Electromagnetic field effects on Υ-meson suppression in PbPb collisions at LHC energies

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Outline

1. Introduction to the topic
2. Our previous work
3. What’s new?
4. Results

Introduction to the topic

The idea behind Υ-meson suppression

Υ mesons = spin-triplet $b\bar{b}$ states

- large b mass
- tight $b\bar{b}$ binding

clean theoretical treatment possible

heavy-ion collision

- N_{coll} nucleon–nucleon collisions
- Υ-meson yield: N_{AA}

proton–proton collision

- 1 nucleon–nucleon collision
- Υ-meson yield: N_{pp}

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- 1 nucleon–nucleon collision
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Idea: Compare the whole to the sum of its parts ...

$\hookrightarrow$ Nuclear modification factor: $R_{AA} = \dfrac{N_{AA}}{N_{\mathrm{coll}} N_{\mathrm{pp}}}$

$R_{AA} < 1$: "suppression"

$R_{AA} > 1$: "enhancement"

Our previous work

Key aspects of our current model (I)

- In-medium Υ properties: pNRQCD formalism [Nendzig, GW, PRC 87 (2013)]
  - energy E
  - damping decay width Γ_{damp}

  $\left.\begin{array}{l} \text{energy } E \\ \text{damping decay width } \Gamma_{\mathrm{damp}} \end{array}\right\}$ complex potential V
  - gluodissociation decay width Γ_{diss}

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$\hookrightarrow$ dissociation by screening, collisional damping, & gluodissociation:

$$\Gamma_{\text{tot}} = \begin{cases} \Gamma_{\text{damp}} + \Gamma_{\text{diss}} & \text{for } E < \lim_{r\to\infty} \operatorname{Re} V \\ \infty & \text{for } E > \lim_{r\to\infty} \operatorname{Re} V \end{cases}$$

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- Decay cascade $\rightarrow$ feed-down from higher to lower excited states

[JH, Nendzig, GW, PRC 95 (2017)]

Key aspects of our current model (II)

- Υ states considered [Vaccaro, Nendzig, GW, EPL 102 (2013)]
  - $l = 0$: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$
  - $l = 1$: $\chi_b(1P)$, $\chi_b(2P)$, $\chi_b(3P)$

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- QGP as perfect fluid of gluons & "massless" u, d, s quarks
  - Bjorken-flow with transverse expansion [Nendzig, GW, JPG:NPP 41 (2015)]
  - large Υ mass $\rightarrow$ Doppler-shifted temperature [JH, Nendzig, GW, PRC 95 (2017)]

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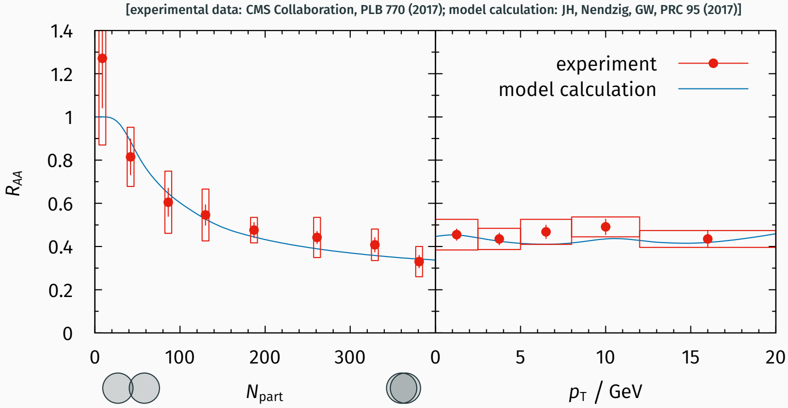
  - large Υ mass $\rightarrow$ Doppler-shifted temperature [JH, Nendzig, GW, PRC 95 (2017)]
- 2 free parameters
  - initial central QGP temperature T_0
  - Υ meson formation time τ_F

Υ(1S) results for PbPb @ 2.76 TeV

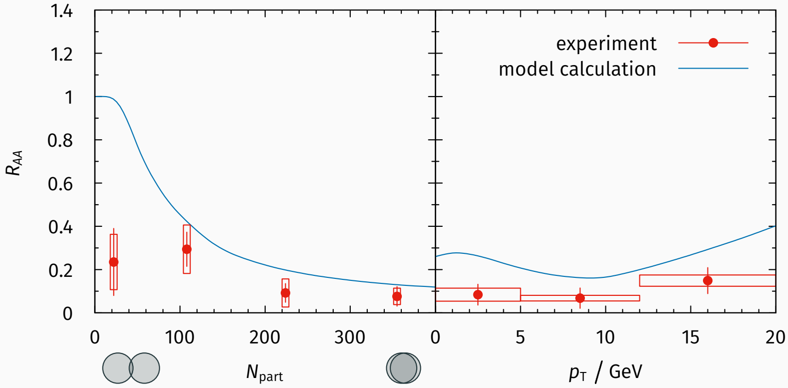


Fit to $R_{AA}(p_T) \rightarrow T_0 = 480$ MeV, $\tau_F = 0.4$ fm

↪ **Current model can describe ground state well.**

Υ(2S) results for PbPb @ 2.76 TeV

[experimental data: CMS Collaboration, PLB 770 (2017); model calculation: JH, Nendzig, GW, PRC 95 (2017)]



⊕ model follows trend in p_{T}-dependent data

⊖ overall missing suppression, especially in peripheral collisions

↪ **Additional suppression mechanisms needed for excited states?**

What’s new?

Υ-meson dissociation through electromagnetic fields

- External electromagnetic field $\rightarrow$ dipole terms in pNRQCD action:

$$V \mapsto V - \vec{p} \cdot \vec{E} - \vec{\mu} \cdot \vec{B}$$

$\hookrightarrow$ electromagnetic contribution to screening

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- Expected magnetic field strength: $B \sim Zeb\gamma/R^3$ [Tuchin, AHEP 2013 (2013)]

Z: proton number, e: elementary charge, b: impact parameter, γ: Lorentz factor, R: nuclear radius

  - $B \propto b$ $\rightarrow$ required centrality dependence
  - e.m. field in pp collision negligible

Electromagnetic field calculation (I)

QGP material properties

- permittivity ε
- permeability μ

$\left.\right\}$ unknown

- conductivity σ

lattice estimates

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- conductivity σ — lattice estimates

$\Longrightarrow$

Conservative estimate [Tuchin, PRC 88 (2013)]

- $\varepsilon \equiv \mu \equiv 1$
- $\sigma \approx 5.8$ MeV [Ding *et al.*, PRD 83 (2011)]

$\Downarrow$ Maxwell's equations

e.m. field of moving point charge

$\Downarrow$ linearity

E, B of two colliding Pb nuclei

Electromagnetic field calculation (II)

- Modeling of Pb nuclei:
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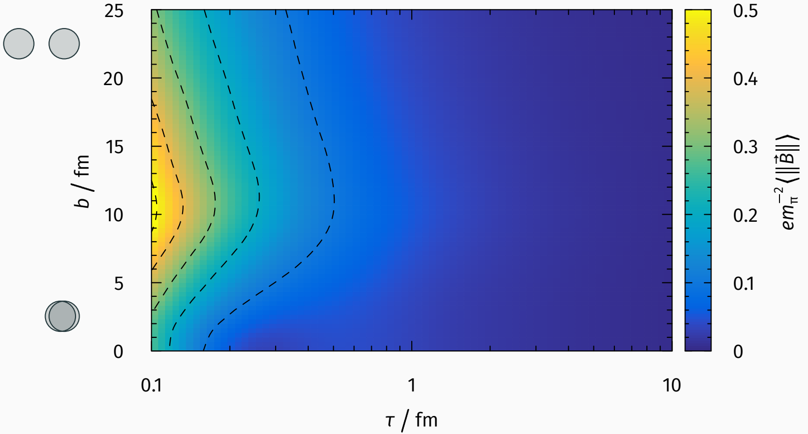
- Modeling of Pb nuclei:
  - *rest frame:* Woods–Saxon shaped
  - *lab frame:* Lorentz-contracted to 2D slabs
- Baryon stopping: *E*, *B* depend very weakly on rapidity
  - neglect separation into participants & spectators
  - uniform deceleration = most probable participant rapidity

$$y = \frac{1}{1+\lambda}\left[y_{\text{beam}} - \ln A^{1/6}\right] + c < y_{\text{beam}}$$

$\lambda = 0.2$: gluon saturation scale exponent, $c = -0.2$: empirical constant

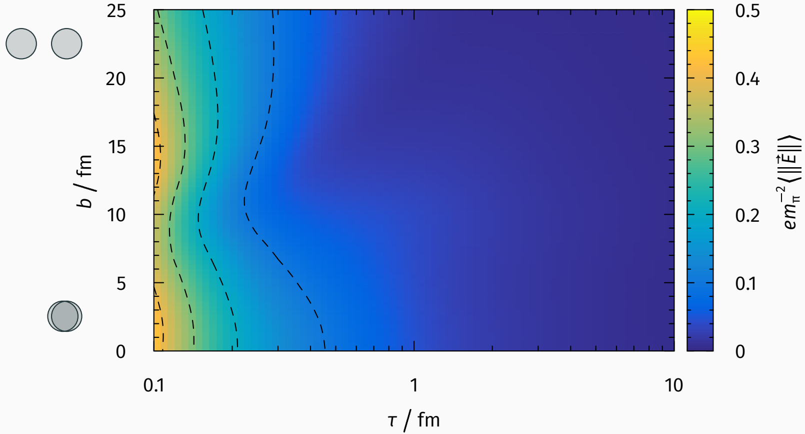
[Mehtar-Tani, GW, PRL 102 (2009); GW, EPJA 52 (2016)]

Magnetic field strength for PbPb @ 2.76 TeV



$$\frac{\left|\vec{\mu}\cdot\vec{B}\right|}{\left|\mathrm{Re}\, V\right|} \lesssim 0.004 \text{ during } \Upsilon \text{ lifetime}$$

Electric field strength for PbPb @ 2.76 TeV



$$\frac{|\vec{p} \cdot \vec{E}|}{|\mathrm{Re}\, V|} \lesssim 0.02 \text{ during } \Upsilon \text{ lifetime}$$

Results

Impact of “electromagnetic screening” on R_{AA}

$\Upsilon(1S)$

$$\left|R_{AA} - R_{AA}^{\vec{B}=\vec{E}=\vec{0}}\right| \lesssim 2 \times 10^{-3}$$

$\hookrightarrow$ ground state unaffected ✓

Impact of "electromagnetic screening" on R_{AA}

Υ(1S)

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$\hookrightarrow$ ground state unaffected ✓

Υ(2S)

$$\left|R_{AA} - R_{AA}^{\vec{B}=\vec{E}=\vec{0}}\right| \lesssim 4 \times 10^{-3}$$

$\hookrightarrow$ effect also negligible ✗

Conclusion: **"Electromagnetic screening" insignificant in LHC Run I**

Outlook

Is further investigation of "electromagnetic *screening*" worthwhile?

- effect on R_{AA} less than 1 %
- E, B depend very weakly on $\sqrt{s}_{\mathrm{NN}}$
- $E, B \sim Z$

$\hookrightarrow$ **Probably not.**

Outlook

Is further investigation of "electromagnetic *screening*" worthwhile?

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$\hookrightarrow$ **Probably not.**

More promising effects related to electromagnetic fields:

- higher order "non-screening" terms in pNRQCD action?
- E, B strongest at small $\tau \;\rightarrow\; \Upsilon$-formation process?

Thank you!

More details on this topic:

[J. Hoelck, G. Wolschin, EPJA (submitted)]

Backup

Kramers–Kronig relations

- Complex permittivity:

$$\hat{\varepsilon}(\omega) = \varepsilon(\omega) + \mathrm{i}\,\frac{\sigma(\omega)}{\omega}$$

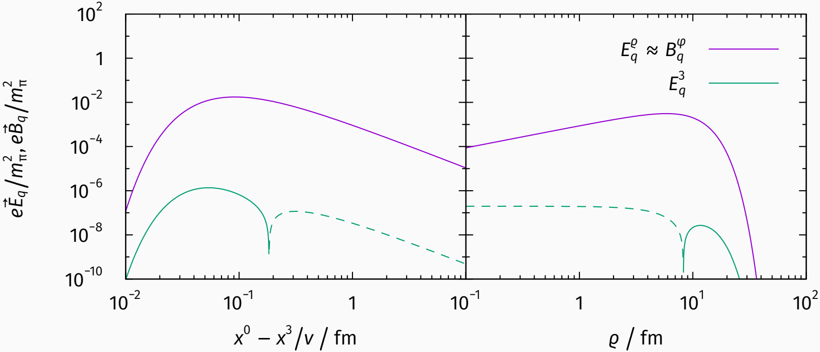
- Causality:

$$\sigma(\omega) = -\frac{\omega}{\pi}\,\mathcal{P}\int_{-\infty}^{\infty} \mathrm{d}\omega'\,\frac{\varepsilon(\omega')}{\omega' - \omega}$$

Preparation: Single moving point-like particle

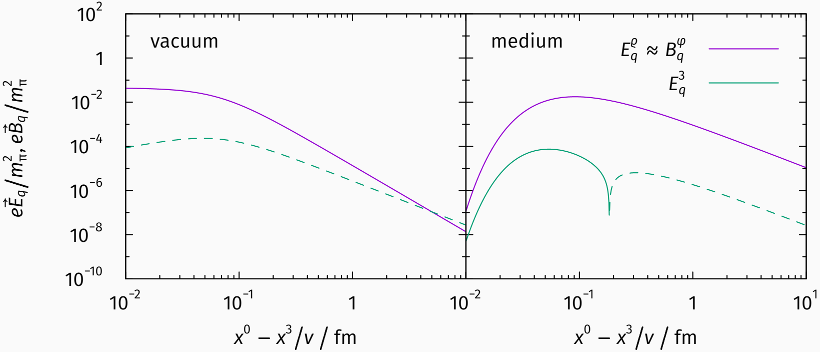
- charge density: $\rho(x^0, \vec{x}) = q\,\delta(x^1)\,\delta(x^2)\,\delta(x^3 - vx^0)$
- current density: $\vec{j}(x^0, \vec{x}) = \underbrace{v\,\rho(x^0, \vec{x})\,\vec{e}_3}_{\text{moving charge}} + \underbrace{\sigma \vec{E}_q(x^0, \vec{x})}_{\text{Ohm's law}}$

(x^0, x^1, x^2, x^3): coordinate frame, q: particle charge, v: particle velocity, $\vec{E}_q$: particle electric field



$\operatorname{artanh}(v) = 7$, $q = +e$; left: $\varrho = \sqrt{(x^1)^2 + (x^2)^2} = 5\,\text{fm}$, right: $x^0 - x^3/v = 0.5\,\text{fm}$

Point charge EMF: vacuum vs. medium



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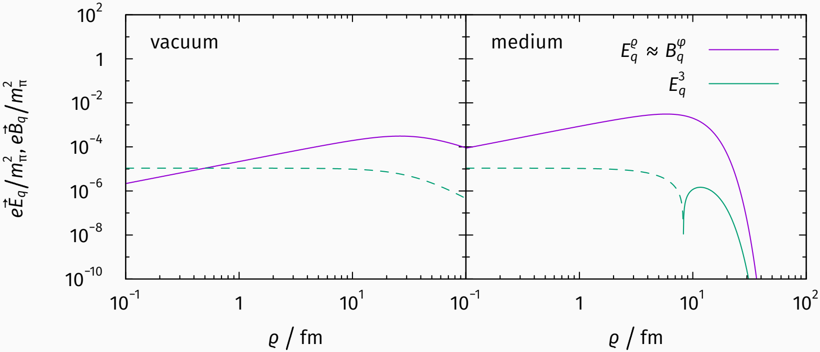


artanh$(v) = 5$, $q = +e$, $t_{\mathrm{eff}} = 0.5\,\mathrm{fm}$

From point charges to nuclei

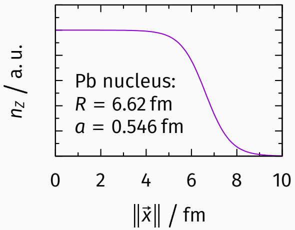
- Nucleus: homogeneous charge distribution
  - *rest frame:* Woods–Saxon shape

$$n_Z(\vec{x}) \propto \left[1 + \exp\left(\frac{\|\vec{x}\| - R}{a}\right)\right]^{-1}$$

R: nuclear radius, a: diffuseness

  - *lab frame:* Lorentz-contracted to 2D slap

$$n_Z^{\mathrm{con}}(\vec{x}) = \delta(x^3) \int \mathrm{d}x^3\, n_Z(\vec{x})$$



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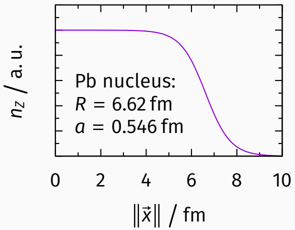

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- Linearity of Maxwell's equations: ($\vec{B}_{\text{nuc}}$ analogously)

$$\vec{E}_{\text{nuc}}(x^0, \vec{x}) = \int \mathrm{d}^3y \, n_Z^{\text{con}}(\vec{y}) \, \vec{E}_q(x^0, \vec{x} - \vec{y})$$

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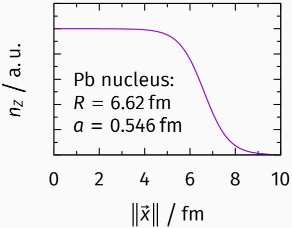

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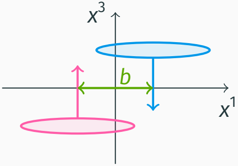
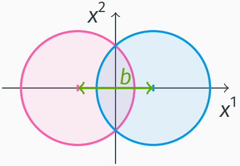
- $n_Z^{\mathrm{con}}(\vec{x}) \equiv n_Z^{\mathrm{con}}(\varrho)\,\delta(x^3) \;\rightarrow\; \vec{E}_{\mathrm{nuc}}, \vec{B}_{\mathrm{nuc}}$ inherit symmetries:

$$\vec{E}_{\mathrm{nuc}} = E^{\varrho}_{\mathrm{nuc}} \vec{e}_{\varrho} + E^{3}_{\mathrm{nuc}} \vec{e}_3 , \qquad \vec{B}_{\mathrm{nuc}} = B^{\varphi}_{\mathrm{nuc}} \vec{e}_{\varphi} , \qquad E^{\varrho}_{\mathrm{nuc}} \approx B^{\varphi}_{\mathrm{nuc}}$$

Two colliding nuclei





- "Naive" ansatz for combined electric field: ($\vec{B}$ analogously)

$$\vec{E}(x^0, \vec{x}) = \vec{E}_{\text{nuc}}(x^0, \vec{x} + \vec{b}/2)\big|_{v>0} + \vec{E}_{\text{nuc}}(x^0, \vec{x} - \vec{b}/2)\big|_{v<0}$$

$\vec{b} = b\vec{e}_1$: impact parameter

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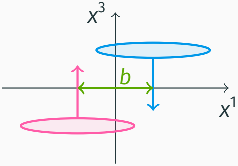

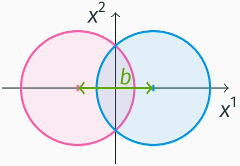

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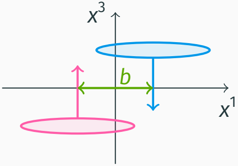

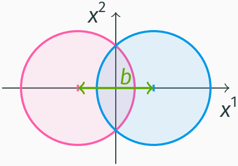

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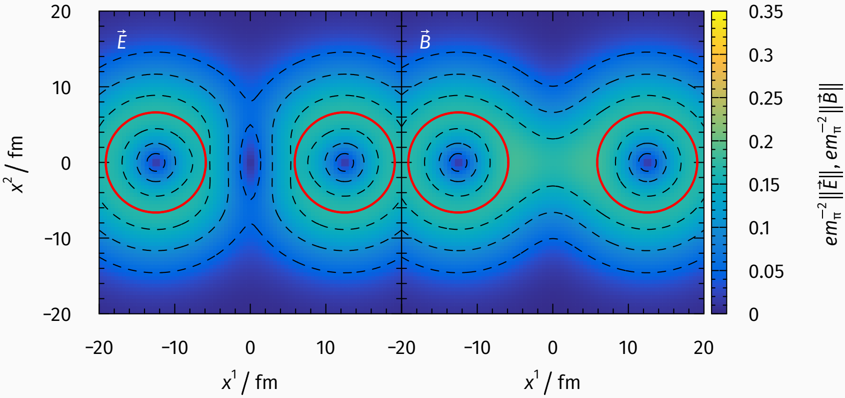
- Value of v? Before/after initial collision at $x^0 = 0$?

$$\operatorname{artanh}(|v|) = \begin{cases} y_{\text{beam}} & \text{for } x^0 < 0 \\ \frac{1}{1+\lambda}\left[y_{\text{beam}} - \ln\left(A^{1/6}\right)\right] + c < y_{\text{beam}} & \text{for } x^0 > 0 \end{cases}$$

$\lambda = 0.2$: gluon saturation scale exponent, $c = -0.2$: empirical constant

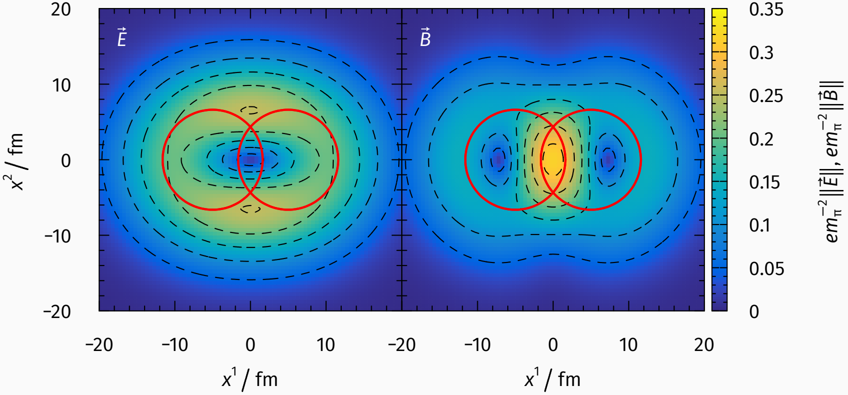
[Mehtar-Tani, GW, PRL 102 (2009); GW, EPJA 52 (2016)]

EMF in transverse plane: b = 25 fm



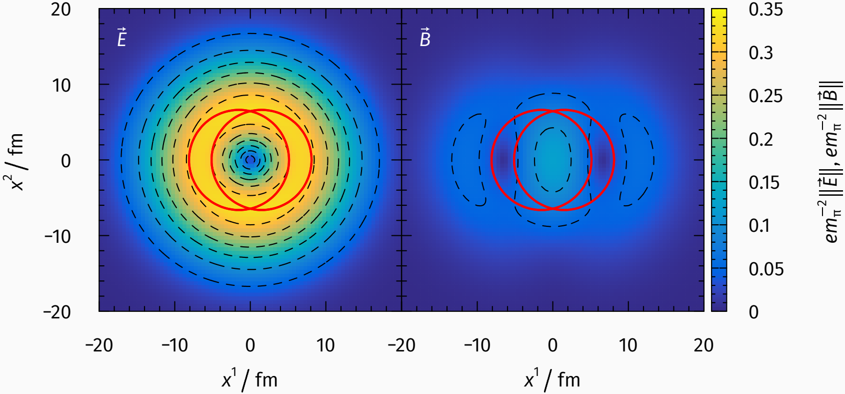
Pb nuclei, $x^0 = 0.5$ fm, $x^3 = 0$ fm, $y_{\text{beam}} = 7.987$

EMF in transverse plane: b = 10 fm



Pb nuclei, x^0 = 0.5 fm, x^3 = 0 fm, y_{beam} = 7.987

EMF in transverse plane: b = 3 fm



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Magnetic dipole term

- $b\bar{b}$ state: two spin configurations
  - $s = 0$: η_b meson, $m_s = 0$
  - $s = 1$: Υ meson, $m_s \in \{-1, 0, +1\}$

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- $b\bar{b}$ state: two spin configurations
  - $s = 0$: η_b meson, $m_s = 0$
  - $s = 1$: Υ meson, $m_s \in \{-1, 0, +1\}$
- $\vec{\mu} = 2\mu_b\vec{\sigma}$ acts on $b\bar{b}$ spin wave function

[Filip, PoS CPOD 2013 (2013)]
[Alford, Strickland, PRD 88 (2013)]

  - mixing of $\Upsilon(s = 1)$ and η_b $(s = 0)$ spin wave functions
  - energy shift: $-\vec{\mu}\cdot\vec{B} \mapsto E_{\mathrm{mag}} = \begin{cases} (-1)^s\Delta & \text{for } m_s = 0 \\ 0 & \text{otherwise} \end{cases}$

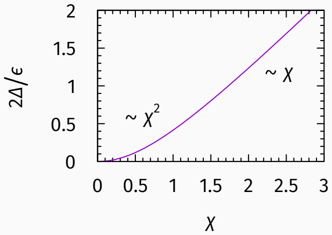
with

s: spin quantum number, m_s: spin projection quantum number

$$\Delta = \frac{\epsilon}{2}\left(\sqrt{1+\chi^2} - 1\right)$$

$$\chi = \frac{4\mu_b\|\vec{B}\|}{\epsilon}$$

$$\epsilon = \left[E\big|_{s=1} - E\big|_{s=0}\right]_{\vec{B}=\vec{0}}$$



Electric dipole term

- $\vec{p} = q_\mathrm{b}\vec{r}$: inner structure of $\mathrm{b}\bar{\mathrm{b}}$ state

  $\hookrightarrow$ cannot be determined for every single meson

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$$-\vec{p} \cdot \vec{E} \;\mapsto\; -q_{\mathrm{b}} r_{\mathrm{RMS}} \left\|\vec{E}\right\| \cos\left(\vartheta\right) = E_{\text{elec}}$$

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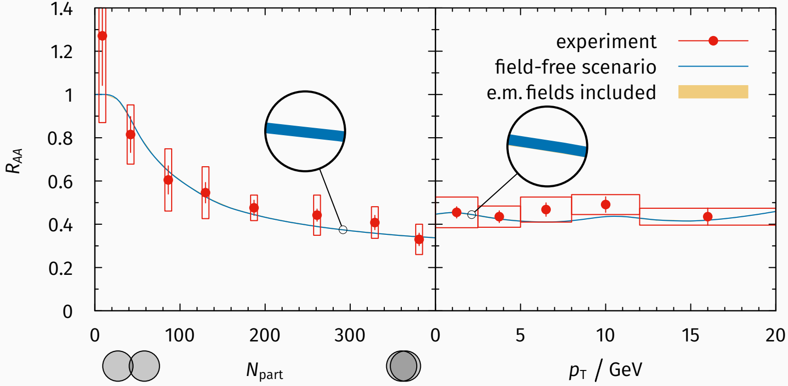
- initial problem remains: value of $\vartheta = \measuredangle\left(\vec{p}, \vec{E}\right)$?

  $\hookrightarrow$ treat as free parameter for now

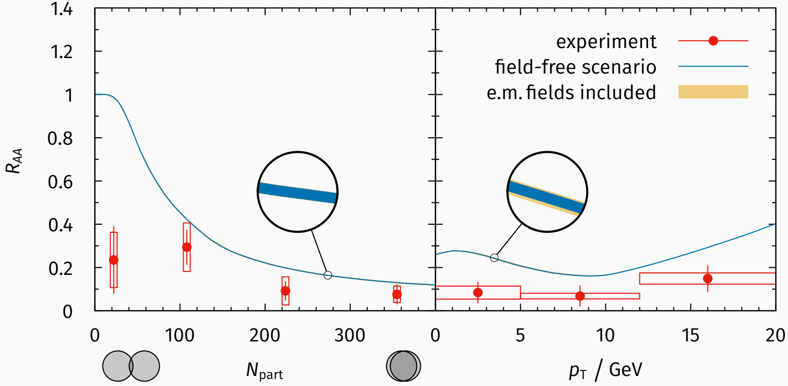
Υ(1S) results for PbPb @ 2.76 TeV



- $R_{AA} - R_{AA}\big|_{\vec{E}=\vec{0}} \lesssim 2 \times 10^{-3}$
- $R_{AA} - R_{AA}\big|_{\vec{B}=\vec{0}} \lesssim 10^{-4}$

$\Big\}$ Υ(1S) unaffected ✓

Υ(2S) results for PbPb @ 2.76 TeV



- $R_{AA} - R_{AA}\big|_{\vec{E}=\vec{0}} \lesssim 4 \times 10^{-3}$
- $R_{AA} - R_{AA}\big|_{\vec{B}=\vec{0}} \lesssim 10^{-4}$

Υ(2S) also unaffected ✗