2016/08/09 The 34st Reimei Workshop

Heavy flavor measurements at PHENIX

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✓ Introduction of heavy flavor measurements

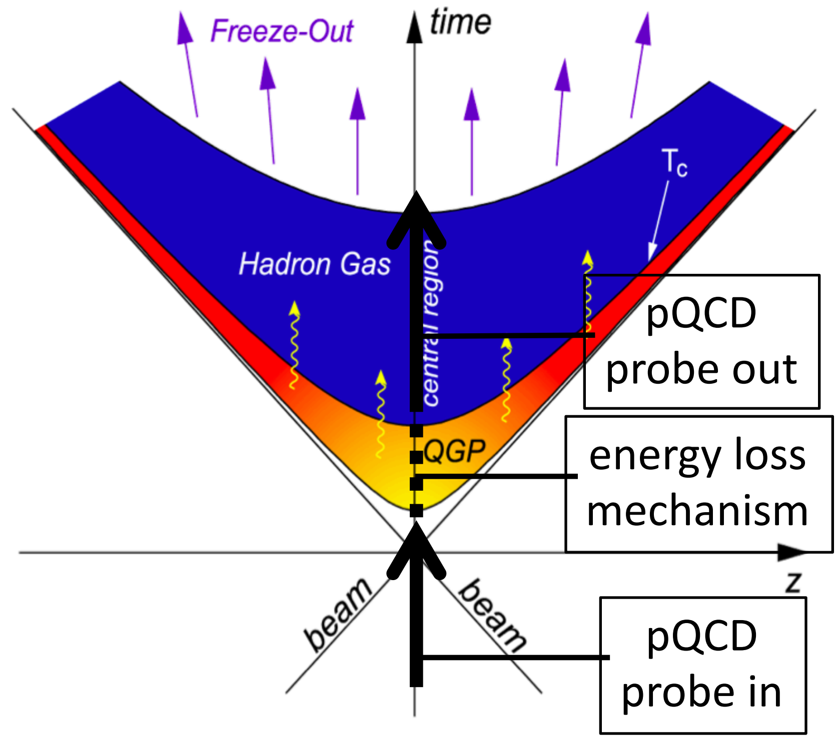
Heavy flavor probe

> large mass

- $m_{c,b} >> \Lambda_{QCD}$ ($>> T_{QGP}$)
- $1/2m_{c,b} << \tau_{form}$
- hardly generated in QGP
- thorough time evolution

> allows some pQCD calculation

model = pQCD + energy loss model



QGP physical property

> HF momentum and space variation → QGP property

> model parameters

- Diffusion constant
- Gluon density

✓ Quark energy loss mechanism in QGP

collisional energy loss

- parton elastic scattering
- Brownian motion via Langevin equation

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi}$$

η_D: friction coefficient
ξ: drift force

radiative energy loss

- Bathe-Heitler for gluon radiation

$$dP_0 \approx \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{dk_\perp^2}{k_\perp^2}$$

> Dead-Cone effect

- strong suppression of HF in small-angle radiation

$$\propto \frac{k_\perp^2 dk_\perp^2}{(k_\perp^2+\omega^2\theta_0^2)^2} \ ,(\theta_0 \equiv \frac{M}{E})$$

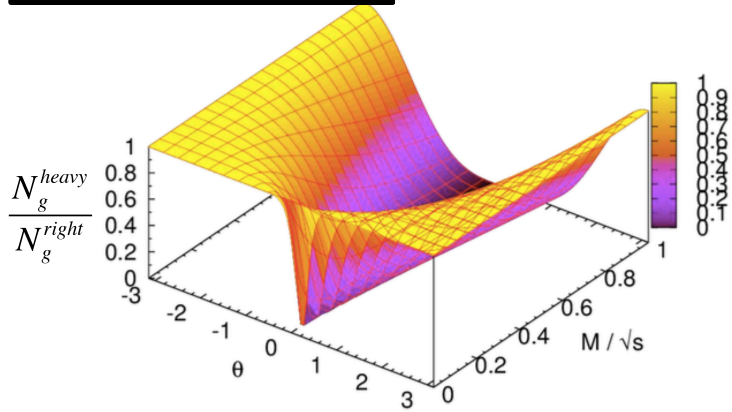
> Landau-Pomeranchuk-Migdal effect

- suppression in high density $\propto \frac{\lambda_{path}}{L_{form}}$

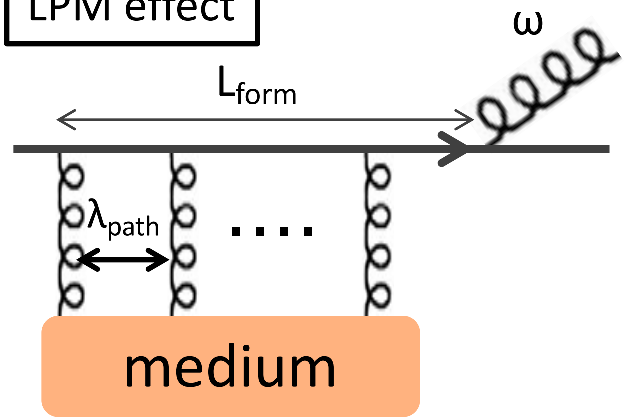
mass ordering

$\Delta E_g > \Delta E_{u,d,s} >(?)\ \Delta E_c >(?)\ \Delta E_b$

Dead-Cone effect

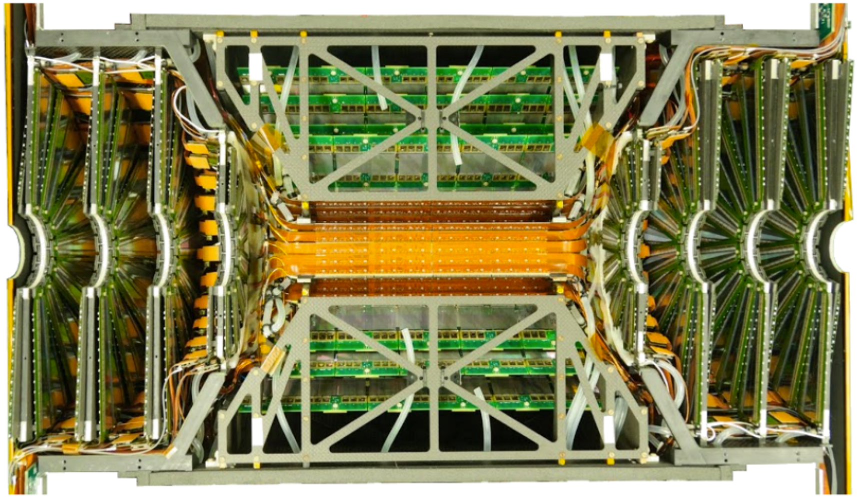


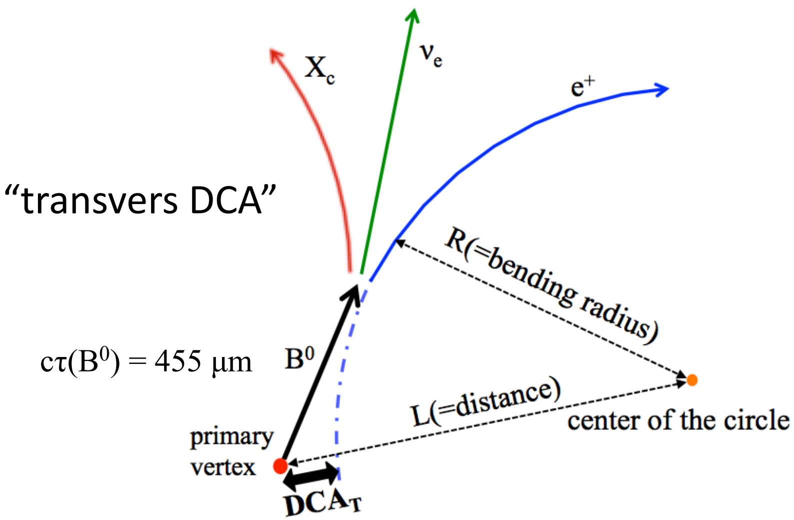
LPM effect



λ_{path}: mean free path
L_{form}: formation length

✓ PHENIX Silicon Vertex Detector (VTX)





Silicon Vertex Detector (VTX)

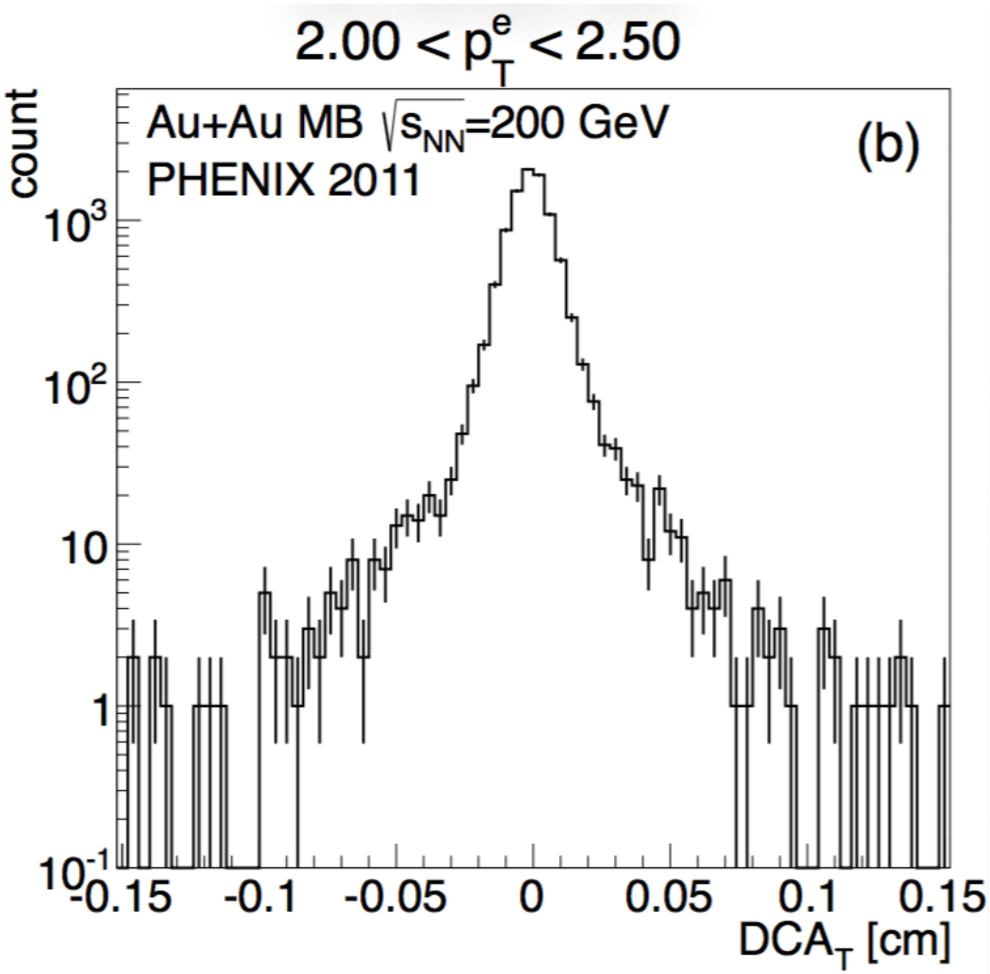
- installed in 2011
- 2 pixel layers + 2 strip layers
  (σ_ϕ = 14.4 μm) (σ_ϕ = 23 μm)
- reconstruct precise collision vertex

Precise displaced tracking

- Distance of Closest Approach (DCA)
- Transverse DCA of a track is defined as
  $DCA_T = L - R$
- depends on parent particle life time and mass
- DCA resolution = 60 μm @ 2.5 GeV
- DCA analysis allows separated measurement of bottom and charm

-> focus on single electron tracks
from smi-leptonic decay channels

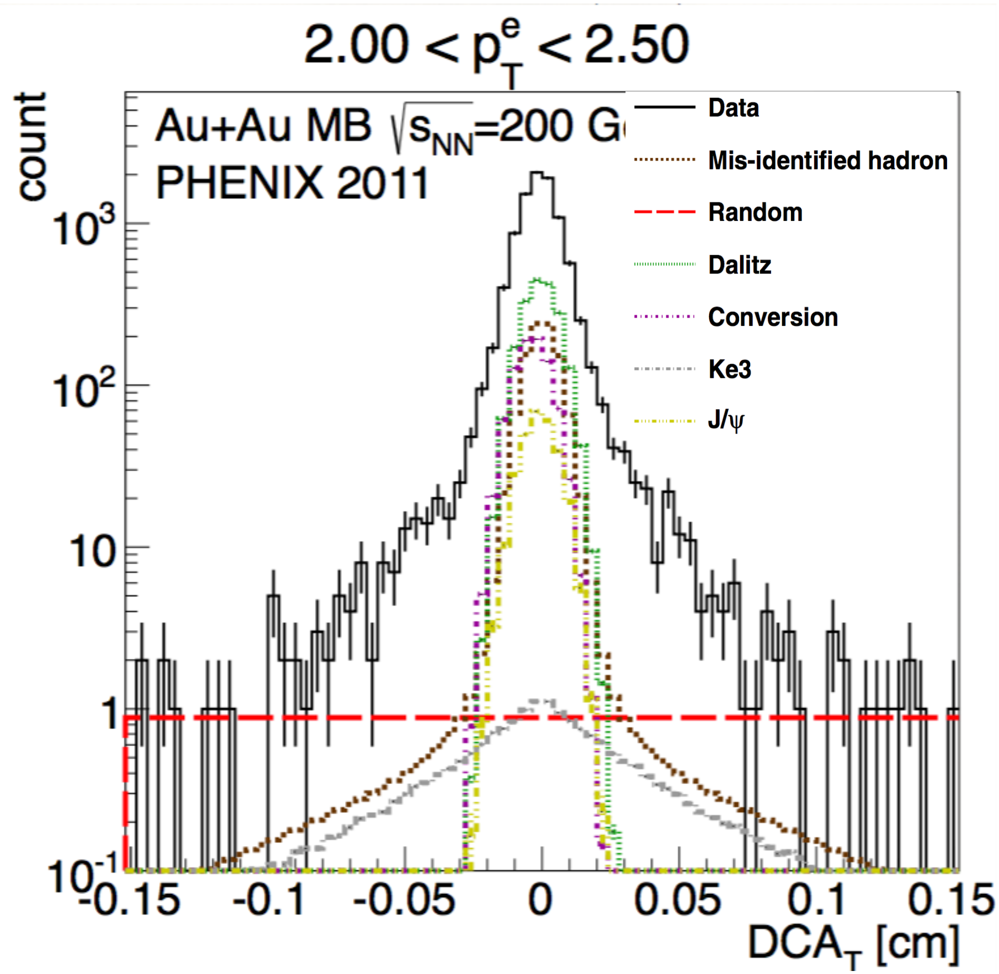
✓ DCA distribution of electrons



DCA distribution of electrons

- $1.5 < p_T < 5.0$
- no efficiency correction

✓ DCA distribution of electrons



DCA distribution of electrons

- $1.5 < p_T < 5.0$
- no efficiency correction

BG normalization and shape

- data driven
  > Mis-hadron, Random
- measured yield + Monte Carlo
  > Photonic, k_{e3}, J/ψ

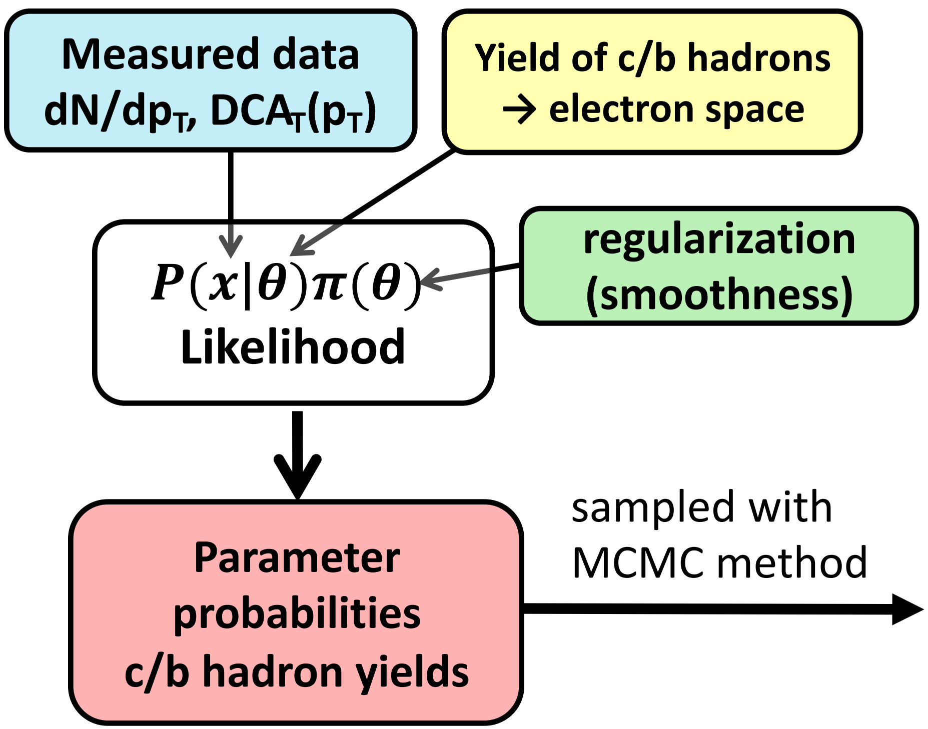
Heavy flavor decay electron

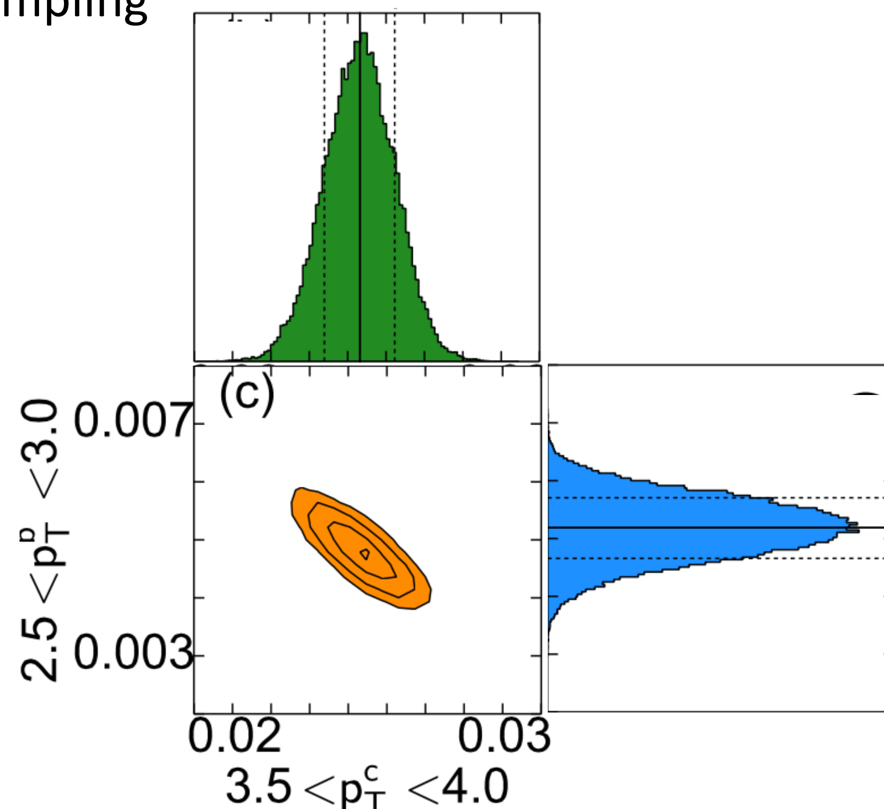
- dominates at $|0.04| < DCA_T < |0.1|$

✓ Bayesian Inference

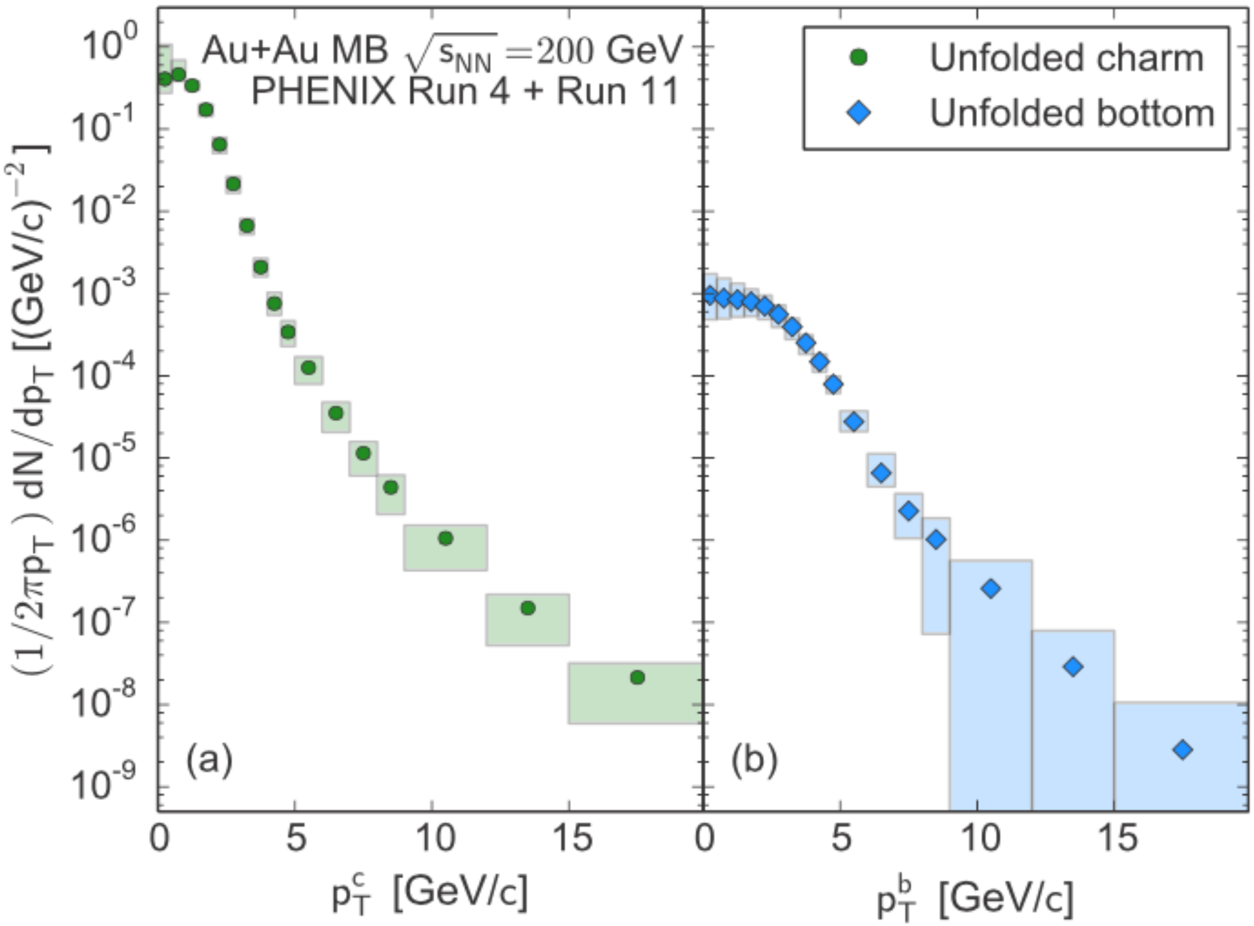
Bayesian Inference technique

- Bayes' theory $P(\theta|x) = \frac{P(x|\theta)\pi(\theta)}{P(x)}$
- c/b decay electron dN/dp_T, $DCA_T(p_T)$ from PHYTIA decay matrix
- employ Markov Chain Monte Carlo for sampling





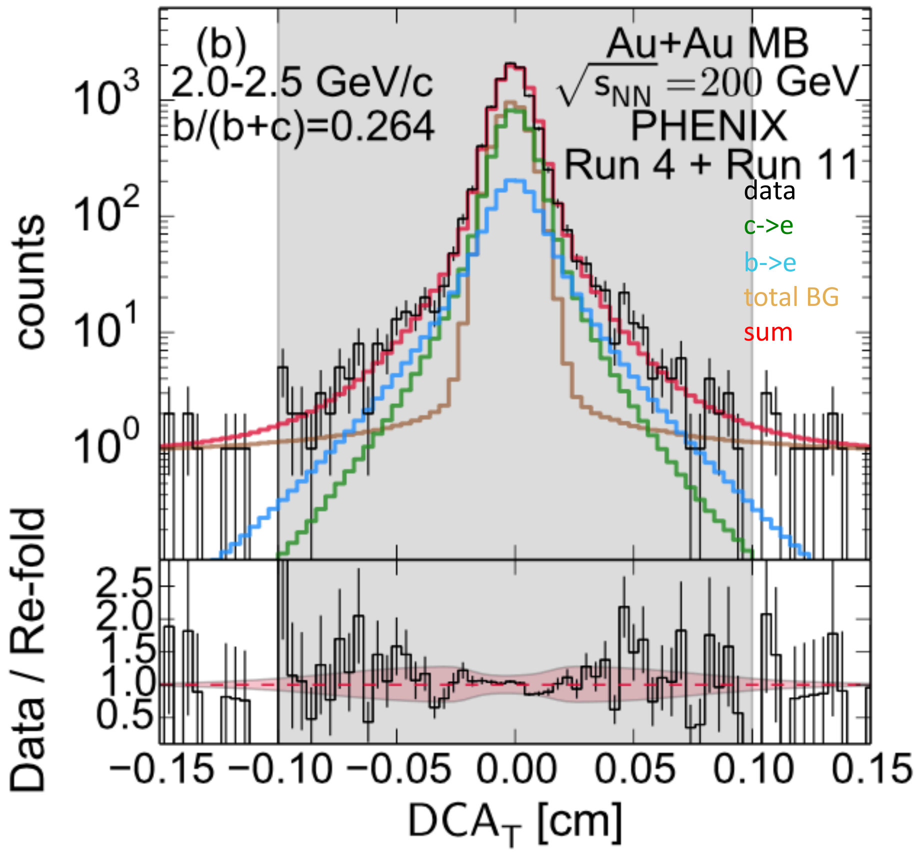
✓ Invariant yield of charm and bottom



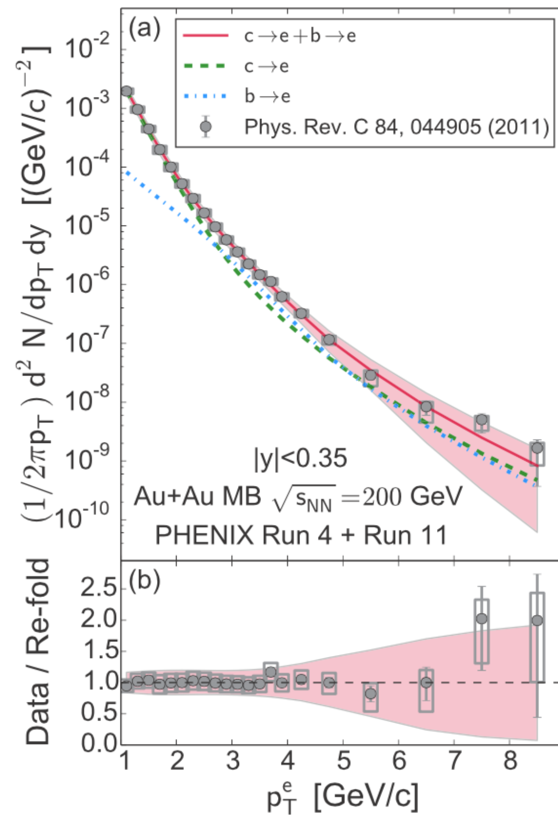
Unfolded invariant yield of charm and bottom

✓ Comparison between data and unfolding

2011 data



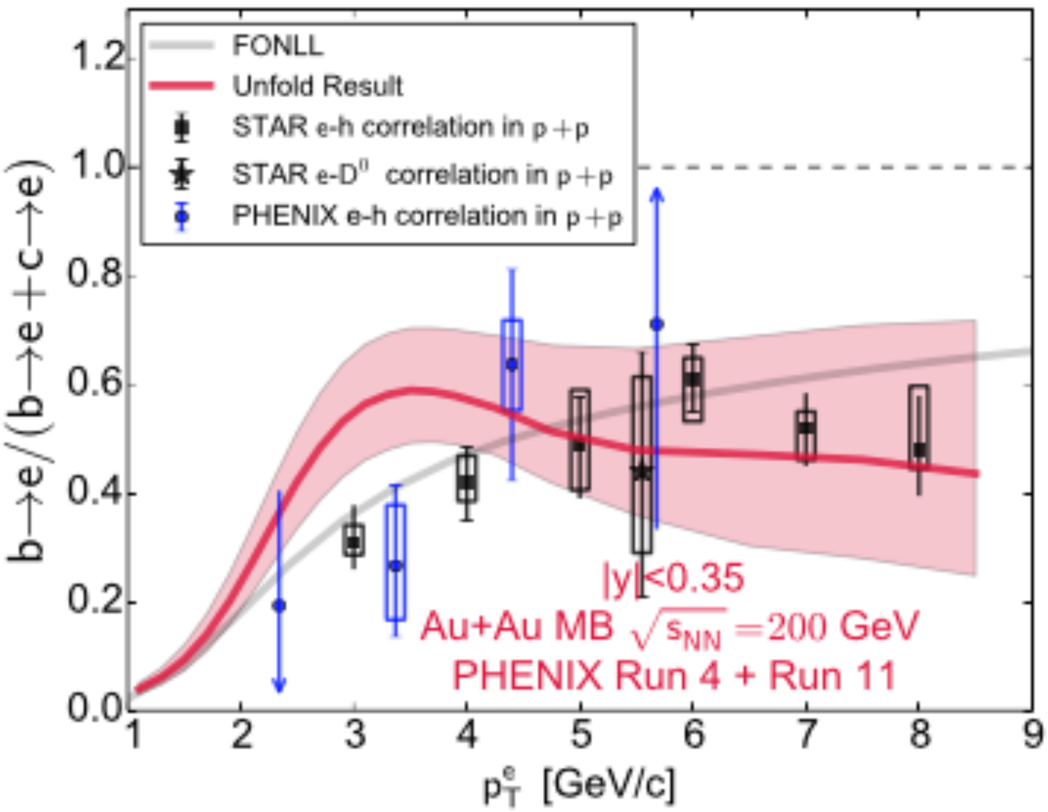
2004 data



Unfolding results agree with measured data well

✓ Bottom electron fraction

Bottom electron fraction



<u>Fraction of bottom electrons</u>

F = (b→e)/(b→e + c→e)

<u>p+p data</u>

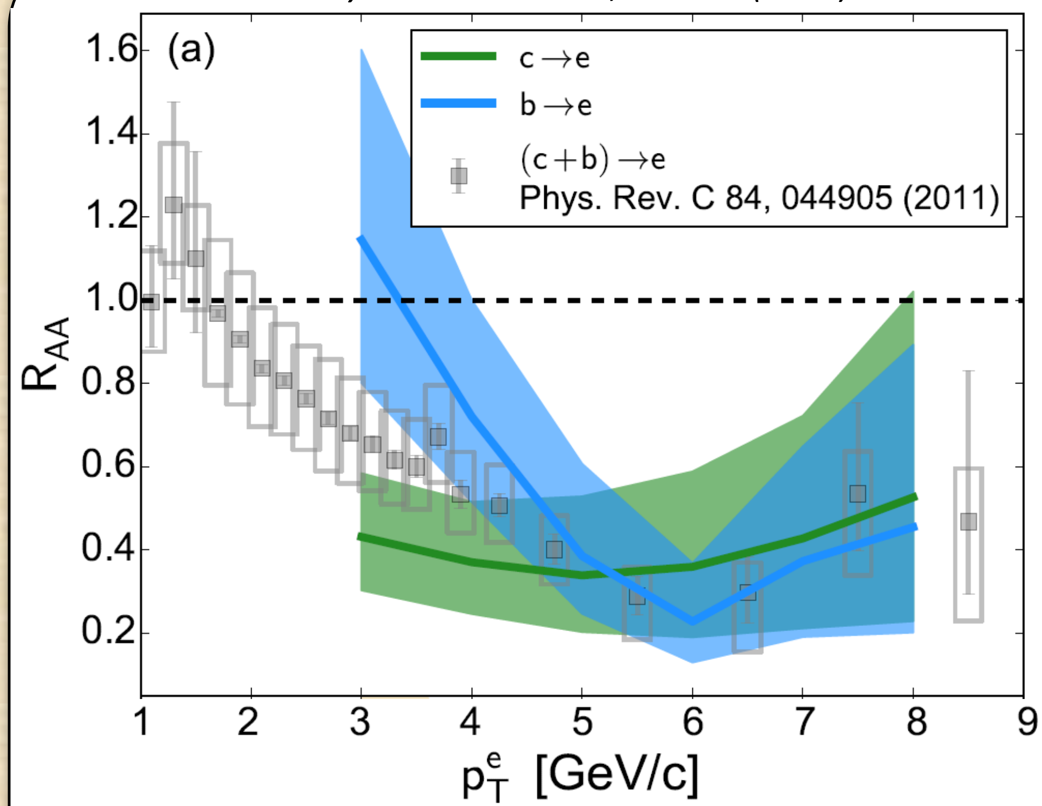
- not generate QGP
- agree with FONLL

<u>Au+Au data</u> (= unfolding)

- difference shape compared to p+p
- significant enhancement at 3 GeV/*c*
- consistent with p+p for high p_T

✓ Nuclear Modification Factor R_{AA}

Physical Review C93, 034904 (2016)



"Calculation of bottom and charm R_{AA}"

- published inclusive HF R_{AA} (Run4)
- b-fraction of AuAu and pp(STAR e-h)

$$R_{AA}^{b\to e} = \frac{F_{AuAu}}{F_{pp}} R_{AA}^{HF}$$

$$R_{AA}^{c\to e} = \frac{(1-F_{AuAu})}{(1-F_{pp})} R_{AA}^{HF}$$

[p_T < 4 GeV/c]

- bottom less suppressed than charm

[4 GeV/c < p_T]

- similarly suppressed

✓ Nuclear Modification Factor R_{AA}

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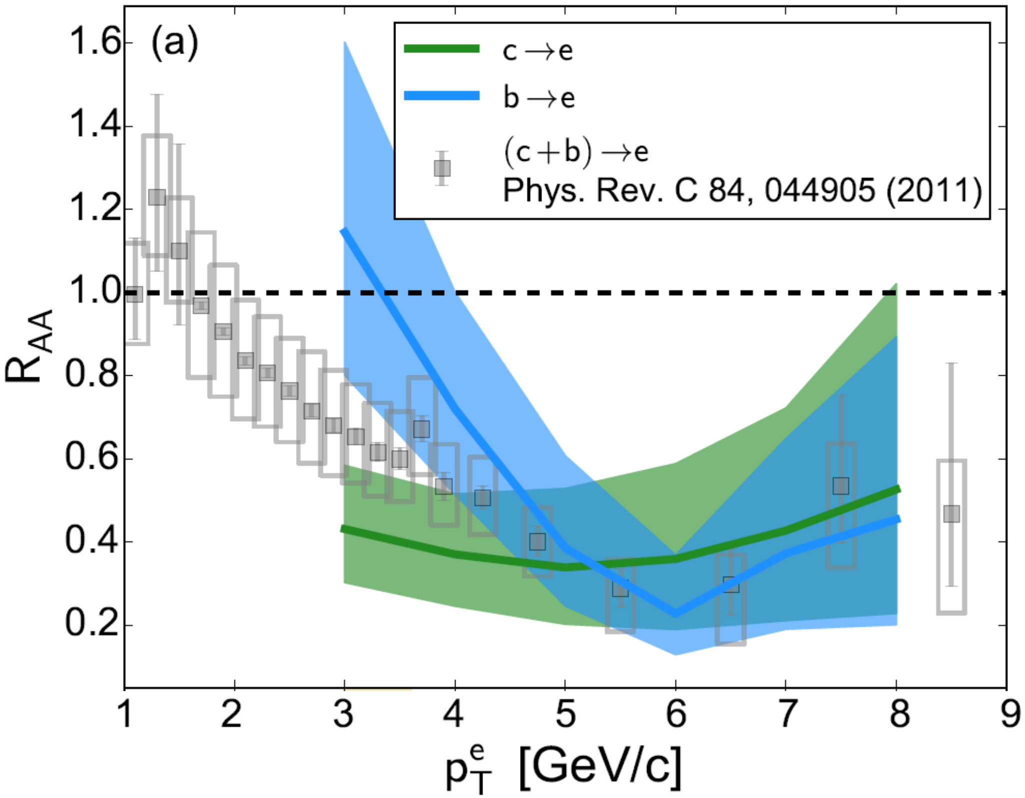

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[$p_T < 4$ GeV/c]

- bottom less suppressed than charm

[4 GeV/c $< p_T$]

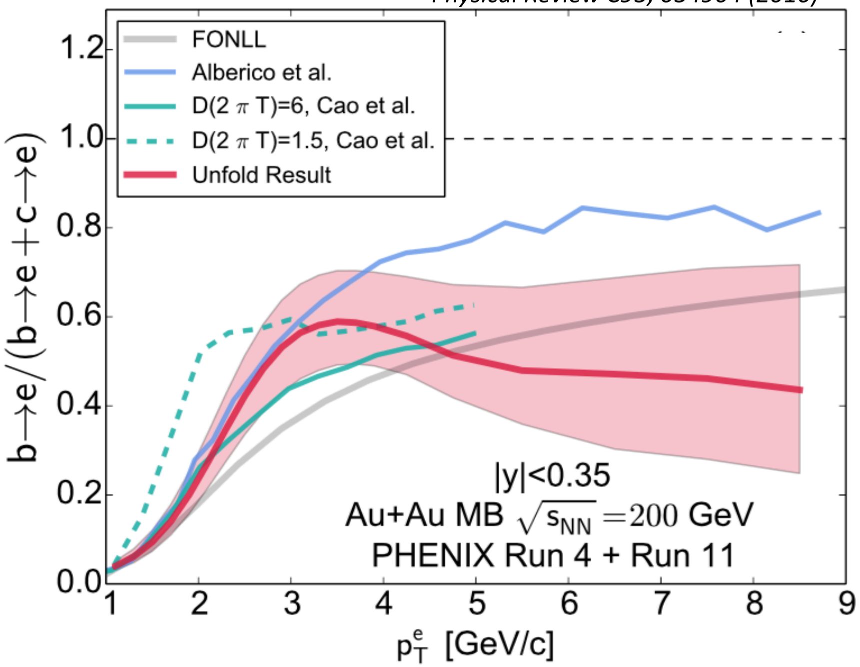
- similarly suppressed

- first measurements at RHIC
  > uncertainty is large
- need precise measurements to confirm mass ordering of c/b energy loss
  > we are analyzing high statistics and quality data (2014~2016)

✓ Comparison between data and models

"Collisional energy loss"

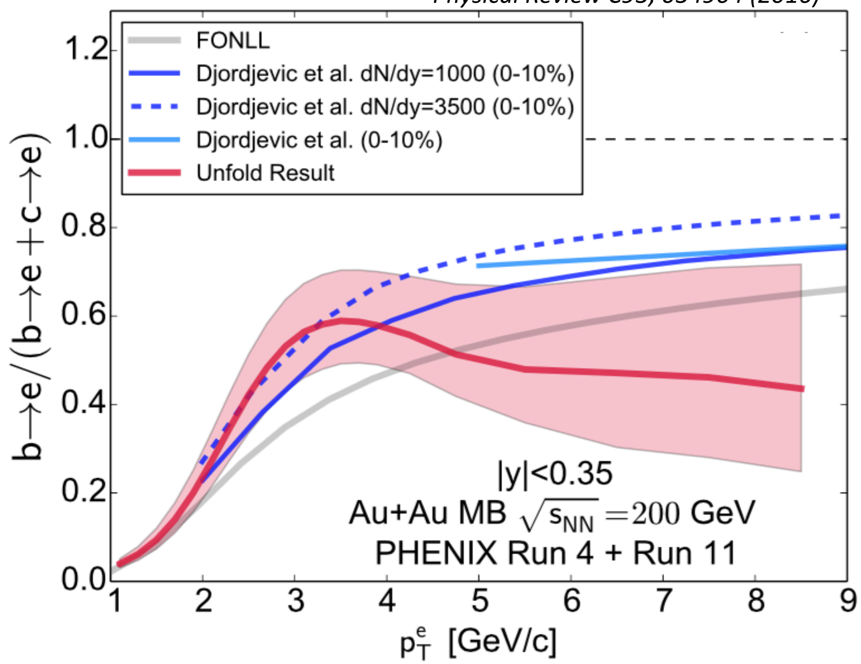
Physical Review C93, 034904 (2016)



"Langevin equation"
- depend on diffusion constant D
- D(2πT) = 6 agree with data
  -> strong coupling

"Radiative energy loss"

Physical Review C93, 034904 (2016)

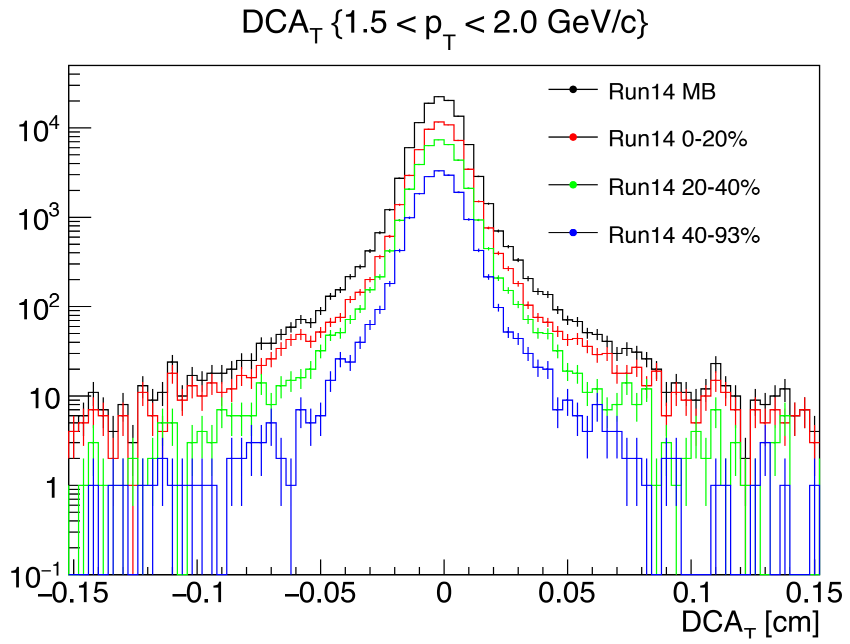


"DGLV model (radiative only)"
- depend on gluon density in QGP
- dNg/dy = 1000~3500(?)
- need more precise measurement...

✓ Future Prospects

"**High statics and quality data in 2014-2016**"

- 2014 Au+Au data x10 statistics compared to 2011
  > broader p_T range (1.0 – 9.0 GeV/c)
  > update invariant yields of HF with centrality and angle
  > suppress sys. uncertainty with new BG normalization
- 2015 p+p data
  > new base line (same method)



"**Analysis goal**"

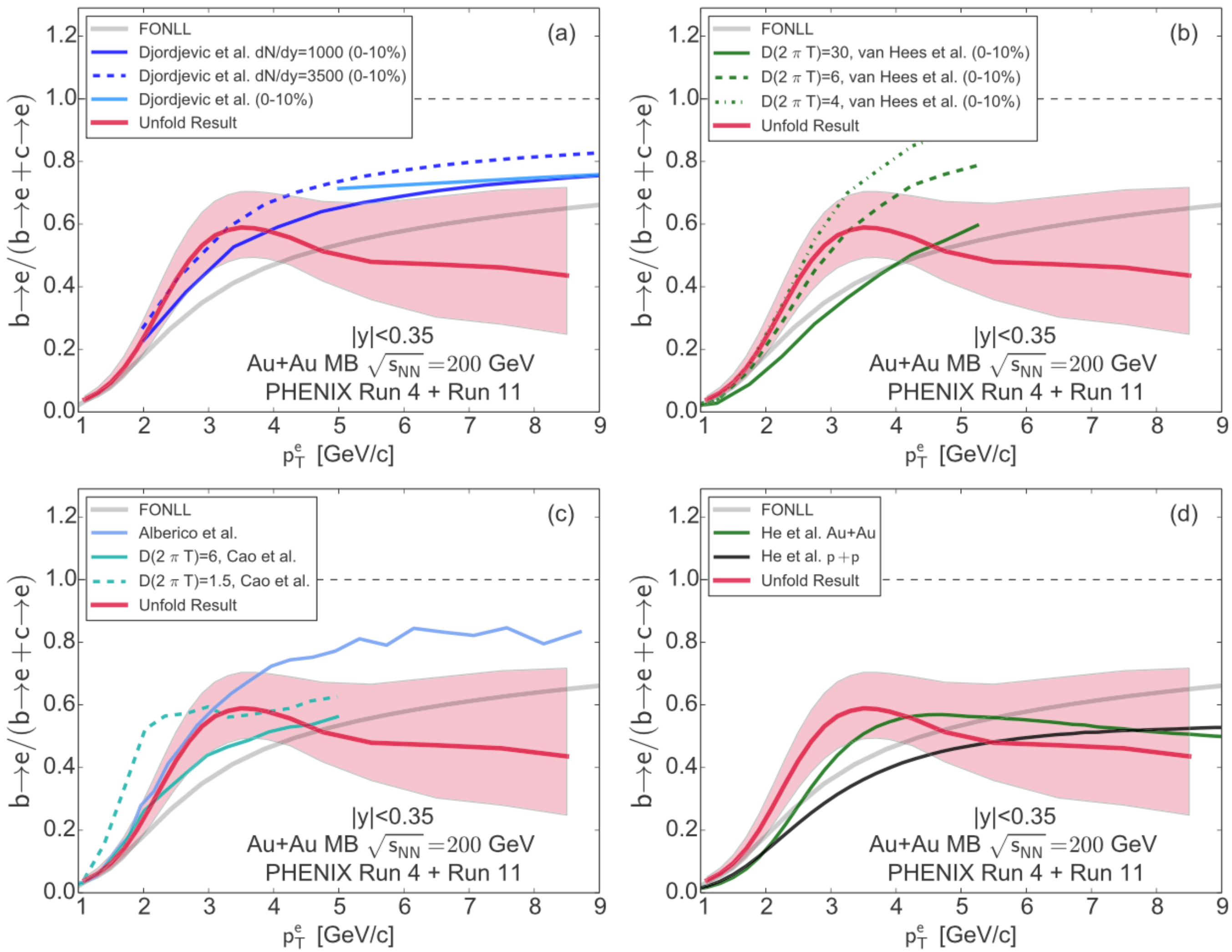
- centrality dependence of R_{AA}
- v_n measurements
  > strong constraint to QGP physical property, D(2πT), dNg/dη

✓ Summary

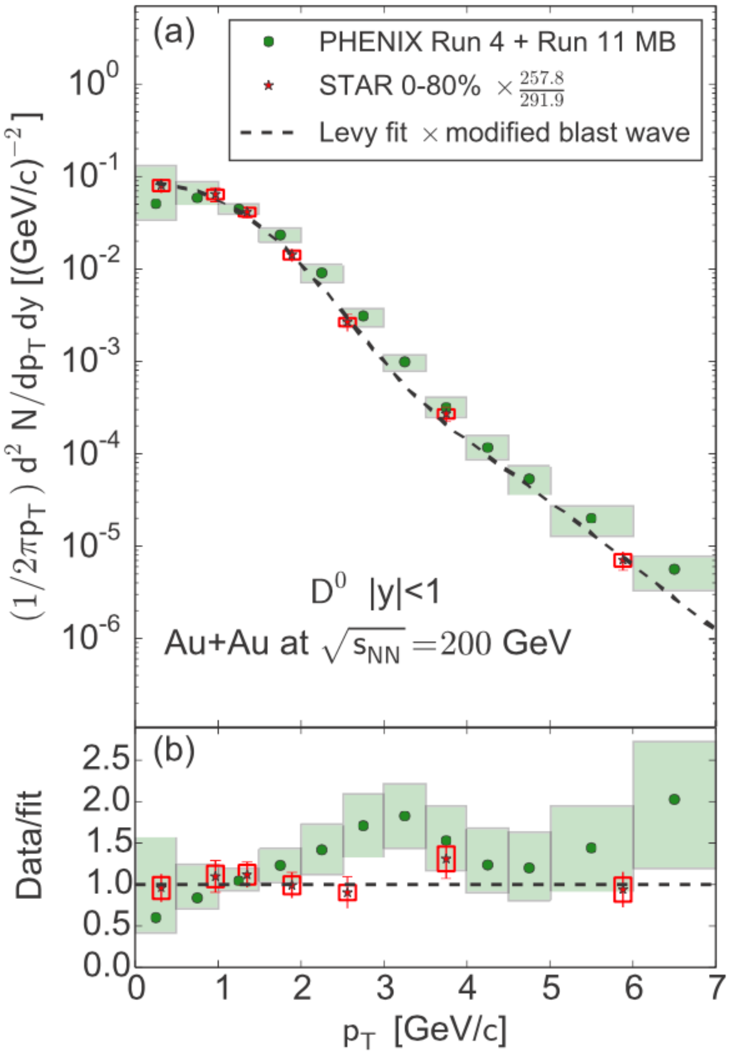
- Heavy flavor is important probe for Quark-Gluon Plasma
- Quark energy loss mechanism
  - Langevin equation →collisional energy loss
  - Bathe Heitler → radiative energy loss
- Measurement of single electrons from charm and bottom
  - used distance of closest approach and Bayesian inference
  - bottom suppression is similar to charm at high p_T, but smaller than charm at low p_T
  - compare between data and energy loss models -> D(2πT) ~ 6, gluon density = 1000~3500
- Future prospects
  - high statistics data (~10 times) in 2014

✓ backup

✓ Comparison between data and models



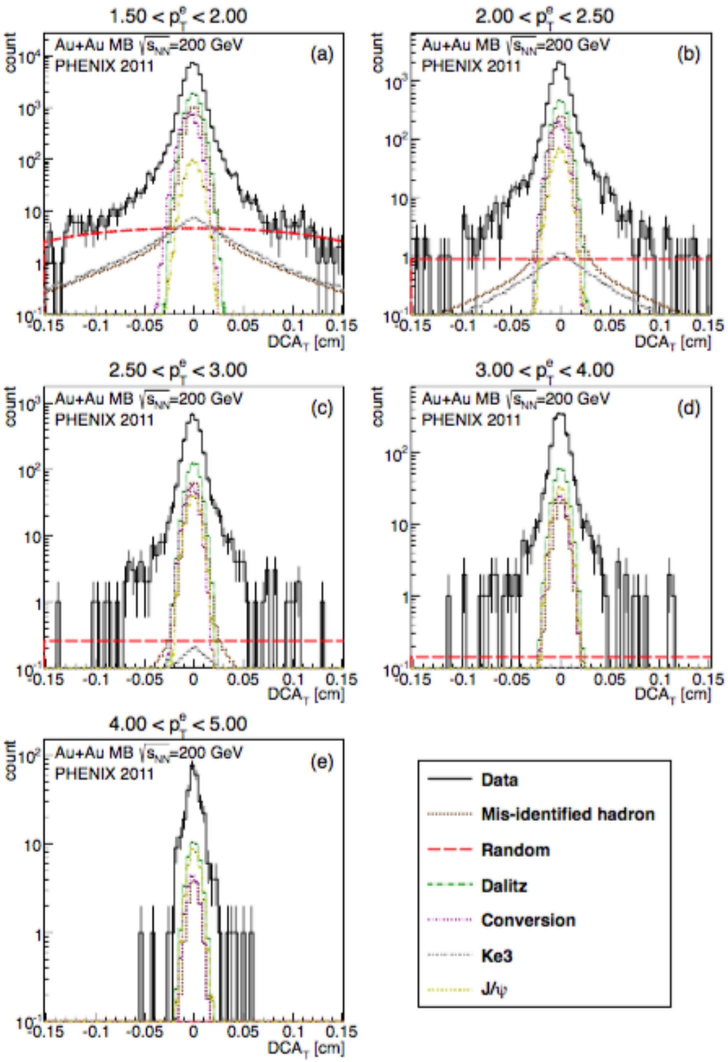
✓ Agreement with measured data



- Yields of D^0 can be calculated by unfolding charm yields + PYTHIA
- Unfolding result agree with STAR D^0 measurement
  > fit Levy function

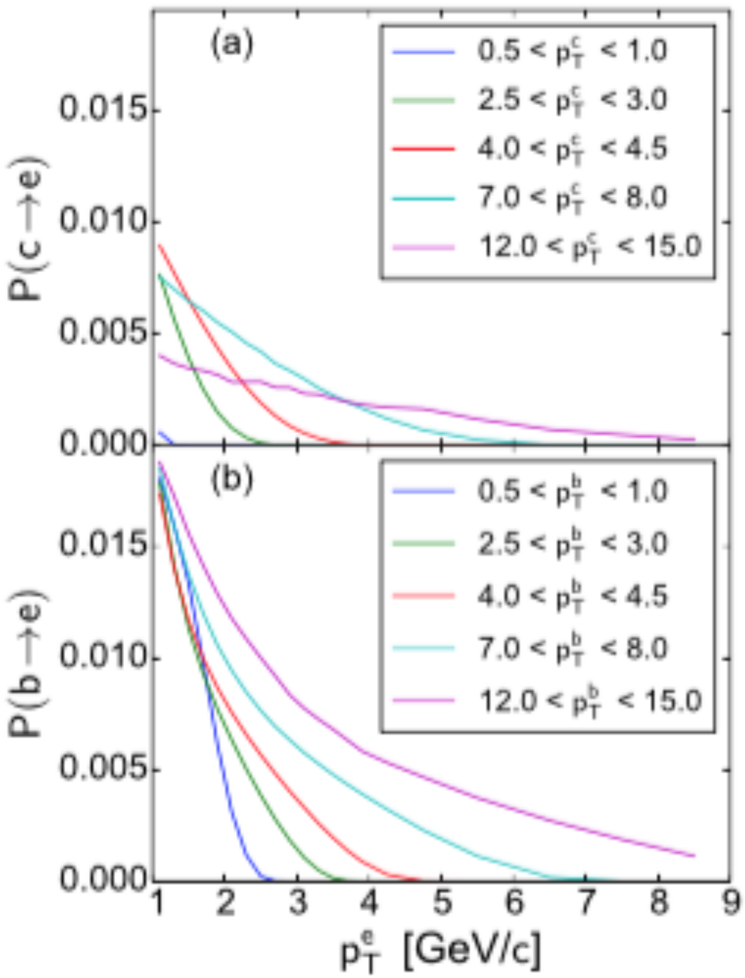
$$
f(p_T) = p_0\left[1 - \frac{(1-p_1)p_T}{p_2}\right]^{1/(1-p_1)} \times \left[1.3\sqrt{2\pi p_4^2}G(p_T, p_3, p_4) + \frac{p_5}{1+e^{-p_T+3}}\right],
$$

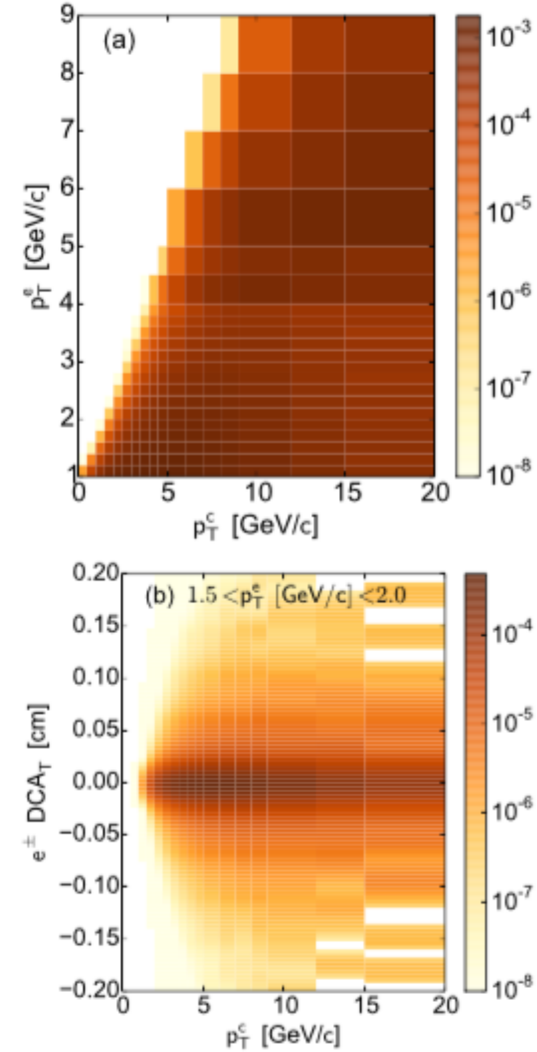
✓ DCA distribution



✓ Decay matrix

decay electron pT matrix





✓ Bayesian Inference

[Bayes' theory]

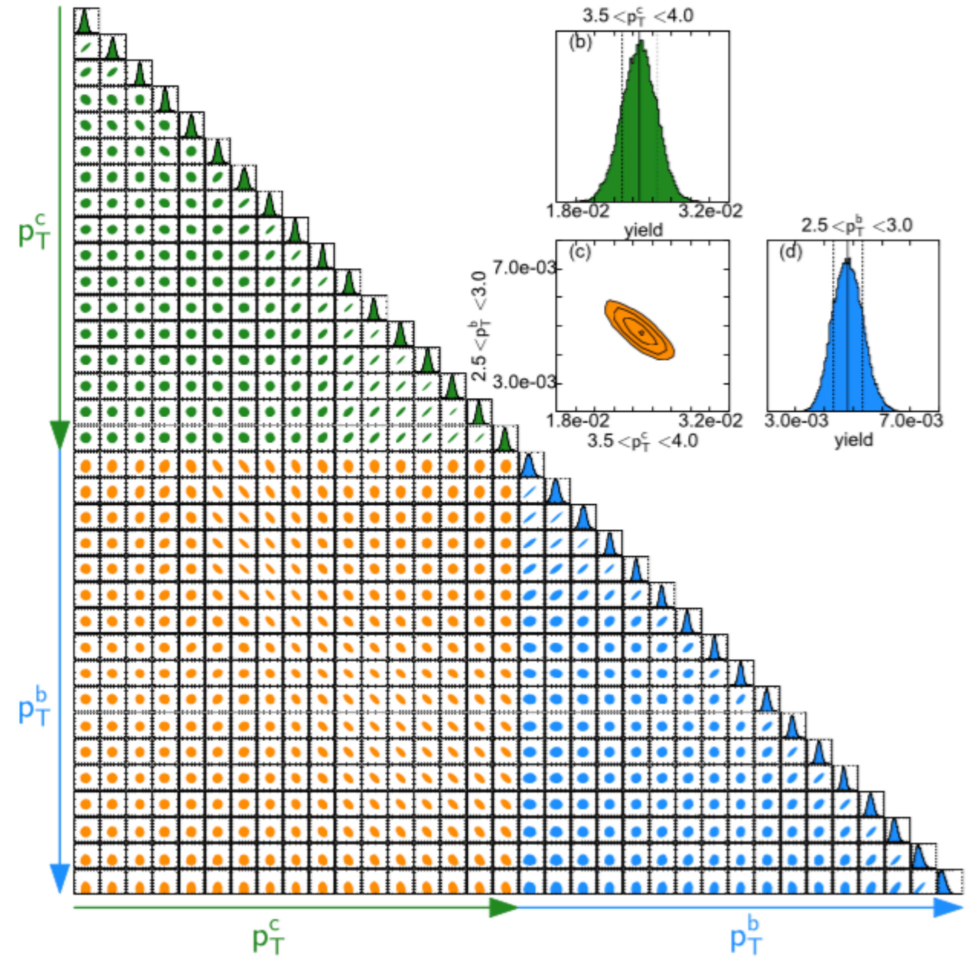
P(θ|x)=P(x|θ)P(θ)/P(x)

- P(θ|x): posterior probability
- P(x|θ): likelihood
- P(θ): prior probability
- P(x): normalization factor

Prior, P(θ)

$$\mathbf{L} = \frac{17}{2}\begin{pmatrix} -1 & 1 & & & & & \\ 1 & -2 & 1 & & & & \\ & 1 & -2 & 1 & & & \\ & & \ddots & \ddots & \ddots & & \\ & & & \ddots & \ddots & \ddots & \\ & & & & 1 & -2 & 1 \\ & & & & & 1 & -2 & 1 \\ & & & & & & 1 & -1 \end{pmatrix}.$$

likelihood, P(x|θ)



✓ Dead-Cone effect

<u>light quark radiation</u>

$$dP_0 \simeq \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{dk_\perp^2}{k_\perp^2} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta^2}{\theta^2}$$

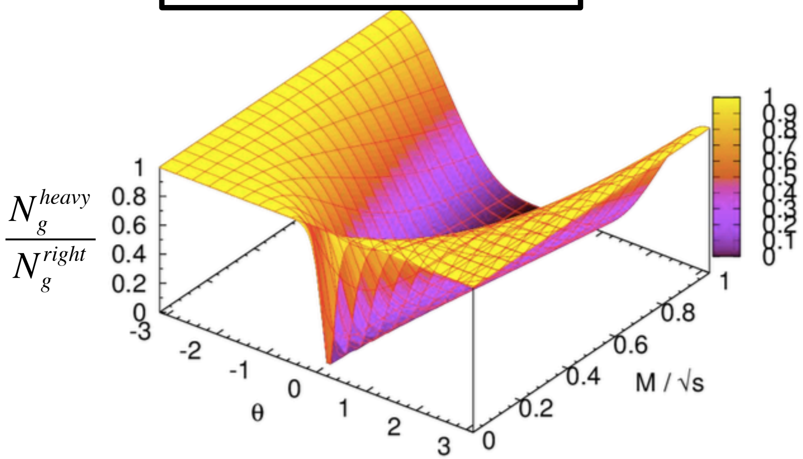
<u>radiation including mass effect</u>

$$dP = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k_\perp^2 \, dk_\perp^2}{(k_\perp^2 + \omega^2\theta_0^2)^2}, \qquad \theta_0 \equiv \frac{M}{E}$$

<u>heavy quark radiation</u>

$$dP_{\rm HQ} = dP_0 \cdot \left(1 + \frac{\theta_0^2}{\theta^2}\right)^{-2}$$

Dead-Cone effect



✓ Collisional energy loss

Brownian motion

- Langevin equation

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi}$$

η_D: coefficient of fraction, ξ: drift force

- diffusion coefficient

$$D = \frac{T}{M\eta_D(0)} = \frac{2T^2}{k}$$

✓ Markov Chain Monte Carlo

Markov Chain

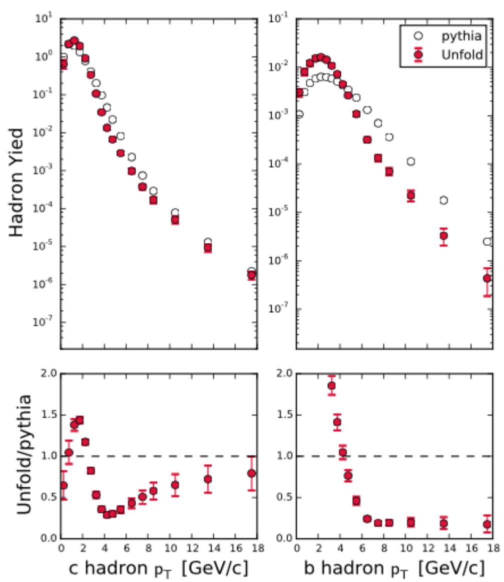
- Markov process = present status depend on previous status only

Algorism

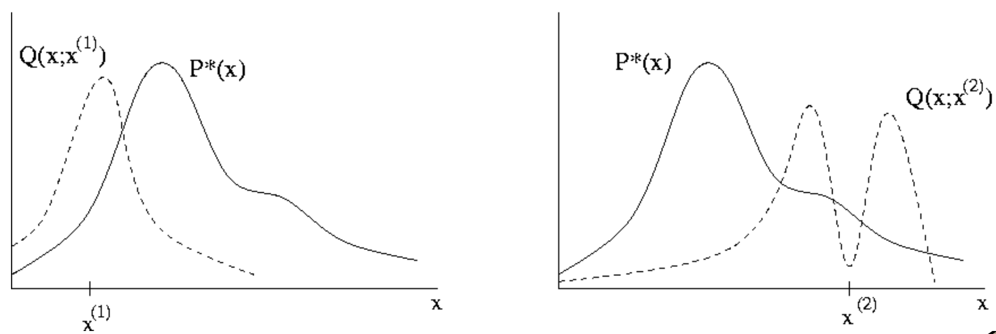
- make a initial input (c/b invariant yields) with PYHIA
- calculate Log likelihood
- compare between present Log likelihood and previous log likelihood

  present > previous -> employ present parameters

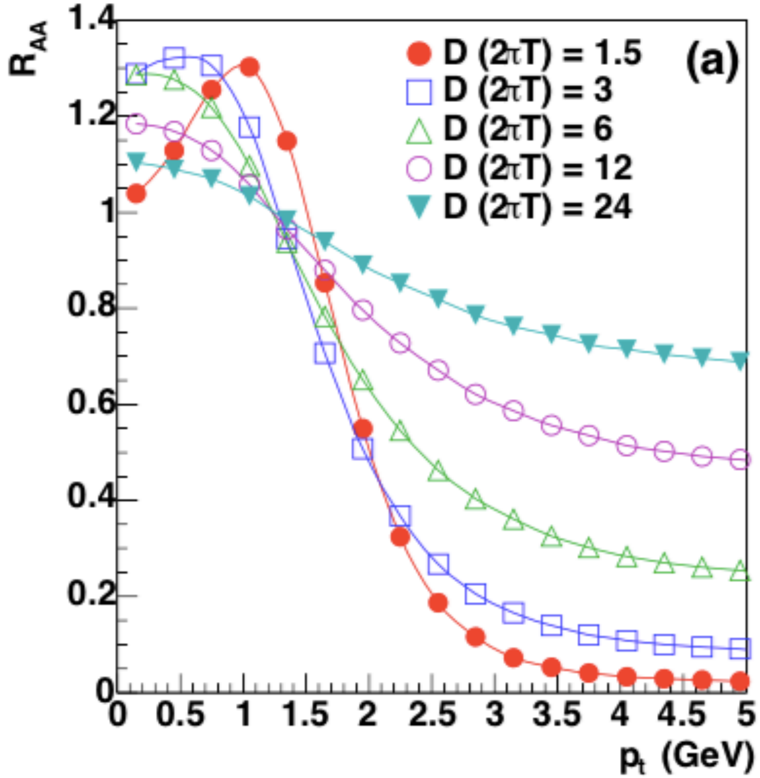
  present < previous -> reject present parameters and employ previous parameters

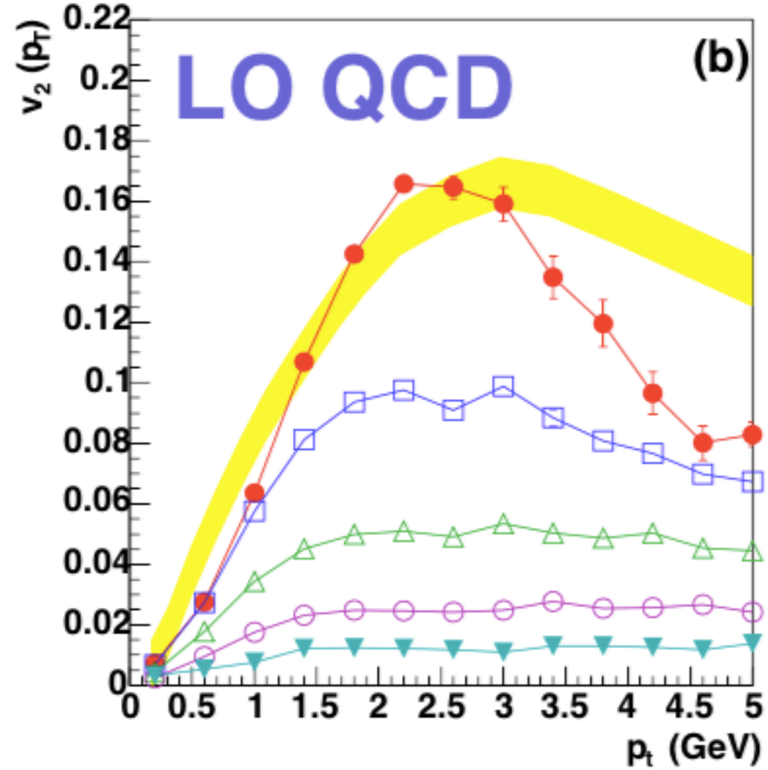


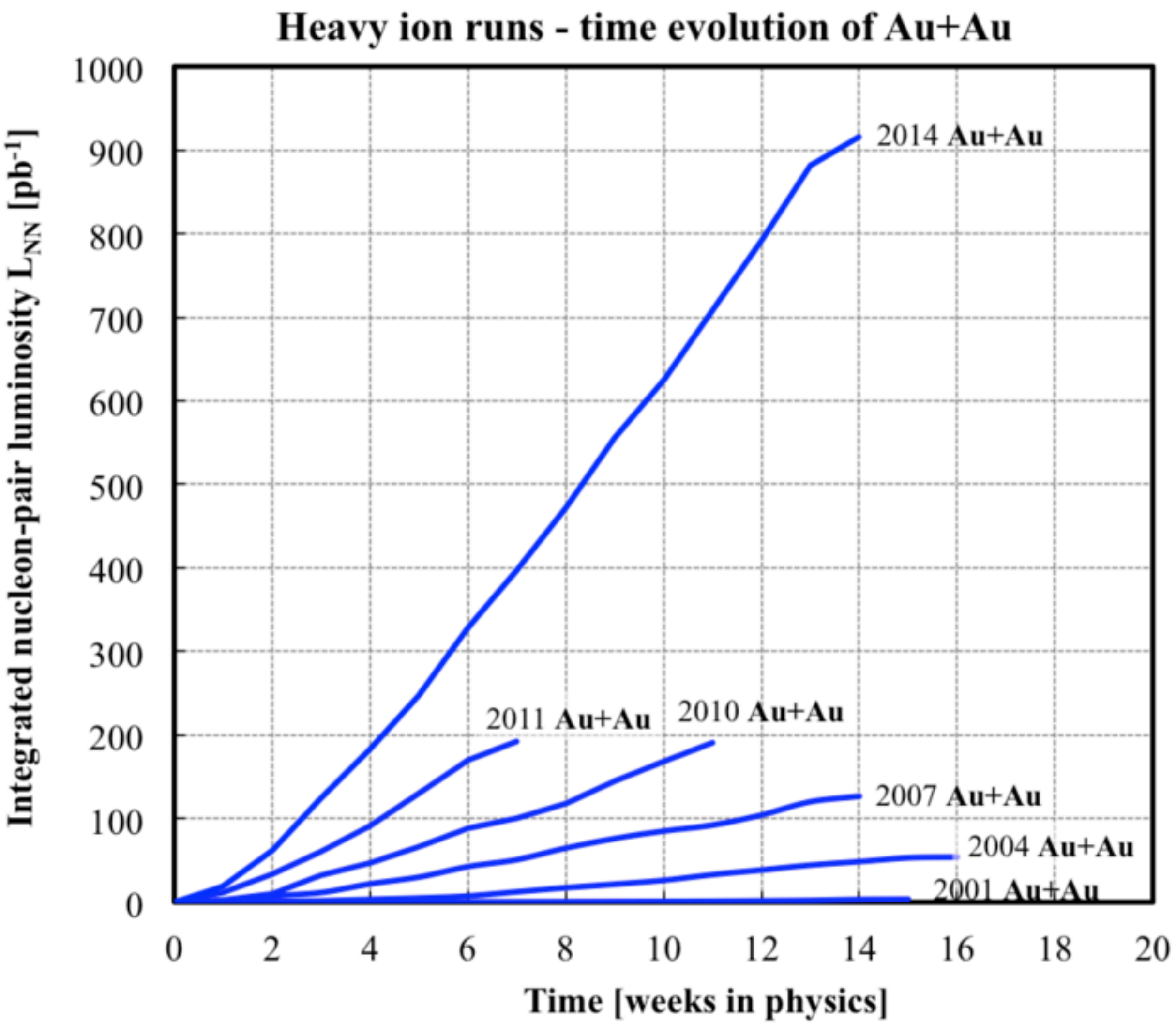
Metropolis-Hasting Algorism



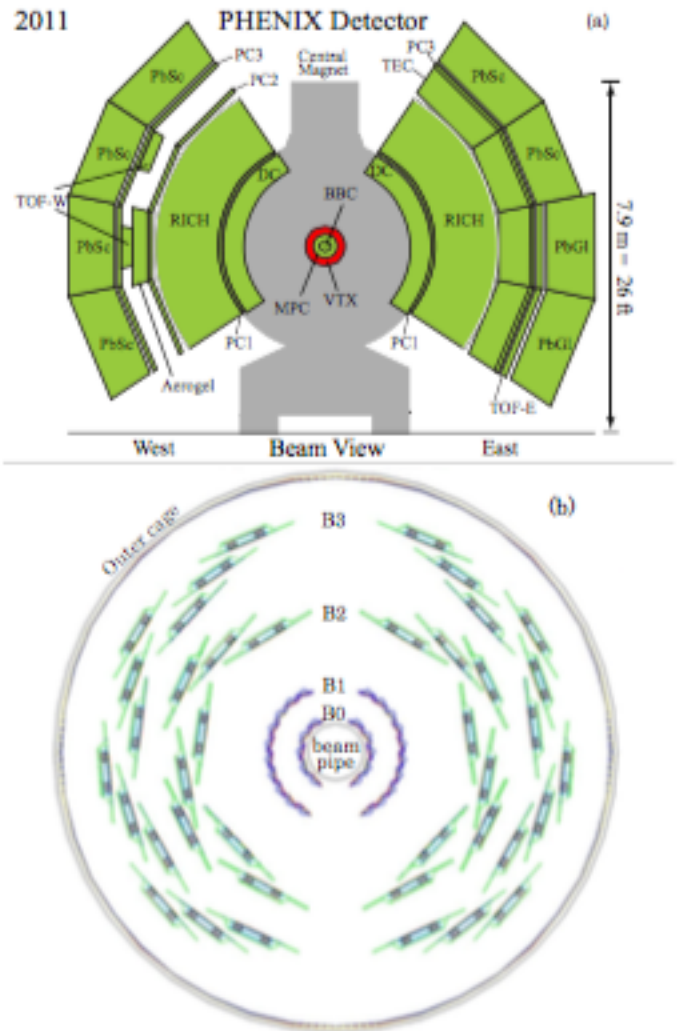
✓ Diffusion constant



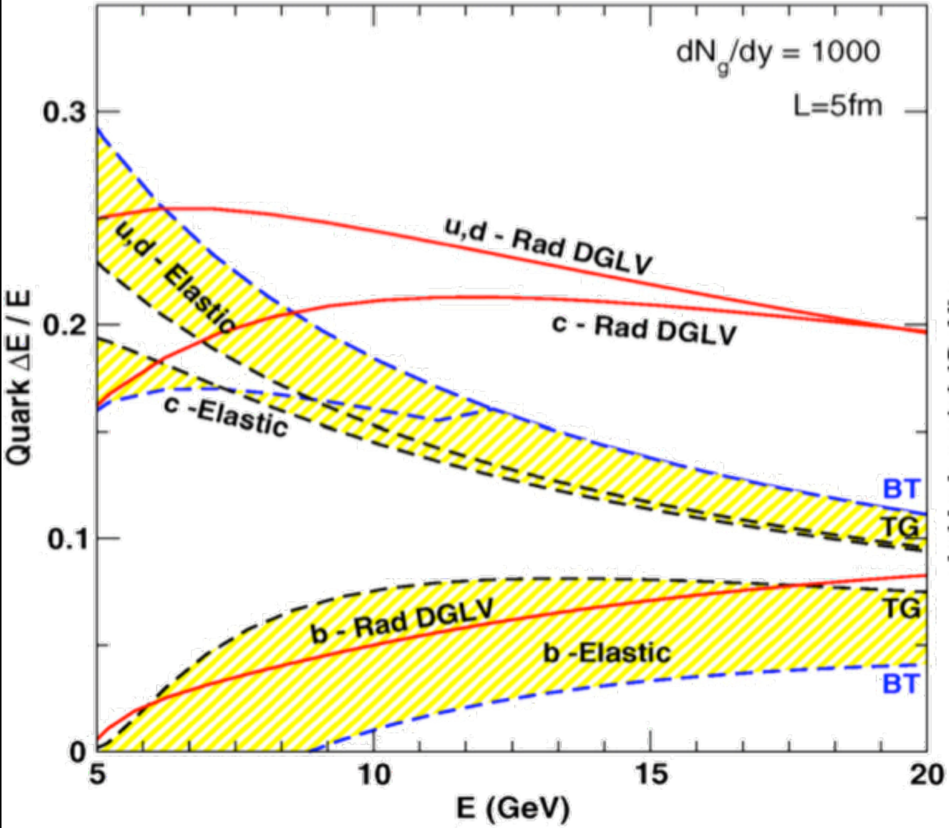


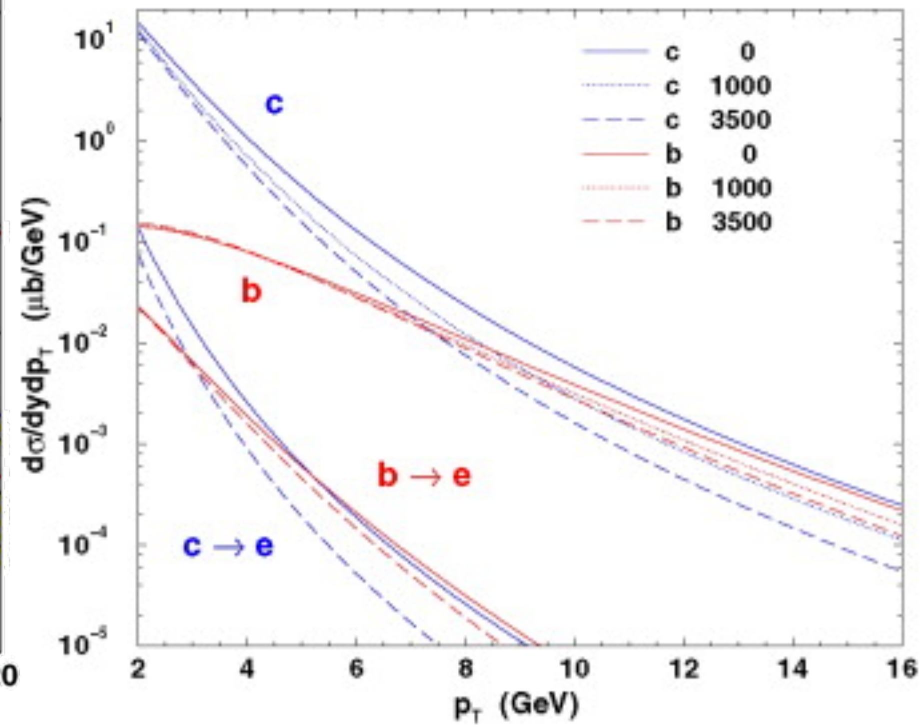


Heavy ion runs - time evolution of Au+Au
Integrated nucleon-pair luminosity L_NN [pb^-1]
Time [weeks in physics]
0
100
200
300
400
500
600
700
800
900
1000
0
2
4
6
8
10
12
14
16
18
20
2014 Au+Au
2011 Au+Au
2010 Au+Au
2007 Au+Au
2004 Au+Au
2001 Au+Au


2011
PHENIX Detector
(a)
PC3
PC2
Central Magnet
TEC
PbSc
PbGl
TOF-W
TOF-E
RICH
DC
BBC
MPC
VTX
PC1
Aerogel
7.9 m = 26 ft
West
Beam View
East
(b)
Outer cage
B3
B2
B1
B0
beam pipe

✓ Energy loss model





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+ collisional energy loss

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η_D: friction coefficient
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- Bathe-Heitler for gluon radiation
- Landau-Pomeranchuk-Migdal effect
  -> suppression of radiation in high density

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- Dead-Cone effect
  -> strong suppression of small-angle radiation

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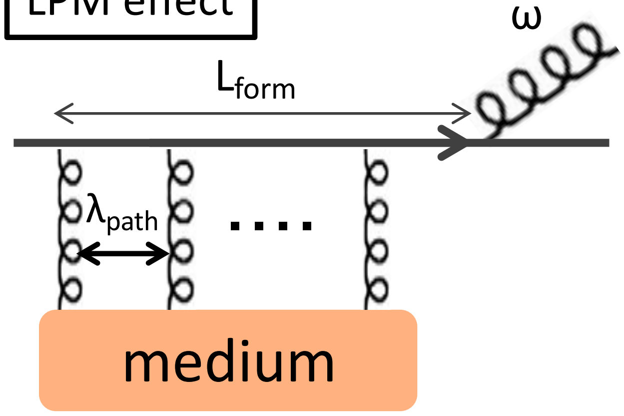
$\Delta E_g > \Delta E_{u,d,s} >(?)\ \Delta E_c >(?)\ \Delta E_b$

LPM effect



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Dead-Cone effect