Quantum Entanglement and Proton-Proton Collisions at the LHC

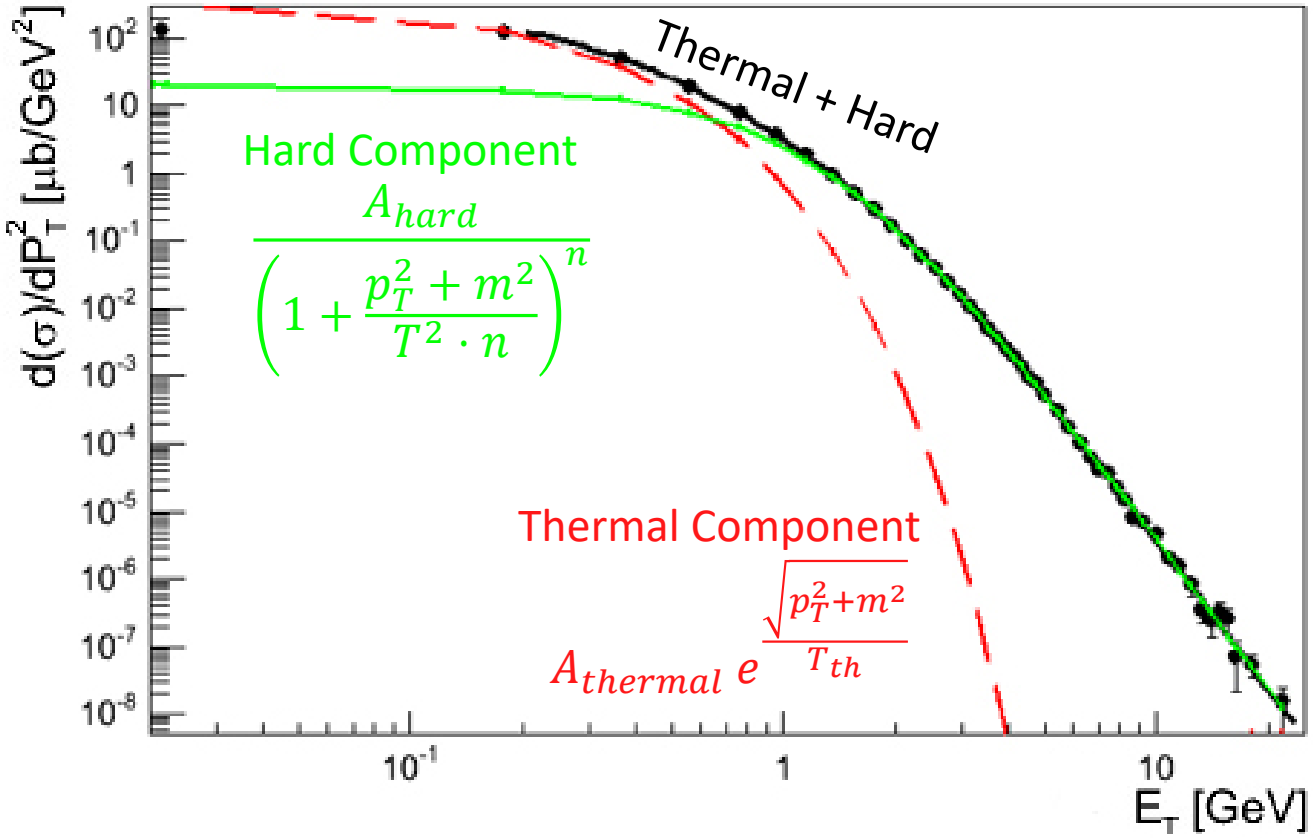
Christian Weber – Yale University

Oliver K. Baker – Yale University

Dmitri Kharzeev – Stony Brook University, Brookhaven National Lab

Charged hadron spectrum in $p\bar{p}$ colissions

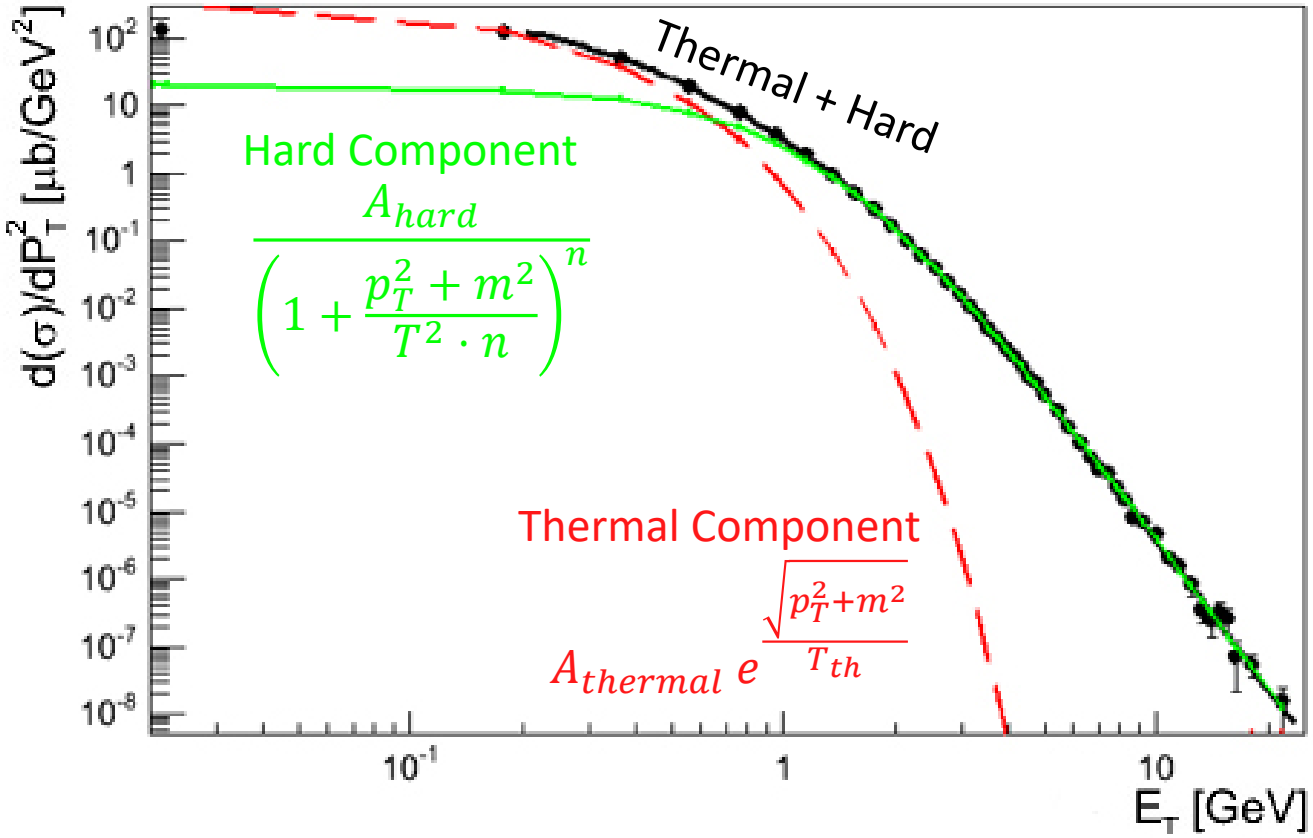
Charged hadron spectrum, UA1 Collaboration



Data: G. Bocquet et al. [UA1 Collaboration], Phys.Lett.B366:434-440,1996
Fits: Bylinkin, A. A. et al. *International Journal of Modern Physics E*, *23*(12), 1450083

Charged hadron spectrum in $p\bar{p}$ colissions

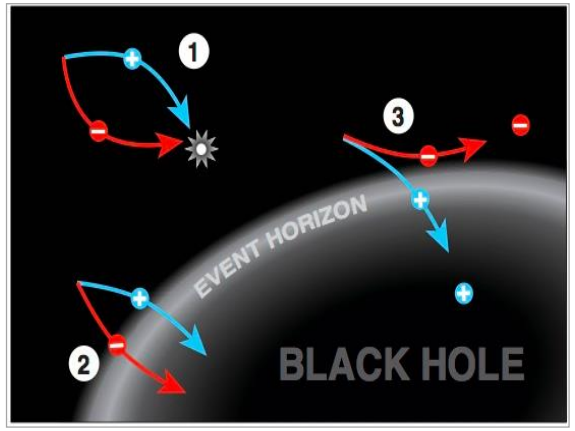
Charged hadron spectrum, UA1 Collaboration

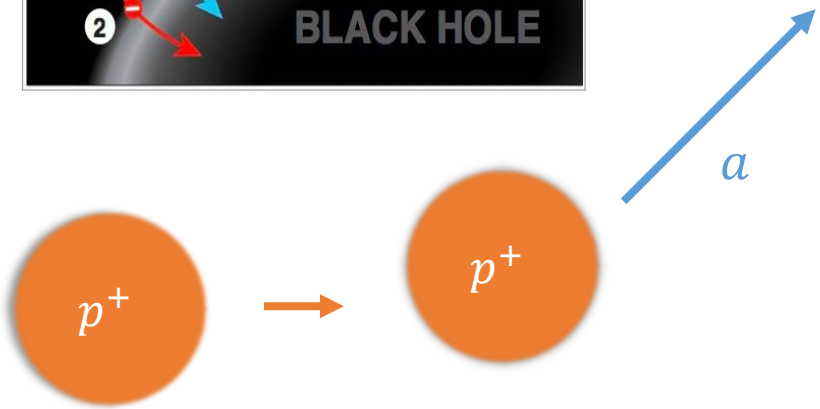


Data: G. Bocquet et al. [UA1 Collaboration], Phys.Lett.B366:434-440,1996
Fits: Bylinkin, A. A. et al. *International Journal of Modern Physics E*, *23*(12), 1450083

Unruh Radiation

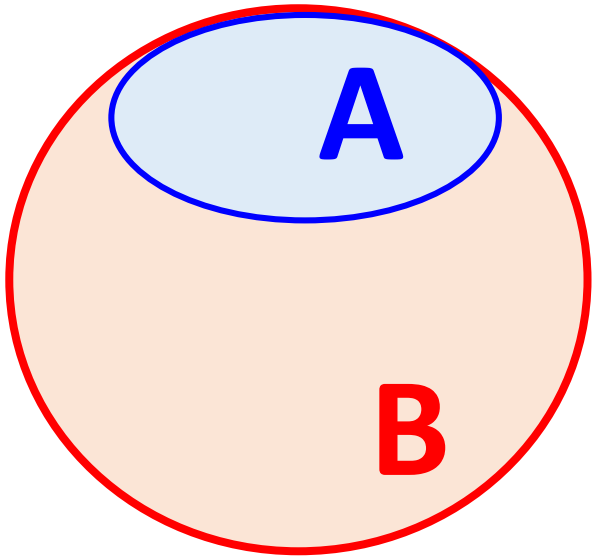
conceptually related to Hawking Radiation





$$T_{unruh} \sim \frac{a}{2\pi}$$

Entanglement Entropy



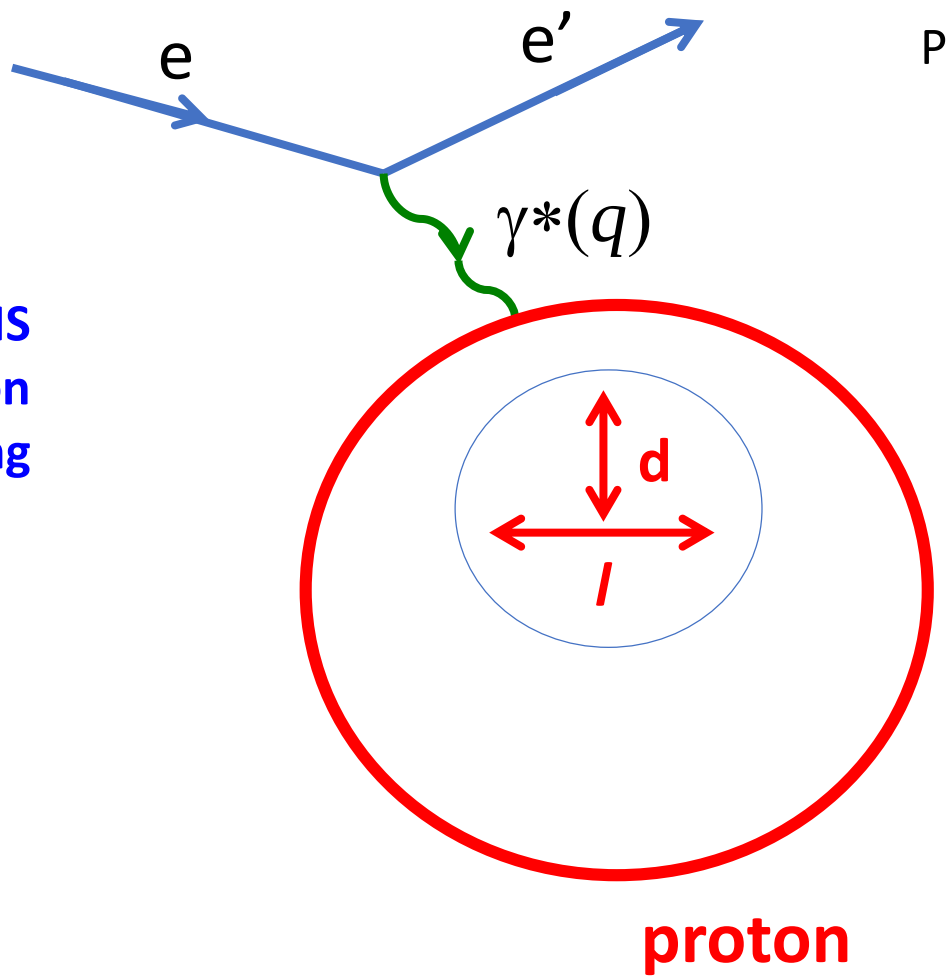
$$|\Psi\rangle \in H_A \otimes H_B$$

$$\rho_{AB} = |\Psi\rangle\langle\Psi|_{AB}$$

reduced density matrix $\rho_A = \sum_j \langle j|_B \left(|\Psi\rangle\langle\Psi|\right) |j\rangle_B = \mathrm{Tr}_B(\rho_{AB})$

entanglement entropy $S(\rho_A) = -\mathrm{Tr}[\rho_A \log \rho_A]$

Example: e-P deep inelastic scattering



This example is for DIS scattering; in proton-proton scattering *dxl* is the colliding protons overlap region.

Proton Volume Probed

transverse scale

$$d \sim \lambda_{\text{deBroglie}} = \frac{h}{|\vec{q}|}$$

longitudinal scale

$$l \sim \frac{1}{mx}$$

m - proton mass

x - parton momentum fraction

proton-proton collisions and entanglement

Proton: pure macrostate consisting of
a region of parton microstates probed in the collision + a region of partons not probed in the collision

$$\left|\Psi_{AB}\right\rangle = \sum_{i,j} c_{ij} \left|\psi_i^A\right\rangle \otimes \left|\psi_j^B\right\rangle$$

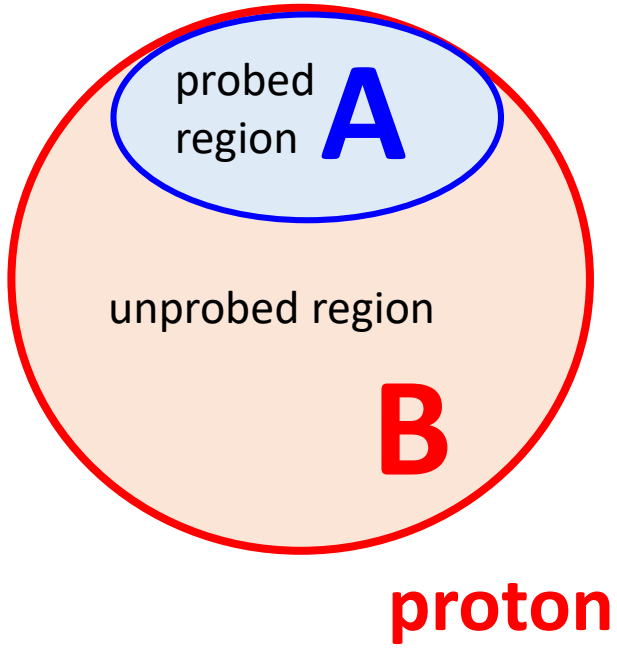
not separable - entangled

$$\left|\Psi_{AB}\right\rangle = \left|\psi_i^A\right\rangle \otimes \left|\psi_j^B\right\rangle$$

separable - not entangled

when only one term contributes the state is separable;
otherwise the state is entangled

region A probed in p-p collision
regions A and B are entangled



proton-proton collisions and entanglement

Proton: pure macrostate consisting of
a region of parton microstates probed in the collision + a region of partons not probed in the collision

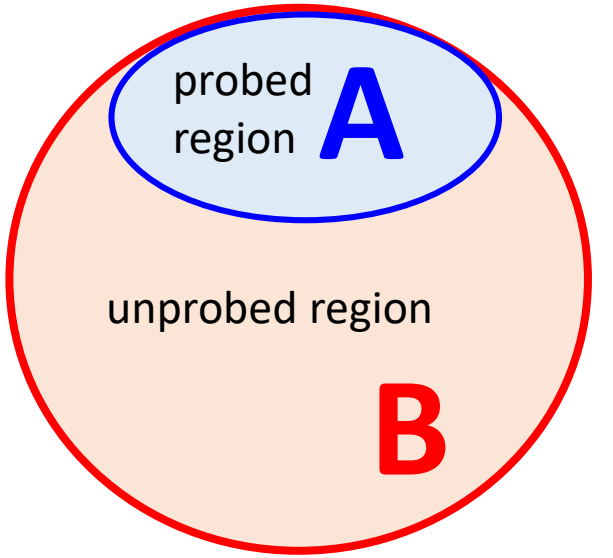
$$\left|\Upsilon_{AB}\right\rangle = \sum_{i,j} c_{ij} \left|\psi_i^A\right\rangle \otimes \left|\psi_j^B\right\rangle$$

Schmidt Decomposition: can find $|\Psi_n^A\rangle, |\Psi_n^B\rangle$ such that

$$|\Psi_{AB}\rangle = \sum_n \alpha_n |\Psi_n^A\rangle |\Psi_n^B\rangle$$

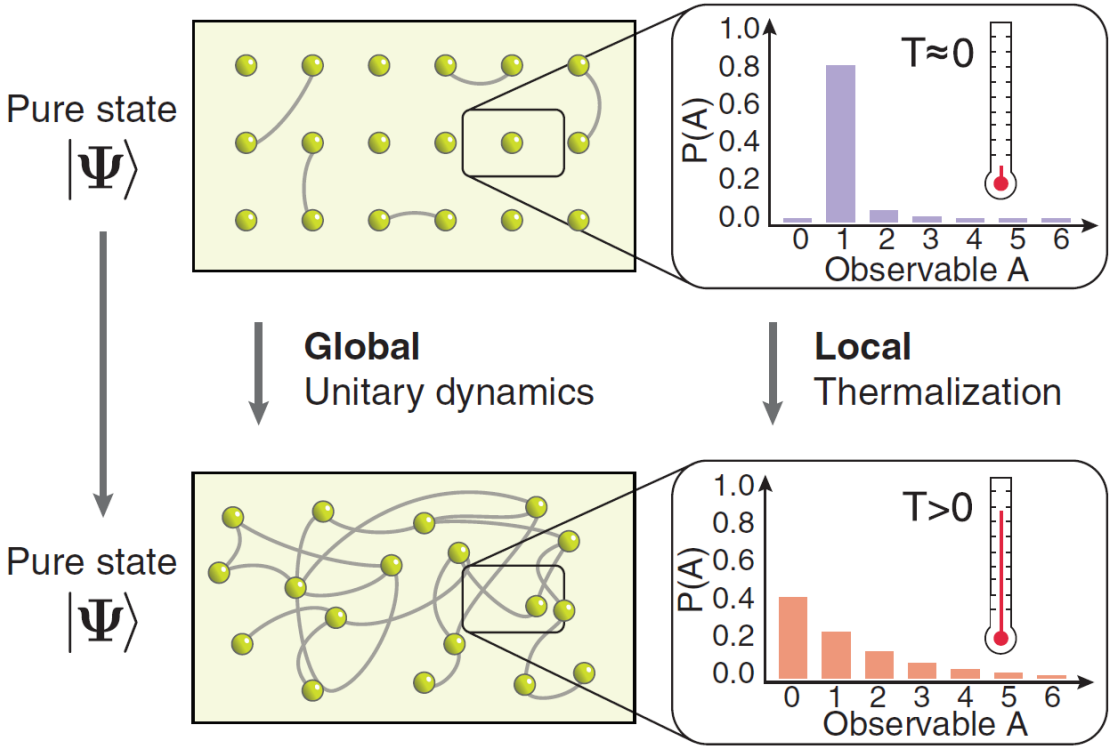
$$\rho_A = \mathrm{tr}_B\, \rho_{AB} = \sum_n \alpha_n^2 |\Psi_n^A\rangle\langle\Psi_n^A|$$

region A probed in p-p collision
regions A and B are entangled



Identify $\alpha_n^2 \equiv p_n$, von Neuman Entropy $S = -\sum_n p_n \ln p_n$

Example: Quantum thermalization through entanglement in an isolated many-body system



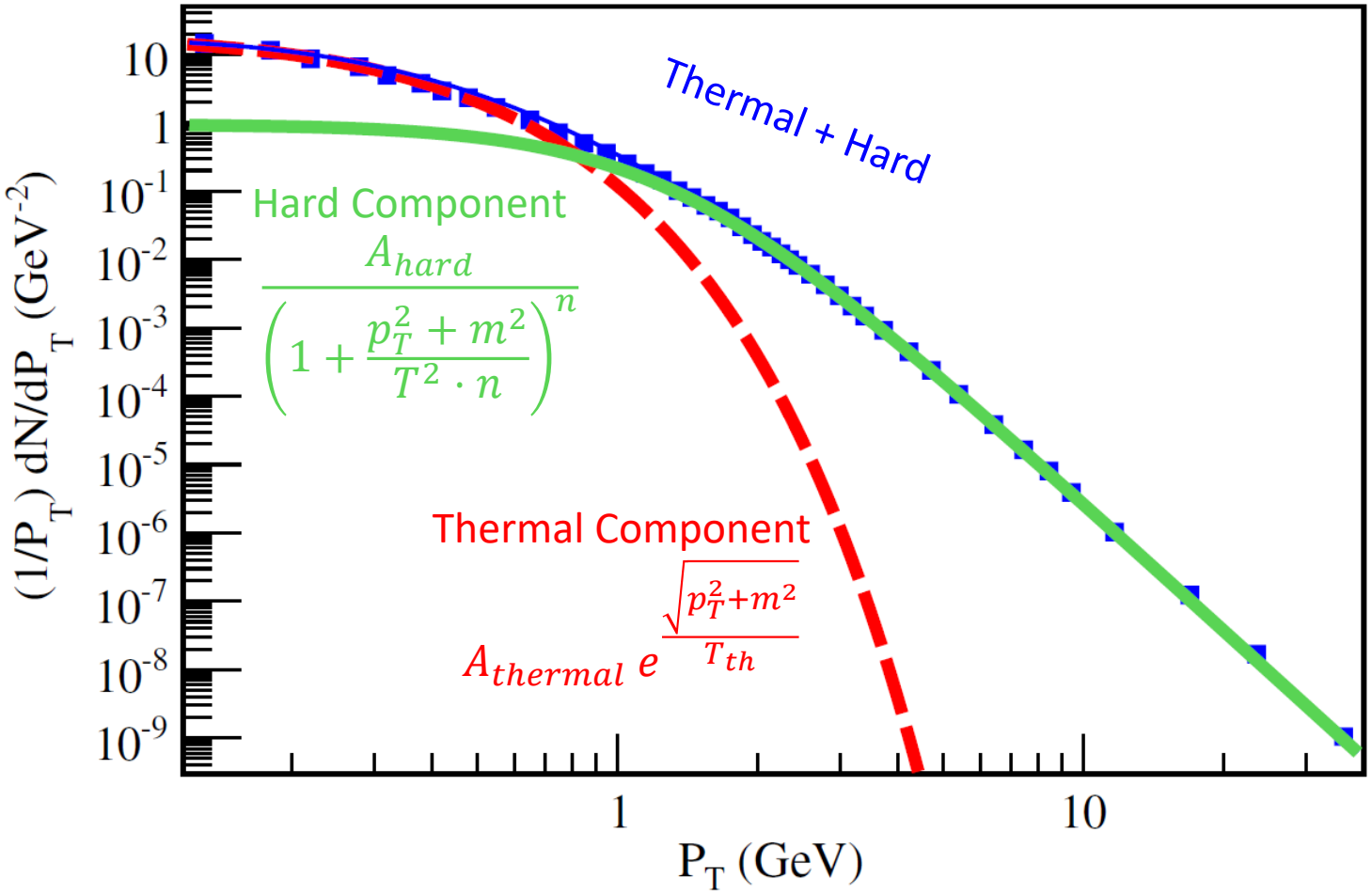
Greiner Lab, Harvard University); Science 353, 794 (2016)

- Isolated quantum state at T=0 (cold Rb atoms), a pure state; subsystems appear pure if negligible entanglement
- Sudden perturbation by a quench (laser firing), full system evolves unitarily, developing significant entanglement between all parts of the system.
- Full state remains pure (zero entropy); entanglement entropy causes subsystems to equilibrate; local, thermal mixed states emerge within globally pure quantum state

Quantum entanglement ➔ entanglement entropy ➔ thermalization; thermal entropy

LHC Data

Transverse momentum distribution of charged hadrons in proton-proton collisions at $\sqrt{s}$ = 13 TeV

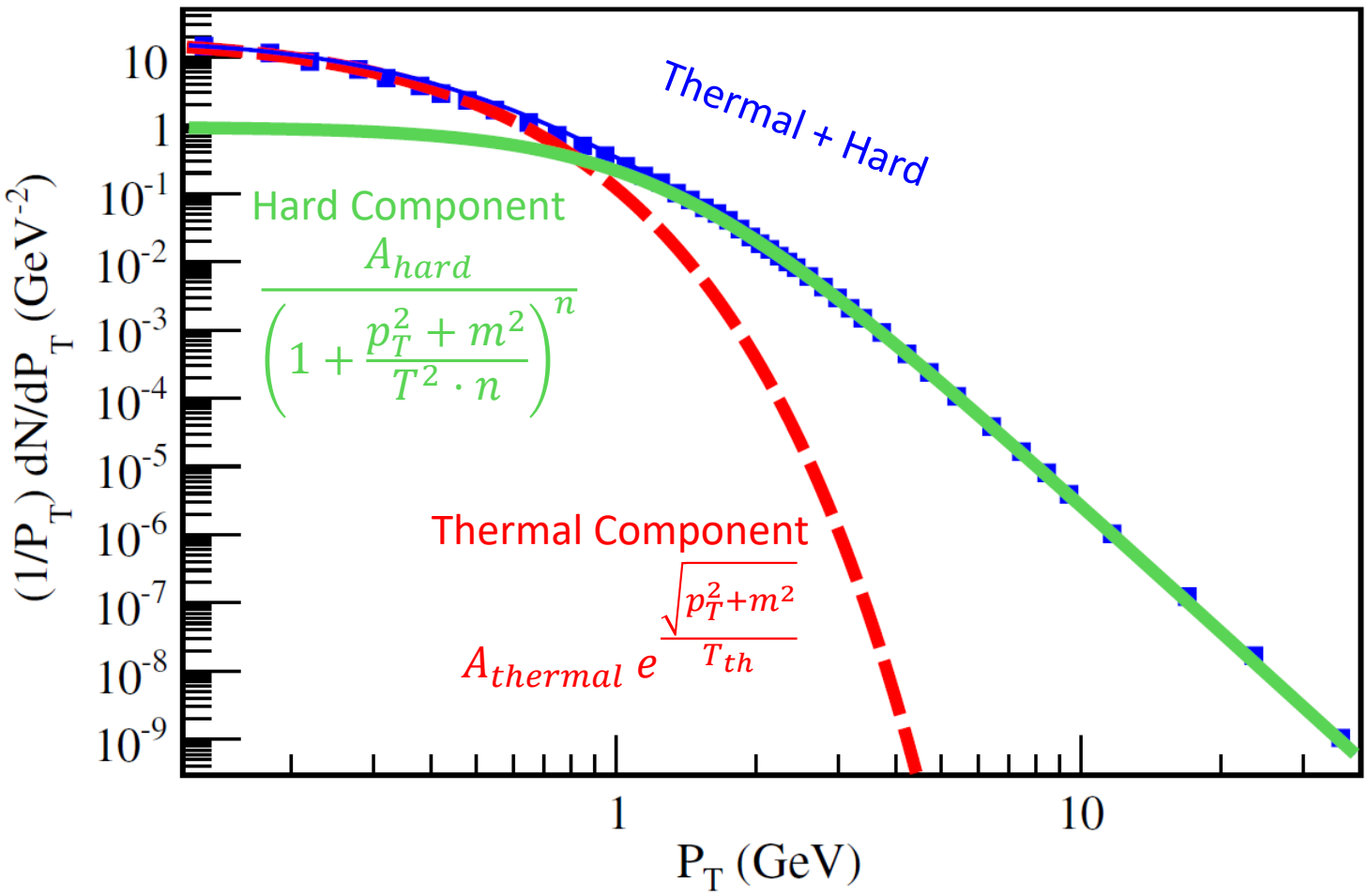


Data: ATLAS collaboration, Eur. Phys. J. C76, 502 (2016); PLB 758 , 67 (2016)

pp collisions

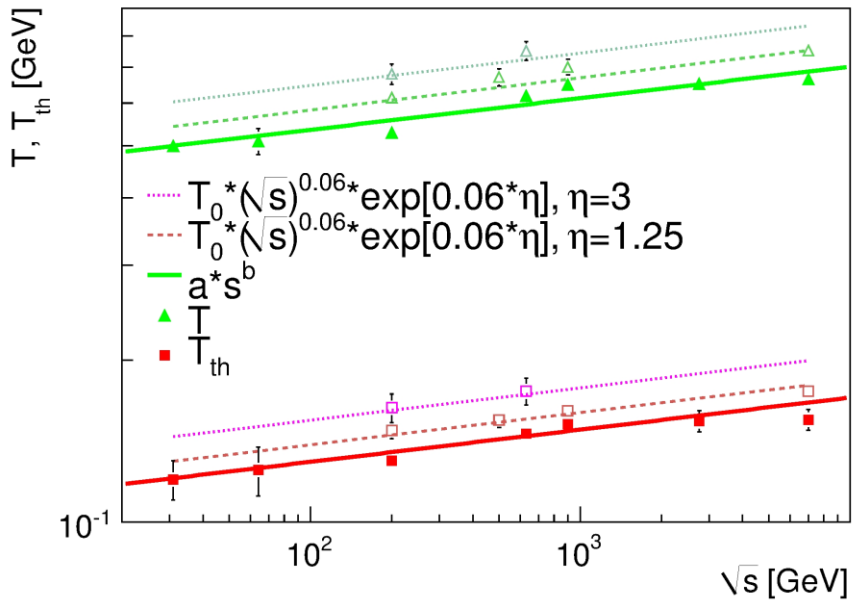
$\sqrt{s}$ = 13 TeV
$|\eta| \leq 2.5$
$\int(\mathrm{lum}) = 151\ \mu b^{-1}$

Transverse momentum distribution of charged hadrons in proton-proton collisions at $\sqrt{s}$ = 13 TeV



Data: ATLAS collaboration, Eur. Phys. J. C76, 502 (2016); PLB 758 , 67 (2016)

Temperature Scaling



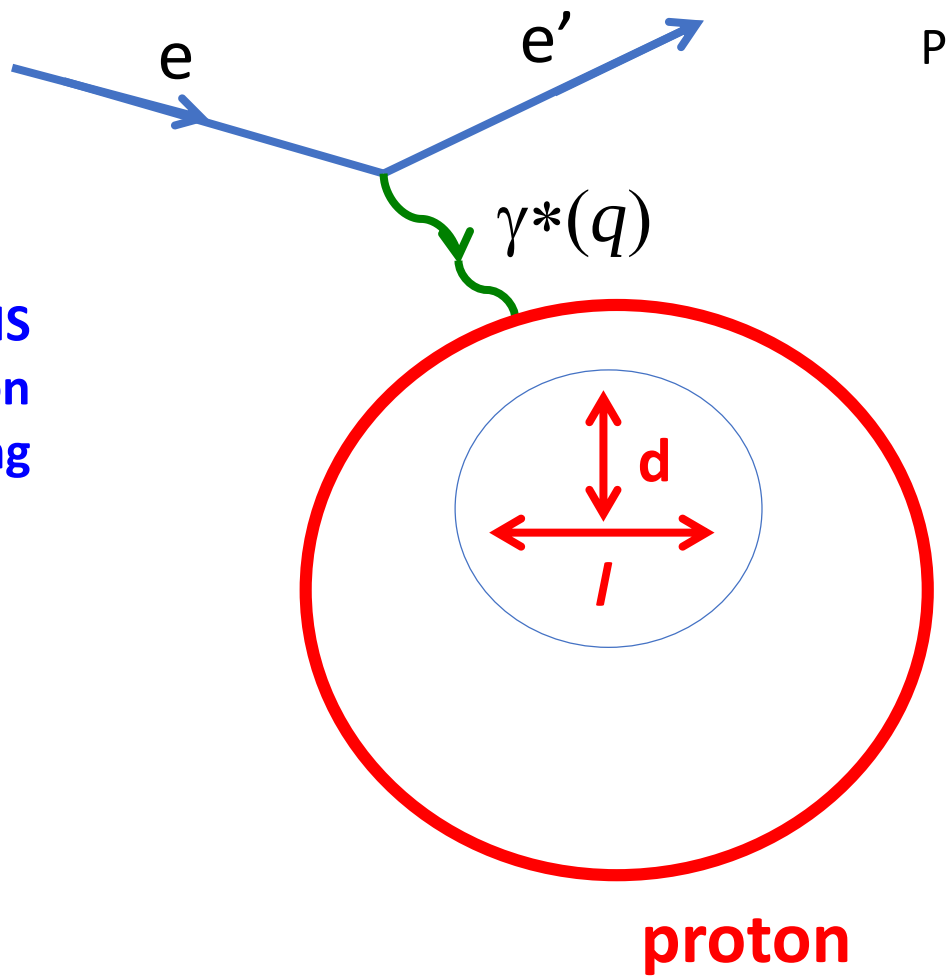
Bylinkin, A. A. et al. *International Journal of Modern Physics E*, 23(12), 1450083

$$T = 409 \cdot (\sqrt{s})^{0.06}\ MeV,$$

$$T_{th} = 98 \cdot (\sqrt{s})^{0.06}\ MeV.$$

Holds true here!

Example: e-P deep inelastic scattering



This example is for DIS scattering; in proton-proton scattering *dxl* is the colliding protons overlap region.

Proton Volume Probed

transverse scale

$$d \sim \lambda_{\text{deBroglie}} = \frac{h}{|\vec{q}|}$$

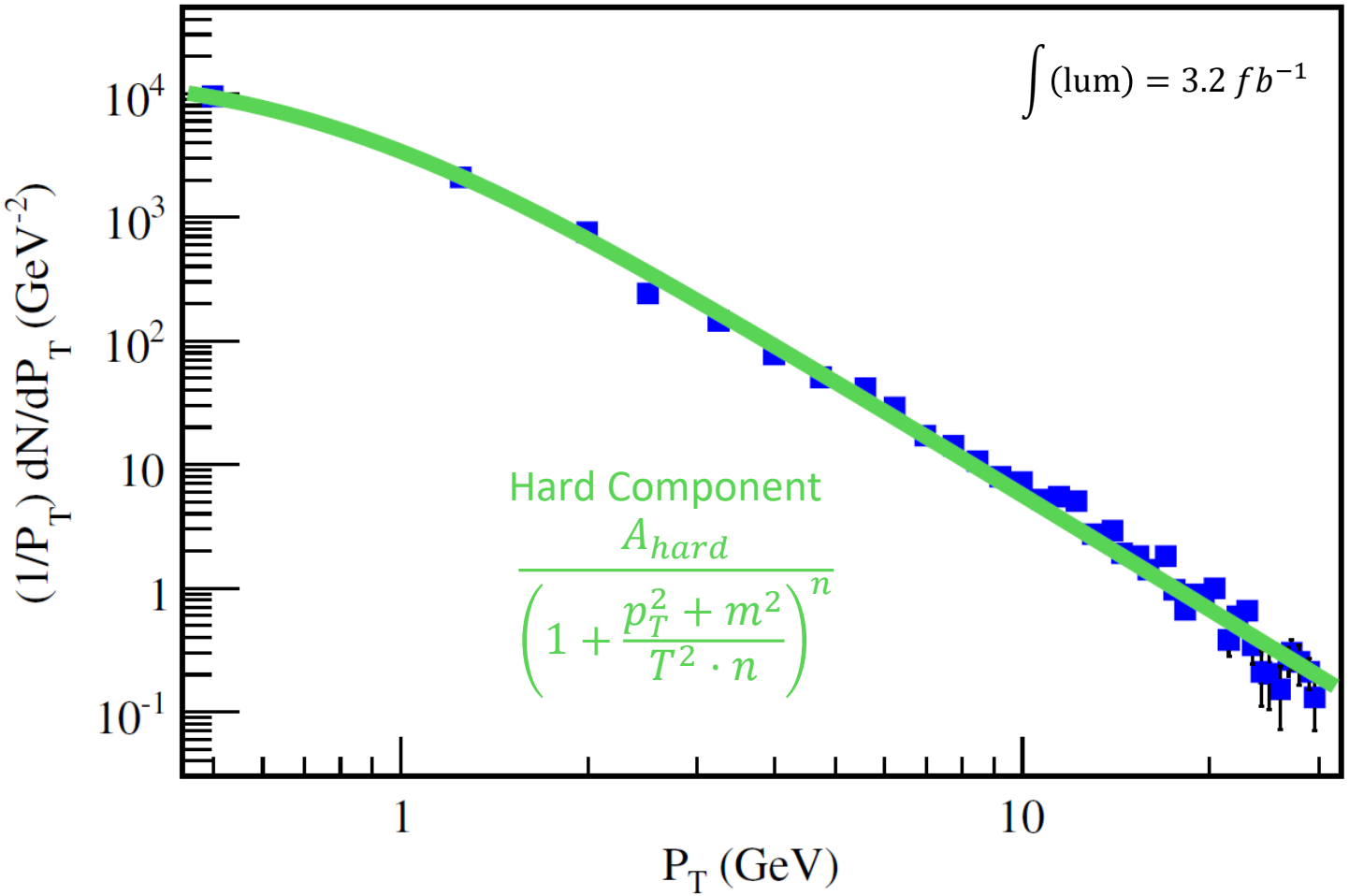
longitudinal scale

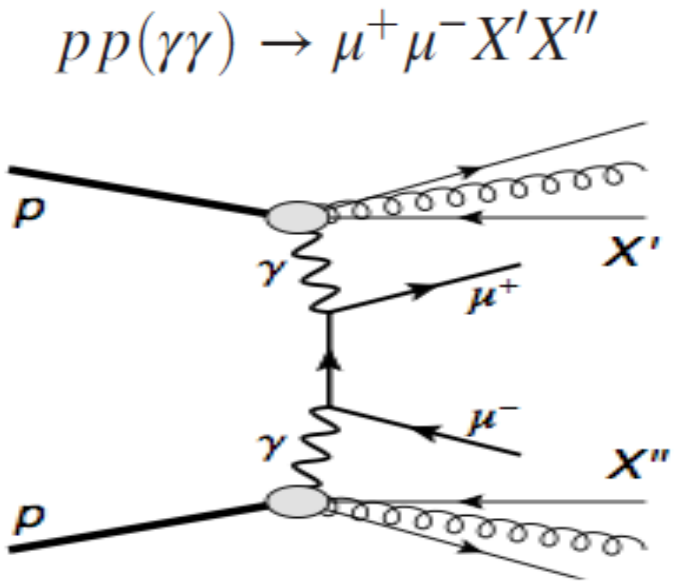
$$l \sim \frac{1}{mx}$$

m - proton mass

x - parton momentum fraction

Di-Muon pair transverse momentum distribution doubly diffractive $\gamma\gamma$ scattering in pp collisions

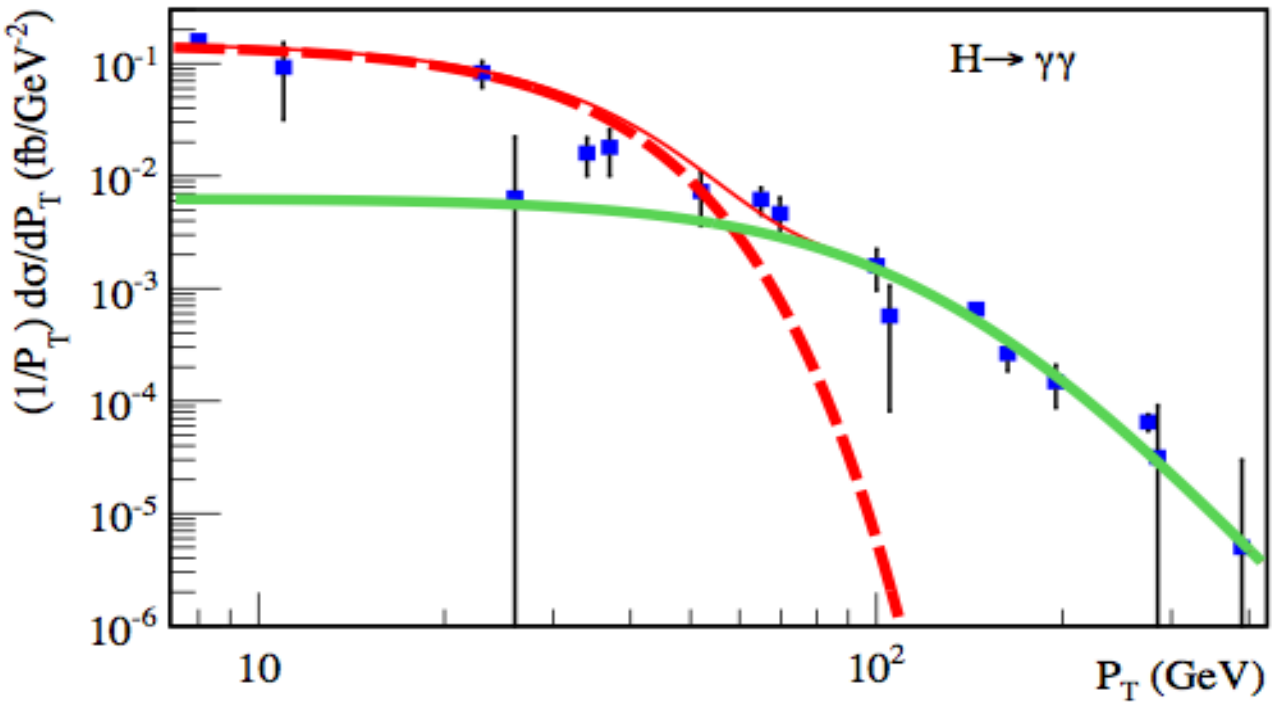


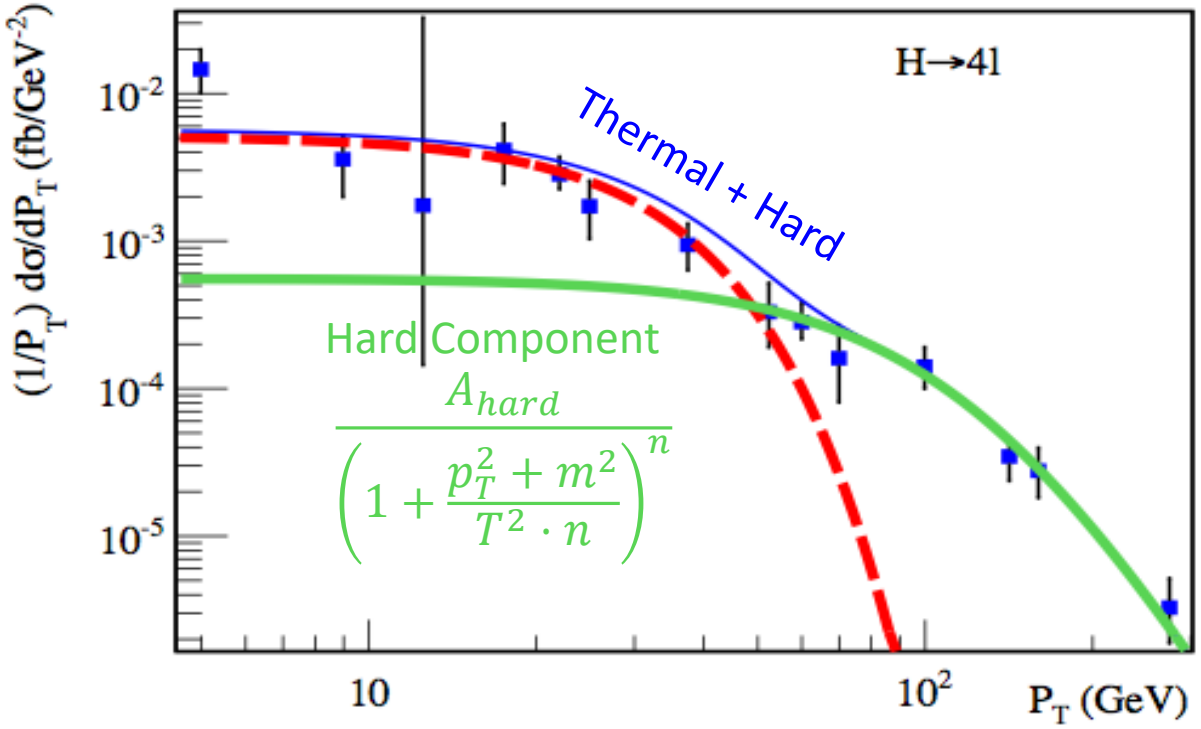


Baker, O. K., & Kharzeev, D. E. (2018). Physical Review D, 98(5), 054007.

Extends to Higgs sector …!

Thermal Component: $A_{thermal}\, e^{\frac{\sqrt{p_T^2+m^2}}{T_{th}}}$



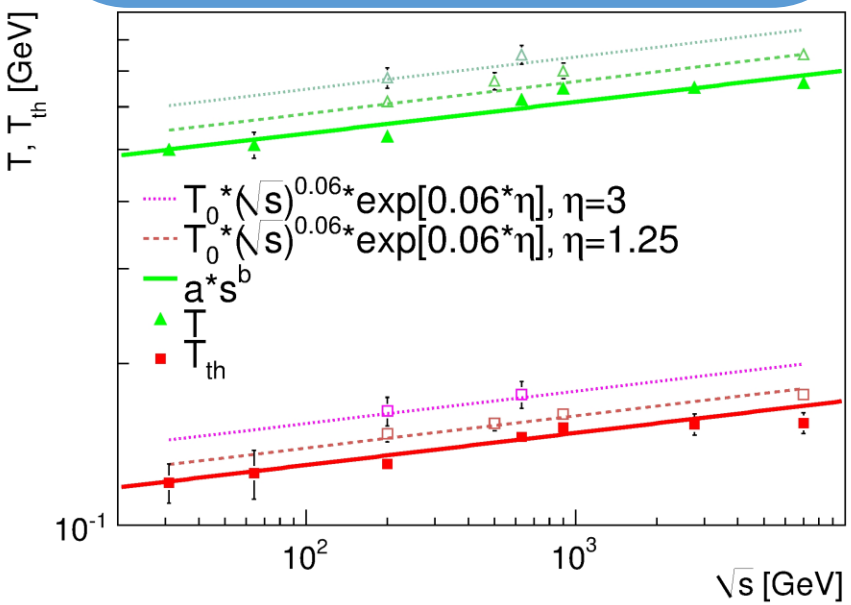


$\int(\text{lum}) = 36.1 + 35.9 fb^{-1}$

Baker, O. K., & Kharzeev, D. E. (2018). Physical Review D, 98(5), 054007.

Higgs temperature anomaly

T_{th}, GeV	T, GeV	R	process
none	0.1 ± 0.02	1.0 ± 0.1	pp $(\gamma\gamma) \to (\mu\mu)$pp
3.5 ± 0.7	14.4 ± 0.3	0.15 ± 0.05	pp$\to$ H $\to \gamma\gamma$
3.5 ± 0.7	14.4 ± 0.3	0.23 ± 0.05	pp$\to$ H $\to$ 4l (e, μ)
0.17 ± 0.03	0.72 ± 0.1	0.16 ± 0.05	pp $\to$ charged hadrons



$$T = 409 \cdot (\sqrt{s})^{0.06}\ MeV,$$

$$T_{th} = 98 \cdot (\sqrt{s})^{0.06}\ MeV.$$

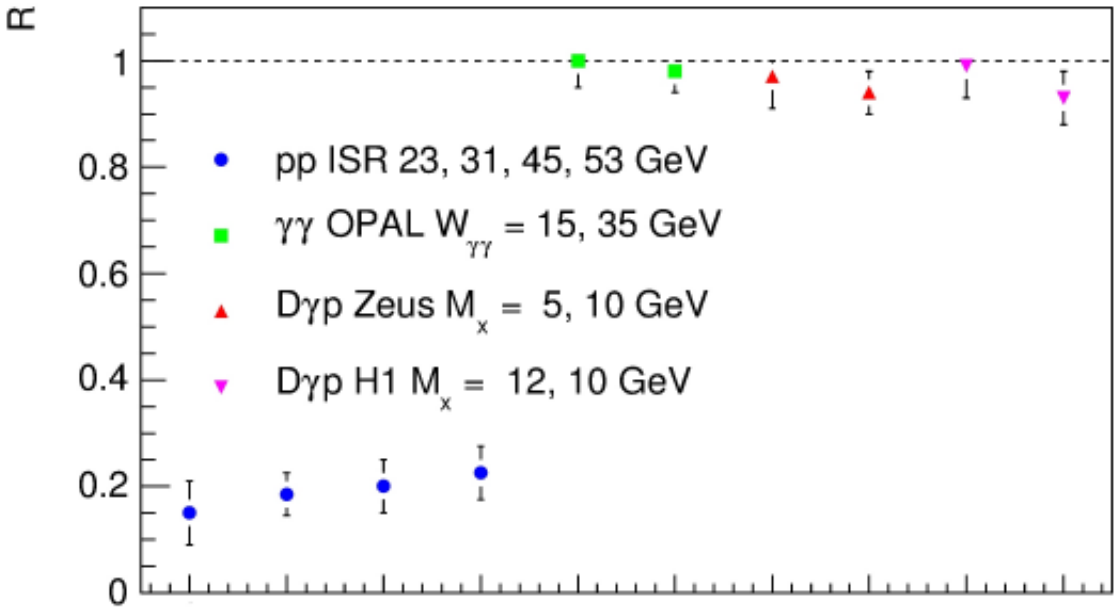
Holds not true for Higgs anymore.

Higgs temperature anomaly

T_{th}, GeV	T, GeV	R	process
none	0.1 ± 0.02	1.0 ± 0.1	pp $(\gamma\gamma) \to (\mu\mu)$pp
3.5 ± 0.7	14.4 ± 0.3	0.15 ± 0.05	pp$\to$ H $\to \gamma\gamma$
3.5 ± 0.7	14.4 ± 0.3	0.23 ± 0.05	pp$\to$ H $\to$ 4l (e, μ)
0.17 ± 0.03	0.72 ± 0.1	0.16 ± 0.05	pp $\to$ charged hadrons

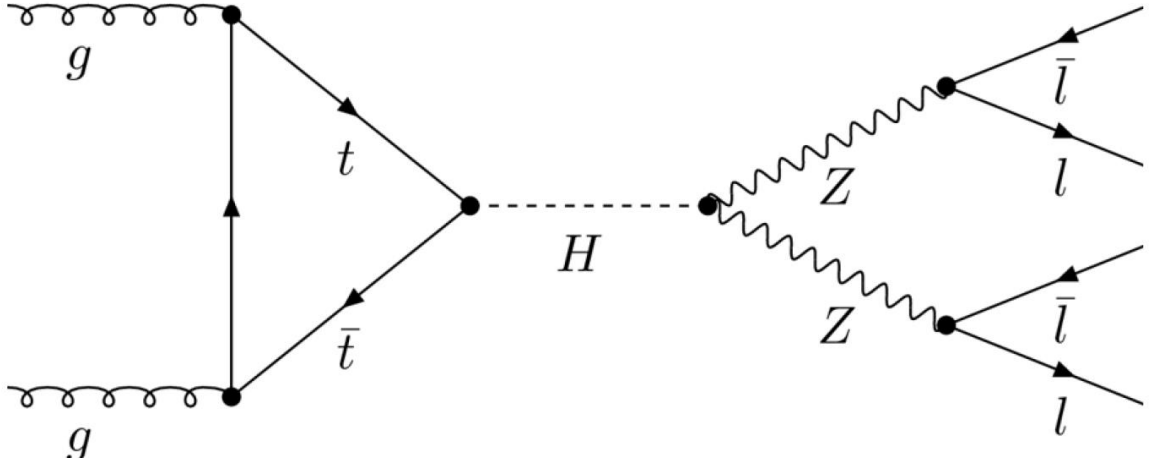
$$R = \frac{T}{T_{th} + T}$$

But R is consistent with other channels.



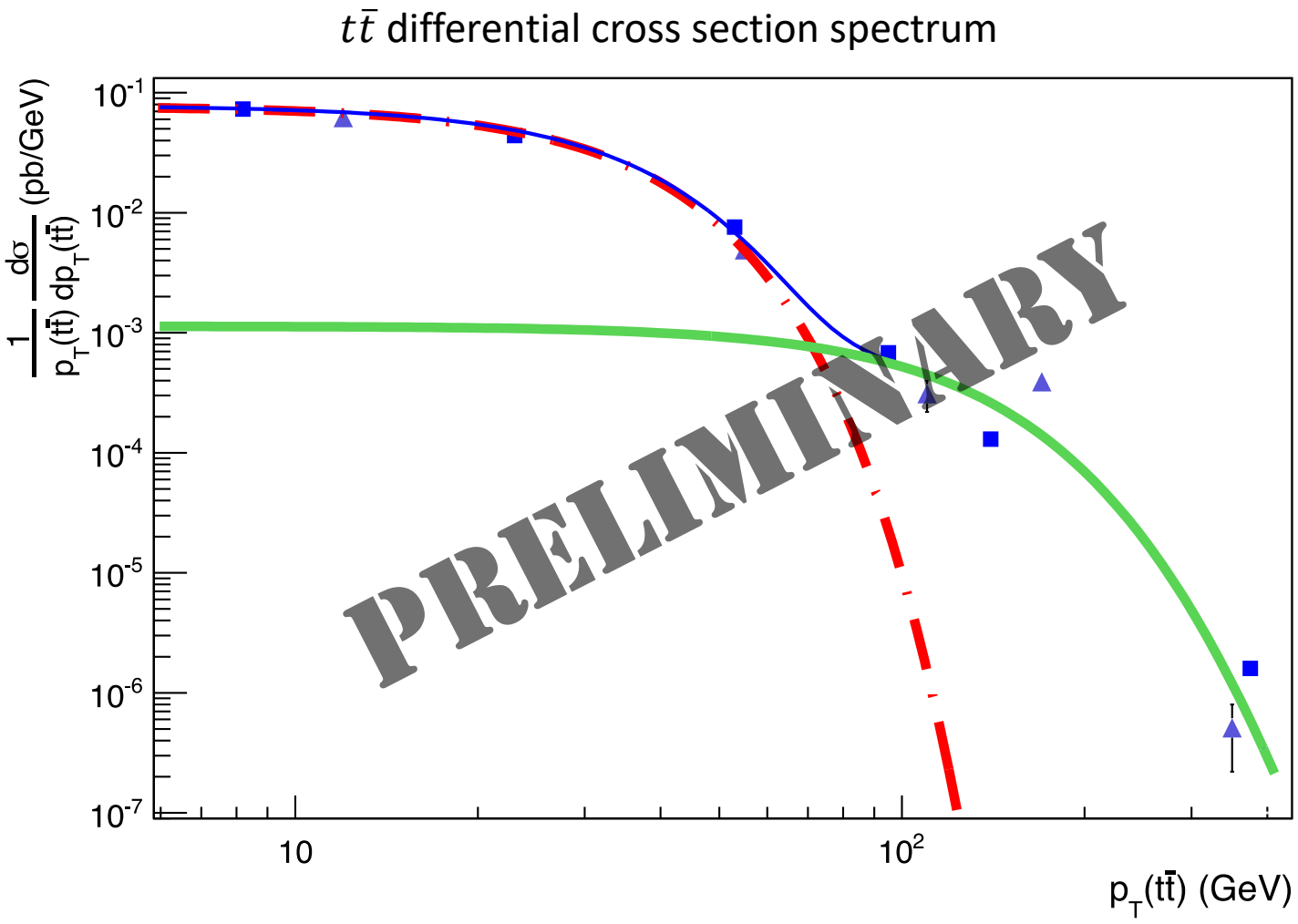
Higgs temperature anomaly

T_{th}, GeV	T, GeV	R	process
none	0.1 ± 0.02	1.0 ± 0.1	pp $(\gamma\gamma) \to (\mu\mu)$pp
3.5 ± 0.7	14.4 ± 0.3	0.15 ± 0.05	pp$\to$ H $\to \gamma\gamma$
3.5 ± 0.7	14.4 ± 0.3	0.23 ± 0.05	pp$\to$ H $\to$ 4l (e, μ)
0.17 ± 0.03	0.72 ± 0.1	0.16 ± 0.05	pp $\to$ charged hadrons



Additional studies . . .

Investigate $t\bar{t}$ transverse momentum distribution at $\sqrt{s}$ =13 TeV



Quantum information science in high energy physics

- Theoretical and experimental studies of thermal radiation and entanglement in pp collisions
- First demonstration of this QIS related effect at highest LHC energies
- Can quantum entanglement be used to address open problems in:
  - hadron structure?
  - dark sector searches?
  - quark confinement?
  - thermalization in HEP?
  - qubit decoherence in quantum computing?

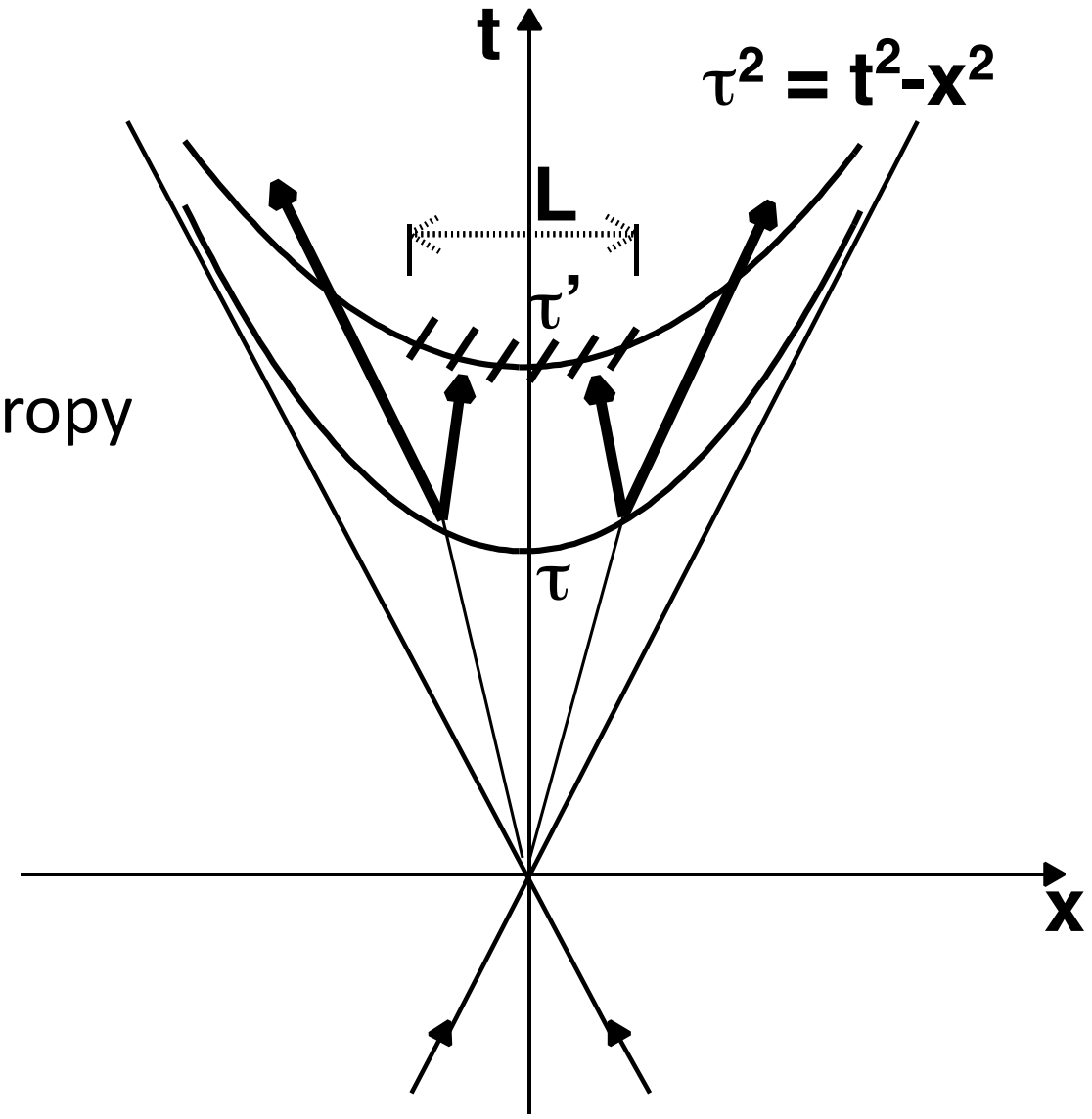
Thank you!

Talk based on:
Baker, Oliver K., and Dmitri E. Kharzeev.

"Thermal radiation and entanglement in proton-proton collisions at energies available at the CERN Large Hadron Collider."

Physical Review D 98.5 (2018): 054007

1+1 conformal field theory

Quench introduces entanglement entropy

$$S(t) \simeq \frac{c}{3} \ln \tau_0 + \frac{\pi c L}{12 \tau_0}$$