CP Violation in Bs Oscillations at ATLAS,CMS and Tevatron in $B_s \to J/\psi\phi$

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On behalf of the ATLAS, CDF, CMS and D0 Collaborations

Outline

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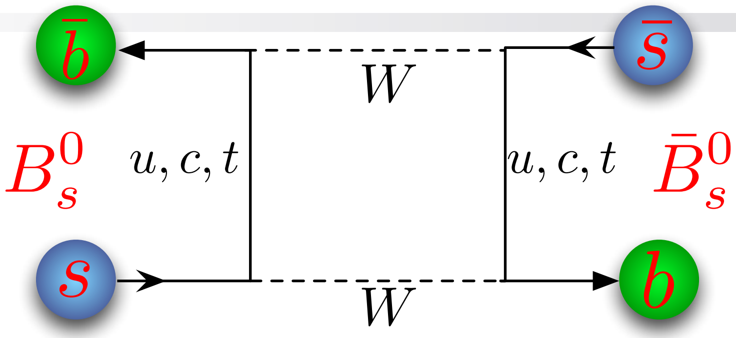
- Introduction
- $B_s \to J/\psi\ \varphi$ overview of analyses from:
  - CDF *PRL 109, 171802 (2012)*
  - D0 *PRD 85, 032006 (2012)*
  - CMS *CMS PAS BPH-11-006 (2012)*
  - New — ATLAS ATLAS-CONF-2013-039 (2013) *Update of JHEP 12 (2012) 072*
- See B. Hoeneisen's presentation for recents results on asymmetry measurements from D0

CP Violation in Bs system

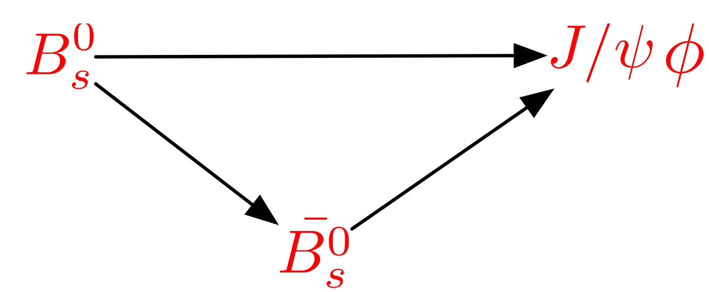


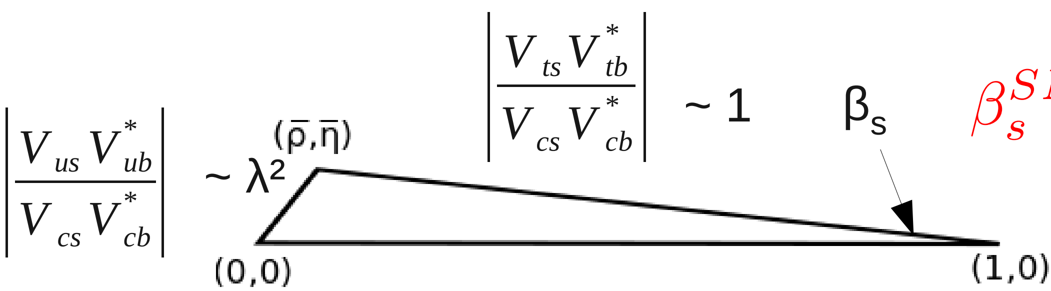
$$i\frac{d}{dt}\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix} = \begin{pmatrix}M_{11} & M_{12}\\M_{12}^* & M_{11}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\\Gamma_{12}^* & \Gamma_{11}\end{pmatrix}\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix}$$

$$|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$

$$|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$

- Mixing between the flavour states give rise to heavy and light mass eigenstates
  - Mass difference now well-measured; $\Delta m_s = m_s^H - m_s^L \approx 2|M_{12}^s|$, $\Delta m_s \approx 17.77 ps^{-1}$
  - Decay width difference (sign established to be Positive): $\Delta\Gamma_s = \Gamma_s^L - \Gamma_s^H$, *O*(10%)
- CP violation in $B_s \to J/\psi\ \phi$ occurs through "interference of mixing and decay" (same final state)
- Experimentally clean decay channel
- The CP-violating phase angle ϕ_s in $B_s \to J/\psi\ \phi$ relates to the CKM matrix elements with $\phi_s \approx -2\beta_s$; $\phi_s \sim -0.04$ in SM.





$$\beta_s^{SM} = \arg\left[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)\right]$$

- If New Physics, contributions most likely to appear through the phase ϕ_s, hence any non-zero observation of this quantity should indicate NP.
- $\phi_s = \phi_s^{SM} + \phi_S^{NP} \approx \phi_S^{NP}$
- Measurements of the other observable quantities (e.g. $\Delta\Gamma$) also test theoretical predictions.

Angular Analysis

- $B_s \to J/\psi\ \varphi$ – pseudo-scalar to vector-vector meson decay
  - CP-even (L=0,2) and CP-odd (L=1) final states
  - Distinguishable through time-dependent angular analysis
  - Results presented here define the 3 angles between final state particles in **Transversity basis**
- From the multi-dimensional fit to the data, the three amplitudes and strong phases can, in principle, be extracted.
- Amplitudes:

A_0 – longitudinal CP-even final state

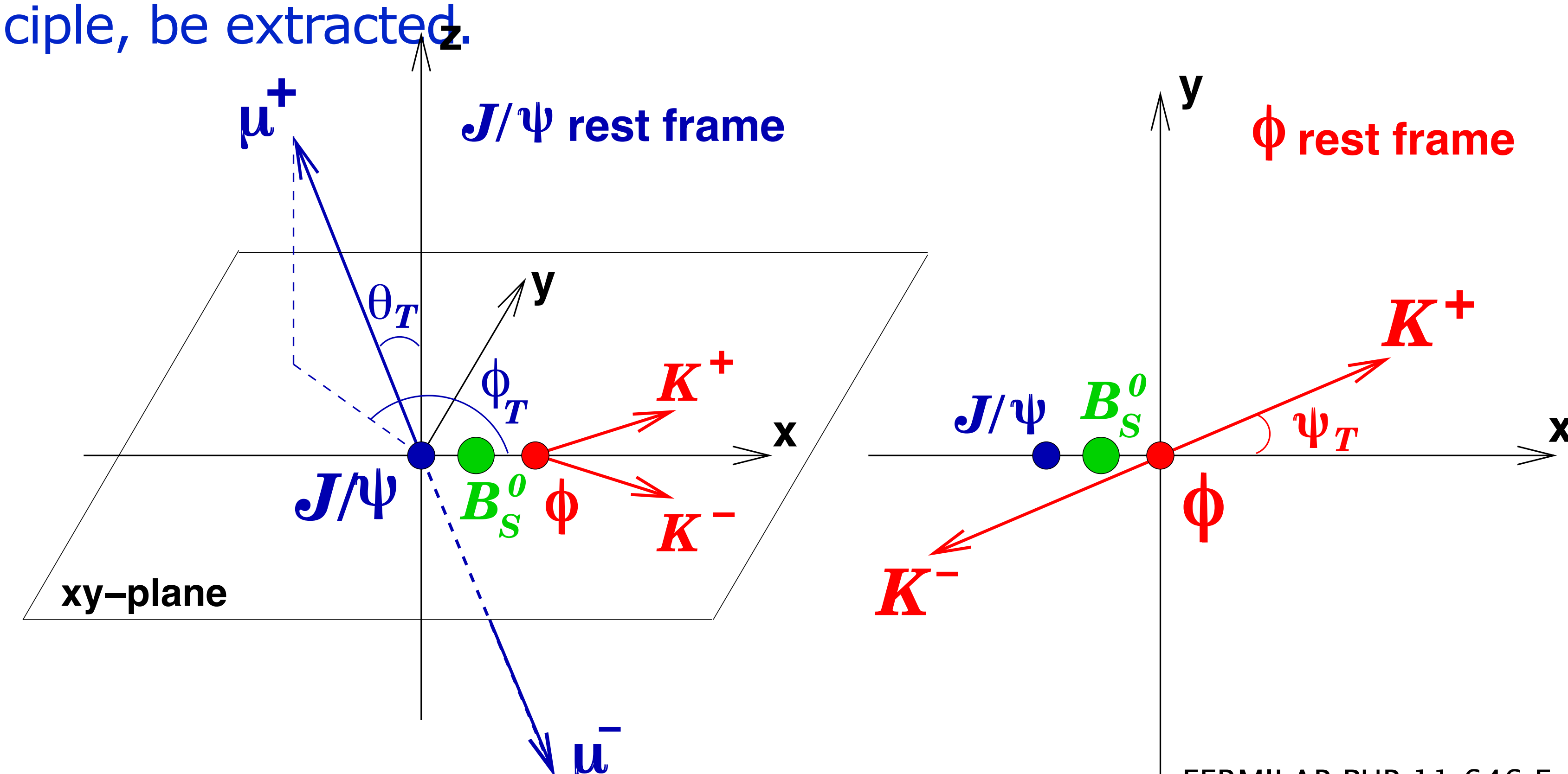
$A_{\|}$ – transverse CP-even

$A_{\perp}$ – transverse CP-odd

- Strong Phases:

$$\delta_0 = 0$$
$$\delta_{\|} = \arg[A_{\|}(0)A_0^*(0)]$$
$$\delta_{\perp} = \arg[A_{\perp}(0)A_0^*(0)]$$

(expect phases ~0 or π)



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θ is the angle between p(μ^+) and the x-y plane in the J/ψ meson rest frame

Φ is the angle between the x-axis and $p_{xy}(\mu^+)$, the projection of the μ+ momentum in the x-y plane, in the J/ψ meson rest frame

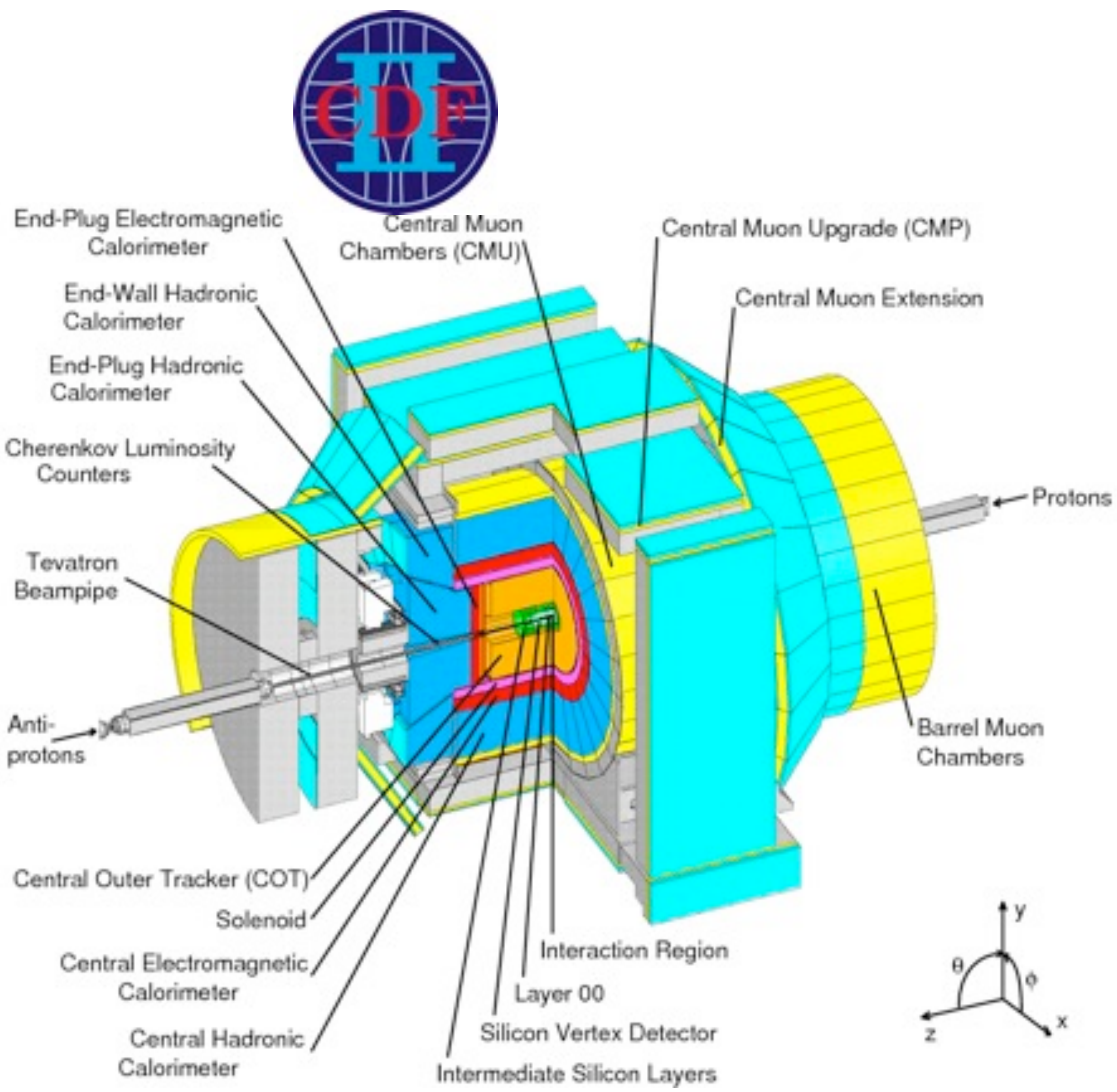
ψ is the angle between p(K+) and –p(J/ψ) in the Φ meson rest frame

General Purpose Detectors

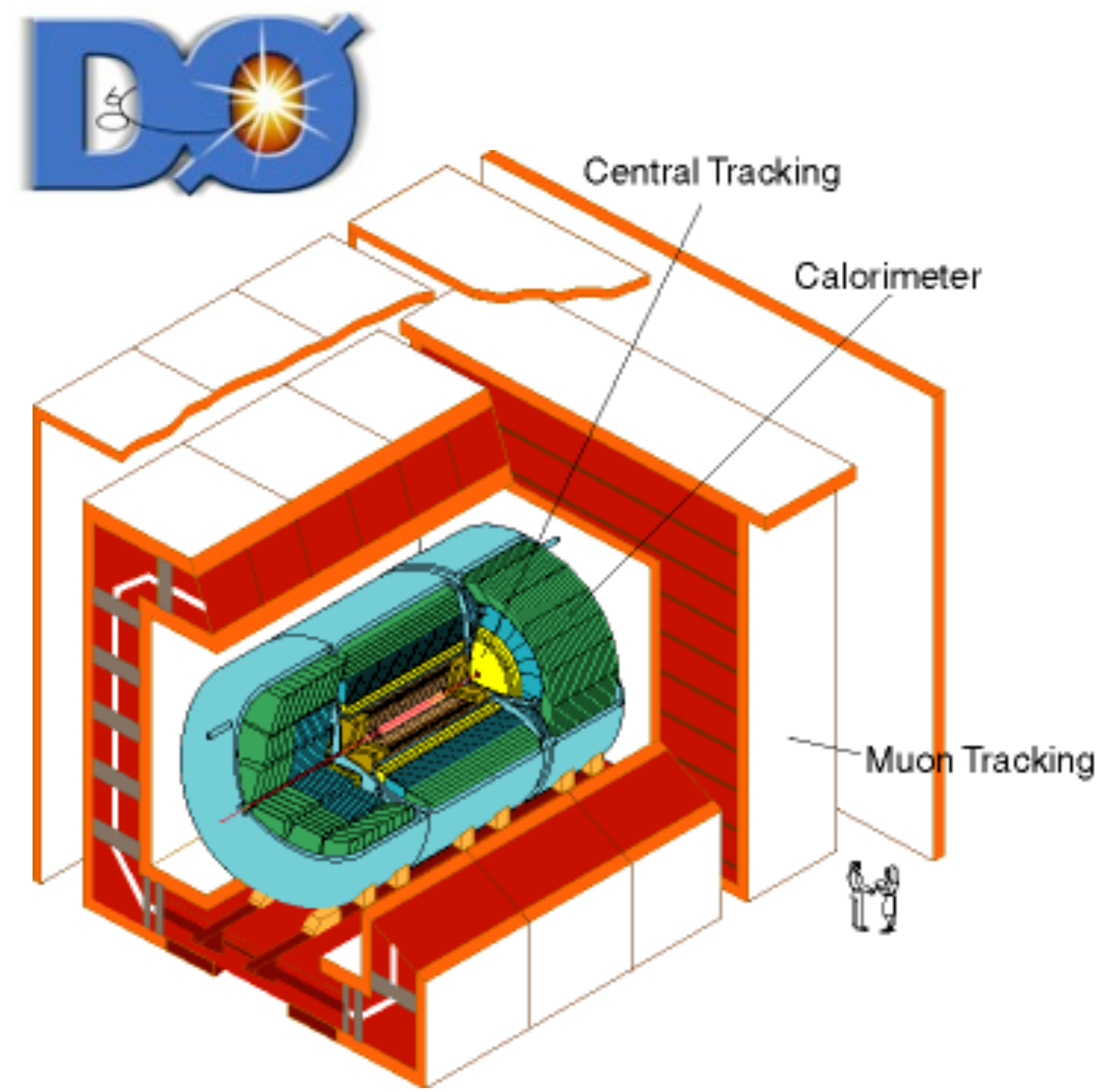
- General Purpose Detectors (GPDs) at Tevatron and LHC:
  - Tevatron – CDF and D0
  - LHC – ATLAS and CMS
- Varied programmes of physics; from high-p_T searches to precision measurements in low-p_T regime.

- Designed to provide ~4π Coverage;
  - Fiducial volume at more central rapidities
    - Enhancement in $bb \to J/\psi$ to $pp \to J/\psi$ cross-section ratio.
- General requirements (with application to B-physics analyses).
  - Silicon and pixel layers –
precision tracking and vertexing;
  - Calorimetry systems – EM and Hadronic Jets;
  - Muon system – trigger, event selection.
- Particle ID (CDF - time-of-flight detector) for Kaon/pion separation
  - Background suppression, initial-state flavour-tagging

Tevatron GPD Detectors



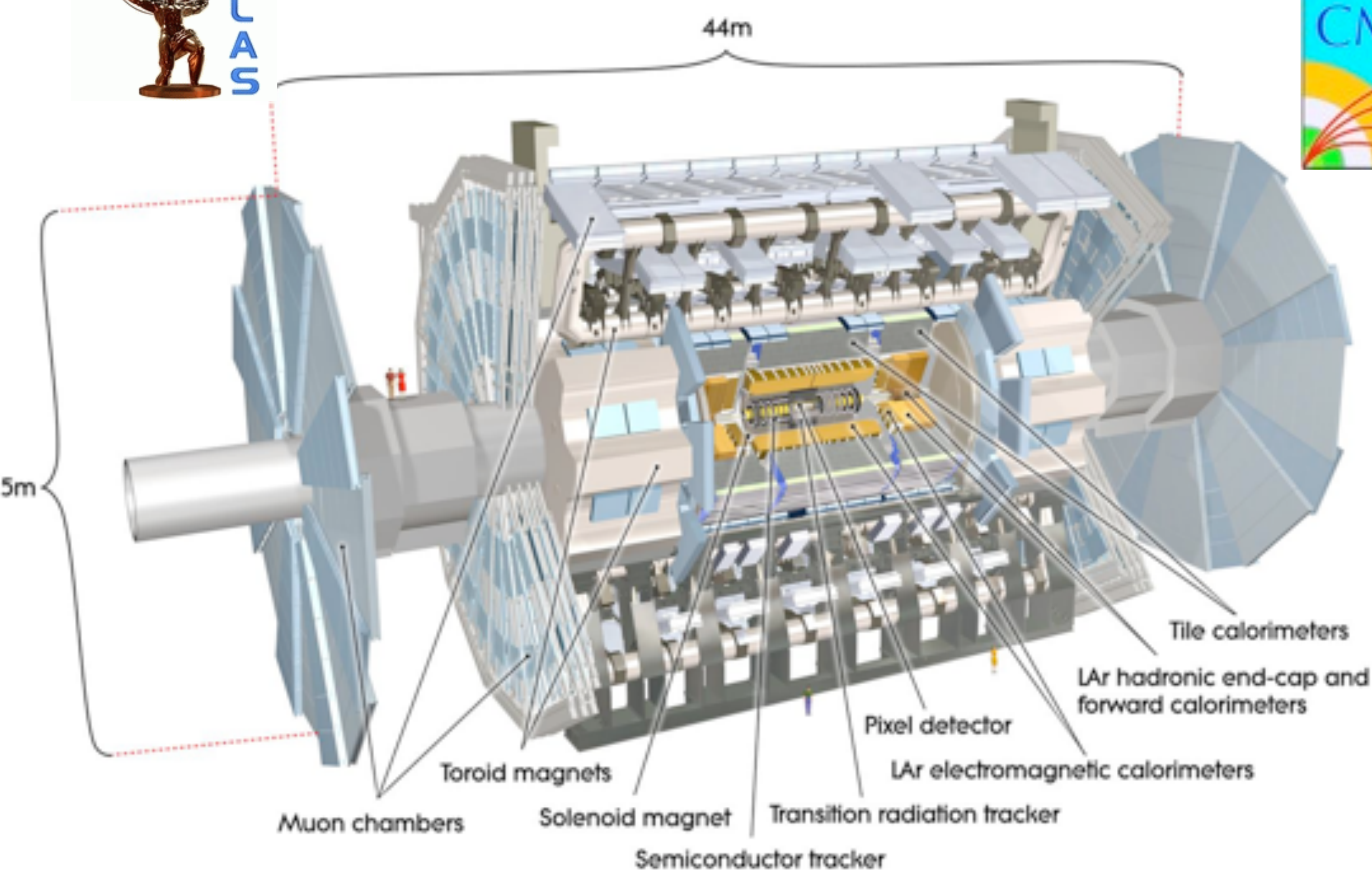
•Particle ID through time-of-flight detector

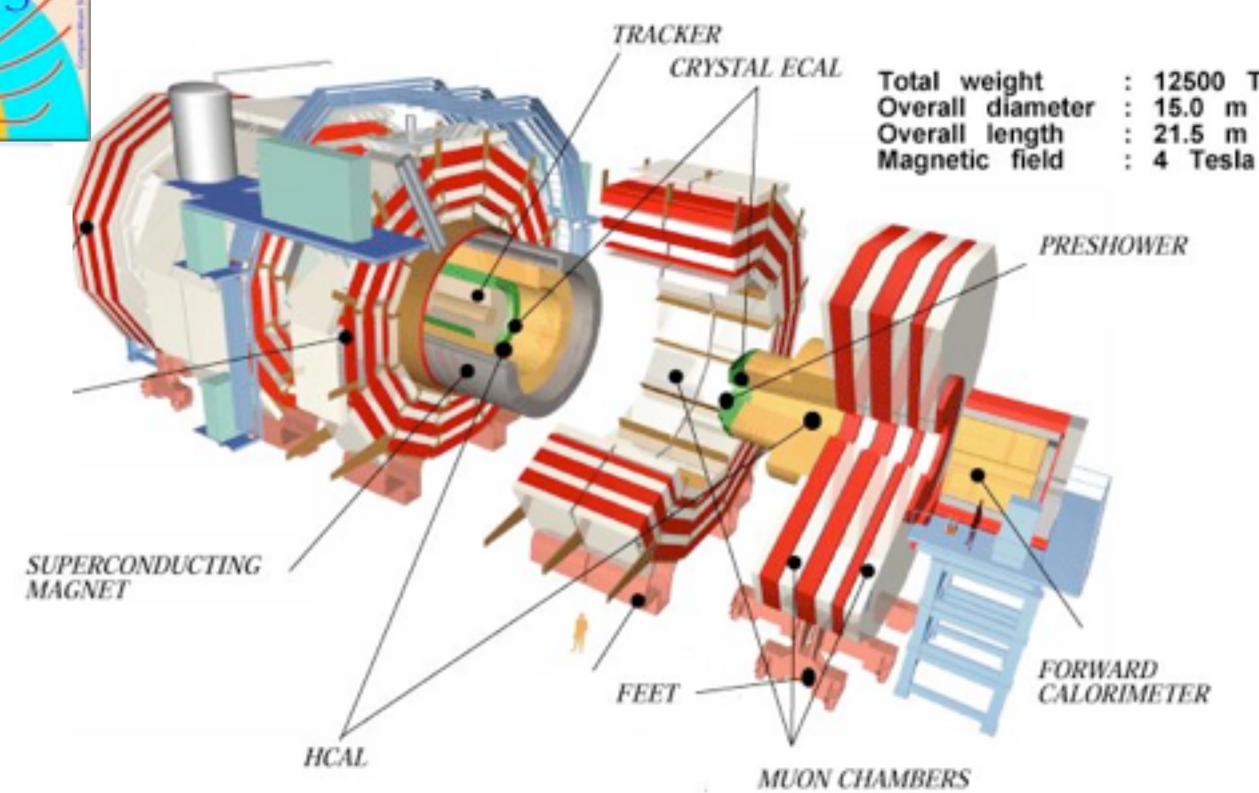


•Coverage in muon system out to $|\eta|<2$

	CDF	D0
Axial Magnetic field	1.4T	1.9T
Track momentum resolution σ/p_T [GeV]$^{-1}$	~0.07%	~0.14%
Lifetime resolution	~90fs	~70fs

LHC GPD Detectors



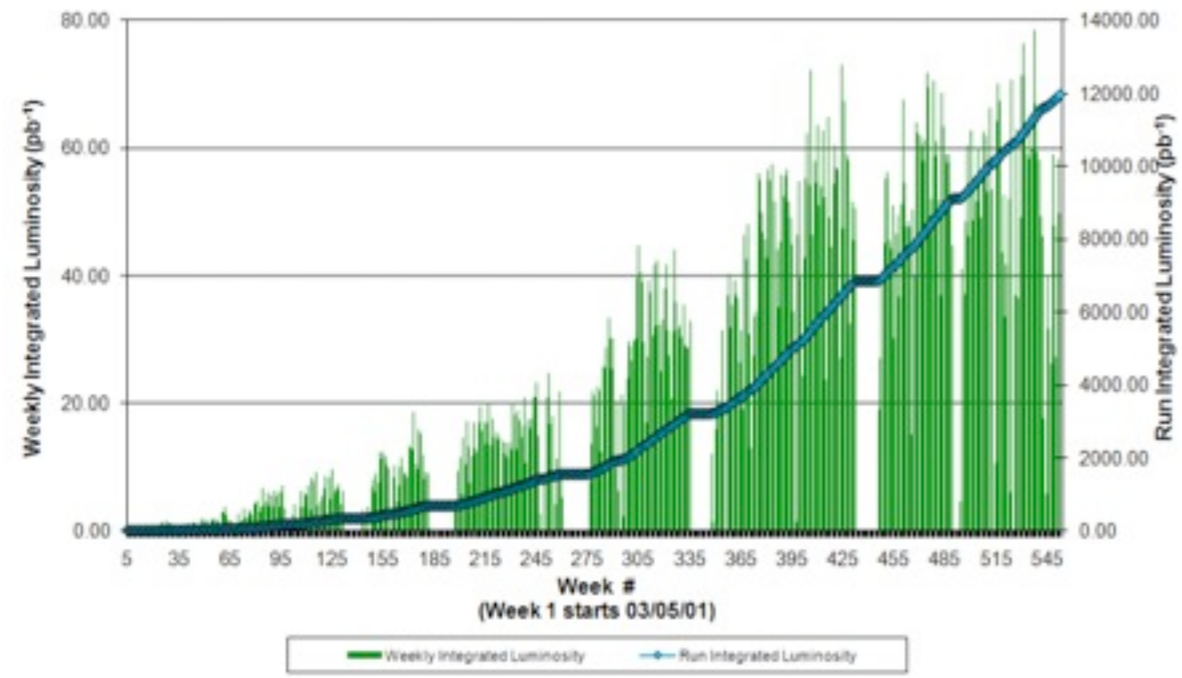


	ATLAS	CMS
Axial Magnetic field	2 T	3.8 T
Track momentum resolution σ/p_T^2 [GeV]$^{-1}$	~0.05%p_T + 0.015	~0.015%p_T + 0.005
Lifetime resolution	~100 fs	~70 fs

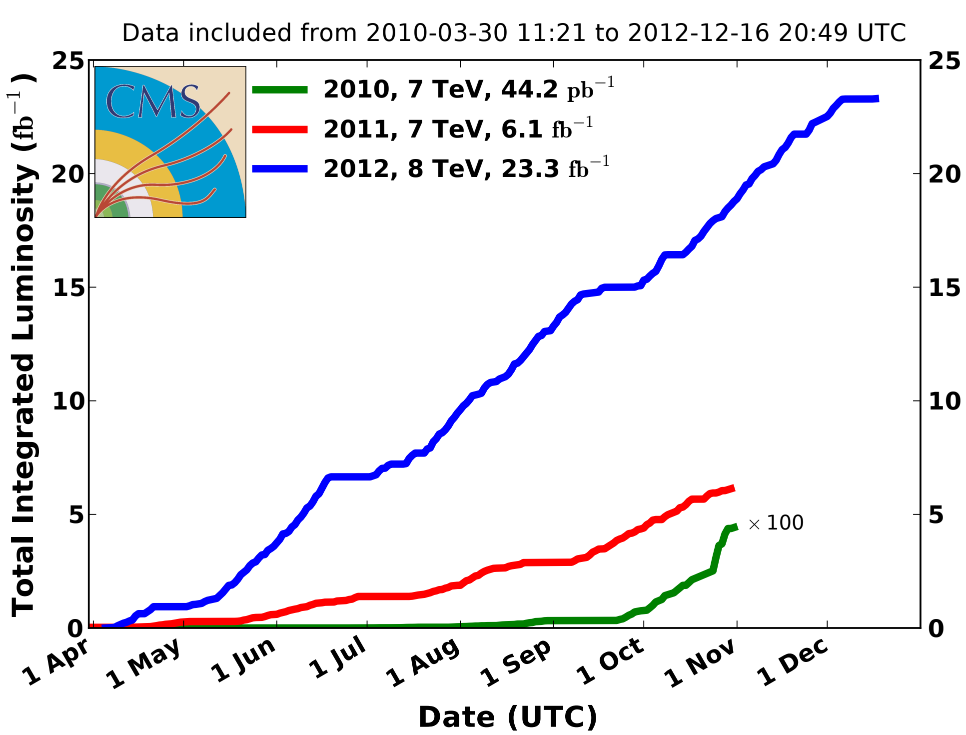
Data Taking

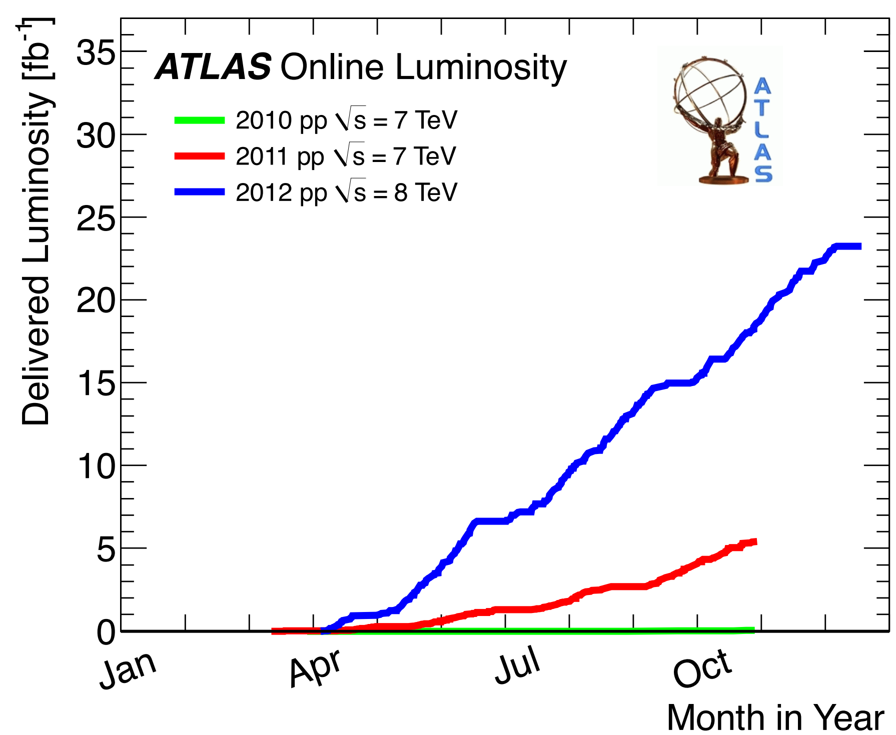
- **Tevatron** Run II proton-antiproton operations at √S = 1.96 TeV completed
  - Each detector accumulated L ~10 fb^{-1} for analysis.
- **LHC** running at 7 TeV in 2011 proton-proton, 8 TeV 2012, (13 TeV 2015)
- ATLAS and CMS collected L ~ 5 fb^{-1} 2011 and ~20 fb^{-1} in 2012.
- Data Taking efficiencies in excess of 90% for all experiments.

Tevatron Run II

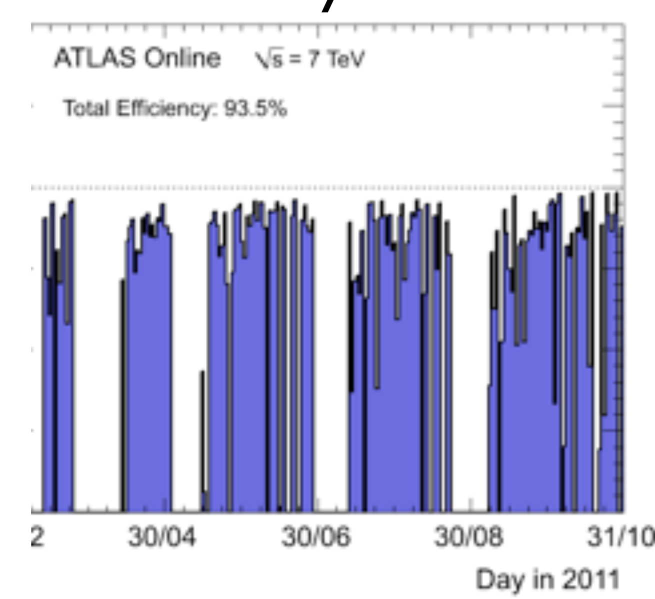


CMS Integrated Luminosity, pp





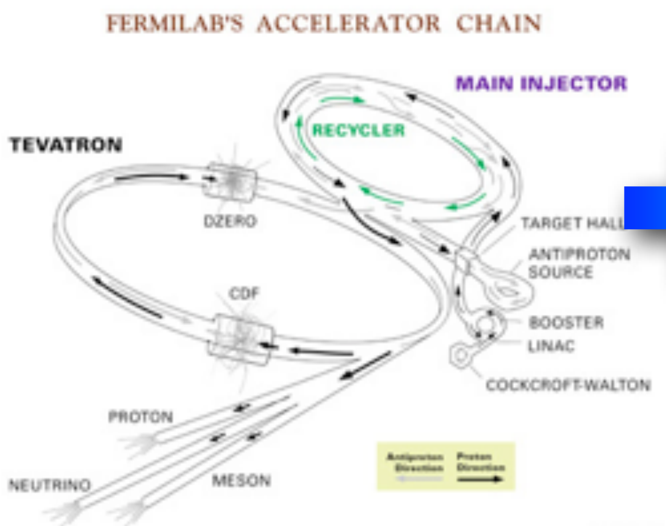
Efficiency ~ 94%



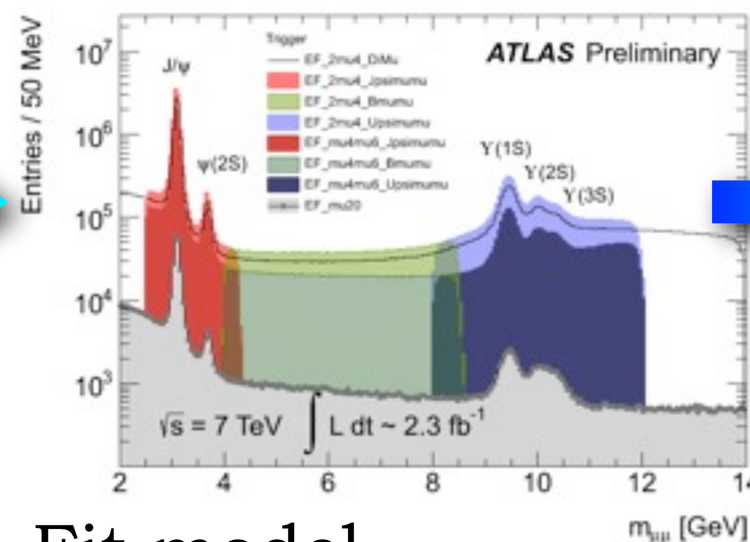
Techniques in Bs → J/ψ φ Analysis

- **General analysis strategy:**

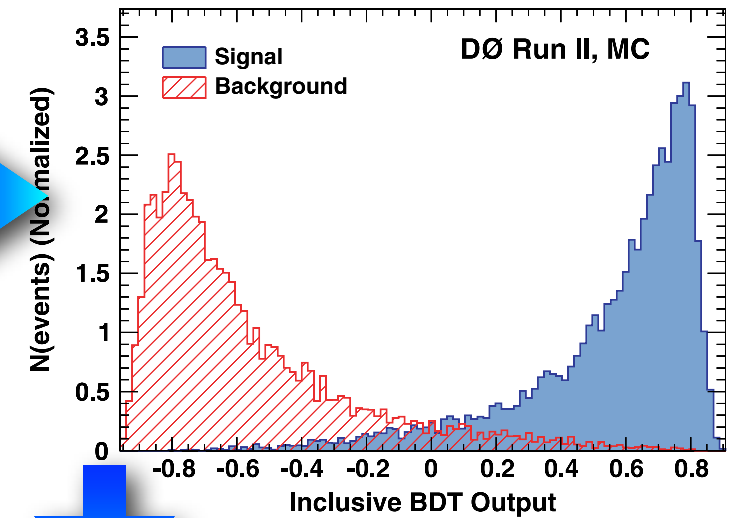
Collisions



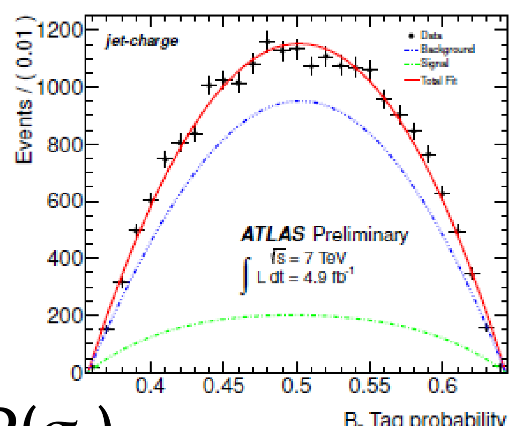
Trigger Optimisation



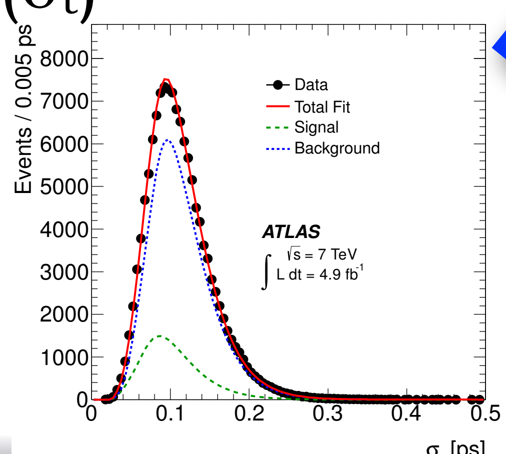
Signal Selection



Initial-State Flavour-Tagging



$P(\sigma_t)$

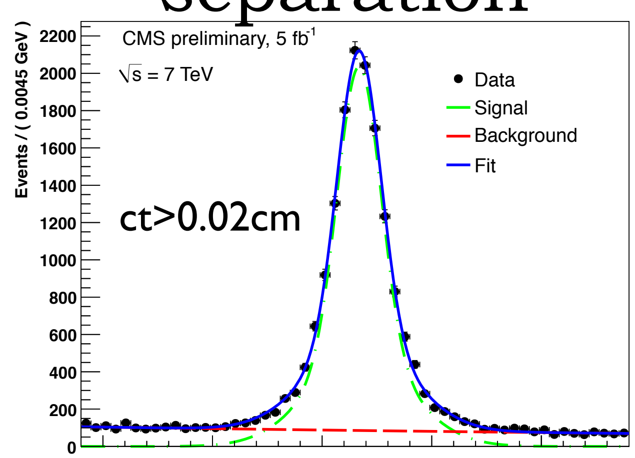


Fit model

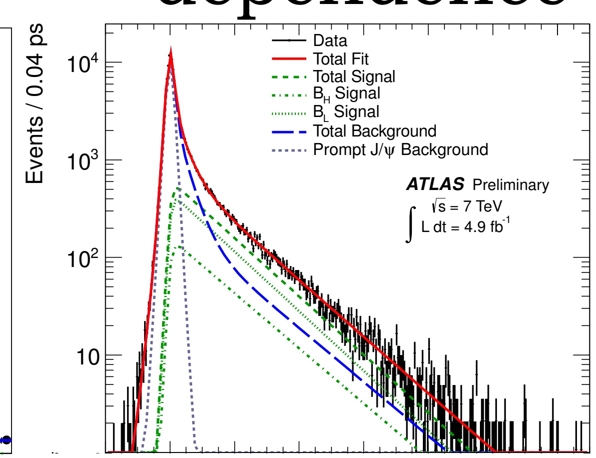
$$\mathcal{L} \propto f_s P_s(m|\sigma_m) P_s(t,\vec{\rho},\xi|\mathcal{D},\sigma_t) P_s(\sigma_t) P_s(\mathcal{D}) + (1-f_s) P_b(m) P_b(t|\sigma_t) P_b(\vec{\rho}) P_b(\sigma_t) P_b(\mathcal{D}),$$

Results!

Signal / background separation

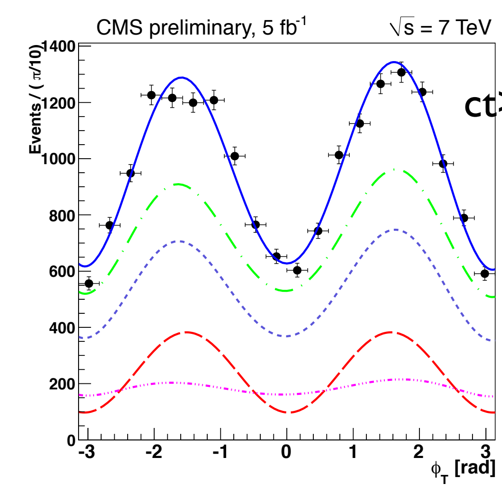


Time dependence



$$t = M_{B_s} \vec{L}_{xy}^{B} \cdot \vec{p}/(p_T^2)$$

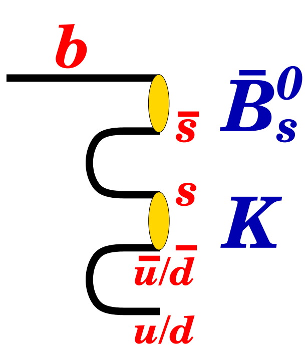
Angular analysis



CDF: Event Selection

PRL 109, 171802 (2012)

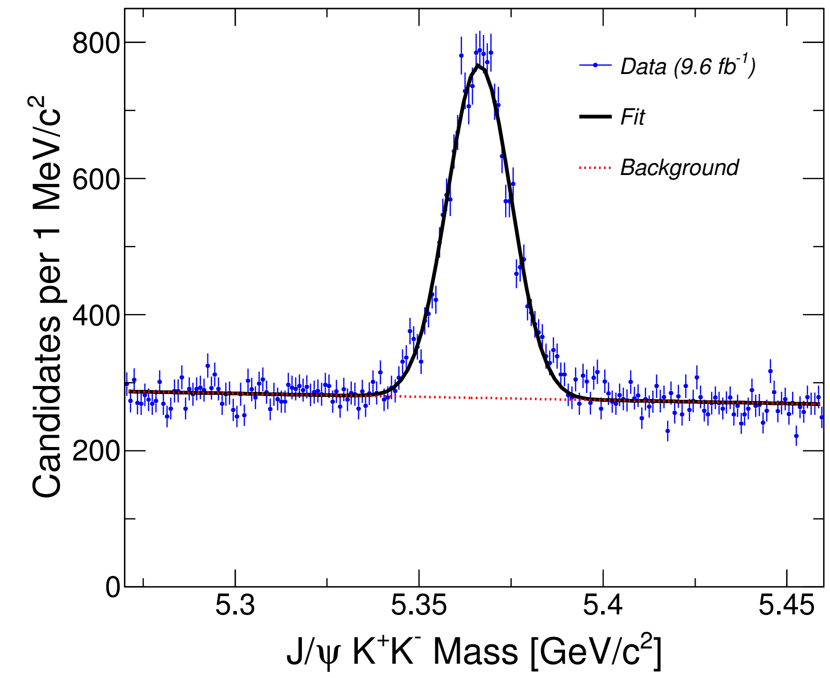
- Analysis using full Run II Dataset at 1.96 TeV (9.6 fb^{-1})
- After basic event selection:
  - Neural Network, trained on signal MC and data sideband for background.
    - Optimised on sensitivity to β_s.
- Observables from the data:
  - m, t, σ(m), σ(t)
  - Three transversity angles
  - Initial state tagging information
- After selections ~ 11k B_s candidates.
- Measured quantities: $\Delta\Gamma_s, \tau_s, |A_\perp|^2, |A_0|^2, \delta_\perp$
- *Tagged* analysis - initial flavour of B meson estimated:
  - Opposite-side tagging (μ,e,jet-charge)
  - Same-side tagging from correlations of Kaon produced in fragmentation (first 5.2 fb^{-1}).

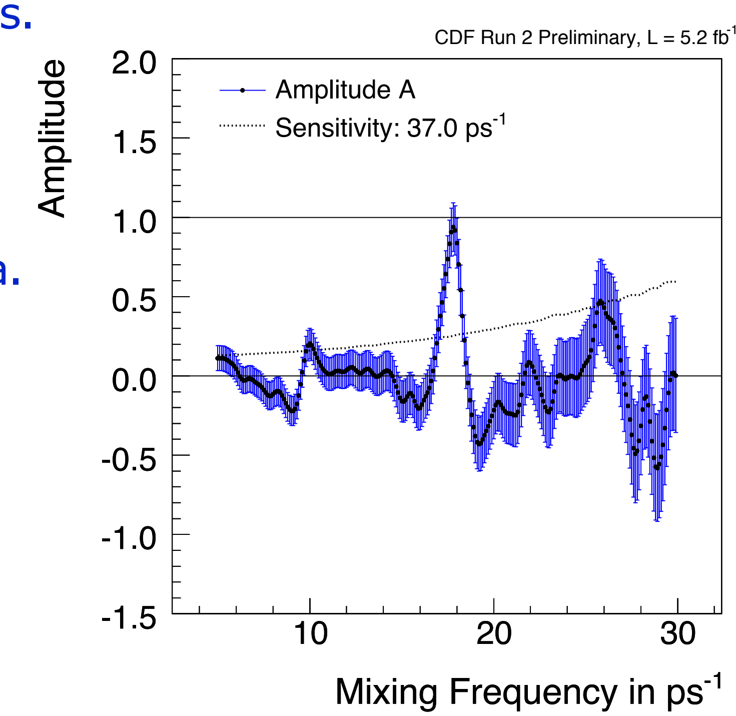


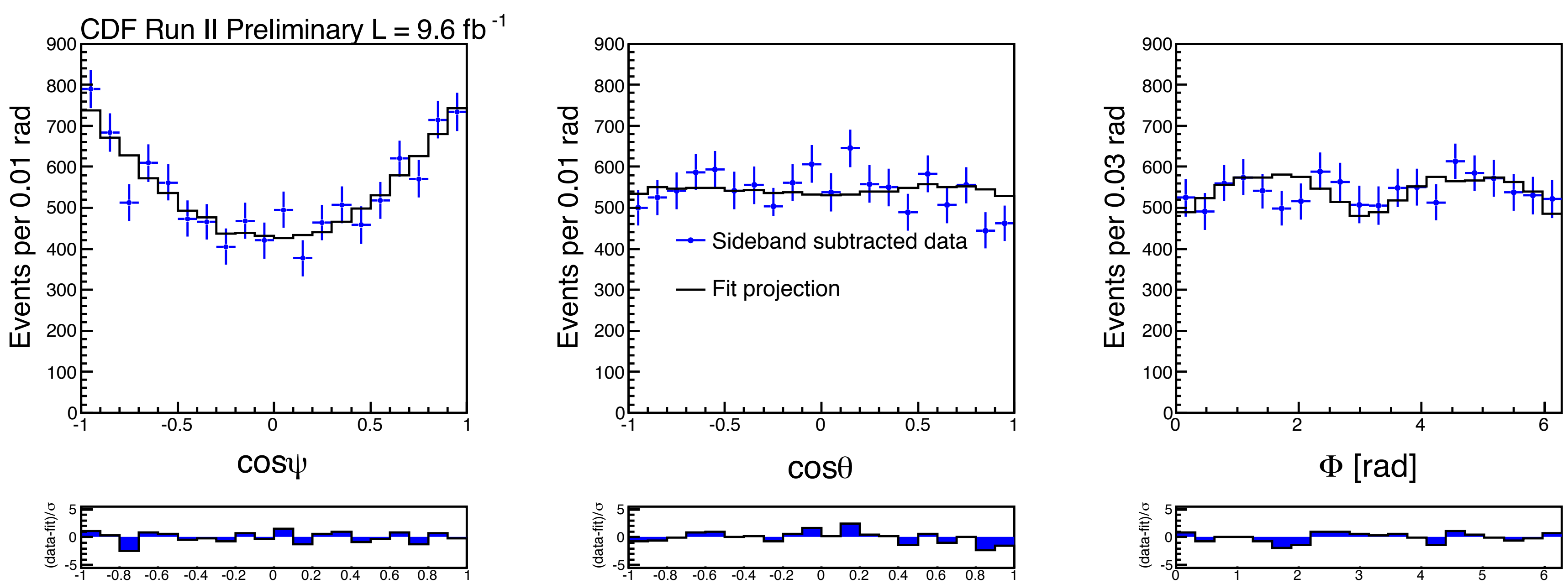
- **Trigger**:
  - low-pT di-muon triggers
  - 2.7 < m(μμ) <4.0 GeV
- **J/ψ**:
  - pT(μ) > 4 GeV
  - $|m(J/\psi) - m^{PDG}(J/\psi)| < 50$MeV
- **φ**:
  - Oppositely-charged track pair
  - pT(K) > 0.4 GeV
  - pT(φ) > 1.0 GeV
  - $|m(\varphi) - m^{PDG}(\varphi)| < 9.5$MeV
- **B_s**:
  - μμKK Vertex fit
  - J/ψ mass constraint
  - pT(J/ψKK) > 1.0 GeV
  - 5.1 < m(J/ψKK) <5.6 GeV
- **NN Variable importance:**
  - Kinematic information
  - Muon and Hadron PID
  - Vertex fit quality

CDF: Fit Model

- $$\mathcal{L} \propto f_s P_s(m|\sigma_m) P_s(t, \vec{\rho}, \xi | \mathcal{D}, \sigma_t) P_s(\sigma_t) P_s(\mathcal{D}) + (1 - f_s) P_b(m) P_b(t|\sigma_t) P_b(\vec{\rho}) P_b(\sigma_t) P_b(\mathcal{D}),$$
- Signal:
  - mass: Gaussian with per-candidate errors
  - proper time and angles for differential decay rates
  - corrected for proper-time and angular efficiencies
- Background:
  - mass: Linear
  - lifetime: Exponentials (+,-,-)
  - resolution: Double Gaussian (σ~90 fs)
- Different distributions for $\mathbf{P_s(\sigma_t)}$ and $\mathbf{P_b(\sigma_t)}$.
  Extracted distributions from sideband-subtracted data – signal –, and sidebands.
- Same-side tagging calibrated using amplitude scan to Bs mixing frequency.
  - Opposite-side tagging calibration from comparison of measured to predicted dilution in $B^{\pm} \to J/\psi K^{\pm}$.
- Plots of fit projection to signal angular distributions in sideband-subtracted data.





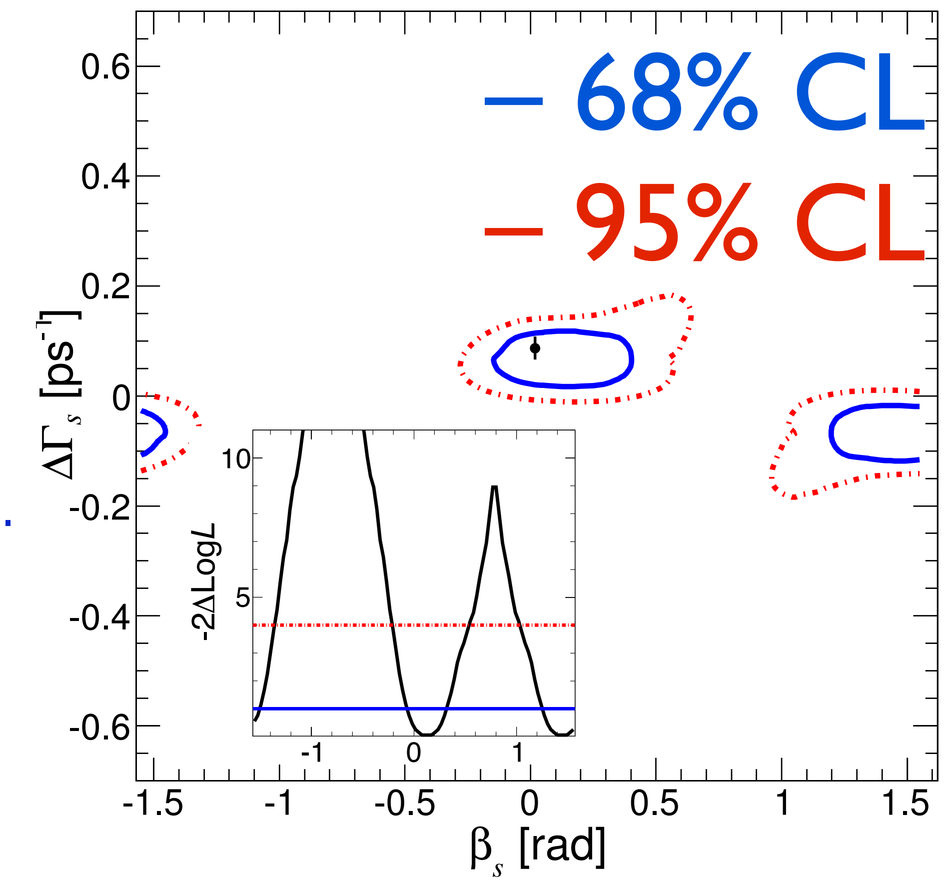


CDF: Results

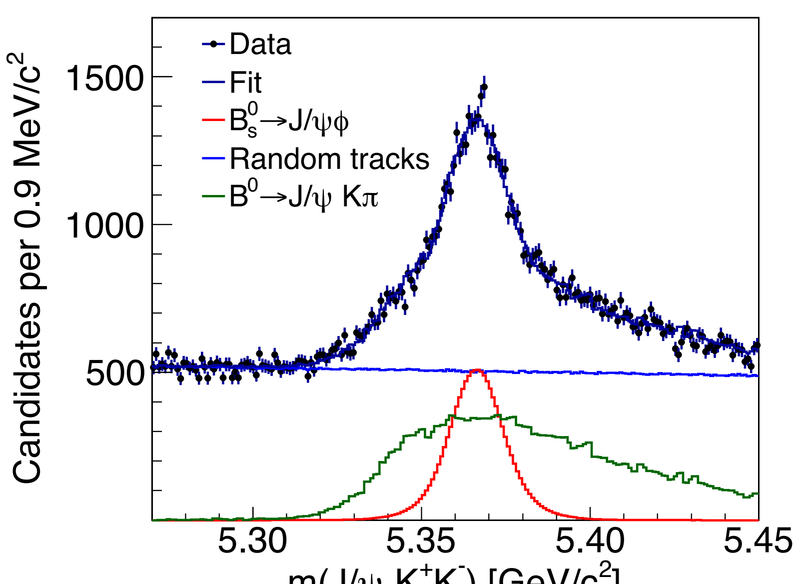
- Fixing β_s to SM prediction yields:

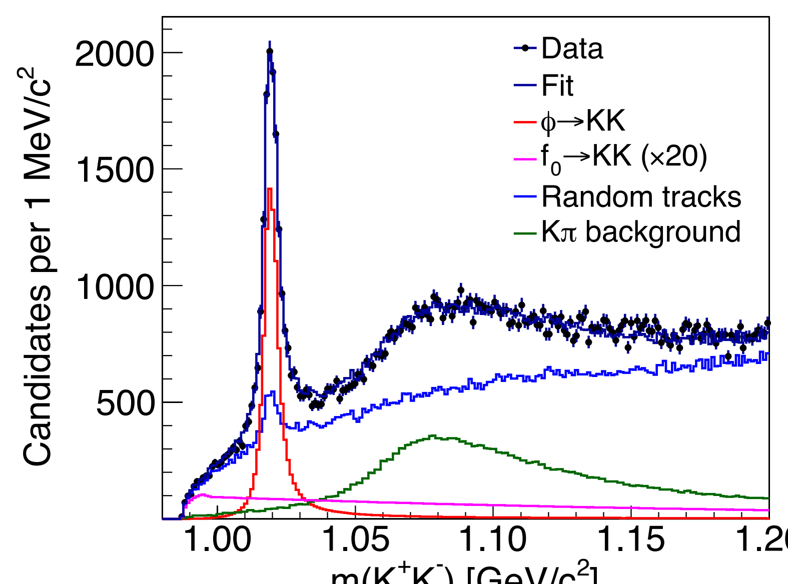
$$
\begin{aligned}
\tau_s &\quad 1.528 \pm 0.019(\quad) \pm 0.009(\quad) \quad , \\
\Delta\Gamma_s &\quad 0.068 \pm 0.026(\quad) \pm 0.009(\quad) \quad ^{-1}, \\
|A_0|^2 &\quad 0.512 \pm 0.012(\quad) \pm 0.018(\quad), \\
|A_{\parallel}|^2 &\quad 0.229 \pm 0.010(\quad) \pm 0.014(\quad), \\
\delta_{\perp} &\quad 2.79 \pm 0.53(\quad) \pm 0.15(\quad).
\end{aligned}
$$

- Correlation between $\Delta\Gamma_s$ and τ_s = 0.52.
- β_s = [-0.06,0.30] @ 68% CL, treating $\Delta\Gamma$ as nuisance parameter and $\Delta\Gamma>0$.
- No significant contribution from S-wave found in the signal sample.
- Systematic uncertainties:
  - $\Delta\Gamma_s$ – background decay-time,
  - τ_s – alignment of the silicon detector,
  - Amplitudes – angular acceptance models.



- Separate study in KK mass spectrum (invariant mass range from threshold, to m(KK) = 1.2 GeV)
  - confirms small S-wave contribution in signal window (0.8±0.2)%,
  - although suggests larger contribution of mis-identified B_0 background (8.0±0.2)% assuming only P-wave B_0 decays.

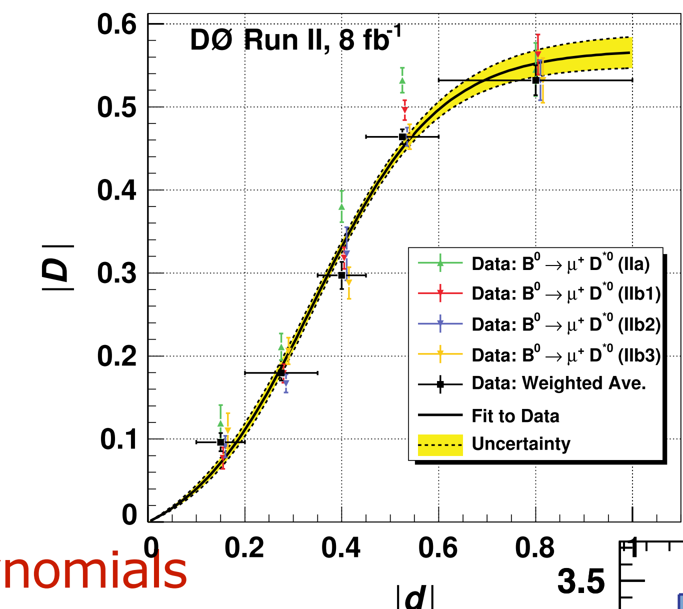




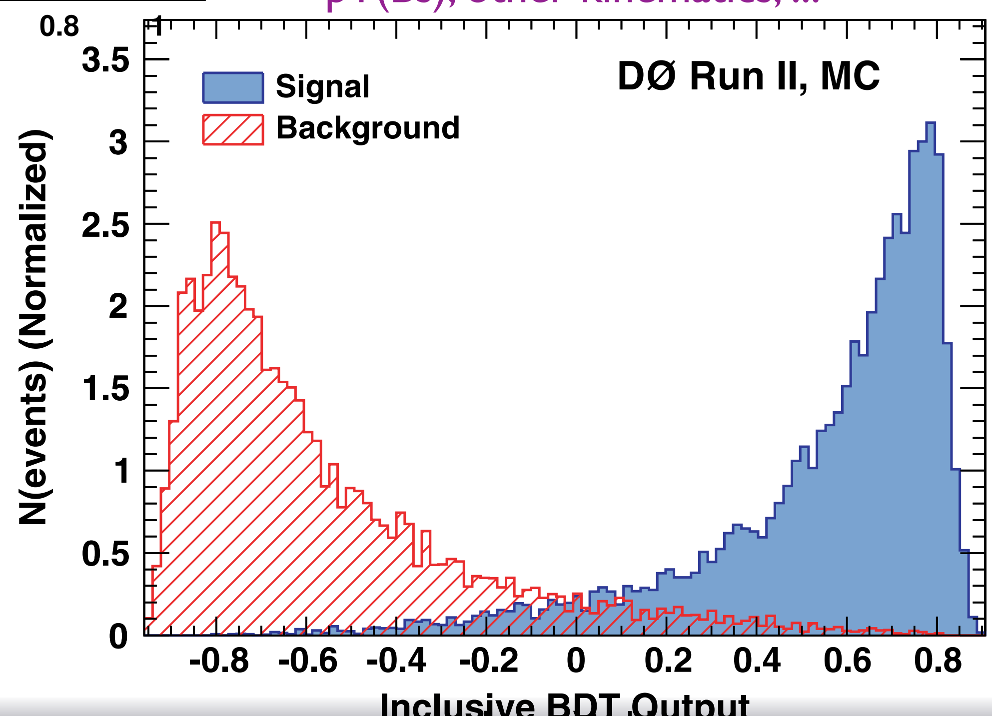
D0: Analysis

PRD 85, 032006 (2012)

- D0 result from L=8.0 fb^{-1} collected during 2002 and 2010 at 1.96 TeV.
- BDT Multivariate analysis
  - Optimised on $S/\sqrt{(S+B)}$,
  - complemented by 'square-cuts' analysis.
- 5,598 ± 113 B_s signal events pass selections.
- Opposite-side tagging (μ,e,SV-q),
- 6D-Likelihood fit using: m, t, σ(t), transversity angles
- Detector acceptance from MC -
  - Parameterised with Legendre polynomials
- Background mass – 1st- and 2nd-order polynomials; 3 exponentials for lifetime (-,+,+), and Legendre and real harmonics expansion coefficients.
- Fraction of S-wave also considered in the fit.



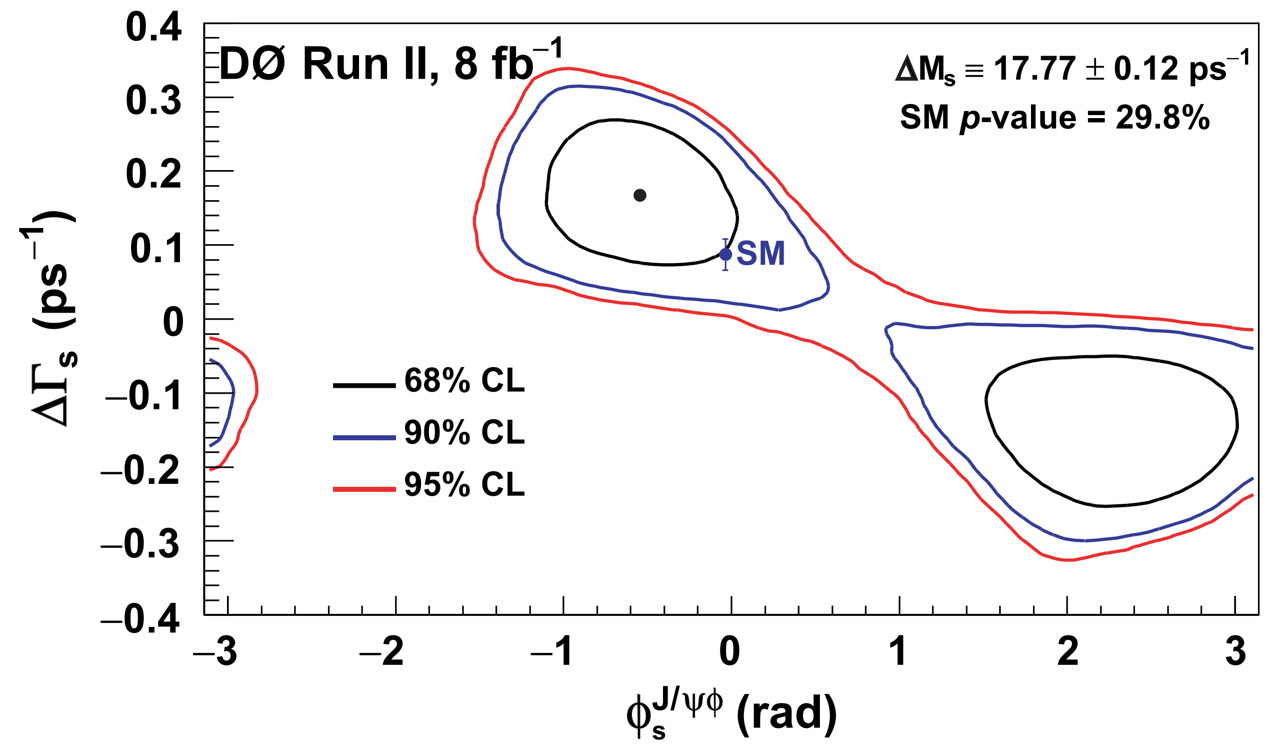
- **Trigger**:
  - low-pT single and di-muon triggers
- **φ**:
  - Oppositely-charged track pair
  - $|m(\varphi) - m^{PDG}(\varphi)| < 30$ MeV
- **B_s**:
  - μμKK Vertex fit
  - J/ψ mass constraint
  - pT(Bs) > 1.0 GeV
  - 5.17 < m(J/ψKK) <5.57 GeV
- **BDT Variable importance:**
  - m(KK)
  - $\Delta R(K,B_s)$
  - Isolation
  - pT(Bs), other kinematics, ...



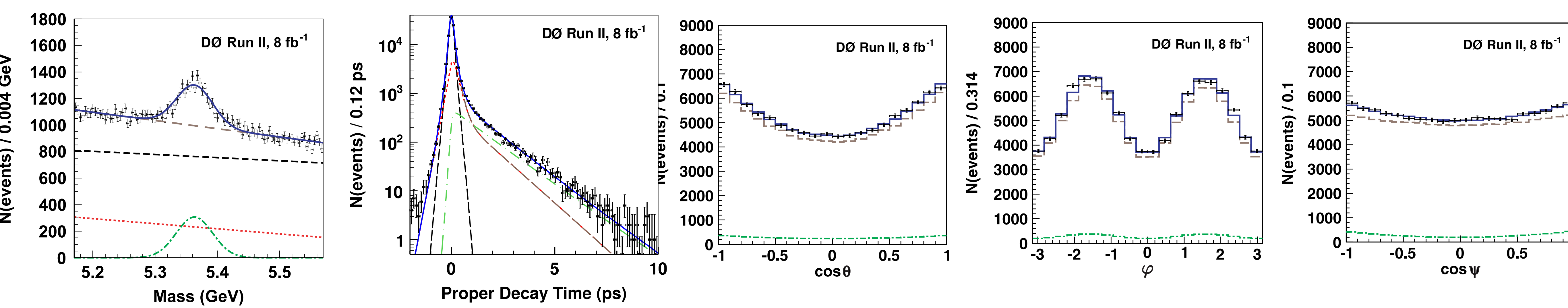
D0: Results

- Markov-chain MC used to estimate final confidence limits.
- Limit cos δ⊥ <0
- Results:

$$\bar{\tau}_s = 1.444^{+0.041}_{-0.033}\ \mathrm{ps}, \quad \Delta\Gamma_s = 0.179^{+0.059}_{-0.060}\ \mathrm{ps}^{-1},$$
$$\phi_s^{J/\psi\phi} = -0.56^{+0.36}_{-0.32}, \quad |A_0|^2 = 0.565 \pm 0.017,$$
$$|A_\parallel|^2 = 0.249^{+0.021}_{-0.022}, \quad \delta_\parallel = 3.15 \pm 0.19,$$
$$\cos(\delta_\perp - \delta_s) = -0.20^{+0.26}_{-0.27}, \quad F_S = 0.173 \pm 0.036.$$



- Strong correlation between δ⊥ and δS;
- Reasonable contribution from non-resonant KK is estimated.
- Projections to fit results shown for all data passing the BDT selections (S/√(S+B) ~ 12.9).



CMS: Event Selection

CMS PAS BPH-11-006

- 2011 7 TeV analysis corresponding to integrated luminosity of 5.0 ± 0.1 fb^{-1}
- 19,000 B_s candidates after selections, in mass range [5.24–5.49] GeV and proper-decay length [0.02–0.3]cm
- Observables:
  - m, t, 3 transversity angles
- 5-d unbinned maximum likelihood fit extracts:
  - $\Delta\Gamma_s, \Gamma_s, |A_\perp|^2, |A_0|^2, \delta_{||}$ $\quad |A_{||}|^2 = 1 - |A_\perp|^2 - |A_0|^2$
- Assumption of no CP violation $\phi_s = 0$ in fit.
- Untagged analysis - equal probability for B_s or $\bar{B}_s$
- S-wave contributions assumed negligible

- **Trigger**:
  - pT(μμ) > 6.9 GeV
  - **L_{xy}/σ_{Lxy} > 3**
  - 2.8 < m(μμ) <3.35 GeV
  - DCA(μ) < 0.5 cm
- **J/ψ**:
  - pT(μ) > 4 GeV
  - $|m(J/\psi) - m^{PDG}(J/\psi)|$ < 150MeV
- **φ**:
  - Oppositely-charged track pair
  - pT(K) > 0.7 GeV
  - $|m(\varphi) - m^{PDG}(\varphi)|$ < 10MeV
- **B_s**:
  - μμKK Vertex fit
  - J/ψ mass constraint
  - Vertex χ^2 probability > 2%
  - 5.2 < m(J/ψKK) <5.65 GeV

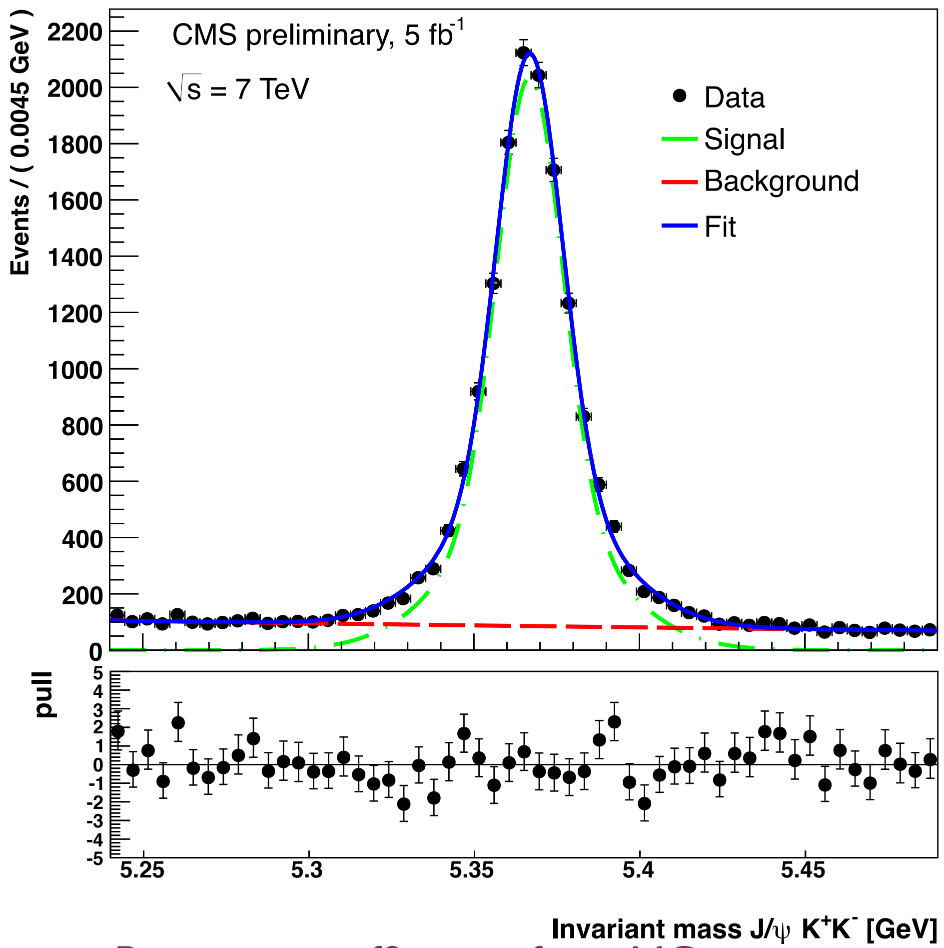
CMS: – Fit Model

- Fit to (reduced) mass distribution fixes narrow Gaussian model.

- 14,456 ± 140 Signal Events
  - Mass position: 5366.8 ± 0.1 MeV
  - Plot shown in mass range [5.24, 5.48], proper decay time [0.02,0.3] cm
- Likelihood function:

$$\begin{aligned} \mathcal{L} &= L_{\text{signal}} + L_{\text{background}} \,, \\ L_{\text{signal}} &= (f(\Theta, t; \alpha) \otimes G(t, \kappa, \sigma(t))]) \cdot M(m) \cdot \epsilon(t)\epsilon(\Theta) \,, \\ L_{\text{background}} &= b(\Theta, t, m) \,, \end{aligned}$$

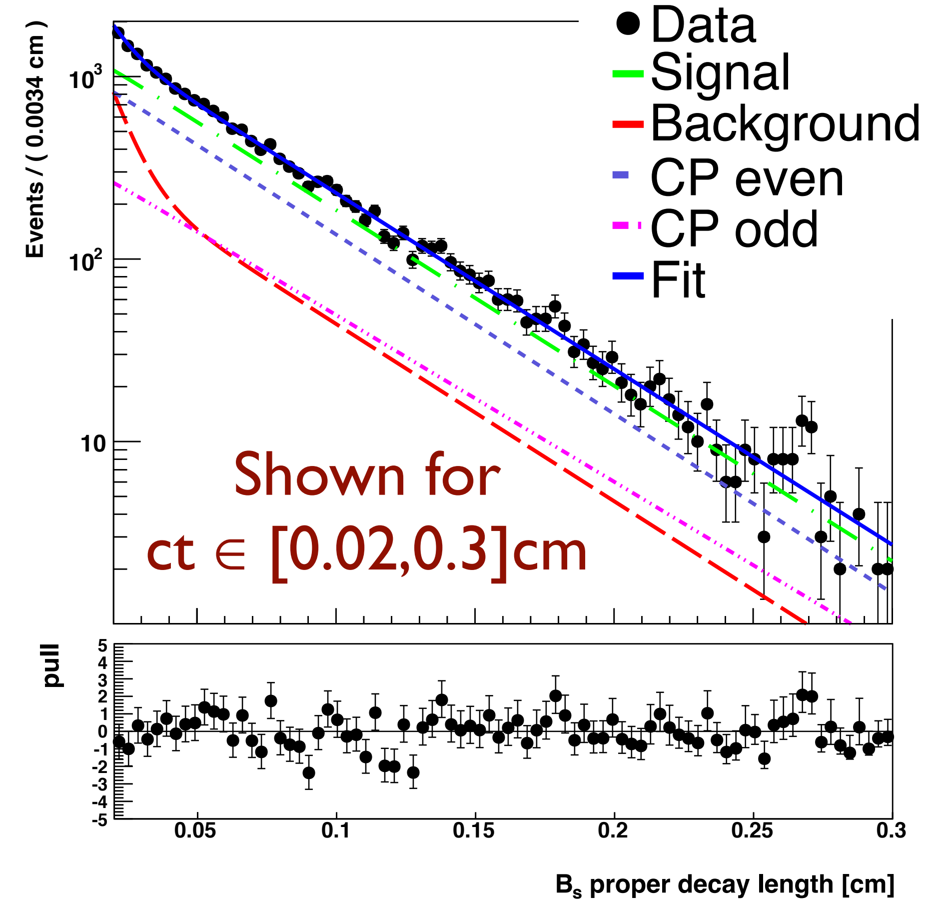
- Signal modelled using:
  - mass: Two Gaussians
  - angular efficiencies from MC
- Background:
  - mass: exponential
  - lifetime: two Gaussian and two exponentials
  - angles from sinusoidal for φ_T, and Legendre polynomials for $\cos(\theta_T)$ and $\cos(\psi_T)$.

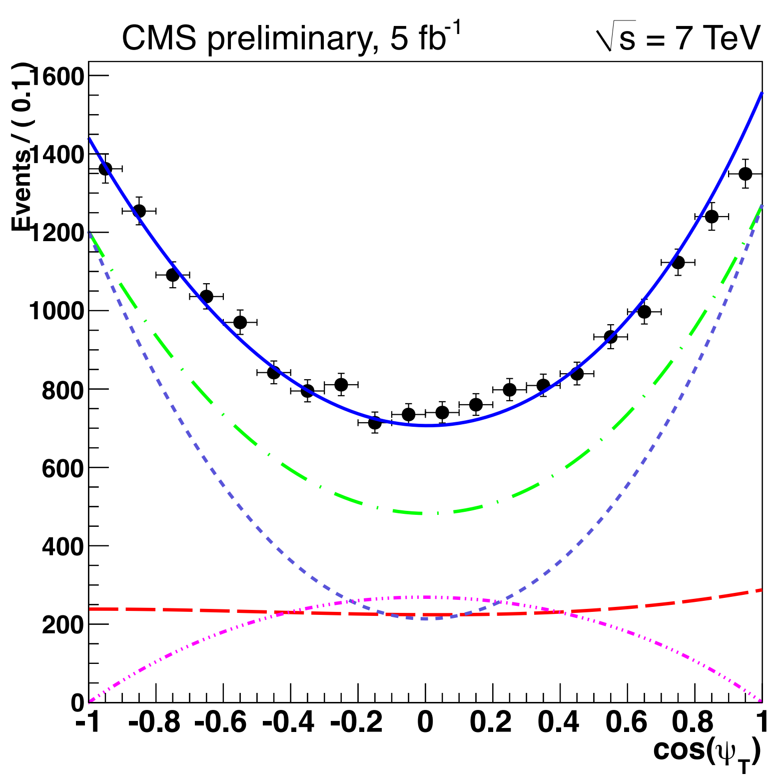


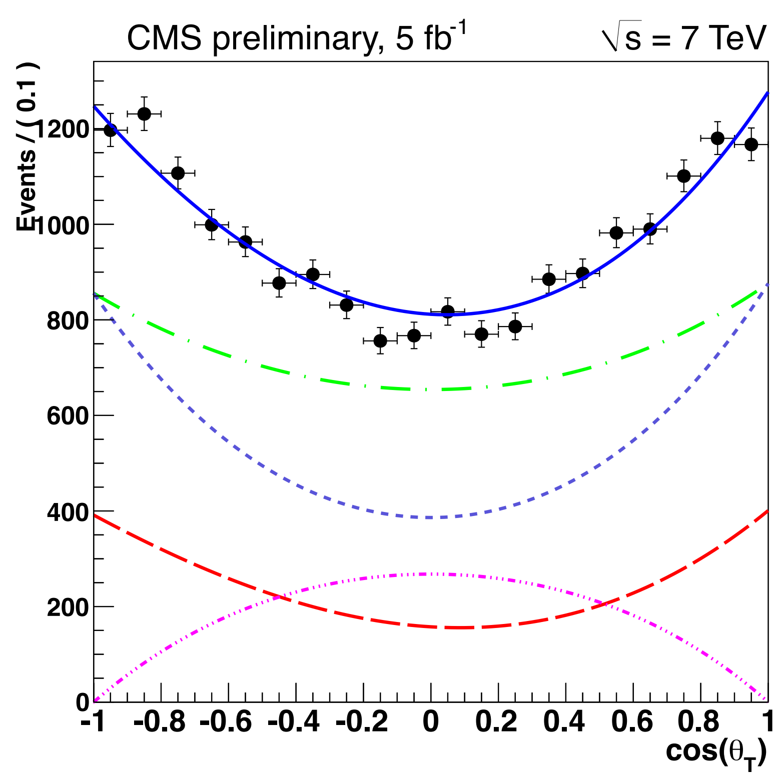
•Proper-time efficiency from MC
•Efficiency is the ratio of selected to generated signal events in bins of proper-time
•Requiring $ct(B_s)$ >0.02cm allows for high and stable efficiency

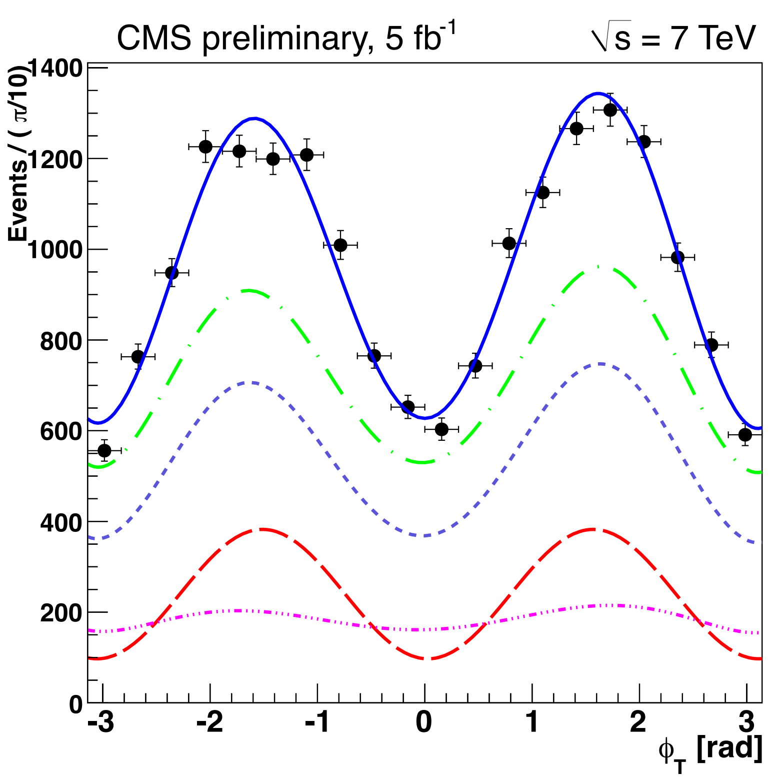
•Angular Efficiency from MC
•Independent parameterisations using Legendre polynomials,
Correlations sufficiently small to be neglected.

- Fit to data sideband determines angular shapes for background description
- Proper-time calibration scale factor extracted from a 2-d mass-lifetime fit to data without Lxy significance requirement.
- Final fit performed in mass,lifetime and angular space (full mass range 5.2 < m(J/ψKK) <5.65 GeV).
- Projections of fit results shown for proper decay length and transversity angles for each component of the fit.









- From the fit:

$$\Delta\Gamma_s = 0.048 \pm 0.024\,(\text{stat.}) \pm 0.003\,(\text{syst.})\,\text{ps}^{-1}\,,$$
$$\tau_{B_s} = 0.04580 \pm 0.00059\,(\text{stat.}) \pm 0.00022\,(\text{syst.})\,\text{cm}\,,$$
$$|A_0|^2 = 0.528 \pm 0.010\,(\text{stat.}) \pm 0.015\,(\text{syst.})\,,$$
$$|A_\perp|^2 = 0.251 \pm 0.013\,(\text{stat.}) \pm 0.014\,(\text{syst.})\,,$$
$$\delta_{||} = 2.79 \pm 0.14\,(\text{stat.}) \pm 0.19\,(\text{syst.})\,\text{rad}\,.$$

- Dominant sources of systematic uncertainties from angular and temporal efficiency models.

Uncertainty source	$\Delta\Gamma_s$ [ps^{-1}]	$c\tau$ [cm]	$\|A_0\|^2$	$\|A_\perp\|^2$	$\delta_{\|\|}$ [rad]
Signal PDF modeling					
Signal mass model	0.00072	0.00012	0.0022	0.0006	0.039
Proper time resolution	0.00170	0.00006	0.0007	0.0000	0.007
ϕ_s approximation	0.00000	0.00001	0.0000	0.0000	0.002
S-wave assumption	0.00109	0.00001	0.0130	0.0066	0.056
Background PDF modeling					
Background mass model	0.00019	0.00000	0.0000	0.0001	0.003
Background lifetime model	0.00040	0.00000	0.0001	0.0002	0.003
Peaking B^0 background	0.00025	0.00006	0.0002	0.0022	0.050
Background angular model	0.00175	0.00003	0.0001	0.0064	0.161
Limited simulation statistics					
Angular efficiency parameters	0.00019	0.00002	0.0057	0.0055	0.037
Temporal efficiency parameters	0.00000	0.00005	0.0000	0.0000	0.000
Temporal efficiency parametrization	0.00181	0.00014	0.0005	0.0007	0.001
Angular efficiency parametrization	0.00063	0.00003	0.0021	0.0086	0.007
Likelihood function bias	0.00000	0.00004	0.0004	0.0000	0.014
Total uncertainty	0.00341	0.00022	0.0146	0.0140	0.187

ATLAS: Event Selection

ATLAS-CONF-2013-039

- 2011 data sample using 4.9 fb^{-1} at 7 TeV
- Preliminary update to previously published untagged analysis: JHEP 12 (2012) 072
  - Same dataset - addition of initial state B-meson flavour tagging
- 131k B_s candidates after selections;
  - mass range [5.15,5.65] GeV.
- Negligible effects from selection of correct primary vertex due to pileup (<μ> ~8).
- No requirement is made on proper-time cut,
  - full prompt contribution considered in fit
- S-wave contributions to the fit are also considered

- **Trigger**:
  - Single and di-muon trigger suite
  - Requiring at least one muon, $p_T(\mu) > 4$ GeV
- **J/ψ**:
  - $pT(\mu) > 4$ GeV
  - $|\eta|$ dependent mass cuts (retains 99.8% of signal)
  - $\chi^2/ndf < 10$
- **φ**:
  - Oppositely-charged track pair
  - $pT(K) > 1.0$ GeV
  - $|m(\varphi) - m^{PDG}(\varphi)| < 11$ MeV
- **B_s**:
  - μμKK Vertex fit
  - J/ψ mass constraint
  - Vertex $\chi^2/ndf < 3$
  - $5.15 < m(J/\psi KK) < 5.65$ GeV

ATLAS: Flavour Tagging

- If initial flavour of B_s meson is known, additional terms appear in the likelihood description of the time-dependent amplitudes:
  - leading to increased sensitivity on φ_s.
- Opposite side tagging, use $b - \bar{b}$ pair correlation to infer initial signal flavour from the other B meson.
- **Muon Tagging**:
  - b→μ transitions are clean tagging method, but diluted from b→c→μ decays.
- **Jet-charge Tagging**:
  - Momentum-weighted track-charge.
- Calibration of tagging method – self-tagging $B^{\pm} \rightarrow J/\psi K^{\pm}$

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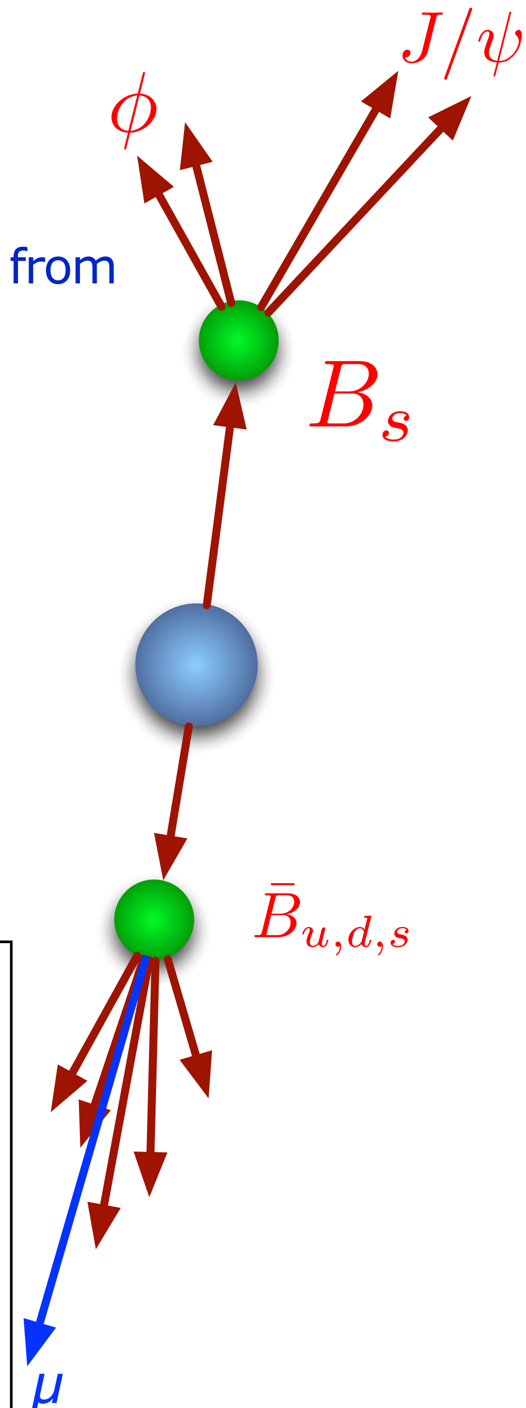


•Muon Tagging:

- •Additional Muon pT(μ)>2.5 GeV, |η| <2.5
- •Originating near the signal primary interaction |Δz| < 5mm
- •Use muon and tracks within cone ΔR<0.5 around muon to construct momentum-weighted muon-cone charge

$$Q_\mu = \frac{\sum_i^{N \text{ tracks}} q^i \cdot (p_T^i)^\kappa}{\sum_i^{N \text{ tracks}} (p_T^i)^\kappa},$$

- •K=1.1 from optimisation to tagging performance

•Jet charge Tagging:

- •In absence of muon use b-tagged jet (Anti-Kt, 0.6 cone size)
- •Use tracks from ΔR<1.0 around jet, originating near signal primary interaction.
- •Construct jet-charge from momentum-weighted charge of the selected tracks

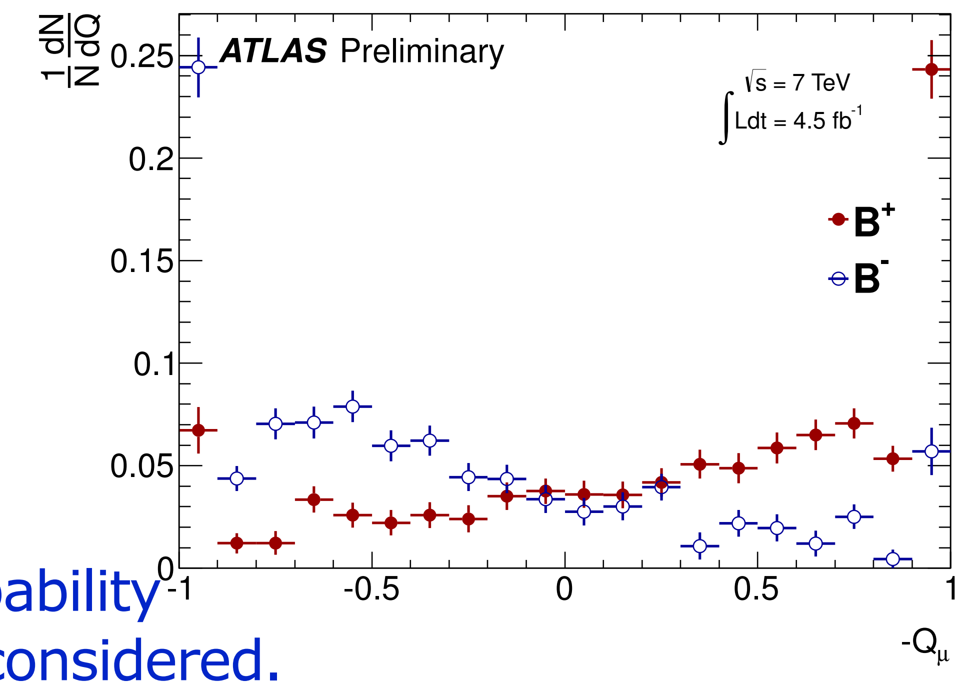
$$Q_{\text{jet}} = \frac{\sum_i^{N \text{ tracks}} q^i \cdot (p_T^i)^\kappa}{\sum_i^{N \text{ tracks}} (p_T^i)^\kappa},$$

- •K=1.1 from optimisation to tagging performance

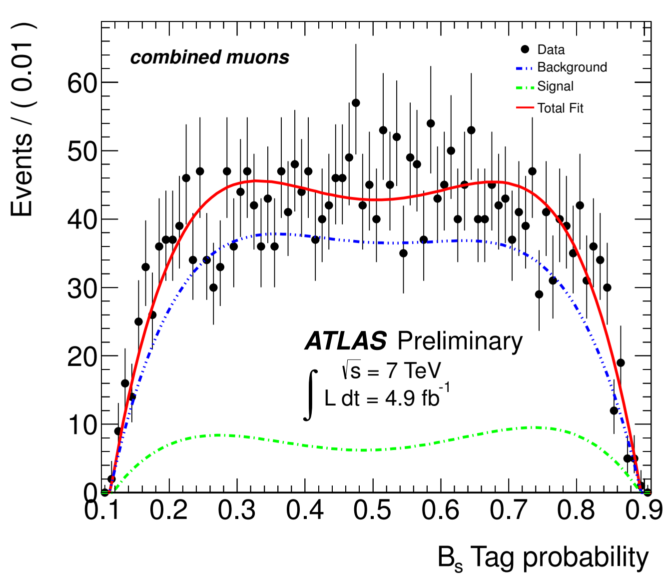
ATLAS: Tagging Performance

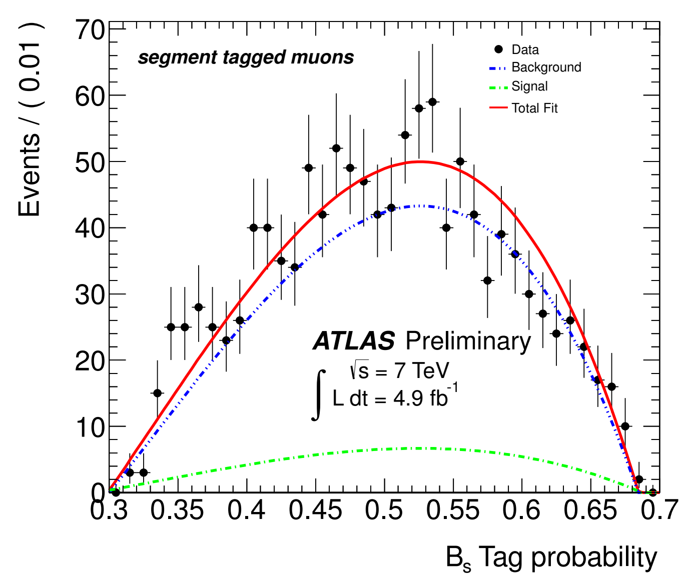
- Tagging performance estimated to be:
  - (1.45 ± 0.05 (stat.))% from $B^{\pm} \rightarrow J/\psi K^{\pm}$

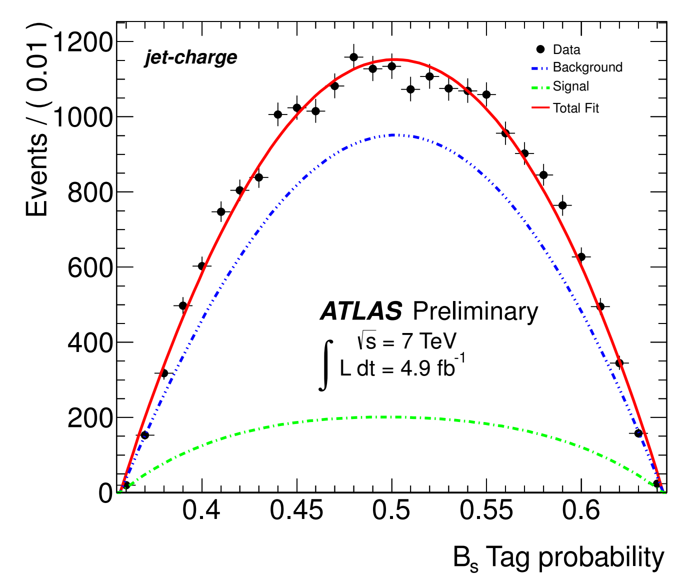
Tagger	Efficiency [%]	Dilution [%]	Tagging Power [%]
Segment Tagged muon	1.08 ± 0.02	36.7 ± 0.7	0.15 ± 0.02
Combined muon	3.37 ± 0.04	50.6 ± 0.5	0.86 ± 0.04
Jet charge	27.7 ± 0.1	12.68 ± 0.06	0.45 ± 0.03
Total	32.1 ± 0.1	21.3 ± 0.08	1.45 ± 0.05



- In likelihood fit to B_s data, the per-candidate probability and **probability distributions** (Punzi terms) are considered.
- Punzi terms are parameterised from fit to sideband-subtracted (signal), and sideband (background) B_s data
- P=0.5 in absence of tagging information.







ATLAS: Fit Model

- Observables:
  - m(J/ψKK), t, σ(m),σ(t)
  - Three transversity angles
  - Tagging probability
- 25 free parameters (Δm fixed in the fit)

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

Muon time dependent trigger efficiency

$$\mathscr{F}_s(m_i, t_i, \Omega_i, P(B|Q)) = P_s(m_i|\sigma_{m_i}) \cdot P_s(\sigma_{m_i}) \cdot P_s(\Omega_i, t_i, P(B|Q)|\sigma_{t_i}) \cdot P_s(\sigma_{t_i}) \cdot P_s(P(B|Q)) \cdot A(\Omega_i, p_{\mathrm{T}i}) \cdot P_s(p_{\mathrm{T}i})$$

9 physics variables to describe $B_s \to J/\psi\Phi$ and S-wave component: ΔΓ , Φs, Γs, $|A_0(0)|^2$, $|A_{\parallel}(0)|^2$, $\delta_{\parallel}$, $\delta_{\perp}$, $|As(0)|^2$ and δs

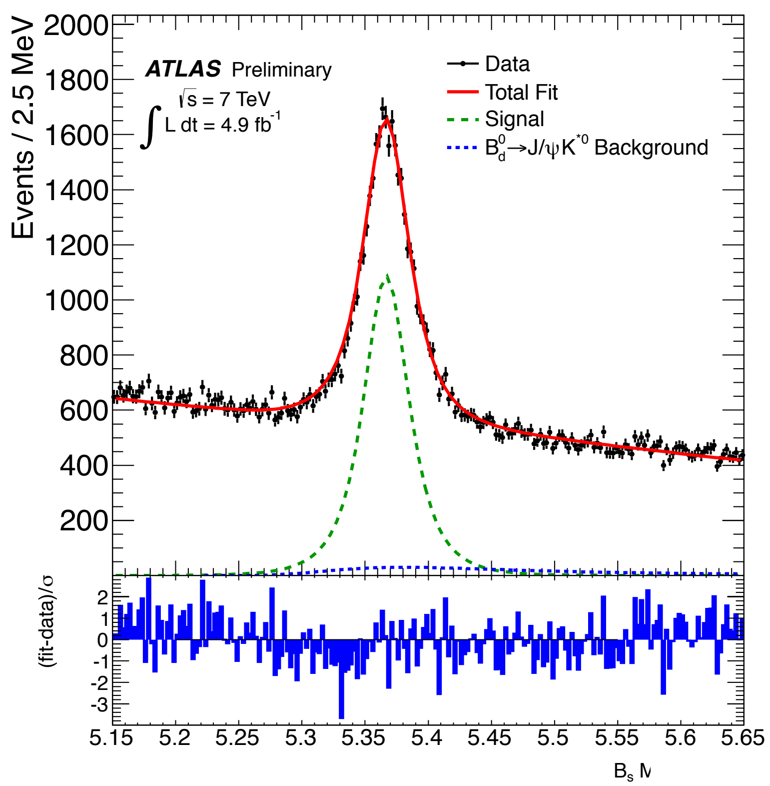
The background due to $B^0 \to J/\psi\ K^{*0}$ and $B^0 \to J/\psi\ K\pi$ (non resonant), described by the parameter f_{B0}, constrained by known branching fractions and acceptance (11% of signal amplitude)

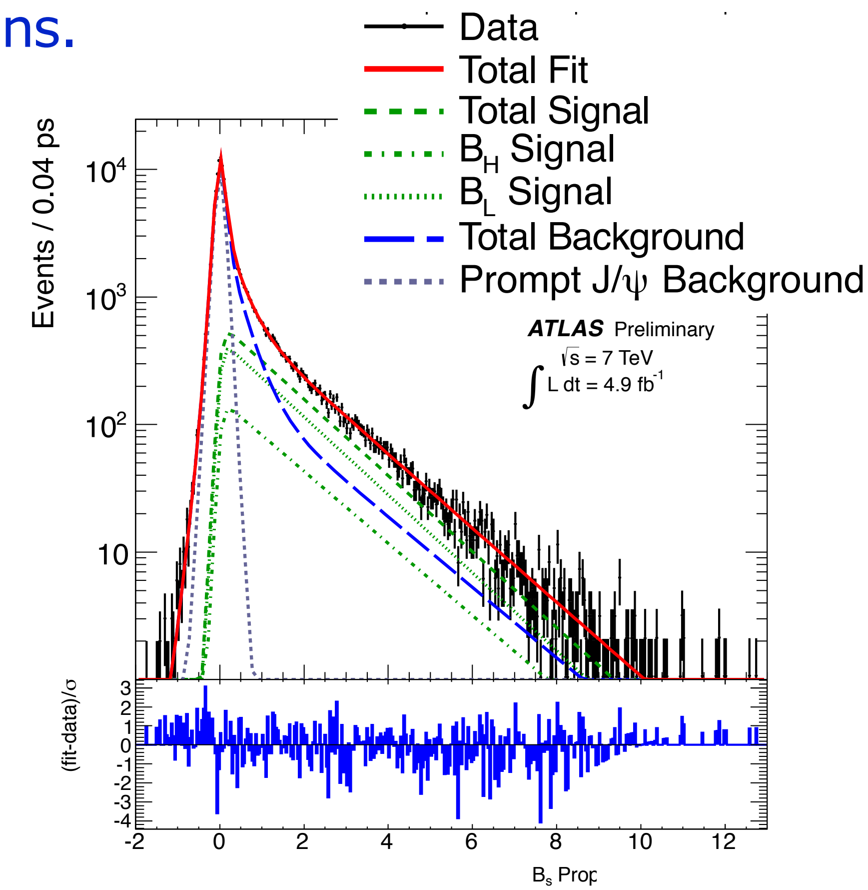
The prompt and non-prompt combinatorial background described with empirical angular distribution. (No K-π discrimination.)

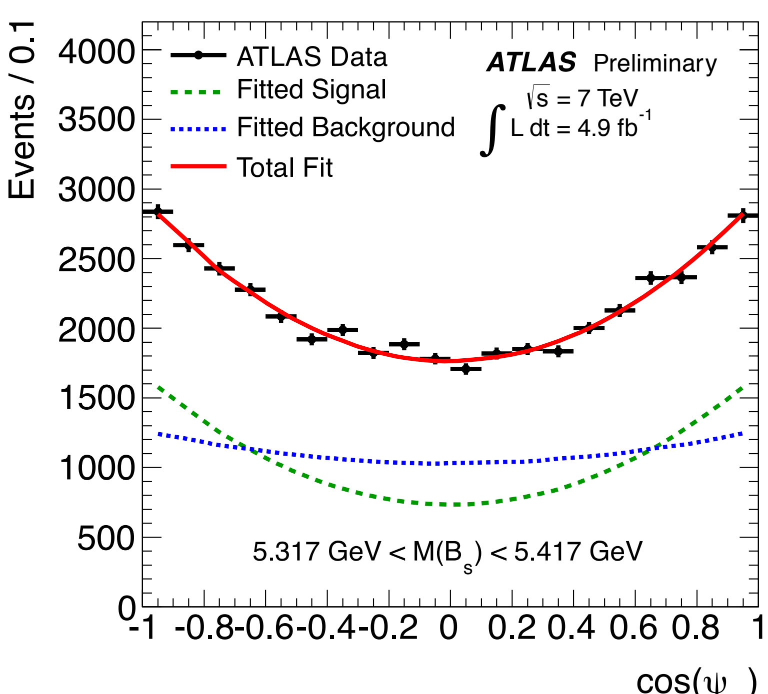
- Signal modelled using:
  - mass: Gaussians (per-event resolution)
  - proper time and angles for differential decay rates convoluted with Gaussian and per-event resolution
  - angular efficiency
- Background:
  - mass: linear
  - Gaussian plus three exponentials (+,+,-)
  - angles from sinusoidal for φ_T, and Legendre polynomials for $\cos(\theta_T)$ and $\cos(\psi_T)$.

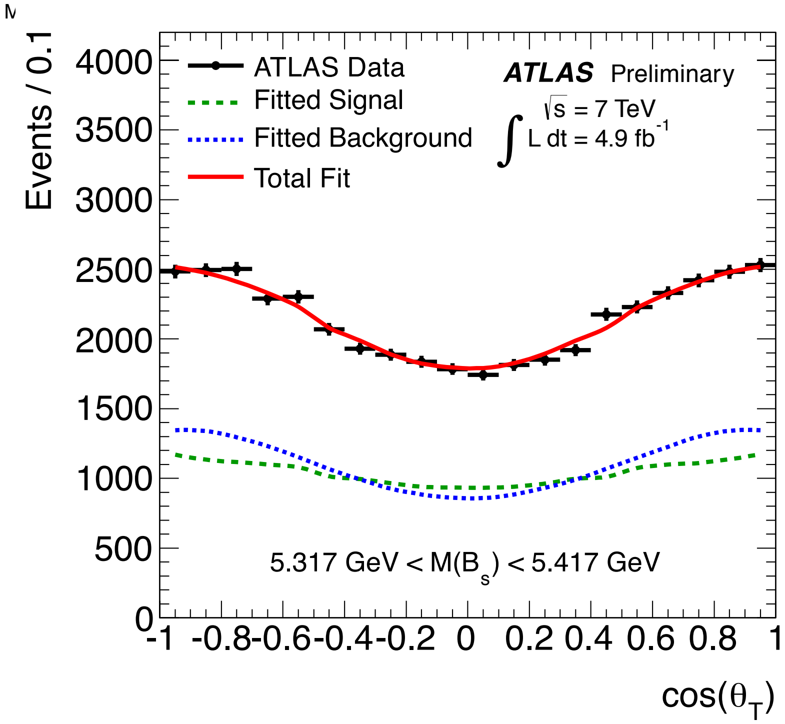
ATLAS: Fit Projections

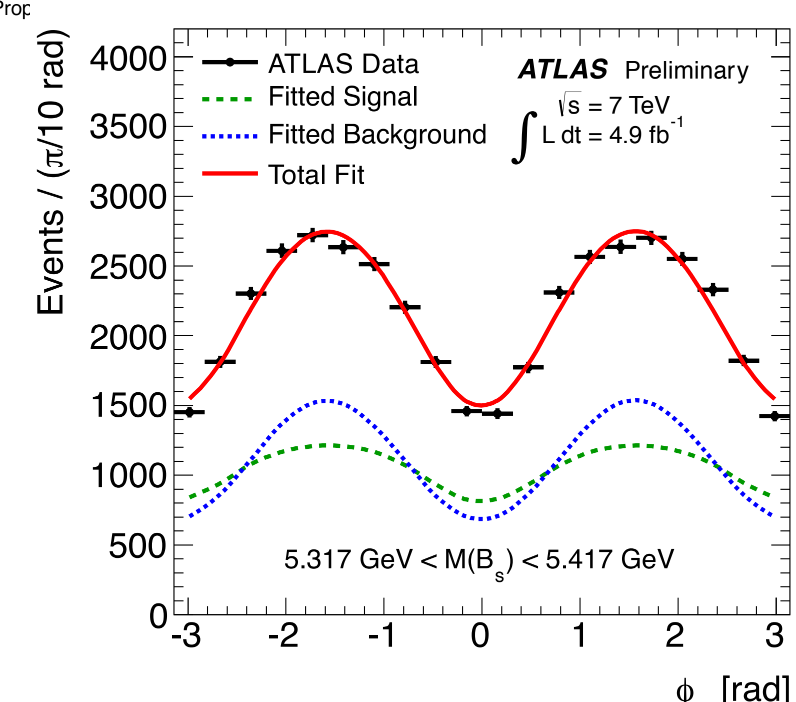
- $22{,}670 \pm 150$ signal B_s events from fit.
- Fit projections to all data passing selections.











ATLAS: Results

- Φ_s within with Standard Model predictions.
- Consistent with previous Untagged analysis.
- S-wave amplitude is compatible with 0.
- $\delta_{||}$ and $\delta_\perp - \delta_S$ are given as 68% CL.
- Tagged analysis provides sufficient sensitivity for **$\delta_\perp$ to be determined from the fit** (previously constrained).
- Dominant **systematics** from **Tagging**, and **Background modelling** (estimated from pseudo-experiment studies)
- Systematic uncertainty from tagging dominated by statistical precision in calibration channel.

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s(rad)	0.12	0.25	0.11
$\Delta\Gamma_s$(ps^{-1})	0.053	0.021	0.009
Γ_s(ps^{-1})	0.677	0.007	0.003
$\lvert A_\parallel(0)\rvert^2$	0.220	0.008	0.009
$\lvert A_0(0)\rvert^2$	0.529	0.006	0.011
$\lvert A_S\rvert^2$	0.024	0.014	0.028
$\delta_\perp$	3.89	0.46	0.13
$\delta_\parallel$	[3.04-3.23]		0.09
$\delta_\perp - \delta_S$	[3.02-3.25]		0.04

cf. Untagged result:
Φ_s = 0.21 ± 0.41 (stat.) ± 0.10 (syst.) rad

Systematics

	ϕ_s (rad)	$\Delta\Gamma_s$ (ps^{-1})	Γ_s (ps^{-1})	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ (rad)	$\delta_\parallel$ (rad)	$\delta_\perp - \delta_S$ (rad)
ID alignment	$<10^{-2}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	-	$<10^{-2}$	$<10^{-2}$	-
Trigger efficiency	$<10^{-2}$	$<10^{-3}$	0.002	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-2}$	$<10^{-2}$	$<10^{-2}$
B_d^0 contribution	0.03	0.001	$<10^{-3}$	$<10^{-3}$	0.005	0.001	0.02	$<10^{-2}$	$<10^{-2}$
Tagging	0.10	0.001	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.002	0.05	$<10^{-2}$	$<10^{-2}$
Models:									
default fit	$<10^{-2}$	0.002	$<10^{-3}$	0.003	0.002	0.006	0.07	0.01	0.01
signal mass	$<10^{-2}$	0.001	$<10^{-3}$	$<10^{-3}$	0.001	$<10^{-3}$	0.03	0.04	0.01
background mass	$<10^{-2}$	0.001	0.001	$<10^{-3}$	$<10^{-3}$	0.002	0.06	0.02	0.02
resolution	0.02	$<10^{-3}$	0.001	0.001	$<10^{-3}$	0.002	0.04	0.02	0.01
background time	0.01	0.001	$<10^{-3}$	0.001	$<10^{-3}$	0.002	0.01	0.02	0.02
background angles	0.02	0.008	0.002	0.008	0.009	0.027	0.06	0.07	0.03
Total	0.11	0.009	0.003	0.009	0.011	0.028	0.13	0.09	0.04

Results – Comparisons

	Φ_s	Stat.	Syst.
ATLAS	0.12	0.25	0.11
CDF	-0.60 – 0.12		
CMS	–		
D0	-0.56	+0.36 / -0.32	

	$\Delta\Gamma_s$ (ps^{-1})	Stat.	Syst.
ATLAS	0.053	0.021	0.009
CDF	0.068	0.026	0.009
CMS	0.048	0.024	0.003
D0	0.179	+0.060 / -0.059	

	$\delta_\perp$ [rad]	Stat.	Syst.
ATLAS	3.89	0.46	0.13
CDF	2.79	0.53	0.15
CMS	–		
D0	$\cos(\delta_\perp-\delta_s) = -0.2$	+0.26 / -0.27	

	Γ_s (ps^{-1})	Stat.	Syst.
ATLAS	0.677	0.007	0.003
CDF	0.654	0.008	0.004
CMS	0.653	0.008	0.003
D0	0.693	+0.016 / -0.020	

	$\lvert A_0\rvert^2$	Stat.	Syst.
ATLAS	0.529	0.006	0.011
CDF	0.512	0.012	0.018
CMS	0.528	0.010	0.015
D0	0.565	±0.017	

	$\lvert A_\parallel\rvert^2$	Stat.	Syst.
ATLAS	0.220	0.008	0.009
CDF	0.229	0.010	0.018
CMS	0.221	<0.016	<0.021
D0	0.249	+0.021 / -0.020	

LHCb-PAPER-2013-002

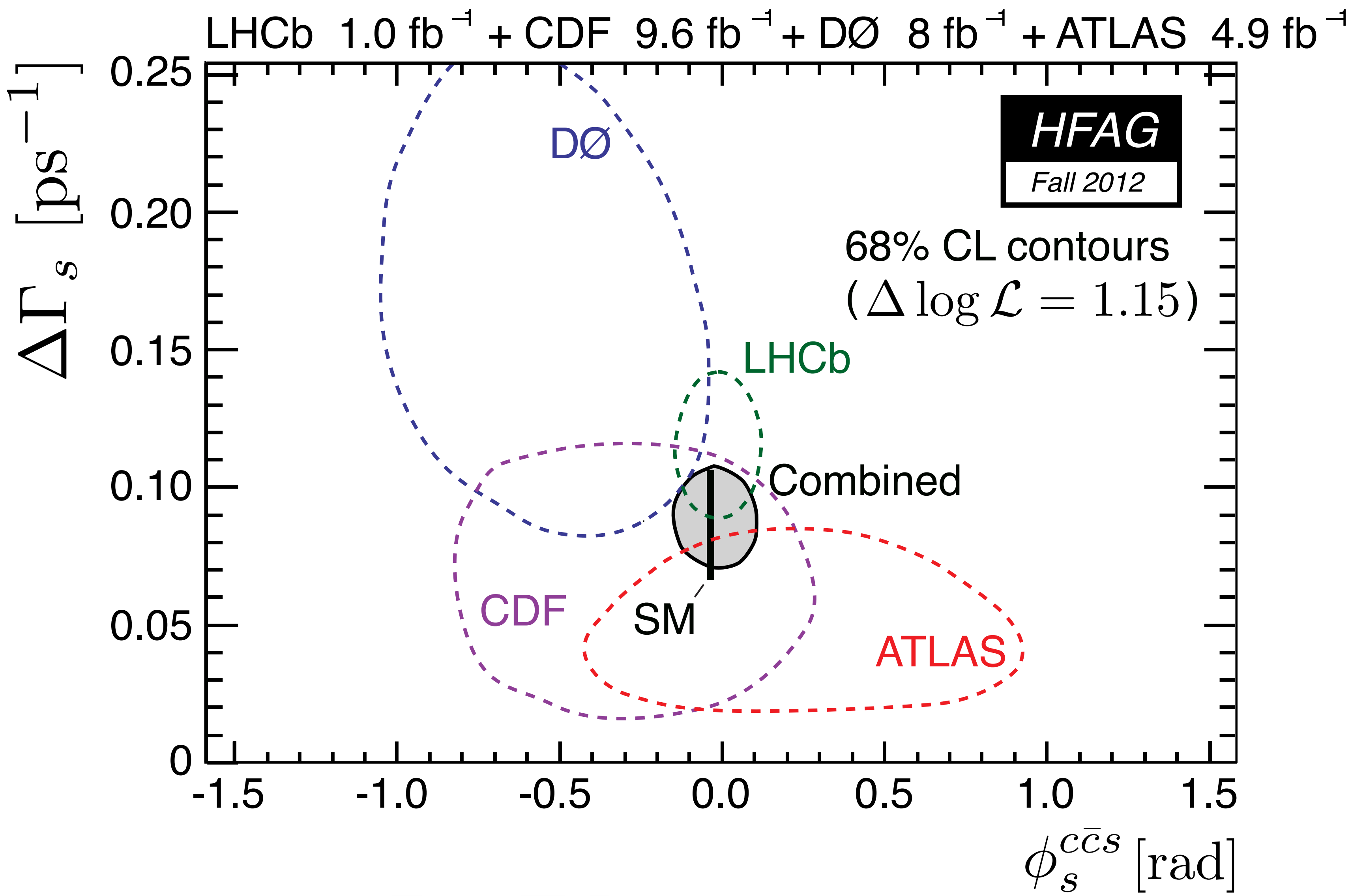
$B_s^0 \to J/\psi\phi$

$$\begin{aligned} \phi_s &= 0.07 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst) rad}, \\ \Gamma_s \equiv (\Gamma_L + \Gamma_H)/2 &= 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst) } ps^{-1}, \\ \Delta\Gamma_s \equiv \Gamma_L - \Gamma_H &= 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst) } ps^{-1}, \end{aligned}$$

$\lvert A_\perp\rvert^2$	$0.249 \pm 0.009 \pm 0.006$
$\lvert A_0\rvert^2$	$0.521 \pm 0.006 \pm 0.010$
$\delta_\parallel$ [rad]	$3.30\,^{+0.13}_{-0.21} \pm 0.08$
$\delta_\perp$ [rad]	$3.07 \pm 0.22 \pm 0.07$

$B_s \to J/\psi\ \phi$: Combination

- Most recent combination from HFAG on $\Delta\Gamma_s$ vs the CP-violating phase

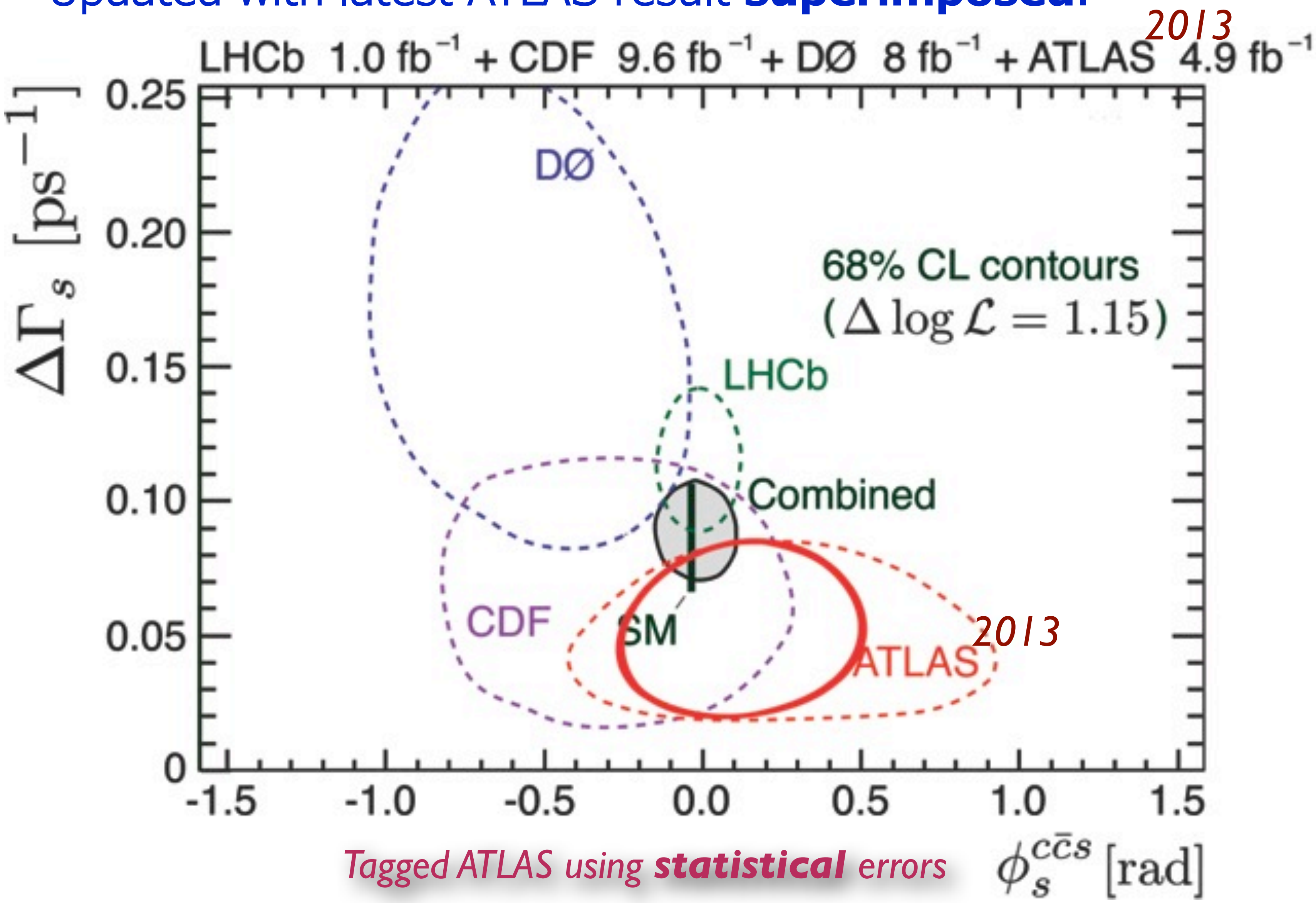


Tagged ATLAS analysis not included

LHCb-Paper-2013-002 latest result not included

Bs → J/ψ ϕ: Combination

- Most recent combination from HFAG on $\Delta\Gamma_s$ vs the CP-violating phase
  - Updated with latest ATLAS result **superimposed**.



*Tagged ATLAS using **statistical** errors*

LHCb-Paper-2013-002 latest result not included

- Tagging improves ATLAS φ_s precision by ~40%
  - $\Delta\Gamma_s$ central value and uncertainty unchanged

Conclusions

- Results presented from ATLAS, CDF, CMS, D0 in $B_s \to J/\psi\ \varphi$
  - In general, good agreement between experiments.
- **D0** and **CDF** provided many pioneering and tantalising measurements on B_s system.
- Current results tending to SM predictions of CP-violating phase in $B_s \to J/\psi\ \varphi$.
  - Analyses with final datasets published or nearing completion.
- Statistically limited in most measured quantities.

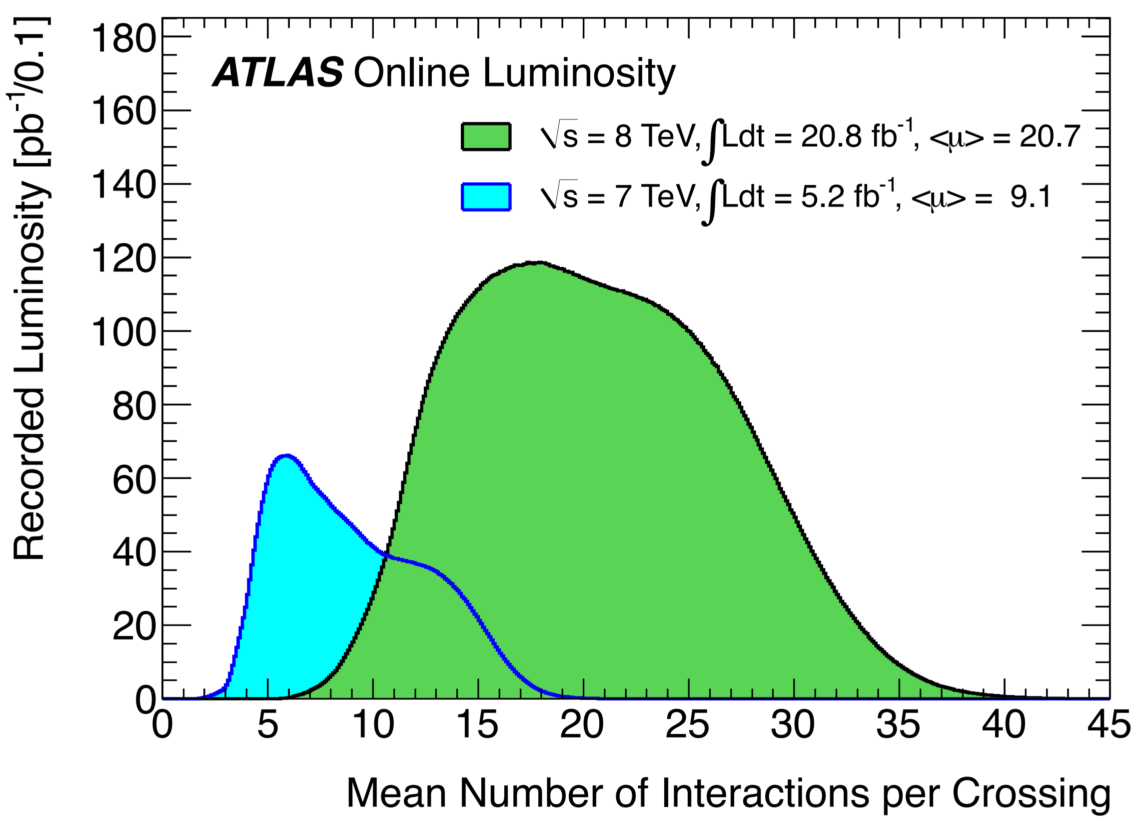
- Future results to come from **ATLAS** and **CMS** analyses using **2012** data samples, in same and complementary channels:
  - Additional dedicated B-physics triggered samples stored unprocessed at time of data-taking.
  - With shutdown of LHC releasing CPU needs, these additional data now being reconstructed and analyses are underway.

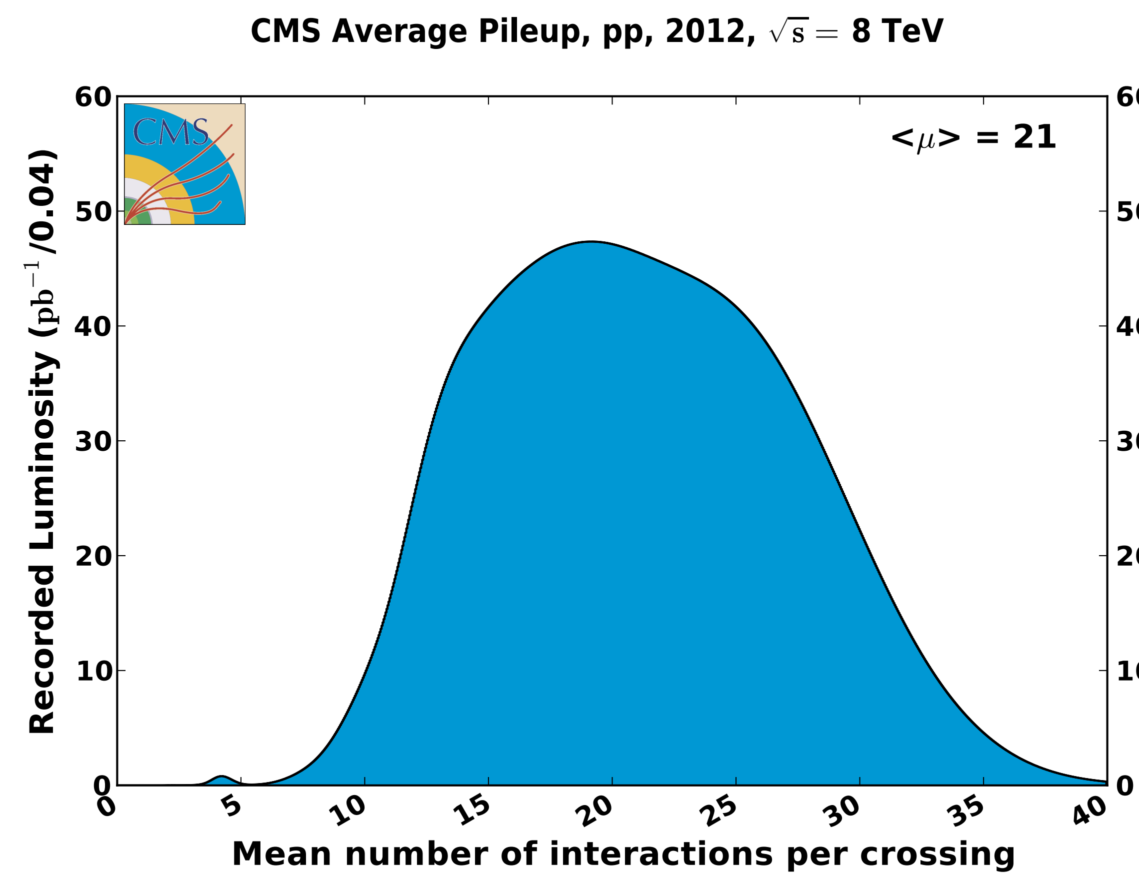
- Expected LHC data-taking resuming in 2015 at ~13 TeV collisions:
  - Stay tuned for future results from the LHC B-physics programmes.

Backup

Pileup at LHC

- Average number of collisons per bunch crossing:
  - ~ 9 in 2011
  - ~ 21 in 2012



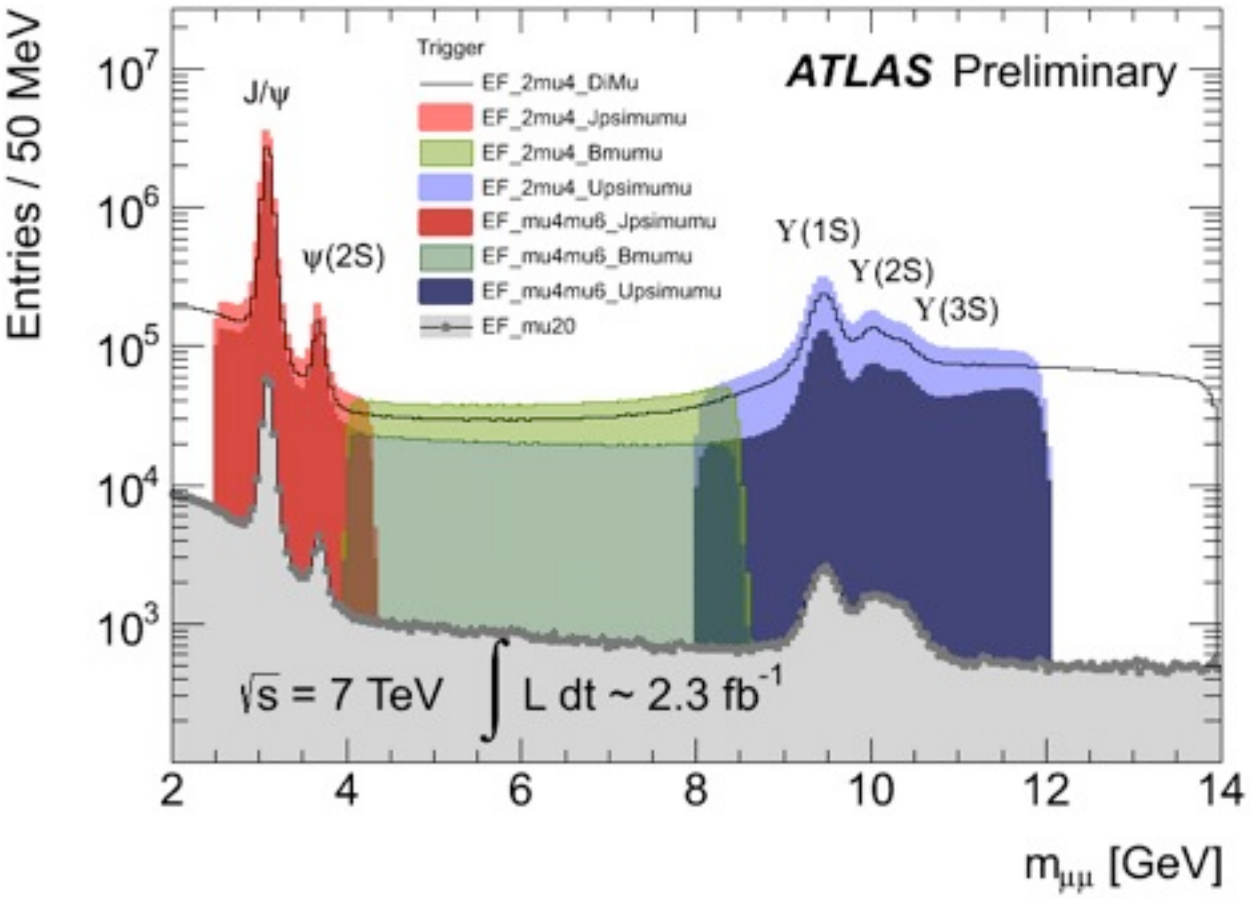


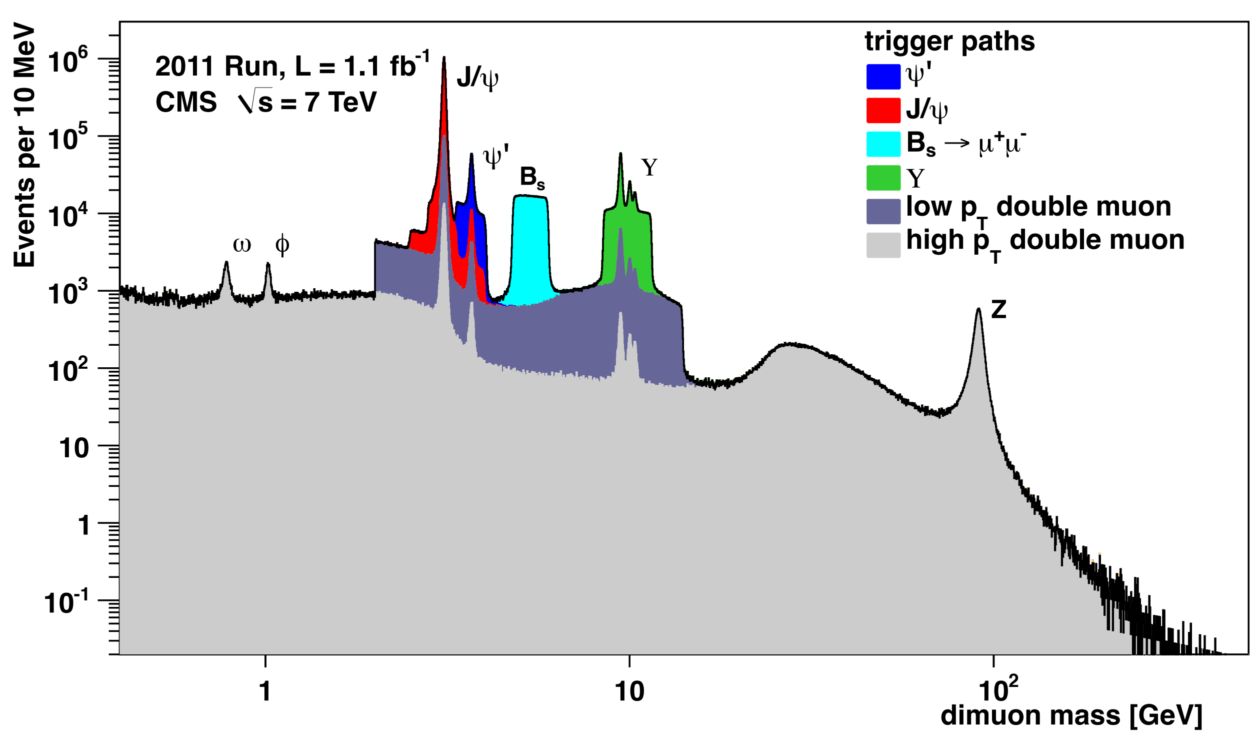
- While effect of pileup minimal in current analyses,
  - Run II running conditions will be additional challenge.

Trigger Selection

- Data selection begins with optimised suite of di-muon or single-muon triggers:

- ATLAS and D0:
  - collect from suite of low-p_T single and di-muon triggers:
- CDF:
  - low-p_T di-muon trigger with $2.7 < m(\mu^+\mu^-) < 4.0$ GeV
- CMS:
  - Optimised trigger selection of non-prompt J/ψ candidates: $2.8 < m(J/\psi) < 3.35$ GeV or $2.9 < m(J/\psi) < 3.3$.
  - $L_{xy}/\sigma_{Lxy} > 3$ transverse decay-length significance cut to reduce prompt background contributions.





Resolving the sign ambiguity

- Decay rate amplitudes are invariant under certain transformations,

$$\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S\} \to \{\pi - \phi_s, -\Delta\Gamma_s, \pi - \delta_\perp, -\delta_\parallel, -\delta_S\}.$$

- Untagged analysis also allows:

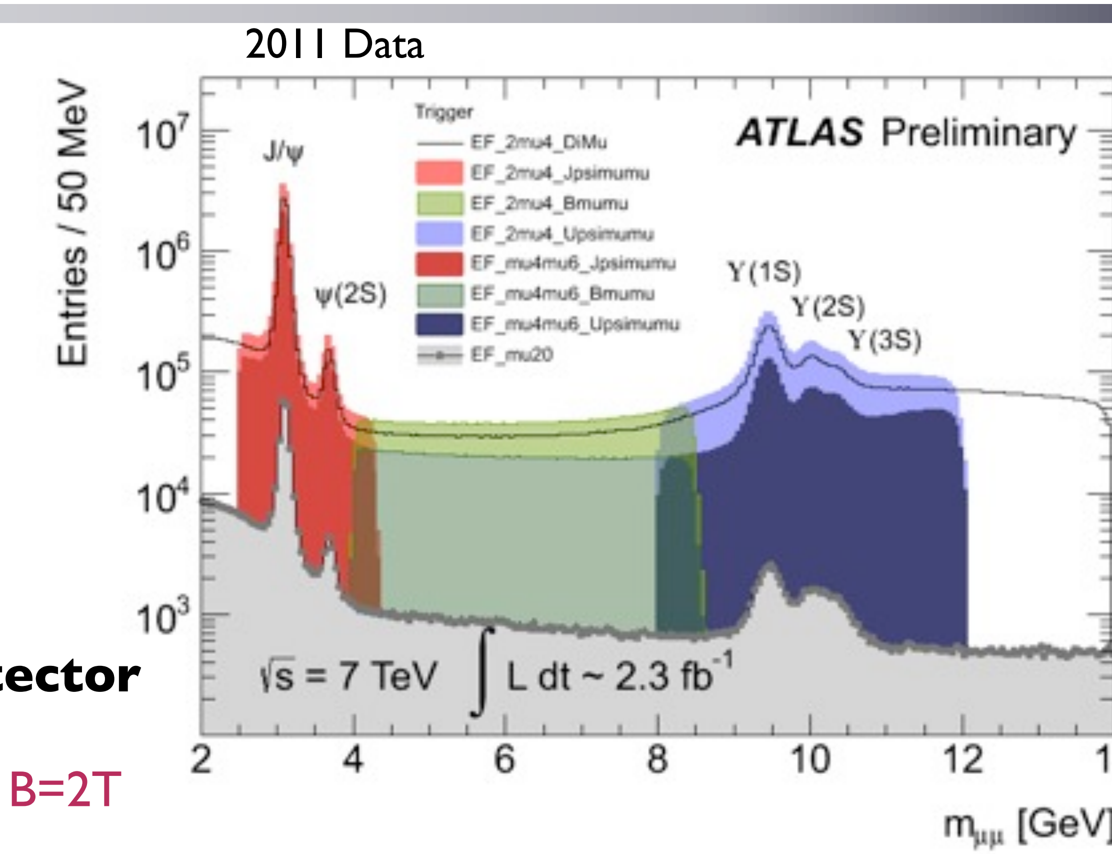
$$\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S\} \to \{-\phi_s, \Delta\Gamma_s, \pi - \delta_\perp, -\delta_\parallel, -\delta_S\}$$

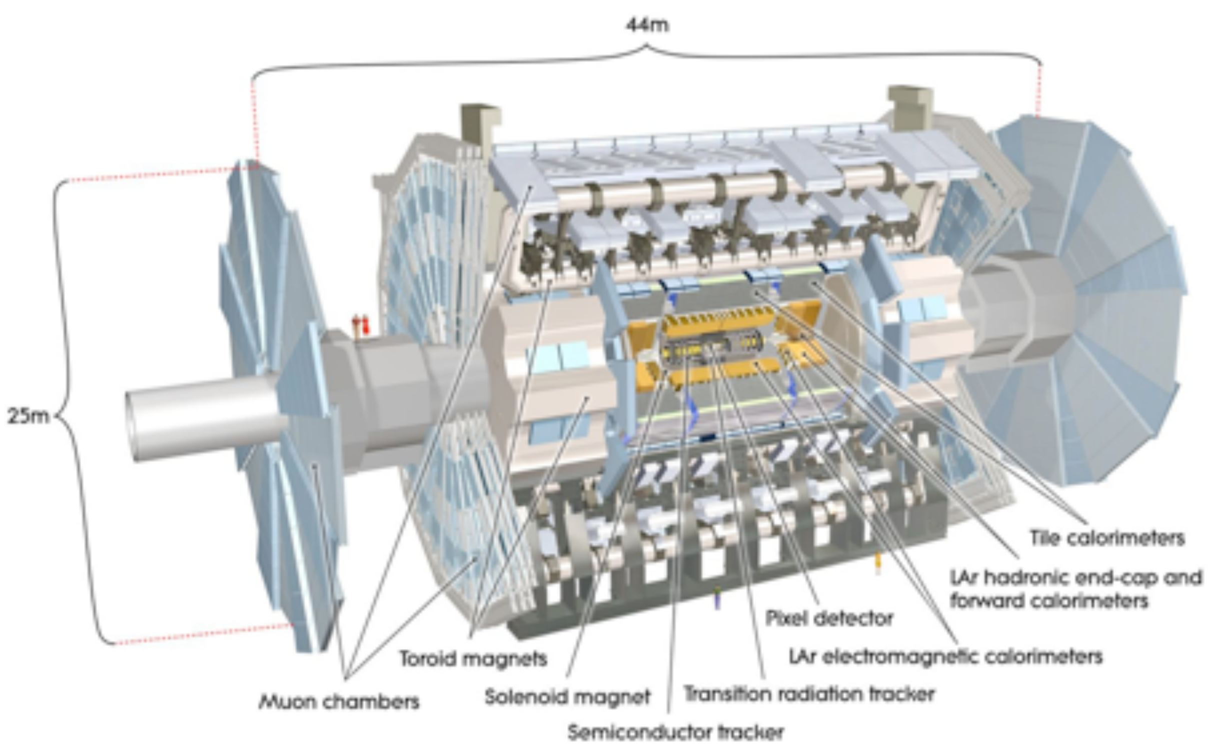
  - Led to a four-fold ambiguity on earlier measurements

- From Tagging, and sign determination of ΔΓs >0 hep-ex:1112.3183 LHCb-PAPER-2011-021
  - Single set of solutions remain

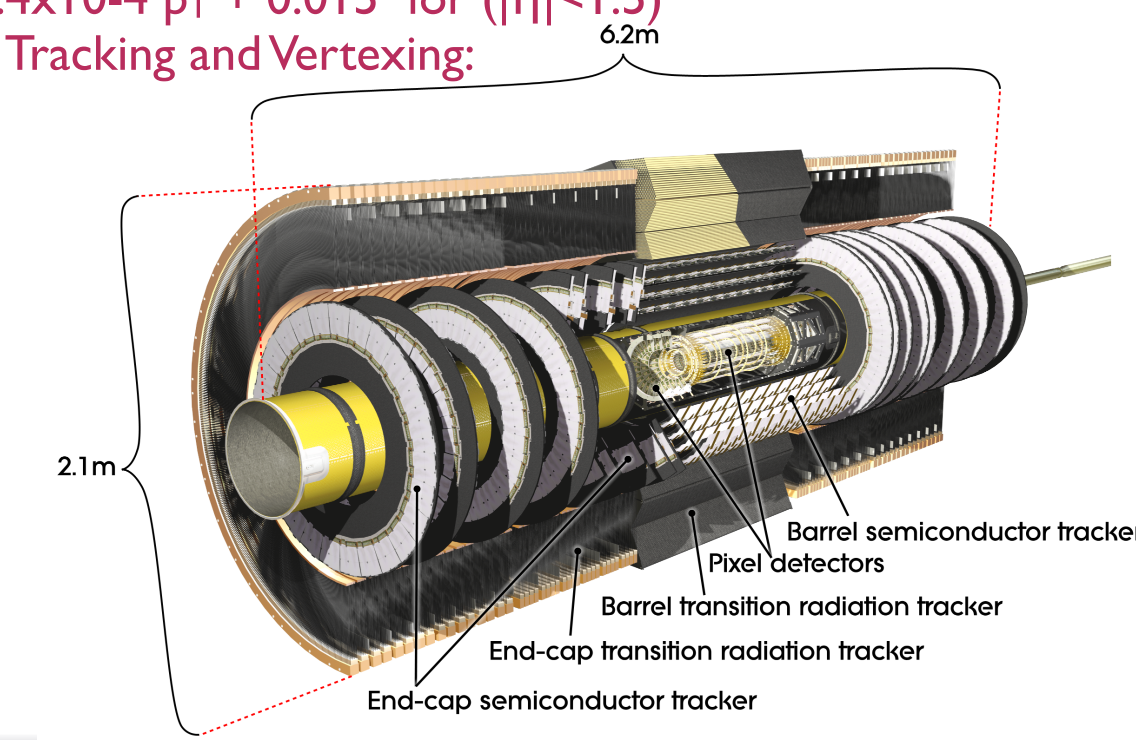
The ATLAS Detector

- Data selection begins with optimised suite of single and di-muon triggers:
  - 3-level system: 40 MHz to *O*(200) Hz
- Muon ID from Muon Spectrometer
- Inner Detector provides precision momentum and lifetime measurements





- **Inner Detector**
  - $|\eta|<2.5$,
  - Solenoid B=2T
  - Si Pixels,
  - Si strips,
  - Transition Radiation Tracker (TRT)
  - $\sigma/p_T \sim 3.4\times10^{-4}\, p_T + 0.015$ for ($|\eta|<1.5$)
  - Used for Tracking and Vertexing:

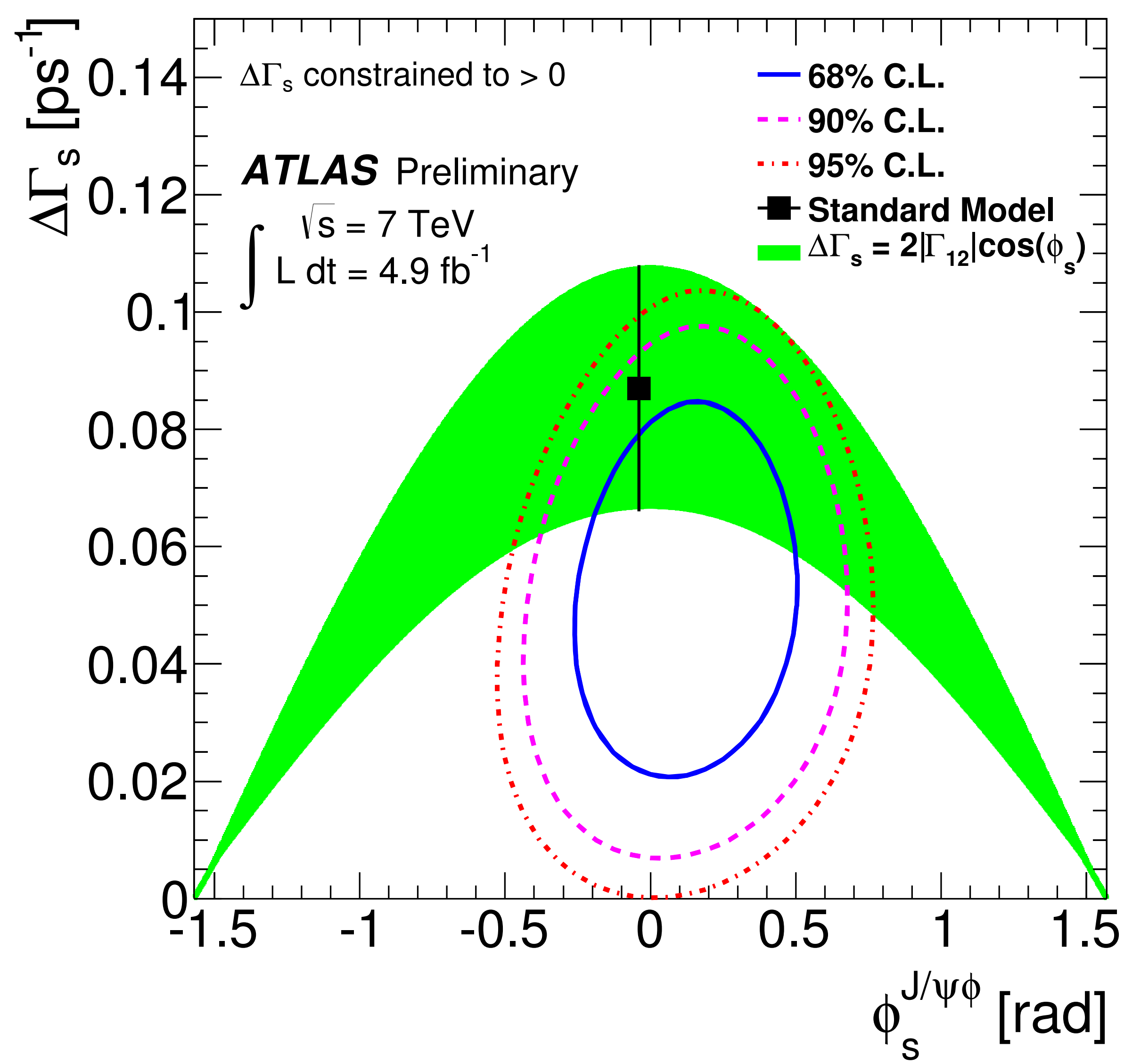


- **Muon Spectrometer**
  - $|\eta|<2.7$
  - Toroid B-Field, average ~0.5T
  - Muon Momentum resolution $\sigma/p < 10\%$ up to ~ 1 TeV

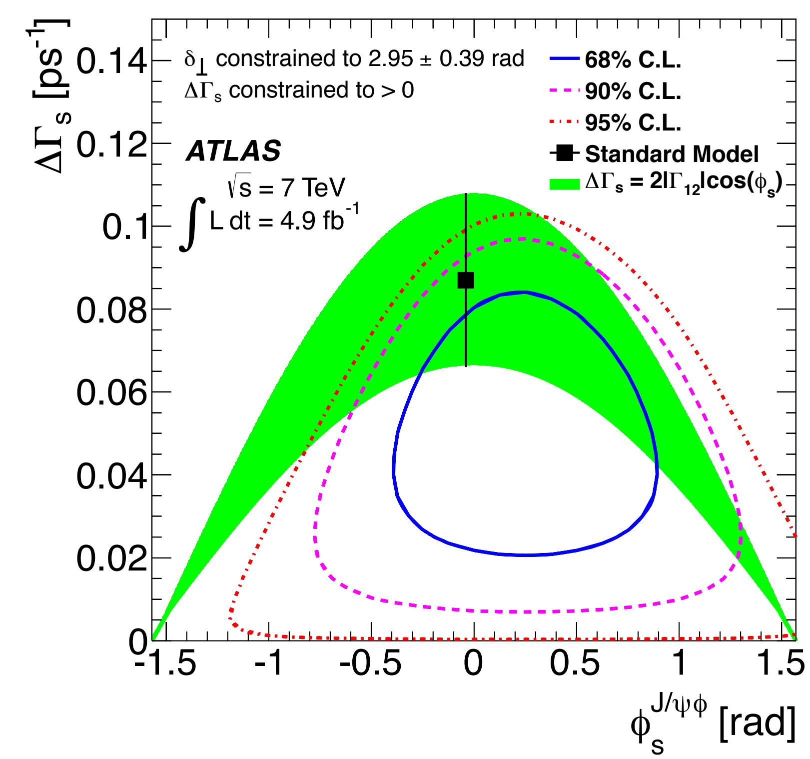
ATLAS: Results

- Tagging improves φ_s precision by ~40%
- $\Delta\Gamma_s$ central value and uncertainty unchanged

Statistical uncertainties only



Untagged



ATLAS - Angles

k	$\mathcal{O}^{(k)}(t)$	$g^{(k)}(\theta_T,\psi_T,\phi_T)$
1	$\frac{1}{2}\lvert A_0(0)\rvert^2\left[(1+\cos\phi_s)e^{-\Gamma_\mathrm{L}^{(s)}t}+(1-\cos\phi_s)e^{-\Gamma_\mathrm{H}^{(s)}t}\pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$
2	$\frac{1}{2}\lvert A_\parallel(0)\rvert^2\left[(1+\cos\phi_s)e^{-\Gamma_\mathrm{L}^{(s)}t}+(1-\cos\phi_s)e^{-\Gamma_\mathrm{H}^{(s)}t}\pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\phi_T)$
3	$\frac{1}{2}\lvert A_\perp(0)\rvert^2\left[(1-\cos\phi_s)e^{-\Gamma_\mathrm{L}^{(s)}t}+(1+\cos\phi_s)e^{-\Gamma_\mathrm{H}^{(s)}t}\mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T\sin^2\theta_T$
4	$\frac{1}{2}\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert\cos\delta_\parallel$ $\left[(1+\cos\phi_s)e^{-\Gamma_\mathrm{L}^{(s)}t}+(1-\cos\phi_s)e^{-\Gamma_\mathrm{H}^{(s)}t}\pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$-\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\phi_T$
5	$\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert[\frac{1}{2}(e^{-\Gamma_\mathrm{L}^{(s)}t}-e^{-\Gamma_\mathrm{H}^{(s)}t})\cos(\delta_\perp-\delta_\parallel)\sin\phi_s$ $\pm e^{-\Gamma_s t}(\sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t)-\cos(\delta_\perp-\delta_\parallel)\cos\phi_s\sin(\Delta m_s t))]$	$\sin^2\psi_T\sin 2\theta_T\sin\phi_T$
6	$\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert[\frac{1}{2}(e^{-\Gamma_\mathrm{L}^{(s)}t}-e^{-\Gamma_\mathrm{H}^{(s)}t})\cos\delta_\perp\sin\phi_s$ $\pm e^{-\Gamma_s t}(\sin\delta_\perp\cos(\Delta m_s t)-\cos\delta_\perp\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\phi_T$
7	$\frac{1}{2}\lvert A_S(0)\rvert^2\left[(1-\cos\phi_s)e^{-\Gamma_\mathrm{L}^{(s)}t}+(1+\cos\phi_s)e^{-\Gamma_\mathrm{H}^{(s)}t}\mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{2}{3}\left(1-\sin\theta_T\cos^2\phi_T\right)$
8	$\lvert A_S\rvert\lvert A_\parallel(0)\rvert[\frac{1}{2}(e^{-\Gamma_\mathrm{L}^{(s)}t}-e^{-\Gamma_\mathrm{H}^{(s)}t})\sin(\delta_\parallel-\delta_S)\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos(\delta_\parallel-\delta_S)\cos(\Delta m_s t)-\sin(\delta_\parallel-\delta_S)\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\phi_T$
9	$\frac{1}{2}\lvert A_S\rvert\lvert A_\perp(0)\rvert\sin(\delta_\perp-\delta_S)$ $\left[(1-\cos\phi_s)e^{-\Gamma_\mathrm{L}^{(s)}t}+(1+\cos\phi_s)e^{-\Gamma_\mathrm{H}^{(s)}t}\mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\phi_T$
10	$\lvert A_0(0)\rvert\lvert A_S(0)\rvert[\frac{1}{2}(e^{-\Gamma_\mathrm{H}^{(s)}t}-e^{-\Gamma_\mathrm{L}^{(s)}t})\sin\delta_S\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos\delta_S\cos(\Delta m_s t)+\sin\delta_S\cos\phi_s\sin(\Delta m_s t))]$	$\frac{4}{3}\sqrt{3}\cos\psi_T\left(1-\sin^2\theta_T\cos^2\phi_T\right)$

Atlas Correlations and Likelihood scans

	ϕ_s	$\Delta\Gamma$	Γ_s	$\lvert A_{\lVert}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\lVert}$	$\delta_{\perp}$	$\delta_{\perp}-\delta_S$
ϕ_s	1.000	0.107	0.026	0.010	0.002	0.029	0.021	-0.043	-0.003
$\Delta\Gamma$		1.000	-0.617	0.105	0.103	0.069	0.006	-0.017	0.001
Γ_s			1.000	-0.093	-0.063	0.034	-0.003	0.001	-0.009
$\lvert A_{\lVert}(0)\rvert^2$				1.000	-0.316	0.077	0.008	0.005	-0.010
$\lvert A_0(0)\rvert^2$					1.000	0.283	- 0.003	-0.016	-0.025
$\lvert A_S(0)\rvert^2$						1.000	-0.011	-0.054	-0.098
$\delta_{\lVert}$							1.000	0.038	0.007
$\delta_{\perp}$								1.000	0.081
$\delta_{\perp}-\delta_S$									1.000

$$\{\phi_s, \Delta\Gamma, \delta_\perp, \delta_{\lVert}\} \rightarrow (\pi - \phi_s, -\Delta\Gamma, \pi - \delta_\perp, 2\pi - \delta_{\lVert})$$

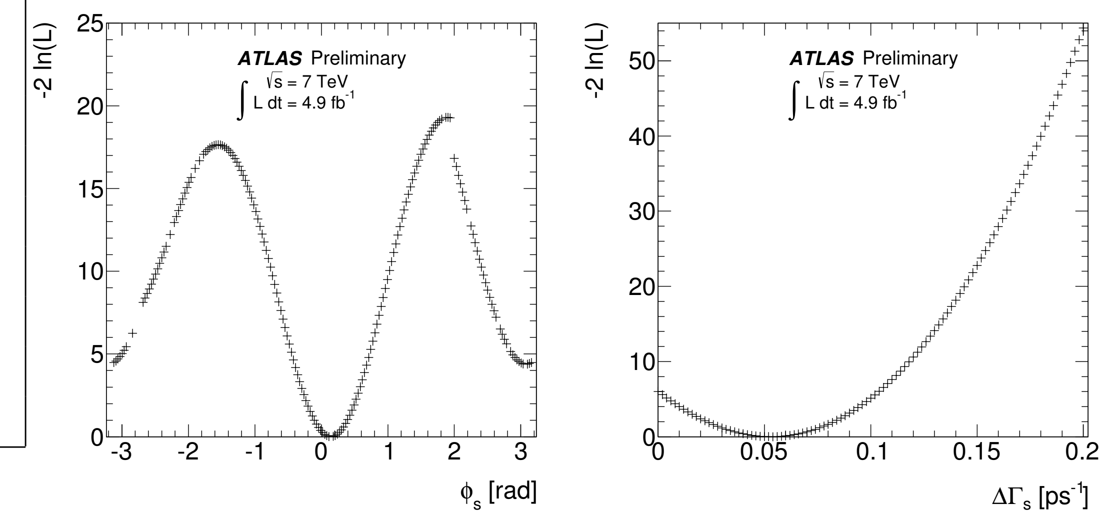


Figure 7: 1D likelihood scans for ϕ_s (left) and $\Delta\Gamma_s$ (right)

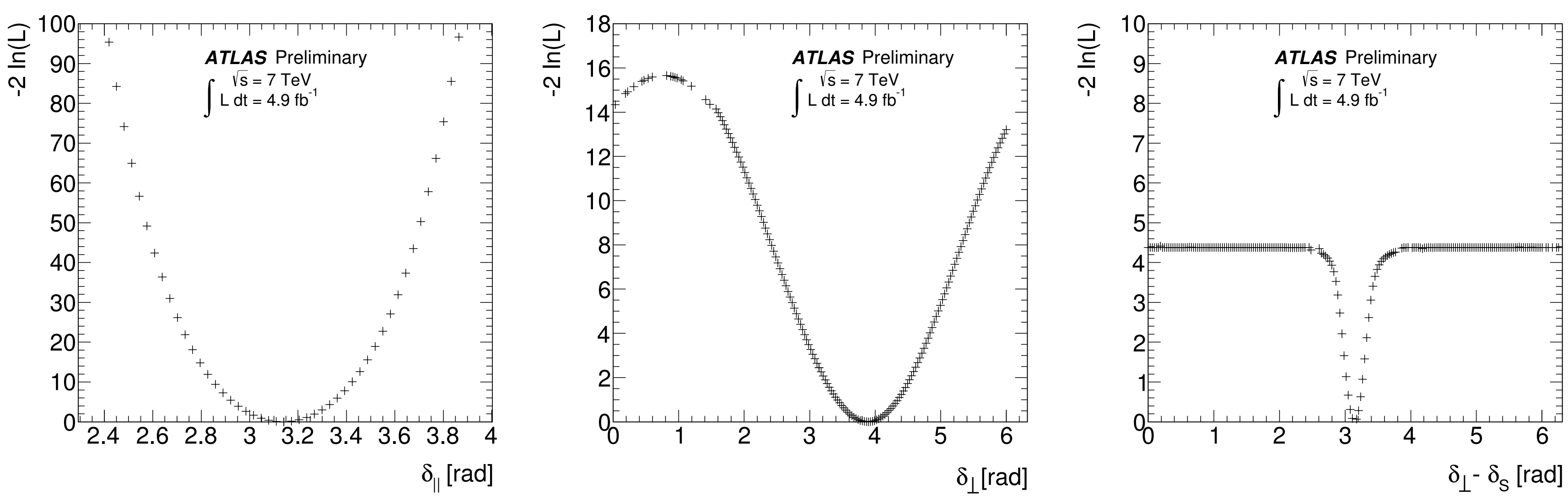
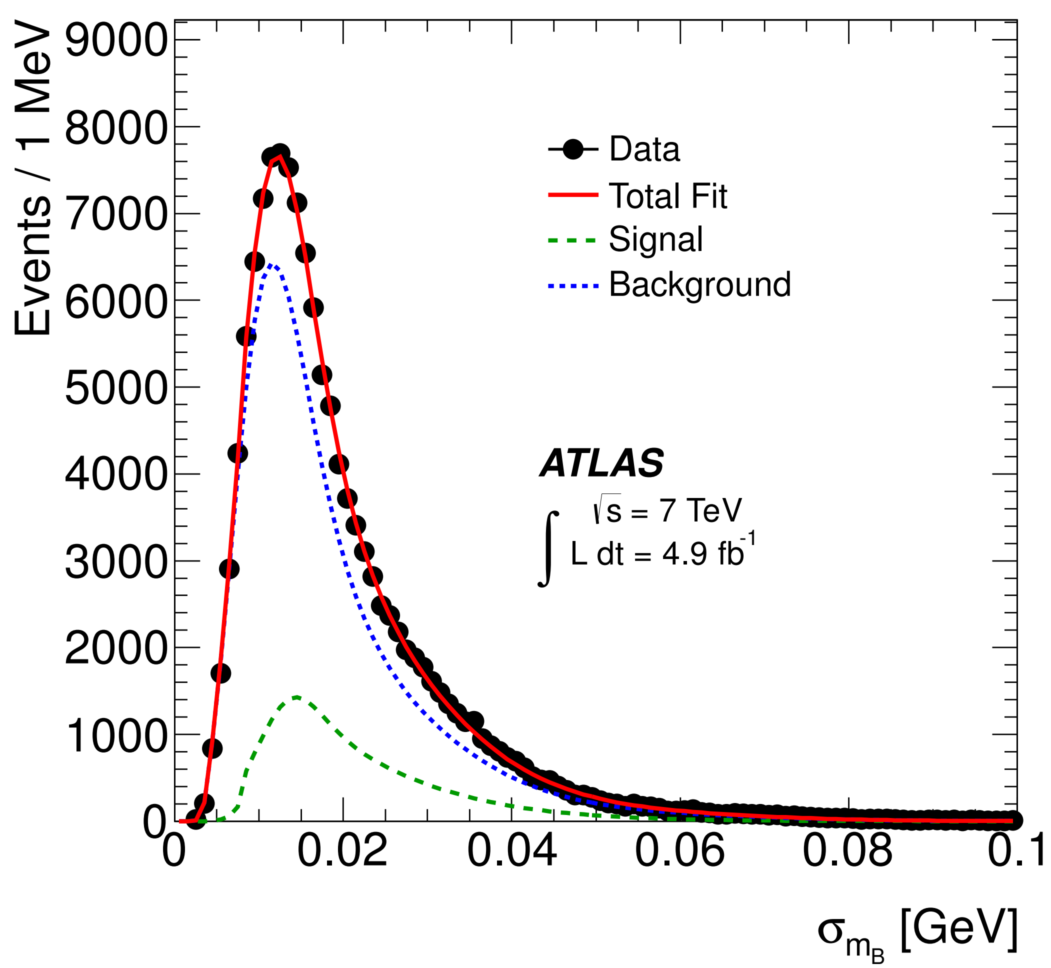
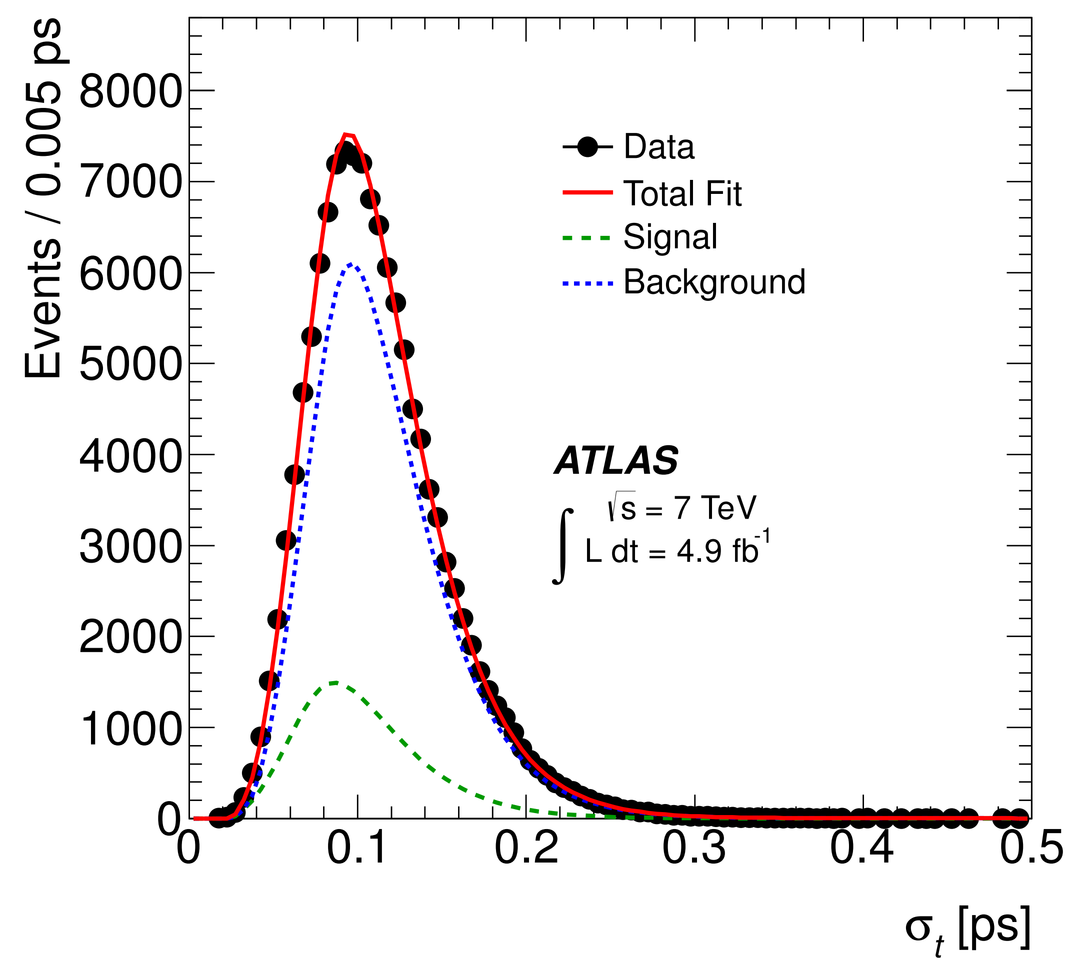


Figure 9: 1D likelihood scans for $\delta_{\lVert}$ (left), $\delta_\perp$ and $\delta_\perp - \delta_S$ (right)

ATLAS - per-candidate resolutions

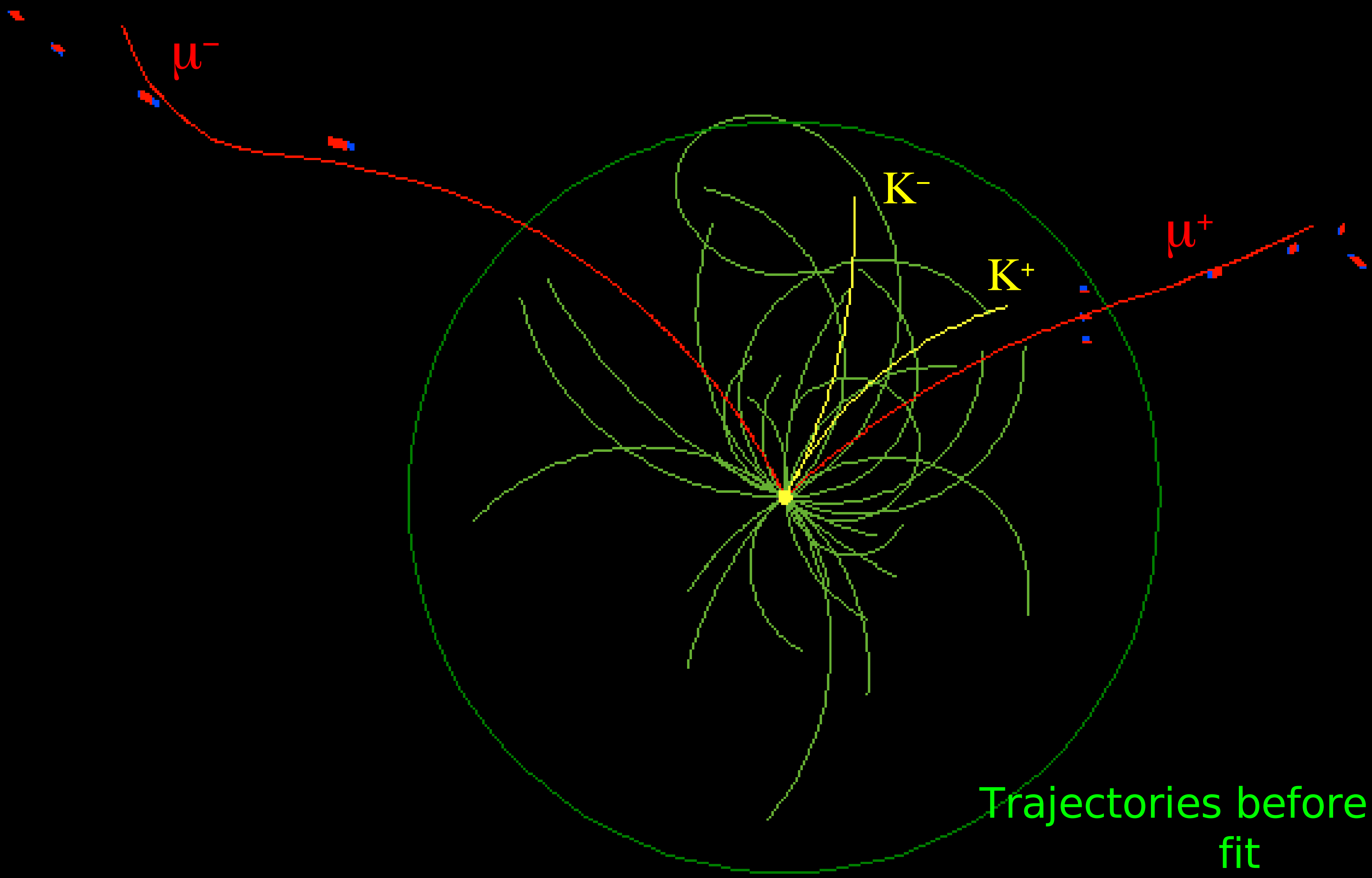
- Per-candidate mass- and lifetime-uncertainty distributions.
- Signal and Background shapes individually modeled for correct usage in likelihood fitting.





$B_s \rightarrow J/\psi\ \phi$ candidate eve

CMS Experiment at LHC, CERN
Data recorded: Sun Jul 4 01:33:41 2010 EDT
Run/Event: 139364 / 20750462
Lumi section: 20



Trajectories before vertex fit
with $p_T > 0.3$ GeV/c in the vicinity of the PV

ATLAS - Systematics

LANCASTER UNIVERSITY

Systematic Uncertainties

ATLAS

	ϕ_s (rad)	$\Delta\Gamma_s$ (ps^{-1})	Γ_s (ps^{-1})	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ (rad)	$\delta_\parallel$ (rad)	$\delta_\perp - \delta_S$ (rad)
ID alignment	$<10^{-2}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	-	$<10^{-2}$	$<10^{-2}$	-
Trigger efficiency	$<10^{-2}$	$<10^{-3}$	0.002	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-2}$	$<10^{-2}$	$<10^{-2}$
B_d^0 contribution	0.03	0.001	$<10^{-3}$	$<10^{-3}$	0.005	0.001	0.02	$<10^{-2}$	$<10^{-2}$
Tagging	0.10	0.001	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.002	0.05	$<10^{-2}$	$<10^{-2}$
Models:									
default fit	$<10^{-2}$	0.002	$<10^{-3}$	0.003	0.002	0.006	0.07	0.01	0.01
signal mass	$<10^{-2}$	0.001	$<10^{-3}$	$<10^{-3}$	0.001	$<10^{-3}$	0.03	0.04	0.01
background mass	$<10^{-2}$	0.001	0.001	$<10^{-3}$	$<10^{-3}$	0.002	0.06	0.02	0.02
resolution	0.02	$<10^{-3}$	0.001	0.001	$<10^{-3}$	0.002	0.04	0.02	0.01
background time	0.01	0.001	$<10^{-3}$	0.001	$<10^{-3}$	0.002	0.01	0.02	0.02
background angles	0.02	0.008	0.002	0.008	0.009	0.027	0.06	0.07	0.03
Total	0.11	0.009	0.003	0.009	0.011	0.028	0.13	0.09	0.04

Uncertainties of fit model derived in pseudo-experiment studies

Effect of residual misalignment studied in signal MC

Uncertainty in trigger selection efficiency

Uncertainty in the calibration of the tag probability

Uncertainty in the relative fraction of B_d background

C. Heller, Beauty 2013, 12.04.2013