First HI at LHC: Inclusive production, correlations and heavy flavours

Hadron Collider Physics Symposium

Evian, 16-20 November 2009

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Alessandria, Italy

Outline

- Heavy Ion capabilities of LHC experiments
- Inclusive production
  - Charged particle multiplicity, $dN/d\eta$
  - p_T spectra (stable particles, resonances), ratios, …
- Correlations
  - Radial, directed (v_1) and elliptic (v_2) flow
  - HBT correlations, fluctuations
- Heavy flavours
  - Open charm, open beauty

Photons, jets and quarkonia covered in next presentation by Olga Kodolova

ALICE

- Experiment designed for Heavy Ion collisions
  - Only dedicated experiment at LHC, must be comprehensive and be able to cover all relevant observables
  - Very robust tracking
    - high-granularity detectors with many space points per track, very low material budget (~10% X_0 for r < 2.5 m and $|\eta|<0.9$) and moderate magnetic field (0.5 T)
  - PID over a very large p_T range
  - Hadrons (barrel), leptons (barrel + muon spectrometer) and photons
  - Very low p_T cutoff (~0.1 GeV/c)
  - Excellent vertexing (6 layers of Si) for charm & beauty

ATLAS

- Primarily designed for p+p interactions
- Excellent capabilities for Pb+Pb interactions:
  - Tracking of charged particles (including muons) in $-2.5 < \eta < 2.5$ (2 T solenoid): 3 layers of pixels, SCT, TRT
  - Total transverse energy
  - *Photons, jets and quarkonia*

CMS

- Primarily designed for p+p interactions
- Excellent capabilities for Pb+Pb interactions:
  - Tracking of charged particles (4 T solenoid) with Inner detector ($|\eta|<2.5$): Si pixels (3 layers in barrel, 2 in endcaps) + Si strips
  - Calorimetry: ECAL ($|\eta|<3$), HCAL ($|\eta|<3$), HF ($3<|\eta|<5$)
  - CASTOR ($5<|\eta|<6.7$)
  - ZDC ($|\eta|>8$)
  - Muons in $|\eta| < 2.4$
  - *Photons, jets and quarkonia*

Inclusive production

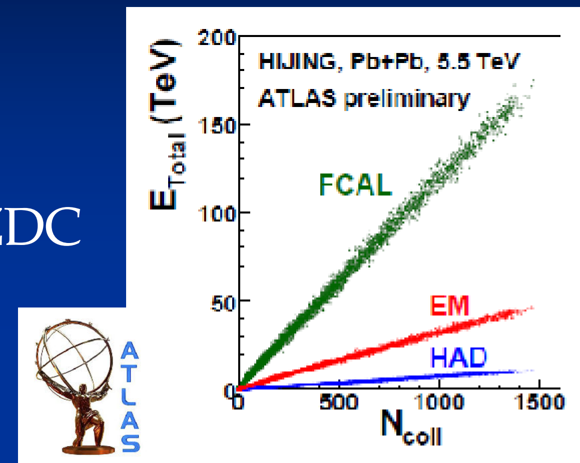
Centrality determination

Goal: subdivide events in centrality classes closely related to b, Npart, Ncoll

ATLAS: total transverse energy (E_T) + LUCID* + ZDC
* LUminosity Cerenkov Integrating Detector

CMS: E_T in forward calorimeters ($3<\eta<6.7$) + neutron ZDC

ALICE: zero degree energy E_{ZDC} + E_{ZEM}



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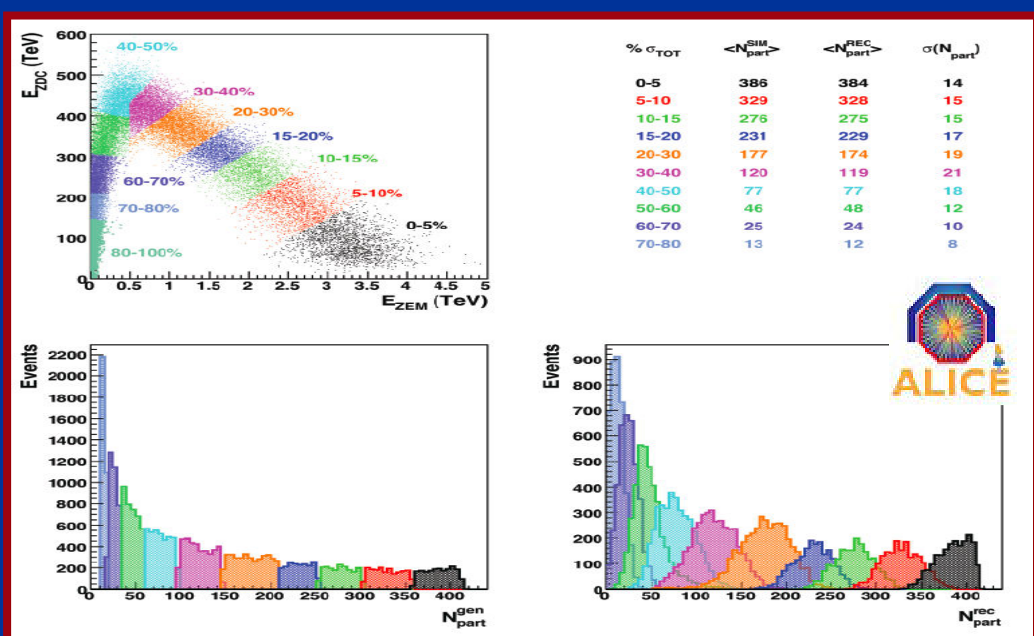

% σ_{TOT}	$<N_{part}^{SIM}>$	$<N_{part}^{REC}>$	$\sigma(N_{part})$
0-5	386	384	14
5-10	329	328	15
10-15	276	275	15
15-20	231	229	17
20-30	177	174	19
30-40	120	119	21
40-50	77	77	18
50-60	46	48	12
60-70	25	24	10
70-80	13	12	8

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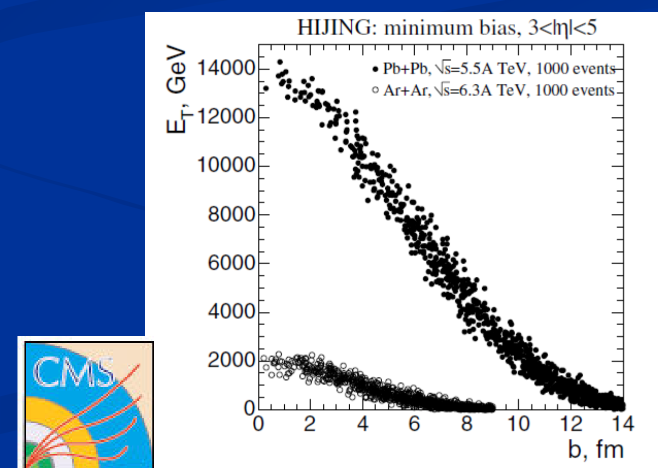

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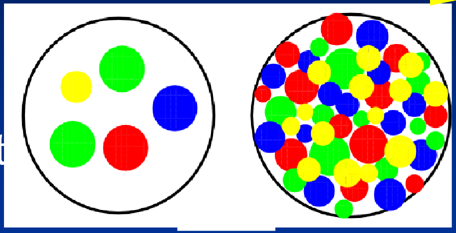
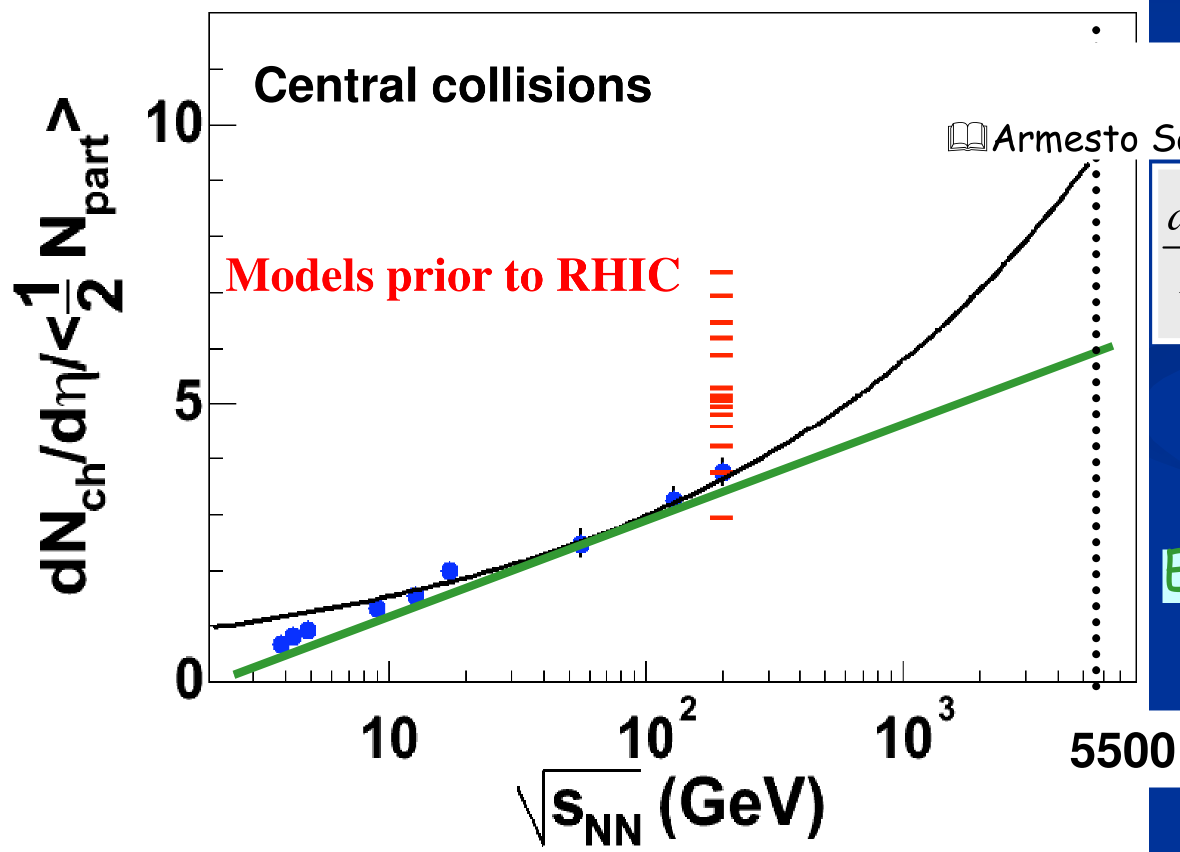
Charged multiplicity at the LHC

- Extrapolation of $dN_{ch}/d\eta_{max}$ vs $\sqrt{s}$:
  - Fit to $dN/d\eta \propto \ln s$ (limiting fragmentation)…
  - … or Saturation model ($dN/d\eta \propto \sqrt{s}^{\lambda}$ with $\lambda=0.288$)?
  - Clearly distinguishable with the first 10k LHC Pb-Pb events

increasing $\sqrt{s}$ – decreasing x





Saturation model

Armesto Salgado Wiedemann, PRL 94 (2005) 022002

$$\left.\frac{dN_{ch}/d\eta}{N_{part}/2}\right|_{\eta=0} \approx 8.2 \Rightarrow \left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0} \approx 1650$$

$$\frac{2}{N_{part}}\left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0} = N_0 \sqrt{s[GeV]}^{\lambda} N_{part}^{\frac{1-\delta}{3\delta}}$$

Extrapolation of $dN/d\eta \propto \ln s$:

$$\left.\frac{dN_{ch}/d\eta}{N_{part}/2}\right|_{\eta=0} \approx 5.5 \Rightarrow \left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0} \approx 1100$$

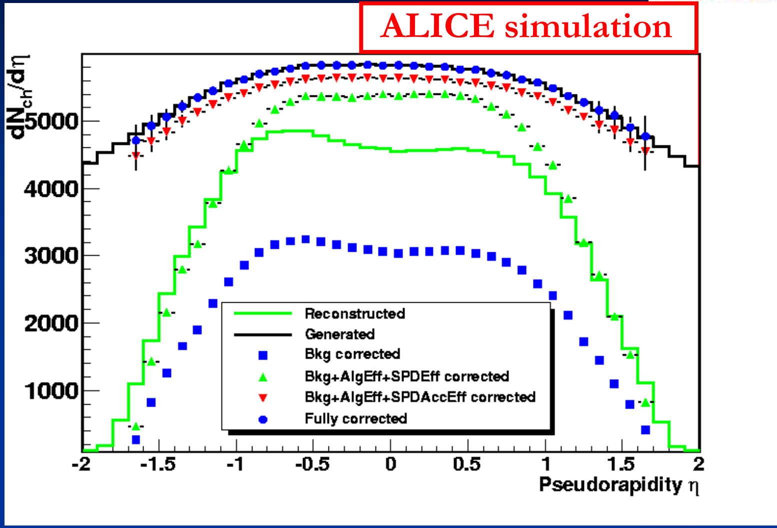
$dN_{ch}/d\eta$

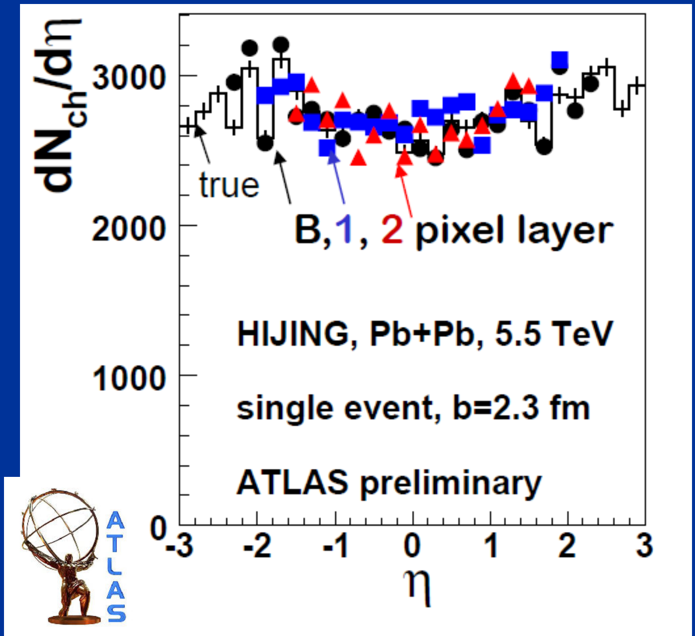
ALICE: tracklets (Si Pixels, layer 1 and 2)
adding Forward Mult. Det.: ~8 units in η

ATLAS: hits in first 3 layers of Si Pixels

CMS: hits in layer 1 of Si Pixels (+ tracklets)

Corrections applied:
- Secondary particles, fakes
- Detector acceptance+efficiency
- Trigger efficiency





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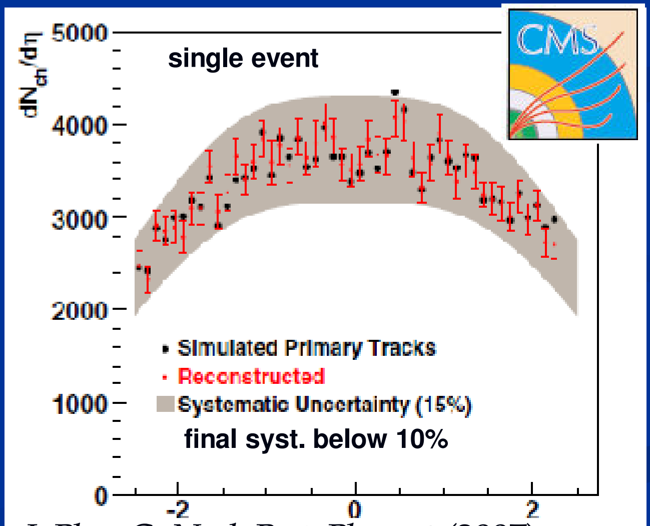

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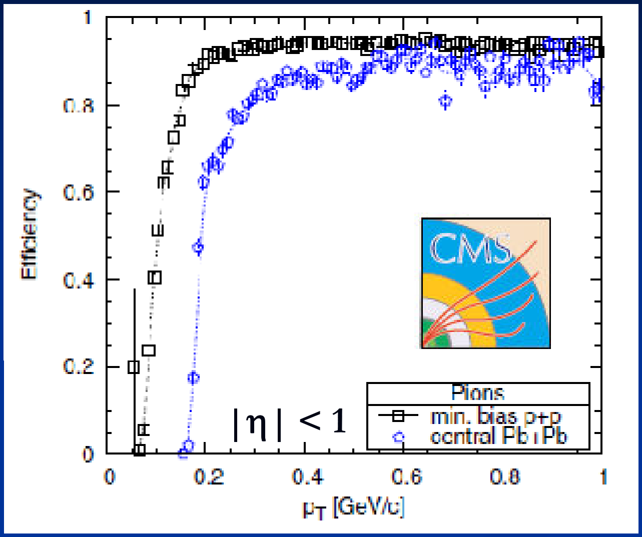
Low p_T tracking

CMS: Si pixels, hit triplet finding algorithm (central Pb-Pb: $p_{T,min}$ set at 175 MeV/c); fake rates below 10% (5%) for $p_T > 0.4$ GeV/c



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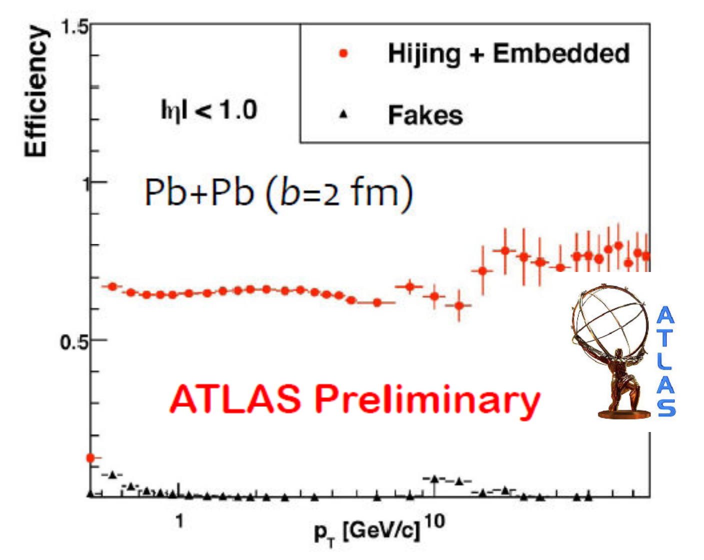
ATLAS: tracks in the inner detector; negligible fake rate above 1 GeV/c



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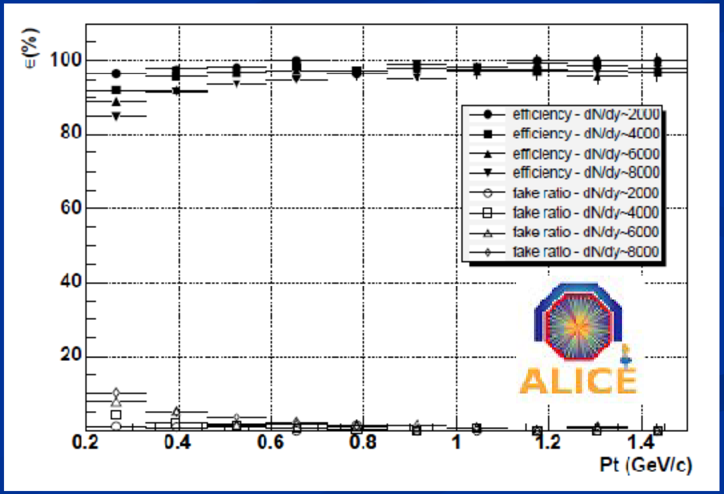
ALICE: algorithmic efficiency for tracks in ITS+TPC; physical efficiency in TPC limited at 90%, can be recovered with ITS standalone tracking

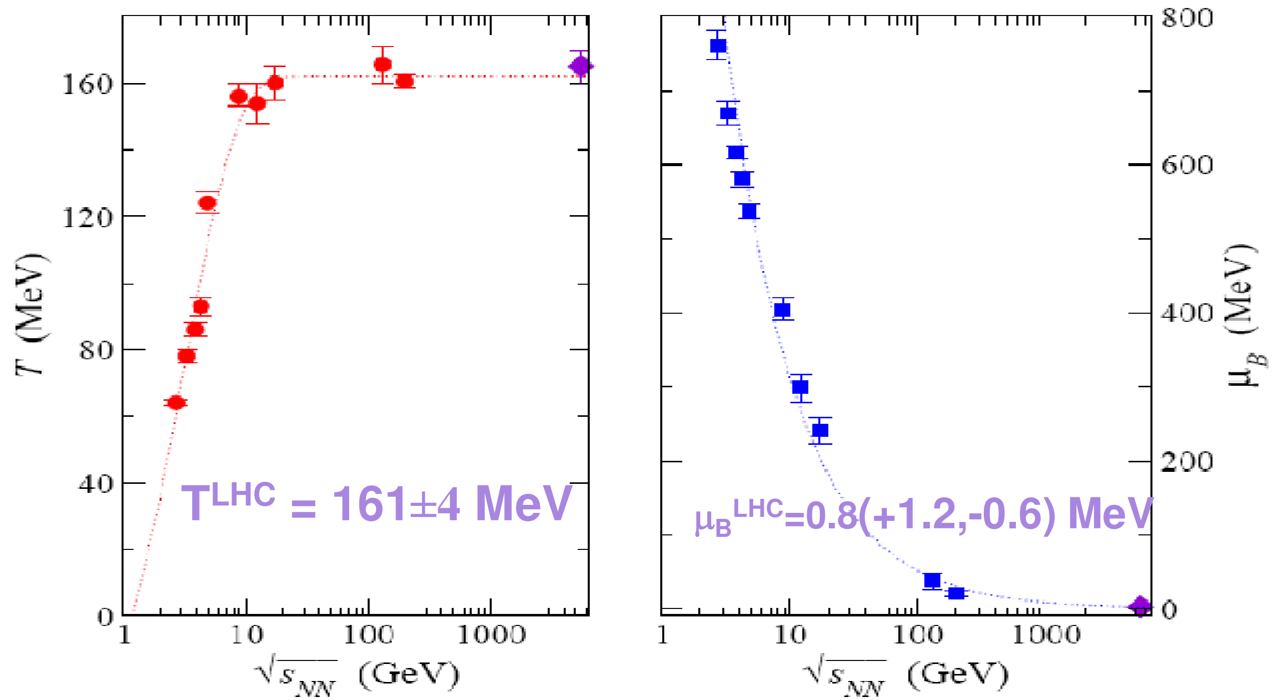


JINST 3 (2008) S08002

Identified particle spectra

Chemical composition

- Statistical model prediction: Temperature T_{ch} increases rapidly at low $\sqrt{s}$, then reaches about 160 MeV at 7-8 GeV and stays constant; chemical potential μ_B decreases continuously with increasing $\sqrt{s}$ *(see e.g. A. Andronic et al., arXiv:0711.0974 [hep-ph])*



Interest for **inclusive particle yields/ratios**, acceptance at low p_T is crucial

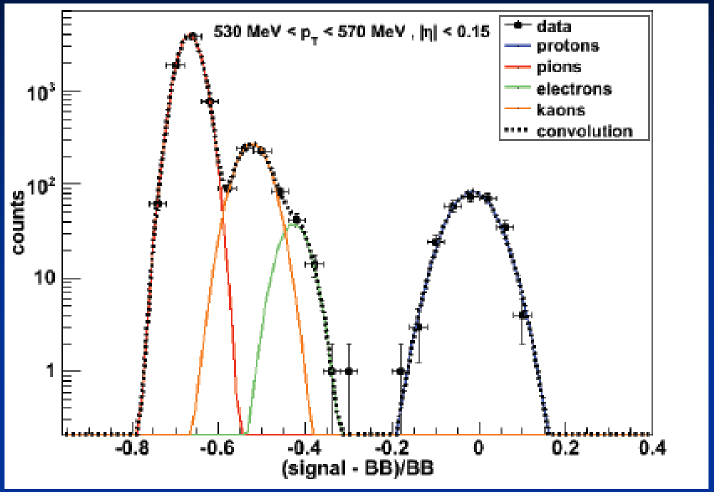
π^-/π^+	K^-/K^+	$\bar{p}/p$	$\bar{\Lambda}/\Lambda$
1.001(0)	0.993(4)	$0.948^{-0.013}_{+0.008}$	$0.997^{-0.011}_{+0.004}$

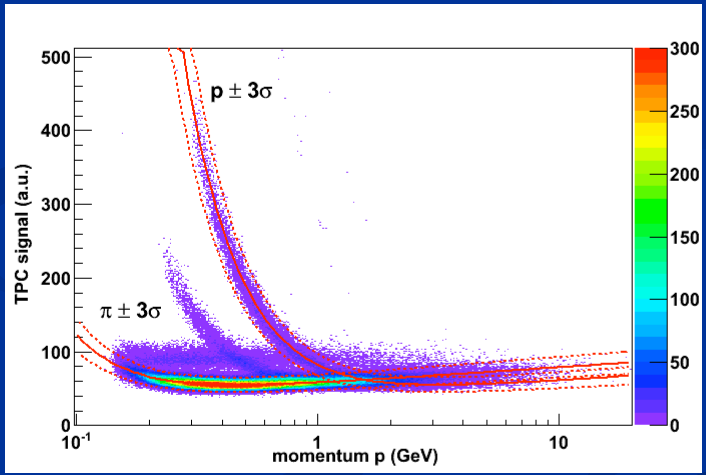
p/π^+	K^+/π^+	K^-/π^-	Λ/π^-
0.074(6)	0.180(0)	0.179(1)	0.040(4)

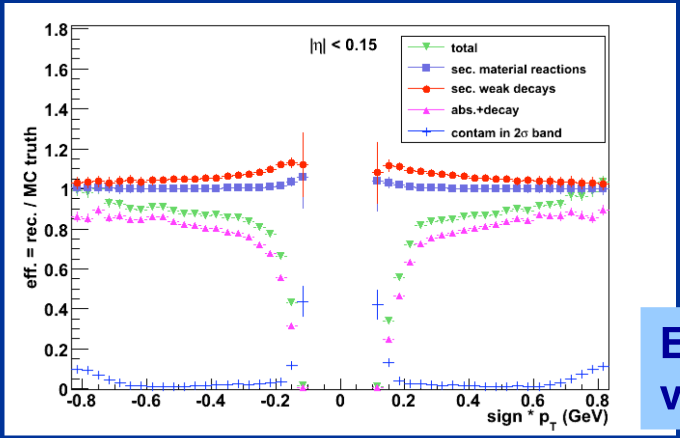
π, K, p spectra (I)

ALICE TPC standalone analysis, 2 PID methods:

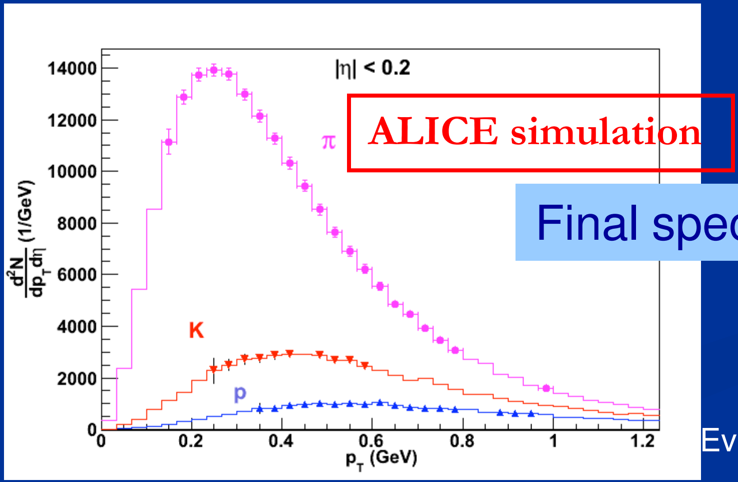
- **A**: in each p_T-bin, histogram with measured dE/dx minus expected dE/dx for π's filled and fitted with a multiple Gauss function;
- **B**: select all particles within a nσ-band around each B-B curve, p_T-bins filled directly







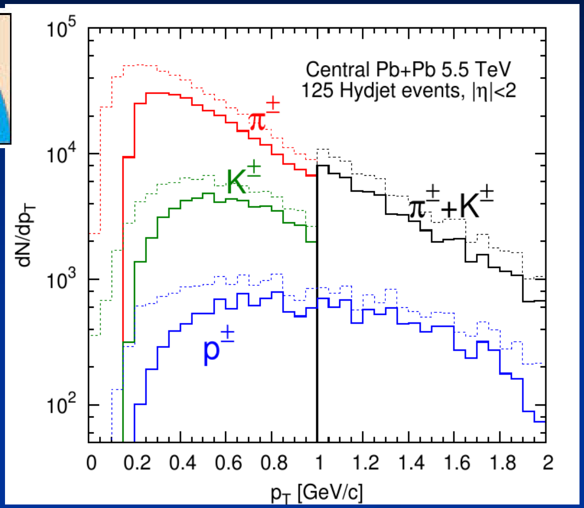
Efficiency, contam. vs p_T



Final spectra

ITS dE/dx (4 Si layers) PID also being studied

π, K, p spectra (II)

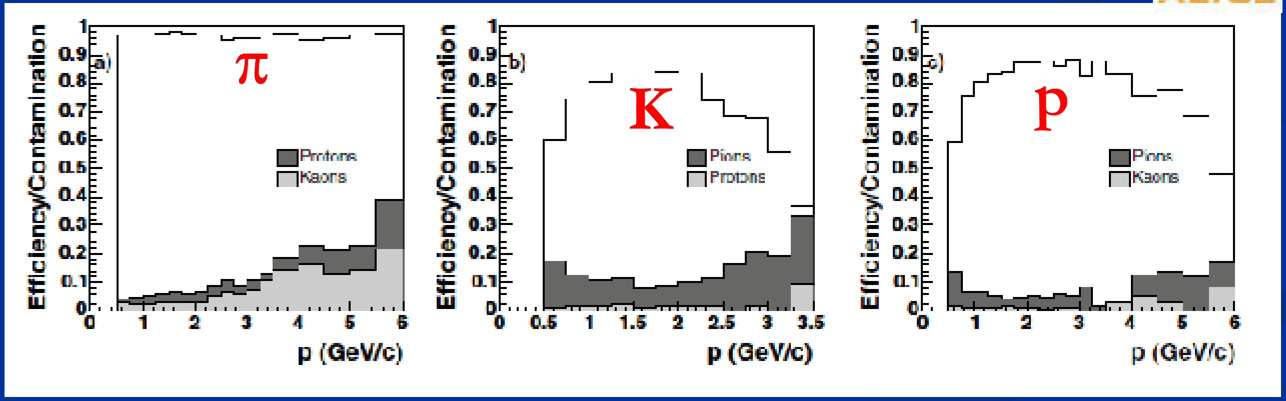


D. d'Enterria QM2008

CMS: PID (**π, K, p** up to 1 GeV/c, **π+K** from **p** up to 2 GeV/c) with dE/dx in the 3 layers of Si pixels

CMS TDR 8.1-Add.1, J. Phys. G. Nucl. Part. Phys. 34 (2007) 2307

ALICE: separation of **π, K, p** up to ~5 GeV/c using the **TOF** signal (~50% of primary particles reach TOF) combined with TPC momentum and TRD tracking



TOF PID algorithm efficiency & contamination, for primary pions, kaons and protons,
in central Pb-Pb collisions.

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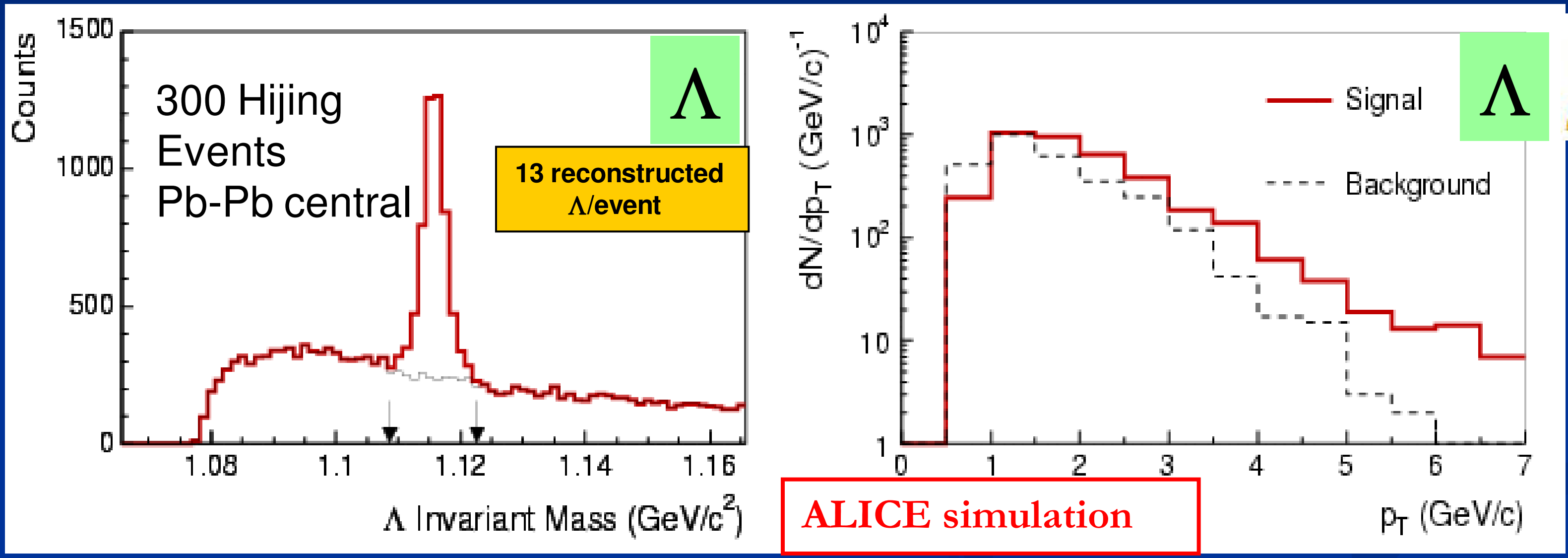
Strange hadrons

ALICE, statistical limit for 1 year: ~ 10^7 central Pb-Pb, 10^9 min. bias pp

p_T ~ 13 - 15 GeV/c for K^+, K^-, K^0_s, Λ p_T ~ 9 - 12 GeV/c for Ξ, Ω



Reconstruction rates:

Λ: 13 / event

Ξ: 0.1 / event

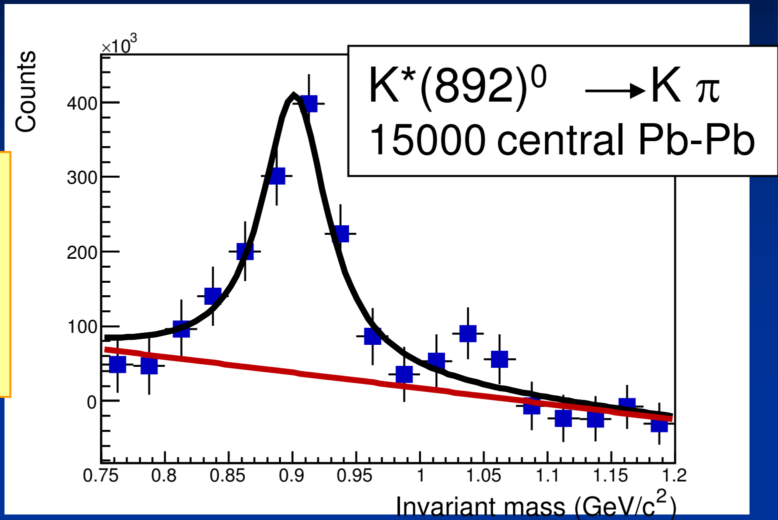
Ω: 0.01 / event

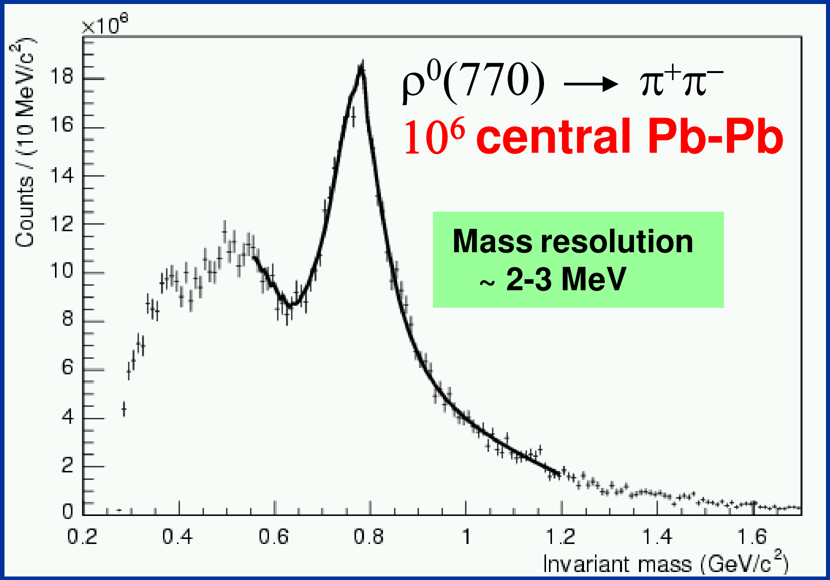
CMS: in low luminosity pp runs, K^0s and Λs can be exclusively identified; for Pb-Pb collisions the inclusive yield can still be extracted with a reasonable background.

Resonances

Partial chiral symmetry restoration & interaction of resonances and/or their daughters with medium can modify properties: peak pos. & width

Resonance	Life-time [fm/c]	Resonance	Life-time [fm/c]
ρ(770)	1.3	Σ*(1385)	5.7
Δ^{++}(1232)	1.7	Λ*(1520)	13
f_0(980)	2.6	ω(783)	23
K*(892)	4.0	ϕ(1020)	45





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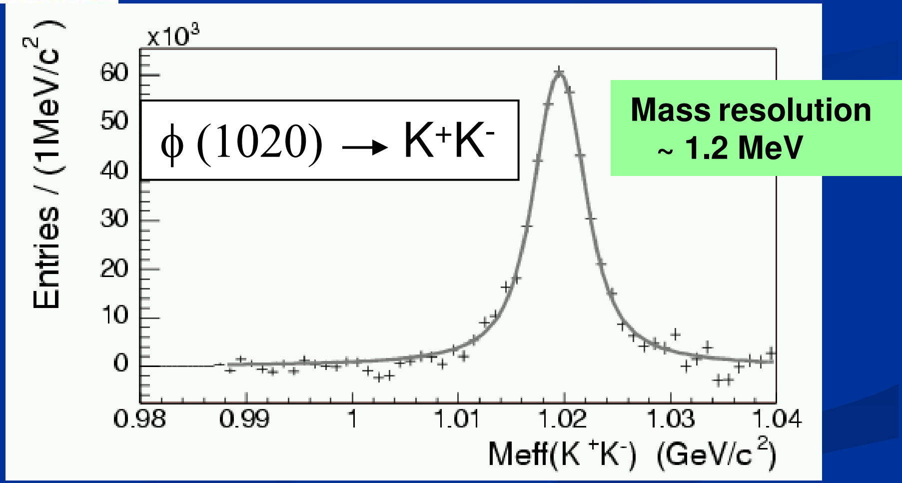


Invariant mass reconstruction, background subtracted (like-sign method)
mass resolutions ~ 1.5 - 3 MeV/c^2 and p_T stat. limits from 8 (ρ) to 15 GeV/c (ϕ, K*)

Correlations

Anisotropic flow

Azimuthal asymmetry in coordinate space (transverse plane):

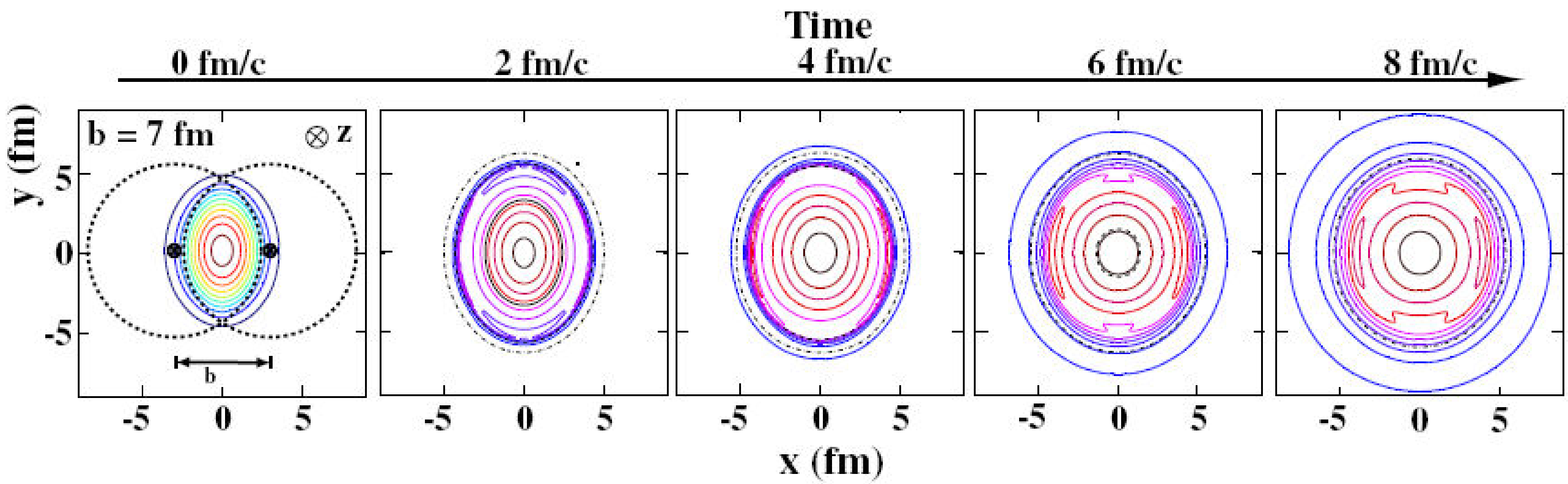


FIG. 10: The created initial transverse energy density profile [44] and its time dependence in coordinate space for a non-central heavy-ion collision. The z-axis is along the colliding beams, the x-axis is defined by the impact parameter **b** (the vector connecting the centers of the colliding heavy-ions, perpendicular on the beam axis).

Kolb + Heinz

produces azimuthal asymmetry in **momentum** space:

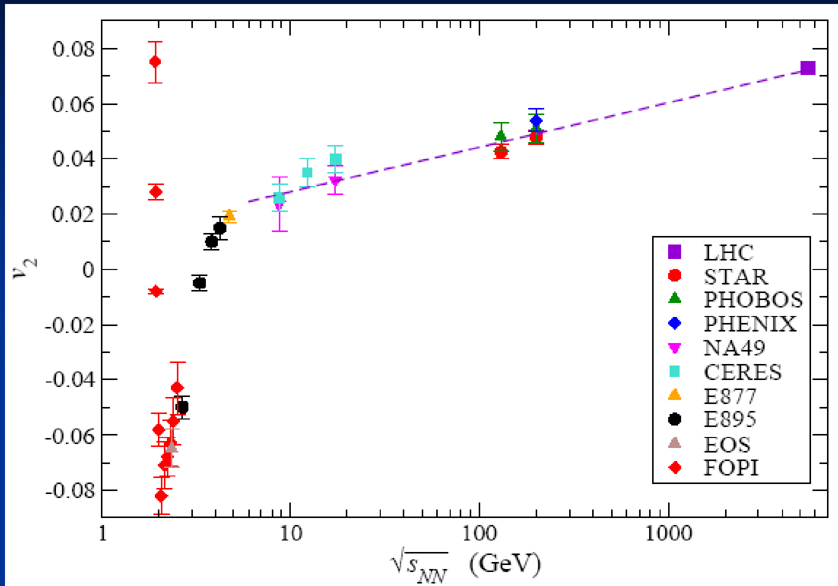
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi)\right]$$

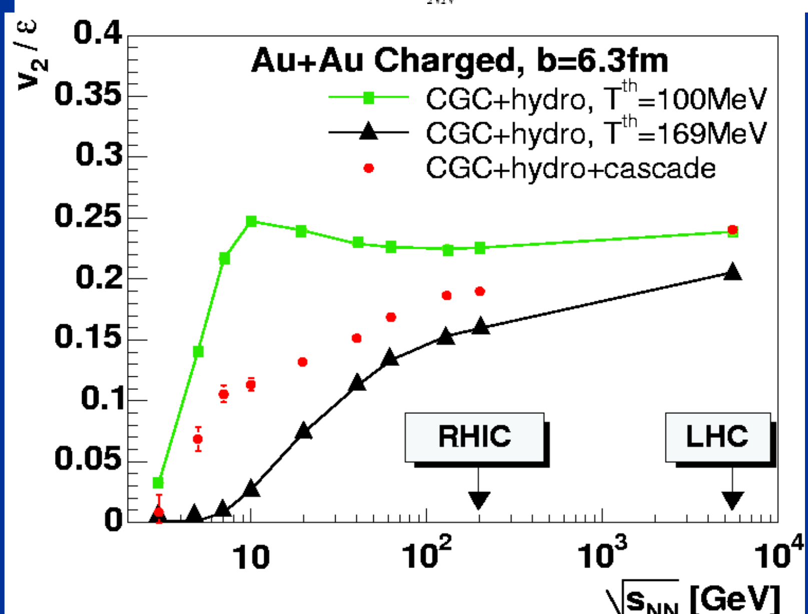
v_1 = directed flow $\quad$ v_2 = elliptic flow

The amount of observed flow depends on **centrality** and on the ***spatial eccentricity*** ε:

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Elliptic flow: expectations at LHC





Elliptic flow is one of the KEY observables for collective effects also at LHC.

From the observed v_2 dependence on $\sqrt{s}$

⬇

one expects p_T-integrated $v_2(0) \sim 0.08$ @ LHC

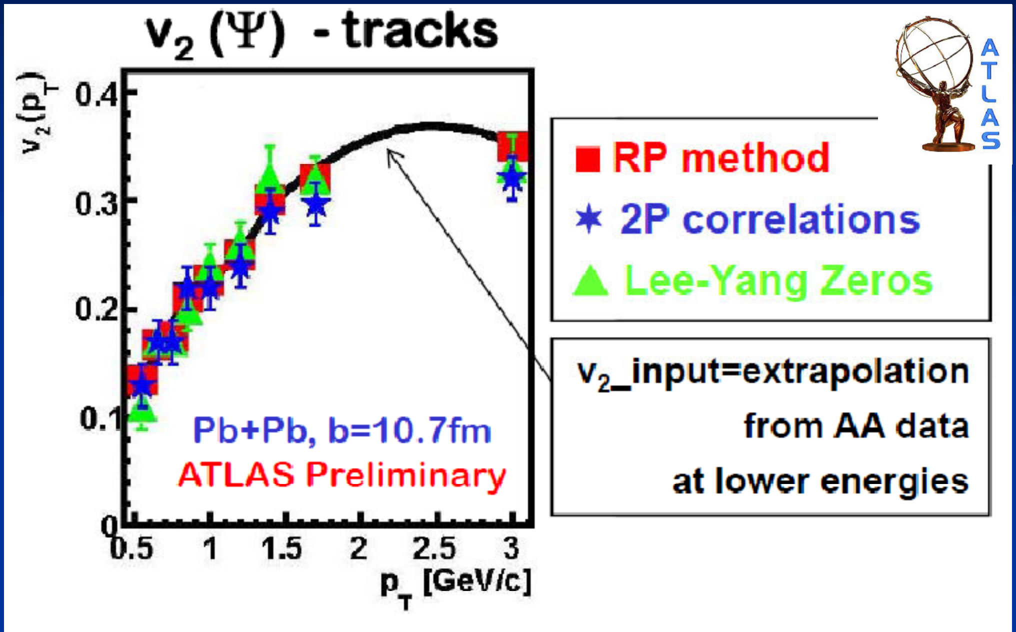
Large signal → easy measurement, but.. beware of non-flow contributions (jets...)!

More insight from p_T dependence and PID

v_2 (elliptic flow) is supposed to **scale** as **eccentricity ε** (different definitions proposed); from hydrodynamics calculations, it appears that the contribution to v_2/ε by the QGP phase (rather than from the cascade) is much larger at LHC with respect to lower energies

T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, QM 2008

Elliptic flow (I)



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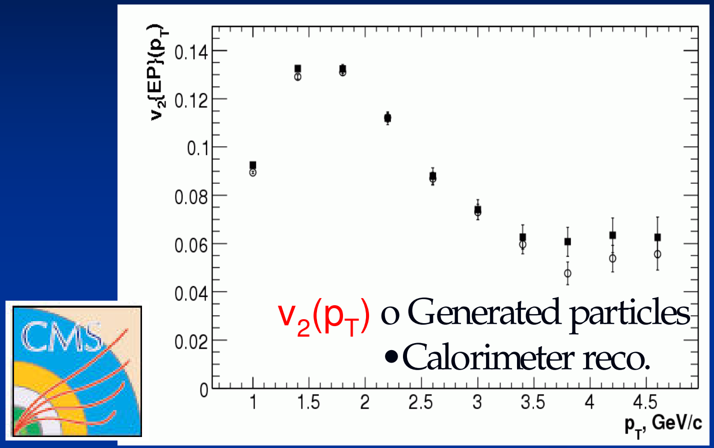
ATLAS elliptic flow measured from:

1) tracks,
2) hits from inner tracking,
3) energy in first layer of calorimeters.

Methods used for v_2 extraction:
Reaction Plane (RP),
2-particle correlations, Lee-Yang Zeros



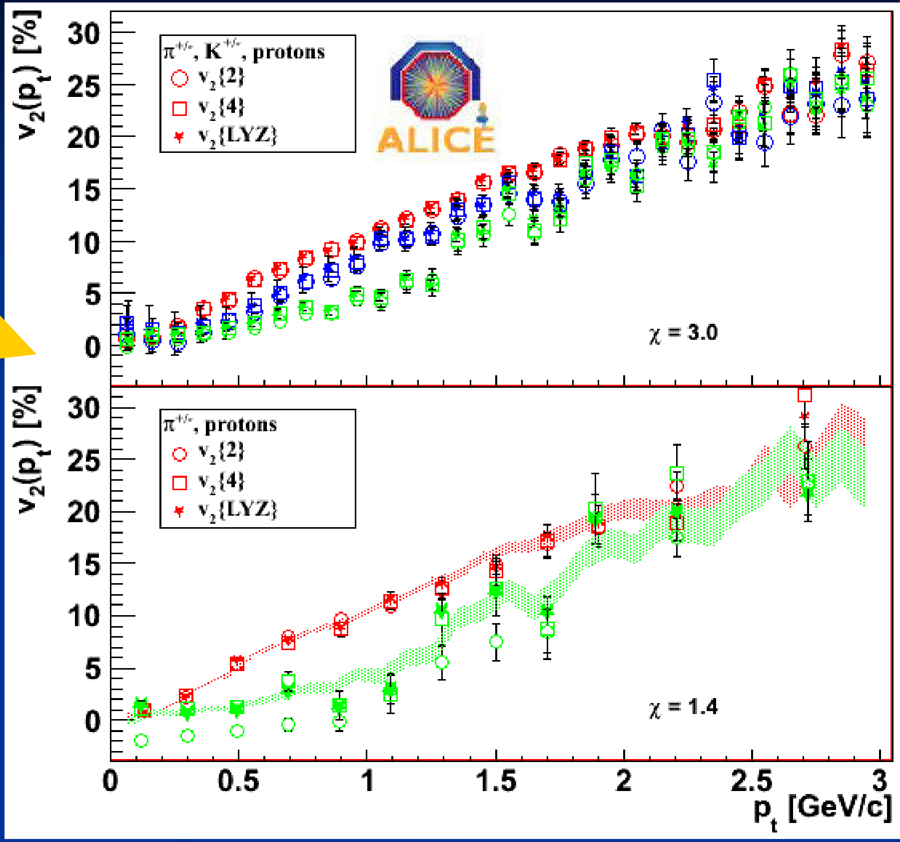
D. d'Enterria QM2008
Hydro model for flow

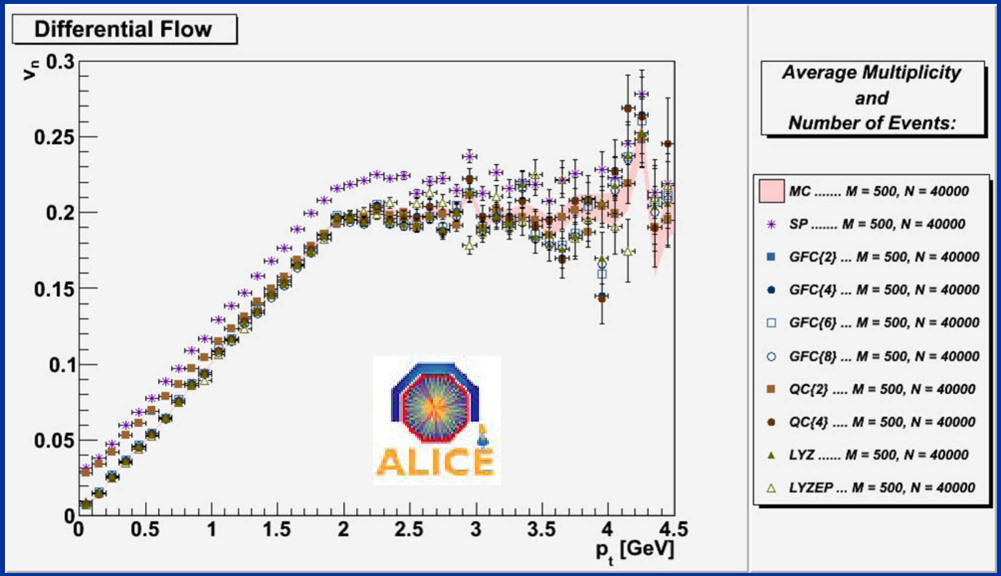
CMS event plane from:
1) ECAL + HCAL (barrel+endcaps),
2) inner tracker.
Methods used for v_2 extraction:
Event Plane (EP), 2-particle correl.,
Cumulants

CMS TDR 8.1-Add.1, J. Phys. G. Nucl. Part. Phys. 34 (2007) 2307

Elliptic flow (II)

For large values of multiplicity M (upper plot) both two-particle and multi-particle methods give correct estimate of flow, while for smaller values of multiplicity (lower plot) only multi-particle methods (v2{4}, v2{LYZ}) correctly estimate flow.
2-particle correlations methods biased by large non-flow correlations (jets, resonances, HBT)





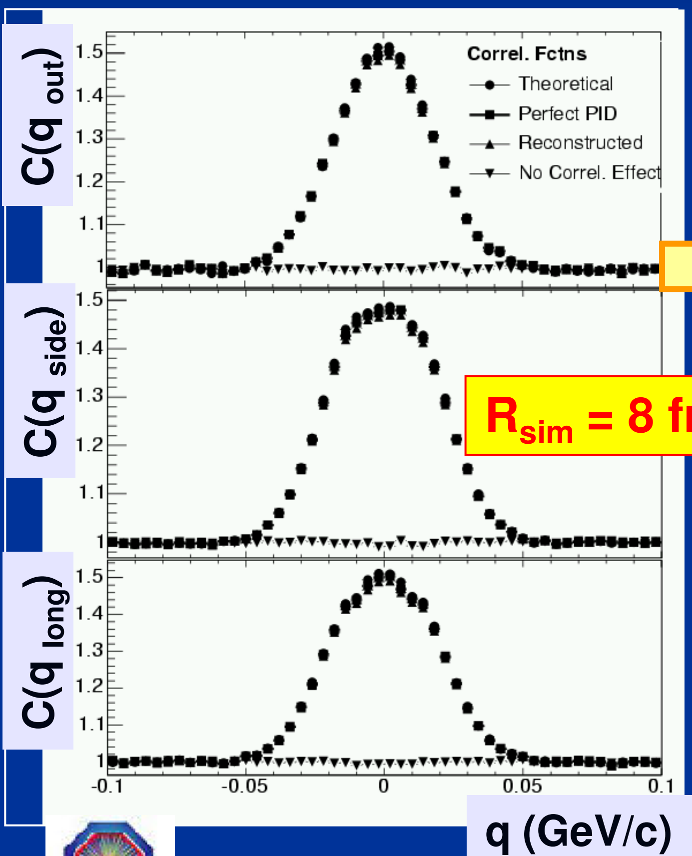
Flow analysis on 500 Pb+Pb hydro + Therminator events, a model based on hydrodynamics and single freeze-out statistical hadronisation including a complete treatment of resonances

40k events, integrated v_2 = 0.087, M = 500, with nonflow
METHODS: SP = Scalar Product; GFC, QC = Cumulants;
LYZ = Lee-Yang Zeroes

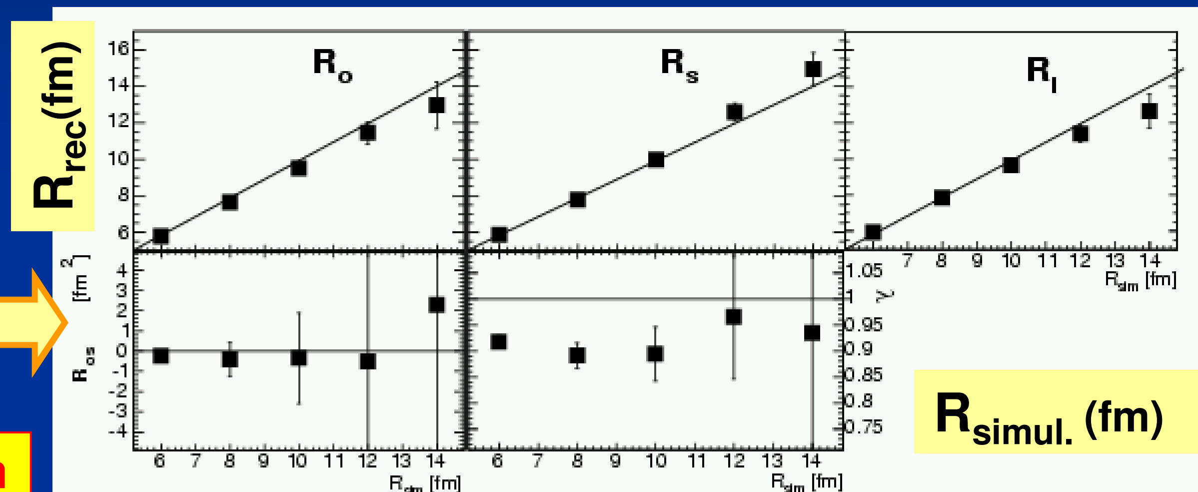
HBT with identical pions

Study of event mixing, two track resolutions, track splitting/merging, pair purity, Coulomb interactions, momentum resolution corrections, PID corrections

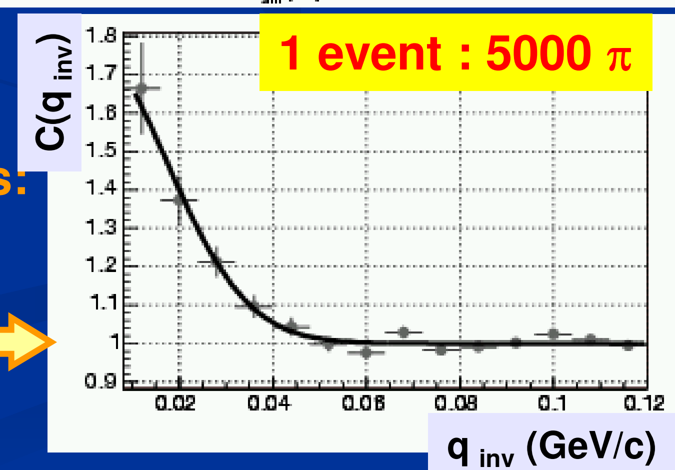
Correlation functions (Pb+Pb)



Radii can be recontructed up to 15-20 fm



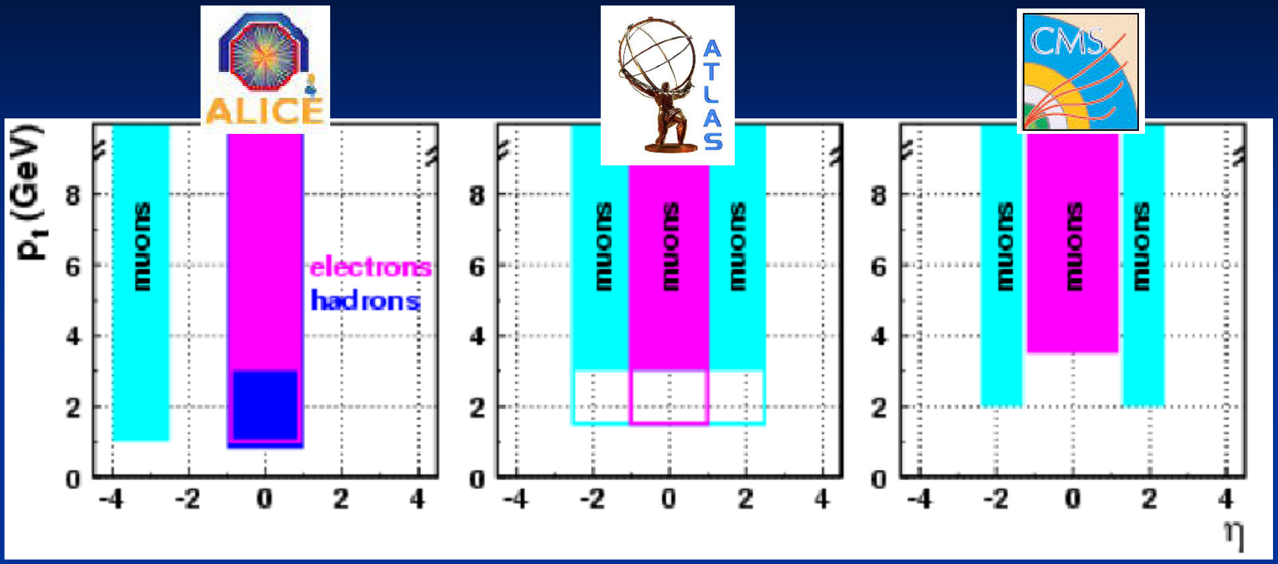
Other possible analyses:
Two kaon & two proton correlations
Single event HBT
Direct photon HBT, …



Heavy flavours

Open Heavy Flavour measurements will provide a natural reference for Quarkonia (see following talk by O. Kodolova)

HF at LHC: acceptances



- Complementarity between experiments:
  - ALICE: **low p_T** reach; **hadrons** (unique measurement, at low and high p_T), electrons (barrel tracker, Si vertexer) and muons (forward spectrometer, no vertexer)
  - ATLAS and CMS: **high p_T** reach (higher luminosity); muons in wide η acceptance; b-tagged jets

HF at LHC: channels studied

- **Beauty:**
  - $B \rightarrow e + X$
  - $B \rightarrow \mu + X$
  - $B \rightarrow J/\psi + X \rightarrow l^+l^- + X$
  - $B \rightarrow$ >5 prongs
  - $(B)B \rightarrow \mu\mu + X$
  - b-tagged jets

- **Charm:**
  - $D^0 \rightarrow K^-\pi^+$
  - $D^+ \rightarrow K^-\pi^+\pi^+$
  - $D^+_s \rightarrow K^-K^+\pi^+$
  - $D^* \rightarrow D^0\pi$
  - $D^0 \rightarrow K\pi\pi\pi$
  - $\Lambda^+_c \rightarrow pK^+\pi^+$

Techniques: tracking, vertexing, e/π ID, μ ID, calorimetry

Physics addressed:

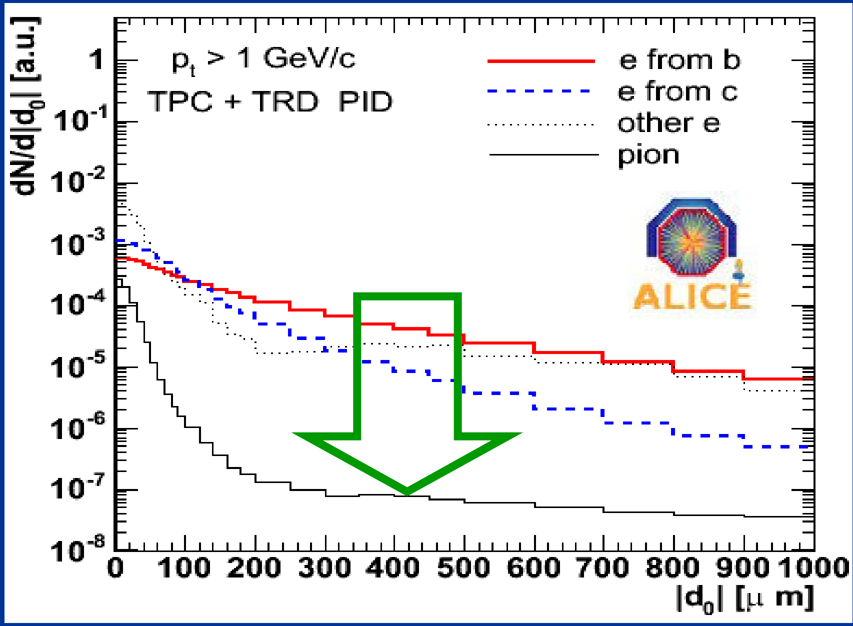
- heavy quark energy loss (R_{AA}, $R_{D/h}$, $R_{B/h}$)
- charm quark flow (v_2 vs. pt)

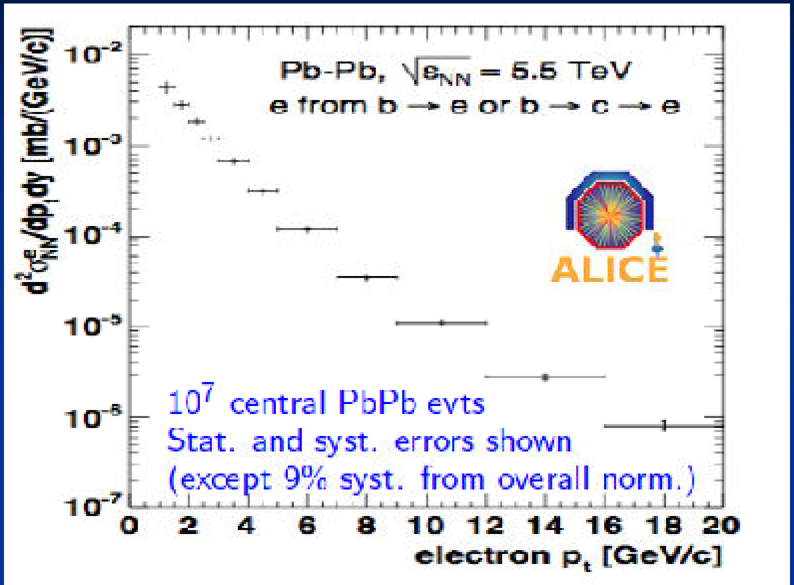
$B \rightarrow e + X$

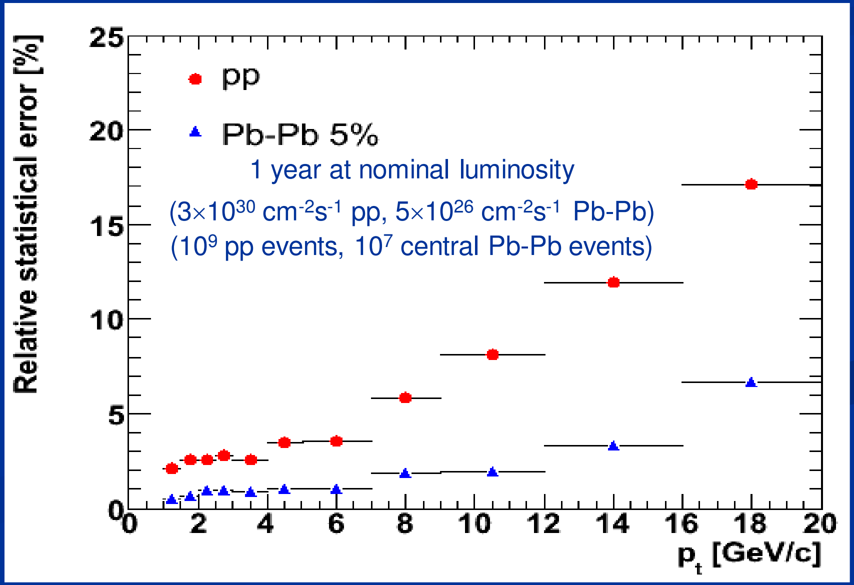
Electron PID: remove most hadrons

d_0 >200 μm: reduce charm and background electrons (γ conv., Dalitz)

d_0 < 600 μm: reduce e's from strange particles

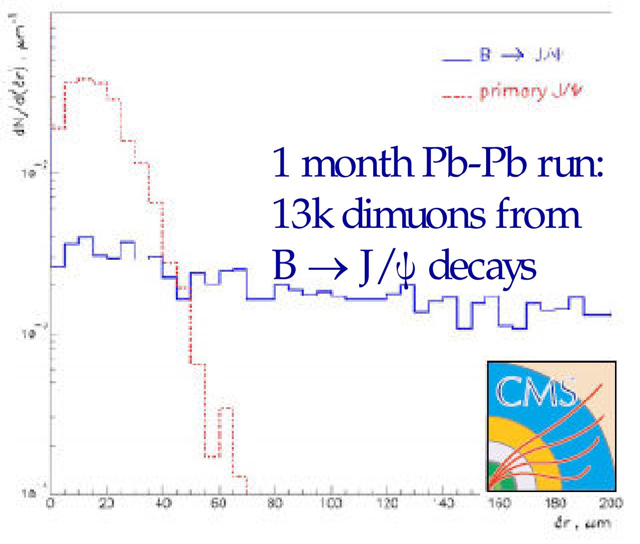


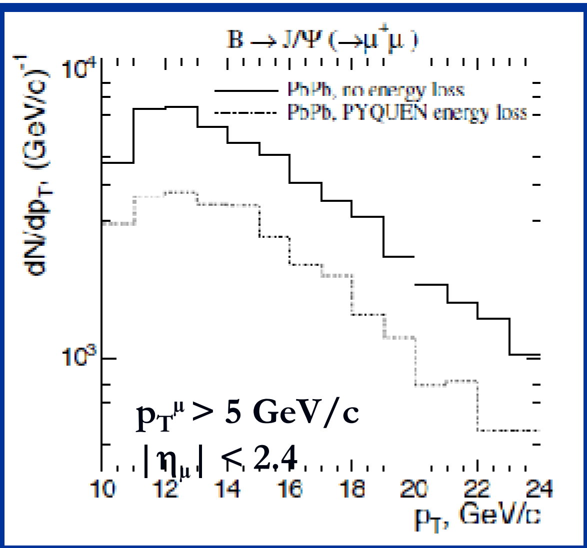


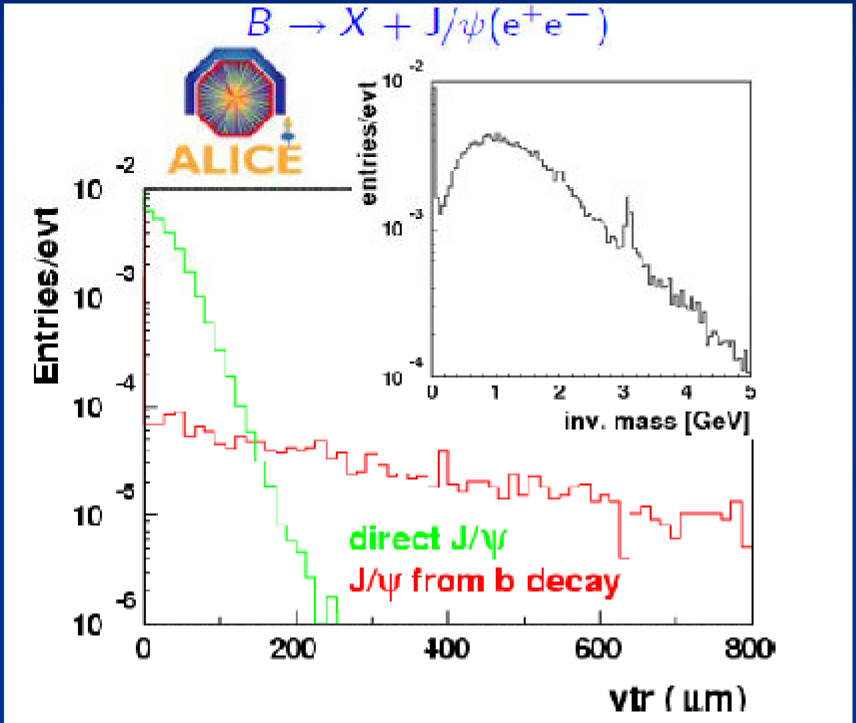


$B \to J/\psi + X \to l^+l^- + X$

B.R.: $B \to J/\psi + X$ = 1.15%,
$J/\psi \to l^+l^-$ = 5.9%.







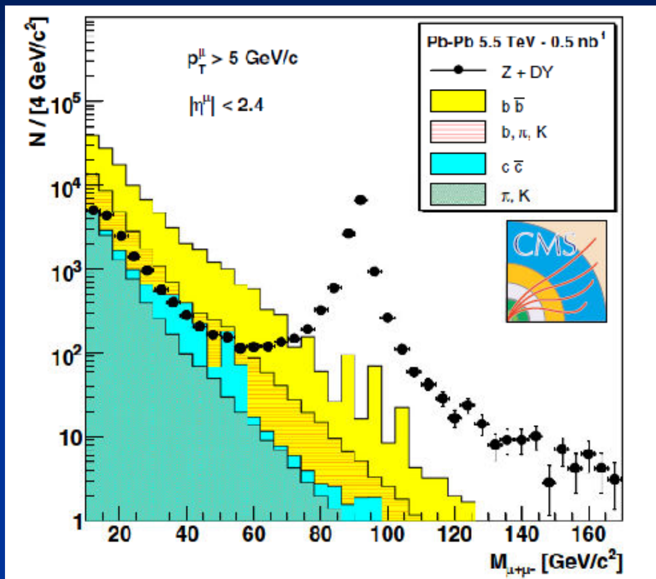
vtr: distance primary-secondary vertex in ⊥ plane

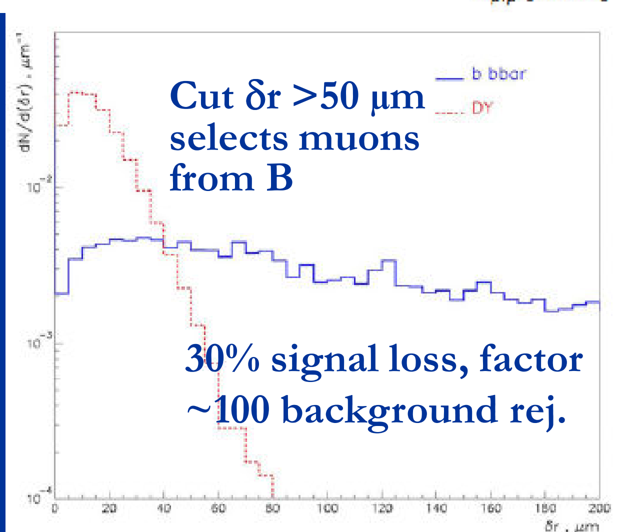
This channel will enable testing of b-quark energy loss, via yield reduction & η distribution narrowing

Minimum lepton p_T: ALICE (e) ~1 GeV/c, CMS (μ) ~5 GeV/c

(B)B → μμ + X

With vertexing (CMS):

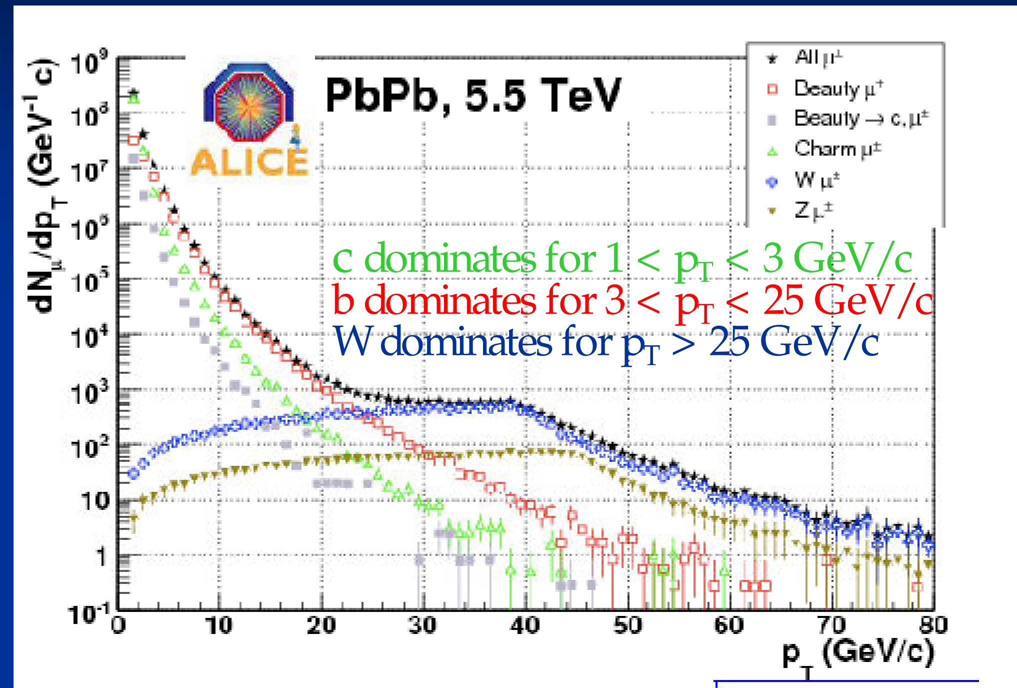




Cut δr >50 μm selects muons from B

30% signal loss, factor ~100 background rej.

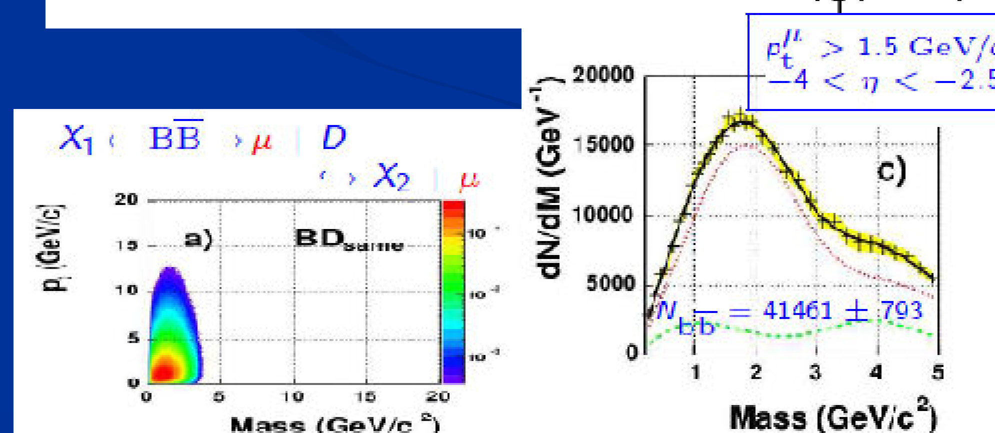
Without vertexing (ALICE):



c dominates for $1 < p_T < 3$ GeV/c

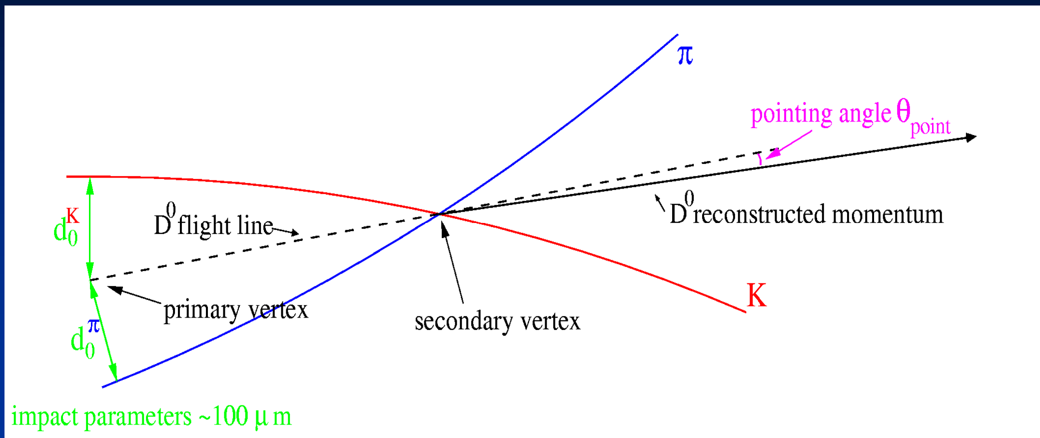
b dominates for $3 < p_T < 25$ GeV/c

W dominates for $p_T > 25$ GeV/c



$p_t^{\mu} > 1.5$ GeV/c
$-4 < \eta < -2.5$

$D^0 \rightarrow K^-\pi^+$



B.R. = 3.8% cτ = 123 µm

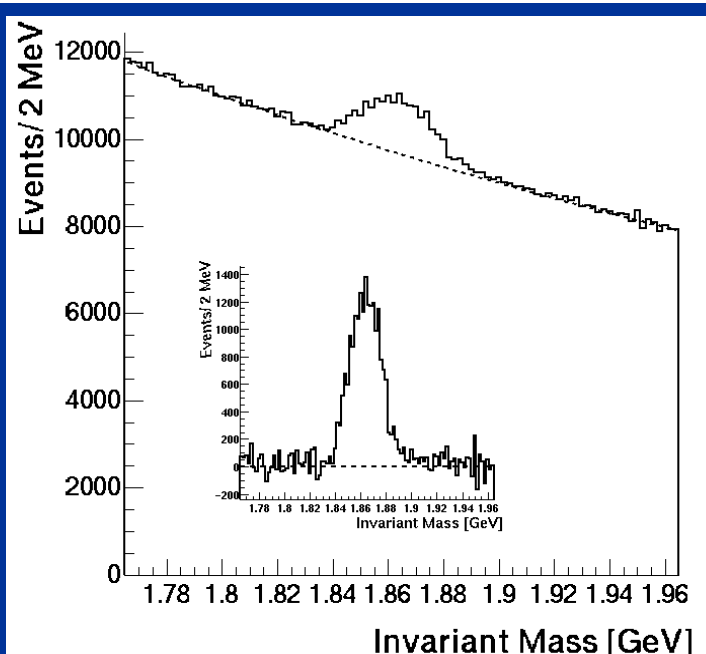
main selection: displaced vertex

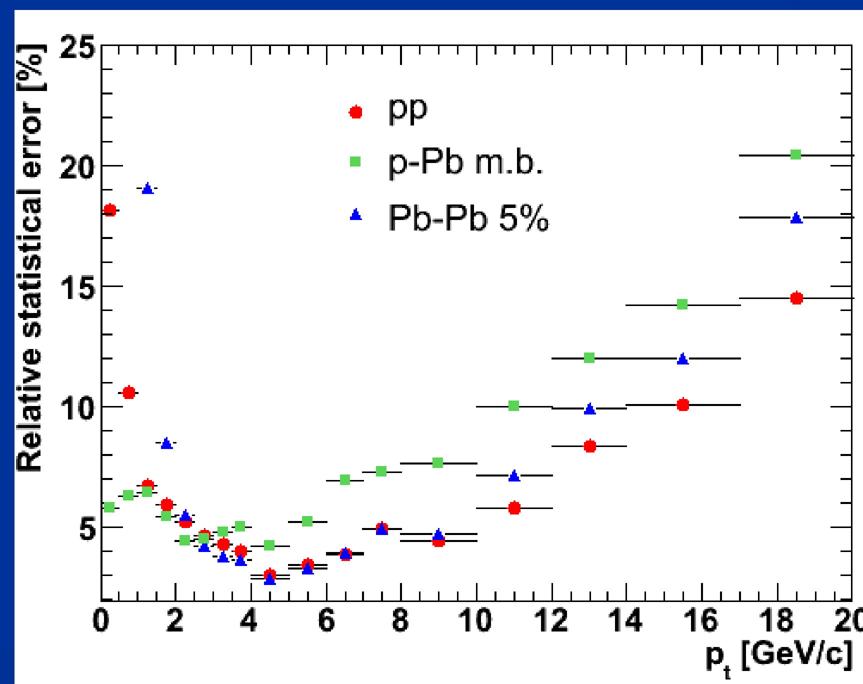
$\cos(\theta_{point})$ and $d_0^\pi \cdot d_0^K$ cuts reduce combinatorial background by ~1000

pp, Pb-Pb: 1 year at nominal luminosity

(10^9 pp events, 10^7 central Pb-Pb events)

p-Pb: 1 month (10^8 events)





ALICE Collaboration, J. Phys. G 32 (2006) 1295;

A. Dainese, QM 2009

Conclusions

- **Rich physics programme** developed by ALICE, ATLAS and CMS for the **first LHC Pb-Pb run** (scheduled at end of the 2009-10 pp run) - analysis procedures well established and tested on the GRID
- Detectors already commissioned with cosmic muons, will be fully calibrated after the first pp run
- **Bulk properties and correlations**: current picture based on RHIC (gluon saturation, statistical hadronization, quark coalescence, …) will be tested at LHC energy
- **Heavy flavours**: copious beauty (and charm) production, many techniques for HF tagging developed: energy loss of heavy quarks will be studied in detail
- A wealth of physics results from the first month of Pb+Pb collisions is eagerly expected!

ALICE References

- ALICE Physics Performance Report:
  - Volume 1: F. Carminati et al., J. Phys. G. Nucl. Part. Phys. 30 (2004) 1517
  - Volume 2: B. Alessandro et al., J. Phys. G. Nucl. Part. Phys. 32 (2006) 1295
- ALICE Detector technical paper:
  - K. Aamodt et al., The ALICE Experiment at the CERN LHC, 2008 JINST 3 S08002.

ATLAS References

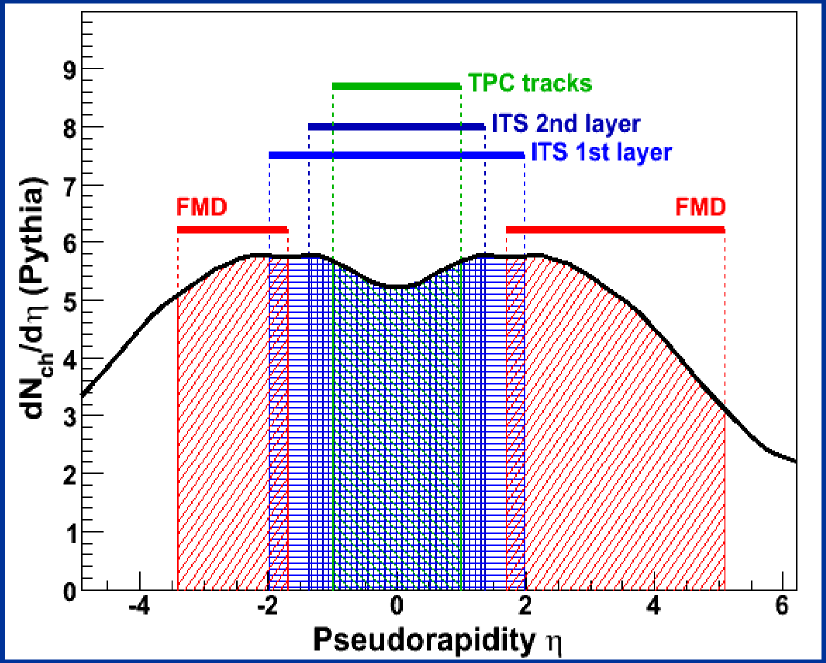
- N. Grau, Heavy-ion physics prospects with the ATLAS detector at the LHC (QM 2008), J. Phys. G: Nucl. Part. Phys. **35** (2008) 104040
- P. Steinberg, Global observables in heavy-ion collisions at the LHC with the ATLAS detector (QM 2008), J. Phys. G: Nucl. Part. Phys. **35** (2008) 104151
- A. Trzupek, "Global Observables for Pb+Pb Collisions from the ATLAS Experiment", ATL-PHYS-PROC-2009-021, Proceedings of PANIC08, 9-14 November 2008, Eilat ISRAEL
- J. Dolejsi, Status of ATLAS and preparation for the Pb+Pb run, (QM 2009) ATL-PHYS-SLIDE-2009-058
- A. Trzupek, "Heavy Ion Physics with the ATLAS Detector at the LHC", ATL-PHYS-PROC-2009-090, Proceedings of HEP 2009, Kraków, Poland , 16-22 July 2009

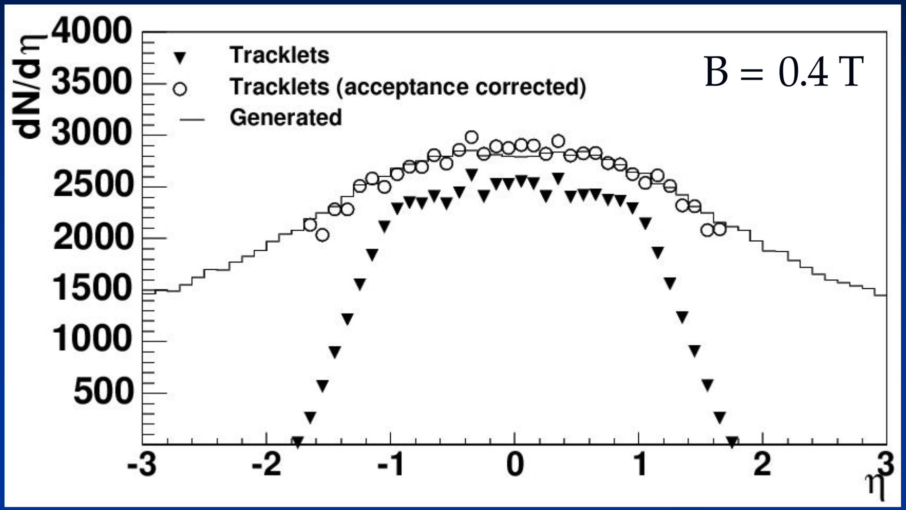
CMS References

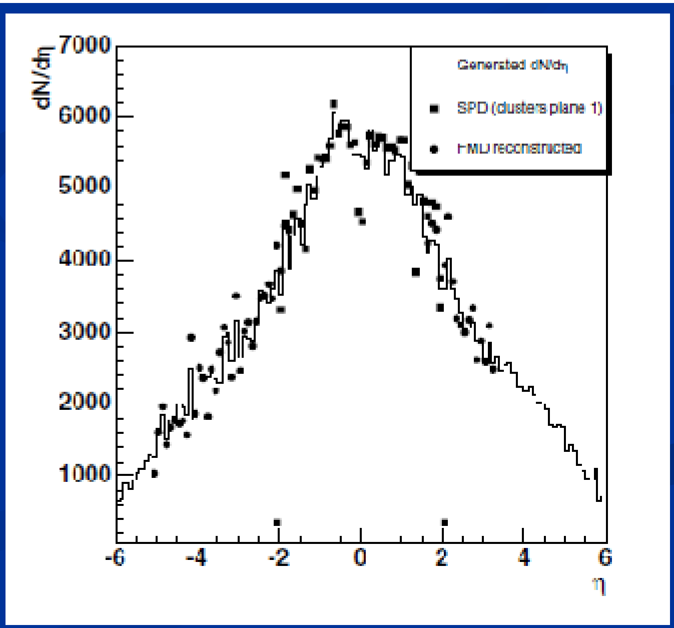
- CMS Physics Technical Design Report: Addendum on High Density QCD with Heavy Ions, The CMS Collaboration *et al* 2007 *J. Phys. G: Nucl. Part. Phys.* **34** 2307-2455
- Charged hadron spectra with pixel "tracklets" (CMS_PAS-QCD-09-002)
- Charged hadron spectra with full tracking (CMS_PAS-QCD-07-001)

BACKUP

dNch/dη in ALICE

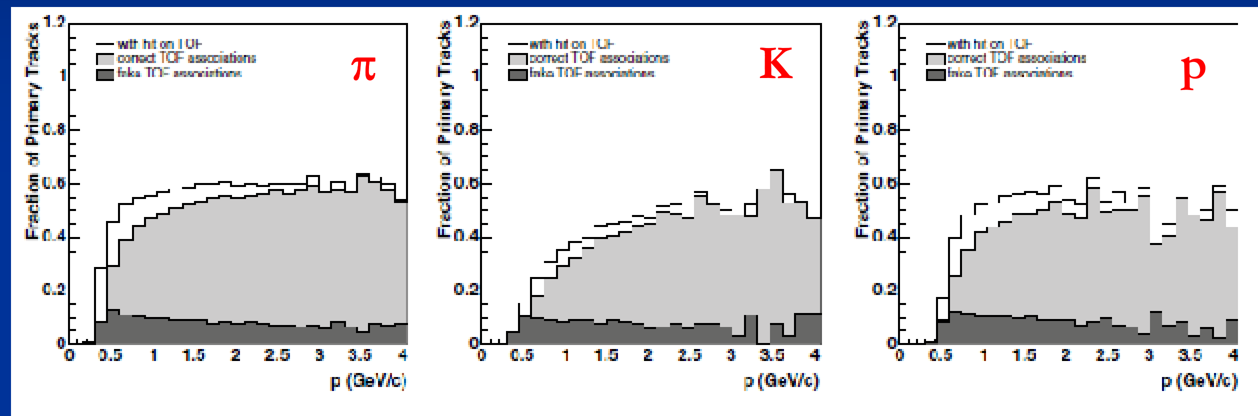


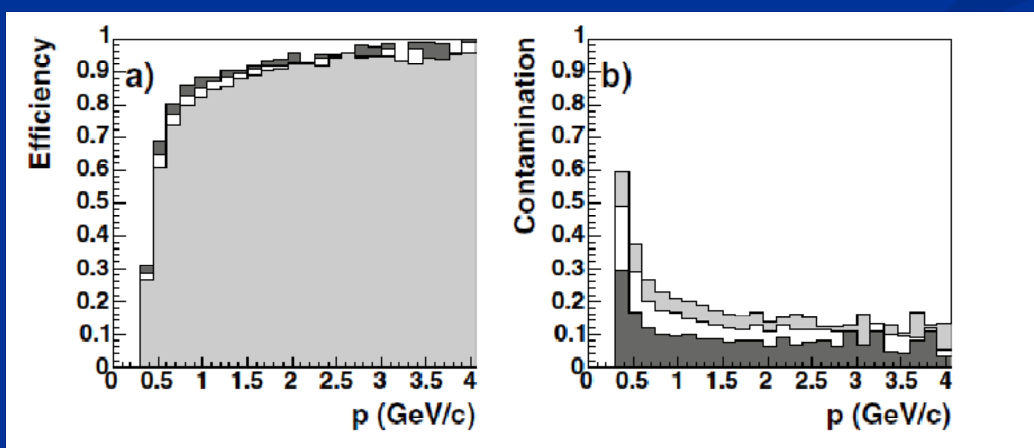




ALICE TOF: performance in Pb-Pb

TPC outer radius 2.6 m, TOF inner radius 3.7 m.
At p_T = 2.5 GeV/c, about 50% of primary particles do NOT hit TOF, due to TOF dead spaces (~15%), decays (K), interaction in TRD material (0.18 absorption lengths).

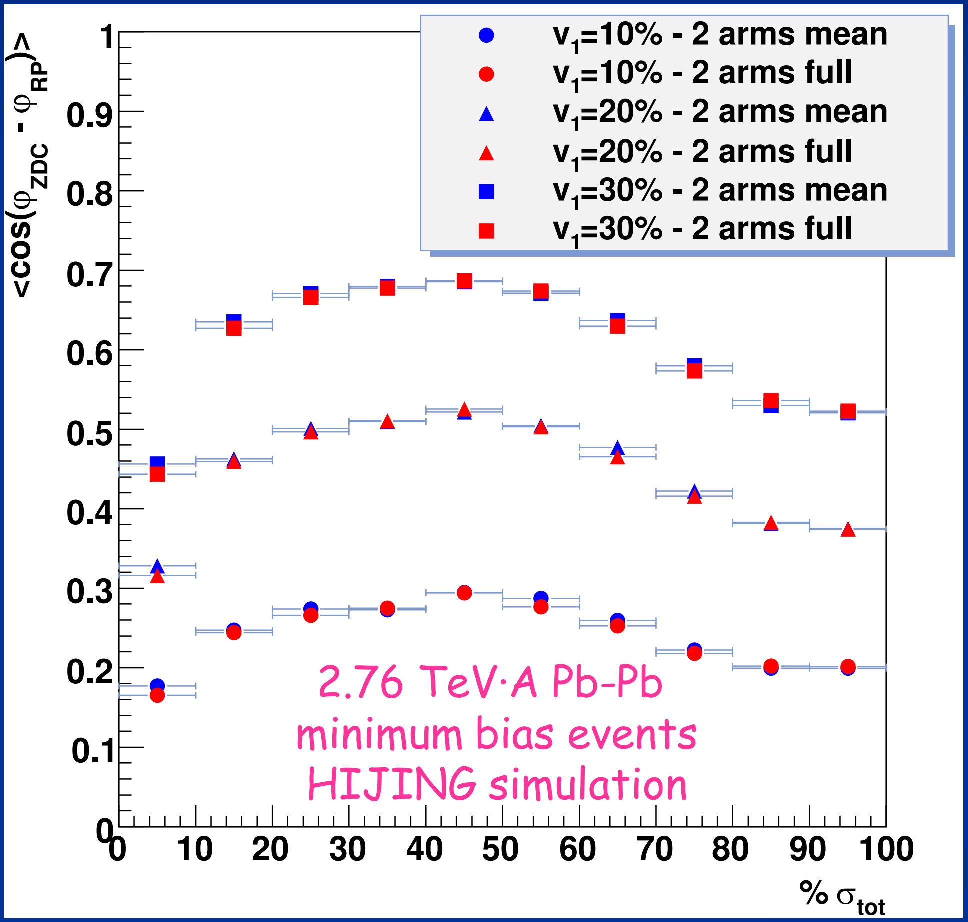


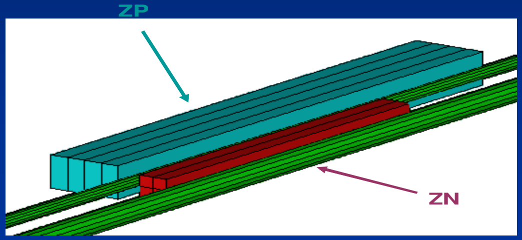


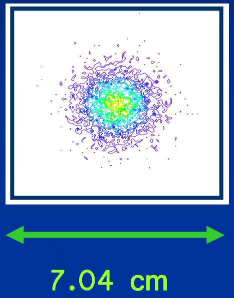
Track-TOF signal matching for $dN_{ch}/d\eta$ = 2000, 5000 and 8000: algorithm efficiency and contamination

Directed flow

- v_1 can be measured in ALICE via spectator neutrons (η>8.7), namely by their centroids as obtained by the two zero-degree 'ZN' calorimeters





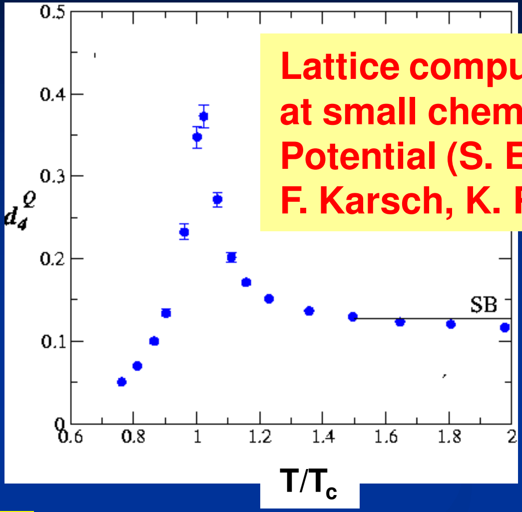


- For a range of plausible v_1 values (10% 20% 30%) at LHC, the first order event plane **resolution** obtained by combining both ZN's is quite adequate
- In addition, this measurement provides the sign of v_2

Event-by-event fluctuations

Fluctuations of temperature, entropy, energy density and of quark number susceptibilities (net charge, isospin, strangeness content) associated with phase transition

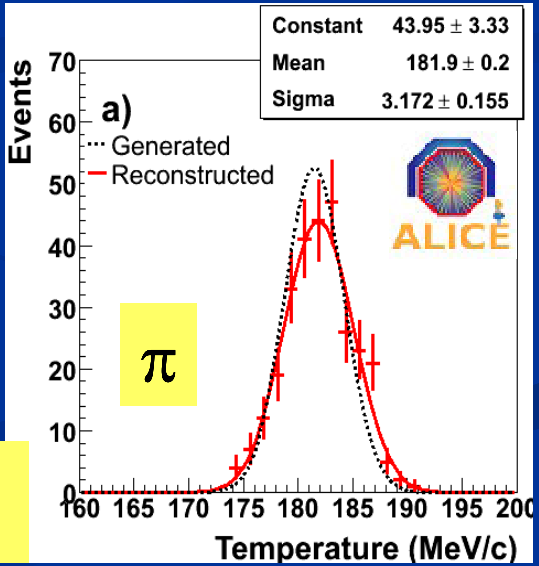
Example: 4th moment of the net charge



Lattice computations at small chemical Potential (S. Ejiri, F. Karsch, K. Redlich)

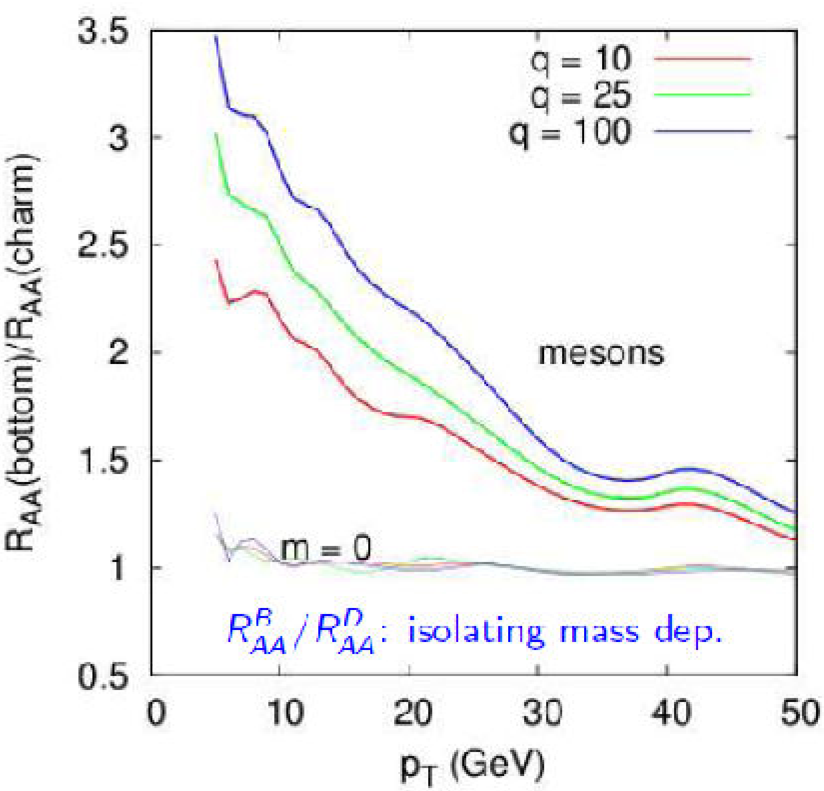
High multiplicities at LHC => ALICE suited for the measurement of event/event fluctuations of $<p_T>$, T multiplicity, particle ratio, strangeness, azimuthal anisotropy, intermediate / high p_T phenomena, long range correlations, balance function, …

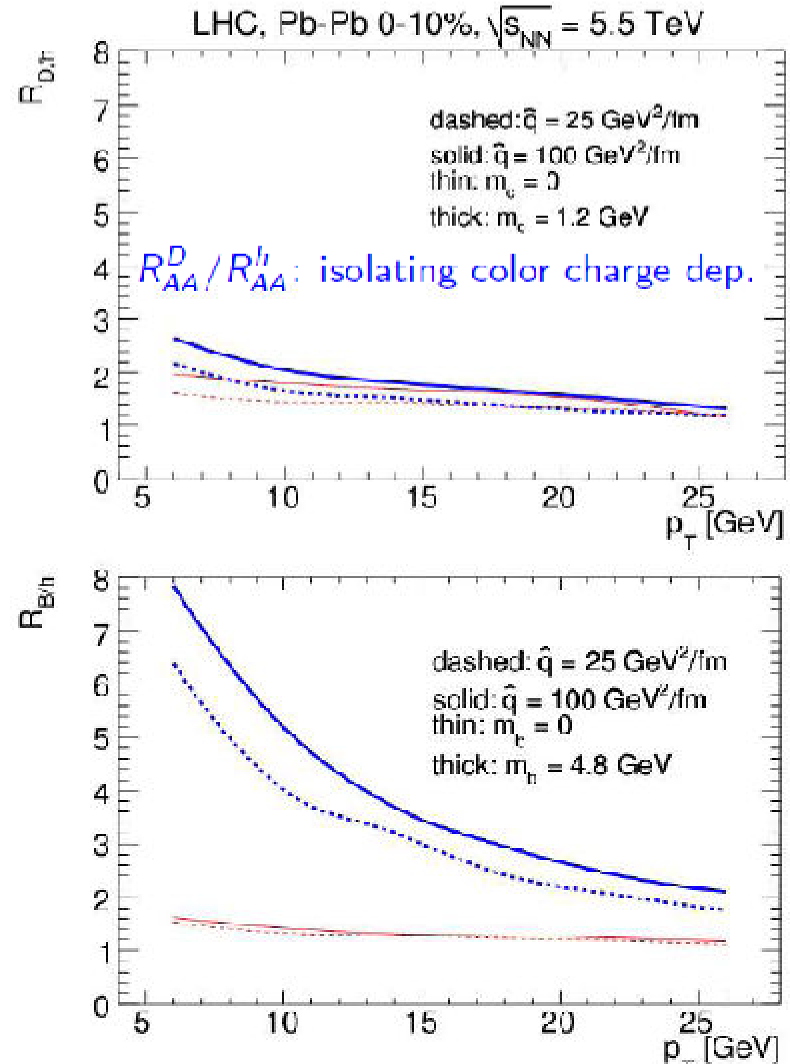
Mini-jets and jets expected to increase strongly the level of fluctuations
Fluctuations of flow ⟶ viscosity
Fluct. of particle ratios ⟶ constraints on statistical models



Resolution σ_T/T: 0.5 % for π

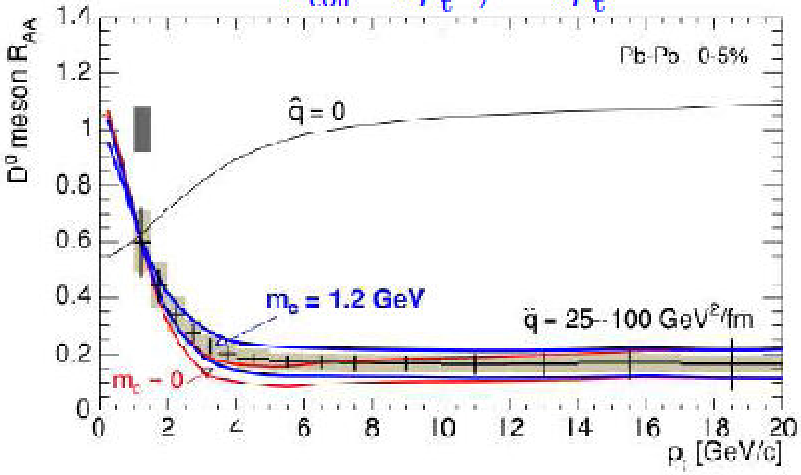
- Significant non-photonic electron suppression at high-p_t measured @ RHIC: heavy flavor energy loss.
- New energy loss aspects can be tested @ LHC:
  - Color charge dependence. $\Delta E_g > \Delta E_q \Rightarrow R^h_{AA} < R^D_{AA}$ (@ high-p_t)
  - Mass dependence. $\Delta E_q > \Delta E_Q \Rightarrow R^D_{AA} < R^B_{AA}$ (@ high-p_t)

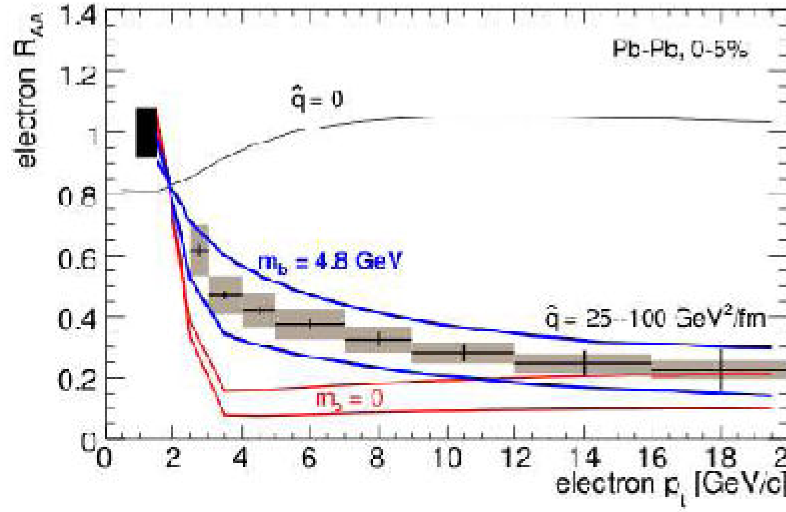




A.Dainese, Eur.Phys.J.C 49 (2007) 135
N.Armesto *et al.*, J.Phys.G 35 (2008) 054001

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{AA}}{dp_t} \Big/ \frac{dN_{pp}}{dp_t}$$

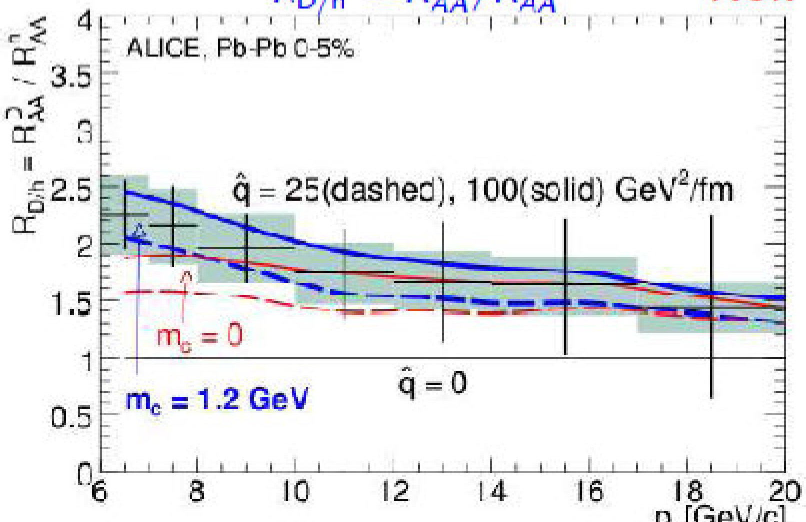




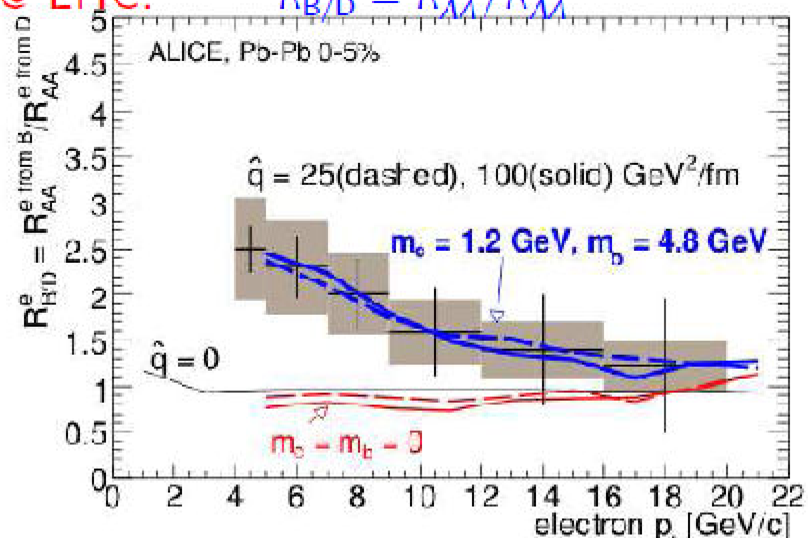
$R_{D/h} = R^{D}_{AA} / R^{h}_{AA}$

New @ LHC!

$R_{B/D} = R^{B}_{AA} / R^{D}_{AA}$



Sensitivity to color charge dependence.



Sensitivity to mass dependence.

Stat.(bars) and syst.(bands) err. in 1 year: 10^7 central PbPb and 10^9 pp evts.

A.Dainese, Nucl.Phys.A 783 (2007) 417
J. Phys. G 32 (2006) 1295

b-jet tagging (Pb+Pb)

- ATLAS: b, c jet tagging with muon ($p_T > 5$ GeV/c) efficiency for b up to 80%, purity: b+c 70%, b 40%

  N. Grau et al., ATL-PHYS-SLIDE-2009-063 (QM 2009), arXiv:0907.4944 [nucl-ex]

- CMS: jet ($|\eta|<3.0$, $E_T > 50$ GeV) with leading μ ($|\eta|<2.4$, $p_T > 5$ GeV/c): 20k b-tagged jets in 1 month of Pb+Pb run - I.P. Lokhtin et al., *Eur. Phys. J.* C **37** (2004) 465–9 (*Preprint* hep-ph/0407109)
- ALICE: under study