Indications of Entanglement Through Thermalization

A Study in Top Quark Pair Production at the LHC

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Quantum tests in Collider Physics

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Acknowledgments

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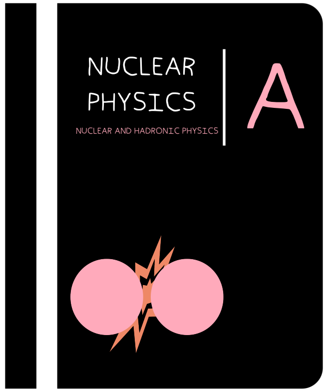
Presentation is derived from:



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Outline

Introduction

$t\bar{t}$ production

t $\bar{t}$

avy Io

Conclusion

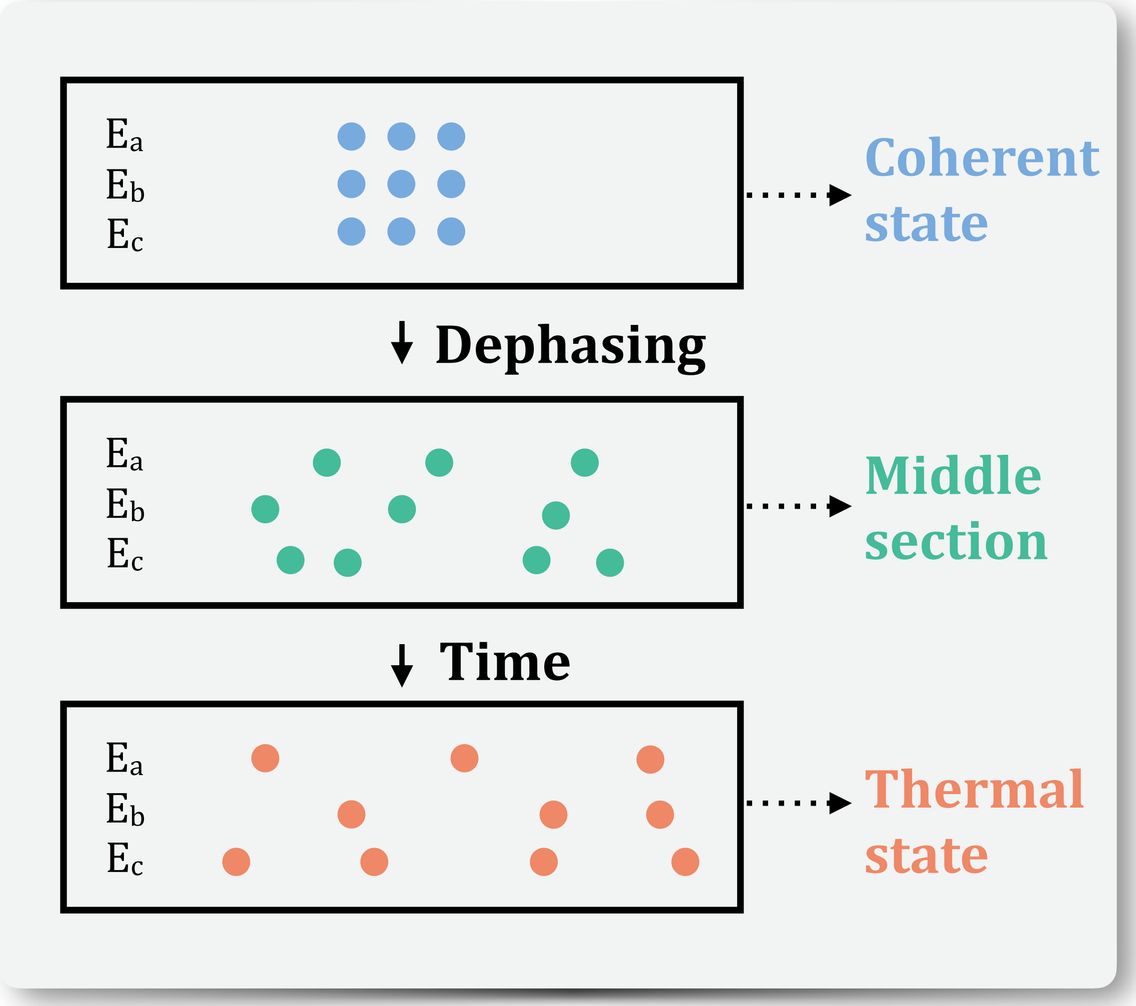
Why does the transverse momentum distribution in $t\bar{t}$ collisions have a thermal component at low p_T?

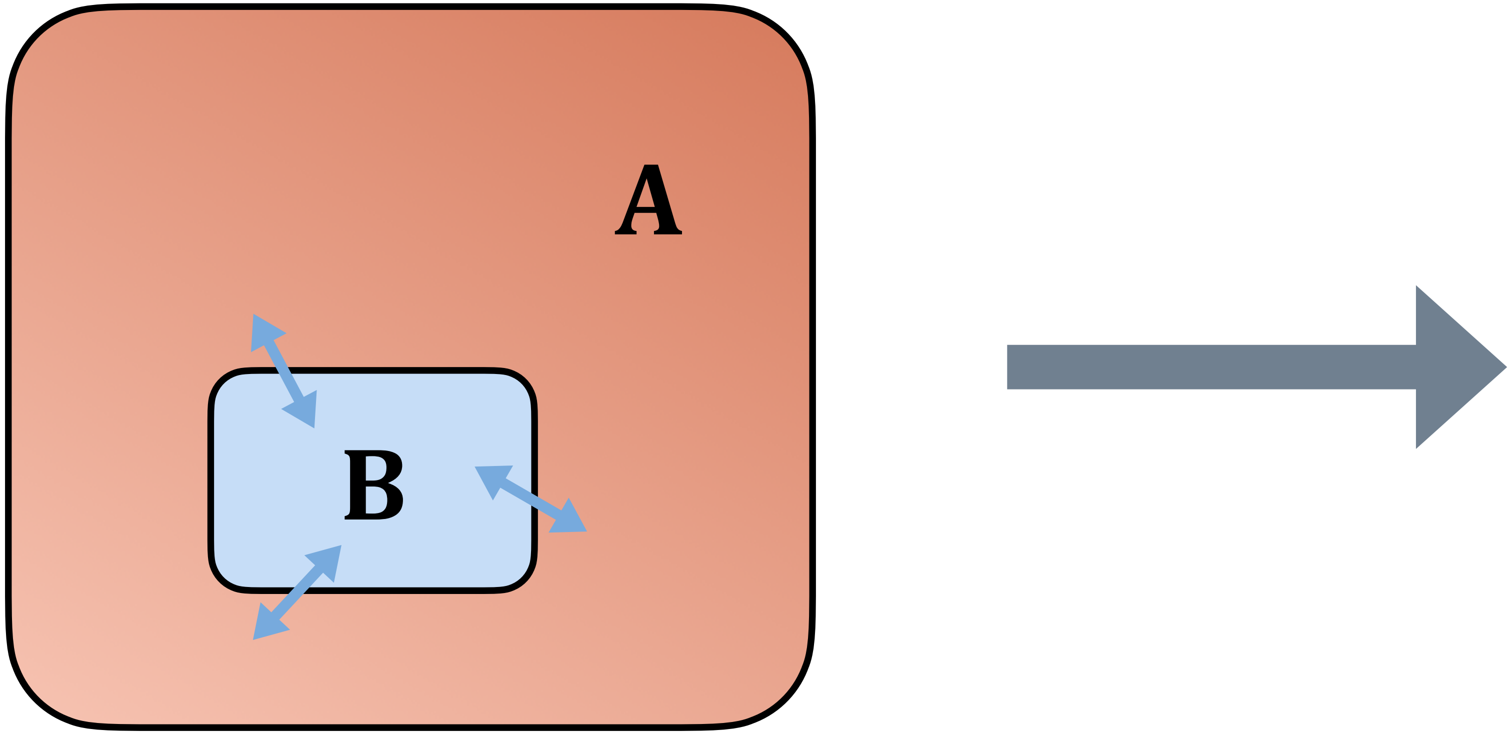
Outline

Introduction

Eigenstate Themalization Hypothesis (ETH)

- Deutsch and Srednicki
- Individual energy eigenstates exhibit thermal properties
- Thermalization w/out time averages





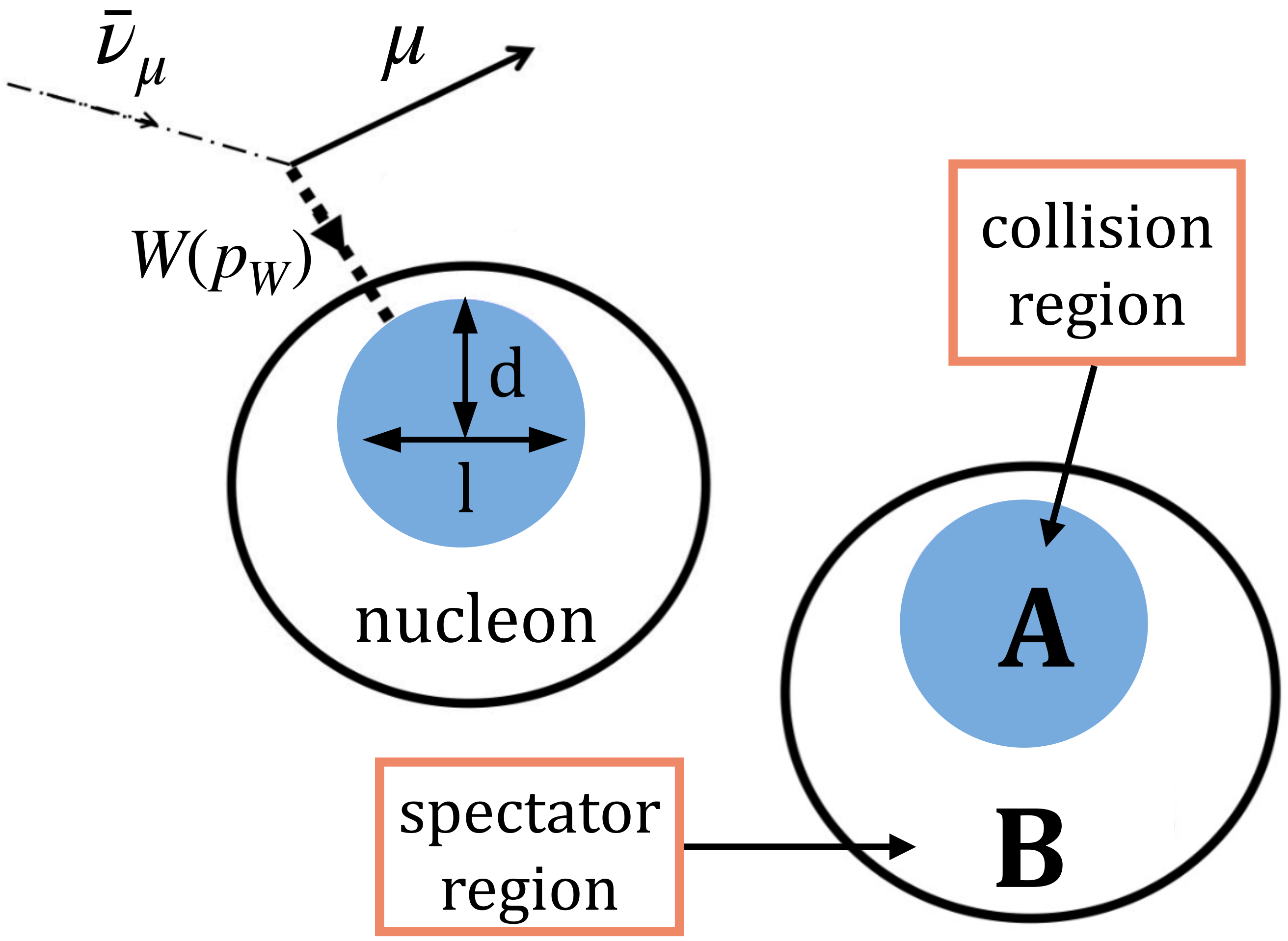
$$\rho_A(t \to \infty) \to e^{-\frac{H}{T_{eff}}}$$

Entanglement between subsystems causes the appearance of thermal behavior.

Diagram is adapted from Romain Vasseur

Neutrino Scattering (weak interaction)

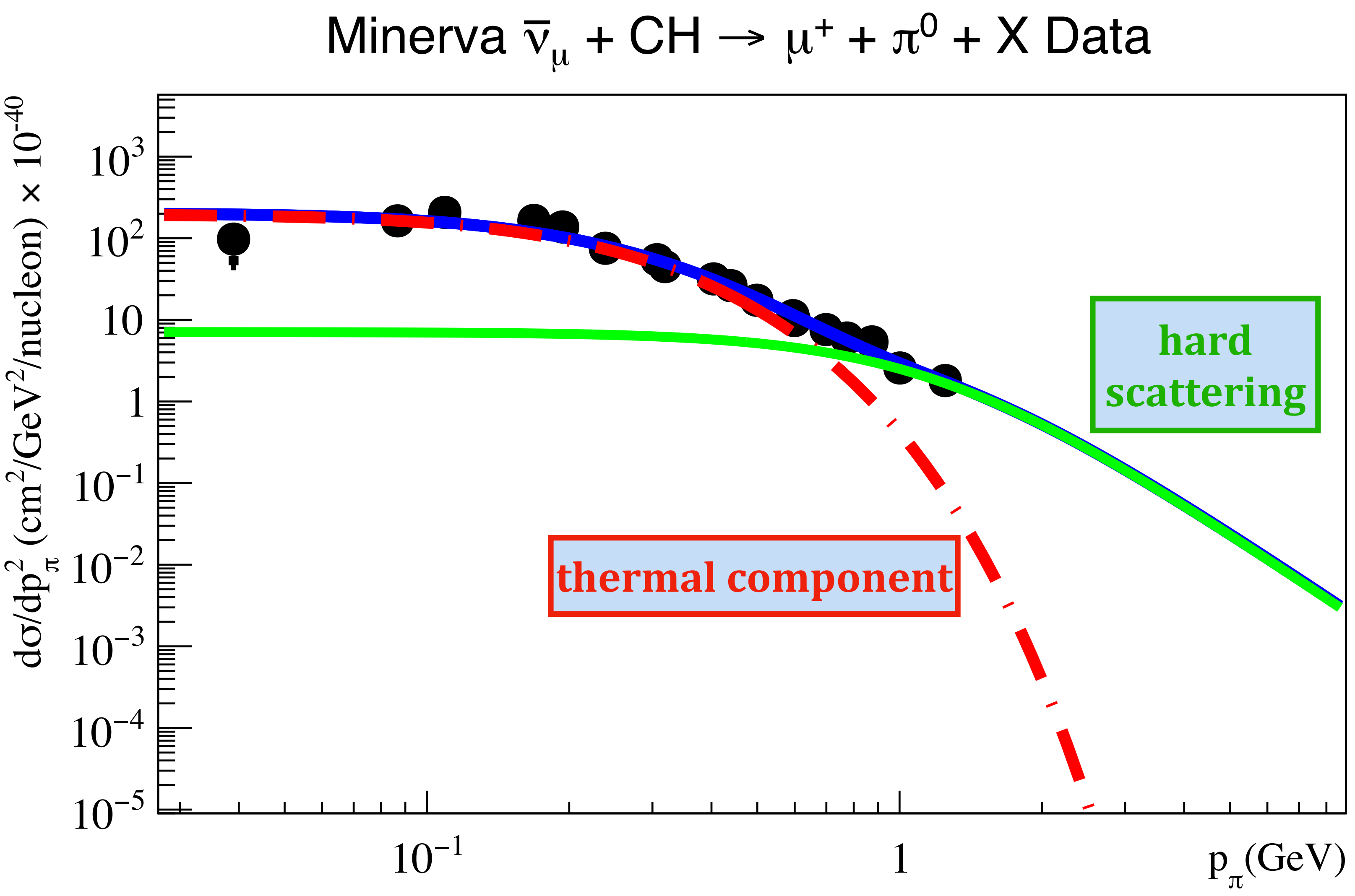
- Nucleon initially in **pure state**
- W boson only samples the region A
- l: longitudinal
- d: transverse



[Iskander, Pan, Tyler, Weber, Baker ’20]

Neutrino Scattering (entanglement)

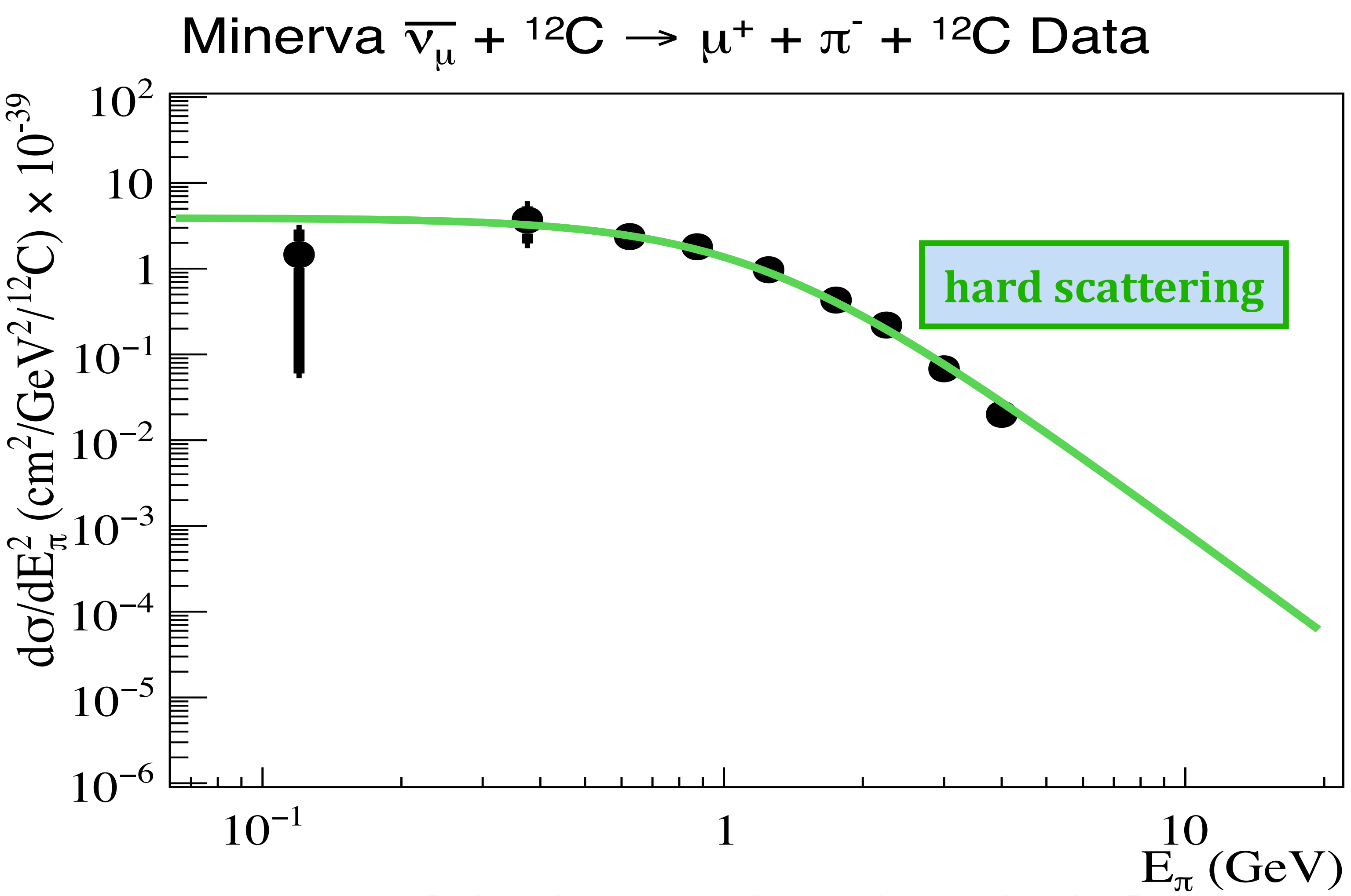
- Neutrino scattering from a nucleus (hydrocarbon)



[Iskander, Pan, Tyler, Weber, Baker ’20]

Neutrino Scattering (no entanglement)

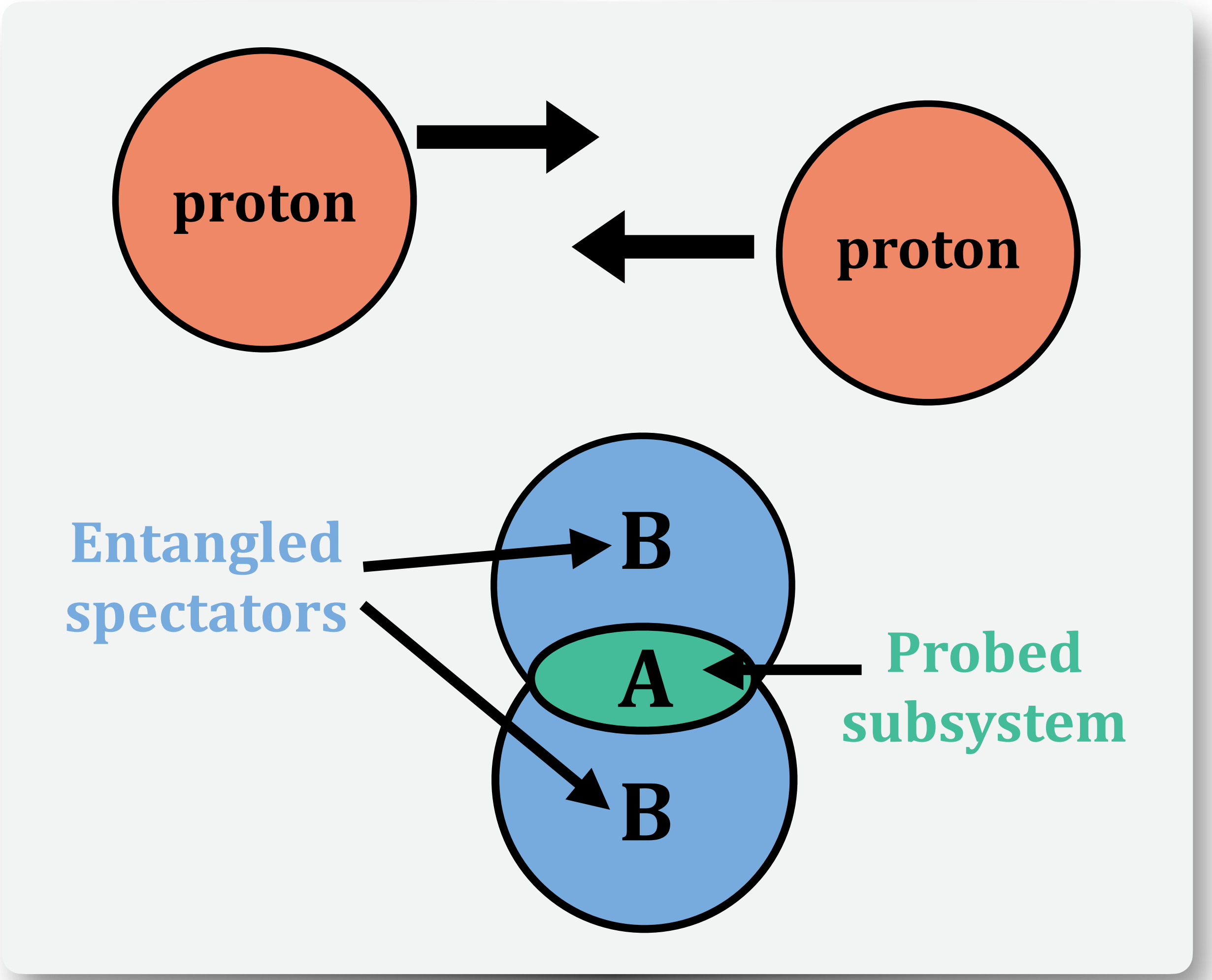
- Diffractive
- Neutrino does not break up ^{12}C
- Neutrino scatters from nucleus as a whole



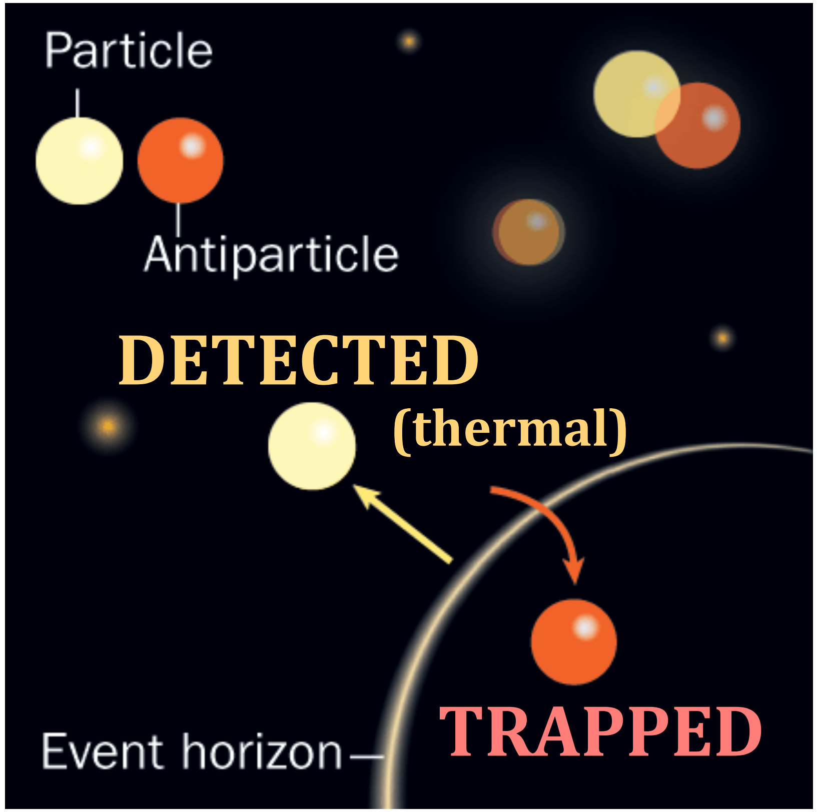
[Iskander, Pan, Tyler, Weber, Baker ’20]

Baker and Kharzeev Proposal

- Entanglement of collision & spectator regions
- Effective temperature: $T_{th} \simeq Q/(2\pi)$
- Probing subsystem reveals mixed state



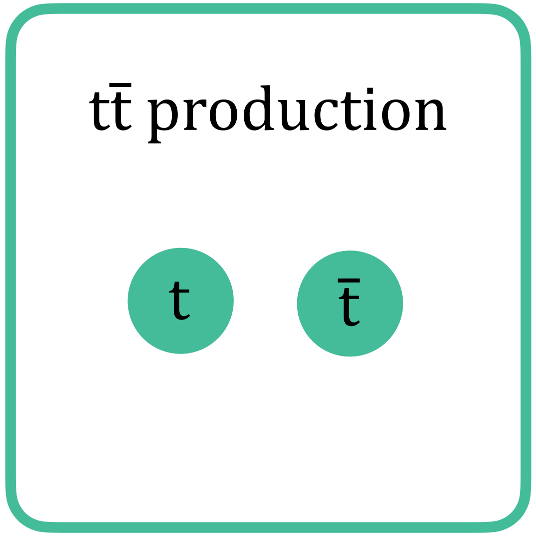
[Baker, Kharzeev '18]



When two entangled particles are at the BH event horizon, one particle escapes and one is trapped.

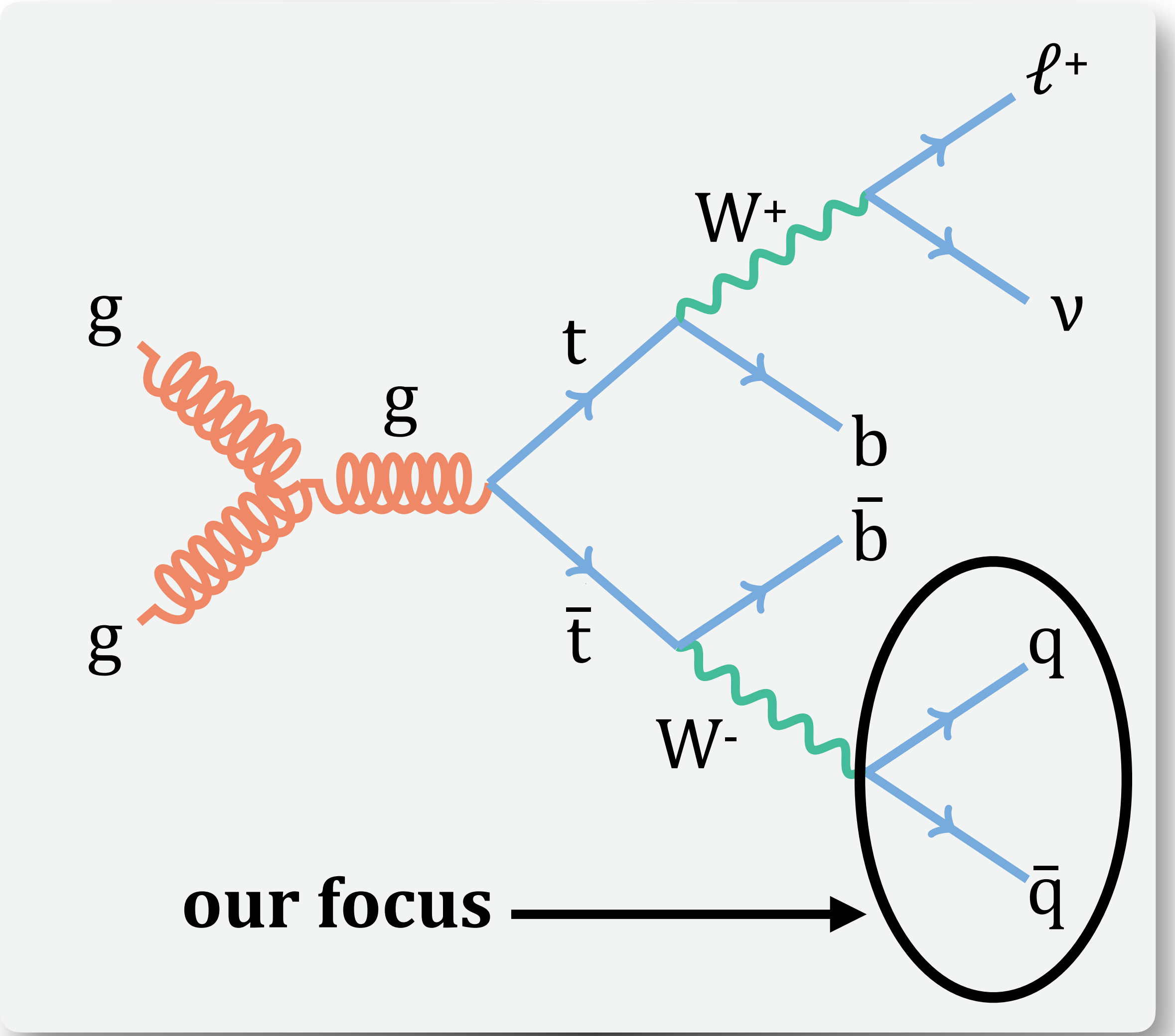
Figure is fromMekhi Dhesi

Outline



Why are top quarks interesting?

- Most massive SM particle
- Decays before hadronizing
- Probes strong interactions



Our focus

- **Transverse momentum** in top quark pairs
- Evidence of entanglement-induced **thermalization**
- Two-component model analysis

Thermal/Hard Scattering

$$\frac{d\sigma}{p_T dp_T} = A_{th} * exp(-m_T/T_{th})$$

$$m_T = \sqrt{m^2 + p_T^2}$$

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

THERMAL

A_{th} and A_{hard}: fitting parameters

n: fitting parameter

m: mass of $t\bar{t}$ pair

m_T: transverse mass

p_T: transverse momentum

$\sqrt{s}$: p-p collision energy (13 GeV)

$\sqrt{s_0}$: constant (1 GeV)

Thermal/Hard Scattering

$$\frac{d\sigma}{p_T dp_T} = A_{th} * exp(-m_T/T_{th})$$

$$m_T = \sqrt{m^2 + p_T^2}$$

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

THERMAL

$$\frac{d\sigma}{p_T dp_T} = \frac{A_{hard}}{(1 + \frac{m_T^2}{T_{hard}^2 n})^n}$$

$$T_{hard} = 0.409 \times \sqrt{(s/s_0)}^{0.06} \ \text{GeV}$$

HARD SCATTERING

A_{th} and A_{hard}: fitting parameters

n: fitting parameter

m: mass of $t\bar{t}$ pair

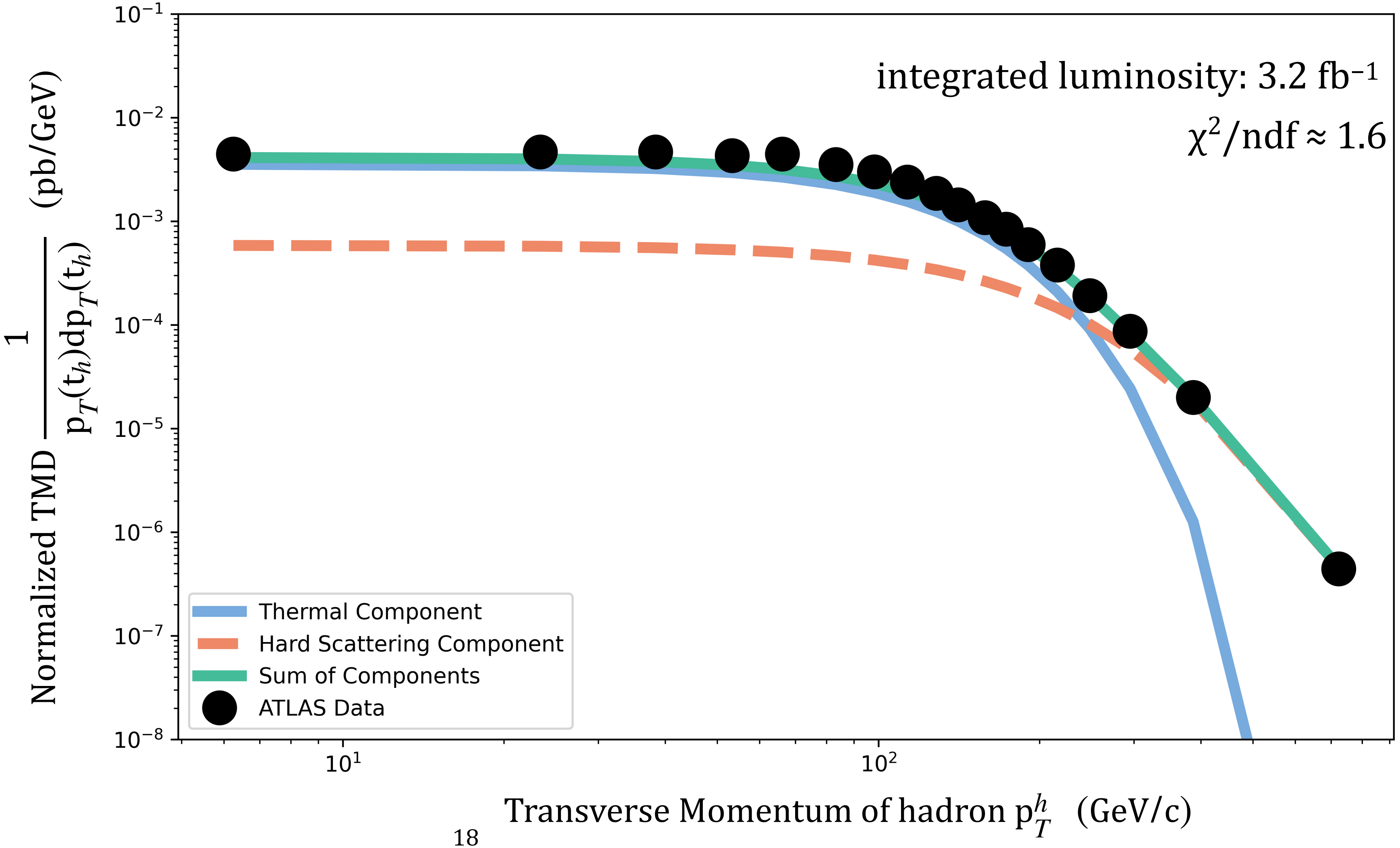
m_T: transverse mass

p_T: transverse momentum

$\sqrt{s}$: p-p collision energy (13 GeV)

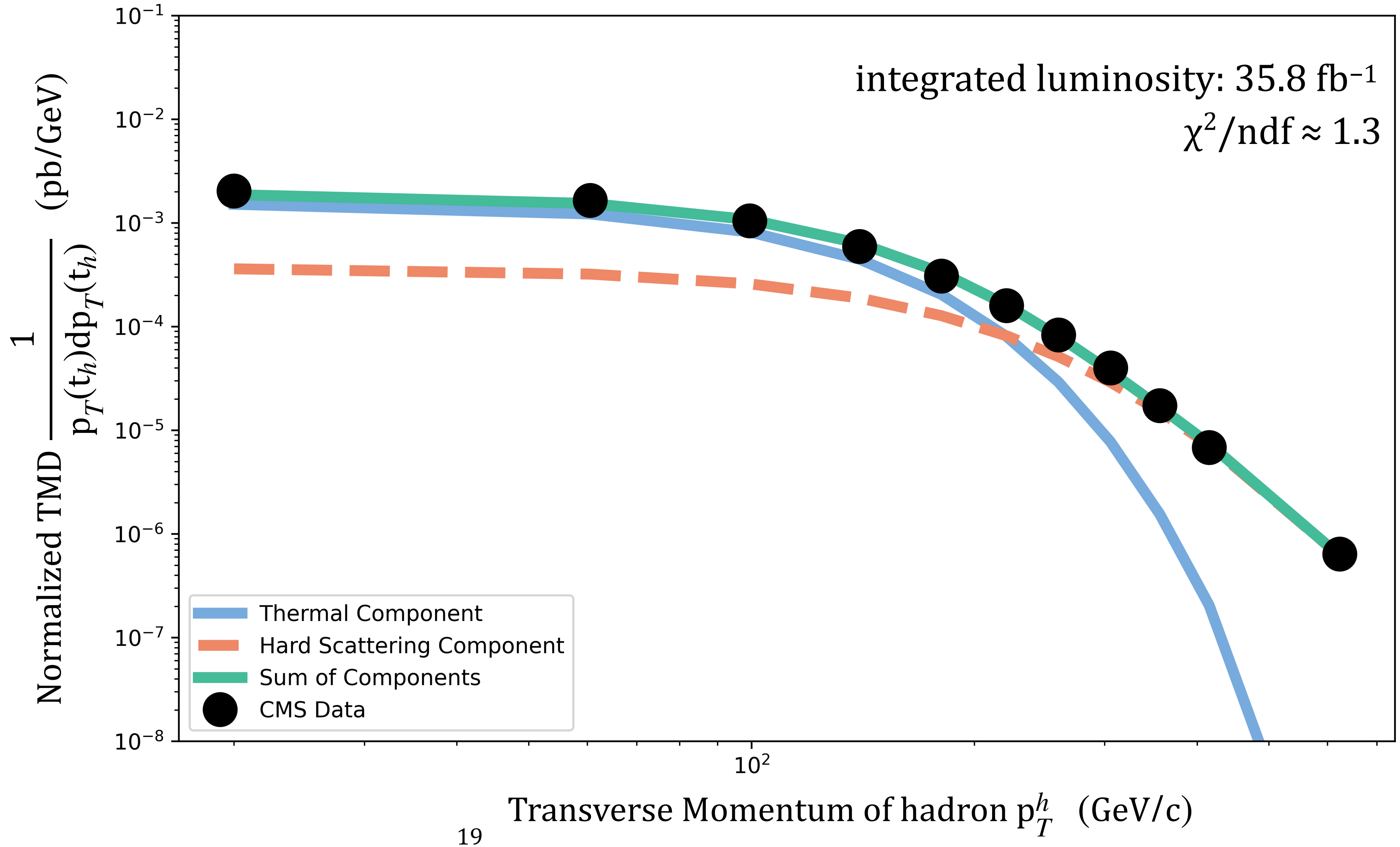
$\sqrt{s_0}$: constant (1 GeV)

TMD — ATLAS



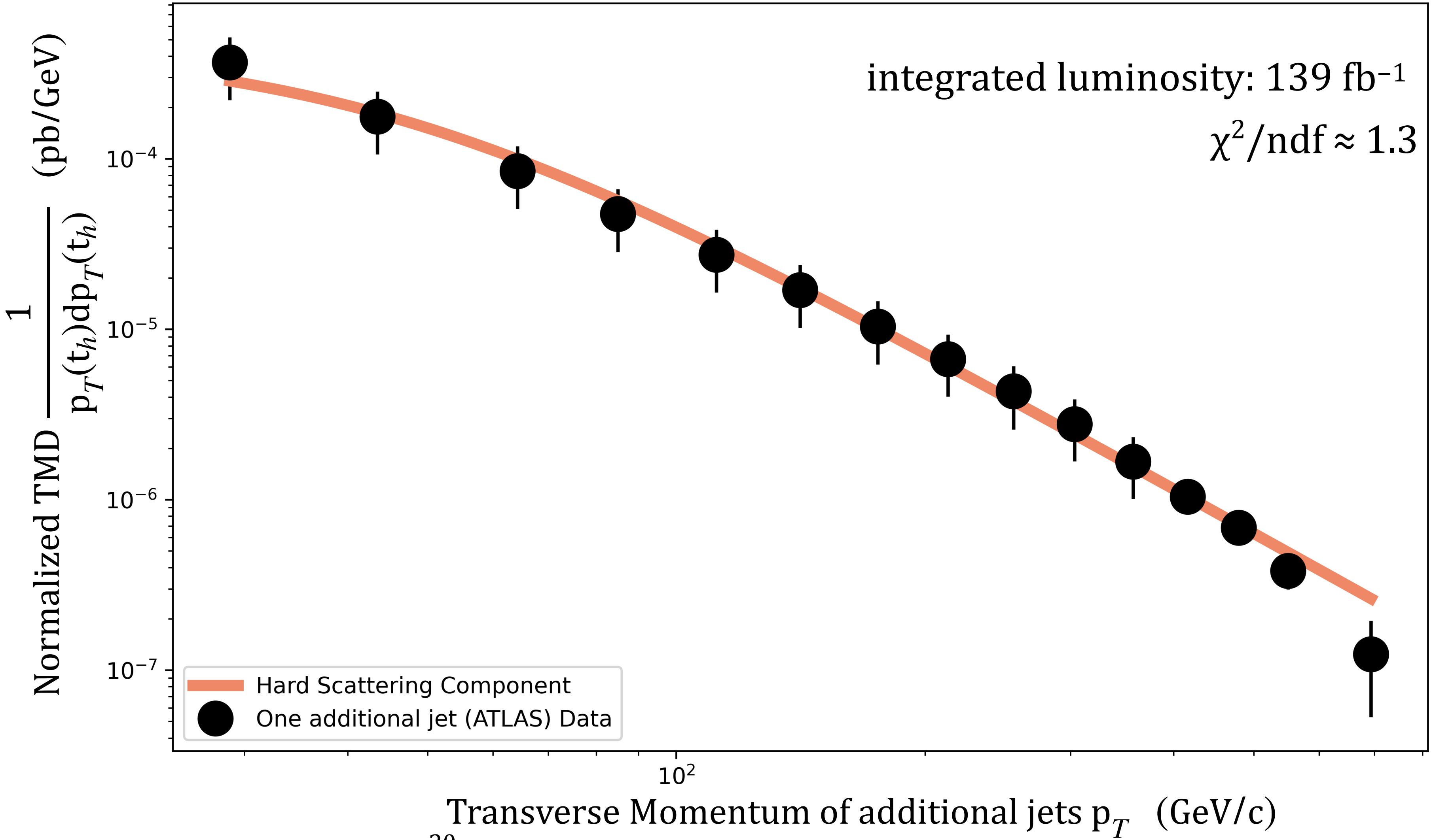
integrated luminosity: 3.2 fb⁻¹
χ^2/ndf ≈ 1.6
Normalized TMD $\frac{1}{p_T(t_h)dp_T(t_h)}$ (pb/GeV)
Transverse Momentum of hadron p_T^h (GeV/c)
Thermal Component
Hard Scattering Component
Sum of Components
ATLAS Data

TMD — CMS


integrated luminosity: 35.8 fb⁻¹
χ^2/ndf ≈ 1.3
Normalized TMD $\frac{1}{p_T(t_h)dp_T(t_h)}$ (pb/GeV)
Transverse Momentum of hadron p_T^h (GeV/c)
Thermal Component
Hard Scattering Component
Sum of Components
CMS Data
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^2

TMD — Additional Jet

- No thermal component
- Additional jet = decoherence
- Control for entanglement model

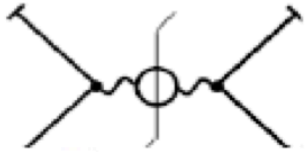
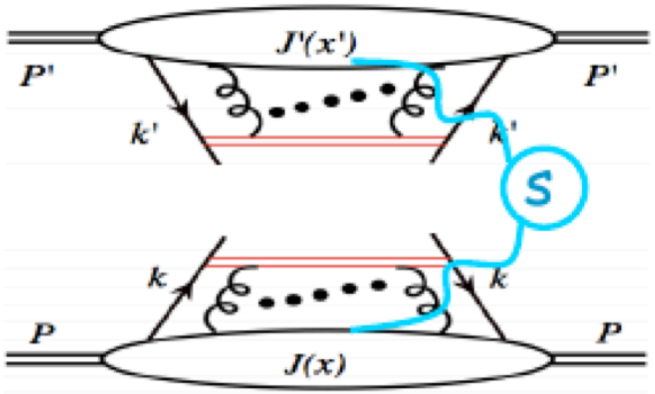


Additional Leading Jet

- Arises from **ISR** or **FSR**
  - **ISR** (**FSR**): Gluon emission from **incoming** (**outgoing**) partons **before** (**after**) hard scattering
- In literature, **ISR**/**FSR** is treated as a **perturbative** correction
- Independent of initial hard scattering that produces $t\bar{t}$ pair

Additional Leading Jet

Hard-part probe	Parton distribution	Power corrections

$\sigma^{DY}_{tot} \sim$  $\otimes$ 

$+ O\left(\frac{1}{QR}\right)$

where tt̄ pair is produced

ISR (perturbative)

FSR (perturbative)

Figure is adapted from Alberto Accardi

Implications for QE

R	Process	Reference
0.16 ± 0.05	$pp \to$ charged hadrons	[1], [2]
0.15 ± 0.05	$pp \to H \to \gamma\gamma$	[1], [2]
0.23 ± 0.05	$pp \to H \to 4l(e, \mu)$	[1], [2]
1.00 ± 0.02	$pp(\gamma\gamma) \to (\mu\mu)X'X''$	[1], [2]
0.13 ± 0.03	$\bar{\nu}_\mu + N \to \mu^+ + \pi^0 + X$	[3]
1.00 ± 0.05	$\bar{\nu}_\mu + {}^{12}C \to \mu^+ + \pi^- + {}^{12}C$	[3]
0.19 ± 0.03	$pp \to t\bar{t} \to WbWb$ (ATLAS)	current work
0.16 ± 0.03	$pp \to t\bar{t} \to WbWb$ (CMS)	current work
1.00 ± 0.05	$pp \to t\bar{t} \to WbWb \to$ jets	current work

$$R = \frac{I_p}{I_e + I_p}$$

[1] Baker, Kharzeev '18

[2] Weber, Baker, Kharzeev, '19

[3] Iskander, Pan, Tyler, Weber, Baker '20

Main Takeaways

- Entanglement $\longrightarrow$ transverse momentum dist. has a **thermal** part (in addition to **hard** component)
- Interaction independent, process dependent
- We show evidence of this for $t\bar{t}$

Key References

- O. Baker, D. Kharzeev, (2017); PRD 98, 054007 (2018)
- G. Iskander, J. Pan, M. Tyler, C. Weber, OKB Phys Lett B 811, 135948 (2020)
- M. Varma, O. Baker, Nuc. Phys A 1042, 122795 (2024)