Hard Probes used in Heavy Ion Collisions to Study QCD at Extreme Energy Densities

Jim Pivarski

on behalf of the CMS Collaboration

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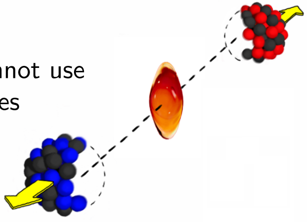
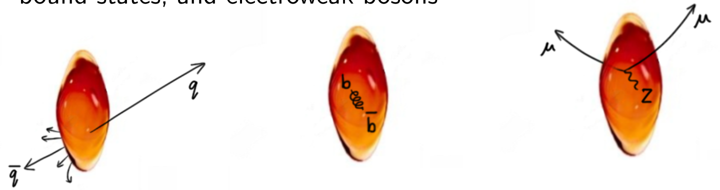
Introduction

- Heavy ion collisions produce a new kind of fluid called a quark-gluon plasma
- It survives such a short time that we cannot use traditional methods to study its properties
- Instead, we look for well-known particle physics processes ("probes") to see how they are modified by the medium



- "Hard" $\rightarrow$ high-energy, perturbative QCD production of dijets, bound states, and electroweak bosons



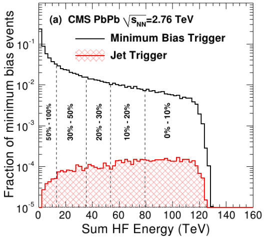
one of the two partons loses energy in the medium

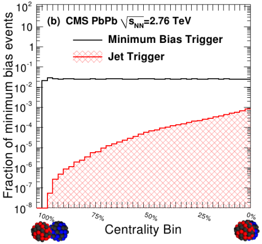
bound particles dissociate in the medium

electroweak bosons not strongly affected

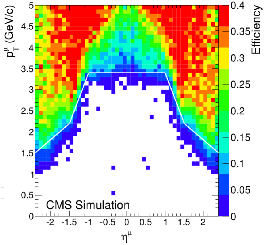
The CMS detector

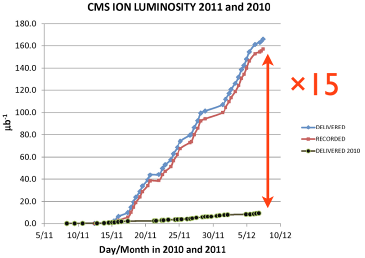
Minimum Bias and Jet triggers





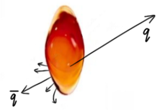
Muon efficiency



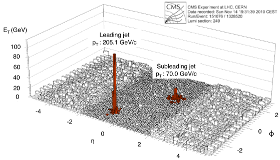


- η coverage: ± 5.2 for jets, ± 2.4 for muons
- High-resolution tracking up to 100's of GeV
- Particle flow jets (get charged particle momenta from tracks)
- 150 μb^{-1} Pb-Pb (Nov 2011) and 231 nb^{-1} of 2.76 TeV pp (Mar 2012)

Jet quenching



- Hard process produces two partons, one loses energy in the medium ("quenched")
- Dramatic enough at the LHC to see it in event displays



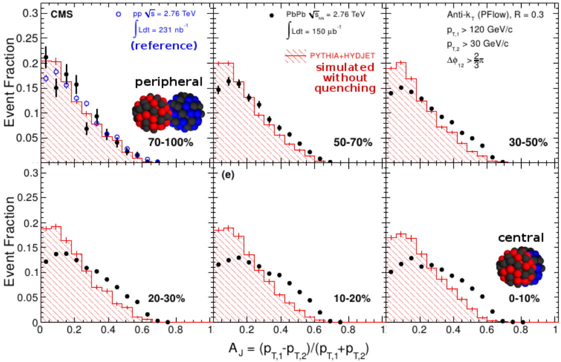
- Quantify with

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

and

$$p_{T,2}/p_{T,1}$$

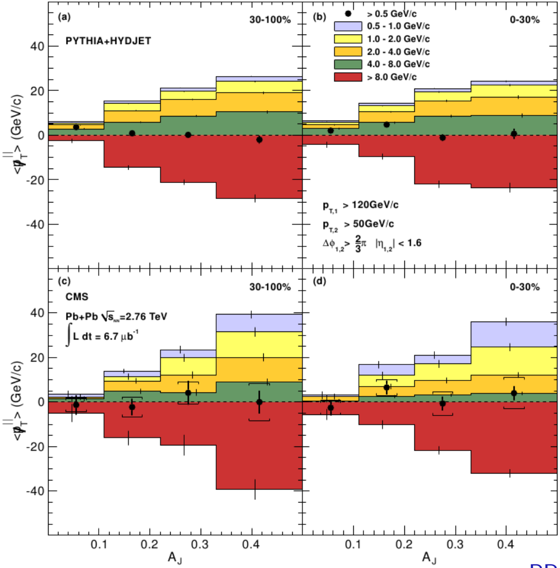
- Calorimeter-only and particle-flow jet algorithms yield similar results



PRC 84 (2011) 024906 and PLB 712 (2012) 176

Missing p_T went into low-p_T particles

$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{i}} -p_{\mathrm{T}}^{\mathrm{i}} \cos\left(\phi_{\mathrm{i}} - \phi_{\mathrm{Leading\ Jet}}\right)$$ versus $$A_J = \frac{p_{\mathrm{T},1} - p_{\mathrm{T},2}}{p_{\mathrm{T},1} + p_{\mathrm{T},2}}$$



PRC 84 (2011) 024906

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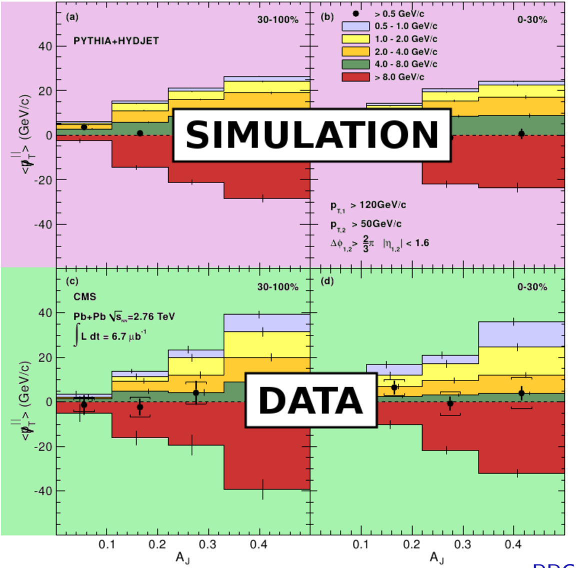

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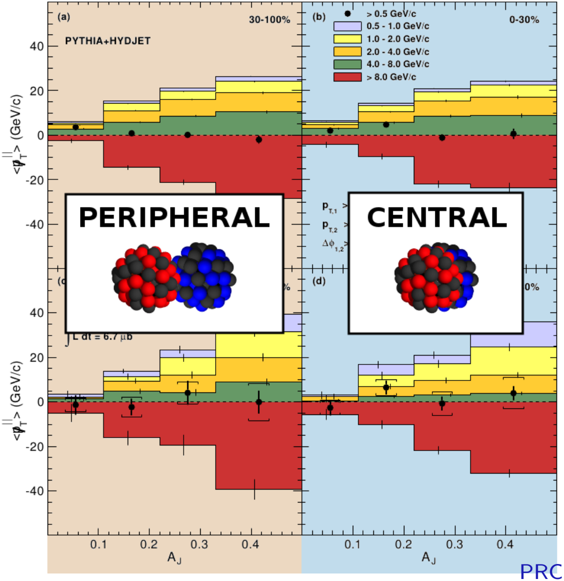

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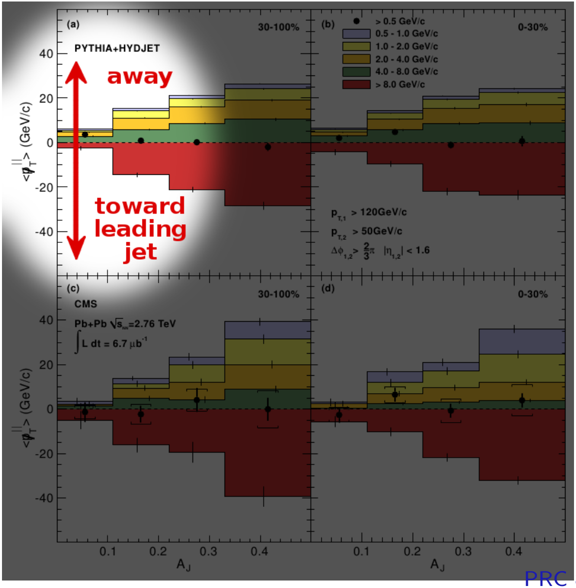

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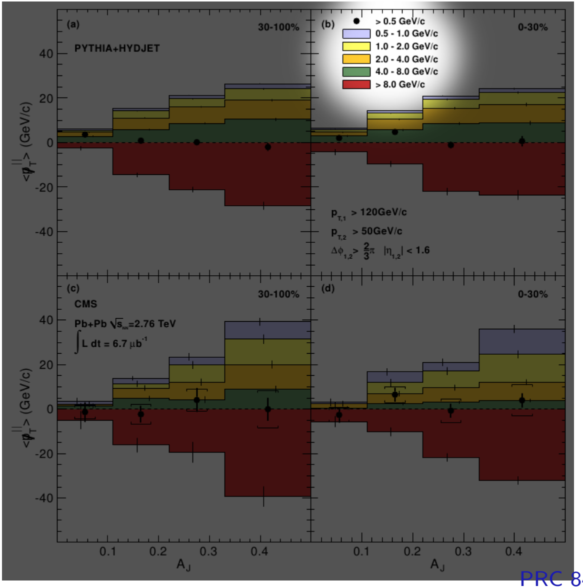

PRC 84 (2011) 024906

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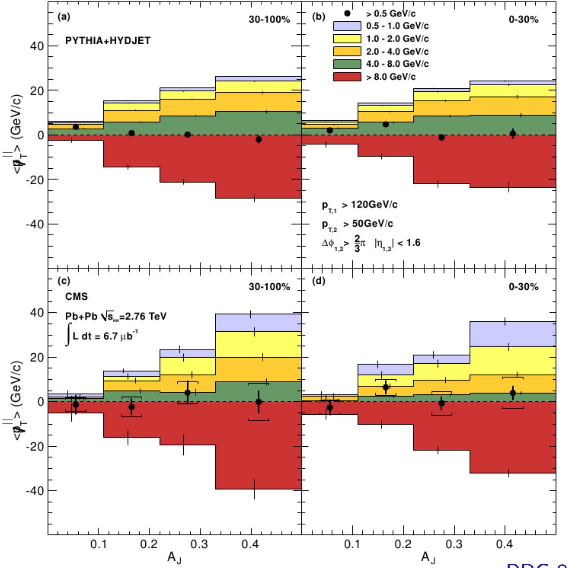

PRC 84 (2011) 024906

Missing p_T went into large-angle particles

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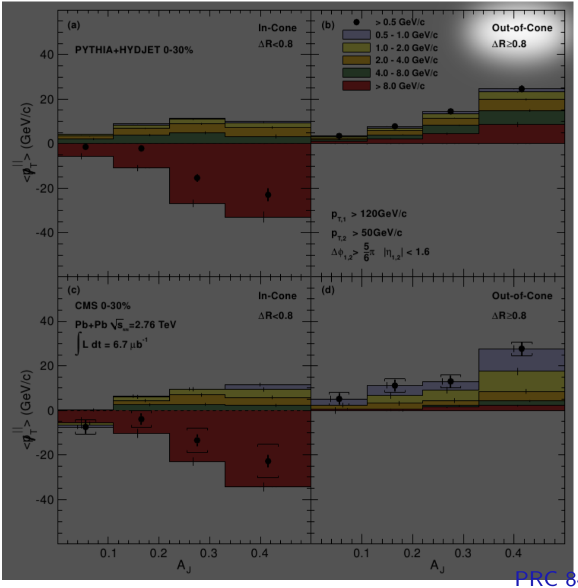

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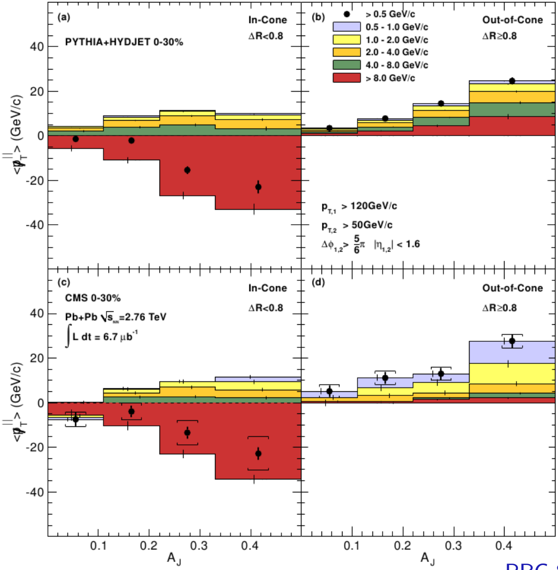
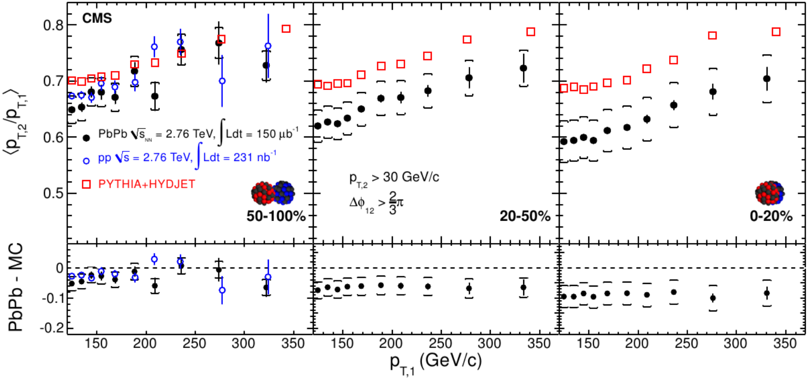


- vertical axis: $\frac{\text{subleading } p_T}{\text{leading } p_T}$ fraction, horizontal axis: leading p_T

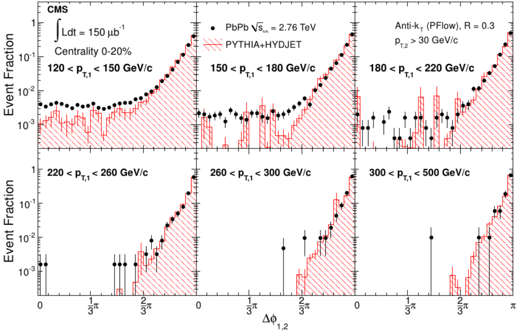


PLB 712 (2012) 176

Negligible angle decorrelation

- Photon-jet pairs produced in $qg \to \gamma q$ and $q\bar{q} \to \gamma g$
- The photon does not interact with the medium, making it a good probe of the initial state of the parton that produced the jet
- Dijets and photon-jet correlations both show large energy loss, rather than angle decorrelation

dijet angular distributions



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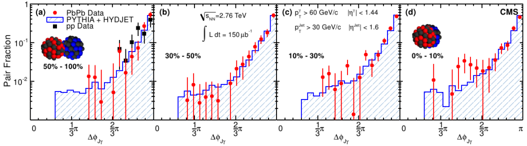
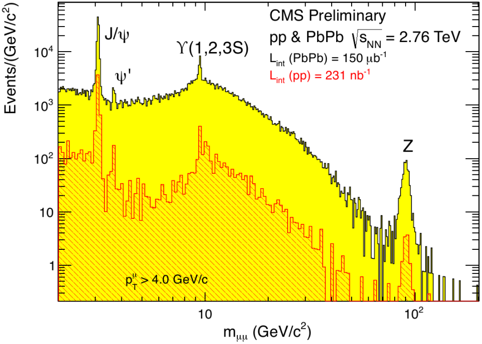
γ-jet angular distributions

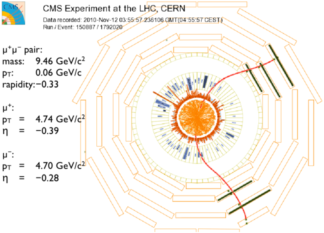


arXiv:1205.0206, submitted to PLB

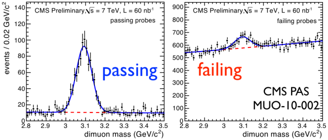
Dimuon spectrum in 2011 heavy ions

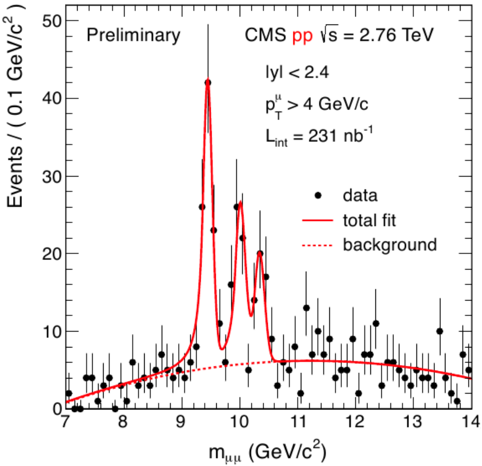


Upsilon candidate



Tag-and-probe example plot

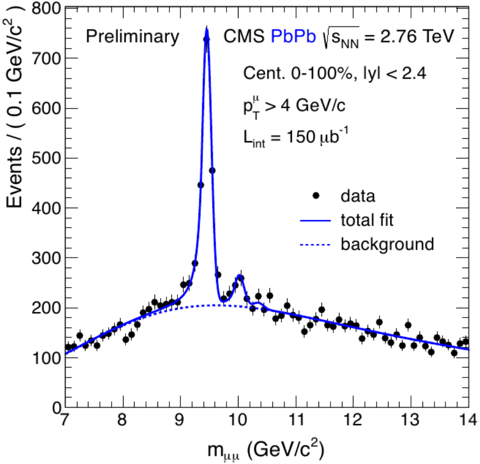




- CMS can resolve the three Υ states

PRL 107 (2011) 052302

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11011



- CMS can resolve the three Υ states
- In heavy ion collisions, all are suppressed, but $\Upsilon(2S)$ and $\Upsilon(3S)$ more than $\Upsilon(1S)$

PRL 107 (2011) 052302

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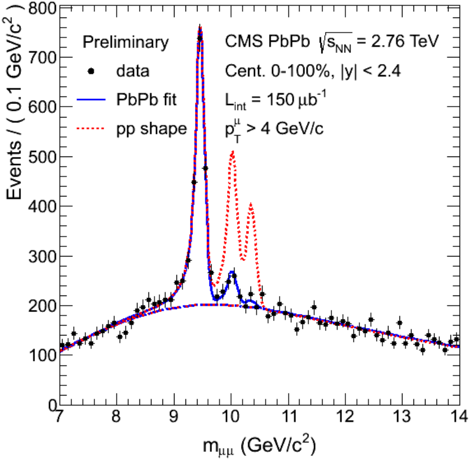


- CMS can resolve the three Υ states
- In heavy ion collisions, all are suppressed, but $\Upsilon(2S)$ and $\Upsilon(3S)$ more than $\Upsilon(1S)$
- Significance of suppression: 5.4σ
- Double ratio $\dfrac{nS/1S|_{\mathrm{Pb\,Pb}}}{nS/1S|_{\mathrm{pp}}}$

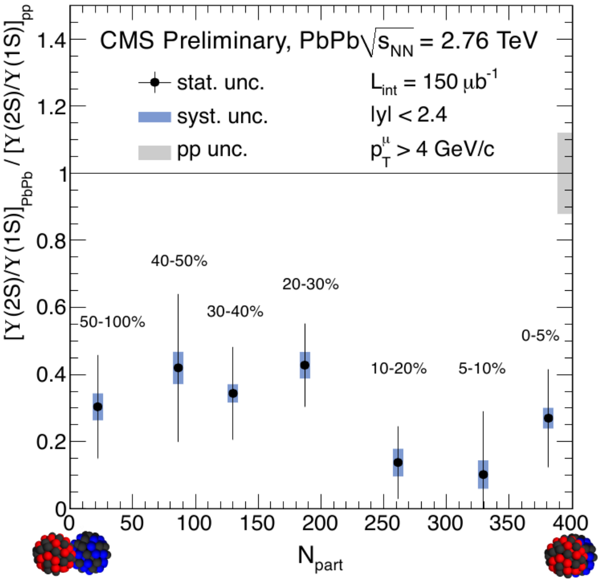
  $2S/1S = 0.21 \pm 0.07 \pm 0.02$

  $3S/1S < 0.1$ (95% C.L.)

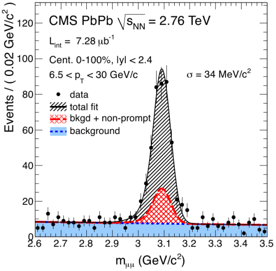
PRL 107 (2011) 052302

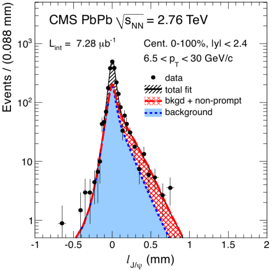
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11011

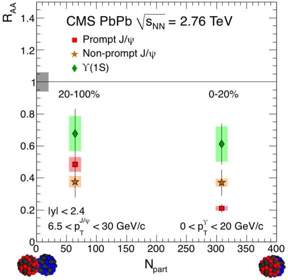
No clear dependence on centrality



J/ψ suppression measured for prompt and non-prompt samples



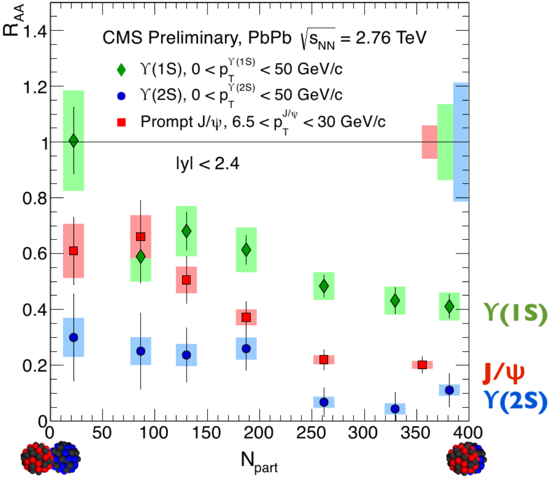




- In $B \to J/\psi\, X$, the secondary vertex from the long-lived B, far from the quark-gluon plasma, can be distinguished from prompt J/ψ production
- $l_{J/\psi}$ is the proper flight distance along the dimuon momentum axis ($l_{J/\psi} < 0$ part of the distribution is purely resolution)
- $R_{AA} = \dfrac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \dfrac{N_{PbPb}(Q\bar{Q})}{N_{pp}(Q\bar{Q})} \cdot \dfrac{\varepsilon_{pp}}{\varepsilon_{PbPb}}$, the nuclear modification factor

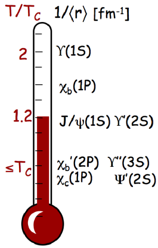
JHEP 1205 (2012) 063

- Suppression of $\Upsilon(1S)$, prompt J/ψ, $\Upsilon(2S)$, and $\Upsilon(3S)$ follow the pattern of their binding energies
- Supports the idea that the medium is screening their potentials



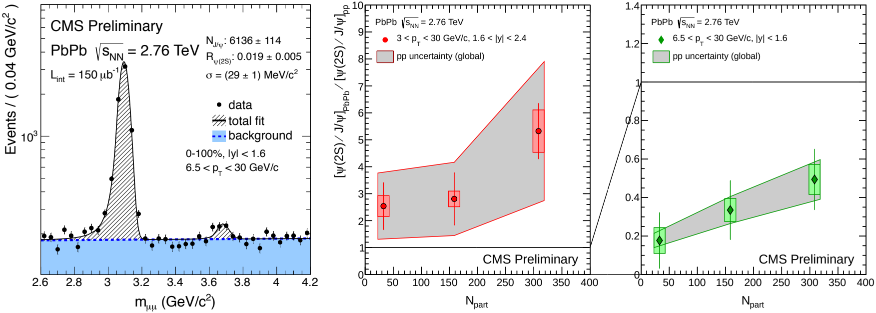
state	J/ψ	χ_c	$\psi'(2S)$
Mass(GeV)	3.10	3.53	3.69
ΔE (GeV)	0.64	0.20	0.05
T_d/T_c	2.1	1.16	1.12

state	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
T_d/T_c	> 4.0	1.60	1.17



PLB 178, 416 (1986)

New: $\psi(2S)$-to-J/ψ double ratio

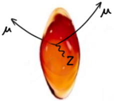


- J/ψ appears more suppressed than $\psi(2S)$ in forward, low p_T region
- $\psi(2S)$ is more suppressed than J/ψ at midrapidity, higher p_T
- Note, however, that uncertainties (mostly from pp reference) are large: the highest point is

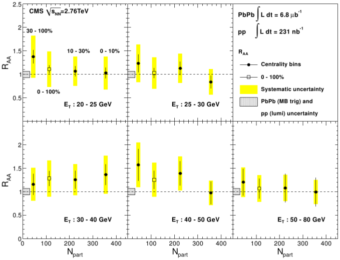
  5.32 ± 1.03 (stat.) $\pm\ 0.79$ (syst.) $\pm\ 2.58$ (pp), or 1.5 sigma from unity

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN12007

Colorless probes are unaffected

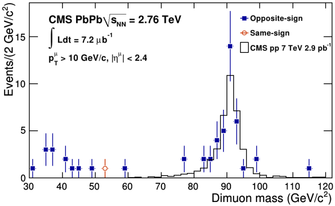


isolated photons



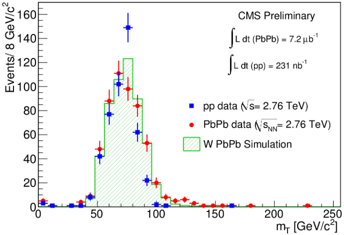
PLB 710 (2012) 256

$Z \to \mu\mu$



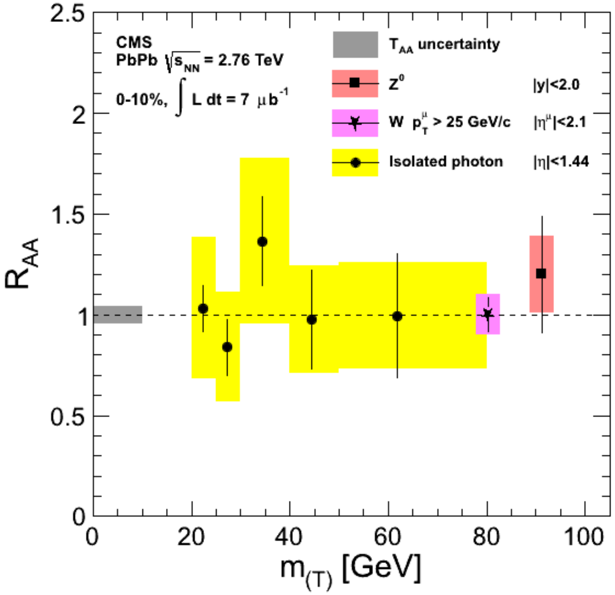
PRL 106 (2011) 212301

$W \to \mu\nu$



arXiv:1205.6334, submitted to PLB

Colorless probes are unaffected



Conclusions

- Jet quenching:
  - Asymmetry in dijets is primarily due to momentum loss into low-p_T, out-of-cone tracks, rather than angular decorrelation or lost particles
  - The effect has little momentum dependence
  - Jet-photon correlations lead to the same conclusion as jet-jet
- Suppression of quarkonia:
  - Measured Upsilon states separately, prompt and non-prompt J/ψ
  - The $\Upsilon(1S)$, J/ψ, $\Upsilon(2S)$, and $\Upsilon(3S)$ follow the pattern of Matsui-Satz screening
  - The $\psi(2S)$ may actually be less suppressed than the J/ψ in the forward, low-p_T region, though the uncertainties are large
- Colorless probes:
  - Production and development of γ, W, and Z are unaffected by the strongly interacting medium
  - Supports the interpretation of jet quenching and suppression of quarkonia as effects that happen *after* they are produced