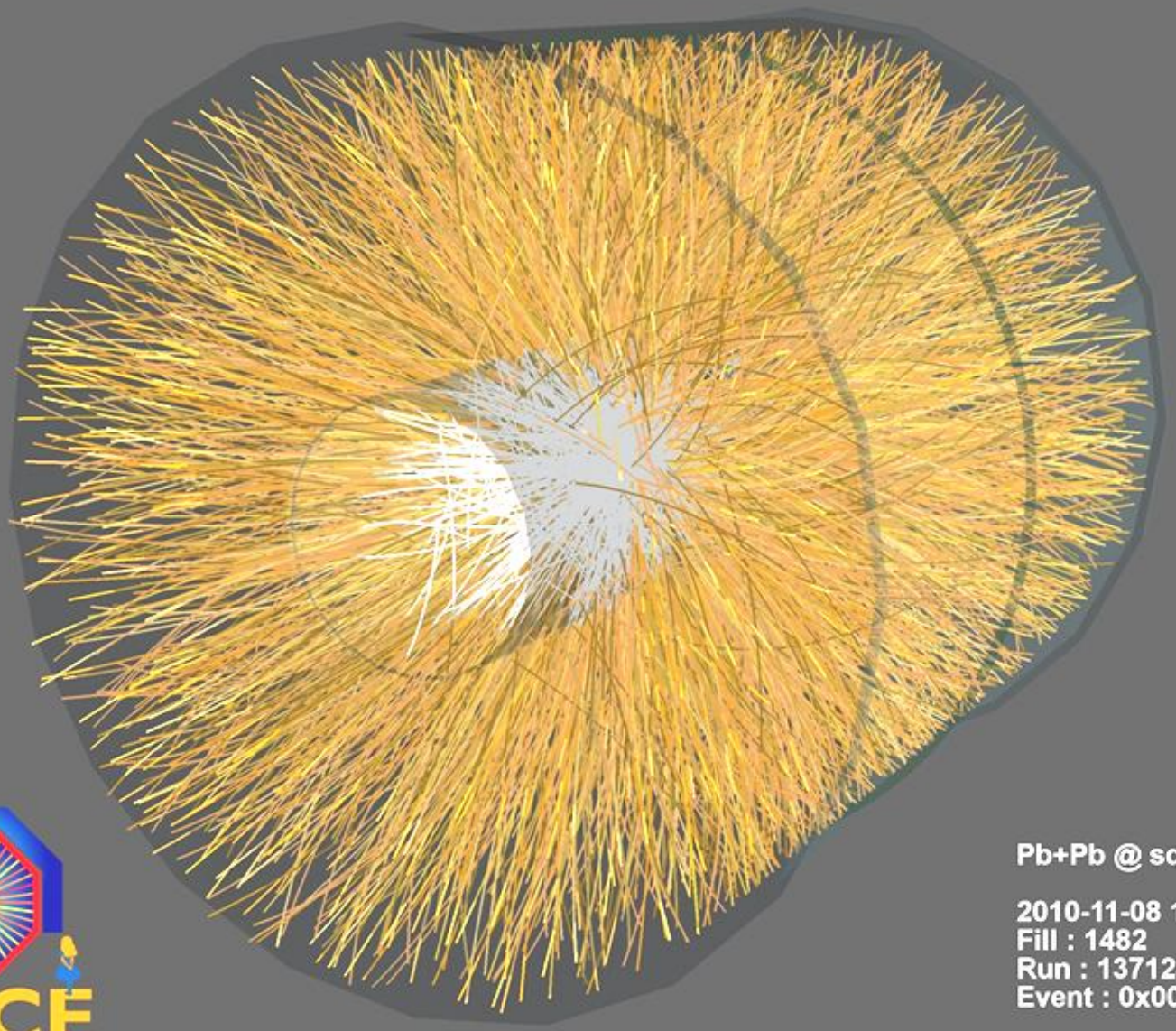

Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

ALICE

ALICE@LHC
A Large Ion Collider Experiment

- A short History of Heavy Ions
- ALICE Experiment
- pp Results
- News from the Ion Run

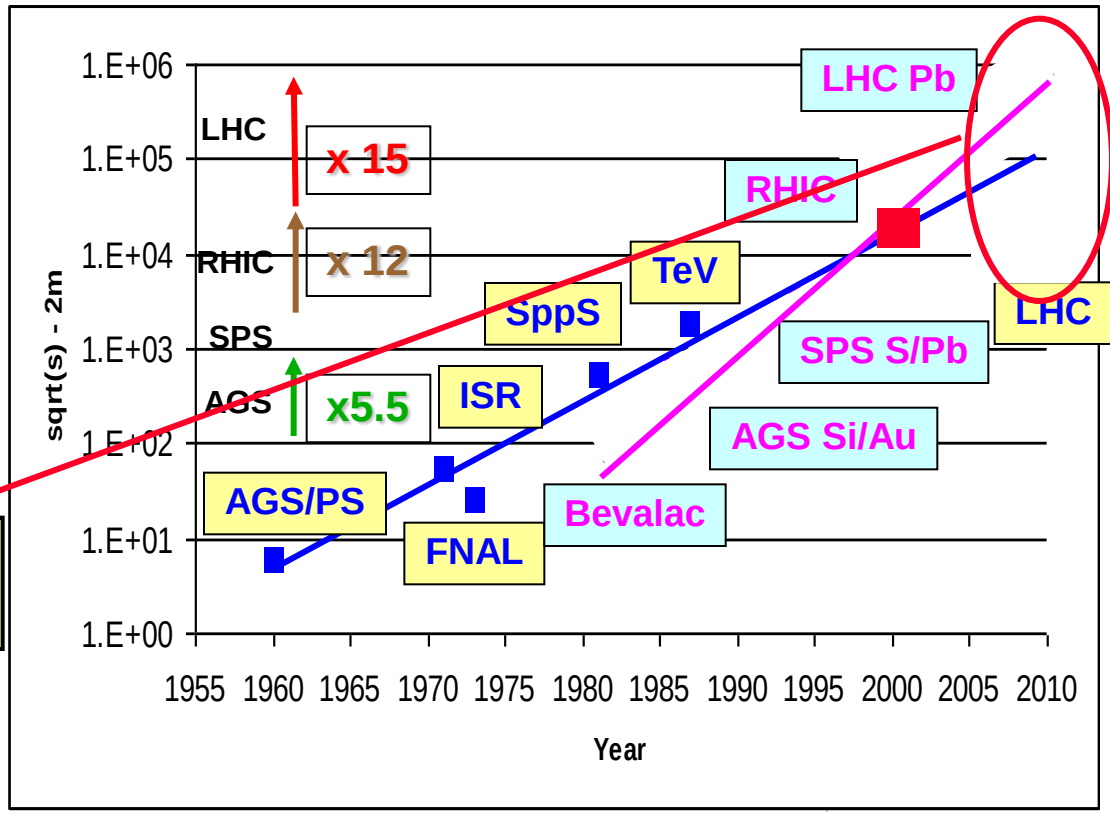
The LHC and Heavy Ions

- **Particle Physics: energy doubling time ~ 4 years**
- **Heavy Ion Physics: doubling time ~ 2 years**
  - ⇨ energy increase by factor 10^4 in ~ 30 years
  - ⇨ starting 70'- to early 80's at Bevalac
    - ✪ field started by a few dozen physicists from a handful of countries
    - ✪ > 2000 physicists active worldwide today

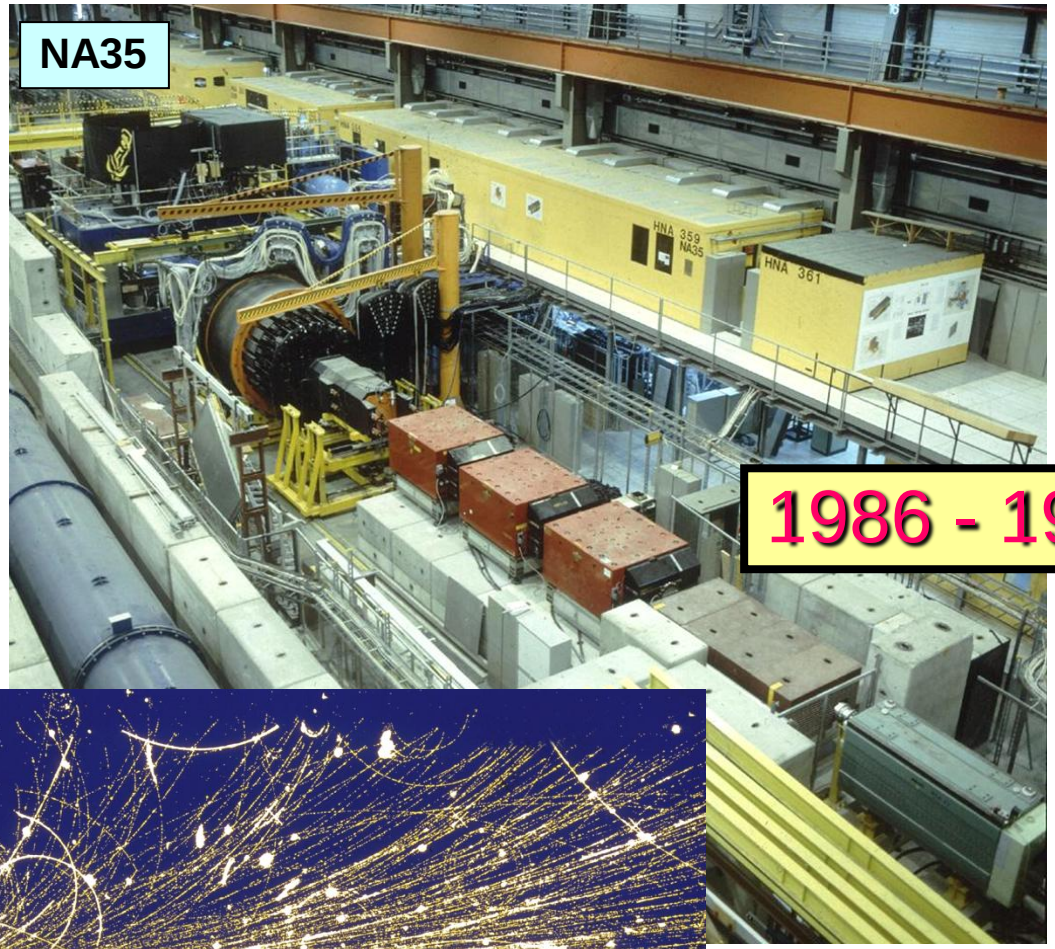
Field went from the periphery into a **central activity** of contemporary **Nuclear Physics**
(and now gets even some HEP guys excited !)

LHC: At the Energy Frontier of both Nuclear and High Energy Physics

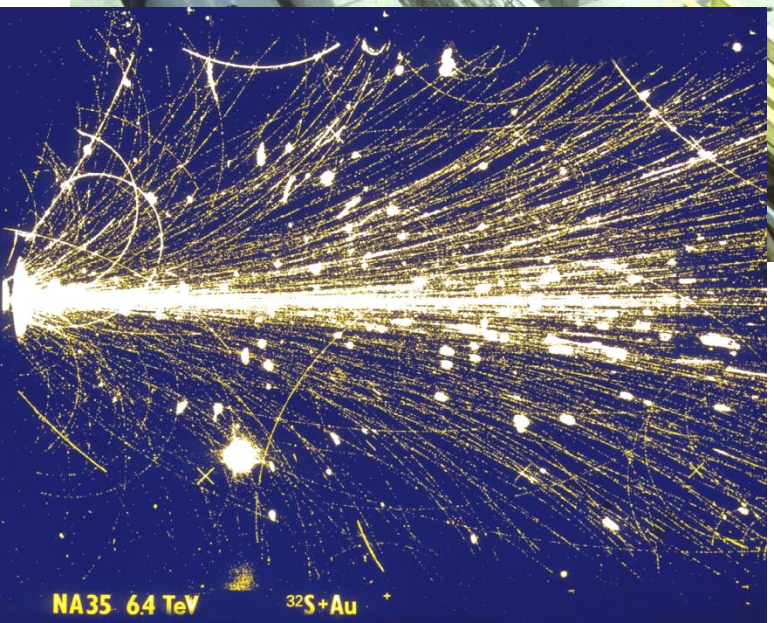
Total center-of-mass energy versus time



First Generation Experiments

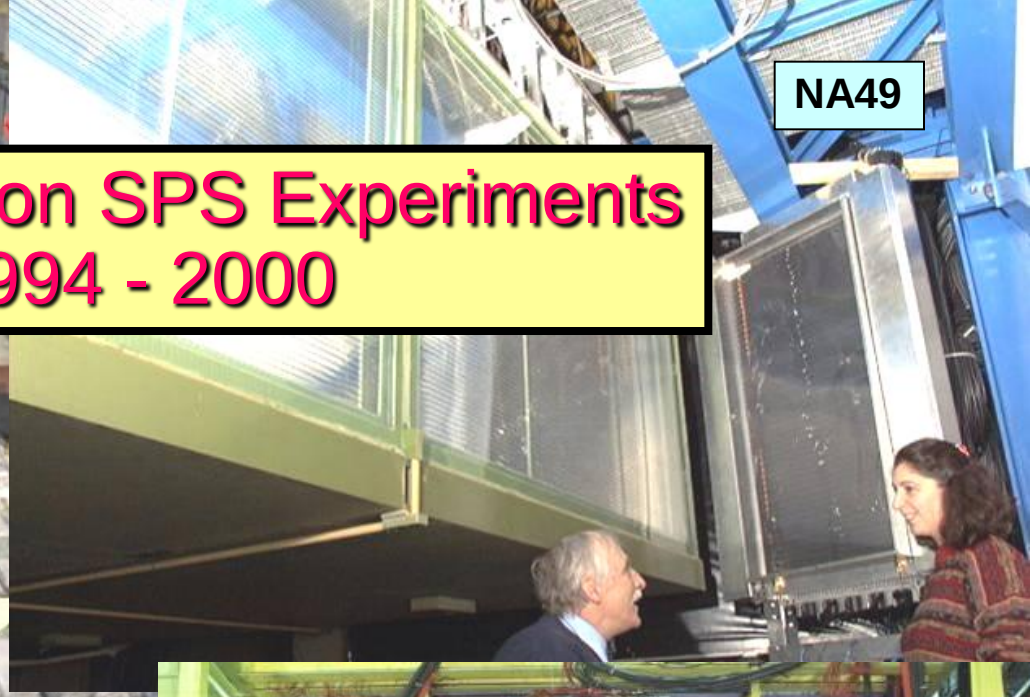


1986 - 1990

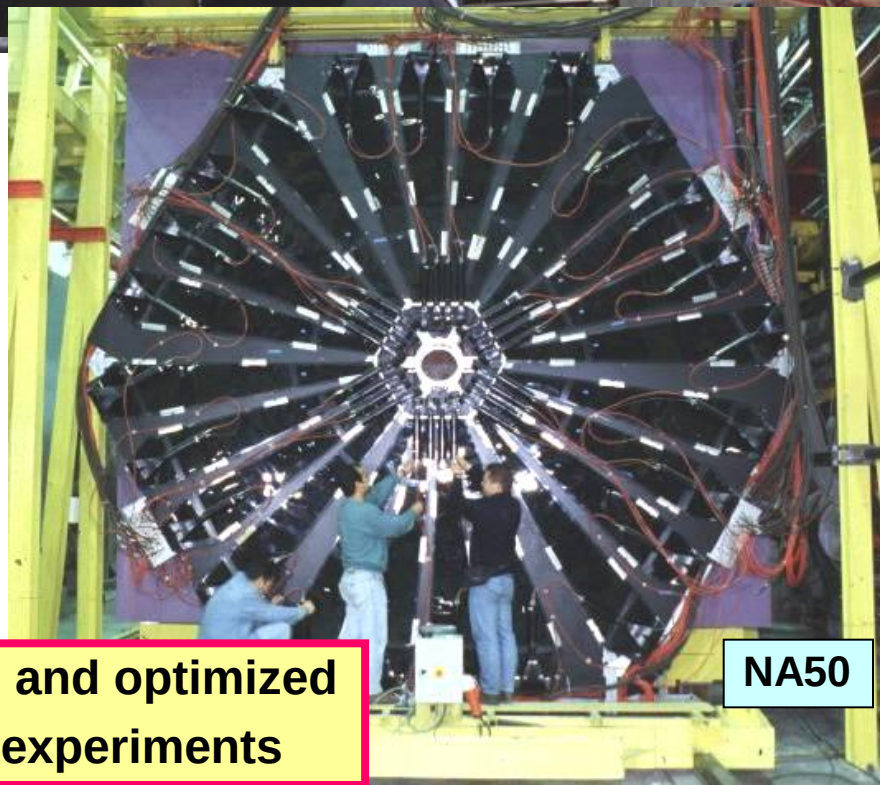


Reusing existing equipment:

UA5 streamer chamber, LBL Plastic Ball,
UA2 CCD camera, NA3 muon spectrometer,
ISR U-calorimeters, ….

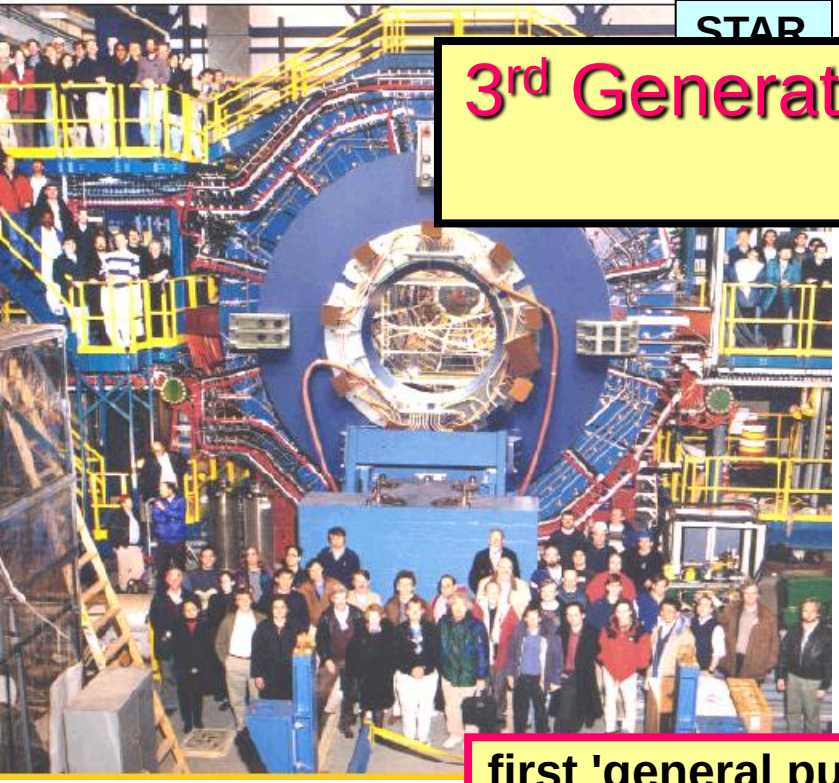


2nd Generation SPS Experiments 1994 - 2000

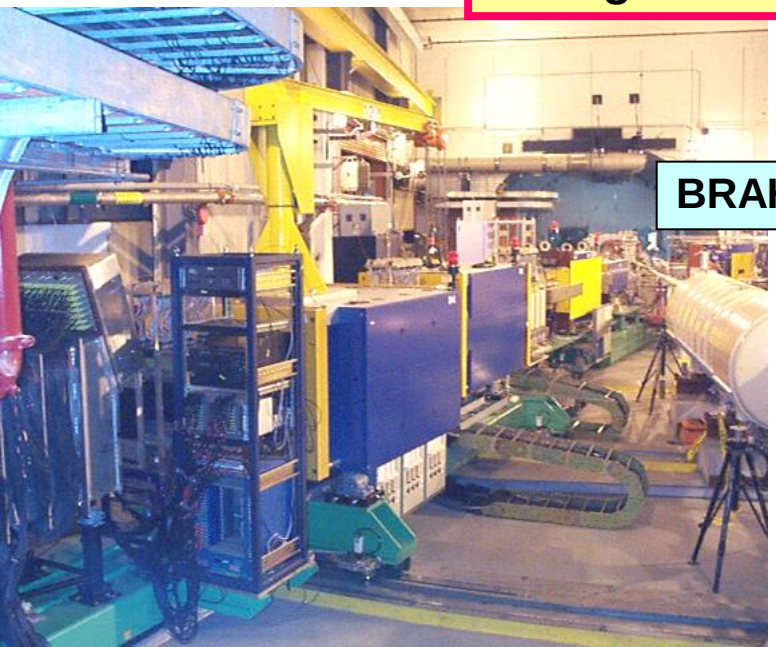


several dedicated and optimized 'special purpose' experiments

3rd Generation: RHIC Experiments > 2000

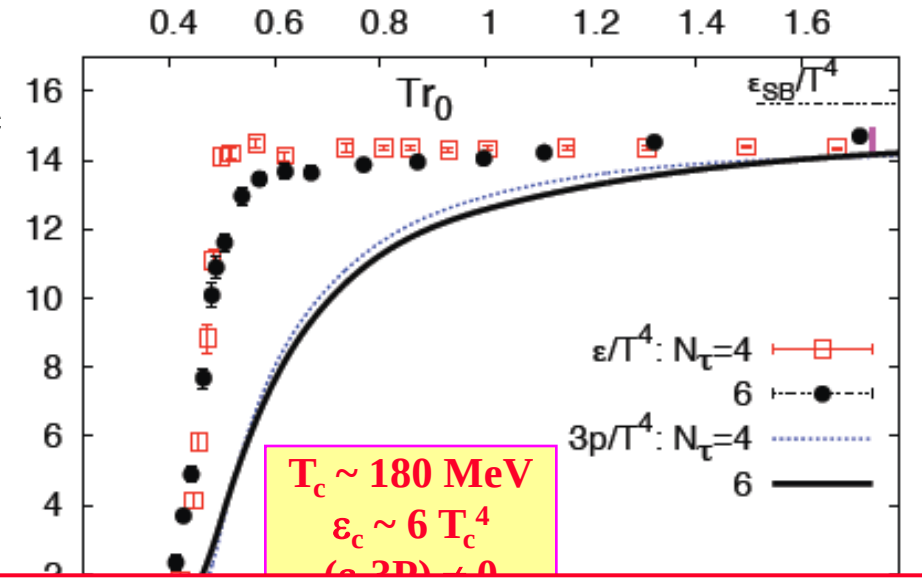


first 'general purpose' collider detectors

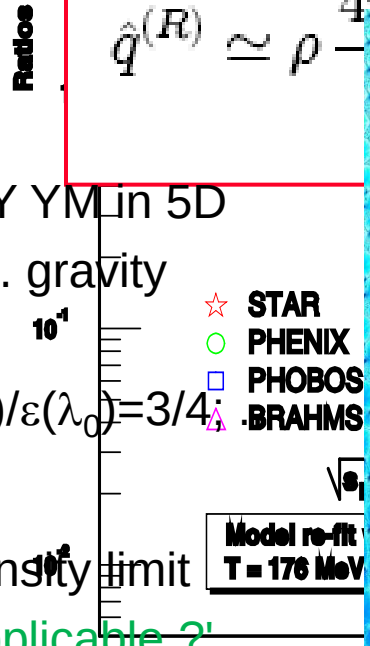


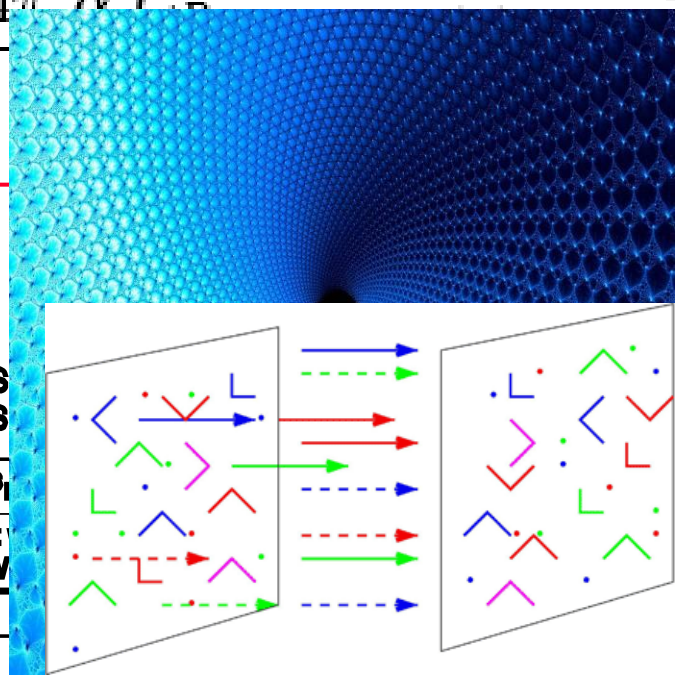
Theory Tools

- **Lattice QCD**
  - ⇨ ideal for thermodynamics(static), EoS, T_c
  - ⇨ difficult to get dynamical quantities
- **Pert. QCD**
  - ⇨ cross sections, dynamical coefficients
  - ⇨ 'right theory, wrong approximation'
- **Phenomenology**
  - ⇨ hydrodynamics, thermal models
  - ⇨ event generators (Phytia, Hijing, ..)
  - ⇨ many parameters/approximations
- **Duality: AdS/CFT**
  - ⇨ 4D gauge theory equivalent to SuSY YM in 5D
  - ⇨ strong coupling => reduced to class. gravity
  - ⇨ 'wrong theory, right approximation'
  - ⇨ remarkable results: $\eta/s = 1/4\pi$; $\varepsilon(\lambda_\infty)/\varepsilon(\lambda_0)=3/4$;
- **Color Glass Condensate**
  - ⇨ initial state: classsical FT in high density limit
  - ⇨ 'right theory, right approximation, applicable ?'



$$\hat{q}^{(R)} \simeq \rho \frac{4\pi^2 \alpha_s C_R}{}$$



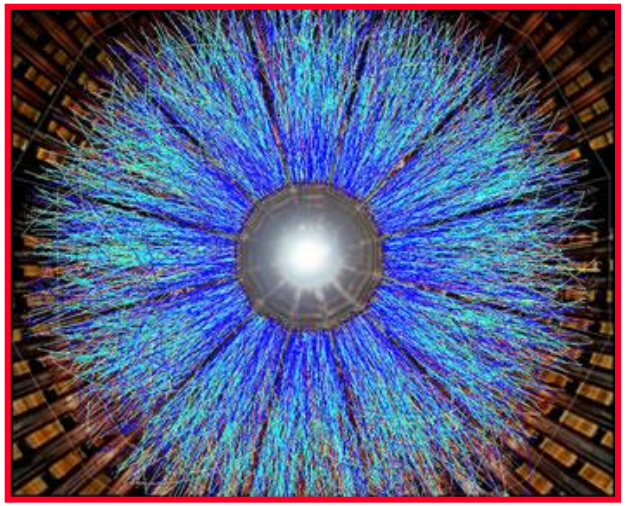


HI @LHC: Constraints and Solutions

- Extreme particle density : $dN_{ch}/d\eta$ expected ~ 2000 – 4000

  x 500 compared to pp@LHC; **x 30** compared to ^{32}S@SPS

  - ⇨ high granularity, 3D detectors
    - ✪ Silicon **pixels** and **drift** detectors, **TPC** with low diffusion gas mixture (Ne-CO_2)
  - ⇨ conservative & redundant tracking
    - ✪ up to ~**200 space points** per track
  - ⇨ large distance to vertex
    - ✪ e.g. emcal at **4.5 m** (typical is 1-2 m !)



- Large dynamic range in p_t:

  from very soft (**0.1 GeV**) to fairly hard (**100 GeV**)

  - ⇨ very thin detector, modest field **0.5 T** (low p_t),
    - ✪ ALICE: **~ 10%X_0** in r < 2.5 m (typical is 50-100%X_0)
    - ✪ vertex detector works as 'standalone low p_t spectrometer' (tracking & PID)
  - ⇨ large lever arm + good hit resolution (large p_t)
    - ✪ B= **0.5T**, tracking **L ~ 3.5m**, **BL^2** ~ like CMS !

HI @LHC: Constraints and Solutions

- Both partons & hadrons matter:

  fragmentation (i.e. hadrons) is part of the signal, not of the problem

  ⇨ partons (heavy quarks): secondary **vertices**, lepton ID

  ⇨ hadrons: use of essentially all known **PID** technologies

  ✪ dE/dx, Cherenkov & transition rad., TOF, calorimeters, muon filter, topological

- Modest Luminosity and interaction rates; short runs

  10 kHZ (Pb-Pb), (< 1/10000 of pp@10^{34}) ~ 1 month/year

  ⇨ allows slow detectors (TPC, SDD), moderate radiation hardness

  ✪ moderate trigger selectivity, no pipelines (mostly 'track & hold' electronics)

  ⇨ large event size (~ 100 MB) + short runs => high throughput DAQ (> 1GB/s)

- Single dedicated heavy ion experiment

  combine capabilities of a handful of more specialized HI expts at AGS/SPS/RHIC

  ✪ 18 detector technologies, several smaller 'special purpose' detectors (HMPID, PHOS, PMD, FMD, ZDC..)

  ✪ central barrel (~ STAR) + forward muon arm (~PHENIX)

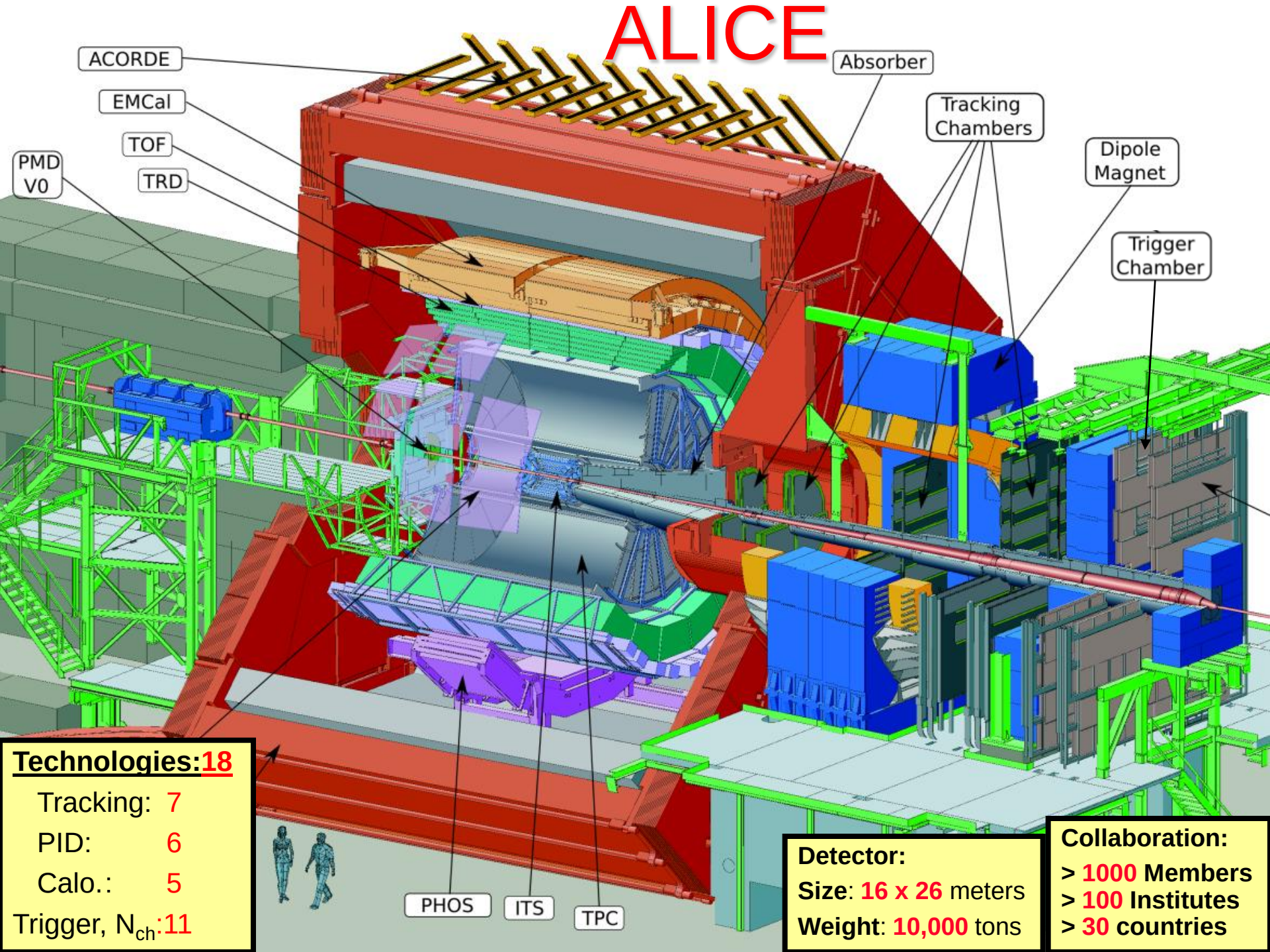
The ALICE recipe:

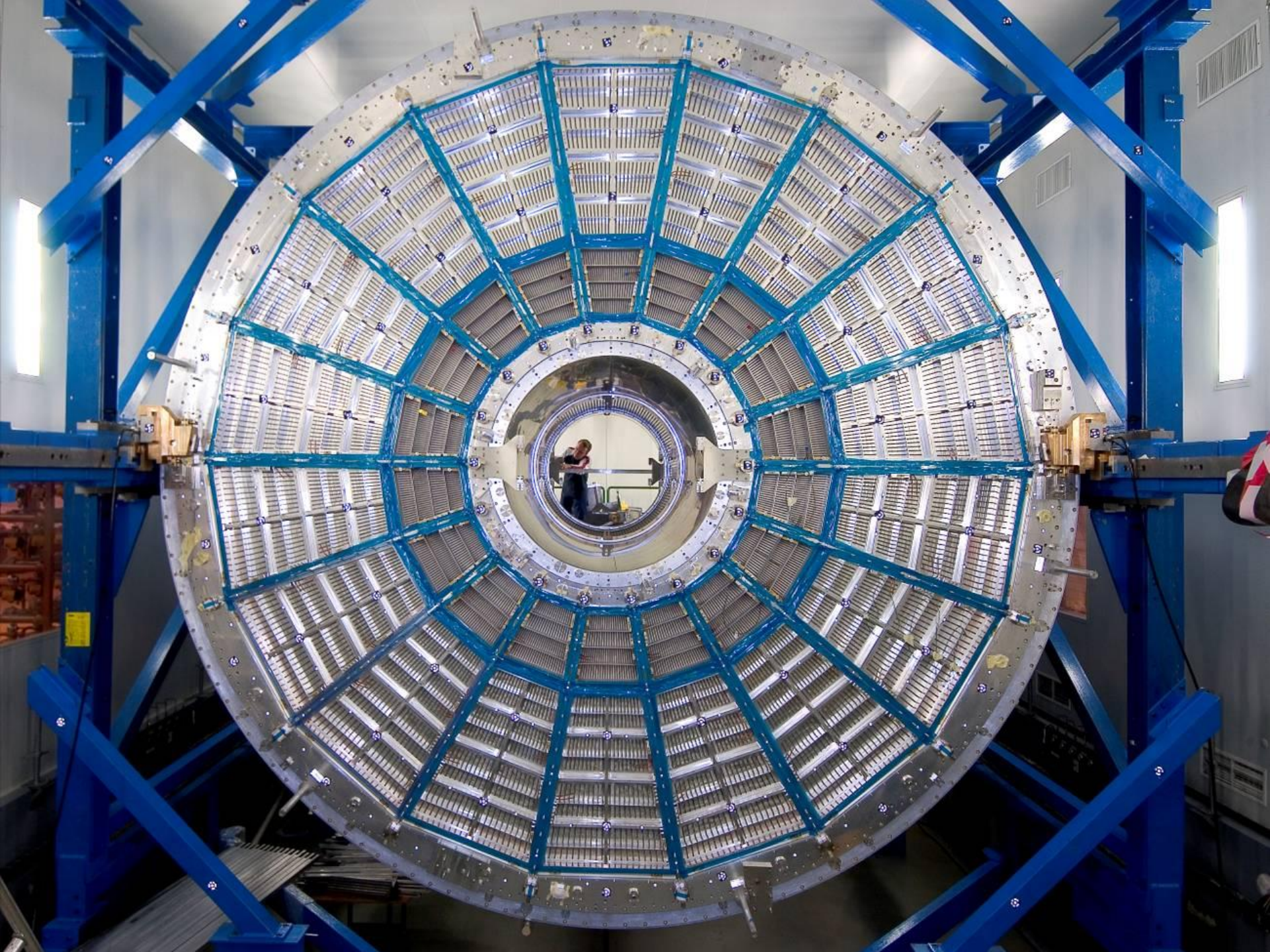
Take a good dose of STAR

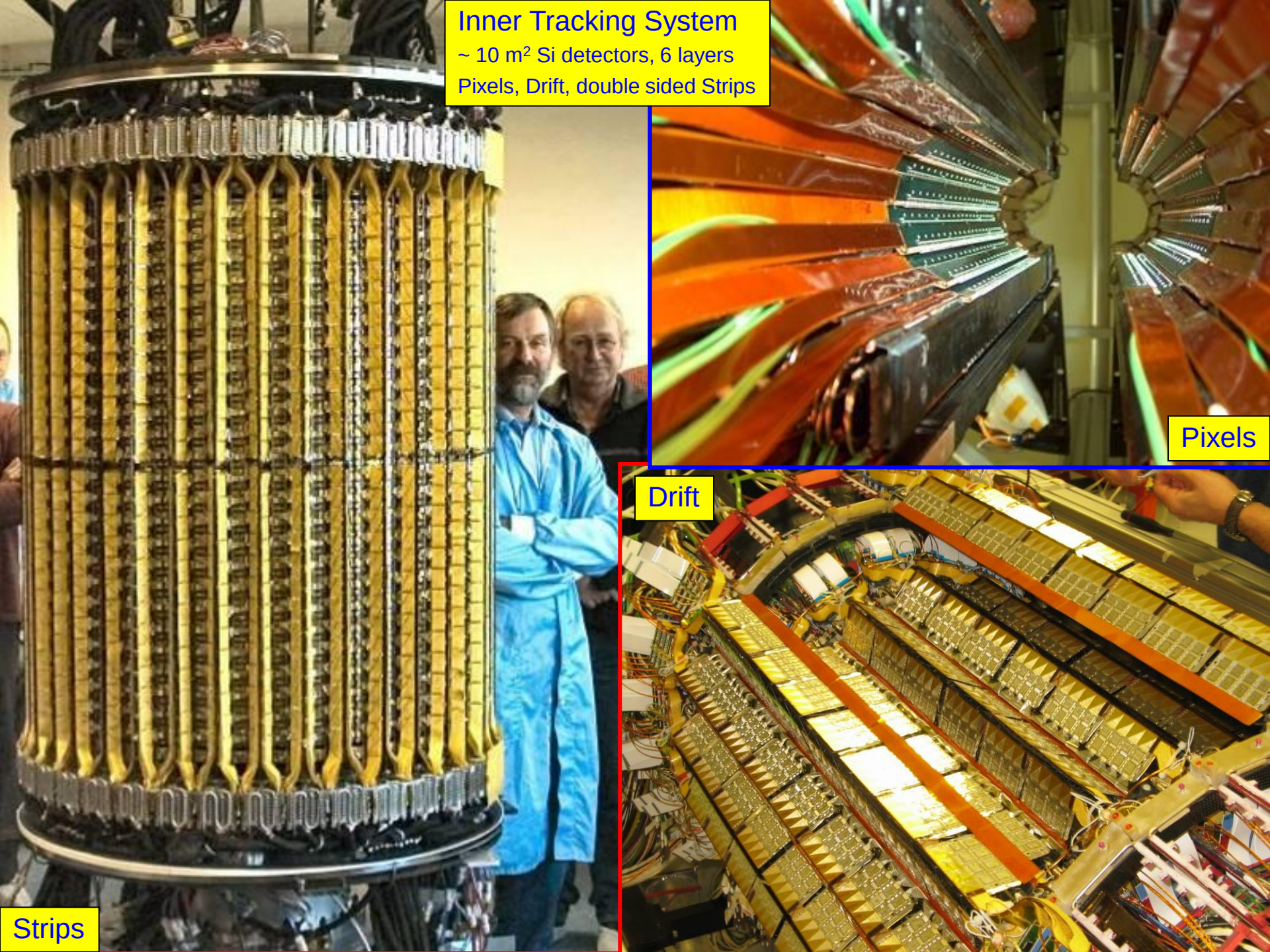
Blend with a generous helping of PHENIX

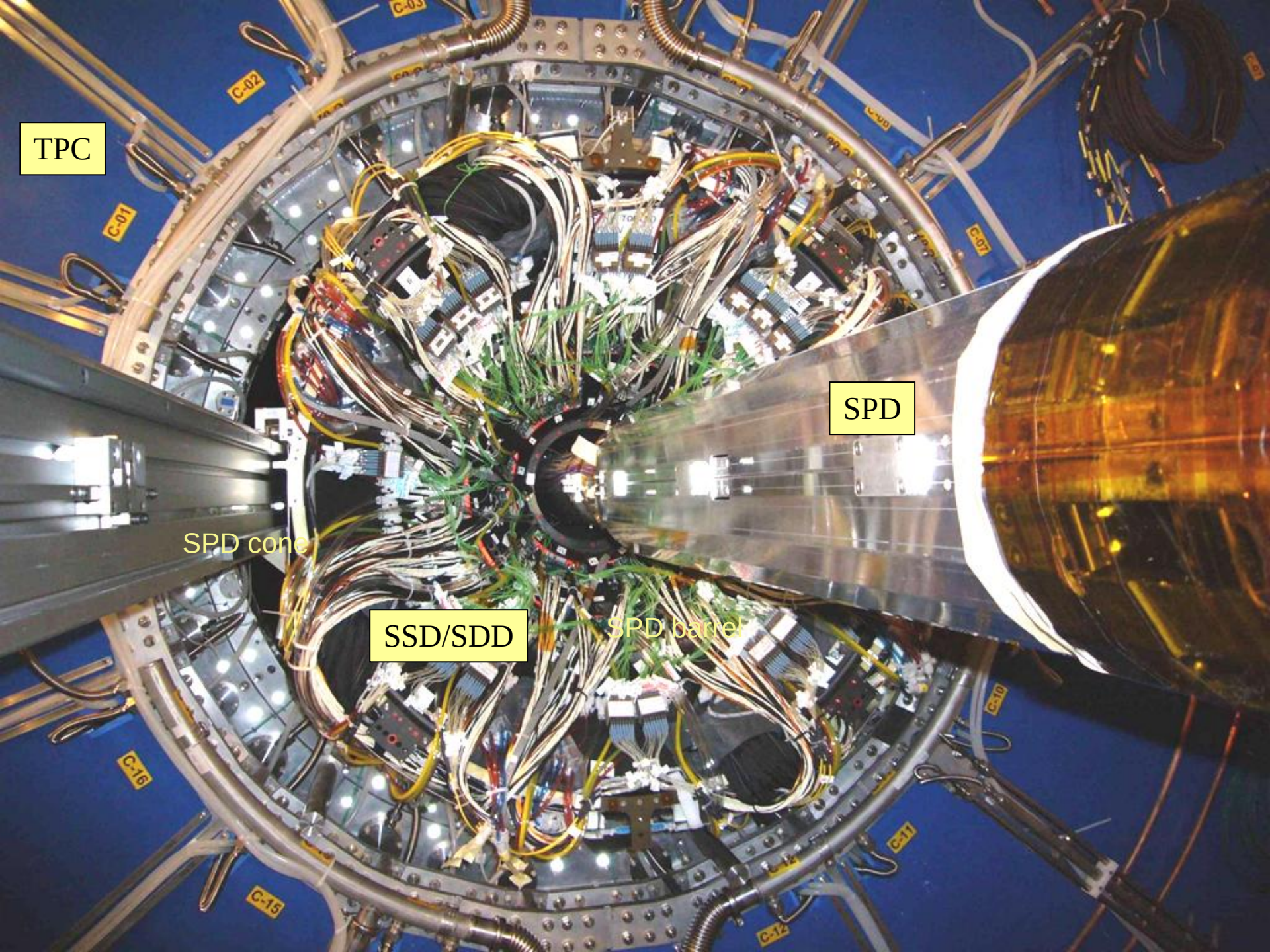
Stir over medium heat (for a loooong time)

Add a sprinkling of PHOBOS


ALICE
ACORDE
EMCal
TOF
TRD
PMD
V0
Absorber
Tracking
Chambers
Dipole
Magnet
Trigger
Chamber
PHOS
ITS
TPC
Technologies:18
Tracking: 7
PID: 6
Calo.: 5
Trigger, N_ch:11
Detector:
Size: 16 x 26 meters
Weight: 10,000 tons
Collaboration:
> 1000 Members
> 100 Institutes
> 30 countries

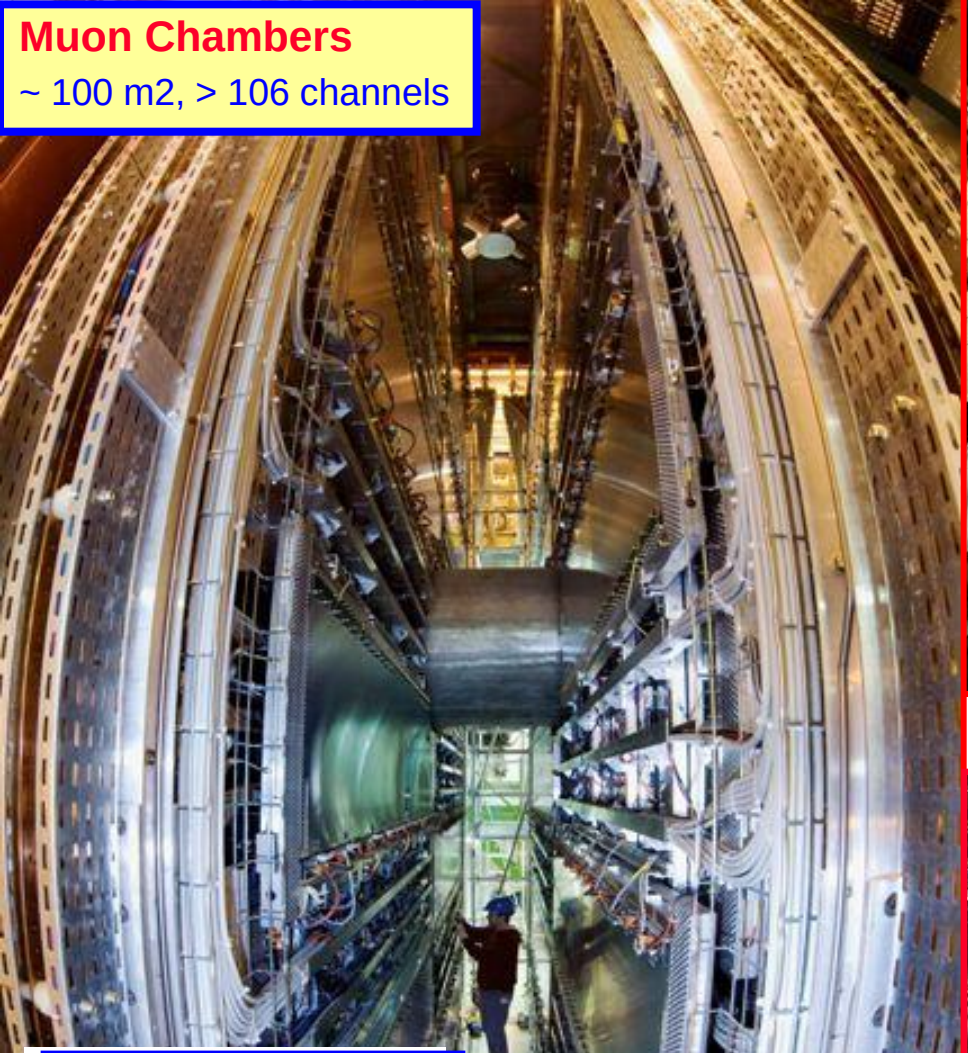



Inner Tracking System
~ 10 m² Si detectors, 6 layers
Pixels, Drift, double sided Strips
Pixels
Drift
Strips

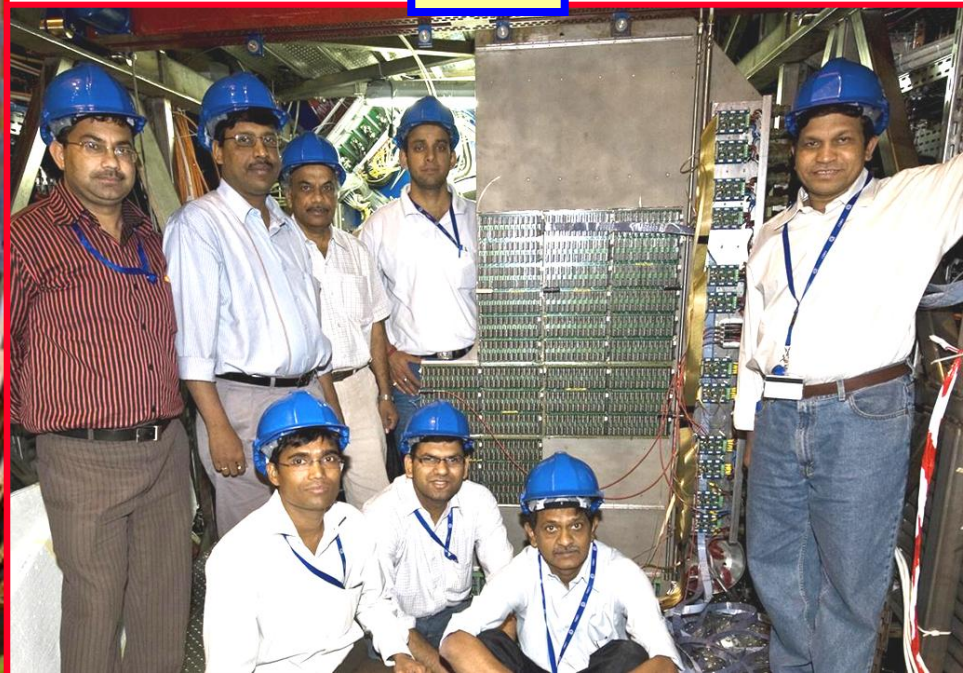

TPC
SPD
SPD cone
SSD/SDD
SPD barrel

Muon Chambers

~ 100 m2, > 106 channels



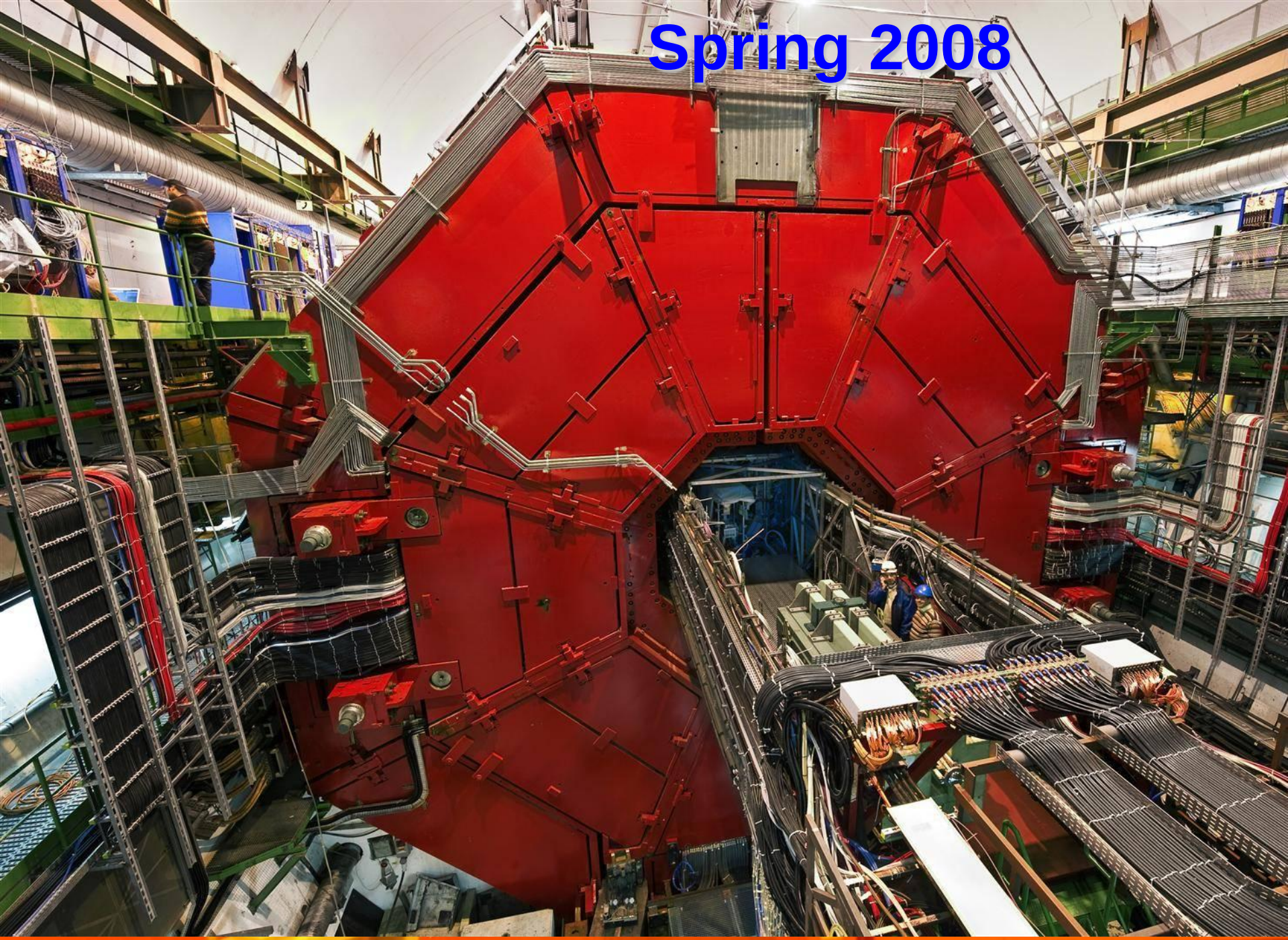
PMD



Manas electronics

‘Made in India’

Spring 2008



Detector Status

Complete since 2008:

ITS, TPC, TOF, HMPID, FMD, T0, V0, ZDC, Muon arm, Acorde PMD , DAQ

Partial installation (2010):

4/10 EMCAL* (approved 2009)

7/18 TRD* (approved 2002)

3/5 PHOS (funding)

~ 60% HLT (High Level Trigger)

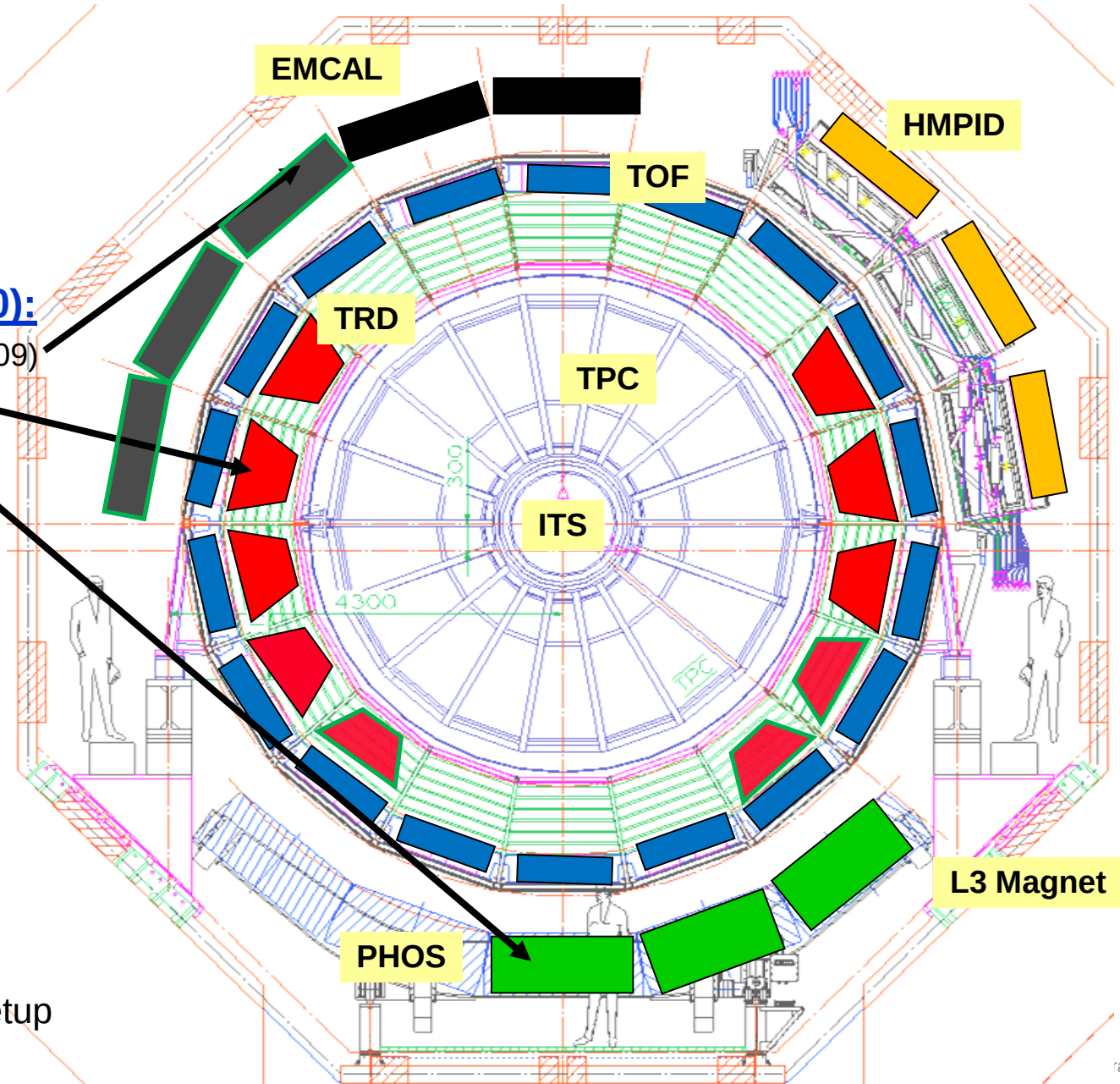
2011

10/10 EMCAL

10/18 TRD

Short Status:
All systems fully operational

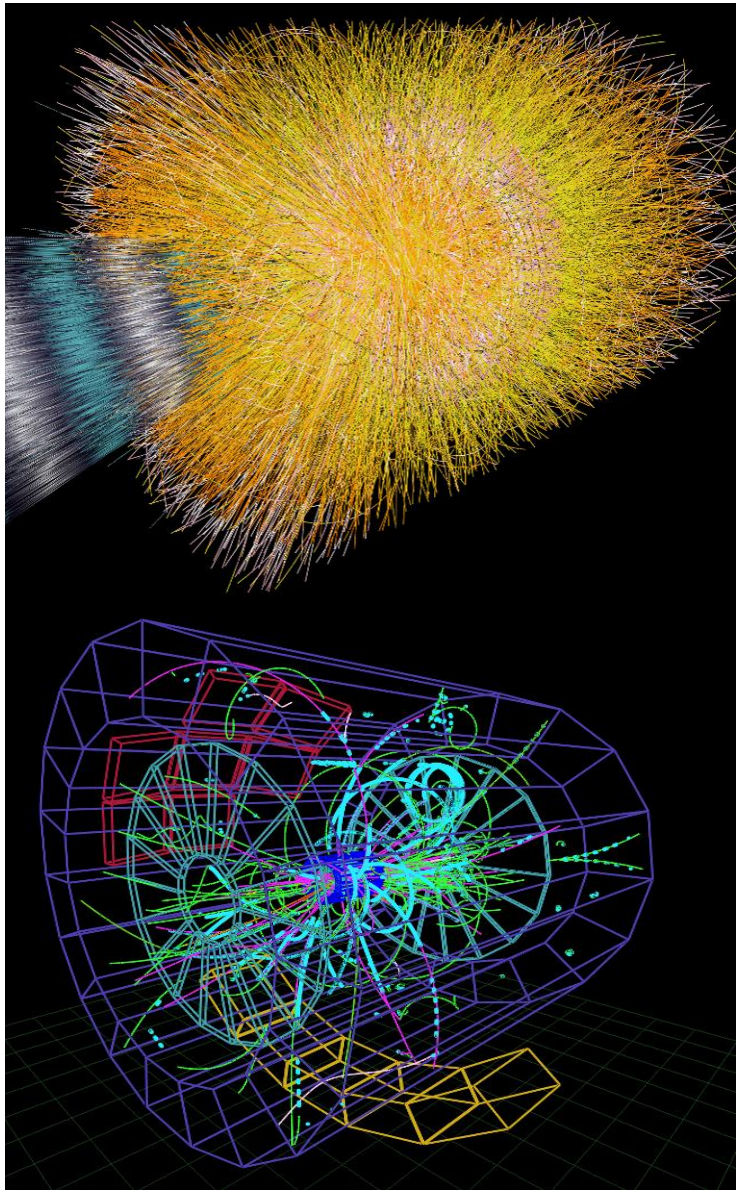
*upgrade to the original setup



pp physics in ALICE

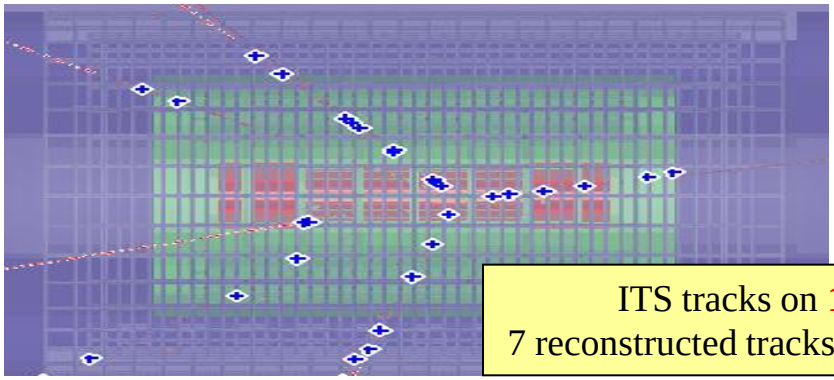
- Core Business is Heavy Ions

- Physics with pp
  - ⇨ collect ‘comparison data’ for heavy ion program
    - ✪ many signals measured ‘relative’ to pp
  - ⇨ comprehensive study of MB@LHC
    - ✪ tuning of Monte Carlo (background to BSM)
  - ⇨ soft & semi-hard QCD
    - ✪ very complementary to other LHC expts
    - ✪ address specific issues of QCD
  - ⇨ very high multiplicity pp events
    - ✪ $dN_{ch}/d\eta$ comparable to HI => mini-plasma ?



Fast Forward to

- September 2008:
  - ⇨ LHC starts with a ‘Big Bang’



ITS tracks on **12.9.2008**
7 reconstructed tracks, common vertex

- November 2009:
  - ⇨ Start of Physics @ LHC

Data Samples

Beam	Energy	# of Events	
pp	900 GeV	300 k MB	2009, analysis finished
pp	900 GeV	~ 8 M MB	2010, partially analyzed
pp	2.36 TeV	~ 40 k MB	2009, only ITS, $dN_{ch}/d\eta$
pp	7 TeV	~ 800 M MB ~ 50 M muons ~ 20 M high N_{ch}	2010
PbPb	2.76 TeV/N	~ 30 M MB	2010
pp	2.76 TeV	~ 70 M MB ~ 20 nb^{-1} (rare triggers)	2011, analysis started

LHC performed exceedingly well:
- increasing pp $\mathcal{L}$ by 10^5 in 2010 ($\mathcal{L} > 2x10^{32}$)
- delivering > 8 μb^{-1} Pb in 4 weeks ($\mathcal{L} > 2x10^{25}$, ~ 1/20 $\mathcal{L}_{max}$)

pp Results: A rich Harvest..

Published Results

- N_{ch} multiplicity & distributions
  - 900 GeV: **EPJC**: Vol. 65 (2010) 111
  - 900 GeV, 2.36 TeV: **EPJC**: Vol. 68 (2010) 89
  - 7 TeV: **EPJC**: Vol. 68 (2010) 345

  } Global event properties

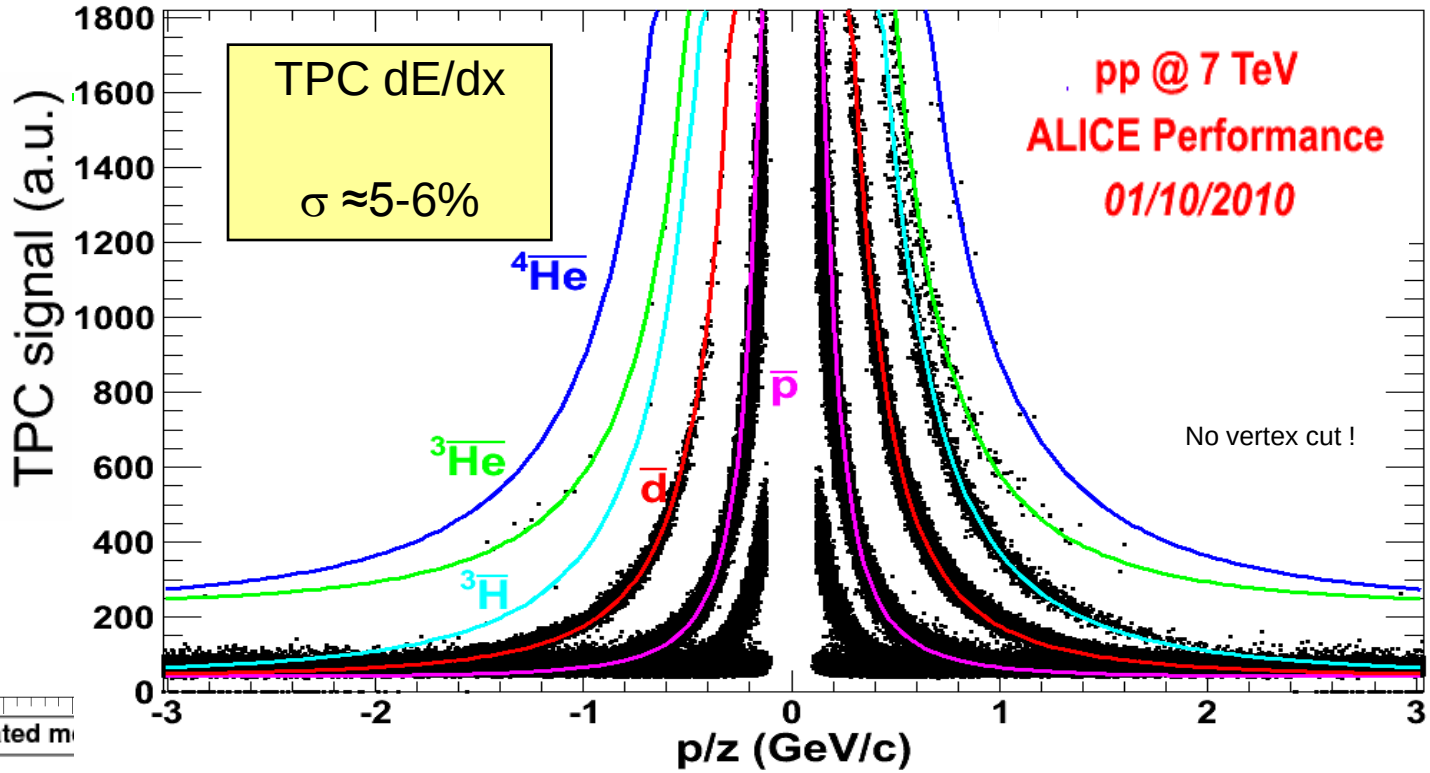
- pbar/p ratio (900 GeV & 7 TeV) **PRL**: Vol. 105 (2010) 072002 → clarifies QCD issue
- Momentum distributions (900 GeV) 1 **LB**: Vol. 693 (2010) 53
- Bose-Einstein correlations (900 GeV) 2 **RD**: Vol. 82 (2010) 052001
- Strangeness (K^0,Λ,Ξ,Ω,ϕ) (900 GeV) **EPJC** Vol. 71 (2011) 1594
- Identified particles (π,K,p) (900 GeV) **arXiv:**1101.4110, acc. EPJC
- Bose-Einstein correlations (7 TeV) 3 **arXiv:**1101.3665, sub. PRD
- Quarkonia J/ψ –> $\mu\mu$, e^+e^- (7 TeV) under collaboration review

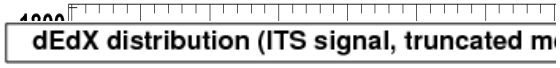
} Comparison Data

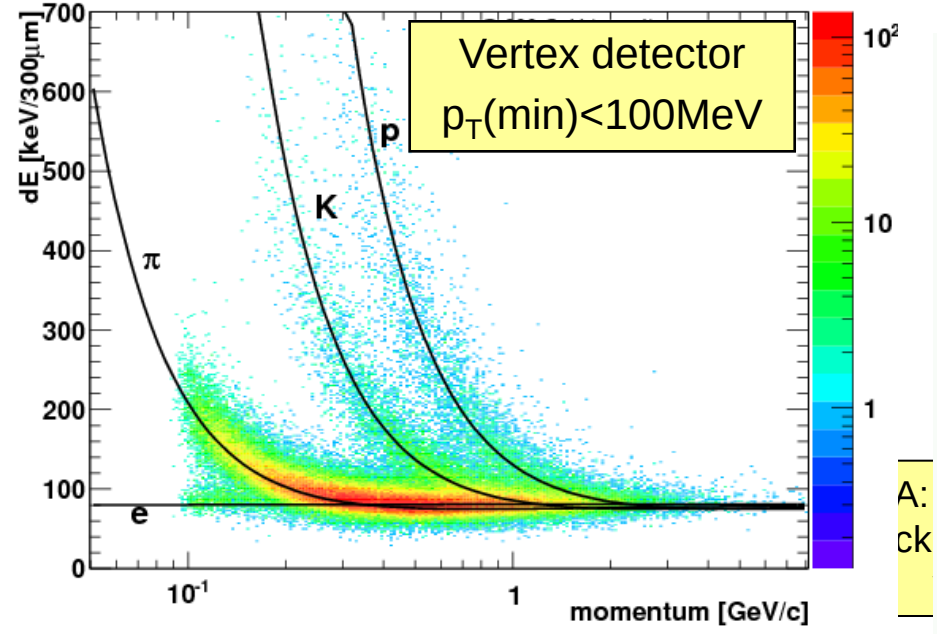
Many ongoing analyses/advanced paper drafts

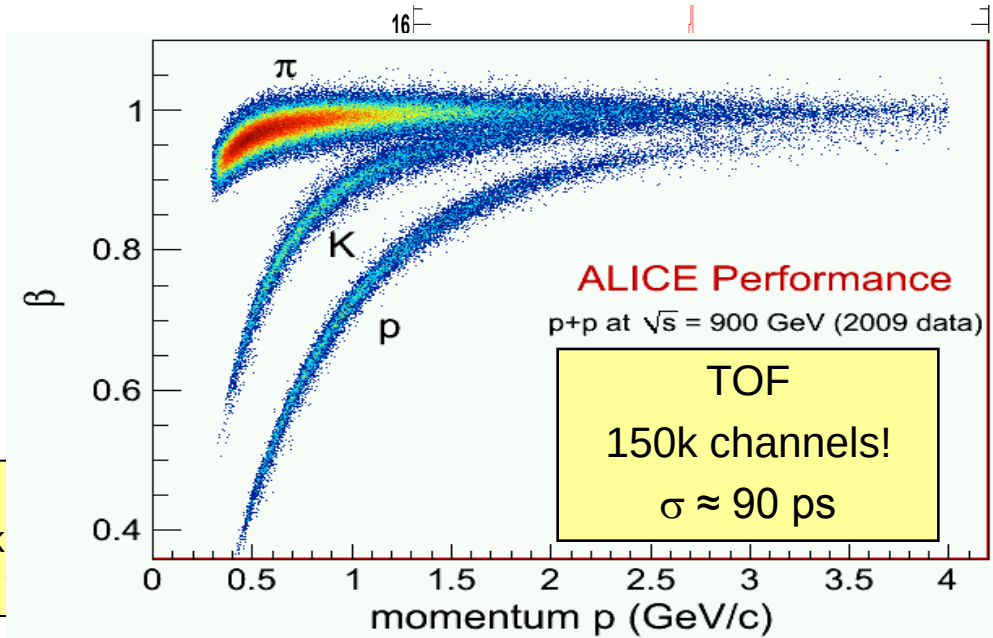
- 7 TeV event properties: spectra, identified particles, strangene[illegible]igh multiplicity 3
- Heavy flavour: charm (D^0,D^+, D*), heavy quarks (c,b) –> μ, e^-
- pQCD: Event topology, jet fragmentation, 2-particle correlations…
- .....

PID detectors

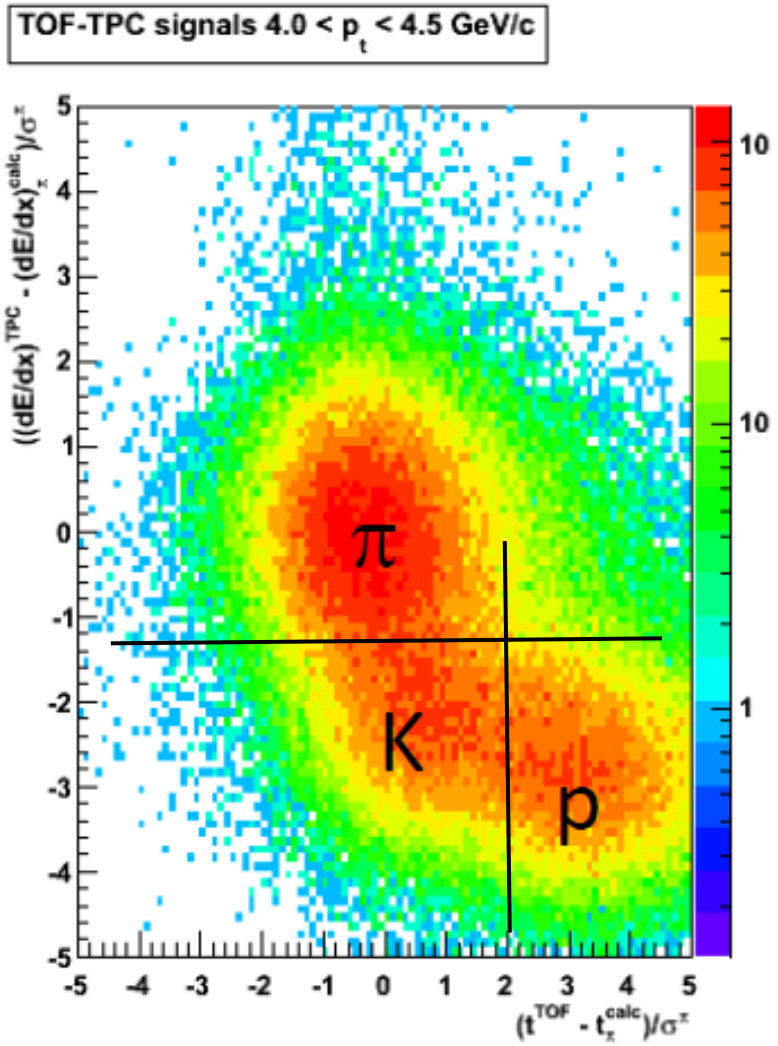


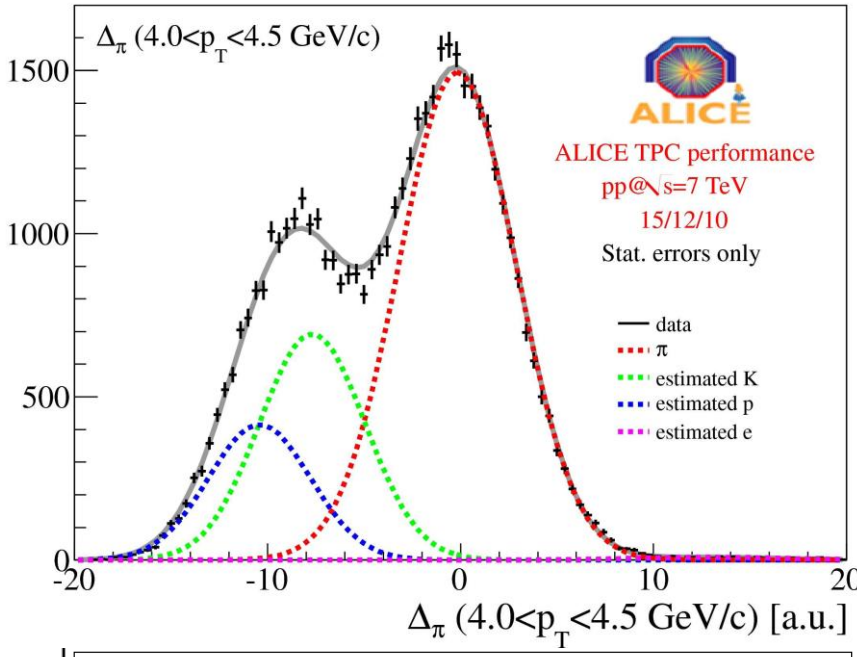


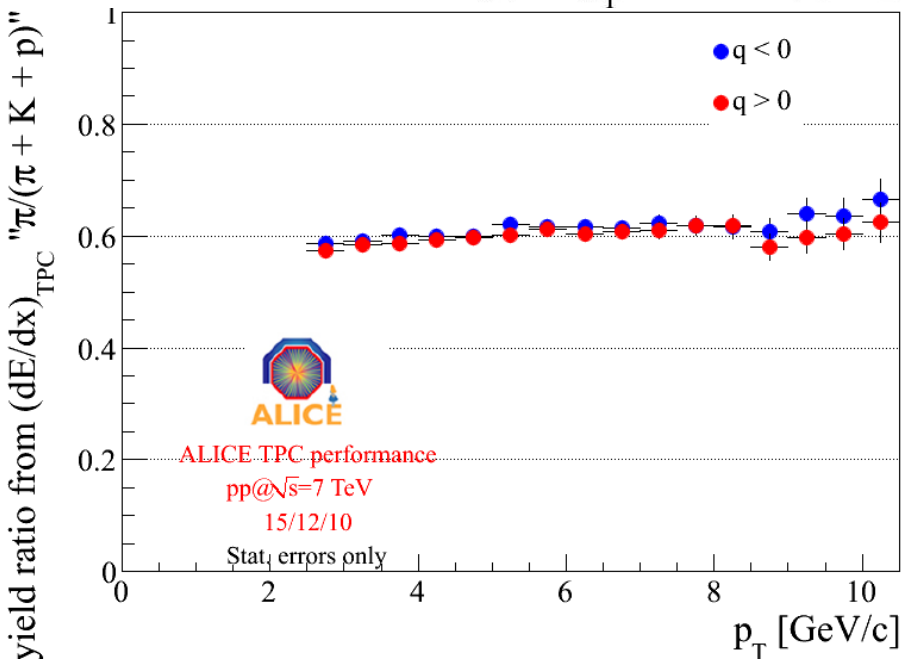




PID at high p_T





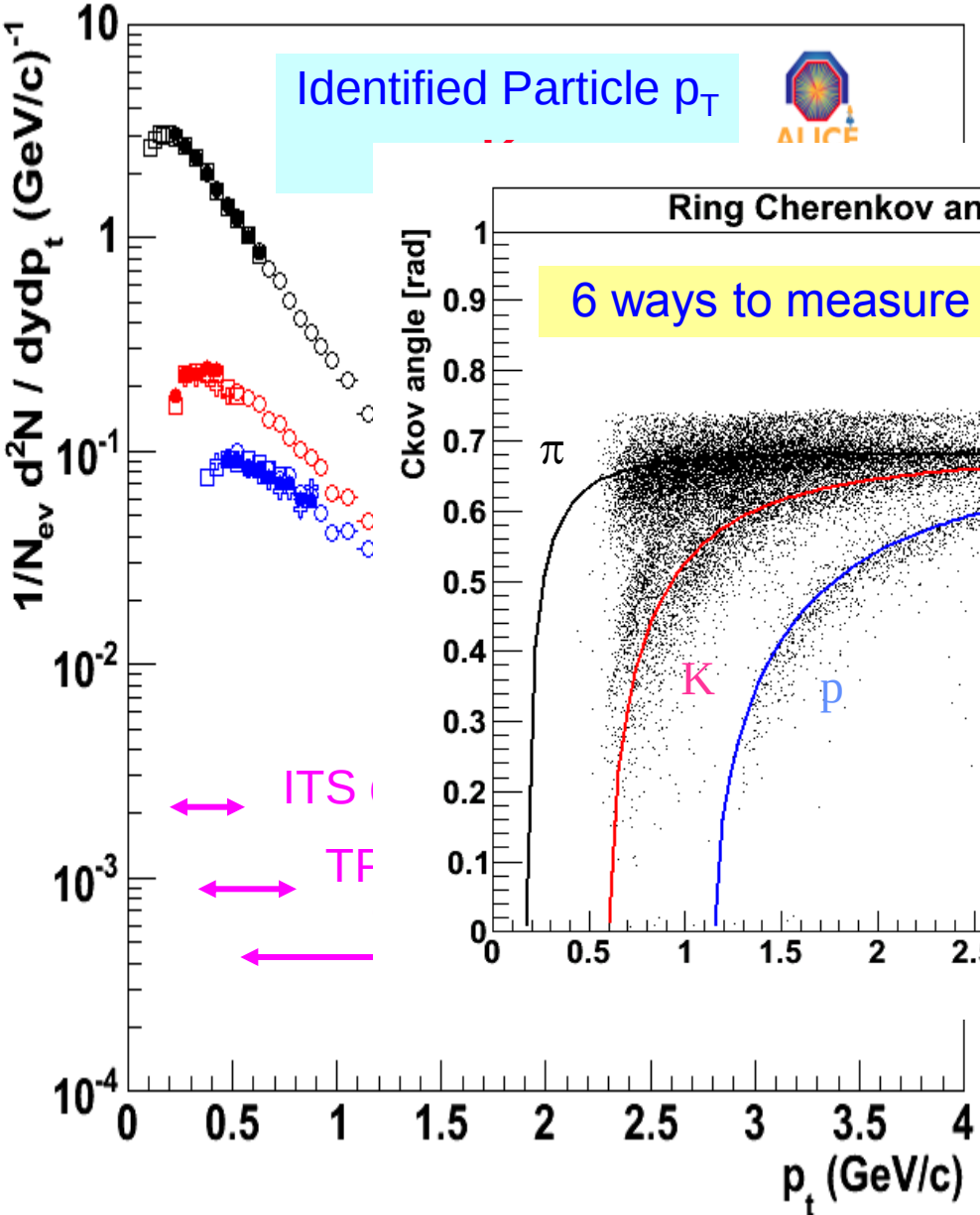


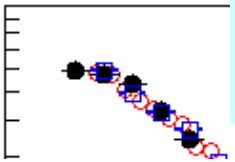
Identified Particles

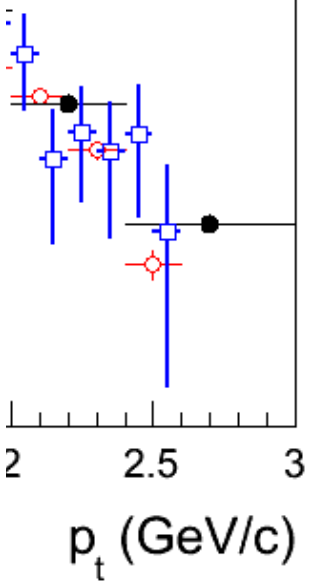
Identified Particle p_T

Kaon p_T distributions
stable & decays

6 ways to measure Kaons …

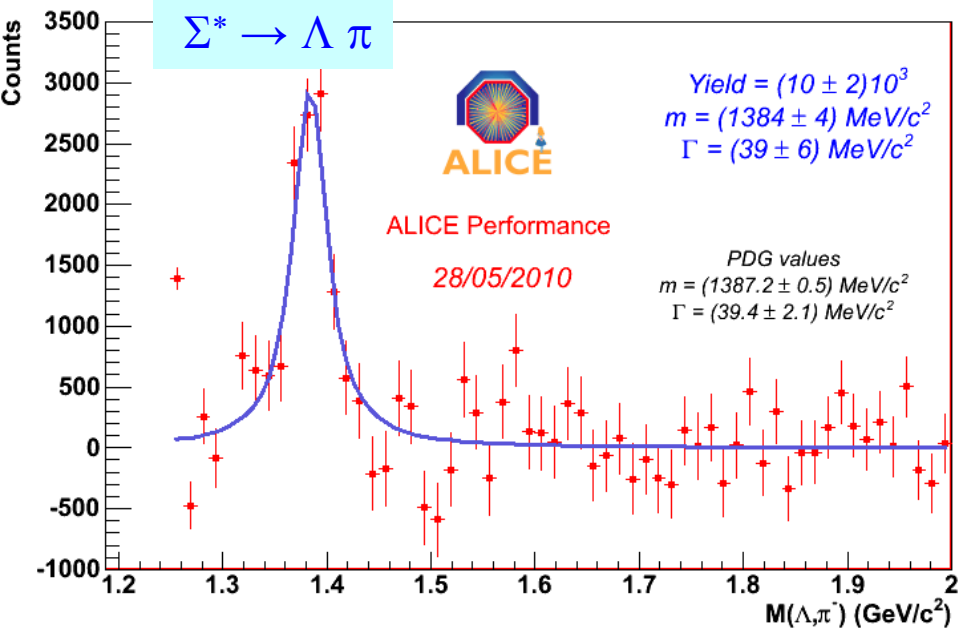


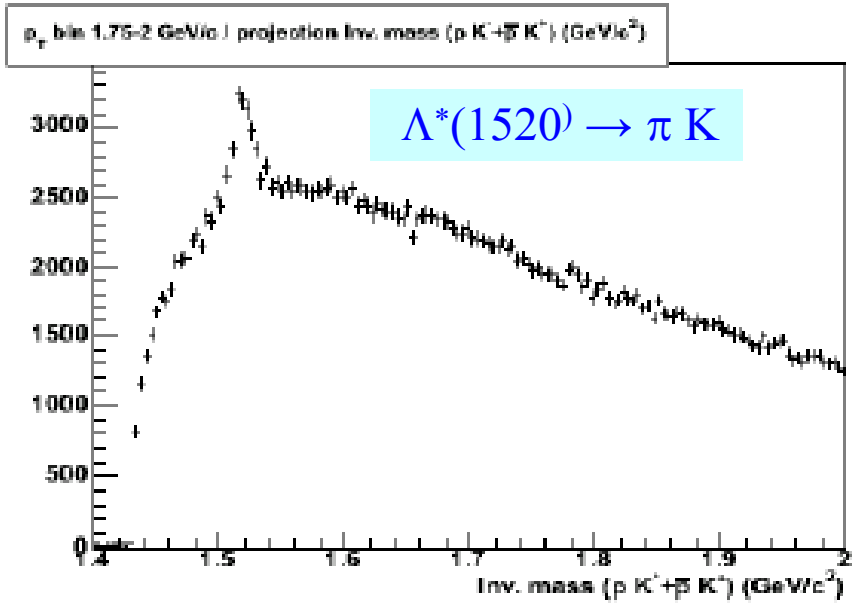


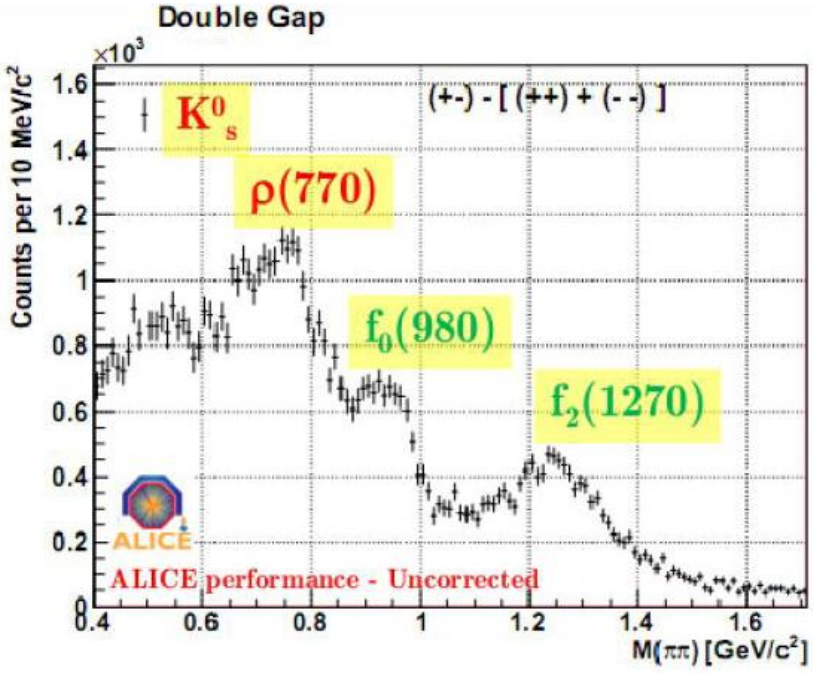


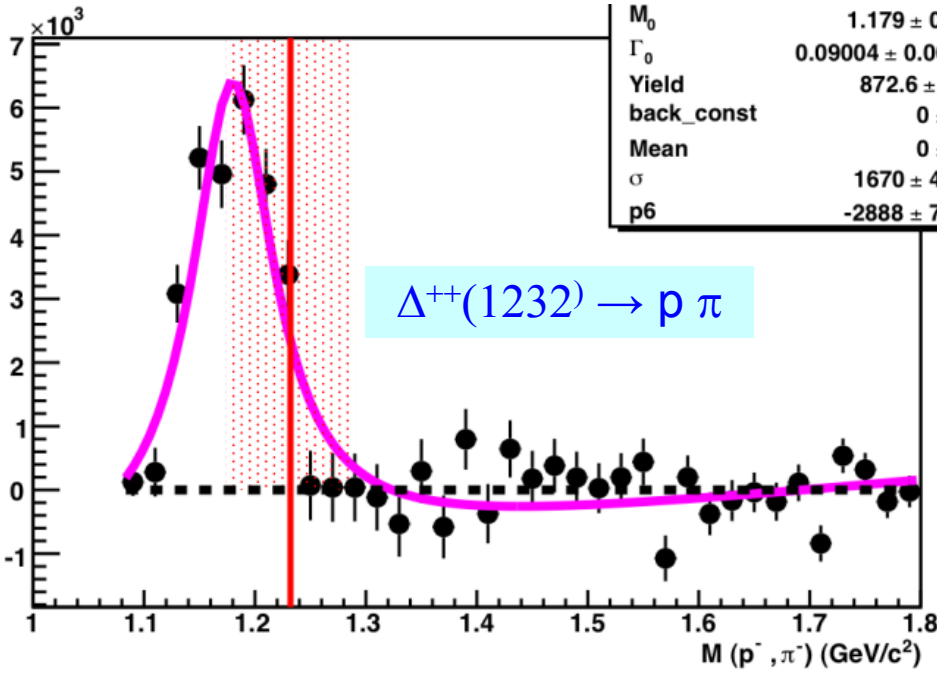
ALICE Performance
Not fully corrected
04/06/2010

Hadronic Resonances..

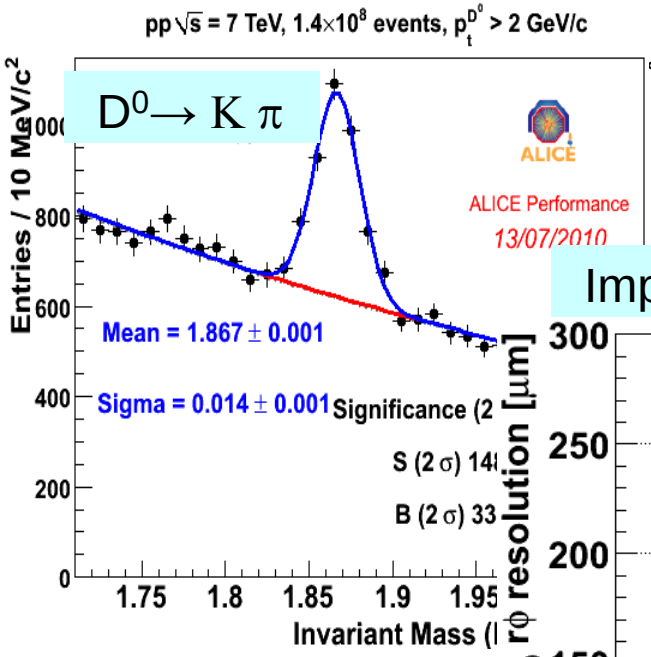


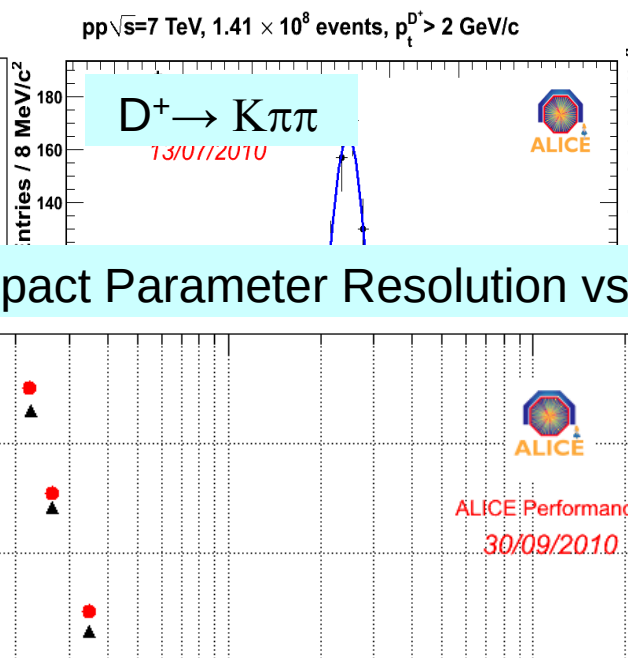


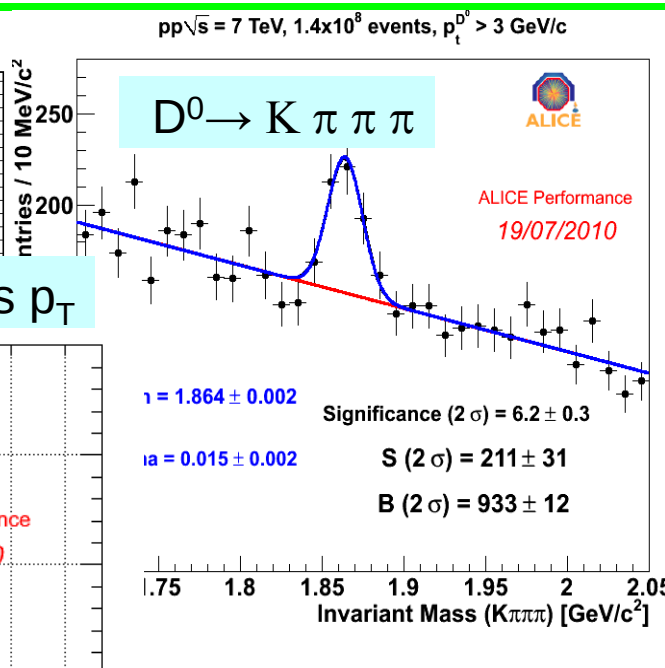


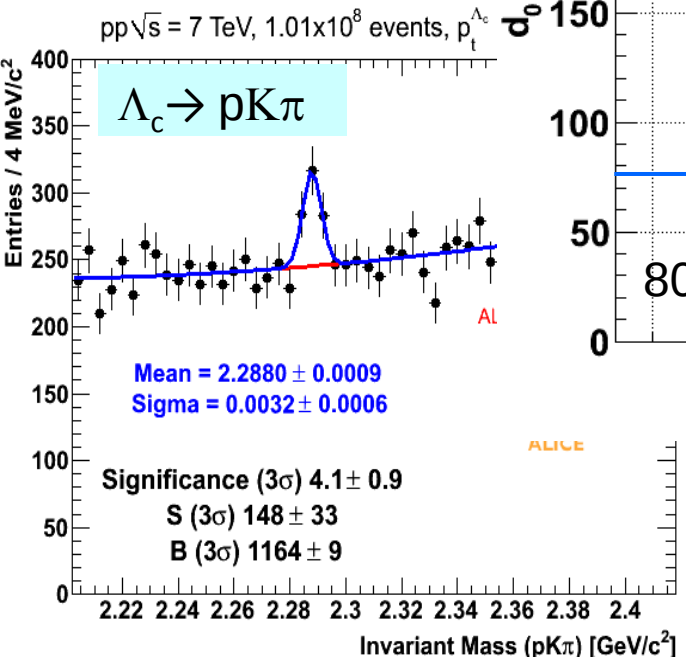


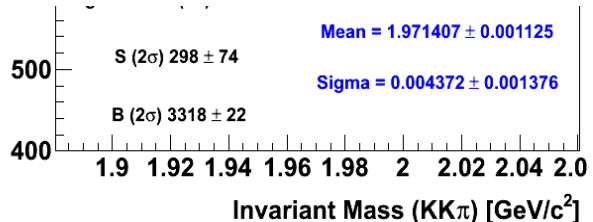
Charm at 7 TeV

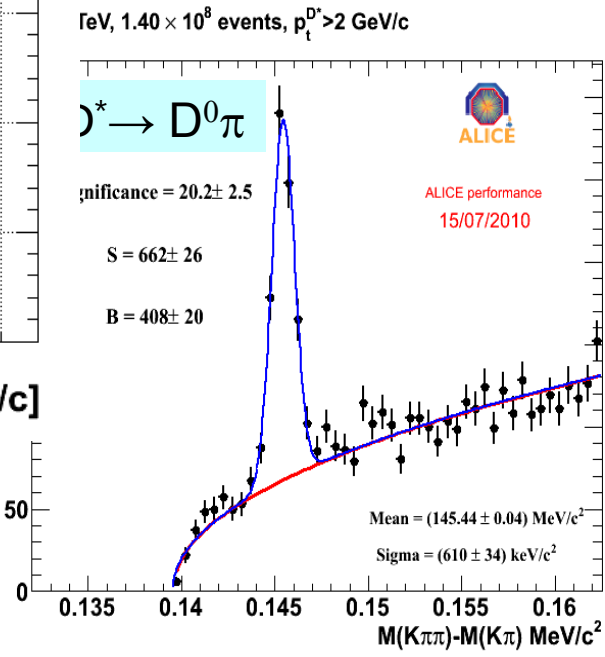










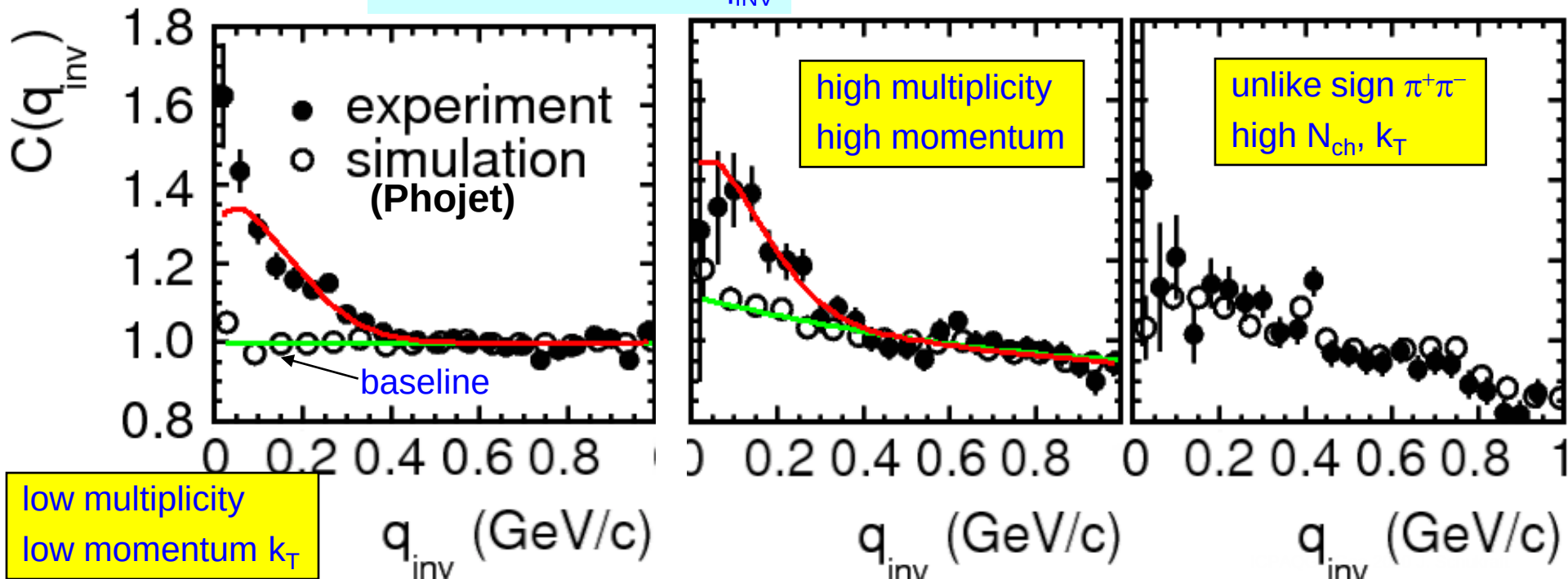


1) Bose Einstein Correlations

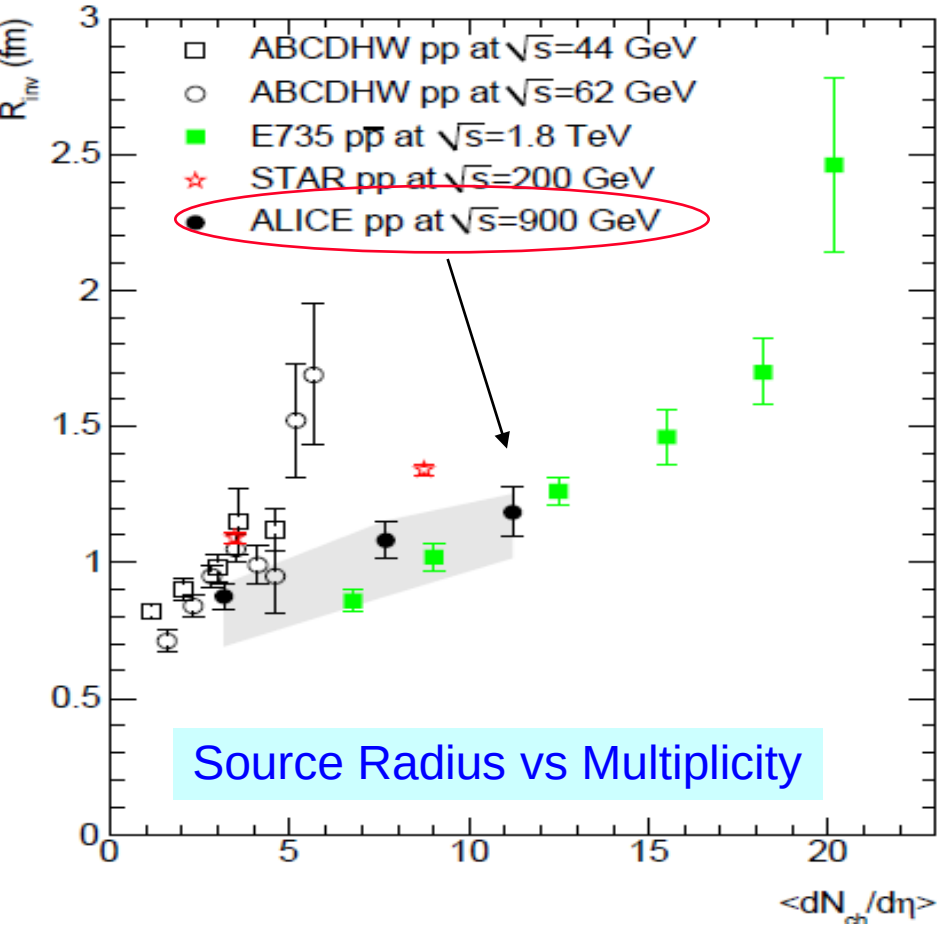
- QM **enhancement** of identical Bosons at small momentum difference
  - ⇨ **'enhancement'** rel. to phase-space **and** any non-BE correlations ('baseline')
    - ✪ non-BE correlations important at high √(s) ('minijets')
    - ✪ less so at RHIC, but definitely at FNAL/LHC !

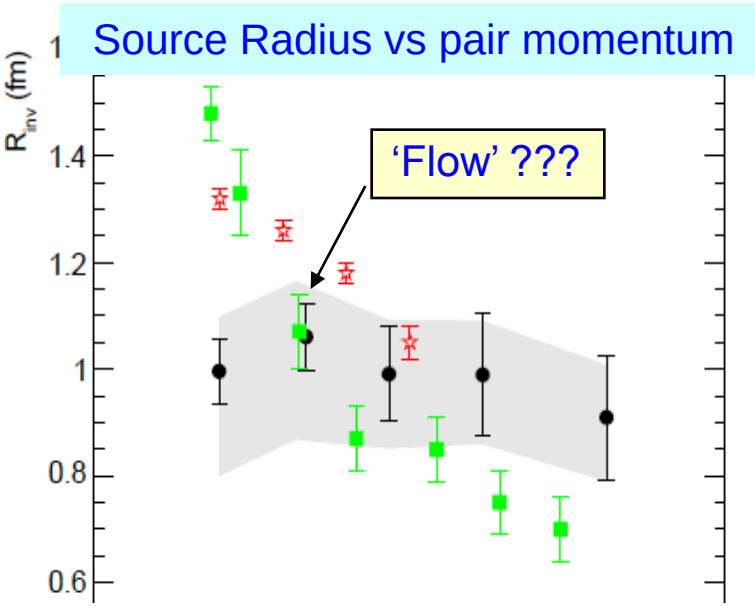
Important Message: At LHC, even MB events show signs of pQCD !
We may not always be able to rely on common wisdom & analysis techniques which were correct at lower energies..

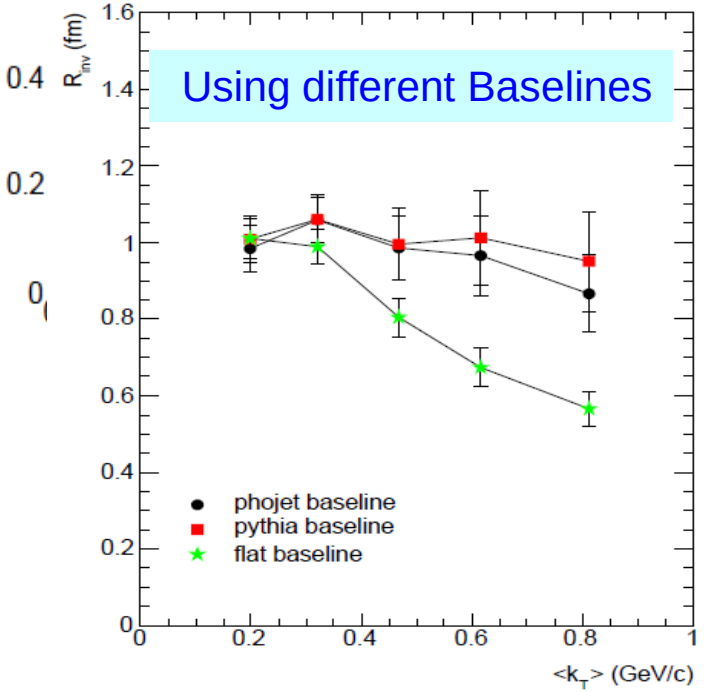
BE enhancement vs q_{INV}



HBT @ 900 GeV







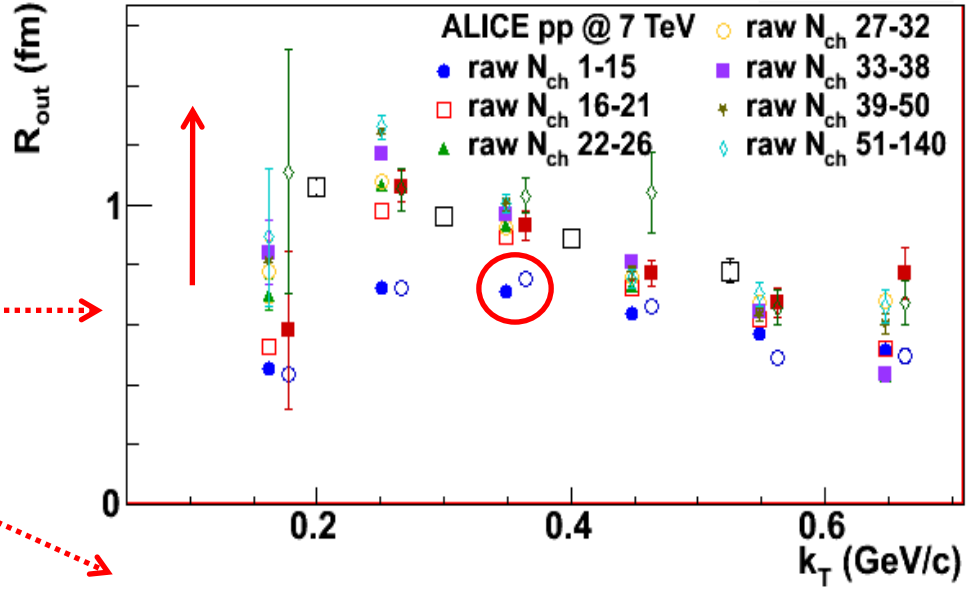
Results:

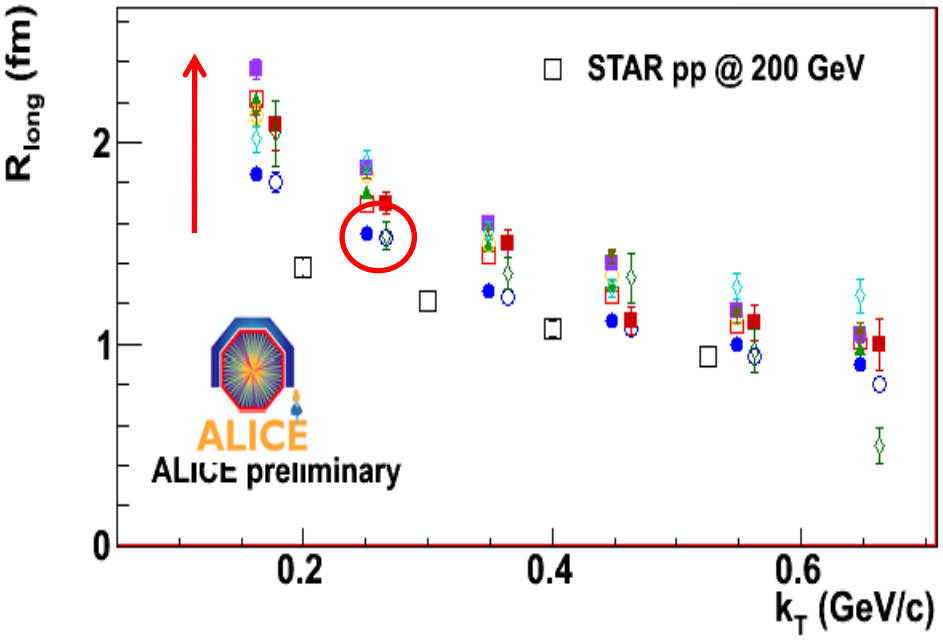
- Radius increases with N_{ch}, comparable to ISR, RHIC, TeV
- much smaller $\langle k_T \rangle$ dependence than at FNAL

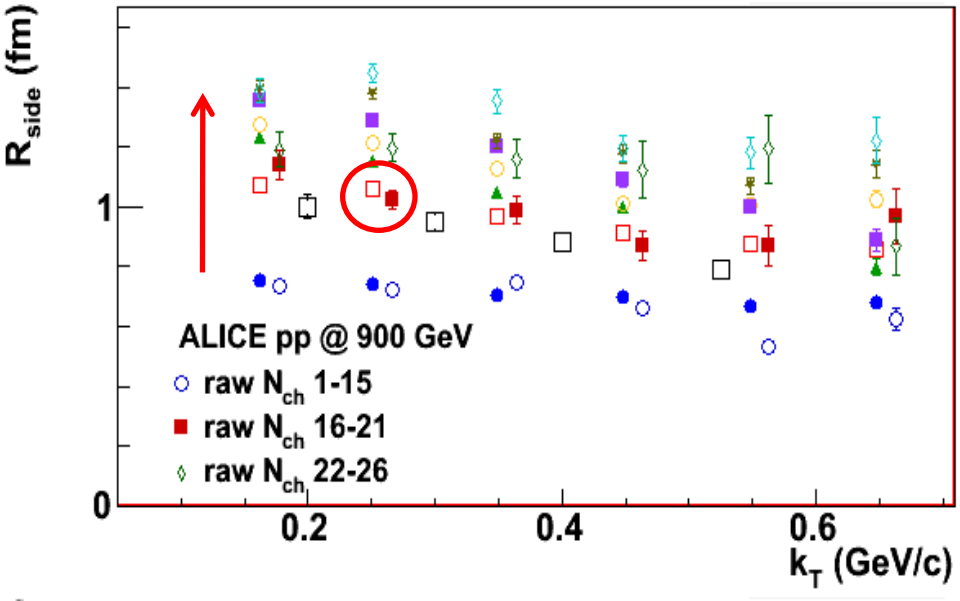
  dependence usually interpreted as sign of 'flow' in heavy ions
  sign. systematic uncertainty from 'baseline' shape
- neglecting non-BE correlations ('flat baseline')
  can cause k_T dependence (at high $\sqrt{s}$)!

HBT @ 7TeV

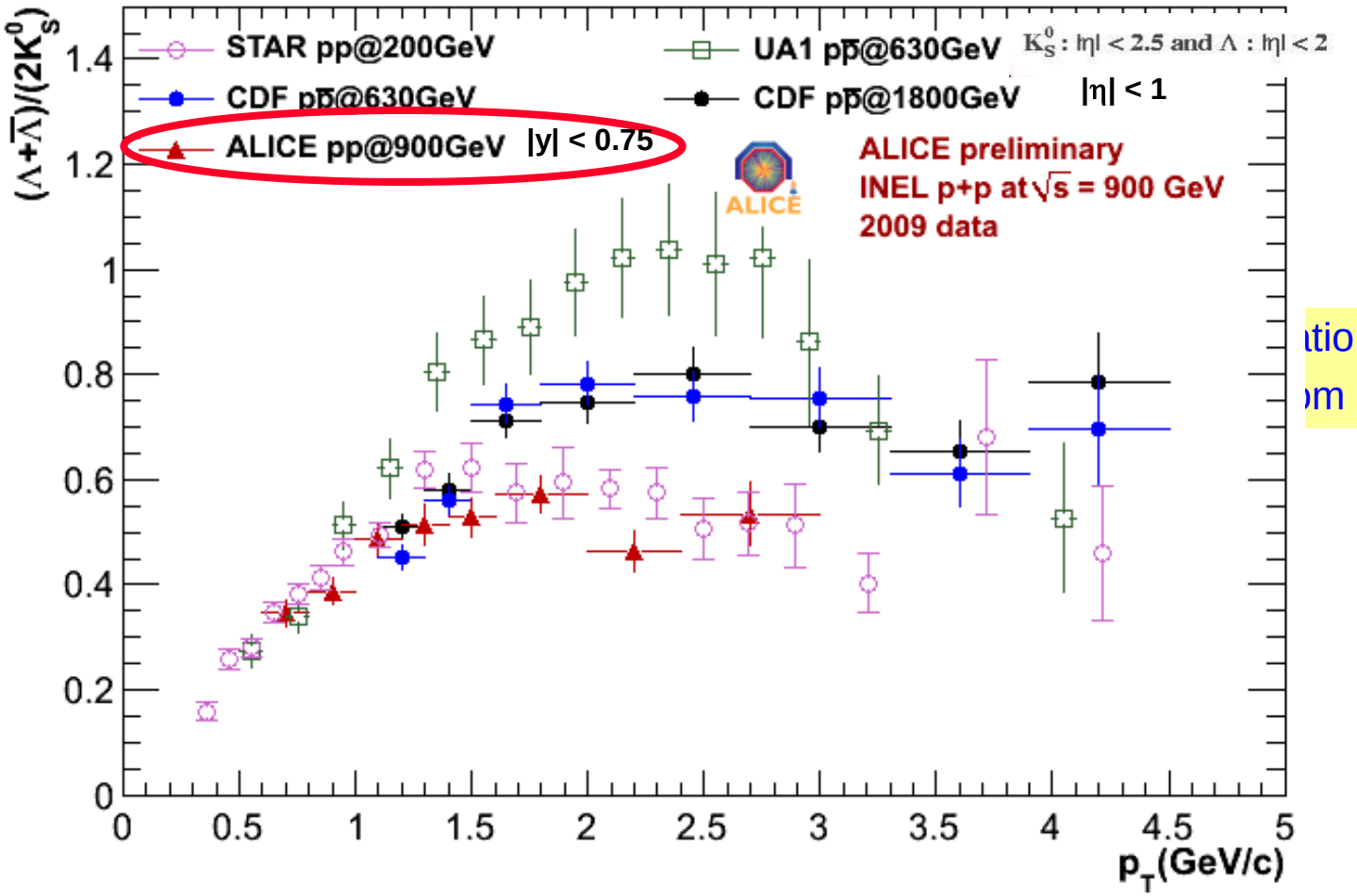
- ‘infinite statistics’: 3D analysis versus N_{ch}, k_T
  - ⇨ pp HBT depends only on N_{ch}, k_T, not √s
  - ⇨ radii (LCMS) grow with multiplicity
  - ⇨ k_T dependence:
    - ✪ significant for R_{long}
    - ✪ develops with N_{ch} for R_{out},
    - ✪ less obvious for R_{side}







2) Λ/K_0^S Ratio 900 GeV



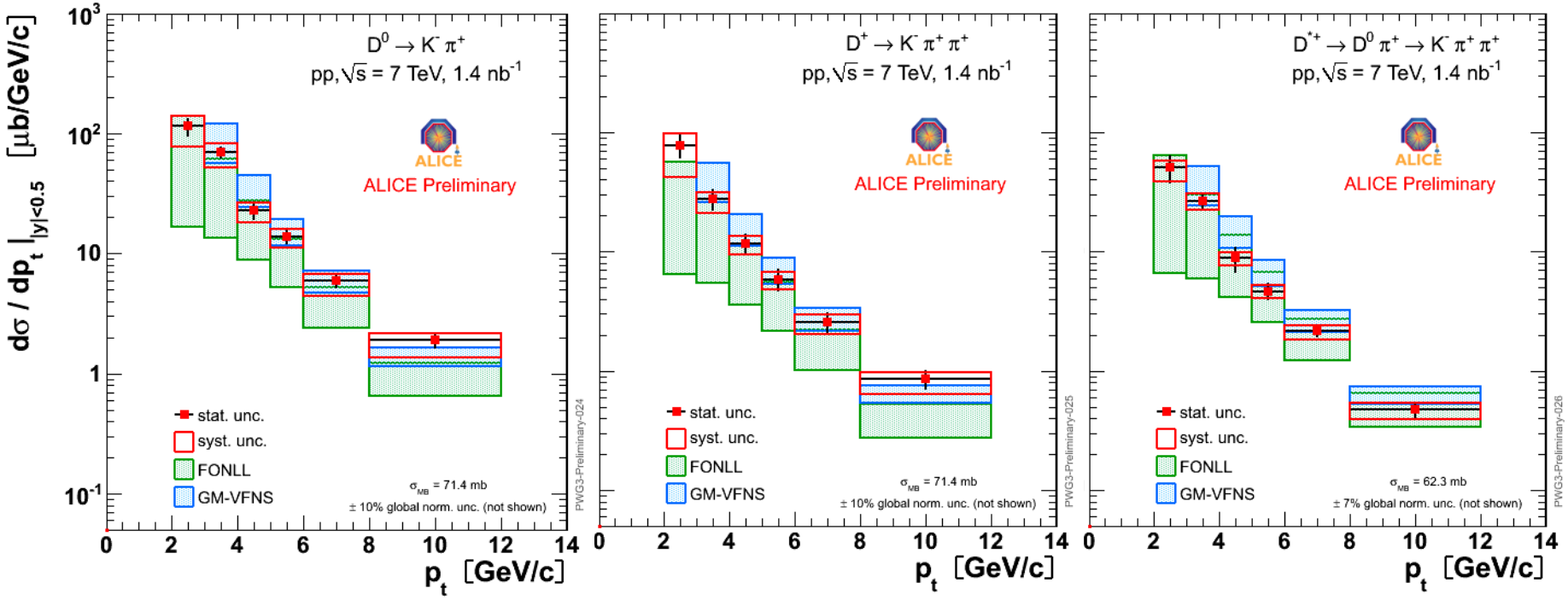
tio:
m QGP

- very good agreement between STAR (200 GeV) and ALICE (900 GeV)
- very different from CDF (630/1800) and UA1 (630) for $p_T > 1.5$ GeV
- UA1(630) and CDF(630) don't agree either …

to be further investigated (different triggers, acceptance, feed-down correction ?)

3) Heavy Flavor

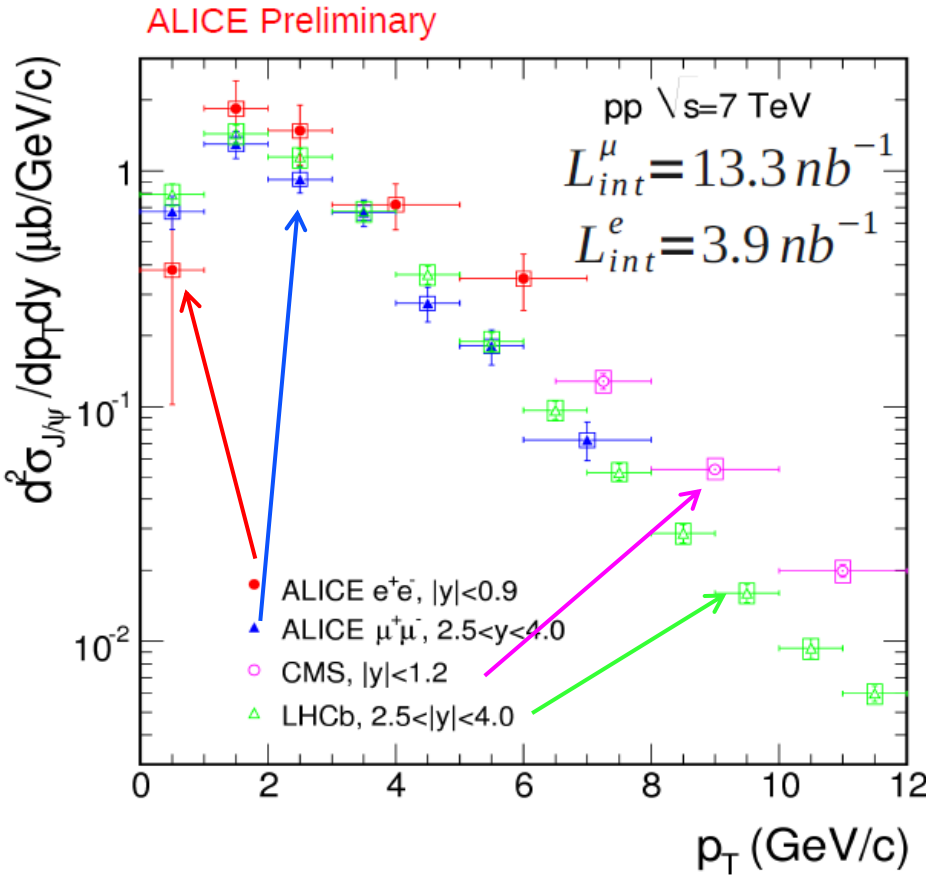
- Cross section D^0, D^+, D^{*+} in 7 TeV pp
  - ⇨ comparison data (charm R_{AA})
  - ⇨ good exercise to get confidence in absolute normalizations
  - ⇨ constrain pQCD calculations at low p_T, where uncertainties are very large

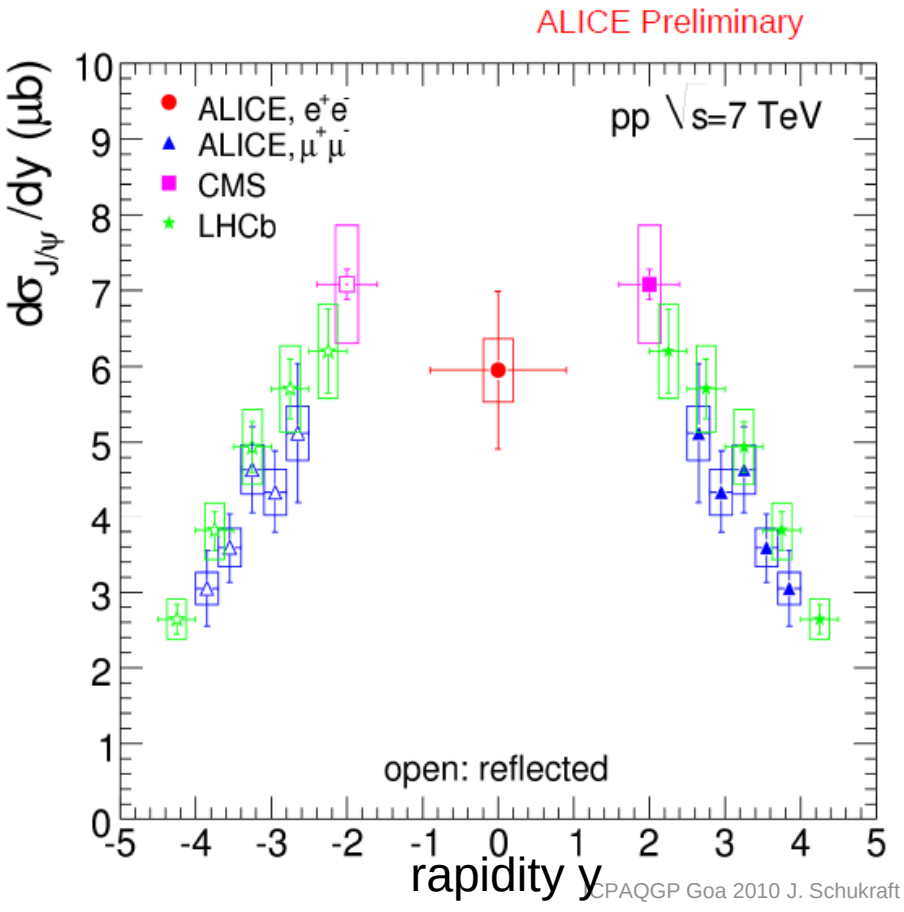


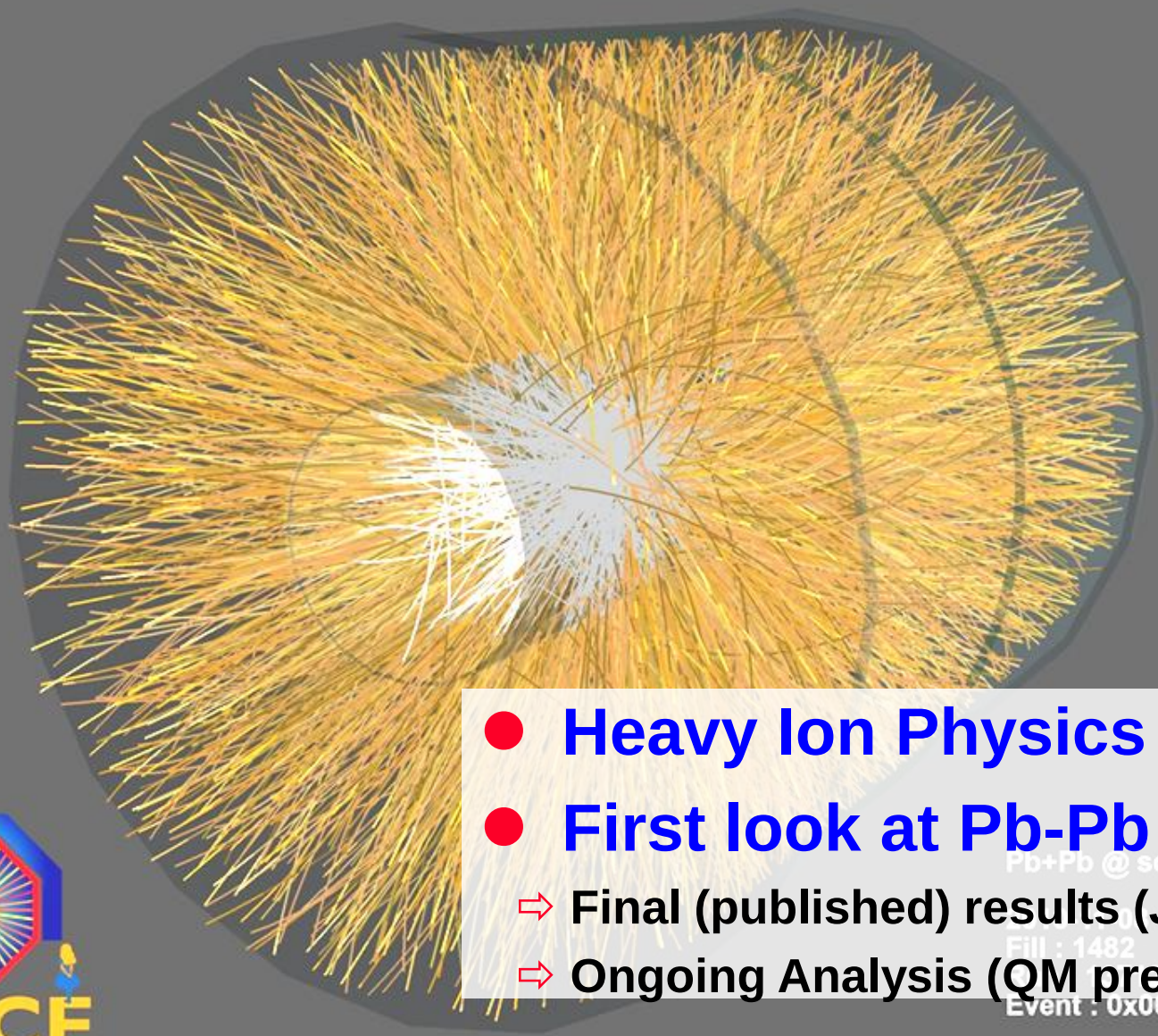
pQCD predictions (FONLL and VFNS) consistent with the data

3) J/Ψ cross section

- ALICE/CMS/LHCb absolute cross sections are consistent
  - ⇨ maybe some 10% difference (but within syst. errors) ?
    - ✪ 10% ain't bad, but eg $dN_{ch}/d\eta$ within 1-3% between ALICE & CMS







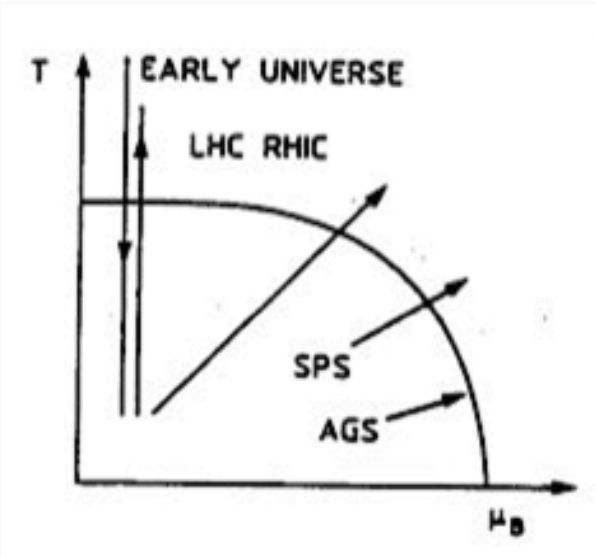
- **Heavy Ion Physics at LHC**
- **First look at Pb-Pb**
  - ⇨ **Final (published) results (Jan 2011)**
  - ⇨ **Ongoing Analysis (QM preview)**

ALICE

Matter under Extreme Conditions

- 'state of matter' at high temperature & energy density: **'The QGP'**
  - ⇨ ground state of QCD & primordial matter of the Universe
    - ✪ partons are **deconfined** (not bound into composite particles)
    - ✪ **chiral symmetry** is restored (partons are ~ massless)
  - ⇨ **'the stuff at high T where ordinary hadrons are no longer the relevant d.o.f'**

- Mission of URHI
  - ⇨ **search** for the QGP phase
  - ⇨ **measure** its properties
  - ⇨ **discover** new aspects of QCD in the strongly coupled regime



Physics is QCD:
strong interaction sector of the Standard Model
(where its strong !)

Role of LHC after RHIC/SPS

⇨ **Search** for the 'QGP' is essentially over

⇨ **Discovery** of QGP is well under way (with fantastic results & surprises at RHIC)

⇨ **Measuring** QGP parameters has just begun

- 1) Quantitative differences

⇨ significantly different state of QGP in terms of energy density, lifetime, volume

⇨ large rate for 'hard probes' : jets, heavy quark states (b,c,Υ,J/Ψ),…

- 2) Test & v[illegible]old !)

> 10 year program

where are we after < 5 months ?

perfect liquid

⇨ Test prediction[illegible]

✪ examples: **flow** ('soft') **Quarkonia suppression** ('hard')

- 3) 'Precision' measurements of QGP parameters

⇨ Quantitative and systematic study of the new state of matter

✪ **Equation-of-State** f(ε,p,T), **viscosity** η (flow), **transport coefficient q̂** (jet quenching), Debye **screening mass** (Quarkonia suppression), …

- 4) Clarify status of some 'Beyond the HI Standard Model' ideas

⇨ support, but no smoking gun yet: CGC, quark coalescence, ..

⇨ some hints, maybe ?: Chiral magnetic effect ('strong CP violation'), Mach cones, ...

- 5) Surprises ?

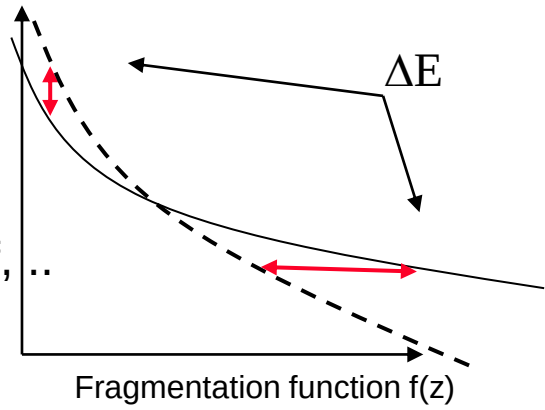
⇨ **we are dealing with QCD in the strong coupling limit !**

‘Jet Quenching’

- Jet quenching: **jet E -> jet E’ (=E-ΔE) + soft gluons (ΔE)**

  modified jet fragmentation function via matter induced gluon radiation/scattering

  => QGP properties



⇨ how much energy is lost ? (measures e.g. **q^**)

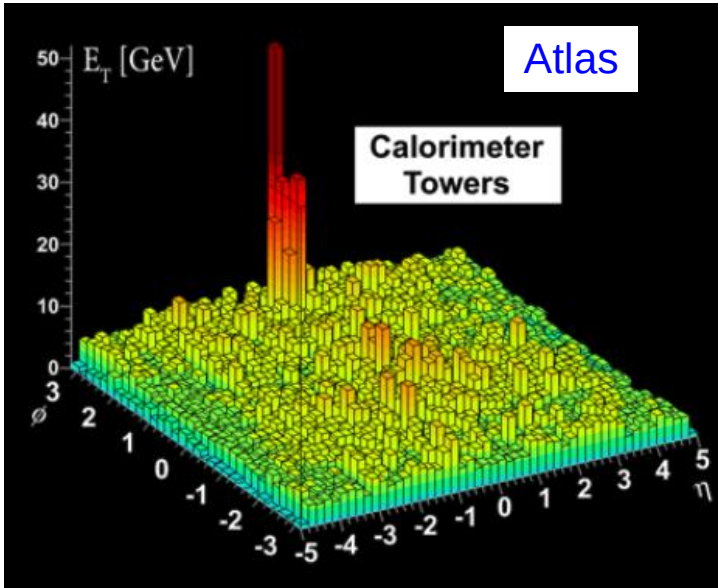
- very difficult question, may depend on jet cone R, p_t-cutoff, ..

⇨ how is it lost ? (e.g. multiple soft or few hard gluons ?)

- look at soft part of f(z), p_t < 2-5 GeV

⇨ ‘response of QGP’ (shock waves, Mach cones ??)

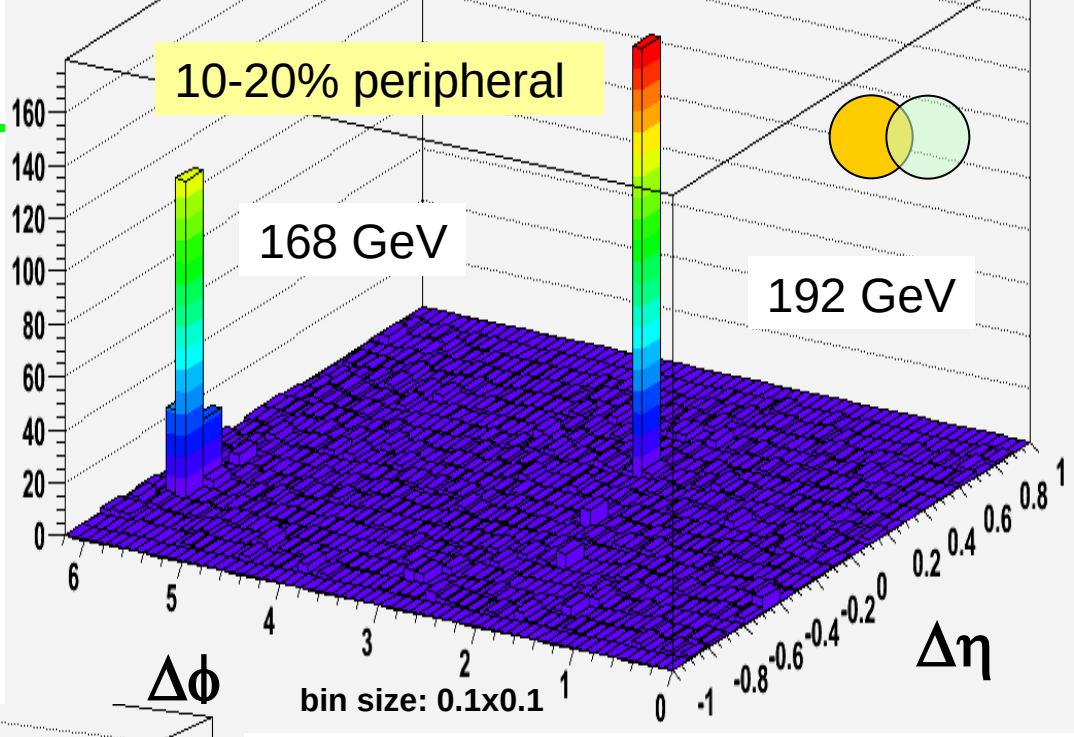
- properties of bulk matter around jet, p_t ~ 1 GeV

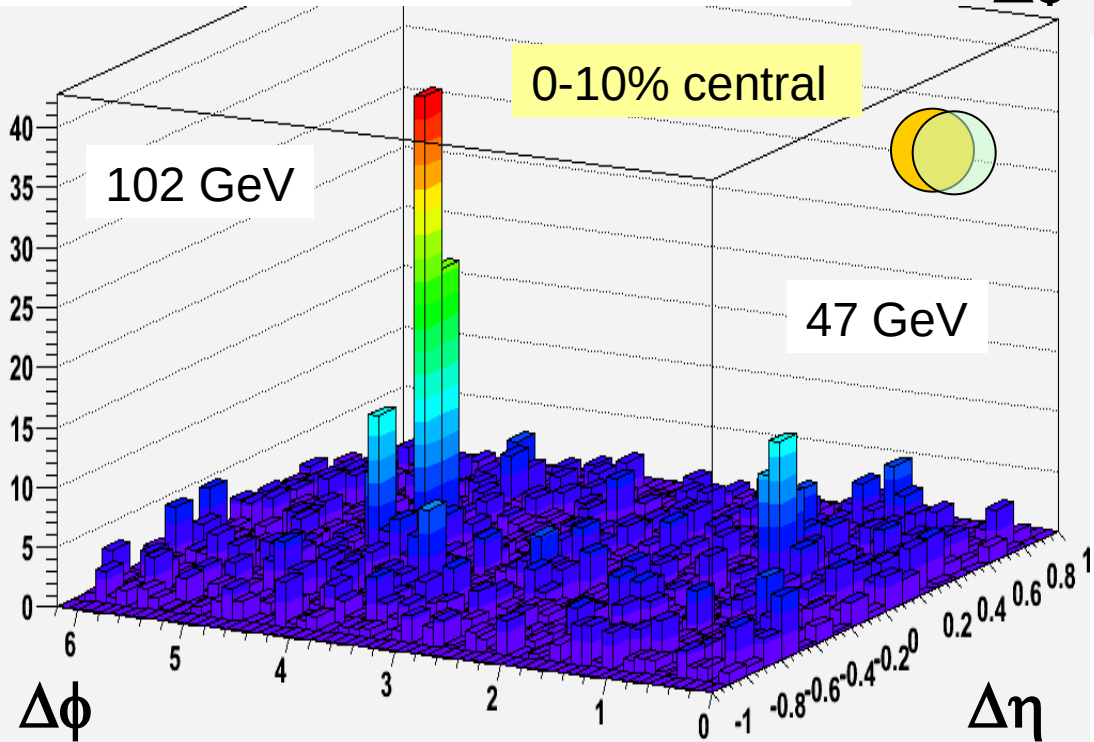


Both Atlas and CMS see very striking effects in the dijet-imbalance for central events !

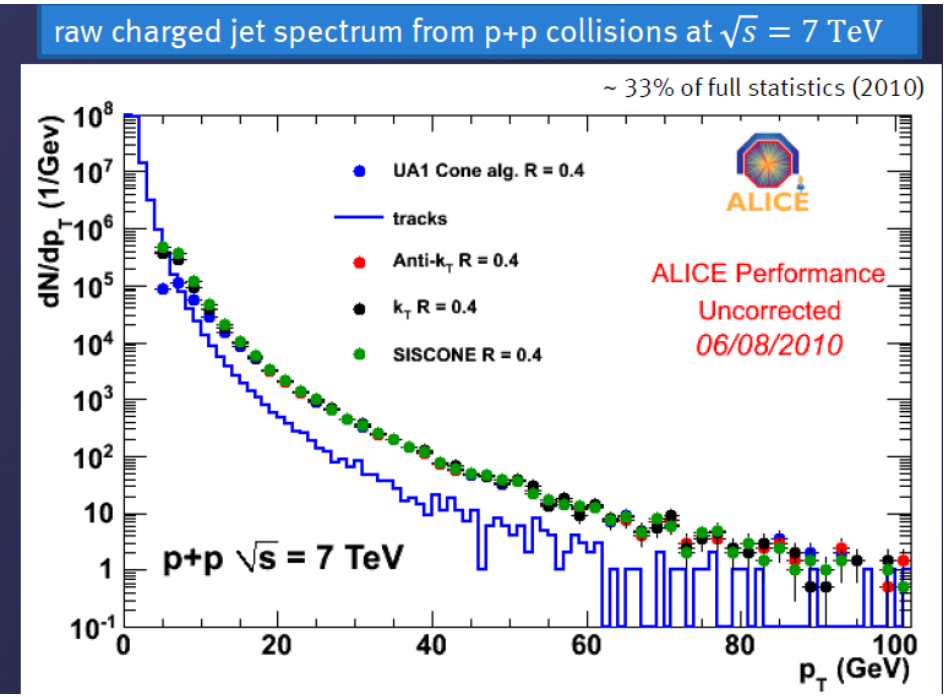
Charged Jets

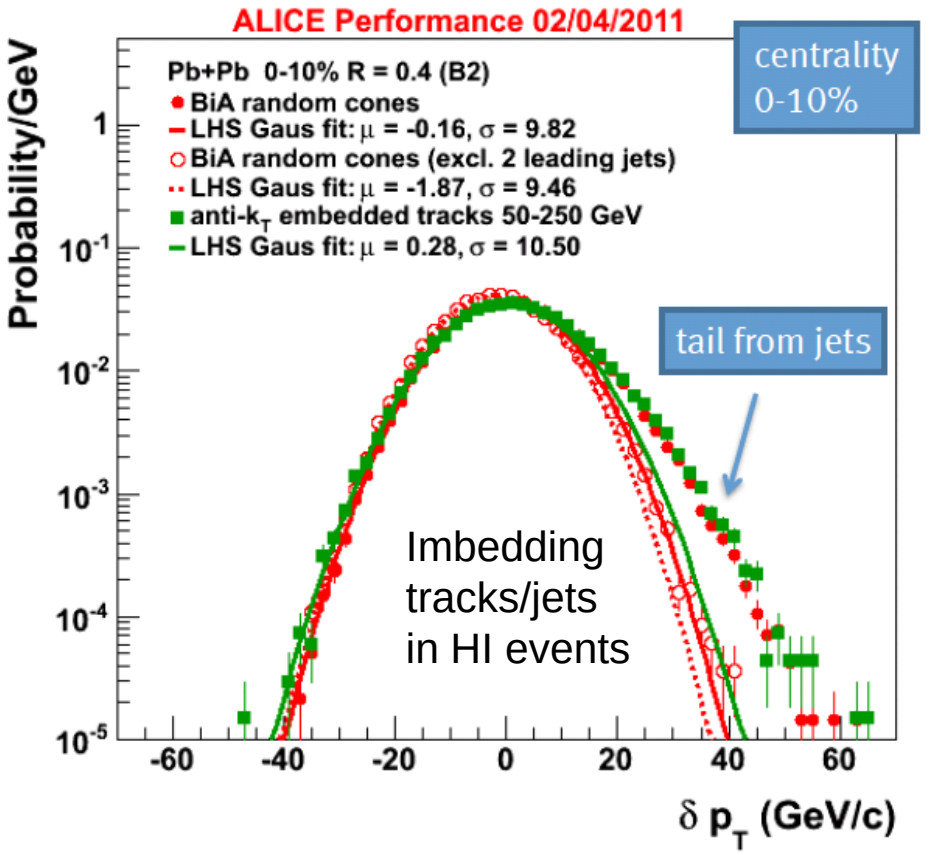
- Jets in ALICE (TPC)
  - ⇨ we see qualitatively a similar effect
  - ⇨ quantitative analysis is ongoing
    - ✪ small acceptance (statistics),
    - ✪ try to include low p_t (study p_t-cut off dependence of imbalance)

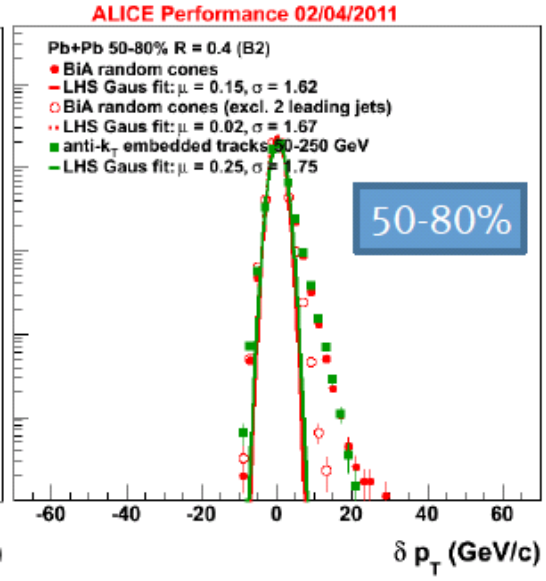




Jet studies with charged Particles





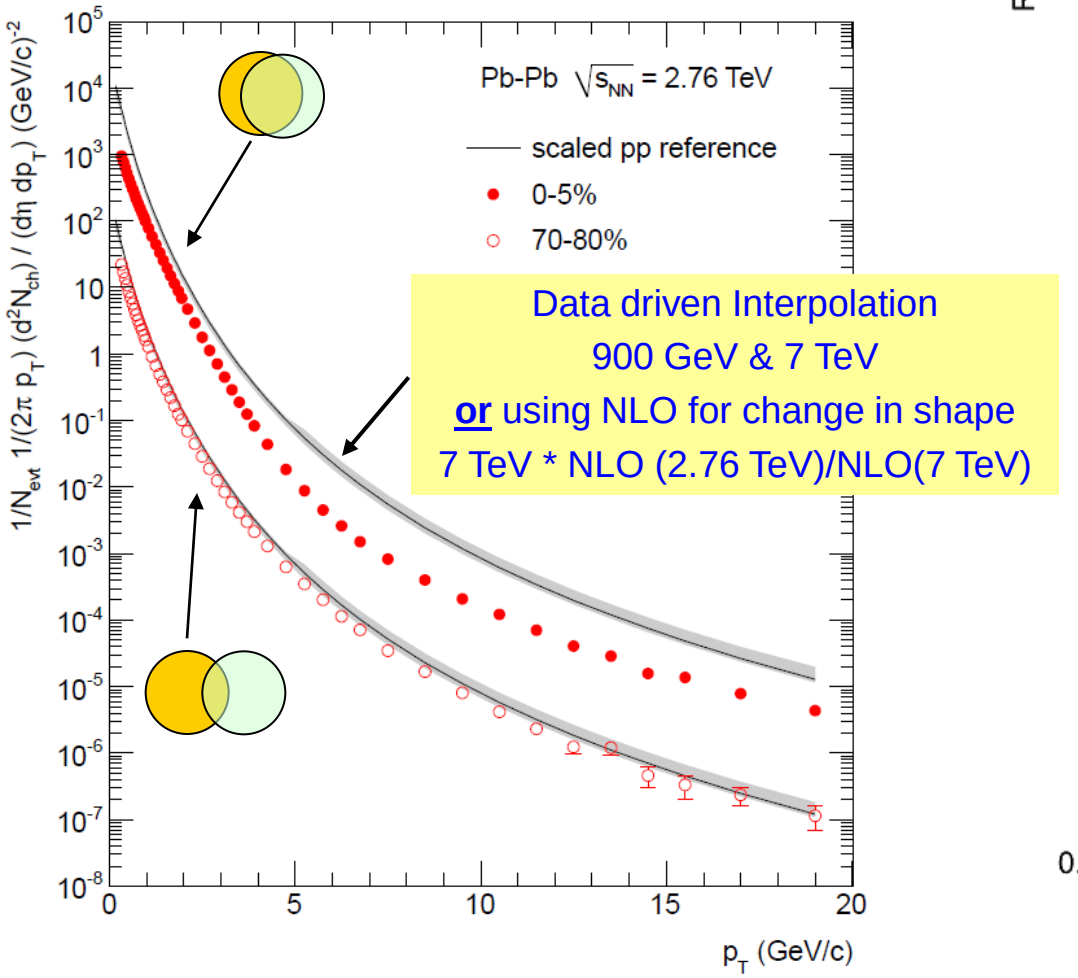


- Test jet-finding algorithms with pp
  - ⇨ UA1 cone, kT, anti-KT, SISCONE etc...
  - ⇨ jet physics will be easier in 2011 (with EMCAL)
- Test background subtraction with embedding
  - ⇨ σ ~ 10 GeV in R=0.4 cones
  - ⇨ non-Gaussian tails from overlapping jets !

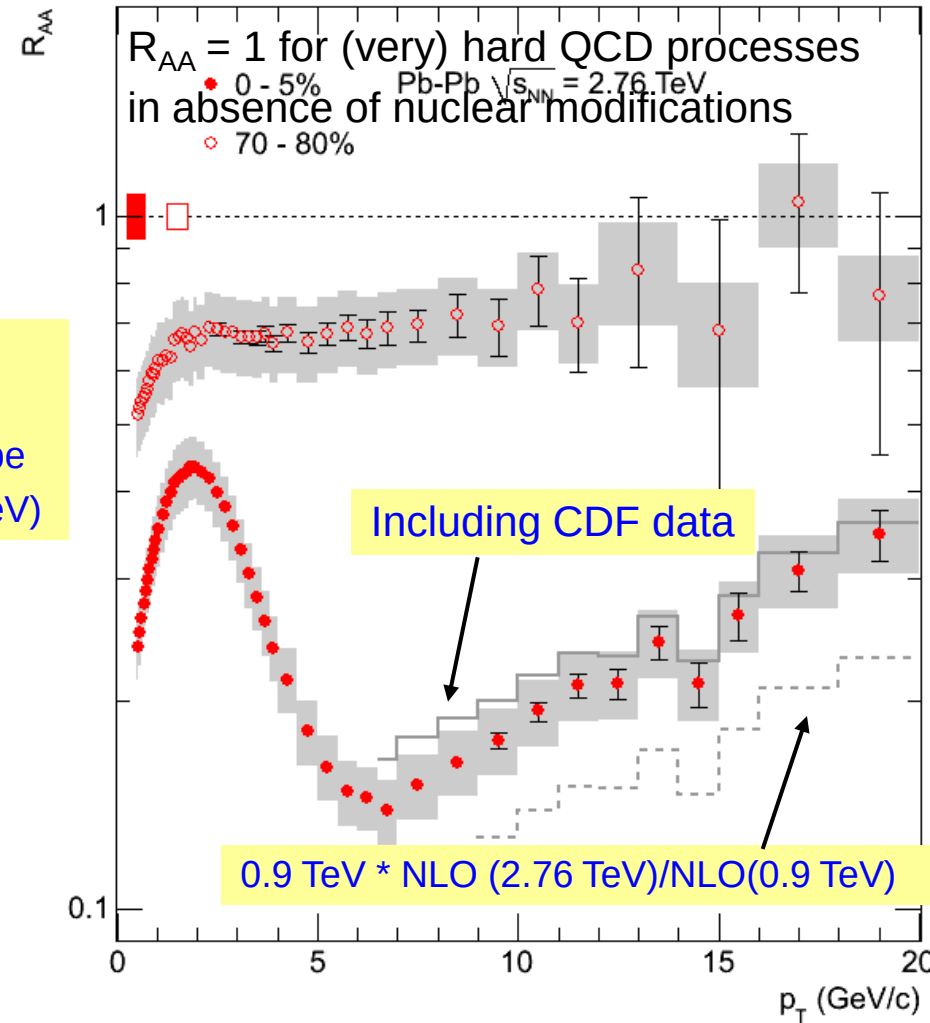
‘Jet Quenching’ as seen by p_t spectra

- Suppression of high p_t particles (~ leading jet fragments)
  - ⇨ significant suppression, minimum ~ 7 GeV
  - ⇨ main systematic error from pp reference
    => need pp at 2.76 TeV !

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\,(1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

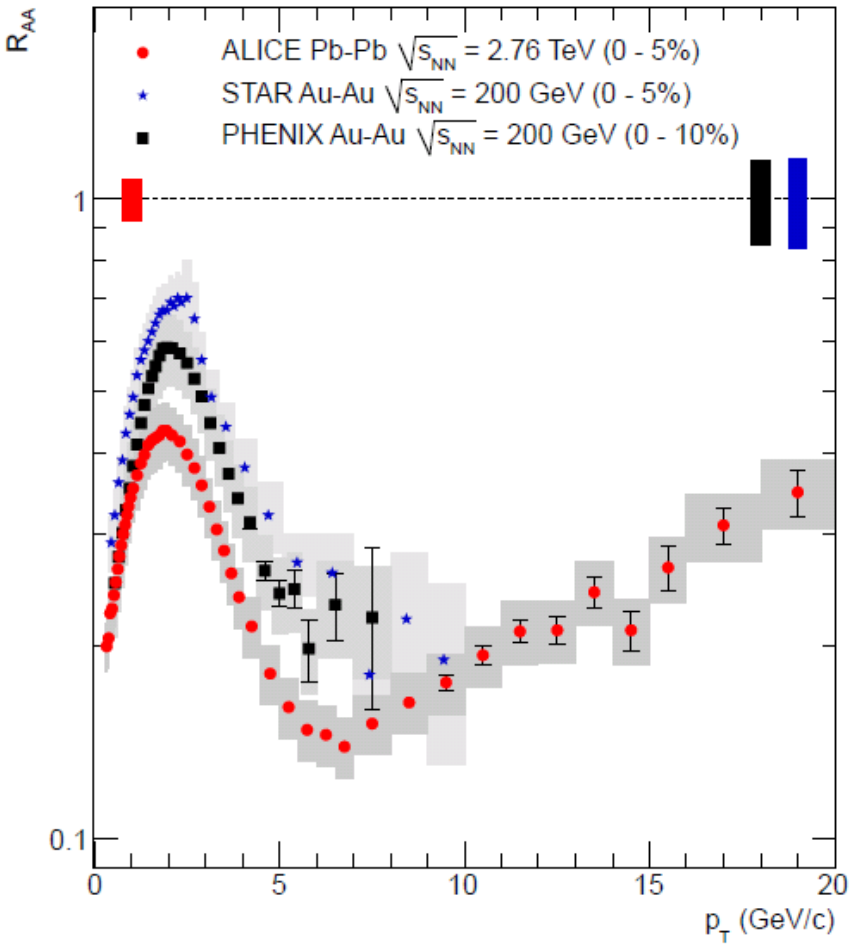


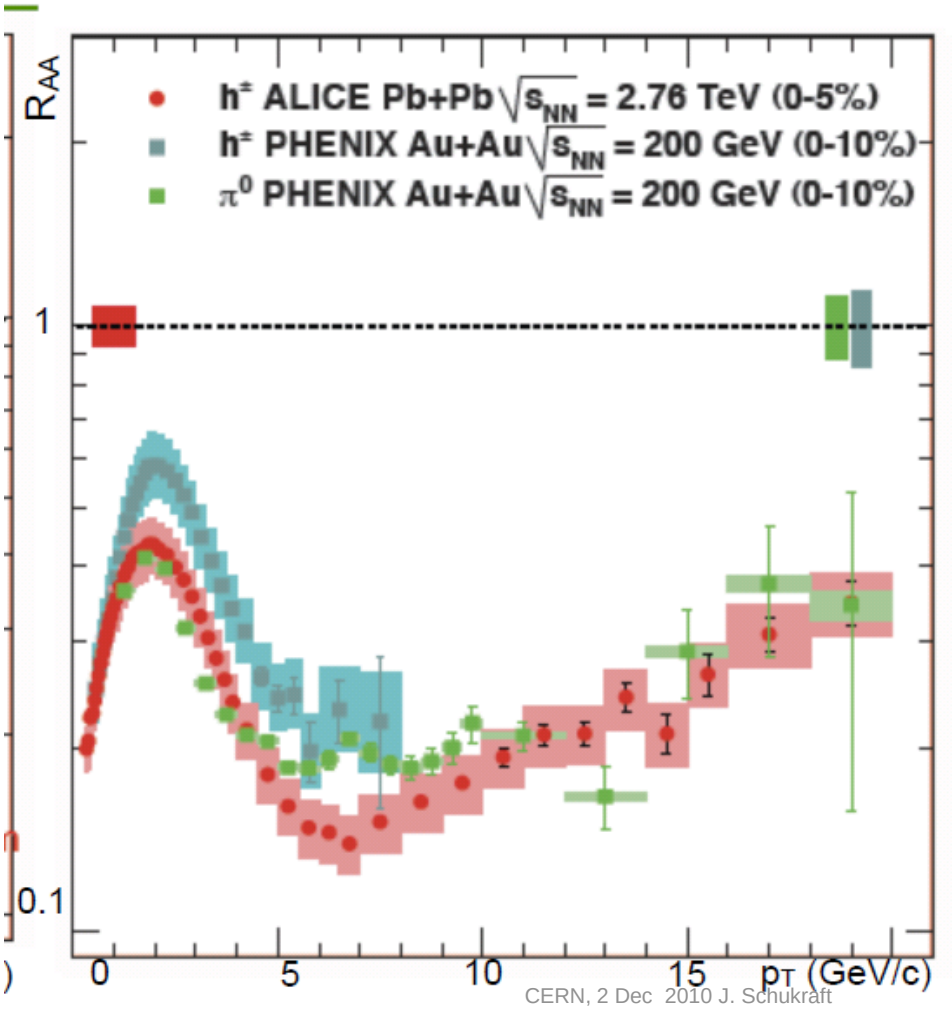
Data driven Interpolation
900 GeV & 7 TeV
or using NLO for change in shape
7 TeV * NLO (2.76 TeV)/NLO(7 TeV)



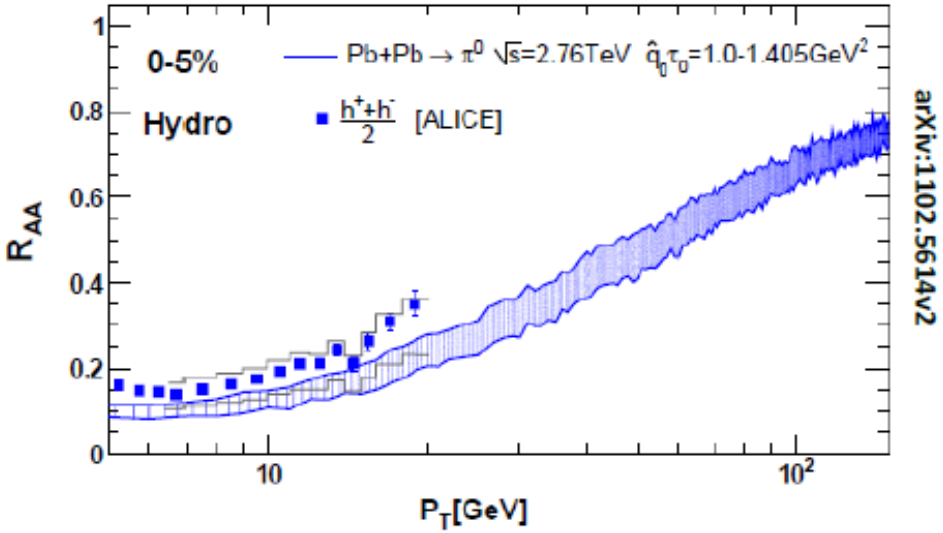
Comparison to RHIC

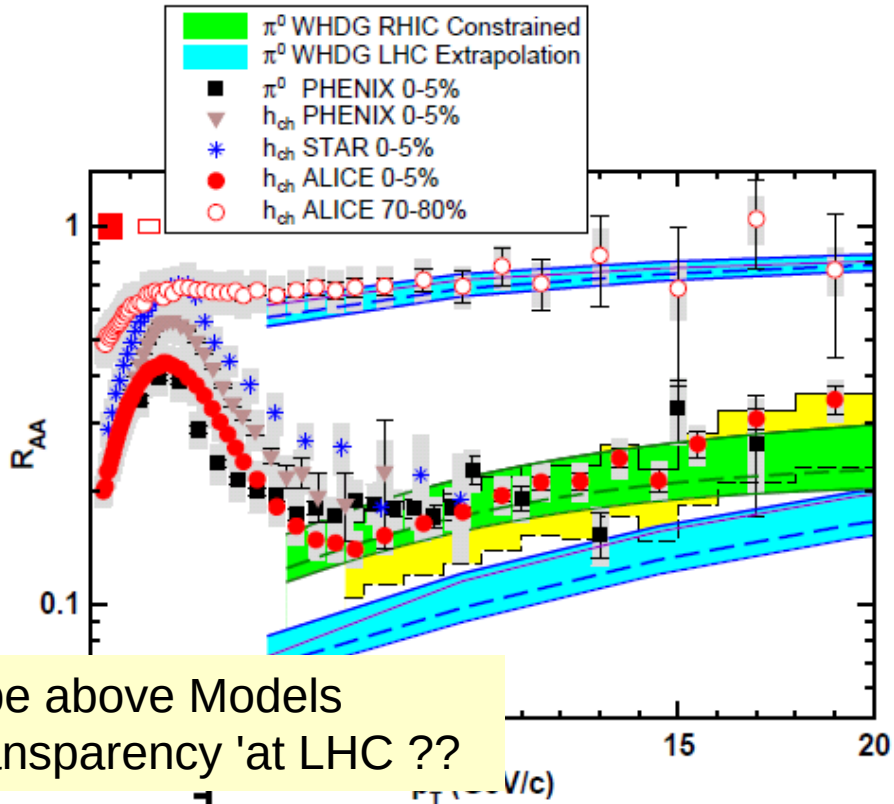
- Minimum R_{AA} ~ 1.5 – 2 x smaller than at RHIC
- Rising with p_t !
  - ambiguous at RHIC with N_{ch},
  - compatible with new Phenix data



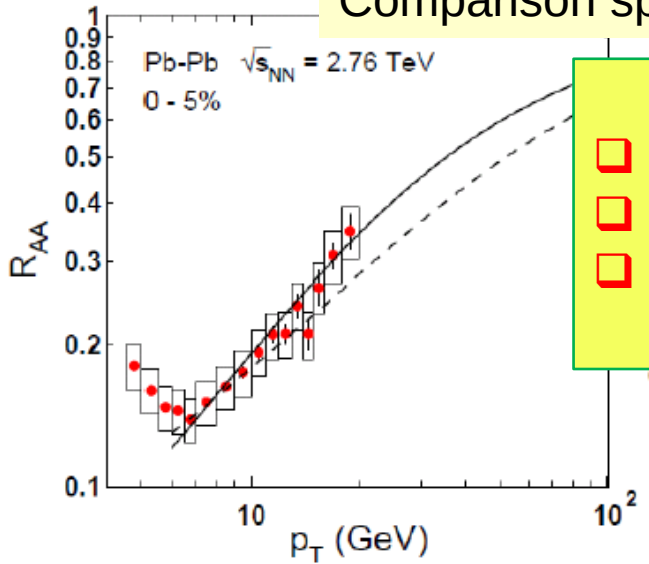


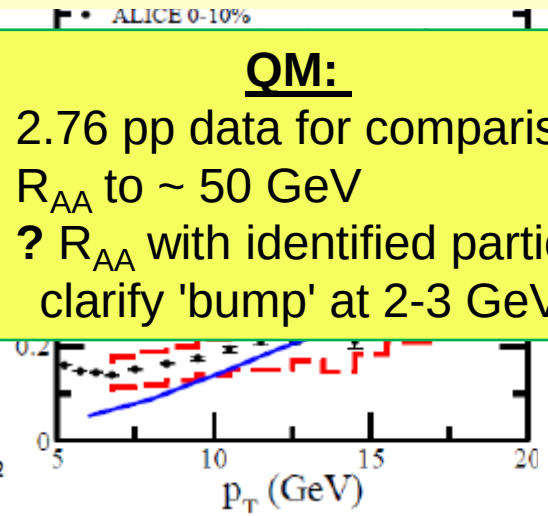
Comparison to Theory





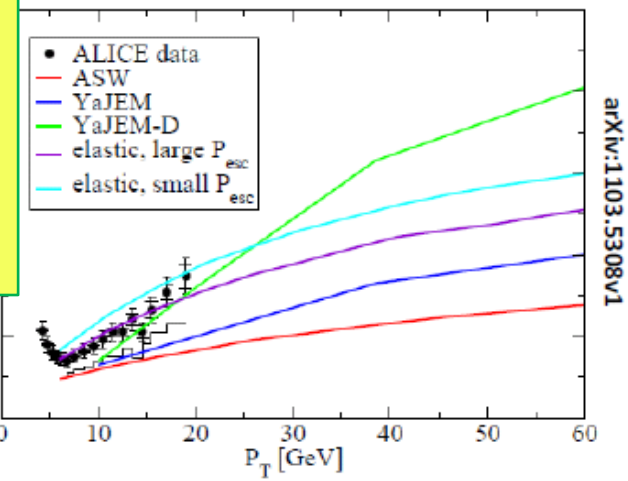
Data has slight tendency to be above Models
Comparison spectrum ? 'Transparency 'at LHC ??





QM:

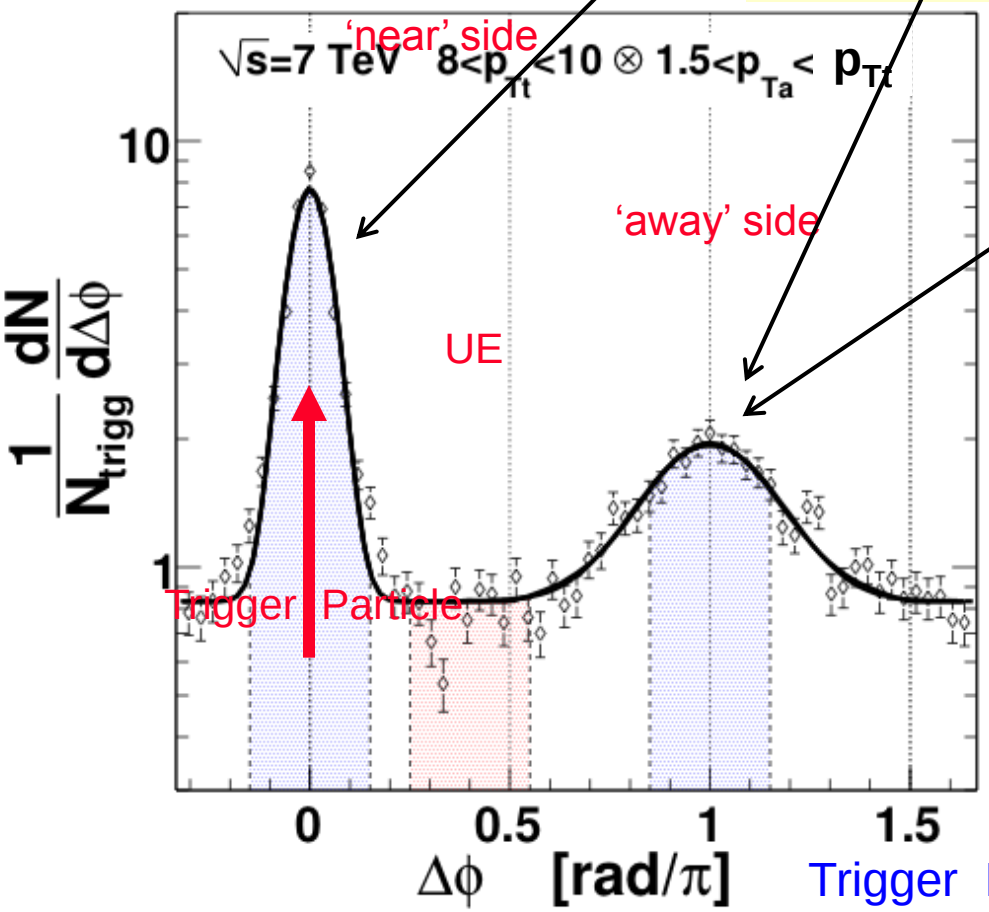
- 2.76 pp data for comparison
- R_{AA} to ~ 50 GeV
- **?** R_{AA} with identified particles clarify 'bump' at 2-3 GeV ?

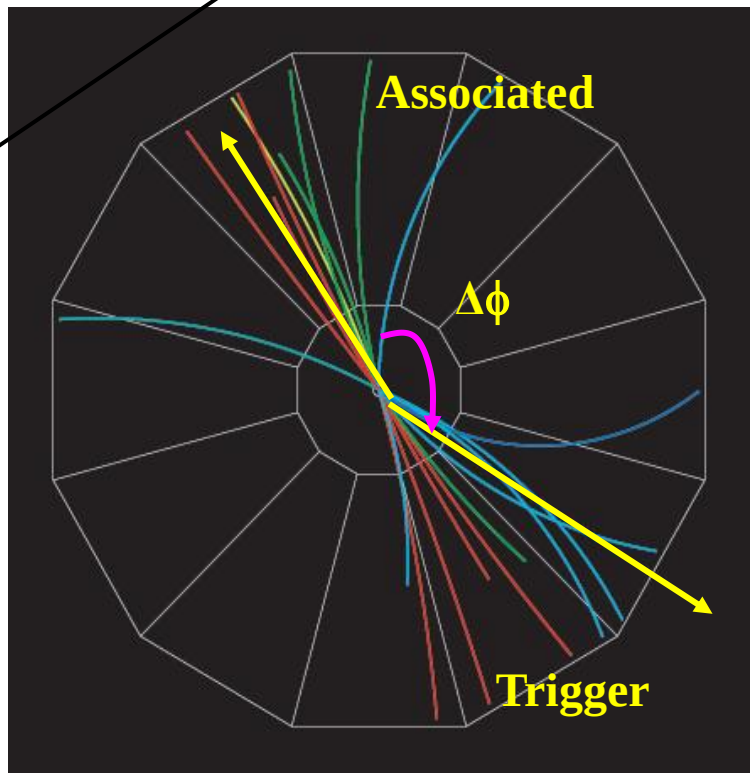


High p_T Particle Correlations

1) Jet quenching:
- disappearance (reappearance) of away side jet
- modification of near side jet ?

2) 'Response of the medium' ?
- shape & origin of the away side structure





Trigger Particle: highest p_T particle in event (p_{Tt})

Associate Particle: all the others (p_{Ta})

Triggered Correlations at RHIC

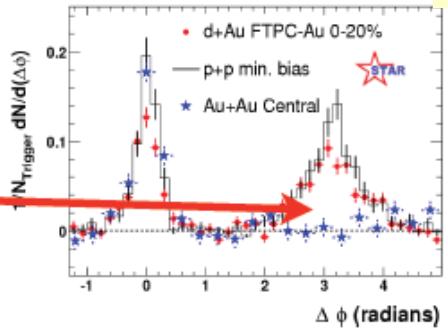
Transparency from A. Adare, WWND2011

A few milestones*

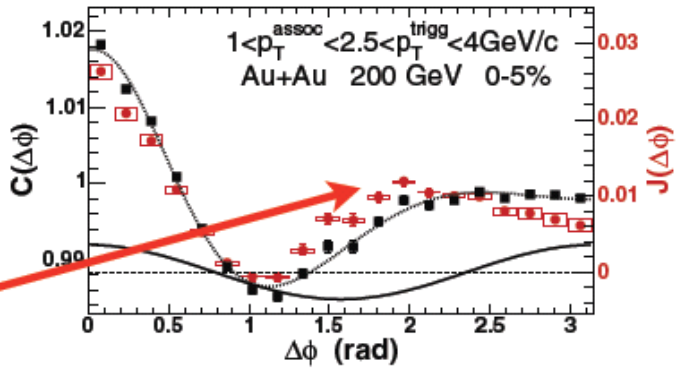
2001 - Jet quenching!

Unexpectedly large suppression

Near side NOT modified !



PRL 97, 052301 (2006), PRL 98, 232302 (2007)



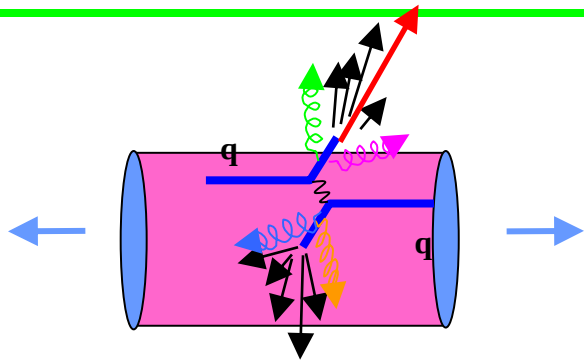
2004 - Away-side shape modification

v_2 + ZYAM paradigm: the "Mach cone era"

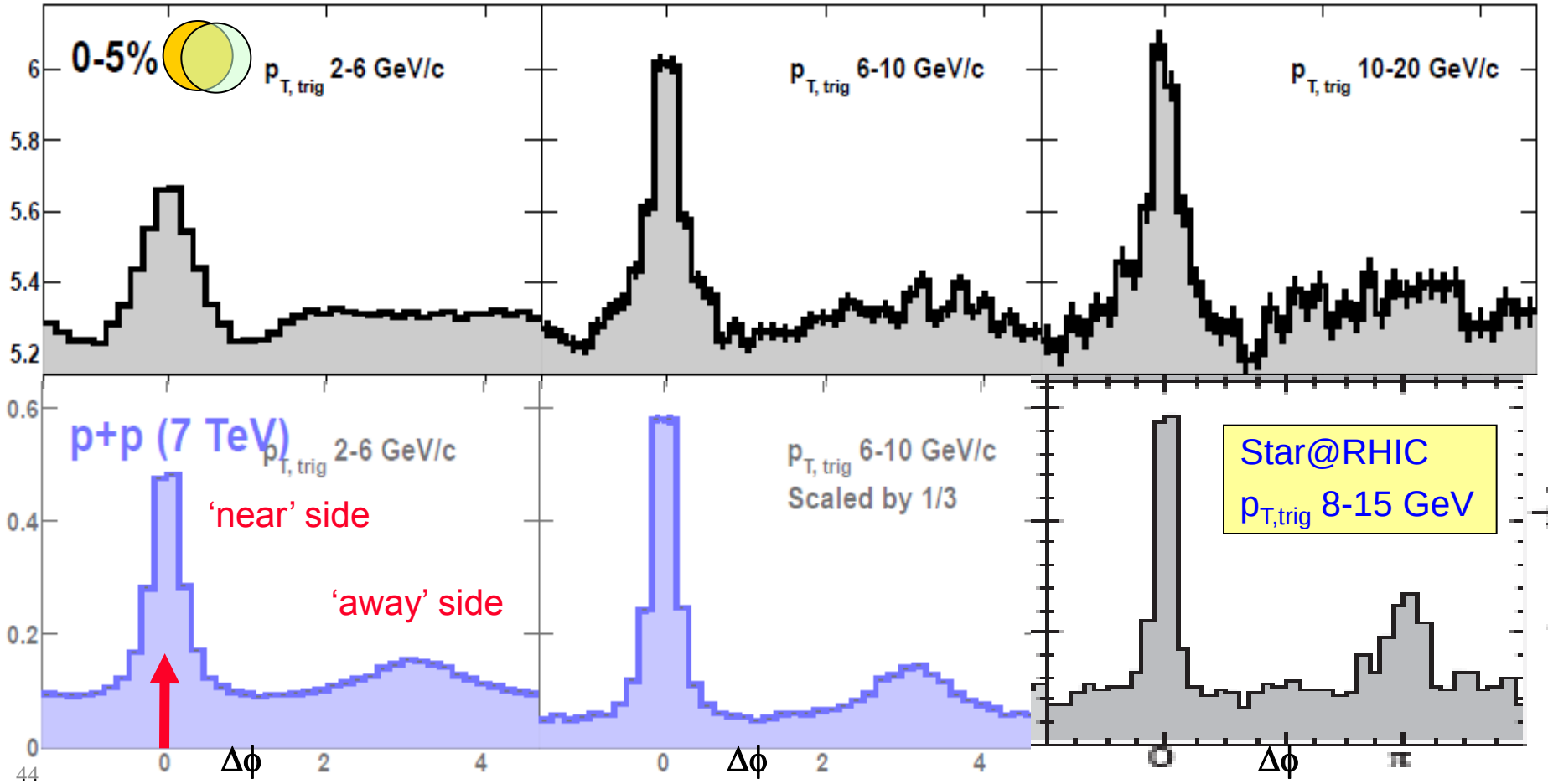
PRL 104, 252301 (2010)

Jet Quenching seen by High p_T Correlations

- classic 'jet quenching signal'
  - ⇨ away side correlation in central Pb-Pb washed out up to $p_{T,trig}$ > 10 GeV



P_T associated 2 – 6 GeV



Quantitative Analysis

- After pedestal (and optionally v_2) subtraction, integrate to obtain yield Y

Near side : $-0.7 < \phi < 0.7$

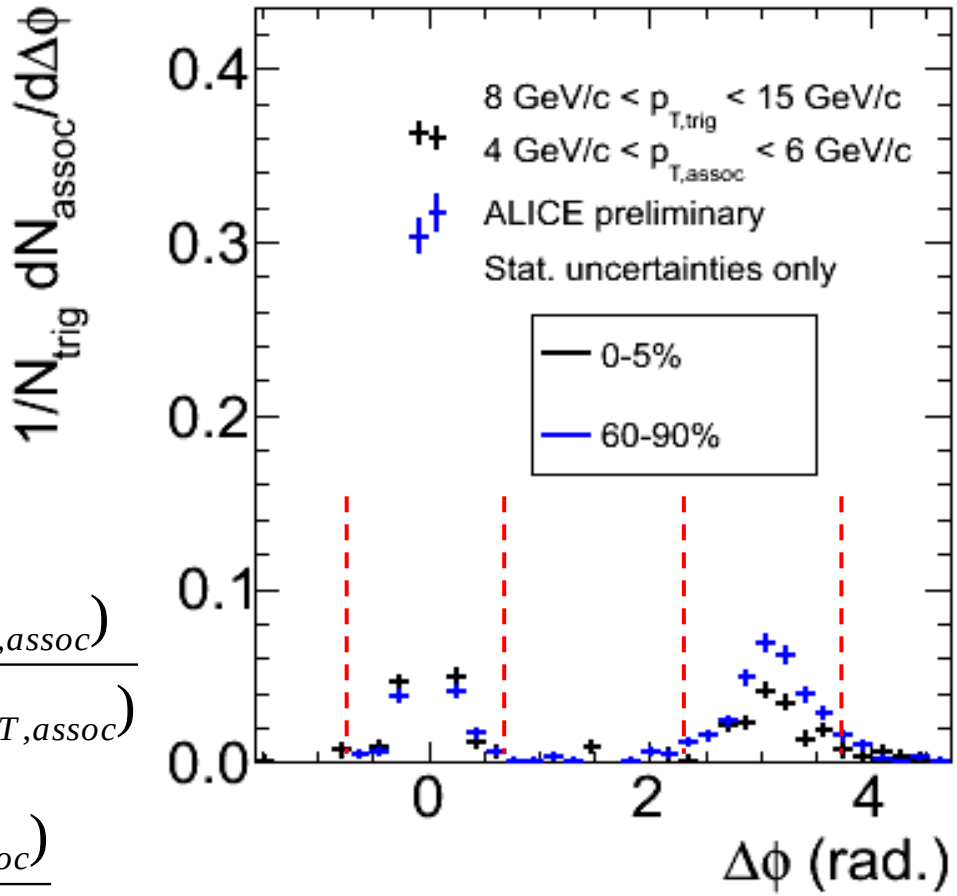
Away side: $-0.7 < \phi - \pi < 0.7$

in bins of p_T (Trigger/Associate)

- Divide yields to obtain I_{CP} and I_{AA}

$$I_{CP}(p_{T,trig}; p_{T,assoc}) = \frac{Y^{AA}_{central}(p_{T,trig}; p_{T,assoc})}{Y^{AA}_{peripheral}(p_{T,trig}; p_{T,assoc})}$$

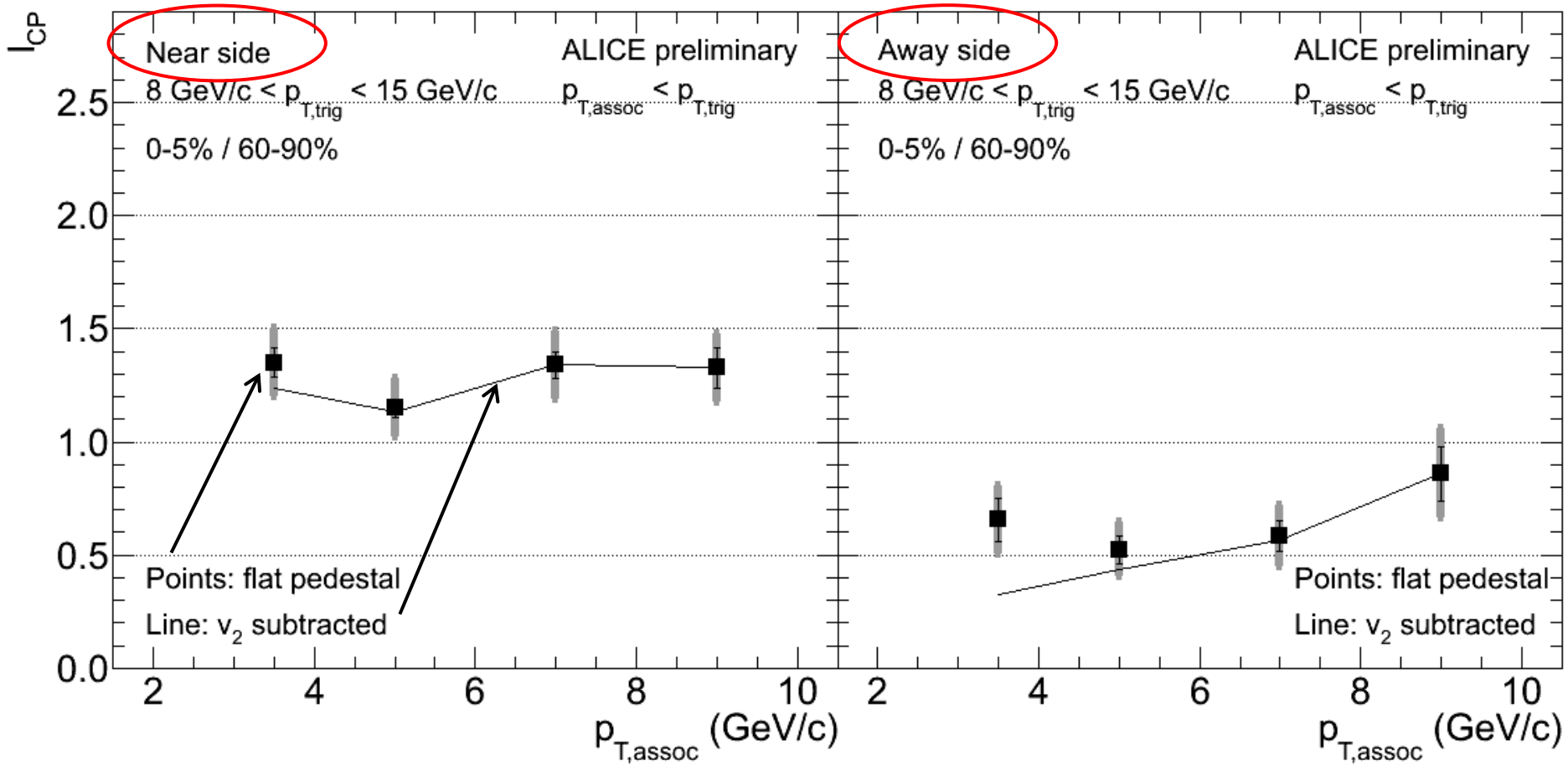
$$I_{AA}(p_{T,trig}; p_{T,assoc}) = \frac{Y^{AA}(p_{T,trig}; p_{T,assoc})}{Y^{pp}(p_{T,trig}; p_{T,assoc})}$$



integration windows

So far, no 2.76 pp data => use Phythia after scaling to fit 0.9 and 7 TeV pp data

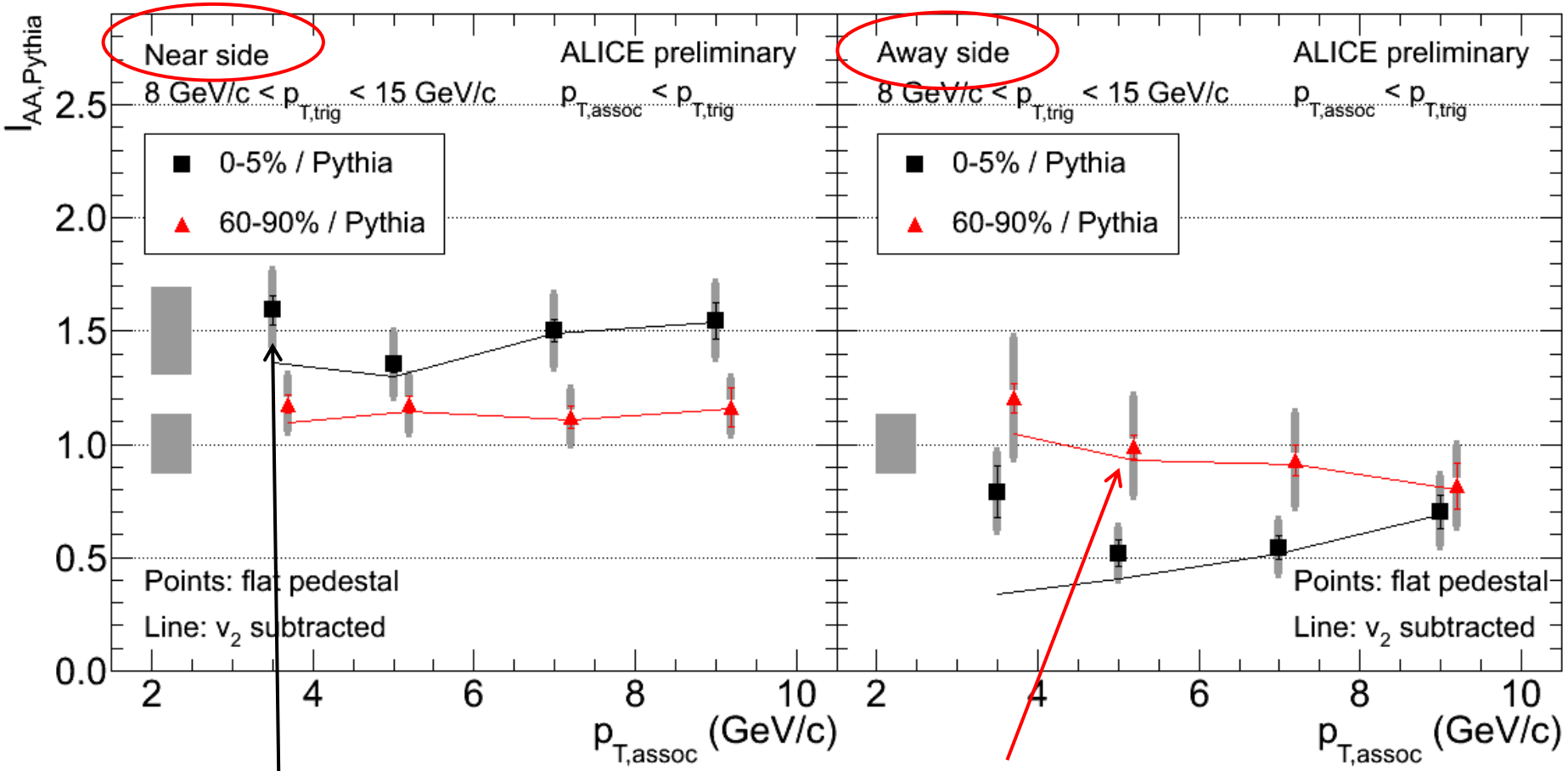
I_{CP} versus p_T(associate)



- Flow contribution small except in lowest bin.
- Away side suppressed: I_{CP} ~ 0.6 … expected from in-medium energy loss
- Slightly enhanced near-side: I_{CP} ~ 1.2 … unexpected and interesting
  Current paradigm: Near side = surface emission = no change to jet properties!

$I_{AA,Pythia}$ (pp comparison = Pythia)

Qualitatively similar to I_{CP}



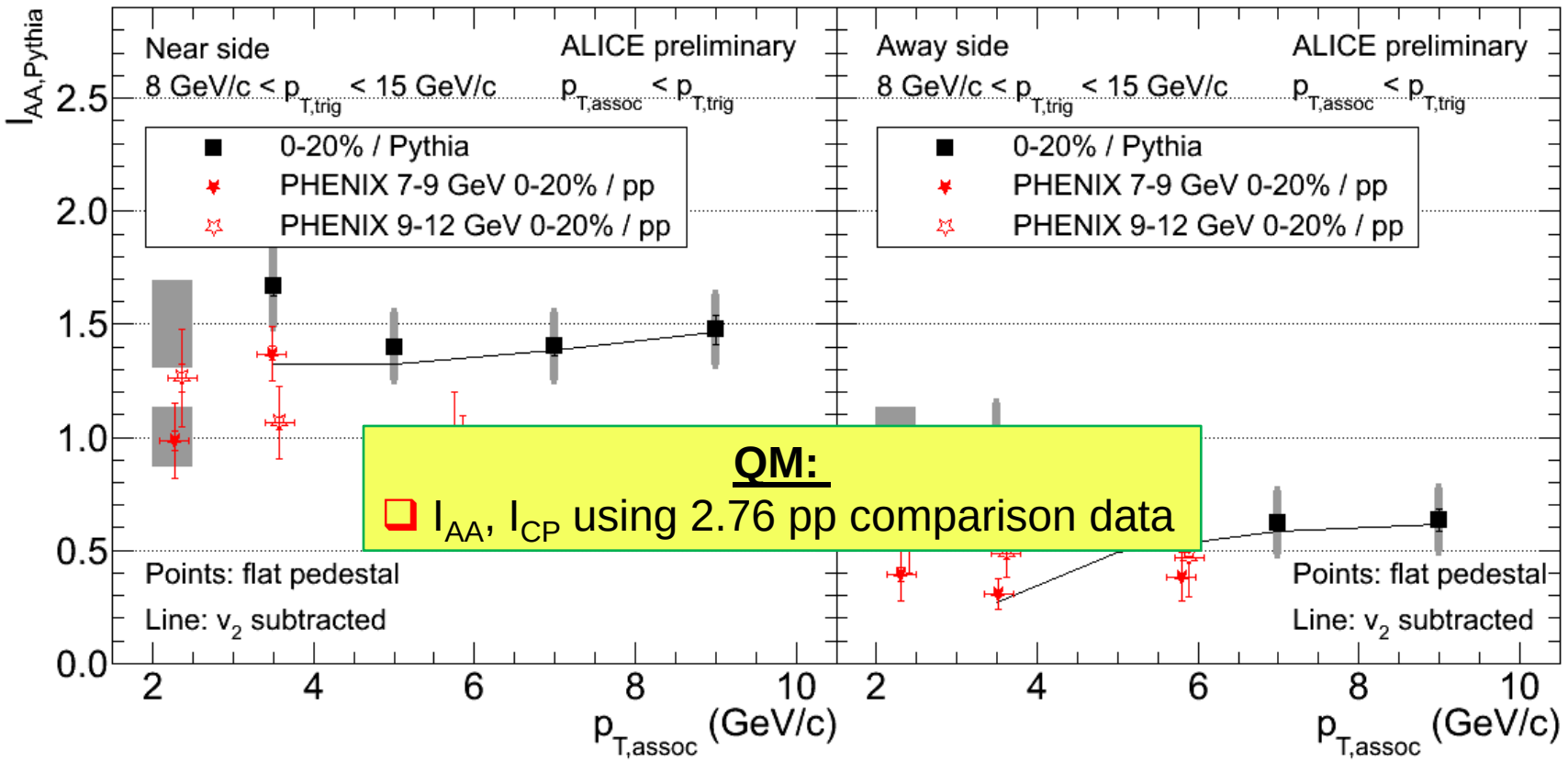
Central events

- Near side enhanced $I_{AA,Pythia}$ ~ 1.5
- Away side suppressed $I_{AA,Pythia}$ ~ 0.5 – 0.7

Peripheral events

- Near side enhanced $I_{AA,Pythia}$ ~ 1.2
- Away side $I_{AA,Pythia}$ consistent with 1

Comparison with Phenix



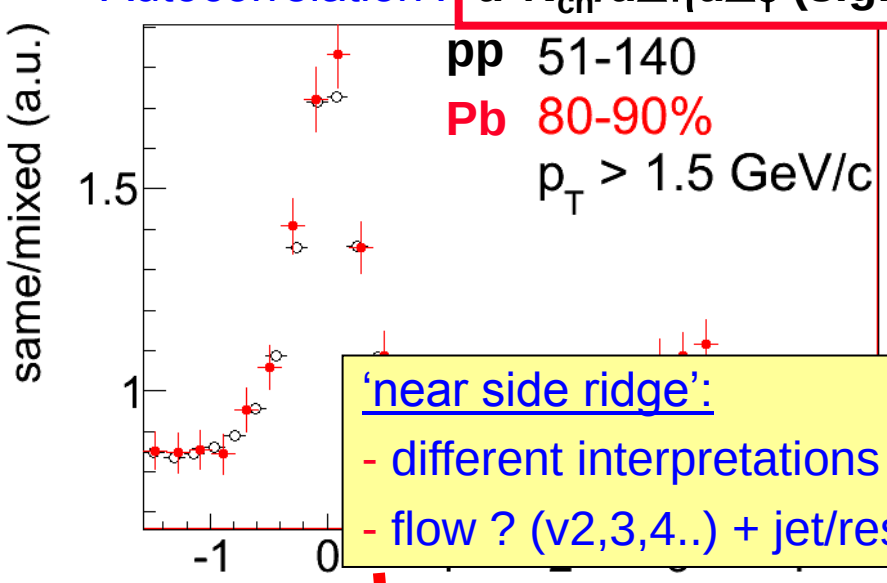
QM:

- I_{AA}, I_{CP} using 2.76 pp comparison data

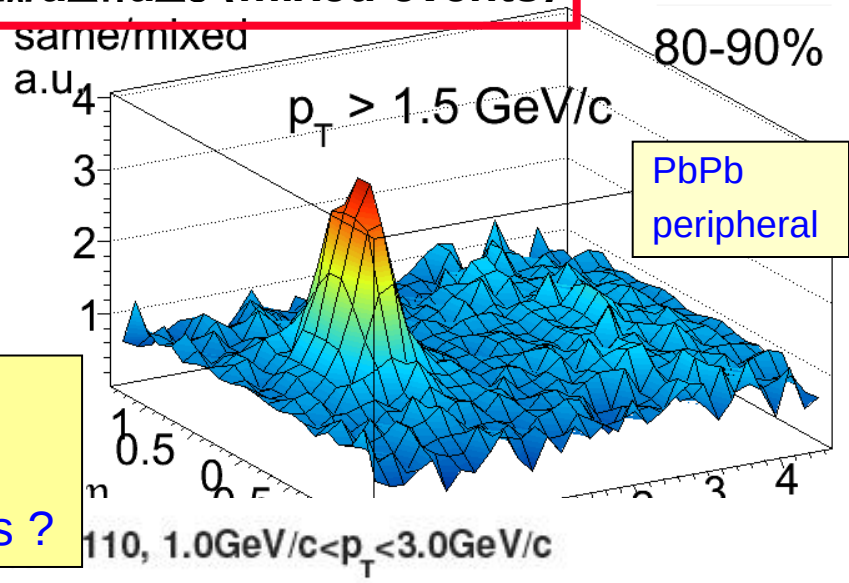
- **!** Different integration windows in ALICE andPHENIX, PHENIX subtracts v_2
- Near side: I_{AA} (Alice) > I_{AA} (Phenix) for p_T > 5 GeV ?
- Away side: I_{AA} seems comparable
- **Conclusions only after using 2.76 pp comparison data**

Jet Quenching (?) seen via Multiparticle Correlations

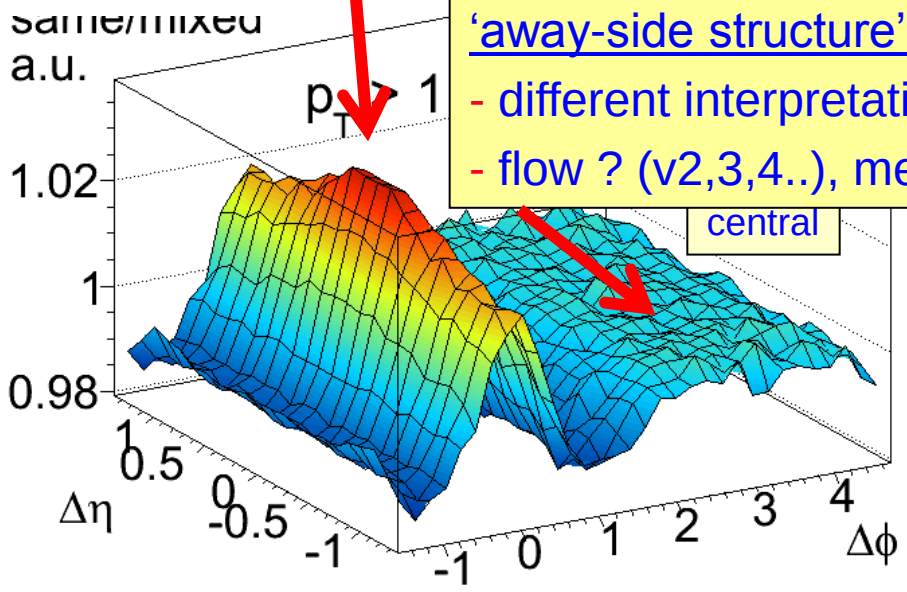
- 'Autocorrelation': $d^2N_{ch}/d\Delta\eta d\Delta\phi$ (signal)/$d^2N_{ch}/d\Delta\eta d\Delta\phi$ (mixed events)

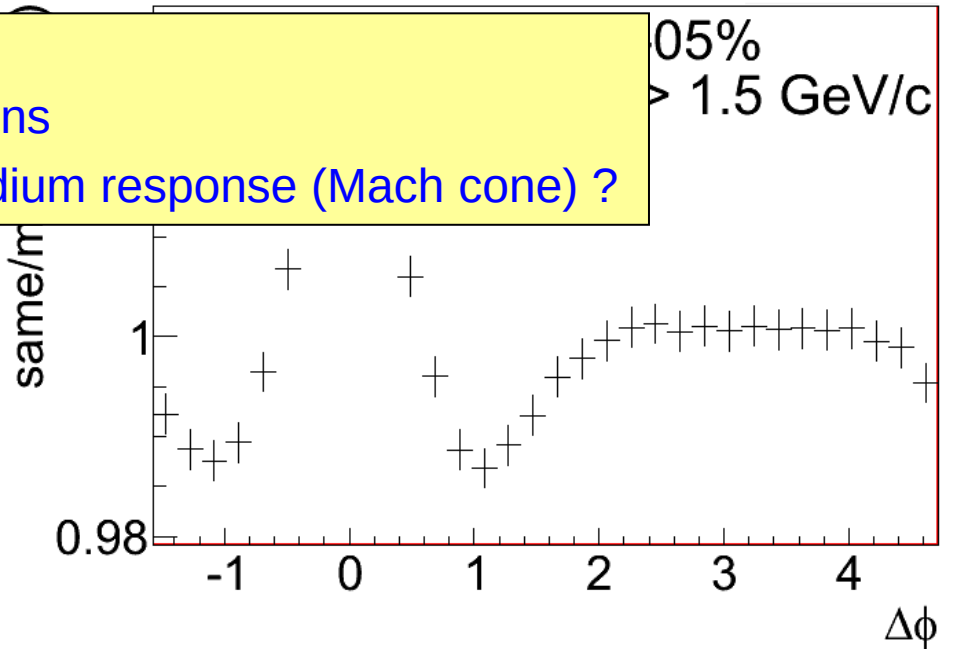


'near side ridge':
- different interpretations
- flow ? (v2,3,4..) + jet/resonances ?

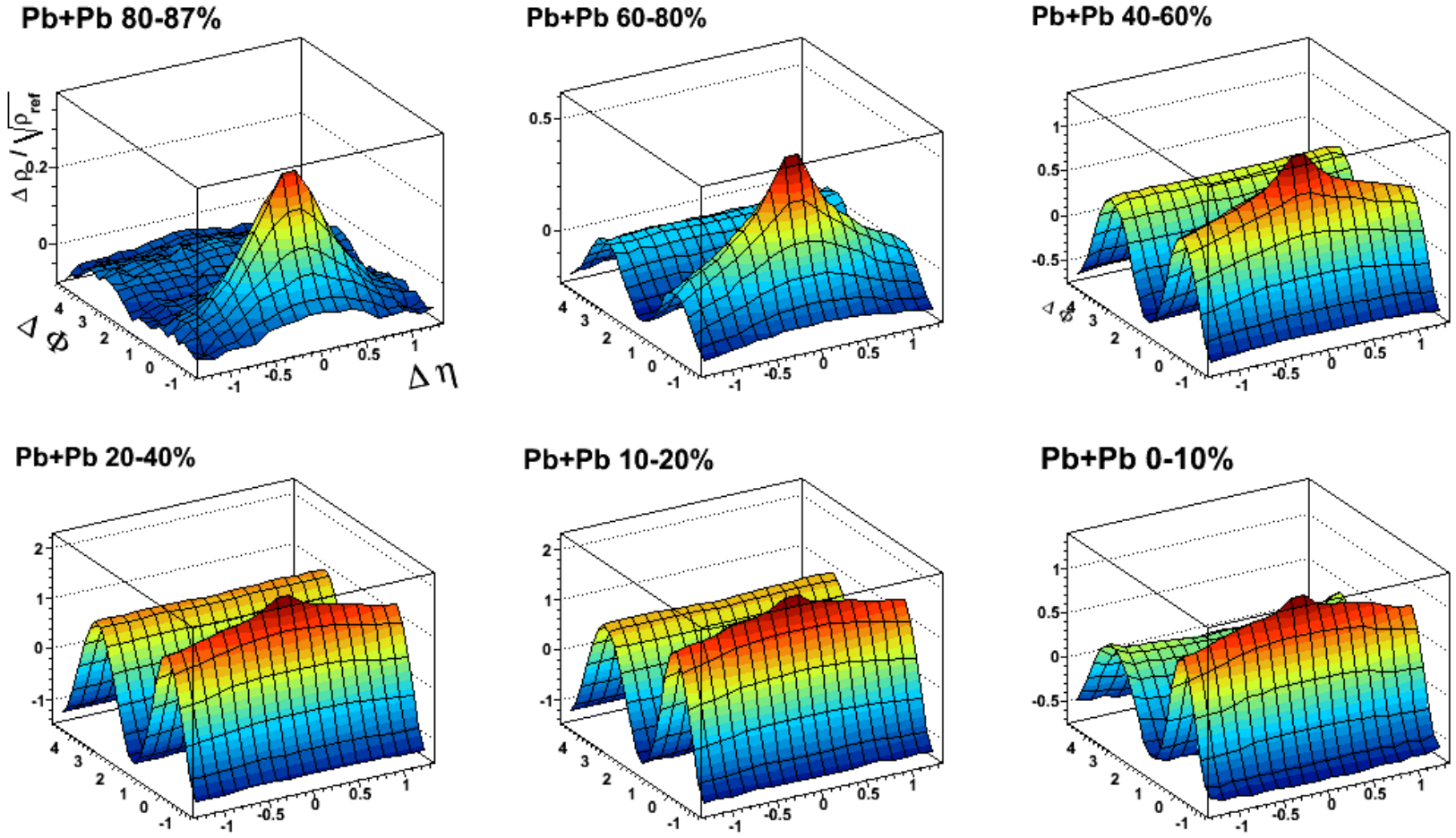


'away-side structure':
- different interpretations
- flow ? (v2,3,4..), medium response (Mach cone) ?





Quantitative Analysis



QM:

- what (if anything) is left besides flow ?
- is there a 'near side eta ridge' ?
- what is the reason for the broad away side structure ?

very interesting (and revealing) charge/centrality/p_T dependences

Role of LHC after RHIC/SPS

- 1) Quantitative differences
  - ⇨ significantly different state of QGP in terms of energy density, lifetime, volume
  - ⇨ large rate for 'hard probes' : jets, heavy quark states (b,c,Υ,J/Ψ),…

- 2) Test & validate the HI 'Standard Model'

- 3) 'Precision' measurements of QGP parameters

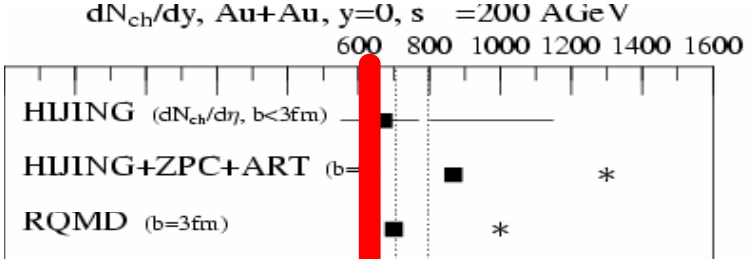
- 4) Clarify status of some 'Beyond the HI Standard Model' ideas

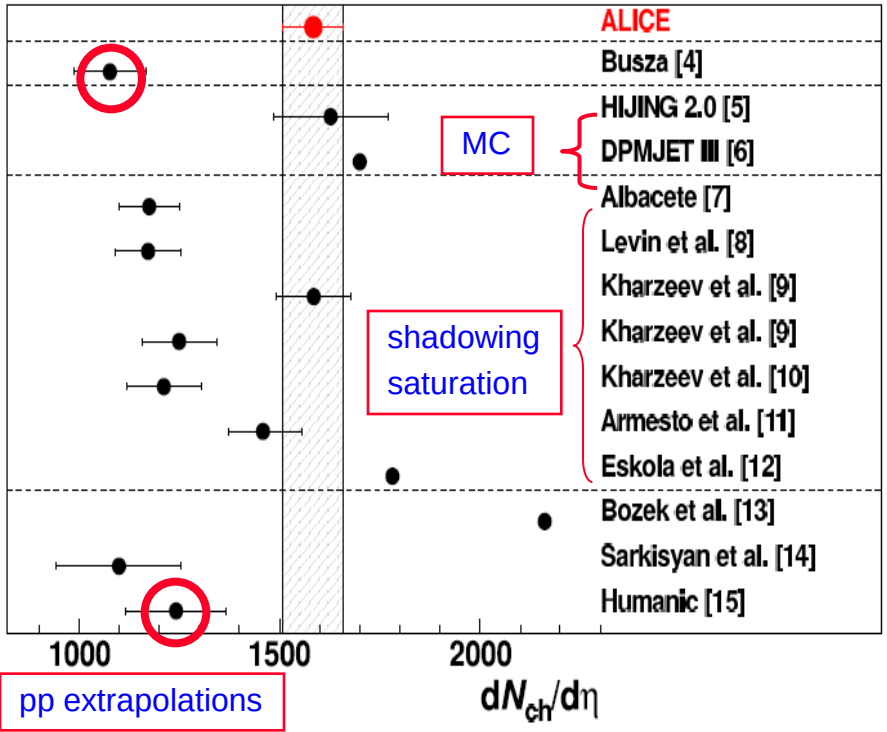
- 5) Surprises ?

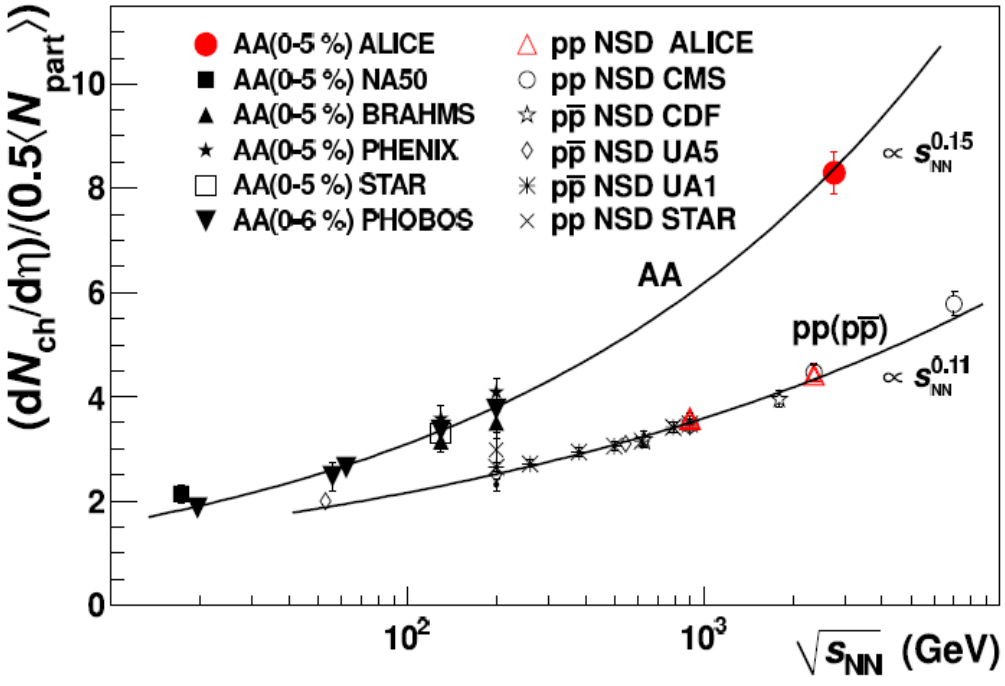
1) What's the Difference ?

- Multiplicity and Energy density ε:
  - ⇨ **$dN_{ch}/d\eta \sim 1600 \pm 76$ (syst)**
    - somewhat on high side of expectations
    - growth with √s faster in AA than pp (√s dependent 'nuclear amplification')
  - ⇨ **Energy density ≈ 3 x RHIC** (fixed τ)
    - lower limit, likely τ_0(LHC) < τ_0(RHIC)

$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dN}{dy} < m_t >$$

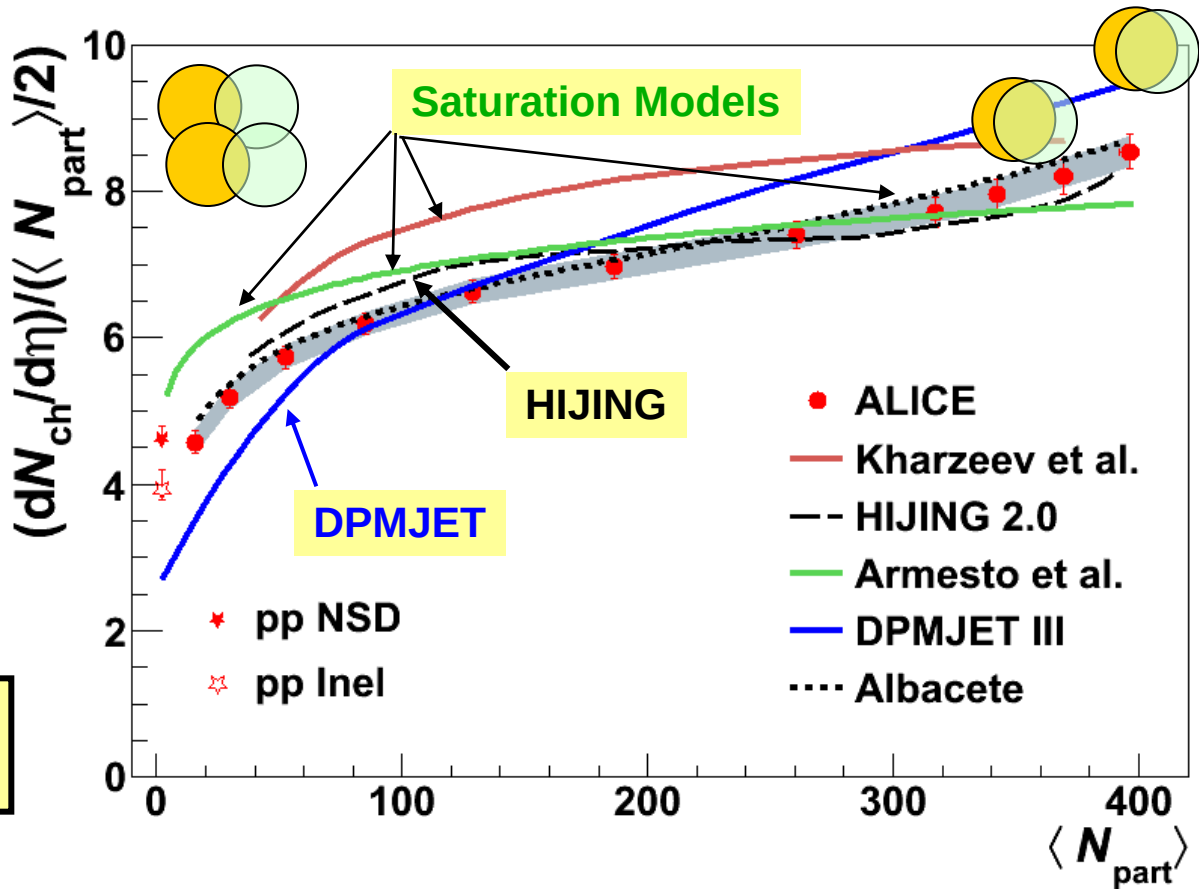






Who gets it right and why ?

- $dN_{ch}/d\eta$ as function of centrality (normalised to 'overlap volume' ~ $N_{participants}$)
  - ⇨ soft process dN_{ch}/d_{η} ~ number of scattered nucleons (strings, participants, …)
    - ✪ 'nuclear amplification' should be energy independent
  - ⇨ (very) hard processes dN_{ch}/d_{η} ~ number of nucleon-nucleon collisions
    - ✪ should get more important with √s **&** with centrality
  - ⇨ DPMJET MC
    - ✪ gets it right for the wrong reason
  - ⇨ HIJING MC
    - ✪ strong centr. dependent **gluon shadowing**
  - ⇨ Others
    - ✪ **saturation models:** Color Glass Condensate, 'geometrical scaling' from HERA/ photonuclear react.

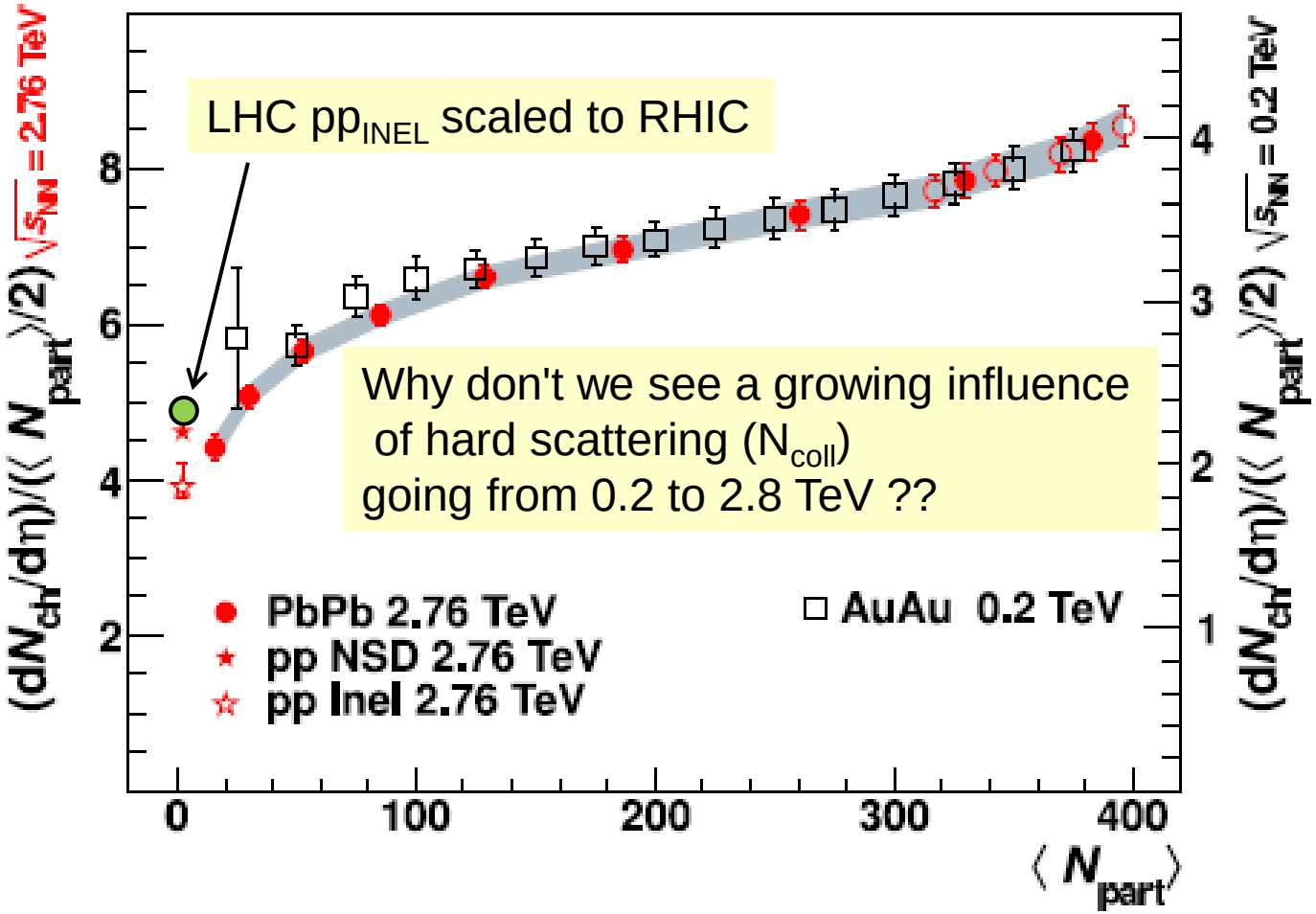


Important constraint for models sensitive to details of saturation

LHC ~ RHIC !!

pp: $N_{ch} \sim s^{0.11}$ AA: $N_{ch} \sim s^{0.15}$

=> expect ~ 25% stronger rise from very peripheral to central at LHC



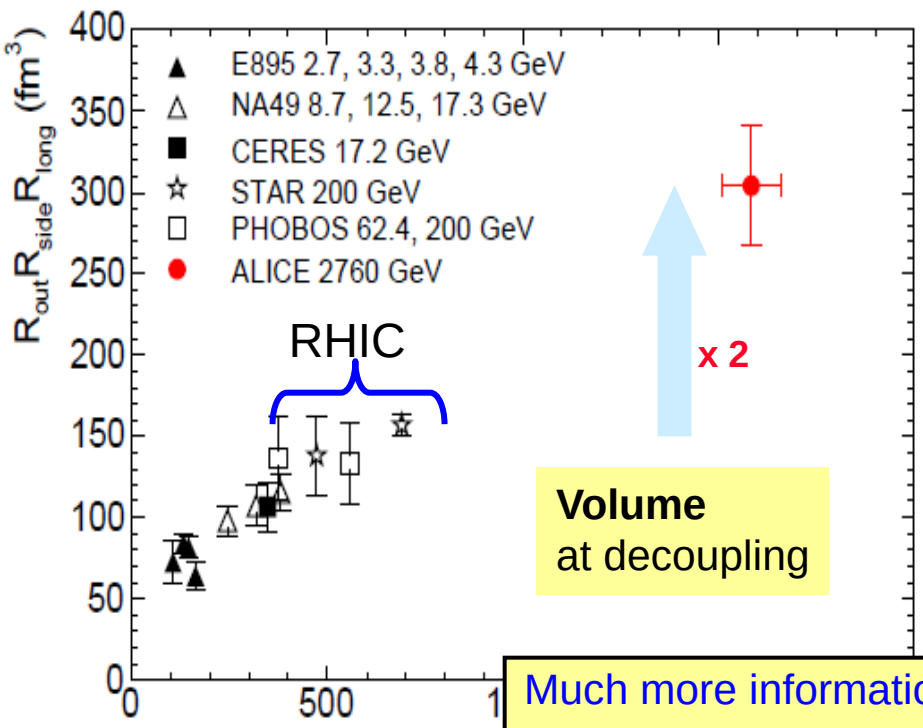
CGC: N_{ch} grows as power law in energy ($s^{0.13}$), but only logarithmically in impact parameter

$$\frac{1}{Npart}\frac{dN}{\eta} = \left(\sqrt{\frac{s}{s_0}}\right)^{\lambda} 2\ln\left[Q_s(s,b)/\Lambda\right]$$

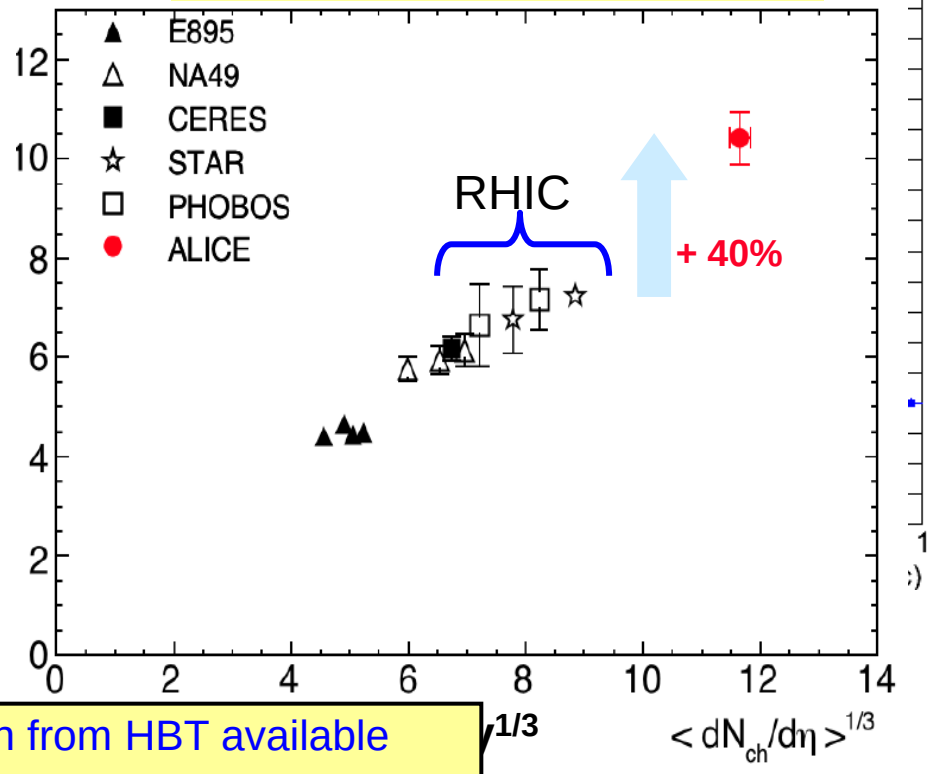
What's the Difference ?

- Volume and lifetime:
  - ⇨ Identical particle interferometry (HBT, Bose-Einstein correlations)
    .
  - ⇨ **Volume ≈ 2 x RHIC** (≈ 300 fm^3)
    - ✪ 'comoving' volume !
  - ⇨ **Lifetime ≈ +30-40%** (≈ 10 fm/c)

Lifetime: from collision to 'freeze-out' (hadron decoupling)



Volume
at decoupling



Much more information from HBT available
(Rout/side/long versus k_T and centrality)

Role of LHC after RHIC/SPS

- 1) Quantitative differences

- 2) Test & validate the HI 'Standard Model'

  QGP = very strongly interacting (almost) perfect liquid

  ⇨ Test predictions/extrapolations from RHIC to LHC

  ✪ examples: **flow** ('soft') **Quarkonia suppression** ('hard')

- 3) 'Precision' measurements of QGP parameters

- 4) Clarify status of some 'Beyond the HI Standard Model' ideas

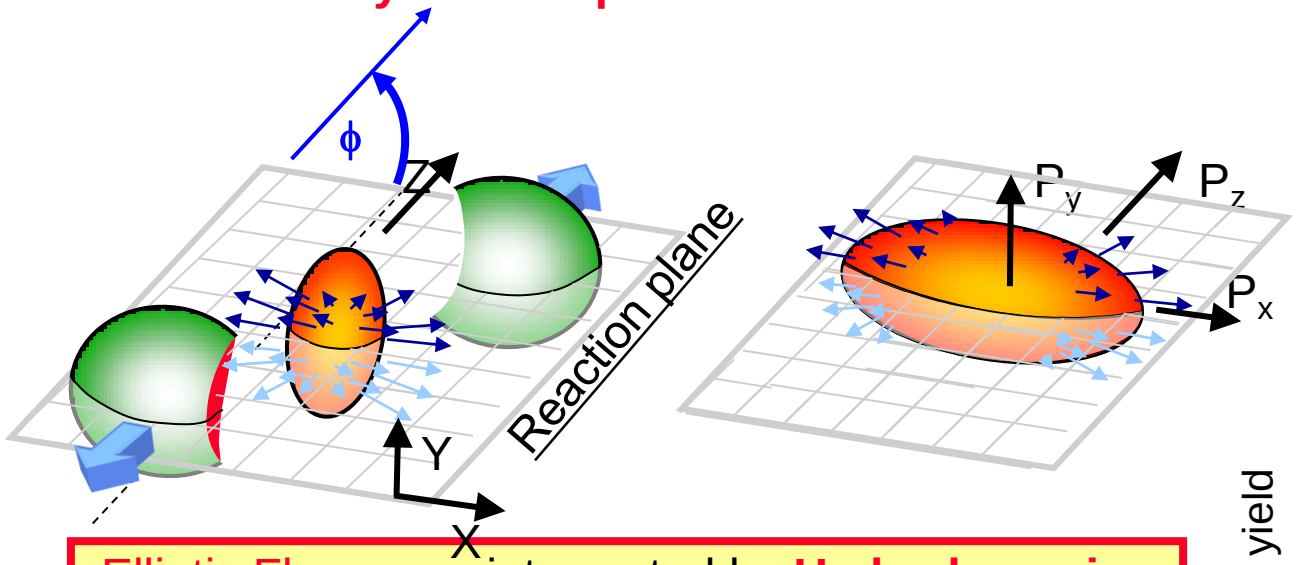
- 5) Surprises ?

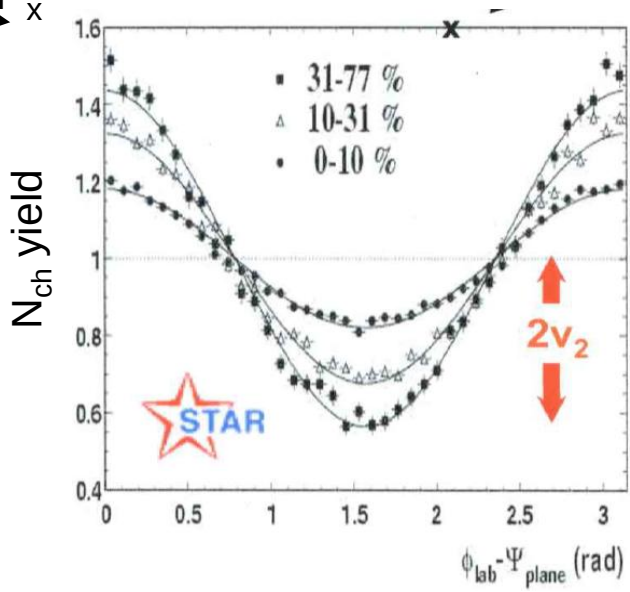
2) Testing the HI 'Standard Model'

- Elliptic Flow: one of the most anticipated answers from LHC

⇨ **experimental observation:** particles are distributed with azimuthally anisotropic around the scattering plane

⇨ **Are we sure Hydro interpretation is correct ?**





Elliptic Flow v_2 as interpreted by **Hydrodynamics**

Pressure gradient converts

spatial anisotropy → momentum anisotropy

→ particle yield anisotropy

Strength of flow depends on:

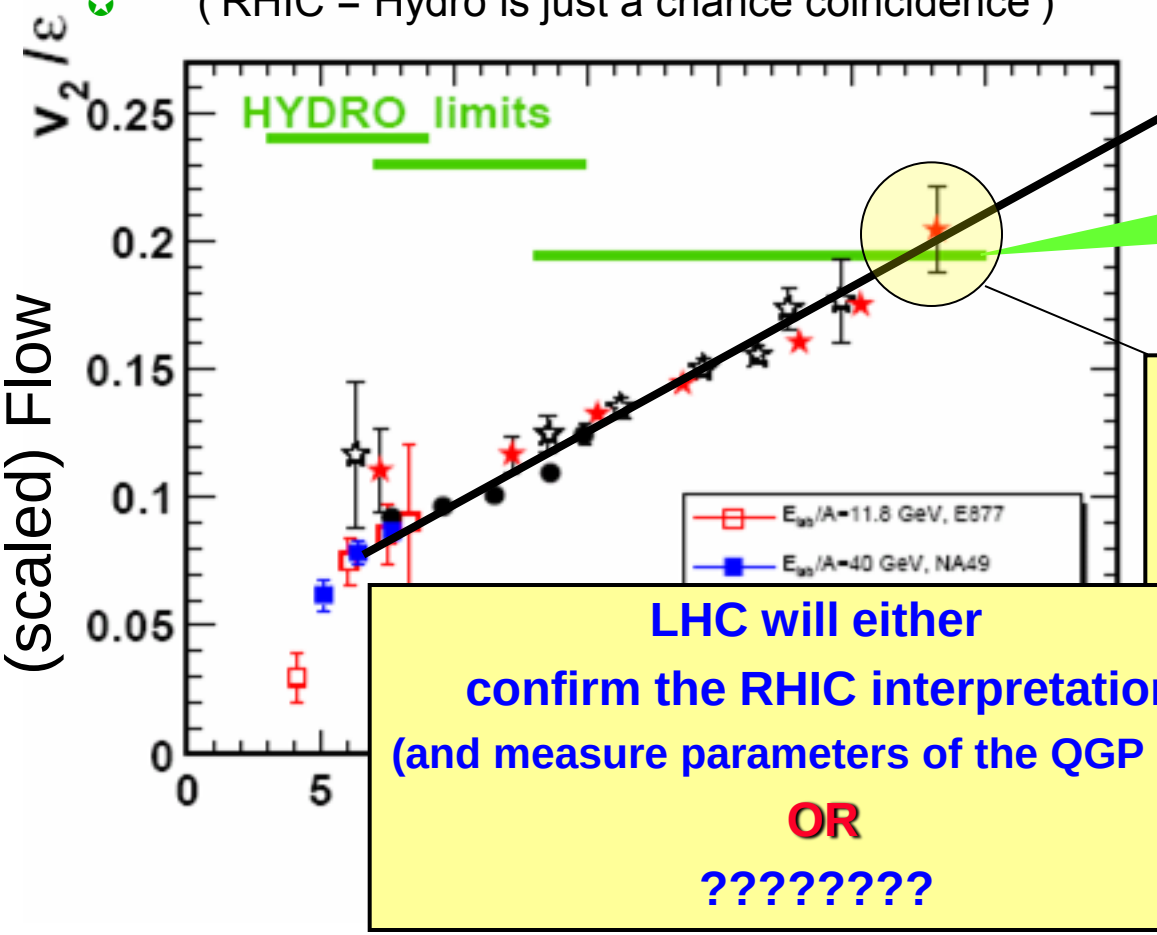
1) Fluid properties (viscosity, EoS, ..)

2) Initial conditions (geometrical shape)

Testing the HI 'Standard Model'

- Hydro seems to work very well for first time at RHIC
  - ⇨ LHC prediction: modest rise (Depending on EoS, viscosity, speed of sound, $dN_{ch}/d\eta$, ..)
    - ✪ ('better than ideal is impossible')
  - ⇨ experimental trend & scaling predicts large increase of flow
    - ✪ ('RHIC = Hydro is just a chance coincidence')

LHC ?



BNL Press release, April 18, 2005:

Data = ideal Hydro

"Perfect" Liquid

New state of matter more remarkable than predicted – raising many new questions

LHC will either

confirm the RHIC interpretation

(and measure parameters of the QGP EoS)

OR

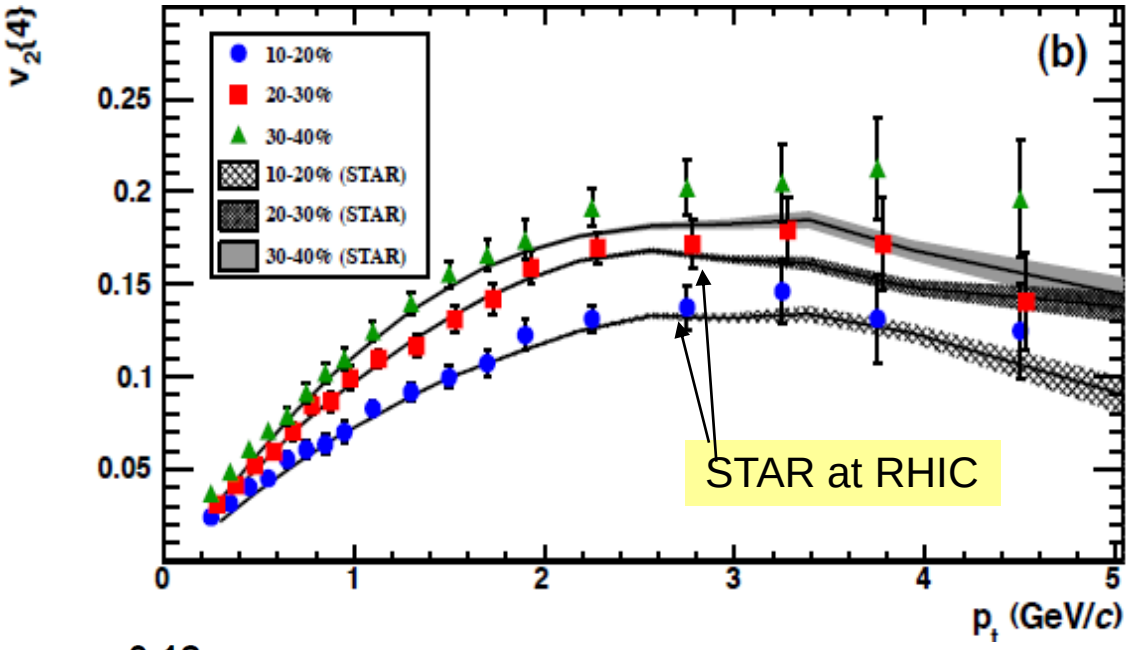
????????

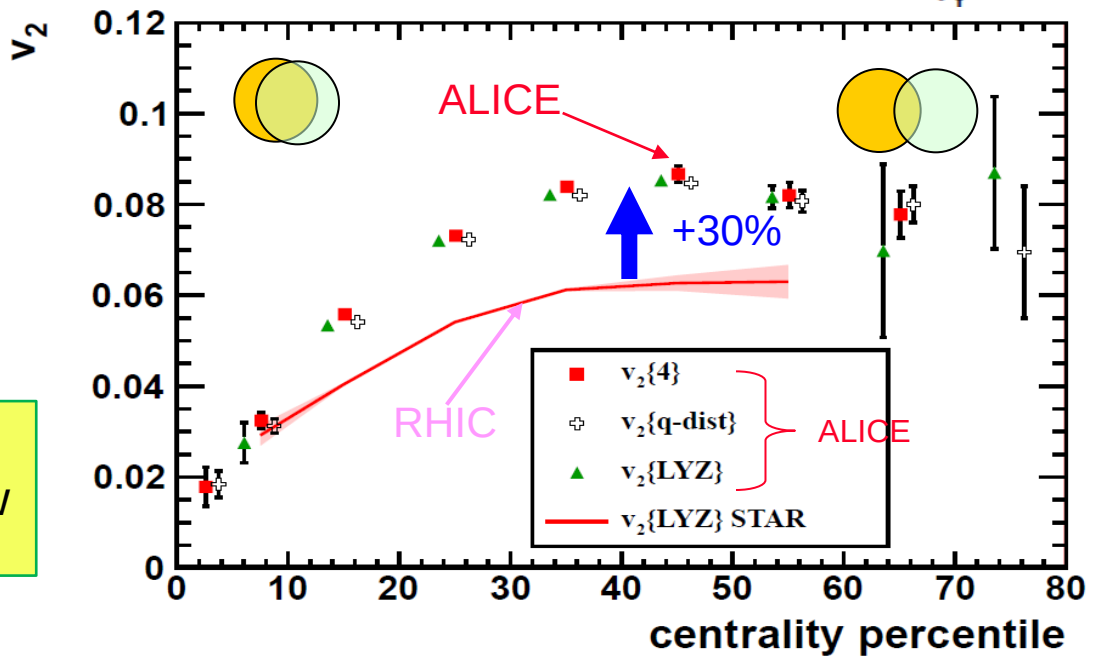
First Elliptic Flow Measurement at LHC

- v_2 as function of p_t
  - ⇨ **practically no change with energy !**
    - ✪ extends towards larger centrality/higher p_t ?

- v_2 integrated over pt
  - ⇨ **30% increase from RHIC**
  - ⇨ $\langle p_t \rangle$ increases with √s
    - ✪ pQCD powerlaw tail ?
  - ⇨ Hydro predicts increased 'radial flow'
    - ✪ very characteristic p_t and mass dependence; **to be confirmed !**

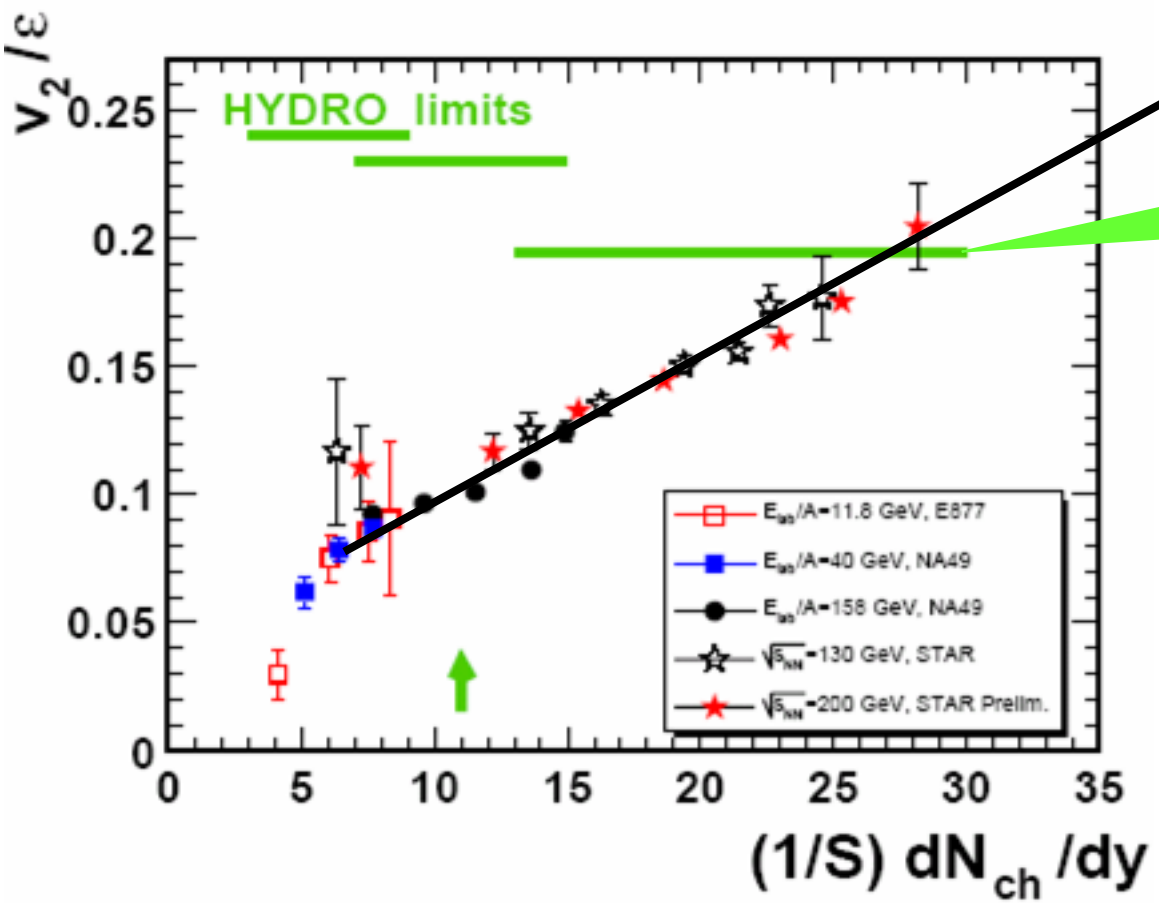
QM:
❑ π/K/p spectra & radial flow





Testing the HI 'Standard Model'

- Hydro passed the first test !
  - ⇨ many more tests of Hydro and the HI-SM to come….



LHC !

CERN Press release, November 26, 2010:

'confirms that the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid)..'

Disclaimer: very rough guesstimate, assuming geometry not to change between RHIC and LHC

Testing Quarkonia Suppression

- Interpretation of SPS & RHIC results ambiguous
  - ⇨ **HI–SM : J/Ψ (Υ', Υ'') suppression stronger** at LHC, Υ suppression depends on T
  - ⇨ **extension** to HISM: **J/Ψ** enhancement, **Υ', Υ''** suppression
    - ✪ recombination of charm pairs to J/Ψ may mask suppression at RHIC

- Partial answer expected from this years data
  - ⇨ normalisation (measured/expected) ongoing
  - ⇨ Υ family will need integrated L ~ 1-2 nb^{-1}

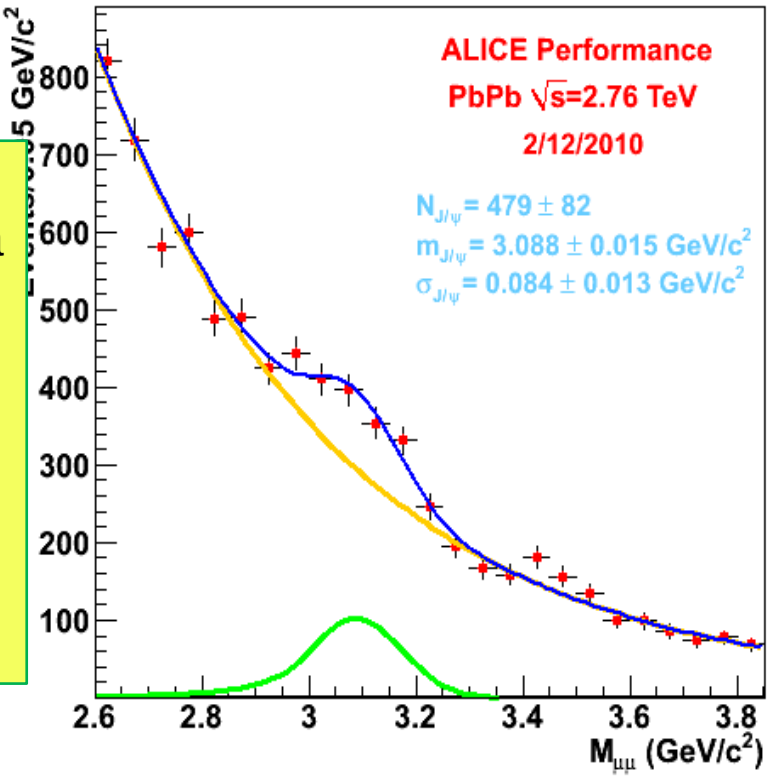
Pb-Pb Min. Bias
expect ~ 2000 J/Ψ

QM:

❑ J/Ψ R_{AA}, R_{CP} using 2.76 pp comparison data

However, we are **missing information** on
- cold nuclear matter suppression
- initial state effects (shadowing)

=> I don't expect a clear picture until we have p-Pb data (possibly in 2013 ?)



Role of LHC after RHIC/SPS

- 1) Quantitative differences
- 2) Test & validate the HI 'Standard Model'

Precision measurements are still a long way ahead, but it looks like we will get there !

- 3) 'Precision' measurements of QGP parameters
  - ⇨ Quantitative and systematic study of the new state of matter
    - ✪ **Equation-of-State** f(ε,p,T), **viscosity** η (flow), **transport coefficient q** (jet quenching), Debye **screening mass** (Quarkonia suppression), …
  - ⇨ Confront with Theory and Models:
    - ✪ **standard tools:** Lattice QCD, pQCD, Thermo- and Hydrodynamics, …
    - ✪ **new tools:** AdS/CFT ('duality'), Classical QFT ('Colour Glass Condensate')
- 4) Clarify status of some 'Beyond the HI Standard Model' ideas
- 5) Surprises ?

3) Towards Precision Measurements

- **ideal hydro → Viscosity η ≈ 0 → zero mean free path !**
  - ⇨ usually use Viscosity/Entropy **η/S** (dimensionless number)
  - ⇨ **RHIC:** QGP almost **ideal fluid**, η/s < 0.2 -0.4

$$\eta = \frac{\sqrt{2mkT}}{\sigma}$$

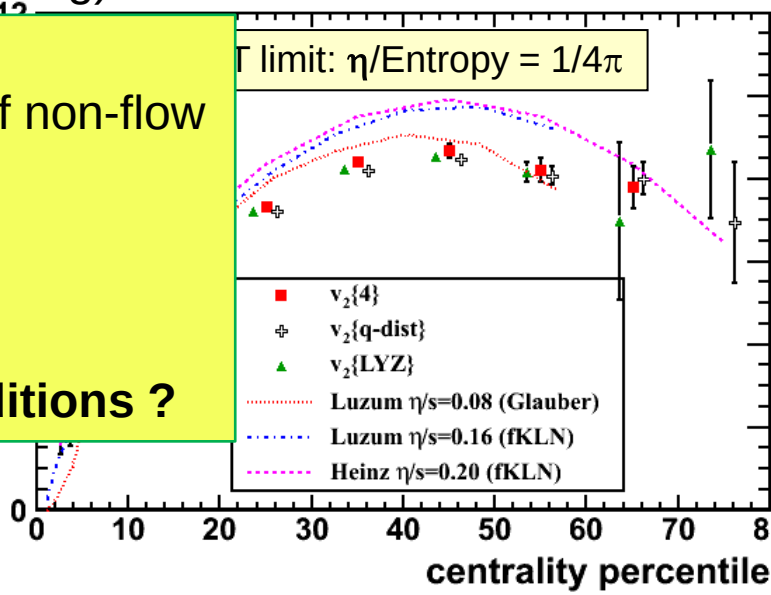
- unexpected result
  - ⇨ QGP though to behave like a gas (weakly interacting)
  - ⇨ closest the
    - ✪ conjectur

QM:

- ❑ improved v_2 precision & estimate of non-flow
- ❑ higher flow harmonics (v_3,v_4,v_5)
- ❑ results on flow fluctuations
- ❑ directed flow (v_1)

? strong constraints on initial conditions ?

- Precisior
  - ⇨ current RH
  - ⇨ η/S < 1/4π
  - ⇨ η/S > 1/4π
  - ⇨ η/S ≈ 1/4π => quantum corrections O(10-30%) !
    - ✪ **20% in v_2 ~ 1/4π => need few % precision**



- Precision: How ?
  - ⇨ fix **initial conditions** (geometrical shape is model dependent, eg Glauber, CGC)
  - ⇨ quantify E-b-E **flow fluctuations** (influence measured v_2, depending on method)
  - ⇨ measure **non-flow correlations** (eg jets)
  - ⇨ **improve theory** precision (3D hydro, 'hadronic afterburner', ...)

Role of LHC after RHIC/SPS

- 1) Quantitative differences
- 2) Test & validate the HI 'Standard Model'
- 3) 'Precision' measurements of QGP parameters
- 4) Clarify status of some 'Beyond the HI Standard Model' ideas
  - ⇨ support, but no smoking gun yet: CGC, quark coalescence, ..
  - ⇨ some hints, maybe ?: Chiral magnetic effect ('strong CP violation'), Mach cones, ...
- 5) Surprises ?

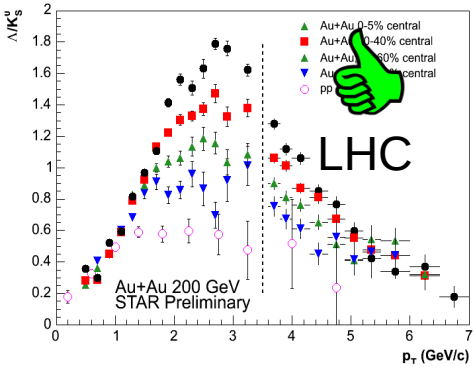
4) Beyond the HI Standard Model (QM preview)

- Extraordinary claims will need extraordinary proof

⇨ **CGC**: sound theory, consistent with several observables, at RHIC & LHC

- N_{ch} production; seems good candidate for initial flow cond. at LHC
- no 'smoking gun signal ?

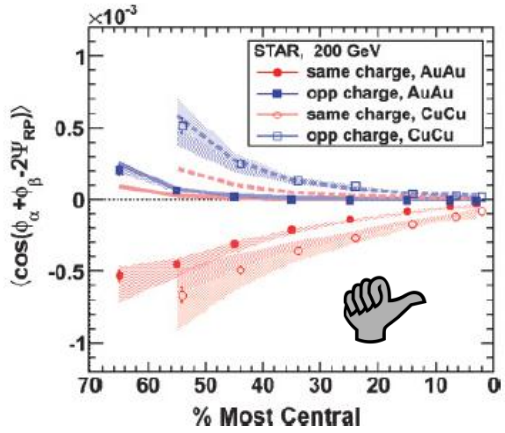
LHC

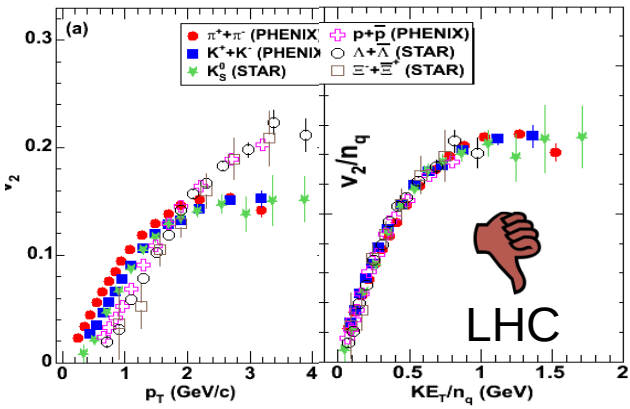


LHC

⇨ **parton coalescence:** 'idea' rather than a quantitative model

- baryon/meson anomaly
- quark number scaling of flow





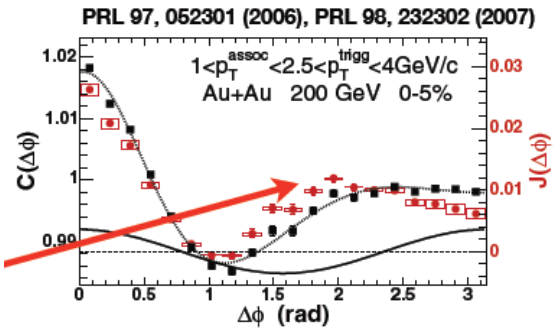
LHC

⇨ **'Strong CP violation/CME'**

- visible at LHC, but ...

⇨ **Mach cones**

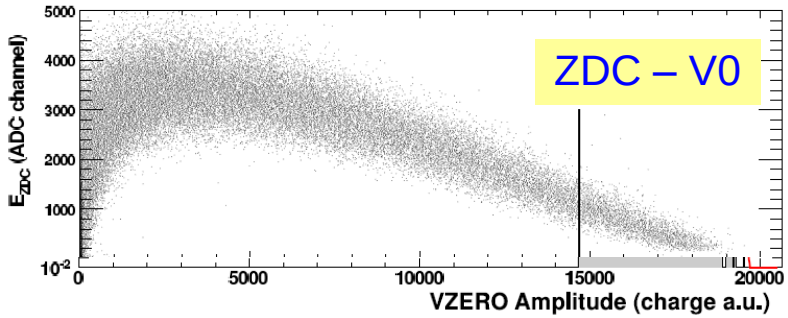
- very visible, but..

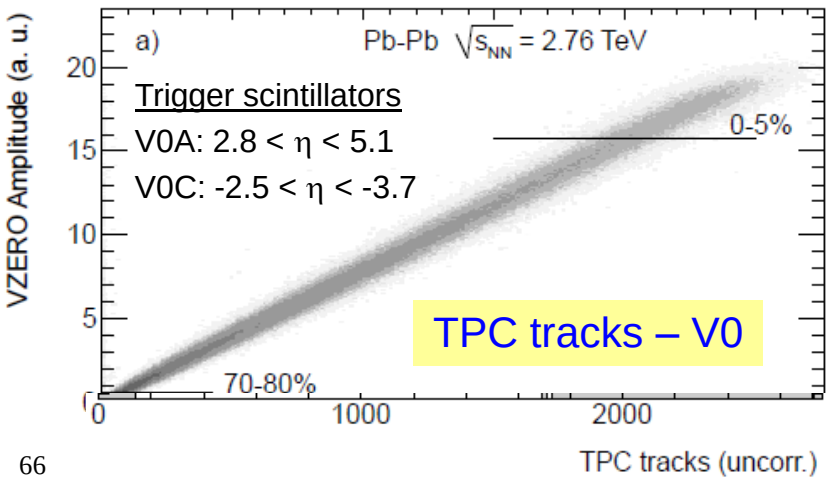


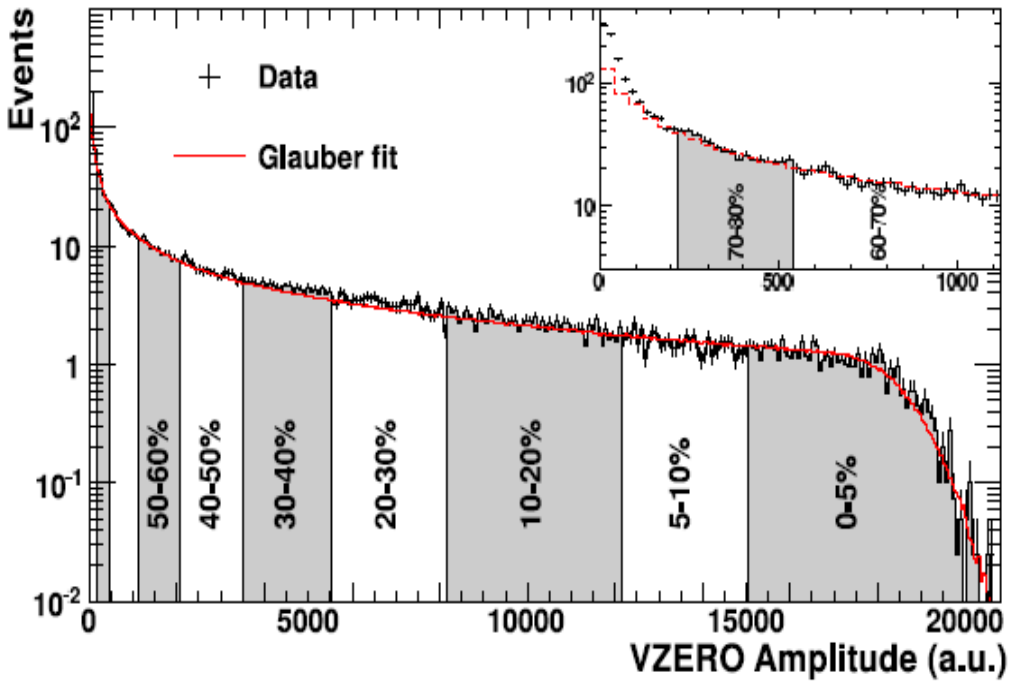
LHC

Bits and Pieces ..

- Centrality determination with Glauber fits:
  - ⇨ very tight correlation of several centrality measures (different acceptance/detectors)
    - ✪ 1/√N is a small number at LHC ! Centrality resolution **< 0.5%** for most central !







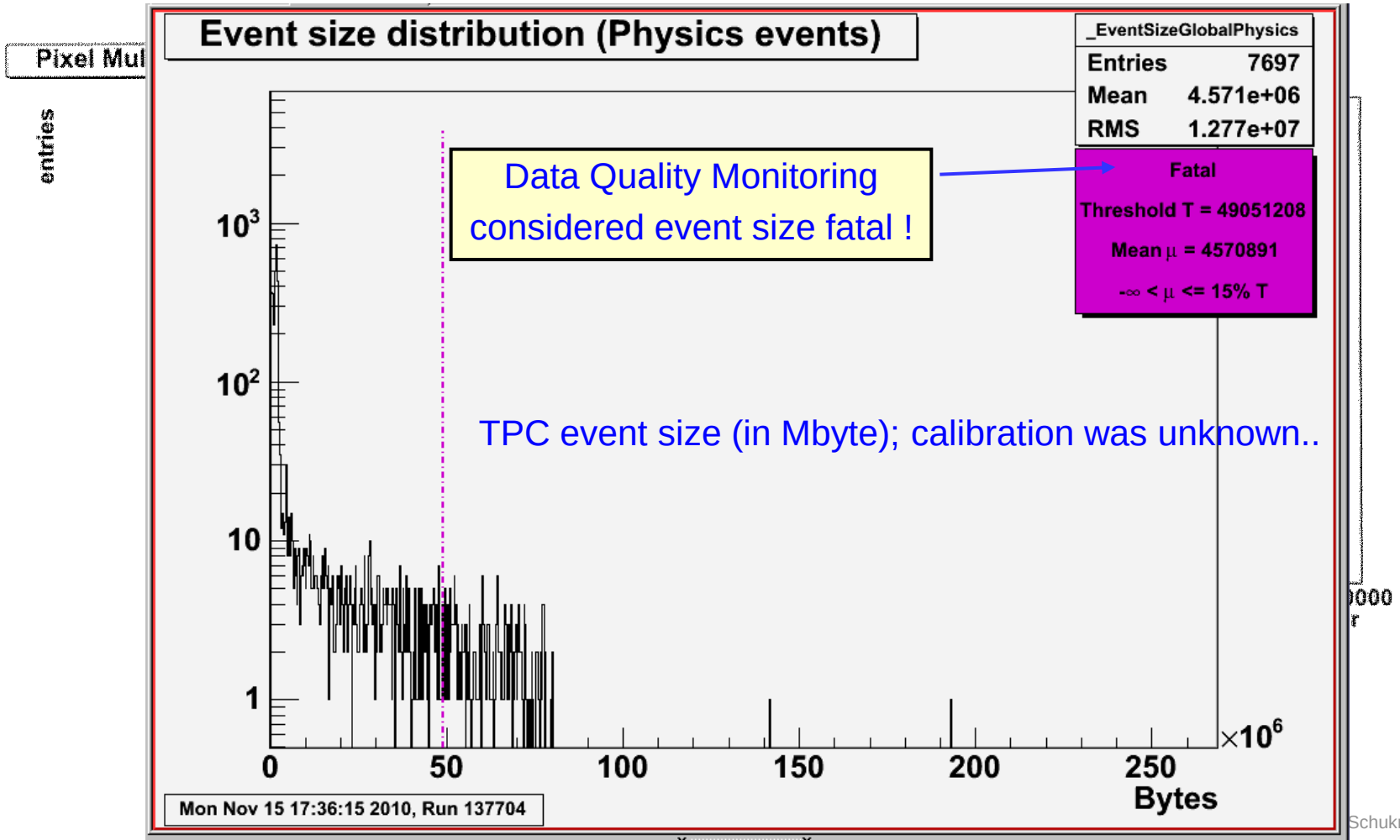
Other Centrality Measures

First Pb-Pb collision!

7-11-2010 13:37 am

A few minutes after the first Pb collisions at LHC:

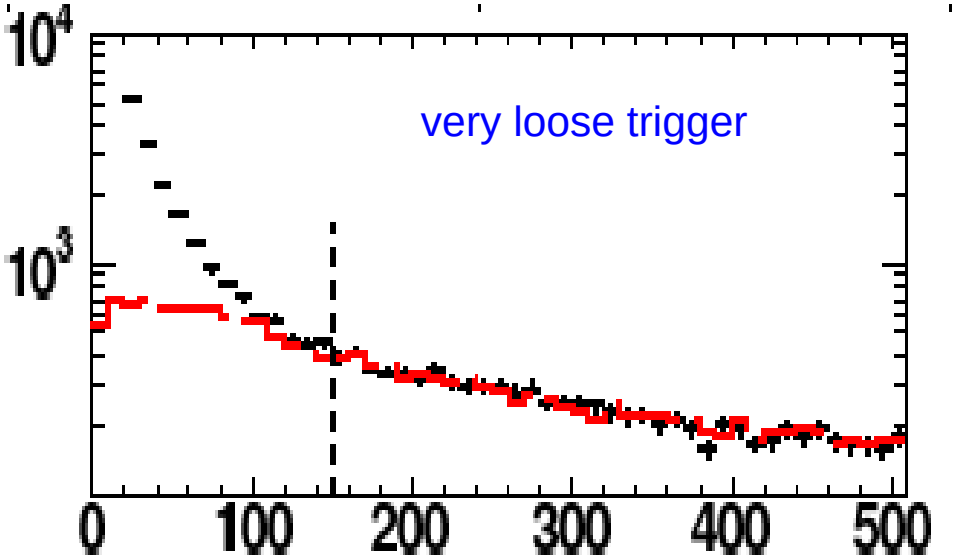
Copy from logbook (predicted calibration: 9 hits = 1 $dN_{ch}/d\eta$)



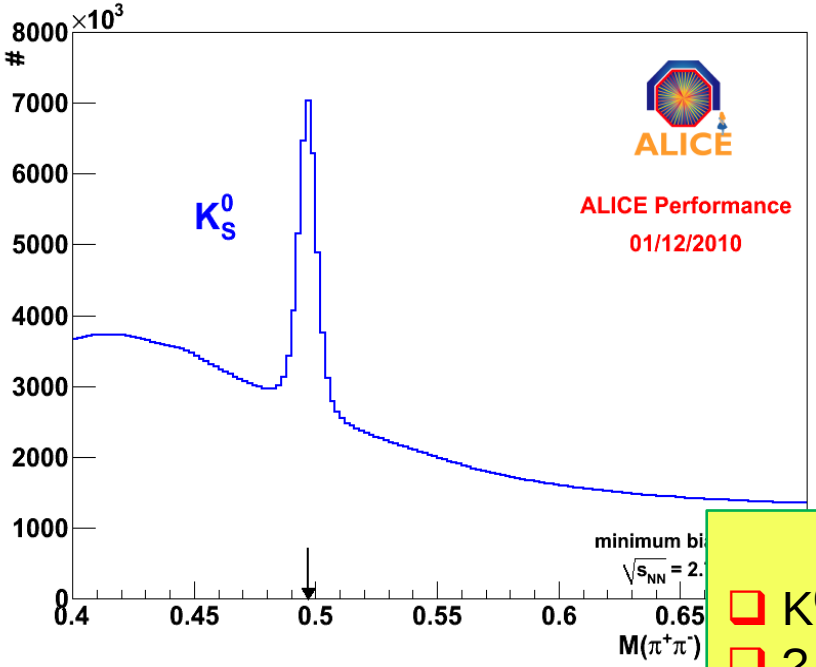
Even QED becomes strong at LHC

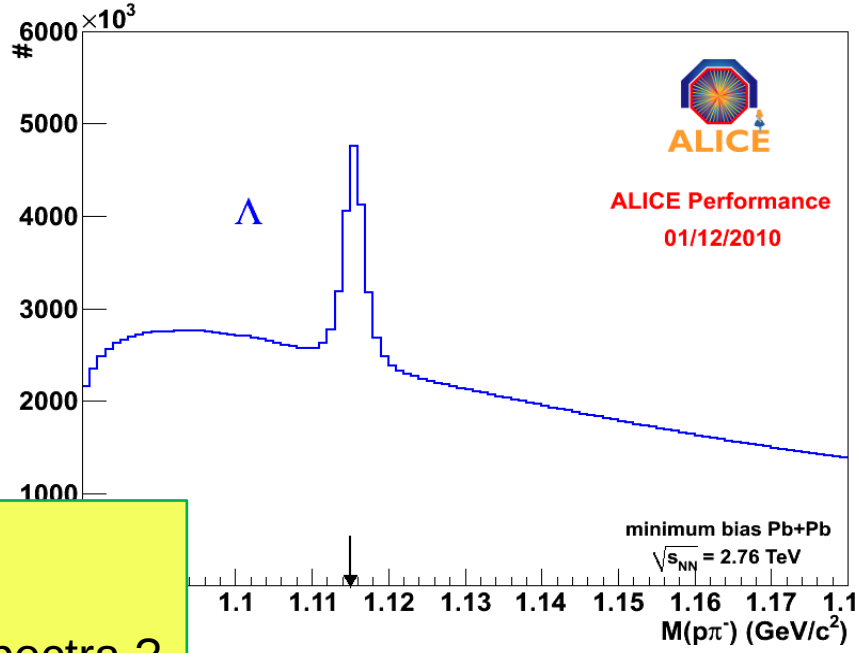
- very large em cross sections:
  - ⇨ QED pair production: hundreds of kbarn
    - ✪ e+e- very soft
  - ⇨ em dissociation ~ 200 barn
    - ✪ one or several neutrons in ZDC, no central particles
  - ⇨ photonuclear reactions: tens of barns (kinematics very similar to pA)
    - ✪ Gamma energy several 100 GeV
  - ⇨ all of the above strongly correlated via impact parameter !
    - ✪ large probability for coincidences

LHC is a very versatile collider:
pp, pA, AA,
$\gamma\gamma$, γA, γ-Pomeron



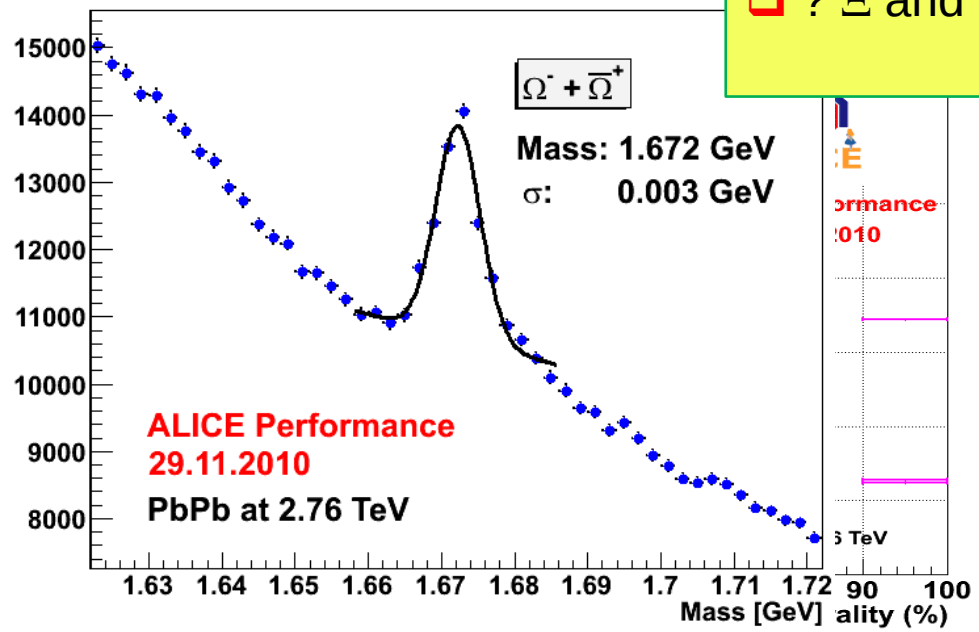
Strangeness in Pb-Pb

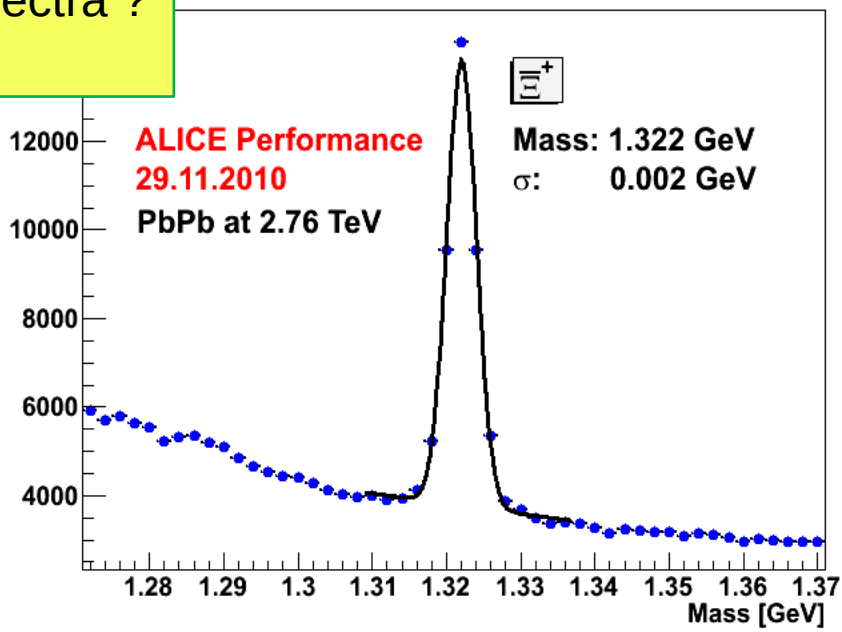




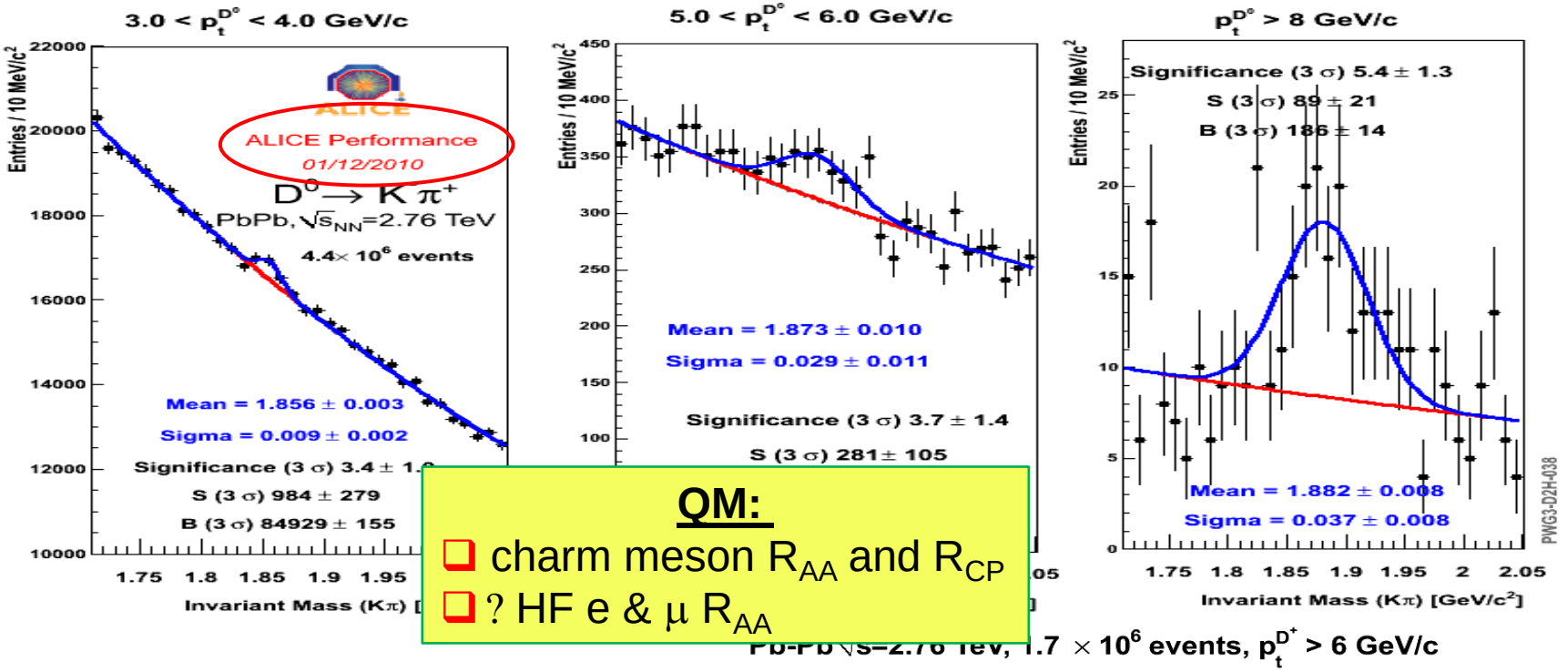
QM:

- K^0/Λ
- ? Ξ and Ω spectra ?





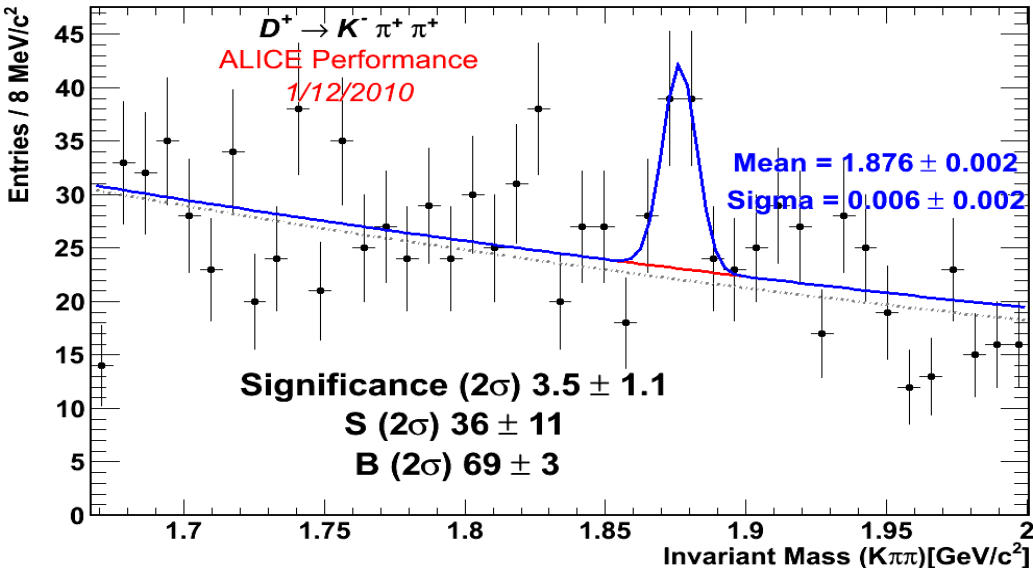
Charm in Pb-Pb



QM:

- charm meson R_{AA} and R_{CP}
- ? HF e & μ R_{AA}

Pb-Pb $\sqrt{s}$=2.76 TeV, 1.7 × 10^6 events, $p_t^{D^+}$ > 6 GeV/c



'Jet quenching' with heavy quarks:

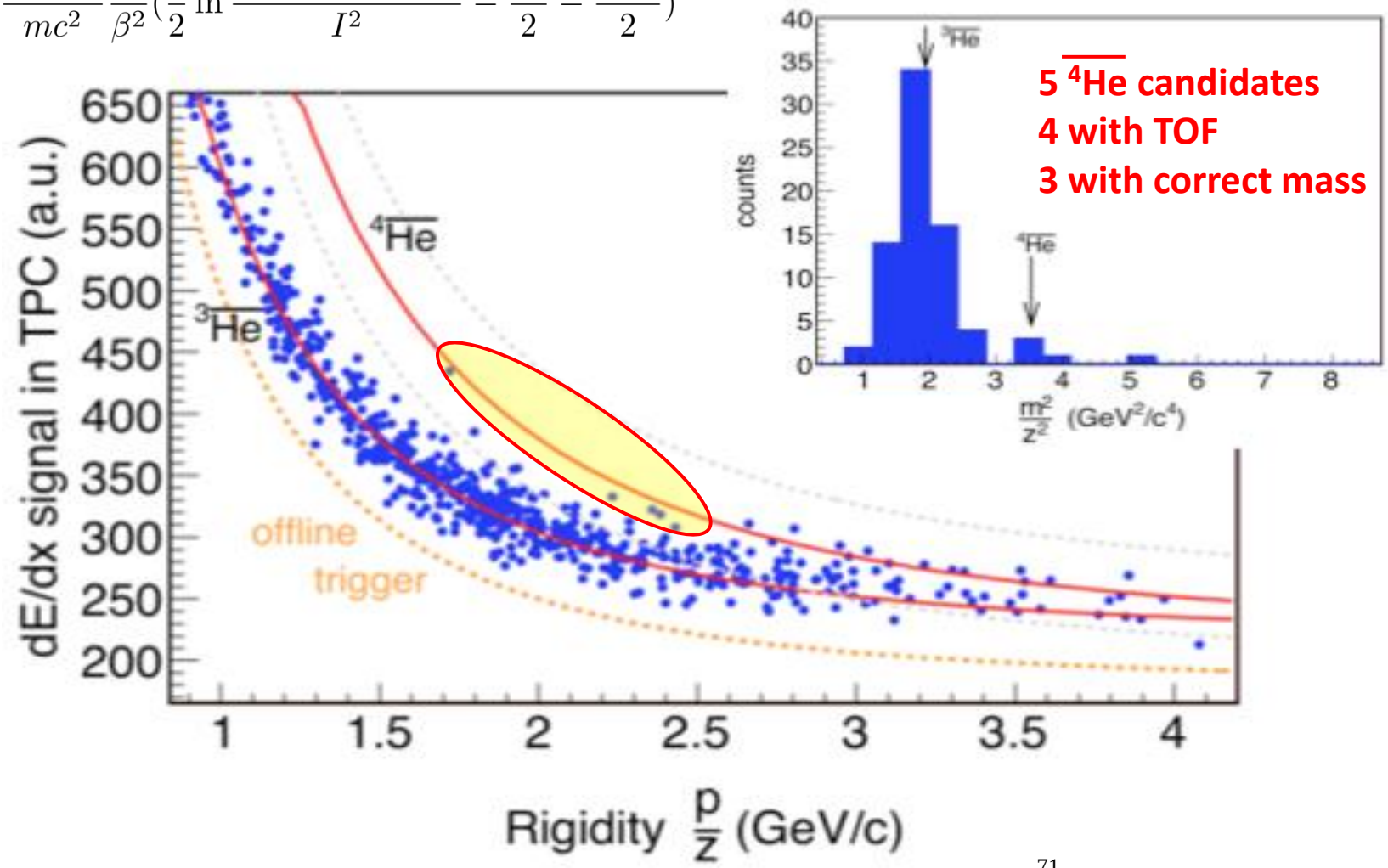
Energy loss depends on

- color charge (quark/gluon)
- mass (light/heavy quarks)

Anti-Nuclei in Pb-Pb

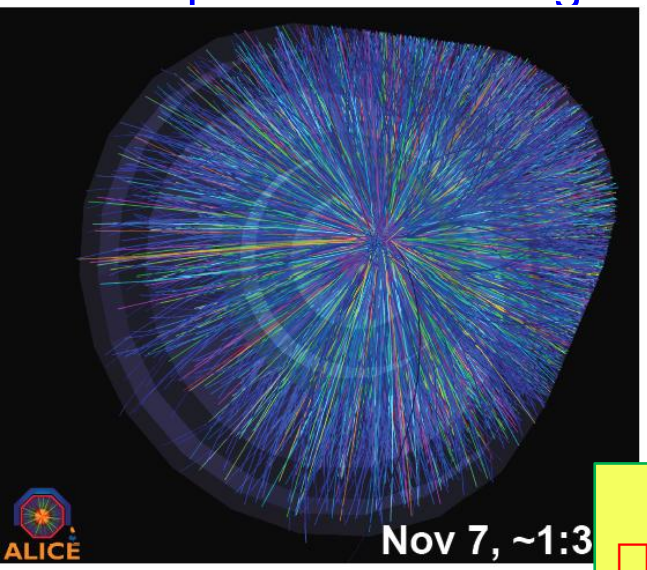
Time of flight (sensitive to m/z-ratio): $m = \frac{z \cdot R}{\sqrt{\gamma^2 - 1}}$

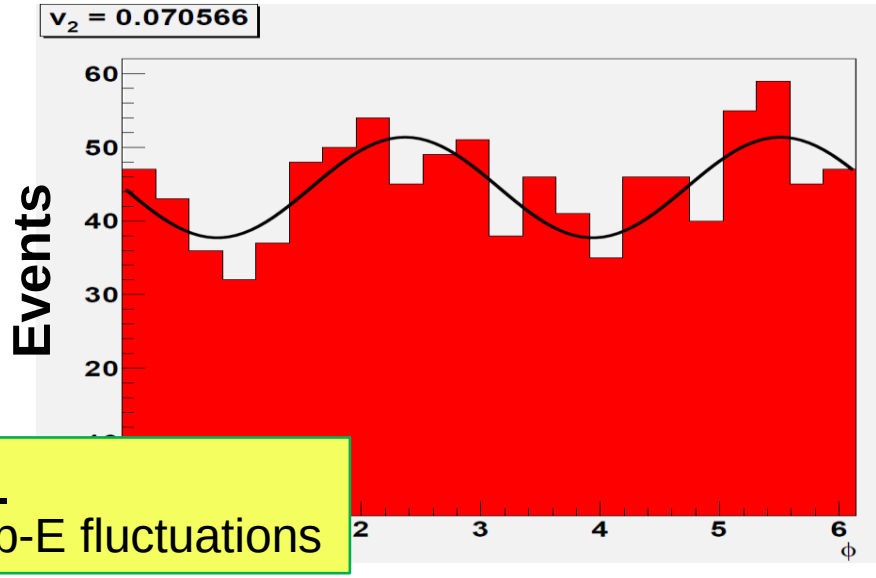
$$< \frac{dE}{dx} >= \frac{4\pi N e^4}{mc^2} \frac{z^2}{\beta^2} (\frac{1}{2} \ln \frac{2mc^2 E_{max} \beta^2 \gamma^2}{I^2} - \frac{\beta^2}{2} - \frac{\delta(\beta)}{2})$$



‘Single Events’

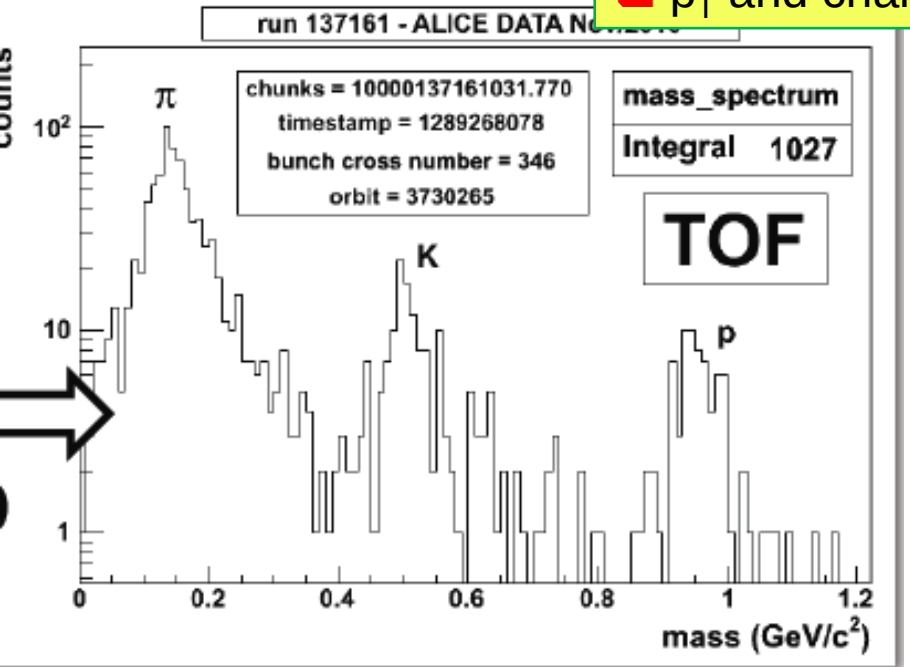
- ‘Properties of average events instead of average event properties’

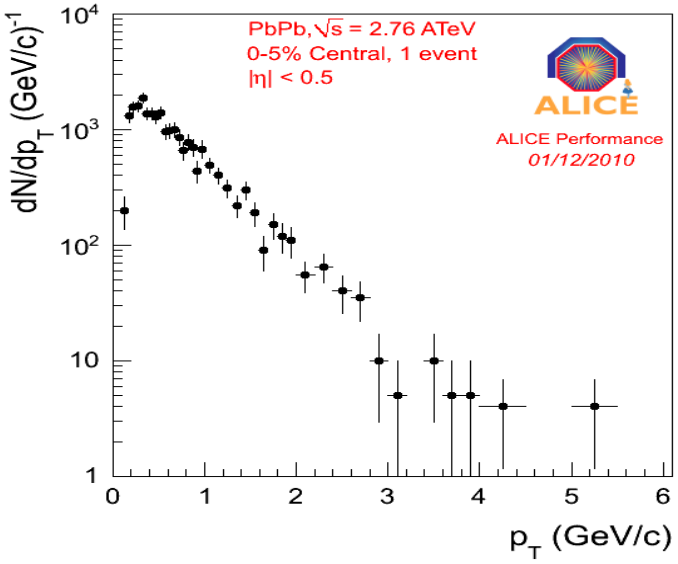




QM:

- p_T and charge E-b-E fluctuations



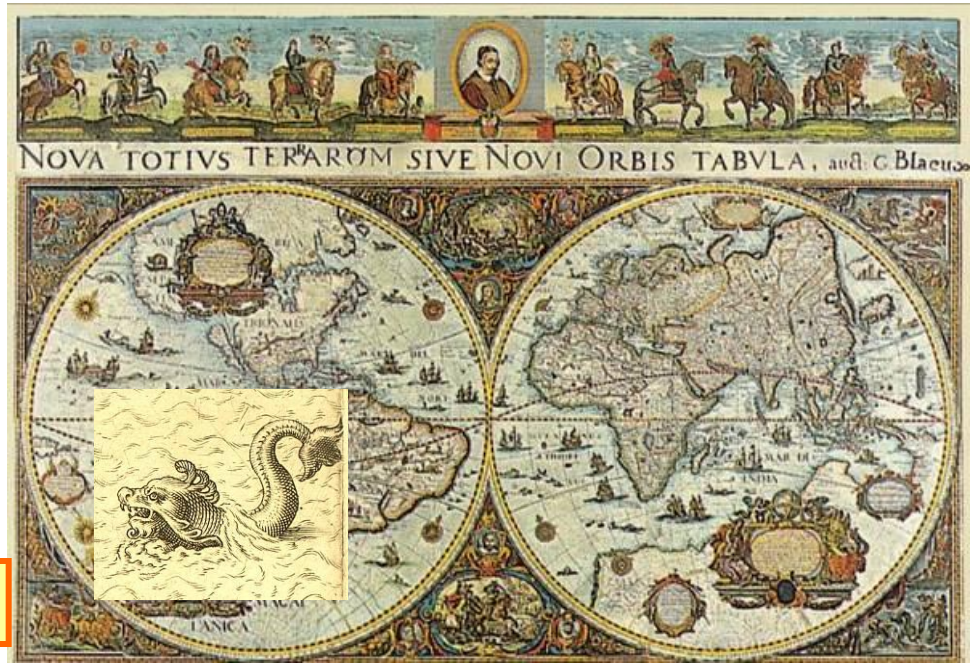


Summary

- LHC is a fantastic ‘Big Bang’ machine
  - ⇨ even for LHC standards, quality of first ion run was outstanding
  - ⇨ very powerful and complementary set of detectors (Atlas/CMS/Alice)

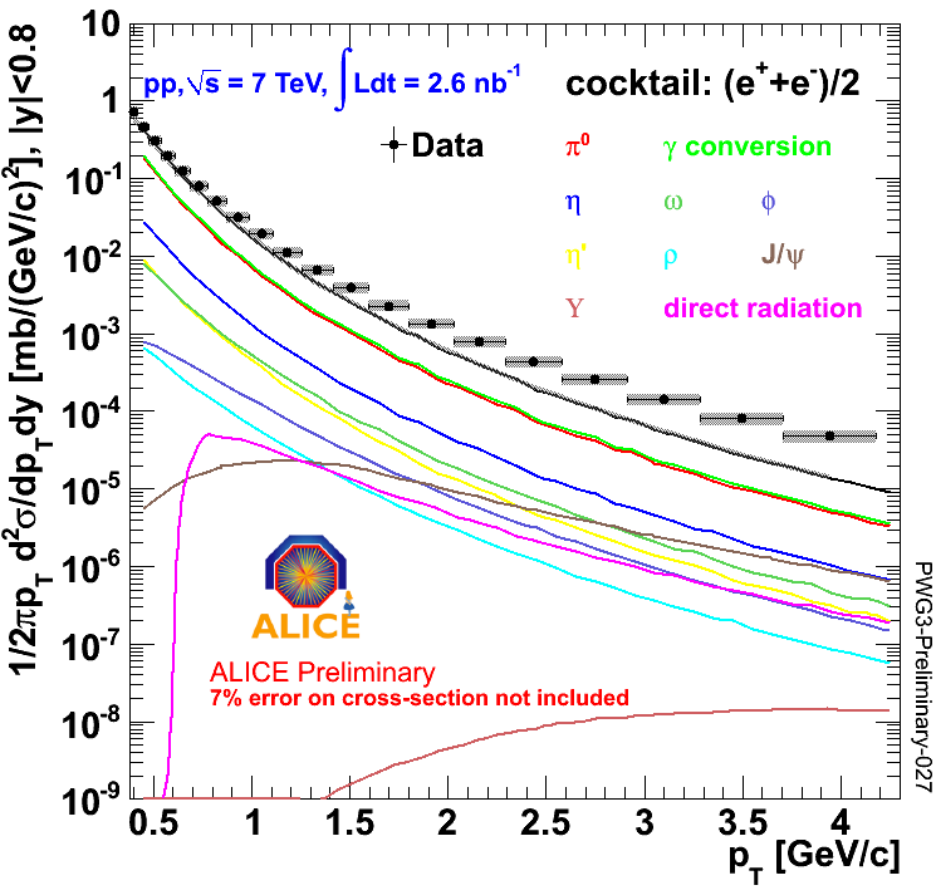
There is plenty of exciting physics (and fun)
at the LHC
exploring QCD in a new domain,
where the strong interaction is really strong !

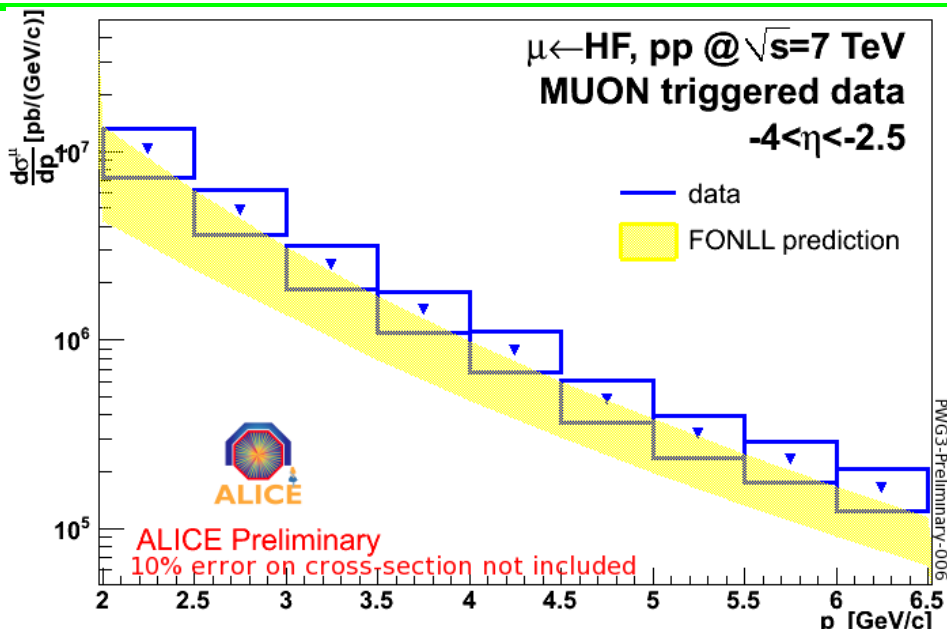
- Looking forward to continue the journey further into the ‘terra incognita’ of HI at LHC

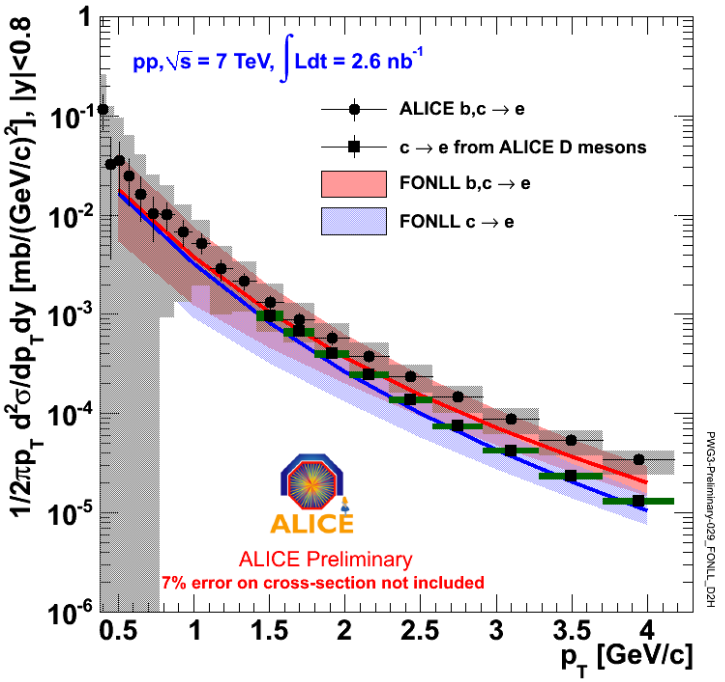


Hic sunt Leones !

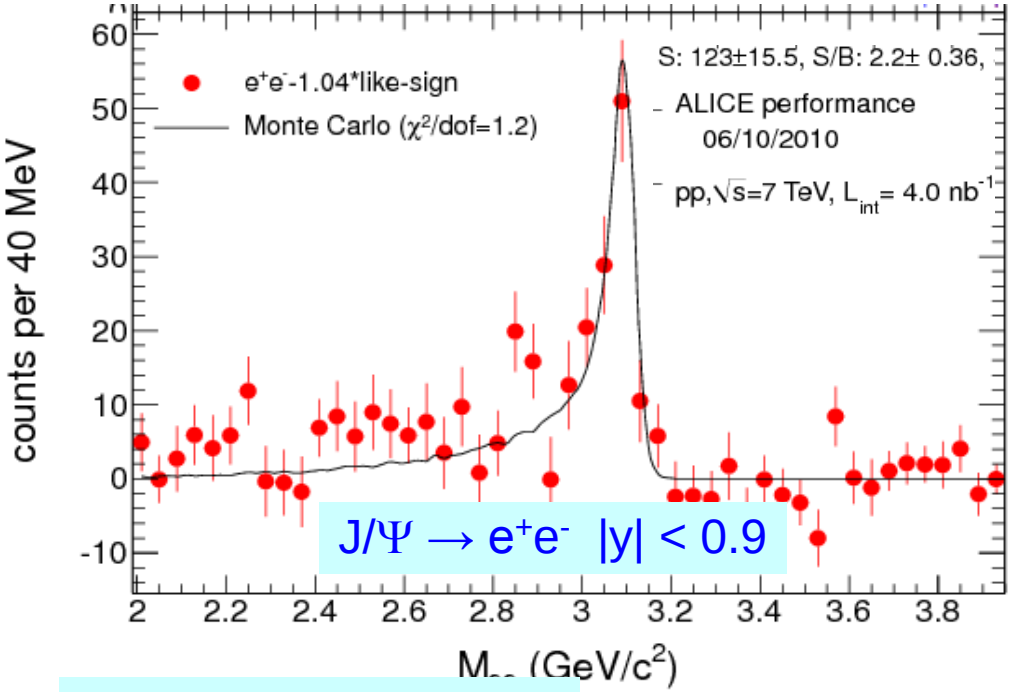
Heavy Flavor Electrons





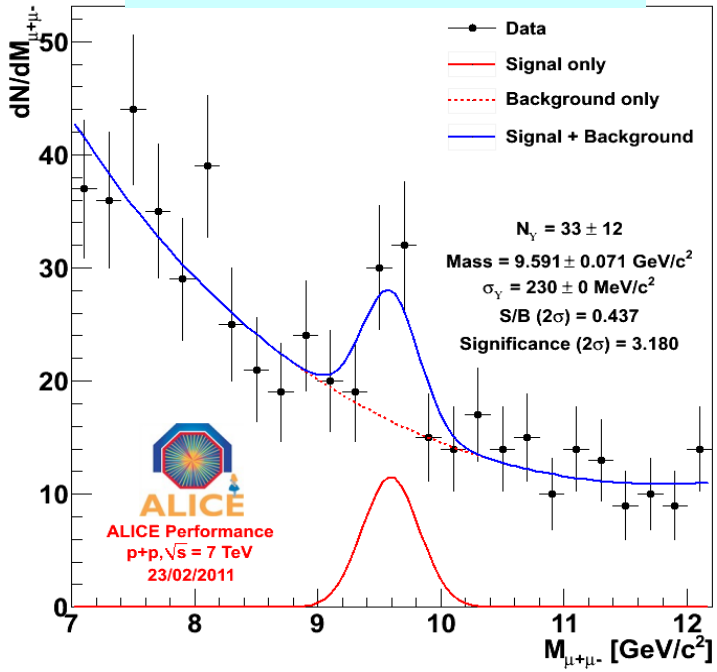


e^+e^- & $\mu^+\mu^-$

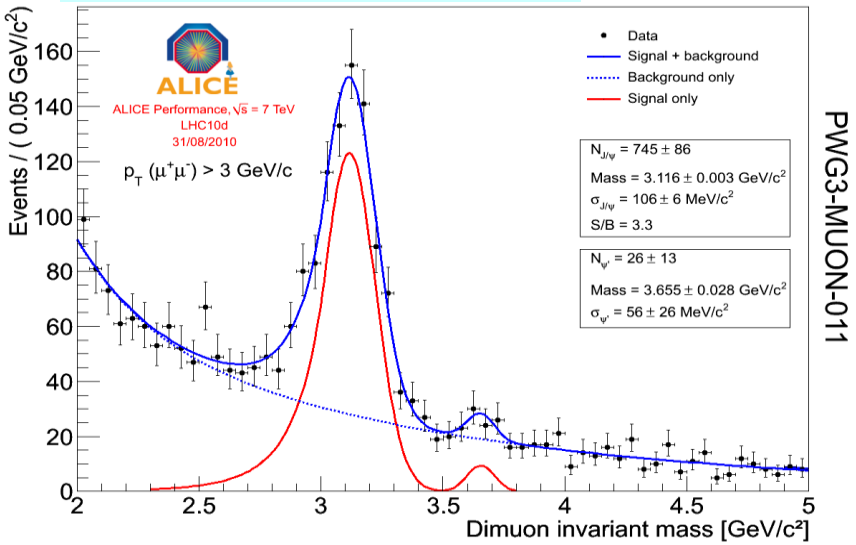


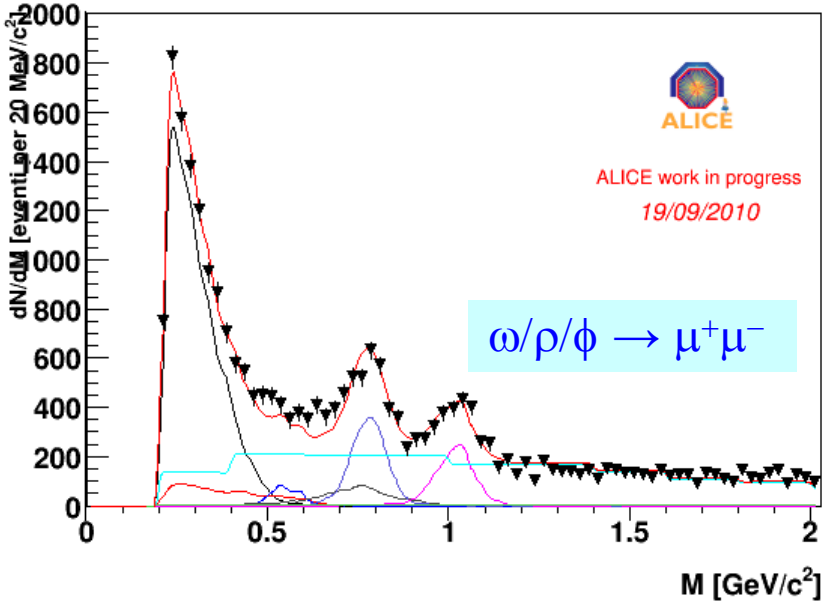
$J/\Psi \rightarrow e^+e^-$ $|y| < 0.9$

? $\Upsilon \rightarrow \mu^+\mu^-$, y = 2.5 - 4



$J/\Psi \rightarrow \mu^+\mu^-$, y = 2.5 - 4





$\omega/\rho/\phi \rightarrow \mu^+\mu^-$