Photon Measurements at PHENIX and ALICE

Ju Hwan Kang
(Yonsei University)

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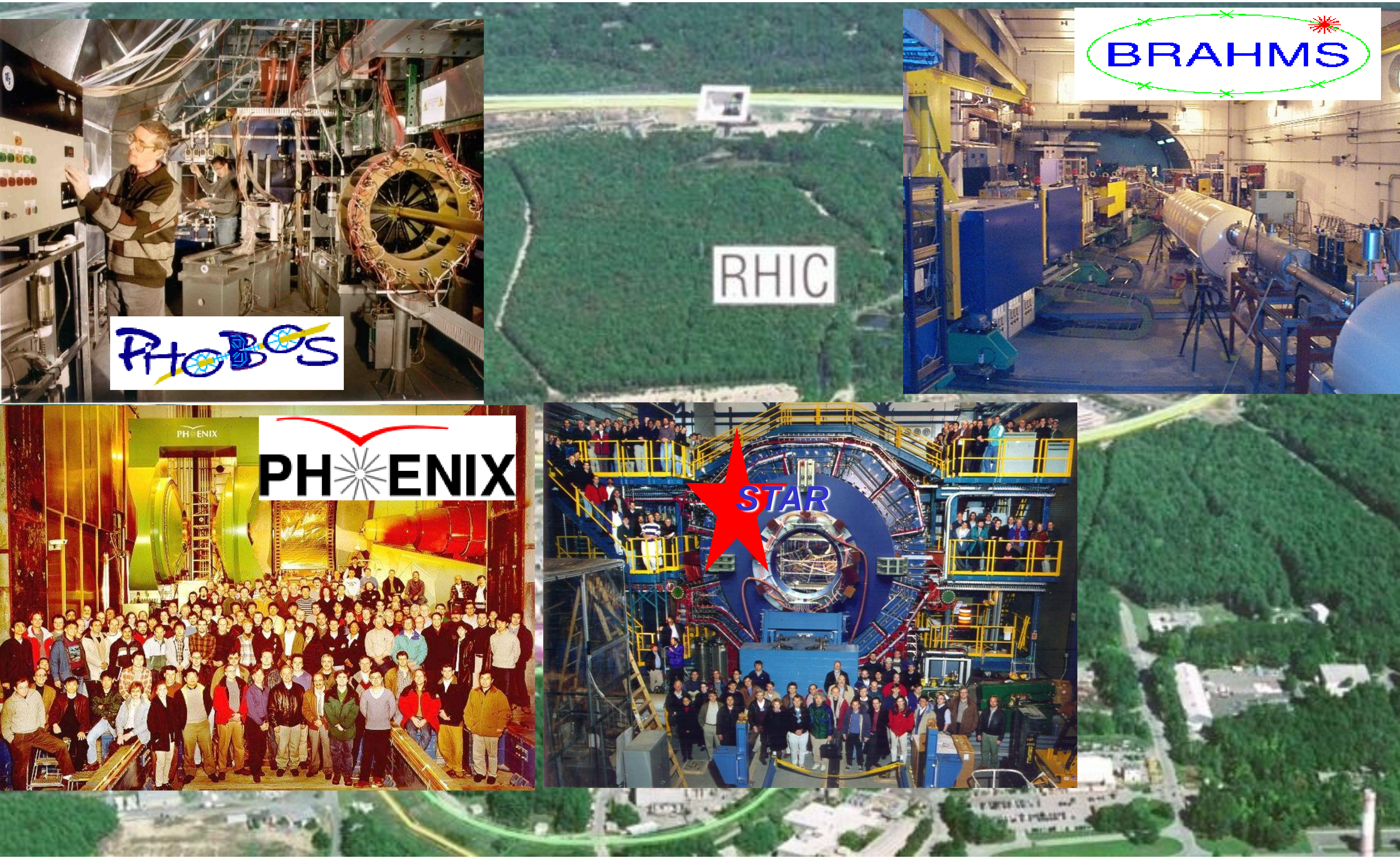
OUTLINE

- RHIC and PHENIX photon mesurement
- Thermal photons from PHENIX
- Photon/electron measurement at ALICE
- π^0 and η mesons by measuring γ and e^+e^- (P+P)
- Very recent results of Pb+Pb at LHC even though these are not related to photon measurements

RHIC's Experiments



Electron pair measurement in PHENIX

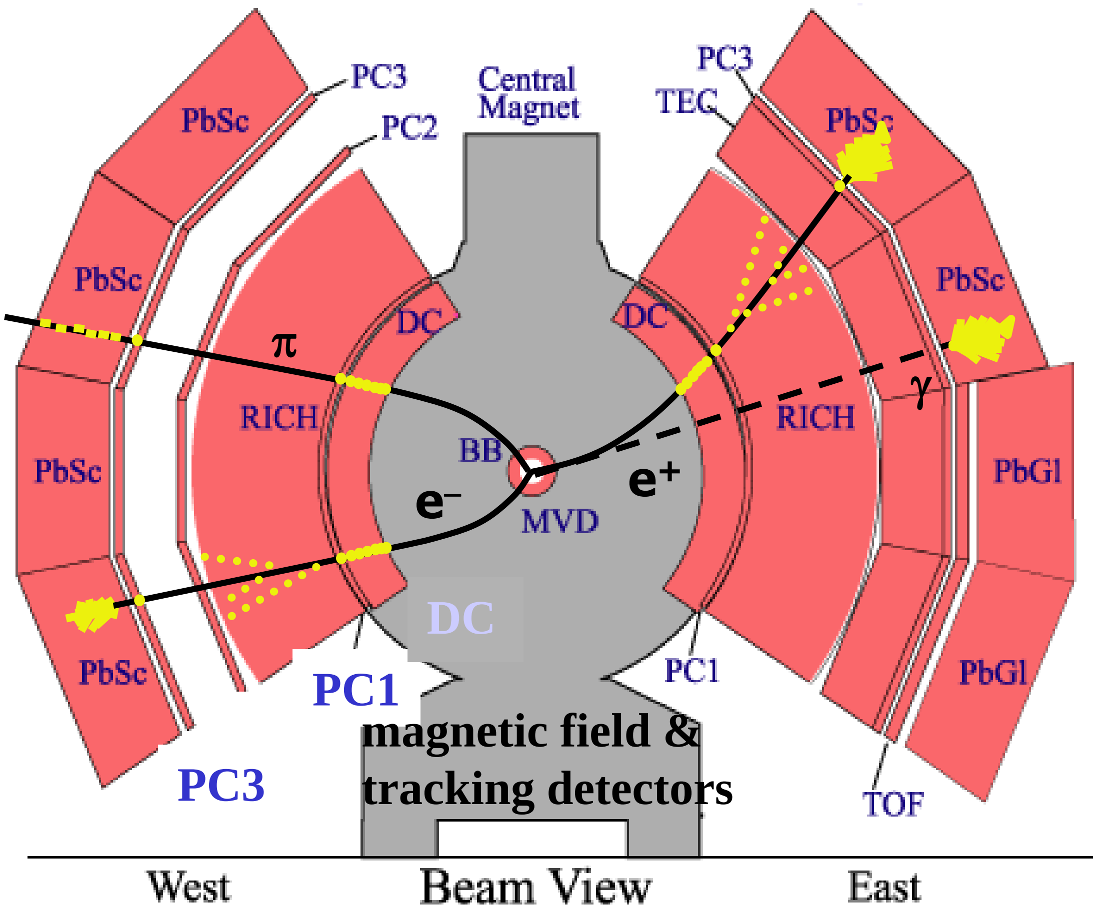
designed to measure rare probes:

Au-Au & p-p spin

+ high rate capability & granularity
+ good mass resolution and particle ID
- limited acceptance

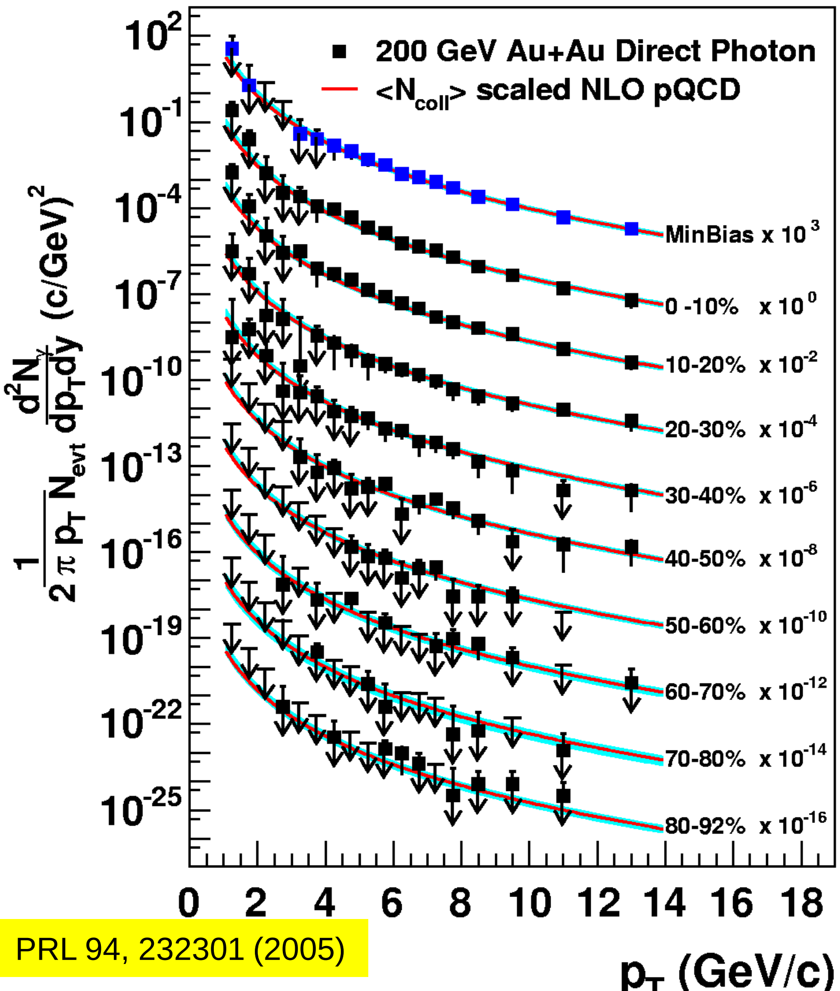
- 2 central arms:

  electrons, photons, hadrons
  - charmonium J/ψ, ψ' -> e^+e^-
  - vector meson r, w, ϕ -> e^+e^-
  - high p_T π^o, π^+, π^-
  - direct photons
  - open charm
  - hadron physics

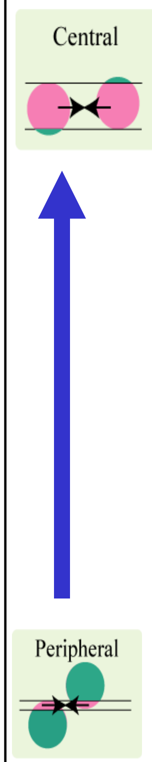


Direct Photons in Au+Au

Blue line: N_{coll} scaled p+p cross-section

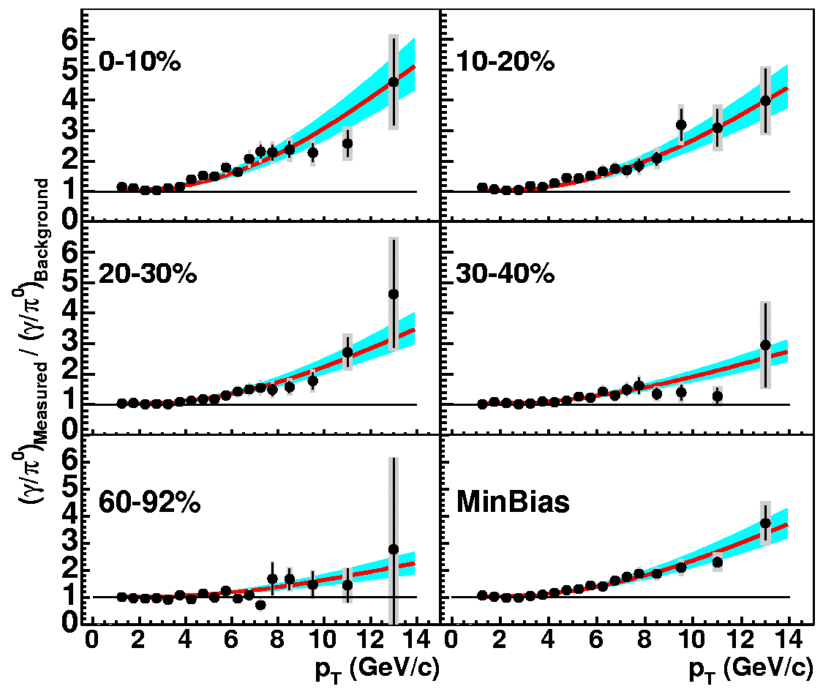


PRL 94, 232301 (2005)



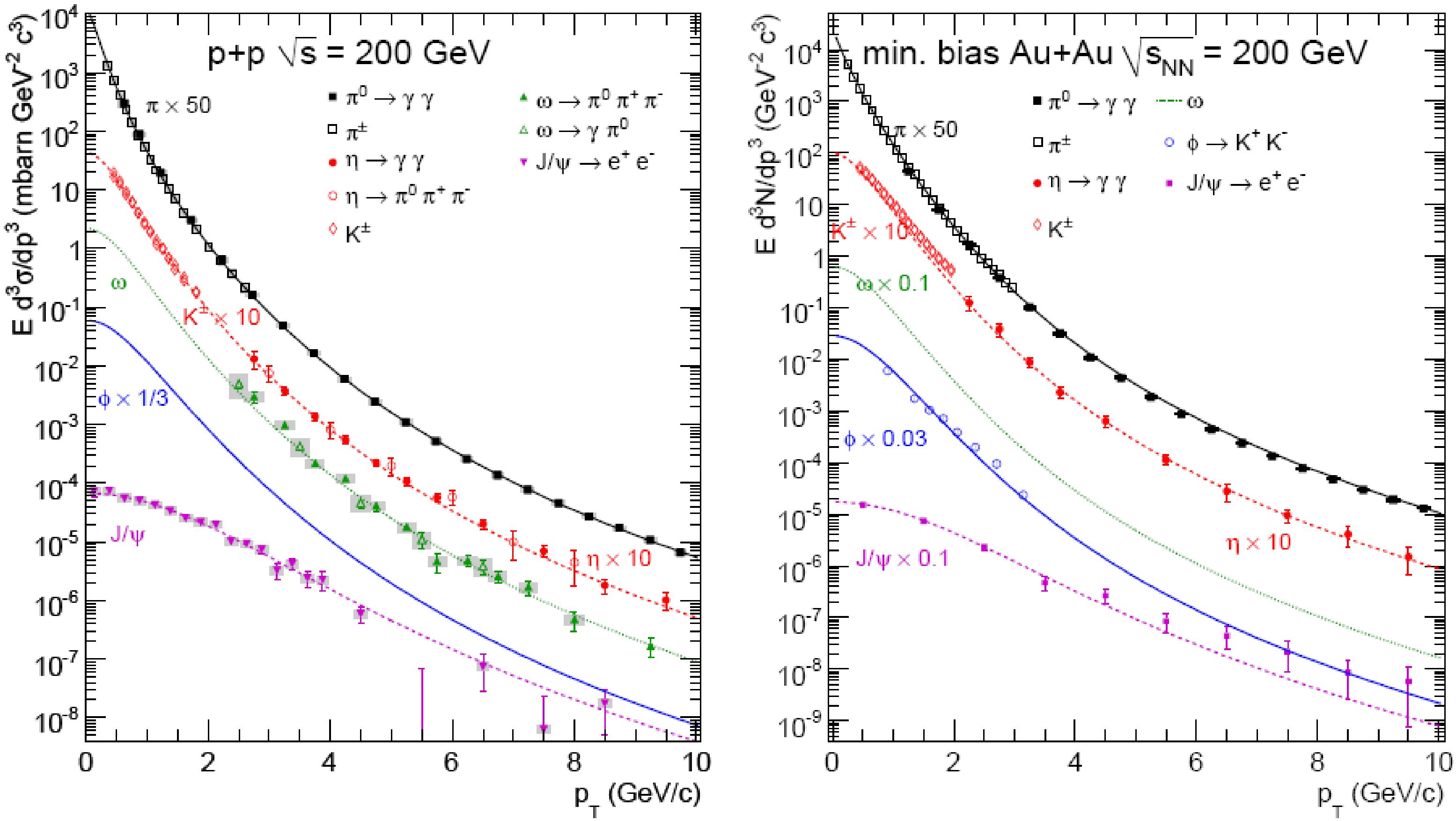
Direct photon is measured as "excess" above hadron decay photons: background photons are based on the decays from measured π^0 and η spectra, also other hadrons (η', ω, Ks^0) assuming m_T scaling.

$$R_\gamma = \frac{(\gamma/\pi^0)_{\text{Measured}}}{(\gamma/\pi^0)_{\text{Background}}} \approx \frac{\gamma_{\text{Measured}}}{\gamma_{\text{Background}}}$$



Au+Au data consistent with pQCD calculation scaled by N_{coll}

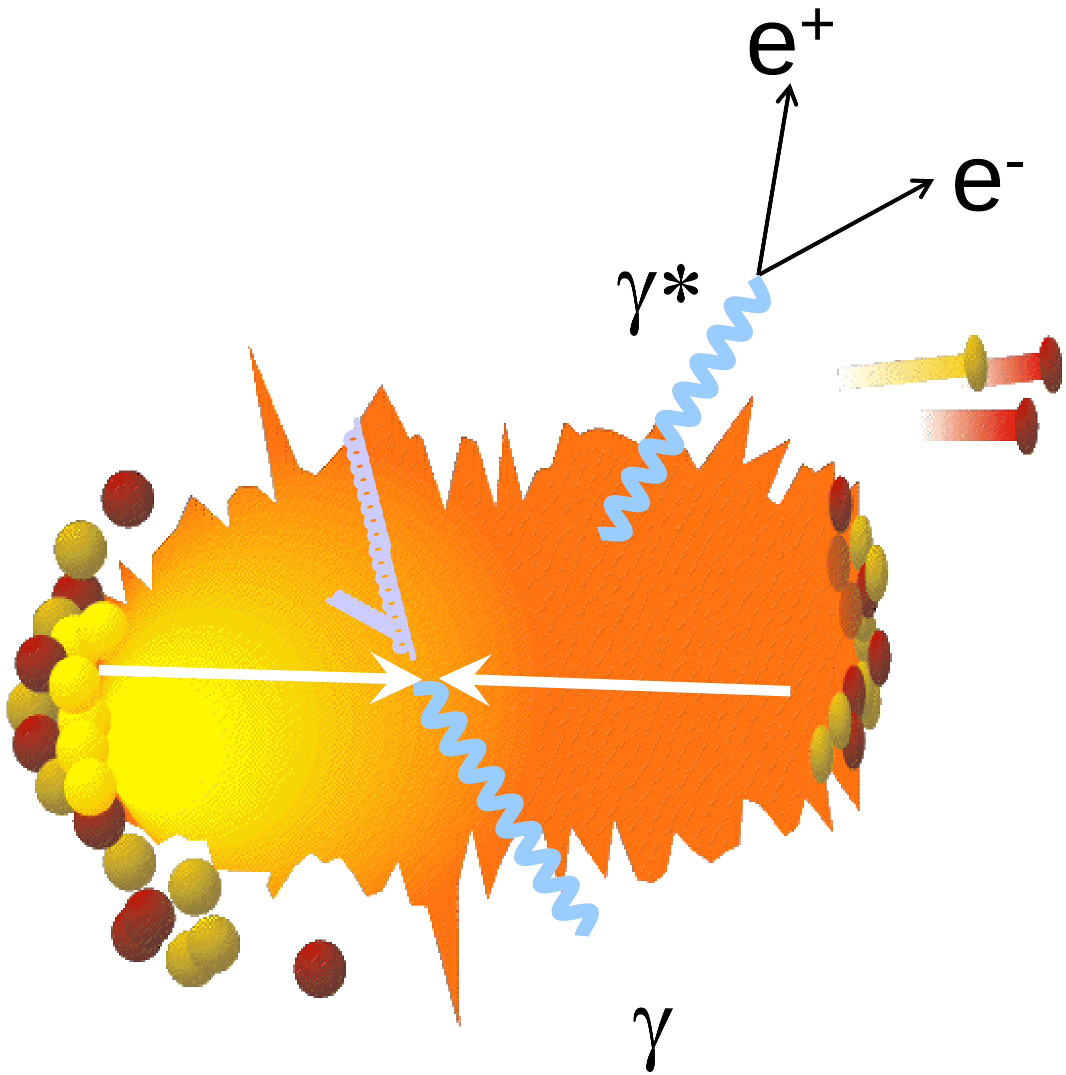
Input hadron spectra for cocktail



$$E\frac{d^3\sigma}{dp^3} = A(e^{-(ap_T+bp_T^2)} + p_T/p_0)^{-n}$$

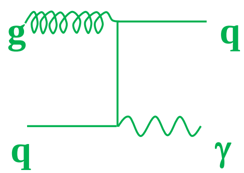
Fitting with a modified Hagedorn function for pion, for all other mesons assume m_T scaling by replacing p_T by $\sqrt{m^2 - m_\pi^2 + (p_T/c)^2}$

Electromagentic probes (photon and lepton pairs)

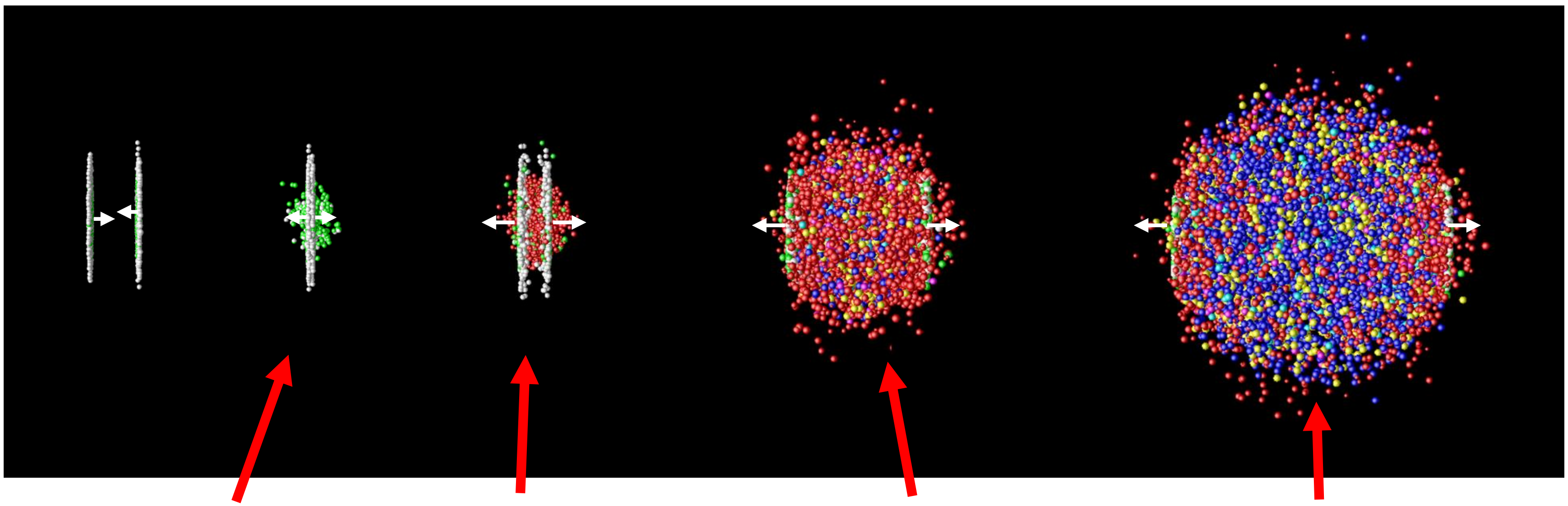


- Photons and lepton pairs are cleanest probes of the dense matter formed at RHIC
- These probes have little interaction with the matter so they carry information deep inside of the matter
  - Temperature of QGP by measuring p_T spectrum of direct photons
  - Thermal photons from QGP is the dominant source of direct photons for $1<p_T<3$ GeV/c

Photons in nucleus-nucleus collisions



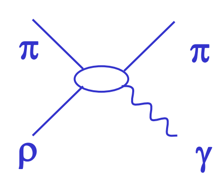
Time →



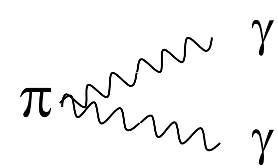
Initial hard parton-parton scatterings
(hard γ)

Thermalized medium (QGP!?),
$T_0 > T_c$,
$T_c \approx 170$ - 190 MeV
(QGP thermal γ)

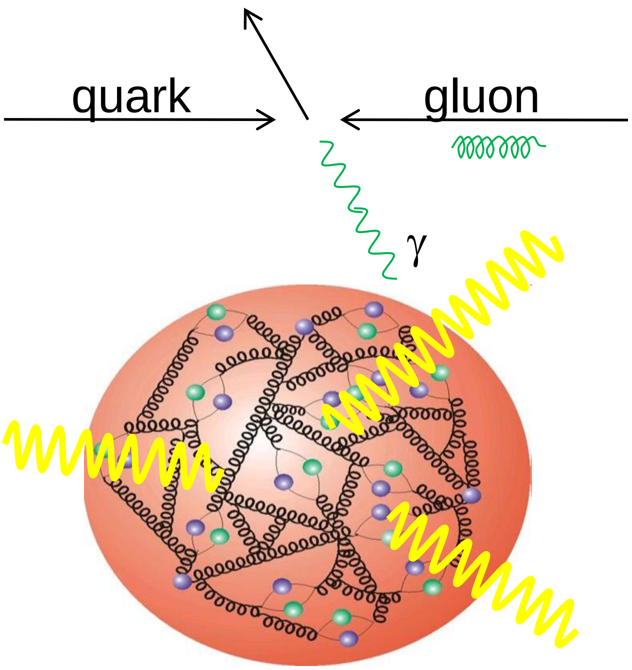
Phase transition QGP → hadron gas
(Low p_T γ)



Freeze-out
(hadron decay γ)

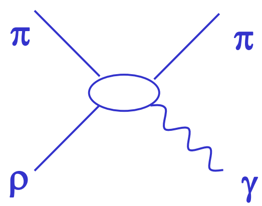


Many sources of photons



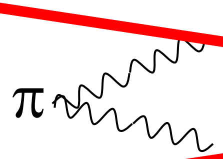
pQCD direct photons from initial *hard scattering* of quarks and gluons

Thermal photons from hot *quark gluon plasma*



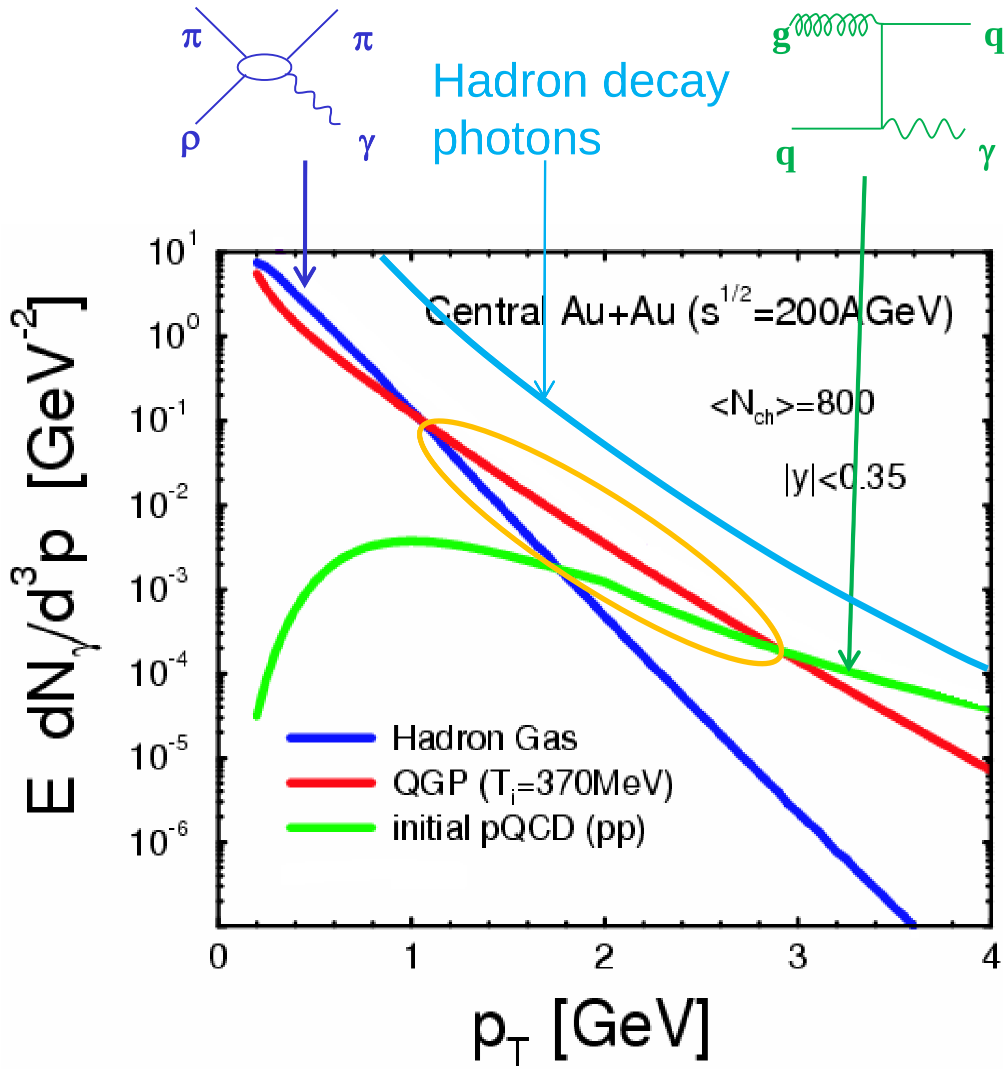
Thermal photons from *hadron gas* after hadronization

background



Decay Photons from hadrons (π^0, η, etc)

Thermal photons (theory prediction)

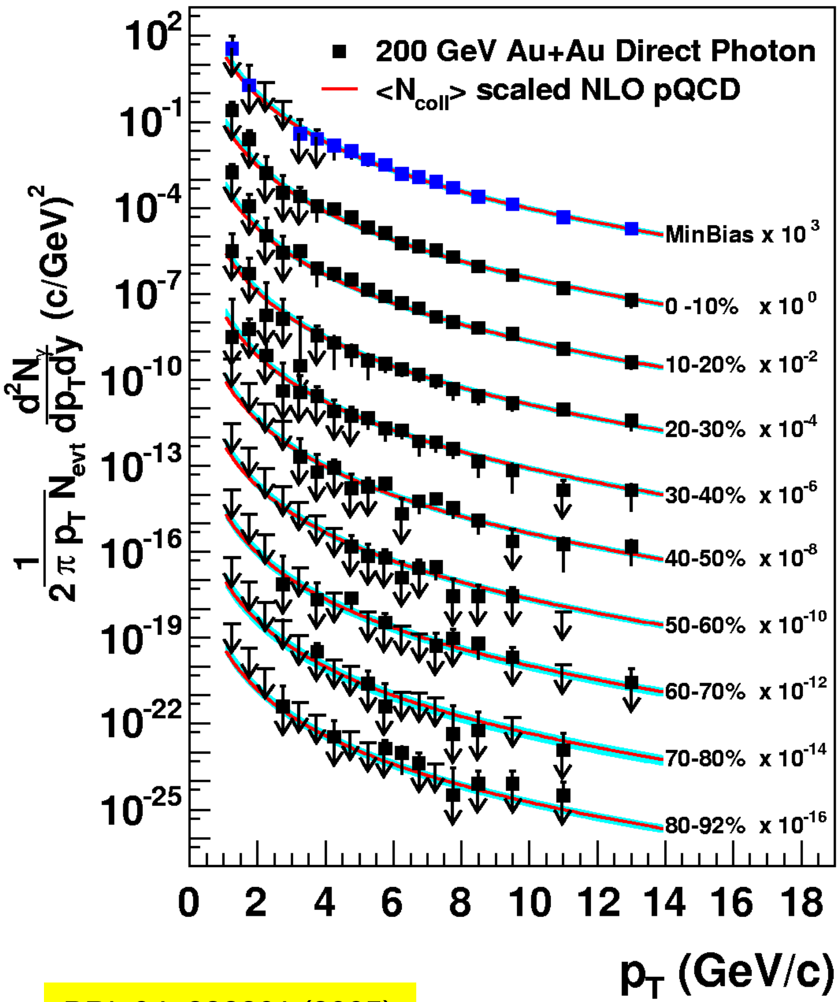


S.Turbide *et al* PRC 69 014903

- High p_T (p_T>3 GeV/c) pQCD photon
- Low p_T (p_T<1 GeV/c) photons from hadronic gas
- Themal photons from QGP is the dominant source of direct photons for $1<p_T<3$ GeV/c
- Measurement is difficult since the expected signal is only 1/10 of photons from hadron decays

Lower p_T photon measurement

Blue line: N_{coll} scaled p+p cross-section



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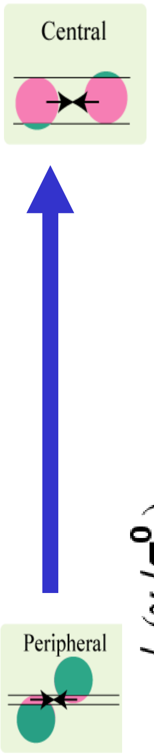
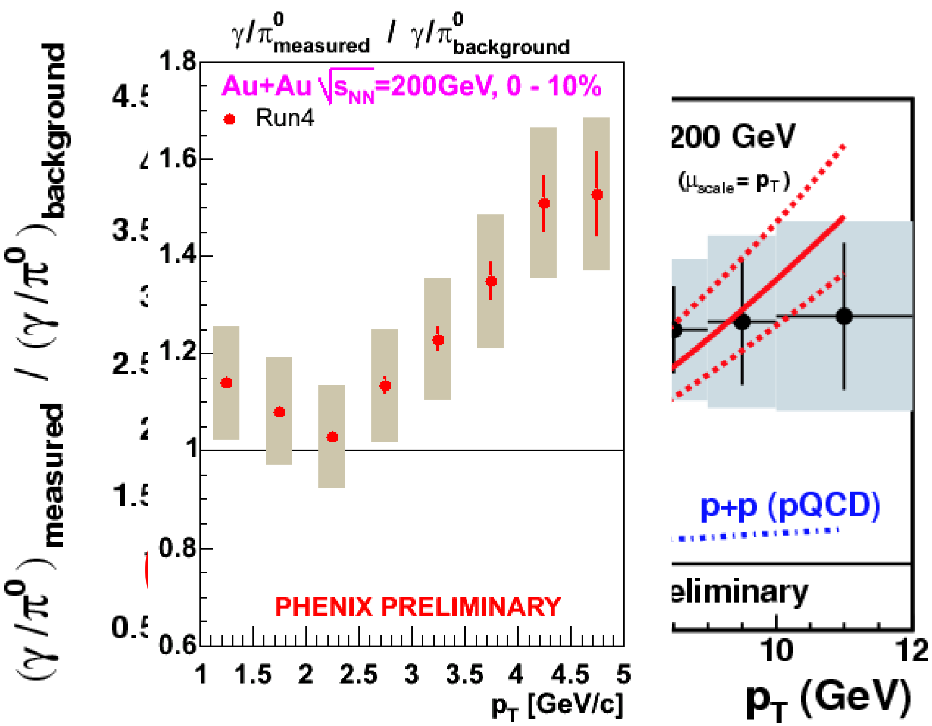
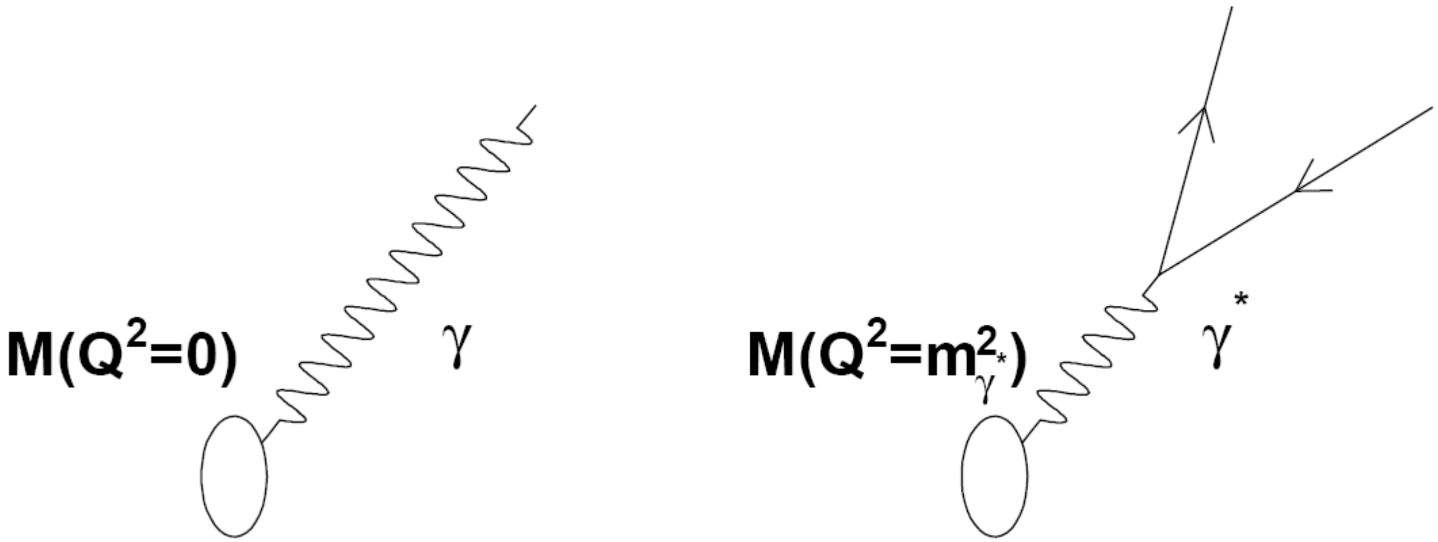


Direct photon is measured as "excess" above hadron decay photons

Measurement at low p_T difficult since the yield of thermal photons is only 1/10 of that of hadron decay photons



Virtual photons to improve S/B



- Source of real photon should also be able to emit virtual photon
- At m→0, the yield of virtual photons is the same as real photon

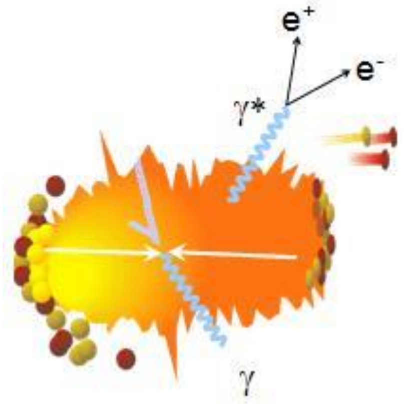
→ Real photon yield can be measured from virtual photon yield, which is observed as low mass e^+e^- pairs

- Advantage: hadron decay background can be substantially reduced since we can remove π^0 decay photons (~80% of background) by requiring $m>m_\pi$

→ S/B is improved by a factor of five

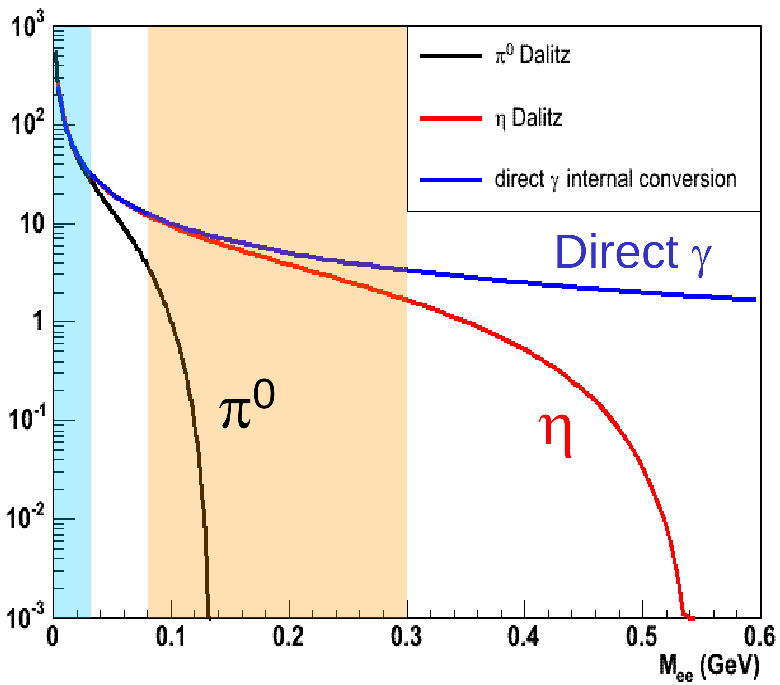
Virtual Photon Measurement

Any source of real γ can emit γ^* with very low mass.
Relation between the γ^* yield and real photon yield is known.



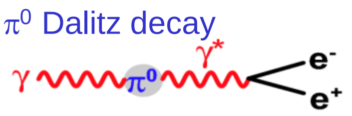
$$\frac{d^2N}{dM_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{M_{ee}^2}}\left(1+\frac{2m_e^2}{M_{ee}^2}\right)\frac{1}{M_{ee}}S(M_{ee},p_t)dN_\gamma$$

Process dependent factor $S(M_{ee},p_t) \equiv \frac{dN_{\gamma^*}}{dN_\gamma}$



- Case of hadrons (π^0, η) (Kroll-Wada)

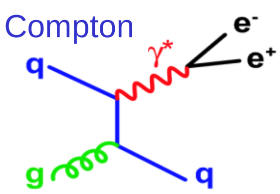
$$S = \left|F\left(M_{ee}^2\right)\right|^2\left(1-\frac{M_{ee}^2}{M_{hadron}^2}\right)^3$$



$S = 0$ at $M_{ee} > M_{hadron}$

- Case of direct γ^*

If $p_T^2 >> M_{ee}^2$ $S = 1$



- For $m>m_\pi$, π^0 background (~80% of background) is removed

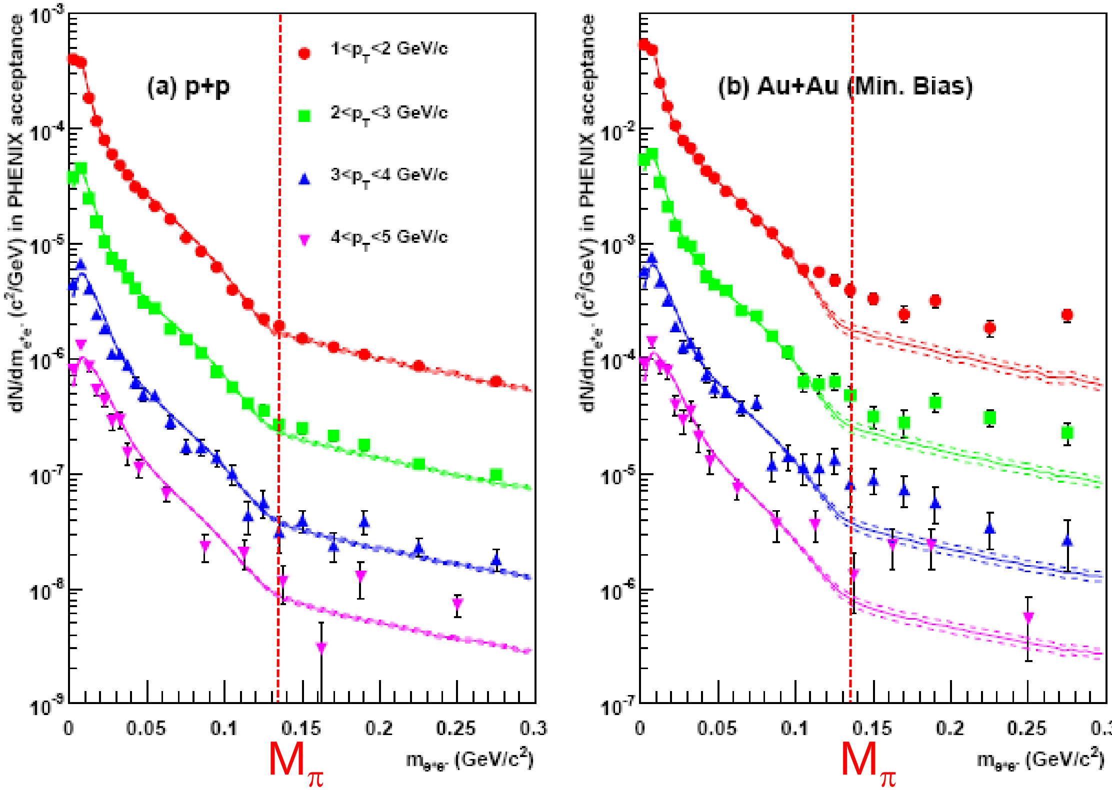
→ S/B is improved by a factor of five

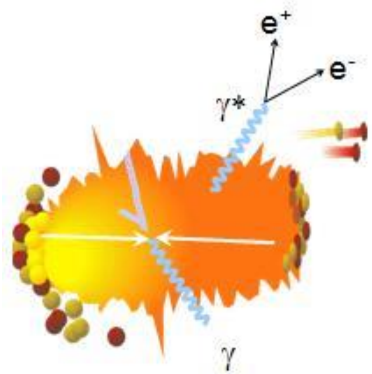
Enhancement of almost real photon

pp

PRL, 104, 132301 (2010)

Au+Au (MB)





Low mass e^+e^- pairs (m<300 MeV) for $1<p_T<5$ GeV/c

p+p:

- Good agreement of p+p data and hadronic decay cocktail (π, η, ω, η', ϕ)

Au+Au:

- Clear enhancement visible above m_π =135 MeV for all p_T

Excess → Emission of almost real photon

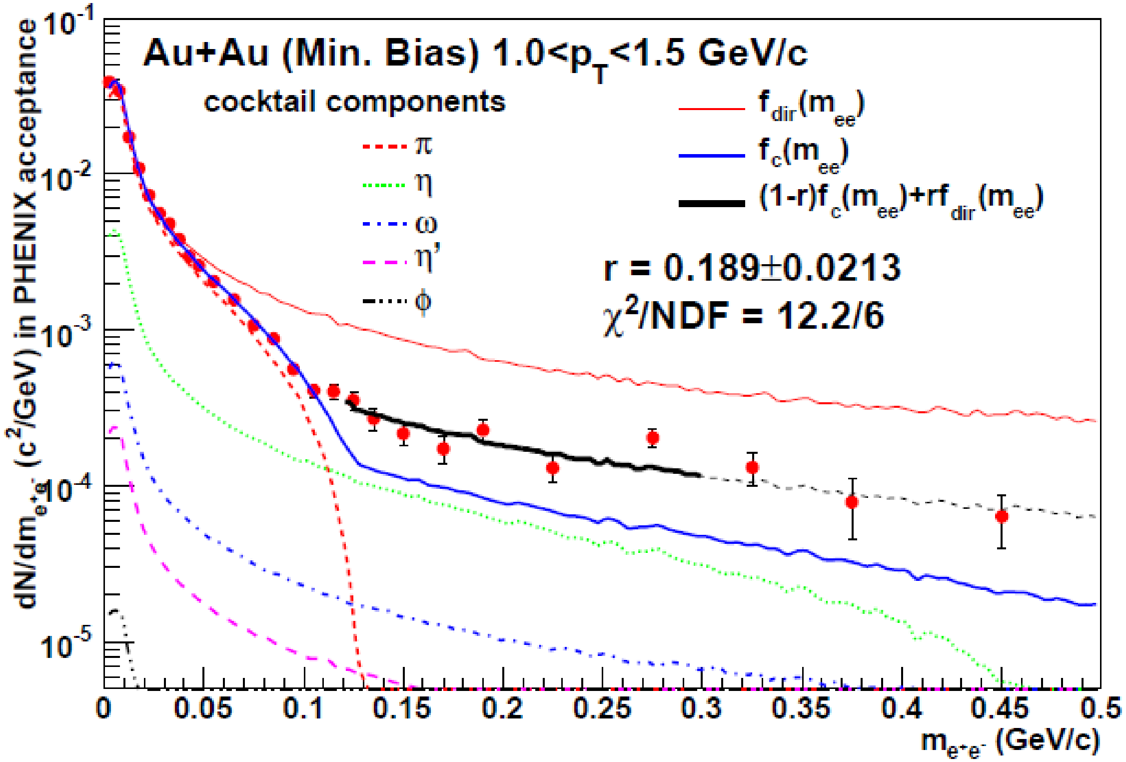
$1 < p_T < 2$ GeV
$2 < p_T < 3$ GeV
$3 < p_T < 4$ GeV
$4 < p_T < 5$ GeV

Extraction of the direct γ signal

$$f(m_{ee}) = (1-r)\cdot f_{\text{cocktail}}(m_{ee}) + r\cdot f_{\text{direct}}(m_{ee})$$

r = direct γ^*/inclusive γ^*

f_{direct} : direct photon shape with S = 1



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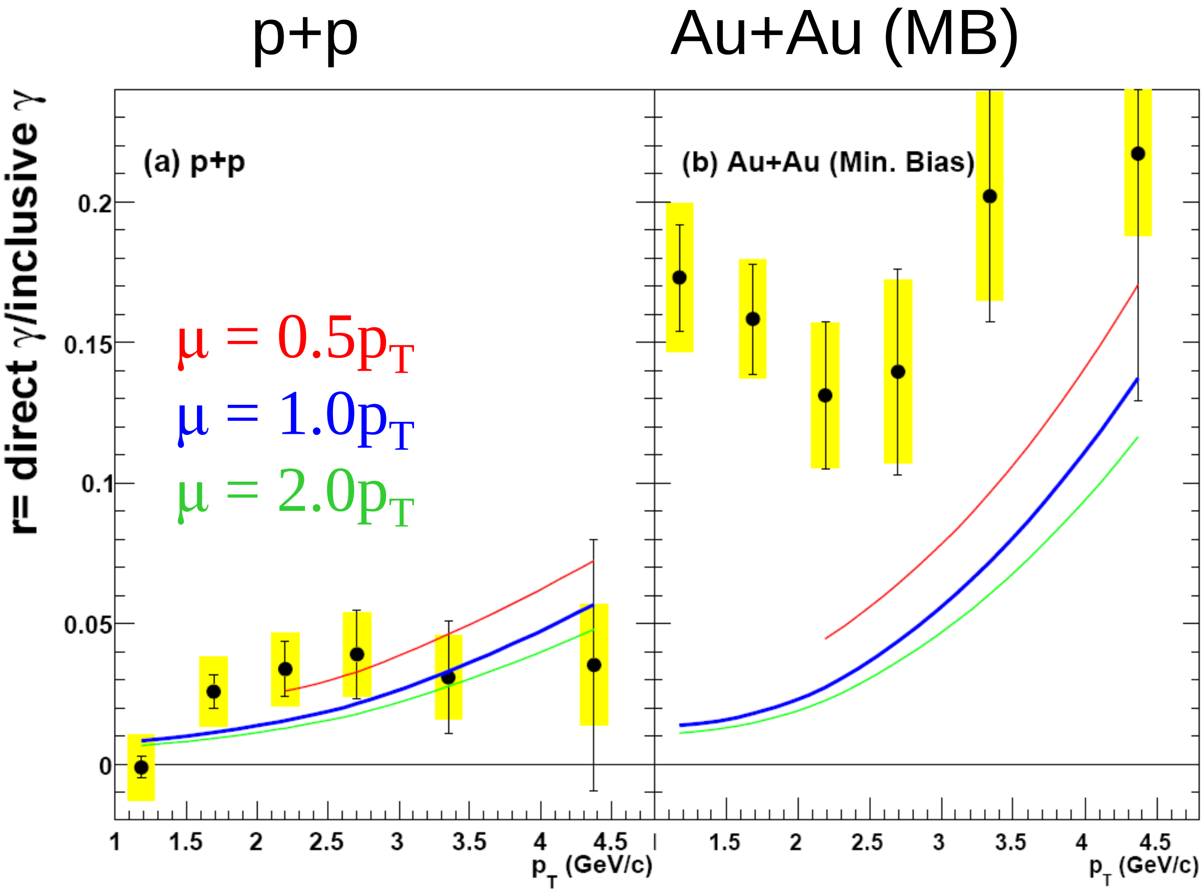
- Interpret deviation from hadronic cocktail (π, η, ω, η', ϕ) as signal from virtual direct photons

- Fit in 120-300MeV/c^2 (insensitive to π^0 yield)

Fraction of direct photons

PRL, 104, 132301 (2010)

r = direct γ/inclusive γ



- Fraction of direct photons
- Compared to direct photons from pQCD

p+p

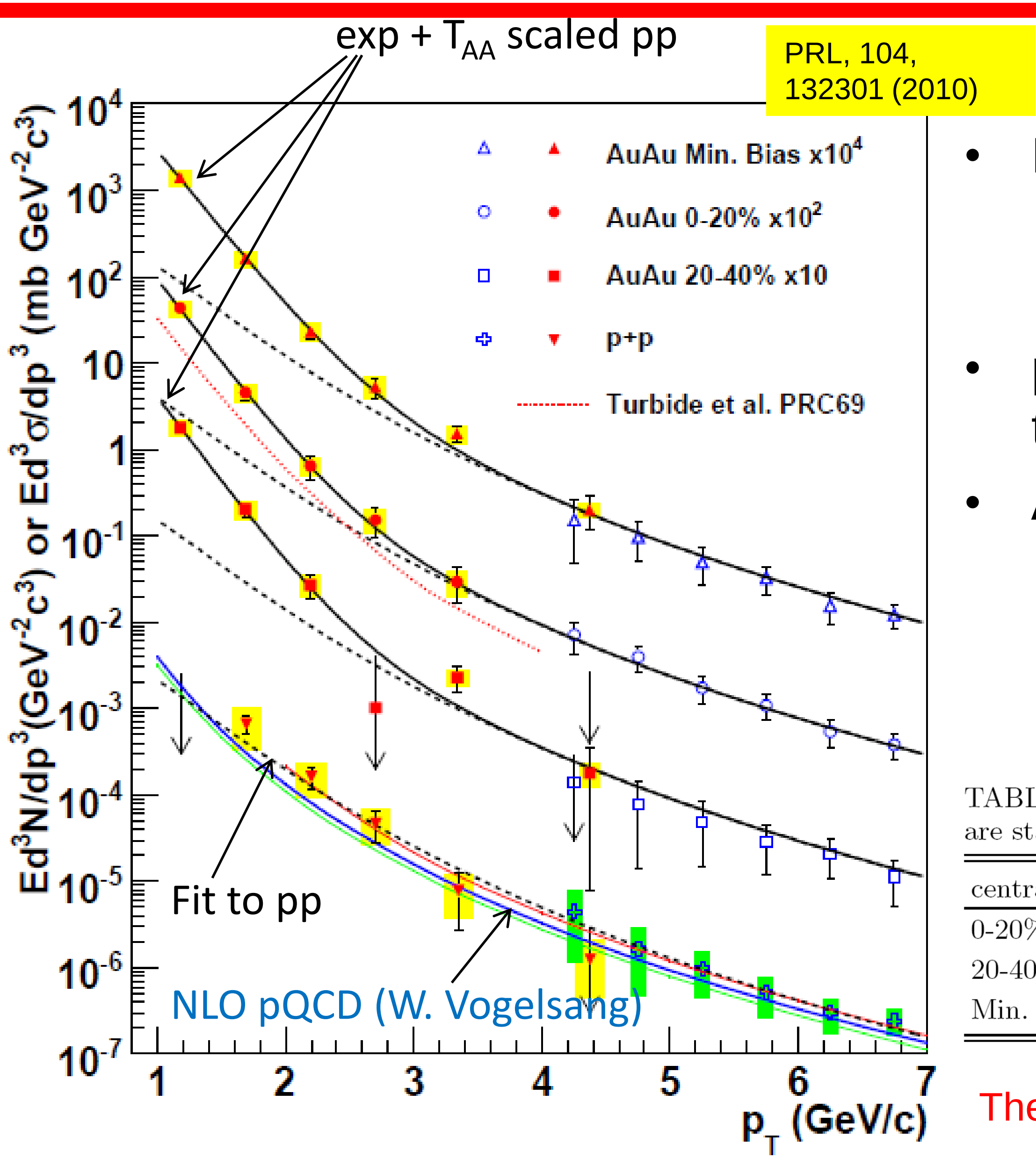
- Consistent with NLO pQCD (gluon compton)

Au+Au

- Clear excess above pQCD (thermal γ ?)

NLO pQCD calculation with 3 different scales by Werner Vogelsang

Direct photon spectra



- Direct photon measurements
  - real (p_T>4GeV)
  - virtual (1<p_T<5GeV)
- pQCD consistent with p+p down to p_T=1GeV/c
- Au+Au = “scaled p+p” + “expon”:

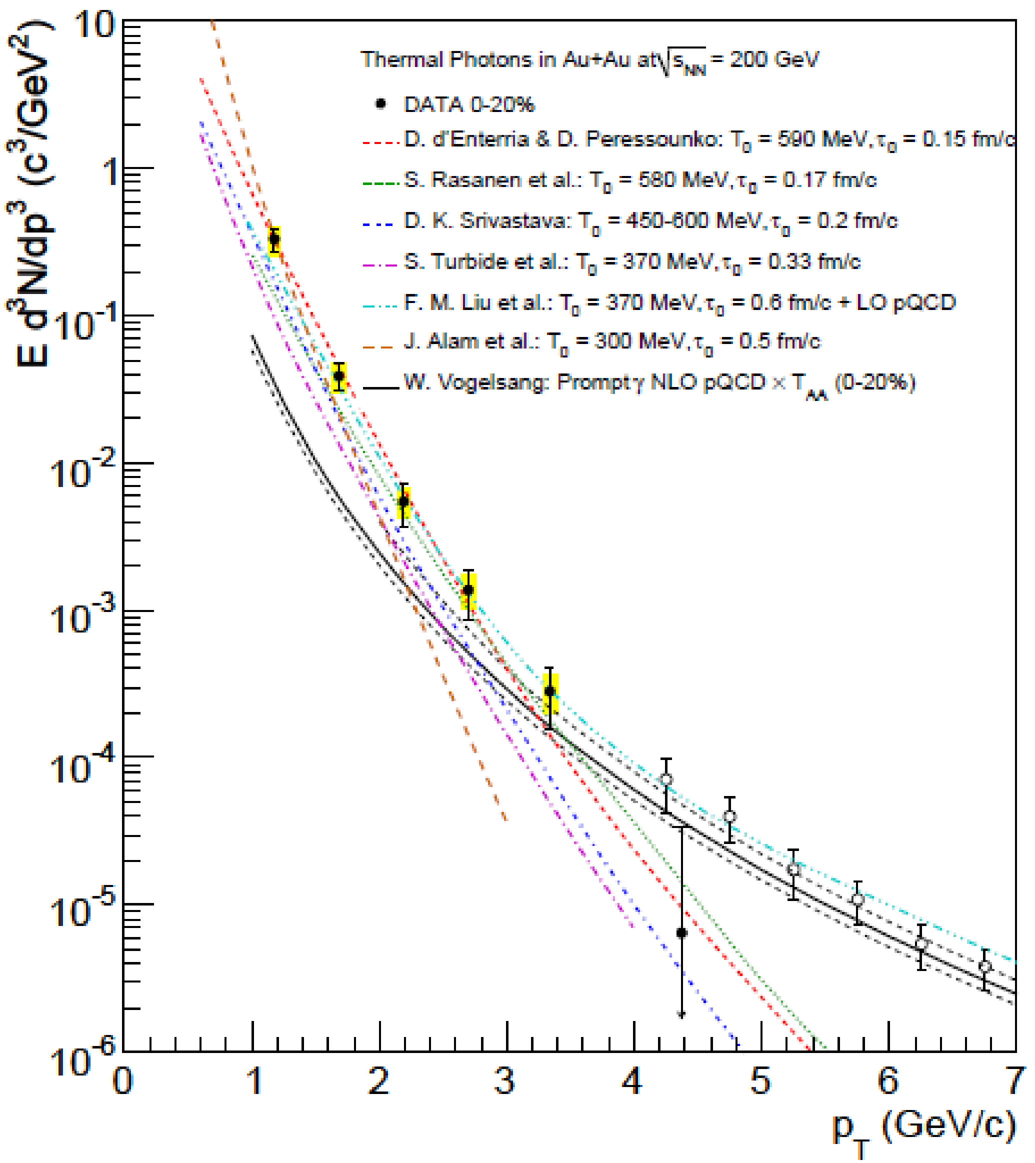
$$f_{Au+Au}(p_T) = \frac{N_{\text{coll}}}{\sigma_{\text{NN}}^{\text{inel}}} \times f_{p+p}(p_T) + B \times e^{-\frac{p_T}{T}}$$

TABLE I: Summary of the fits. The first and second errors are statistical and systematic, respectively.

centrality	$dN/dy(p_T > 1\text{GeV}/c)$	T(MeV)	χ^2/DOF
0-20%	$1.50 \pm 0.23 \pm 0.35$	$221 \pm 19 \pm 19$	4.7/4
20-40%	$0.65 \pm 0.08 \pm 0.15$	$217 \pm 18 \pm 16$	5.0/3
Min. Bias	$0.49 \pm 0.05 \pm 0.11$	$233 \pm 14 \pm 19$	3.2/4

The inverse slope T_{AuAu} > T_c ~ 170 MeV

Theory comparison



Hydrodynamical models are compared with the data

D.d'Enterria &D.Peressounko

T=590MeV, τ_0=0.15fm/c

S. Rasanen et al.

T=580MeV, τ_0=0.17fm/c

D. K. Srivastava

T=450-600MeV, τ_0=0.2fm/c

S. Turbide et al.

T=370MeV, τ_0=0.33fm/c

J. Alam et al.

T=300MeV, τ_0=0.5fm/c

F.M. Liu et al.

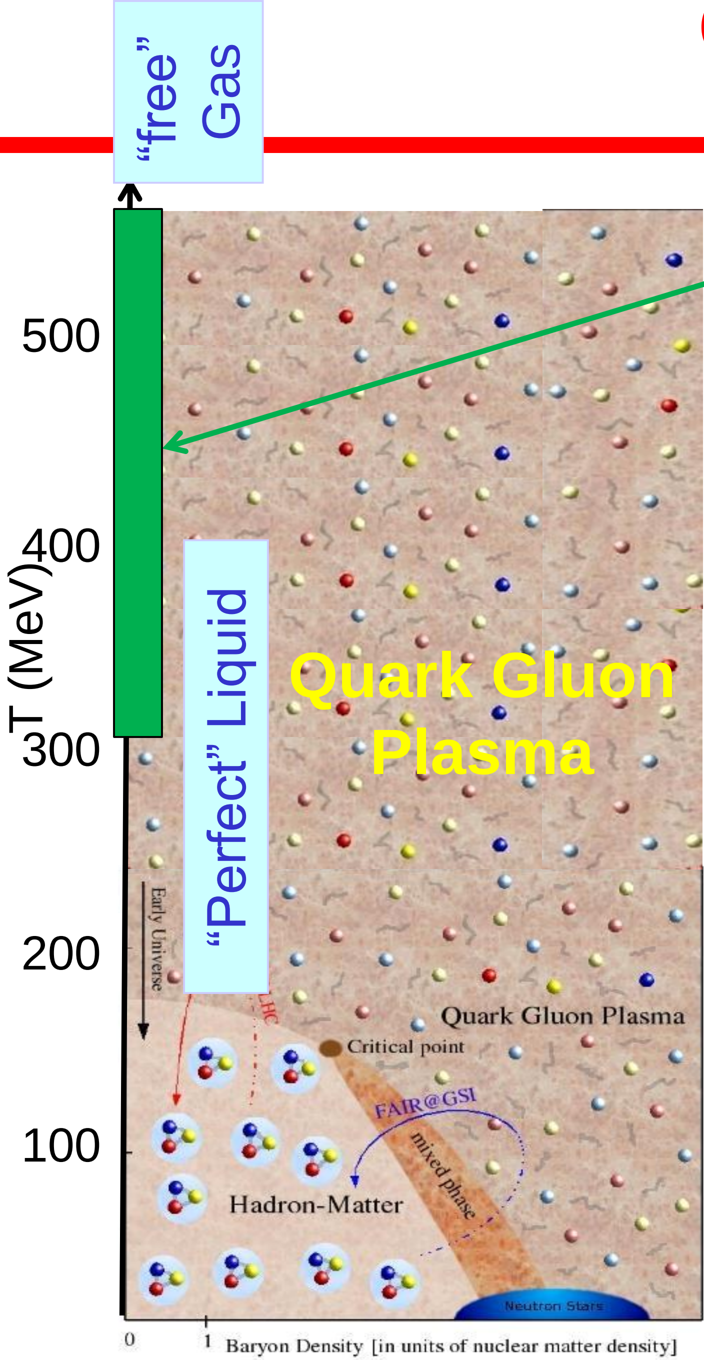
T=370MeV, τ_0=0.6 fm/c

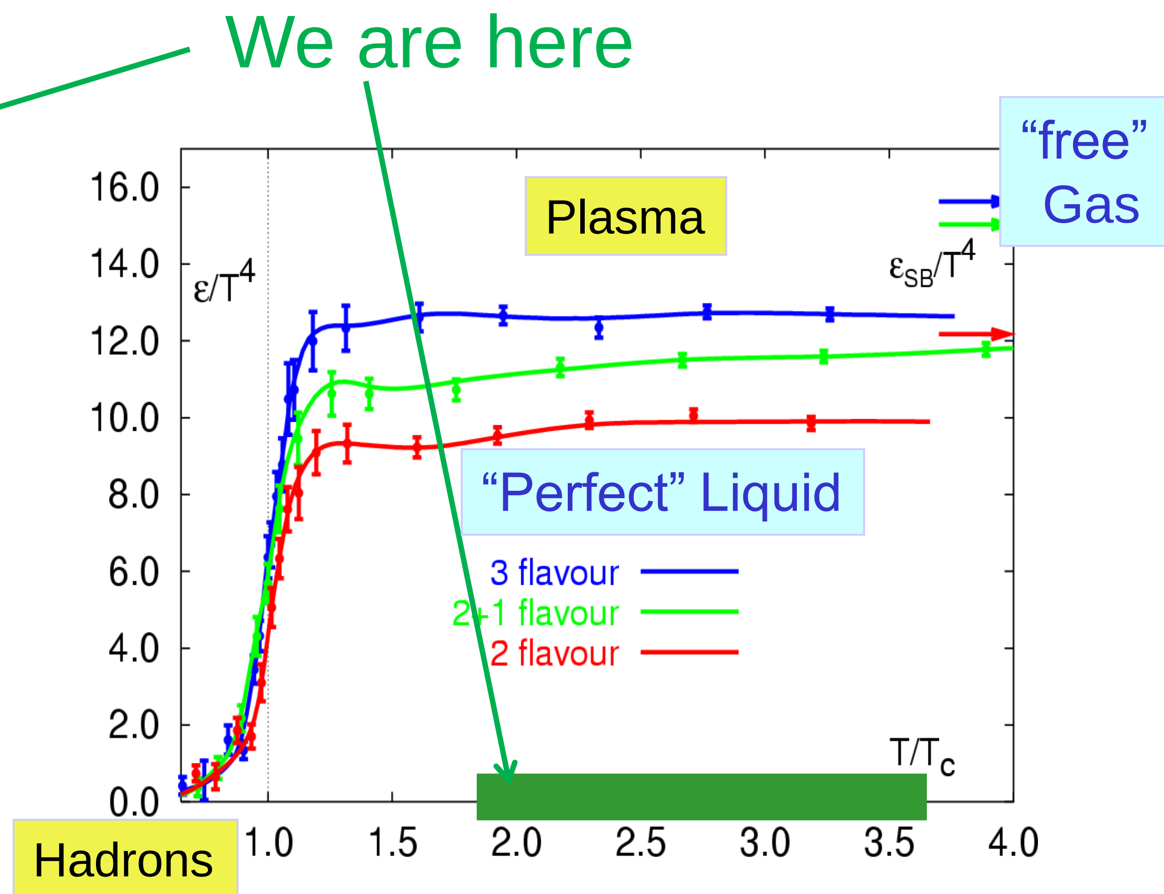
Hydrodynamical models are in qualitative agreement with the data

Comparison with models

- Direct photon yield in p+p is consistent with pQCD, but direct photon yield in Au+Au is much larger.
- If direct photons in Au+Au are of thermal origin, the inverse slope is related to the initial temperature T_{init} .
- Hydrodynamical models with T_{init}=300-600MeV at the plasma formation time t_0=0.6-0.15 fm/c are in qualitative agreement with the data. T_{init} is about 1.5 to 3.0 time T_{avg} due to the space time evolution.
- Lattice QCD predicts a phase transition to quark gluon plasma at T_c ~ 170 MeV

On the Map





T_c ~ 170 MeV; ε ~ 1 GeV/fm^3

At these temperature, QGP is *"perfect" liquid.*

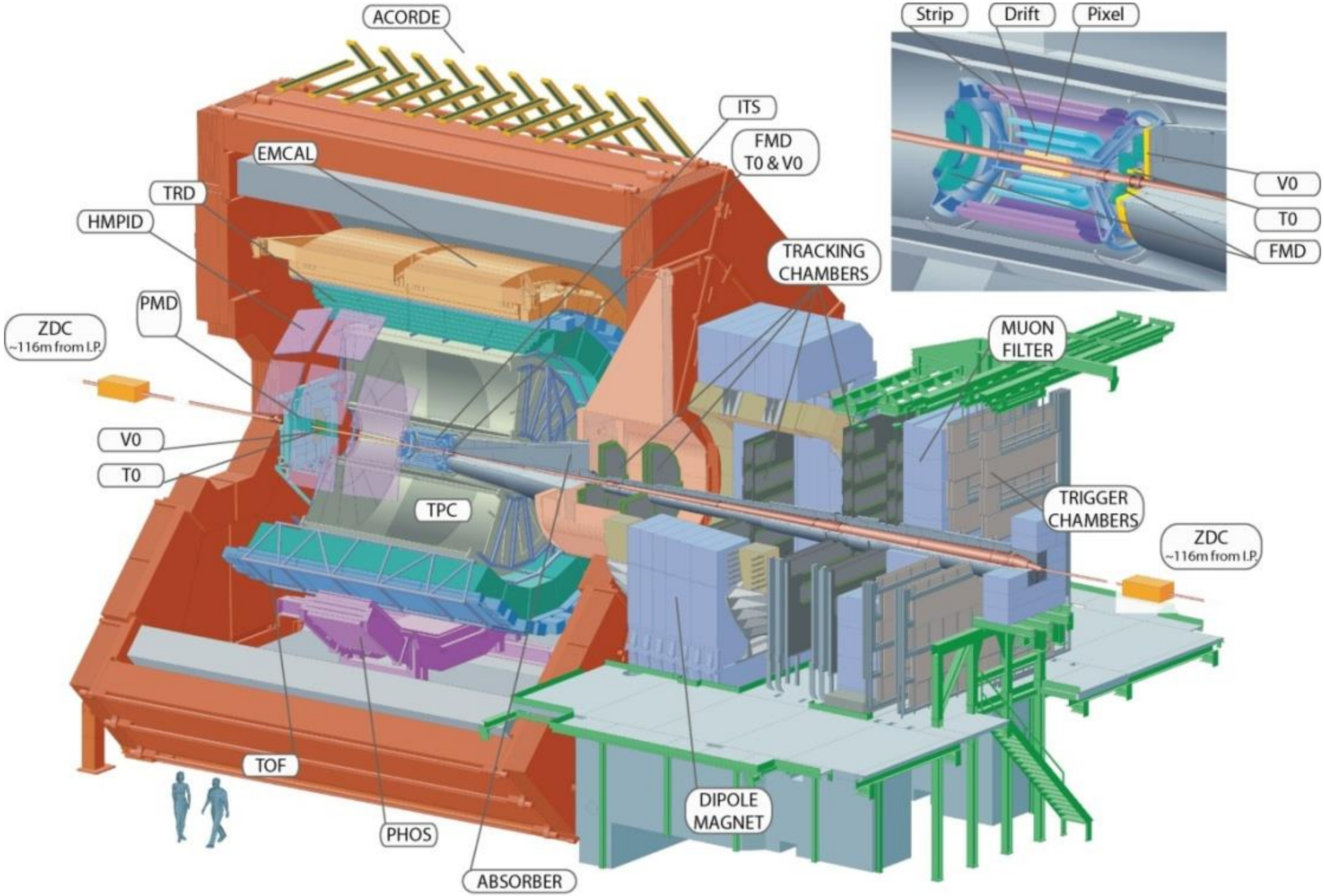
At higher temperature, it can become *"gas"*

To study even hotter QCD matter…

ALICE
(A Large Ion Collider Experiment)
at LHC

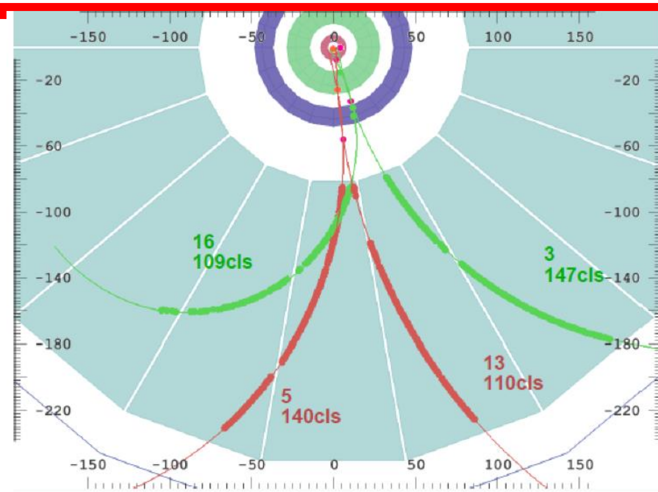

LHC
SPS
ALICE

ALICE: The dedicated HI Experiment



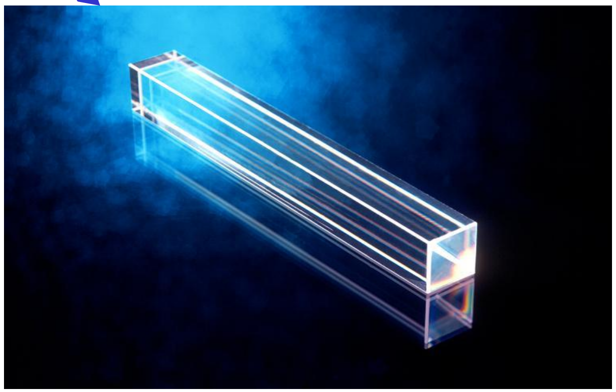
Photon and electron PID

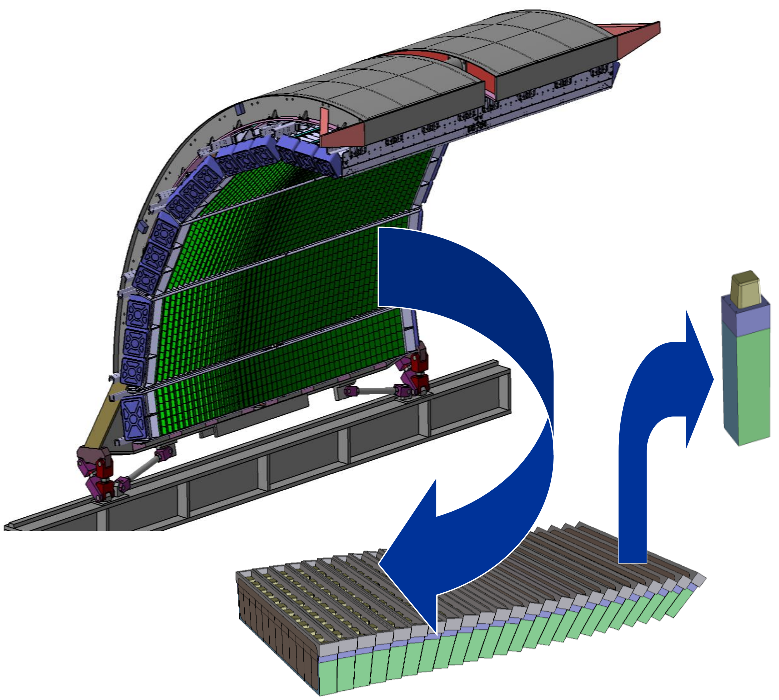
Electrons (or virtual photons):
ITS (dE/dx)
TPC (dE/dx)
TOF (β)
TRD (Transition Radiation)
EMCAL(EM shower)
PHOS(EM shower)



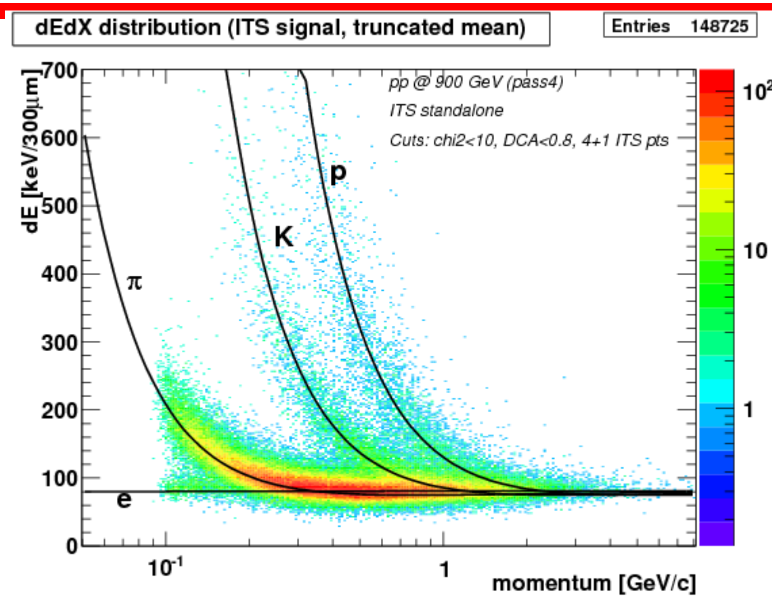
h-> $\gamma+\gamma$ -> $e^+e^-e^+e^-$

Photons:
EMCAL(Pb/Sc Shashlik)
PHOS (lead-tungstate crystals, $PbWO_4$):
High granularity and resolution to focus on low and moderate p_T

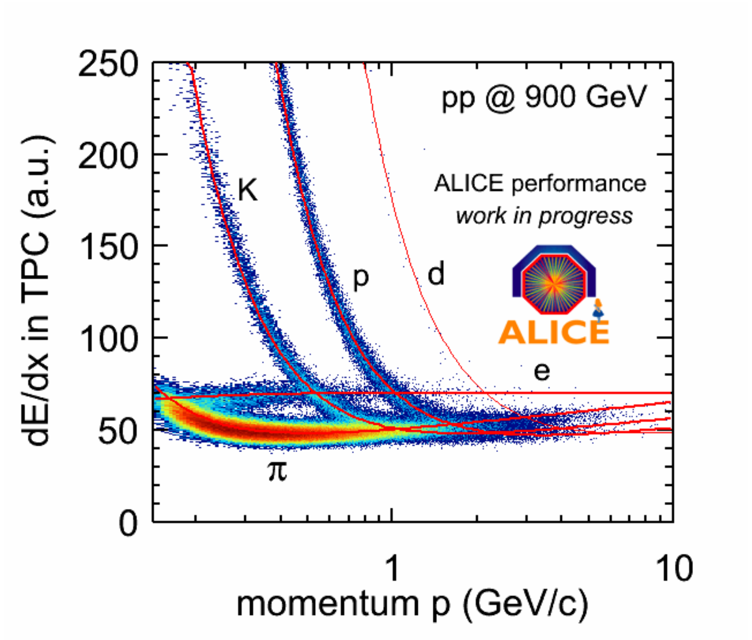


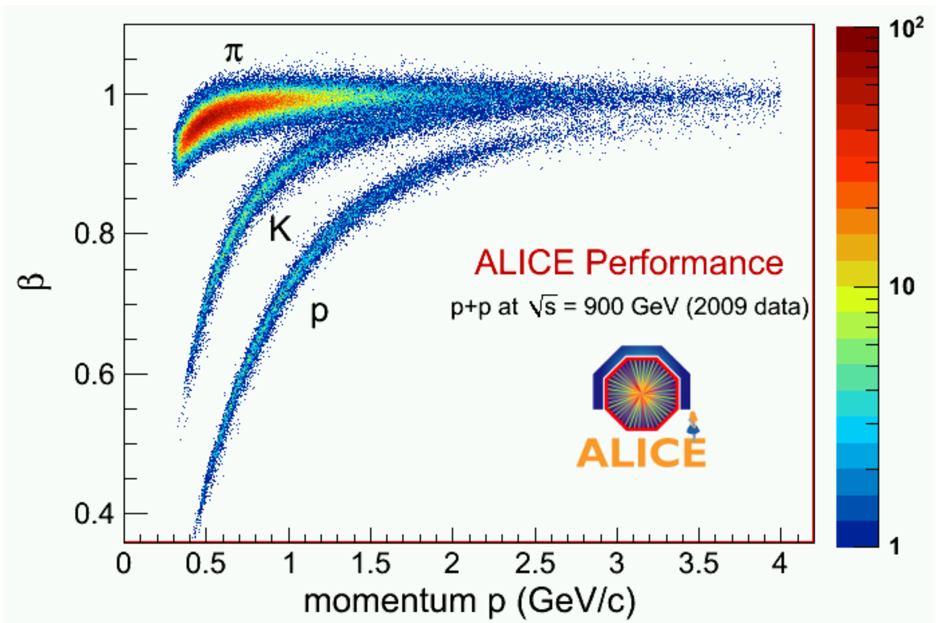


Low p_T electron PID

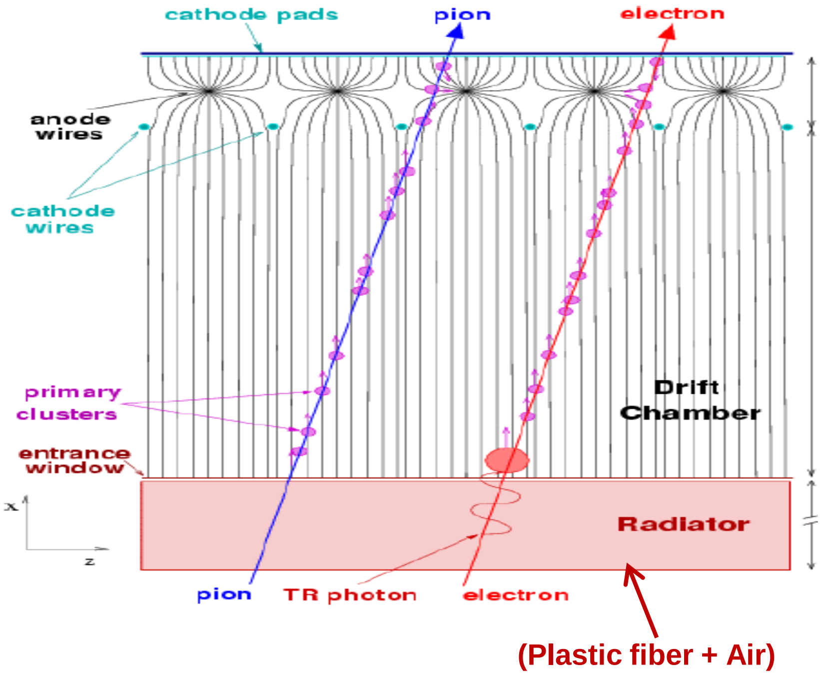


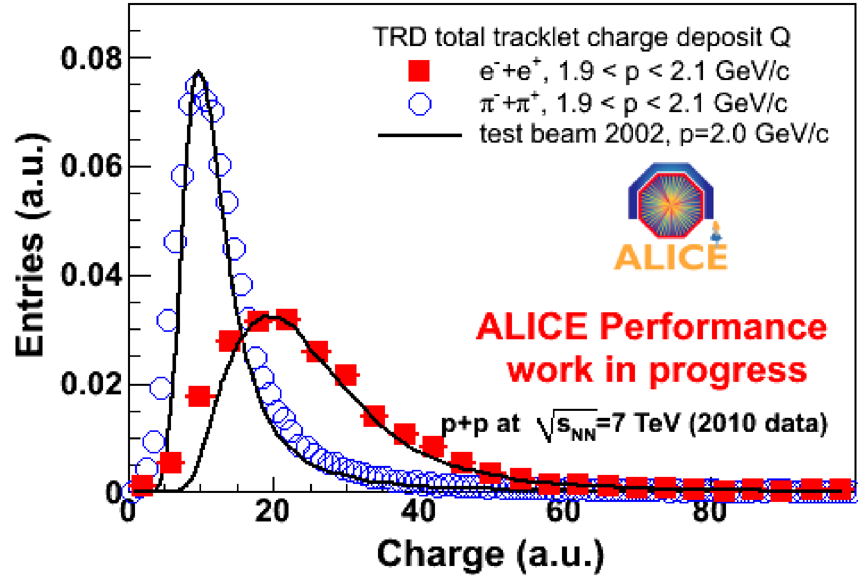
- ITS (dE/dx)
- TPC (dE/dx)
- TOF(β to reject non-electron tracks)

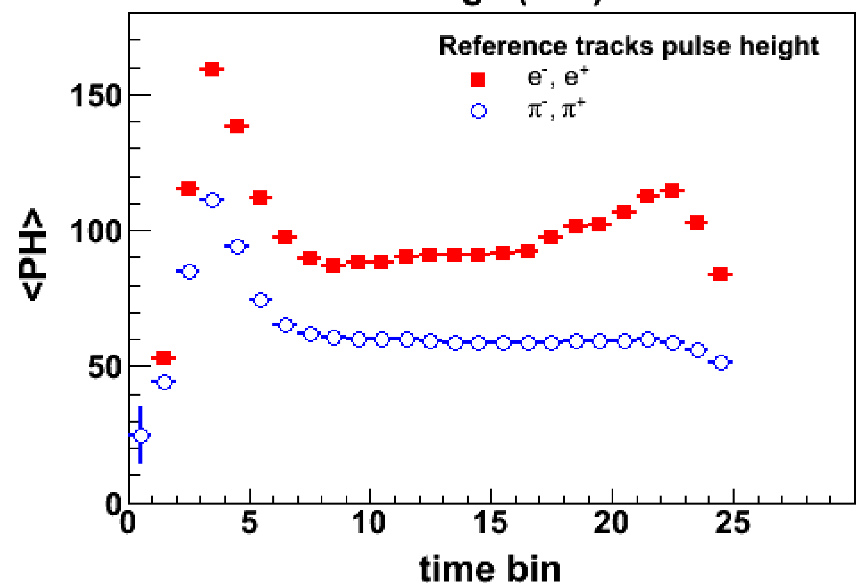




TRD for high p_T electron PID

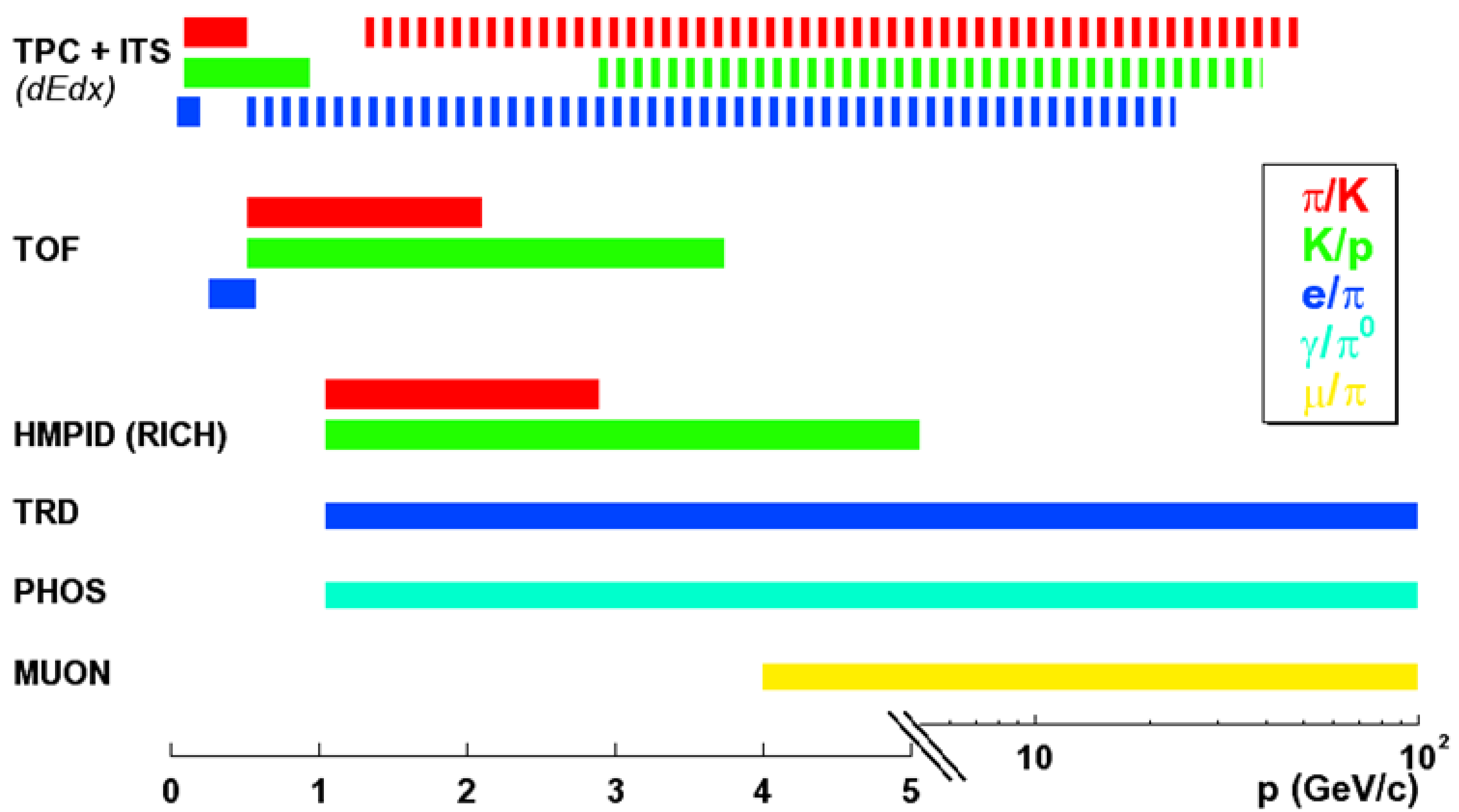




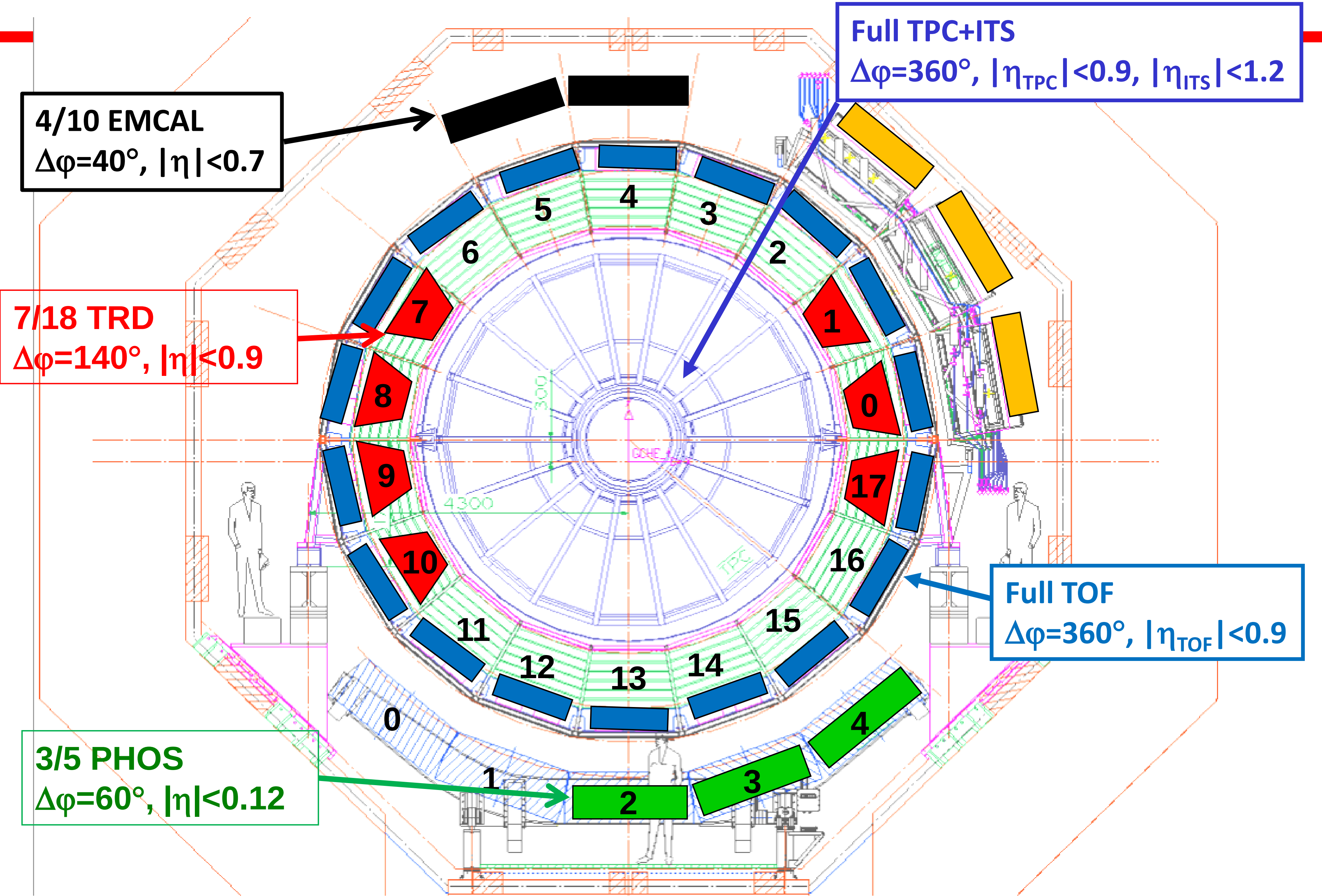


- Transition radiation (TR) is produced if a highly relativistic (γ>900) particle traverses many boundaries between materials
- 7 TRD modules currently installed
- Due to limited acceptance currently **not included in PID for dielectrons**

PID in ALICE


TPC + ITS
(dEdx)
TOF
HMPID (RICH)
TRD
PHOS
MUON
π/K
K/p
e/π
γ/π⁰
μ/π
0
1
2
3
4
5
10
10²
p (GeV/c)

ALICE setup for 2010



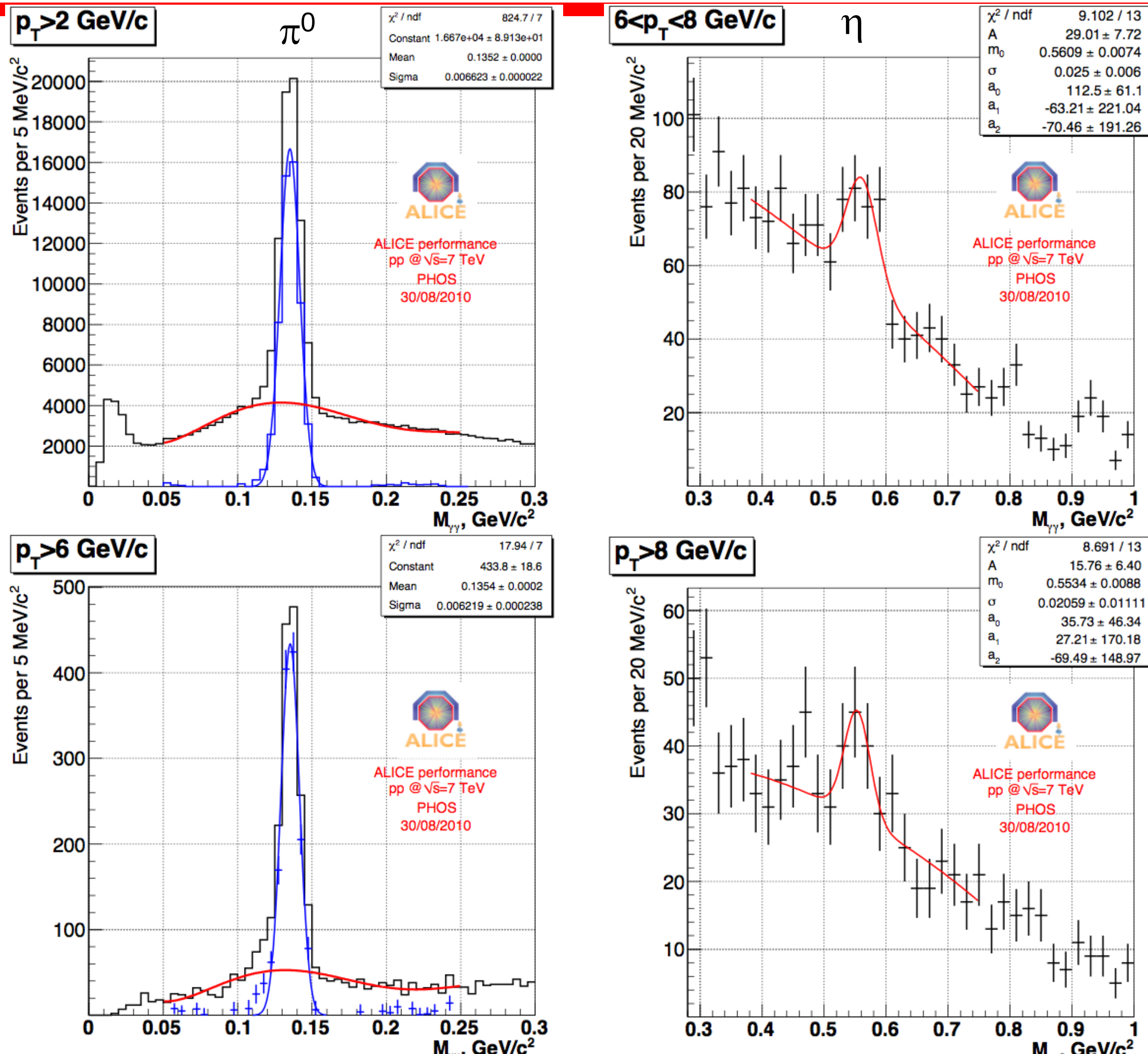
Neutral meson measurement in ALICE

- ALICE provides 3 independent ways to identify π^0 and η mesons, through invariant mass analysis of photon pairs and external conversion electrons:
  - H-> $\gamma + \gamma$ (both on PHOS or EMCAL)
  - H-> $\gamma + \gamma$, $\gamma \rightarrow e^+e^-$ (CTS, PHOS or EMCAL)
  - H-> $\gamma + \gamma$, $\gamma \rightarrow e^+e^-$, $\gamma \rightarrow e^+e^-$ (CTS: ITS,TPC,TRD,TOF)

- Performance plots, p+p at 7 TeV, coming next

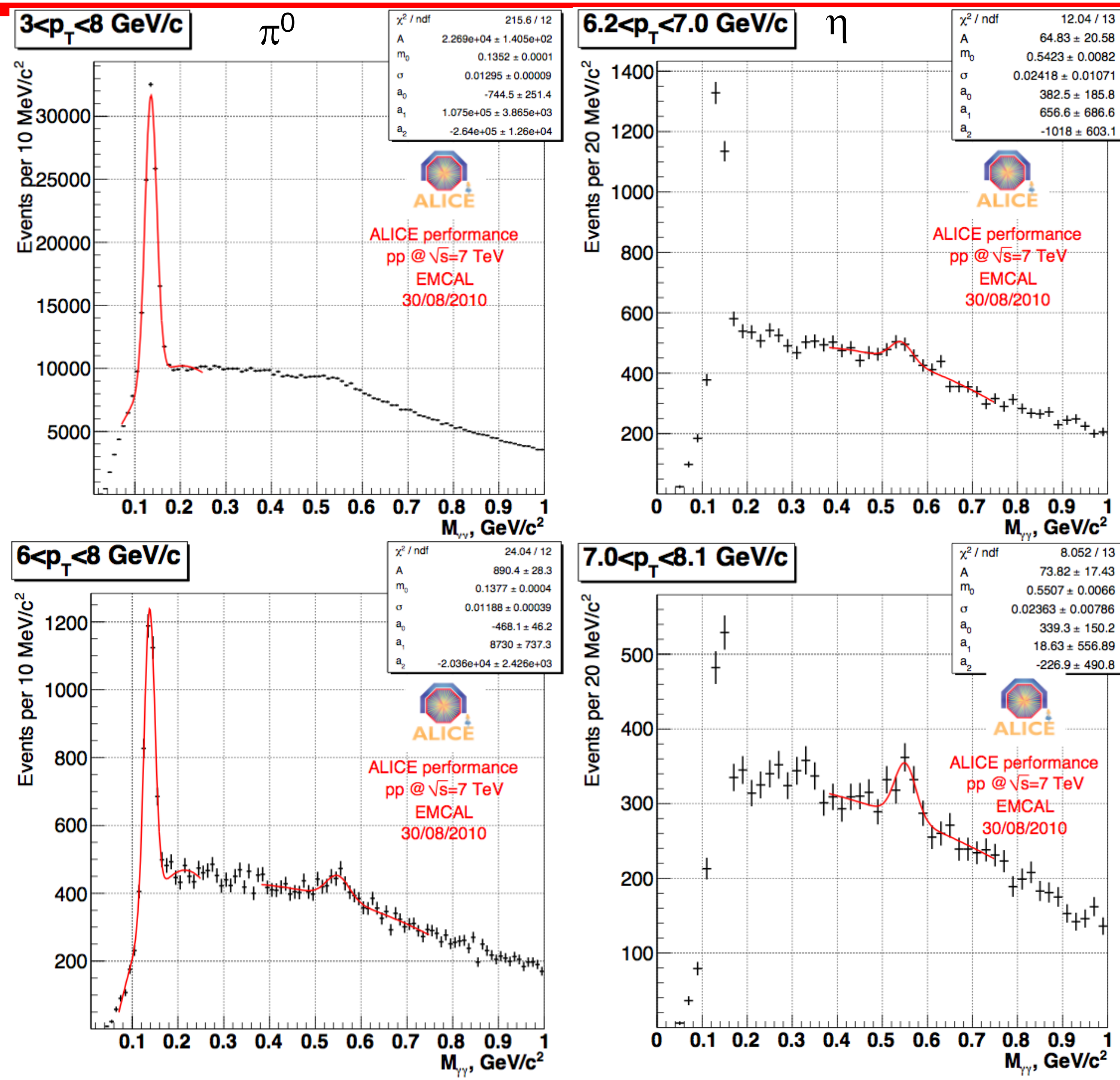
PHOS h-> γ+γ

- 175 million minimum bias events.
- Cluster selection (better tuning under study).
  - E_{cl}>0.3 GeV
  - $N_{cell} \geq 3$
- π^0 plots lines:
  - Red line: fit to combinatorial.
  - Blue points: histogram minus combinatorial fit.
  - Blue line: - fit of blue points.



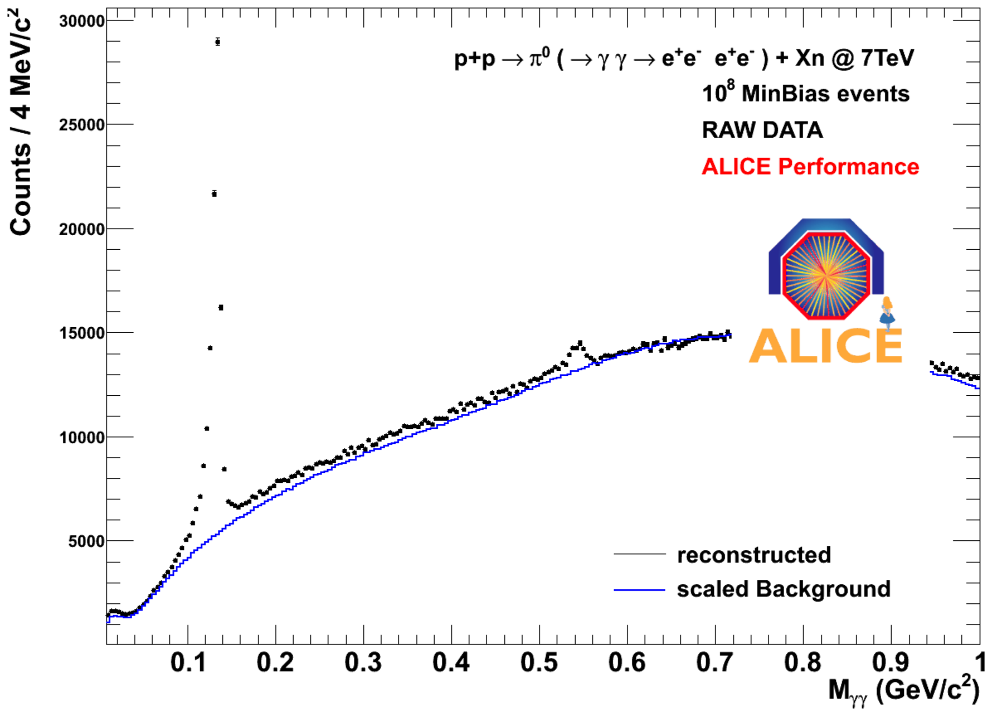
EMCAL h-> γ+γ

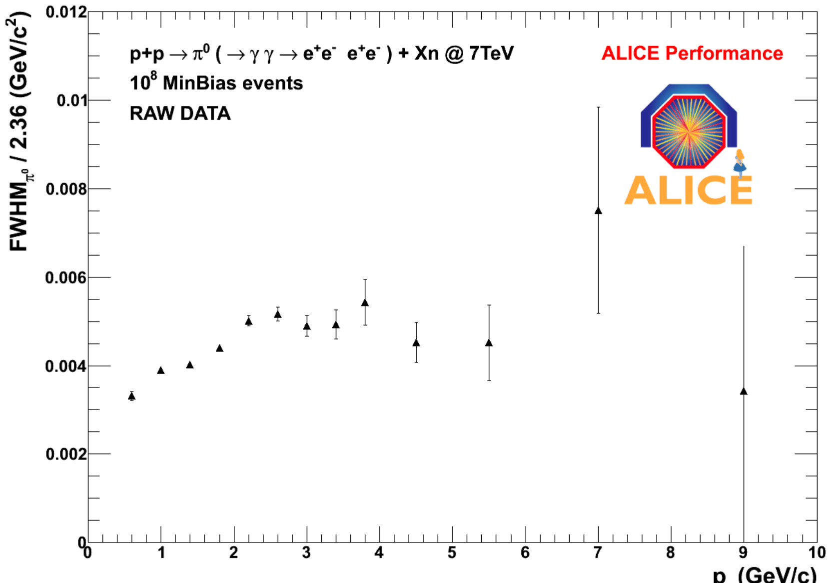
- 188 million minimum bias events.
- Cluster selection (better tuning under study)
  - E_{cl}>0.3 GeV
  - $N_{cell}\geq 2$

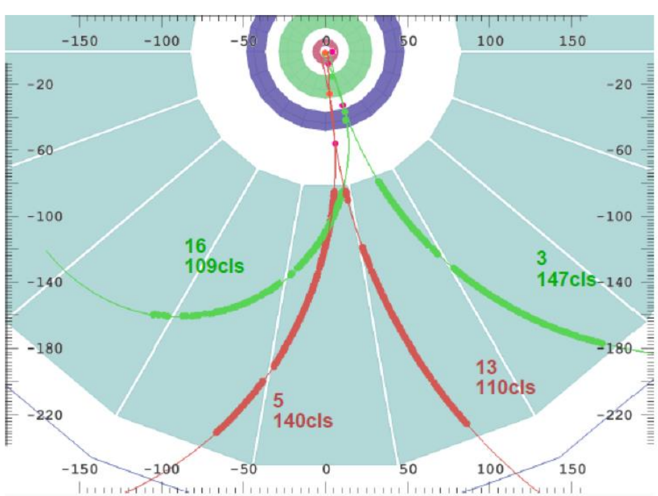


CTS h-> γ+γ -> $e^+e^-e^+e^-$

- For p_T > 1 GeV
  - Photon conversion probability of about 8%
  - Photon reconstruction efficiency is of 70% with close to 100% purity

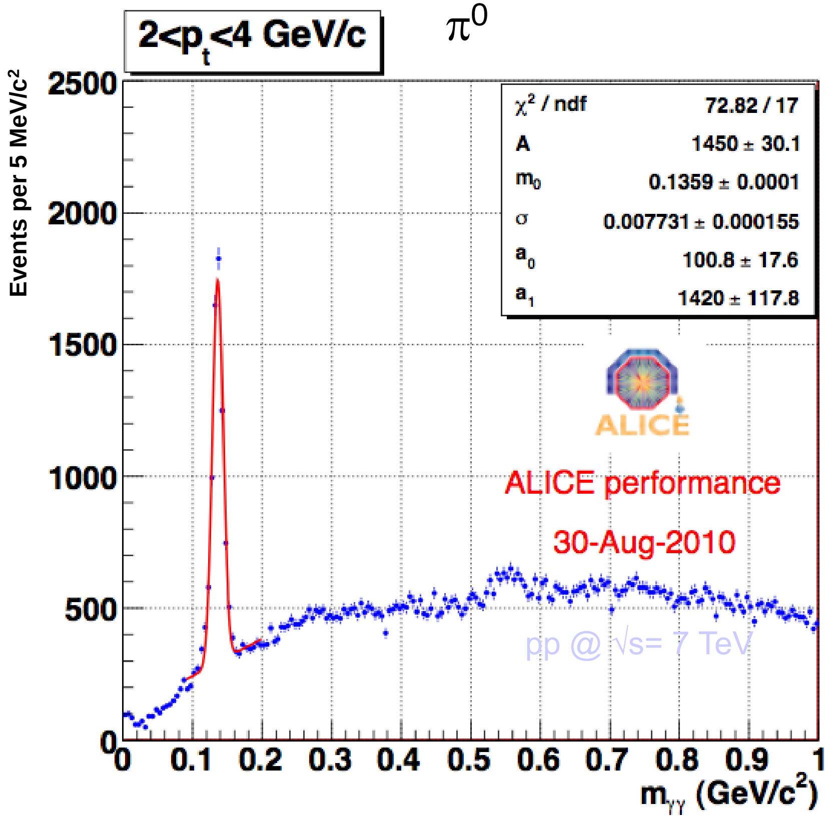




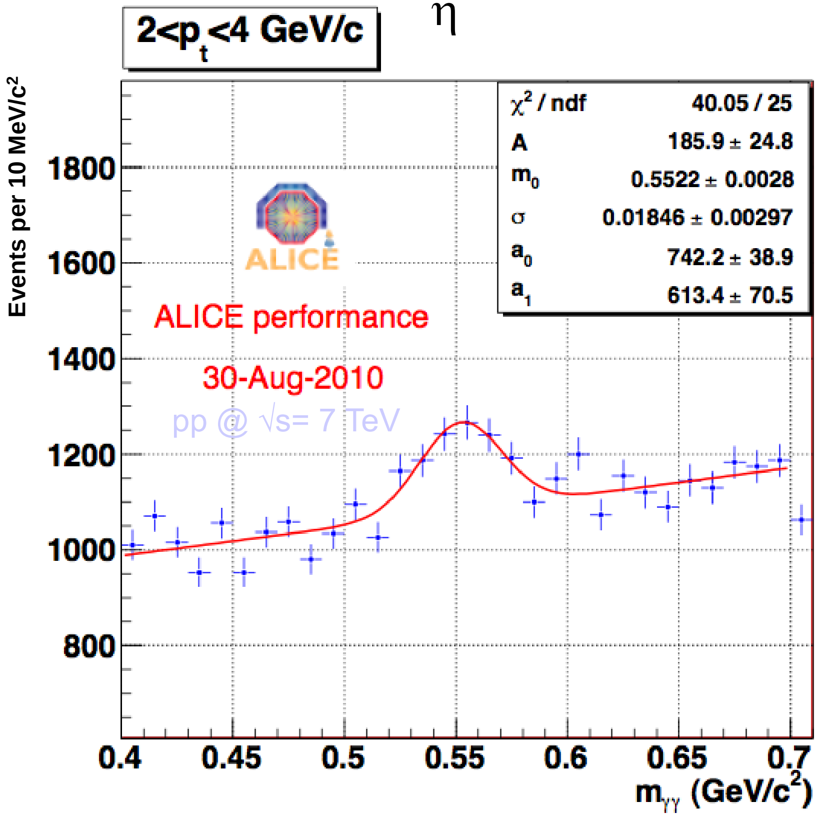


PHOS-CTS h-> $\gamma+\gamma$ -> $e^+e^-\gamma$

π^0



η



140 million p+p events at 7 TeV

π^0 can be identified with p_T>0.5 GeV/c
η is visible with p_T>2 GeV/c

Summary and outlook

- ALICE has identified π^0 and η neutral mesons with its calorimeters and central tracking system.

- The agreement between the analysis seems to converge, but work is needed, specially on calibration and non linearity effects in the calorimeters.

- We expect to measure π^0 in the range $0.3 < p_T < 30$ GeV and η in the range $0.6 < p_T < 10$ GeV in very near future.

- Direct photon measurement can be followed after understanding the photon backgrounds from hadron decays, so needs measured hadron spectra for the cocktail method.

“Possible” HI plan at LHC

Studying QGP Era (MB)

2010 (official)-$\sqrt{s_{NN}}$ = 2.76 TeVPb+ Pb(4 weeks) L~1025$cm^{-2}s^{-1}$
2011 (anticipated)-$\sqrt{s_{NN}}$ = 2.76 TeVPb+ Pb(4 weeks) L ~ few 1026$cm^{-2}s^{-1}$
2012 (official)–Shutdown for maintenance, installation & repair
2013-$\sqrt{s_{NN}}$ = 5.5 TeV Pb+ Pb, L~1027$cm^{-2}s^{-1}$
2014-$\sqrt{s_{NN}}$ = 5.5 TeV Pb+ Pb, L~1027$cm^{-2}s^{-1}$

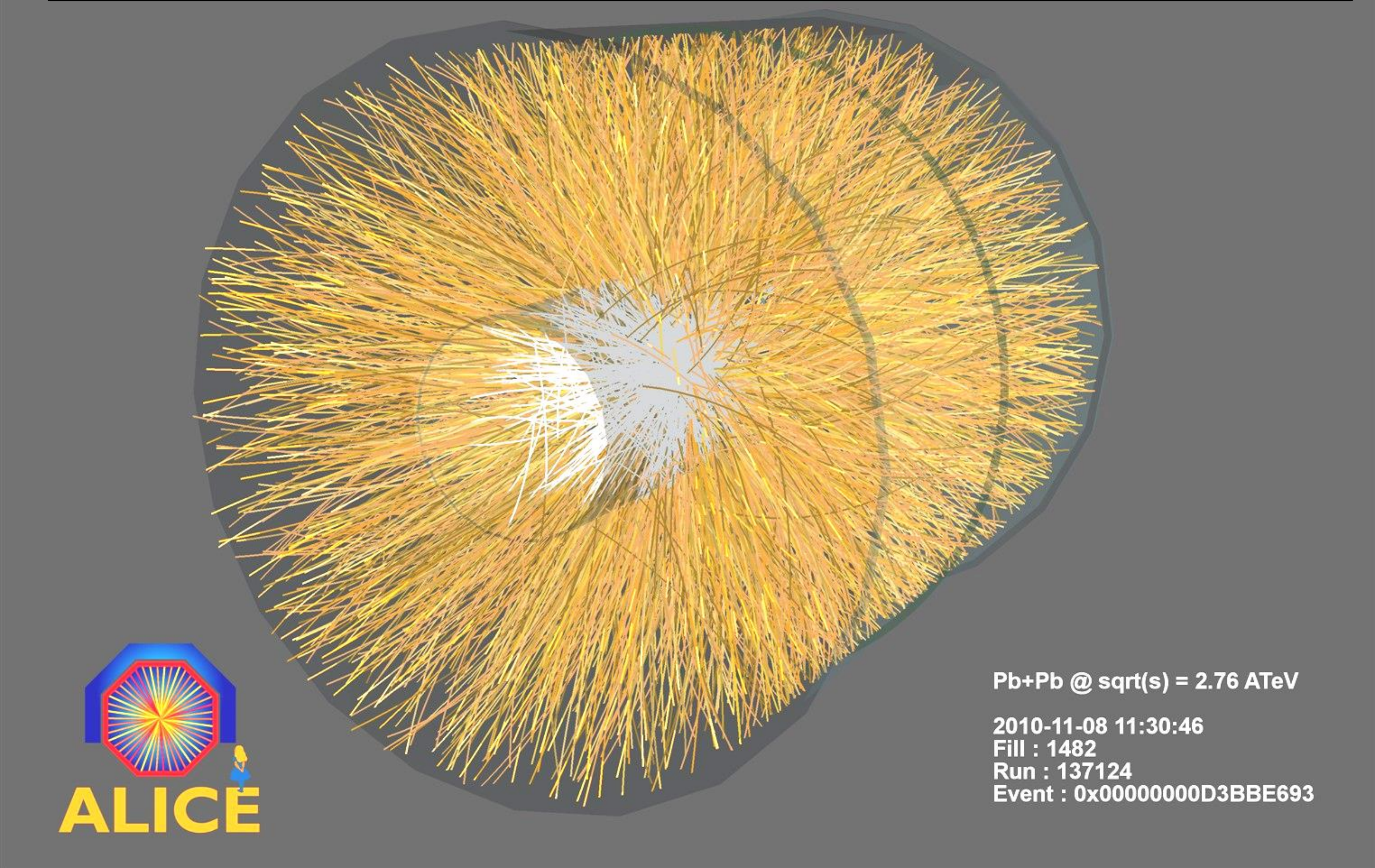
Control experiments

2015–$\sqrt{s_{NN}}$ = 8.8 TeV p + Pb & Pb+ p or lighter A + A
2016–Shutdown –LINAC4 /Collimation/RF & detector upgrade
2017–$\sqrt{s_{NN}}$ = 5.5 TeV lighter A + A or $\sqrt{s_{NN}}$= 8.8TeV p+Pb/Pb+p

Detail Studying Era (rare probes)

2018–$\sqrt{s_{NN}}$ = 5.5 TeV high L Pb+ Pb for hard probe physics
2019–$\sqrt{s_{NN}}$ = 5.5 TeV high L Pb+ Pb for hard probe physics
2020–Shutdown–…. upgrades

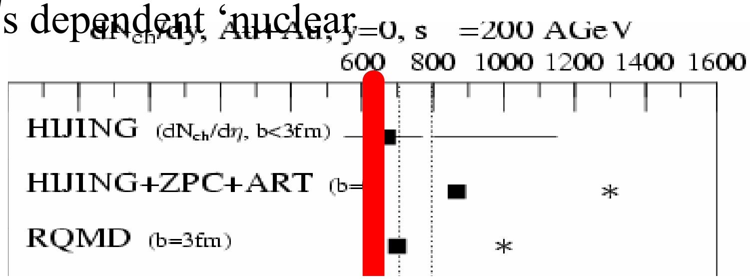
‘Little Bang’

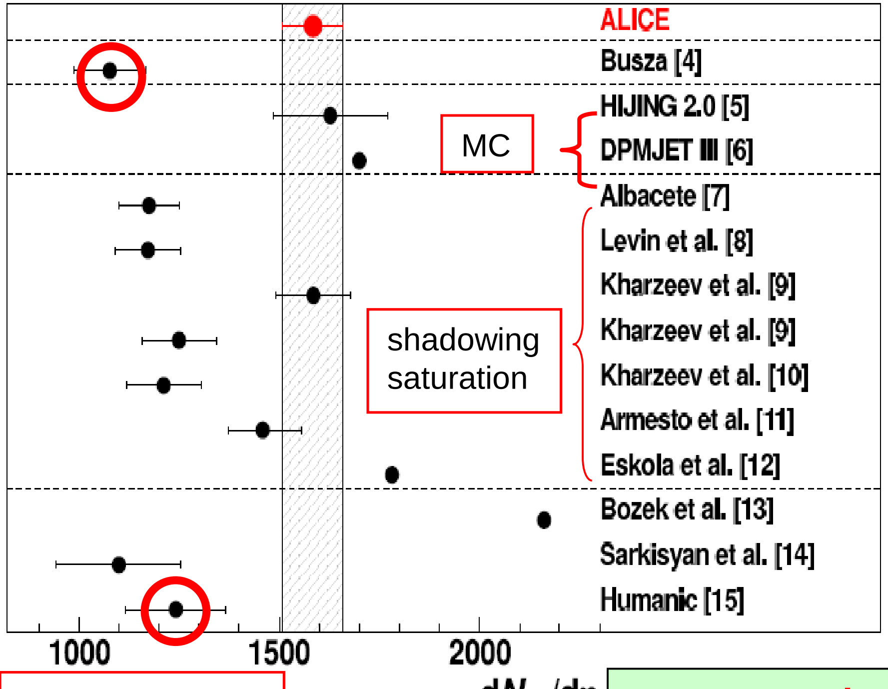

Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
ALICE

1) What's the Difference ?

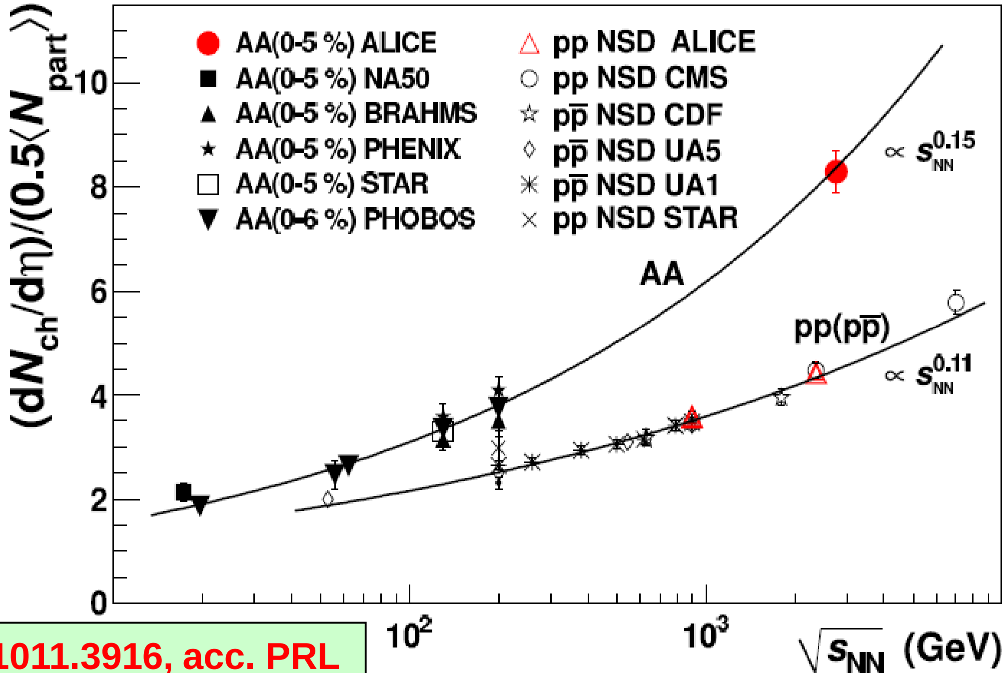
- Multiplicity and Energy density ε:
  - **$dN_{ch}/d\eta \sim 1600 \pm 76$ (syst)**
    - somewhat on high side of expectations
    - growth with √s faster in AA than pp (√s dependent 'nuclear amplification')
  - **Energy density ≈ 3 x RHIC** (fixed τ)
    - lower limit, likely τ_0(LHC) < τ_0(RHIC)

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



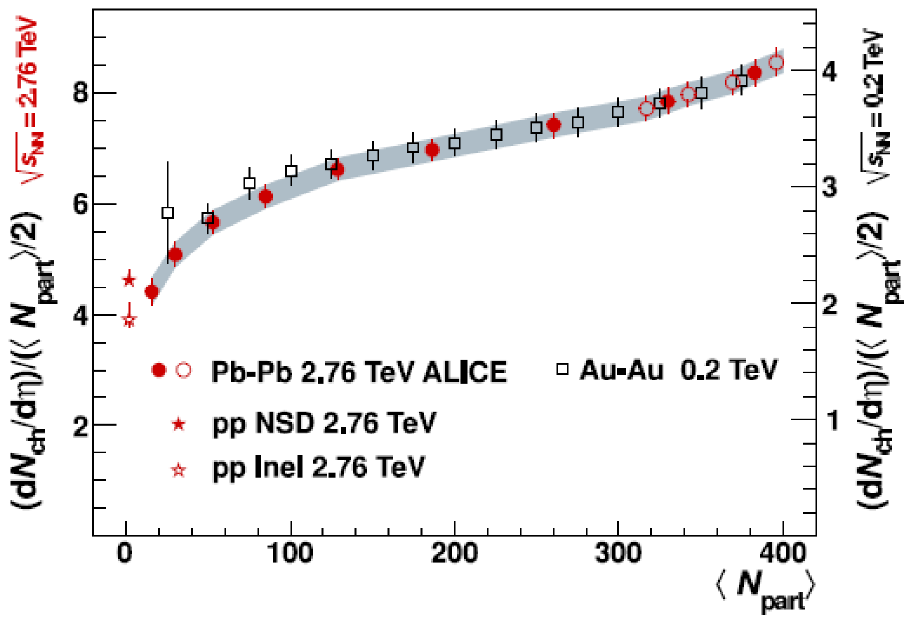


pp extrapolations

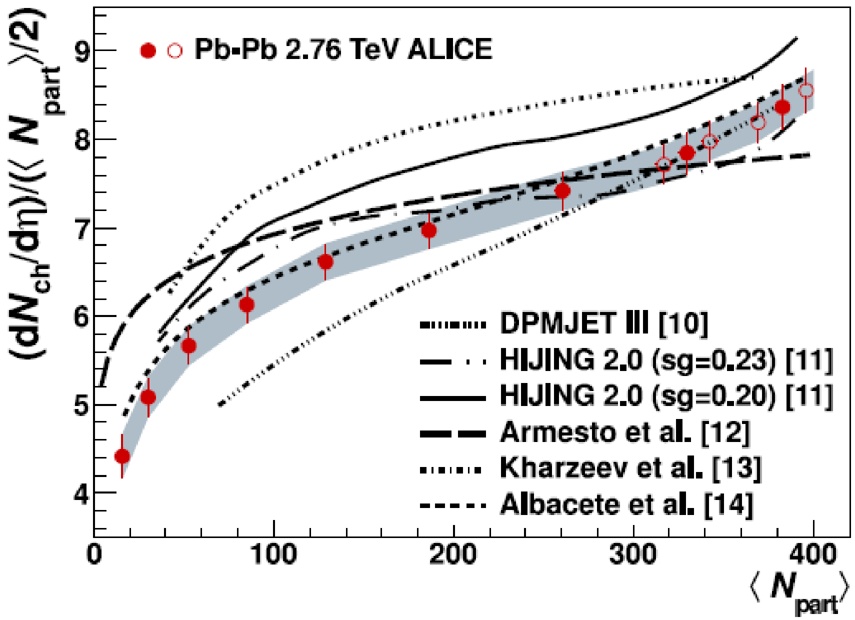


17 Nov: arXiv:1011.3916, acc. PRL

Centrality dependence



Dependence of (dNch/dη) / (Npart/2) on the number of participants:



Comparison of (dNch/dη) / (Npart/2) with model calculations

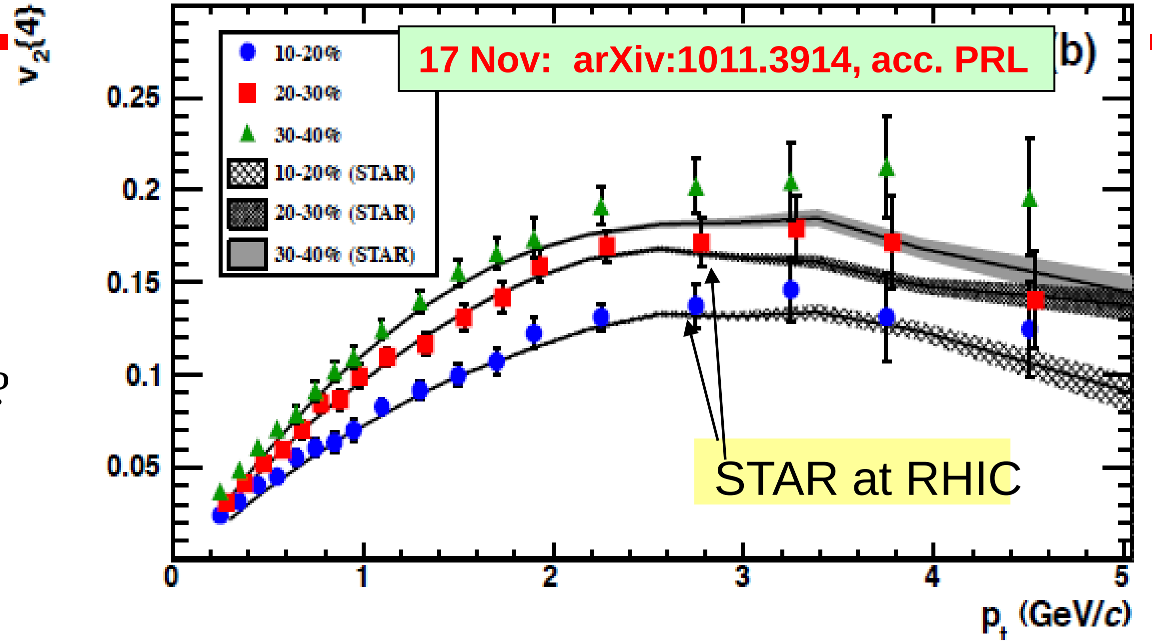
The ratio of scales on left and right = 2.1.
Non-single-diffractive (elastic and single-diffractive events removed) and inelastic pp value by interpolating between data at 2.36 and 7 TeV.
Point-to-point, uncorrelated uncertainties (error bars), correlated uncertainties grey band.
Statistical errors are negligible.

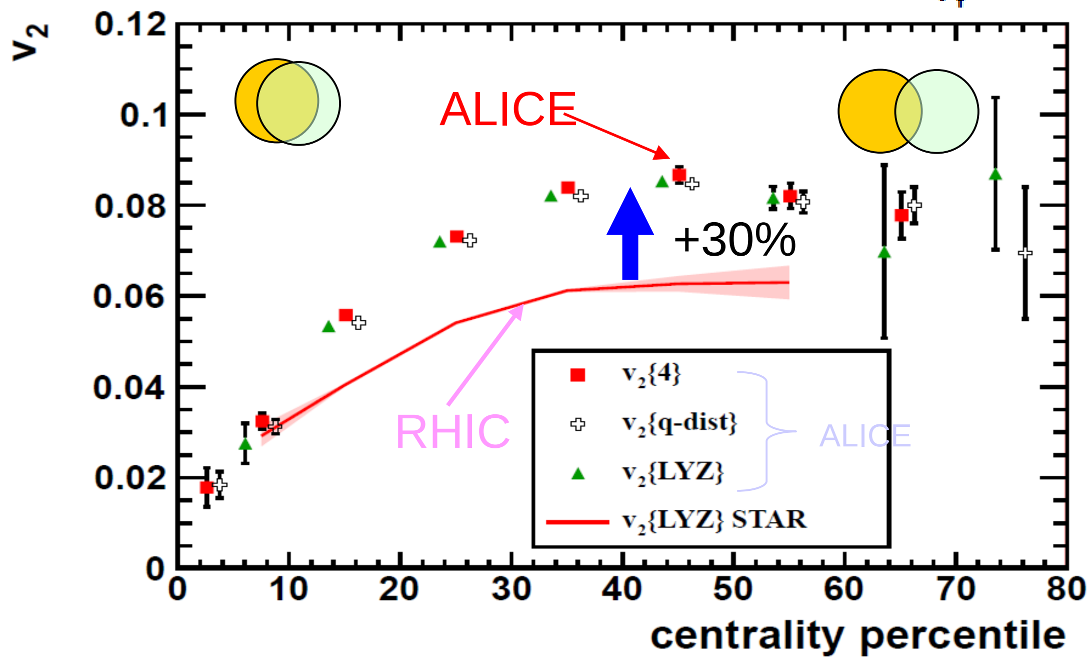
- Two broad categories of models:
  - Models combining pQCD processes (e.g. jets and mini-jets) with soft interactions.
  - Saturation models with various parametrizations for the energy and centrality dependence of the saturation scale.

8 Dec: arXiv:sub/0159822, sub. PRL

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**
  - $<p_t>$ increases with $\sqrt{s}$
    - pQCD powerlaw tail ?
  - Hydro predicts increased ‘radial flow’
    - very characteristic p_t and mass dependence; **to be confirmed !**

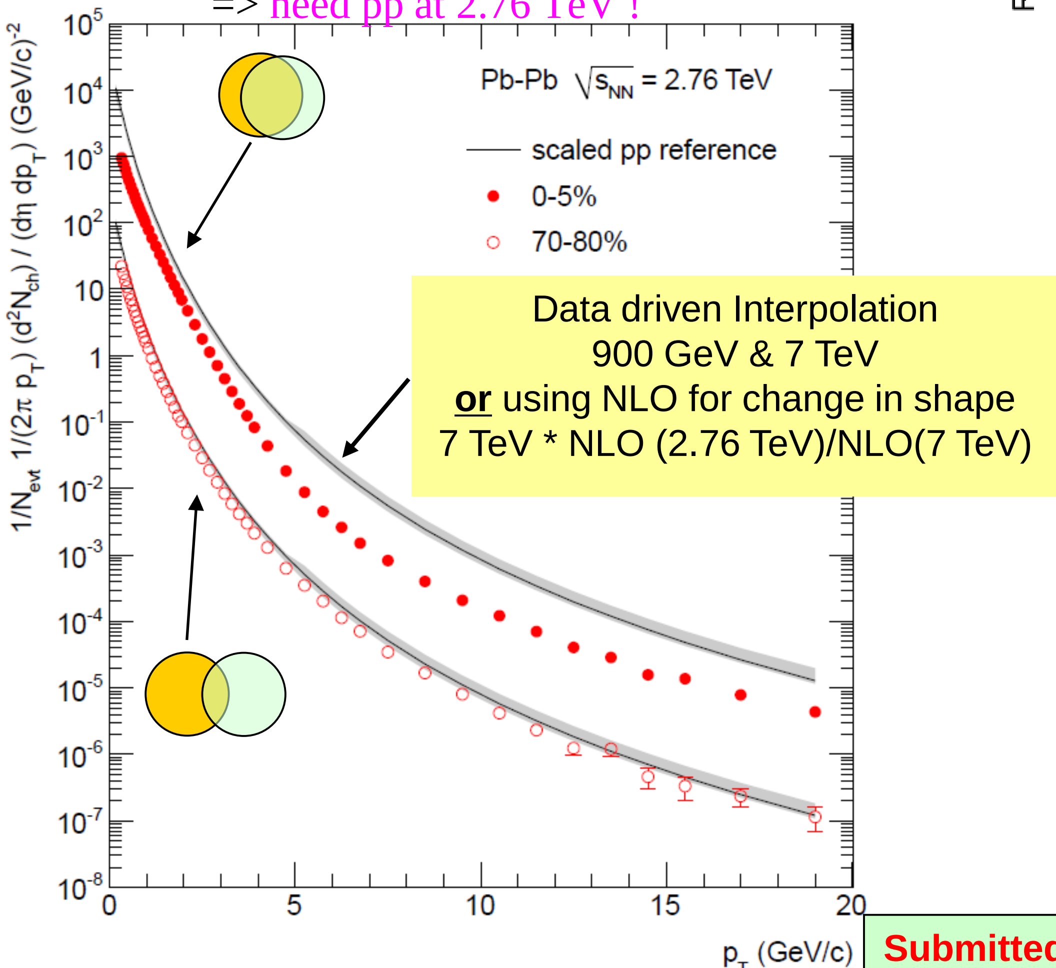


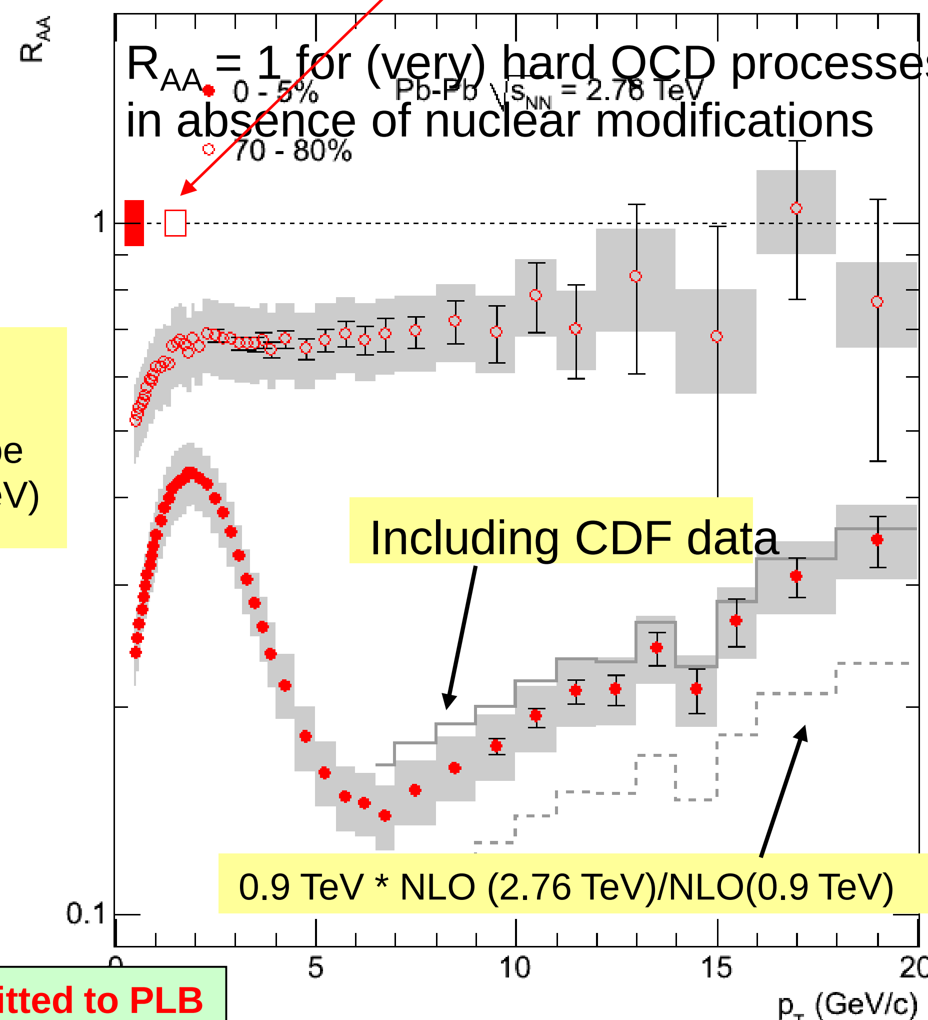


'Jet Quenching' as seen by p_t spectra

- Suppression of high p_t particles (~ leading jet fragments)
  - Minimum R_{AA} ~ 1.5 ~ 2 times smaller than at RHIC
  - Rising with p_t ! (ambiguous at RHIC !)
  - accuracy limited by pp reference
    => need pp at 2.76 TeV !

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

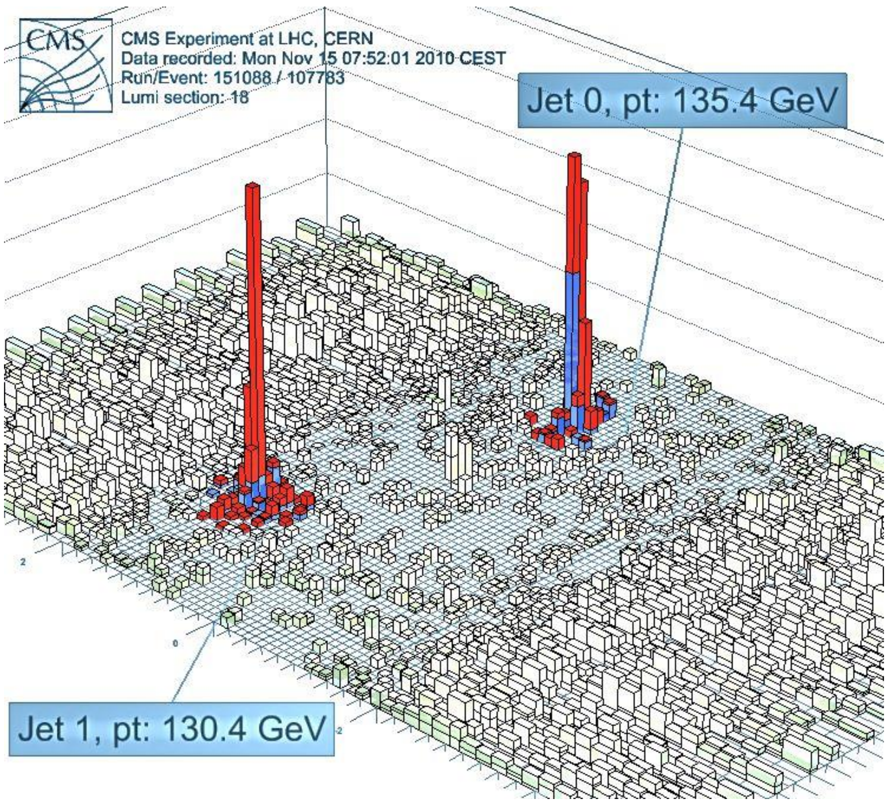


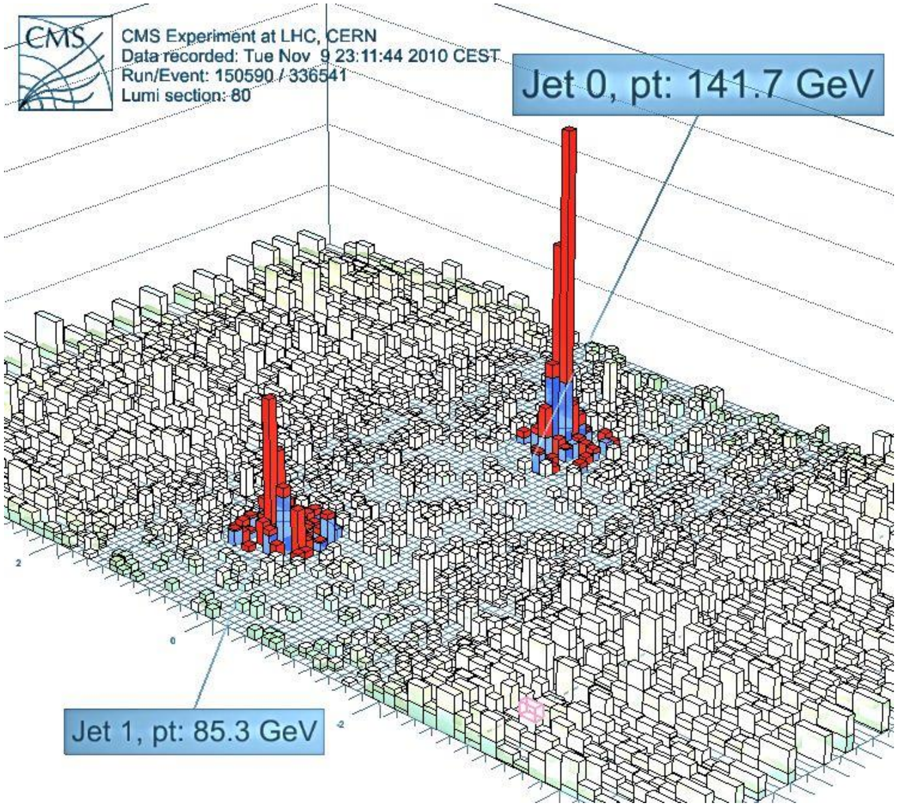


Submitted to PLB

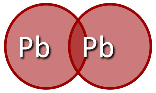
Dijet event candidates in CMS

- First hours of LHC running
  - We see dijet events
  - We see dijets with unbalanced energy: is this real?

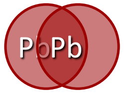




Dijet energy imbalance

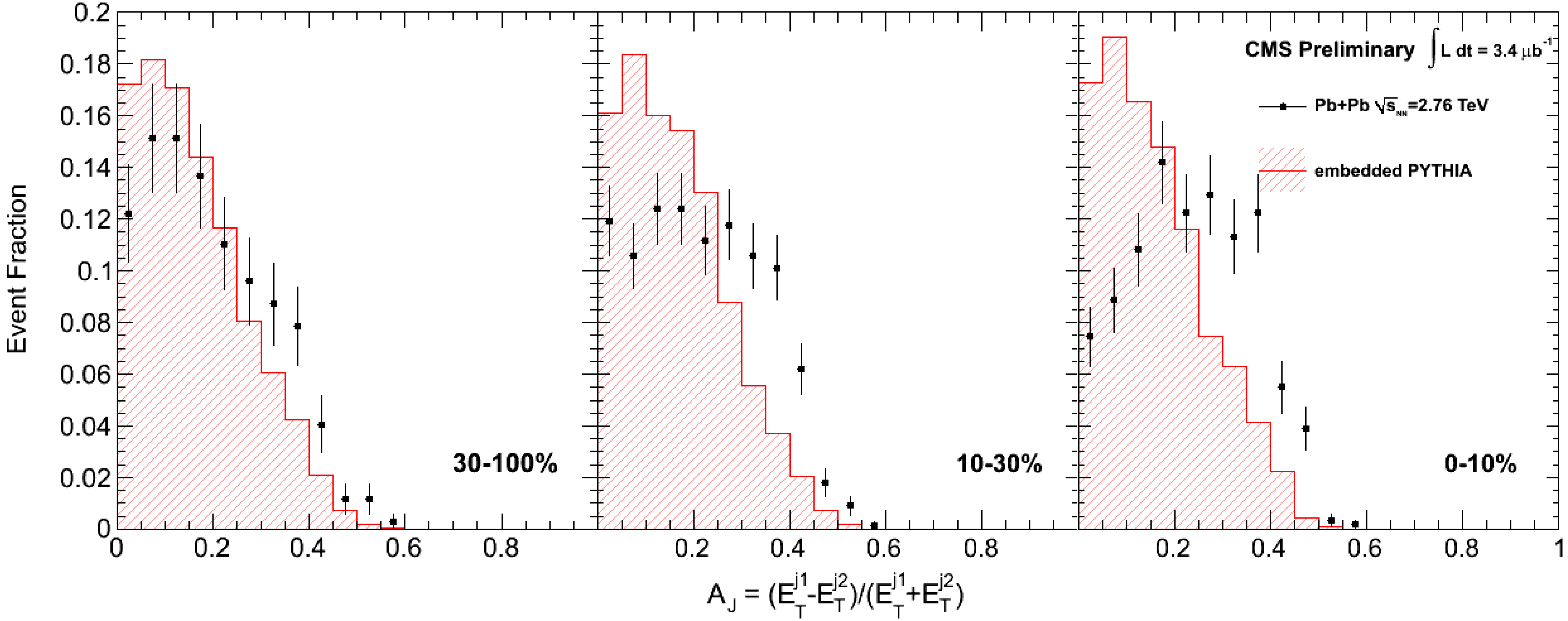


Semi-Peripheral



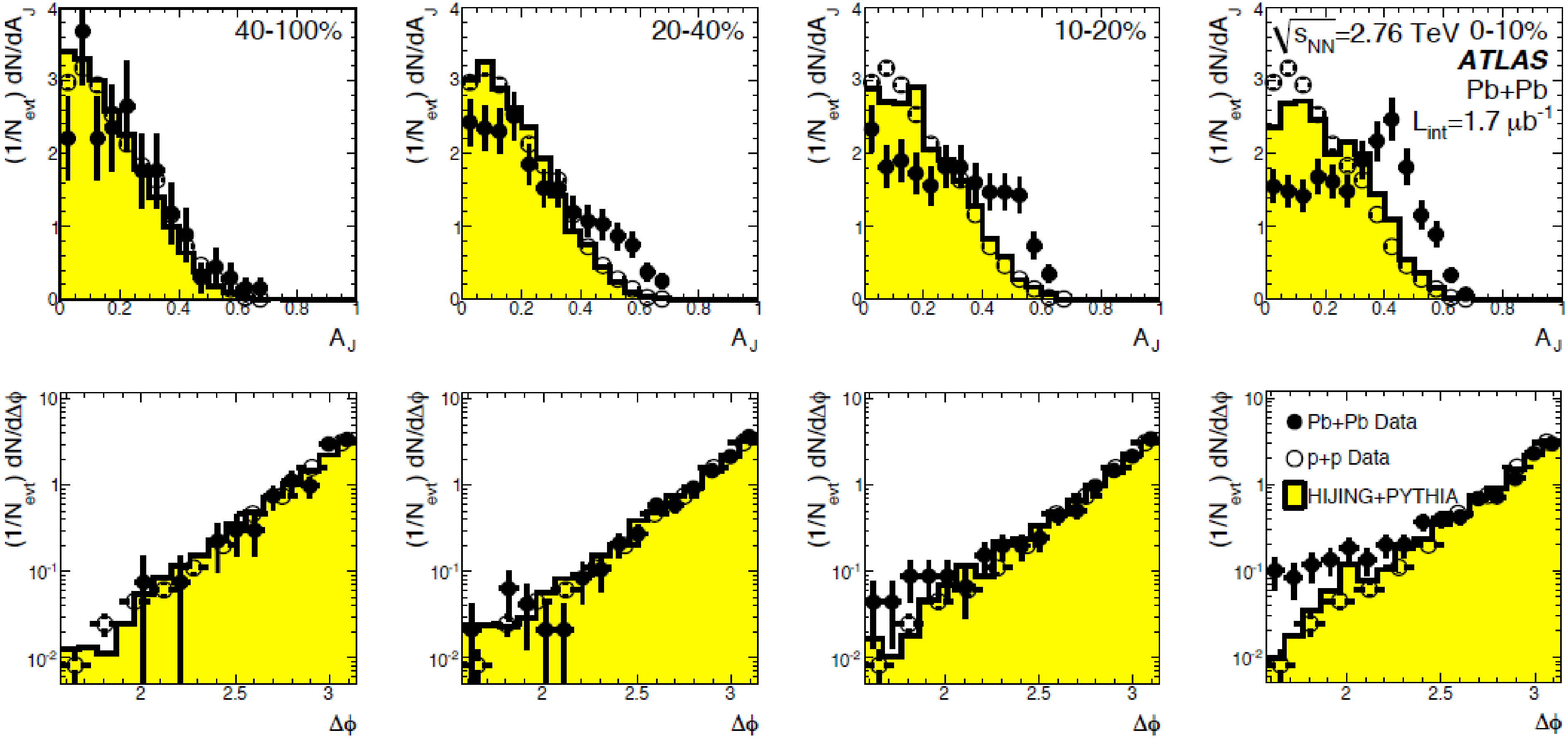
Semi-Central

Central



A significant dijet imbalance, well beyond that expected from unquenched MC, appears with increasing collision centrality

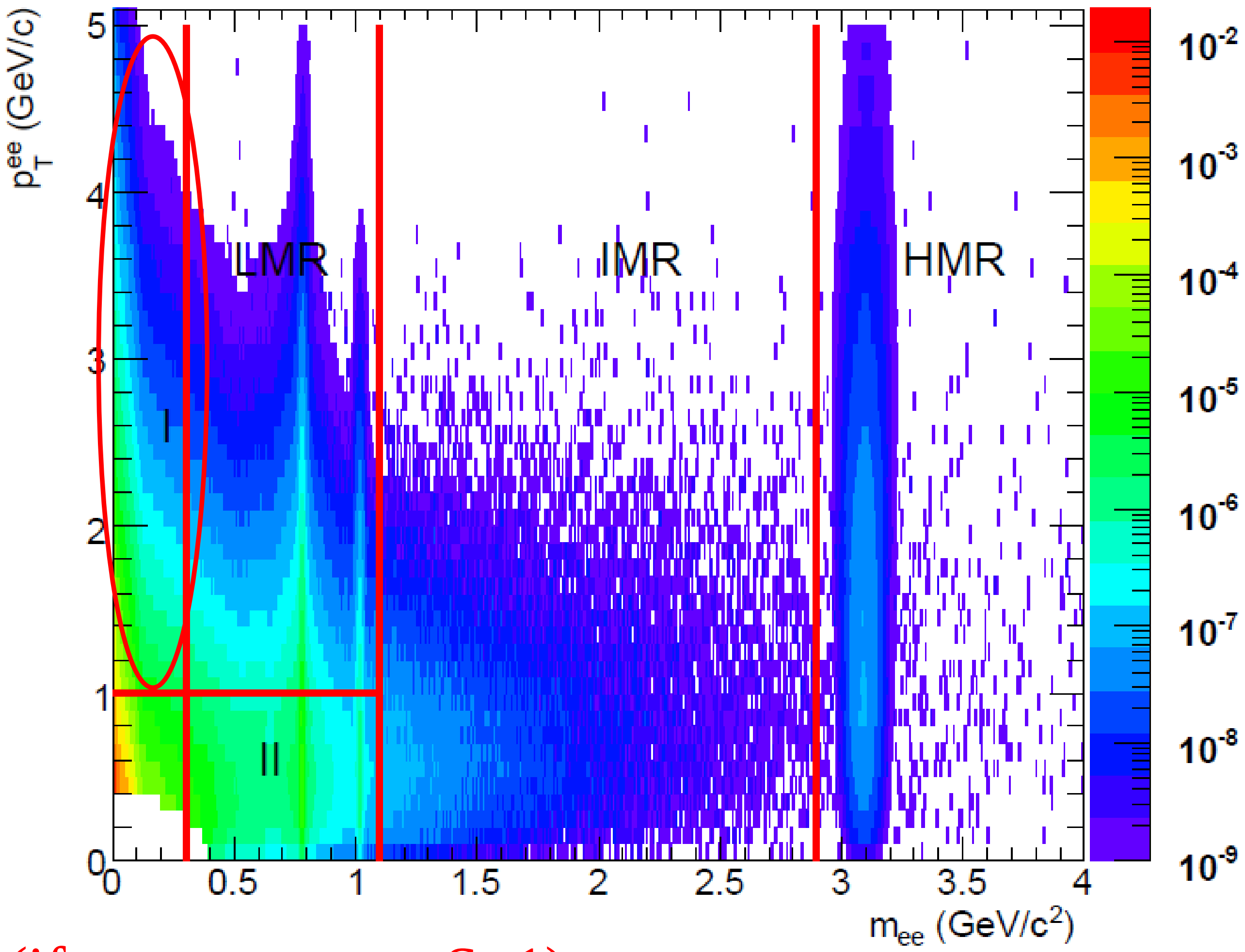
Similar results from ATLAS



di-jet asymmetry (A_J), acoplanarity ($\Delta\varphi$)

Backups

e^+e^- pairs from the cocktail

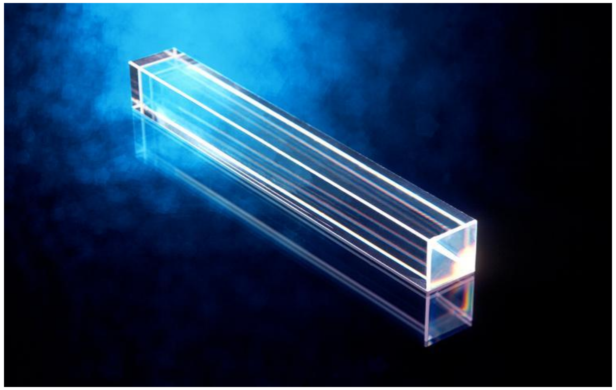


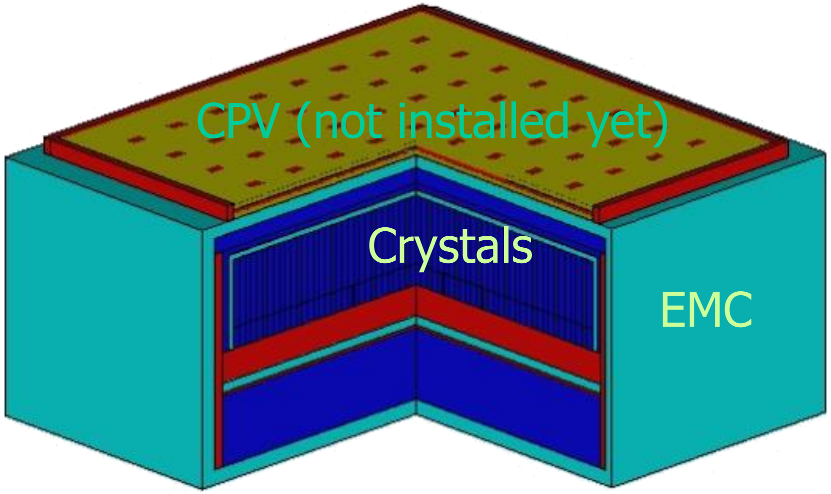
LMR I (if $p_T >> m_{ee}$ => S=1): m<300 MeV & 1<p_T<5 GeV/c

quasi-real virtual photon region. Low mass e^+e^- pairs produced by real photons

LMR II : dilepton production is expected to be dominated by the hadronic gas phase (mass modification?)

PHOton Spectrometer: PHOS

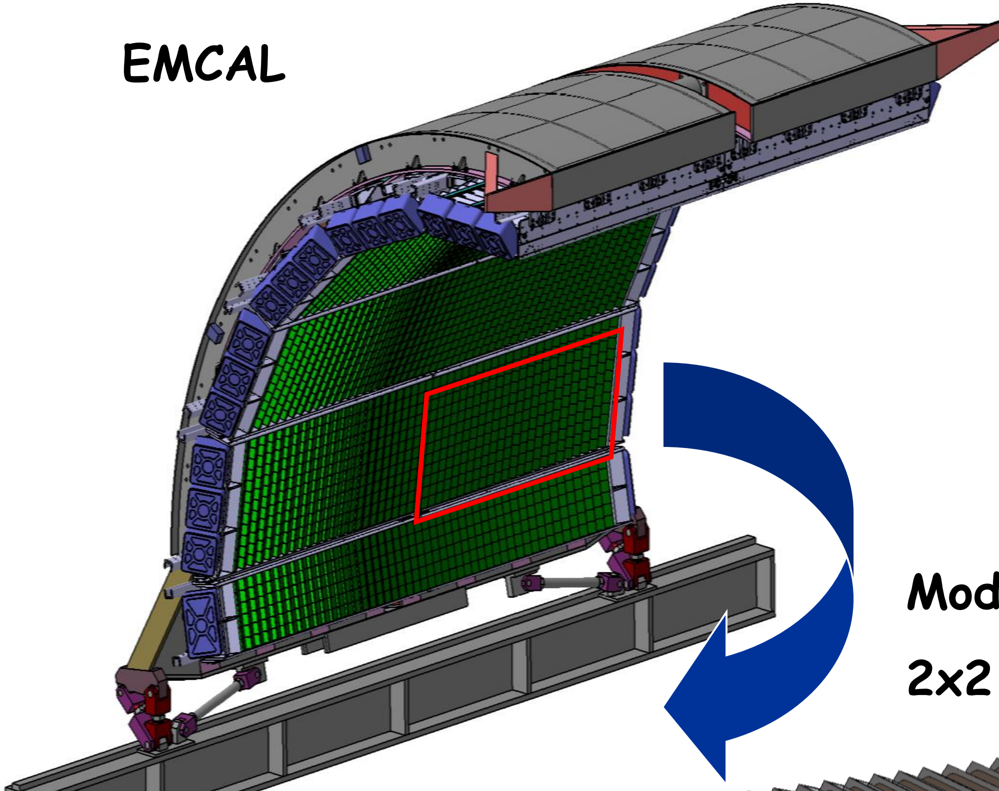




- High granularity and resolution spectrometer:
  - 10,752 (17,920) lead-tungstate crystals ($PbWO_4$), 3(5) modules (56×64 crystals per module)
  - crystal size: $22 \times 22 \times 180\ mm^3$
  - depth in radiation length: 20
  - Distance to IP: 4.4 m
  - Acceptance:
    - pseudo-rapidity [-0.12,0.12]
    - azimuthal angle 60°(100°)
  - For E > 10 GeV, $\Delta E/E < 1.5\%$ and $\sigma_x = [0.5,2.5]$ mm

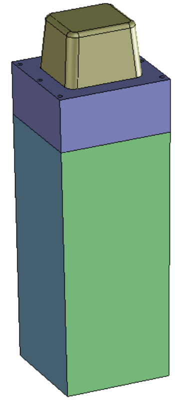
- Focus on low and moderate p_T
  - High resolution π^0 and η
  - Thermal photons

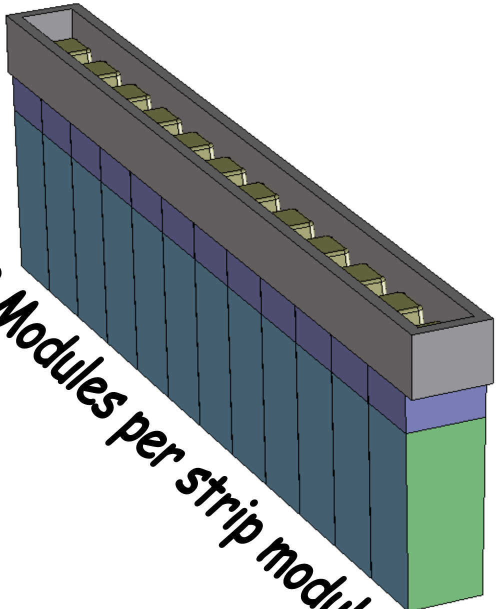
EMCAL

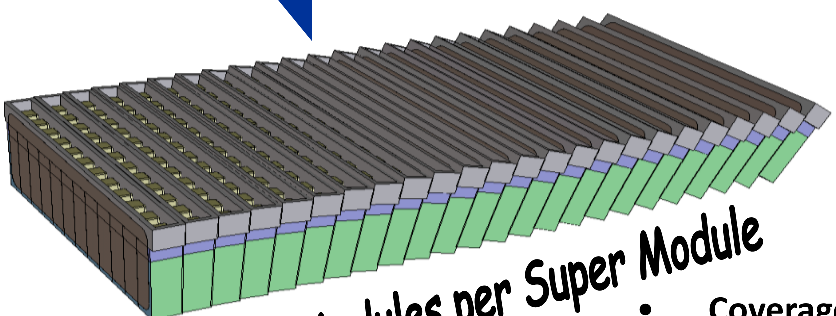


Pb/Sc Shashlik

- 4k (11K) channels
- 4 Super Modules for 2009-2010 runs
- Complete (10 SM) for 2011? runs





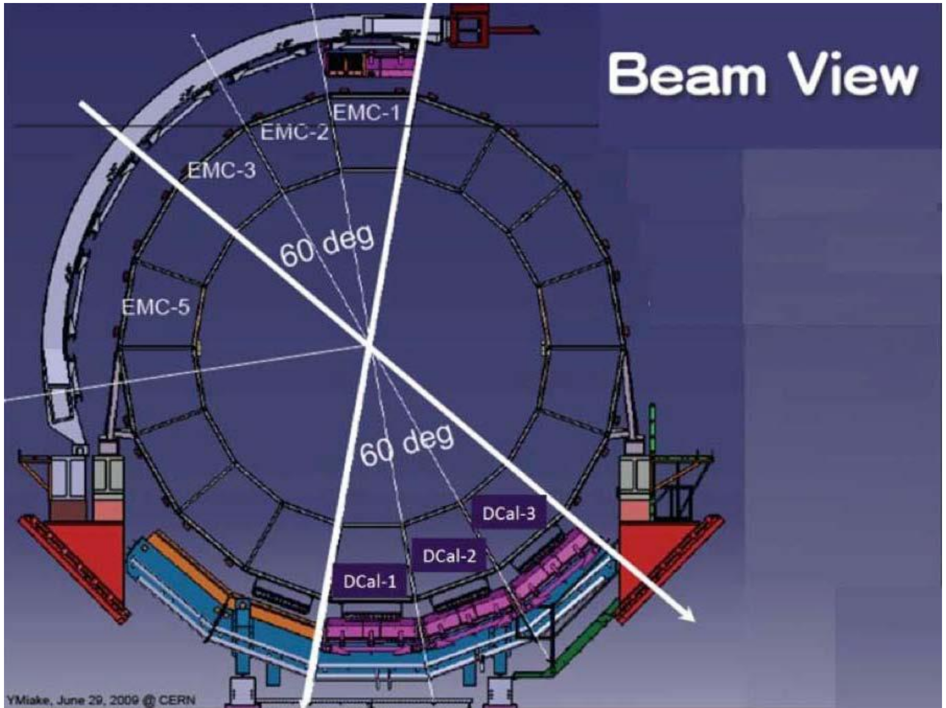


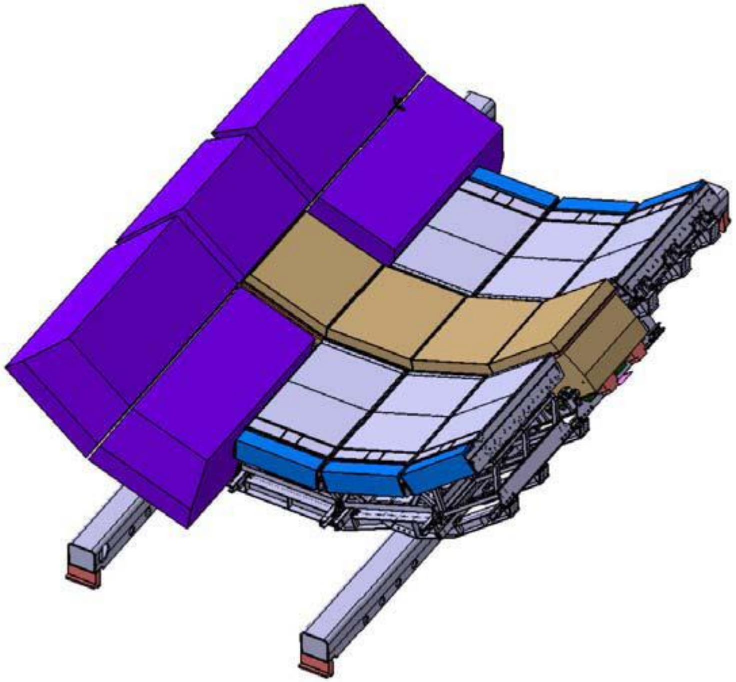
- **Coverage $\Delta\eta$=1.4, $\Delta\phi$=40° (107°)**
- **Distance to IP: 4.3 m**
- **Granularity $\delta\eta = \delta\phi = 0.014$**
- **Resolution $\delta E/E$=11%/$\sqrt{E}$, σ_x=[3,50] mm**
- **Focus on moderate to high p_T**
  - **π^0 and η**
  - **prompt direct photon**
  - **jet**

Di-jet Calorimeter

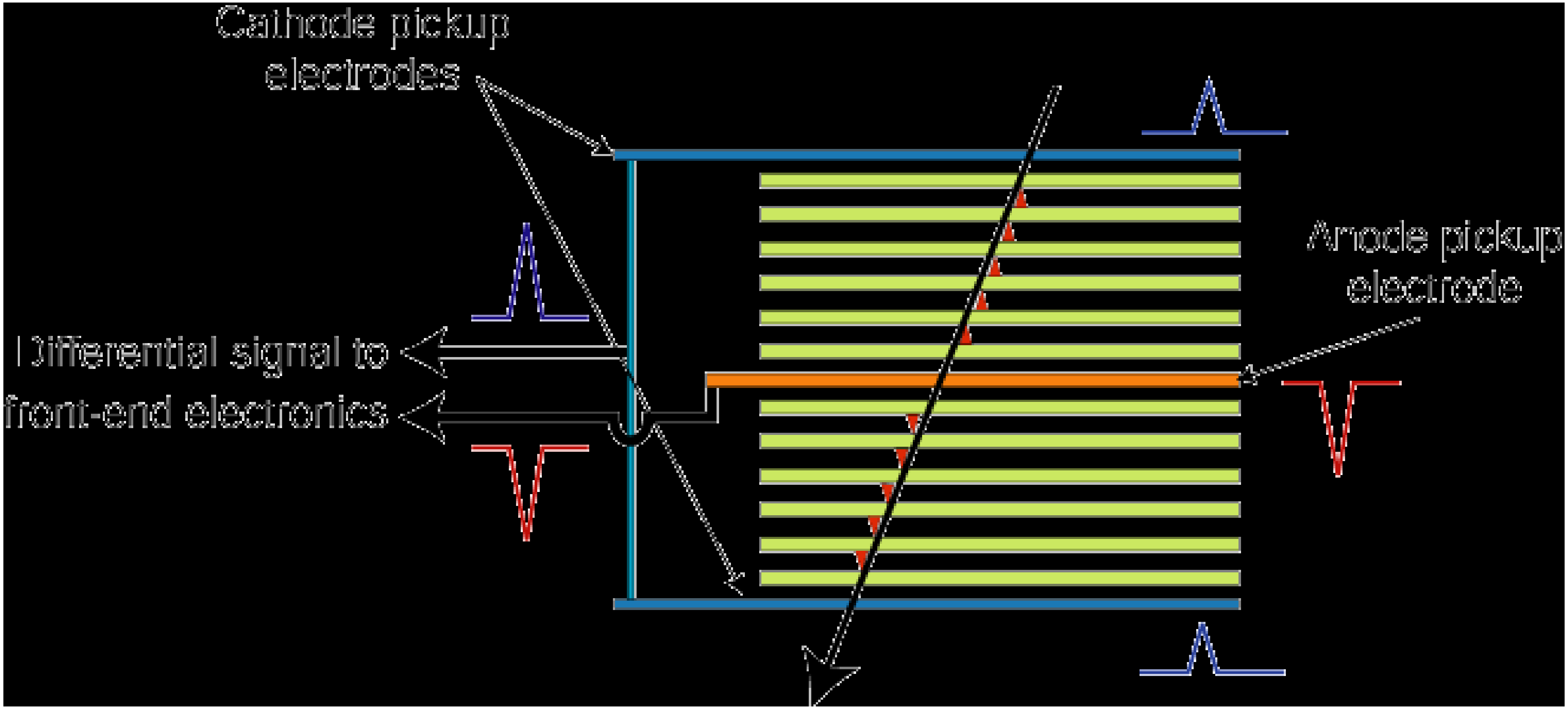
60% extension of EMCal acceptance
Incorporate PHOS and DCAL modules
to produce a single, large EM calorimeter
patch back-to-back with EMCAL.

$\Delta\eta \times \Delta\varphi = 1.4 \times 0.7$



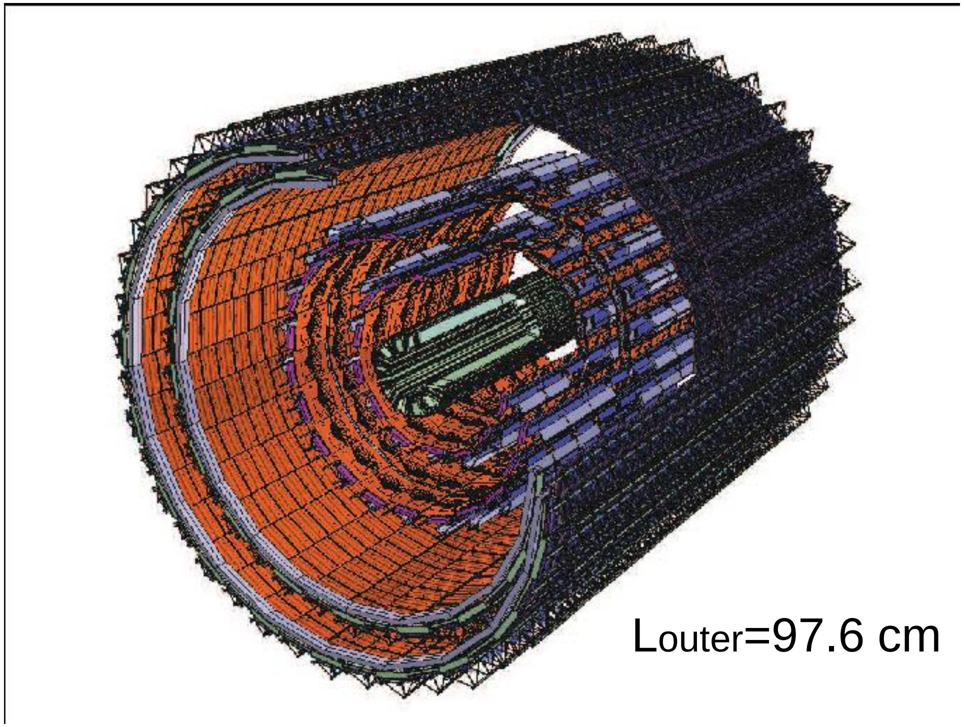


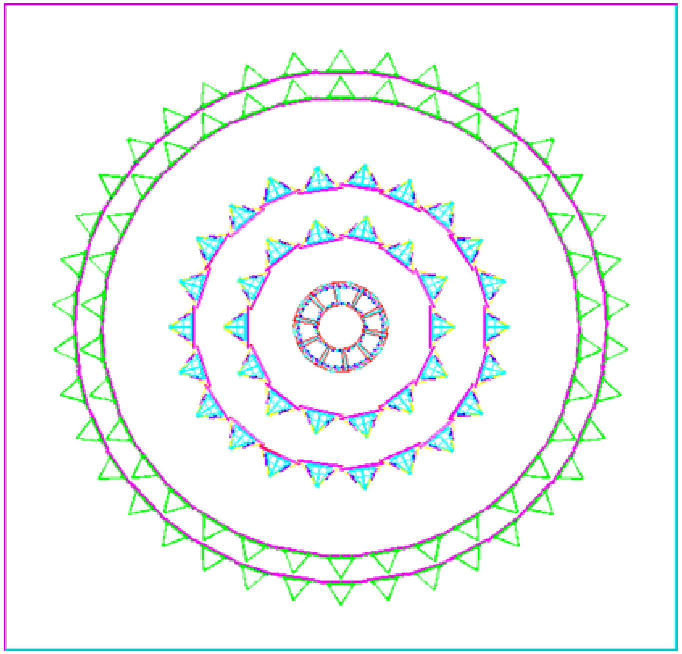
TOF



Cathode pickup
electrodes
Anode pickup
electrode
Differential signal to
front-end electronics

ITS





R_{outer}=43.6 cm

- 6 different layers
- 2xSPD: inner radius 3.9 cm, 9.8 M channels, 0.2 m2
- 2xSDD: 133k channels, 1.3 m2
- 2xSSD: 2.6M channels, 4.75 m2