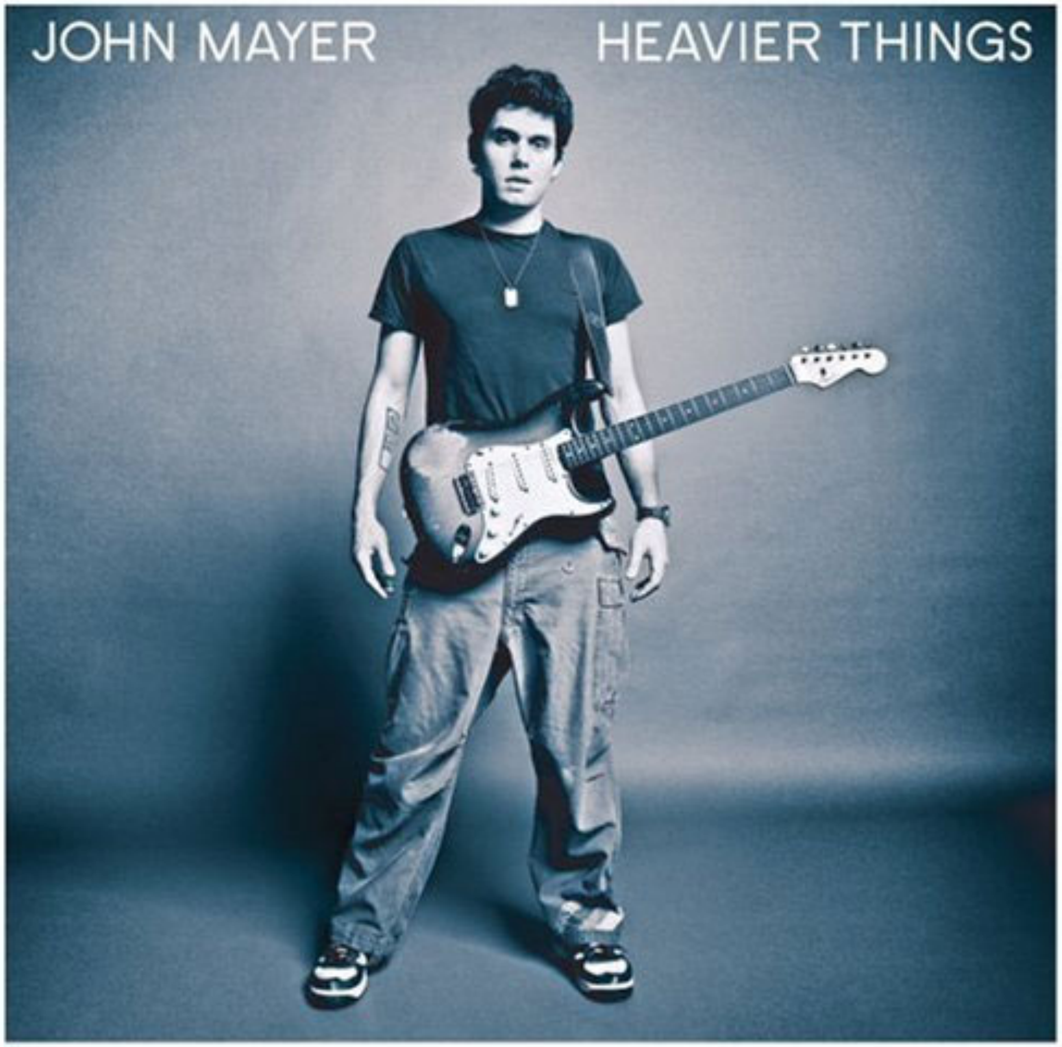


Heavy Flavour

Thomas J. LeCompte
Argonne National Laboratory

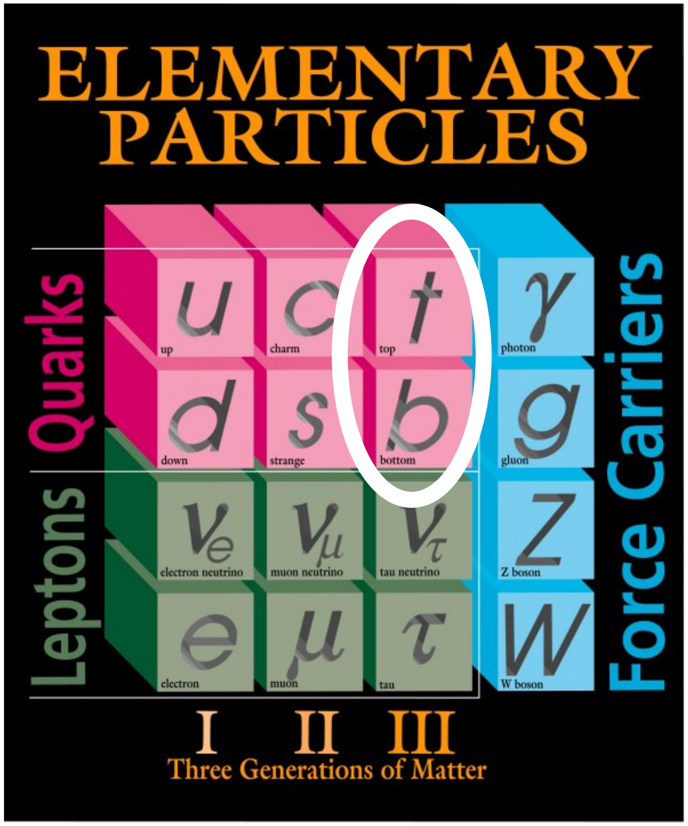
Before We Start

STOP ME if I go too fast or you have questions!!

I know I talk too fast, so please interrupt me – my goal is not to cover as much material as possible: it's to *uncover* as much material as possible

Heavy Flavor…From Top To Bottom

- I'm going to talk about the top and the bottom quarks
- I'm an experimenter, so I will focus on hows and whys:
  - How do we know what we know?
  - Why is this interesting?



Fermilab 95-759

Reminder: Cabibbo-Kobiyashi-Maskawa Matrix

$$\begin{pmatrix} d_W \\ s_W \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix} \quad \Longrightarrow \quad \begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$

Can be expressed in terms of three angles and one phase – the 9 terms are not independent

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3 - \sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3 + \sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3 + \cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3 - \cos\theta_2\cos\theta_3 e^{i\delta} \end{pmatrix}$$

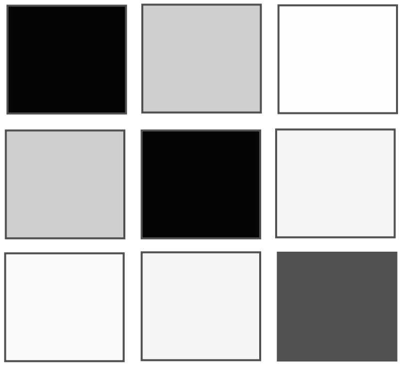
$$\approx \begin{pmatrix} .974 & .227 & .004 \\ .227 & .973 & .042 \\ .008 & .042 & .999 \end{pmatrix}$$

Aside: the phase here gives rise to CP violation. Three is the minimum number of families for this to happen.

CKM Matrix II

$$\approx \begin{pmatrix} .974 & .227 & .004 \\ .227 & .973 & .042 \\ .008 & .042 & .999 \end{pmatrix}$$

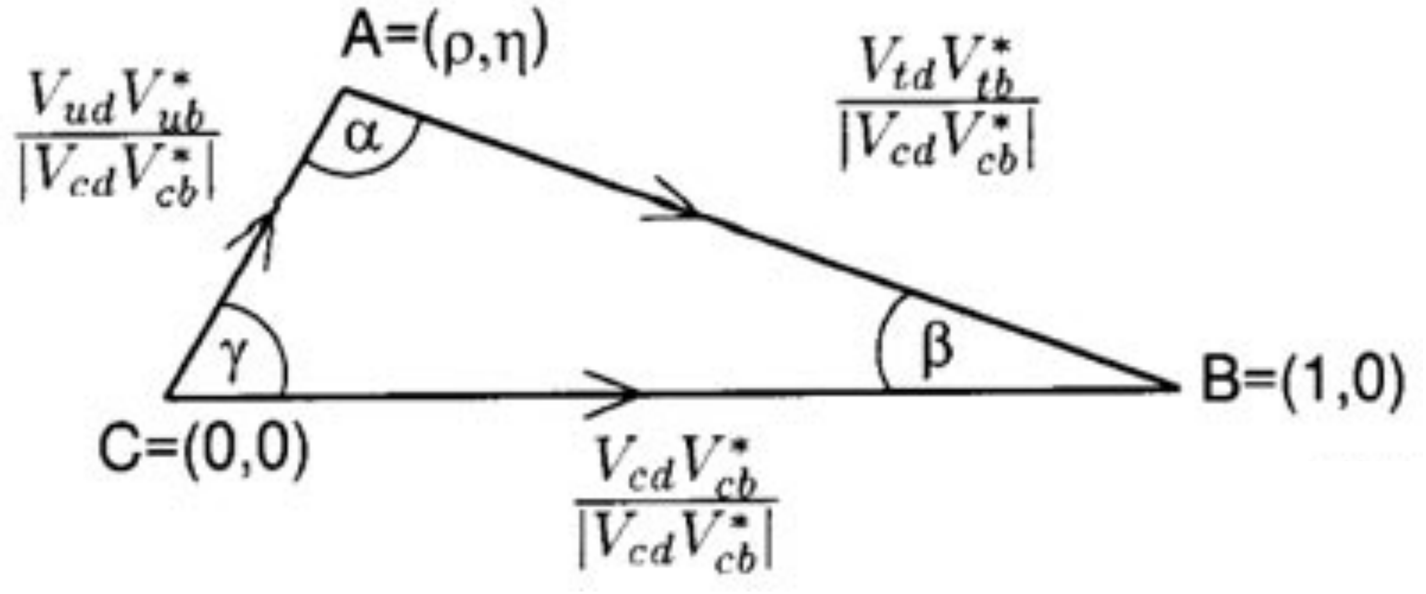
Numbers don't give me a very good intuition for what's going on



Here the shading reflects the magnitude
of the components: black = 1 and white = 0.

- Because the CKM matrix appears squared in any observable, it acts even more like a diagonal matrix
  - The weak interaction apparently does not like to cross family boundaries

“The” Unitarity Triangle



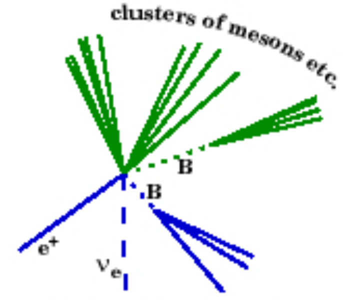
- “The” is a terrible (but common) way to describe this phenomenon
  - There are six unitarity triangles (but not all are independent).

- Magnitudes of CKM matrix elements give the sides
- Phases of CKM matrix elements give the angles
- Non-unitarity of the 3x3 CKM (for instance, a 4th family) causes the “triangle” not to close.

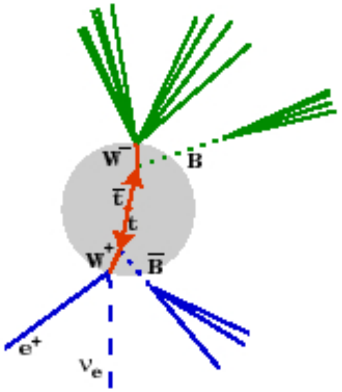
Top Quarks

- The CKM matrix tells us the 1st key fact about top quarks
  - BF(t →Wb) ≈ 100%
- Top quarks events are categorized by how the W's decay:
  - "dileptons" (4/81)
  - "lepton + jets" (24/81)
  - "all hadronic" (36/81)

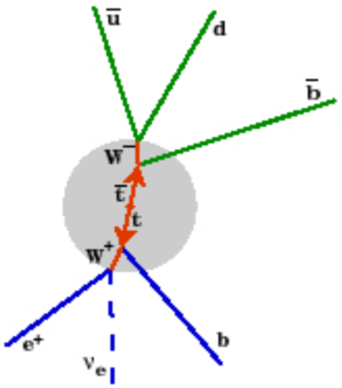

Detector View



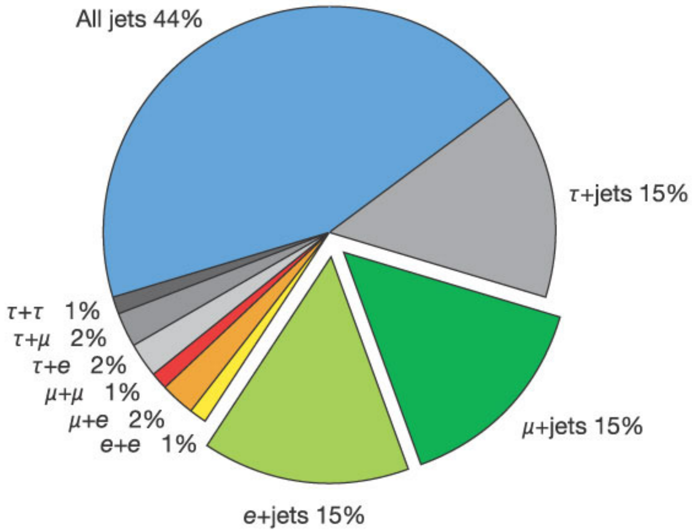
Computer Reconstruction

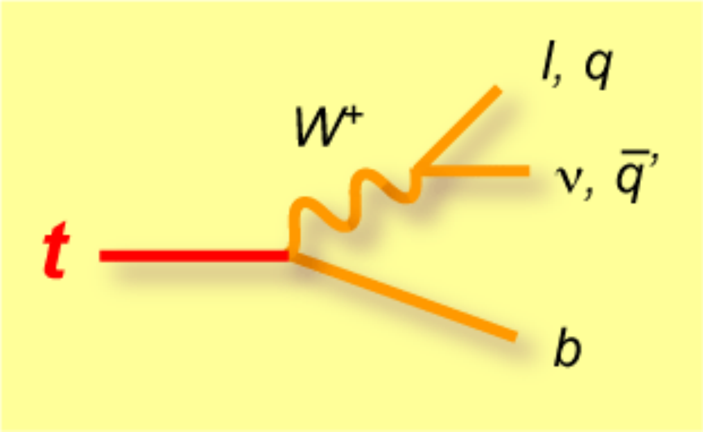


Physicist Interpretation



Quark View





An Early Top Event

e + 4 jet event

40758_44414

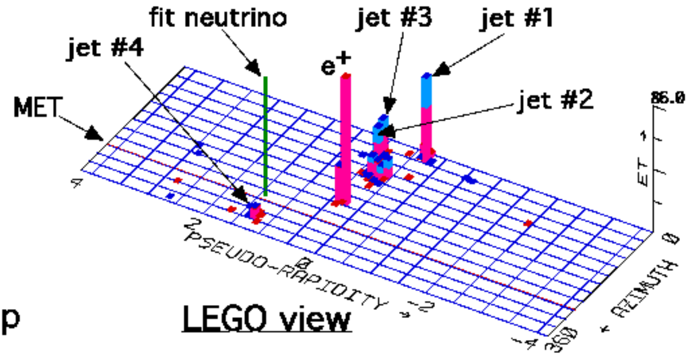
24-September, 1992

TWO jets tagged by SVX

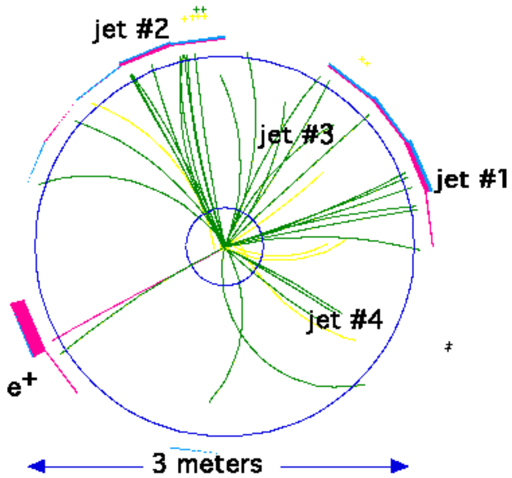
fit top mass is 170 +- 10 GeV

e^+, Missing E_t, jet #4 from top

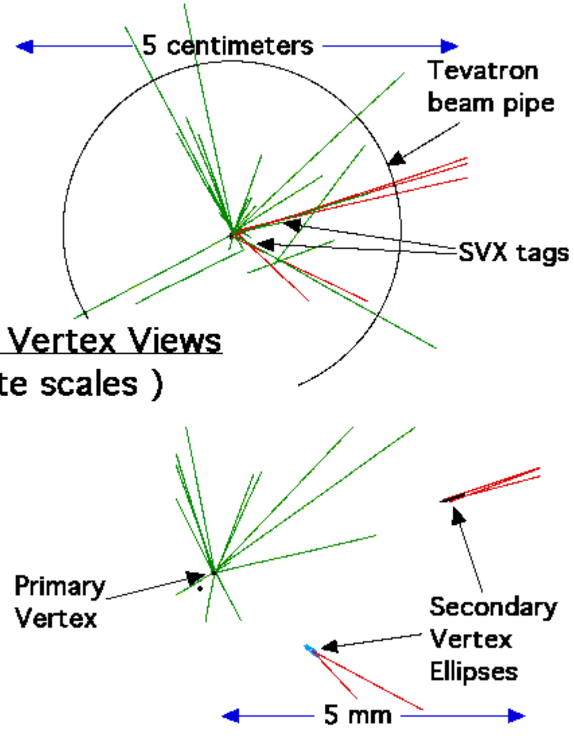
jets 1,2,3 from top (2&3 from W)



LEGO view



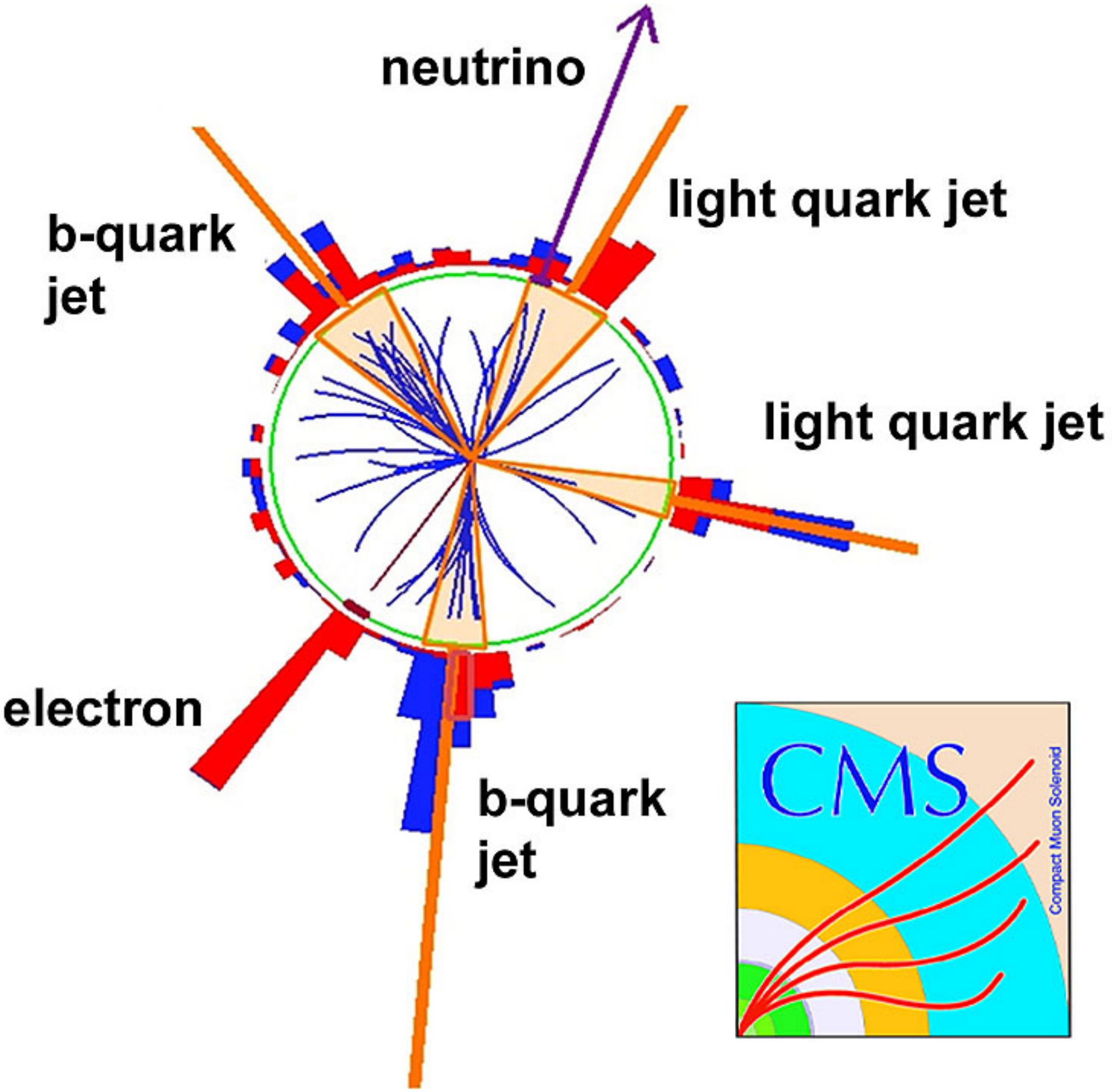
Tracking View



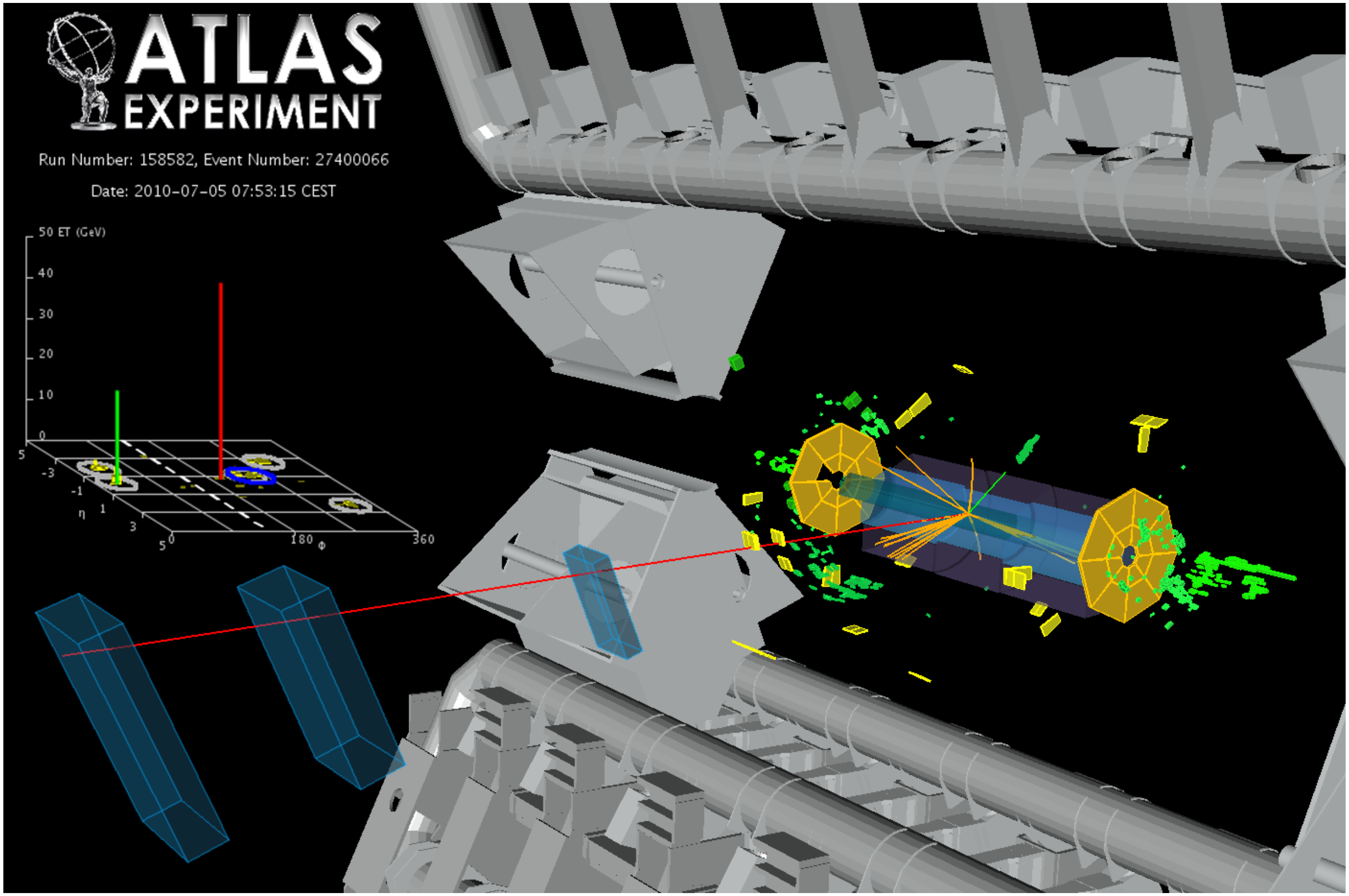
Two Vertex Views

(note scales)

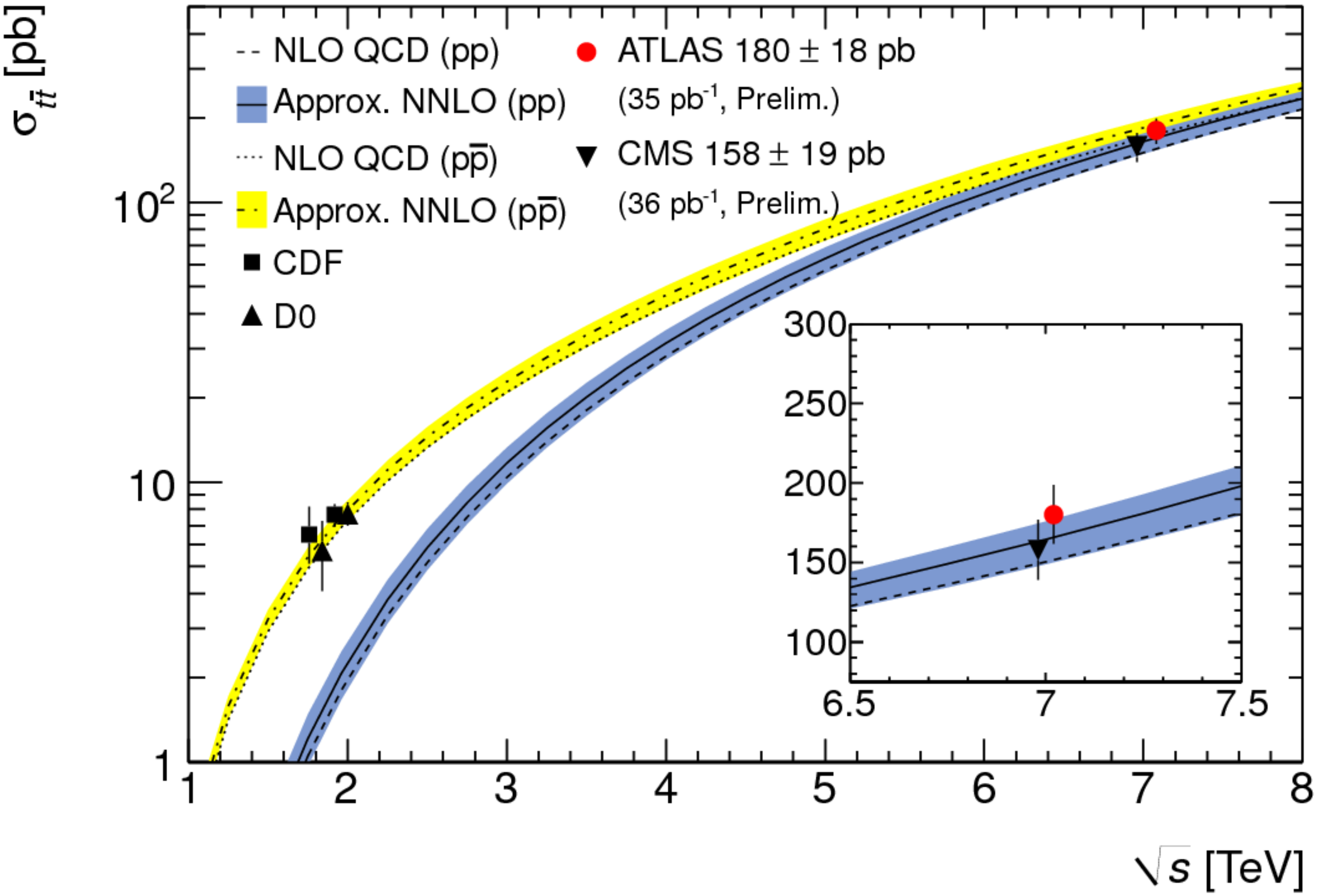
And One More Recent



And One To Show The Improvement in Graphics



Top Quark Pair Production



Expected Reaction:

Why so Boring?

- How did I know this would get you to yawning?
- Because data and theory *agree*.
- We make more progress by seeing a *disagreement* between data and theory.
  - They can't both be right. (They can, however, both be wrong)

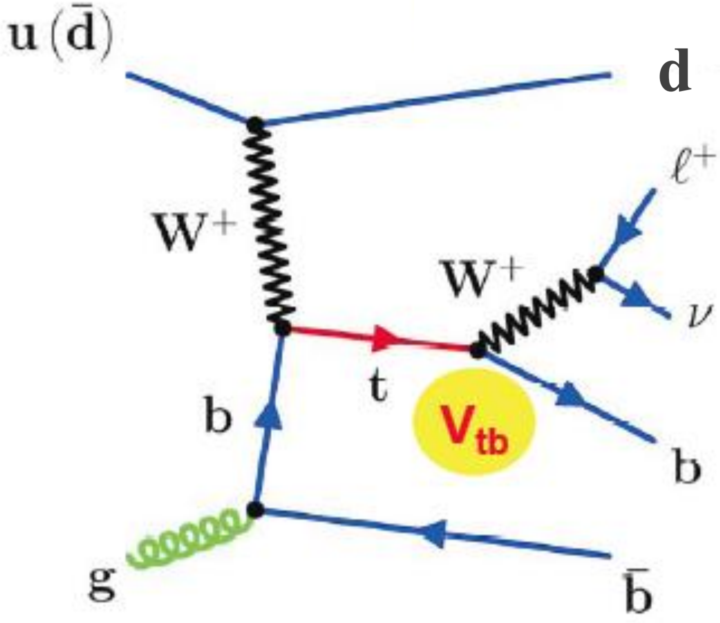
The Dog That Didn't Bark

- Consider the following supersymmetric model:
  - A stop squark weighing close to 175 GeV
  - A light LSP
  - A chargino that weighs close to 80 GeV
  - No other funny business

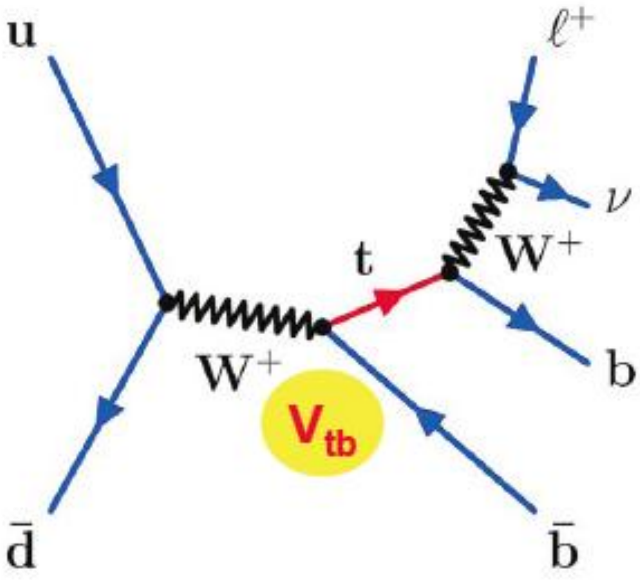
$$\tilde{t} \rightarrow \chi^{+} b \approx t \rightarrow Wb$$

- Now the stop decays look very much like top decays
  - Identical final states, and near-identical kinematics
    - The stop "hides" under the top.
- Where it can't hide is the overall rate – the cross-section is about 30% of the top's
  - We could see a 10% discrepancy, so at 3σ we exclude this.

Single Top – A Less Boring Example



t-channel



s-channel

Theoretical cross section predictions at $\sqrt{s} = 1.96$ TeV

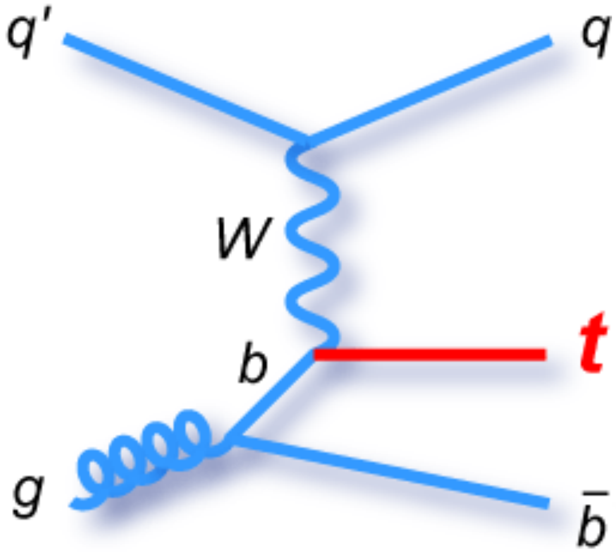
1.98 ± 0.25 pb

0.88 ± 0.11 pb

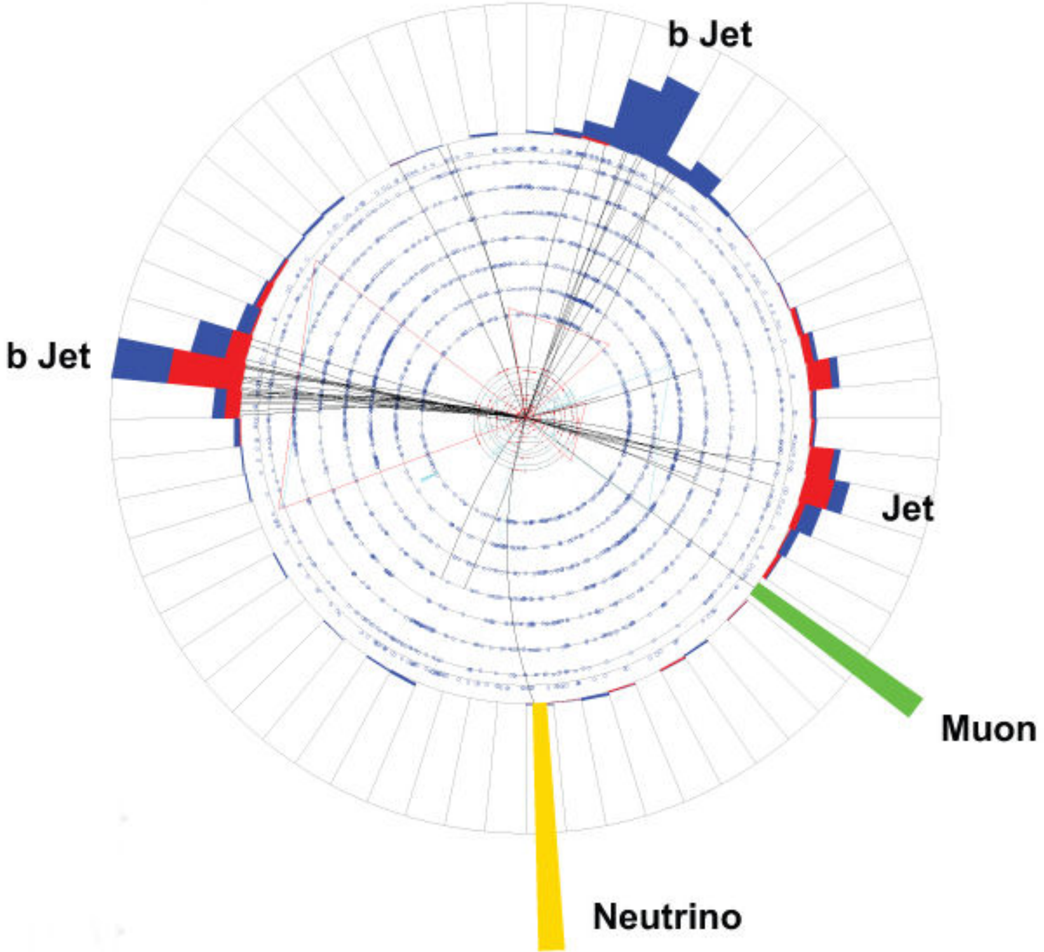
- Directly probes Vtb.
- This is electroweak production – but note that it is comparable to QCD production of ttbar. Why?

The Sort of Events We Look For

You have:
- one and only one top
- a second b-jet
- (possibly) additional jets

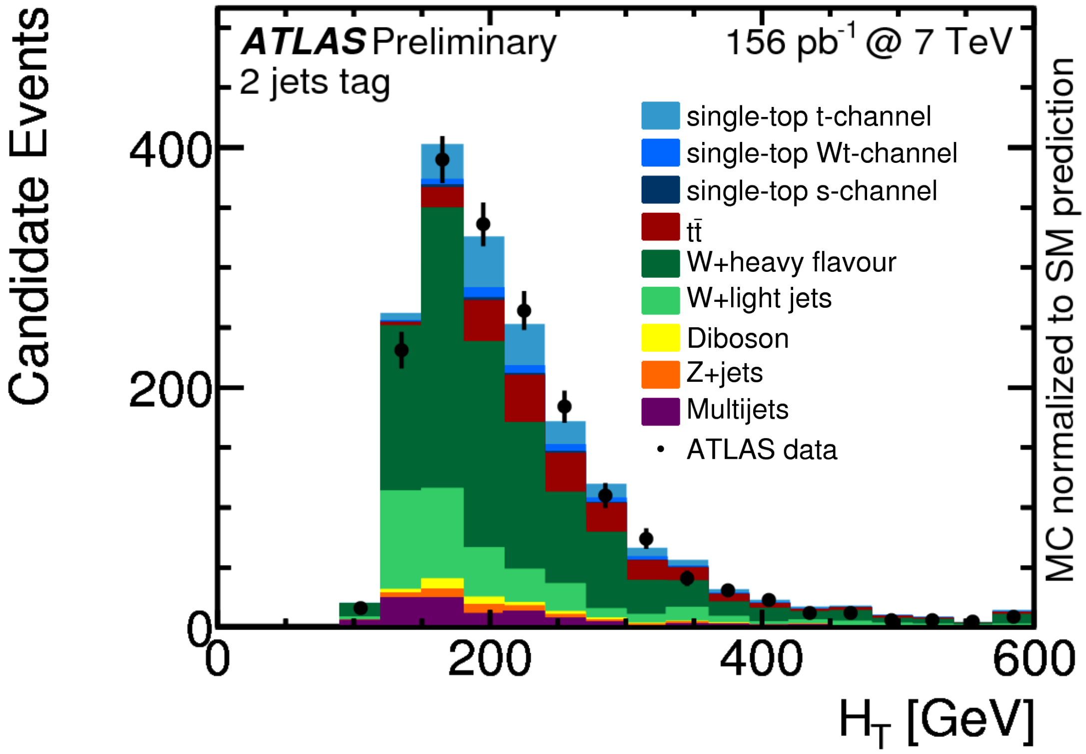


D0 event



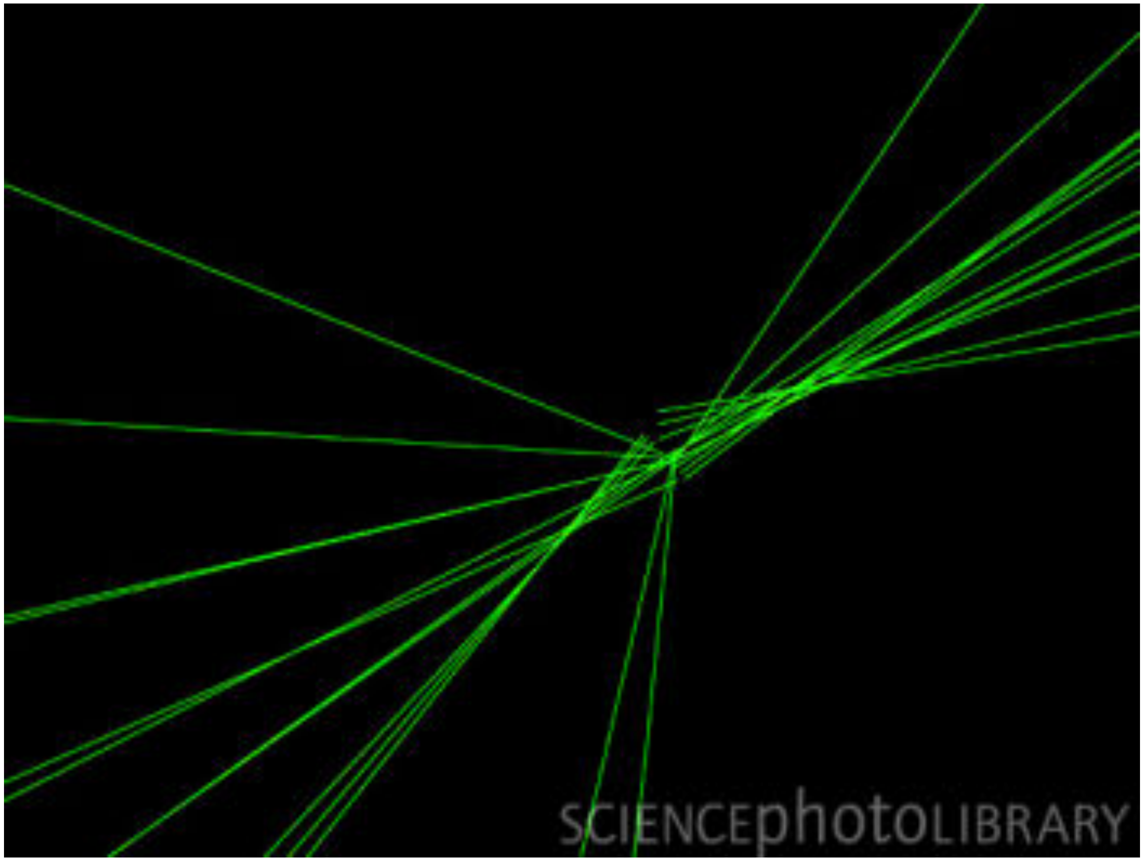
The Data

- The rate of single top is close to expected.
  - That means Vtb is near 1, again, as the SM predicts.
- The backgrounds are difficult
  - There are so many of them.
  - The uncertainty on the background is larger than the predicted signal. This makes an ordinary counting experiment impossible.



Maybe the result isn't so exciting, but the fact that it can be measured at all is amazing.

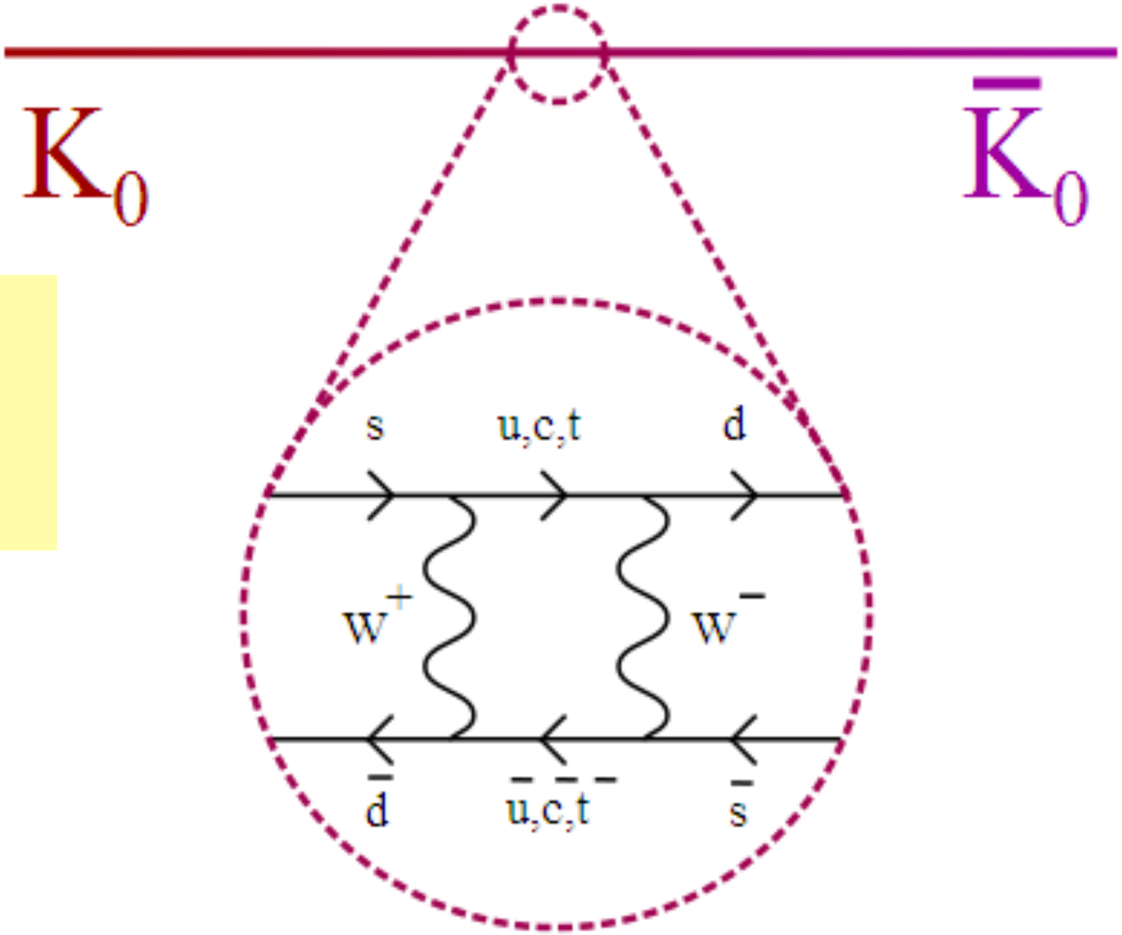
Turning to B's



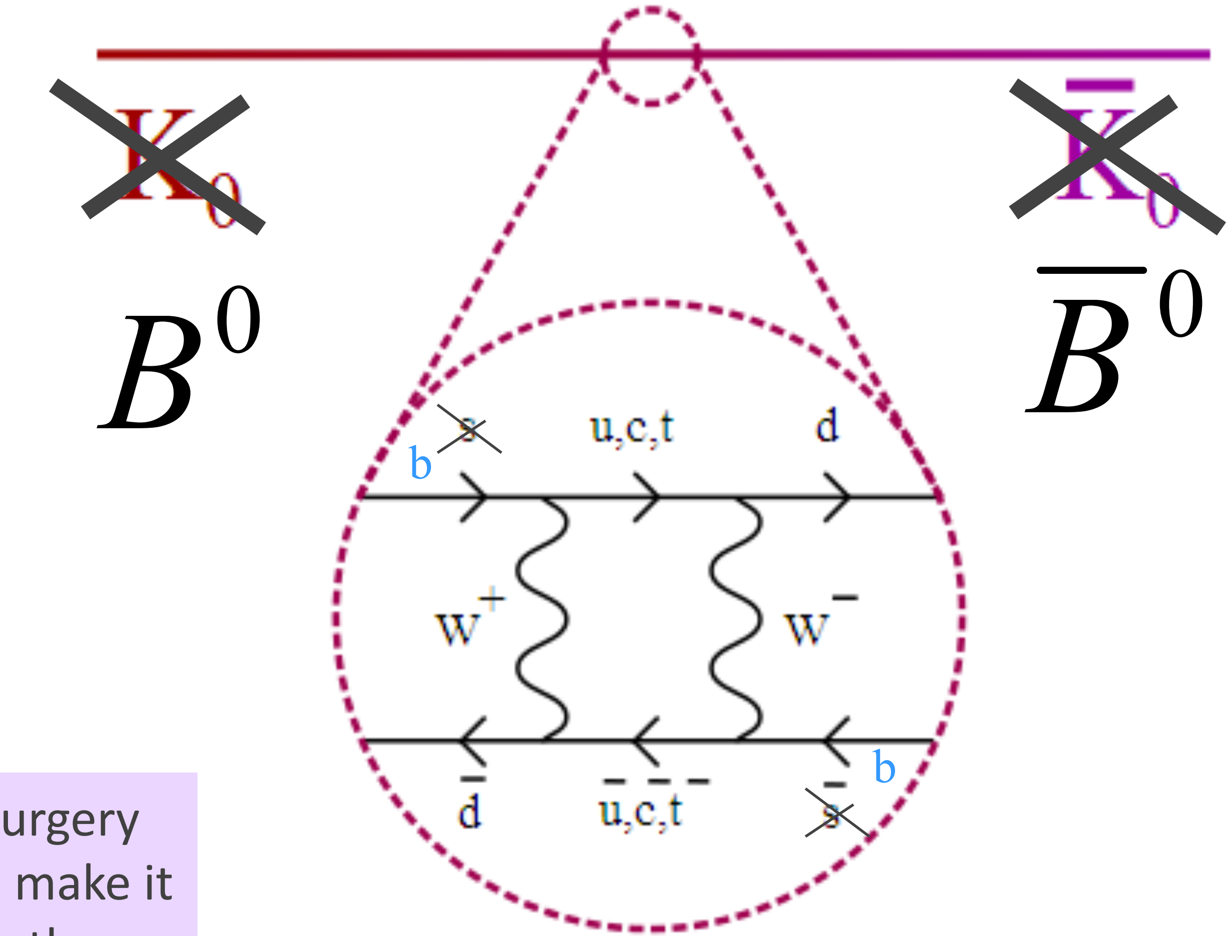
Apart from being a good transition slide, this points out the key feature in b-identification- b's live a long time. (cτ is about ½ a millimeter).

Mixing

A second-order weak interaction allows us to turn a neutral meson into its antiparticle.

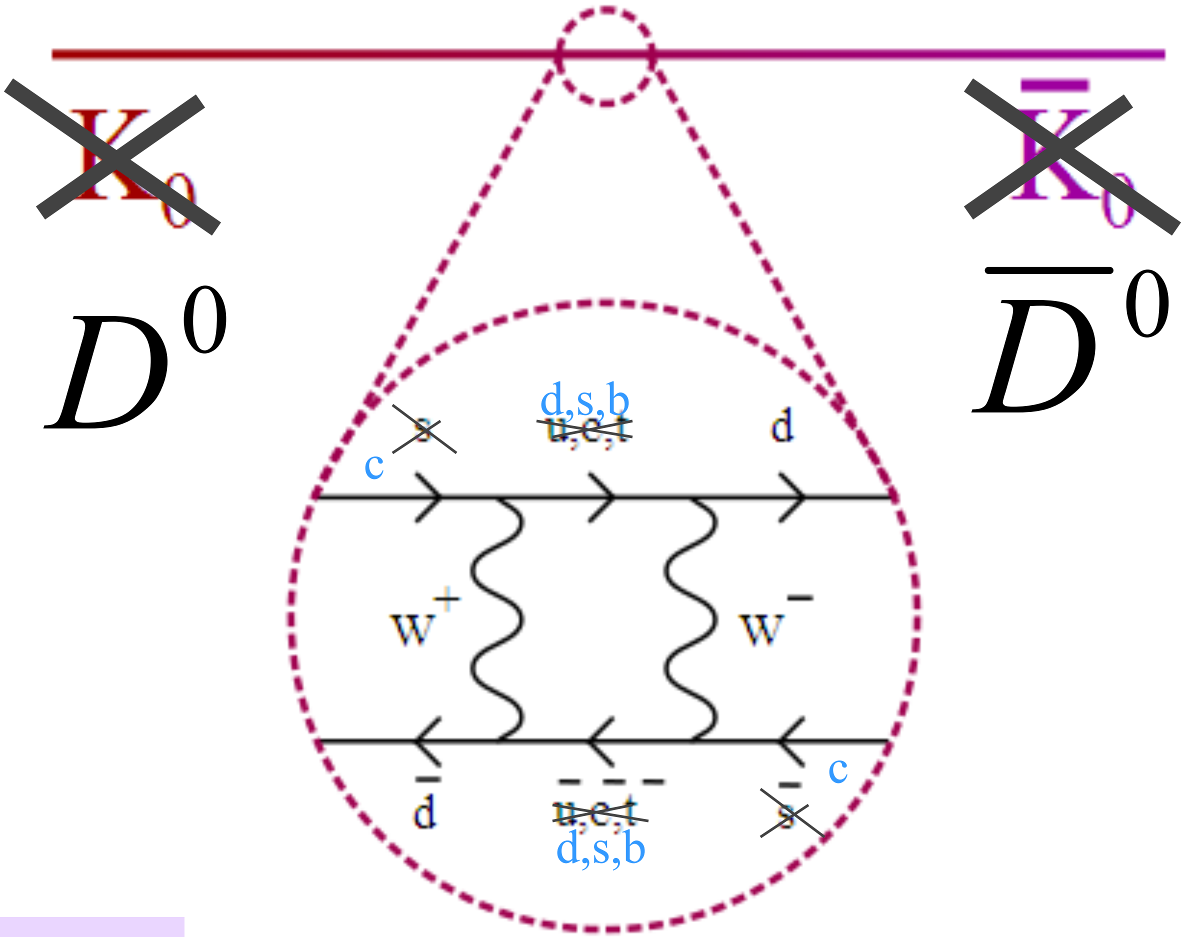


Mixing II



We can do some surgery on this diagram to make it work for particles other than kaons, like B's.

Mixing III

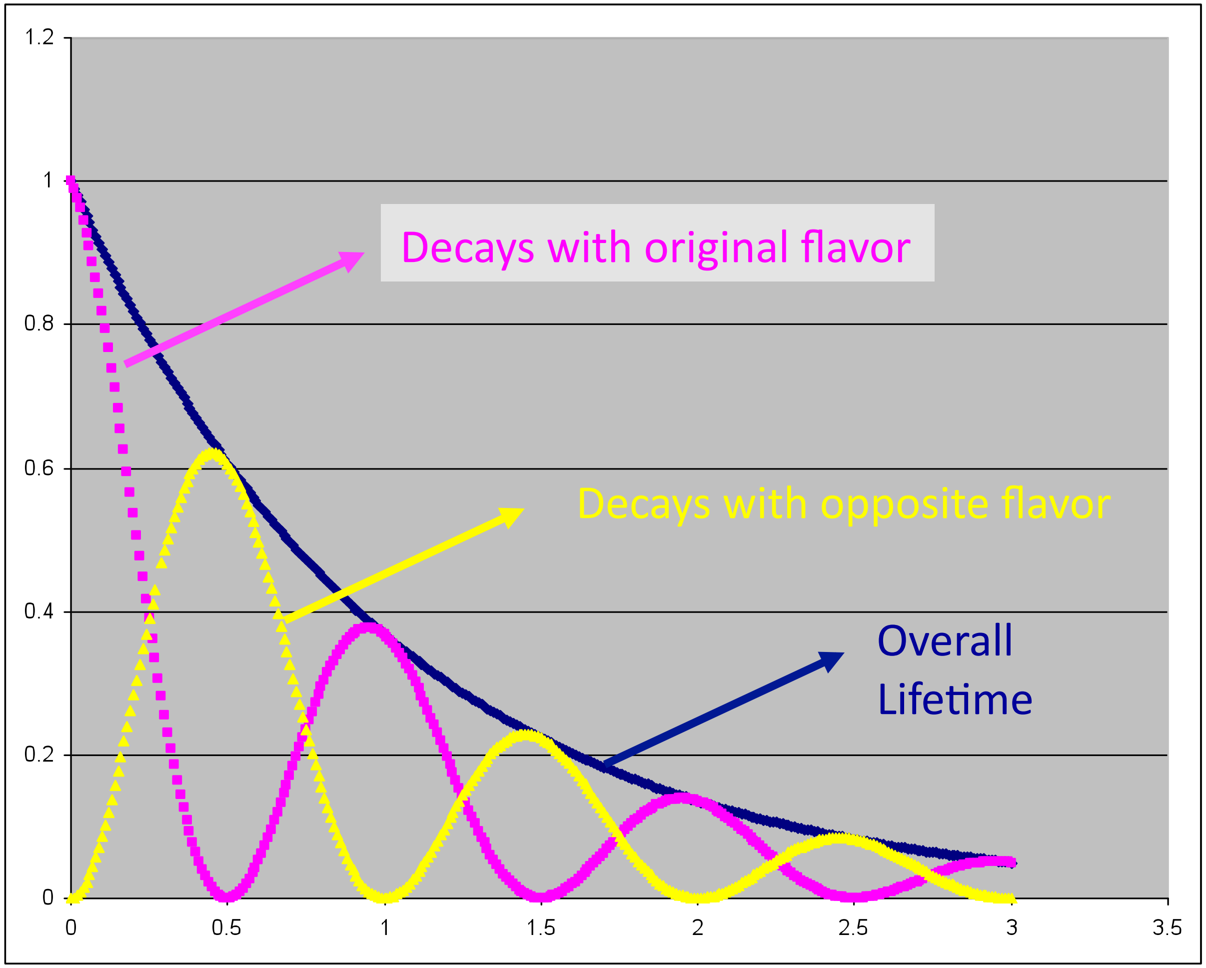


Or even D's

Some Mixing Facts

It is useful to discuss mixing in terms of a variable unimaginatively called “x”.

X is the mixing frequency in units of the lifetime – i.e. a particle mixes on average before it decays.



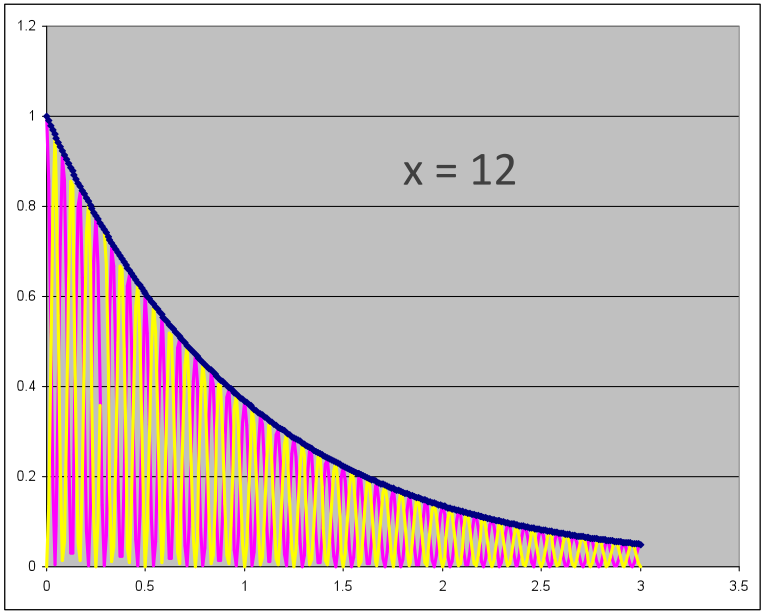
Time (in units of lifetime)

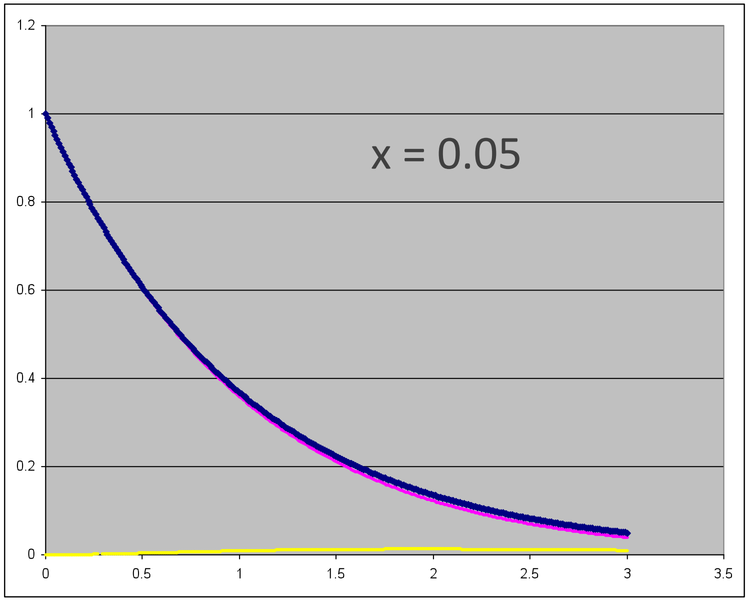
This has x = .774 which is equal to x_d for the B_d meson.

More Mixing Facts

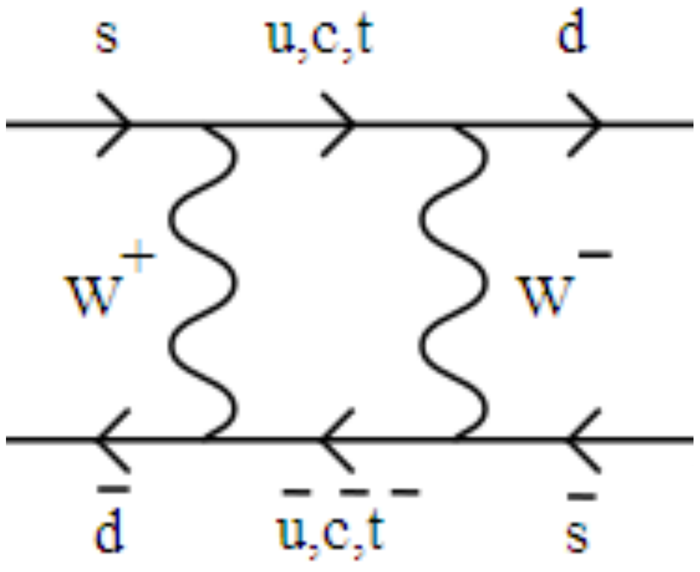
- K's and B's mix like crazy
  - K_L has x near 200
  - B_d has x_d = .774
  - B_s has x_s = 26.2
- D's hardly mix at all
  - x is around a percent
  - (there is also y mixing, which I won't discuss)

WHY?





The Magic of Mixing



- The mixing rate has the virtual quark mass in the *numerator*.
  - The heaviest quark dominates.
- K's and B's mix through the t-quark. The D meson has to mix through a b-quark, which is 35x lighter.
- The same calculation explains why the B_s mixes so much more readily than the B_d.
  - Indeed, this tells us that the branching fraction BF(t → Ws) is larger than BF(t → Wd). Even though we haven't seen either decay.

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_{B_d} f_{B_d}^2 B_{B_d} \eta_B m_t^2 f_2(m_t^2/M_W^2) |V_{td}^* V_{tb}|^2,$$

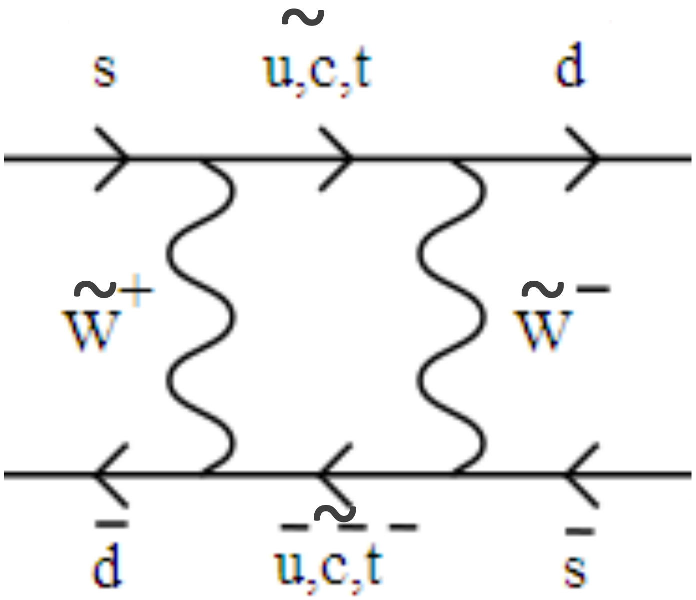
$$\Delta m_s = \frac{G_F^2}{6\pi^2} m_{B_s} f_{B_s}^2 B_{B_s} \eta_B m_t^2 f_2(m_t^2/M_W^2) |V_{ts}^* V_{tb}|^2$$

and

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s} f_{B_s}^2 B_{B_s}}{m_{B_d} f_{B_d}^2 B_{B_d}} \left| \frac{V_{ts}}{V_{td}} \right|^2 .$$

The Magic of Mixing II

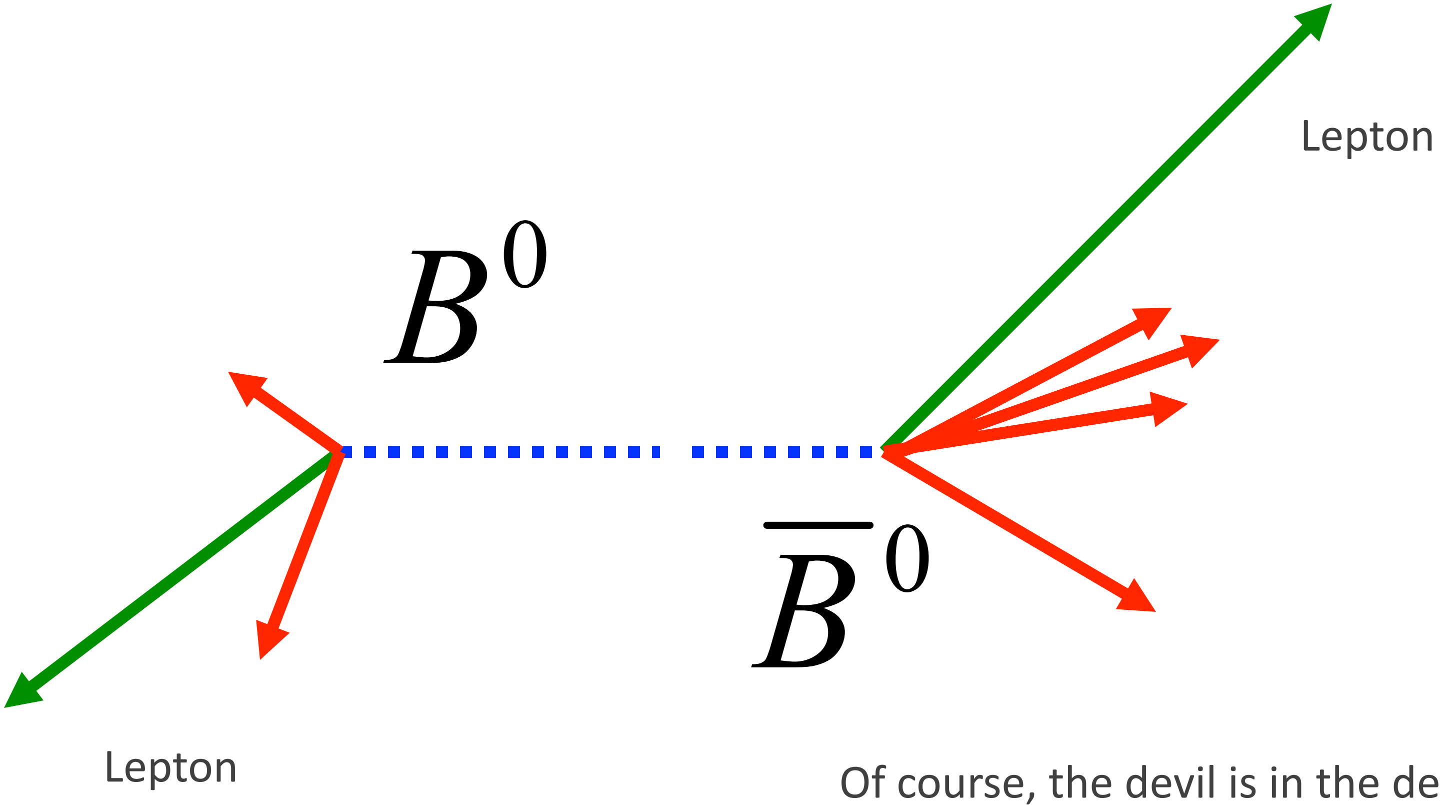
- The mixing rate has the virtual quark mass in the *numerator*.
  - The heaviest quark dominates.
- I can make the box supersymmetric by sprinkling twiddles around.
- Even with very, very heavy sparticles, I can have a very large SUSY-induced mixing:
  - Mixing "touches" the physics at a very high scale.



$$\frac{m_t^2}{m_W^2} \Rightarrow \frac{m_{\tilde{W}}^2}{m_{\tilde{t}}^2}$$

Experimentally, How It Works

- B’s are produced in pairs of opposite flavor.
- When one decays, I know the flavor of the other.



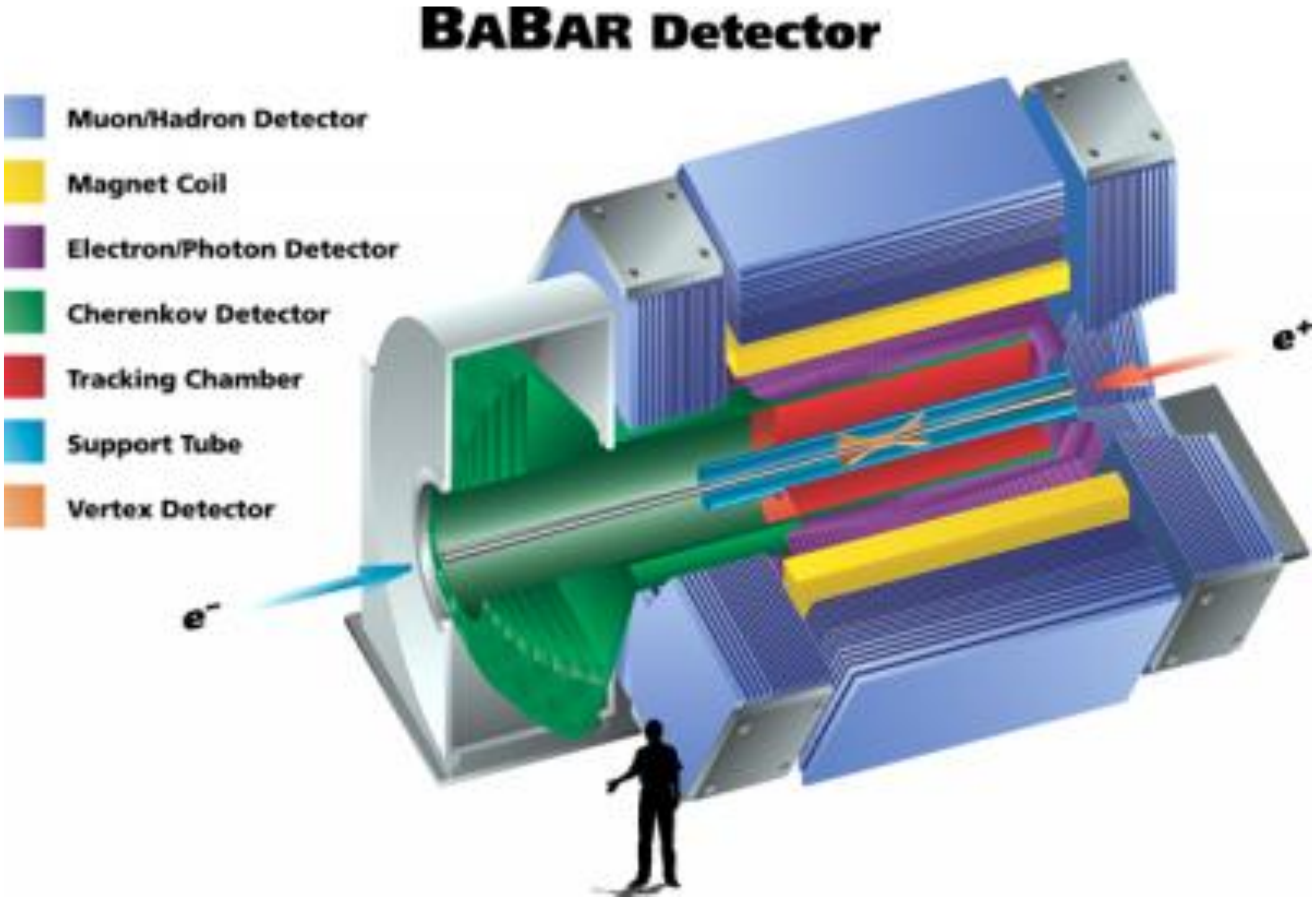
Of course, the devil is in the details…

Now is a Good Time to Discuss The Major Players

Experiment	Years	Beam	Number of b pairs
ARGUS	1982-1992	e^+e^-	Few 100K
CLEO	1979-2000	e^+e^-	~ 10M
UA1	1981-1993	p-pbar	~ 500 M
CDF	1992–2011	p-pbar	~ 40 B
D0	2001-2011	p-pbar	~ 40 B
BaBar	1999-2008	e^+e^- (asym.)	~400 M
Belle	1999-present	e^+e^- (asym.)	~700 M

Mixing was discovered by the observation of same-sign lepton pairs by ARGUS and UA1

An Example e+e- Detector



Electrons vs. Hadrons

- At an e+e- machine works like this: $e^{+}e^{-} \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$

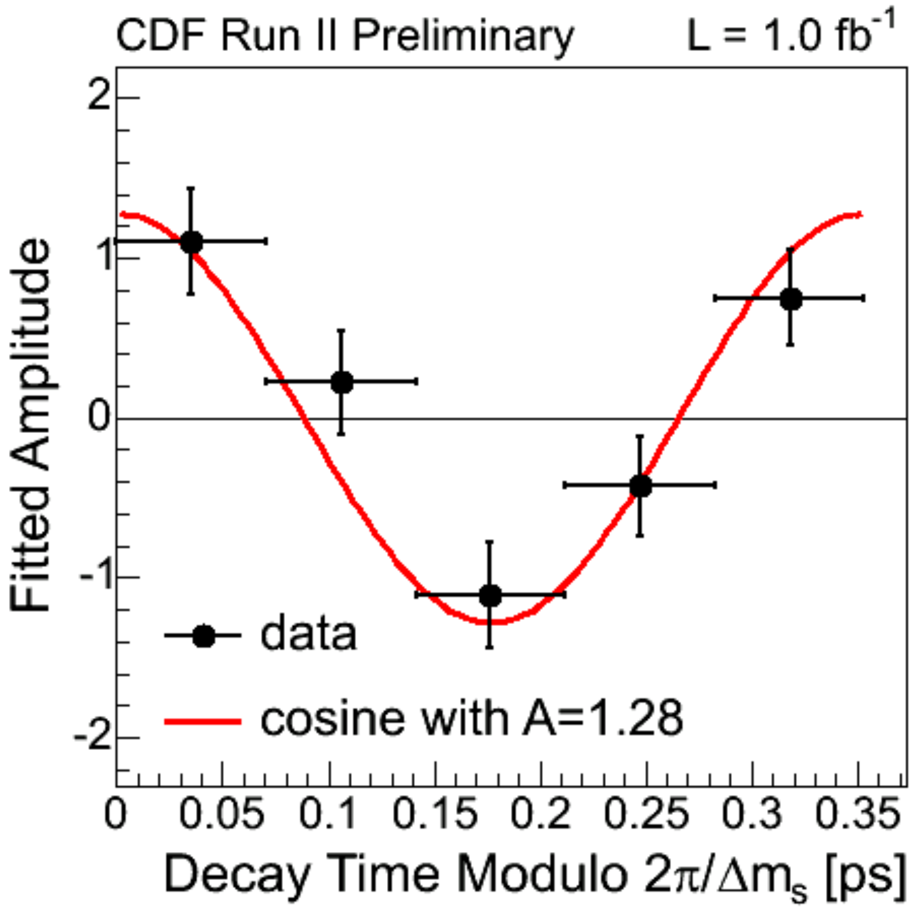
- A hadron machine can produce 100's or 1000's times as many B's.
- However, the number of useful B's is much smaller.
  - You need to be able to trigger on them – that usually means a leptonic decay (1/10), or sometimes a long flight distance
  - Hadron colliders are less good at detecting neutral particles (LHCb is an exception) –so you want decays with zero photons or neutrons
  - Often you need a significant boost to reconstruct all of the decay products

$$B^{+} \rightarrow J/\psi K^{+}, J/\psi \rightarrow \mu^{+}\mu^{-}$$

1% x 6% =.0006

Bs mixing: some data

- Bs's mix fast – 26.2 times faster than they decay.
- CDF took the mixing curve, and "wrapped it around itself" 26.2 times.
  - This integrates out over the amplitude, and lets us see the phase.
- The scale on this plot is 350 fs – about 1/10th of a millimeter.



CP-violation

$$\begin{tikzcd}
B^0 \arrow[rr] \arrow[dr] & & J/\psi + K_S^0 \\
& \overline{B}^0 \arrow[ur] &
\end{tikzcd}$$

- You can see CP violation in the *interference* between two amplitudes:
  - In this case, through the direct and mixed path to two final states.
  - Probes phases in the unitarity triangle

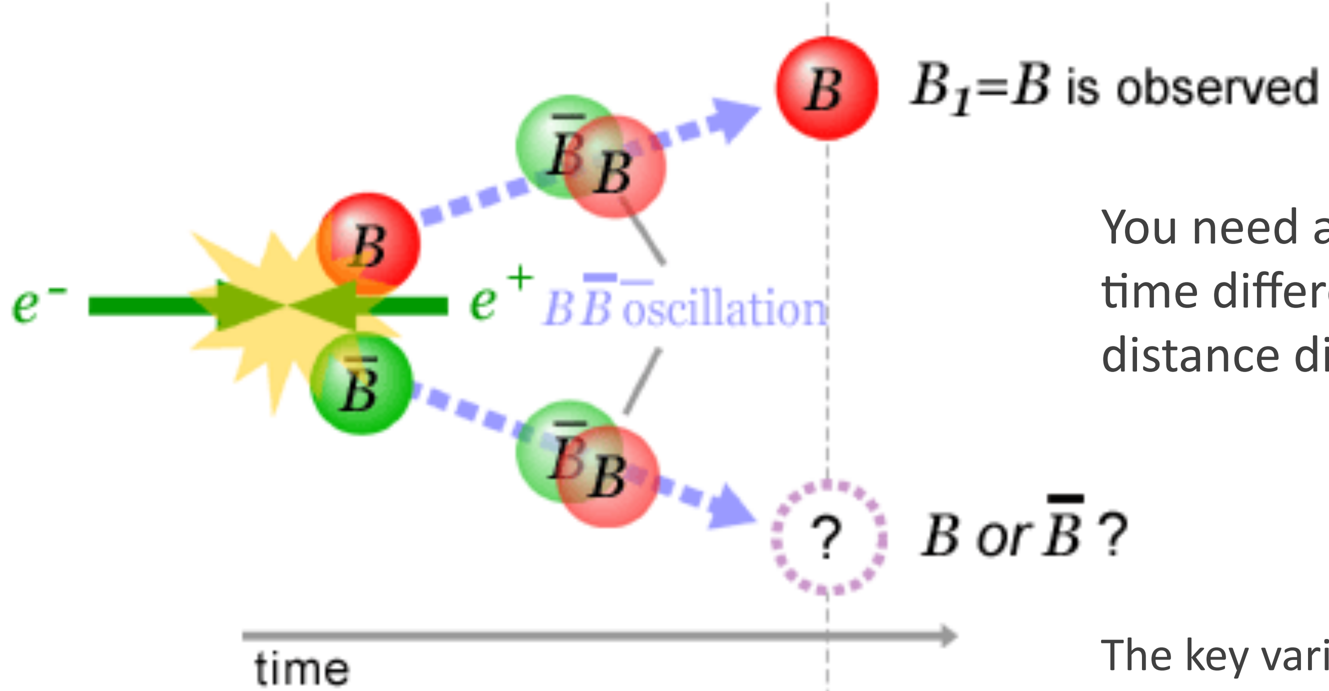
- With interference effects, effects are strongest with two comparable amplitudes.
  - $(a+b)^2 = a^2 + 2ab + b^2$

- In kaons, the effects are small. Because B's mix like crazy, and because even without mixing you can have two different Feynman diagrams leading to the same final states, the CP asymmetries can be large – like 60%. (For kaons, they are a part per thousand)

A multi-hour lecture in itself!

Why Asymmetric B-Factories?

This is a consequence of the weirdness of quantum mechanics.

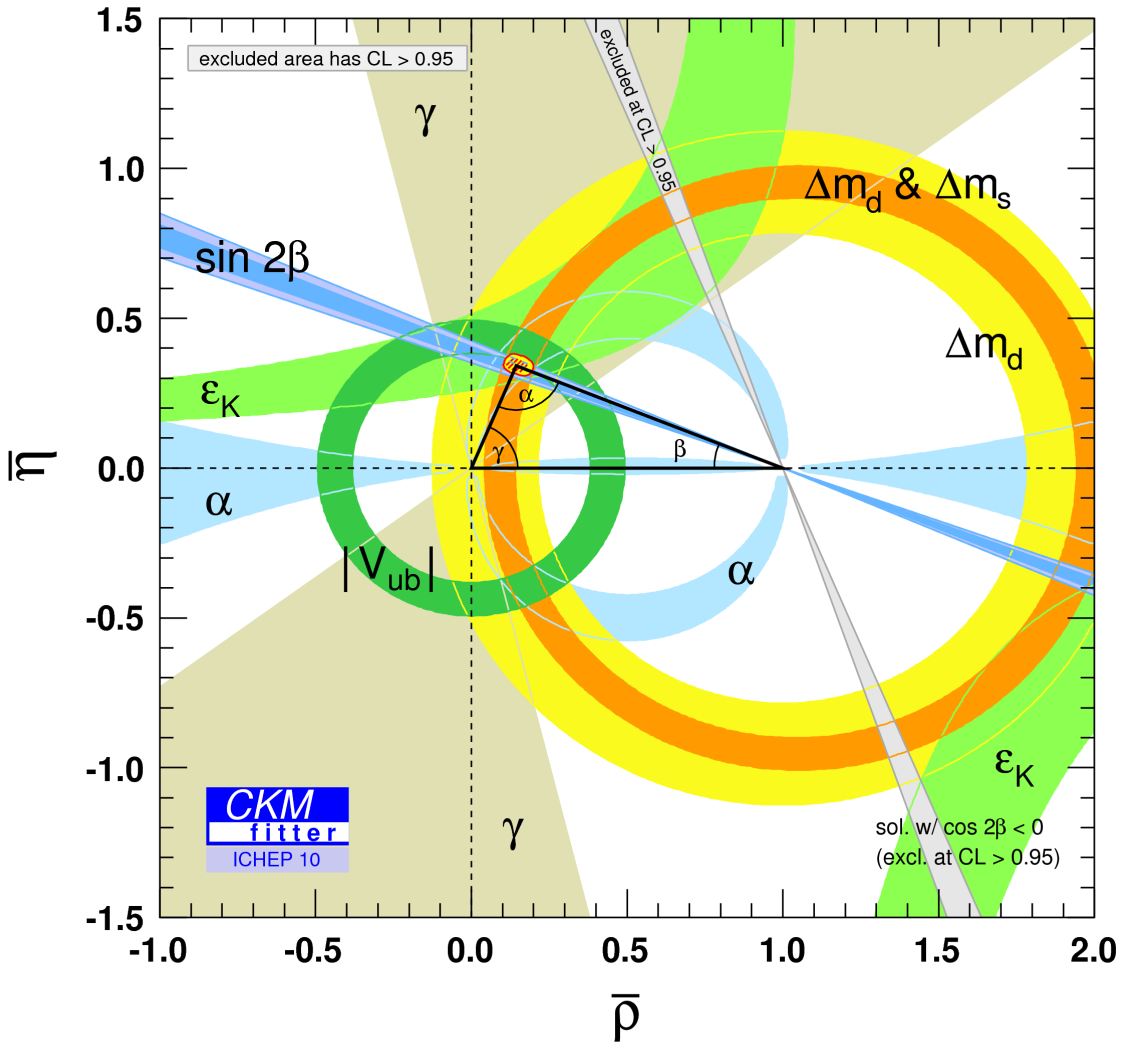


You need a boot to turn a time difference into a distance difference.

The key variable in oscillations is not t, but Δt.

When does a neutral B meson know its flavour?

Combining all Measurements



Global fits of all the measurements – sides and angles – suggest the unitarity triangle is either closed, or very close to closed.

A Fourth Generation?

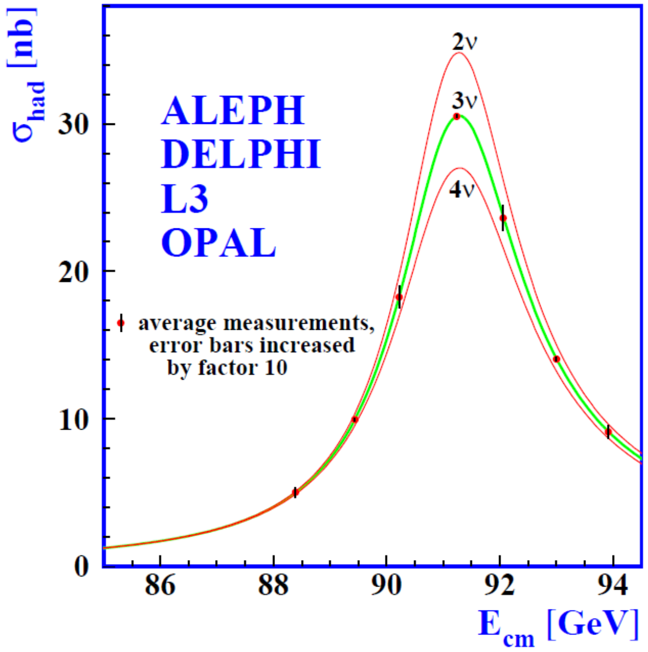
$$\begin{pmatrix} e \\ \nu_e \\ u \\ d \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \\ c \\ s \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \\ t \\ b \end{pmatrix} + \begin{pmatrix} \sigma \\ \nu_\sigma \\ t' \\ b' \end{pmatrix} ?$$

A Fourth Generation

- There are severe electroweak constraints on such a generation.

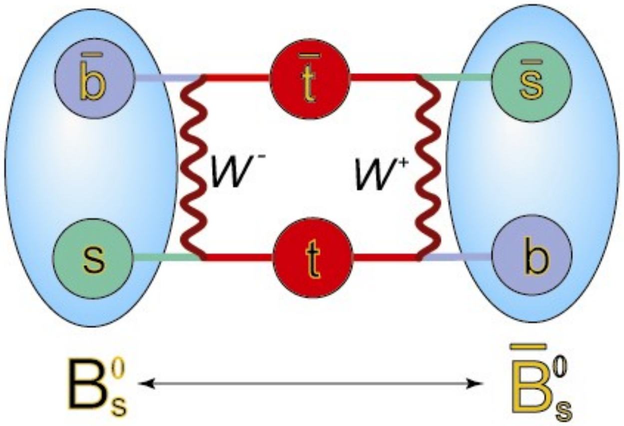
- First, the neutrino must be heavy (>45 GeV)
  - Otherwise the Z would decay to these neutrinos, which would be visible in the Z width and branching fractions (20% invisible).

- Next, the quark and lepton doublets need to be almost degenerate:
  - The W mass loops are sensitive to the mass differences between doublet members
    - The top and bottom already have “saturated” this.



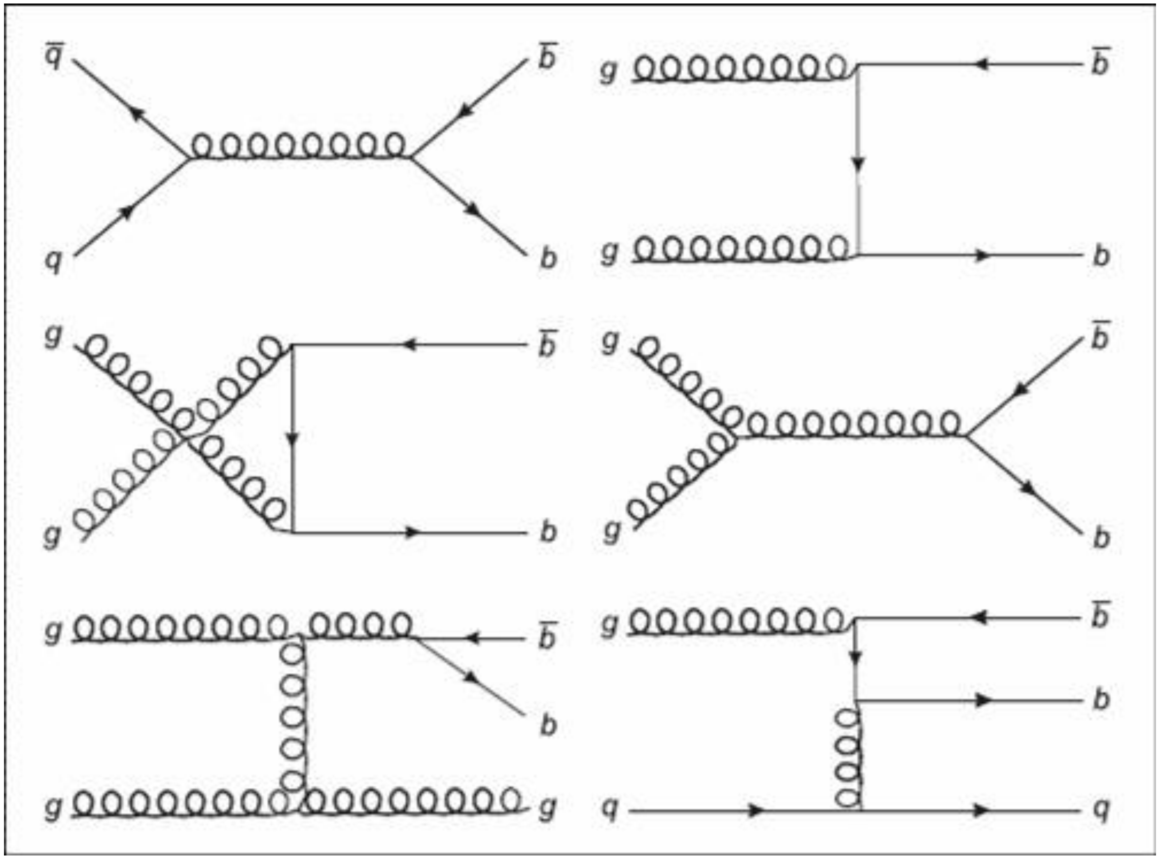
A Tight Fit

- In addition to precision EWK, there are other difficulties a 4th generation faces:
  - Remember, neutral K's and B's mix quickly, but neutral D's mix slowly.
  - With 3 generations, this is because the heaviest u-type quark (top) is much heavier than the heaviest d-type quark (bottom)
  - With a heavy, degenerate 4th generation, this is no longer true: it would have to be due to CKM suppression
    - Adds 3 new angles and 2 new phases: enough to do this.



- It's possible to have a 4th generation, but all of the parameters associated with it have to magically conspire to make it look like there are exactly 3 generations.

B-quark Production

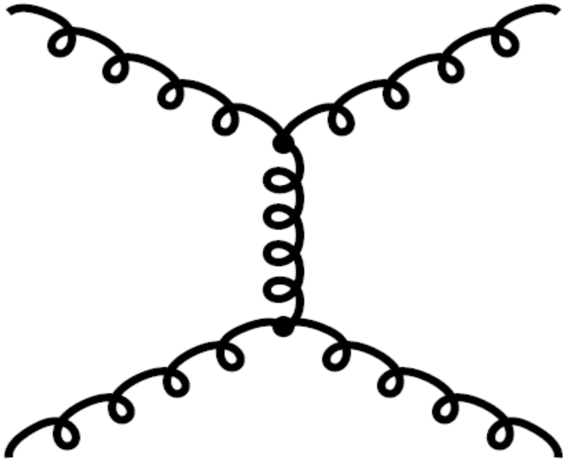


We organize these diagrams as “flavour creation”, “flavour excitation” and “gluon splitting”.

At collider energies, the NLO contributions are huge.

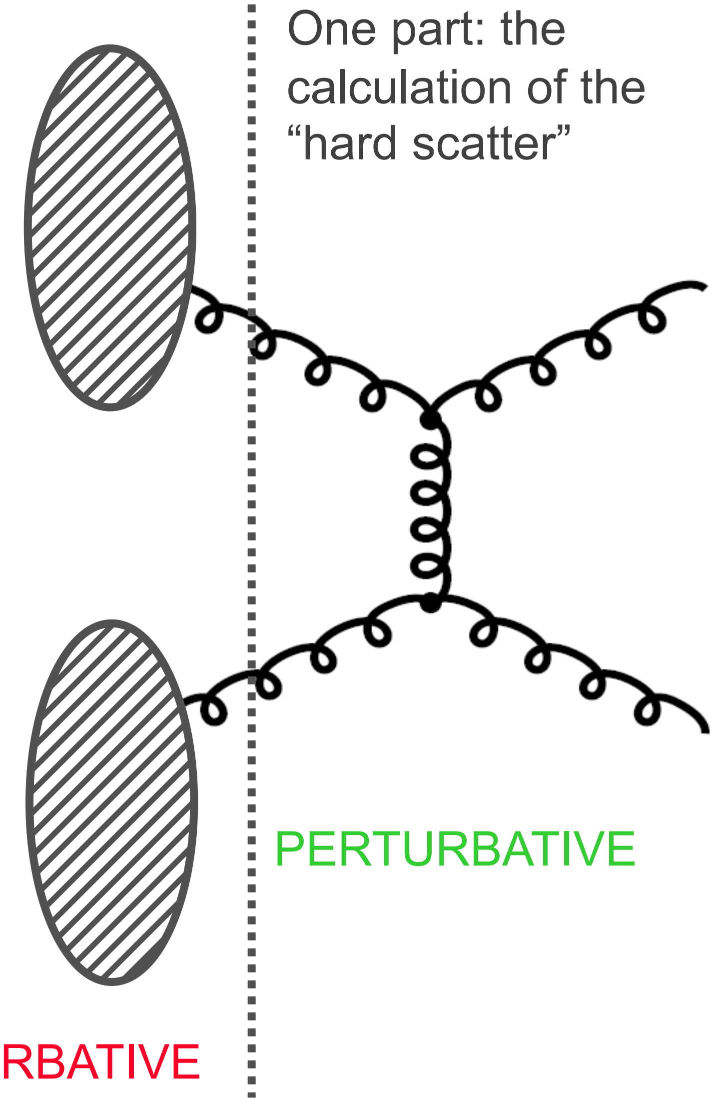
Reminder: Portrait of a Simple QCD Calculation

One part: the
calculation of the
“hard scatter”



PERTURBATIVE

Reminder: Portrait of a Simple QCD Calculation



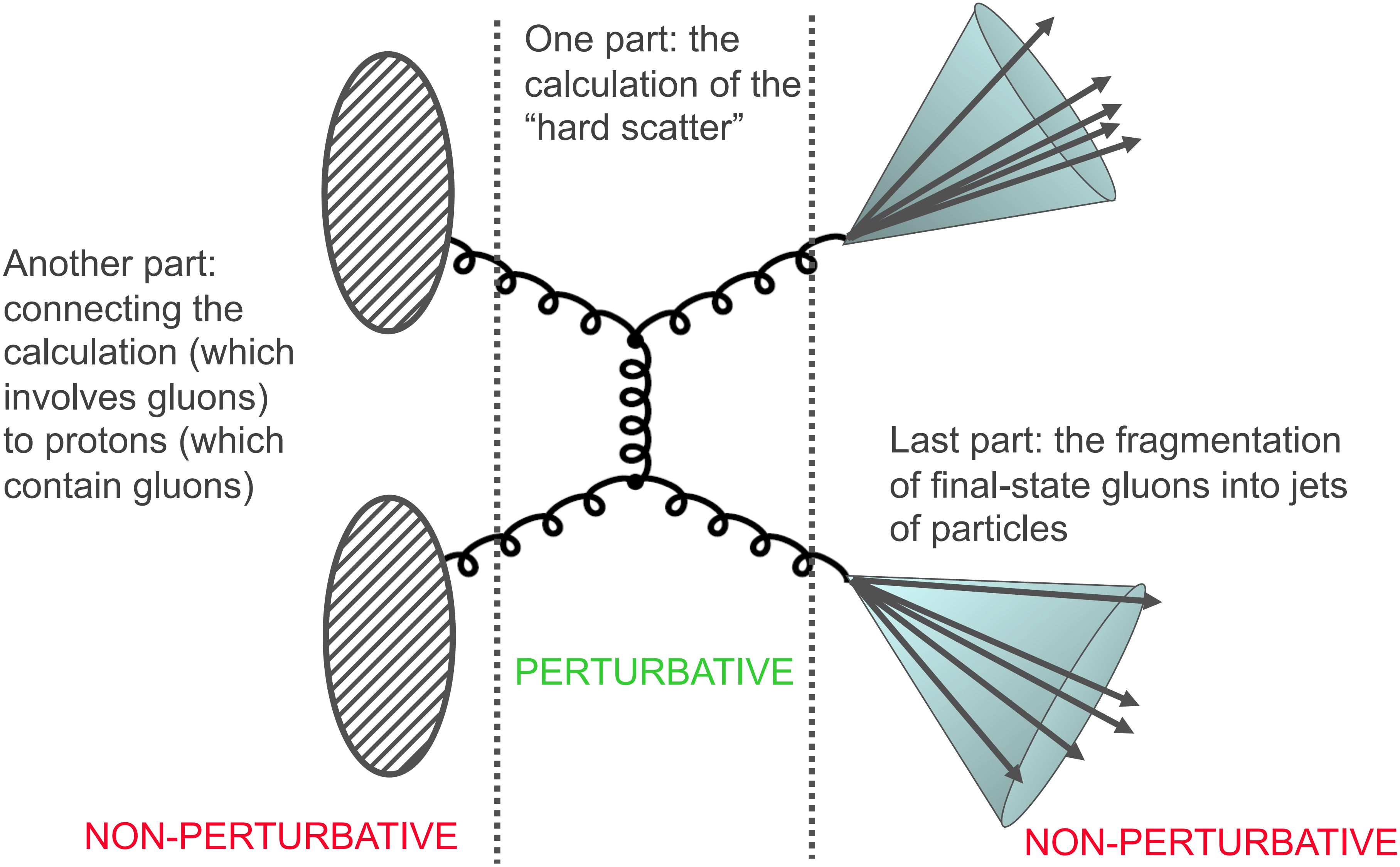
One part: the calculation of the "hard scatter"

Another part: connecting the calculation (which involves gluons) to protons (which contain gluons)

PERTURBATIVE

NON-PERTURBATIVE

Reminder: Portrait of a Simple QCD Calculation



One part: the calculation of the “hard scatter”

Another part: connecting the calculation (which involves gluons) to protons (which contain gluons)

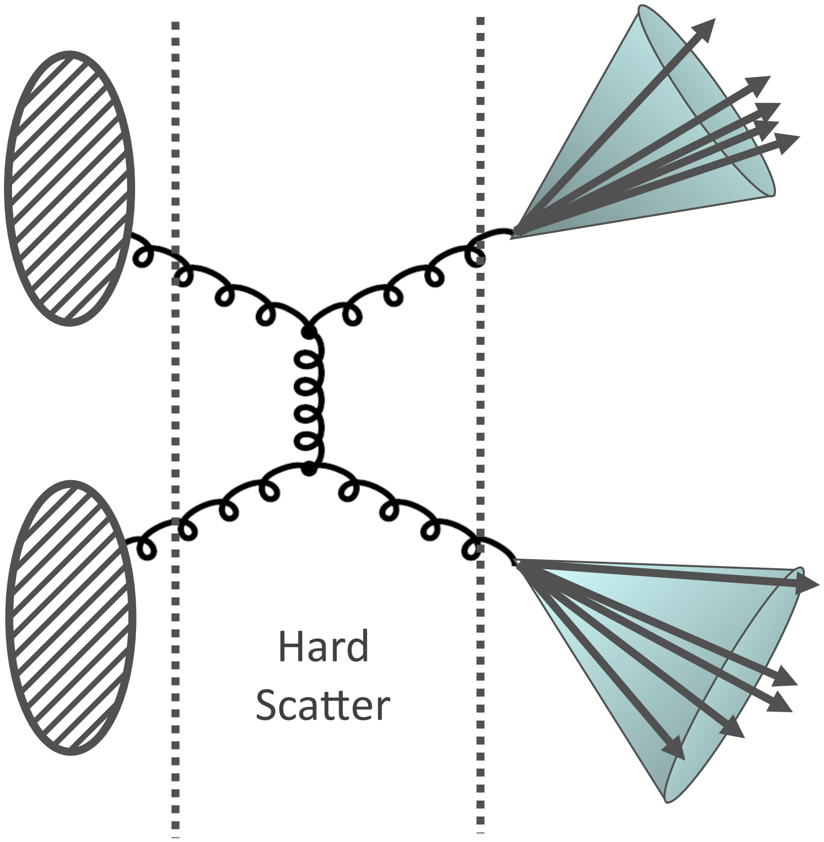
Last part: the fragmentation of final-state gluons into jets of particles

PERTURBATIVE

NON-PERTURBATIVE

NON-PERTURBATIVE

Comparison with Experiment



Hard
Scatter

Parton
densities

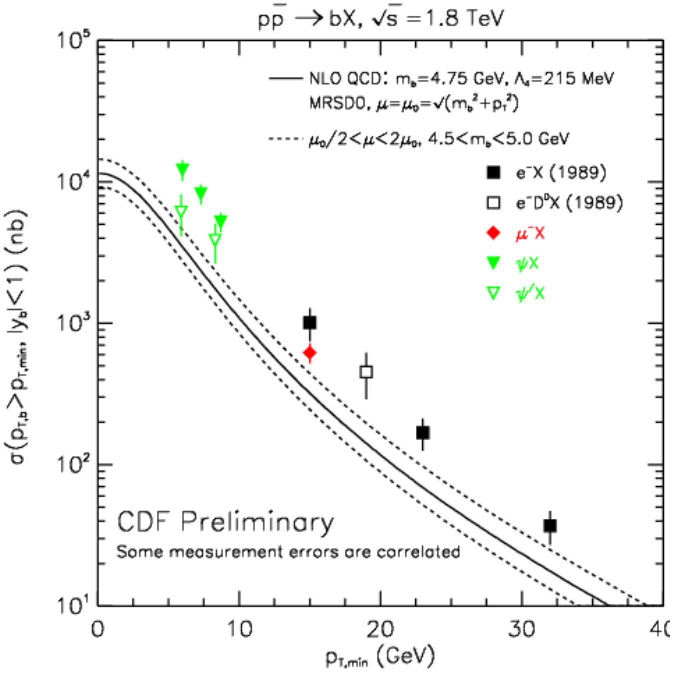
Fragmentation

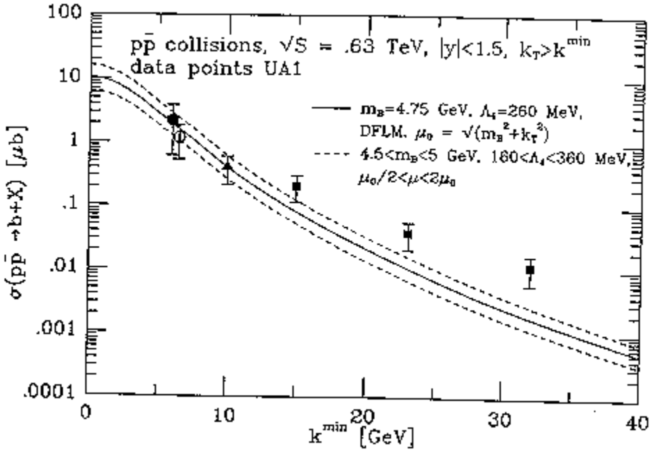
- Our experience has been that progress is made when we already know 2 of the 3 parts.
  - Experiment then constrains the third.
- It is possible to gain information when this is not true, but the situation is much more confusing.

The b-quark cross-section saga

- At DPF92, CDF reported bottom quark cross-sections a factor of at least two greater than theory.
- This was at a center of mass energy of 1800 GeV.
- The 1989 UA1 measurements at 630 GeV agreed better with theory
    - However, both theoretical and experimental uncertainties were substantially larger.

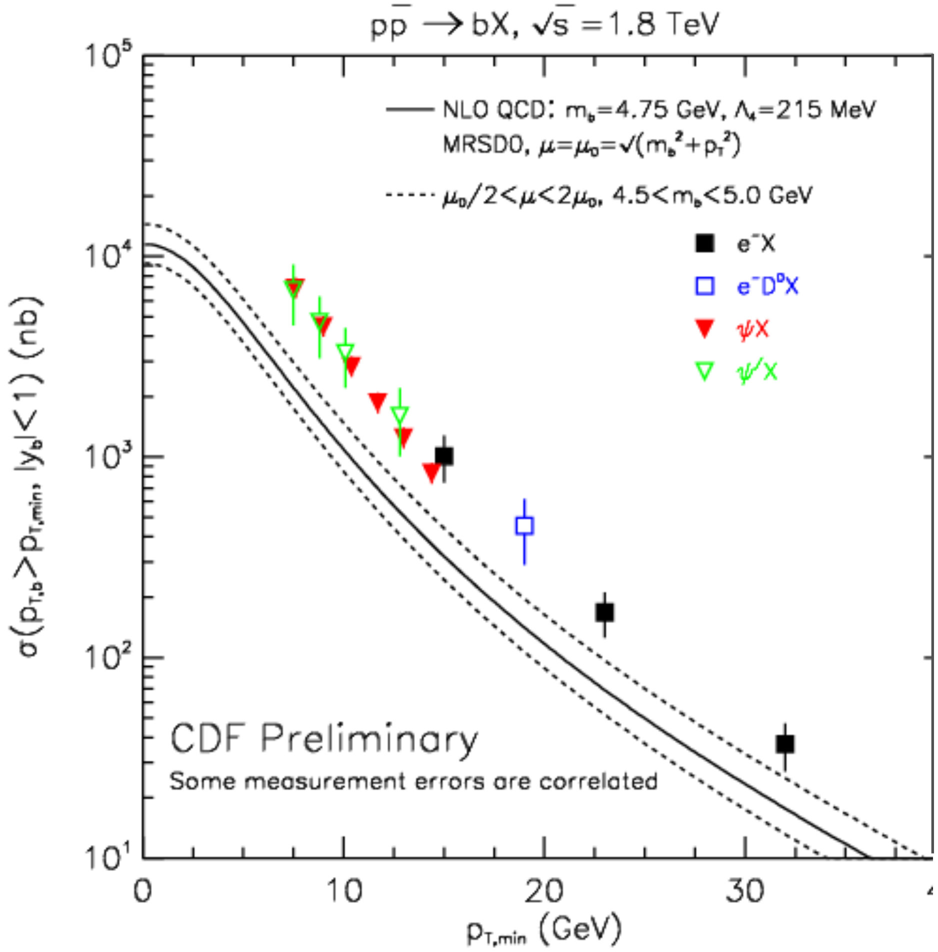
Community reaction: someone (i.e. CDF) probably mismeasured something. Wait a while and this will go away.



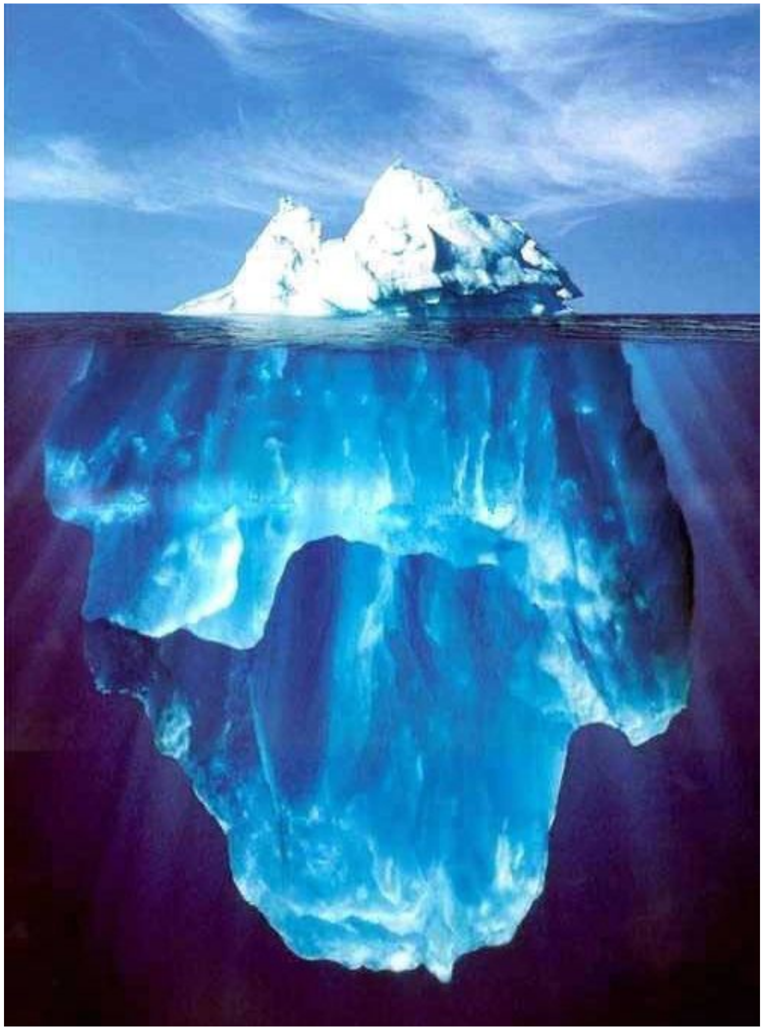


But, it didn’t go away.

- More recent CDF measurements showed the same difficulty – the theory underpredicts the data by the same factor
- This problem was not going away
- Note that CDF (and also D0) measures only the high p_T tail of the cross-section
  - Most b’s were invisible.



Commentary on measuring the top 10% of something



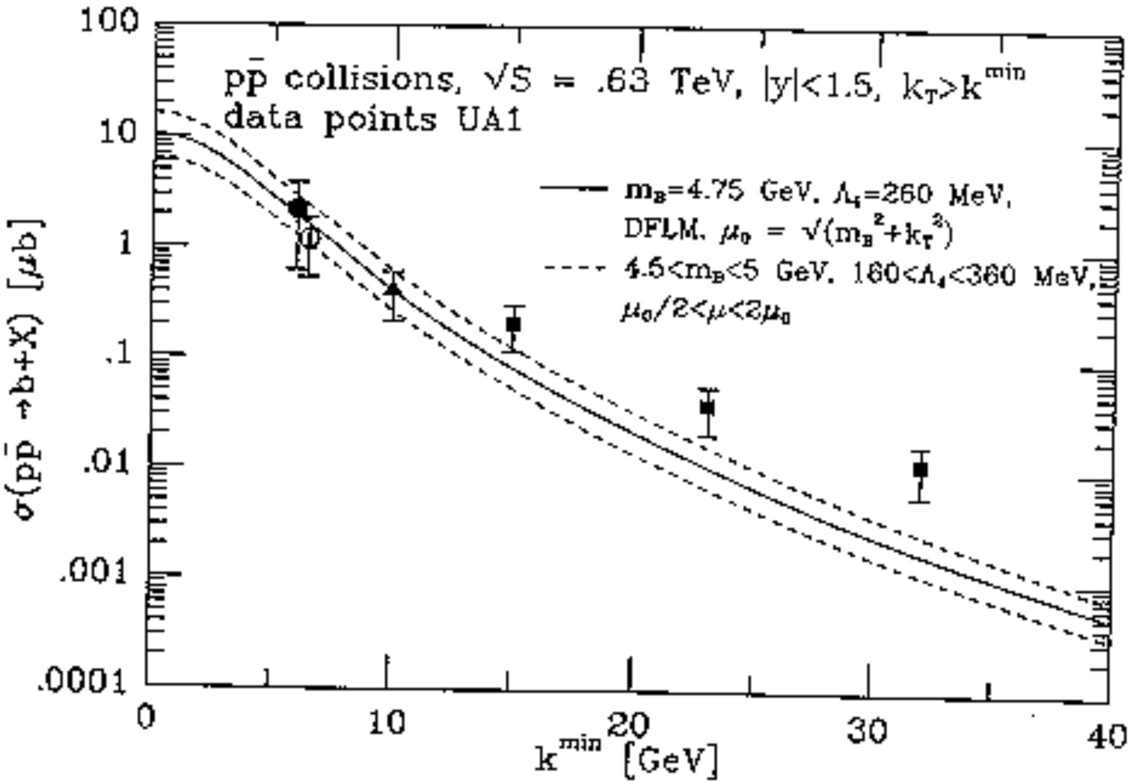
Just how important could the other 90% be anyway?

Understanding the x-axis: p_T(min)

- Ideally, one would like to measure the differential cross-section $d\sigma/dp_T$.
  - Allows comparison with theory in magnitude and shape of the cross-section.

- If this is difficult, one could quote just the total cross-section.
  - Many experiments are insensitive to the cross-section below a p_T threshold.
  - It makes no sense to quote the total cross-section if you have no acceptance to anything below (e.g.) 10 GeV, where the bulk of the cross-section is.
  - To deal with this, experiments quote the cross-section at a certain p_T(min): the point where 90% of the *b*'s lie above.
    - This 90% is pure convention – we could have picked some other number

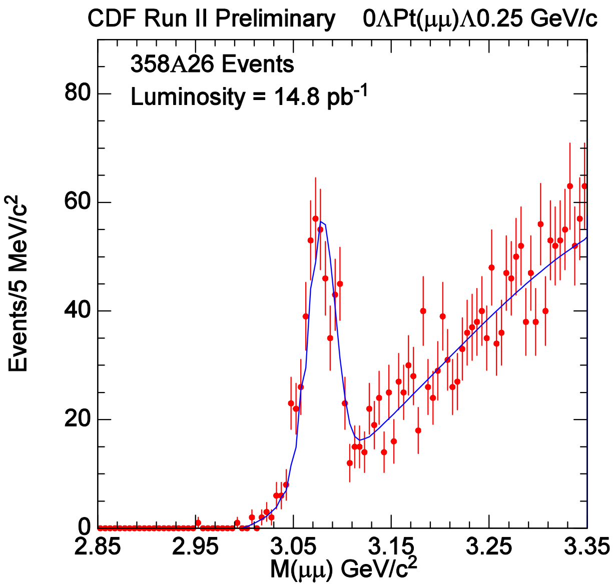
A Comment On Sociology



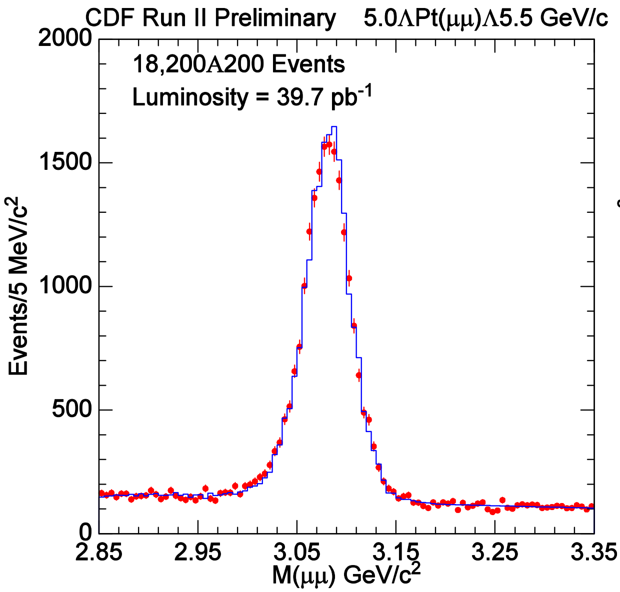
Is this “agreement”?

This was eventually resolved, building on a set of CDF measurements a few years ago.

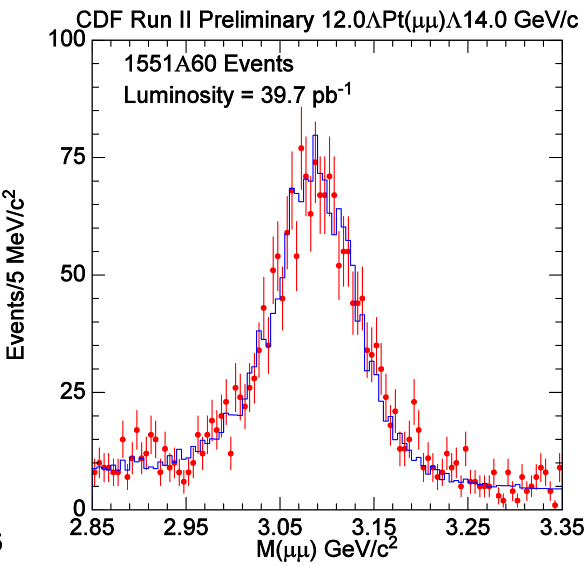
Step 1: Measure the J/ψ yield in selected p_T bins



p_T < 250 MeV (lowest bin)



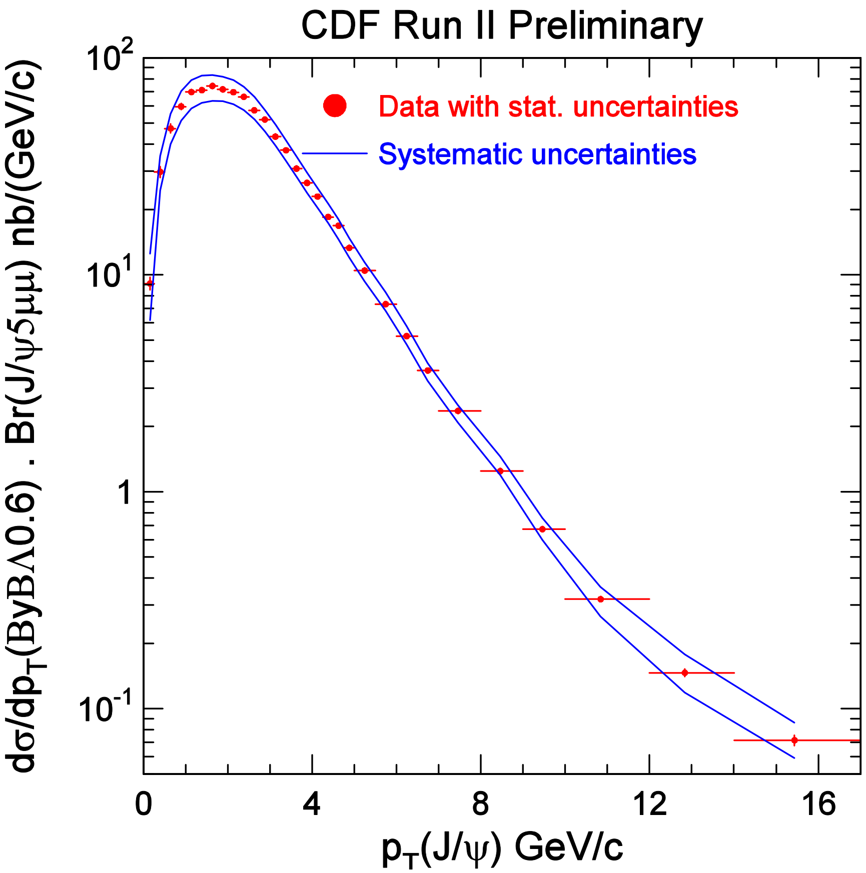
5.0 < p_T < 5.5 GeV

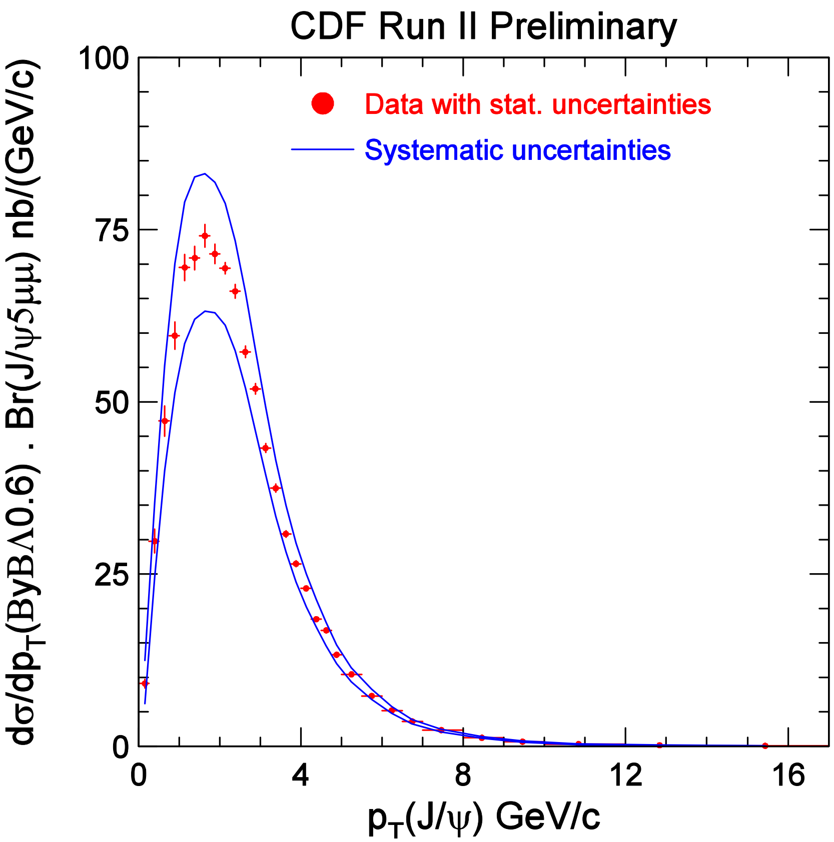


12 < p_T < 14 GeV

Yield is fit in each bin, corrected for acceptance and efficiency, and the cross-section bin-by-bin is calculated.

Step 2: Convert This To a Cross-Section



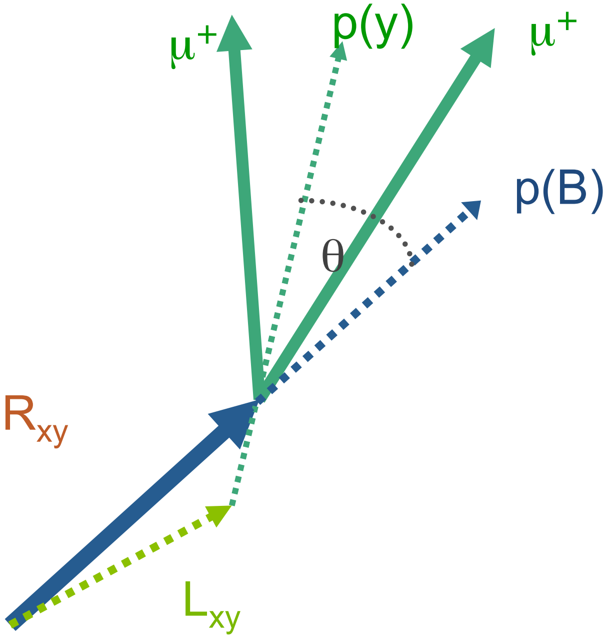


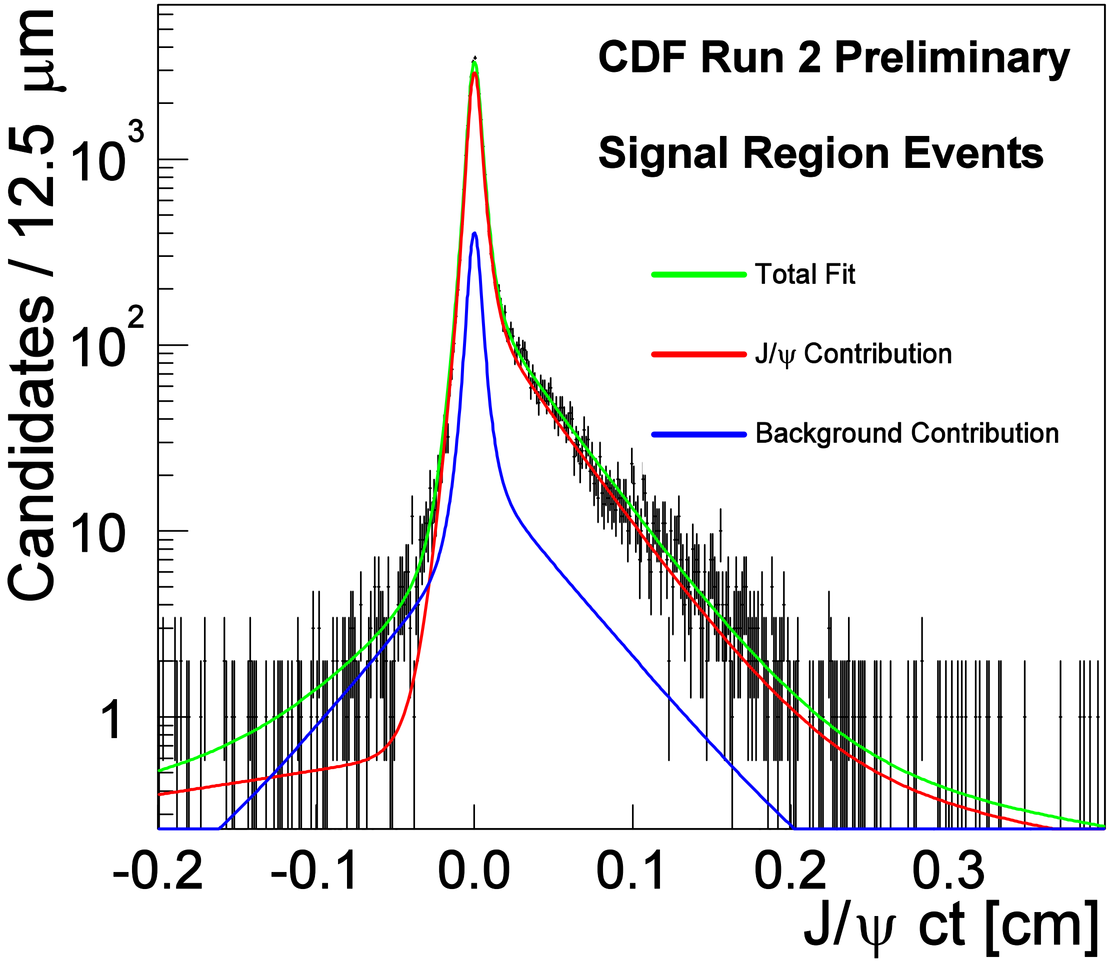
$$\sigma \cdot BF(J/\psi \rightarrow \mu\mu) = 240 \pm 1^{+35}_{-28}\ \text{nb}$$

(for |y| < 0.6)

Step 3: Measure the Fraction of J/ψ’s from b’s

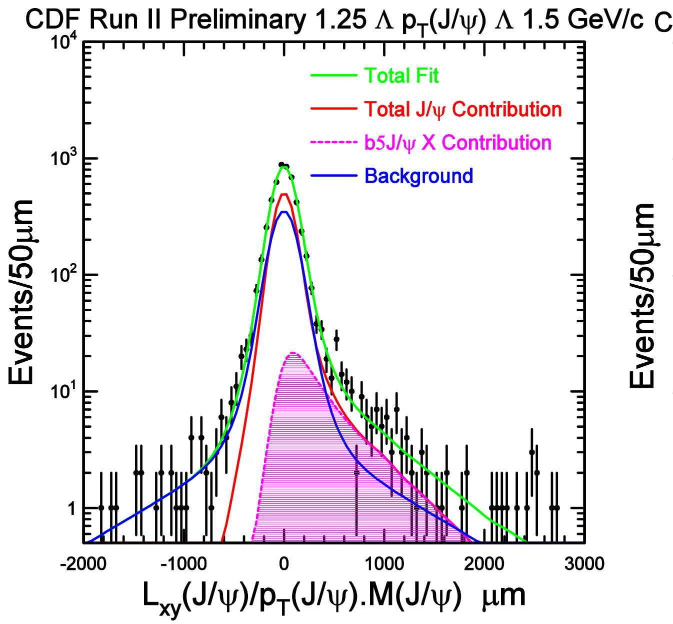
- Most J/ψ’s do not come from b’s. But a sizeable fraction are produced mm away from the interaction point. These are b daughters.





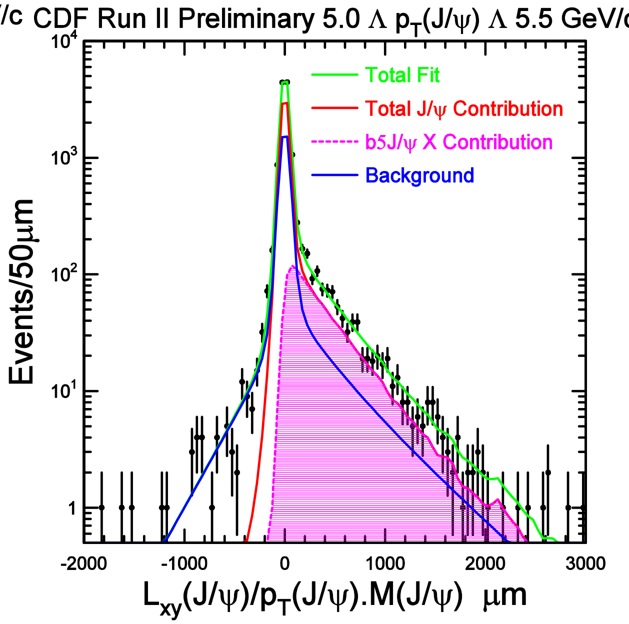
Step 3 (continued) - Do this in each bin of p_T.

1.25 < p_T < 1.5 GeV (lowest bin)



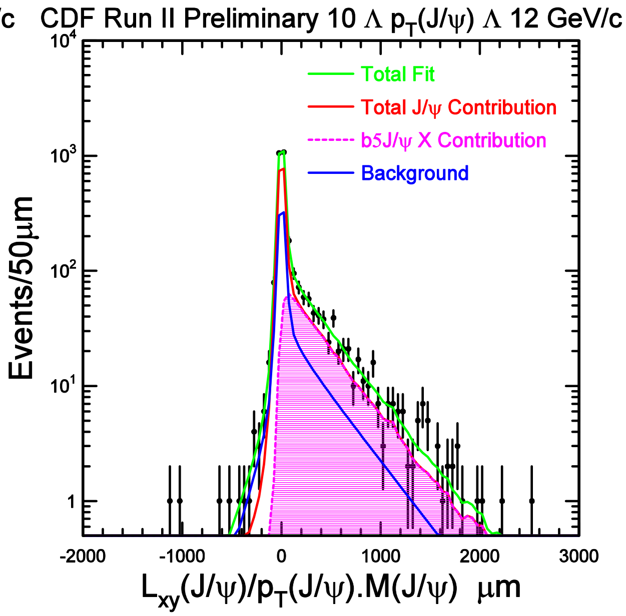
9.7 ± 1.0 % b's

5.0 < p_T < 5.5 GeV



14.3 ± 0.5 % b's

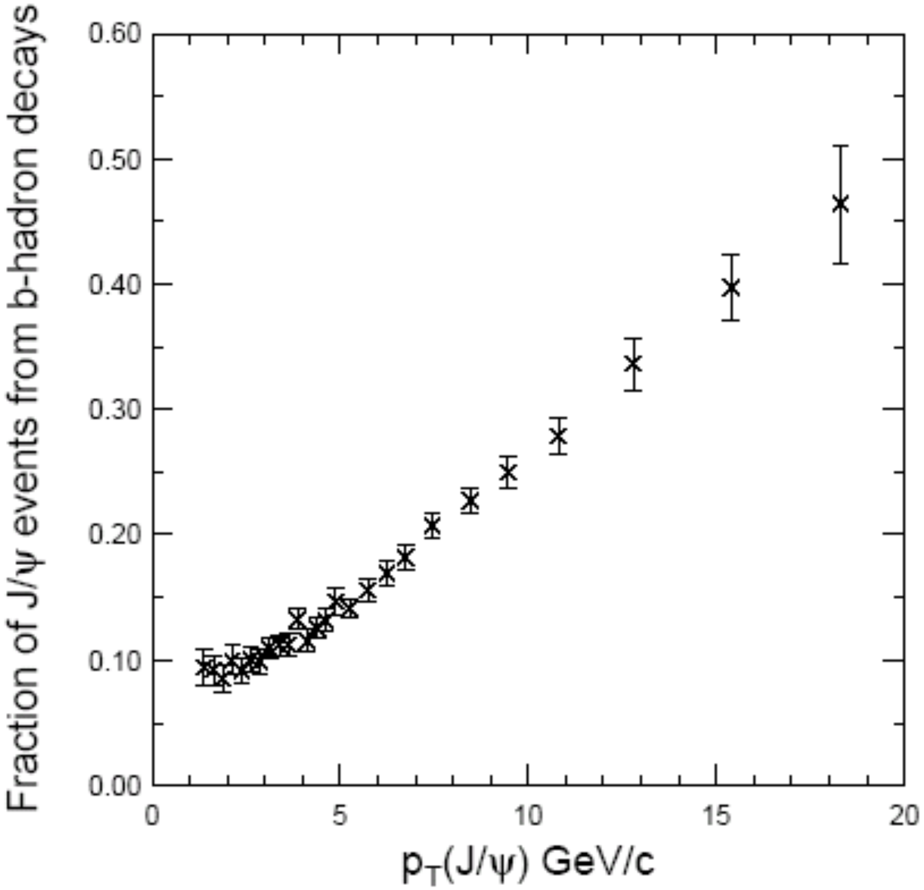
10 < p_T < 12 GeV



27.9 ± 1.0 % b's

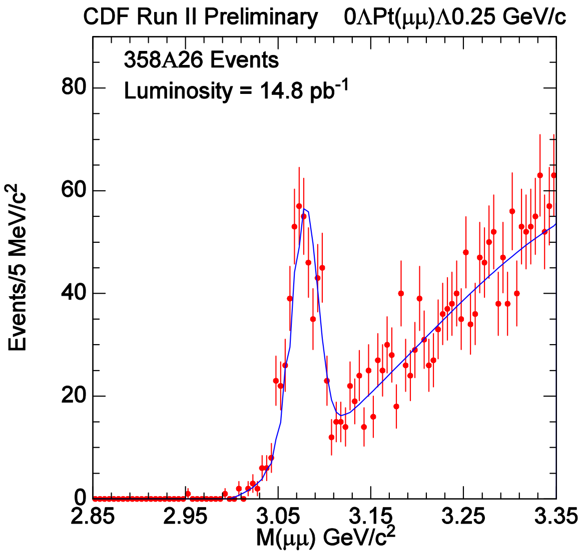
The Fraction of J/ψ’s from b’s

- The outcome of Step 3
- The trend is clear
  - High transverse momentum means a larger beauty component
- “Flattening out” at low p_T is because the J/ψ p_T is dominated by B decay kinematics, not $p_T(B)$

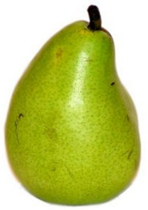


The LHC experiments see exactly the same thing. It’s not at all clear why.

Why is the lowest bin at 1.25 GeV?

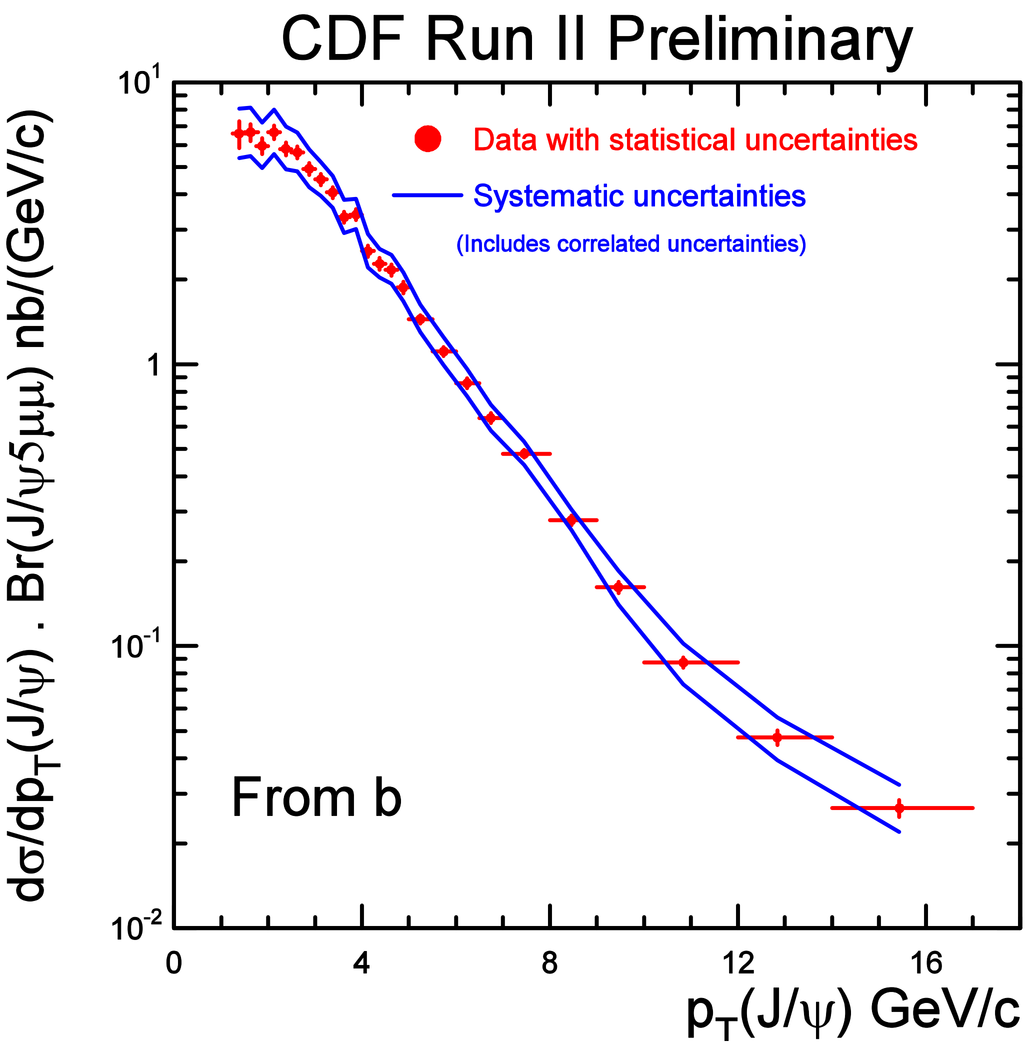


- The fit has problems converging down here
  - It's bitten by four factors at once:
    - The b fraction is small: about 9%
    - The J/ψ acceptance (and therefore yield) is small
      - At 1 GeV, acceptance is 20% of what it is at 2 GeV
    - The variable Lxy (=Rxy cos(θ)) loses separation power
      - Not because the flight distance is small
      - Because the J/ψ flight direction is no longer aligned along the b flight direction
      - B's are being miscategorized as prompt
    - The sideband subtraction becomes less certain:
      - We lose the left sideband



- However, CDF has already reached $p_T(b) = 0$ at 1.25 GeV
  - Pushing lower improves the precision of the measurement, but
  - it does not improve the p_T reach!

Step 4: Infer the J/ψ-from-b Cross-section



CDF almost gets to the turnover at low p_T.

This is what CDF considers the primary measurement and should be used to compare with theory – points are uncorrelated

Approximately 80% of the cross-section is measured.

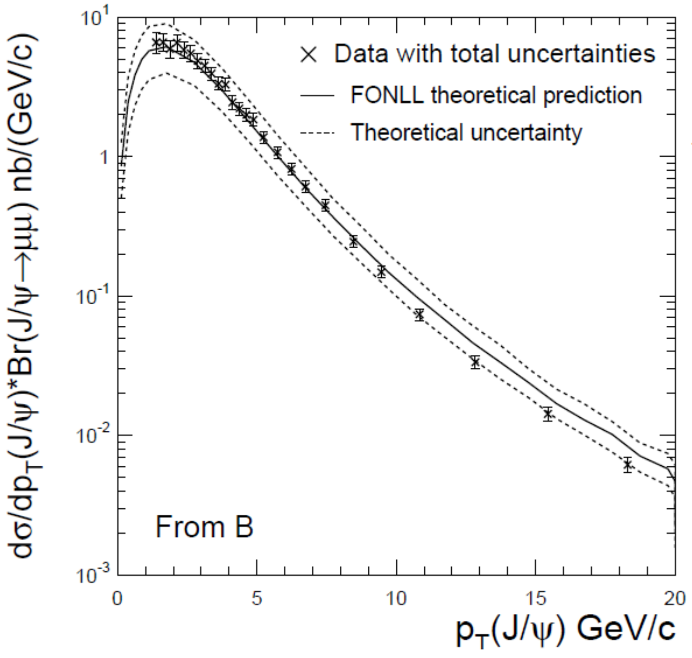
The Total Cross-Section

- CDF corrects this to σ(b):
  - Remove the 5.88% J/ψ branching fraction to mu pairs
  - Remove the 1.16% b-hadron (inclusive) branching fraction to J/ψ + X
  - Correct to ±1.0 units of rapidity vs. ±0.6
  - Divide by two to get the single flavor b cross-section

$$\sigma = 29.4 \pm 0.4^{+4.1}_{-3.9} \; \mu b$$

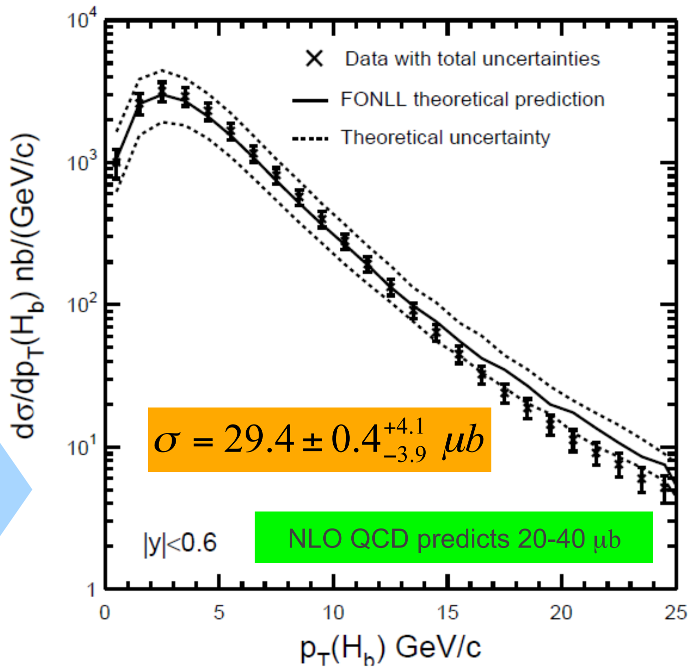
NLO QCD predicts 20-40 μb

The Answer:



CDF measured J/ψ from b decays

Allowing unfolding to the b x-sec



$$\sigma = 29.4 \pm 0.4^{+4.1}_{-3.9}\ \mu b$$

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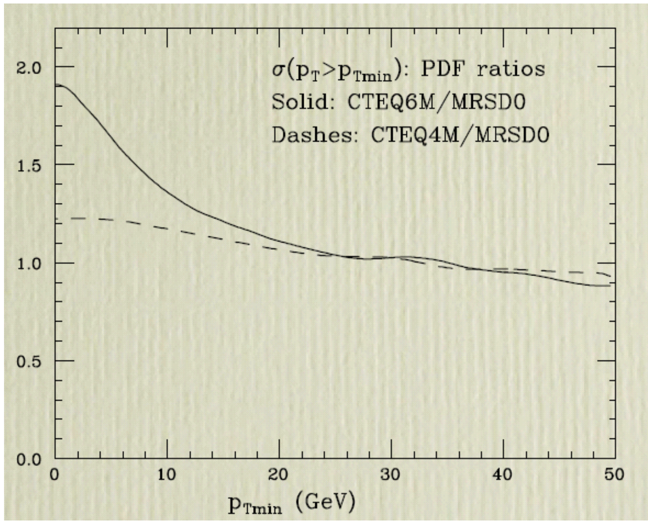
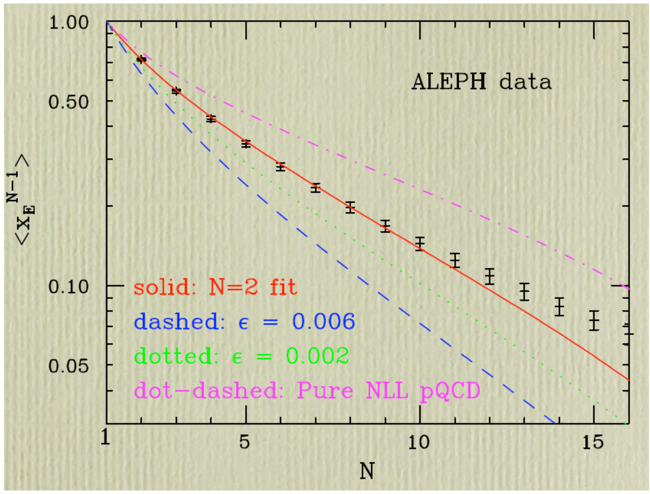
- Since the *total* cross-section agreed, but the high-p_T portion did not, we had a shape problem, not a size problem.
  - The spectrum was stiffer than previously thought – causing us to mistake one for the other.
- Understanding fragmentation was the key – getting from the σ(b-quark) calculation to the σ(b-hadron) measurement.
  - Once that was understood, the other parts (PDFs and detailed calculation) followed.
  - All three contributed at some level.

What Happened?

- PDF's changed
  - About a 20% effect
- Calculations available to NLL
  - About a 20% effect
- Fragmentation functions changed
  - remember, pQCD predicts quark production, but experiments measure hadron production
  - Fragmentation cannot change the total cross section, but does change the spectrum
  - About a 20-50% effect

All these pull in the same direction, so the agreement is now substantially better than in the past.



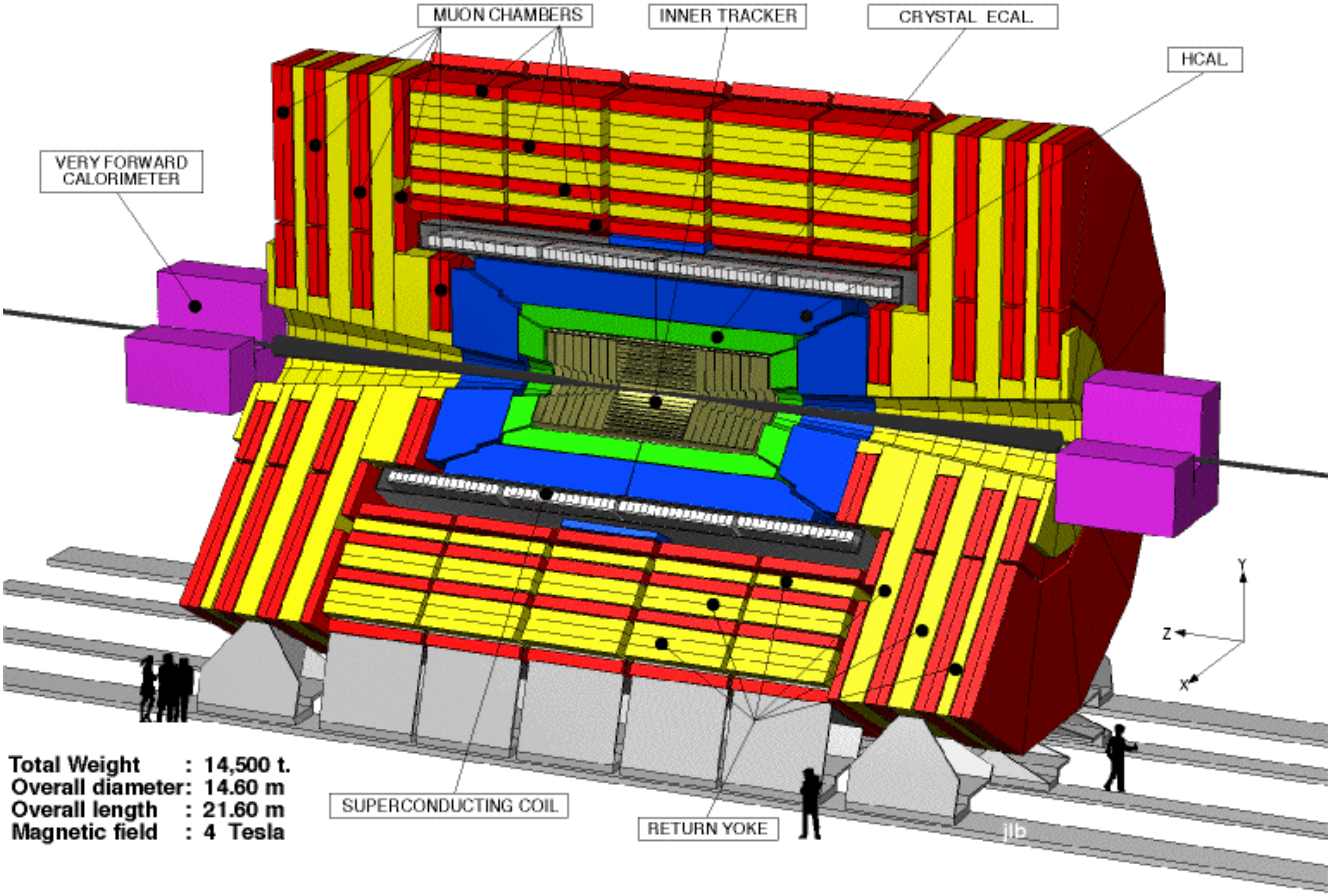


From M. Mangano

The Future

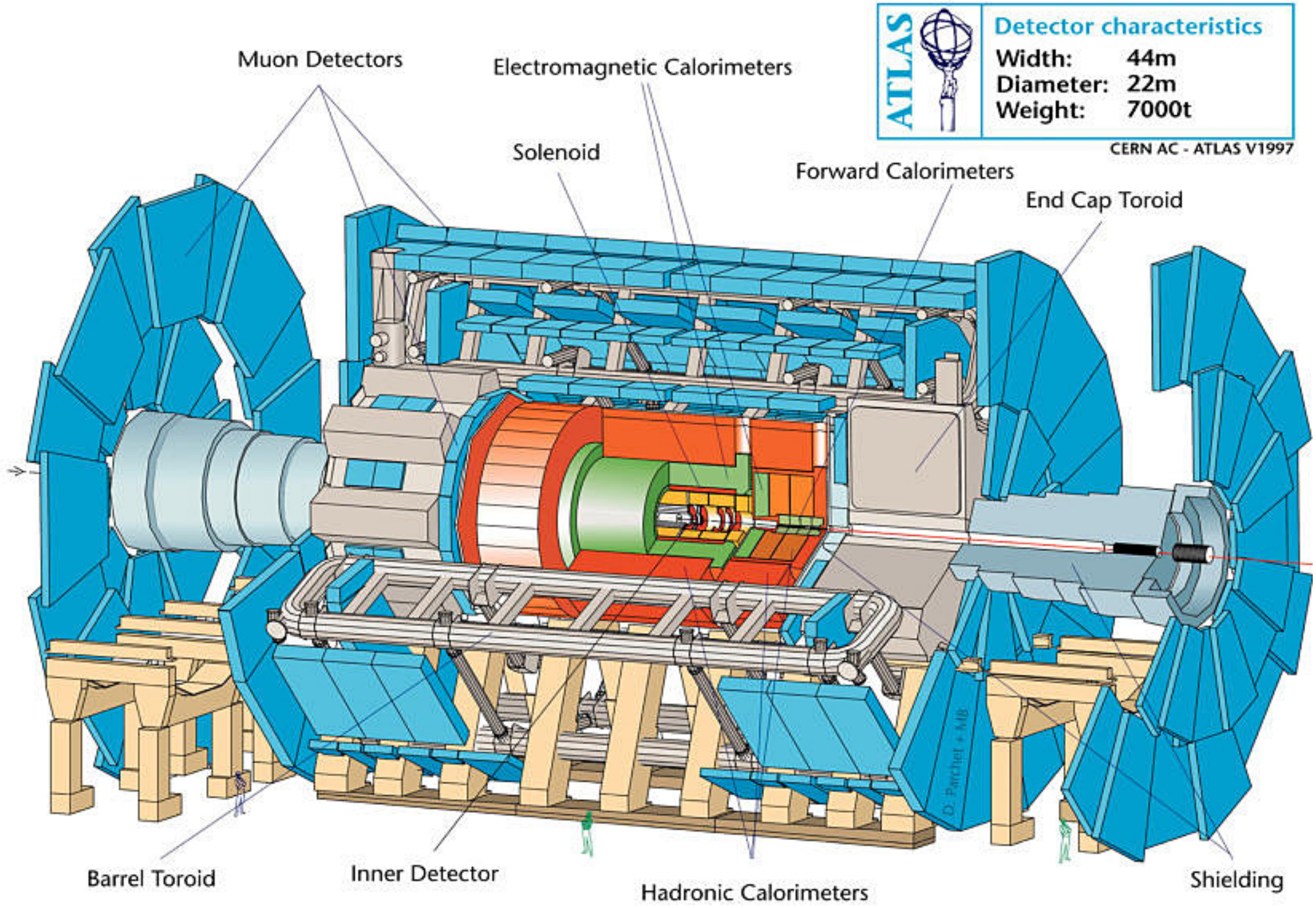
- ATLAS and CMS have already collected top samples comparable to CDF and D0
  - Of course "collected" and "analyzed" are two different things
  - Ultimately, they will have samples hundreds (thousands?) of times larger.
- LHCb has been enormously successful so far – there is a real hope it can reach e+e-like event understanding with pp-like rates.
  - If I gave this lecture a week from today, they would surely be a major player.
- BELLE is still running (or will after KEK recovers from the tragic earthquake.
- There is talk of a "Super B-factory" with ~50x the luminosity.

The Compact Muon Solenoid



Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

ATLAS = A Toroidal LHC ApparatuS

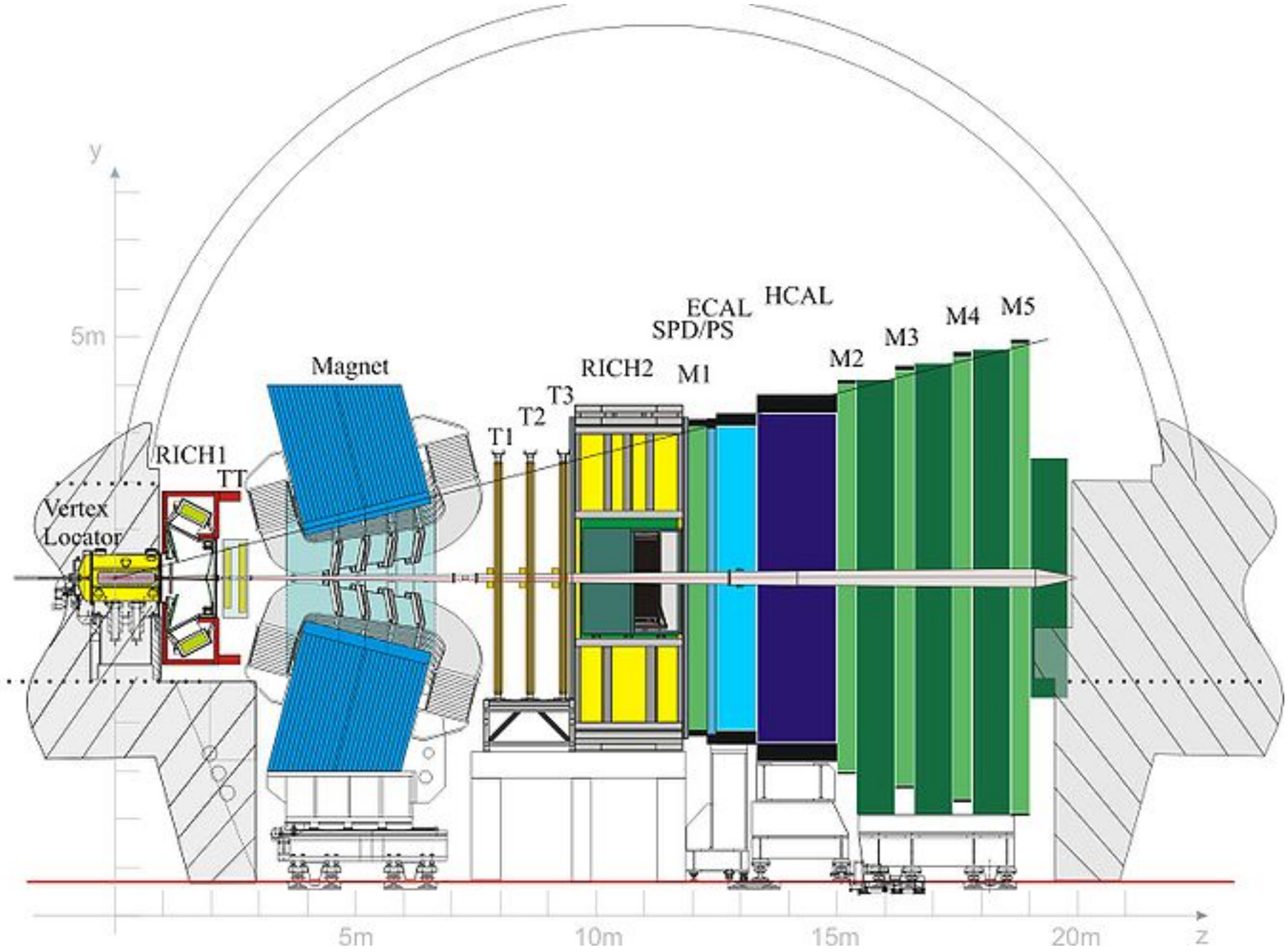


Detector characteristics

Width:	44m
Diameter:	22m
Weight:	7000t

CERN AC - ATLAS V1997

LHCb



y
5m
Vertex
Locator
RICH1
TT
Magnet
T1
T2
T3
RICH2
SPD/PS
ECAL
M1
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

Things To Remember

- Thus far, top quarks behave exactly as predicted. Unfortunately.
- There is a rich phenomenology in B quark physics
  - e.g. mixing, CP-violation
  - This is largely due to having multiple amplitudes for a given process, often of comparable size.
- Again, the predictions are borne out in the data
  - There is no evidence that the 3x3 CKM matrix is inadequate to explain anything
- The years-old b-quark discrepancy was eventually solved
  - Patience is a virtue
  - A "QCD Prediction" is not a simple thing
  - I *didn't* tell you about all the blind alleys people went down. Progress is not a linear thing.

Emergency Abridged Slides

The b-quark cross-section saga

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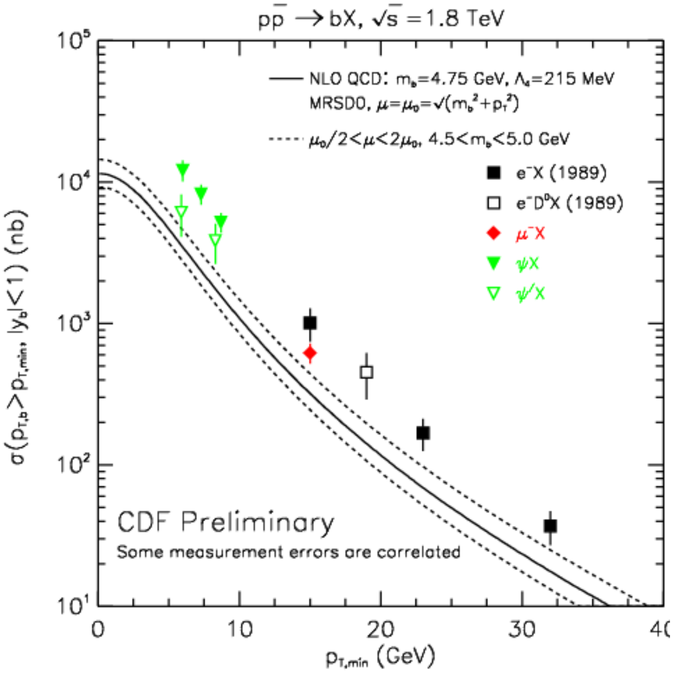

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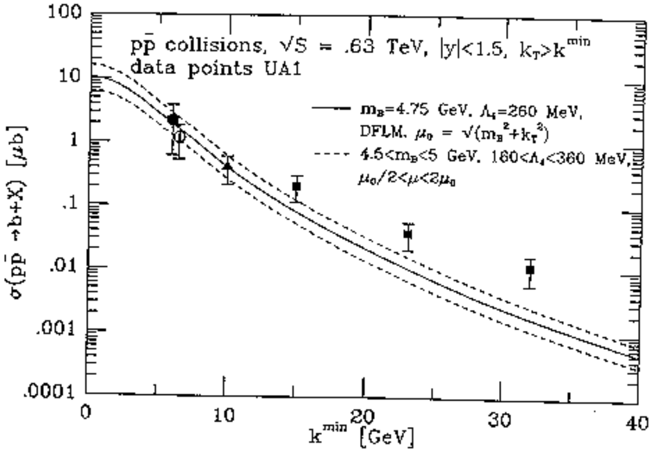

But, it didn't go away.

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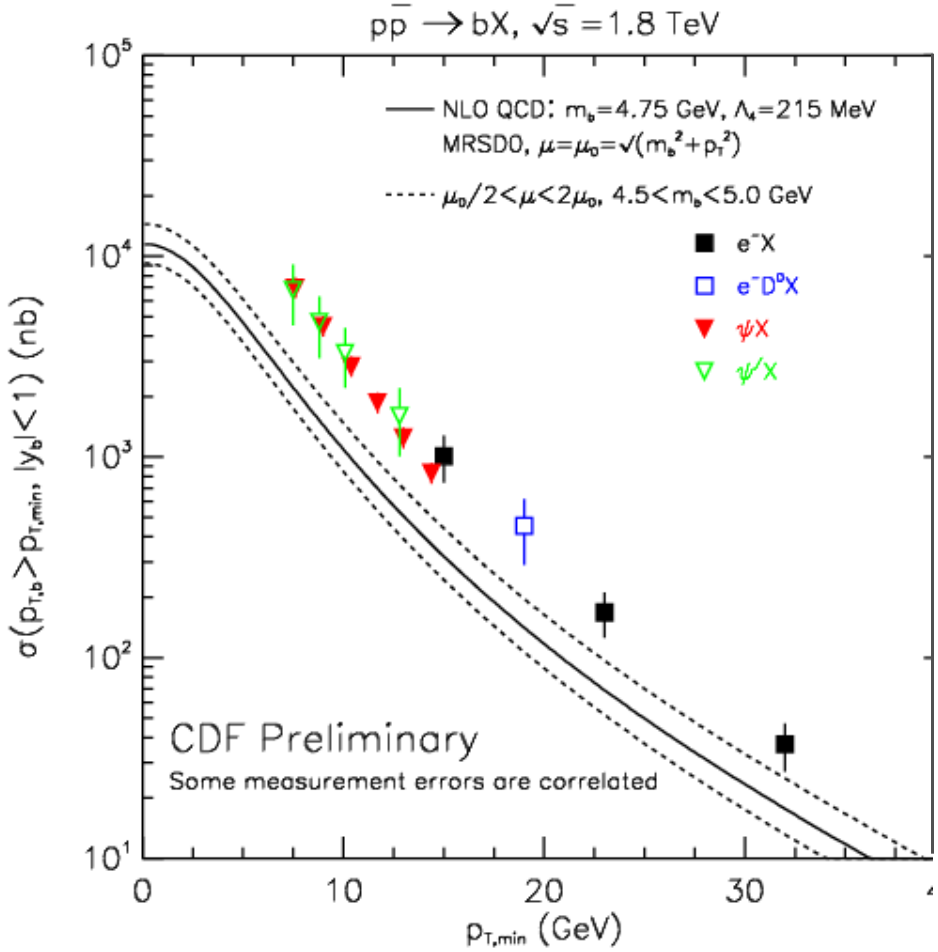
  - Most b's were invisible.



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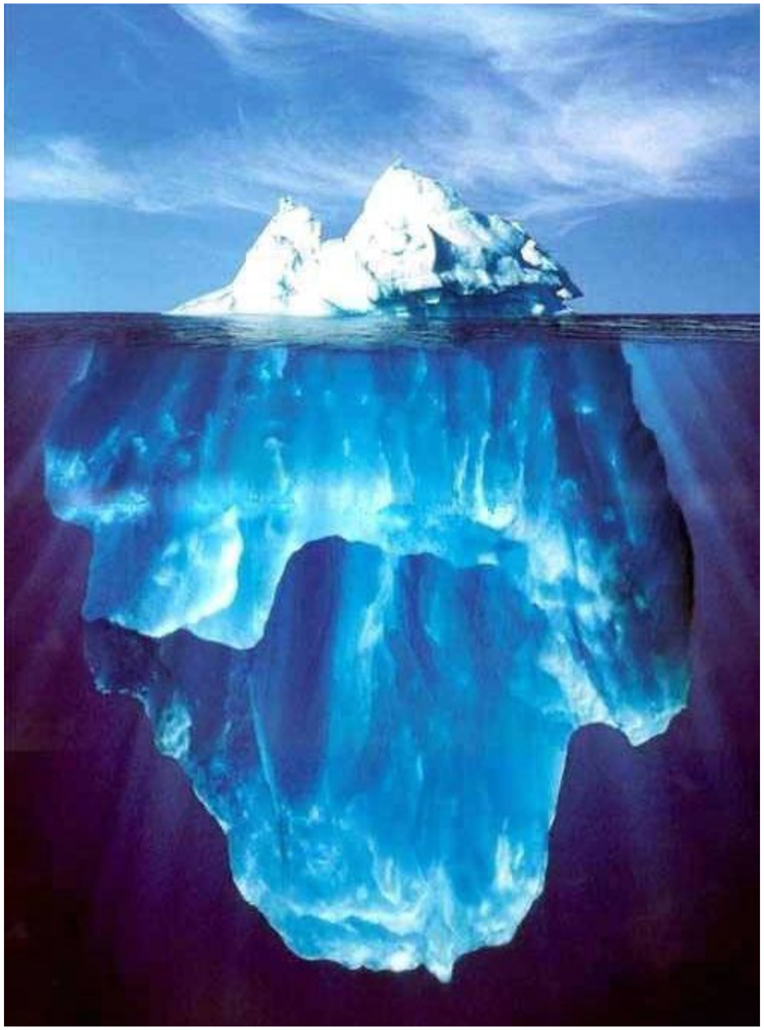
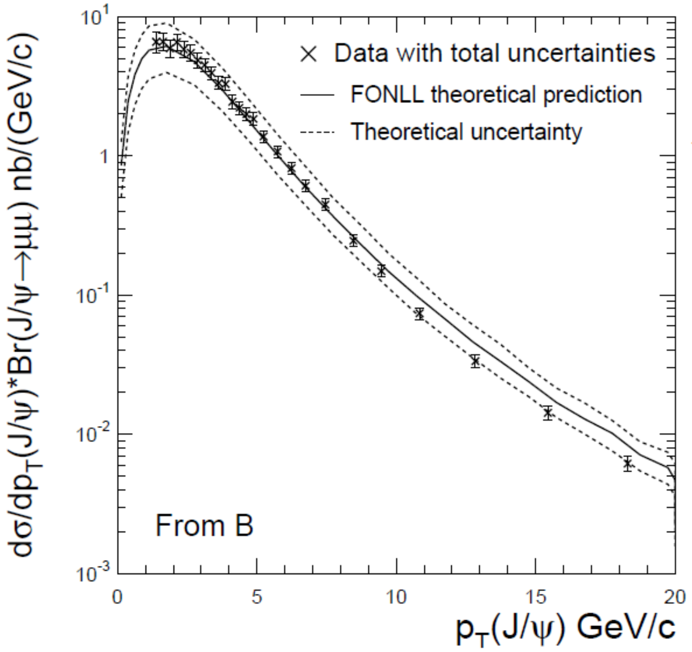


Just how important could the other 90% be anyway?

The Answer:



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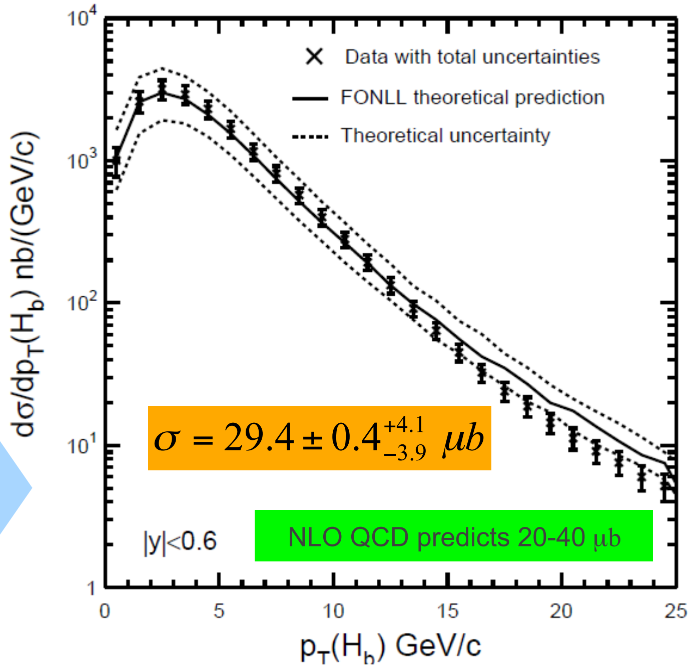

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