Measurements of μμ pairs from charm, bottom, and Drell-Yan in $p+p$ and p+Au at $\sqrt{s_{NN}}$ =200 GeV with PHENIX at RHIC

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Nuclear Physics Seminar
BNL, 06-19-2018

- Introduction
- Heavy flavor production
- Probing cold nuclear matter effects
- Summary

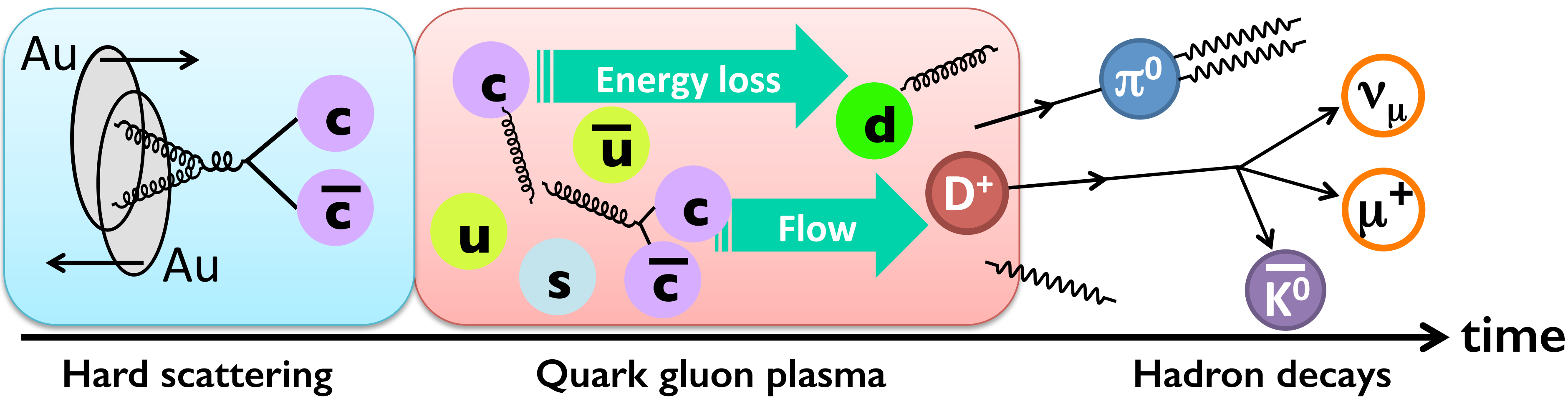
Probing nuclear matter with heavy flavor

p+p → No Nuclear Matter
- Baseline measurement
- Test pQCD calculations

p/d+A → Cold Nuclear Matter
Initial state effects
Final state effects

A+A → Quark gluon plasma
Hot and cold nuclear matter effects

Heavy flavor produced at the early stages of the collision
- Classic probe to study cold and hot nuclear matter effects



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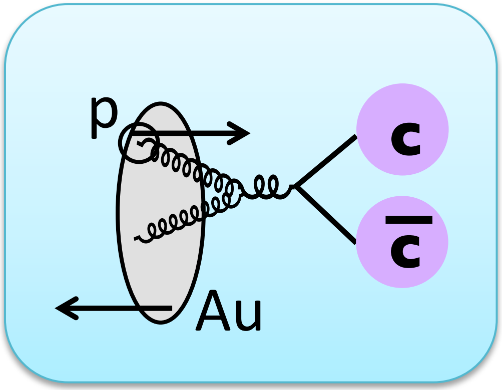
- **Modification of PDFs in nuclei**
  - **(Anti-) shadowing**
- **Other initial/final state effects**
  - **Multiple scattering**
  - **Energy loss**
  - **Flow**



time

Hard scattering **Hadron decays**

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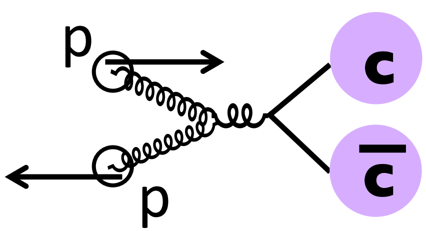

Probing nuclear matter with heavy flavor

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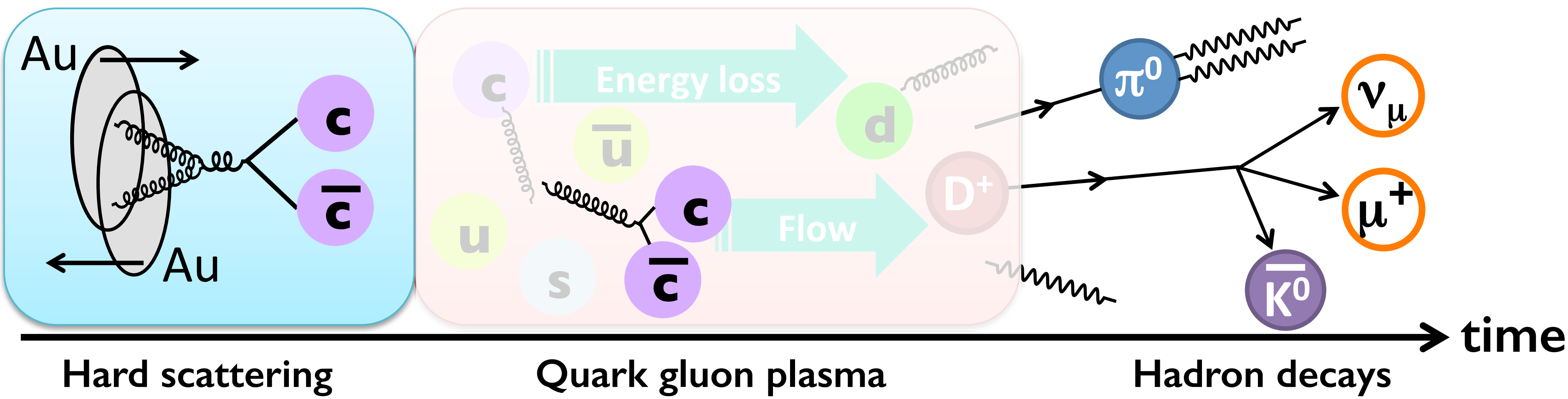
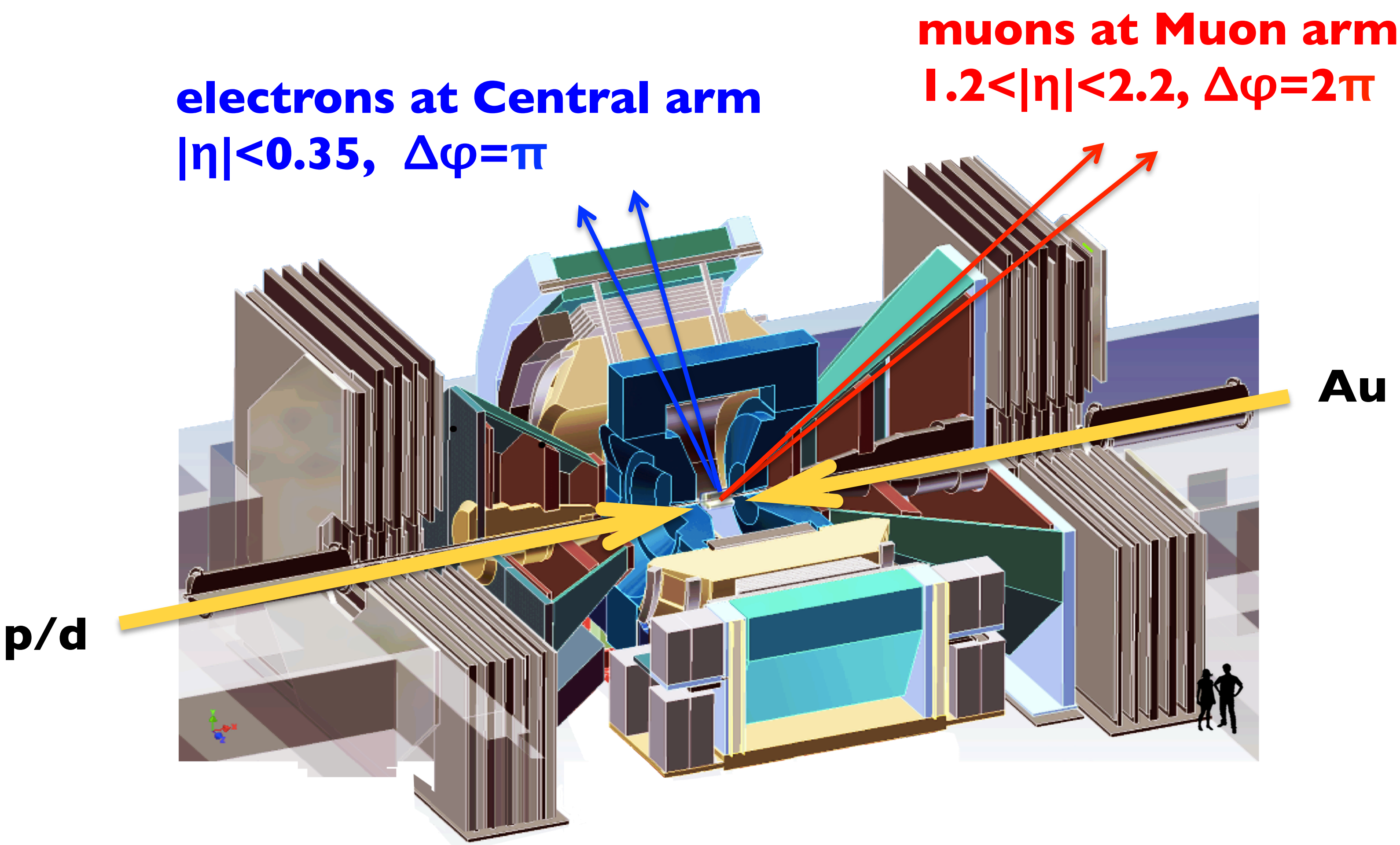
Heavy flavor produced at the early stages of the collision (?)
- Classic probe to study cold and hot nuclear matter effects

Need good understanding HF in small systems to interpret A+A data!!

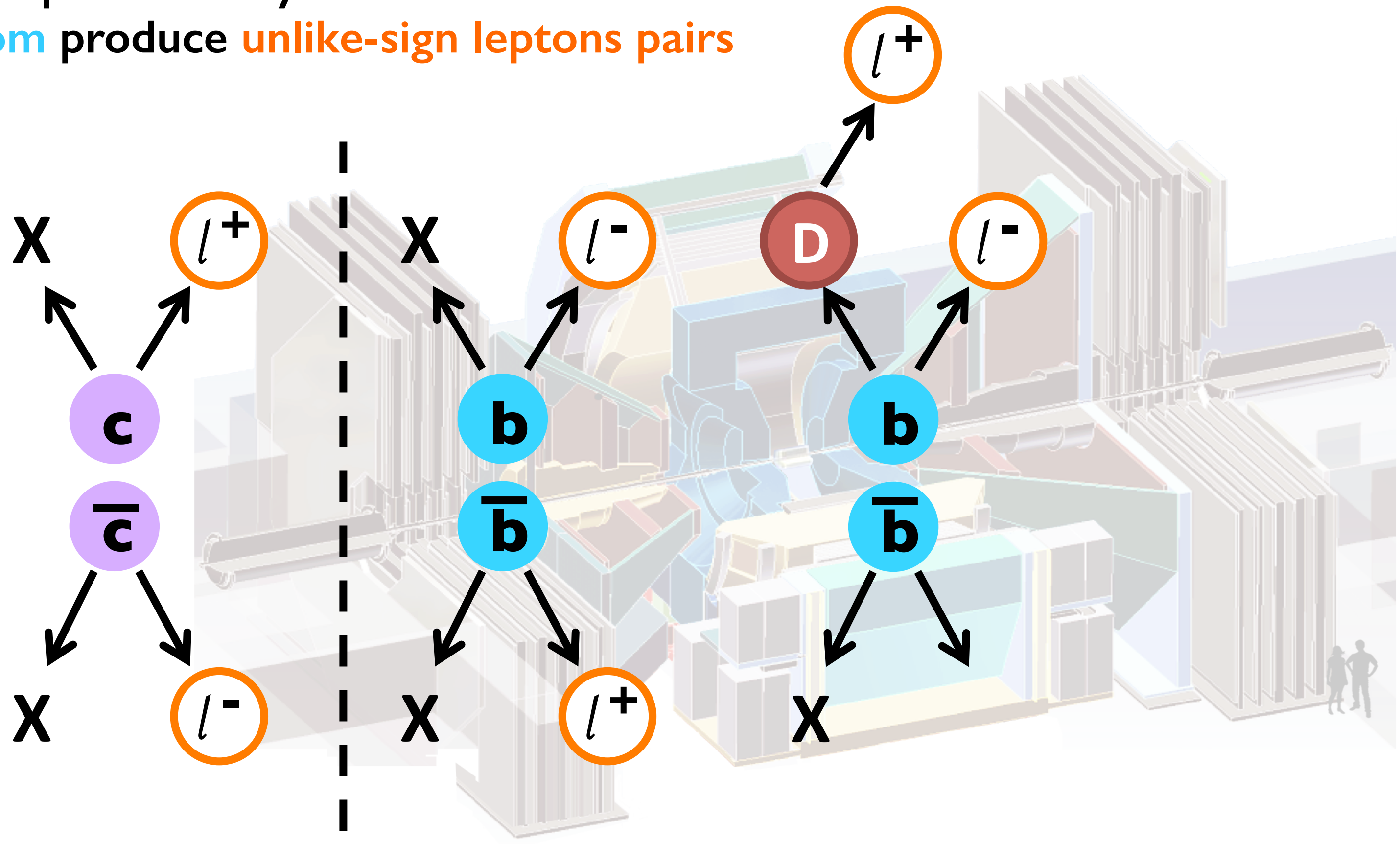


The PHENIX detector



Measuring dileptons with PHENIX

Semi-leptonic decays from Charm and Bottom produce unlike-sign leptons pairs



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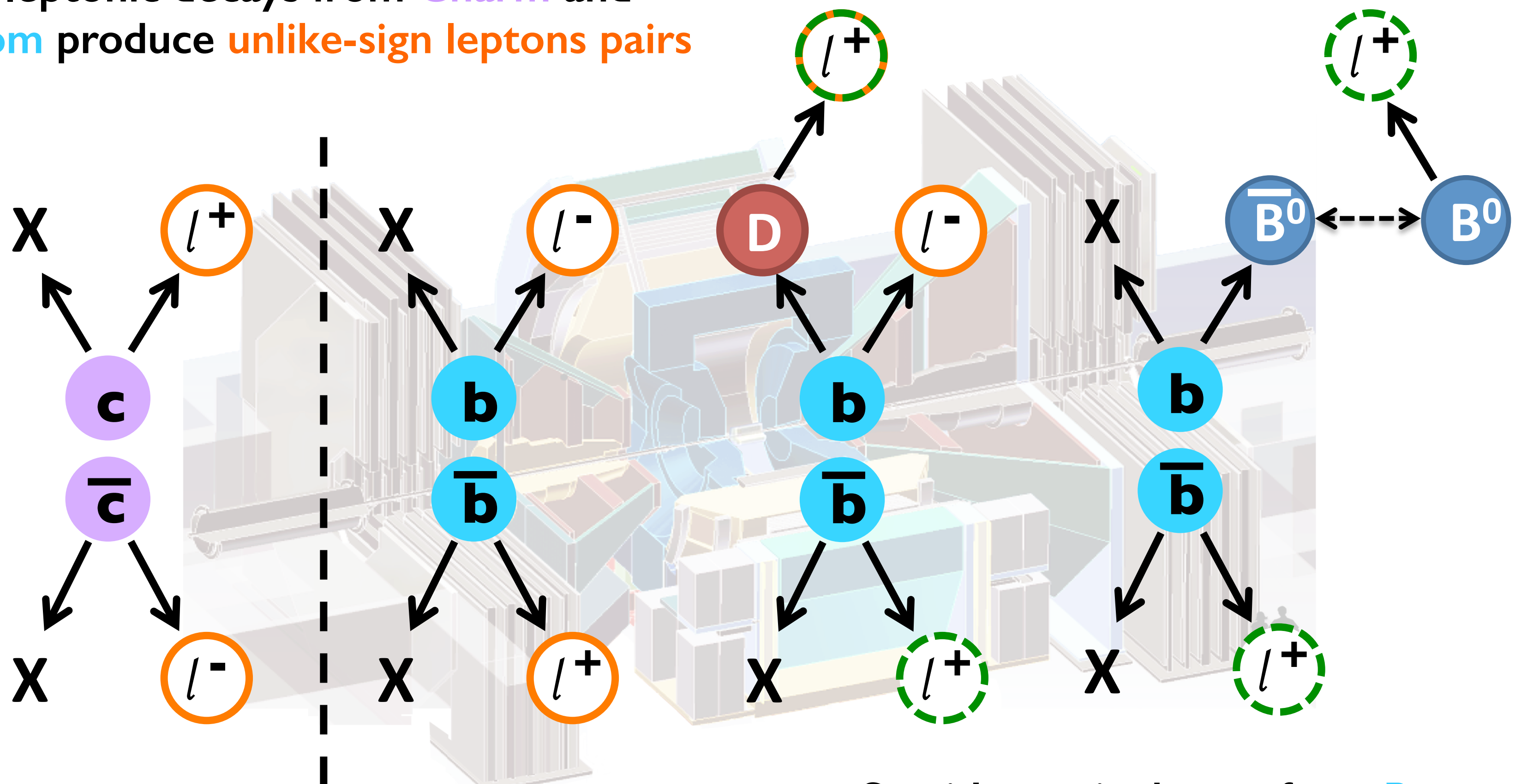
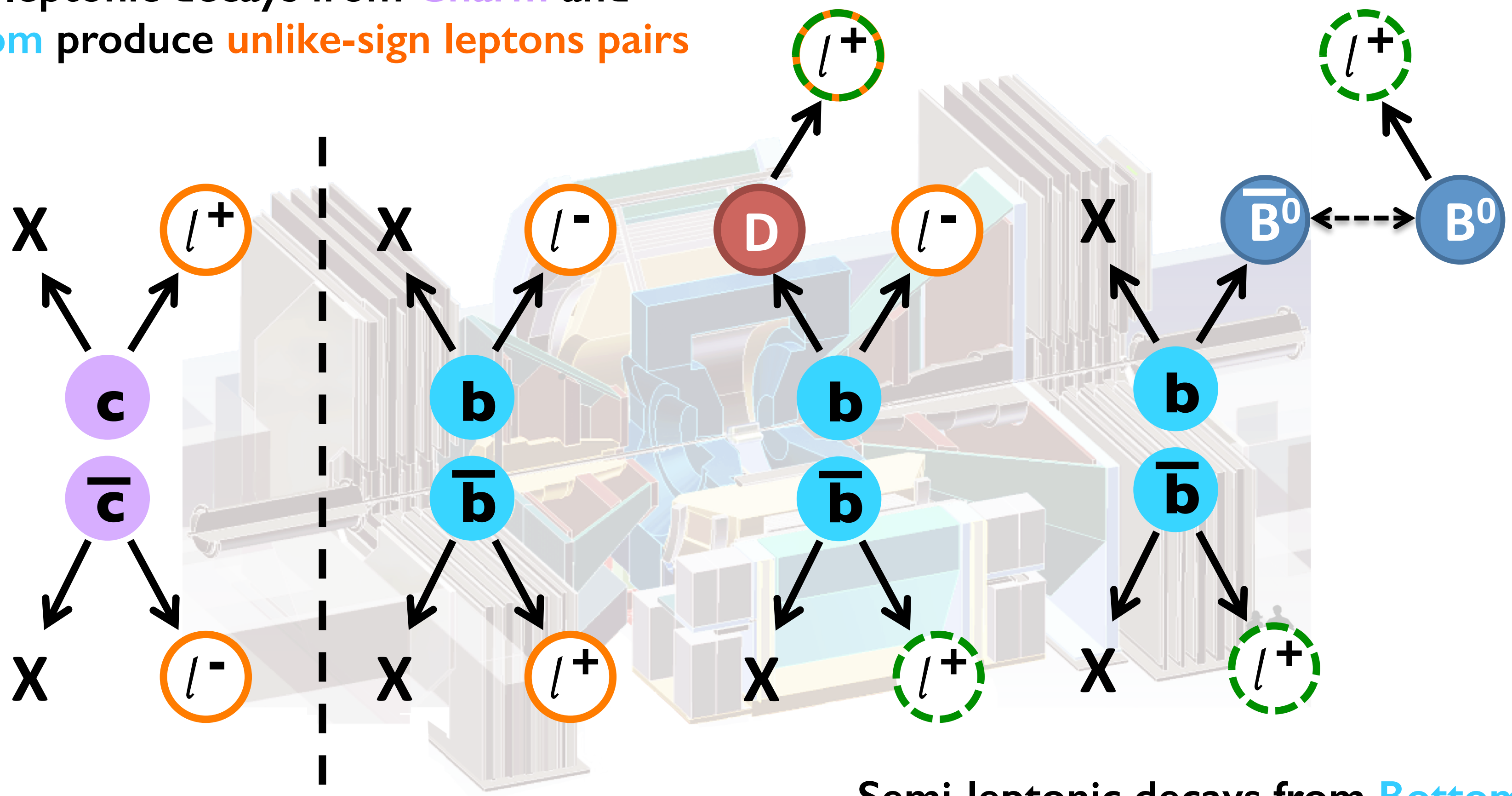


Semi-leptonic decays from Bottom can also produce like-sign lepton pairs

Why dileptons?

- **Charm-bottom separation without reconstruction of secondary vertex**
  - Charm/bottom dominates different regions of dilepton phase space
- **Opportunity to study pair correlations**

Semi-leptonic decays from Charm and Bottom produce unlike-sign leptons pairs



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1. **Studying heavy flavor production** *in p+p collisions*
2. **Probing cold nuclear matter effects** *in p+A collisions*

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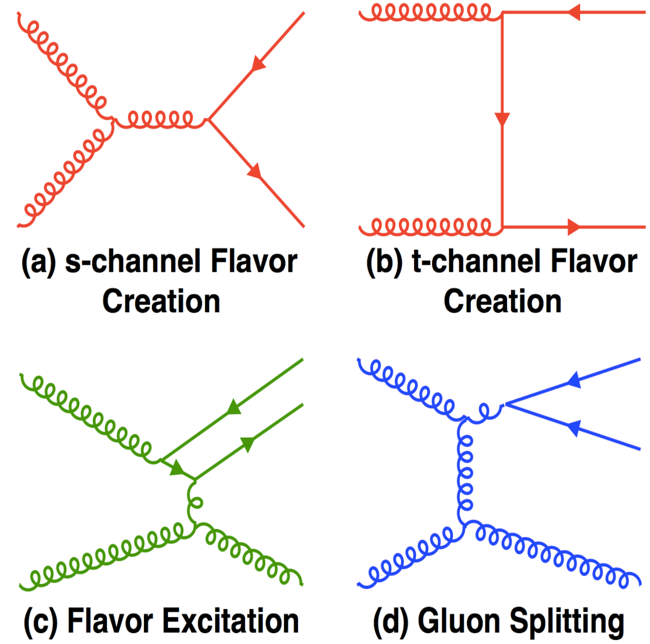
2. **Probing cold nuclear matter effects** *in p+A collisions*

Heavy flavor event generators

- **Shower Monte Carlos**
  - e.g. PYTHIA, HERWIG
  - Leading order matrix elements
  - NLO effects emulated via parton shower approach
  - Separate calculations for each process
  - Ignores interference effects

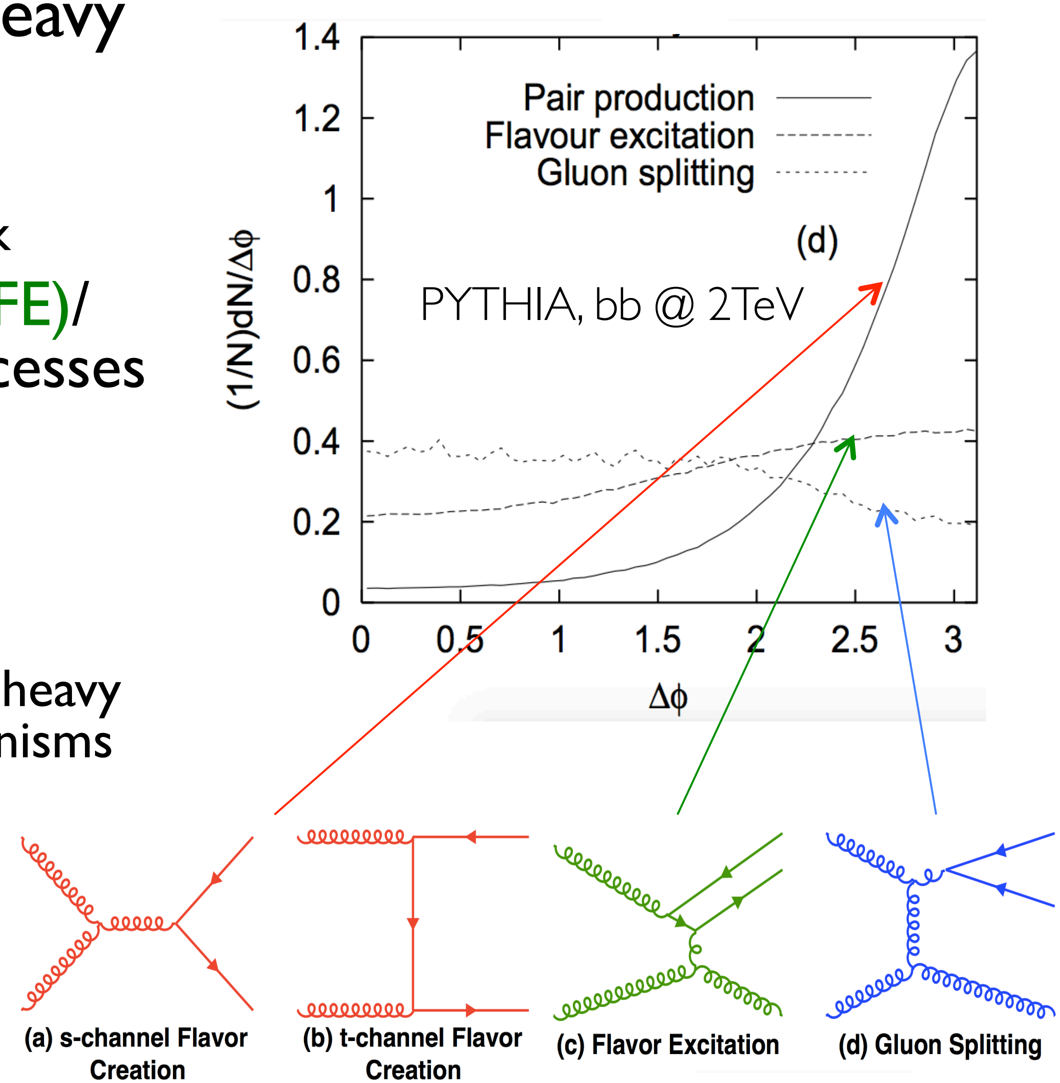


- **NLO + PS**
  - e.g. MC@NLO, POWHEG
  - NLO matrix elements
  - Interfaced to shower Monte Carlos like PYTHIA, HERWIG
  - Different methodologies (e.g. negative weights, p_T veto) to avoid double counting

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) processes
    - 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



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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

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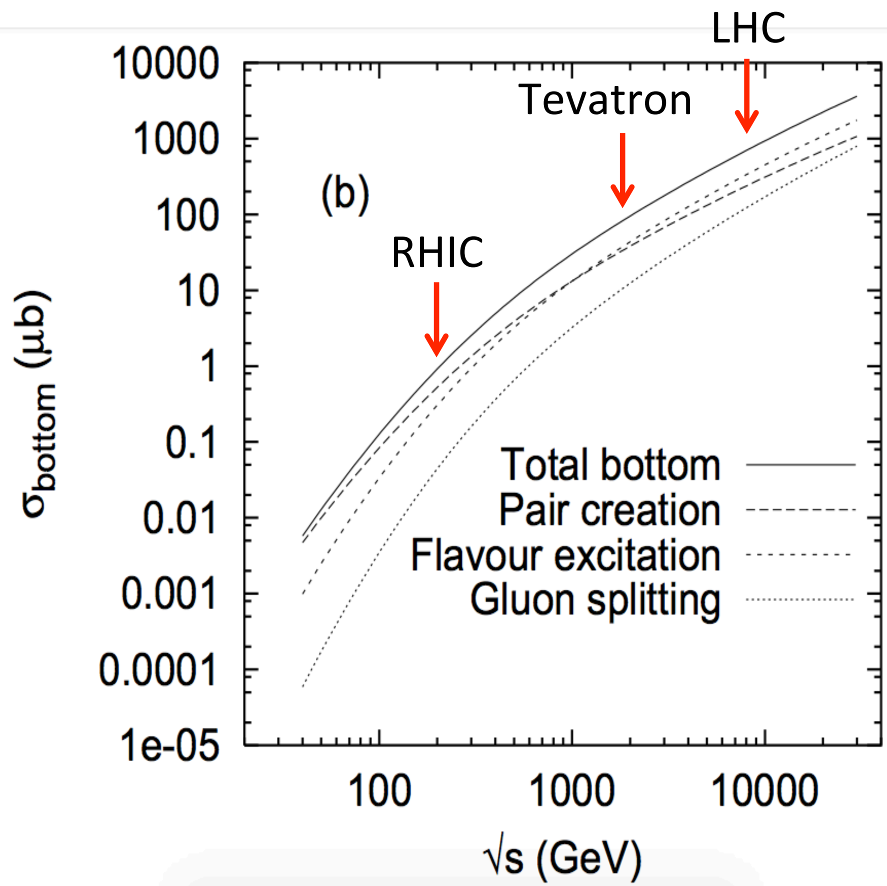
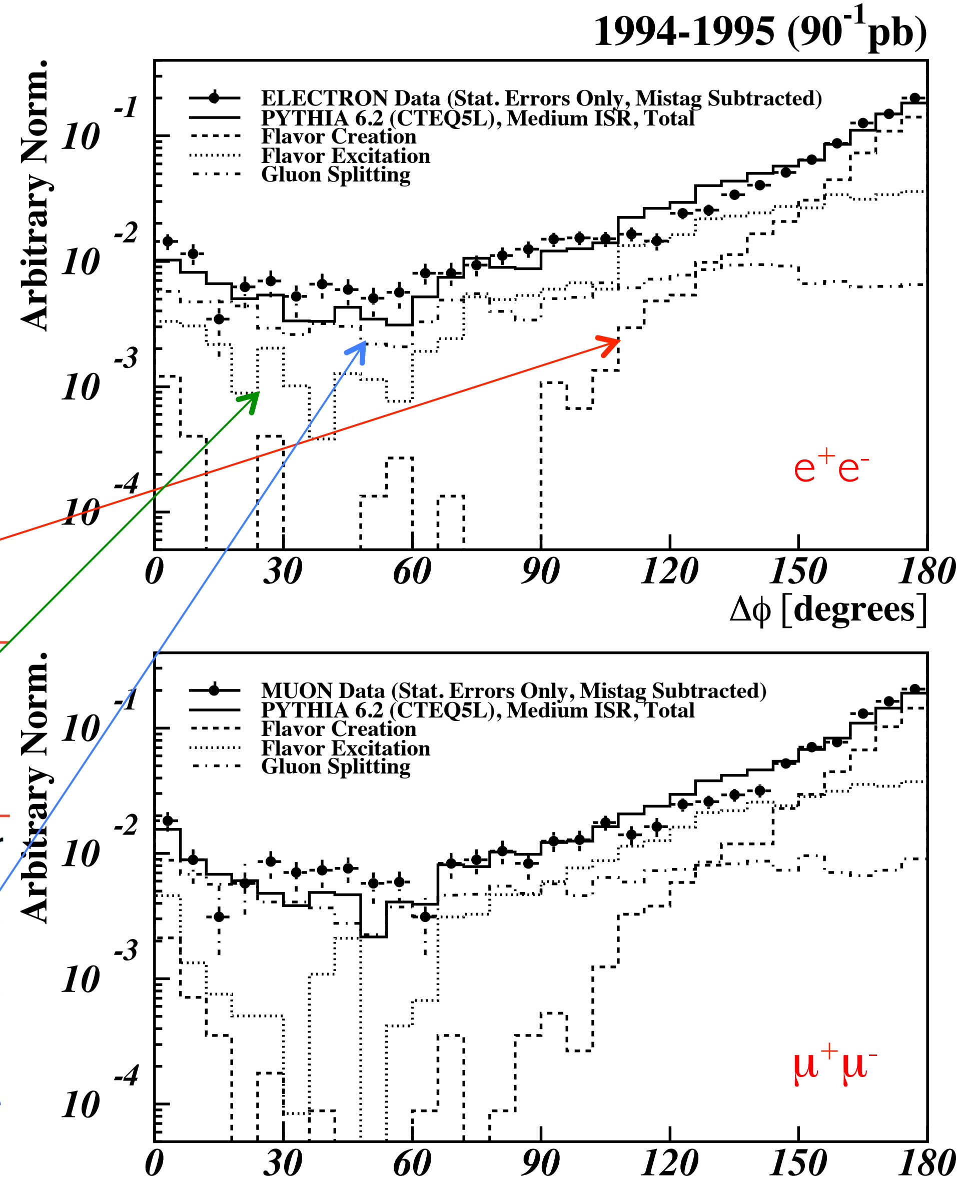
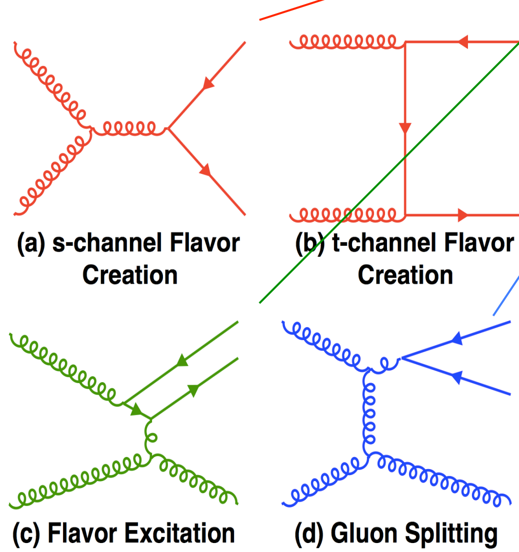


$b\bar{b}$ azimuthal correlations in $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV

- **Higher order processes dominate over flavor creation at small opening angles.**

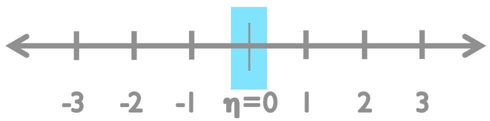
- **Flavor excitation and gluon splitting play a significant role in bb production at 1.8TeV.**

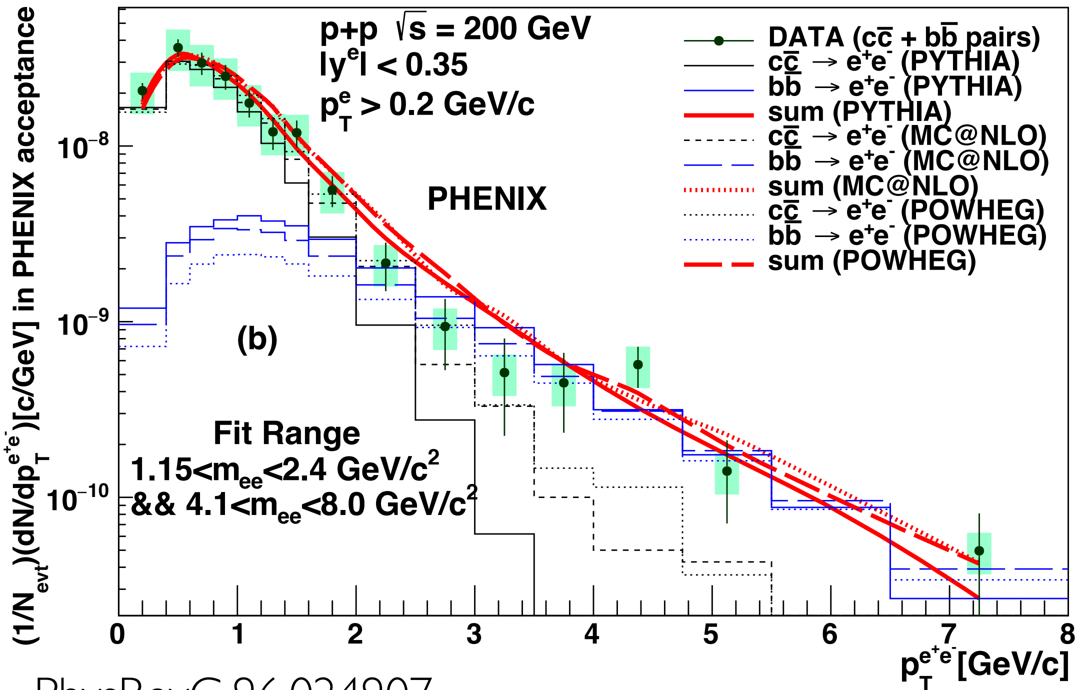




Phys.Rev.D71.092001

Mid-mid rapidity HF pairs in p+p, 200 GeV





PhysRevC.96.024907

- **Significant model dependence in cc**
- **Data can be reasonably described by different models**

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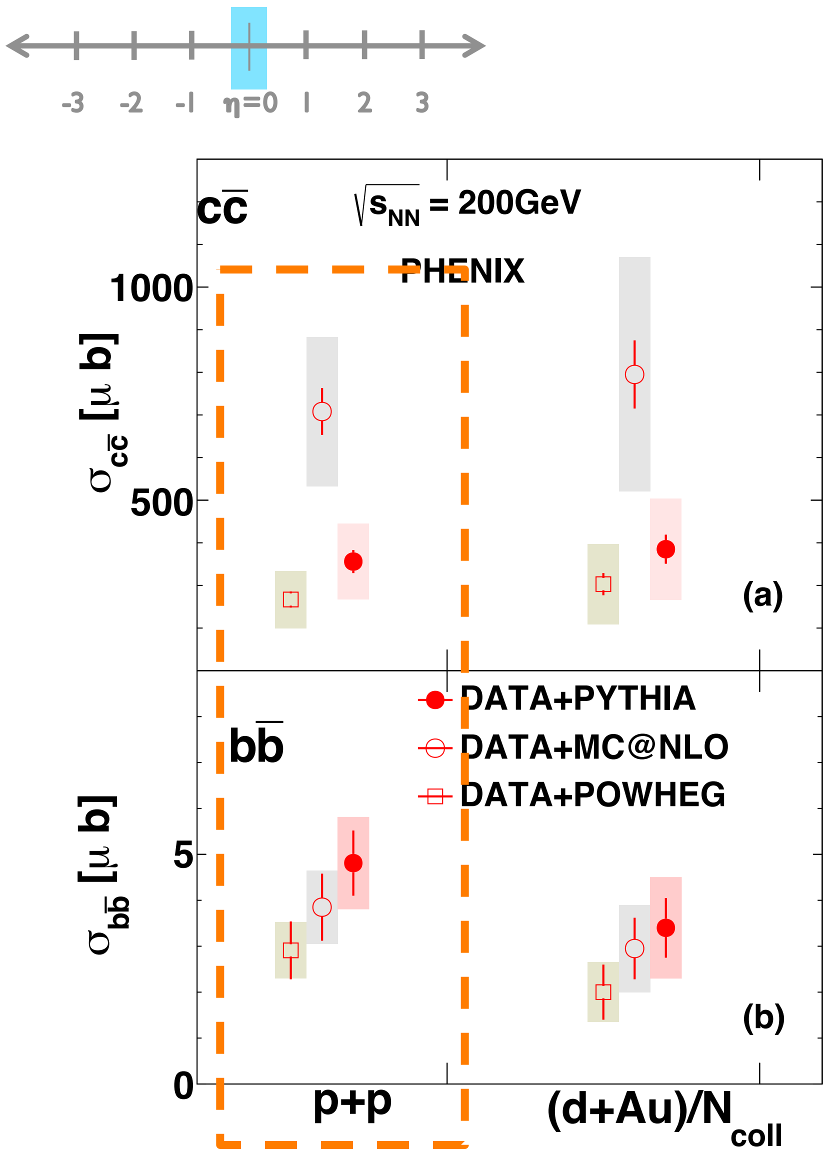
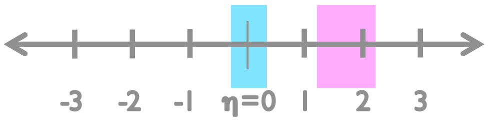


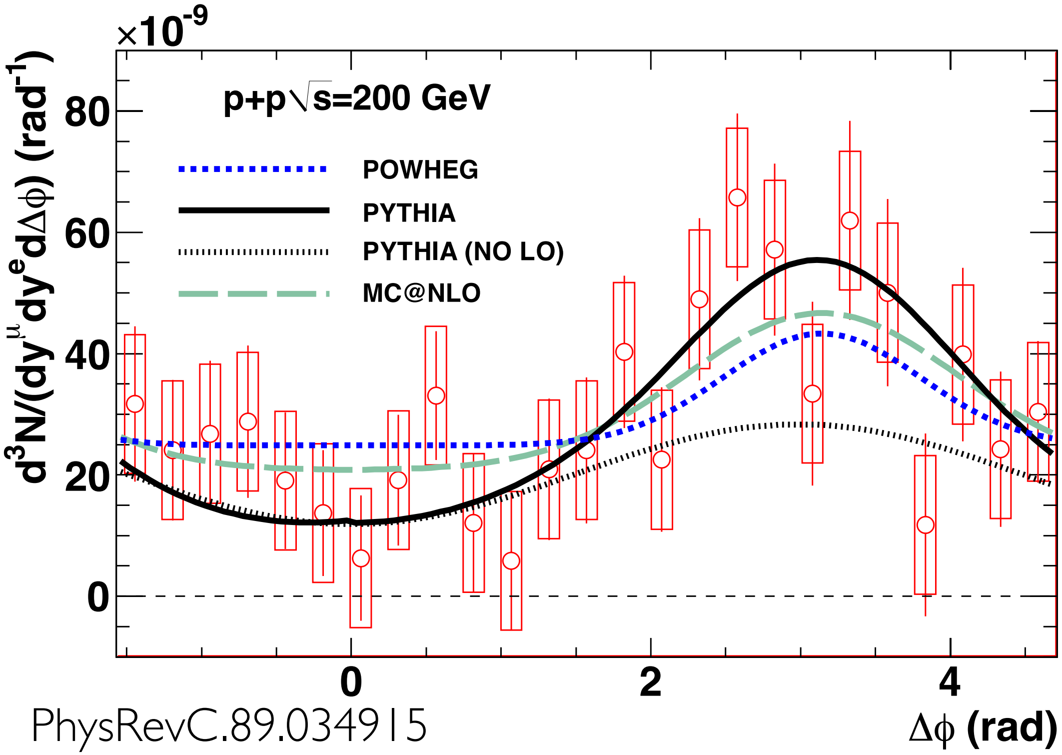
PhysRevC.96.024907

- Model dependence in cc more apparent when extrapolating to 4π phase space
- bb is less model dependent
  - distributions dominated by decay kinematics

Mid-fwd rapidity HF pairs in p+p, 200 GeV



- **Significant model dependence of differential distributions from cc**



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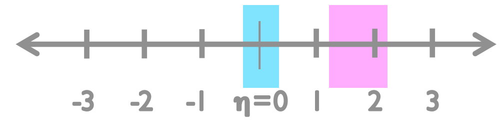

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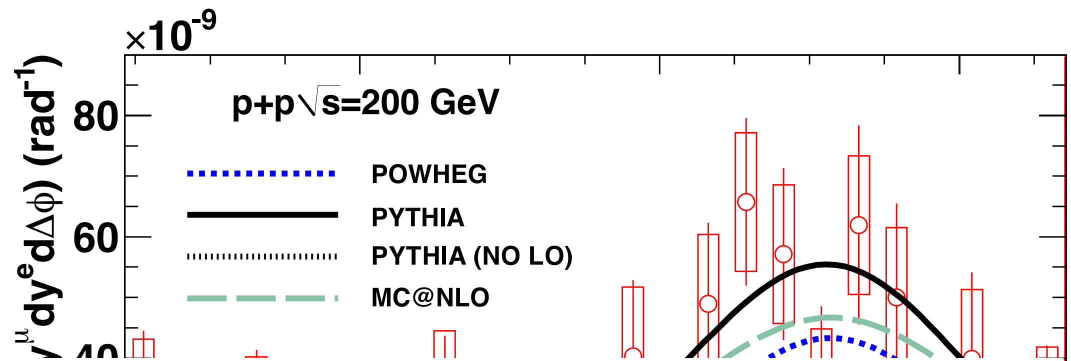
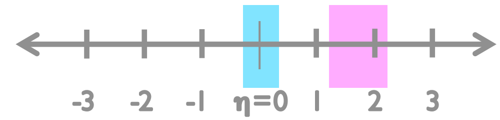


TABLE II: Table of measured $c\bar{c}$ cross sections from previous PHENIX analysis and from Monte Carlo generators compared to the e–μ correlations in this analysis.

description	$\sigma_{c\bar{c}}$ (μb)
PYTHIA e–μ	340±29(stat)±116(syst)
POWHEG e–μ	511±44(stat)±198(syst)
MC@NLO e–μ	764±64(stat)±284(syst)
Combined e–μ	538±46(stat)±197(data syst)±174(model syst)
PHENIX single $e^{\pm}$ [24]	567±57(stat)±224(syst)
PHENIX dilepton (e^+e^-) [27]	554±39(stat)±142(data syst)±200(model syst)

Mid-fwd rapidity HF pairs in p+p, 200 GeV



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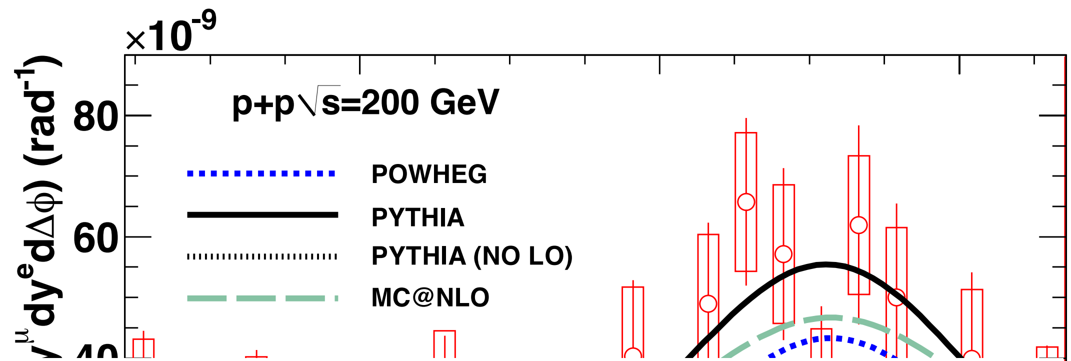

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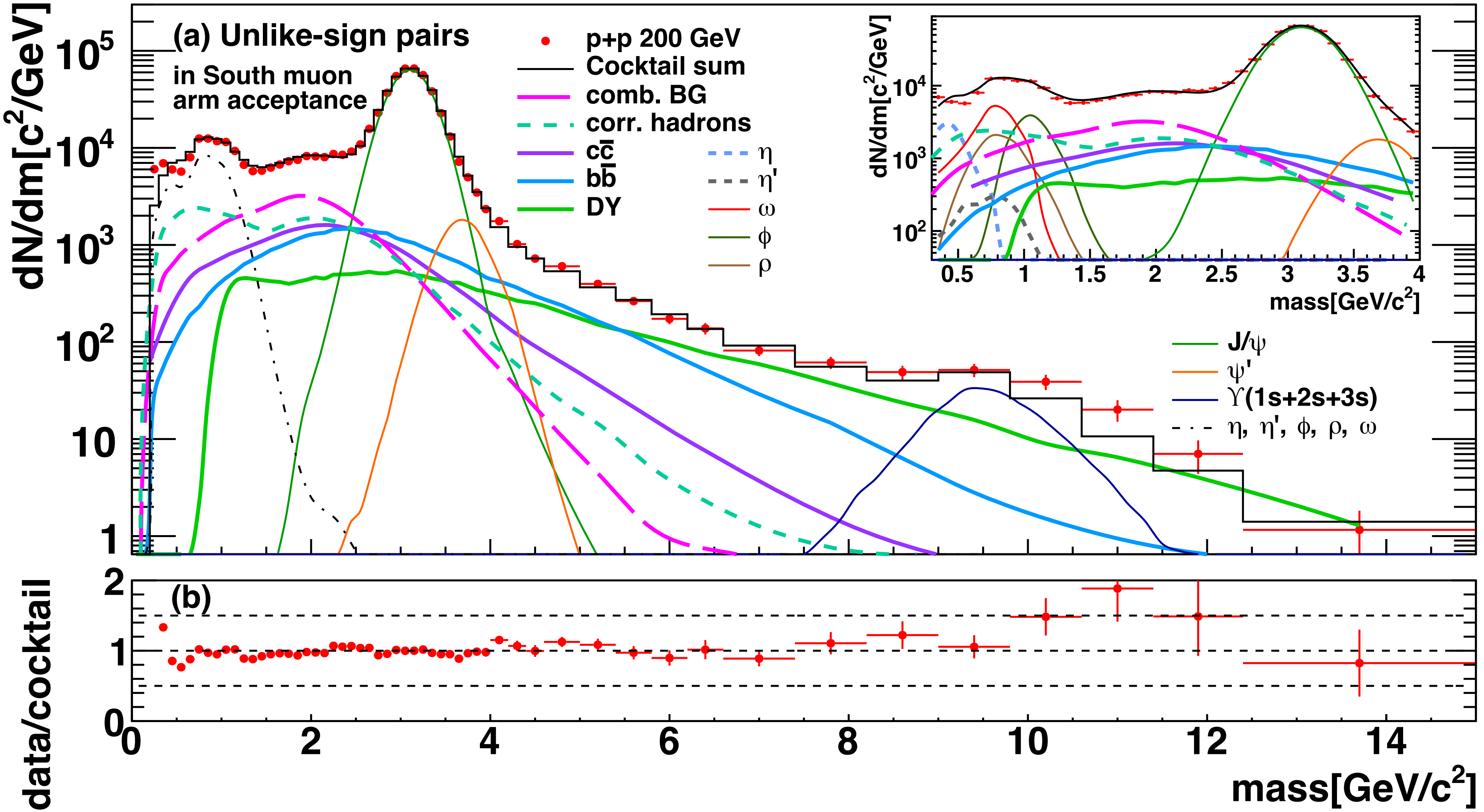
Lack of understanding in HF production in p+p. More constraints on model needed!

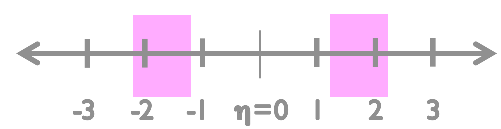
First measurement of the dimuon continuum at RHIC

Unlike-sign pairs

arXiv:1805.02448

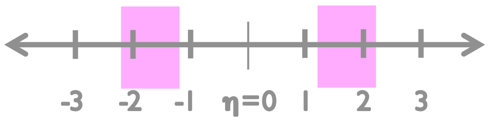


- Cocktail describes unlike-sign data well



Dimuon cocktail

- **Hadron decays**
  - η, η'
  - ϕ, ρ, ω
  - J/ψ, $\psi(2s)$
  - Υ(1s,2s,3s)
  - K^0, $K^{\pm}$, $\pi^{\pm}$
- **Heavy flavor**
  - Charm
  - Bottom
- **Drell-Yan**



Input rapidity/p_T distributions constrained by existing data whenever possible.

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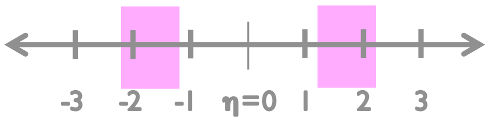


Input rapidity/p_T distributions constrained by existing data whenever possible.

Simulations run through GEANT4 and reconstruction chain.

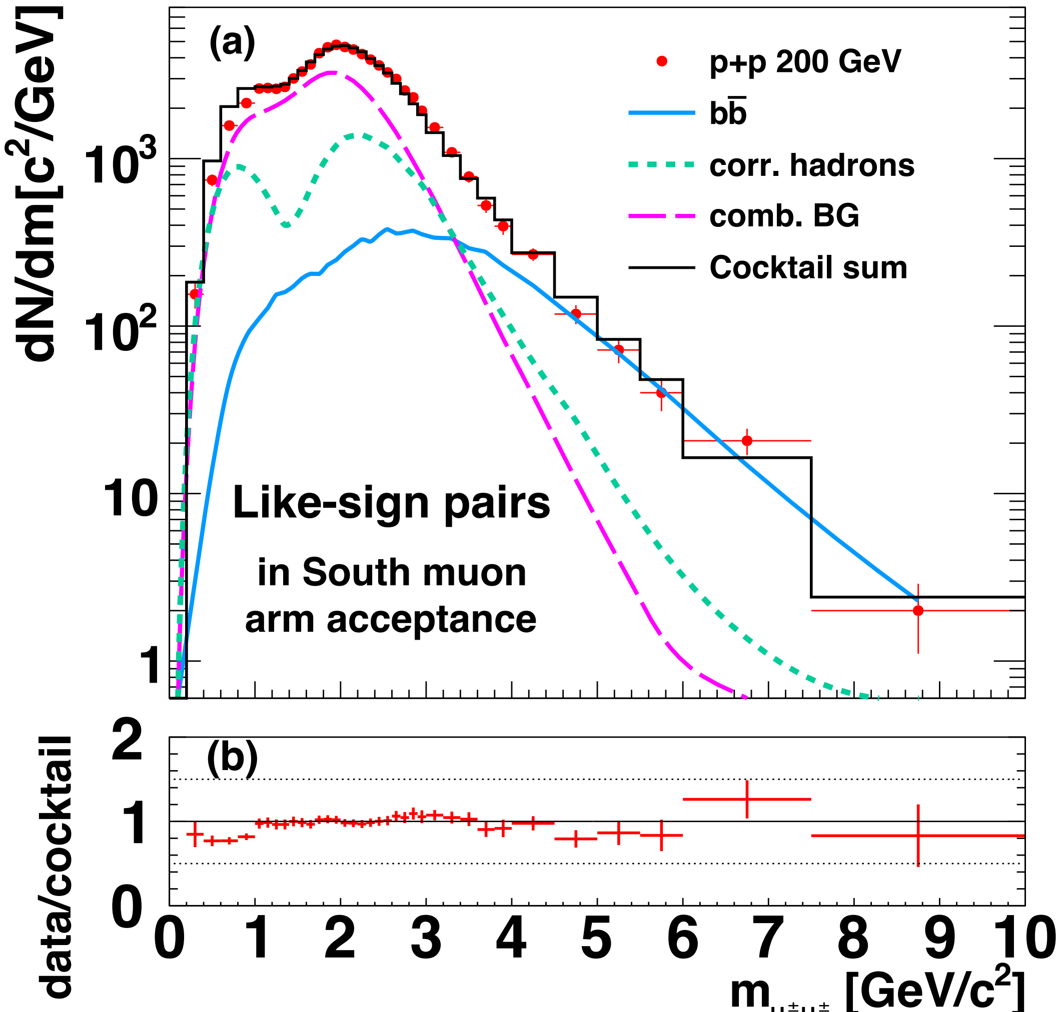
Normalizations of underlined components obtained via mass-p_T fit.

First measurement of the dimuon continuum at RHIC

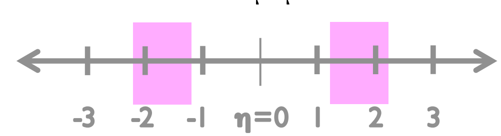
Unlike-sign pairs

Like-sign pairs

arXiv:1805.02448



- Simultaneous fitting in mass-p_T using unlike-and like-sign spectra
- Cocktail describes unlike-sign data and like-sign data well

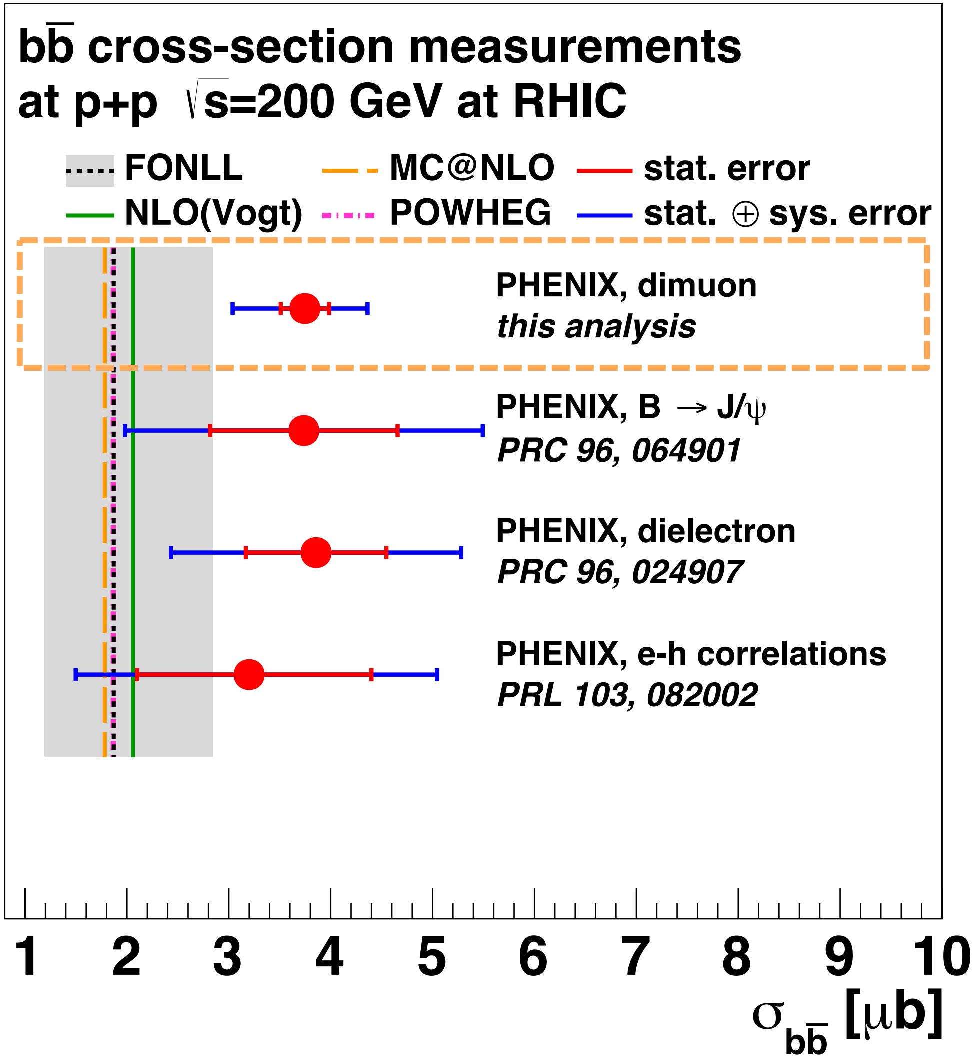


bb cross-section; comparison with other RHIC measurements

High mass like-sign pairs is dominated by dimuon pairs from bottom:

- Extrapolate to 4π phase space

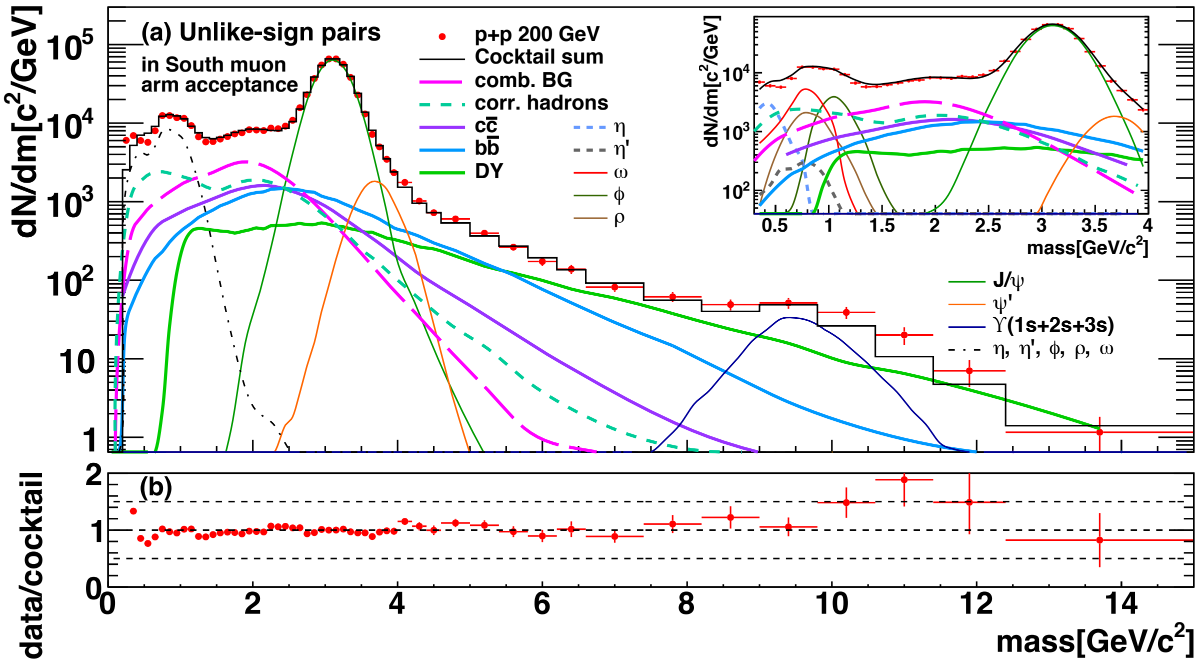
arXiv:1805.02448



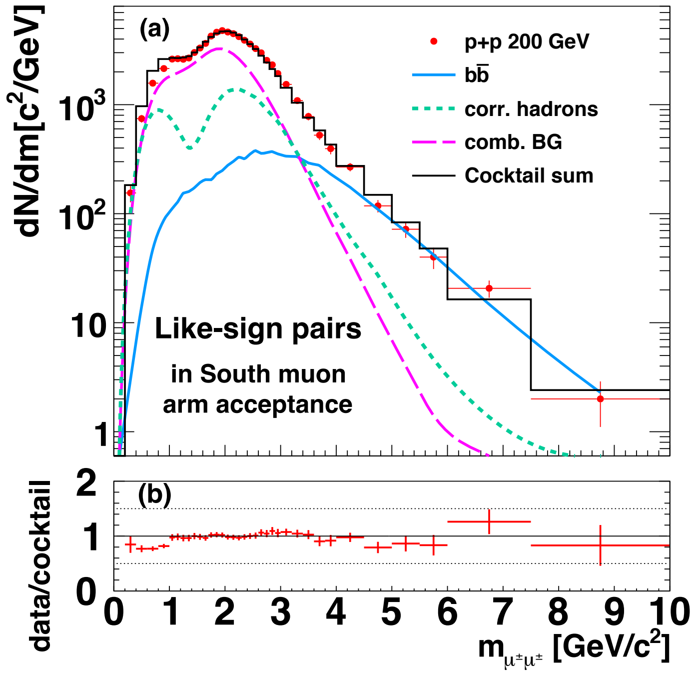
- **Consistent with other RHIC measurements at 200 GeV**
- **Data is consistent with FONLL within large theoretical uncertainties**
- **Data is 2x from central FONLL value**

Measuring dimuons

Unlike-sign pairs



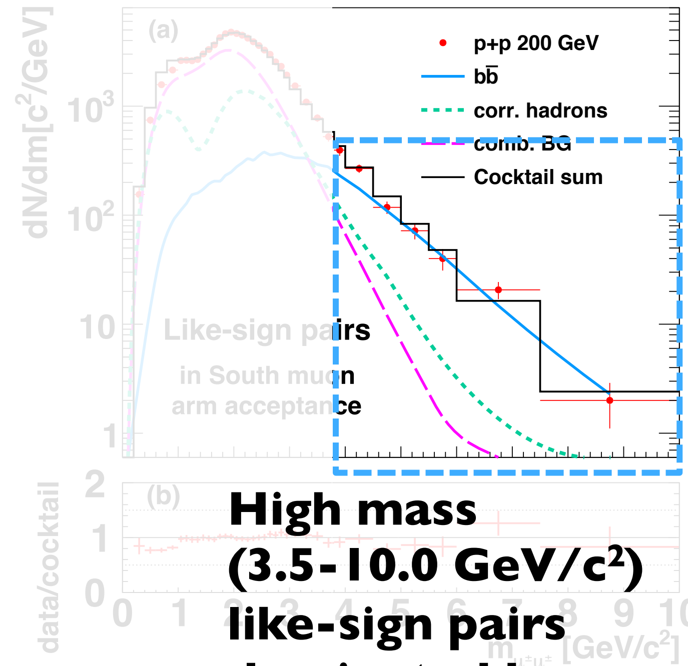
Like-sign pairs



Measuring dimuons

Unlike-sign pairs

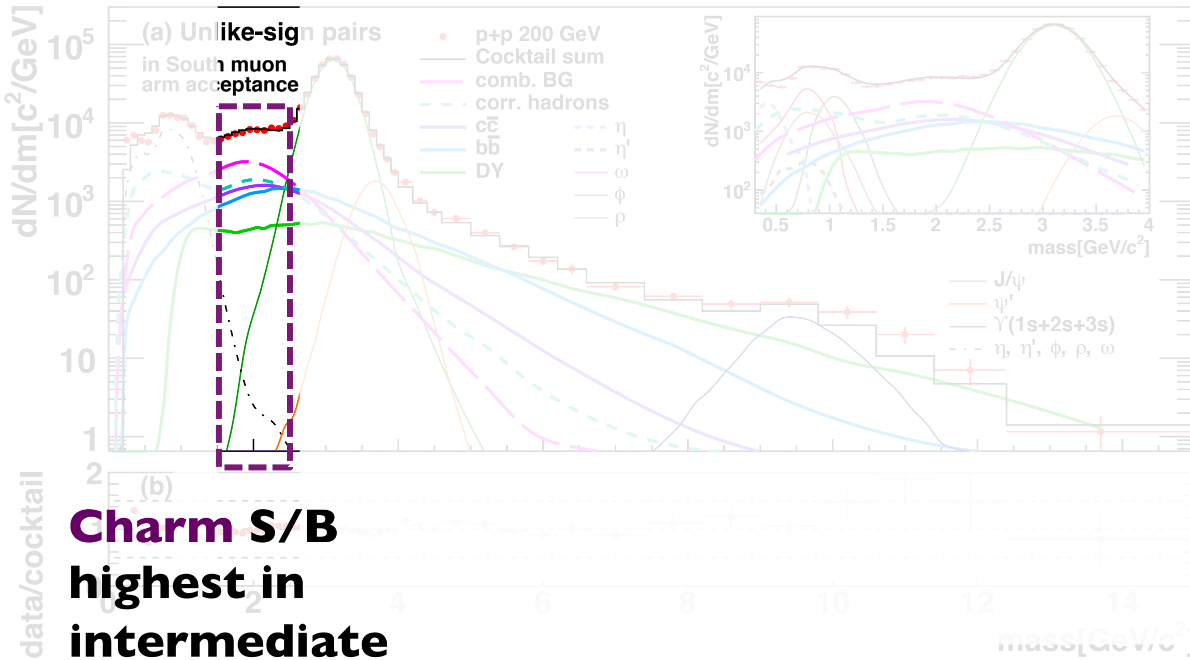
Like-sign pairs



High mass (3.5-10.0 GeV/c²) like-sign pairs dominated by Bottom

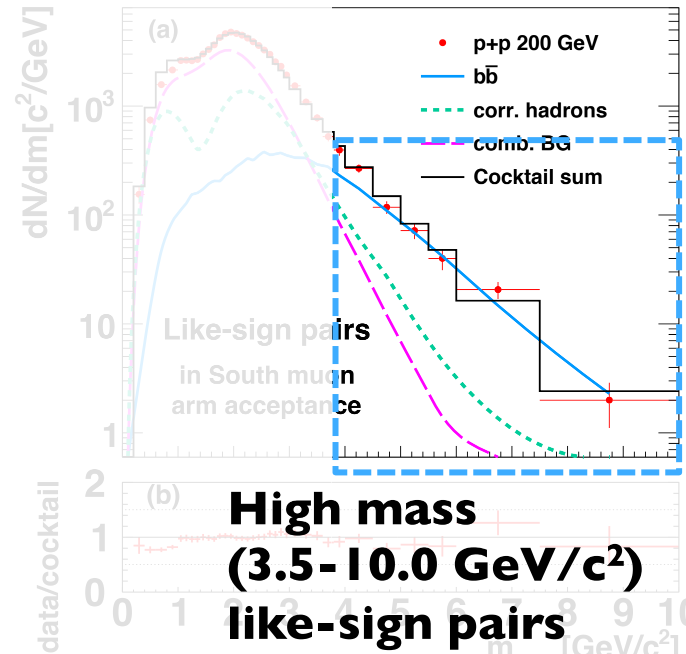
Measuring dimuons

Unlike-sign pairs



Charm S/B highest in intermediate mass region (1.5-2.5 GeV/c²)

Like-sign pairs

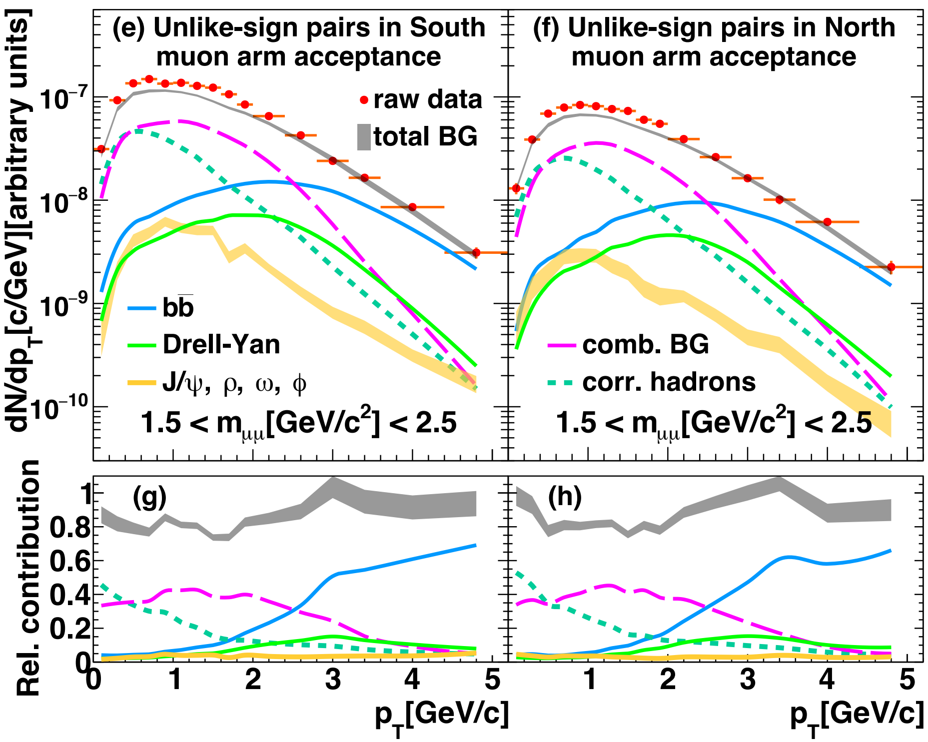


High mass (3.5-10.0 GeV/c²) like-sign pairs dominated by Bottom

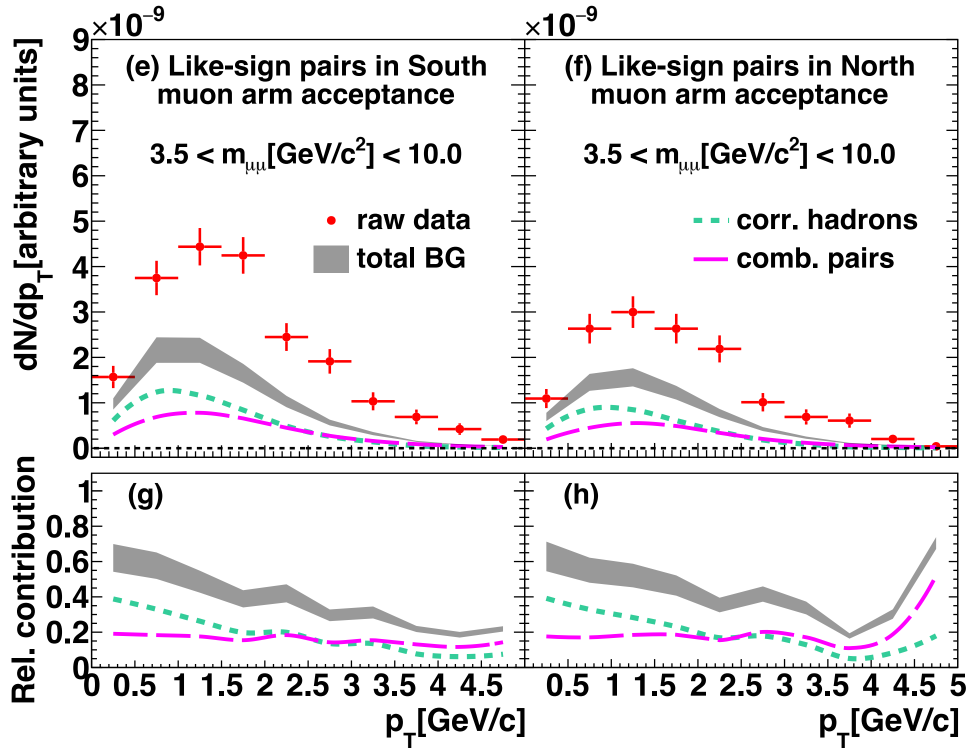
Charm and bottom pair p_T (signal extraction)

- **Subtract cocktail components other than signal pairs (charm/bottom) from data as a function of pair p_T.**

Charm

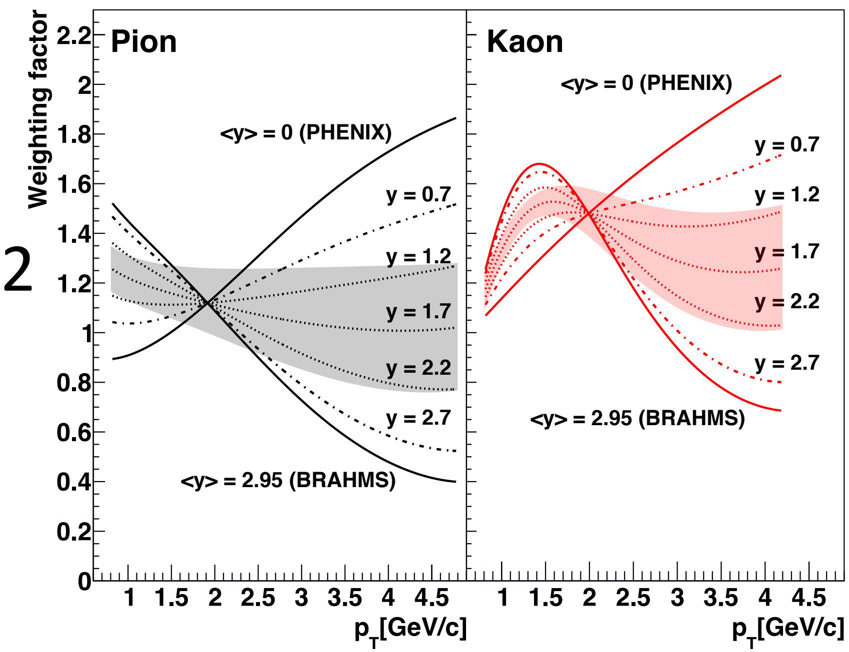


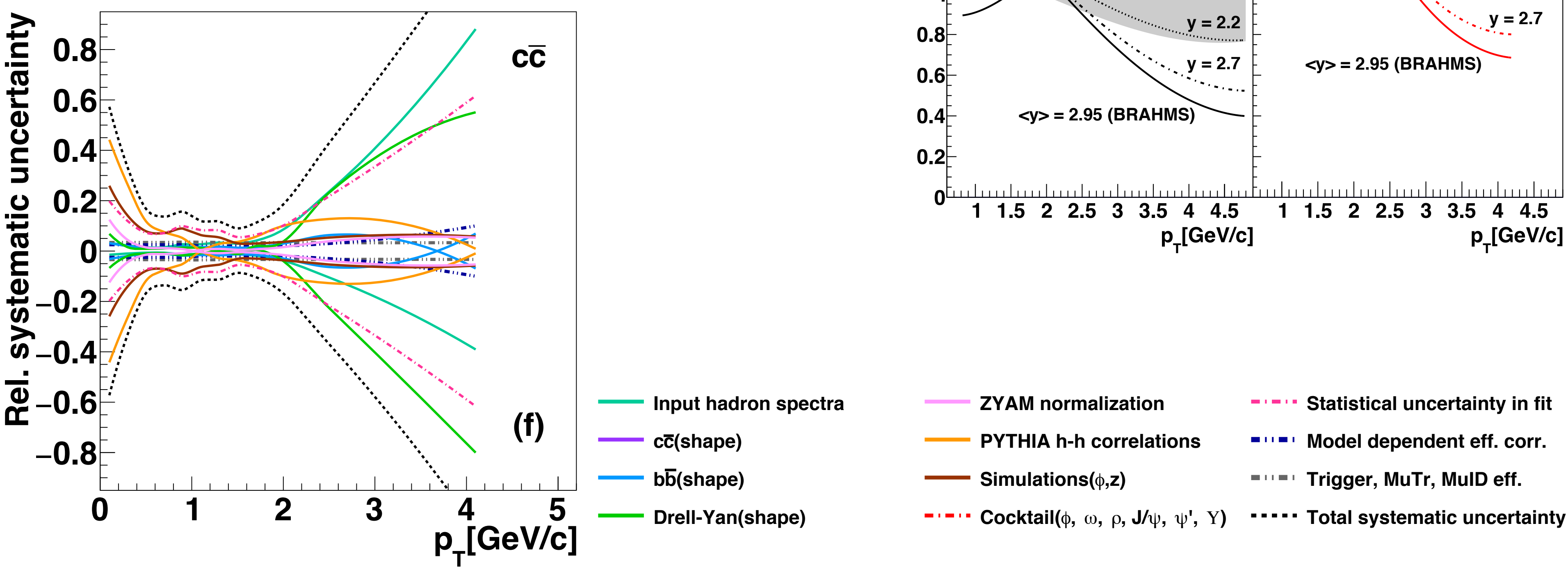
Bottom



Systematic uncertainties

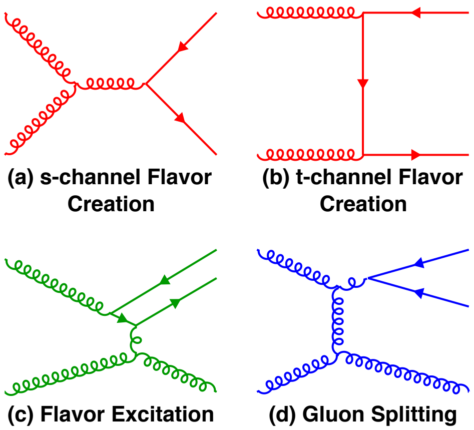
- **Multiple backgrounds sources**
  - →Multiple systematic uncertainties sources
  - – Most dominant source: Input pion/kaon spectra
  - – No measurement at 1.2<|η|<2.2



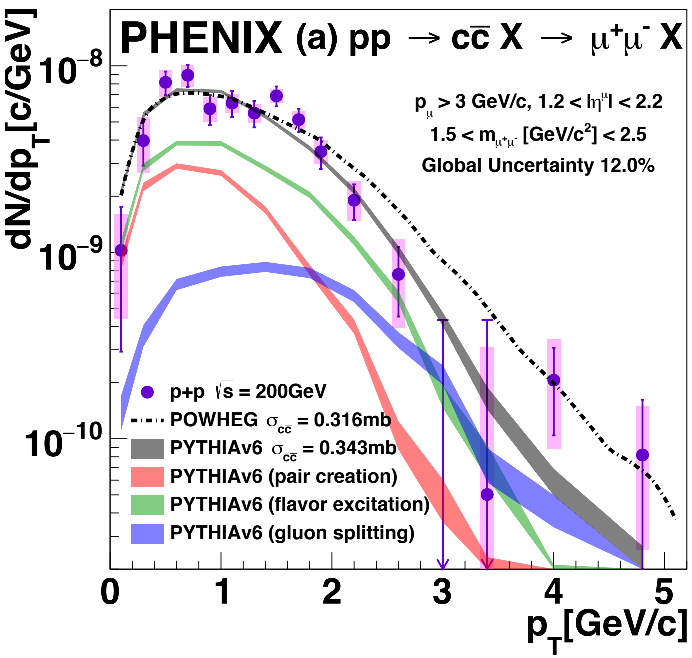


Charm and bottom pair p_T

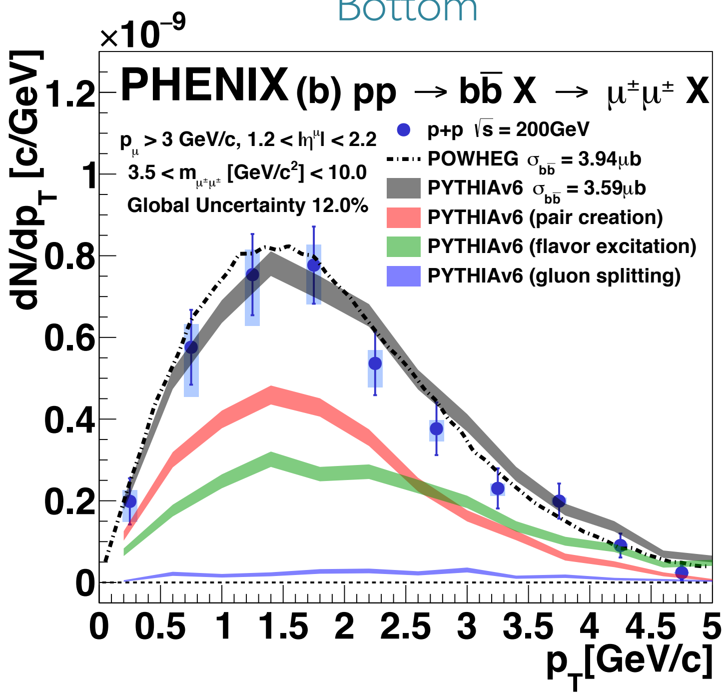
- Extract charm and bottom in separate kinematic regions
- Charm and bottom dimuon pair p_T compared to PYTHIA Tune A and POWHEG
  - Theoretical curves normalized with cross-sections from fitting technique



Charm



Bottom



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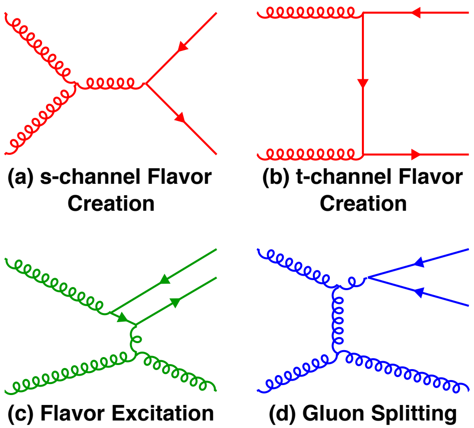
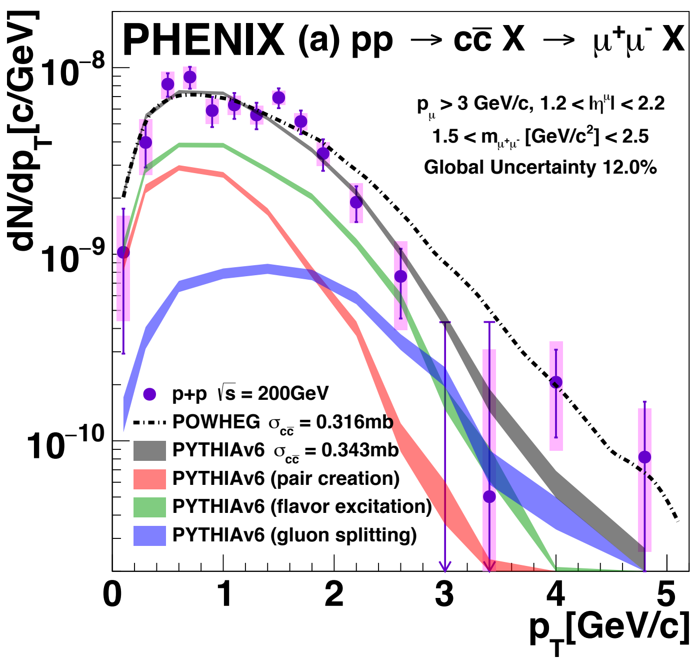


Charm



- **POWHEG predicts harder p_T spectrum compared to PYTHIA.**

Charm and bottom pair p_T

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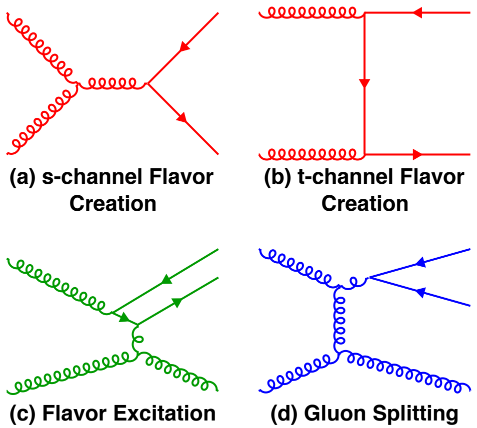
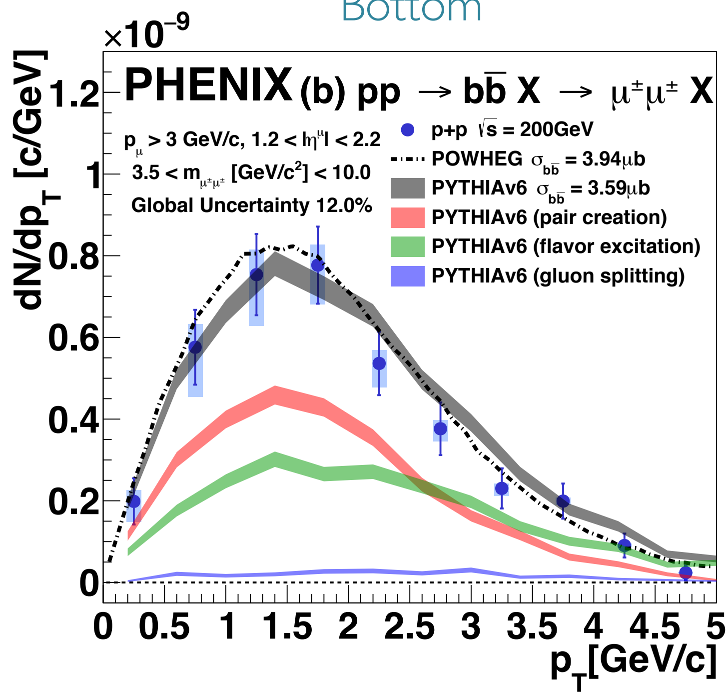


- **Less model dependence for bottom.**
- **Both models consistent with data.**

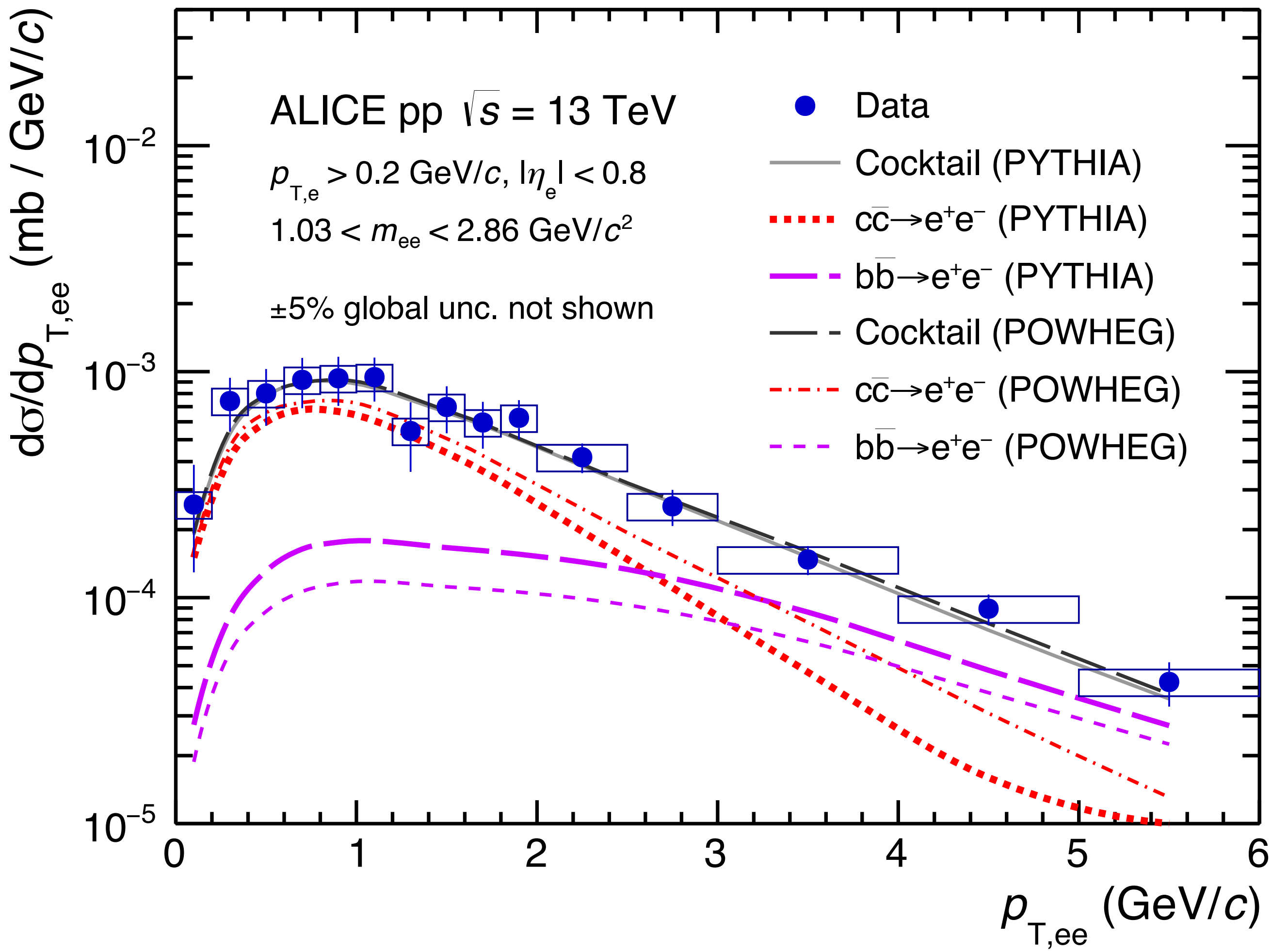
Bottom



Heavy flavor dielectrons in p+p, 13TeV

arXiv:1805.04407

- **cc model dependence at 13TeV also.**
  - POHWEG pair p_T harder than PYTHIA



Charm and bottom azimuthal correlations

- Extract charm and bottom in separate kinematic regions
- Charm and bottom dimuon $\Delta\phi$ compared to PYTHIA Tune A and POWHEG
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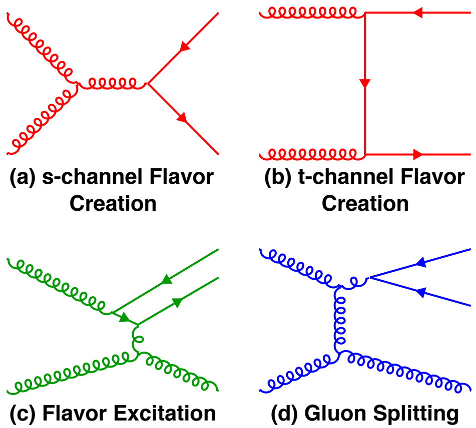
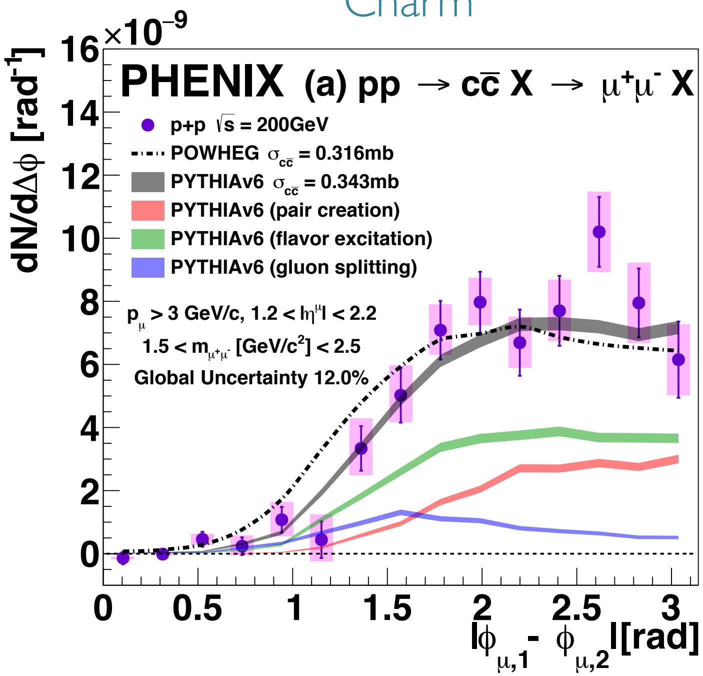


Charm



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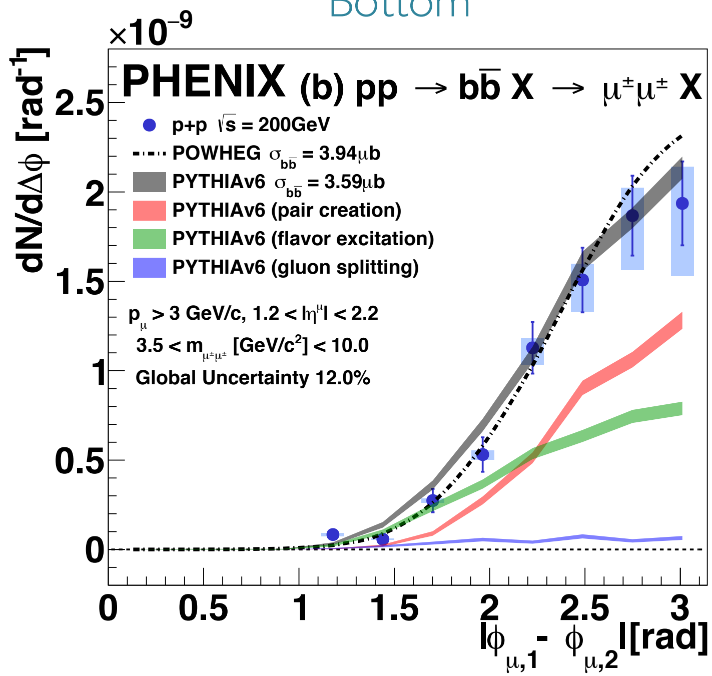

Charm and bottom azimuthal correlations

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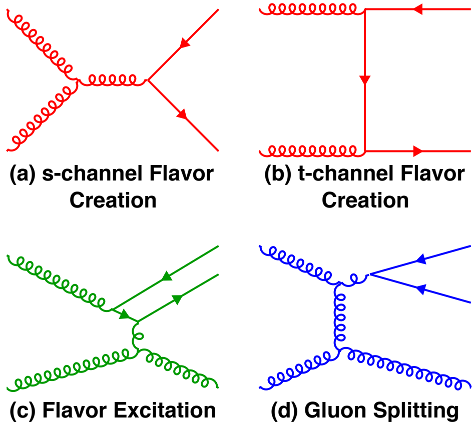
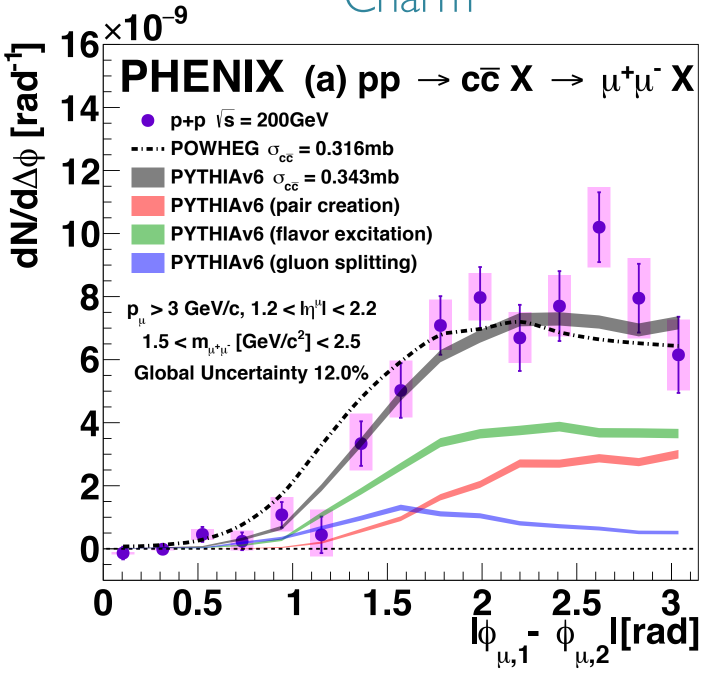
- Charm and bottom dimuon Δϕ compared to PYTHIA Tune A and POWHEG
  - Theoretical curves normalized with cross-sections from fitting technique



Charm

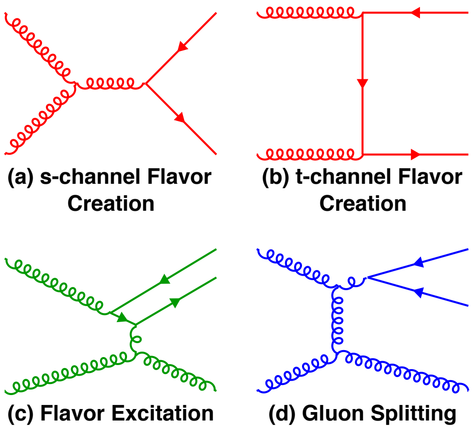


- **POWHEG predicts broader distributions compared to PYTHIA.**
- **Data favors PYTHIA description.**

	PYTHIA	POWHEG
χ^2/NDF	20.1/14	35.8/14

Charm and bottom azimuthal correlations

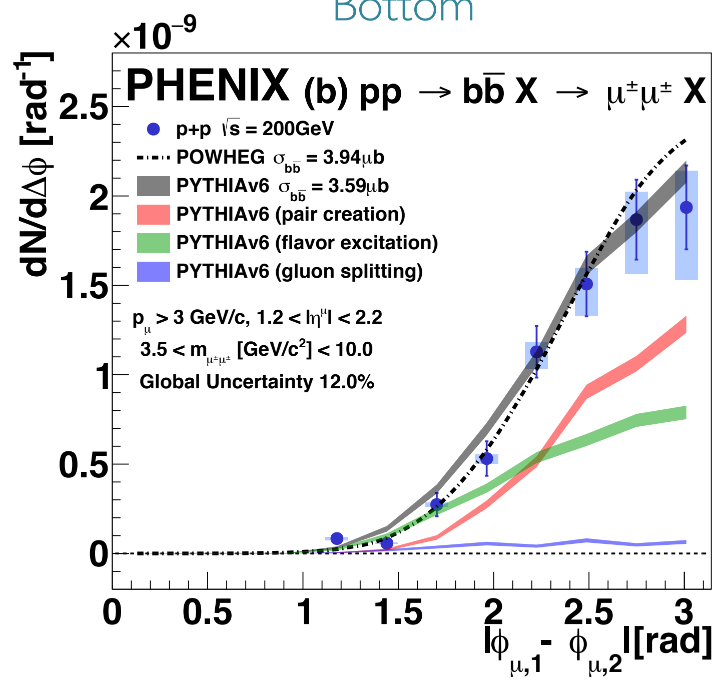
- Extract charm and bottom in separate kinematic regions
- Charm and bottom dimuon $\Delta\phi$ compared to PYTHIA Tune A and POWHEG
  - Theoretical curves normalized with cross-sections from fitting technique



- **PYTHIA and POWHEG both describes bottom well to within uncertainties.**

	PYTHIA	POWHEG
χ^2/NDF	9.8/7	7.2/7

Bottom



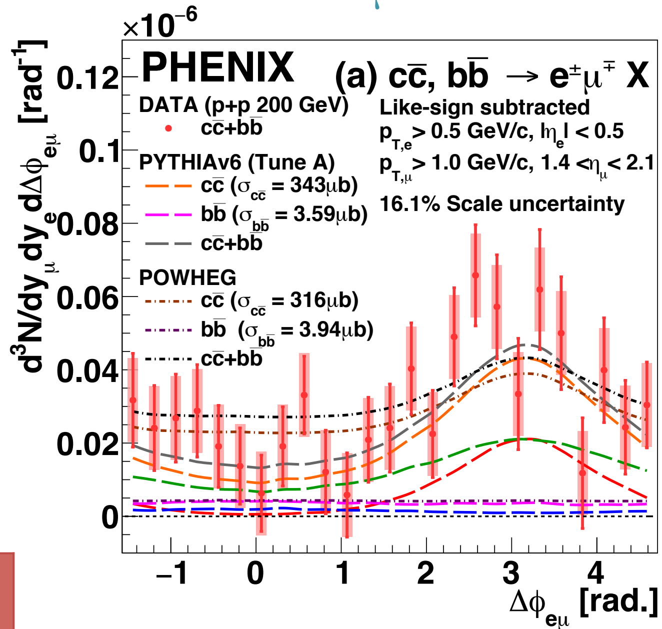
Extrapolating beyond the measured phase space

- Theoretical curves normalized with same cross-sections from μμ analysis
- ee and eμ yields are dominated by charm

- **PYTHIA tune A consistent with data over wide kinematic range**
- **Distributions from POWHEG are broader than data in all data sets.**

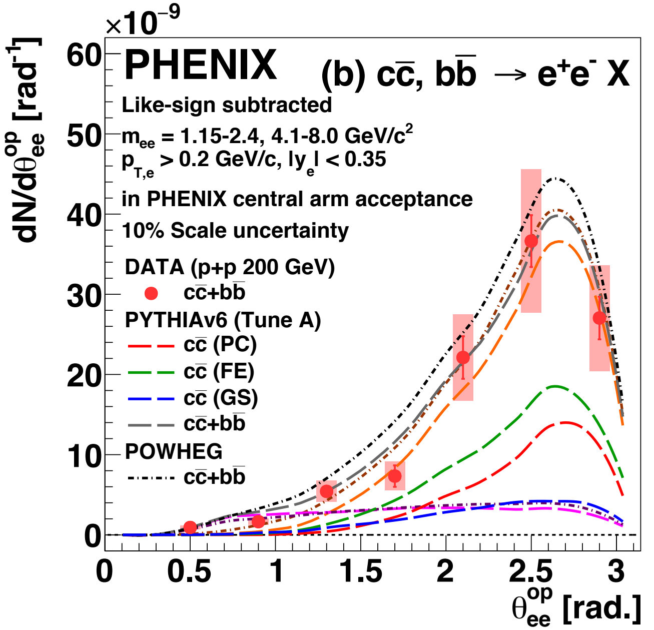
	PYTHIA	POWHEG
χ^2/NDF	59.6/47	94.2/47

eμ



PhysRevC.89.034915

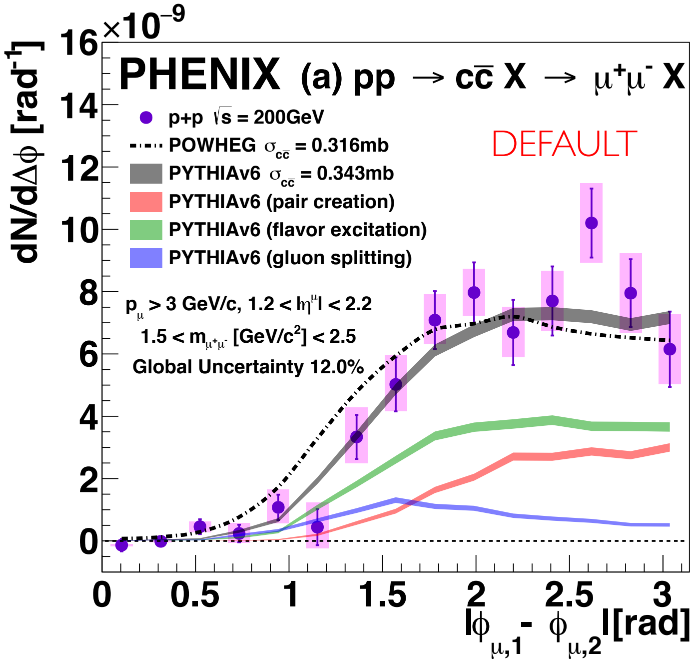
ee



PhysRevC.96.024907

Bayesian analysis using PYTHIA tune A

- Fit pair creation (PC), flavor excitation (FE) and gluon splitting (GS) shapes to data **(D)**
  - cc → e^+e^-, $e^+\mu^-$, $\mu^+\mu^-$
  - bb → $\mu^\pm\mu^\pm$
- Bayesian approach
  - Nuisance parameters account for systematic uncertainties
  - Uniform prior
    - $0 < F_{PC}, F_{FE}, F_{GS} < 1$
    - $F_{PC} + F_{FE} + F_{GS} = 1$
    - F_{PC}, F_{FE}, F_{GS} are the relative contributions of PC, FE and GS in 4π respectively.
  - Monte-Carlo sampling



Bayesian analysis: The assumptions

- **PYTHIA Tune A settings**
  - Initial state/final state radiation (PARP(67) = 4.0)
  - Fragmentation (PARJ(21) = 0.36)
  - Quark masses

  - Tune A describes multiple observables from CDF to RHIC energies well

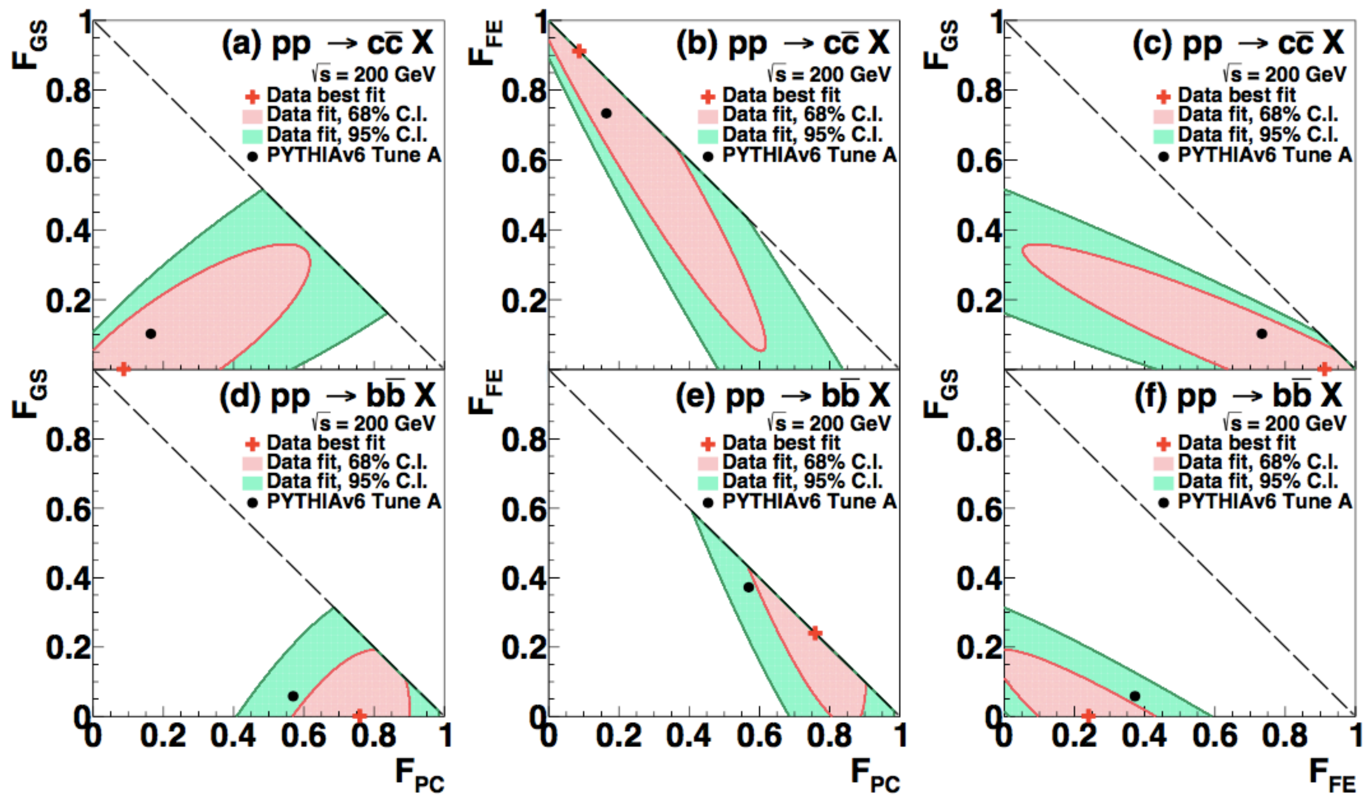
- **Interference between production processes**
  - Underlying assumption of PYTHIA

Open to suggestions!

Bayesian analysis using PYTHIA tune A

- **68% and 95% credible intervals constructed from posterior probability density**

arXiv:1805.04075



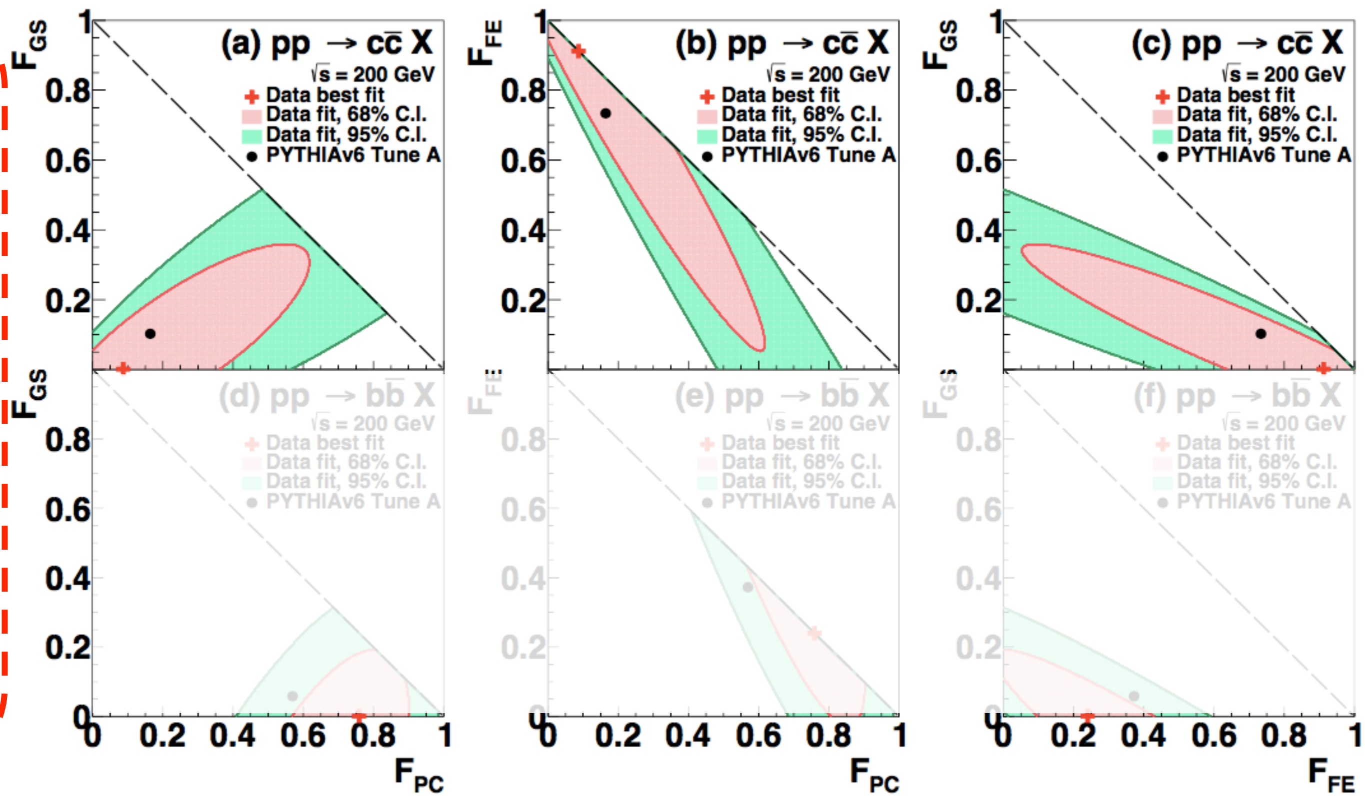
Bayesian analysis using PYTHIA tune A

- 68% and 95% credible intervals constructed from posterior probability density

arXiv:1805.04075

Charm

- **Supports scenario in which flavor excitation dominates cc production.**
- **Data favors $F_{FE} > F_{PC} > F_{GS}$**
- **95% C.I. upper limit for GS is 52%.**



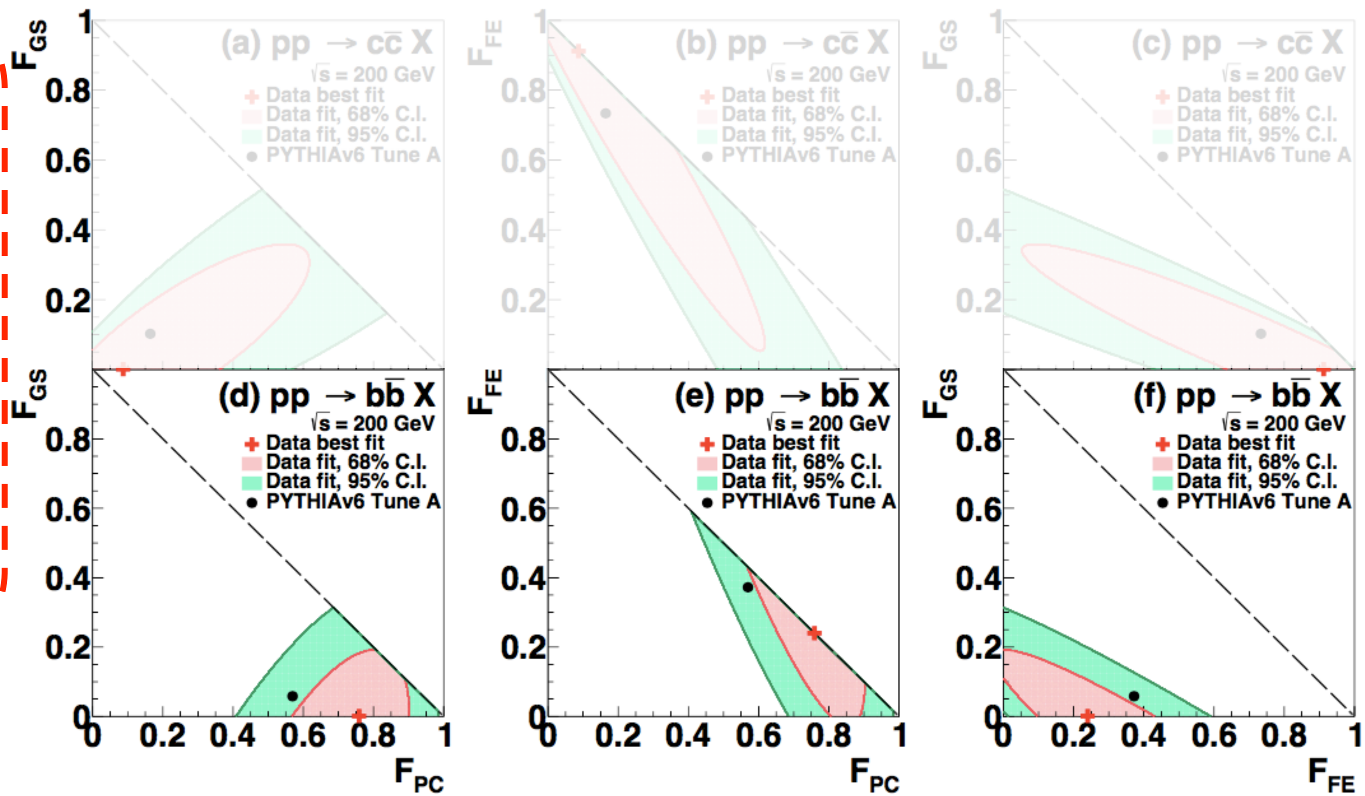
Bayesian analysis using PYTHIA tune A

- 68% and 95% credible intervals constructed from posterior probability density

arXiv:1805.04075

Bottom

- **Dominant source is leading order pair creation**
- **Data favors $F_{PC}>F_{FE}>F_{GS}$**
- **95% C.I. upper limit for GS is 31%.**



Implications

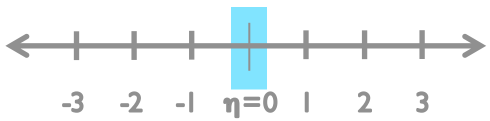
- Based on PC/FE/GS shapes from PYTHIA Tune A:
  - Dominant production mechanism for bottom at 200 GeV is leading order PC
  - Small gluon splitting contribution at RHIC energies

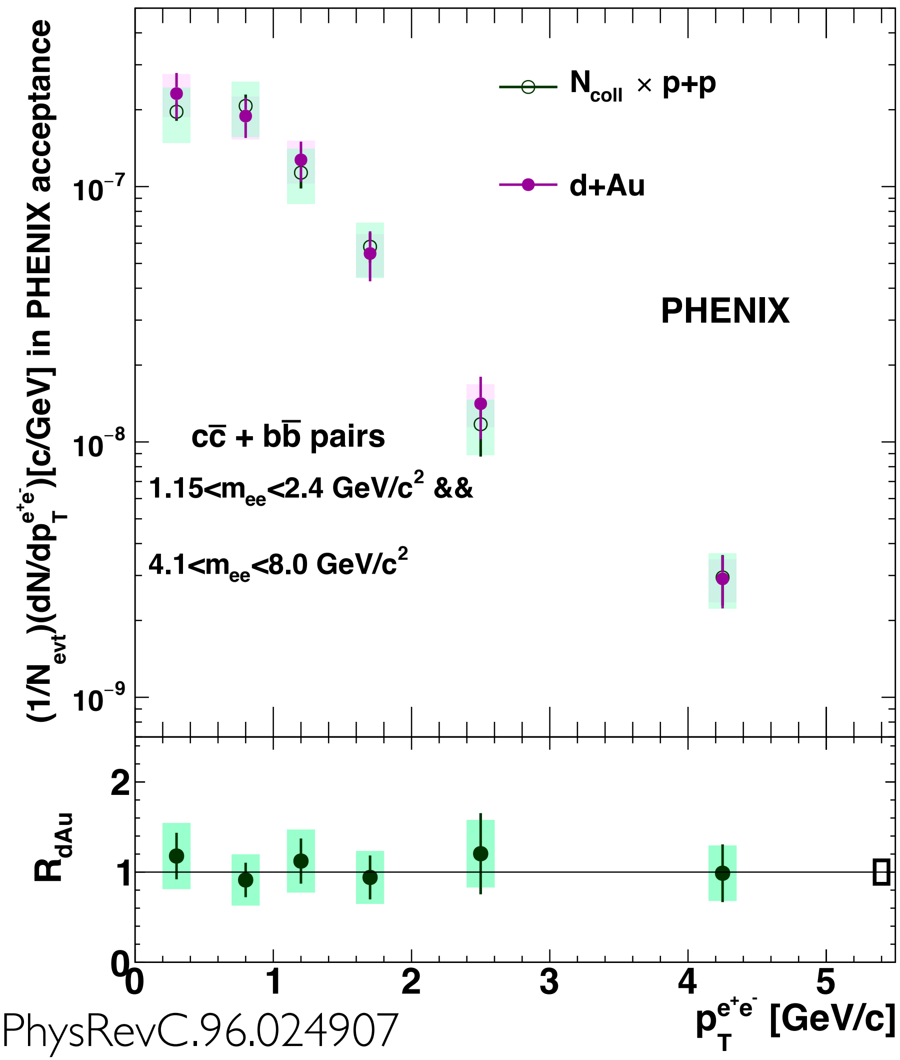
- Bottom may be utilized to study initial gluon dynamics at RHIC energies
- Clean interpretation of bottom measurements at RHIC energies
  - Gluon splitting complicate interpretation of heavy flavor A+A data
- Similar measurements in p+A: probe process dependent cold nuclear matter effects

- Contrasts to LHC energies where NLO processes dominate

1. **Studying heavy flavor production** *in p+p collisions*
2. **Probing cold nuclear matter effects** *in p+A collisions*

Mid-mid rapidity HF pairs in d+Au, 200 GeV

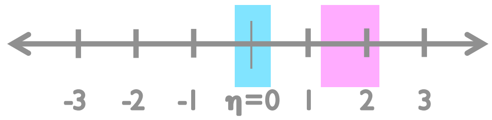




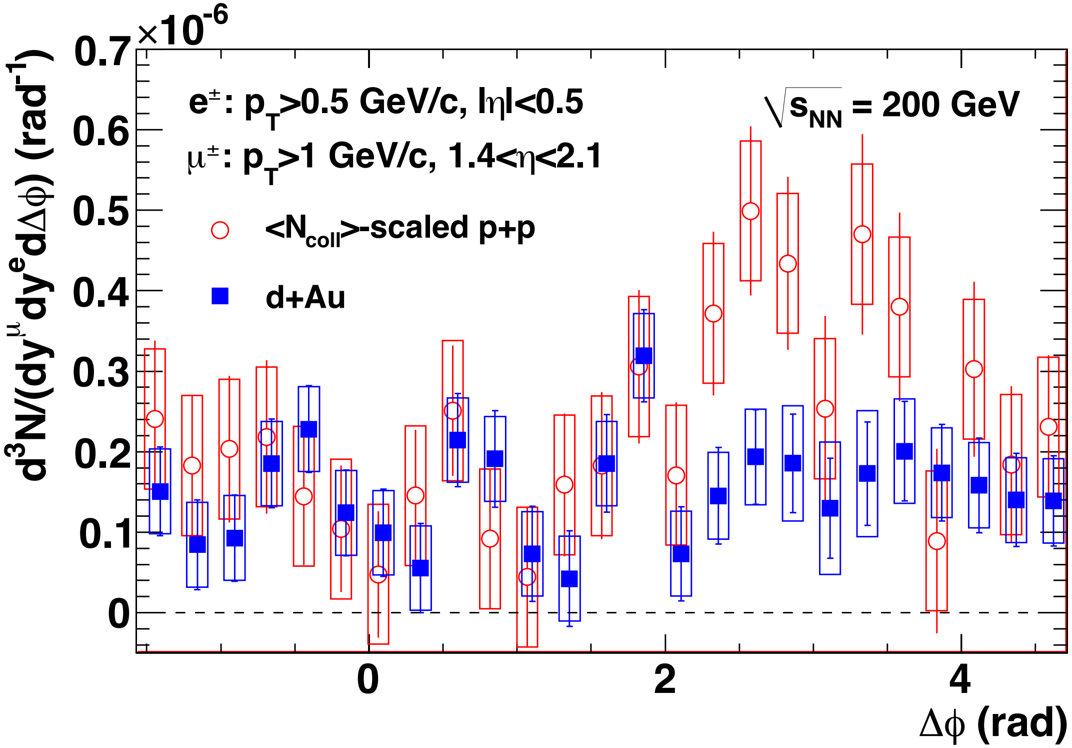
- **No nuclear modification observed in d+Au to within experimental uncertainties**

PhysRevC.96.024907

Mid-fwd rapidity HF pairs in **d+Au, 200 GeV**

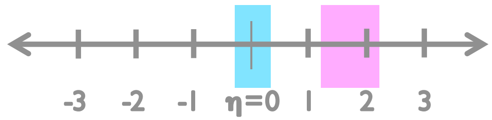


- **Suppression of away-side peak in d+Au**
- **Shadowing? Multiple scattering? Gluon saturation? Flow?**

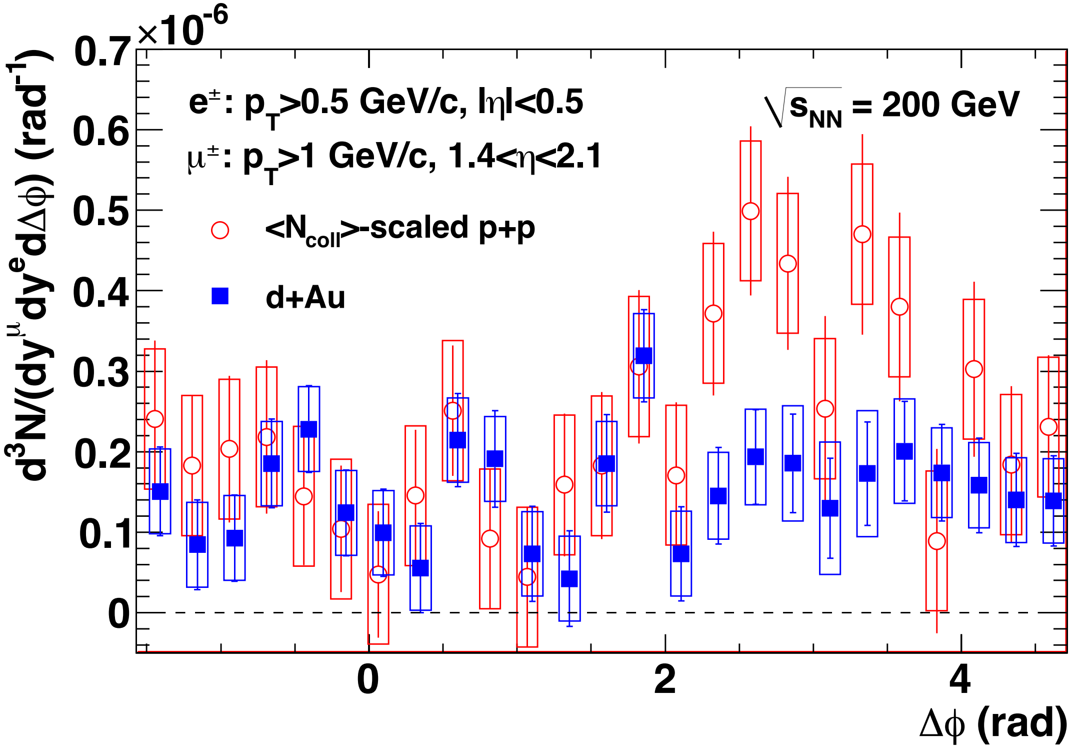


PhysRevC.89.034915

Mid-fwd rapidity HF pairs in **d+Au, 200 GeV**



- **Suppression of away-side peak in d+Au**
- **Shadowing? Multiple scattering? Gluon saturation? Flow?**



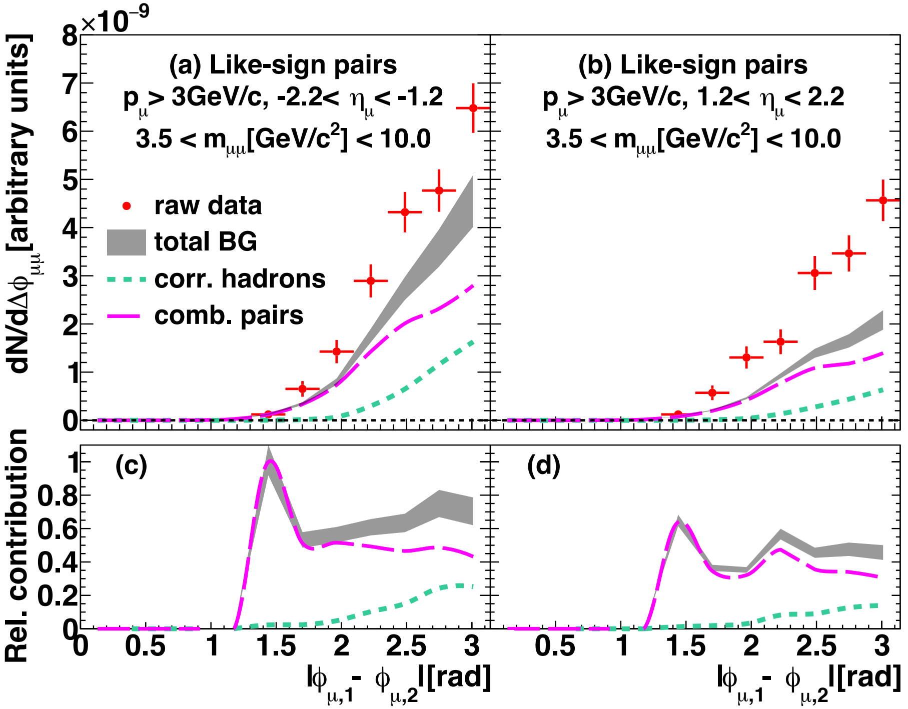
What about fwd-fwd rapidity?

PhysRevC.89.034915

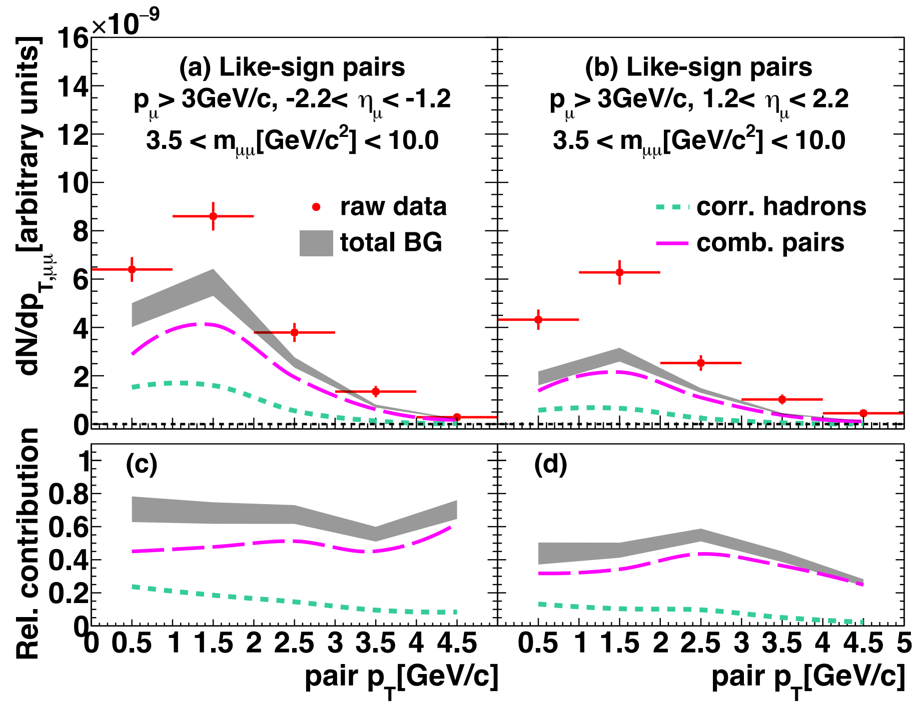
Bottom like-sign dimuons in p+Au (signal extraction)

- p+p analysis method applied to p+Au collisions at 200 GeV.
- Modification of hadronic background estimated from forward hadron measurements.

Azimuthal opening angle



Pair p_T

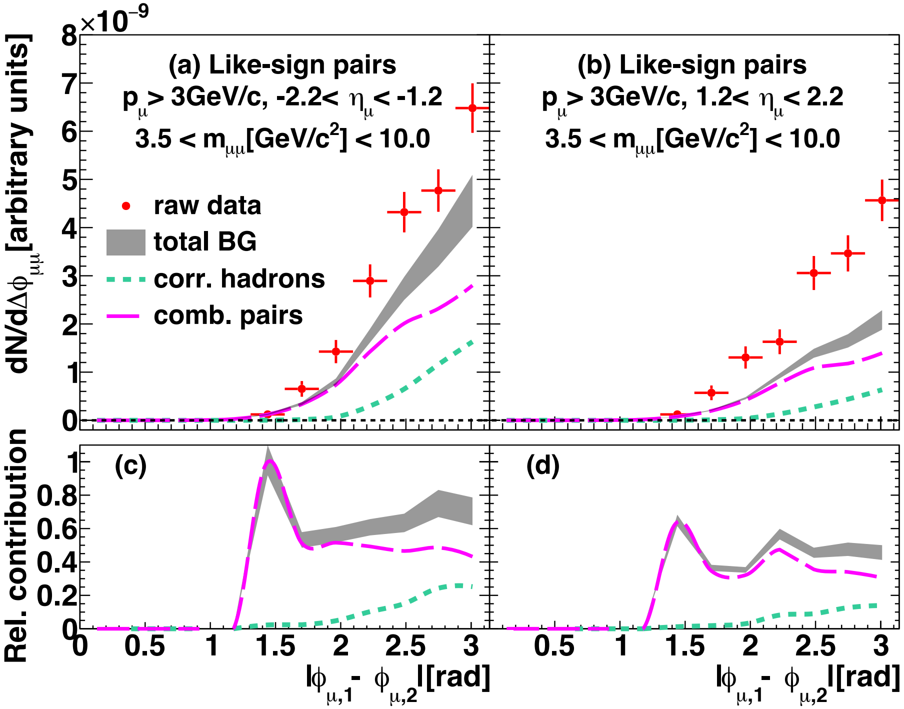


Bottom like-sign dimuons in p+Au (signal extraction)

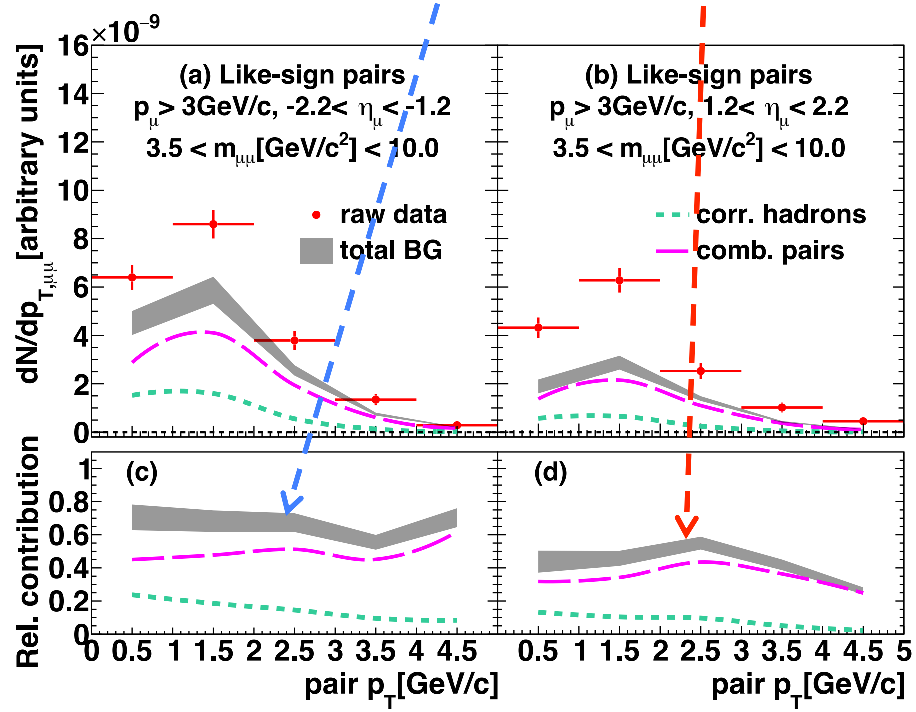
- p+p analysis method applied to p+Au collisions at 200 GeV.
- Modification of hadronic background estimated from forward hadron measurements.

Background levels higher for Au-going side compared to p-going side due to higher multiplicity

Azimuthal opening angle

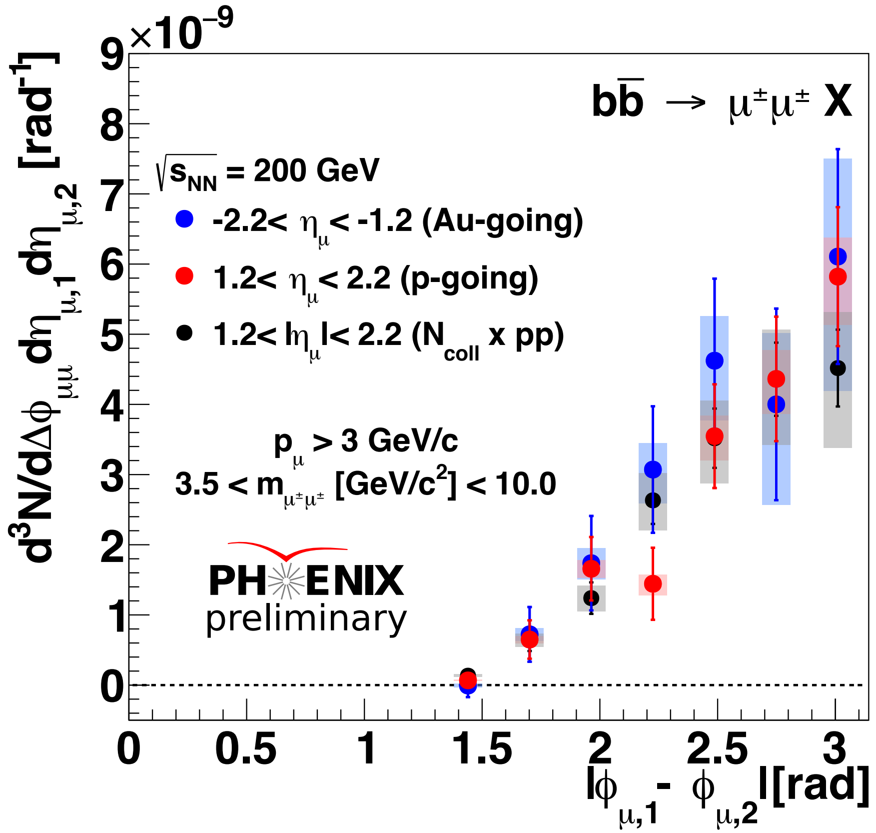


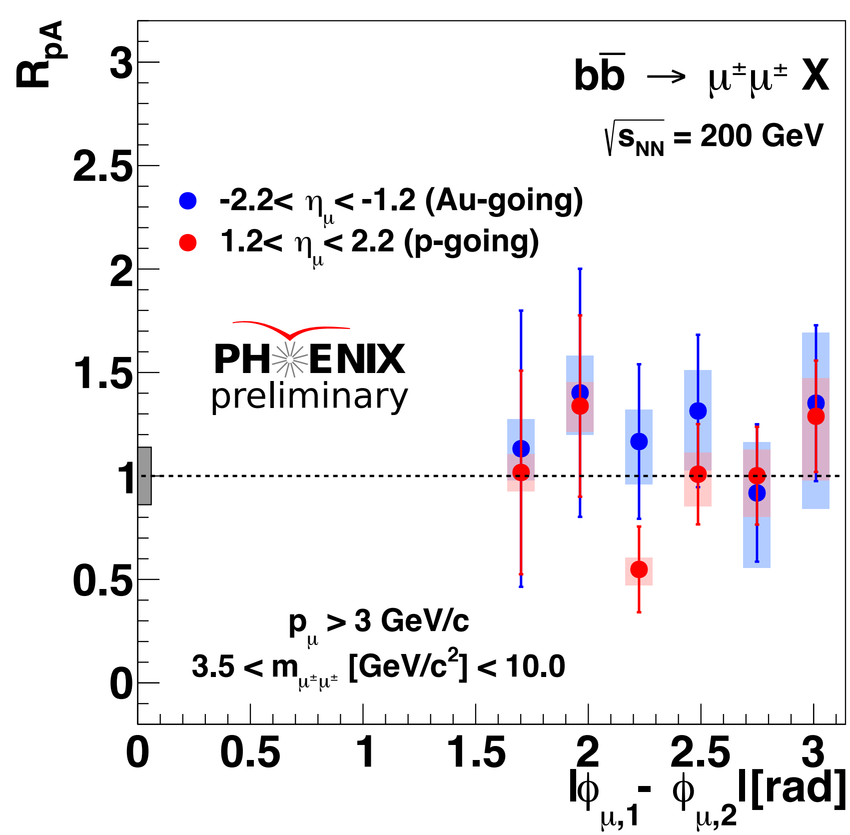
Pair p_T



Bottom azimuthal correlations in p+Au

- **Integrated yield of dimuons from bb in measured phase space in p+Au consistent with binary scaled p+p**
- **No modification of azimuthal correlations within uncertainties**

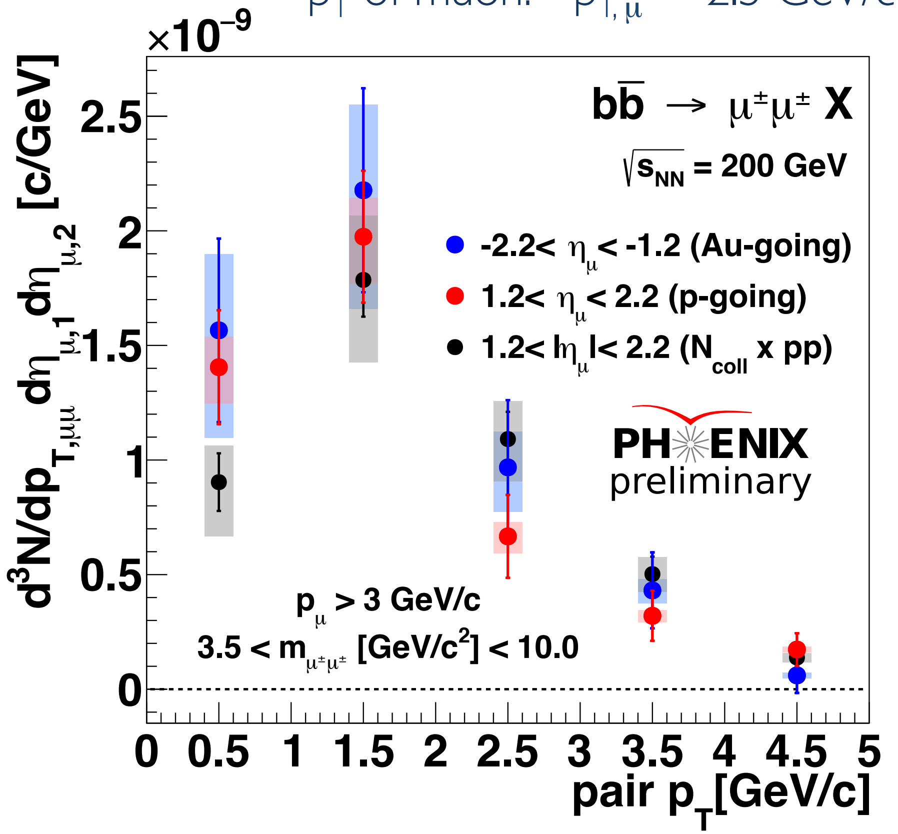


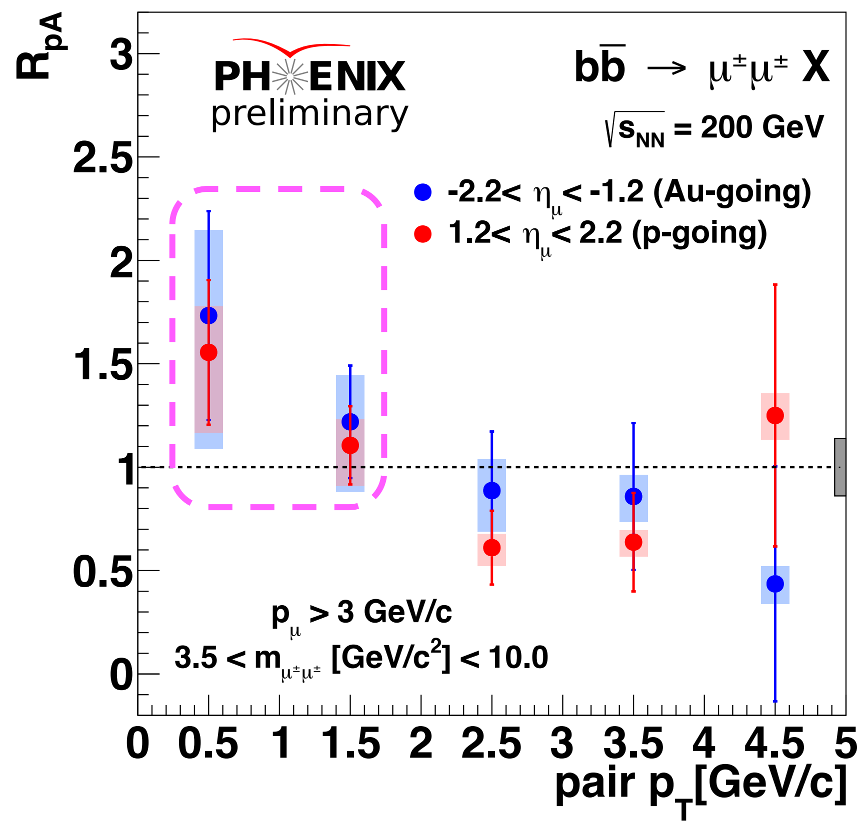


Bottom pair p_T in p+Au

- **Small enhancement at low pair p_T**
- **Followed by decreasing trend**

Kinematic constraints limits single p_T of muon: $<p_{T,\mu}>$~2.5 GeV/c

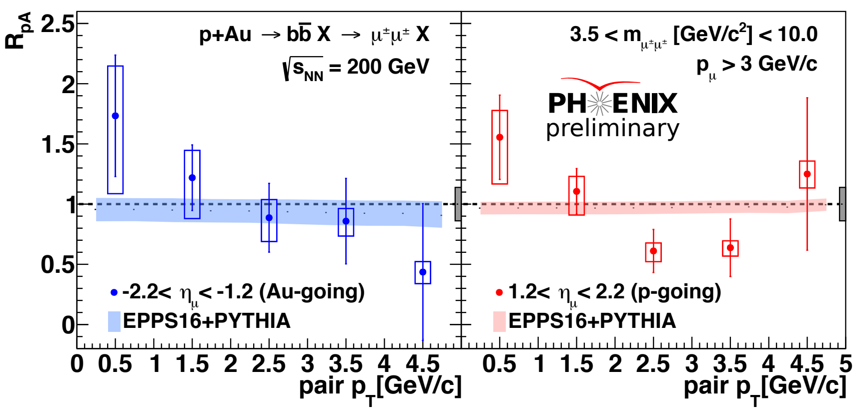




Cold nuclear matter effects at forward/backward

- **Enhancement of μμ from bottom not described by EPPS16**

μμ from bottom (<$p_{T,\mu}$>~2.5 GeV/c)



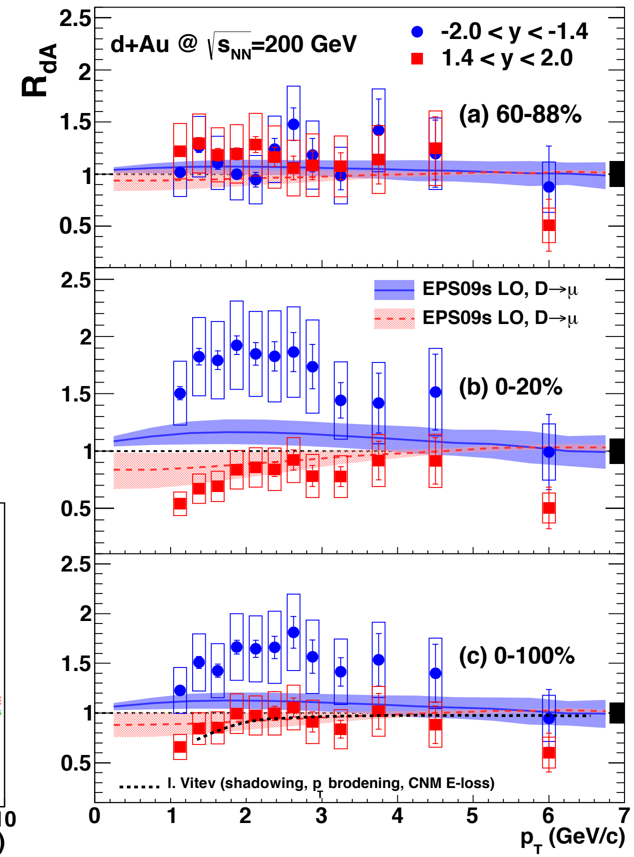
Cold nuclear matter effects at forward/backward

- **Enhancement of μμ from bottom not described by EPPS16**

- **Common mechanism behind modifications for charm/charged hadrons?**

single μ from charm+botton

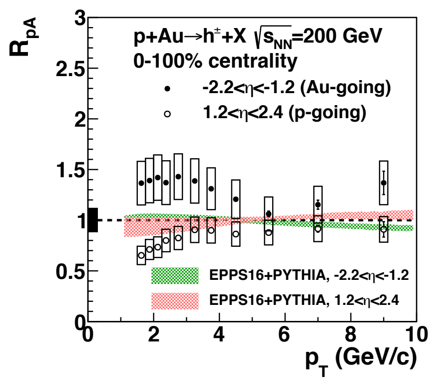
PhysRevLett.112.252301



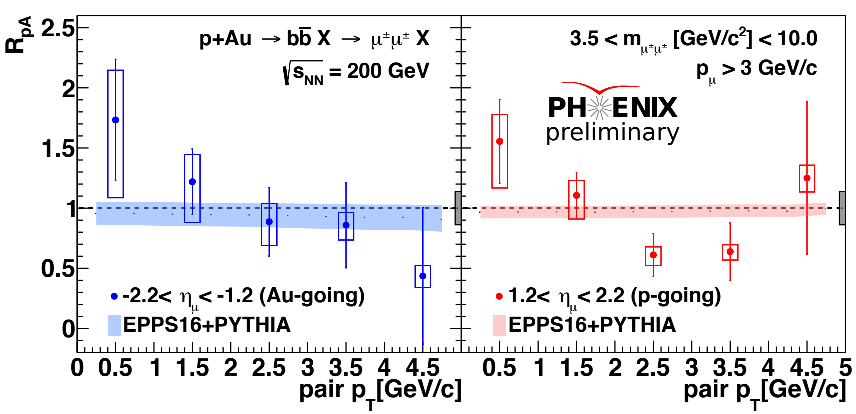
Multiple scattering of partons within nuclear medium?

- **collisional energy loss/angular broadening**

charged hadrons

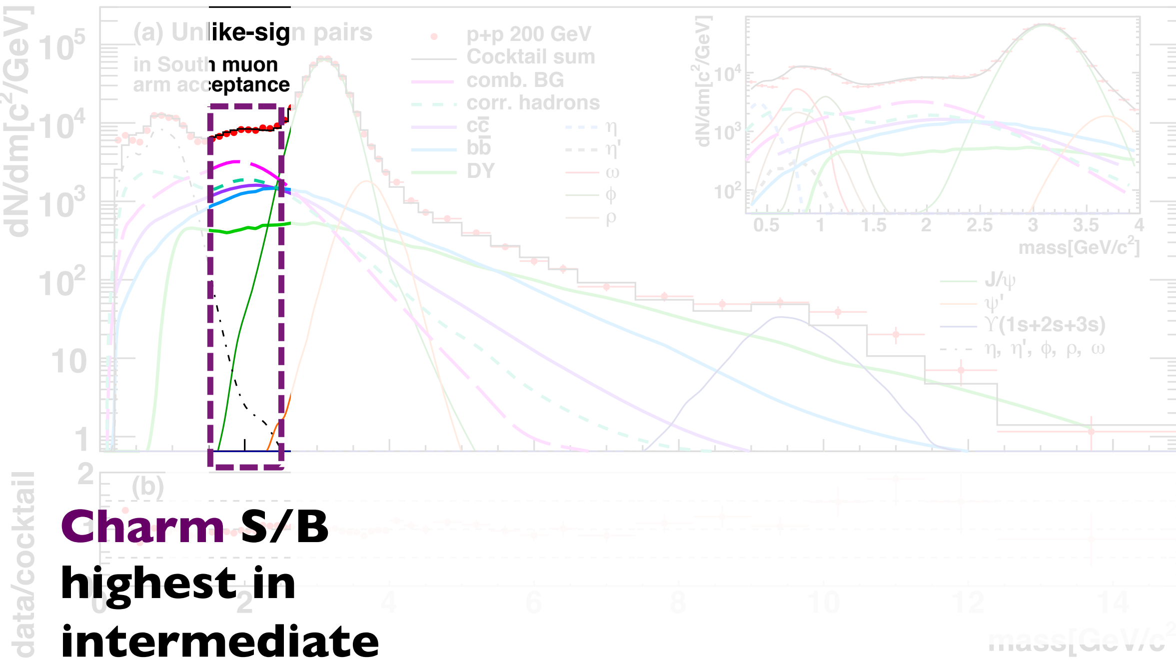


μμ from bottom (<$p_{T,\mu}$>~2.5 GeV/c)



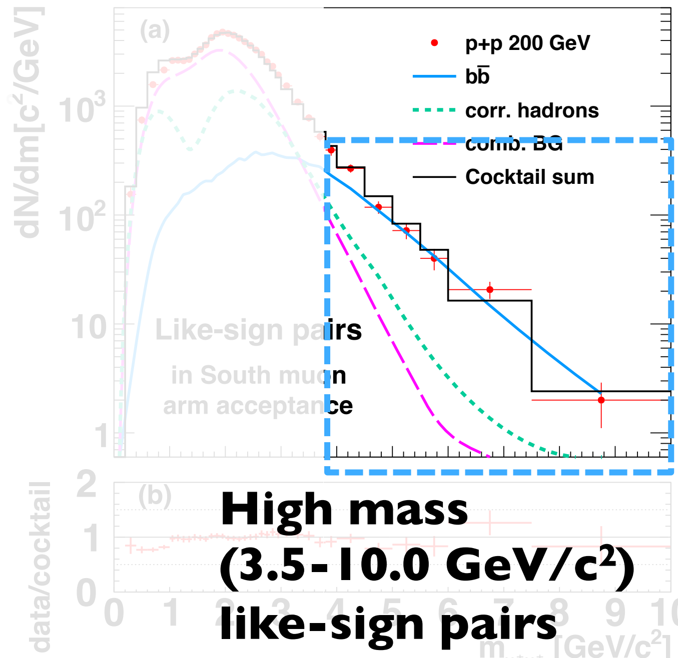
An unexpected opportunity

Unlike-sign pairs



Charm S/B highest in intermediate mass region (1.5-2.5 GeV/c²)

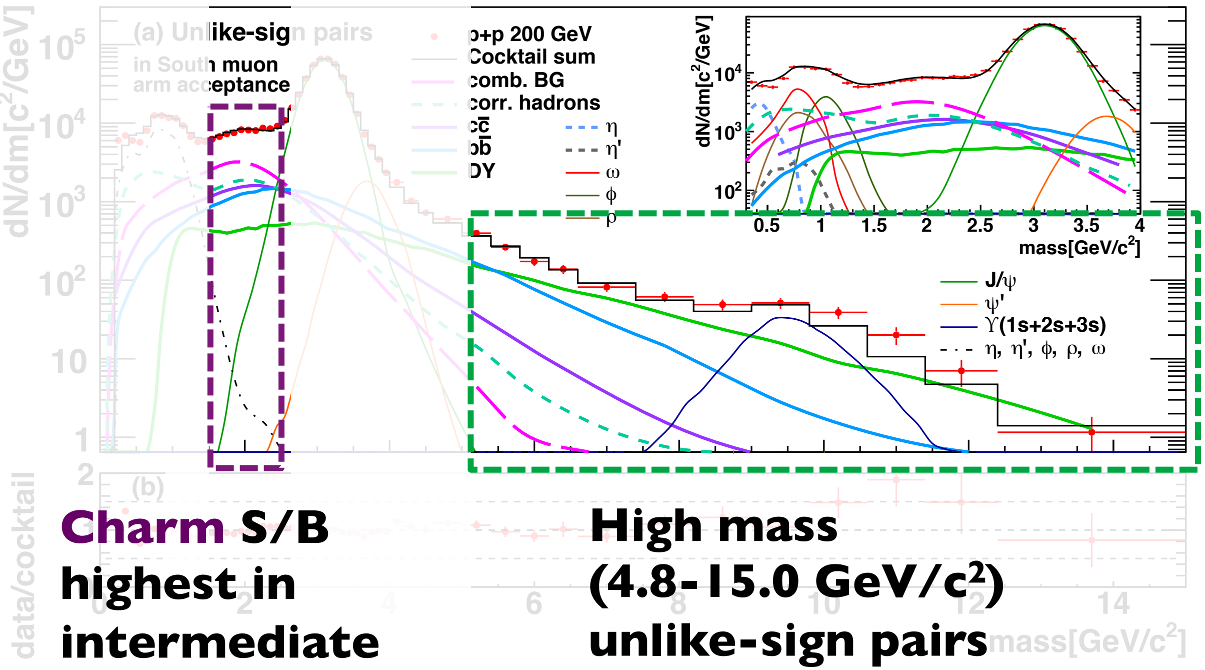
Like-sign pairs



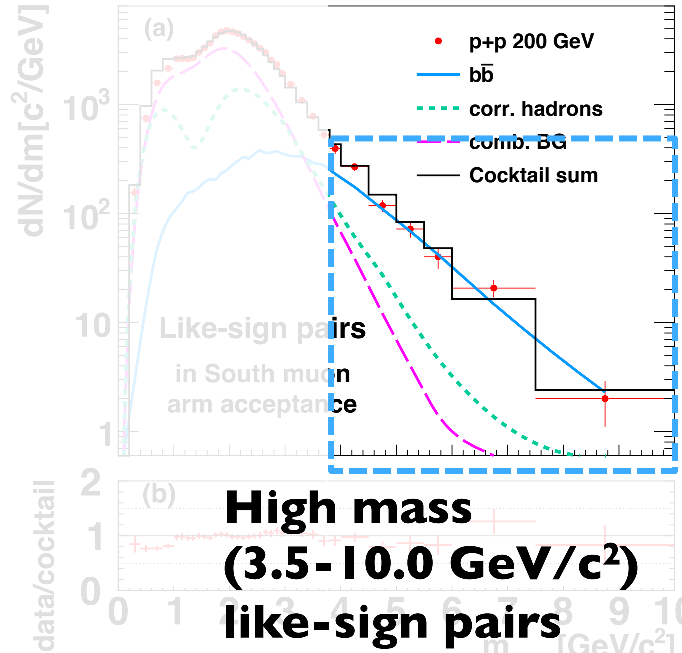
High mass (3.5-10.0 GeV/c²) like-sign pairs dominated by Bottom

An unexpected opportunity

Unlike-sign pairs



Like-sign pairs



Charm S/B highest in intermediate mass region (1.5-2.5 GeV/c²)

High mass (4.8-15.0 GeV/c²) unlike-sign pairs dominated by Drell-Yan

High mass (3.5-10.0 GeV/c²) like-sign pairs dominated by Bottom

Drell-Yan: probing initial state effects

- **Not affected by final state interactions**
- **p+A: clean probe of initial state effects**
  - **(anti-)Shadowing**
  - **energy loss/scattering of quarks passing through nucleus**

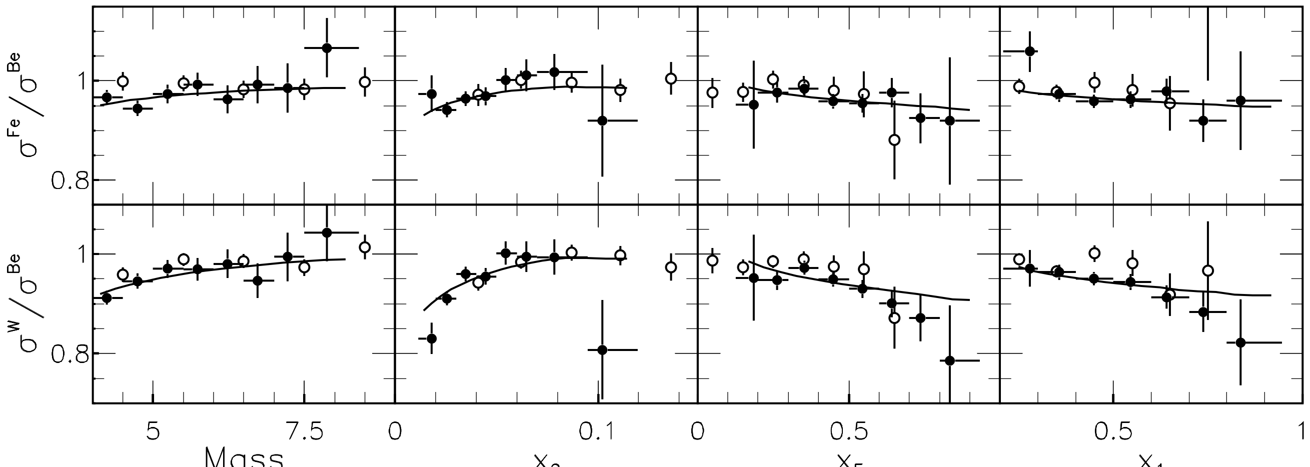
- **EKS98: DIS results are used to constrain shadowing function**
- **Shadowing in Drell-Yan found to be quantitatively similar to that in DIS**

PhysRevLett.83.2304

Solid: Fe/Be, W/Be from 800GeV/c p-Be,Fe,W(E866)

Open: Fe/C, W/C from 800GeV/c p-C,Fe,W(E772)

Line: Shadowing calculations (EKS98, MRST)



Drell-Yan: probing initial state effects

- **Not affected by final state interactions**
- **p+A: clean probe of initial state effects**
  - **(anti-)Shadowing**
  - **scattering/energy loss of quarks passing through nucleus**

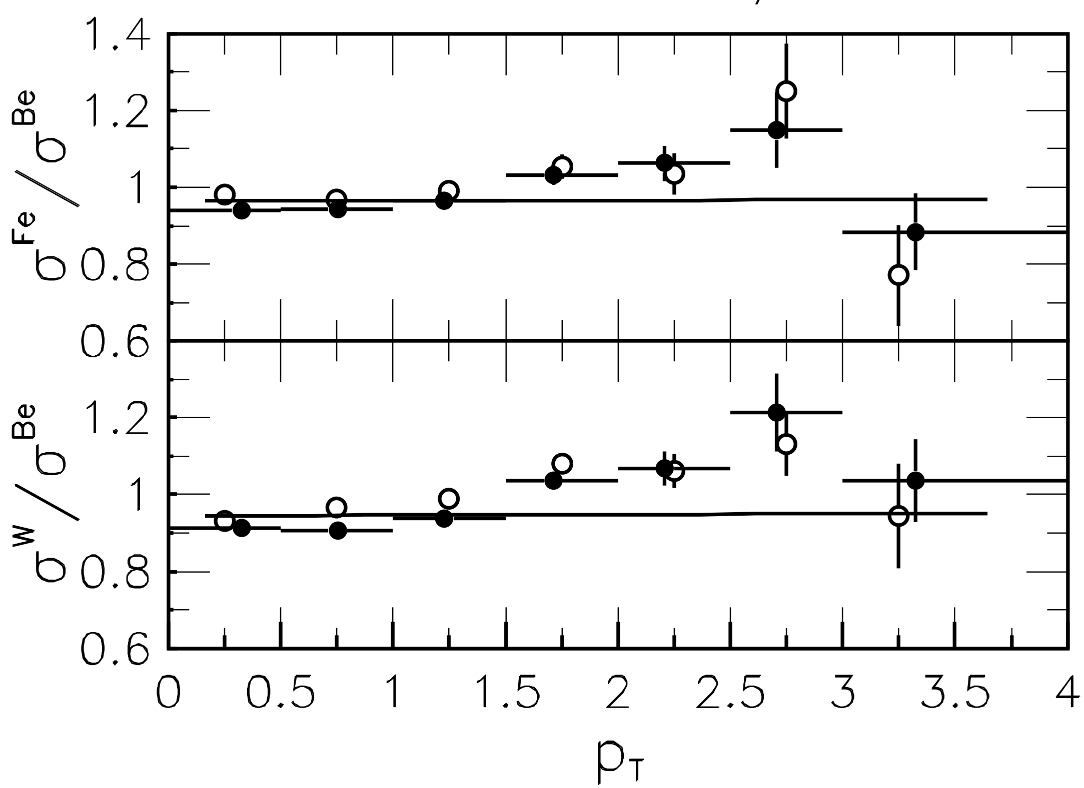
- **clear p_T dependence**
- **Characteristic of multiple scattering of incident partons traversing the nucleus**

Solid: Fe/Be, W/Be from 800GeV/c p-Be,Fe,W(E866)

Open: Fe/C, W/C from 800GeV/c p-C,Fe,W(E772)

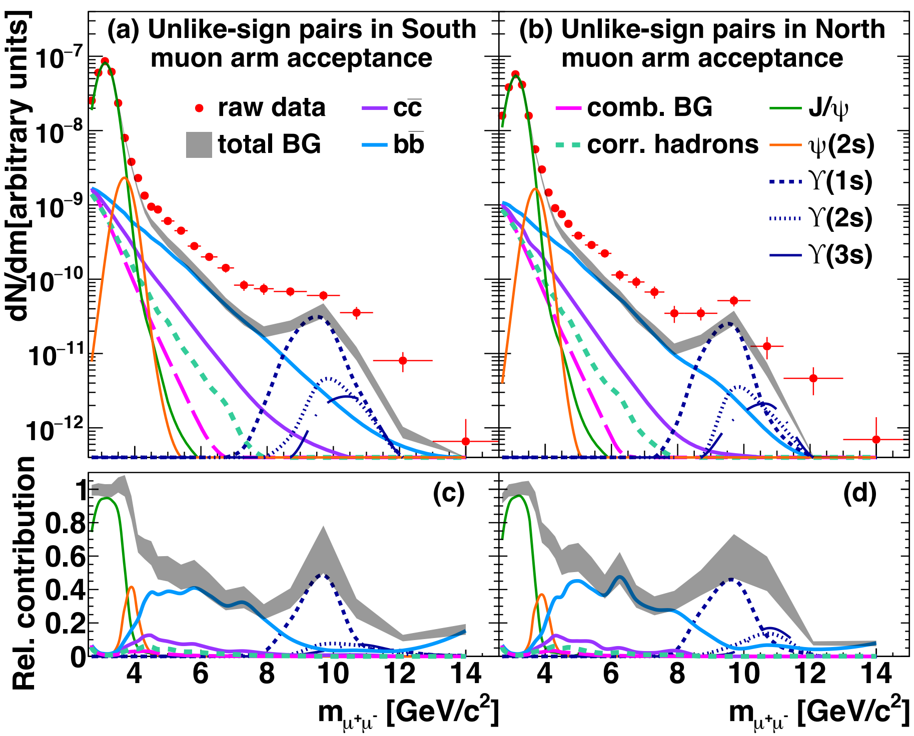
Line: Shadowing calculations (EKS98, MRST)

PhysRevLett.83.2304

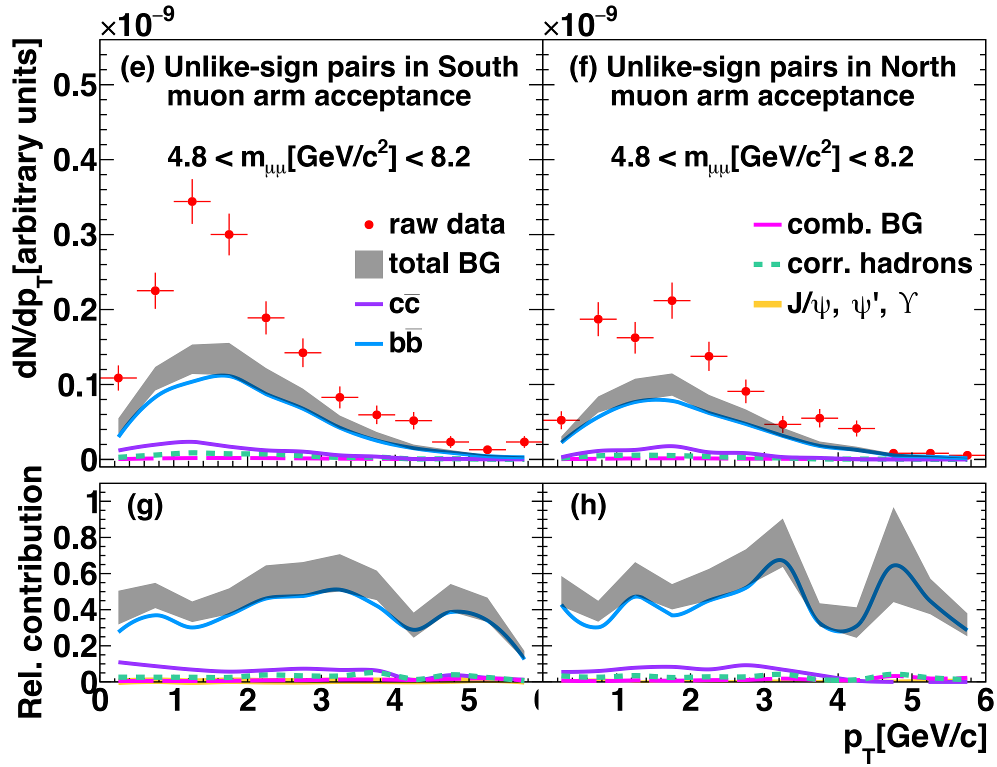


Drell-Yan (signal extraction, p+p)

mass

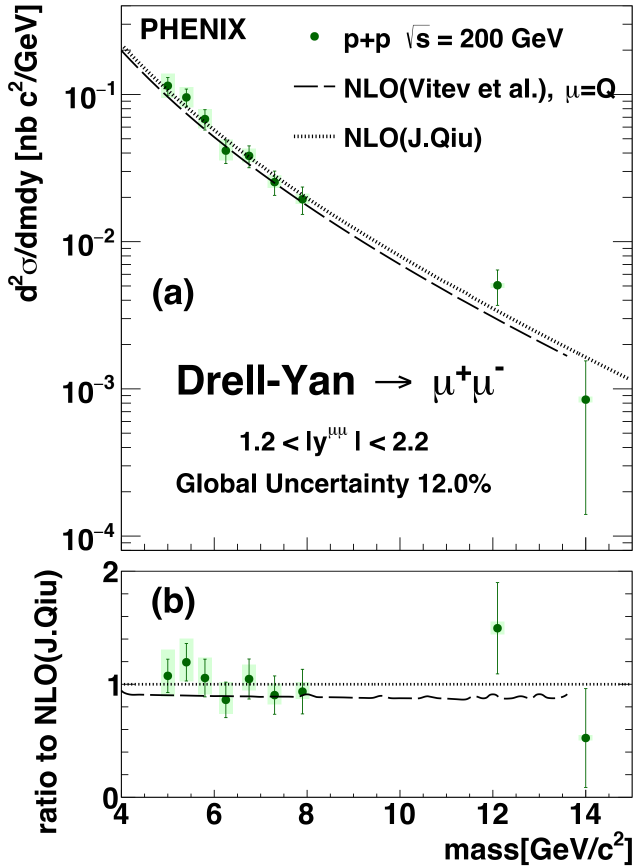


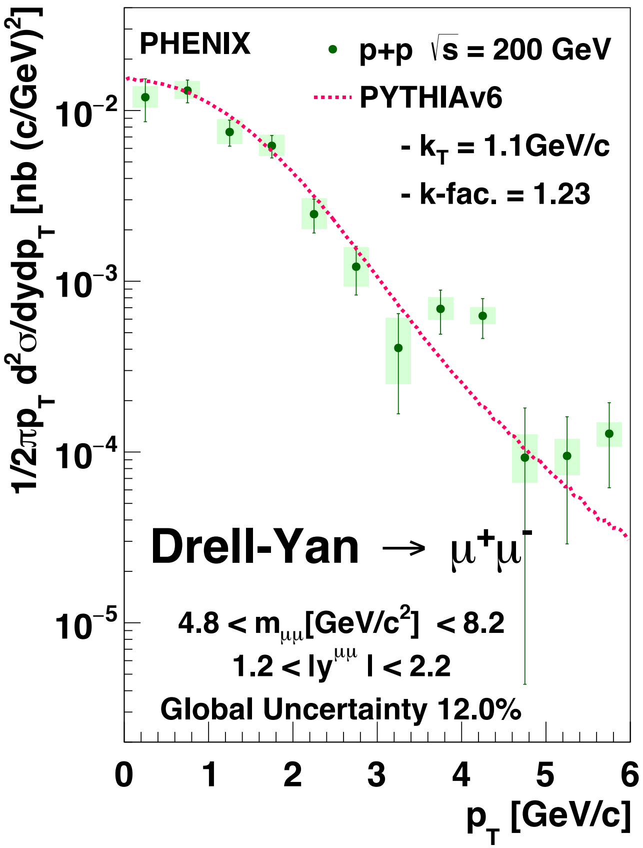
p_T



p+p Drell-Yan cross-section, 200 GeV

- First Drell-Yan measurement at RHIC energies





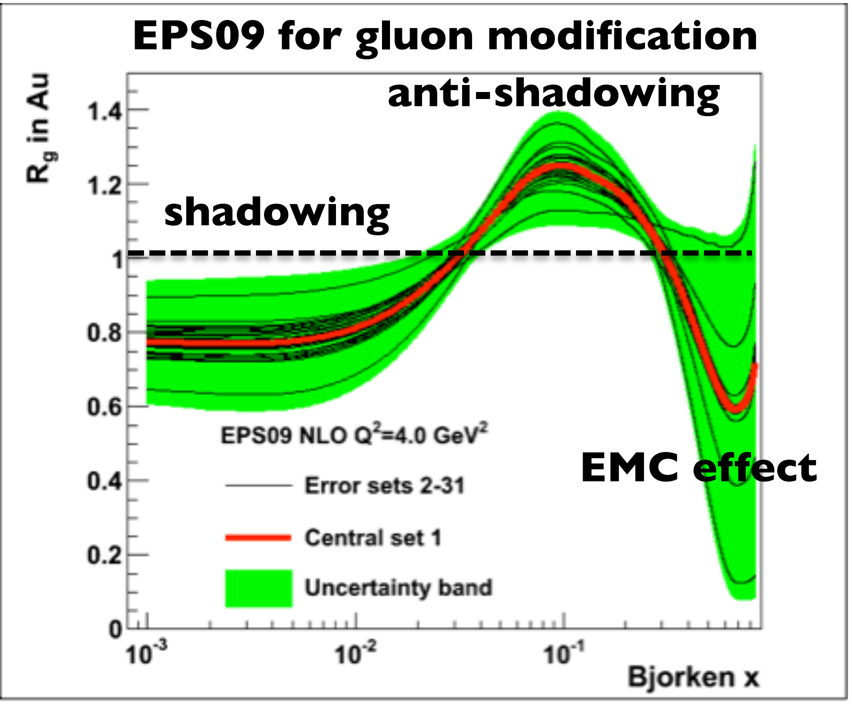
- **Consistent with NLO calculations**
- **p+Au analysis ongoing..**

Summary and prospects

- **Presented first measurement of dimuon continuum at p+p and p+Au 200 GeV at RHIC.**
- p+p:
  - **bb cross-section about 2x FONLL central value.**
  - Bayesian analysis based on PYTHIA tune A:
    - **Indicates that dominant source of bb production is leading order pair creation at 200 GeV.**
    - **Small fraction of gluon splitting in bottom allows clean interpretation of bottom HI data at RHIC energies.**
- p+Au:
  - Bottom yield at low pair p_T shows small enhancement, followed by decreasing trend.

- DY in p+Au: probe initial state effects, nPDFs.
- cc correlations in p+Au: probe cold nuclear matter effects.

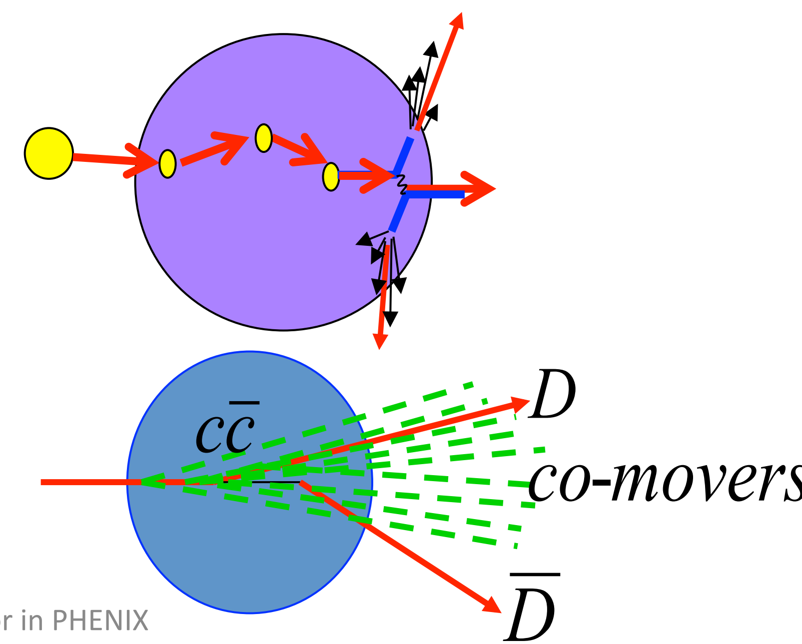
Backup



Heavy quarks can be sensitive to various effects:

Parton distribution functions in nuclei are modified compared to those in nucleon

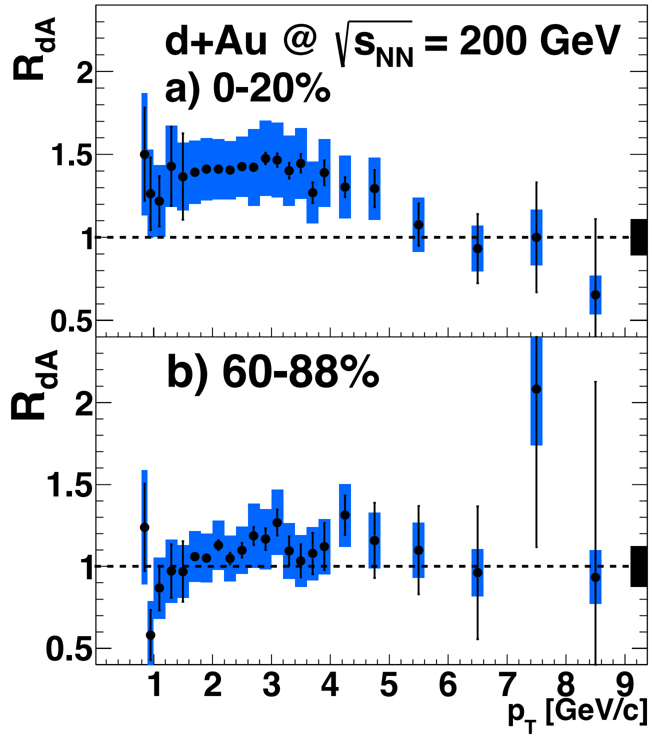
Scattering with nuclear matter:
(Initial-state or final-state interaction)
- **transverse momentum broadening**
- **energy loss**
- **break-up of bound states**



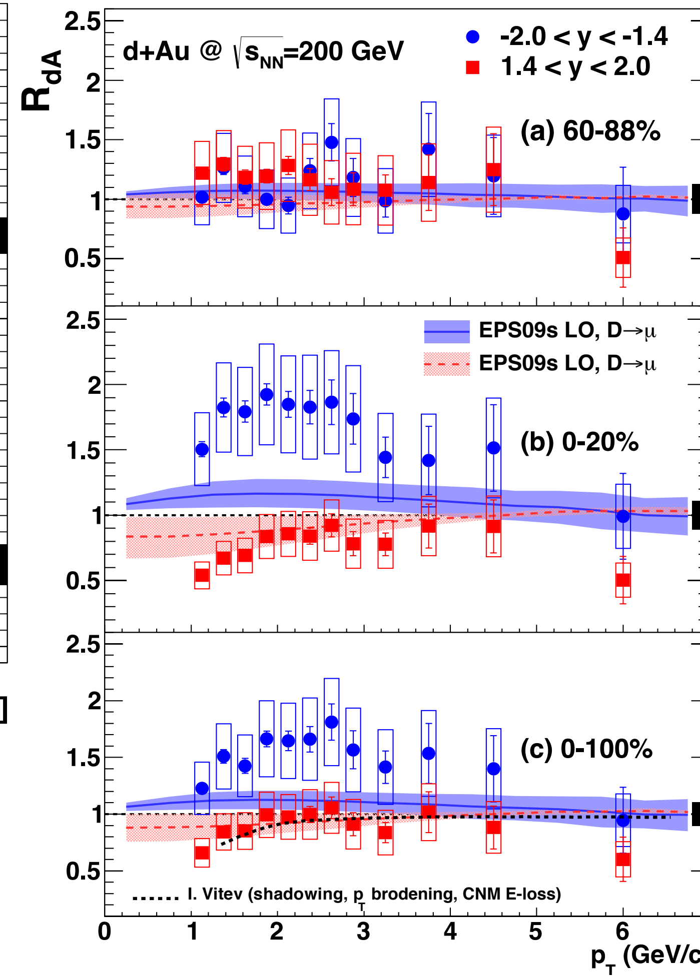
Cold nuclear matter effects with heavy flavor at 200 GeV

- **Modification of PDFs in nuclei**
  - **(Anti-) shadowing**
  - **Rapidity dependent enhancement (suppression)**
  - **Data not described by EPS09s**
- **Presence of other initial/final state effects**
  - **Multiple scattering**
  - **Energy loss**
  - **Flow**
  - **…**
  - **Not well understood**

Mid-rapidity



Fwd/bwd-rapidity



Details on the Bayesian analysis

- **Generate distributions for FC, FE, GS ($Y_{\alpha,i,j}$) separately.**

$$T_{i,j}(\mathbf{F}, \sigma_{HF}) = \sigma_{HF} \sum_{\alpha} F_{\alpha} Y_{\alpha,i,j},$$

  - **F_{α} is the fraction of the α process in 4π phase space.**
  - **σ_{HF} is the total cross-section.**
  - **$T_{i,j}$ is the predicted yield for the jth bin in the ith data set, for a certain set of fractions F_{α} and total cross-section σ_{HF}.**

- **Introduce nuisance parameters n, for each source of systematic uncertainty.**

$$\chi^2 = \sum_i \sum_j \sum_k \left[\frac{D_{i,j} - T_{i,j}(\mathbf{F}, \sigma_{HF}) + n_{i,k}\sigma^{sys}_{i,j,k}}{\sigma^{stat}_{i,j}}\right]^2,$$

Details on the Bayesian analysis

- **Bayes' rule**

$$P(\mathbf{F}, \sigma_{\mathrm{HF}}, \mathbf{n}|D) = \frac{P(\mathbf{D}|\mathbf{F}, \sigma_{\mathrm{HF}}, \mathbf{n}) \cdot P(\mathbf{F}, \sigma_{\mathrm{HF}}, \mathbf{n})}{P(\mathbf{D})}.$$

Likelihood: $e^{-\frac{\chi^2}{2}}$

Prior:

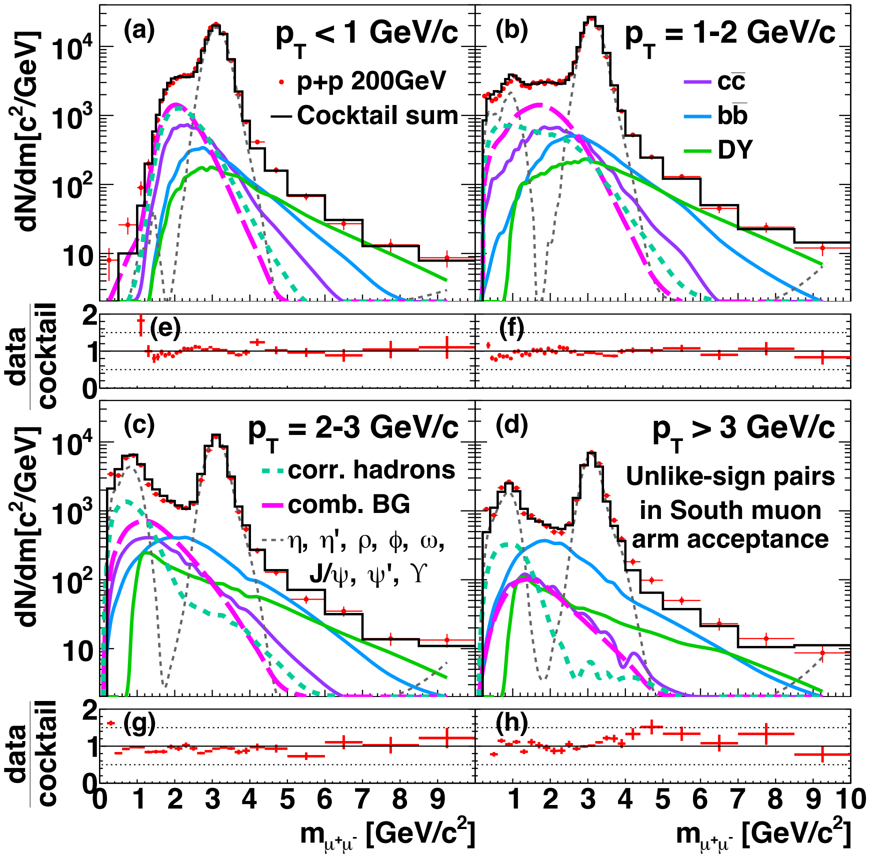
$$0 < F_{PC} < 1,$$
$$0 < F_{FE} < 1,$$
$$0 < F_{GS} < 1,$$
$$F_{PC} + F_{FE} + F_{GS} = 1.$$

Evidence: Constant factors, unimportant for current analysis

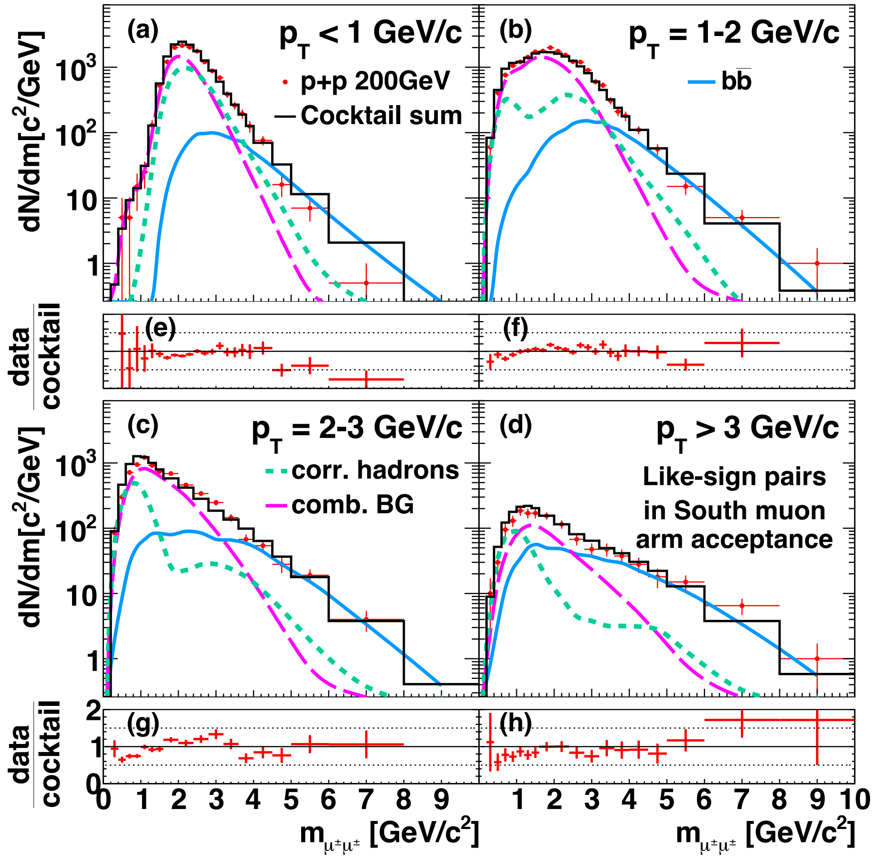
- **σ_{HF} constrained by fitting to data**
- **Sample over n to obtain $P(\mathbf{F}|D)$**

Fitting in mass-p_T (p+p)

Unlike-sign pairs

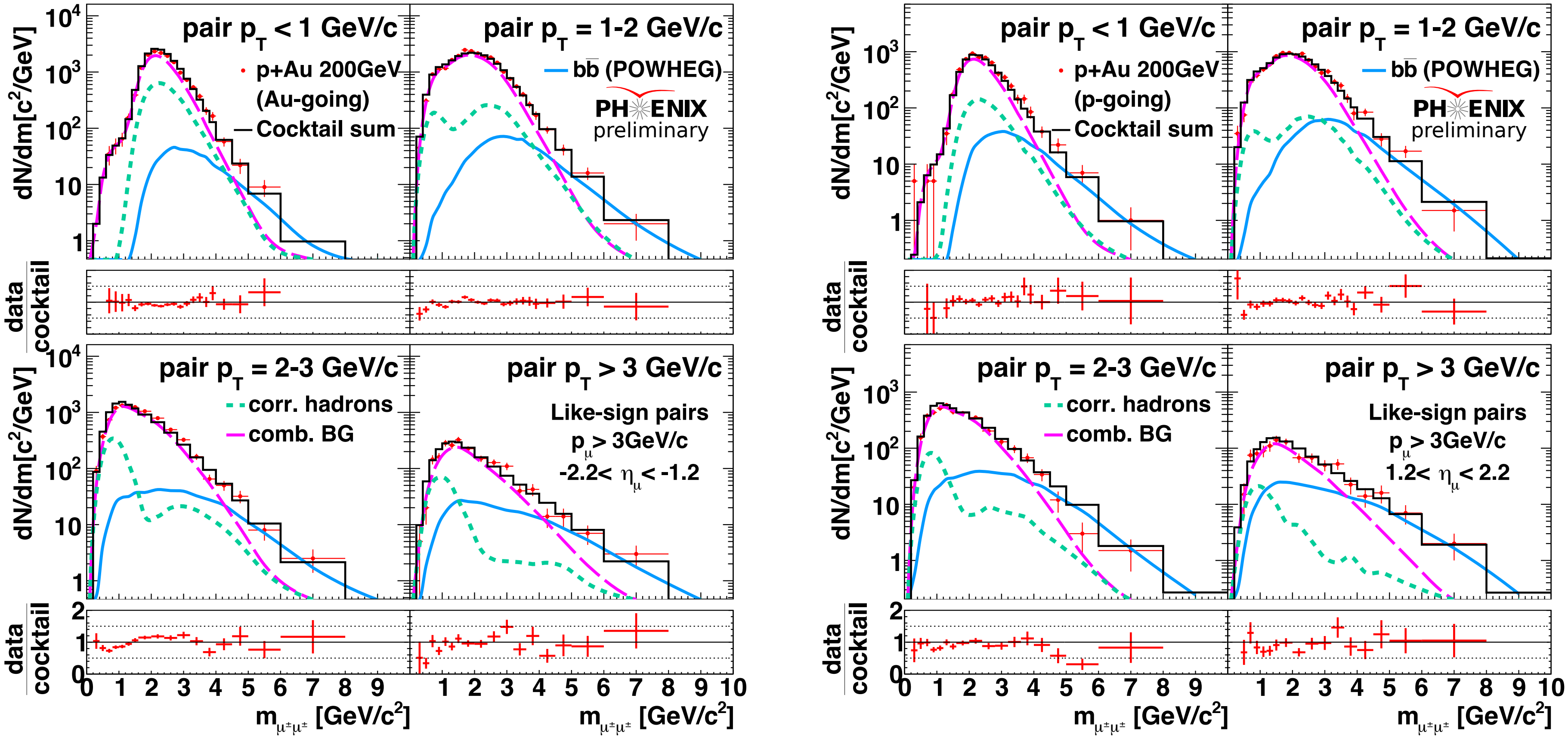


Like-sign pairs



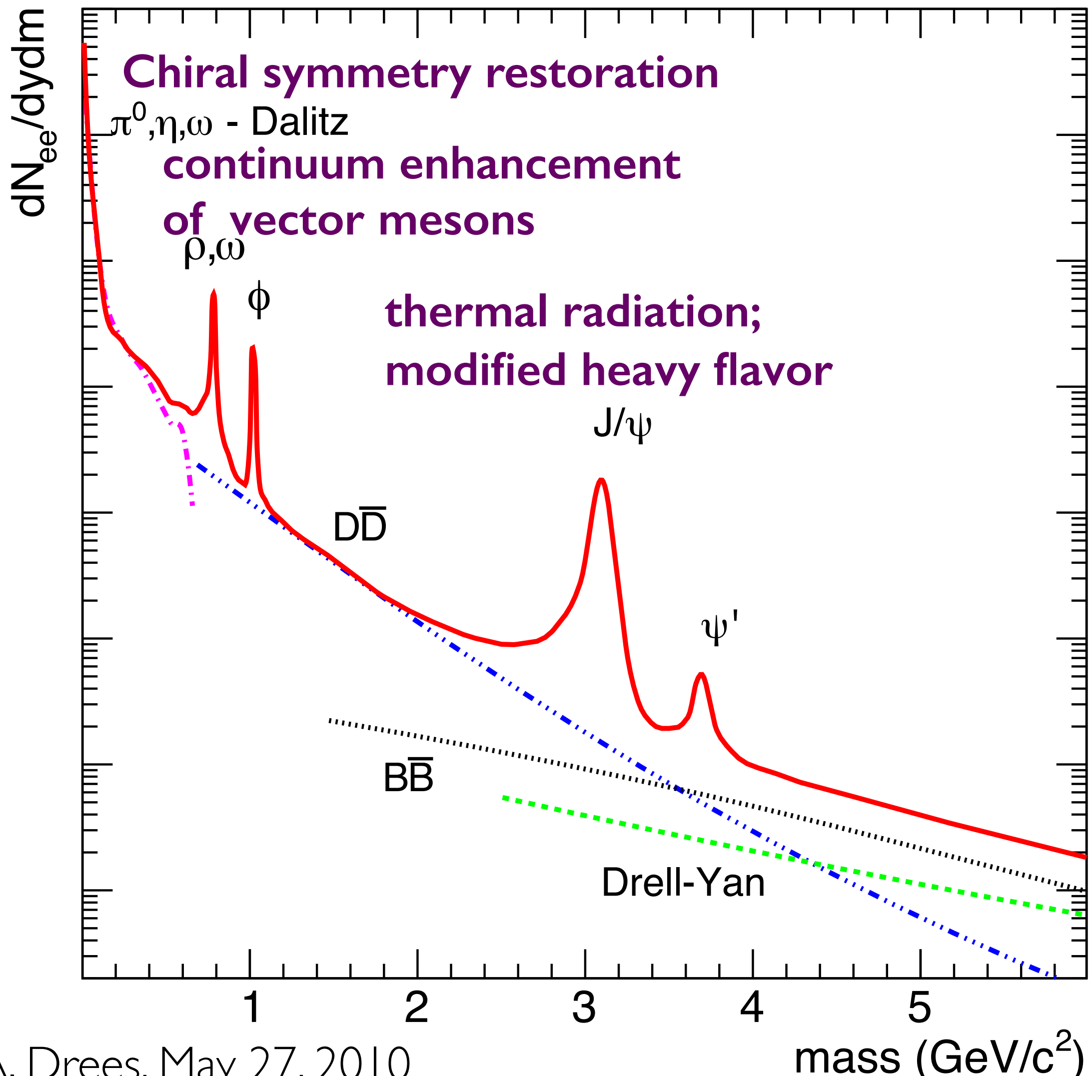
Fitting in mass-p_T (p+Au)

Au-going p-going



Lepton-pair continuum physics

Modifications due to QCD phase transition

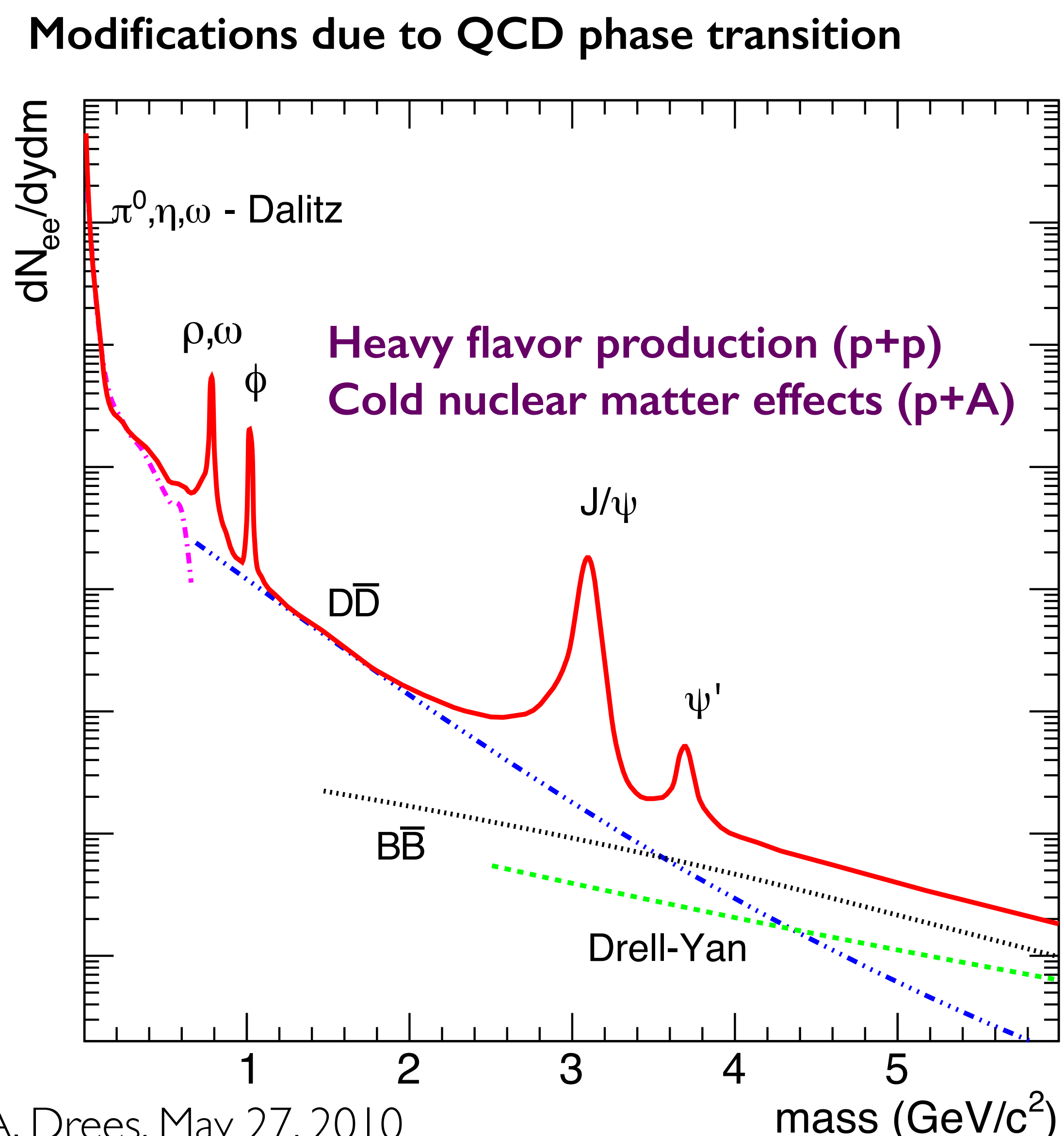


A. Drees, May 27, 2010

- **Sources long after collision**
  - π, η, ω decays
  - (ρ), ω, φ decays
- **Early in collision**
  - J/ψ, ψ' decays
  - Open heavy flavor
  - Drell-Yan
  - Direct radiation
- **Baseline from p+p**

- **Thermal radiation**
  - in dileptons and photons
  - temperature evolution
- **Medium modifications of meson**
  - $\pi\pi \rightarrow \rho \rightarrow l^+l^-$
  - chiral symmetry restoration
- **Medium effects on hard probes**
  - Heavy flavor energy loss/ decorrelations(?)

Lepton-pair continuum physics



A. Drees, May 27, 2010

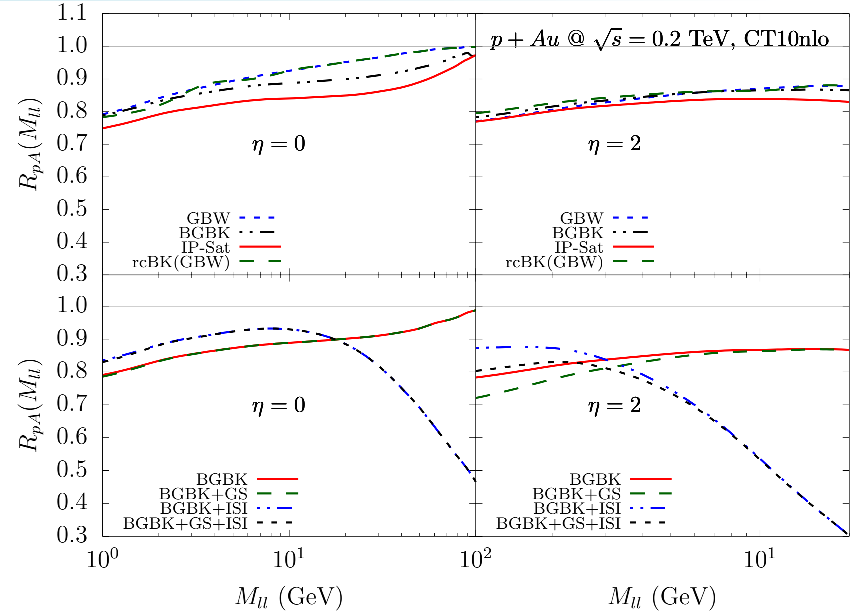
- **Sources long after collision**
  - π, η, ω decays
  - (ρ), ω, ϕ decays
- **Early in collision**
  - J/ψ, ψ' decays
  - Open heavy flavor
  - Drell-Yan
  - Direct radiation
- **Baseline from p+p, p/d+A**

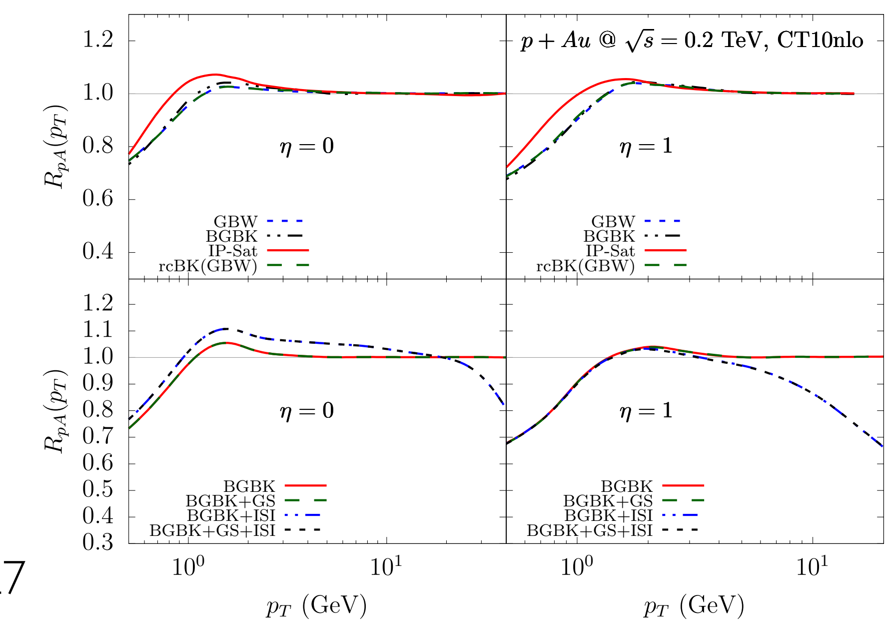
- **Thermal radiation**
  - in dileptons and photons
  - temperature evolution
- **Medium modifications of meson**
  - $\pi\pi \rightarrow \rho \rightarrow l^+l^-$
  - chiral symmetry restoration
- **Medium effects on hard probes**
  - Heavy flavor energy loss/ decorrelations(?)

Drell-Yan process

- **Not affected by final state interactions**
  - **p+A: clean probe of initial state effects**
  - **Initial state interactions(ISI)**
    - **Large suppression at large m (x_F)**
    - **Significant suppression at large p_T**
    - **Stronger at forward rapidities**
  - **Gluon shadowing(GS)**
    - **Suppression in the forward region**
  - **Saturation effects**

Expected to be
non-dominant at RHIC, but not LHC





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