Prospects for Flavor Physics at ATLAS and CMS

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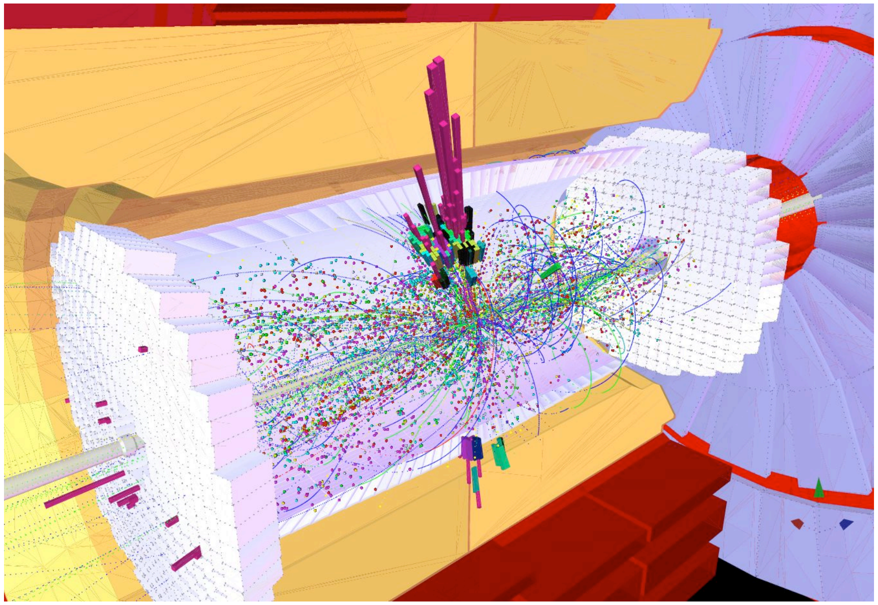
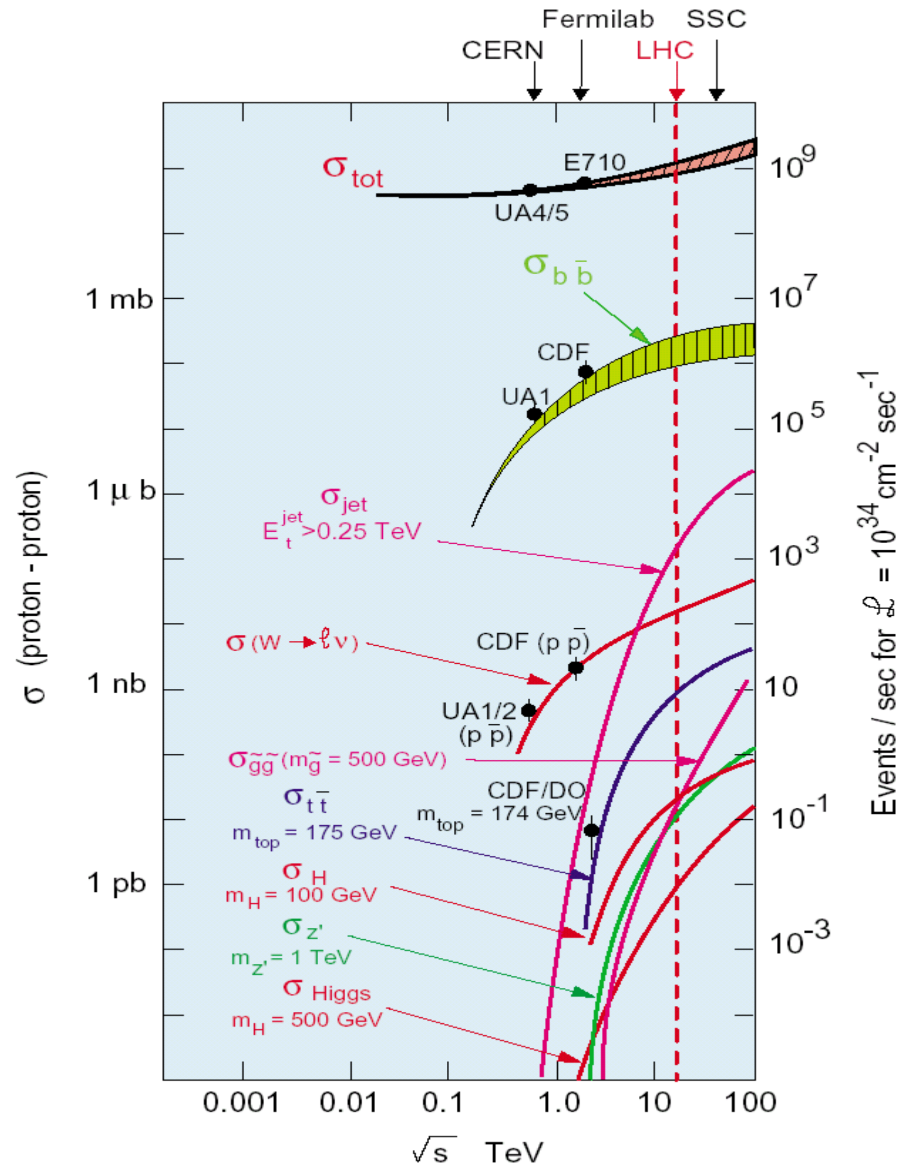


B Physics at ATLAS and CMS

- p-p collisions at $\sqrt{s}$ = 10-14 TeV:
  σ (bb) ≈ 100-400 μb
  10^5 bb pairs /s @ L=10^{33} $cm^{-2}s^{-1}$
  Large statistics allow precision measurements of B hadrons
- LHC ratio $\sigma(bb) / \sigma_{tot}$ is higher compared to earlier accelerators → higher muon rate from B events
- ATLAS / CMS are general purpose detectors, however B physics requirements are taken into account in detector and trigger: good muon coverage and robust muon and di-muon triggers



Wide Range of SM and New Physics

Early data period:

- $\int L < 100\ pb^{-1}$
  - Measurements of J/Ψ, Υ and open b quark production cross section: QCD tests at new energy frontier
  - Early extraction of exclusive decays, like $B^+ \rightarrow J/\Psi\ K^+$, $B_d^0 \rightarrow J/\Psi\ K^{0*}$, $B_s \rightarrow J/\Psi\ \Phi$
  - J/Ψ, Υ and exclusive B channels provide test of detector calibration and monitoring (mass, lifetime, etc)
- $\int L = 200\ pb^{-1} - 1\ fb^{-1}$
  - Improve precision of lifetime measurements
  - Set new limit for $B_s \rightarrow \mu\ \mu$
  - Improve measurements of B_c and Λ_b

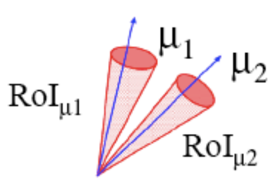
Main data period:

- $\int L > 10\ fb^{-1}$
  - Rare and semi-rare decays: $B_s \rightarrow \mu\ \mu$, $b \rightarrow s(d)\ \mu\ \mu$
  - CP violating B_s mixing phase: $B_s \rightarrow J/\Psi\ \Phi$, $B_s \rightarrow D_s\ \pi(a1)$
  - Λ_b polarization: $\Lambda_b \rightarrow \Lambda\ J/\Psi$
  - Full study of B_c and other heavy flavor hadrons
  - Lepton flavor violating search: $\tau^- \rightarrow \mu^-\ \mu^+\ \mu^-$

B Physics Triggers

ATLAS

- Three levels
- Level 1 hardware trigger (L1) ~2.5 μs
  - Identifies Regions of Interest (RoI)
  - 40 MHz → 100 kHz
- Level 2 software trigger (L2) ~10 ms
  - Muon and inner detectors in L1 RoI
  - 100 kHz → 1 kHz
- Event Filter (EF) ~1 s
  - Refine L2 using offline-like analysis; full event, alignment and calibration
  - 1 kHz → 100 Hz
- B physics triggers
- L1: μ μ with p_T > 4 GeV or μ combined with jet or EM RoI
- L2: topological μ μ trigger; L1 μ plus 2nd μ; hadron triggers
- High luminosity: topological μ μ trigger with increased p_T threshold (6 GeV)



C M S

- Two levels
- Level 1 hardware trigger (L1) ~3.2 μs
  - Muon detectors and calorimeter
  - 40 MHz → 100 kHz
- High level software trigger (HLT) ~1 s
  - Fast local reconstruction similar to offline analysis – all subdetectors
  - 100 kHz → 150 Hz
- B physics triggers
- L1: μ μ with p_T > 3 GeV or μ with p_T > 7 GeV, increasing to 7 and 14 GeV at higher luminosity
- HLT: Exclusive + inclusive B triggers (pixel vertices, track pairs with given mass, partial reconstruction) ~5 Hz
- Displaced μ μ vertex from beam line allows keeping μ μ with p_T > 3 GeV in the HLT

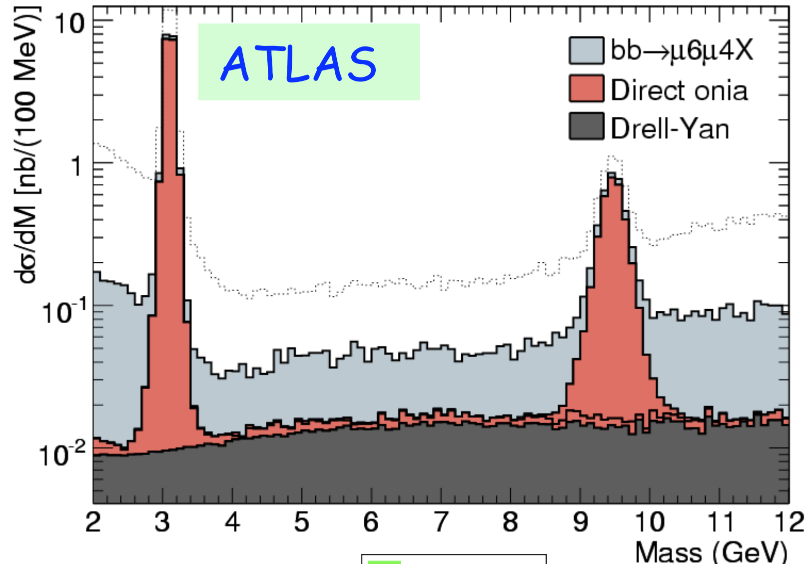
Quarkonia Production

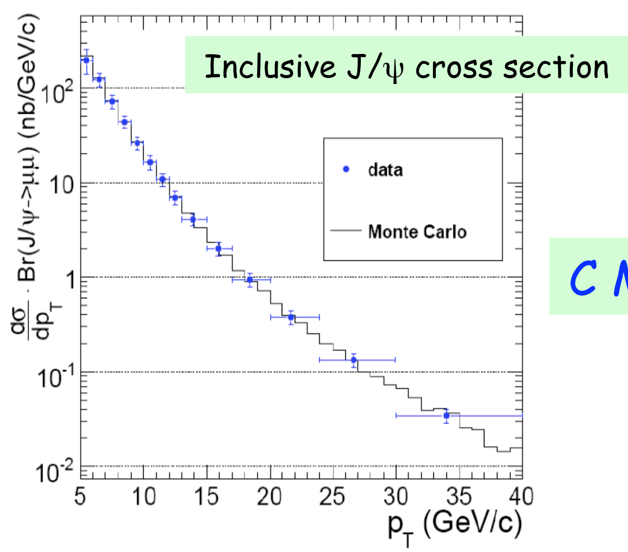
- Among first measurements from early data
- Theoretical interest:
  - Production mechanism
  - polarization
- Clean signature:
  - Calibration
  - Event monitoring

10 pb^{-1}:

S/B = 60 for J/ψ and 10 for Υ

$d\sigma/dp_T$ ~ 1% for J/ψ , ~5% for Υ





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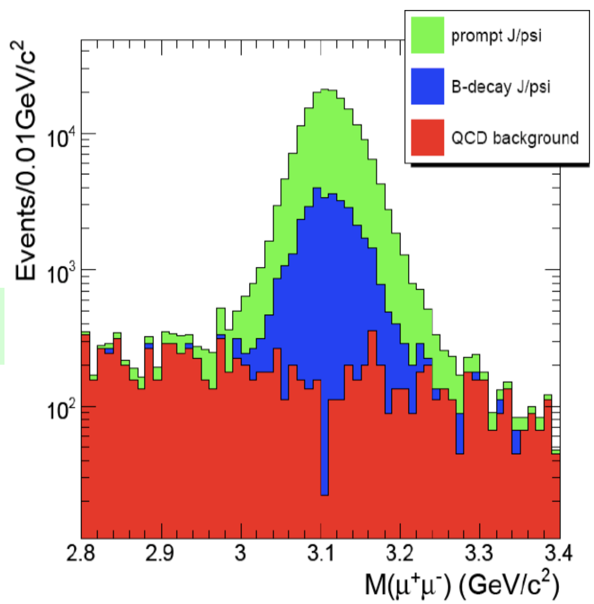
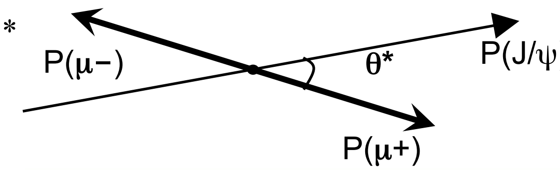
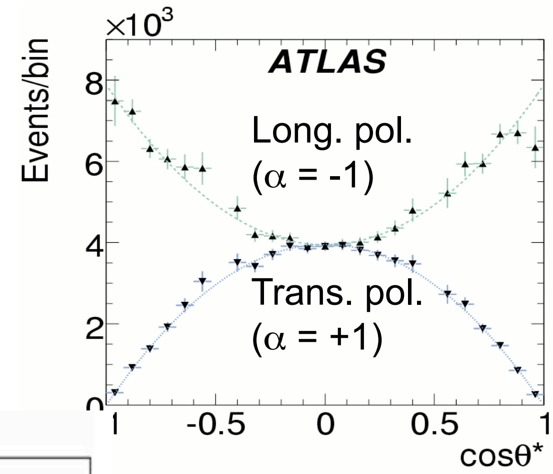


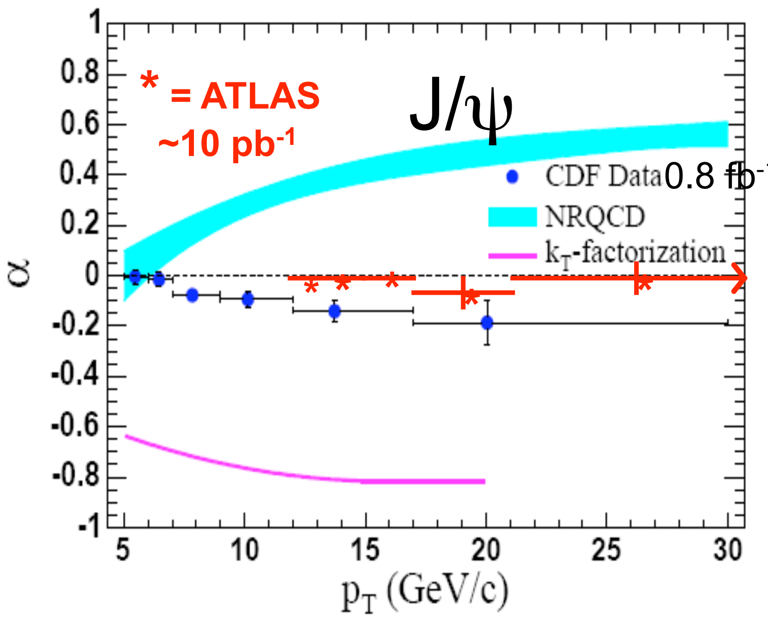
Quarkonia Polarization

- Measure high p_T polarization to distinguish production models
- Use single μ plus > 0.5 GeV track
- 10 pb^{-1}: same precision for J/ψ pol. as Tevatron with ~1 fb^{-1} - but with interesting high p_T data!
- Same precision for Υ polarization can be reached after ~100 pb^{-1}

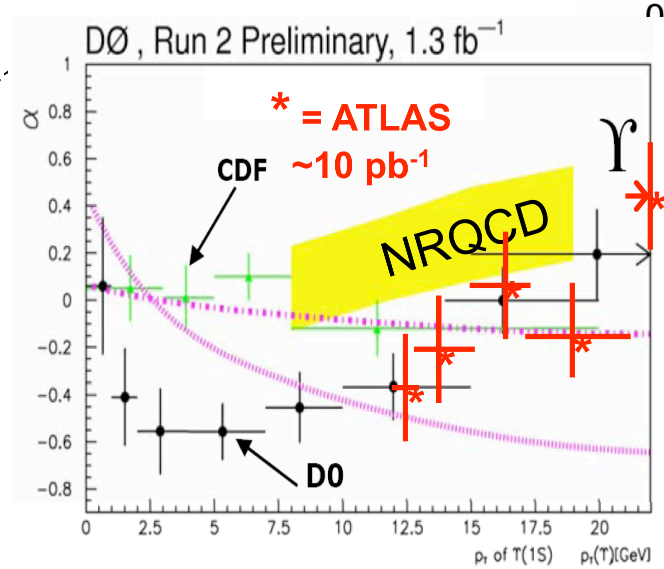
$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha \cos^2\theta^*$$





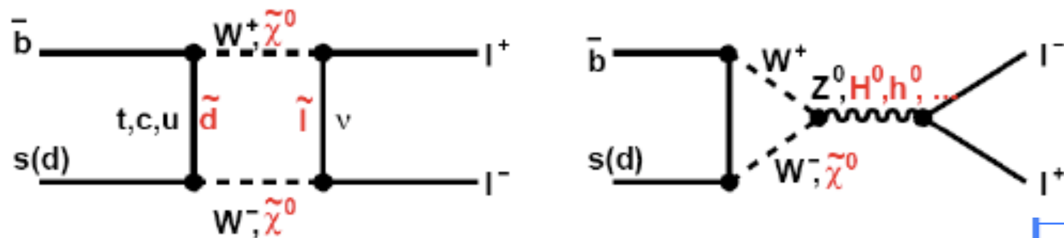


ATLAS assuming α=0



Rare Decay $B_s \to \mu\,\mu$

- $B_s \to \ell^+ \ell^-$ is forbidden at tree level but can proceed through higher order FCNC process

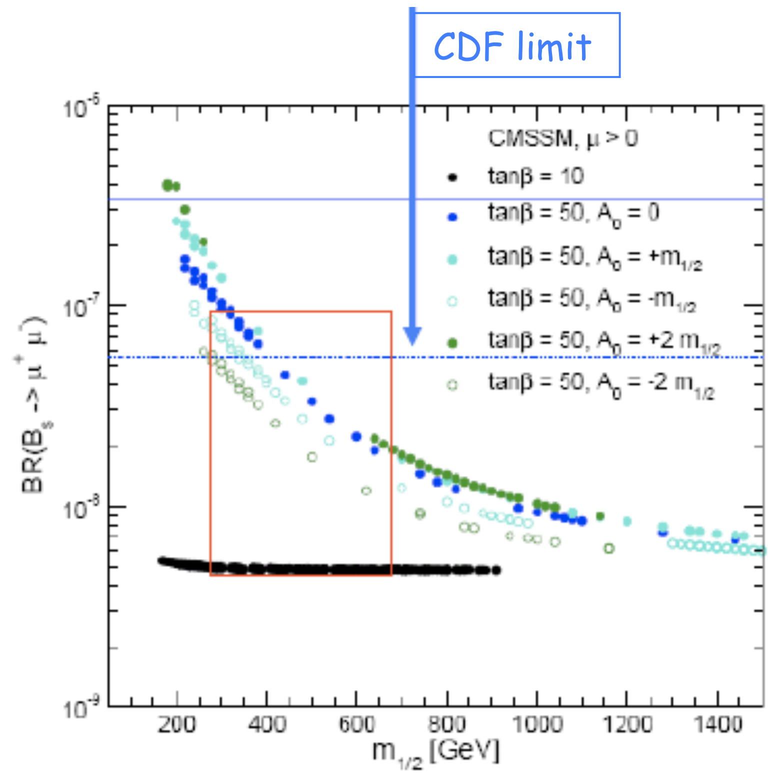


- $BR(B_s \to \mu+\ \mu-) = (3.42 \pm 0.46) \times 10^{-9}$ in SM

- Current 95% CL limits from Tevatron (2 fb^{-1})
  CDF : $58 \times 10^{-9} \sim 17 \times BR_{SM}$
  D0 : $93 \times 10^{-9} \sim 27 \times BR_{SM}$

- SUSY can strongly enhance BR, e.g. $BR(B_s \to \mu^+ \mu^-) \approx$ up to 100×10^{-9} within the constrained MSSM for high tanβ values (J. Ellis et al., hep-ph/0411216)

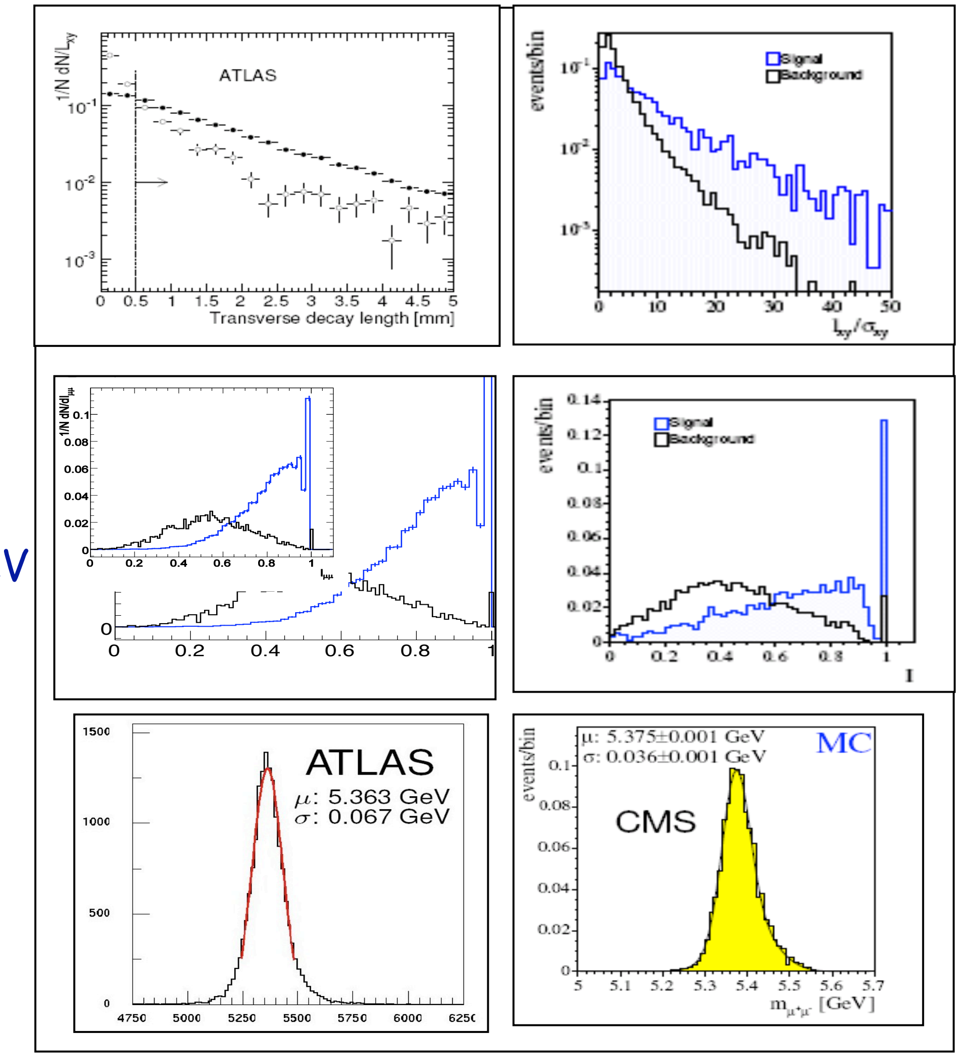
$250 < m_{1/2} < 650$ GeV
$\Rightarrow BR(B_s \to \mu\,\mu) \approx 5 \times 10^{-9} - 10^{-7}$



$B_s \to \mu\,\mu$ Selection

ATLAS & CMS

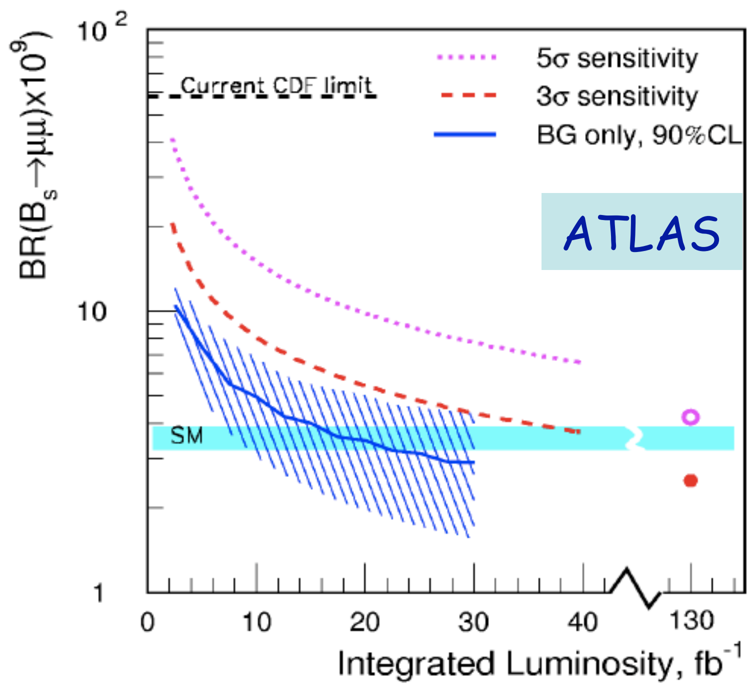
- $\mu\,\mu$ trigger at low and nominal LHC luminosity $10^{34}\ cm^{-2}s^{-1}$
- Background rejection:
- Significance of decay length
  ATLAS $L_{xy}/\sigma_{xy} > 11$, CMS $L_{xy}/\sigma_{xy} > 18$
- Isolation $I_{\mu\mu} = p_T^{\mu\mu}/(p_T^{\mu\mu} + \Sigma\, p_{Ti}(\Delta R))$
  CMS $I_{\mu\mu} > 0.85$, $0.3 < \Delta R < 1.2$, $p_T > 0.9$ GeV
  ATLAS $I_{\mu\mu} > 0.9$, $\Delta R < 1.0$, $p_T > 1$ GeV
- Angle between $p(\mu\,\mu)$ and direction to PV
  ATLAS < 1^o, CMS < 5.7^o
- Mass window around $m(B_s)$
  ATLAS (-70, 140) MeV
  CMS ± 100 MeV



$B_s \to \mu\,\mu$ Results

Statistics after cuts with 10 fb^{-1}	BR	ATLAS	CMS
Signal $B_s \to \mu\mu$	$3.4 \cdot 10^{-9}$	5.7 ± 2.0	6.1 ± 2.1
$bb \to \mu\mu X$	$2 \cdot 10^{-2}$	14 + 13 -10	14 +22 -14
Evts with fake muons			
$B_s \to K^+K^-$	$2 \cdot 10^{-5}$	0.015	<0.3
$B_s \to K^- \mu^+ \nu_\mu$	$\sim 10^{-4}$	negligible	negligible
Rare backgrounds			
$B_c \to J/\psi\ (\mu^+\mu^-)\ell^+\nu_\ell$	$< 10^{-4}$	negligible	negligible
$B^+ \to \mu^+\mu^-\ell^+\nu_\ell$	$< 5 \cdot 10^{-6}$	"	"
$B^0_d \to \pi^0 \mu^+\mu^-$	$\sim 2 \cdot 10^{-8}$	"	"
$B^0_s \to \mu^+ \mu^- \gamma$	$\sim 2 \cdot 10^{-8}$	"	"

signal cross section is translated to BR by the reference process $B^+ \to J/\Psi\ K^+$



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

- 2 fb^{-1} BR ≤ 2×10^{-8}
- 30 fb^{-1} ≈ SM prediction region
- 3σ evidence after 3 years @ 10^{33}
- 5σ observation after 1 year @ 10^{34}

Weak Phase of B_s Mixing

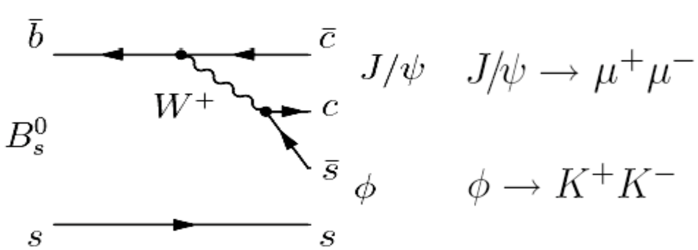
- Important CPV measurement at LHC

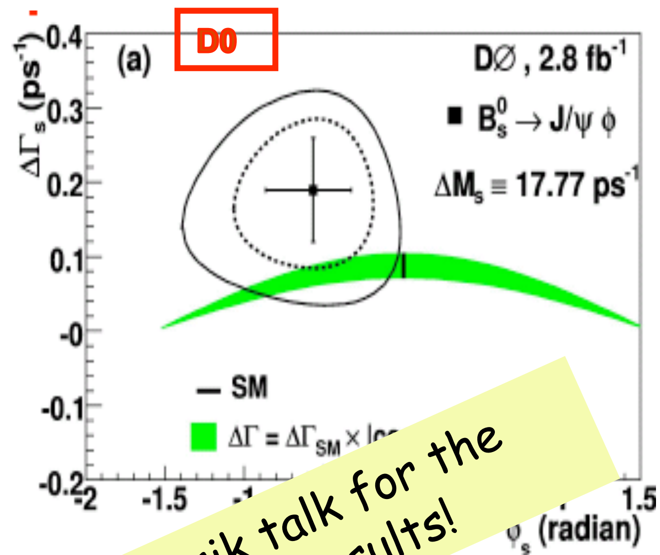
- Weak phase of B_s mixing is precisely predicted within SM
  $\phi_s^{SM} = -\arg(V_{ts}2) = -2\lambda 2\eta = -0.0368 \pm 0.0018$

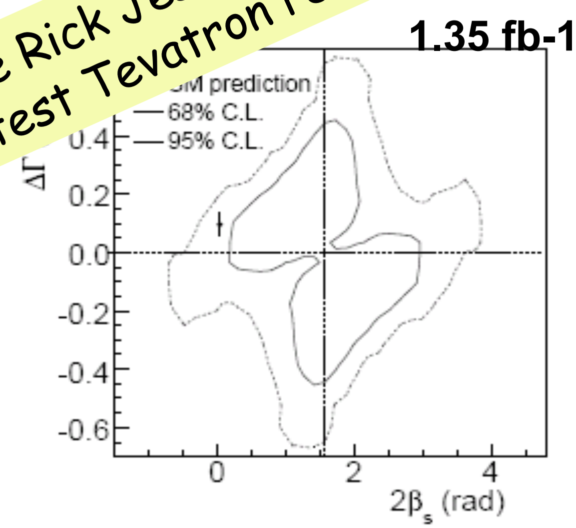
- ϕ_s sensitive to New Physics, e.g. Little Higgs model with T-parity predicts larger ϕ_s

- CDF and D0 bounds on $\Delta\Gamma_s - \phi_s$
  Conclusion: assuming SM values $\Delta\Gamma_s = 0.096$ ps^{-1} and $\phi_s = -0.04$, probability of deviation as large as the observed data is 15% (CDF) and 6.6% (D0)

- Experimentally most feasible channel is:
  $B_s \to J/\Psi\ (\mu\mu)\ \Phi\ (K\ K)$







See Rick Jesik talk for the latest Tevatron results!

ϕ_s Results

$B_s \rightarrow J/\Psi(\mu\ \mu)\ \Phi(K\ K)$

Experimental advantage:
- Good trigger and BG suppression
- 3 angles, proper time, flavour tag
- Indep. determination of uncertainties

Large statistics allow multivariable analysis:
- Likelihood fit for 5 parameters (ϕ_s, Γ_s, $\Delta\Gamma_s$, $A_\perp$, $A_{||}$) while δ_1, δ_2 constrained from $B_d \rightarrow J/\psi\ K^*$ and Δm_s from $B_s \rightarrow D_s \pi$

- Uncertainty $\delta\phi_s \approx 0.07$ for each experiment -- new physics?!

	ATLAS	CMS
Luminosity	**30 fb-1**	
Statistics	240000	260000
Background	30%	33%
	Dominated by $B_d \rightarrow J/\psi\ K^*$ $B_d \rightarrow J/\psi\ K^+\pi^-$	
Time resol	83 fs	77 fs
Mass resol	16.6 MeV	14 MeV
Flav tagging	μ, e, Qjet	μ, e, Qjet
ϕ_s	Similar	0.068
$\Delta\Gamma s$	results	12%
Γs	for	0.9%
$A_\parallel$	ATLAS	0.8%
$A_\perp$		2.7%
Δm_s (ps-1)	17.77 +- 0.12	
$\delta 1 \delta 2$	Fixed from $B_d \rightarrow J/\psi\ K^*$	

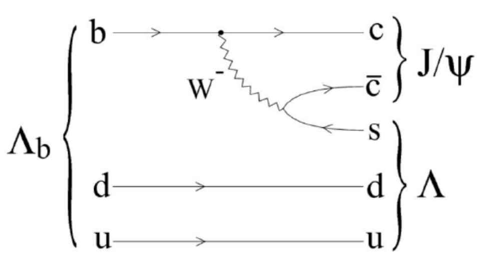
Λ_b Polarization

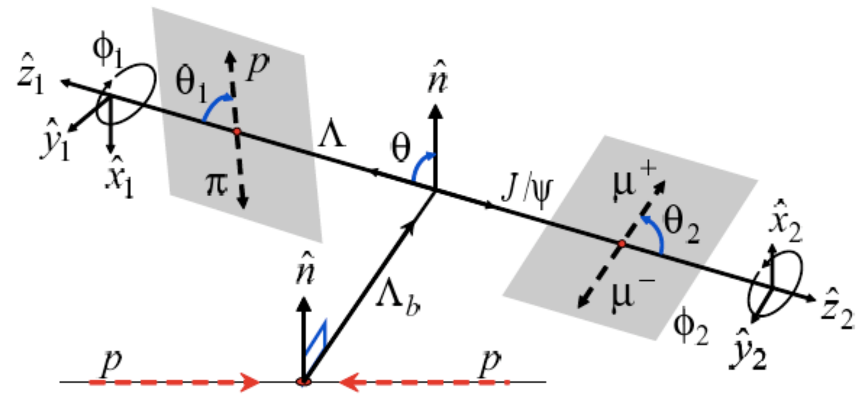
Motivation:
Parity violating $\alpha_{\Lambda b}$ parameter provides test of heavy quark factorization models and pQCD

Hyperons display large polarization even at large p_T but most models predict zero polarization – new physics!

Λ_b polarization $\boldsymbol{P}$ and $\alpha_{\Lambda b}$ from

$\Lambda_b \rightarrow J/\Psi(\mu\mu)\ \Lambda(p\ \pi)$





Five angles θ, θ_1, θ_2, ϕ_1, ϕ_2
Full decay angular distribution:

$$w(\vec{\theta},\vec{A},P) = \frac{1}{(4\pi)^3}\sum_{i=0}^{i=19} f_{1i}(\vec{A})\ f_{2i}(P,\alpha_\Lambda)\ F_i(\vec{\theta})$$

Helicity amplitudes *a+*, *a-*, *b+*, *b-*

$$\alpha_{\Lambda_b} = \frac{|a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2}{|a_+|^2 + |a_-|^2 + |b_+|^2 + |b_-|^2}.$$

7 unknown parameters: $\alpha_b, P_b, |a_+|^2 + |a_-|^2, |a_+|^2 - |a_-|^2, \alpha_+ - \beta_-, \alpha_- - \beta_-, \beta_+ - \beta_-$

Λ_b Polarization Results

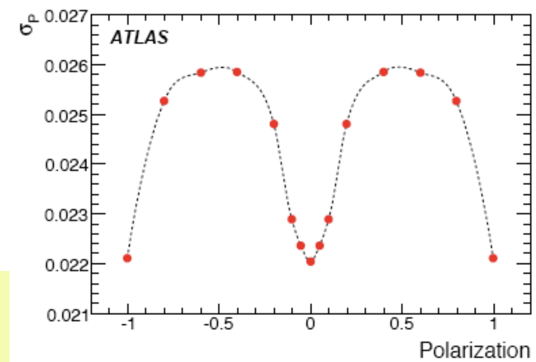
ATLAS

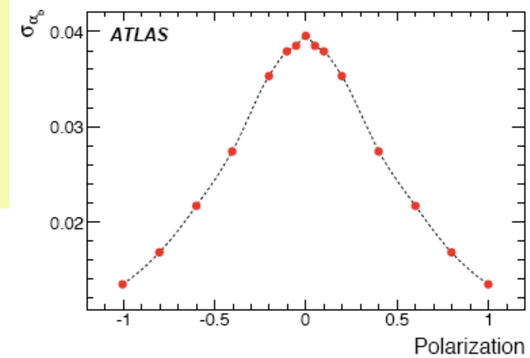
level−1 trigger: with p_T threshold	one muon		two muons	
	4 GeV	6 GeV	4GeV	6GeV
level−2 trigger:	TrigDiMuon		Topological trigger	
J/ψ reconstruction efficiency including level-1 and level-2 triggers	42%	39%	27.5%	10%
Λ reconstruction efficiency	15%			
Λ_b overall efficiency	6.1%	5.9%	5.4%	3.5%

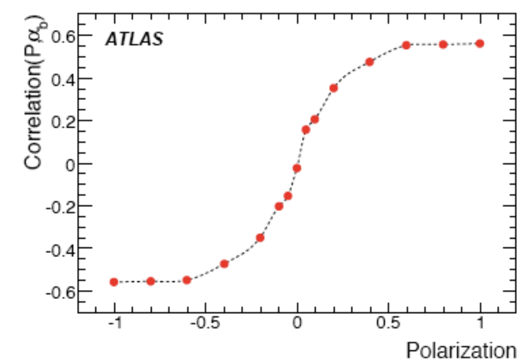
30 fb^{-1}:~13500 events

Expected errors →

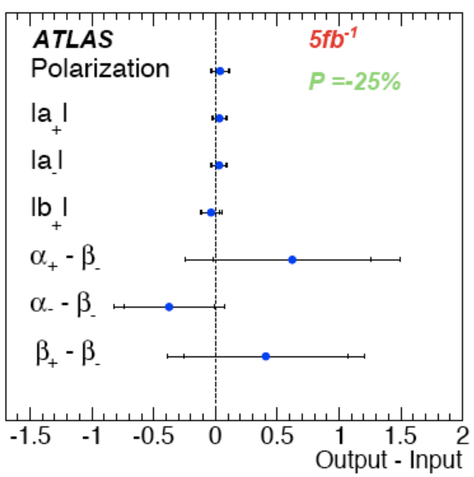
Can measure $\alpha_{\Lambda b}$ even for $P = 0$

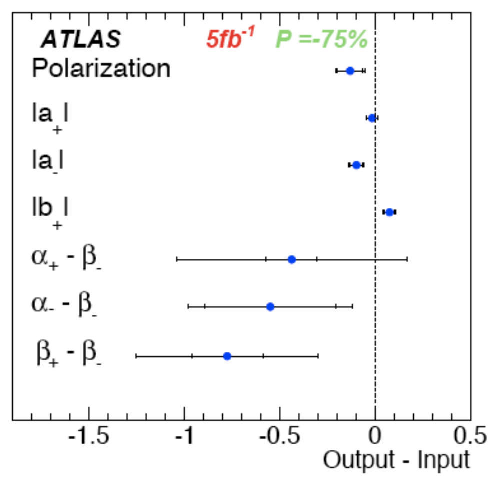






Fit results for 5 fb^{-1}:





Lepton Flavor Violation in $\tau \rightarrow 3\,\mu$

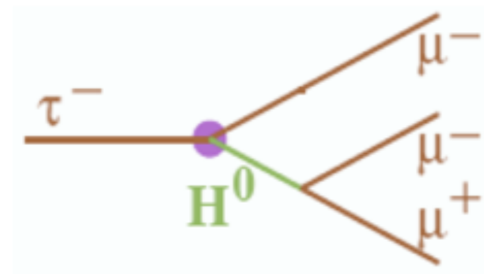
SM with massive neutrinos allows lepton flavor violation but small neutrino masses keep rate too low for observation < 10^{-30}

Many SM extensions allow greater LFV and a much larger $BR(\tau \rightarrow 3\,\mu)$; generally BR ~ $10^{-(7-10)}$

Current limits:

BR < 3.2 10^{-8} @ 90% C.L. from Belle

BR < 5.3 10^{-8} @ 90% C.L. from BaBar



Total τ cross section ~ 120μb ➔ $10^{11}\,\tau\,/fb^{-1}$

Sources of τ leptons:

Decay	N_τ / 10 fb^{-1}
$W \rightarrow \tau\,\nu_\tau$	1.7×10^{8}
$Z \rightarrow \tau\,\tau$	3.2×10^{7}
$B^0 \rightarrow \tau\,X$	4.0×10^{11}
$B^\pm \rightarrow \tau\,X$	3.8×10^{11}
$B_s \rightarrow \tau\,X$	7.9×10^{10}
$D_s \rightarrow \tau\,X$	1.5×10^{12}

Most τ leptons are from b and c quarks

Clean experimental signature suitable triggers

LFV in $\tau \rightarrow 3\,\mu$

CMS

Present analysis: $\tau \rightarrow 3\,\mu$ from W decays

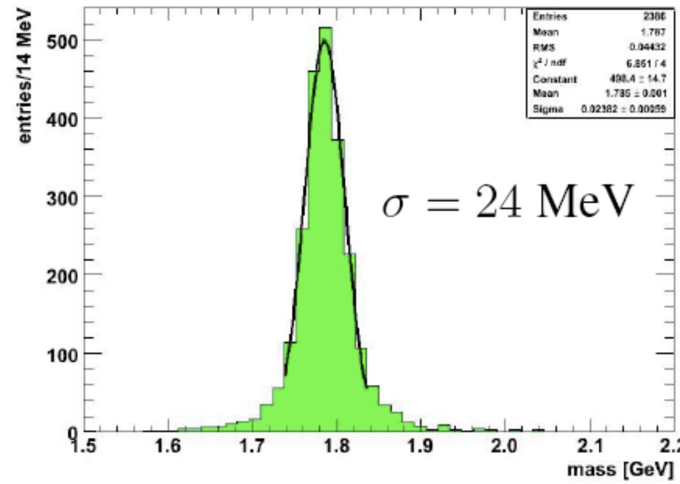
HLT: 2 μ with $p_T > 7$ GeV or 1 μ with $p_T > 19$ GeV

3 muons with $m(3\mu)-m(\tau) < 25$ MeV

Largest background from $D_s \rightarrow \mu\,\nu\,\phi(\mu\mu)$
Veto the ϕ mass region for any $\mu\mu$ pair

Calculated sensitivity:

BR < 7.0 (3.8) × 10^{-8} @ 95% C.L.
with 10 (30) fb^{-1}



$\tau \rightarrow 3\,\mu$ mass

Summary

ATLAS and CMS are well suited to do heavy flavor physics thanks to

- Outstanding tracking systems allow for precise reconstruction of tracks and measurements of vertices
- Excellent muon systems allow for triggering and reconstruction of dimuon final states

Wide array of heavy flavor physics is possible including new physics searches, rare decay searches, and precise mass and lifetime measurements, a few examples

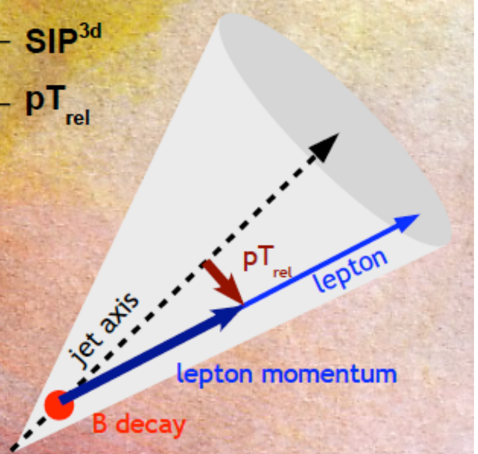
- Heavy quark and onium production measurements provide excellent tests of QCD at the new energy with early data ($<10^{33}$)
- For $B_s \to \mu\mu$: 3σ evidence in 3 years @10^{33}, reach 5σ observation after 1 year at nominal LHC luminosity (10^{34})
- CPV in $B_s \to J/\psi(\mu\mu)\ \phi(KK)$ in 3 years @10^{33} ➔ $\delta(\phi_s) \approx 0.07$ – could prove new physics if large ϕ_s
- With 30 fb^{-1} achieve sensitivity to measure Λ_b polarization $\boldsymbol{P}$ and decay asymmetry $\alpha_{\Lambda b}$ with a few percent uncertainty

See ATLAS and CMS B physics web pages for more…

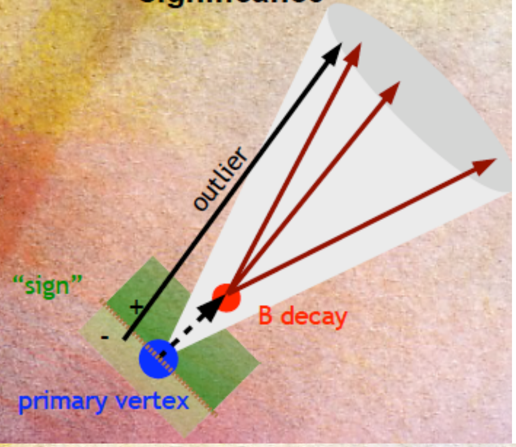
Backup Slides

b tagging algorithms

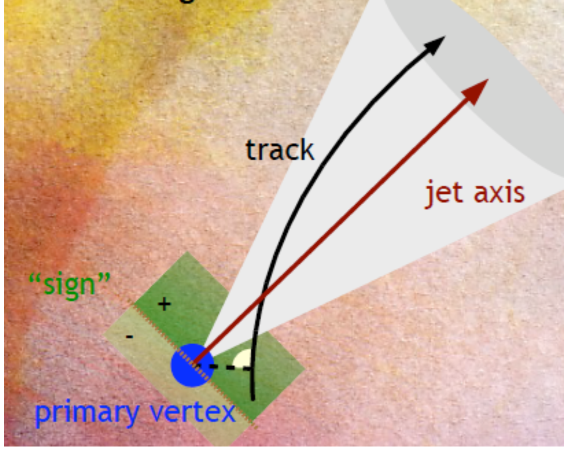
- "soft" muons and electrons in jets
  - SIP^{3d}
  - pT_{rel}



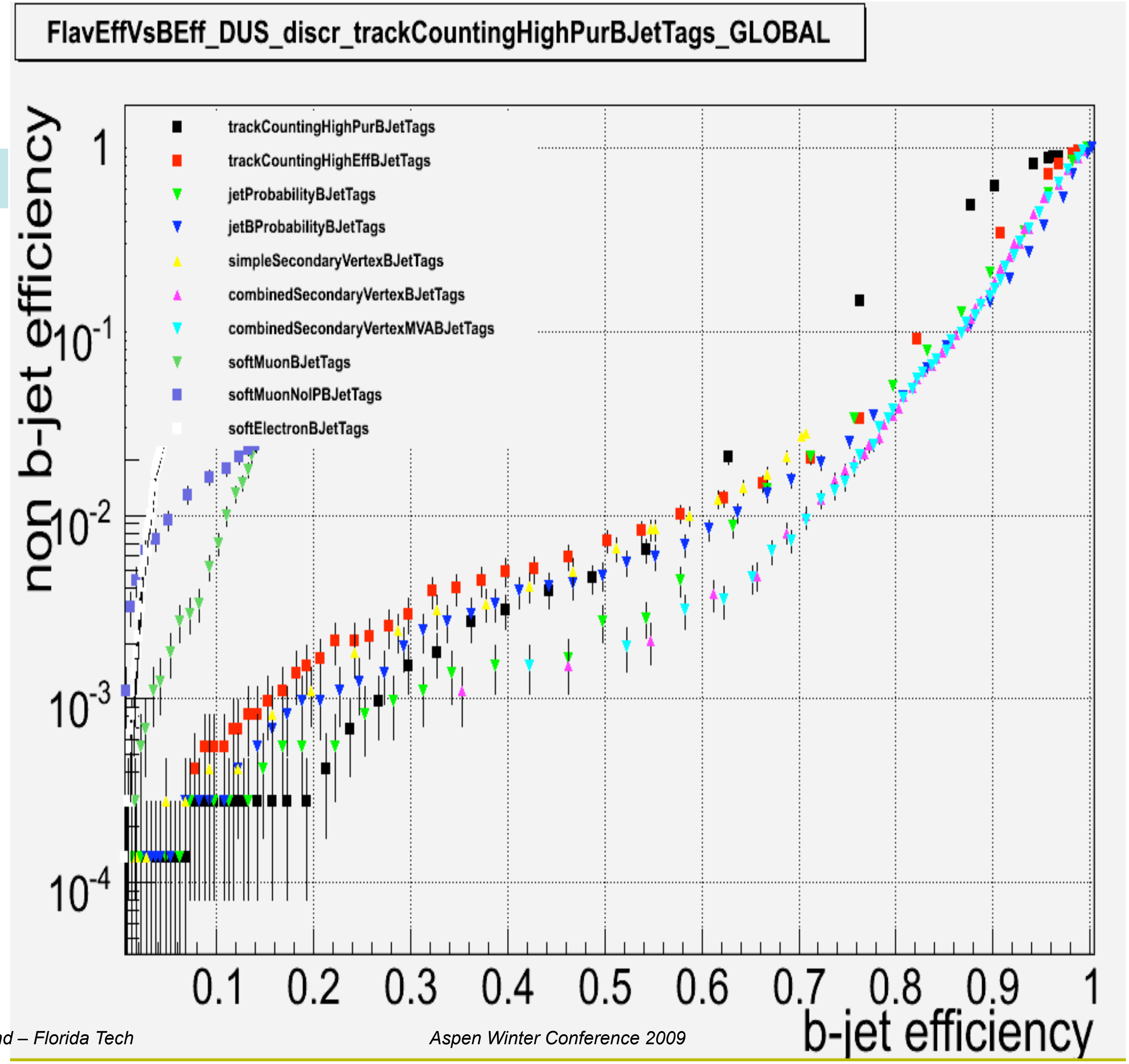
- Secondary Vertex
  - Signed, 3d, flight distance significance



- Signed Impact Parameter
  - Significance



- All algorithms have...
  - a "simple" version which require no calibrations
    - The discriminator is the presence of a reconstructed object plus a single observable
    - Suitable for startup (allowing for misalignment)
  - a "complex" version which requires calibrations or training
    - Combine many observables with an MVA tool (Likelihood, NN)
    - Require calibrations (on real data)
    - Not suitable for startup
  - a "negative tagger" version (simple and/or complex)
    - Expect light jets to have symmetric distribution
      - Impact parameter, flight distance
    - Can be used to model non-b jets background for calibration on data
    - See tomorrow's talk by Jeremy
  - been studied in the STARTUP, misaligned scenario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simpleSecondaryVertexBJetTags
combinedSecondaryVertexBJetTags
combinedSecondaryVertexMVABJetTags
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C M S

b acceptance

- ATLAS/CMS
  - $|\eta| < 2.5/2.4$
    - Tracker/muon detector acceptance
  - high-P_t muon trigger
  - b-tagged jet trigger
    - Muon+b-Jet trigger
- LHCb
  - Forward spectrometer
    - $1.9 < \eta < 4.9$
  - much softer p_t triggers