Comparison of Inclusive Jet Cross Sections with Single Particle Inclusive Production

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Remembrance of Things Past
Compare π^0s at FNAL with Jets at LHC

FNAL E63 @ C0
1974

INCLUSIVE π^0 PRODUCTION BY HIGH-ENERGY PROTONS

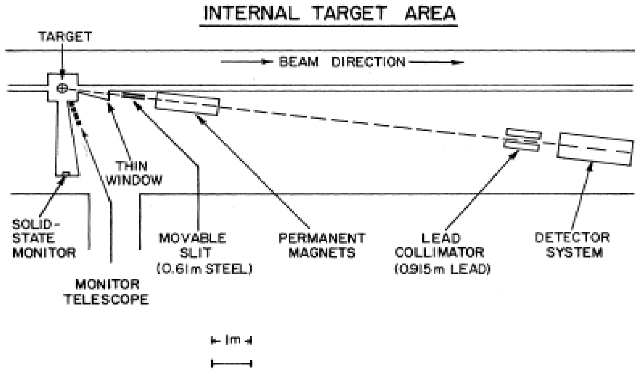


FIG. 1. Typical layout of the experimental apparatus.

14 INCLUSIVE π^0 PRODUCTION BY HIGH-ENERGY PROTONS 1215

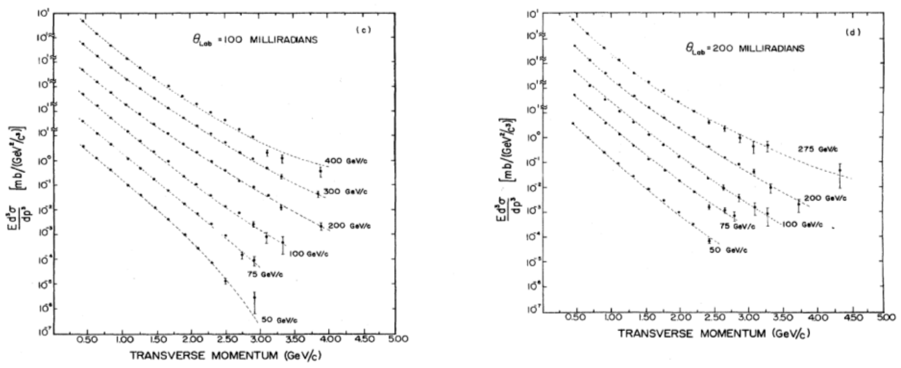
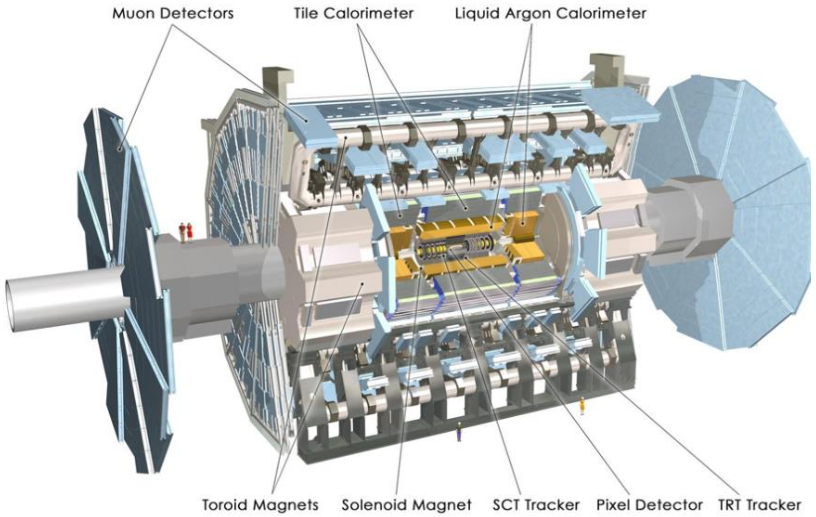
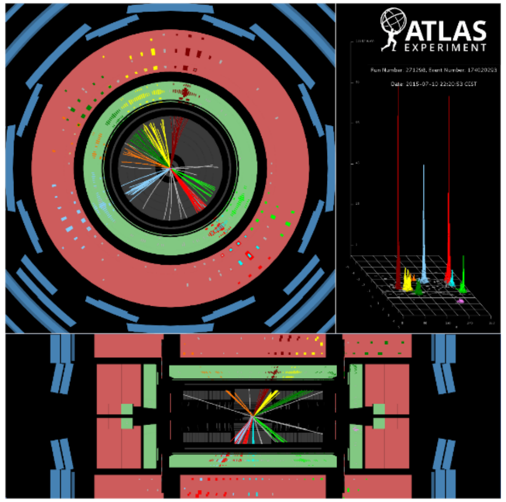
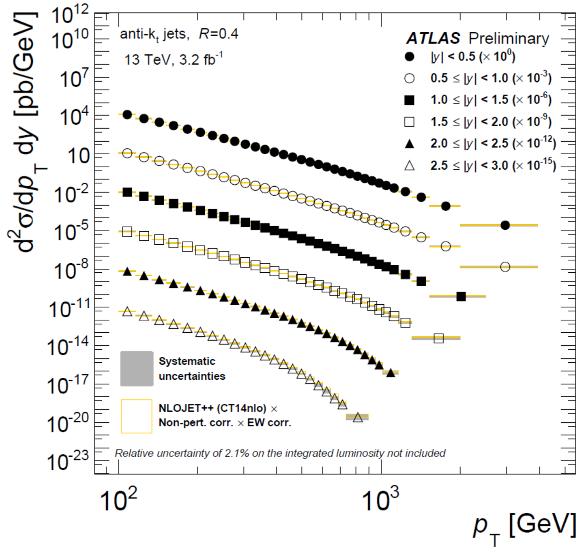


FIG. 10. π^0 invariant cross sections as a function of transverse momentum for various incident proton beam momenta, at laboratory angles (a) 30 mrad, (b) 65 mrad, (c) 100 mrad, and (d) 200 mrad.

LHC ATLAS @ Point 1





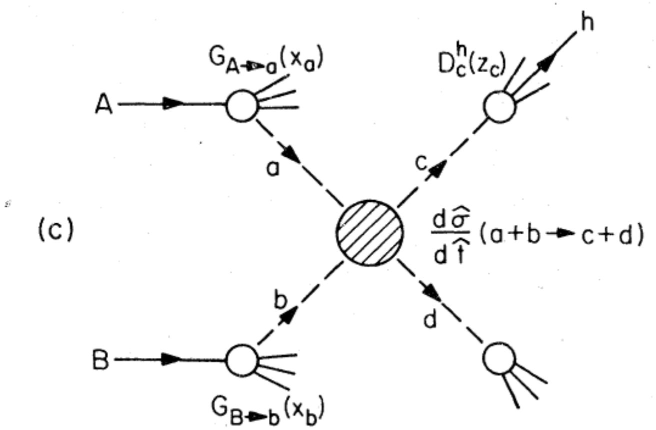


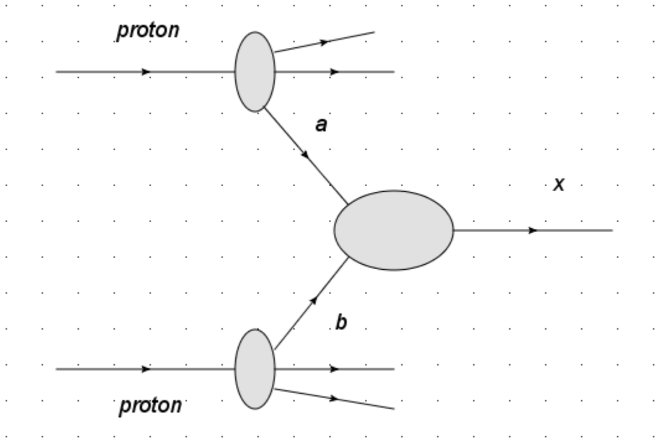
Single Particle Inclusive & Jet Inclusive Production

Particles: h

Jets: X

LO Dimension





$$E\frac{d^3\sigma}{dp^3} \sim \frac{d^2\sigma}{dp_T^2\,dy} \sim \frac{d\hat{\sigma}_{ab}\left(\alpha_s(\mu_R^2), s/\mu_R^2, s/\mu_F^2\right)}{d\hat{t}}$$

$$\sim \frac{cm^2}{GeV^2} \sim \frac{1}{GeV^4}$$

2 → 2 scattering

~ $1/GeV^6$ for 2 → 3 scattering

Particles: h

$$Ed\sigma/d^3p(s,t,u;A+B\to h+X) = \int_{x_a^{min}}^{1} dx_a \int_{x_b^{min}}^{1} dx_b\, G_{A\to a}(x_a) G_{B\to b}(x_b) D_c^h(z_c) \frac{1}{z_c}\frac{1}{\pi}\frac{d\hat{\sigma}}{d\hat{t}}(\hat{s},\hat{t};q_a+q_b\to q_a'+q_b')$$

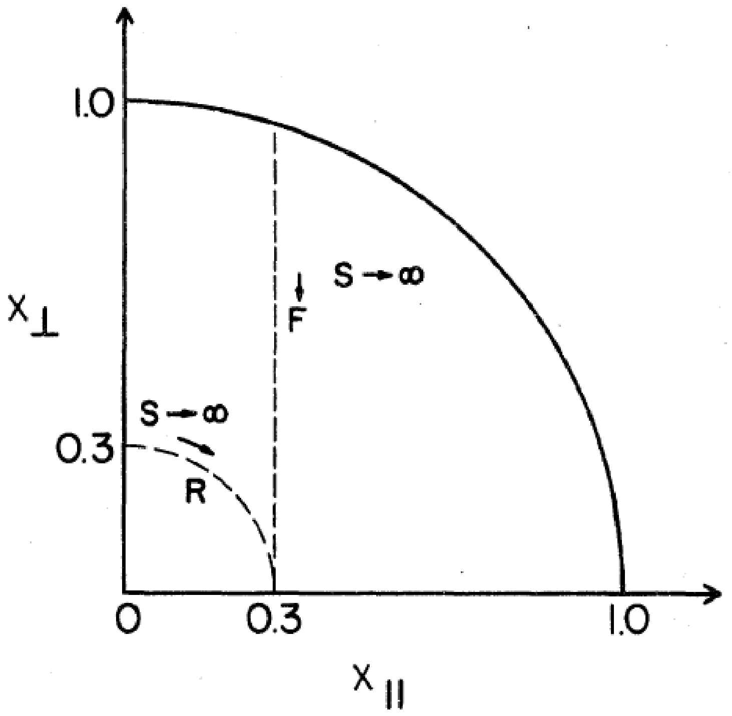
F, F & F

Jets: X

$$E\frac{d^3\sigma}{dp^3} = \sum_{a,b}\int dx_1 dx_2\, f_a(x_1,\mu_F^2)\, f_b(x_2,\mu_F^2)\frac{d\hat{\sigma}_{ab}\left(\alpha_s(\mu_R^2), s/\mu_R^2, s/\mu_F^2\right)}{d\hat{t}} \otimes Frag \otimes Had$$

QCD Factorization Theorem

P_T & "Other" Variable: Rapidity & Radial X_R



x_R is a "final state" scaling variable that controls kinematic boundary suppression that is not respected by $x_{||}$ and x_T .

Rapidity and pseudo rapidity:

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \approx \eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Radial scaling x_R:

$$x_R = \frac{E}{E_{\max}} = \frac{2\sqrt{\left(p_T^2\cosh^2(y)(1+(m_J^2/p_T^2)\tanh^2(y))+m_J^2\right)}}{\sqrt{s-m_{QN}^2}}$$

$$\approx \frac{2p_T\cosh(y)}{\sqrt{s}}\sqrt{\left(1+\frac{m_J^2}{p_T^2}\tanh^2(y)\right)}$$

$$\approx \frac{2p_T\cosh(\eta)}{\sqrt{s}}$$

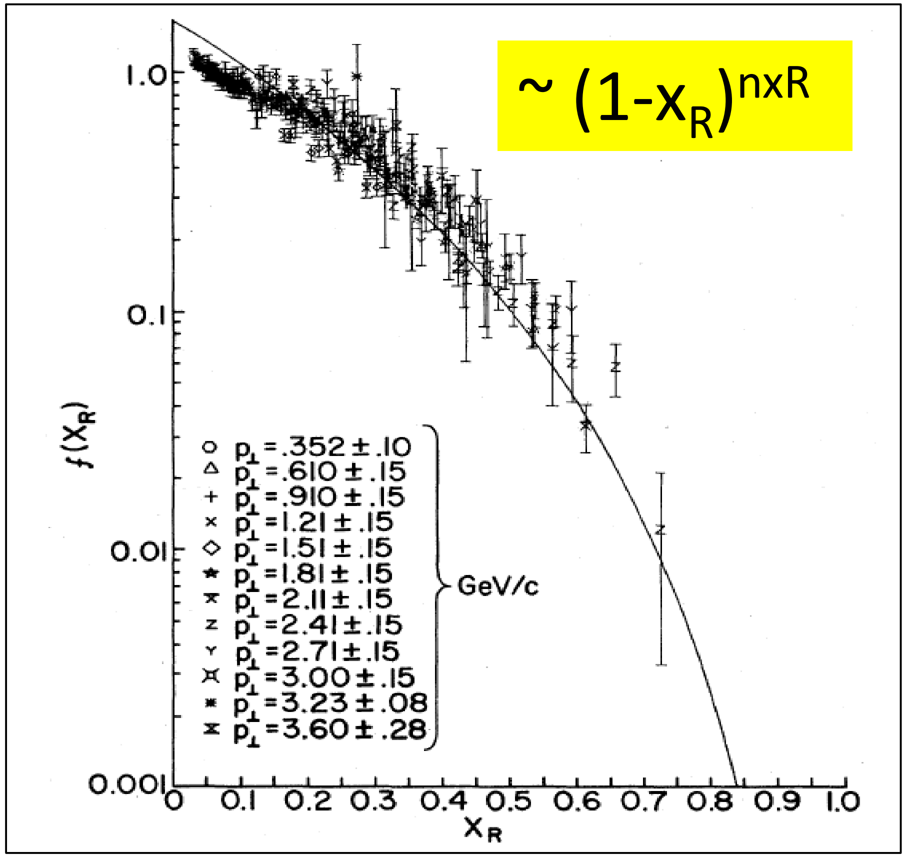
m_{QN}=mass to satisfy QN conservation

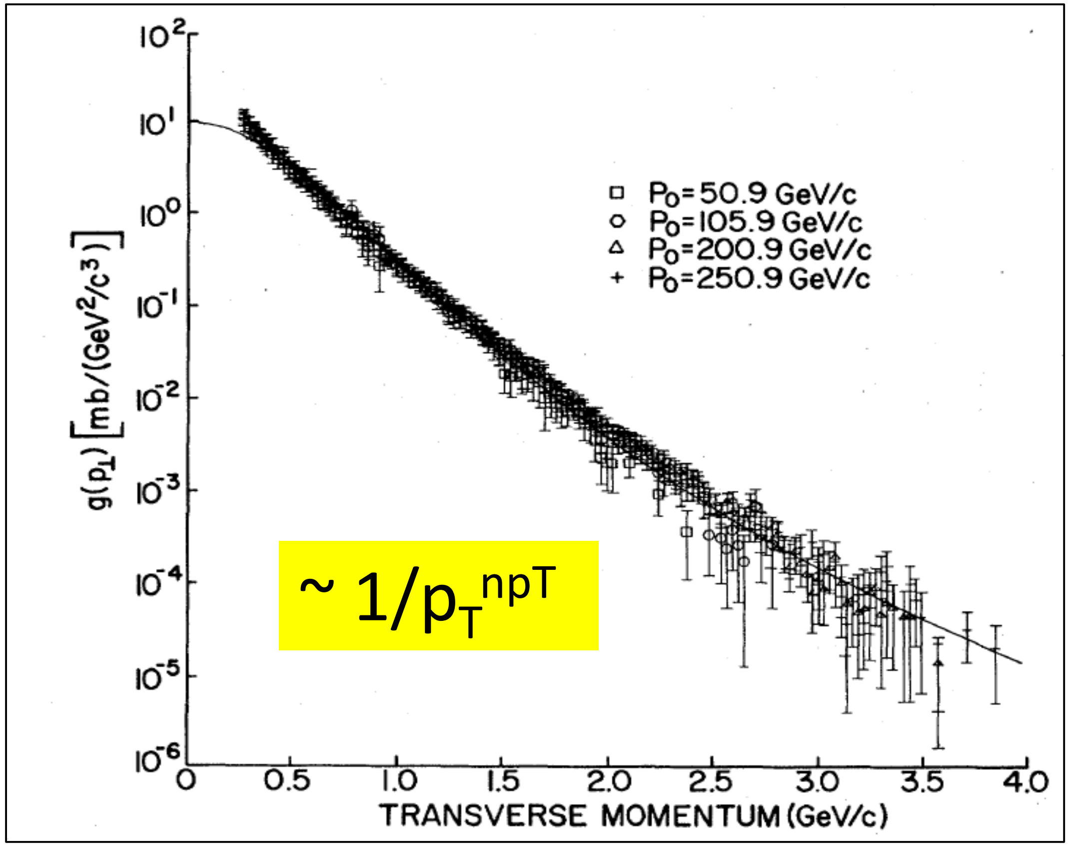
E and E_{max} are energy of jet (particle) and maximum energy, respectively in the COM. m_J is mass of jet (particle).

Radial Scaling in Inclusive p-p π^0 Production

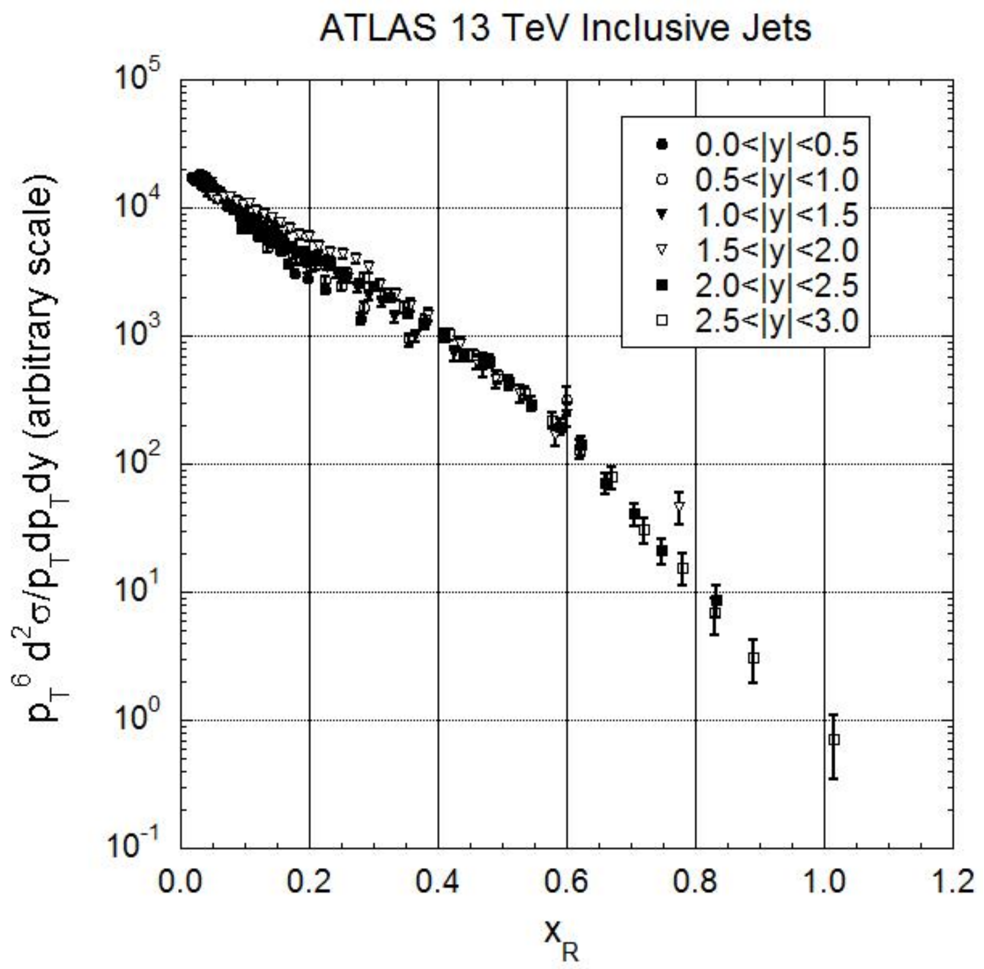
$$E\,\frac{d^3\sigma}{dp^3} = F(s, p_T, x_R) \approx F(p_T, x_R) \sim A(p_T) f(x_R)$$

D. C. Carey, … FET Phys. Rev. Lett. 33, No. 5, 327 (29 July 1974)

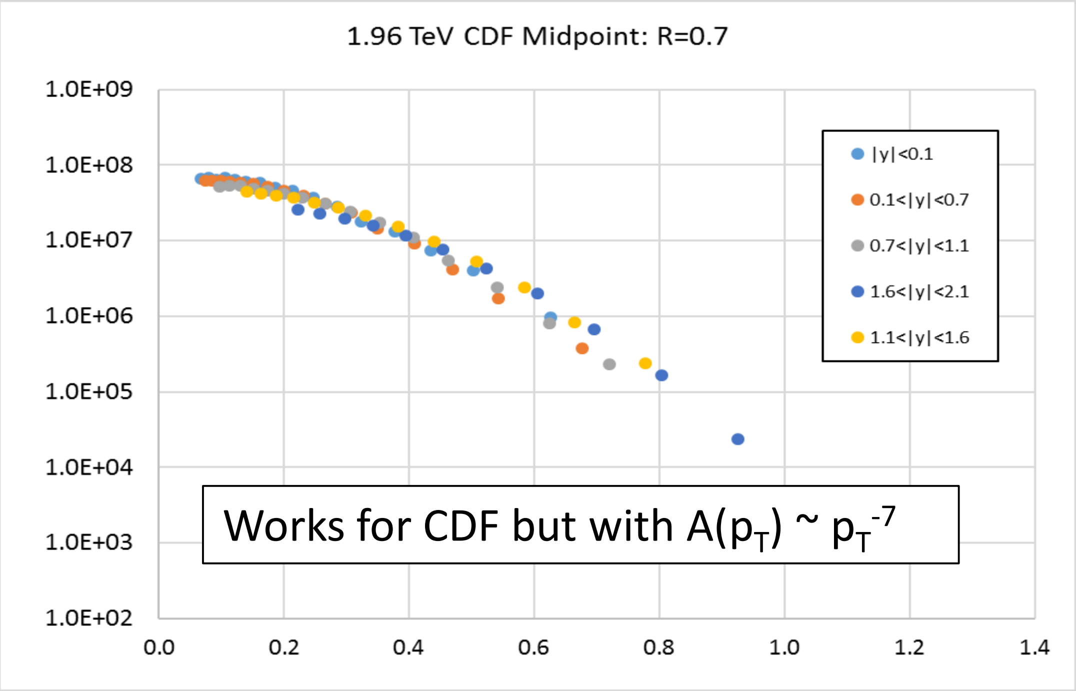




$A(p_T) \sim p_T^{-6}$

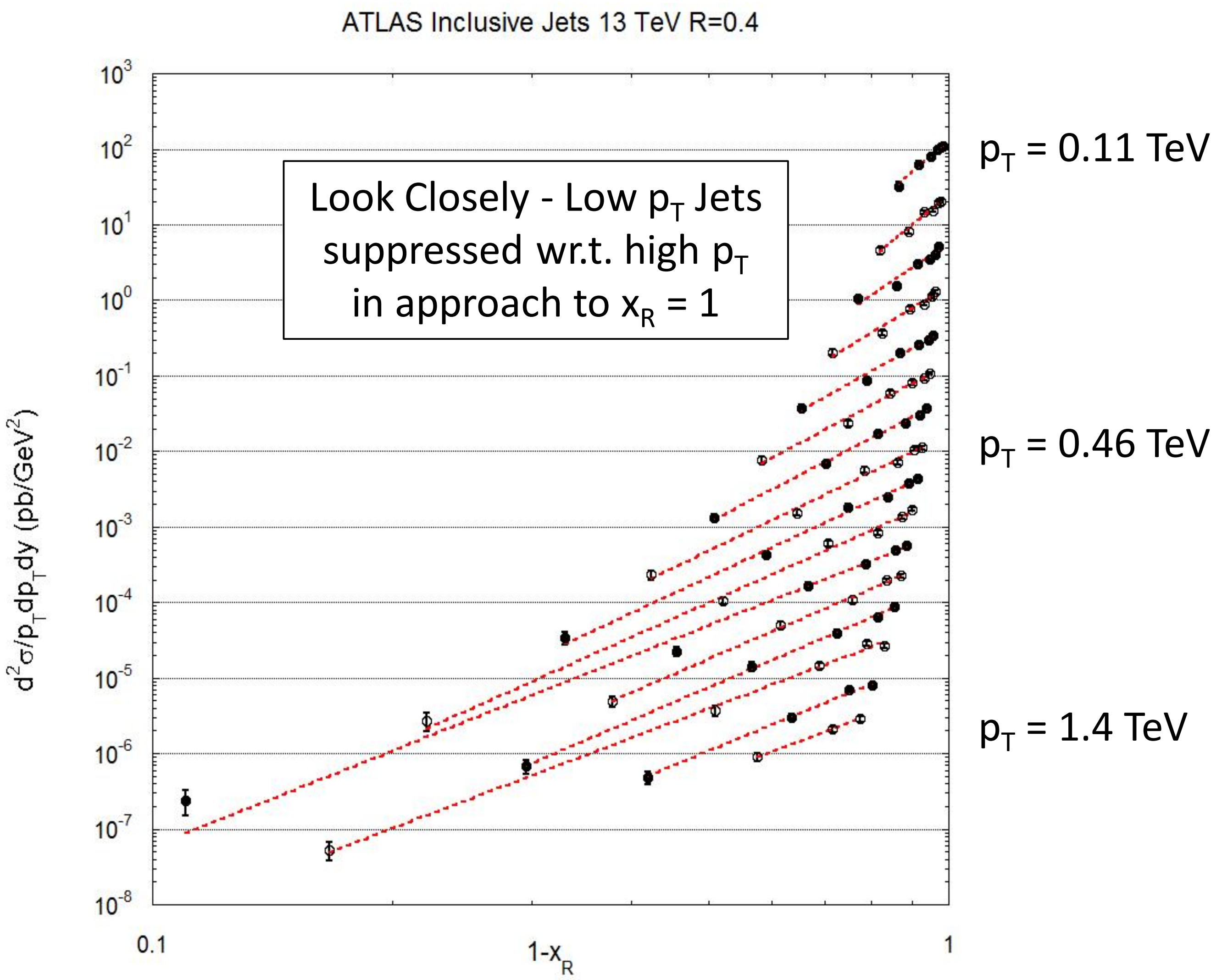


Find an approximate Radial Scaling for Inclusive Jet Production – similar to that observed in single particle inclusive production.



Works for CDF but with $A(p_T) \sim p_T^{-7}$

13 TeV ATLAS Jets – constant p_T vs. $(1-x_R)$

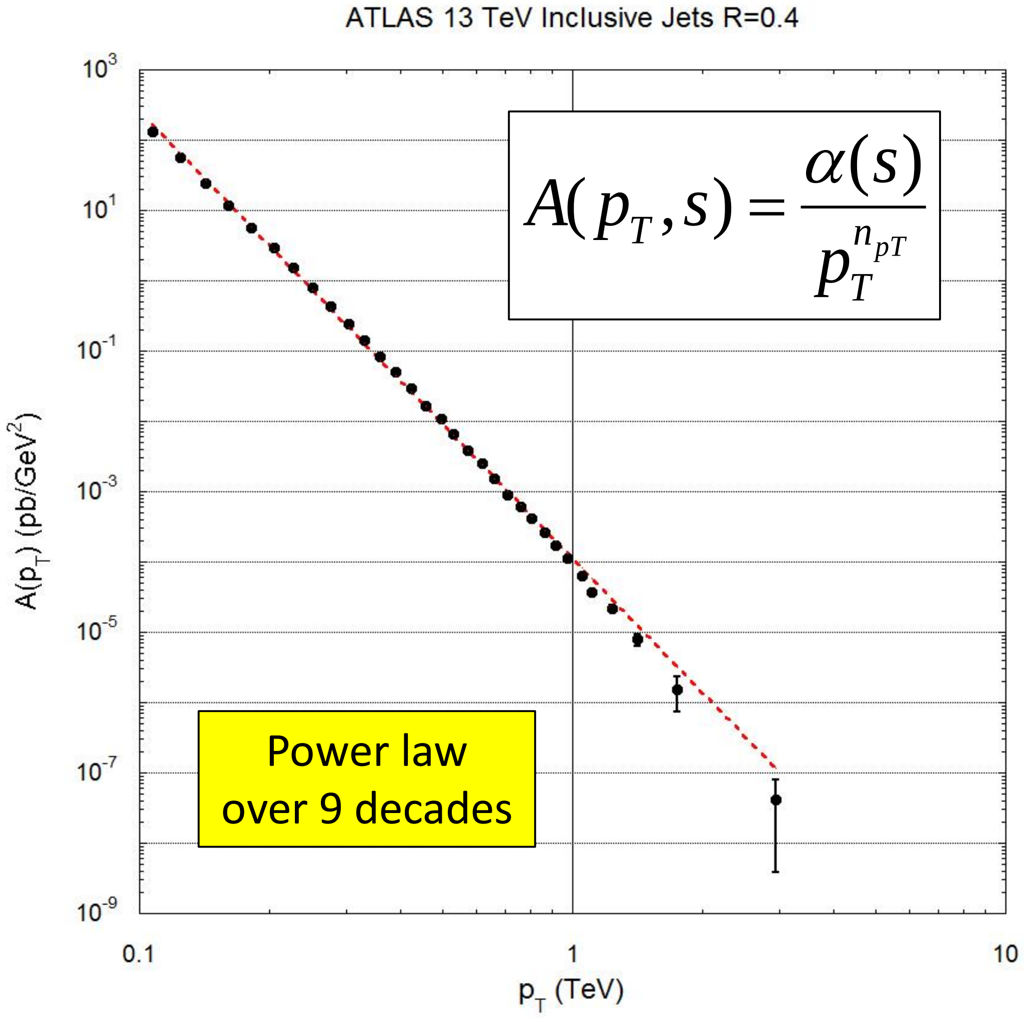


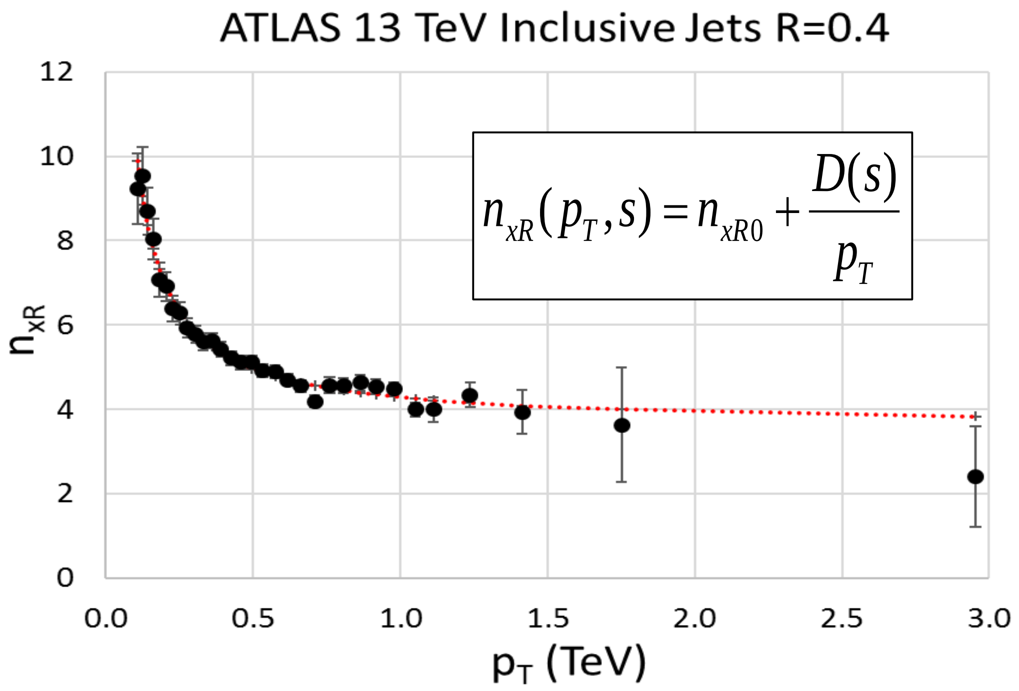
A more refined analysis is to determine $A(p_T)$ by power-law fits in $(1-x_R)$ for constant p_T:

$$\frac{d^2\sigma}{p_T dp_T d\eta} \sim A(p_T)(1-x_R)^{n_{xR}}$$

Now study the behavior of $A(p_T)$ and n_{xR} as function of p_T, √s and process.

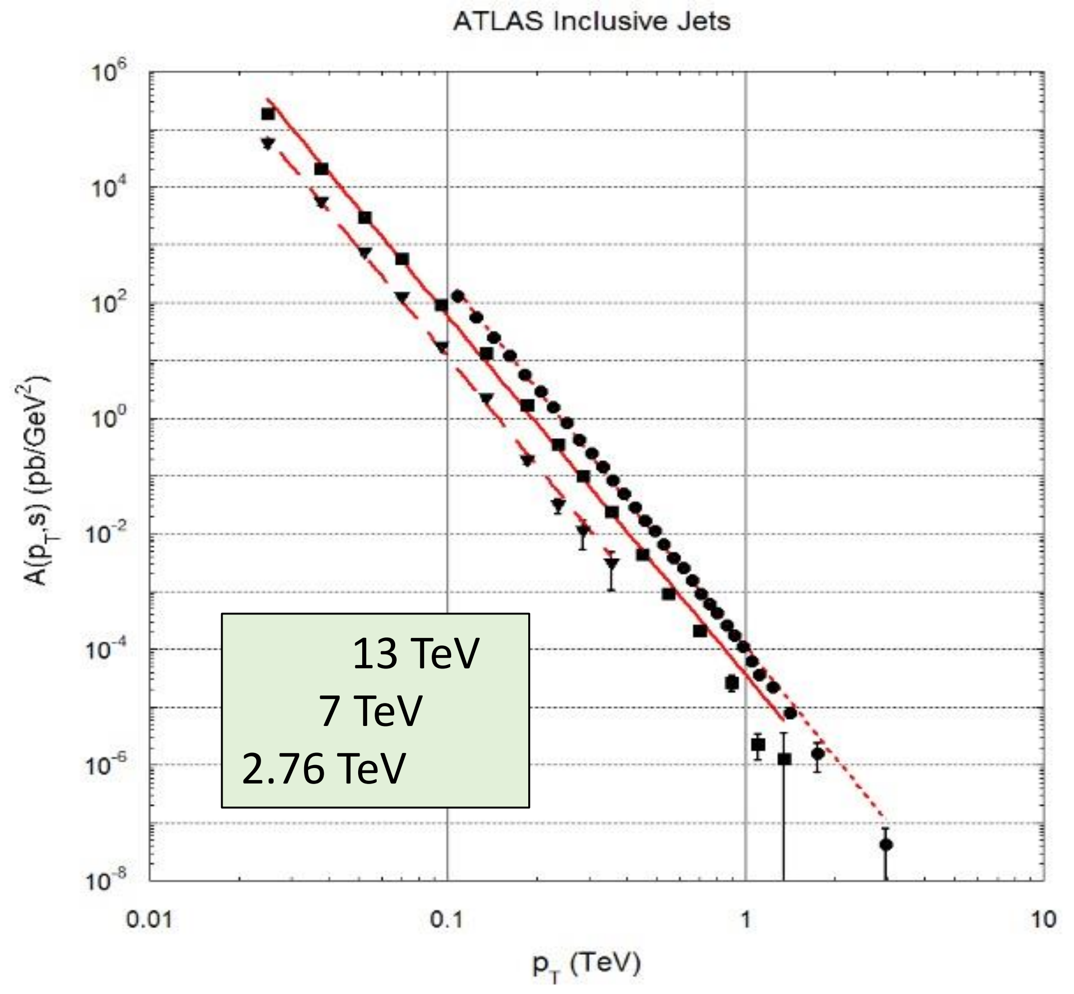
Fit Parameters 13 TeV ATLAS Inclusive Jets

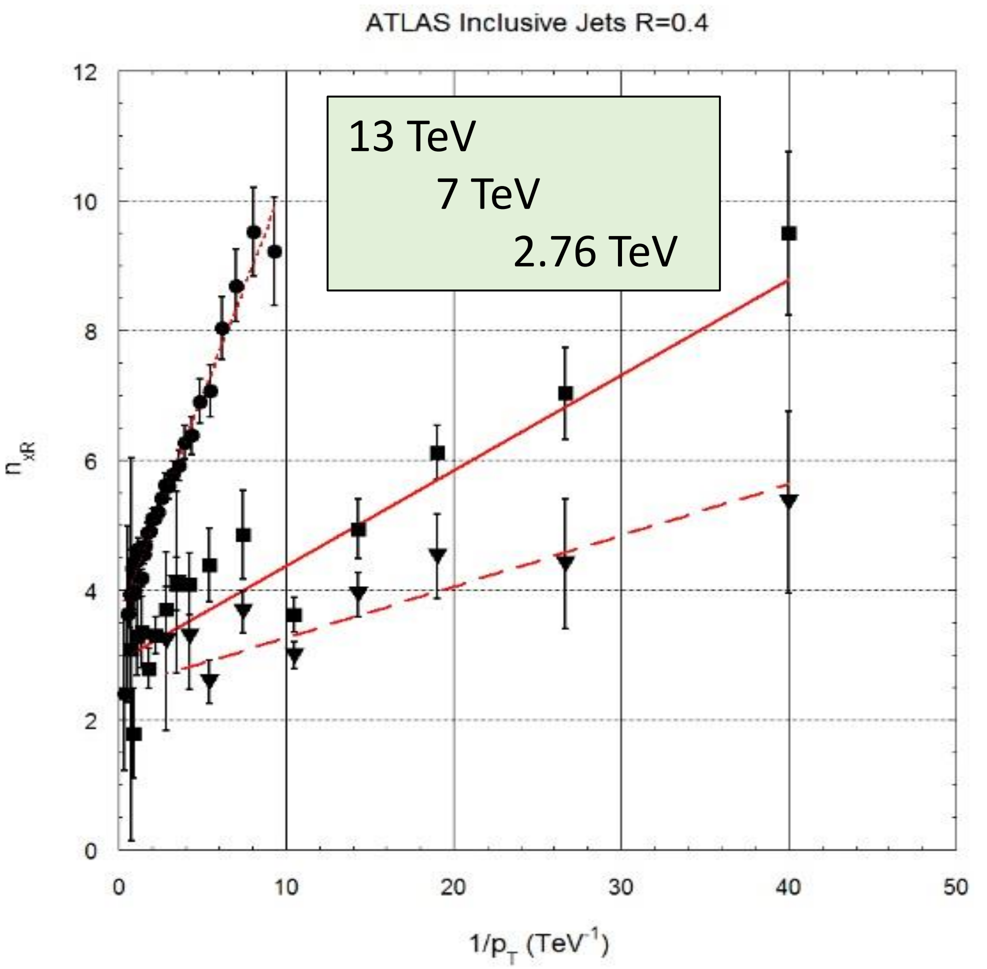




$\alpha(s) = (1.13 \pm 0.02) \times 10^{-4}$ (pb/GeV^2) TeV^{npT}
$n_{pT} = 6.36 \pm 0.01$
$D(s) = 0.68 \pm 0.03$ (TeV^{-1})
$n_{xR}0 = 3.61 \pm 0.07$

ATLAS Jets at Other p-p √s Energies

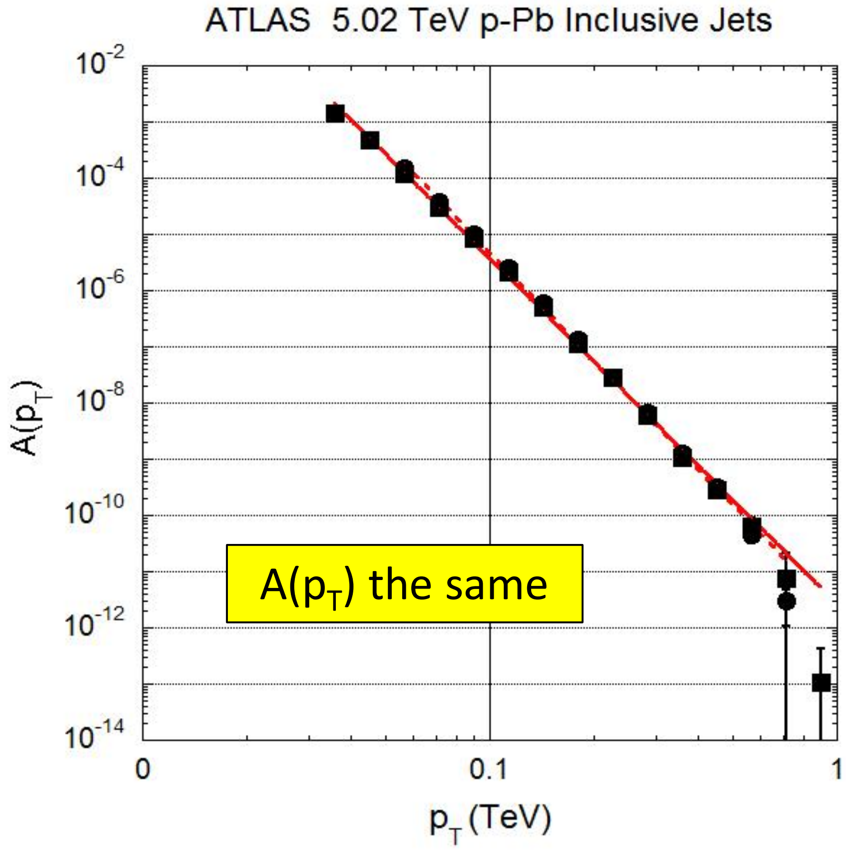


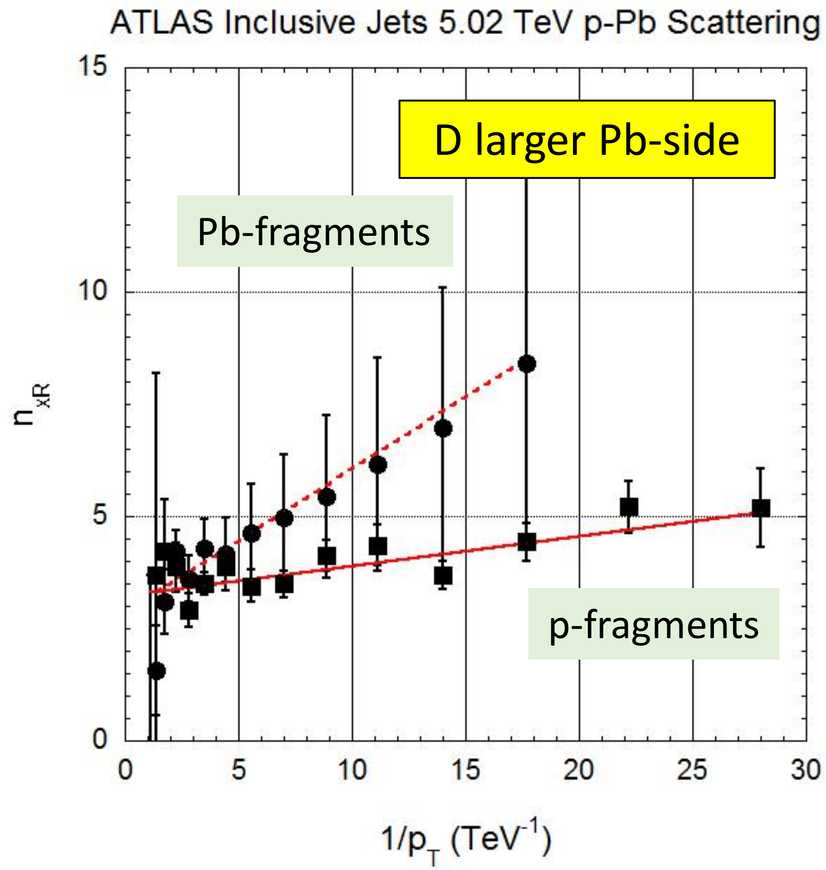


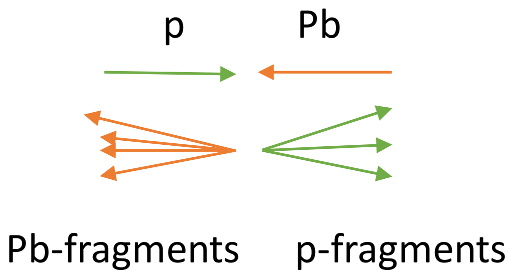
$\alpha(s)$ grows with s
npT ≈ constant
D(s) grows with s
nxR0 ≈ constant

ATLAS p-Pb Jets $\sqrt{s_{nn}}$ = 5.02 TeV

- Compare p-fragmentation side with Pb-fragmentation side (0%-90%)







	n_{pT}
p-side	6.15 ± 0.04
Pb-side	6.43 ± 0.07

	D	nxR0
p-side	0.07± 0.02	3.2 ± 0.2
Pb-side	0.3 ± 0.1	2.9 ± 0.5

Summary of Inclusive Jets CDF, D0, ATLAS, CMS

√s (TeV)	α (pb/GeV^2) TeV^{npT}	n_{pT}	χ^2 /d.f.	d.f.
1.96 p̄-p CDF	(0.9 ± 0.2) x 10^{-6}	7.03 ± 0.08	4	13
1.96 p̄-p D0	(1.3 ± 0.1) x 10^{-6}	6.90 ± 0.05	1.2	25
2.76 p-p ATLAS	(6.0 ± 1.0) x 10^{-6}	6.29 ± 0.06	3.4	8
7 p-p ATLAS	(3.7 ± 0.2) x 10^{-5}	6.21 ± 0.03	32	14
8 p-p CMS	(2.98 ± 0.04) x 10^{-5}	6.73 ± 0.01	28	33
13 p-p ATLAS	(1.13 ± 0.02) x10^{-4}	6.36 ± 0.01	8	30
13 p-p CMS	(1.06 ± 0.04) x10^{-4}	6.40 ± 0.03	2	27

√s (TeV)	D (TeV^{-1})	n_{xR0}	χ^2 /d.f.	d.f.
1.96 p̄-p CDF	0.06 ± 0.04	3.7 ± 0.3	0.2	13
1.96 p̄-p D0	0.00 ± 0.02	4.2 ± 0.2	2.0	25
2.76 p-p ATLAS	0.08 ± 0.03	2.5 ± 0.3	1.2	8
5.02 p-Pb p-side ATLAS	0.07± 0.02	3.2 ± 0.2	0.8	13
7 p-p ATLAS	0.15 ± 0.02	2.9 ± 0.2	1.7	14
8 p-p CMS	0.22 ± 0.01	2.96 ± 0.03	1.2	33
13 p-p ATLAS	0.68 ± 0.03	3.61 ± 0.07	0.8	30
13 p-p CMS	0.34 ± 0.09	3.5 ± 0.2	0.3	27

$$\frac{d^2\sigma}{p_T dp_T dy}(s, p_T, y; \alpha, n_{pT}, D, n_{xR0}) = \frac{\alpha(s)}{p_T^{n_{pT}}}(1 - x_R)^{\frac{D(s)}{p_T} + n_{xR0}}$$

$$x_R = \frac{E}{E_{\max}} = \frac{2\sqrt{\left(p_T^2 \cosh^2(y)(1 + (m_J^2/p_T^2)\tanh^2(y)) + m_J^2\right)}}{\sqrt{s}}$$

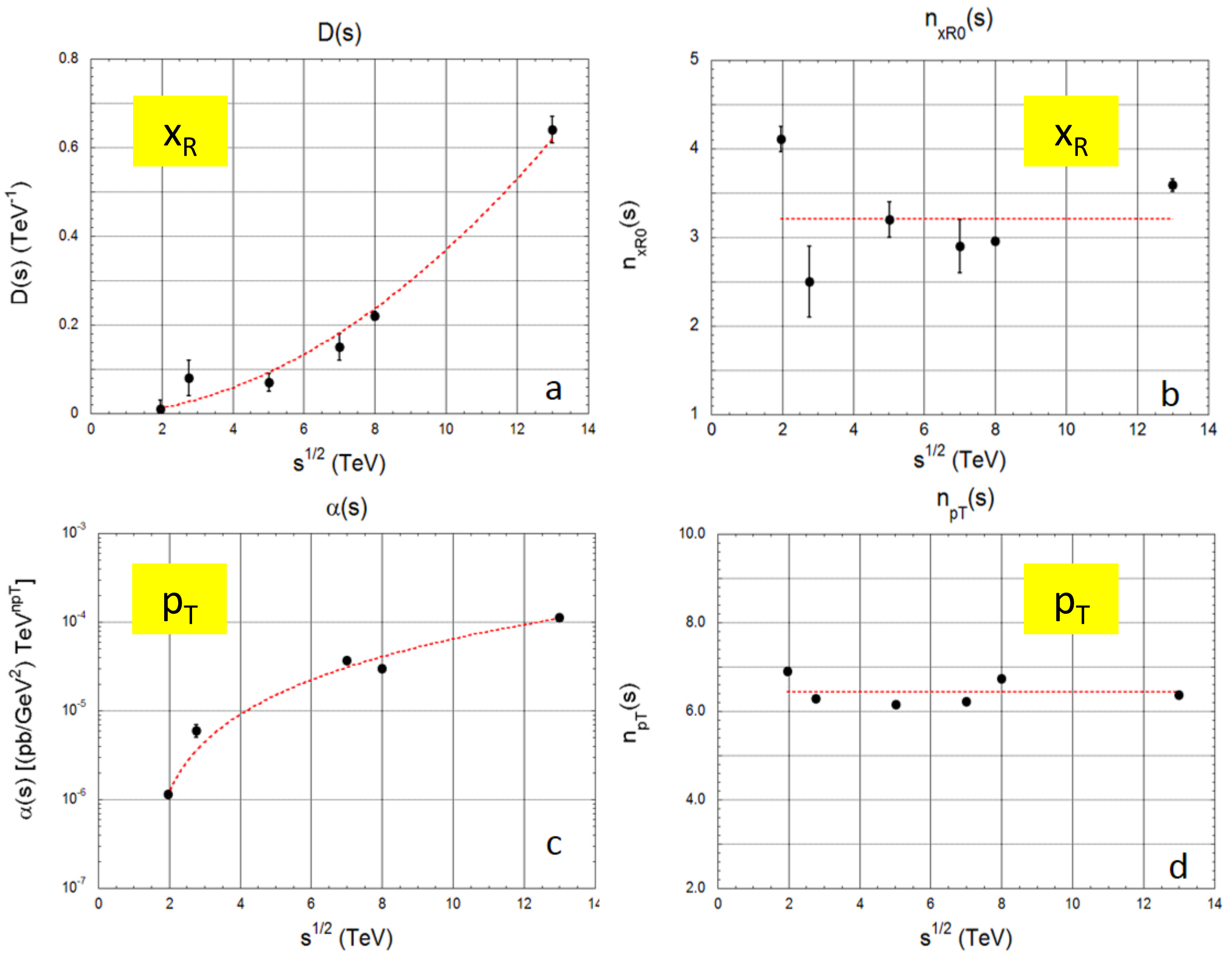
$$\approx \frac{2 p_T \cosh(y)}{\sqrt{s}} \sqrt{\left(1 + \frac{m_J^2}{p_T^2}\tanh^2(y)\right)}$$

where: $m_J/p_T < R/\sqrt{2} = 0.28$ for

$$R = \sqrt{\left(\Delta\phi^2 + \Delta\eta^2\right)}$$

(D. W. Kolodrubetz, et al., "Factorization for Jet Radius Logarithms in Jet Mass Spectra at the LHC", arXiv:1605.08038v1)

Inclusive Jet Fit Parameters in p_T and x_R



Conclusions:

<u>pT - behavior</u>

npT ≈ constant = 6.5 ± 0.3

α(s) grows linearly with s

Quality of power-law fits in pT is low.

Better fit:

$$A(p_T, s) = \exp\left(\beta(s)\left(\ln(p_T)\right)^2\right)\frac{\alpha(s)}{p_T^{\,n_{pT}}}$$

<u>(1-x_R) behavior</u>

nxR0 ≈ constant = 3.3 ± 0.5

D(s) grows linearly with s

Same √s data combined:

$(D0 \otimes CDF, ATLAS \otimes CMS)$

Single Particle Inclusive Reactions

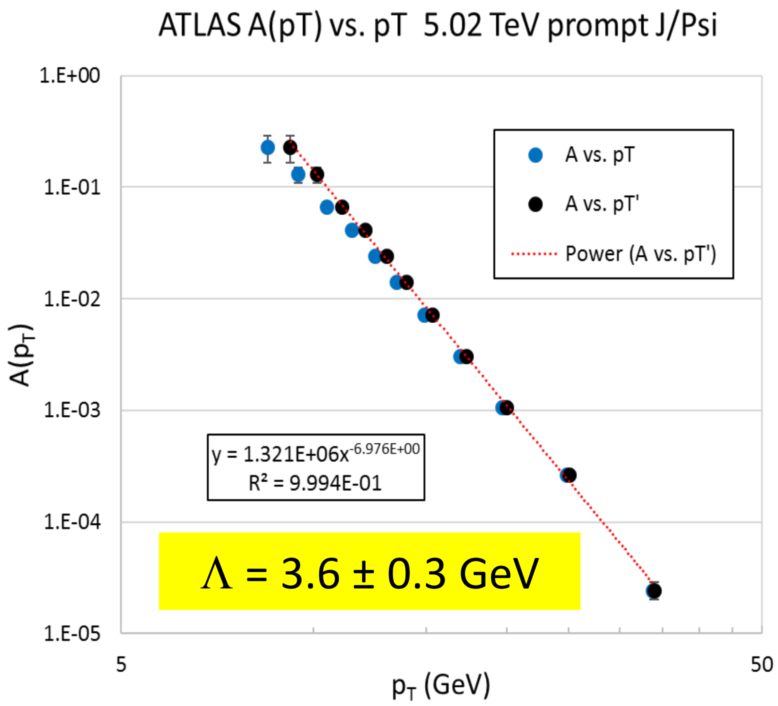
$$\frac{d^2\sigma}{p_T dp_T dy}(s,p_T,y;\alpha,\Lambda,n_{pT},m,D,n_{xR0})$$

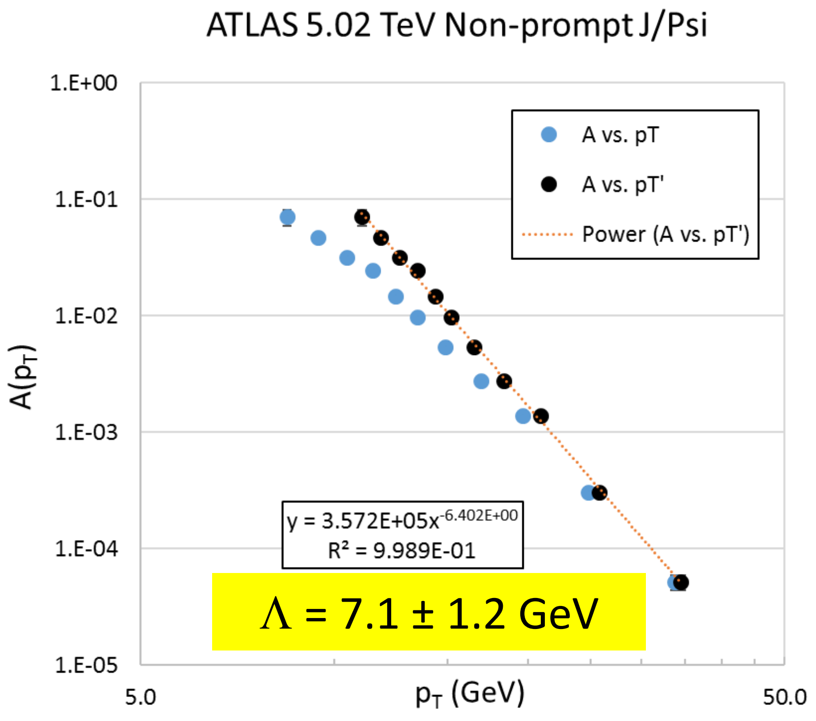
$$=\frac{\alpha(s)}{\left(\Lambda^2+p_T^2\right)^{\frac{n_{pT}}{2}}}\left(1-\frac{2\sqrt{\left(p_T^2\cosh^2(y)(1+(m^2/p_T^2)\tanh^2(y))+m^2\right)}}{\sqrt{s}}\right)^{\frac{D(s)}{p_T}+n_{xR0}}$$

$$=\frac{\alpha(s)}{\left(\Lambda^2+p_T^2\right)^{\frac{n_{pT}}{2}}}\left(1-x_R\right)^{\frac{D(s)}{p_T}+n_{xR0}}$$

$$p_T'=\sqrt{\left(\Lambda^2+p_T^2\right)}$$

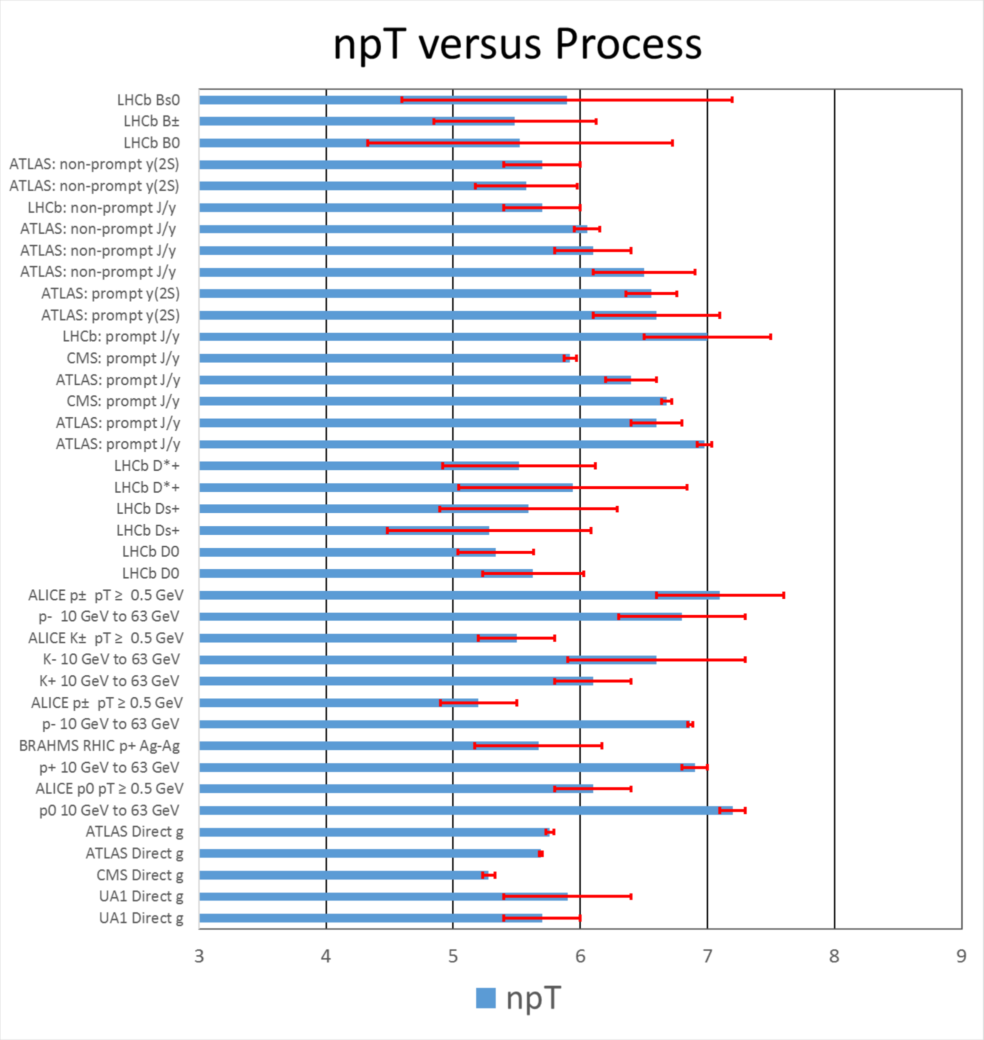
Parameterization of cross section at low p_T needs another term Λ (transverse mass $\otimes$ intrinsic k_T)





$A(p_T)$: Single Particle Inclusive 0.063 TeV ≤ √s ≤ 13 TeV

Index	Single Particle Inclusive Process	√s (TeV)	Λ(GeV)	σ(Λ)	n_{pT}	σ(n_{pT})	<Λ> (GeV)	<σ(Λ)>
1	UA1 Direct γ	0.546			5.7	0.3		
2	UA1 Direct γ	0.63			5.9	0.5		
3	CMS Direct γ	7			5.28	0.05		
4	ATLAS Direct γ	8			5.69	0.01		
5	ATLAS Direct γ	13			5.76	0.03		
6	π^0 10 GeV to 63 GeV	0.063	0.653	0.001	7.2	0.1		
7	ALICE π^0 $p_T \geq 0.5$ GeV	2.76	0.8	0.2	6.1	0.3		
8	π^+ 10 GeV to 63 GeV	0.063	0.60	0.02	6.9	0.1		
9	BRAHMS RHIC π^+ Ag-Ag	0.062	0.56	0.07	5.7	0.5		
10	π^- 10 GeV to 63 GeV	0.063	0.607	0.004	6.86	0.02		
11	ALICE $\pi^\pm$ $p_T \geq 0.5$ GeV	7	0.61	0.10	5.2	0.3	0.77	0.09
12	K^+ 10 GeV to 63 GeV	0.063	0.61	0.08	6.1	0.3		
13	K^- 10 GeV to 63 GeV	0.063	0.8	0.1	6.6	0.7		
14	ALICE $K^\pm$ $p_T \geq 0.5$ GeV	7	0.94	0.10	5.5	0.3		
15	p^- 10 GeV to 63 GeV	0.063	0.9	0.1	6.8	0.5		
16	ALICE $p^\pm$ $p_T \geq 0.5$ GeV	7	1.4	0.2	7.1	0.5		
17	LHCb D0	5	2.6	0.3	5.6	0.4		
18	LHCb D0	13	2.7	0.3	5.3	0.3		
19	LHCb Ds^+	5	2.5	0.8	5.3	0.8	2.80	0.25
20	LHCb Ds^+	13	3.1	0.8	5.6	0.7		
21	LHCb D^{*+}	5	2.8	0.7	5.9	0.9		
22	LHCb D^{*+}	13	3.1	0.7	5.5	0.6		
23	ATLAS: prompt J/Ψ	5.02	3.6	0.3	7.0	0.1		
24	ATLAS: prompt J/Ψ	7	2.7	1.6	6.6	0.2		
25	CMS: prompt J/Ψ	7			6.7	0.04	3.6	0.5
26	ATLAS: prompt J/Ψ	8	3.0	1.7	6.4	0.2		
27	CMS: prompt J/Ψ	13			5.92	0.05		
28	LHCb: prompt J/Ψ	13	4.4	0.4	7.0	0.5		
29	ATLAS: prompt Ψ(2S)	7	4.1	2.5	6.6	0.5	4.3	2.0
30	ATLAS: prompt Ψ(2S)	8	4.5	1.5	6.6	0.2		
31	ATLAS: non-prompt J/Ψ	5.02	7.1	1.2	6.5	0.4		
32	ATLAS: non-prompt J/Ψ	7	5.8	1.6	6.1	0.3	6.2	1.0
33	ATLAS: non-prompt J/Ψ	8	7.4	0.7	6.1	0.1		
34	LHCb: non-prompt J/Ψ	13	4.6	0.3	5.7	0.3		
35	ATLAS: non-prompt Ψ(2S)	7	4.1	2.8	5.6	0.4	4.8	2.3
36	ATLAS: non-prompt Ψ(2S)	8	5.4	1.7	5.7	0.3		
37	LHCb B0	7	6.5	2.2	5.5	1.2		
38	LHCb B±	7	6.4	1.1	5.5	0.6	6.7	0.3
39	LHCb Bs0	7	7.1	2.2	5.9	1.3		
				<n_{pT}>	6.1	0.6		



All single particles:
$n_{pT} = 6.1 \pm 0.6$

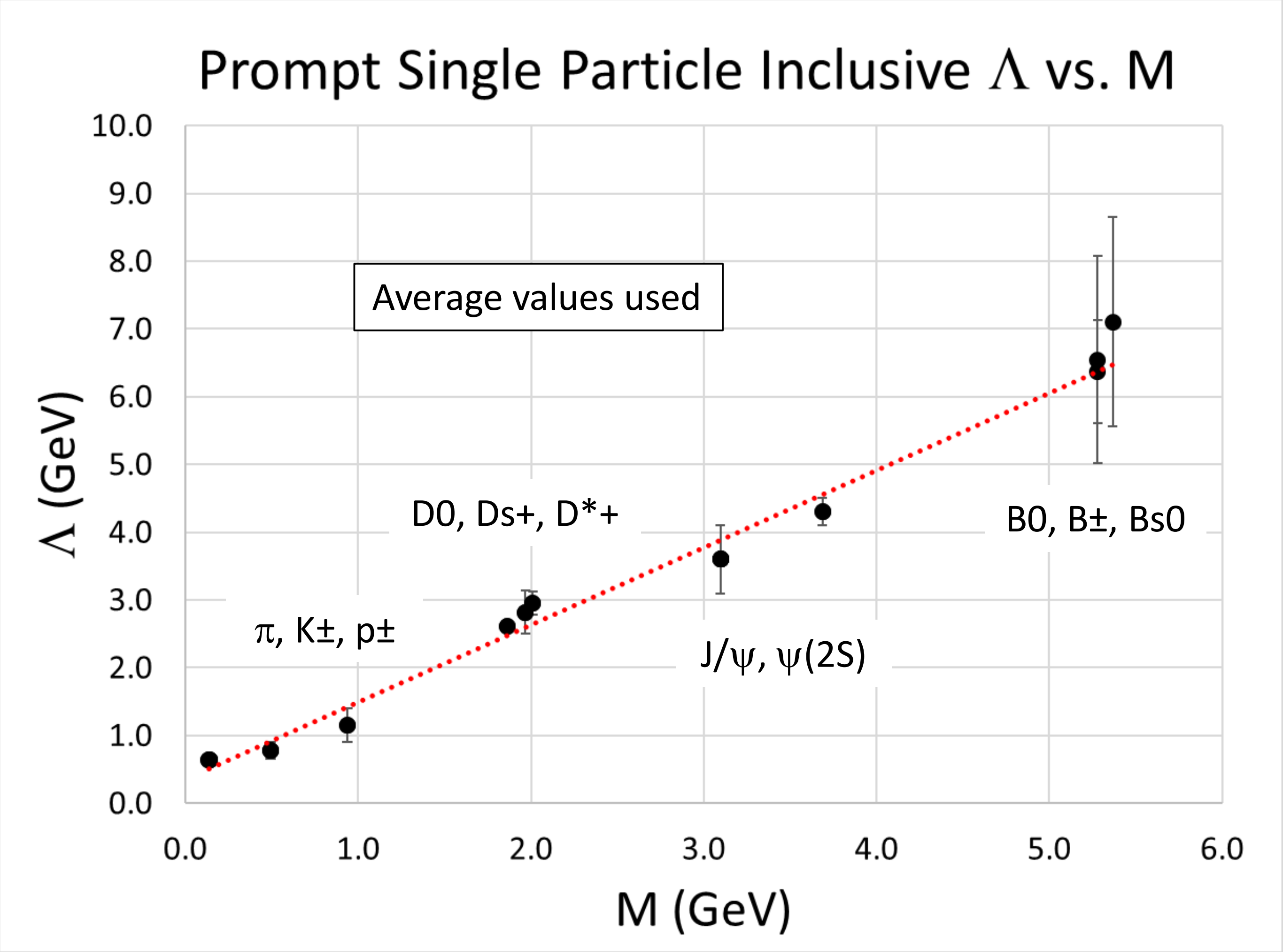
Direct Gamma:
$n_{pT} = 5.7 \pm 0.2$

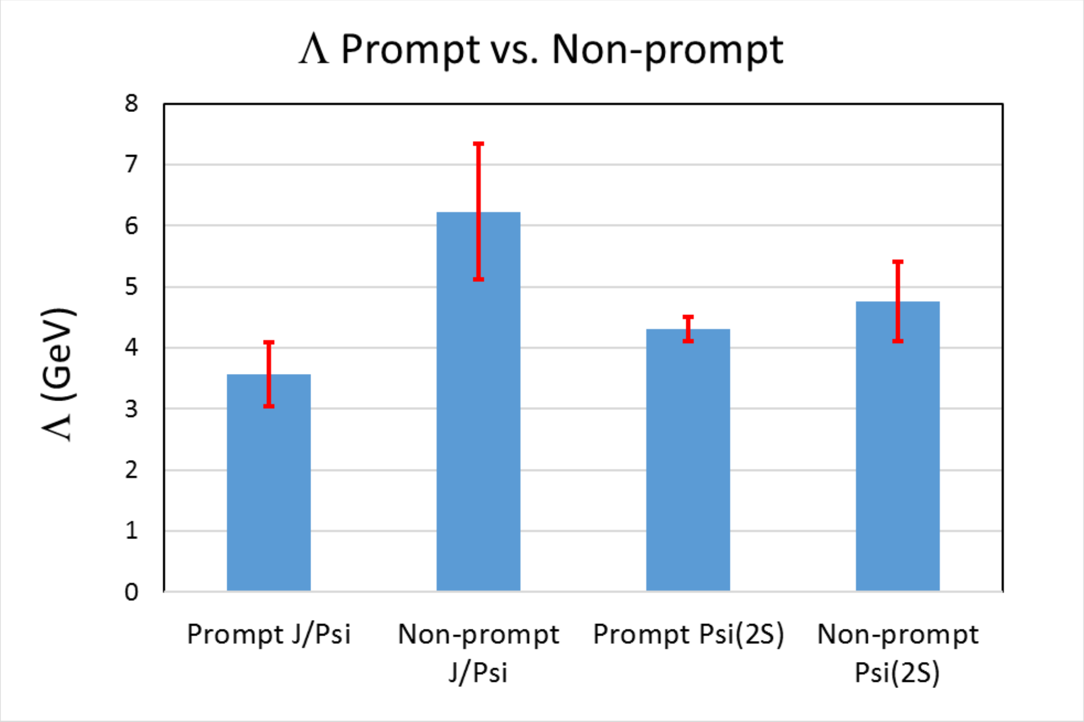
Jets:
$n_{pT} = 6.5 \pm 0.3$

Everything (48):
$n_{pT} = 6.2 \pm 0.6$

$n_{pT} = 4$ disfavored by 4 σ

Λ Parameter





- Λ parameter for prompt single particle inclusive is linear with mass of particle: Λ = 1.1 M + 0.4 (GeV)
- Λ for non-prompt tends to be larger than Λ prompt (J/ψ) but better data needed ψ(2S).

QCD through the Prism of Radial Scaling

- The p_T- dependence of the invariant inclusive cross sections seems to be independent of process and energy over a wide range as a power law: **$1/p_T^{(6.2 \pm 0.6)}$** in the limit $x_R \rightarrow 0$. "Higher Twists" have been known to dominate for a long time but this analysis demonstrates this widely. **All are consistent with the dimension of 2 → 3 scattering**.
- The x_R dependence is consistent with a power law **$(1\text{-}x_R)^{nxR}$**, where n_{xR} is qualitatively dependent on the number of spectator quarks.
- At **high √s** and **HI** collisions $nx_R = D/p_T + nx_{R0}$ → **Jets at low p_T strongly suppressed.**
- Determining Λ gives a hint of **production mechanism** ~ linear with mass direct, larger for indirect production.
- The data are well-represented by pQCD calculations to NLO (PHYTHIA, SHERPA, JetPhox, PeTer). Experiment authors show agreement with simulations but generally do not try to factorize the pT-dependence from the y or x_R dependence. Doing so would show commonalities and highlight differences. **What about 100 TeV?**

Preliminary version of this work:
F. E. Taylor, "*Radial Scaling in Inclusive Jet Production at Hadron Colliders*", https://arxiv.org/abs/1704.07341, [v1] Mon, 24 Apr 2017

Backup

Inclusive Jets & Inclusive Single Particles

$n_{pT} \approx 6$ independent of process in $x_R \to 0$ limit.
Λ depends linearly on mass of particle.
$\alpha(s)$ and $D(s)$ are roughly linear in s for jets.
$n_{xR0} \approx$ constant for inclusive jets

$$\frac{d^2\sigma}{p_T dp_T dy}(s, p_T, y; \alpha, \Lambda, n_{pT}, m, D, n_{xR0})$$

$$= \frac{\alpha(s)}{\left(\Lambda^2 + p_T^2\right)^{\frac{n_{pT}}{2}}} \left(1 - \frac{2\sqrt{\left(p_T^2 \cosh^2(y)(1 + (m^2/p_T^2)\tanh^2(y)) + m^2\right)}}{\sqrt{s}}\right)^{\frac{D(s)}{p_T} + n_{x_R 0}}$$

$$= \frac{\alpha(s)}{\left(\Lambda^2 + p_T^2\right)^{\frac{n_{pT}}{2}}} \left(1 - x_R\right)^{\frac{D(s)}{p_T} + n_{x_R 0}}$$

Preliminary version of this work:
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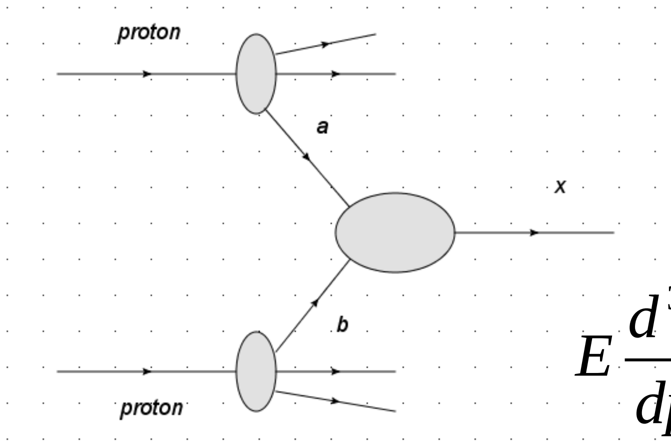
The Paradigm for Inclusive Jet Production



Jets are produced by hard parton scattering (qq → qq, gg →gg, gq →gq). The scattered parton hadronizes into a jet of particles.

QCD Factorization Theorem

$$E\frac{d^3\sigma}{dp^3} = \sum_{a,b}\int dx_1 dx_2\, f_a(x_1,\mu_F^2)\, f_b(x_2,\mu_F^2)\,\frac{d\hat{\sigma}_{ab}\left(\alpha_s(\mu_R^2), s/\mu_R^2, s/\mu_F^2\right)}{d\hat{t}} \otimes Frag \otimes Had$$

These *10s of parameters and factors* are put together in simulations of inclusive jet production at the LHC.

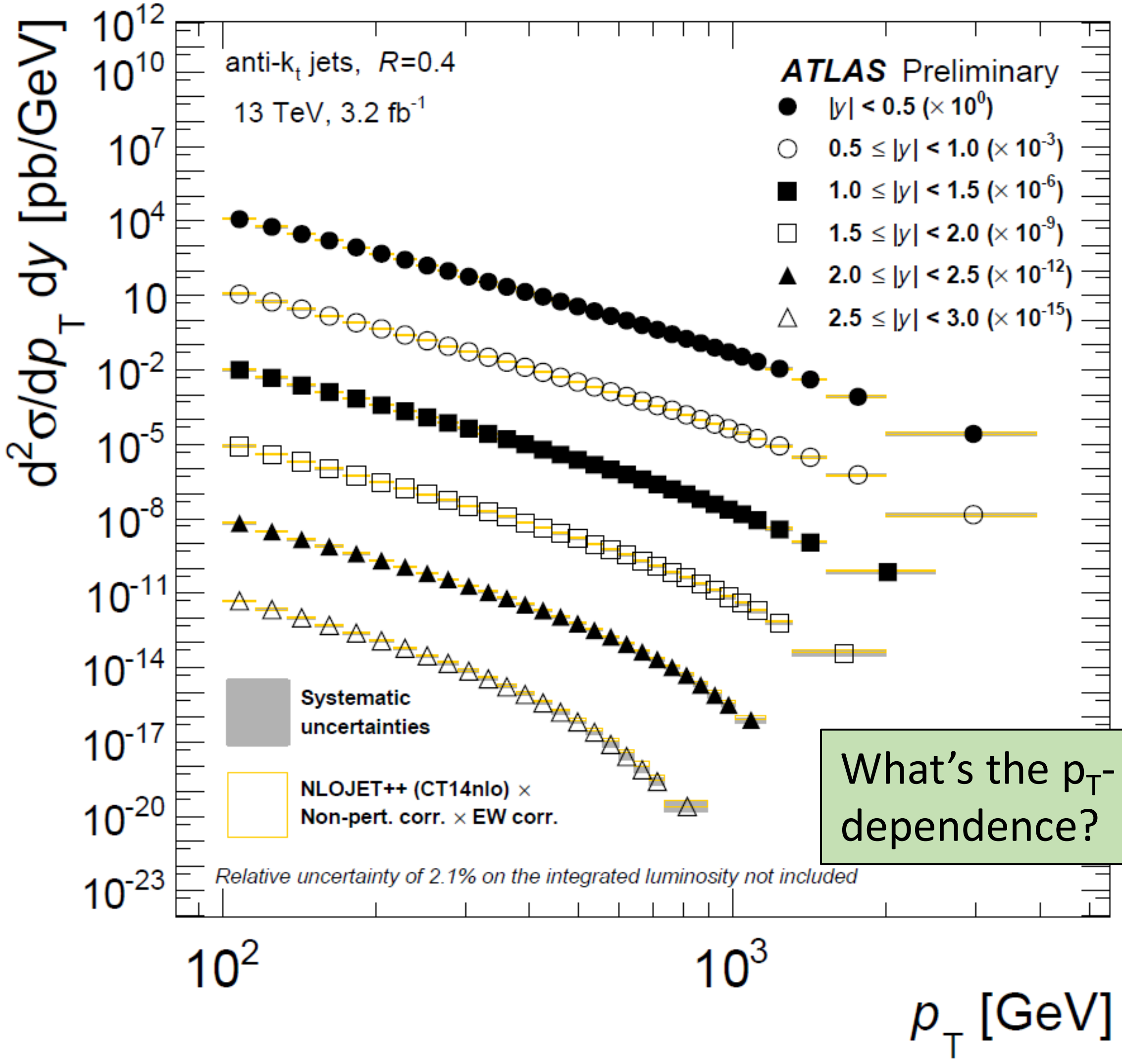
Dimensions:

$$E\frac{d^3\sigma}{dp^3} \sim \frac{d^2\sigma}{dp_T^2 dy} \sim \frac{d\hat{\sigma}_{ab}\left(\alpha_s(\mu_R^2), s/\mu_R^2, s/\mu_F^2\right)}{d\hat{t}}$$

$$\sim \frac{cm^2}{GeV^2} \sim \frac{1}{GeV^4}$$

Would expect invariant cross section to show $1/p_T^4$ behavior if LO scattering dominates

ATLAS Inclusive Jet Production at 13 TeV



What's the p_T-dependence?

- Jets defined by anti-k_t algorithm with $R=(\Delta\phi^2+\Delta y^2)^{1/2} = 0.4$
- Pythia 8.186 with A14 tune, NLOjet++. Involves integrations & summations using Monte Carlo methods
- Data compared to NLO pQCD calculation **2 -> 2 + NLO processes**, leading logarithmic p_T-ordered parton shower, hadronization with the Lund string model.

ATLAS NOTE
ATLAS-CONF-2016-092
21st August 2016

P_T Line Counting, Higher Twists, Diquarks

- Dimensional Analysis M ~ $[\text{cm}]^{nA - 4}$ $$\frac{d^2\sigma}{p_T dp_T dy} \sim \frac{|M|^2}{\hat{s}^2} \qquad \frac{d^2\sigma}{p_T dp_T dy} \sim \frac{1}{p_T^{2n_A-4}}$$

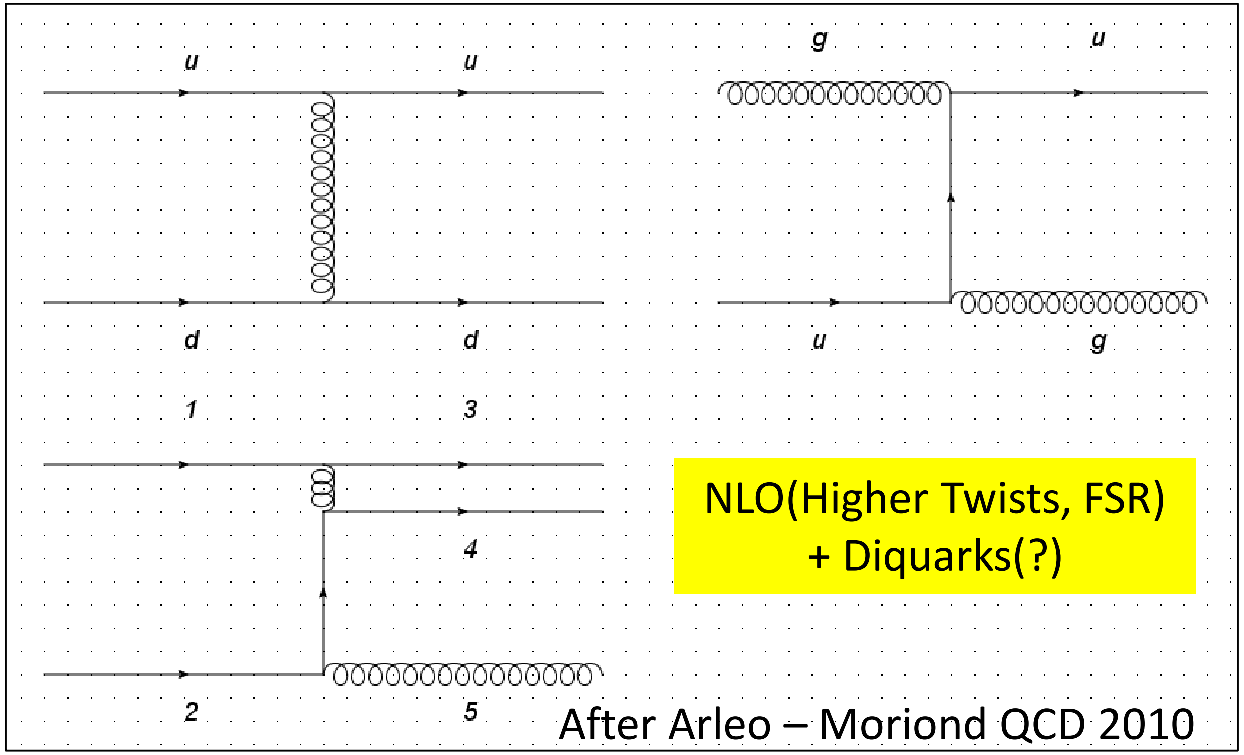
  n_A = number of active fields

$$\frac{d^2\sigma}{p_T dp_T dy} \sim \frac{1}{p_T^4}$$

$n_A = 4$ 2 → 2 scattering
HIDDEN $x_R \to 0$

$$\frac{d^2\sigma}{p_T dp_T dy} \sim \frac{1}{p_T^6}$$

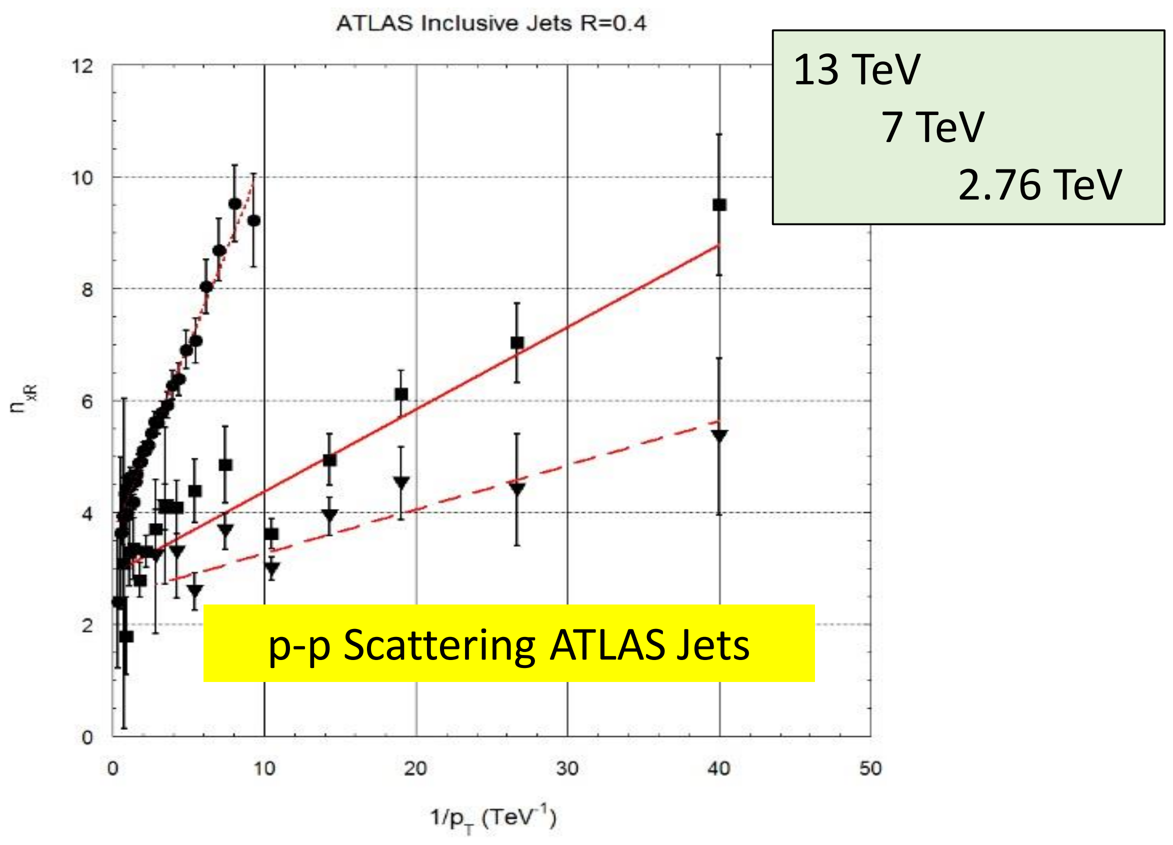
$n_A = 5$ 2 → 3 scattering
DOMINATES $x_R \to 0$

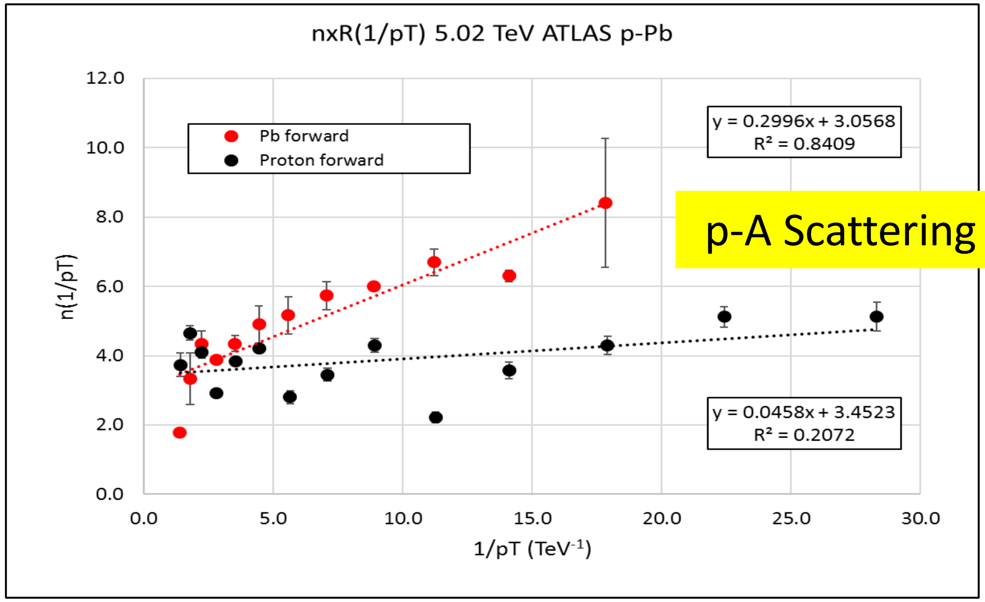


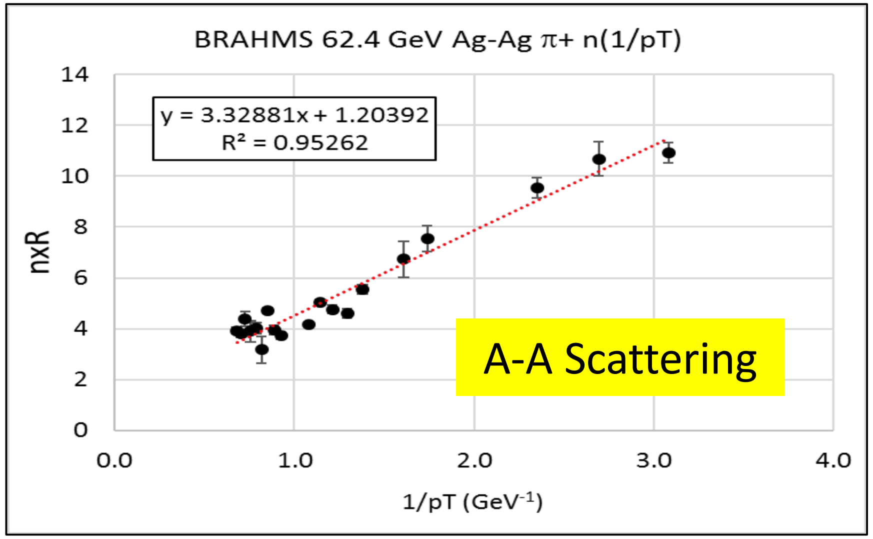
After Arleo – Moriond QCD 2010

(Diquarks: Selem, Wilczek, Jaffe, Berger, Gottschalk, Sivers, Brodsky, …)

X_R Jets in p-p, p-A, A-A have similar behavior



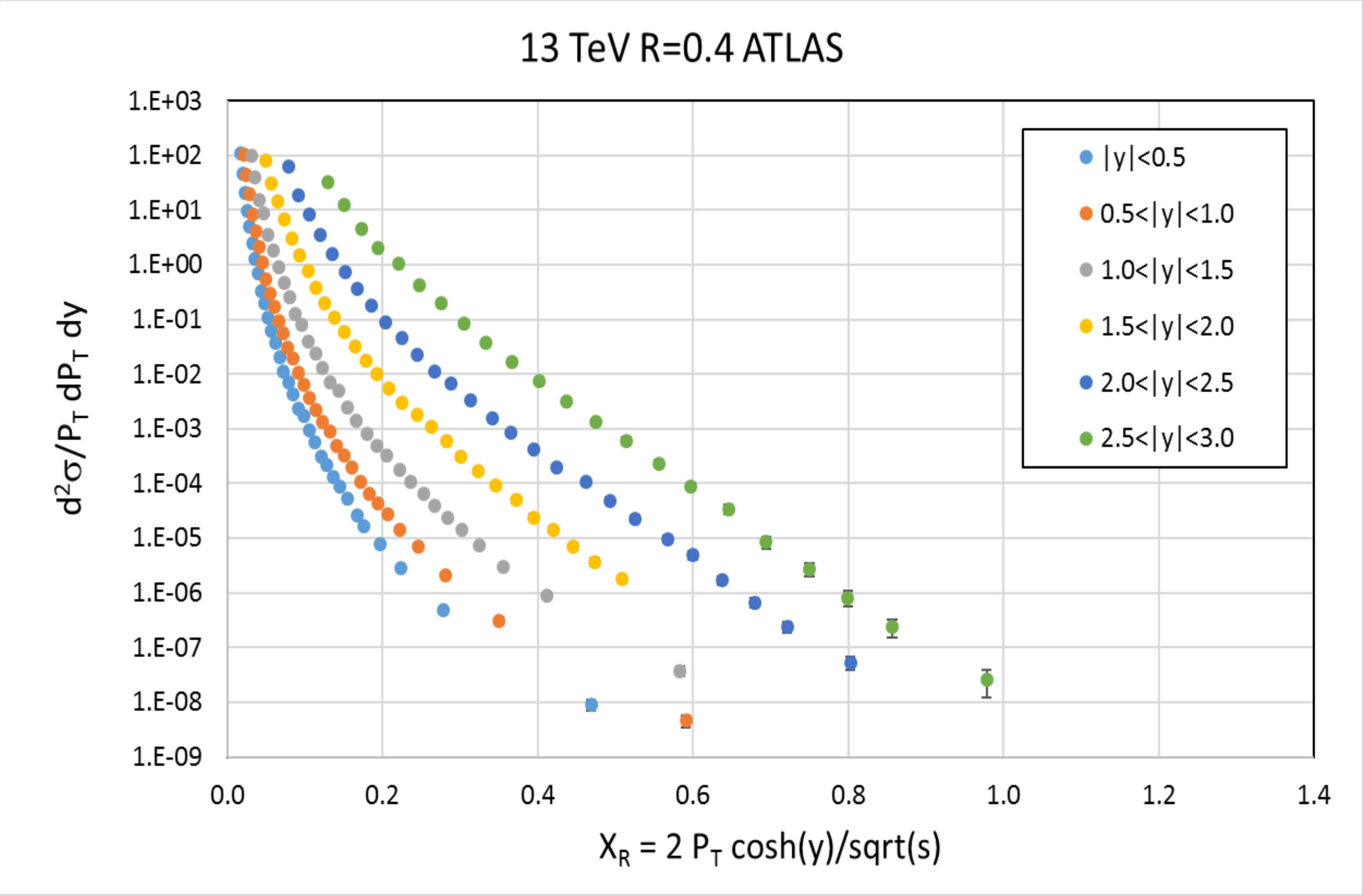




Only fitting errors shown

All behave: $$(1-x_R)^{(D/p_T+n_{0\,xR})}$$

13 TeV ATLAS Jets Plotted as a function of x_R



If there is a hard 2 → 2 scattering core by <u>naive dimensional analysis</u> then:

$$\frac{d\sigma(ab \to x)}{dQ^2} \sim \frac{1}{Q^4} \to \frac{d^2\sigma(pp \to Jets)}{p_T dp_T dy} \sim \frac{1}{p_T^4}$$

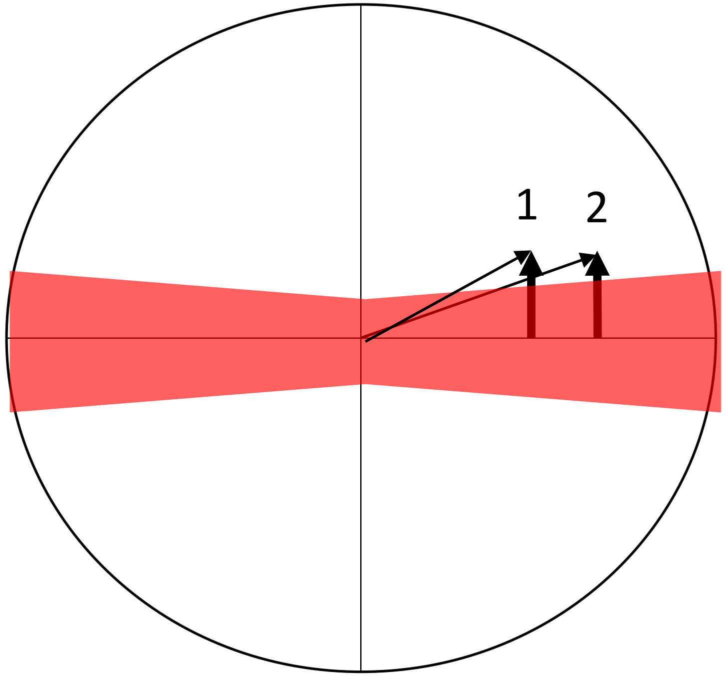
Thus would expect:

$$p_T^4 \left(\frac{d^2\sigma(pp \to Jets)}{p_T dp_T dy} \sim \frac{1}{p_T^4} \right) \sim F(x_R)$$

Note: Have approximated η by y

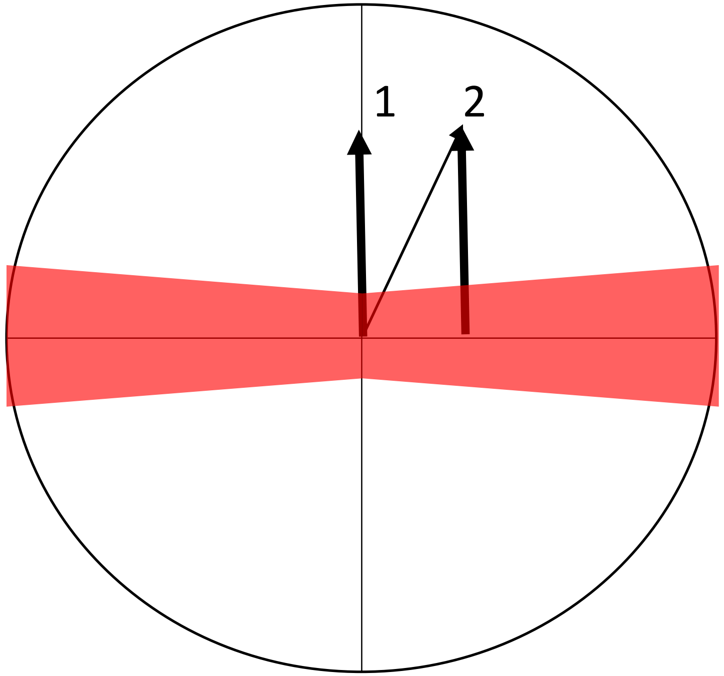
Physical Picture: Inclusive Jets & Pions

Low pT



Choose 4 points in phase space: ($p_{TL,H}$, x_{R1}, x_{R2})

High pT



$$R(p_T;\{x_{R1},x_{R2}\}) = \frac{\sigma_1}{\sigma_2} = \frac{(1-x_{R1})^{(\frac{D(p_T)}{p_T}+n_{xR0})}}{(1-x_{R2})^{(\frac{D(p_T)}{p_T}+n_{xR0})}}$$

"Beam fragmentation region"

"Beam fragmentation region" augmented by increasing √s and/or by increasing beam A in Heavy Ion Collisions.

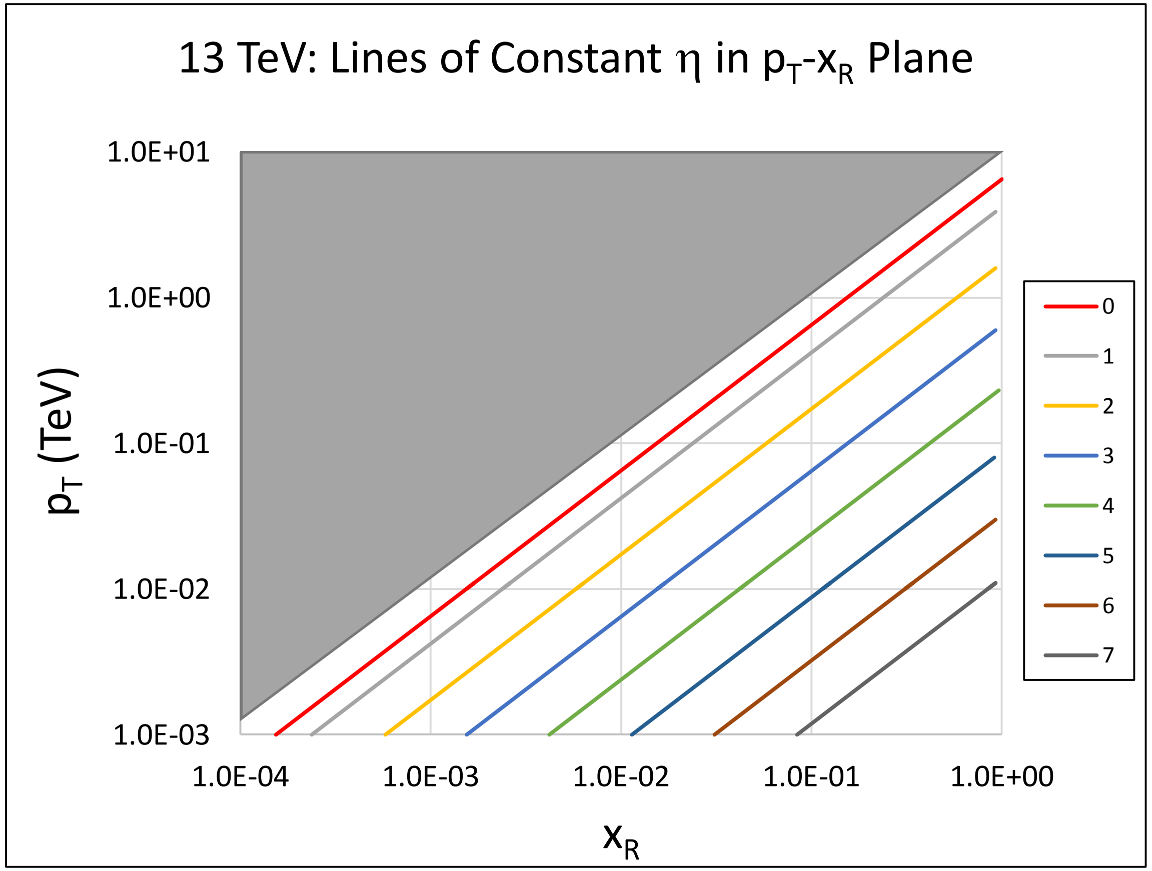
Jet quenching in both cases. Same Physics?

Jet strongly attenuated on approach to kinematic boundary because of large "D" term

$$R(p_{TLow};\{x_{R1},x_{R2}\}) < R(p_{THigh};\{x_{R1},x_{R2}\})$$

Jet less strongly attenuated on approach to kinematic boundary because "D" term -> 0

η verses x_R



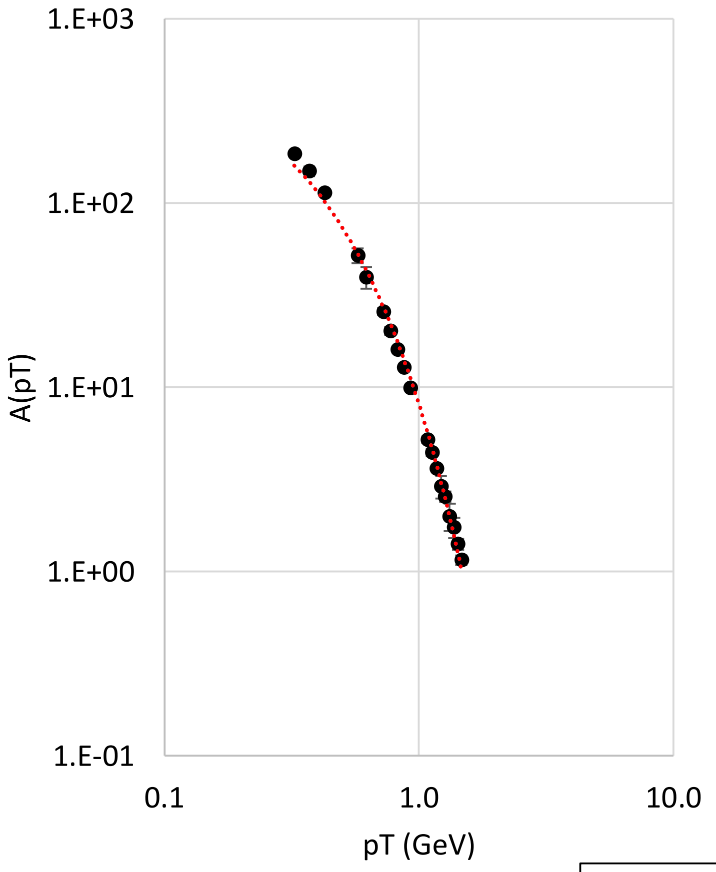
$$\eta(x_R, s, p_T) = \ln\left(\frac{x_R\sqrt{s}}{2p_T} + \sqrt{\frac{x_R s}{4p_T^2} - 1}\right)$$

$$\eta_{max} = \ln\left(\frac{\sqrt{s}}{2p_T} + \sqrt{\frac{s}{4p_T^2} - 1}\right)$$

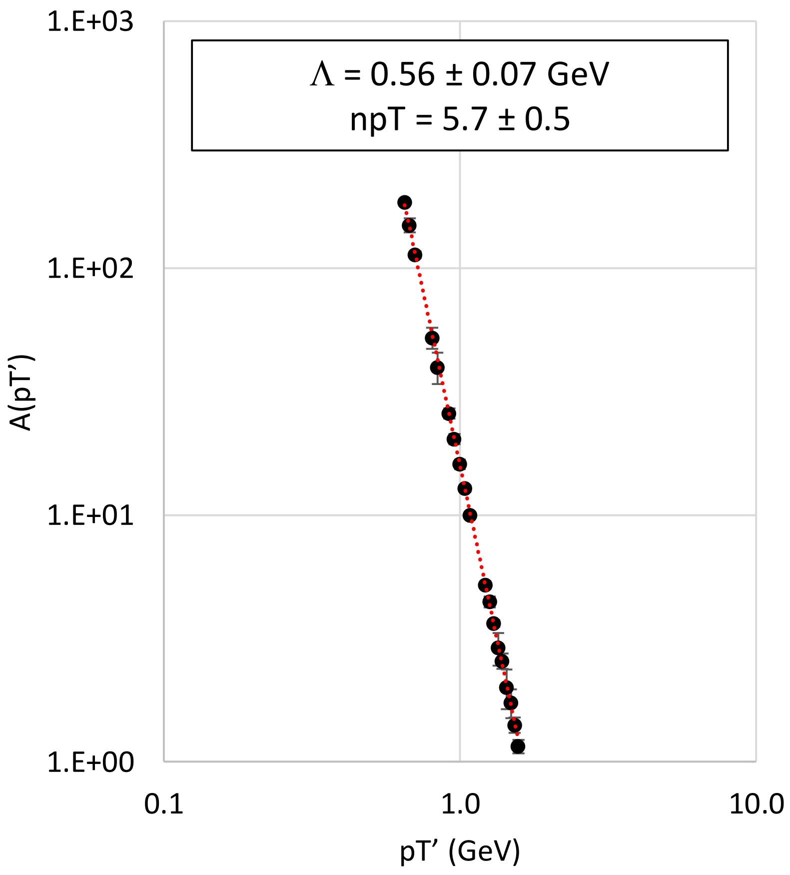
Analyses in constant η couples p_T and x_R so that the hard scattering part of **$d^2\sigma/p_T dp_T d\eta$** that is characterized by p_T is entangled with a change in x_R – the kinematic boundary parameter.

BRAHMS π^+ from Ag-Ag Collisions 62.4 GeV

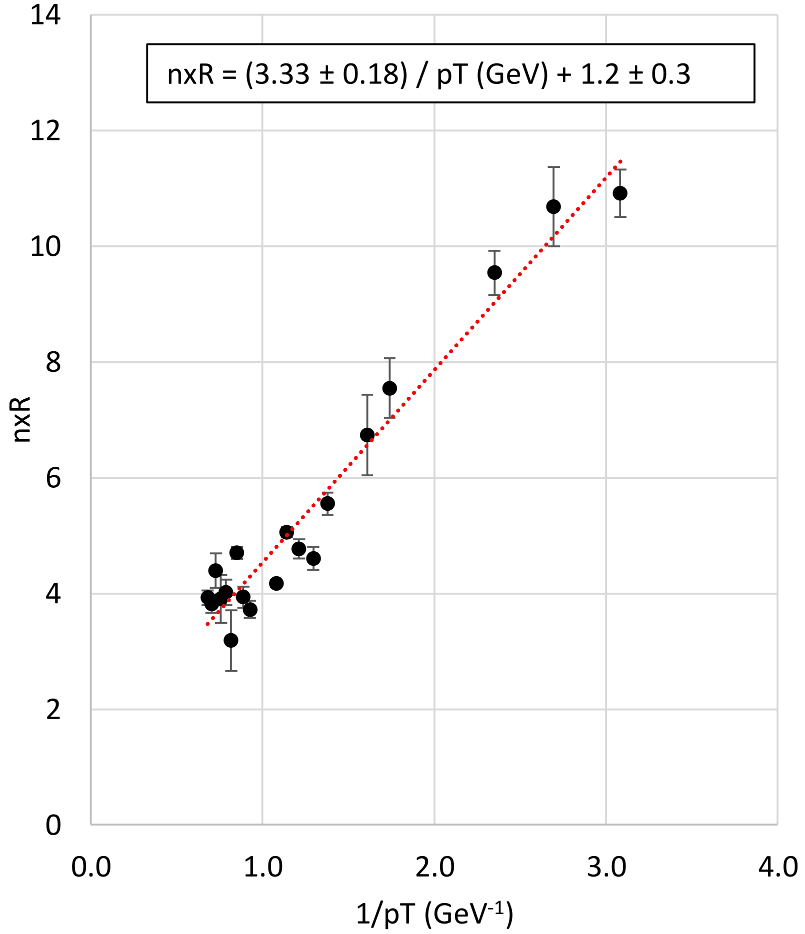
$A(p_T)$ vs. p_T



$A(p_T')$ vs. $p_T' = (\Lambda^2+p_T^2)^{1/2}$

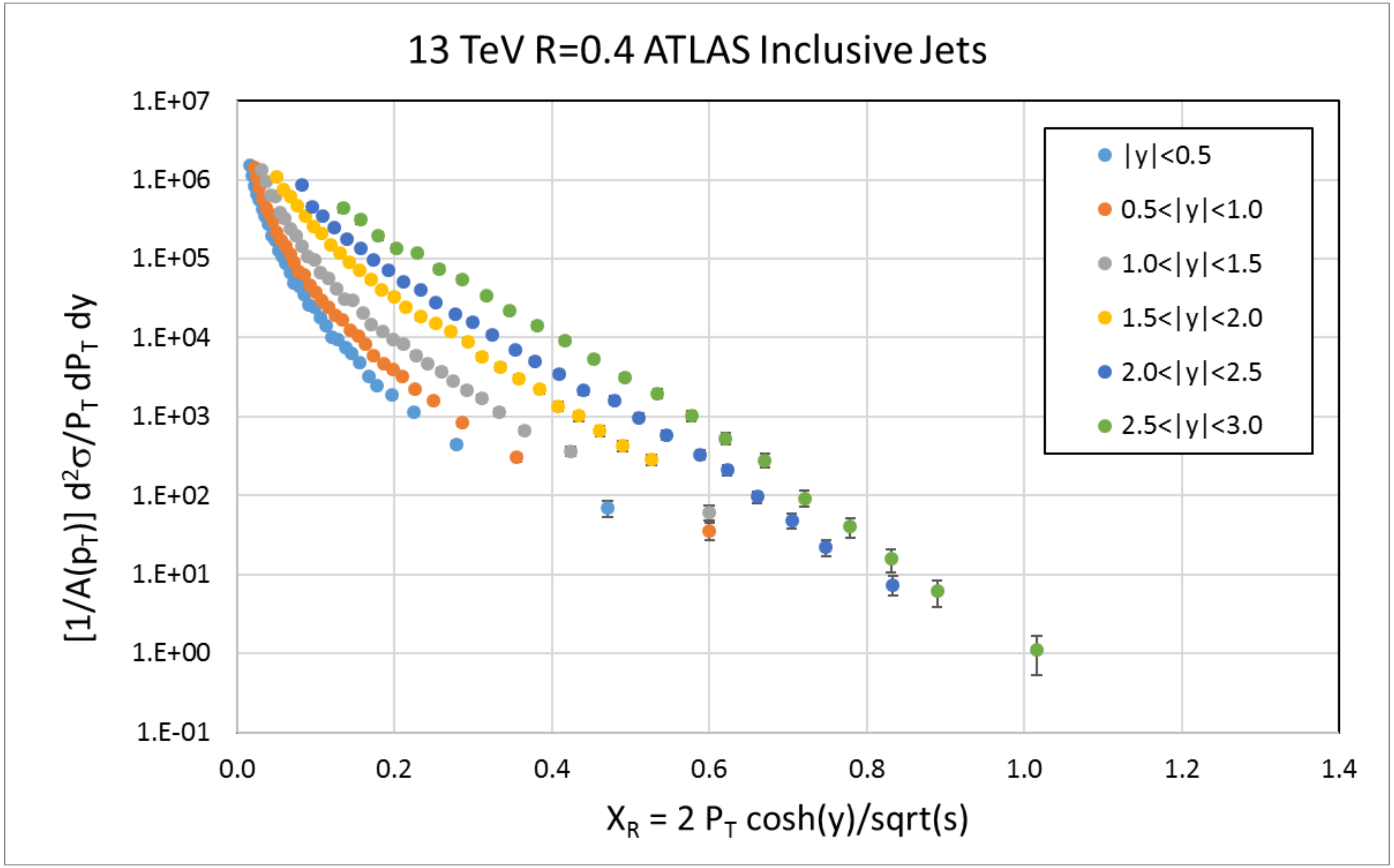


$nxR(1/p_T)$ vs. $1/p_T$



$$A(p_T) = \alpha_0 \frac{\Lambda^{n_{pT}-4}}{\left(\Lambda^2 + p_T^2\right)^{\frac{n_{pT}}{2}}}$$

13 TeV ATLAS Inclusive Jets - Using $A(p_T) \sim p_T^{-4}$



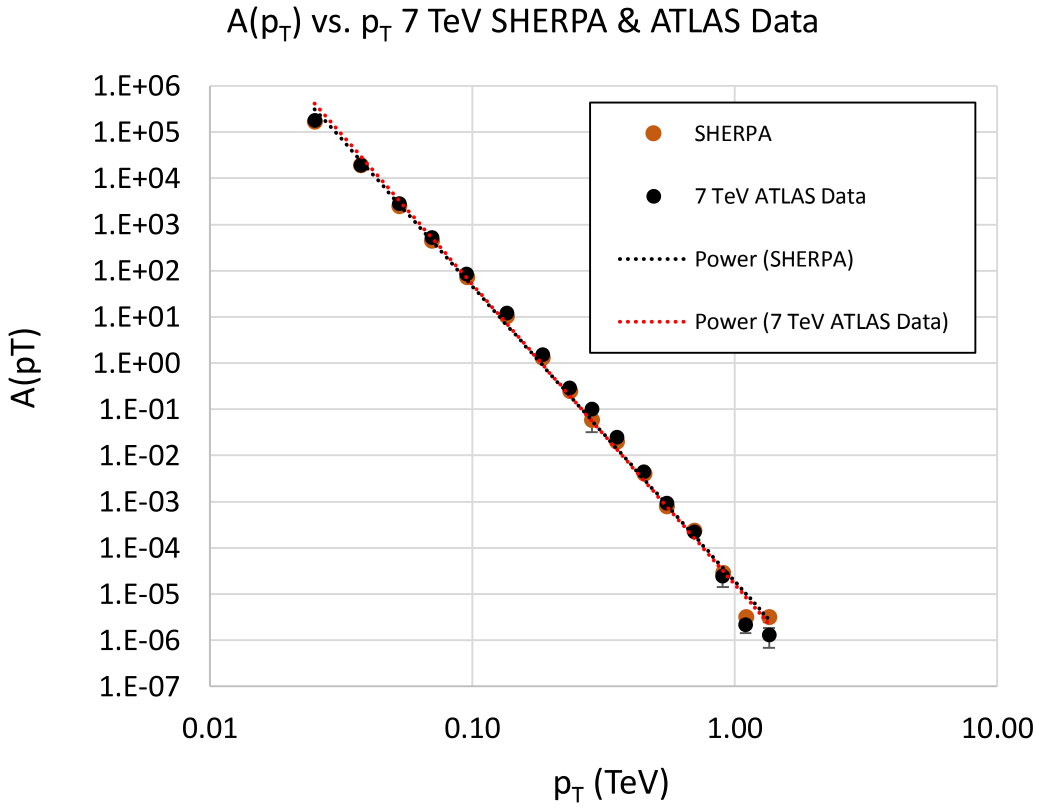
Naively, does not indicate hard 2 → 2 scatterings – such as:

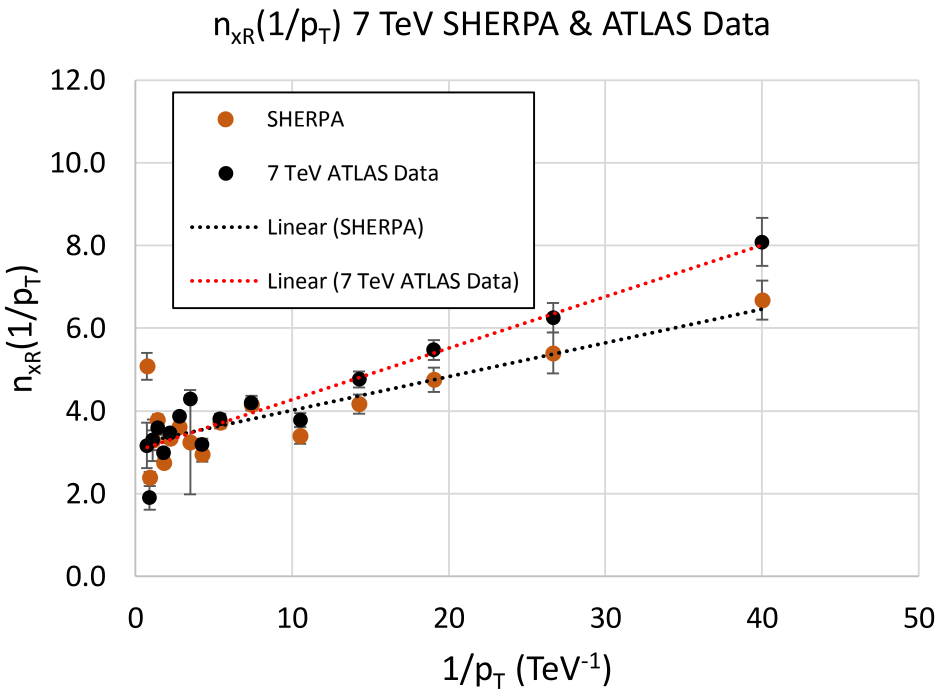
qq→qq
gg→gg
gq→gq

are dominating.

Note: plotted errors are statistical and systematic errors added in quadrature.

SHERPA MC 7 TeV ATLAS





SLAC-PUB 15216
"Uncertainties in NLO + parton shower matched simulations of inclusive jet and dijet production"; Stefan Hoche, Marek Schonherr
Radial scaling analysis reveals systematic difference in n(1/pT).

Data: α = (1.608 ± 0.434)x10^{-5}
n_{pT} = 6.499 ± 0.0125

Data: D=0.125 ± 0.0112
n_{0xR}=3.03 ± 0.16

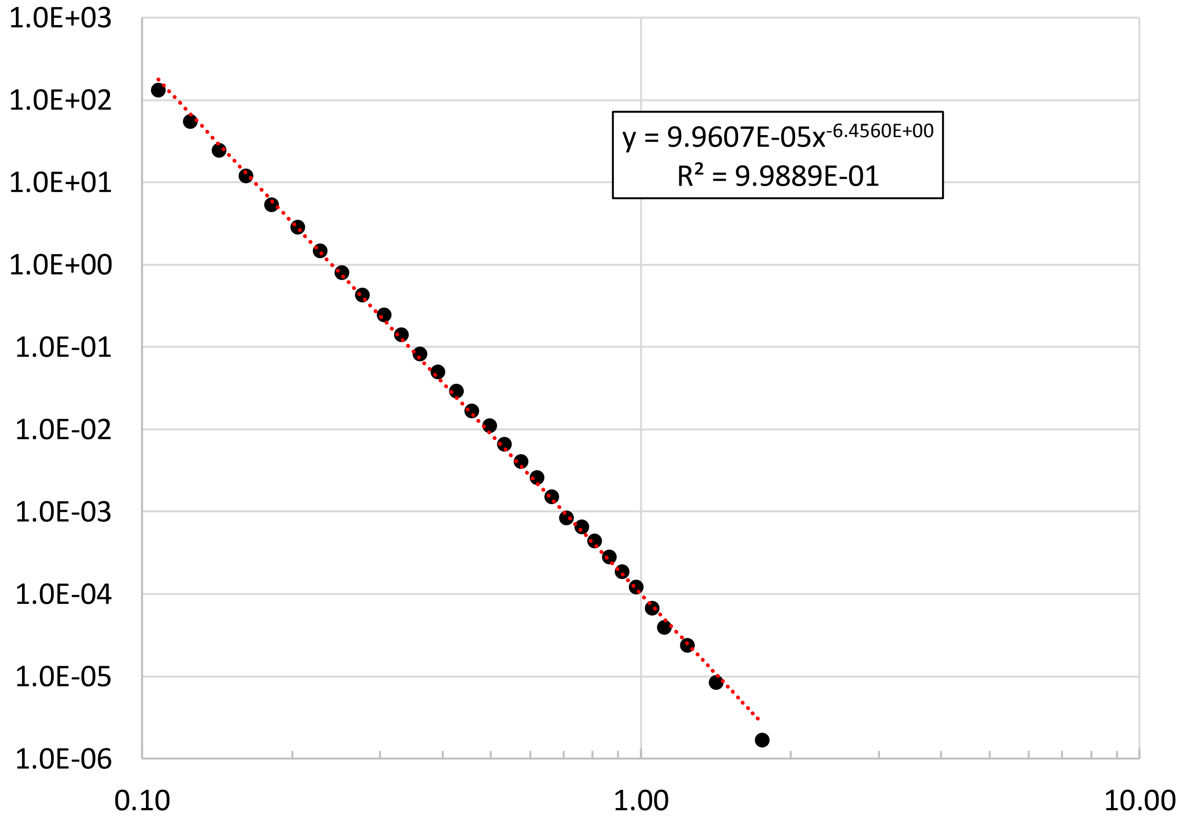
SHERPA: α =(1.895 ± 0.353)x10^{-5}
n_{pT} = 6.380 ± 0.089

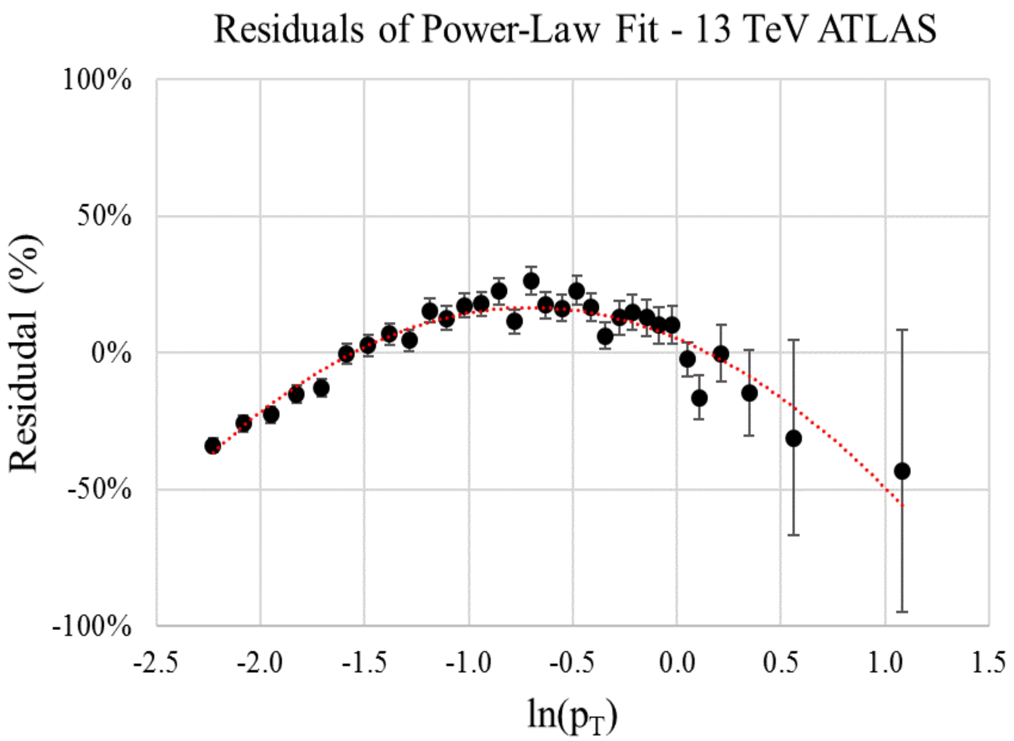
SHERPA: D=0.082 ± 0.015
n_{0xR} = 3.19 ± 0.21

SHERPA underestimates D

Power Law in p_T not 'Perfect'

ATLAS 13 TeV R=0.4 $A(p_T)$ vs. p_T





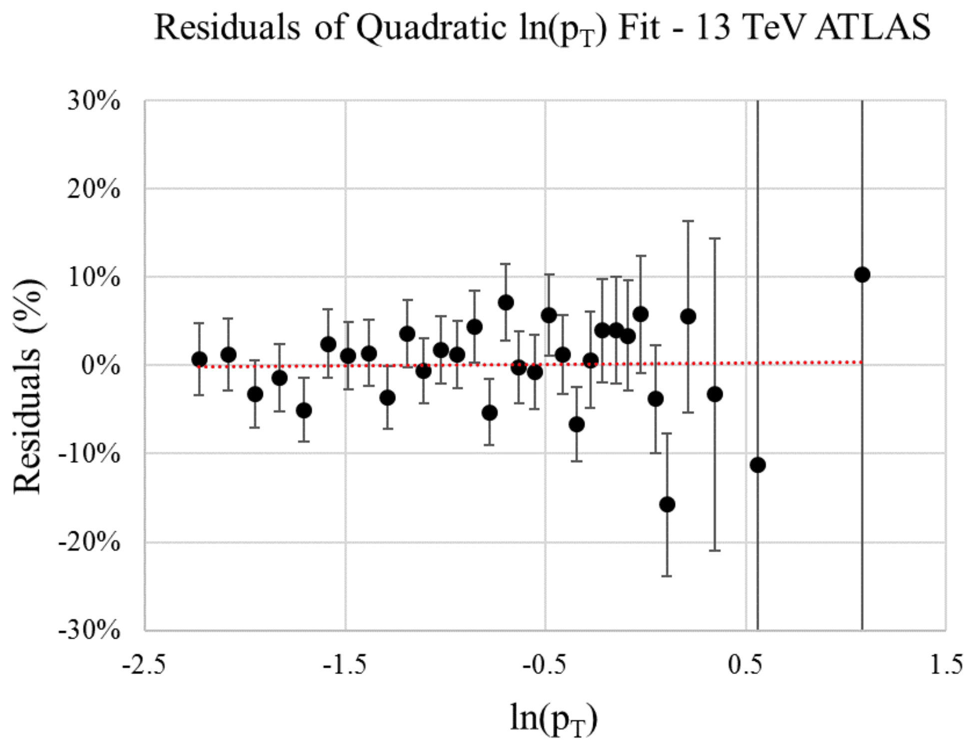
Fit is good over 8 decades but there is a systematic deviation from the power law of ± 20%

$A(p_T,s)$ Quadratic Fit in $\ln(p_T)$

$$\ln\left(A(p_T,s)\right) = \beta(s)\ln(p_T)^2 - n_{p_T}\ln(p_T) + \rho(s)$$

$$A(p_T,s) = \exp\left(\beta(s)\left(\ln(p_T)\right)^2\right)\frac{\alpha(s)}{p_T^{\,n_{pT}}}$$

√s (TeV)	β	α (pb/GeV^2) TeV^{npT}	n_{pT}	χ^2 /d.f.	d.f.
1.96 p̄-p CDF 1.96 p̄-p D0	0.03 ± 0.2	(1.6 ± 0.8) x 10^{-6}	6.7 ± 0.6	0.92	38
2.76 p-p ATLAS	-0.23 ± 0.09	(1.3 ± 0.6) x 10^{-6}	7.5 ± 0.4	1.17	7
7 p-p ATLAS	-0.38 ± 0.05	(1.0 ± 0.1) x 10^{-5}	7.8 ± 0.2	2.50	13
8 p-p CMS	-0.38 ± 0.02	(2.1 ± 0.1) x 10^{-5}	7.62 ± 0.05	4.3	32
13 p-p ATLAS	-0.26 ± 0.01	(9.2 ± 0.1) x10^{-5}	6.92 ± 0.02	0.77	29
13 p-p CMS	-0.32 ± 0.04	(8.7 ± 0.2) x10^{-5}	7.03 ± 0.07	0.48	26



dσ/dη in Toy Model

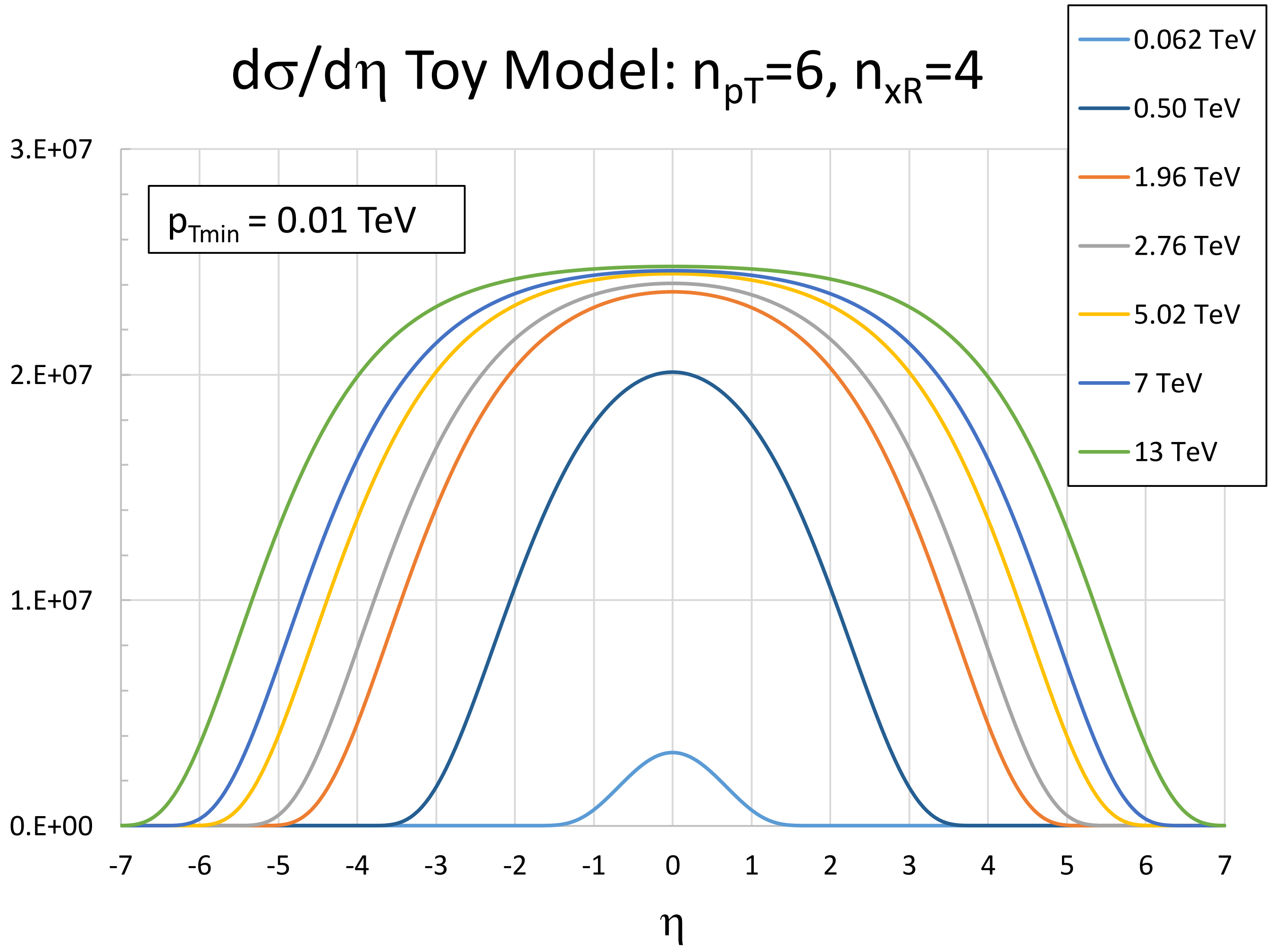
$$\frac{d\sigma}{d\eta} = \int_{p_{T\min}}^{p_{T\max}} \frac{d^2\sigma}{p_T dp_T d\eta} p_T dp_T = \int_{p_{T\min}}^{p_{T\max}} \frac{a}{p_T^{\,n_{pT}}} \left(1 - \frac{2p_T}{\sqrt{s}} \cosh(\eta)\right)^{n_{xR}} p_T dp_T$$

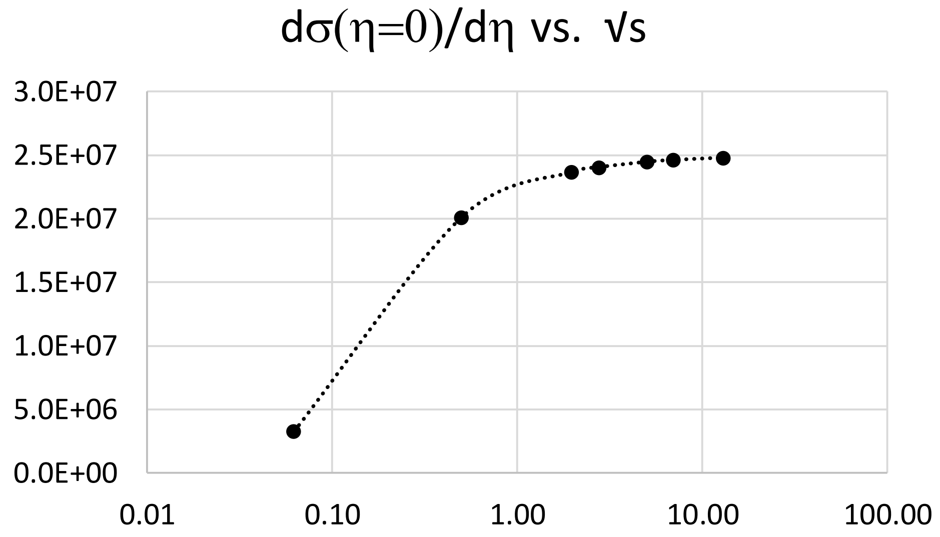
$$\frac{d\sigma\left(p_{T\min}, p_{T\max}\right)}{d\eta} = aF\left(p_{T\min}, p_{T\max}, \frac{\cosh(\eta)}{\sqrt{s}}\right)$$

p_{Tmin} is the minimum transverse momentum cut ($p_T \geq p_{Tmin}$)

For fixed p_{Tmin} and parameter a, all η dependence through cosh(η)/√s

Pseudo-rapidity Plateau in Toy Model



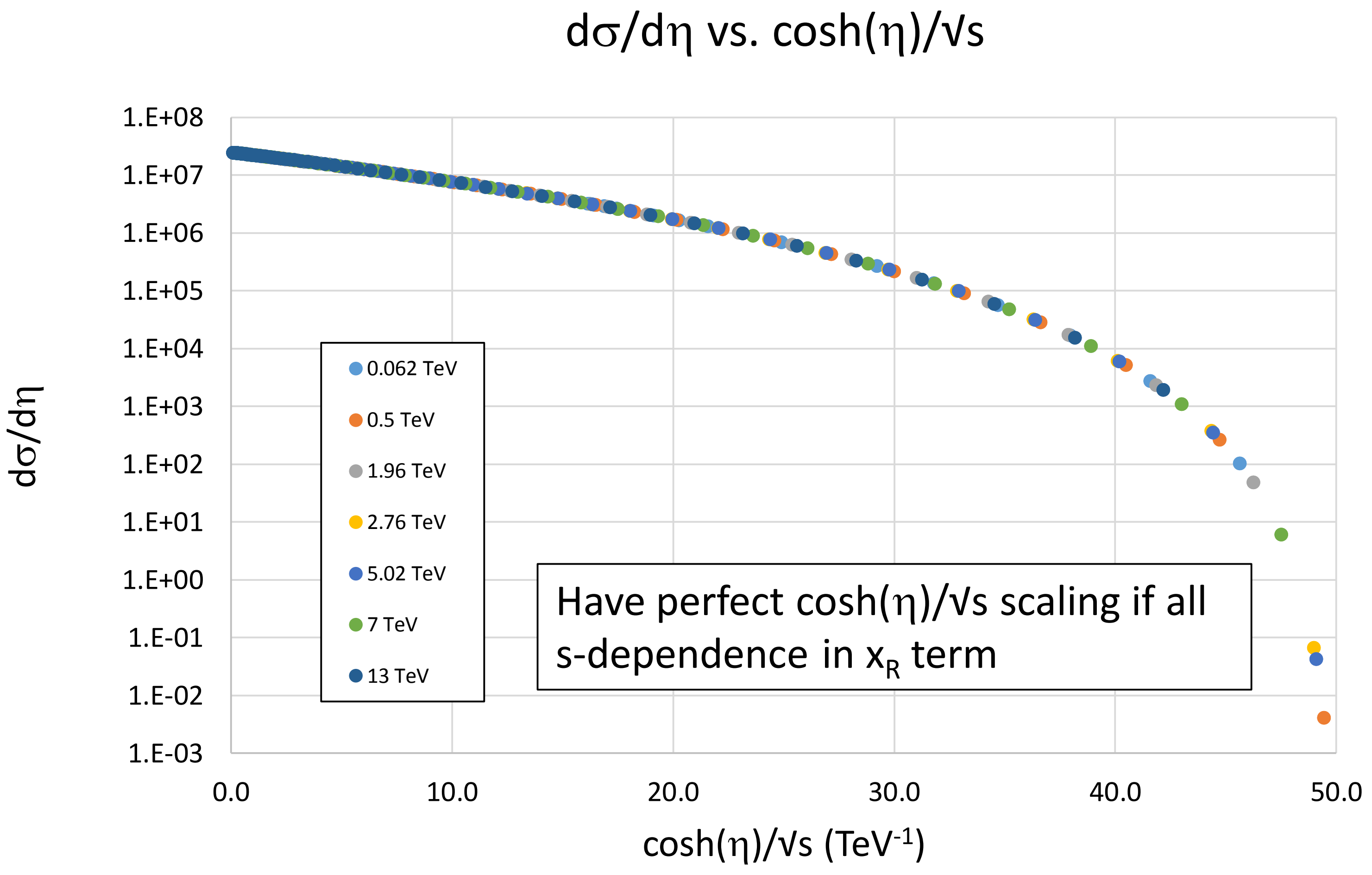


Width of plateau controlled by kinematic limit:

$$\eta_{\max} = \ln\left(\frac{\sqrt{s}}{2p_T} + \sqrt{\frac{s}{4p_T^2} - 1} \right)$$

dN/dη on plateau η ≈ 0 grows by kinematics – (no QCD required)

dN/dη is a function of cosh(η)/√s



Toy Model
$n_{pT} = 6$
$n_{xR} = 4$
p_{Tmin} = 10 GeV

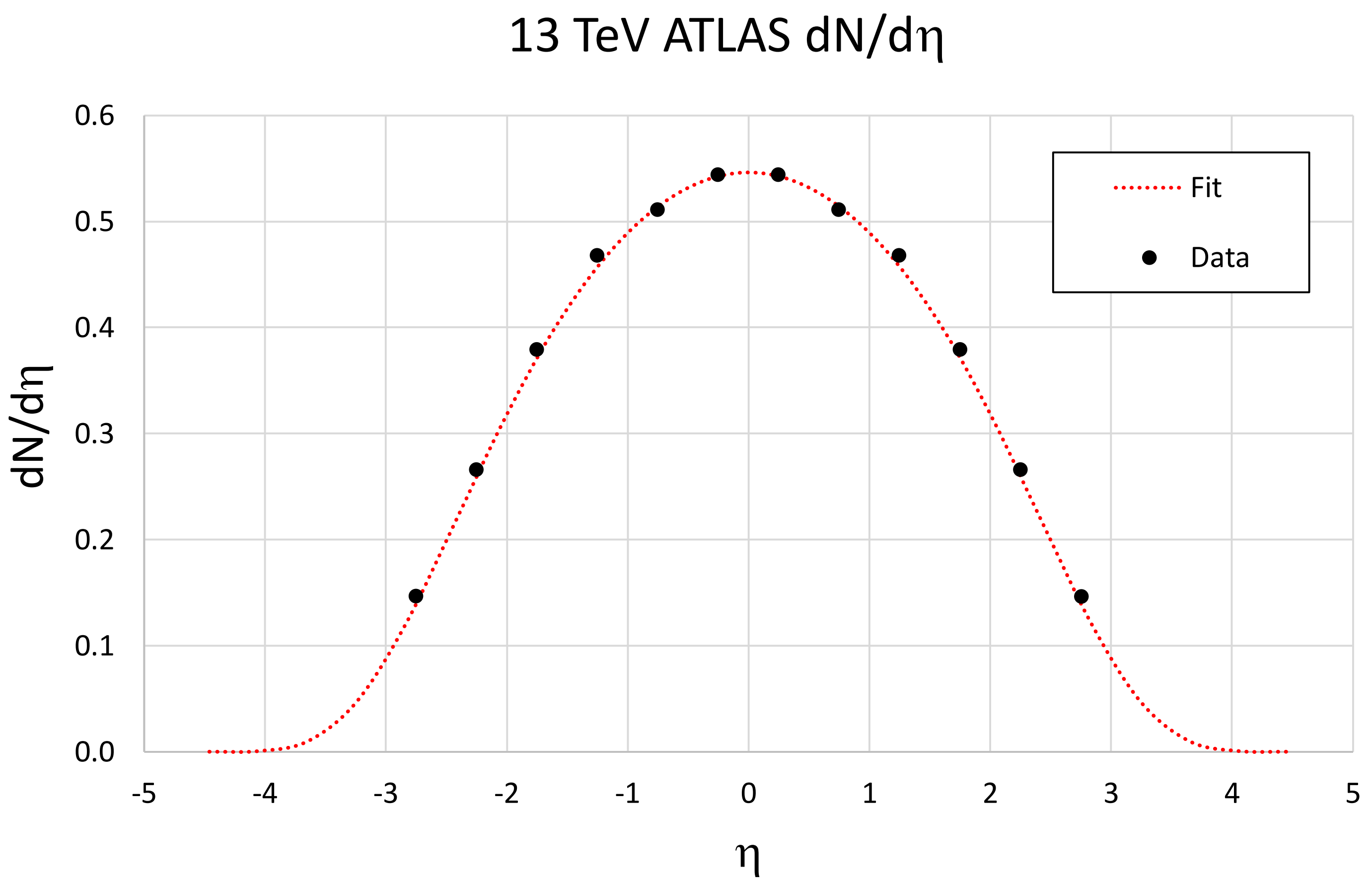
First shown in (1979):
"Interpretation of the Rise in Central Rapidity Density in Terms of Radial Scaling",

R. W. Ellsworth,

16th International Cosmic Ray Conference, Vol. 7. Published by the Institute for Cosmic Ray Research, University of Tokyo

http://adsabs.harvard.edu/abs/1979ICRC....7..333E

Check of Rapidity Distribution of Jets



- Fit: $p_T > 0.1$ TeV with numerical integration of fit function un-normalized.

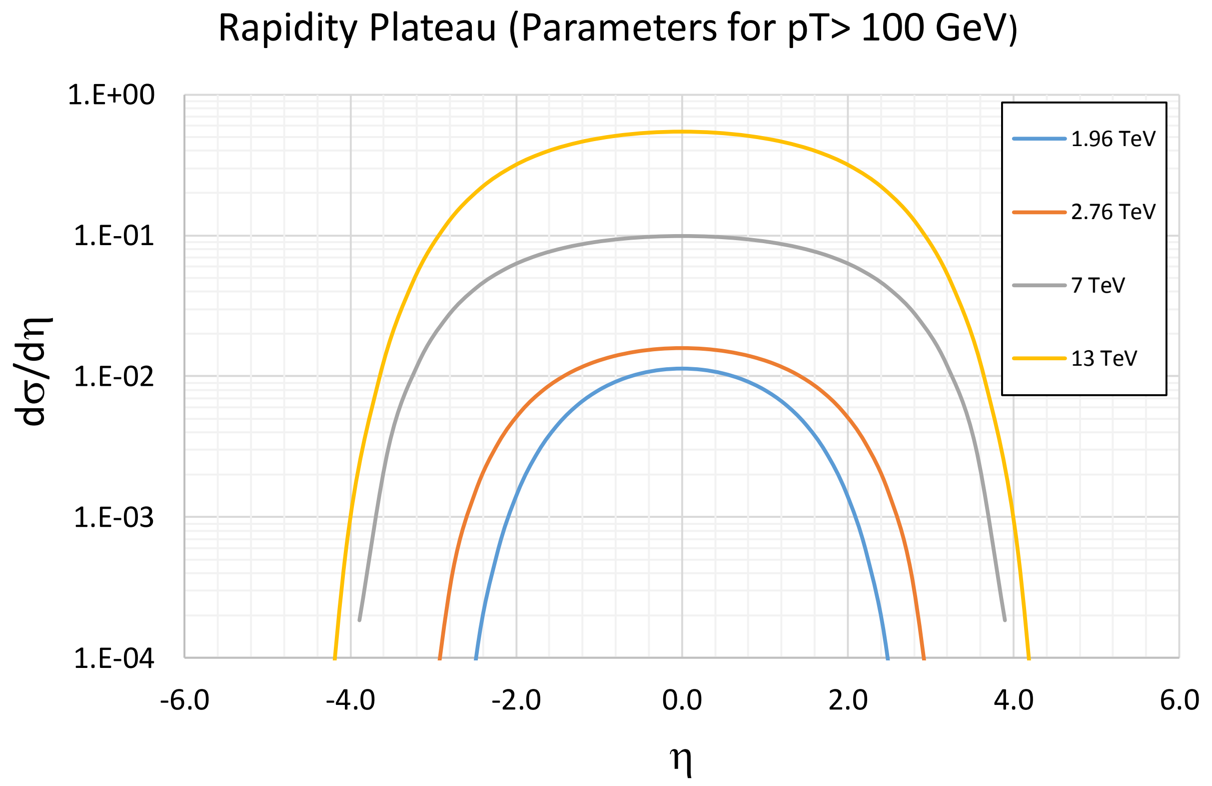
$$\frac{d^2\sigma}{p_T dp_T d\eta} \sim A(p_T)(1-x_R)^n$$

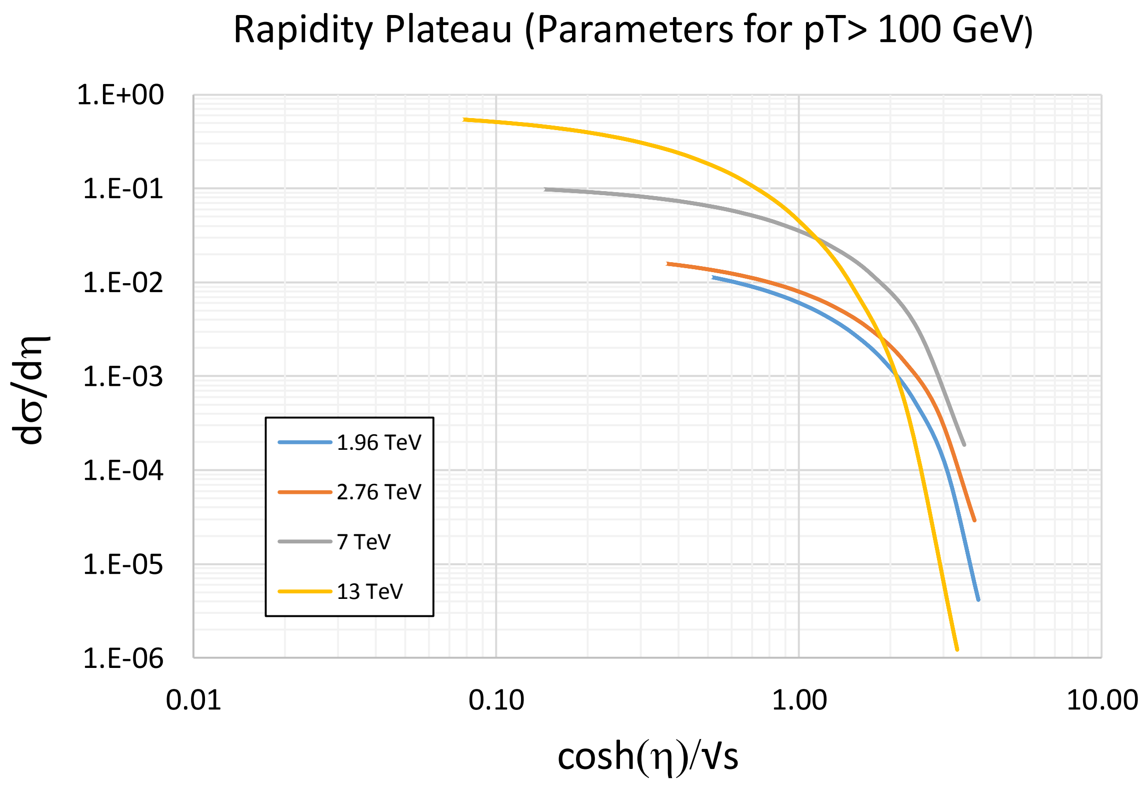
- Data:

$$\frac{dN}{d\eta} \sim \sum_i \frac{d^2\sigma_i}{p_{Ti} dp_T d\eta} p_{Ti} \Delta p_T$$

Pseudo-rapidity Distribution for Measured Jets

Used the fits of the inclusive jet cross sections: {$\alpha(\sqrt{s})$, npT($\sqrt{s}$), D($\sqrt{s}$), $n_{0xR}(\sqrt{s})$} CDF & ATLAS

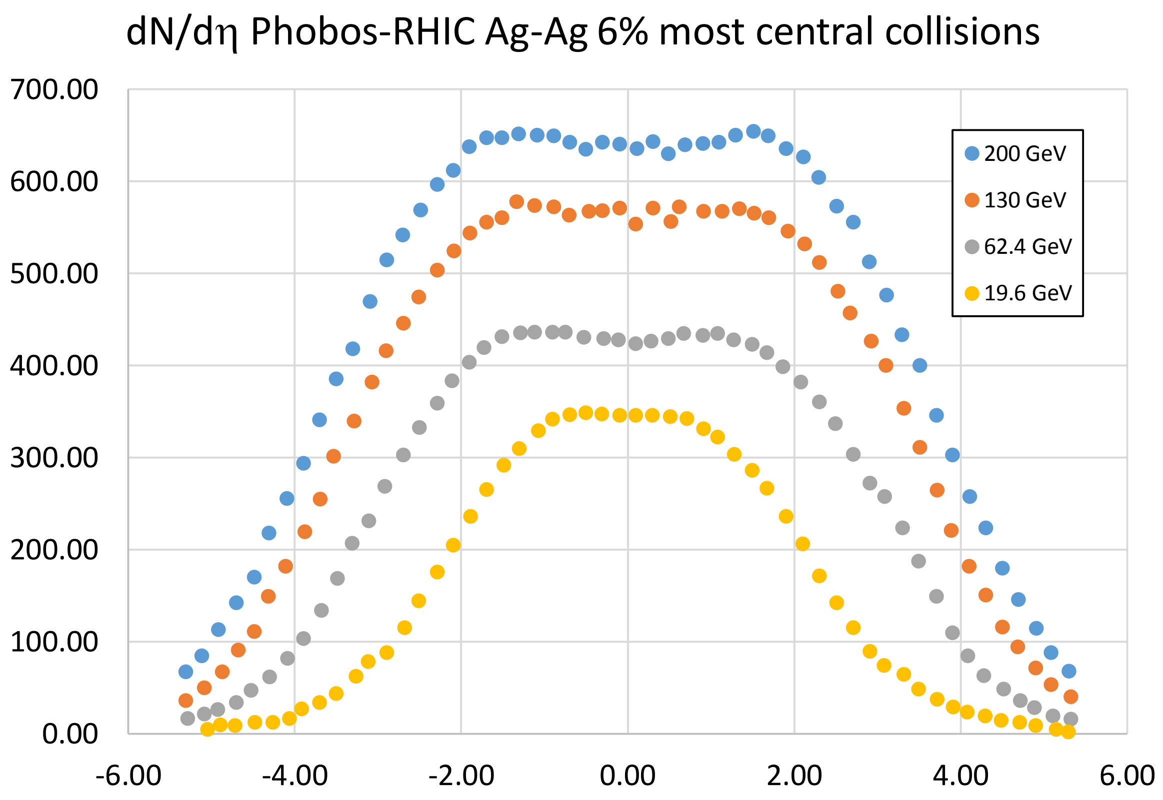


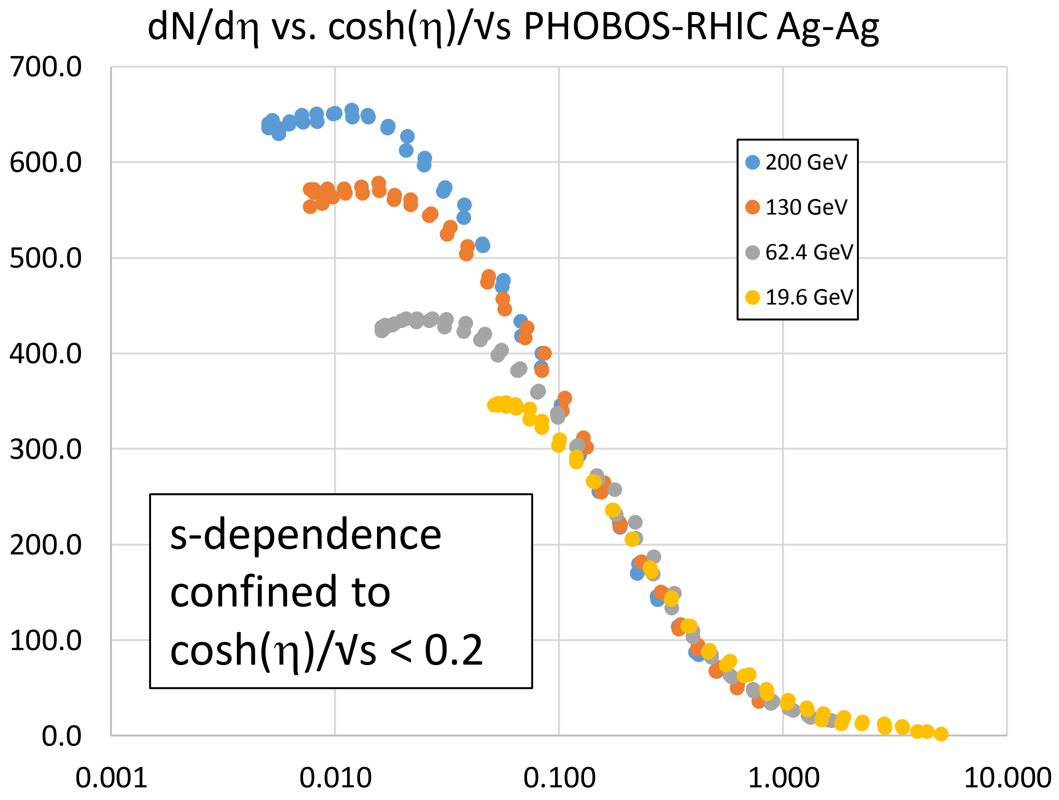


13 TeV is different because of large 'D' term for nxR = D/pT+n0xR

PHOBOS dN/dη

B.B. Black, et al.
arXiv:nucl-ex/0509034v1 28 Sep 2005
B-field = 0 (very low pTmin)





Region of scaling is high η. Note that cosh(η)/√s scaling similar to η' scaling – see backup.

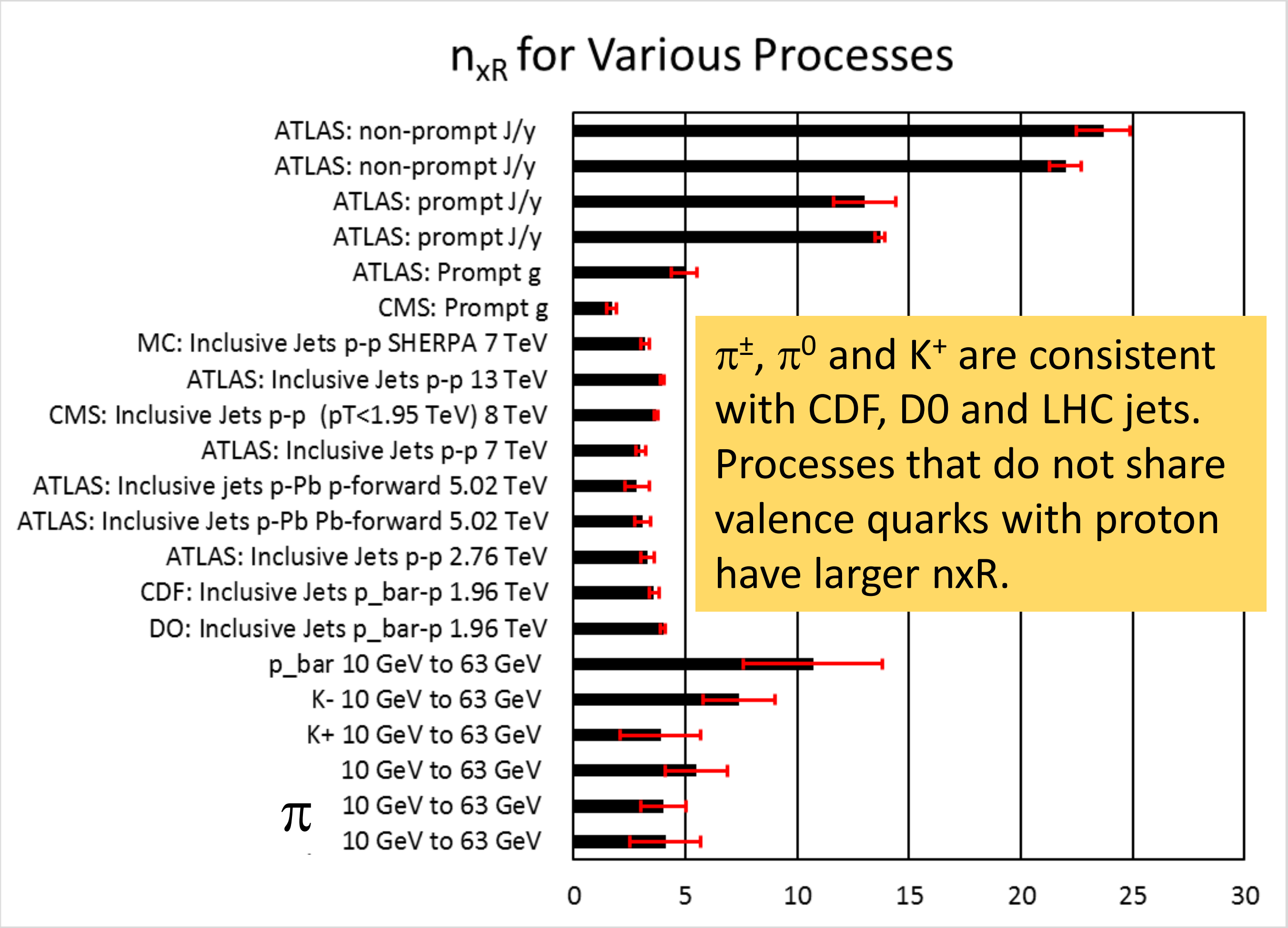
What about the x_R-Dependence

- Inclusive cross section roughly factorizes: $\sigma \sim A(p_T)\ (1-x_R)^{nxR}$

  - Would expect that $n_{xR} = n_{xR}(\sqrt{s}, p_T, \text{process})$ to characterize the fragmentation and hadronization of primordial quark/gluon.
  - Quark line-counting rules suggest $n_{spectator}$,the number of non-participating quarks in the primary collision, controls the $(1-x_R)$ power:

$$\frac{d^2\sigma}{p_T dp_T dy} \sim A(p_T)(1-x_R)^{2n_{spectator}-1}$$

Summary of $(1-x_R)^{n_{xR}}$ Power



Notes:

1. Qualitatively $n_{xR} \approx 2\, n_{spectator} - 1$
2. In cases where n_{xR} is roughly independent of p_T the average values and standard deviations are plotted.
3. In cases where there is a significant $1/p_T$ dependence the value n_{xR0} is plotted, where: $n_{xR}(1/p_T) = D/p_T + n_{xR0}$ and the error of n_{xR0} is shown.
4. Caveat: J/ψ data show inconsistencies among experiments. Trend shown is consistent but details not clear. See backup.

Parton-Parton Elastic Scattering – 2 Examples

Functions of the Mandelstam variables s, t, u and α_s. All have dimensions of (energy)$^{-4}$.

$$\frac{d\hat{\sigma}\left(\hat{s},\hat{t},\hat{u};ud \to ud\right)}{d\hat{t}} = \frac{4\pi\alpha_s^2}{9\hat{t}^2}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}^2}$$

$$\frac{d\hat{\sigma}\left(\hat{s},\hat{t},\hat{u};gg \to gg\right)}{d\hat{s}} = \frac{9\pi\alpha_s^2}{2\hat{s}^2}\left(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$$

$$\hat{s} = \left(p_a + p_b\right)^2 = \frac{s}{4}\left(x_1 + x_2\right)^2$$

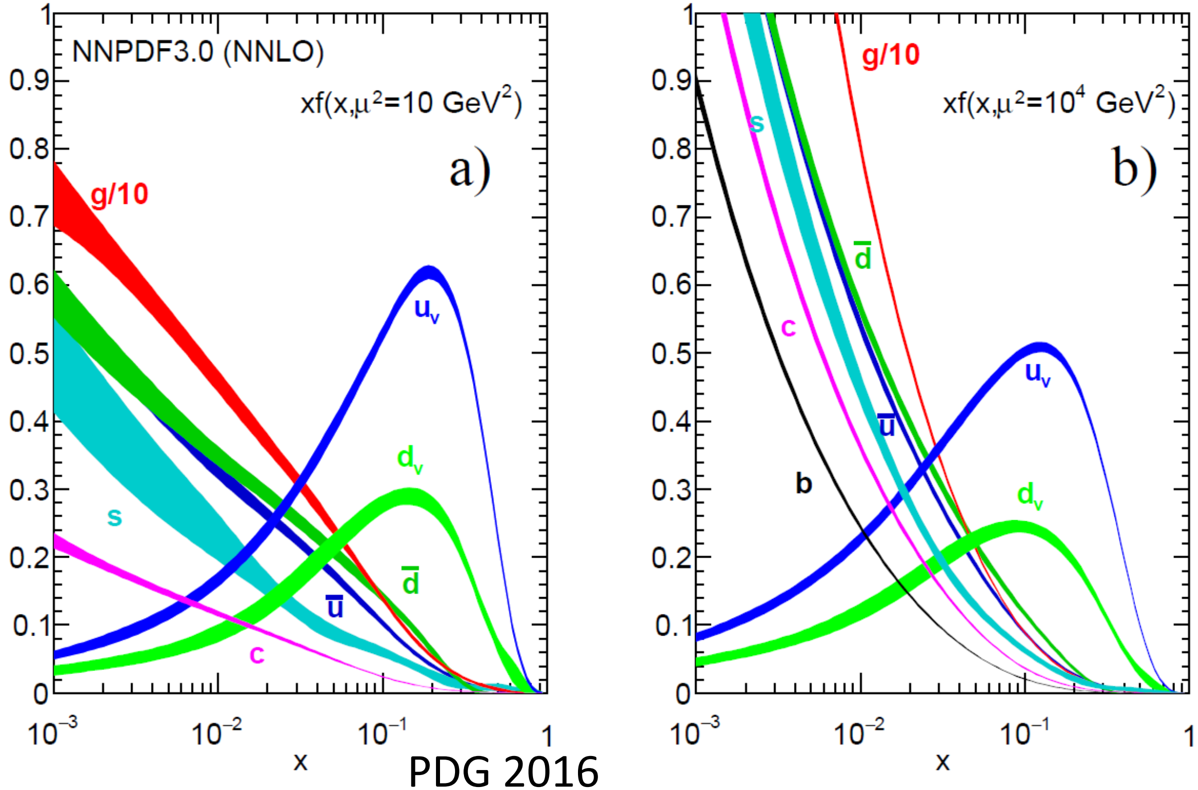
$$\cos\theta = \left(1-\frac{p_T^2}{\hat{s}}\right)^{1/2}$$

$$\hat{t} = -\frac{\hat{s}}{2}(1-\cos\theta)$$

$$\hat{u} = -\frac{\hat{s}}{2}(1+\cos\theta)$$

PDF and DGLAP Evolution and Splitting Functions

Parton Distribution Functions (mostly from DIS Lepton-Nucleon Scattering):

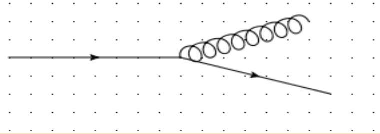


PDG 2016

DGLAP evolution and splitting functions:

$$\frac{\partial f_a}{\partial \ln \mu^2} \sim \frac{\alpha_s(\mu^2)}{2\pi} \sum_b \left(P_{ab} \otimes f_b\right)$$

$$P_{qg}(x) = \frac{1}{2}\left[x^2 + (1-x)^2\right]...$$



These *10s of parameters and factors* are put together in simulations of inclusive jet production at the LHC.

Integrate over x_R to find p_T Dependence

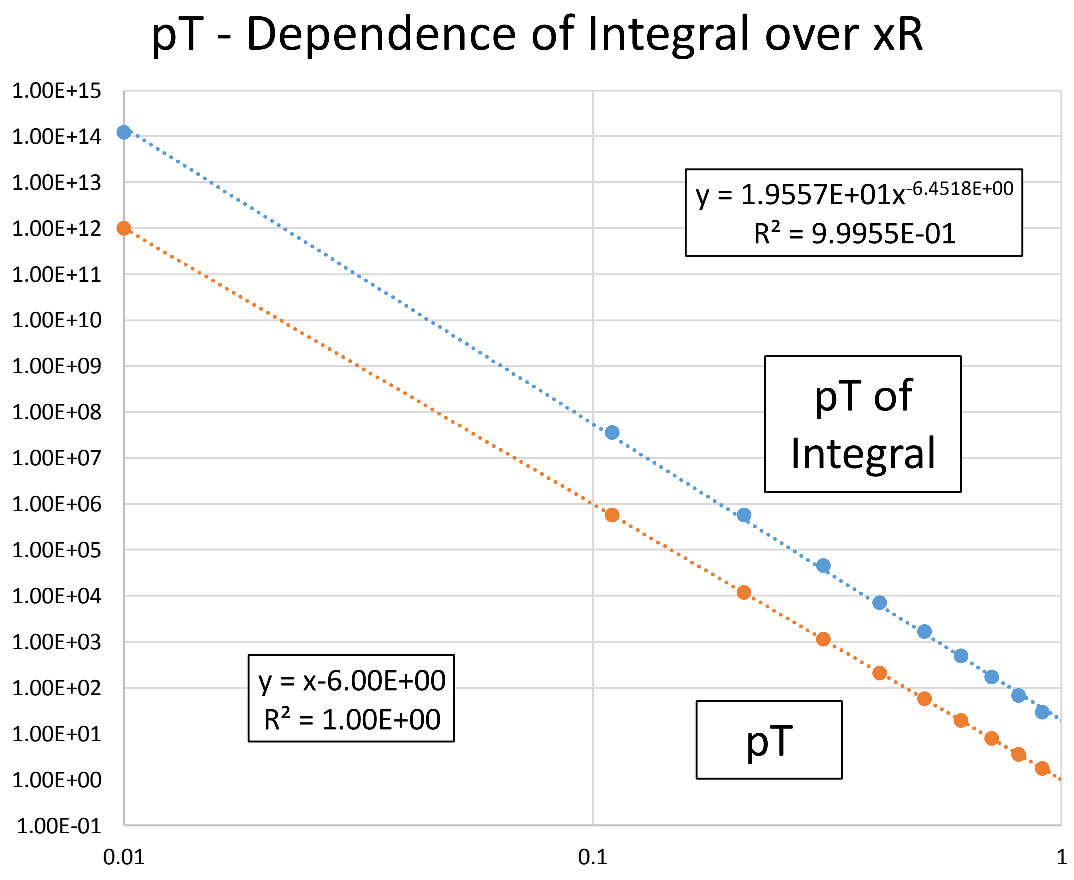
- J. Thaler suggested:

$$\frac{1}{p_T^{neff}} \sim \int_{x_{R\min}}^{1} \frac{d^2\sigma}{p_T dp_T dy} \begin{pmatrix} p_T & y \\ p_T & x_R \end{pmatrix}_J dx_R$$

$$= \int_{x_{R\min}}^{1} \frac{d^2\sigma}{p_T dp_T dy} \frac{2}{\sqrt{x_R^2 - x_{R\min}^2}} dx_R$$

$$x_{R\min} = \frac{2p_T}{\sqrt{s}}$$

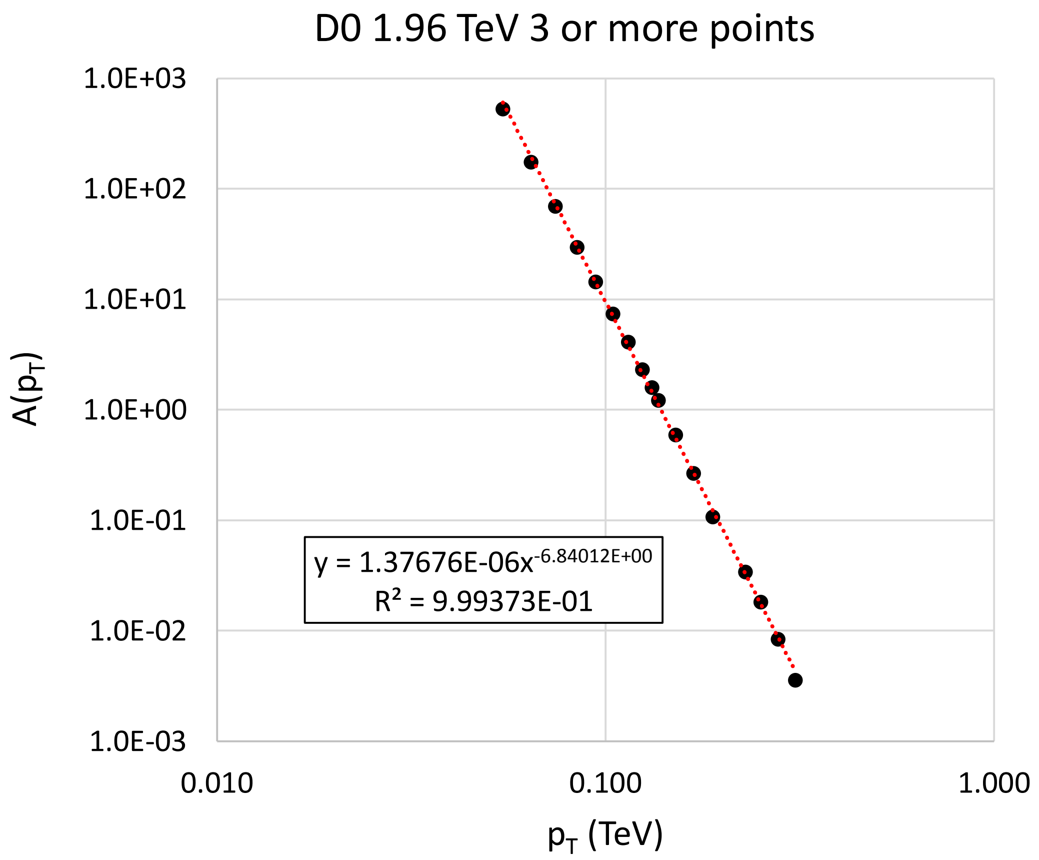
n_{pT} increases from 6.0 to 6.45.
Tested with toy model.

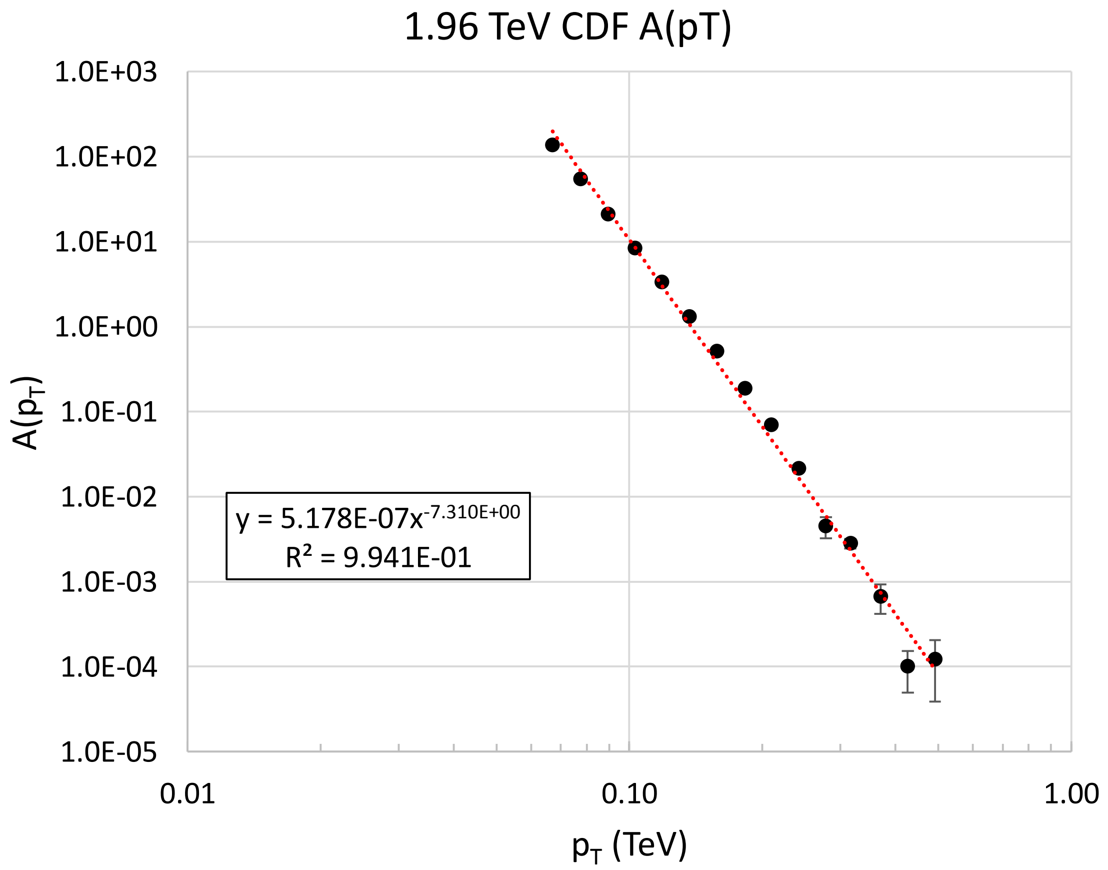


Interesting suggestion – integration can be extended to determine the moments of the “fragmentation” function $(1-x_R)^{nxR}$.

p_bar-p Inclusive Jet Production

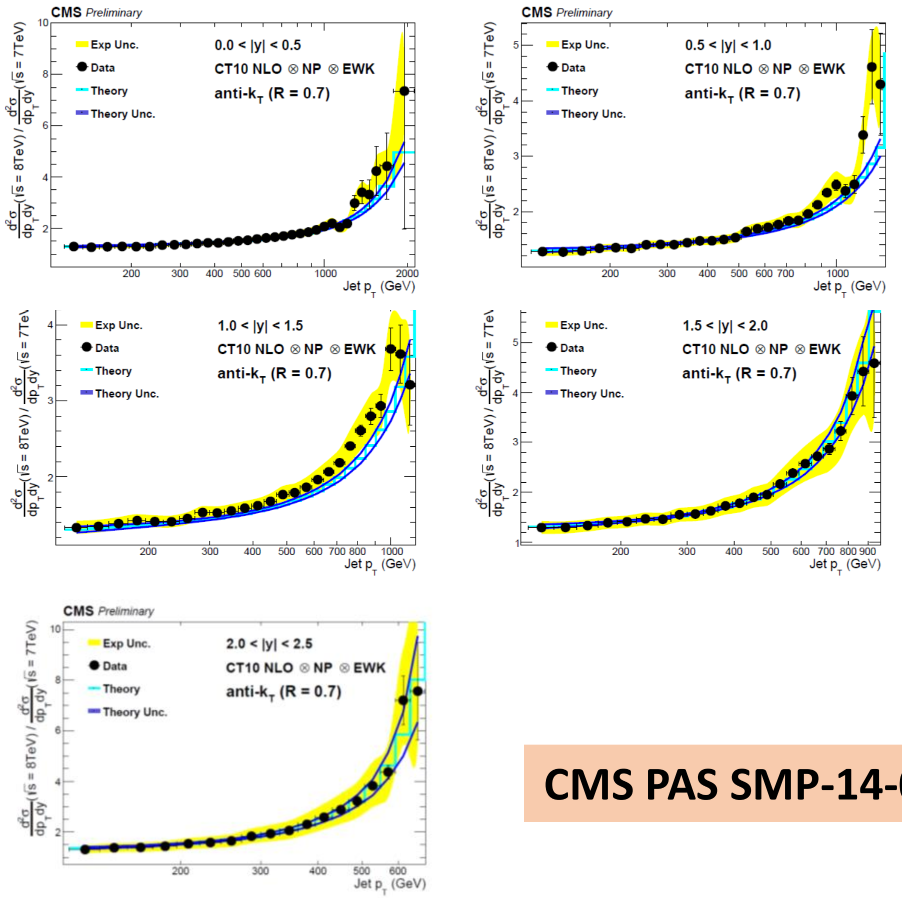
- Valence q-anti-q scattering/annihilation



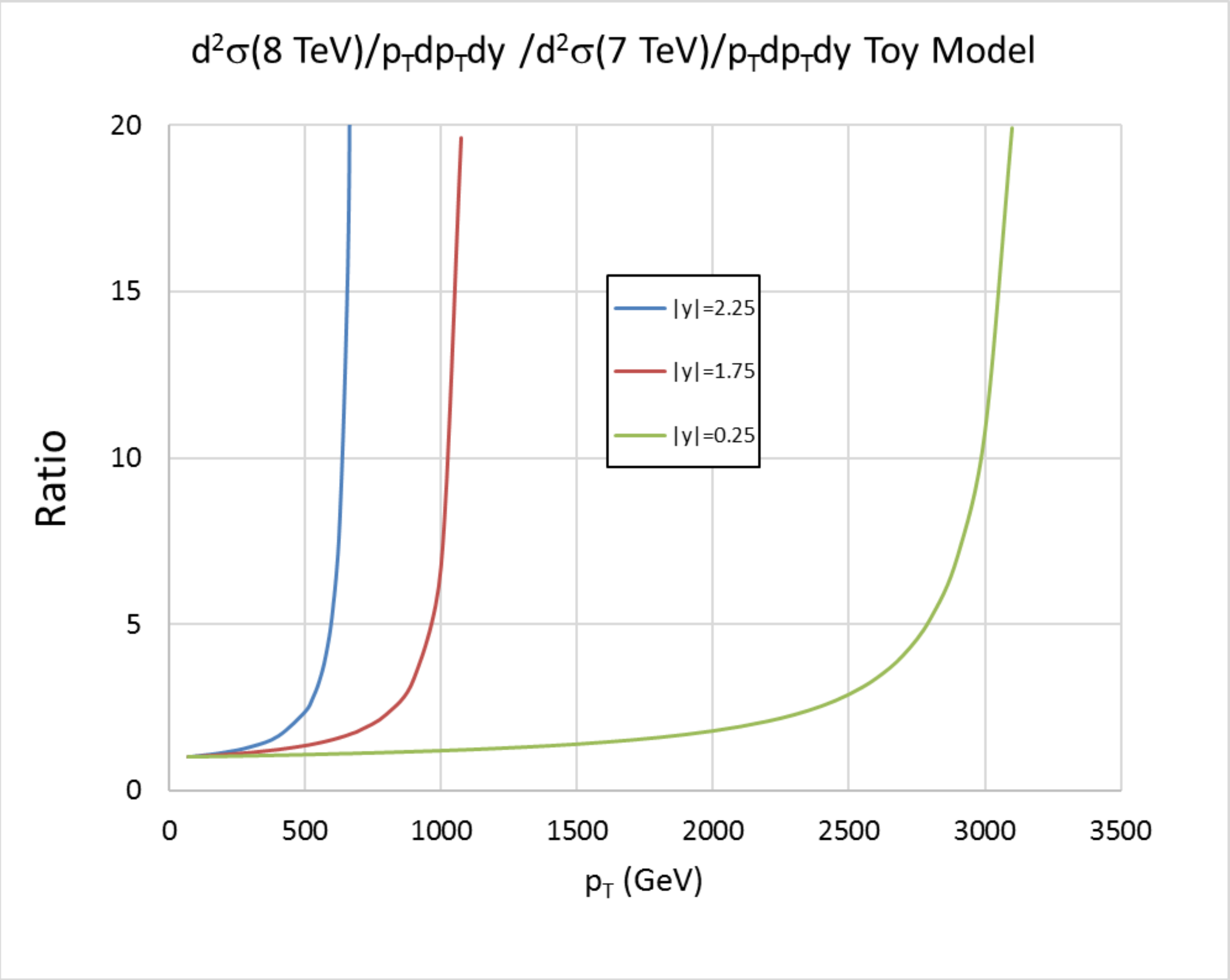


An Example of x_R-dependence near Kinematic Boundary

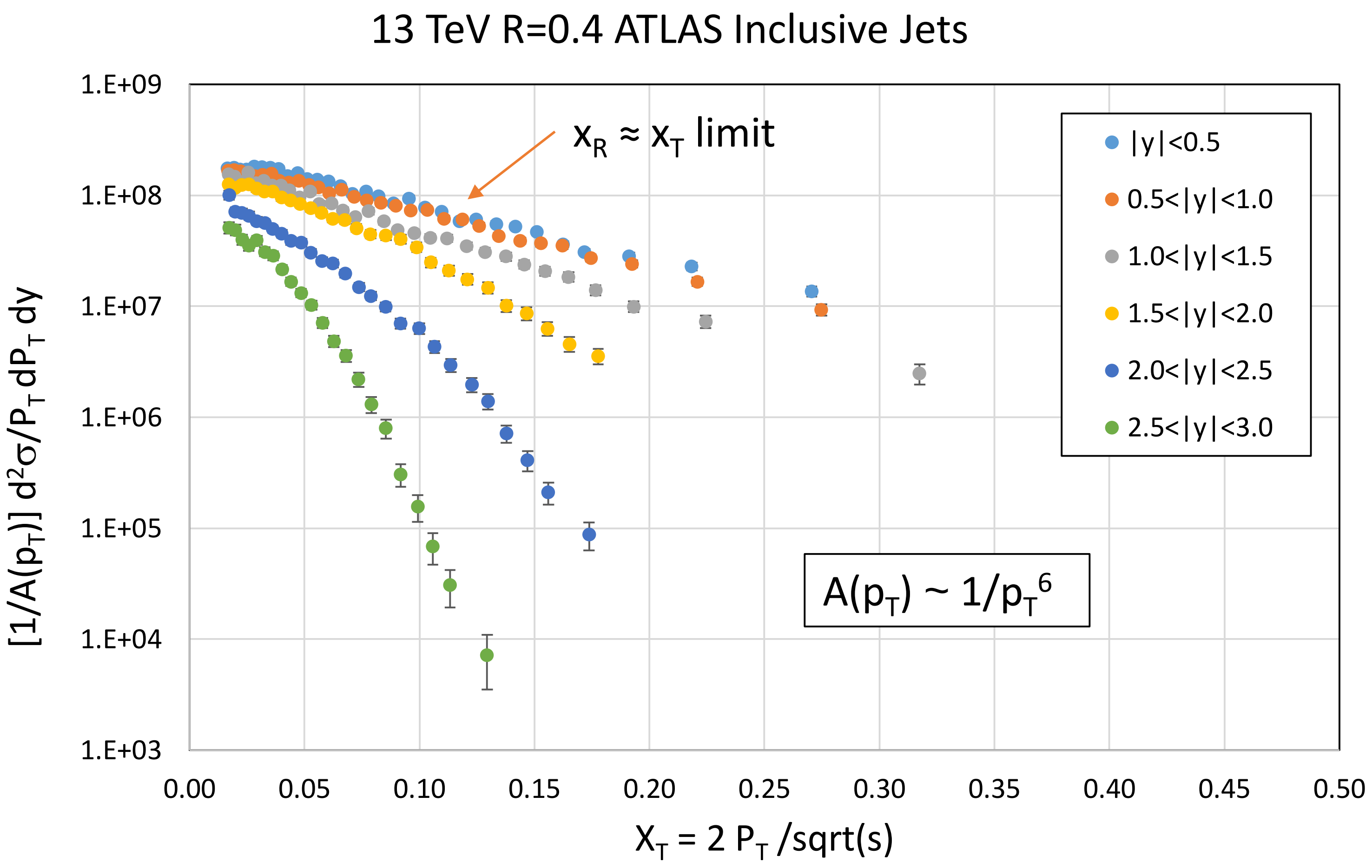
- CMS Inclusive Jets 8 TeV / 7 TeV



CMS PAS SMP-14-001



Arleo, et al.* – x_T Analysis to Determine n_{pT}



$$E\frac{d^3\sigma}{dp^3}(ab \rightarrow cX) = \frac{F(x_T,\theta)}{p_T^n}$$

Studied the approach to x_T scaling, evident for small |y| but misses the main feature. Scaling is in x_R not x_T namely $F(x_T,\theta) = F(x_R)$ and the jet cross sections grow with increasing s through the amplitude term $\alpha(s)$.

*[Arleo,Brodsky,Hwang and Sickles; arXiv:0911.4604v2, PRL 105,06200 (2010)]

Replication of the Analysis – Assume x_T Scaling

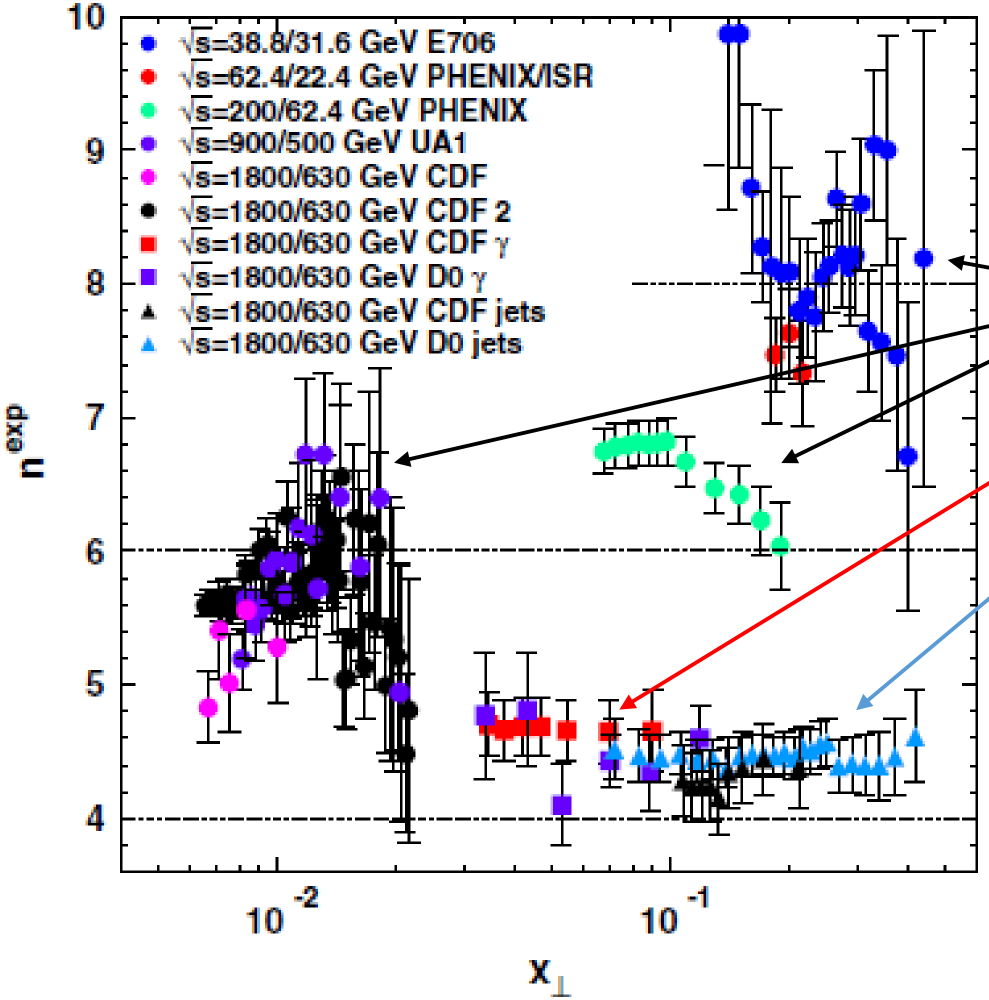
- Assume

$$\sigma^{inv} \equiv E\frac{d^3\sigma}{dp^3}(AB \to CX) = \frac{F(x_T,\theta)}{p_T^n}$$

$$\sigma^{inv}(AB \to CX) \propto \frac{(1-x_T)^{2n_{spectator}-1}}{p_T^{2n_{active}-4}}$$

$$n^{\exp} = \frac{-\ln\left(\sigma^{inv}(x_T,\sqrt{s_1})/\sigma^{inv}(x_T,\sqrt{s_2})\right)}{\ln\left(\sqrt{s_1}/\sqrt{s_2}\right)}$$

Arleo - continued



x_T analysis: power of p_T depends on x_T and process.

$h^{\pm}/\pi^0$ – circles

γ – squares

Jets – triangles

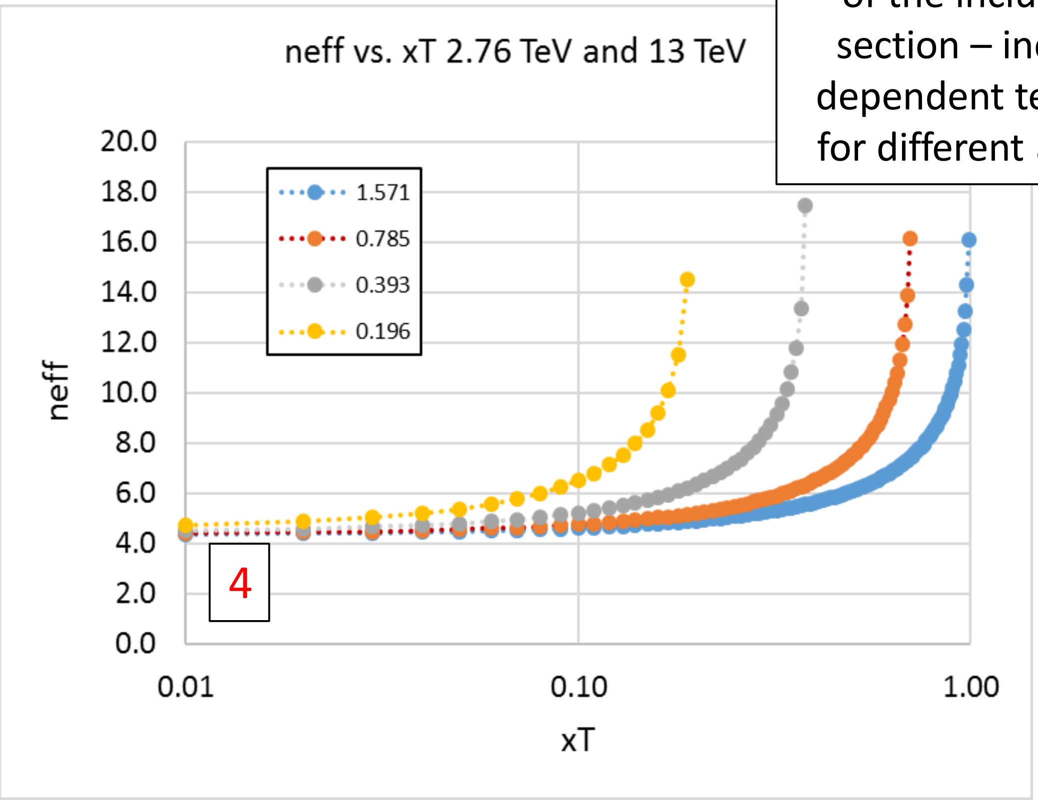
n^{exp} determined in a two component model by variation in x_T and p_T for two values of √s.

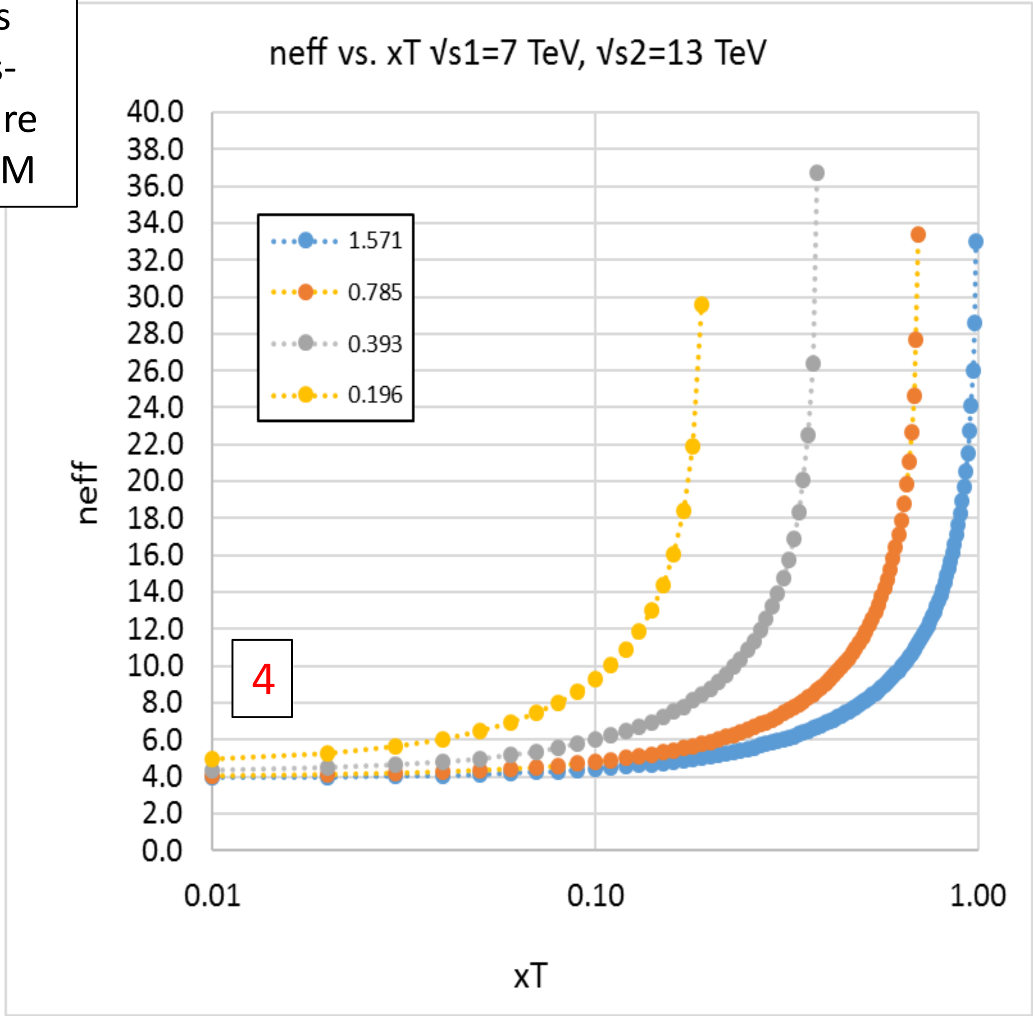
The x_R analysis finds power of p_T independent of process within errors: $n_{pT} = 6.5 \pm 0.4$

Fig. from Arleo, et al.; arXiv:0911.4604v2, PRL 105,06200 (2010)

n_{eff} without correction term using ATLAS Jet Fits

Use the full parameterization of the inclusive Jet cross section – including the s-dependent terms. Plots are for different angles in COM





Find n_{eff} -> 4 as x_T -> 0

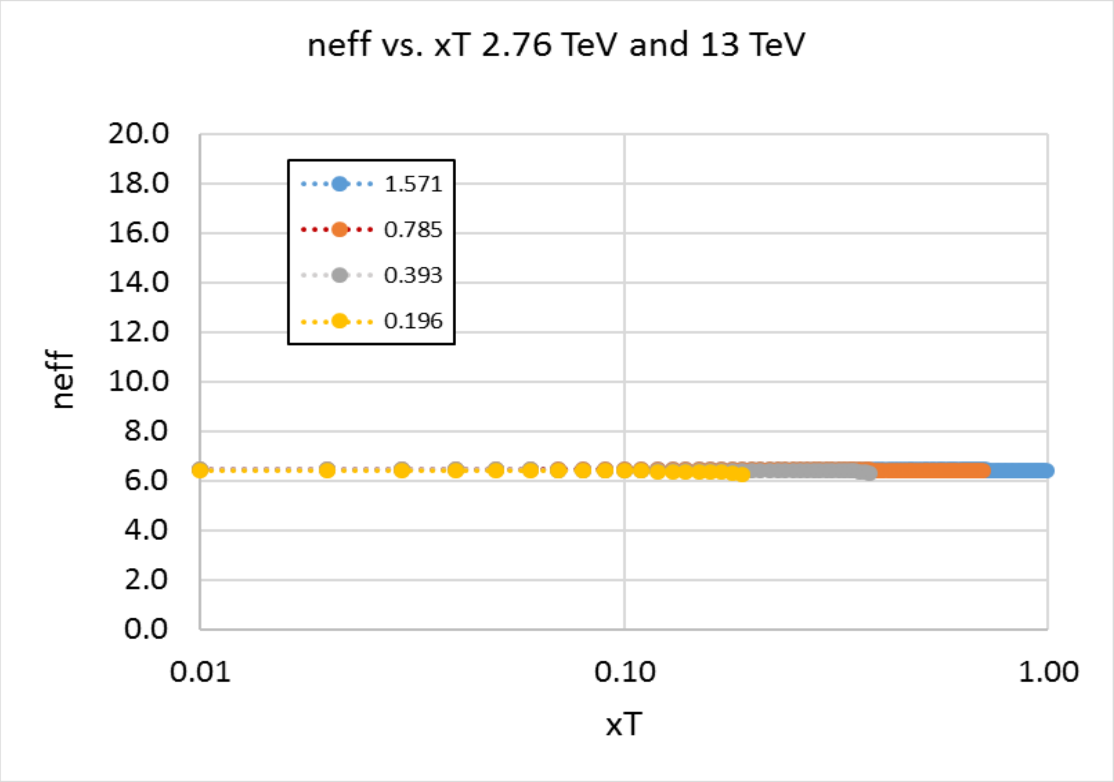
Must formulate the cross sections with this:

- Assume

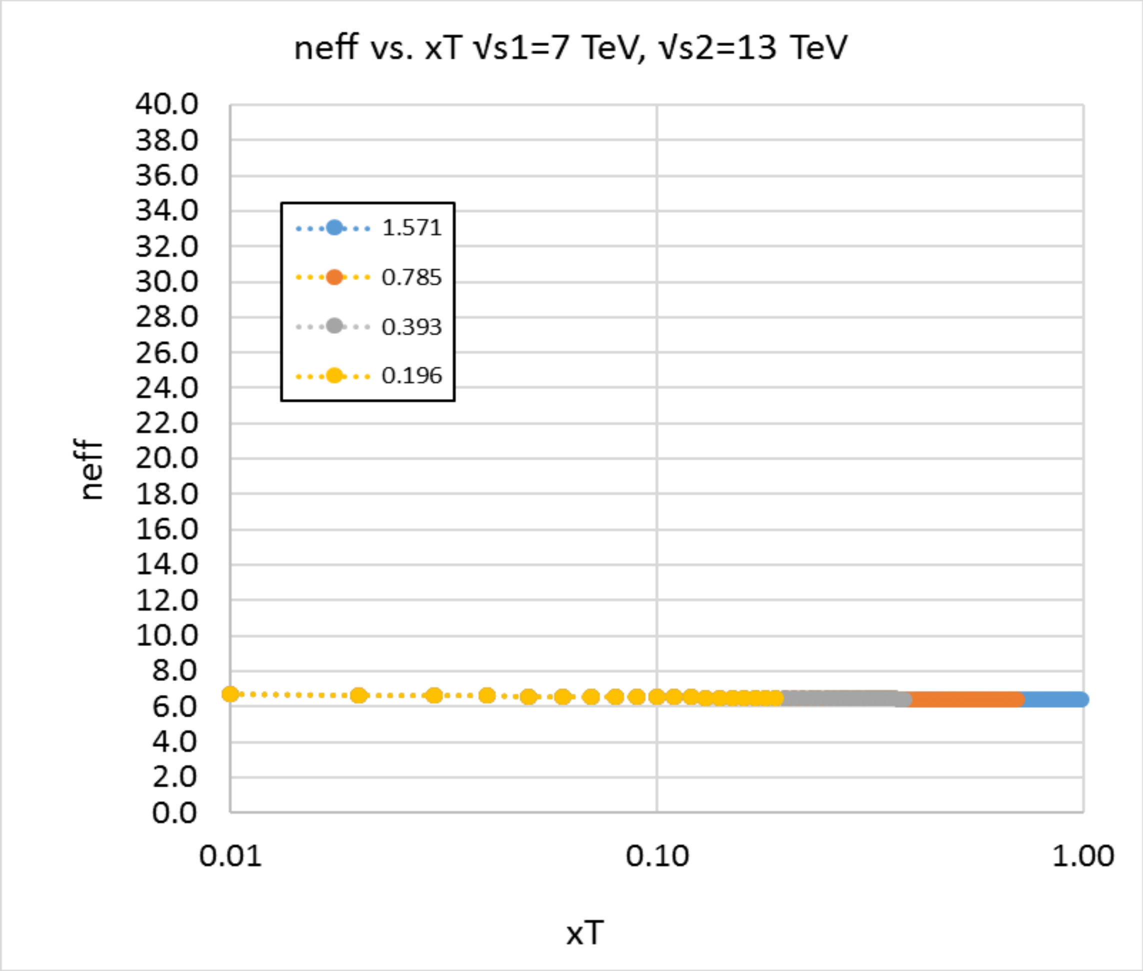
$$\sigma^{inv} \equiv E\frac{d^3\sigma}{dp^3}(AB \to CX) = \frac{\alpha\left(\sqrt{s}\right)\left(1-x_R\right)^{nx_R\left(\sqrt{s},pT\right)}}{p_T^n}$$

$$n^{\exp} = \frac{-\ln\left(\sigma^{inv}(x_T,\sqrt{s_1})/\sigma^{inv}(x_T,\sqrt{s_2})\right)+\ln\left(\alpha(\sqrt{s_1})/\alpha(\sqrt{s_2})\right)}{\ln\left(\sqrt{s_1}/\sqrt{s_2}\right)}$$

n_{eff} with the $\alpha(s)$ cross section amplitude term



Hence n_{eff} -> 4 as x_T -> 0 is a result of neglecting the '$\alpha(s)$' term that contains important overall normalization that corrects $n_{eff} \approx 4$ to $n_{eff} \approx 6$.



Diquarks

Flavor Decomposition of the Elastic Nucleon Electromagnetic Form Factors

G. D. Cates, C. W. de Jager, S. Riordan, and B. Wojtsekhowski

Phys. Rev. Lett. 106, 252003 – Published 22 June 2011

arXiv:1103.1808v1 [nucl-ex] 9 Mar 2011

Diquark correlations in baryons on the lattice with overlap quarks

Ronald Babich, et al.

arXiv:hep-lat/0701023v2 19 Oct 2007

Strong diquark correlations inside the proton

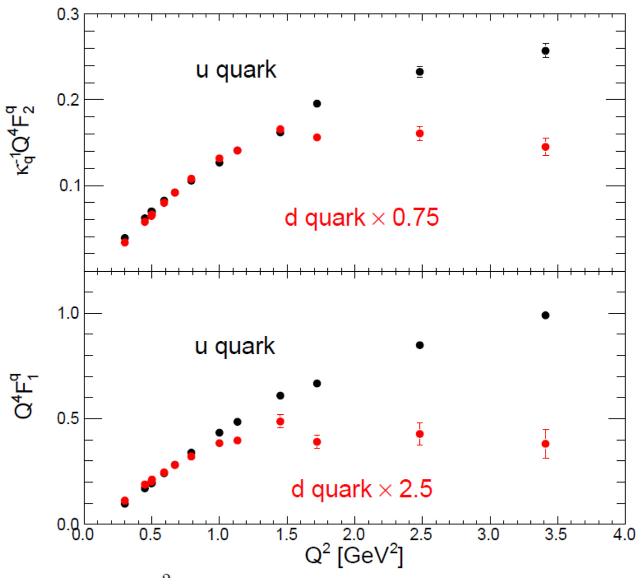
Jorge Segovia

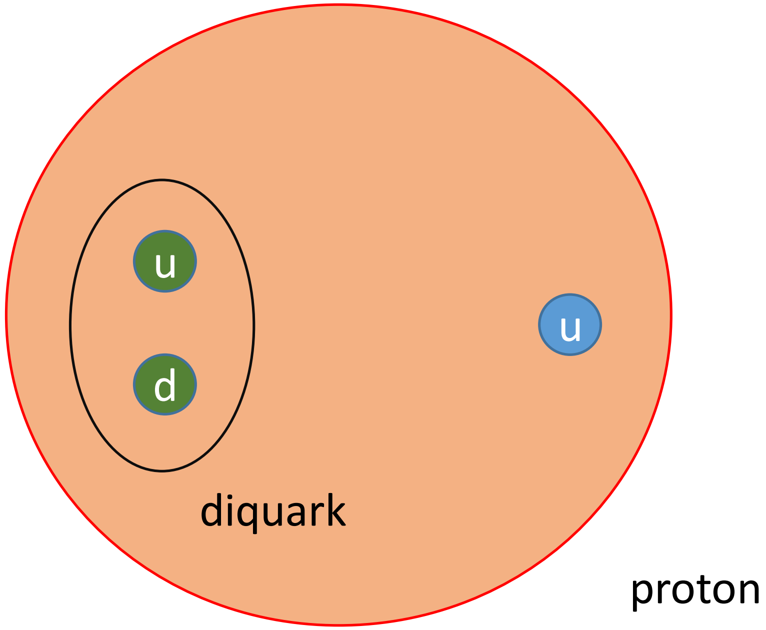
EPJ Web of Conferences 113, 05025 (2016)

Hadron Systematics and Emergent Diquarks

Alexander Selema and Frank Wilczek

arXiv:hep-ph/0602128v1 14 Feb 2006





Cates, et al. conclude that d-quark contribution to the proton form-factor appears to be suppressed from no-diquark assumption.