What Constitutes a Complete Analysis?

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- Preamble
- An Answer
- Guidelines
- An Example
- Closing Remarks

Preamble

- There is no one way to perform data analysis
  - Depends a bit on what the analysis aims to do
    - Cross section measurement?
    - Determination of a particle property?
    - Search for something new?
  - Depends a bit on your style/taste
- Some practices and implementations are better than others
  - I'll aim to summarize the better ones
  - My opinion based on my experiences
- Apologies if this is overly pedantic or patronizing
  - I hope to provide something useful

An Answer

Q:What constitutes a complete analysis?

A: A suite of studies which together provide a coherent and thorough description of a particular set of data events

- Should cover all aspects necessary to understand and characterize these events
- Should be well documented via internal notes
- Should be subjected to peer review

Rules of Thumb

- Look before you leap
  - Plan your analysis strategy carefully
- Trust but verify
  - Always ask yourself, “Does this make sense?”
- A stitch in time saves nine
  - Sweat the (relevant) details, it will save time in the long run

An Example

- As an illustrative example I'll use one of CDF's first Run-II publications
  - Search for the FCNC Decay $B_s \dashrightarrow \mu^+\mu^-$
  - A relatively simple analysis

- Can't cover all the details, but will try to highlight things which illustrate the "Rules of Thumb"

- Obviously the specifics vary from analysis to analysis and among experiments, but hopefully useful as a concrete example

B2μμ Introduction

- In the Standard Model (SM) the decay $B_s \dashrightarrow \mu^+\mu^-$ is a FCNC decay that can only occur through loop diagrams and is thus very suppressed
- However, a wide array of New Physics models predict Branching Ratios (BR) that are orders of magnitude larger than what's predicted in the SM
- An observarion of these decays at the Tevatron would be unambiguous evidence of New Physics

B2μμ Introduction

- The experimental signature is very simple for this decay: $B_s \to \mu^+\mu^-$
  - Two oppositely charged muons
  - The μμ invariant mass = M_{Bs}
  - Since the B_s has a "long" lifetime of 440 μm, the μμ pair will often originate from a point displaced from the primary p-pbar vertex
- Initially S/B ~ 10^{-8}, the challenge is to suppress the background
  - Gluon splitting, B^*/Λ_b --> μμX, combinatorics, B --> hh (ππ, πK, KK)

B2μμ Method

$$BR(B_s \rightarrow \mu^+\mu^-) = \frac{(N_{candidates} - N_{bg})}{\alpha \cdot \varepsilon_{total} \cdot \sigma_{Bs} \cdot \int Ldt}$$

This measurement requires that we:

- demonstrate understanding of background, N_{bg}
- accurately estimate $\alpha\varepsilon$
- know our normalization
- intelligently optimize cuts

Since SM predicts 0 events, this is really a "search"

- more rigorous about testing N_{bg} estimate
- emphasis on performing an unbiased optimization

The suite of B2mm studies

- The analysis note: cdf-6397 (42 pages)
  – Optimization, bgd estimates+xchecks, answer
- The additional notes used as inputs:
  – cdf-6104 Geo+Kinematic Acceptance (16 pgs)
  – cdf-7314 Di-muon Trigger efficiencies (226 pgs)
  – cdf-6347, 6114, 6835 Muon Reco (53 pgs)
  – cdf-6394 COT efficiency (54)
  – cdf-6318 SVX efficiency (18)
  – cdf-6331 primary vertex efficiency (4)
  – cdf-6273 hadrons faking muons (44)

>400 pages of Supporting documentation

Look before you leap

- While analyses are in general more iterative than linear, there are a few things that are quite helpful to do from the start
- Spend time thinking about the measurement with the goal of identifying those aspects which will drive the sensitivity
  - Analytic error propagation often a good start
  - Toy MC or MC truth level studies also very helpful in
    - What are the important physics effects?
    - What geometric and kinematic limitations do the detector and/or trigger introduce?
    - What are the most important instrumental effects?
  - The goal is to emerge with an understanding that helps prioritize which things need to be precisely understood and at what scale (1% or 10%?) and which don't

Look before you leap

- With the above information in hand, spend some time thinking about a plan of attack
  - What plots, figures, and tables will be important?
  - What data sets will you need?
  - What triggers do these data sets use?
  - What Monte Carlo (MC) samples will you need?

LBYL: B2μμ Example

- Anticipating that the end result will most likely be a limit, I used a Bayesian method to understand how the limit changes as I varied:
  - Uncertainty on signal acceptance
  - Uncertainty on background acceptance
  - Mean number of expected background events
- I learned
  - Insensitive to Δb as long as $\Delta b<\text{sqrt}(b)$
  - Limit degrades in proportion to Δs
  - You can tolerate a larger b if it comes with a large gain in signal acceptance

LBYL: B2μμ Example

- Using this one can outline the analysis and anticipate needing the following:
  - Signal/search data set: DiMuons
  - Samples to measure signal efficiencies: use J/Psi-->μμ collected on same or similar DiMuon triggers (pT spectrum?)
  - Samples to measure trigger efficiency: unbiased, inclusive, single-leg muon triggers (use probe-and-tag, double leg correlations? If prescaled, lumi correlations?)
  - Sample to estimate combinatoric background: mass sidebands in DiMuon data set (correlations between dimuon mass and other discriminating variables? functional form?)

LBYL: B2μμ Example

- Using this one can outline the analysis and anticipate needing the following:
  - Clean HF control sample for checks in signal efficiency: B-->J/Psi K (3-track vs 2-track vtx? kinematics different?)
  - Luminosity accounting: from DB (accounting specific to your trigger? Any missing events?) from relative normalization: B-->J/PsiK (which trigger?)
  - Bgnd xchecks: sidebands in same trigger (which sidebands best? Correlations?) jet triggers? (trigger biases?)
  - MC: B-->μμ, B-->hh, B-->J/PsiK, generic b-bbar production+decay (pT spectrum? Occupancies? Resolutions? All faithful models of the data?)

Trust but verify

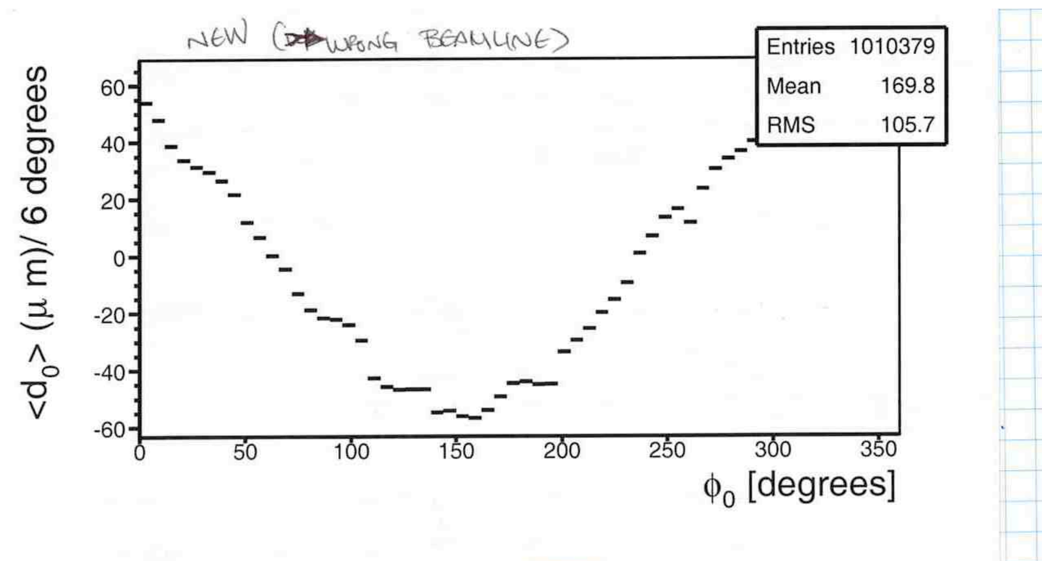
- Unlikely you'll do everything for your analysis, but good to know where to find more detailed information if necessary
  - Dataset definitions
  - Trigger requirements and thresholds
  - Location and access to (raw-ish) data
  - Variable definitions in the ntuple
  - Location and access to source code and alignment and calibration details

Trust But Verify

- Probably inefficient to know all of that a priori, a more pragmatic approach is to learn those things as you need them. How do you know when you need them?
- b/c at every step you're making plots and calculating ratios/efficiencies/etc and asking yourself, "Does that make sense? Is that what I expect?"
  - e.g. d0 vs phi, MET vs phi, muon eta, trigger track eta, pT spectra, vs instan. Lumi, vs. #reco'd vertices
  - e.g. x-checks using intelligently chosen background control samples
- As first generation analyzers of a new experiment, this is particularly important

TBV: B2μμ Example

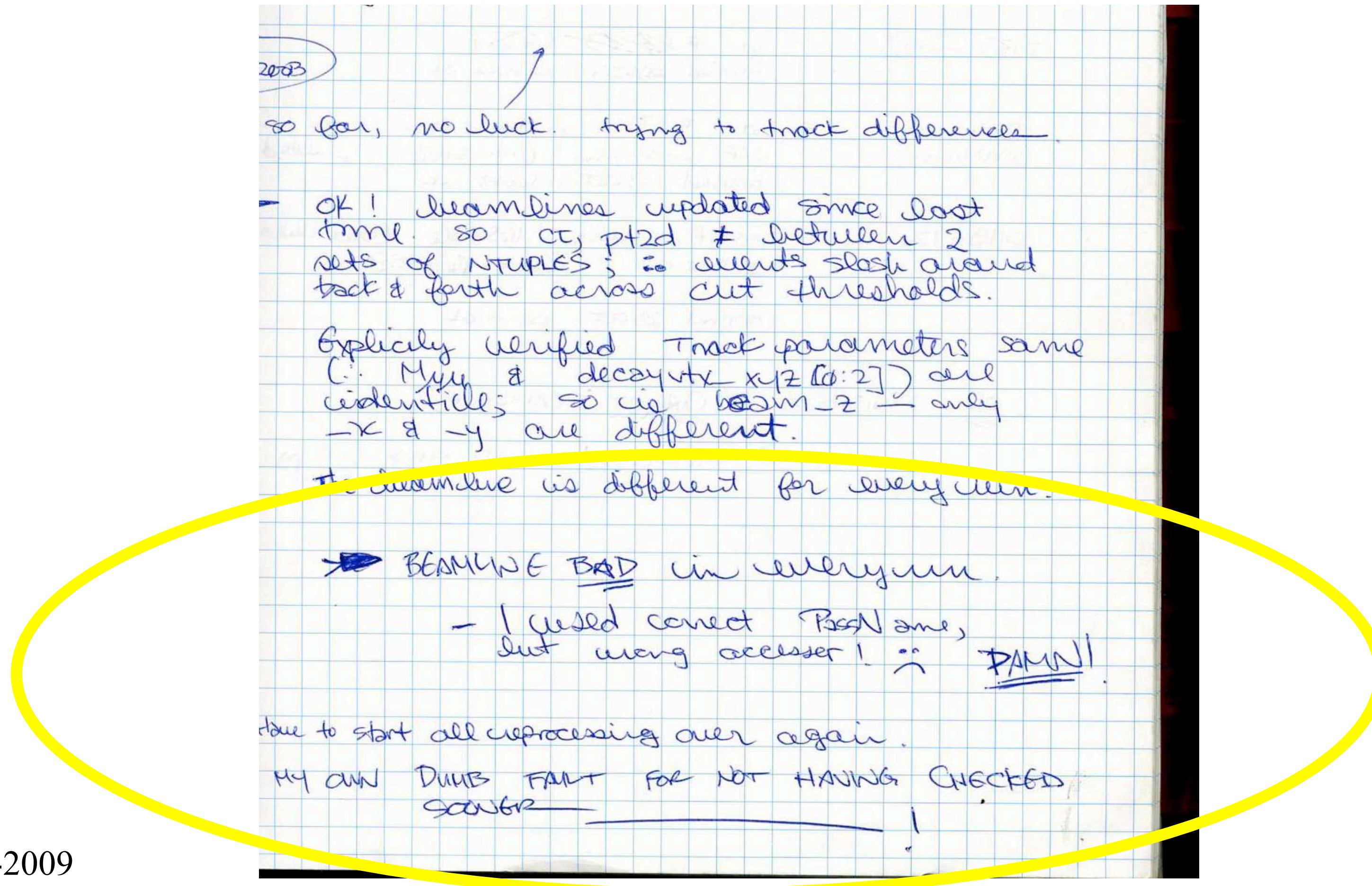
- TBV important b/c between raw data and your plots lots of opportunity for a mistake



- are you calculating d0 wrt the actual beamline?
- are you specifying a consistent set of beamine and tracker alignments?
- did your executable pick-up the alignments and beamlines you intended it to?
- given the status of the tracker alignment, what variations should you expect?
- does it matter if this is data or MC?

TBV: B2μμ Example

- In this case I had messed-up… but caught it early so I hadn't wasted too much time!



2003

so far, no luck. trying to track differences.

OK! beamlines updated since last time. so ct, pt2d ≠ between 2 sets of NTUPLES; ∴ events slosh around back & forth across cut thresholds.

Explicitly verified Track parameters same (∴ Mμμ & decay vtx x/y/z [0:2]) are identical; so is beam_z — only _x & _y are different.

The beamline is different for every run.

→ BEAMLINE BAD in every run.

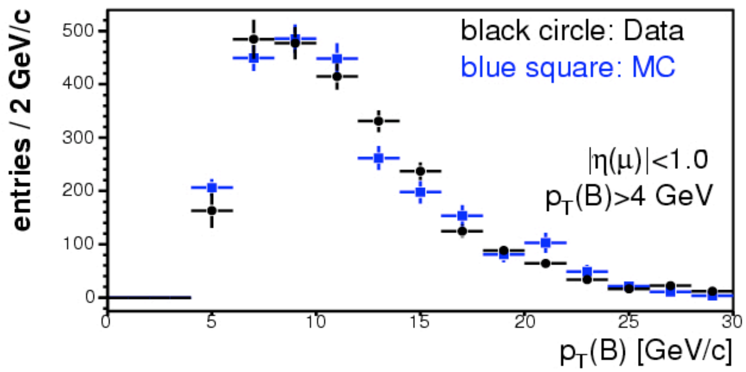
– I used correct PassName, but wrong accessor! :(DAMN!

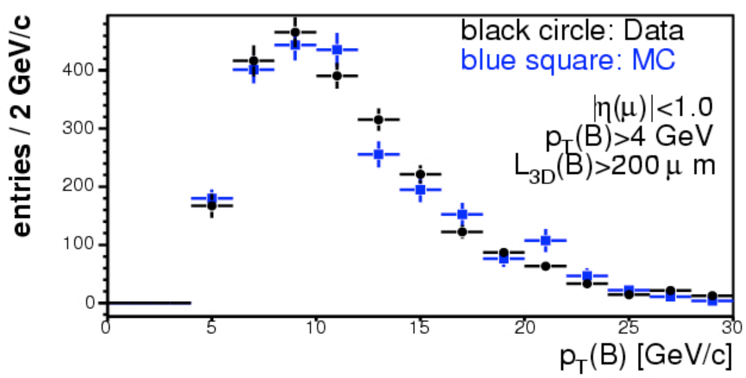
Have to start all reprocessing over again.

MY OWN DUMB FAULT FOR NOT HAVING CHECKED SOONER!

TBV: B2μμ Example

- Is the MC generated the way you need it to be?

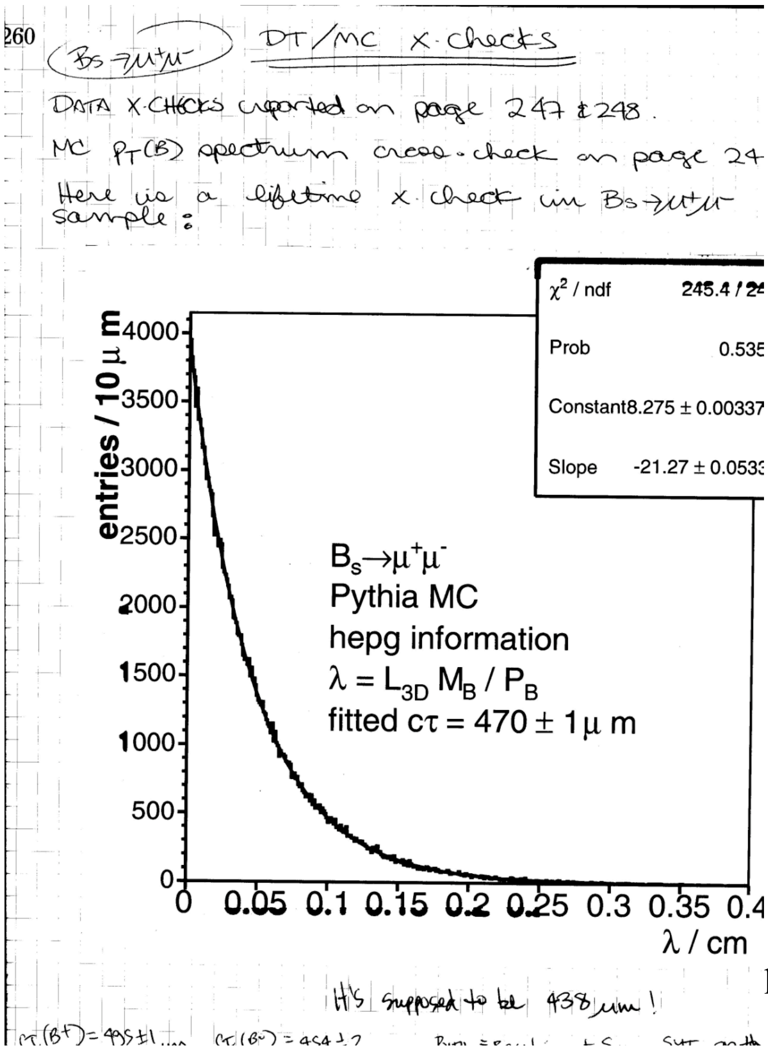




- MC can only be trusted to the extent that it accurately models the data.
- Detailed comparisons necessary for *each* analysis.
  - –pT spectra?
  - – lumi profile?
  - – root(s)?
  - – all processes included?
  - – resolutions, occupancies?

TBV: B2μμ Example

- Is the MC generated the way you need it to be?



In this case it turned out I had specified the right lifetime in one tcl but it got overridden by another that was automatically called (unless you ask it not to be).

Even with MC, lots of opportunity for mistakes.

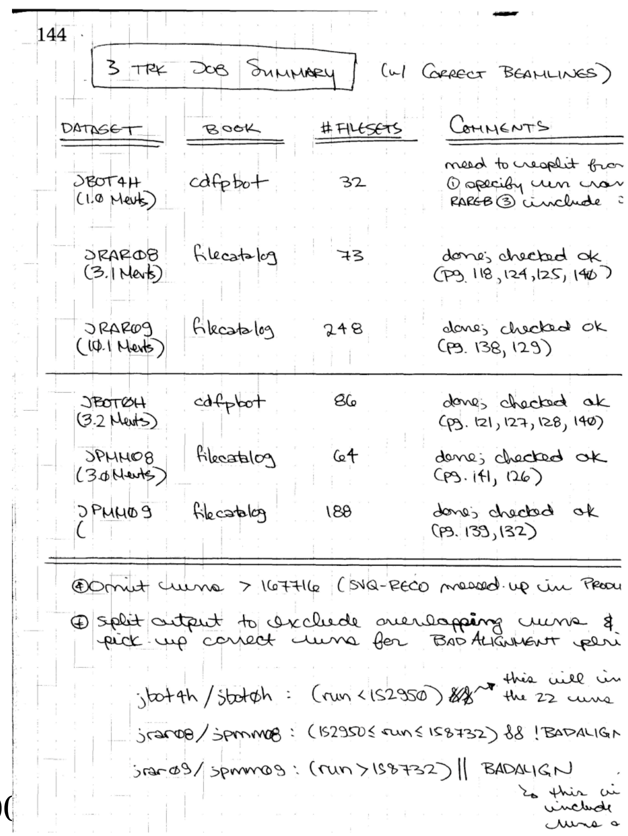
TBV: B2$\mu\mu$ Example

- Lots of opportunity for the luminosity actually used in your analysis to be different from the "advertised" CMS luminosity collected
  - Trigger prescales, or trigger troubles
  - Troubles with a sub-detector required for your analysis
  - Dropped events or files during data processing
  - Dropped events or files during ntupling
  - Dropped events or files when making analysis plots/numbers

Requires standard DB with relevant information

TBV: B2μμ Example

- Careful book-keeping required… scale determined by A) your determination to keep as much data as possible B) scale set by your initial studies



144

3 TRK JOB SUMMARY (w/ CORRECT BEAMLINES)

DATASET	BOOK	# FILESETS	COMMENTS
JBOT4H (1.0 Mevts)	cdfpbot	32	need to resplit from ① specify run ran RAREB ③ include
JRAR08 (3.1 Mevts)	filecatalog	73	done; checked ok (pg. 118, 124, 125, 140)
JRAR09 (10.1 Mevts)	filecatalog	248	done; checked ok (pg. 138, 129)
JBOT0H (3.2 Mevts)	cdfpbot	86	done; checked ok (pg. 121, 127, 128, 140)
JPMM08 (3.0 Mevts)	filecatalog	64	done; checked ok (pg. 141, 126)
JPMM09 (	filecatalog	188	done; checked ok (pg. 139, 132)

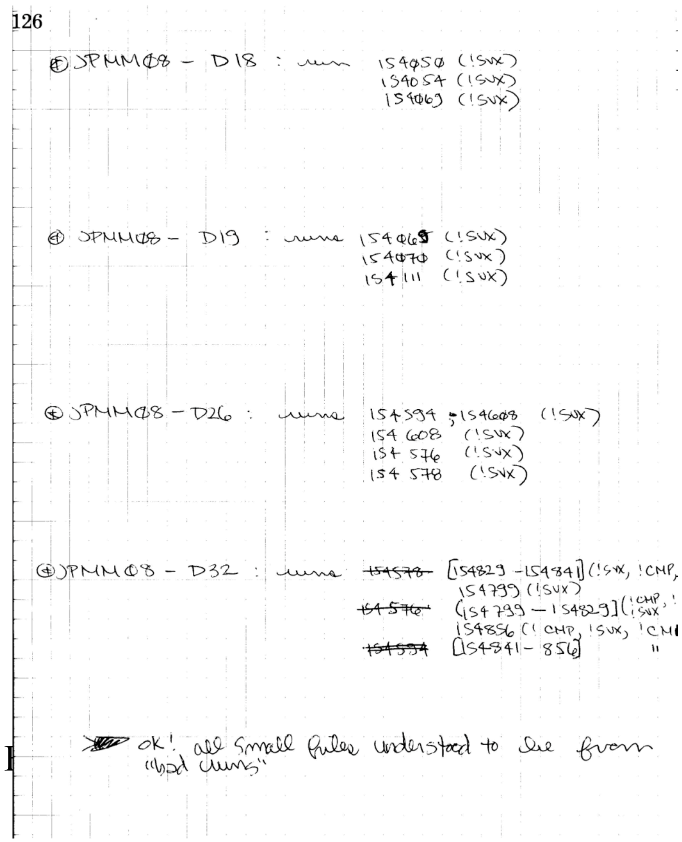
⊕ Omit runs > 167716 (SVQ-RECO messed up in Prod

⊕ split output to exclude overlapping runs & pick up correct runs for BAD ALIGNMENT peri

jbot4h / jbot0h : (run < 152950) && → this will in the 22 runs

jrar08 / jpmm08 : (152950 ≤ run ≤ 158732) && !BADALIGN

jrar09 / jpmm09 : (run > 158732) || BADALIGN → this will include runs



126

⊕ JPMM08 – D18 : runs 154050 (!SVX) 154054 (!SVX) 154069 (!SVX)

⊕ JPMM08 – D19 : runs 154065 (!SVX) 154070 (!SVX) 154111 (!SVX)

⊕ JPMM08 – D26 : runs 154594 ; 154608 (!SVX) 154 608 (!SVX) 154 576 (!SVX) 154 578 (!SVX)

⊕ JPMM08 – D32 : runs ~~154578~~ [154829 – 154841] (!SVX, !CMP, 154799 (!SVX) ~~154576~~ [154799 – 154829] (!CMP, !SVX) 154856 (!CMP, !SVX, !CMU ~~154594~~ [154841 – 856] "

ok! all small files understood to be from "bad runs"

A stitch in time saves nine

- Be systematic/thorough/redundant in your approach… it will save you time in the long run
  - Follow your plan as best you can
  - When you spot a problem, take the time to understand it
  - Don't skip steps to get to the "answer"… it'll be inconclusive until you've demonstrated that all the inputs make sense

ASITSN: B2μμ Example

- Obtaining a self-consistent set of acceptances and efficiencies requires some forethought:

```
* ==============================================================
* --- DEFINITIONS RELEVANT FOR TOTAL ACCEPTANCE*EFFICIENCY
* ==============================================================

We define our acceptance and efficiency like this for Bs-->mumu:

            #(pass L1,L3,offline reconstruction,quality and analysis cuts)
alpha*eff = -----------------------------------------------------------------,
                         #(Bs-->mumu in our kinematic box)

where the kinematic box is defined as Bs with  pt>6GeV and |rapidity|<1.
This is the same kinematic box to which runI measurements of B cross-
sections
are normalized.



The acceptance is defined as:

          #(Bs-->mumu within trigger, muon, COT, and SVX fiducial region)
 alpha = ---------------------------------------------------------------------.
                       #(Bs-->mumu in our kinematic box)

The muon, COT and SVX fiduciality are driven by detector geometry.  The
trigger "fiduciality" additionally requires the muons from the Bs->MuMu
decay to satisfy the kinematic requirements of >=1 of the RAREB_DIMUON
triggers we use.  Details are available in CDF-6204.  The fiduciality
requirements are discussed in more detail below.
```

```
The total efficiency can be broken up into the following pieces:

 eff = eff(COT)*eff(SVX)*eff(muon)*eff(analysis cuts)*eff(L1)*eff(L3).

We have checked to make sure that the pieces of the efficiency
are measured in a consistent way.  The various efficiencies are measured
relative to offline quantities.  Only the COT reconstruction efficiency
is an absolute measurement.  The full expression is given below:

alpha*eff = alpha*eff(COT)*eff(muon)*eff(SVX)
                 *eff(L1)*eff(L3)*eff(analysis cuts).


      #(fiducial)       #(COT)        #(muon,COT)   #(SVX,muon,COT)
    = ----------- * -------------- * ----------- * ---------------
      #(kin. box)     #(fiducial)       #(COT)       #(muon,COT)

                    #(L1,muon,SVX,COT)   #(L3,L1,muon,SVX,COT)
                  * ------------------ * ---------------------
                     #(muon,SVX,COT)      #(L1,muon,SVX,COT)

                    #(cuts,L3,L1,muon,SVX,COT)
                  * --------------------------
                      #(L3,L1,muon,SVX,COT)


      #(cuts,L3,L1,muon,SVX,COT)
    = --------------------------
            #(kin. box)
```

ASITSN: B2μμ Example

- Obtaining a self-consistent set of acceptances and efficiencies requires some forethought:

```
* ============================================================
* --- DETAILS REGARDING FIDUCIALITY
* ============================================================

A charged particle is taken to be "COT fiducial" if its helix satisfies

                 |z_track(r=r_max_cot)| < |z_max_cot|,

or, more specifically,

                 |z_track(r=136cm)| < 155 cm.

The choices for exit radius and z threshold are driven by the XFT
requirements
in the trigger.  Since the XFT demands 11-of-12 hits in all four axial SL,
our fiducial requirements demand a track to traverse all four axial SL.



A COT track (passing our COT quality cuts, which are the same as the
DefTrack
requirements) is taken to be "SVX fiducial" if it extrapolates through at
least 3 layers of the SVX.  This is only a geometric requirement.   Three
layers is the minimum number of layers a track can traverse and still
possibly
satisfy our SVX quality cuts.  Our SVX quality cuts are:

            ( #SVX rphi hits >= 3 )
         && ( #SVX-rphi hits >= (#active-SVX-layers-traversed - 1) ).

These criteria were selected to eliminate those classes of tracks which
anamolously contribute to the negative tails of the signed-impact-parameter
distribution.  Note that, due to the lower bound imposed by our fiducial
requirements, #active-SVX-layers-traversed is a number between 3-5.
```

For the muon fiducial definition, we impose the same requirement as offline CMU reconstruction and require both muon tracks to register >=3 hits in the CMU chamber. Note: the acceptance is computed from MC, which has 100% efficient CMU chambers (muon reconstruction efficiency is taken from the data). Furthermore, since we demand a track with 3/4 hits, any track that scatters into the chamber cracks is not included in the numerator of the acceptance (eg. a track that would be flagged as fiducial by the muon fiducial tool but actually scattered into the gap between CMU chambers).

The muon reconstruction efficiency (CDF-6347) was measured requiring the track
to be at least 10cm away from the edge of the CMU chamber. This cut was NOT imposed to avoid the edge effect of the CMU chamber but to avoid the effect of multiple scattering (cf. first paragraph of section 4 on page 4). We have
already accounted for the effect of multiple scattering in our acceptance measurement. If a track that scatters into the crack is also counted as muon
reconstruction inefficiency, then we would be double counting the multiple scattering effect. Now, what about the issue of the CMU chamber edge effect?
This point was also addressed in CDF-6347. They have measured the CMU reconstruction efficiency using high pT muon tracks from Z0 decays without the 10cm cut. The resulting efficiency is consistent with the measurement using the J/psi sample. From that, one concludes that the edge effect is negligible. Still, the difference is included in the systematic uncertainty.

ASITSN: B2μμ Example

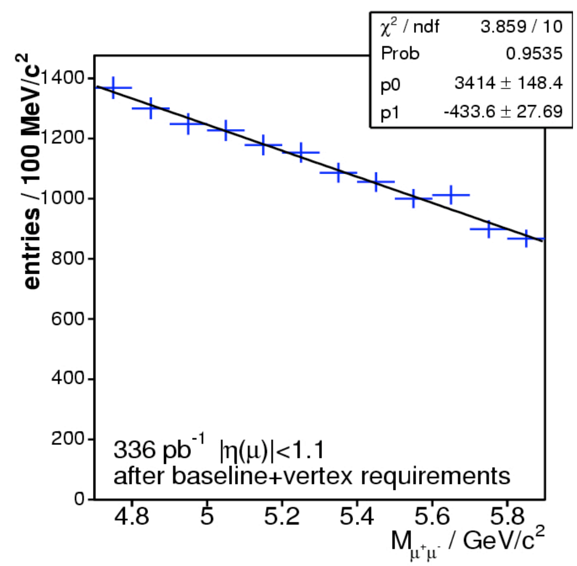
- Carefully validate your background estimates before jumping to the answer
  - Multiple background control samples often required in order to demonstrate understanding of the various components… or at least that any agreement between observation and prediction in a single sample not an "accident"
  - Often helpful to be as quantitative as possible about the agreement
  - Choose control samples for which your background methodology is expected to work

ASITSN: B2μμ Example

- Use control samples to alidate your background estimates
  - But first verify that your methodology should work for these samples

	Background Control Samples			
	OS+	OS-	SS+	SS-
ρ(Iso-cτ)	-0.143	-0.014	0.014	0.033
ρ(Iso-ΔΦ)	0.005	-0.078	-0.015	-0.017
ρ(Iso-M)	0.006	0.014	-0.023	-0.018
ρ(cτ-M)	-0.005	-0.005	-0.020	0.005
ρ(ΔΦ-M)	0.028	0.022	0.069	0.026
ρ(ΔΦ-ct)	-0.249	-0.267	-0.208	-0.201

(Mass and Iso uncorrelated with other variables and mass linear in shape… OK!)



ASITSN: B2$\mu\mu$ Example

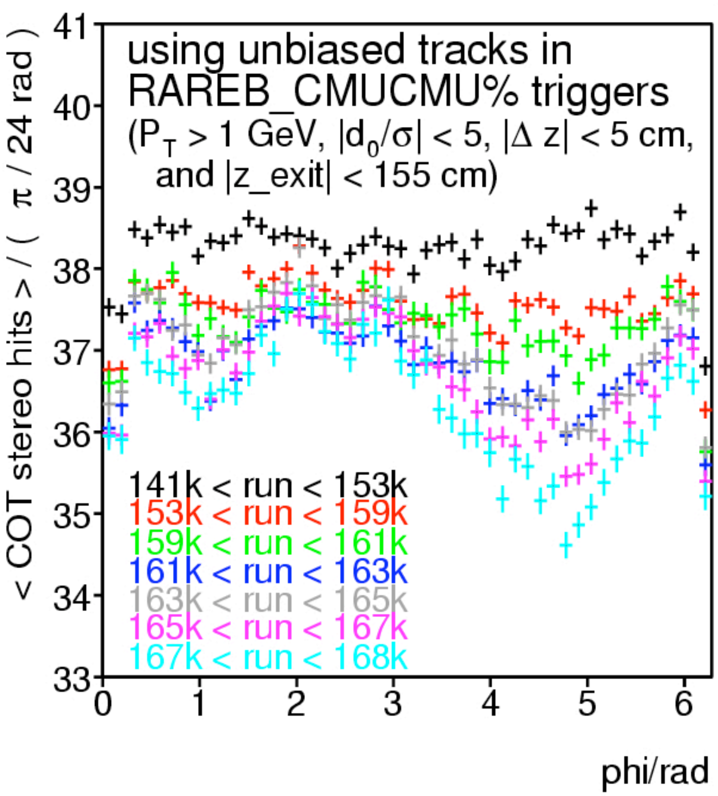
	Sample	N(expctd)	N(obsrvd)	$\mathcal{P}(>=\mathrm{obs} \mid \mathrm{exp})$
Loose cuts	OS-	8.09 +/- 1.57	12	12%
	SS+	3.64 +/- 0.69	3	86%
	SS-	4.79 +/- 0.85	3	70%
	Sum	16.52 +/- 2.56	18	
Default cuts	OS-	3.03 +/- 0.70	5	19%
	SS+	1.22 +/- 0.27	1	81%
	SS-	1.64 +/- 0.33	1	70%
	Sum	5.89 +/- 1.02	7	
Tight cuts	OS-	0.64 +/- 0.22	1	47%
	SS+	0.27 +/- 0.08	0	76%
	SS-	0.20 +/- 0.07	0	82%
	Sum	1.11 +/- 0.27	1	

Closing Remarks

- Be prepared for surprises
  - Especially at start-up
- The peer review process can be grueling
  - Don’t take it personally
  - Skeptical criticism is an important part of the scientific process, it almost always results in a stronger and more thoroughly understood analysis
  - Persevere
- This will be a very exciting time - have fun and enjoy

Surprises: B2μμ Example

- Early in Run-II CDF's COT tracking chamber was losing gain… concentrated at bottom of chamber



- introduced a phi dependence
- important especially for all multi-track analyses (e.g. B2μμ)
- affected all track based triggers (e.g. B2μμ)
- geometric correlations introduced
- later understood and repaired… so there's a time dependence to these effects

Closing Remarks

Thank you for your attention