lectures on 'hard probes' for quark-gluon plasma diagnosis

- introductory remarks, QGP and hard processes
- lecture 1 heavy quarks and QGP
- lecture 2 jets and jet quenching
- lecture 3 quarkonia

pbm
EJC, Villa Clythia, Frejus, Oct. 2013

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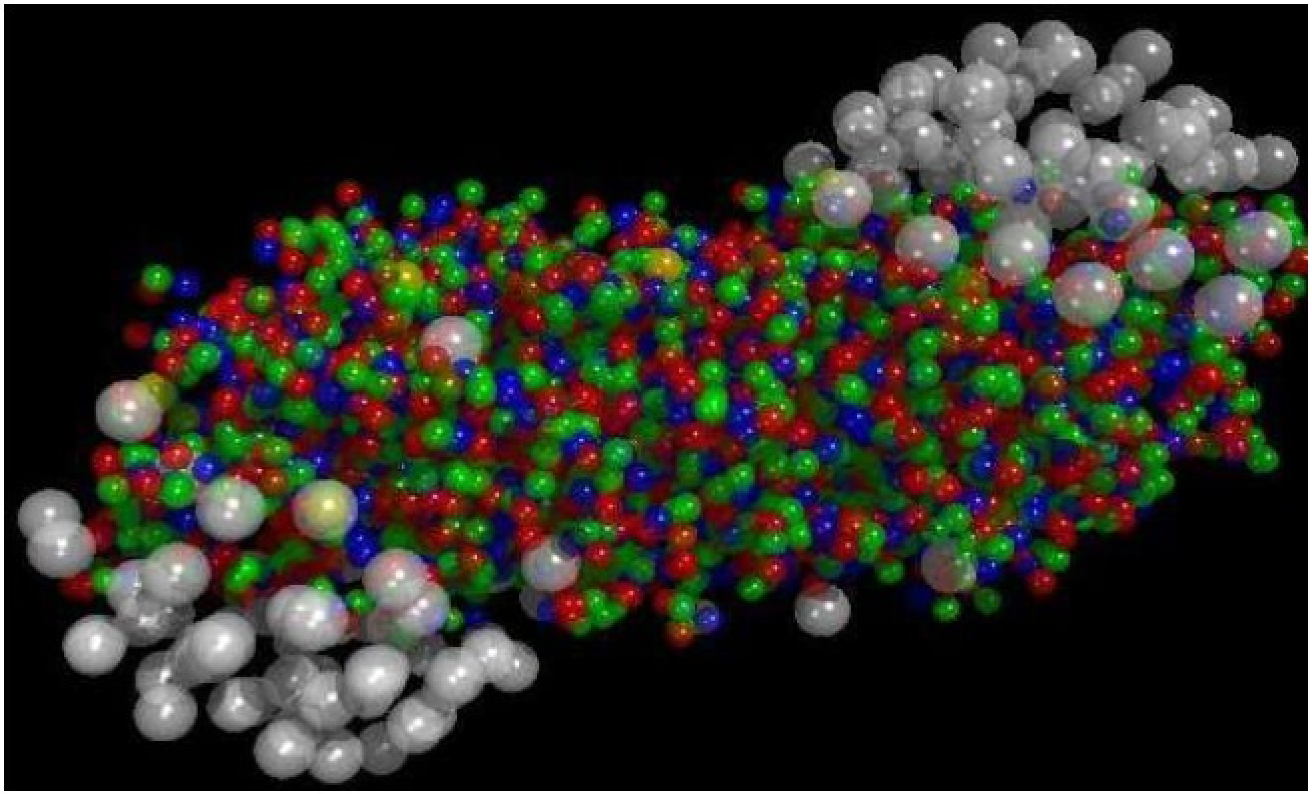
Quark-gluon plasma –a new state of matter- deconfined quarks and gluons



in relativistic nucleus-nucleus collisions, a new state of matter is produced, in which colored quarks and gluons roam freely

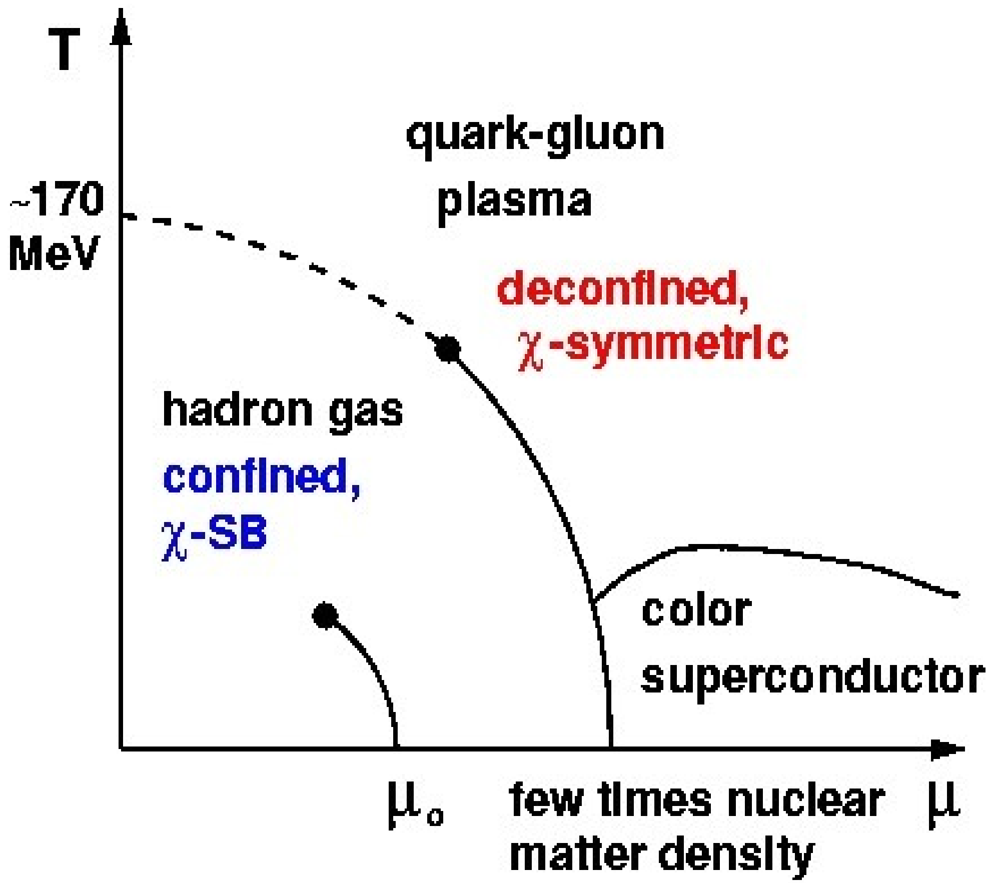
Simulation: UrQMD, Frankfurt

The phase diagram of strongly interacting matter

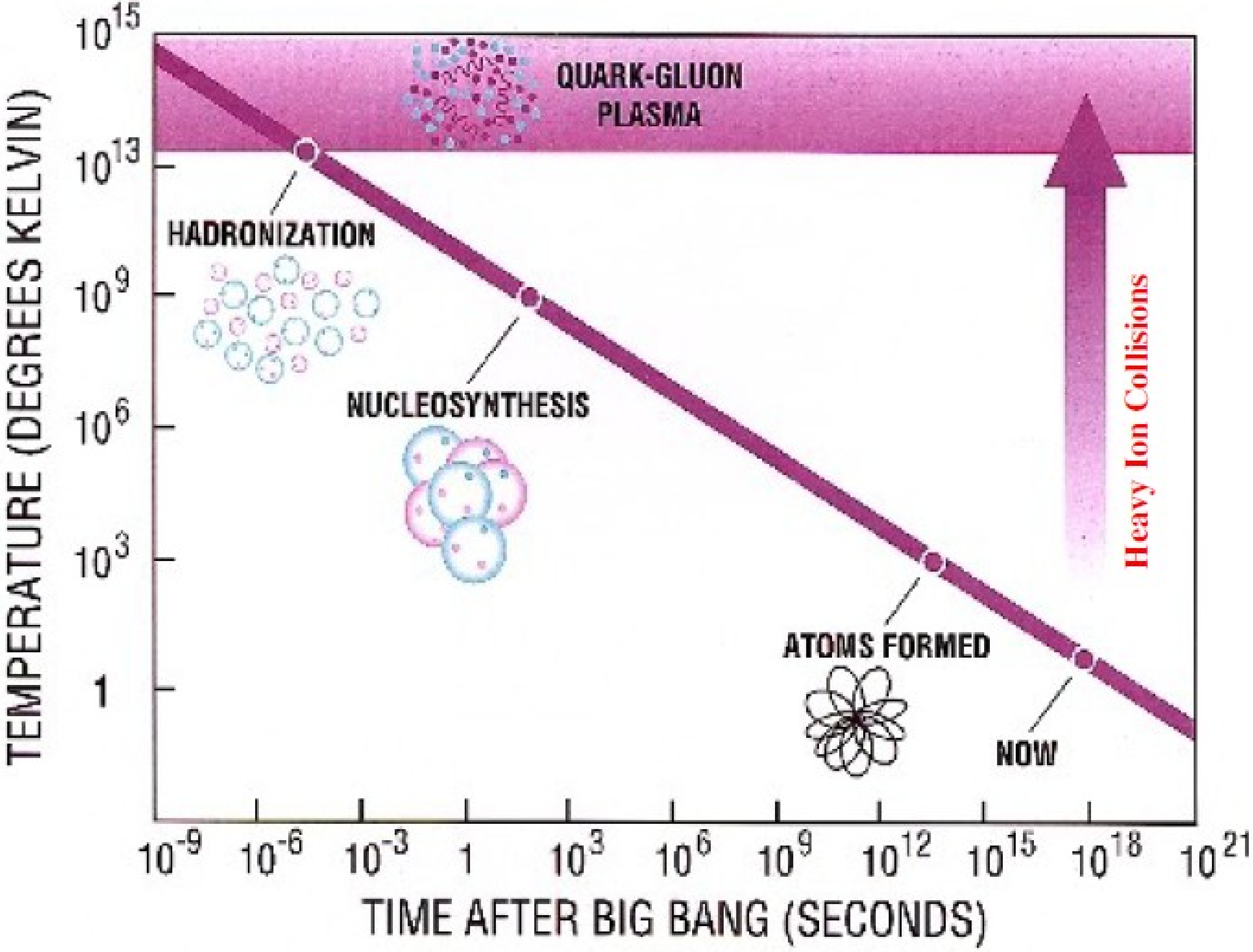
at low temperature and normal density
colored quarks and gluons are bound in colorless hadrons - confinement
chiral symmetry is spontaneously broken (generating 99% of proton mass e.g.)
1972 QCD (Gross, Politzer, Wilczek)
asymptotic freedom at small distances

at high temperature and/or high density
quarks and gluons freed from confinement
-> new state of strongly interacting matter
1975 (Collins/Perry and Cabibbo/Parisi)

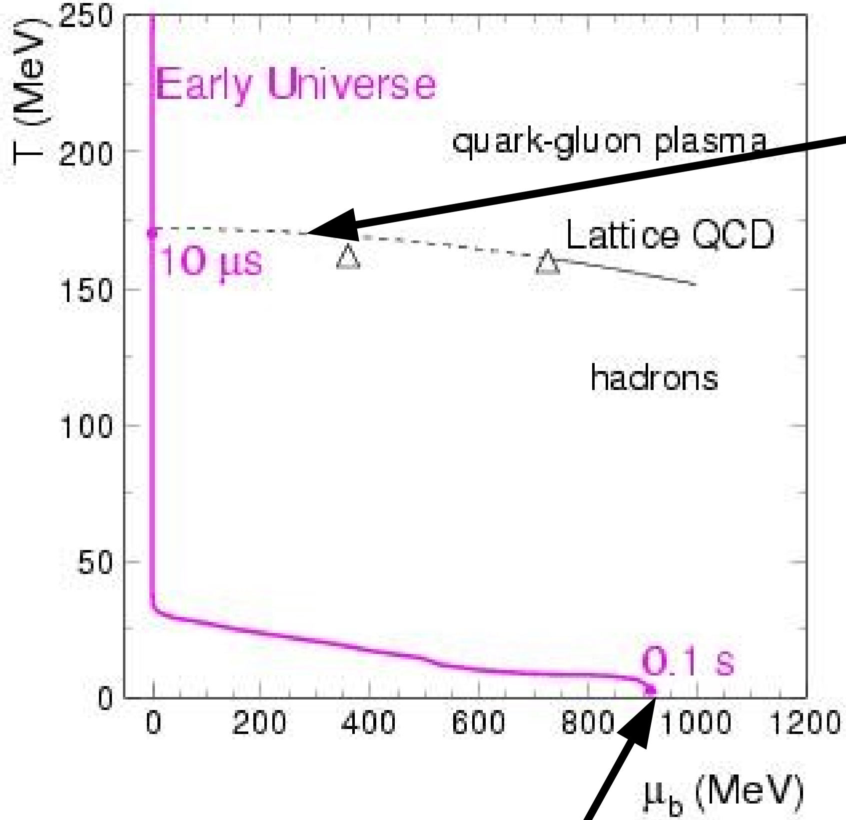
now called **Quark-Gluon Plasma (QGP)**



Quark-gluon plasma and the early universe



Evolution of the Early Universe



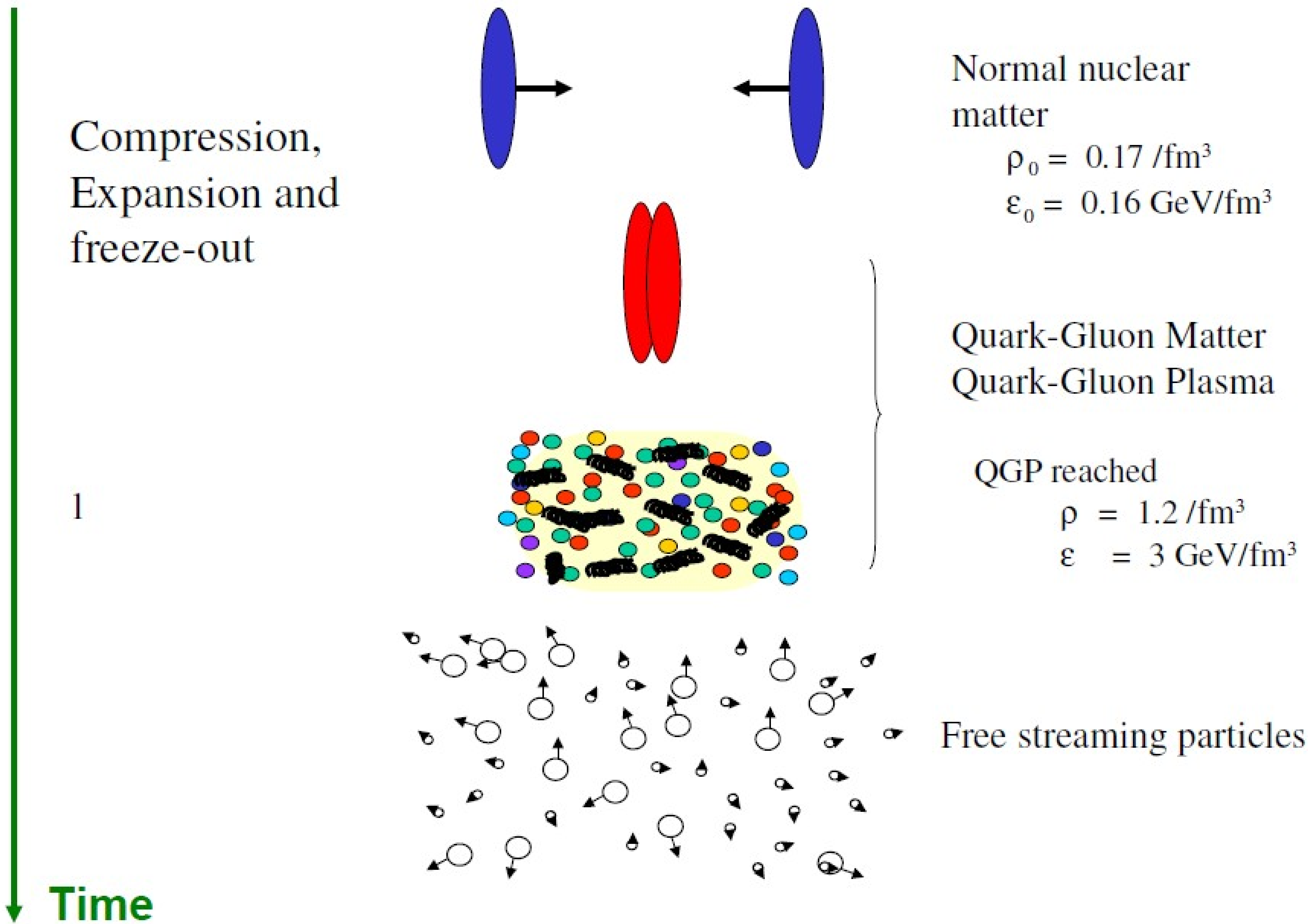
QCD Phase Boundary

Homogeneous Universe in
Equilibrium, this matter can
only be investigated in nuclear collisions

- Charge neutrality
- Net lepton number = net baryon number
- Constant entropy/baryon

neutrinos decouple and light nuclei begin to be formed

How to create QGP in the laboratory?

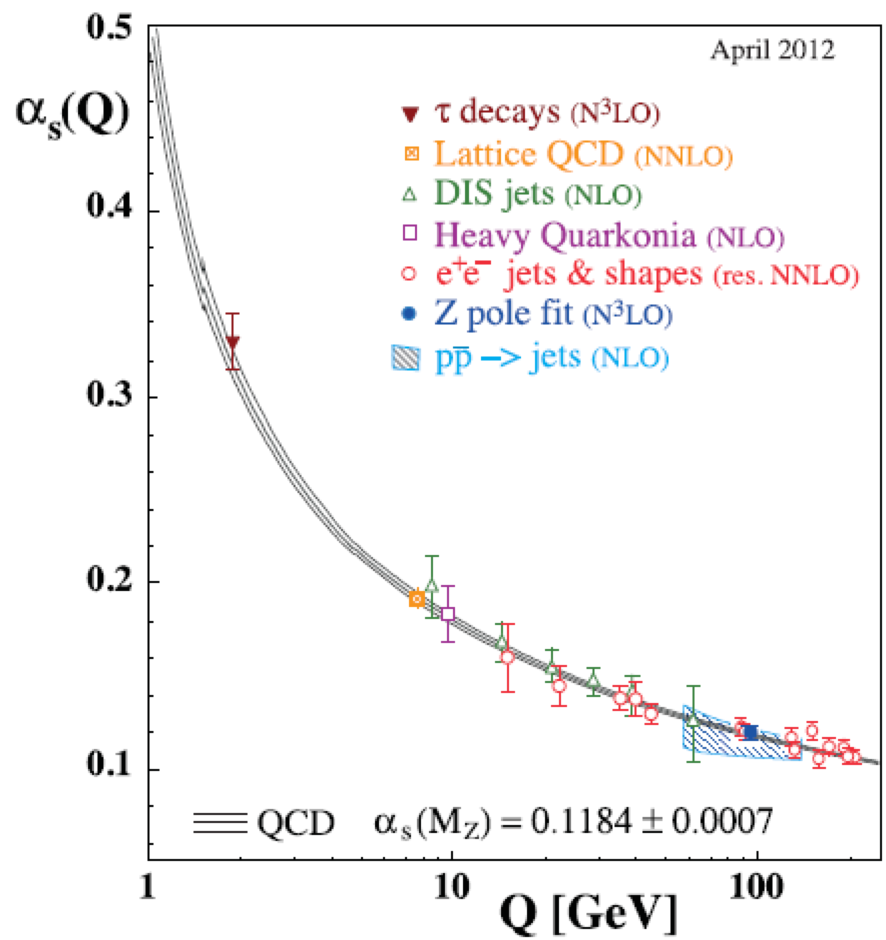


what are 'hard probes'?

Hard probes are observables which involve an energy or mass scale Q^2 >> (Lambda_QCD)^2

$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln(Q^2/\Lambda^2)}$$

$$\Lambda \approx 0.1 \text{ GeV for } \alpha_s(M_{Z^0} \equiv 91.2 \text{ GeV}) = 0.12$$



for such processes, production can be precisely computed in pQCD

in QGP physics, we are interested in studying their propagation in and interaction with the QGP medium

The Large Hadron Collider (LHC)

27 km long, 8 sectors

1232 dipole magnets (15m, 30 tonnes each) to bend the beams

Cooled with **120 tonnes of He at 1.9 K**

pp: 2808 bunches/ring, each 1.15×10^{11} protons (8 min filling time)

Design luminosity: **10^{34} $cm^{-2}s^{-1}$**

PbPb: 592 bunches/ring, each 7×10^{7} Pb ions

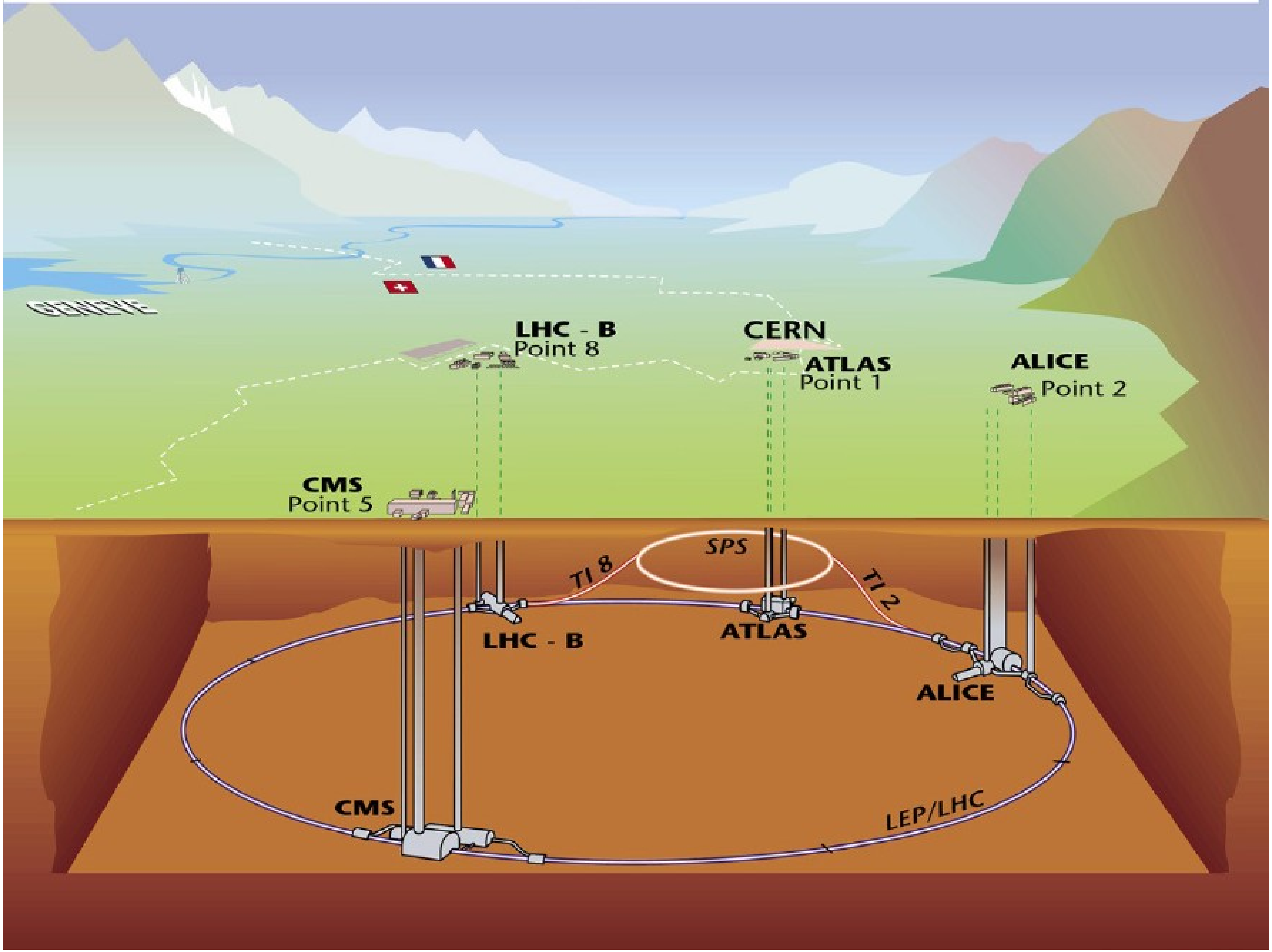
Design luminosity: 10^{27} $cm^{-2}s^{-1}$

Transverse r.m.s beam size: **16 μm**, r.m.s. bunch length: 7.5 cm

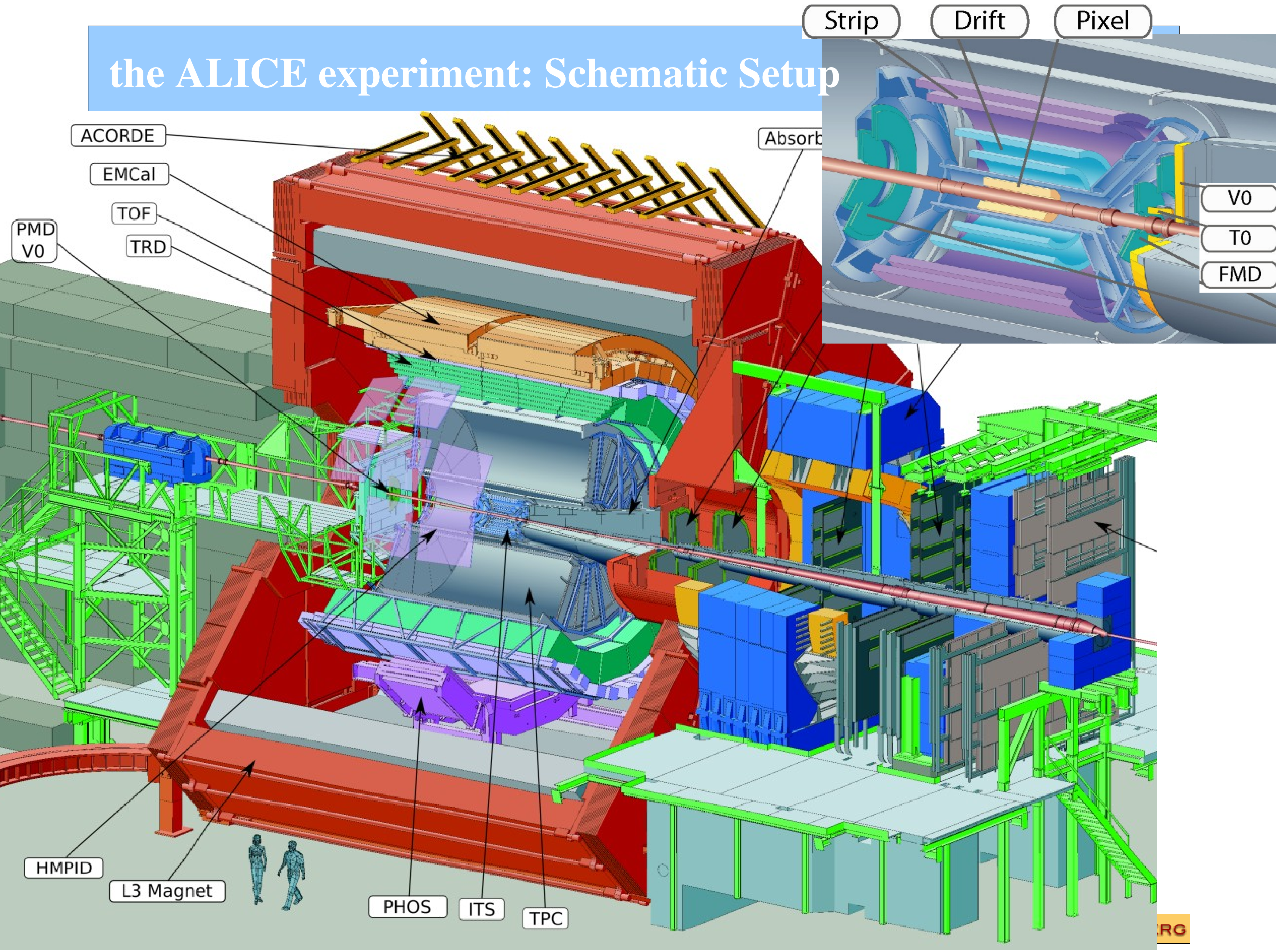
Beam kinetic energy: 362 MJ per beam (1 MJ melts 2 kg copper)

Total stored electromagnetic energy: **8.5 GJ** (dipole magnets only)

Overall view of the LHC experiments.

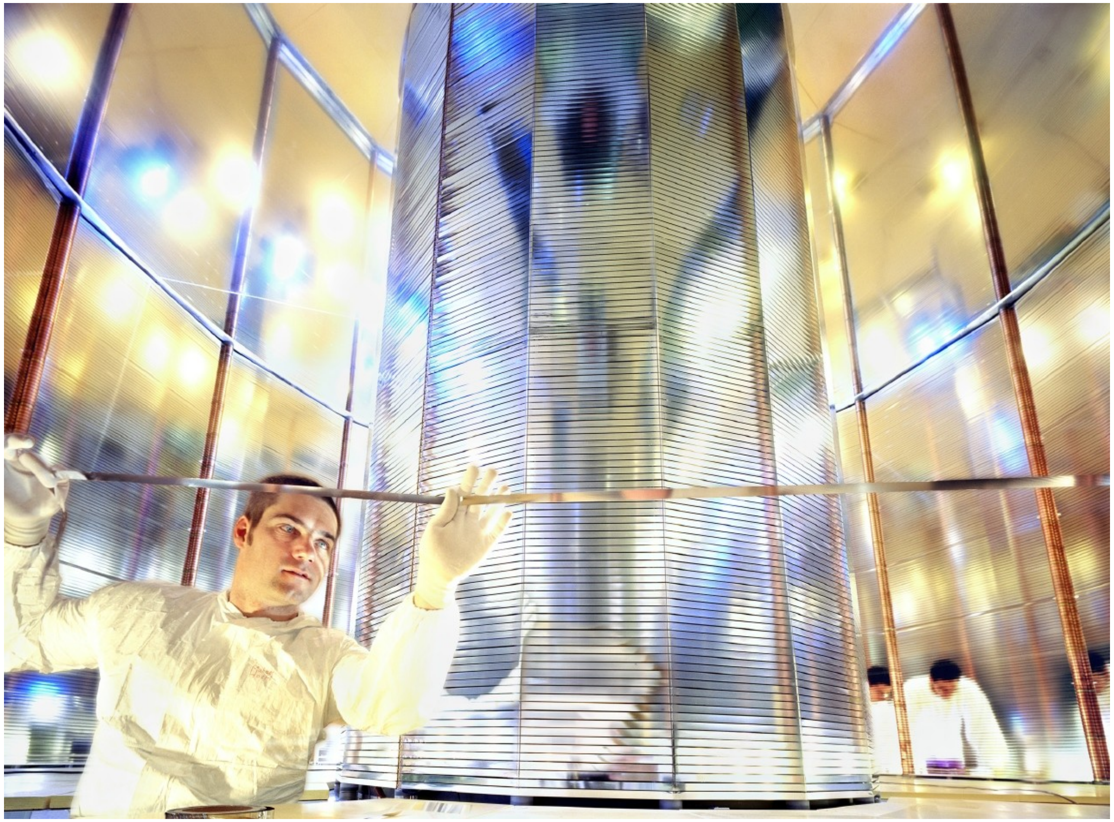


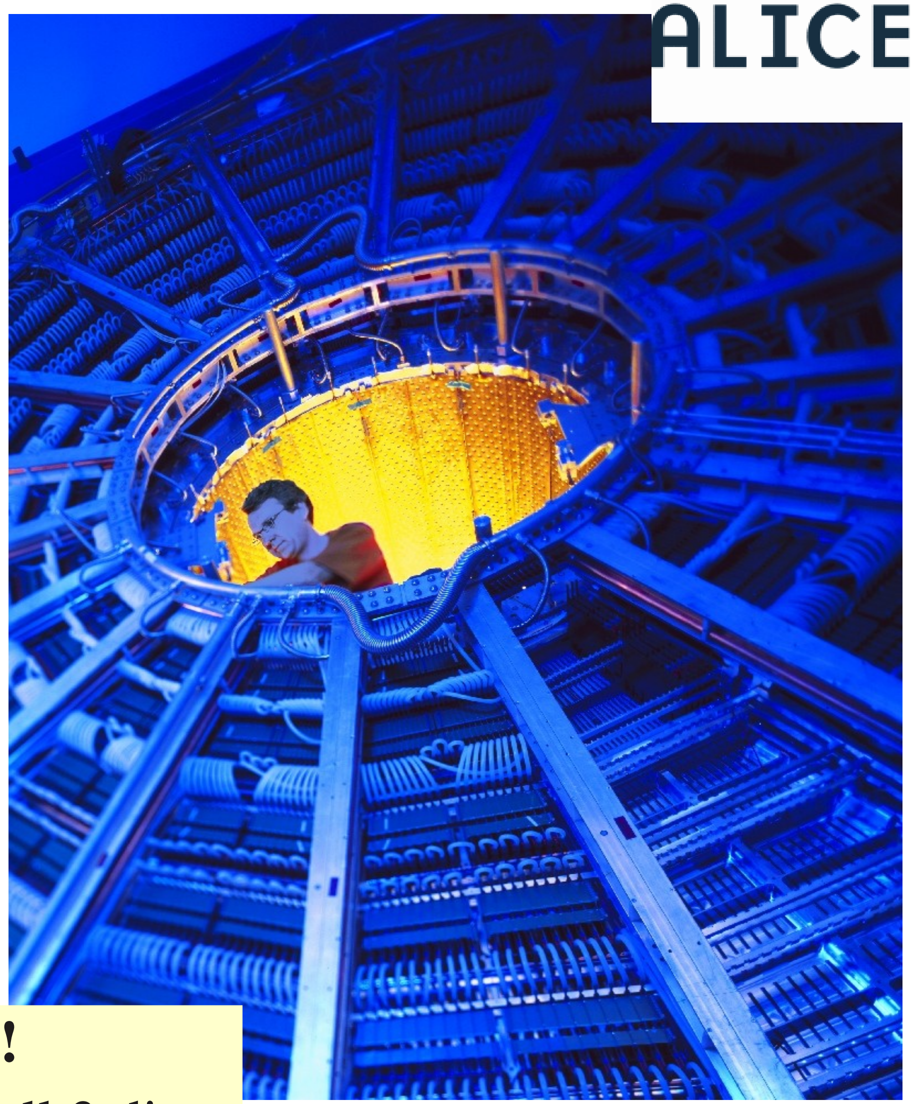
the ALICE experiment: Schematic Setup



the TPC (Time Projection Chamber) - 3D reconstruction of up to 15 000 tracks of charged particles per event

with 95 m^3 the largest TPC ever





560 million read-out pixels!

precision better than 500 μm in all 3 dim.

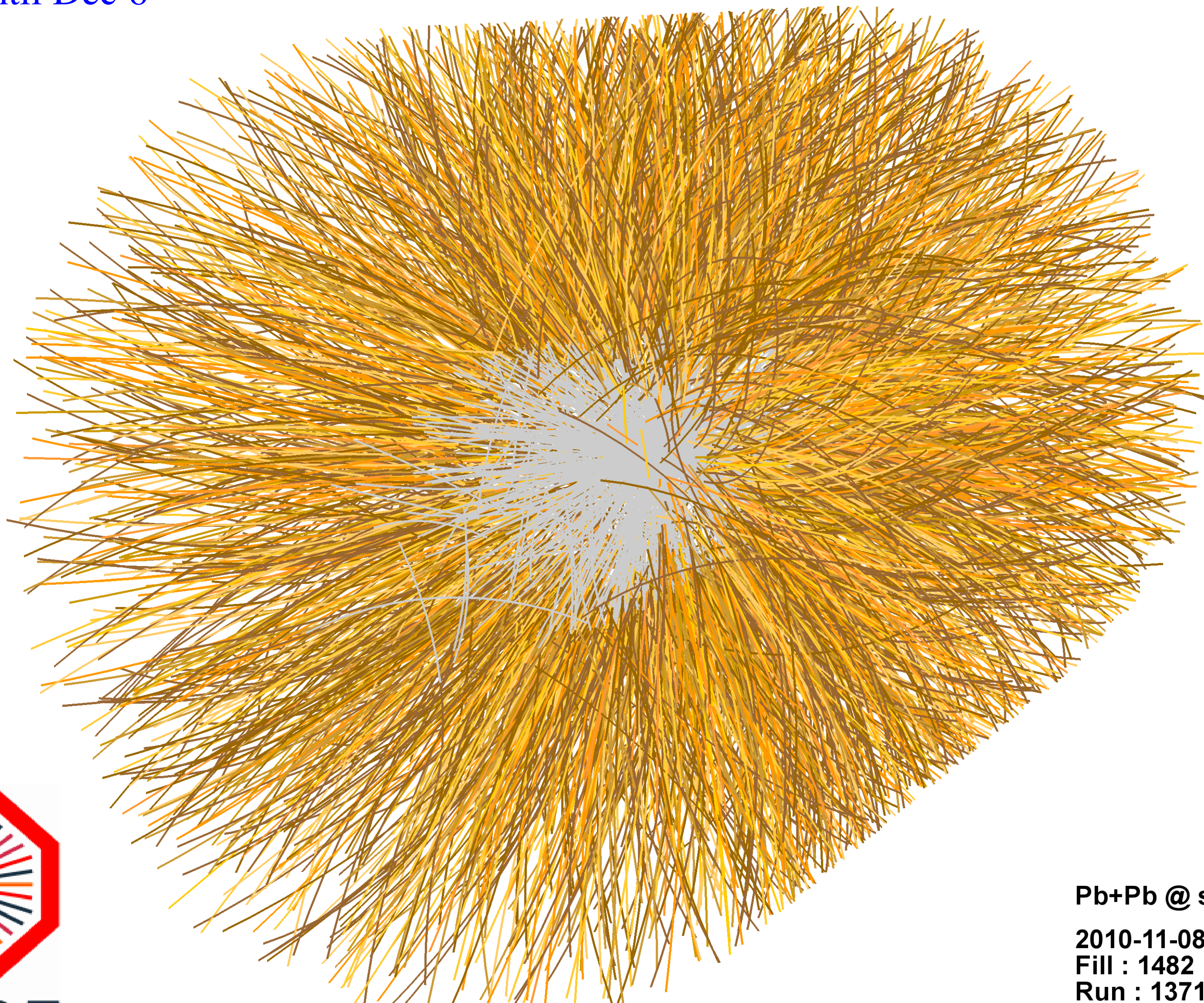
180 space and charge points per track

The interior of the TPC, 2004

first PbPb collisions at LHC at $\sqrt{s}$ = 2.76 A TeV

setup for ion collisions: November 4
first collisions with stable beams:
November 8 until Dec 6

already in Dec 2010
5 publications in PRL and PLB



ALICE

and the fun started

Lecture 1
Open Charm and Open Beauty from SPS to LHC Energy

- reminder of basics
- discussion of time scales and open charm conservation equation
- results for RHIC and LHCenergy in pp collisions
- results for RHIC and LHC energy in AA collisions
- an aside on photon production

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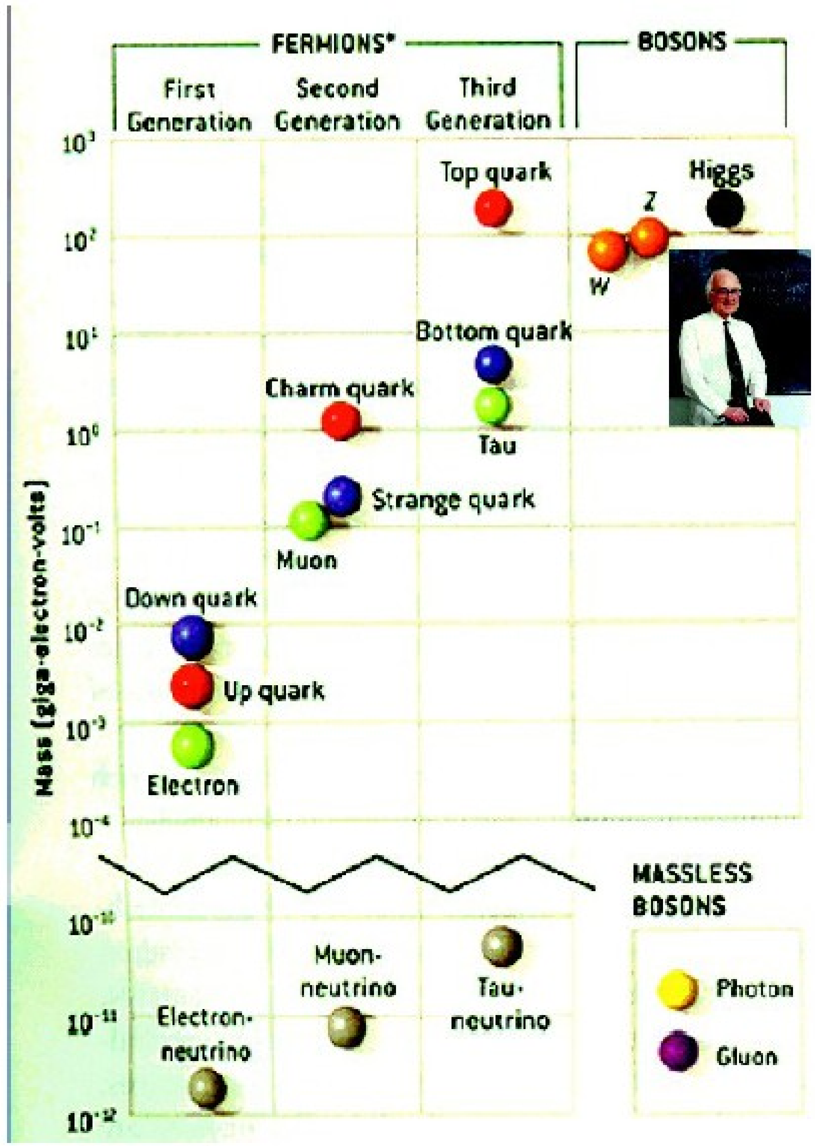

FERMIONS*
BOSONS
First Generation
Second Generation
Third Generation
Mass (giga-electron-volts)
Top quark
Higgs
Z
W
Bottom quark
Charm quark
Tau
Strange quark
Muon
Down quark
Up quark
Electron
MASSLESS BOSONS
Muon-neutrino
Tau-neutrino
Electron-neutrino
Photon
Gluon

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor		Mass GeV/c^2	Electric charge
ν_L	lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e	electron	0.000511	–1
ν_M	middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ	muon	0.106	–1
ν_H	heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ	tau	1.777	–1

Quarks spin =1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.002	2/3
d	down	0.005	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	173	2/3
b	bottom	4.2	–1/3

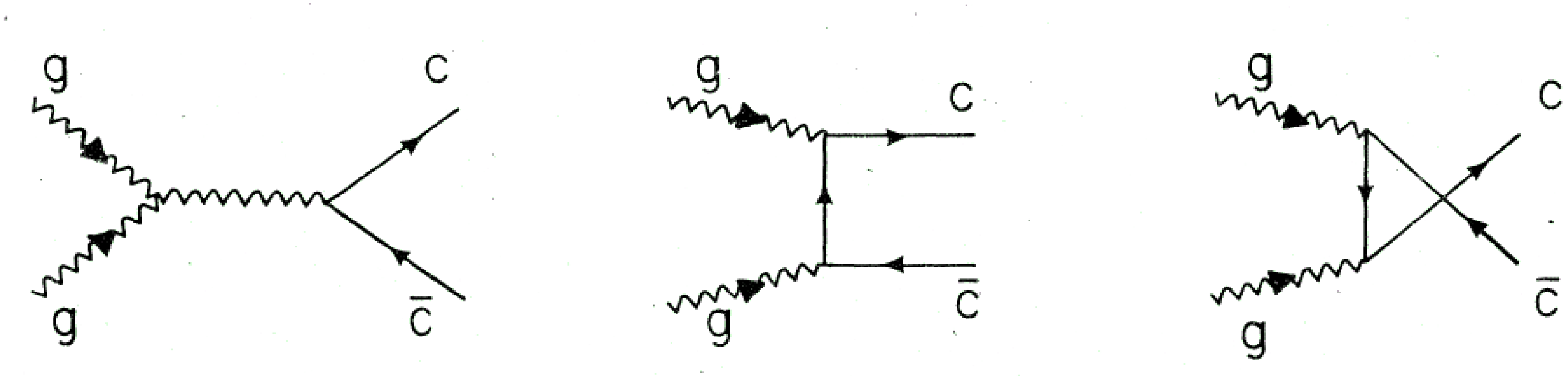
Remarks on production of open charm and charmonia

- charm quark mass >> Λ_{QCD} production described in QCD perturbation theory
- all calculations employ gluon fusion as starting point
- argument is energy independent until global energy conservation very close to threshold becomes important
- production of charm quark pairs takes place at timescale $1/m_c$
  $m_c = 1.5$ GeV --> $t_c = 0.13$ fm
- to build up wave function of mesons including those with open charm needs about t = 1fm --> charm production and charmed hadron formation are decoupled
- overall cross section is due to production of charm quark pairs
- time scale is much too short to dress the charm quarks essential to take current quarks

Cross section for charm production

based on M. Glueck, J. F. Owens, E. Reya,
Phys. Rev. D17 (1978) 2324

in leading order there are 3 important diagrams:



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differential cross section

$$\frac{d\sigma^{gg\to c\bar{c}}}{dt} = \frac{\pi\alpha_s^2}{64s^2}\left(12M_{ss} + \tfrac{16}{3}M_{tt} + \tfrac{16}{3}M_{uu}\right.$$

$$\left. + 6M_{st} + 6M_{su} - \tfrac{2}{3}M_{tu}\right), \qquad \text{(A1)}$$

with

$$M_{ss} = \frac{4}{s^2}(t-m^2)(u-m^2),$$

$$M_{tt} = \frac{-2}{(t-M^2)^2}\left[4m^4 - (t-m^2)(u-m^2)\right.$$

$$\left. + 2m^2(t-m^2)\right],$$

$$M_{uu} = \frac{-2}{(u-m^2)^2}\left[4m^4 - (u-m^2)(t-m^2)\right.$$

$$\left. + 2m^2(u-m^2)\right], \qquad \text{(A2)}$$

$$M_{st} = \frac{4}{s(t-m^2)}\left[m^4 - t(s+t)\right],$$

$$M_{su} = \frac{4}{s(u-m^2)}\left[m^4 - u(s+u)\right],$$

$$M_{tu} = \frac{-4m^2}{(t-m^2)(u-m^2)}\left[4m^2 + (t-m^2) + (u-m^2)\right],$$

total cross section

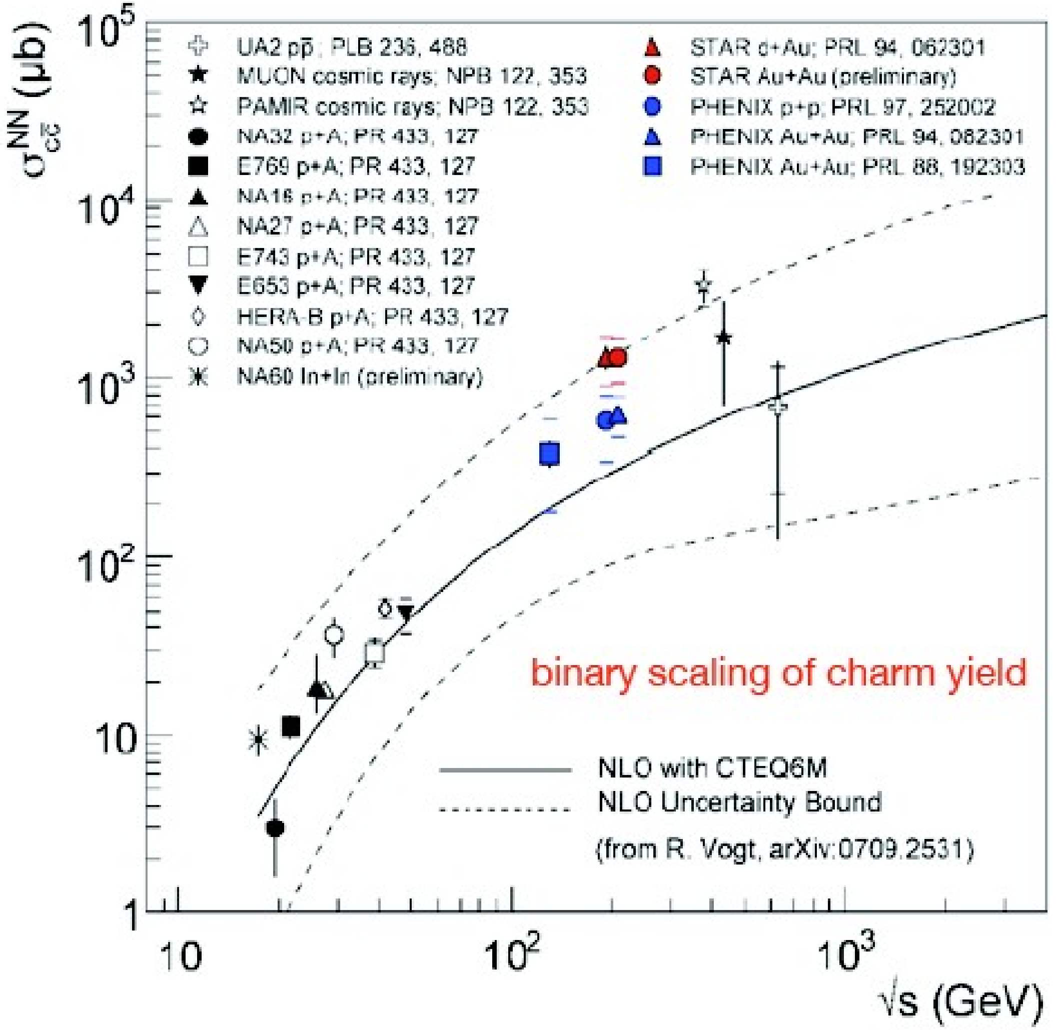
$$\sigma^{gg\to c\bar{c}} = \frac{\pi\alpha_s^2}{64s}\Bigg[12\left(\tfrac{2}{3}+\tfrac{1}{3}\gamma\right)(1-\gamma)^{1/2}+\tfrac{16}{3}\left((4+2\gamma)\ln\frac{1+(1-\gamma)^{1/2}}{1-(1-\gamma)^{1/2}}-4(1+\gamma)(1-\gamma)^{1/2}\right)$$

$$+6\left(2\gamma\ln\frac{1+(1-\gamma)^{1/2}}{1-(1-\gamma)^{1/2}}-4(1+\gamma)(1-\gamma)^{1/2}\right)-\tfrac{2}{3}2\gamma(1-\gamma)\ln\frac{1+(1-\gamma)^{1/2}}{1-(1-\gamma)^{1/2}}\Bigg]$$

with $\gamma \equiv 4m^2/s \leqslant 1$.

this result plus NLO/NNLO/FONLL corrections are currently the basis of all open charm calculations (see, e.g., the calculations by Cacciari et al., discussed below.

heavy quark production in pp collisions situation before LHC turned on



Measurement of open charm cross section in pp collisions at the LHC

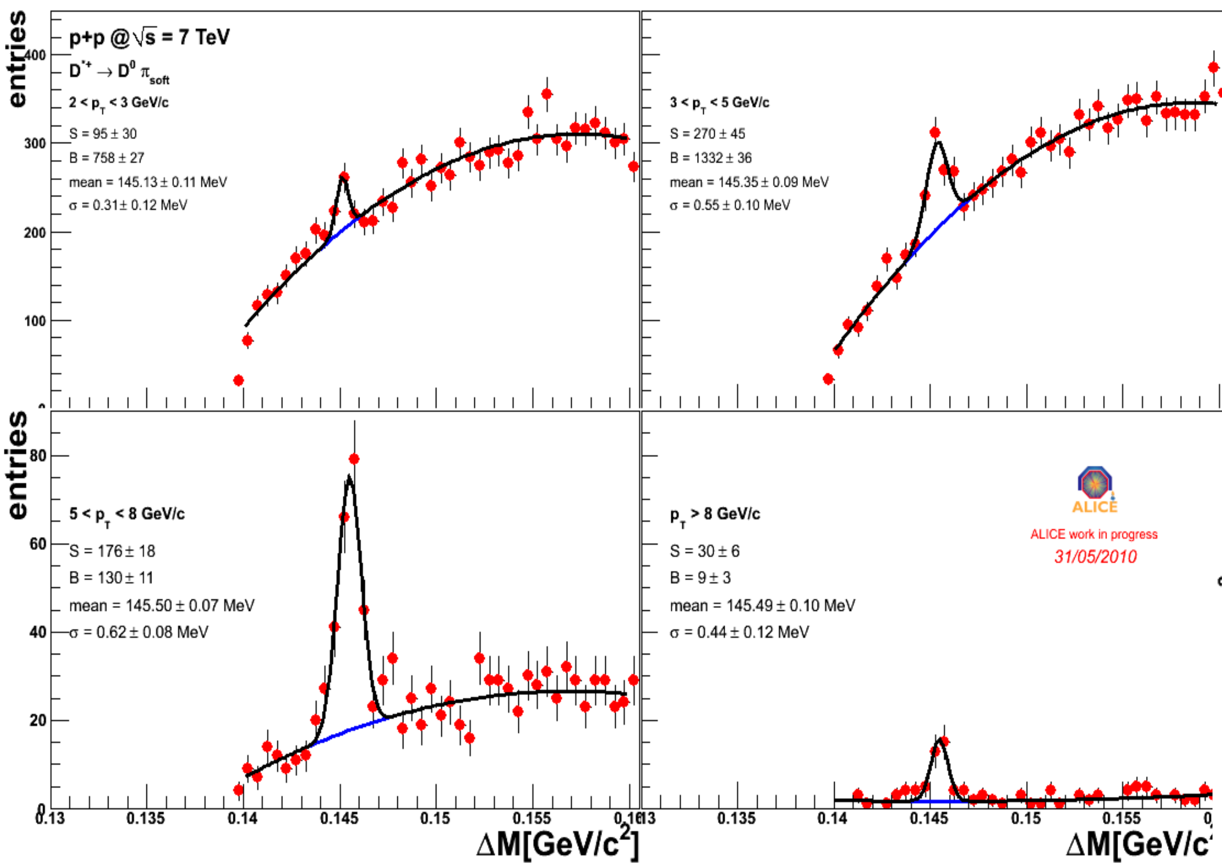
all LHC experiments contribute

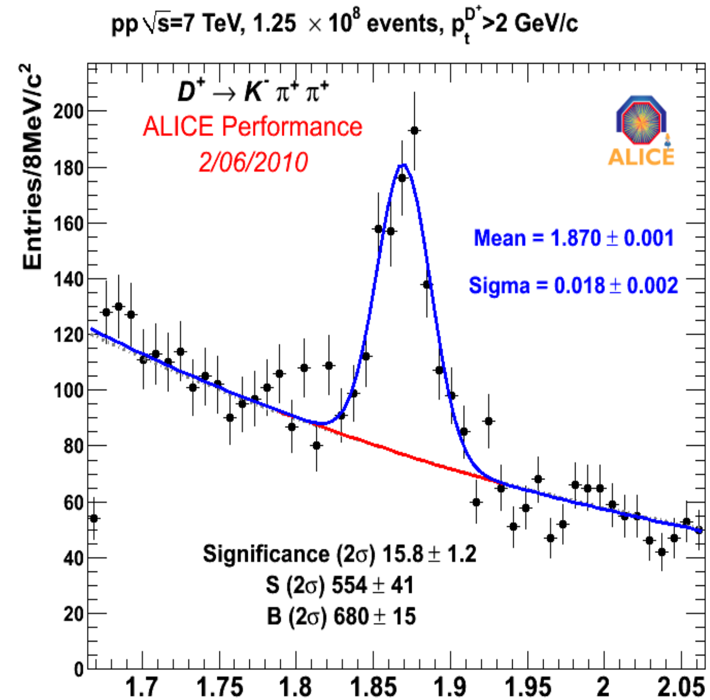
ALICE at pt > 2 GeV/c and 0 < y < 4
ATLAS and CMS at pt > 6 GeV/c 0 < y < 2.5
LHCb at pt > 2 GeV/c and 2.5 < y < 4

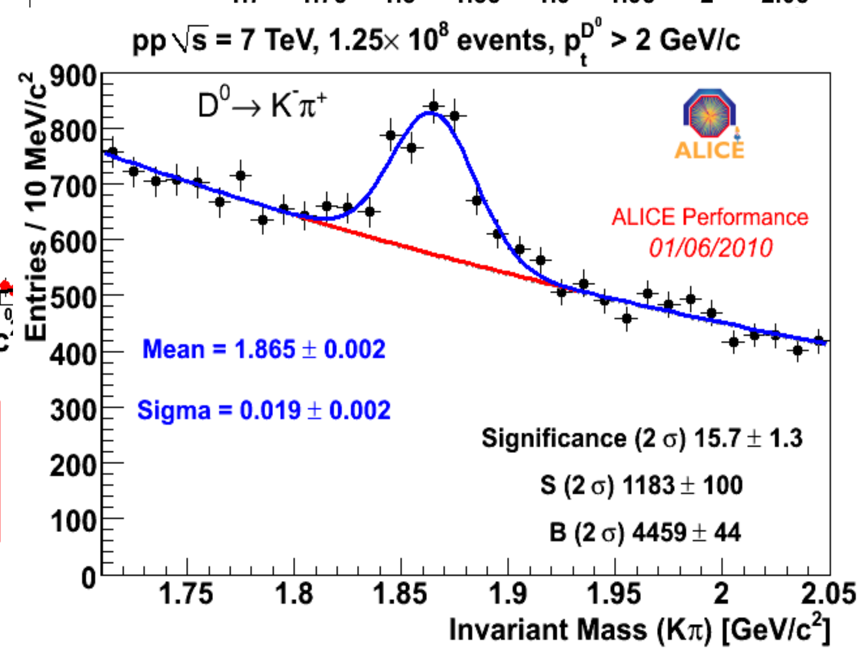
all detectors employ sophisticated Si vertex detectors

D^0, D^+ and D^{0*} in 7 TeV pp data

1.25 10^8 events

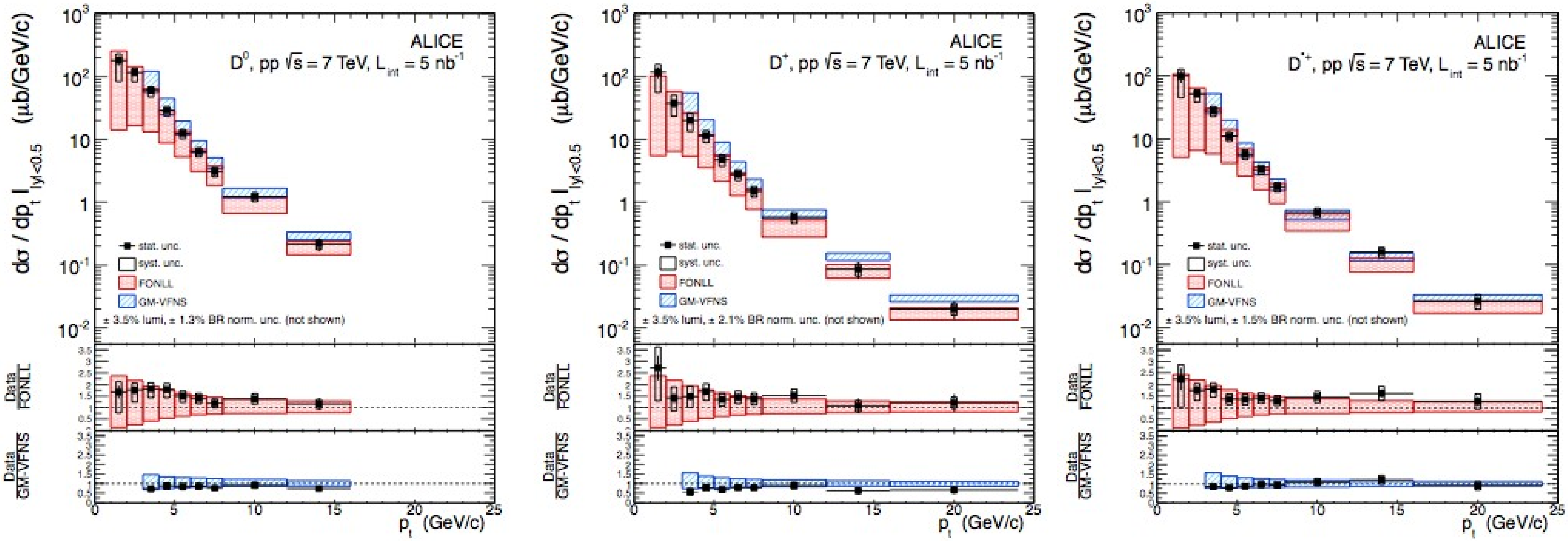






for 10^9 events, expect to measure open charm for $p_t = 0.5 – 15$ GeV/c

measurements agree well with state of the art pQCD calculations



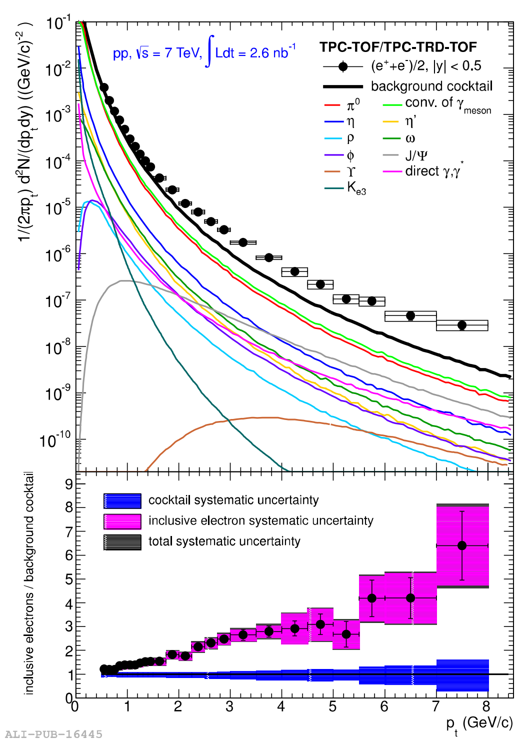
JHEP1201(2012)128

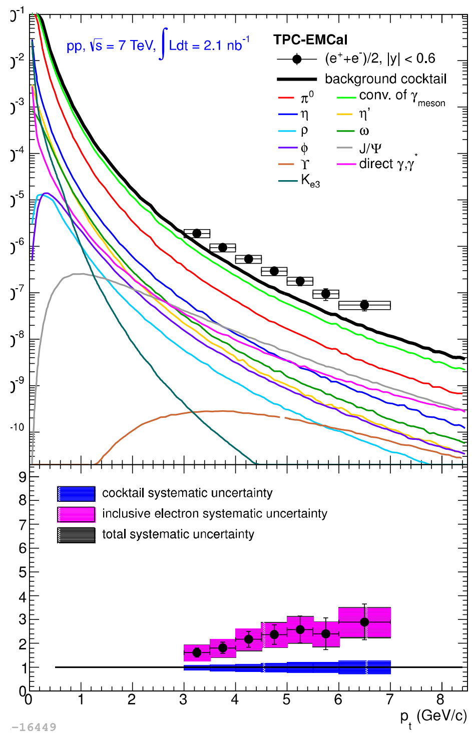
FONLL: Cacciari et al., arXiv:1205.6344
GM-VFNS: Kniehl et al., arXiv:1202.0439

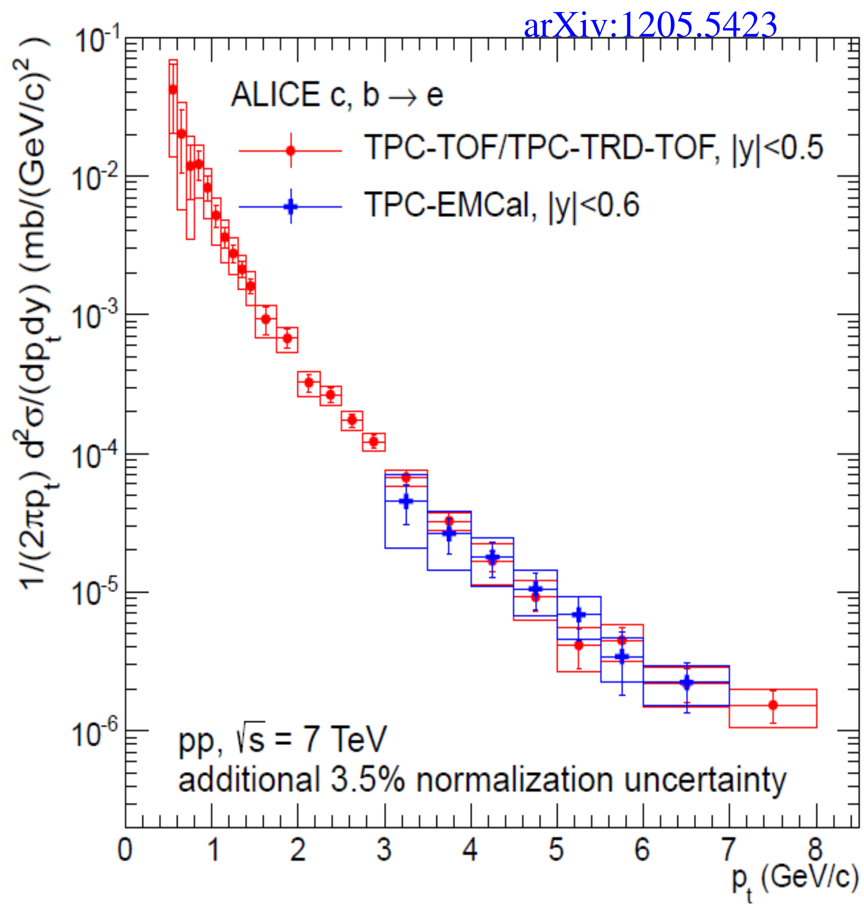
data are compared to perturbative QCD calculations
reasonable agreement
- at upper end of FONLL and at lower end of GM-VFNS
measure 80% of charm cross section for |y| < 0.5

charm and beauty via semi-leptonic decays

Inclusive electron spectrum from 2 PID methods: TPC-TOF-TRD and TPC-EMCAL



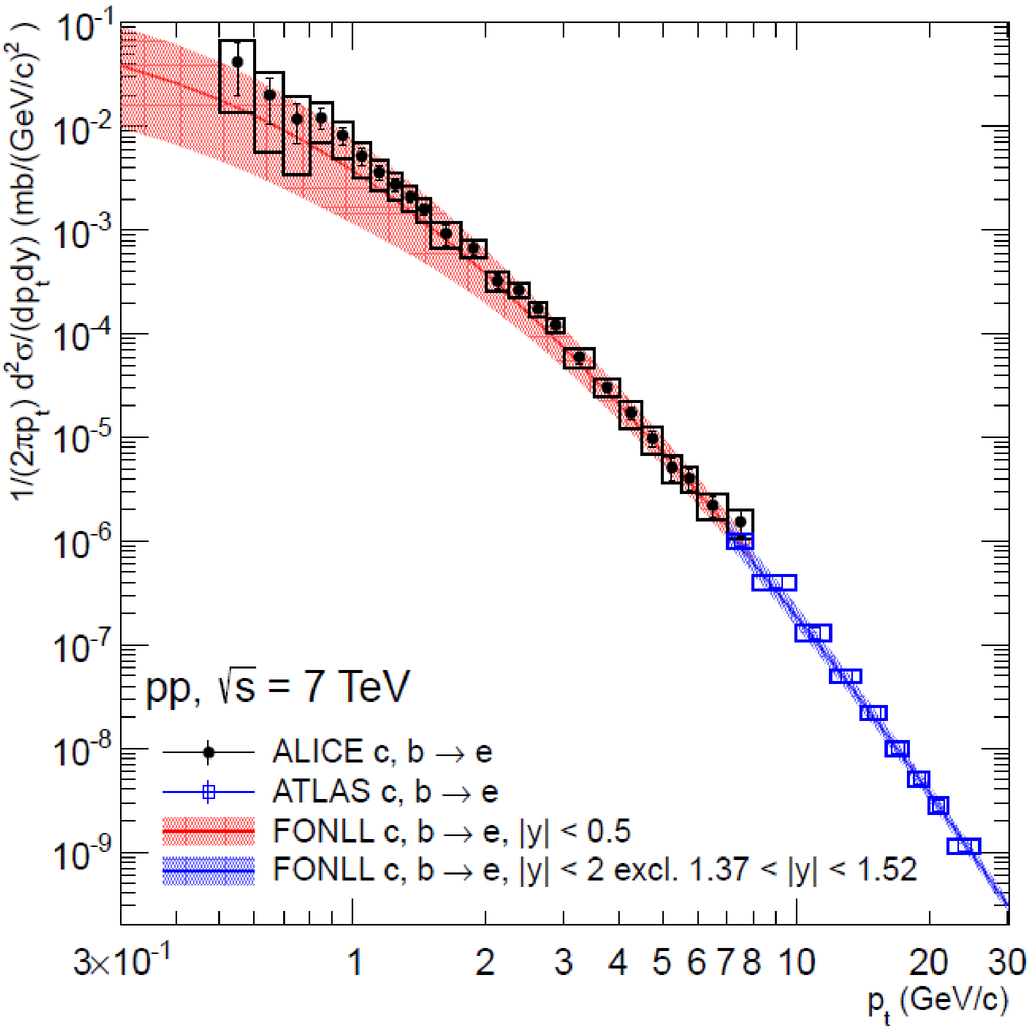




subtract hadronic decay cocktail using measurements where possible (π^0, η, m_t scaling for other mesons, J/ψ), direct γ from pQCD

electrons from c and b decays

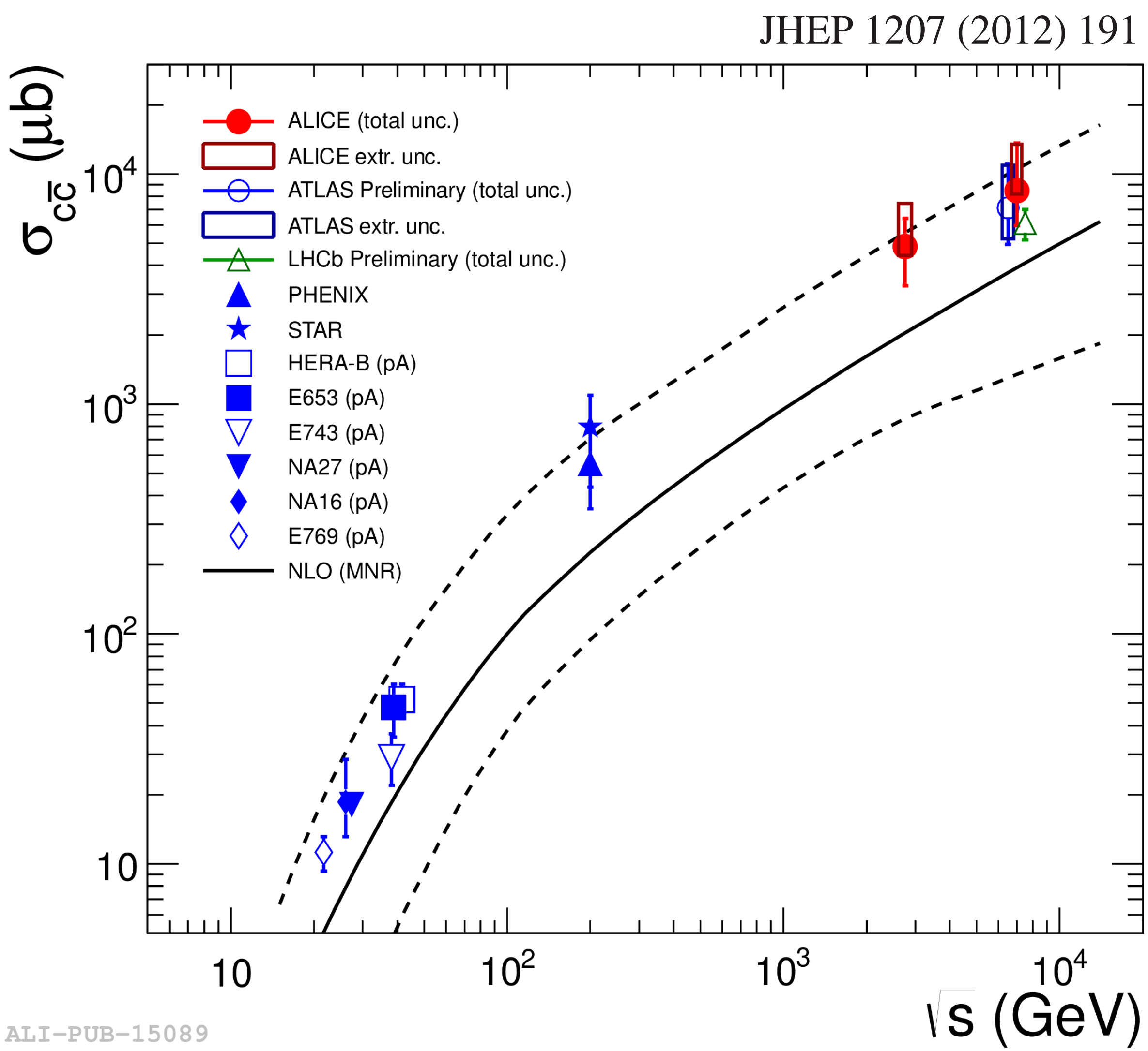
charm and beauty electrons compared to pQCD



- ALICE data complimentary to ATLAS measurement at higher pt (somewhat larger y-interval)
- good agreement with pQCD
- at upper end of FONLL range for p_t < 3 GeV/c where charm dominates

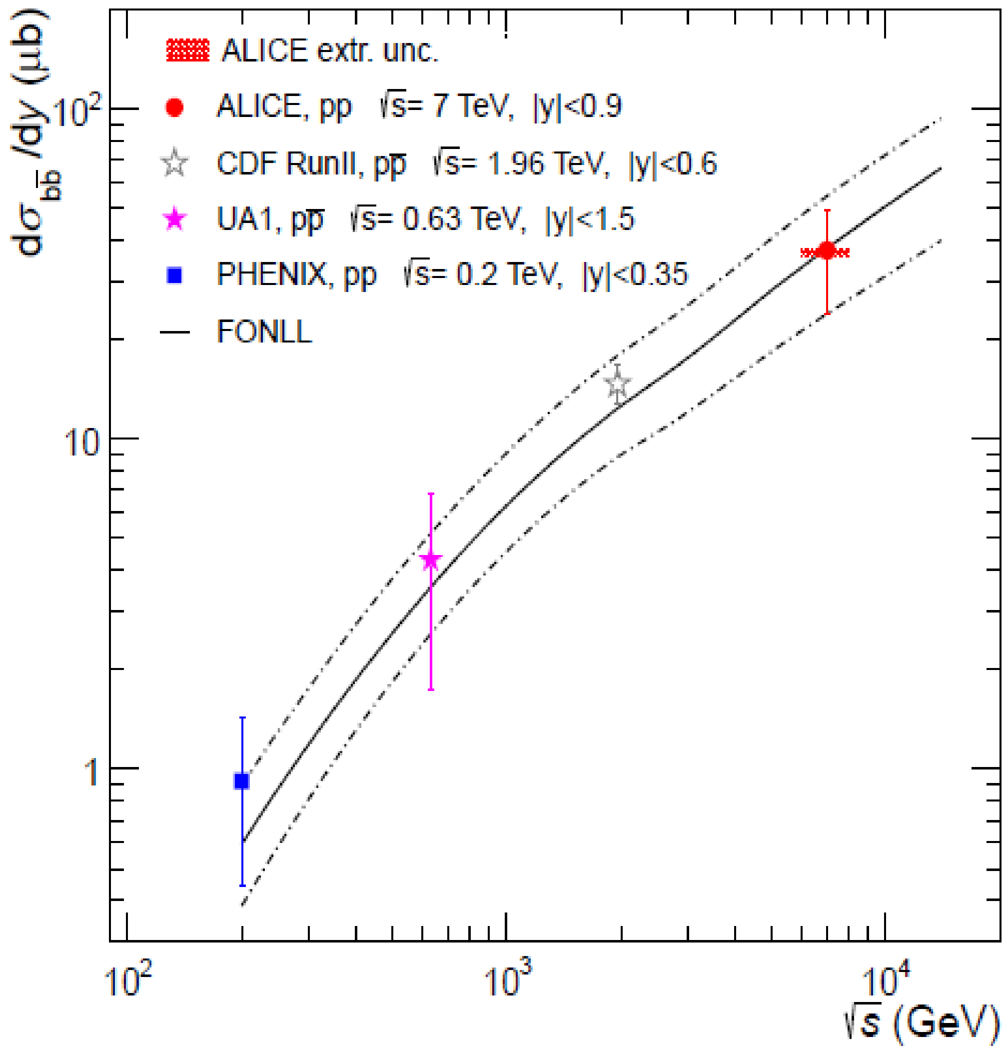
arXiv:1205.5423
ATLAS: PLB707 (2012) 438
FONLL: Cacciari et al., arXiv:1205.6344

a first try at the total ccbar cross section in pp collisions



- good agreement between ALICE, ATLAS and LHCb
- large syst. error due to extrapolation to low pt, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL

beauty cross section in pp and ppbar collisions



Open heavy flavor production and the QGP

1. m_q >> Lambda_QCD   charm quark production is independent of the medium formed in the collision (see above)

2. propagation of heavy quarks in the medium can be used to diagnose it

energy loss – thermalization – hydrodynamic flow

interaction with the hot/dense QCD medium

- energy loss
  - dependence on medium density and volume
  - color charge dependent (Casimir factor) → $\Delta E_{gluon} > \Delta E_{quark}$
  - parton mass dependent (dead cone effect: Dokshitzer & Kharzeev, PLB 519(2001)199) → $\Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- thermalization
  - dependence on transport properties of the medium

Formation time of quarkonia

heavy quark velocity in charmonium rest frame:

v = 0.55 for J/ψ see, e.g. G.T. Bodwin et al., hep-ph/0611002

minimum formation time: t = radius/v = 0.45 fm

see also: Huefner, Ivanov, Kopeliovich, and Tarasov,
Phys. Rev. D62 (2000) 094022; J.P. Blaizot and J.Y. Ollitrault,
Phys. Rev. D39 (1989) 232
formation time of order 1 fm

formation time is not short compared to plasma formation time
especially at high energy

formation time of open charm hadrons not well understood

presumably similar to charmonia

separation of time scales for initial hard process and late hadronization/hadron formation is called „factorization“

rigorously proven for deep inelastic scattering

charm conservation equation

no medium effect

$$\sigma_{c\bar{c}} = 1/2\ [\sigma_{D^+} + \sigma_{D^-} + \sigma_{D^0} + \sigma_{\bar{D}^0} + \sigma_{\Lambda_c} + \sigma_{\bar{\Lambda}_c} \cdots]$$

medium effects on charmed hadrons affect redistribution of charm, but not overall cross section

it is not consistent with the charm conservation equation to reduce all charmed hadron masses in the medium for an enhanced cross section

gluon radiation by a quark traversing a medium

from Dokshitzer & Kharzeev, Phys.Lett. B519 (2001) 199-206
we get for the probability of radiation of a gluon with energy ω
by a quark with mass M and energy E

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

$$k_\perp^2 \simeq \sqrt{\hat{q}\,\omega} \qquad \hat{q} \equiv \rho \int \frac{d\sigma}{dq^2}\, q^2 \, dq^2 \qquad C_F = \frac{N_c^2 - 1}{2N_c}$$

here the density of scatterers in the medium is encoded in q^

'dead cone' effect for charm quarks

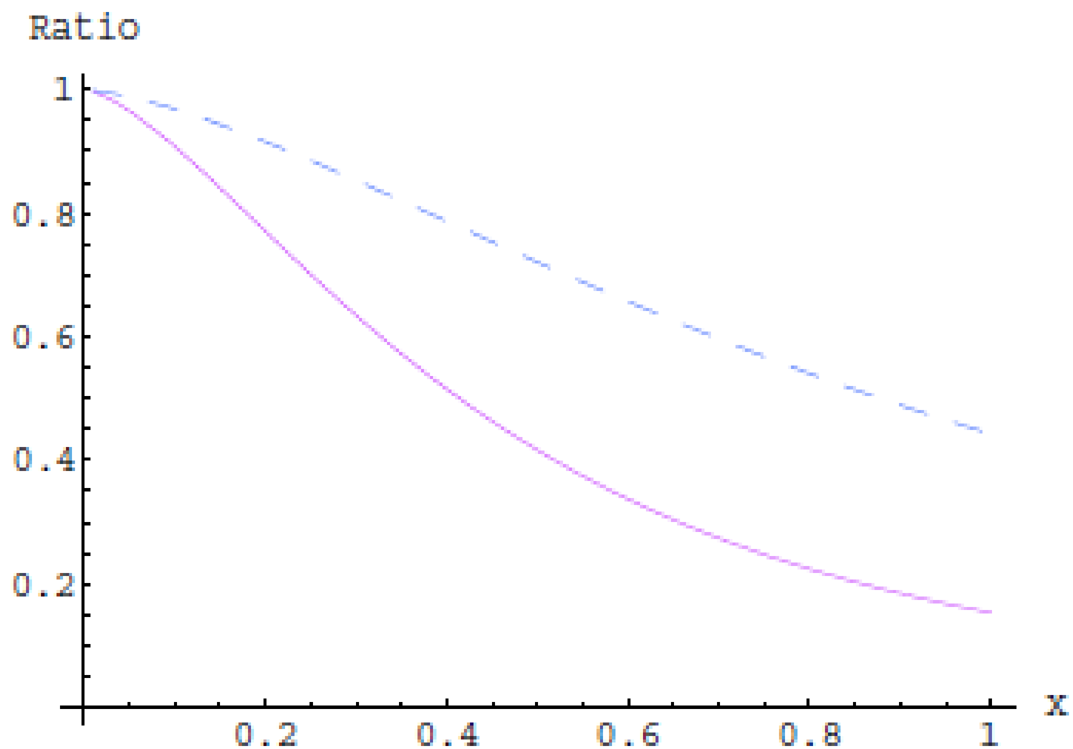


Figure 1: Ratio of gluon emission spectra off charm and light quarks for quark momenta $p_\perp = 10\,\mathrm{GeV}$ (solid line) and $p_\perp = 100\,\mathrm{GeV}$ (dashed); $x = \omega/p_\perp$.

now open charm and open beauty in AA collisions

how to quantify the effect of the medium?

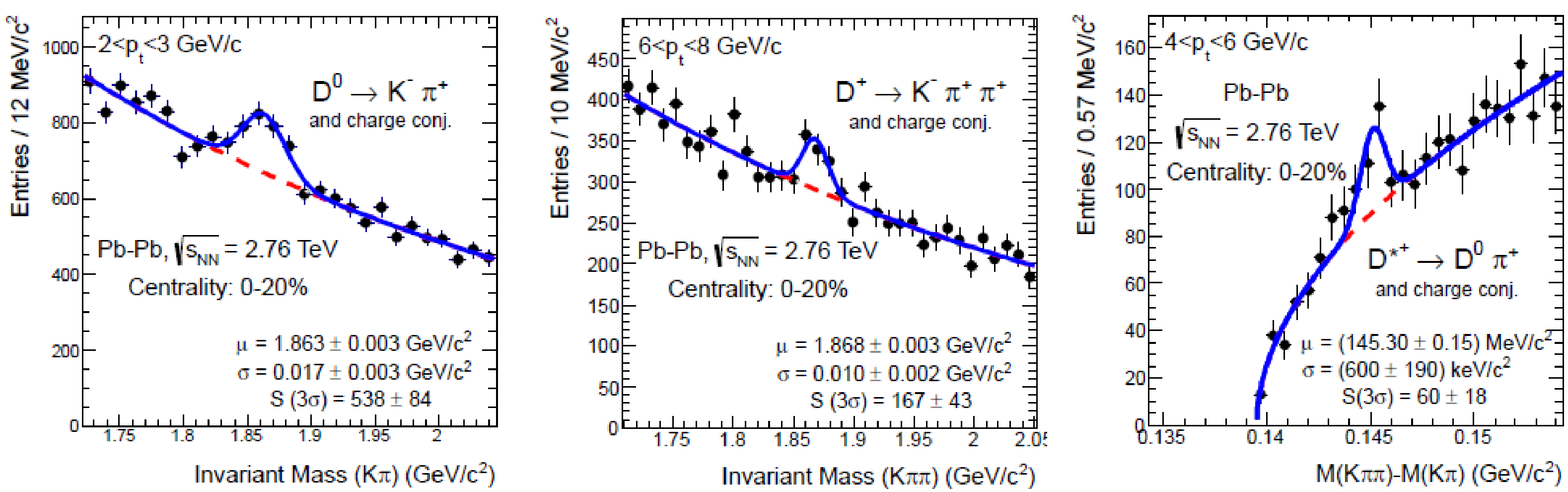
R_{AA}=yield(AA)/(N_{coll} yield(pp))

R_AA = medium/vacuum

R_AA = 1 if no dense medium is formed
or
if one looks at electro-weak probes

D meson signals in Pb Pb collisions

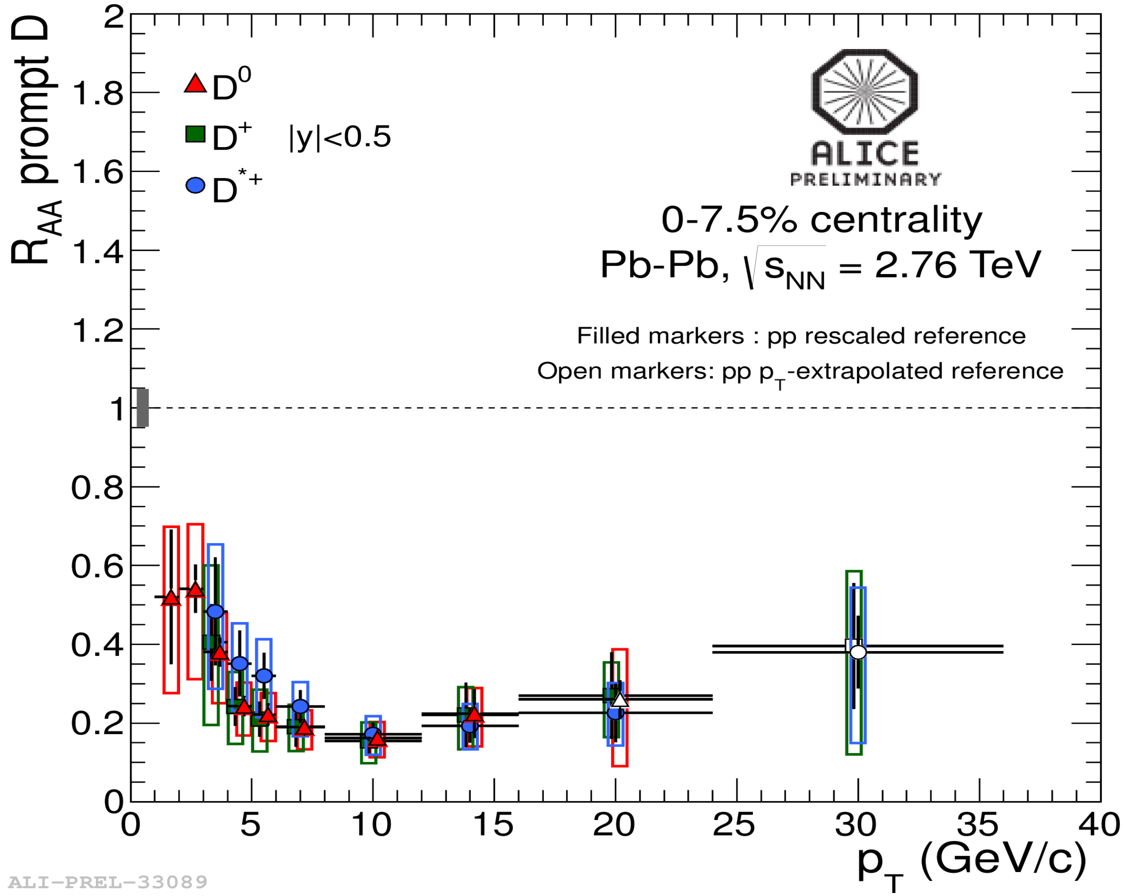
measurement:
reconstruction of hadronic decays of D-mesons (ALICE)
semi-leptonic decays into electrons (ATLAS, ALICE)
“ into muons (ATLAS, ALICE)



data: ALICE arXiv:1203.2160

suppression of charm at LHC energy

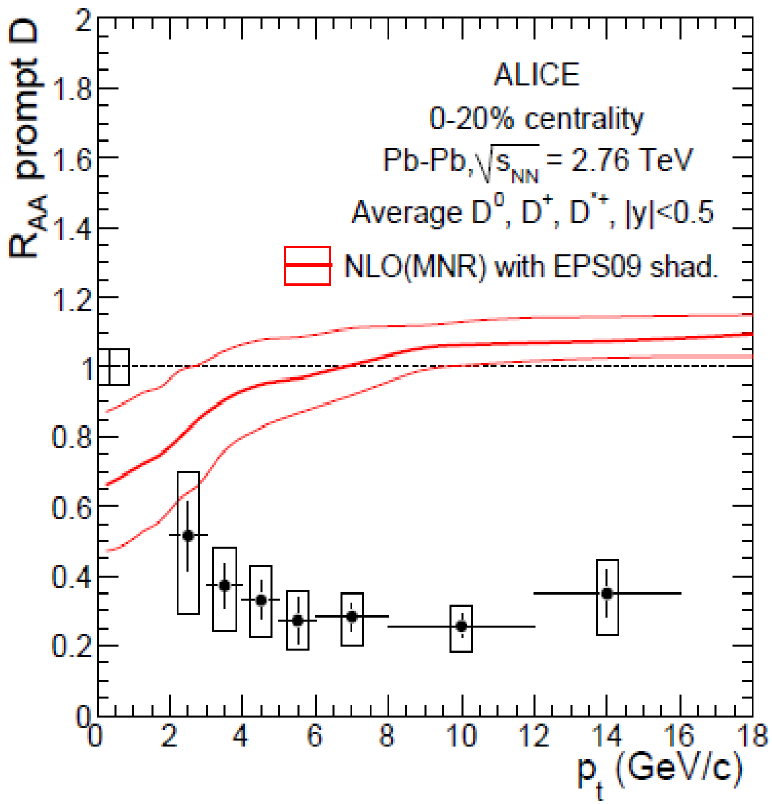
pp reference at 2.76 TeV: measured 7 TeV spectrum scaled with FONLL
cross checked with 2.76 TeV measurement (large uncertainty due to limited luminosity)

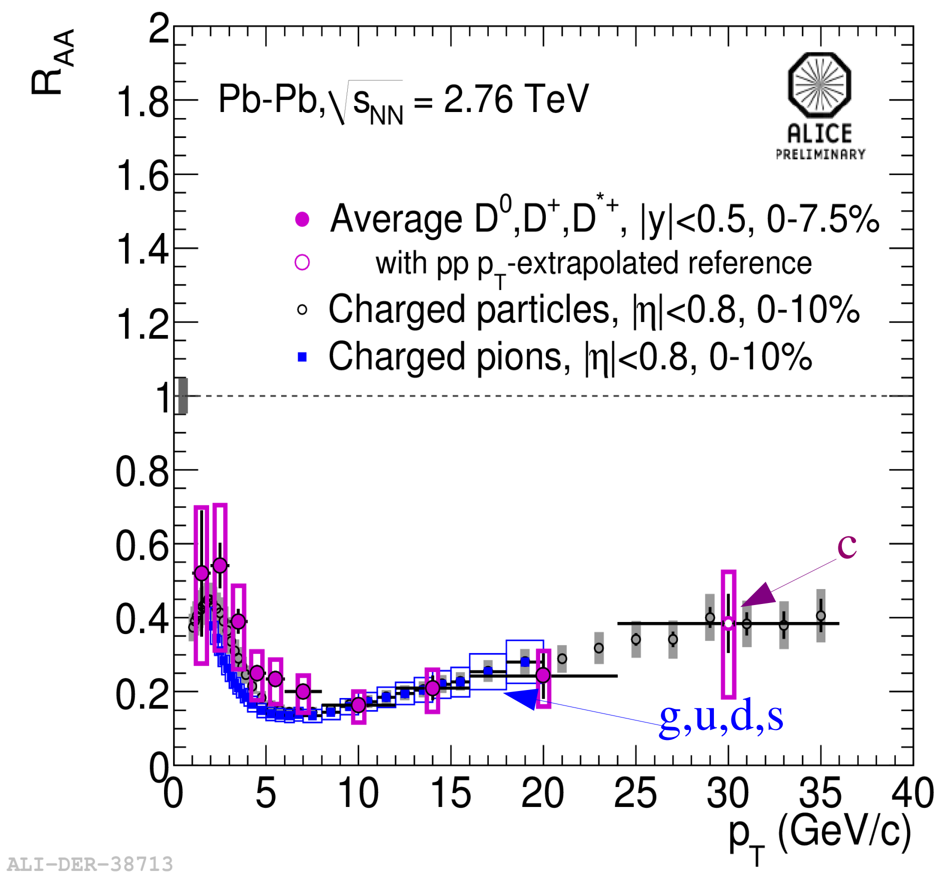


energy loss for all species of D-mesons within errors equal - not trivial
energy loss of central collisions very significant - suppr. factor 5 for 5-15 GeV/c

suppression of charm at LHC energ

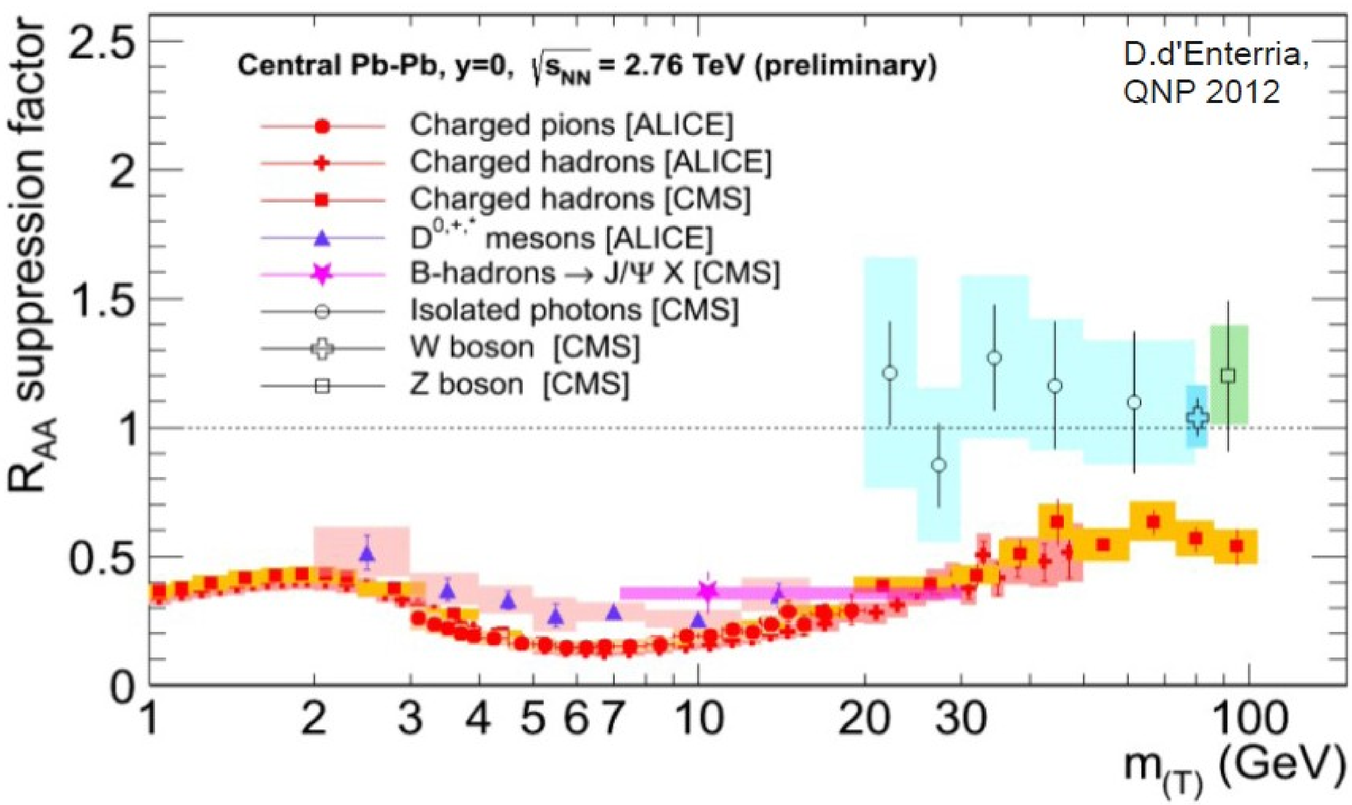
comparison to EPS09 shadowing:
suppression not an initial state effect
will be measured directly in pPb collisions





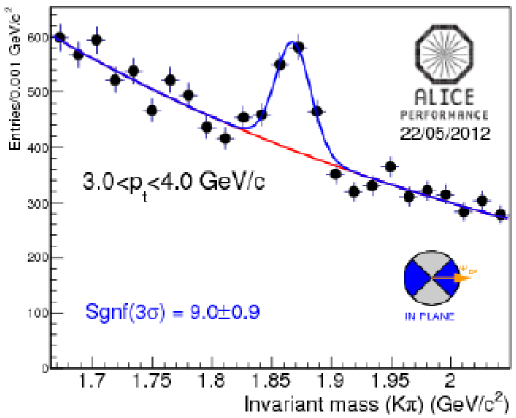
energy loss of charm quarks only slightly less than that for light quark → thermalization

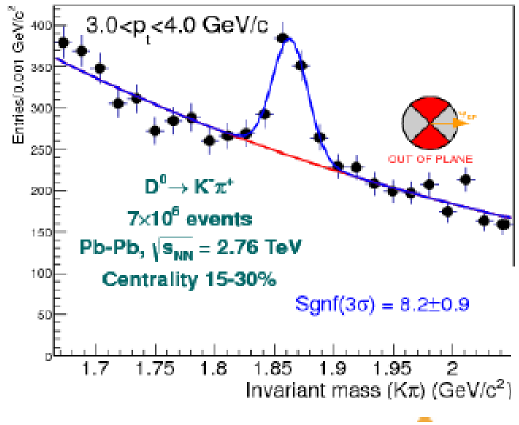
Suppression only for Strongly Interacting Hard Probes



photons, Z and W scale with number of binary collisions in PbPb – not affected by medium
→ demonstrates that charged particle suppression is medium effect: energy loss in QGP

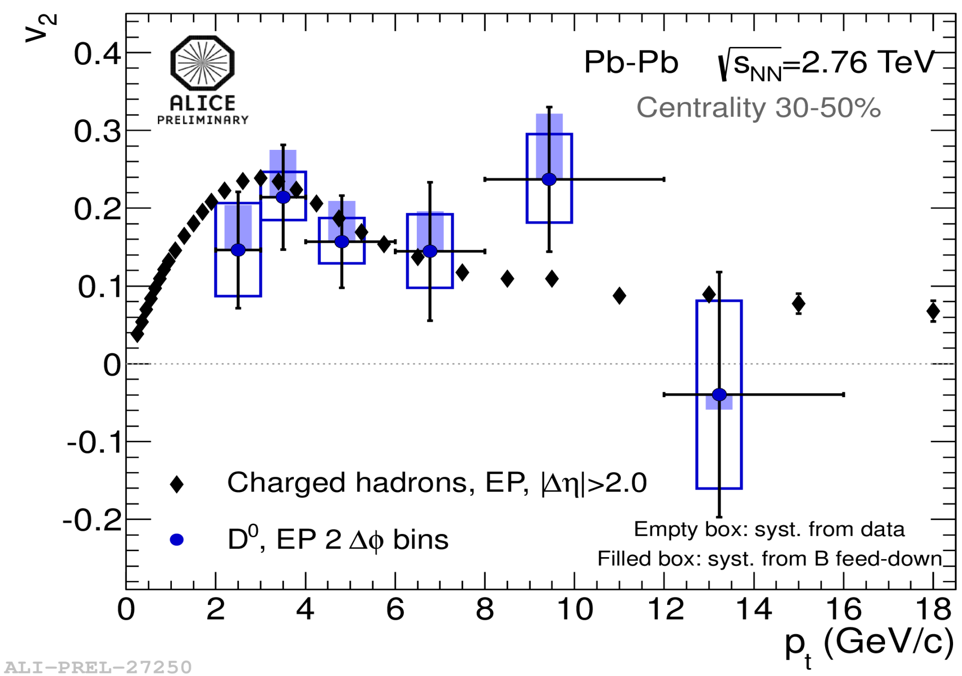
charm Quarks also Exhibit Elliptic Flow





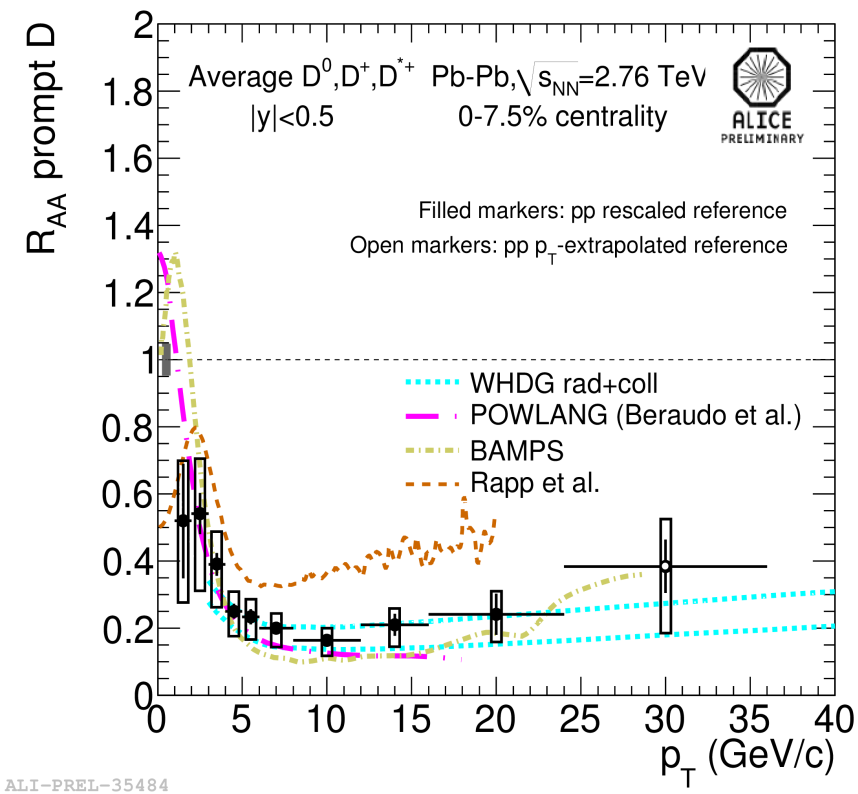
$$v_2 = \frac{\pi}{4}\frac{N_{IN}-N_{OUT}}{N_{IN}+N_{OUT}}$$

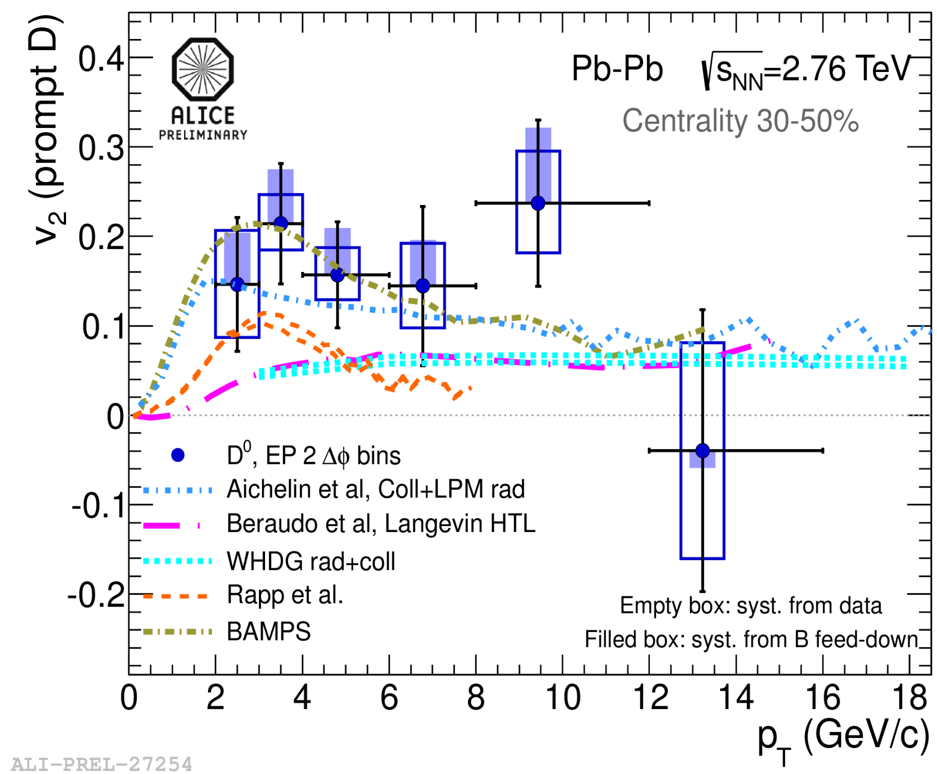
2 centrality classes
event plane from TPC
corrected for B-feed down (FONLL)



non-zero elliptic flow for 3 σ effect for D^0 2-6 GeV/c
within errors charmed hadron v_2 equal to that of all charged hadrons

model description of energy loss and flow of D-mesons



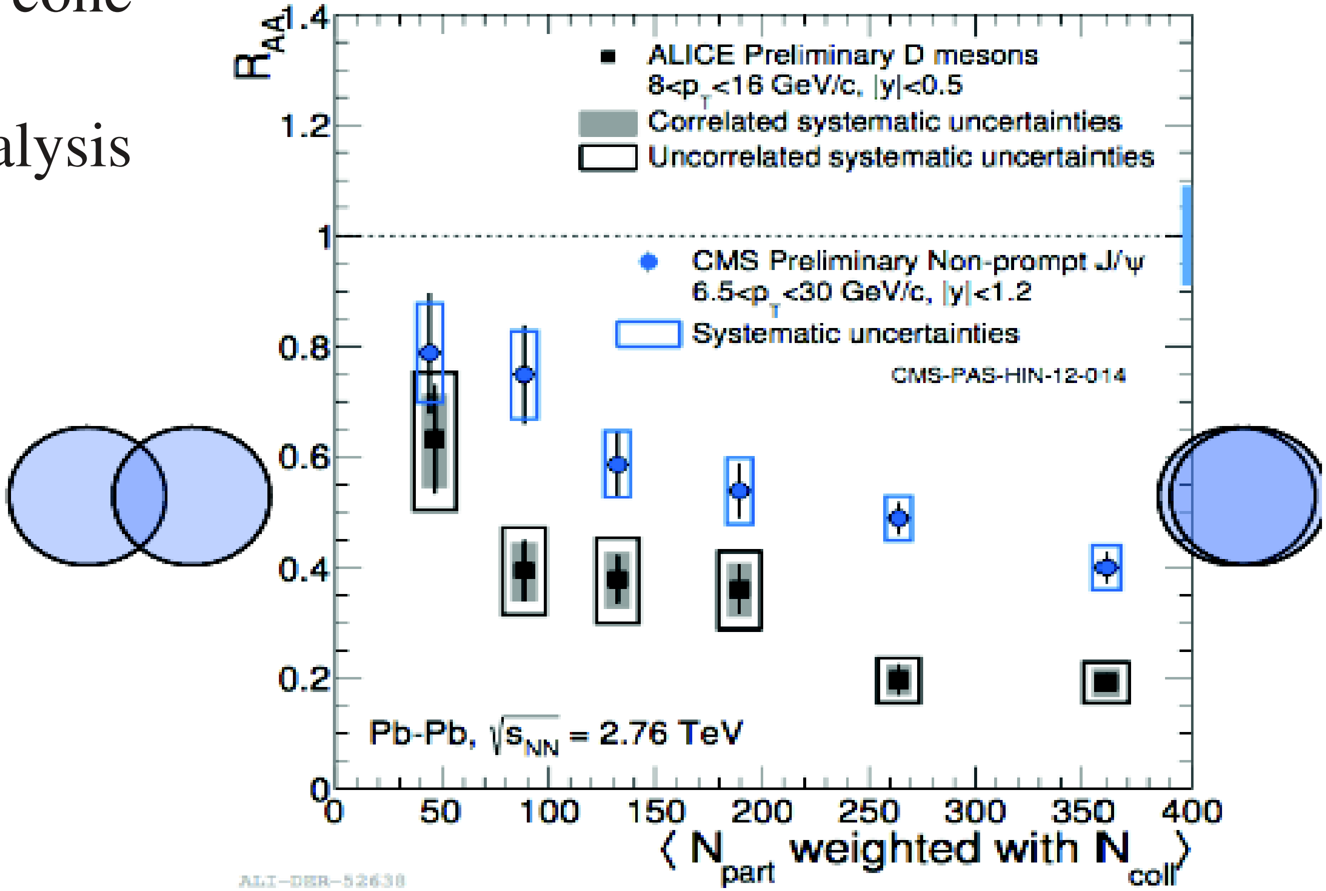


both are determined by transport properties of the medium (QGP)
simultaneous description still a challenge for some models

comparison of suppression for b-quarks and c-quarks

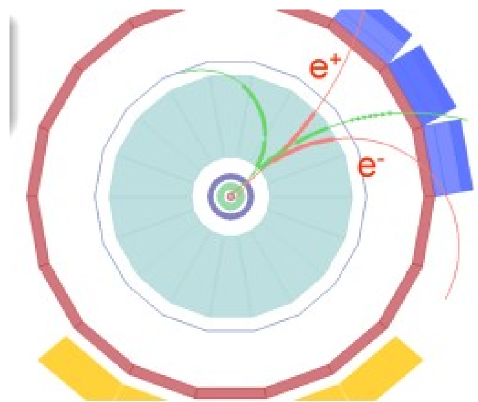
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

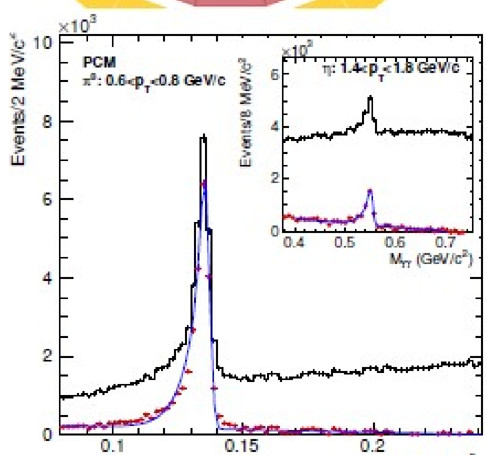
is this the dead-cone effect? need quantitative analysis



Measurement of the fireball temperature via photon emission

Photons and neutral mesons measured via the conversion method in the ALICE TPC, see, .e.g, M. Wilde (ALICE coll.) QM2012

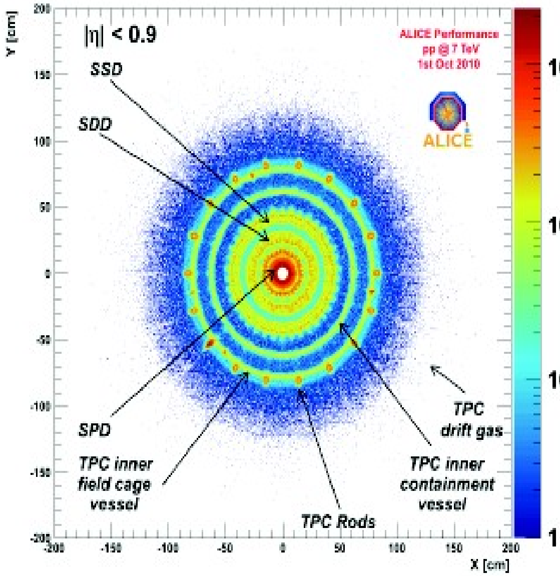


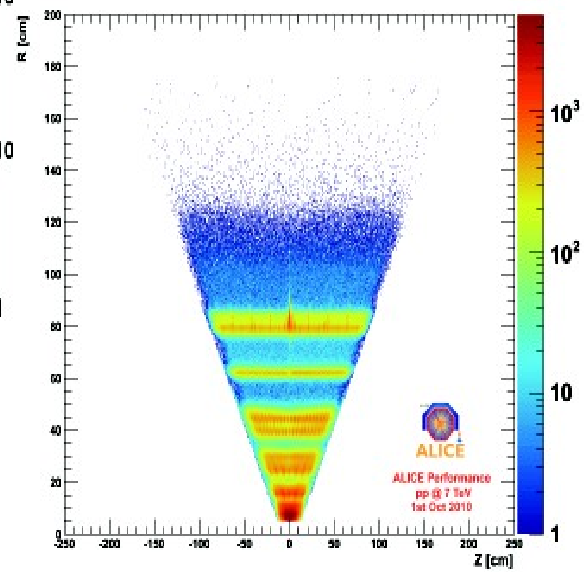


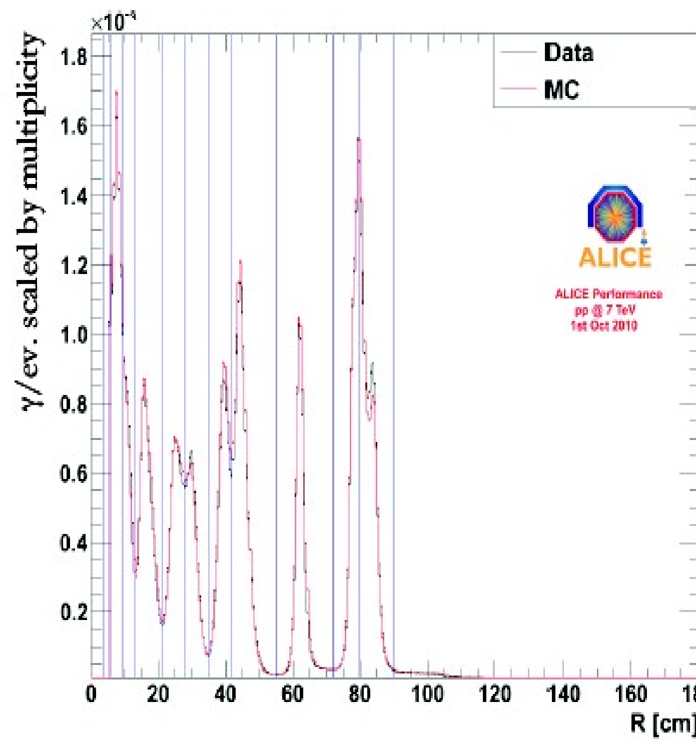
arXiv:1205.5724v1

γ-ray tomography of ALICE

Conversions provide a γ-ray tomography of ALICE.
Very useful tool to check the material budget.
For ALICE this is very well known (down to ± 6% accuracy).







Resolution:
Better than 3 cm in R, 1.5 cm in Z and 2.5 mrad in Φ.

method

- Direct Photon Signal: $\gamma_{direct} = \gamma_{inc} - \gamma_{decay} = (1 - \frac{\gamma_{decay}}{\gamma_{inc}}) \cdot \gamma_{inc}$

- Double Ratio: $\frac{\gamma_{inc}}{\pi^0} / \frac{\gamma_{decay}}{\pi^0_{param}} \approx \frac{\gamma_{inc}}{\gamma_{decay}}$ if > 1 direct photon signal

  $\rightarrow$ cancellation of uncertainties

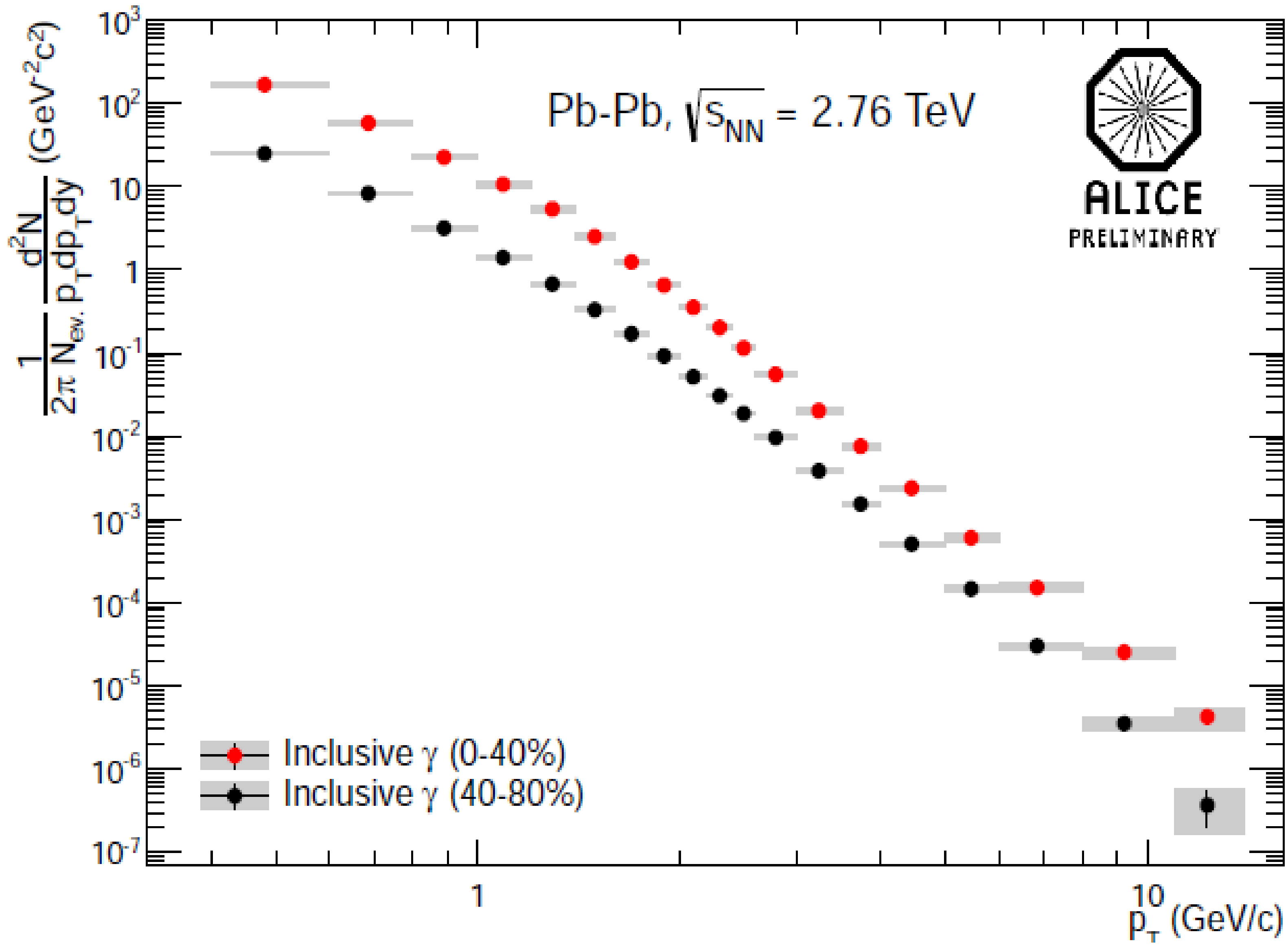
- Numerator: Inclusive γ spectrum per π^0
- Denominator: Sum of all decay photons per π^0

  Decay photons are obtained by a cocktail calculation

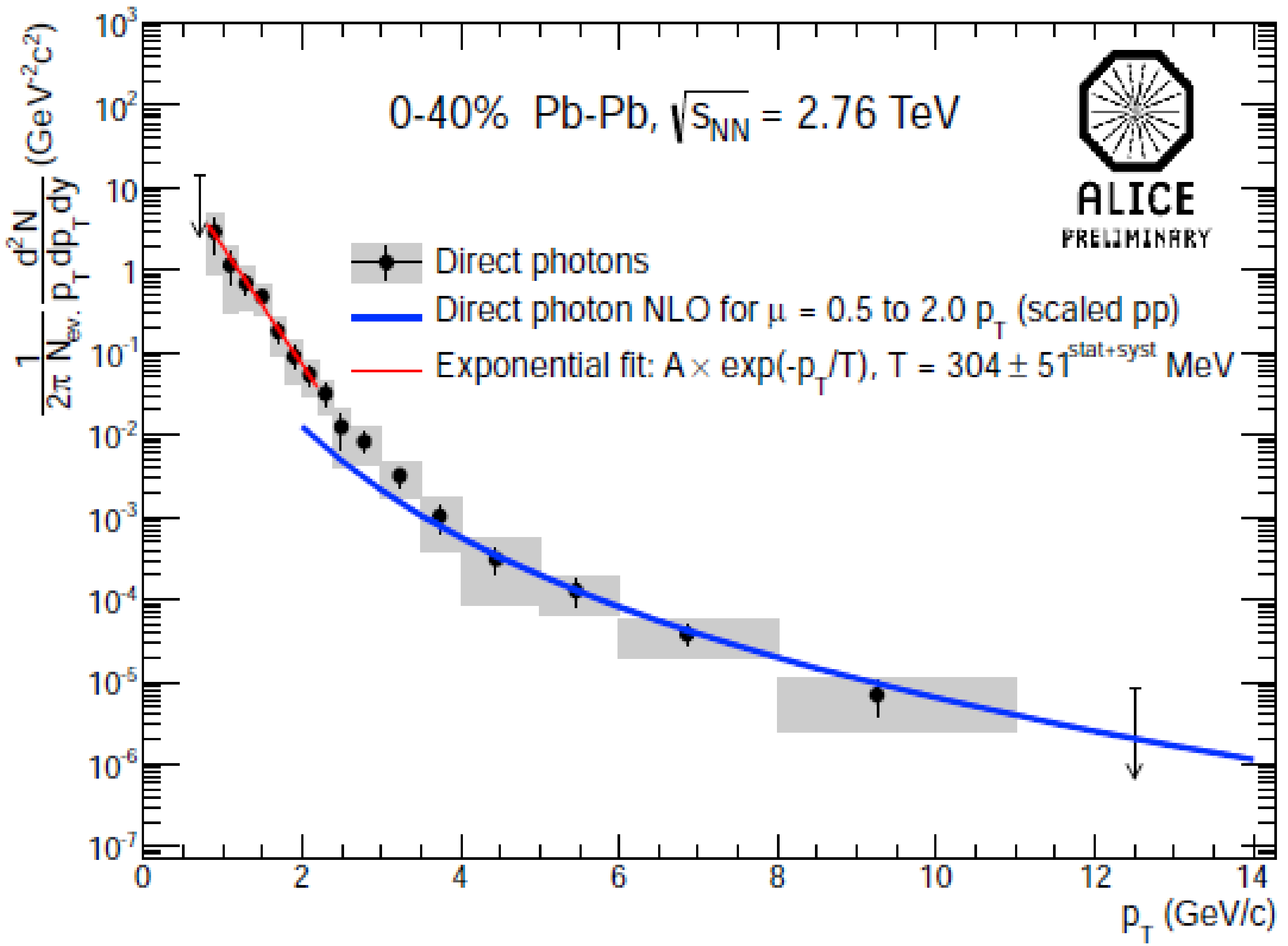
- Photons and π^0s are measured via conversion method

  $\pi^0 \rightarrow \gamma + \gamma$, $\gamma \rightarrow e^+e^-$

Inclusive photon measurement in Pb-Pb collisions

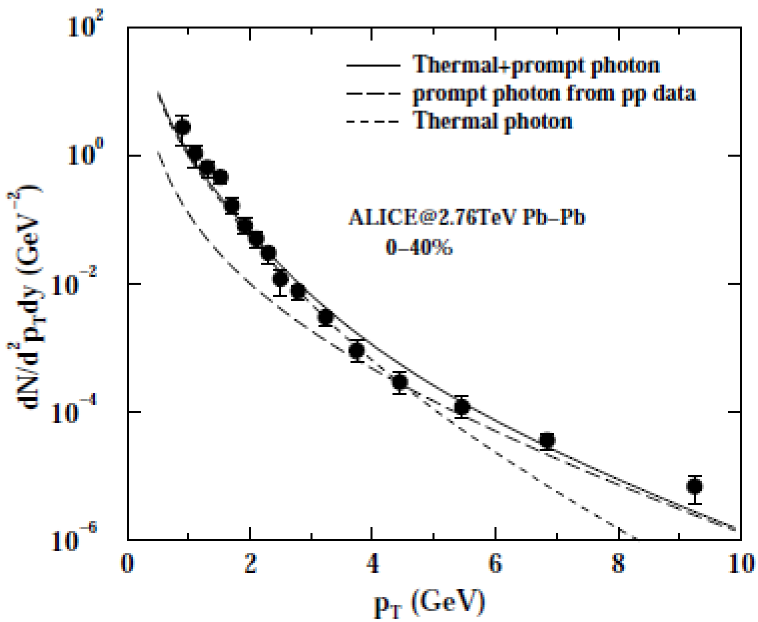


Final result



average T = 304 +/- 51 MeV highest ever measured temperature

Interpretation in terms of fireball parameters



Sukanya Mitra, Payal Mohanty, Sabyasachi Ghosh, Sourav Sarkar, Jan-e Alam. Mar 4, 2013.

e-Print: arXiv:1303.0675

TABLE I: The values of various parameters - thermalization time (τ_i), initial temperature (T_i) and hadronic multiplicity dN/dy - used in the present calculations.

$\sqrt{s_{NN}}$	2.76 TeV
centrality	0-40%
$\frac{dN}{dy}$	1212
τ_i	0.1 fm
T_i	553 MeV
T_c	175 MeV
T_f	100 MeV
EoS	Lattice QCD

note: T_i = 3.2 x T_c

Thermal photons also exhibit flow

most hydro-models produce little flow for thermal photons

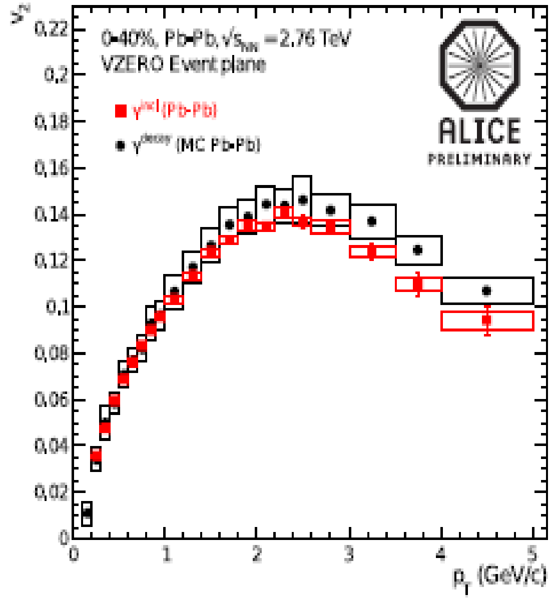


Figure 4: Inclusive photon $v_2^{\gamma,\mathrm{inc}}$ and decay photon $v_2^{\gamma,\mathrm{bg}}$ in 0–40 % Pb-Pb collisions.

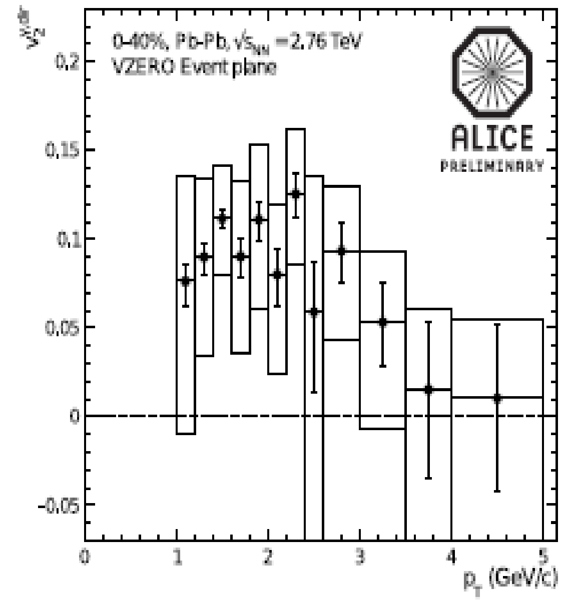


Figure 5: Direct-photon $v_2^{\gamma,\mathrm{dir}}$ in 0–40 % Pb-Pb collisions.

see the 2 papers for a (conflicting) analysis

O. Linnyk, V.P. Konchakovski, W. Cassing, E.L. Bratkovskaya. Apr 25, 2013.

e-Print: arXiv:1304.7030

Ralf Rapp (Texas A-M, Cyclotron Inst. & Texas A-M). Oct 2011. 30 pp.

Published in Acta Phys.Polon. B42 (2011) 2823-2852

Phenix results on thermal photons and Rapp's interpretation
arXiv:1110.4345

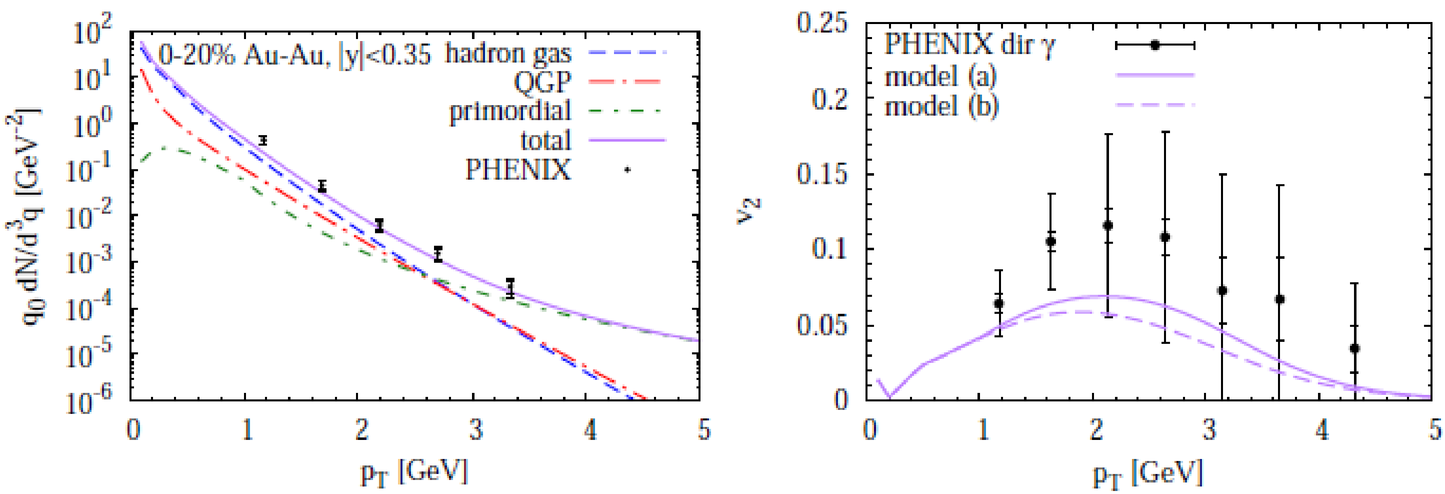


Fig. 14. Transverse-momentum spectra (left panel) and elliptic flow (right panel) of direct photons in 0-20% central Au-Au($\sqrt{s}$=200 AGeV) collisions at RHIC, compared to PHENIX data [49, 54]. The curves are calculations [55] with a realistic fireball evolution employing thermal QGP and hadronic rates which are "dual" around T_c, corresponding to Fig. 9.

In this approach, large initial temperatures are not required, and the spectral shapes are due to very strong radial flow.
Precision measurements are needed to separate the different approaches.