Measurement of open charm mesons in p+p collisions at 510 GeV in STAR

Subhadip Pal

Faculty of Nuclear Sciences and Physical Engineering
Czech Technical University in Prague

June 11, 2026; Jefferson Lab CEBAF Center

Outline

- Part I : Physics motivations
  - What are the interests in proton+proton collisions?
  - Open charm production as a function of transverse momentum in proton+proton collisions

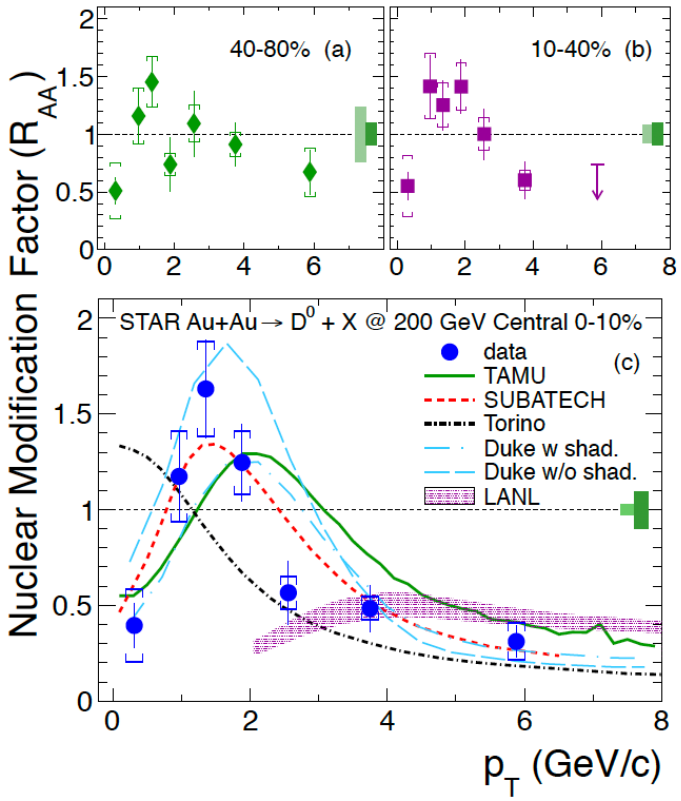
- Part II : My Current Analysis Work
  - STAR detector
  - Measurement of the D^0 and D^* production cross-section

Proton+Proton (p+p) Collision System

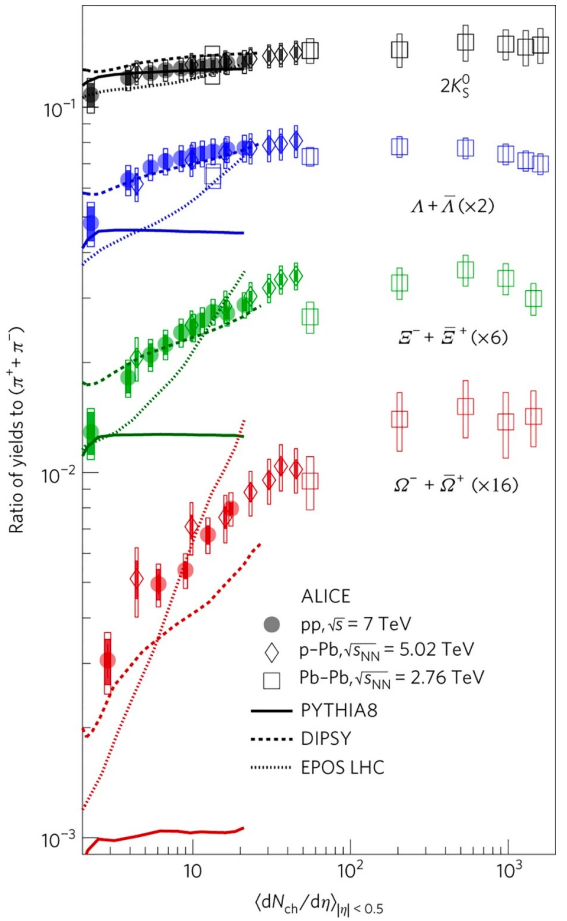
- Why studying proton+proton?
  - Test of the QCD
  - Historically p+p is a reference system
  - no QGP in p+p ⇒ reference for p+A and A+A systems

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} \sim \frac{QCD\ \text{medium}}{QCD\ \text{vacuum}}$$

- Recently typical effect of heavy-ion phenomenology has been observed in p+p high multiplicity
  - strangeness enhancement ⇒ originally proposed as a QGP signature



[Phys. Rev. Lett. **113**, 142301 (2014)]



[Nature Physics 13, 535–539 (2017)]

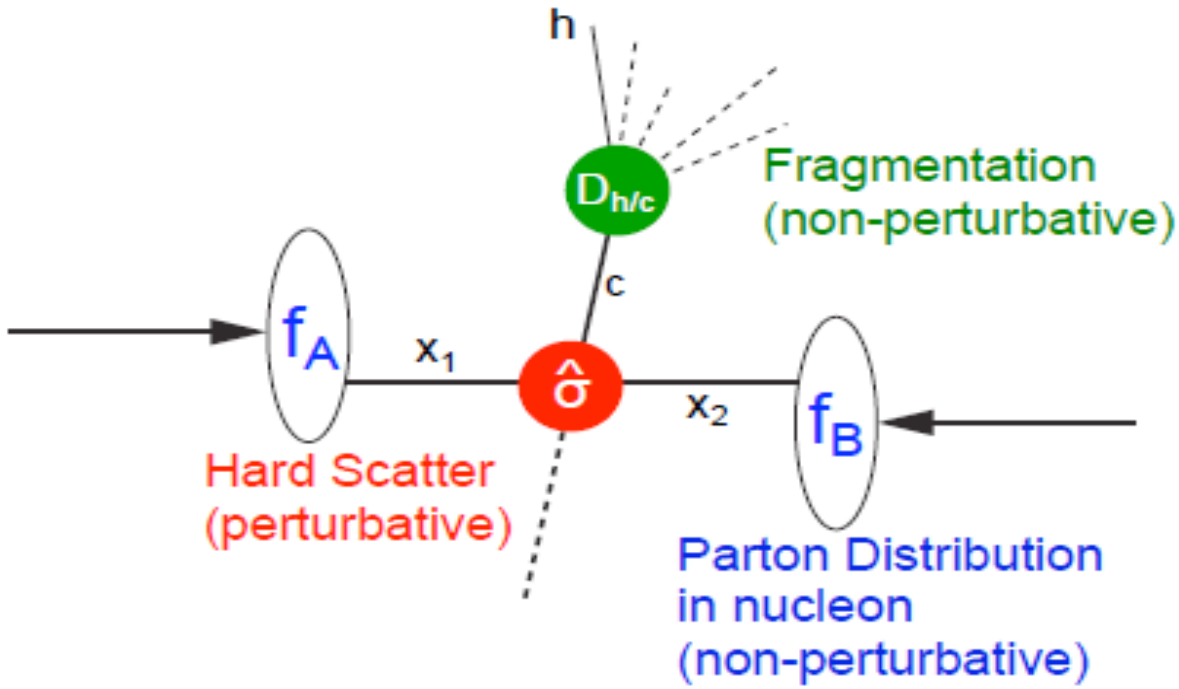
Heavy flavor production in p+p collisions

Heavy flavour quarks : $m_c \simeq 1.3$ GeV/c^2 , $m_b \simeq 4.2$ GeV/c^2 >> $\Lambda_{QCD} \simeq 0.2$ GeV

- Heavy-flavour production in p+p collisions:
  test perturbative QCD
  - Large quark mass (m_Q) provides a hard scale (perturbative regime)
  - Cross sections can be calculated with pQCD **down to low p_T**

- Factorization approach: convolution of
  - **PDFs in nucleon**
  - **Cross section** at **partonic** level (***pQCD***)
  - **Fragmentation** (parton → hadron)

- Data compared to **pQCD calculations:**
  - k_T-factorization scheme
  - Fixed Order with Next to Leading Log resummation **(FONLL)**



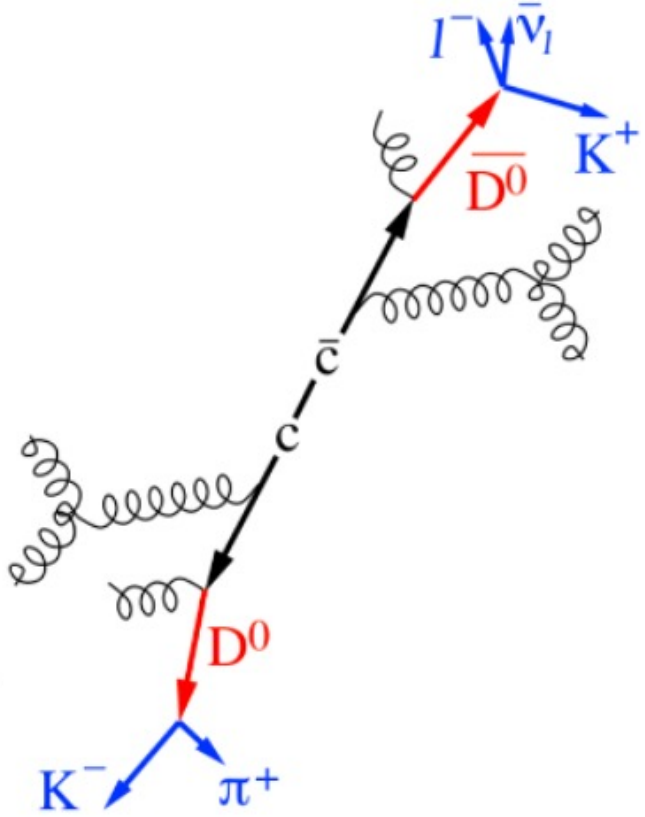
Eur. Phys. J. C **76**, 107 (2016)

D^0 Meson

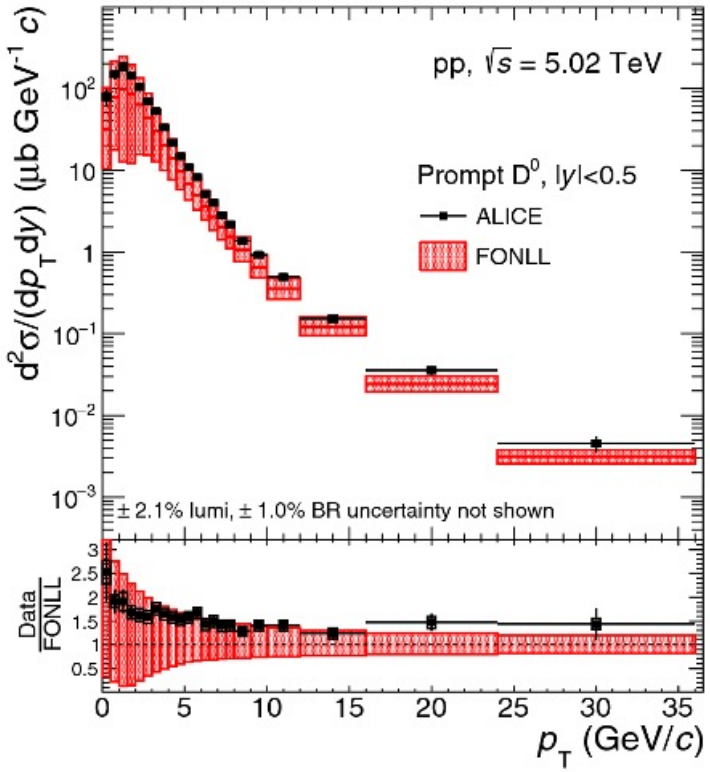
- Consist of charm quark c and antiquark up $\bar{u}$.
- Lightest charm particle
- Mass

  $m = (1864.84 \pm 0.05)\ MeV/c^2$
- Decay length $c\tau = 123.01\ \mu m$
- $D^0 \rightarrow K^-\pi^+$

  BR (3.947 ± 0.03) %

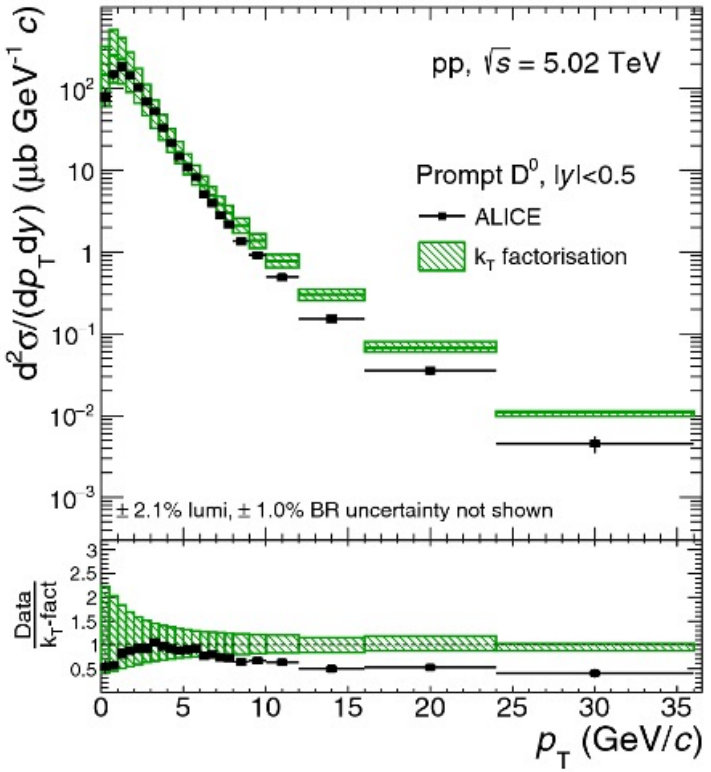


D meson measurements of LHC and RHIC

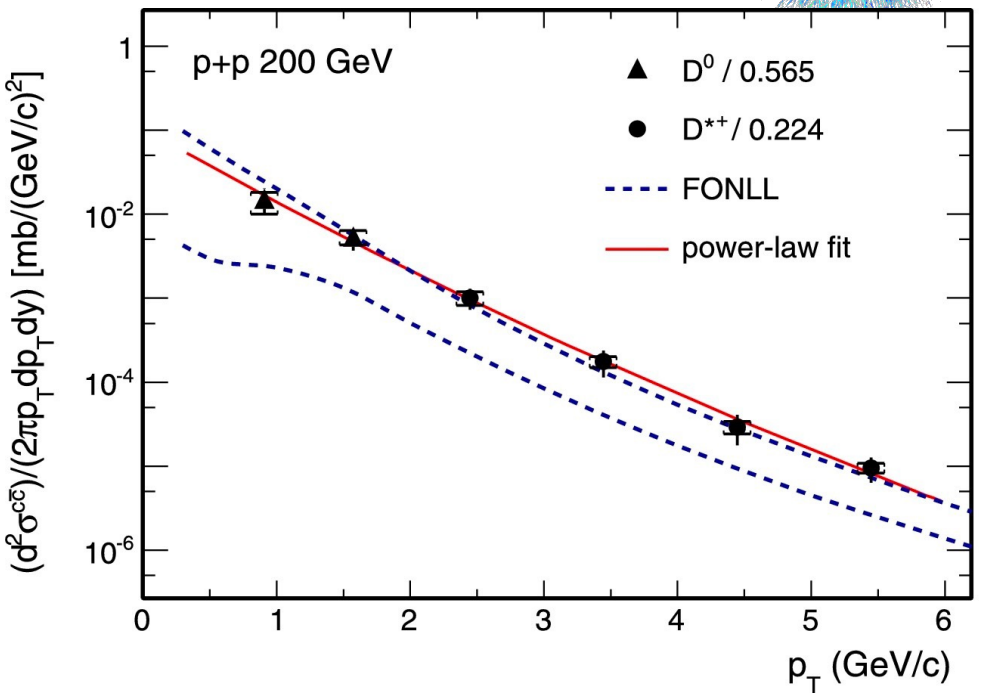


❑ Data lying on the upper edge of the FONLL band

Eur. Phys. J. C 79, 388 (2019)



❑ Data described well upto $p_T < 7$ GeV/c with k_T factorisation



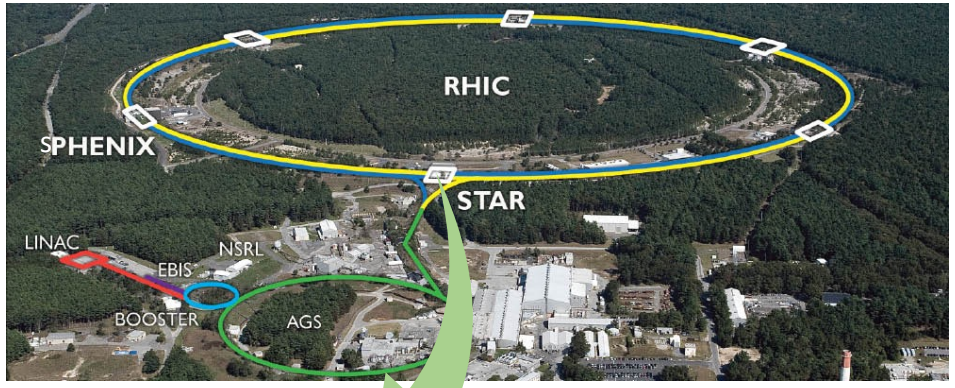
❑ Data are consistent with the upper limit of the FONLL pQCD calculation

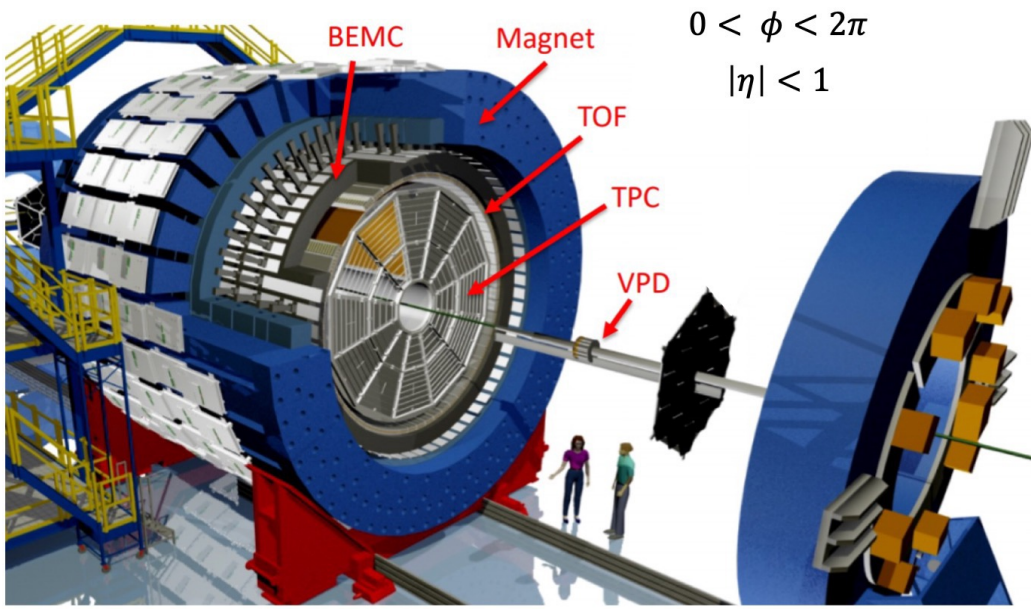
Phys. Rev. D 86, 072013 (2012)

❑ Goal of my current work:

- To measure the p_T-differential $c\bar{c}$ meson production cross sections in p+p collisions at $\sqrt{s}$ = 510 GeV in STAR and compare with theoretical predictions.

STAR Experiment at RHIC





$0 < \phi < 2\pi$

$|\eta| < 1$

Adapted from Yang, Yi. The STAR Detector Upgrades for the BES-II and Beyond Physics Program.

- **Vertex Position Detector (VPD):**
  - Lead converters and plastic scintillators measure the position of the primary vertex and also to serve as a Minimum Bias trigger.
- **Time Projection Chamber (TPC):**
  - Tracking, Gas chamber for momentum measurement, charged particle identification (PID) via energy loss.
- **Time of Flight (TOF):**
  - Time of flight of particles for PID.
- **Barrel Electromagnetic Calorimeter (BEMC):**
  - Measurement of deposited energy of particles and also to serve as a High Tower Trigger.

Data Analysis

- Proton+proton collisions at √s = 510 GeV from Run 17 at STAR.

- Hadronic decay channels are used to reconstruct D^0 and D^*.

$$D^0(\bar{D}^0) \xrightarrow{B.R.=3.947\%} K^{\mp}\pi^{\pm}$$

$$D^{*\pm} \xrightarrow{B.R.=67.7\%} D^0(\bar{D}^0)\pi_s^{\pm} \xrightarrow{B.R.=3.947\%} K^{\mp}\pi^{\pm}\pi_s^{\pm}$$

- Dataset with Minimum Bias trigger:

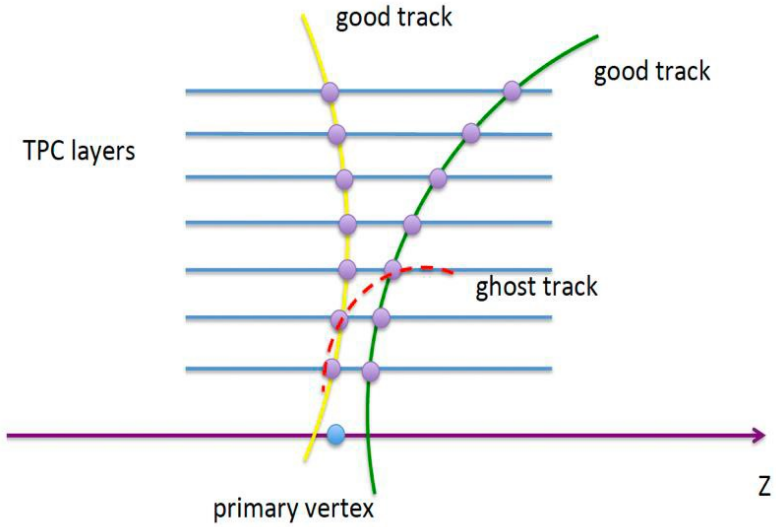
- Event Selection ⟶ Track Selection ⟶ Particle Identification ⟶ Signal Extraction ⟶ Raw-Yield Calculation ⟶ Efficiencies and Systematic Uncertanties

Event and Track Selection

- Event Selection
  - Pass the minimum bias trigger
  - $|V_z^{TPC}| < 60$ cm
  - $|V_z^{VPD} - V_z^{TPC}| < 4$ cm
  - $-0.3 \text{ cm} < V_x^{TPC} < 0.14$ cm
  - $-0.26 \text{ cm} < V_y^{TPC} < 0.02$ cm

~ 271 million events accepted out of
~ 1 billion triggered events

- Track Selection
  - number of TPC fit points > 18
  - $\frac{\text{number of TPC fit points}}{\text{number of max possible fit points}} > 0.52$
  - DCA to primary vertex < 1.5 cm.
  - $p_T > 0.2$ GeV/c
  - $|\eta| < 1.0$

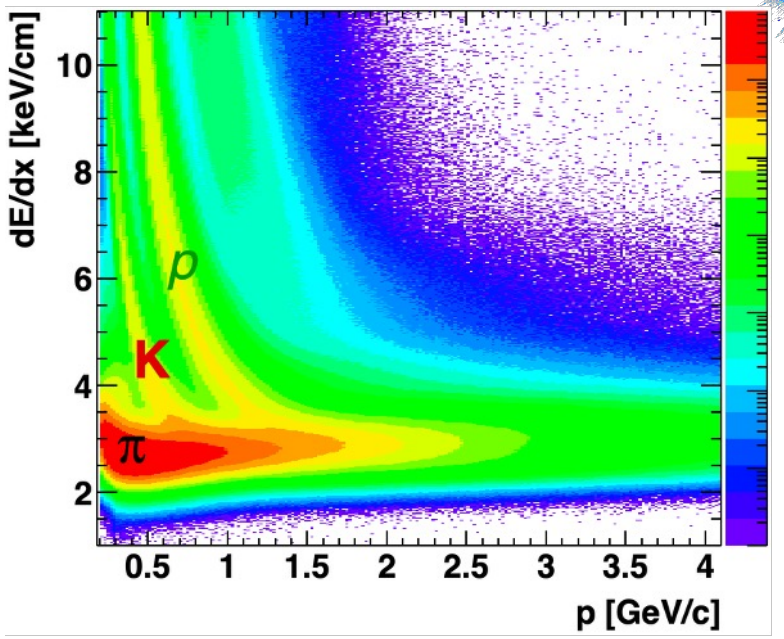


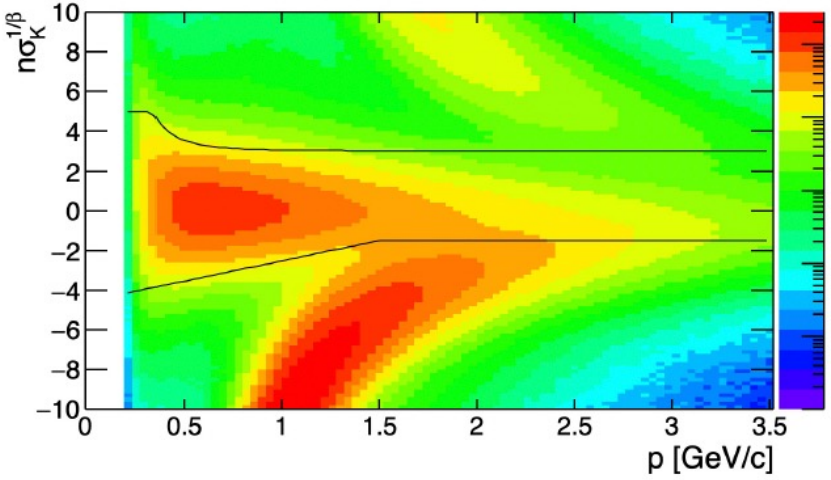
Particle Identification

$$n\sigma^{dE/dx} = \frac{\ln(dE/dx)_{\text{measured}} - \ln(dE/dx)_{\text{expected}}}{\sigma_{\ln(dE/dx)}}$$

$$n\sigma^{1/\beta} = \frac{1/\beta_{\text{measured}} - 1/\beta_{\text{expected}}}{\sigma_{1/\beta}}$$

	$p_T \leq 1.6$ GeV/c	$p_T > 1.6$ GeV/c
Kaons	$-2.5 < n\sigma_K^{dE/dx} < 3.0$ p dependent cut on $n\sigma_K^{1/\beta}$	$-2.5 < n\sigma_K^{dE/dx} < 3.0$ p dependent cut on $n\sigma_K^{1/\beta}$
Pions	$-3.0 < n\sigma_\pi^{dE/dx} < 3.0$ p dependent cut on $n\sigma_\pi^{1/\beta}$	$-3.0 < n\sigma_\pi^{dE/dx} < 3.0$ if TOF matched p dependent cut on $n\sigma_\pi^{1/\beta}$ if TOF matched $-2.5 < n\sigma_\pi^{dE/dx} < 2.5$ if no TOF info



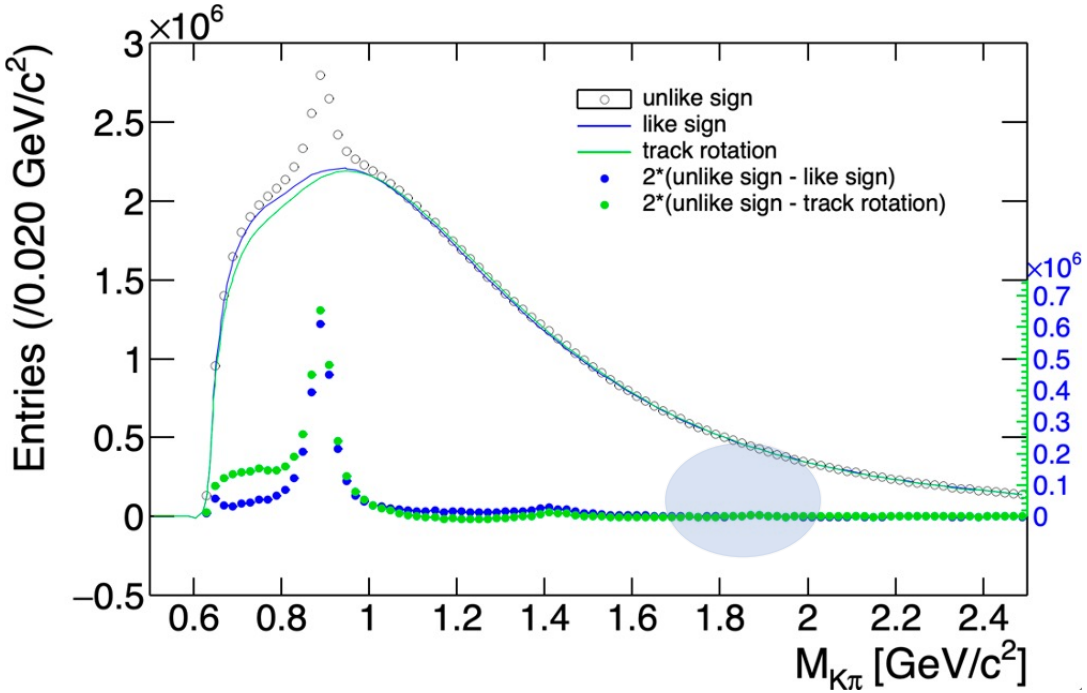


D^0 Analysis - Candidates and Combinatorial Background

- D^0 and $\overline{D^0}$ analyzed together to enhance signal for the measurement of charm production cross-section.

$$D^0(\bar{D}^0) \xrightarrow{B.R.=3.947\%} K^{\mp}\pi^{\pm}$$

- Unlike-sign pions and kaons were paired [$K^-\pi^+$, $K^+\pi^-$]



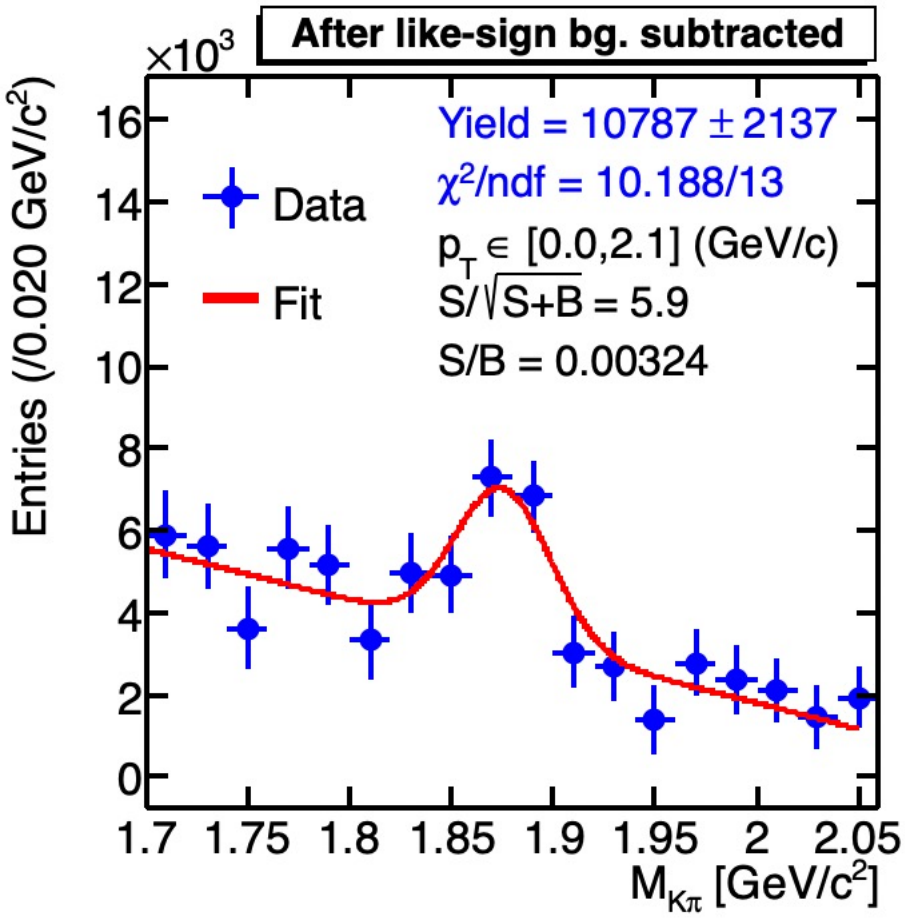
<u>For Combinatorial Background</u>

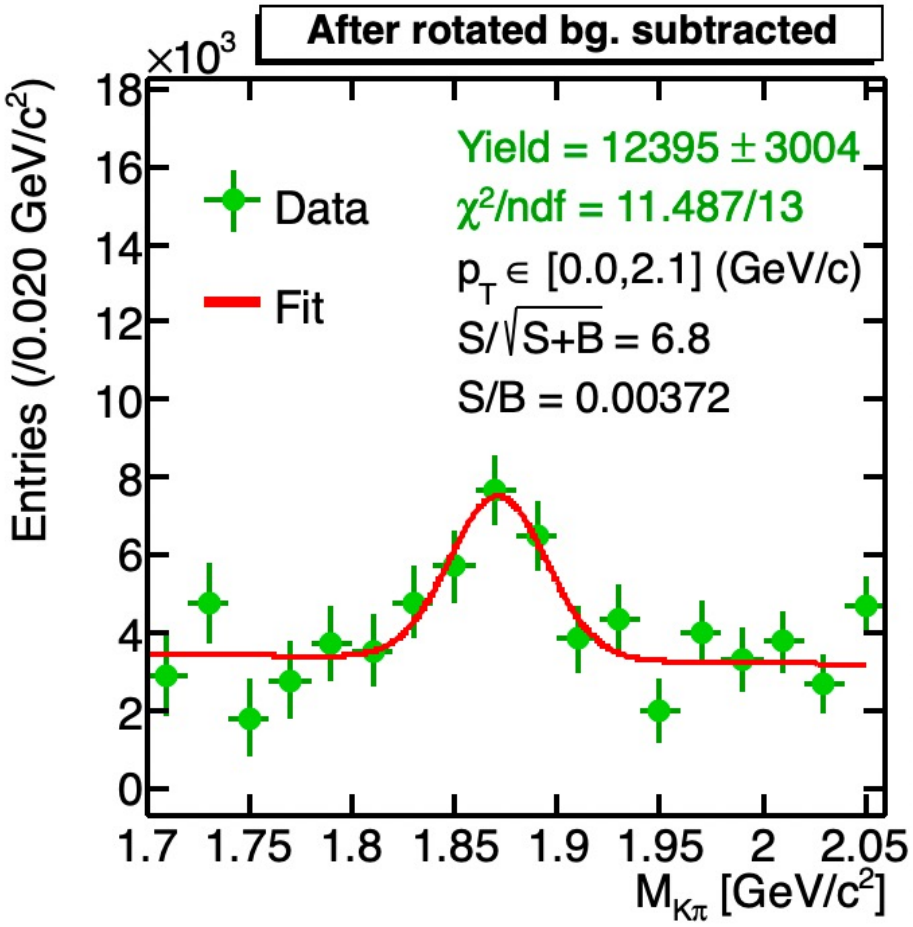
- Like-sign combination:
  - Pion tracks are paired with kaon tracks of the same charge.

- Track-Rotation:
  - Pion tracks are paired with kaon tracks with reversed 3-momentum (180° rotation).

$$m_{D^0} = \sqrt{(E_\pi + E_K)^2 - (\overrightarrow{p_\pi} + \overrightarrow{p_K})^2}$$

D^0 Analysis - Invariant Mass Distribution





- Background subtracted data were fitted with Gaussian +linear.
- Raw Yield is extracted from the area under the fitted Gaussian.
- Raw-yields from like-sign and track-rotation backgrounds agree within the uncertainties.

D* reconstruction - Background Estimation

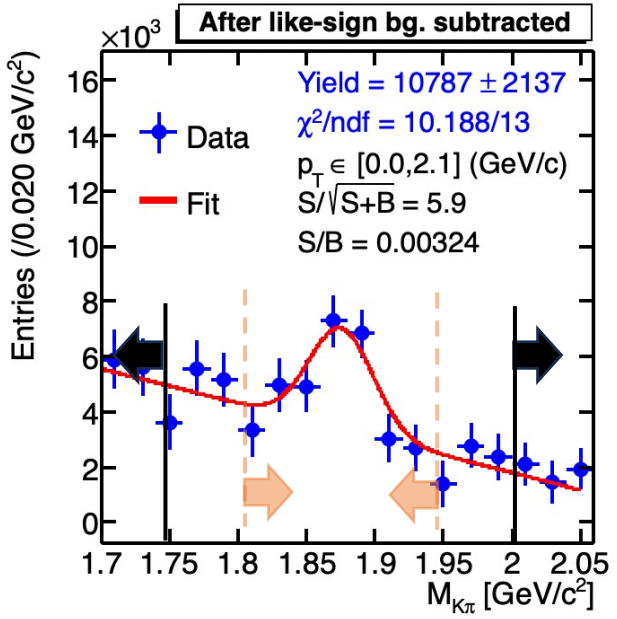
- Wrong-sign Method:
  - In the triplet of daughter particles, π had the opposite sign to π_s.

$$D^{*\pm} \xrightarrow{B.R.=67.7\%} D^0(\bar{D}^0)\pi_s^{\pm} \xrightarrow{B.R.=3.947\%} K^{\mp}\pi^{\pm}\pi_s^{\pm}$$

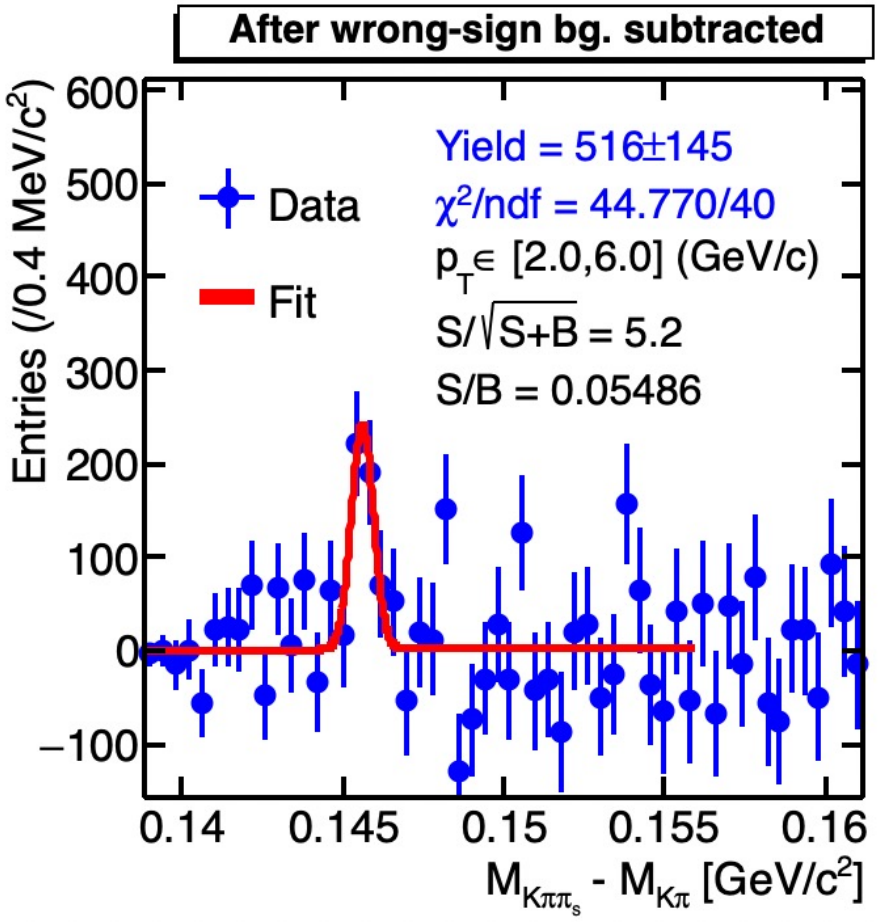
- Side-band Combination:
  - M_D had been lying between 1.64 and 1.74 or 2.01 and 2.11 GeV/c^2, i.e. outside the D^0 mass window.

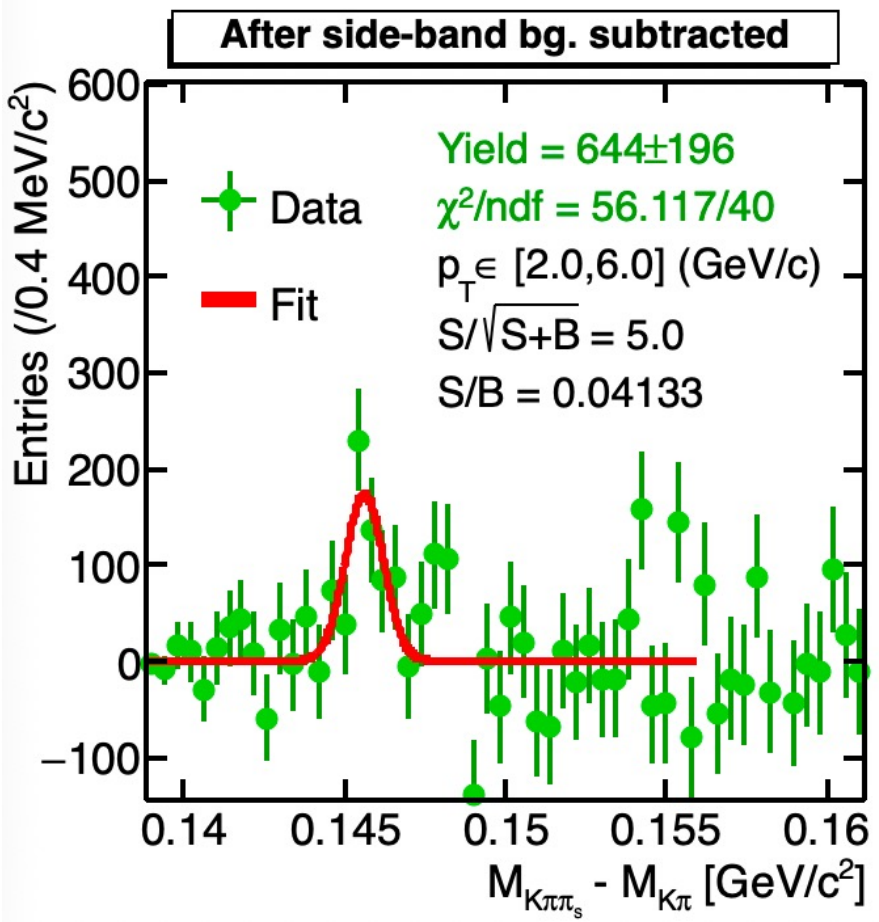
D^0 mass window:
$1.8 < M_D < 1.95$ GeV/c^2

- Raw yield of the D* meson is calculated as the area of the peak around 145.4. MeV/c^2 in $\Delta M = M_{K^{\mp}\pi^{\pm}\pi^{\pm}} - M_{K^{\mp}\pi^{\pm}}$, where, $M_{K^{\mp}\pi^{\pm}}$ is within D^0 mass window.



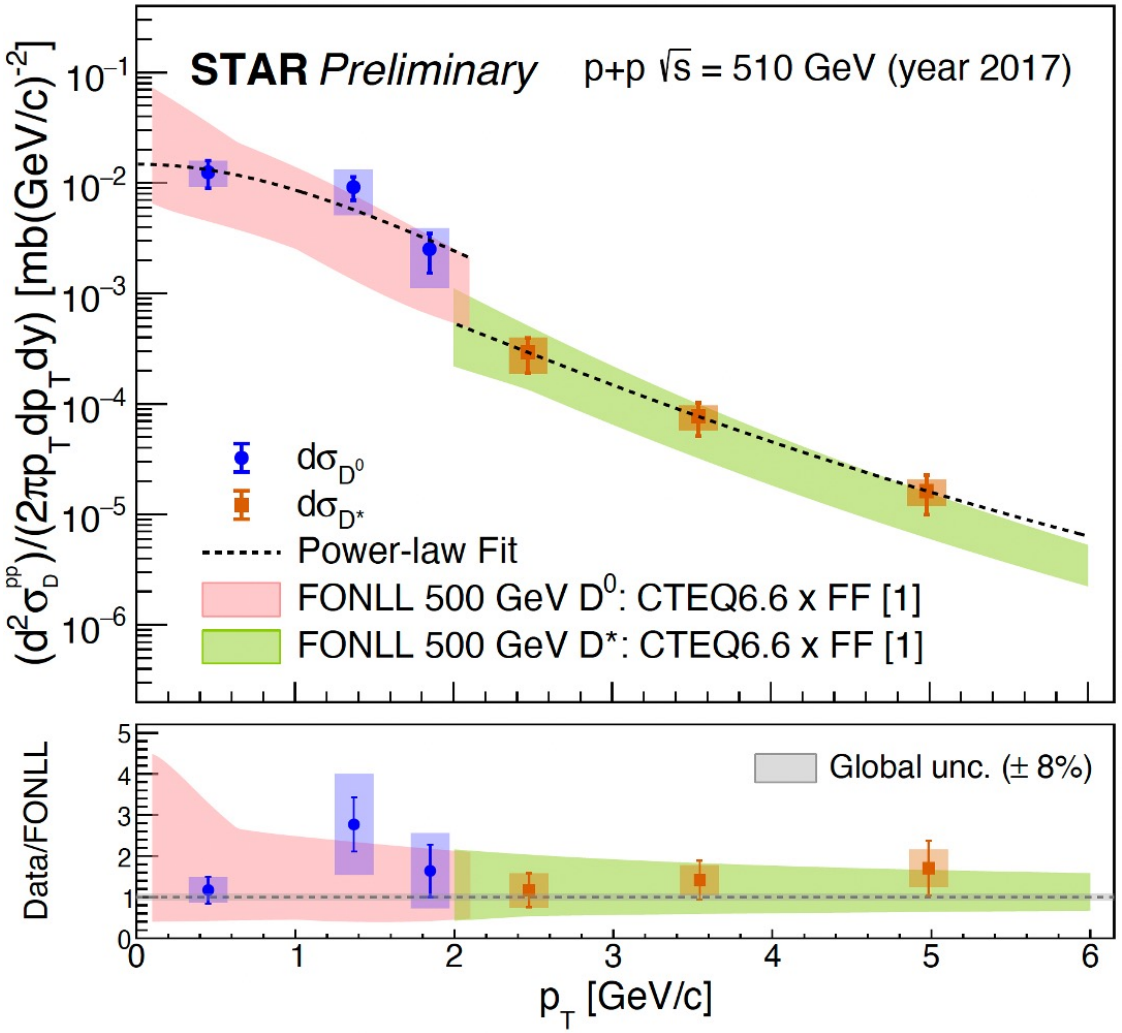
D* reconstruction – ΔM distribution

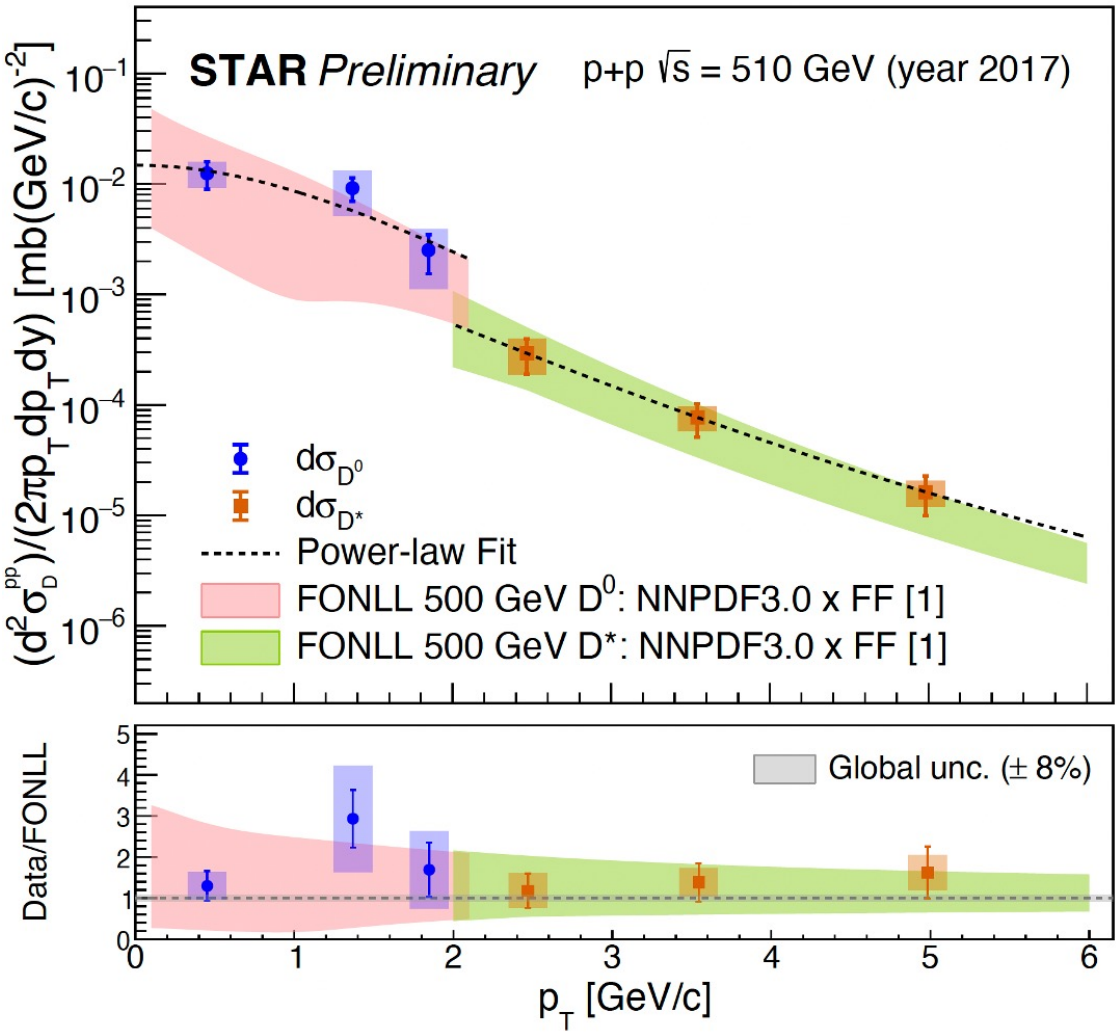




- Background subtracted data were fitted with Gaussian +linear.
- Raw Yield is extracted from the area under the fitted Gaussian.
- Raw-yields from wrong-sign and side-band backgrounds agree within the uncertainties.

D meson production cross-section



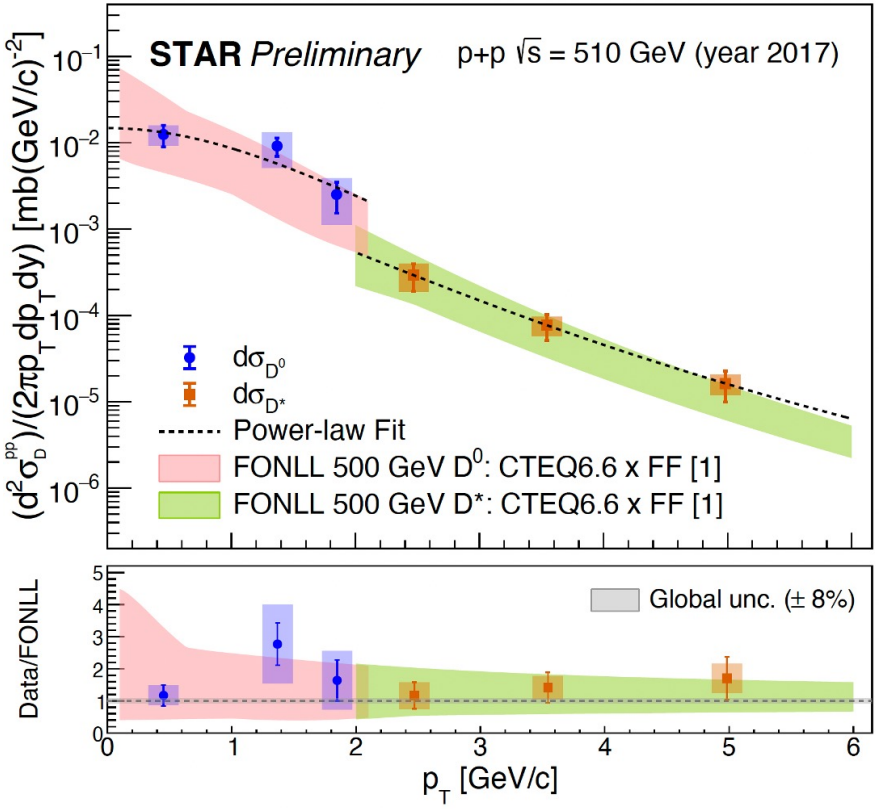


- Invariant cross-sections for D^0 and D* in p+p collisions at √s = 510 GeV are in good agreement with pQCD (FONLL) predictions using both CTEQ6.6 (left) and NNPDF3.0 (right) PDFs.

Summary and Outlook

- The measured D meson production cross-sections are consistent with the upper edge of the FONLL pQCD predictions within the current experimental uncertainties.

- The results will provide essential constraints on the energy dependence of charm production cross-sections, bridging the kinematic gap between RHIC (200 GeV) and LHC energies (2.76 TeV and above) and refining the theoretical baseline for heavy-ion studies.

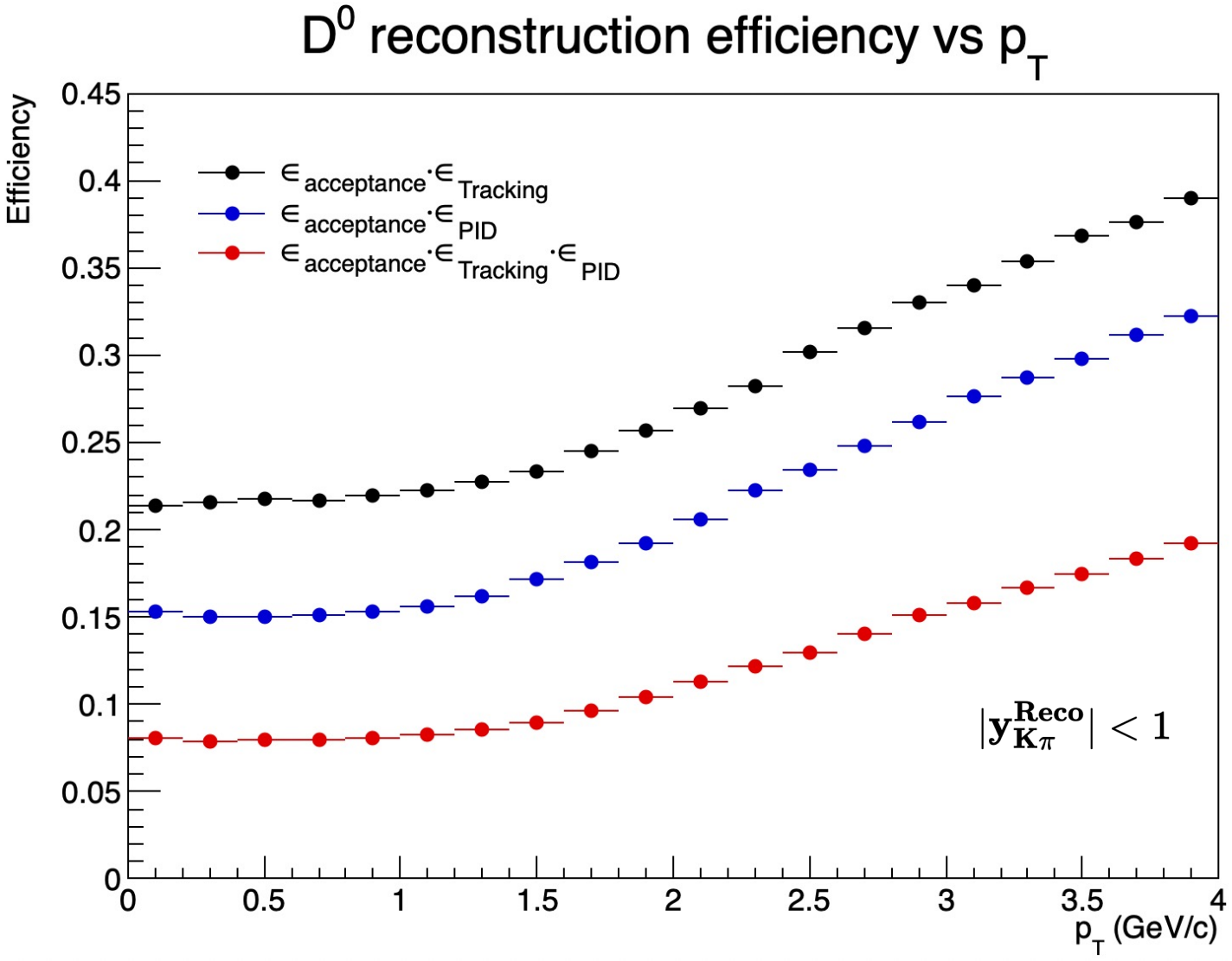


Thank You

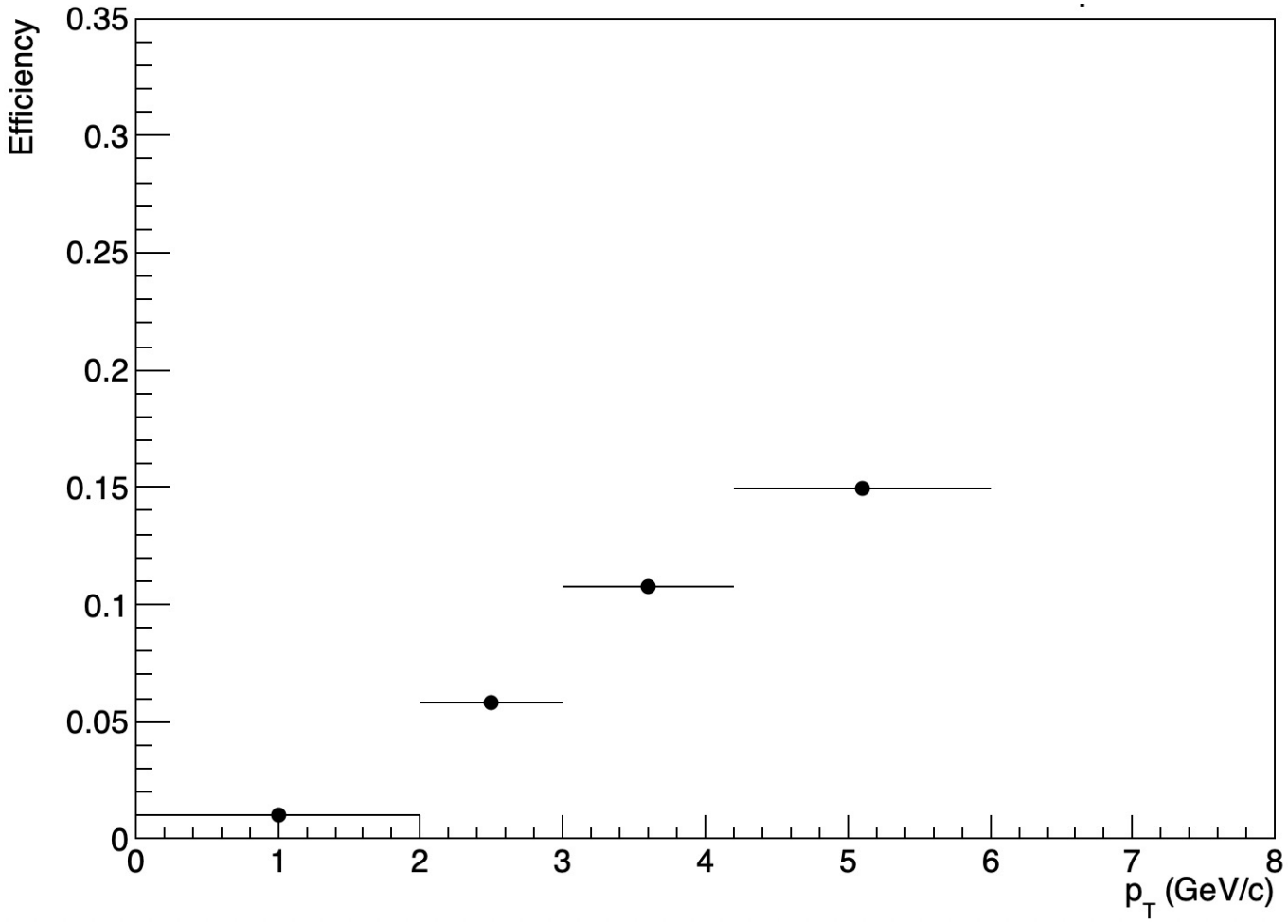
Backup

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\bigg|_{y=0} = \frac{\mathrm{d}^2\sigma}{2\pi p_T \mathrm{d}p_T \mathrm{d}y}\bigg|_{y=0} = \frac{1}{2}\frac{1}{2\pi}\frac{\sigma^{\mathrm{NSD}}\beta}{N f_c \Gamma}\frac{Y}{p_T \Delta p_T \Delta y}\frac{1}{\varepsilon}$$

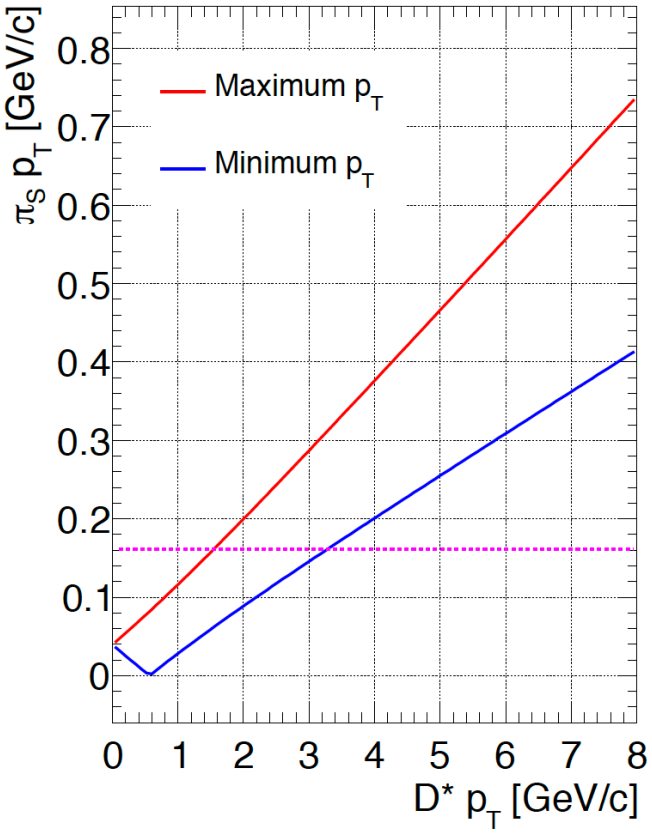
D^0 Reconstruction Efficiency



D^* Reconstruction Efficiency



- If TOF has been used to identify the D* decay daughters the track needs to have a p_T of at least 0.16 GeV/c. Based on the D* decay kinetics, the D* p_T in that case ranges from 1.5 – 3.0 GeV/c.



.1: Kinematically possible values of the soft pion transverse momentum from the $D^* \rightarrow D^0\pi_S$ decay.