Heavy Ion Physics Results from CMS

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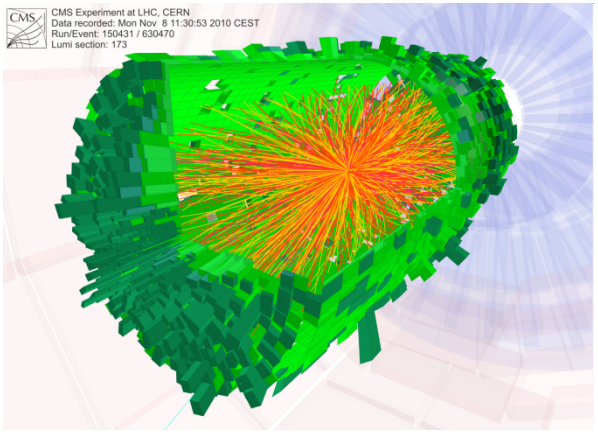
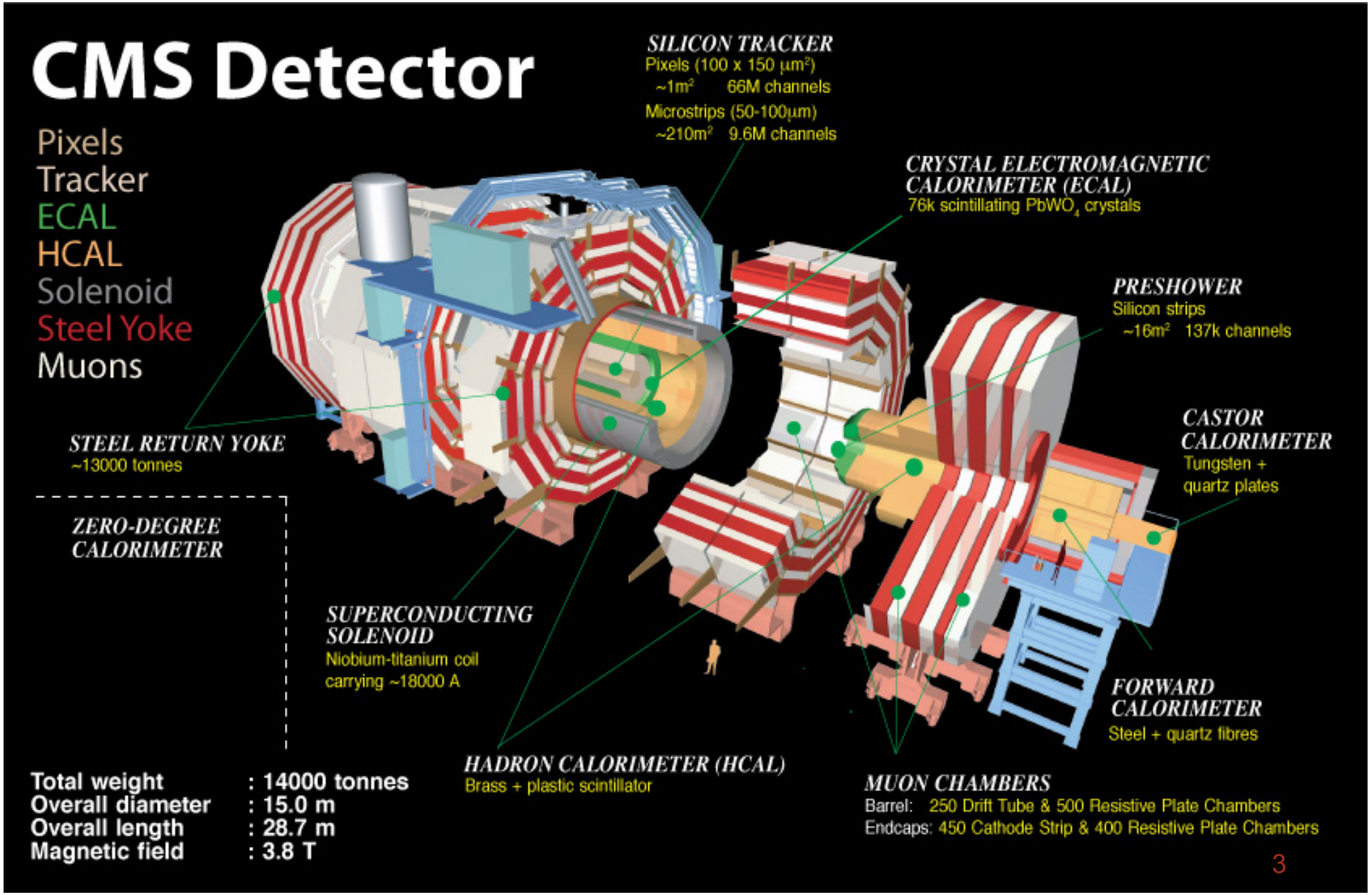


XXVI Rencontres de Physique de la Vallee d'Aoste,
28th Feb 2012, La Thuile, Italy

Heavy Ion Physics

- Hadron deconfinement: quark-gluon ‘soup’
  - First microseconds after the Big Bang
  - $T > 150\text{-}180\ \text{MeV}/k_B$ and $\varepsilon > 1\ \text{GeV/fm}^3$ needed
  - Experimental tool: heavy ion collisions
- First indications at the CERN SPS
  - Charmonium suppression, strangeness enhancement
- Extensive studies at BNL, RHIC
  - Operating since 2000, $\sqrt{s_{NN}}=0.2$ TeV
  - High p_T hadron suppression, elliptic flow, thermal photons
- At LHC, new energy frontier, new ‘probes’
  - jets, Z, W, photons, Y mesons
  - The CMS experiment is well adapted to measure these

Compact Muon Solenoid



Comprehensive list of topics

- Multiplicity and transverse energy
  - $dN_{ch}/d\eta \approx 1600$ and $dE_T/d\eta \approx 2$ TeV !
- Particle correlations
  - Elliptic flow and higher harmonics (*high p_T)
  - Di-hadron correlations (the “ridge”)
- Standard candles: Electroweak bosons
  - Isolated photons
  - $Z \rightarrow \mu\mu$ (signal for $Z \rightarrow ee$)
  - $W \rightarrow \mu\nu$
- Quarkonium suppression
  - J/ψ
  - Υ ground and excited states
- Jet quenching
  - High p_T particle suppression*
  - Di-jet imbalance
  - Di-jets with momentum dependence*
  - Fragmentation functions

JHEP 08 (2011) 141
PAS HIN-11-003

PAS HIN-10-002 & 11-005
JHEP 07 (2011) 076
arXiv: 1201.3158

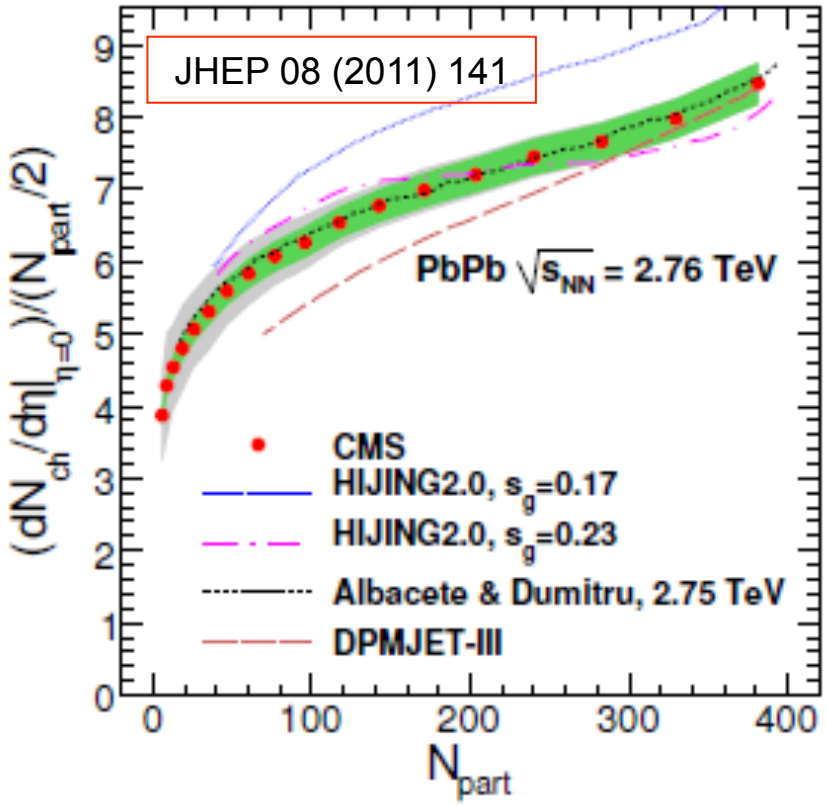
arXiv: 1201.3093, acc.PLB
PRL 106 (2011) 212301
New preliminary result

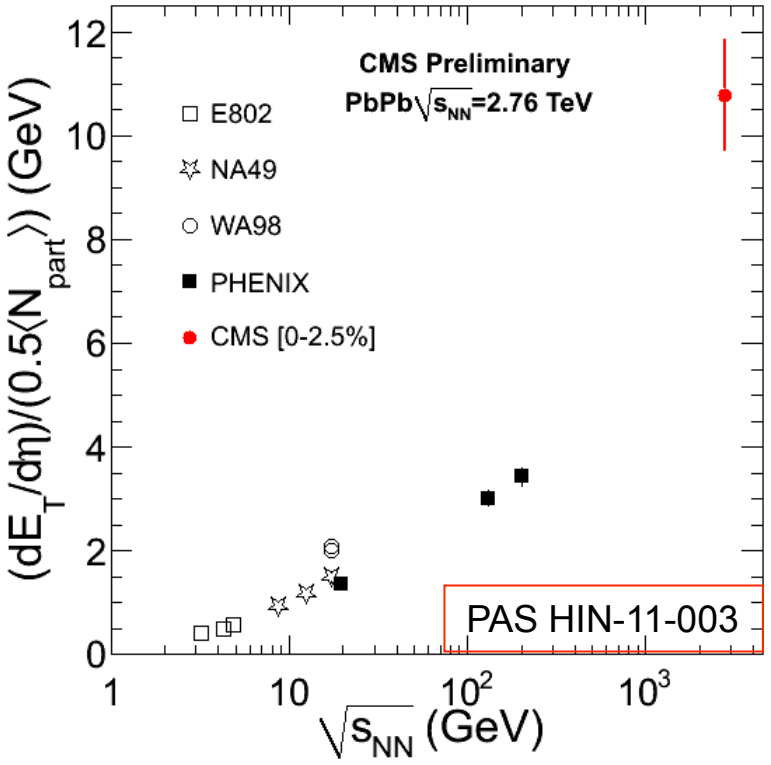
arXiv:1201.5069
PRL 107 (2011) 052302

arXiv:1202.2554, acc EPJC
PRC 84 (2011) 024906
arXiv:1202.5022
PAS HIN-11-004

*includes 2011 data

Total multiplicity and transverse energy

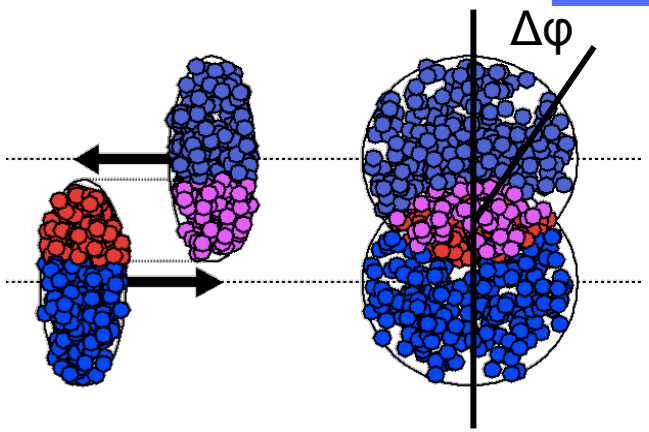




- Up to 1600 charged particles per pseudo rapidity unit
- Centrality dependence providing inputs to (initial state) models

- Up to 2 TeV per unit of pseudorapidity
- 3 times larger than at RHIC; 100 times larger than nuclear densities

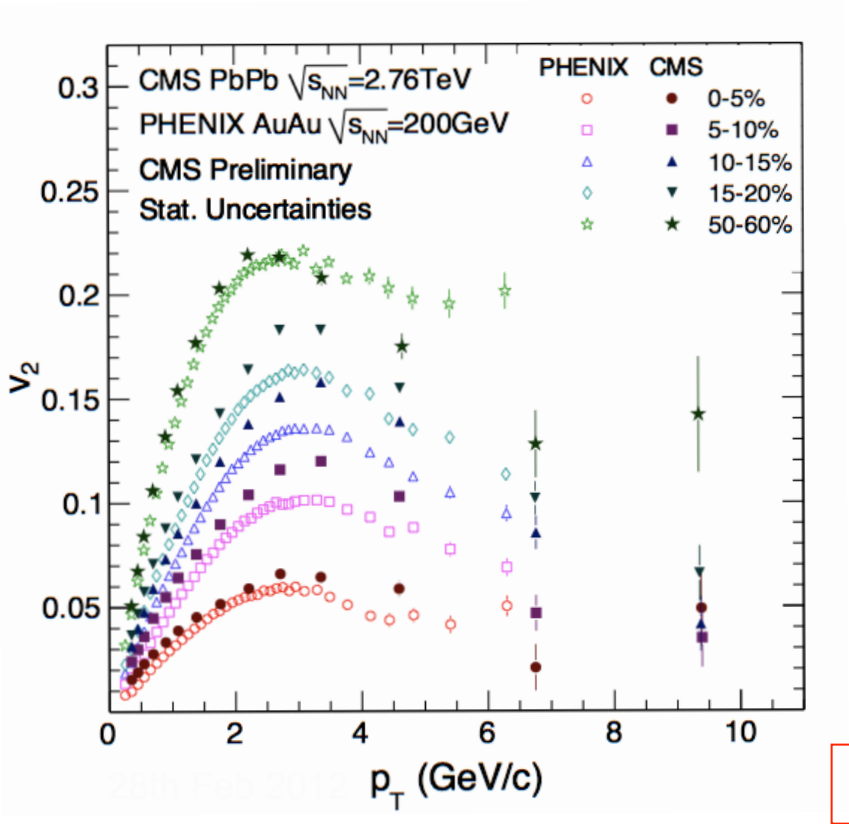
Elliptic flow

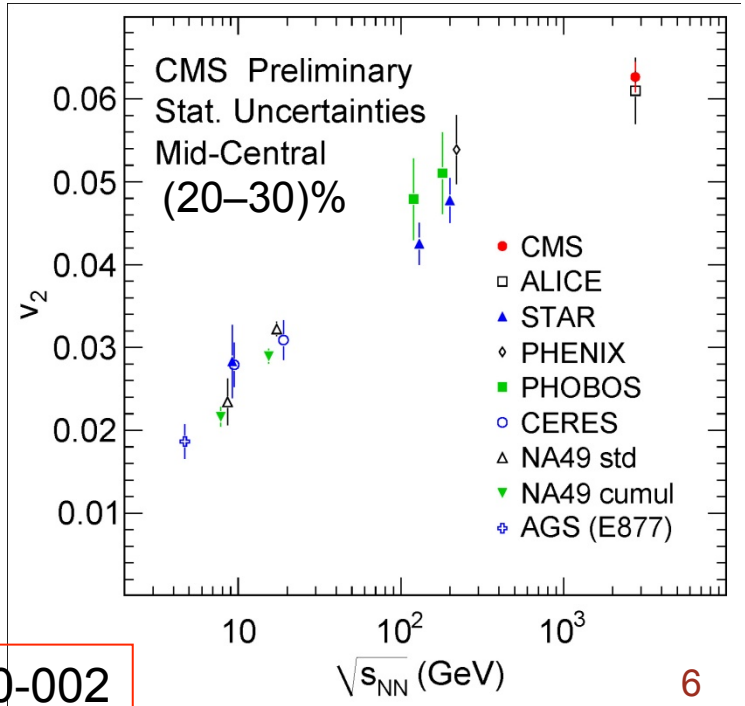


- $v_2 = \langle \cos 2\varphi \rangle =$

= 2nd Fourier coefficient of the azimuthal distribution of particles wrt reaction plane

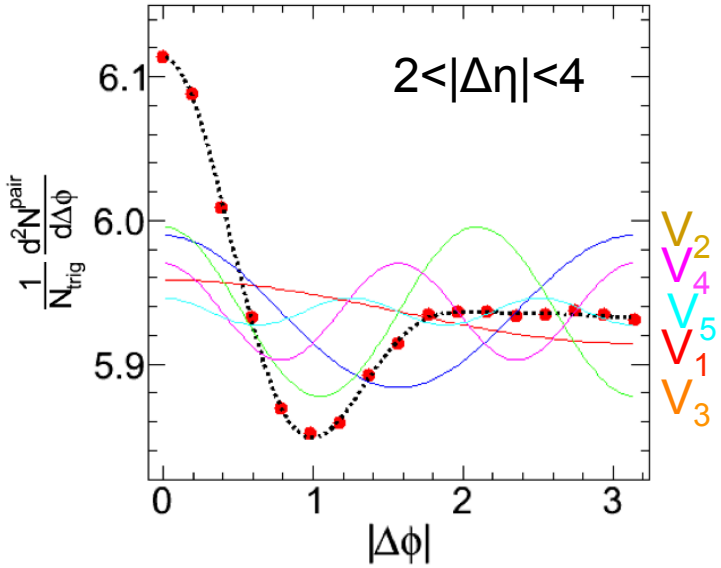
- Modest raise w.r. to lower energy experiments (higher $\langle p_T \rangle$)

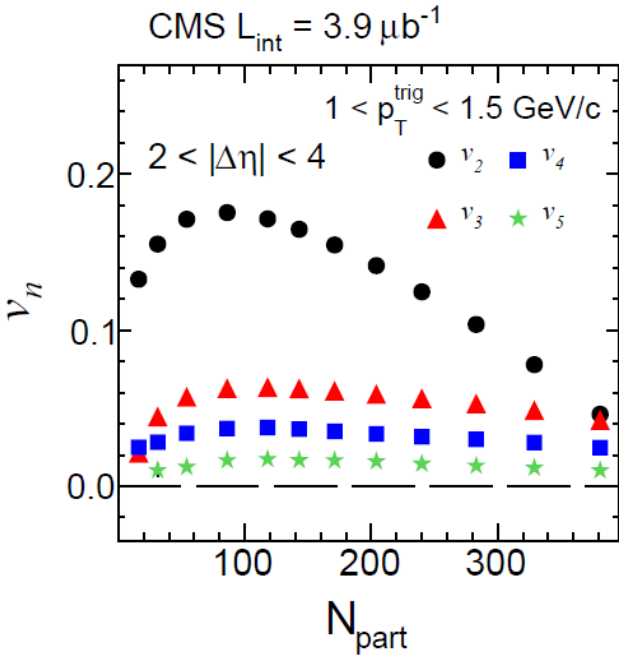




PAS HIN-10-002

Higher harmonics





1 < p_T^{trig} < 1.5 GeV
1 < p_T^{assoc} < 3 GeV

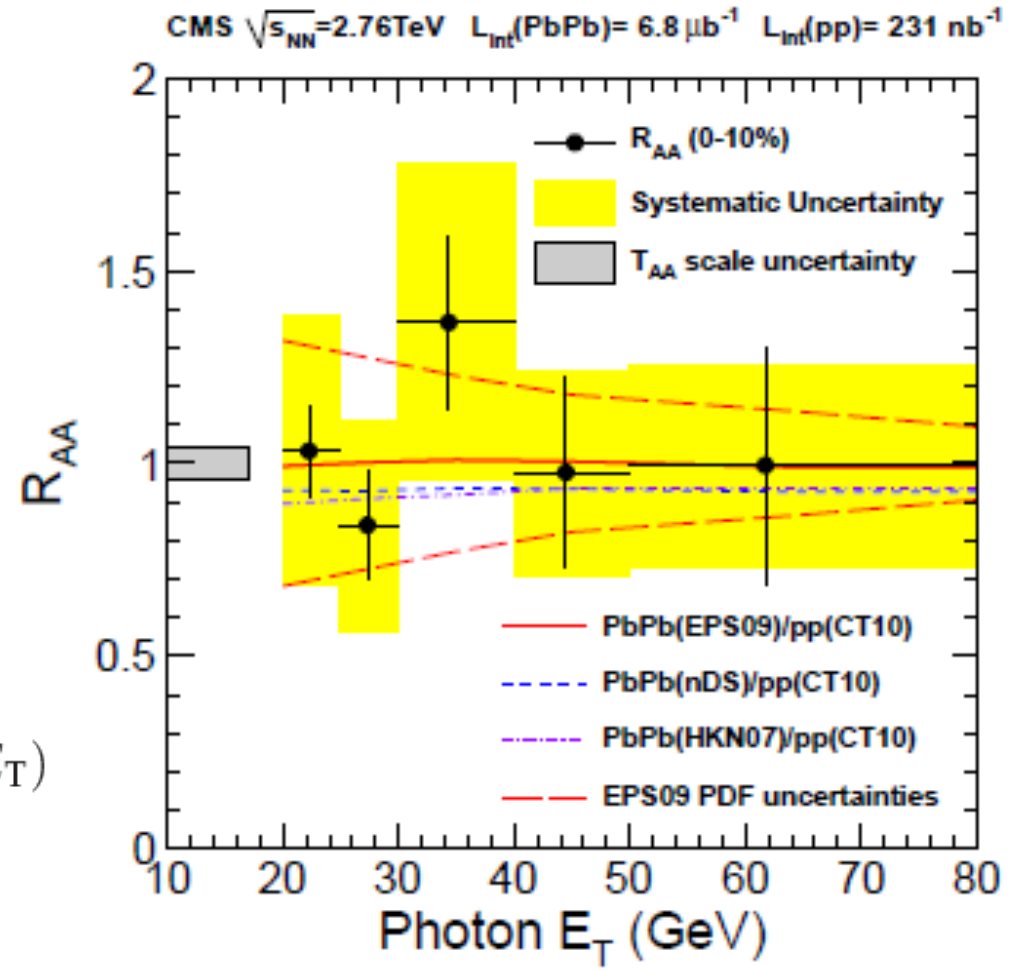
arXiv:1201.3158
HIN-11-005

- In the long range region (2<|Δη|<4), dihadron harmonics shown to factorize and reflect the single particle harmonics
  - not for high p_T v_2, probably reflecting jet correlations
- The "ridge" in PbPb is well modeled by single particle harmonics and could just reflect collective motion (v_2) and overlap region fluctuations (v_n)

New probes: isolated photons

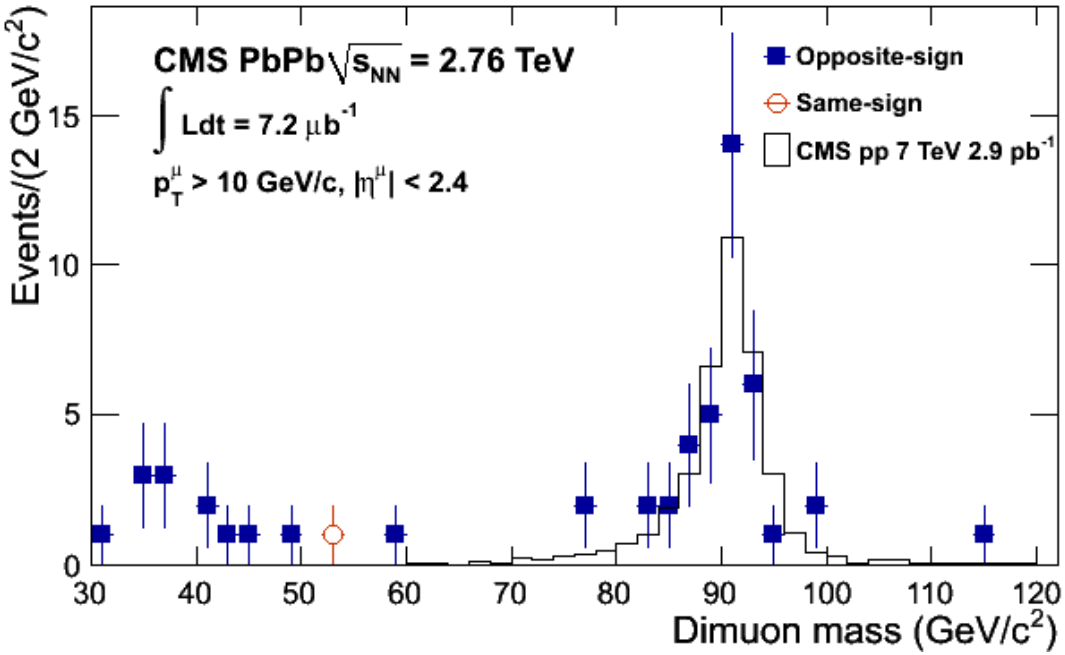
- Photons are unmodified
  - 20-30% uncertainty, mostly due to background

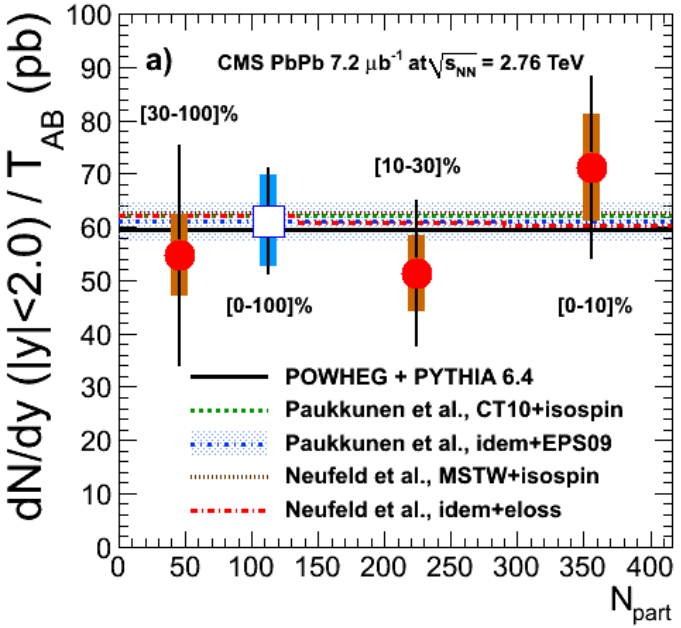
$$R_{\mathrm{AA}} = dN^{\gamma}_{\mathrm{PbPb}}/dE^{\gamma}_{\mathrm{T}}/(T_{\mathrm{AA}} \times d\sigma^{\gamma}_{\mathrm{pp}}/dE_{\mathrm{T}})$$



arXiv:1201.3093

New probes: Z bosons



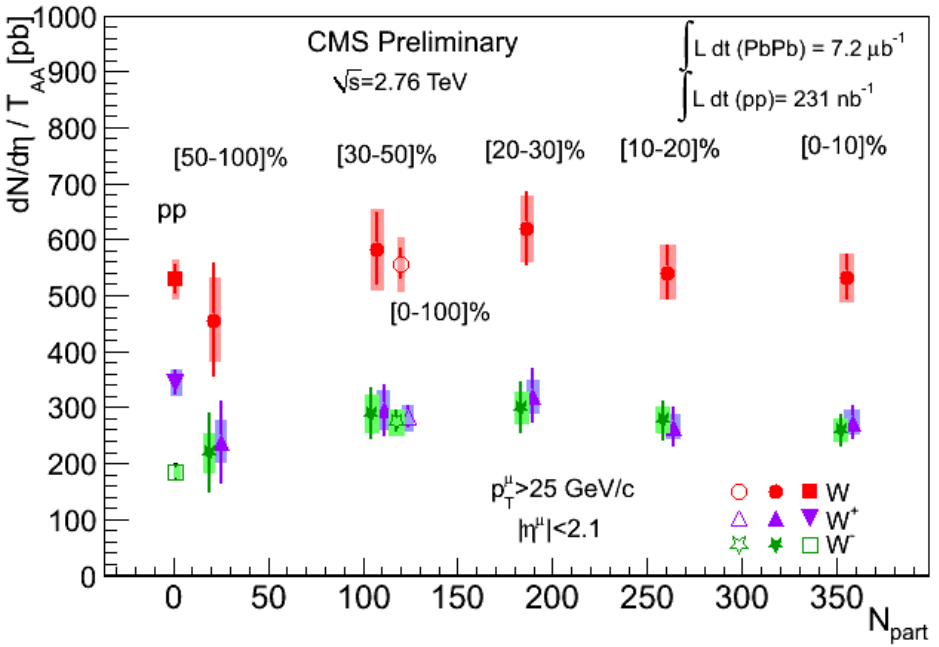


- 39 counts over a negligible background
- No R_{AA} here, but direct comparison to solid theory: no modifications

PRL106 (2011) 212301

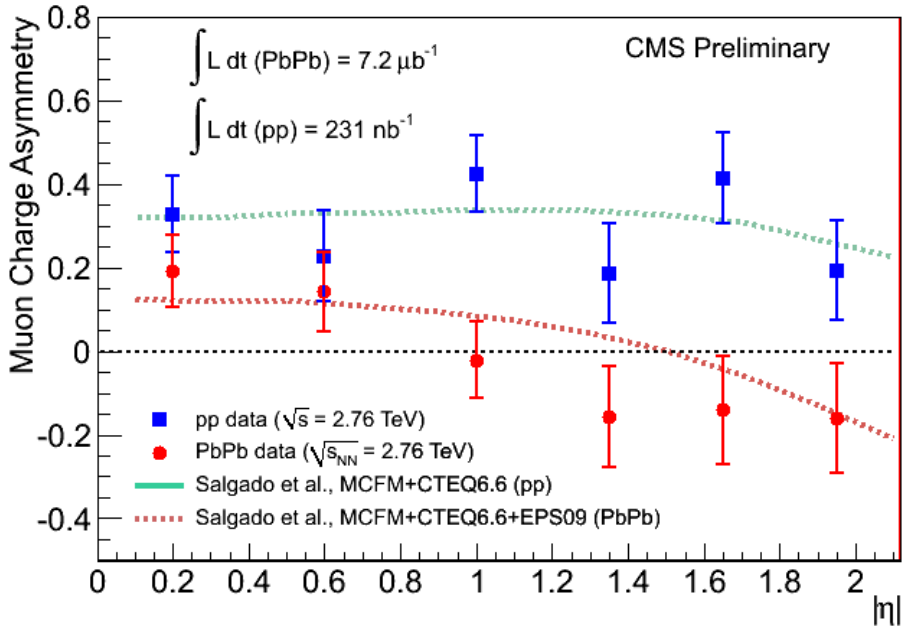
New probes: W bosons

- No centrality dependence
  - $R_{AA}(W^+) \approx 0.7$
  - $R_{AA}(W^-) \approx 1.3$
  - $R_{AA}(W) = 1.04 \pm 0.07 \pm 0.12$



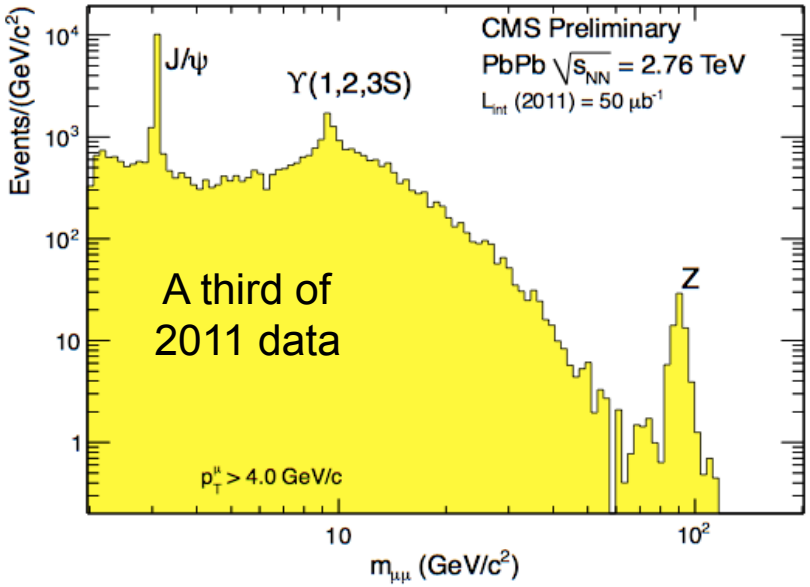
- Due to isospin effect, we expect:
  - $R_{AA}(W^+) \text{ != } R_{AA}(W^-) \text{ != } 1$

- Muon charge asymmetry
  - $(W^+ - W^-) / (W^+ + W^-)$
  - Also matching predictions

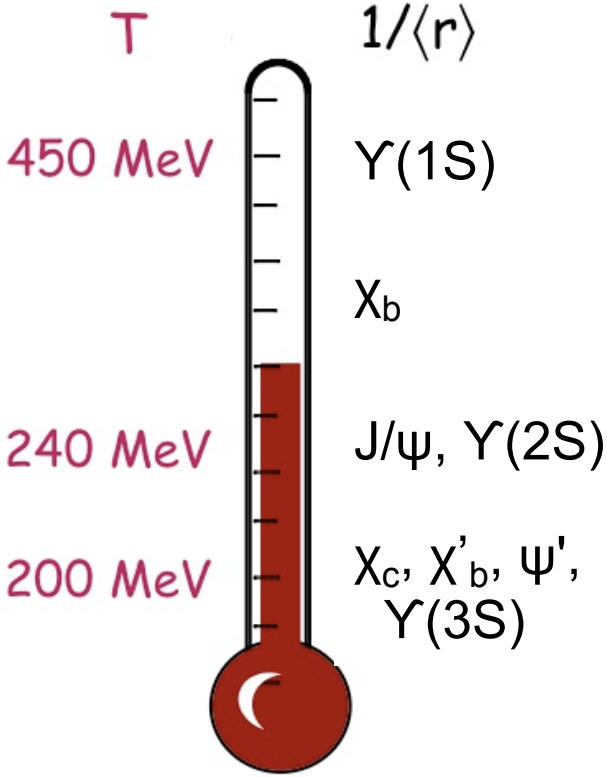


Quarkonium suppression

- Old predicted signature of the QGP
  - Quarkonia should melt one after the other, depending on their binding energy
  - Recent example of melting temperatures →
- SPS/RHIC:
  - no/marginal access to the (yet unresolved) Υ family
  - J/ψ and ψ' studied in detail
- LHC:

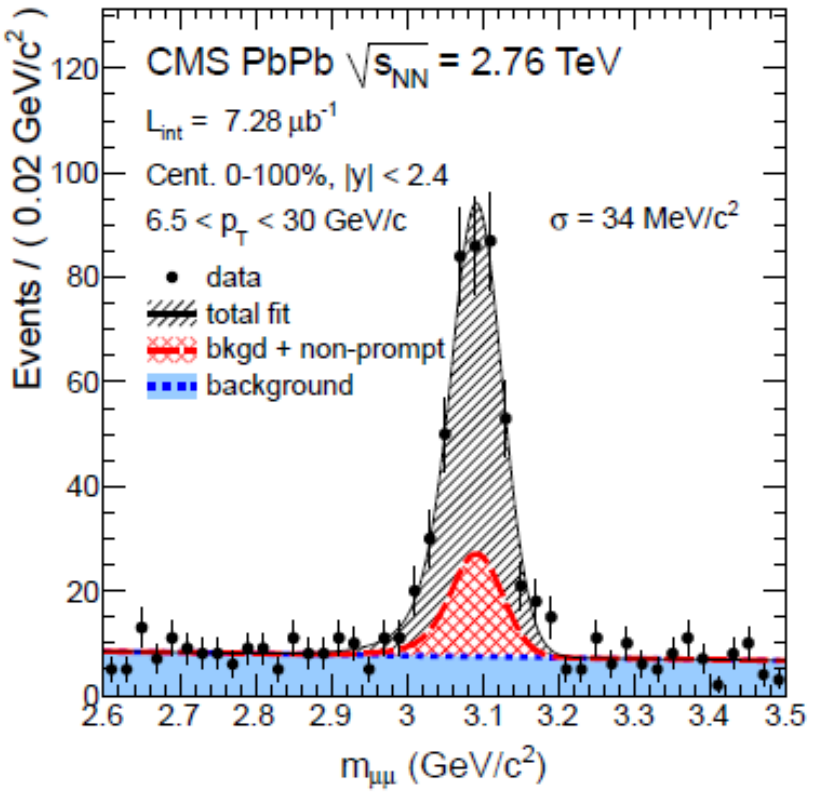


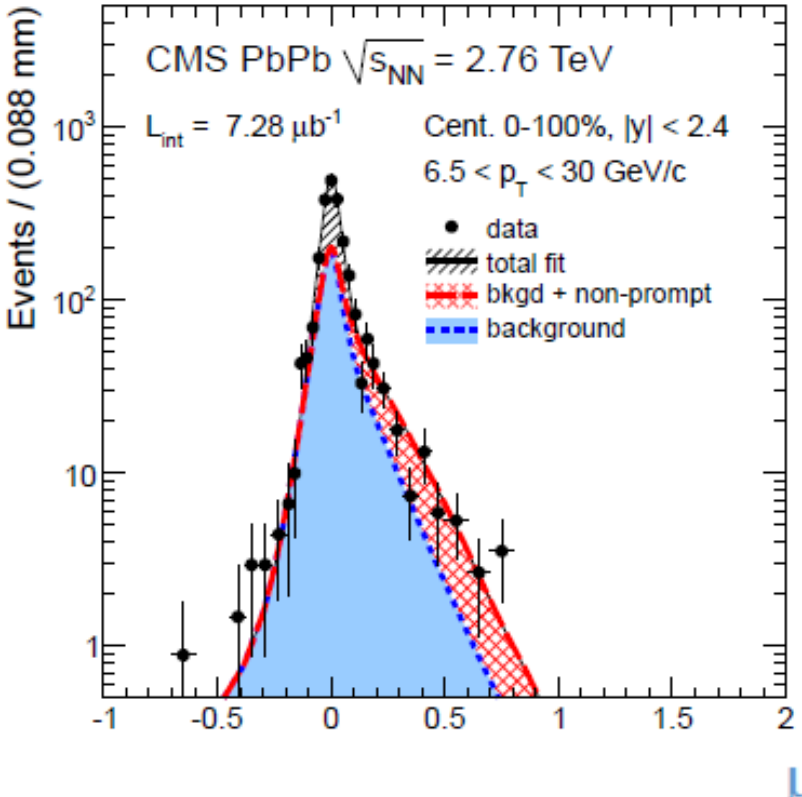
Matsui & Satz, PLB168 (1986) 415



Mocsy, EPJC61 (2009) 705
BNL workshop, June'09

At the LHC, B → J/ψ is significant

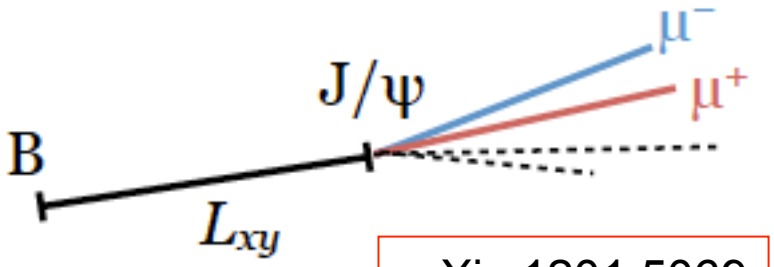




inclusive J/ψ

J/ψ ← B | prompt J/ψ

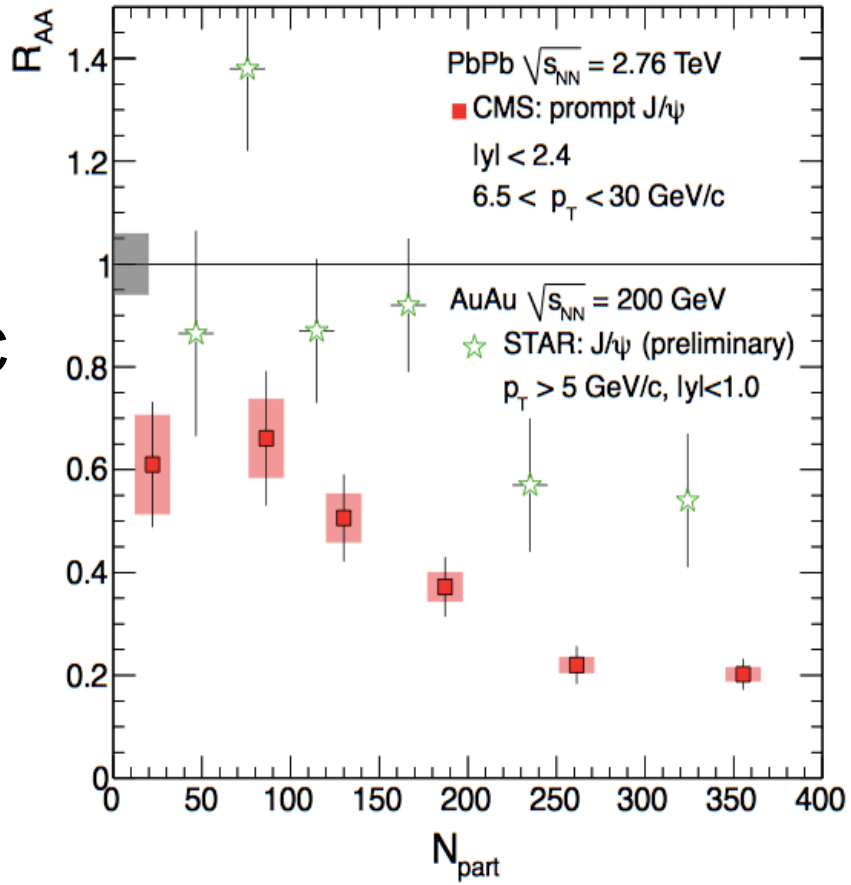
direct J/ψ | J/ψ ← ψ', χ_c



arXiv:1201.5069

Prompt J/ψ suppression

- CMS J/ψ p_T > 6.5 GeV/*c*
  - Material and B-field
- More suppression than at RHIC
  - CMS (p_T > 6.5 GeV/*c*) <
    < STAR (p_T > 5 GeV/*c*)

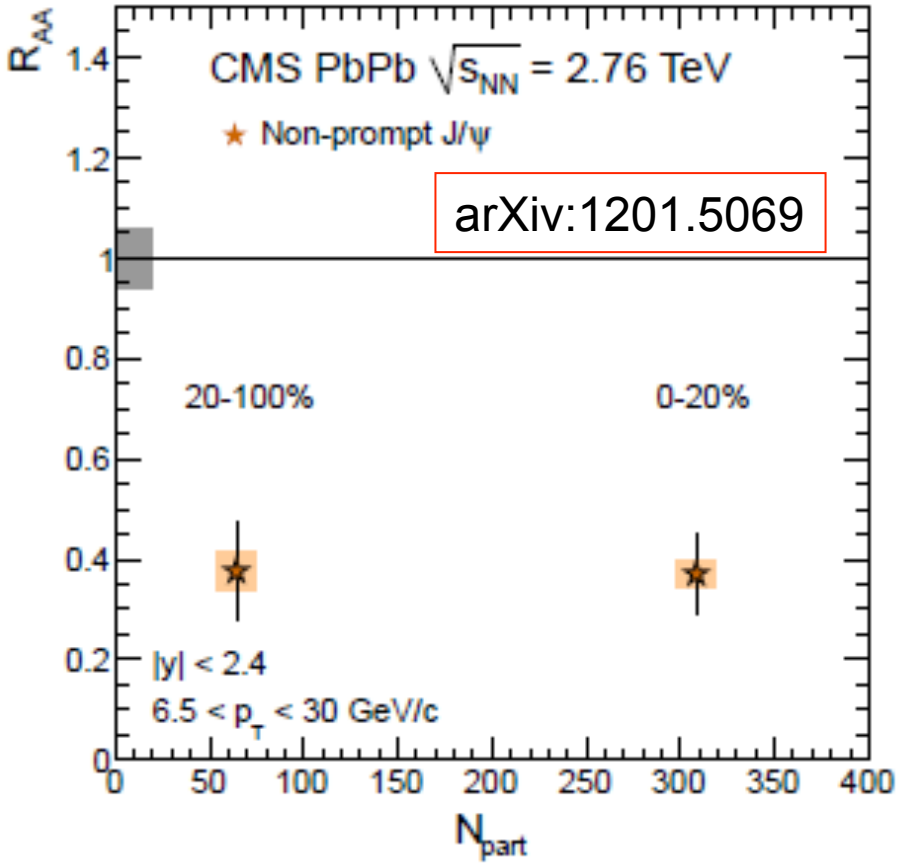


R_{AA} = 0.20 ± 0.03 ± 0.01 ± 0.01 (central)

arXiv:1201.5069

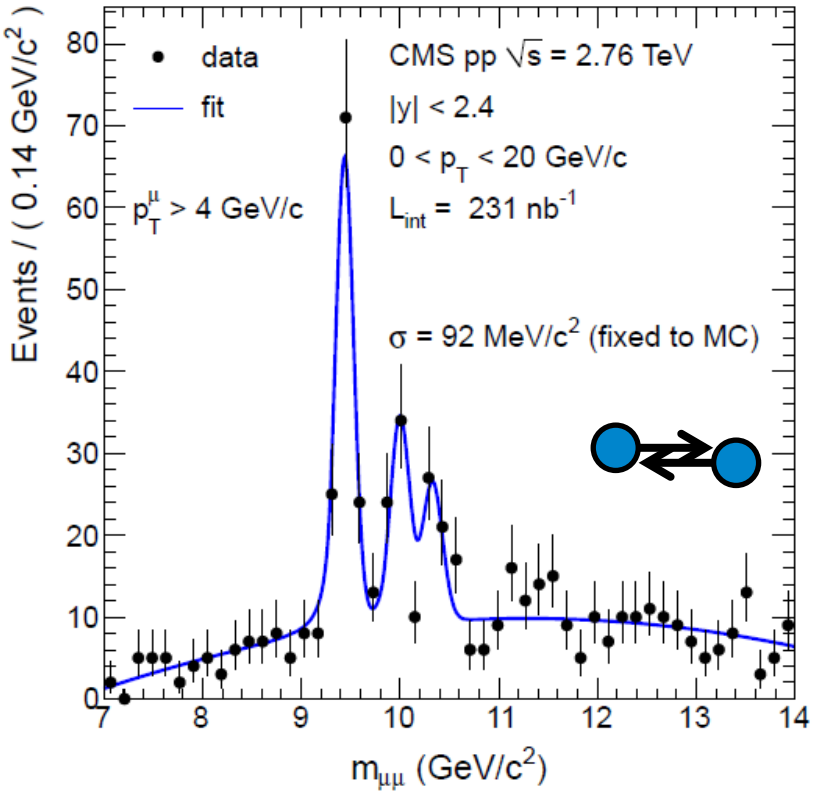
B → J/ψ suppression

- First measurement in heavy-ion collisions
- J/ψ coming from B decay are strongly suppressed
- b-quark energy loss / quenching ?

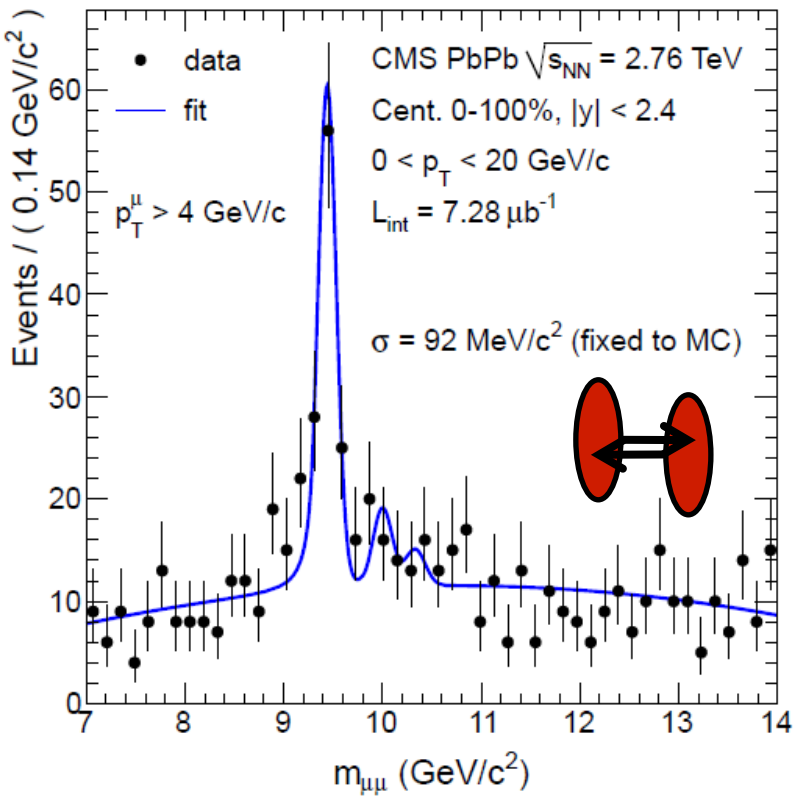


R_{AA} = 0.38 ± 0.07 ± 0.02 ± 0.03 (min. bias)

Υ excited states: suppression



minimum bias collisions



$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

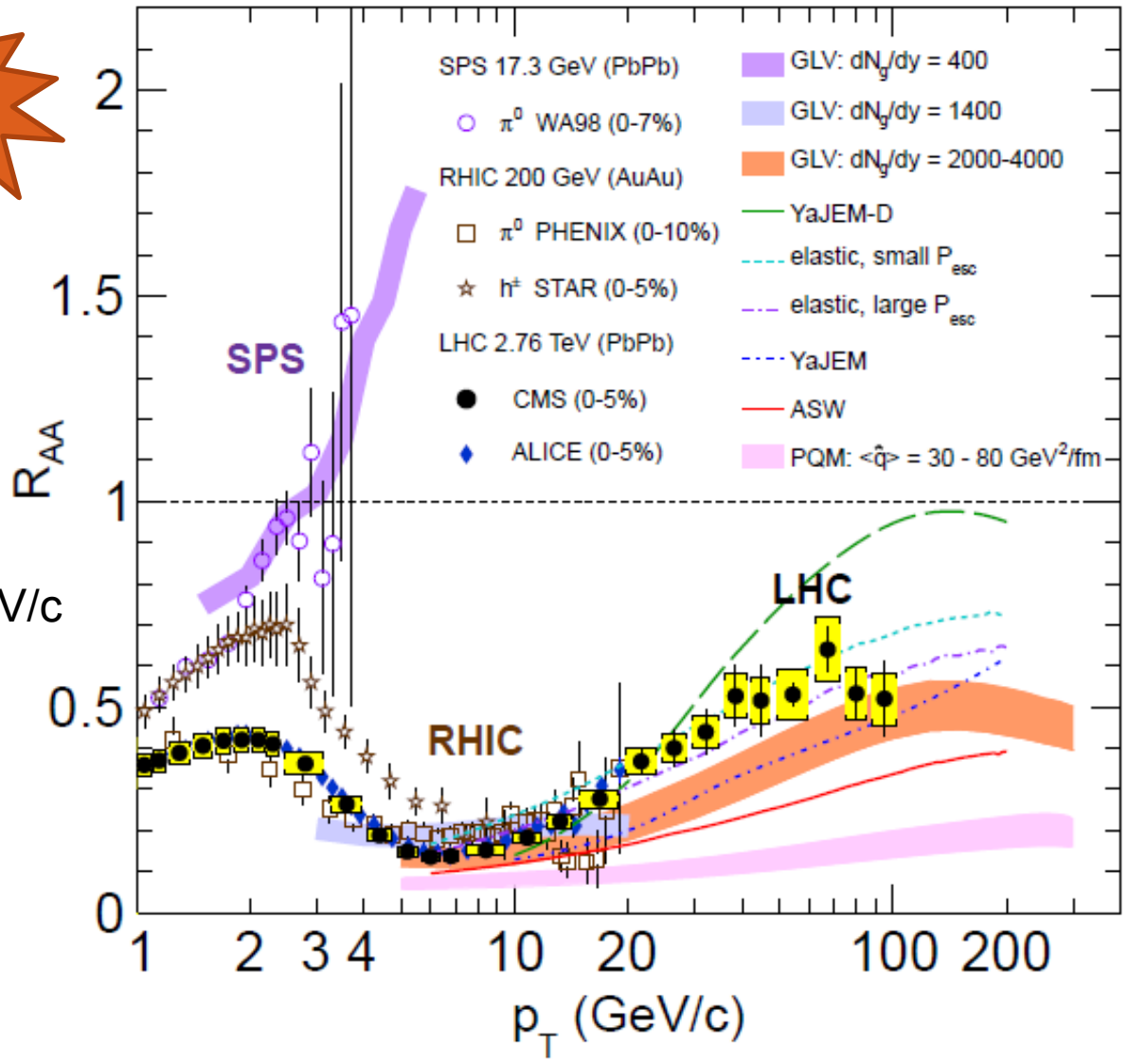
PRL 107 (2011) 052302

Charged particle R_{AA} to high p_T

2011 data

$$R_{AA}(p_T) = \frac{d^2N_{ch}^{AA}/dp_T d\eta}{\langle T_{AA}\rangle\, d^2\sigma_{ch}^{NN}/dp_T d\eta}$$

- p_T-reach extended to 100 GeV/c
- Increase, followed by a fairly flat region above 35 GeV/c



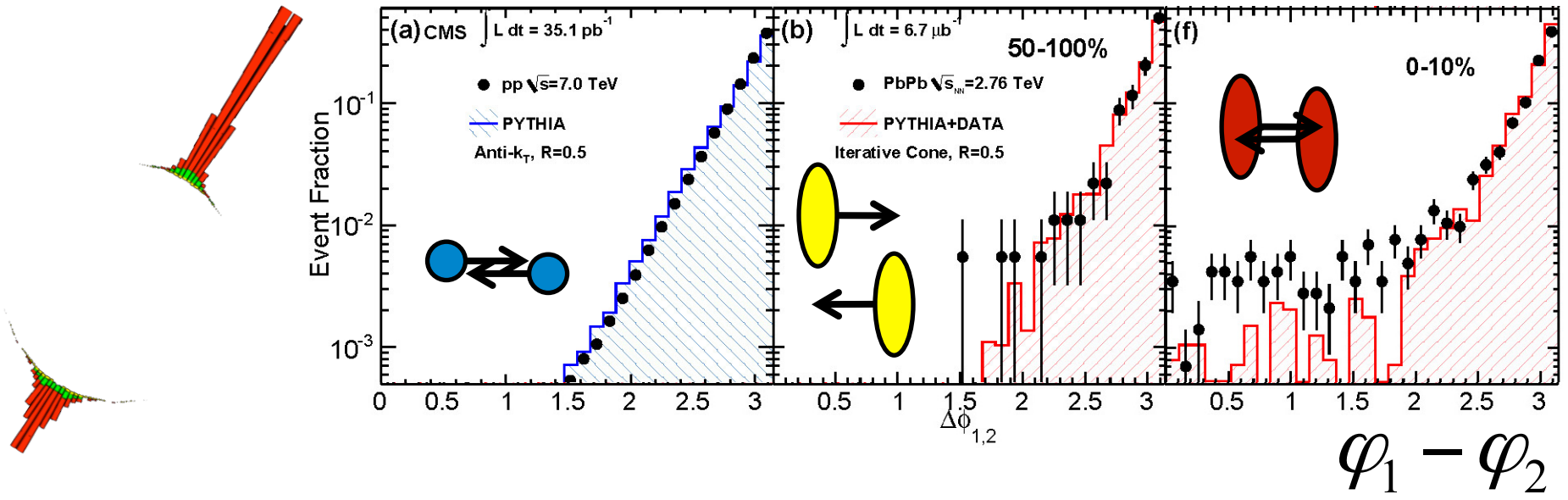
arXiv:1202.2554

central collisions

Di-jet imbalance

- The leading jet of $E_T^1 > 120$ GeV (trigger efficiency) and the
- sub-leading jet $E_T^2 > 50$ GeV (above background)

stay essentially back-to back ($\Delta\varphi = \pi$) but…



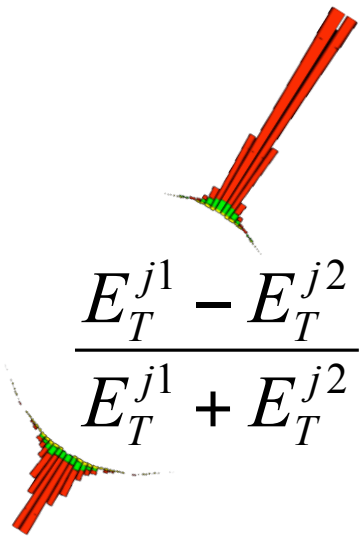
PRC84 (2011) 024906

Di-jet imbalance

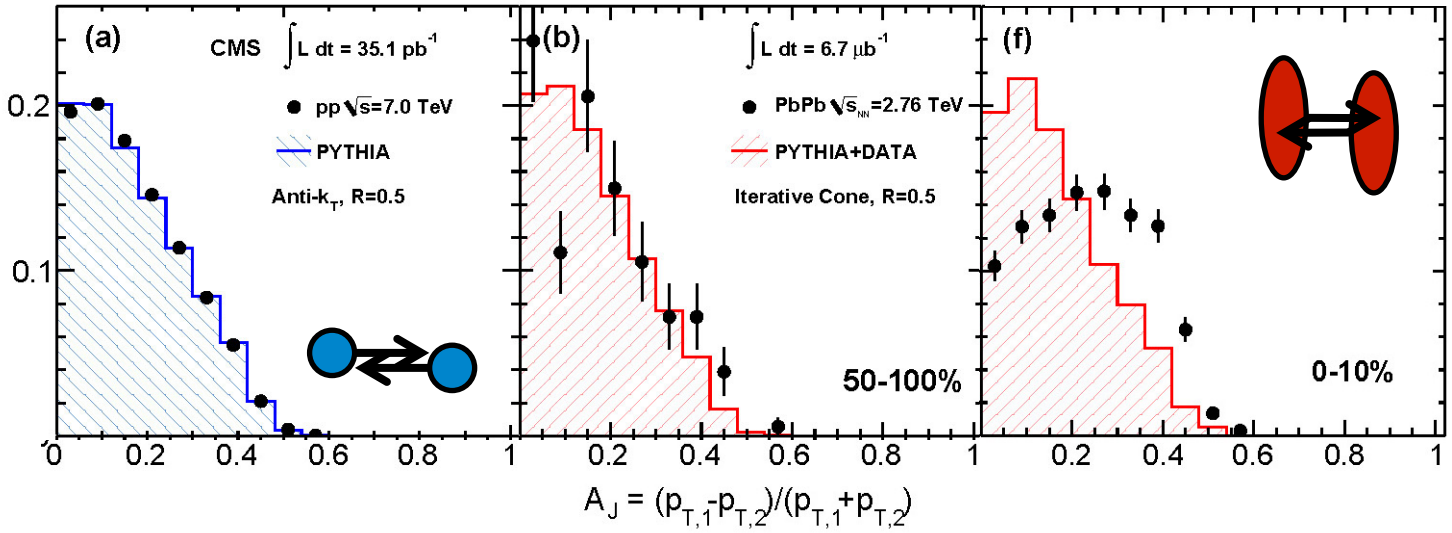
- The leading jet of $E_T^1 > 120$ GeV (trigger efficiency) and the
- sub-leading jet $E_T^2 > 50$ GeV (above background)

stay essentially back-to back ($\Delta\varphi = \pi$) but…

- highly unbalanced ($E_T^1 > E_T^2$) in central collisions:



$$\frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}}$$



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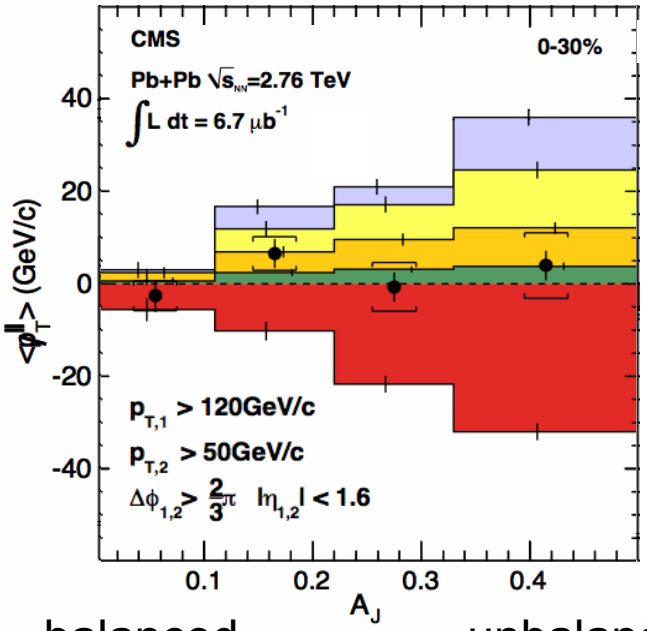
Finding back the missing energy…

$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{Tracks}} -p_{\mathrm{T}}^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$



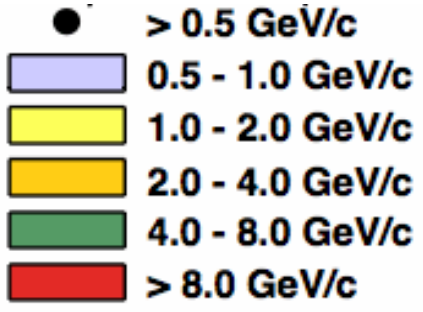
balanced dijets

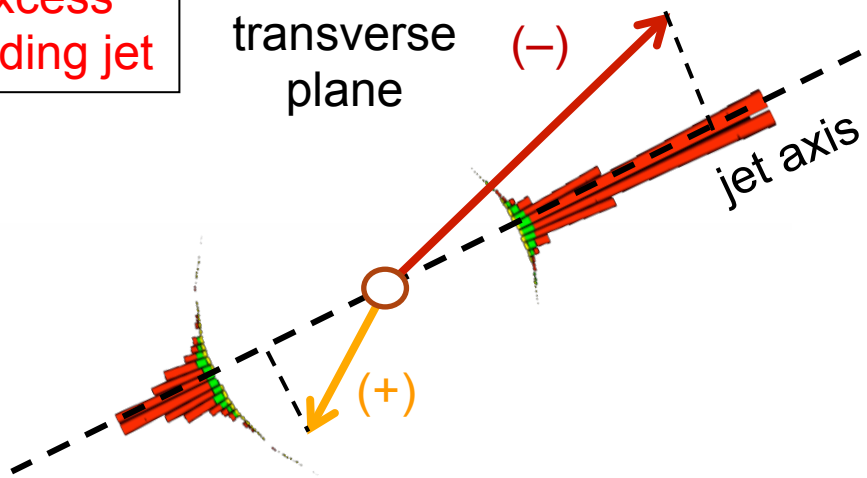
unbalanced dijets

Low p_T excess away from leading jet

Overall balance!

High p_T excess towards leading jet





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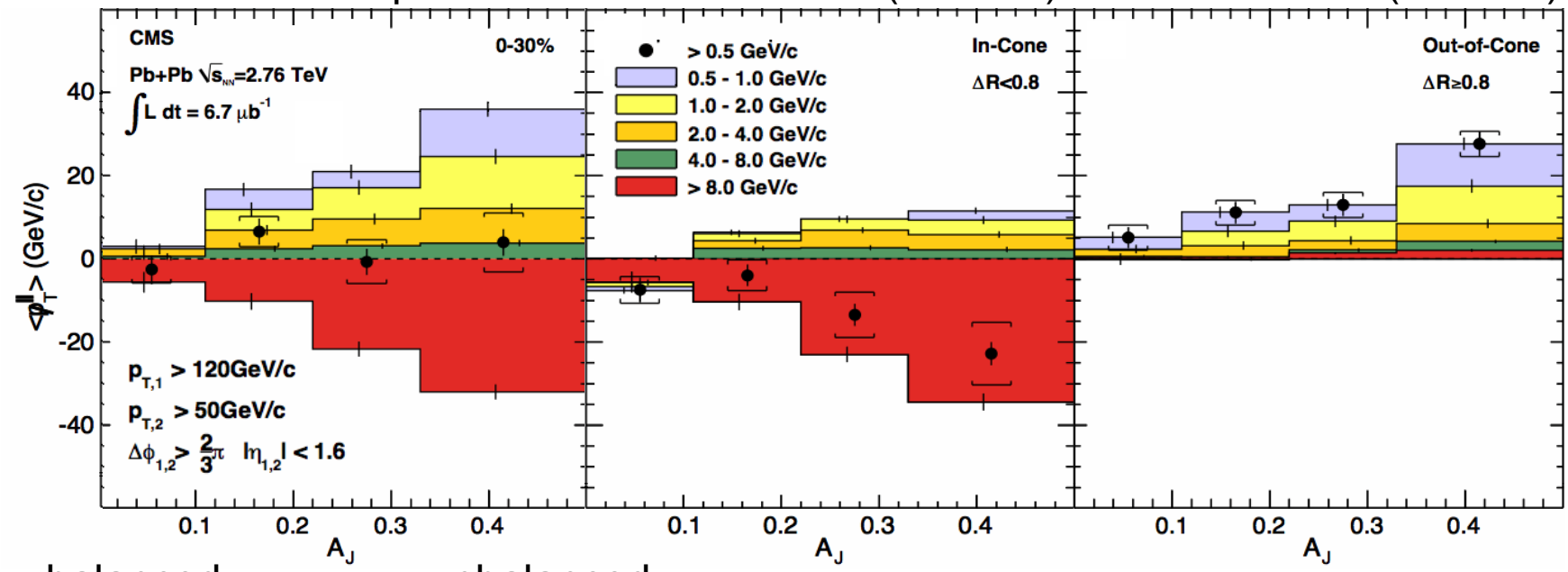
… in low momentum, out-of-cone tracks

All particles | in cone (ΔR<0.8) | out-of-cone (ΔR>0.8)



balanced dijets

unbalanced dijets

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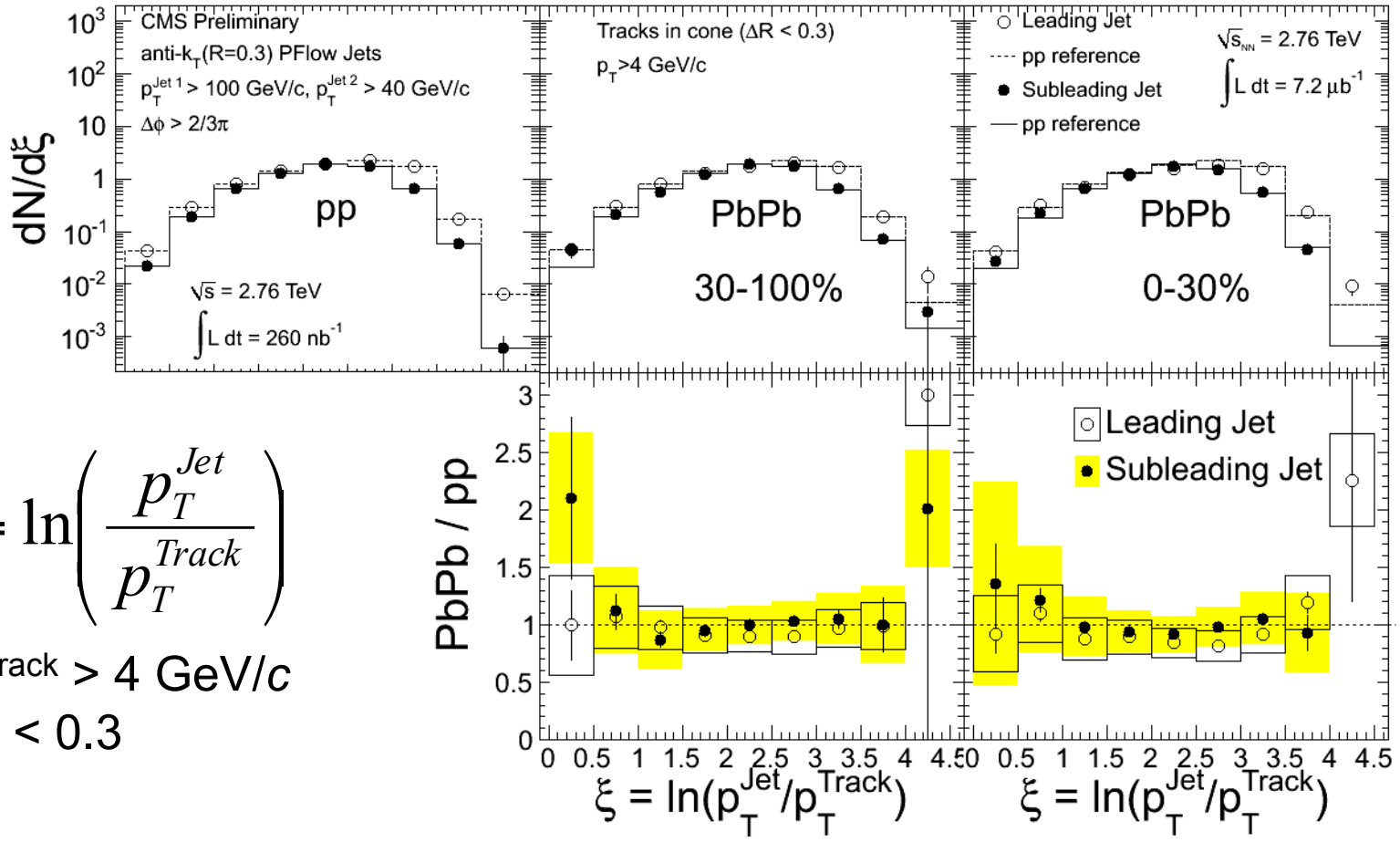
Fragmentation functions



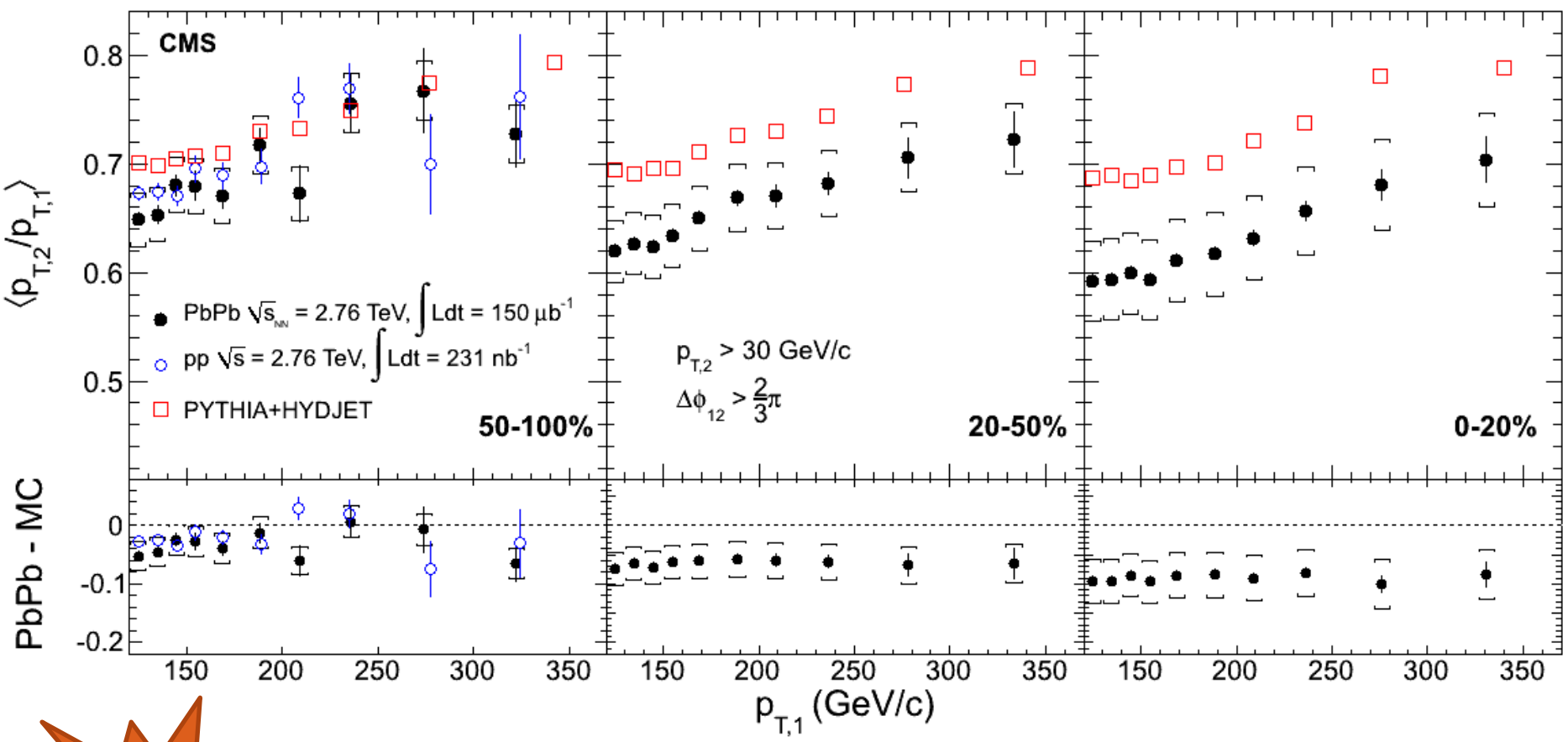
$$\xi = \ln\left(\frac{p_T^{Jet}}{p_T^{Track}}\right)$$

p_T^{Track} > 4 GeV/*c*
ΔR < 0.3

- Surviving jets are essentially unmodified, even the sub-leading (quenched) one

PAS HIN-11-004

p_T-dependence of jet quenching



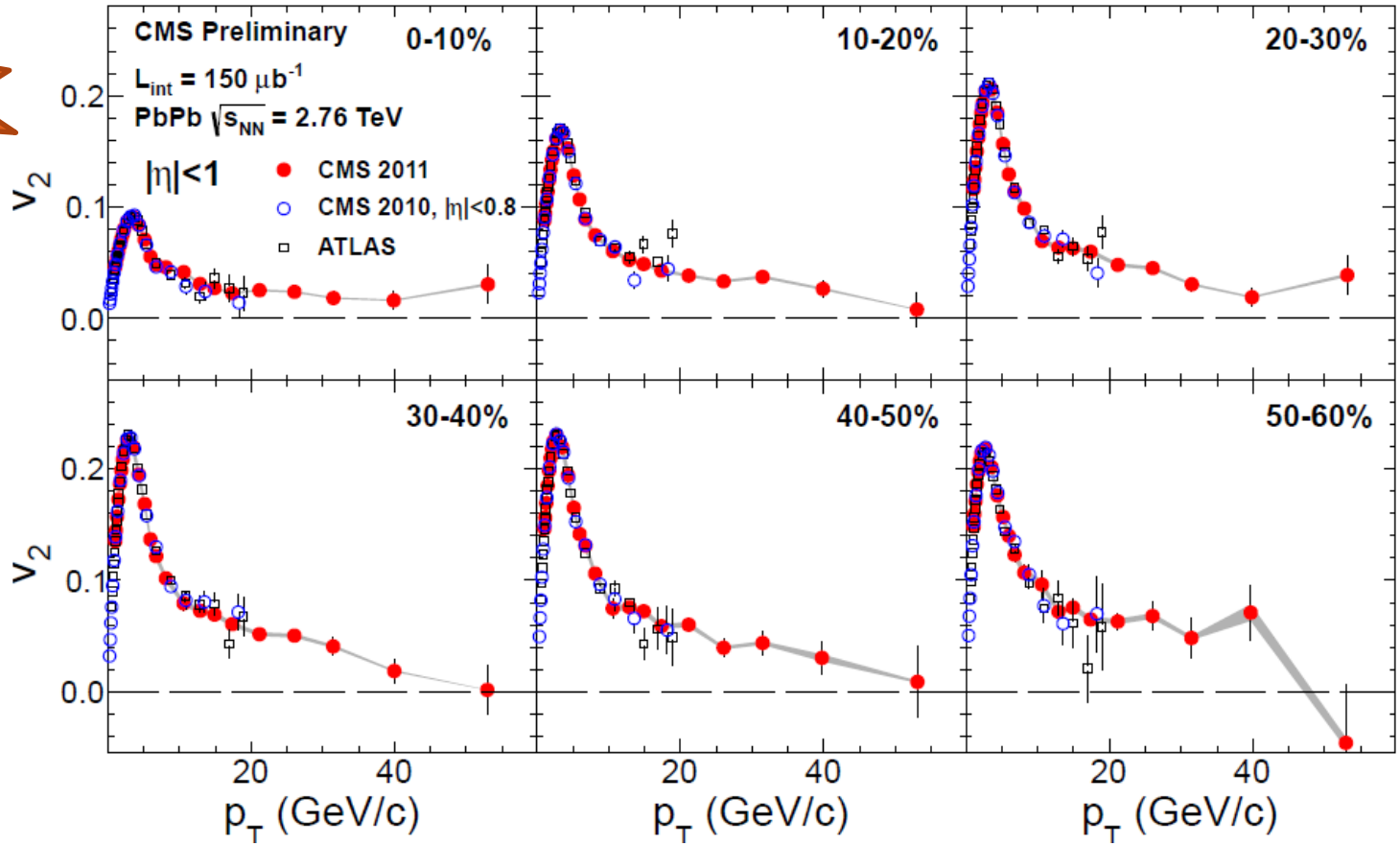
2011 data

- $p_{T,2}/p_{T,1}$ increases with p_T
  - Less jet splitting, better resolution
  - Reference is PYTHIA+HIDJET
- In central events, significant energy loss!

arXiv:1202.5022

Azimuthal angle dependence: v_2 at high p_T

2011 data



- v_2 measurement extended up to 60 GeV/c
  - Full 2011 statistics, high-p_T track trigger
- Anisotropy driven by the jet energy loss
  - Gradual decrease, at high p_T compatible with zero in mid-central collisions

Conclusions

- Photons, Z and W are unmodified by the created medium
- First steps toward γ-jet and Z-jet measurements
  - Photons and Z acting as in-situ calibrators of opposite jet…
  - First time accessible in heavy-ion collisions
- J/ψ, ϒ excited states and high p_T charged particles are suppressed
- B → J/ψ
  - Decays outside the medium, reflects the fate of the b quark
  - B-mesons are also suppressed
  - b-quark energy loss?
- Large imbalance of di-jet energies
  - But, angular correlation is conserved
- Energy imbalance compensated by low p_T particles over a large angle
- Jet fragmentation independent of energy loss

10 submitted papers on PbPb collisions

~20x more data from 2011 already producing results