Quantum Entanglement and Entanglement Entropy in Higgs Boson Decay to Vector Bosons

Quantum Entanglement in High Energy Physics Workshop
Collegium Maius, Jagiellonian University, Cracow, Poland
10-May-2023

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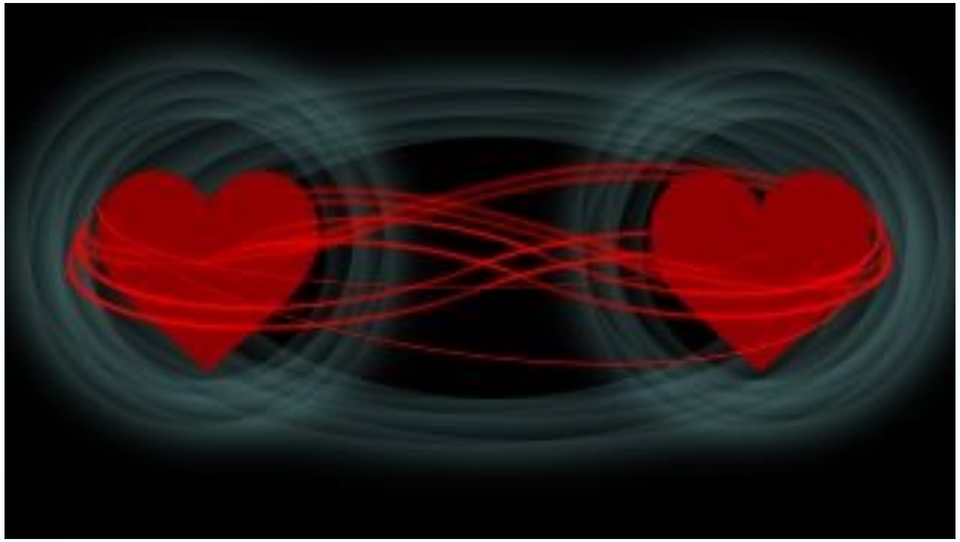
Entanglement . . .

Webster

- to wrap or twist together
- the condition of being deeply involved
  - their entanglement in politics
- to involve in a perplexing or troublesome situation
  - became *entangled* in a lawsuit
- to make complicated
  - the story is *entangled* with legends

Quantum Entanglement



". . love between entangled particles. . . "

- Elementary particles described by wave functions
- Entanglement between different parts of wave function
- We know of no classical counterpart

Questions . . .

- **What is quantum entanglement in HEP?**
- **What is entanglement entropy in HEP?**
- **What is the connection to black holes?**
- **Is there experimental HEP data to support this claim?**
- **Where is this headed . . . ?**

The Physics . . .

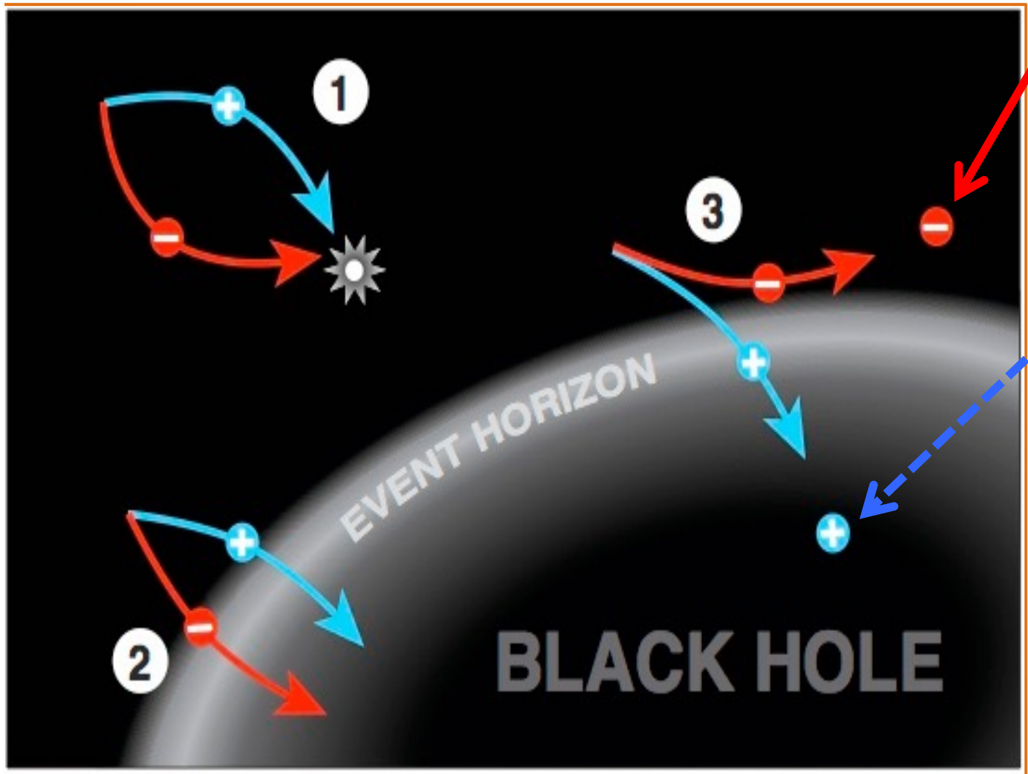
- apparent thermalization in high energy collisions
  - (surprising?) thermal features in HEP collisions
  - inferred from presence of exponential component and thermal hadron abundances in p_T (transverse momentum) distribution
- parton scattering → strong color fields →huge deceleration; short times (quench)
  - produces thermal radiation akin to Hawking/Unruh radiation
- can be viewed as resulting from quantum entanglement inside nucleon wave function
  - additional examples in nuclear, atomic, and condensed matter physics

Entanglement at Black Hole Event Horizon

black hole event horizon

detected (thermal)

undetected



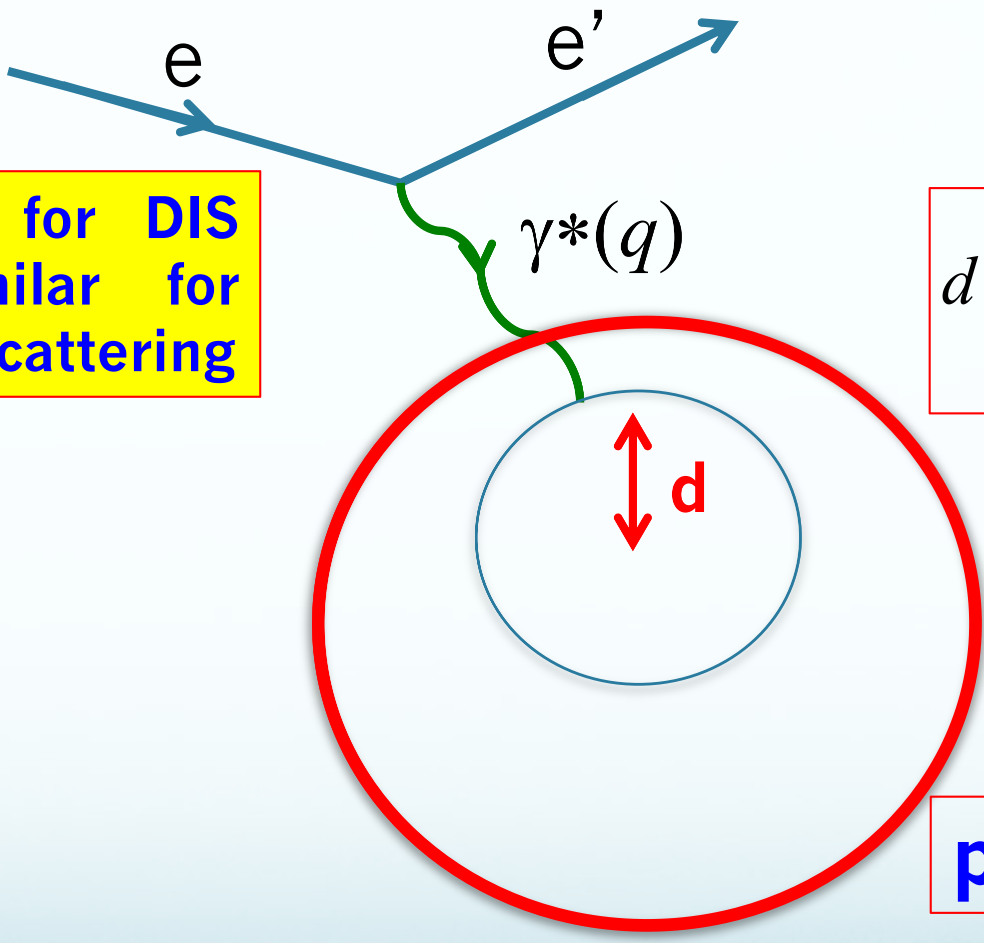
at BH, one particle escapes and one particle is trapped inside the BH event horizon

- Hawking radiation at event horizon
- black holes - thermodynamic behavior
  - black holes have entropy
- entropy between two regions scale with the area of their mutual boundary

High Energy Physics Examples

Example: e-N DIS Scattering

This example is for DIS scattering; similar for neutrino-nucleus scattering



transvese

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

proton

Example: e-N DIS Scattering

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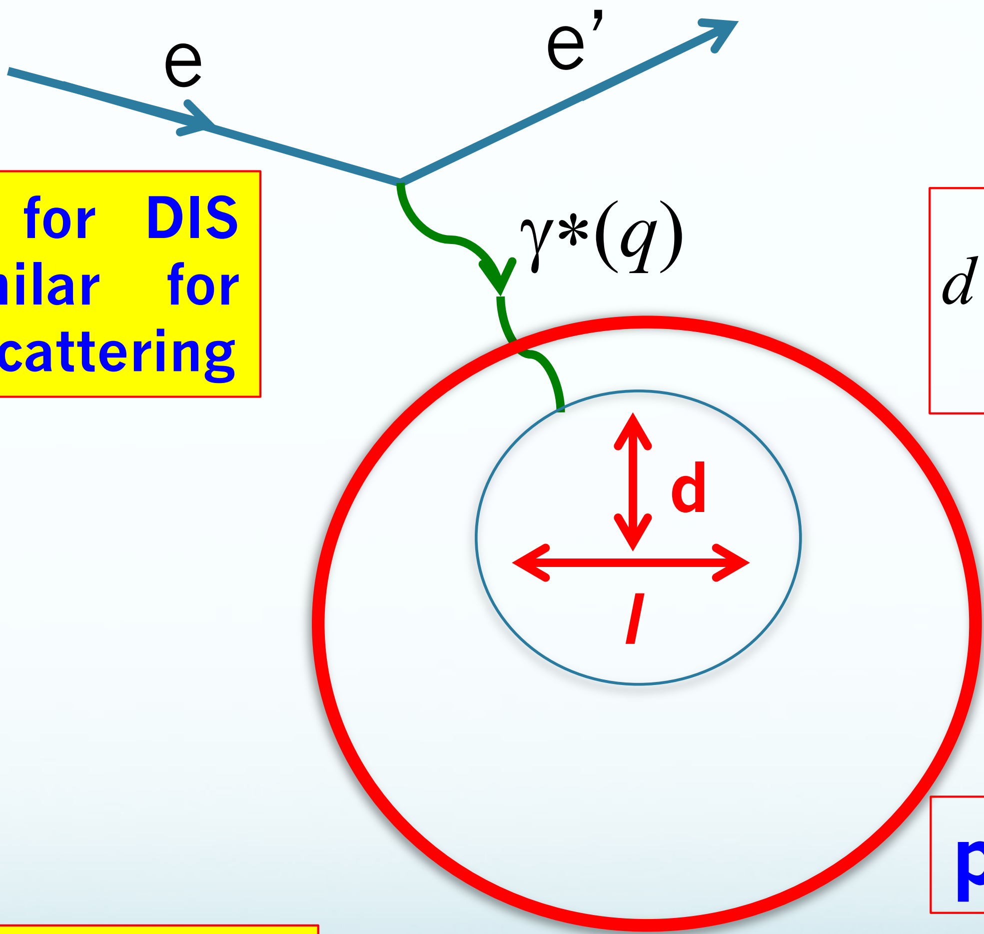


transvese

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

longitudinal

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

proton

m - proton mass
x - parton momentum fraction

HEP Collisions and Entanglement

Mixed quantum state – a statistical ensemble of quantum states

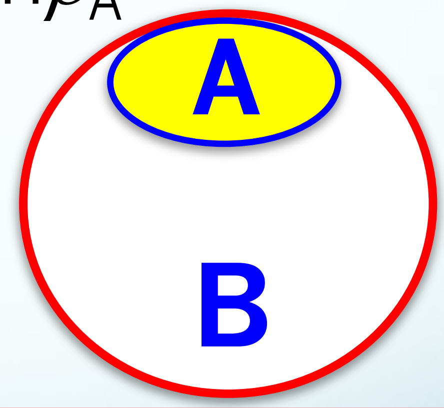
$$\rho_A = \mathrm{tr}_B \rho_{AB} = \sum_n \alpha_n^2 \left|\Psi_n^A\right\rangle \left|\Psi_n^A\right\rangle$$

where $\alpha_n^2 = p_n$

and $$S = -\sum_n p_n \ln p_n$$

$S(\rho_A) = -\mathrm{Tr}\ \rho_A \ln \rho_A$

proton



S is the von Neumann entropy of subregion A; results from the entanglement between regions A and B; interpreted as the entanglement entropy; related to Shannon or Information entropy

HEP Collisions and Entanglement

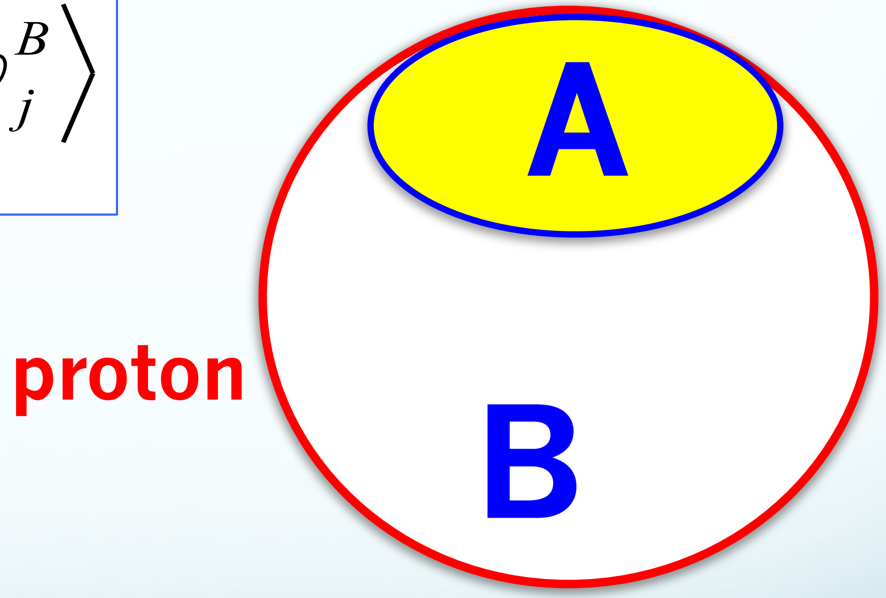
pure quantum state
single term

$$\left|\Psi_{AB}\right\rangle = \left|\varphi_i^A\right\rangle \otimes \left|\varphi_j^B\right\rangle$$

separable – not entangled

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

not separable - entangled



mixed quantum state
sum of terms

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

(okb, DE Kharzeev, (2017); PRD 98, 054007 (2018))

Thermal (Exponential) and Hard Scattering (Power Law) Components

$$\frac{1}{N_{ev}}\frac{1}{2\pi P_T}\frac{d^2N_{ev}}{d\eta\, dP_T} \sim A_{therm}\exp(-m_T/T_{th})$$

$$T_{th} = 0.098\left(\sqrt{s/s_0}\right)^{0.06}\ \text{GeV}$$

$$\frac{1}{N_{ev}}\frac{1}{2\pi P_T}\frac{d^2N_{ev}}{d\eta\, dP_T} \sim \frac{A_{hard}}{\left(1+\frac{m_T^2}{T_{hs}^2\cdot n}\right)^2}$$

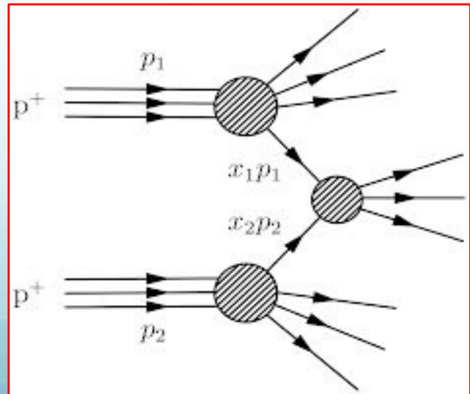
$$T_{hs} = 0.409\left(\sqrt{s/s_0}\right)^{0.06}\ \text{GeV}$$

$\sqrt{s}$: *center of mass energy*

s_0 : 1 GeV^2

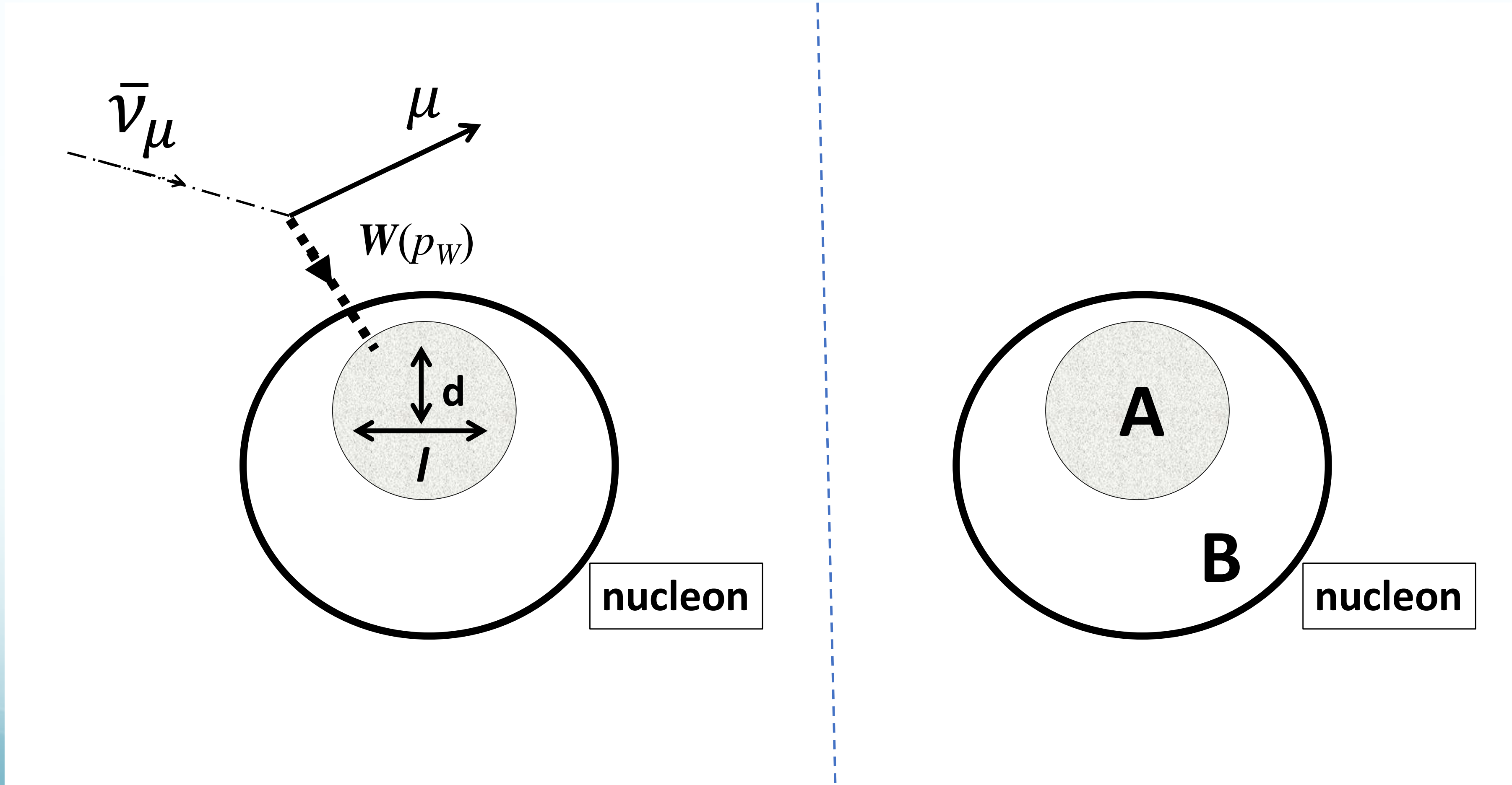
m_T : transverse mass $\sqrt{m^2+P_T^2}$

n : parameter



Neutrino Scattering

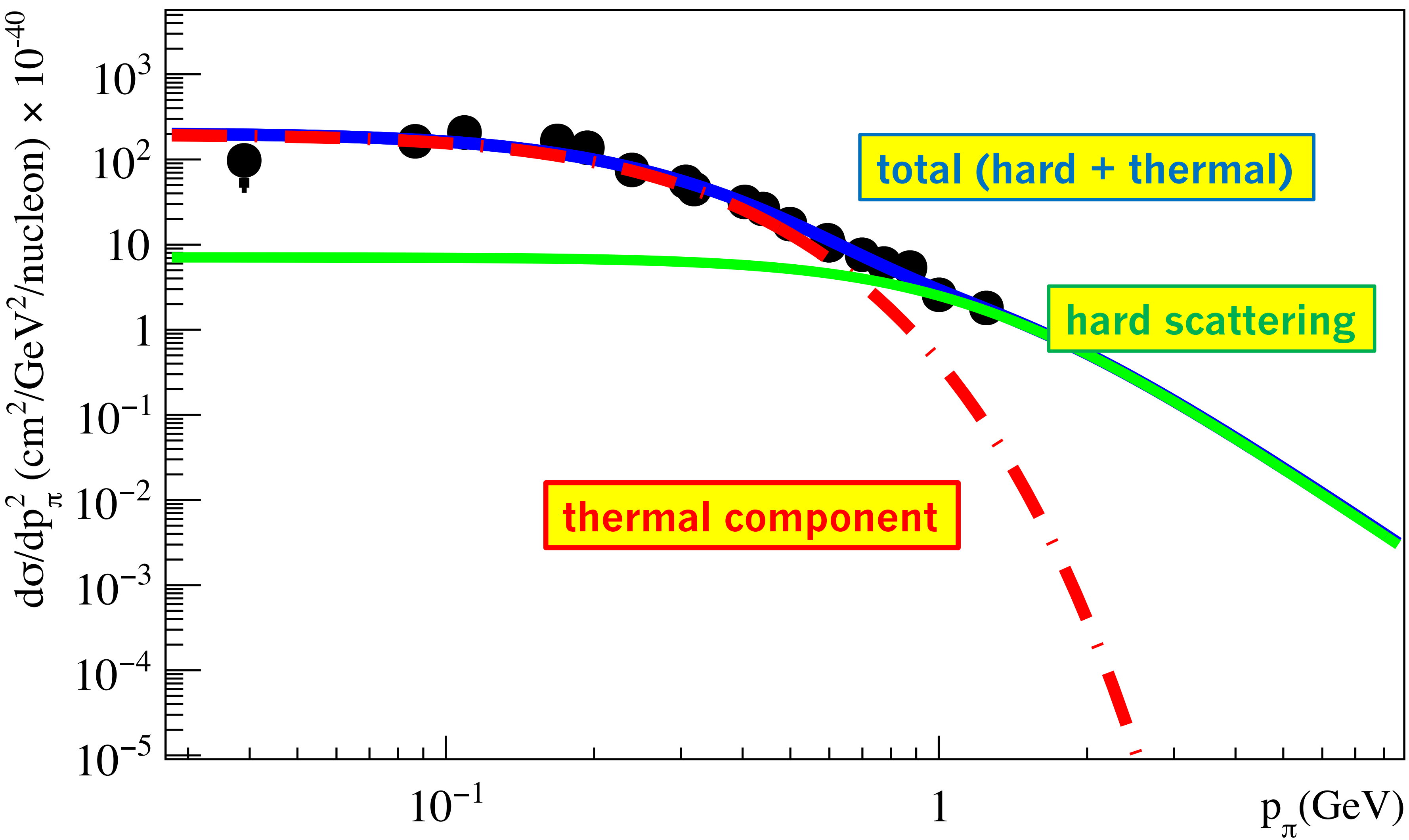
charged current weak interaction



G. Iskander, J. Pan, M. Tyler, C. Weber, OKB
Phys Lett B 811, 135948 (2020)

Neutrino Scattering

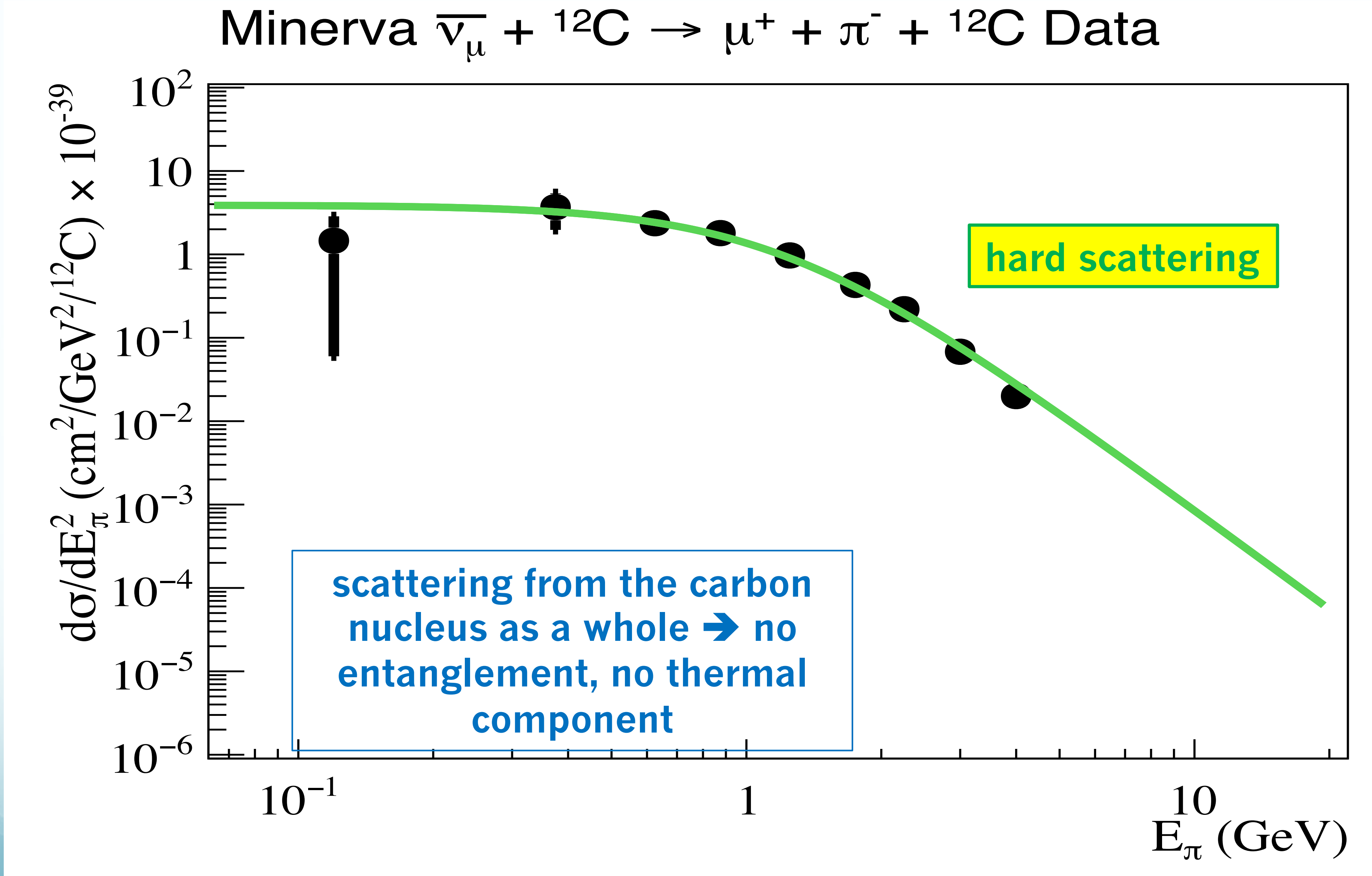
Minerva $\bar{\nu}_\mu + CH \rightarrow \mu^+ + \pi^0 + X$ Data



R=0.15

G. Iskander, J. Pan, M. Tyler, C. Weber, OKB
Phys Lett B 811, 135948 (2020)

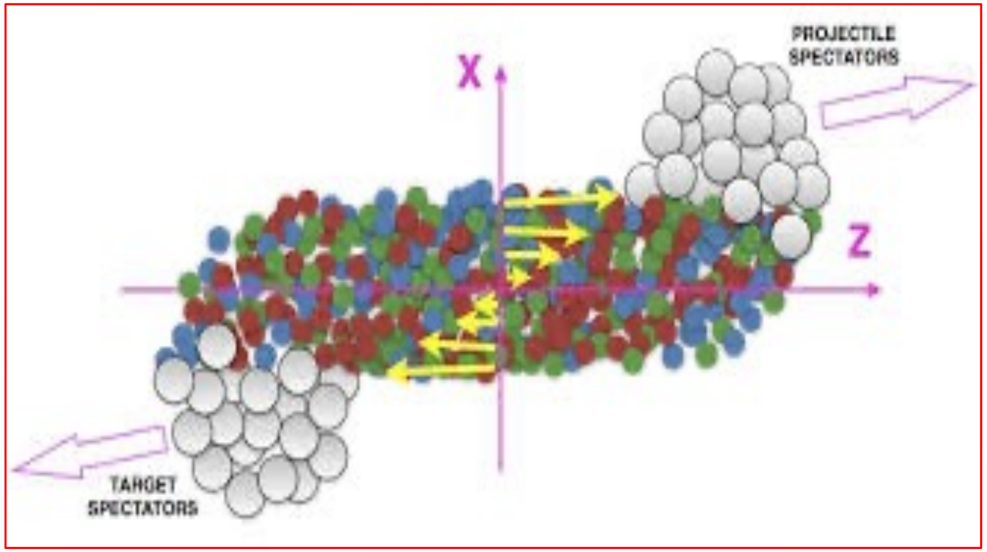
Neutrino Scattering

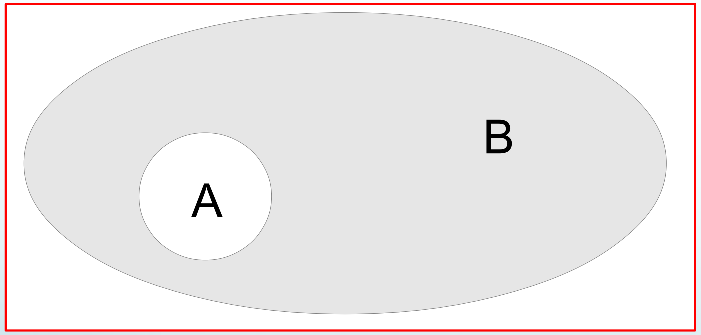


G. Iskander, J. Pan, M. Tyler, C. Weber, OKB
Phys Lett B 811, 135948 (2020)

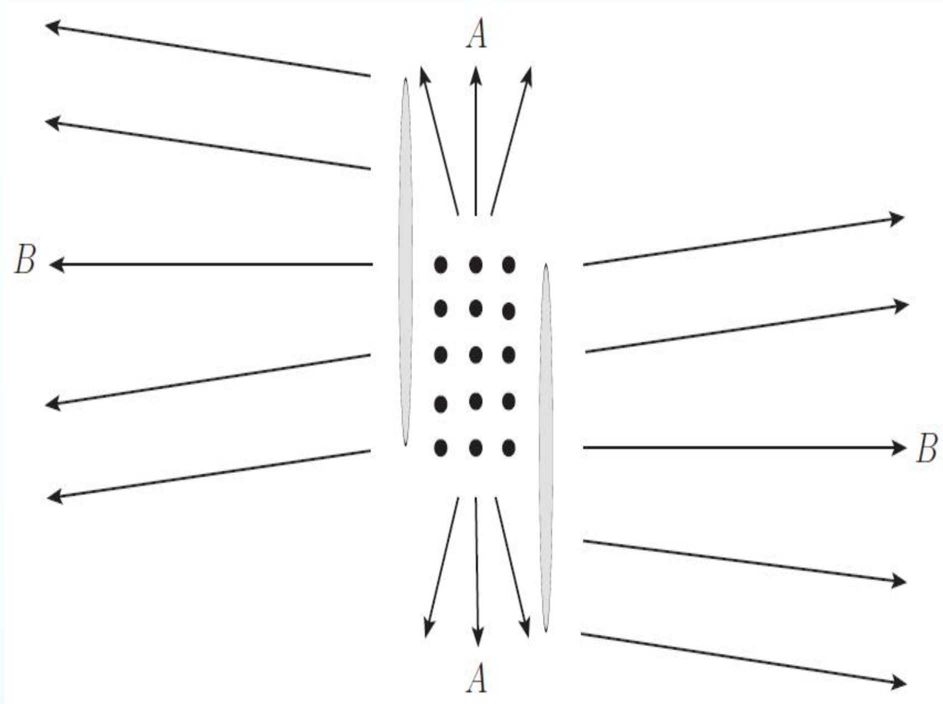
Additional examples: heavy ions and cold atoms

Entanglement in Heavy Ion Collisions





overlap region A; collision



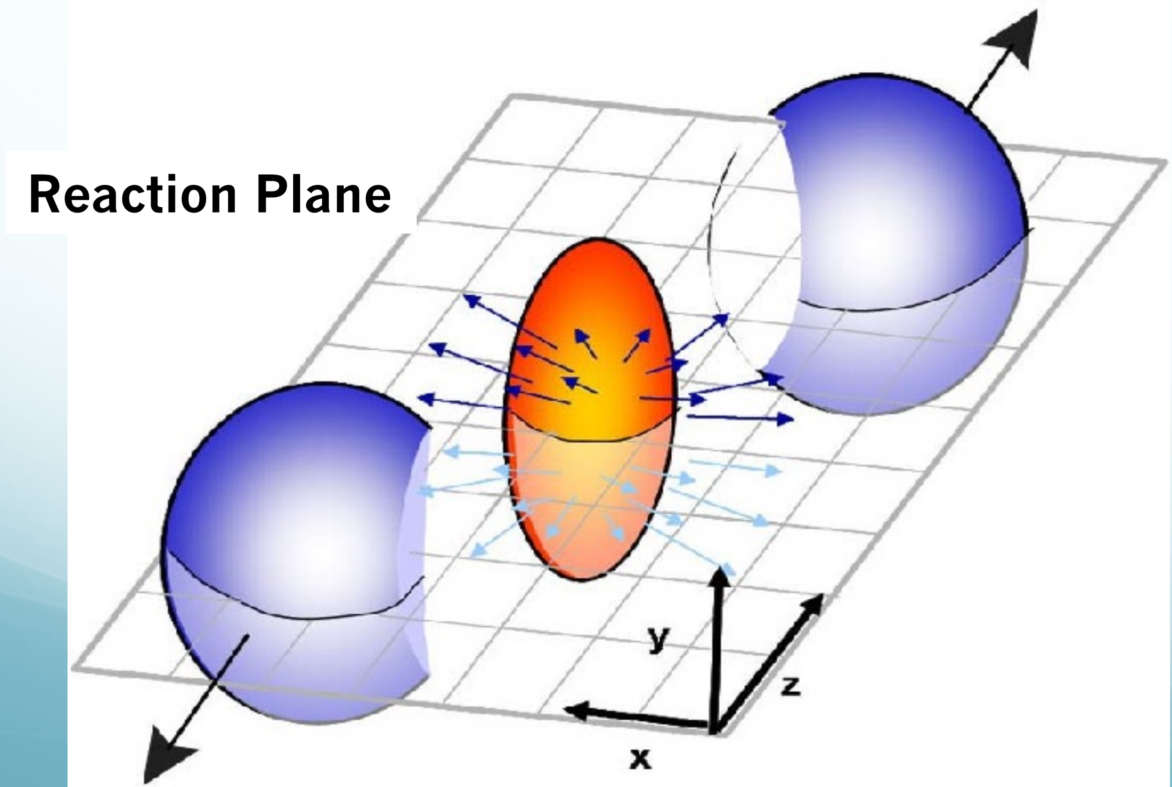
region B; no collision

Ho and Hsu,
Entanglement and Fast Quantum Thermalization in Heavy Ion Collisions
Phys. Lett. A 18, 1650110 (2016)

Elliptic Flow in pp and HI Collisions

$$v_n(p_T, y) = \langle \cos[n(\phi - \psi_{RP})] \rangle$$

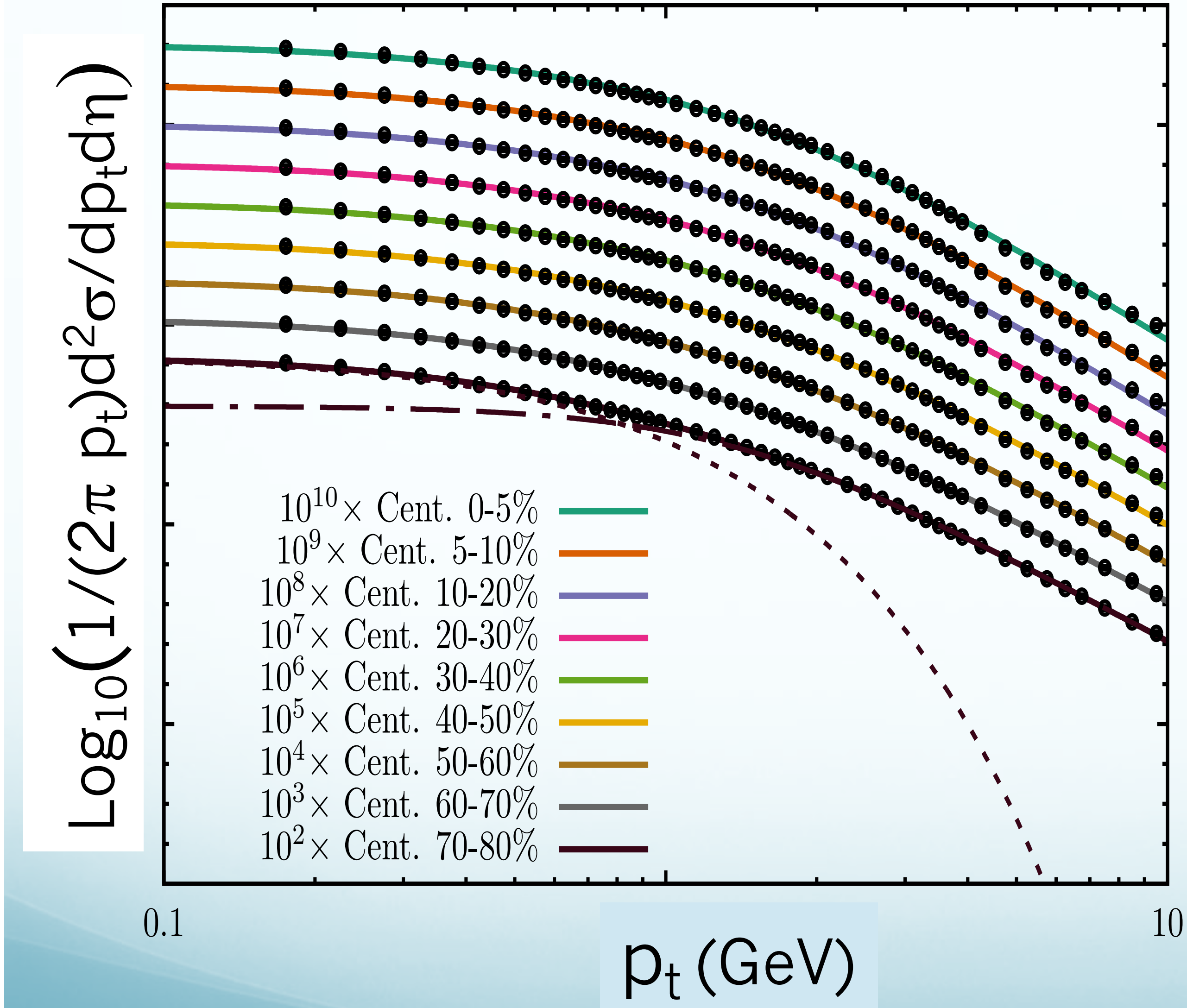
- Fourier coefficients, v_n,
- characterize anisotropic flow patterns
- averaged over all particles in an event



v_2 :elliptic flow

$$\frac{dv_2}{dp_T} \approx \frac{v_2}{\langle p_T \rangle}$$

Thermal Behavior and Entanglement in Pb-Pb Collisions



- **Pb-Pb collisions**

$\sqrt{s_{NN}}$ = 2.76 TeV

- **centrality;**

70%-80% ➔ 0%-5%

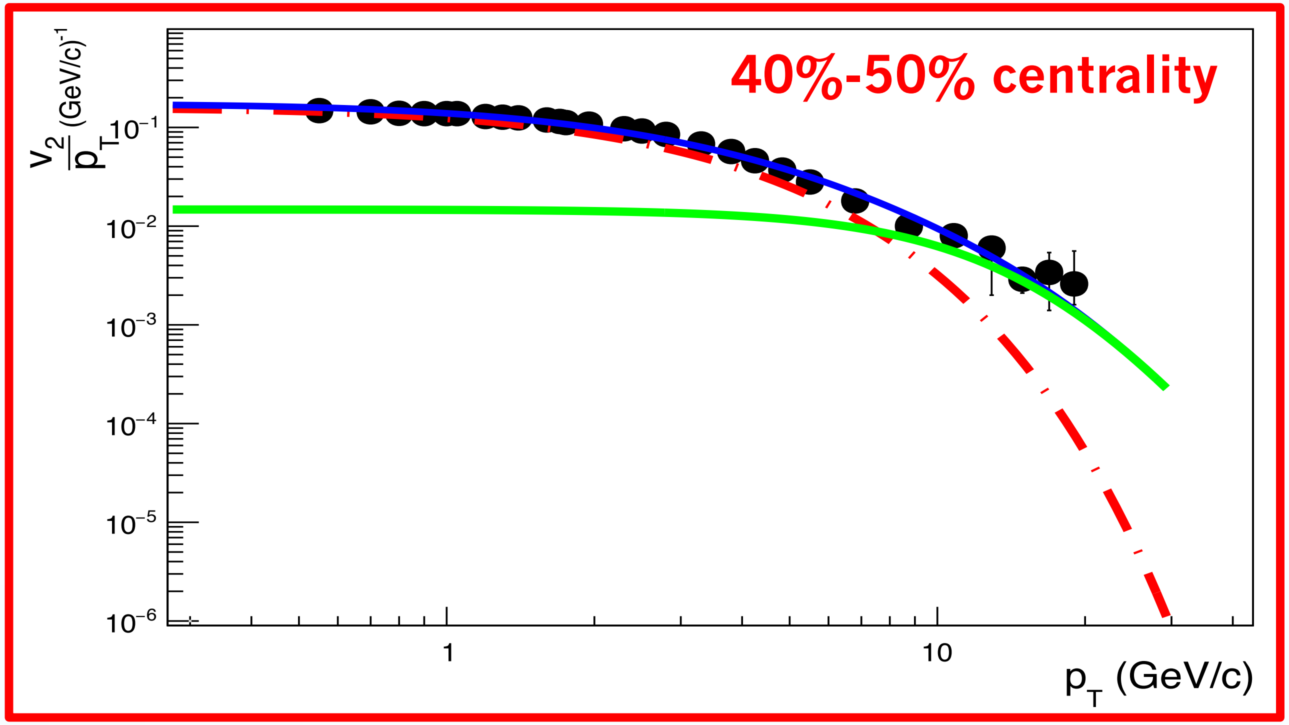
- $R = \frac{H}{H+E}$

(intergral under curves)

H: power law E: exponential

Feal, Pajares, Vazquez, Phys. Rev. C 99, 015205 (2019)

Elliptic Flow in PbPb collisions



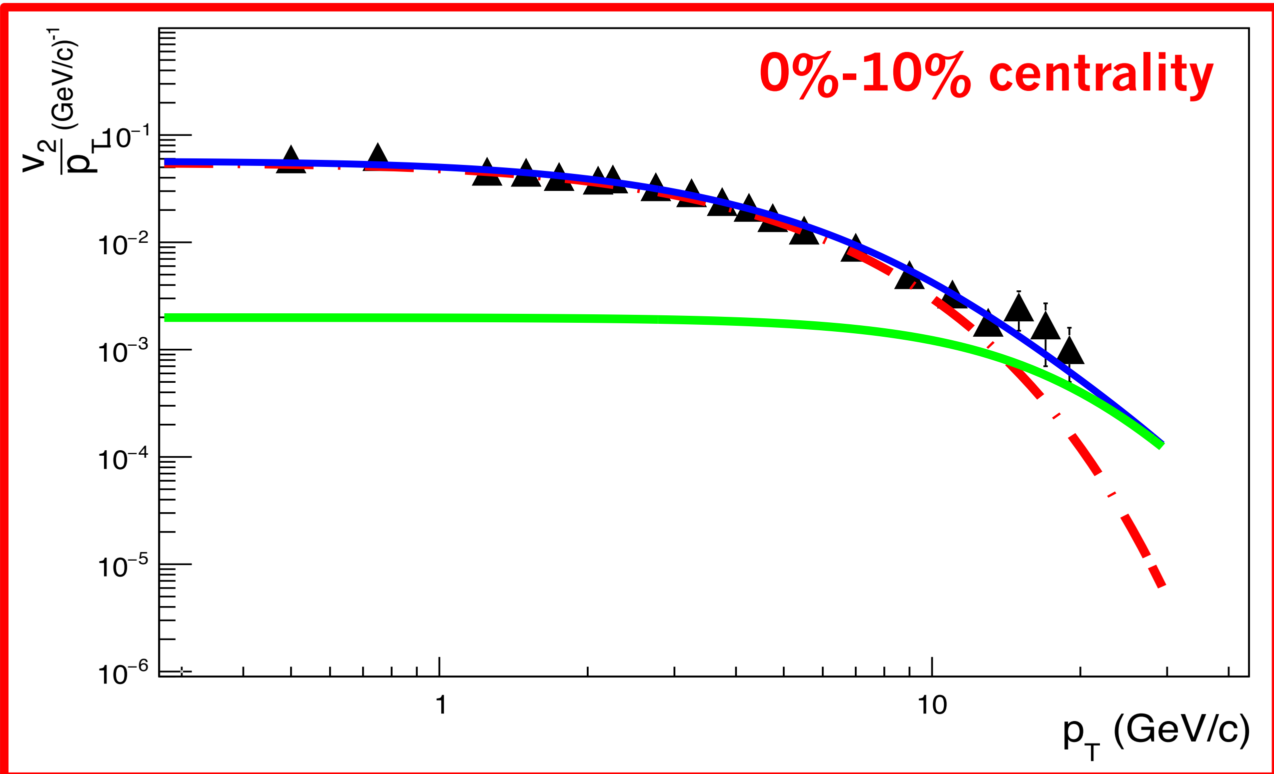


Table 1: Centrality versus R

Centrality	$R \pm 0.0003$
0-10%	0.115
20-30%	0.215
40-50%	0.152
70-80%	0.144
p-p	0.193

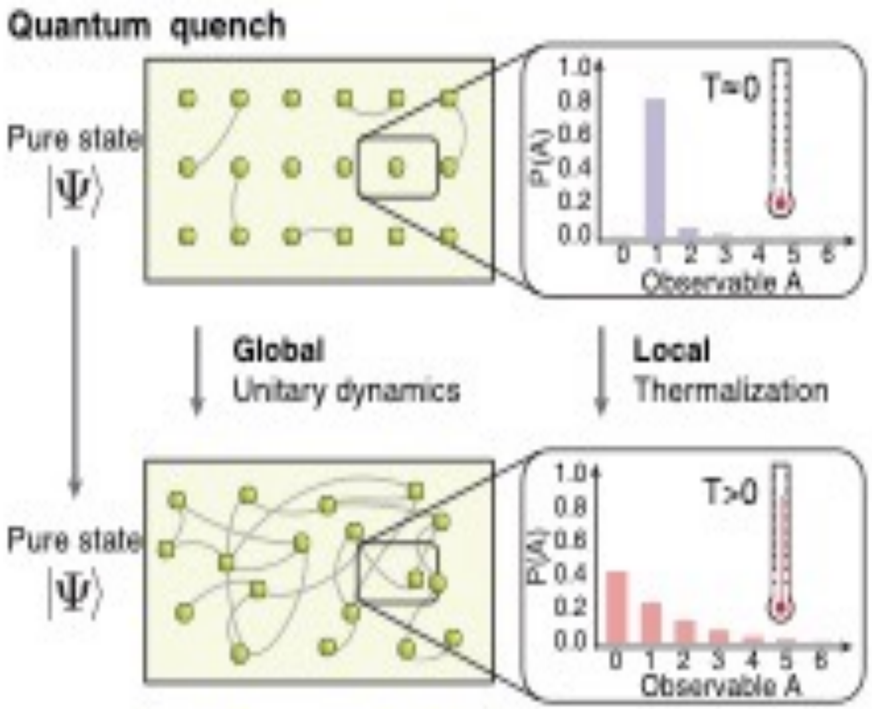
$$R = \frac{I_{hs}}{I_t + I_{hs}}$$

I is area under curves

Example From Cold Atom Physics

Quantum thermalization through entanglement in an isolated many-body system (Greiner Lab, Harvard University); Science 353, 794 (2016)

Quantum entanglement ➔ entanglement entropy ➔ thermalization; thermal entropy



- 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

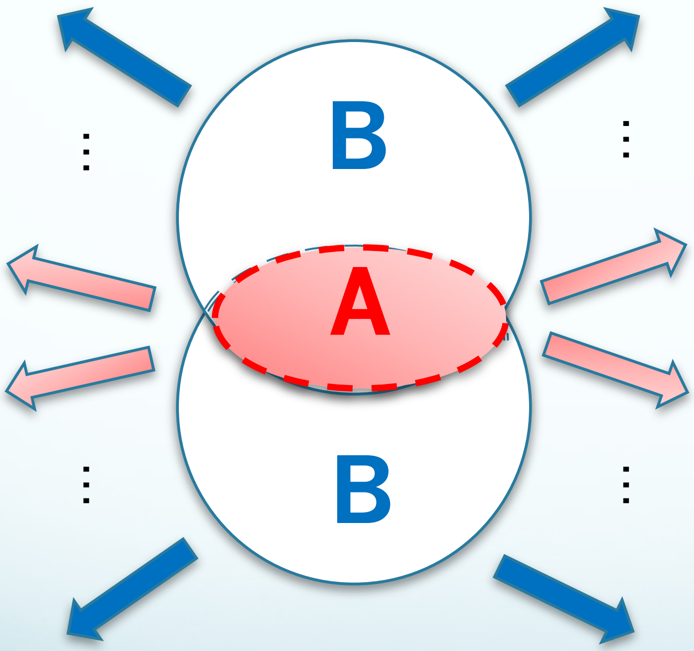
Ho and Hsu,

High Energy Physics example proton-proton collisions

(okb, DE Kharzeev, (2017); PRD 98, 054007 (2018))

Proton-Proton Collisions

proton-proton collisions at LHC energies mediated by gluon-gluon "fusion" mainly; short range compared to DIS



proton can be described as a pure macrostate consisting of a region of parton microstates probed in the collison and a region of parton microstates NOT probed in the collision

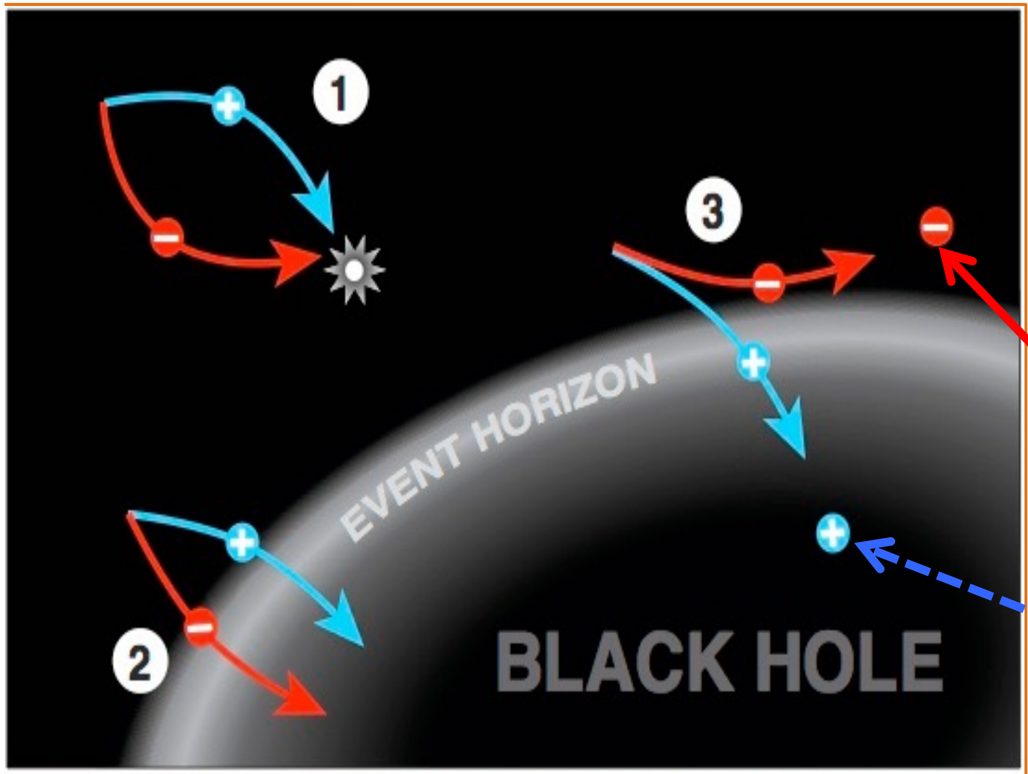
region A probed in p-p collision; regions A and B are entangled

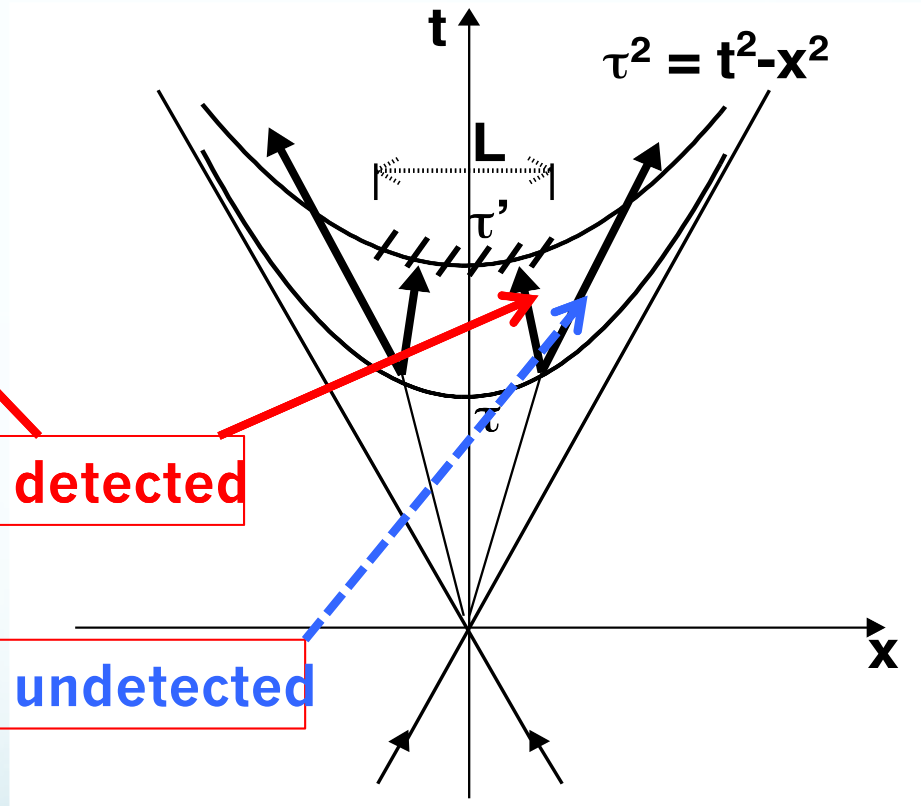
(okb, DE Kharzeev, (2017); PRD 98, 054007 (2018))

Entanglement in Proton-Proton Collisions and at Black Holes

black hole event horizon

proton-proton collision





detected

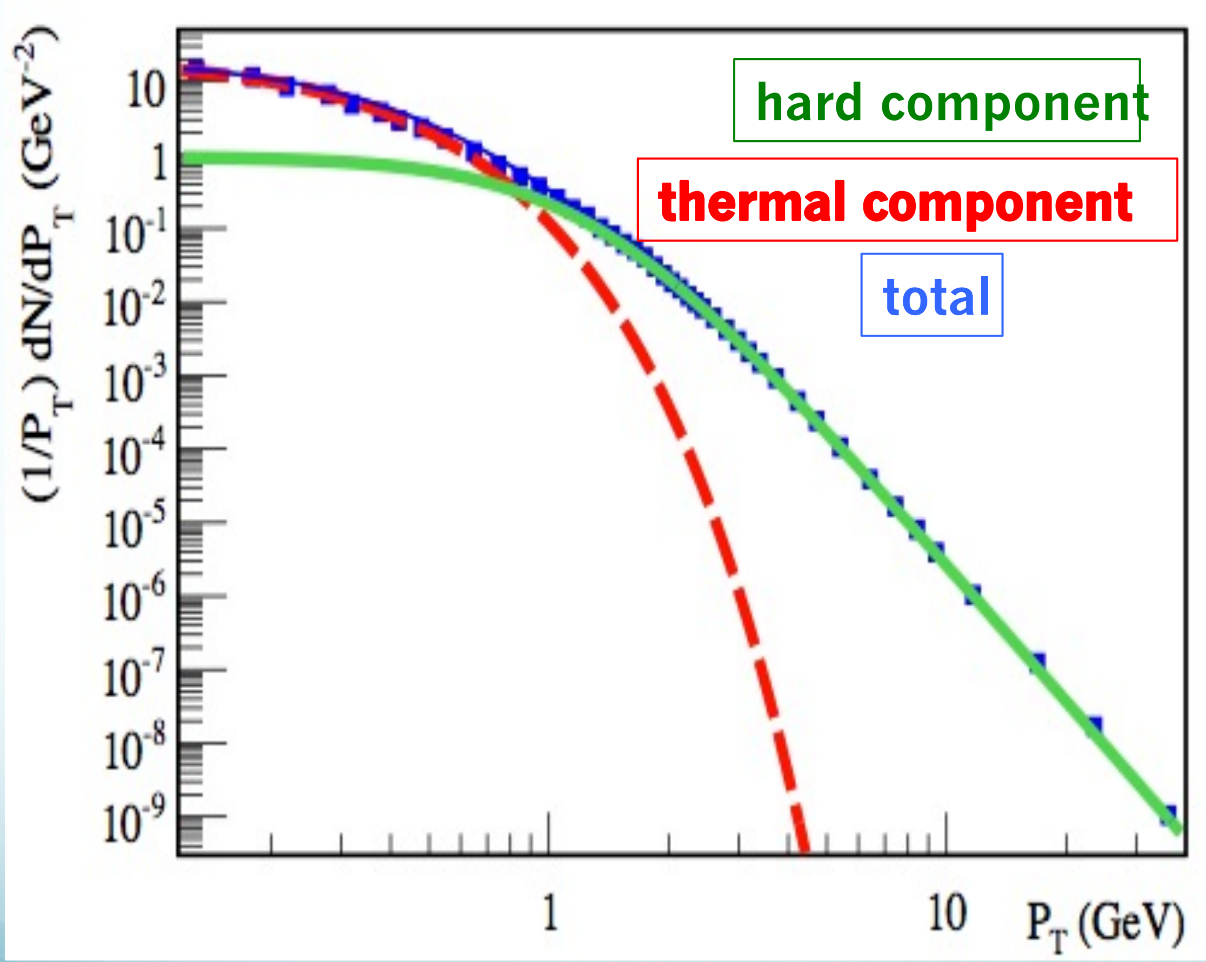
undetected

at BH, one particle escapes and one particle is trapped inside the BH event horizon

in pp collision, one region is probed and the complimentary region is not probed

(okb, DE Kharzeev, (2017); PRD 98, 054007 (2018))

Example at LHC: Charged Particle Normalized p_T Distribution



normalized transverse momentum distribution

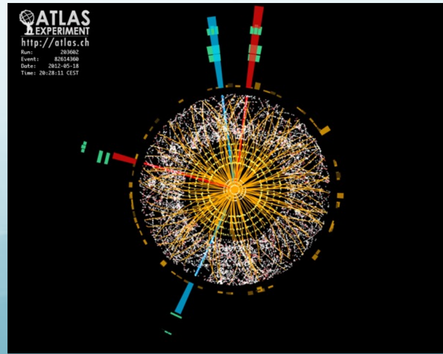
pp collisions

$\sqrt{s} = 13$ TeV

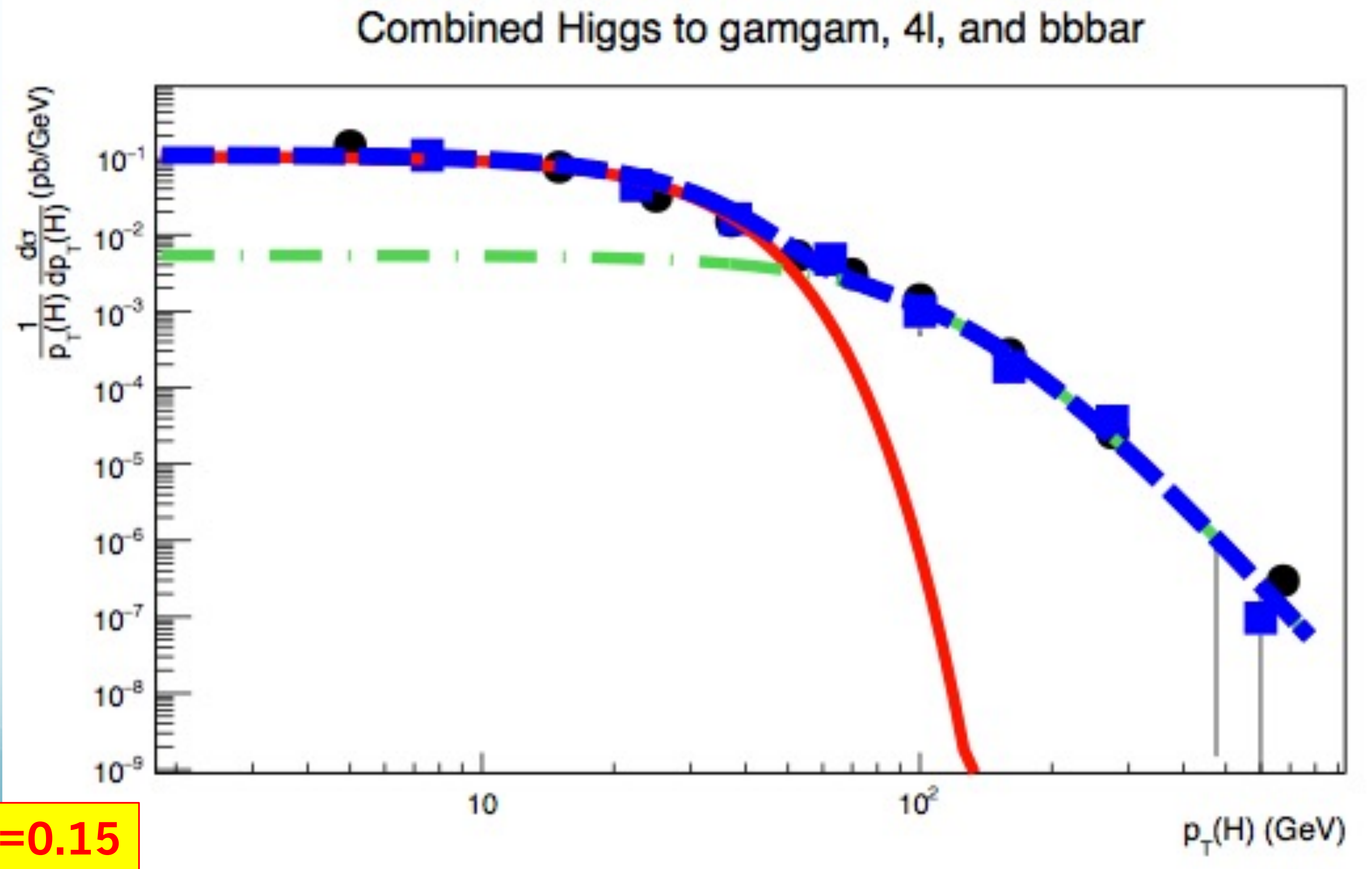
$|\eta| \leq 2.5$

$\int(\mathrm{lum}) = 151 \mu b^{-1}$

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



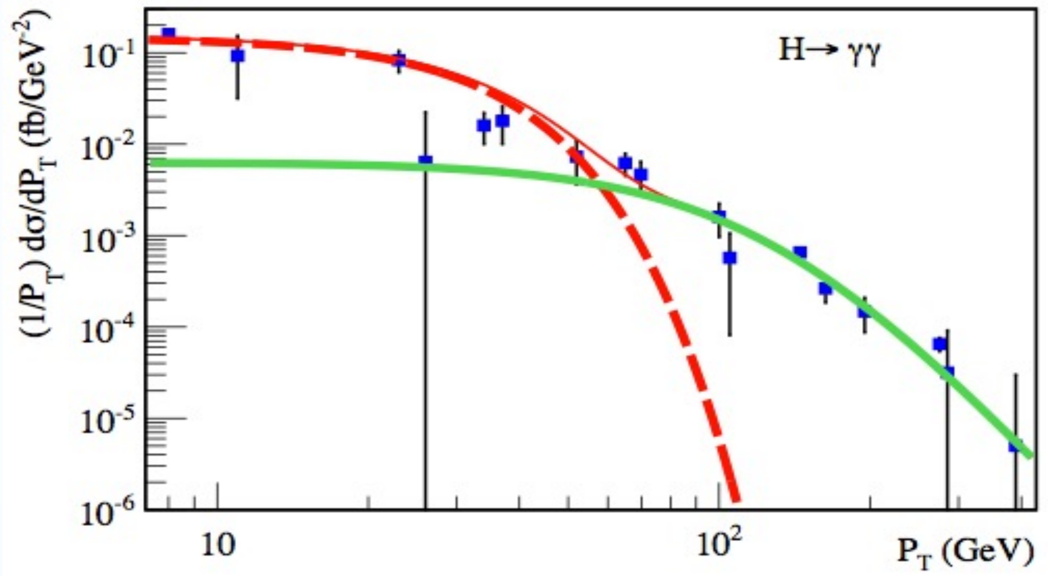
Higgs Combination:
ATLAS: 139 fb^{-1} (black circle); CMS 36 fb^{-1} (blue squares)

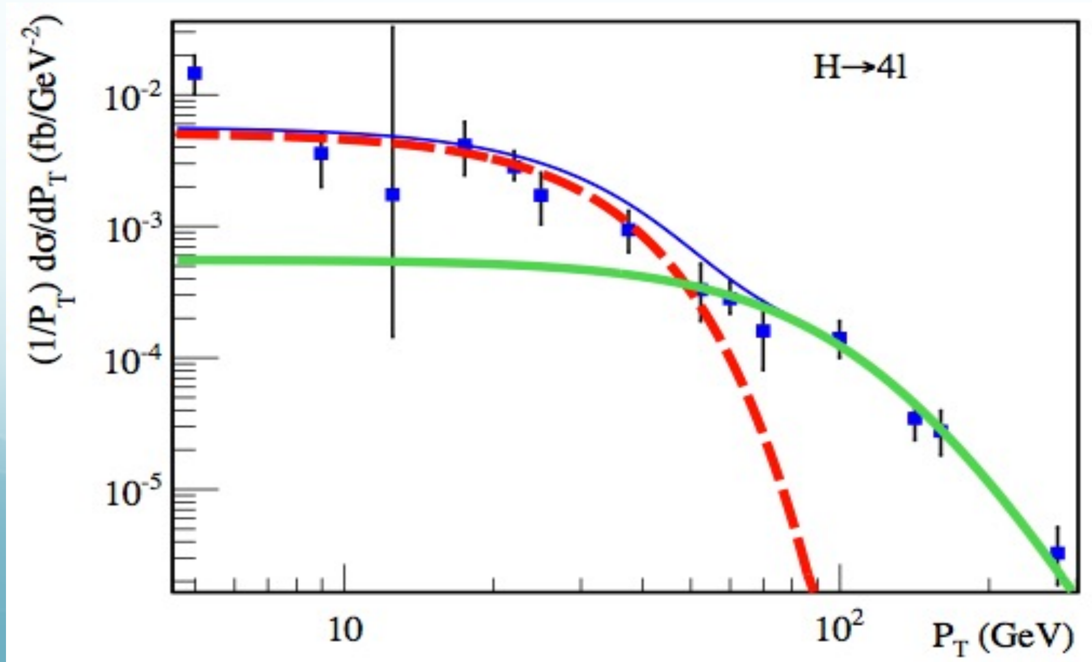


R=0.15

Extends to Higgs Sector ....!

(okb, DE Kharzeev, (2017); PRD 98, 054007 (2018))





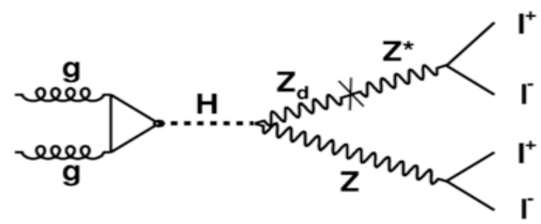
hard component

thermal component

total

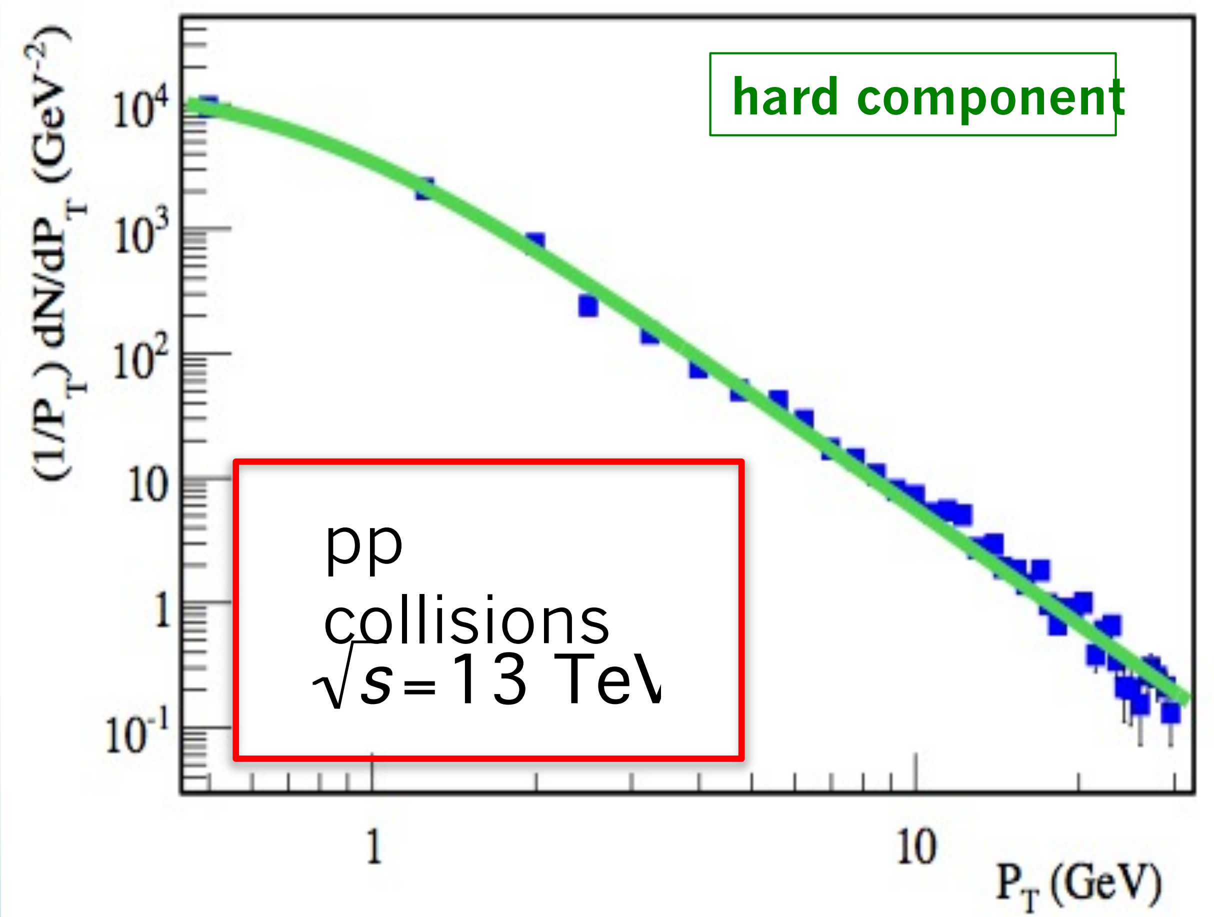
the ATLAS Collaboration
High Energ. Phys., 2017:132 (**2017**); LHCP2017, Shanghai, China, June **2017**

the CMS Collaboration
J. Tao on behalf of the CMS collaboration,arXiv:1708.09215, 1 (**2017**); LHCP2017, Shanghai, China, June **2017**



Diffractive Production; No Thermal Component?

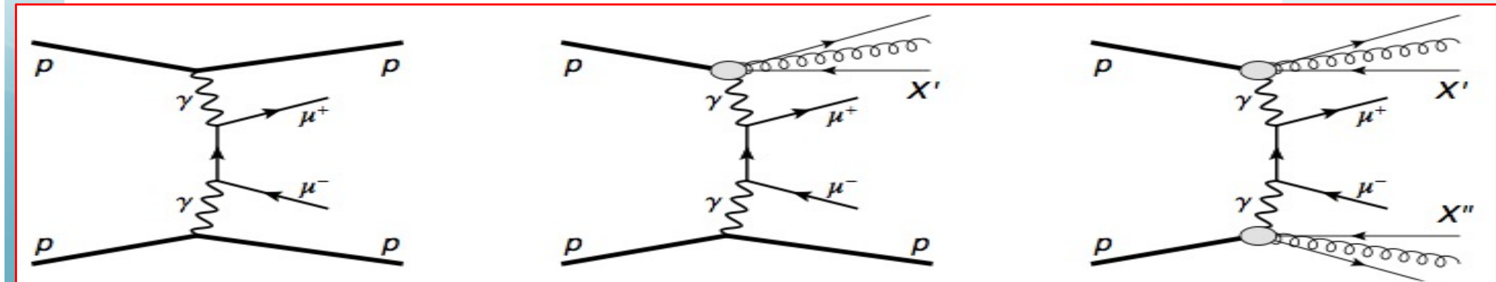
$$(pp)\gamma\gamma \to \mu^+\mu^-(X'X'')$$



should be no thermal component according to proposed mechanism

the ATLAS Collaboration arXiV:1708.04053 (2017)

thermal component absent



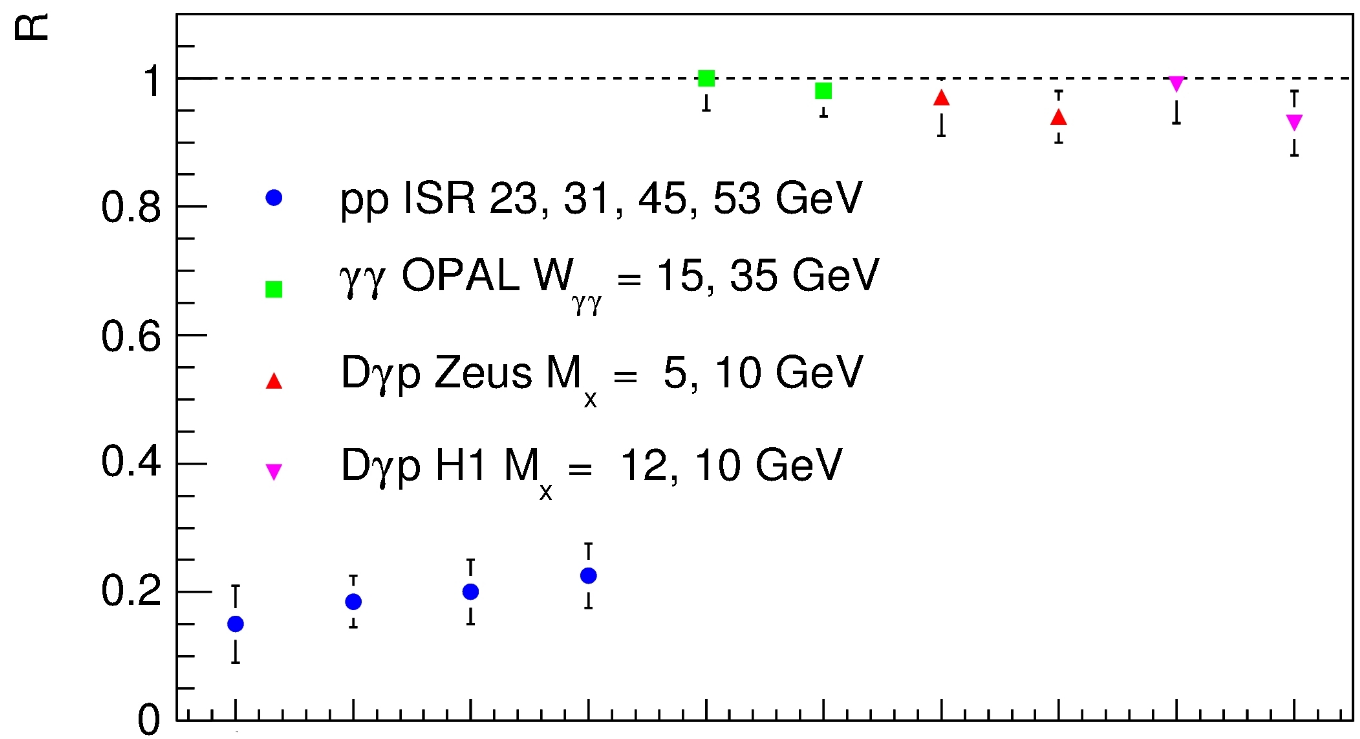
diffractive processes

(okb, DE Kharzeev, (2017); PRD 98, 054007 (2018))

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

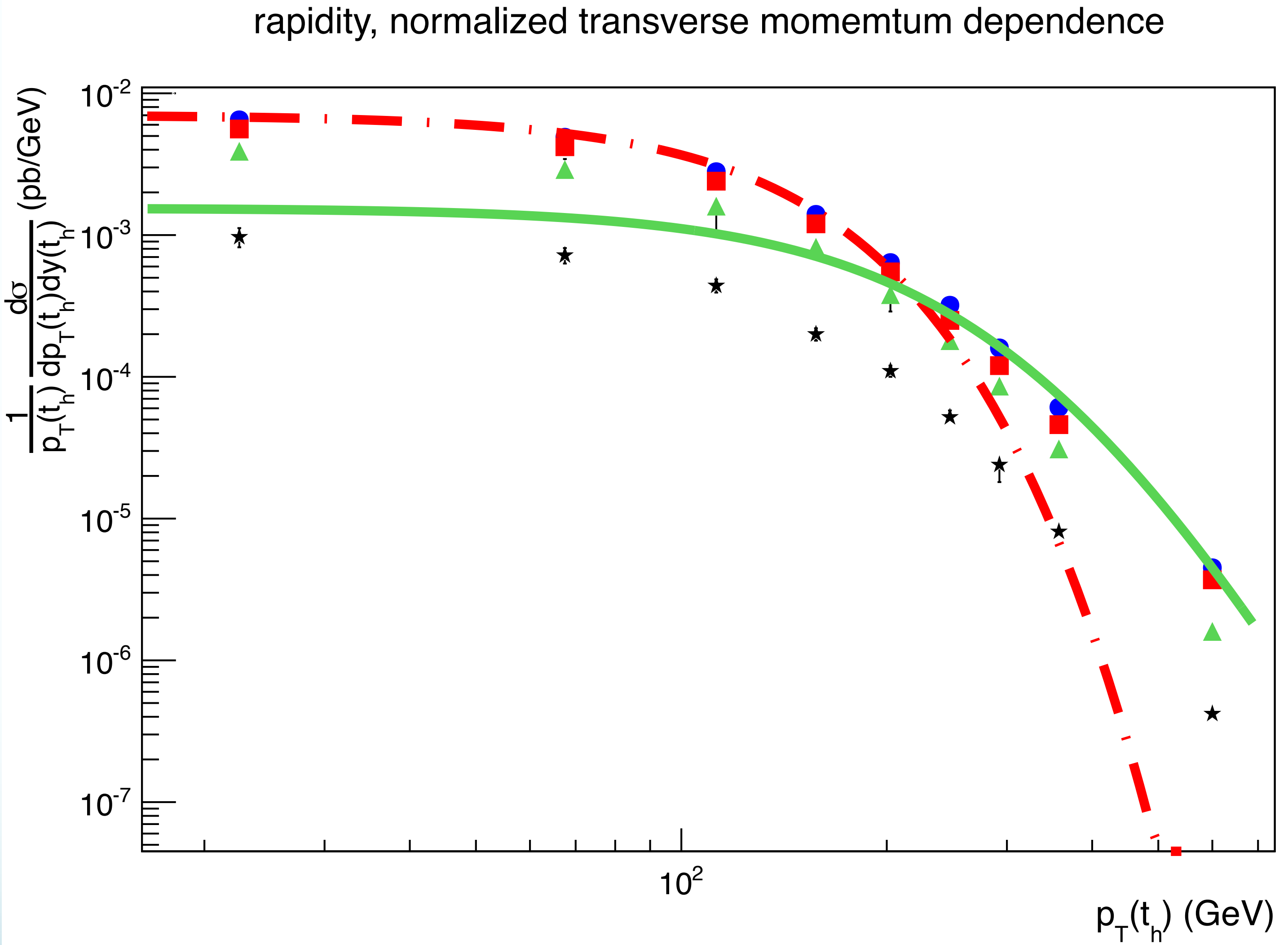
this original study

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



previous published results

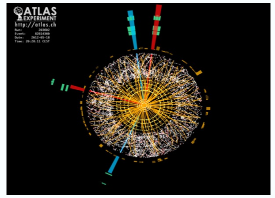
ttbar Analysis; Thermal Component Present



Normalized double differential cross section versus transverse momentum; four rapidity regions, (0.0-0.5), (0.5-1.0), (1.0-1.5), (1.5-20).

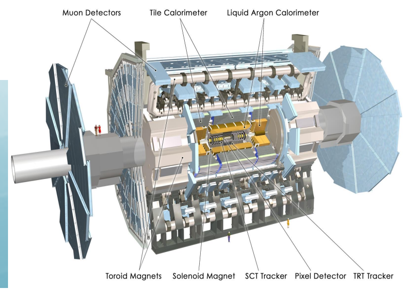
Quantum Information Science in High Energy Physics

summary



- quantum entanglement proposed as a universal phenomenon underlying the behavior of strongly interacting systems across vastly different scales
- theoretical and experimental studies of thermal radiation and entanglement in HEP collisions
  - first demonstration of this QIS related effect at highest LHC energies and in weak interactions;
  - can quantum entanglement be used to address open problems in:
    - Bell Inequality Violation?
    - hadron structure?
    - quark confinement?
    - qubit decoherence in quantum computing?

Entanglement dynamics



Additional References

“thermal radiation and entanglement in proton-proton collisions at the LHC” **Phys. Rev. D 98, 054007 (2018);** ; **arXiv:1712.04558 (2017)**) (okb, DE Kharzeev)

inaugural workshop at SBU “quantum entanglement at collider energies” (2018); https://indico.bnl.gov/event/4350/

Thermal Hadronization and Hawking-Unfuh Radidation in QCD; (P. Castorina, D. Kharzeev, H. Satz); Eur. Phys. J. C52, 187 (2007)

The origin of the thermal component in the transverse momentum spectra in high energy hadronic processes, A. A. Bylinkin, D.E. Kharzeev, A. A. Rostovtsev; Physics Archives hep-ph:arXiv:1407.4087

Current Ongoing Study:

Quantum Entanglement and Bell's Inequality Violation using Higgs → ZZ* → 4lep (e,μ)

in collaboration with
E. Gabrielli (Triest) and T. Lagouri (UTA)

still in analysis phase
initial results, but not to be shown yet