$b\bar{b}$ Production at Forward Rapidity in p+p Collisions at $\sqrt{s} = 510$ GeV

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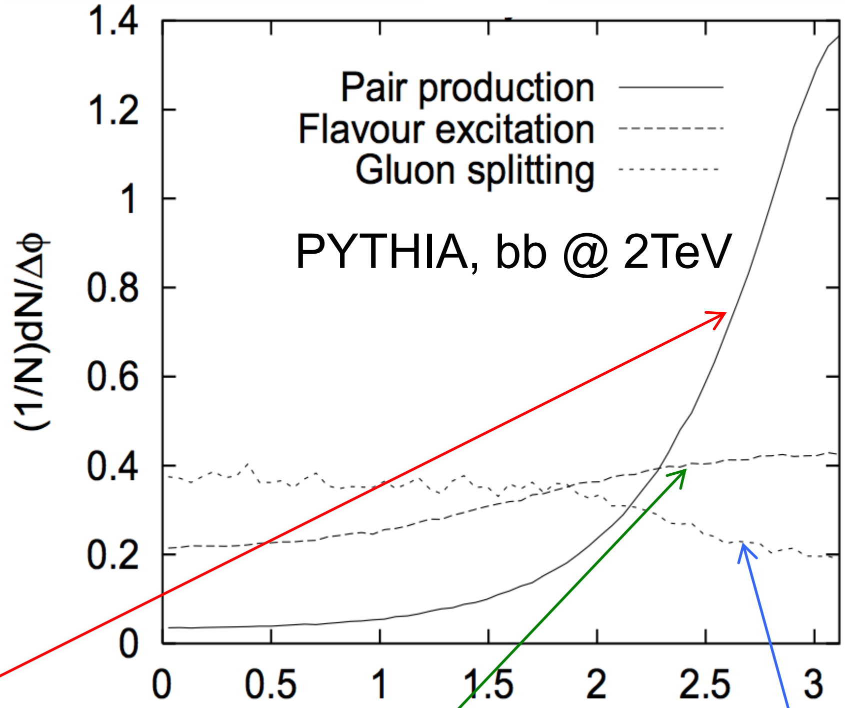
Motivation

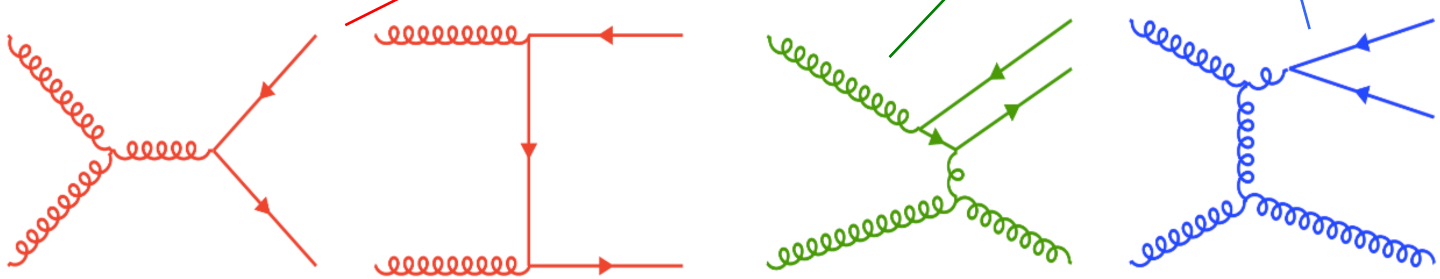
- Heavy-flavor quarks (c, b) play a unique role in studying QCD in the vacuum as well as in the nuclear medium at finite temperature.
  - Because of its large mass, $m_b \gg \Lambda_{QCD}$, the *b*-quark production cross section can be reliably calculated by including next-to-leading order (*NLO*) processes, especially at high center of mass energies.
  - The measurement of the $b\bar{b}$ production cross section over a wide range of colliding energies in hadron-hadron collisions provides:
    - a meaningful test of *p*QCD theory calculations
    - a baseline measurement for studying modifications of heavy quark production in heavy ion collisions.

Heavy Flavor Correlations

- Azimuthal correlations – a unique probe to study heavy flavor production
  - LO flavor creation (FC)
    - strong back-to-back peak
  - NLO flavor excitation (FE)/ gluon splitting (GS)
    - broader azimuthal angle distributions
  - Measuring azimuthal correlations can disentangle different heavy flavor production mechanisms

Production and Hadronization of Heavy Quarks, Eur.Phys.J.C17, 137-161 (2000)





(a) s-channel Flavor Creation

(b) t-channel Flavor Creation

(c) Flavor Excitation

(d) Gluon Splitting

Heavy Flavor Correlations

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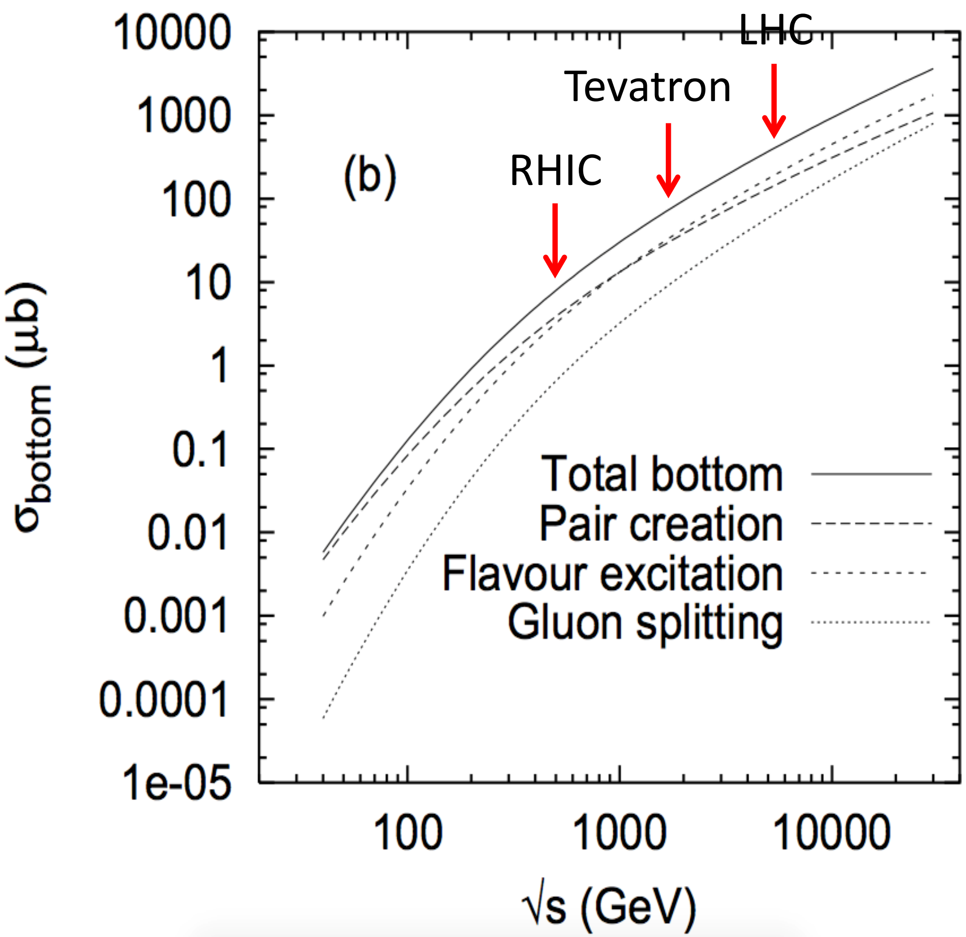
  - Measuring azimuthal correlations can disentangle different heavy flavor production mechanisms
  - Study energy dependence of HF production
    - GS contribution increases as beam energy increases.

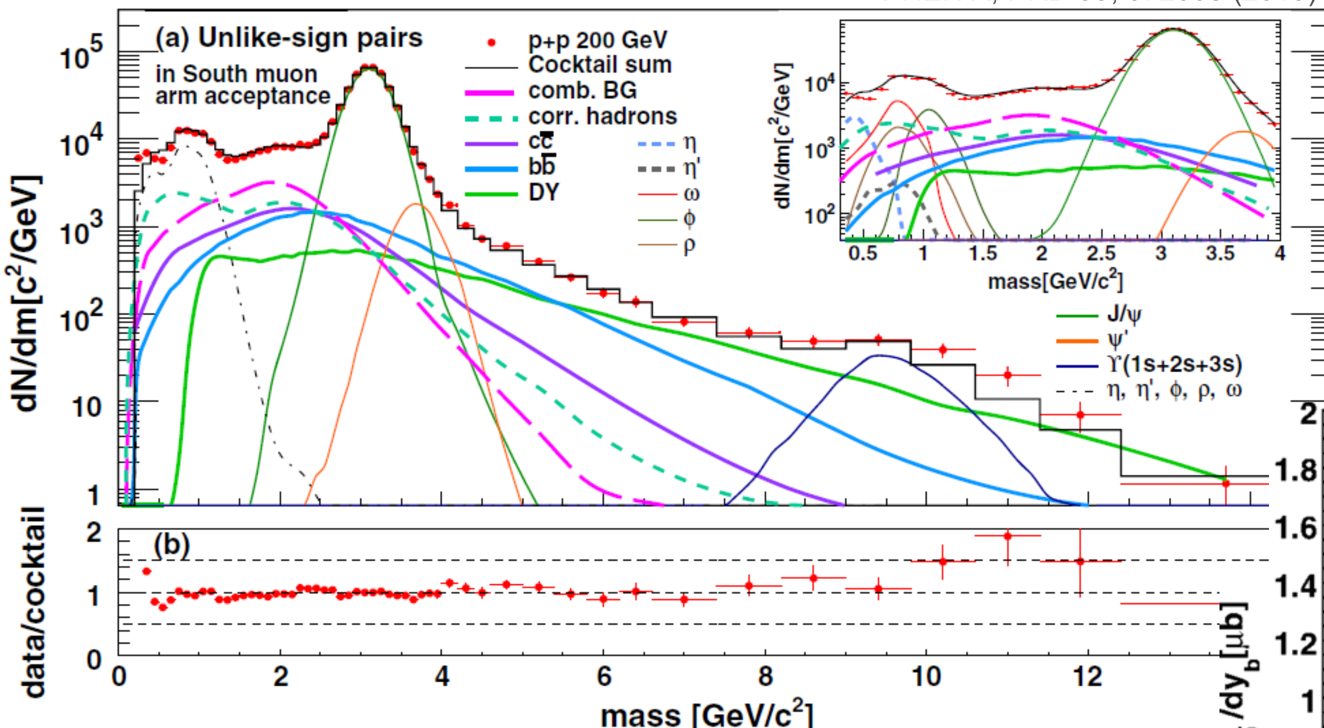
Production and Hadronization of Heavy Quarks, Eur.Phys.J.C17, 137-161 (2000)



Previous PHENIX $b\bar{b}$ Results

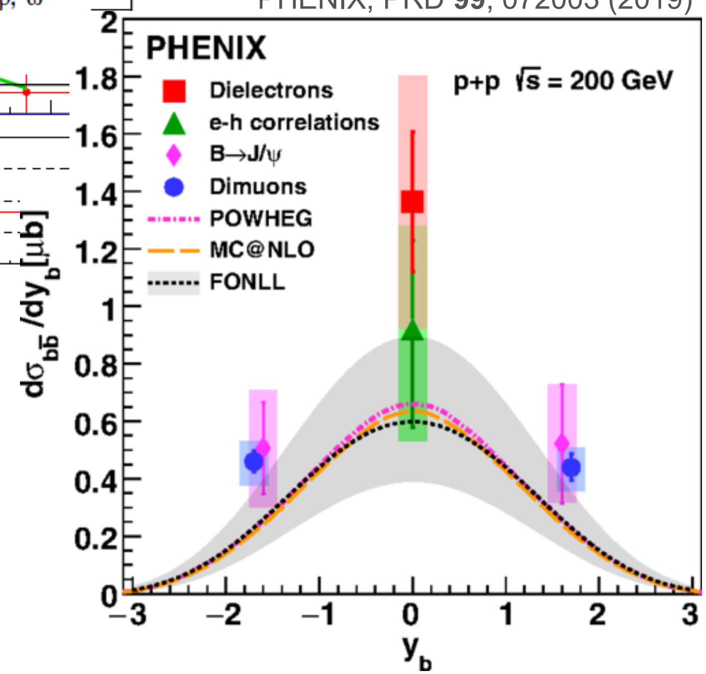
- Without displaced vertex *b*-tagging capability at PHENIX, *b*-quark production has been studied using dileptons from heavy quark

PHENIX, PRD **99**, 072003 (2019)



Inclusive $\mu^{+}\mu^{-}$ pair mass distributions from p+p collisions at $\sqrt{s}$=200 GeV over the mass range from 0 to 15 GeV/c^2.

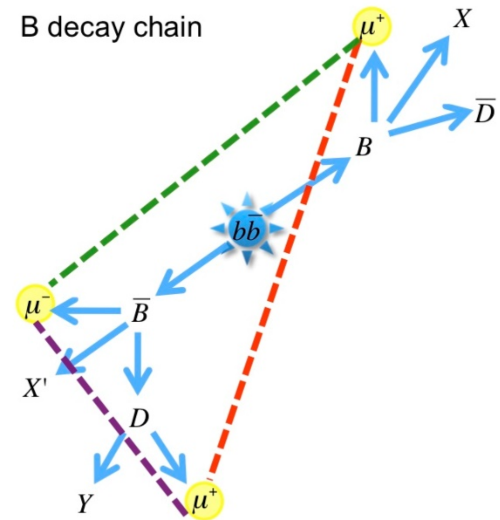
PHENIX, PRD **99**, 072003 (2019)

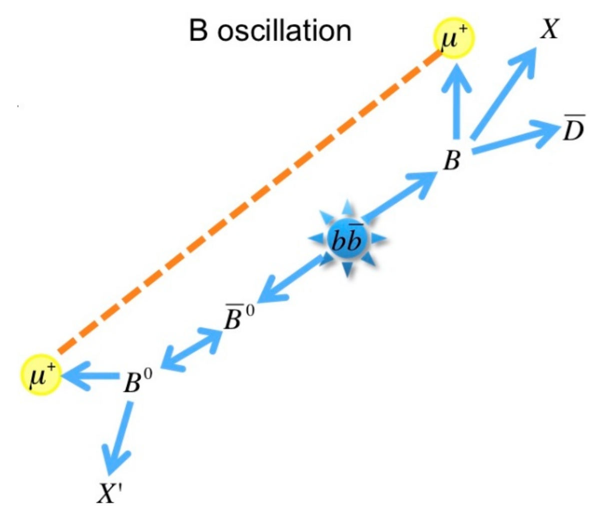


Rapidity density $d\sigma_{b\bar{b}}/dy$ in p+p collisions at $\sqrt{s}$ = 200 GeV measured in PHENIX via various channels compared to theoretical calculations. Here, y_b is the rapidity of a *b* quark.

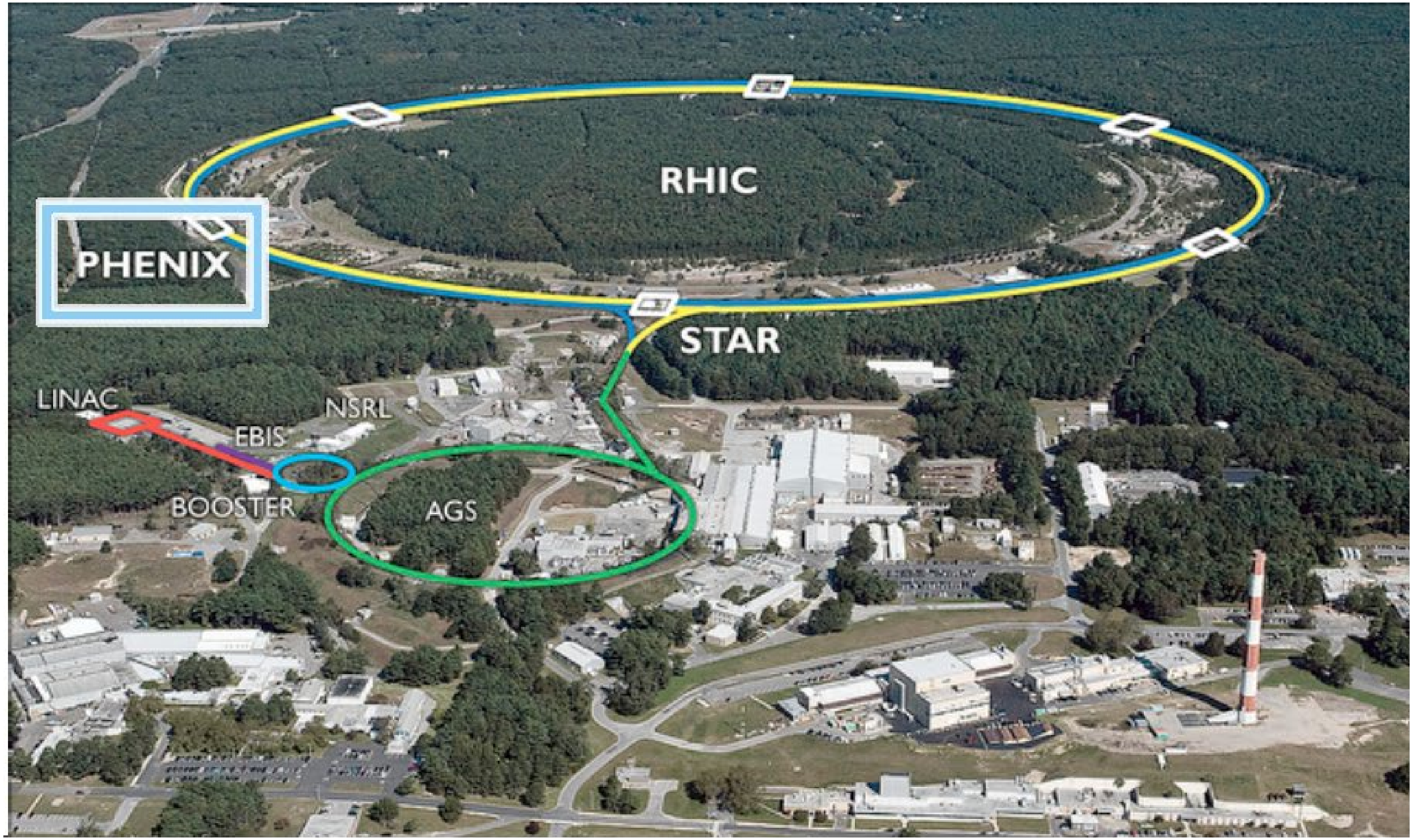
Using the like-sign

- Without displaced vertex *b*-tagging capability at PHENIX, *b*-quark production has been studied using dileptons from heavy quark
- In the mass region between 5 and 10 GeV, the predominant source of correlated like-sign dimuons will come from the decay of *B* meson pairs.
  - Drell-Yan process and quarkonia decays can only yield unlike-sign pairs!
  - *D* mesons do not oscillate and cannot produce like-sign pairs in the primary decay channel.
  - There is a small amount of contamination from hadronic background (< 10%).
- The number of correlated like-sign dimuons due to neutral *B* meson oscillation is directly related to the total number of open bottom meson pairs and thus can provide a way of constraining the open bottom contribution to the dimuon continuum in the high mass region.



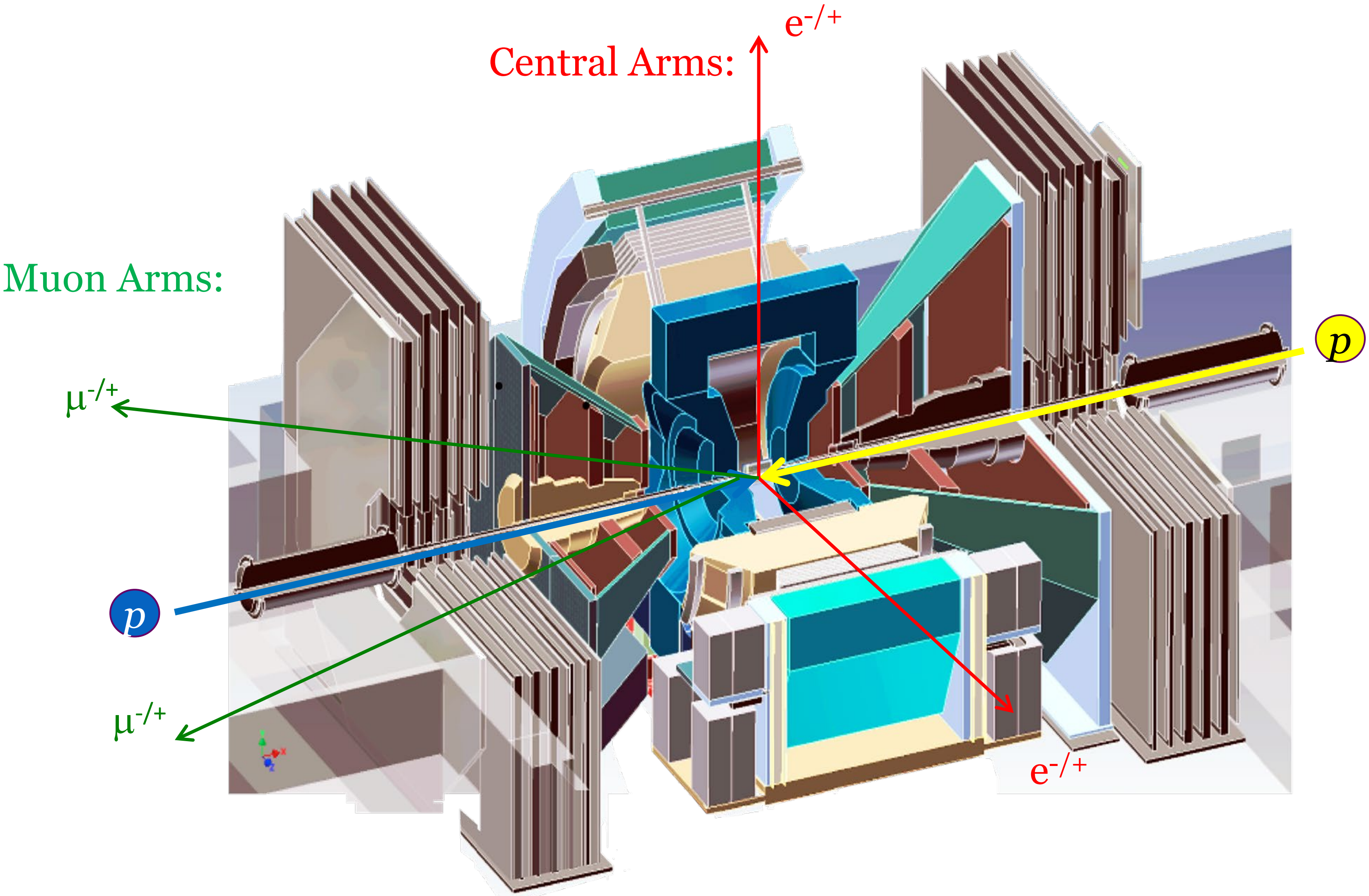


The Relativistic Heavy Ion Collider (RHIC)



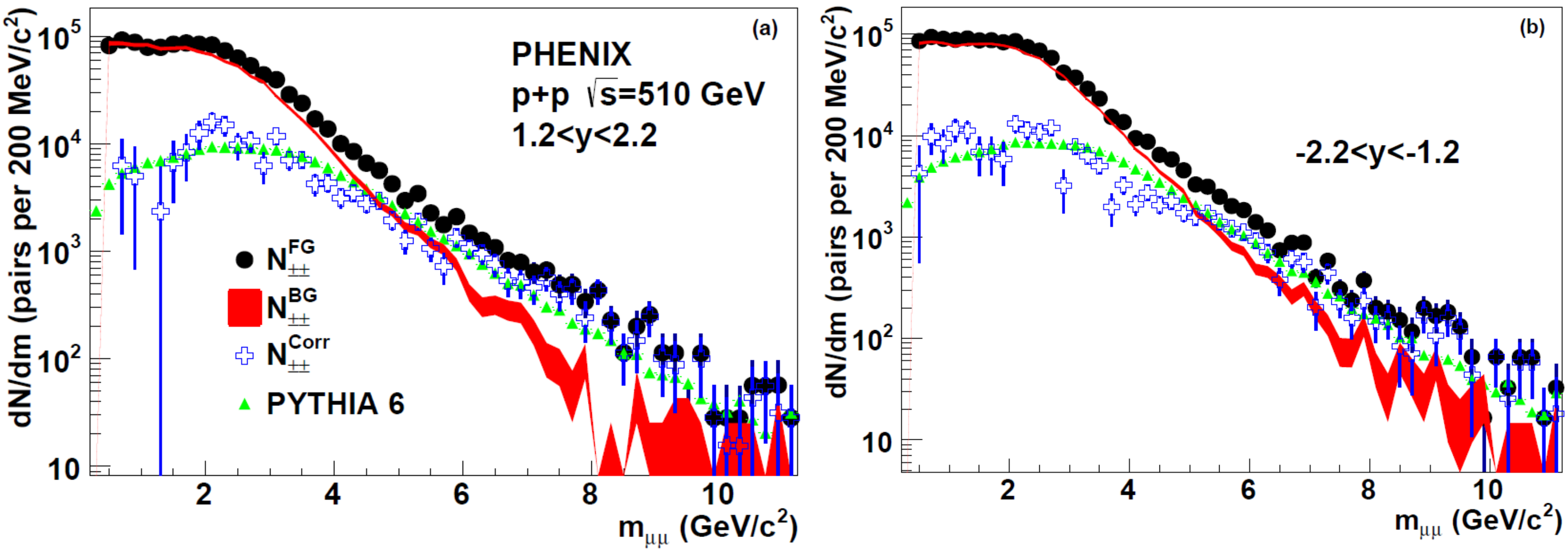
- RHIC is an extremely versatile machine, located at Brookhaven National Lab (BNL), that has collided a variety of collision species at various energies
- PHENIX finished its last run in 2016.

The PHENIX Detector



- Large rapidity coverage: 1.2<|y|<2.2 and |y|<0.35
- PHENIX recorded *p*+*p* collisions @ $\sqrt{s_{NN}}$ = 510 GeV in 2013.

Invariant Mass Spectra

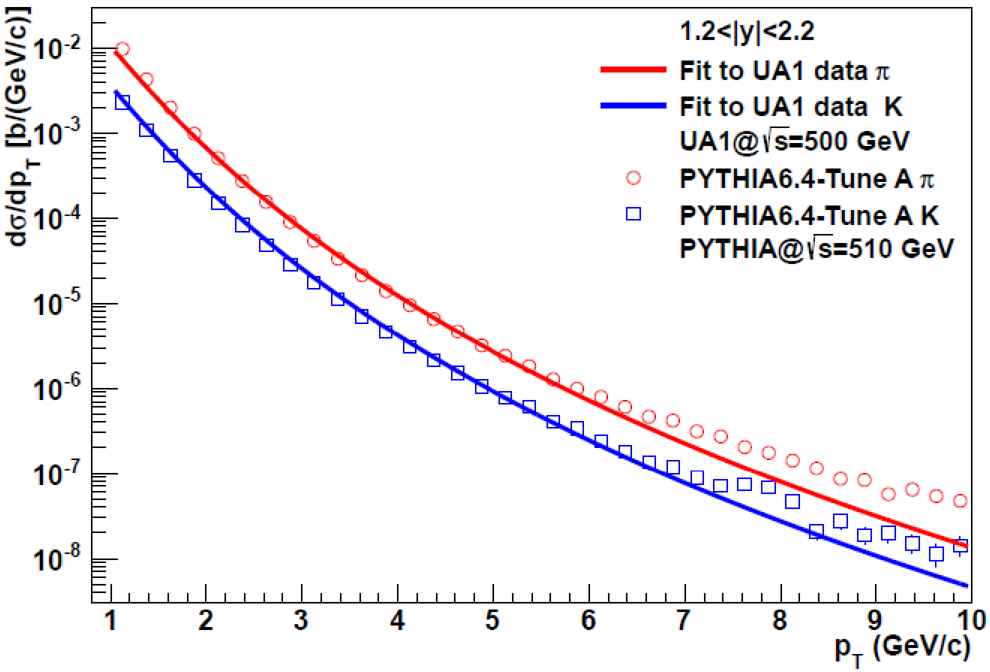


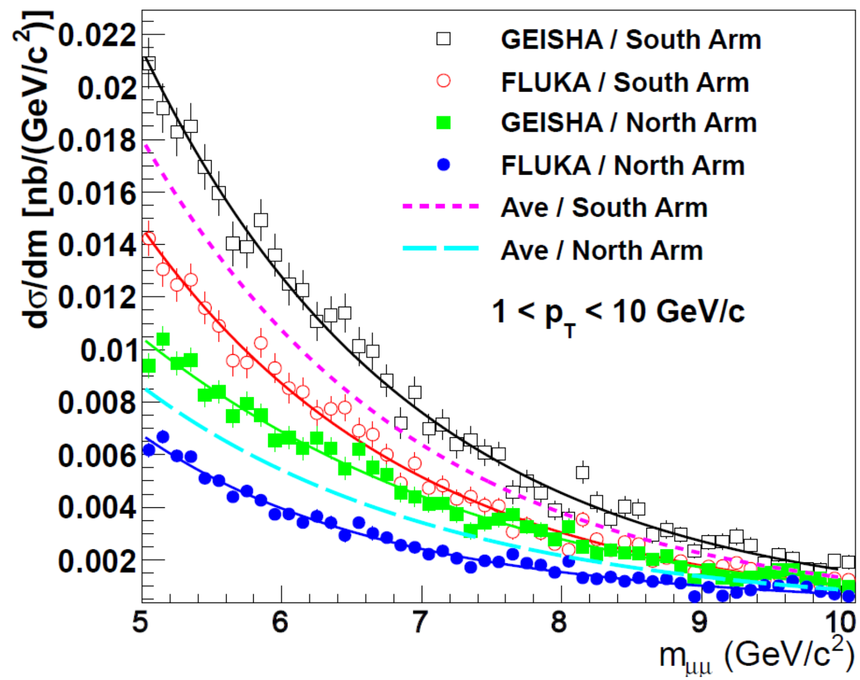
- Normalized **mixed event background** subtraction, $R = N^{FG} / N^{BG}$
- Iteratively remove bb-signal in the low mass region
  - Samples PYTHIA 6 bottom shape in MB from 250 Billion events

$$R = \frac{N^{FG} - N^{bb}}{N^{BG}}$$

- **Correlated Signal = FG - BG**

Hadronic Background





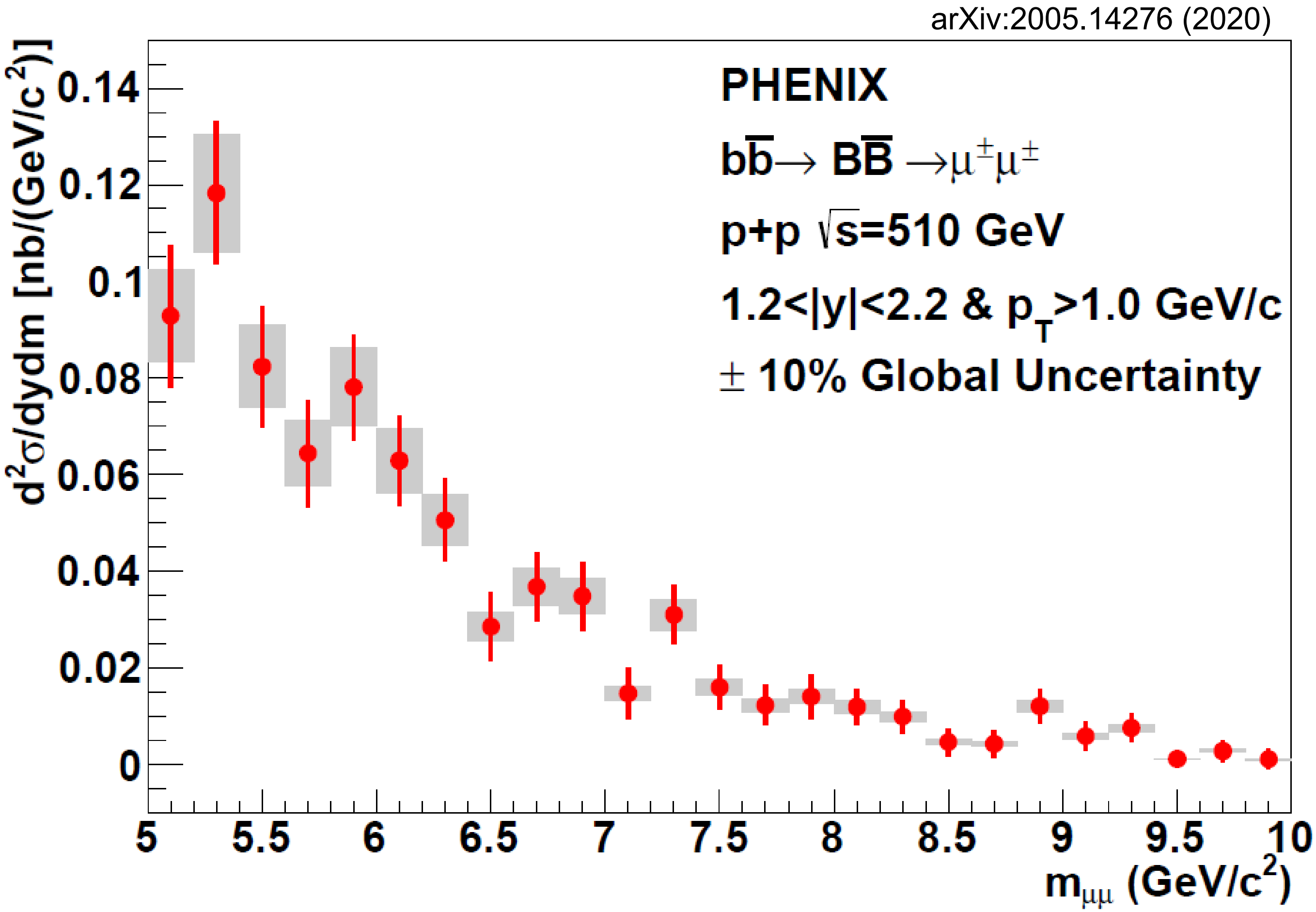
- Extract hadron survival probability (two different hadron interaction packages: GEISHA & FLUKA)
- Pythia generated pairs are weighted by the pair survival probability through the muon arms.
- Mixed event BG is normalized in similar manner to that of the data.

Systematic Uncertainties

- Point-to-point correlated uncertainty which allows the data points to move coherently within the quoted range to some degree (type-B)
- An overall (global) normalization uncertainty (type-C)

Source	Value	Type	
Signal extraction	±3.6%	B	Like-sign pairs / all pairs
Acceptance × efficiency	±7.9%	B	Like-sign pairs / all pairs
MuID Efficiency	±4.0%	B	Like-sign pairs / all pairs
MuTr Efficiency	±5.3%	B	Like-sign pairs / all pairs
Hadronic background	±3.4%	B	Like-sign pairs / all pairs
$\alpha(m)$	±1.9%	B	all pairs
β	±4.5%	B	all pairs
Total	±12.4%	B	
BBC efficiency	±10.0%	C	
Branching ratio (B→ μ + X)	±0.28%	C	σ_{tot} extrapolation
Model dependence	±18.1%	C	σ_{tot} extrapolation
Total	±20.7%	C	

Like-sign Differential Cross Section



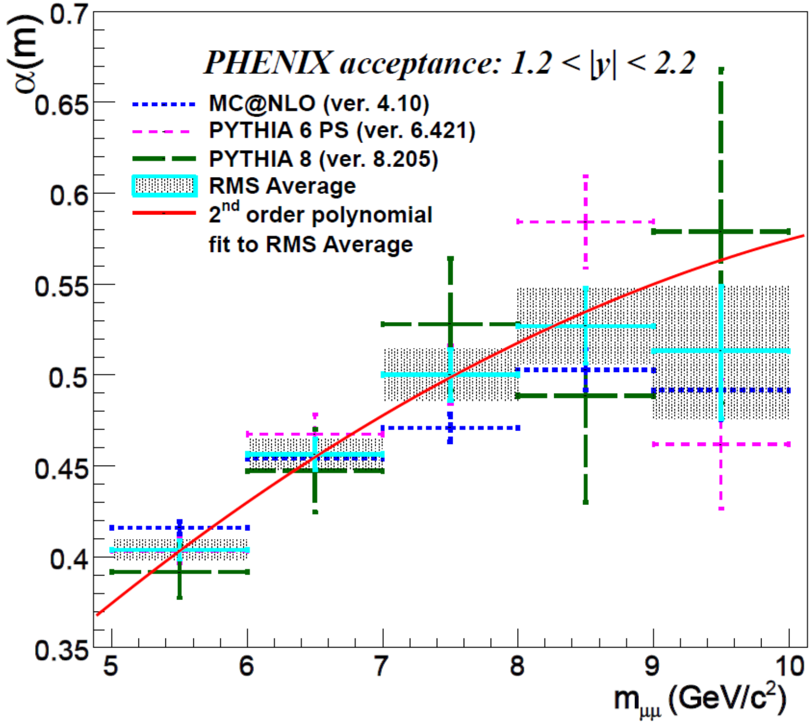
$$d\sigma_{b\bar{b}\rightarrow\mu^{\pm}\mu^{\pm}}/dy = 0.16 \pm 0.01\ (\text{stat}) \pm\ 0.02\ (\text{type} - \text{B sys}) \pm\ 0.02\ (\text{global sys})\ \text{nb}$$

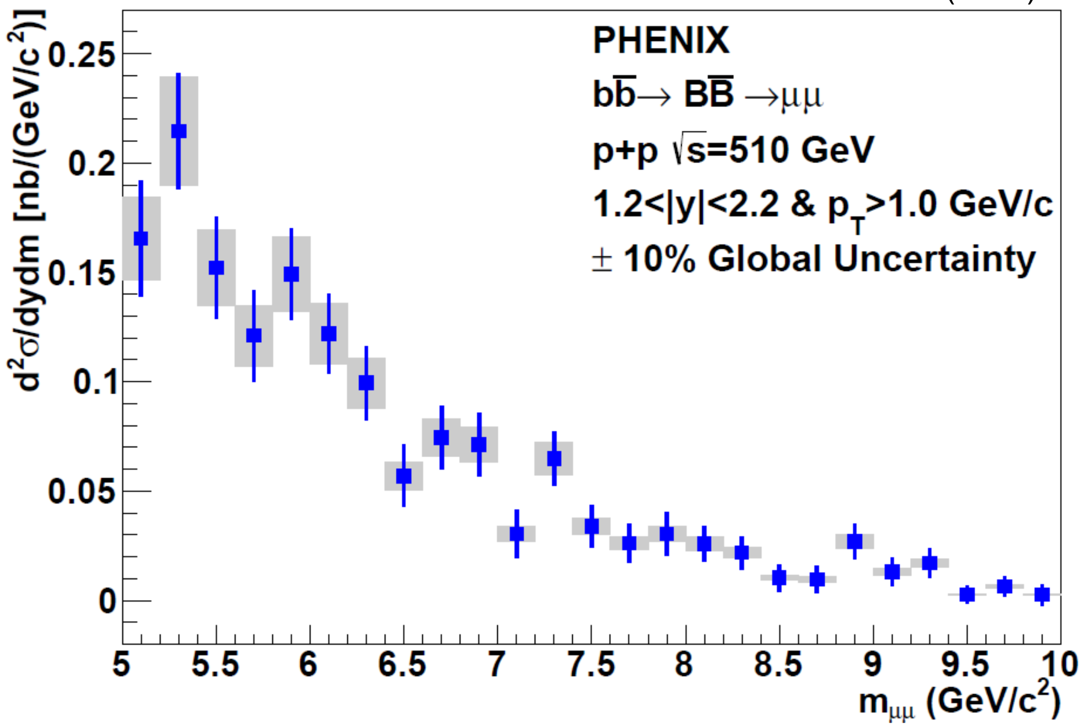
Differential cross section

$$\frac{d^2\sigma_{b\bar{b}\to B\bar{B}\to\mu\mu}}{dydm} = \frac{\alpha(m)}{\beta}\frac{d^2\sigma_{b\bar{b}\to B\bar{B}\to\mu^\pm\mu^\pm}}{dydm}$$

$$\alpha(m) = \frac{b\bar{b}\to B\bar{B}\to\mu^\pm\mu^\pm\ (\mathrm{osc})}{b\bar{b}\to B\bar{B}\to\mu^\pm\mu^\pm} \qquad \beta = \frac{b\bar{b}\to B\bar{B}\to\mu^\pm\mu^\pm\ (\mathrm{osc})}{b\bar{b}\to B\bar{B}\to\mu\mu} = 0.22 \pm 0.01$$

arXiv:2005.14276 (2020)



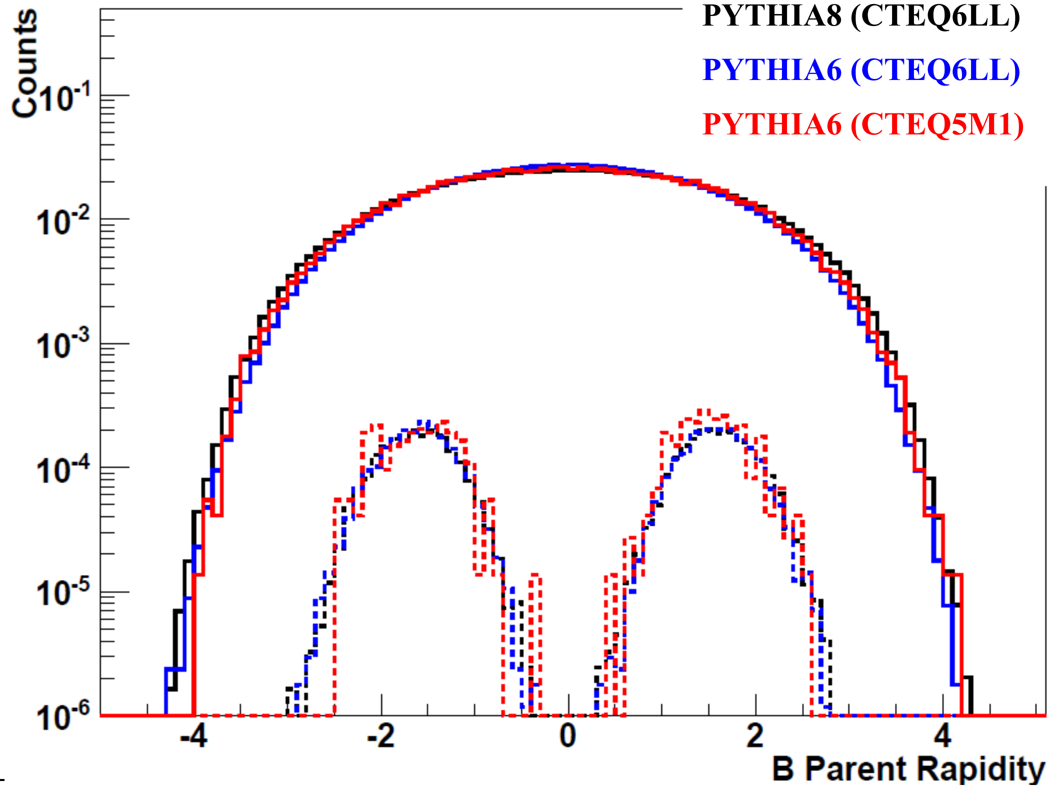


$$d\sigma_{b\bar{b}\to\mu\mu}/dy = 0.31 \pm 0.01\ (\mathrm{stat}) \pm\ 0.04\ (\mathrm{type-B\ sys}) \pm 0.03\ (\mathrm{global\ sys})\ \mathrm{nb}$$

Total Cross Section

$$\sigma_{b\bar{b}} = \frac{d\sigma_{b\bar{b}\to\mu\mu}}{dy} \times \frac{1}{scale} \times \frac{1}{(BR_{B\to\mu})^2}$$

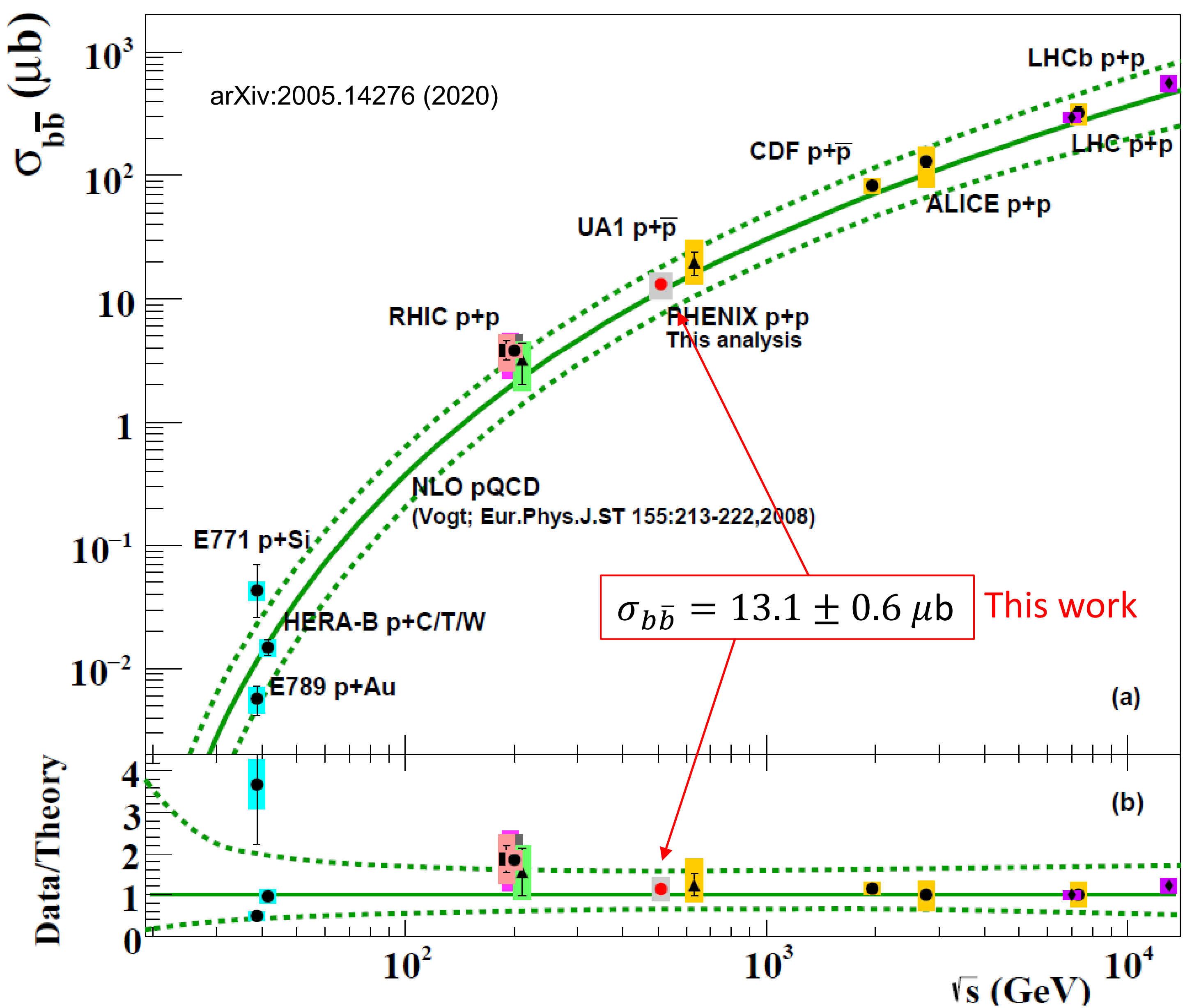
- $BR_{B\longrightarrow\mu} = 10.99\%$
- $scale = 0.00196$



Simulation	Scale Factor	
PYTHIA 6 (CTEQ6LL)	0.002067	
PYHTIA 8 (CTEQ6LL)	0.002096	
MC@NLO (CTEQ5M)	0.001126	
PYTHIA 6 (CTEQ5M1)	0.002546	
Ave Value	0.001959	± 0.000355

Global uncertainty of 18.1%.

Total Cross Section

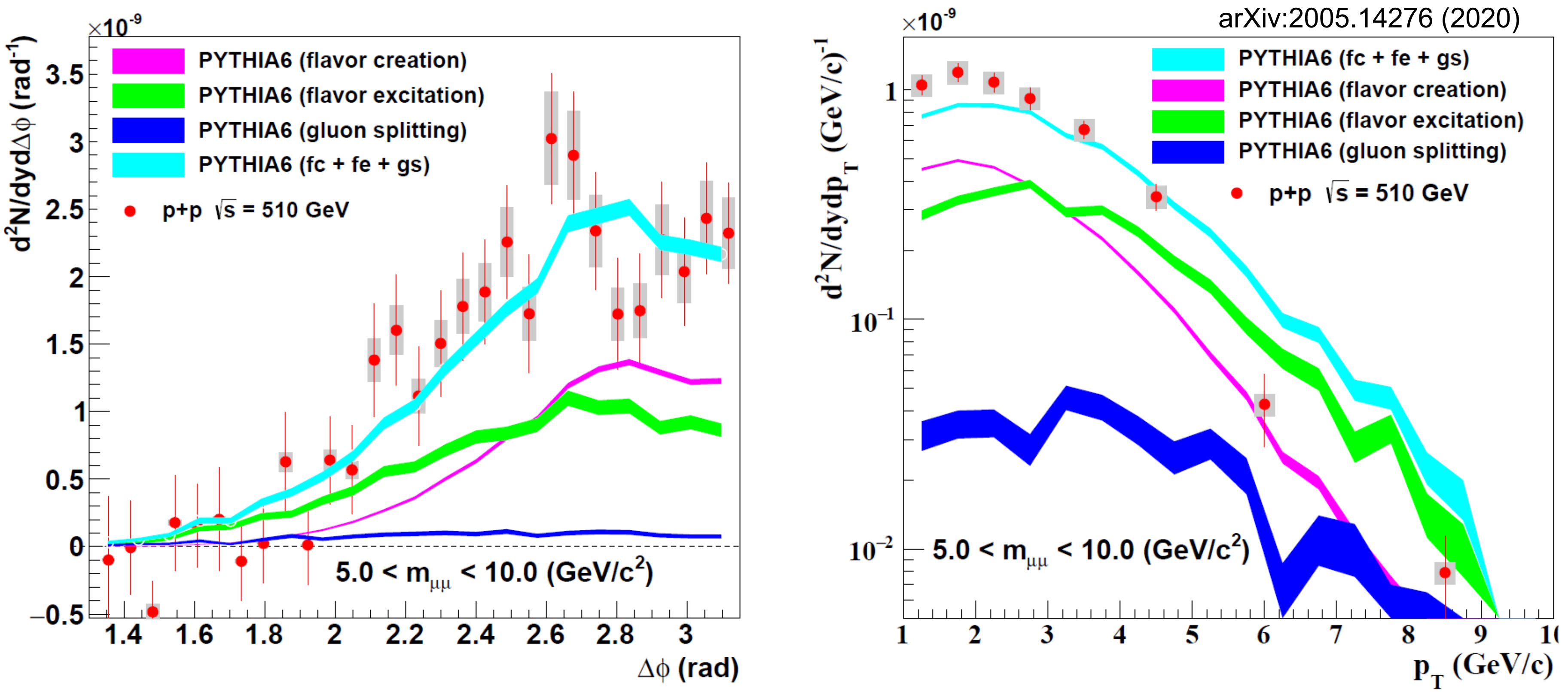


At $\sqrt{s} = 510$ GeV, the NLO pQCD

$\sigma_{b\bar{b}} = 11.5^{+6.5}_{-3.9}\ \mu$b

- Consistent with NLO pQCD within uncertainties

Azimuthal correlations and pair p_T



- The data have a wider azimuthal distribution and a steeper p_T distribution but still consistent with ps pythia6 within uncertainties.
- These results show similar behavior to that observed at 200 GeV $\Rightarrow$ the data favors a dominant mix of flavor creation and flavor excitation subprocesses over gluon splitting.

Summary & Conclusions

- First measurements of the differential cross section for dimuons from bottom quark-antiquark production in p+p collisions at $\sqrt{s}$ = 510 GeV.
- The extrapolated total cross section is consistent with NLO pQCD calculations within uncertainties.
  - This agreement with NLO pQCD calculations at $\sqrt{s}$ = 510 GeV is better than what was observed at 200 GeV, indicating a better match with NLO pQCD calculations at higher energies.
- The azimuthal opening angle between the muons from bb decays and the pair p_T distributions are compared to distributions generated using ps pythia6, which includes NLO processes.
  - While the data tend to have a wider azimuthal distribution and present a steeper pT distribution, both are still consistent within uncertainties with ps pythia6, where flavor creation and flavor excitation subprocesses are dominant. This is similar to what was observed at 200 GeV.

Thank You

for your attention

Backup

Acceptance & Reconstruction Efficiency