Heavy Ion Physics in ATLAS and CMS

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For **and** **Collaborations**

Overview

- **From RHIC to LHC**

- **ATLAS and CMS detectors**

- **QCD matter in the soft sector**

  $dN_{ch}/d\eta$

  low p_T π/K/p spectra

  Eliptic flow

- **QCD matter in the hard sector**

  high-p_T hadrons, jets, photon-jet

  Qqbar suppression

  Y-l+l- photoproduction

- **High and low pt tracking**

- **Muon reconstruction**

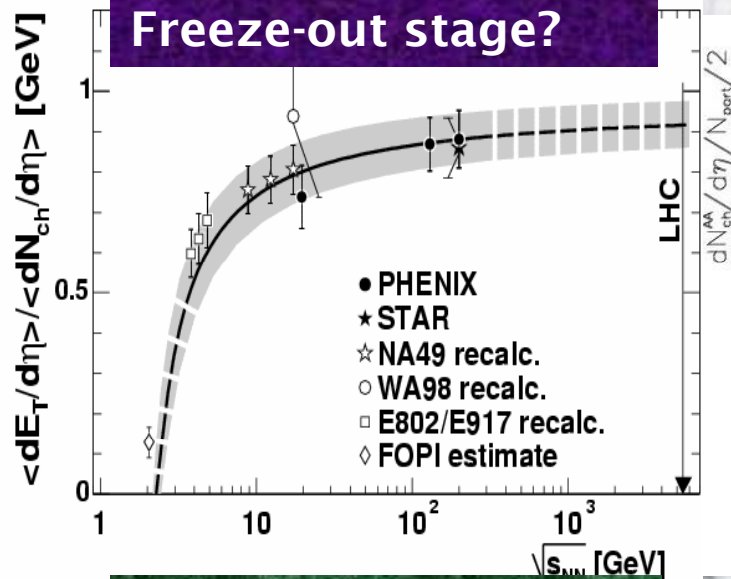- **Jet reconstruction**

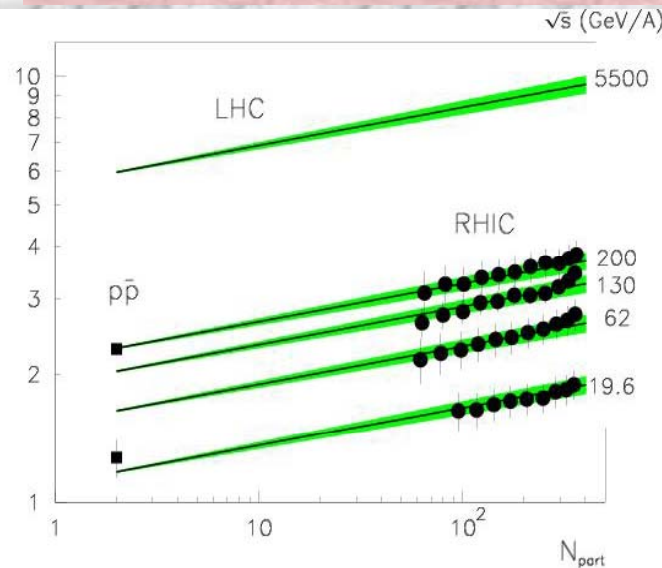- **Photon reconstruction**

- **Event plane**

- **Event centrality**
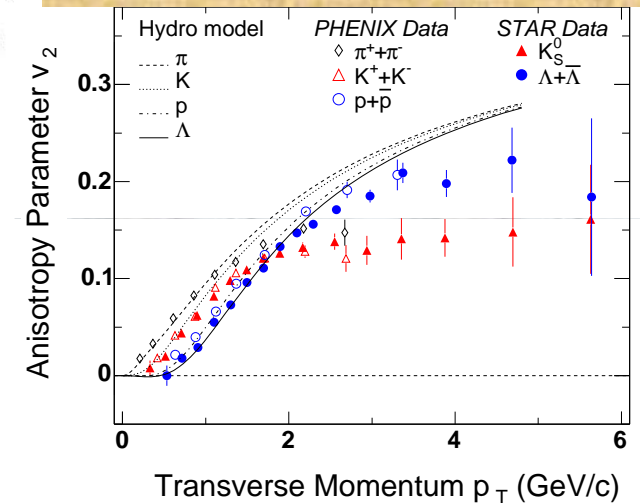
Some evidences from RHIC
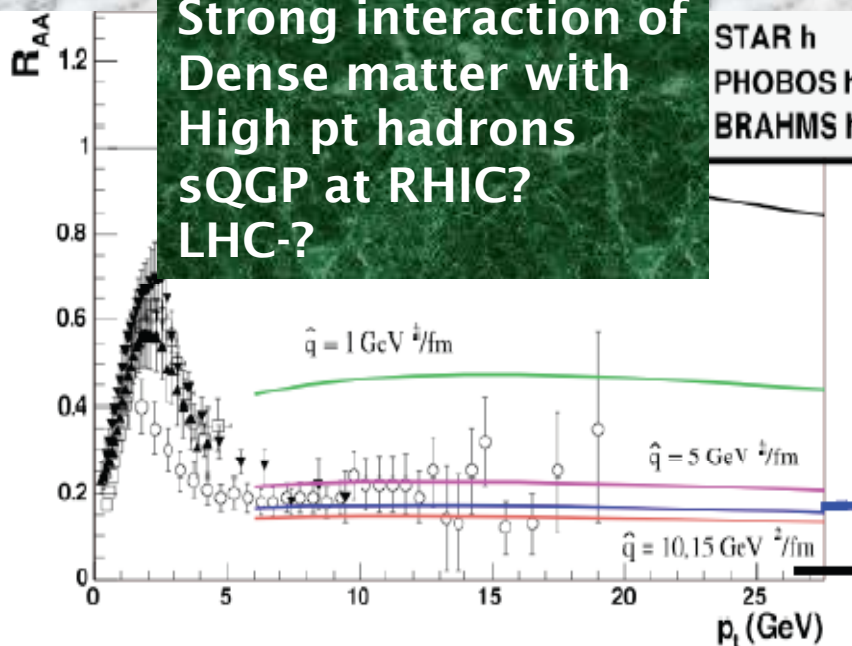
Local equilibrium in Freeze-out stage?
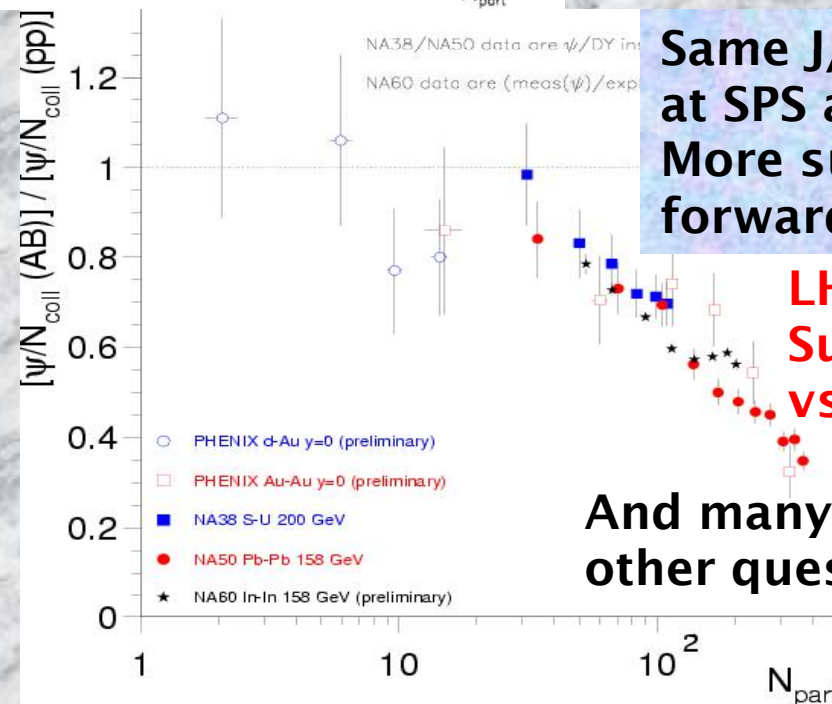
Calor Glass Condensate?

Deflection from Hydro – Viscosity?

Strong interaction of Dense matter with High pt hadrons sQGP at RHIC? LHC-?

**Same J/ψ suppression at SPS and RHIC More suppression in forward**

LHC--? Suppression vs regeneration?

**And many other questions to LHC**

From RHIC (200 GeV/n-n) to LHC (5500 GeV/n-n)

- **Initial state fully in the saturated CGC regime**
- **Initial energy density ~5 times higher**
- **Lifetime of a quark-gluon plasma much longer**
- **Large rates of hard probes over a broad kinematical range**
- **Plenty of heavy quarks (b,c)**
- **Weakly interacting probes become available (Z^0, $W^\pm$)**
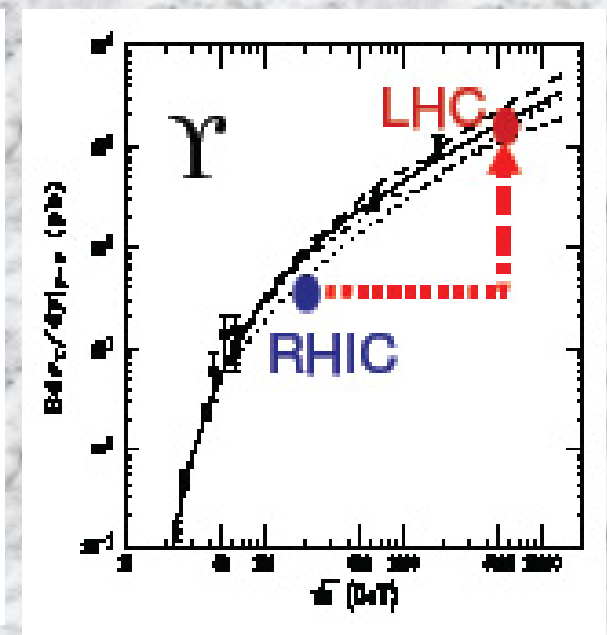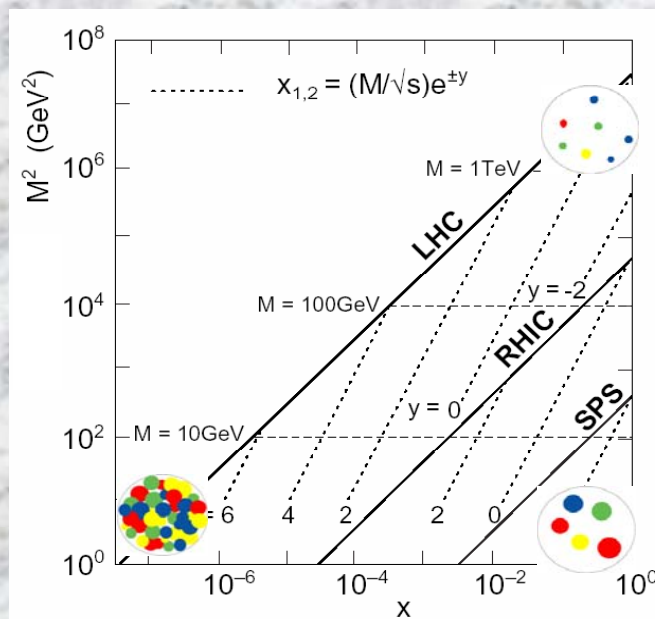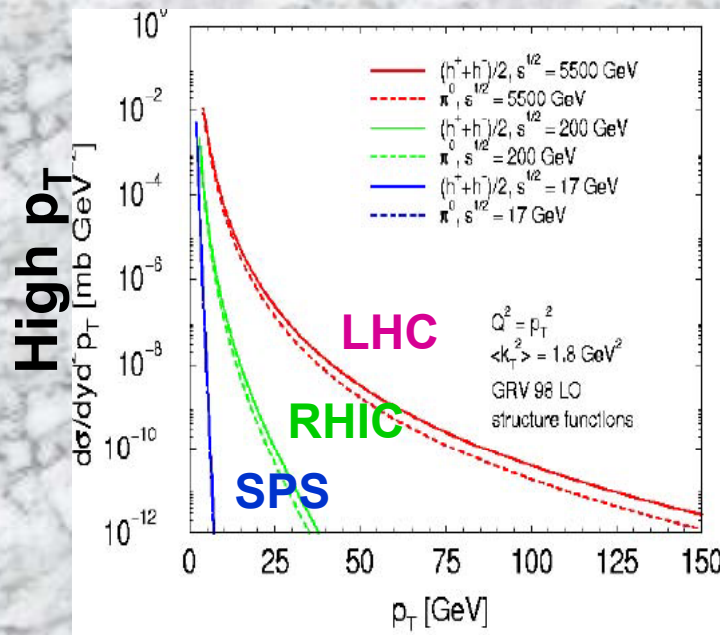
ATLAS and CMS acceptances

ATLAS:
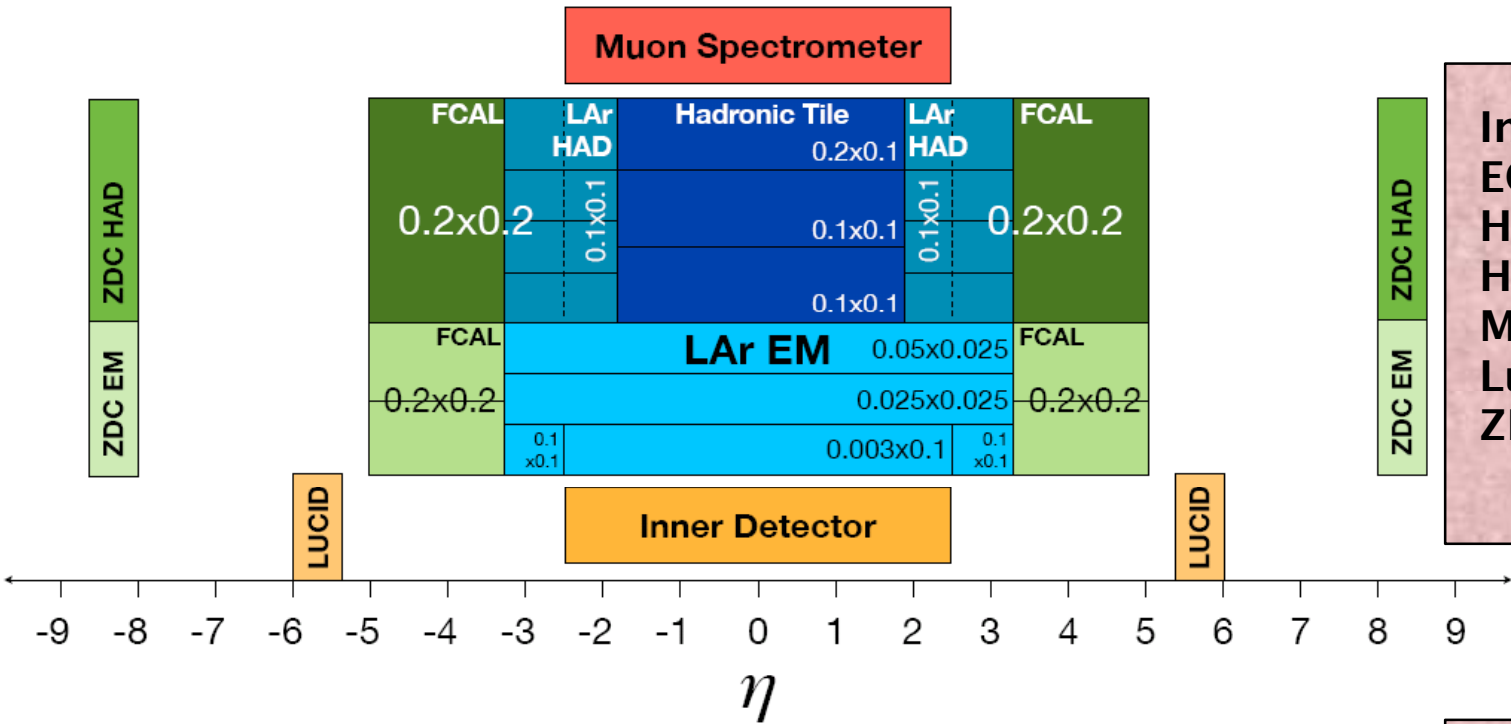
Inner detector ($|\eta|<2.5$)
ECAL ($|\eta|<3.2$)
HCAL ($|\eta|<3.2$)
HF ($3.2<|\eta|<5$)
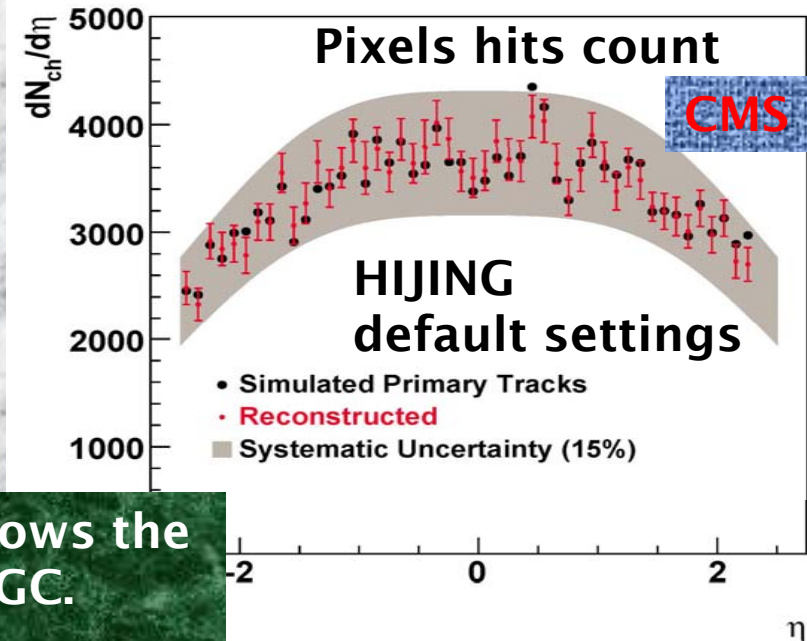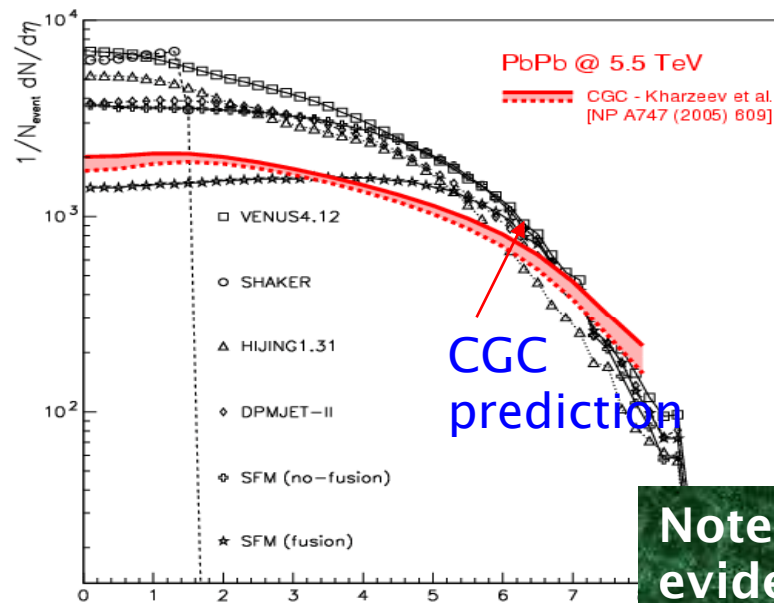Muon ($|\eta|<2.7$)
Lucid ($5.5<|\eta|<6$)
ZDC ($|\eta|>8$)

CMS:

Inner detector ($|\eta|<2.5$)
ECAL ($|\eta|<3$)
HCAL ($|\eta|<3$)
HF ($3<|\eta|<5$)
Muon ($|\eta|<2.4$)
Castor ($5<|\eta|<6.7$)
ZDC ($|\eta|>8$)

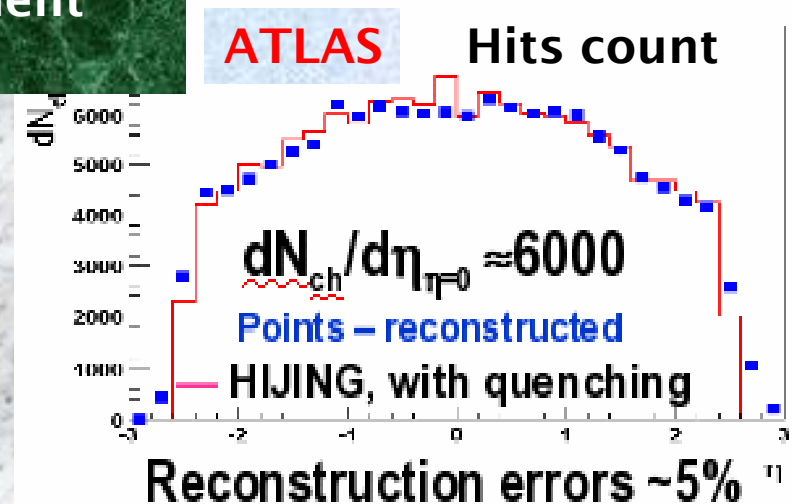**Different technologies but close acceptances – possibility to cross-check.**

Bulk ("hydro") measurements in AA collisions

Charged particle multiplicity ~ gluon density

PbPb @ 5.5 TeV
CGC - Kharzeev et al.
[NP A747 (2005) 609]

□ VENUS4.12
○ SHAKER
△ HIJING1.31
◇ DPMJET–II
✦ SFM (no–fusion)
★ SFM (fusion)

CGC prediction

Pixels hits count

CMS

HIJING default settings

- **Simulated Primary Tracks**
- **Reconstructed**
- **Systematic Uncertainty (15%)**

Note: RHIC shows the evidence of CGC.

First measurement At LHC

ATLAS Tracklets with vertex constraints

ATLAS   Hits count

$dN_{ch}/d\eta_{\eta=0} \approx 6000$

Points – reconstructed

HIJING, with quenching

Reconstruction errors ~5%
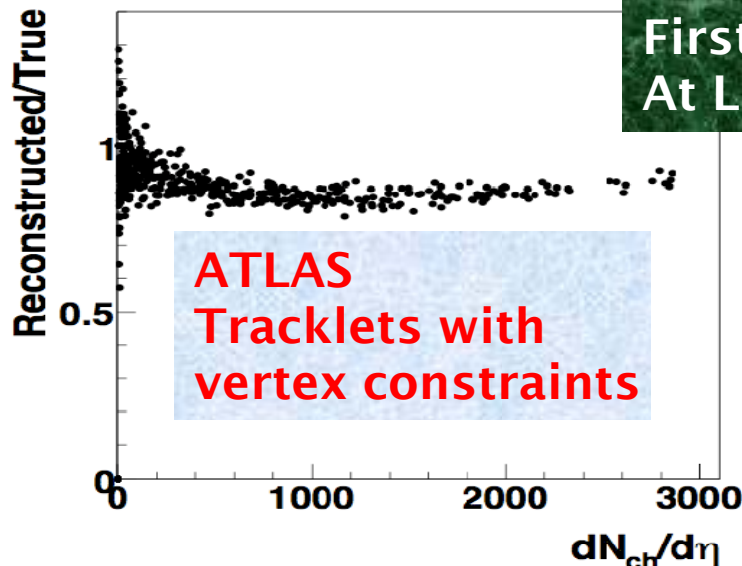
Simple measurements via hits count in pixels accomplished with dE/dx cut or tracklets with vertex constraints

Soft hadron spectra (CMS) ~ medium equation of state
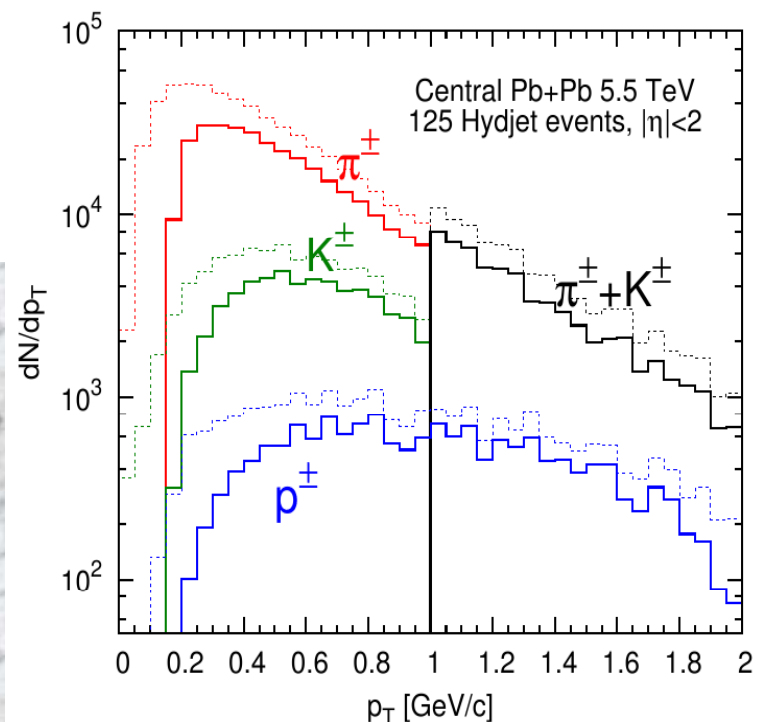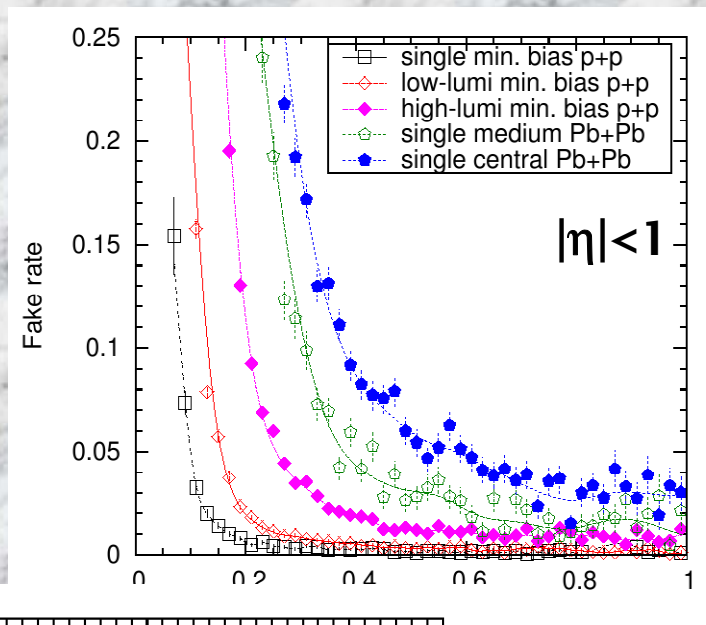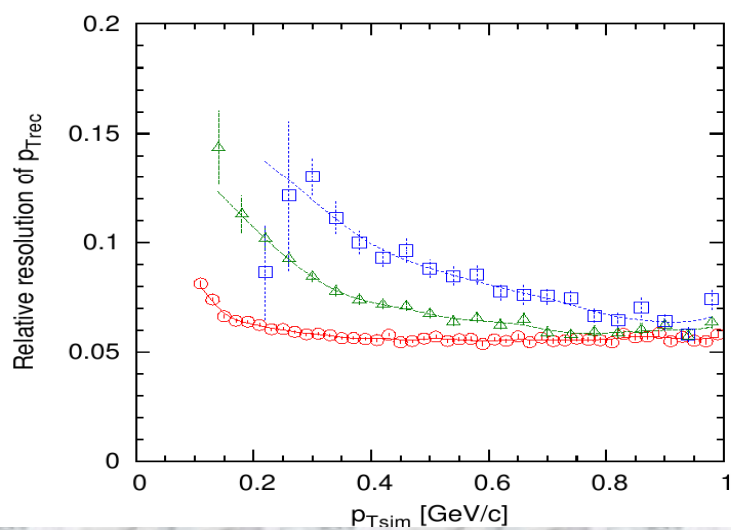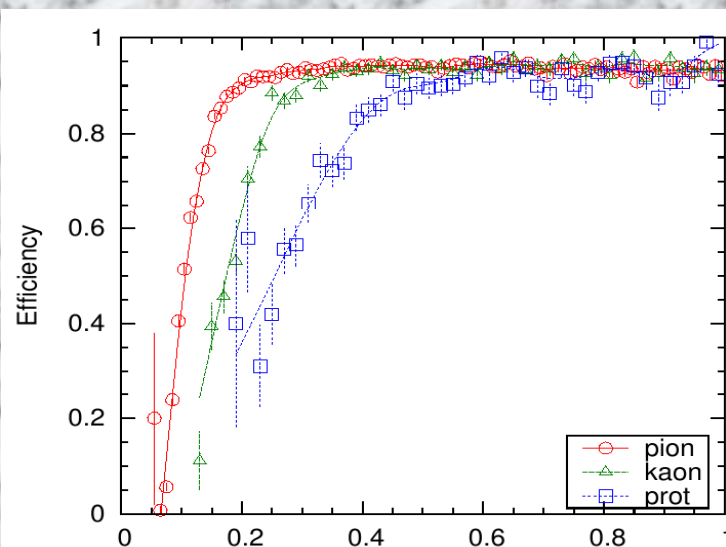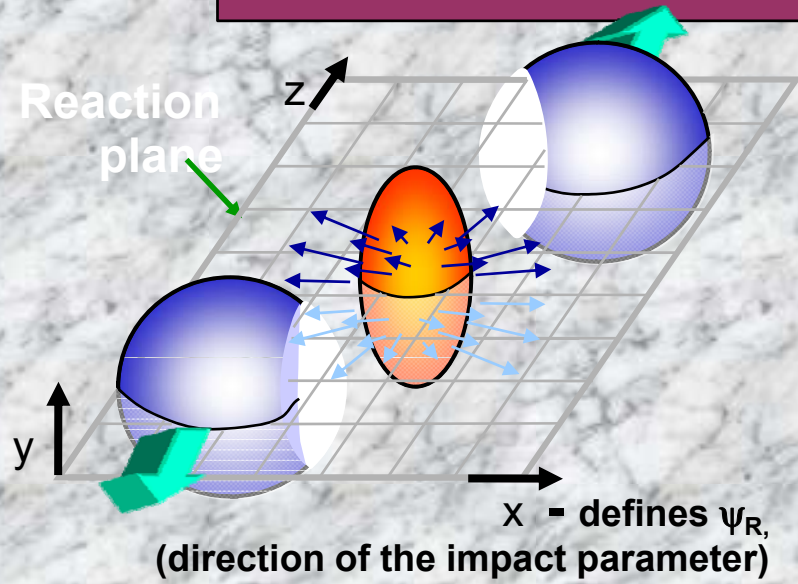
Single hadron (π+-, K+-, p) pT spectra in pT~0.2-2 GeV/c

PID via dE/dx (Gaussian unfolding)

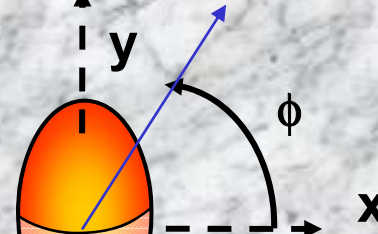**Collective radial flow, hadron ratios, thermalization time, medium equation of state constraints**

Eliptic flow: medium viscosity

Reaction plane

x — defines ψ_R, (direction of the impact parameter)

Initial **spatial** anisotropy

Final **momentum** anisotropy
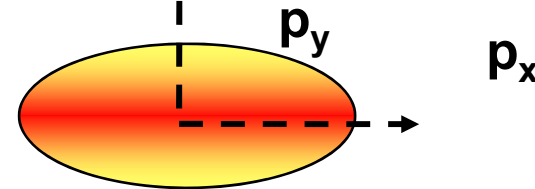
$$dN/d(\phi - \psi_R) = N_0 (1 + 2v_1\cos(\phi - \psi_R) + 2v_2\cos(2(\phi - \psi_R)) + ...)$$

Elliptic Flow: v_2

$$v_2 = <\cos 2(\phi - \psi_R)> \equiv \left\langle \left(\frac{p_x}{p_T}\right)^2 - \left(\frac{p_y}{p_T}\right)^2 \right\rangle$$

LHC

hydro limit (QGP-EoS)
hydro limit (H-EoS)

- ● STAR AuAu-200 GeV
- ■ PHOBOS AuAu-200 GeV
- ■ STAR AuAu-130 GeV
- ● STAR AuAu-62.4 GeV
- ▼ STAR CuCu-200 GeV
- ▲ PHOBOS CuCu-200 GeV
- ★ STAR CuCu-62.4 GeV
- ⊕ PHOBOS CuCu-62.4 GeV
- □ NA49 AuAu-17.3 GeV
- △ NA49 AuAu-8.8 GeV
- ◇ BNL-E877 -5.0 GeV

v_2/ε_{part}

$(1/A_T) dN_{ch}/d\eta$ (fm^{-2})
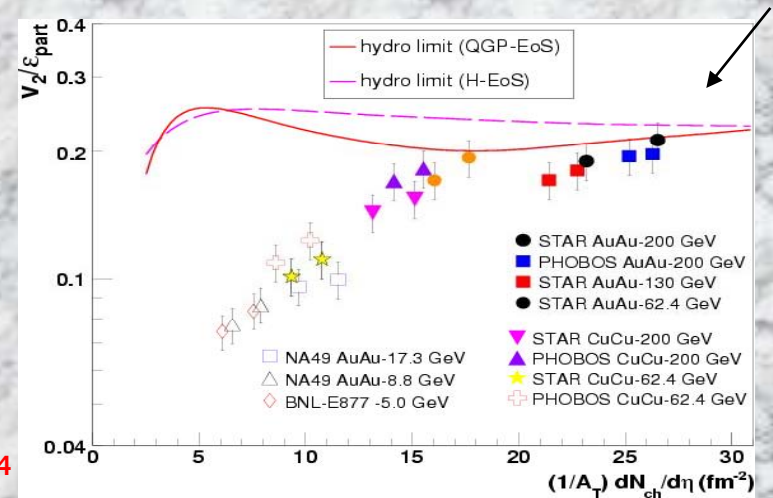
Eliptic flow: ATLAS

Flow was included in HIJING based on Poskanzer and Voloshin [PRC 58 (1998) 1671]. Parametrization was taking from RHIC
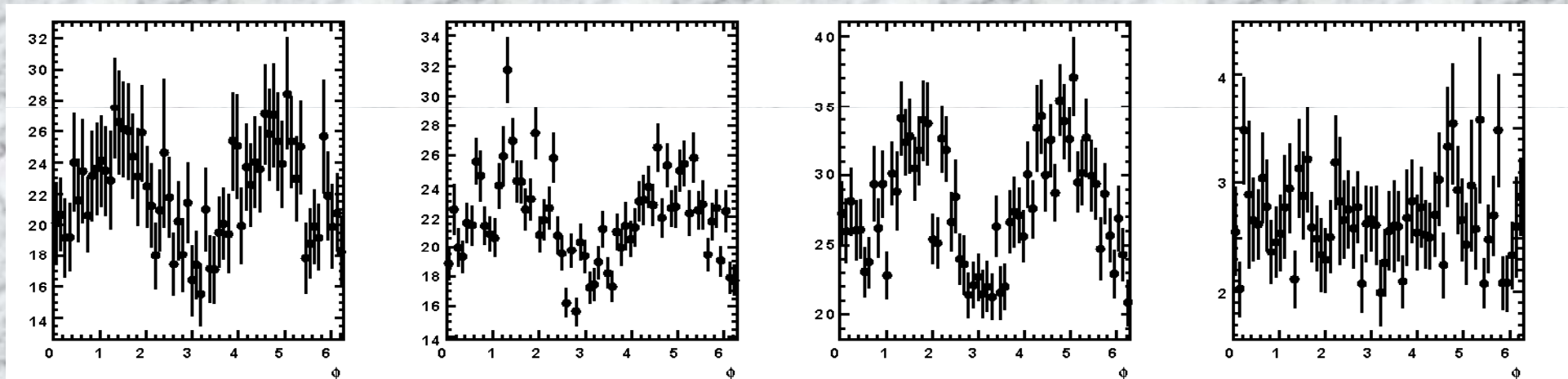
- **Azimuthal E_T distribution in different barrel EM calorimeter layers ($|\eta|<1.5$)**

Pb + Pb, b = 10.7 fm

v_2 signal measured using reconstructed tracks ($p_T > 0.5$ GeV/c) while reaction plane estimated from the energy depositions in FCAL

Eliptic flow: CMS

Two methods:
 1. Using reaction plane determination with Calorimeters and tracker
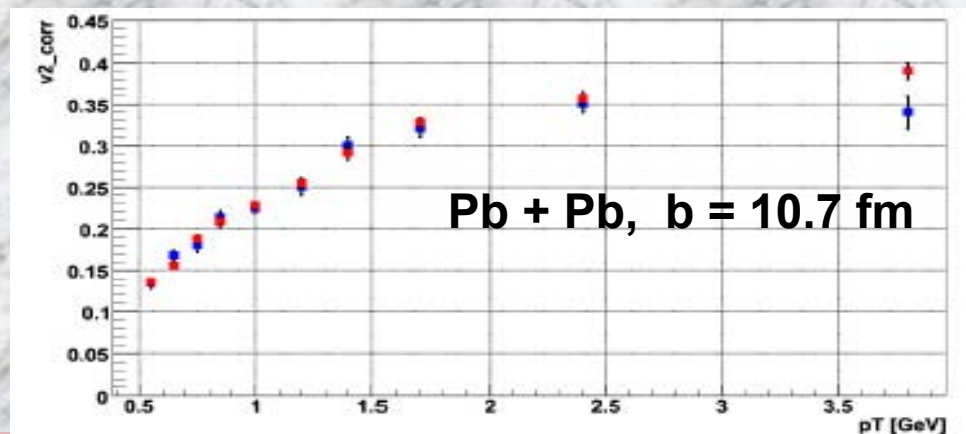 2. Cumulant analysis: using two and multi particle correlations

$$\cos(2(\phi_1 - \phi_2)) = v_2^2$$
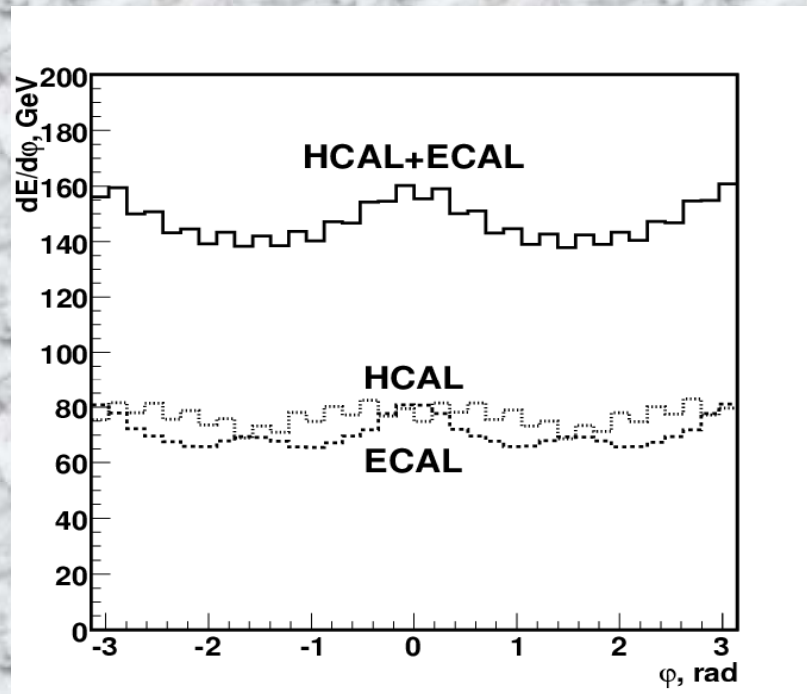
Azimuthal E_T distribution in different calorimeter layers

χ^2 / ndf = 0.005351 / -3

Constant 0.05805 ± 0.03600

Mean 0.003975 ± 0.458203

Sigma 0.3658 ± 0.4635
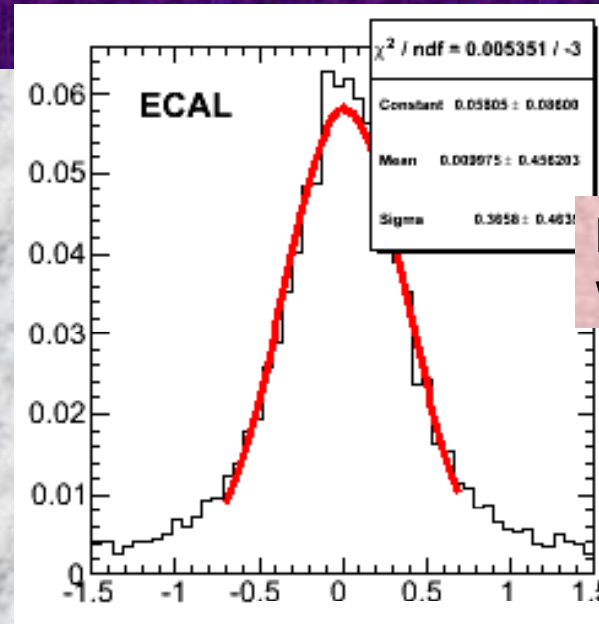
Event plane resolution with ECAL: 0.37 radian

V2 with tracker
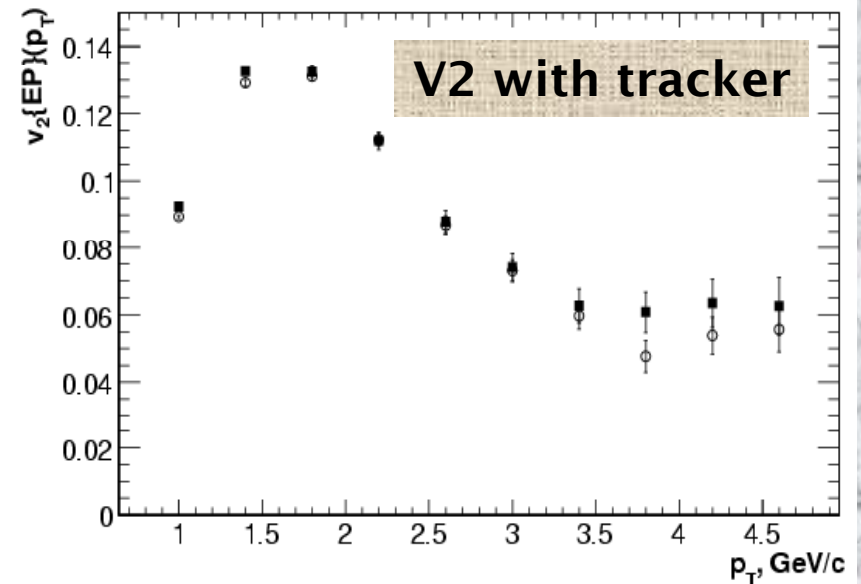
Hard probes of QCD matter:

Qaurkonia and heavy quarks
Jets and high-p_T hadrons

CMS trigger system is designed for 10^{34} (pp events) with 40 MHz bunch crossing frequency.
Two levels system: Level 1 and High Level Trigger

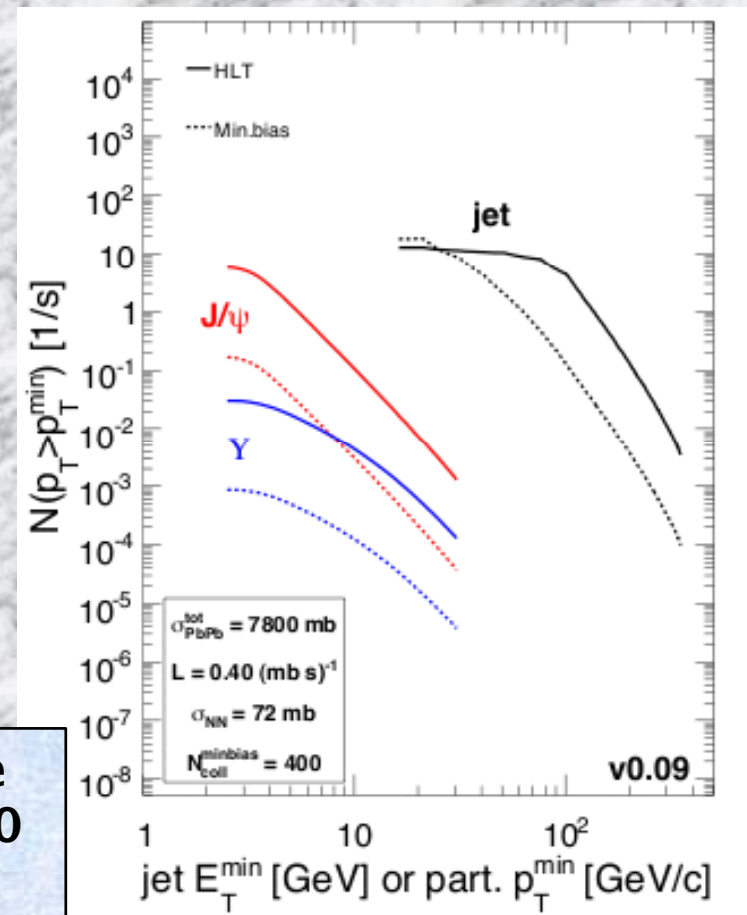| pp 40 MHz	Level 1 1/400 100 KHz, 1MB →	DAQ/HLT 100 KHz	DAQ/HLT 1/600 150 Hz, 1.5 MB →	Offline 150 Hz
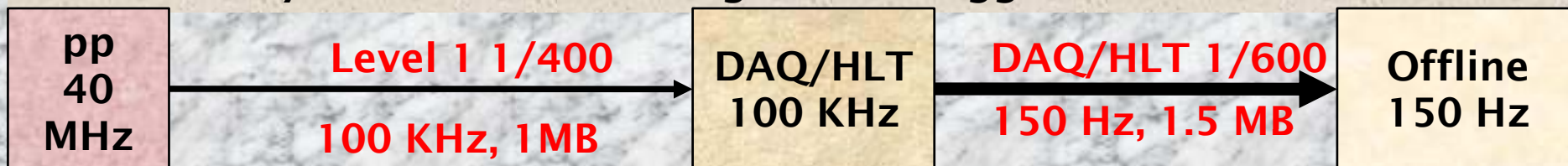
PbPb:

Luminosity(cm-2s-1): 10^{27}
(factor 5 lower relative to pp)

Bunch crossing rate (KHz):   8
(factor 12.5 relative to pp)

Event size after L1(MB):
            2.5 (Minbias)
            10 (Central)

HLT
Min.bias

10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}

jet

J/ψ

Y

$N(p_T > p_T^{min})$ [1/s]

σ_{PbPb}^{tot} = 7800 mb
L = 0.40 (mb s)$^{-1}$
σ_{NN} = 72 mb
$N_{coll}^{minbias}$ = 400

v0.09

1   10 10^2
jet E_T^{min} [GeV] or part. p_T^{min} [GeV/c]

Pb-Pb 8 KHz	1/1 →	DAQ/HLT 8 KHz	1/80-1/800 →	Offline 10—100 Hz
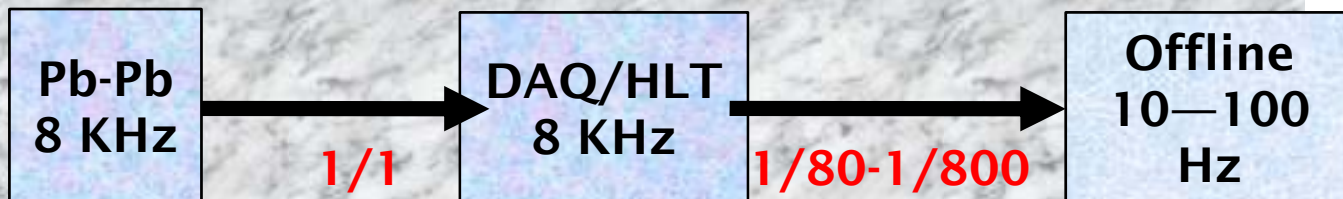
Jet finders in ATLAS and CMS for HI

ATLAS
Cone, R=0.4, with background
Subtraction
Kt, D=0.6, un-subtracted
Events (Cacciari,Salam)

$dN/d\eta = 2700$

- Cone
▲ k_T

CMS
Iterative cone (R>=0.5) with
background subtraction

E_T^{rec} vs E_T^{gen}

$dN_{ch}/d\eta = 5000$

$dN/d\eta = 2700$

- Cone
▲ k_T

BARREL
$|\eta|_{jet\ MC} \leq 0.3$

▲ - Purity
☐ - Efficiency
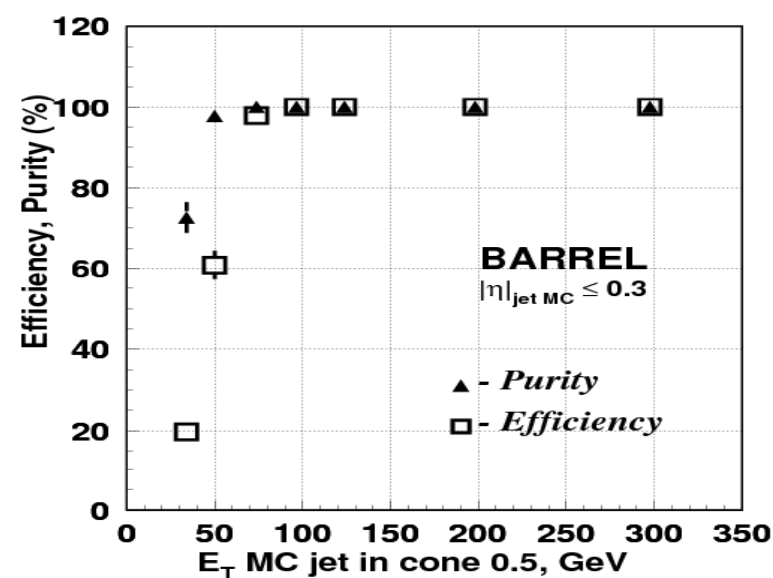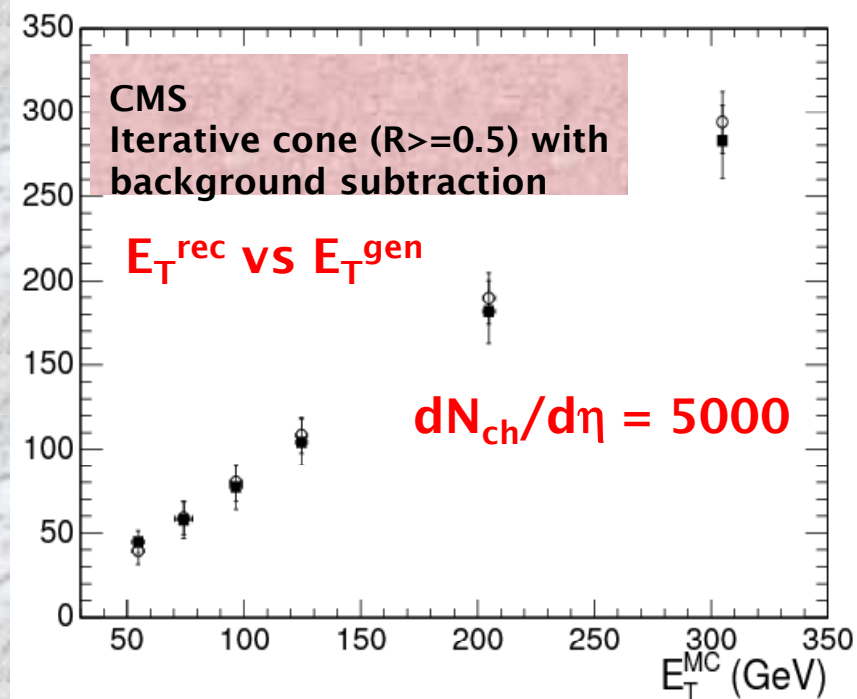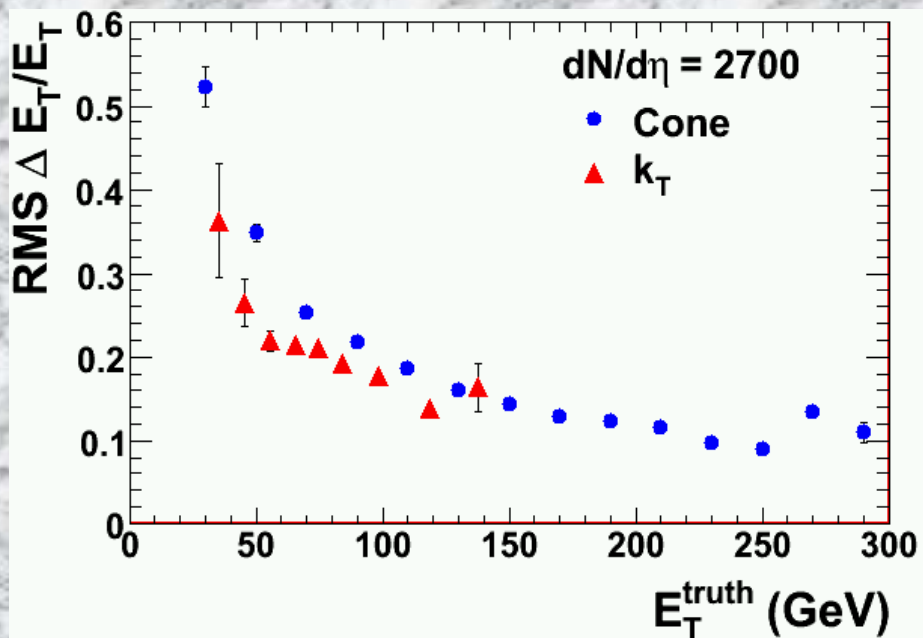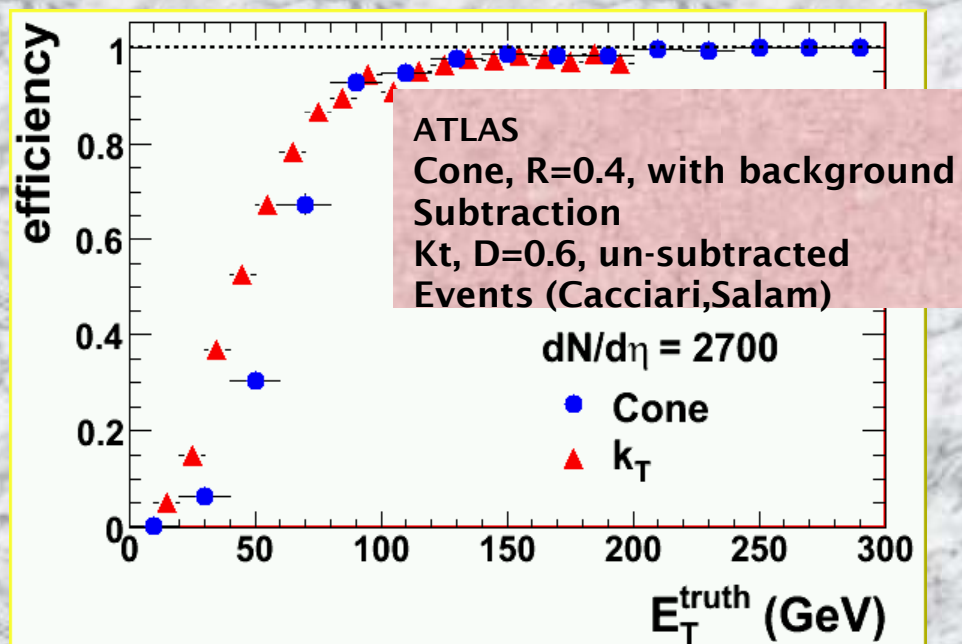
High-pt tracking in ATLAS and CMS

ATLAS without TRT

3 pixel layers and 4 double-sided strip layers

CMS full tracker

3 pixel layers in barrel,
2 pixel layers in endcap
Silicon layers: 10 in barrel
11 in endcap

Pb+Pb 5500 GeV/A, b=2.3 fm, |η|<1

Efficiency

Fake rate

Efficiency ~ 70 %, fake rate ~ 1%

Resolution: barrel – 1%

endcap 2-2.5%
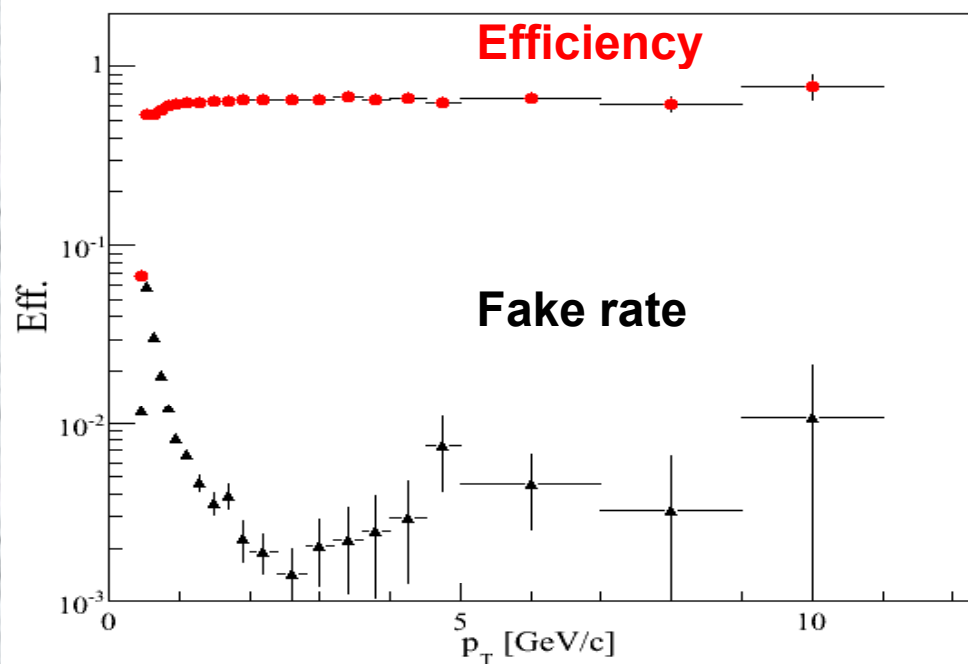
For p_T: 1 - 10 GeV/c:
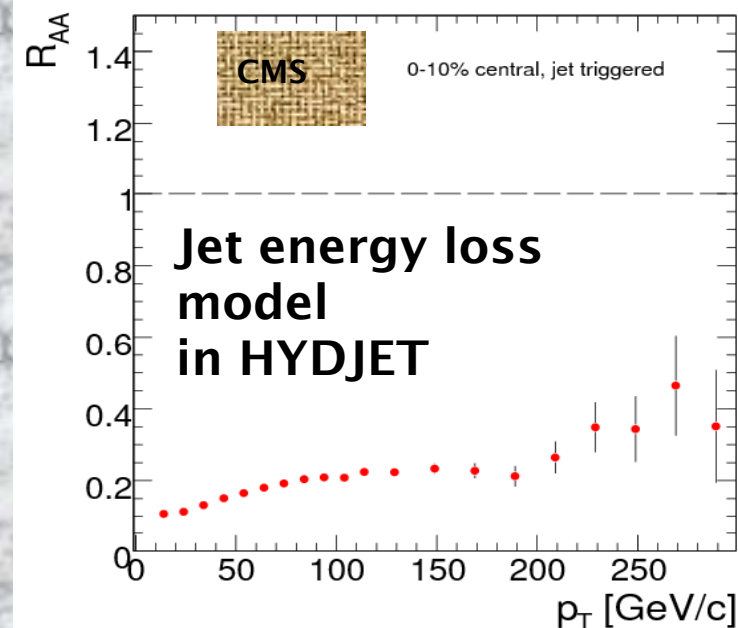**efficiency ~ 70 %, fake rate ~ 1%**
Momentum resolution ~ 3% (2% - barrel, 4-5% end-caps)
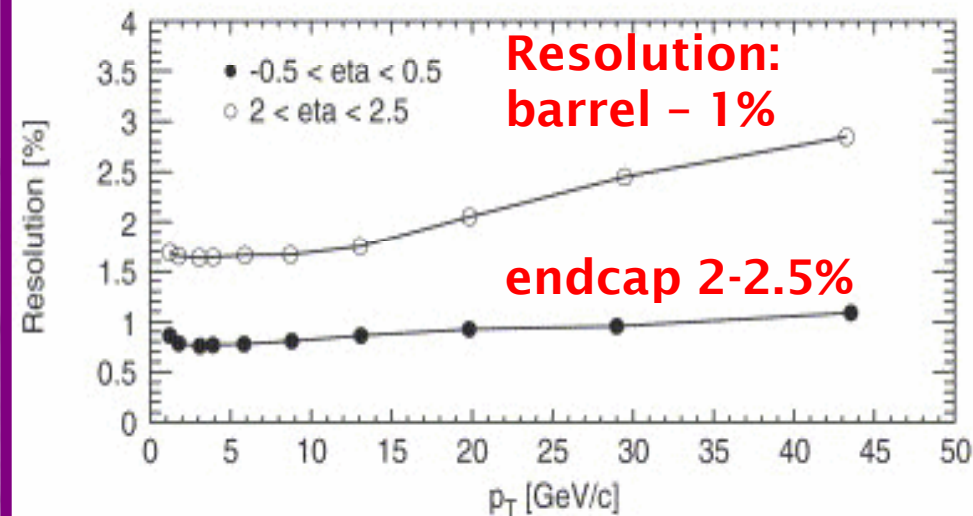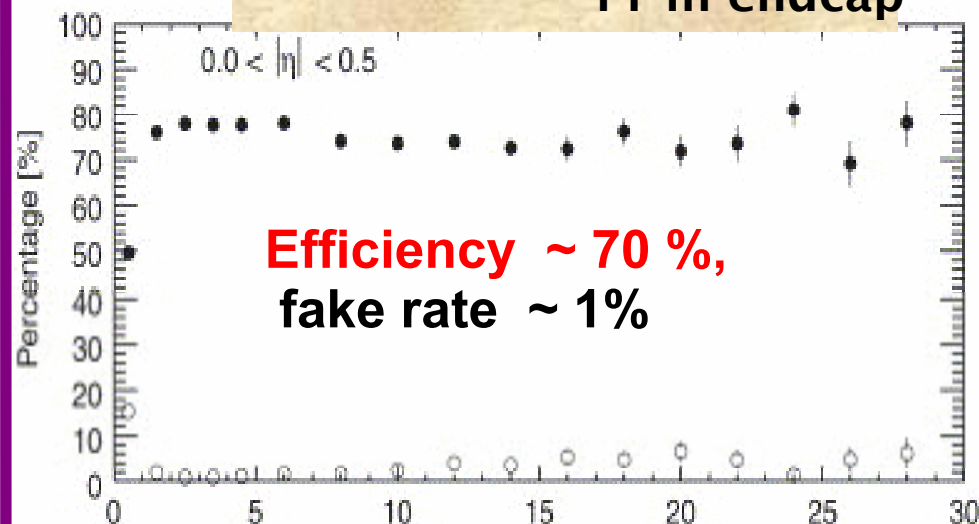
High-pt hadron spectra (ATLAS and CMS)

ATLAS:
HIJING,
b=2 fm

Centrality: 0.50

$|\eta| < 0.5$

$dN_{chg}/d\eta = 2700$

No jet trigger

CMS:
different
centrality
bins
for 0.5 nb^{-1}

Charged particles | η|<2.5
0-10% central
10-20% central, x 10^{-2}
20-30% central, x 10^{-4}
30-40% central, x 10^{-6}
40-50% central, x 10^{-8}
50-60% central, x 10^{-10}
60-70% central, x 10^{-12}
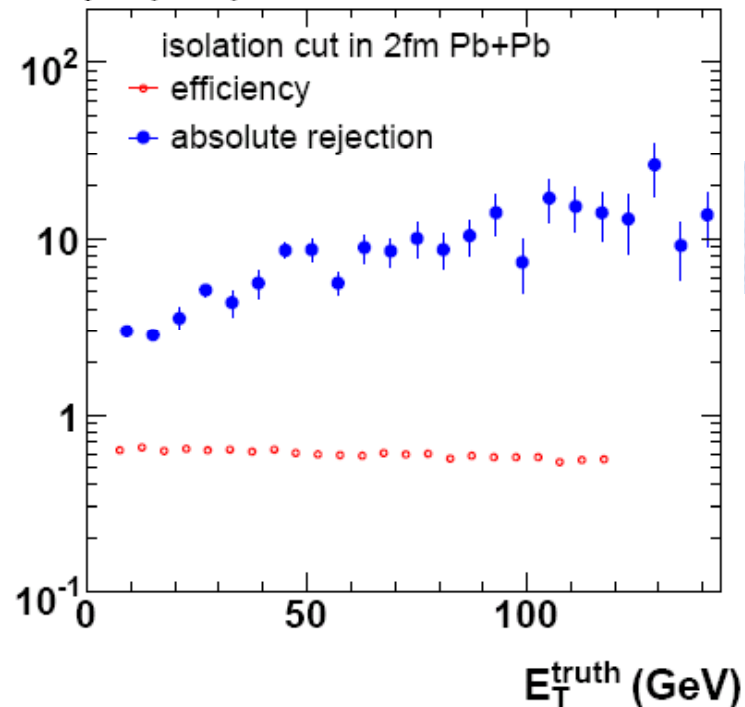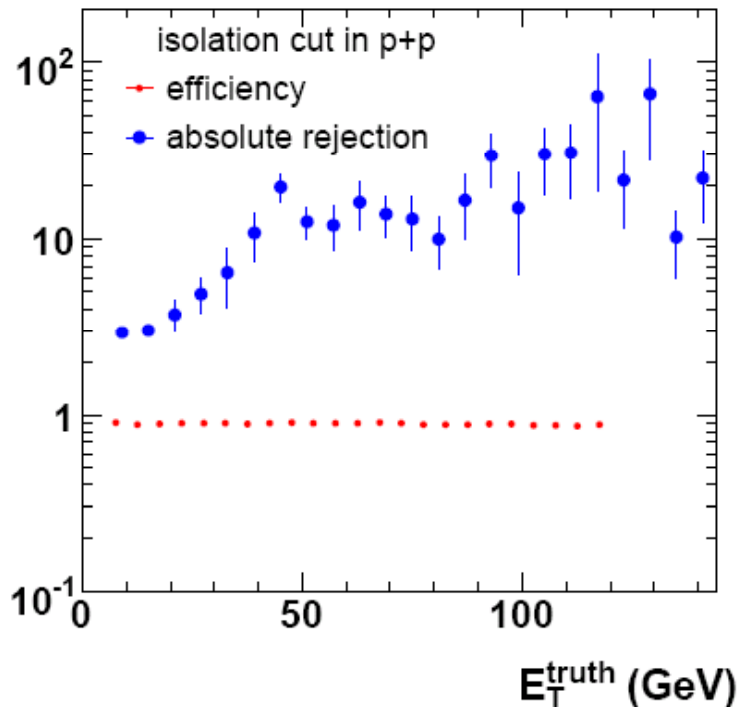70-80% central, x 10^{-14}
80-90% central, x 10^{-16}

jet trigger data
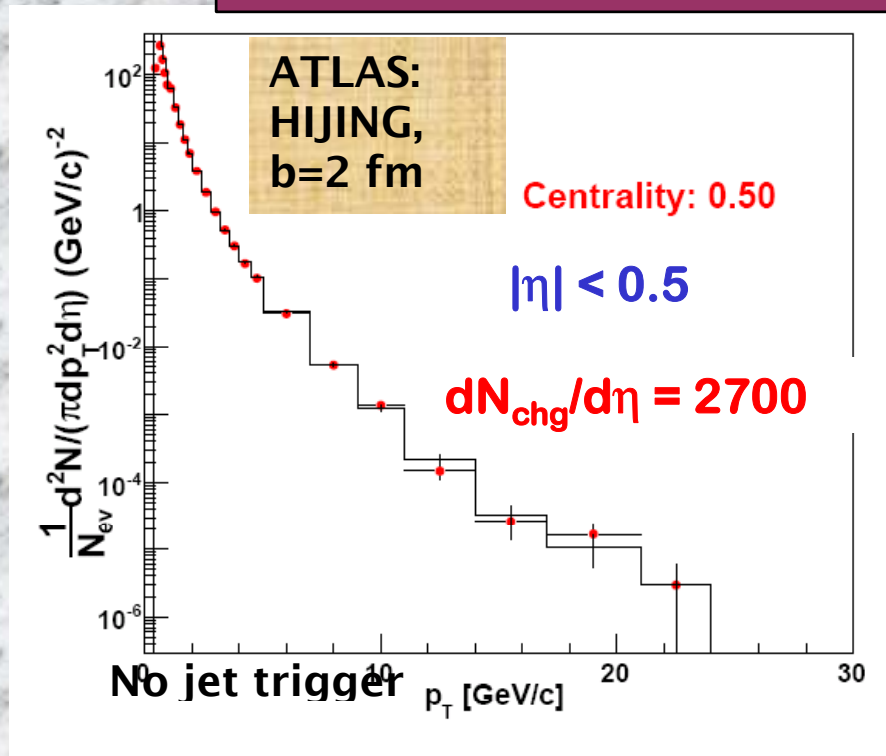
$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

Nuclear modification function reach for 0.5 nb^{-1}

CMS   0-10% central, jet triggered

Jet energy loss model in HYDJET

Photons (ATLAS)

Spectra for 0.5 nb^{-1}
for neutral hadron R_{AA} = 1 (worst case)
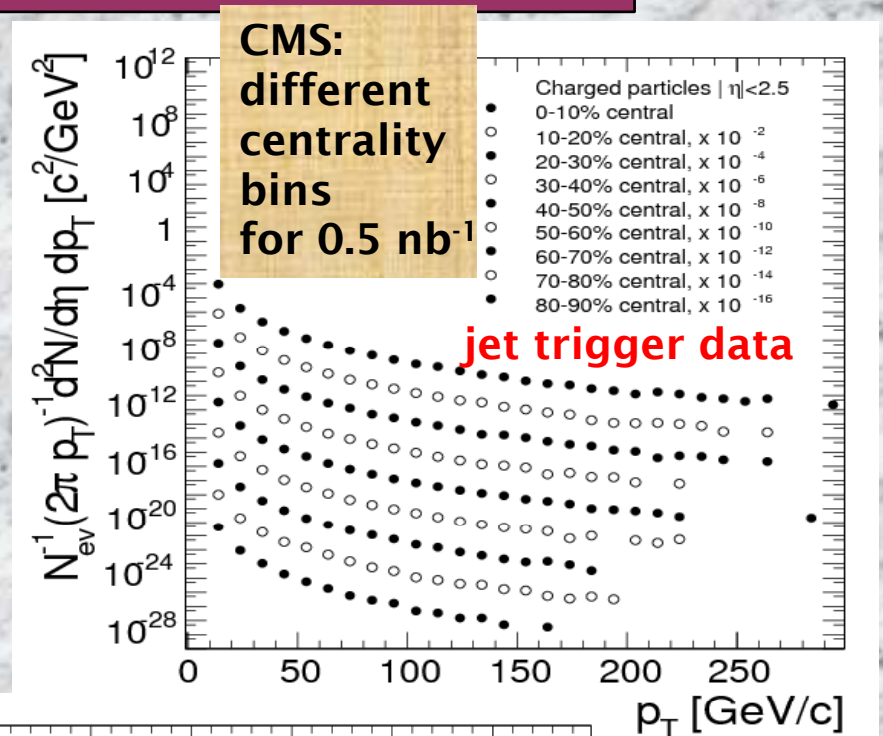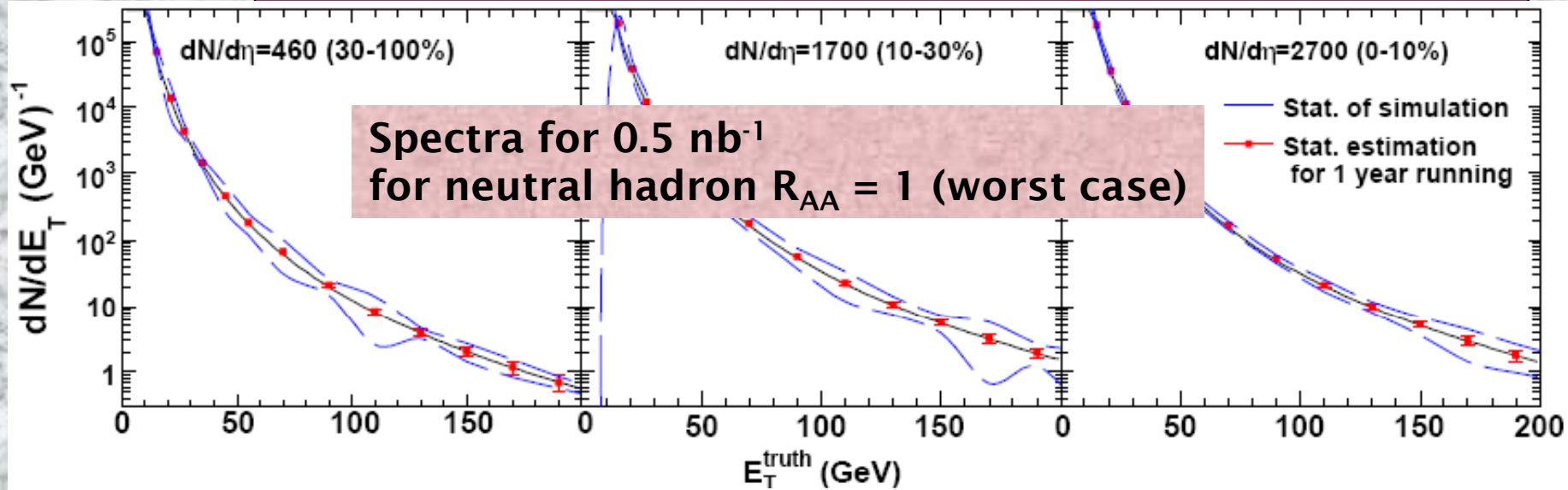
Isolation in tracker and ECAL (R=0.2)

Alternative method: Direct identification in first EM sampling layer give possibility to measure photons in jets

Photon reconstruction (CMS)
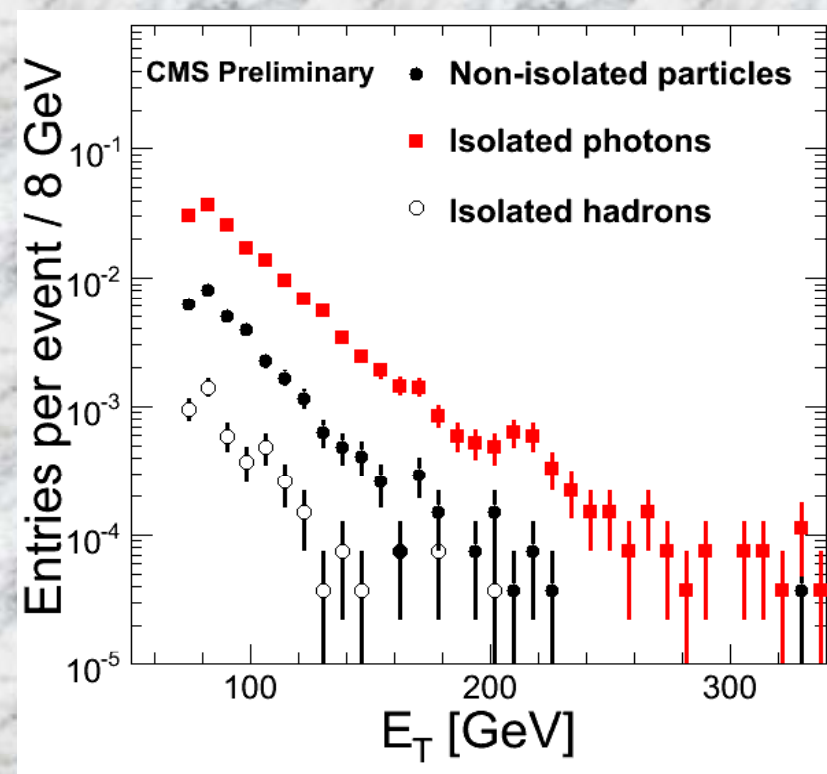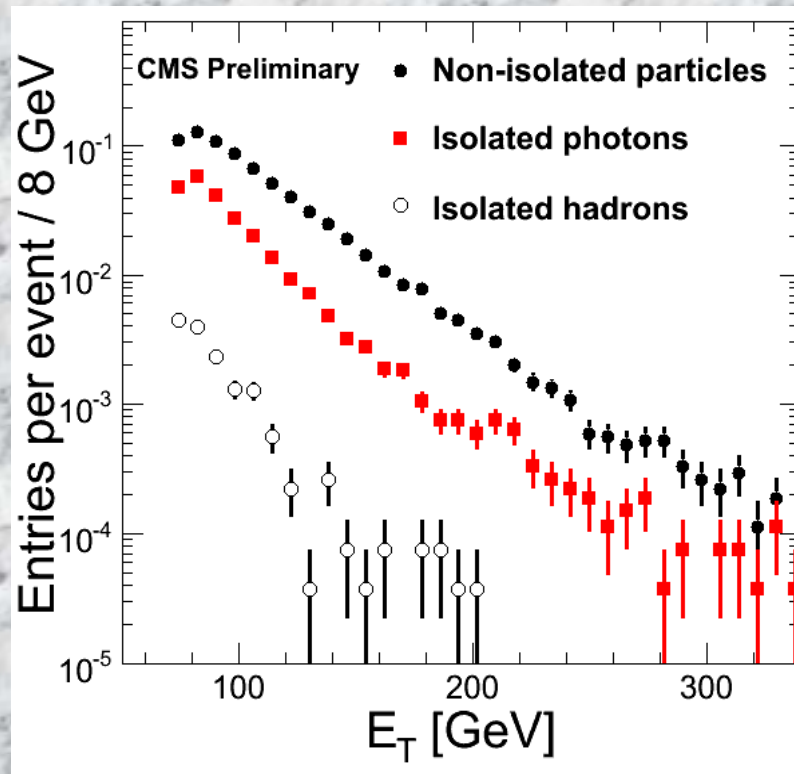
Photon reconstruction with Island Algorithm
Photon ID using Multi-Variate Analysis
with 21 variables grouped into 3 sets:
ECAL cluster shape
and ECAL/HCAL/Tracker isolation cuts

Performance:

Efficiency = 60%
Fake = 3.5%
S/B=4.5

Fragmentation function measurements (ATLAS and CMS)
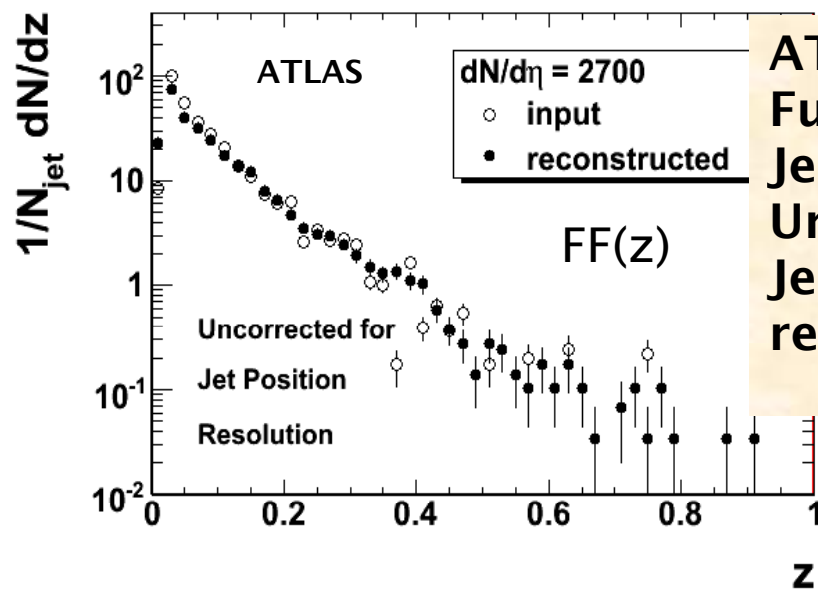
ATLAS:
Function relative to Jet parameters, Uncorrected for Jet position and resolution

CMS:
γ+jet events are used UE background subtracted using R=0.5 cone transverse to jet direction Functions relative To photon energy
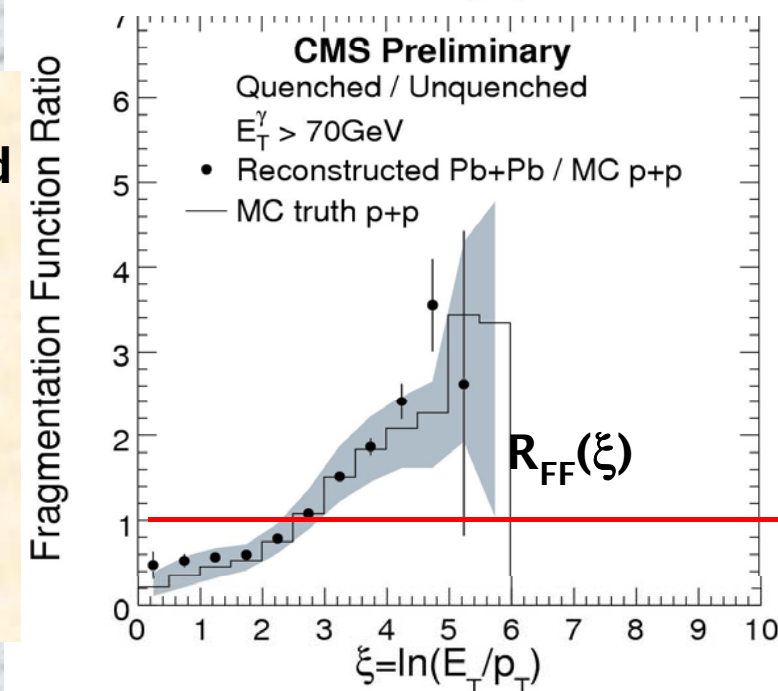
Dissociation of quarkonia: hot QCD thermometer

- **Suppression:** RHIC comparable to SPS
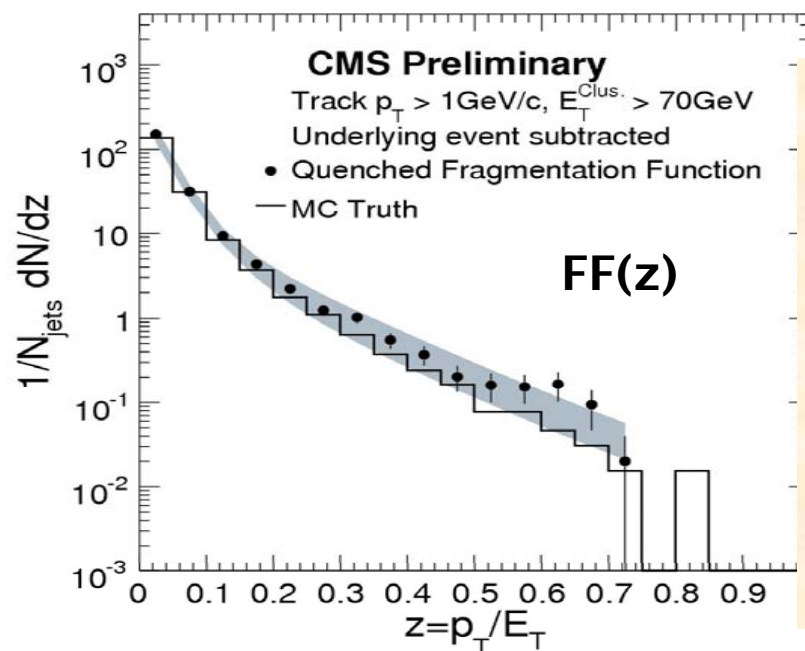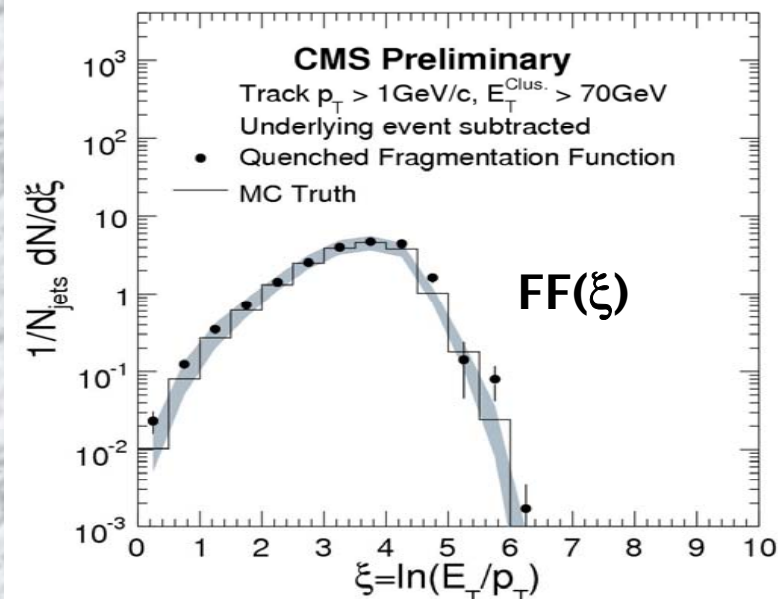- **Regeneration** compensate screening
- **J/Ψ** not screened at RHIC ($T_D \sim 2T_c$)
- LHC: **recombination** or **suppression**

Suppression of C'onium states
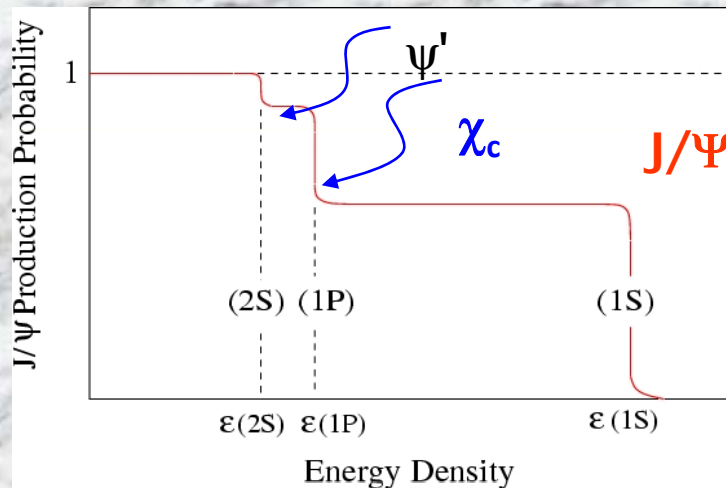
- **Υ Large Cross-section:** 20 RHIC
- **Υ** melts only at LHC: $T_D \sim 4\ T_C$
- Less amount of bb(bar) pairs: **less regeneration**
- Much **cleaner probe** than J/Ψ

Suppression of B'onium states
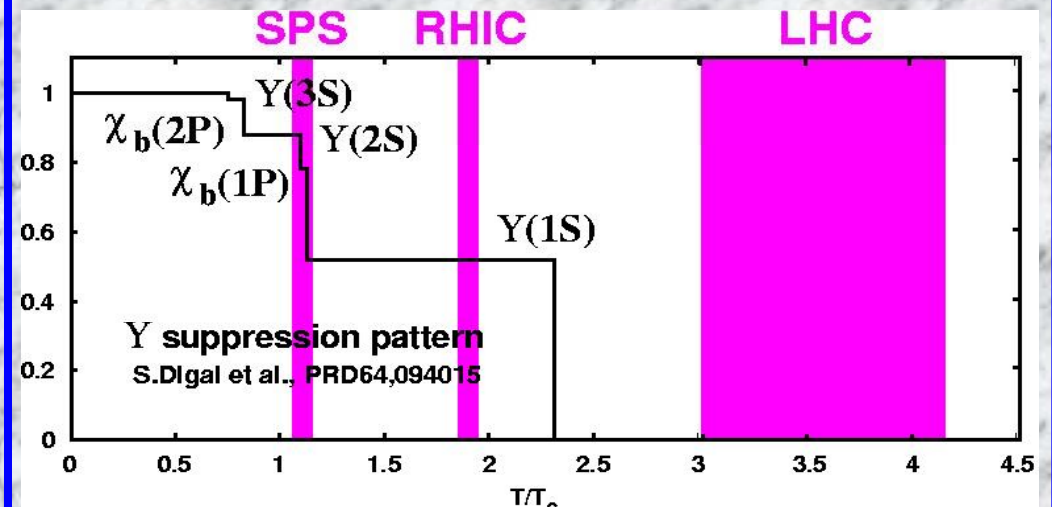
- **Quarkonia: J/ψ (BR:5.9%), Y (BR:2.5%)**
- **Background: combinatorial due- to decays from π/K, b-,c- production**

J/ψ measurements (ATLAS and CMS)

"tagging" method

ATLAS

dN/dp$_T$

full reconstruction, pT cut 1.5 GeV/c

full reconstruction, p$_T$ cut 3 GeV/c

J/ψ p$_T$ (GeV)

CMS

J/ψ rate in 0.5 nb^{-1}

- produced
- reconstructed (low multiplicity)
- reconstructed (high multiplicity)

Events/0.4 GeV

Expected rate (per month, 10^6 s, 0.5 nb^{-1}):
J/ψ ~ 180 kevents

p$_T$, GeV/c

dN/dm

J/ψ

ψ'

Mass resolution 68 MeV/c2

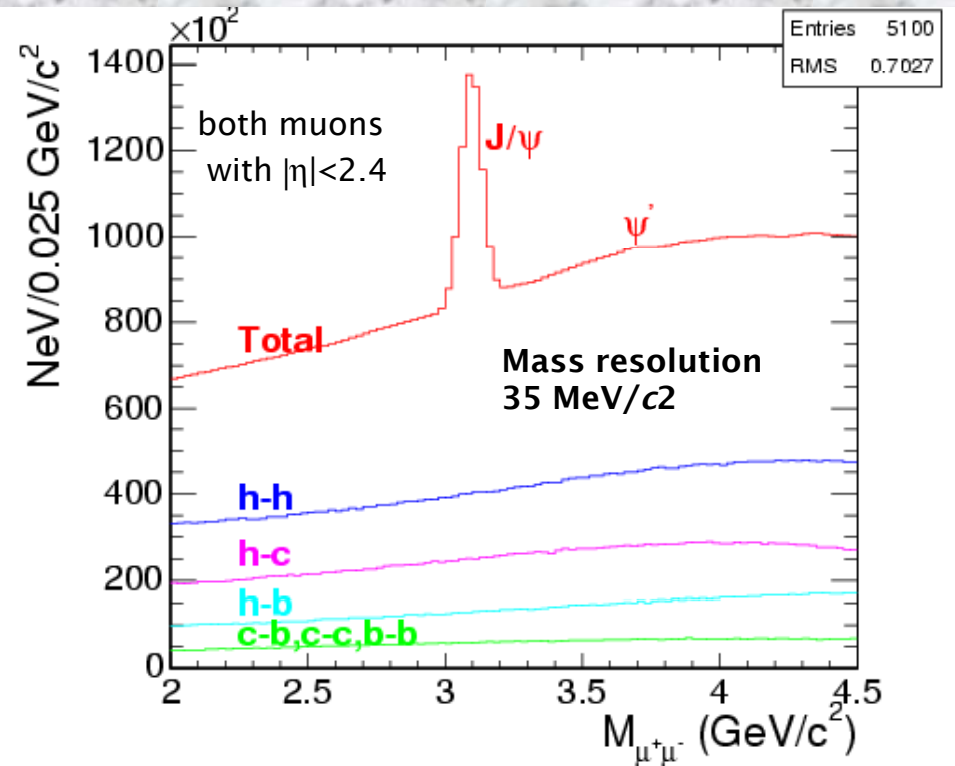**~100k J/ψ per month, tagging method**

ψ'

μ$^+$μ$^-$ invariant mass (GeV/c^2)

NeV/0.025 GeV/c^2

×10^2

Entries 5100
RMS 0.7027

both muons with |η|<2.4

J/ψ

ψ'

Total

Mass resolution 35 MeV/c2

h-h

h-c

h-b

c-b,c-c,b-b

M$_{\mu^+\mu^-}$ (GeV/c^2)

t LHC, Split, Cr

Upsilon measurements (ATLAS and CMS)

Summary

The excellent capabilities of ATLAS and CMS give the unique possibility of measuring both soft and hard probes of the dense medium state:

> Multiplicity
> soft and hard spectra of charged particles
> photons
> Jets
> Quarkonia
>
> some other probes that are not covered by presentation:
> > Ultra-peripheral collisions
> > Dihadron and dijet correlations
> > HBT
> >
> > ….

The close p_T-eta acceptance of ATLAS and CMS detectors allows to cross-check measurements done with different technologies.

Summary

Heavy Ion Physics program at LHC starts with the FIRST pp data

Backup slides

Upsilon measurements (ATLAS)
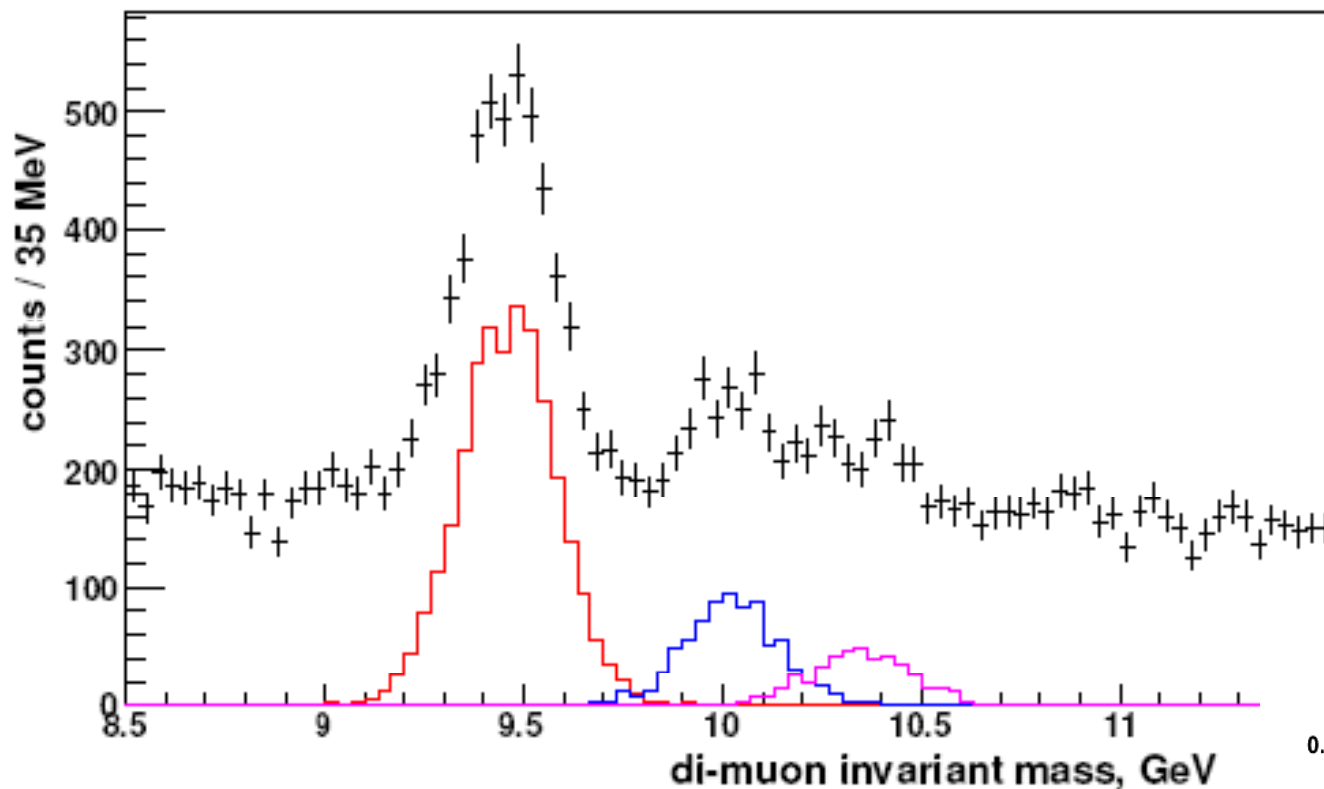
Υ, Υ', Υ'' in estimated background for 0.25 nb^{-1} integrated luminosity.

Barrel region only, |η|<1.

- Signal and background (without quenching!)
- For barrel muon spectrometers (e.g.)
  - Average mass resolution, 125 MeV
    - 15 k total Υ, Υ', Υ'' for 0.25 nb^{-1}.

Excellent mass resolution:

σ_Y = 54 MeV/c^2 |η|<0.8,
σ_Y = 90 MeV/c^2 |η|<2.4

Signal/Background:

1 (0.1) for Y in |η|<0.8 (|η|<2.4)

Expected rate (per month, 10^6s, 0.5 nb^{-1}):

Y ~ 25 kevents, Y' ~ 7 kevents, Y" ~ 4 kevents

|η|<2.4

σ = 54 MeV/c^2

|η|<0.8

both muons with |η|<0.8

"high" multiplicity

$dN_{ch}/d\eta|_{\eta=0}$ = 5000

|η|<2.4
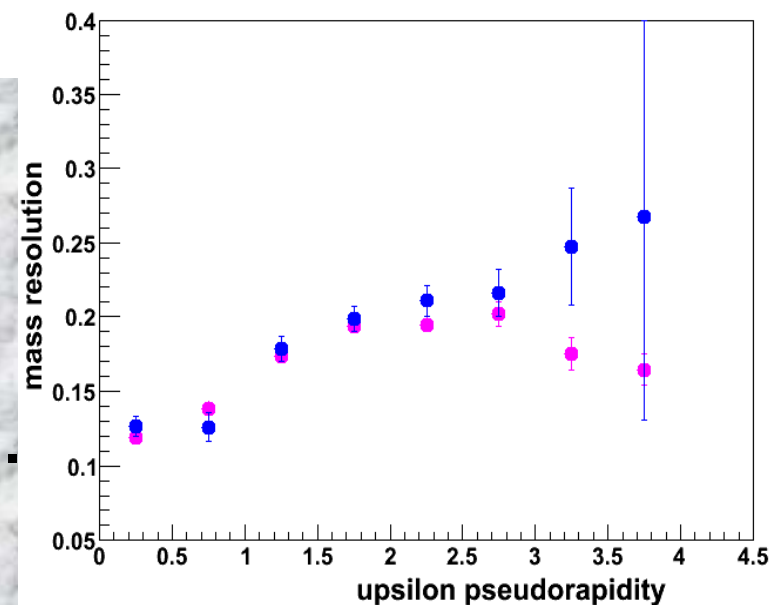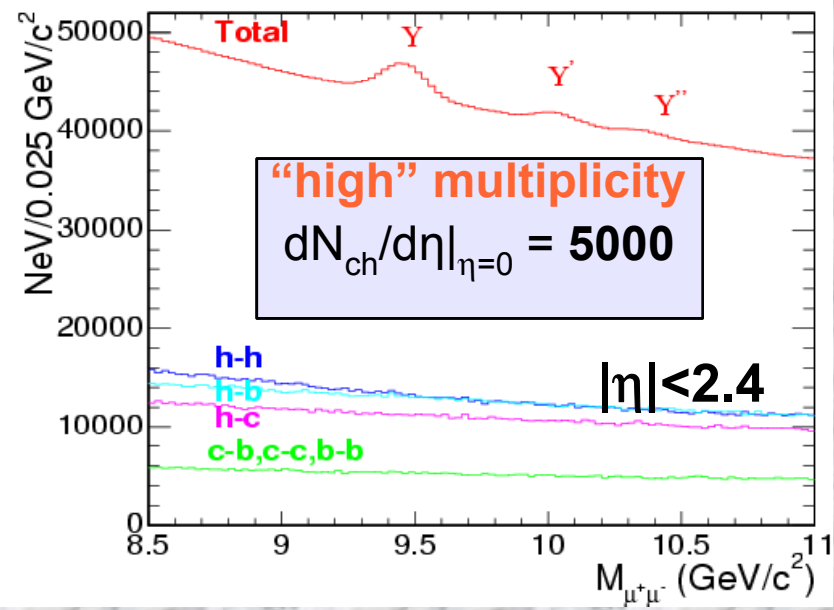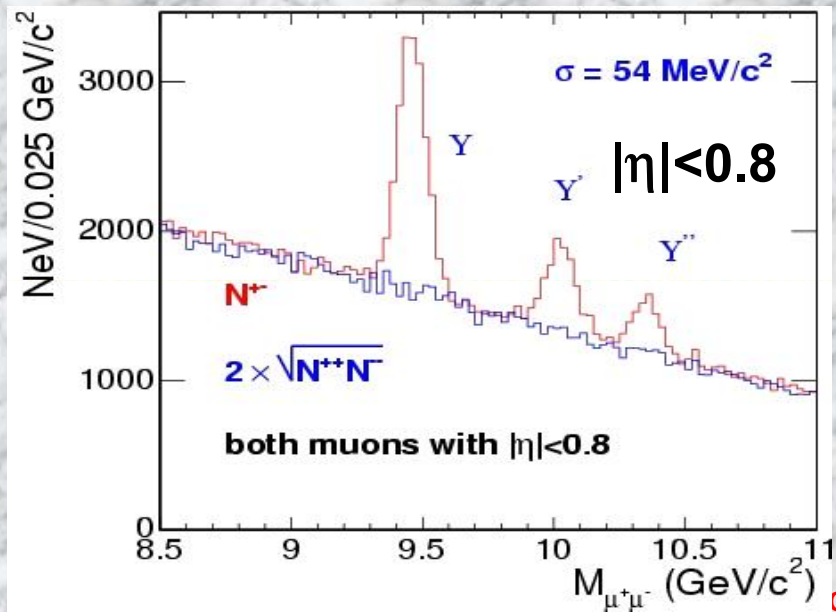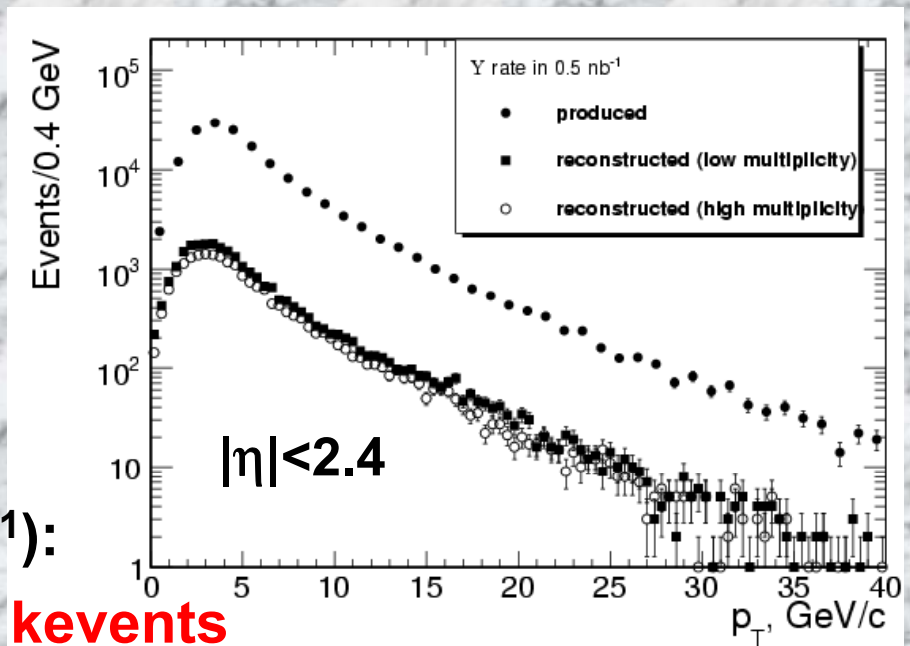
J/ψ measurements (CMS)

Excellent mass resolution:

$\sigma_{J/\psi}$ = **35 MeV/c^2**, both muons with |η|<2.4

Signal/Background:

~5(1) for J/ψ in |η|<0.8 (|η|<2.4)

Expected rate (per month, 10^6s, 0.5 nb^{-1}):

J/ψ ~ 180 kevents

J/ψ rate in 0.5 nb^{-1}
- ● produced
- ■ reconstructed (low multiplicity)
- ○ reconstructed (high multiplicity)

J/ψ

N^{+-}

"low" multiplicity
$dN_{ch}/d\eta|_{\eta=0}$ = **2500**

ψ'

$N^{+-} - 2 \times \sqrt{N^{++}N^{--}}$

J/ψ

ψ'

Total

"high" multiplicity
$dN_{ch}/d\eta|_{\eta=0}$ = **5000**

h-h

h-c

h-b

c-b,c-c,b-b
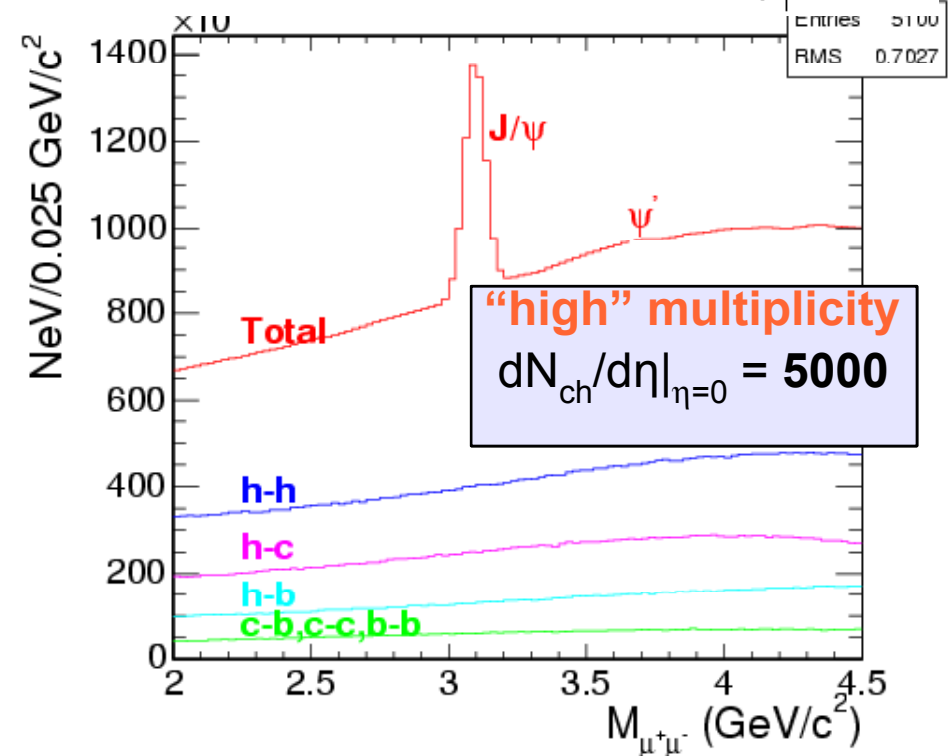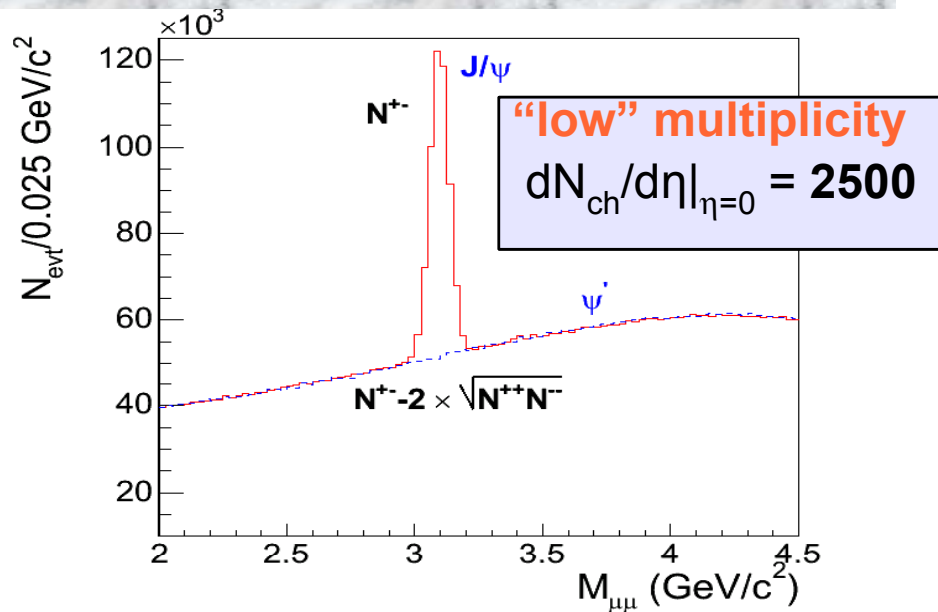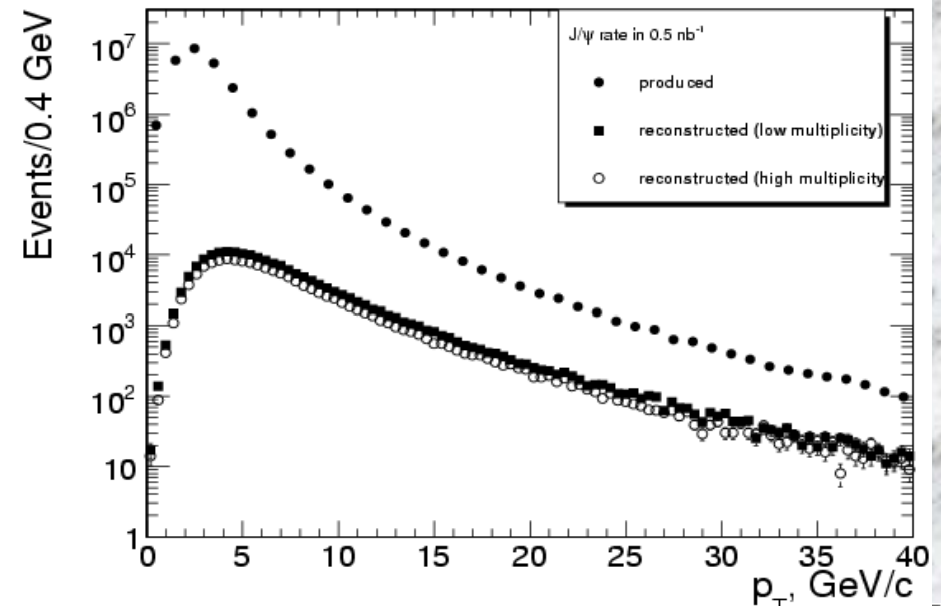
Jet finders in CMS for HI

Iterative cone (R>=0.5) with background subtraction:

mean value is determined on an event-by-event basis: pile-up subtraction algorithm

calculate average energy and dispersion in tower (in eta rings)

for each event

subtract average energy and dispersion from each tower

find jets with a jet finder algorithm (any) using the new

tower energies

recalculate average energy and dispersion using towers

free of jets recalculate jet energies

$dN_{ch}/d\eta = 5000$

ENDCAP
$1.6 \le |\eta|_{jet\ MC} \le 1.9$

▲ - *Purity*

Without bkgnd

E_T^{rec} vs E_T^{gen}

With PbPb

Jet energy resolution

BARREL
$|\eta|_{jet\ MC} \le 0.5$

With background

W/o background

○ without background
■ with background, dN/dη=5000

E_T MC jet in cone 0.5, GeV

Jet E_T resolution, (%) reco cone 0.5

E_T^{MC} (GeV)

BARREL
$|\eta|_{jet\ MC} \le 0.3$

▲ - *Purity*
□ - *Efficiency*

E_T MC jet in cone 0.5, GeV
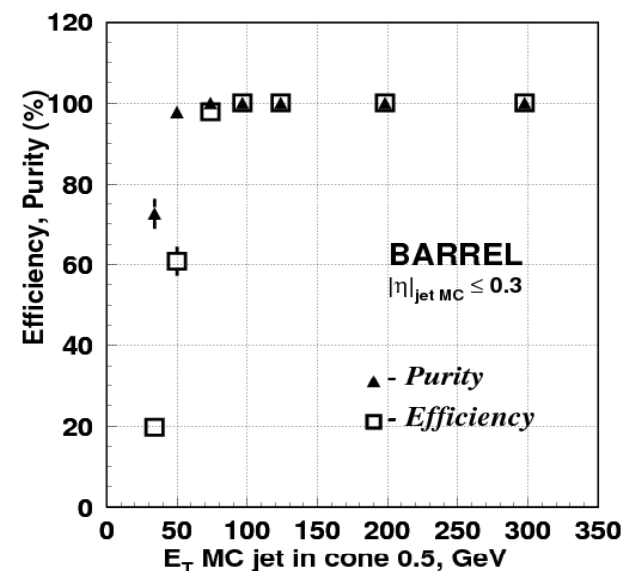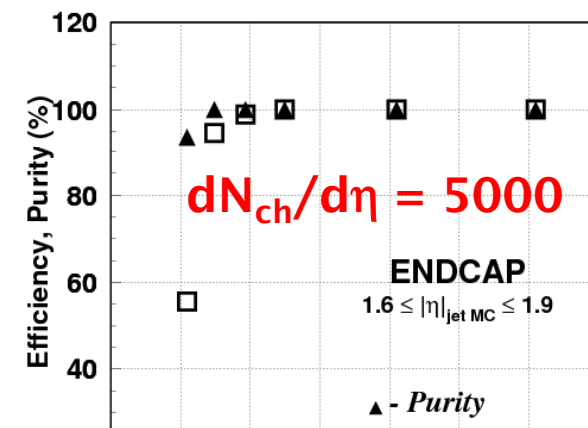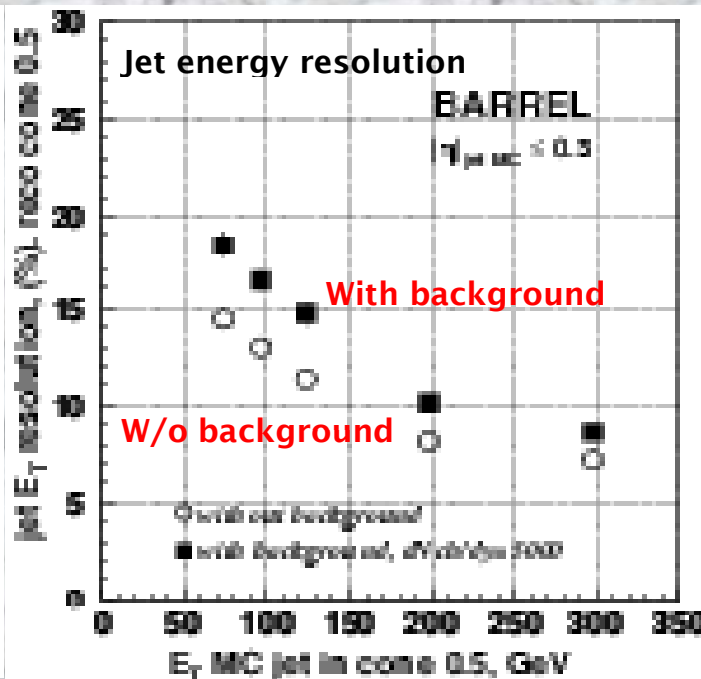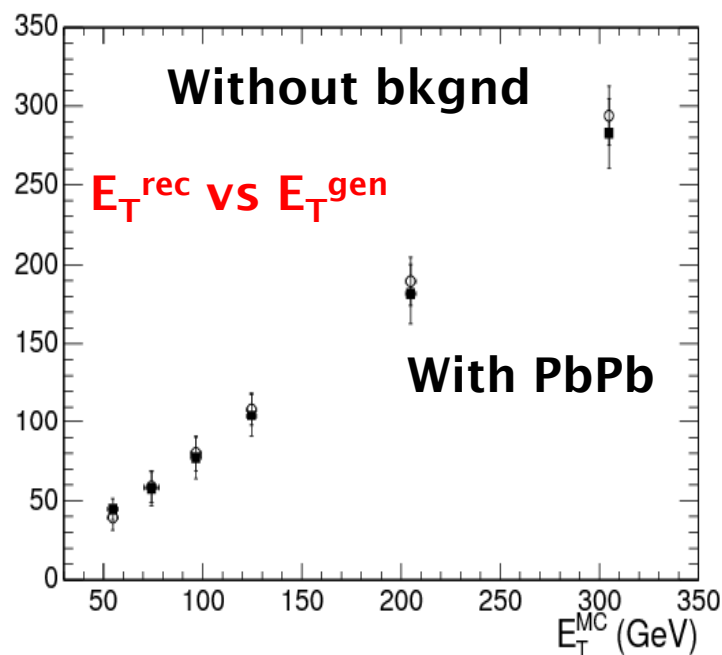
Space resolution is less then the size of calorimeter tower

ATLAS and CMS detectors for heavy ions
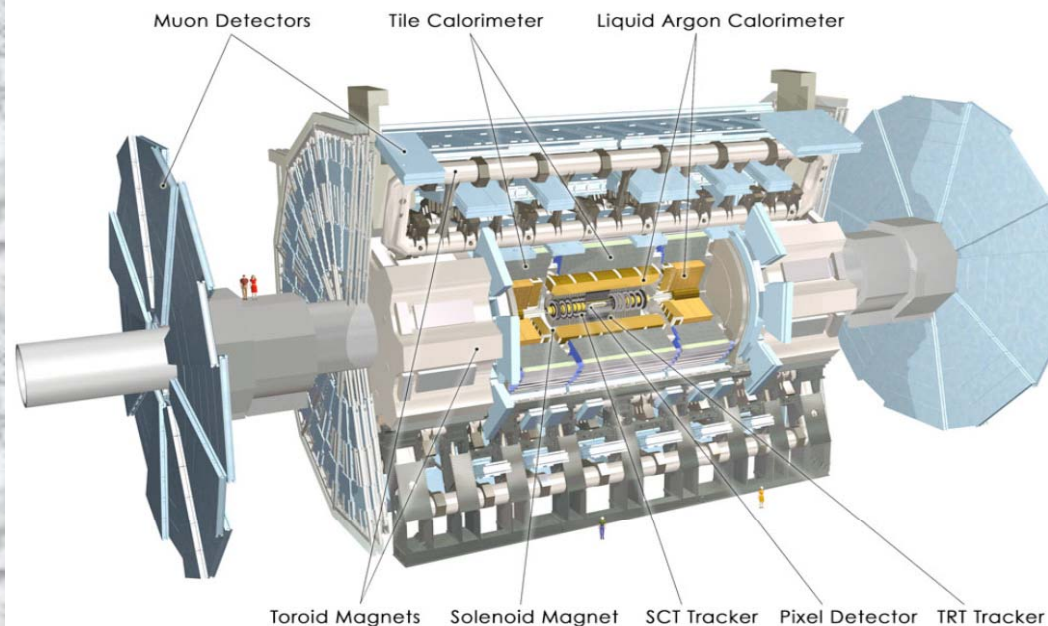
- Tracker: Silicon (Silicons: pixels+strips; TRT)
- Electromagnetic calorimeter (LAr+absorber)
- Central hadron calorimeter
    barrel (Lar+absorber),
    endcap (plastic+absorber)
- Forward calorimeter
    (Lar+absorber)
- Muon chambers
  Monitored Drift Tubes (MDT)+RPC (barrel),
  MDT + Cathod Strip Chambers
(CSC)+TGC(endcap)
- Zero-degree calorimeter
  2 T magnetic field (solenoid + toroid)
momentum resolution 3% for pt<10 GeV/c with
silicons only
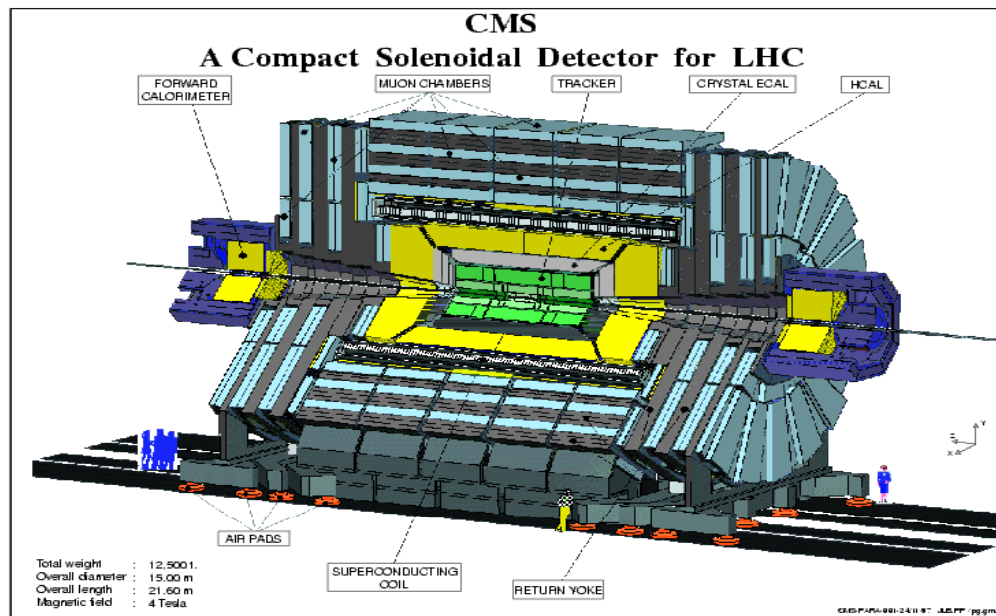
- Silicon Tracker (Pixels and Strip)
- Electromagnetic Calorimeter (PbWO4)
- Central hadron Calorimeter
        (plastic + brass absorber)
- Forward calorimeter (Quartz-fiber and ferum)
- Muon Chambers (Drift tubes in barrel,
        Cathod strip chambers in endcap, RPC)
- CASTOR
- Zero-degree calorimeter
+ TOTEM

4 T magnetic field (solenoid), 2 T return yoke
momentum resolution < 2% for pT<100 GeV
Fast DAQ allows to take almost all events
to HLT farm

Ultra-peripheral collisions

- **At LHC the accelerated Pb nucleus can produce strong electromagnetic field**
  - **due to the coherent action of the $Z = 82$ proton charges**

Equivalent photon flux $E\gamma_{max} \sim 80$ GeV

γ+Pb: cm $E_{max} \approx 1.$ TeV/n (~3×e+p HERA)

$\gamma + \gamma$: cm E_{max} **≈ 160 GeV (~LEP)**

- **Measure the gluon distribution function in the nucleus (γPb)**
  - **low background**
  - **simpler initial state**
- **γPb→Υ photo-production in CMS**
  - **Unexplored (x, Q^2) regime:**
  - **Pin down amount of low-x suppression in the Pb nuclear PDF (compared to the proton PDF)**
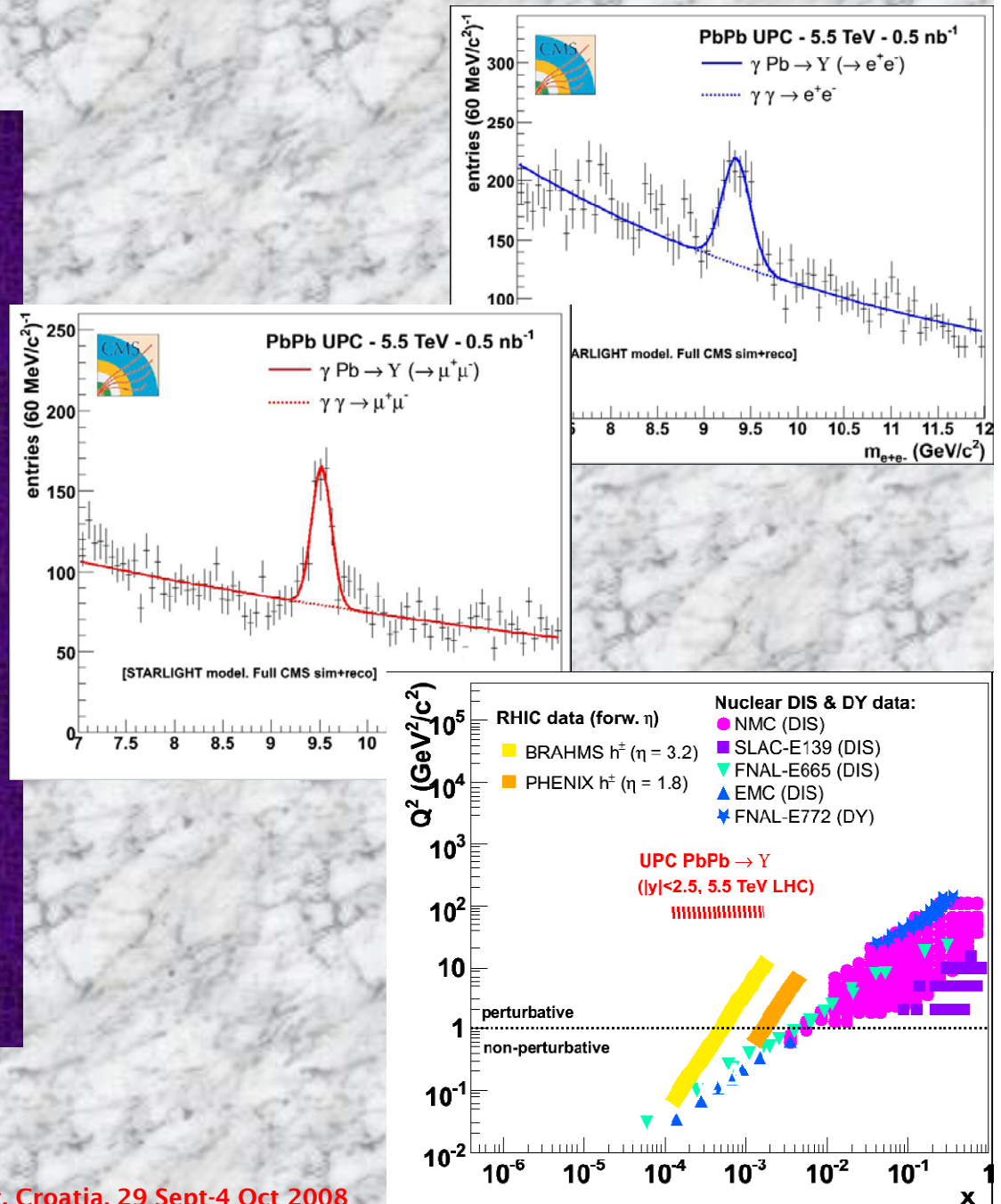
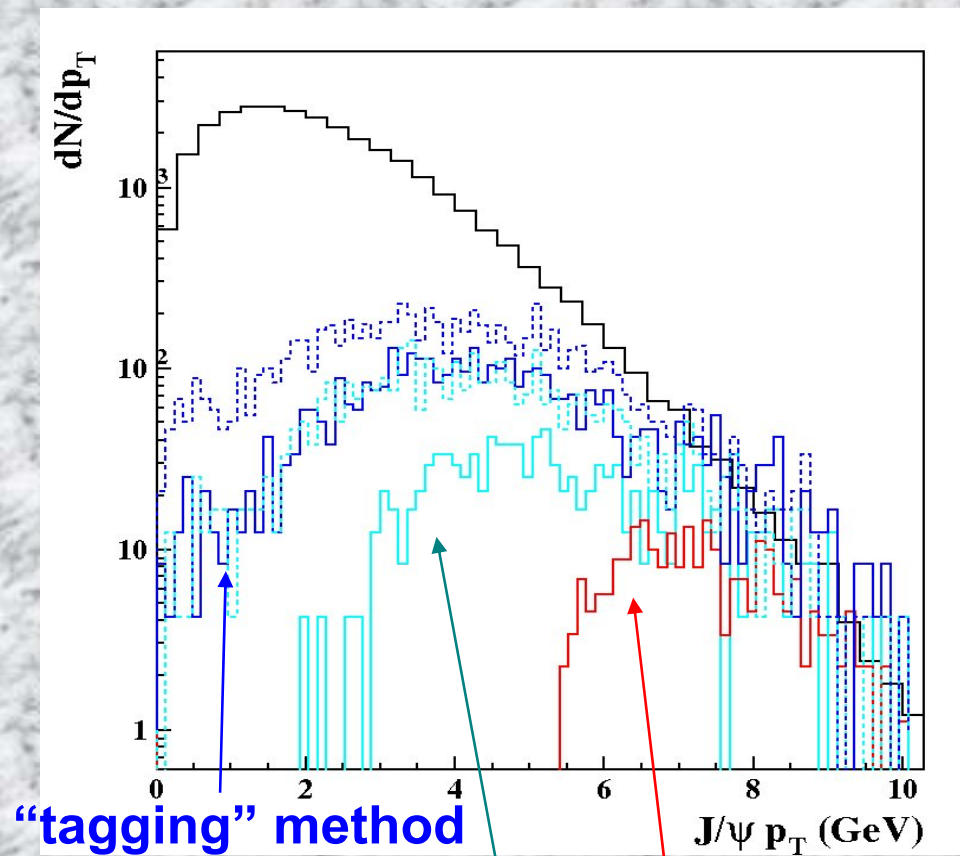Main problem: low acceptance due to minimum muon p_T ~ 1.5 GeV/*c*
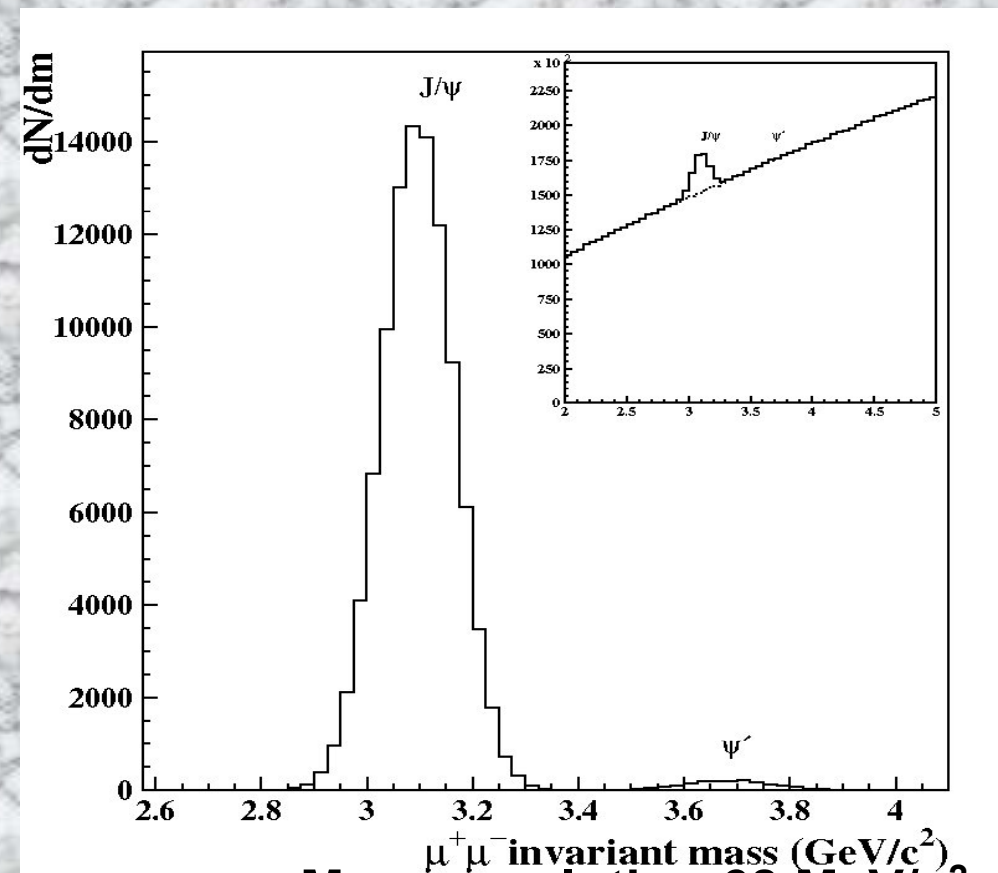
Two methods considered:
- both muons fully reconstructed
- "tagging method" for one muon *(increase the statistics of J/ψ with low p_T)*

"tagging" method

full reconstruction, p_T cut 1.5 GeV/*c*

full reconstruction, p_T cut 3 GeV/*c*

Mass resolution 68 MeV/*c*^{2}

~100k J/ψ per month, tagging method

J/ψ and Upsilon rates (ATLAS)

Y

Field	full	full	full	half	half	half
$|\eta|$ (max)	1	2	2.5	1	2	2.5
Acceptance x efficiency	4.7%	12.5%	17.5%	4.9%	13.8%	19.3%
	(2.6%)	(8.1%)	(12.0%)	(2.6%)	(8.9%)	(13.4%)
Mass resolution (MeV)	123	145	159	126	162	176
S/B	0.3	0.2	0.2	0.3	0.2	0.2
	(0.4)	(0.3)	(0.3)	(0.55)	(0.3)	(0.3)
$S/\sqrt{S+B}$	37	46	55	37	50	60
	(31)	(45)	(55)	(34)	(48)	(60)
Rate/month	5700	15000	21200	5900	16800	23400
	(3100)	(10000)	(14600)	(3100)	(10800)	(16300)

J/ψ

Field	full	full	half
p_T (min) (GeV)	3	1.5	1.5
Acceptance x efficiency	0.055%	0.530%	1.100%
	(0.039%)	(0.151%)	(0.529%)
Mass resolution (MeV)	68	68	76
S/B	0.4	0.15	0.15
	(0.5)	(0.2)	(0.25)
$S/\sqrt{S+B}$	56	113	164
	(52)	(72)	(140)
Rate/month	11000	104000	216000
	(8000)	(30000)	(104000)

Fragmentation function measurements (ATLAS)

- "Raw" evaluation of
  - J_T distribution
  - Fragmentation func.
  - $p_T > 2$ GeV/c, $|\eta| < 2.5$
    - Jet $E_T^{rec} > 70$ GeV
- With constant (for simplicity) 70% correction for tracking efficiency
- Reproduce both shape and absolute yield, both J_T and D(Z)