Quantum Information Science in pp Collisions at the Energy Frontier

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DPF 2019 at Northeastern University

Ridge Liu, Yale University

Christian Weber, Yale University

O. Keith Baker, Yale University

Dmitri Kharzeev, Stony Brook University and Brookhaven National Laboratory

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Outline

1. Entanglement in particle collisions
   i. Examples
      a) Charged hadrons
      b) Diffractive Drell-Yan processes
   ii. R value
2. Results
   i. Higgs production and decay
   ii. Top-antitop quark pair production
3. Next steps

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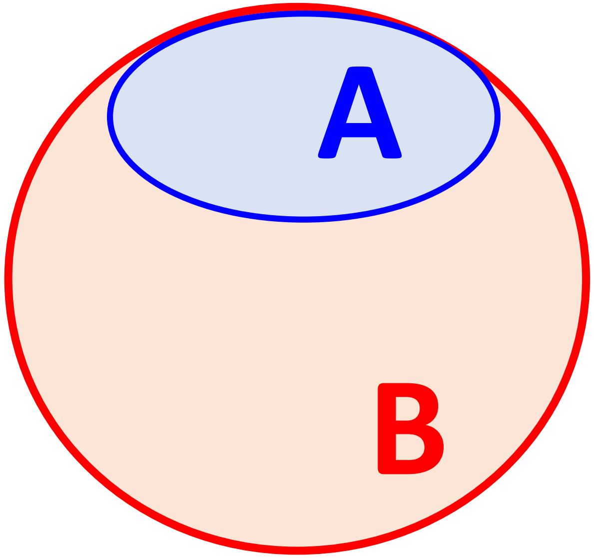
Entanglement



- Pure quantum state – can be described using a single ket $|\psi\rangle$
- Mixed quantum state – a statistical ensemble of quantum states $\rho = \sum p_i |\psi_i\rangle\langle\psi_i|$

- To describe a subsystem, take the partial trace – generically a mixed state

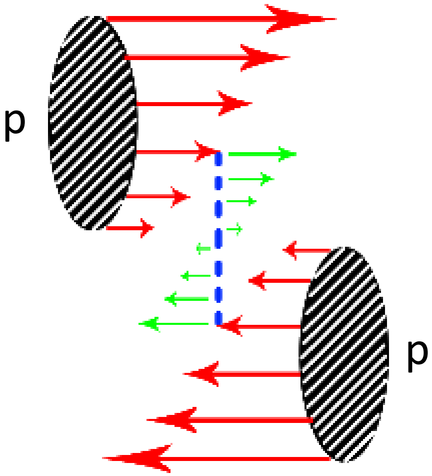
$$\rho_A = \mathrm{Tr}_B \rho_{AB}$$

- Von Neumann entropy of subregion A
  - If the entire system is a pure state, then S is called the entanglement entropy.

$$S[\rho_A] = -\mathrm{Tr}\rho_A \log \rho_A$$

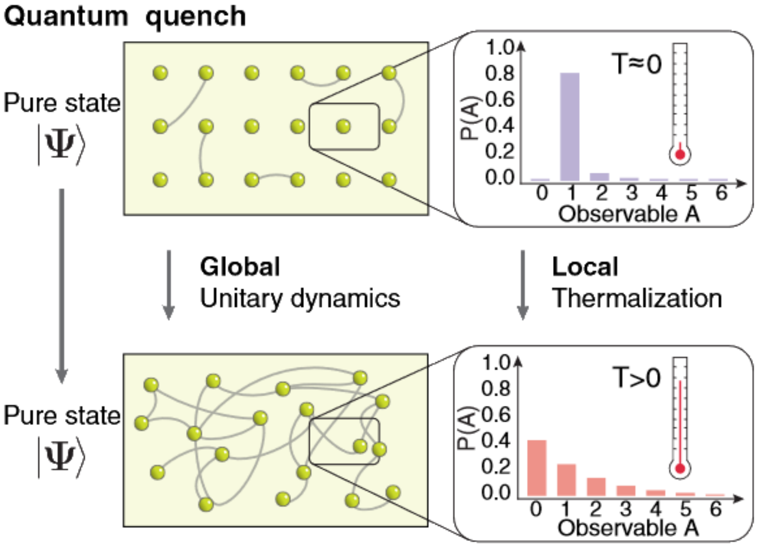
Entanglement in pp collisions

- Collisions can be probes of subregions



A. A. Bylinkin and A. A. Rostovtsev,
Nucl. Phys. B, 888(2014), arXiv:1404.7302 [hep-ph]

- Entanglement can lead to thermal behavior
  - Observed in cold atom systems
    - Kaufman et al., Science 353, 794(2016)
  - Discussion in heavy-ion collisions
    - C. M. Ho and S. D. H. Hsu,
      Mod. Phys. Lett. A 18, 1650110 (2016)



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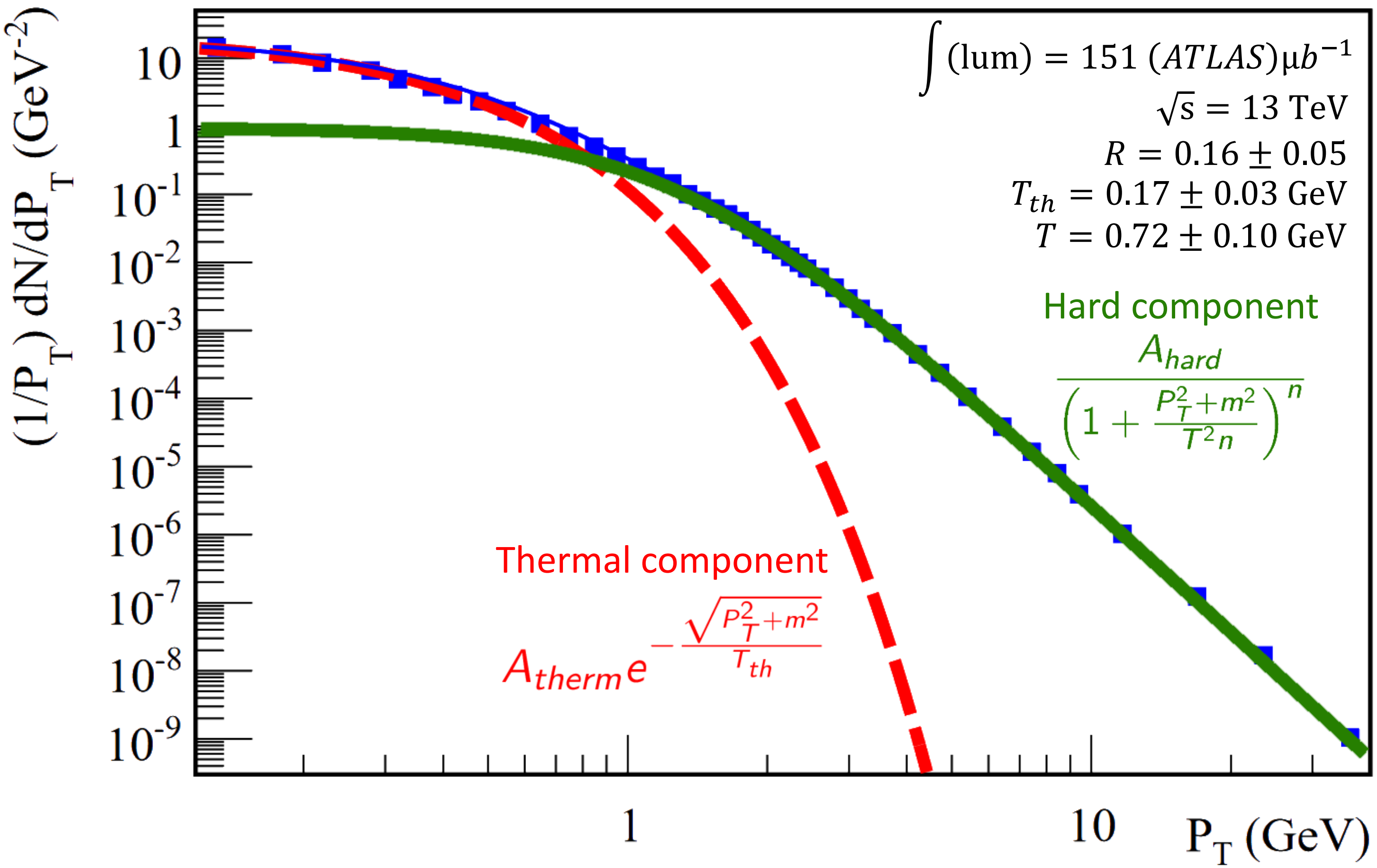
Example: charged hadrons



Claim: nonzero thermal component corresponds to probe of subregion

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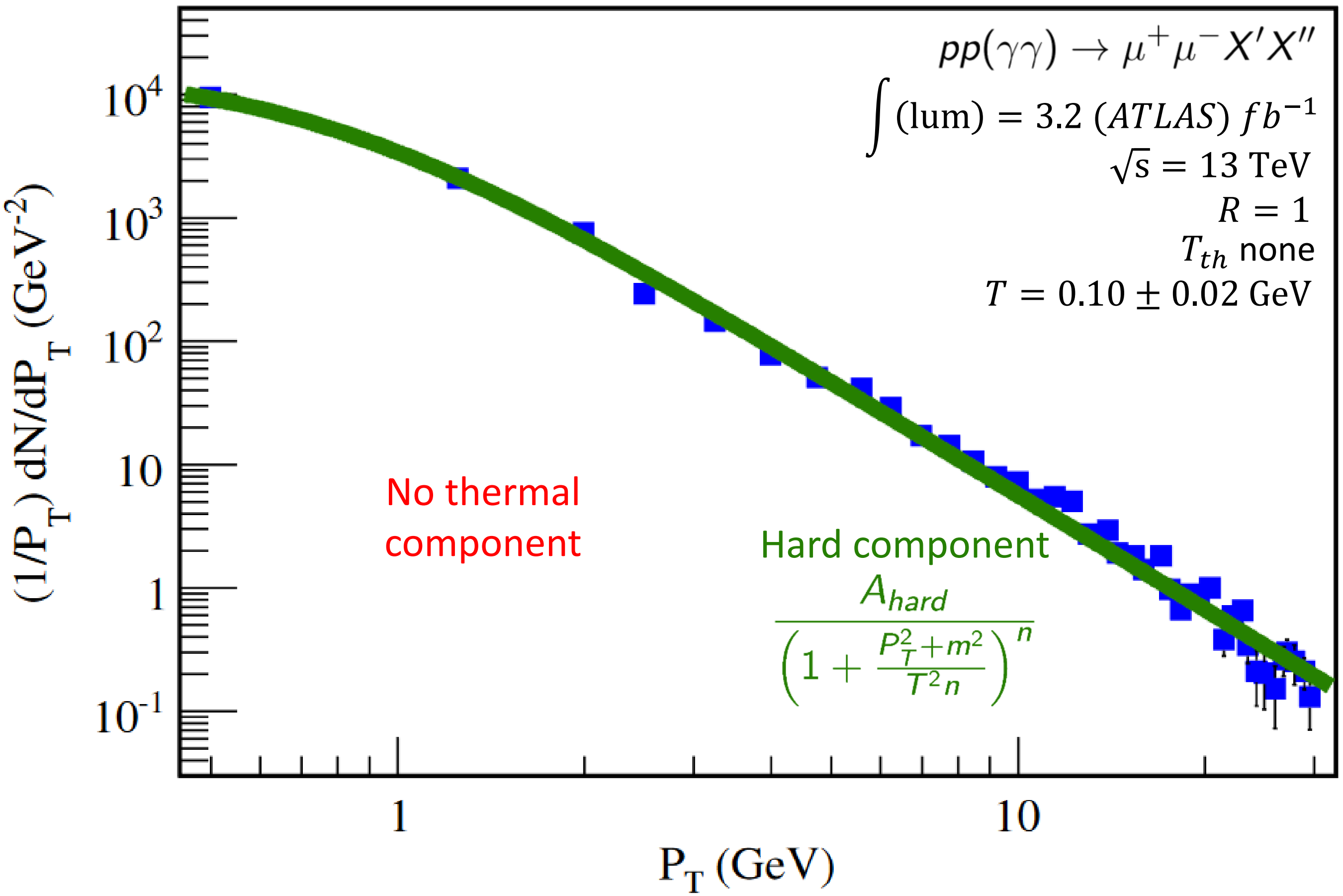
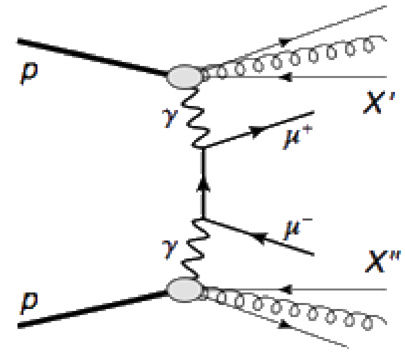
O. K. Baker and D. E. Kharzeev, Phys. Rev. D98, 054007(2018), arXiv:1712.04558 [hep-ph]

Example: Diffractive Drell-Yan





Photons interact coherently with entire proton – not a subregion

Interaction probes the entire proton → no entropy from entanglement!

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O. K. Baker and D. E. Kharzeev, Phys. Rev. D98, 054007(2018), arXiv:1712.04558 [hep-ph]

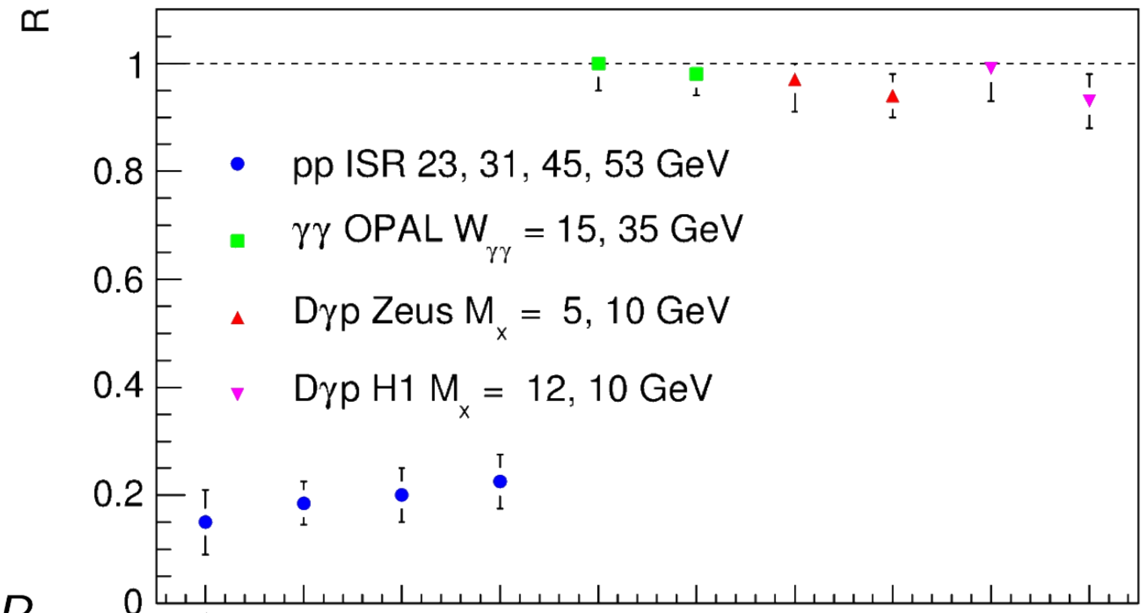
R

Seems to indicate presence/absence of entanglement

$$R = \frac{H}{T+H}$$

$$T = \int A_{therm} e^{-\frac{\sqrt{P_T^2+m^2}}{T_{th}}} dP_T$$

$$H = \int \frac{A_{hard}}{\left(1+\frac{P_T^2+m^2}{T^2 n}\right)^n} dP_T$$



R	process
0.16 ± 0.05	$pp \to$ charged hadrons
1.0 ± 0.1	$pp(\gamma\gamma) \to (\mu\mu)X'X''$

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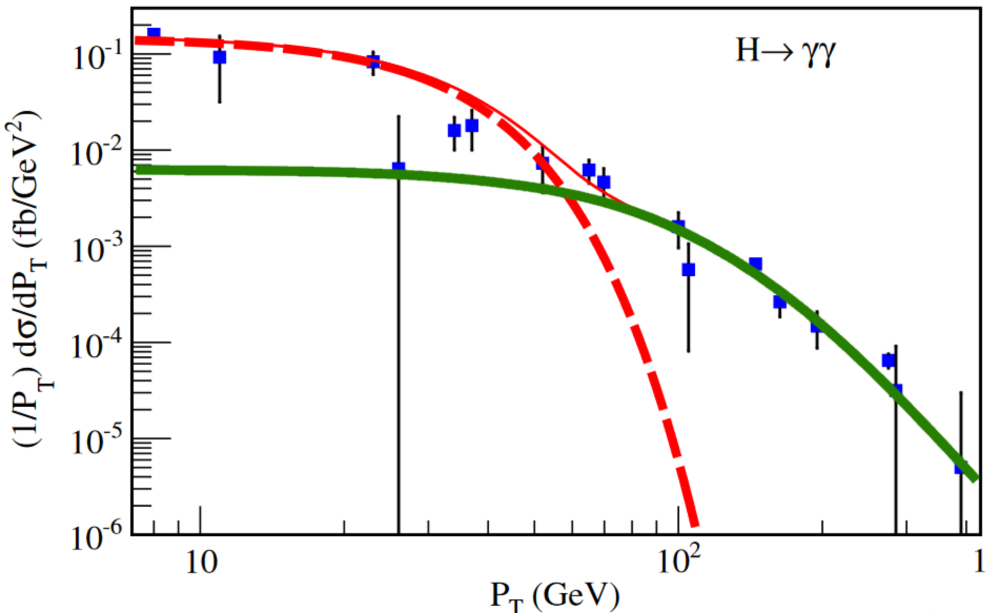
Results: Higgs channels



Diphoton channel (left):

$\sqrt{s} = 13$ TeV

$R = 0.15 \pm 0.05$

$T_{th} = 3.5 \pm 0.7$ GeV

$T = 14.4 \pm 0.3$ GeV

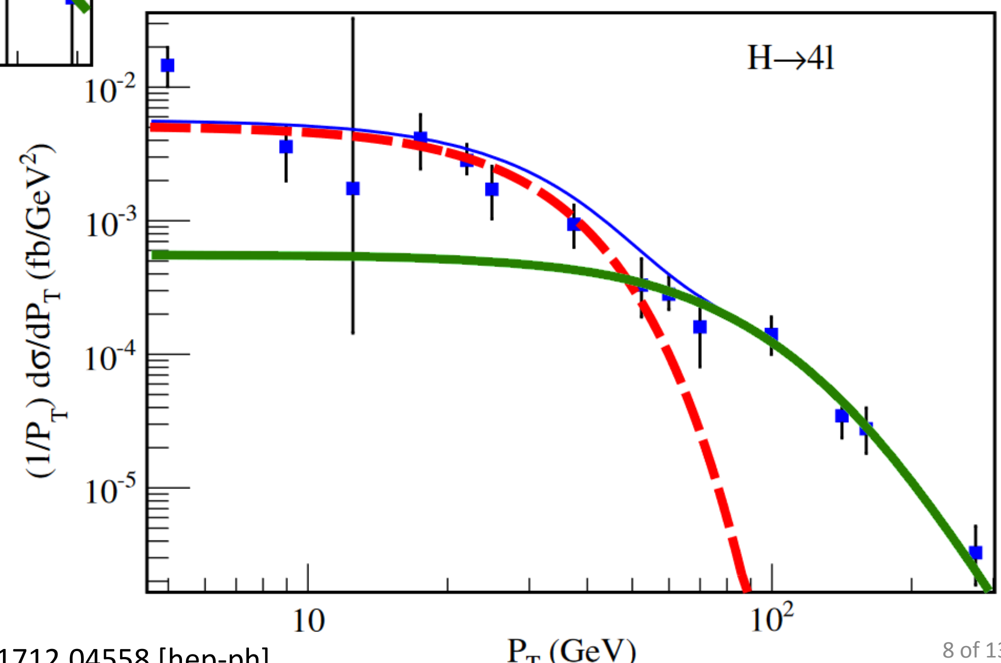
$\int(\text{lum}) = 36.1\ (ATLAS) + 35.9(CMS) fb^{-1}$

Thermal component

$$A_{therm} e^{-\frac{\sqrt{P_T^2+m^2}}{T_{th}}}$$

Hard component

$$\frac{A_{hard}}{\left(1+\frac{P_T^2+m^2}{T^2 n}\right)^n}$$



4-lepton channel (right):

$\int(\text{lum}) = 36.1\ (ATLAS) + 35.9(CMS) fb^{-1}$

$\sqrt{s} = 13$ TeV

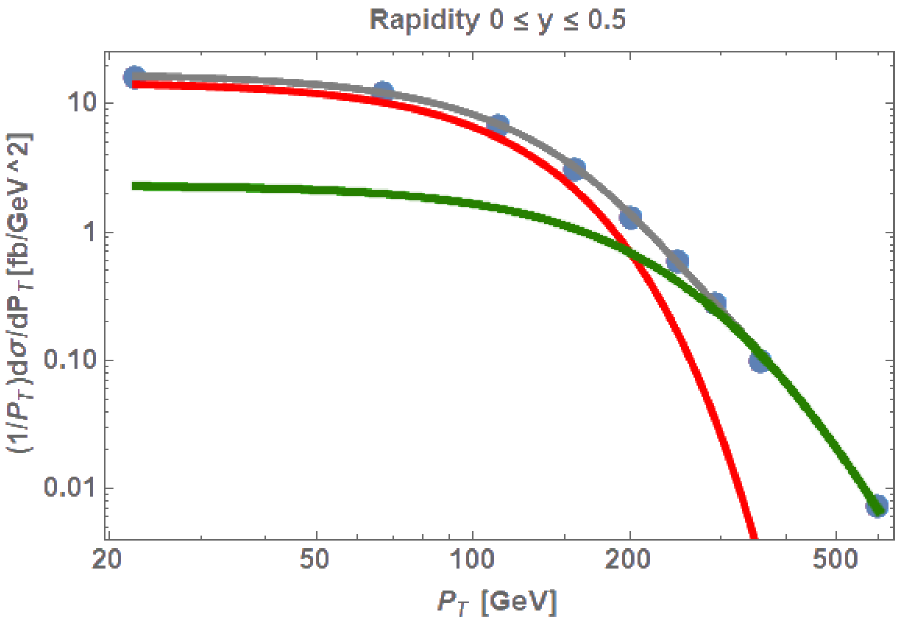
$R = 0.23 \pm 0.05$

$T_{th} = 3.5 \pm 0.7$ GeV

$T = 14.4 \pm 0.3$ GeV

O. K. Baker and D. E. Kharzeev, Phys. Rev. D98, 054007(2018), arXiv:1712.04558 [hep-ph]

Results: $t\bar{t}$ pair



Low rapidity (left):

$\sqrt{s} = 13$ TeV

$R = 0.20 \pm 0.05$

$T_{th} = 17 \pm 1$ GeV

$T = 9 \pm 1$ GeV

$\int(\text{lum}) = 36.1\ (ATLAS) + 35.9(CMS) fb^{-1}$

Thermal component

$A_{therm} e^{-\frac{\sqrt{P_T^2+m^2}}{T_{th}}}$

Hard component

$\frac{A_{hard}}{\left(1+\frac{P_T^2+m^2}{T^2 n}\right)^n}$

High rapidity (right):

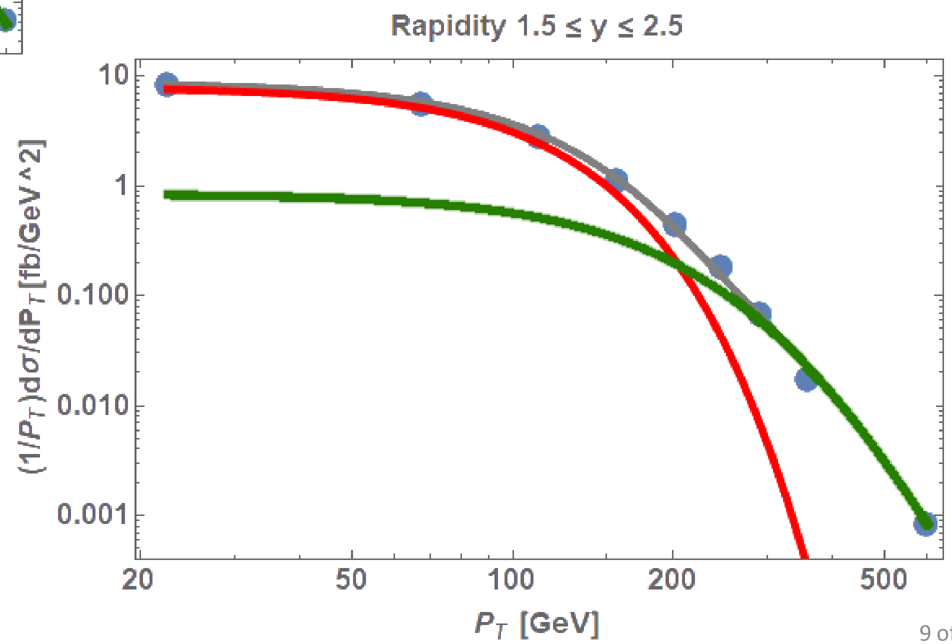
$\sqrt{s} = 13$ TeV

$R = 0.16 \pm 0.05$

$T_{th} = 14 \pm 1$ GeV

$T = 20 \pm 1$ GeV

$\int(\text{lum}) = 36.1\ (ATLAS) + 35.9(CMS) fb^{-1}$



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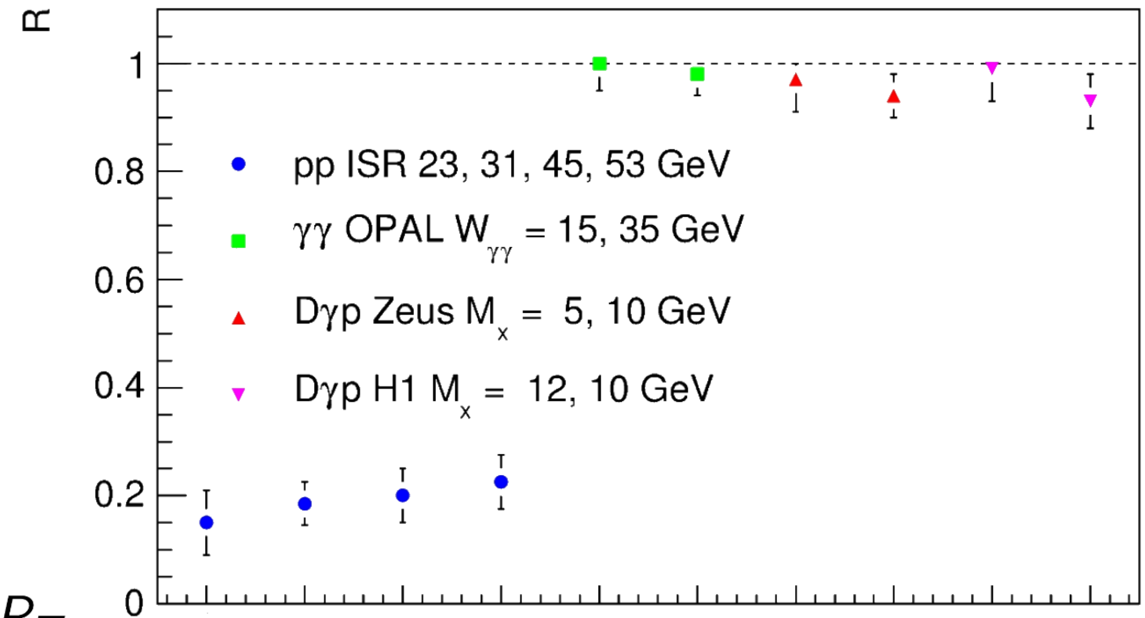

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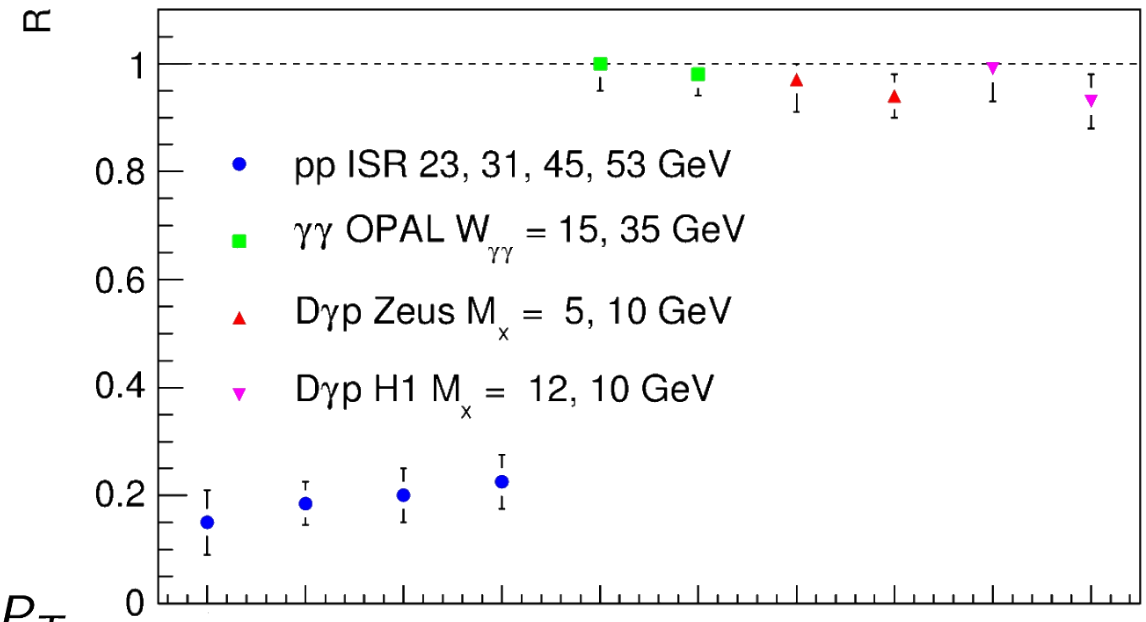

R	process
0.16 ± 0.05	pp $\to$ charged hadrons
1.0 ± 0.1	pp$(\gamma\gamma) \to (\mu\mu)X'X''$
0.15 ± 0.05	pp $\to$ H $\to \gamma\gamma$
0.23 ± 0.05	pp $\to$ H $\to$ 4l(e,μ)
0.20 ± 0.05	pp $\to t\bar{t}$ (low rapidity: $0 \leq y \leq 0.5$)
0.16 ± 0.05	pp $\to t\bar{t}$ (high rapidity: $1.5 \leq y \leq 2.5$)

All consistent!

A. A. Bylinkin and A. A. Rostovtsev, Nucl. Phys. B, 888(2014), arXiv:1404.7302 [hep-ph]
O. K. Baker and D. E. Kharzeev, Phys. Rev. D98, 054007(2018), arXiv:1712.04558 [hep-ph]

Summary and next steps

1. R is the same for all processes with entanglement we considered: from pions to Higgs to ttbar

2. Can we gain some information about parton distribution functions? – see our poster!

3. Can we construct a quantity that would be sensitive to the existence of new phenomena, e.g. dark sector physics?

References

1. O. K. Baker and D. E. Kharzeev, Phys. Rev. D98, 054007(2018), arXiv:1712.04558 [hep-ph]

2. A. A. Bylinkin and A. A. Rostovtsev, Nucl. Phys. B, 888(2014), arXiv:1404.7302 [hep-ph]

3. A. M. Kaufman et al., Science 353, 794(2016)

4. C. M. Ho and S. D. H. Hsu, Mod. Phys. Lett. A 18, 1650110 (2016)