$D^{\pm}$ Meson Production in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV at STAR

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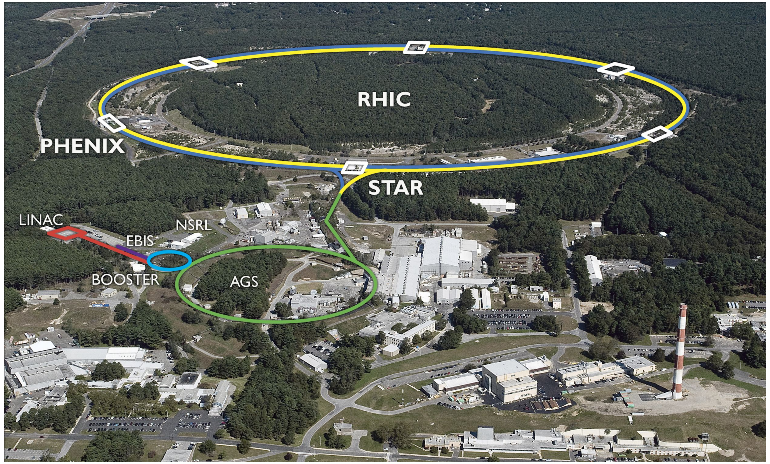
Outline

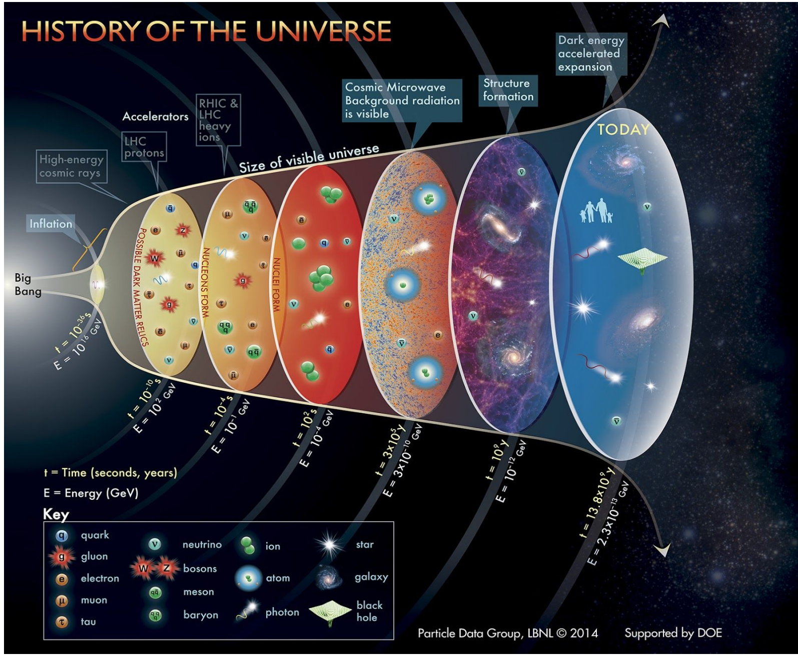
1. Physics Motivation
2. Heavy-ion Collisions and QGP
3. STAR Experiment
4. $D^{\pm}$ Analysis in Au+Au Collisions
5. Improvement Using TMVA
6. Summary and Outlook

1 - Physics Motivation

Physics Motivation

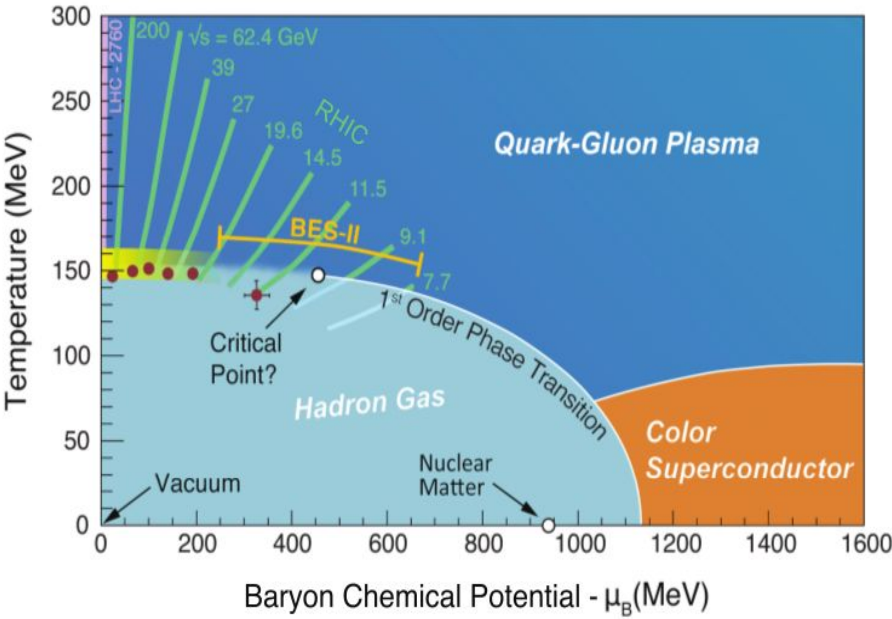
- We want to study early Universe
- QGP present at $\tau \sim 10^{-6}$ s
- Created today in A+A collisions





QCD Phase Diagram

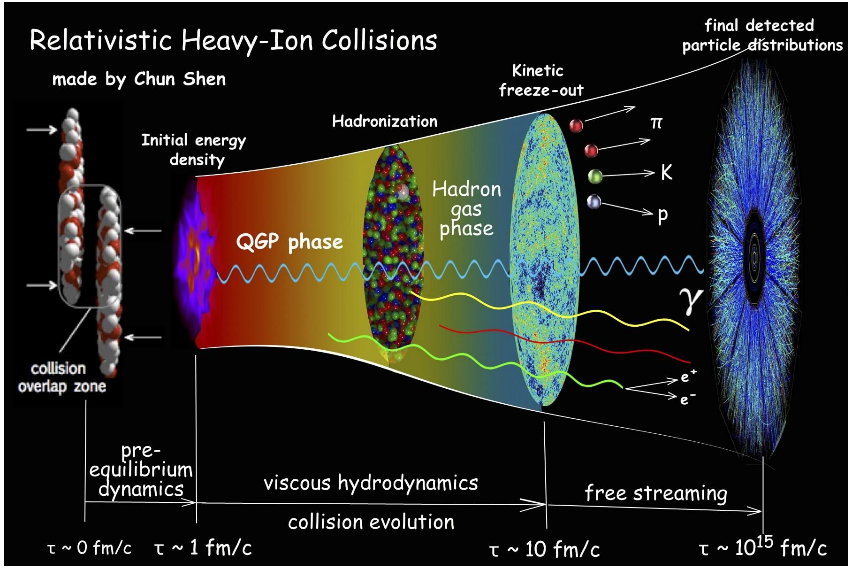
- Matter can exist in multiple phases
- QGP at high temperatures
- Phase transition at T~170 MeV
- Smooth crossover observed
- Critical point? - BES II

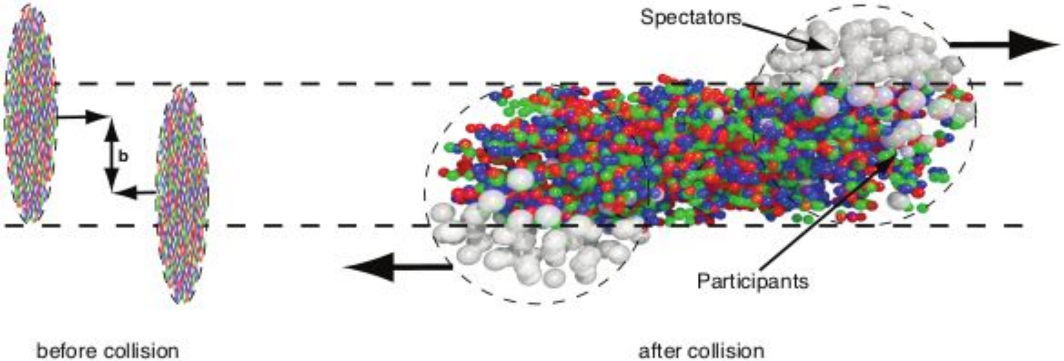


2 - Heavy-ion Collisions and QGP

Physics of Heavy-Ion Collisions

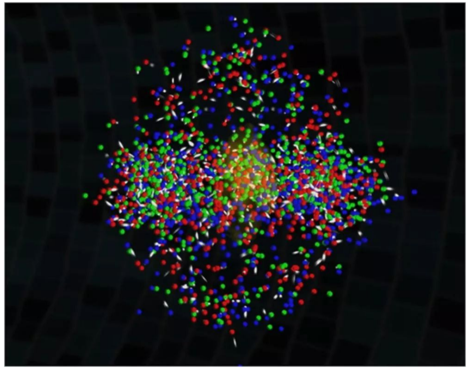
- Evolution governed by centrality
- Hard scattering between partons
- QGP hydrodynamic evolution
- Hadronization
- Chemical and kinetic freeze-out
- Final products (π, K, p, $l^{\pm}$, γ)





Quark-Gluon Plasma

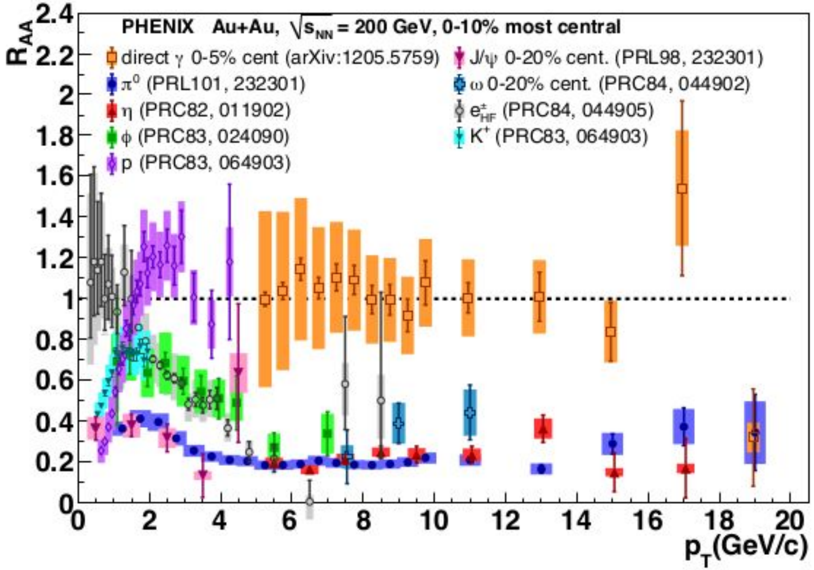
- Hottest, densest, least viscous, most vortical superfluid
- Partons are quasi-free
- Confirmed in 2004 at RHIC
- Impossible to observe directly
- We study interactions within the medium
- Probes: jets, collectivity, quarkonia, **energy loss**,...



Parton Energy Loss

- High-energy partons lose energy in QGP via elastic collisions and gluon radiation
- Yield at specific p_T modified
- Nuclear modification factor:

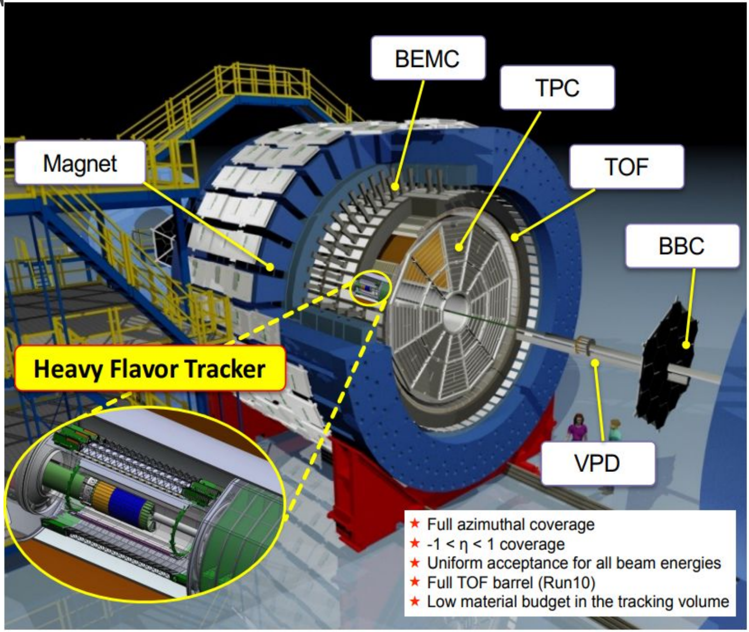
$$R_{AA} = \frac{\frac{d^2 N_{AA}}{dp_T dy}}{\langle N_{coll} \rangle \times \frac{d^2 N_{pp}}{dp_T dy}}$$



3 - STAR Experiment

STAR Experiment

- Located at Brookhaven National Lab, USA
- TPC - Time Projection Chamber
  - Tracking
  - Particle identification via energy loss (dE/dx)
- TOF - Time-of-Flight detector
  - Particle identification via flight time (1/β)
  - Extend identification at p > 1 GeV/c



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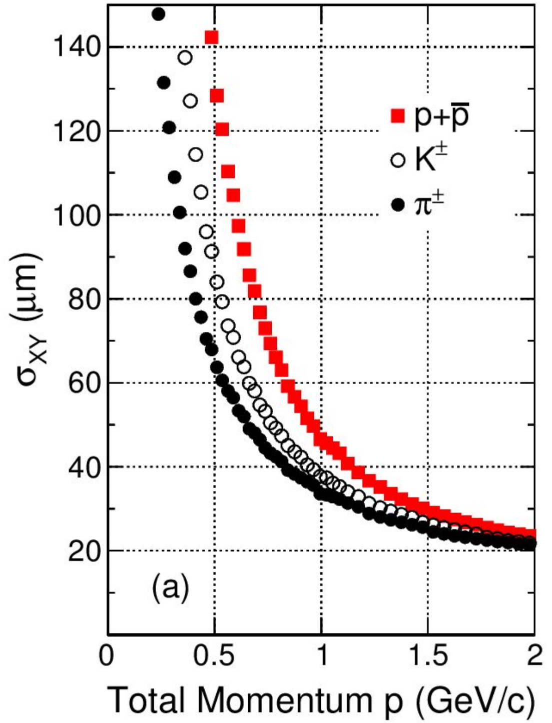
- HFT - Heavy Flavor Tracker
  - operating in 2014-2016
  - 2 layers of silicon pixel and 2 layers of strip detectors (one not used in 2014)
  - excellent spatial resolution (σ~ 46 μm for 750 MeV/c kaons)
  - topological reconstruction of open-charm hadrons eg. Λ_c, $D^{\pm}$, D^0, D_s



4 - $D^{\pm}$ Analysis in Au+Au Collisions

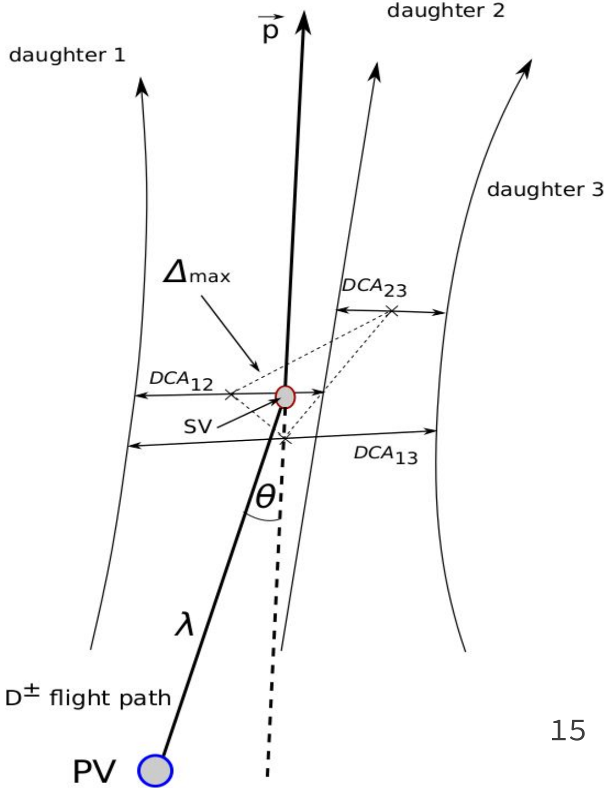
$D^{\pm}$ Meson

- $D^{\pm}$ production - one way to study c quark interaction in QGP
- c quarks created during hard scattering
- Significant energy loss observed in D^0 production

Quark content	$\mathrm{c\bar{d}}$, $\mathrm{\bar{c}d}$
$m_{\mathrm{D}^{\pm}}$ [MeV/c^2]	1869.5 ± 0.4
τ [ps]	1.040 ± 0.007
λ [μm]	312 ± 2
Decay channel	$\mathrm{D}^{\pm} \rightarrow \mathrm{K}^{\mp}\pi^{\pm}\pi^{\pm}$
BR [%]	8.98 ± 0.28

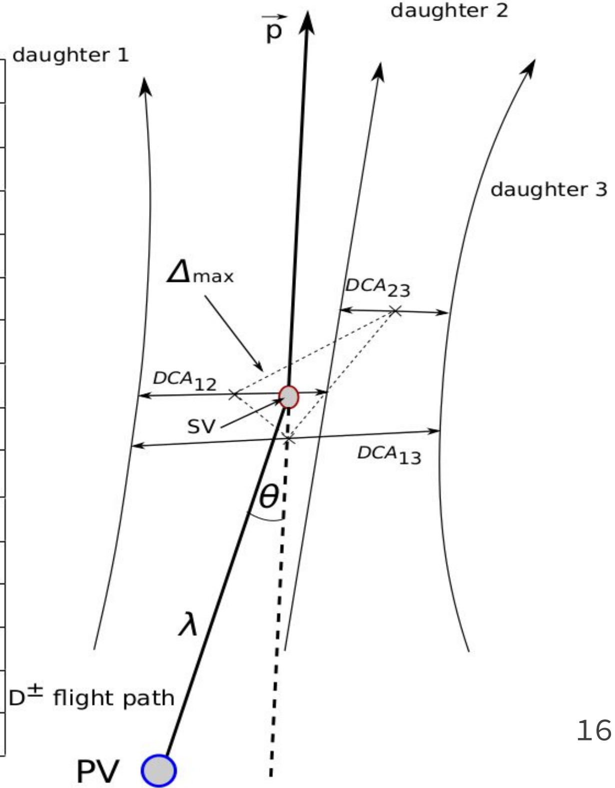
Analysis Method

- 860 M minimum-bias Au+Au $\sqrt{s_{NN}}$ = 200 GeV
- $D^{\pm}$ -> $K^{\mp}$ $\pi^{\pm}$ $\pi^{\pm}$, BR: (8.98±0.28) %
- Other Kππ combinations - background
- PID using TPC, TOF when available
- Topological variables:
  - DCA of K and π to the primary vertex
  - $D^{\pm}$ decay length λ
  - Pointing angle cosθ
  - Maximum distance of pair vertices (Δ_{max})
  - DCA of Kπ and ππ pairs (DCA_{12} , DCA_{23} , DCA_{13})



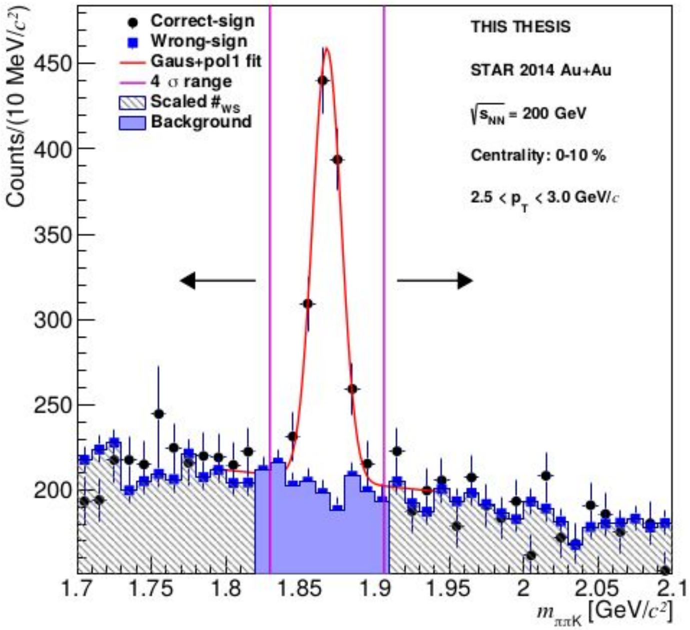
Selection Criteria

Type	Cut	Value(s)
Event Selection	Primary vertex (PV) position	$\lvert V_{\mathrm{z}} \rvert < 6$ cm
	PV positions from TPC and VPD	$\lvert V_{\mathrm{z}} - V_{\mathrm{z}}^{\mathrm{VPD}} \rvert < 3$ cm
Track Selection	TPC Hits	$N_{\mathrm{TPC}} > 20$
	HFT Hits	2 PXL and IST
	Pseudorapidity	$\lvert \eta \rvert < 1$
	Daughter transverse momentum	$p_{\mathrm{T}} > 0.5$ GeV/c
Particle Identification	TPC energy loss - pions	$\lvert n_{\sigma}^{\pi} \rvert < 3$
	TPC energy loss - kaons	$\lvert n_{\sigma}^{\mathrm{K}} \rvert < 2$
	Particle flight time	$\lvert \frac{1}{\beta} - \frac{1}{\beta_{\mathrm{th}}} \rvert < 0.03$
Topological Cuts	Daughter pairs DCA	$DCA_{\mathrm{pair}} < 80$ μm
	Decay length	$30 < \lambda < 2000$ μm
	Maximum distance of pair vertices	$\Delta_{\max} < 200$ μm
	Pointing angle	$\cos\theta > 0.998$
	Pion DCA to PV	$DCA_{\pi} > 100$ μm
	Kaon DCA to PV	$DCA_{\mathrm{K}} > 80$ μm



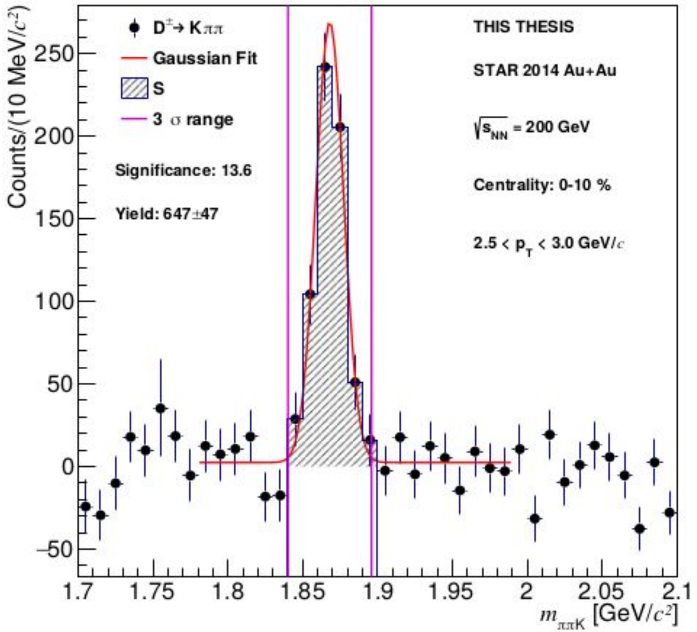
Raw Yield Extraction

- Estimate background from wrong-signs
- Scale background by (# of correct-signs)/(# of wrong-signs) outside 4 σ of signal peak
- Subtract background



Raw Yield Extraction

- Estimate background from wrong-signs
- Scale background by (# of correct-signs)/(# of wrong-signs) outside 4 σ of signal peak
- Subtract background
- Obtain raw yield using bin counting method inside 3 σ
- Calculate $D^{\pm}$ signal significance
- Significance varies between 3.2 and 13.7 in 0-10 % centrality bin
- Also studied 10-40, 40-80, 0-80 % in the $1 < p_T < 8$ GeV/c range



Yield Correction

- Raw Yield -> Invariant Yield

$$\frac{1}{2\pi p_{\mathrm{T}}}\frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} = \frac{1}{2\pi p_{\mathrm{T}}}\frac{Y_{\mathrm{raw}}}{N_{\mathrm{ch}} \cdot N_{\mathrm{evt}} \cdot BR \cdot \Delta p_{\mathrm{T}} \cdot \Delta y \cdot Eff(p_{\mathrm{T}})}$$

Subject to correction ($2\pi p_{\mathrm{T}}$)

N_{ch}: 2 (D^+,D^-)

BR: 8.98±0.28

Δy: 2

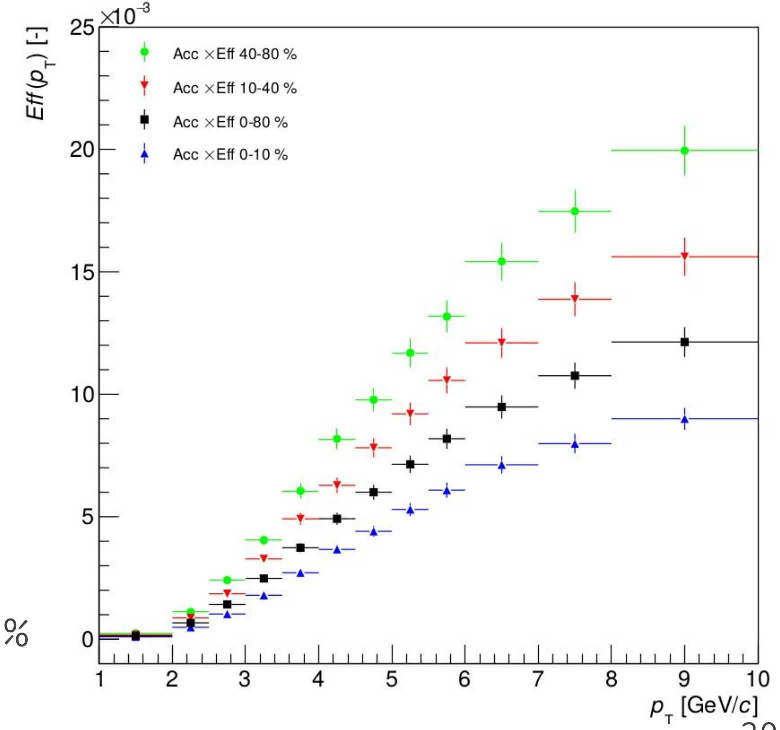
$Eff(p_{\mathrm{T}})$: Detector AcceptanceXEfficiency

N_{evt}:

Centrality [%]	N_{evt} [-]
0 – 10	102 916 176
10 – 40	320 439 616
40 – 80	435 890 688
0 – 80	859 246 464

Detector AcceptanceXEfficiency

- Data-driven Fast Simulator
  - Obtain the V_Z distribution (data)
  - Generate $D^{\pm}$ mesons flat in p_T and y
  - Decay to $K^{\mp}\pi^{\pm}\pi^{\pm}$ using EvtGen
  - Smear momentum (K and π embedding)
  - Smear DCA for daughters (data)
  - Apply HFT matching efficiency (data)
  - Apply TPC reconstruction efficiency (embedding)
  - Reconstruct $D^{\pm}$ with analysis cuts
- Validated by HIJING+GEANT4 within 5 %

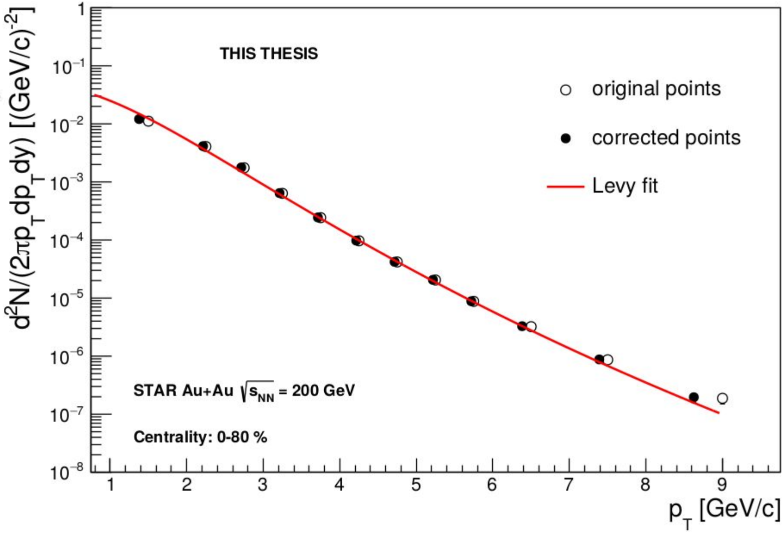


p_T Point Correction

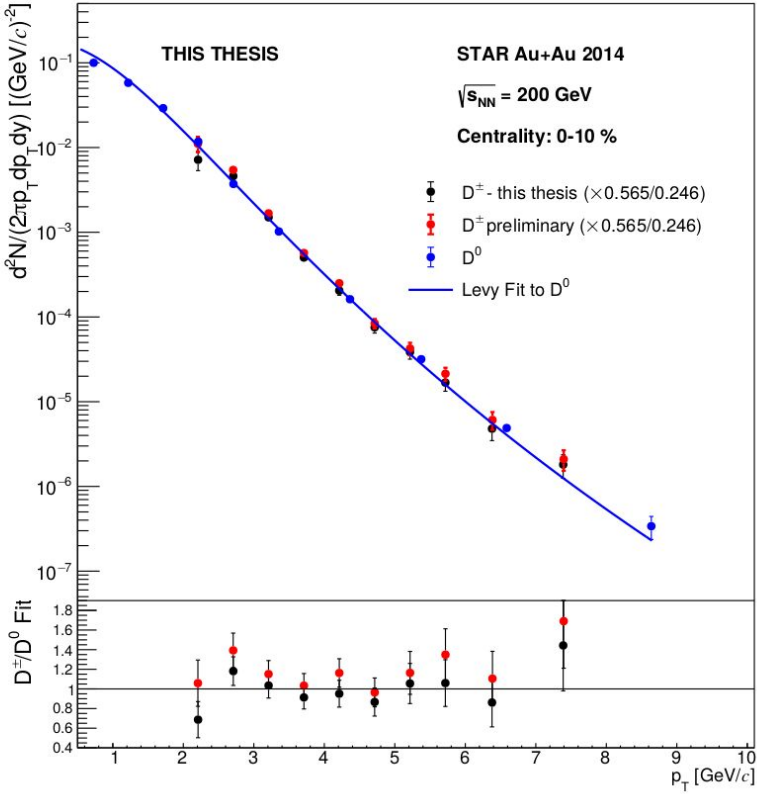
- p_T points not in correct place
- Levy fit to the spectrum

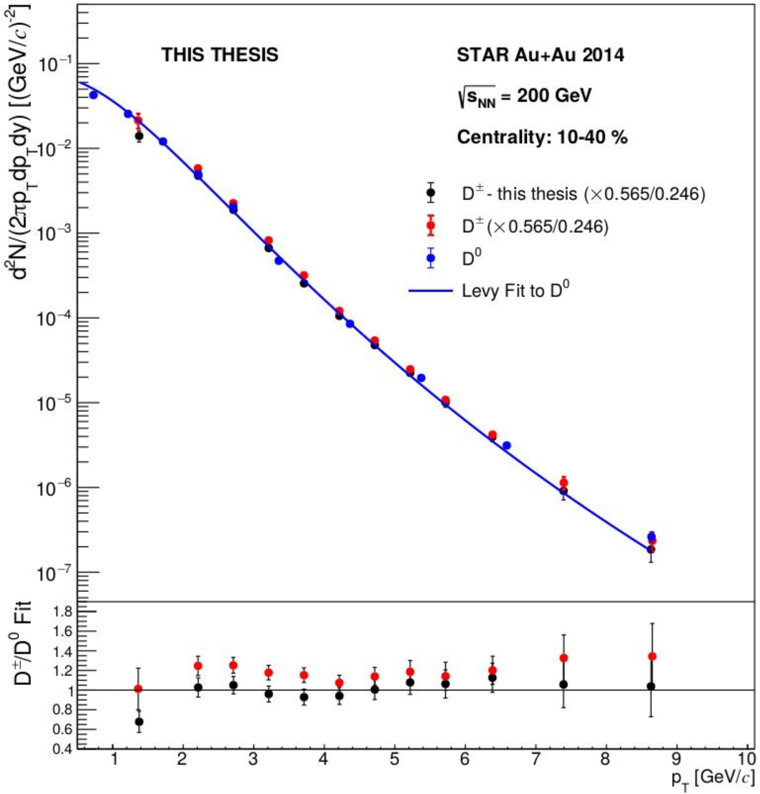
$$f(p_{\mathrm{T}}) = \frac{1}{2\pi}\frac{\mathrm{d}N}{\mathrm{d}y} \cdot \frac{(n-1)(n-2)}{(nT+m)(m(n-1)+nT)} \cdot \left(\frac{nT+\sqrt{p_T^2+m^2}}{nT+m}\right)^{-n}$$

- Iterative process to find mean value inside bins
- Larger effect for wider bins



D± Spectra


THIS THESIS
STAR Au+Au 2014
$\sqrt{s_{NN}}$ = 200 GeV
Centrality: 0-10 %
D± - this thesis (×0.565/0.246)
D± preliminary (×0.565/0.246)
D0
Levy Fit to D0
d2N/(2πpTdpTdy) [(GeV/c)-2]
D±/D0 Fit
pT [GeV/c]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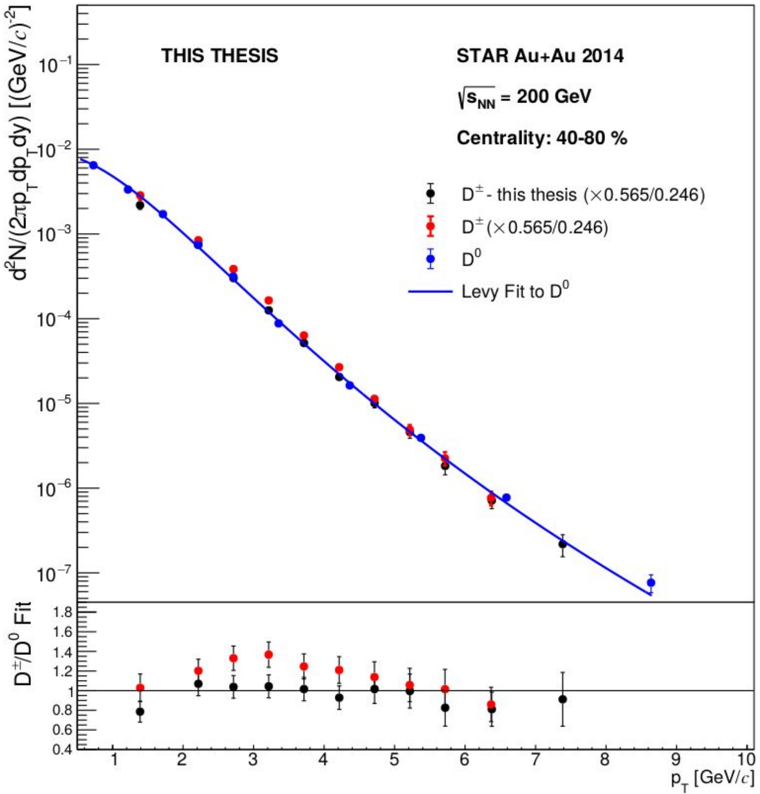
D± Spectra



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Centrality: 40-80 %
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D± (×0.565/0.246)
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Levy Fit to D0
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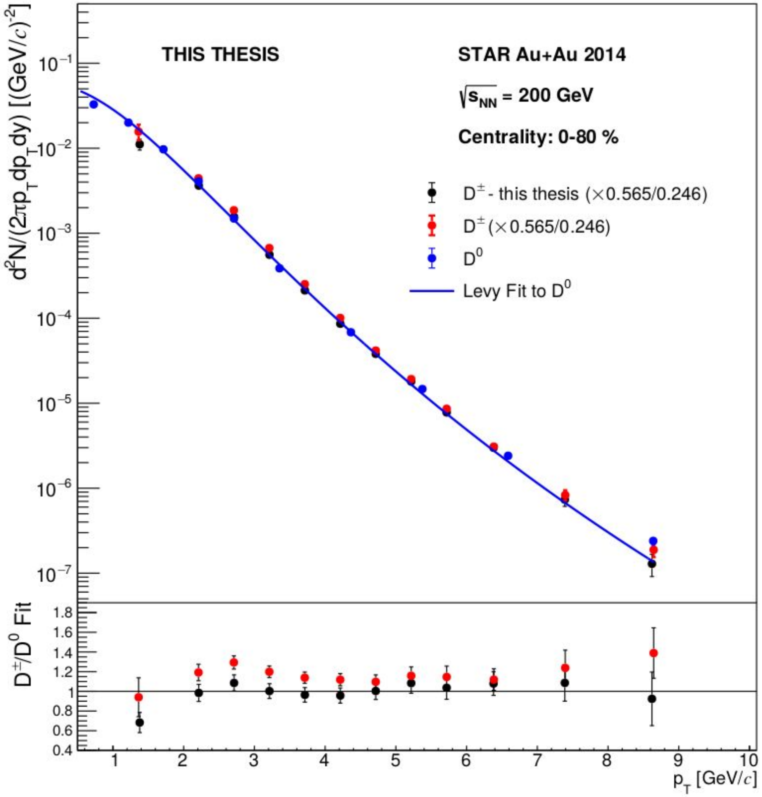
D±/D0 Fit
pT [GeV/c]

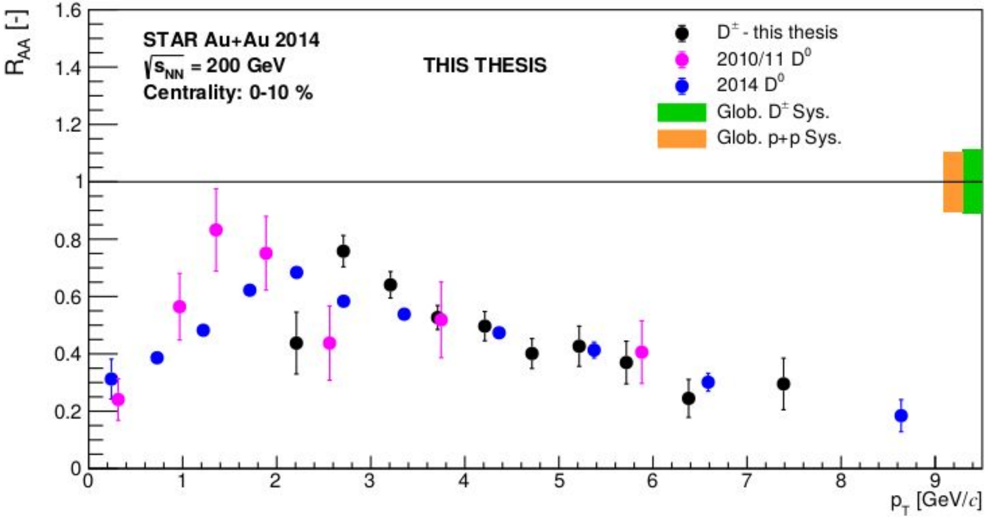


THIS THESIS
STAR Au+Au 2014
$\sqrt{s_{NN}}$ = 200 GeV
Centrality: 0-80 %
D± - this thesis (×0.565/0.246)
D± (×0.565/0.246)
D0
Levy Fit to D0
d2N/(2πpTdpTdy) [(GeV/c)-2]
D±/D0 Fit
pT [GeV/c]

$D^{\pm}$ Nuclear Modification Factor

- Spectra compared to scaled p+p reference

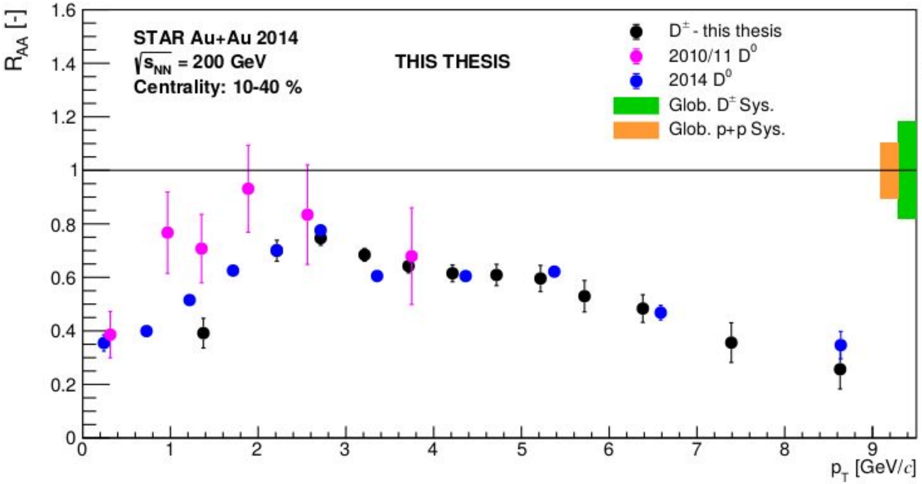
Centrality [%]	N_{coll} [-]
0 – 10	959.65±36.53
10 – 40	401.80±54.50
40 – 80	58.07±33.02
0 – 80	373.00±73.45

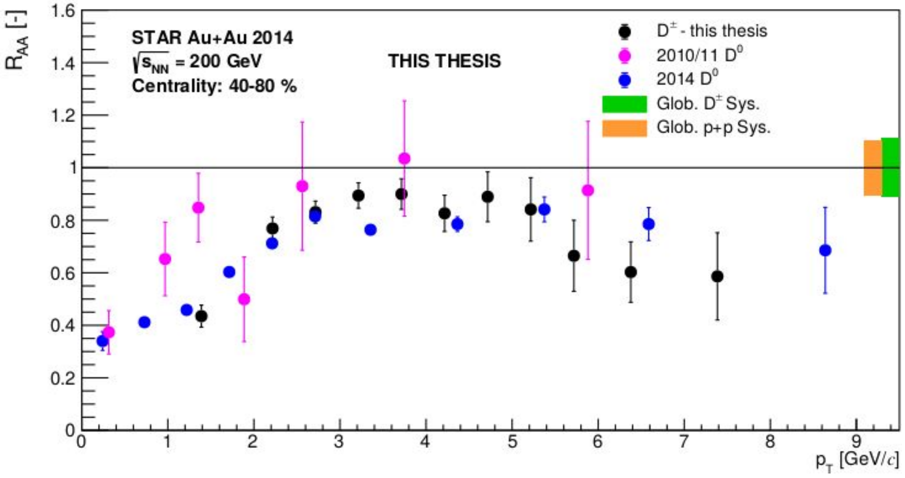


- Significant $D^{\pm}$ production suppression observed
- Consistent with D^0 results

$D^{\pm}$ Nuclear Modification Factor

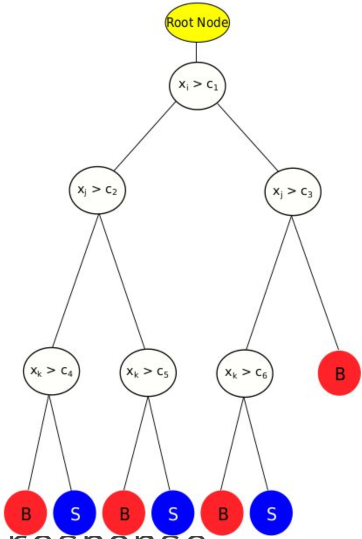
- Suppression also observed in more peripheral collisions
- Significant energy losses of charm quarks inside QGP
- Precise measurement enabled by HFT





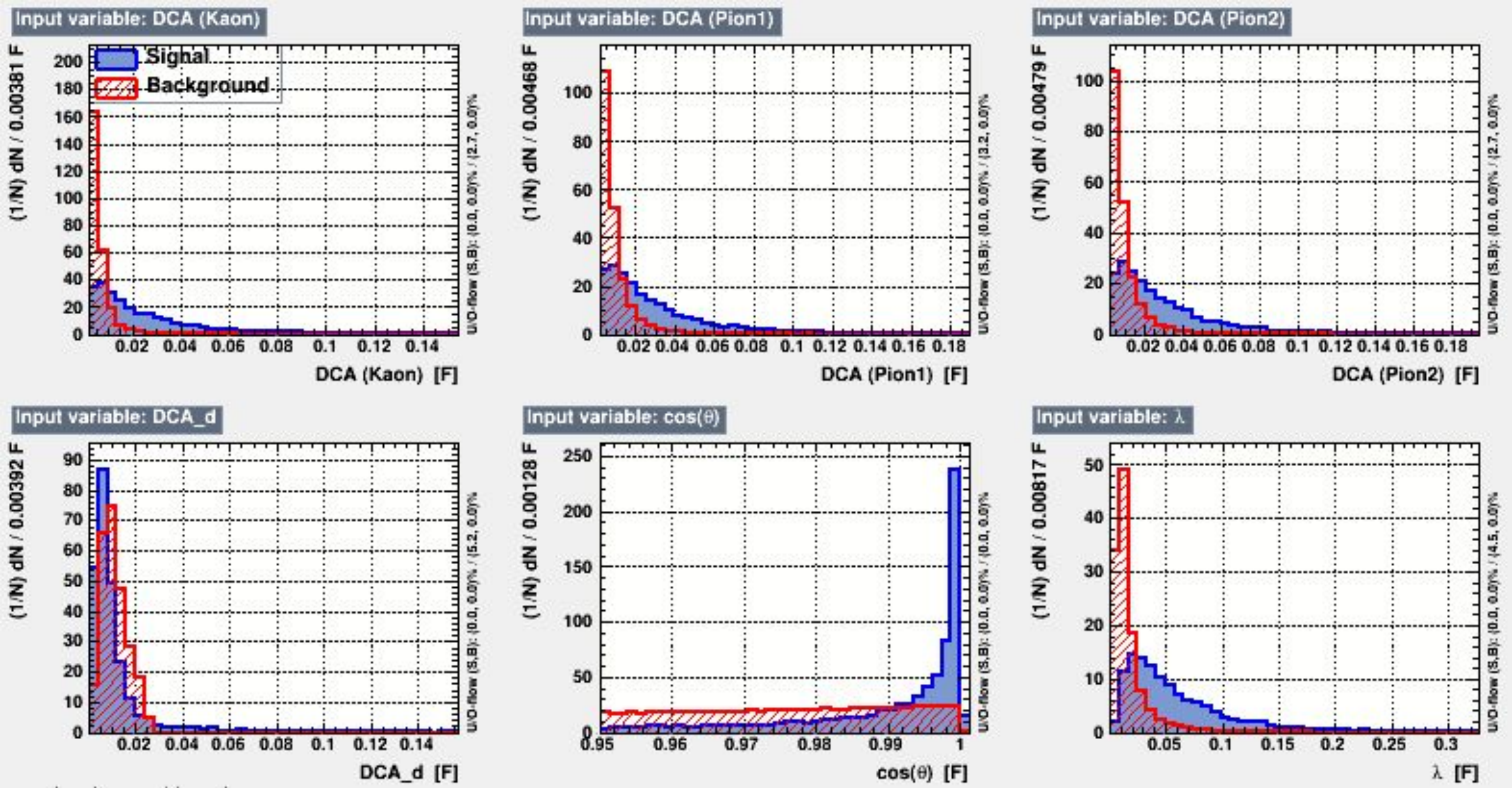
5 - Improvement Using TMVA

Improvement Using TMVA:BDT



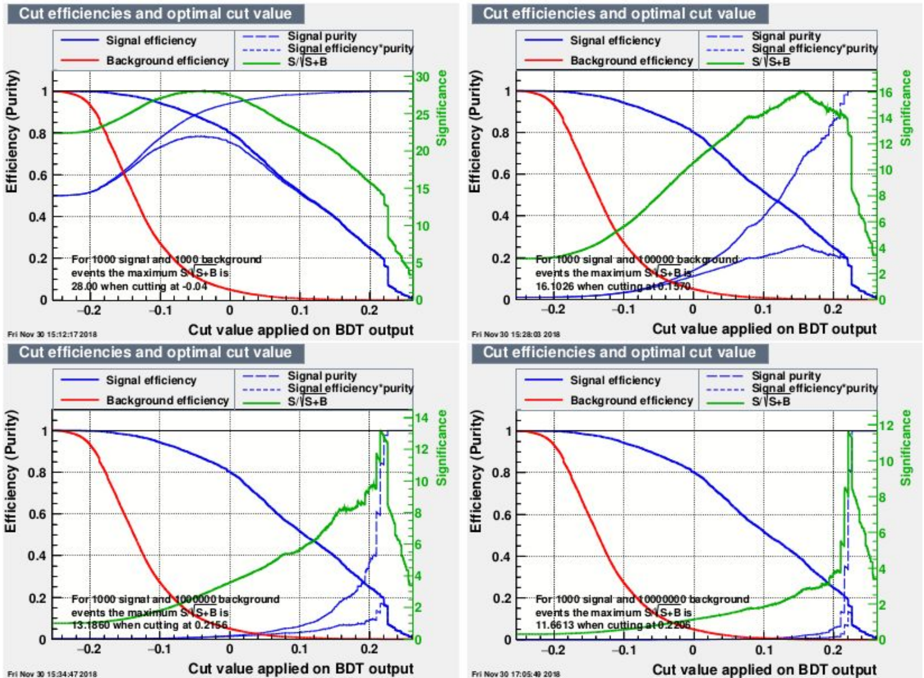
- we use Boosted Decision Trees (BDT) to improve signal significance
- training signal sample from FastSim (8.37 M)
- background from data - wrong-signs (8.41 M)
- variables used for optimization:
  - DCA_K, $DCA_{\pi 12}$, DCA_{pair}
  - $\cos\theta$, λ
- 850 trees with depth 3 (standard settings) - boosting
- dependence on variables boiled down to 1 number - BDT response (-1 = pure background, 1 = pure signal in ideal case)

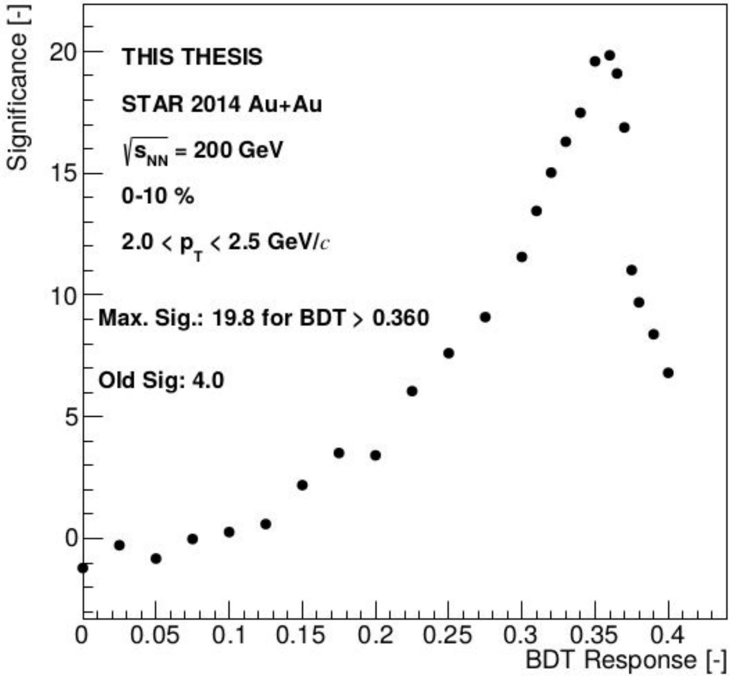
Topological Variable Distributions



Significance Scan

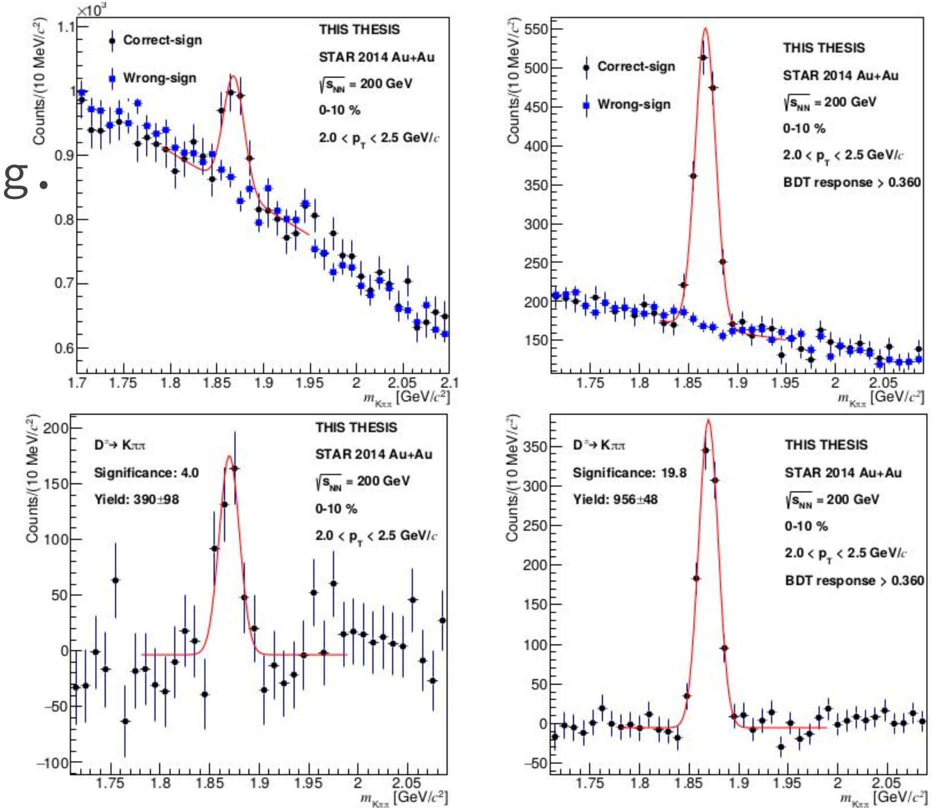
- How to select optimal BDT cut value?





Comparison: Rectangular Cuts vs. TMVA:BDT

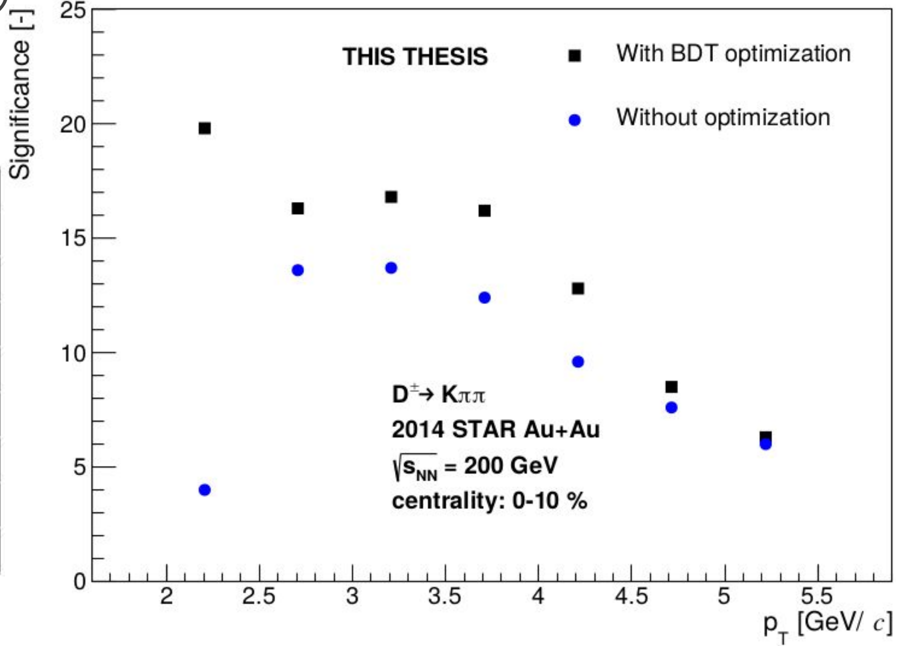
- No peak in wrong-signs
- Largest improvement of Sig. in the lowest p_T



Comparison: Rectangular Cuts vs. TMVA:BDT

- STAR 2014 Au+Au at $\sqrt{s_{NN}}$ = 200 GeV, 0-10 % most central collisions (103.0 M events)

p_T range [GeV/c]	Rectangular cuts		BDT optimization	
	Yield [-]	Sig. [-]	Yield [-]	Sig. [-]
2.0-2.5	390±98	4.0	956±48	19.8
2.5-3.0	647±47	13.6	1013±62	16.3
3.0-3.5	437±32	13.7	534±32	16.8
3.5-4.0	256±21	12.4	461±28	16.3
4.0-4.5	160±17	9.6	207±16	12.8
4.5-5.0	79±10	7.6	113±13	8.5
5.0-5.5	54±9	6.0	85±14	6.3



6 - Summary and Outlook

Summary

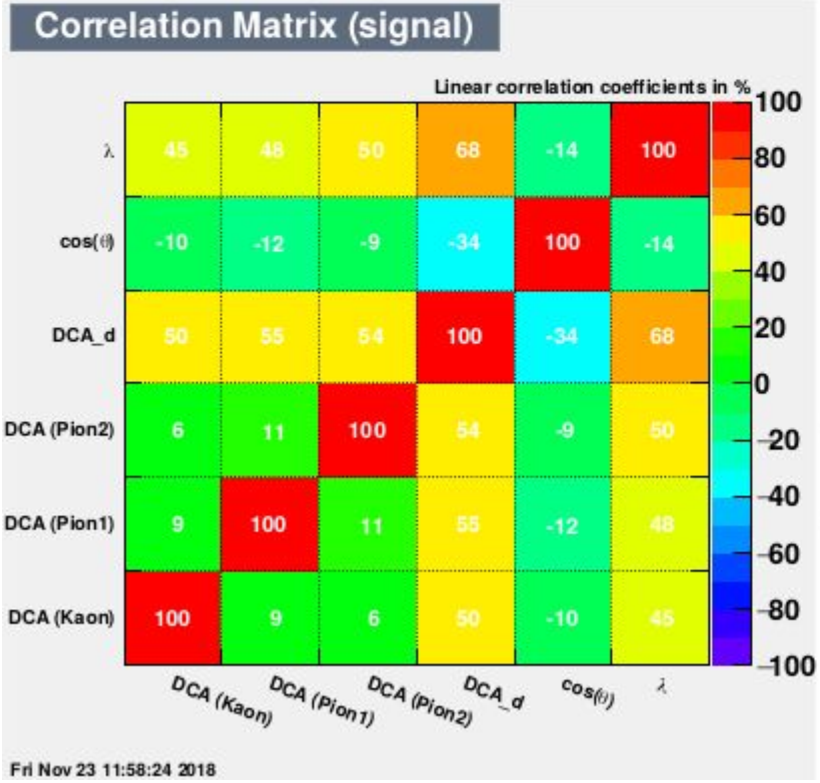
- QGP is created in high-energy heavy-ion collisions
- Charm quarks serve as a probe inside the medium
- HFT allowed precise reconstruction of $D^{\pm}$ at STAR
- Results indicate significant energy loss of c quark in the QGP
- Signal significance can be substantially improved by application of TMVA:BDT, especially at low p_T

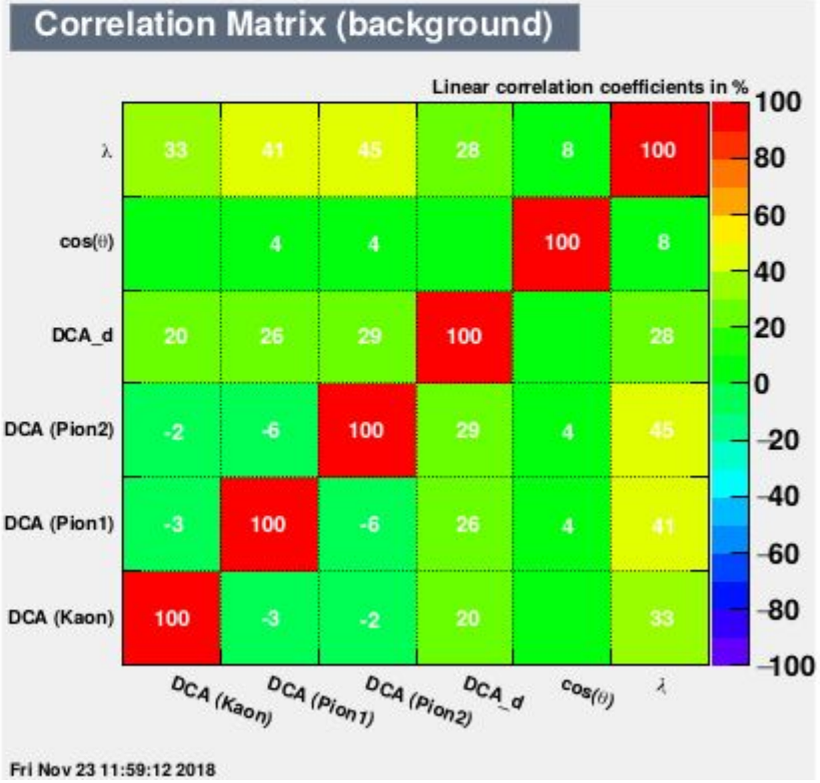
Outlook

- Apply TMVA:BDT on all available p_T and centrality bins
- Calculate reconstruction efficiency with BDT
- Precisely determine systematic errors
- Combine with 2016 results and publish

BACKUP

Correlation Matrices





Overtraining check