Search for rare B decays in ATLAS

Alessandro Cerri, CERN

Search..? Or Search..!

- LHCb and CMS have already produced public results on rare B decays
- Why not ATLAS?
- A few silly rumors:
  - No adequate trigger
  - Poor invariant mass resolution makes it impossible
  - Please let me know if there's any other floating around!
- My hope was to bring here today the first public result, and, well… delays happen…
- I want however to tickle your interest on certain aspects of this analysis which might be overlooked, borrowing examples from our projections and other experiments

Not quite!

- What will I discuss today?
  - Overview of the analysis as described in publicly approved results
  - Rumors and reality: a few reasons why indeed we know that this analysis is viable with ATLAS (and actually well under way)
  - Experiment, theory and phenomenology: a few aspects of this kind of analysis that you should keep in mind when listening to experimentalists

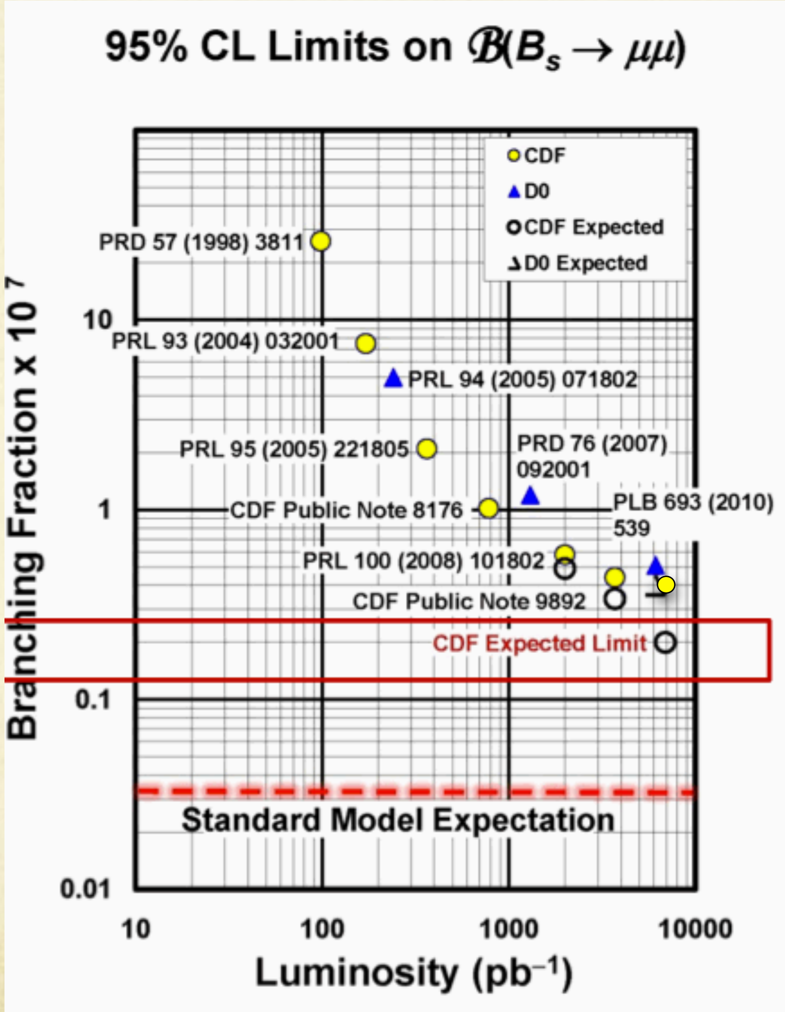
Part I

How you shall we read results on the subject

Let's begin from (other's) results

- Much ado about nothing, or… noting?
  - Filled vs empty symbols: increasing discrepancy of predicted vs measured
  - Possible reasons:
    1. Approaching signal sensitivity
    2. Systematics (e.g. under estimation of the background)

- Let's go with 1, did you consider:
  1. Are experimental points for the same symbol independent?
  2. What is the difference between filled and empty going to do vs luminosity?
  3. What is the relationship between these experimental points and measurements of a BR?



Introduction

Imagine you have observed a signal and want to measure BR of $B_s \rightarrow \mu\mu$:

$$BR(B_s \to \mu\mu) = \frac{N_{B_s \to \mu\mu}}{\alpha_{B_s \to \mu\mu} \varepsilon^{tot}_{B_s \to \mu\mu}} \cdot \frac{\alpha_{reference} \varepsilon^{tot}_{reference}}{N_{reference}} \cdot \boxed{\frac{f_{reference}}{f_s} \cdot BR(reference)}$$

PDG For $J/\psi K^+$: 1.69±13%

- Measure a relative BR to factor out uncertainties:
  - Luminosity
  - Production mechanisms
  - Selection, reconstruction, analysis efficiencies and acceptances

This analysis is mostly about extracting relative efficiencies and acceptances, as well as the technique used to derive N_{Bs}

Single Event Sensitivity

$$BR(B_s \to \mu\mu) = \frac{N_{B_s \to \mu\mu}}{\alpha_{B_s \to \mu\mu}\varepsilon^{tot}_{B_s \to \mu\mu}} \cdot \frac{\alpha_{reference}\varepsilon^{tot}_{reference}}{N_{reference}} \cdot \frac{f_{reference}}{f_s} \cdot BR(reference) =$$

$$N_{B_s \to \mu\mu} \left[\frac{1}{\alpha_{B_s \to \mu\mu}\varepsilon^{tot}_{B_s \to \mu\mu}} \cdot \frac{\alpha_{reference}\varepsilon^{tot}_{reference}}{N_{reference}} \cdot \frac{f_{reference}}{f_s} \cdot BR(reference) \right]$$

- Scale factor “translating” upper-limit on N_{Bs} to upper-limit on BR
- Very useful to gauge the reach of an experiment however:
  - Not accounting for uncertainties on relative efficiencies, PDG numbers
  - The same experiment can behave extremely well or extremely bad depending on the average expected Nobs, i.e. with large/small background!

Back to the real world!

- Main uncertainty actually comes $N_{Bs\rightarrow\mu\mu}$ which is extracted with some variation of counting events in a tiny S/B environment:
  - (Nobs,Nbck)➔Nsig
  - Statistically delicate procedure
  - Upper limit estimation vs measurement: in most approaches two different things!

- The remainder (B^+ yield, relative efficiencies and acceptances, PDG inputs) can have rather generous uncertainties (10-20%) with marginal effect on the limit

N_{obs} to N_{sig}, big deal?

- Short answer:
  - Unambiguous if you can tell there's a signal by eye
  - Often ambiguous otherwise
- How, why? Well known issues with certain low event count approaches:
  - More background for the same N_{obs} ➔ more stringent limit on signal
  - Non-physical limits and/or measurements (e.g. infer negative N_{sig})
  - Flip-flopping (choice btw limit and measurement based on data)

A few numerical examples

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ Γ_{38}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.2 \times 10^{-8}$	90	[115] ABAZOV	10S	D0	$p\bar{p}$ at 1.96 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.7 \times 10^{-8}$	90	[115] AALTONEN	08I	CDF	$p\bar{p}$ at 1.96 TeV
$<9.4 \times 10^{-8}$	90	[116] ABAZOV	07Q	D0	$p\bar{p}$ at 1.96 TeV
$<4.1 \times 10^{-7}$	90	[117] ABAZOV	05E	D0	$p\bar{p}$ at 1.96 TeV
$<1.5 \times 10^{-7}$	90	[118] ABULENCIA	05	CDF	$p\bar{p}$ at 1.96 TeV
$<5.8 \times 10^{-7}$	90	[119] ACOSTA	04D	CDF	
$<2.0 \times 10^{-6}$	90	[120] ABE	98	CDF	
$<3.8 \times 10^{-5}$	90	[121] ACCIARRI	97B	L3	
$<8.4 \times 10^{-6}$	90	[122] ABE	96L	CDF	

Nobs	Nback	Nsig
4 [5,16,...]	4 [...]	CDF 2011
1079	1091±25	ABAZOV 10S
0 [4,11]	0.7±0.1 [3.7,10.3]	AALTONEN 08I
2	1.24±1	ABAZOV 07Q
4	3.7±1.1	ABAZOV 05E
0	0.81±0.12	ABULENCIA 05
1	1.1±0.3	ACOSTA 04D
1	2.6	ACCIARRI 97B
1	0	ABE 96L

How important?

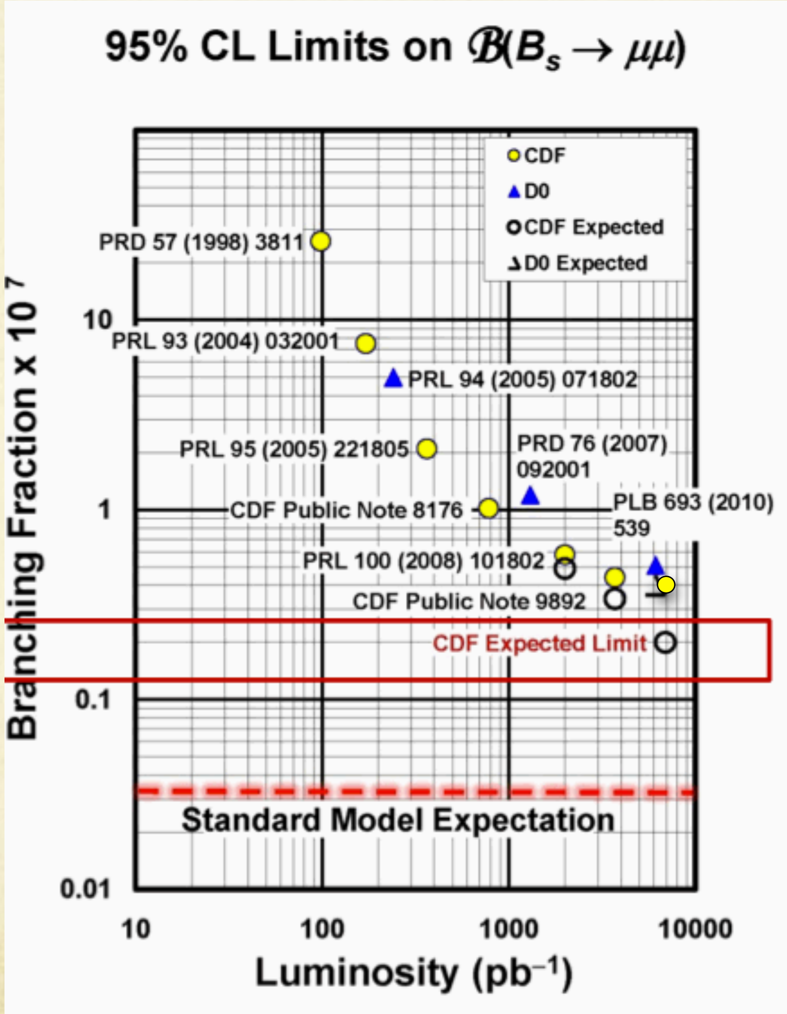
A numerical toy exercise (N_{obs},N_{bck})➔Upper Limit on N_{sig}:

(0,3)➔2.3	(3,3)➔4.37	(3,0)➔6.68
(0,3)➔-XXX	(3,3)➔3.68	(3,0)➔6.68
(0,3)➔2.3	(3,3)➔5.49	(3,0)➔6.68
(0,3)➔1.08	(3,3)➔4.42	(3,0)➔6.74

- The statistical method we use to derive the answer in a low-statistics experiment MATTERS A LOT
- Comparing and combining makes sense if the same common approach is used
- For large statistics, all this is irrelevant (i.e.: when you see a peak, it's a peak, no matter how you measure it!!!)

Let's read those results, again:

- Circles and triangles: not the same language
- In fact, even circles with circles and triangles with triangles speak different languages, rather consistent though
- I was careful in highlightig discrepancies c-c or t-t in the same paper exactly for this reason!



What about those numerical examples?

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ Γ_{38}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.2 \times 10^{-8}$	90	[115] ABAZOV	10S	D0	$p\overline{p}$ at 1.96 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.7 \times 10^{-8}$	90	[115] AALTONEN	08I	CDF	$p\overline{p}$ at 1.96 TeV
$<9.4 \times 10^{-8}$	90	[116] ABAZOV	07Q	D0	$p\overline{p}$ at 1.96 TeV
$<4.1 \times 10^{-7}$	90	[117] ABAZOV	05E	D0	$p\overline{p}$ at 1.96 TeV
$<1.5 \times 10^{-7}$	90	[118] ABULENCIA	05	CDF	$p\overline{p}$ at 1.96 TeV
$<5.8 \times 10^{-7}$	90	[119] ACOSTA	04D	CDF	
$<2.0 \times 10^{-6}$	90	[120] ABE	98	CDF	
$<3.8 \times 10^{-5}$	90	[121] ACCIARRI	97B	L3	
$<8.4 \times 10^{-6}$	90	[122] ABE	96L	CDF	

Nobs	Nback	Nsig
4 [5,16,...]	4 [...]	CDF 2011
1079	1091±25	ABAZOV 10S
0 [4,11]	0.7±0.1 [3.7,10.3]	AALTONEN 08I
2	1.24±1	ABAZOV 07Q
4	3.7±1.1	ABAZOV 05E
0	0.81±0.12	ABULENCIA 05
1	1.1±0.3	ACOSTA 04D
1	2.6	ACCIARRI 97B
1	0	ABE 96L

Thousands!

Few!

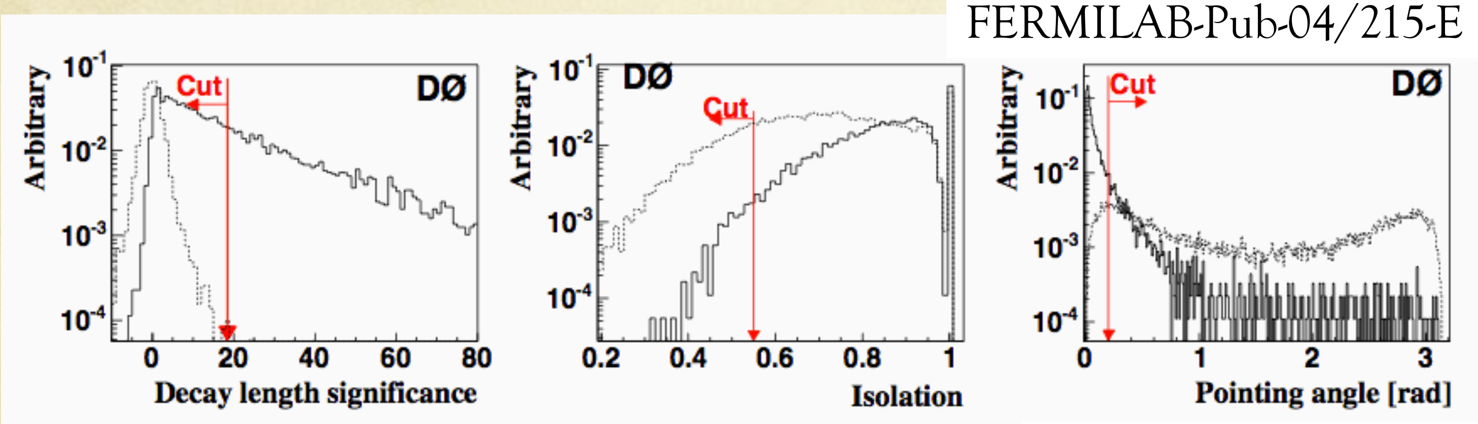
And then... what's in the square brackets?

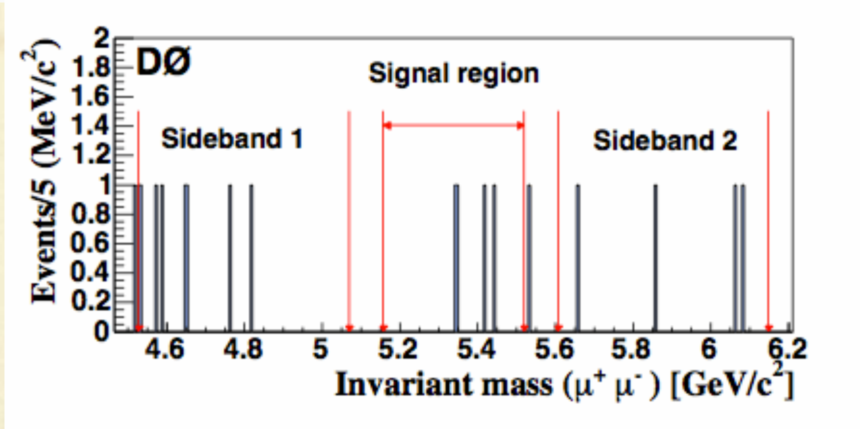
Different analysis approaches

- Pure "cut and count":
  - N variables, optimize in an N-dim space
  - Cut and count surviving events
- MVA "cut and count":
  - N variables ➔ 1 classifier (NN, BDT, XYZ)
  - Optimize cut
  - Count surviving events
- MVA "binned cut and count":
  - N variables ➔ 1 classifier
  - Optimize cuts
  - Count surviving events in each bin (1D, 2D)
- MVA fit:
  - N variables ➔ 1 classifier
  - Fit classifier distribution i.e. compare against S+B and B likelihood

Pure cut and count

FERMILAB-Pub-04/215-E



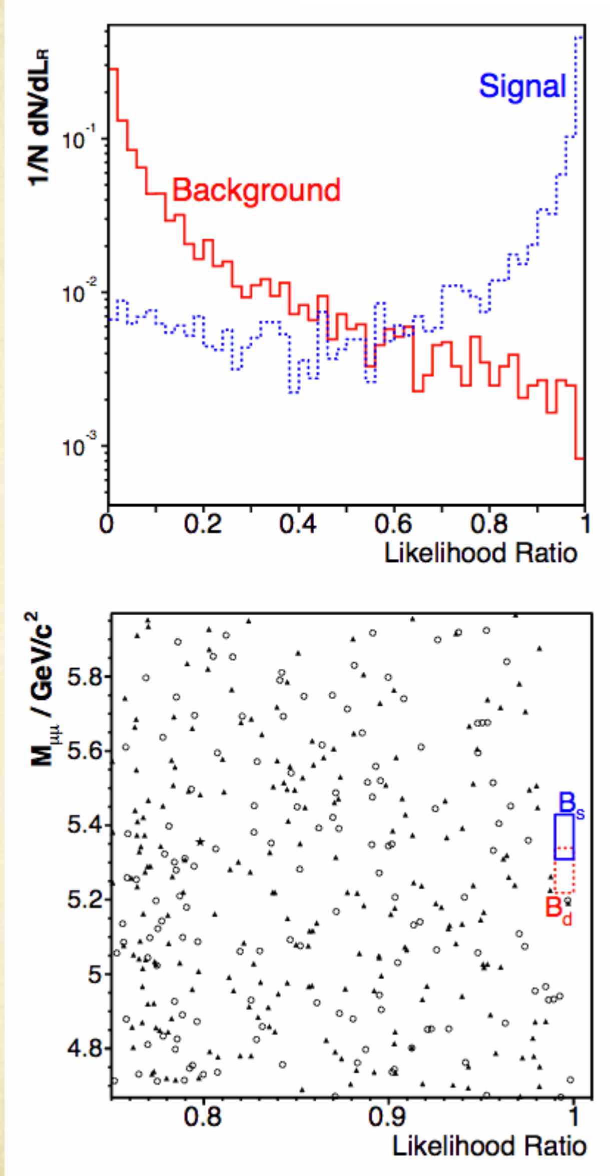


- Clear, straightforward, physically meaningful cuts
- Limited sensitivity (no use whatsoever of shapes)
- Robustness to systematics

MVA cut and count

PRL 95 221805

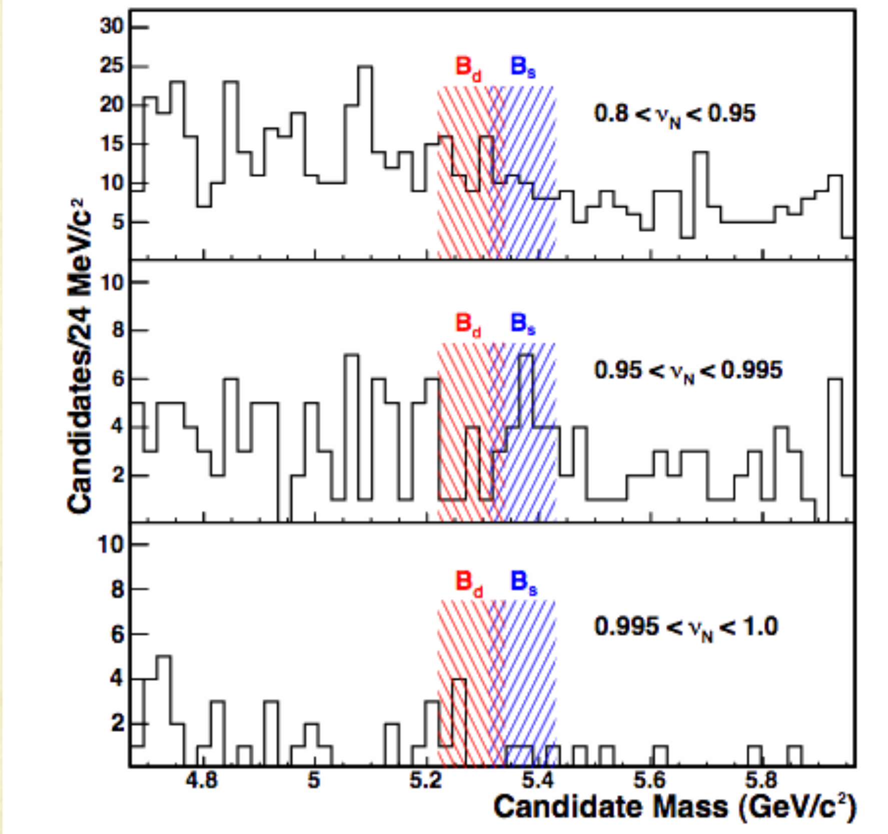
- Build a combined variable "q" that discriminates S and B
- Optimize cut in (m,q)
- Count!
- Improved sensitivity:
  - Even with same variables, correlations can be better exploited
  - Can use more variables
- Robustness:
  - Two sharp cuts on well defined variables



MVA Binned cut & count

- Again a combined classifier…
- Exploit not only the "q" bin with highest expected S/B, but also "some" below
- Exploit more variables
- Exploit more of the data to extract information
- How many bins?
  - More: increase use of information but also sensitivity to systematics
  - Less: more robust, less powerful

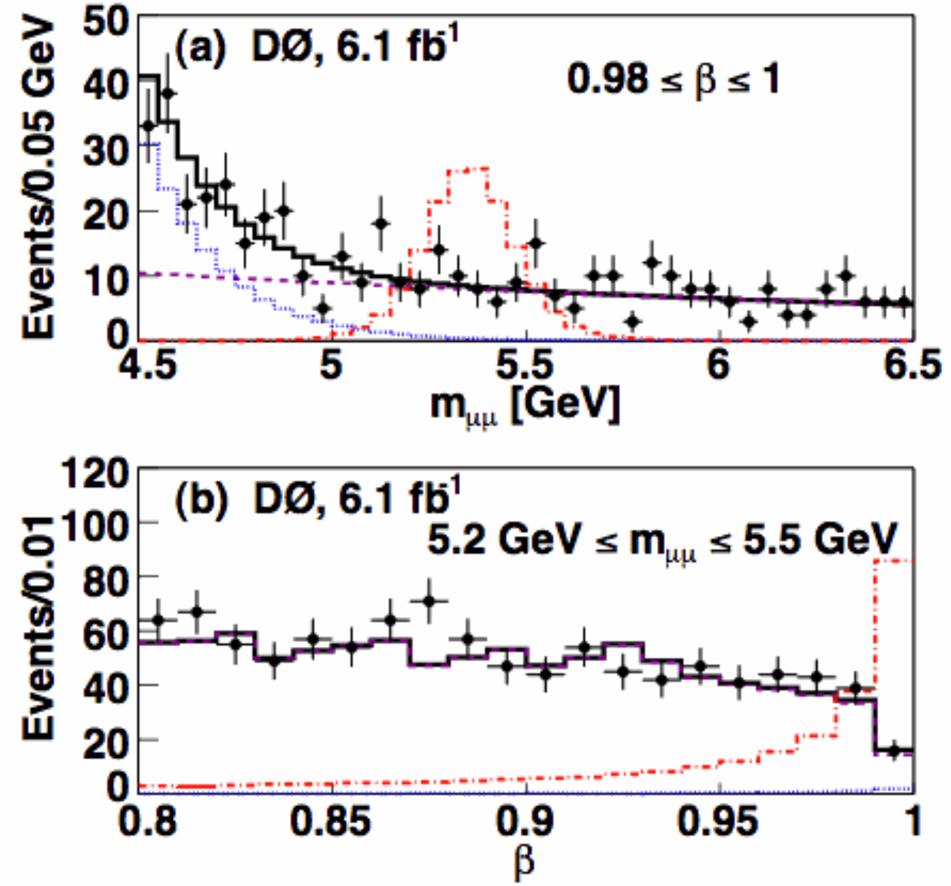
PRL 100 101802



MVA "Fit"

- Maximal use of information contained in the events (except, in this example, for the binning)
- Maximal sensitivity also to systematics!
- Do you realize why the title says "Fit" rather than Fit?

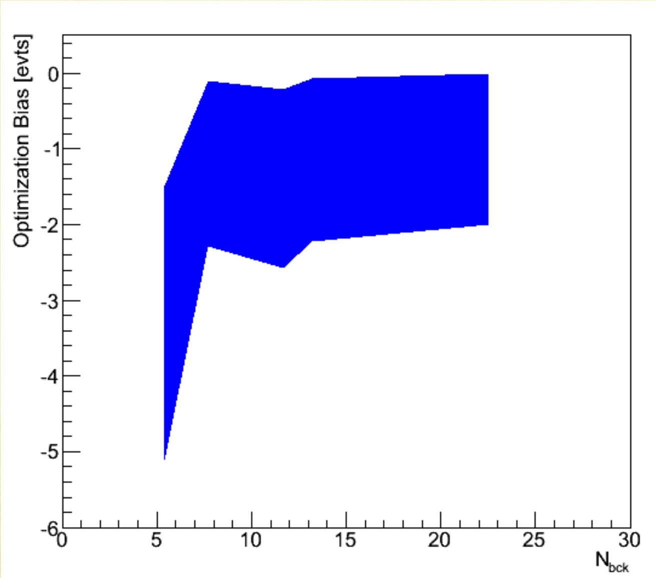
FERMILAB-PUB-10-202-E



Cut optimization/classifier tuning

At the cost of being pedantic:

- Two independent background samples are needed!
  - Cut optimization and/or classifier tuning
  - Background extrapolation (extraction of N_{bck})
- If same sample used for both then you can (and will) get a bias!



A simple toy experiment:
•Generate N_{bck} events with Poisson distribution
•Optimize selection on sidebands
•Measure (y axis) bias on Nbck after optimized cut

The bias is sizeable especially for low event counts!

Conclusions I

- As long as we wander in the dark, the exact upper limit is strongly dependent on the statistical technique used
- Larger datasets (increased luminosity) and better use of the information in the datasets improve the "sensitivity" (no matter how it is defined)
  - Beware of robustness though!
- At discovery and beyond, all results are consistent, for a real signal and well behaved analyses
- Searches can be very involuted from the point of view of the analysis techniques: progressing using the simpler as a cross-check for the most complicated is essential!
- Beware of where you step when you optimize!

Part II

What ATLAS promised, few years back?
Will we maintain our promise?

Rules of the game

- I cannot quote or mention non approved work in progress
- What I will discuss are mostly results which have been public since years
- Discussion oriented towards addressing common misconceptions about why we didn't publish a result **yet**
- ...again: expect a result soon!

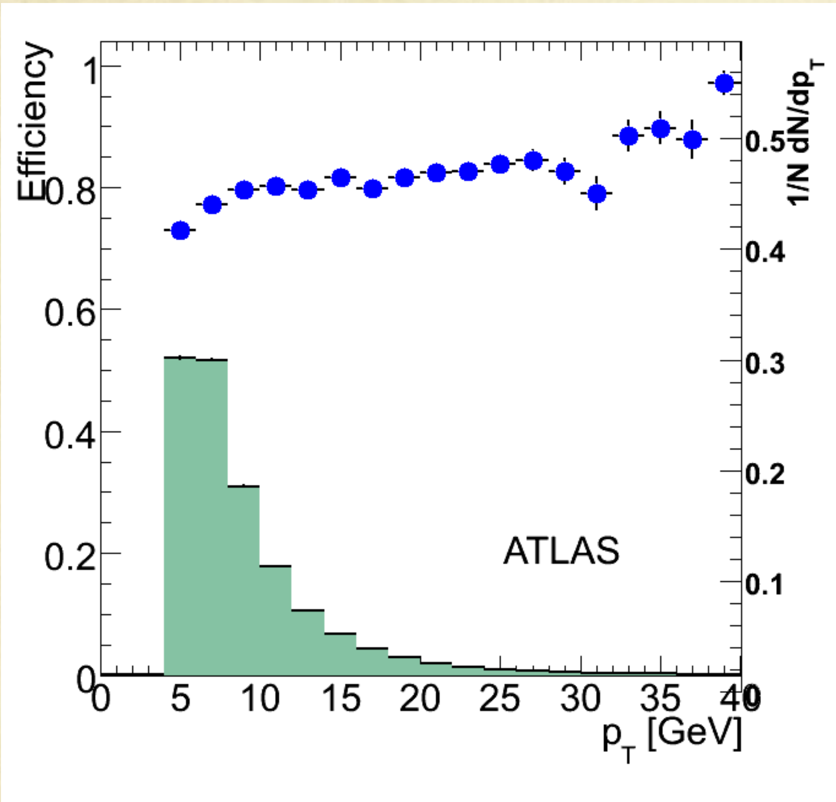
ATLAS performance in B→μμ

A few critical ingredients to the analysis which are sometimes questioned:

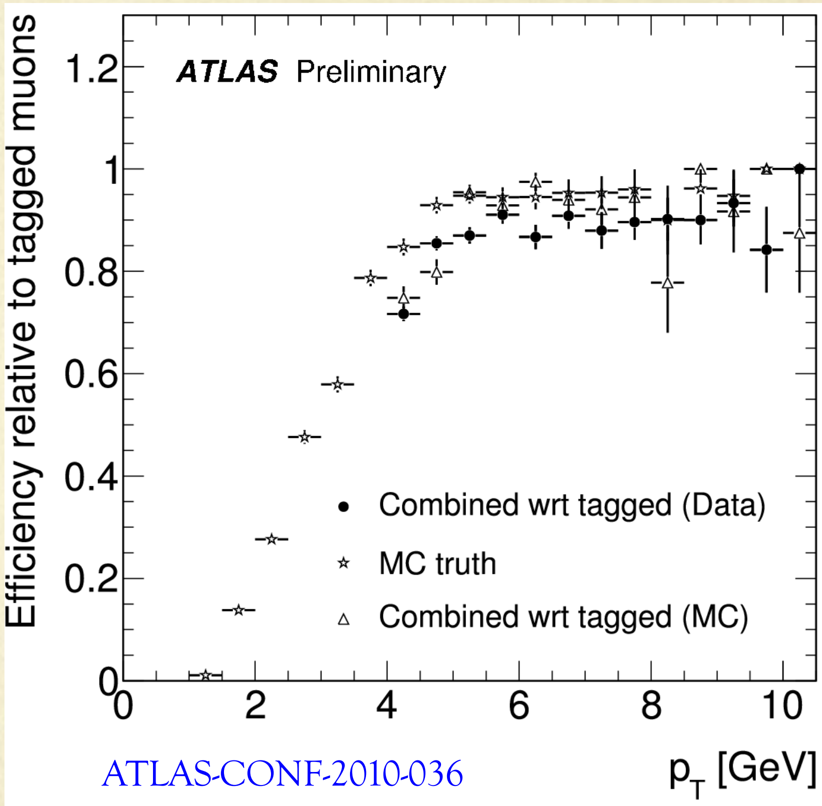
- Trigger efficiency
- Reconstruction efficiency
- Mass resolution
- Proper time/vertexing resolution
- Any other?

Muon reconstruction

CSC assumption



ATLAS observed and simulated



Perfectly consistent with expectations! Even better!

Trigger Efficiency

- For B➔μμ we select two 4 GeV muons at trigger level, and confirm them in reconstruction
- Many studies already performed (e.g. J/ψ production cross-section) which prove our degree of understanding of trigger efficiencies, and the consistency with expectations!

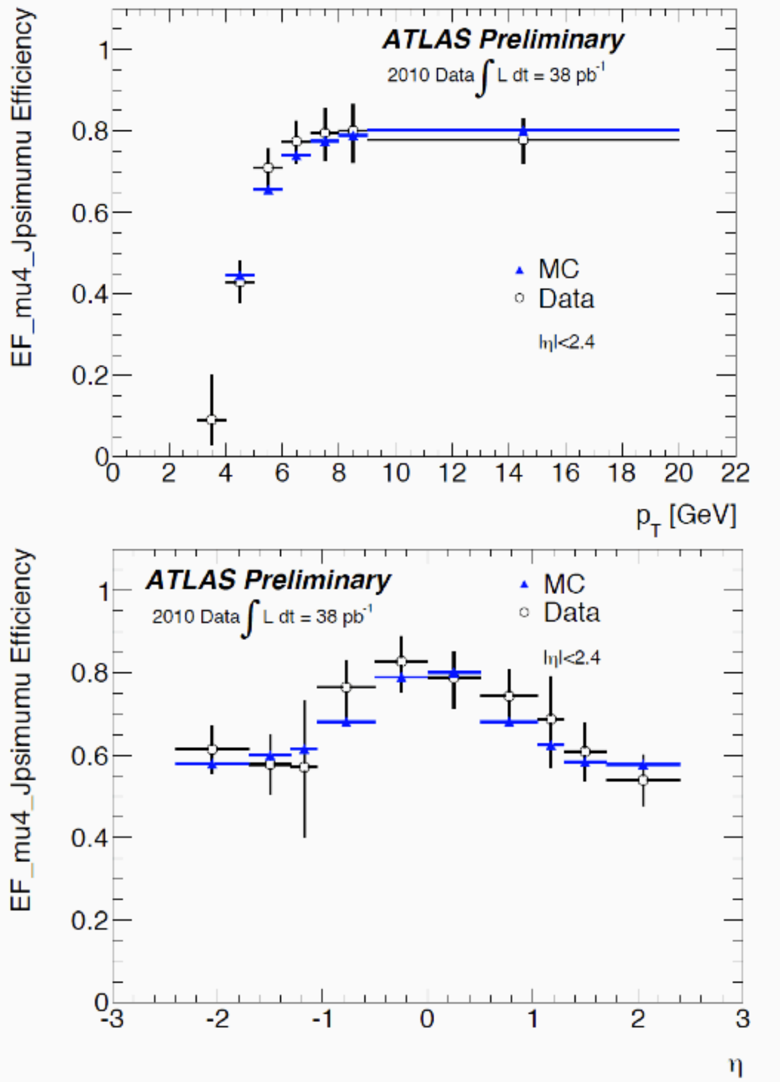
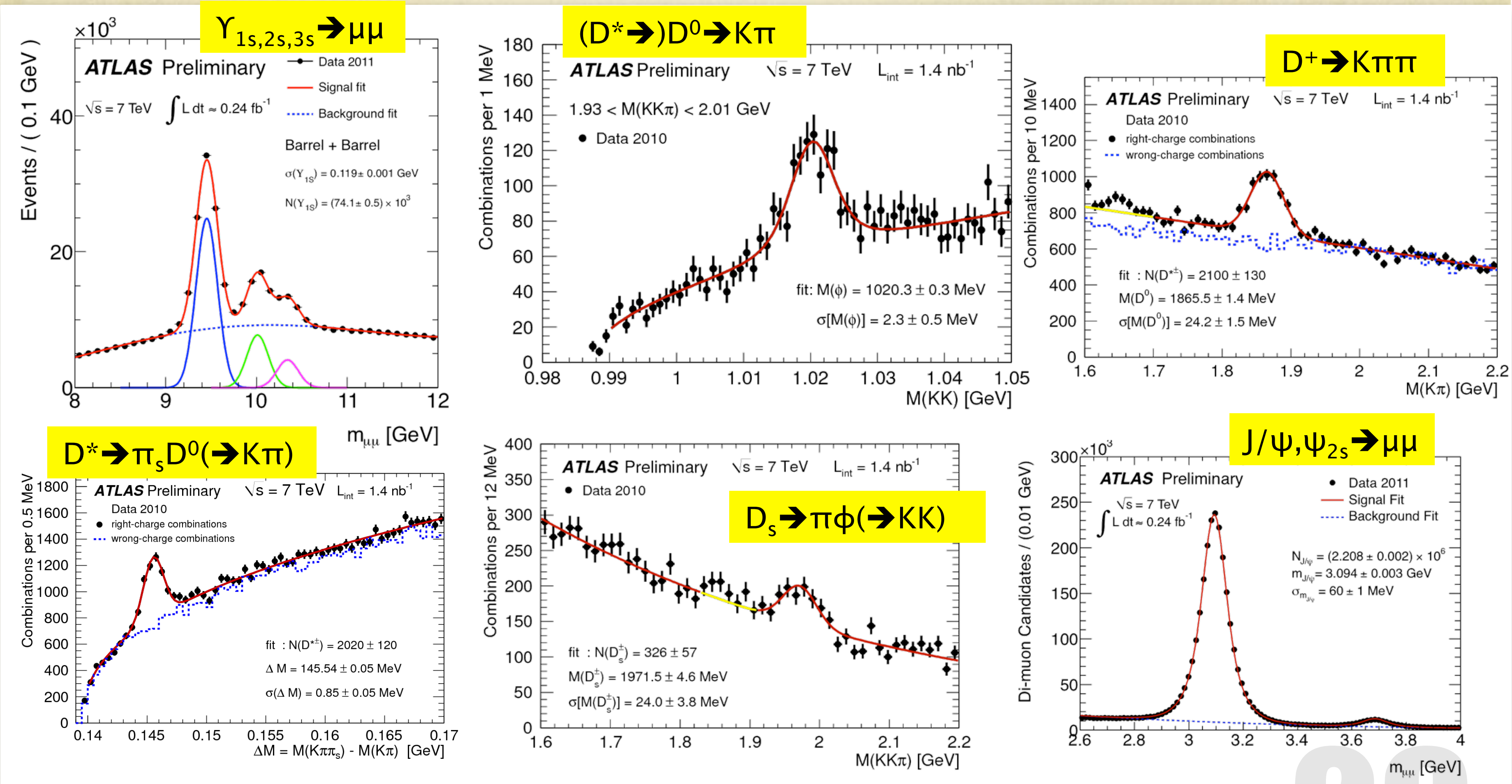
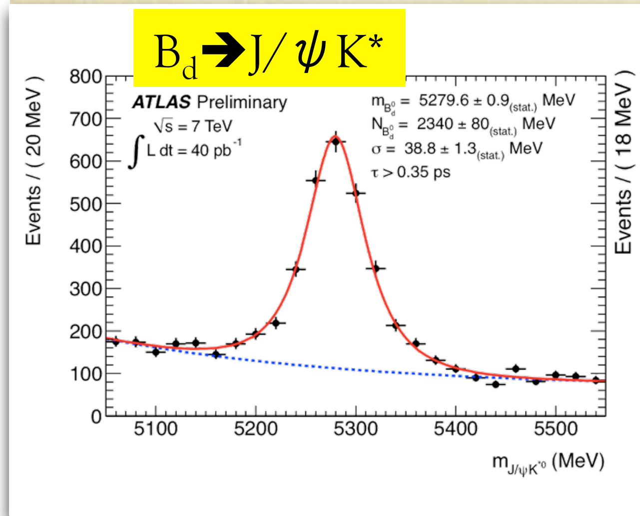


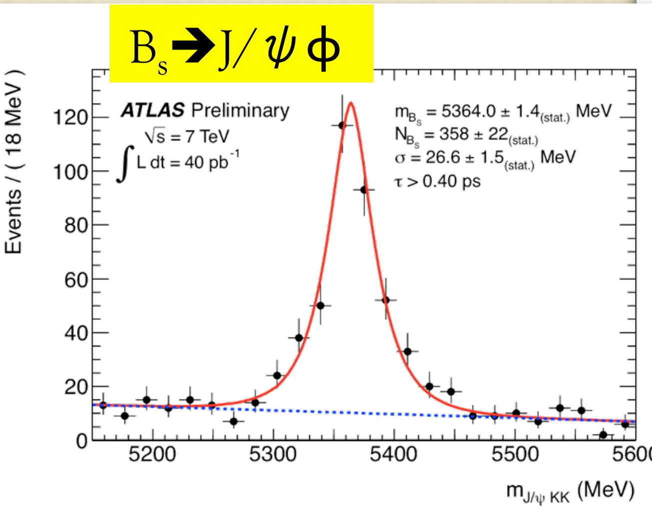
Figure 2: Efficiency of **EF_mu4_Jpsimumu** as a function of the p_T (top) and η (bottom) of the reconstructed muon with higher p_T in the di-muon pair [2] .

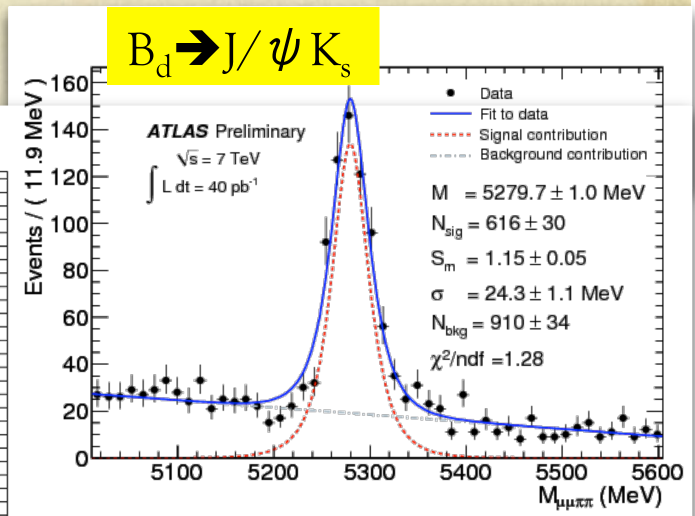
Trigger & reconstr. efficiency I

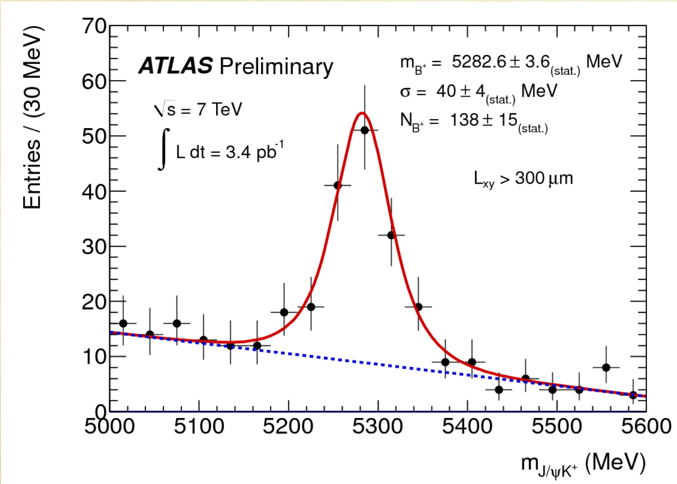


Trigger & reconstr. efficiency II



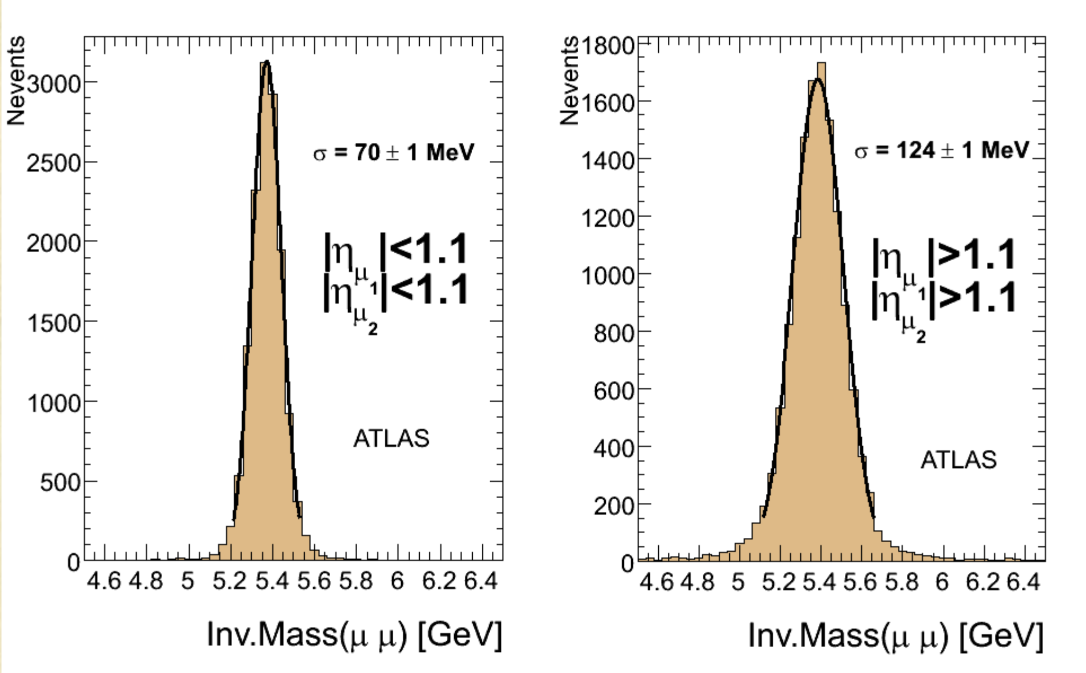






- Yields perfectly consistent with expectations from CSC studies
- Most of these signals based on identical di-muon trigger used for rare decays
    - Mass-window for rare decays shifted higher➔smaller di-muon background

Mass Resolution



REM: detector alignment knowledge is improving with integrated luminosity, and the spectrometer resolution will follow this trend as well!

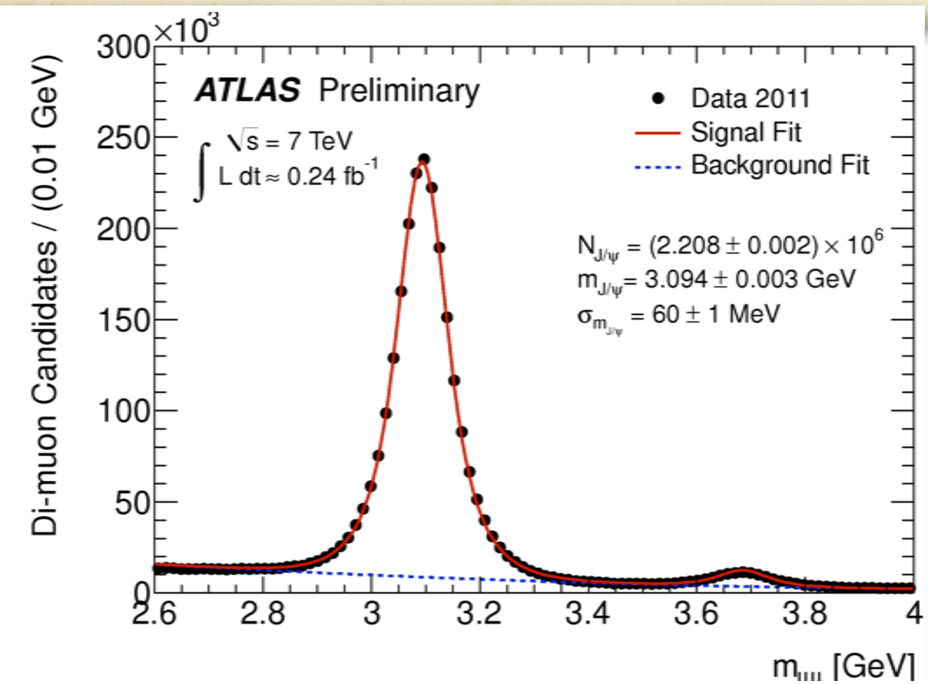
- CSC document predicts 70-124 MeV
- I don't have a signal, so I can't compare 1-1 however many other peaks are extremely well reproduced in data/MC
- About 2x the resolution quoted in the CMS paper

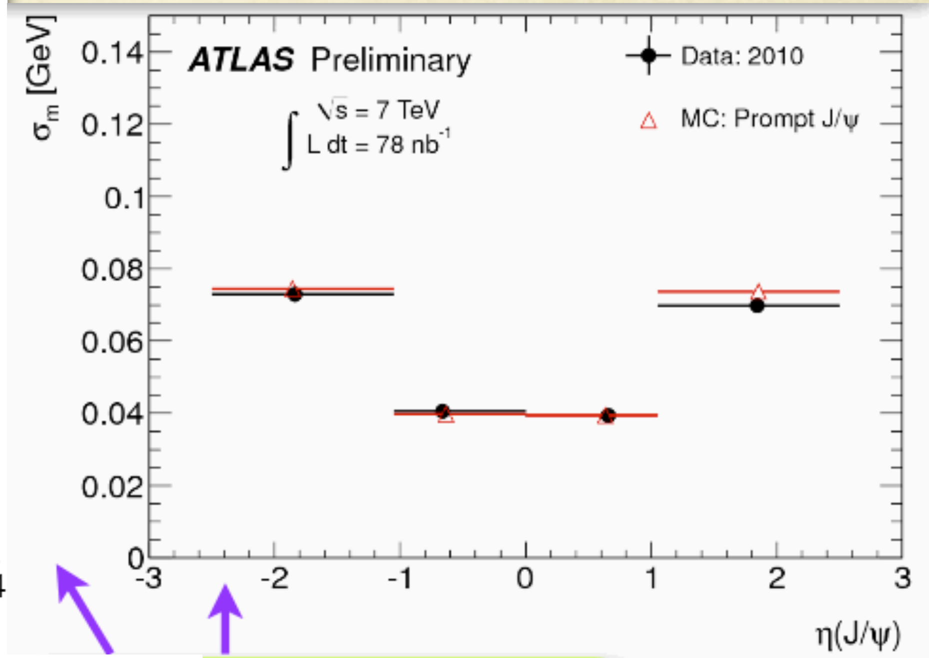
The dimuon mass resolution for signal events depends on the pseudorapidity of the B candidate and ranges from 36 MeV for $\eta \approx 0$, to 85 MeV for $|\eta| > 1.8$, as determined from simulated signal.

CMS-BPH-11-002

Data/MC dimuon resolution

- $J/\psi \rightarrow \mu\mu$, fit 2-track vertex
- Mass value and dependency on $\eta\,(J/\psi)$ consistent with PDG/MC:

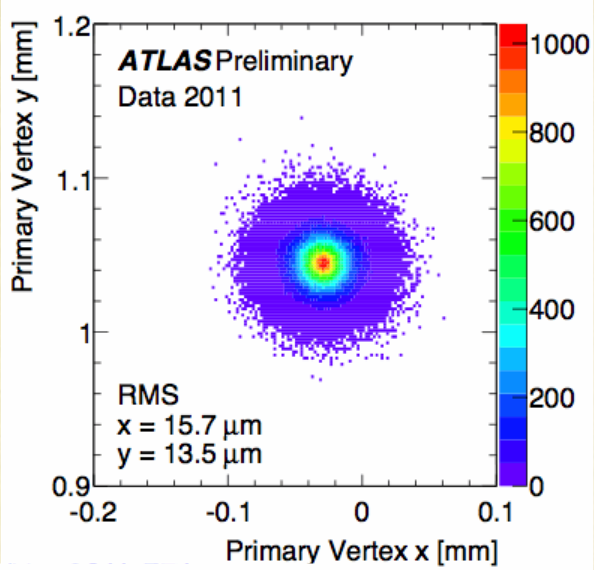


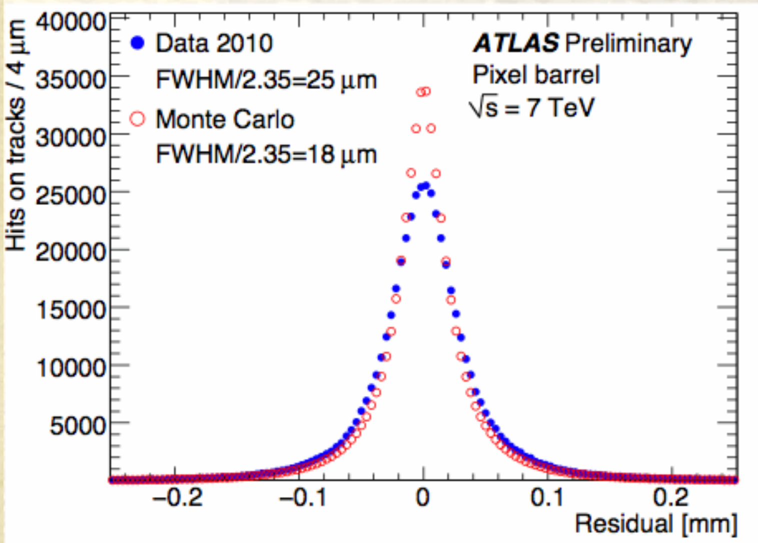


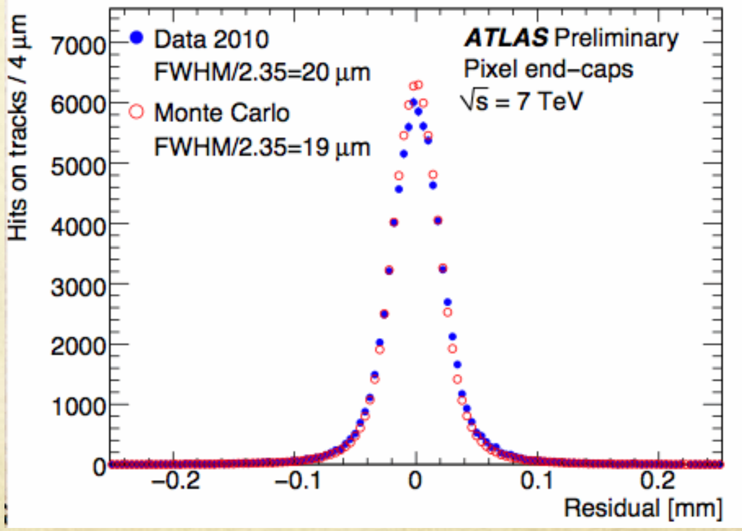
ATLAS-CONF-2010-078

Proper-time & vertexing?

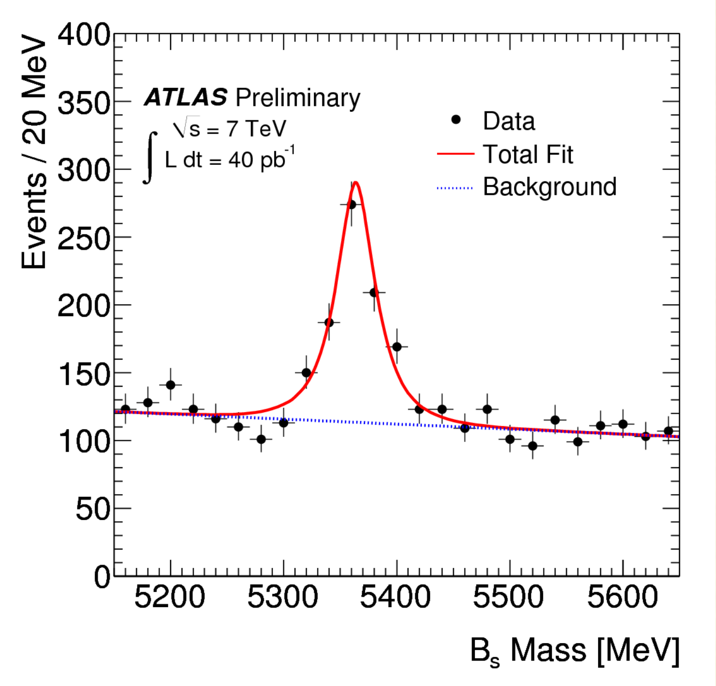
- PV determined with 13-16 μm precision
- Tracker residuals within expected performance, not fully consistent with simulation, but well within specs!

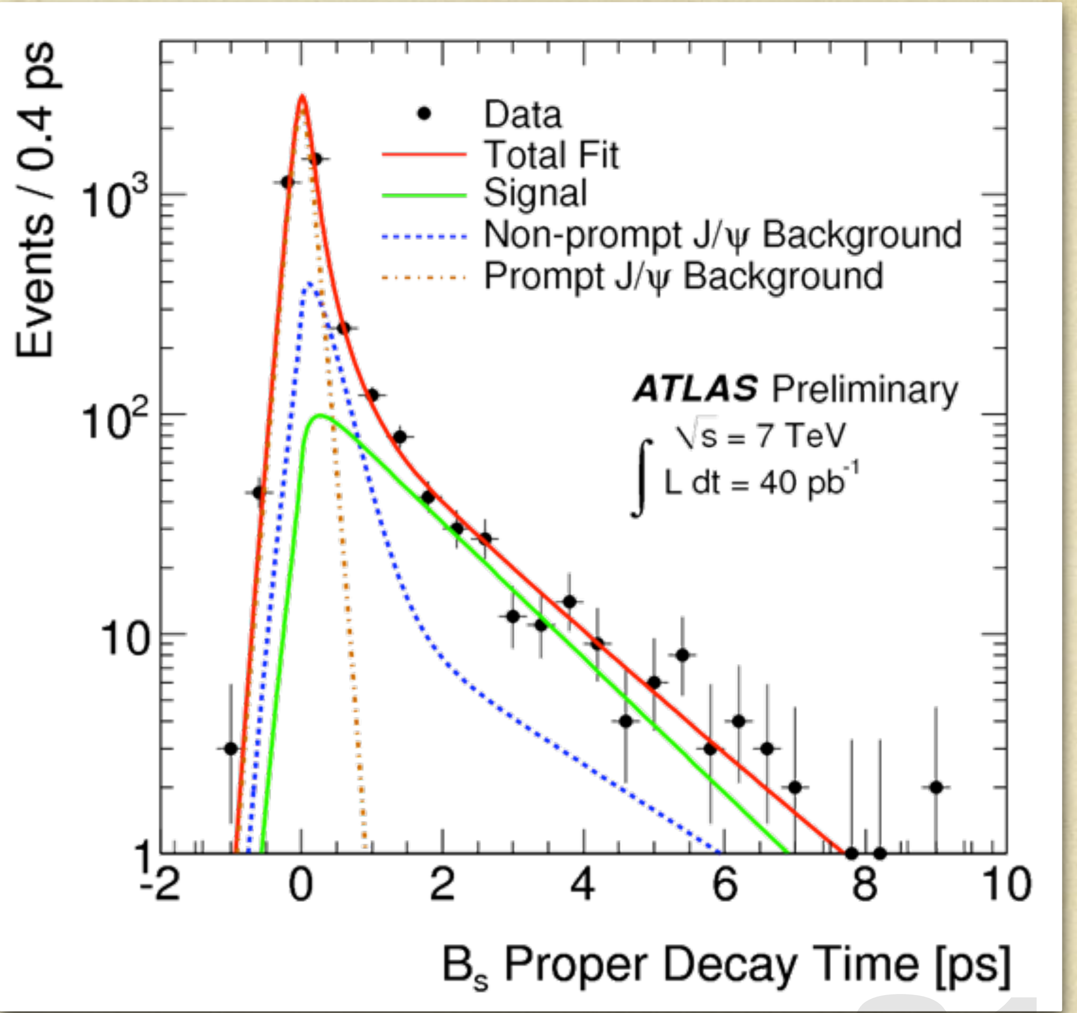






A Benchmark: Bs lifetime





$$m_{B_s} = (5363.7 \pm 1.2)\text{MeV}$$

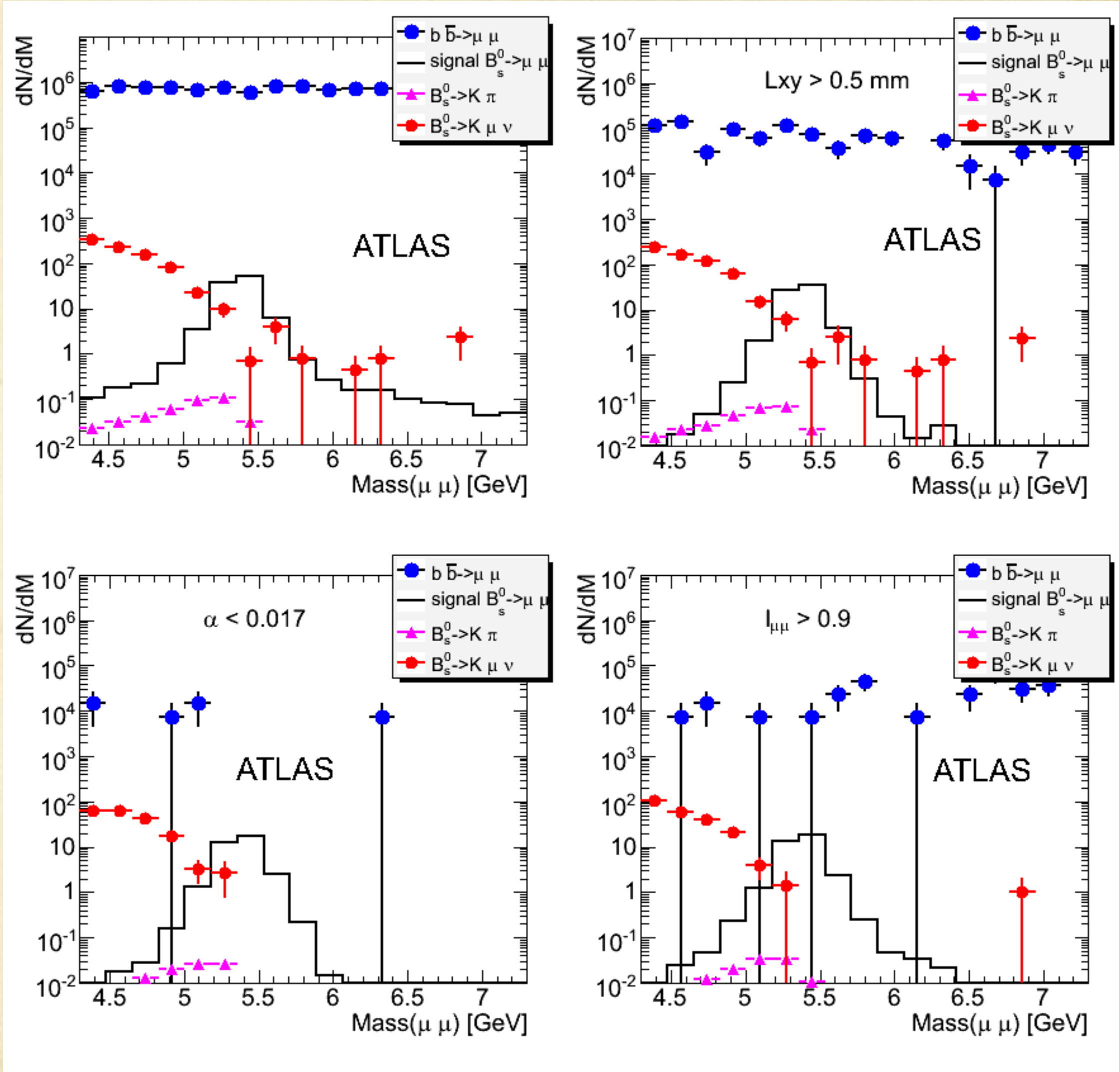
$$\sigma_m = (24.8 \pm 1.2)\ \text{MeV}$$

$$\tau_{B_s} = (1.41 \pm 0.08 \pm 0.05)\ \text{ps}$$

- Good agreement with PDG
- Reasonable S/B, well within expectations
- Resolutions under control!

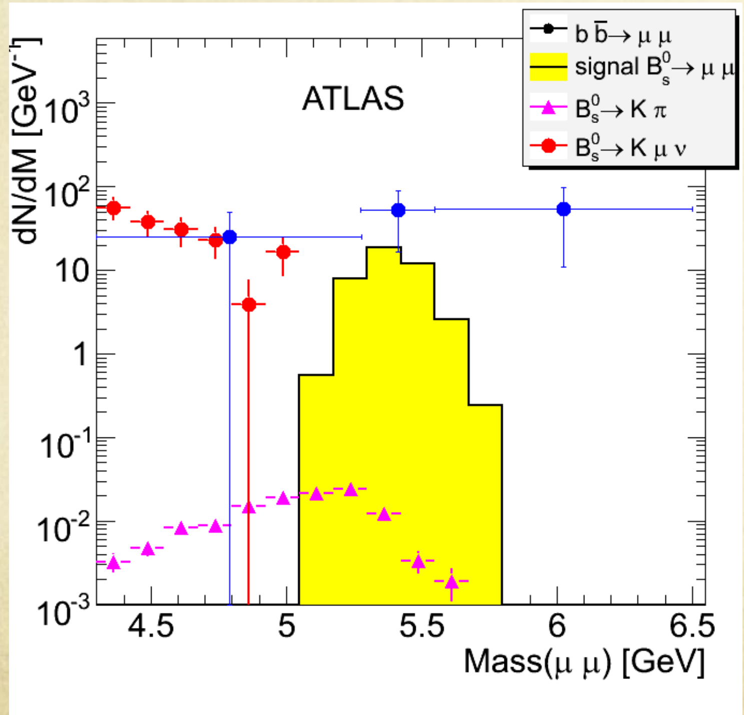
The CSC estimate

- Pure cut & count exercise
- MC based
- Background modeled with bb➔μμ, B➔hh and B➔Kl ν
- Large uncertainties due to assumptions on BR, production cross-sections etc!



The CSC estimate II

Selection cut	$B_s^0 \to \mu^+\mu^-$ efficiency
$I_{\mu\mu} > 0.9$	0.24
$L_{xy} > 0.5\text{mm}$	0.26
$\alpha < 0.017$ rad	0.23
Mass in $[-\sigma, 2\sigma]$	0.76
TOTAL	0.04
Events yield	5.7



- Projection to 10 fb^{-1}
- bb➔μμ, B➔hh and B➔Klν taken into acount
- SES @ 10 fb^{-1} estimated back-of-the-envelope:
  - Assuming B(B➔μμ) $3.5 \cdot 10^{-9}$:
  - $SES_{10fb} = (3.5/5.7) \cdot 10^{-9} \approx 6 \cdot 10^{-10}$

Scaling just by luminosity:

$SES_{3fb} \approx 1.1 \cdot 10^{-9}$

Compare to CMS@ 1fb^{-1}: $SES_{CMS} \approx 2 \cdot 10^{-9}$

Take all this with a grain of salt: it's a back-of -the-envelope extrapolation from numbers dating back to before data taking!

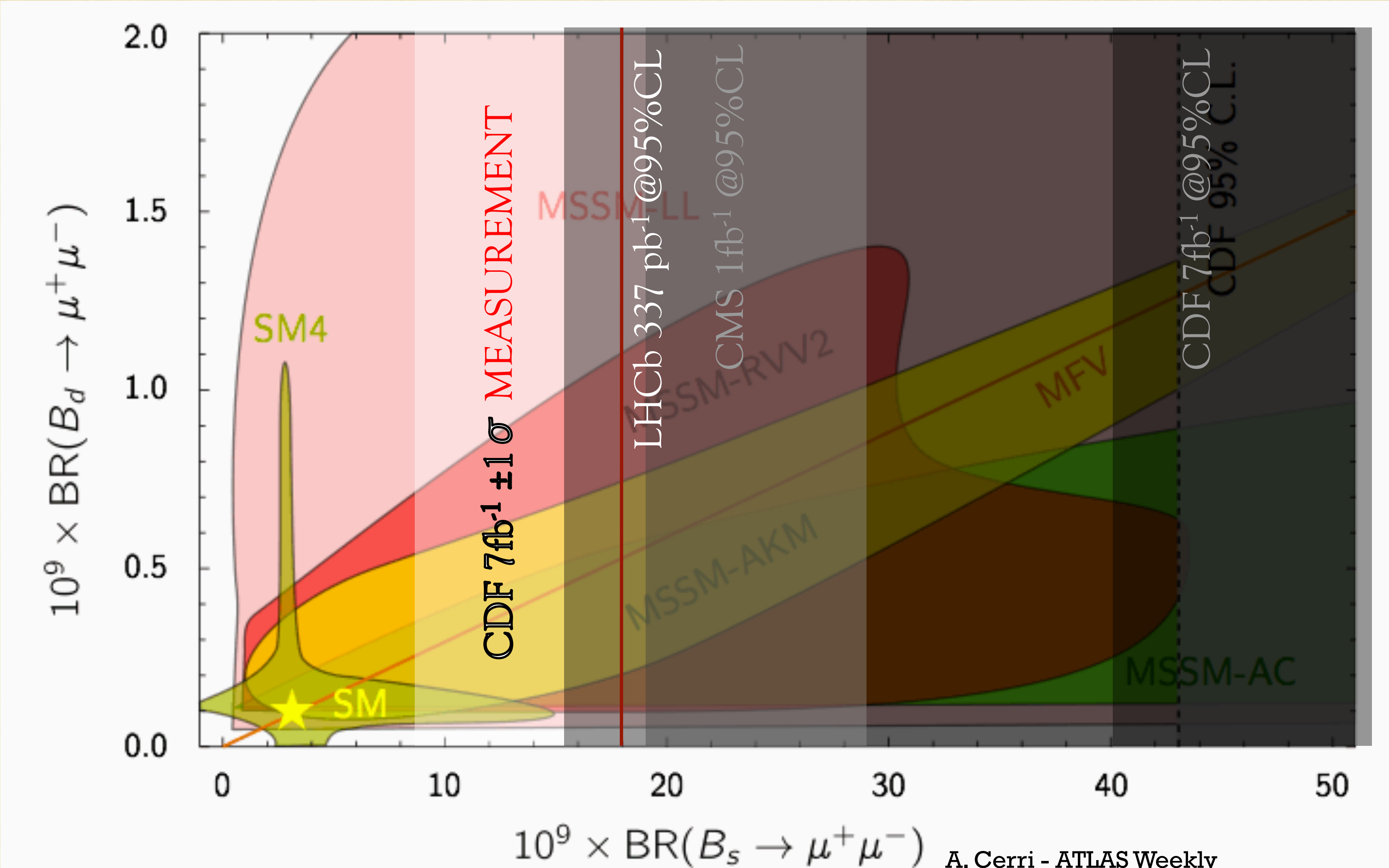
CSC estimate

A few things to keep in mind:

- MC based
- Effect of background not taken into account in SES
- Don't quote this as the "ATLAS reach": you will get the actual number soon!

Another quick back-of-the envelope estimate could be done taking the CMS numbers and correcting for mass resolution effects (≈sqrt(2))…

The current landscape



I hope that looking at this raises a few questions...

Questions

- Is the white band consistent/inconsistent with the rest?
- Are all the upper limits speaking the same "statistical language"?

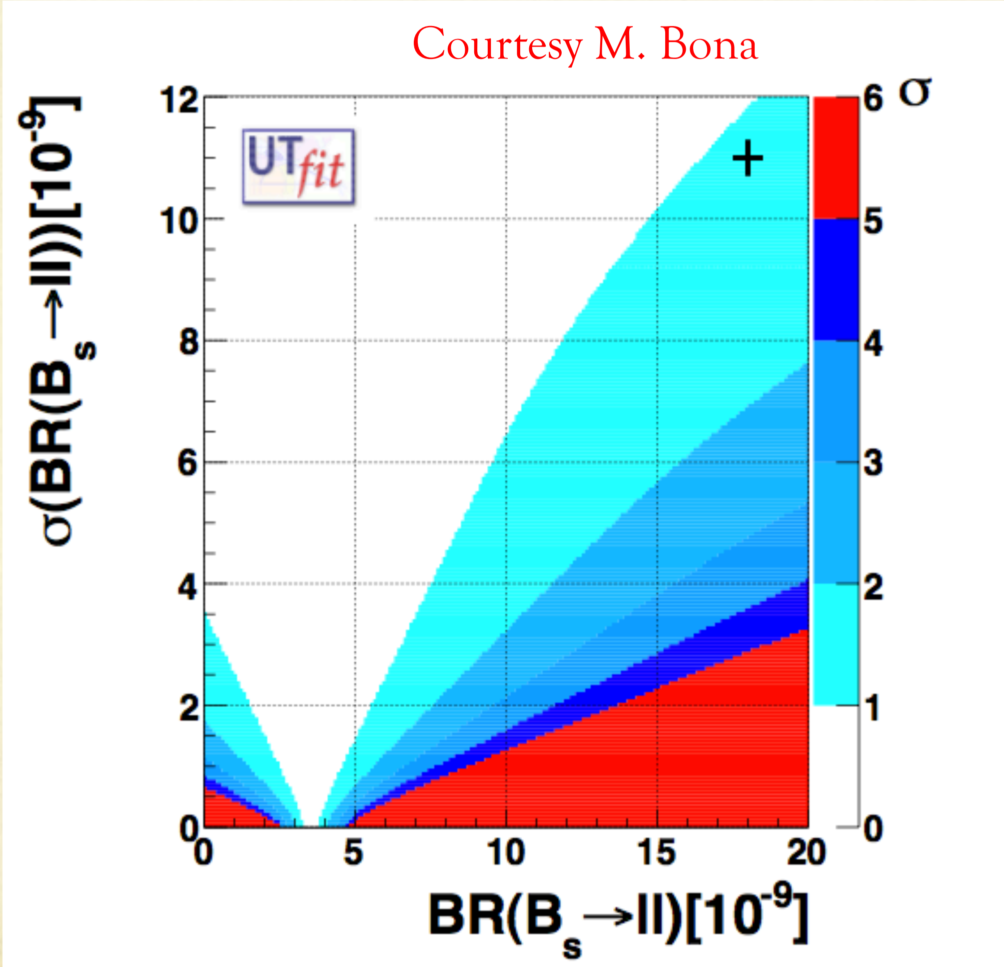
My questions!

- Why nobody looks below SM?
- Did you see any horizontal line? Do you know why?

Answer to question #1:

- Contours are gaussian-equivalent iso-probability lines
- Cross is the CDF measurement

What do you think? Is it incompatible at all?!?



Conclusions

- When you look at these results, there may be significant small prints
- A little late… yes! But we are aiming at an healthy defendable and well understood result
- Many studies ongoing in ATLAS, thousands of physicists and yet… we're late basically because resource-limited!
- Be patient: we won't disappoint you!

We want to produce an high-quality well-understood result!
You'll hear about it, shortly!