High Energy Frontier – Recent Results from the LHC: Heavy Ions III

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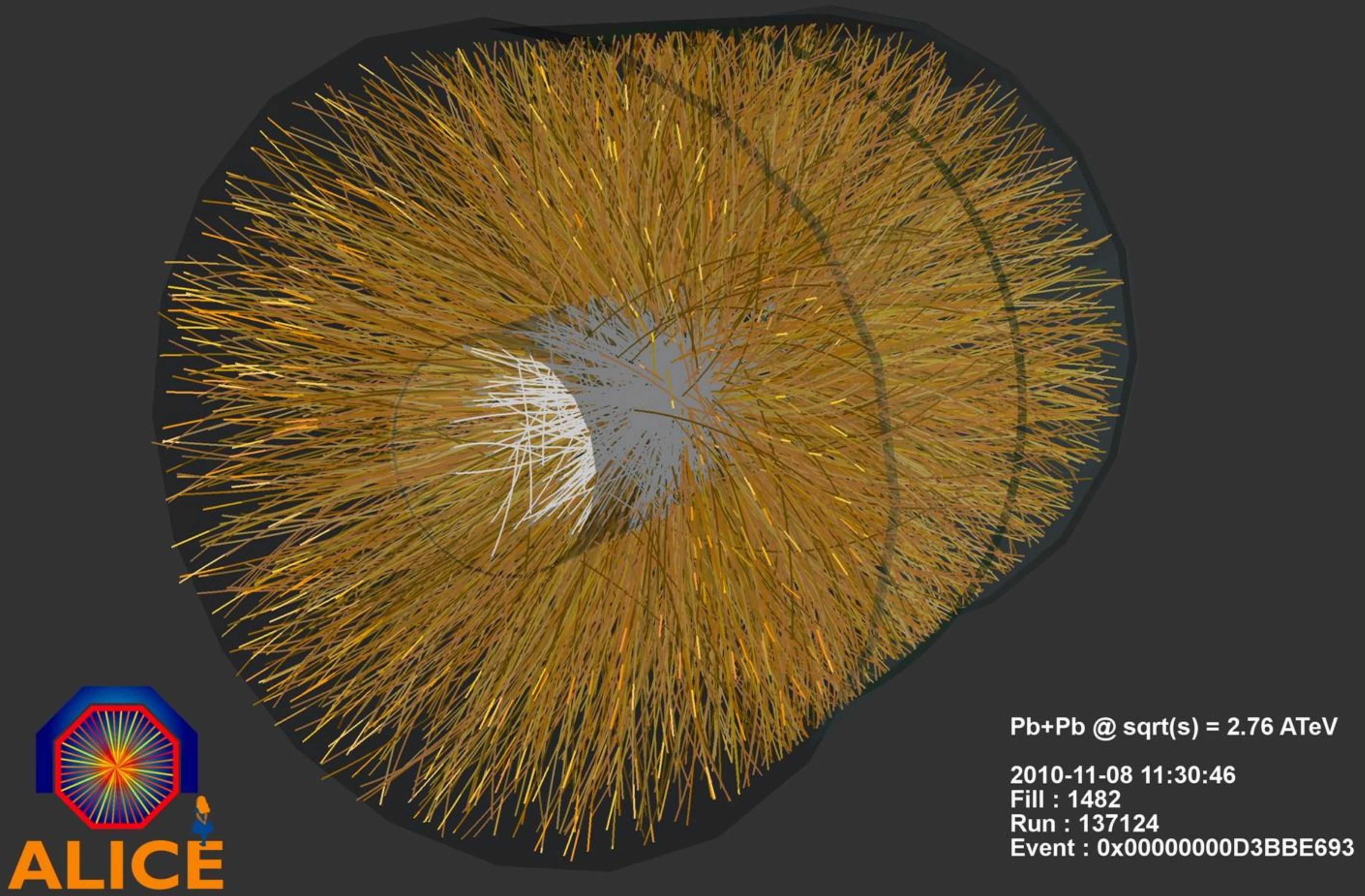
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Outline

- lecture 1 (22.11.): introduction
  - basics of relativistic heavy-ion collisions
- lecture 2 (29.11.): soft probes
  - hadron yields & spectra
  - hydrodynamics & collective motion
- lecture 3 (13.12.): hard probes
  - jets
  - heavy-flavor hadrons
- lecture 4 (20.12.): quarkonia & el.magn. probes
  - quest for J/ψ suppression/enhancement
  - direct & thermal photons
  - dileptons

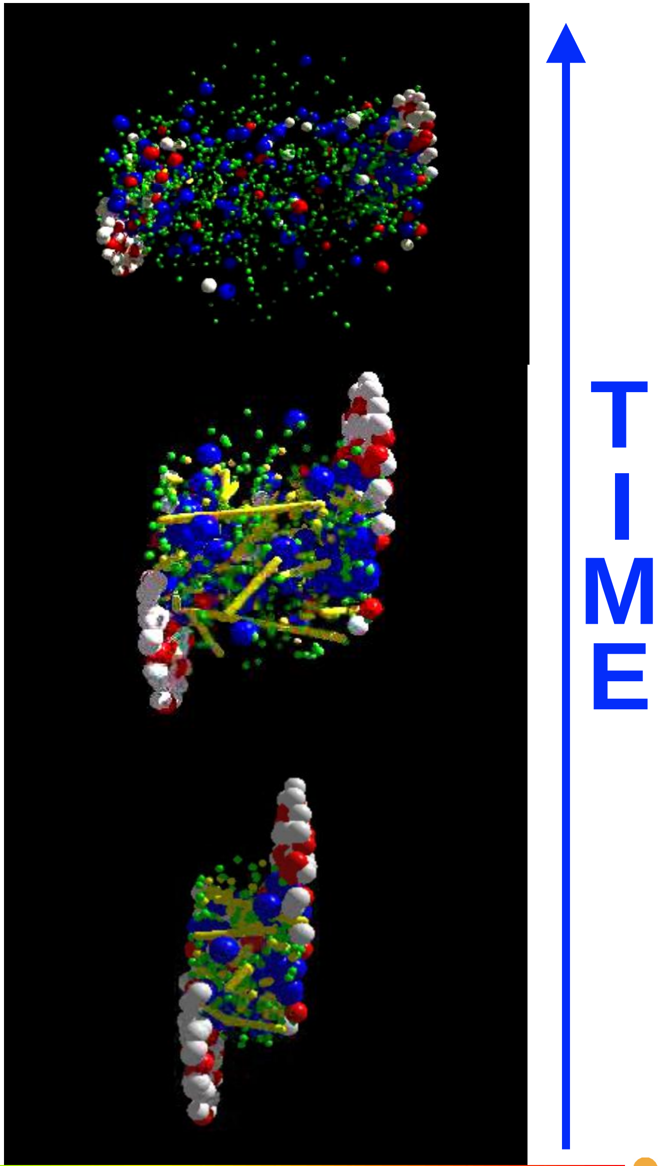
Hard probes

- basic idea:
  particles from hard parton scattering as probes of the hot and dense medium
- production of particles with large momentum
  - jets
  - jet quenching
- production of particles with large mass
  - W & Z bosons
  - hadrons carrying heavy quarks (charm, beauty)

Phases of an AA collision

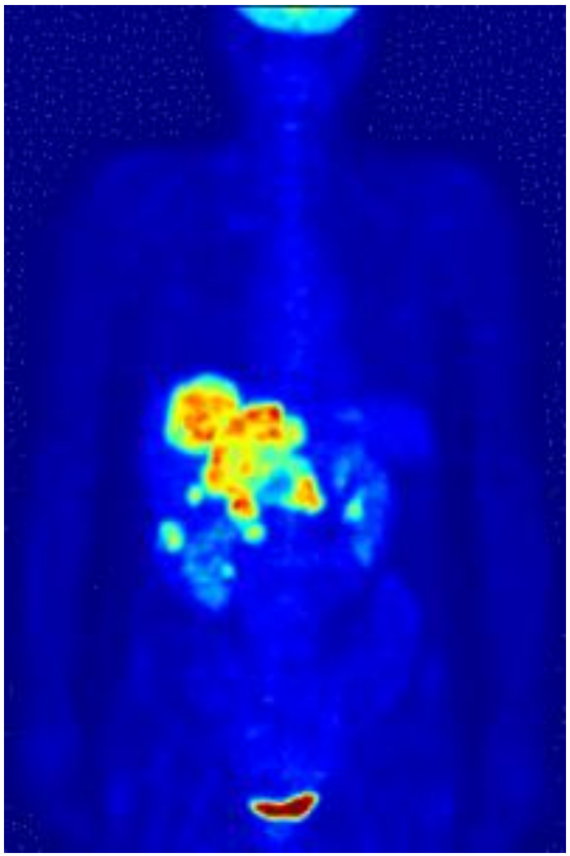
- investigation of an extreme system
  - short lived: ~10^{-22} s (~30 fm/c)
  - small volume: ~10^{-42} m^3 (~1000 fm^3)
  - large energy: ~8 x 10^{-5} J (~500 TeV)

- different observables to characterize different phases of the collision
  1. final state
     yield and momentum distributions of produced particles
     ⇨ thermalization, hadrochemistry
  2. initial state
     hydrodynamic expansion
  3. how to catch a glimpse of the hot and dense phase?

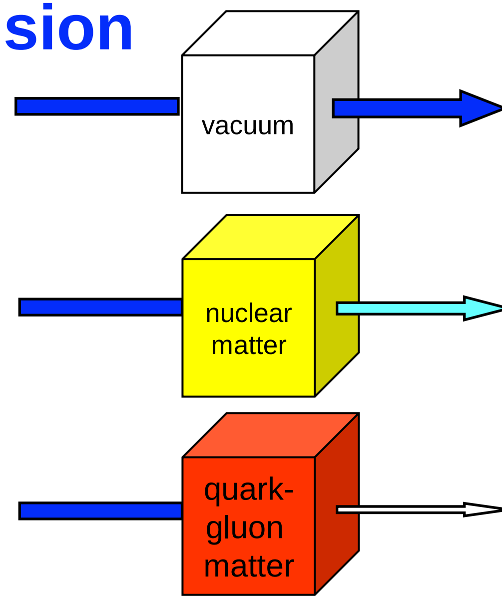


A view inside

- a view back to the year 1909
  - Geiger, Marsden, and Rutherford discover the atomic nucleus by scattering α particles on an Aluminum foil
- tomography – investigation of matter using probes

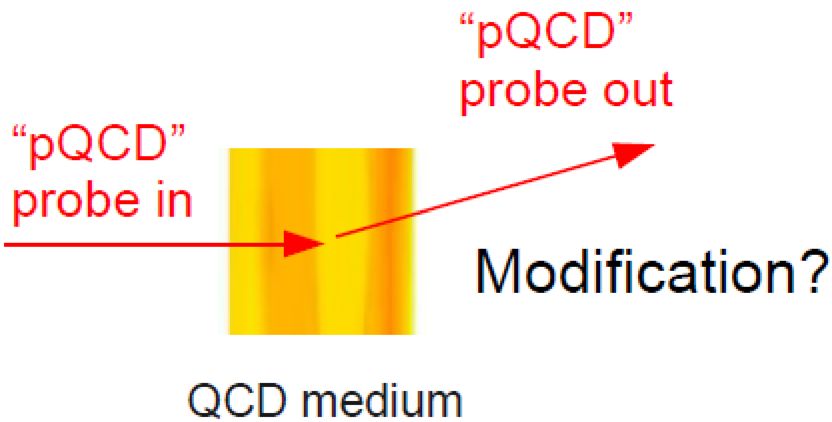


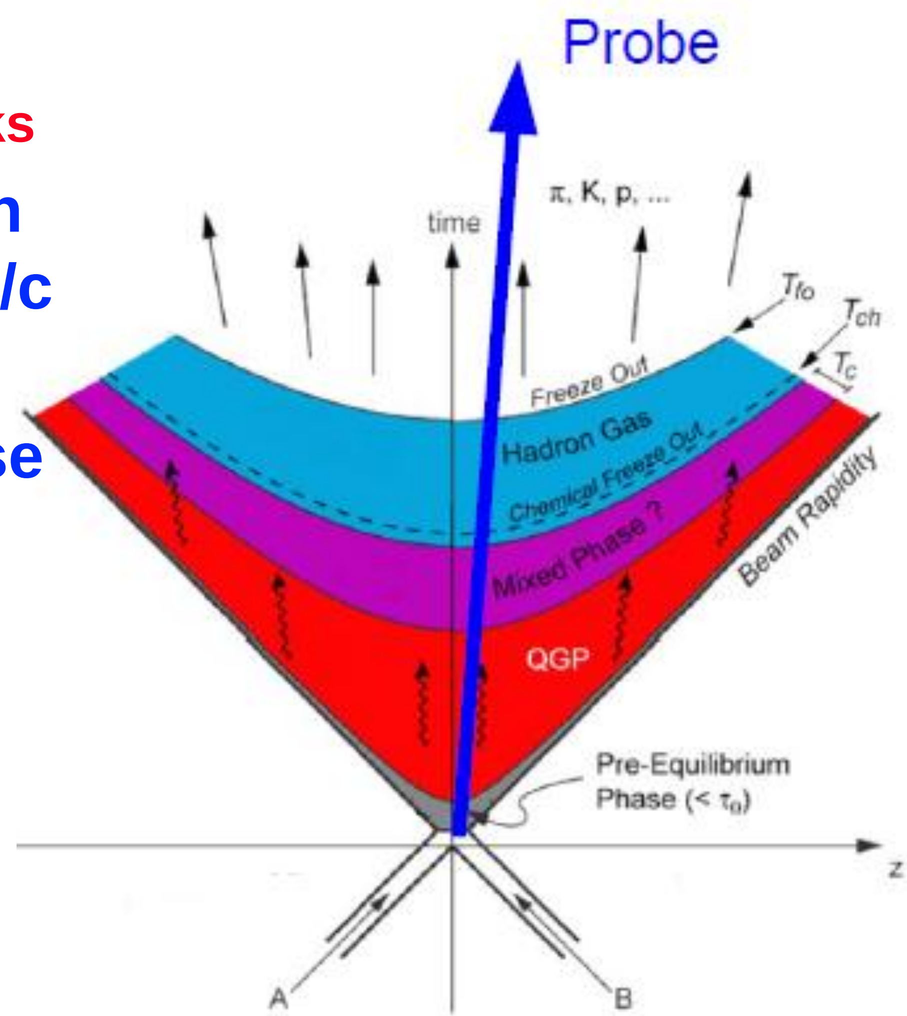
  - calibrated probe
  - calibrated interaction
  - ➔ scattering experiment can reveal properties of the matter investigated
- nucleus-nucleus collision
  - "external" probe excluded
  - probe has to be generated in the early phase of the collision (before the medium forms)



Tomography of QCD matter

- hard (large Q^2) probes of QCD matter
  - jets, photons, W, Z, heavy quarks
- self generated in the collision at $t \sim 1/Q$ (or $t \sim 1/m$) < 0.1 fm/c
- "tomographic" probes of the hottest and densest phase of the collision





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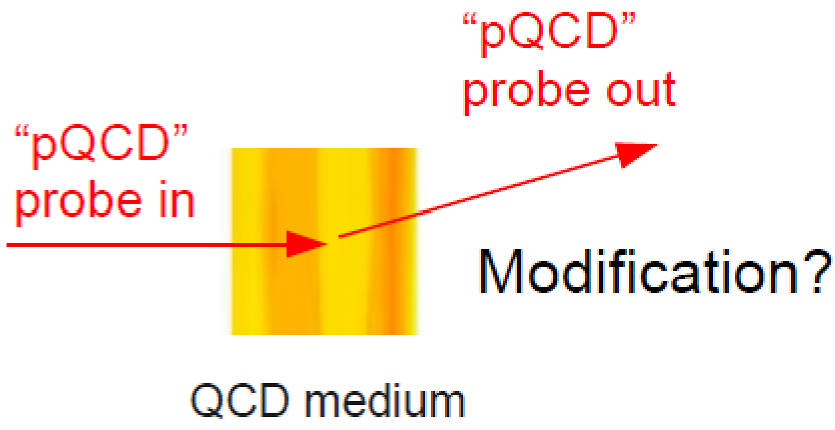
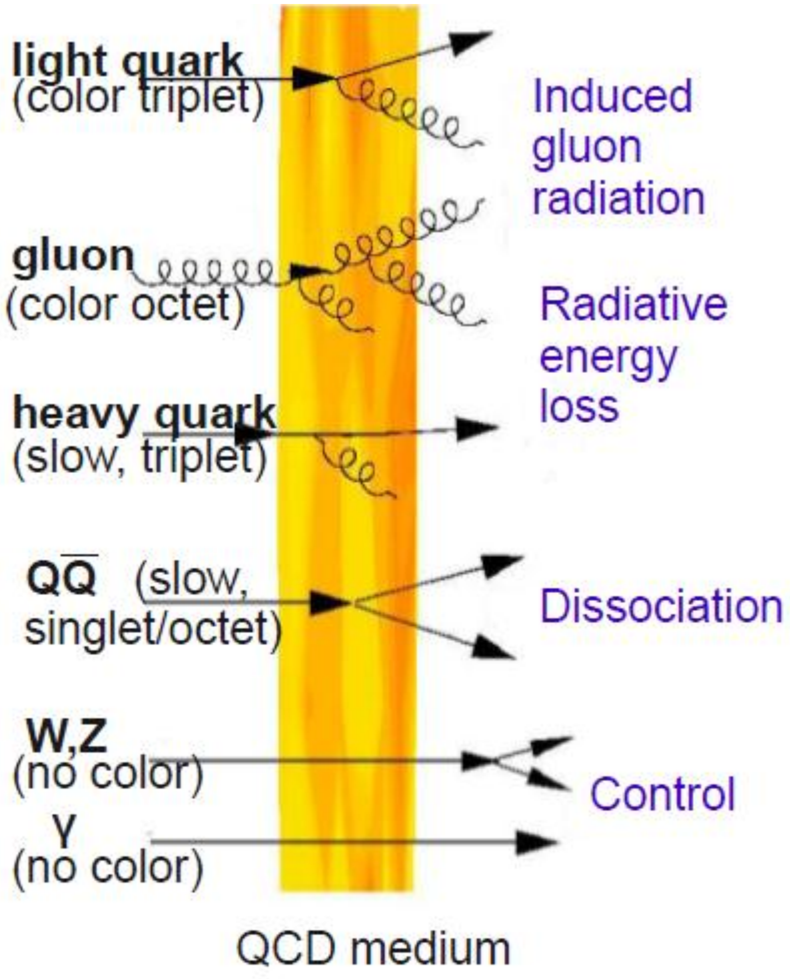
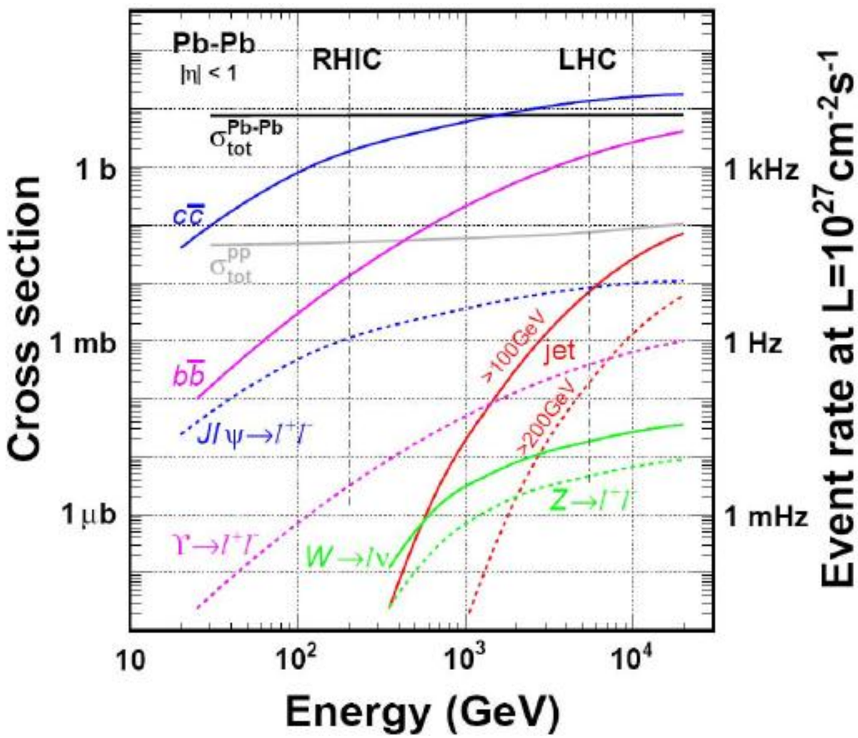
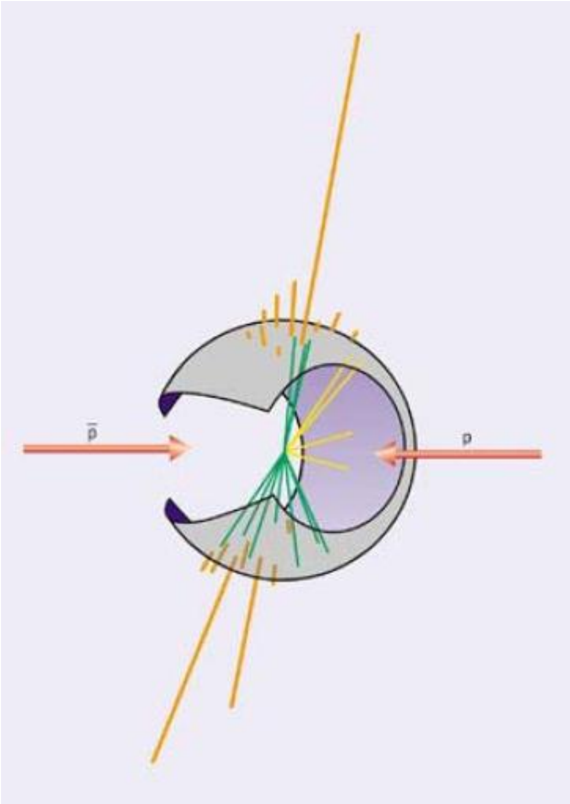




Jets

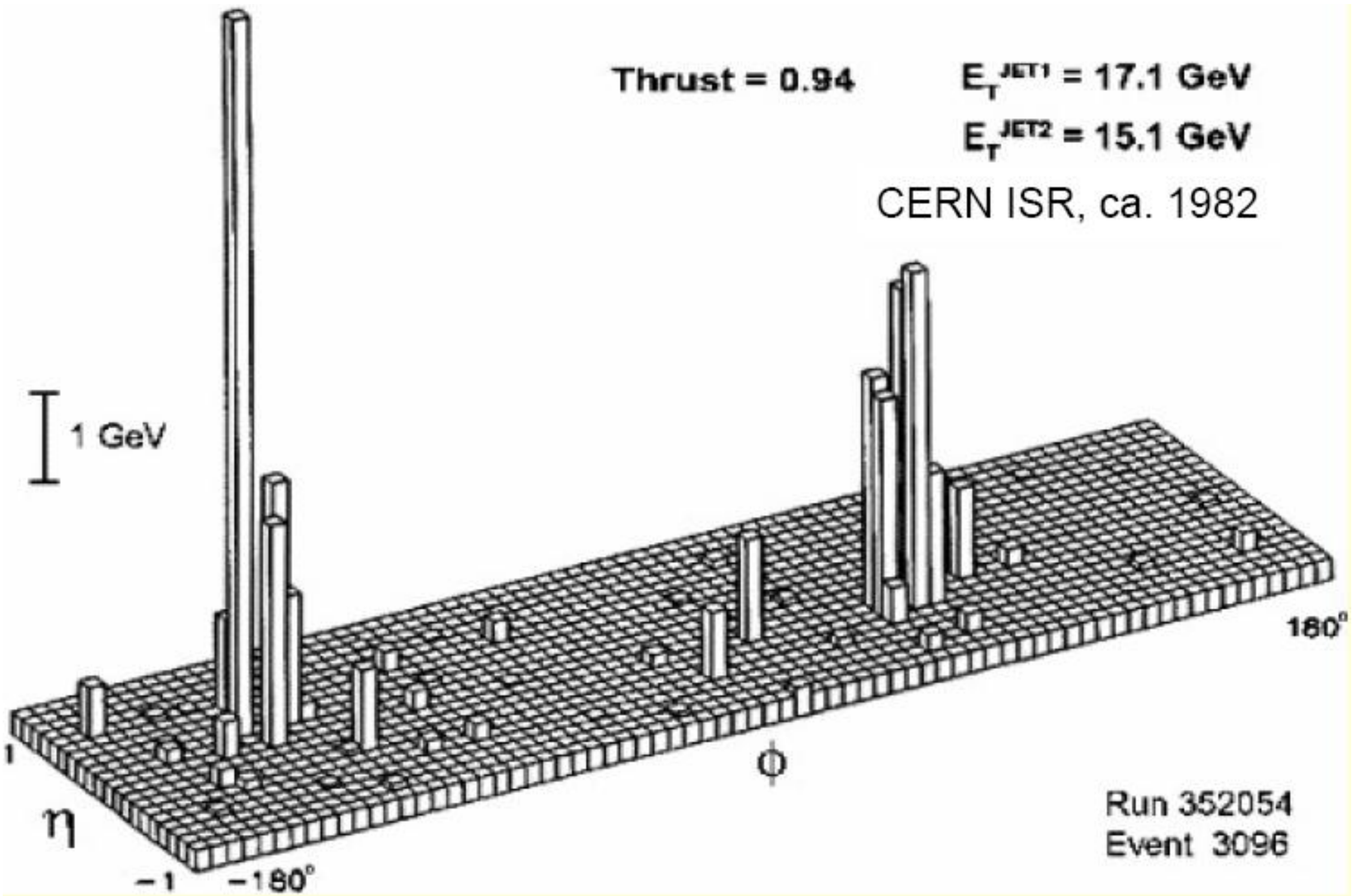
- correlated high p_T particles
- discovery: ~1980
- confirmation of QCD
- jet production cross section





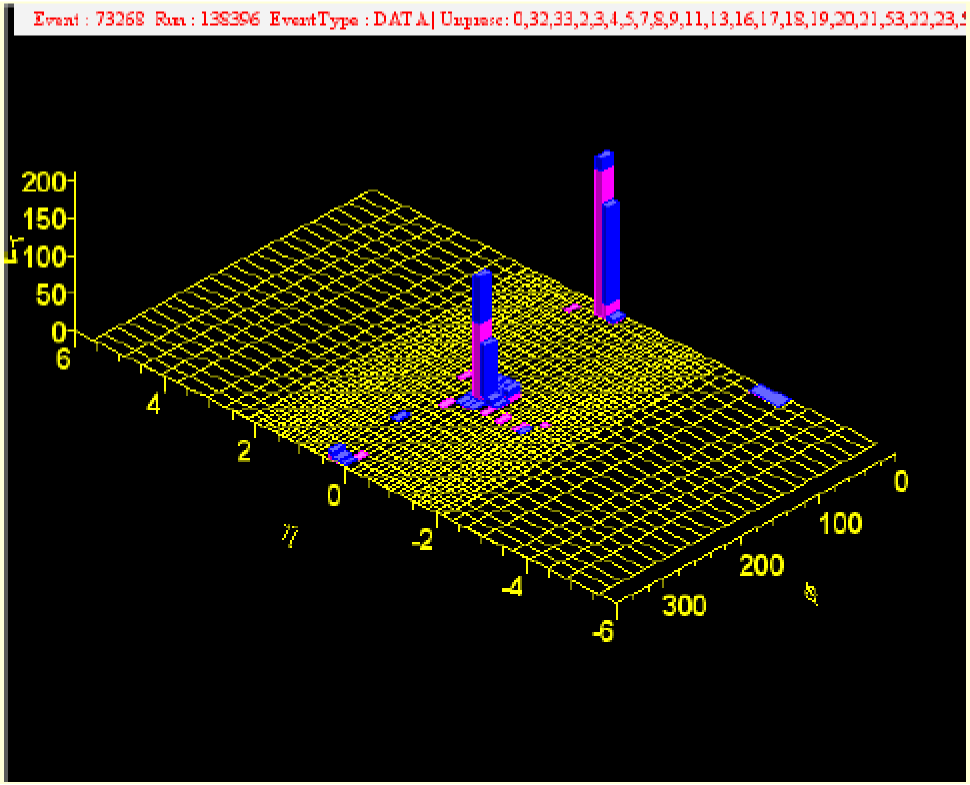
UA2 2-jet event, ~1982

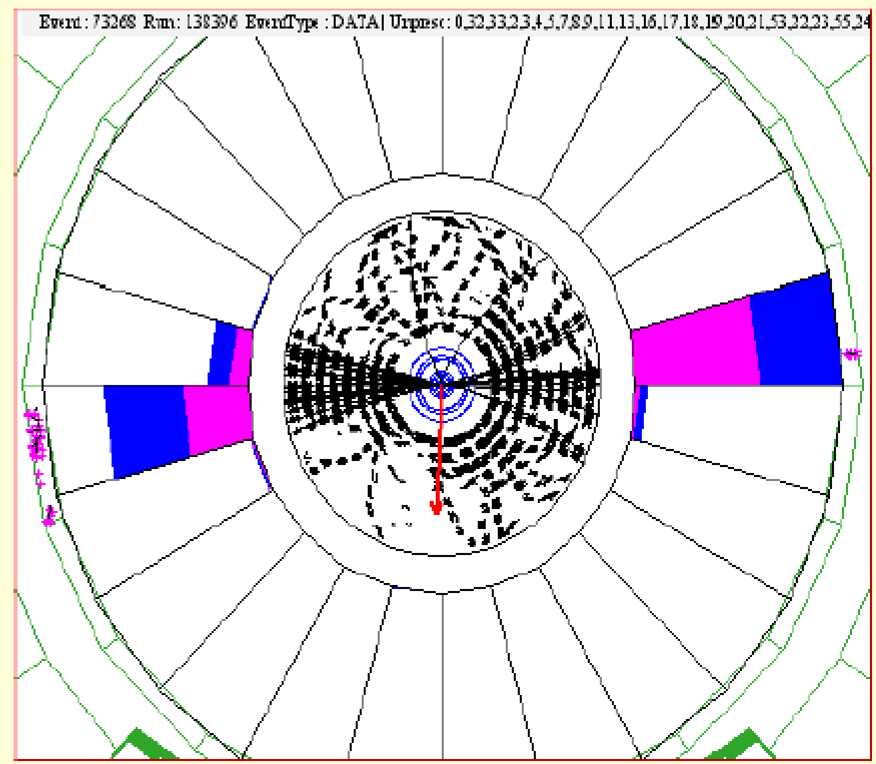
Jets in pp @ $\sqrt{s}$ = 63 GeV



Jets at the Tevatron

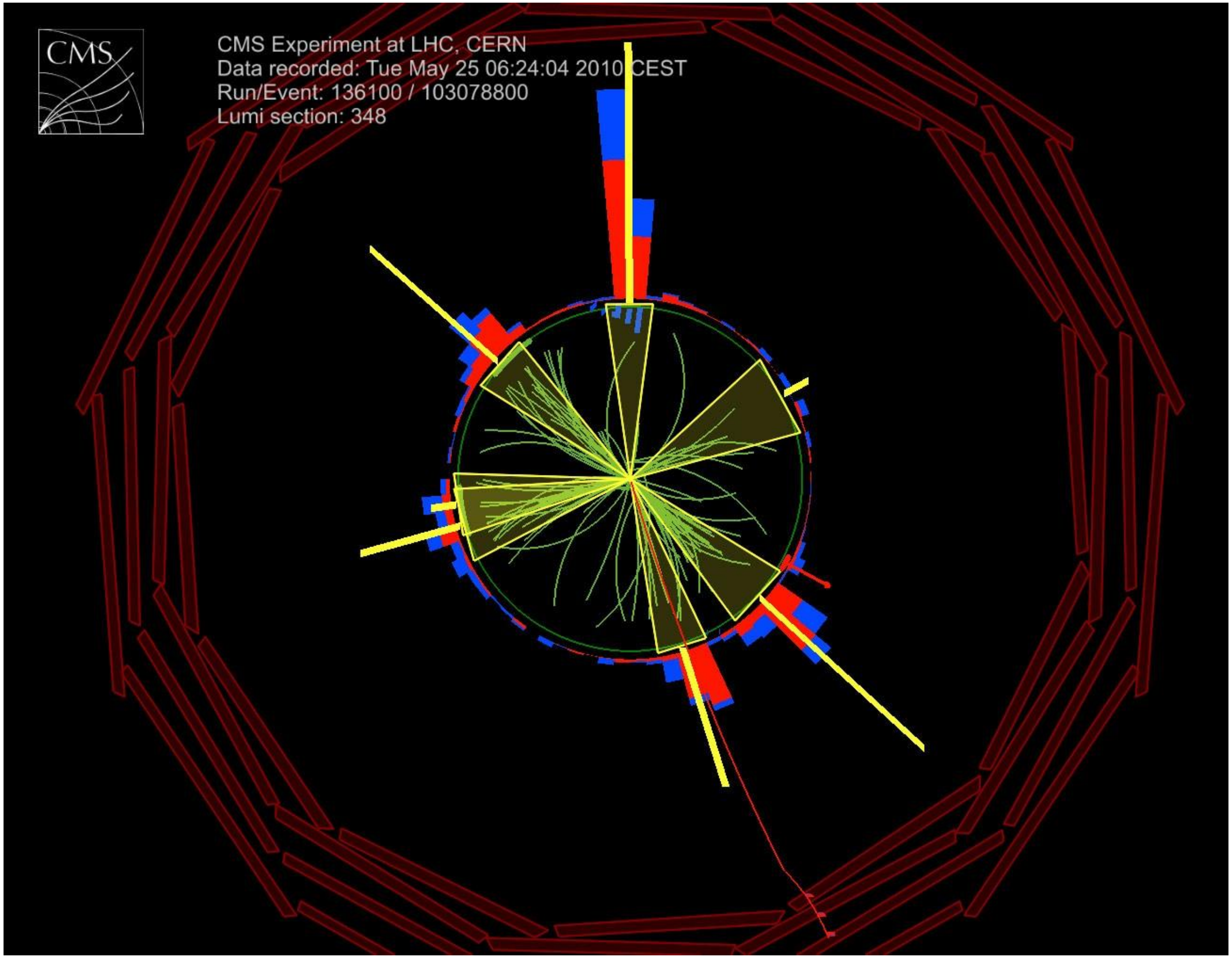
- **di-jet event in proton-antiproton collisions @ √s = 1,8 TeV**





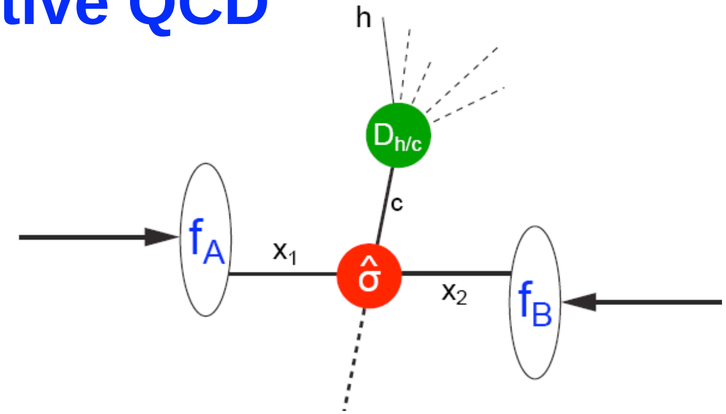
Jets at the LHC

- multi-jet event in pp @ √s = 7 TeV in CMS



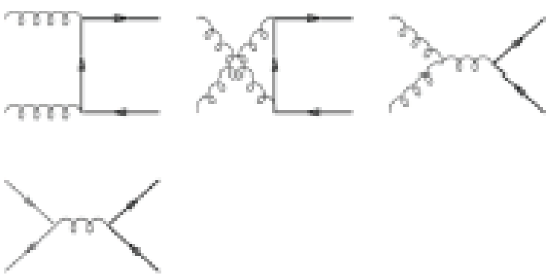
Hard scattering: „theory“

- hard scattering treatment: perturbative QCD
  - large momentum transfer Q^2
    - – large transverse momentum p_T and/or
    - – large mass m
- hadron production in AB collisions
  - pQCD + factorization + universality
    (Collins, Soper, Sterman Nucl. Phys. B263(1986)37)

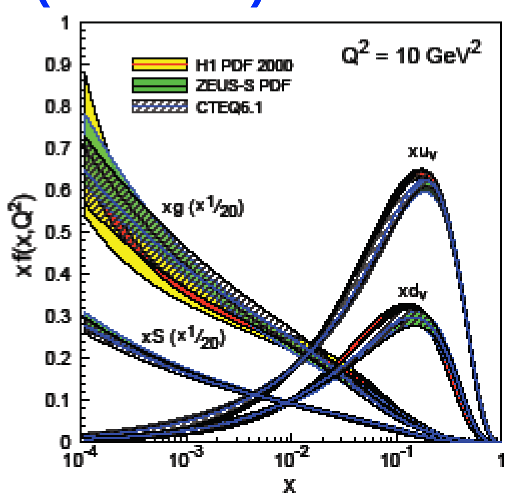


$$E\frac{d^3\sigma_h}{dp^3} \propto \sum_{a,b,c,d} \int dz_c dx_1 dx_2 \frac{s}{z_c^2} f_{i/A}(x_1, Q^2) f_{j/B}(x_2, Q^2)\, D_{h/c}(z_c, Q^2) \frac{d\hat{\sigma}^{(ab\rightarrow cd)}}{dt} \delta(s+u+t) + \mathcal{O}\left(\frac{\Lambda}{m}\right)^p$$

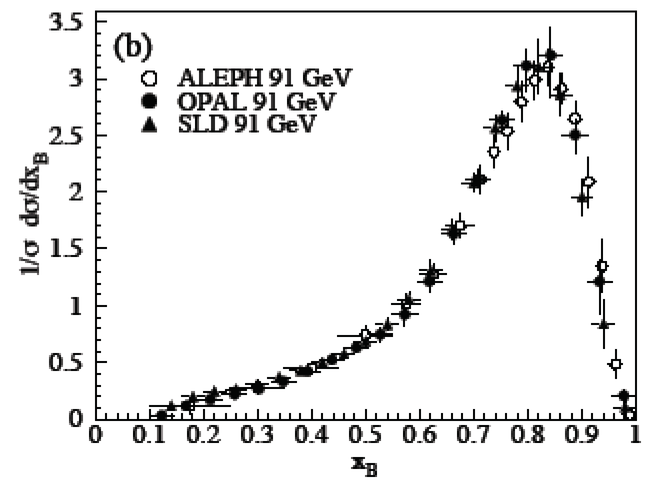
perturbative QCD:
parton-parton cross section (calculable in pQCD in orders of α_s, i.e.. LO, NLO, NNLO, ...)



structure functions:
partons in initial state (from DIS)

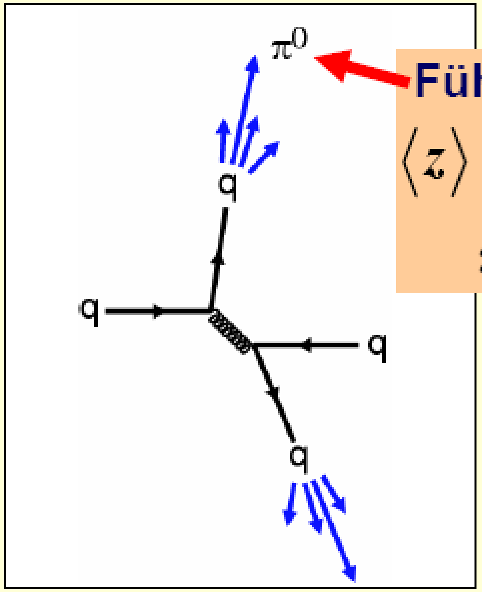


fragmentation:
jets → hadrons (measured, e.g. in ee collisions)



How to measure jet production

- (leading) particle at high p_T
- angular correlations of 2 (or more) particles



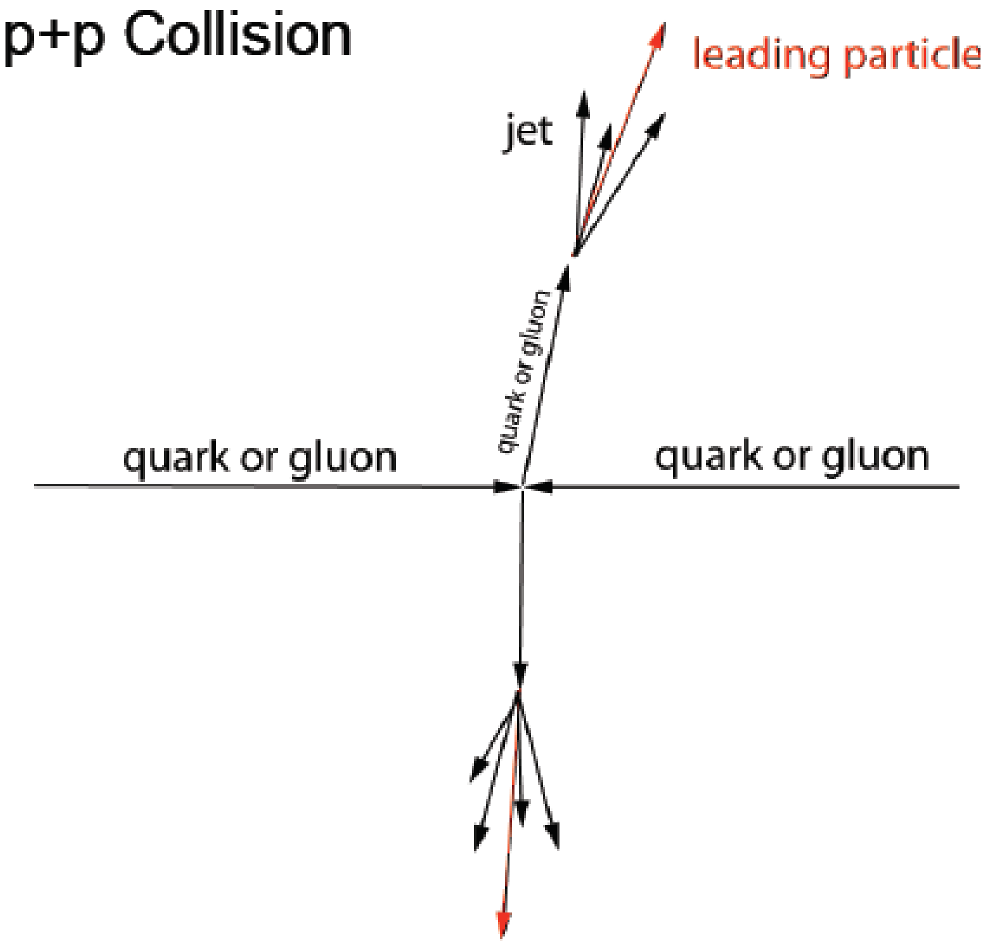
Führendes Hadron:

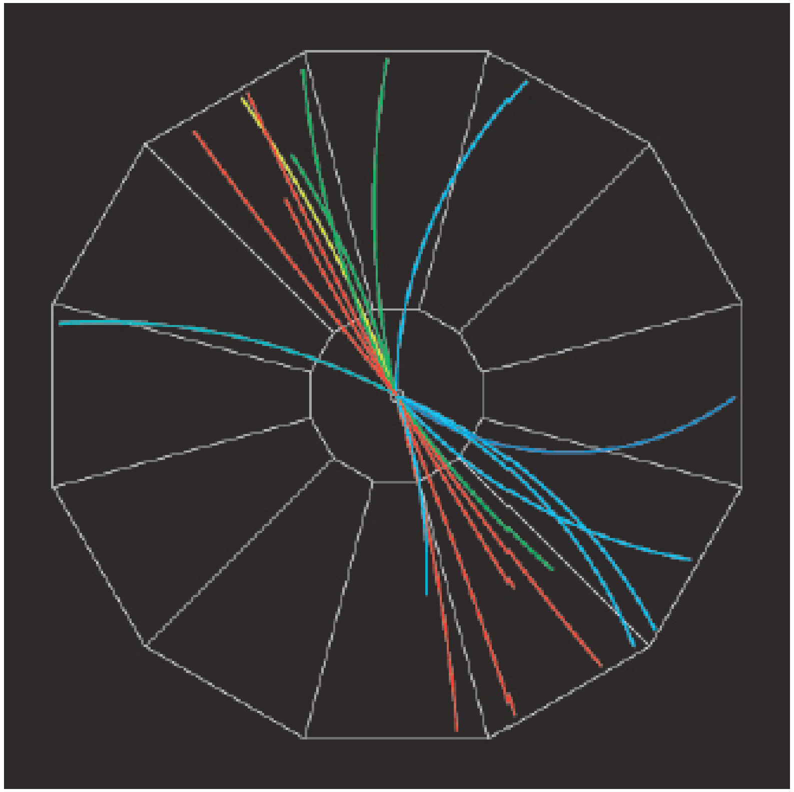
$$\langle z \rangle = \langle p_{\text{hadron}} / p_{\text{parton}} \rangle \approx 0.25$$

K. Reygers

- „complete“ jet reconstruction on an event-by-event basis (hadrons → scattered partons)
  - feasible in pp collisions
  - more difficult (but possible) in nucleus-nucleus collisions

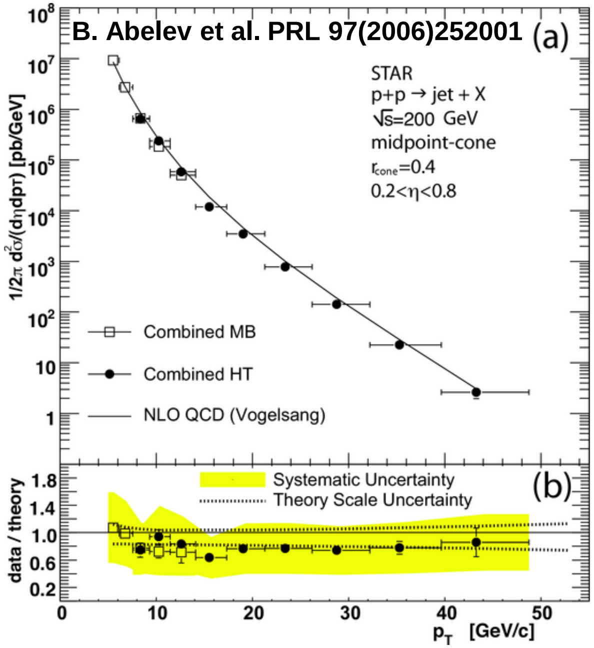
Calibration in pp collisions

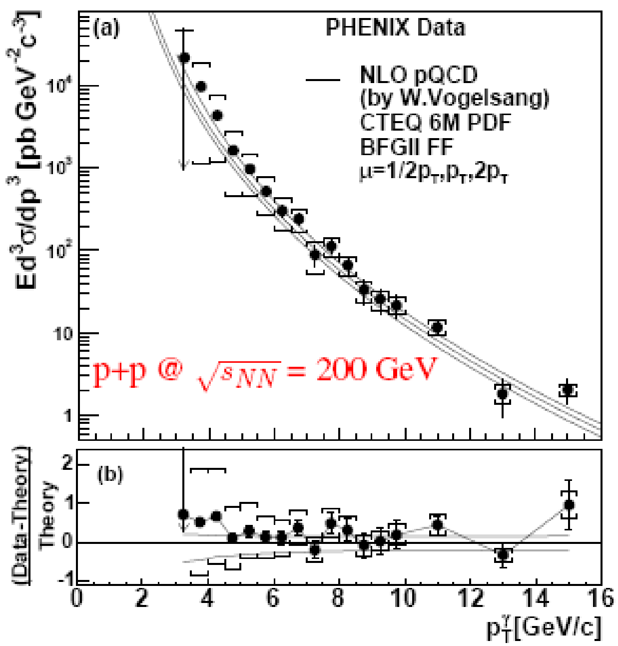


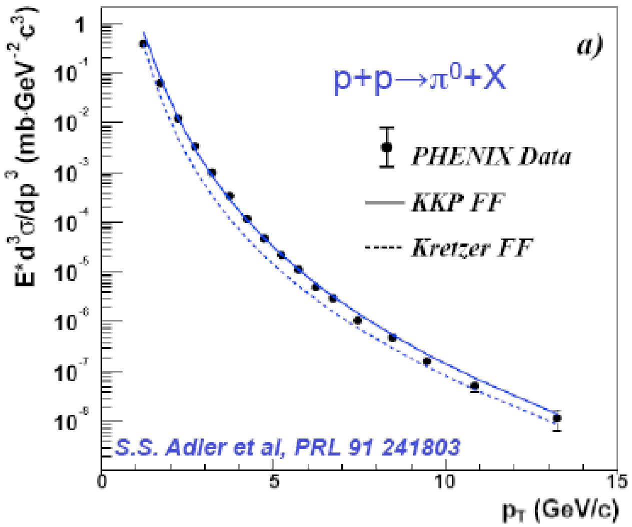


Hard probes: pp @ RHIC

- jets
- photons
- hadrons

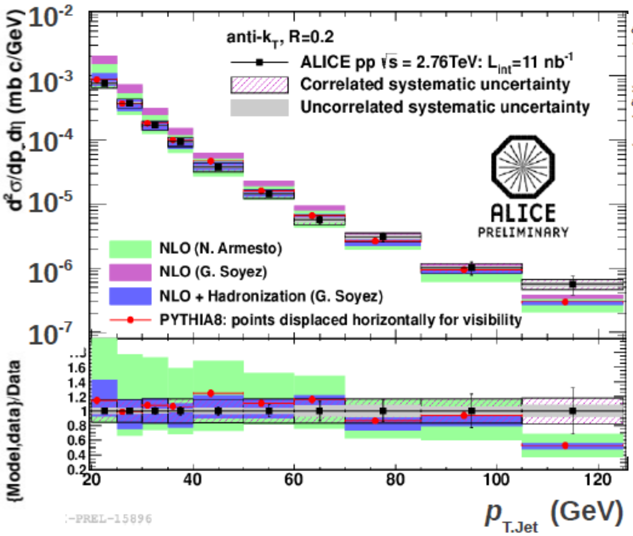


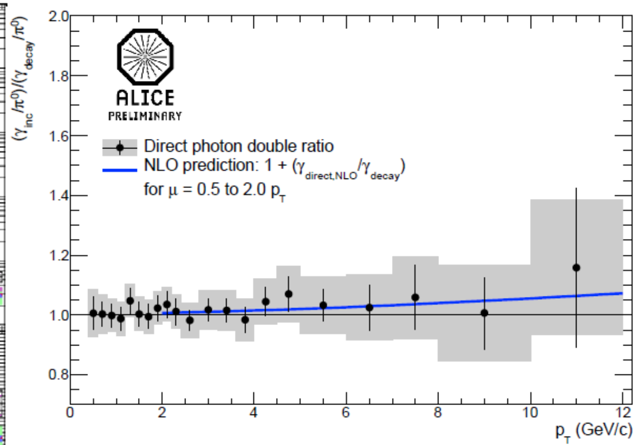


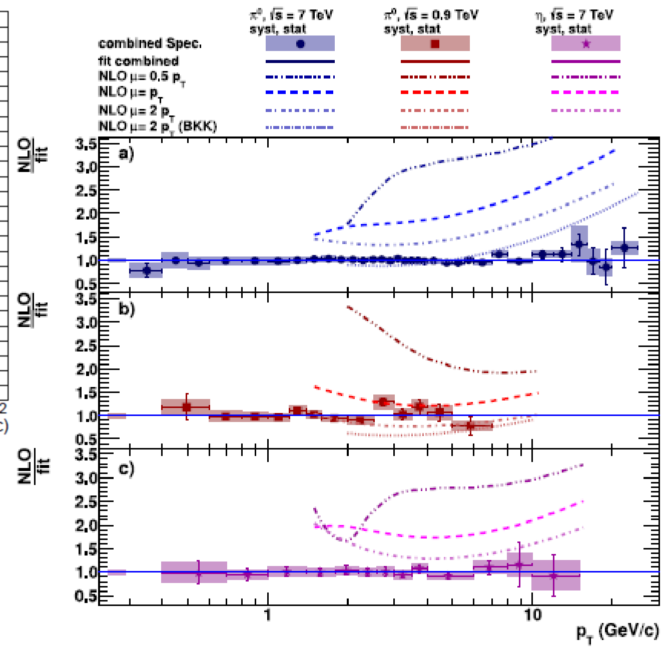


Hard probes: pp @ LHC

- **jets**
- **photons**
- **hadrons**

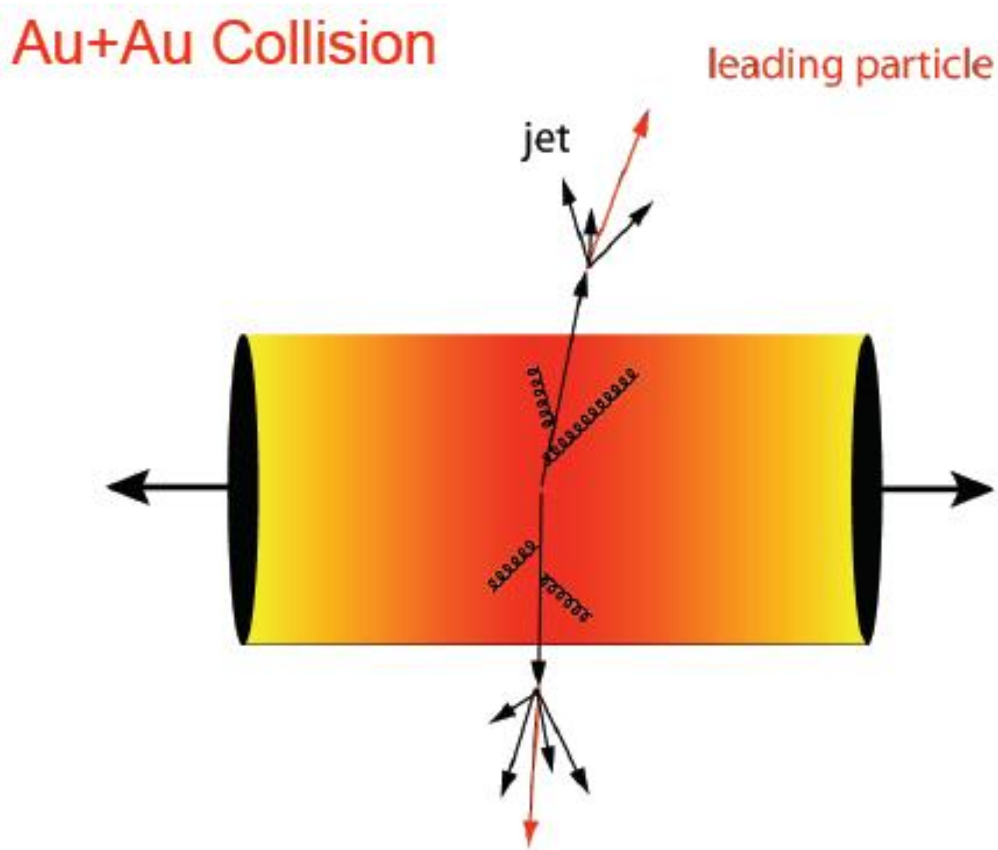


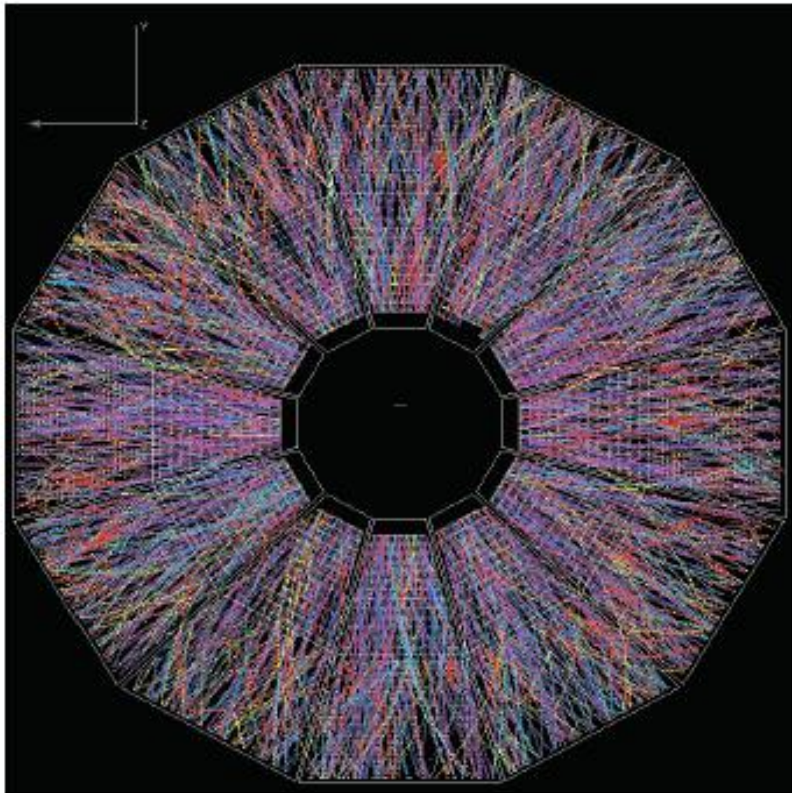




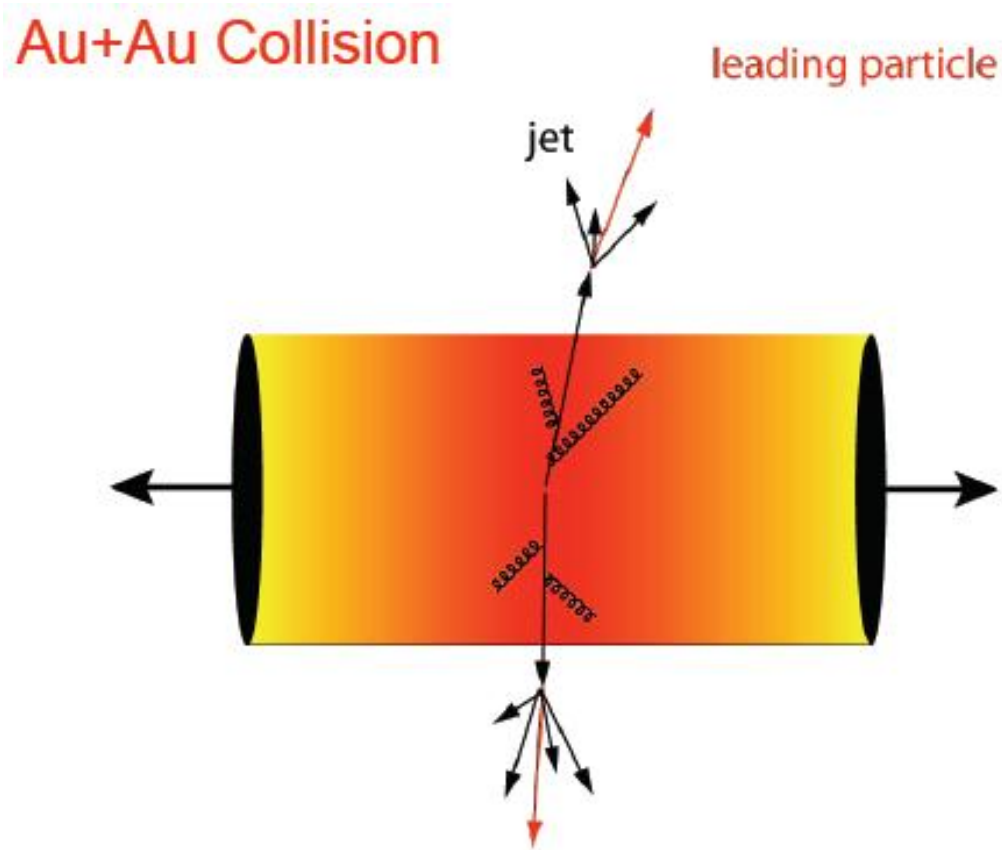
- **extensive hard probe measurements at RHIC and the LHC**
- **data are consistent with pQCD calculations within experimental and theoretical uncertainties**

Jets in the medium

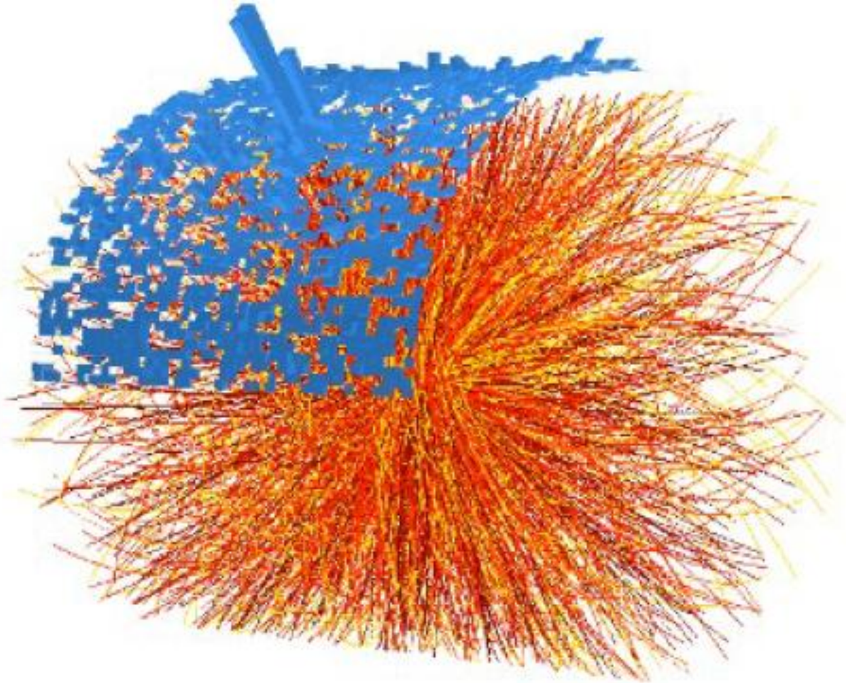




Jets in the medium



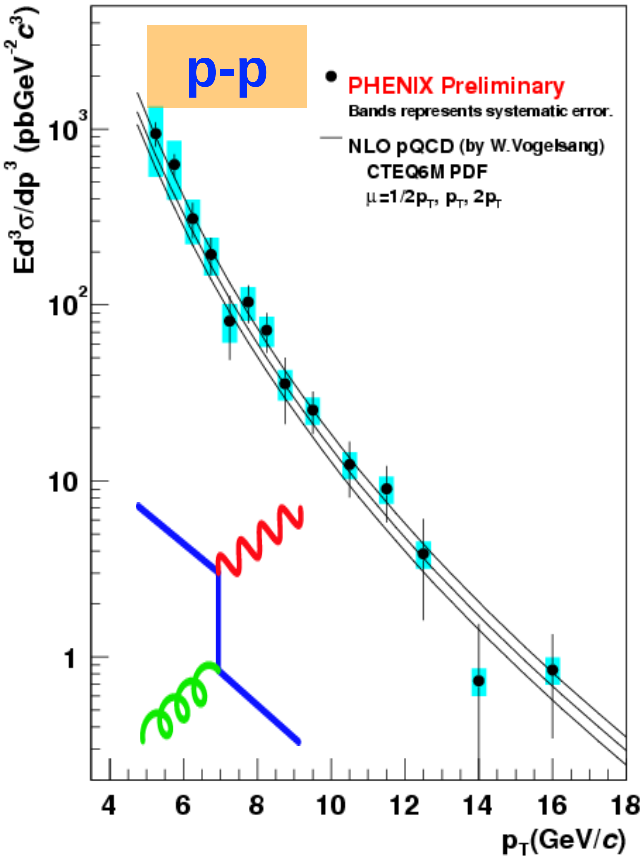
very high p_T jets stick out of the underlying event

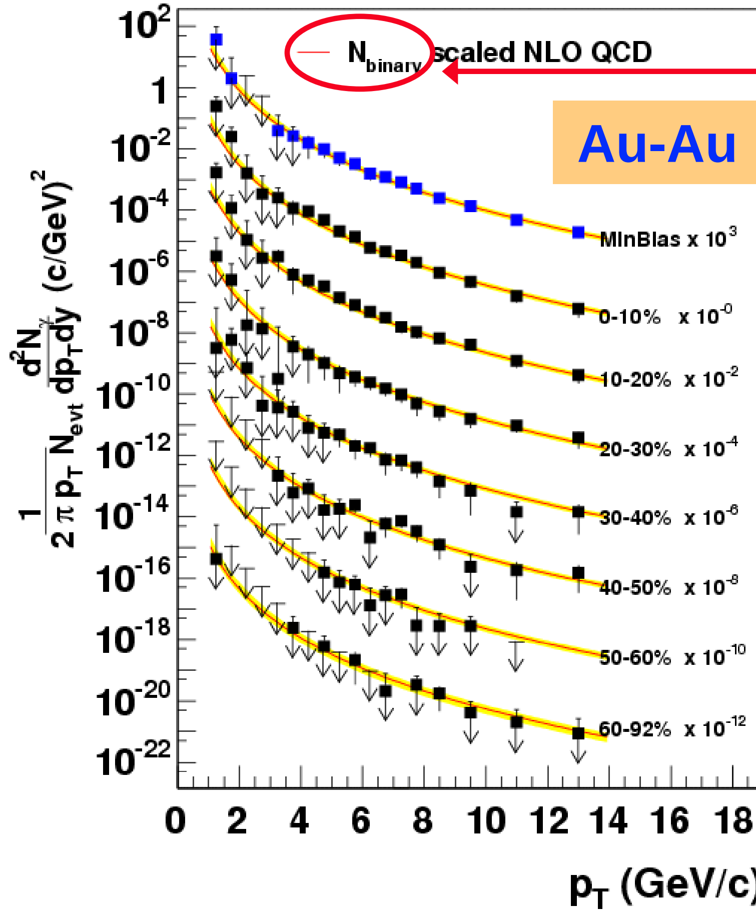


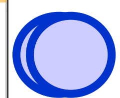
- how to quantify the interaction of the probe with the medium?

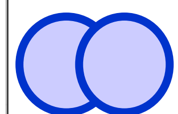
Direct photons at $\sqrt{s_{NN}}$=200 GeV

- photons from quark-gluon Compton scattering







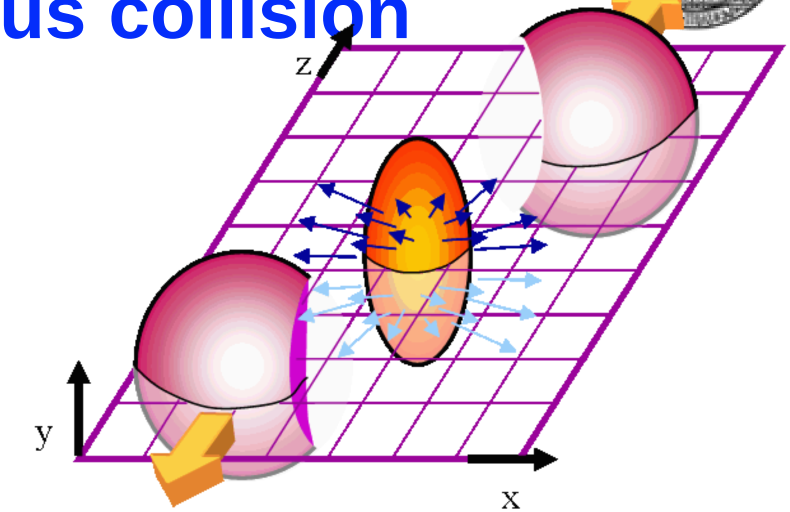


N_{binary}: number of "binary" collisions, determined from the collision geometry (Glauber)

- direct photons = calibrated probe
- no strong final state interaction

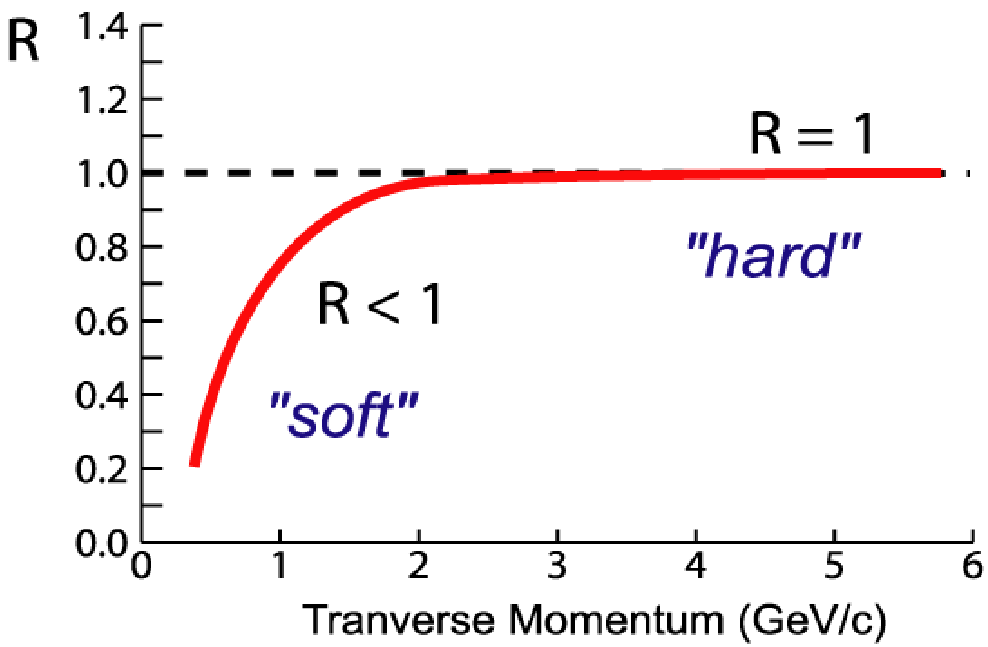
Nuclear modification factor R_{AA}

- geometry of a nucleus-nucleus collision
  - participating nucleons: N_{part}
  - binary collisions: N_{bin}



- nuclear modification factor:

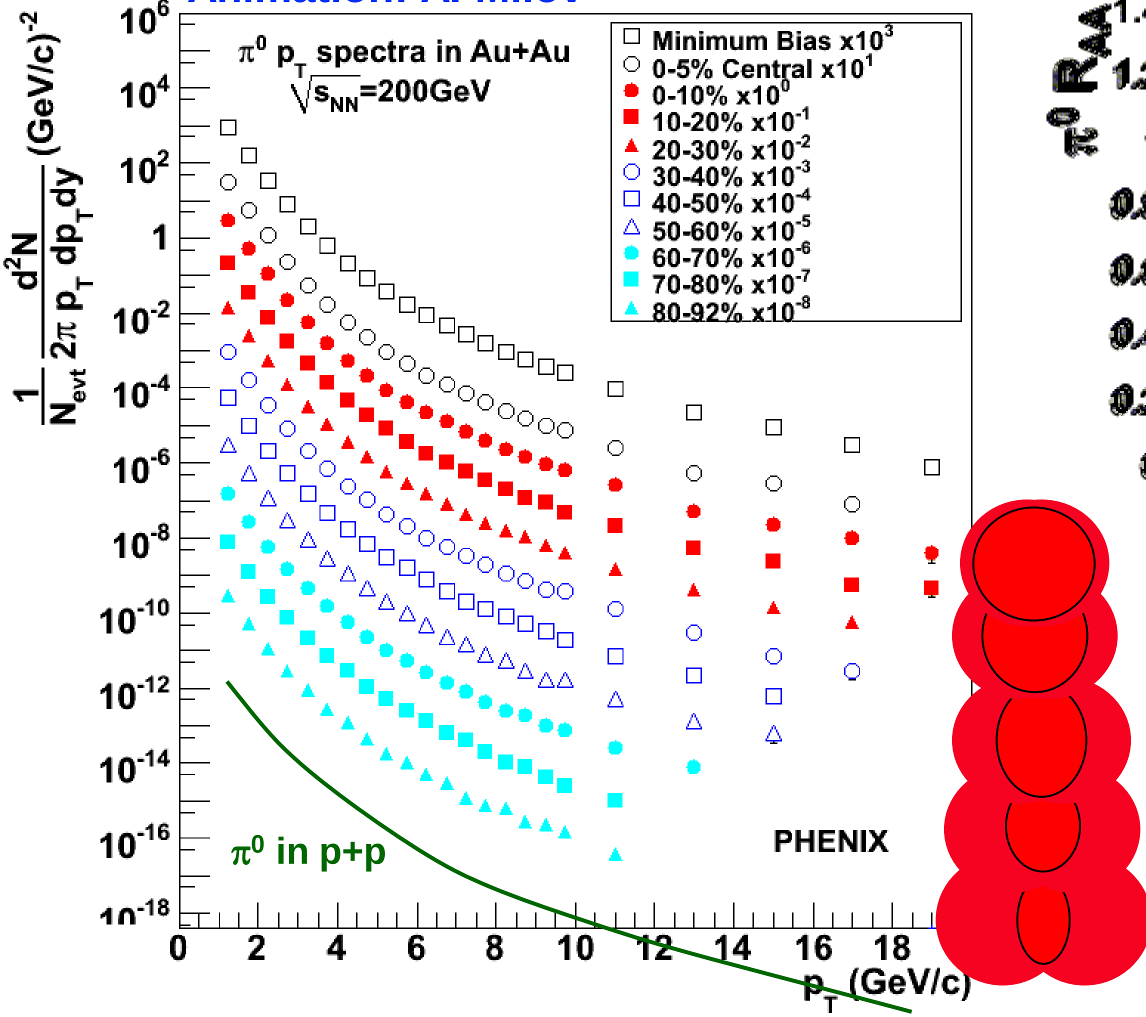
$$R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{T_{AA}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

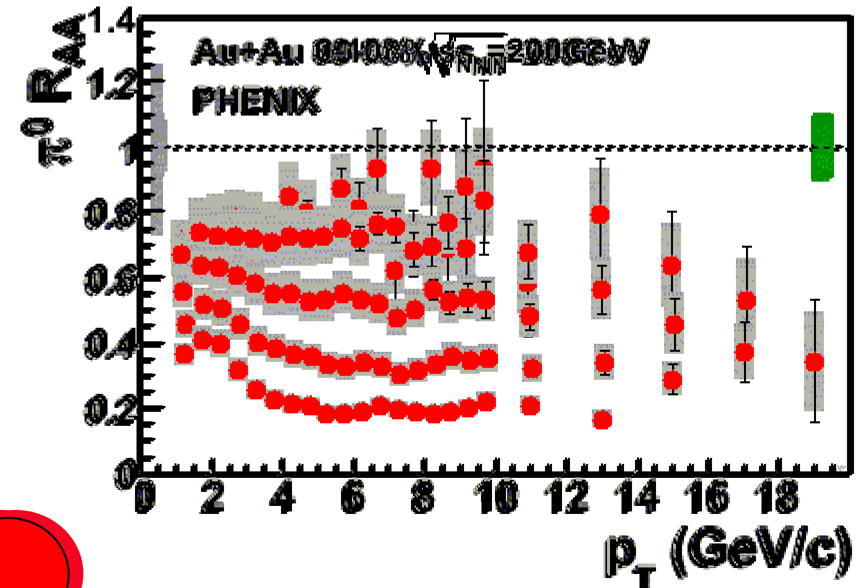


- no medium effect
  - AA collisions as sum of N_{bin} independendet pp collisions
    - $R_{AA} = 1$ at high p_T (particle production dominated by hard processes)
- medium effect
  - $R_{AA} \neq 1$ at high p_T

π^0 in Au+Au collisions at RHIC

Animation: A. Milov



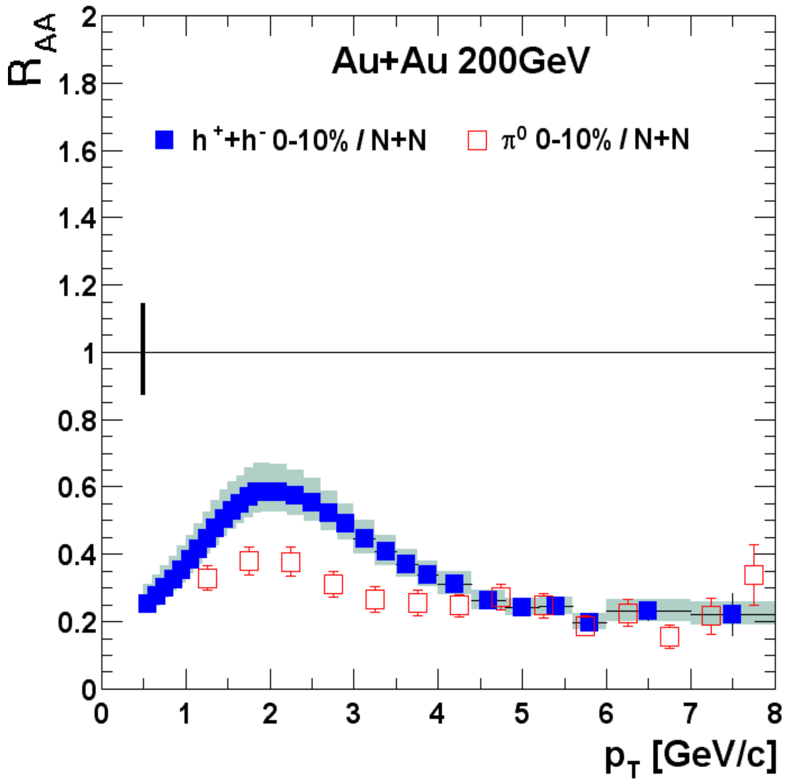


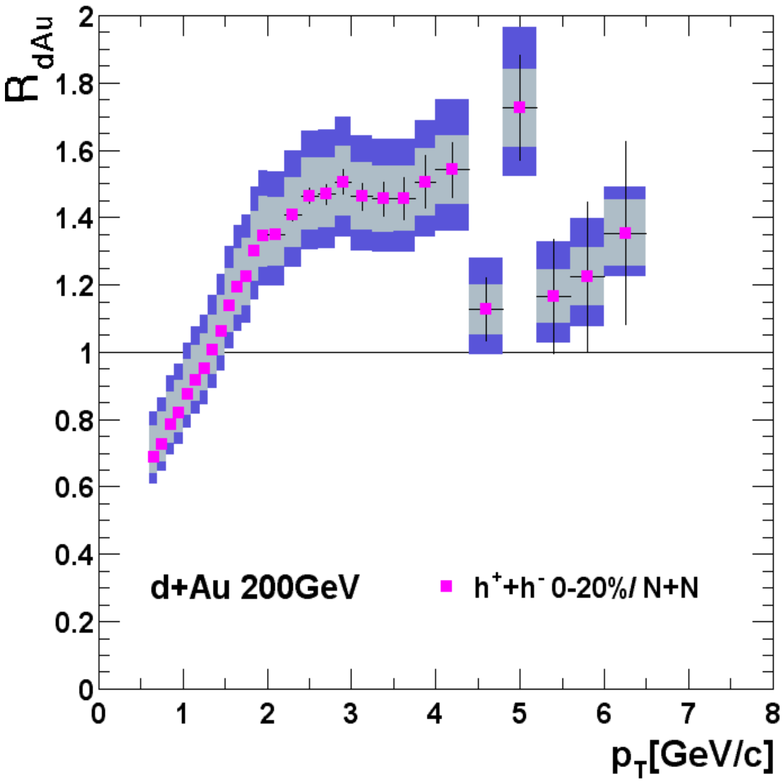
- peripheral collisions
  - probe survives
  - Au+Au = N_{bin} x pp
- central collisions
  - suppression of pions at high p_T by a factor of ~5!

- interpretation is not trivial!

Control: d+Au @ 200 GeV

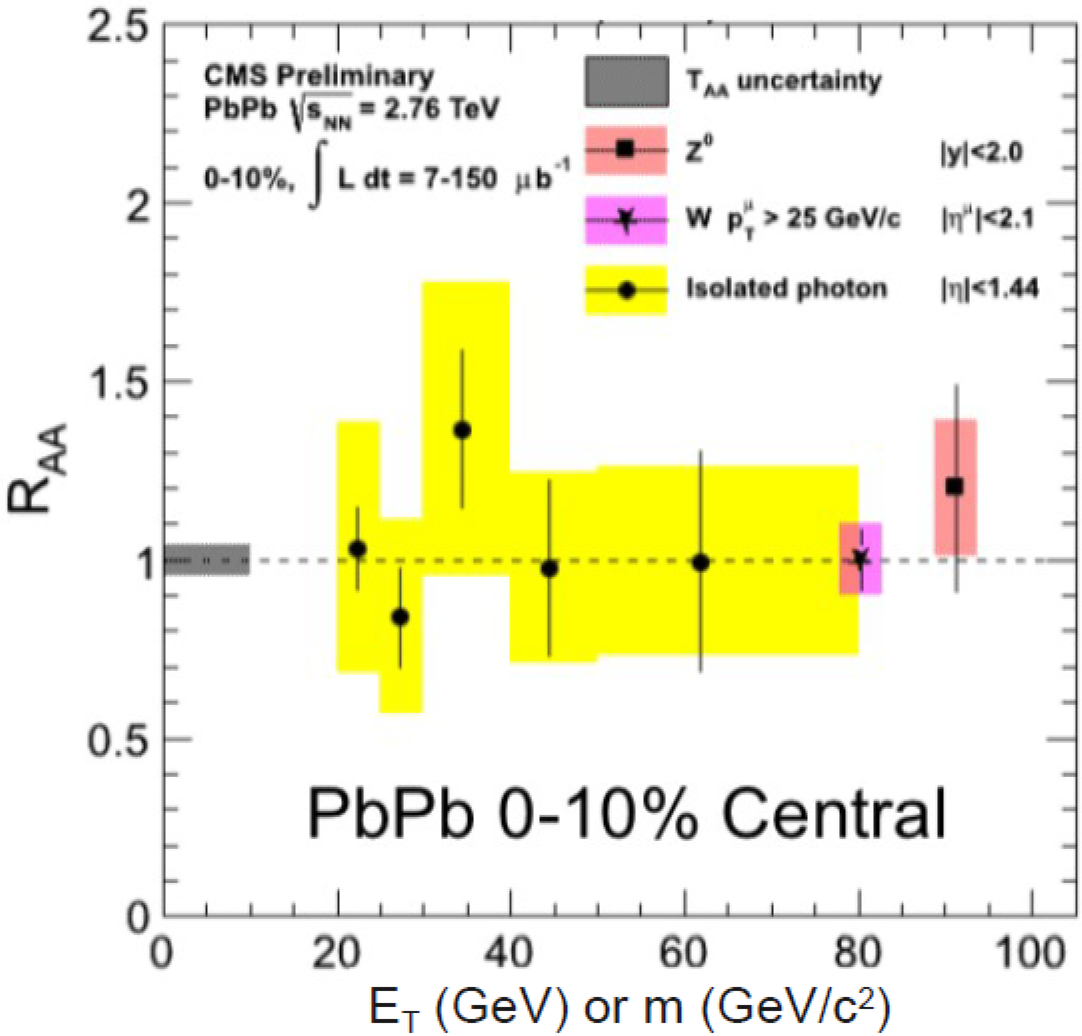
- potential explanations for π^0 suppression
  - interaction of pions with the medium produced in Au+Au collisions → final state effect
  - reduced parton density in the Au nucleus compared to the proton → initial state effect





Control probes at the LHC

- photons, W, Z follow the expected scaling

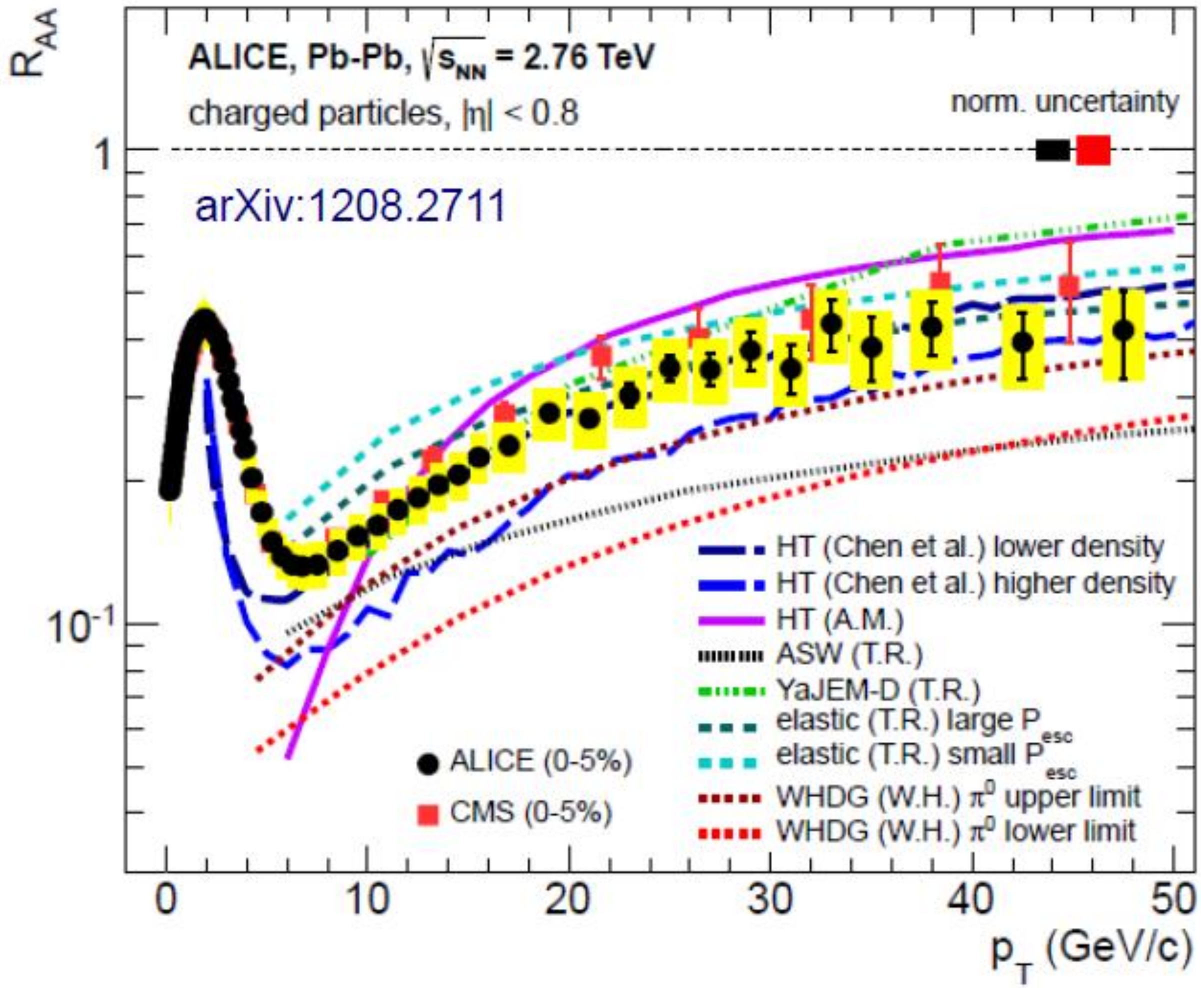


Isolated γ:
ATLAS, ATLAS-CONF-2012-051
CMS, PLB 710 (2012) 256

Z boson:
ATLAS, arXiv:1210.6486
ATLAS, PLB 697 (2011) 294]]
CMS, PRL 106 (2011) 212301

W boson:
ATLAS, ATLAS-CONF-2011-78
CMS, PLB 715 (2012) 66

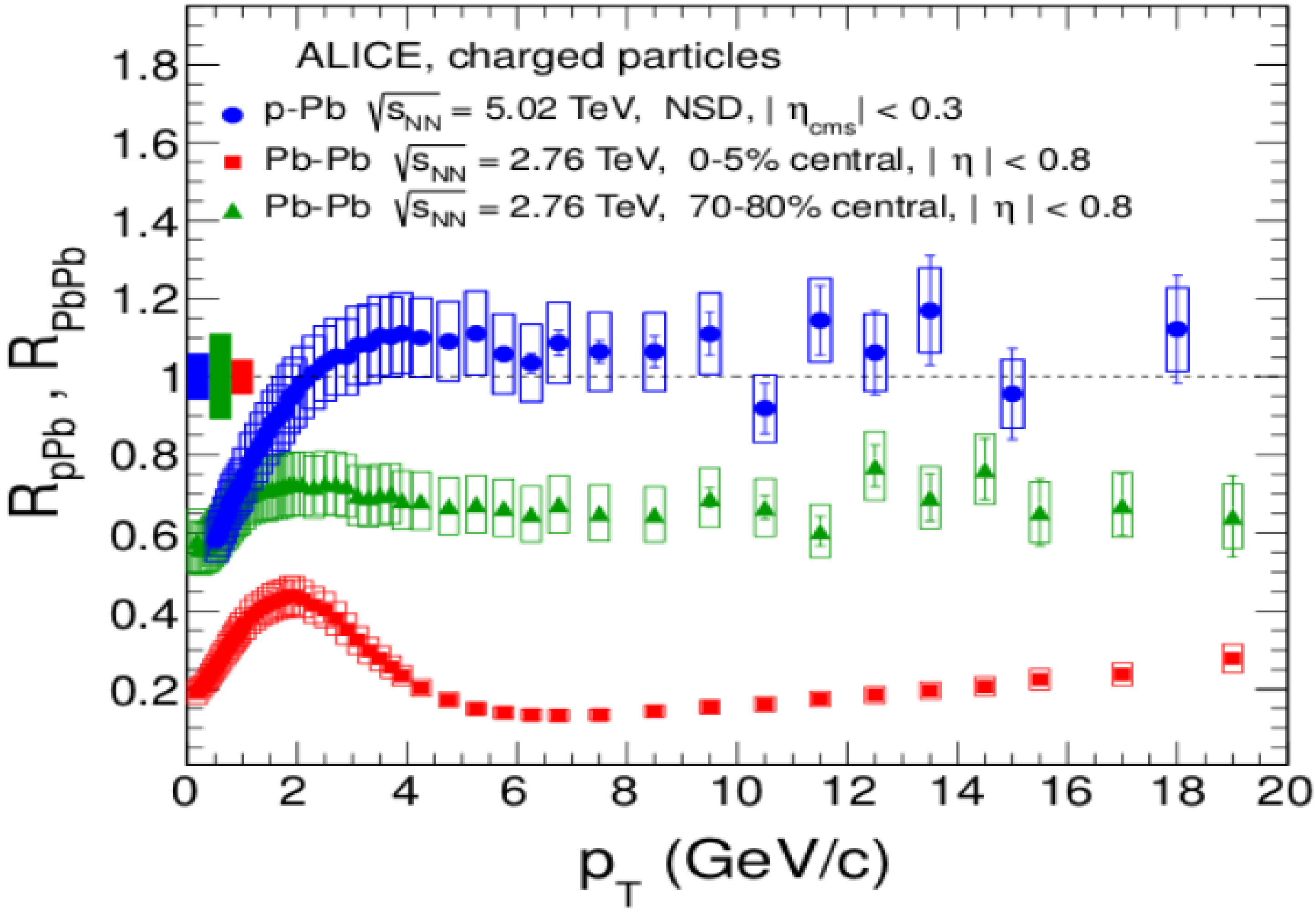
Charged particle R_{AA} at the LHC



- strong suppression: maximum close to 7 GeV/c, followed by slow rise → sensitivity to energy dependence of quenching or initial state effect?

R_{AA} in p+Pb at the LHC

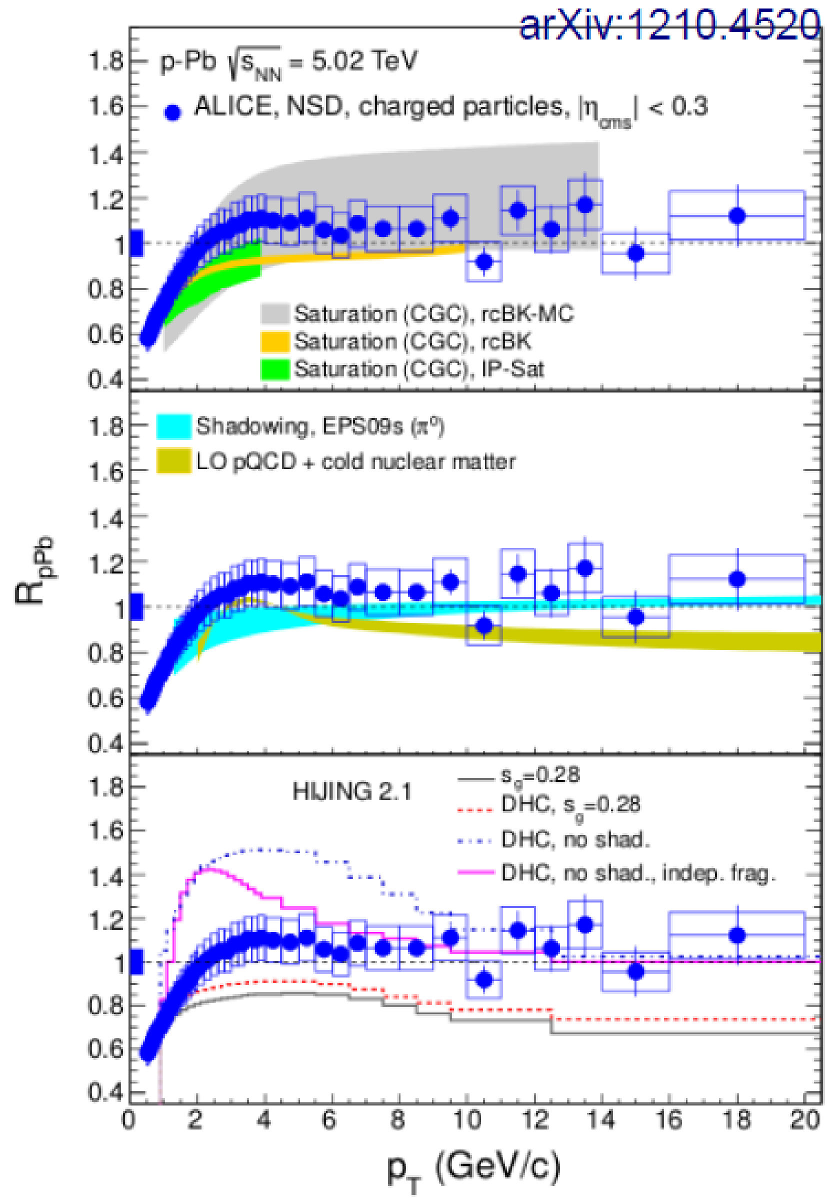
arXiv:1210.4520



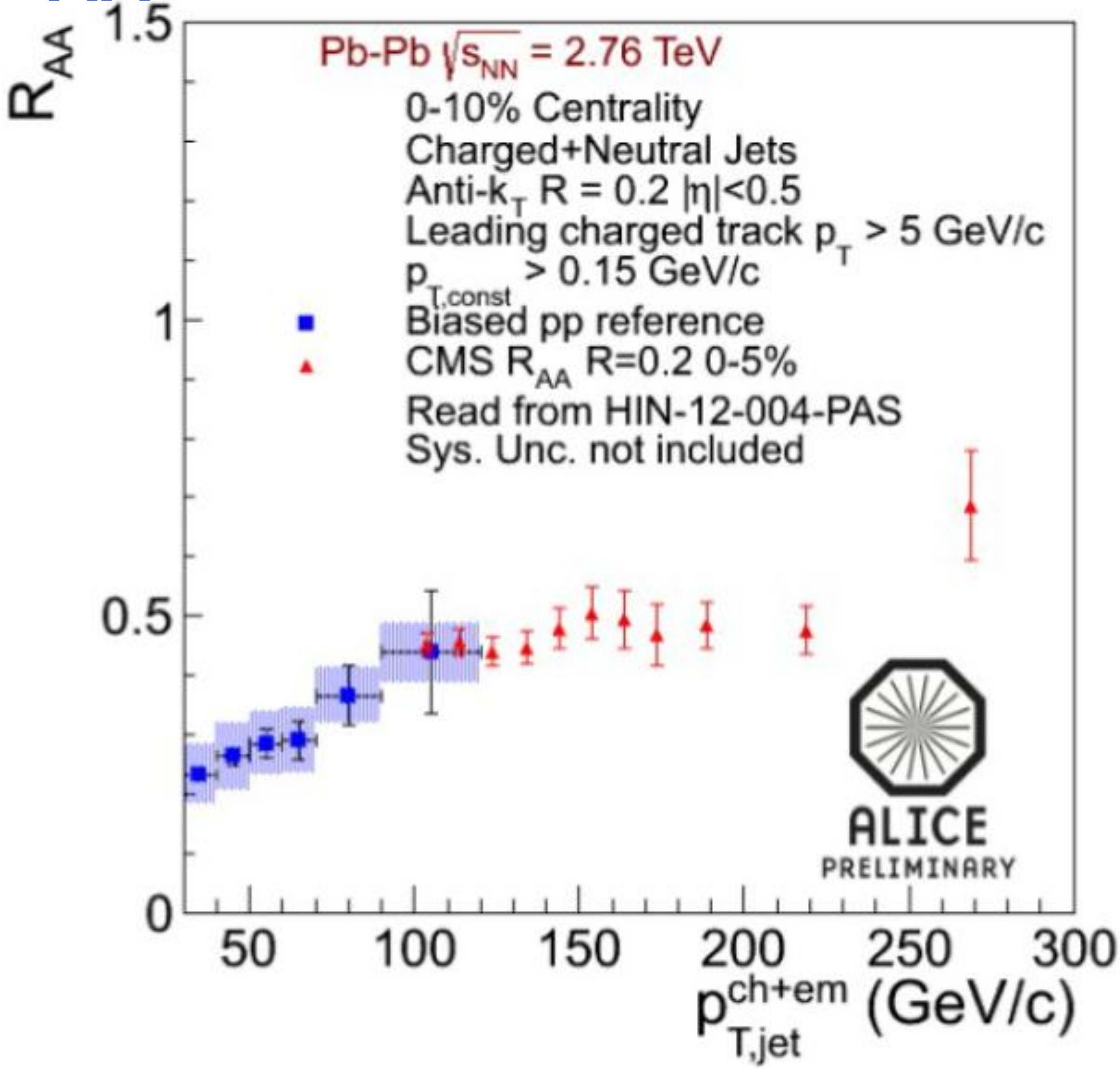
- **approximate binary scaling of charged particle yields at high p_T → initial state effects are small**

p+Pb: models vs. data

- most models describe R_{pPb} reasonably well at high p_T
- differences mainly at low p_T

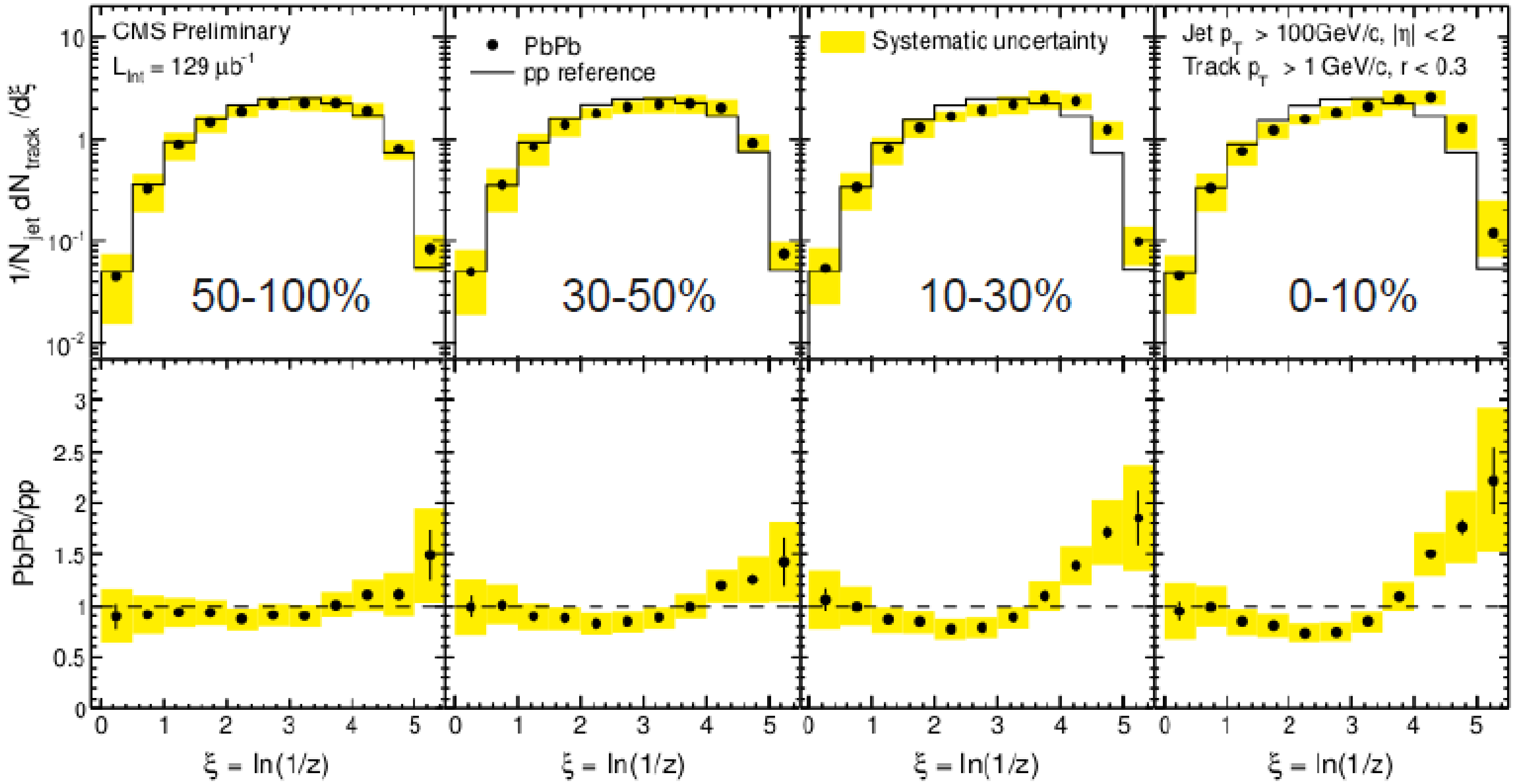


Jet R_{AA} in central collisions



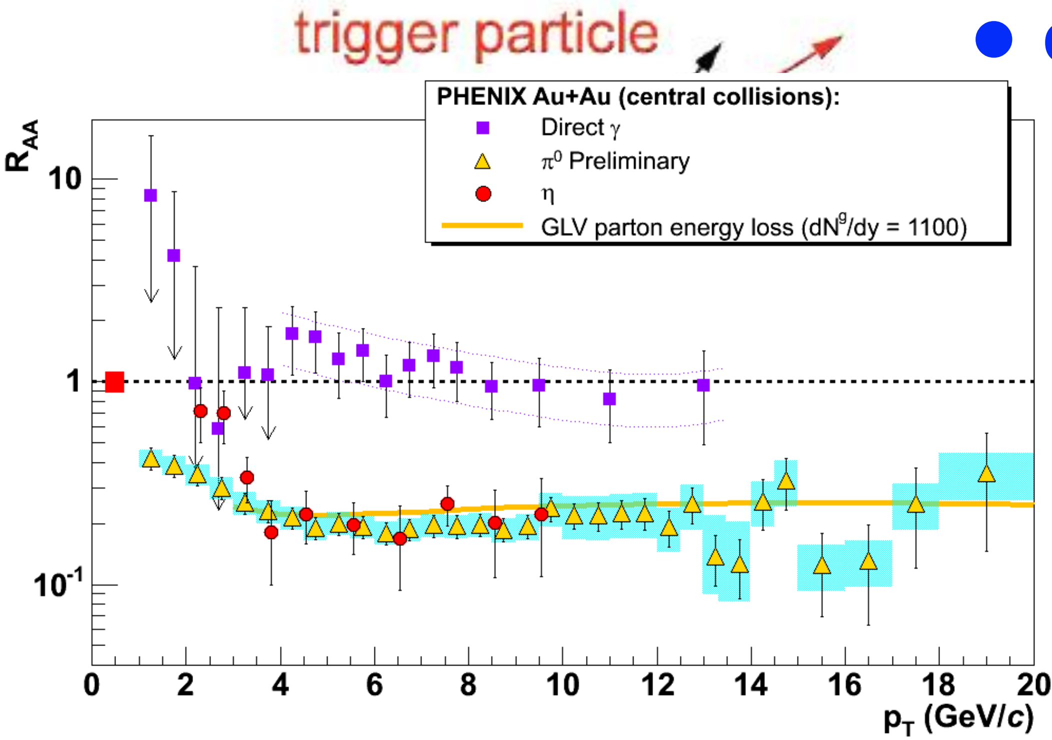
Jet fragmentation function

CMS-HIN-12-013

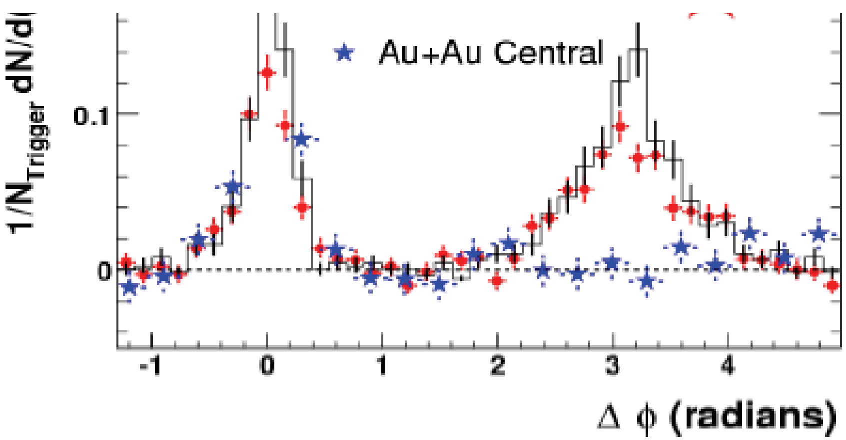


- **fragmentation function is modified**
  → more particles at low p_T (below 3 GeV/c)
  in central PbPb collisions compared to pp

Hard probes in HI collisions



- observation
  - photons, W, Z are not suppresses
    - no strong interaction
    - yields scale with N_{bin}
  - hadron suppression
    - not observed in d+Au & p+Pb collisions → no dense medium
    - strong suppression in central AA collisions

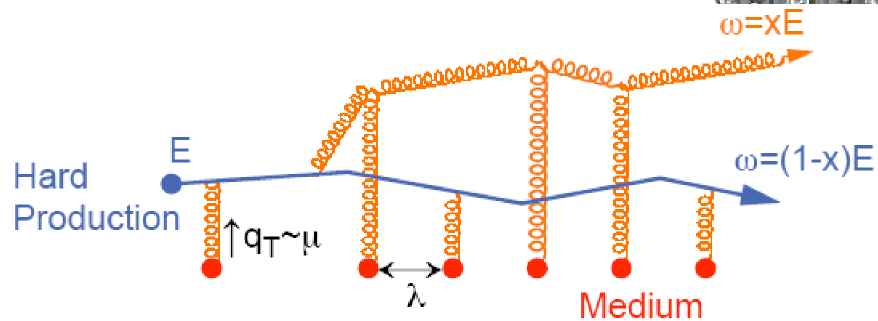


- azimuthal angle correlation
  - away-side jets disappear in central AA collisions → absorption in the medium?

→ a lot to learn from angular correlations

How do partons loose energy?

- elastic energy loss
- radiative energy loss
  - emission of gluons while the parton propagates through the dense, color charged medium



- parton energy loss ↔ medium properties
- parameters to characterize the medium‘s opacity
  - transport coefficient $\hat{q}$
    - momentum transfer ($<p_T^2>$) per unit path length from the medium to a hard gluon
  - gluon density dN_g / dy
  - energy density ε_0

Opacity estimates at RHIC

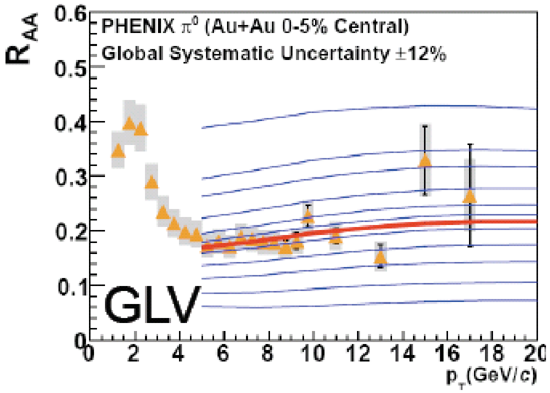
Model	Opacity Parameter
PQM	$\langle \hat{q} \rangle = 13.2\ (+2.1\ -3.2)\ \mathrm{GeV^2/fm}$
GLV	$dN_g/dy = 1400\ (+270\ -150)$
WHDG	$dN_g/dy = 1400\ (+200\ -375)$
ZOWW	$\varepsilon_0 = 1.9\ (+0.2\ -0.5)\ \mathrm{GeV/fm^3}$

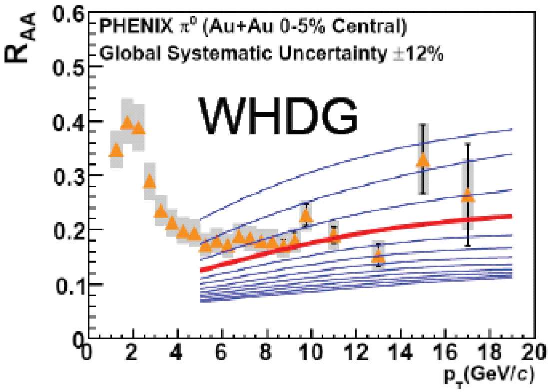
PQM: A. Dainese, C. Loizides, G. Paic, Eur. Phys. J C38: 461 (2005). C. Loizides, Eur. Phys. J.C49, 339 (2007).

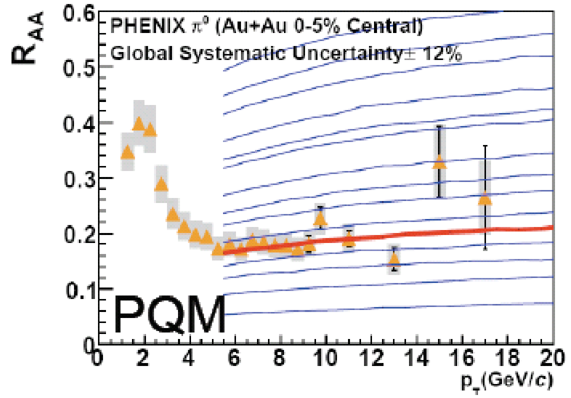
GLV: I. Vitev, Phys. Lett. B639, 38 (2006). M. Gyulassy, P. Levai, I. Vitev, Nucl. Phys. B571, 197 (2000).

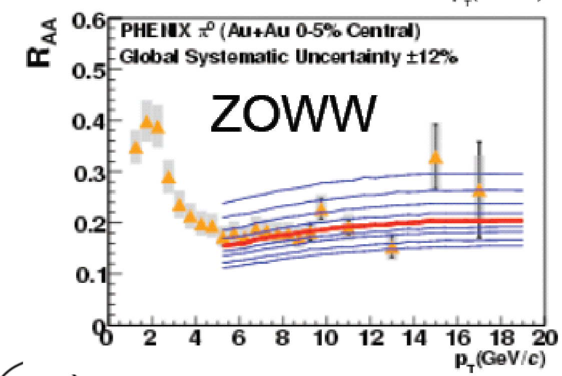
WHDG: W.A. Horowitz, S. Wicks, M. Djordjevic, M. Gyulassy,in preparation; S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy, Nucl. Phys. A 783, 493 (2007); S. Wicks, W. Horowitz, M. Djordjevic,M. Gyulassy, Nucl. Phys. A 784, 426 (2007).

ZOWW: H. Zhang, J.F. Owens, E. Wang, X-N Wang, Phys Rev. Lett. 98: 212301 (2007).









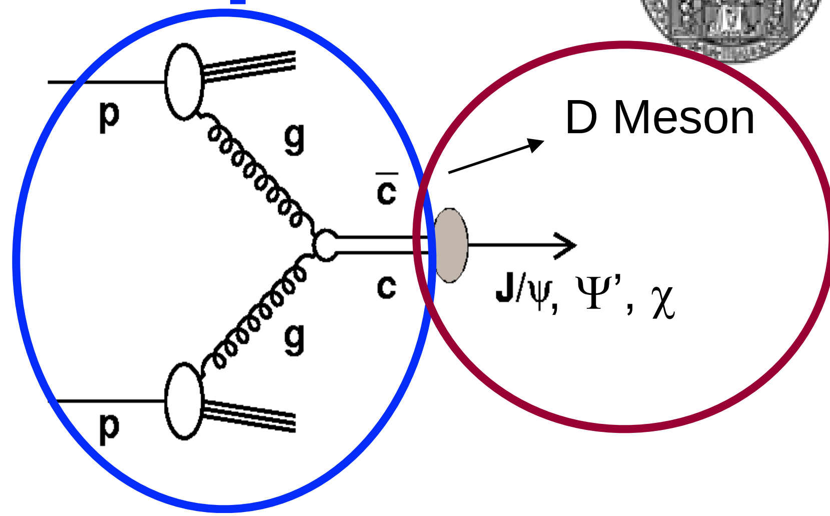
- only experimental uncertainties considered
- additional theoretical uncertainties exist
- radiative energy loss describe pion suppression

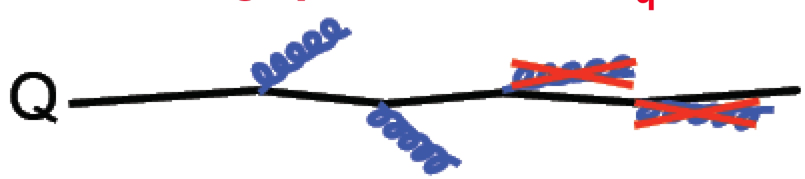
Summary: jets

- jets in pp collisions
  - pQCD calculations are in reasonable agreement with measured cross sections
- jets in AA collisions
  - partons from hard scattering interact with the hot and dense medium produced in AA collisions
  - measurement of nuclear modification factor R_{AA} indicates energy loss of scattered partons
  - measured hadron R_{AA} consistent with radiative energy loss scenario in a QGP
  - jet observable are sensitive to QGP parameters
  - detailed studies are ongoing, in particular at the LHC

Heavy quarks as hard probes

- heavy quarks ($c\bar{c}$, $b\bar{b}$)
  - hard process ($m_q >> \Lambda_{QCD}$)
  - bound states (J/ψ, Υ)
- complementary probes
- radiative energy loss
  - color (Casimir) factor
  - "dead cone" effect
    (Dokshitzer & Kharzeev, PLB 519(2001)199)
    → energy loss decreases with increasing quark mass m_q



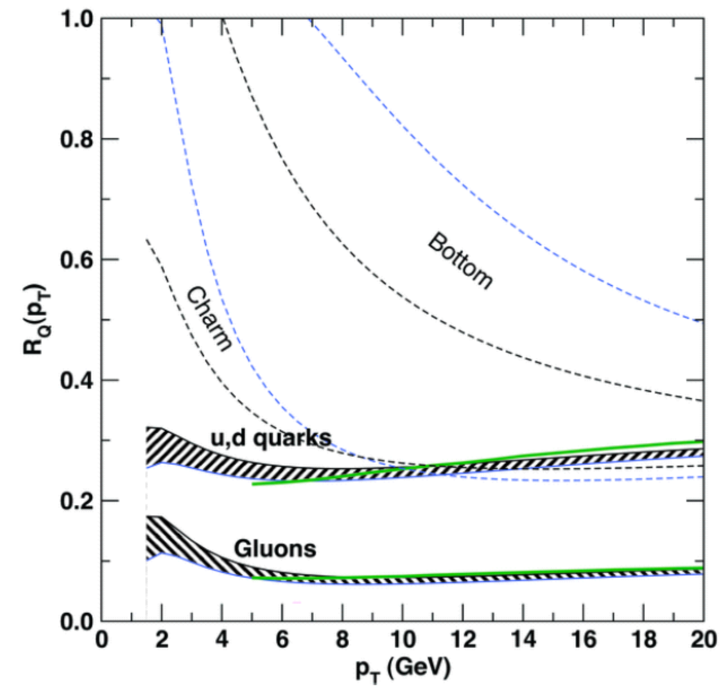


$\Delta E_{loss}(g) > \Delta E_{loss}(q) > \Delta E_{loss}(Q)$

(color factor) (dead-cone effect)

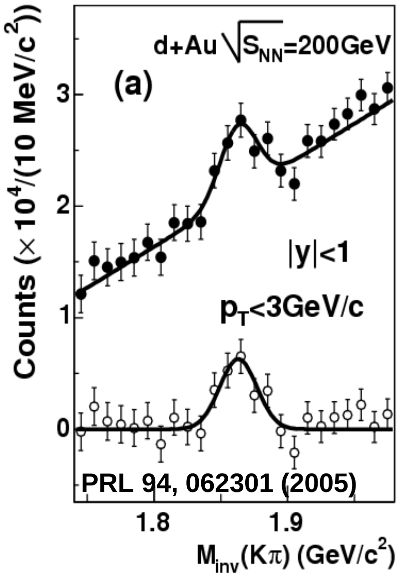
Check $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

Wicks et al, Nucl. Phys. A784 (2007) 426

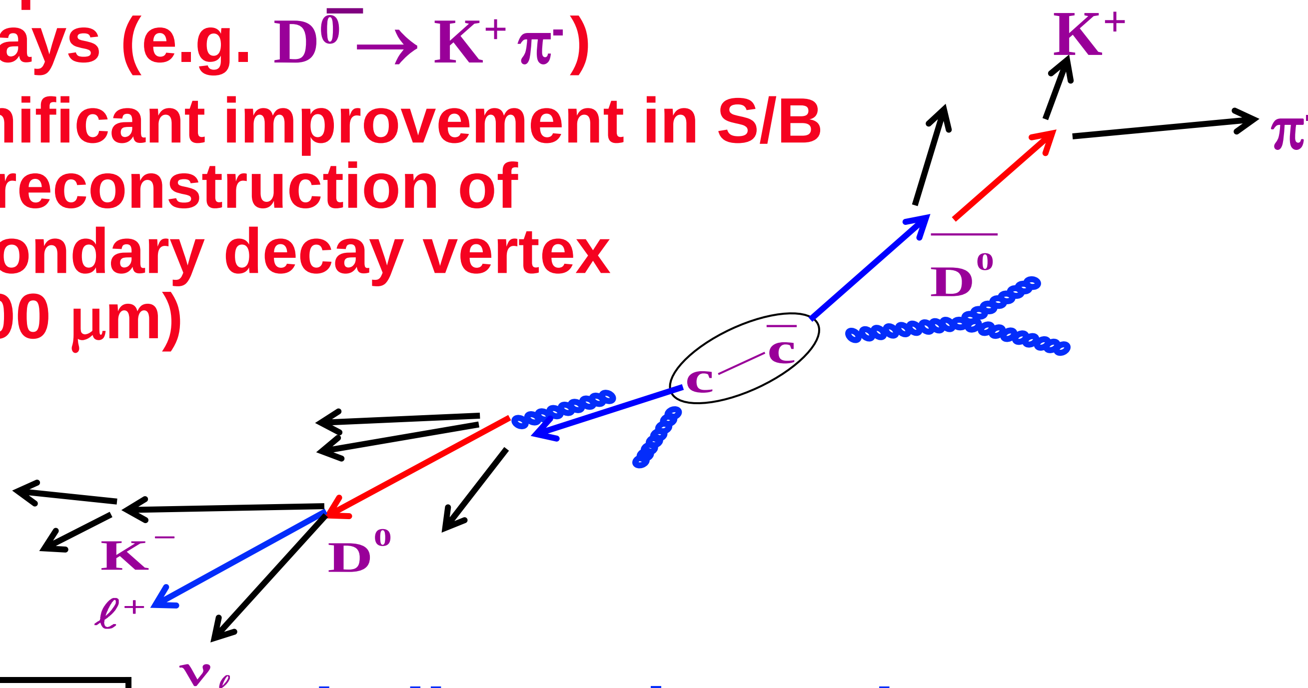


How to measure heavy quarks

- ideal (difficult at high multiplicity)



- complete reconstruction of decays (e.g. $\overline{D^0} \rightarrow K^+\pi^-$)
- significant improvement in S/B via reconstruction of secondary decay vertex (~100 μm)

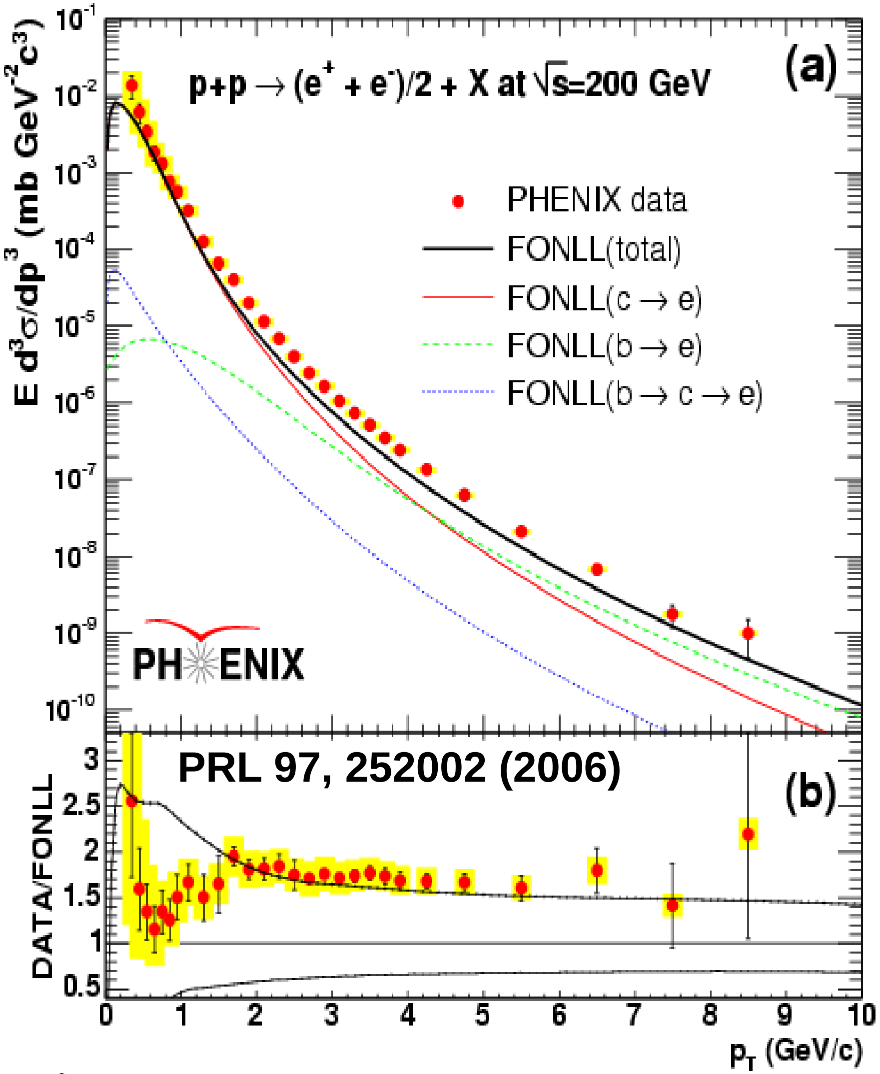


Meson	$D^\pm$ (D^0)
Mass	1.87 (1.87) GeV
BR D^0 --> Kπ	(3.85 ± 0.10) %
BR D --> e +X	17.2 (6.7) %
BR D --> μ +X	17.2 (6.6) %

- indirect alternative
  - contribution of semileptonic heavy-flavor hadron decays to single (pair) lepton spectra

e± from HQ at RHIC: pp

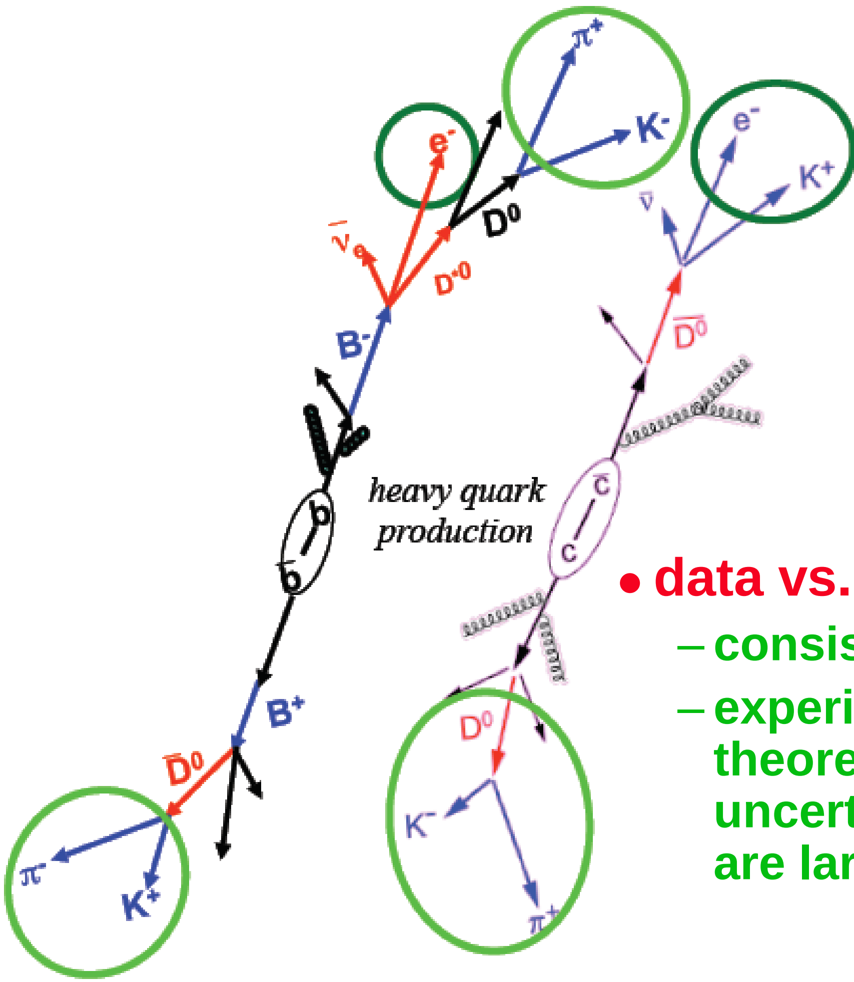
- data in comparison with FONLL pQCD
  (Fixed Order Next-to- Leading Log: Cacciari, Nason, Vogt PRL 95(2005)122001))

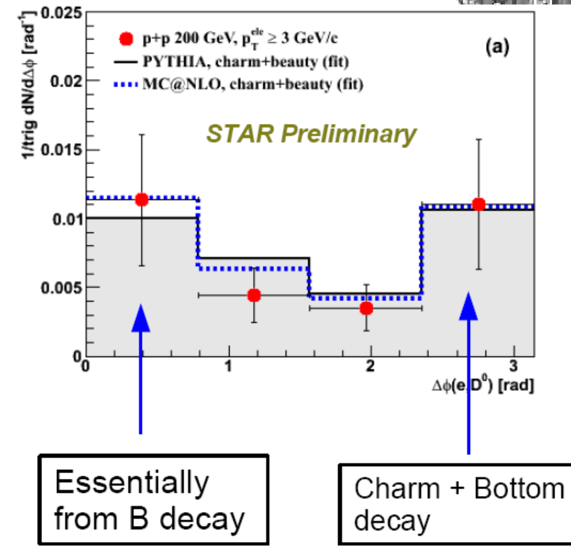


- e± from charm/beauty hadron decays
  - at upper limit of theoretical uncertainties
  - similar to charm measurements elsewhere
    - DESY (photo production)
    - FNAL (hadro production)
- high p_T
  - bottom decays start to dominate

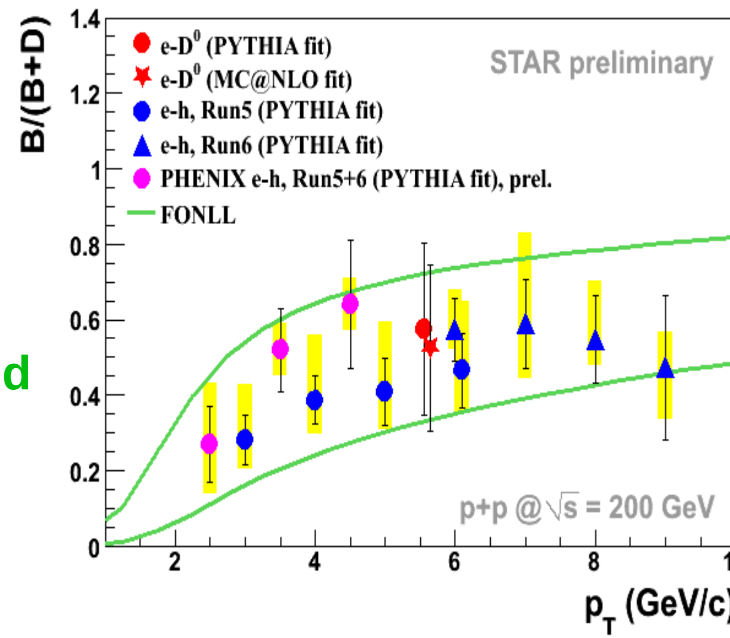
Separation of c→e and b→e

- **electron-hadron correlations**
  - **differences between charm and bottom**
  - **e-D^0 azimuthal angular correlation**



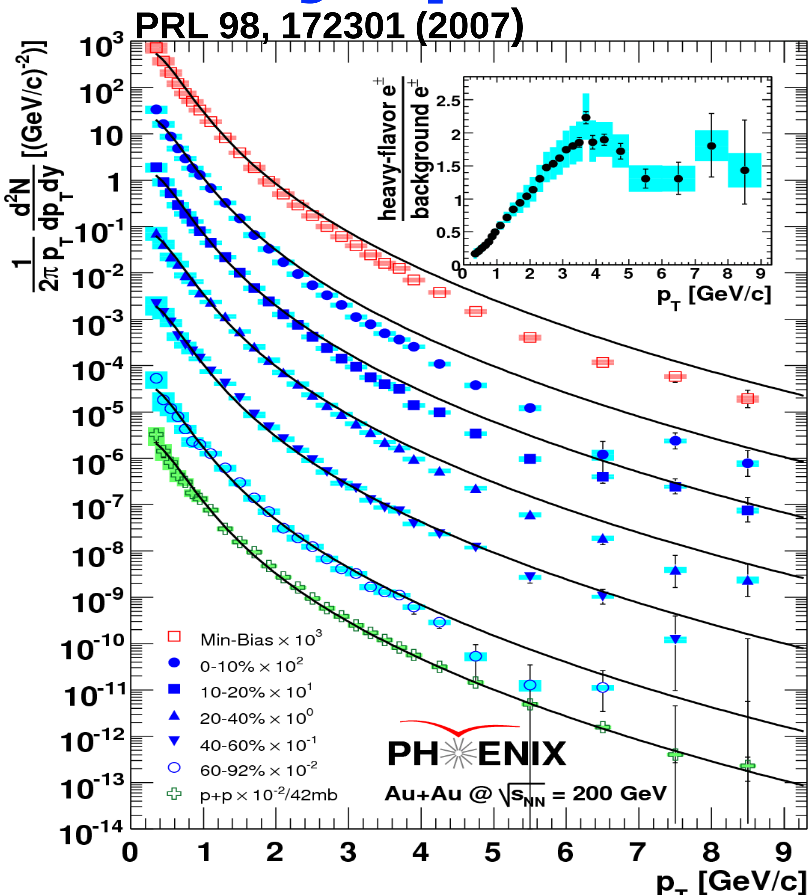


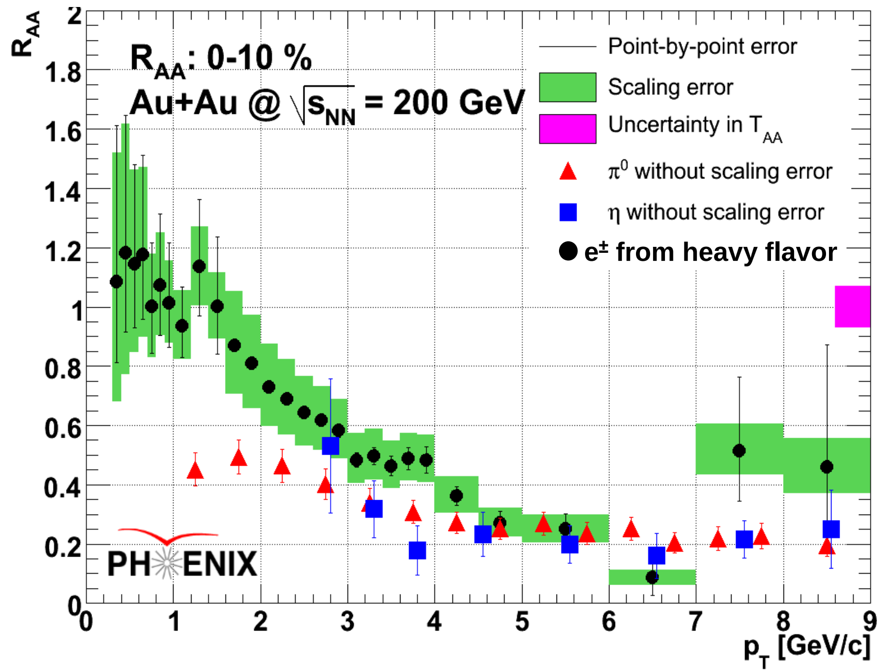
- **data vs. pQCD**
  - consistent
  - experimental and theoretical uncertainties are large



Heavy quarks as medium probes

PRL 98, 172301 (2007)

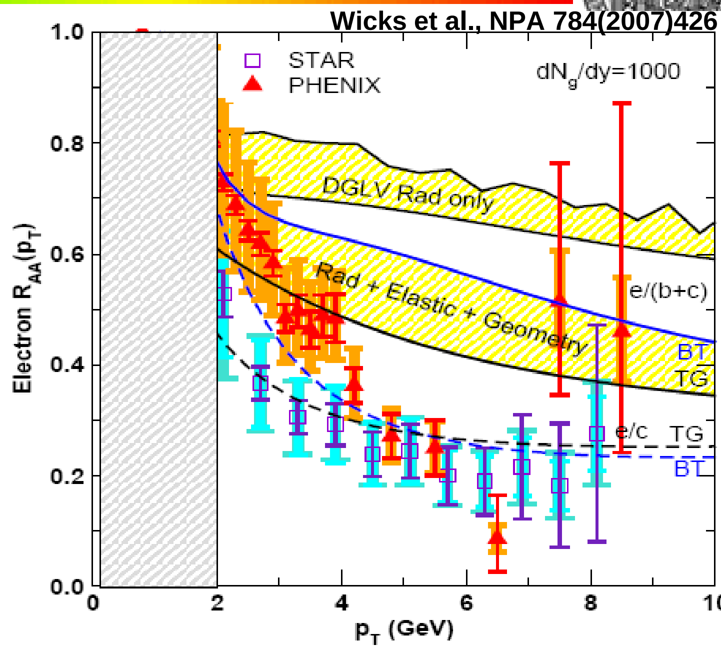




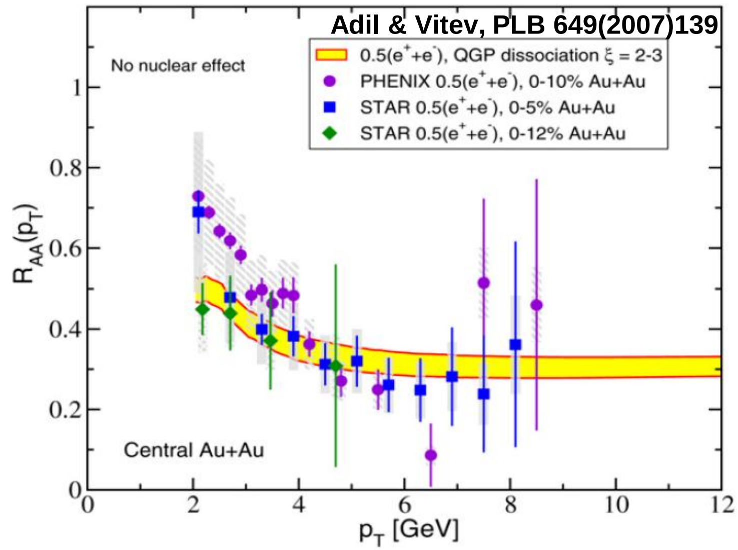
- R_{AA} ~ 1 at low p_T
  - charm production scales with N_{bin} (as expected)
- $R_{AA}(c,b \rightarrow e^{\pm})$ ~ $R_{AA}(\pi^0)$ ~ $R_{AA}(\eta)$ at high p_T
  - mass hierarchy expected from radiative energy loss not observed!

Energy loss mechanism?

- $e^{\pm}$ R_{AA}: data vs. ΔE models
  - radiative energy loss only
    - Djordjevic et al., PLB 632(2006)81
    - Armesto et al., PLB 637(2006)362)
    - → not sufficient
  - additional elastic energy loss
    - Wicks et al., NPA 784(2007)426
    - van Hees & Rapp, PRC 73(2006)034913
    - → significant improvement, but still not perfect

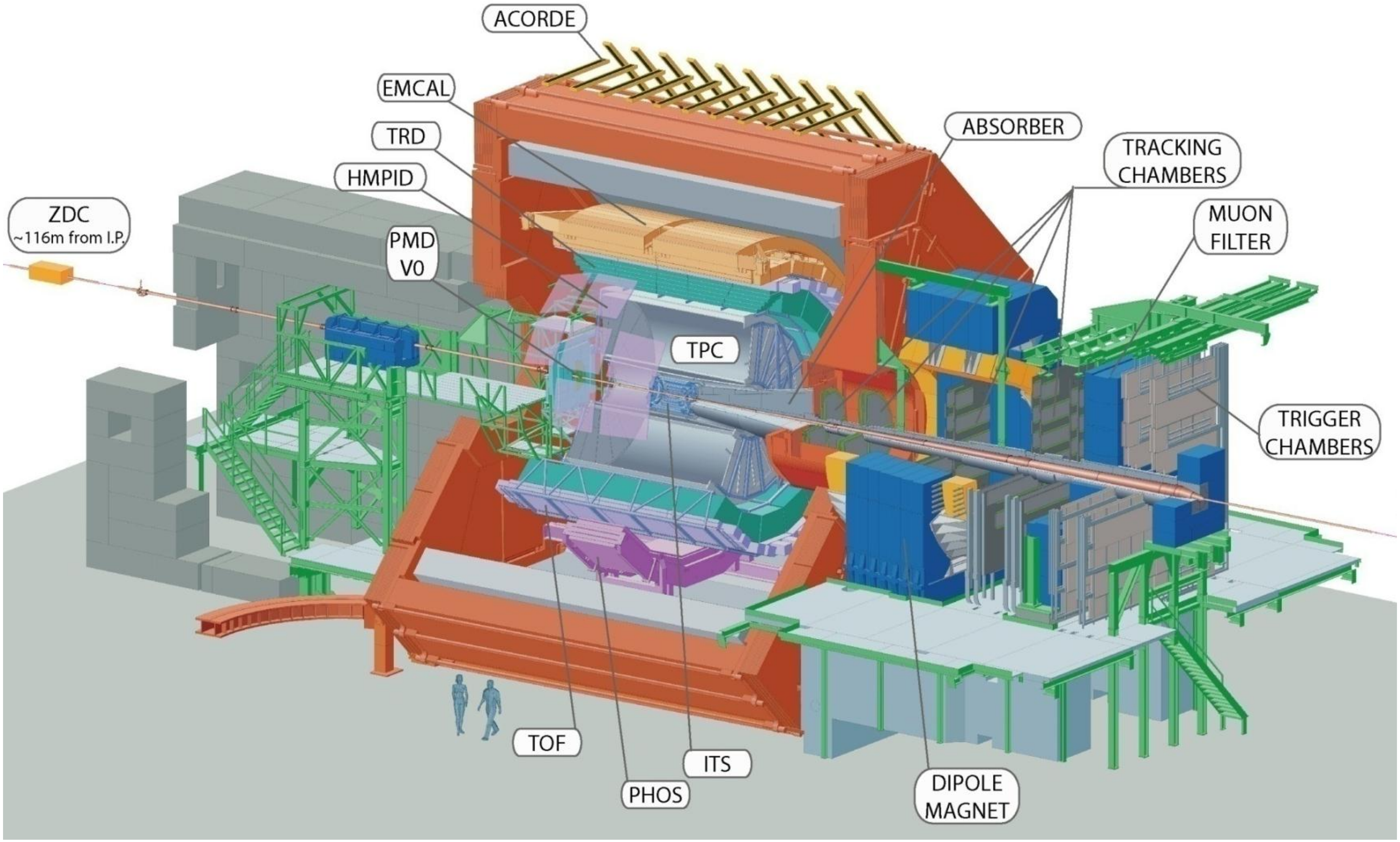


- alternative approaches
  - cascade of hadron formation and dissociation in medium
    - Adil & Vitev, PLB 649(2007)139
  - increased baryon/meson ratio (as observed in light quark sector)
    - Sorensen & Dong, PRC 74(2006)024902
    - Martinez, Gadrat, Crochet, PLB 663(2008)55

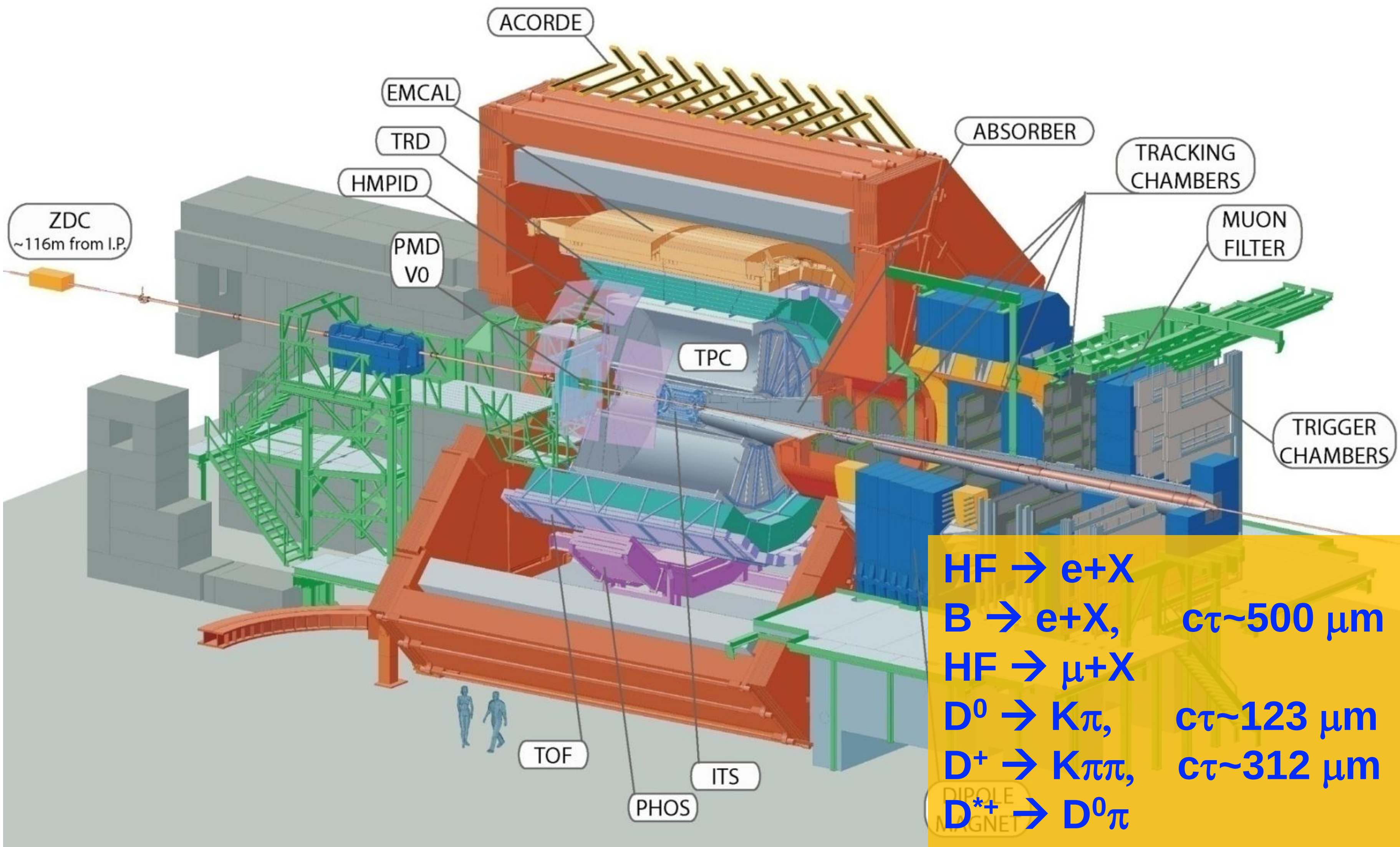


→ measurement of heavy hadrons needed!

Heavy flavor with ALICE



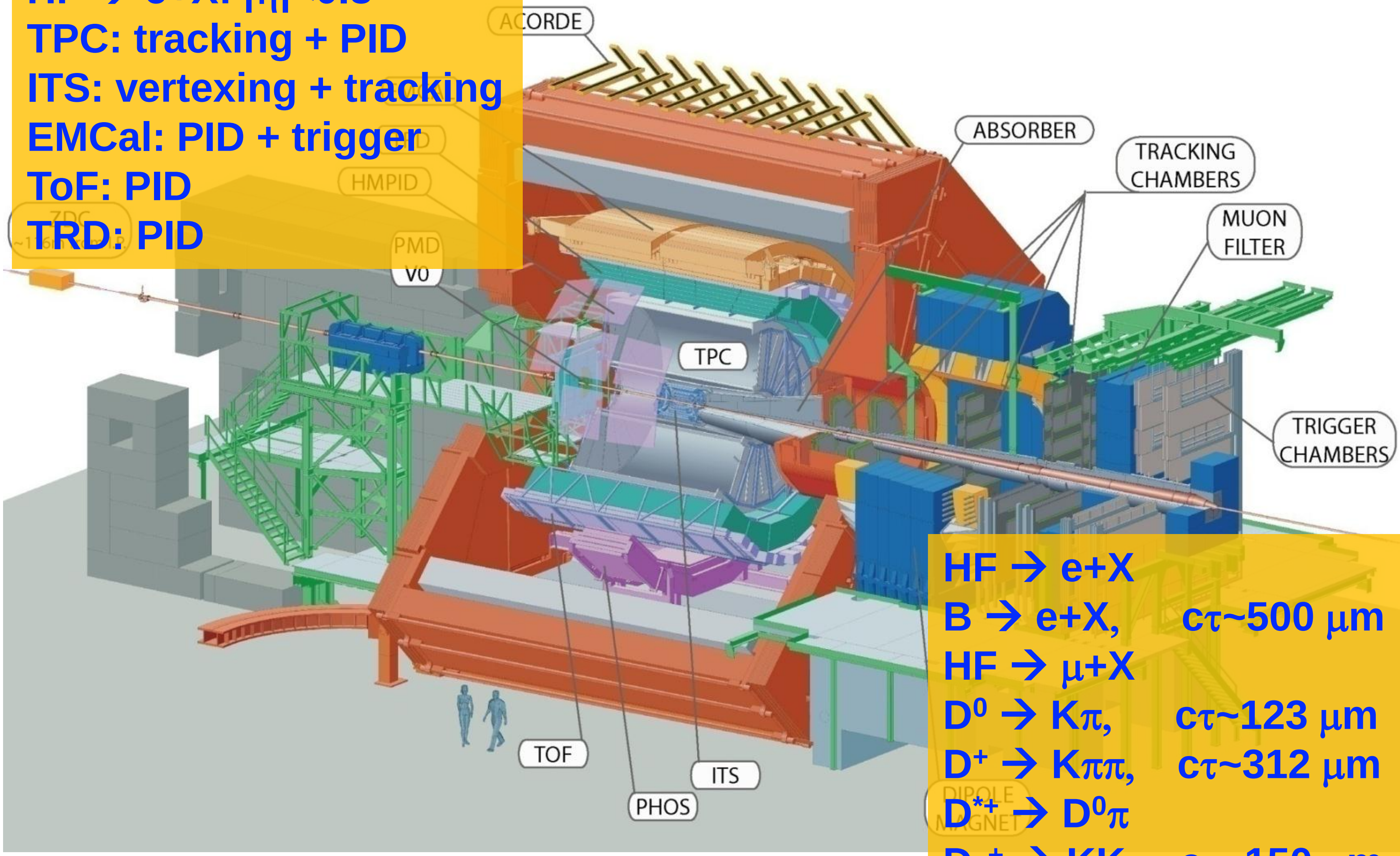
Heavy flavor with ALICE



HF → e+X
B → e+X, $c\tau \sim 500\ \mu m$
HF → μ+X
D^0 → Kπ, $c\tau \sim 123\ \mu m$
D^+ → Kππ, $c\tau \sim 312\ \mu m$
D^{*+} → $D^0\pi$
D_s^+ → KKπ, $c\tau \sim 150\ \mu m$

Heavy flavor with ALICE

HF → e+X: |η|<0.8
TPC: tracking + PID
ITS: vertexing + tracking
EMCal: PID + trigger
ToF: PID
TRD: PID

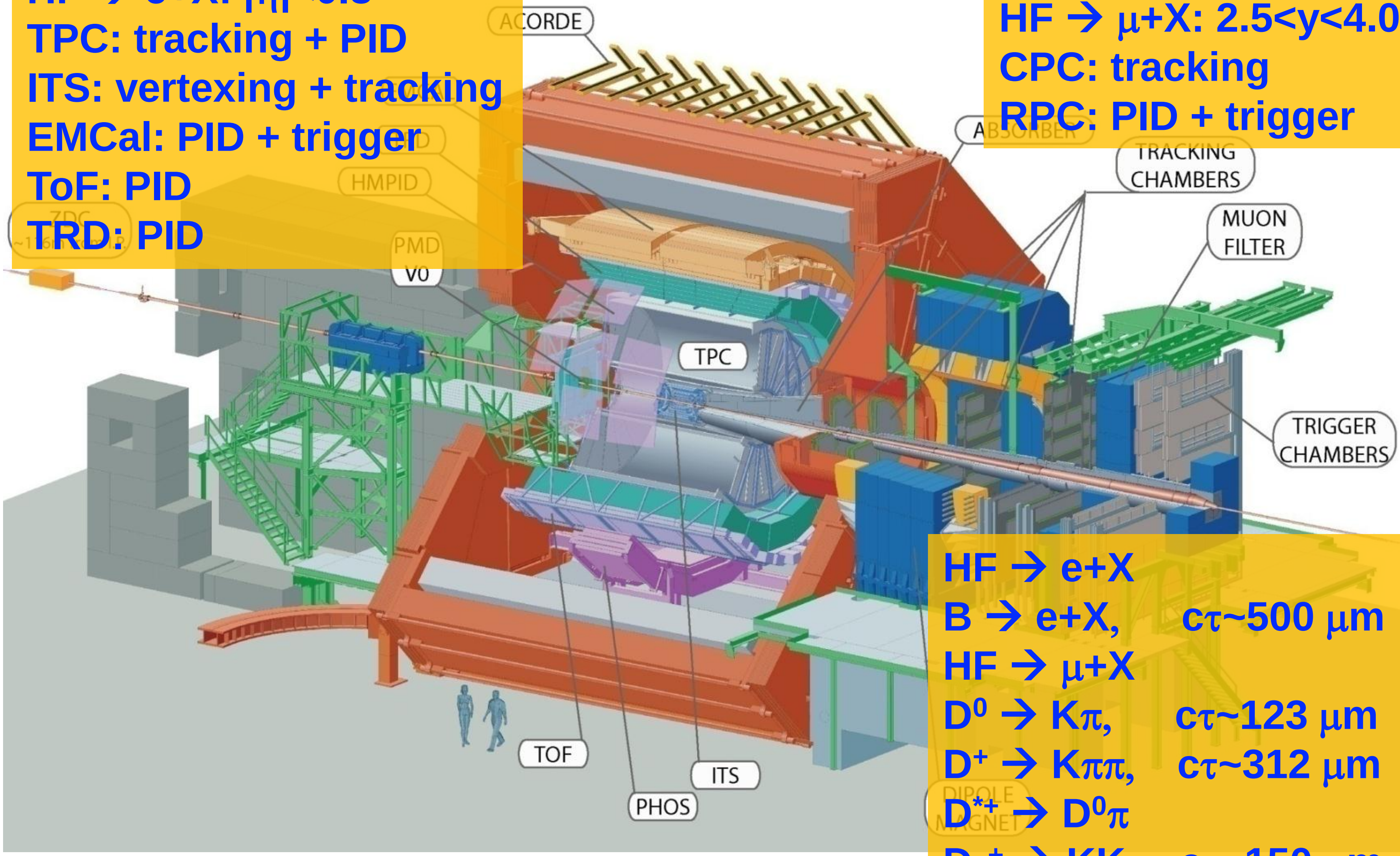


HF → e+X
B → e+X, $c\tau$~500 μm
HF → μ+X
D^0 → Kπ, $c\tau$~123 μm
D^+ → Kππ, $c\tau$~312 μm
D^{*+} → $D^0\pi$
D_s^+ → KKπ, $c\tau$~150 μm

Heavy flavor with ALICE

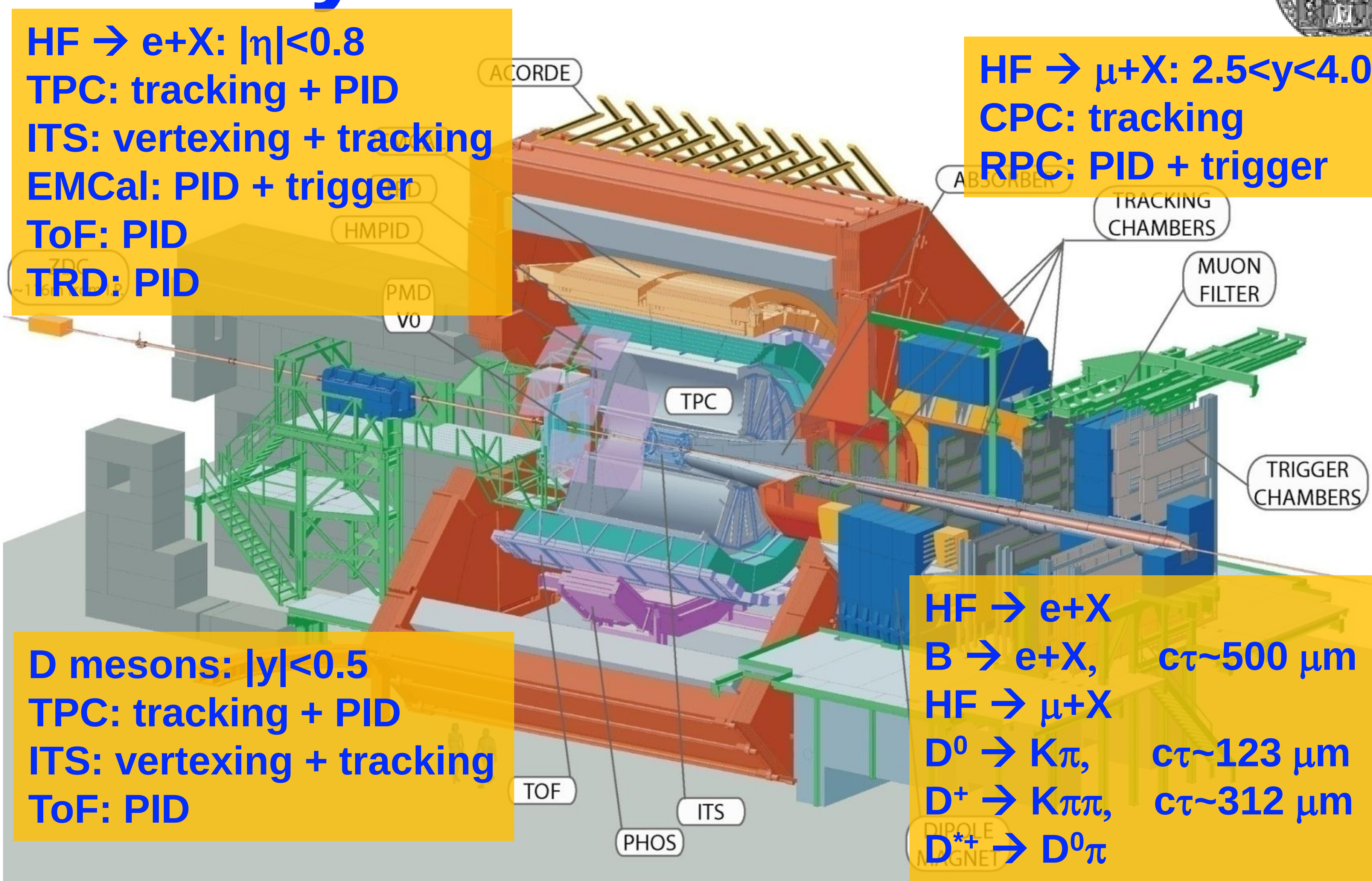
HF → e+X: |η|<0.8
TPC: tracking + PID
ITS: vertexing + tracking
EMCal: PID + trigger
ToF: PID
TRD: PID

HF → μ+X: 2.5<y<4.0
CPC: tracking
RPC: PID + trigger



HF → e+X
B → e+X, $c\tau$~500 μm
HF → μ+X
D^0 → Kπ, $c\tau$~123 μm
D^+ → Kππ, $c\tau$~312 μm
D^{*+} → $D^0\pi$
D_s^+ → KKπ, $c\tau$~150 μm

Heavy flavor with ALICE



HF → e+X: |η|<0.8
TPC: tracking + PID
ITS: vertexing + tracking
EMCal: PID + trigger
ToF: PID
TRD: PID

HF → μ+X: 2.5<y<4.0
CPC: tracking
RPC: PID + trigger

D mesons: |y|<0.5
TPC: tracking + PID
ITS: vertexing + tracking
ToF: PID

HF → e+X	
B → e+X,	cτ~500 μm
HF → μ+X	
D^0 → Kπ,	cτ~123 μm
D^+ → Kππ,	cτ~312 μm
D^{*+} → D^0π	
D_s^+ → KKπ,	cτ~150 μm

HEAVY FLAVOR MEASUREMENTS IN PP COLLISIONS

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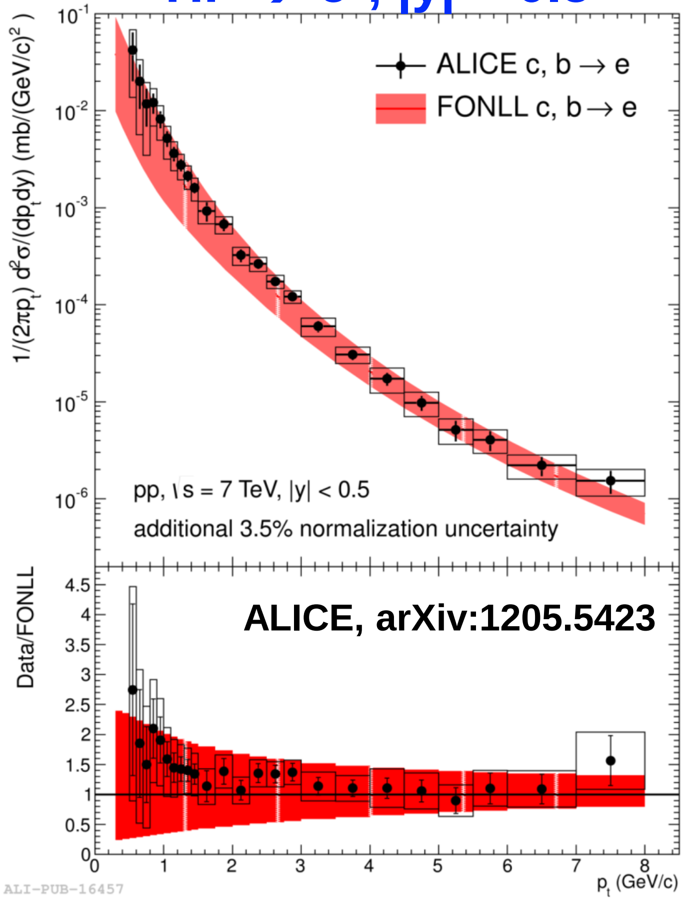
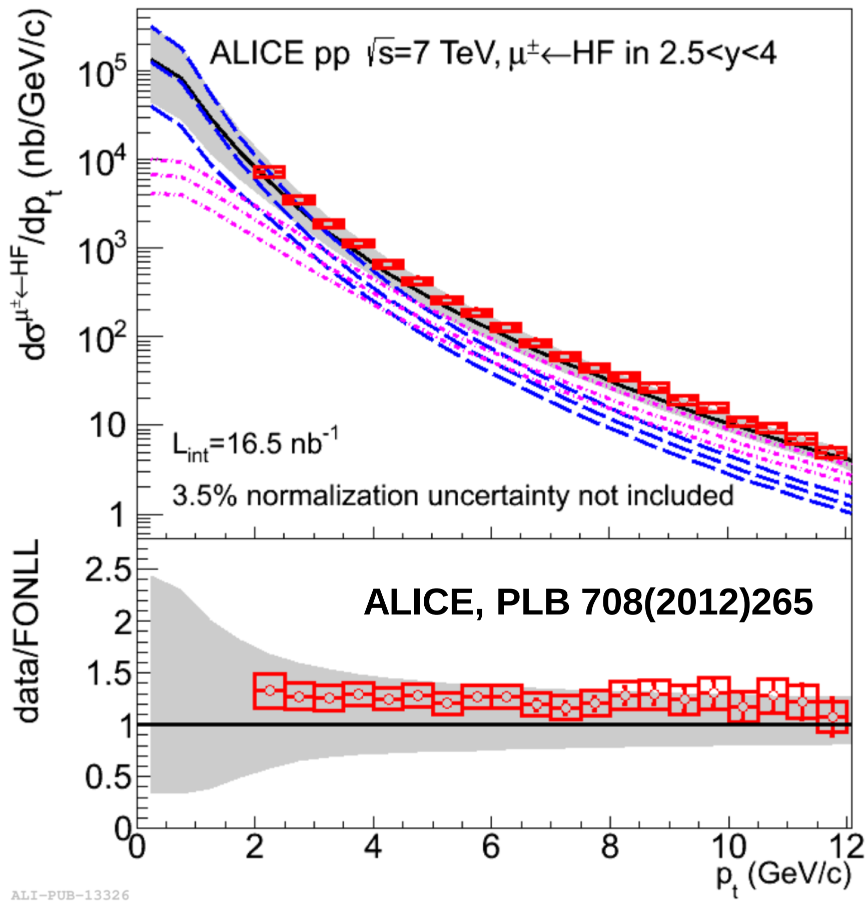
pQCD at work?

HF → leptons: pp at √s = 7 TeV

HF → e±, |y| < 0.5



HF → μ±, 2.5 < y < 4.0



- Fixed-Order-Next-to-Leading-Log (FONLL, Cacciari et al., arXiv:1205.6344) pQCD calculations agree reasonably well with measured HF decay lepton differential cross sections

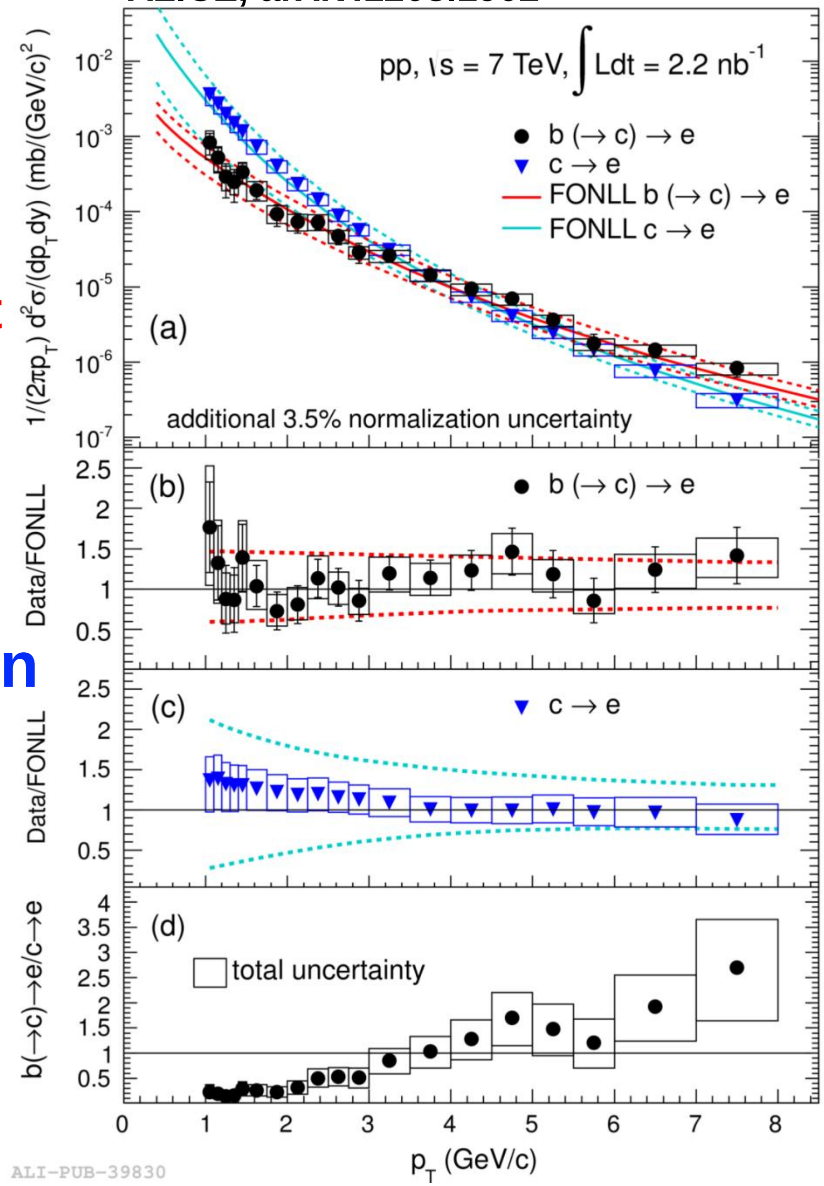
Beauty → $e^{\pm}$: pp at $\sqrt{s}$ = 7 TeV

- measurement of electrons from b-hadron decays
  - |y|<0.5
  - cτ ~ 500 μm for B hadrons → $e^{\pm}$ selection via p_T dependent impact parameter (d_0) cut (e.g. $|d_0|$ > 250 μm for p_T ~ 2.5 GeV/c)
  - cocktail subtraction of remaining background

→differential b→$e^{\pm}$ cross section (c→$e^{\pm}$ = HF→$e^{\pm}$ - b→$e^{\pm}$)

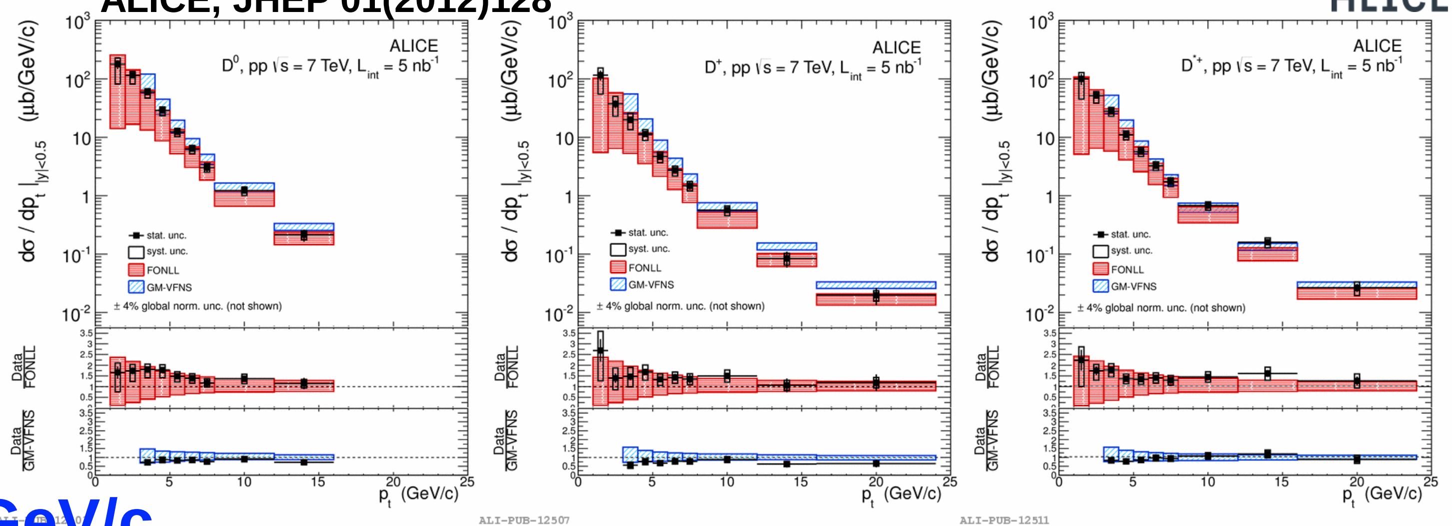
→FONLL describes both b→$e^{\pm}$ and c→$e^{\pm}$ differential cross sections

ALICE, arXiv:1208.1902



D mesons: pp at $\sqrt{s}$ = 7 TeV

ALICE, JHEP 01(2012)128

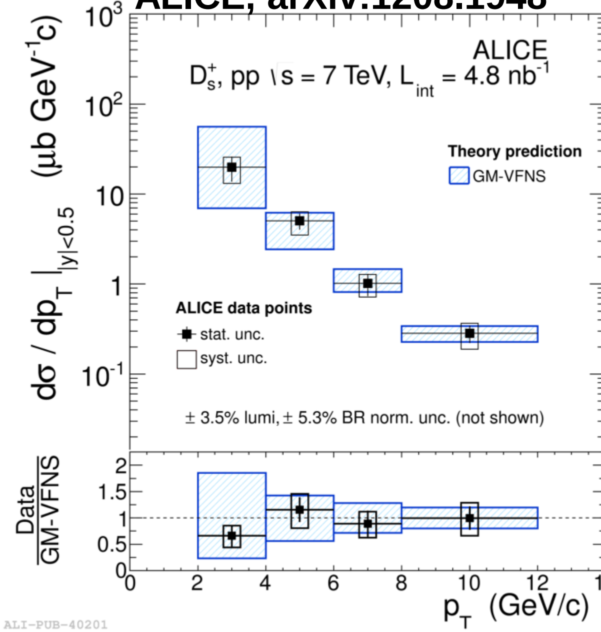


- differential D^0, D^+, and D^{*+} cross sections measured in the range $1 < p_T < 24$ GeV/c

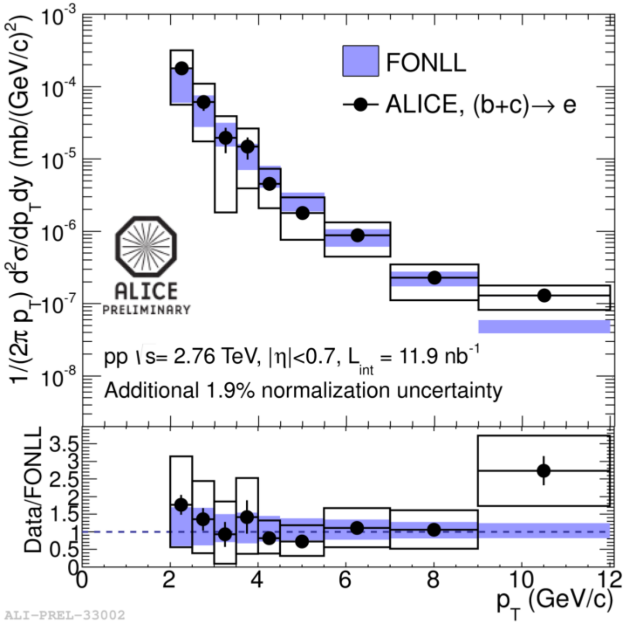
- p_T-differential D_s^+ cross section measured for $2 < p_T < 12$ GeV/c

→ FONLL and GM-VFNS (Kniehl et al., arXiv:1202.0439) pQCD calculations in good agreement with measured cross sections

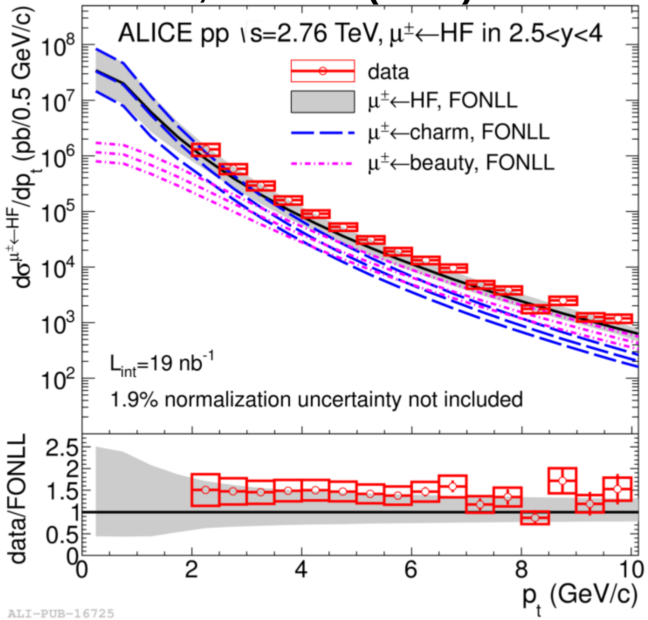
ALICE, arXiv:1208.1948



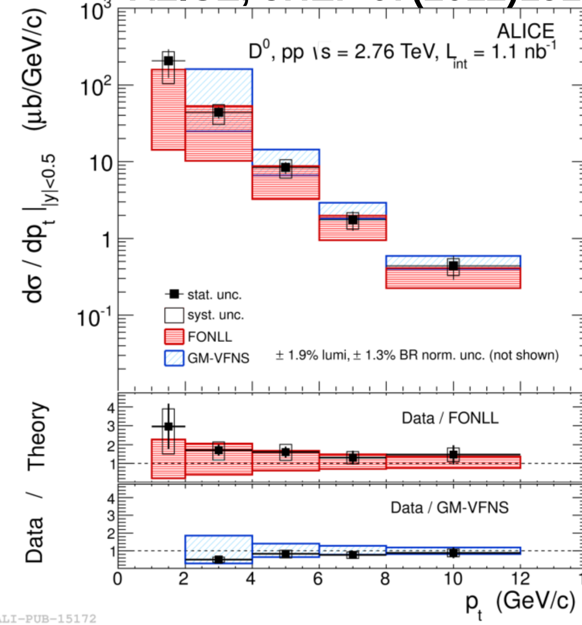
HF data: pp at √s = 2.76 TeV



ALICE, PRL 109(2012)112301



ALICE, JHEP 07(2012)191

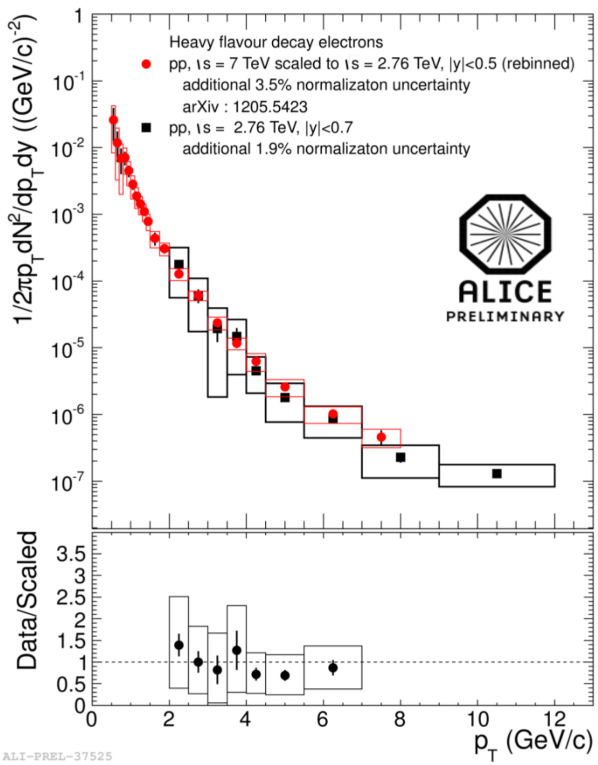


- **FONLL and GM-VFNS pQCD calculations describe HF cross sections for pp collisions at √s = 2.76 TeV**

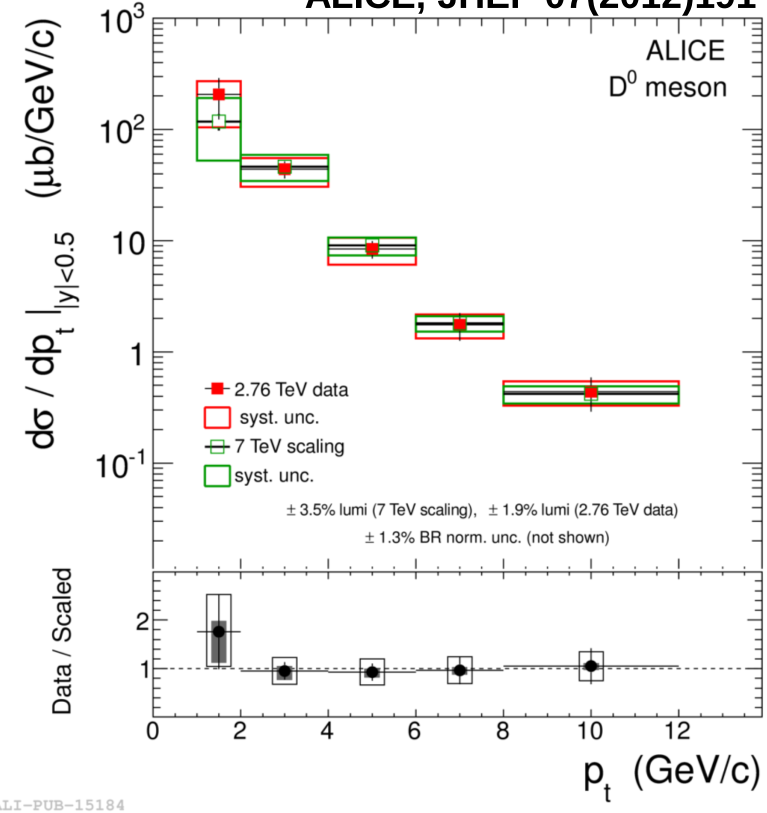
→ experimental baseline for Pb-Pb collisions, but limited statistics for e± and D mesons

Baseline for Pb-Pb data at $\sqrt{s_{NN}}$ = 2.76 TeV

- HF → $\mu^{\pm}$: pp data at $\sqrt{s}$ = 2.76 TeV
- HF → $e^{\pm}$ and D mesons: 7 TeV pp data scaled to 2.76 TeV
  - scaling factor: ratio of FONLL cross sections at 2.76 and 7 TeV
  - scaled and measured cross sections at 2.76 TeV
    →compatible with each other



ALICE, JHEP 07(2012)191

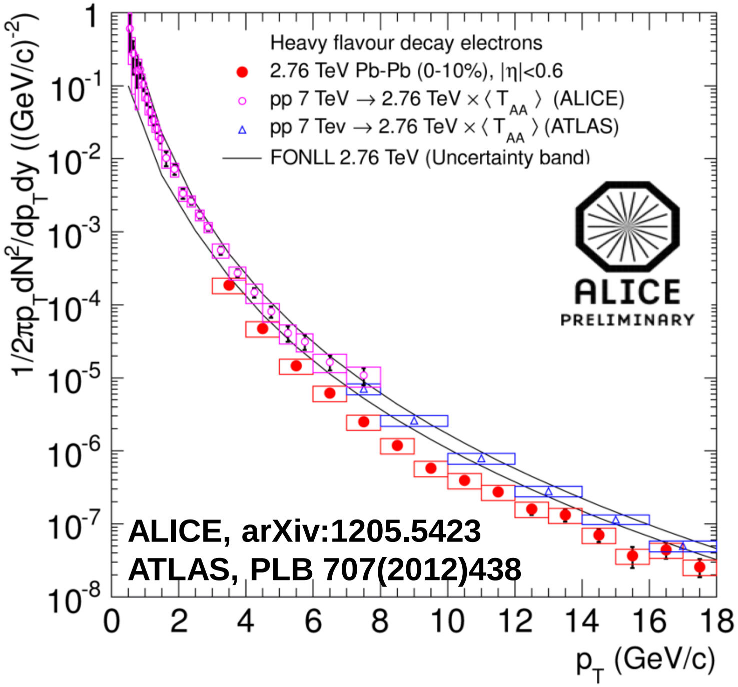


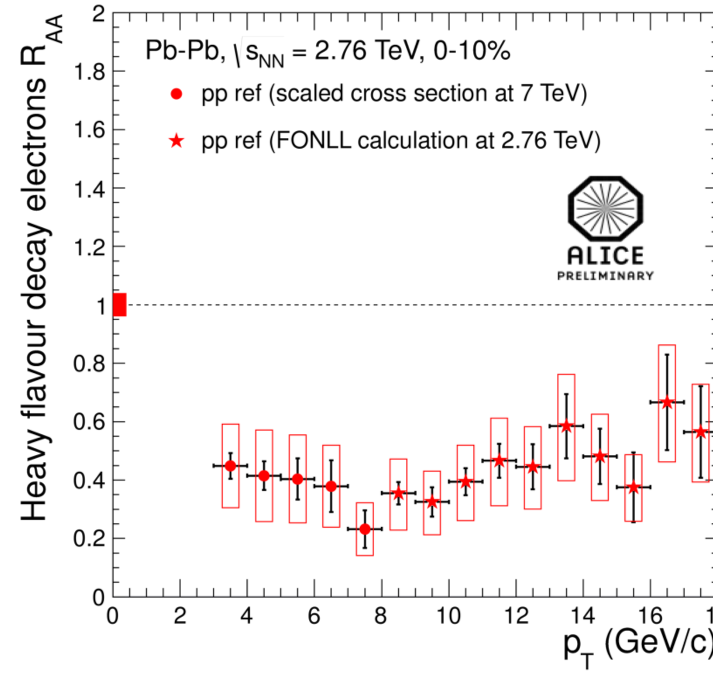
HEAVY FLAVOR MEASUREMENTS IN Pb-Pb COLLISIONS

-

effects of the hot and dense medium?

HF → $e^{\pm}$: 0-10% central Pb-Pb





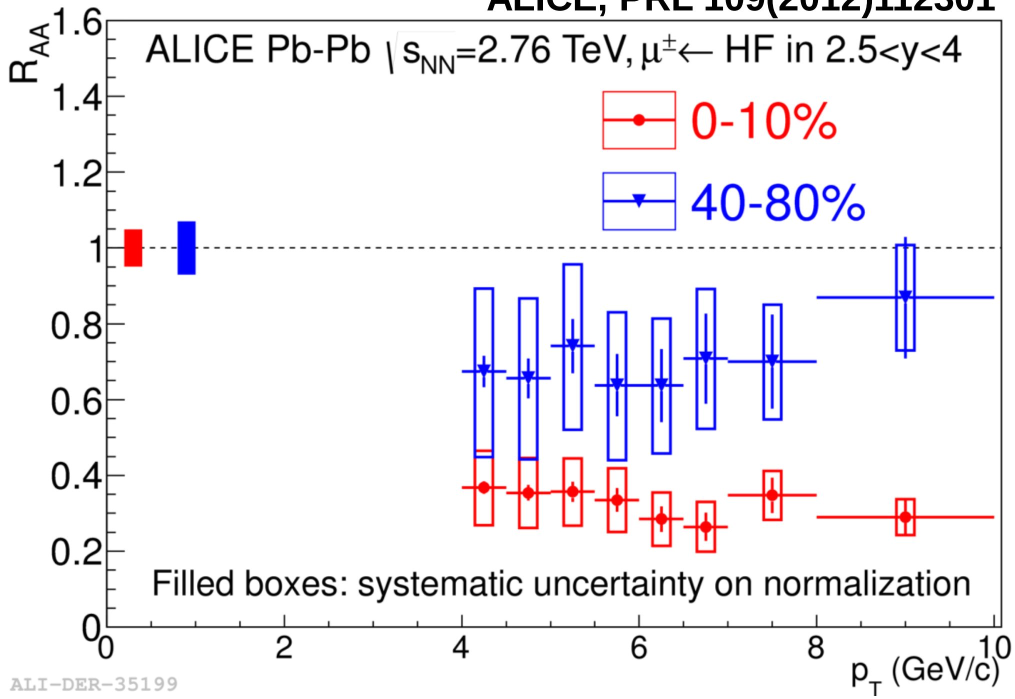
$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

- HF→$e^{\pm}$ measurement using 2011 Pb-Pb data (EMCal trigger)
- electron identification with TPC and EMCal
- background from other electron sources subtracted via invariant mass analysis (Dalitz decays and γ conversions) and cocktail
- pp reference: scaled 7 TeV pp data and FONLL (at high p_T)

→ strong suppression observed over the full p_T range

HF → $\mu^{\pm}$: 0-10% central Pb-Pb

ALICE, PRL 109(2012)112301



- HF→$\mu^{\pm}$ measurement using 2010 Pb-Pb data (MB and muon triggers)
- background $\mu^{\pm}$ from decays of π, K subtracted
  - π, K cross sections extrapolated from mid-rapidity data
  - assumption:

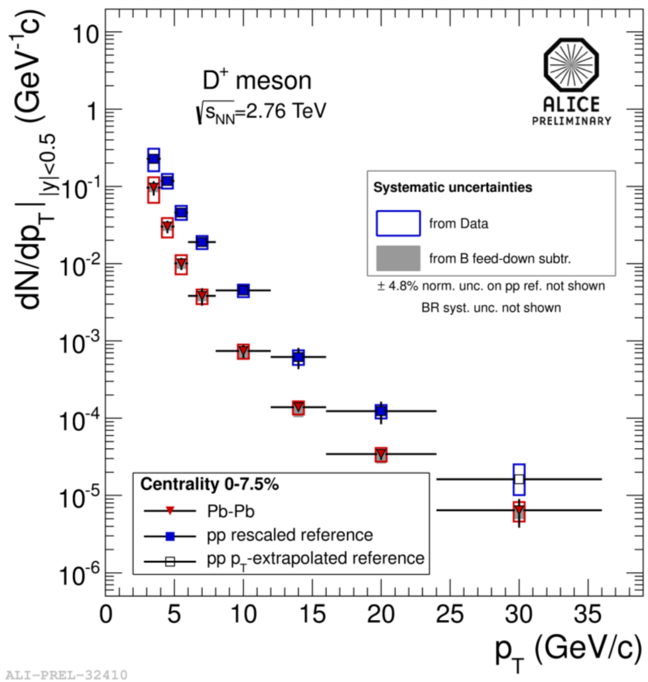
$0 < R_{AA}^{\pi,K}(2.5<y<4) < 2\, R_{AA}^{\pi,K}(y\sim0)$

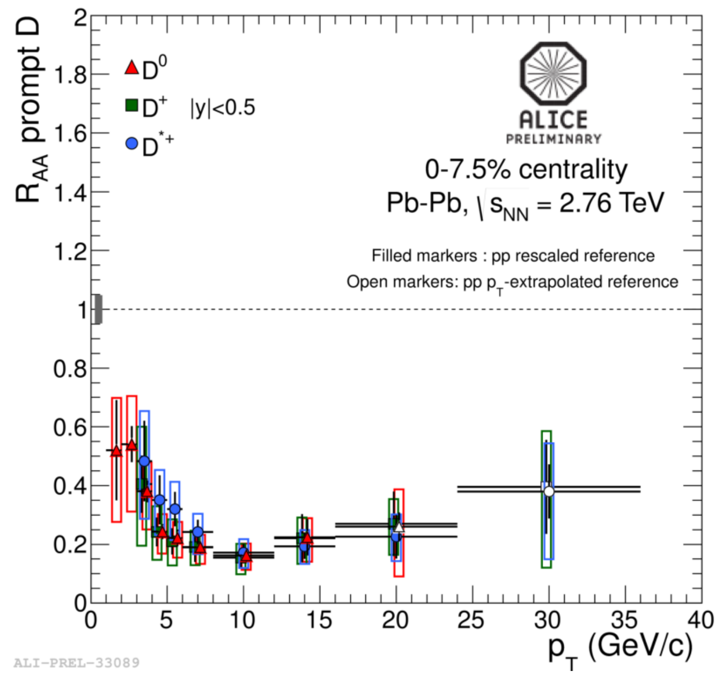
- pp reference: measured 2.76 TeV pp data

→ strong suppression observed in the 10% most central collisions

→ less suppression in more peripheral collisions

D mesons: 0-7.5% central Pb-Pb





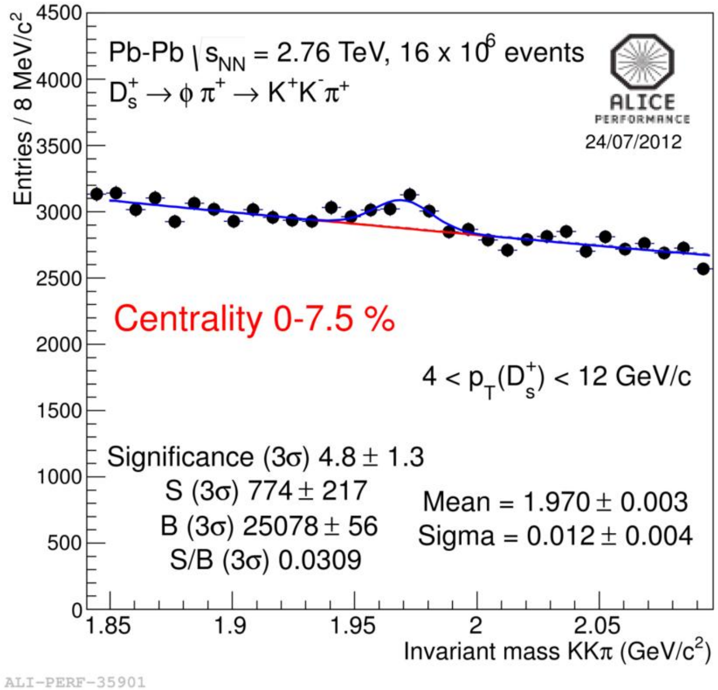
- **D-meson measurement using 2011 Pb-Pb data (MB and centrality triggers)**
- **prompt D mesons: feed-down from B decays subtracted**
  - **assumption: 1/3 < $R_{AA}(D \leftarrow B)/R_{AA}(D)$<3**
- **pp reference: scaled 7 TeV pp data and high-p_T pQCD extrapolation**

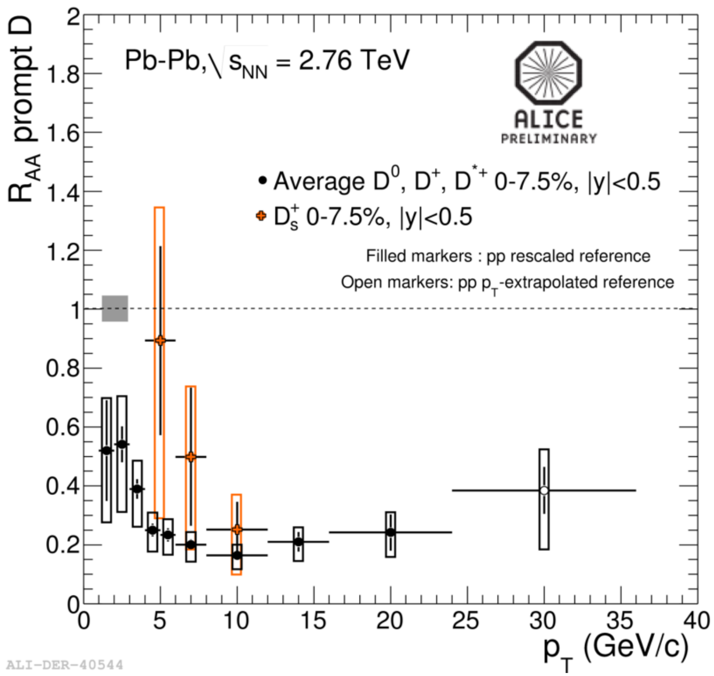
  → strong suppression of D meson in central Pb-Pb collisions

First D_s^+ measurement

- enhancement of strange w.r.t. non-strange D mesons at intermediate p_T through in-medium hadronization?

(Kuznetsova & Rafelski, EPJ C51(2007)113; He et al., arXiv:1204.4442; Andronic et al., arXiv:0708.1488)

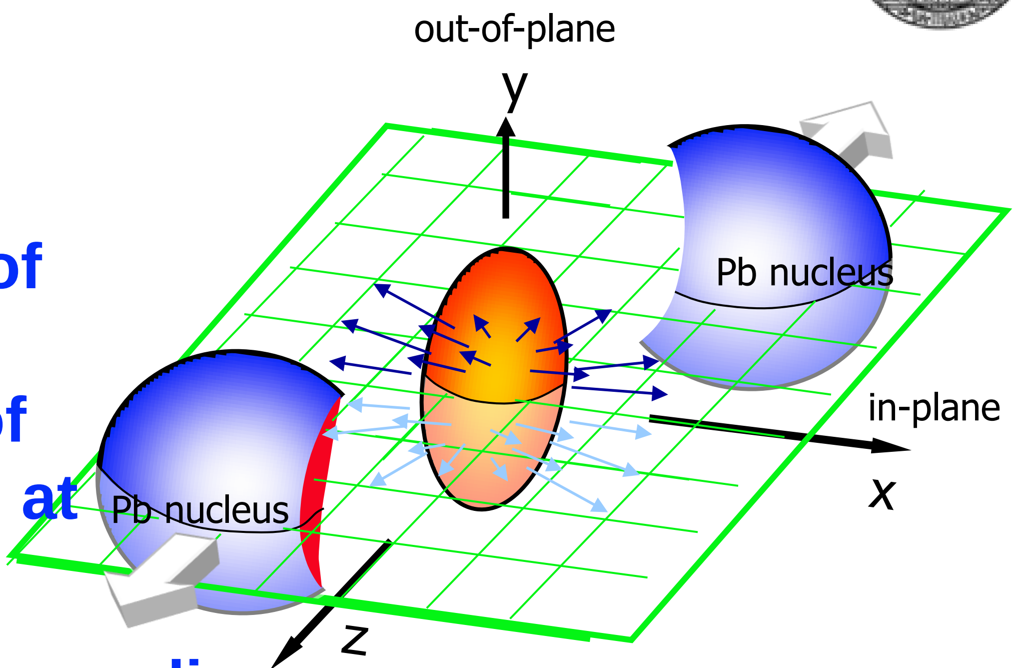




- first measurement of D_s^+ cross section and R_{AA}
- observed suppression similar to non-strange D-meson suppression

→ need better precision for conclusive statement

Azimuthal anisotropy



- initial state of produced QCD medium
  → spatial asymmetry
- path length dependence of heavy-quark energy loss
  → azimuthal anisotropy of heavy-flavor suppression at high p_T?
- dynamical evolution of the medium
  → collective motion (flow) at low p_T
  → final state momentum asymmetry

$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_T\, d\varphi\, dp_T\, dy}\sum_{n=0}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)$$

- do heavy quarks flow/thermalize?

  → focus on elliptic flow strength v_2

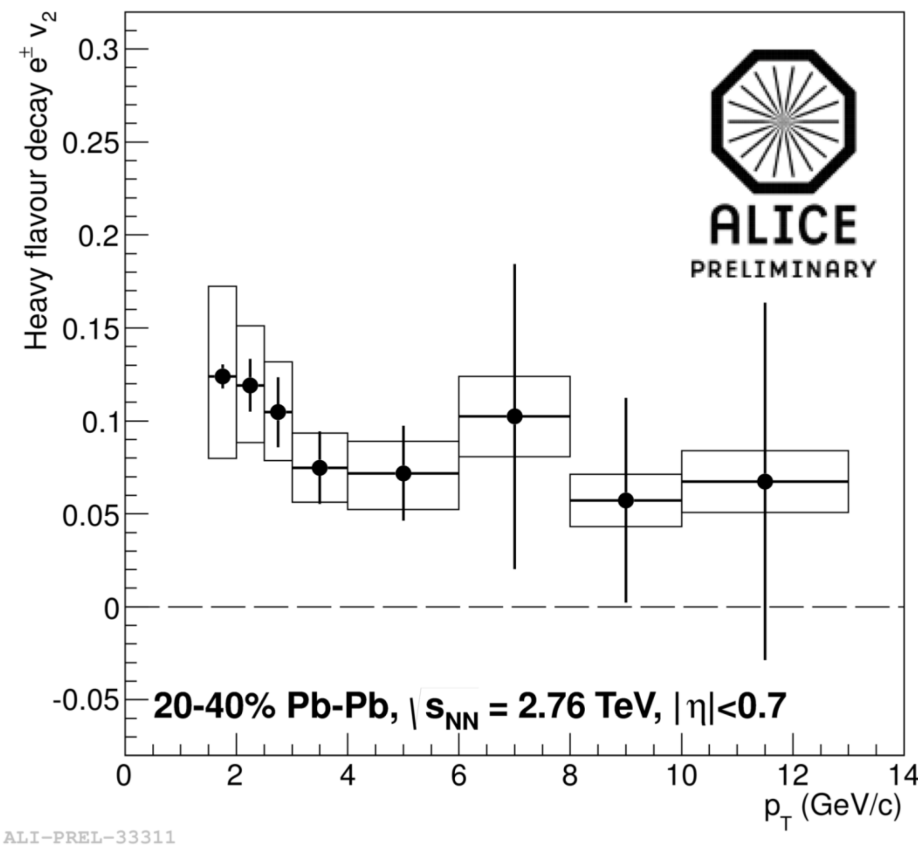
v_2 of HF → $e^\pm$: 20-40% central Pb-Pb

- HF→$e^\pm$ measurement: 2010 & 2011 Pb-Pb data
- electron identification
  - TPC-TOF (MB/centr. trigger)
  - TPC-EMCal (EMCal/centr. trigger)
- v_2 measurement: event plane method

$$v_2^{e\,HF} = \frac{(1+\alpha)v_2^{e\,incl.} - v_2^{e\,backg.}}{\alpha}$$

with $\alpha = N^{e\,HF} / N^{e\,backg.}$

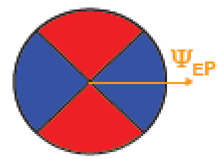
- background electrons
  - mainly from π^0, η Dalitz decays and photon conversions
  - v_2 calculated via cocktail using measured meson v_2



→ heavy-flavor electron $v_2 > 0$ at low p_T

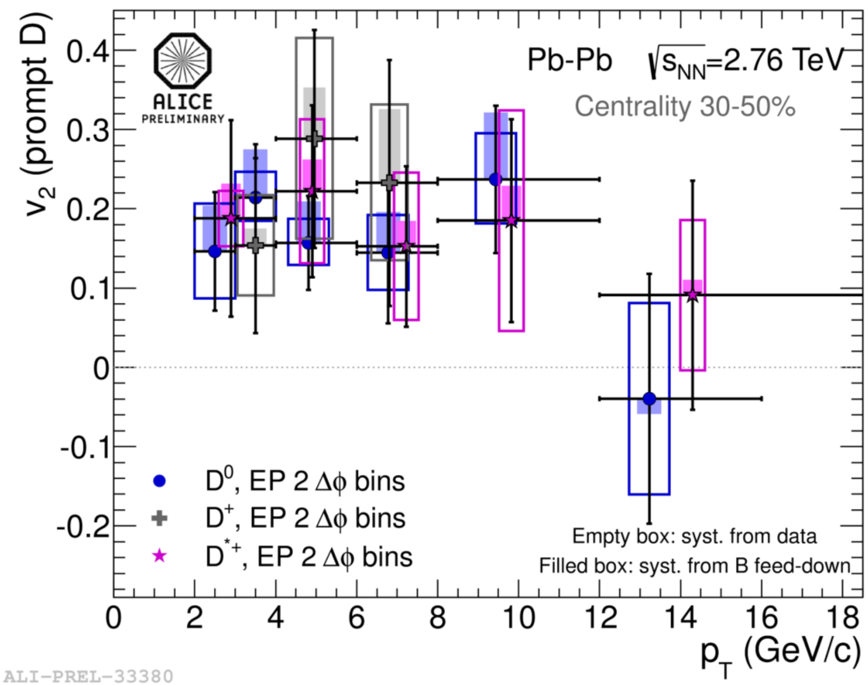
D-meson v_2

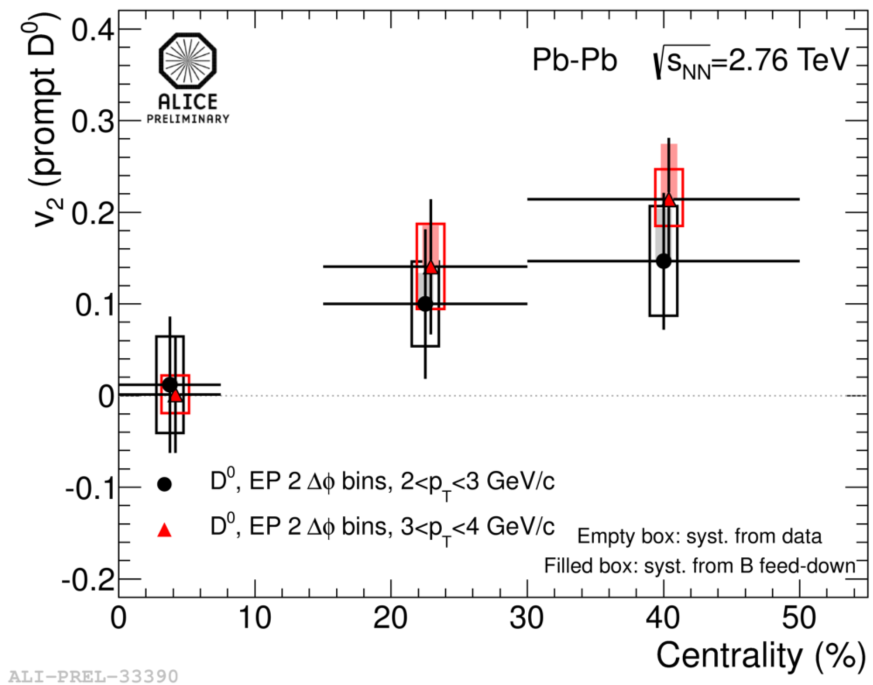
- **D measurement: 2011 Pb-Pb data (MB/centr. triggers)**
- **v_2 measurement: event plane method**



$$v_2 = \frac{1}{R}\frac{\pi}{4}\frac{N^{in-plane} - N^{out-of-plane}}{N^{in-plane} + N^{out-of-plane}}$$

with R = event plane resolution



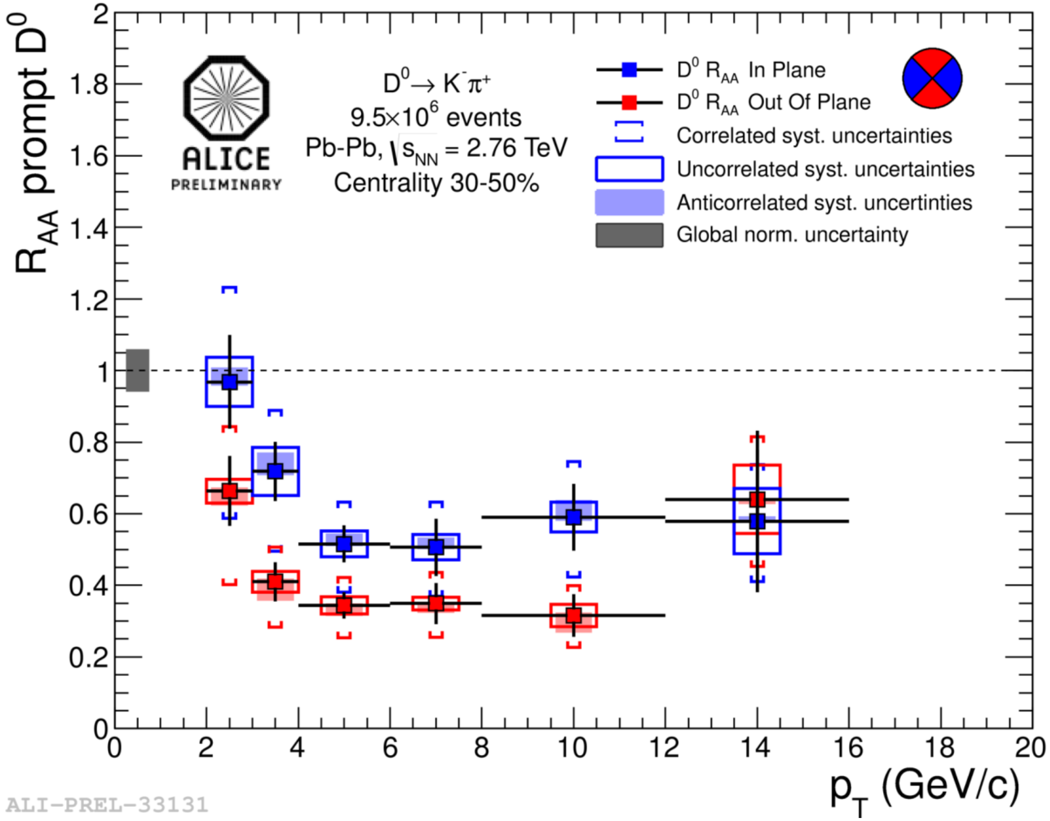


→ **indication of $v_2 > 0$, consistent for all D-meson species**

→ **indication of centrality dependence at low p_T**

D^0-meson R_{AA} vs. event plane

- **mid-central (30-50%) Pb-Pb collisions**



- **$p_T \leq 10$ GeV/c: suppression of D^0 meson out-of-plane larger than in-plane**
  - → elliptic flow at low p_T?
  - → path length dependence at high p_T?

HEAVY FLAVOR MEASUREMENTS IN Pb-Pb COLLISIONS

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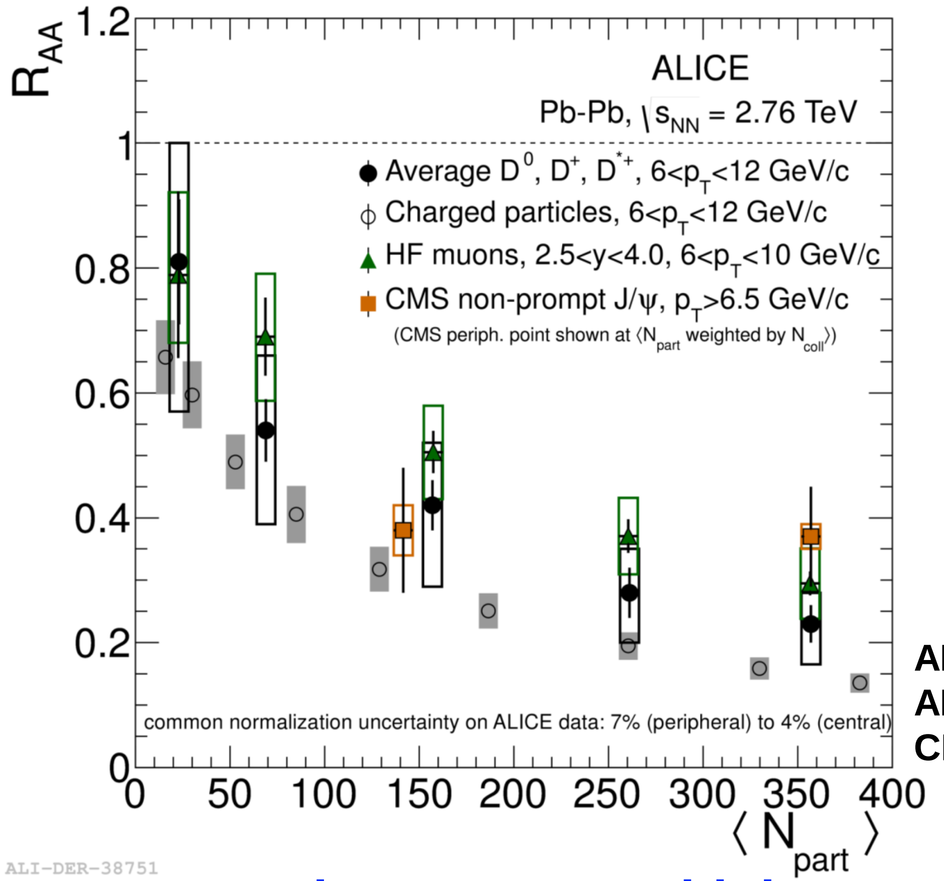
DATA & MODELS

Centrality dependence of HF R_{AA}

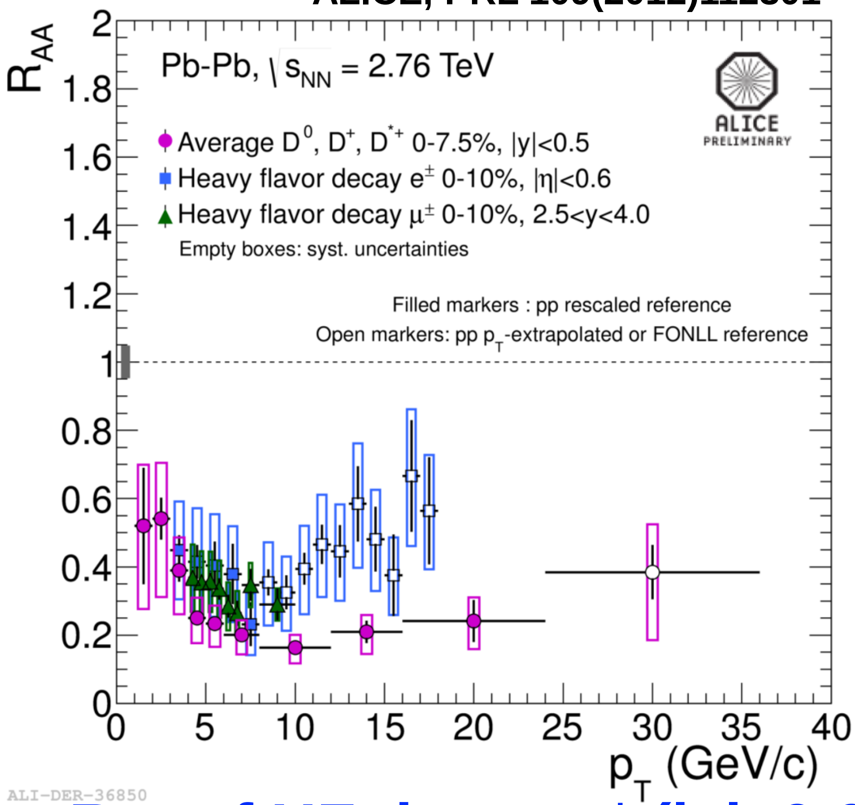


ALICE, arXiv:1203.2160
ALICE, PRL 109(2012)112301
CMS, JHEP 05(2012)063

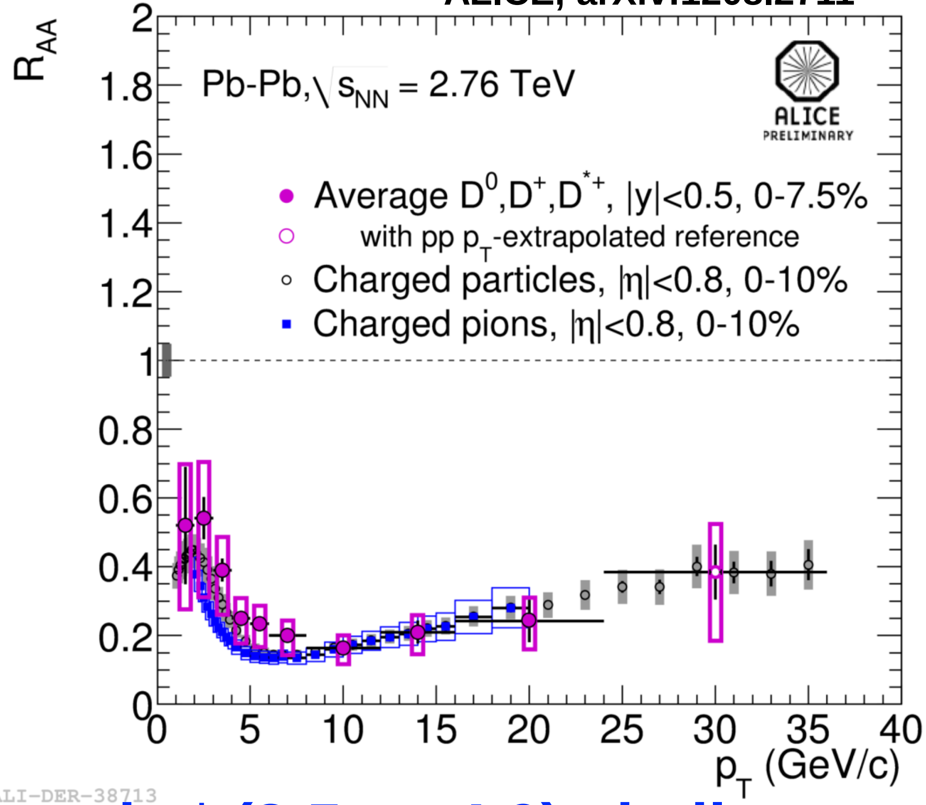
- R_{AA} of D mesons and HF muons at high p_T
  → similar trend with centrality
- charged particle R_{AA} < D-meson R_{AA}?
  → data not conclusive
- beauty R_{AA}: non-prompt J/ψ consistent with HF muons

R_{AA}: p_T dependence in central Pb-Pb

ALICE, PRL 109(2012)112301



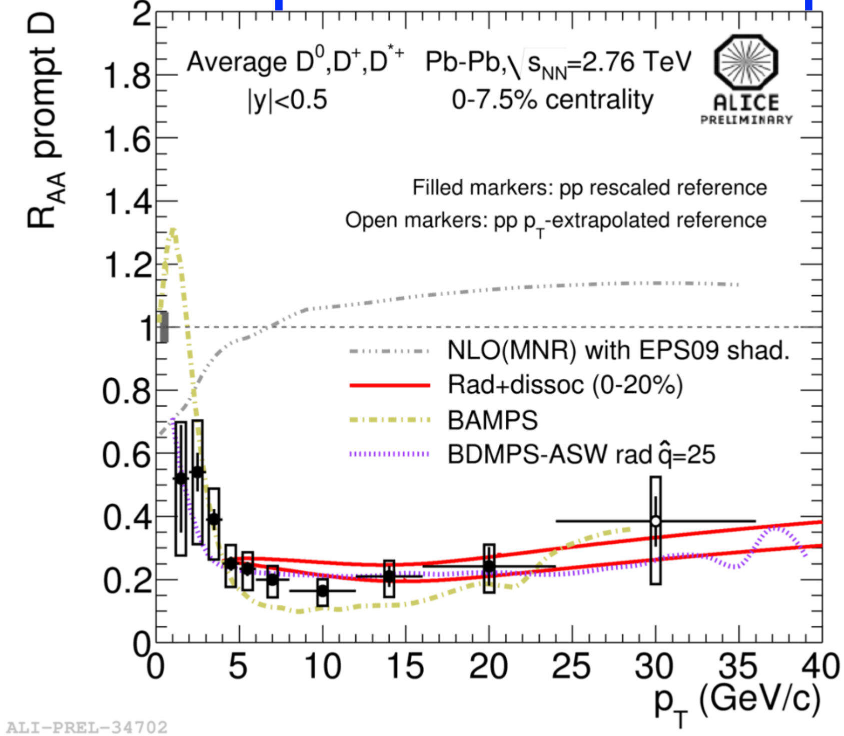
ALICE, arXiv:1208.2711

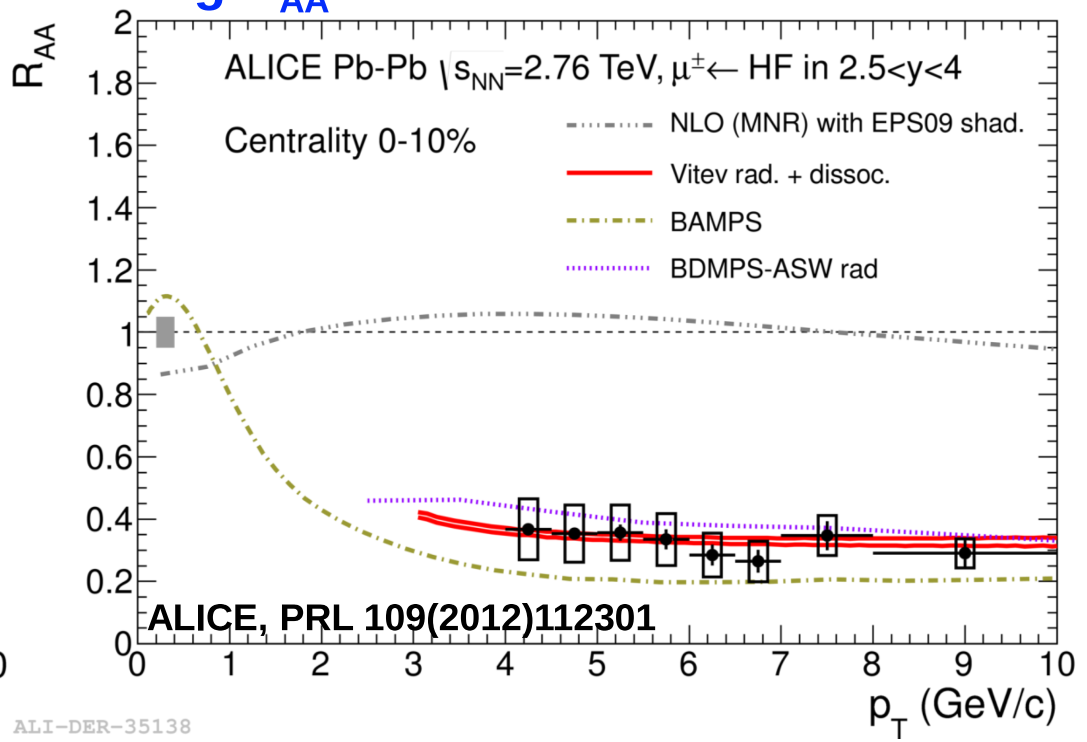


- R_{AA} of HF decay $e^\pm$ (|y|<0.6) and $\mu^\pm$ (2.5<y<4.0) similar
- compatible with R_{AA} of D mesons (|y|<0.5), taking into account decay kinematics: $p_T^e \sim 0.5\ p_T^{HF}$ at high p_T
- R_{AA} of D-mesons, charged particles, and $\pi^\pm$ similar

R_{AA} vs. models in central Pb-Pb

comparison with models predicting R_{AA} of HF muons and D mesons

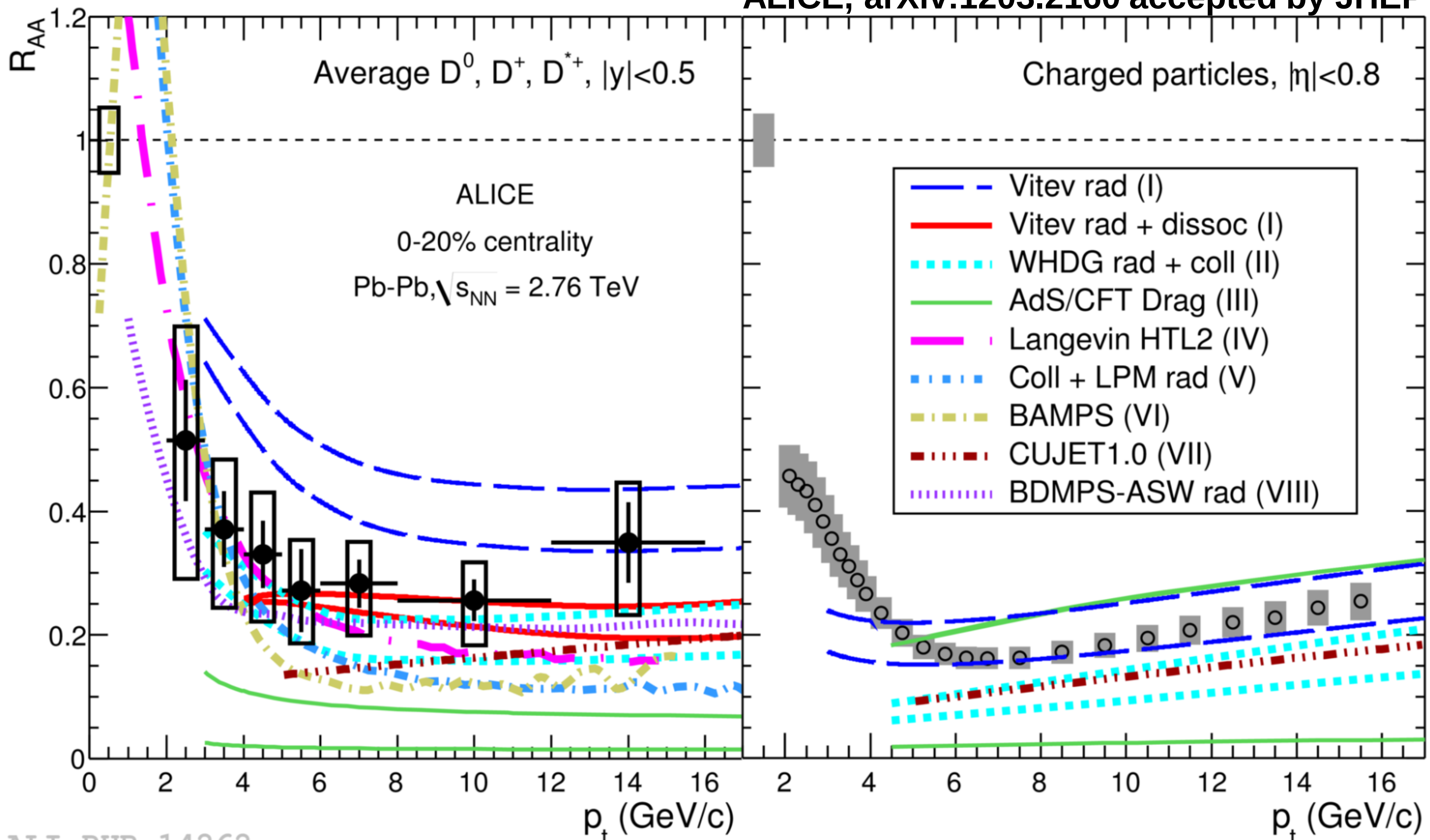




- **R_{AA} of HF decay $\mu^{\pm}$ and D mesons can not be explained by shadowing alone in the range p_T > 4 GeV/c**
  - **→ final state effects are dominant**
  - **→ p-Pb data are needed to quantify initial state effects**
- **models with final state effects describe the data well**

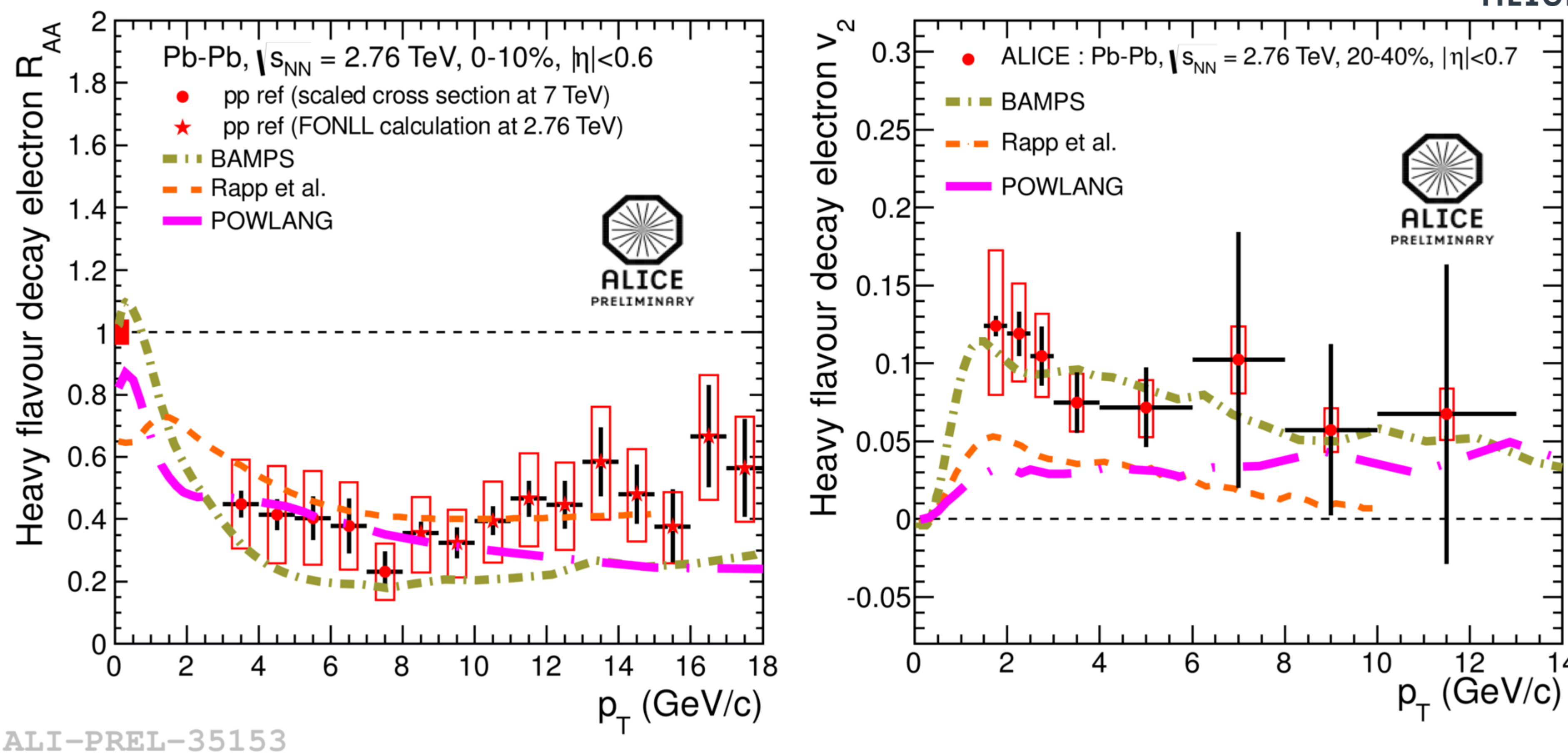
R_{AA} vs. models in central Pb-Pb

ALICE, arXiv:1203.2160 accepted by JHEP



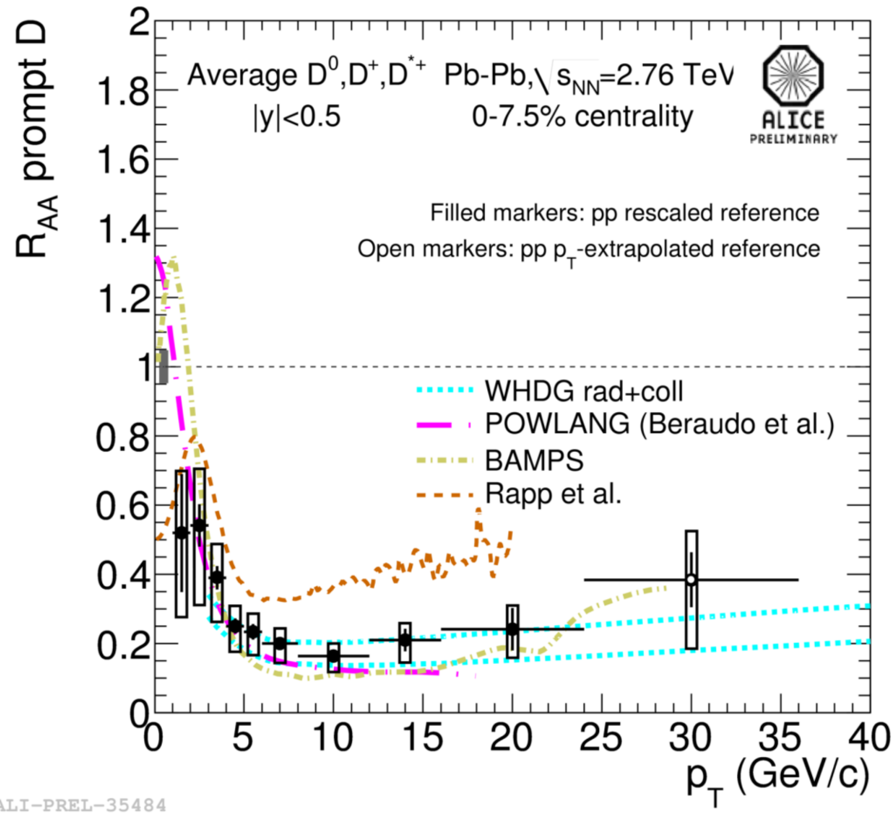
- **models describe R_{AA} of D mesons and charged particles reasonably well**
  - **AdS/CFT: underestimates charm R_{AA} and has limited predictive power for charged particle R_{AA}**

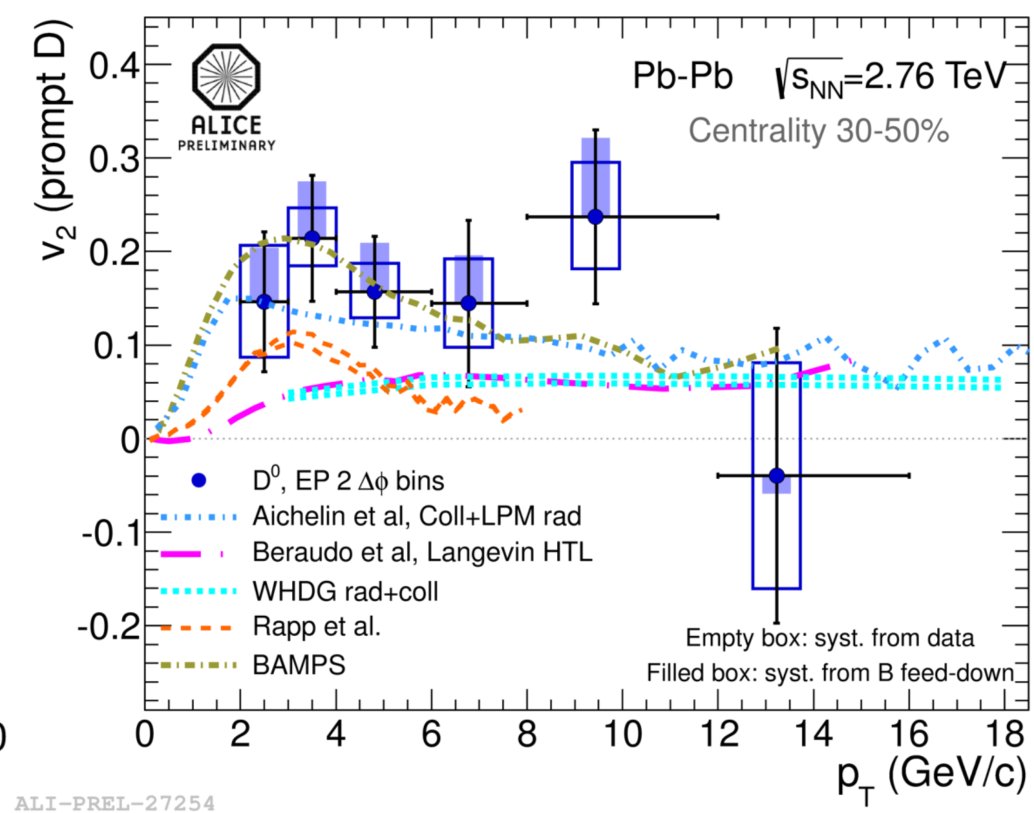
HF → $e^{\pm}$: R_{AA} and v_2



- simultaneous description of R_{AA} and v_2 of HF→$e^{\pm}$ presents a challenge for models

D mesons: R_{AA} and v_2





- **simultaneous description of R_{AA} and v_2 of D mesons presents a challenge for models**

Summary: heavy quarks

- **heavy-flavor production in pp collisions**
  - pQCD calculations are in reasonable agreement with measured cross sections
- **heavy-flavor in Pb-Pb collisions at the LHC**
  - $e^{\pm}$ and $\mu^{\pm}$ from HF decays as well as D mesons are strongly suppressed at high p_T in central collisions
    - R_{AA} shows similar trends with p_T and centrality for D mesons, charged particles and pions
  - $e^{\pm}$ from HF decays and D mesons show an azimuthal anisotropy (v_2>0) at intermediate p_T
    - hint of centrality dependence of D^0-meson anisotropy at low p_T
  - models including energy loss of HF in the medium describe heavy-flavor R_{AA} data reasonably well
    - simultaneous description of R_{AA} and v_2 remains a challenge
- **initial state effects → upcoming p-Pb run**