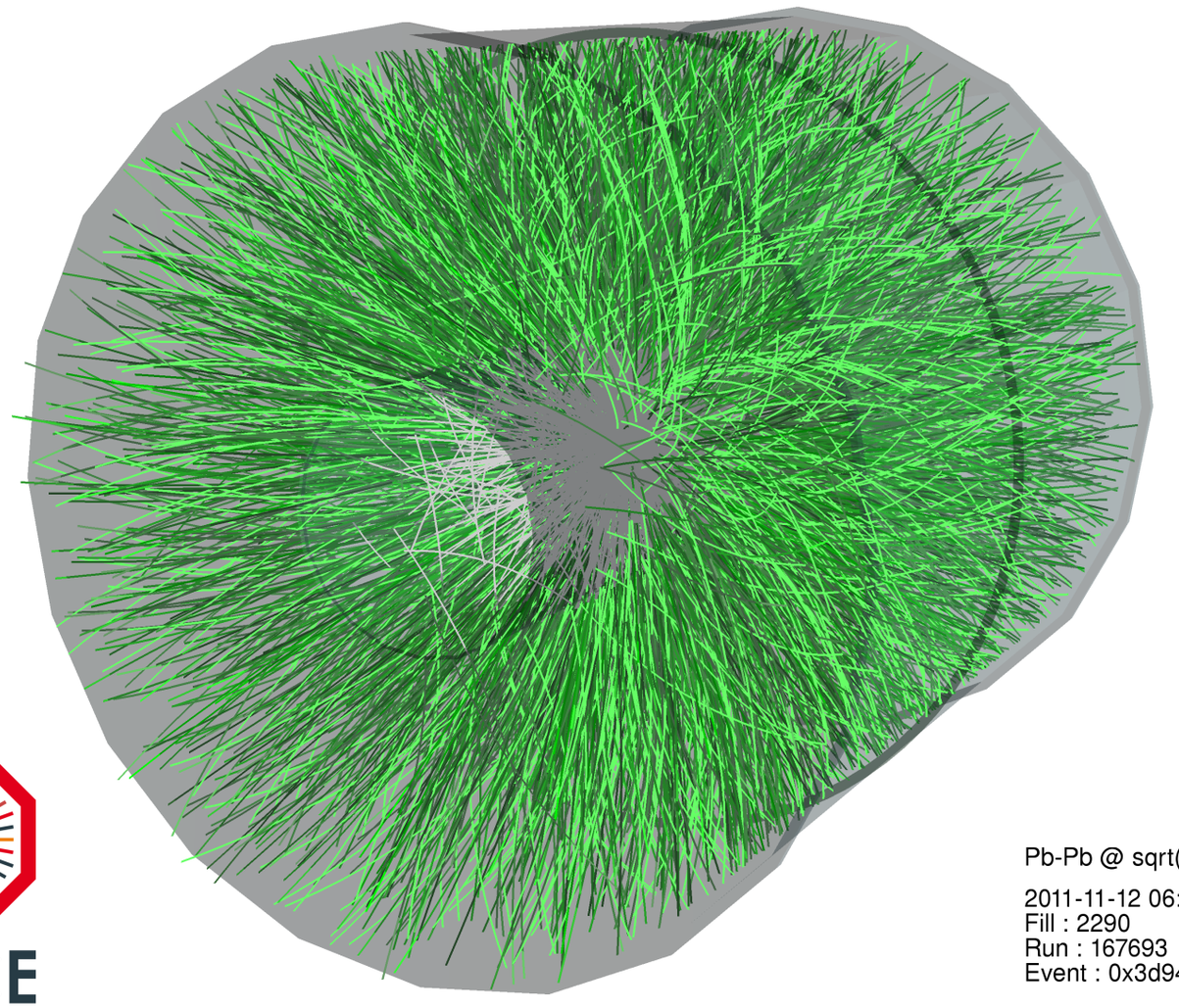
Holographic 3-jet Events in Strongly Coupled Yang-Mills Plasma

Jorge Casalderrey-Solana
(in collaboration with A. Ficnar)

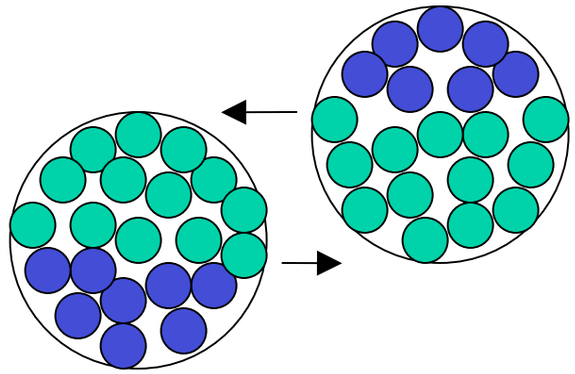
Heavy Ion Collisions at the LHC



Pb-Pb @ sqrt(s) = 2.76 ATeV

2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

ALICE
A JOURNEY OF DISCOVERY



➤ Up to 400 participating nucleons

➤ About 20.000 particles

➤ E_T ~1 GeV per particles

➤ Very large initial energy density

$$\varepsilon = \frac{1}{\pi R^2 \tau} \frac{dE_t}{dy}$$

$\varepsilon\tau \sim 16$ GeV/(fm^{2}c)

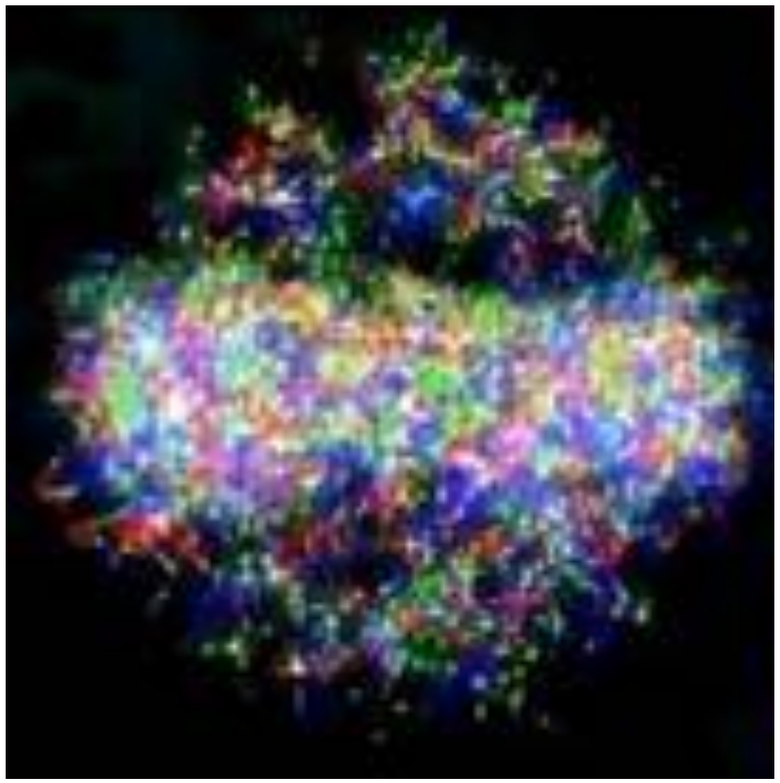
The Little Bang

Very strong collective effects

- Emission of 20.000 particles correlated with the impact parameter

- Correlation measured in terms of Fourier coefficients

- Hydrodynamic explosion



The quark gluon plasma is a very good fluid

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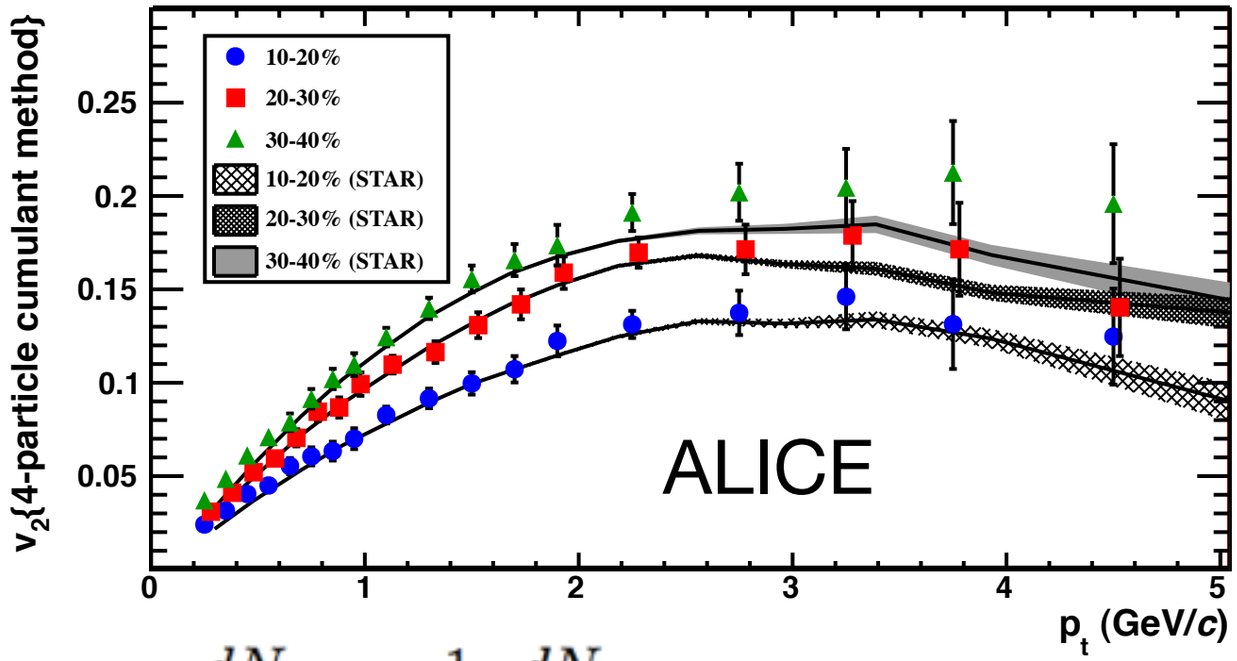

$$\frac{dN}{d^2p_T d\phi} = \frac{1}{2\pi}\frac{dN}{d^2p_T}\left(1 + 2v_2(p_t)\cos 2\phi + \ldots\right)$$

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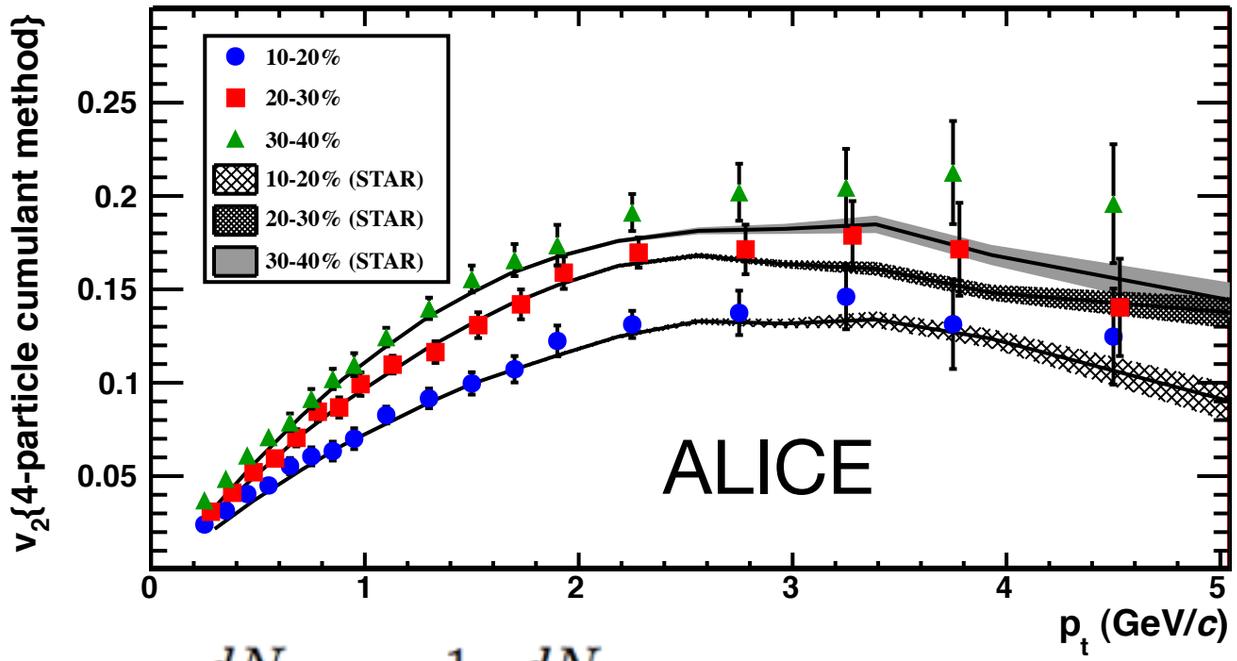


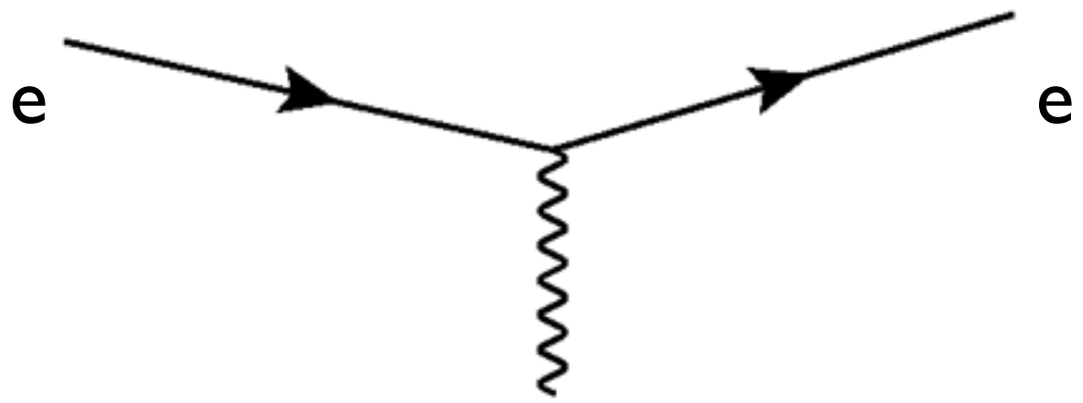
$$\frac{dN}{d^2p_T d\phi} = \frac{1}{2\pi}\frac{dN}{d^2p_T}\left(1 + 2v_2(p_t)\cos 2\phi + ...\right)$$

$$\left(\frac{\eta}{s}\right)_{T_c} = 0.08 \pm 0.05$$

J. Bernhard, J.S. Moreland, S. Bass, J. Liu, U. Heinz arXiv:1605.03954

Microscopic Structure of Plasma

- Can we probe the system?



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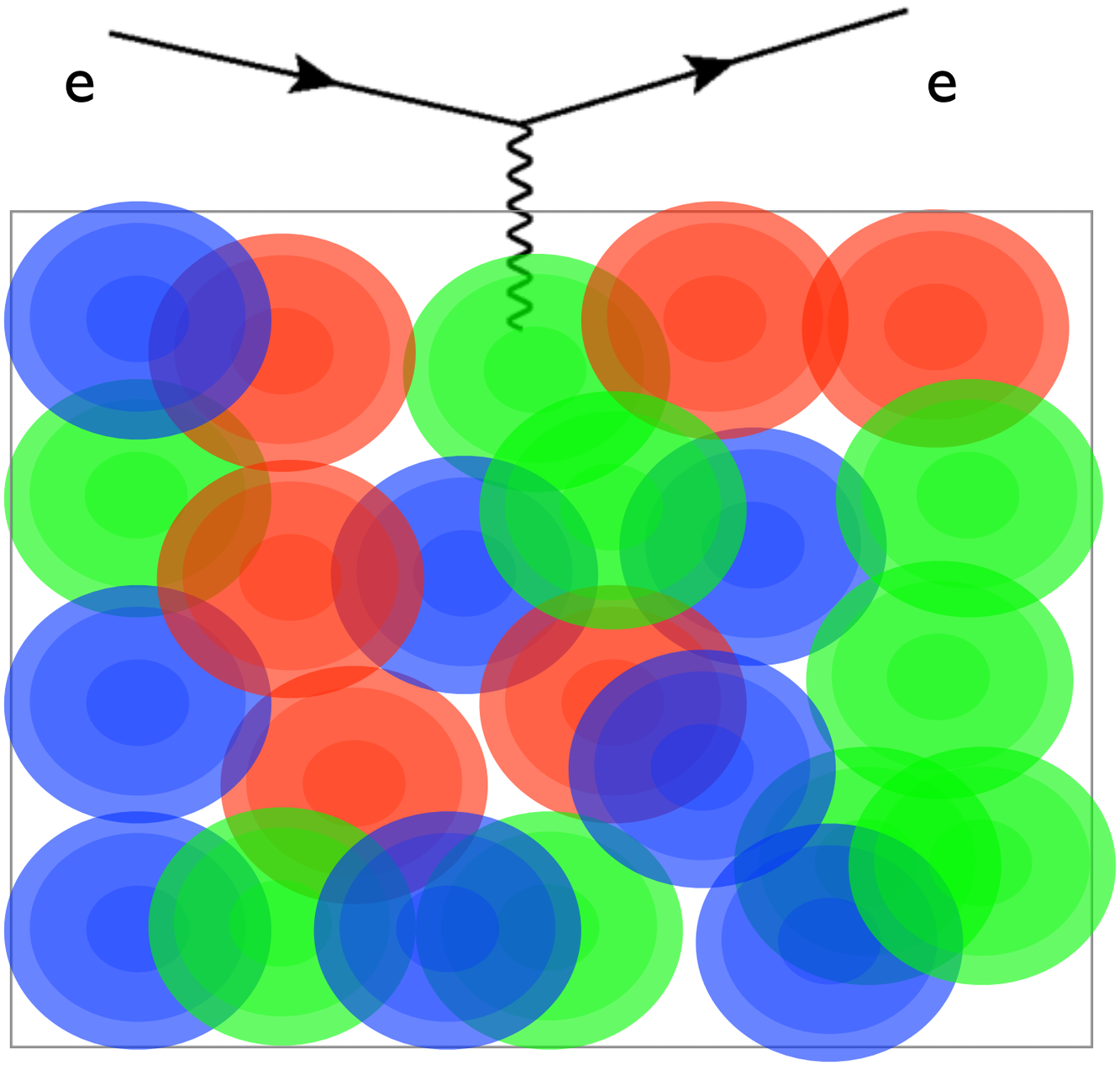
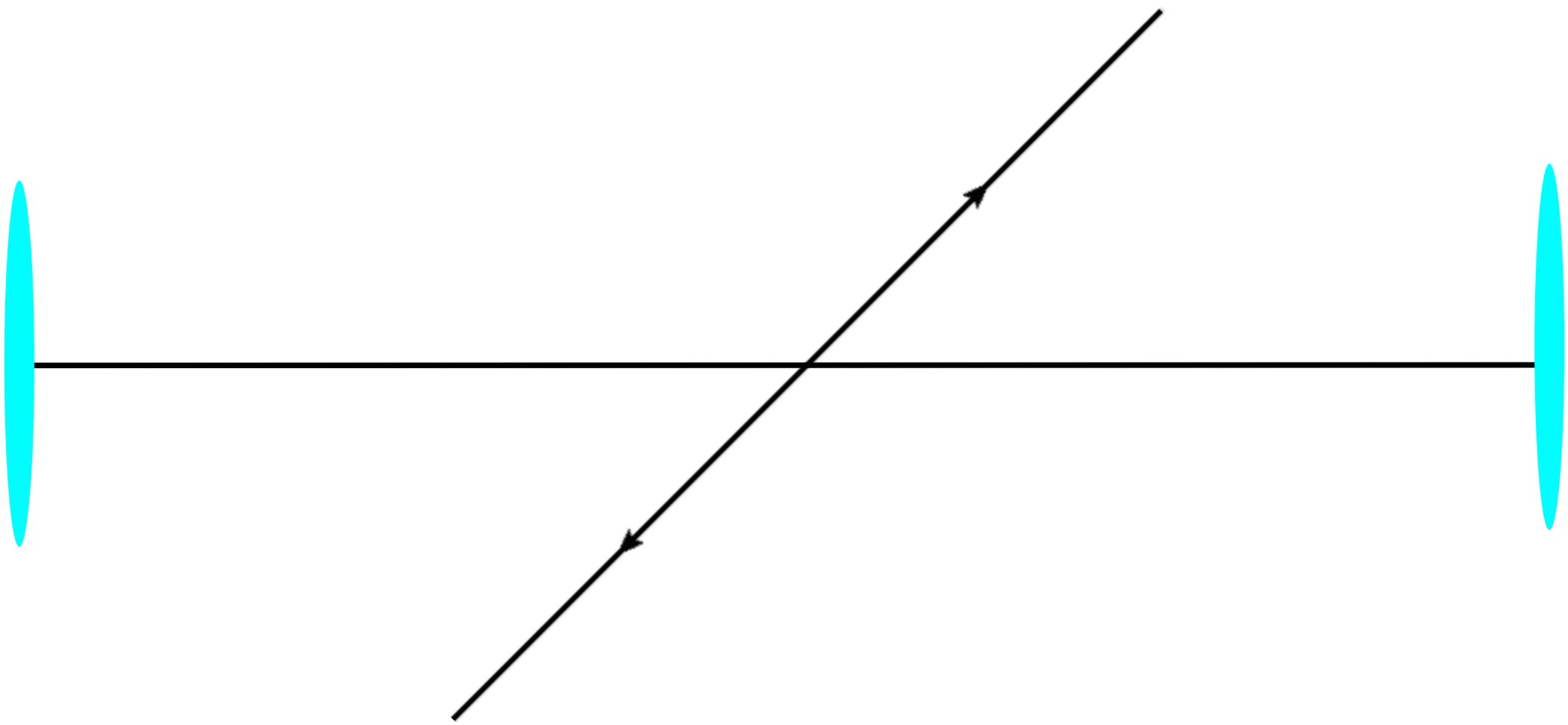


Jets

- Energetic Quarks are produced in pairs



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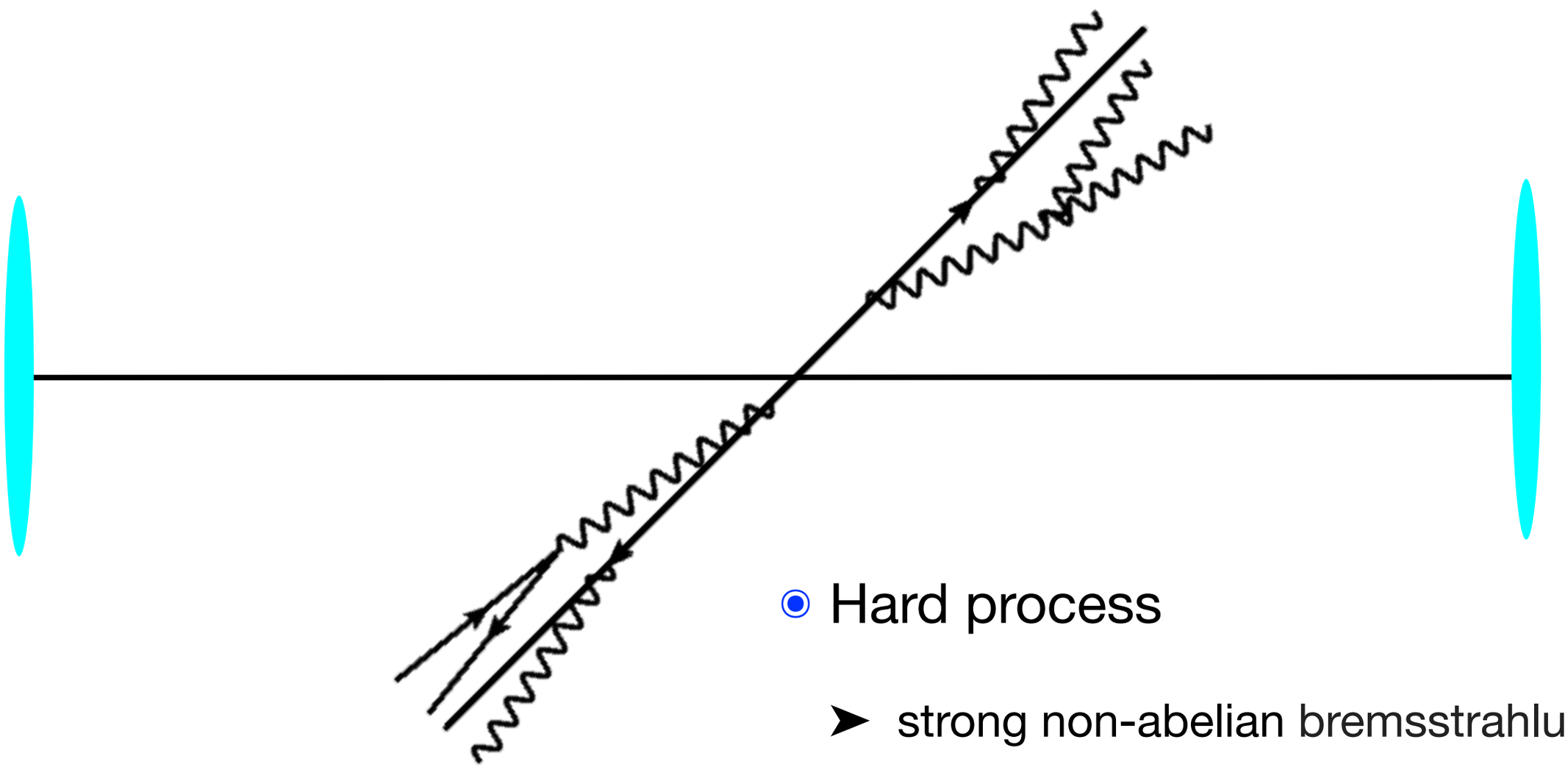

- Hard process
  - ➤ strong non-abelian bremsstrahlung

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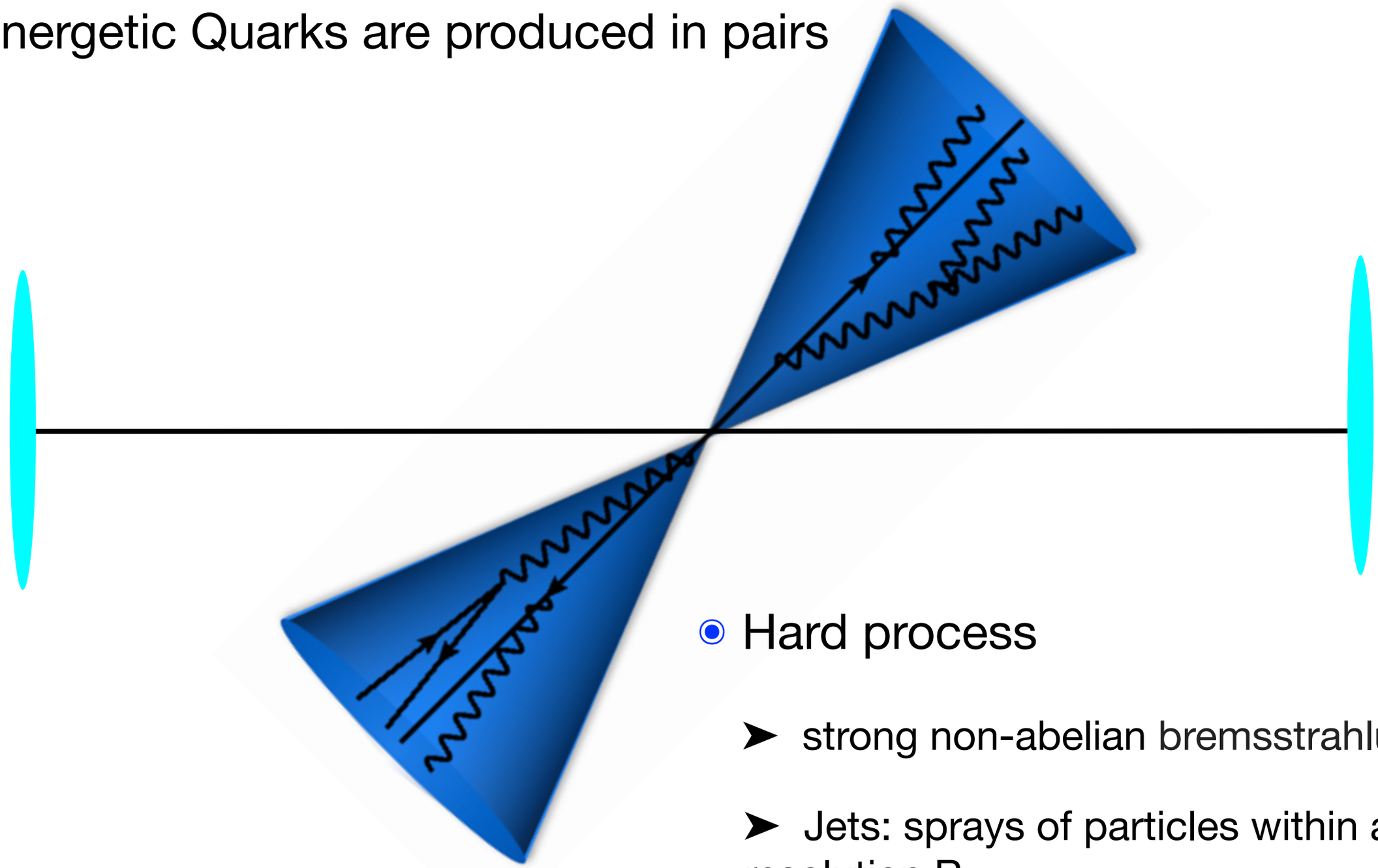
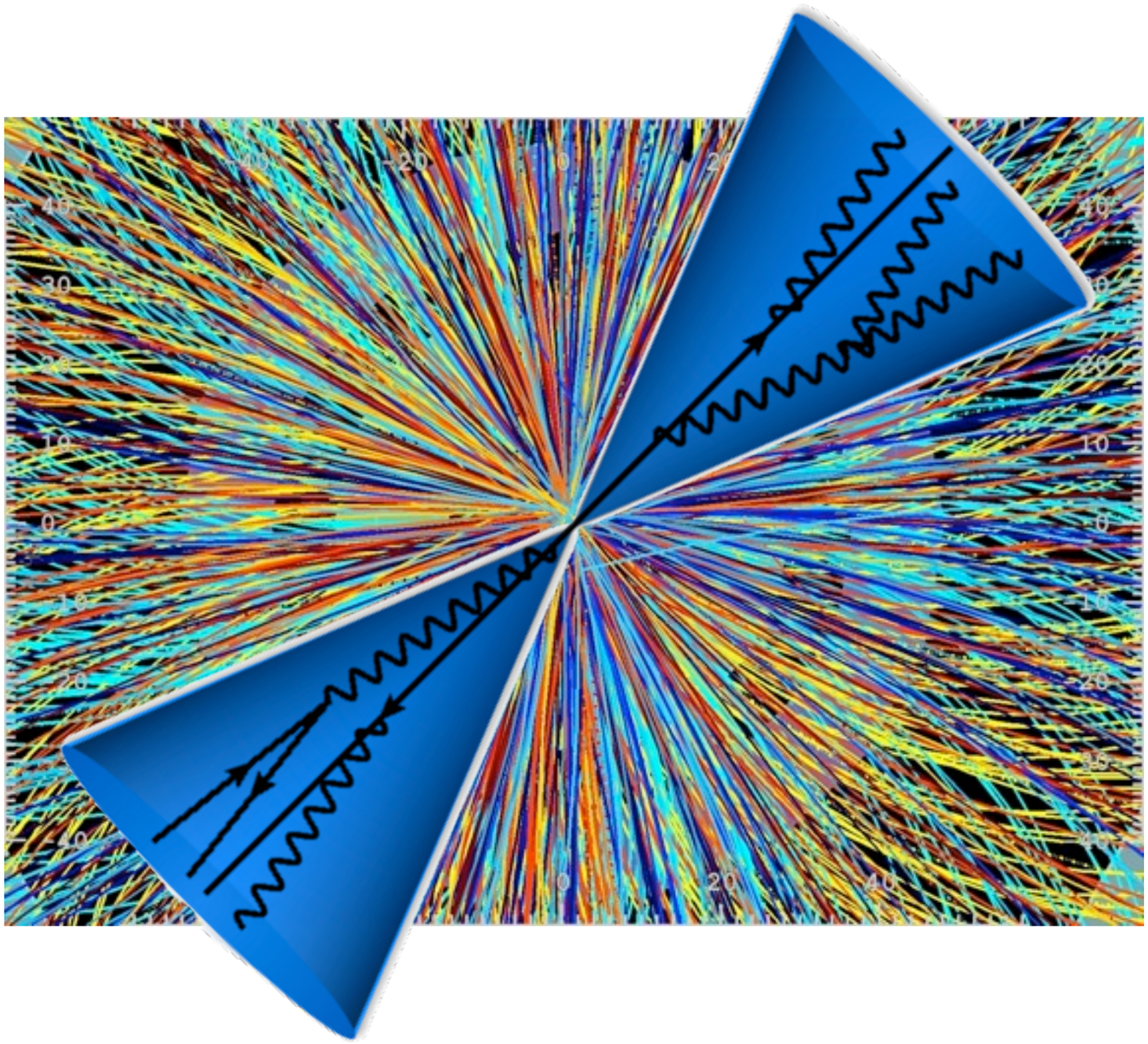


- Hard process
  - ➤ strong non-abelian bremsstrahlung
  - ➤ Jets: sprays of particles within a fixed resolution R

Jets as Probes



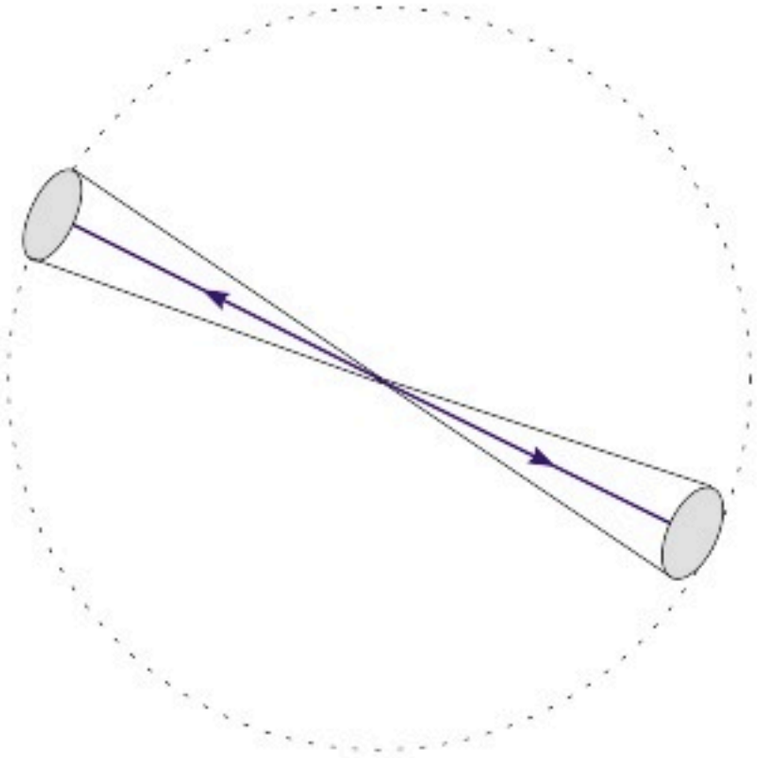
How do jets interact with a plasma without quasiparticles?

Can we use the gauge/string to understand those interaction?

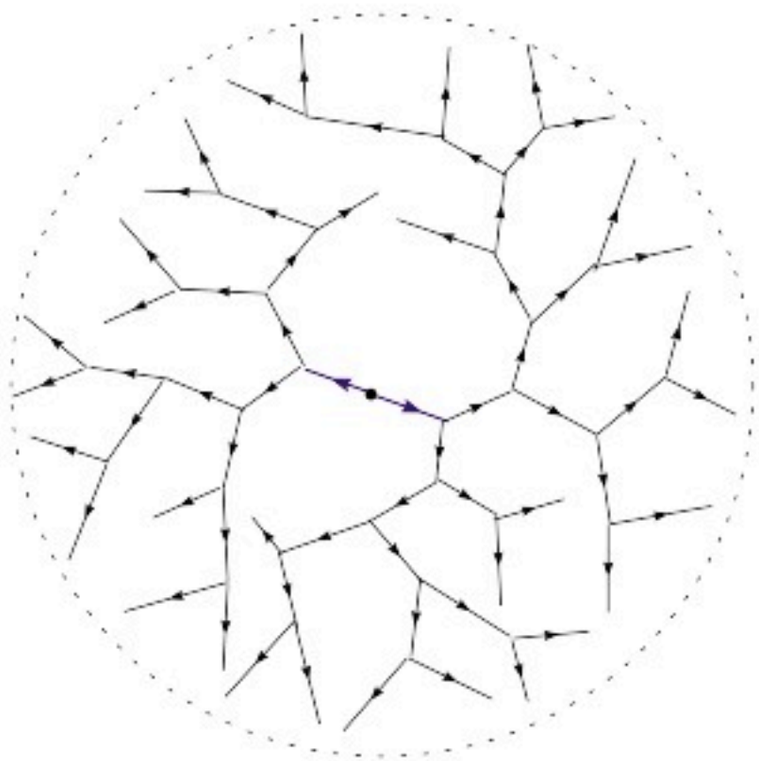
No Jets at Strong Coupling

- No jets at strong in N=4 at strong coupling!

Hofman and Maldacena 08
Iancu, Mueller, Hatta 08



weak coupling e+e- decay



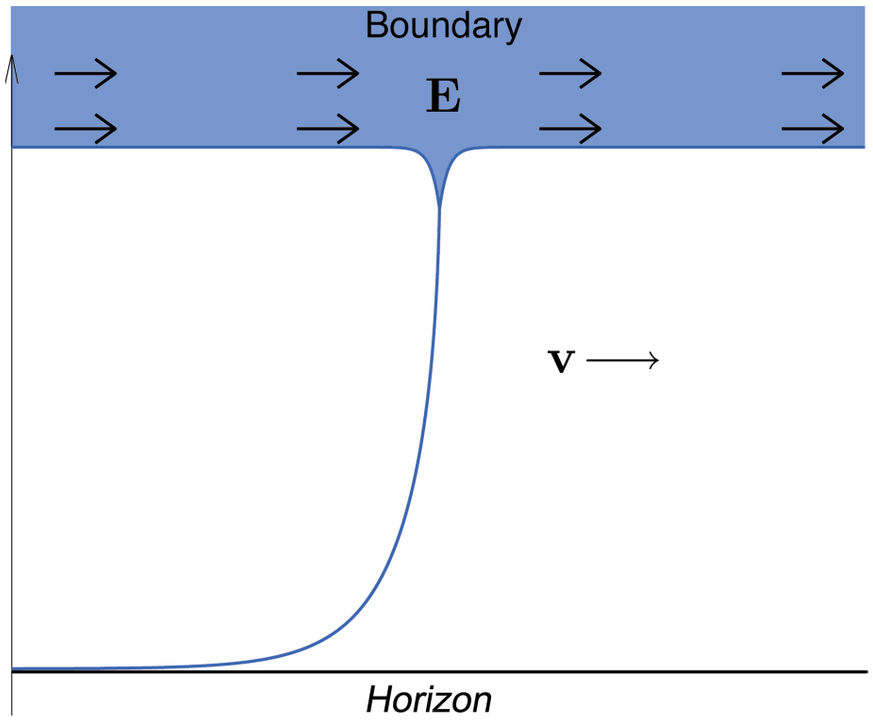
- No asymptotic freedom.
- A serious problem for hard probes

Eloss at strong coupling

- Heavy Quark ⇔ classical string attached to boundary

Herzong, Karch, Kovtun,Kozcaz, Yaffe (2006)

S. Gubser (2006)



- Energy loss ⇔ flux of momentum along the string

$$\frac{dp}{dt} = -\eta_D p \qquad \text{Langevin}$$

$$\eta_D = \frac{\pi\sqrt{\lambda}T^3}{2MT} \qquad \Rightarrow \qquad D \approx \frac{1}{2\pi T}\left(\frac{1.5}{\alpha_{sym}N}\right)^{1/2}$$

JCS & Teaney (2006)

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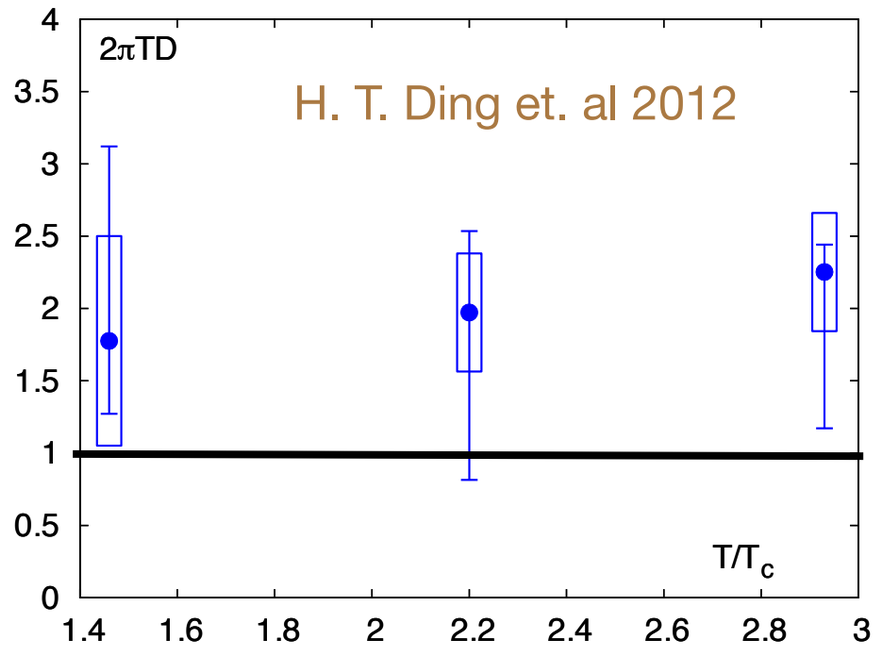
Heavy (charm) quarks



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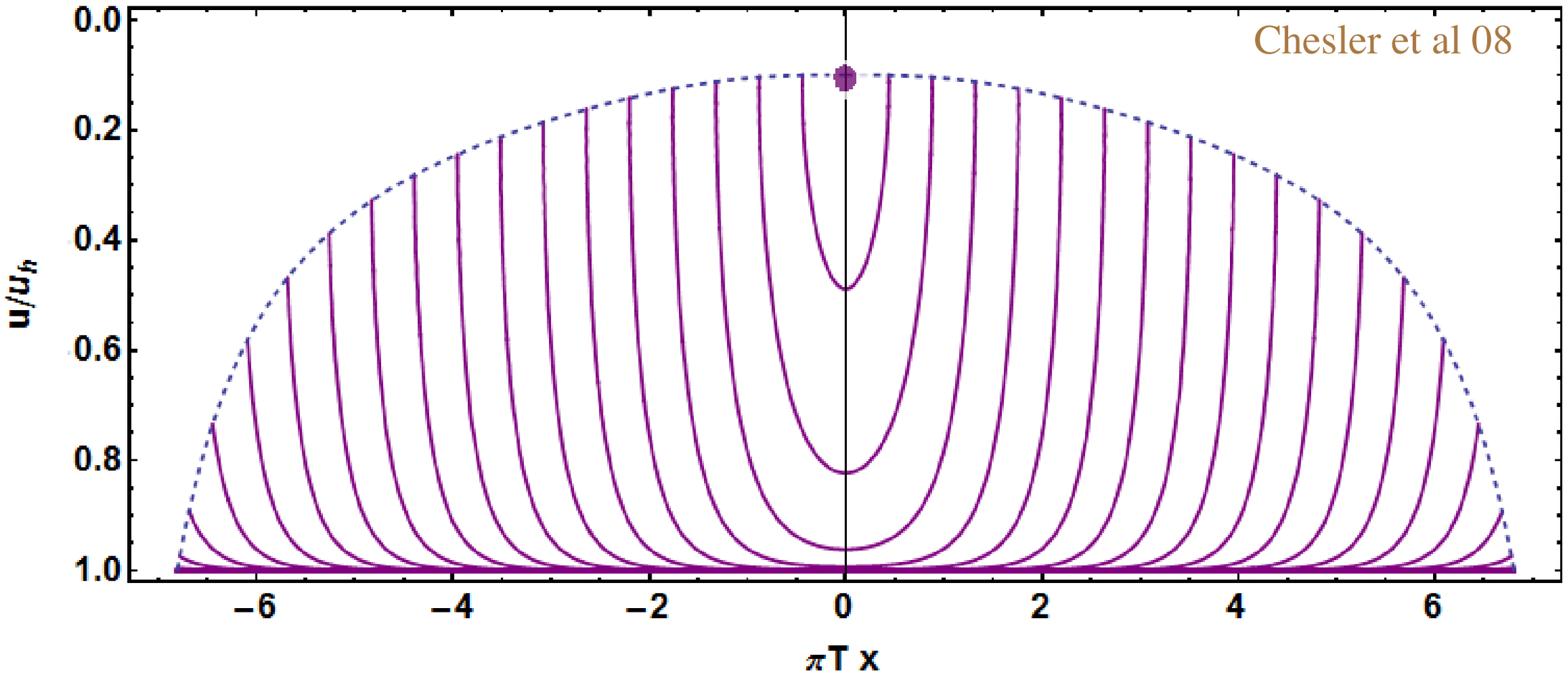
- Compatible with lattice extractions!

Jet Proxies at Strong Coupling



- Energetic (open) string generated from a point.
- Quenching of the string ⇔ falling through horizon
- Stopping distance: $x_{\rm stop} = \dfrac{\pi^{4/3}\mathcal{C}}{\pi T}\left(\dfrac{E_{\rm in}}{\sqrt{\lambda}\pi T}\right)^{1/3}$

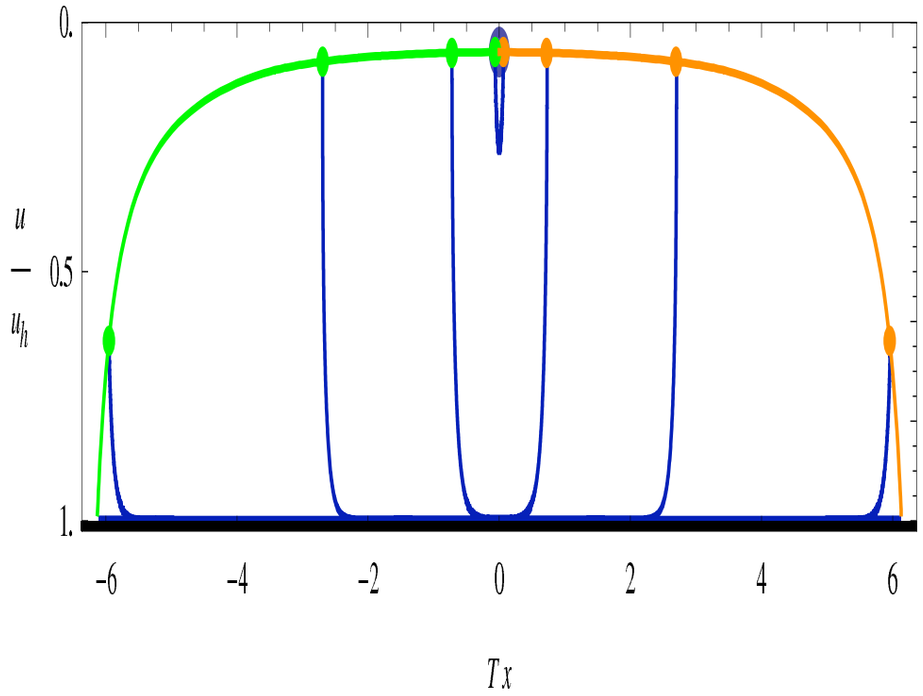
Chesler et al 08

Ficnar & Gubser 13

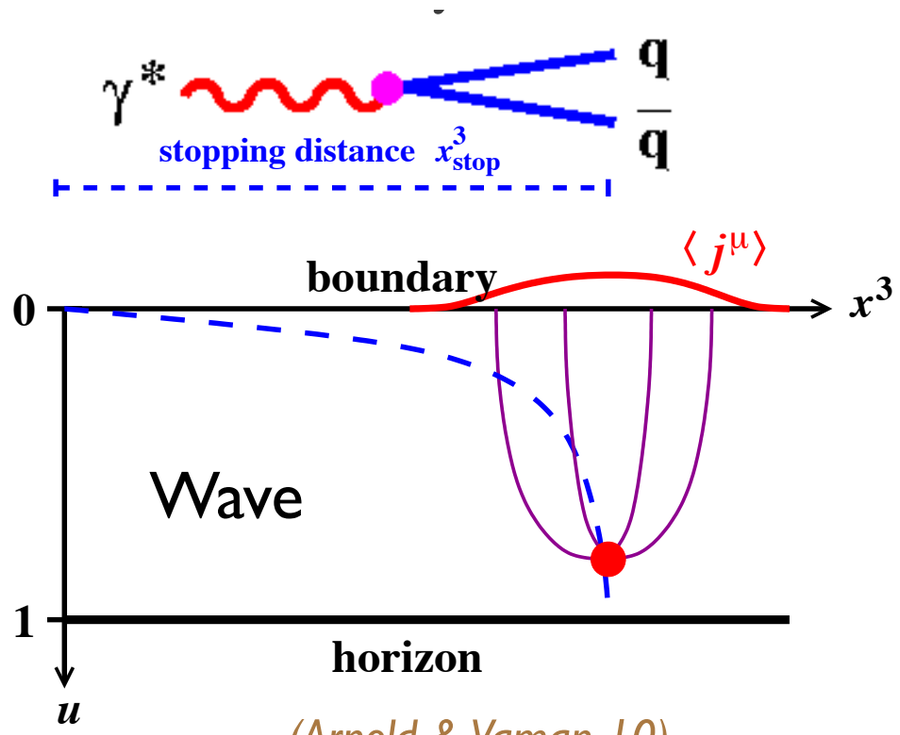
Energetic Excitations

Q-Qbar pair: string

(Chesler, Jensen, Karch, Yaffe 08)



Boosted virtual photon



(Arnold & Vaman 10)

$$x_{\rm stop} = \frac{1}{2\,\kappa_{\rm sc}}\,\frac{E_{\rm in}^{1/3}}{T^{4/3}}$$

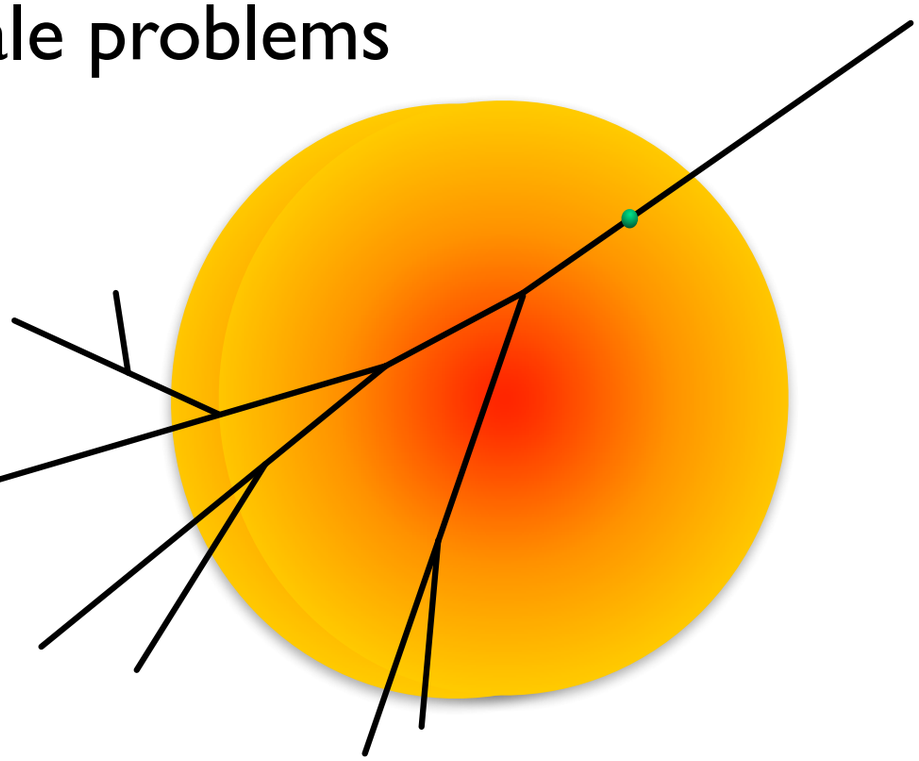
$$\kappa_{\rm sc} \;=\; 1.05\,\lambda^{1/6},$$

$$\kappa_{\rm SC} \propto\; \lambda^{0}$$

A Hybrid Model

- Jet interaction with medium is a multi-scale problems
  - ➤ Hard production (perturbative)
  - ➤ Hard evolutions (perturbative)
  - ➤ Exchanges at medium scale
  - ➤ Soft jet fragments

} strong coupling



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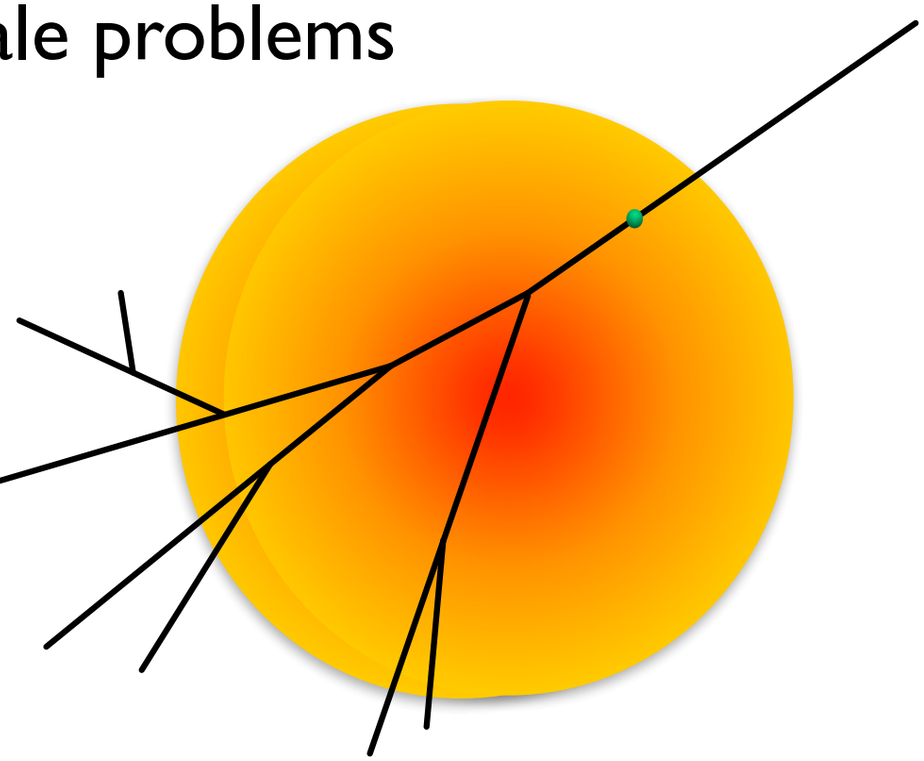


- Simple (and phenomenological) approach

JCS, Gulhan, Milhano, Pablos and Rajagopal 2014, 2015

  - ➤ Leave jet evolution unmodified (Q>>T)
  - ➤ Each in-medium parton losses energy (not necessarily perturbative)
  - ➤ Neglect in-medium radiation (first approximation)

Energy Loss Rate

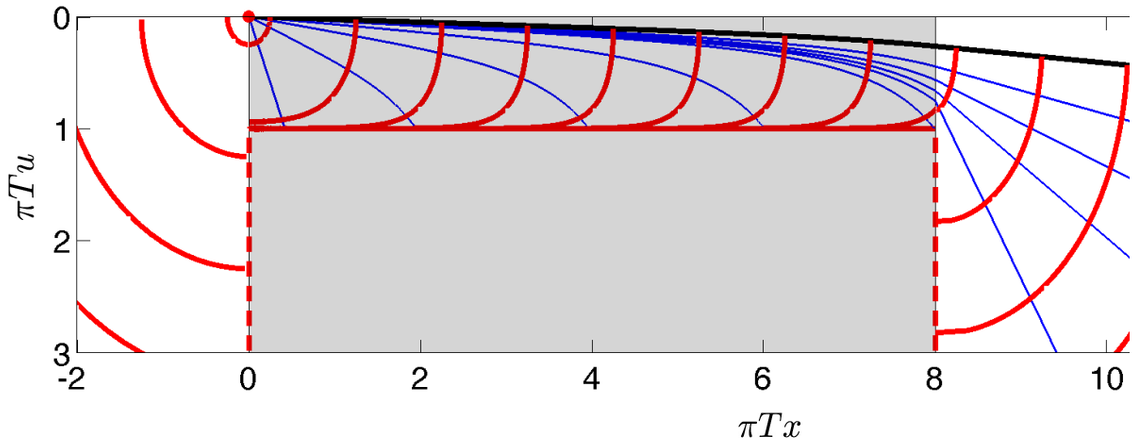
- Energy loss of light quarks crossing a slab of plasma

$$\frac{1}{E_{\rm in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{\rm stop}^2}\frac{1}{\sqrt{x_{\rm stop}^2 - x^2}}$$

$$x_{\rm stop} = \frac{1}{2\,\kappa_{\rm sc}}\frac{E_{\rm in}^{1/3}}{T^{4/3}}\,,$$

Chesler & Rajagopal 14

Chesler & Rajagopal 15



- κ_{SC} is not robust
  - ➤ $\kappa_{SC} \sim \lambda^{1/6}$ ($\lambda \sim g^2 N_c$) in string computations

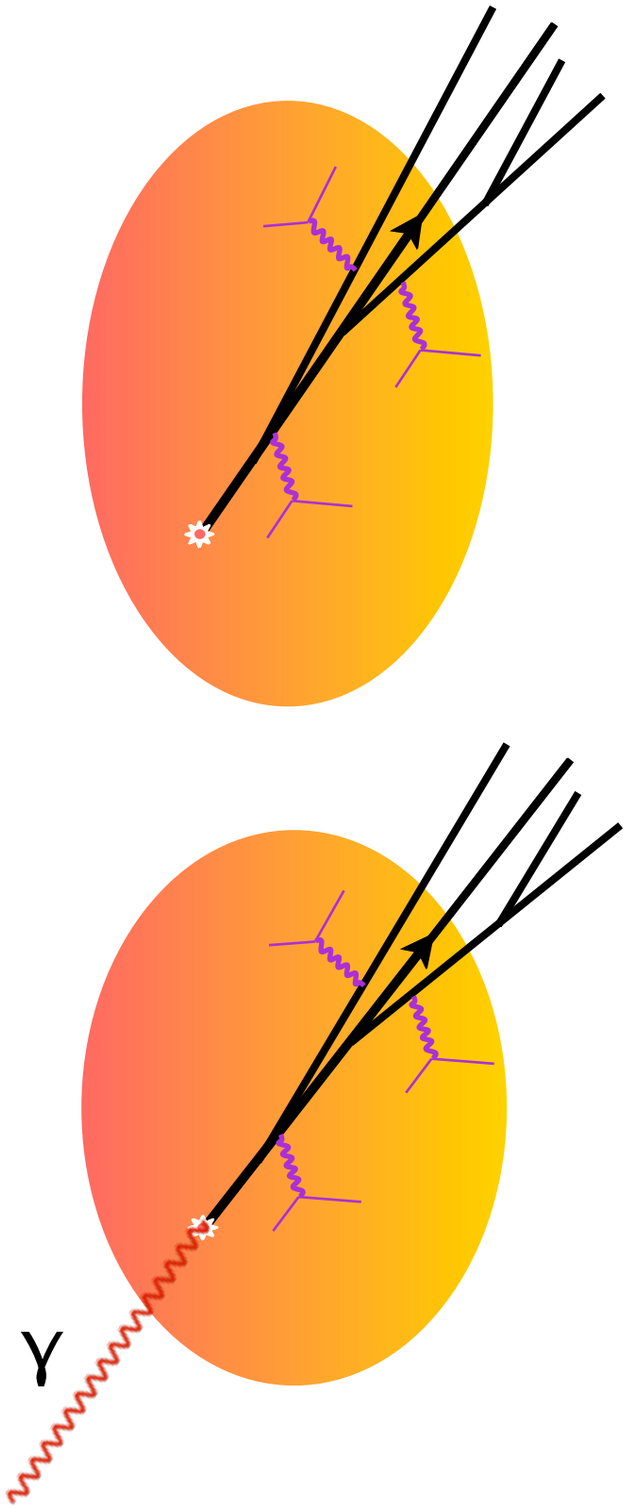
    Gubser et al 08, Chesler et al. 08, Ficnar and Gubser 13, Chesler & Rajagopal 14
  - ➤ $\kappa_{SC} \sim \lambda^{0}$ ($\lambda \sim g^2 N_c$) in U(1) field decays

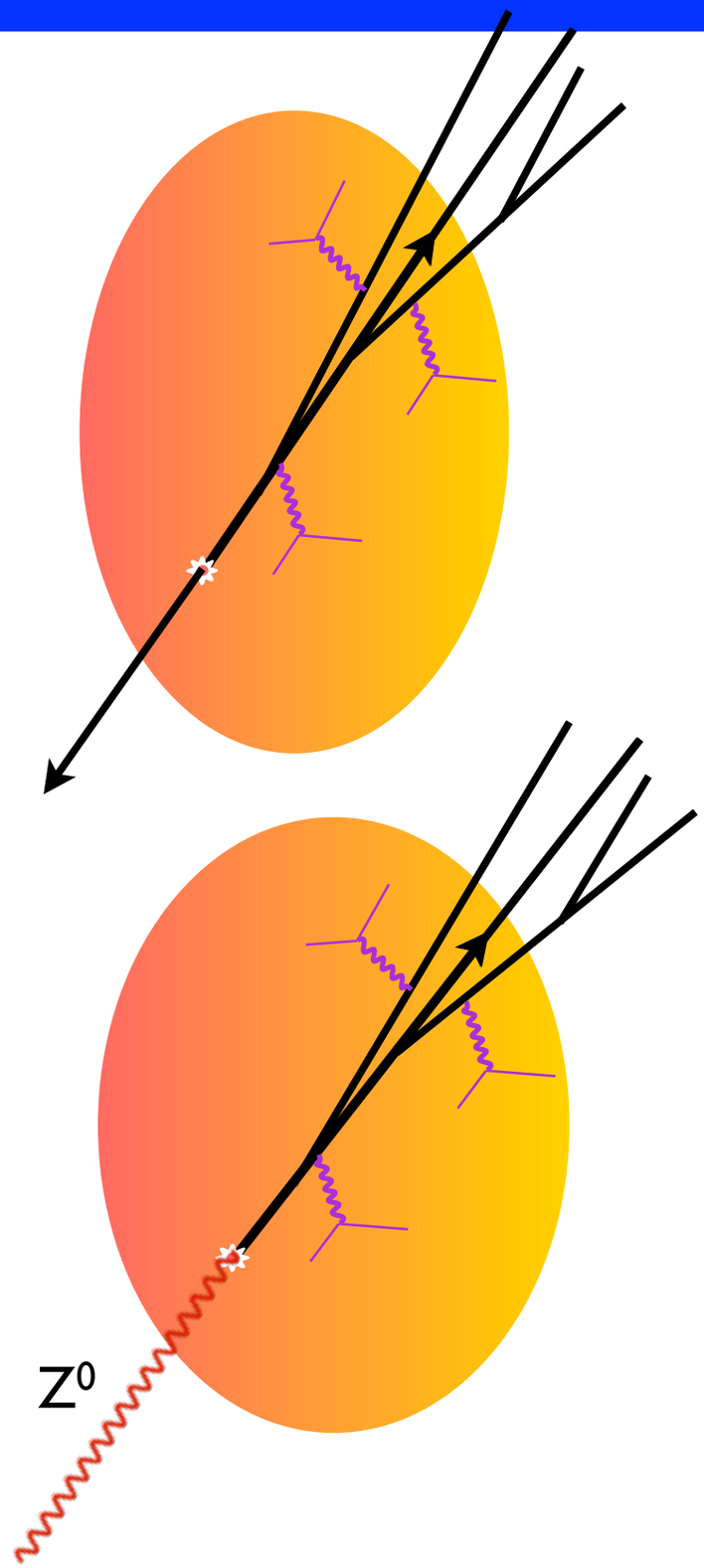
    Hatta, Iancu and Mueller 08, Arnold & Vaman 10

} order one ($\lambda \sim 10$)

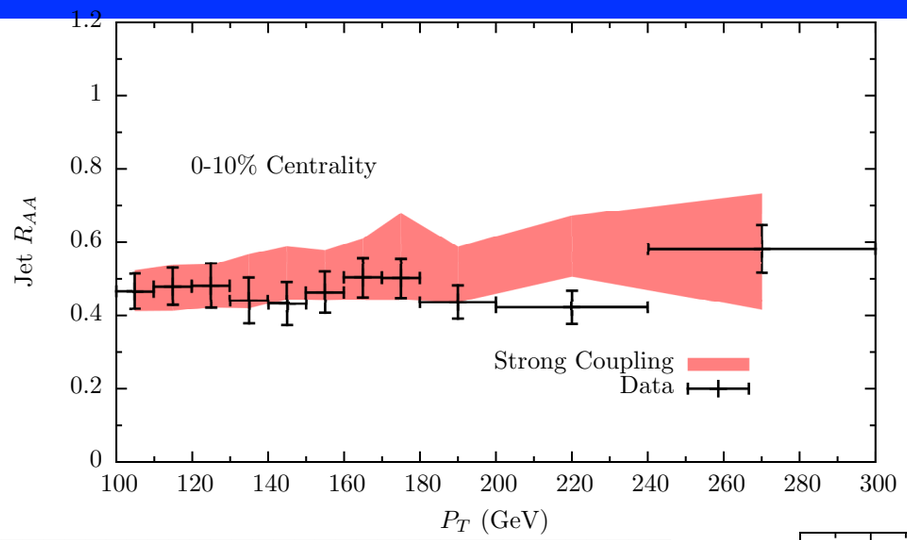
- We use κ_{SC} as a fitting parameter

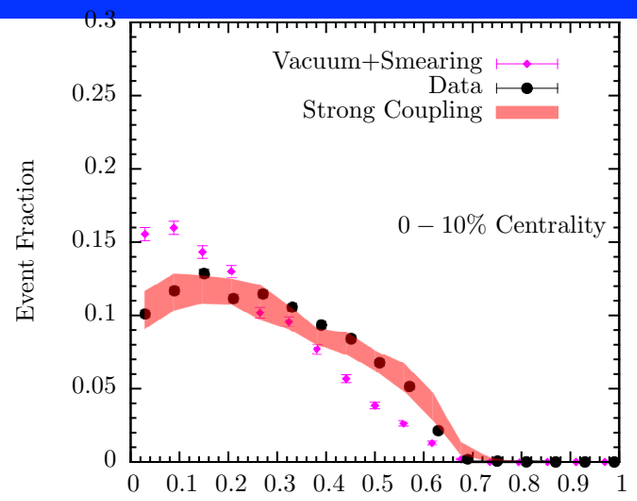
Observables

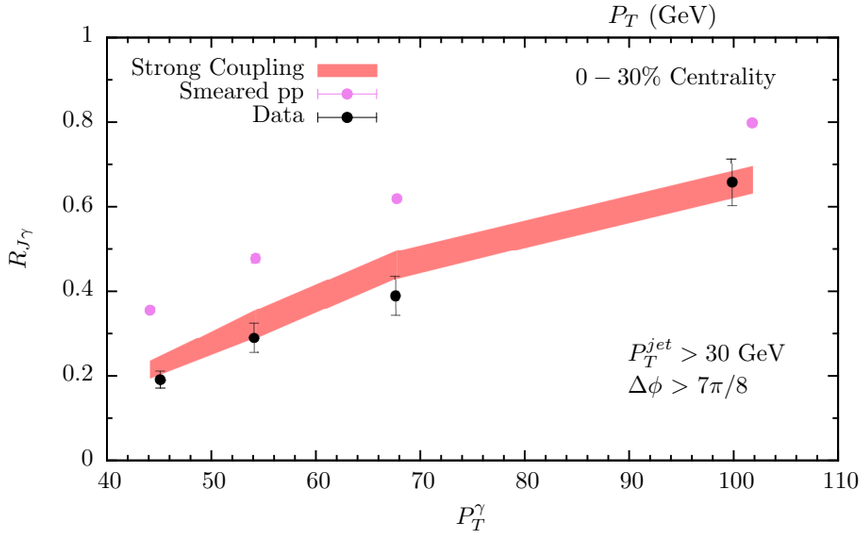


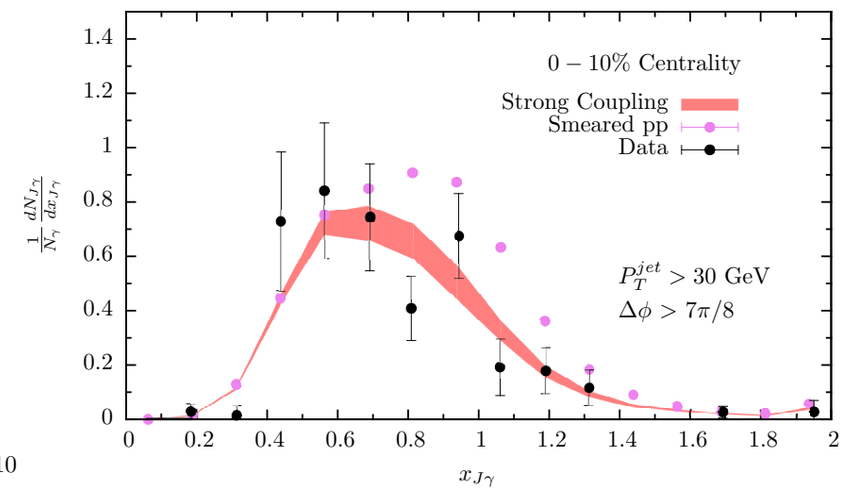


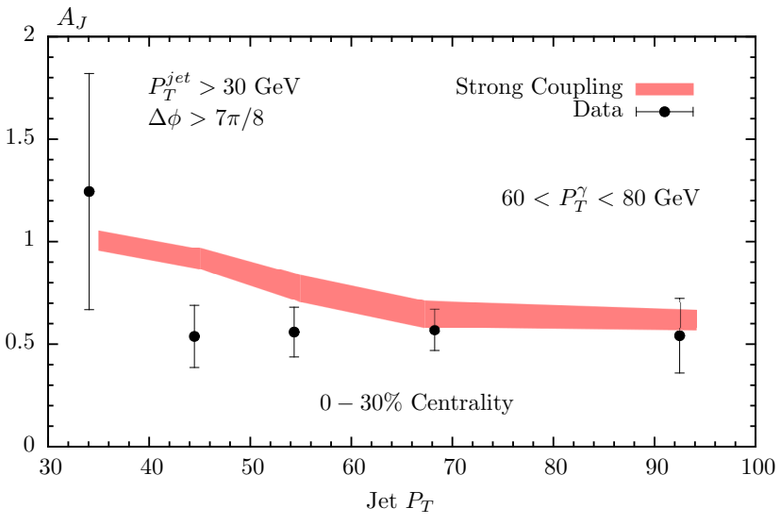
Success of the Hybrid Model

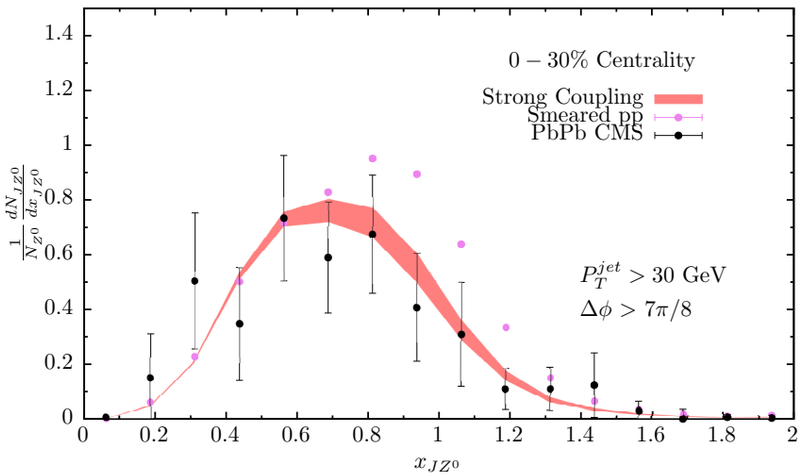


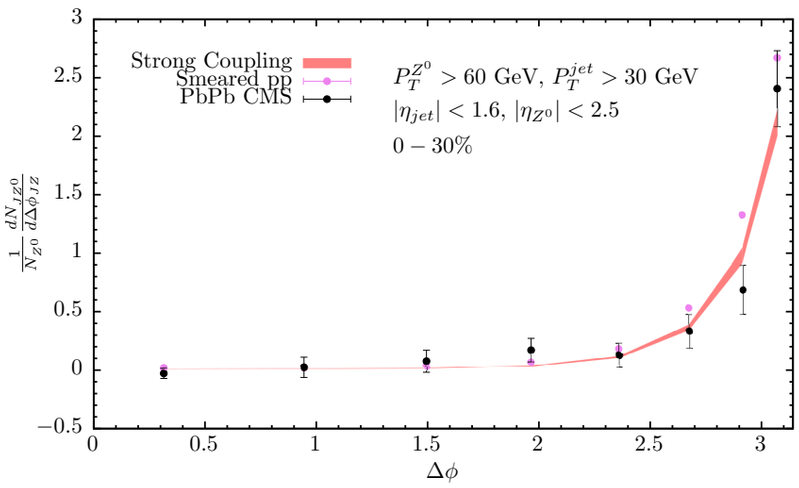












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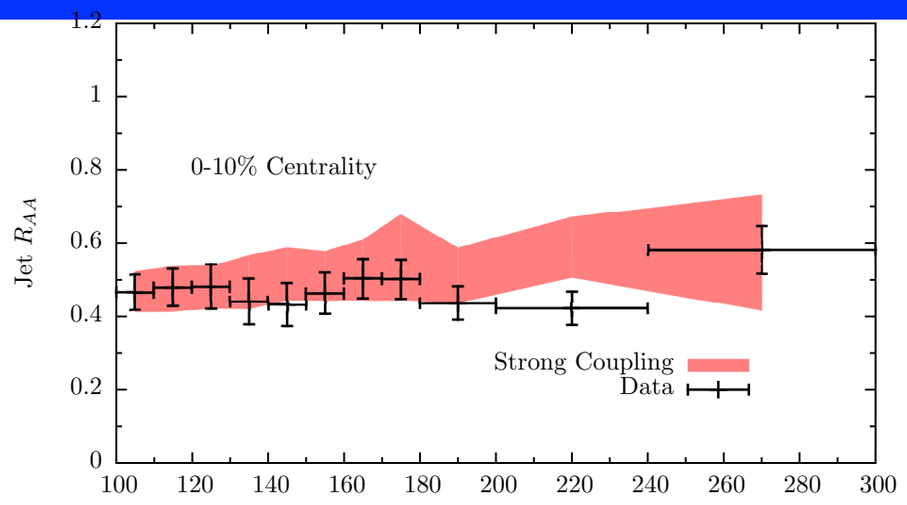
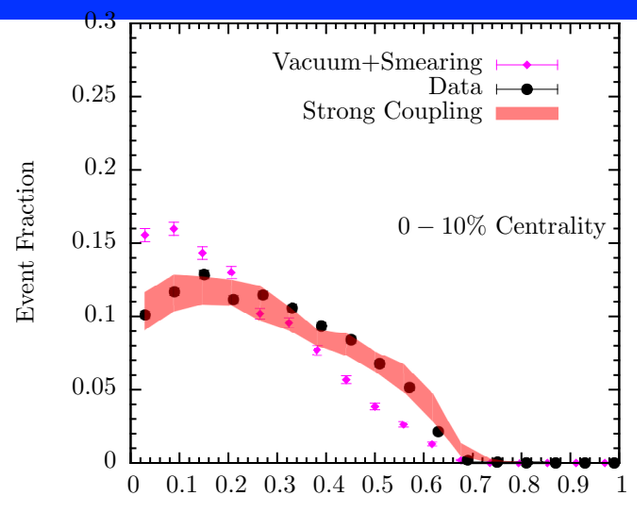
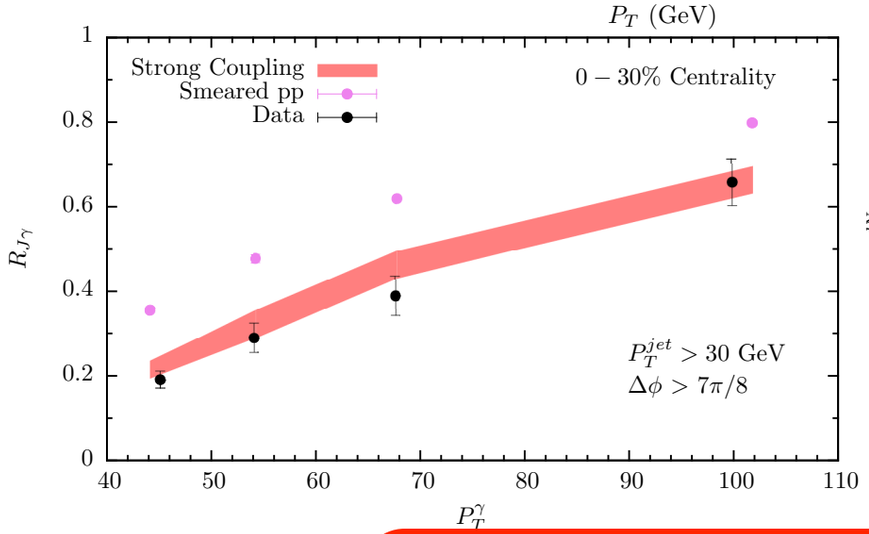
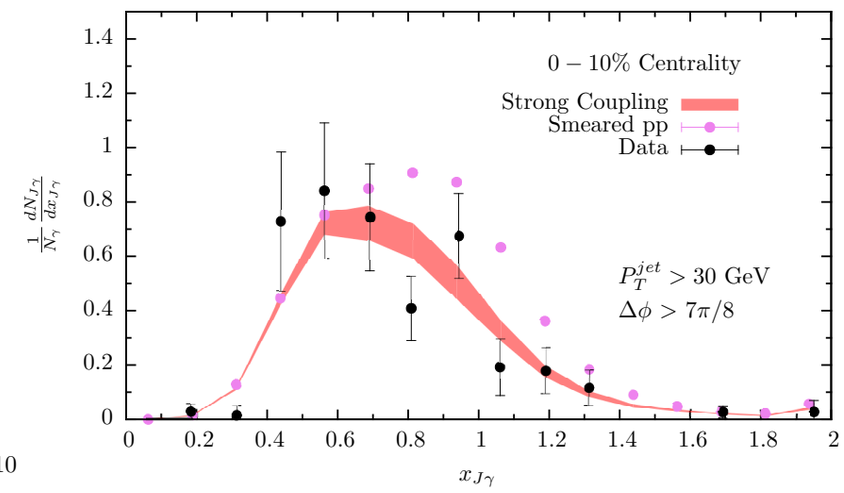
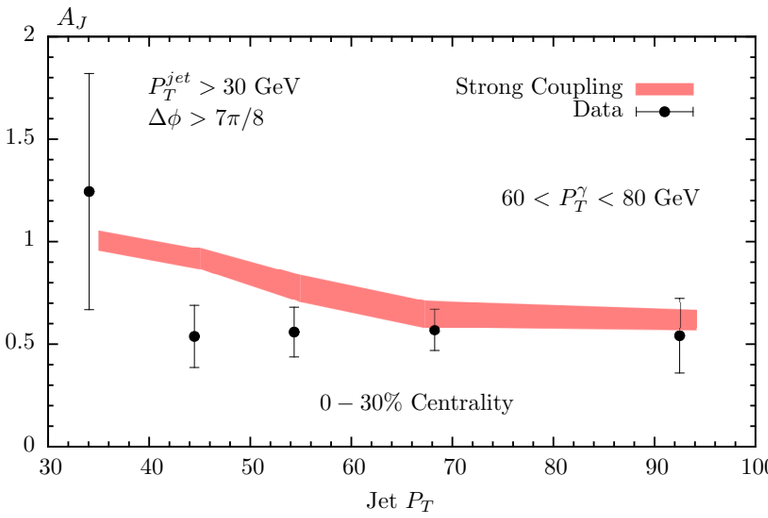
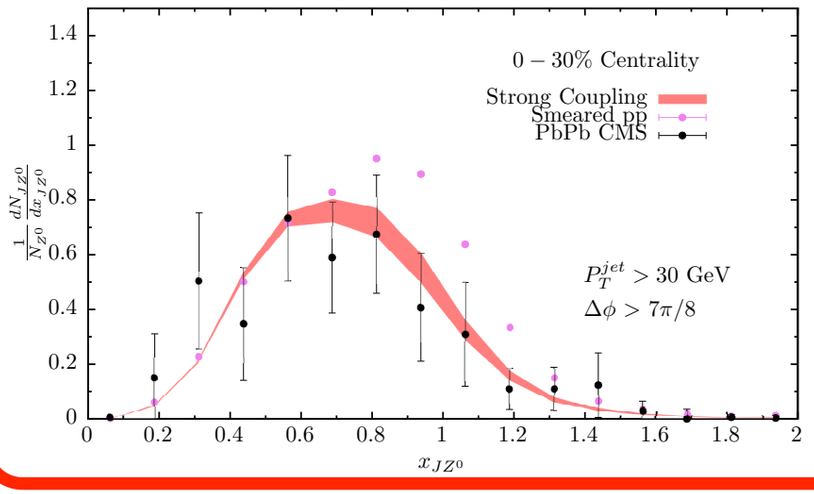


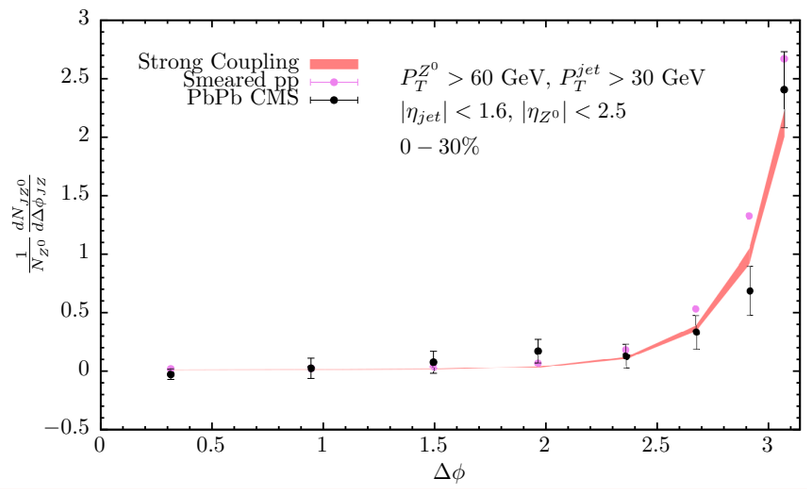








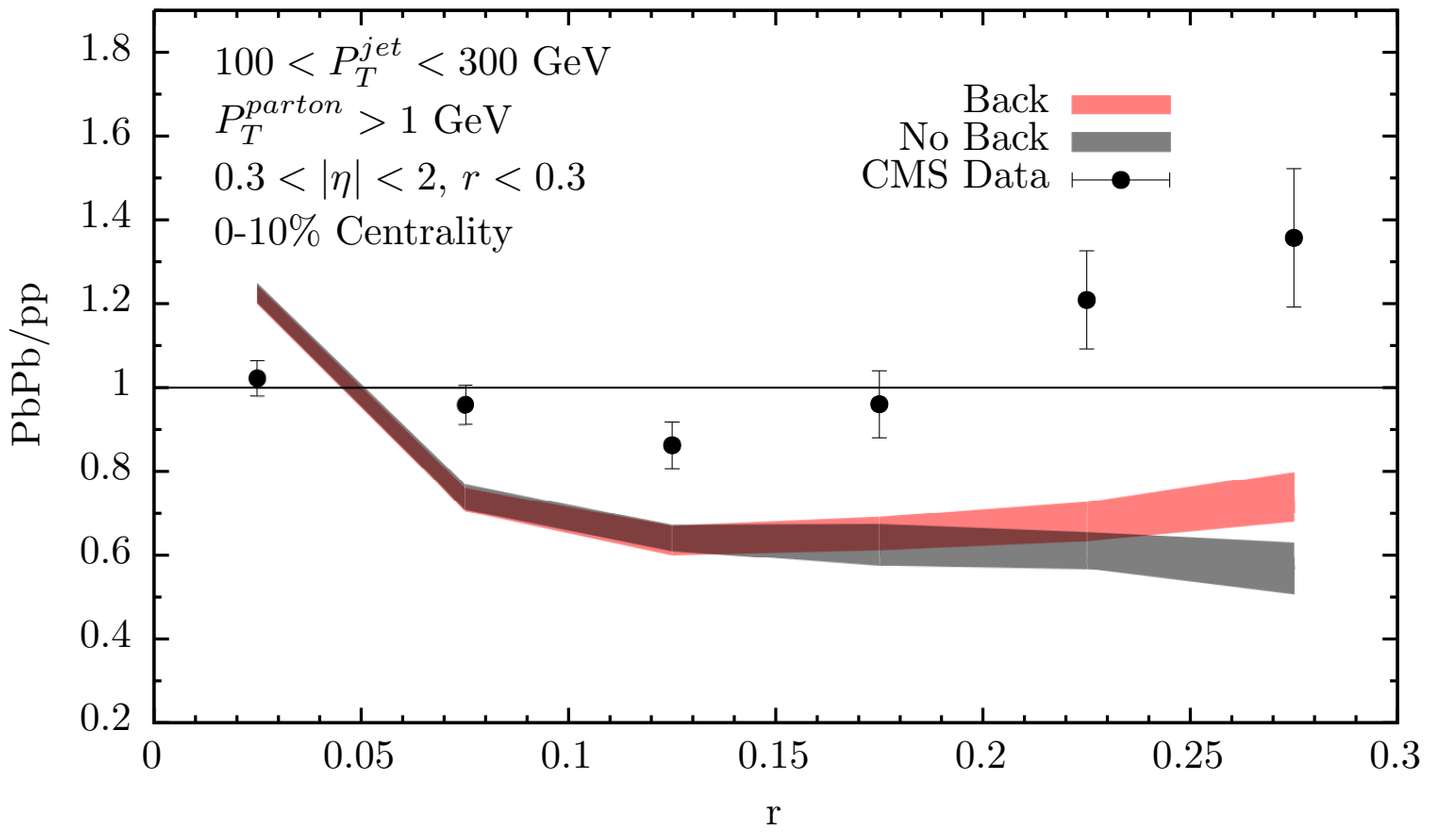


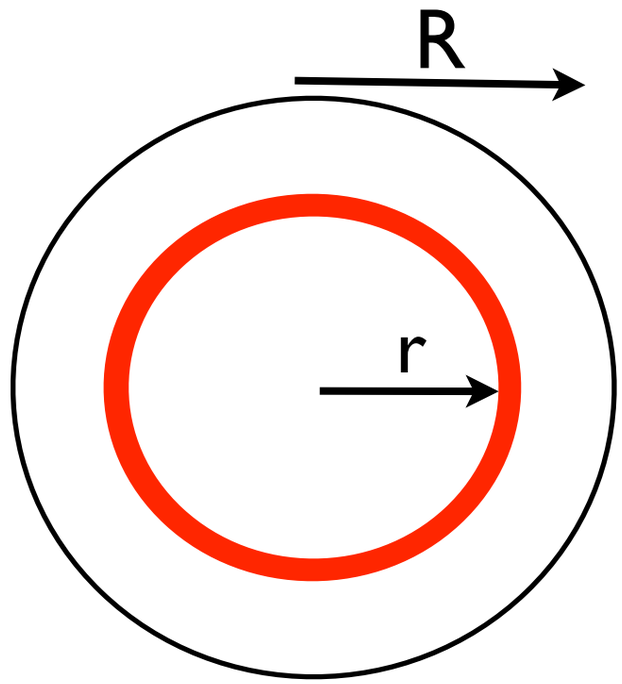


Predictions!

Not Everything Works

JCS, Gulhan, Milhano, Pablos and Rajagopal to appear



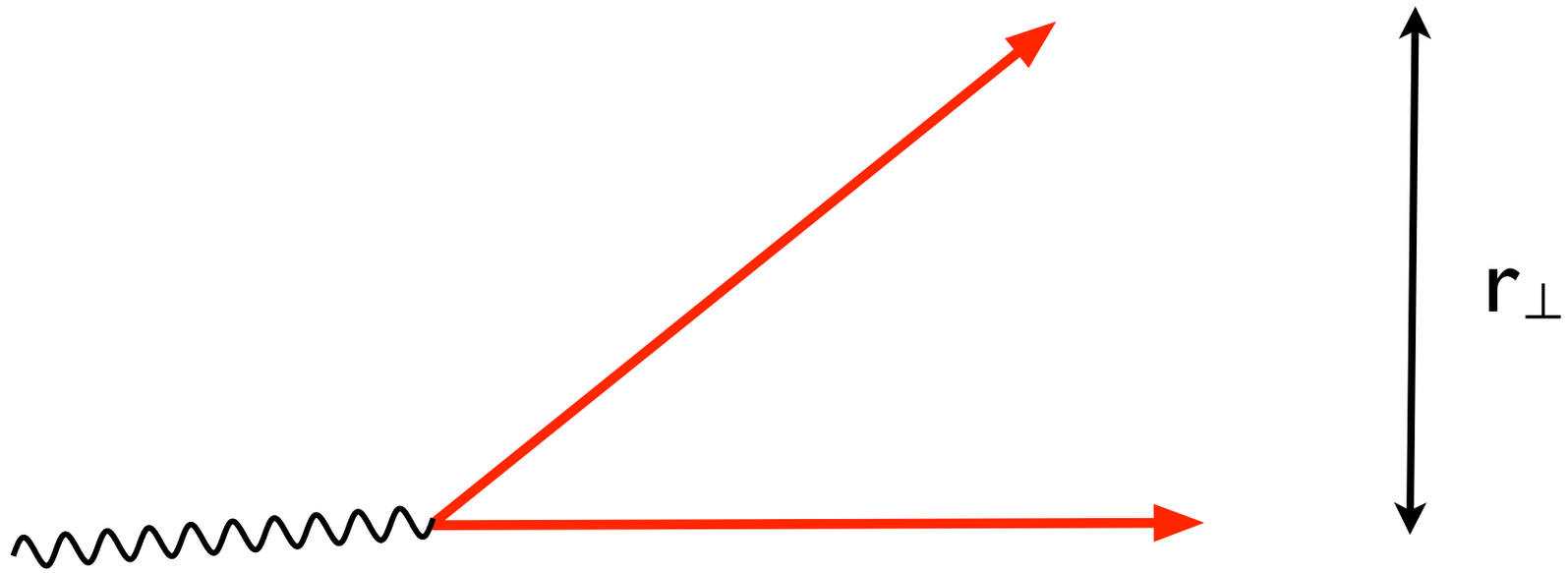


➤ Angular distribution of jet energy incorrectly described

➤ Crucially dependent on multiple parton propagation

Transverse Size Resolution

- Perturbative analysis of multiple partons



- Colour exchanges decorrelate the currents

JCS, Iancu **arXiv:1105.1760**

Mehtar-Tani, Tywoniuk, Salgado **arXiv:1009.2965, 1102.4317**

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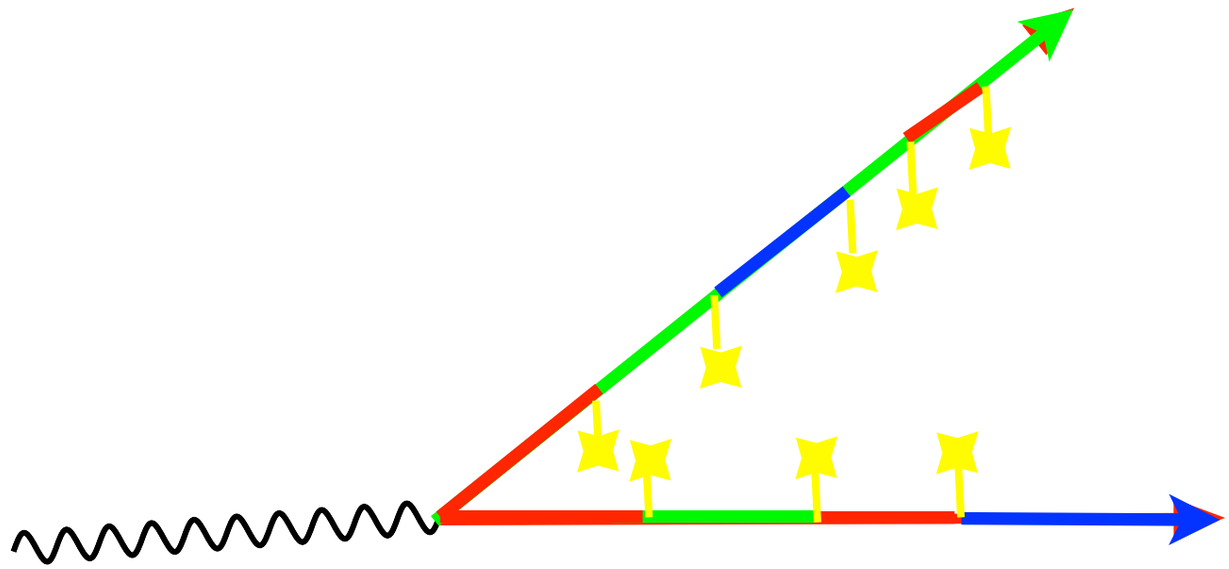

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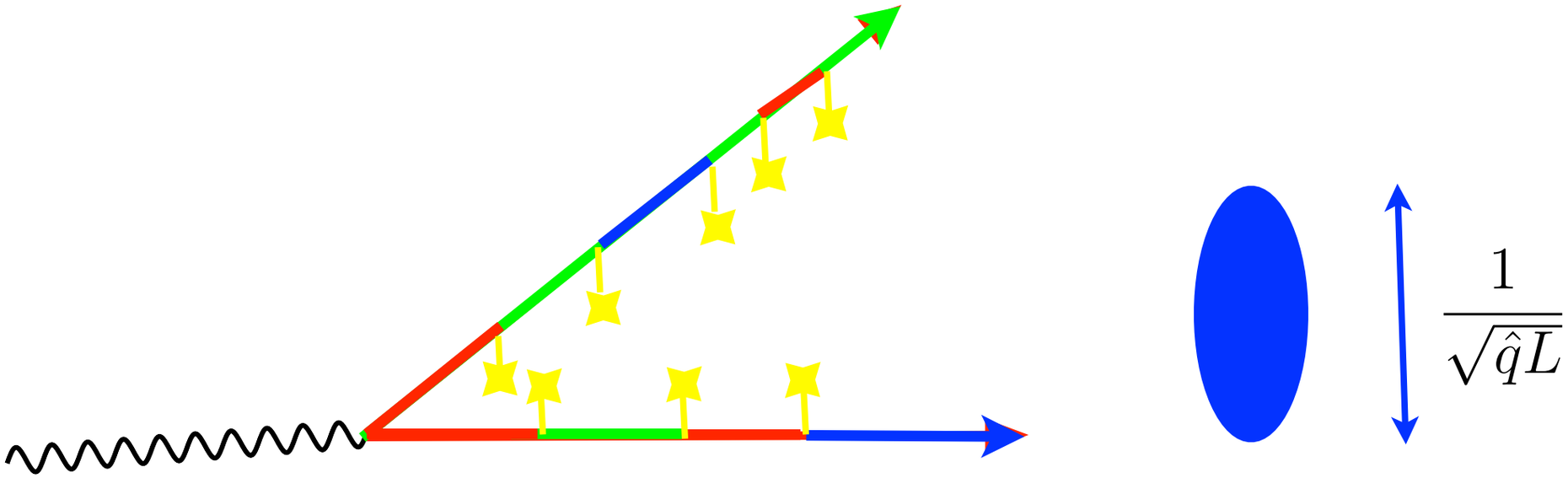

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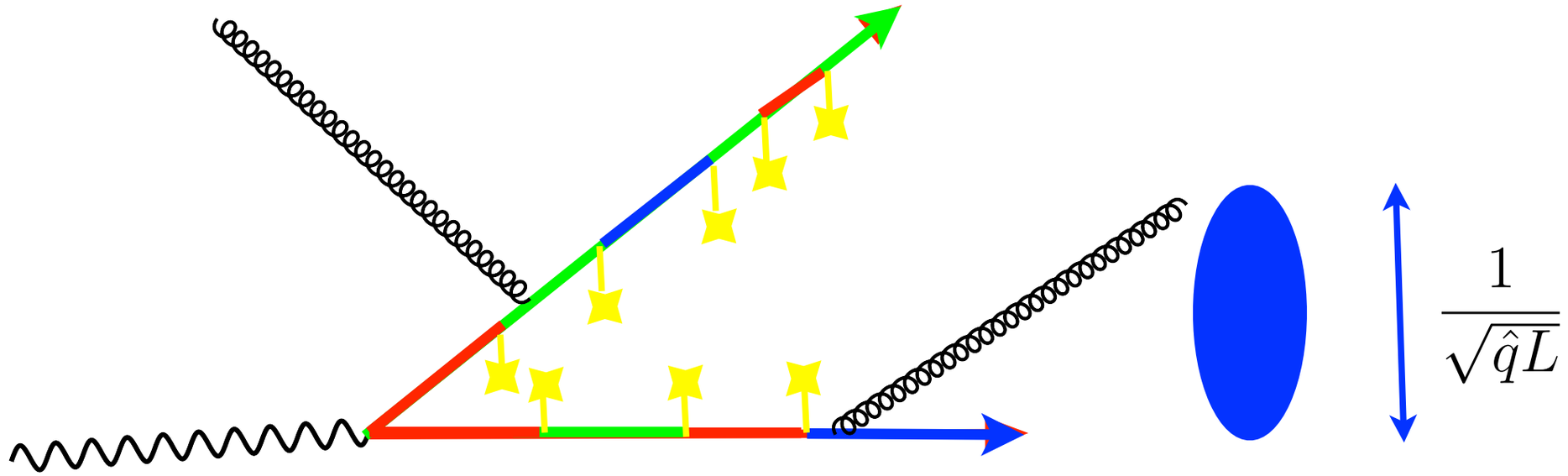

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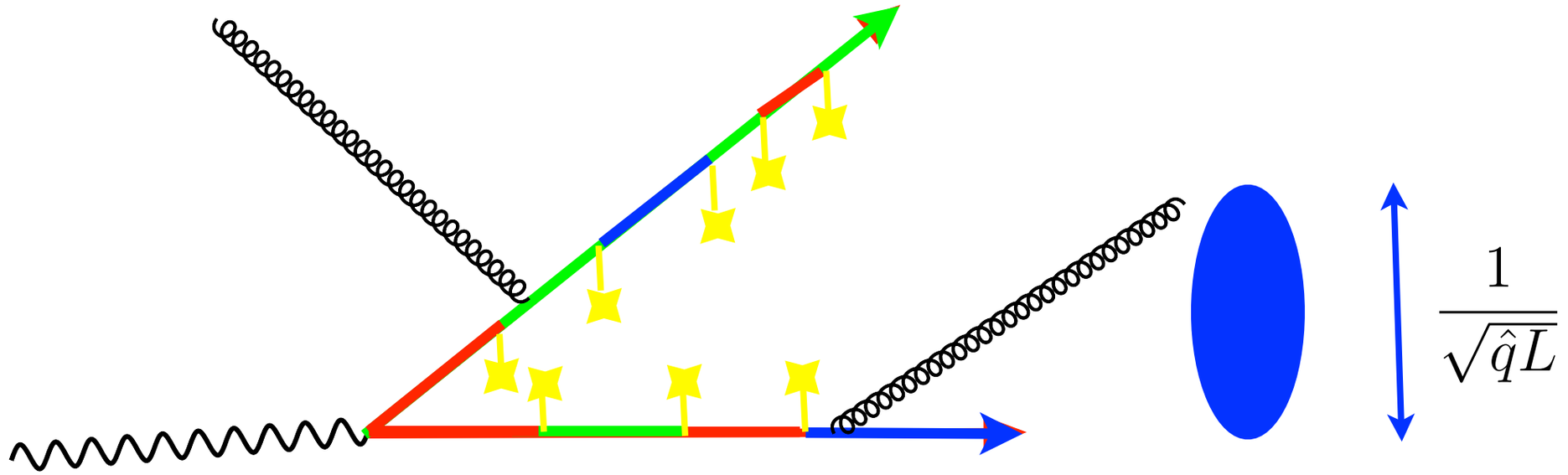

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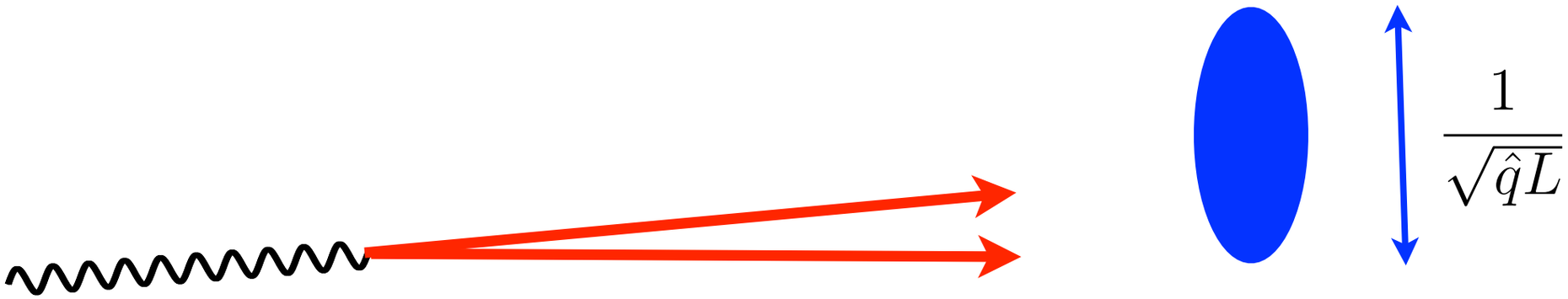
$$\hat{q} = \frac{(\text{mean transferred momentum})^2}{\text{length}} \sim \frac{m_D^2}{\lambda_{\text{m. f. p}}}$$

Transverse Size Resolution

- Perturbative analysis of multiple partons



- Colour exchanges decorrelate the currents

JCS, Iancu **arXiv:1105.1760**

Mehtar-Tani, Tywoniuk, Salgado **arXiv:1009.2965, 1102.4317**

arXiv:1112.5031, 1205.5739

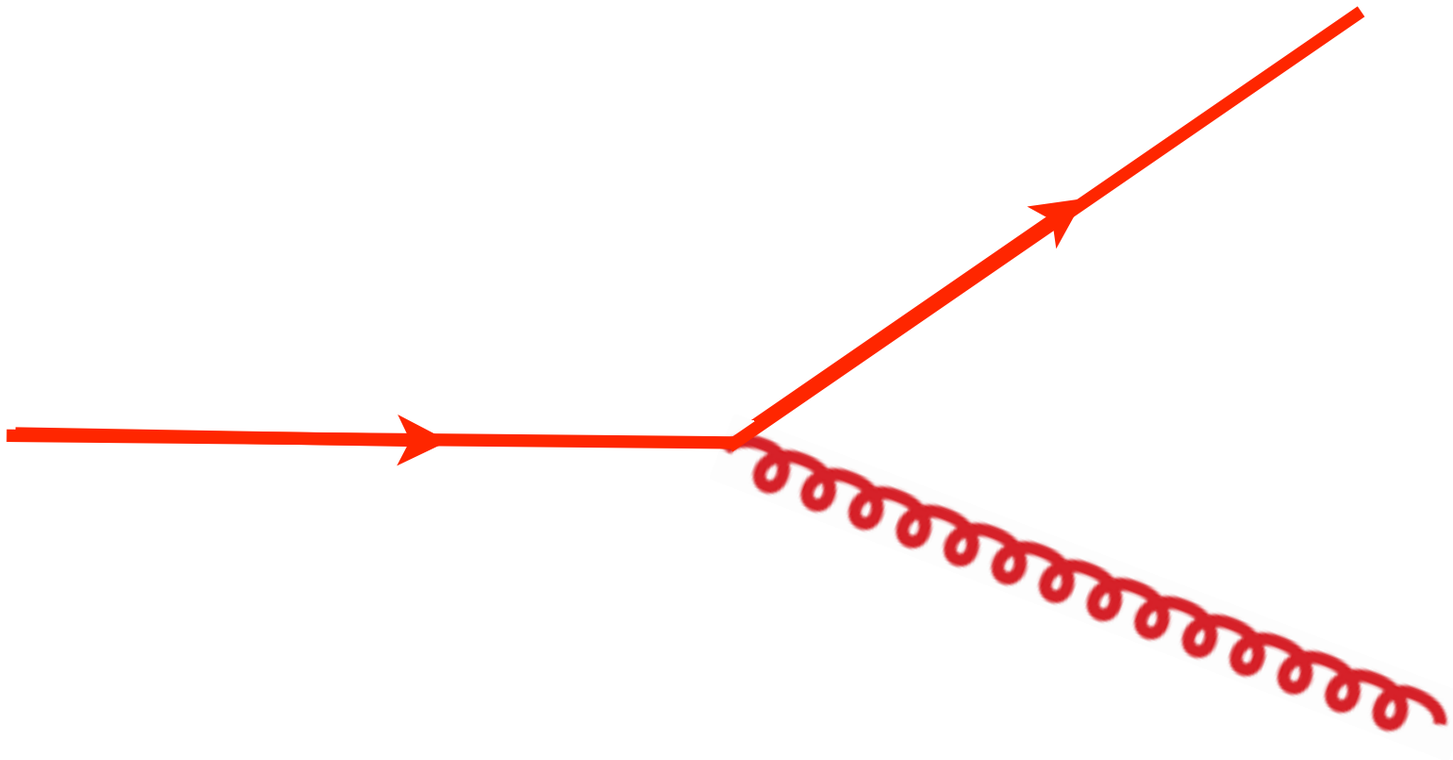
JCS, Pablos and Tywoniuk **arXiv:1512.07561**

- Fragments at small angles cannot be resolved

$$\hat{q} = \frac{(\text{mean transferred momentum})^2}{\text{length}} \sim \frac{m_D^2}{\lambda_{\text{m. f. p}}}$$

3-Jet events

➤ Hard gluon emission by an energetic q-$\bar{q}$ pair.



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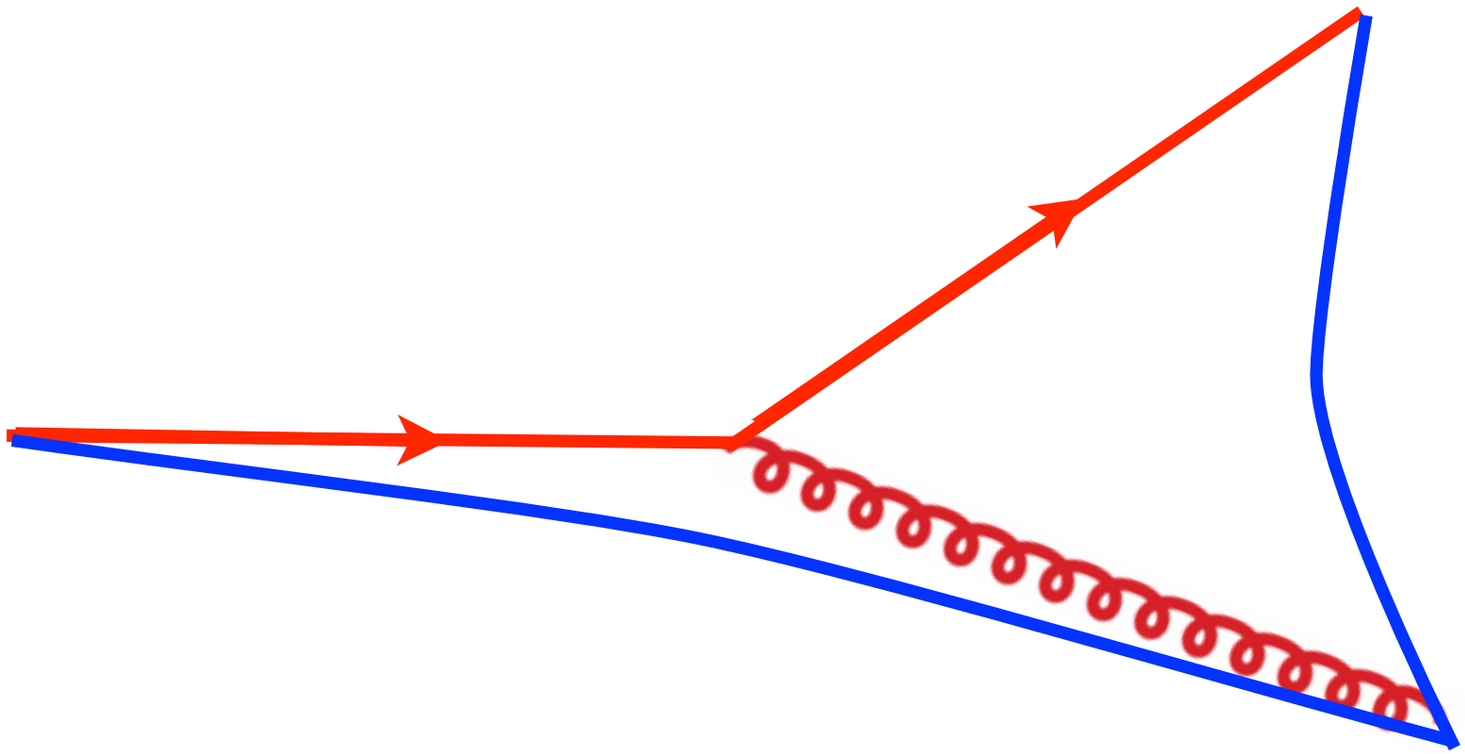
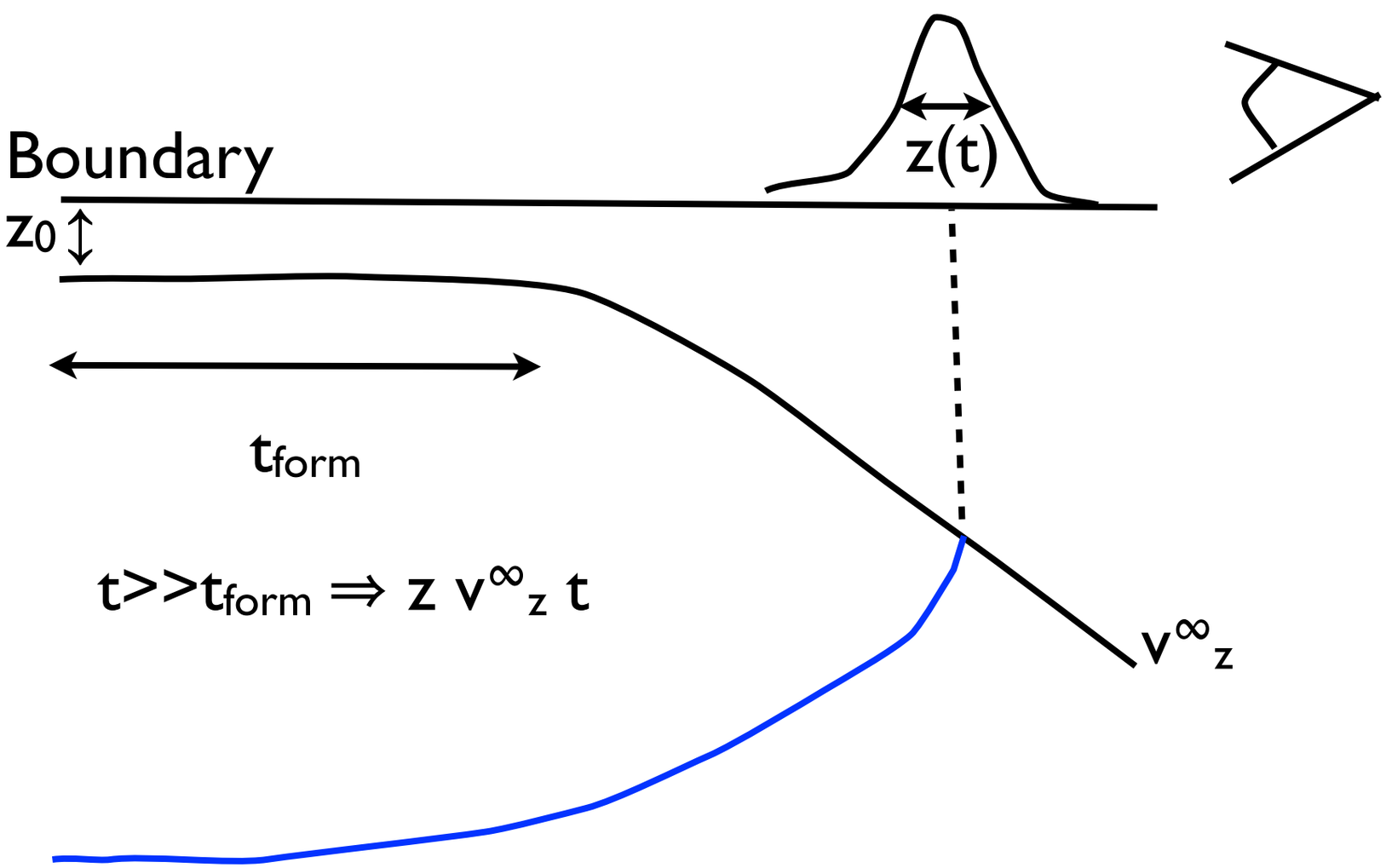
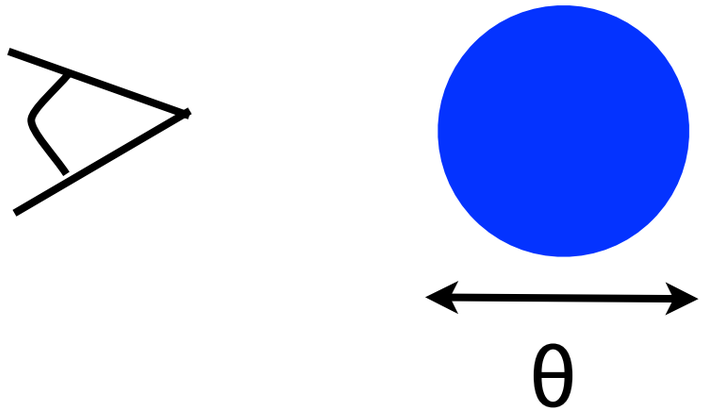


➤ Soft fields between colour objects

Lund string model: gluons associated to kinks in the string

Basics of “Jets” in Vacuum



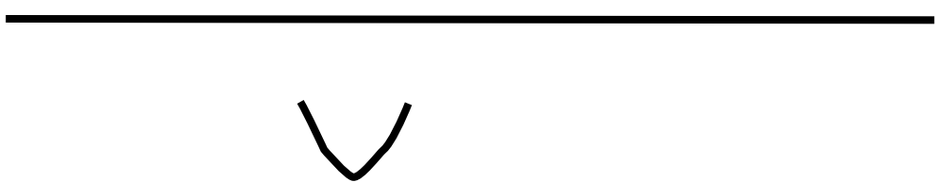


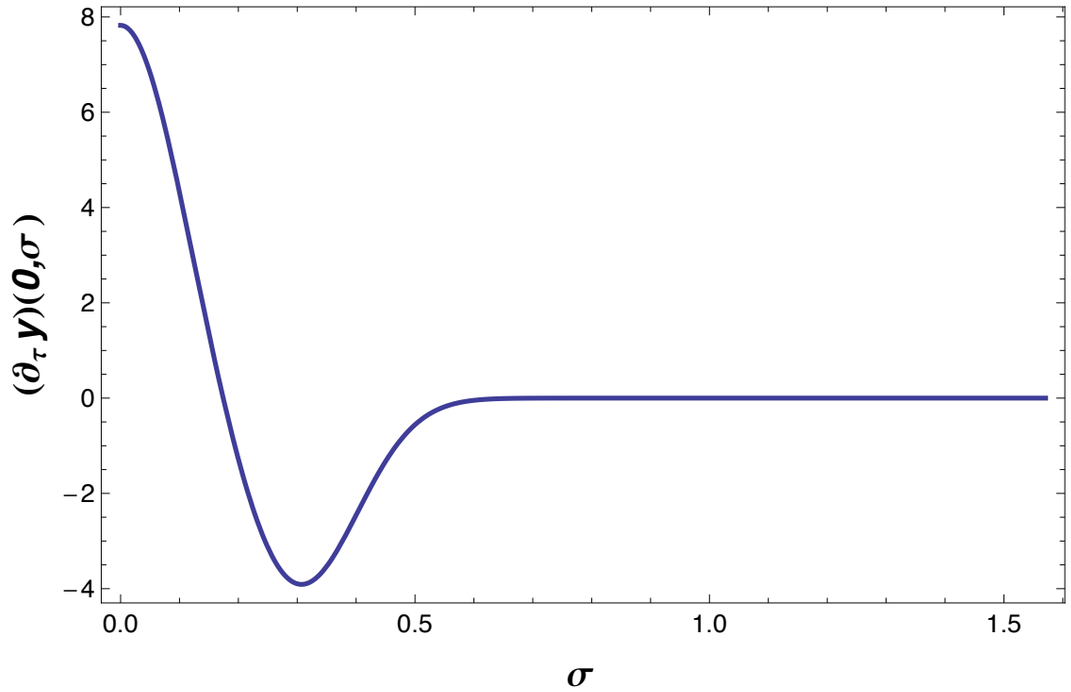
➤ Most of the energy over a fixed angular size θ “quark”

➤ String bits far from the quark carry less energy distributed at wider angles.

“Soft Gluonic Fields”

Creating a “Gluon” Jet

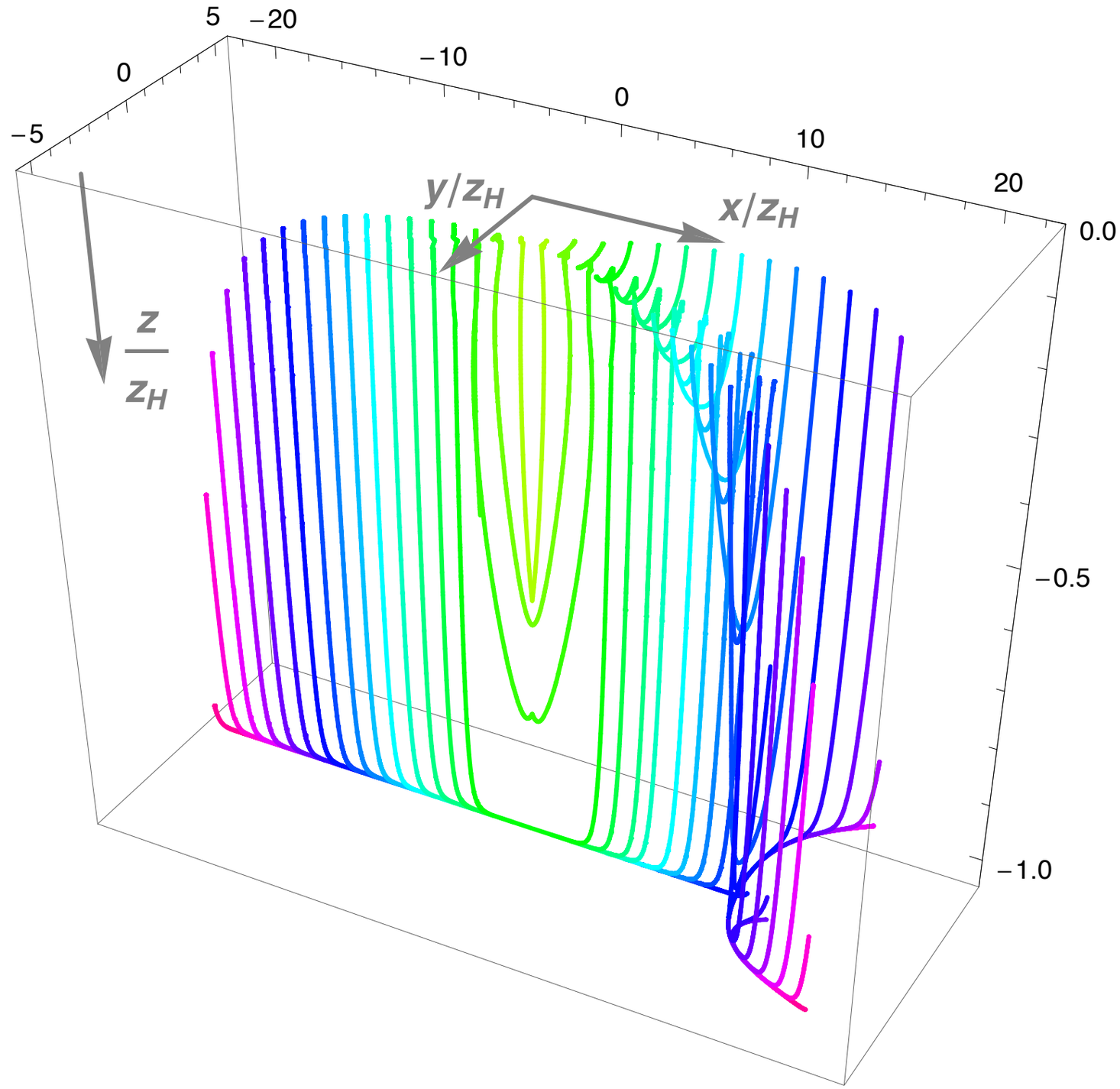




- At initial time, add transverse momentum.
  - Add a lot of momentum in a string bit away from endpoint
  - Creates a localized excitations (without flavor)
  - Stretches two string pieces “Gluon”

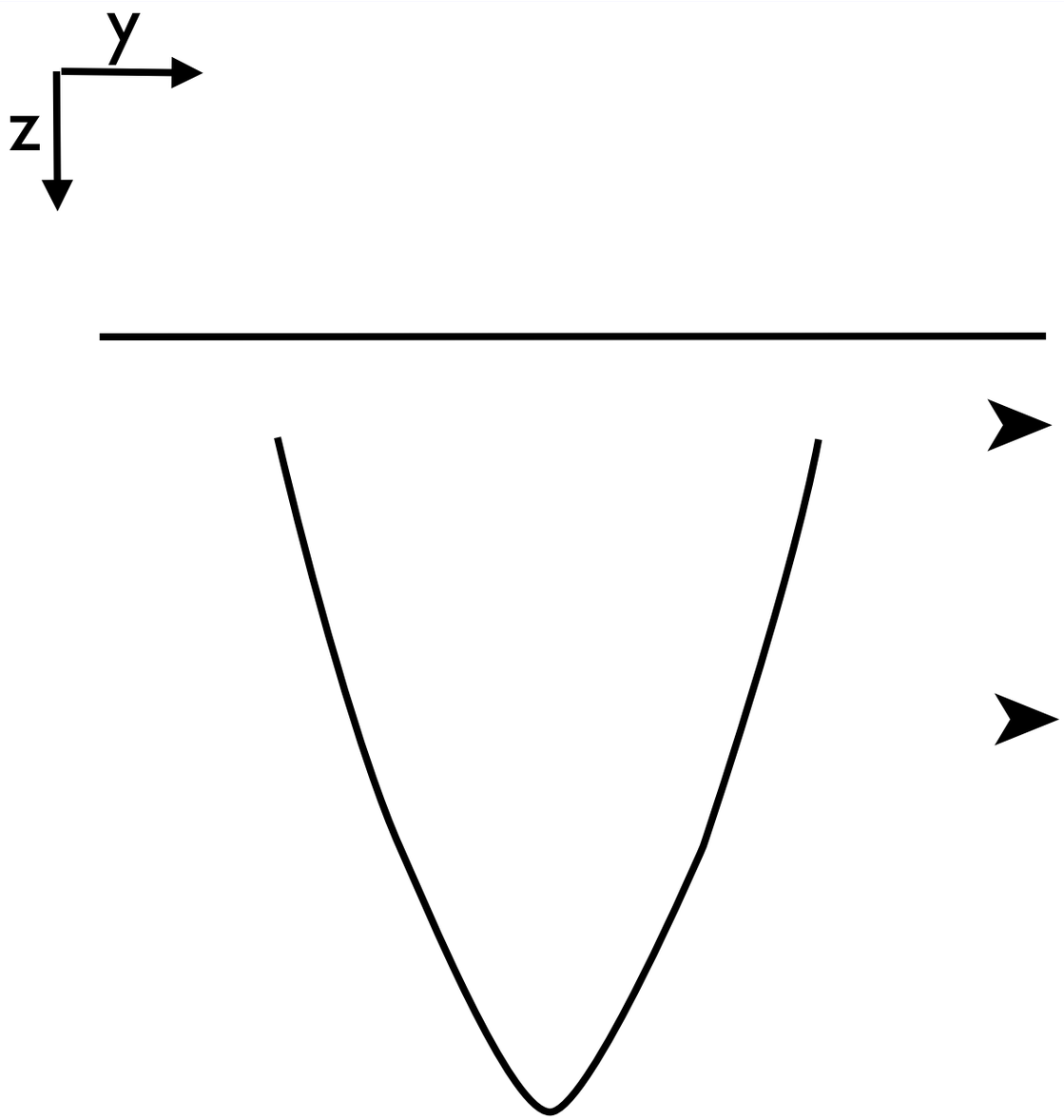
Gubser 08

A 3-Jet Event in Plasma



JCS, Ficnar 1512.00371

Conditions for 3 Jets



➤ Well separated endpoint and "kink"

$$\theta_{qg} \gg \theta_q = v_q^\infty \qquad \theta_{qg} \gg \theta_g = v_q^\infty$$

➤ U-Shaped string:

$$\theta_{gg} \ll \theta_m = v_m^\infty$$

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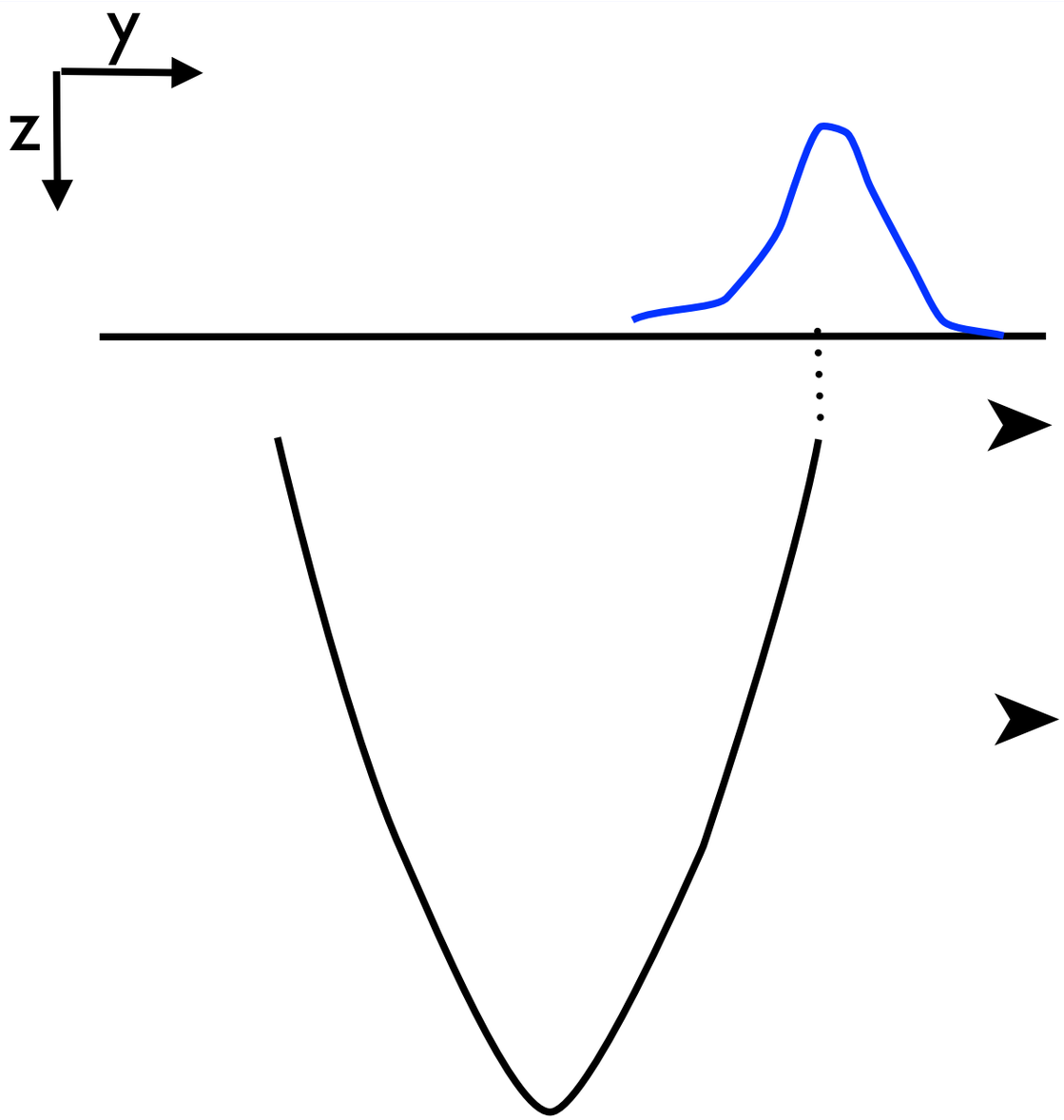

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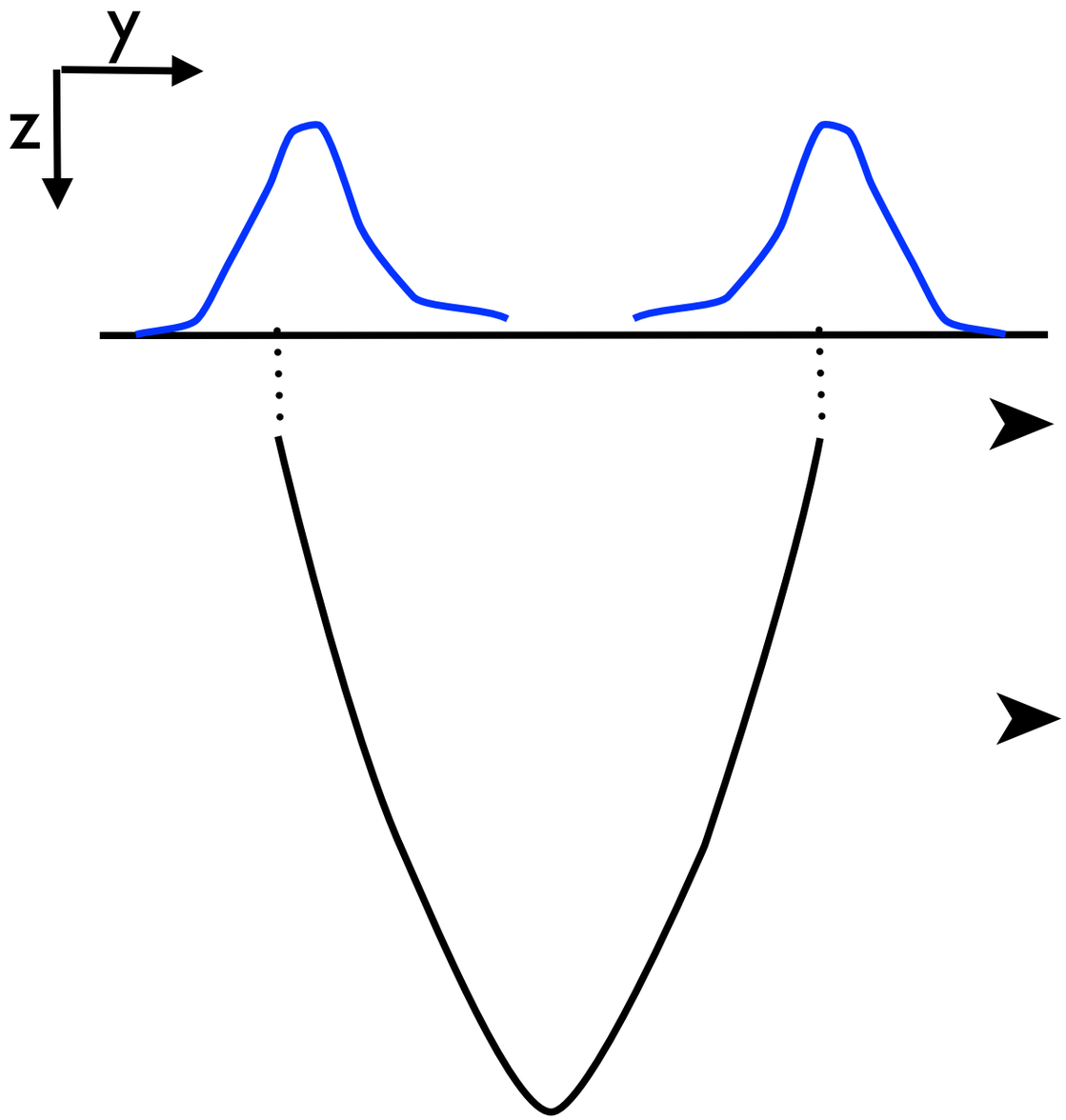

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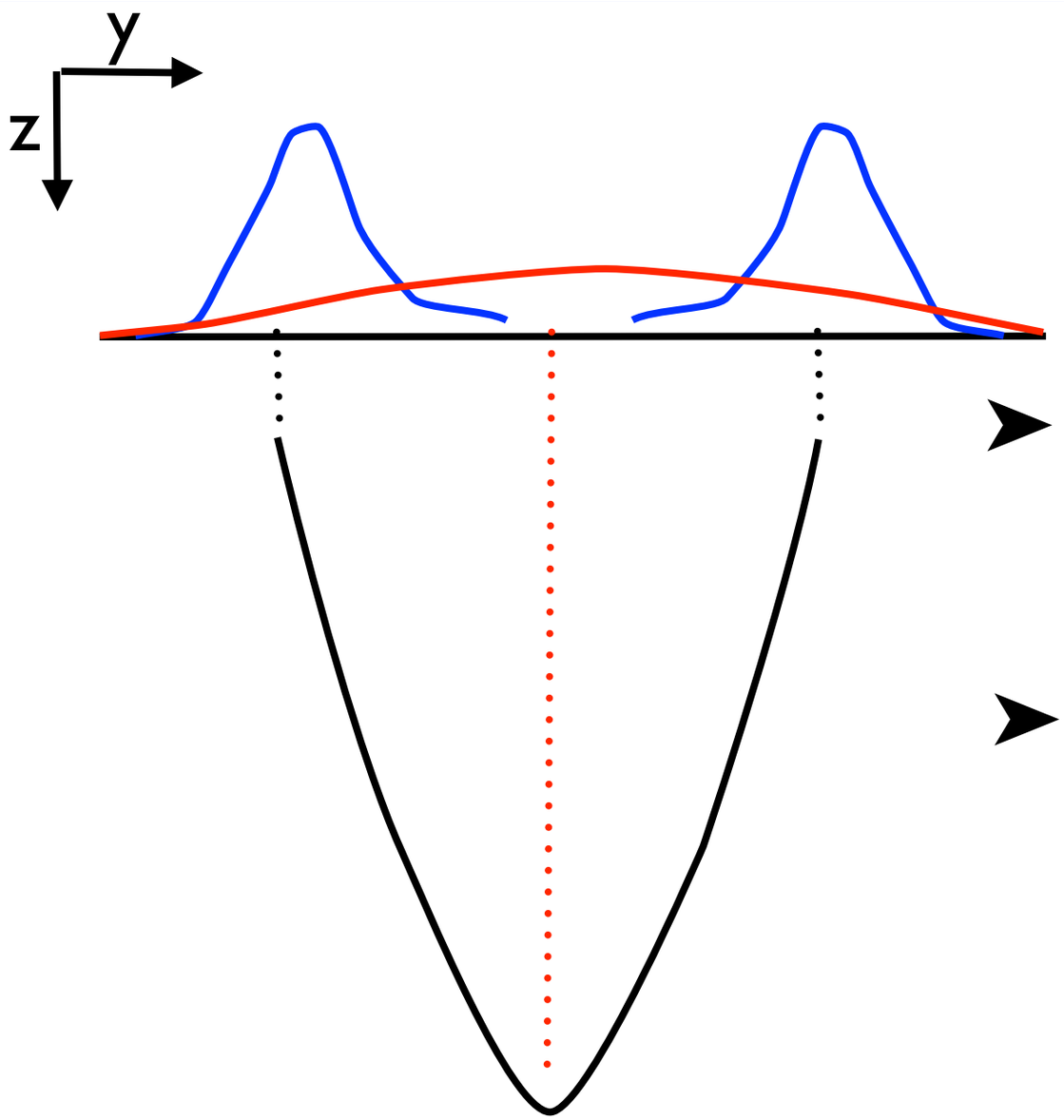

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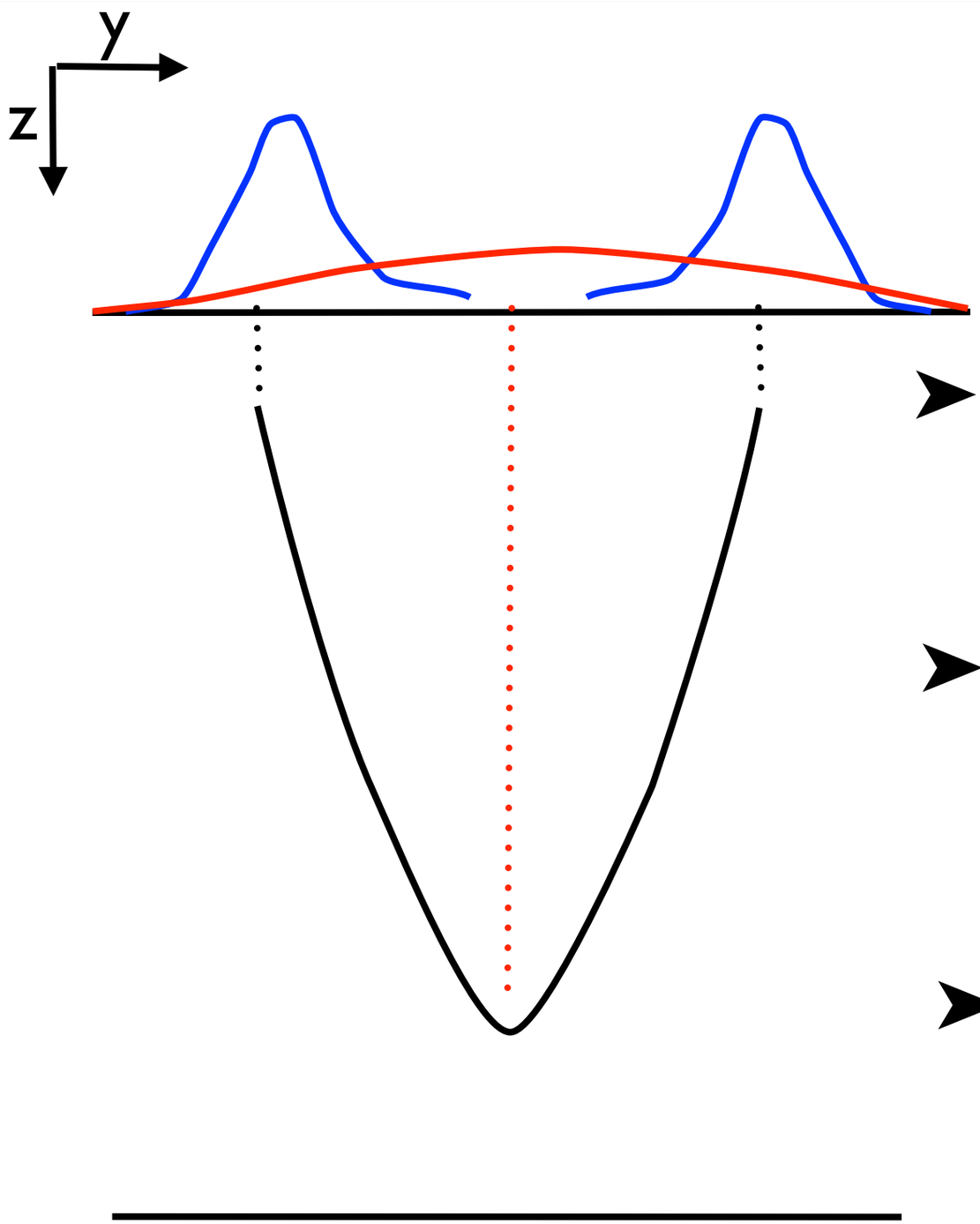

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➤ U-Shaped string:

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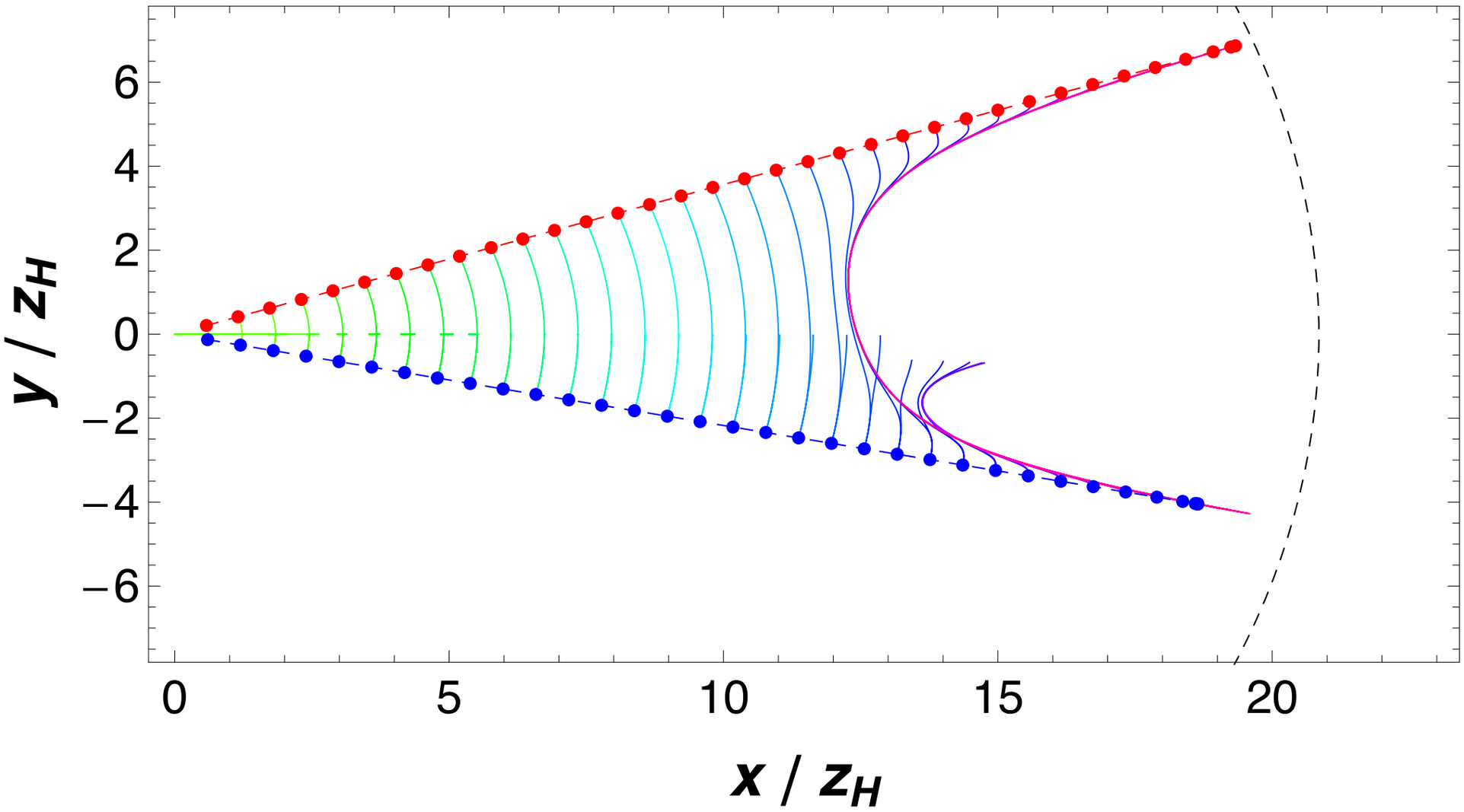
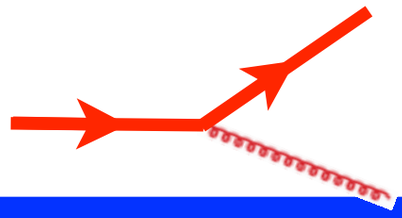
➤ Finite T ⇔ black brane horizon

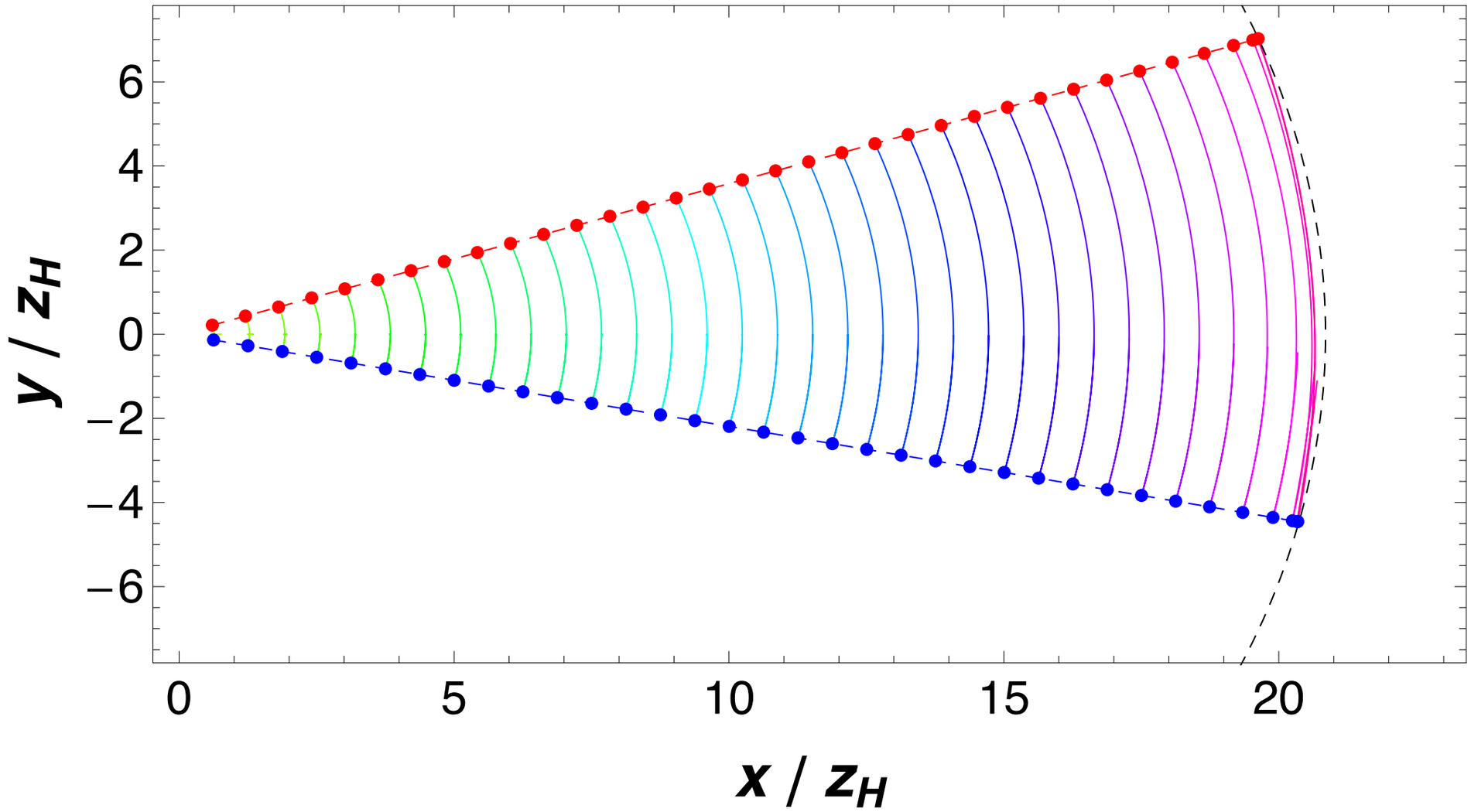
➤ different string pieces fall at different times

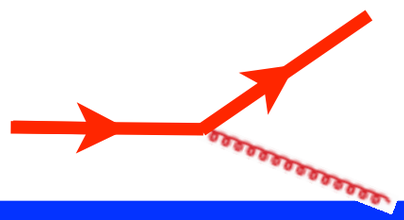
Resolved Strings



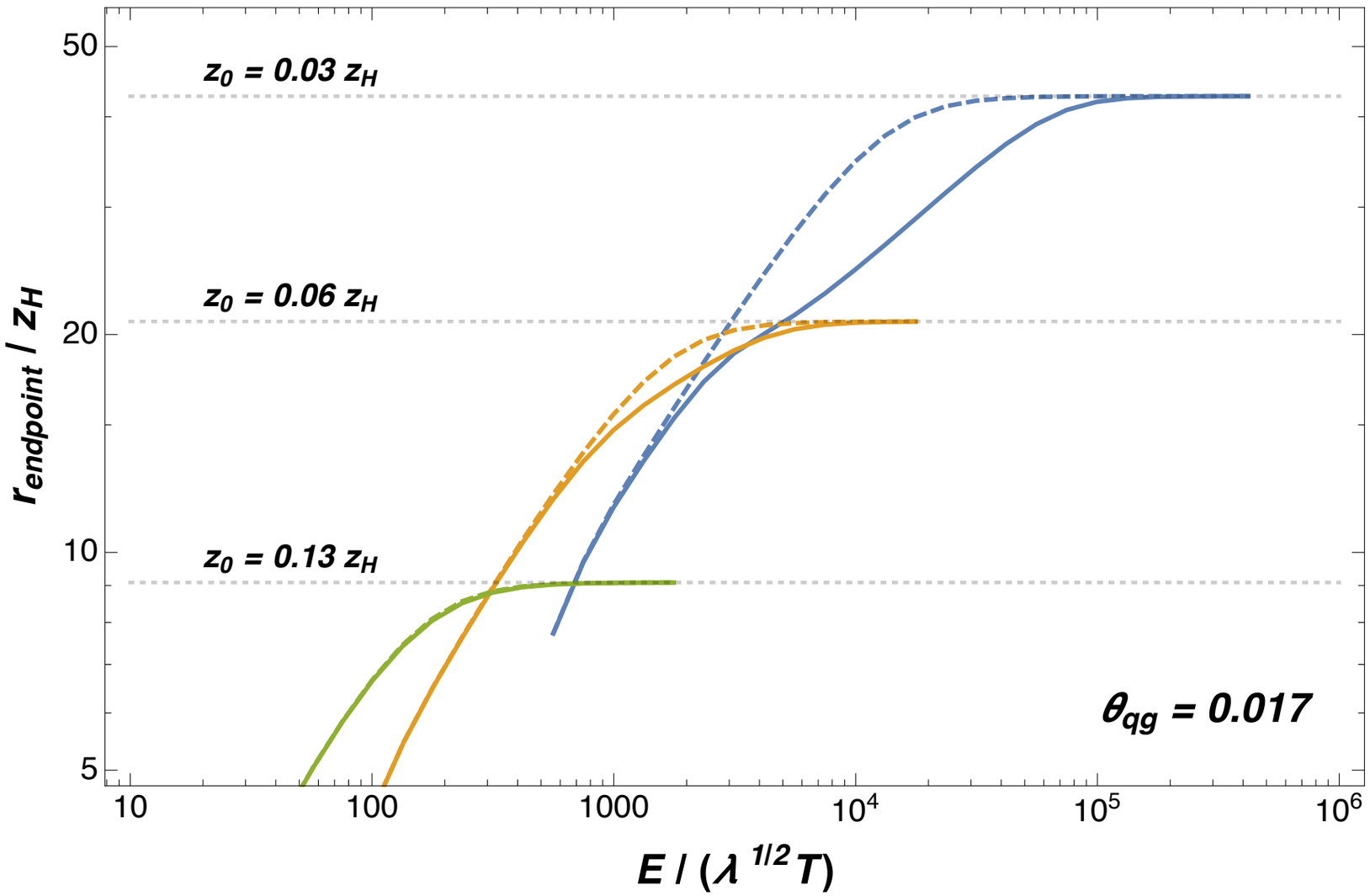


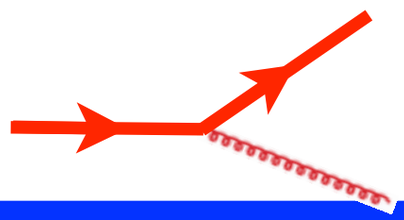
Unresolved Strings





Resolution and Stopping





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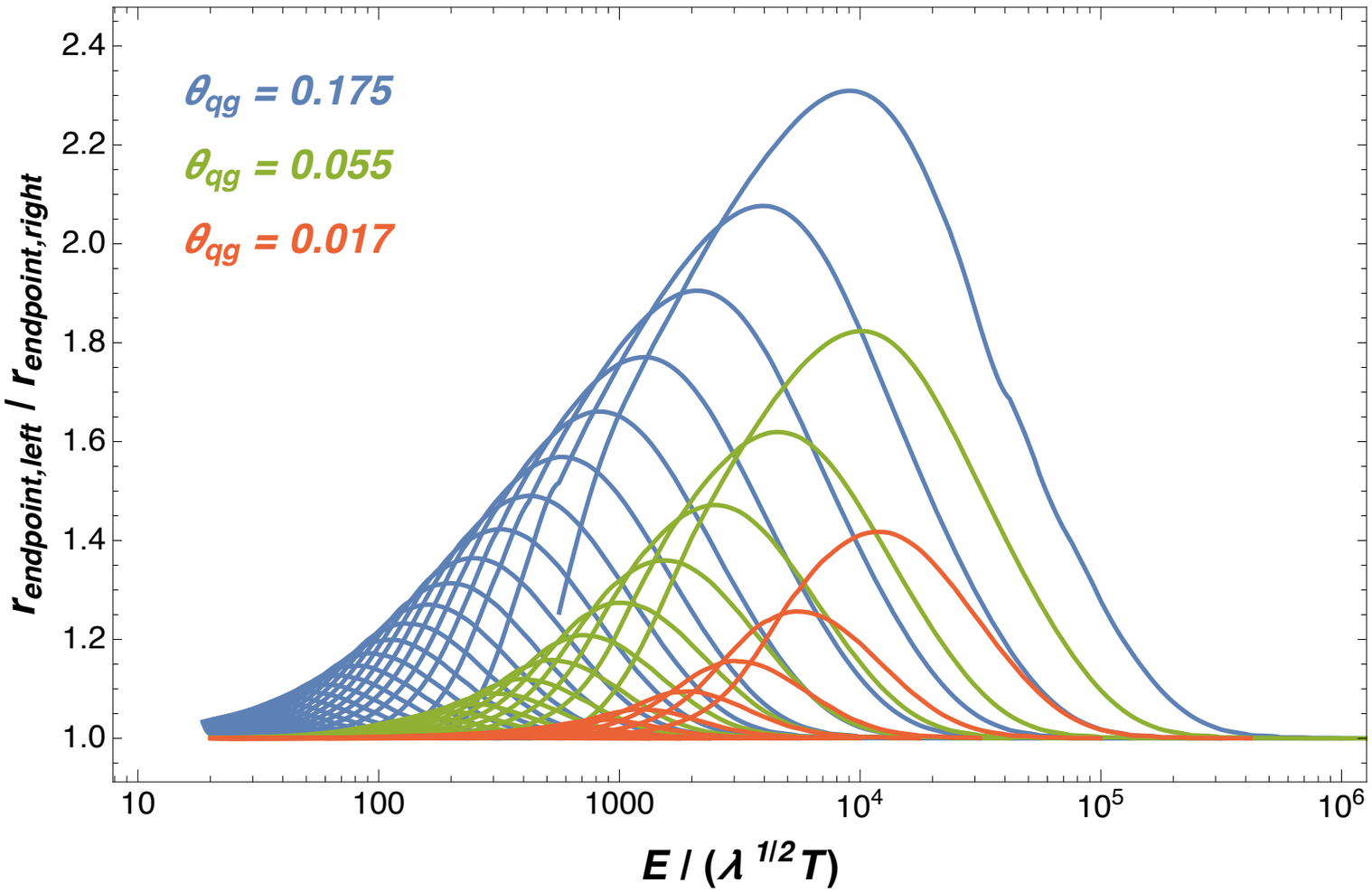
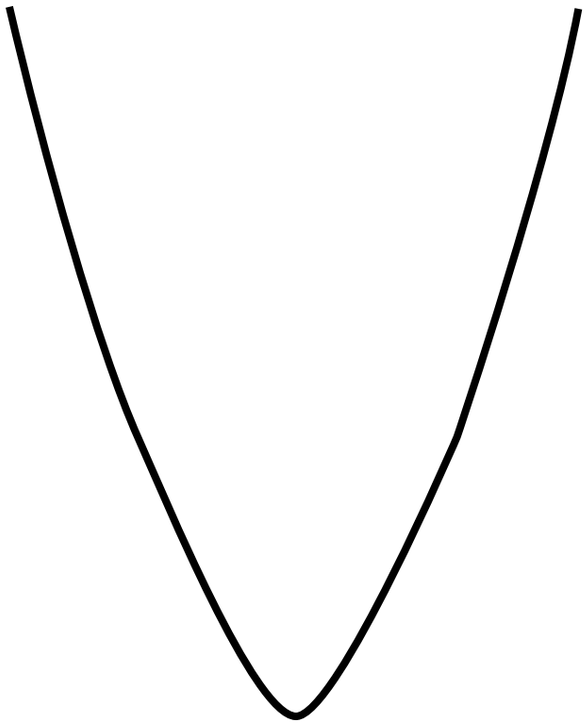


Resolution Angle

➤ Motion of the string at different angles

Gluon Quark



➤ In vacuum (high energy)

$$\ddot{z} = 2\left(\frac{\tau_f L^2}{\varepsilon(\theta)}\right)^2 \frac{t^2}{z^5}$$

$$\tau_{\rm form} = \left(8\pi z_0^3 \,\frac{\varepsilon(\theta)}{\sqrt{\lambda}}\right)^{1/2} \qquad v_z^\infty(\theta) = \mathcal{C}\left(2\pi z_0 \,\frac{\varepsilon(\theta)}{\sqrt{\lambda}}\right)^{-1/2}$$

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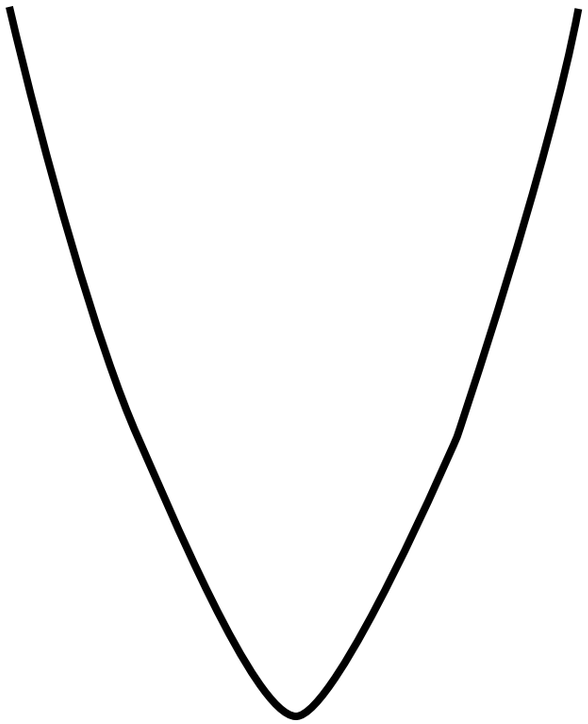

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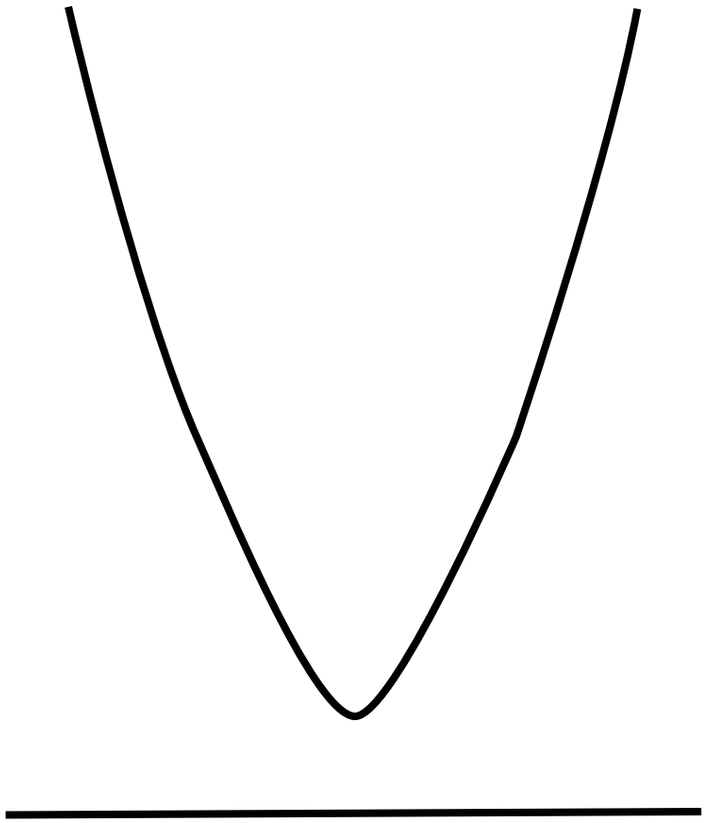

➤ In plasma (close to the boundary)

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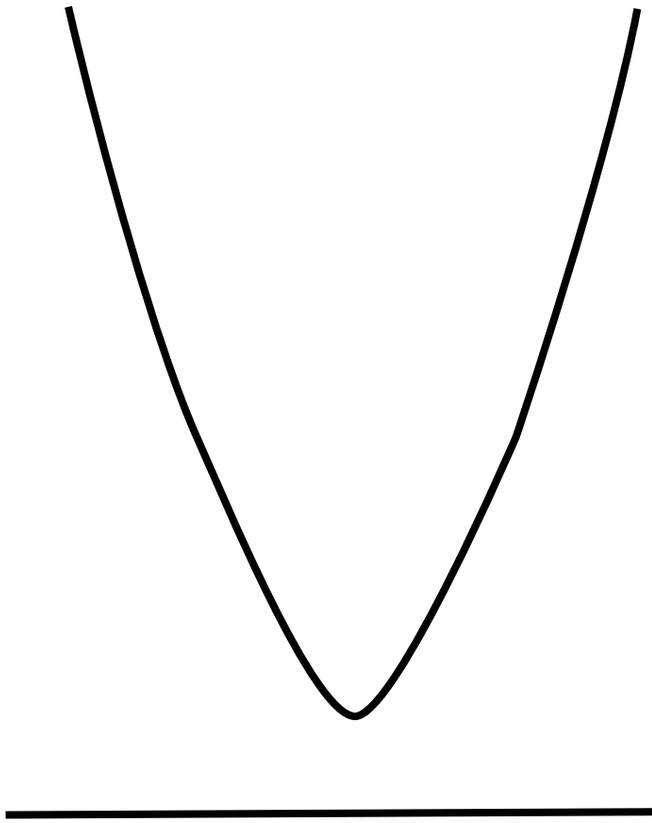

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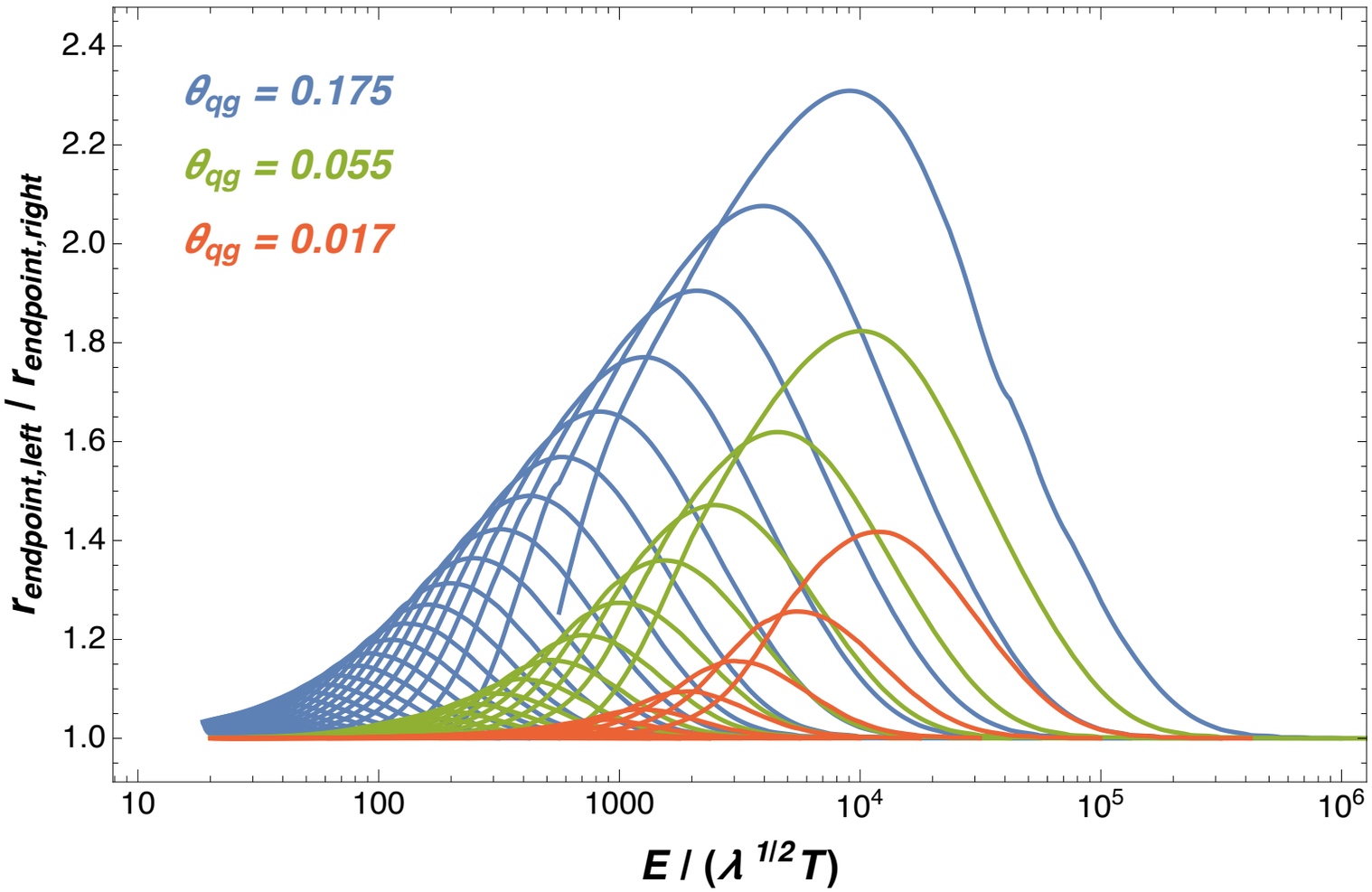
➤ Resolution criterium

$$\tau_{\rm form} > x_{\rm stop},$$

$$\theta_{\rm unresolved} < 8\frac{\Gamma(3/4)^2}{\Gamma(5/4)^2}\frac{z_0^5}{z_H^4}\frac{E_{qg}}{\sqrt{\lambda}} < 8\frac{\Gamma(3/4)^2}{\Gamma(5/4)^2}\frac{z_0^5}{z_H^4}\frac{E}{\sqrt{\lambda}}$$

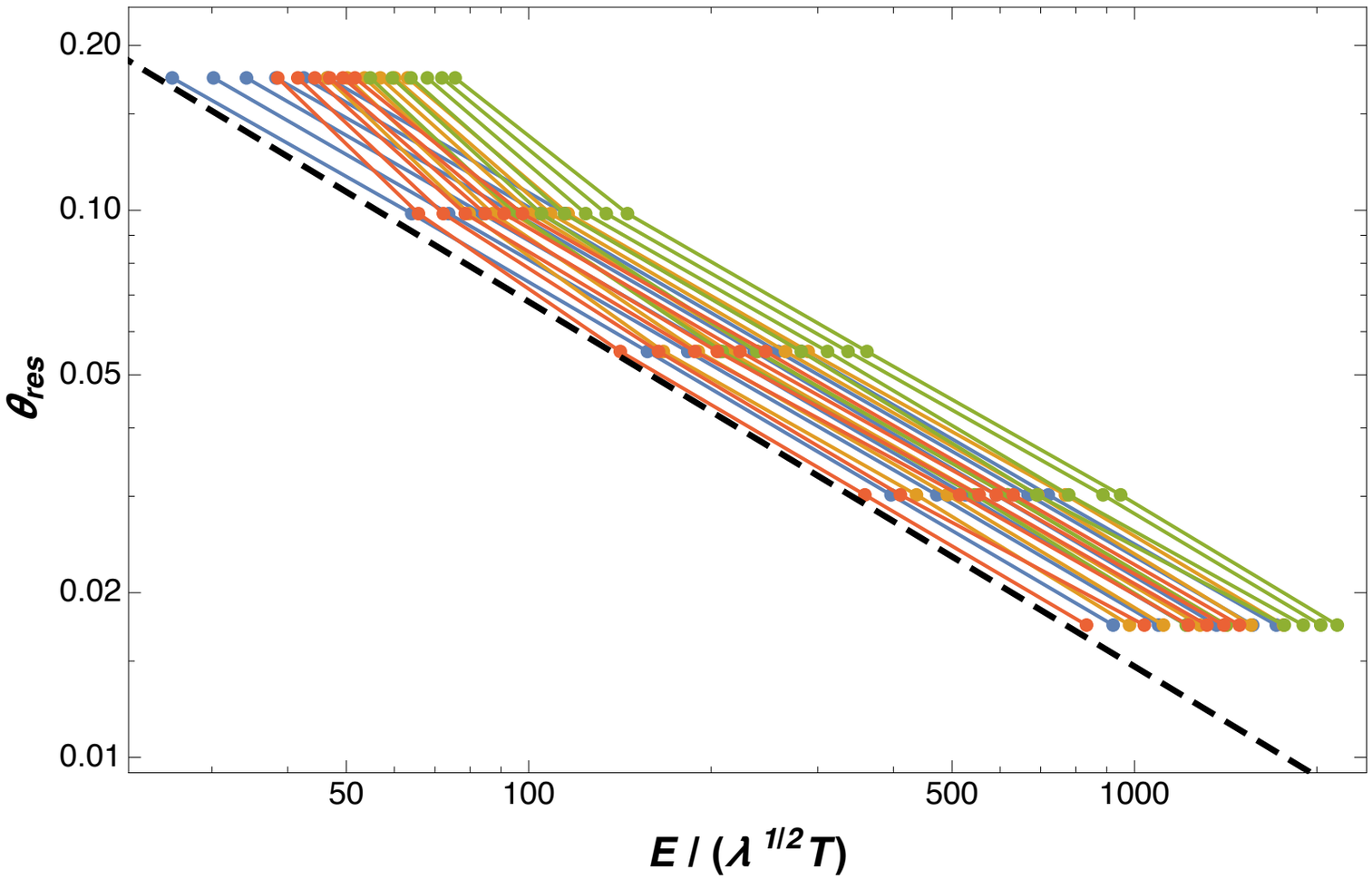
Numerics



$$\theta_{\rm res} = \frac{2^{4/3}}{\pi} \frac{\Gamma(3/4)^2}{\Gamma(5/4)^2} \left(\frac{E}{\sqrt{\lambda} T} \right)^{-2/3}$$

JCS and Ficnar 1512.00371

Numerics



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JCS and Ficnar 1512.00371

Conclusions

- First analysis of "multi jets" in holography
- Simple physical picture
  - Resolution organizes the number of effective emitters
- A characteristic jet energy dependence of the resolution angle
  - Is it universal?
  - Can we use it as a signal of strong coupling?

Conclusions

- First analysis of "multi jets" in holography
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  - Resolution organizes the number of effective emitters

(Similar picture in perturbation theory
JCS, Mehtar-Tani,Tywoniuk, Salgado 12)

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  - Is it universal?
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Strong vs Weak

- Resolution angle infinite medium

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$$\theta_{\rm res}^{\rm dense} \sim \frac{1}{\sqrt{\hat{q}L^3}}$$

Finite length medium

- Infinite medium, maximal length= stopping distance $\Delta x_{\rm stop}^{pQCD} \sim \sqrt{\frac{E}{\hat{q}}}$

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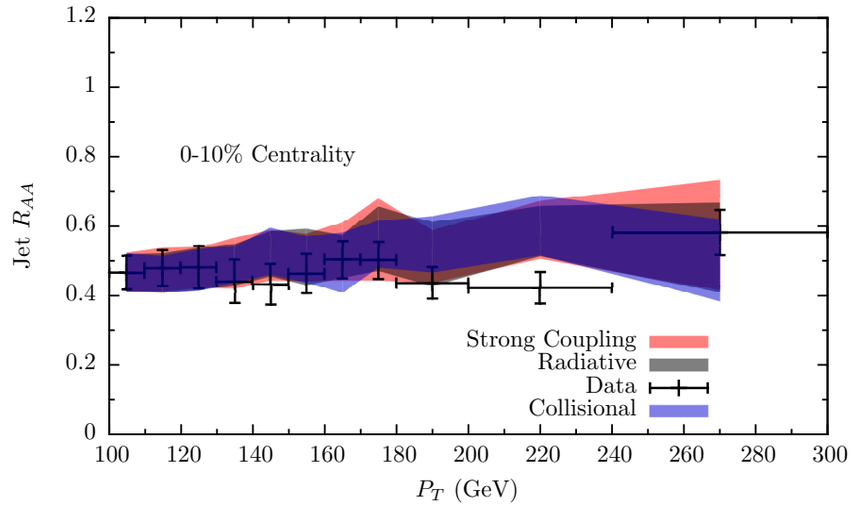
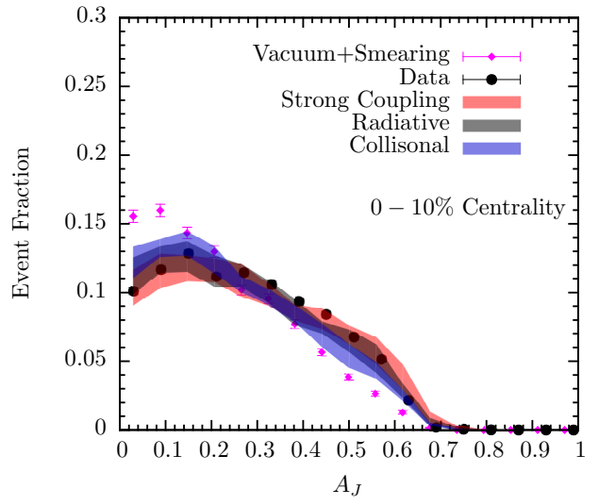
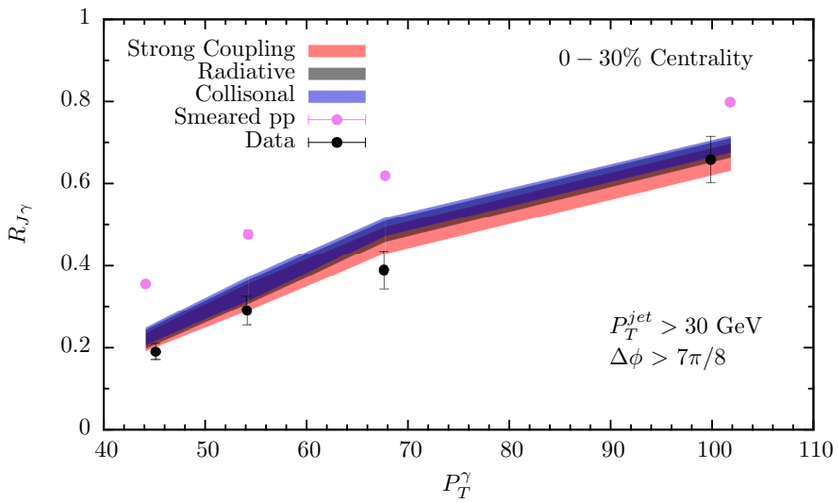
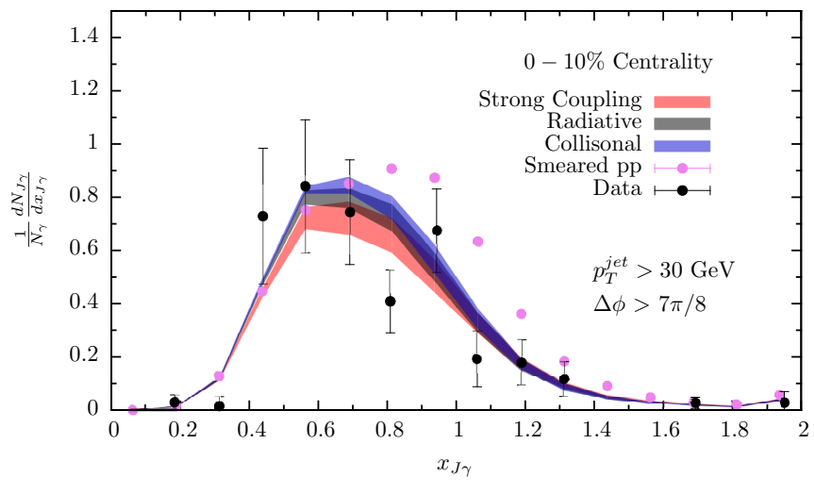
- Fluctuations in jet energy loss may help distinguish between the different microscopic realisations

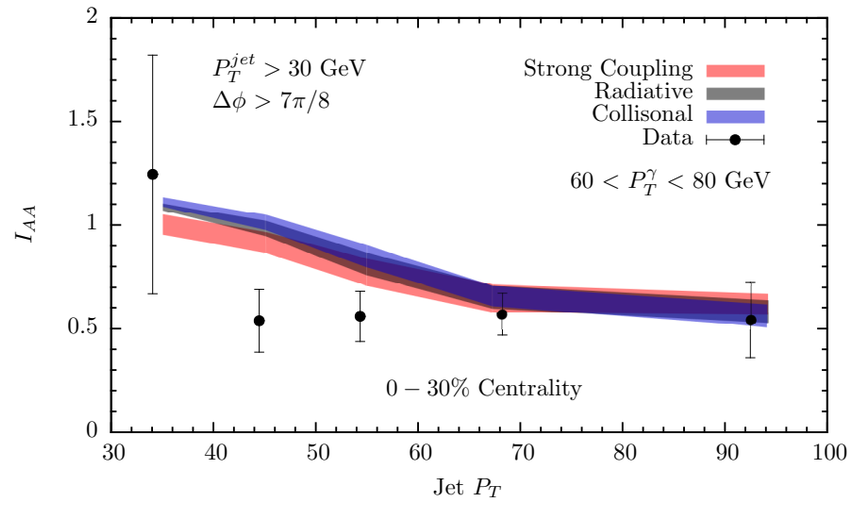
Insensitivity

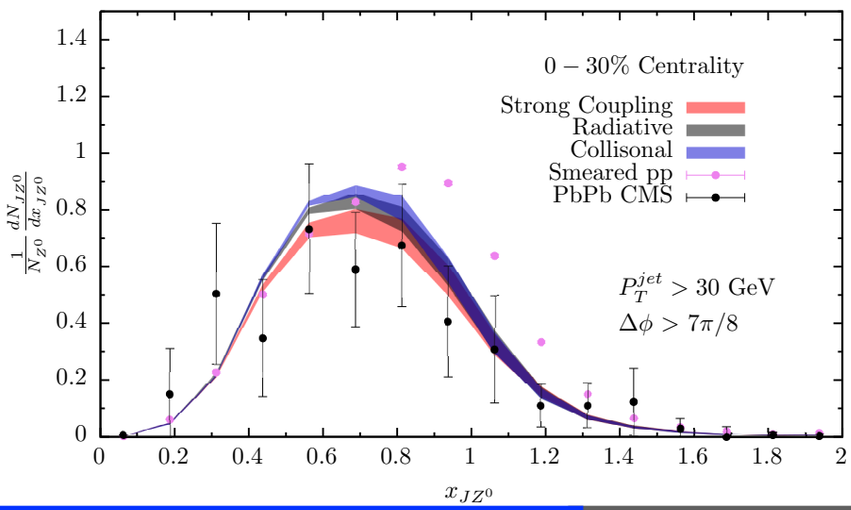


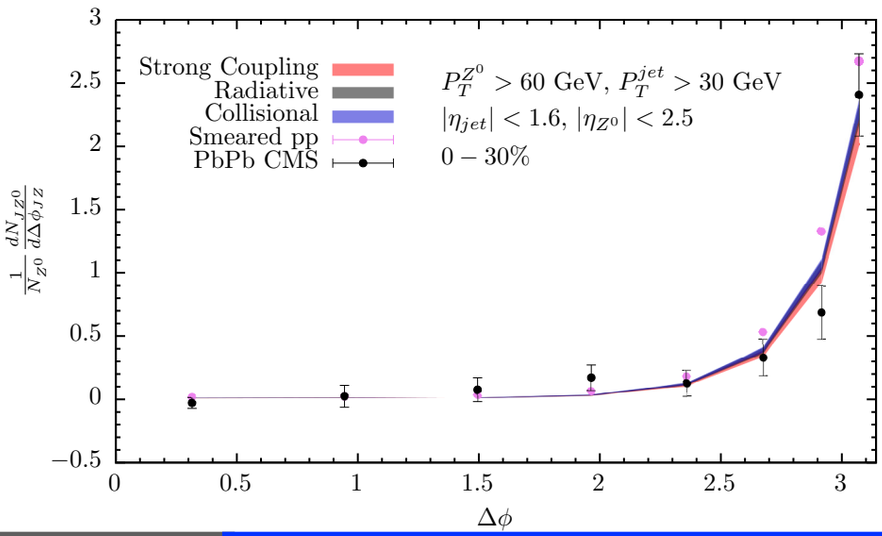






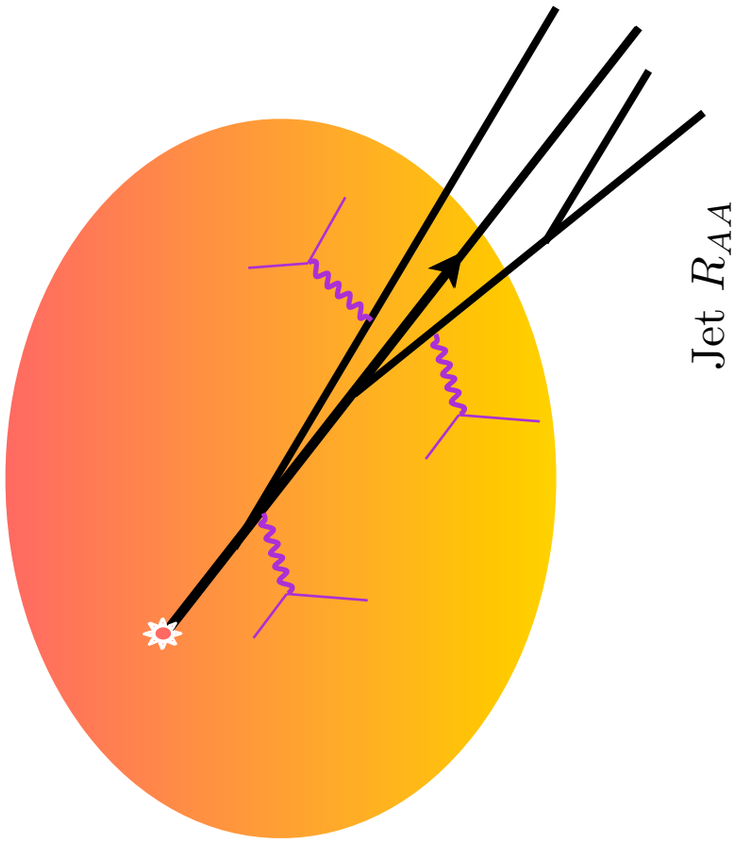


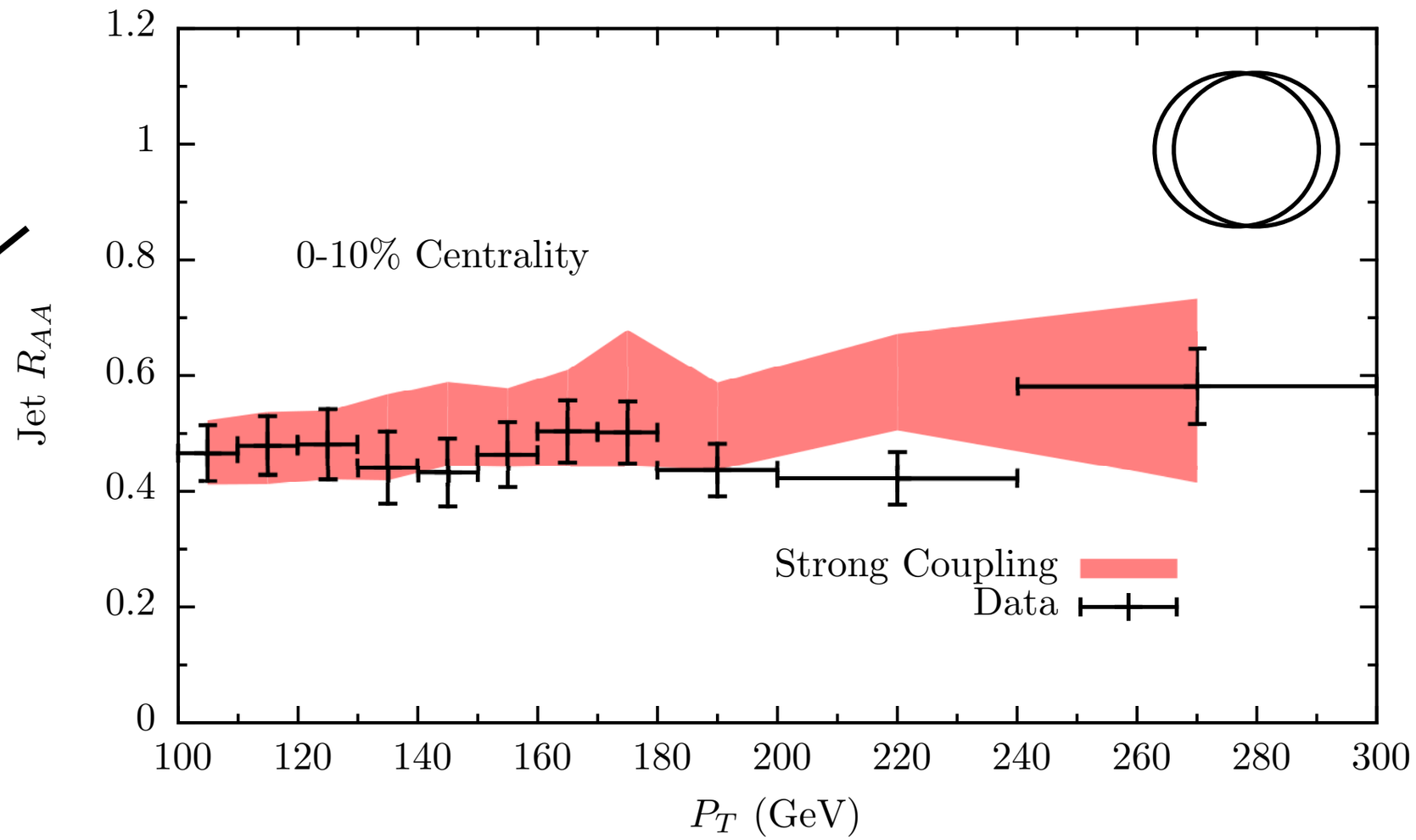




Observable: RAA

JCS, Gulhan, Milhano, Pablos and Rajagopal 2015





Fitted value

$$R_{AA} = \frac{\text{number of jets in A} - \text{A}}{\text{number of collisions} \times \text{number of jets in p} - \text{p}}$$

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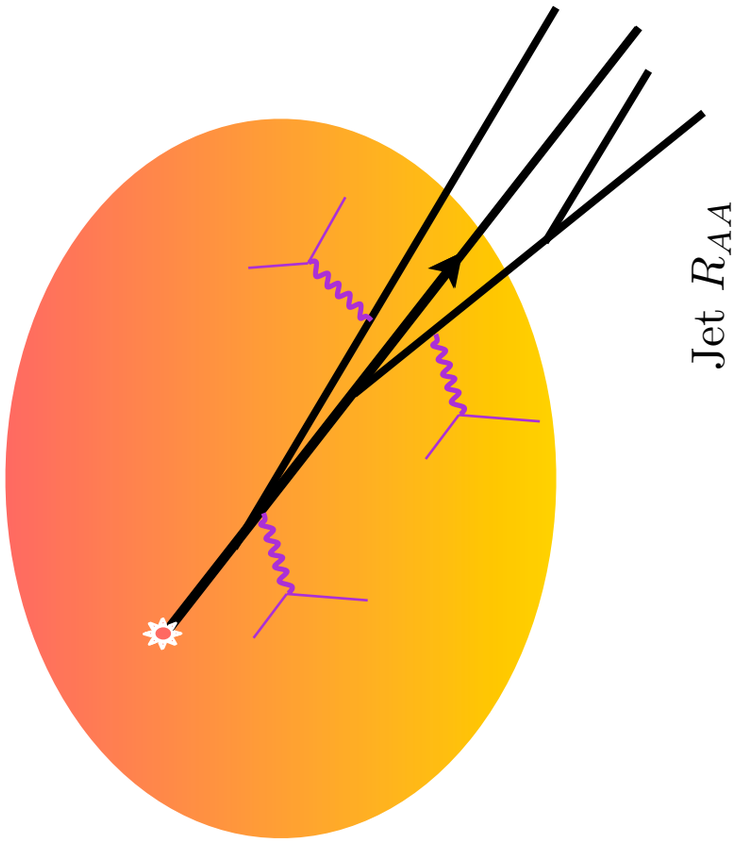
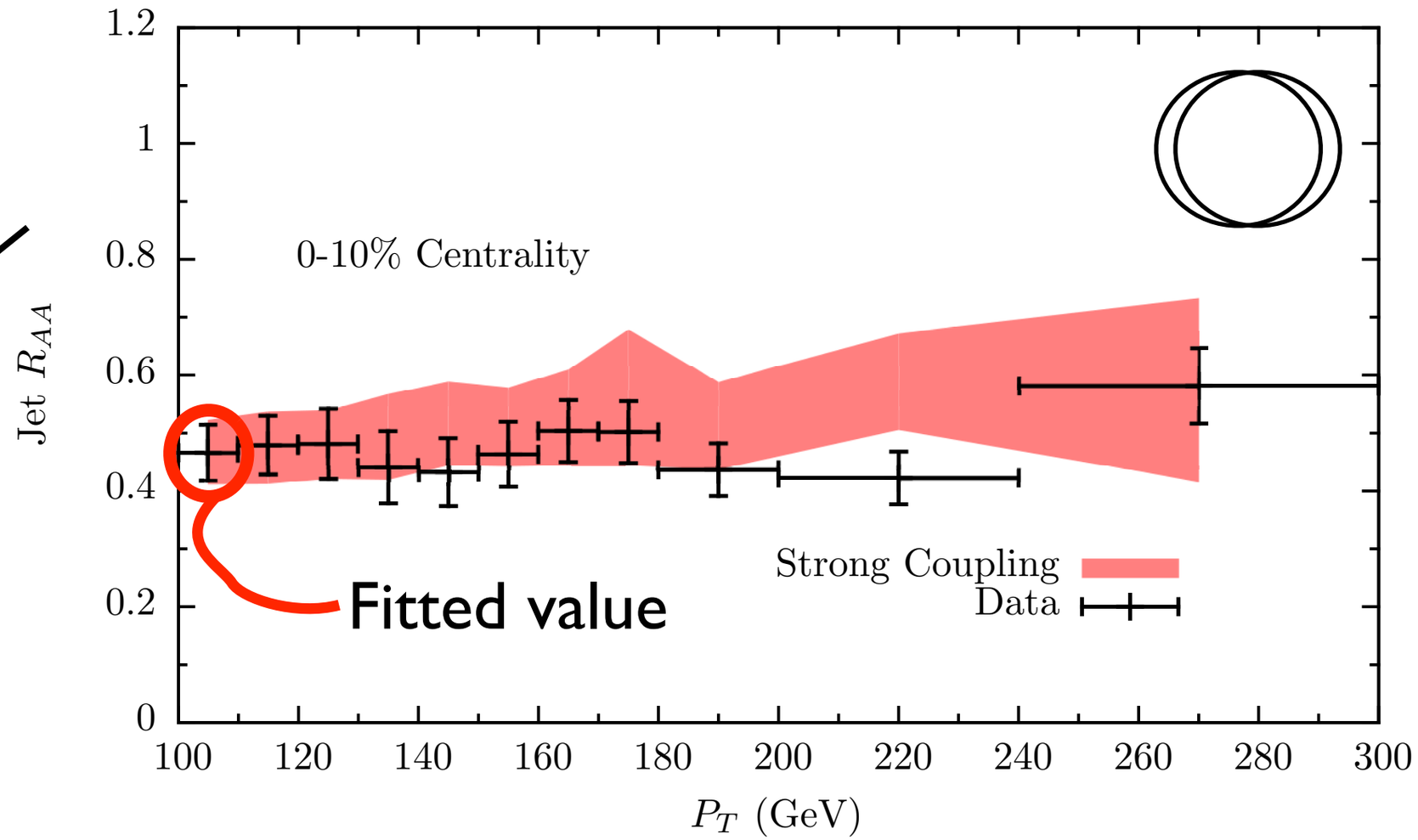


JCS, Gulhan, Milhano, Pablos and Rajagopal 2015



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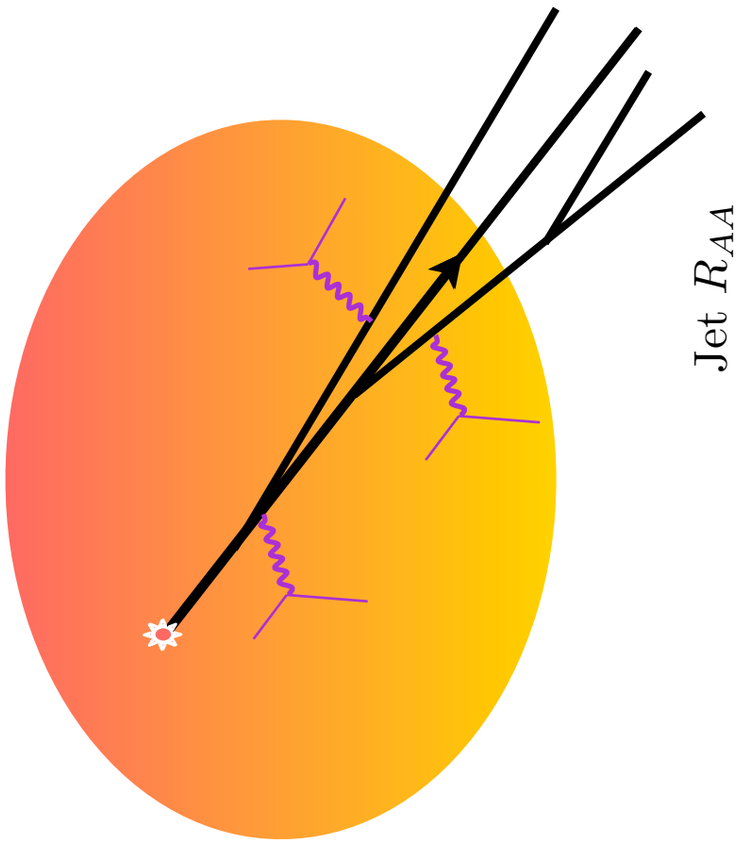
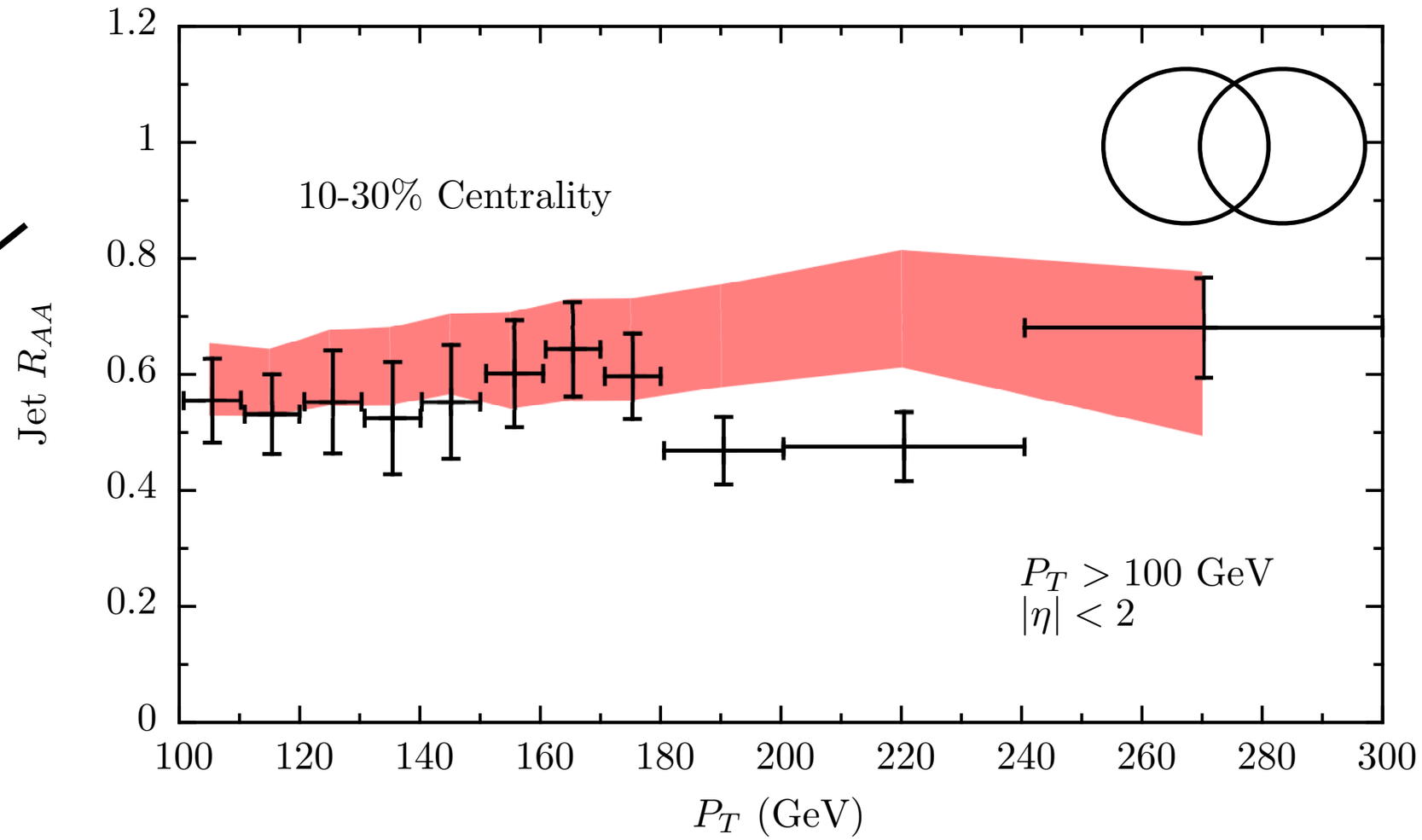


JCS, Gulhan, Milhano, Pablos and Rajagopal 2015



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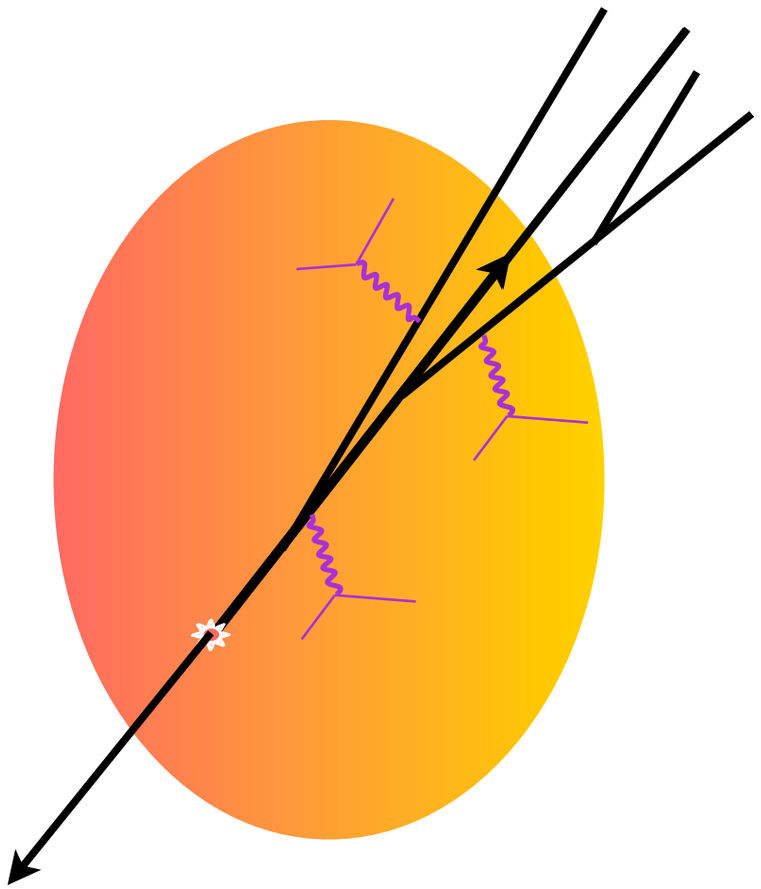
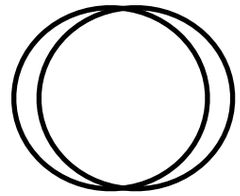
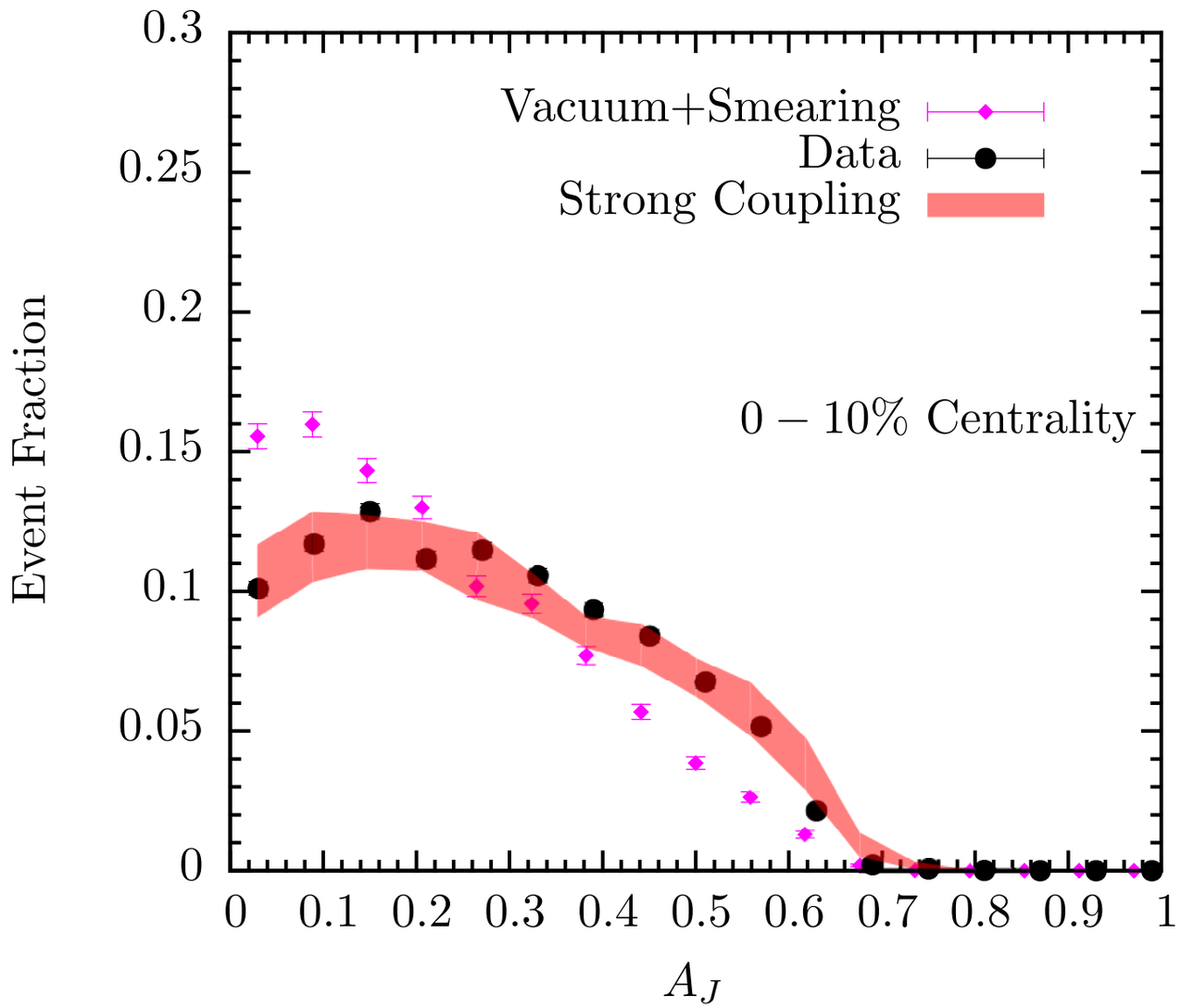
Dijets

JCS, Gulhan, Milhano, Pablos and Rajagopal 2015



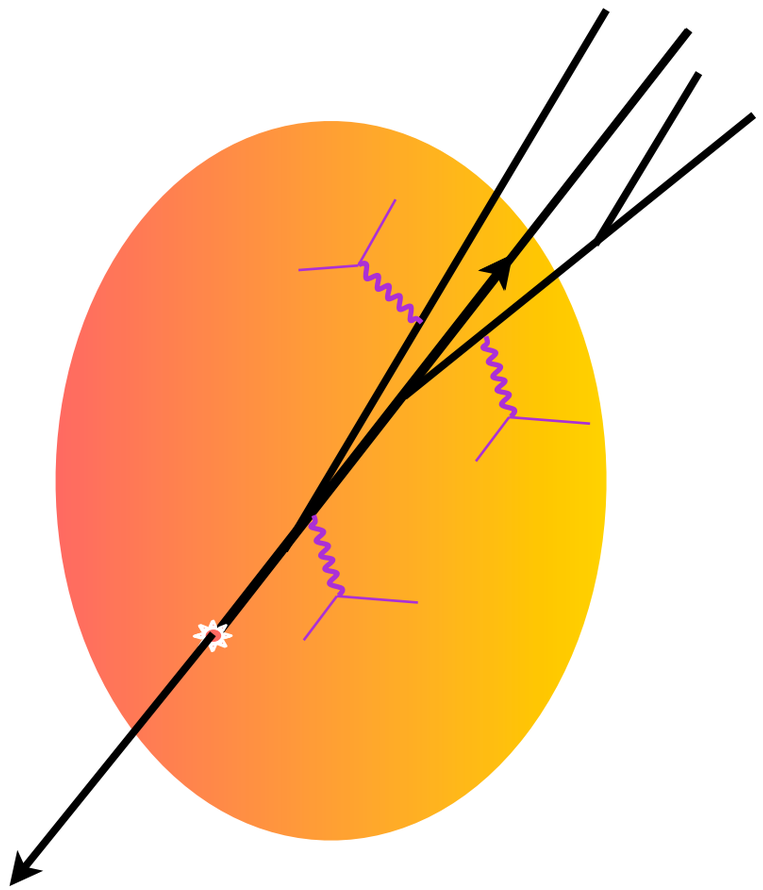


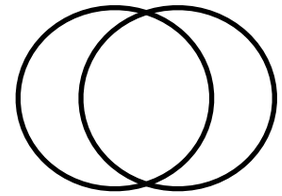


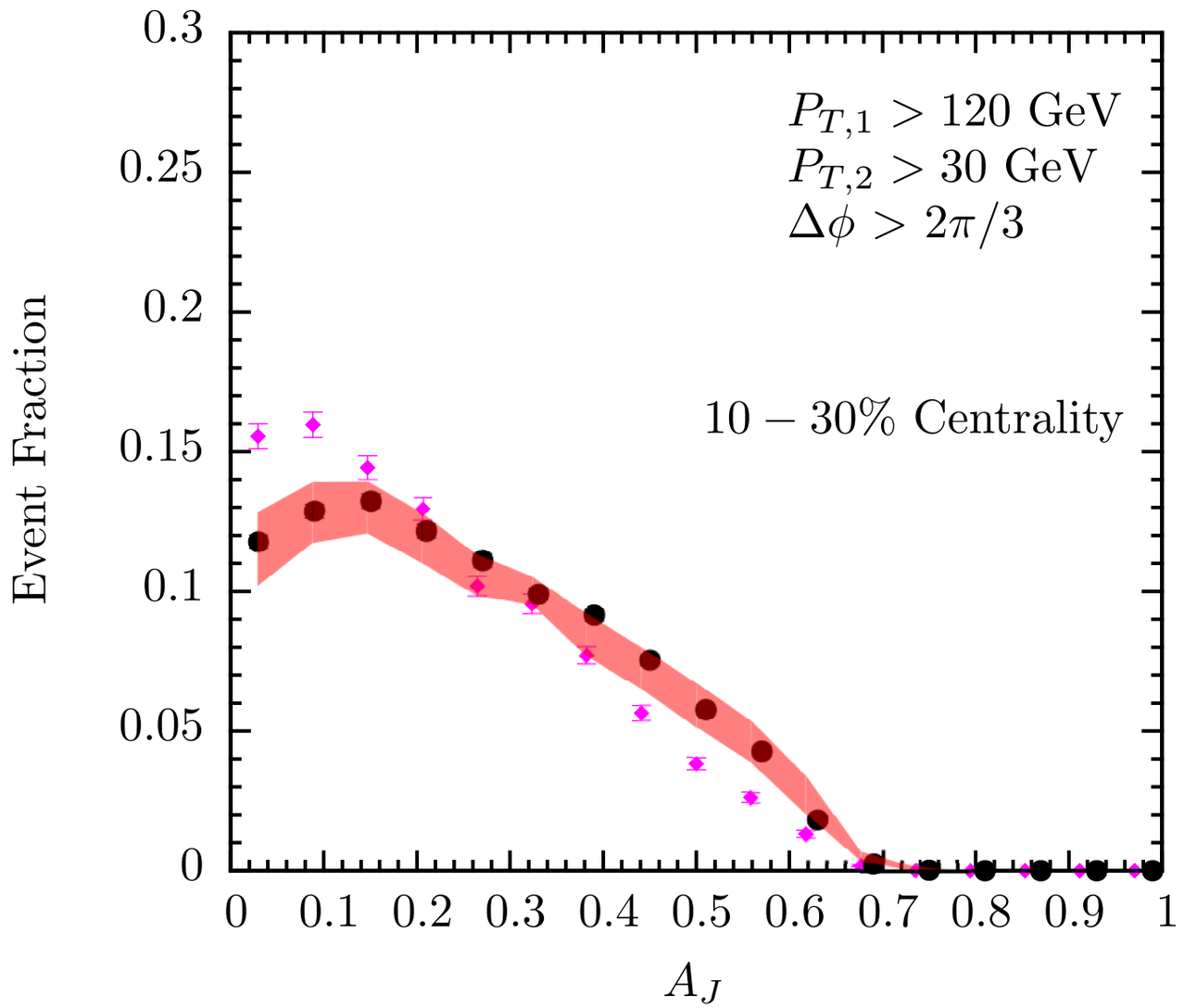
$$A_J = \frac{p_{T_1} - p_{T_2}}{p_{T_1} + p_{T_2}}$$

Dijets

JCS, Gulhan, Milhano, Pablos and Rajagopal 2015



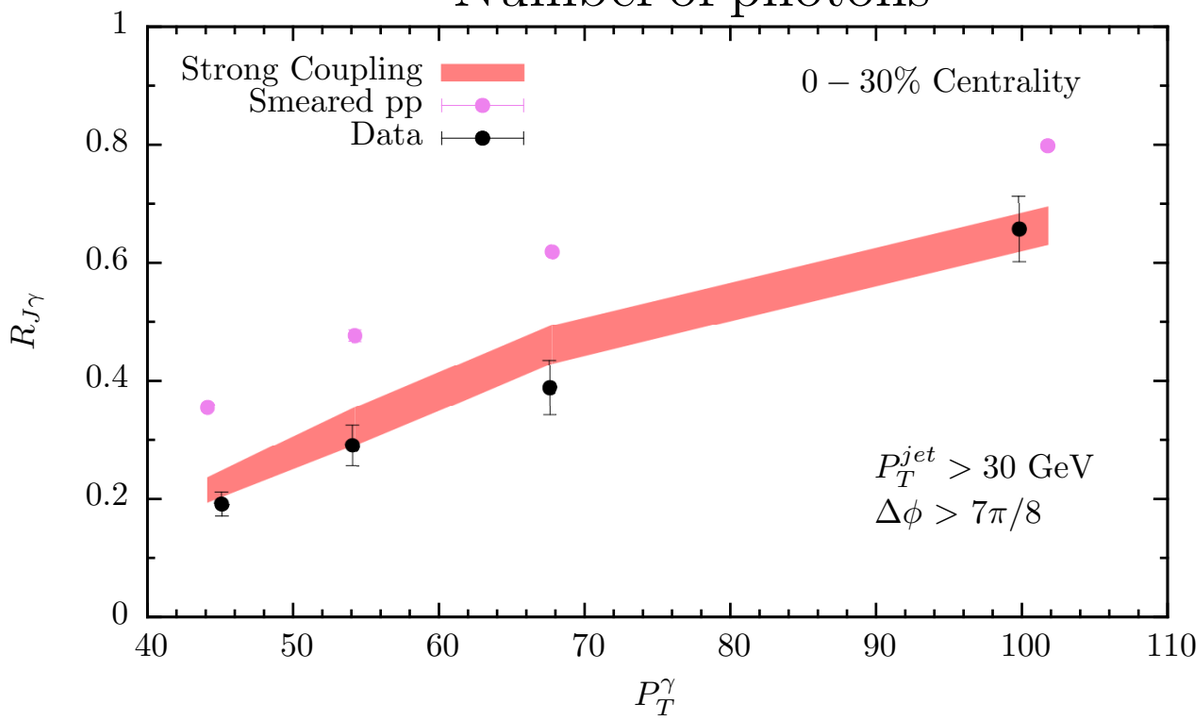


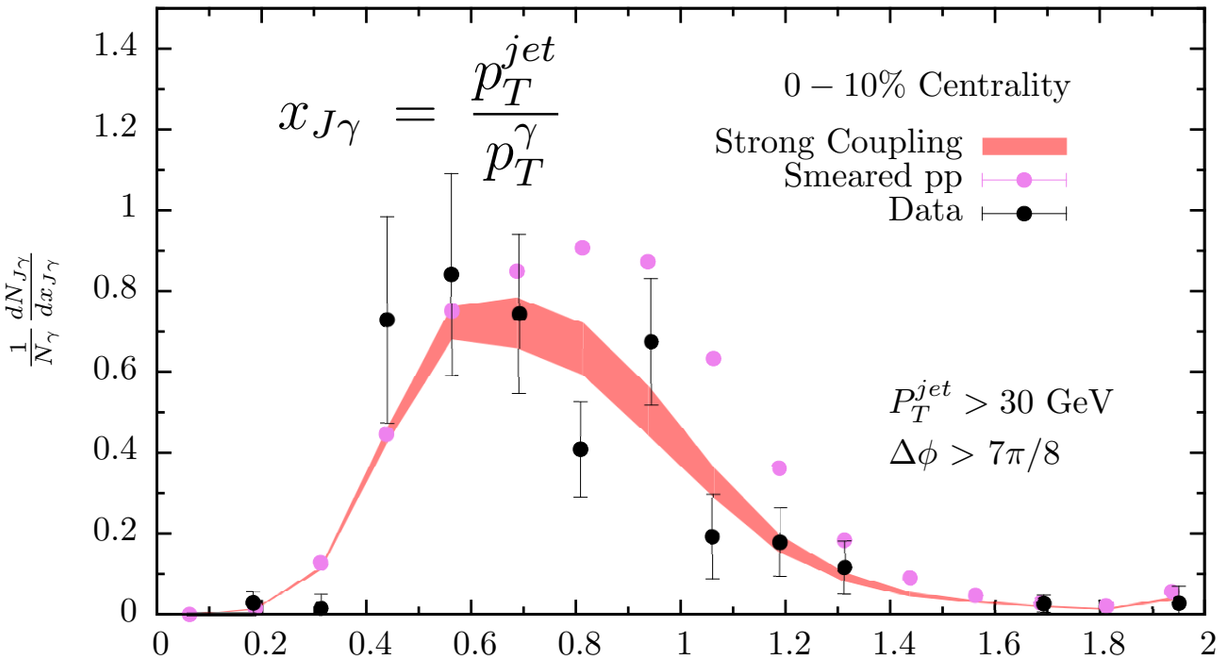


$$A_J = \frac{p_{T_1} - p_{T_2}}{p_{T_1} + p_{T_2}}$$

Photon - Jet

$$R_{J\gamma} = \frac{\text{Number of jets}}{\text{Number of photons}}$$





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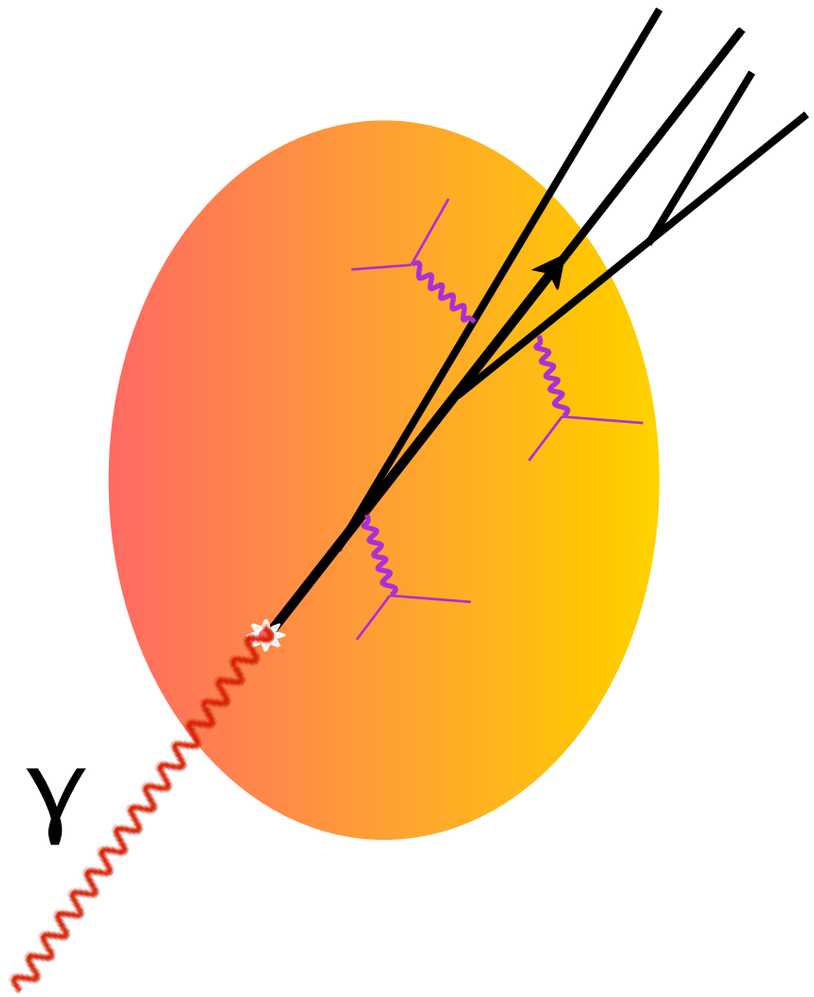
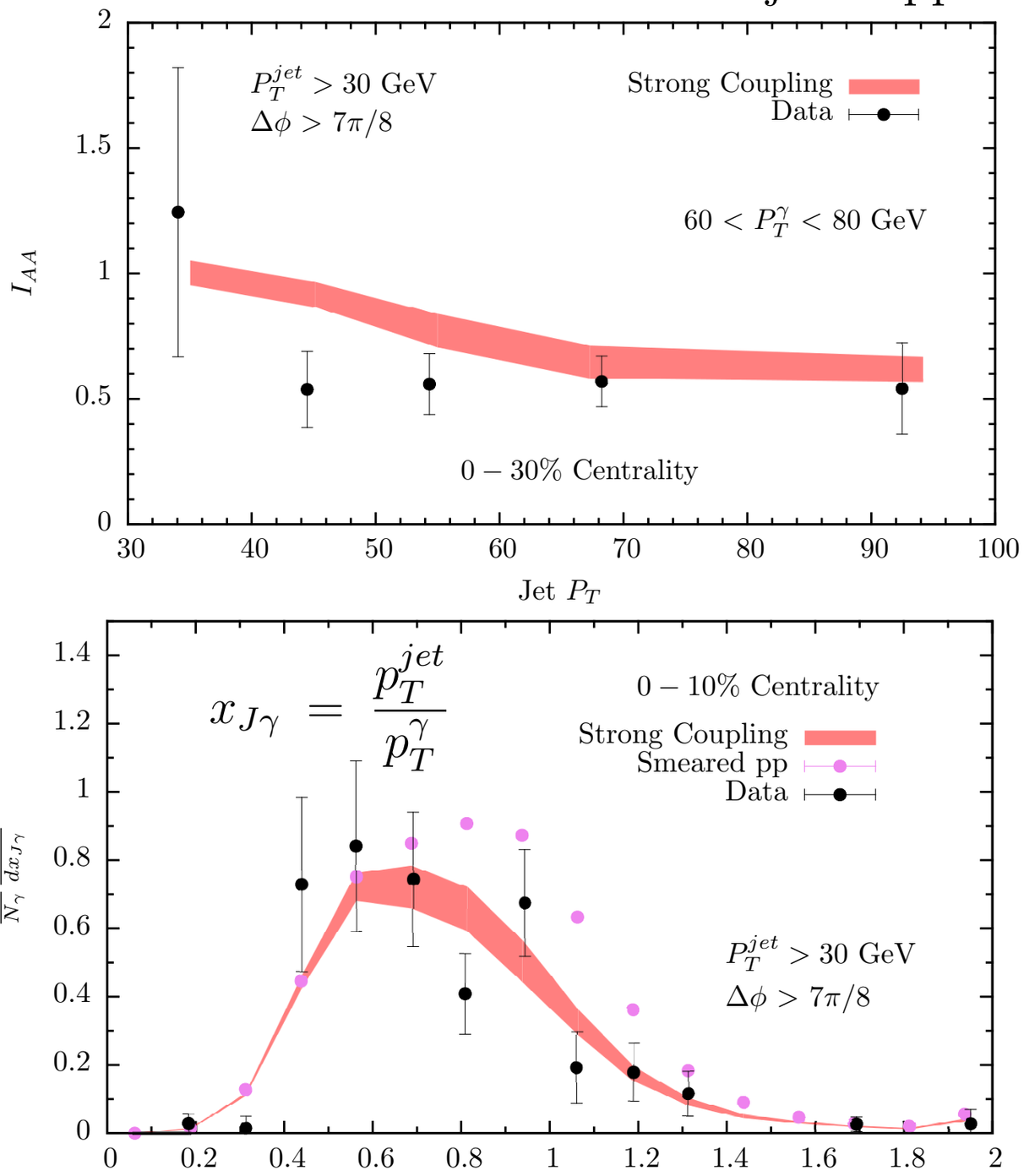


Photon - Jet

$$I_{AA} = \frac{\text{Number of associated jets in PbPb}}{\text{Number of associated jets in pp}}$$



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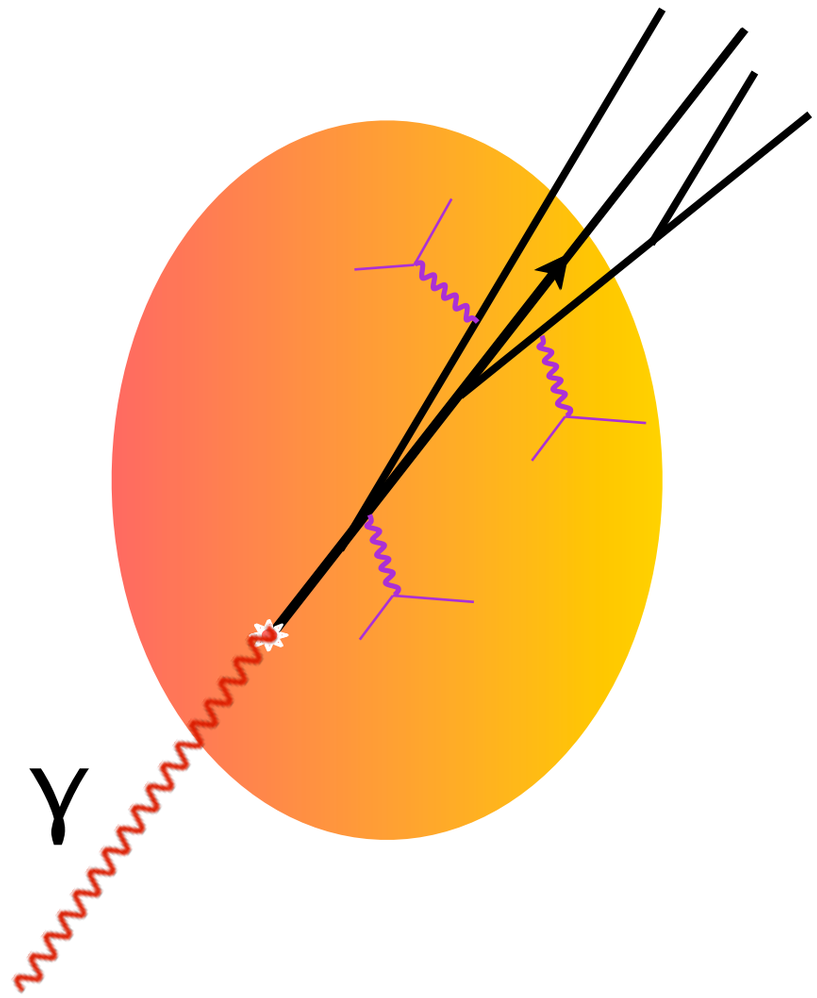
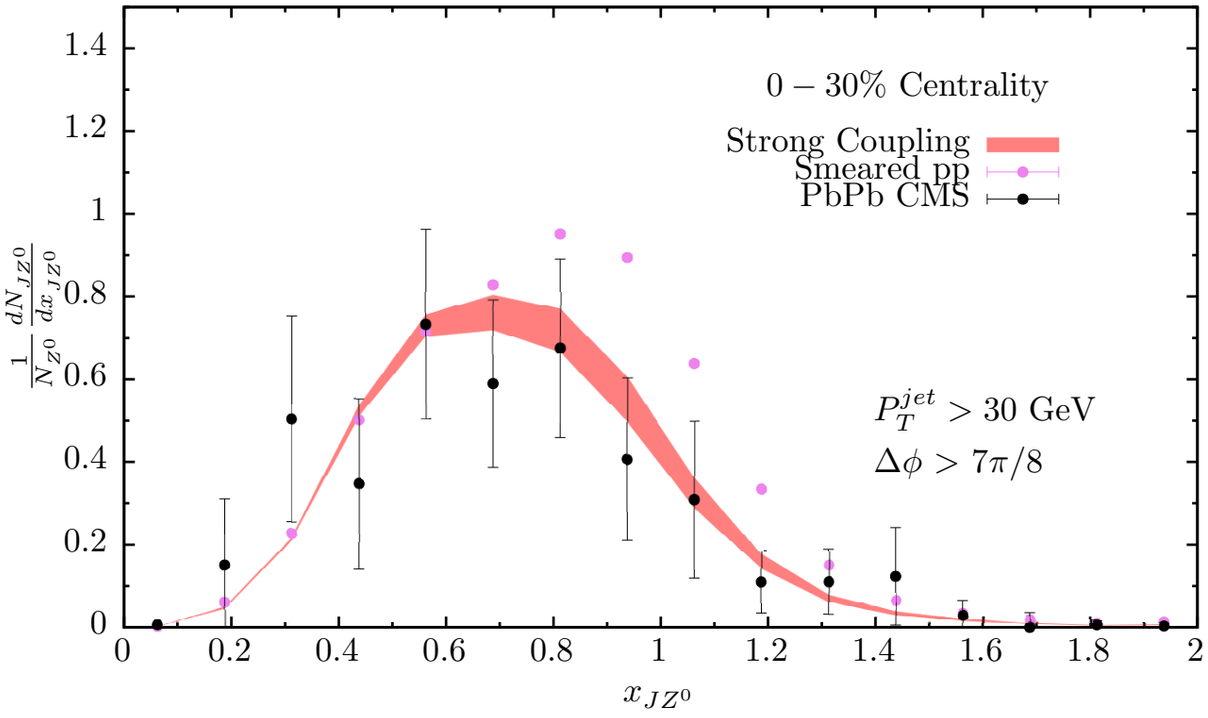
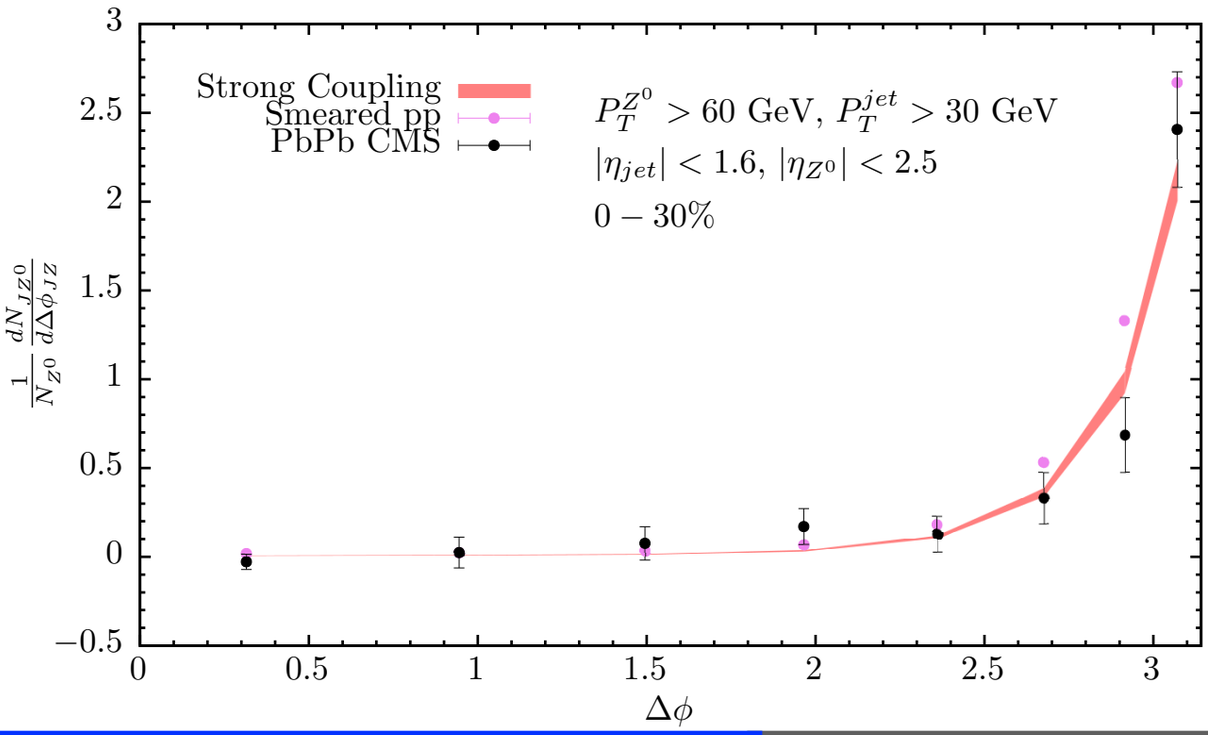


Predictions





$x_{JZ} = \frac{E_{jet}}{E_Z}$