Higher-twist dynamics in large $p_\perp$ hadron production

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Heavy Ion Forum

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Outline

- Motivations
  - Scaling laws in inclusive processes
- Data analysis
  - hadron, photon, and jet scaling properties from fixed-target to colliders
  - comparing with NLO expectations
  - interpretations
- Phenomenology
  - predictions in p p collisions at RHIC and LHC
  - heavy ion collisions

References

Brodsky, Sickles, Phys. Lett. B668 (2008) 111

FA, Brodsky, Hwang, Sickles, in preparation

Dimensional analysis

Scattering amplitude $1\ 2 \cdots \to \ldots n$ has dimension

$$\mathcal{M} \sim [\mathrm{length}]^{n-4}$$

Consequence

In a conformal theory (no intrinsic scale), scaling of inclusive particle production

$$E\ \frac{d\sigma}{d^3p}(A\ B\ \to C\ X) \sim \frac{|\mathcal{M}|^2}{s^2} = \frac{F(x_\perp, \vartheta^{\mathrm{cm}})}{p_\perp^{2n_{\mathrm{active}}-4}}$$

where n_{active} is the number of fields participating to the hard process

$x_\perp = 2p_\perp/\sqrt{s}$ and ϑ^{cm}: ratios of invariants

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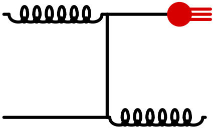
Let's take the inclusive pion production as an example...

Scaling laws in inclusive pion production

- Conventional pQCD picture (leading twist): $2 \to 2$ process followed by fragmentation into a pion on long time scales



$$n_{\mathrm{active}} = 4 \to n = 4 \; (= 2 \times 4 - 4)$$

$$E \, \frac{d\sigma}{d^3p}(p \; p \; \to \pi \; X) \sim \frac{F(x_\perp, \vartheta^{\mathrm{cm}})}{p_\perp^4}$$

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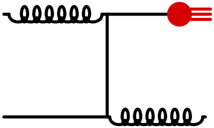

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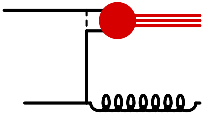
$$E\,\frac{d\sigma}{d^3p}(p\ p\ \to \pi\ X) \sim \frac{F(x_\perp, \vartheta^{\rm cm})}{p_\perp^4}$$

- Direct higher-twist picture: pion produced directly in the hard process



$$n_{\rm active} = 5 \to n = 6 \ (= 2 \times 5 - 4)$$

$$E\,\frac{d\sigma}{d^3p}(p\ p\ \to \pi\ X) \sim \frac{F'(x_\perp, \vartheta^{\rm cm})}{p_\perp^6}$$

Scaling laws in inclusive pion production

- Conventional pQCD picture (leading twist): $2 \to 2$ process followed by fragmentation into a pion on long time scales

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Remarks

- $F(x_\perp)$ falls faster than $F'(x_\perp)$ with $x_\perp$ from the larger number of spectator partons [Brodsky Burkardt Schmidt 1995]

$$F(x_\perp) \sim (1 - x_\perp)^{2n_{\rm spectator} - 1 + 2\Delta s}$$

- Higher-twist processes naturally suppressed at large $p_\perp$

Higher-twist contributions possible at high $x_\perp$ and not too large $p_\perp$

[Sivers Brodsky Blankenbecler 1975]

Scaling violations

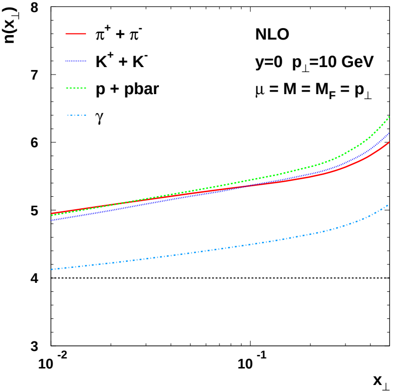
QCD is not conformal

Scaling violations expected from

- running coupling
- evolution of parton densities and fragmentation functions

Scaling exponent greater than 4 even in leading-twist QCD

Scaling violations



- Slight increase of n^h with $x_\perp$ from $n^h \simeq 5$ to 6
- Smaller exponent in the photon sector: $n^\gamma \simeq n^h - 1$
  - lesser scaling violations due to (almost) no fragmentation component
- Almost no difference between hadron species

Scaling violations

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This analysis: systematic comparison between data and NLO expectations

Data analysis

- Scaling exponent extracted by comparing $x_\perp$ spectra at two $\sqrt{s}$

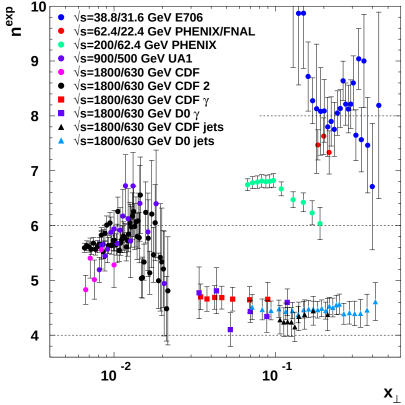
$$n^{\rm exp}(x_\perp) \equiv -\frac{\ln\left[\sigma^{\rm inv}(x_\perp, \sqrt{s_1}) / \sigma^{\rm inv}(x_\perp, \sqrt{s_2})\right]}{\ln\left(\sqrt{s_1}/\sqrt{s_2}\right)}$$

  within the same experiment in order to reduce systematic errors
- Particle production at mid-rapidity
  - hadrons (π and $h^\pm$), prompt photons, jets
- Data sets
  - most recent measurements: CDF, D0, E706, PHENIX
  - ...as well as older ISR data

Data analysis

exp.	part.	$\sqrt{s}$	$p_\perp$	$x_\perp$	N
E706	π^0	31.6 / 38.8	2 – 9	10^{-1} – 4.10^{-1}	25
PHENIX/ISR	π^0	62.4 / 22.4	2 – 7	2.10^{-2} – 2.10^{-2}	3
PHENIX	π^0	62.4 / 200	2 – 19	7.10^{-2} – 2.10^{-1}	12
UA1	$h^\pm$	500 / 900	2 – 9	8.10^{-3} – 2.10^{-2}	18
CDF	$h^\pm$	630 / 1800	2 – 9	7.10^{-3} – 10^{-2}	5
CDF	tracks	630 / 1800	2 – 19	7.10^{-3} – 2.10^{-2}	52
CDF	γ	630 / 1800	11 – 81	3.10^{-2} – 9.10^{-2}	7
D0	γ	630 / 1800	11 – 107	3.10^{-2} – 10^{-1}	6
CDF	jets	546 / 1800	29 – 190	10^{-1} – 2.10^{-1}	9
D0	jets	630 / 1800	23 – 376	8.10^{-2} – 4.10^{-1}	23

Results



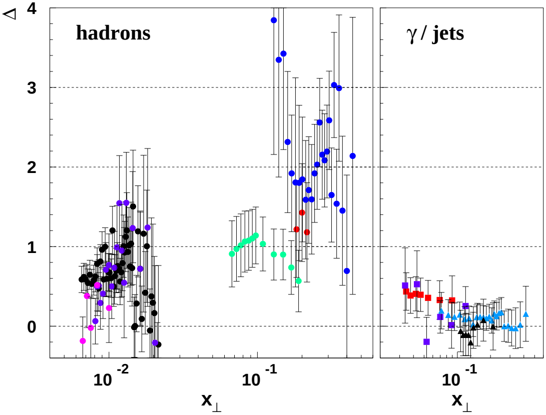
- Significant increase of the hadron n^{exp} with $x_\perp$
  - $n^{\text{exp}} \simeq 8$ at large $x_\perp$
- Huge contrast with photons and jets!
  - n^{exp} constant and slight above 4 at all $x_\perp$

ISR data

Exp.	h	$\langle x_\perp \rangle$	$n_{\rm data}$	$\langle n_{\rm exp} \rangle$
ABCS	π^0	0.34 ± 0.05	5	5.7 ± 0.7
ABCSY	π^0	0.16 ± 0.04	15	8.1 ± 0.3
ACHM	π^0	0.20 ± 0.07	75	7.0 ± 0.1
BS 73	$\pi^\pm$	0.12 ± 0.02	5	9.0 ± 0.6
BS 75	$\pi^\pm$	0.15 ± 0.03	5	7.6 ± 0.2
	$K^\pm$	0.15 ± 0.03	5	7.2 ± 0.3
	$p/\bar{p}$	0.15 ± 0.03	5	8.4 ± 0.3
CCR	π^0	0.22 ± 0.07	45	8.2 ± 0.1
CCOR	π^0	0.31 ± 0.08	27	6.2 ± 0.1
CCRS	π^0,$\pi^\pm$	0.20 ± 0.06	157	8.5 ± 0.1
CP	$\pi^\pm$	0.36 ± 0.11	11	7.6 ± 0.2
	$K^\pm$	0.36 ± 0.11	11	7.6 ± 0.3
	$p/\bar{p}$	0.35 ± 0.11	10	8.8 ± 0.2
CSZ	π^0	0.28 ± 0.05	9	6.2 ± 0.7
R806	π^0	0.23 ± 0.08	30	8.0 ± 0.2

Results compatible with older ISR data

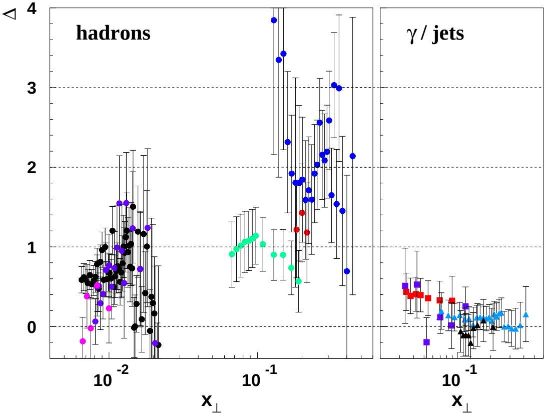
Comparing to QCD



NLO calculations carried out within the experimental kinematics ($p_\perp$, $\sqrt{s}$)

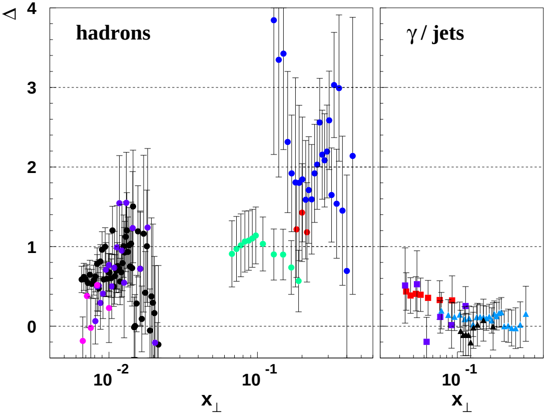
$$\Delta(x_\perp) \equiv n^{\mathrm{exp}} - n^{\mathrm{NLO}}$$

Comparing to QCD



- $\Delta^h \simeq 0.5 - 2$ from small to large $x_\perp$
- $\Delta^{\gamma/\mathrm{jets}}$ consistent with 0
- Error bars include theoretical uncertainty $\mu = p_\perp/2$ to $2p_\perp$

Comparing to QCD



Clear hierarchy

Tevatron	$x_\perp \sim 10^{-2}$	$\Delta \simeq 0.5$
RHIC	$x_\perp \sim 10^{-1}$	$\Delta \simeq 1$
fixed target	$x_\perp \sim$ few times 10^{-1}	$\Delta \simeq 2$

Interpretations

Resumation of large "threshold" logs $\ln(1 - x_\perp)$ could explain part of the data. However,

- no effects in photons/jets despite the large $x_\perp$
- data – theory discrepancy even at small $x_\perp \sim 10^{-2}$

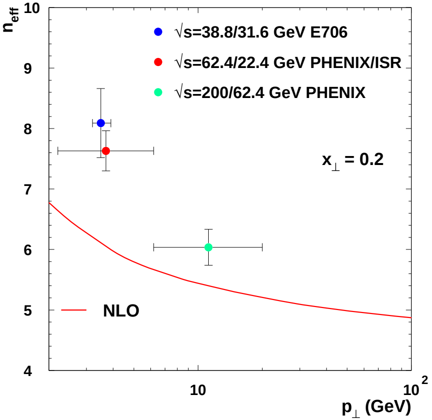
Most natural explanation

Higher-twist contributions $q\ \bar{q}\ \rightarrow g\ \pi$ and $q\ g\ \rightarrow q\ \pi$

- HT effects absent in photon and jet production
- scale dependence
- meson vs. baryon behavior

Scale dependence

Pion scaling exponent extracted vs. $p_\perp$ at fixed $x_\perp$



- QCD slowly approaches $n = 4$ in the Bjorken limit ($s \to \infty$, fixed $x_\perp$)
- data – theory discrepancy larger at smaller $p_\perp$

Scale dependence

Pion scaling exponent extracted vs. $p_\perp$ at fixed $x_\perp$

2-component toy-model

$$\sigma^{\rm model}(pp \to \pi\ {\rm X}) \propto \frac{A(x_\perp)}{p_\perp^4} + \frac{B(x_\perp)}{p_\perp^6}$$

Define effective exponent

$$\begin{aligned} n_{\rm eff}(x_\perp, p_\perp, B/A) &\equiv -\frac{\partial \ln \sigma^{\rm model}}{\partial \ln p_\perp} + n^{\rm NLO}(x_\perp, p_\perp) - 4 \\ &= \frac{2B/A}{p_\perp^2 + B/A} + n^{\rm NLO}(x_\perp, p_\perp) \end{aligned}$$

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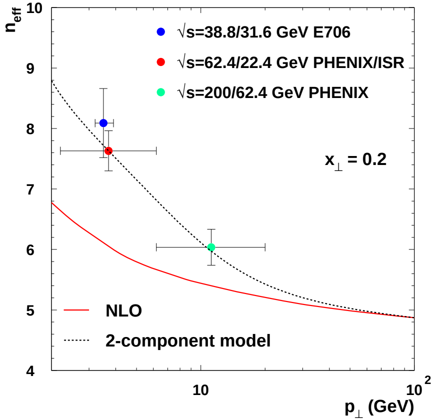
Limits

$$n_{\rm eff}(x_\perp, p_\perp) = n^{\rm NLO}(x_\perp, p_\perp) \qquad \text{for } B \ll A \times p_\perp^2$$

$$n_{\rm eff}(x_\perp, p_\perp) = n^{\rm NLO}(x_\perp, p_\perp) + 2 \qquad \text{for } B \gg A \times p_\perp^2$$

Scale dependence

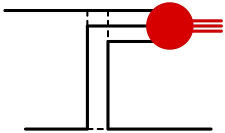


- Fit gives $[B(x_\perp)/A(x_\perp)]^{1/2} \simeq 4 - 7$ GeV
- Significantly reduced because of trigger bias effect
  - $[B(x_\perp)/A(x_\perp)]^{1/2} \simeq 1$ GeV

Baryon vs. meson production

Which scaling behavior for higher-twist baryon production?

Take for instance proton production



$n_{\mathrm{active}} = 6$

$$E\,\frac{d\sigma}{d^3p}(p\;p\;\rightarrow p\;X) \sim \frac{F(x_\perp, \vartheta^{\mathrm{cm}})}{p_\perp^8}$$

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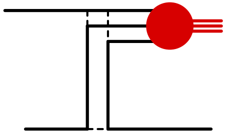

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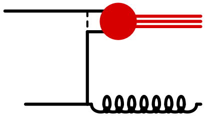
... which contrasts with pion scaling exponents



$n_{\mathrm{active}} = 5$

$$E\,\frac{d\sigma}{d^3p}(p\ p\ \to \pi\ X) \sim \frac{F'(x_\perp, \vartheta^{\mathrm{cm}})}{p_\perp^6}$$

Baryon vs. meson production

Protons minus pions results

	$n^p - n^\pi$
QCD NLO	$\simeq 0$
Higher-twist picture	$\simeq 2$
Experiment (ISR)	$\simeq 1$

Results consistent with a mixture of LT and HT "direct" components

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Hadrochemistry as a useful probe of production dynamics at large $p_\perp$

Need for good hadron identification capabilities (π, K, p) at the LHC !

RHIC/LHC predictions

Global fit

$n^{\mathrm{fit}}(x_\perp, p_\perp)$ extracted from a fit to Tevatron, PHENIX, and E706 data

$$n^{\mathrm{fit}}(x_\perp, p_\perp) = 4 + p_1 \, (-\log x_\perp)^{p_2} \, / \, (\log(p_\perp/\Lambda))^{p_3}$$

$$\delta n^{\mathrm{fit}} = \left[\sum_{i,j=0}^{3} \frac{\partial n^{\mathrm{fit}}}{\partial p_i} \delta p_i \times V_{ij} \times \frac{\partial n^{\mathrm{fit}}}{\partial p_j} \delta p_j \right]^{1/2}$$

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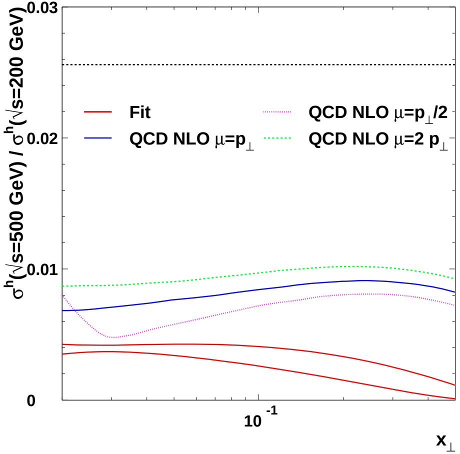
Predictions at RHIC and LHC

$$R_{\sqrt{s_1}/\sqrt{s_2}}(x_\perp) \equiv \left(\sqrt{s_2}/\sqrt{s_1}\right)^{n^{\rm fit}(x_\perp, p_\perp = x_\perp \sqrt{s}/2)}$$

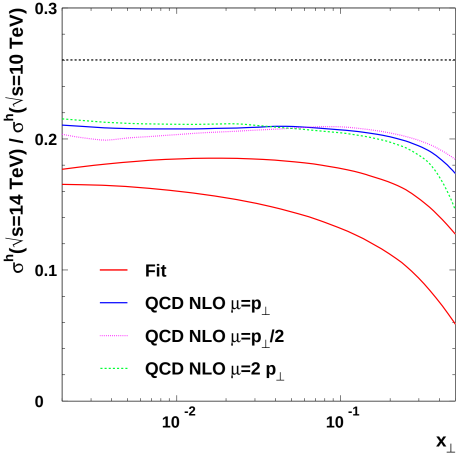
	$\sqrt{s_1}$	$\sqrt{s_2}$
RHIC	500 GeV	200 GeV
LHC	14 TeV	10 TeV

RHIC/LHC predictions



- Ratio well below the conformal limit expectation, even within NLO
- Possible breakdown of NLO visible between 200 and 500 GeV

RHIC/LHC predictions



- Differences also expected at the LHC
- Still preliminary!

Isolated hadrons

Leading twist

Hadrons accompanied by a significant hadronic activity $\Rightarrow$ inside jets

Higher twist

Color-singlet produced in the hard process $\Rightarrow$ “isolated” hadrons

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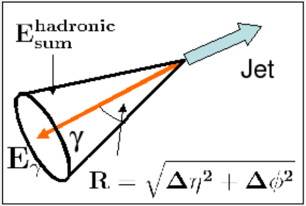
Idea: use isolation criteria to filter the leading twist component

$$E_\perp^{\mathrm{had}} \leq E_\perp^{\mathrm{max}} = \varepsilon\ p_\perp^h$$

for particles inside a cone

$$(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R^2$$



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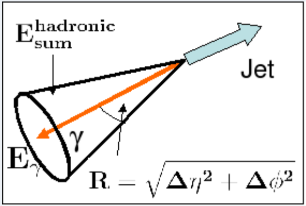


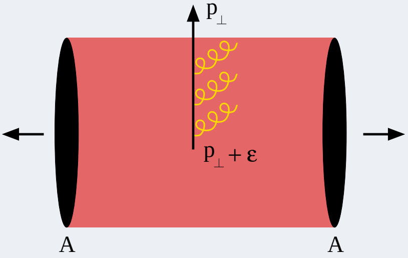
Consequence

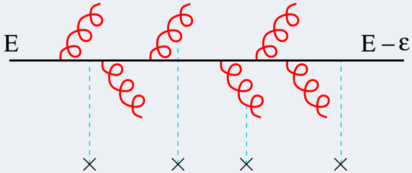
Enhanced scaling exponent for isolated hadrons

$$n^h_{\rm isolated} > n^h_{\rm inclusive}$$

Heavy ion collisions

Jet quenching picture

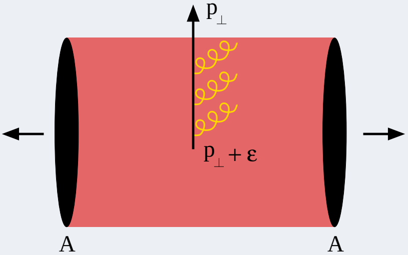


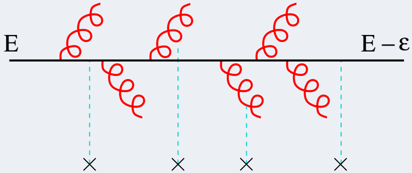


Multiple scattering and energy loss of a colored parton in the dense QCD medium leading to a depletion of high $p_\perp$ hadrons

[Bjorken 82; Gyulassy, Wang 92]

Jet quenching picture





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[Bjorken 82; Gyulassy, Wang 92]

What happens at higher twist?

Heavy ion collisions

- Dense medium acts as a filter of leading-twist components because of energy loss processes
- Only color-singlet compact configurations are able to go through the medium because of color transparency (small configurations $r \sim p_{\perp}^{-1}$)

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Picture

- Mixture of leading twist and higher twist contributions in p p collisions

$$n^{\rm NLO} < n^{\rm exp} < n^{\rm HT}$$

- Higher twist "rich" sample in central A A collisions

$$n^{\rm exp} \simeq n^{\rm HT}$$

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$$n^{\mathrm{NLO}} < n^{\mathrm{exp}} < n^{\mathrm{HT}}$$

- Higher twist "rich" sample in central A A collisions

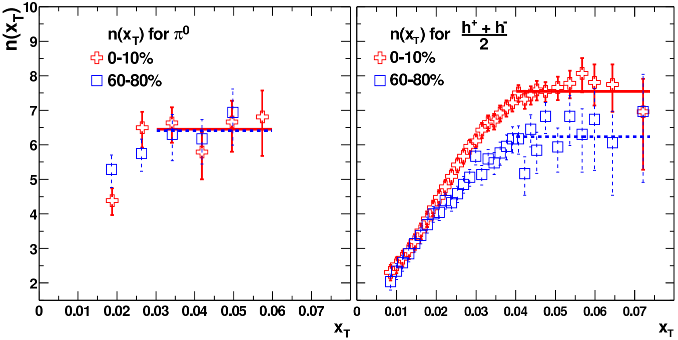
$$n^{\mathrm{exp}} \simeq n^{\mathrm{HT}}$$

Consequence

Smooth increase of n^{exp} from peripheral to central collisions

[Brodsky, Sickles 2008]

Centrality dependence of scaling exponent



- Seen experimentally for charged hadrons (i.e. including protons)
  - $n^{\text{central}} - n^{\text{periph}} \simeq 2$

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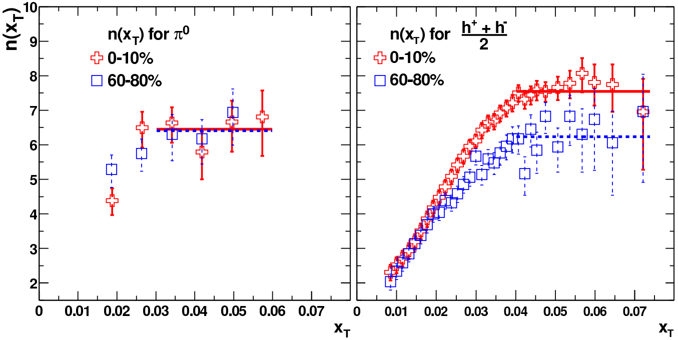
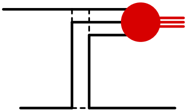


- Seen experimentally for charged hadrons (i.e. including protons)
  - $n^{\rm central} - n^{\rm periph} \simeq 2$
- Why is this not seen for pions?
  - smaller HT contribution in pions than in protons at large $x_\perp$

HT contribution to meson vs. baryon

Proton production cross section :

$$u\ d\ \rightarrow ud \qquad n_{\text{spectator}} = 6 \quad \Rightarrow \quad 2n_{\text{spectator}} - 1 = 11$$
$$u\ d\ \rightarrow (uud)\bar{u} \qquad n_{\text{spectator}} = 4 \quad \Rightarrow \quad 2n_{\text{spectator}} - 1 = 7$$



$$E\,\frac{d\sigma}{d^3p}(p\,p\ \rightarrow p\,X) \sim A\,\frac{(1-x_{\perp})^{11}}{p_{\perp}^4} + B\,\frac{(1-x_{\perp})^{7}}{p_{\perp}^8}$$

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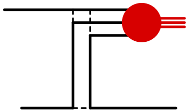

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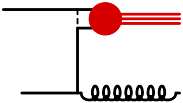
Pion production cross section

$$u\ d\ \rightarrow ud \qquad n_{\rm spectator} = 5 \quad \Rightarrow \quad 2n_{\rm spectator} - 1 = 9$$
$$u\ \bar{d}\ \rightarrow (u\bar{d})g \qquad n_{\rm spectator} = 5 \quad \Rightarrow \quad 2n_{\rm spectator} - 1 = 9$$



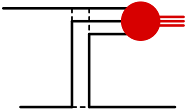
$$E\,\frac{d\sigma}{d^3p}(p\,p\ \rightarrow \pi\,X) \sim A\ \frac{(1-x_\perp)^{9}}{p_\perp^4} + B\ \frac{(1-x_\perp)^9}{p_\perp^6}$$

HT contribution to meson vs. baryon

Proton production cross section :

$$u\ d \to ud \qquad n_{\text{spectator}} = 6 \quad \Rightarrow \quad 2n_{\text{spectator}} - 1 = 11$$

$$u\ d \to (uud)\bar{u} \qquad n_{\text{spectator}} = 4 \quad \Rightarrow \quad 2n_{\text{spectator}} - 1 = 7$$

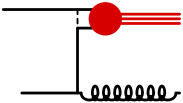


$$E\,\frac{d\sigma}{d^3p}(p\,p \to p\,X) \sim A\,\frac{(1-x_\perp)^{11}}{p_\perp^4} + B\,\frac{(1-x_\perp)^{7}}{p_\perp^8}$$

Pion production cross section

$$u\ d \to ud \qquad n_{\text{spectator}} = 5 \quad \Rightarrow \quad 2n_{\text{spectator}} - 1 = 9$$

$$u\ \bar{d} \to (u\bar{d})g \qquad n_{\text{spectator}} = 5 \quad \Rightarrow \quad 2n_{\text{spectator}} - 1 = 9$$

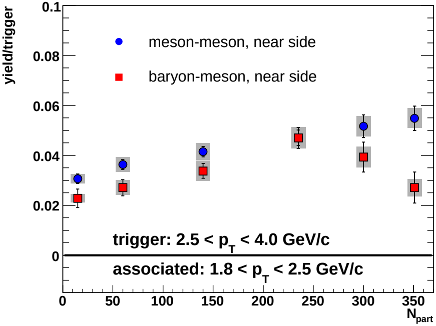


$$E\,\frac{d\sigma}{d^3p}(p\,p \to \pi\,X) \sim A\,\frac{(1-x_\perp)^{9}}{p_\perp^4} + B\,\frac{(1-x_\perp)^{9}}{p_\perp^6}$$

HT contribution larger for baryons than for mesons at large $x_\perp$!

Associated multiplicity

Different behavior of same-side correlations using pion and proton triggers



- pion trigger: linear increase of the multiplicity with centrality ($N_{\rm part}$)
  - enhanced production due to medium-induced radiation (?)
- proton trigger: decrease with centrality in most central collisions
  - direct proton production without associated particle production

Proton over pion suppression

Most challenging observation at RHIC

Protons less suppressed than pions in Au Au collisions

Parton energy loss leads to :

- stronger suppression for gluon jets than for quark jets
- stronger suppression for softer (i.e. steeper) fragmentation functions

$\Rightarrow$ larger suppression in the proton channel than in the pion chanel

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Qualitative explanation

- Proton production
  - LT component suppressed due to energy loss
  - HT component not suppressed (color transparency)
- Pion production
  - LT component suppressed due to energy loss
  - HT component not suppressed but smaller than for baryons

$$R^{p}_{\mathrm{AA}} > R^{\pi}_{\mathrm{AA}}$$

Summary

- Scaling laws
  - powerful probe of hadron production dynamics
- Analysis
  - exponents systematically extracted from hadron, photon and jet data
  - significant discrepancy in the hadron sector, esp. at large $x_\perp$
  - supports a non-negligible higher-twist contribution in large $p_\perp$ hadron production (first seen at ISR)
- Phenomenology
  - ratio of $x_\perp$ spectra predicted in p p collisions at RHIC and LHC
  - possible breakdown of NLO QCD could also be seen at these energies
  - heavy-ion collisions : qualitative explanation of several features of RHIC data due to color transparency