Neutral B meson oscillation and prospects for b physics at PHENIX

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LANL Nuclear Physics Seminar

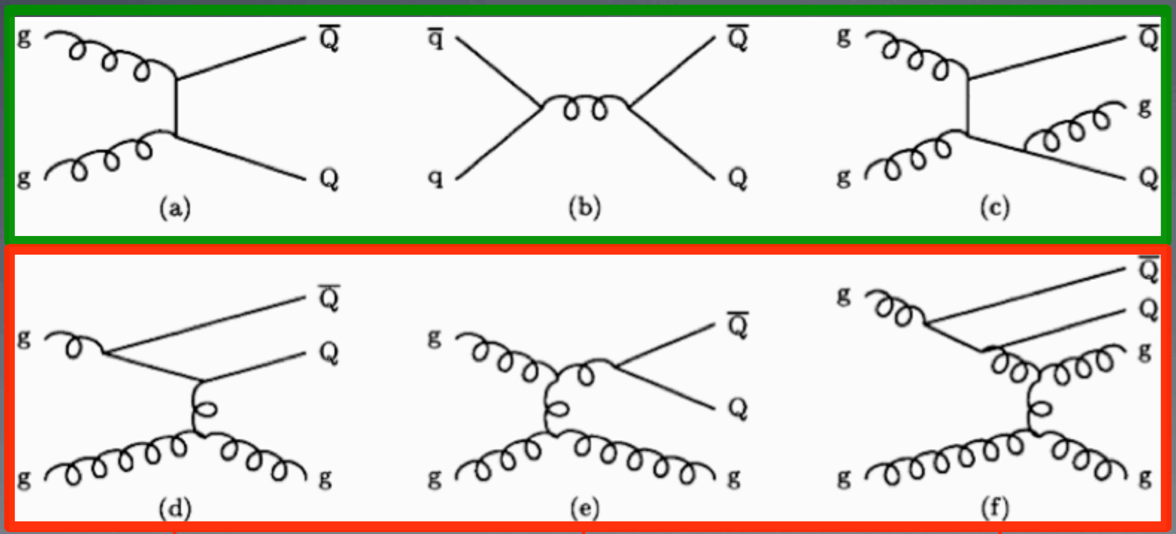
9/10/12

Outline

- Heavy Flavor Production & Decay
- BB Oscillation
  - Theory
  - Experiment
- B Physics at PHENIX
- Summary & Conclusions

Heavy Flavor Production

$$pp \xrightarrow{pQCD} Q \xrightarrow{frag.} H_Q \xrightarrow{decay} l$$



Leading Order pair creation

Next to Leading Order

Flavor excitation

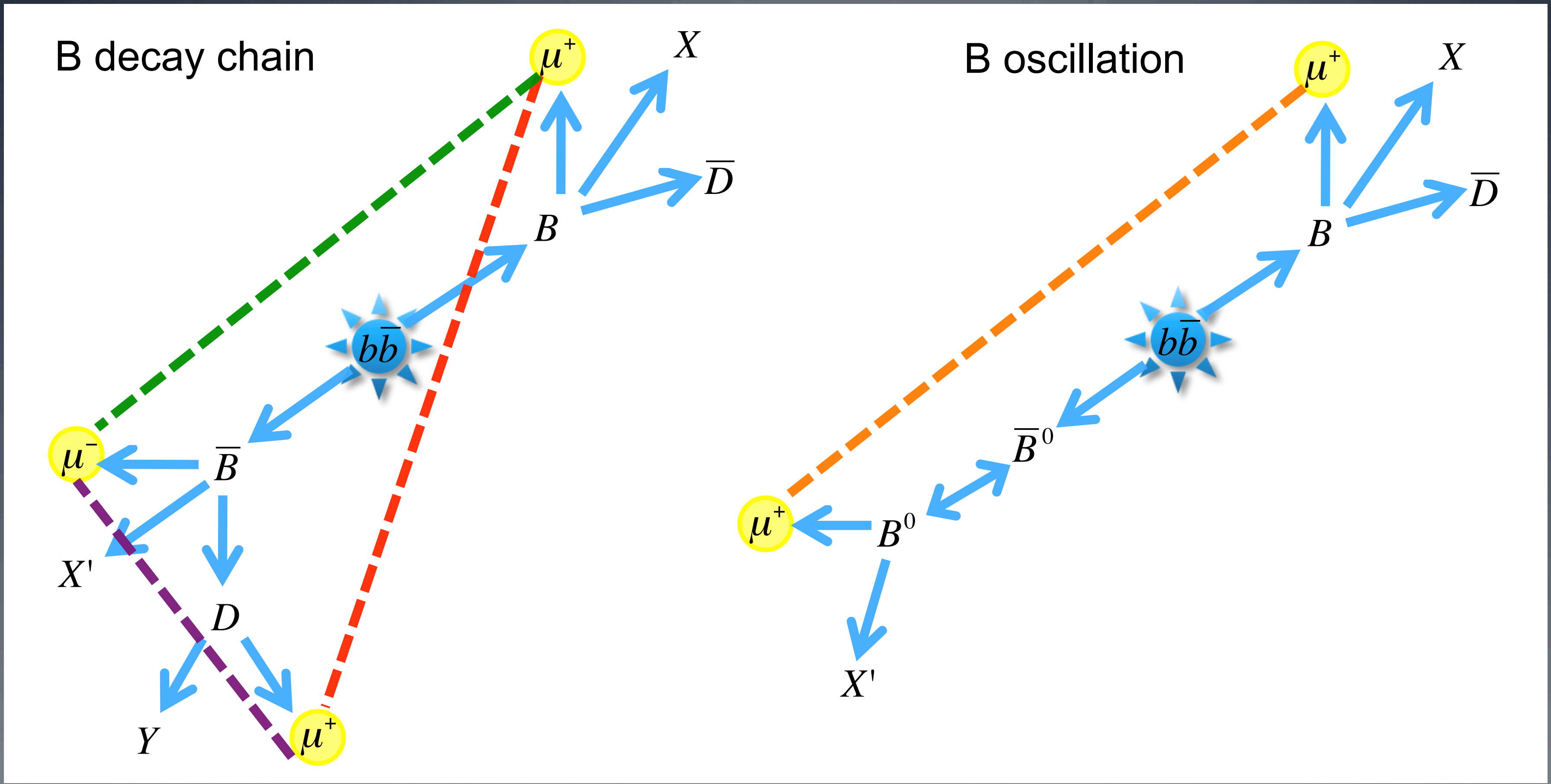
Gluon splitting

Gluon splitting with flavor excitation

Why Study b Quarks?

- b quark production can be used as a test of pQCD theory.
- b quarks are produced early in the collision due to their large mass (~4.2 GeV).
- IF a medium is produced, the heavy quark will interact strongly as it propagates through the medium and can be used to probe medium properties.

B Decay



Like-sign pair: high inv mass
Unlike-sign pair: high inv mass
Unlike-sign pair: low inv mass

Like-sign pair due to oscillation: high inv mass

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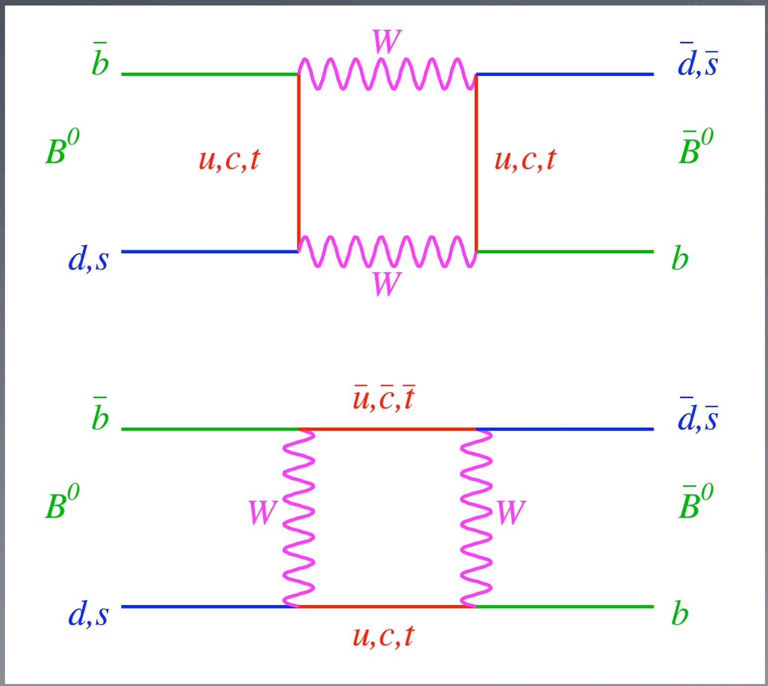
Neutral B Meson Oscillation

- Similar to Kaon system, neutral mesons can oscillate between its particle and antiparticle.
- This is a result of higher order flavor changing weak interactions.



Flavor changing occurs through the exchange of a W boson or top-type quark.

In B oscillation, occurs predominately through the top quark loop

Cabibbo-Kobayashi-Maskawa Matrix

- For quarks, mass eigenstates ≠ weak eigenstates.
  - Mass eigenstates are observed through decay products. B_L^0, B_H^0
  - Weak eigenstates are effected by weak force. $B^0, \overline{B}^0$

- The CKM matrix relates weak eigenstates to mass eigenstates.

Weak eigenstates

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

Mass eigenstates

Cabibbo-Kobayashi-Maskawa Matrix

- The magnitude of each element reflects the strength of the quark couplings.

$$V = \begin{pmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{pmatrix}$$

  - Quarks in the same generation are more strongly coupled than those in different generations.

- Values of the matrix elements are found experimentally.

K. Nakamura et al., “Review of Particle Physics: The CKM Quark-Mixing Matrix,” J. Phys G 37, 150 (2010).

Hamiltonian

- Once a B meson is produced, it can be described by its mass and decay width:

$$H\begin{pmatrix} B^0 \\ \overline{B}^0 \end{pmatrix} = \begin{pmatrix} M_B - \frac{i}{2}\Gamma_B & \Delta m_B - \frac{i}{2}\Delta\Gamma_B \\ (\Delta m_B)^* - \frac{i}{2}(\Delta\Gamma_B)^* & M_B - \frac{i}{2}\Gamma_B \end{pmatrix}\begin{pmatrix} B^0 \\ \overline{B}^0 \end{pmatrix}$$

- In the absence of mixing, the off diagonal matrix elements vanish.
- Oscillation frequency is proportional to the mass difference between the eigenstates given by $\Delta m = m_H - m_L$.
- For B mesons, $\Delta\Gamma$ is assumed to be zero.

Mixing Parameter

- The degree of mixing can be described by the time-integrated mixing parameter χ . This is the probability that a neutral B meson oscillates before it decays.
  - For B^0_d system, χ_d = 0.186
  - For B^0_s system, χ_s = 0.499
  - These values have been determined experimentally!
- For a b admixture, a weighted average of χ can be used:

$$\overline{\chi} = \frac{\Gamma(B^0 \to \overline{B}^0 \to l^+ X)}{\Gamma(B \to l^\pm X)} = f_d \chi_d + f_s \chi_s = 0.126$$

  - Branching fraction f_d= 0.401
  - Branching fraction f_s= 0.103

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Experimental Studies of B Oscillations

- The collision system, energy, and boost provide access to different physics.

e+e-

$\Upsilon(4s)$
- ARGUS
- CLEO

No boost

- BaBar
- Belle

Z^0
- SCL
- LEP experiments

$p\bar{p}$

Tevatron:
CDF
DØ

CP symmetric
Initial states

pp

LHC:
LHCb

CP asymmetric
Initial states

- Boost and (a)symmetry of the states are important when studying CP violation.

Observation of B^o_d Oscillation

- Neutral B meson oscillation was first observed by the ARGUS Collaboration at DORIS in 1987.

Volume 192, number 1,2 PHYSICS LETTERS B 25 June 1987

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

- e+e- collisions operating at the Υ(4s) resonance. This energy is high enough to create pairs of B^+B^- and $B^o\bar{B}^o$, but not $B^o_s\bar{B}^o_s$.
- Evidence for B oscillation:
  - Fully reconstruct an event (right). Υ(4s) -> $B^o\bar{B}^o$.
  - Look for an excess of like-sign dilepton events.

$$\boxed{\chi = 0.17 \pm 0.05}$$

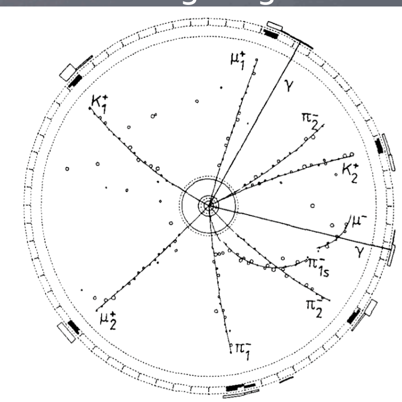

Fig. 2. Completely reconstructed event consisting of the decay Υ(4S) → B^0B^0.

(Indirect) Observation of B^0_s Oscillation

Volume 186, number 2 PHYSICS LETTERS B 5 March 1987

SEARCH FOR B^0–$\bar{B}^0$ OSCILLATIONS AT THE CERN PROTON–ANTIPROTON COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

- Searched for BB oscillation using $p\bar{p}$ collisions at $\sqrt{s}$ = 546 & 630 GeV.
  - At this high energy, B^0 and B^0_s can be produced.
  - Since this is not operating at a resonance, the bb pair can hadronize incoherently.
- Were able to measure the time-integrated neutral B meson systems, but could not separate B^0 from B^0_s.

$$\boxed{\overline{\chi} = 0.121 \pm 0.047}$$

B^o_d Oscillation Frequency

- Using a time-dependent analysis, the ALEPH collaboration was the first to report the oscillation frequency in B^o_d.

Physics Letters B 313 (1993) 498–508
North-Holland

PHYSICS LETTERS B

Observation of the time dependence of B_d^0–$\overline{B_d^0}$ mixing

ALEPH Collaboration

- e+e- collisions operating at the Z^o resonance.

- Events are tagged based on the B->D*->KX channel. The final lepton charge tags whether the event is like-sign or unlike-sign.

$$\boxed{\Delta m_d = 0.52^{+0.10}_{-0.11}(\mathrm{stat})^{+0.04}_{-0.03}(\mathrm{syst})\mathrm{ps}^{-1}}$$

$$\boxed{\Delta m_d = 3.44^{+0.65}_{-0.70}(\mathrm{stat})^{+0.26}_{-0.20}(\mathrm{syst}) \times 10^{-4}\,\mathrm{eV/c}^2}$$

B^0_s Oscillation Frequency

- The first determination of Δm_s was reported by the CDF Collaboration.

PRL **97,** 062003 (2006) PHYSICAL REVIEW LETTERS week ending 11 AUGUST 2006

Measurement of the B^0_s-$\bar{B}^0_s$ Oscillation Frequency

- $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV at Fermilab Tevatron.
- Used a time-dependent method.
  - Tag the B when it is produced based on a same-side Kaon.
  - Look at the final decay products of the B to see whether the meson oscillated before decay.

$$\boxed{\Delta m_s = 17.31^{+0.33}_{-0.18}(\text{stat}) \pm 0.07(\text{syst})\text{ps}^{-1}}$$

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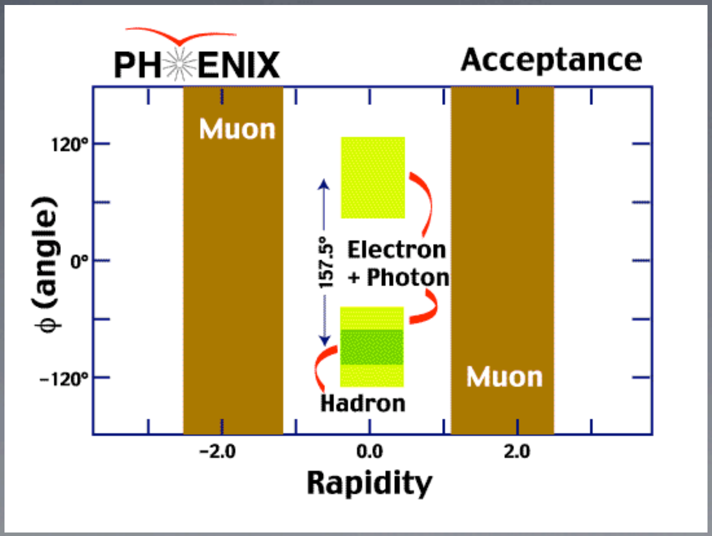
Relativistic Heavy Ion Collider

PHENIX



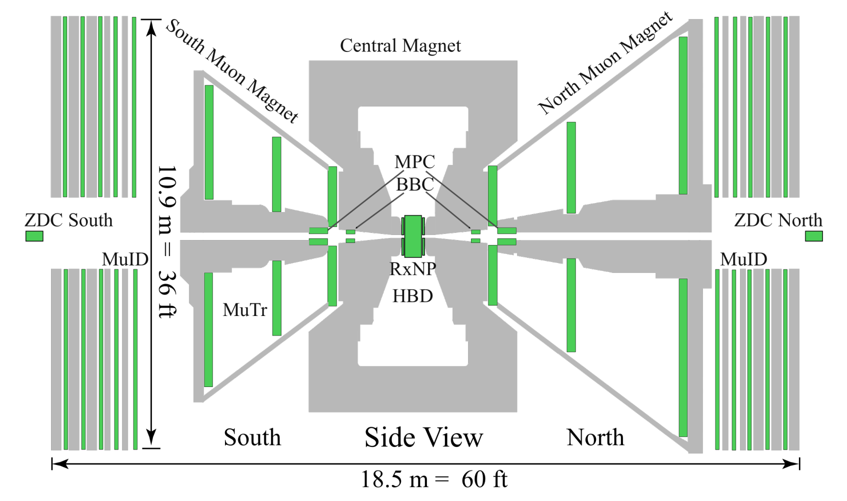
Central arms:
Hadrons, photons, electrons

- $J/\psi \rightarrow e^+e^-$; $\psi' \rightarrow e^+e^-$; $\chi_c \rightarrow e^+e^-\gamma$;
- $|\eta| < 0.35$
- $p_e > 0.2$ GeV/c
- $\Delta\phi = \pi$ (2 arms x $\pi/2$)

Forward rapidity arms:
Muons

- $J/\psi \rightarrow \mu^+\mu^-$; $\Upsilon \rightarrow \mu^+\mu^-$
- $1.2 < |\eta| < 2.2$
- $p_\mu > 1$ GeV/c
- $\Delta\phi = 2\pi$

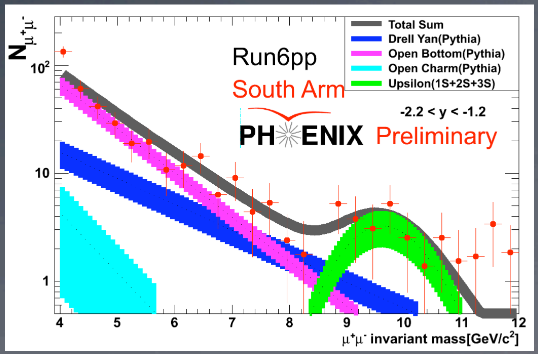
Muon Arms

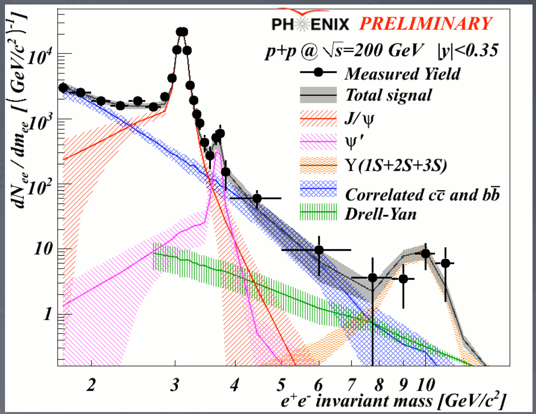


- Muon Tracker (MuTr) consists of 3 stations of cathode strip chambers. (Effort lead by the LANL Group!)
  - the hits position of a muon track are determined in each station.
  - the momentum is reconstructed based on the amount of bending in the strong magnetic field.
- Muon Identifier (MuID) consists of alternating layers of steel absorbers and Iarocci tubes.
  - triggers on muons with a π/μ rejection ratio ~10^{-4}

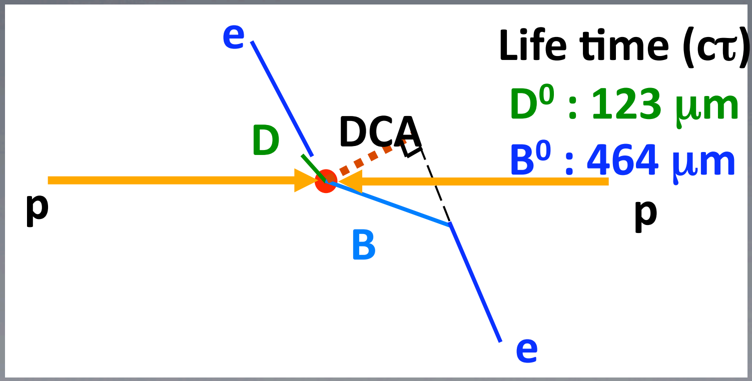
Previous & Current B Physics Results

- Use a cocktail to extract the open bottom contribution in the unlike-sign dilepton.



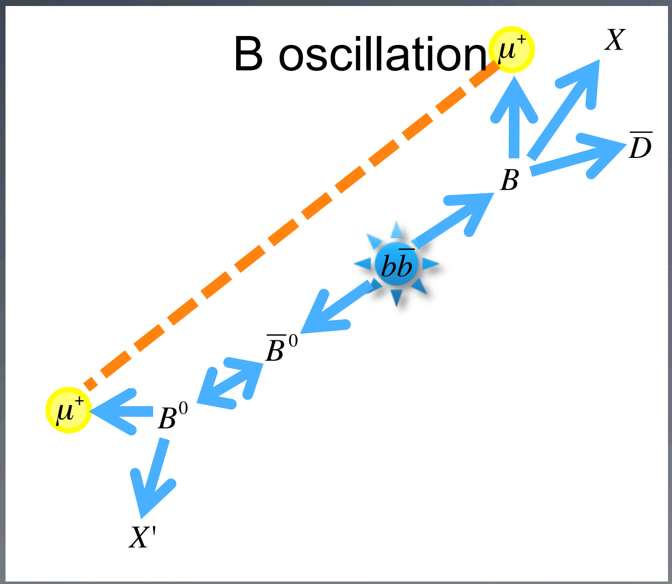


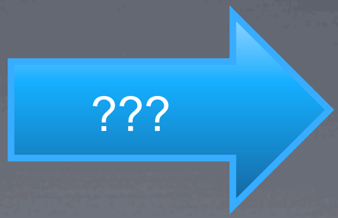
- Using vertex information.



New Method

- Neutral B meson oscillation has been well established. Can we use this phenomena to study $b\bar{b}$ production?





$$\sigma_{b\bar{b}}$$

- Use ~6pb^{-1} of p+p data collected in 2009 at $\sqrt{s}$ = 500 GeV.
- Look at the like-sign dimuon signal!

Sources of Dimuons

- In the high mass region, the predominant source of like-sign dimuons is from B decay along with some hadronic background.

	N^{+-}	$N^{\pm\pm}$
$m_{\mu\mu} < 4$ GeV	Quarkonia (J/ψ, ψ') b-decay chain (same b) Drell-Yan	c-decay chain
$m_{\mu\mu} > 4$ GeV	Drell-Yan Quarkonia (Υ family) b-decay chain (diff b) $b\bar{b} \rightarrow \mu\mu$ (prompt) $c\bar{c} \rightarrow \mu\mu$ (prompt)	$b\bar{b} \rightarrow \mu\mu$ (prompt with osc) b-decay chain (diff b) Hadronic background

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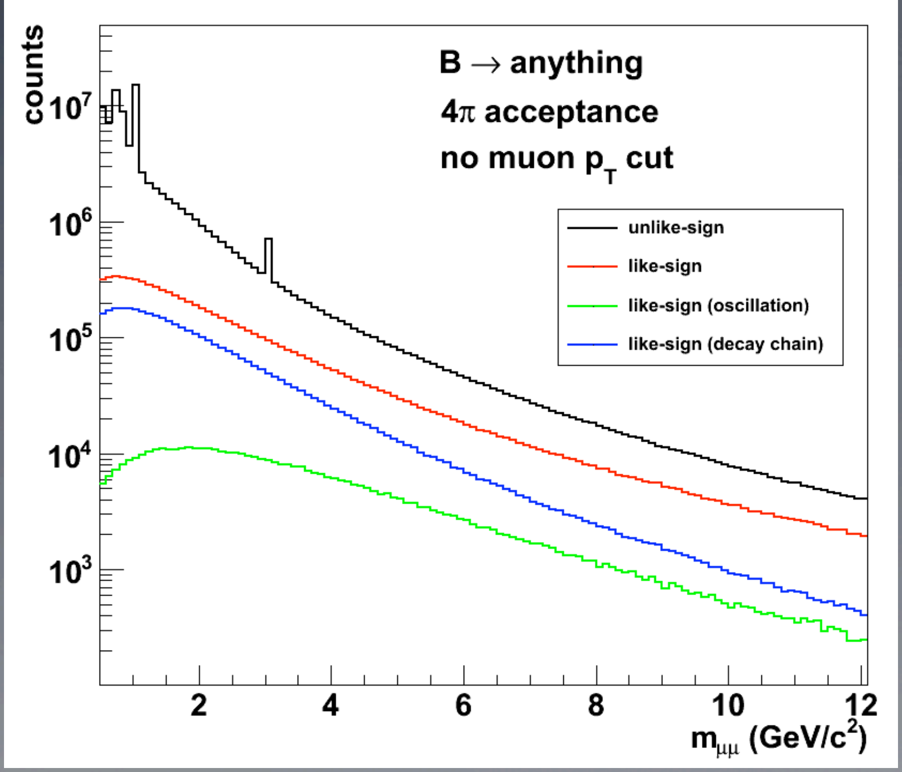
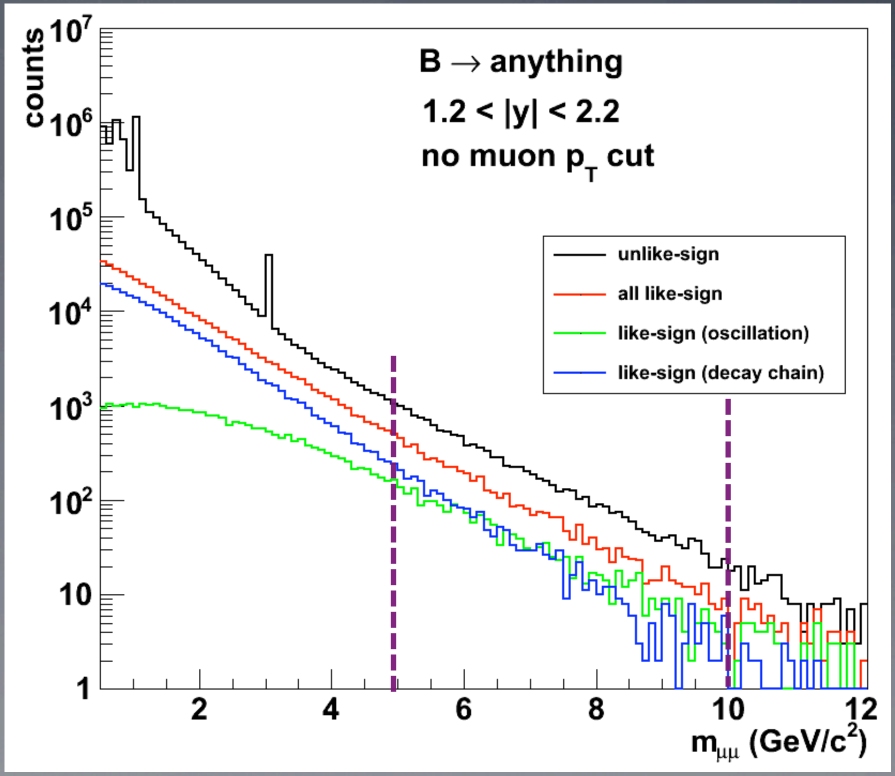
Simulation Spectra

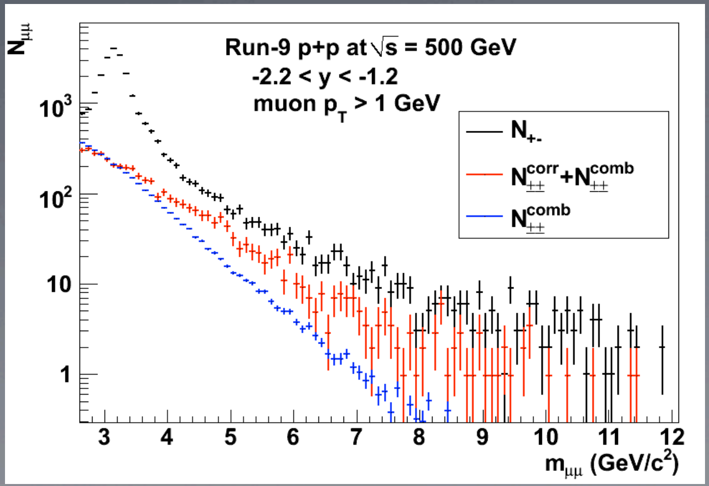
- Pythia, a Monte Carlo event generator, is used to extract certain values necessary for this analysis.
- Events were generated at NLO in minimum bias mode.

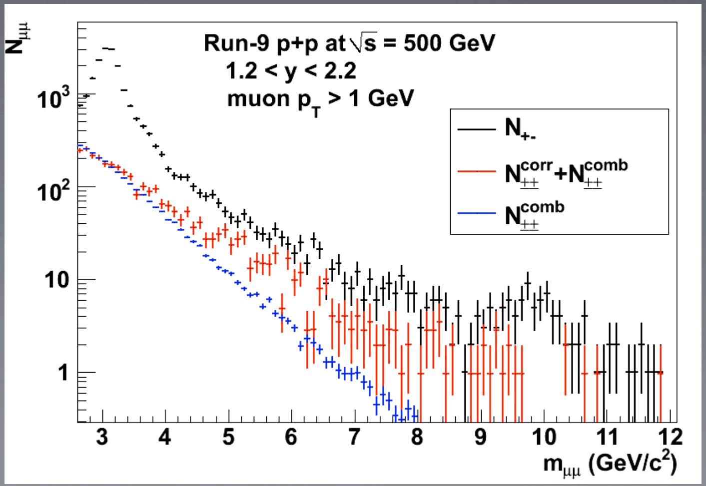




Signal Extraction

- This analysis uses the properties of both like-sign and mixed-event background subtraction techniques to extract the like-sign correlated dimuons.[1]
  - Like-sign technique pairs like-sign muons in the same event and will consist of BOTH combinatorial and correlated pairs.
  - Mixed-event technique pairs like-sign muons from different events and will ONLY contain combinatorial pairs.



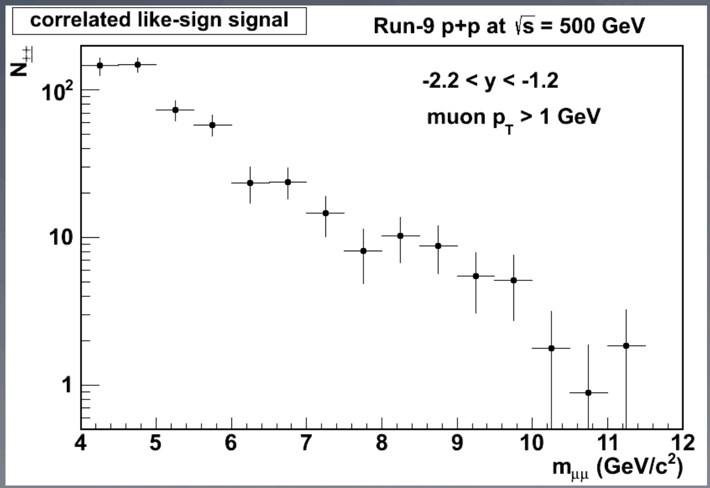


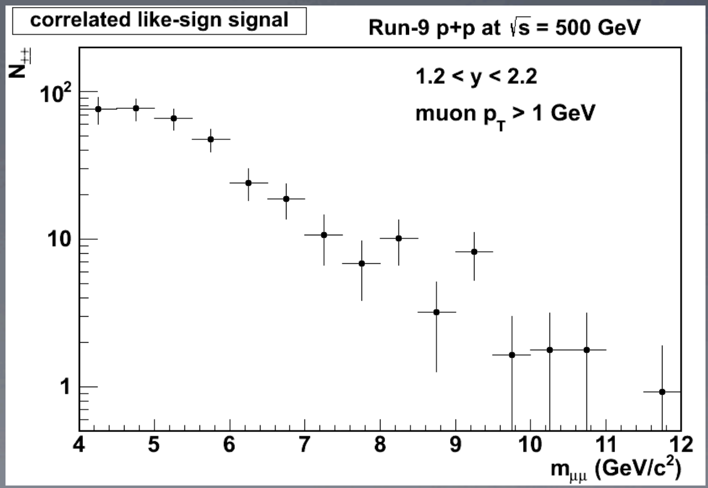
[1] P. Crochet and P. Braun-Munzinger, Nuclear Instruments and Methods in Phys. Research A 484 (2002) 564.

Signal Extraction

- To find the number of like-sign correlated pairs, pairs in mixed event were subtracted from pairs within the same event.

$$N_{\pm\pm}^{corr} = N_{\pm\pm}^{like} - N_{\pm\pm}^{mixed}$$

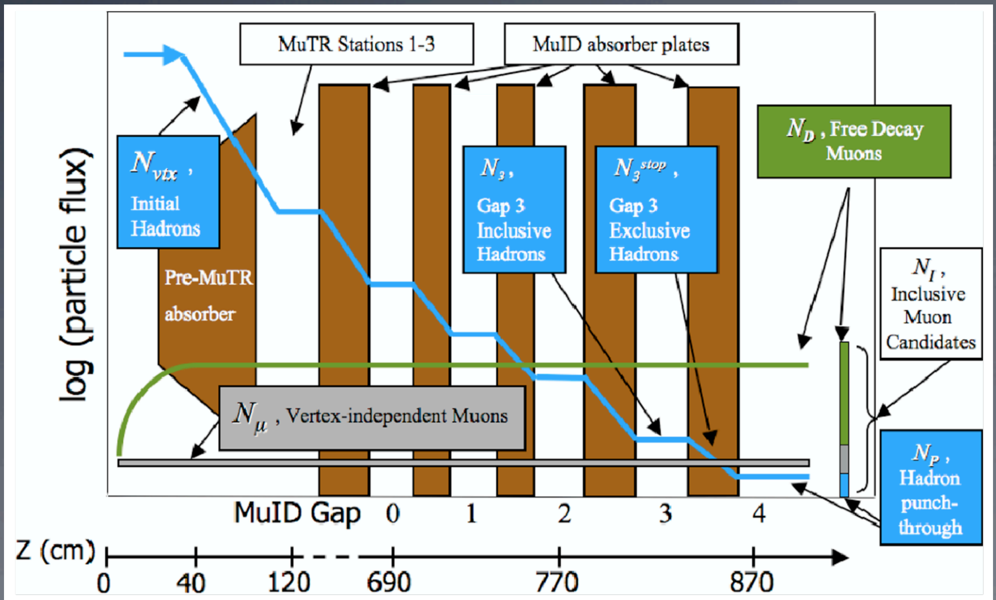




- Need to find the contributions from hadronic background and B signal!

Hadronic Background

- In the Muon Arms, the primary source of hadronic background originates from:

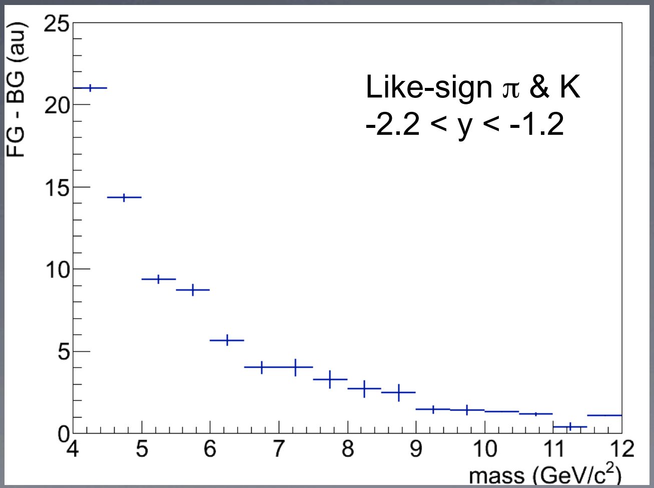


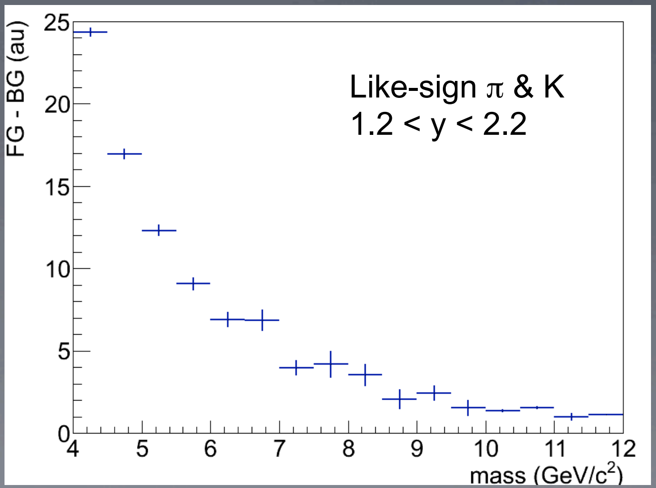
- <u>In-flight decays</u>- π & K that decay before the absorber layer.
- <u>Background tracks</u>- π & K that decay within the detector.
- <u>Punch-through hadrons</u>- π & K that traverse the detector.

- Background subtraction will not fully remove the contribution from hadronic background.

Hadronic Background

- To account for any hadronic background that may be in the data, an extensive simulation was run.
  - π & K were generated and run through the PHENIX detector simulation chain to find the probability that a hadron survive.
  - The invariant mass was constructed for like-sign in the same event and in mixed events to mimic data.





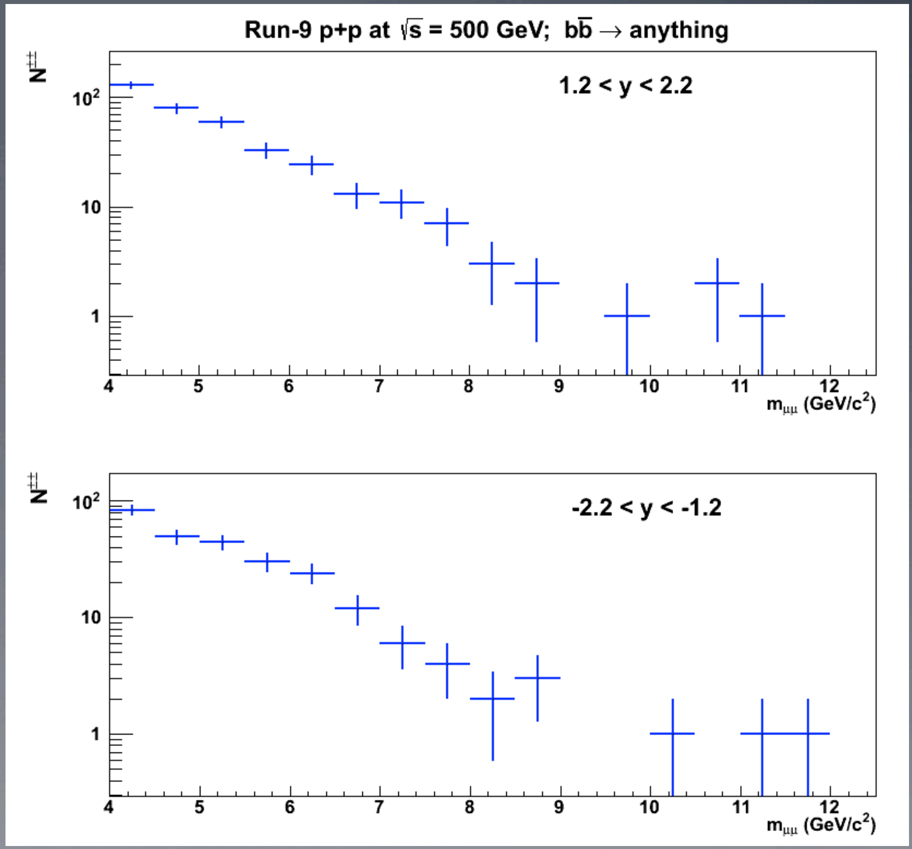
- The four simulations were averaged and fit with an exponential function.

Open Bottom from Simulation

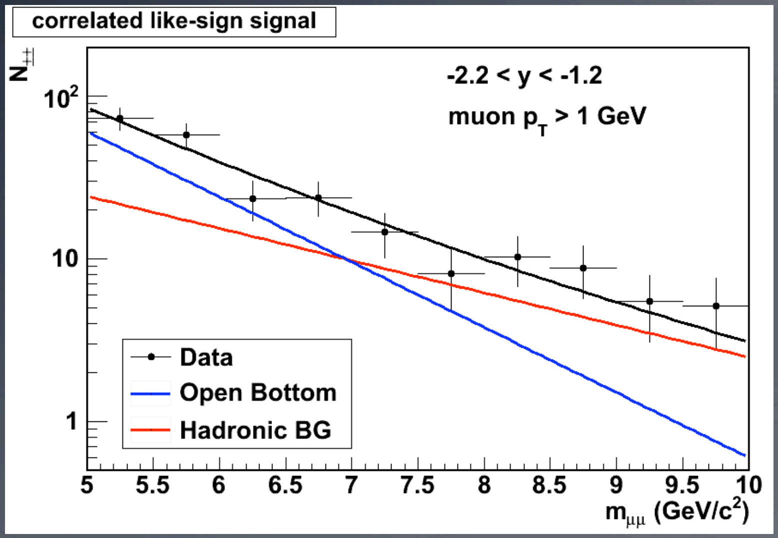
- Simulation was used to determine the line shape of like-sign dimuons from open bottom decay.

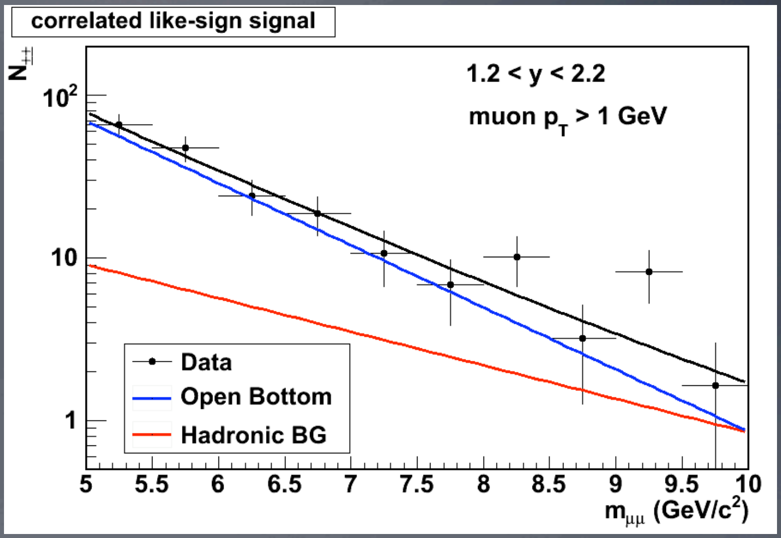
- Like-sign pairs include contributions from decay chain and oscillation.

- Fit the resulting spectra with an exponential function to get the line shape.



Component Analysis





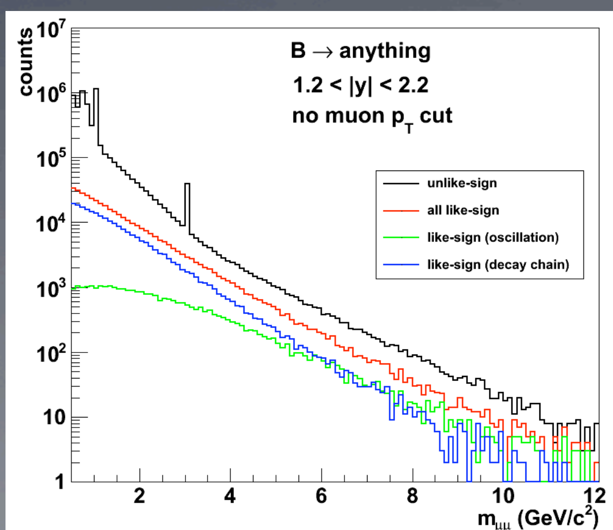
- The raw data was fit with a double exponential function.

$$\boxed{F(m) = \underbrace{p_0 \exp(-m/p_1)}_{\text{Hadronic background contribution}} + \underbrace{p_2 \exp(-m/p_3)}_{\text{Open Bottom contribution}}}$$

- Slopes were fixed from simulation, and the amplitude were allowed to float.

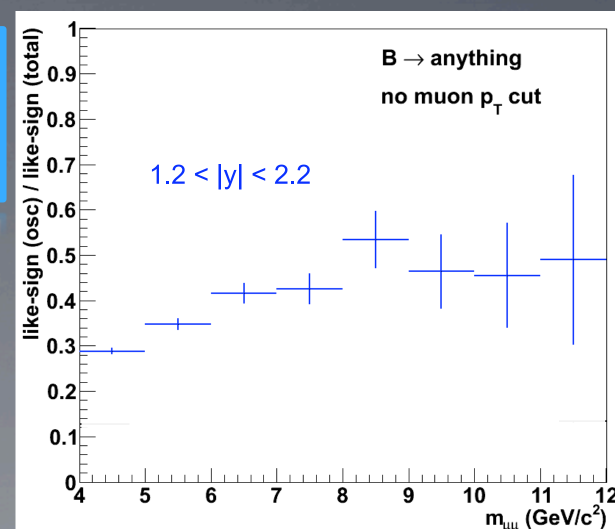
Separate Sources of Like-Sign Dimuons

- Need to know what percent of the correlated like-sign dimuons are due to primary/primary decay from oscillation.
- Pythia, is used to separate the like-sign dimuons due to oscillation from the total like-sign signal.



$$\alpha(m) = \frac{b\bar{b} \rightarrow BB^0_{osc} \rightarrow \mu^{\pm}\mu^{\pm}}{b\bar{b} \rightarrow BB \rightarrow \mu^{\pm}\mu^{\pm}}$$

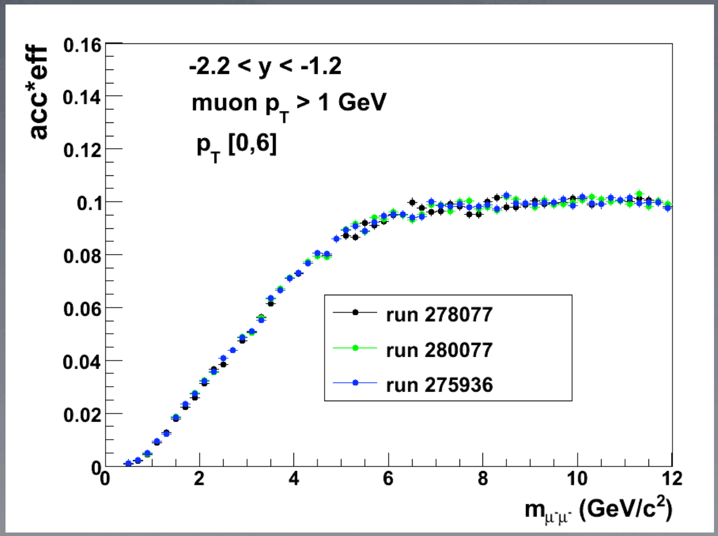
Define α(m)

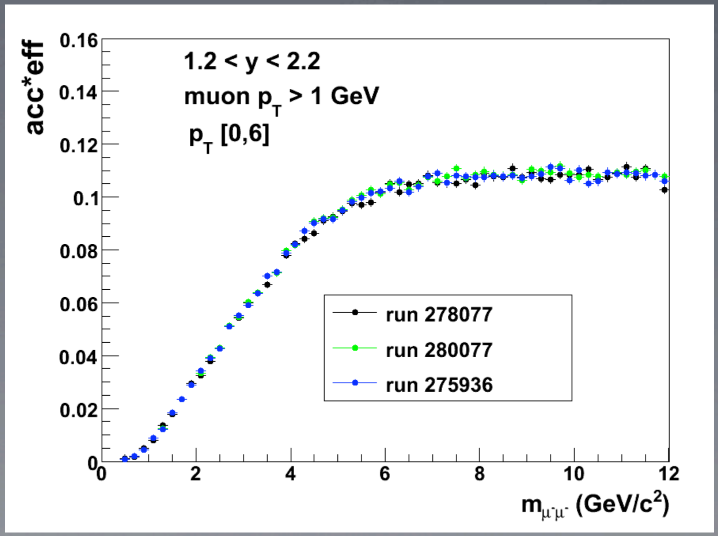


Acc*Eff Correction

- To correct for detector effects, events were generated with flat mass (0.5-15 GeV), flat p_T (0-12 GeV) and flat rapidity ($1 < |y| < 2.5$) and run through the PHENIX detector simulation chain.

$$acc * eff = \frac{\#\ \text{of dimuons reconstructed}}{\#\ \text{of dimuons generated}}$$





Calculating the Number of BB

- The total number of BB mesons can now be calculated.
- Use Pythia again to convert from the number of like-sign pairs due to oscillation to the total number of BB pairs that decay into dimuons.

$$\beta = \frac{b\bar{b} \to BB^0_{osc} \to \mu^{\pm}\mu^{\pm}}{b\bar{b} \to BB \to \mu\mu} = 0.213$$

- Now, apply the conversion factor to our data.

$$N_{BB} = \alpha(m) * \frac{N^{corr}_{\pm\pm}}{A\varepsilon} * \left(\frac{1}{\beta}\right)$$

Calculating the Cross Section

- First, calculate the invariant yield in each arm.

$$\frac{dN_{BB\to\mu\mu}}{dy} = \frac{1}{\Delta y}\frac{N_{BB\to\mu\mu}}{(A\varepsilon)\varepsilon_{HS}^{BBC}}\frac{\varepsilon_{MB}^{BBC}}{N_{MB}^{BBC}}$$

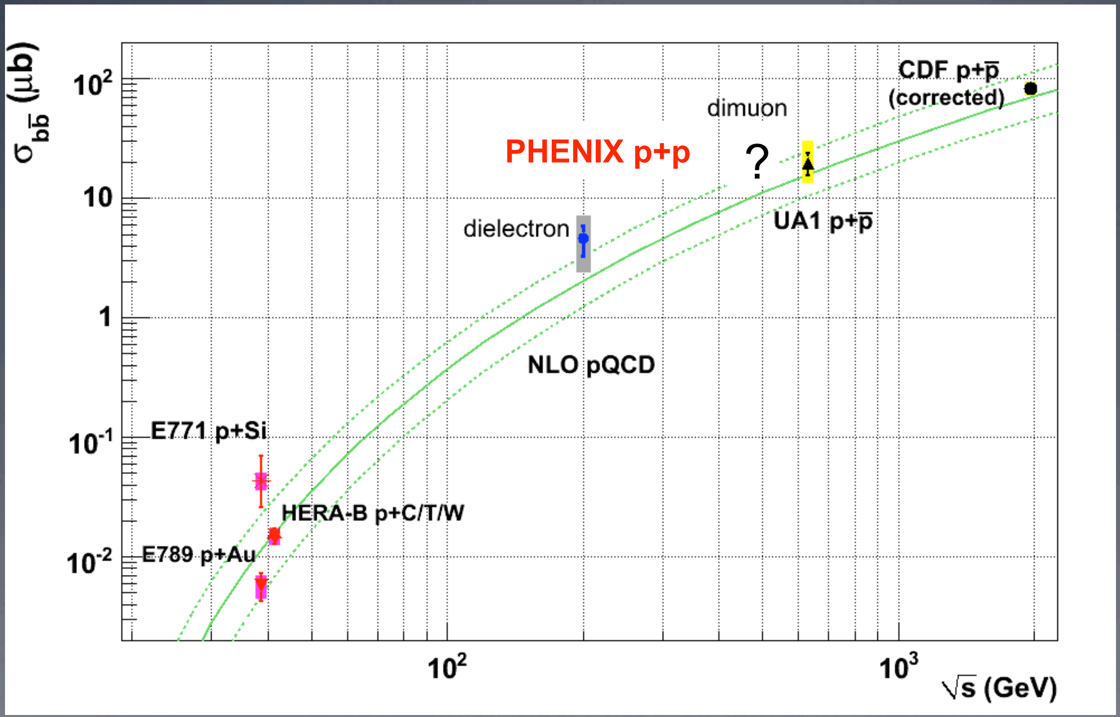
- Convert from invariant yield to differential cross section:

$$\frac{d\sigma_{bb\to\mu\mu}}{dy} = \frac{dN_{BB\to\mu\mu}}{dy}\sigma_{total}$$

- Finally, to compare with pQCD theory, need to calculate the total cross section:

$$\sigma_{b\bar{b}} = \frac{d\sigma_{bb\to\mu\mu}}{dy} * \frac{1}{scale} * \frac{1}{BR_{B\to\mu}^2}$$

The Big Question



- This analysis is ongoing and very close to final!

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Summary & Conclusions

- The phenomena of neutral meson oscillation is well established both theoretically and experimentally.
- The correlated like-sign signal in the high mass region is strongly bottom enriched.
- Using the properties of B meson oscillation, one can study the production of b quarks based on the like-sign signal.
- In the future, this method can be applied to heavy ion collision systems to study the modification of b production in a medium.

THANK YOU

Back up slides

B meson summary

Particle	composition	mass	Branching fraction
B+ (B-)	$u\bar{b}$ ($\bar{u}b$)	5.279 GeV	0.401±0.008
B0 (B0)	$d\bar{b}$ ($\bar{d}b$)	5.280 GeV	0.401±0.008
B0s (B0s)	$s\bar{b}$ ($\bar{s}b$)	5.367 GeV	0.103±0.006
B+c (B-c)	$c\bar{b}$ ($\bar{c}b$)	6.277 GeV	-
b-baryon	qqb, qbb, bbb, …	5.619-6.071 GeV	0.093±0.016

J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012) (URL: http://pdg.lbl.gov)

Time-Dependent Mixing

- After a B^0 meson is produced it can be described at some time t as

$$\Psi(t) = a(t)\left|B^0\right\rangle + b(t)\left|\overline{B}^0\right\rangle$$

- The evolution of the B state can be described by the Schrodinger equation by it's mass and decay matrices

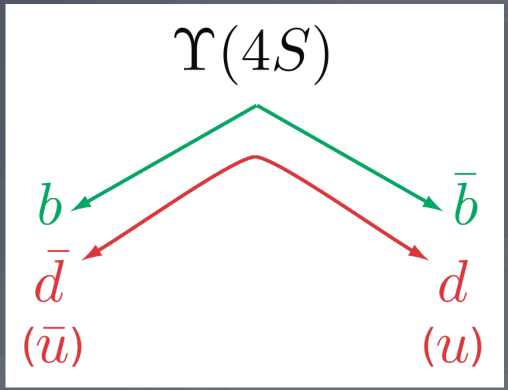
$$i\frac{d\Psi(t)}{dt} = H\Psi(t) = (M - \frac{i}{2}\Gamma)\Psi(t)$$

Where

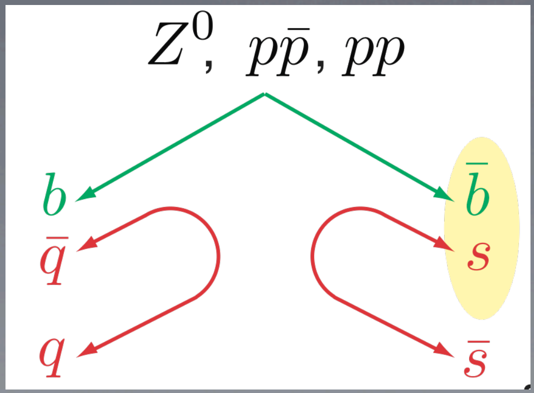
$$M - \frac{i}{2}\Gamma = \begin{pmatrix} M_B - \frac{i}{2}\Gamma_B & \Delta m_B - \frac{i}{2}\Delta\Gamma_B \\ (\Delta m_B)^* - \frac{i}{2}(\Delta\Gamma_B)^* & M_B - \frac{i}{2}\Gamma_B \end{pmatrix}$$

B Meson Pair Production

- For collisions at $\Upsilon(4s)$ resonance, production of B mesons is correlated:



- For collisions at Z^0, $\bar{p}p$, pp production is uncorrelated:



Images from http://www.indiana.edu/~lorentz/sme2012/VanKooten.pdf

Open Bottom Simulation Setup

- Generated 70M bb events in PYTHIA. Once created, the b could hadronize and decay independently.

Parameter	Index 1	Index 2	Setting	Meaning
msel	5			bottom production, isub = 81, 82, 84, 85
pmas	5	1	4.1	set mass at 4.1 GeV
mstp	51		7	CTEQ 5L, leading order PDF
mstp	32		4	set Q_2 scale = 4
mstp	33	1		use k factor
parp	91		1.5	set instrinsic kt value = 1.5
parp	31		3.4	set k factor = 3.4
pytune			103	

Jet Simulation Setup

- Generated 10M minimum bias events in PYTHIA using Tune A parameters and z-vertex from data.

Parameter	Index	Setting	Meaning
msel	1		generate only QCD high pT processes
mstp	51	7	CTEQ 5L, leading order PDF
parp	67	4.0	set hard scattering scale μ^2
parp	82	2.0	turn off p_T for multiparticle interactions at reference energy scale 0.5
parp	84	0.4	radius of the core Gaussian matter
parp	85	0.9	probability that two gluons are produced with colors connected to the nearest neighbors
parp	86	0.95	probability that two gluons are produced with PARP 85 conditions or closed loop
parp	89	1800	reference energy scale of the turn-off pT
parp	90	0.25	energy dependence of the turn-off pT

- Tune A parameters were used by PHENIX to study double helicity asymmetry in jets[1]

[1] A. Adare, et al., "Event Structure and Double Helicity Asymmetry in Jet Production from Polarized p+p Collisions at 200 GeV," Phys. Rev. D 84, 012006 (2011).