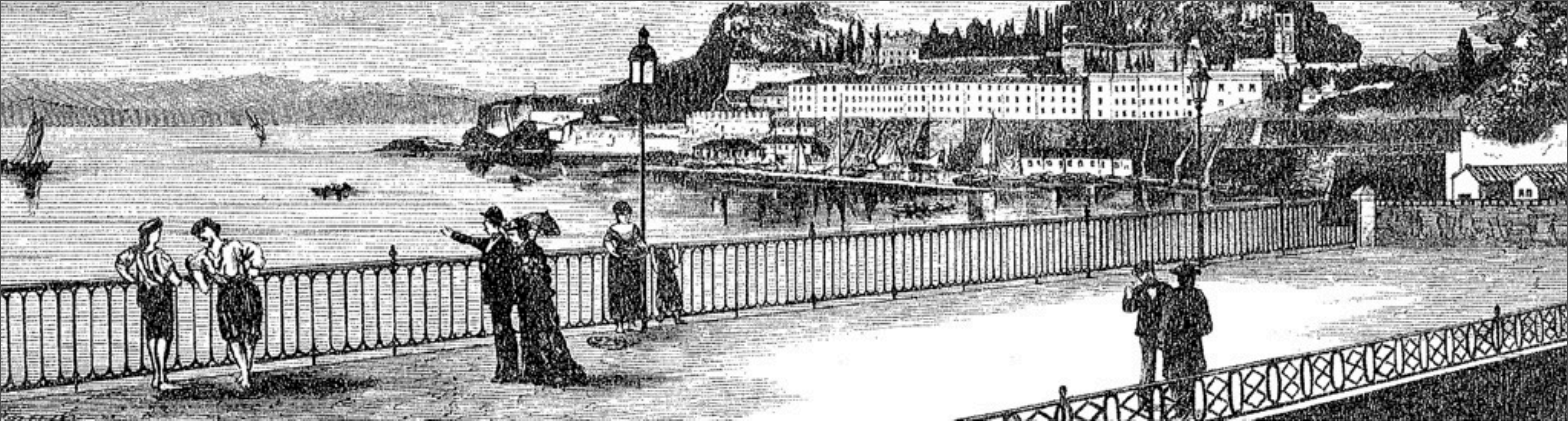


Heavy Flavor Physics with the ATLAS detector

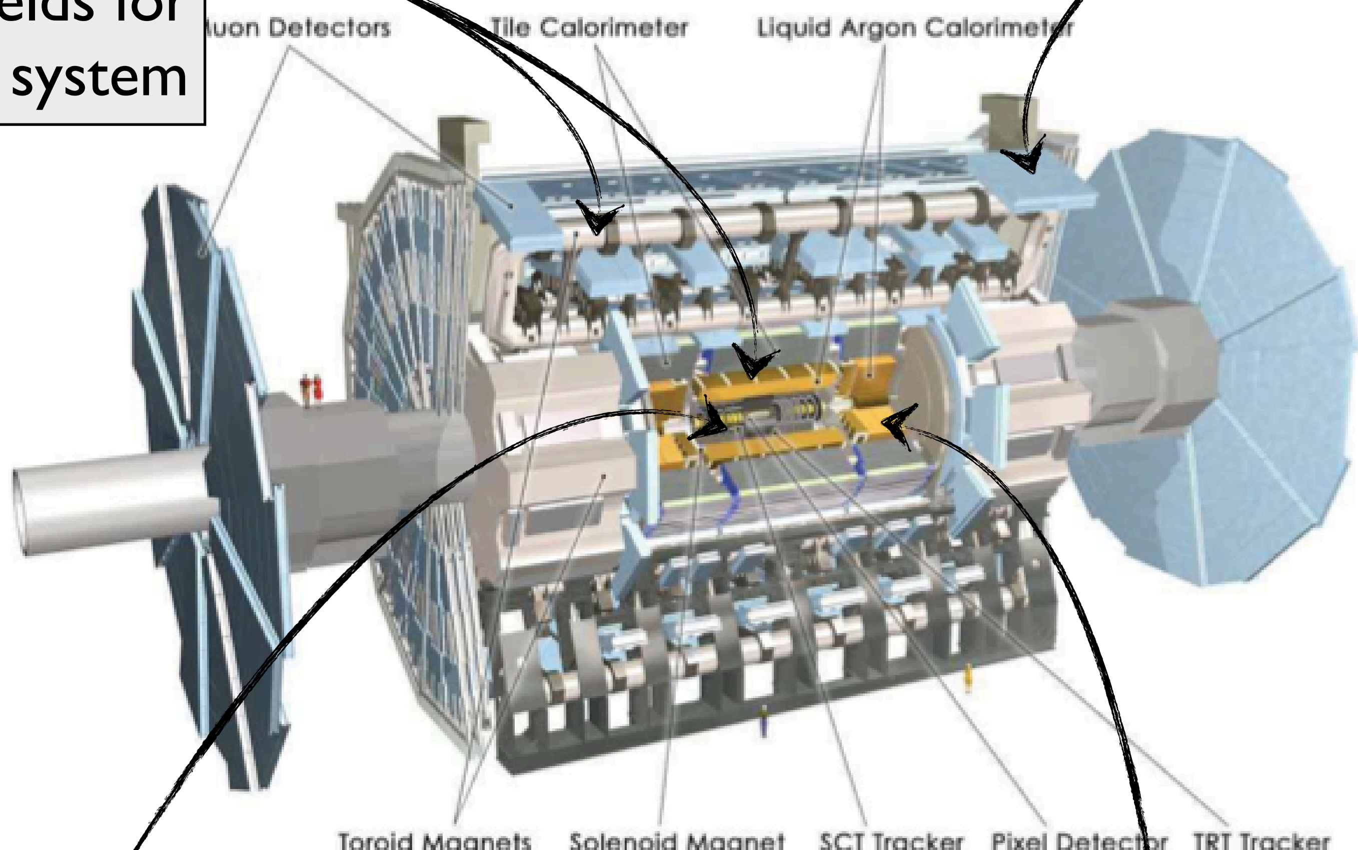
Charilaos Tsarouchas - CERN
ATLAS collaboration

Summer School and Workshop on the Standard Model and Beyond
September 8 - 17, 2012

The ATLAS detector

magnets
provide bending fields for tracker and muon system

muon detectors (|η|<2.7)
measure directions and momenta of muons



Inner detectors (|η|<2.4)
measure directions and momenta of charged particles

- primary/secondary vertices
- B/D mesons ~ 0.5/0.3mm
- $\sigma p/p \approx$ 3-5 %

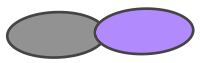
electromagnetic (EM) calorimeter
absorb and measure the energies of electrons, photons

Triggers for B Physics

- LHC is designed with a maximum bunch crossing at 40MHz
- ATLAS trigger designed to record events at ~200Hz*
- Reduction factor ~**10^5**

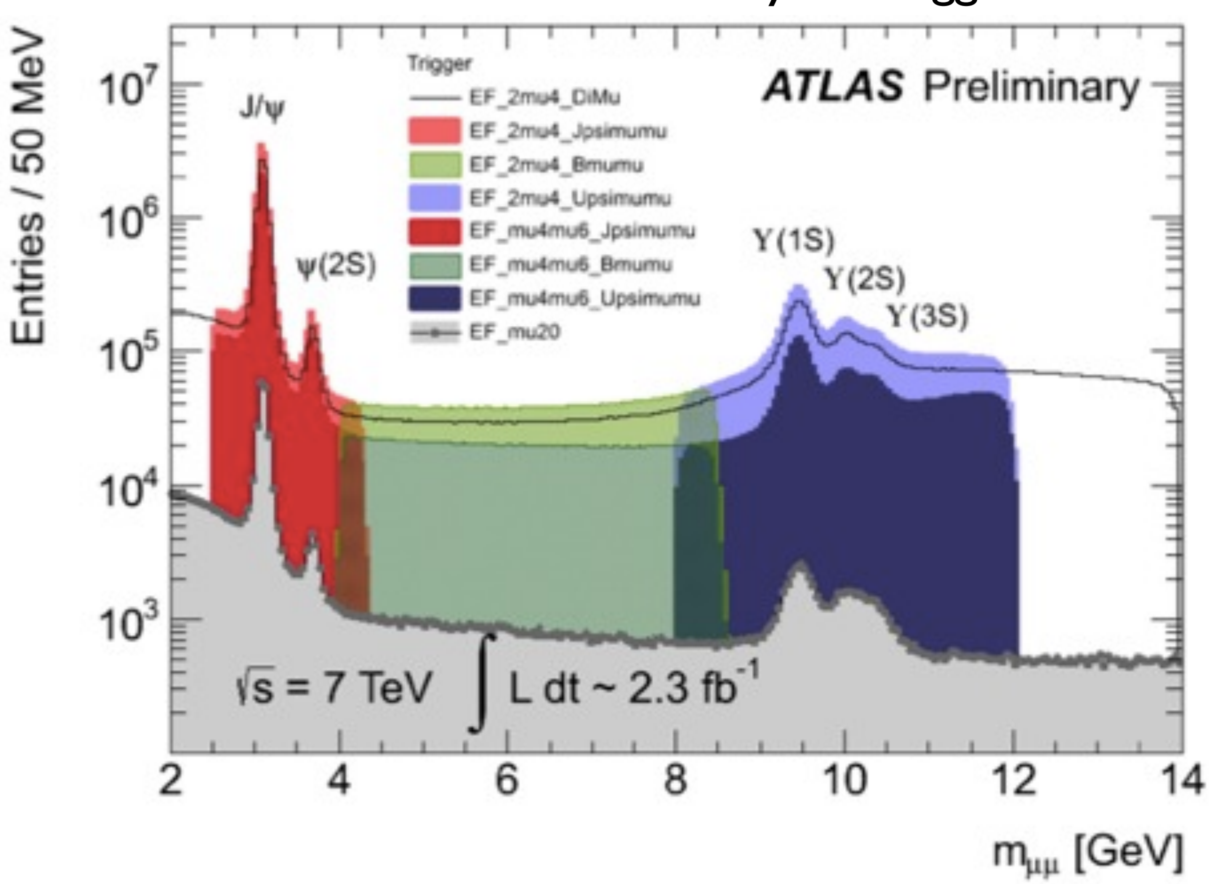
Event Filter	200 Hz
level 2	~3 kHz
level 1	75 kHz

- At LHC design energy, ~1%† of collisions contain $b\bar{b}$ pair

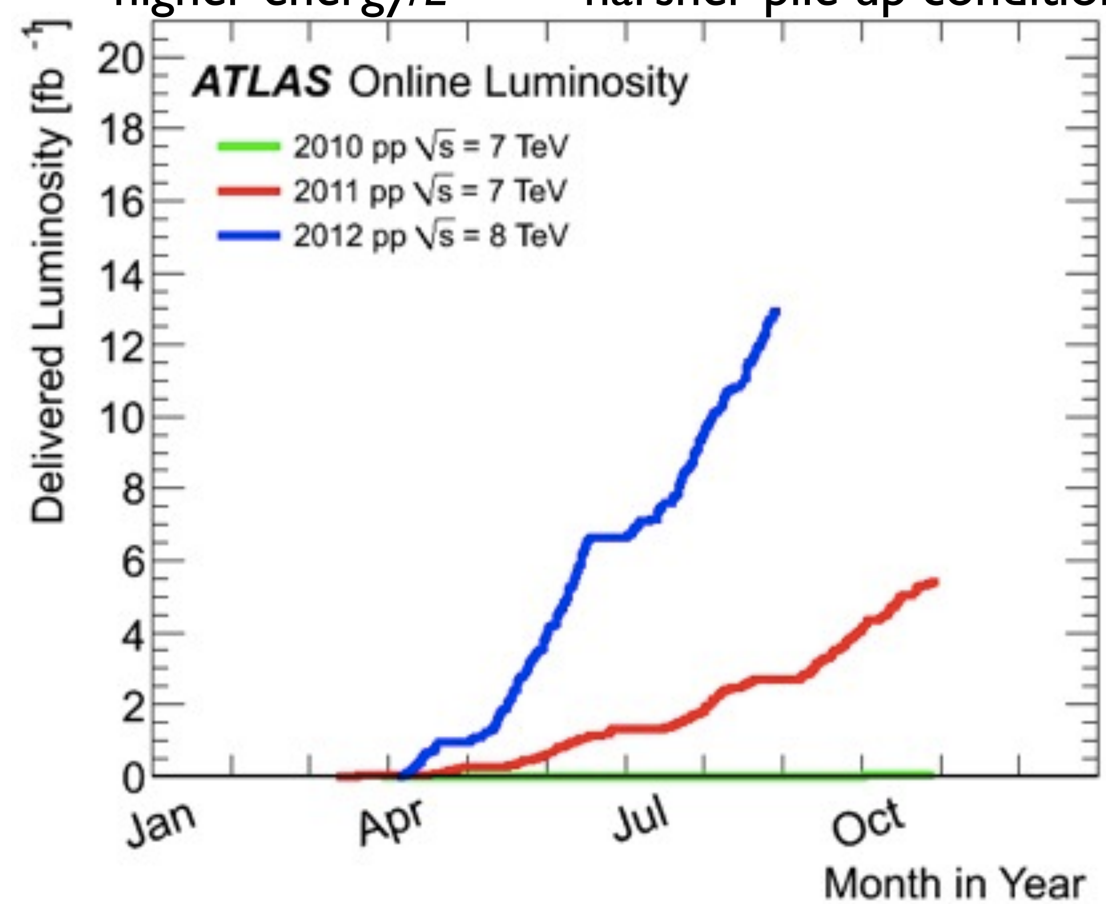
p →  ← p

- BPhysics recording bandwidth limited, 5−10% of ATLAS total trigger resources
- BPhysics triggers → highly selective

ATLAS di-muon B Physics triggers



higher energy/$L^{Inst.}$ → harsher pile up conditions

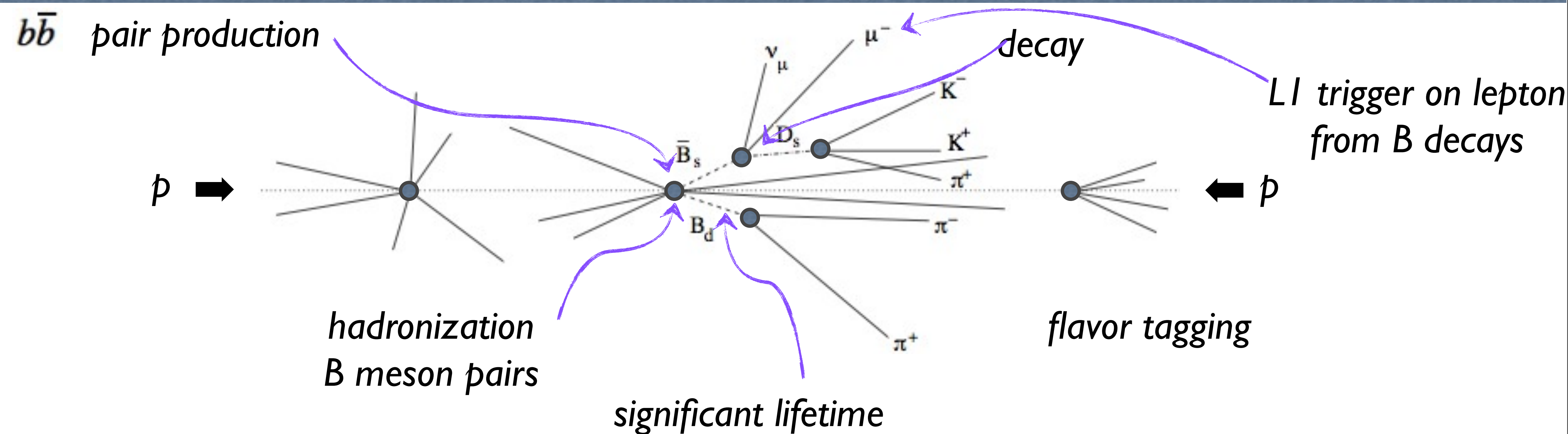


* Numbers from "Performance of the ATLAS Trigger System in 2010" , arXiv:1110.1530

† Numbers form "Perspectives on LHC Physics", ISBN: 978-981-277-975-5

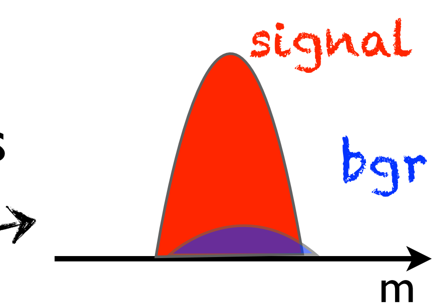
B physics experimental points

example



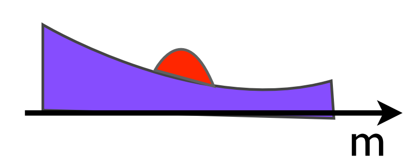
<u>signal</u>

- reconstruct decay of interest and study e.g. inv. mass, lifetime, polarization of particles



<u>background</u>

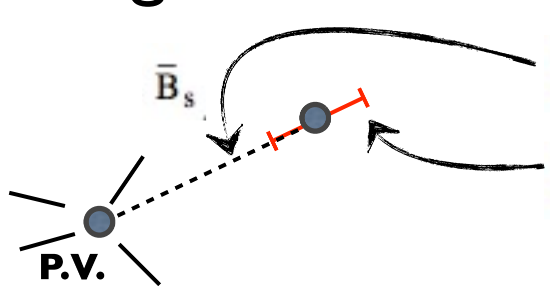
- fake signals, e.g. $B^0 \to \pi^+\pi^-$ misconstructed $B^0 \to K^+\pi^-$ (~correct mass/width)
- combinatoric bgr, e.g. $J/\psi \to \mu^+\mu^-$ and another μ (compatible but from other vtx)
- interaction with detector material (photons$\to e^-e^+$, h$\to$inelastic collisions)
- misconstructed tracks/misconstructed vertices



- cross section of b production quite small part of total cross section
- some interesting B physics processes with *Br* ~ 10^{-6}

} often we deal with small signals

<u>finding the needle in a haystack, key points</u>



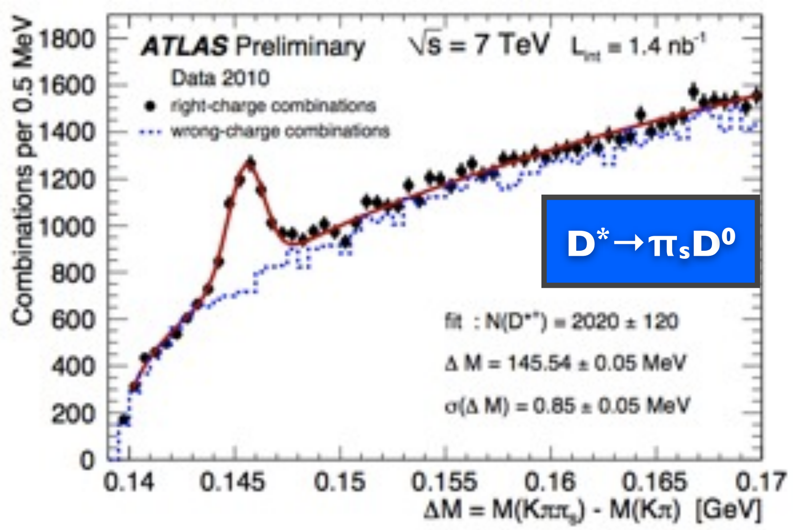
- *b, c* hadrons long lifetimes allow *b,c* physics to be extracted from bgr
- improved vertex resolution reduces background sources

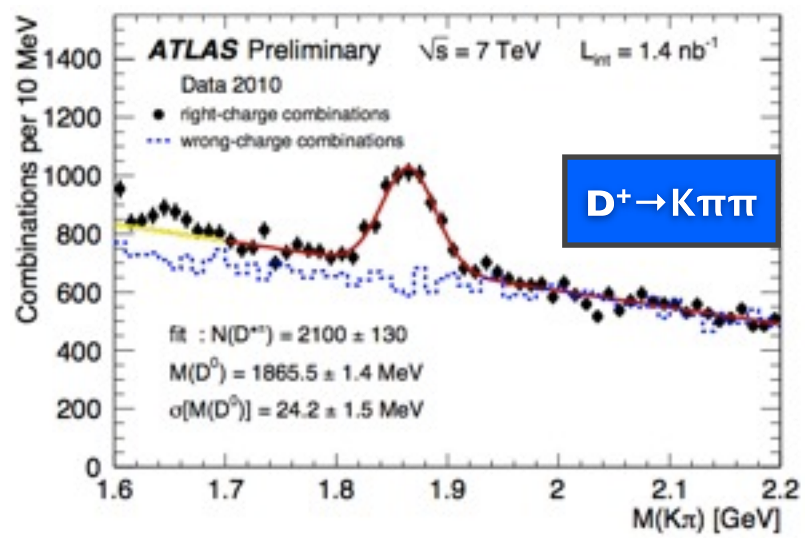
Open Charm/Beauty and Baryons

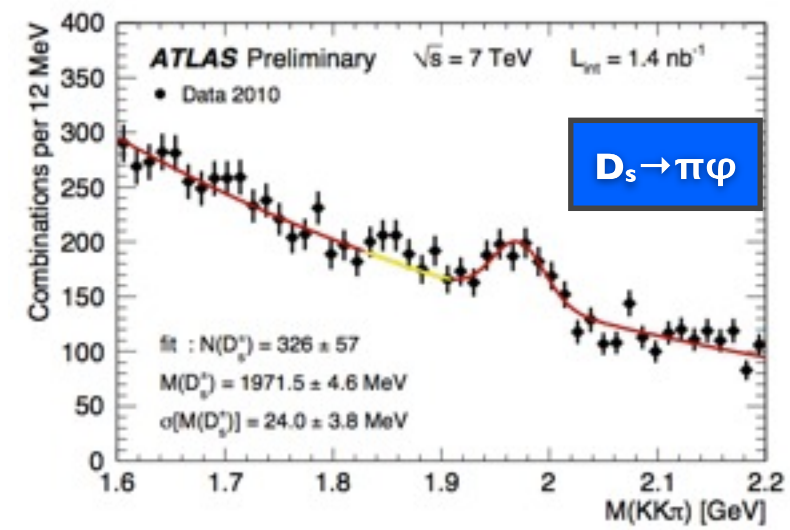
- ‘open’: c(b) quark with another not cbar(bbar) quark (distinguish from quarkonia)
- compare with previous measurements and test validity of QCD calculations

Observations of D, $B^{\pm}$, B^0_d, B^0_s, Λ_b, $B^{\pm}_c$ (ATLAS-CONF-2010-034, ATLAS-CONF-2010-098, ATLAS-CONF-2010-050, ATLAS-CONF-2011-124, ATLAS-CONF-2011-092, ATLAS-CONF-2012-028)

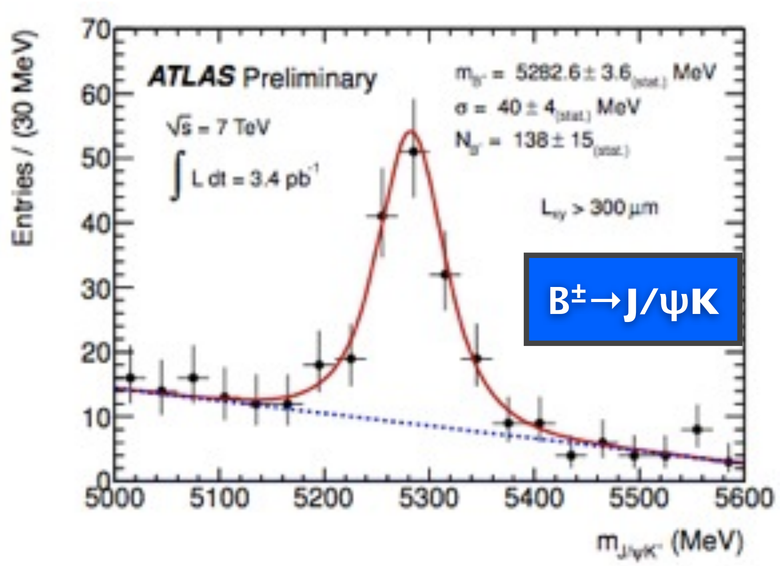
Differential and Integrated cross sections $D^{\pm}$,D^{*} (ATLAS-CONF-2011-017)

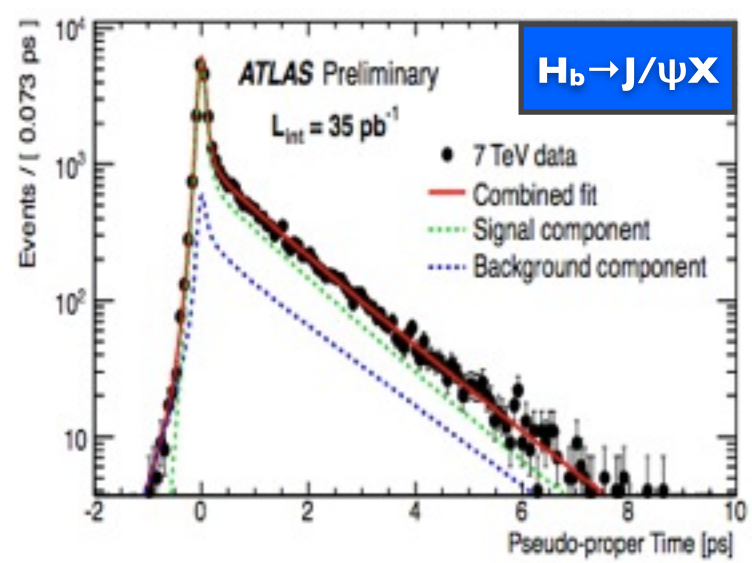


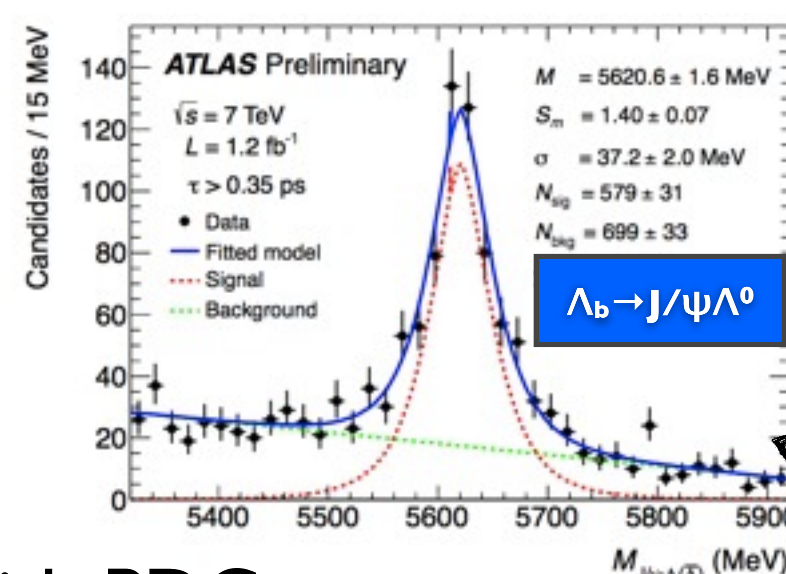




(few examples)





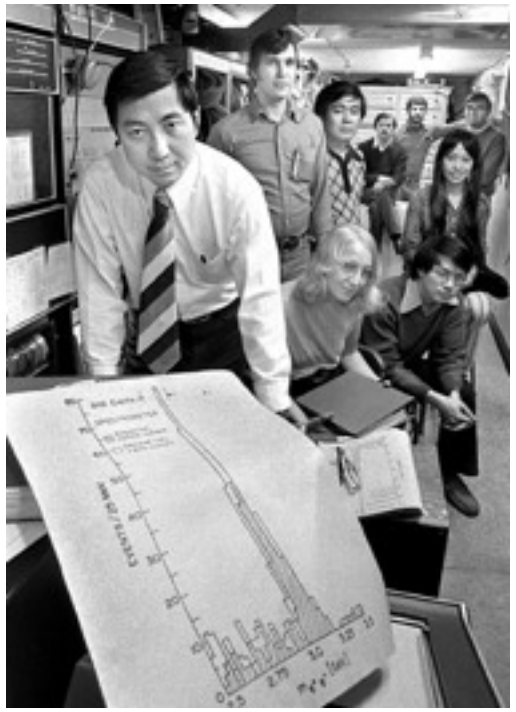


➡ mass fits, inclusive/exclusive lifetimes consistent with PDG

➡ detector’s performance as expected

Λ_b mass: best single experiment measurement

Charmonium



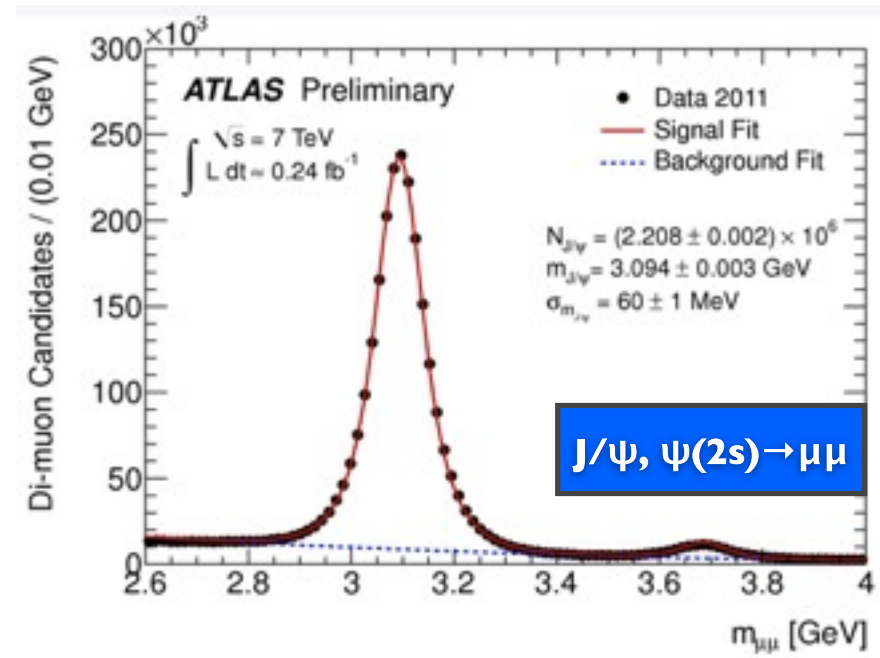
S.Ting and his research team 1974

- J/ψ observed in1974.
- Still no clear understanding of quarkonium production mechanisms which explain both cross section and spin alignment.

➛ quarkonium studies: insight into QCD

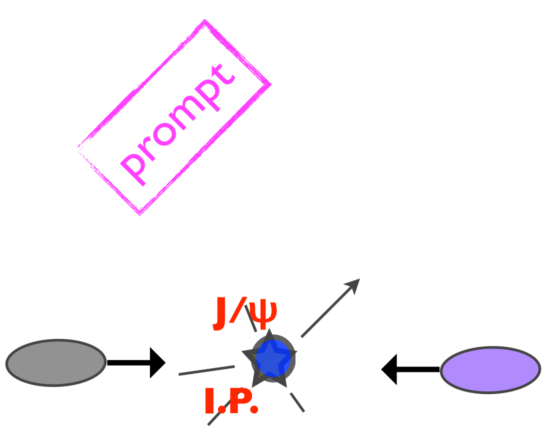
Observation of J/ψ, $\psi(2s)$

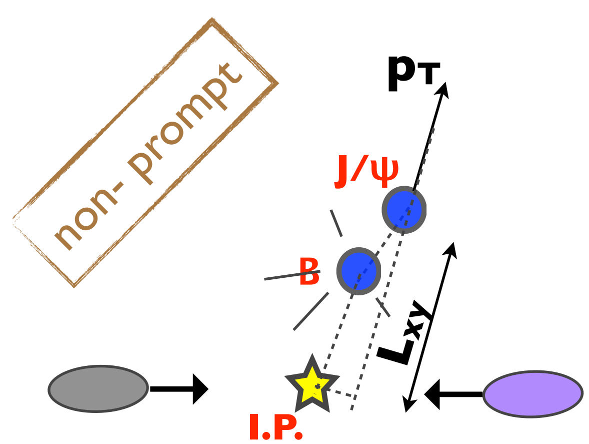
(ATLAS-CONF-2010-045)

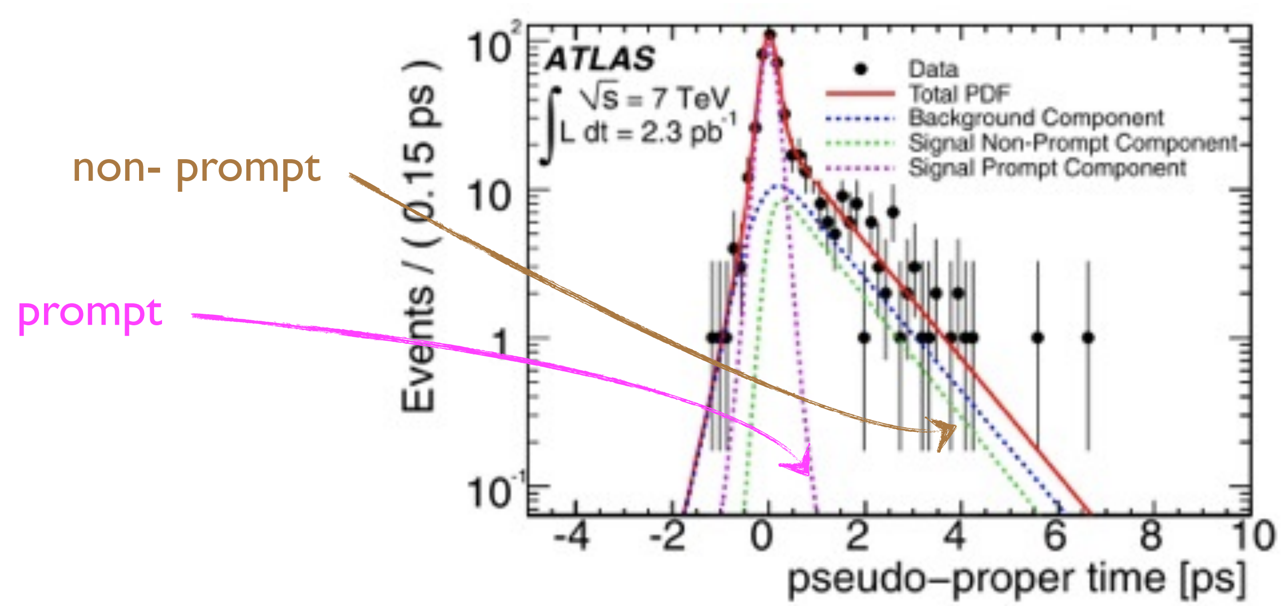


Differential cross section inclusive prompt/non prompt

(Nucl. Phys. B, Vol. 850, issue 3, 27/09/2011 pp. 387-444)







Charmonium

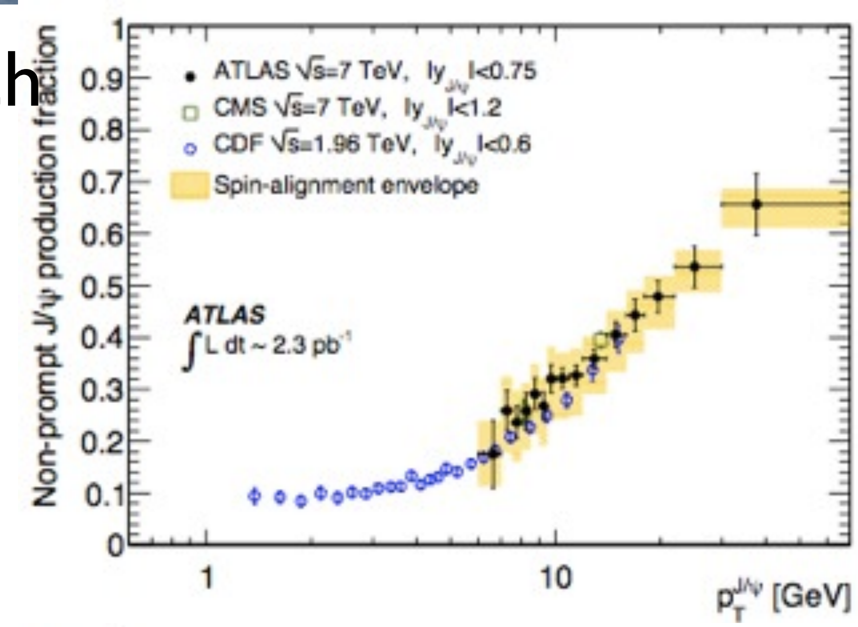
Number of J/ψ corrected for kinematic acceptance which depends on J/ψ spin alignment (not known in LHC)

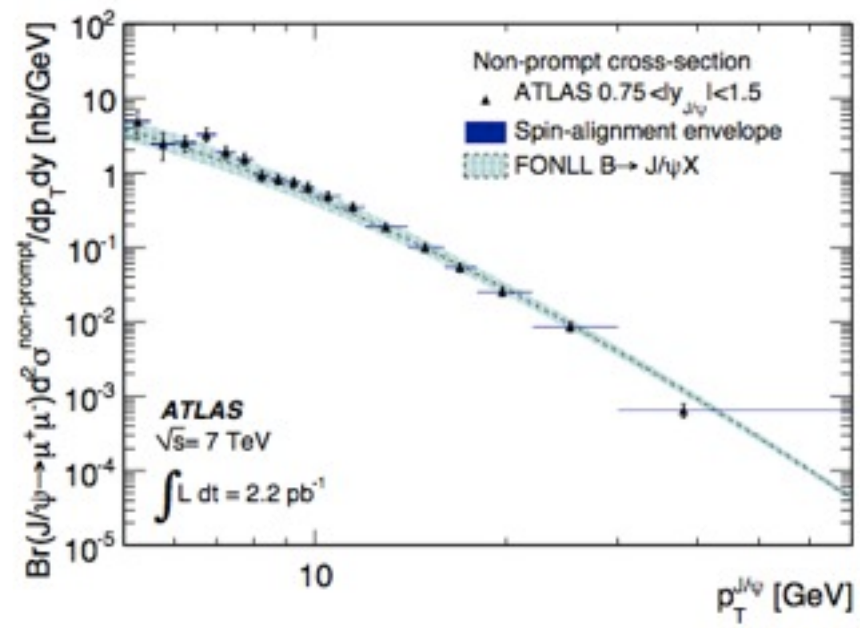
- 5 spin alignment scenarios considered
- extreme cases for acceptance corrections
- spin-alignment envelope

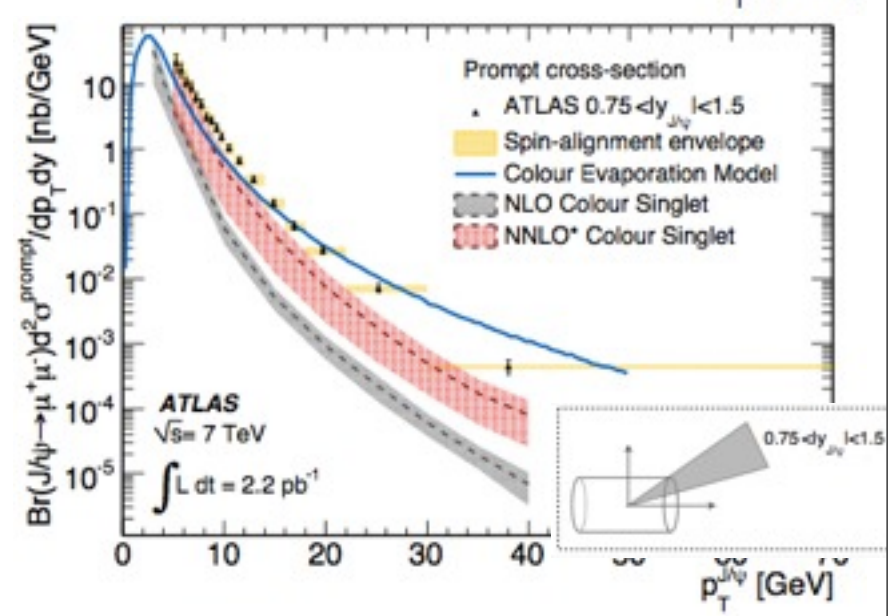
➡ Non prompt/Prompt fraction
results compared with CDF (lower energy)
reasonable agreement
→ fraction independent of collision energy

➡ Non prompt cross section
- FONLL* shape: ✓ scale: ✓

➡ Prompt cross section
- CEM shape: ✗ scale: ~✓
- CSM(NLO) shape: ~✓ scale: ✗
- COM(NNLO) shape: ~✓ scale: ~✓

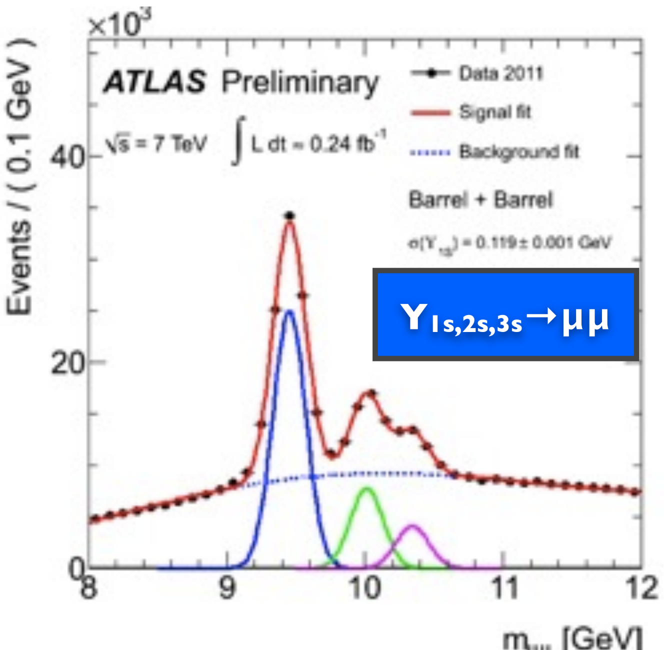






*Fixed-Order Next-to-Leading Log

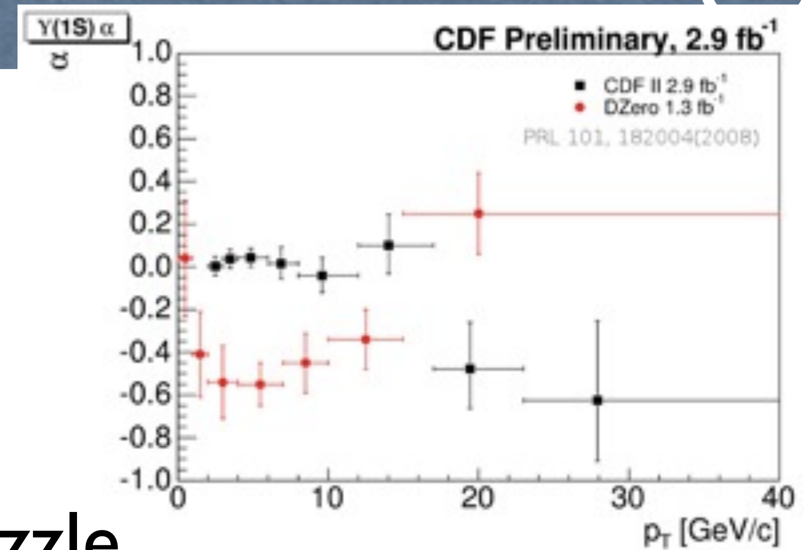
Bottomonium



(Phys. Lett. B705, 9-27 (2011) arXiv:1106.5325)

- No conclusive coherent theoretical picture for *Υ* hadroproduction
- CDF, D0 disagree concerning *Υ* spin alignment

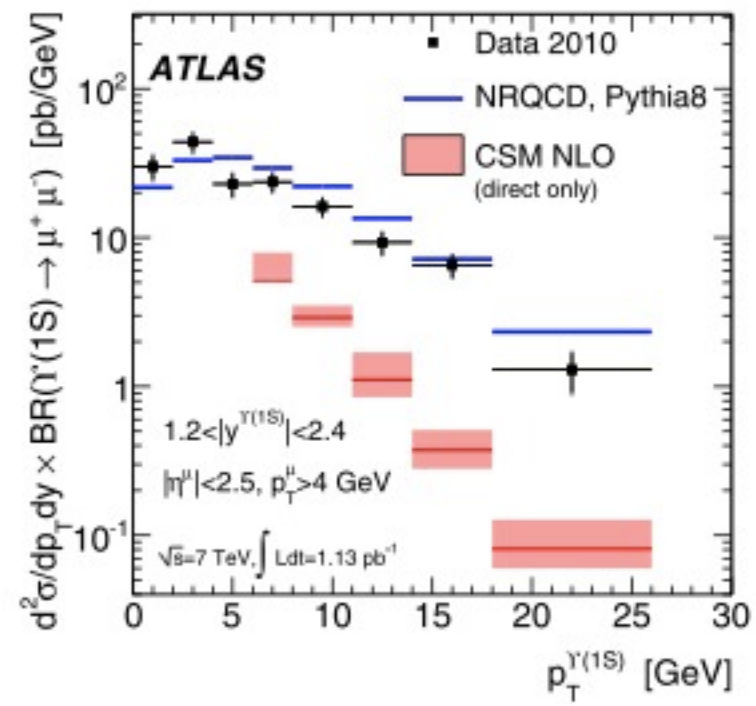
➛ LHC experiments shed light on puzzle



Υ(1s) measurement production cross section

- Measurement within ATLAS fiducial volume - factors out spin alignment uncertainty

➡ *Υ*(1S) cross section
- CSM(NLO) ✗
- NRQCD ~✓



New χ_b state observation, $\chi_b(3P)$

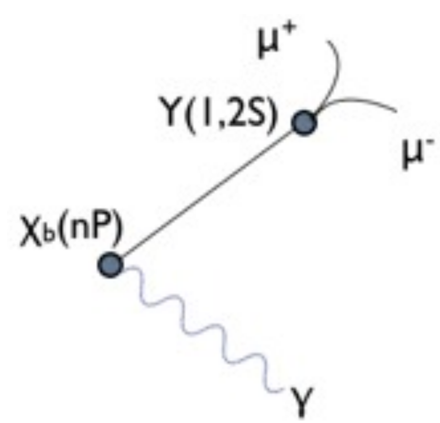
(Phys. Rev. Lett. arXiv:1112:5154)

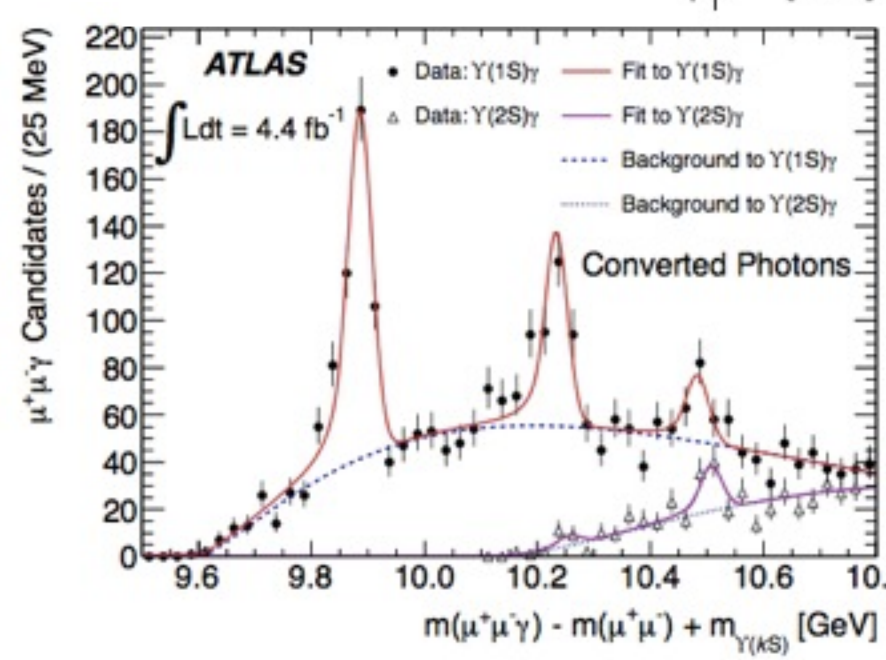
- state reconstructed through radiative decays

➡ first LHC new structure !

➡ found at 10.5GeV with significance > 6σ

➡ consistent with theoretical predictions

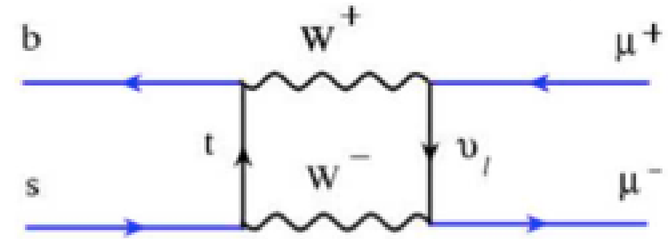


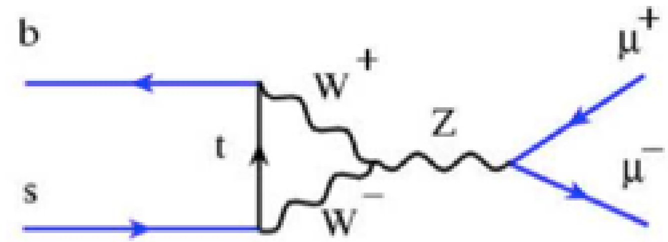


$B_s \to \mu^+\mu^-$

ATLAS 2011 data: 2.4fb^{-1}

- Br($B_s \to \mu^+\mu^-$) highly suppressed, SM (FCNC)
- SM contributions from W-box, Z-penguin diagrams
- small theoretical uncertainties
- clear experimental signature
- measurement sensitive to NP





decay channel	theoretical expectations
$B_s \to \mu\mu$	$(3.2 +/- 0.2) \times 10^{-9}$
$B_d \to \mu\mu$	$(1.1 +/- 0.1) \times 10^{-10}$

Buras arXibv:1009.1303

- NP models with extended Higgs sector enhance the branching ratio

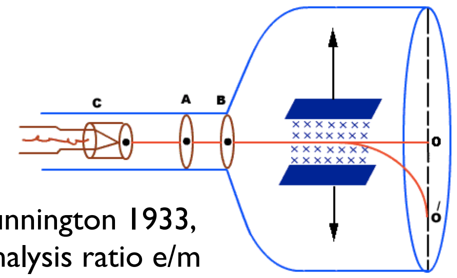
e.g. of SUSY models with few free parameters give

$$\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{CMSSM}}}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}}} \approx 1.2^{+0.8}_{-0.2} \qquad \frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{NUHM1}}}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}}} \approx 1.9^{+1.0}_{-0.9}$$

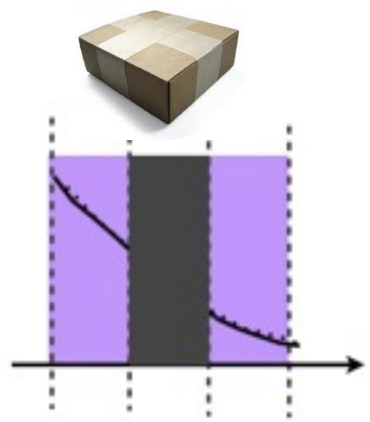
Search for rare decay $B_s \to \mu^+\mu^-$ with ATLAS detector

(Phys.Lett. B713 (2012) 387)

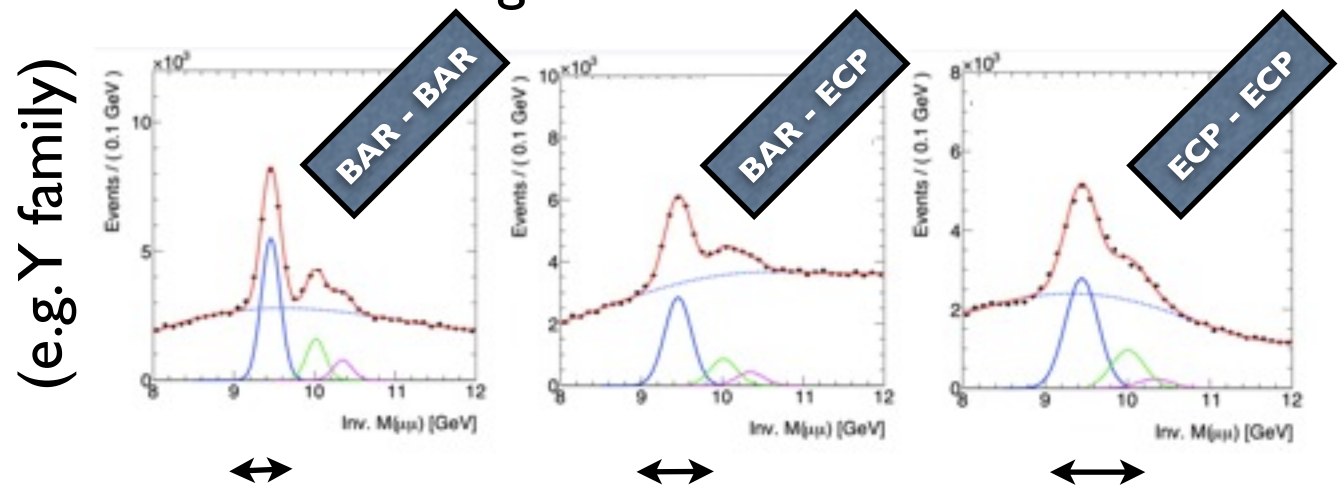
$B_s \to \mu^+\mu^-$ Analysis Strategy



F.G. Dunnington 1933, blind analysis ratio e/m

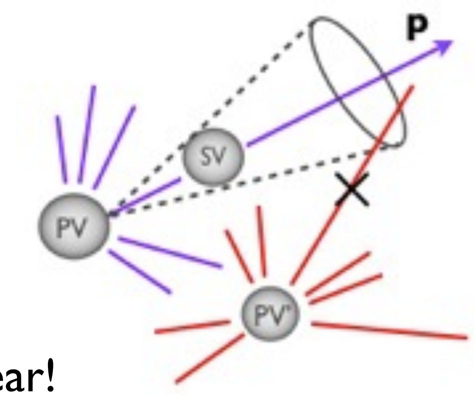


resolution degradation →

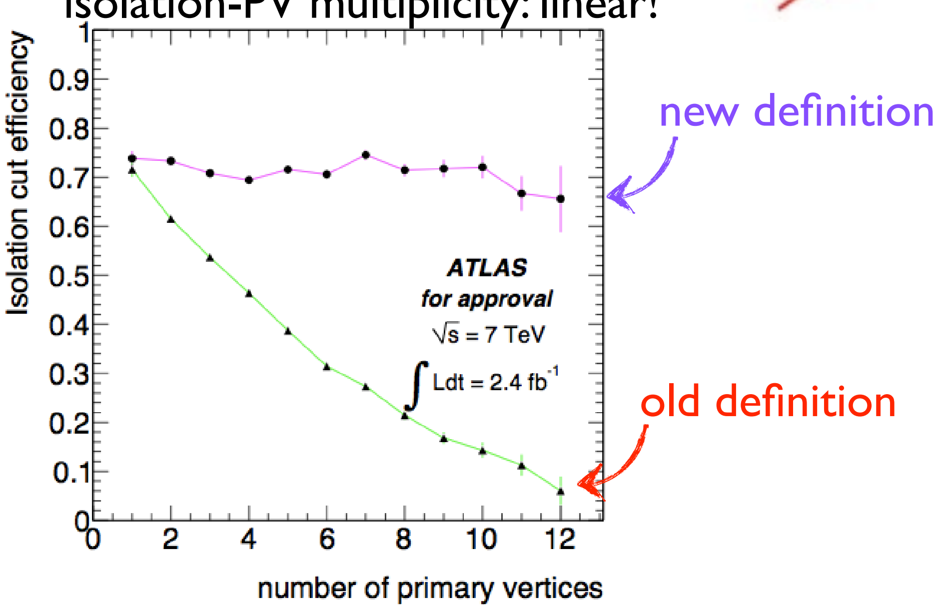


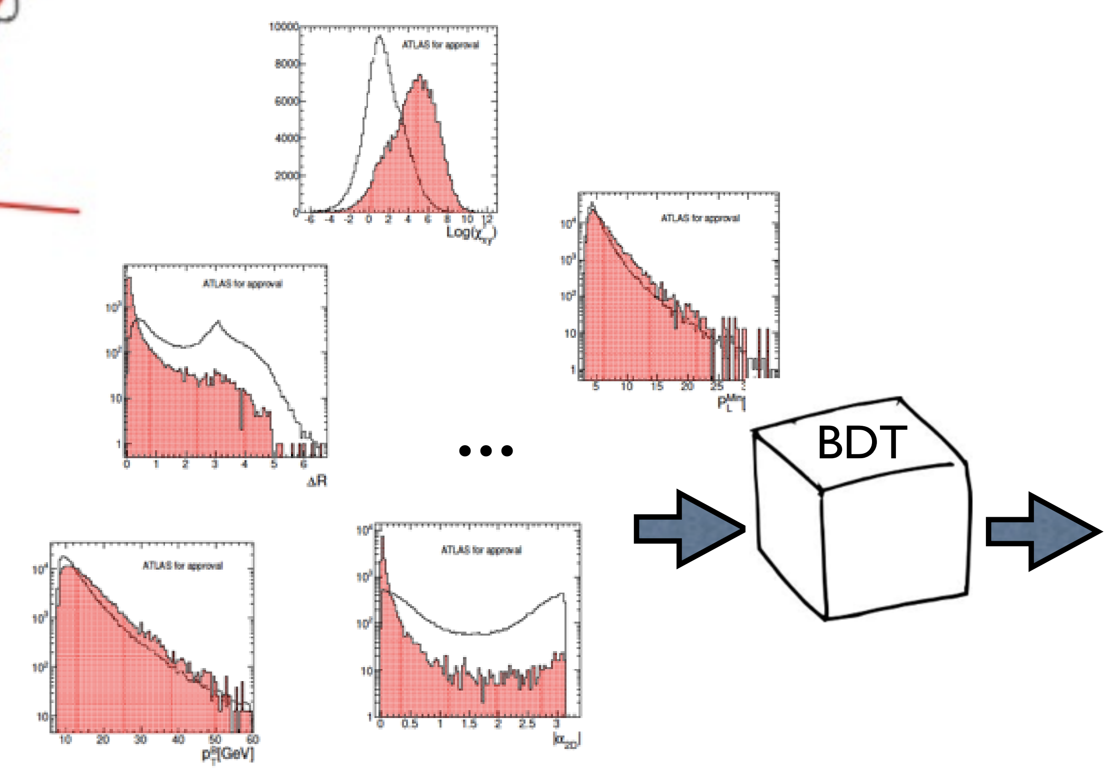
- small signal, blind analysis
- sample split in 3 categories
- reference channel → minimization of systematic uncertainty A,ε $B^{\pm} \to J/\psi K^{\pm}$
- need of high separation power: 14 separation variables, multivariate BDT analysis

Enhanced isolation definition

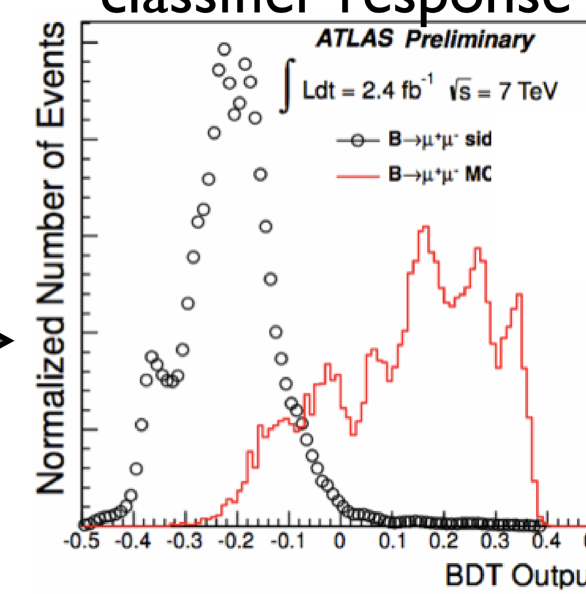


isolation-PV multiplicity: linear!





classifier response



$B_s \to \mu^+\mu^-$ Measurements

signal

$$N_{B_s\to\mu\mu} = L_{Int}\cdot\sigma_{B_s}\cdot Br(B_s\to\mu\mu)\cdot a_{B_s\to\mu\mu}\cdot\varepsilon^{tot}_{B_s\to\mu\mu}$$

$$N_{B^\pm\to J/\psi K^\pm} = L_{Int}\cdot\sigma_{B^\pm}\cdot Br(B^\pm\to J/\psi K^\pm\to\mu\mu K^\pm)\cdot a_{B^\pm\to J/\psi K^\pm}\cdot\varepsilon^{tot}_{B^\pm\to J/\psi K^\pm}$$

reference

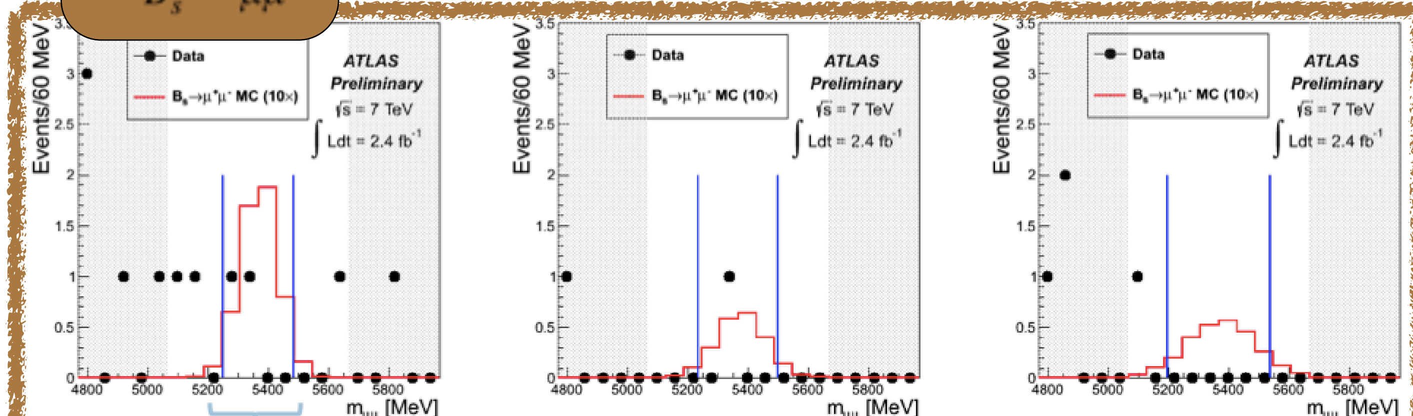
$$\Rightarrow Br(B_s\to\mu\mu) = Br(B^\pm\to J/\psi K^\pm\to\mu\mu K^\pm)\frac{f_u}{f_s}\times\frac{N_{B_s\to\mu\mu}}{N_{B^\pm\to J/\psi K^\pm}}\times\frac{a_{B^\pm\to J/\psi K^\pm}\cdot\varepsilon^{tot}_{B^\pm\to J/\psi K^\pm}}{a_{B_s\to\mu\mu}\cdot\varepsilon^{tot}_{B_s\to\mu\mu}}$$

PDG, LHCb

B_s, B^{ref} Yield (**data**)

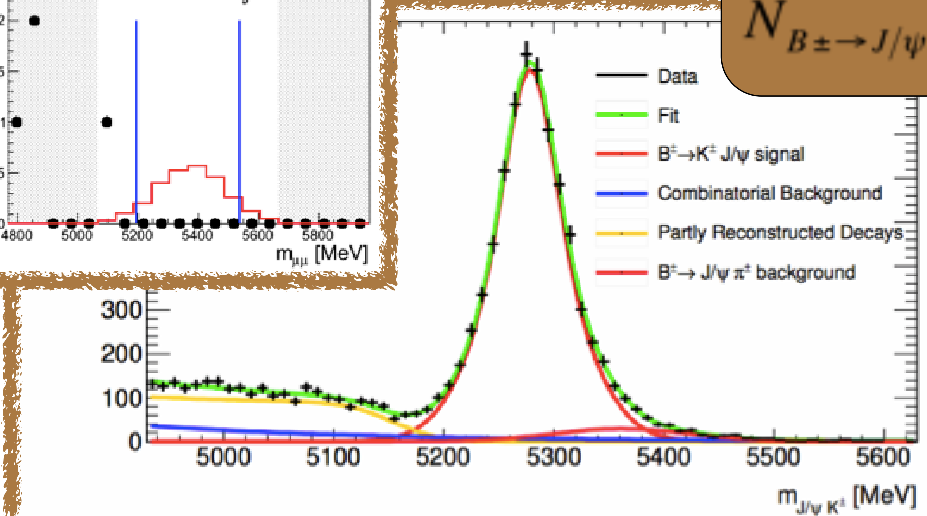
acceptance/efficiency ratio (**MC**)

$N_{B_s\to\mu\mu}$



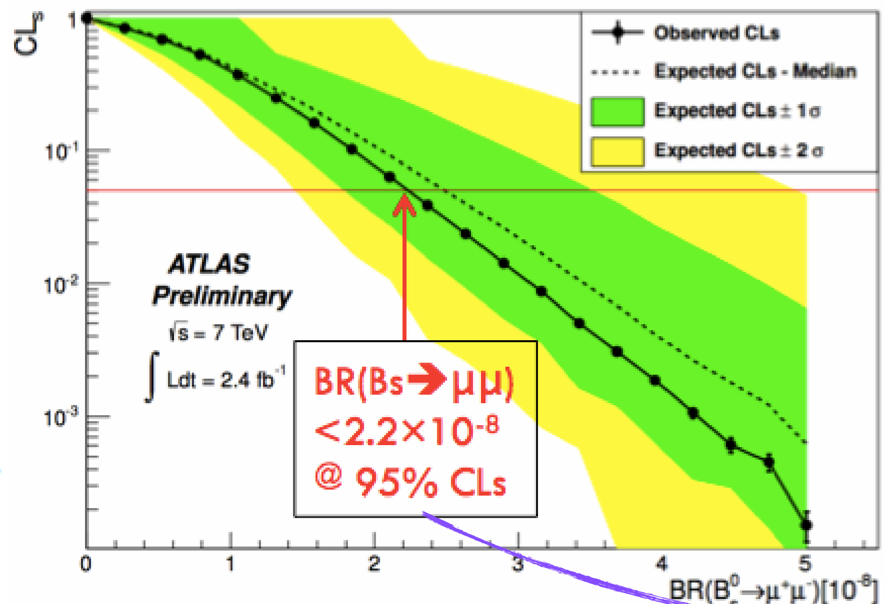
- observed in SR 2/1/0 ev.
- continuum bgr 6.1ev.
- resonant bgr 0.24 ev.

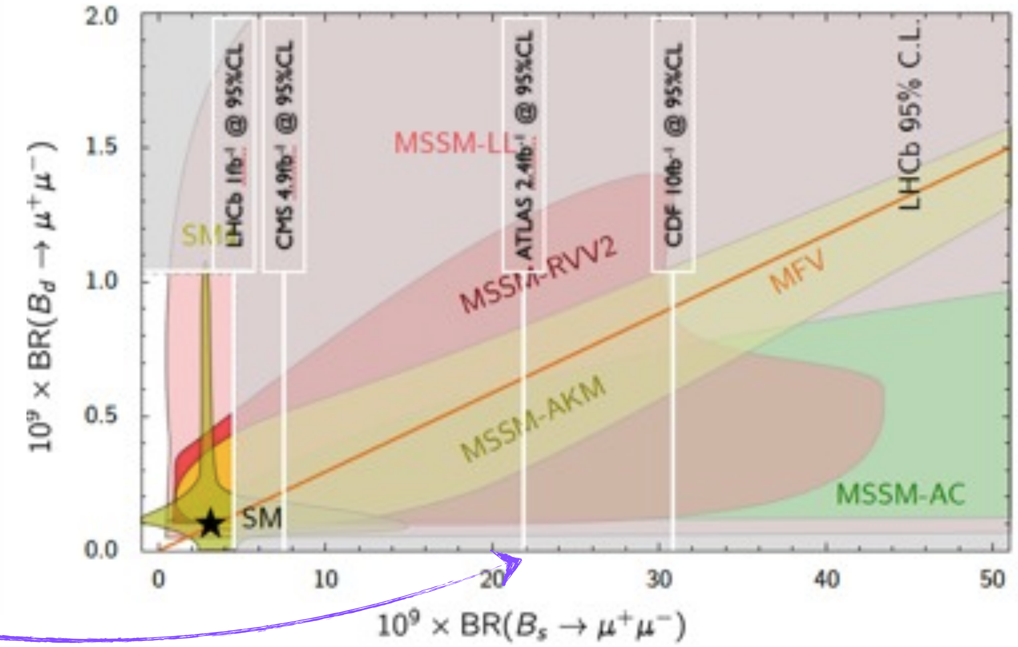
$N_{B\pm\to J/\psi K\pm}$



$\lvert\eta_{max}\rvert$ Range	$R^i_{A\epsilon}$	Δ % Stat.	Δ % Syst.
0-1.0	0.274	3.1	3.1
1.0-1.5	0.202	4.8	5.5
1.5-2.5	0.143	5.3	5.9

$B_s \to \mu^+\mu^-$ Extraction of Limit





$B(B_s \to \mu^+\mu^-) < 2.2 \times 10^{-8}$ @95%CL

Search for rare decay $B_s \to \mu^+\mu^-$ with ATLAS, CMS, LHCb

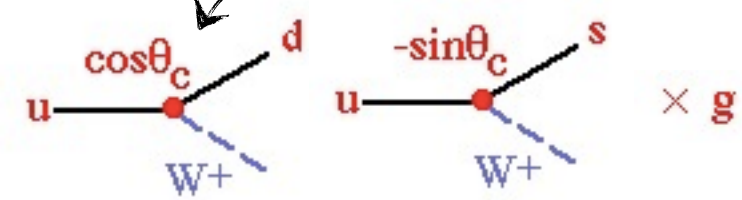
(ATLAS-CONF-2012-061)

C.L.	bkg only 90%	bkg only 95%	SM + bkg 90%	SM + bkg 95%	**Observed 90%**	**Observed 95%**
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.9	2.3	5.4	6.1	**3.7**	**4.2**

$B(B_s \to \mu^+\mu^-) < 4.2 \times 10^{-9}$ @95%CL

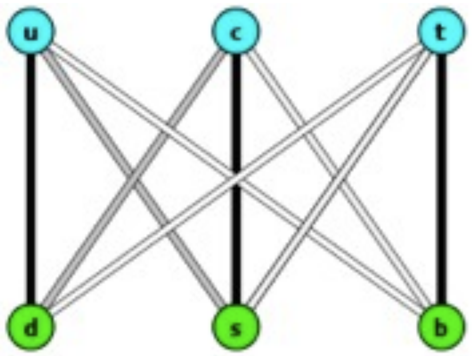
- ➡ combined ATLAS, CMS, LHCb limit: best existing limit
- ➡ No significant NP enhancement with respect to SM
- ➡ Still room for NP can be probed with higher $L^{Int.}$

Cabbibo's angle



Weak interactions not respect quark generations

In SM the mass D^T=(d,s,b) and the flavor D'^T=(d',s',b') eigenstate bases are misaligned. Corrected by the V_{CKM} matrix



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

vectors phase redefinition ➛ reduction
- 3 'generalized cabbibo angles' θ_{12} θ_{23} θ_{13}
- 1 complex phase δ

single source CP violation within SM

Standard

$$\hat{V}_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

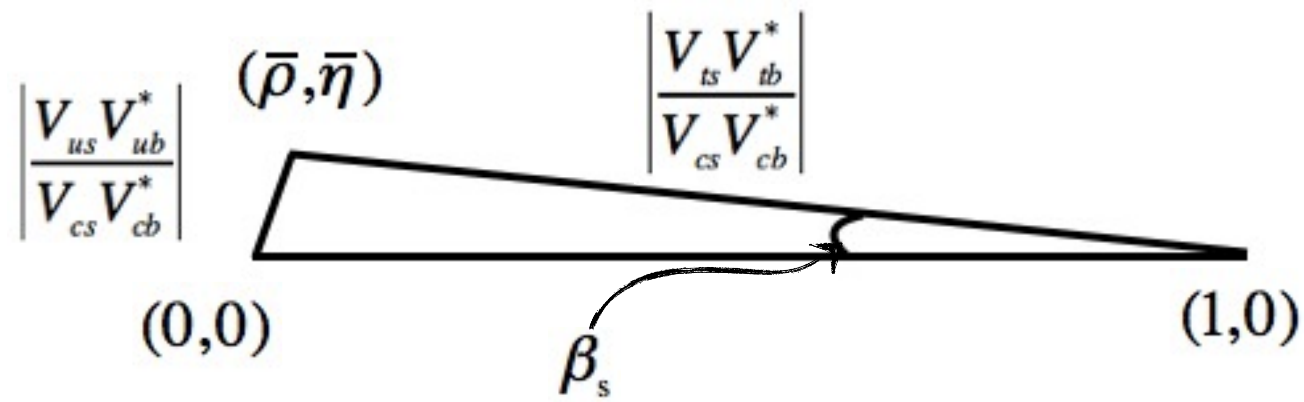
Wolfenstein

$$\hat{V} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda + \mathcal{O}(\lambda^7) & A\lambda^3(\varrho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\varrho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 + \mathcal{O}(\lambda^8) \\ A\lambda^3(1 - \bar{\varrho} - i\bar{\eta}) & -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\varrho + i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

λ A ρ η

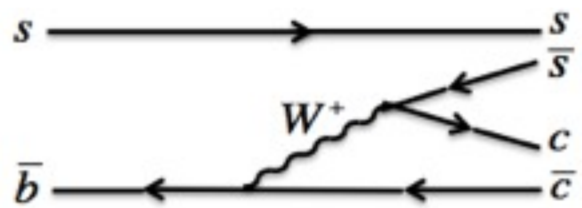
$B_s \to J/\psi\varphi$

V_{CKM} unitary since it relates two orthonormal bases of a 3-D space
Unitarity leads to 12 relations
e.g. $V_{us}V^*_{ub} + V_{cs}V^*_{cb} + V_{ts}V^*_{tb} = 0$
represents triangle in complex plane

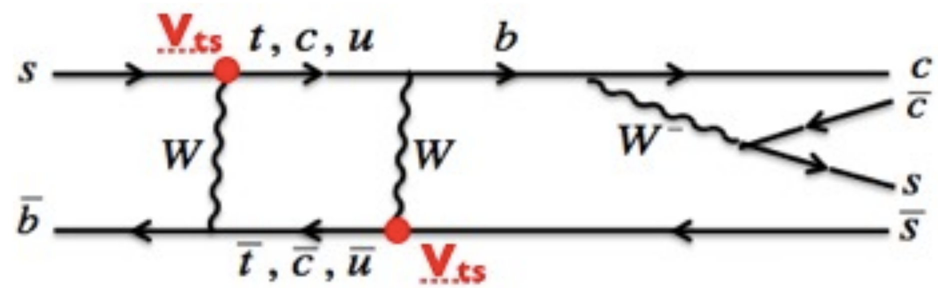


$V_{ts} = -|V_{ts}|e^{-i\beta_s}$

$B_s \to f$



$B_s \to \bar{B}_s \to f$

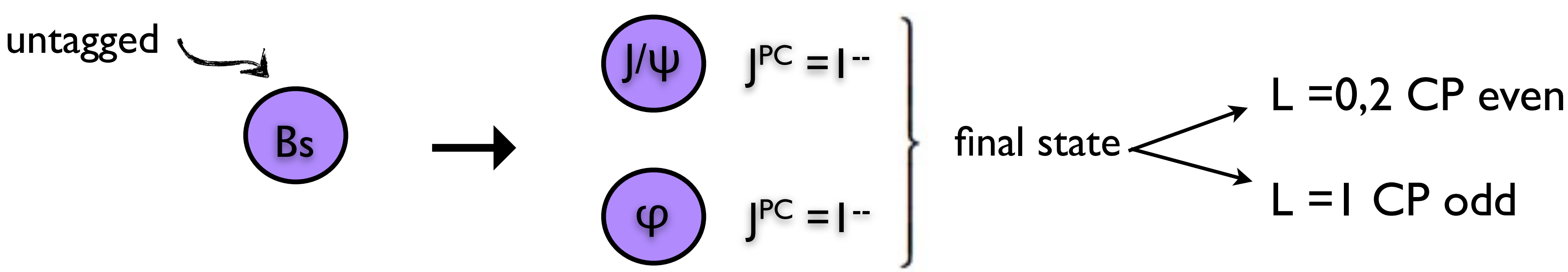


($m_{u,c} << m_t$) only top sector contributes significantly

CP asymmetry is dominated by CP violation in interference between decays with and without mixing

$\varphi_s \approx -2\beta_s$

The mass eigenstates B_S,B_L deviate from the CP eigenstates as described in SM by the mixing phase φ_s



Final states can be statistically separated by defining their angular configuration (transversity basis)

- ➛ theory: precise values for φ_s = 0.036±0.002 [Charles et al. 2005] $\Delta\Gamma_s$ = 0.087±0.021 [Lenz and Nierste 2011]
- ➛ new physics may contribute to φ_s

$B_s \to J/\psi\varphi$, the fit

(arXiv:1208.0572v1)

Time-dependent angular analysis of the $B_s \to J/\psi\varphi$ and extraction of φ_s, $\Delta\Gamma_s$

parameters of $B_s \to J/\psi\varphi$ extracted from unbinned maximum likelihood fit

signal fraction

trig. eff.

B^0 background fraction

constrain of $\delta_\perp$ to recent LHCb measurement

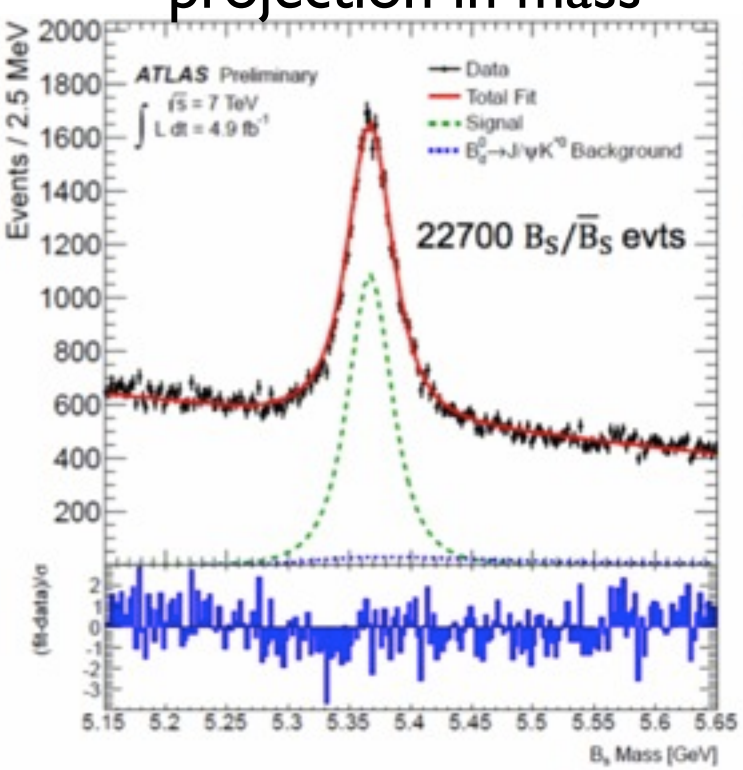
$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_s \cdot \mathcal{F}_s(m_i, t_i, \Omega_i) + f_s \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \Omega_i) + (1 - f_s \cdot (1 + f_{B^0})) \mathcal{F}_{bkg}(m_i, t_i, \Omega_i)) \} + \ln P(\delta_\perp)$$

signal PDF

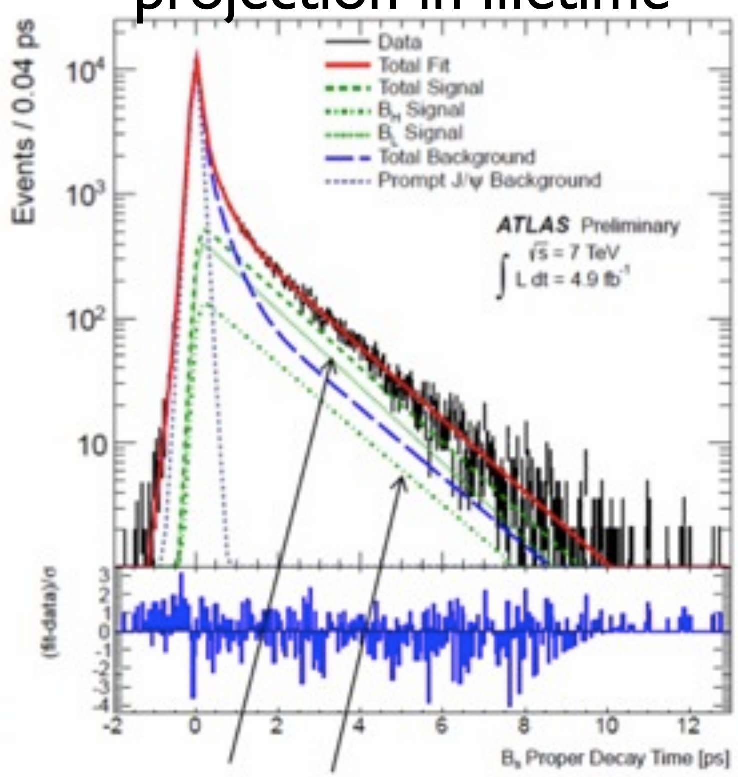
background PDF $B^0 \to J/\psi K^*$, $B^0 \to J/\psi K^+\pi^-$

background PDF

projection in mass

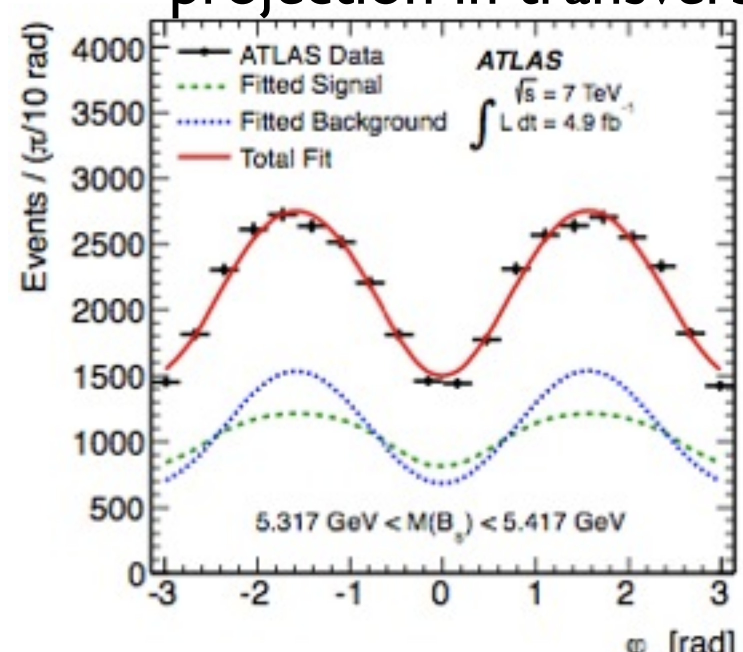


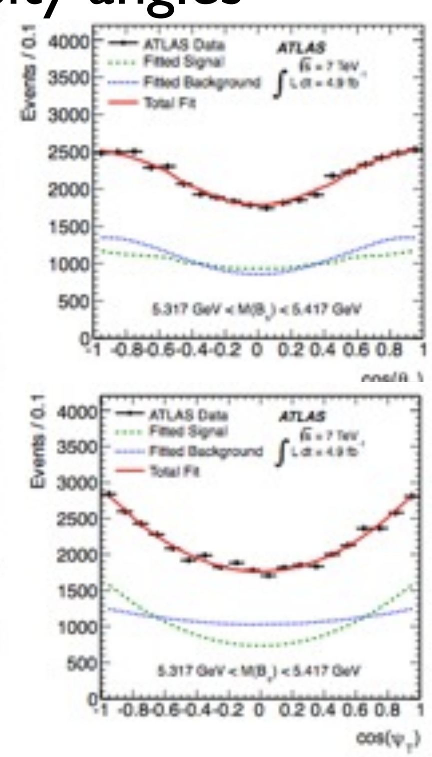
projection in lifetime



$\Delta\Gamma_S = \Gamma_L - \Gamma_H$

projection in transversity angles

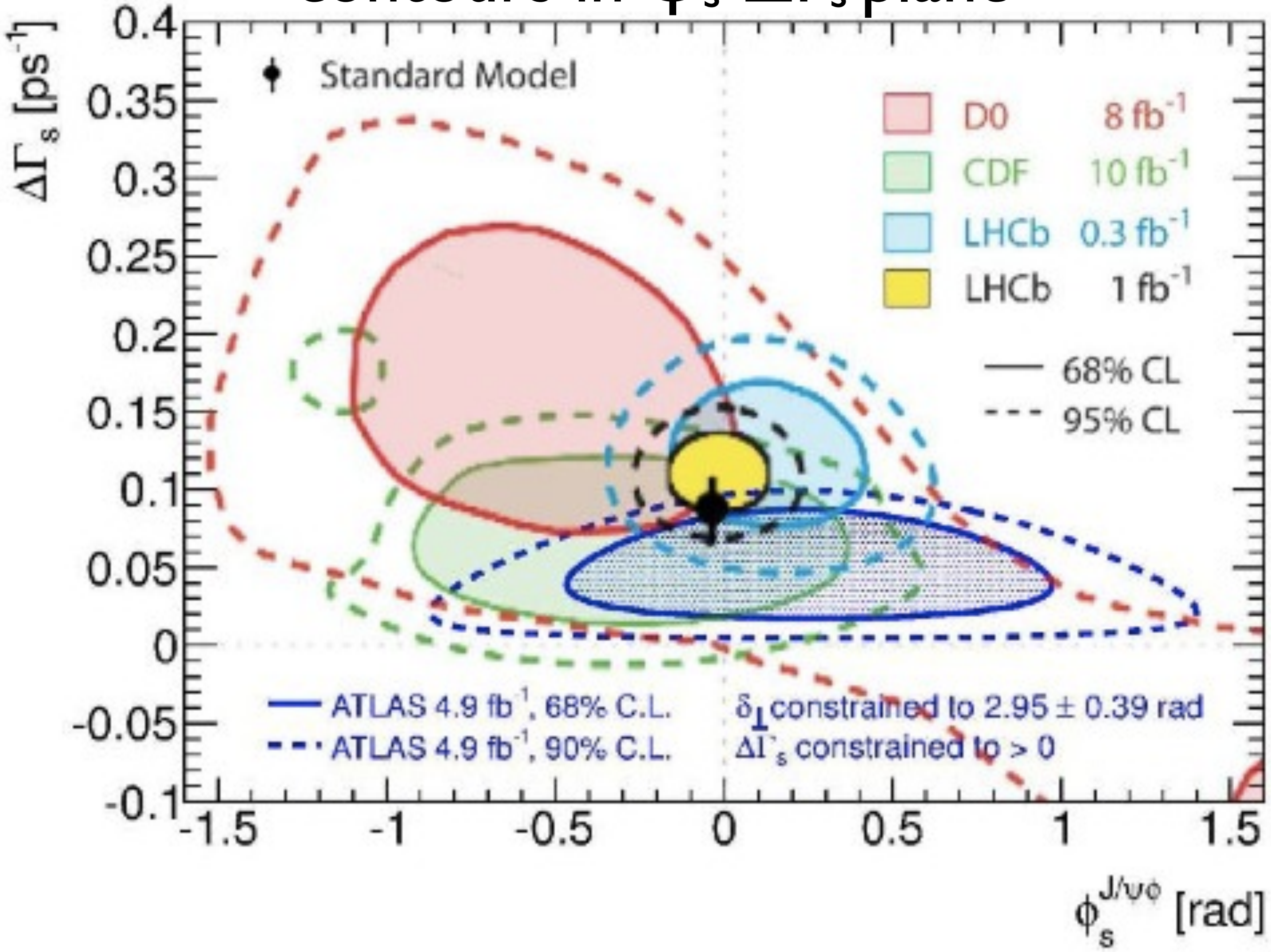




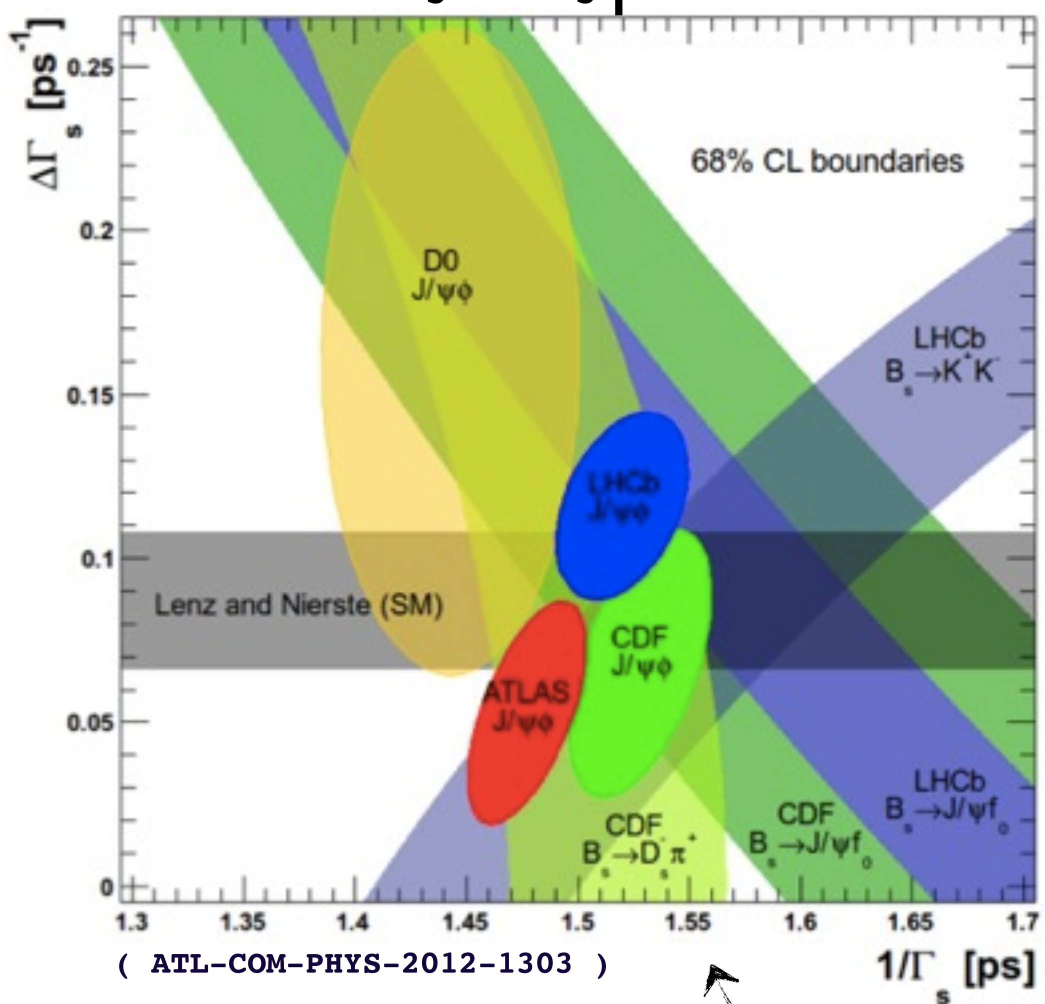
used to measure the absolute values of the transversity amplitudes A_0 $A_\perp$ $A_\parallel$ A_S

$B_s \to J/\psi\varphi$, the results

contours in φ_s-$\Delta\Gamma_s$ plane



$\Delta\Gamma_s$-$1/\Gamma_s$ plane



(ATL-COM-PHYS-2012-1303)

plane where the measurement is most precise

- ➡ φ_s within 1σ of the expected SM value
- ➡ consistency with other experiments
- ➡ big effect from NP ruled out

Conclusions

- ATLAS BPhysics program is very successful!
  - data taking with good signal collection efficiencies
  - benchmark channels well assessed

- New frontiers explored
  - $\chi_b(3P)$ discovery, first new particle at LHC
  - rare B decays
  - φ_s from $B_s \to J/\psi\varphi$ decay

- Stay tuned
  - improvements/updates in pipeline
  - still a lot of useful information in tape

    $B_s \to \mu\mu$ e.g. use all data, add muon spectrometer information

    $B_s \to J/\psi\varphi$ e.g. use all data, add flavor tagging

Backup slides

$B_s \to \mu^+\mu^-$

- minimise systematic uncertainty in A,ε
- picked among modes abundant enough: not statistically limiting factor in the extraction of limit

signal

$$\frac{N_{B_S \to \mu\mu} = L_{Int} \cdot \sigma_{B_S} \cdot Br(B_S \to \mu\mu) \cdot a_{B_S \to \mu\mu} \cdot \varepsilon^{tot}_{B_S \to \mu\mu}}{N_{B^\pm \to J/\psi K^\pm} = L_{Int} \cdot \sigma_{B^\pm} \cdot Br(B^\pm \to J/\psi K^\pm \to \mu\mu K^\pm) \cdot a_{B^\pm \to J/\psi K^\pm} \cdot \varepsilon^{tot}_{B^\pm \to J/\psi K^\pm}} \Rightarrow$$

reference

$$\Rightarrow Br(B_S \to \mu\mu) = Br(B^\pm \to J/\psi K^\pm \to \mu\mu K^\pm) \frac{f_u}{f_s} \times \frac{N_{B_S \to \mu\mu}}{N_{B^\pm \to J/\psi K^\pm}} \times \frac{a_{B^\pm \to J/\psi K^\pm} \cdot \varepsilon^{tot}_{B^\pm \to J/\psi K^\pm}}{a_{B_S \to \mu\mu} \cdot \varepsilon^{tot}_{B_S \to \mu\mu}}$$

(cyan) data from PDG and recent measurements of LHCb

- $Br(B^\pm \to J/\psi K^\pm) = (6.01 \pm 0.21) \cdot 10^{-5}$
- $\frac{f_u}{f_s} = 0.267 \pm 0.021$ (difference in b-quark fragmentation probabilities)

(green) Yield for the signal channel of B_s and reference channel B^{ref}

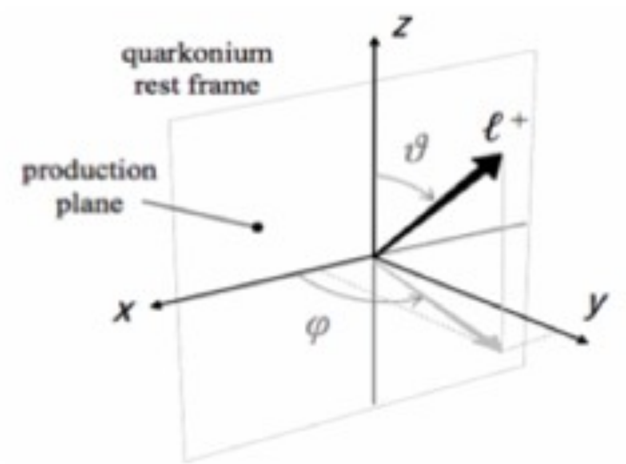
- Data

(yellow) Ratio of geometrical acceptance and efficiencies

- MC

Quarkonium polarization

The quarkonium polarization is measured via the angular distribution of its decay products



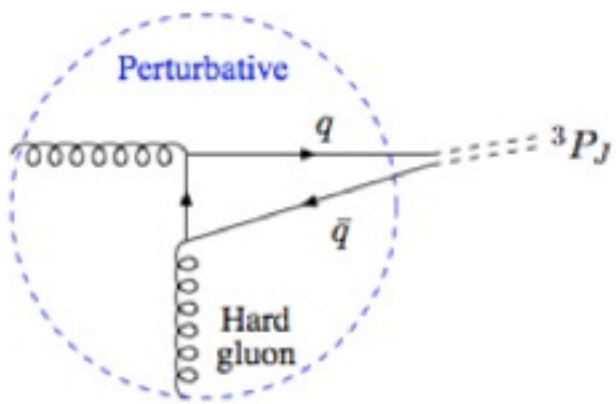
$$dN/d\Omega \propto [\,1 + \lambda_\theta \cos^2(\theta) + \lambda_\varphi \sin^2(\theta)\cos(2\varphi) + \lambda_{\theta\varphi} \sin(2\theta)\cos(\varphi)\,] / (1+\lambda_\theta/3)$$

$$\varepsilon(\text{total}) = \varepsilon(\text{trig}|\text{id}) \cdot \varepsilon(\text{id}|\text{track}) \cdot \varepsilon(\text{track}|\text{accepted})$$

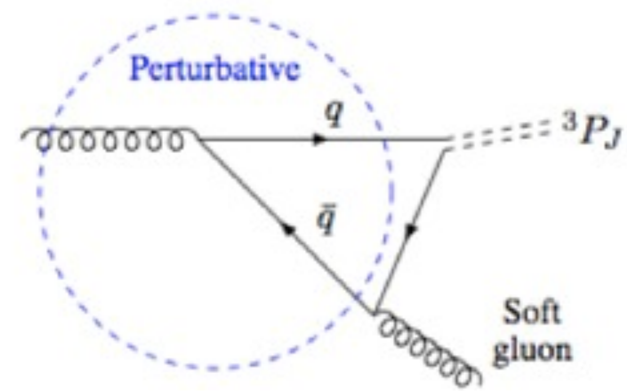
➡ Acceptance depends on production polarization

CSM - COM

CSM



COM



B decay example

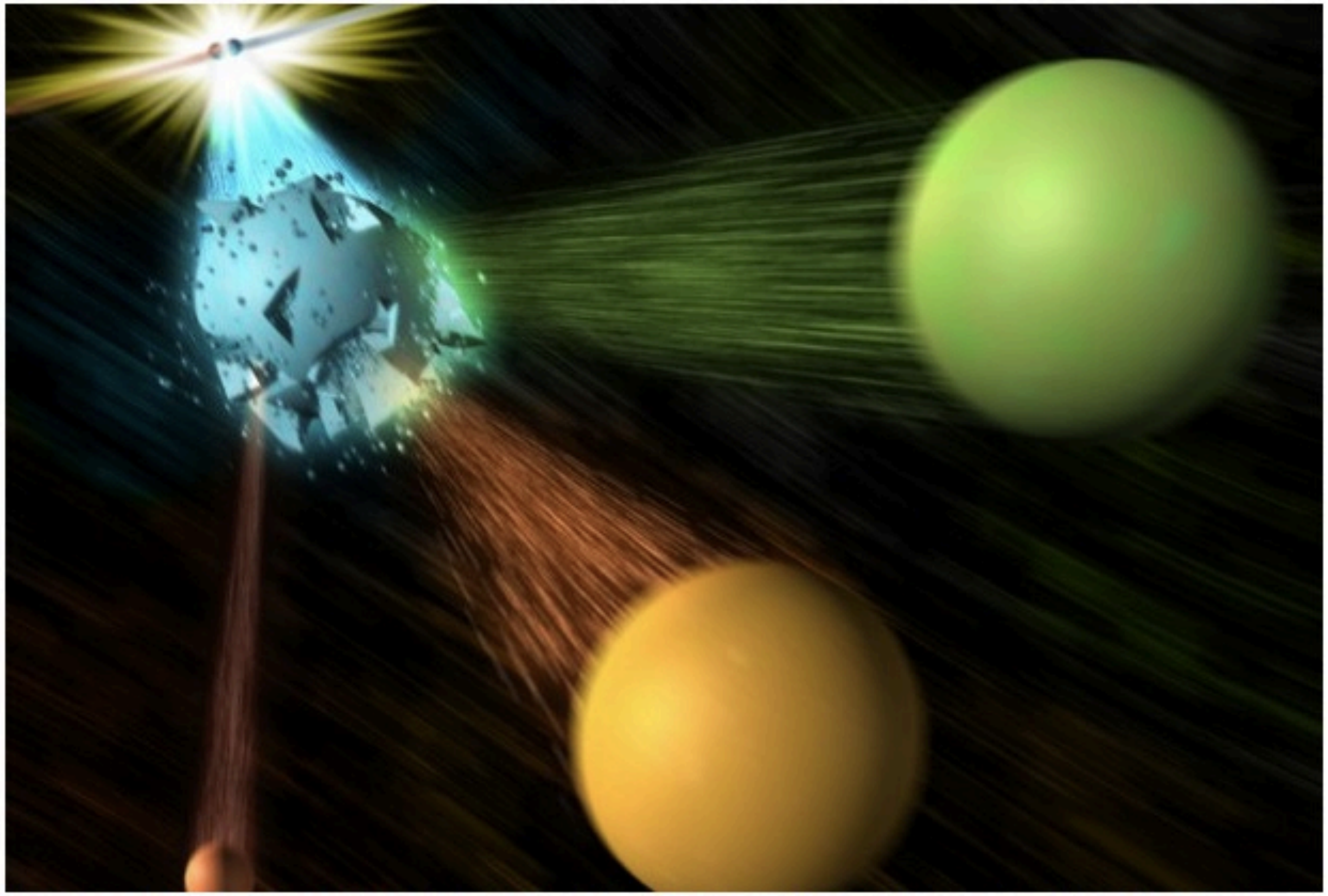


Image Caption: The latest results from the BaBar experiment may suggest a surplus over Standard Model predictions of a type of particle decay called "B to D-star-tau-nu." In this conceptual art, an electron and positron collide, resulting in a B meson (not shown) and an antimatter B-bar meson, which then decays into a D meson and a tau lepton as well as a smaller antineutrino. Image by Greg Stewart, SLAC National Accelerator Laboratory