Reconstruction of $D^{\pm}$ mesons in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV by the STAR experiment

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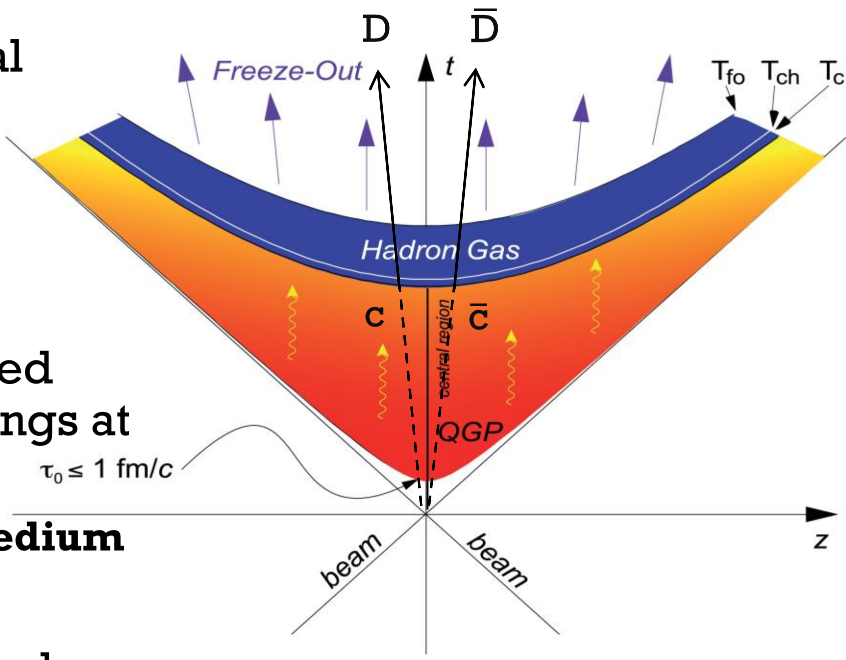
MINISTRY OF EDUCATION,
YOUTH AND SPORTS

PHYSICS MOTIVATION

- **Quark-Gluon Plasma** (QGP) can be studied using relativistic heavy-ion collisions
- Only indirect study through production of final state hadrons
  - Light flavor hadrons
  - **Heavy flavor hadrons**
- At RHIC energies, **charm quarks** are produced predominantly through hard partonic scatterings at **early stage** of Au+Au collisions
  - They experience **the whole evolution of the medium**
- **Charm quark energy loss** in the medium can be studied by measurement of open-charm meson nuclear **modification factor** $\boldsymbol{R_{AA}}$



D^0 NUCLEAR MODIFICATION FACTOR

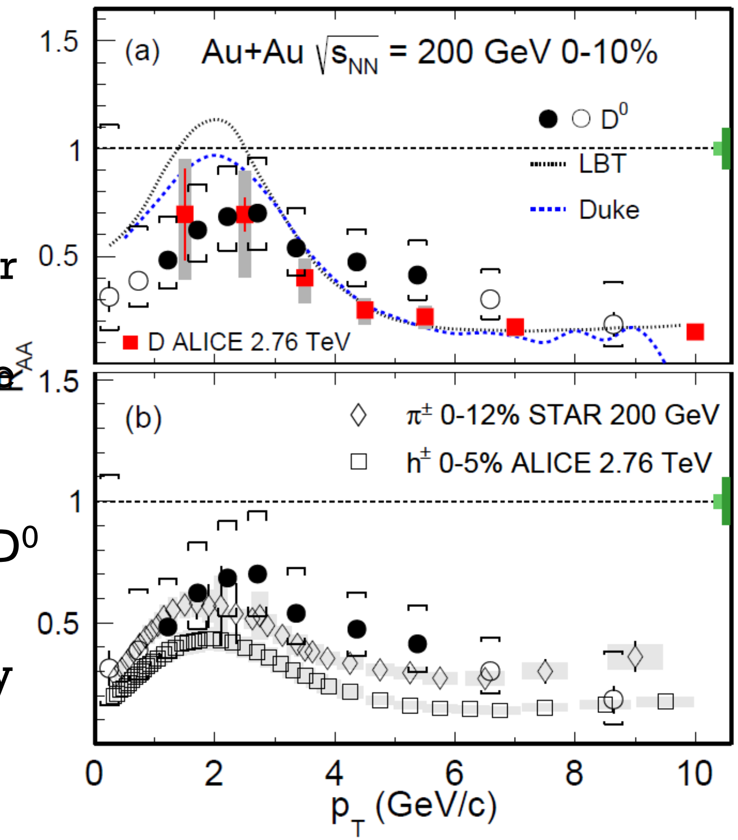
D^0 (STAR): Phys. Rev. C 99, 034908, (2019).
π$^\pm$ (STAR): Phys. Lett. B 655, 104 (2007).
D (ALICE): JHEP 03, 081 (2016).
h$^\pm$ (ALICE): Phys. Lett. B 720, 52 (2013).
LBT: Phys. Rev. C 94, 014909, (2016).
Duke: Phys. Rev. C 97, 014907, (2018).

- Nuclear modification factor:

$$R_{AA}(p_T) = \frac{dN_D^{AA}/dp_T}{\langle N_{coll}\rangle\, dN_D^{pp}/dp_T}$$

- D^0 mesons suppressed in central Au+Au collisions
  - Strong interactions between charm quarks and the medium
  - Suppression of D^0 mesons comparable to light flavor hadrons at RHIC and D mesons at LHC
  - Reproduced by models incorporating both radiative and collisional energy losses, and collective flow

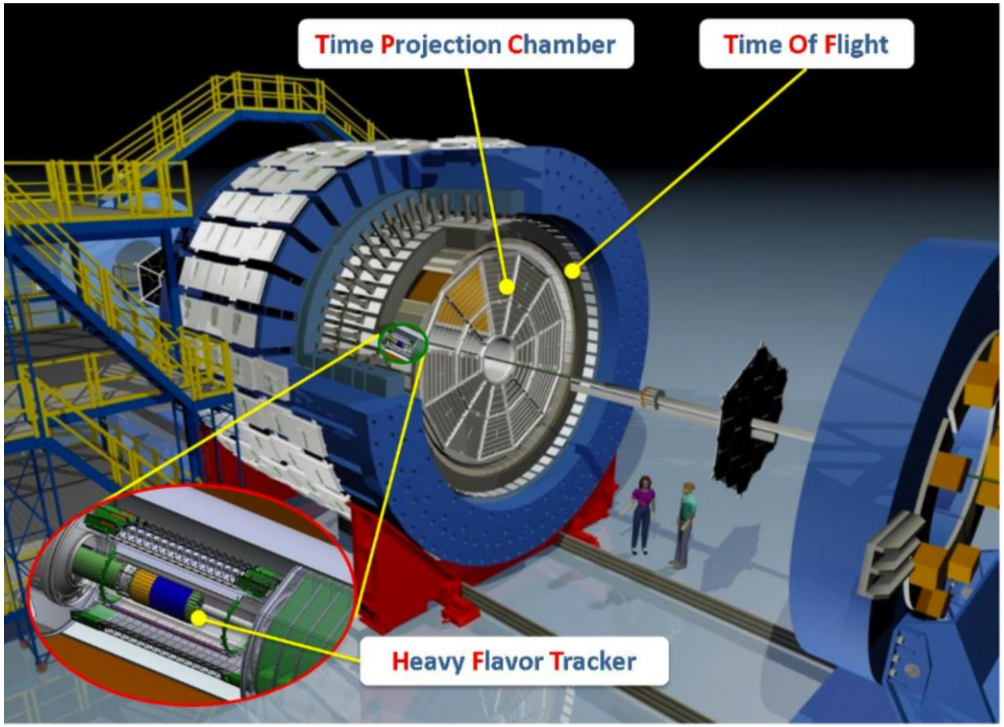
- Measurement of $D^\pm$ is complementary to that of D^0
  - Independent cross-check of the D^0 measurement
  - First measurement of $D^\pm$ at STAR – three body decay

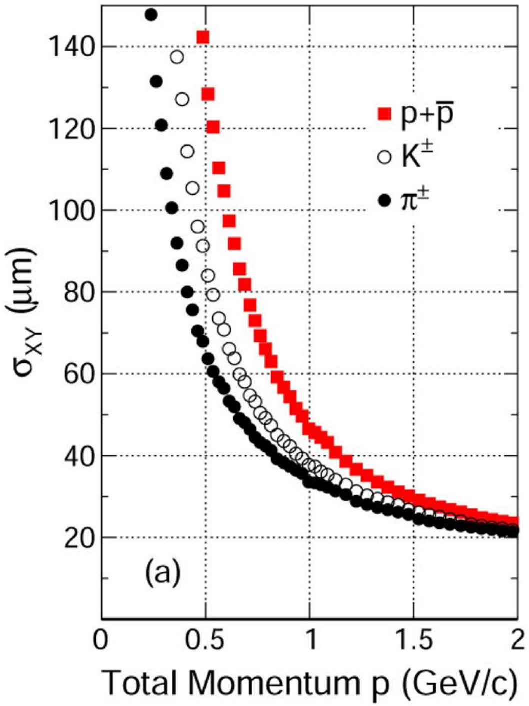


STAR DETECTOR

- **S**olenoidal **T**racker **At** **R**HIC
- **Heavy Flavor Tracker** (HFT, 2014–2016) is a 4-layer silicon detector
  - MAPS – 2 innermost layers, Strip detectors – 2 outer layers
- **Time Projection Chamber** (TPC) and **Time Of Flight** (TOF)
  - Particle momentum (TPC) and identification (TPC and TOF)

PRL 118 212301 (2017)



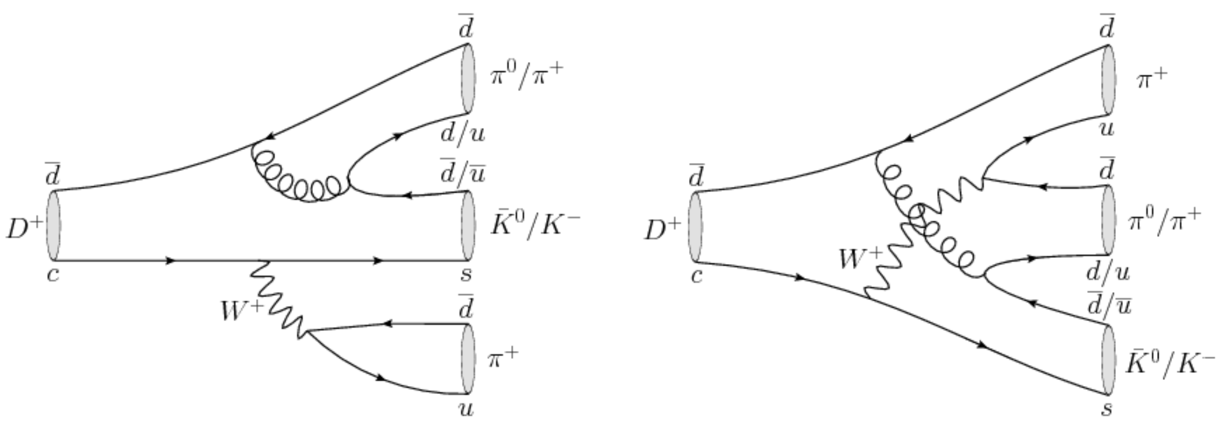


$D^{\pm}$ MEASUREMENTS WITH THE HFT

- The data used in this analysis are from 2016 for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

- Total of ca. 1.3B good minimum bias events after event selection

- The HFT allows direct topological reconstruction of $D^{\pm}$ mesons through their hadronic decay
  - $D^+ \rightarrow K^-\pi^+\pi^+$ $c\tau = (311.8 \pm 2.1)$ μm $BR = (8.98 \pm 0.28)$ %*



(a) (b)

JHEP 1510 (2015) 142

*Value of *BR* is updated regularly:

2014: *BR* = (9.13 ± 0.19) %

2016: *BR* = (9.46 ± 0.24) %

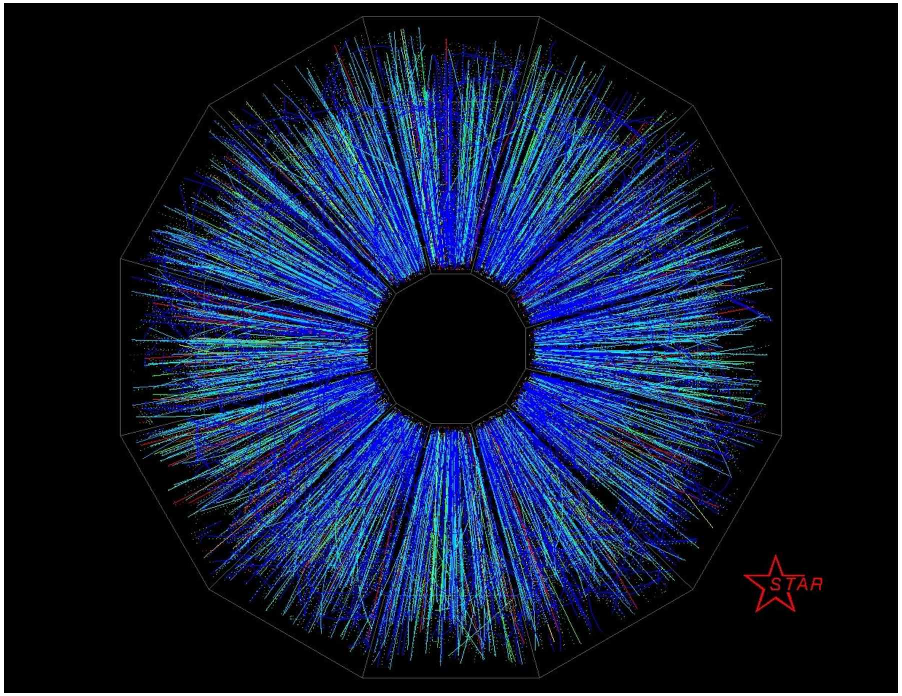
2018: *BR* = (8.98 ± 0.28) %

2019: *BR* = (9.38 ± 0.16) %

All values taken from PDG overview from given year.

EVENT AND TRACK SELECTION, PID

- Event selection cuts
  - Position of primary vertex along the beam axis
- Track selection cuts
  - p_{T} – suppresses combinatorial background from low-p_{T} particles
  - $|\eta| < 1$ – detector acceptance
  - Minimum number of hits in the TPC for each track – good track quality
  - Minimum number of hits in the HFT
- Particle identification (PID)
  - TPC – energy loss of charged particles in the TPC gas
  - TOF – velocity of the charged particles
- Topological cuts
  - Possible only with use of the HFT
  - Constrain topology of the reconstructed secondary vertex
  - Suppress combinatorial background



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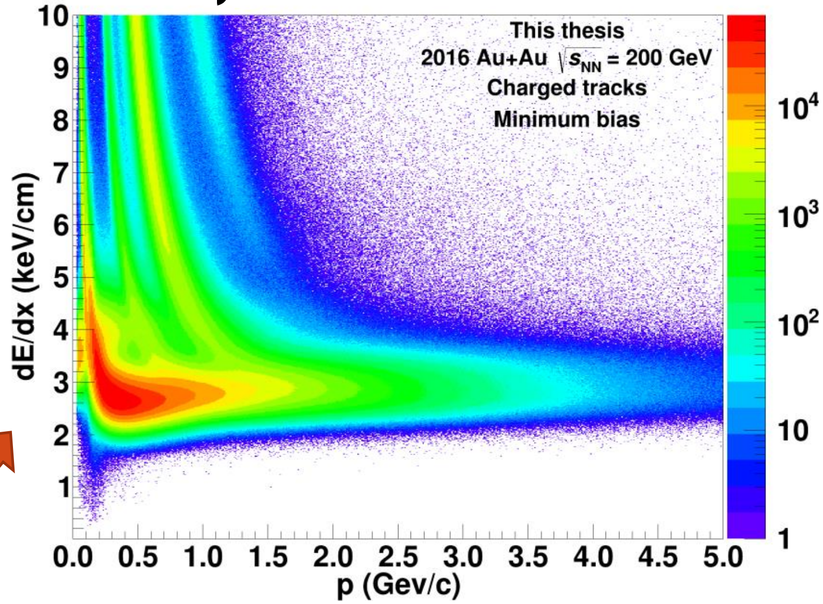

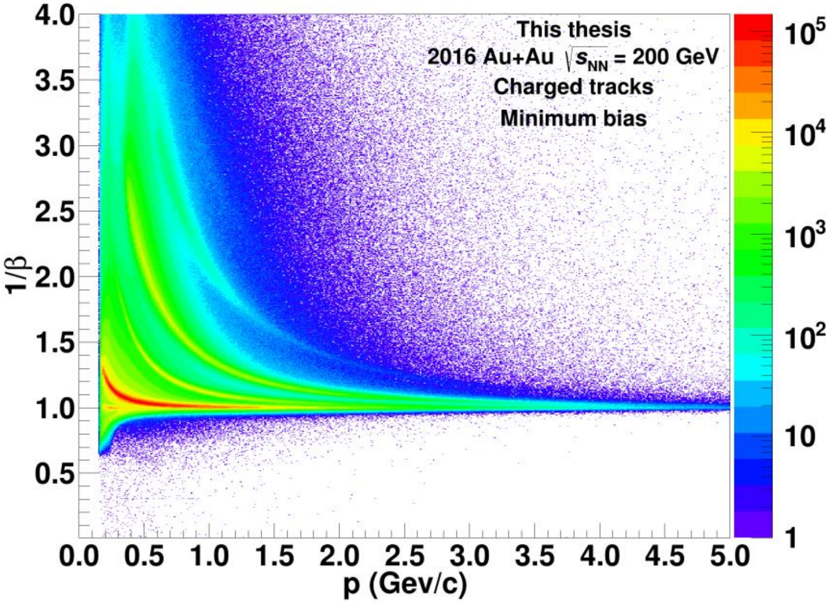

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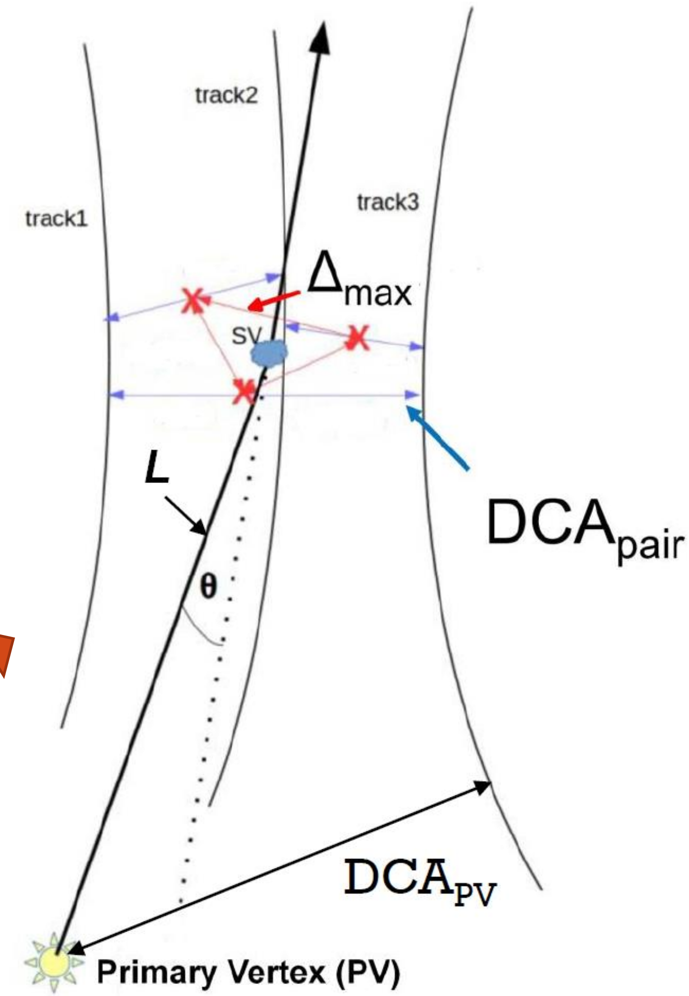


EVENT AND TRACK SELECTION, PID

- Example of analysis cuts for $D^{\pm}$ reconstruction using the HFT
- Event selection cuts
  - Position of primary vertex along the beam axis
- Track selection cuts
  - p_T – suppresses combinatorial background from low-p_T particles
  - nHitsFit – large number of TPC hits used for track reconstruction to ensure good track quality
  - Hit in at least three layers of the HFT
- PID: HFT+TPC+(TOF)
  - Hybrid TOF = use TOF only for tracks with valid TOF information
- Topological cuts
  - Possible only with use of the HFT
  - Constrain topology of the reconstructed secondary vertex
  - Suppress combinatorial background
  - Optimization using the TMVA

Event selection cuts		$\lvert V_z \rvert < 6$ cm
		$\lvert V_z - V_{z(VPD)} \rvert < 3$ cm
Track selection cuts		$p_T > 500$ MeV/c
		$\lvert \eta \rvert < 1$
		nHitsFit > 20
		nHitsFit/nHitsMax > 0.52
		HFT track = PXL1+PXL2+(IST or SSD)
PID cuts	TPC	$\lvert n\sigma_{\pi} \rvert < 3$
		$\lvert n\sigma_{K} \rvert < 2$
	Hybrid TOF	$\lvert 1/\beta - 1/\beta_{\pi} \rvert < 0.03$
		$\lvert 1/\beta - 1/\beta_{K} \rvert < 0.03$
Topological cuts (no optimization)		$DCA_{pair} < 80$ μm
		30 μm $< L_{D^{\pm}} < 2000$ μm
		$\cos(\vartheta) > 0.998$
		$\Delta_{max} < 200$ μm
		$DCA_{\pi\text{-}PV} > 100$ μm
		$DCA_{K\text{-}PV} > 80$ μm

SELECTION CRITERIA OPTIMIZATION

- Rectangular cuts optimization using TMVA
- **Signal sample**
  - From data-driven fast-simulator
  - 160M simulated $D^{\pm}$ decays with same pre-cuts as used to produce candidates tree
- **Background sample**
  - From data
  - Wrong-sign $K\pi\pi$ triplets
- **Number of signal events (before TMVA cuts)**
  - Estimated using measured D^0 spectrum in Run14

$$(Y_{\mathrm{raw}})_{D^{\pm}} = \left(\frac{\mathrm{d}^2 N}{2\pi p_{\mathrm{T}}\,\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right)_{D^0} 2\,\pi\, N_{\mathrm{evt}}\, BR_{D^{\pm}}\, p_{\mathrm{T}} \Delta p_{\mathrm{T}} \Delta y\; \varepsilon(p_{\mathrm{T}}) \frac{f_{c\to D^{\pm}}}{f_{c\to D^0}}$$

- **Number of background events (before TMVA cuts)**
  - From data

TRAINING PROCEDURE

- Cuts optimization (CutsSA)
- Set the TMVA optimized variables
  - Look for max/min value
- TMVA goes from signal efficiency $\varepsilon_S = 0$ to $\varepsilon_S = 1$
- For each ε_S minimizes background efficiency ε_B
- The optimal set of cuts – at maximum significance:

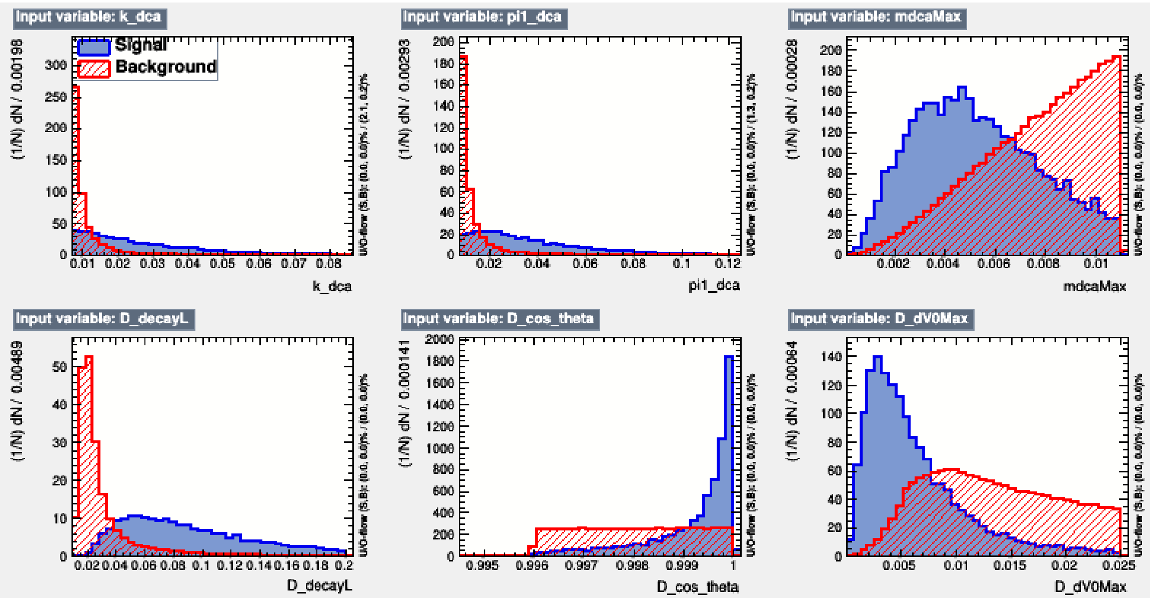
$$\Sigma = \frac{S}{\sqrt{S+B}} = \frac{\varepsilon_S N_S}{\sqrt{\varepsilon_S N_S + \varepsilon_B N_B}}$$

where N_S (N_B) is number of signal (background) events before optimization

- N_S estimated from D^0 Run14 invariant spectrum
  - Calculate expected $D^{\pm}$ raw yield from D^0 invariant yield
- N_B estimated from $D^{\pm}$ candidates tree
  - Number of background events under the $D^{\pm}$ mass peak

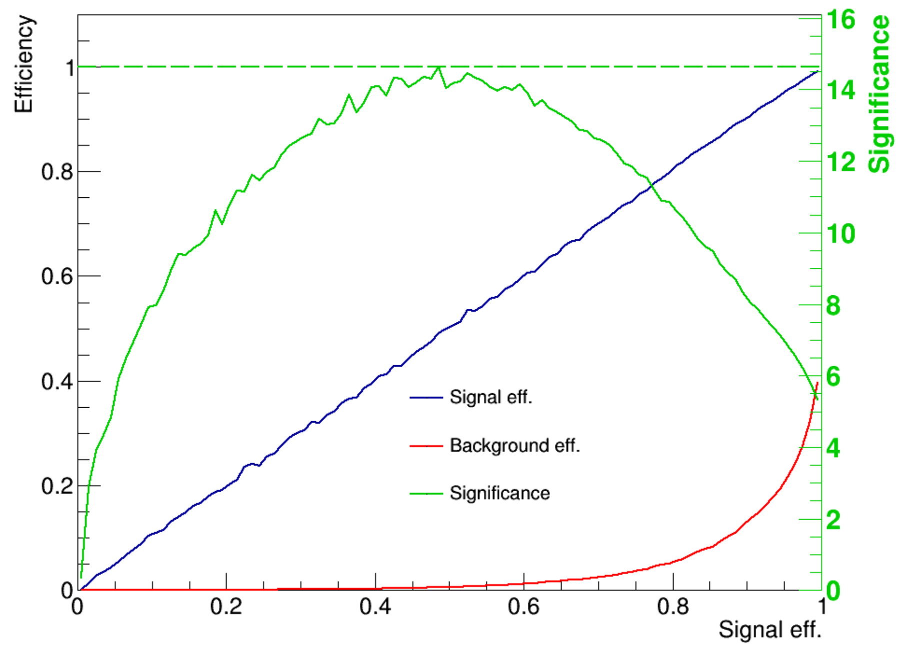
TRAINING – EXAMPLE FOR ONE BIN

STAR



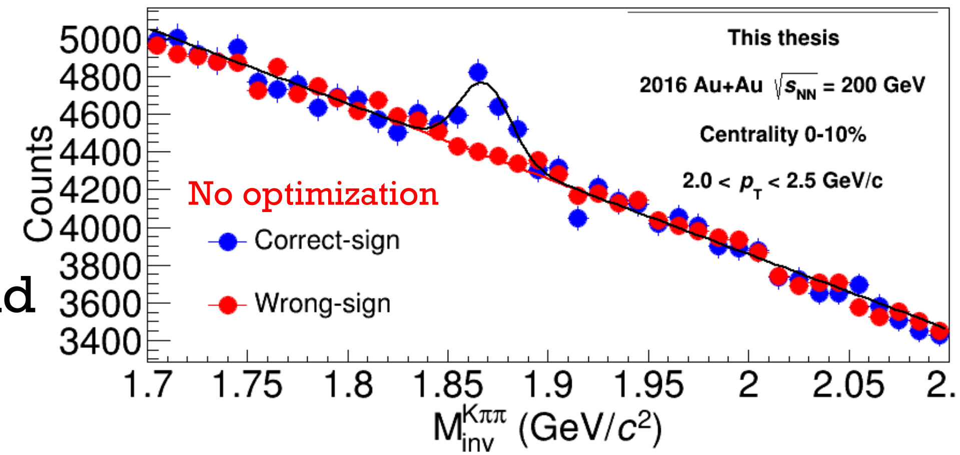
- Centrality 0-10%
- $3 < p_T < 4$ GeV/c
- (top) Signal (blue) and background (red) distributions used for the training

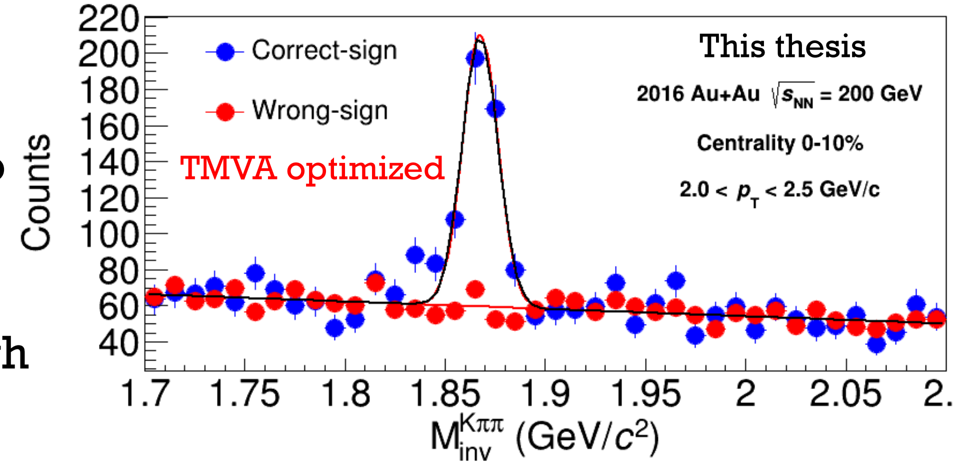
- (bottom) Signal eff. (blue), background eff. (red) and significance (green) all vs. signal efficiency in the same bin
- The significance plot corresponds to expected **703 signal** and **41 448 background** events



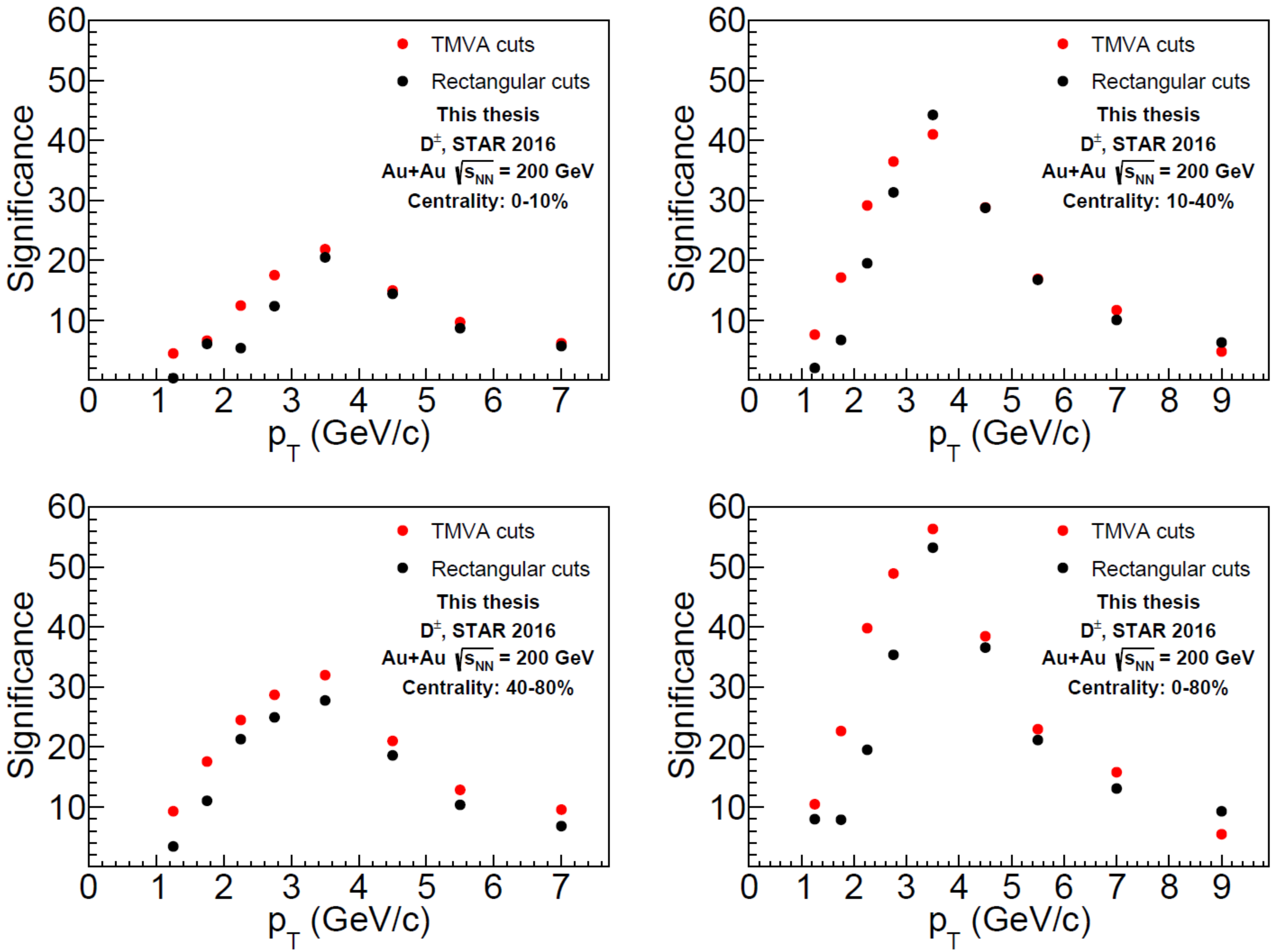
TRAINING RESULT – RAW YIELD

- Improvement of raw yield extraction
- Significantly reduced background for p_T < 3 GeV/c
- Raw yield significance improvement with TMVA cuts
  - Improvement of significance up to by factor of 3
  - TMVA is most efficient in low p_T
  - No significant improvement in high p_T due to very little background



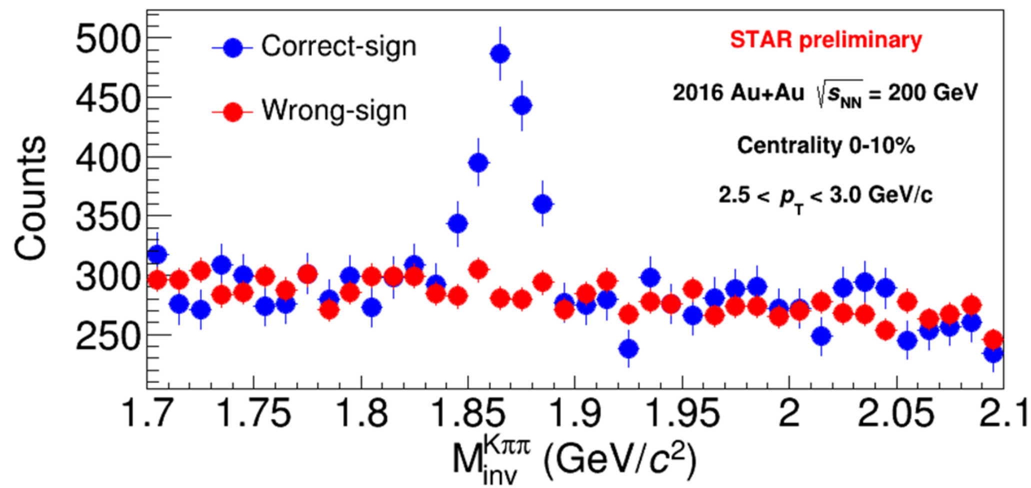


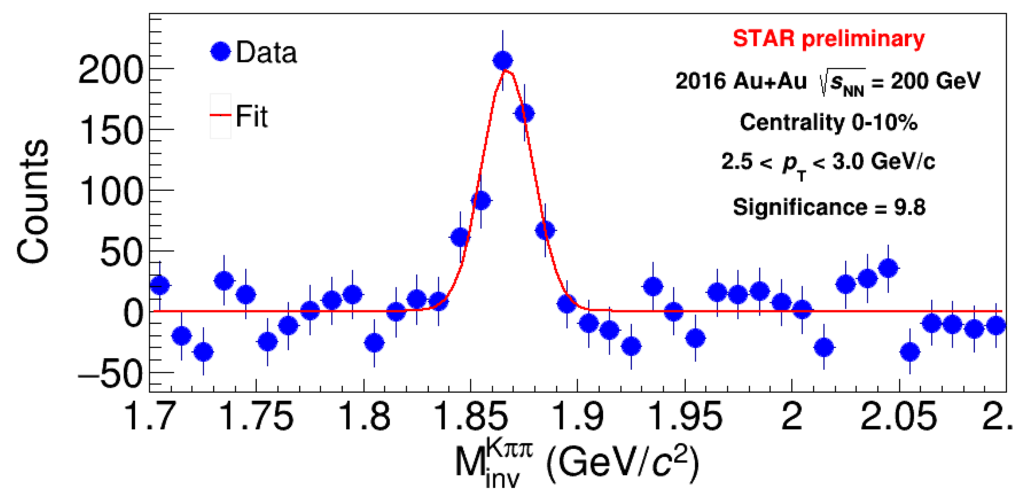
TRAINING RESULT – YIELD SIGNIFICANCE



RAW YIELD EXTRACTION

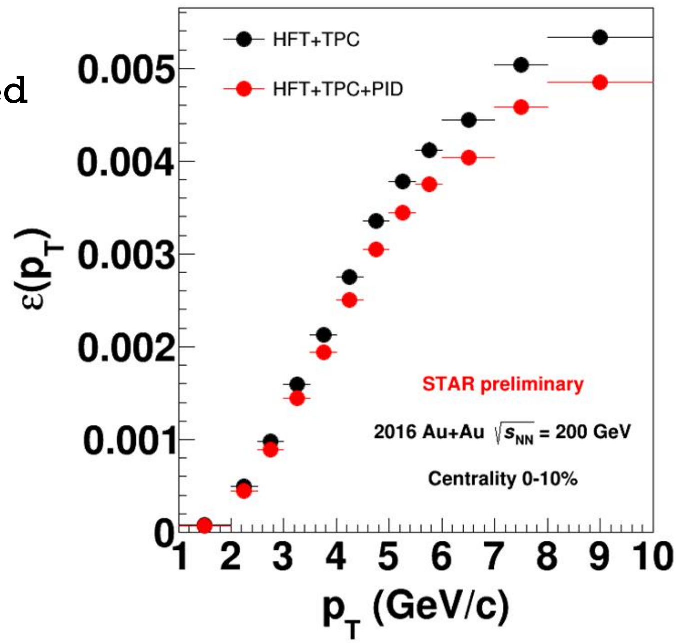
- $D^{\pm}$ **signal** is extracted from $K\pi\pi$ invariant mass $M_{inv}^{K\pi\pi}$ spectrum
- **Background:** wrong-sign spectrum scaled using regions outside the mass peak
- The wrong-sign spectrum is subtracted from the correct-sign spectrum
- The spectrum after subtraction is fitted with Gaussian function by χ^2 fit
- The raw yield Y_{raw} is calculated by the bin-counting method in $\pm 3\sigma$ region
- Only raw yields with significance > 3 accepted for further analysis





DETECTOR AND ACCEPTANCE CORRECTIONS

- **HFT+TPC efficiency** determined by data-driven fast-simulator with inputs from data and TPC embedding
  - $D^{\pm}$ are decayed by EvtGen
  - Detector efficiency and resolution effects are applied to the $D^{\pm}$ decayed daughters:
    - HFT matching efficiency (data)
    - DCA resolution (data)
    - Primary vertex position along beam axis (data)
    - TPC momentum resolution (embedding)
    - TPC tracking efficiency (embedding)
  - Efficiency $\varepsilon(p_{\mathrm{T}})$ obtained from fraction of simulated $D^{\pm}$ passing the analysis cuts



- **PID efficiency** of TPC and TOF
  - Enriched K sample at low p_{T} from data using strict TOF or TPC PID cuts
  - Pure π sample obtained by reconstruction of K_S^0

$D^{\pm}$ INVARIANT SPECTRUM

- Invariant yield is calculated according to:

$$\frac{\mathrm{d}^2 N}{2\pi p_{\mathrm{T}}\,\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} = \frac{Y_{\mathrm{raw}}}{2\,\pi\,N_{\mathrm{evt}}\,BR\,p_{\mathrm{T}}\Delta p_{\mathrm{T}}\Delta y\,\varepsilon(p_{\mathrm{T}})}$$

- Y_{raw} = raw yield, N_{evt} = number of events, BR = branching ratio, $\varepsilon(p_{\mathrm{T}})$ = total $D^{\pm}$ reconstruction efficiency

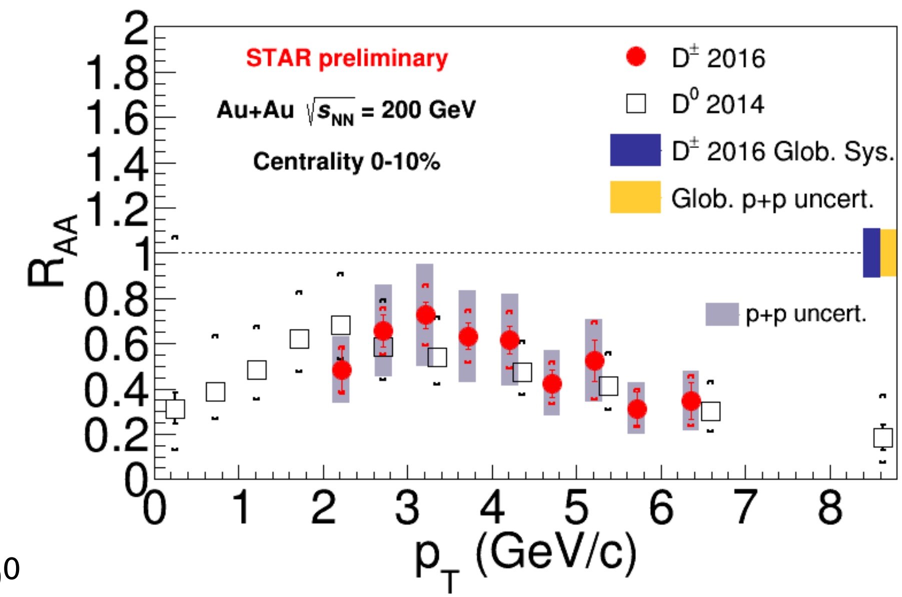
- Collision centrality classes: 0-10%, 10-40%, 40-80%, 0-80%
  - Determined from charged track multiplicity in TPC and Glauber model simulation

$D^{\pm}$ NUCLEAR MODIFICATION FACTOR

- Nuclear modification factor:

$$R_{AA}(p_T) = \frac{dN_D^{AA}/dp_T}{\langle N_{coll} \rangle \, dN_D^{pp}/dp_T}$$

- Reference: combined D^0 and D* measurement in 200 GeV p+p collisions using 2009 data
- High-p_T $D^{\pm}$ and D^0 suppressed in central Au+Au collisions
  - Strong interactions between charm quarks and the medium
- Similar level of suppression for $D^{\pm}$ and D^0
- This figure – official STAR preliminary, first presented at QM2018 in Venice



STAR D^0 and D* p+p reference: Phys. Rev. D 86 072013

CONCLUSION

- STAR has extensively studied production of open-charm mesons in heavy-ion collisions utilizing the Heavy-Flavor Tracker
- The HFT allows direct topological reconstruction of hadronic decays of open-charm mesons
- The topological selection criteria are optimized using the TMVA
  - Improvement of significance of $D^{\pm}$ mass peak for $p_T < 4$ GeV/c
  - Improvement of $D^{\pm}$ raw yield extraction
- The $D^{\pm}$ nuclear modification factor is consistent with that of D^0
  - D^0 and $D^{\pm}$ mesons are significantly suppressed at high-p_T in central Au+Au collisions
  - The c quarks interact strongly with the QGP

THANK YOU FOR ATTENTION

Acknowledgement: This presentation is supported by OPVVV grant CZ.02.1.01/0.0/0.0/16_013/0001569 of the Ministry of Education, Youth and Sports of the Czech Republic

21 BACKUP

SYSTEMATIC UNCERTAINTIES

- Raw yield vs. fit function
  - Bin counting vs. fit

- Cuts variation
  - Manual for rectangular cuts
  - ±30% in signal efficiency in TMVA
  - Calculate invariant yield with varied cuts
    - Compare to analysis cuts
    - Take larger value (tight vs. loose cuts) as a sys. err.
    - Fit all sys. err. points with a linear function – take this as sys err.

- Tracking efficiency systematic error
  - Variate nHitsFit from 20 to 25
    - In data and in embedding
  - Double ratio vs. p_{T}
  - Used pions from embedding as a reference
  - Same procedure as used for D^0

RAW YIELD EXTRACTION – NEW

- $D^{\pm}$ signal is extracted from Kππ invariant mass $M_{\mathrm{inv}}^{\mathrm{K}\pi\pi}$ spectrum
- Background: wrong-sign spectrum scaled using regions outside the mass peak
- The wrong-sign spectrum is fitted by linear function
- The correct-sign spectrum is fitted by Gauss+linear using binned likelihood method
- The raw yield Y_{raw} is calculated from parameters of the fit in $\pm 3\sigma$ region
- This method will be used for final results – in progress
- Only raw yields with significance > 3 accepted for further analysis