Open Heavy Flavor in p+p collisions with STAR at RHIC

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for the STAR Collaboration

3rd Heavy Flavor Meet - 2019
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Outline

I Introduction

II STAR experiment

III D meson transverse momentum spectra in p+p

IV Total cross section of ccbar

V Azimuthal angular correlations

VI Heavy Flavor -> Non Photonic Electrons

VII Conclusions and outlook

I Introduction

Goals of the STAR experiment at RHIC and relevance of Heavy Flavor

Goals of the STAR experiment:

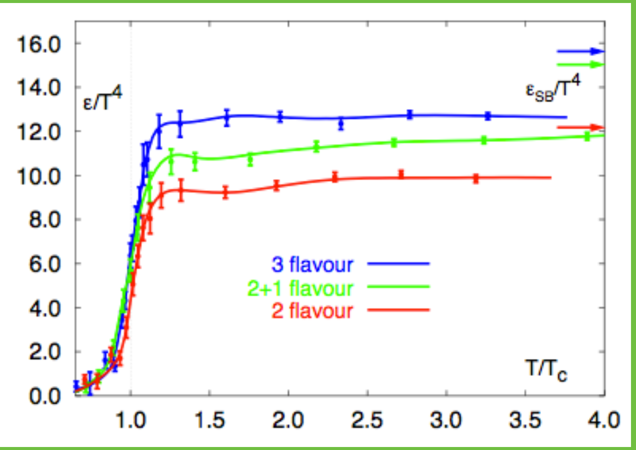
- Studies of the QCD phase transition between hadronic and partonic phase and of the sQGP formed in A+A collisions at RHIC.
- Search for new phenomena
- Origin of the spin of the nucleon using polarized p+p collisions.

sQGP: expected to be u, d, s, ubar, dbar, sbar, g state.

Heavy quarks (c,b) at RHIC are produced in hard processes in the initial stage of the collision and witness all the stages of the evolution of a heavy ion reaction

They are expected to be witnessing modifications which can reveal the characteristics of the medium they traverse

Zero net baryon density



F. Karsch, Lect. Notes Phys. 583 (2002) 209, hep-lat/0106019

Heavy Flavor

Open Heavy Flavor in p+p collisions allow to:

Test models and understand HF production in p+p and in A+A collisions

Infer the modifications in A+A with respect to p+p (quenching in A+A) to extract characteristics of the sQGP

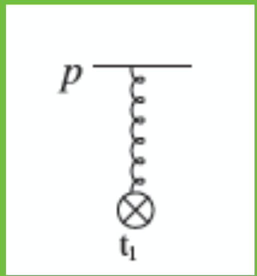
Allow to use HF to search for mass hierarchy of radiative energy loss

Help to understand quarkonia

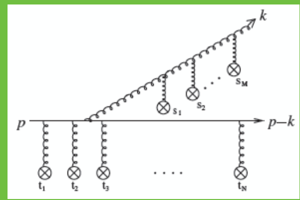
Heavy Flavor and mass hierarchy of quenching

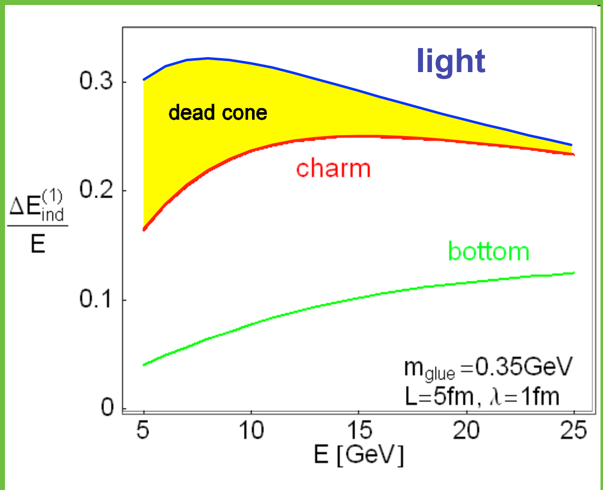
Partons interact with the hot and dense medium created in heavy ion collisions and loose energy through eg gluon radiation

Collisional “elastic” energy loss: elastic interaction with the medium



Radiative energy loss: parton radiation due to interaction with the medium





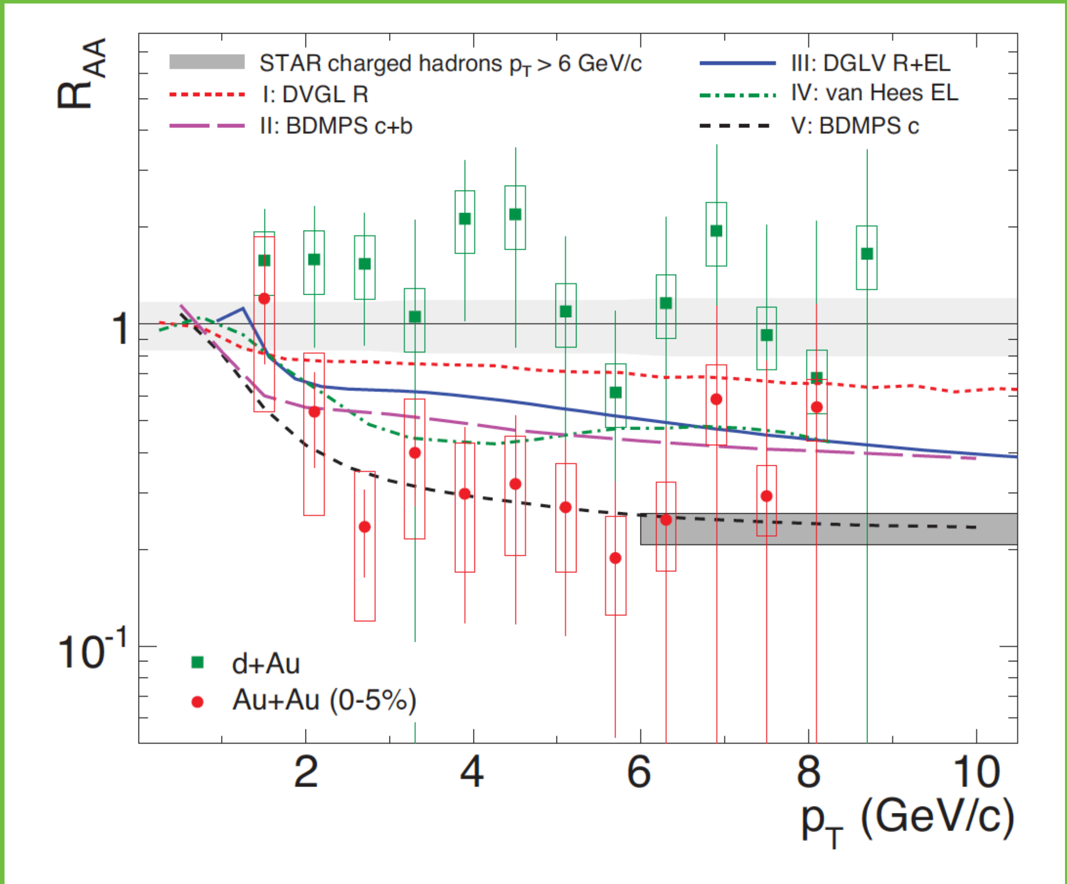
M.Djordjevic PRL 94 (2004)

Quarks are expected to exhibit different radiative energy loss depending on their mass (D.Kharzeev et al. Phys Letter B. 519:1999)

-> We expect a hierarchy of suppression due to radiative energy loss
b should loose less energy than c which should loose less energ than u,d,s

A good measurement of D and B in p+p collisions is crucial for the understanding of D and B production in A+A and especially to interpret energy loss effects in A+A with respect to p+p collisions

Heavy Flavor quenching



Au+Au 200 GeV 0-5%: Heavy Flavor -> electrons suppressed like charged hadrons versus pT

STAR coll., PRL113,14,142301 (2014), Erratum: PRL121,22, 229901 (2018),arXiv:1404.6185, arXiv: 1809.08737

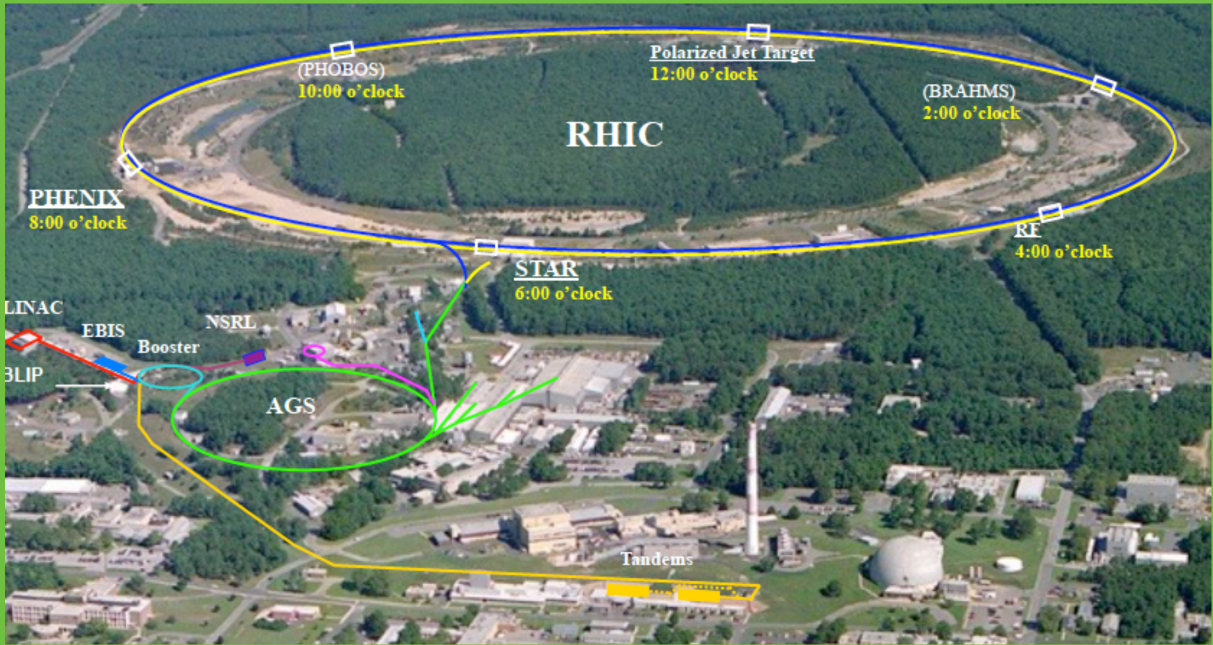
BROOKHAVEN NATIONAL LABORATORY

STAR

II The STAR experiment at the Relativistic Heavy Ion Collider (RHIC)

Relativistic Heavy Ion Collider

at the Brookhaven Lab, Long Island, New York, USA



RHIC has been exploring nuclear matter at extreme conditions over the last 18 years, since 2000

4 experiments initially:
STAR PHENIX
BRAHMS PHOBOS

Still runing: STAR

Still analysing data: PHENIX

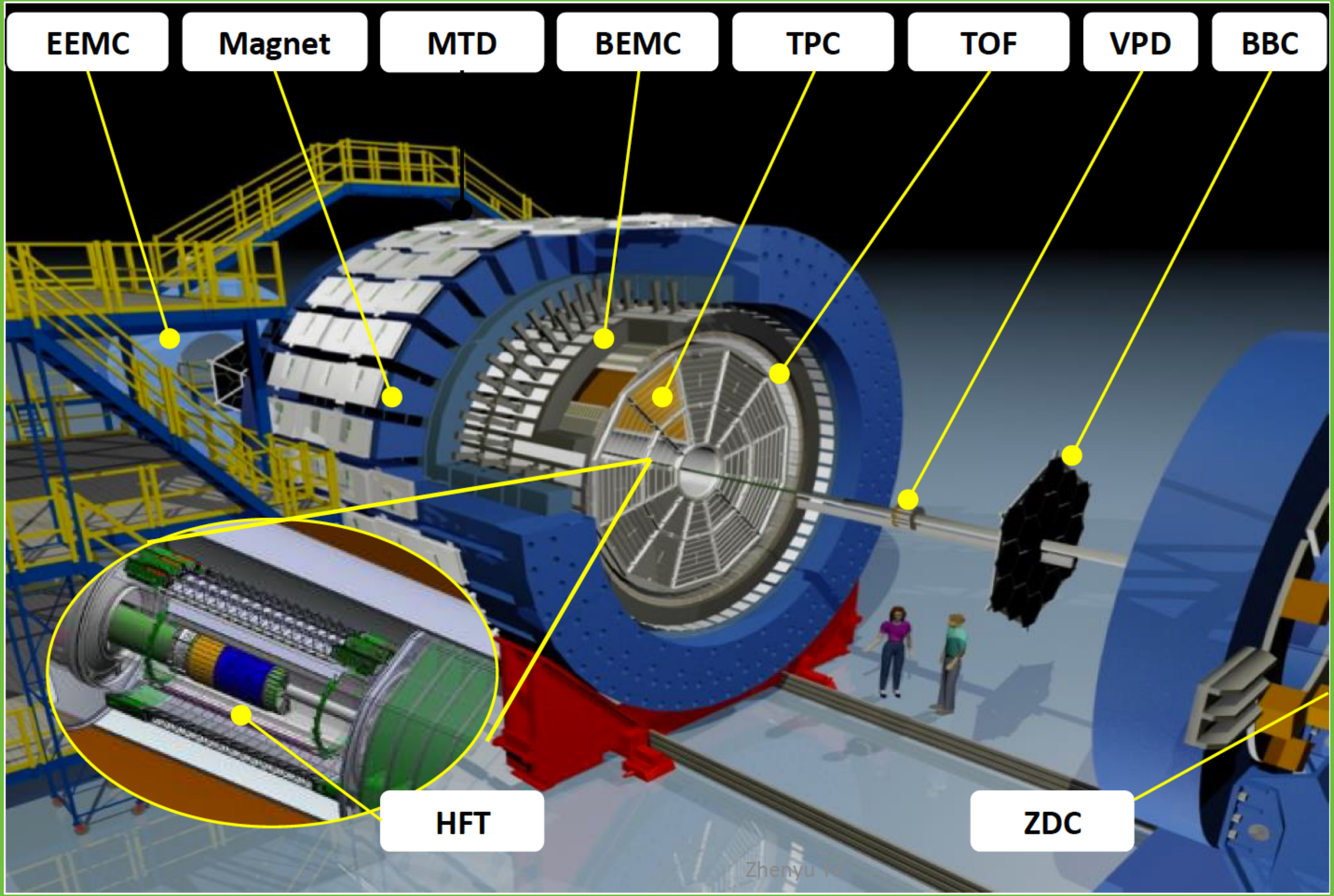
Main colliding systems:

p+p, p+A, d+Au, Cu+Cu, Au+Au
Cu+Au, U+U, Zr+Zr, Ru+Ru

Main energies A+A :

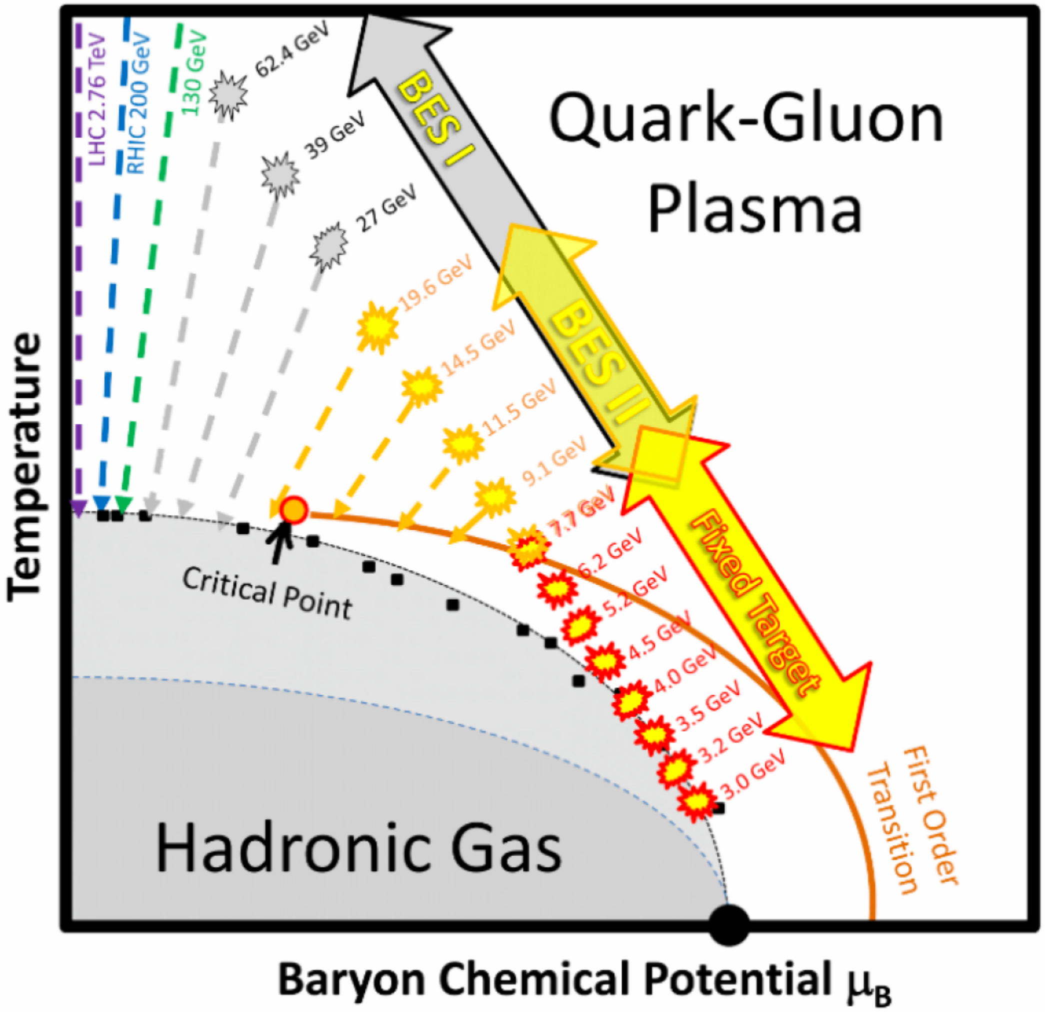
$\sqrt{s_{NN}}$ = 62, 130, 200 GeV
and low energy scan
7.7, 11.5, 19.6, 22.4, 27, 39, 54 GeV
+ Fixed target

The STAR detector



- **Tracking and PID (full 2π)**
  TPC: $|\eta| < 1$
  TOF: $|\eta| < 1$
  BEMC: $|\eta| < 1$
  EEMC: $1 < \eta < 2$
  HFT (2014-2016): $|\eta| < 1$
  MTD (2014+): $|\eta| < 0.5$
- **MB trigger and event plane reconstruction**
  BBC: $3.3 < |\eta| < 5$
  EPD (2018+): $2.1 < |\eta| < 5.1$
  FMS: $2.5 < \eta < 4$
  VPD: $4.2 < |\eta| < 5$
  ZDC: $6.5 < |\eta| < 7.5$
- **On-going/future upgrades**
  iTPC (2019+): $|\eta| < 1.5$
  eTOF (2019+): $-1.6 < \eta < -1$
  FCS (2021+): $2.5 < \eta < 4$
  FTS (2021+): $2.5 < \eta < 4$

STAR



RHIC Top Energy

p+p, p+Al, p+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Ru+Ru, Zr+Zr, Au+Au, U+U

- QCD at high energy density/temperature
- Properties of QGP, EoS
- Spin of quarks and gluons

Beam Energy Scan

Au+Au at $\sqrt{s_{NN}}$ = 7.7 - 62 GeV

- QCD phase transition
- Search for critical point
- Turn-off of QGP signatures

Fixed-Target Program

Au+Au at $\sqrt{s_{NN}}$ = 3.0 - 7.7 GeV

- High baryon density (μ_B ~ 420 - 720 MeV)

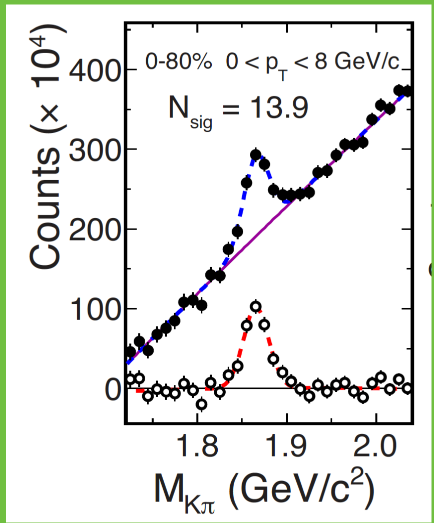
Gang Wang 3

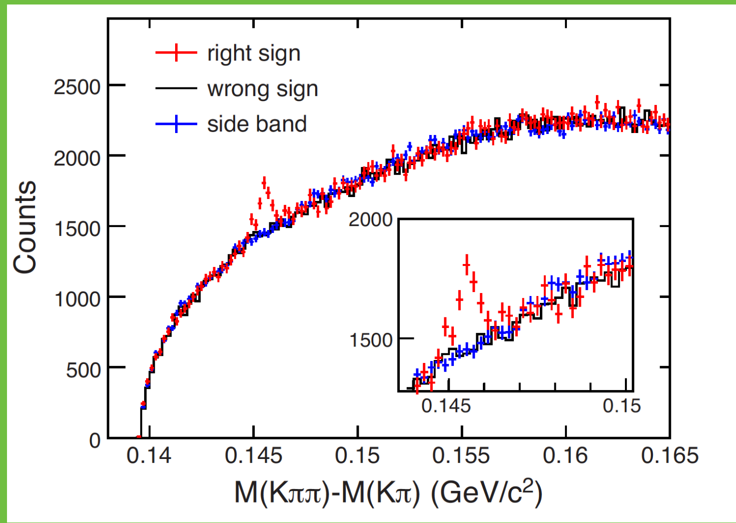
Methods of HF identification used in STAR

Non photonic electrons from semileptonic decays of heavy flavor without and with displaced vertex information (via the HFT)

Reconstruction (inv. mass) of the hadronic decay of charm without and with secondary vertex reconstruction (bia the HFT)

Electron-hadron, D-electron azimuthal angular correlations. allow to measure B/(B+C) vs pT





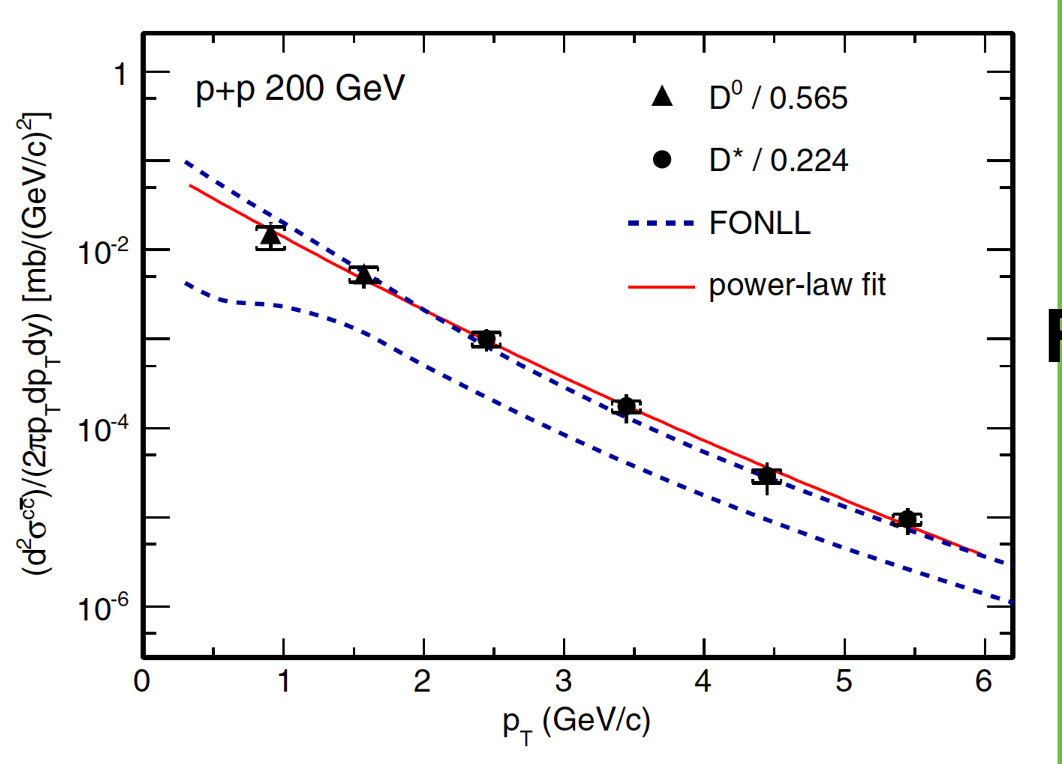
III Transverse momentum spectra of HF in p+p collisions

Transverse momentum spectra of HF in p+p collisions at 200 GeV

Charm pT spectra infered from D0 and D* in p +p at 200 GeV

Data set: minimum bias p+p collisions 200 GeV of 2009 run

STAR Coll., Phys.Rev.D 86, 072013 (2012)

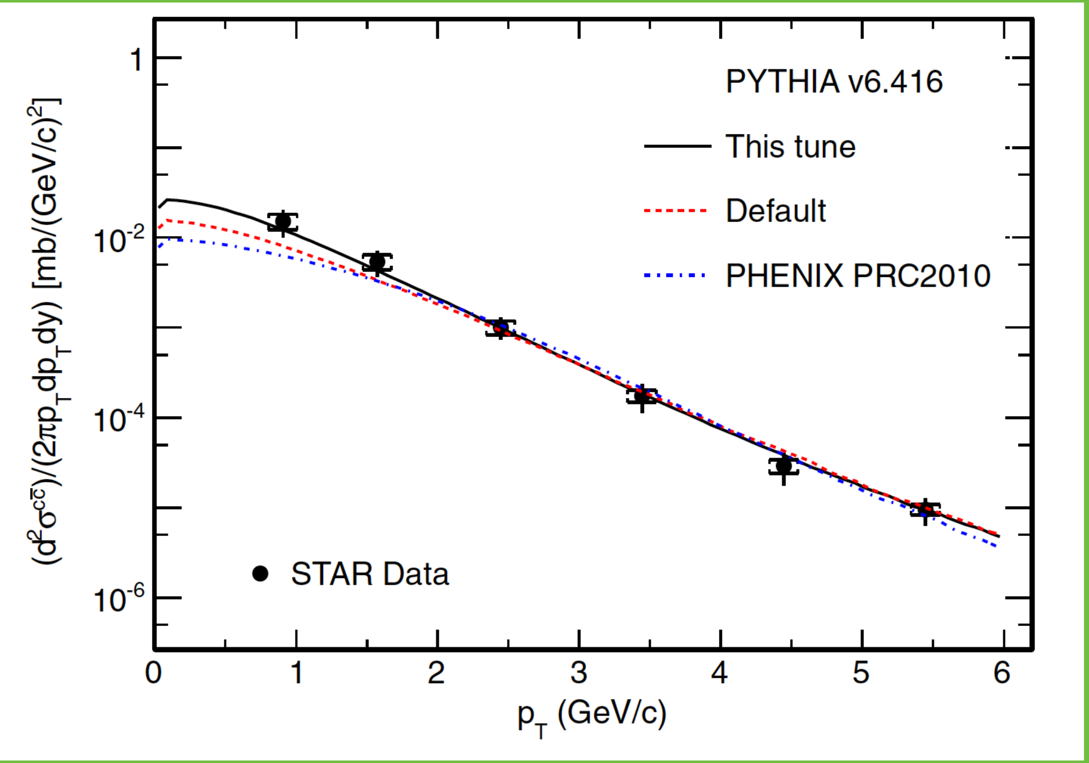


Data consistent with FONLL within uncertainties

c and cbar production as a function of pT in p+p at 200 GeV which has been inferred from D0 (triangles) and D* (circles)

Charm pT spectra infered from D0 and D* in p+p at 200 GeV

STAR Coll., Phys.Rev.D 86, 072013 (2012)

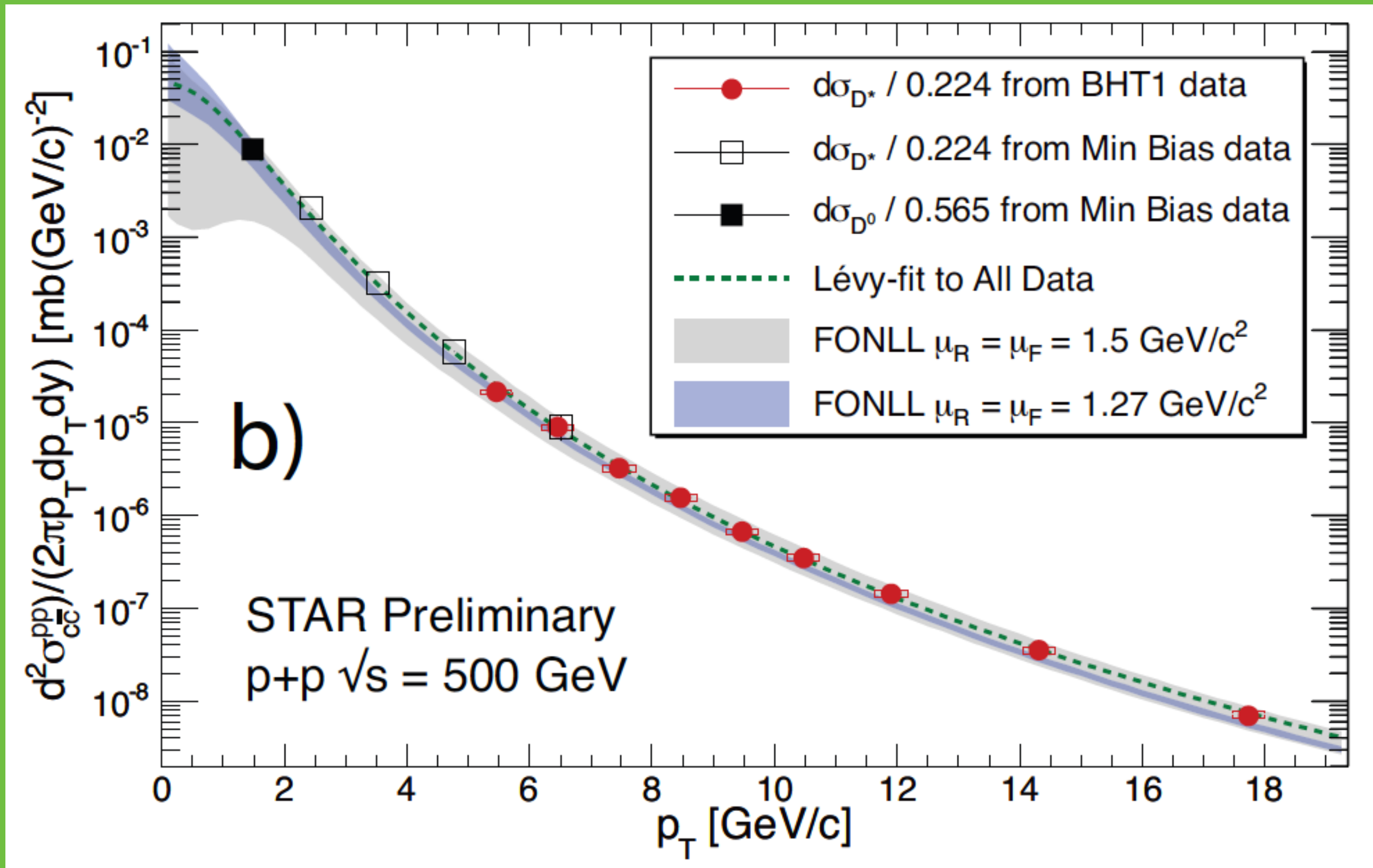


Default and best PYTHIA tune to data (STAR ad PHENIX)

Transverse momentum spectra of HF in p+p collisions at 500 GeV

Charm quark pT spectrum in p+p at 500 GeV

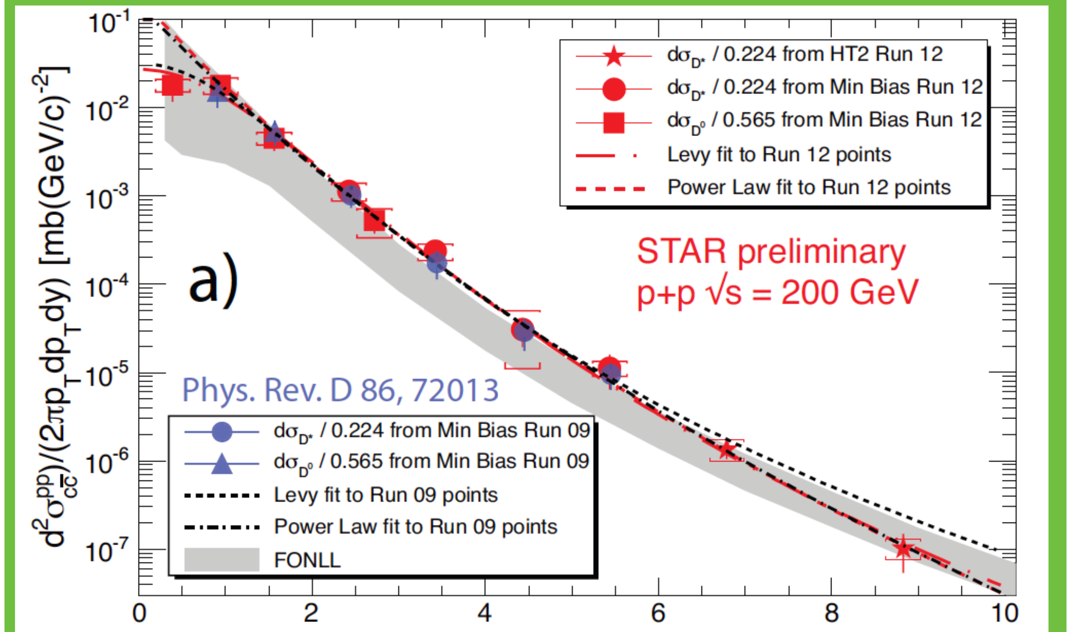
Preliminary p+p 500 GeV
Charm cross section infered from D0 and D* data



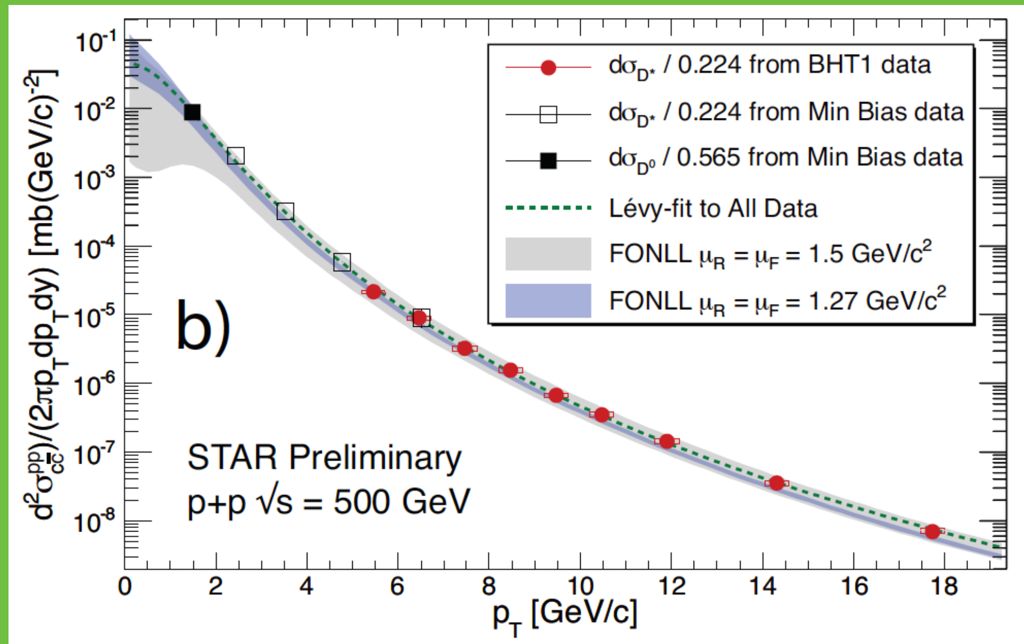
- pT acceptance extended to 20 GeV
- Consistent with FONLL

Charm pT spectra infered from D0 and D* in p+p at 200 and 500 GeV

p+p 200 GeV preliminary



p+p 500 GeV preliminary

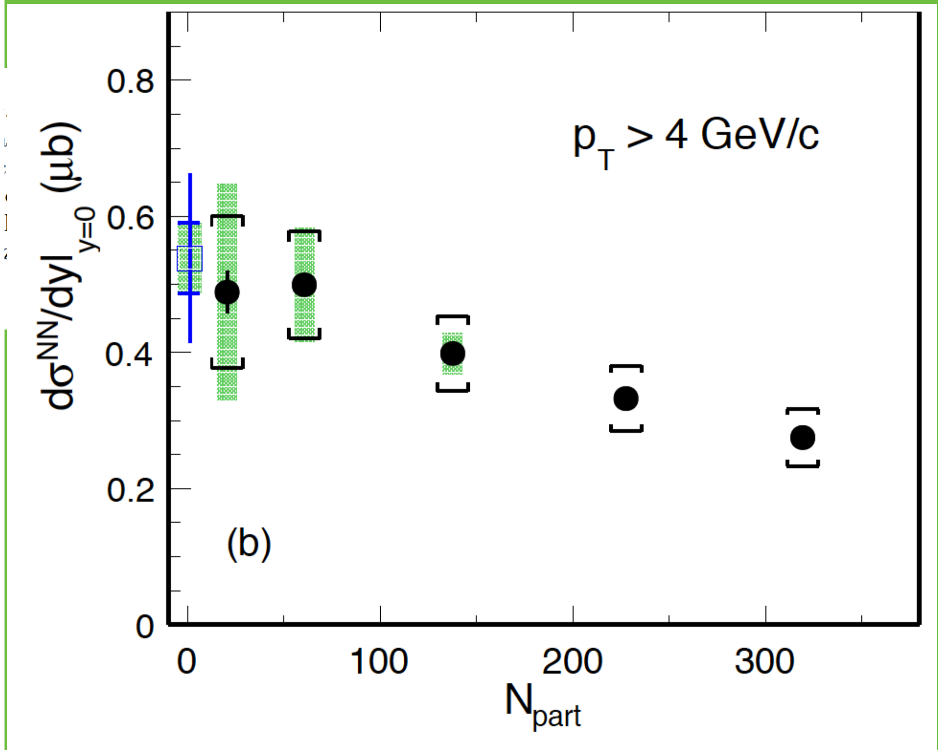


IV Cross section ccbar

D0 with pT > 4 GeV in p+p and Au+Au 200 GeV

arXiv:1812.10224 [nucl-ex]

pT > 4 GeV cross section of D0 per Nuleon-Nucleon collision



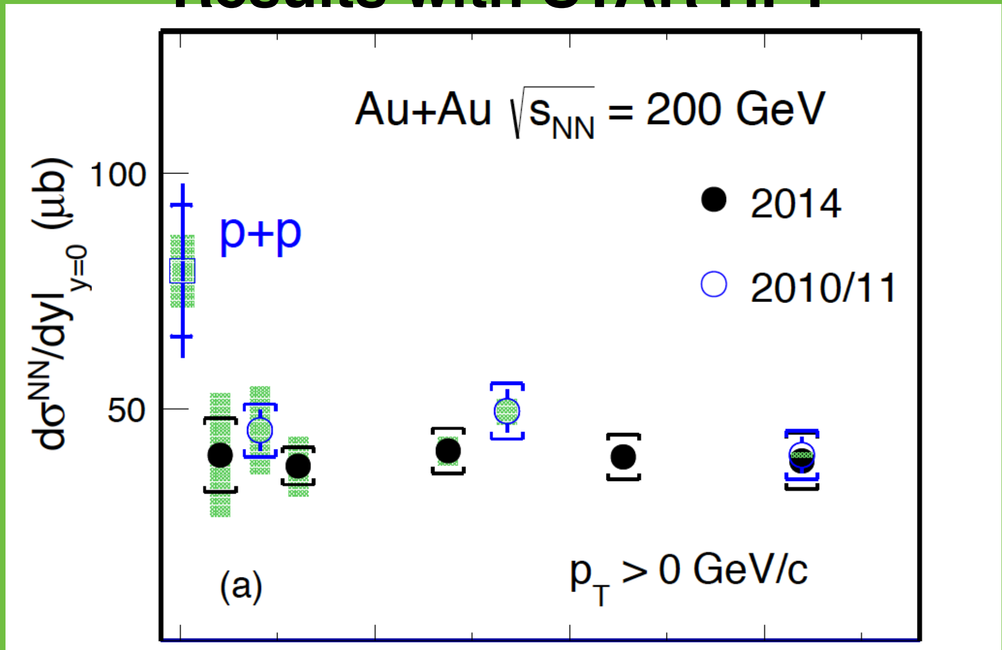
- Peripheral Au+Au D0 with pT > 4 GeV are consistent with p+p collisions

- High pT D0 cross section per NN collision in Au+Au decrease with enhancing centrality

-> can be a consequence of quenching of charm at high pT

D0 pT-integrated cross section per Nucleon Nucleon collision

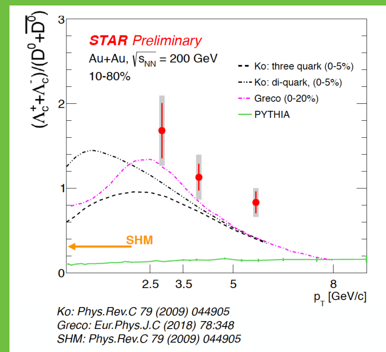
Results with STAR HFT



arXiv:1812.10224 [nucl-ex]

- D0 Au+Au cross section per NN collision at full pT is lower than p+p 200 GeV

Can be due to Cold Nucl Matter effects and/or quark coalescence and ssbar enhancement -> enhancing Lambda_c and D+_s and reducing D0



-D0 Au+Au in full pT per NN coll. are constant vs Centrality ->
D0 seem proportional to the number of binary NN collisions despite overall reduction from p+p value

-

Total charm cross section in p+p and in Au+Au collisions at 200 GeV using various hadrons

Observed: Lambda_c and Ds enhancement and suppression of D0 -> To estimate total charm cross section measurement of many different charmed hadrons are needed

pT integrated charm cross section at midrapidity

Charm Hadron		Cross-section (μb)
AuAu 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
pp 200 GeV	**Total**	**130 ± 30 ± 26**

*** derived using Λ_c^+ / D^0 ratio in 10-80%**

STAR preliminary

- The total charm cross section in Au+Au is found to be consistent with p+p collisions within uncertainties

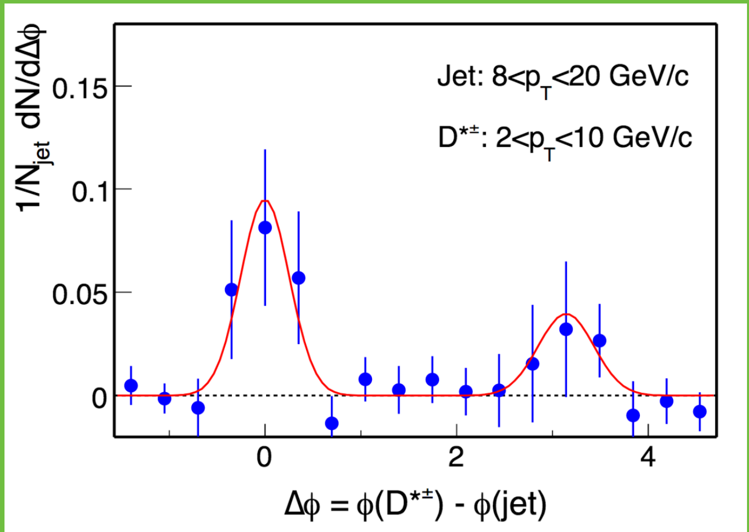
Production mechanisms of charm in p+p collisions at 200 GEV

Study charm production mechanisms with D* content in jets in p+p colliions at 200 GeV

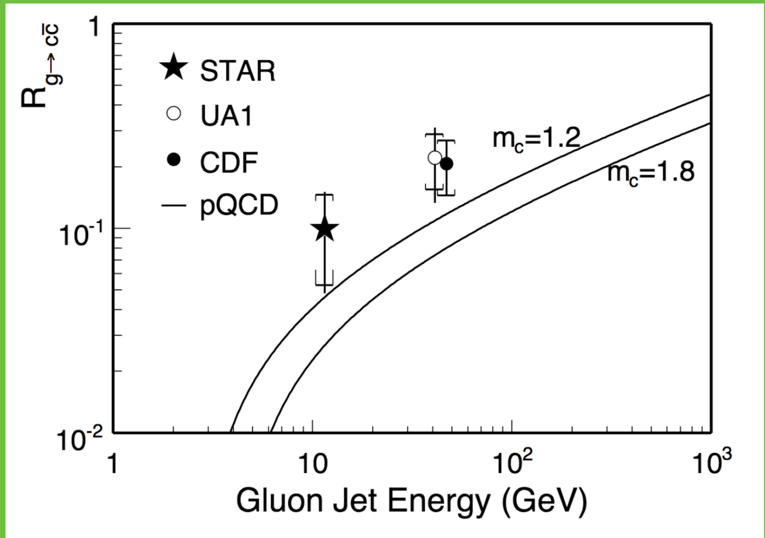
STAR, PRD 79, 112006 (2009), arXiv:0901.0740

Investigate gluon splitting g-> ccbar versus gluon fusion gg-> ccbar production mechanisms

D* - jet Deltaphi



R(g -> ccbar)



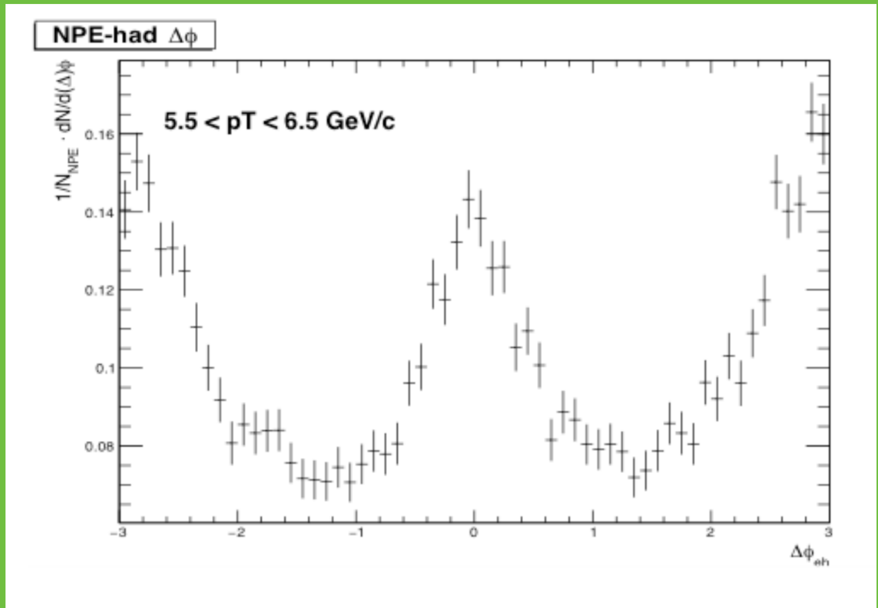
Charm content in jets in p+p collisions at 200 GeV has a small contribution from gluon splitting g-> ccbar and is dominated by jets initiated by charm quarks

V Azimuthal angular correlations

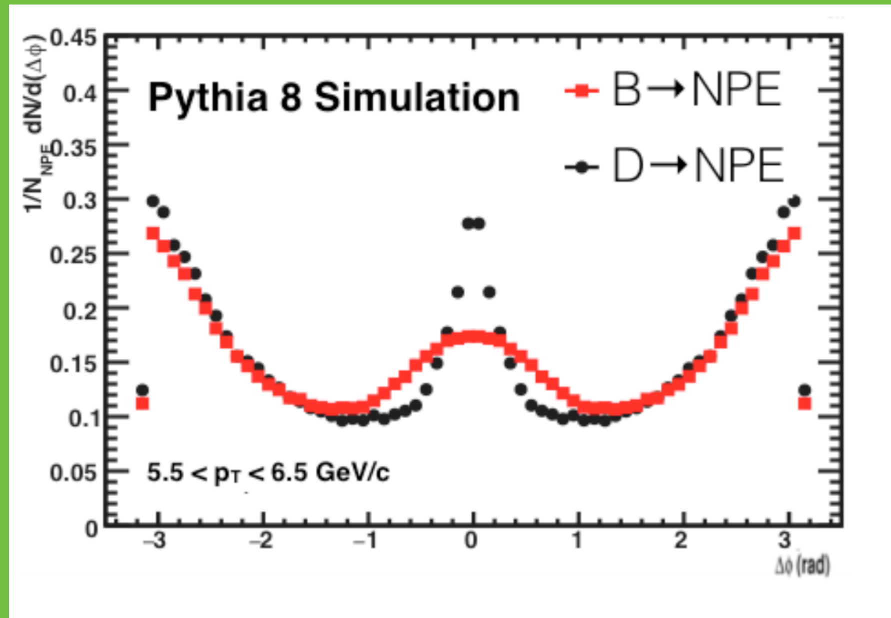
Non photonic electron - hadron
Azimuthal angular correlations
p+p 200 GeV

Non photonic electrons - hadron correlation -> extract B and C components

STAR data NPE-hadron



PYTHIA



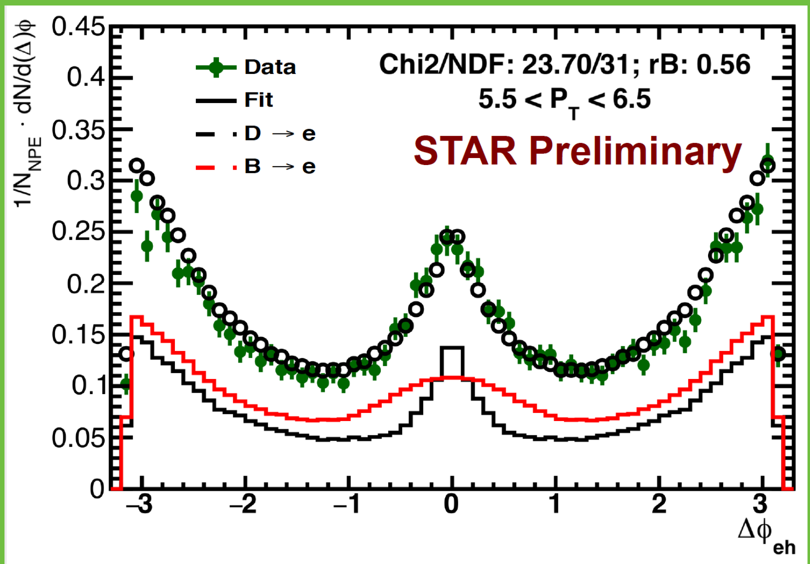
NPE-hadron angular correlations allow to extract B and C contribution via the use of Monte Carlo (PYTHIA). PYTHIA shows the different angular correlations of B and C (exept at high pT).
The data are fitted with function to extract B and C components

$$\Delta\phi_{exp} = (R \times \Delta\phi_B + (1 - R) \times \Delta\phi_D) \times Norm$$

R= fit parameter = B/NPE

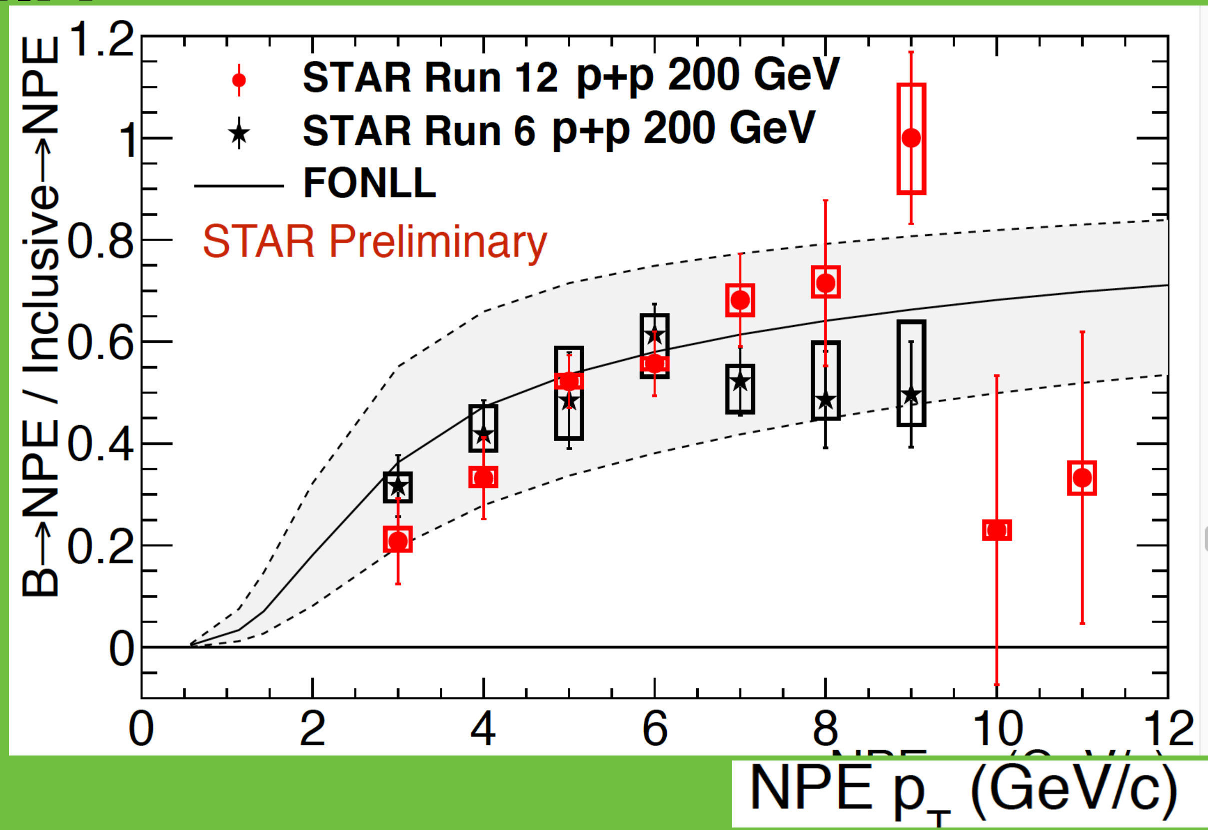
B/NPE vs pT from electron-hadron correlations in p+p 200 GeV

p+p 200 GeV and PYTHIA



STAR Run 6: Phys.Rev.Lett. 105, 202301 (2010)
FONLL: Phys.Rev.Lett. 95 122001 (Preprint hep-ph/0502203)

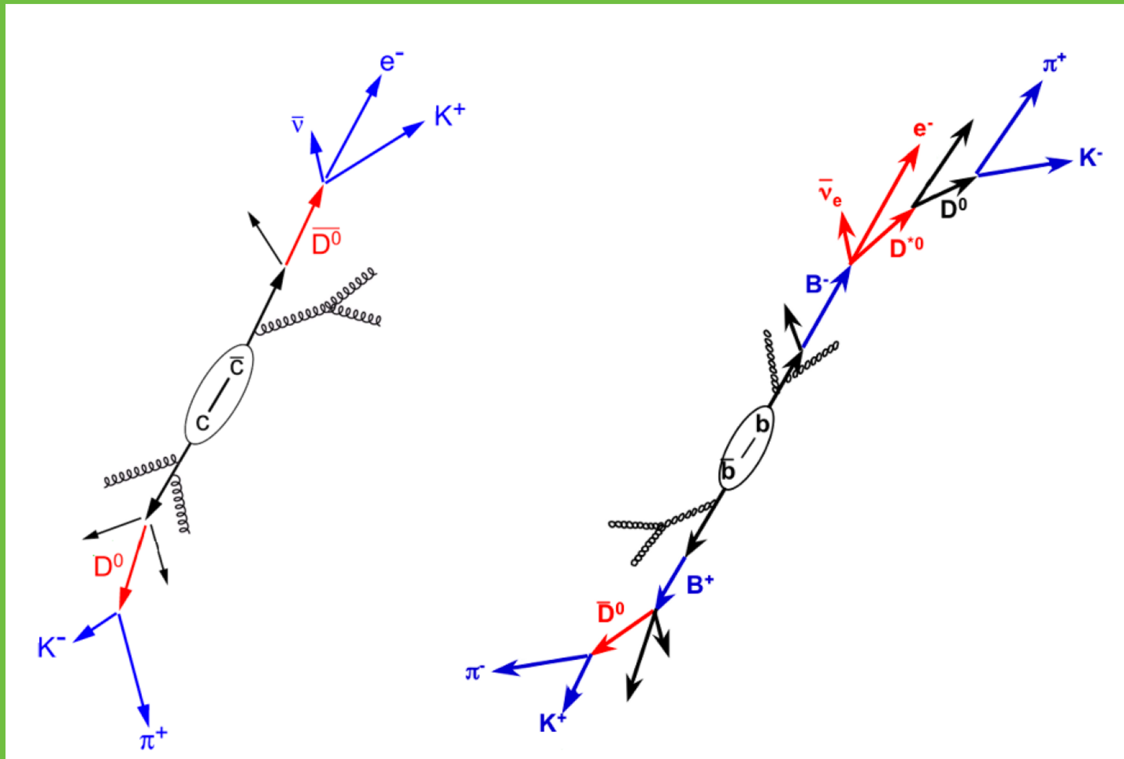
p+p 200 GeV



- Preliminary results agree within errors with previous published STAR results in the region pT <8.5 GeV
- STAR results agree with FONLL
- New results improve systematic error

Non photonic electron - D0
Azimuthal angular correlations
p+p 200 GeV

D-NPE correlations



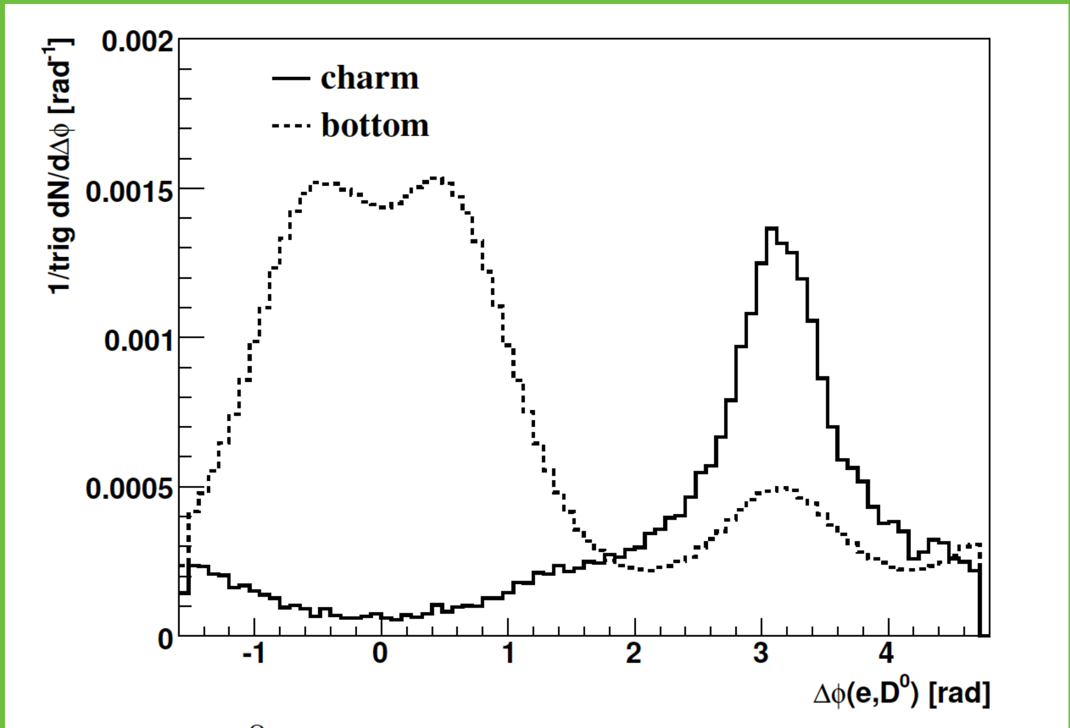
Example:

For ccbar initial state -> D0 and electron Deltaphi=pi, charge of K=charge of electron

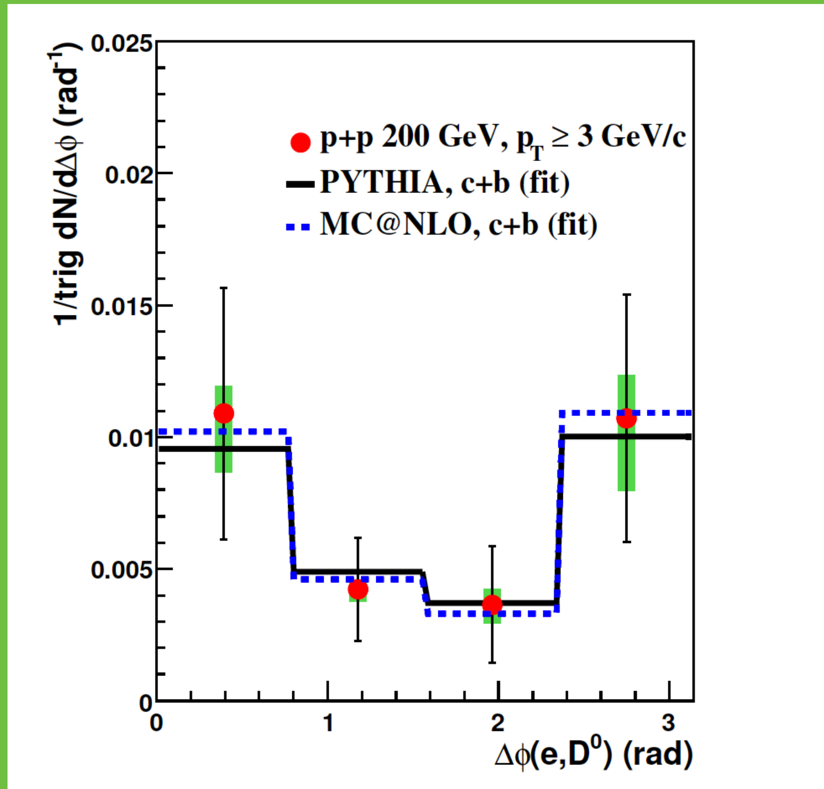
For bbbar initial production -> D0 and electron Deltaphi=0, charge K opposite of charge of electron

D-NPE correlations

PYTHIA

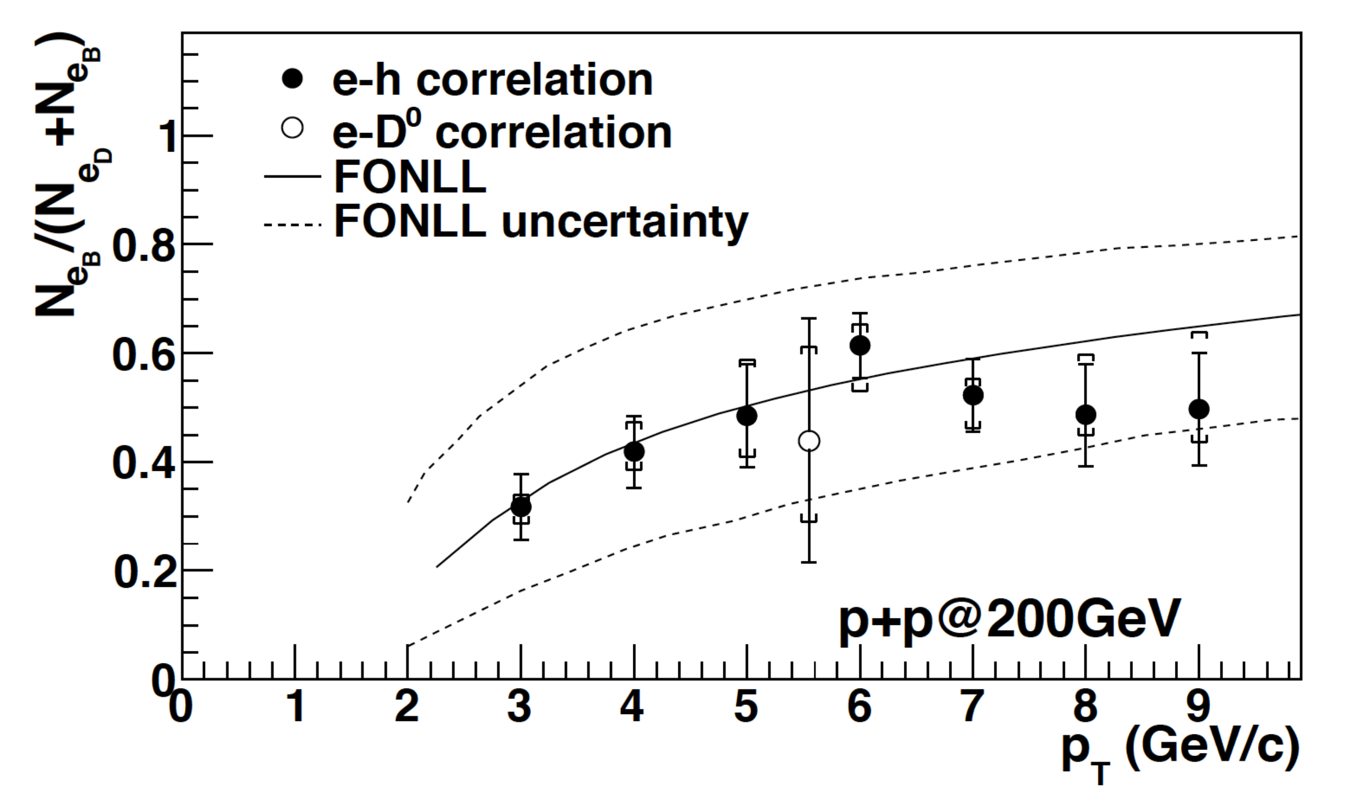


Data p+p 200 GeV



STAR coll., PRL105,202301 (2010),arXiv:1007.12

B/NPE vs pT in p+p collisions at 200 GeV

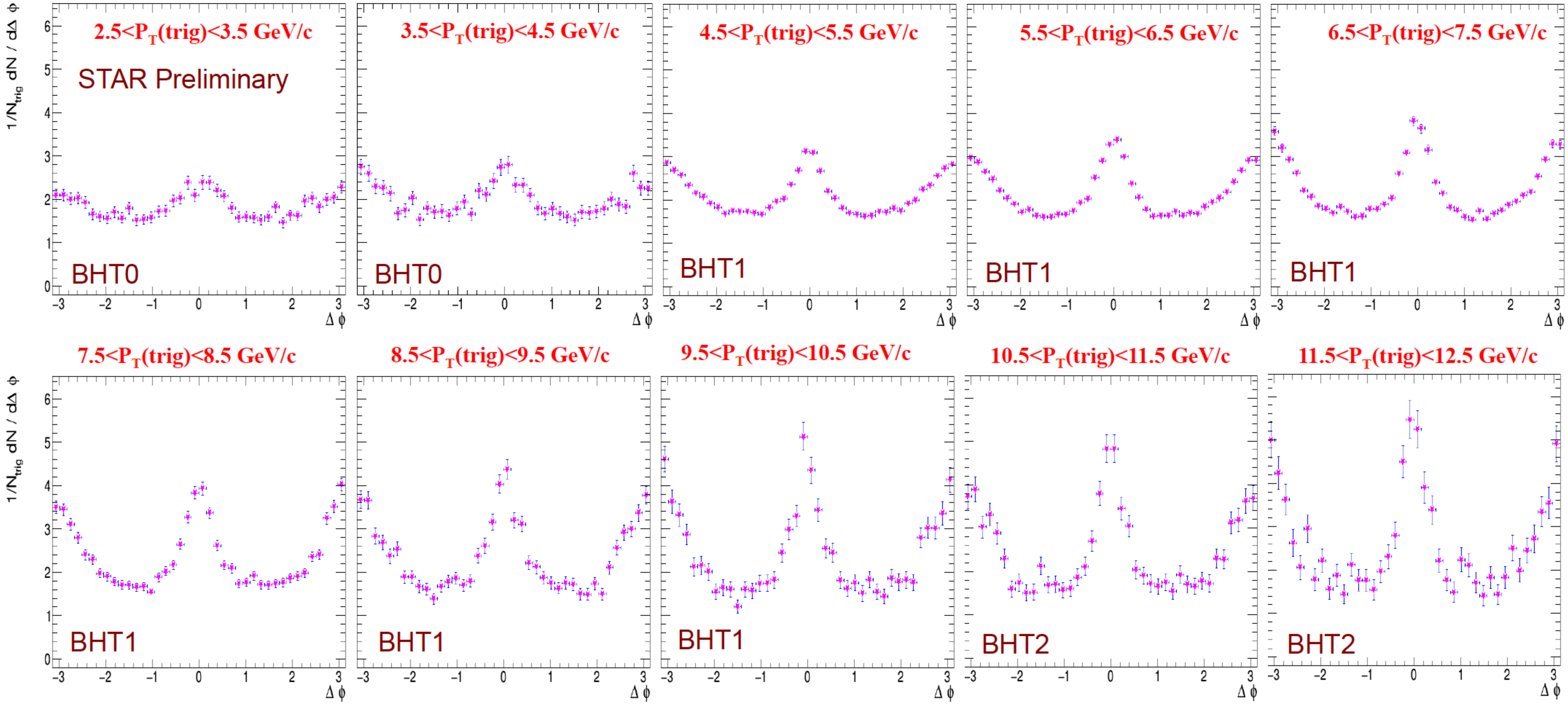


D-NPE correlations agree with NPE-hadron correlations and FONLL

STAR coll., PRL105,202301 (2010),arXiv:1007.12

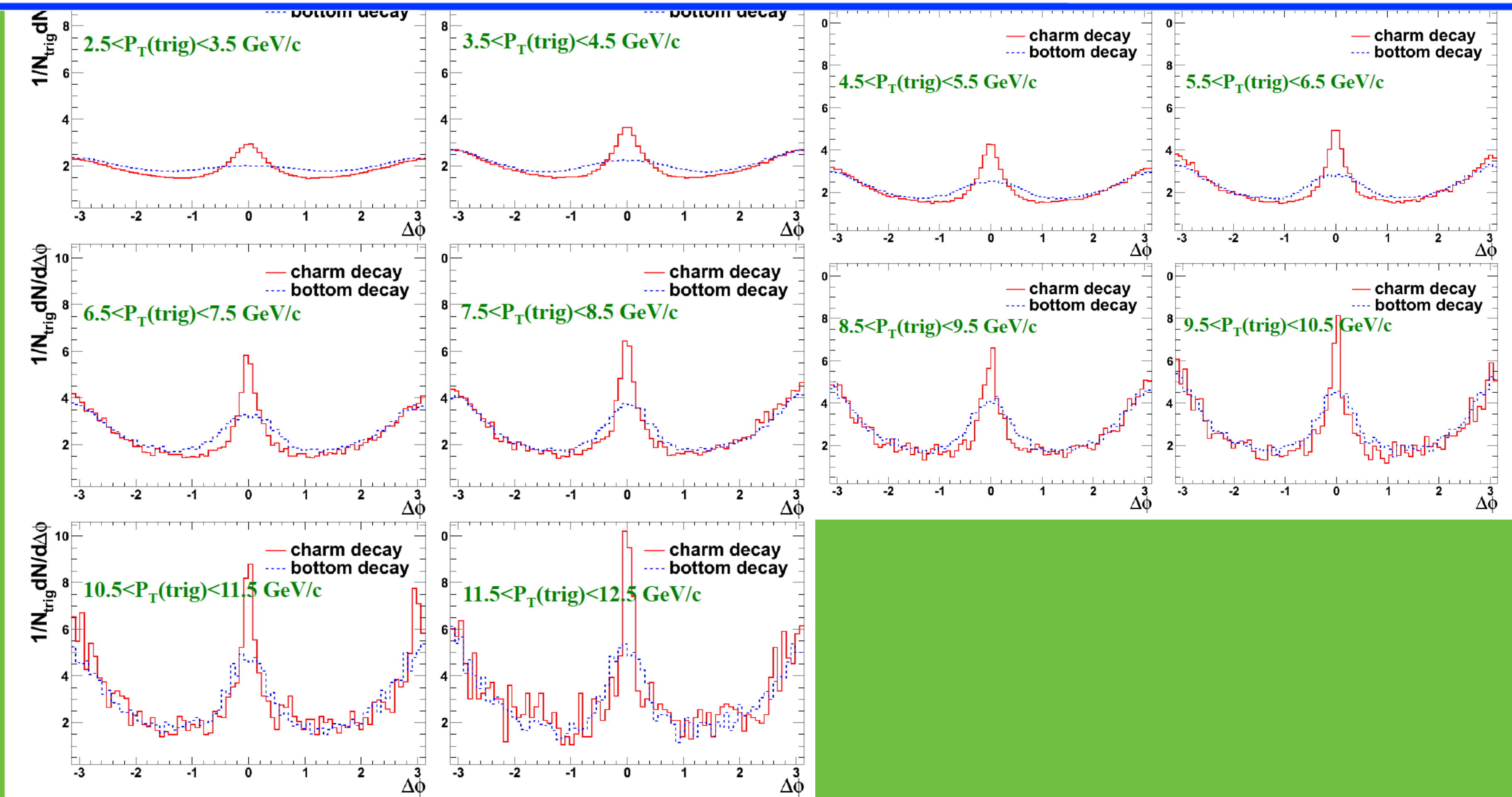
Non photonic electron - hadron
Azimuthal angular correlations
p+p 500 GeV

NPE-h correlation in 500 GeV p+p Collisions



- Raw correlation w/o efficiency correction
- Associated hadron with $p_T > 0.3$ GeV/c
- Clear azimuthal correlation on the near-side, and the correlation signal increases as NPE p_T increases.

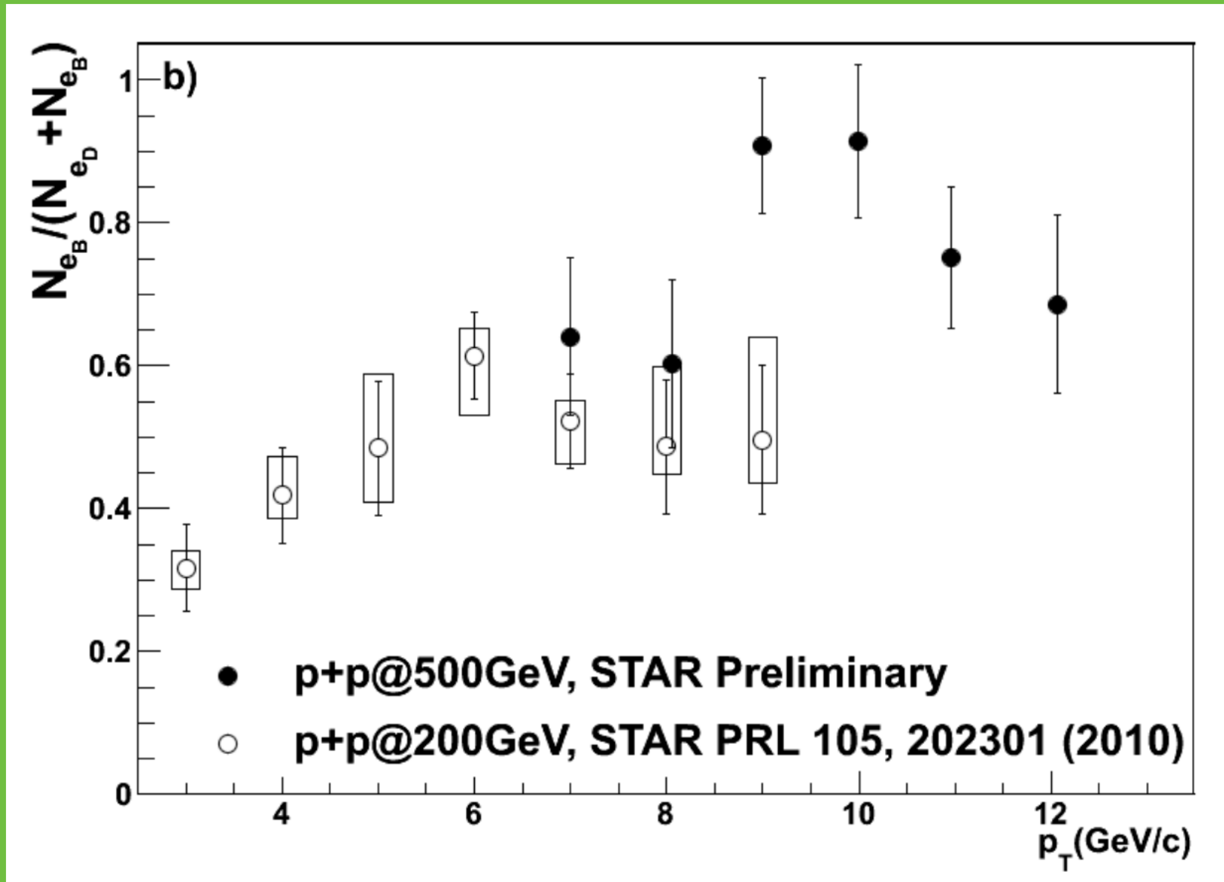
PYTHIA Simulation for 500 GeV p+p Collisions



- Significant difference between D and B decays on the near-side at low p_T
- Correlation signal increases as trigger p_T increases
- Difference between e(D)-h and e(B)-h correlation decreases as trigger p_T increases

B/NPE vs pT in p+p at 500 GeV

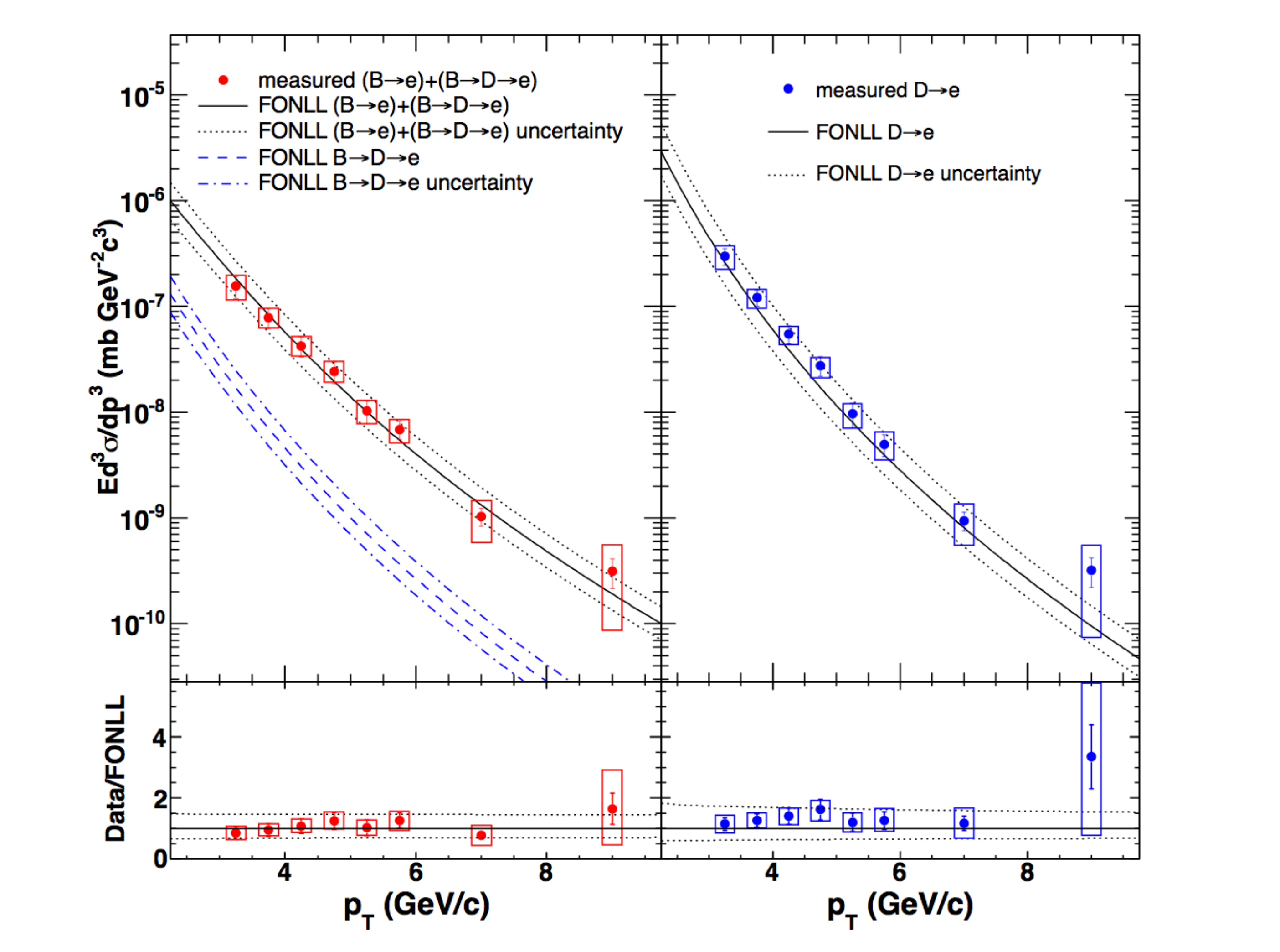
STAR preliminary



VI Heavy Flavor -> Non Photonic Electrons p+p 200 GeV

NPE at high pT in p+p collisions at 200 GeV

PRD 83, 052006 (2011), arXiv:1102.2611



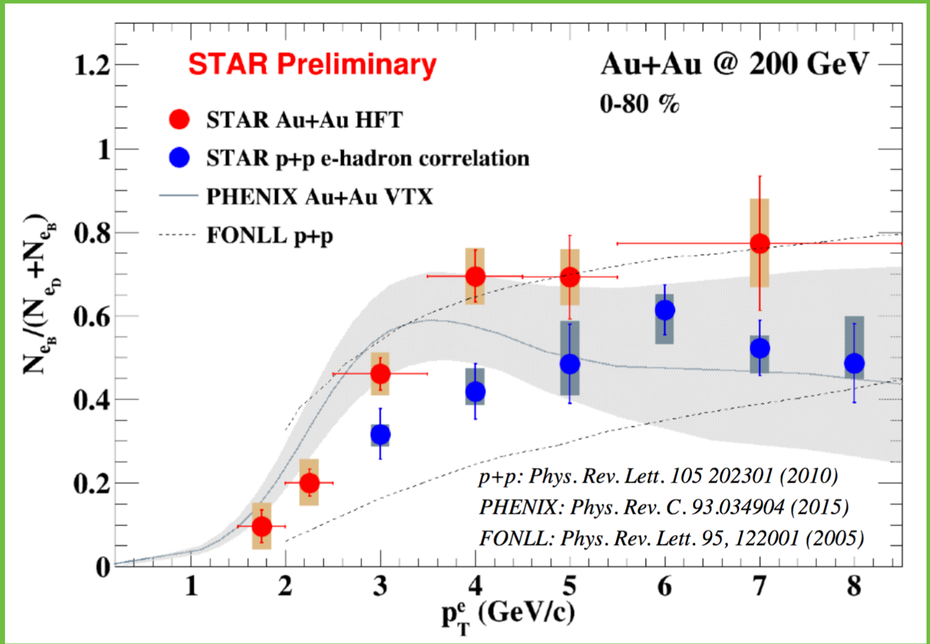
B->e and C->e contributions to Non Photonic Electrons vs pT in p+p collisions at 200 GeV and comparison to model

Heavy Flavor -> Non Photonic Electrons (NPE)

With HFT (Au+Au) and use of electron DCA compared to p+p 200 GeV

B/NPE vs pT in p+p and Au+Au 200 GeV and the B->e and D->e RAA vs pT in Au+Au

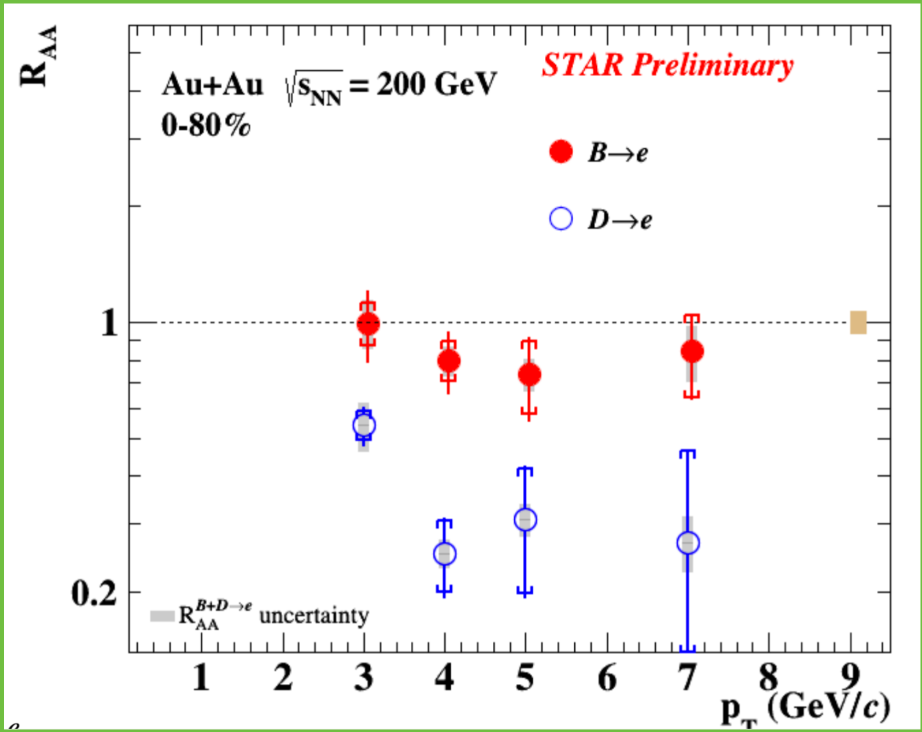
STAR HFT result



Blue points: p+p collisions 200 GeV B/(B+C) from e-hadron correlations

Red points: Au+Au 0-80% centrality with HFT B/(B+C) from fit to extract B and C contributions to the electrons using the electron DCA information

B/NPE vs pT in p+p and Au+Au 200 GeV and the B->e and D->e RAA vs pT in Au+Au



$$R_{AA}^{B\to e} = \frac{f_{Au+Au}^{B\to e}}{f_{p+p}^{B\to e}} R_{AA}^{inc.e}, \quad R_{AA}^{D\to e} = \frac{1-f_{Au+Au}^{B\to e}}{1-f_{p+p}^{B\to e}} R_{AA}^{inc.e}$$

B/NPE vs pT in Au+Au 0-80% with HFT

$R_{AA}(e_D) < R_{AA}(e_B)$ (~2σ at 3-8 GeV/c)

-In agreement with mass hierarchy of parton energy loss

VII Conclusions and outlook

Conclusions

STAR has a wealth of new results using the latest detector upgrades and dedicated RHIC runs with high statistics

D0, D* pT spectra in pp 200 GeV collisions agree with FONLL
Preliminary D0, D* pT spectra in p+p 500 GeV collisions extend acceptance to 20 GeV and agree with FONLL

B/NPE vs pT measured in p+p 200 GeV and 500 GeV via corellations

D0 cross section per NN binary collision in Au+Au is lower than p+p collisions 200 GeV, while it remains constant vs centrality

Conclusions

Total charm cross section in p+p 200 GeV agrees with Au+Au 200 GeV

RAA(B->e) > RAA(C->e) for Au+Au collisions 200 GeV using information of DCA of electron (Via HFT) suggest mass hierarchy of Heavy Flavor suppression at high pT

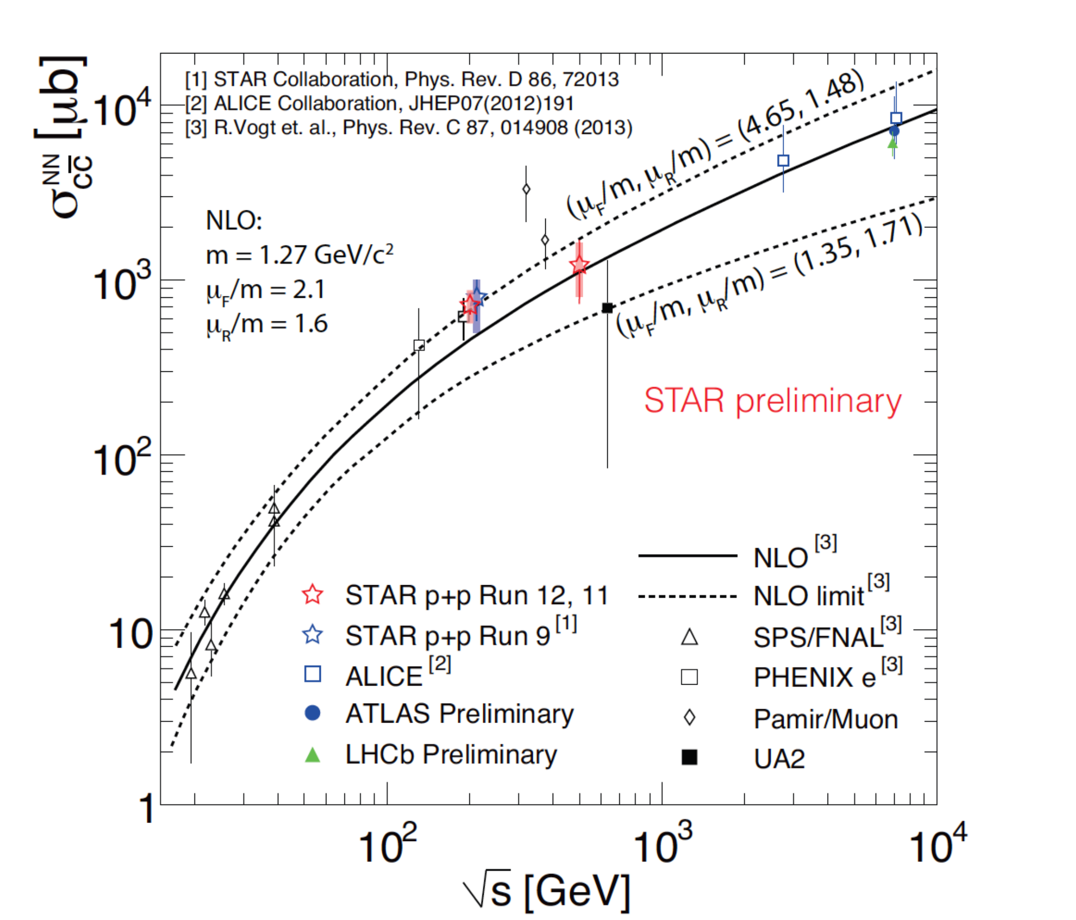
New results on Heavy flavor will be coming soon out of the large data sets with and without HFT.

Thank you very much

Nothing is Higher than Knowledge

BAACKUP SLIDES

Total charm cross section vs collision energy

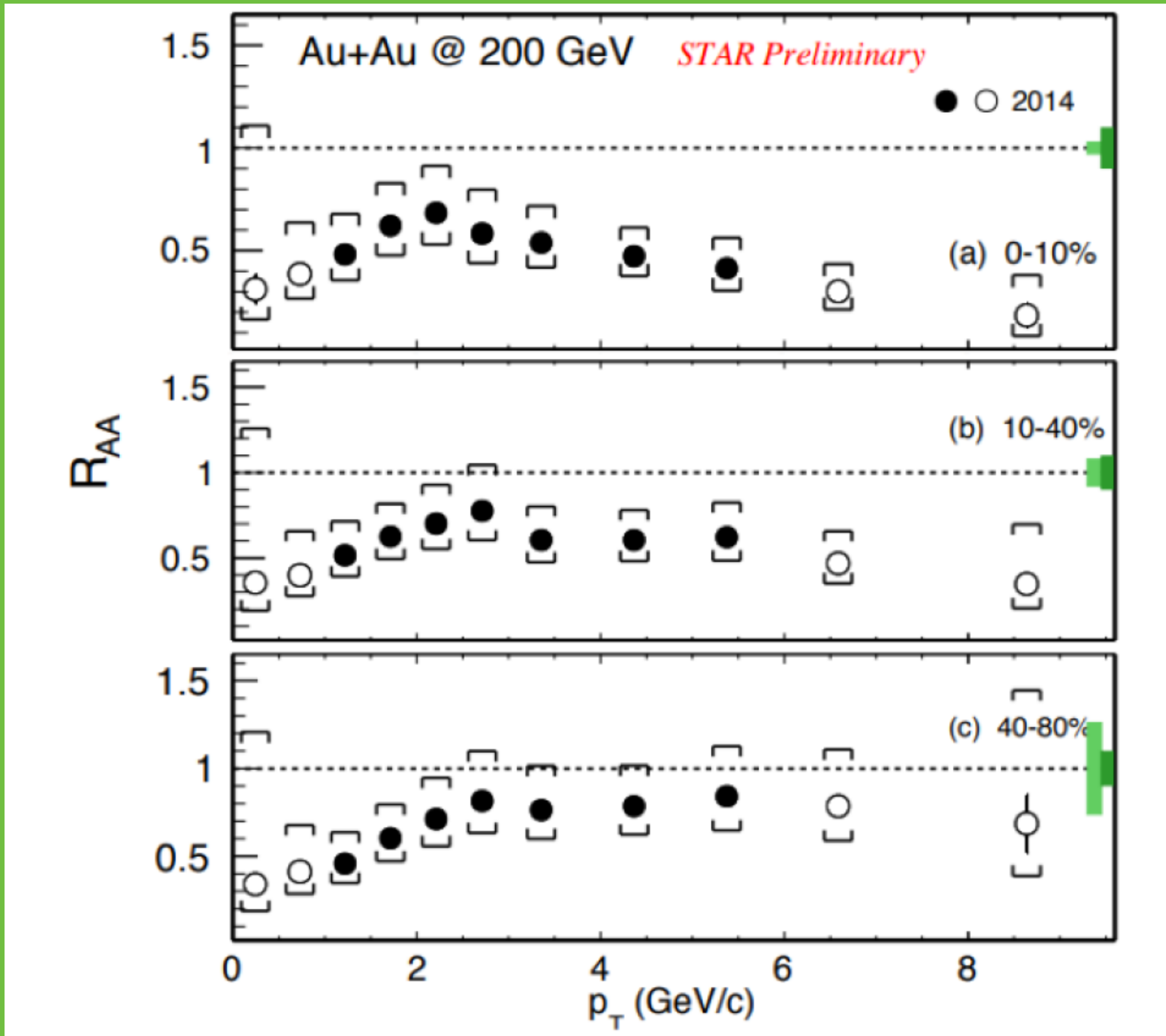


Preliminary

Full acceptance production cross section for charm Infered from D0 and D*

Total ccbar cross section of STAR in p+p 200 and p+p 500 GeV agrees with NLO (line)

D^0 R_{AA} suppression in Au+Au collisions at 200 GeV

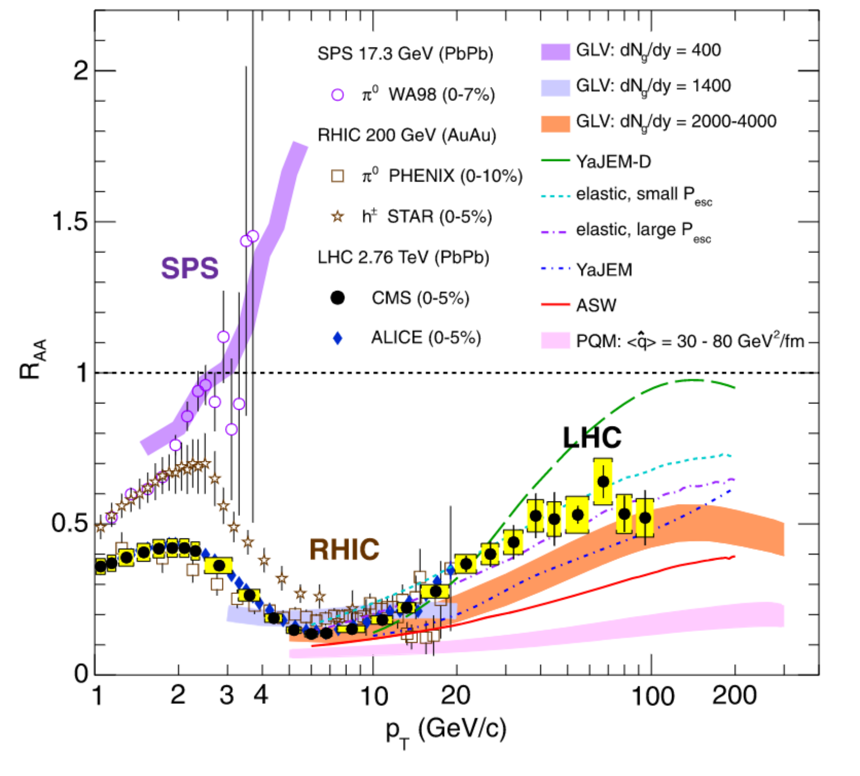


D^0 at low p_T is suppressed without exhibiting significant centrality deendence

D^0 at high p_T in Au+Au collisions is more suppressed in central collisions

Using the STAR HFT silicon detector

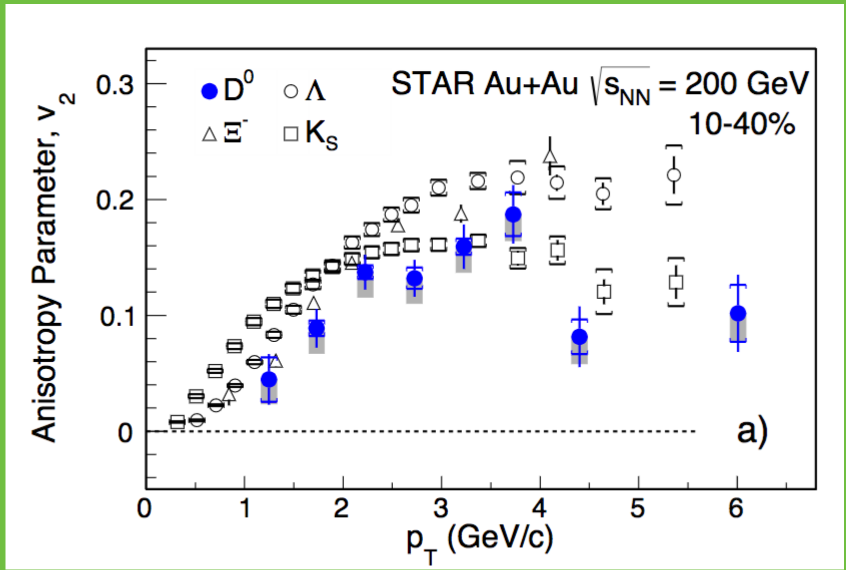
P_T dependence of R_{AA} of hadrons in A+A collisions at different collision energies

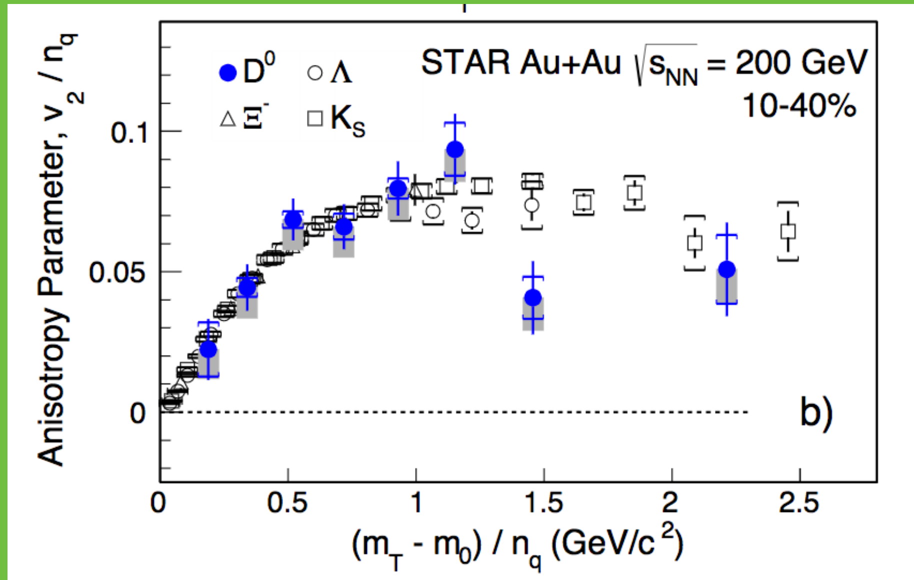


CMS, EPJC (2012) 72:1945

R_{AA} compared to models for energy loss allowing an estimate of gluon density dN/ dy(gluon)

D^0 elliptic flow vs p_T in Au+Au collisions at 200 GeV





Phys. Rev. Lett. 118 (2017) 212301
https://arxiv.org/pdf/1701.06060.pdf

D^0 v_2/n(q) in Au+Au collisions at 200 GeV and with 10-40% centrality is consistent with that of other hadrons,suggesting that charm quarks exhibit the same strong collective behaviour as light quarks and may be close to thermal equilibrium

Table 8: Event statistics (in millions) needed in BES-II for various observables. This table updat
estimates originally documented in Ref. [45].

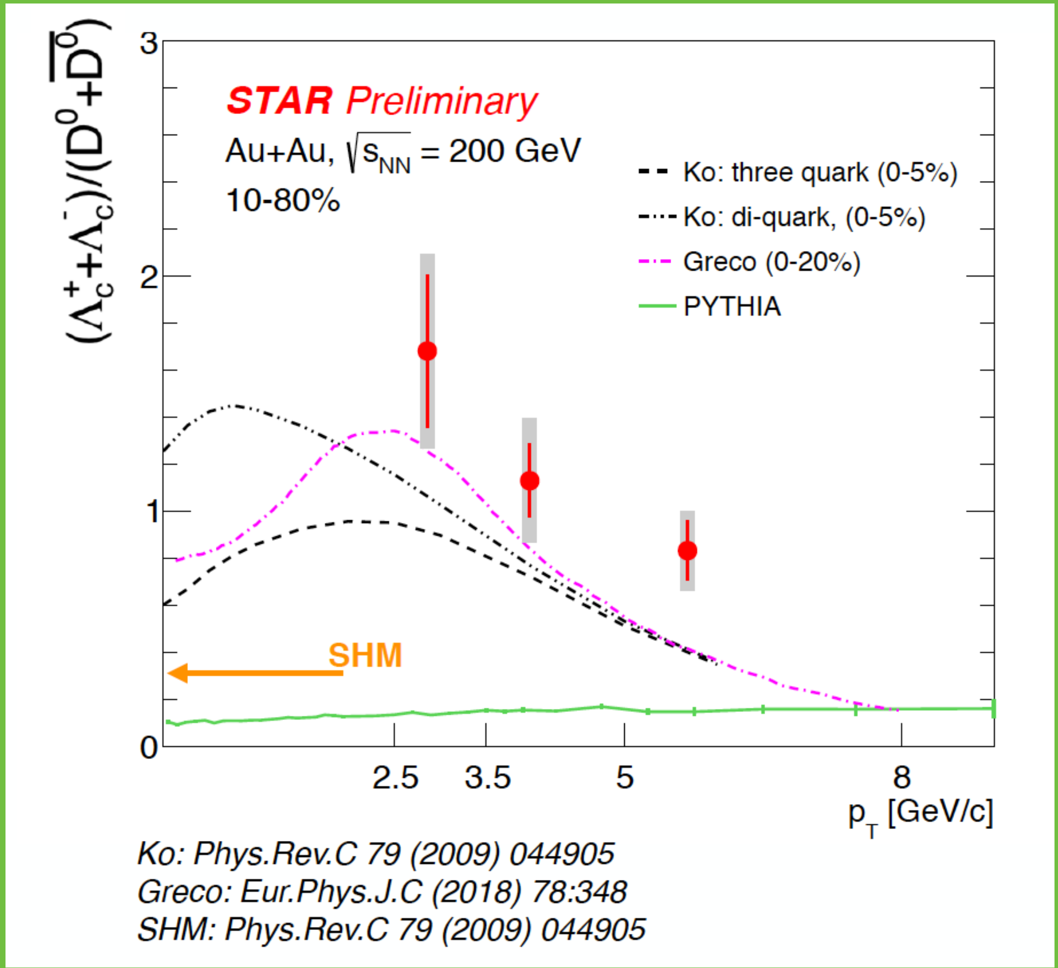
Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to $p_T = 5$ GeV/c	-		160	125	92
Elliptic Flow (ϕ mesons)	80	120	160	160	320
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	20	30	35	45	50
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	70	85	100	170	340
Dileptons	100	160	230	300	400
$>5\sigma$ Magnetic Field Significance	50	80	110	150	200
Required Number of Events	100	160	230	300	400

+100M for each FXT energy

Typically factor 20 more than for BES-I

STAR BES-II goals

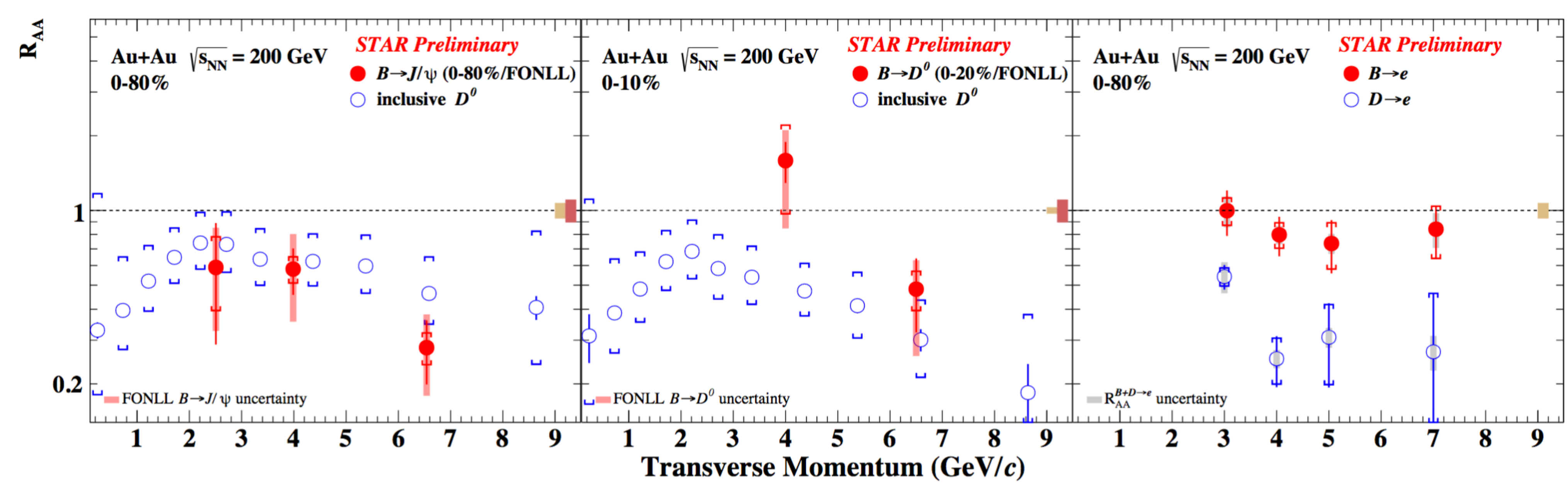
Lambda_c/D in Au+Au 200 GeV



- Strong enhancement of Λ_c production compared to PYTHIA calculations
- Suggest coalescence hadronization of charm quarks in QGP at intermediate p_T (2-6 GeV/c)

Beauty suppression in Au+Au 200 GeV using displaced vertex inormation (via HFT)

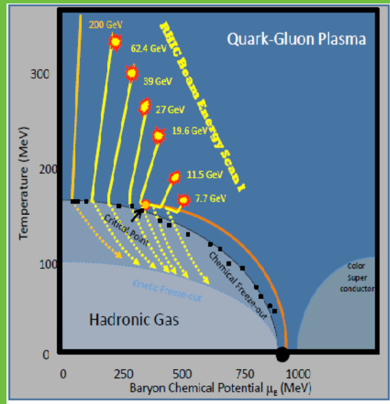
B->J/psi Au+Au 0-80% +HFT | **B->D0 Au+Au 0-10% +HFT** | **B->e and D->e Au+Au 0-80% +HFT**

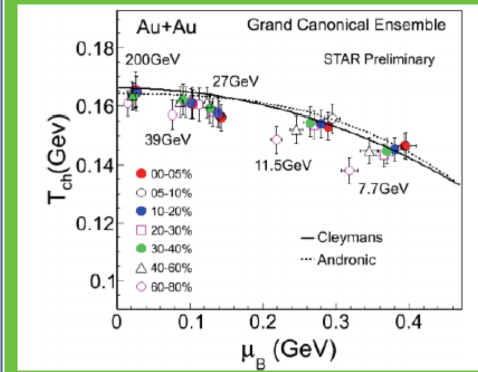


Preliminary data on RAA of B in Au+Au at 200GeV using displaced vertex information with the HFT show:

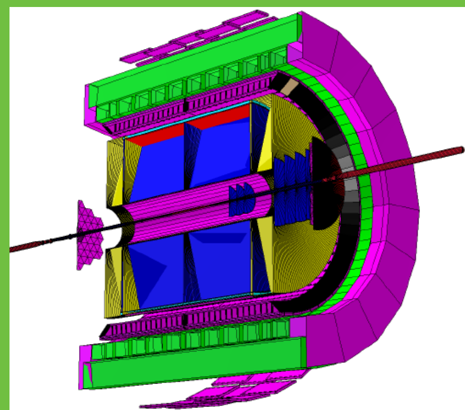
- **B->J/Psi Au+Au 0-80%: B is strongly suppressed**
- **B->D0 Au+Au 0-10%: B is strongly suppressed**
- **B->e and D->e Au+Au 0-80%: B less suppessed than C**

STAR future plans





Beam Energy Scan (BES) II 2019-2020
Will continue the BES I program
"Hot" QCD, search for a possible critical point and discontinuities in the energy dependence of QGP signatures
-> FAIR and NICA



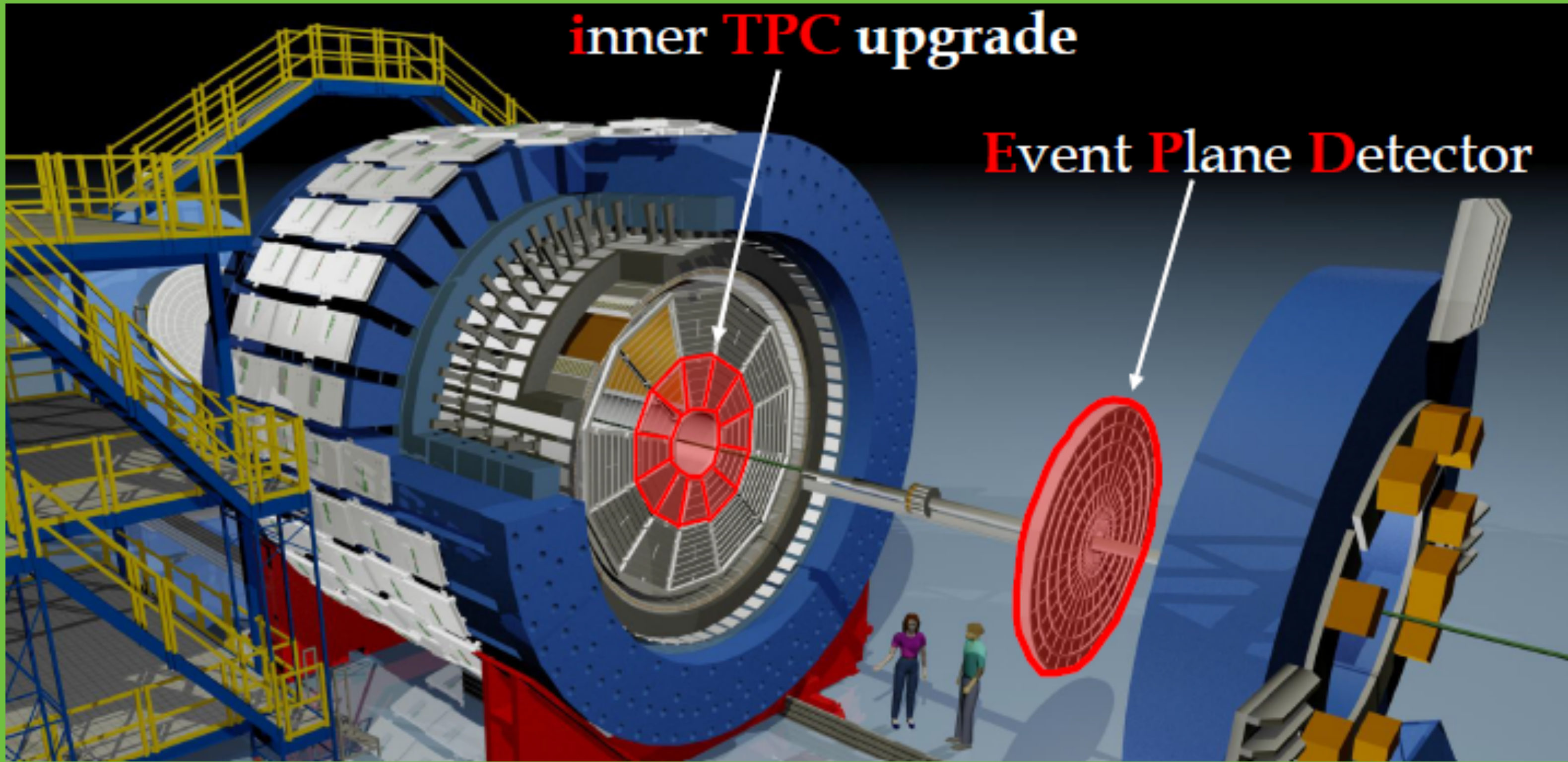
STAR forward rapidity program (2.5-eta-4): Hcal, Ecal, tracking (Silicon and sTGCs)
"Cold" QCD, Proton TMDs, gluon saturation
Test Electron Ion Colider (EIC) detector technologies
Milestone: 2021 p+p run and sPHENIX data taking 2022+
-> EIC

BES-II

STAR goals

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events
9.8	19.6	205	4.5 weeks	400M
7.3	14.5	260	5.5 weeks	300M
5.75	11.5	315	5 weeks	230M
4.55	9.1	370	9.5 weeks	160M
3.85	7.7	420	12 weeks	100M
31.2	7.7 (FXT)	420	2 days	100M
19.5	6.2 (FXT)	487	2 days	100M
13.5	5.2 (FXT)	541	2 days	100M
9.8	4.5 (FXT)	589	2 days	100M
7.3	3.9 (FXT)	633	2 days	100M
5.75	3.5 (FXT)	666	2 days	100M
4.55	3.2 (FXT)	699	2 days	100M
3.85	3.0 (FXT)	721	2 days	100M

STAR upgrades

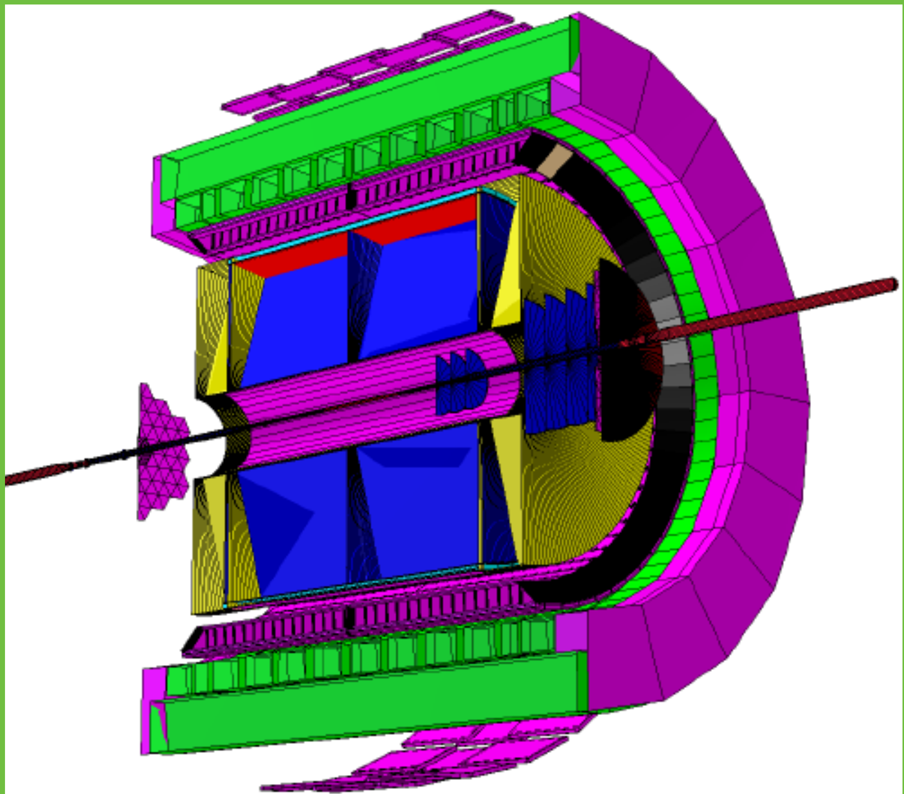


iTPC: inner sector of TPC. Extends peudorapidity acceptance from 1 to 1.5. Improves dE/dx

Endcap TOF: particle identification 0.9-eta-1.5

Event Plane Detector: will provide better and independent determination of centrality and event plane

STAR forward rapidity program



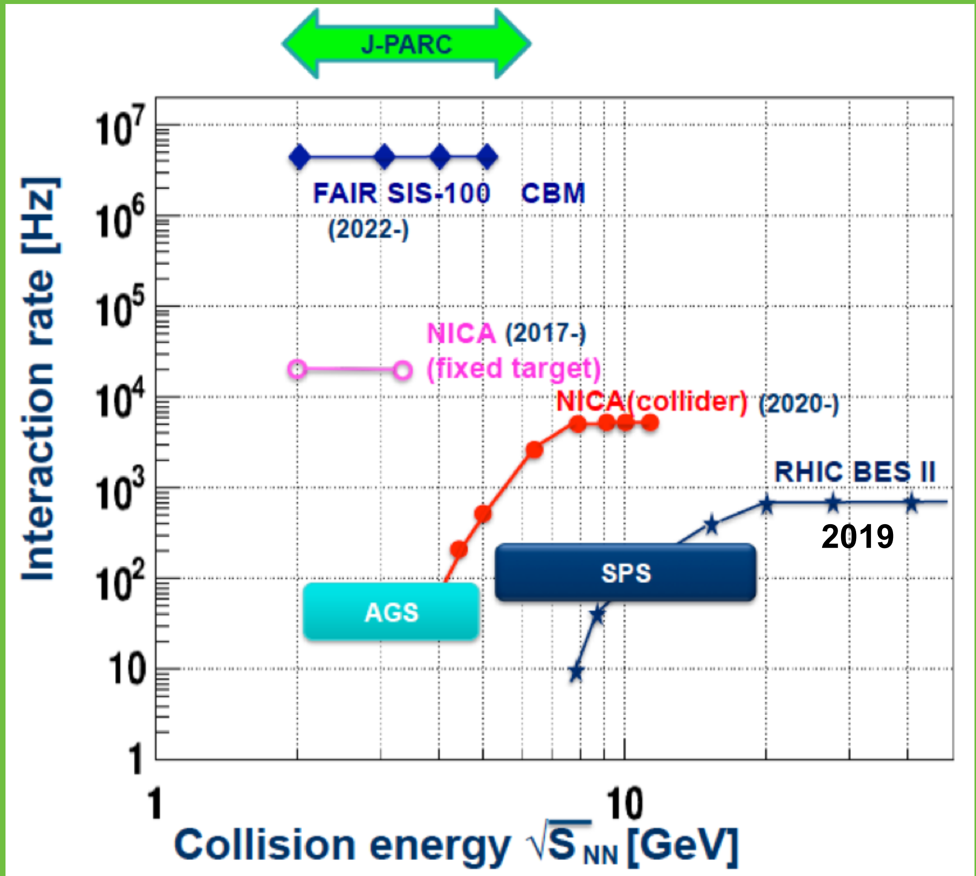
3 Silicon discs

4 Small-strip Thin Gap Chambers

ECal: use upgraded PHENIX PbSc calorimeter

HCal: Iron-scintillator

Energy scans with Heavy Ions
Future: BESII, NICA, FAIR, J-PARC



T. Sakaguchi, QM2017

Center of mass energy (sqrt(s)NN) of facilities for future heavy ion runs:
FAIR: 2-6 (10) GeV, NICA: 4-11 GeV, RHIC: 7 (2.5) - 200 GeV LHC: 2.76, 5 TeV, J-PARC: 1-10 GeV
FCC (100 km circular ring, p+p at sqrt(s)=100 TeV, Pb+Pb at sqrt(s)=39 TeV)