Measurement of the open charm cross-section

in 200 GeV Cu+Cu collisions using STAR @ RHIC

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for the STAR collaboration

Physics motivations

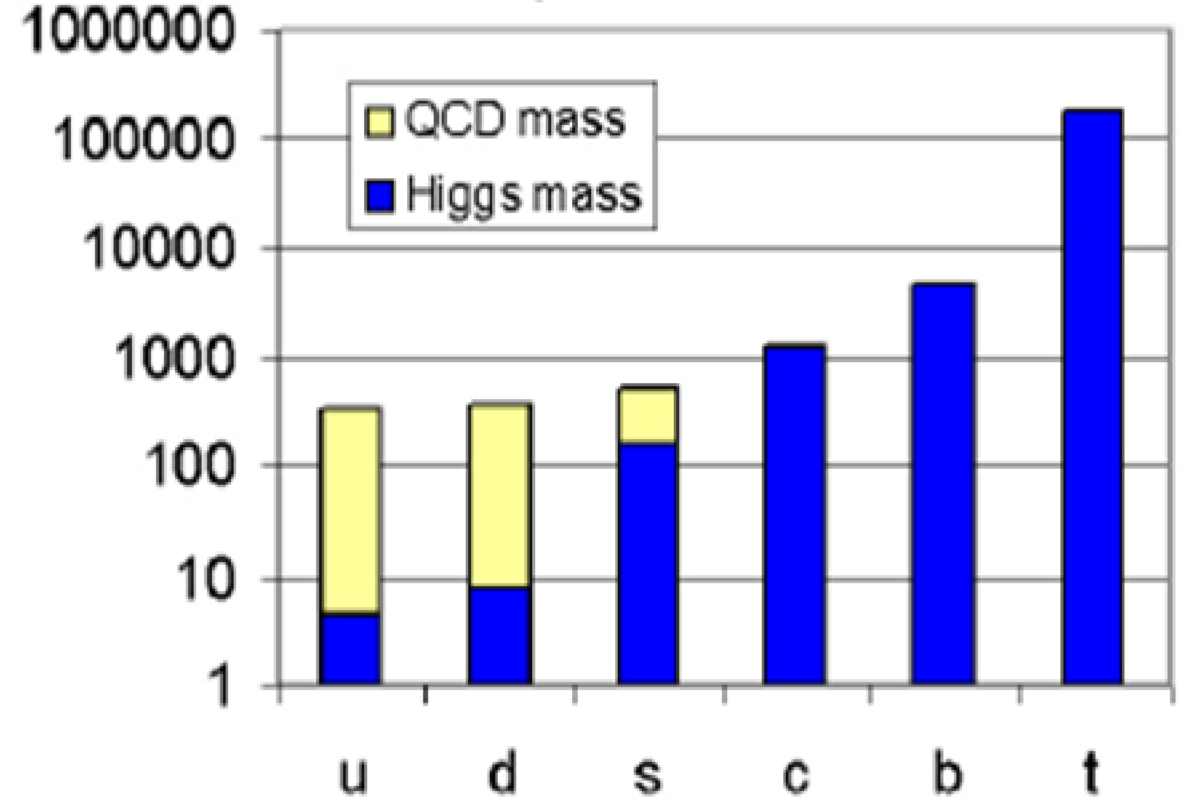
Charm:

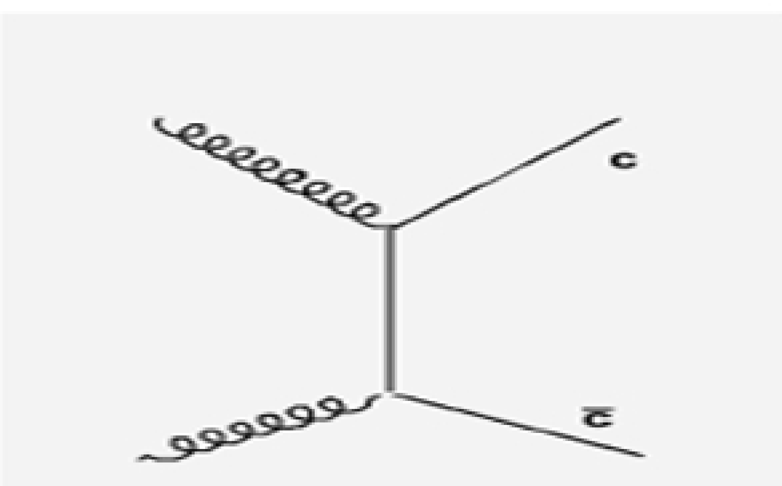
- is primarily produced by **gluon fusion**
  - little contribution from **gluon splitting**
    (see talk by A. Mischke and poster by X. Dong).
- **is sensitive to early stage of the collision**
  (quark produced at $\tau \sim \hbar / 2m_Q c^2 \sim 0.1\ fm/c$)
- has an undisturbed **mass**
- large uncertainty in pQCD
  - α_s large
  - **gluon PDF** undetermined

  for $P_T < M_c$

  → the cross-section is little constrained by theory

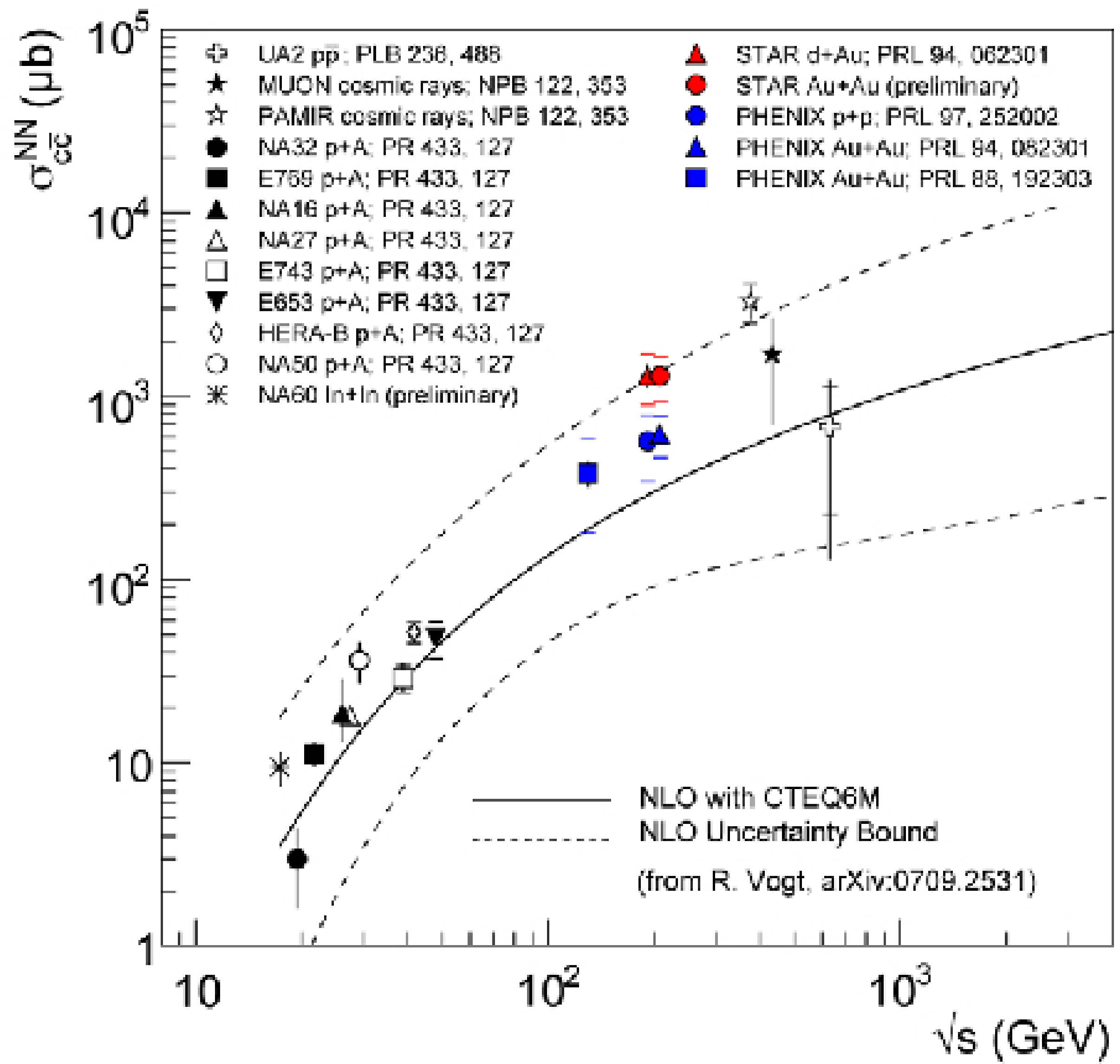
B. Müller, nucl-th/0404015



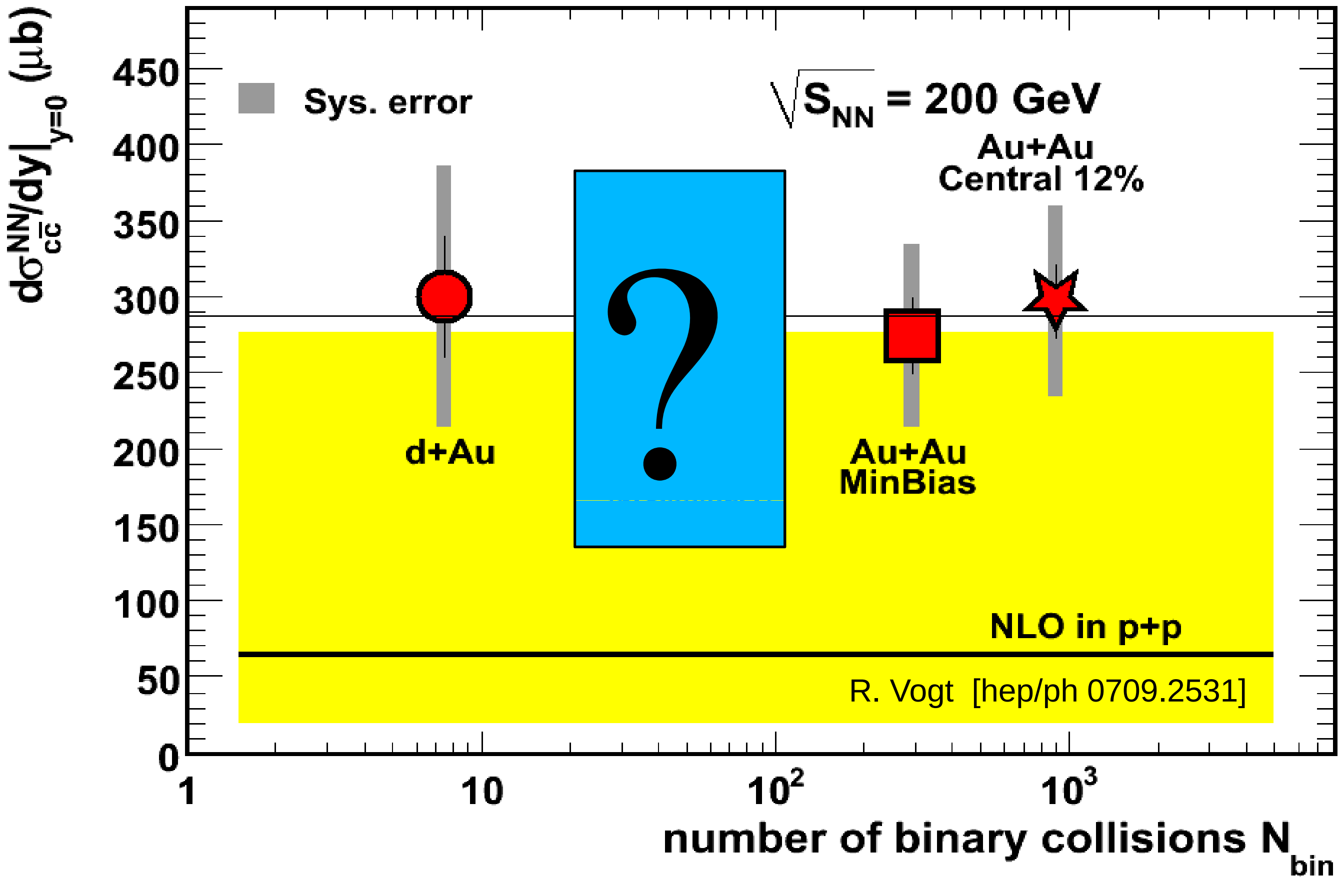


NLO: $301 \, ^{+1000}_{-210}$ μb

R. Vogt hep/ph 0709.2531



Binary scaling



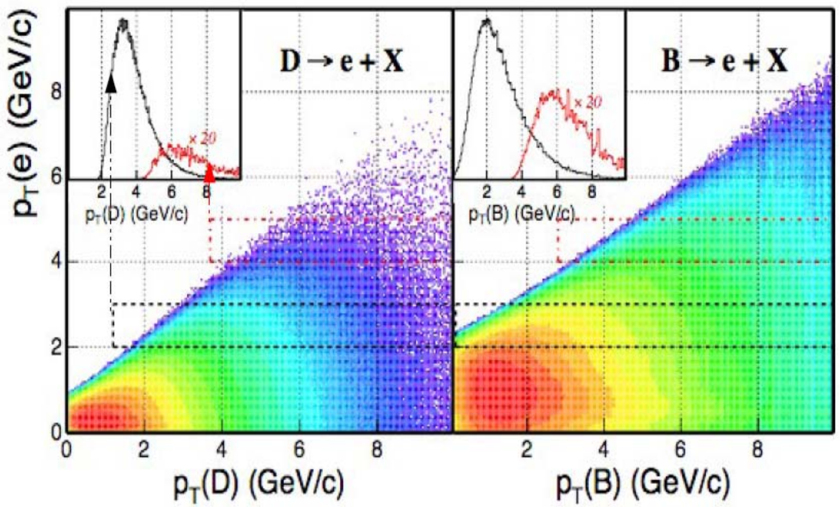
Charm production is a hard process: expect binary scaling.
Data so far supports this ⇒ d+Au to Au+Au.
What about Cu+Cu?

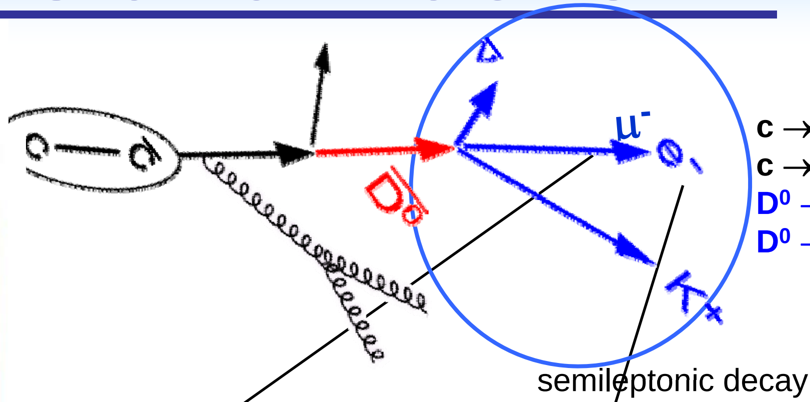
Open charm measurements

via semileptonic decays

Electrons and Muons….

Measured by STAR and PHENIX





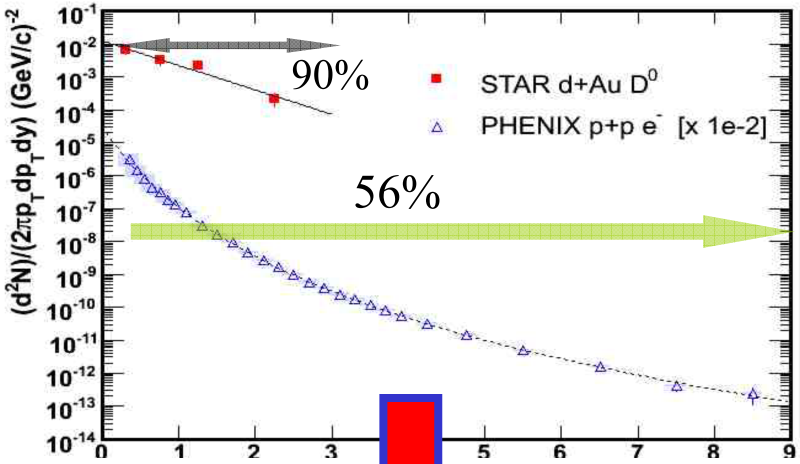
$c \to e^+ + X$
$c \to \mu^+ + X$
$D^0 \to e^+ + X$ (6.87 %)
$D^0 \to \mu^+ + X$

o **muon** from heavy quark semileptonic decay

o **electron** from heavy quark semileptonic decay

- ⬆ Straightforward using detectors with **e^- PID** (TPC, EMC and TOF)
- ⬇ Background is difficult to assess (photonic)
- ⬇ Limited to higher **P_T**
- ⬇ **e^-** does not reflect full **D** kinematics

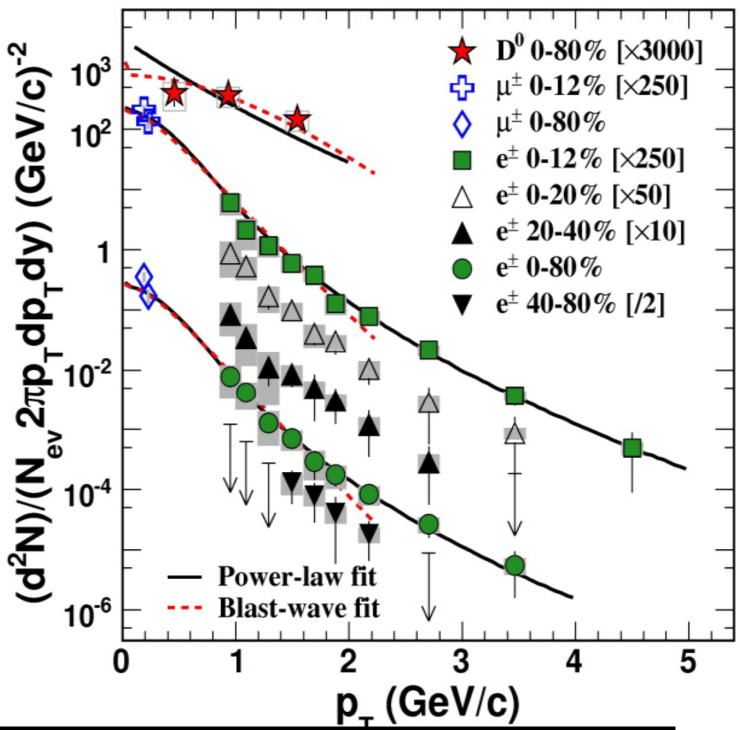
Charm Cross-Section to Date



- Precise measurements at low P_T are important
- e^- are weakly correlated to heavy quarks (fraction coming from both D and B)

→ **Need direct measurements**

Non photonic electrons, Muons and D mesons



Cross-section measurements so far:

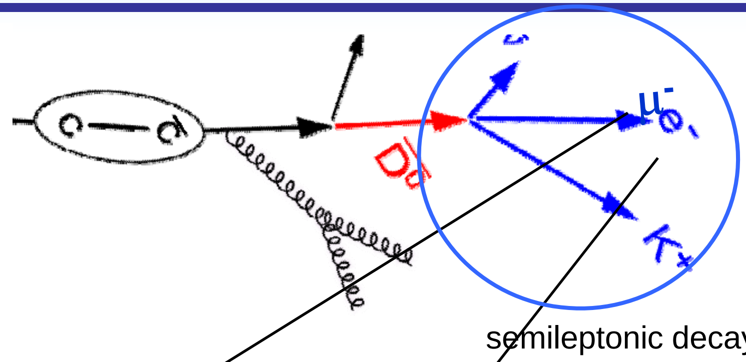
		p+p	Au+Au (MinBias)	d+Au
STAR	driven by D mesons		1.26 ± 0.09 ± 0.23	1.4 ± 0.2 ± 0.4
PHENIX	from electrons	0.567 ± 0.057 ± 0.224	0.622 ± 0.057 ± 0.160	

What about Cu+Cu?

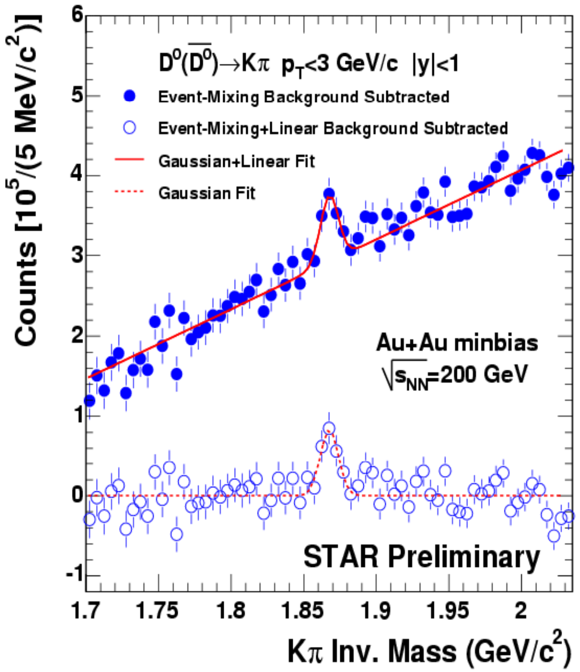
Open charm measurements

via hadronic decays

Direct reconstruction



$c \rightarrow e^+$ + anything
$c \rightarrow \mu^+$ + anything
$D^0 \rightarrow e^+$ + anything
$D^0 \rightarrow \mu^+$ + anything



- o **muon** from heavy quark semileptonic decay
- o **electron** from heavy quark semileptonic decay
- o **hadronic** “Direct“ D^0 reconstruction

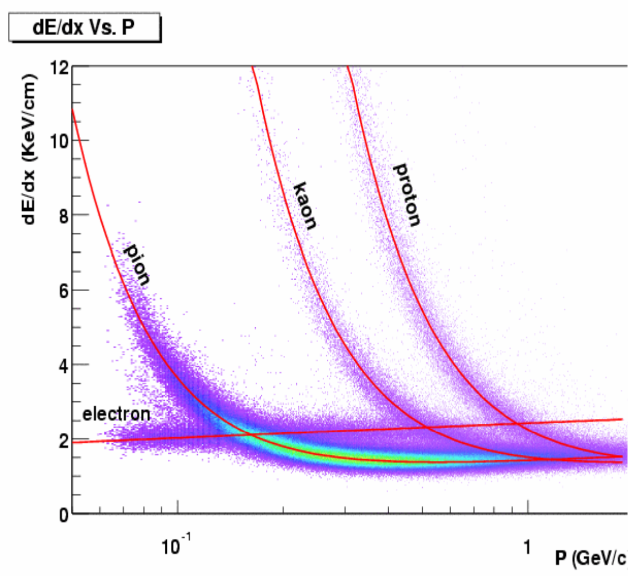
(event. Mixing technique)

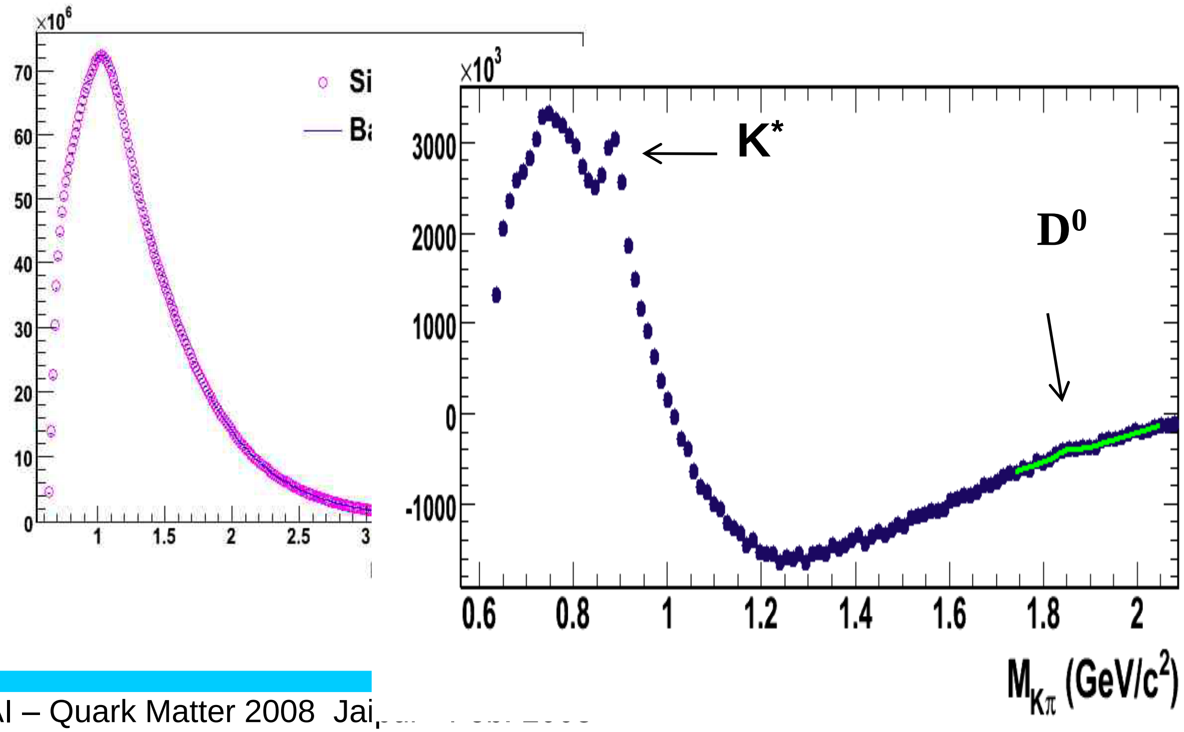
D^0 hadronic decay
reconstructed in minimum bias collision
(unique @ RHIC)

- ⬆ Direct measurement, covers **large fraction** of the **cross-section**
- ⬇ **Large** combinatorial background
- ⬇ High precision **vertexing** is needed

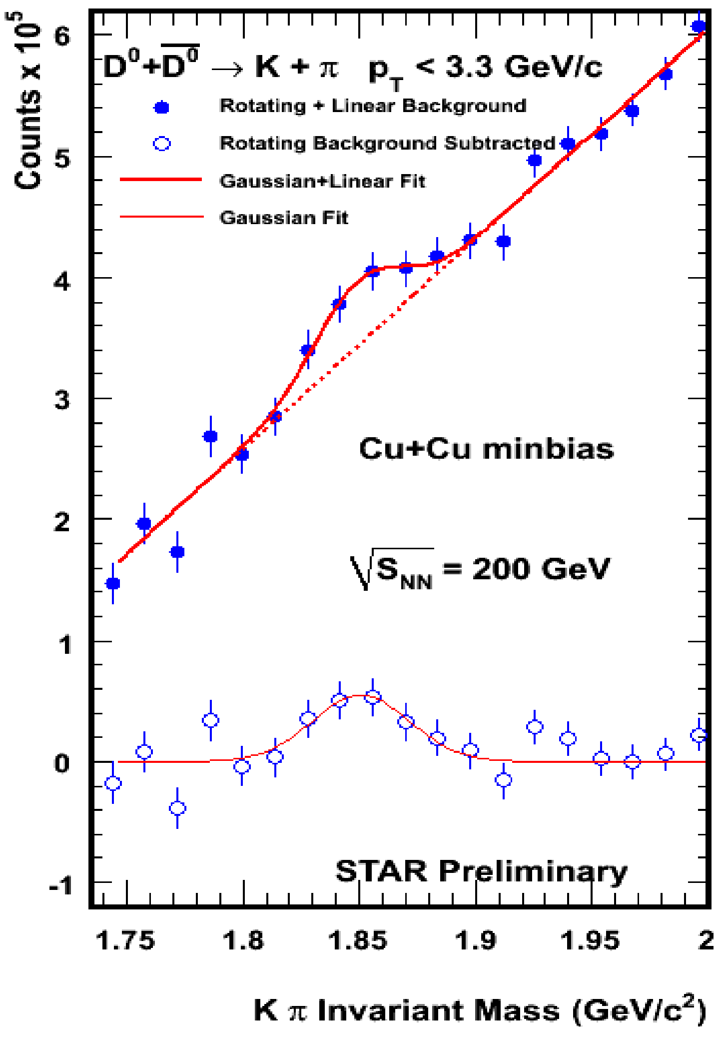
Direct D^0 reconstruction in STAR

- Pions and Kaons are selected using the TPC
- Combine “same event” pairs ⇒ signal+background
- Combine pairs coming from different events ⇒ background
  (“mixed events” or “track rotating ”)
- After subtraction ⇒ signal





Cu+Cu collisions @ 200 GeV



~ 28 Million events used

All the statistics available

Cu+Cu « minimum bias » (RHIC run V)

❖ After track rotating or mixed event subtraction: residual background

❖ Low S/B ratio:

$$\frac{S}{B} \approx \frac{1}{600}$$

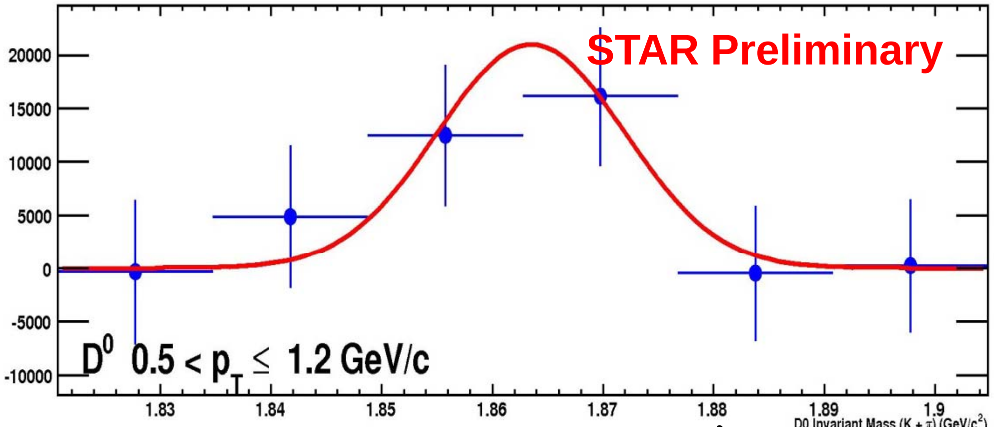
$$\frac{S}{\sqrt{S+B}} \approx 4$$

❖ Measurement only possible because of large S (~ 150 000)

❖ Large STAR acceptance !

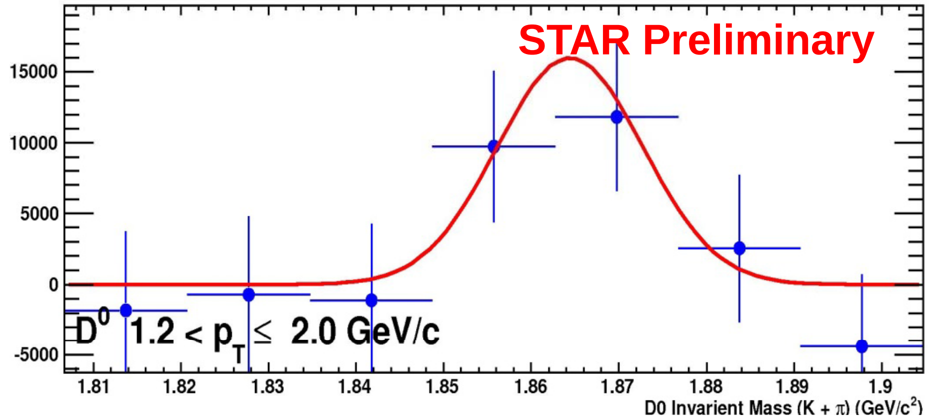
→ Challenging measurement

p_T bins

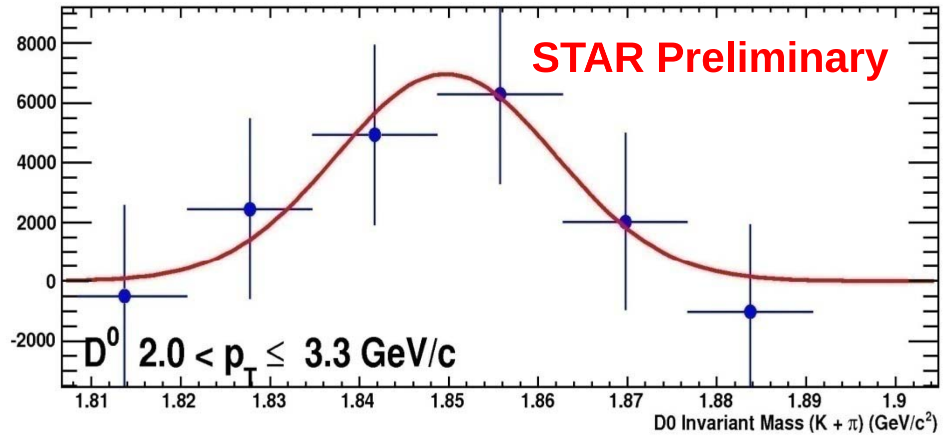


D^0 Mass in **agreement with the PDG**

(M_{D^0} =1864.84 ± 0.17 MeV/c^2)

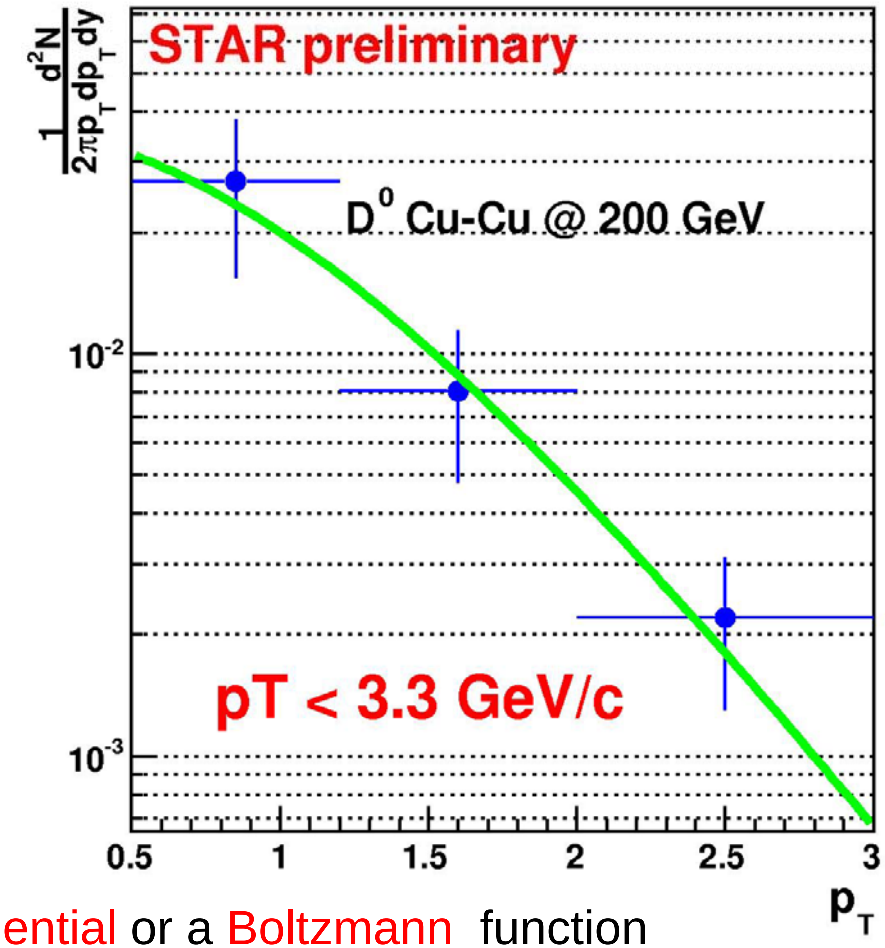


P_T (GeV/c)	**Mass** (GeV/c^2)	**Width** (MeV)
0.5-1.2	1.864 ± 0.005	8.4 ± 8.7
1.2-2.0	1.864 ± 0.005	8.3 ± 13
2.0-3.3	1.850 ± 0.015	12 ± 18



Spectra

After corrections:



$\frac{D^0 + \overline{D^0}}{2}$ Preliminary

$dN/dy = 0.18 \pm 0.035$

Fit using an Exponential or a Boltzmann function

→ **same results** (within stat. errors).

Extraction of the cross-section

$$\sigma_{c\bar{c}}^{NN} = \frac{dN_{D^0}^{Cu+Cu}}{dy} \times \frac{\sigma_{inel}^{pp}}{N_{bin}^{Cu+Cu}} \times \frac{f}{R}$$

$$dN_{D^0} / dy = 0.18 +/- 0.035 \text{ (stat.)}$$

Number of binary collisions (Glauber)

$$N_{binary}^{Cu+Cu} = 51.5 + 1.0 - 2.9$$

Inelastic cross-section in p+p (UA5)

$$\sigma_{inel}^{pp} = 41.8 +/- 0.6 \text{ mb}$$

Conversion to full rapidity (Pythia)

$$f = 4.7 \pm 0.7$$

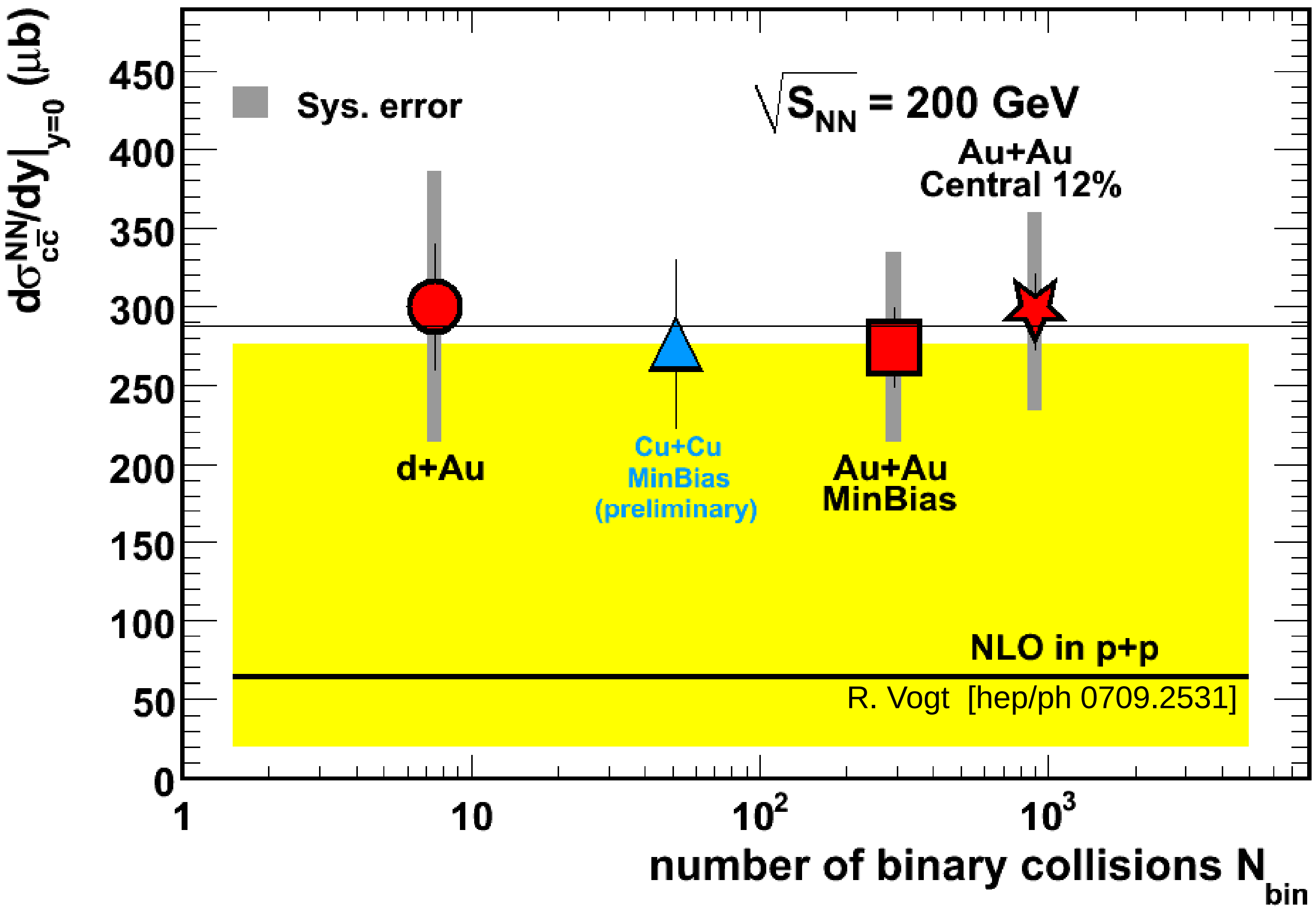
Ratio obtained from e^+e^- collisions

$$R = N_{D^0} / N_{c\bar{c}} = 0.54 \pm 0.05$$

STAR Preliminary:

$$\Rightarrow \sigma_{c\bar{c}}^{NN} = 1.30 \pm 0.25 \, (stat.) \, mb$$

d σ/dy in STAR...



- Accurate background subtraction is crucial
- Systematic study is ongoing

Scaling with the number of binary collisions from d+Au to Au+Au **confirmed in Cu+Cu.**

Summary

Today:

- The charm cross-section was measured in Cu+Cu @ 200 GeV ; $\sigma_{c\bar{c}}^{NN} = 1.30 \pm 0.25\, mb$
- A direct measurement in Cu-Cu is **consistent with a scaling of the cross-section with N_{bin} (at low pT)**.
- Theory: **large uncertainty in pQCD calculations** and **data points are needed.**

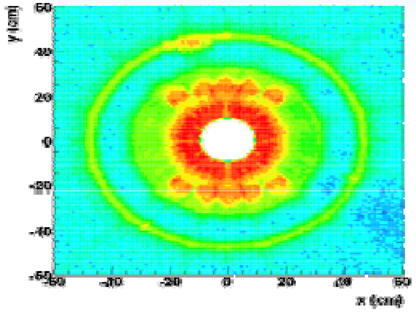
In the Future:

- STAR **low material runs**
- use of **SSD/SVT** and eventually the **HFT** upgrade (2010-2012)

will allow:

- **precise measurements** of the charm cross-section
- direct **topological** measurements of charm and of its **anisotropy parameter V_2,** R_{AA}, R_{CP}
- isolation of the **bottom contributions**

Outlook



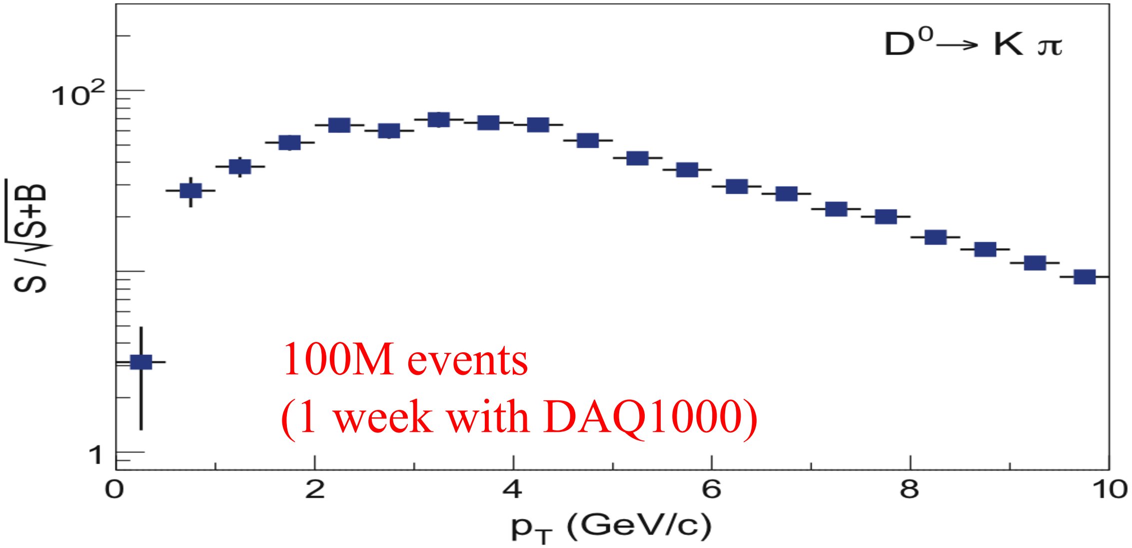
❖ Low material run (without the SVT/SSD)
→ low radiation length in run VIII
→ reduce the photonic background

❖ Reconstructing the secondary vertex with SVT/SSD in Au+Au (run VII)

❖ « Upgrade » for RHIC2

and especially

The future STAR ***Heavy Flavor Tracker***



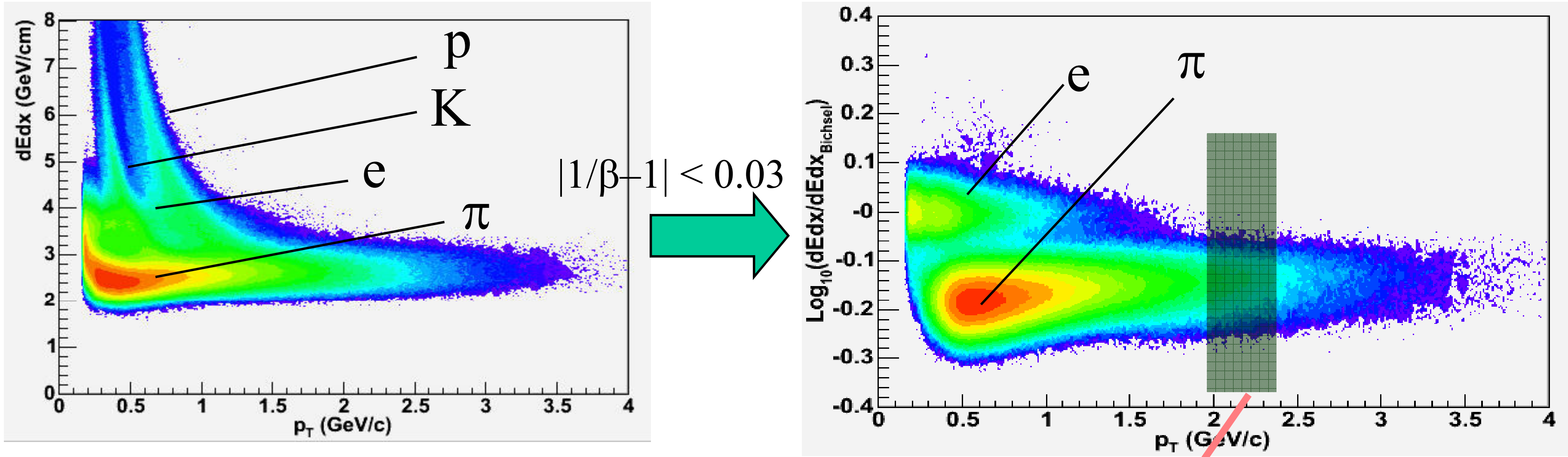
→ **Direct and topological measurements of charm and precise V_2**

See the HFT poster
by Jan Kapitan
(for the STAR HFT collaboration)

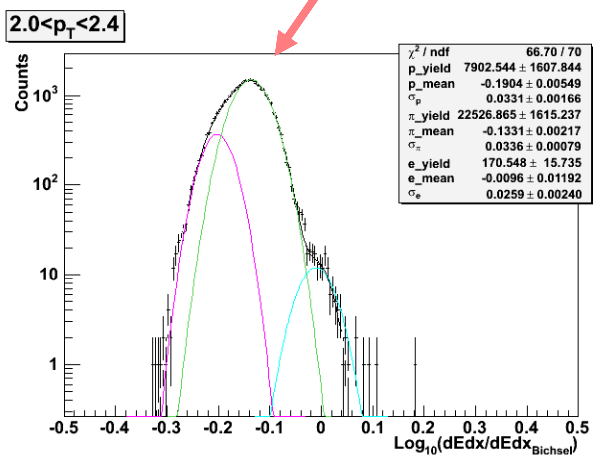
Backup

PID

Electron ID - TOF

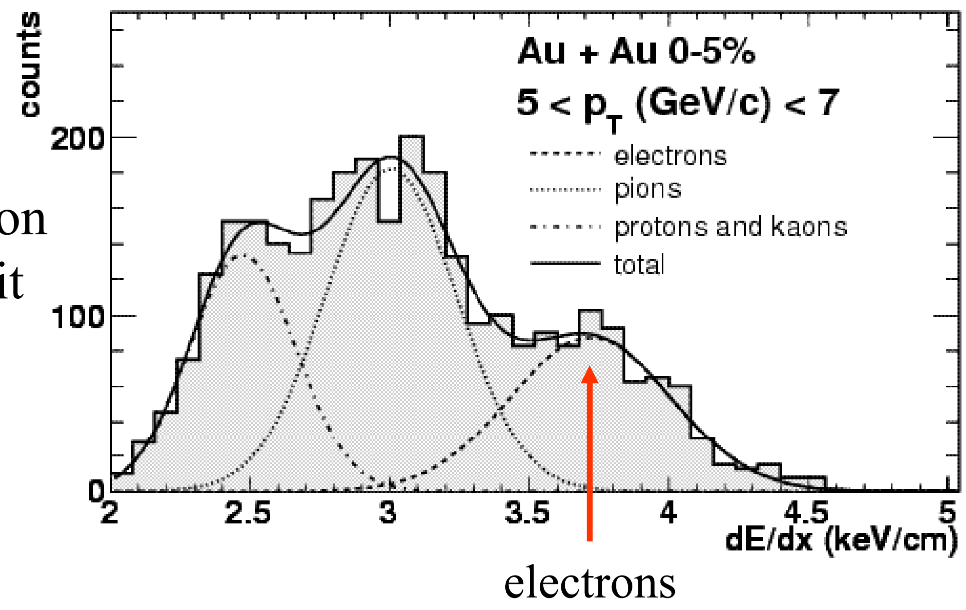


- TOF measures particle velocity
- TPC measures particle energy loss
- The cut $|1/\beta-1|<0.03$ with TOF excludes kaons and protons
- TPC dE/dx further separates the electron and pion bands

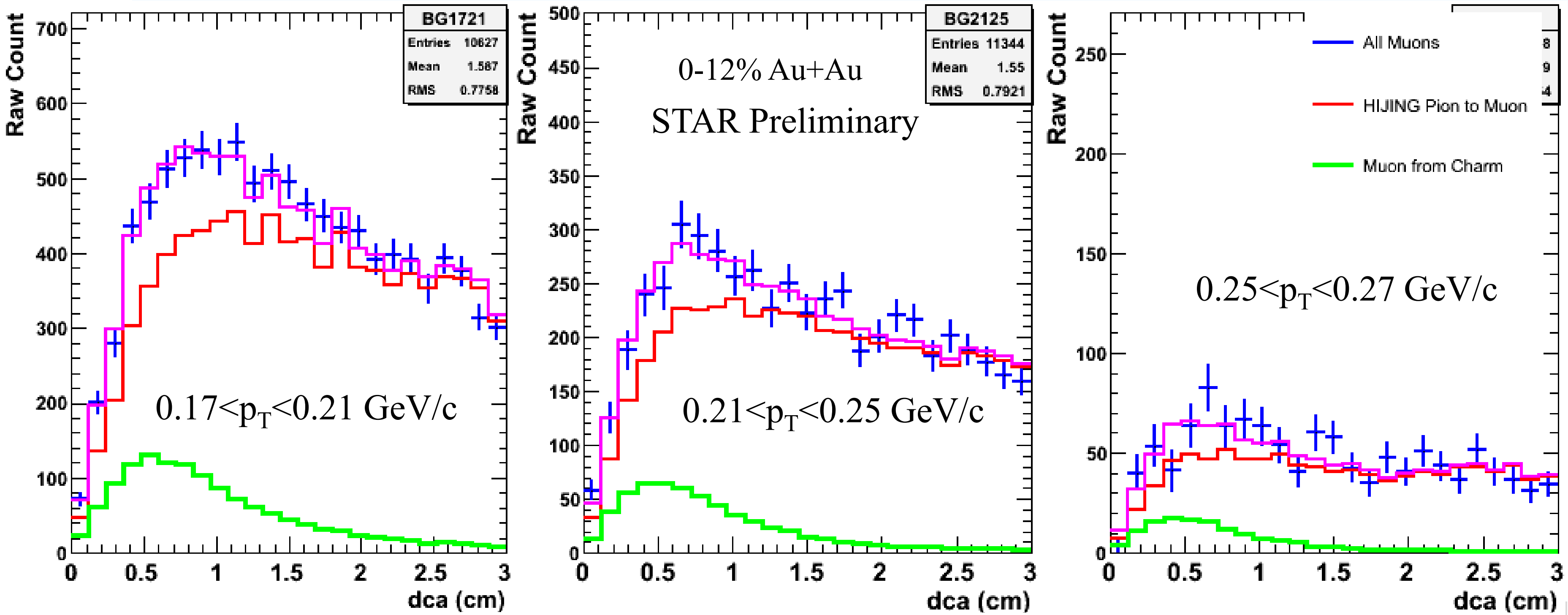


Electron ID - EMC

- Charged tracks selected by TPC
- EMC Tower hits association with TPC tracks required
- Momentum/Energy ratio is cut to be around one for electron candidates
- Shower size measured by Shower Max Detector (SMD)
  - Small shower size for hadrons
  - Large shower size for electrons
- Both inclusive electron yield and hadron contamination obtained from Gaussian fit



Muon ID – TPC + TOF



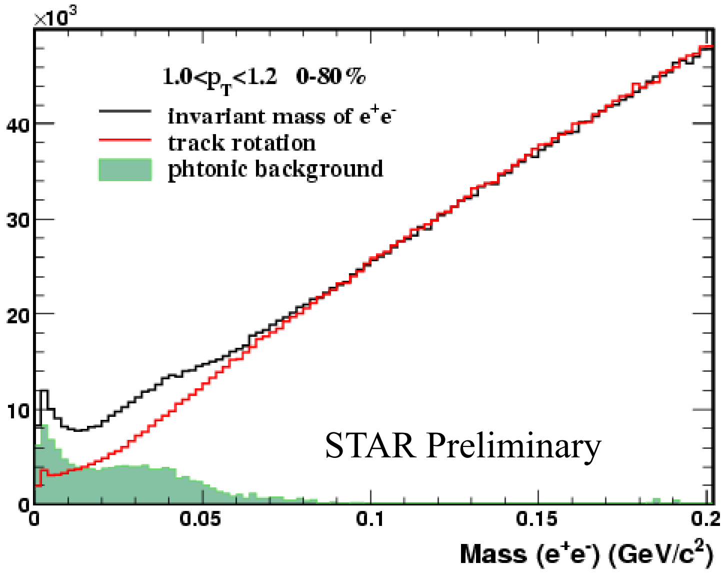
$D^0 \rightarrow \mu^+ + anything$ Branch Ratio: $(6.5 \pm 0.8)\%$

- Muon and pion bands slightly separated at low momentum in TPC
- TOF can further help to identify muons in mass^2 distribution
- Backgrounds are mainly from $\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \nu^{\mu}$ decays, can be subtracted from DCA distributions $\Rightarrow$ charm decayed muons!!

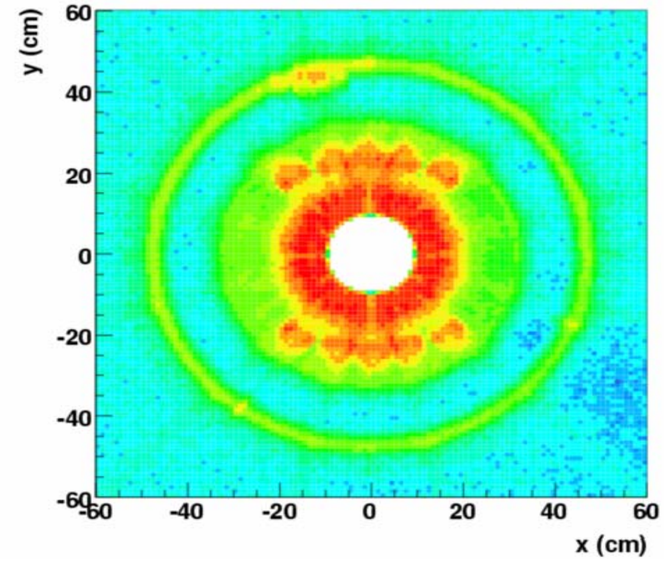
Photonic Background

γ conversion
π^0 Dalitz decay
η Dalitz decay
Kaon decay
vector meson decays

} Dominant source at low p_T

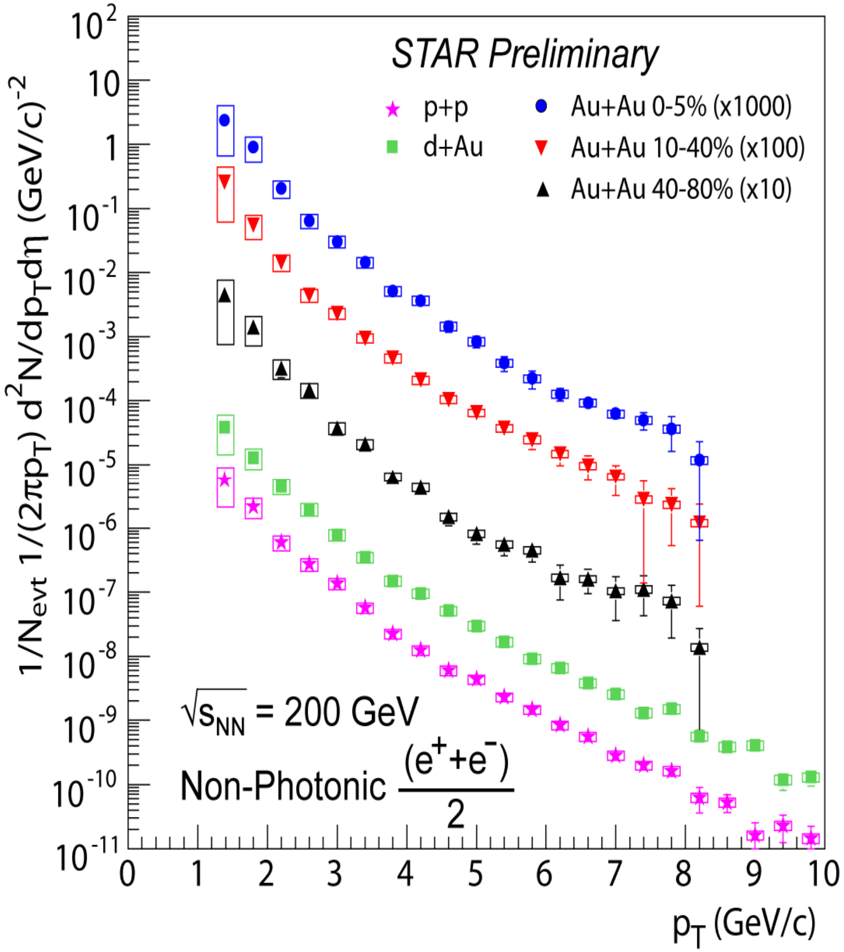


- For each tagged e^+(e^-), we select a partner e^- (e^+) identified only with the TPC and calculate the invariant mass of the pair.
- Combinatorial background reconstructed by track rotating or like-sign technique.
- Photonic background is subtracted in a statistical manner: Nphotonic = (un_like – rotating)/bkgrd_eff



NPE

Non Photonic Electron Spectra

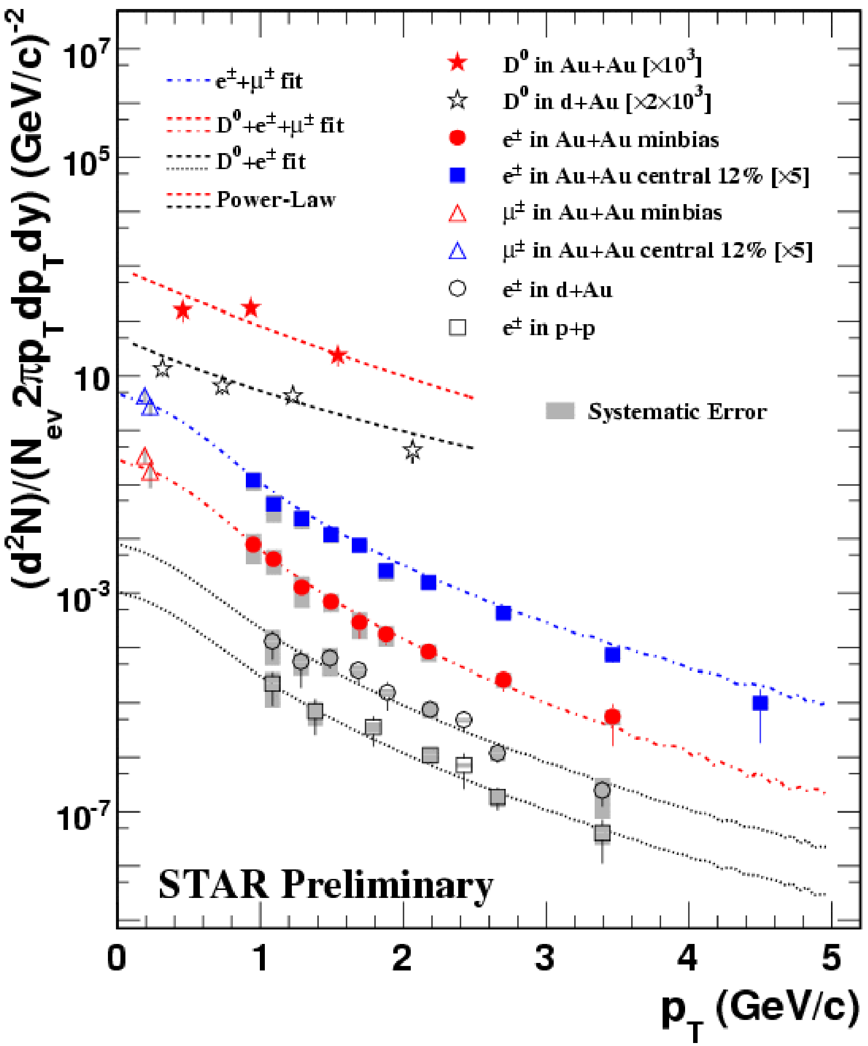


- TOF non-photonic electron spectra are measured in p+p, d+Au, Au+Au minbias, 0-12%, 0-20%, 20-40%, 40-80%

- EMC non-photonic electron spectra are measured in p+p, d+Au, Au+Au 0-5%, 10-40%, 40-80%

- Non-photonic electron spectra measured by TOF and EMC are consistent with each other by proper N_{bin} scaling

Combined Fit



D^0, $e^{\pm}$, $\mu^{\pm}$ combined fit

- Power-law function with parameters dN/dy, $<p_T>$ and n to describe the D^0 spectrum
- Generate $D^0 \rightarrow e$ decay kinematics according to the above parameters
- Vary (dN/dy, $<p_T>$, n) to get the min. χ^2 by comparing power-law to D^0 data and the decayed e shape to $e^{\pm}$ and $\mu^{\pm}$ data
- Spectra difference between $e^{\pm}$ and $\mu^{\pm}$ ~5% (included into sys. error)
- Advantage: D^0 and $\mu^{\pm}$ constrain low p_T $e^{\pm}$ constrains higher p_T

Others

The charm cross-section

$$\sigma_Q(S,m^2) = \sum_{i,j} dx_1 dx_2 \hat{\sigma}_{ij}(x_1 x_2 S, m^2; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2) F_{i/A}(x_1,\mu_F) F_{i/B}(x_2,\mu_F) + O\left(\frac{\Lambda}{m}\right)^p$$

Hard scattering | Parton Distribution Functions (**PDF)** | Corrections

Calculation:

- NLO QCD + resummations
- minimal & properly extracted NP fragm.
- **Simulation (MC) of decay**

$$pp \xrightarrow{pQCD} Q \xrightarrow{NP\,fragm.} H_Q \xrightarrow{decay} e$$

For predicting total cross sections one can stop here

NLO: 301^{+1000}_{-210} μb

R. Vogt hep/ph 0709.2531

FONLL: $256^{+400}_{-146}\,\mu b$

M. Cacciari *et al.*, *PRL 95 (2005) 122001*

Experiment :

$$\frac{d\sigma_H}{dp_T} = \frac{d\sigma_Q}{dp_T} \otimes D^{np}$$

- **pQCD + PDF** → $\frac{d\sigma_Q}{dp_T}$
- **Fragmentation Functions** → D^{np}
- $\frac{d\sigma_H}{dp_T}$: ***Measured (differential) cross section***
- $\frac{d\sigma_Q}{dp_T}$: NLO (+NLL) calculation
- D^{np}: non-perturbative fragmentation (usually extracted from e+e- data)

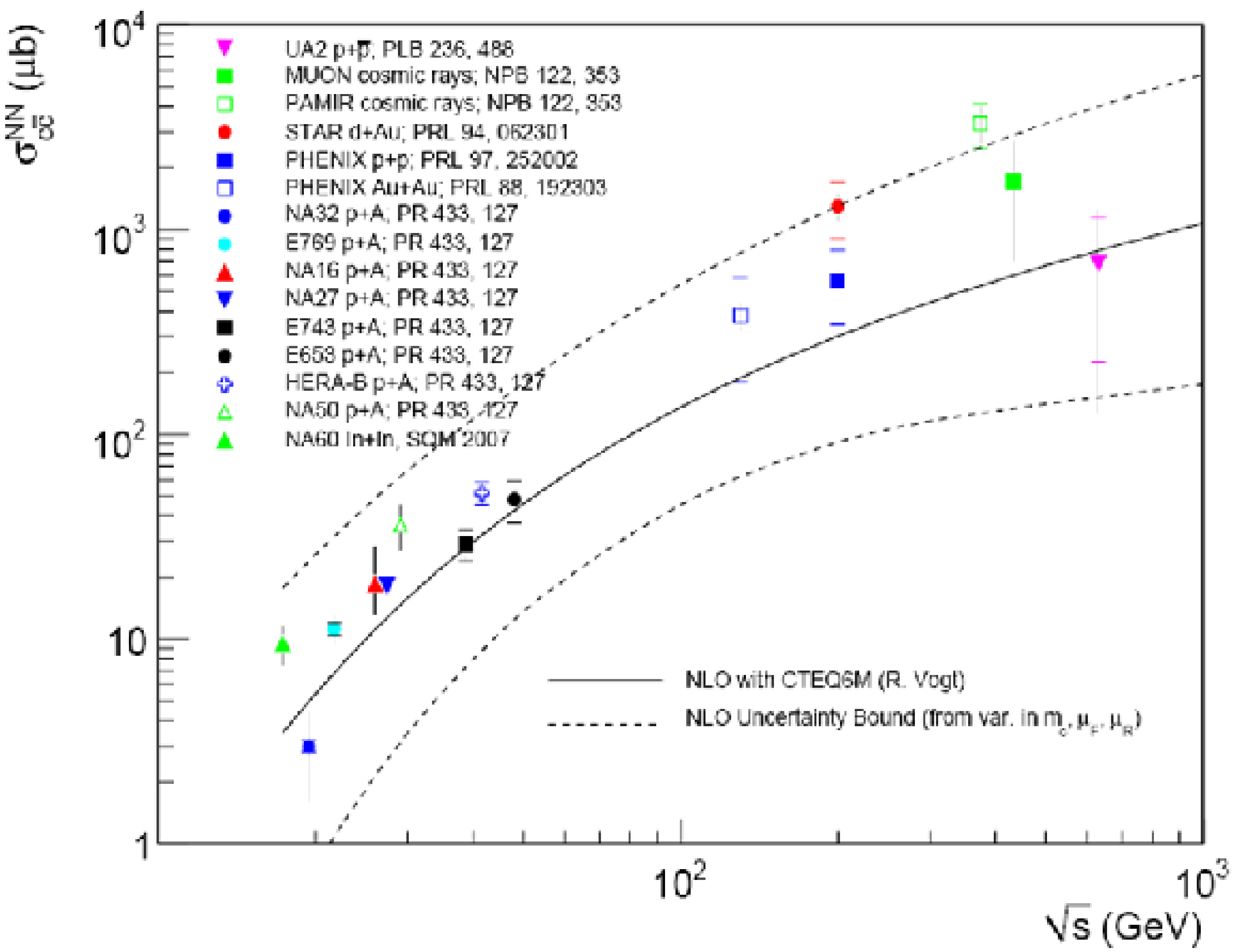
Cross-section – How well is the calculation constrained?

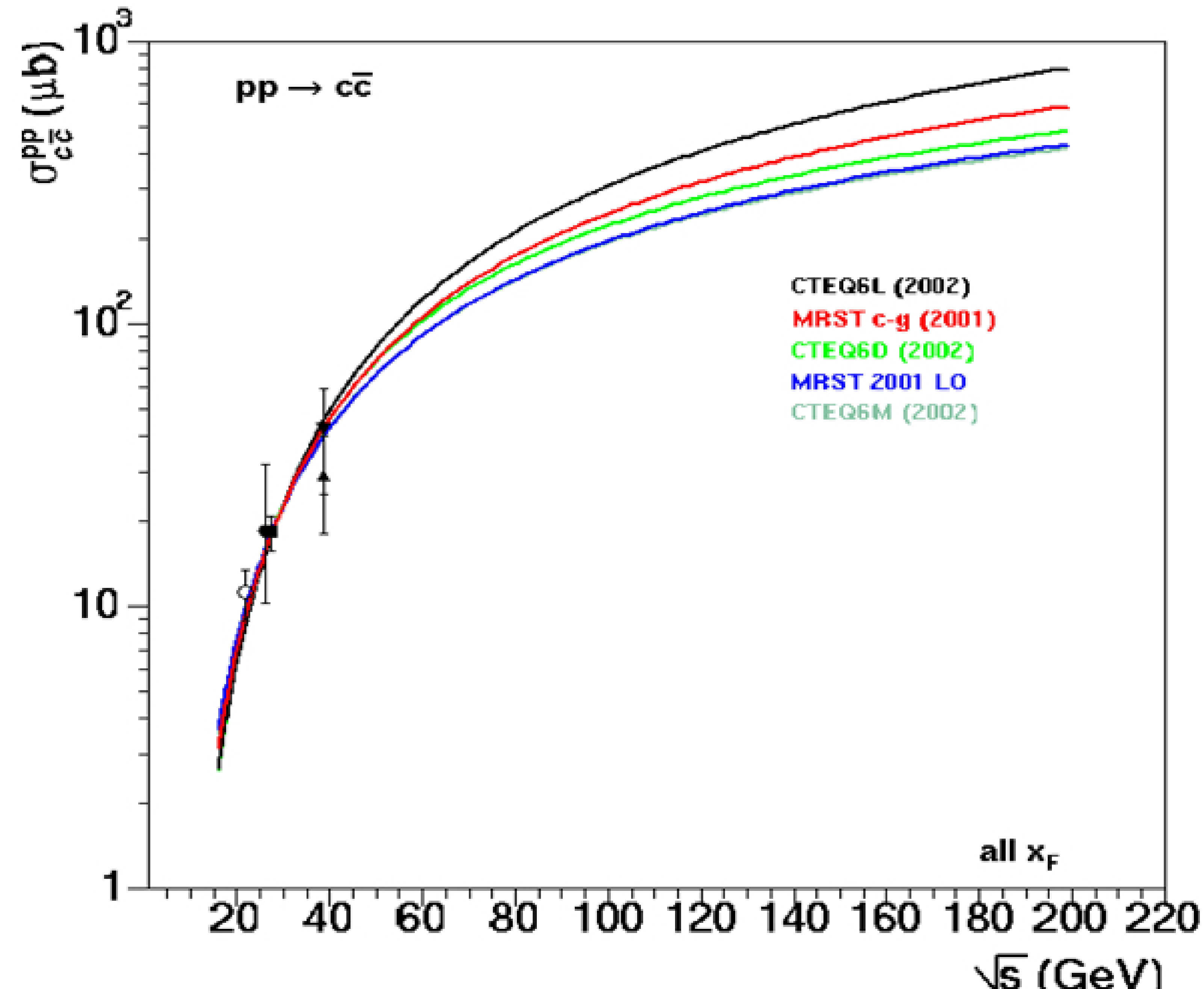
- Energy
- Charm quark mass (m_c)
- Scales
  - m_R : fragmentation scale
  - m_F : factorization scale
  - a_s : strong coupling
- PDF used
- Fragmentation Functions (FF) non perturbative inserted in a perturbative calculation

Example:

FONLL:		$\mu_F = \mu_R = \mu = \sqrt{p_T^2 + m_c^2}, m_c = 1.2GeV/c^2$
PYTHIA:	CTEQ5M1, MSEL=1	
NLO:	MRST	$\mu = 2m_c, m_c = 1.2GeV/c^2$

H. Wöhri and C. Lourenço Jphys G Nucl Part Phys 30 (2004)315

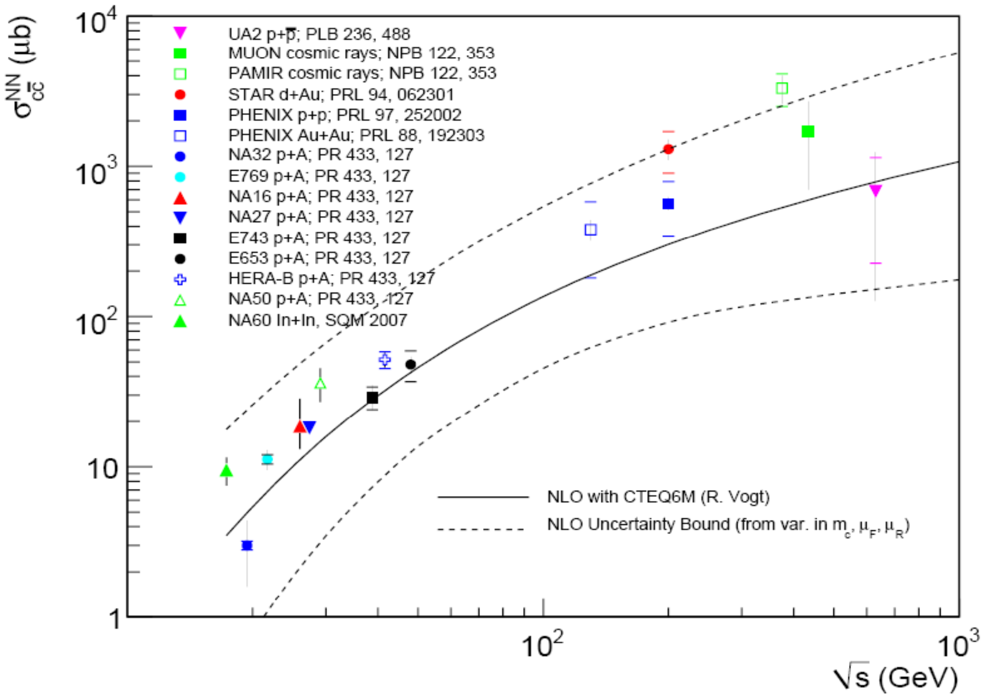




How to compare measurements to calculations ?

Using QCD (and pQCD) :
- Heavy flavor cross-section can be correctly predicted
- Differential cross-section (as function of momentum, rapidity or energy…), requires « **adding a <u>minimal</u>, <u>self-consistent and universal</u> set of non perturbative input parameters »**

Matteo Cacciari
ISMD 2007



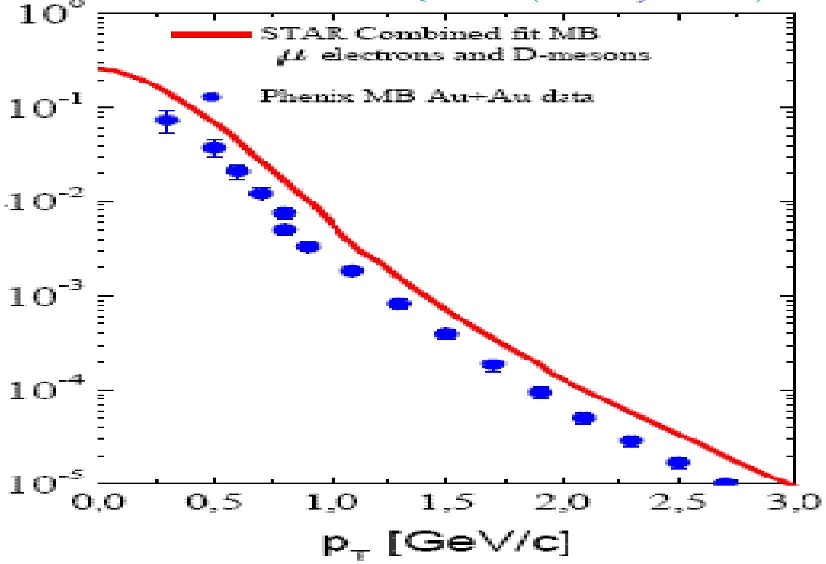
To make an accurate comparison, one should:
- Use **dedicated theoretical tools** (FONLL and now NNLO)
- Use **adequate parameters** (mass, renormalization and factorization scales, coupling), Partons Distribution Functions (PDF) and Fragmentation Functions (FF).
- <u>**Minimize extrapolations and deconvolutions** between measurements and theory</u>

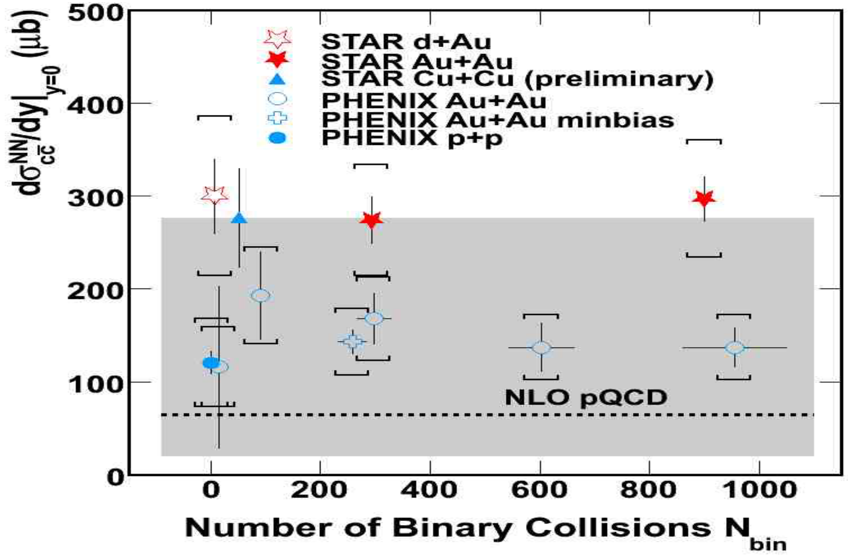
→ **If and only if** all those conditions are satisfied, **a good agreement between measurements and calculations can be reached**

→In real life, the error band is large and data points are needed...

PHENIX vs. STAR

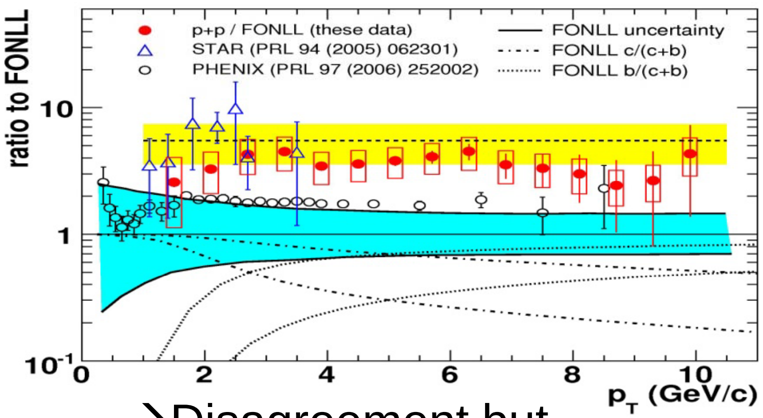
A. Suaide QM2006 (nucl-ex/0702035)





- Spectra shapes are the same. STAR and PHENIX are seeing the same scaling with Nbin.

STAR PRL 98 (2007) 192301

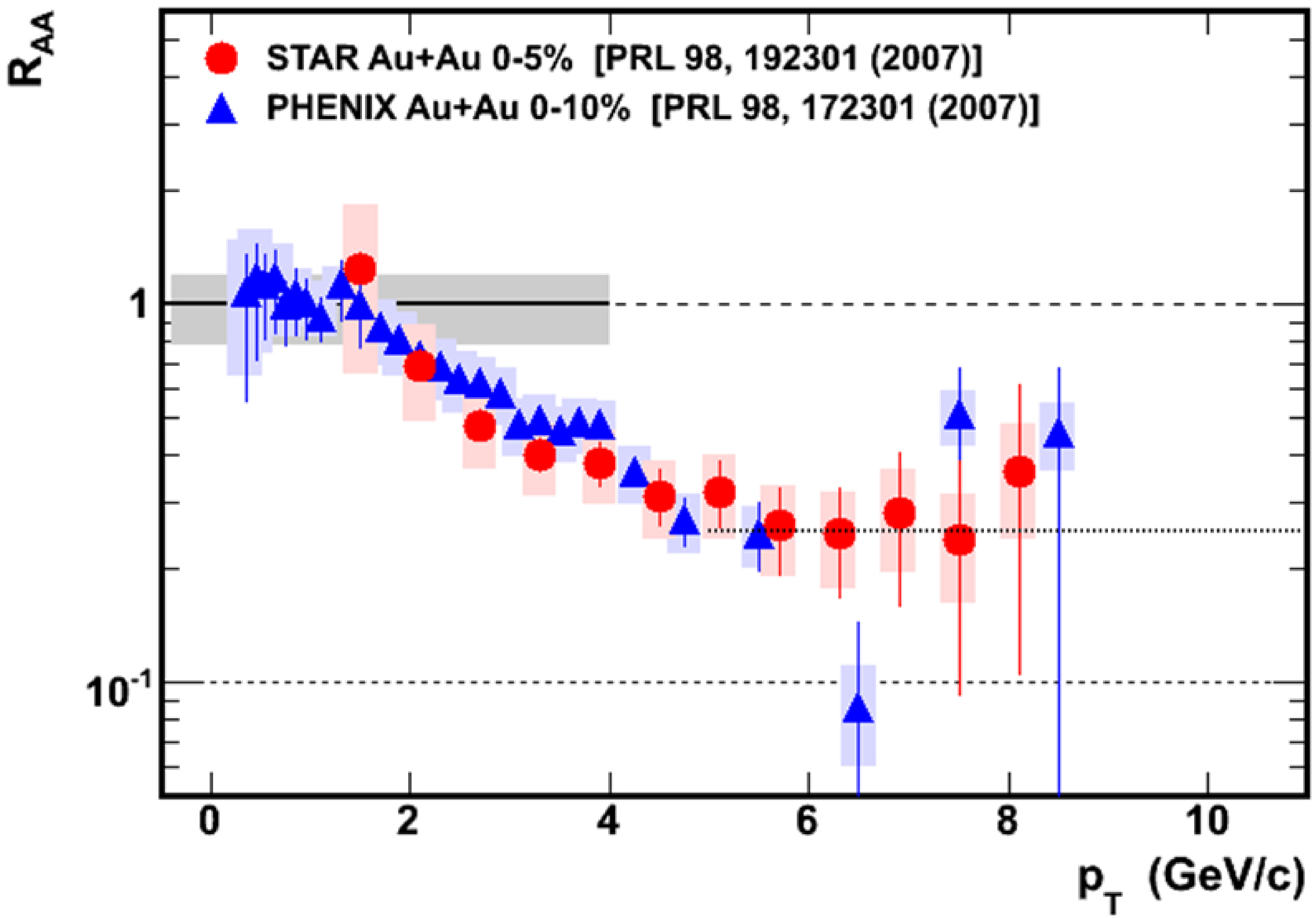


-The value of the cross-section is not the same (factor 2 to 3)

- STAR and PHENIX are both above FONLL predictions…

→Disagreement but let's look at the R_{AA} …

R_{AA}: (e^-) from d+Au to Au+Au central



Dead cone effect not observed …
(non photonic e^-)

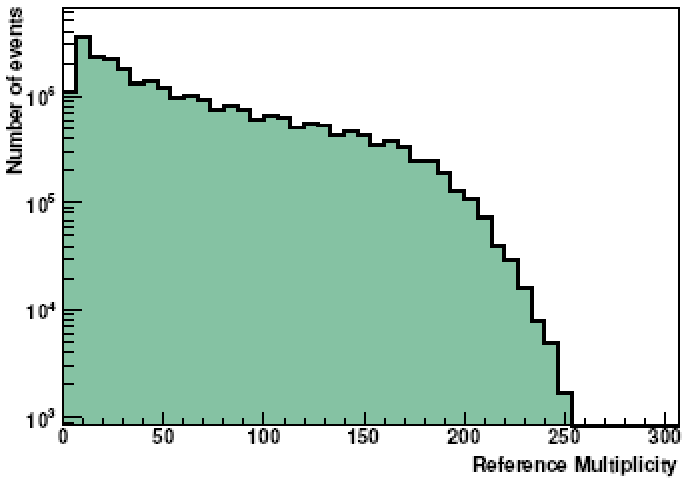
R_{AA} in agreement between STAR and PHENIX
→Is there a normalization issue?

D^0 Analysys

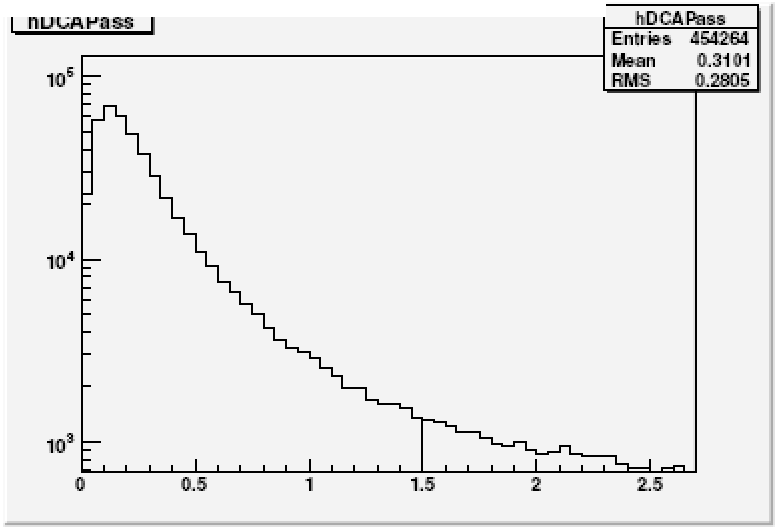
Cuts

Primary vertex -30 cm < Vz < 30 cm

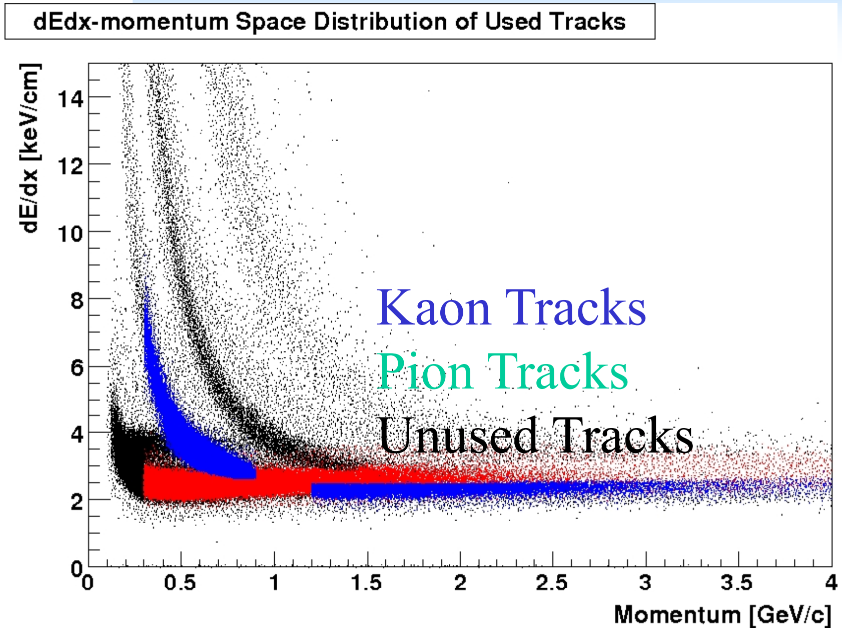
P (track)	$p > 0.3 GeV/c$
p_T (track)	$p_T > 0.2 GeV/c$
nFitPts	> 22
Global DCA	< 1.5 cm
Pseudo-rapidity	η (-1,1)
Pair rapidity	(-1,1)
$n\sigma_\pi$	(-1.8,1.8)
$n\sigma_K$	(-1.8,1.8)

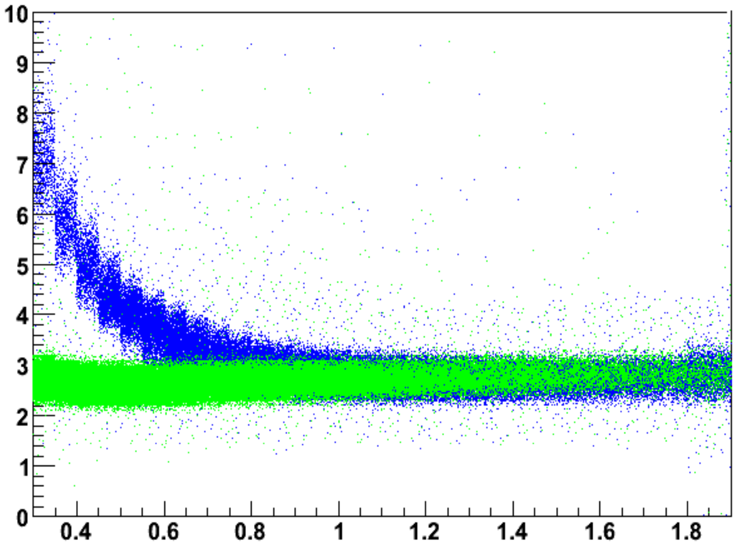


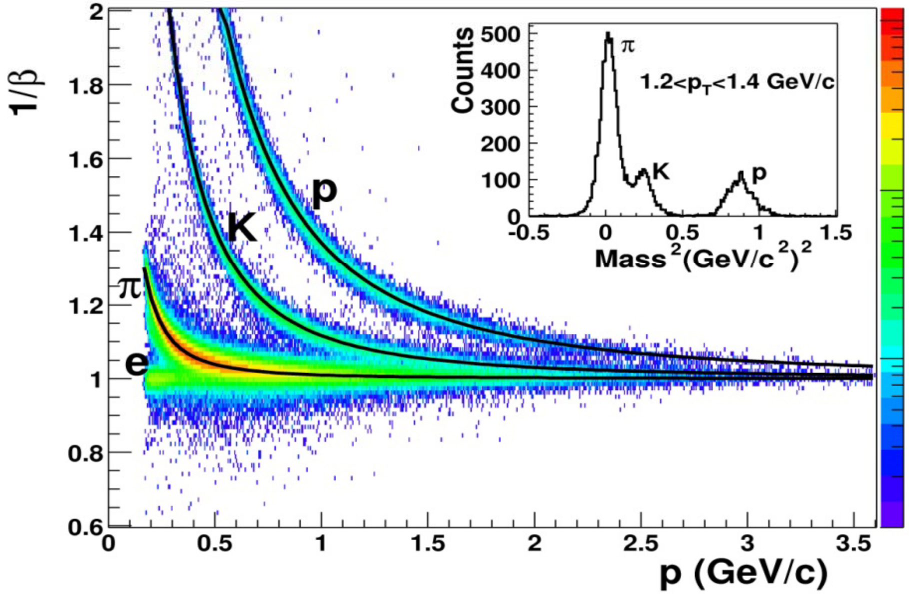
0-60% selected



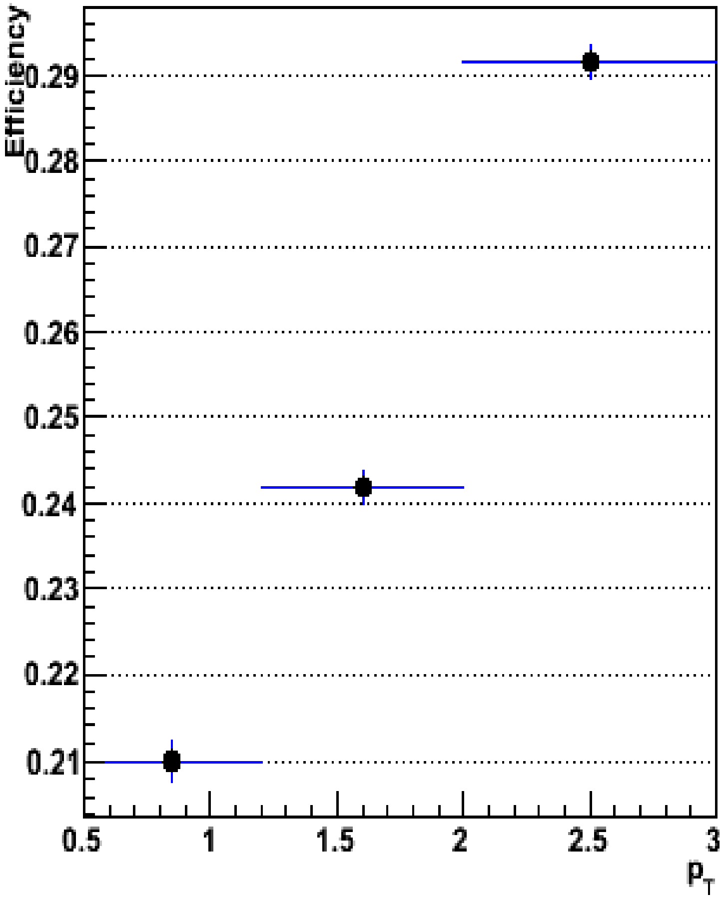
PID

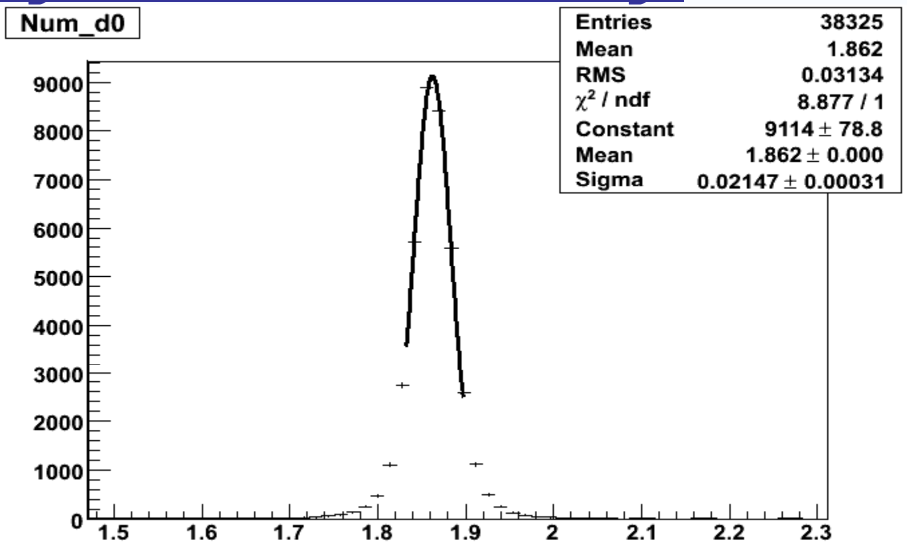

dEdx-momentum Space Distribution of Used Tracks
dE/dx [keV/cm]
Momentum [GeV/c]
Kaon Tracks
Pion Tracks
Unused Tracks

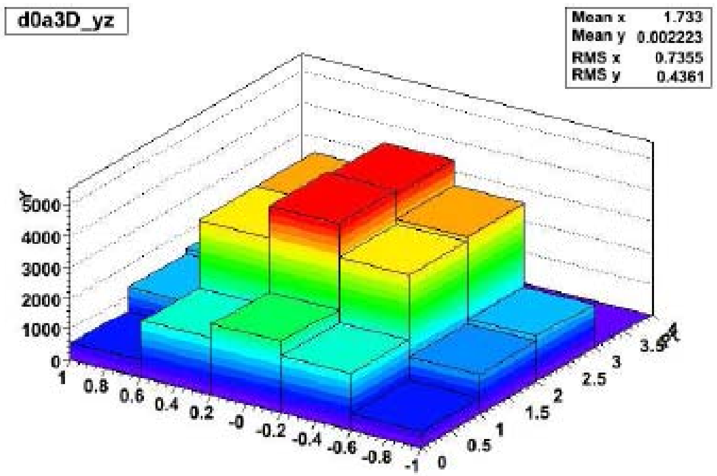



1/β
p (GeV/c)
p
K
π
e
Counts
Mass²(GeV/c²)²
1.2<p_T<1.4 GeV/c

MC study / Efficiency

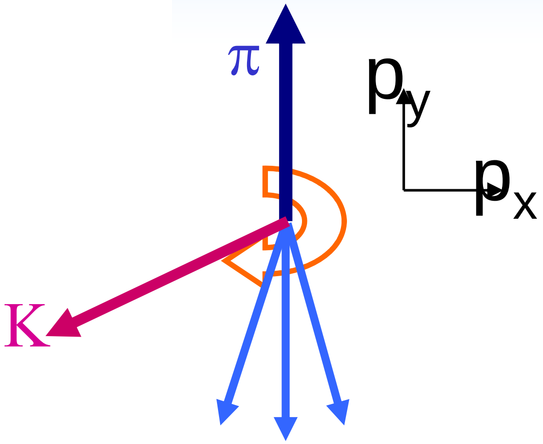






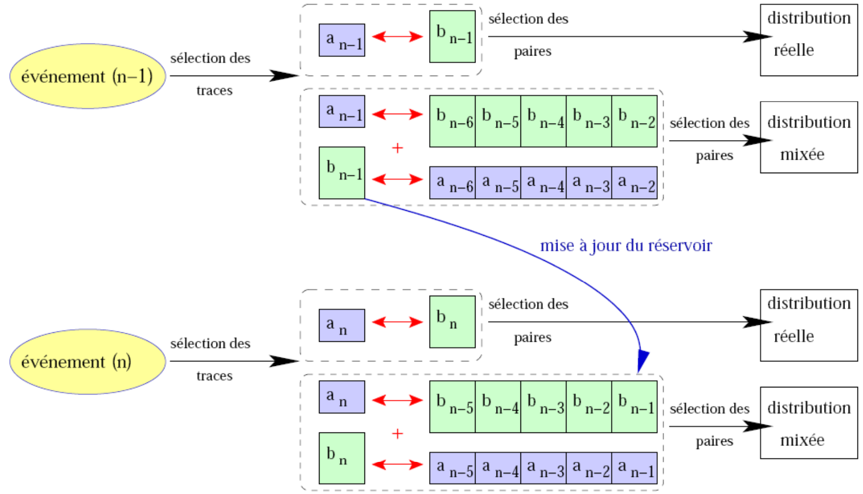
Background subtraction

Comparison between event mixing and track rotating

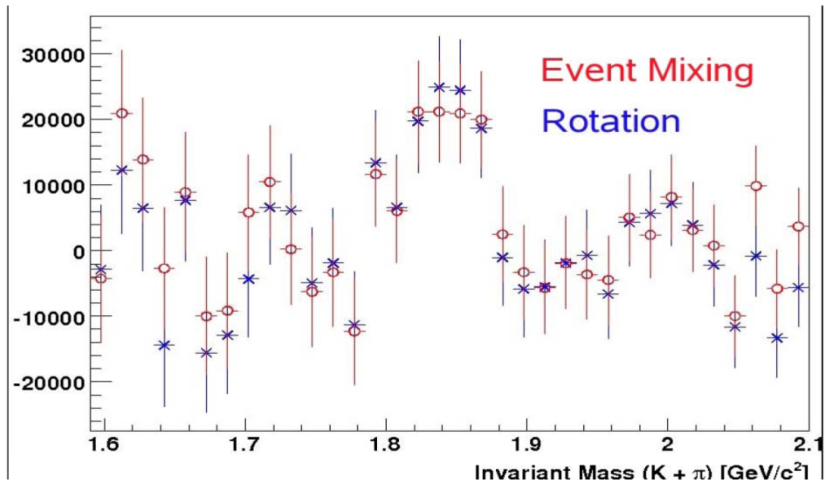


5 degree
Rotations

Flow effects?



Flow effects?



Only one 180° Rotation
larger stat error
(more background fluctuations)

Comparison

Gaussian Sigma Widths:

pt = 0.3 to 1.3 GeV/c: 0.0153678 +/- 0.00572157 GeV/c

pt = 1.3 to 2.3 GeV/c: 0.0236813 +/- 0.00567134 GeV/c

pt = 3.3 to 4.3 GeV/c: 0.0244258 +/- 0.00856235 GeV/c

Means:

pt = 0.3 to 1.3 GeV/c: 1.84149 +/- 0.00683789 GeV/c^2

pt = 1.3 to 2.3 GeV/c: 1.84372 +/- 0.0086616 GeV/c^2

pt = 2.3 to 3.3 GeV/c: 1.85005 +/- 0.0105118 GeV/c^2

obtained using
5 degree
Rotations

Normalisation

Normalisation factor: as a function of the invariant mass:

$$\alpha = \frac{\int Dreal}{\int Dmix}$$

(with $\alpha \approx 1$ if rotating with only 1 rotation)

Then make the difference in order to substract:

$$Dfinal = Dreal - \alpha . Dmix$$

Systematics

under progress

❖ Background subtraction method
1 versus several rotations / event mixing (and normalization)
→ Flow effects?
❖ Range of the Invariant mass fit
❖ Function used to subtract the residual background
(1st order polynomial versus 3 order polynomial)
❖ Bin width
❖ Cuts (& PID)

Data correction

- Efficiency
- Number of events
- PID
- Branching ratio

- MC Temperature correction