still under investigation
    - ➢ No data from B-factories
- ➢ This measurement compares its total and differential production cross-section w.r.t. the $B^{\pm}$
    - ➢Bc → $J/\Psi\pi^{\pm}$ vs $B^{\pm}$ → $J/\Psi K^{\pm}$







Hint of a dependence from PT of the Bc cross-section w.r.t. the $B^{\pm}$ one

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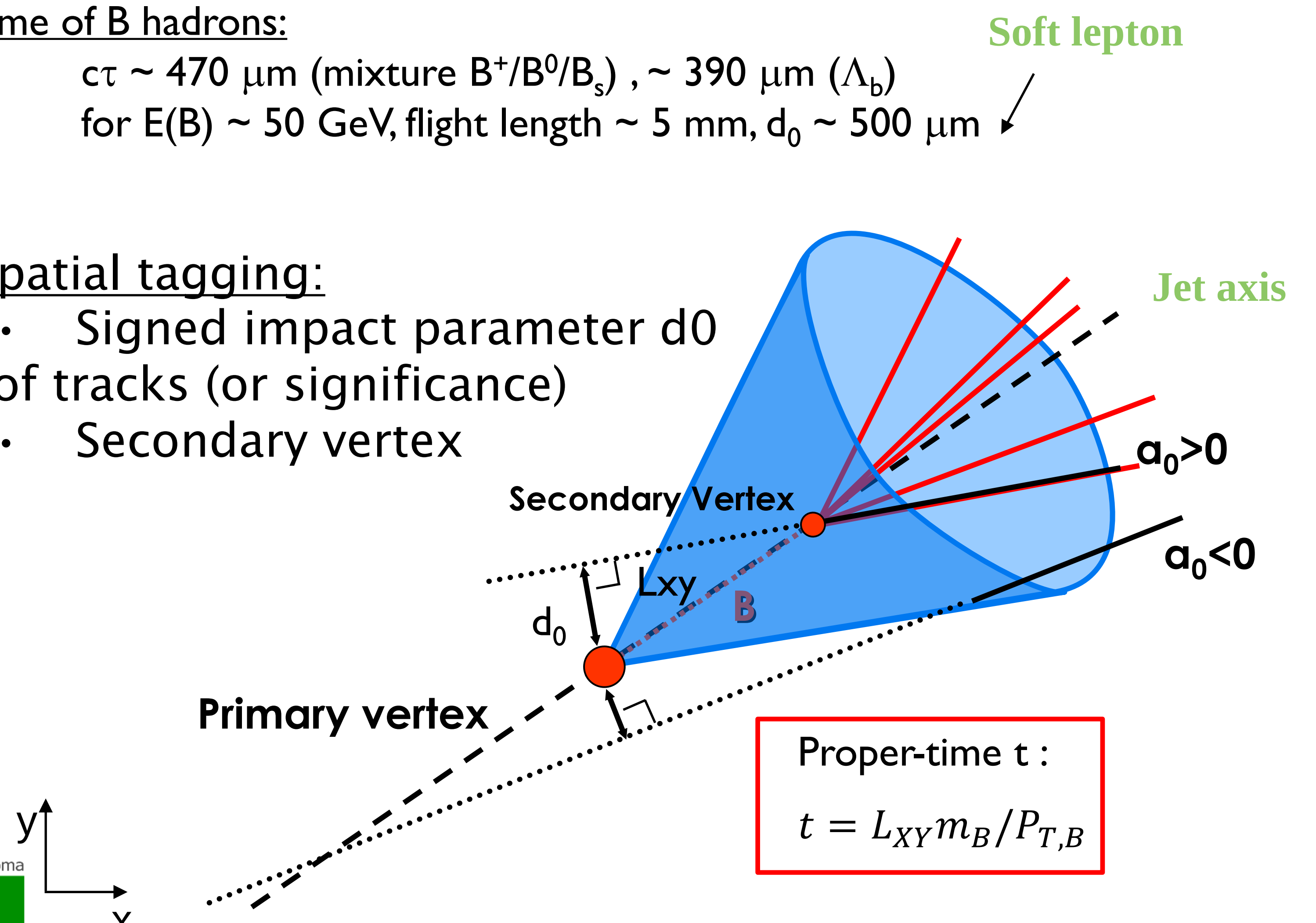
Phys. Rev. D 104 (2021) 012010

B-mesons lifetime

Hard fragmentation of b quarks $x_B \sim 70\%$
High mass $m_B \sim 5$ GeV
Lifetime of B hadrons:
$c\tau \sim 470\ \mu m$ (mixture $B^+/B^0/B_s$) , $\sim 390\ \mu m$ (Λ_b)
for E(B) ~ 50 GeV, flight length ~ 5 mm, $d_0 \sim 500\ \mu m$

➔ Spatial tagging:
- Signed impact parameter d0 of tracks (or significance)
- Secondary vertex



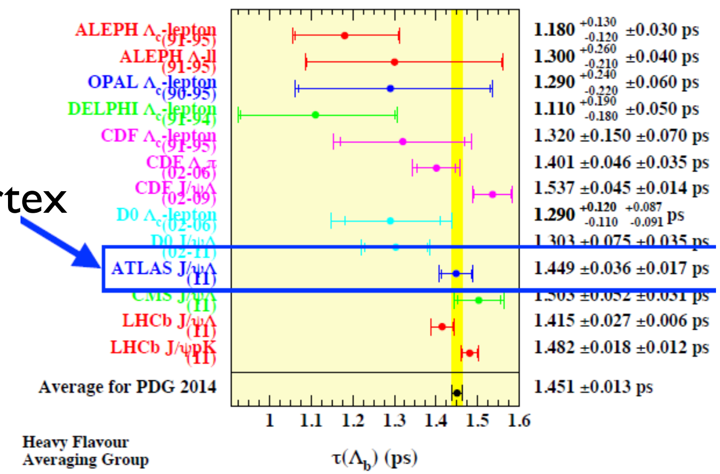
Proper-time t :

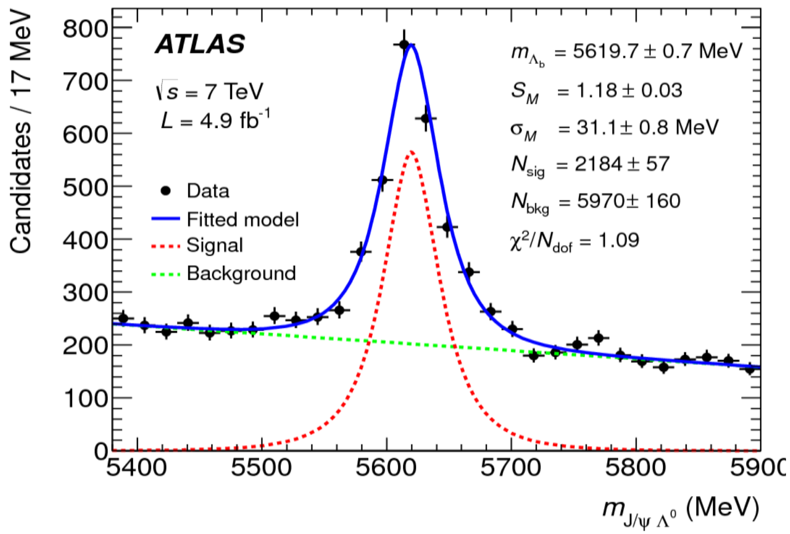
$$t = L_{XY} m_B / P_{T,B}$$

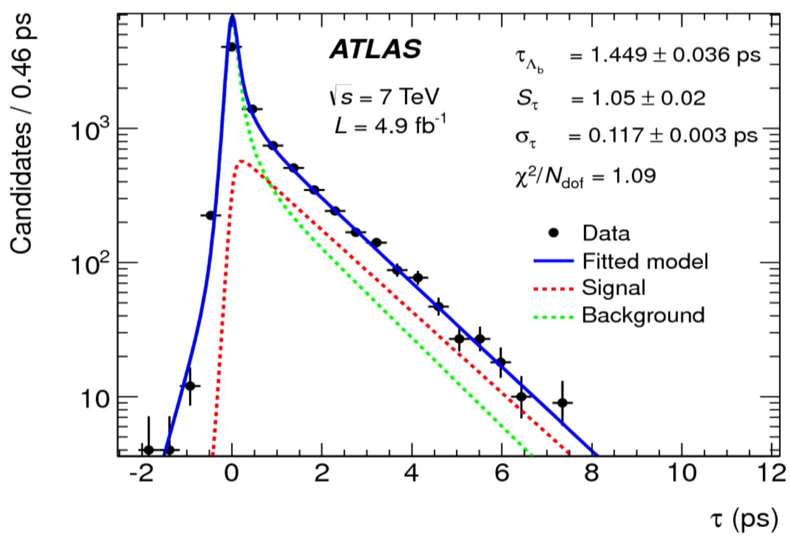
Λ^0_b lifetime measurement

https://prd.aps.org/abstract/PRD/v87/i3/e032002

- Look at $\Lambda^0_b \to J/\psi(\mu+\mu-)\Lambda^o(p\pi-)$
- Lightest baryon with b-quark
- Not tested at B-factories (too heavy)
- 4 charged tracks pointing to a secondary vertex
- J/Ψ and Λ^o mass windows used
- Simultaneous fit of mass and lifetime
- To reduce the systematics, measure of $R=\tau(\Lambda_b)/\tau(B_d)$ where $B_d \to J/\psi(\mu+\mu-)K_s(\pi+\pi-)$
- Value 0.960±0.025(stat)±0.016(syst) is:
  - Between CDF and D0 measurements
  - In agreement with heavy-quark expansion and NLO QCD calculations

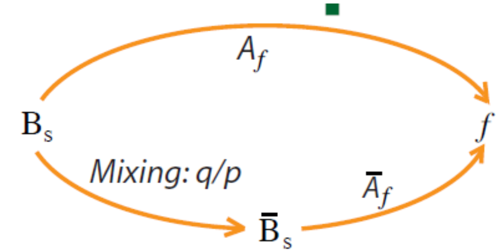


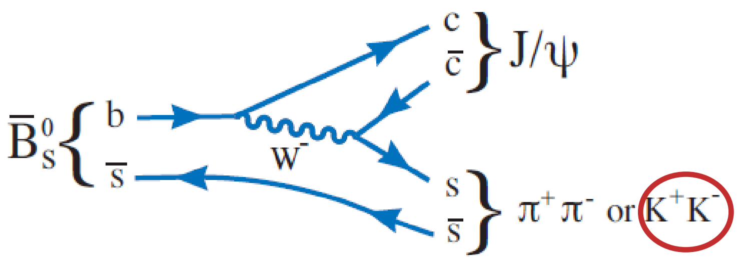




CPV in Bs → J/ΨΦ

- Interference between mixing and decay

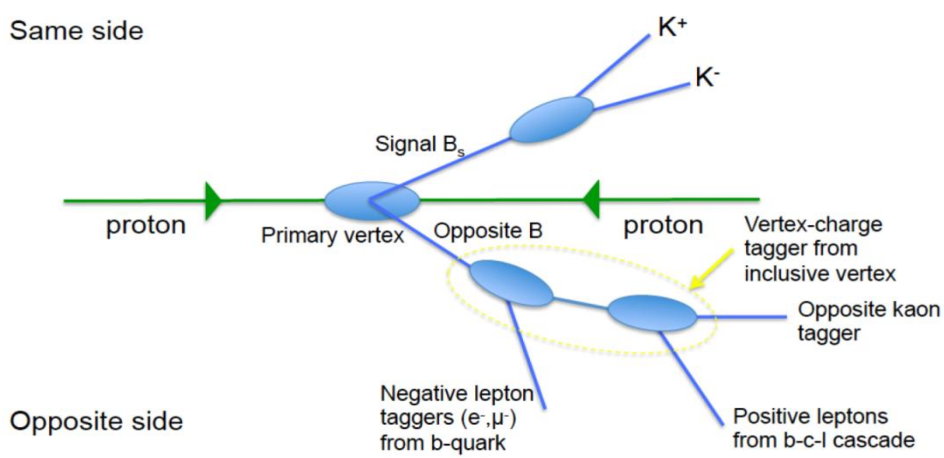




$$\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.04 \text{ rad}$$

Small CPV phase in SM → Ideal place for New-Physics!

- Essential ingredients at hadron colliders:
  - Good time (spatial) resolution to measure the oscillation accurately
  - Flavour tagging (i.e. distinguish the "Bs side" of the event)



Muons, electrons and jets used as taggers

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Bs → J/ΨΦ amplitudes

$$|A_0|^2(t) = |A_0|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)],$$

$$|A_\parallel(t)|^2 = |A_\parallel|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)],$$

$$|A_\perp(t)|^2 = |A_\perp|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)],$$

$$\Im(A_\parallel^*(t)\, A_\perp(t)) = |A_\parallel||A_\perp|e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp - \delta_\parallel)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m t)],$$

$$\Re(A_0^*(t)\, A_\parallel(t)) = |A_0||A_\parallel|e^{-\Gamma_s t}\cos(\delta_\parallel - \delta_0)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)],$$

$$\Im(A_0^*(t)\, A_\perp(t)) = |A_0||A_\perp|e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_0)\cos(\Delta m t)],$$

$$|A_s(t)|^2 = |A_s|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t],$$

$$\Re(A_s^*(t)A_\parallel(t)) = |A_s||A_\parallel|e^{-\Gamma_s t}[-\sin(\delta_\parallel - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel - \delta_s)\ \cos\phi_s \sin(\Delta m t) + \cos(\delta_\parallel - \delta_s)\cos(\Delta m t)],$$

$$\Im(A_s^*(t)A_\perp(t)) = |A_s||A_\perp|e^{-\Gamma_s t}\sin(\delta_\perp - \delta_s)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)],$$

$$\Re(A_s^*(t)A_0(t)) = |A_s||A_0|e^{-\Gamma_s t}[-\sin(\delta_0 - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_0 - \delta_s)\cos\phi_s \sin(\Delta m t) + \cos(\delta_0 - \delta_s)\cos(\Delta m t)].$$

Life easier for CP eigenstates (e.g. J/Ψf⁰)

only term for $f=f_{cp}$

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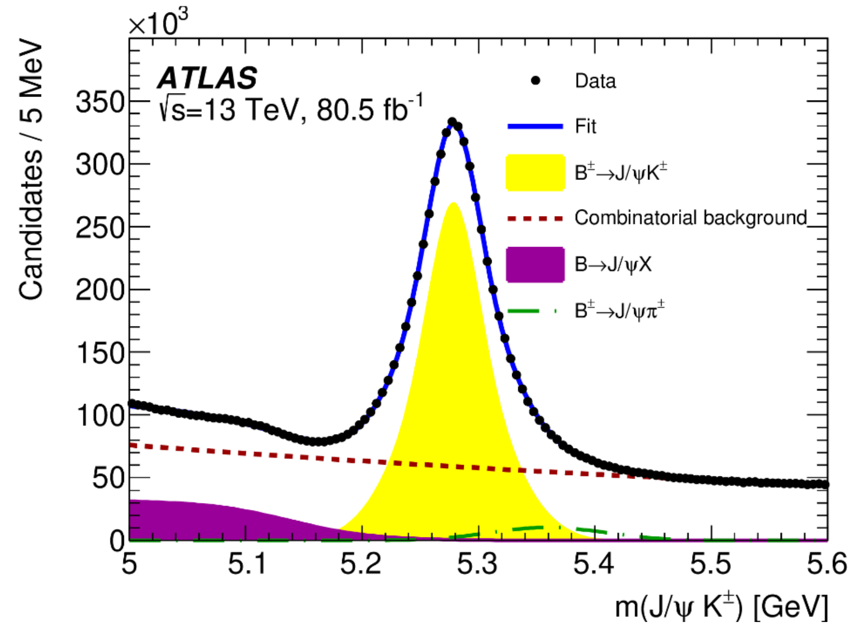
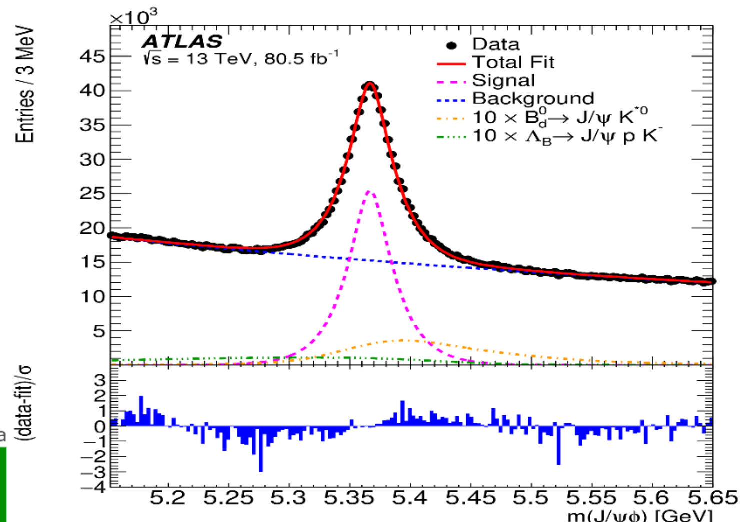
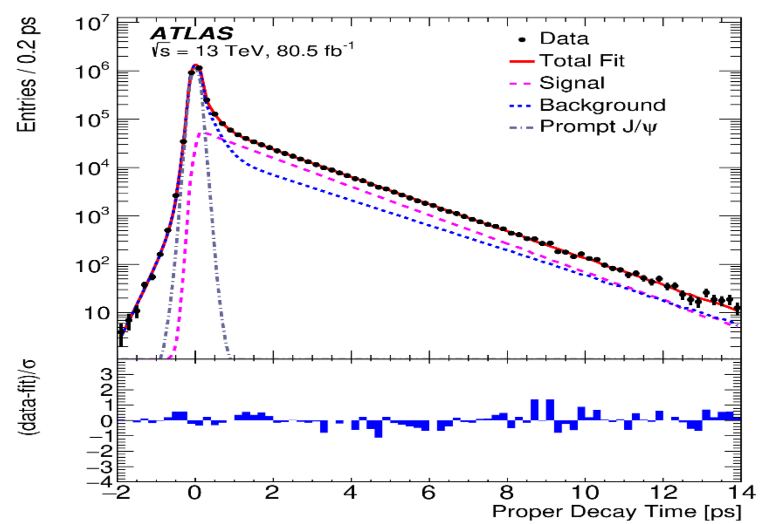
Bs → J/ΨΦ measurement

https://link.springer.com/article/10.1140/epjc/s10052-021-09011-0

- Flavour tagging calibration done using **$B^{\pm}$ → $J/\Psi K^{\pm}$**
- Information on $B^{\pm}$ flavour extracted from the kaon charge
- Flavour tagging probability affect significantly the precision on the extraction of the parameters
- Total tagging power: 1.75%
- Angular analysis with 10 amplitude functions is done (J/ΨΦ is not a CP eigenstate!!)







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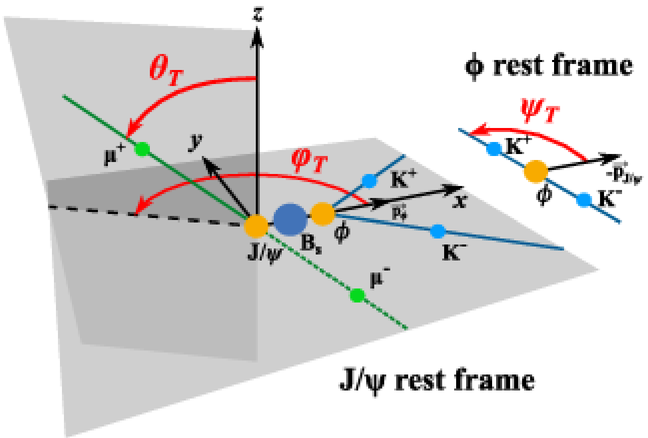
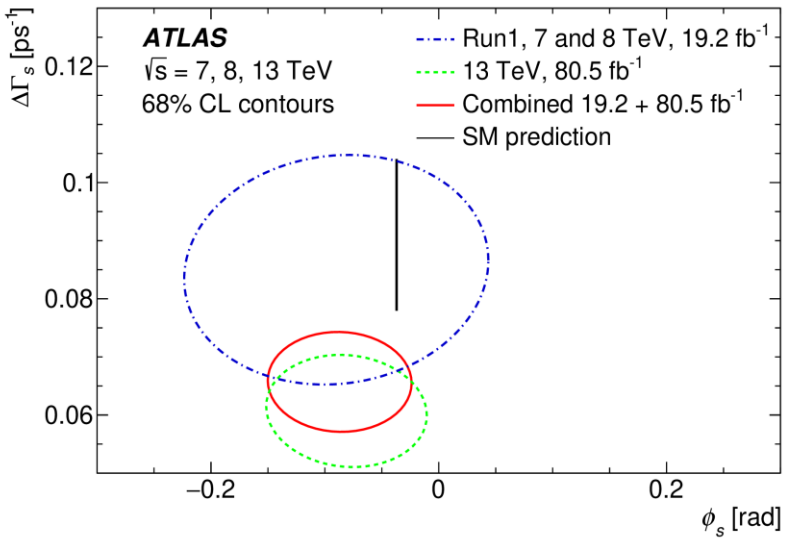
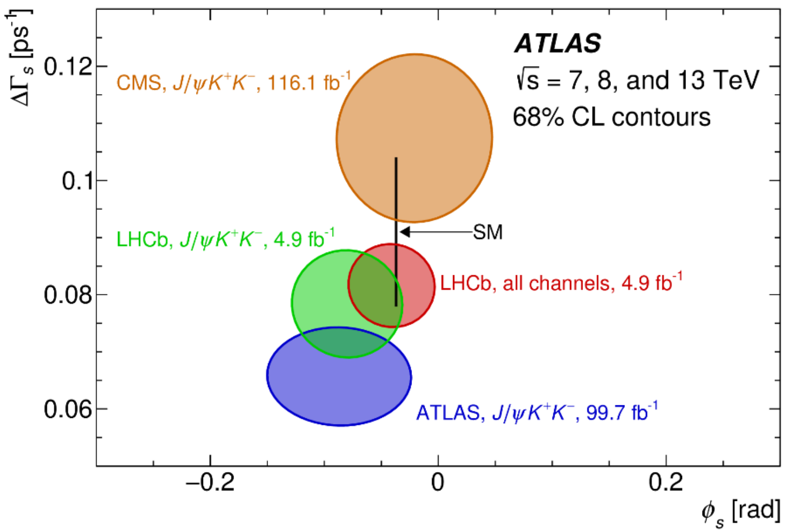
Bs → J/ΨΦ measurement

https://link.springer.com/article/10.1140/epjc/s10052-021-09011-0

- Extract the 10 parameters from a global simultaneous fit to the various distributions (mass, angles, etc)
- Focus on three parameters:
  - Γ_s (decay width)
  - $\Delta\Gamma_s$ (difference of the widths)
  - Φ_s (the CPV weak-phase)







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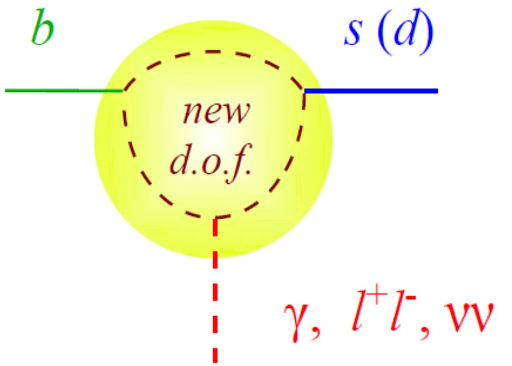
Rare decays

Similarly to ΔF=2 mixings, rare decays mediated by *Flavour Changing Neutral Current* (FCNC) amplitudes are useful probes for *precision* tests of flavor dynamics beyond the SM



- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- Predicted with high precision within the SM at the partonic level: NNLO pert. calculations available for all the main B modes ($m_b \gg \Lambda_{QCD}$)
- The key point is the relation between patonic & hadronic worlds

Fully inclusive decays
usually good precision thanks to heavy-quark symmetry

$$\Gamma(b \to s\gamma) \xrightarrow{m_b \to \infty} \Gamma(B \to X_s \gamma)$$

Exclusive decays
generally more difficult than inclusive, with some notable exceptions:

$B \to (0, K, K^*) + \mu^-\mu^+$

$B(s) \to \mu^+\mu^-$

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Bs,d→μμ BR measurement

- **Rare but clean** decay suppressed by FCNC in the SM
  - BR(Bs→μμ) = (3.66 ± 0.14) x10^{-9}
  - BR(Bd→μμ) = (1.03 ± 0.05) x10^{-10}

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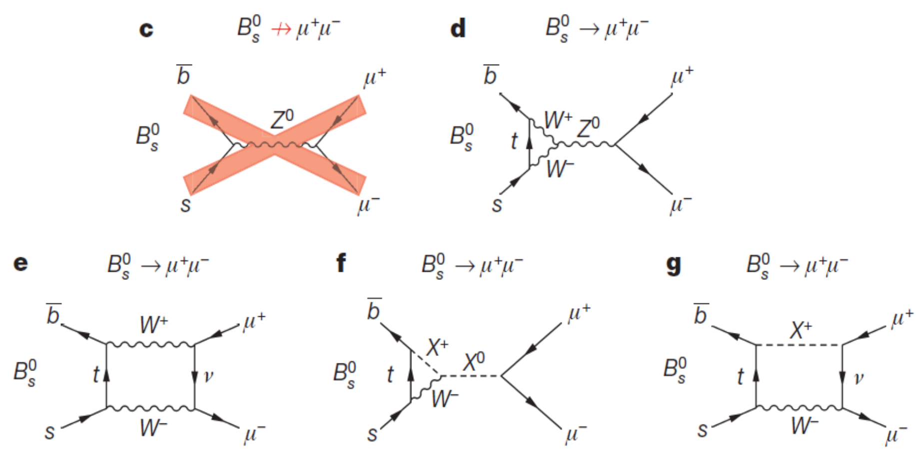
- **Three suppression factors:**
  - FCNC processes forbidden at tree-level
  - CKM elements (V_{ts} , V_{td})
  - Helicity suppression (0^- state going into two fermions)
- **Sensitive to New Physics** contributions through loops
- **Disclaimer:** deviations from this value can be interpreted as "hints" that some NP is out there, **BUT** no deviations doesn't mean no NP!



$B_{s,d}$→μμ BR measurement: state-of-the-art

- Measurements by CMS and LHCb:

BR(B_s→μμ) = ($2.9^{+0.7}_{-0.6} \pm 0.2\ (frag.)$) x10^{-9} (CMS)
BR(B_d→μμ) = ($0.8^{+1.4}_{-1.3}$) x10^{-10} (CMS)

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BR(B_s→μμ) = ($3.09^{+0.46+0.15}_{-0.43-0.11}$) x10^{-9} (LHCb)
BR(B_d→μμ) = (< 2.6) x10^{-10} (LHCb)

arXiv: [hep-ex] 2108.09283

- Analysis strategy:

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N(B^0_{(s)} \to \mu^+\mu^-) \times [\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)] \times \frac{f_u}{f_{s/d}} \times \frac{1}{\mathcal{D}_{\text{norm}}}$$

$$\mathcal{D}_{\text{norm}} = \sum_k N^k_{J/\psi K^\pm} \alpha_k \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^\pm}}\right)_k$$

Hadronisation probabilities

Number of Bs/Bd events from an unbinned ML fit to m(μμ) distribution

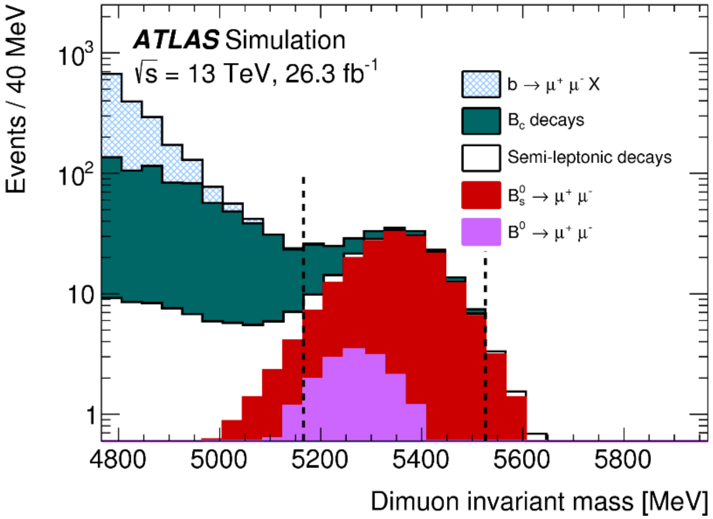
Reference channel: $B^\pm$→J/ψ$K^\pm$ Extracted from an unbinned ML fit to m(μμ$K^\pm$) distribution

Trigger categories and luminosity prescales*

Acceptance and efficiencies from simulation

Backgrounds

- Main backgrounds for the measurement:
  - Combinatorial background: real muons coming from the decay chain of b and $\bar{b}$ initial quarks
  - Partially reconstructed B decays: real muons coming from B → μμ+X decays
  - "Peaking background": Bs/Bd → hh (where h = π, K) decays when both hadrons are misidentified as muons



- "Fake muons": π, K misidentified as muons fulfilling the muon and vertex selection criteria.
  - Present in partially reconstructed (e.g. B→μhX) and in the "peaking background".

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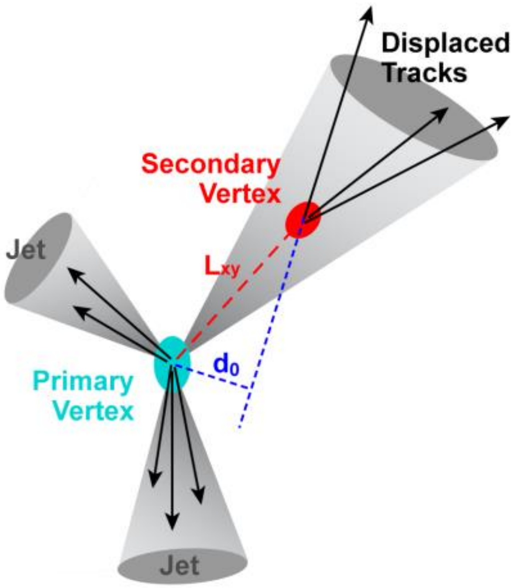
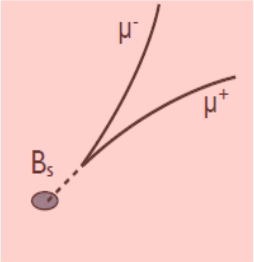
Combinatorial background

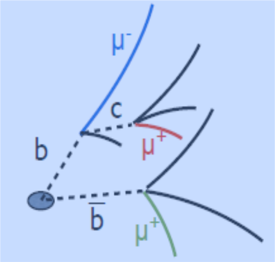
- Real muons from semileptonic heavy-quark decays
- Dominated by $b\bar{b} \rightarrow \mu\mu X$ decays
- Largest background component.
- BDT is applied (c-BDT) to reduce its contribution
  - B-meson kinematic
  - Secondary vertex displacement (L_{xy}, d_0)
  - Properties of muons
  - Rest of the event (X^2 w.r.t other vertices, B isolation…)



- Signal efficiency: 54%
- Background reduction: ~10^3



Signal



Background (bbar → μ⁺ μ⁻X)

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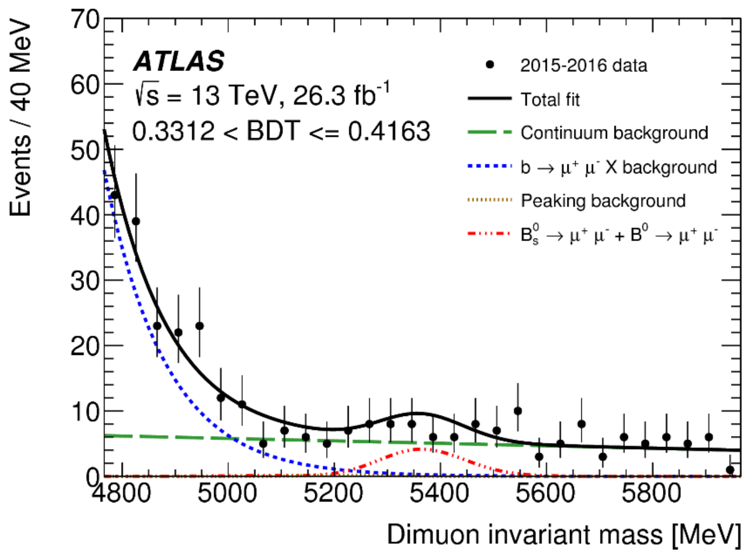
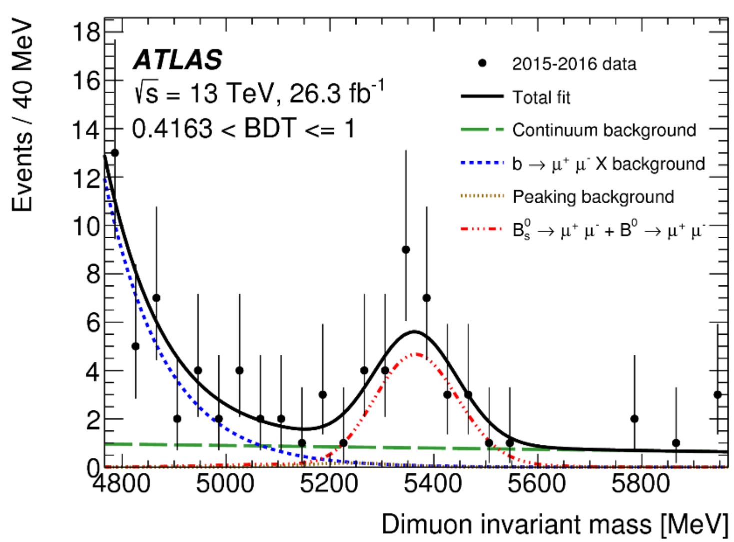
$B_{s,d} \to \mu\mu$ BR measurement

- BR extracted w.r.t to a well know high statistics reference channel ($B^\pm \to J/\psi K^\pm$) → reduce systematics
- Blind analysis
- High reduction and control of the backgrounds (both from fake muons and combinatorial)
- Simultaneous fit for the two channels in the di-muon invariant mass in 4 BDT regions (with different S/B ratio)





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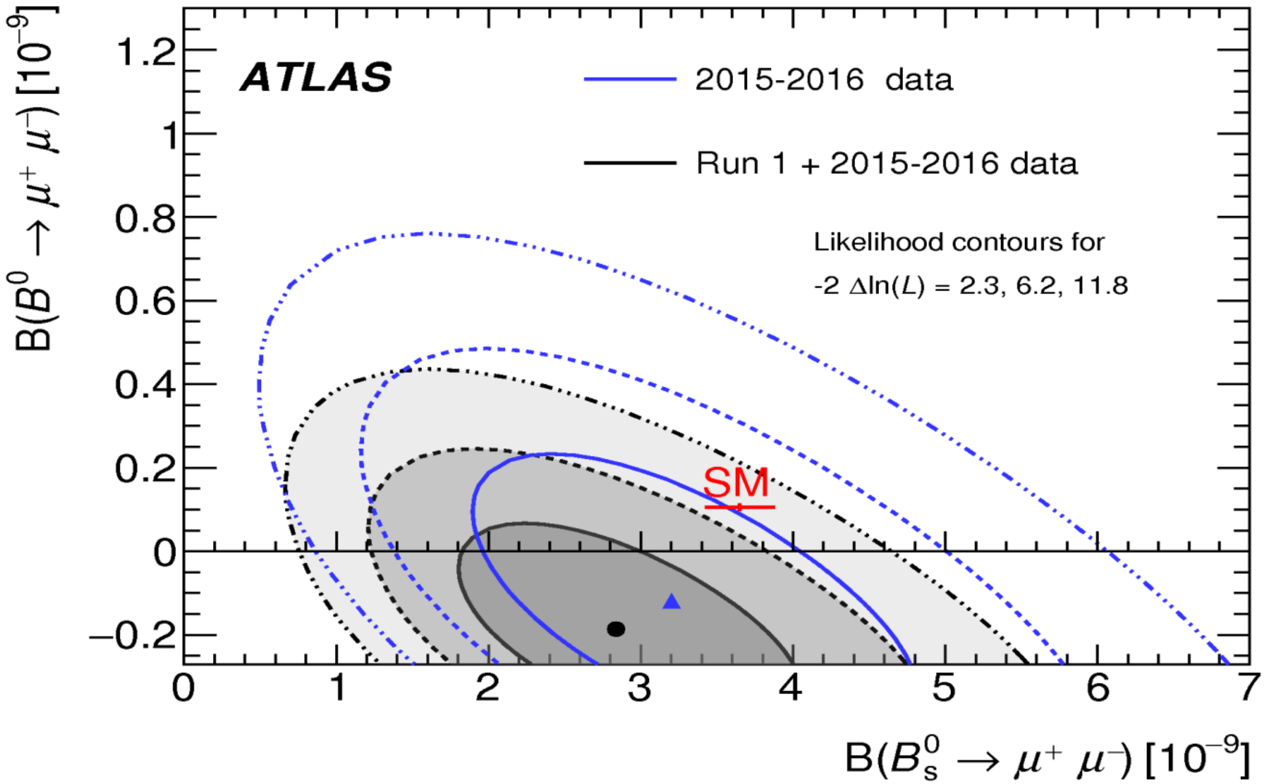
BR extraction

- Likelihood contours in the BR($B_{s,d}$ →μμ) plane



BR(Bs) = $2.8^{+0.8}_{-0.7}$ x10^{-9} (stat. ± syst.)

BR(Bd) < 2.1x10^{-10} (95% CL)

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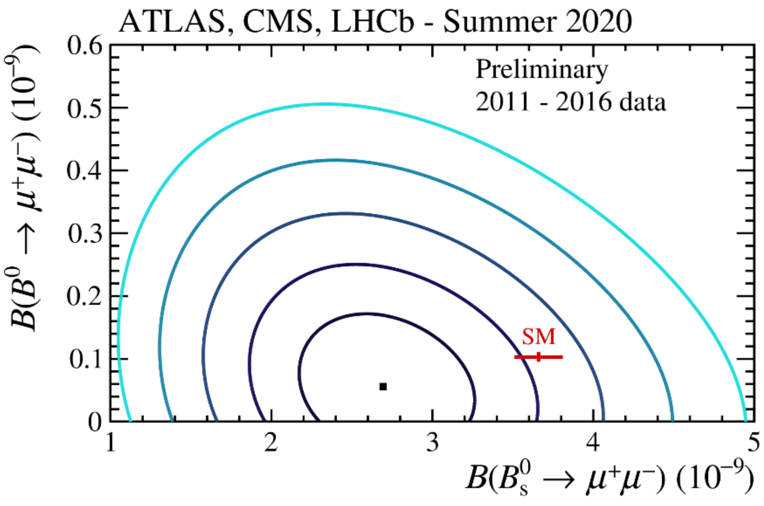
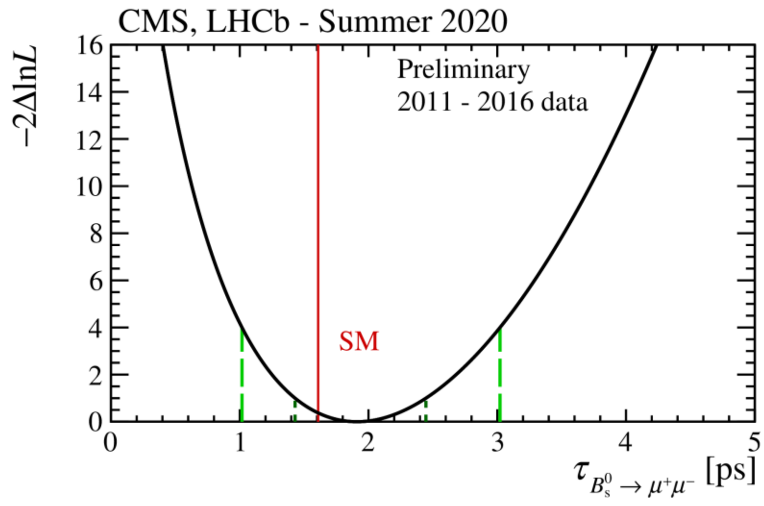
ATLAS+CMS+LHCb combination

- Effort to combine the three measurements
  - First ATLAS+CMS+LHCb combination!
  - Effective $B_s \rightarrow \mu\mu$ lifetime CMS+LHCB combination included

- Combination of the three likelihoods
  - Measurements dominated by the statistical uncertainty





Note the 2.3σ "tension" w.r.t. the Standard Model prediction…

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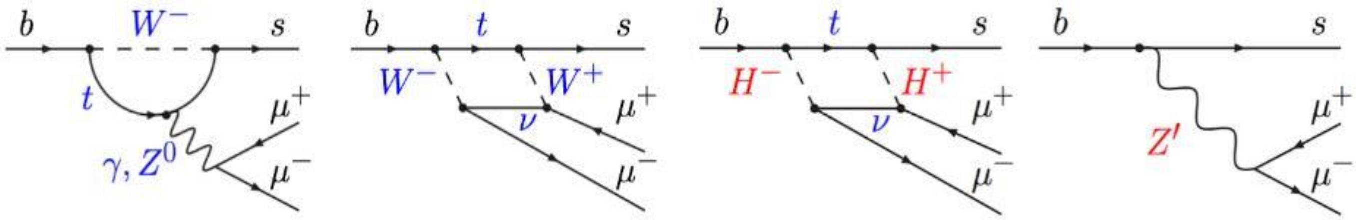
The "flavour anomalies" puzzle

- Most intriguing (and compelling) set of measurements suggesting a deviation from the SM predictions:
- In the last 5 years several measurements showed a disagreement with the SM predictions
- Main characters:

  - b → $s\ell\ell$ transitions

    - Flavour Changing Neutral Current (FCNC) $b \to s(d)l^+l^-$ decays, such as $B^0 \to K^{*0}\mu^+\mu^-$, are forbidden at tree level in the SM



  - Test of the Leptonic Universality (i.e. electrons and muons have the same couplings?)

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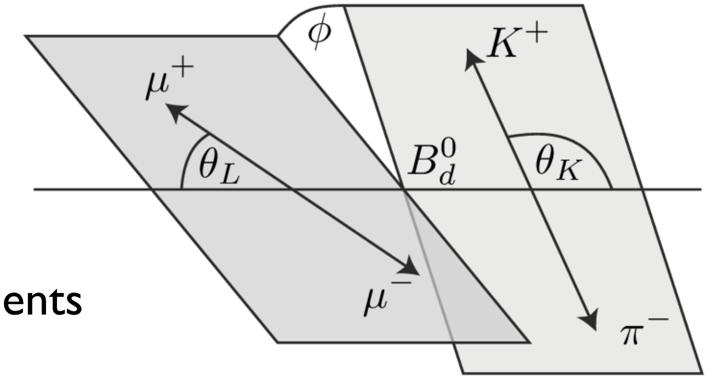
The "flavour anomalies" puzzle

- First evidence: the angular analysis of several decays of B mesons into a strange meson and a muon-antimuon pair
  - $B^0 \rightarrow K^*(K\pi)\mu^+\mu^-$
  - $B^+ \rightarrow K^+\mu^+\mu^-$
  - $B^0_s \rightarrow \Phi(KK)\mu^+\mu^-$
- All these decays can happen through the J/Ψ but the interesting region is away from the resonance (i.e. non-resonant region)
- The decay amplitude can be written as a function of three angles and the invariant mass squared $\mathbf{q^2}$ of the $\mu^+\mu^-$ pair.

- A fit in the four variables allows to extract helicity amplitudes that can be translated into Wilson coefficients and/or optimised variables P_i'



$$L = L_{SM} + \sum_i c_i \frac{O_i}{\Lambda_{NP}^2}$$

Wilson coefficients

- P_i' less sensitive to form factor uncertainties at leading order.

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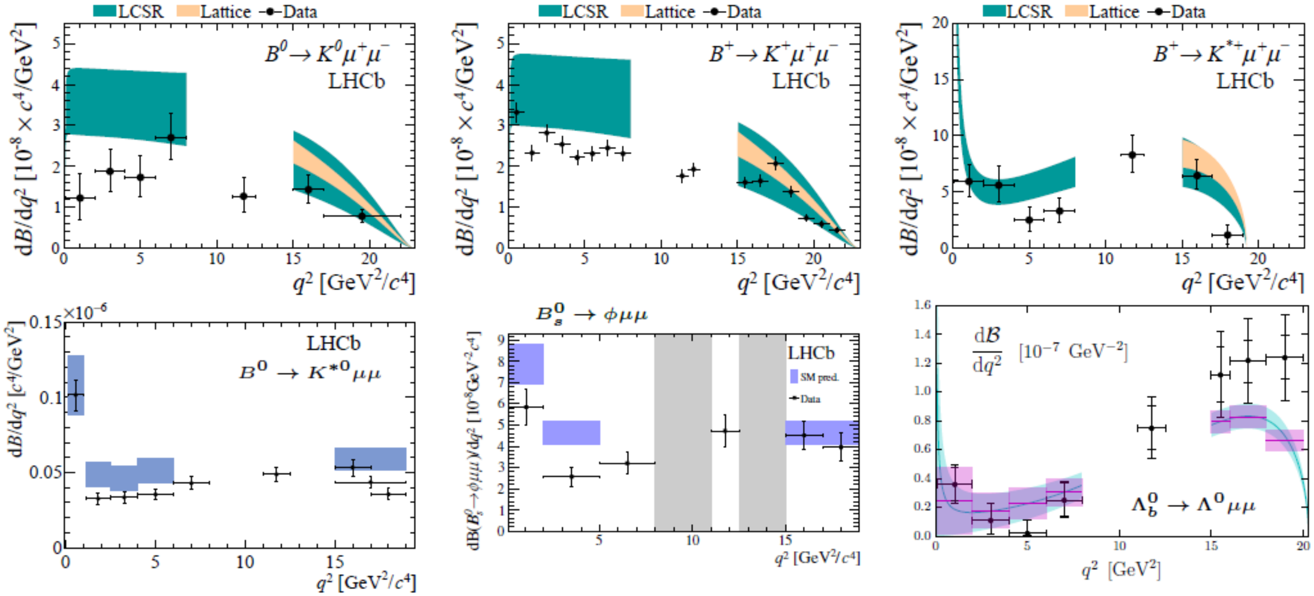
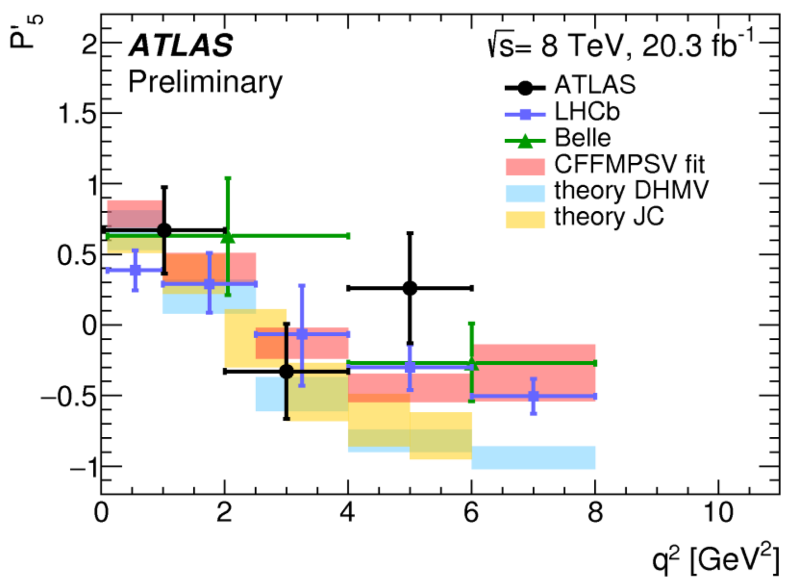
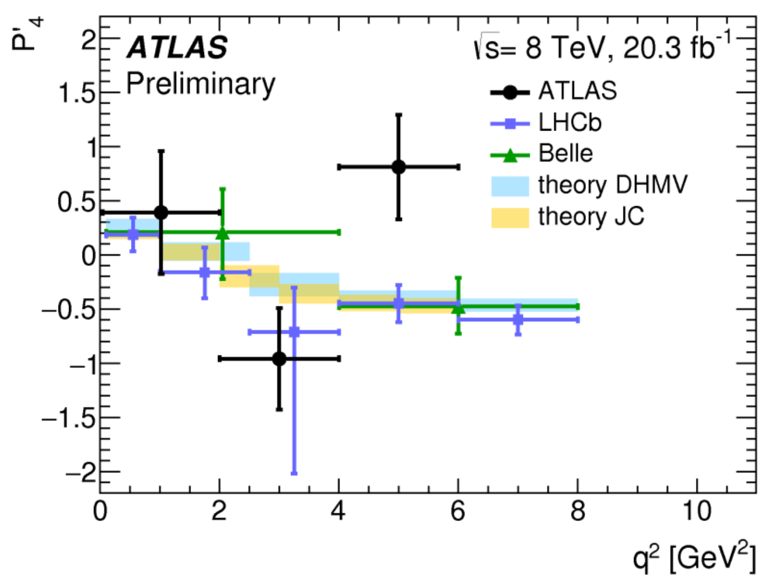
The "flavour anomalies" puzzle

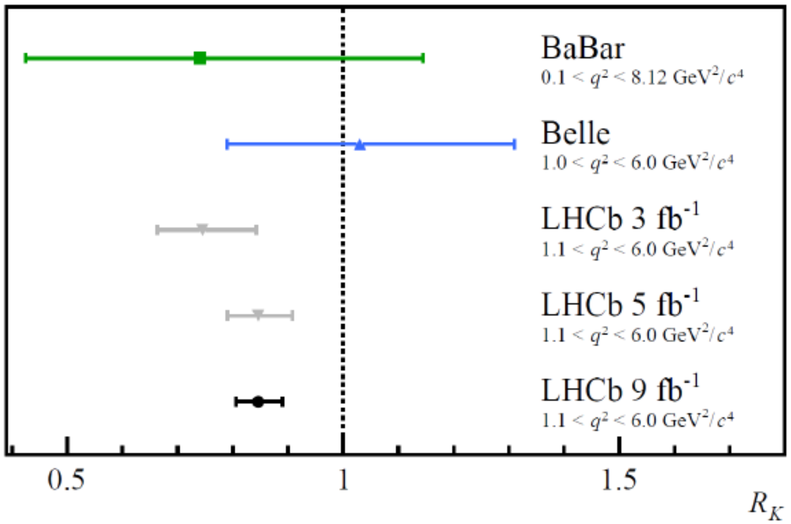


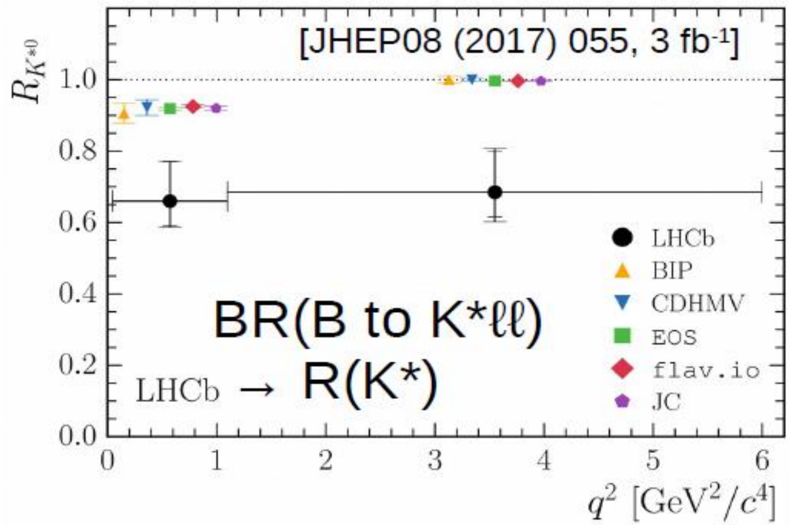




The "flavour anomalies" puzzle

- These deviations were found in the di-muon final state…. Do we see the same also in the electron channel? And what about the tau channel?
- Idea: measure ratios between the two channels!
  - Strong reduction of the theoretical uncertainties
  - Define R(K,K*) as the ratio between BRs in electrons/muons
  - Define R(D,D*) for the charged current processes B→Dℓν





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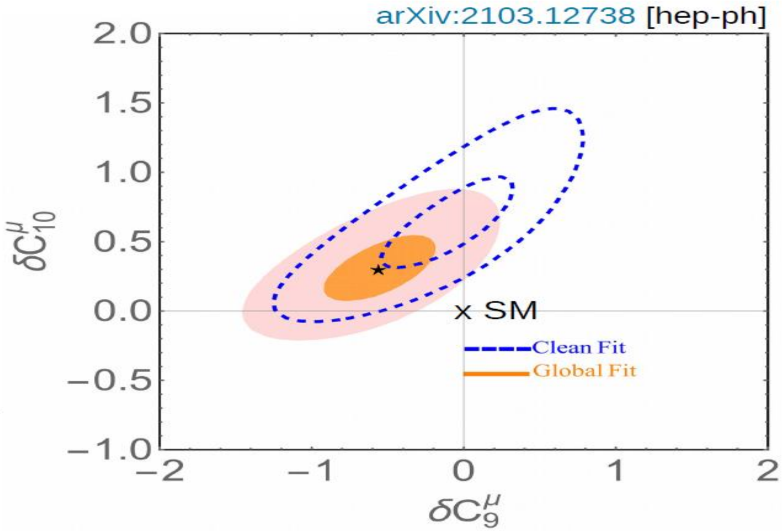
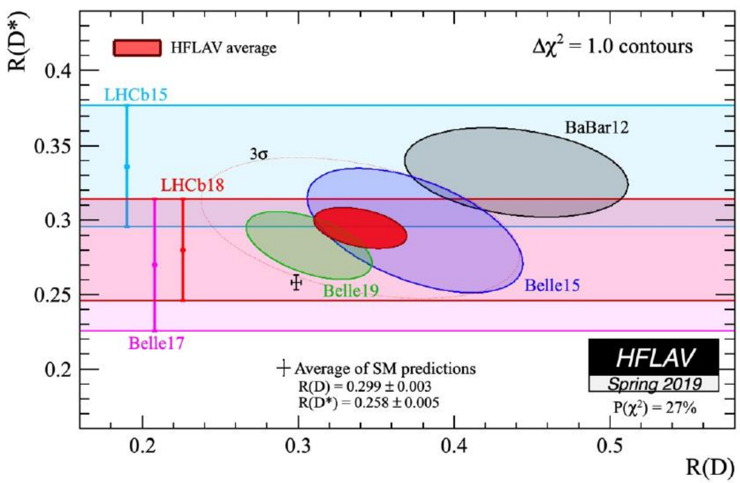
The "flavour anomalies" puzzle

- If one puts together all measurements involving b → sll transitions the significance of the deviation from the SM is between 3 to 4σ …
- … and similarly for the B→Dℓν transitions…

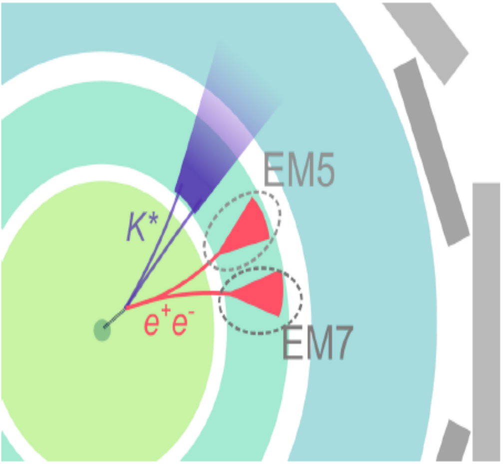


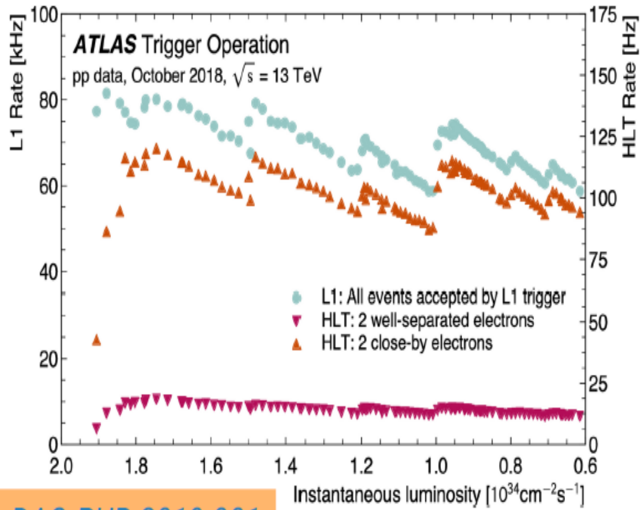


- And not to forget the muon g-2 recent result…
- More measurements (and theoretical calculations) with higher precision will be done in the next years to confirm or deny these deviations!

R(K*) in ATLAS ??

- Target $B \to K^{(*)}ee$
- L1 triggers: new topological triggers which look for a pair of soft electrons with low mass, or a soft "jet" near an electron (the jet assumed to combine two electrons)
  - to reduce rates also require additional muons from other B hadrons in event
- Software HLT dielectron low-mass triggers:
  - some seeded by the L1 topological triggers
  - also triggers that look at **all** events accepted by the L1 – very powerful
- Deployed mid-2018, ran for ~ 40 fb^{-1}





ATL-DAQ-PUB-2019-001

Conclusions & outlooks

- Highlights in flavour physics by ATLAS from Run1 and Run 2 data analysis have been shown

- The ATLAS programme in flavour physics is quite rich and cover a good portion of the most interesting topics in the domain

- ATLAS is competitive with LHCb (despite the different performance and environment) in few channels. Among them:
  - CPV with the analysis of the Bs → J/ΨΦ decay
  - Measurement of the BR($B_{s,d}$ →μμ) rare decay

- New measurements using the full Run1+Run2 statistics are ongoing: stay tuned!

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BACKUP

Flavour in the SM

Particle physics is described with good accuracy by a simple and *economical* theory:

$$\mathscr{L}_{SM} = \mathscr{L}_{gauge}(A_a, \psi_i) + \mathscr{L}_{Higgs}(\phi, A_a, \psi_i)$$

- *Natural*
- Experimentally tested with high accuracy
- Stable with respect to quantum corrections
- Highly symmetric:
  - $SU(3)_c \times SU(2)_L \times U(1)_Y$ *local symmetry*
  - *Global flavor symmetry*

$$\mathscr{L}_{gauge} = \Sigma_a - \frac{1}{4g_a^2}(F_{\mu\nu}^a)^2 + \Sigma_\psi \Sigma_i \overline{\psi}_i i\not{D}\psi_i$$

Flavour in the SM

Particle physics is described with good accuracy by a simple and *economical* theory:

$$\mathscr{L}_{SM} = \mathscr{L}_{gauge}(A_a, \psi_i) + \mathscr{L}_{Higgs}(\phi, A_a, \psi_i)$$

- *Natural*
- Experimentally tested with high accuracy
- Stable with respect to quantum corrections
- Highly symmetric

- *Ad hoc*
- Necessary to describe data [*clear indication of a non-invariant vacuum*] weakly tested in its dynamical form
- Not stable with respect to quantum corrections
- Origin of the flavor structure of the model [*and of all the problems of the model…*]

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Flavour in the SM

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge}(A_a, \psi_i) + \mathcal{L}_{Higgs}(\phi, A_a, \psi_i)$$

3 identical replica of the basic fermion family $[\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow$ huge flavor-degeneracy

$$\sum_{\psi = Q_L, u_R, d_R, L_L, e_R} \sum_{i=1..3} \overline{\psi}_i \, i \not{D} \, \psi_i \qquad Q_L = \begin{bmatrix} u_L \\ d_L \end{bmatrix}, \quad u_R, \quad d_R, \quad L_L = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}, \quad e_R$$

Within the SM the flavor-degeneracy is broken only by the Yukawa interaction:

in the quark sector:

$$\bar{Q}_L^{\,i} Y_D^{ik} d_R^k \phi + h.c. \rightarrow \bar{d}_L^{\,i} M_D^{ik} d_R^k + \ldots$$

$$\bar{Q}_L^{\,i} Y_U^{ik} u_R^k \phi_c + h.c. \rightarrow \bar{u}_L^{\,i} M_U^{ik} u_R^k + \ldots$$

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Flavour in the SM

The Y are not hermitian → diagonalized by bi-unitary transformations:

$$V_D^+ Y_D U_D = \mathrm{diag}(y_b, y_s, y_d)$$
$$V_U^+ Y_U U_U = \mathrm{diag}(y_t, y_c, y_u)$$

$$y_i = \frac{2^{1/2} m_{q_i}}{\langle \phi \rangle} \approx \frac{m_{q_i}}{174 \text{ GeV}}$$

The residual flavor symmetry let us to choose a (gauge-invariant) flavor basis where only one of the two Yukawas is diagonal:

$$Y_D = \mathrm{diag}(y_d, y_s, y_b)$$
$$Y_U = V^+ \times \mathrm{diag}(y_u, y_c, y_t)$$

or

$$Y_D = V \times \mathrm{diag}(y_d, y_s, y_b)$$
$$Y_U = \mathrm{diag}(y_u, y_c, y_t)$$

→ unitary matrix

$$\bar{Q}_L^i Y_D^{ik} d_R^k \phi \rightarrow \bar{d}_L^i M_D^{ik} d_R^k + \ldots \qquad M_D = \mathrm{diag}(m_d, m_s, m_b)$$
$$\bar{Q}_L^i Y_U^{ik} u_R^k \phi_c \rightarrow \bar{u}_L^i M_U^{ik} u_R^k + \ldots \qquad M_U = V^+ \times \mathrm{diag}(m_u, m_c, m_t)$$

To diagonalize also the second mass matrix we need to rotate separately u_L & d_L (non gauge-invariant basis) ⇒ V appears in charged-current gauge interactions:

$$J_W^\mu = \bar{u}_L \gamma^\mu d_L \rightarrow \bar{u}_L V \gamma^\mu d_L$$

→ Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix

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CKM Matrix

$$J_W^{\mu} = \bar{u}_L \gamma^{\mu} d_L \rightarrow \bar{u}_L V \gamma^{\mu} d_L$$

Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix

$$V V^{+} = I \qquad V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

The SM quark flavor sector is described by 10 observable parameters:

- 6 quark masses
- 3+1 CKM parameters

- 3 real parameters (rotational angles)
  +
- 1 complex phase (source of CP violation)

Note that:

- The rotation of the right-handed sector is not observable
- Neutral currents remain flavor diagonal

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CKM Matrix properties

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

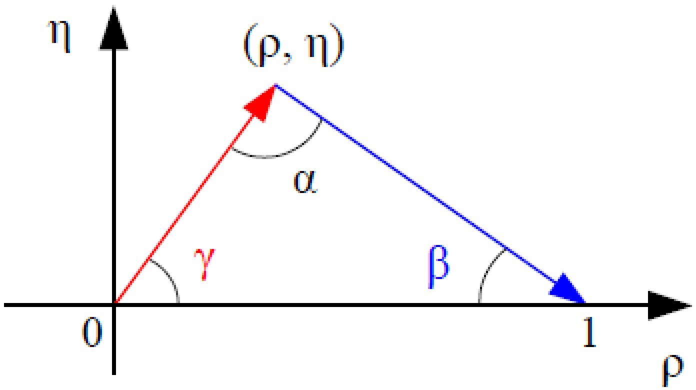
Experimental indication of a strongly hierarchical structure:

$$\approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

$$V_{CKM} V_{CKM}^{+} = I$$

The $b \to d$ UT triangle:

$$V_{ub}^{*} V_{ud} + V_{cb}^{*} V_{cd} + V_{tb}^{*} V_{td} = 0$$



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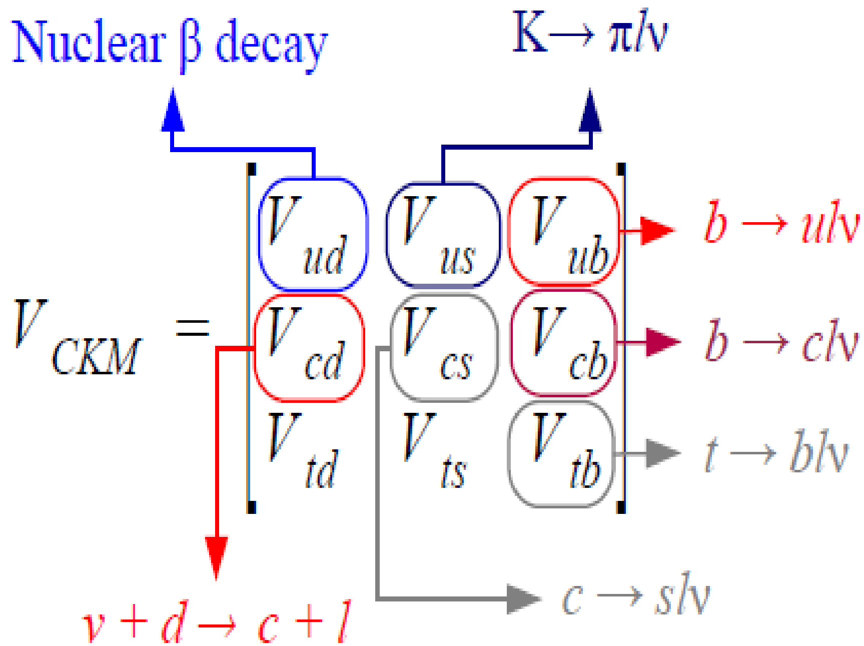
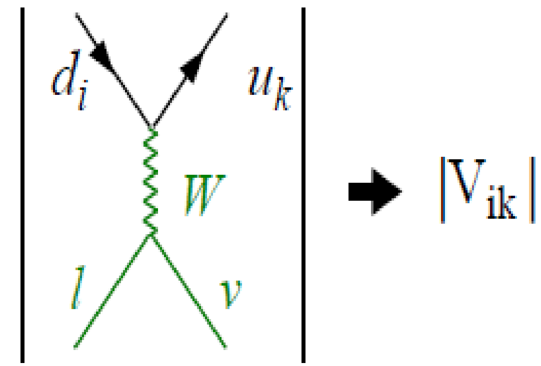
CKM Matrix properties



Once we assume unitarity, the CKM matrix can be <u>completely determined</u> using only exp. info from processes mediated <u>by tree-level</u> c.c. amplitudes

Excellent determination (error ~ 0.1%)
Very good determination (error ~ 0.5%)
Good determination (error ~ 2 %)
Sizable error (5-15 %)
Not competitive with unitarity constraints



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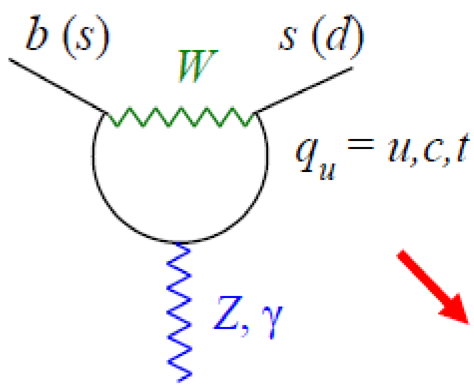
CKM Matrix properties

The only CKM elements we cannot access via tree-level processes are V_{ts} & V_{td}

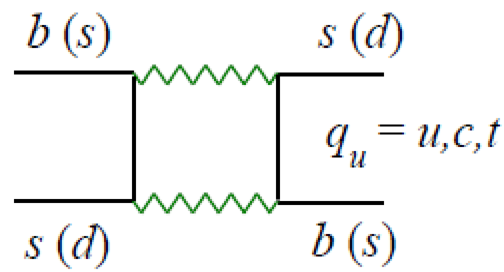
↓

Loop-induced amplitudes:

$\Delta F = 1$ FCNC



$\Delta F = 2$ (neutral-meson mixing)



GIM mechanism

[large top-quark contribution: $A \sim m_t^2\, V_{tq}^{*}\, V_{tb}$]

- Rare B decays
  [$B \to X_s \gamma$, $B \to K^{(*)} l^+ l^-$, $B_{s,d} \to l^+ l^-$, ...]
- Rare K decays
  [$K \to \pi \nu\nu$, ...]
- $B_{d(s)}$- $\bar{B}_{d(s)}$ mixing
- K^0- $\bar{K}^0$ mixing

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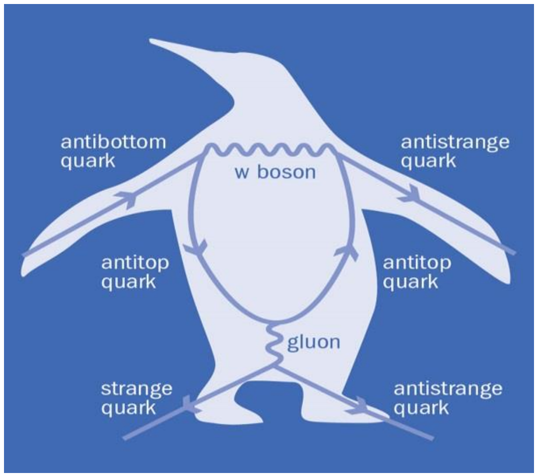

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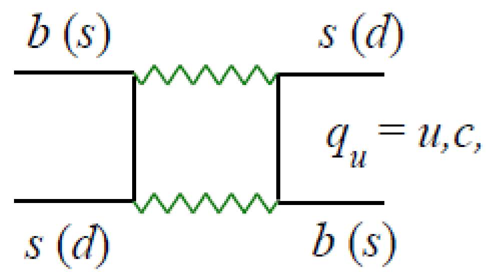

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CKM Matrix properties

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

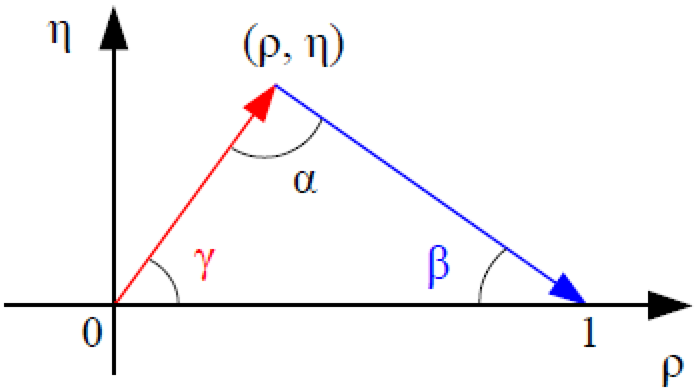
Experimental indication of a strongly hierarchical structure:

$$\approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

$$V_{CKM} V^{+}_{CKM} = I$$

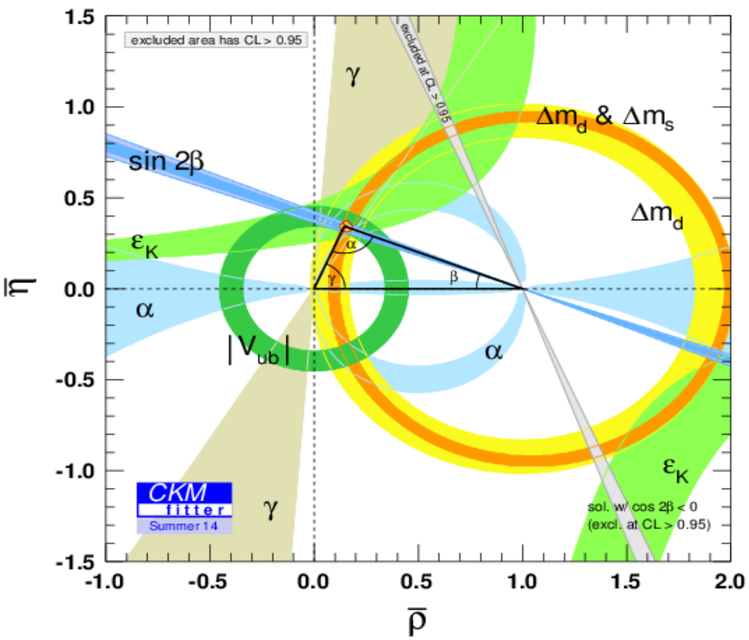
The b → d UT triangle:

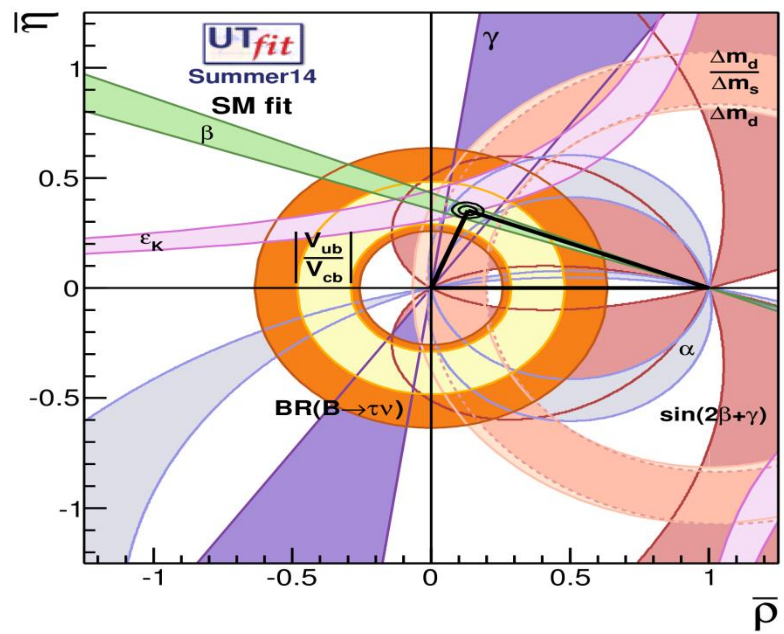
$$V_{ub}^{*} V_{ud} + V_{cb}^{*} V_{cd} + V_{tb}^{*} V_{td} = 0$$



CKM Matrix properties

At the moment, all measurements are compatible and consistent each other and confirm the success of the CKM picture





And the agreement is even more impressive if one consider also other measurements (like Bs mixing phase) not entering in the fit. Is there something else interesting in this area?

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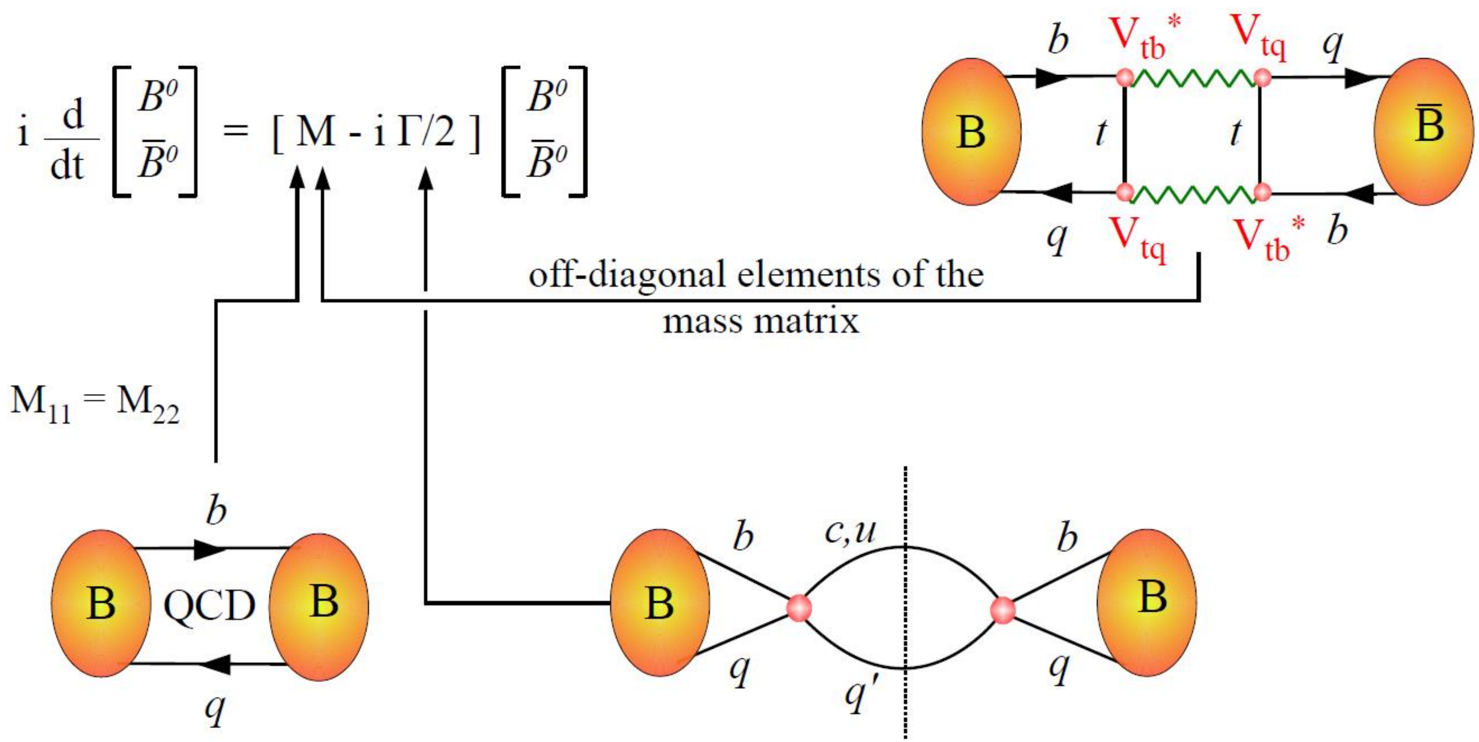
Neutral mesons mixing

- Neutral mesons (K, D ,B) can transform into their own antiparticle through 2nd order weak interaction processes
- This happens because interactions eigenstates are not the same as mass eigenstates
- Let's focus on the Bs case (it means q is the s quark)



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Neutral mesons mixing (2)

- Writing M and Γ explicitly we have:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11} - \Gamma_{11}/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12}^* - i\Gamma_{12}^*/2 & M_{22} - i\Gamma_{22}/2 \end{pmatrix}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

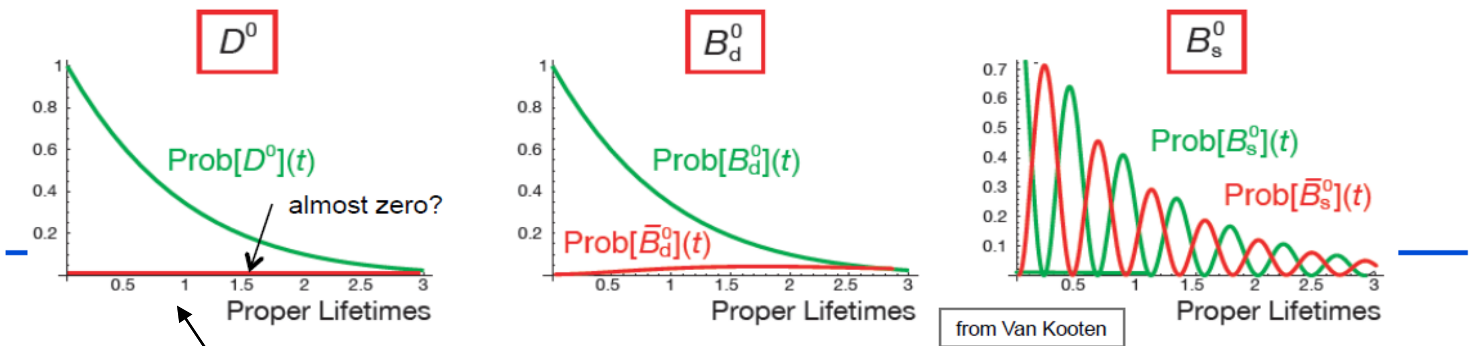
- The mass and the lifetime of the physical eigenstates are then:

$B_{d,s}$ mass eigenstates: $|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$ $\quad |B_H\rangle = p|\bar{B}^0\rangle + q|B^0\rangle$

$$mB_s = (M_H+M_L)/2,\ \Delta M = M_H-M_L,$$

$$1/\tau_{Bs} = \Gamma = (\Gamma_H+\Gamma_L)/2,\ \Delta\Gamma = \Gamma_L-\Gamma_H,$$

$|q^2|+|p^2| = 1$



Just found by LHCb!

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CPV in neutral mesons mixing

- Given these conditions, how an eventual asymmetry would evolve?
- **N.B.** To measure an asymmetry, one has to identify a number of final states f **common** between the particle and the antiparticle!!

Consider
$$a[f(t)] = \frac{\Gamma(\bar{M} \to f) - \Gamma(M \to f)}{\Gamma(\bar{M} \to f) + \Gamma(M \to f)}$$
where *f* is a CP eigenstate

Define $A_f \equiv A(M \to f),\ \bar{A}_f \equiv A(\bar{M} \to f),\quad \lambda_f = \frac{p}{q}\frac{\bar{A}_f}{A_f}$

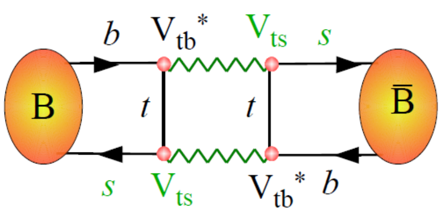
λ_f is a function of V_{ij} in SM

See Nierste arXiv:0904.1869 [hep-ph]

$$\Gamma(M \to f) = N_f |A_f|^2 e^{-\Gamma t}\left(\cosh\frac{\Delta\Gamma t}{2} - \mathrm{Re}\,\lambda_f \sinh\frac{\Delta\Gamma t}{2} - \mathrm{Im}\,\lambda_f \sin(\Delta M t)\right)$$

$$\Gamma(\bar{M} \to f) = N_f |A_f|^2 e^{-\Gamma t}\left(\cosh\frac{\Delta\Gamma t}{2} - \mathrm{Re}\,\lambda_f \sinh\frac{\Delta\Gamma t}{2} + \mathrm{Im}\,\lambda_f \sin(\Delta M t)\right)$$

- B mesons is a good place to look at CPV but:



Bd → $\frac{q}{p} = \frac{(V_{tb}^* V_{td})^2}{|(V_{tb} V_{td}^*)^2|} = e^{-2i\beta}$ → Large CPV phase in SM

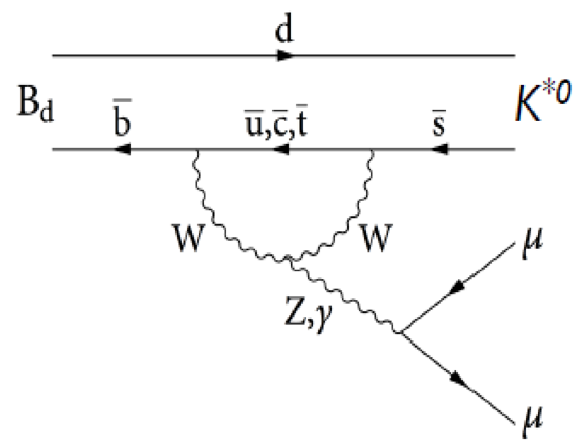
Bs → $\frac{q}{p} = \frac{(V_{tb}^* V_{ts})^2}{|(V_{tb} V_{ts}^*)^2|} = \underbrace{1 + i\,O(\lambda^2)}_{e^{-2i\beta_s}}$ → Negligible CPV phase, BUT large oscillation frequency

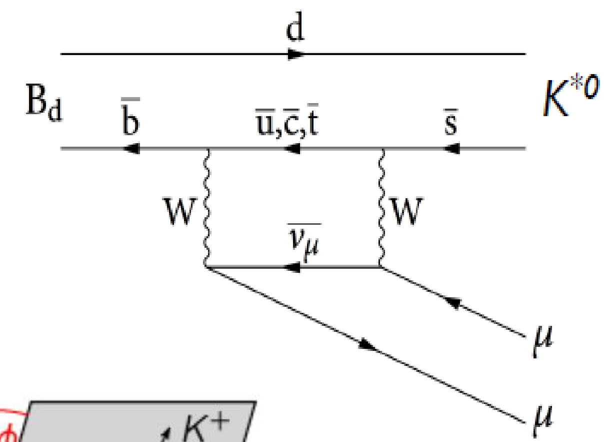
$|\Delta m_{Bs}| \sim \lambda^{-2} |\Delta m_{Bd}|$

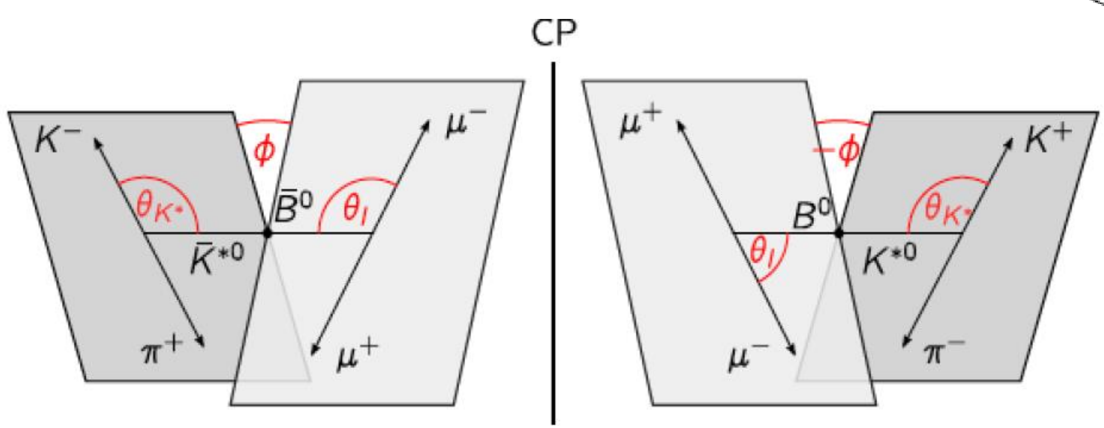
$\sim 18\ ps^{-1}$ $\sim 0.5\ ps^{-1}$

$B_d \rightarrow \mu\mu K^*$

- Similarly to Bs→μμ this channel is "clean" in terms of theoretical calculations and sensitive to any NP contribution through loop effects
- SM prediction for BR = $(1.06 \pm 0.10) \times 10^{-6}$
- Additional interest on differential distributions → Access to several variables related to CP asymmetry of the process
- Most interesting region for NP is far from the J/Ψ and Ψ(2s) resonance peak in $m^2(\mu\mu)$ spectrum → Try to access experimentally to the low $m^2(\mu\mu)$ region



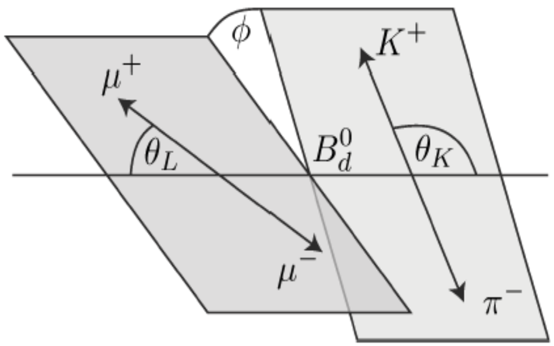


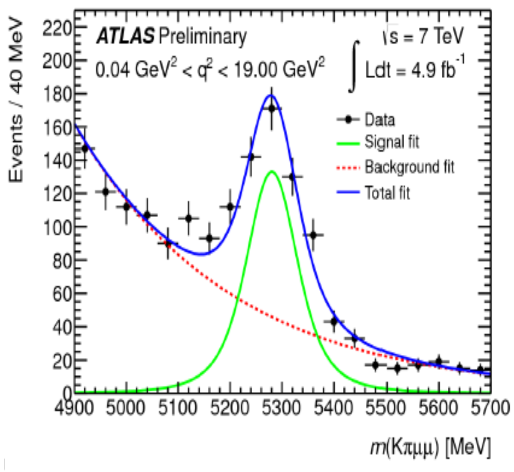


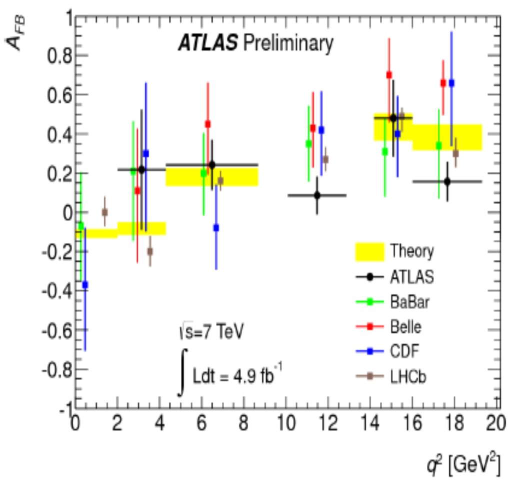
$B_d \rightarrow \mu\mu K^*$ measurement

ATLAS-CONF-2013-038

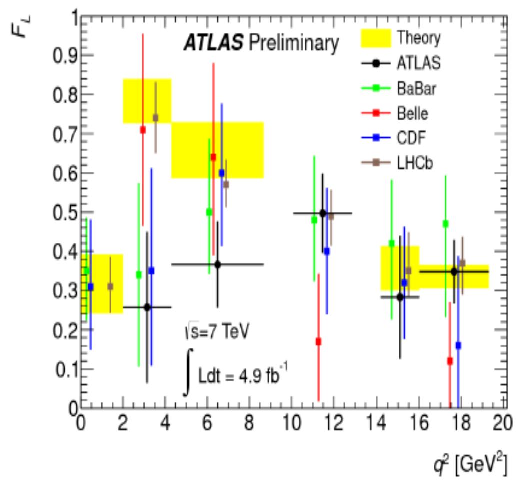
- Full chain: $B_d \rightarrow \mu\mu K^* \rightarrow \mu\mu K^+\pi^-$
- 4 variables describes the kinematics: three angles and $q^2 = m^2(\mu\mu)$
- Experimental limitations/problems:
  - Trigger → Cuts on $P^T(\mu) > 4$ or 6 GeV reduce the statistics al low q^2 values
  - Find the two tracks associated to K/π
  - Exclude muons from J/Ψ and Ψ(2s)
- 2 steps fit (before in m(μμ) then in the angular distributions) to extract A_{FB} and F_L







A_{FB} from angle between μ+ and B momenta in the μμ rest frame



F_L is the K* longitudinal polarisation fraction

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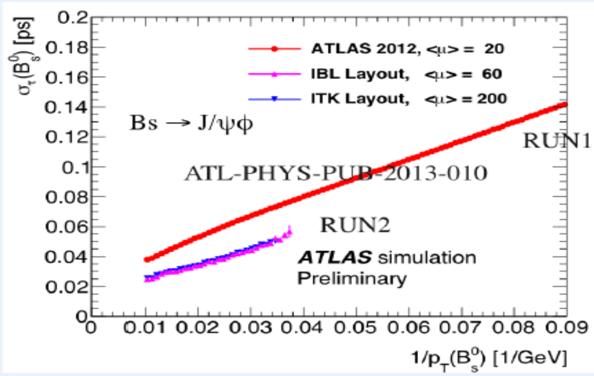
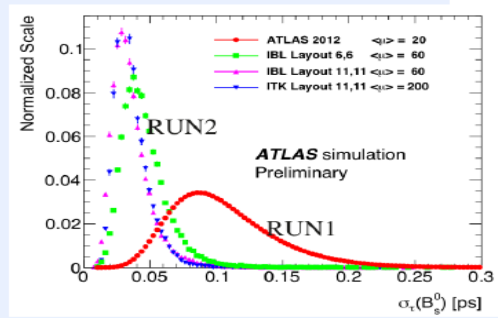
Challenges for Run II

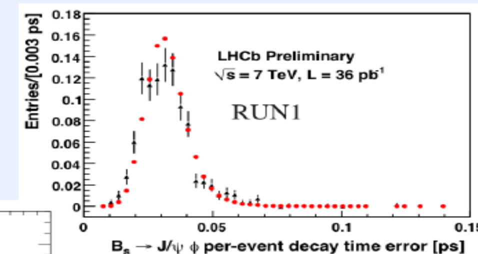
- Run II means high energy and high luminosity → More data but more pileup!
- Main work now is on the trigger: low-P_T muon L1 triggers used in Run I will not be usable anymore
- Two ways:
  - Increase the thresholds → No benefit from high statistics
  - Be smart → L1 topological trigger (L1Topo)!
- L1Topo uses the whole information of the muon RoI (PT, η, Φ) to compute at L1 the kinematic quantities for all di-muon pairs in the event
- This means:
  - Reduction of background from random di-muon pairs → Lower bandwidth usage → Can keep P_T thresholds low
  - Signal efficiency almost preserved
- Studies ongoing to define the best possible thresholds in di-muon mass and angular distance to be used in different conditions of instantaneous luminosities.
- ATLAS Sussex group is leading the effort

ATLAS Bs → J/ψφ with IBL at RUN2 compared to RUN1



- ATLAS time resolution for $B_s \to J/\psi\phi$ improves at RUN2 by factor of ~30% comparing to RUN1 (for the same pT values)





- LHCb vertex upgrade - but not at RUN2: ATLAS have unique opportunity to measure with resolution similar to LHCb.
- In 2012 ATLAS $B_s \to J/\psi\phi$ statistics 2 x bigger than LHCb
- At RUN2 B-triggers (especially pT thresholds) - important for ATLAS to be able to lead a CPV precision in Bs.

If we can retain low trigger thresholds, ATLAS can produce the worlds best measurement of ϕ_s using Run 2.

- Rare decays will strongly depend on topological trigger!
- Low q^2 region in μμK* will be almost completely inaccessible without it.

Conclusions

- Main B-physics results from ATLAS experiment using 7 TeV data collected during the Run I data-taking campaign have been presented
- ATLAS can be competitive in several measurements with LHCb and CMS
- No significant deviations from the Standard Model predictions have been seen only some tension (e.g. differential cross-sections for quarkonia)
- Rare decays measurements ($B_{s/d} \rightarrow \mu\mu$ and $B_d \rightarrow \mu\mu K^*$) with full Run I statistics are being finished
- This is the natural place to look for New-Physics phenomena through indirect effects on some measured quantity (asymmetries, branching ratios, angular distributions) in Run II. The best has yet to come!!!