Inclusive Jet Production at the Large Hadron Collider meets an Old Friend – the π^0

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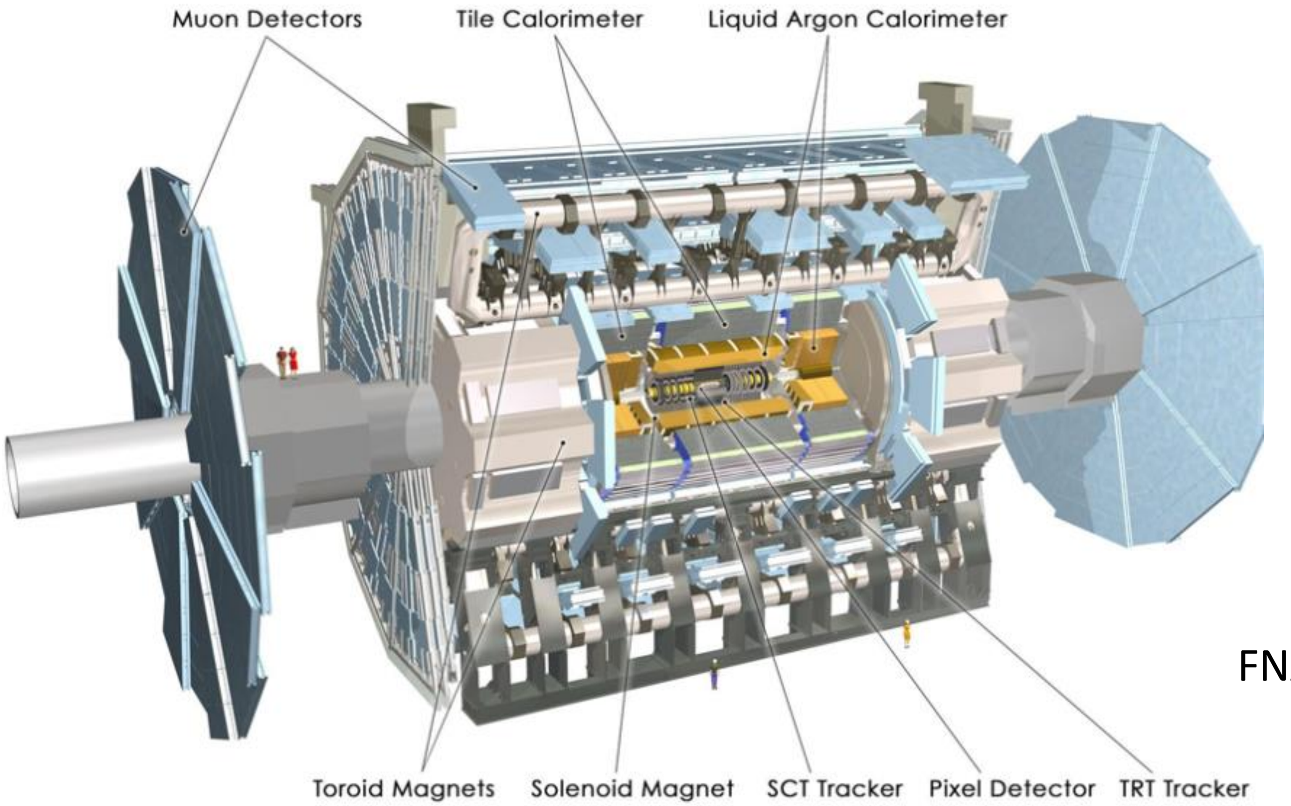
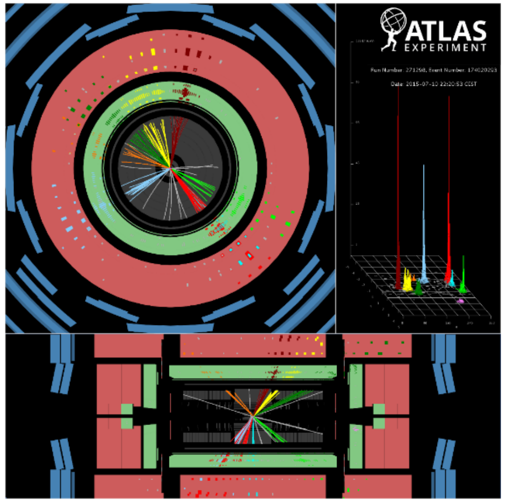
MITLNS

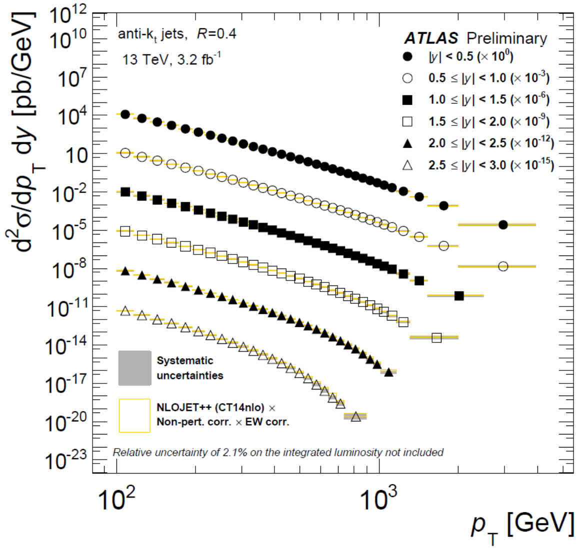
January 24, 2017

Jets at LHC & π^0s at FNAL

LHC ATLAS







FNAL E63

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

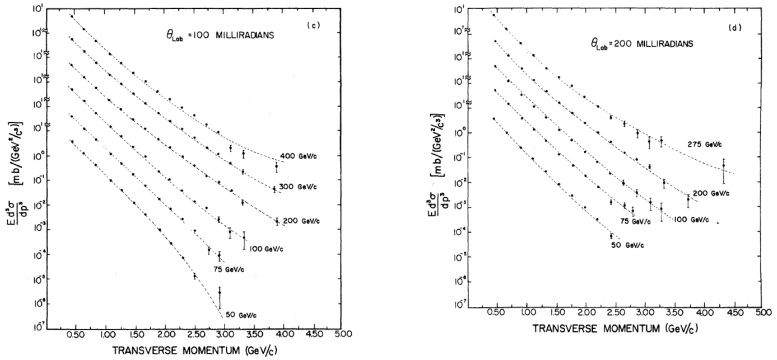


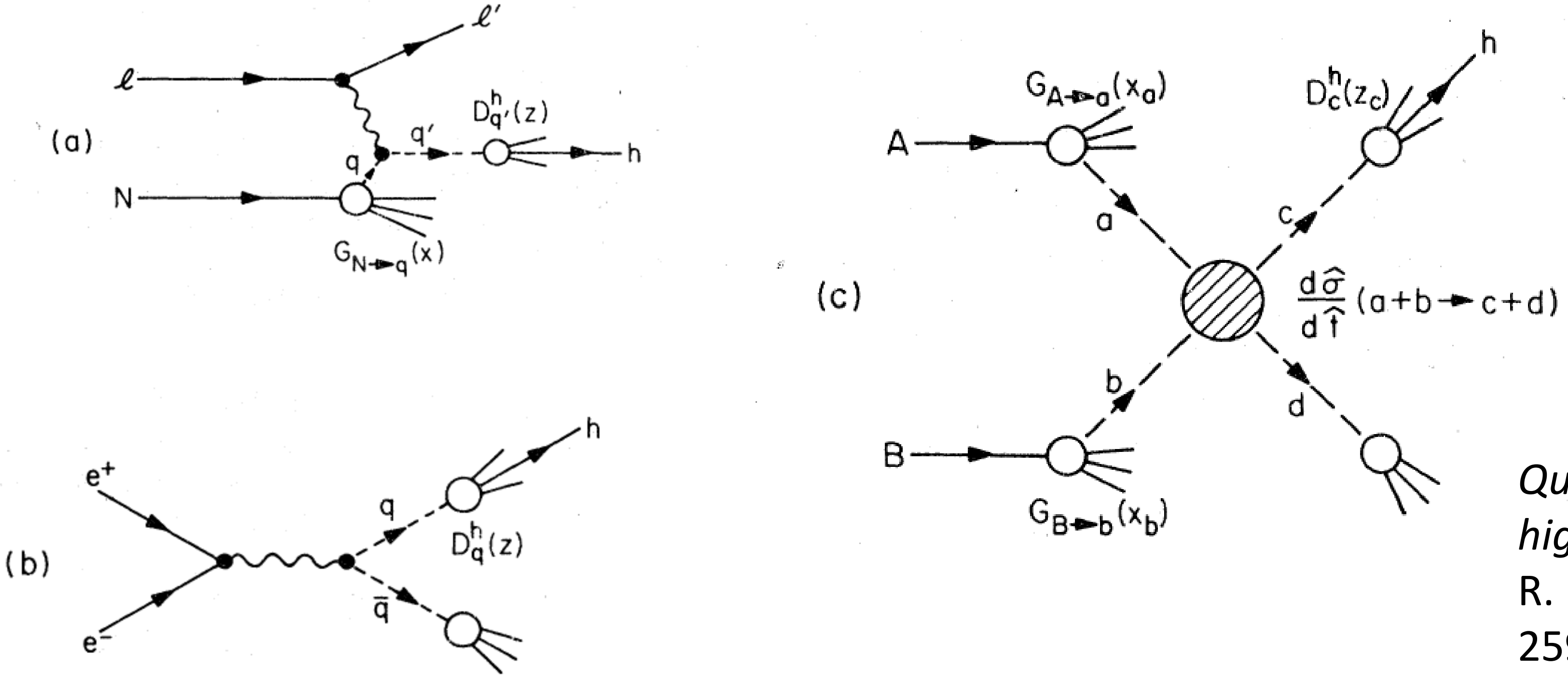
FIG. 10. π^0 invariant cross sections as a function of transverse momentum for various incident proton beam momenta, at laboratory angles (a) 30 mrad, (b) 65 mrad, (c) 100 mrad, and (d) 200 mrad.

Prospective

- Some 45 years ago the highest energy in proton-proton collisions was at the Intersecting Storage Ring (ISR) at CERN at energy ~ 60 GeV. FNAL and the SPS at CERN were fixed target machines and could achieve COM energies of ~ 27 GeV.
  - The concepts of Jets, the Gluon and QCD were just being developed in this era.
- Many experiments were performed at that time to measure the inclusive rate of single particle production – such as $p + p \rightarrow \pi^0 + X$, where only the π^0 was measured. These experiments were hadronic analogs to deep inelastic electron scattering: $e^- + p \rightarrow e^- + X$.
- Is there any similarity between the systematics observed at these low energies with those of experiments now performed at the large hadron collider?
- In the era of highly sophisticated QCD analyses by large analysis teams is there anything that can be learned by "just looking" at the data?

The Paradigm for Single Particle Inclusive Production

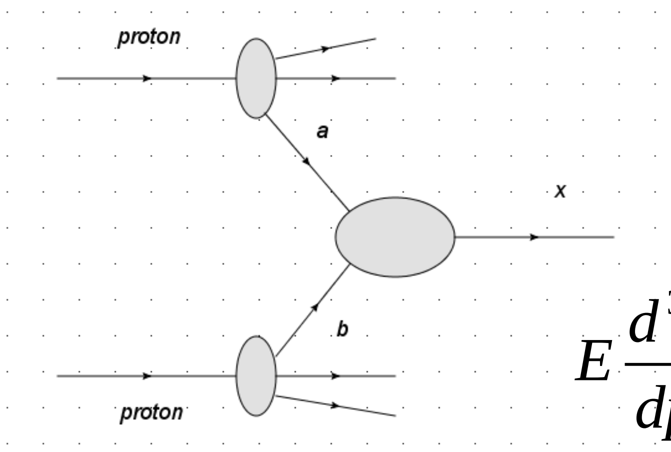
$$E d\sigma/d^3p(s,t,u;A+B\to h+X)=\int_{x_a^{\min}}^{1} dx_a \int_{x_b^{\min}}^{1} dx_b\, G_{A\to a}(x_a) G_{B\to b}(x_b) D_c^h(z_c)\,\frac{1}{z_c}\,\frac{1}{\pi}\,\frac{d\hat{\sigma}}{d\hat{t}}(\hat{s},\hat{t};q_a+q_b\to q_a'+q_b')$$



Field and Feynman

Quark elastic scattering as a source of high - transverse - momentum mesons,
R. D. Field and R. P. Feynman, PRD 15 , 2590 (1977)

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

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

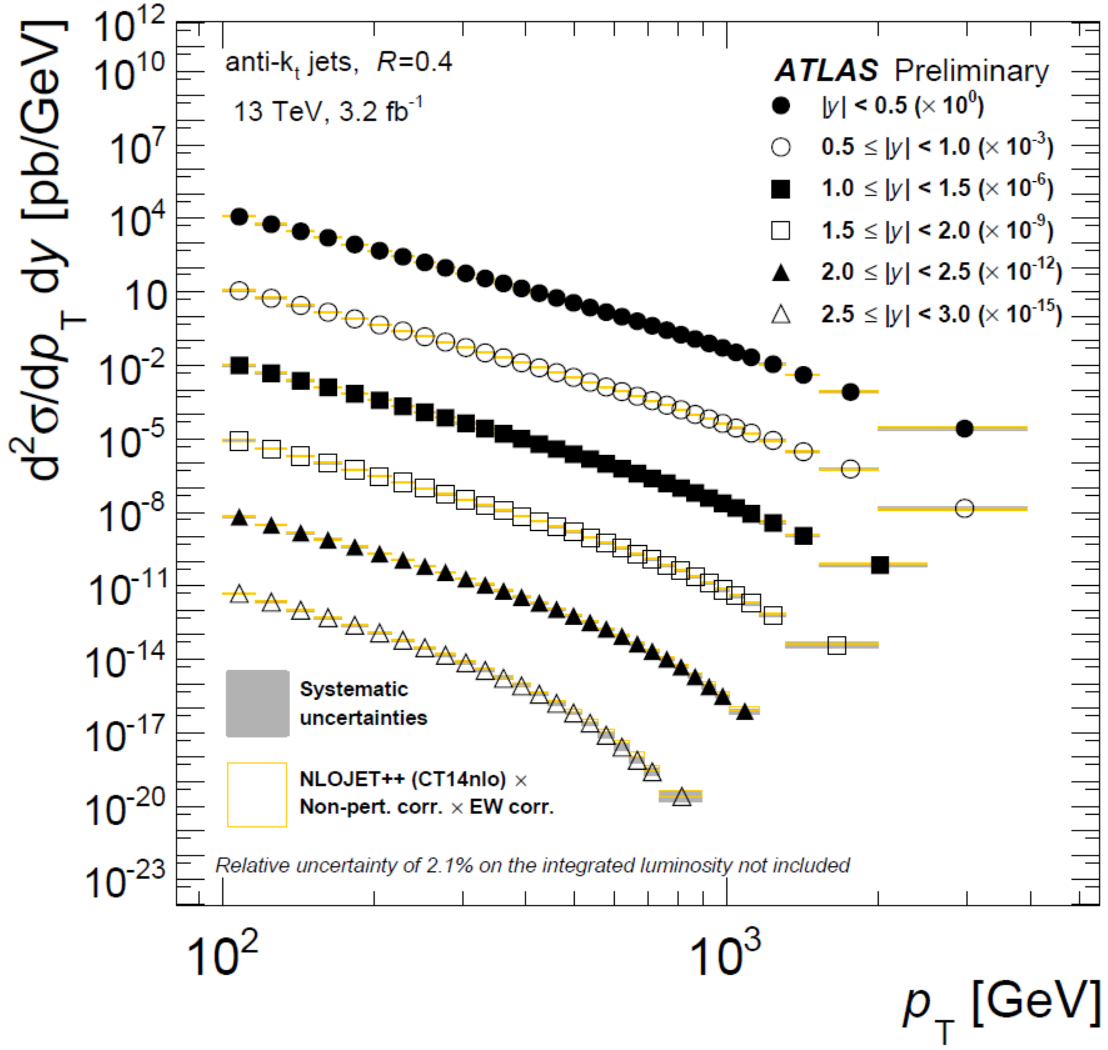
These *10s of parameters and factors* are put together in simulations of inclusive jet production at the LHC.

Dimensions:

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

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

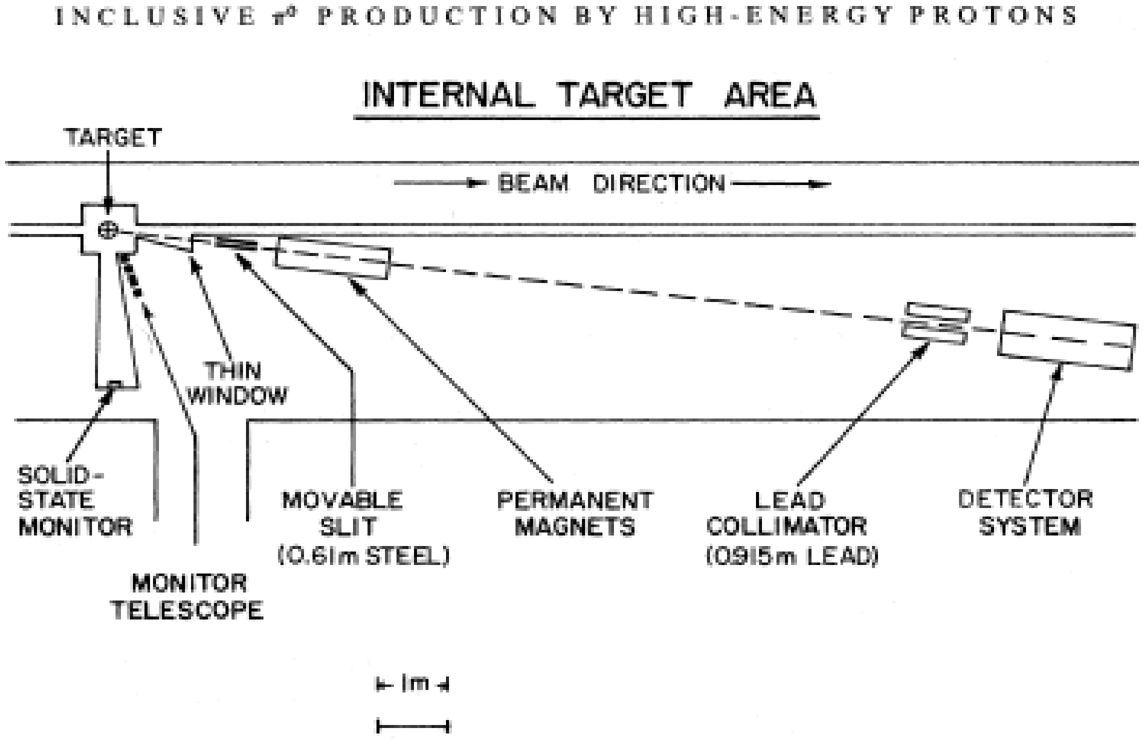
ATLAS Inclusive Jet Production at 13 TeV



- 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 including **2 -> 2 processes**, leading logarithmic p_T-ordered parton shower, hadronization with the Lund string model.

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

E63 FNAL circa 1972



Broad energy and angle coverage provided an “aerial photography of kinematic landscape”:

θ = 30 to 275 milli-radians, P_{beam} = 50 to 400 GeV

Detected single γ and used Sternheimer analysis to determine π^0 kinematics:

$$\sigma_\pi(k) \sim -k\,\frac{\partial \sigma_\gamma(k)}{\partial k}$$

Carey, Johnson, Kammerud, Peters, Ritchie, Roberts, Sauer, Shafer, Theriot, Walker, Taylor; Phys. Rev. Lett. 33, No. 5, 327 (29 July 1974) + several pubs

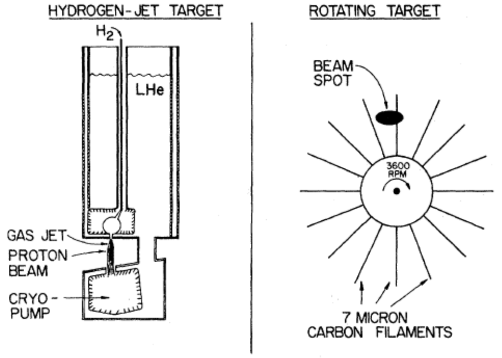


FIG. 2. Basic elements of the hydrogen-jet and rotating targets used in the experiment.

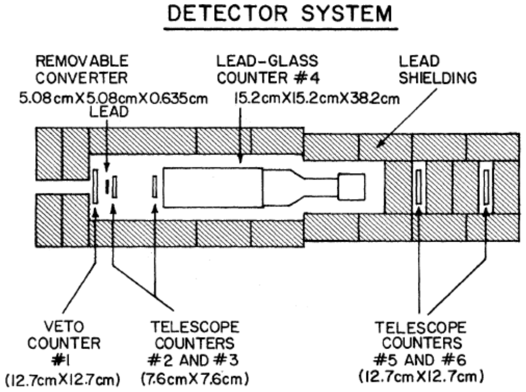


FIG. 3. Plan view of the detectors and surrounding shielding.

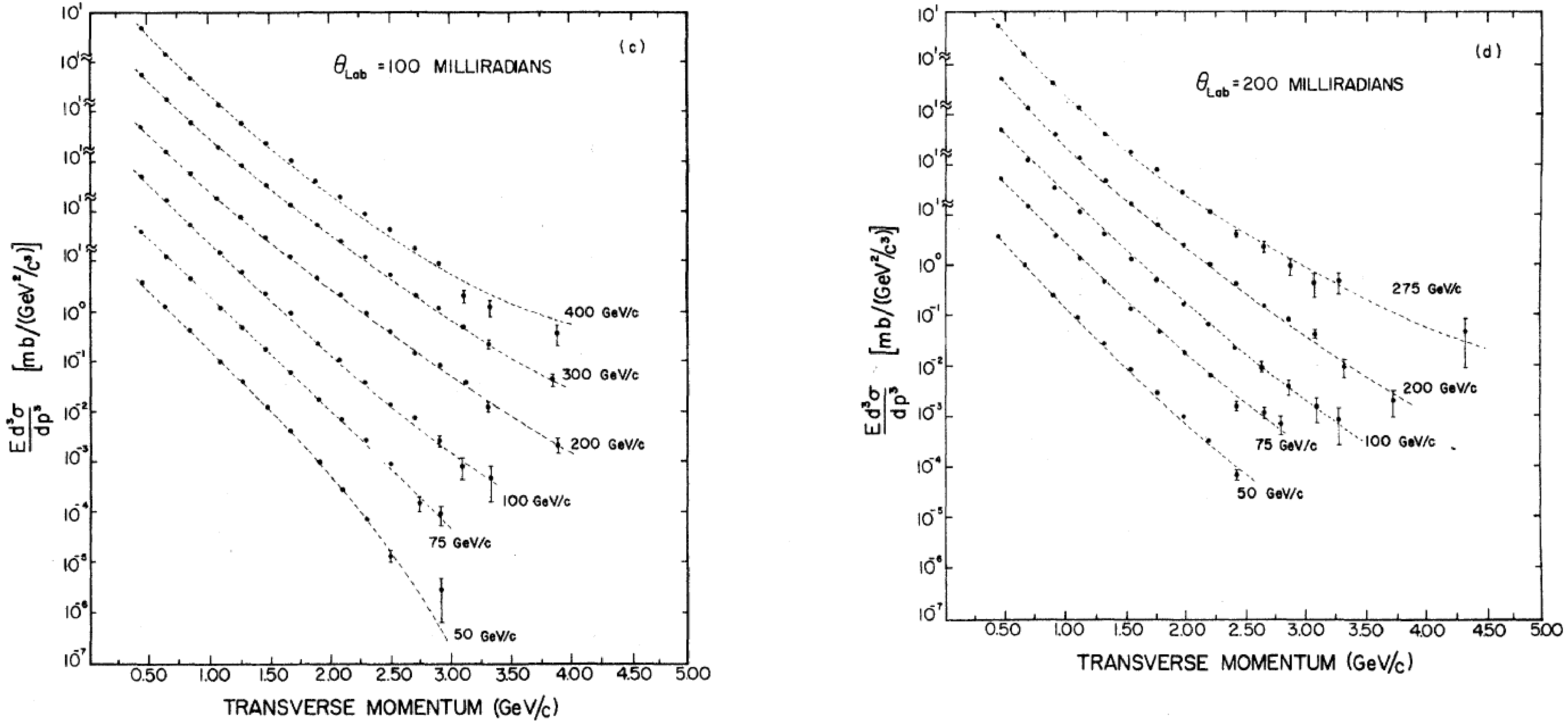
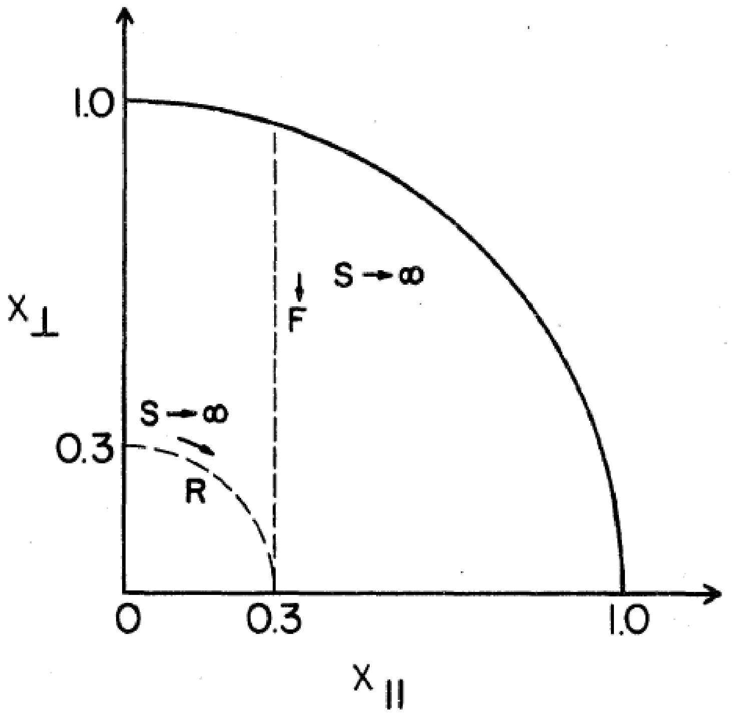


FIG. 10. π^0 invariant cross sections as a function of transverse momentum for various incident proton beam momenta, at laboratory angles (a) 30 mrad, (b) 65 mrad, (c) 100 mrad, and (d) 200 mrad.

Radial Scaling variable X_R



x_R is a "final state" scaling variable that controls kinematic boundary effects that affect $x_{Feynman}$ 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:

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

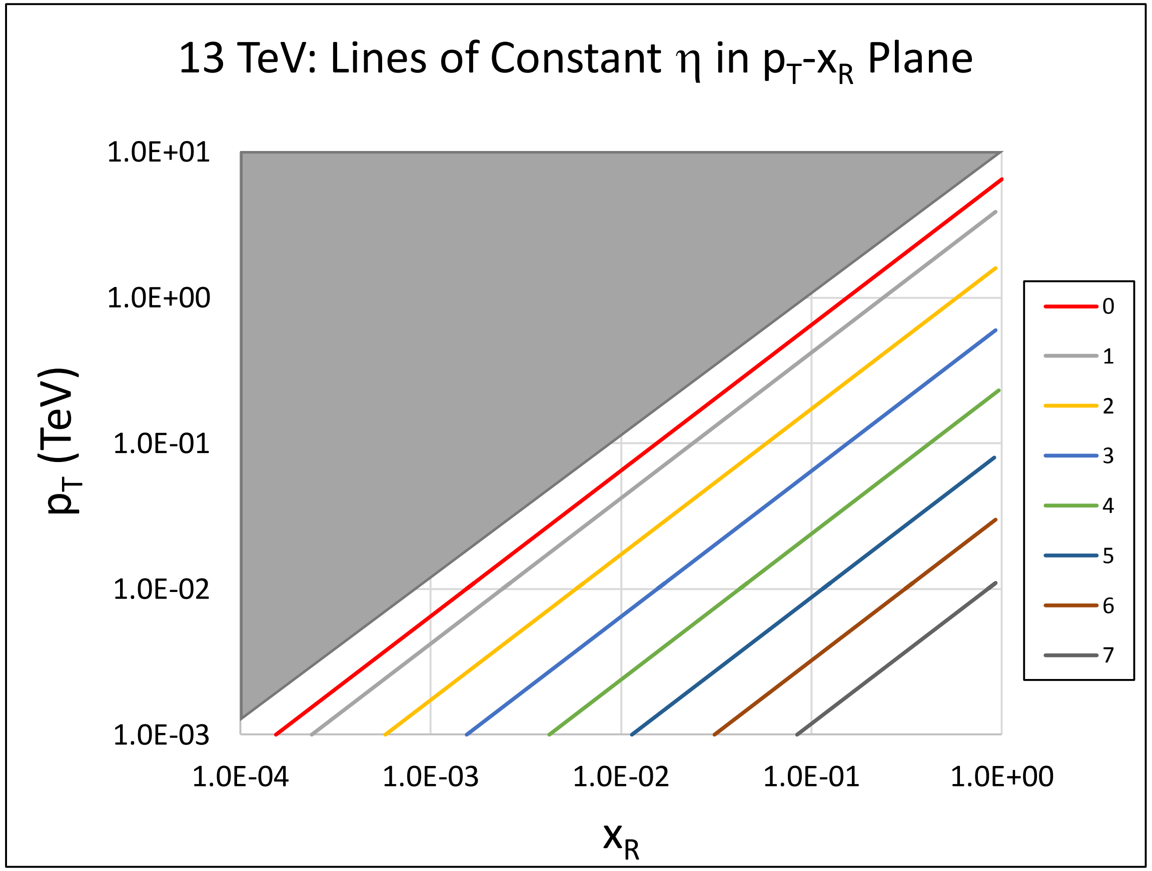
$$\approx \frac{2p_T\cosh(y)}{\sqrt{s}}\sqrt{\left(1+\frac{m_J^2}{p_T^2}\tanh^2(y)\right)}$$

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

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).

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.

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)

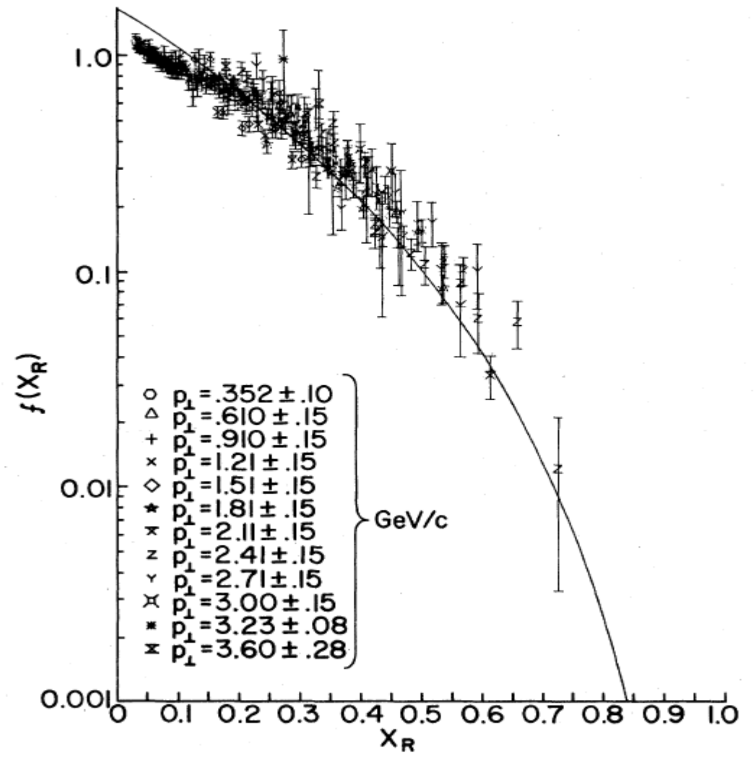


FIG. 2. The functions $f(x_R)$ calculated for twelve fixed $p_\perp$ values for the 80-mrad data are compared with each other and with the functional form $(1-x_R)^4$.

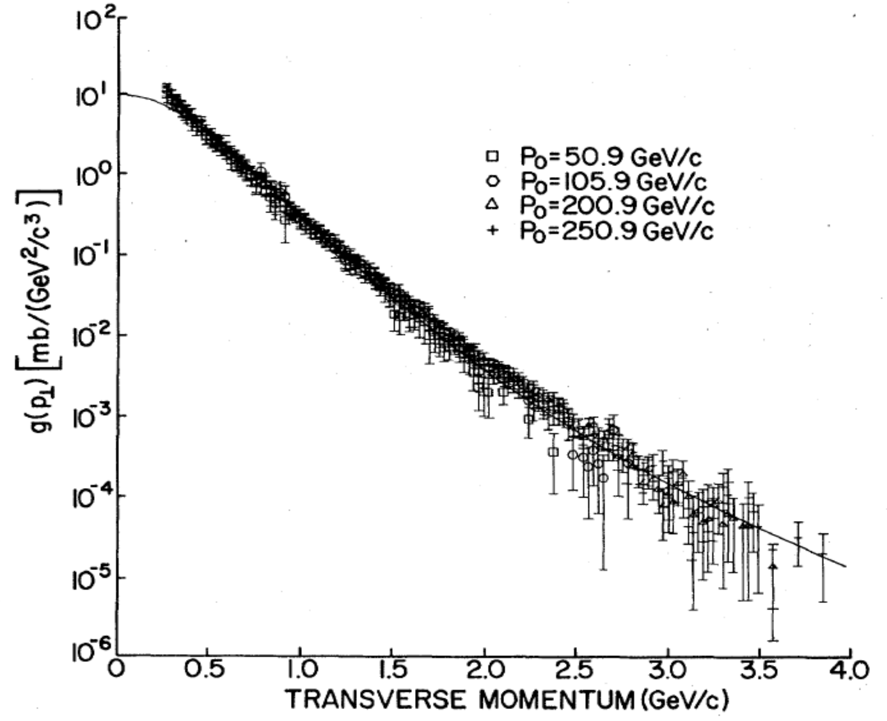
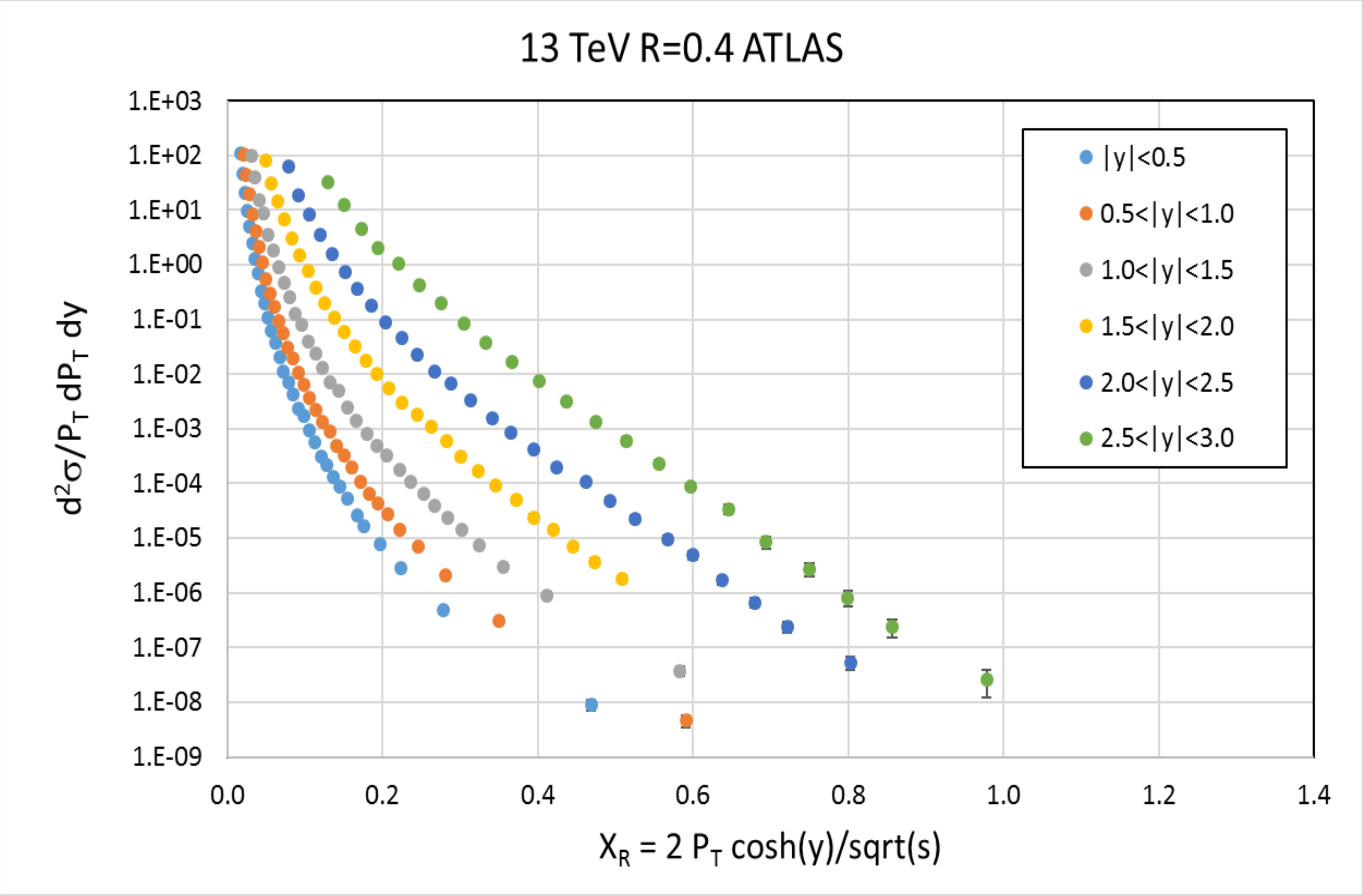


FIG. 3. The functions $g(p_\perp)$ calculated for four incident momenta at 80 mrad are compared with each other and with the functional form $(p_\perp^2+0.86)^{-4.5}$.

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:

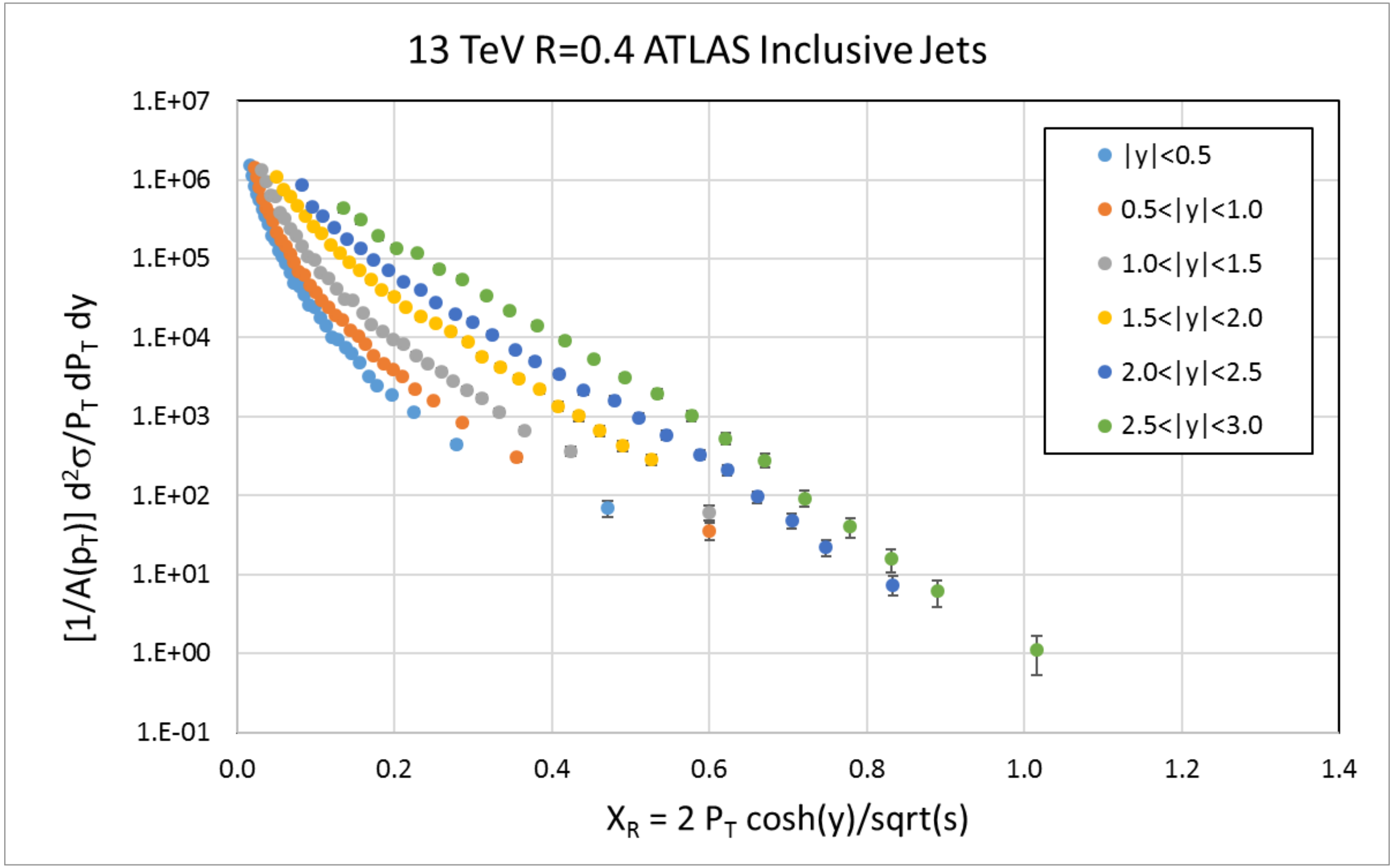
$$\frac{d\sigma(ab \to x)}{dQ^2} \sim \frac{1}{Q^4} \to \frac{d^2\sigma(pp \to Jets)}{p_T dp_T dy} \sim \frac{1}{p_T^4}$$

thus:

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

Note: Have approximated η by y

Using $A(p_T) \sim p_T^{-4}$



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

qq→qq

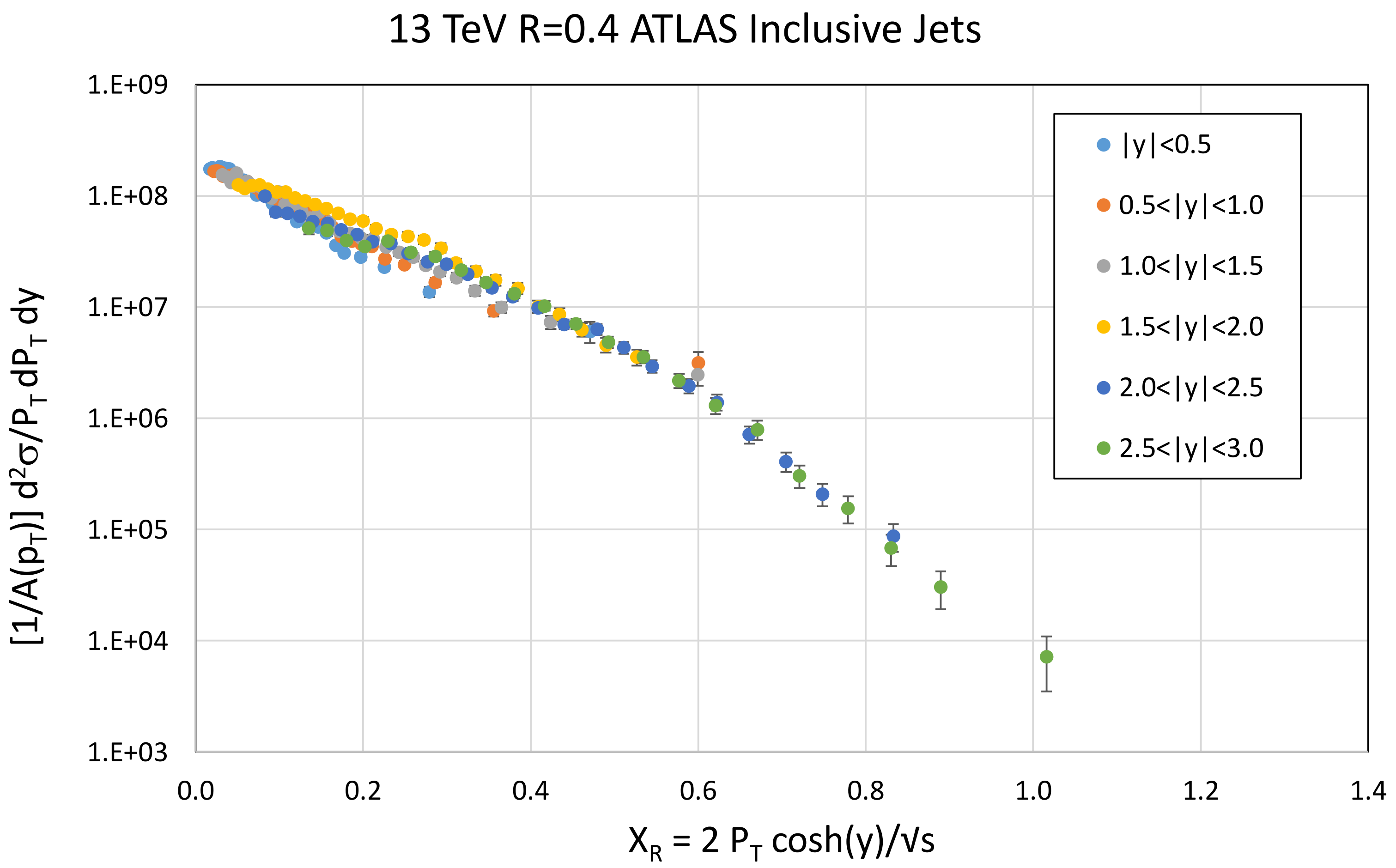
gg→gg

gq→gq

are dominating.

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

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

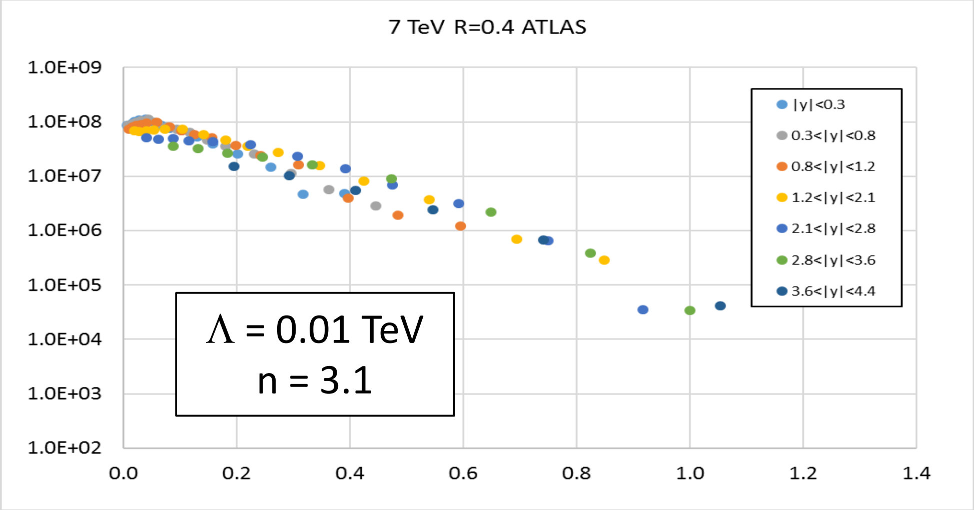


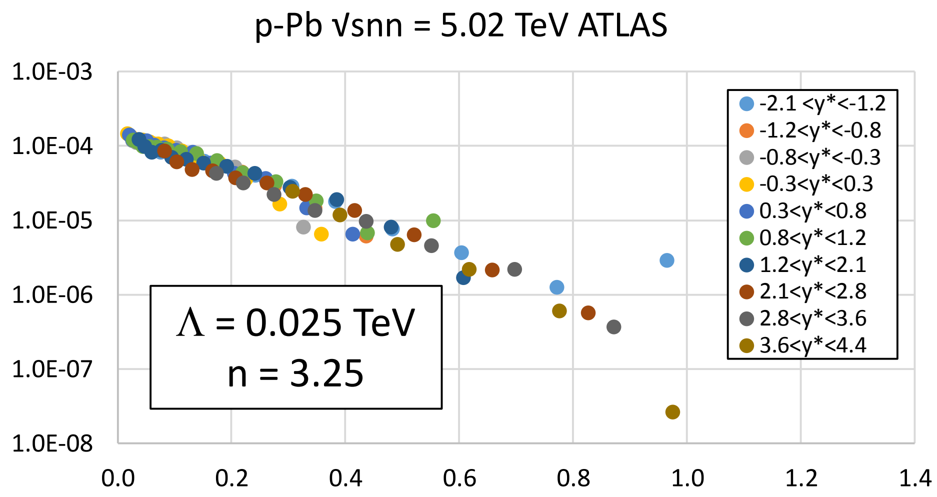
$$A(p_T) = 1 \Big/ \left(1 + \frac{p_T^2}{\Lambda^2}\right)^{n_{pT}/2}$$

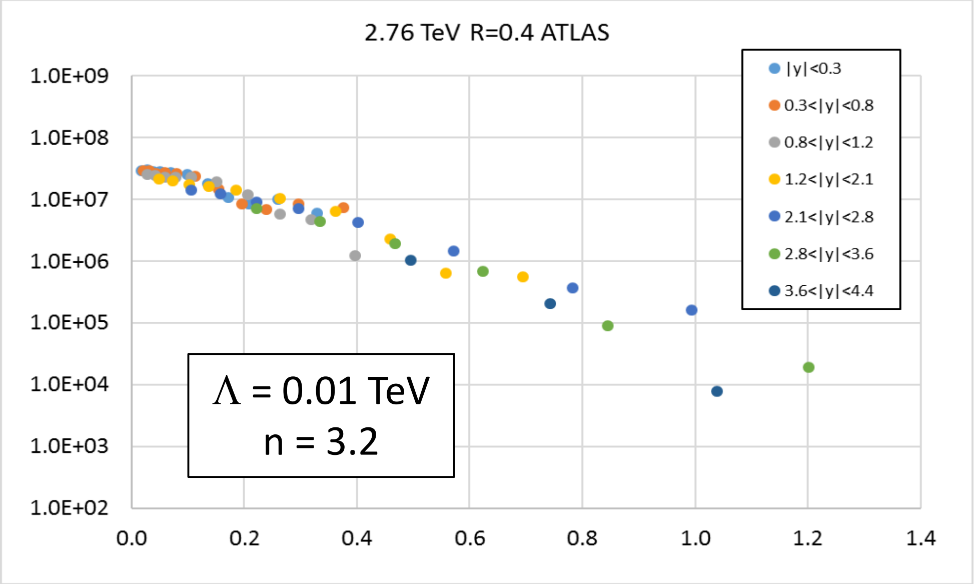
Λ = 0.01 TeV, $n_{pT}/2$ = 3.0, p_T in TeV

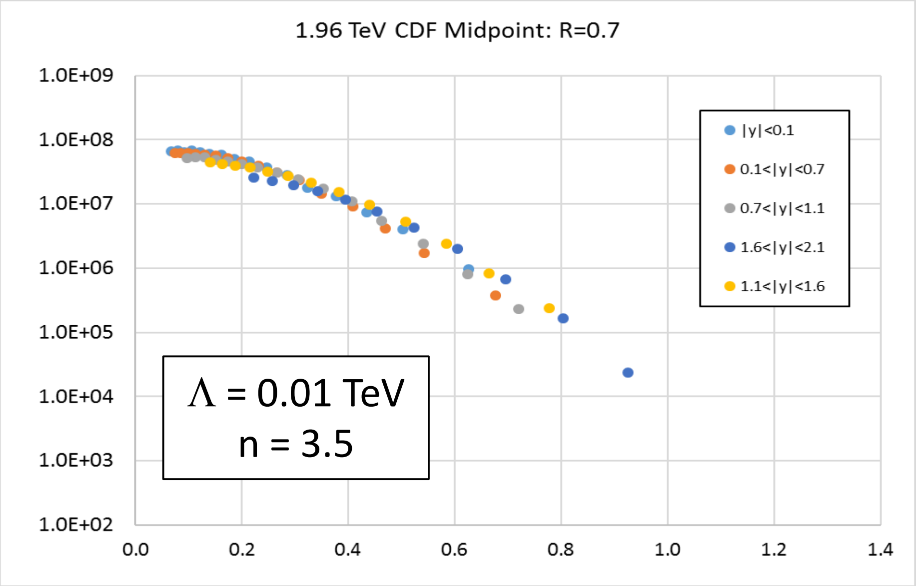
ATLAS NOTE
ATLAS-CONF-2016-092
21st August 2016
scanned figure 2
Errors systematic and statistical

Other Measurements: ATLAS & CDF

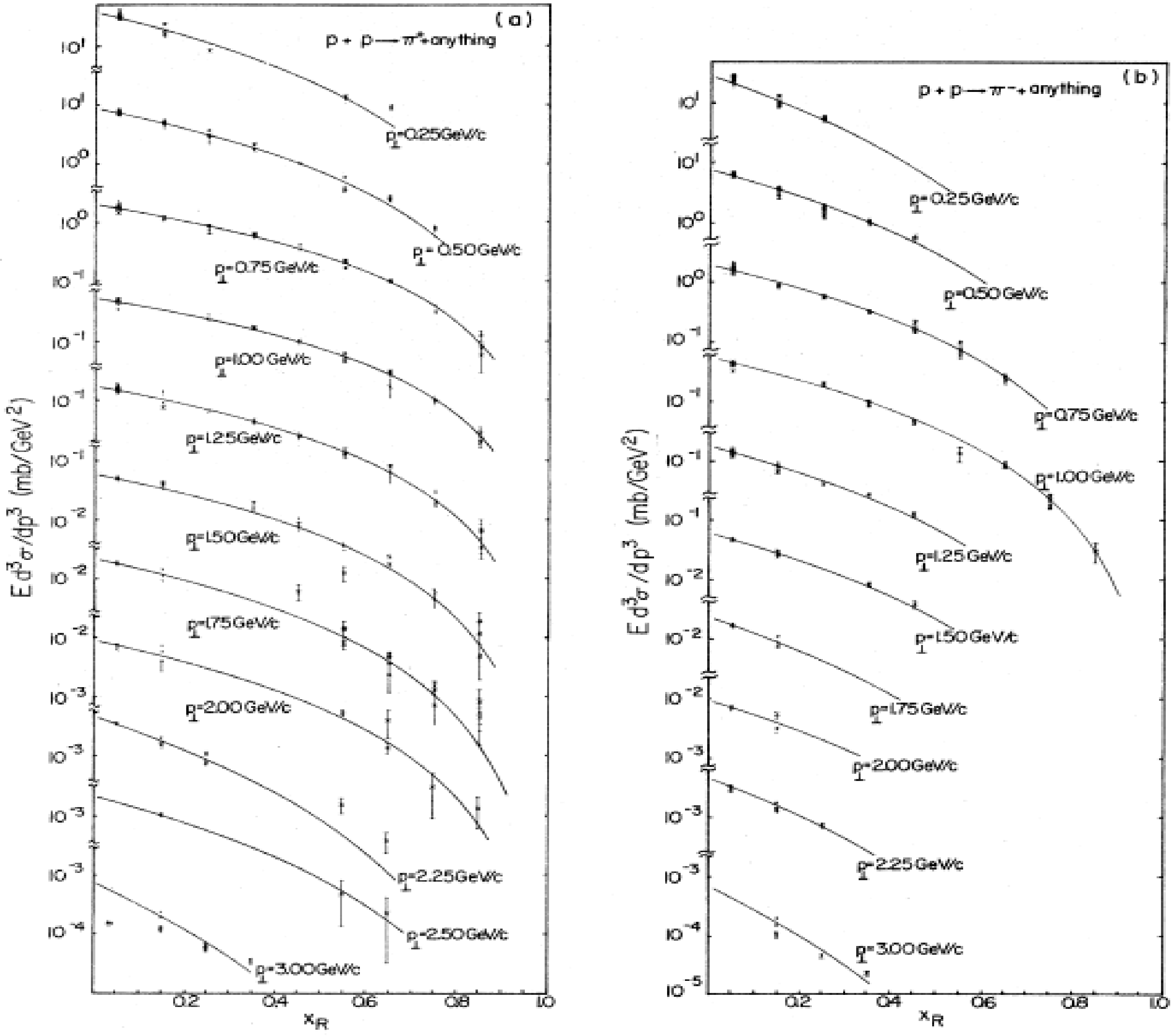








Refine the Analysis as in 1976



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

for constant p_T as a function of $(1-x_R)$ to determine $A(p_T)$. The behavior of $A(p_T)$ conveys information about the hard scattering and separates primordial hard scattering from fragmentation. Note that the limit $x_R \rightarrow 0$ is extrapolating behavior smaller than $x_{Rmin}=2p_T/\sqrt{s}$ and is effectively letting $\sqrt{s}\rightarrow\infty$ for finite p_T with $p_T \gg \Lambda$.

FET et al. PRD 14, 5, 1217, (1976)

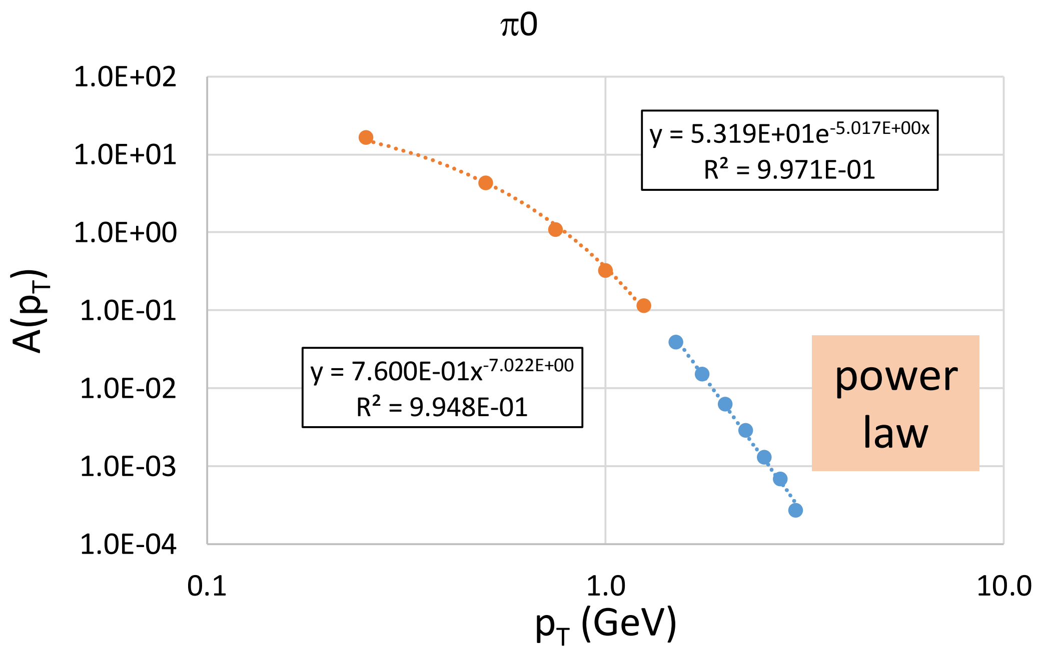
Behavior of π^0

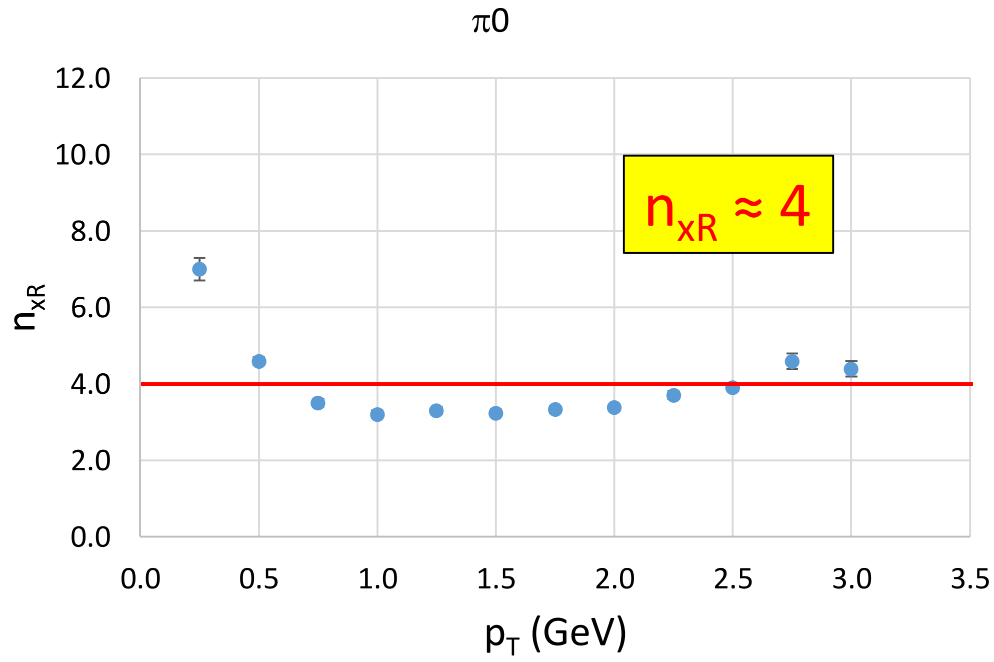
$Ed^3\sigma/dp^3 \sim A(p_T)\,F(x_R)$

$A(p_T) \sim (1/p_T)^{7.02 \pm 0.23}$ for $p_T \geq 1.25$ GeV

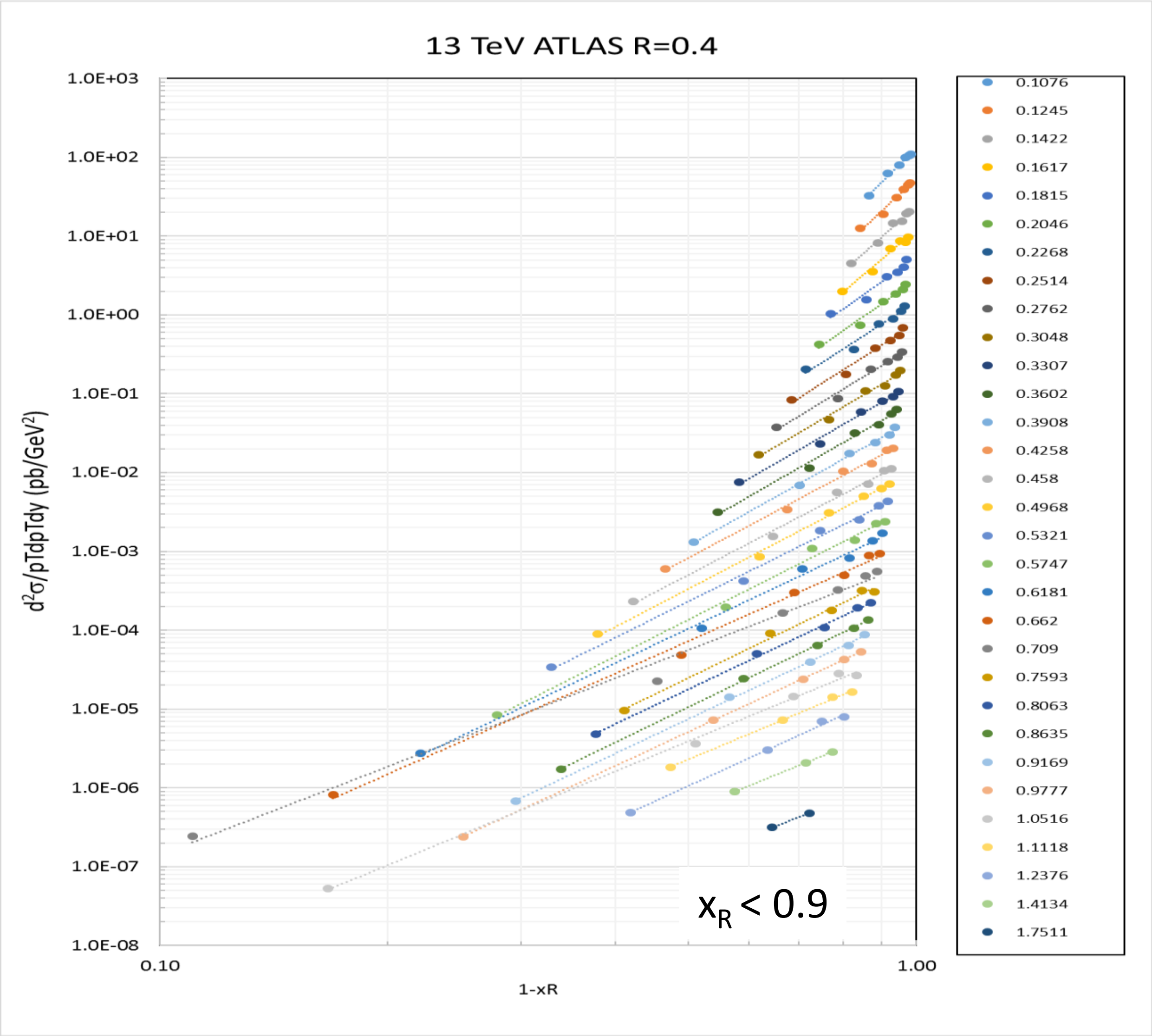
$F(x_R) \sim (1-x_R)^{4.0 \pm 1.0}$ (no p_T cut)

Table IV from FET et al. PRD 14, 5, 1217, (1976)





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

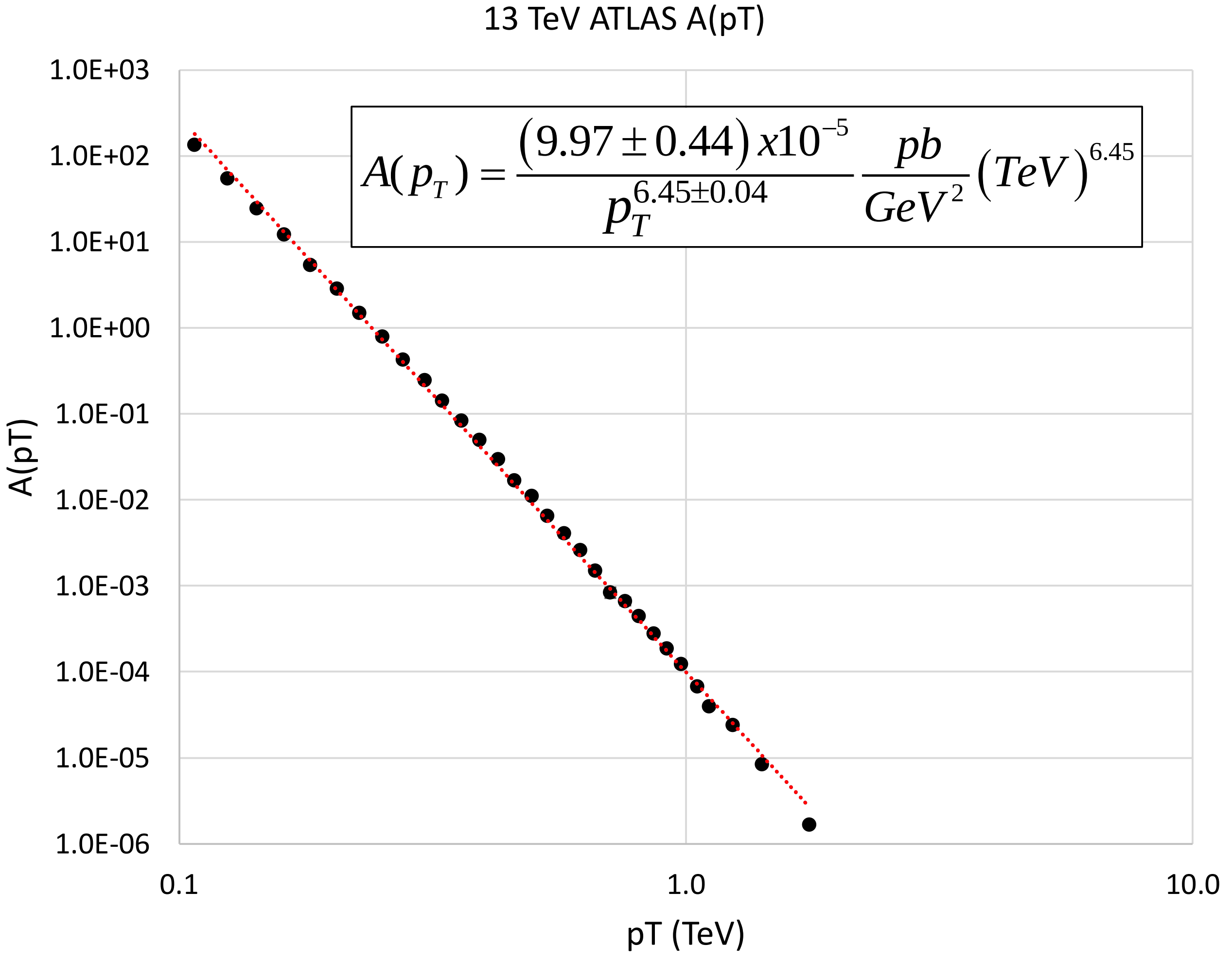


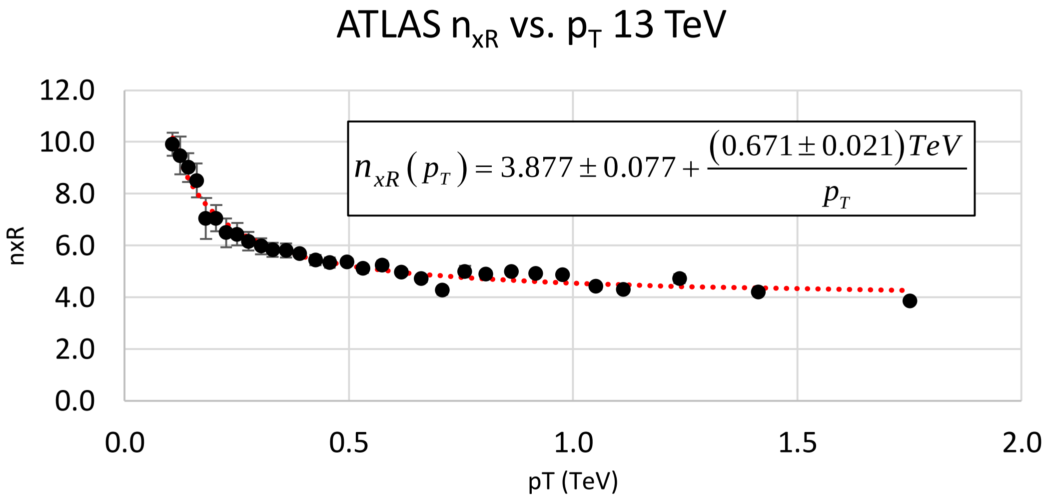
Find the same behavior as seen in the π^0 study 40 years ago.

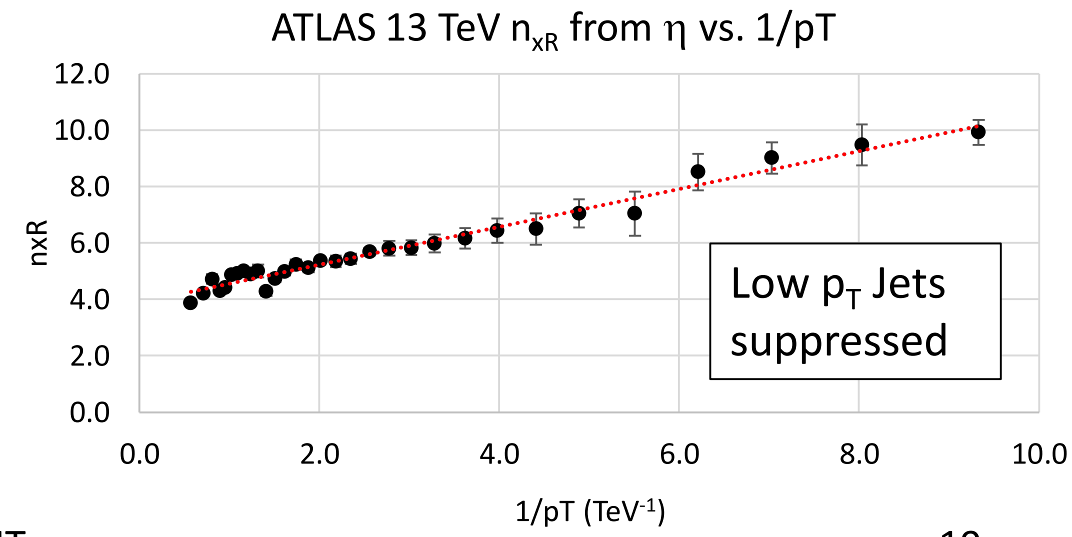
$$\frac{d^2\sigma}{p_T dp_T d\eta} \sim A(p_T)(1-x_R)^{n_{xR}}$$

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

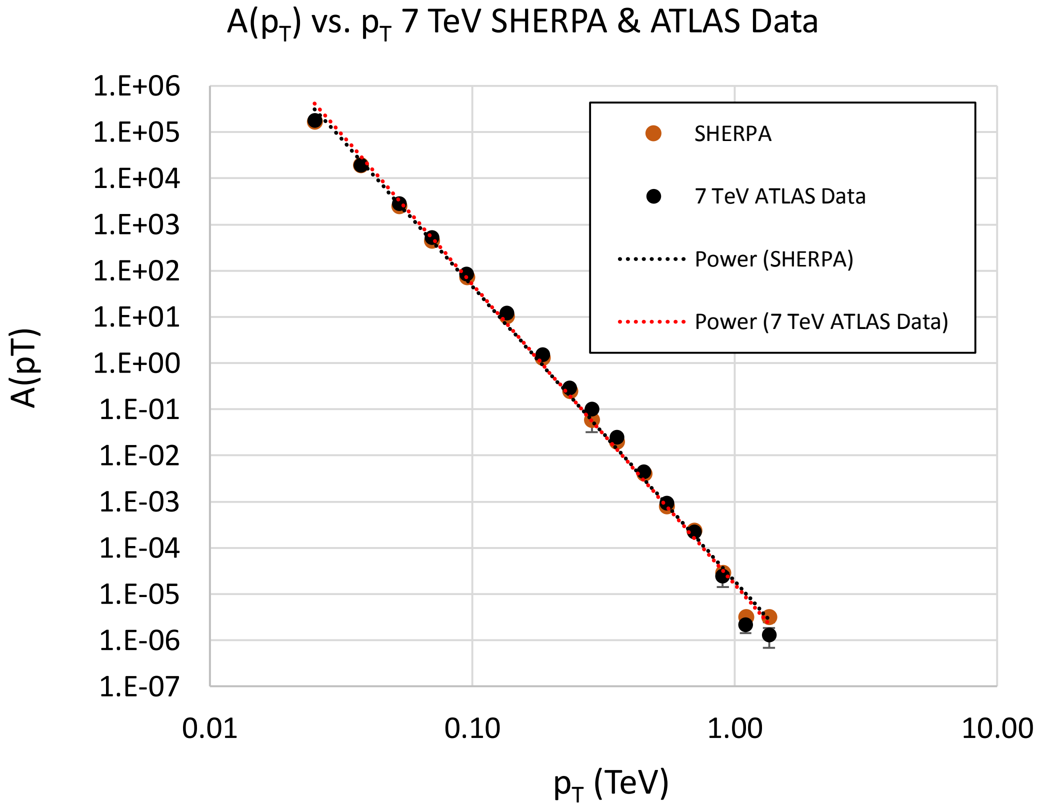
Fit Parameters 13 TeV ATLAS Inclusive Jets

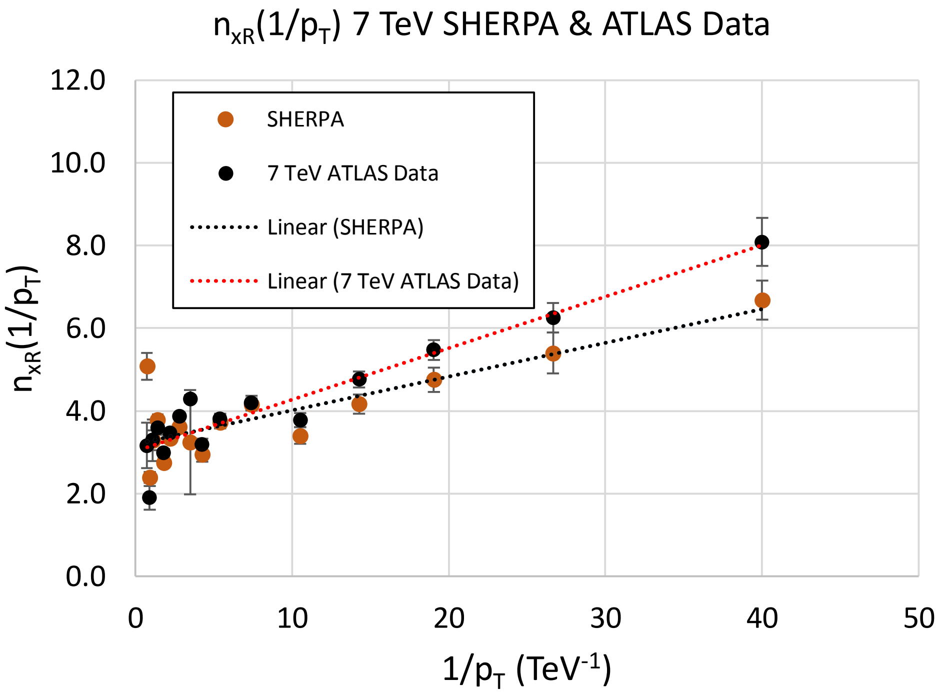






SHERPA MC 7 TeV ATLAS





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

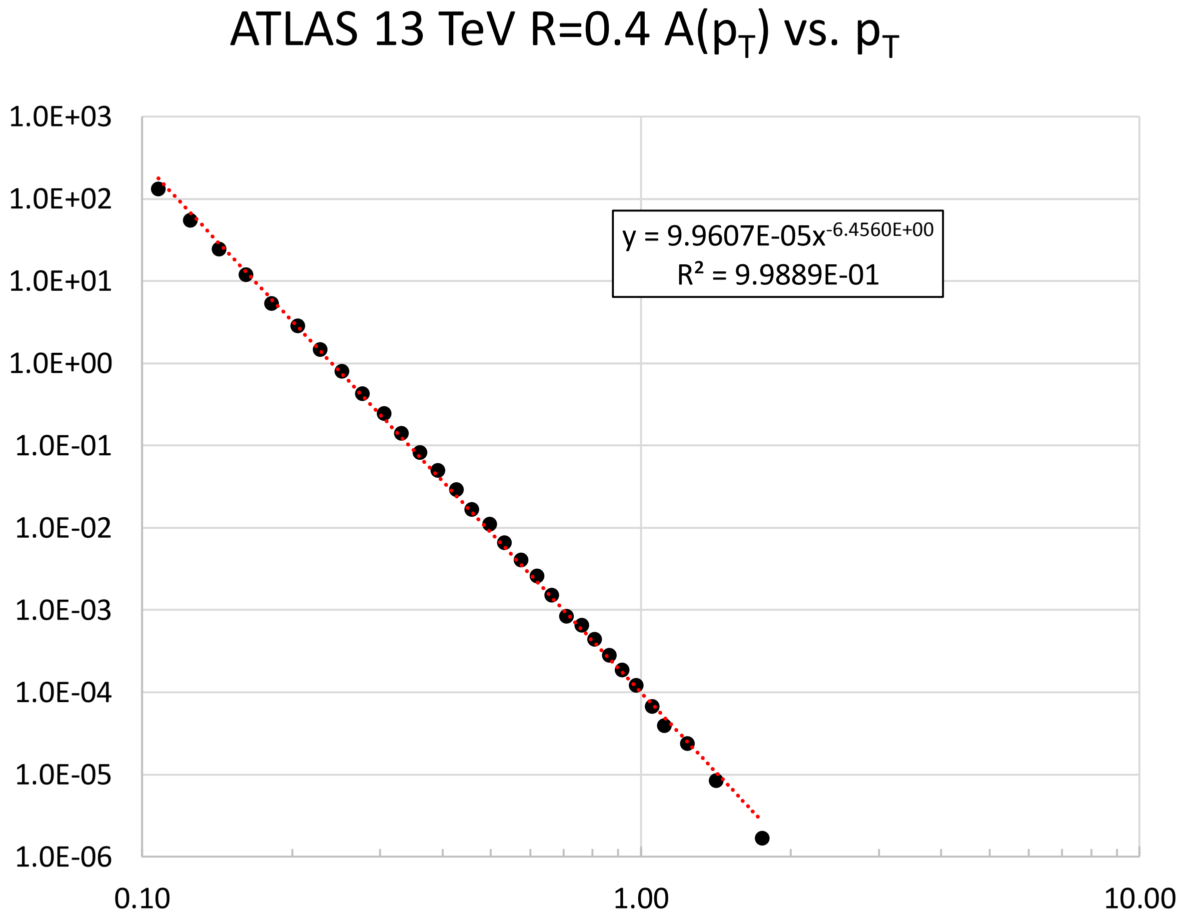
Data: D=0.125 ± 0.0112
n_{0xR}=3.03 ± 0.16

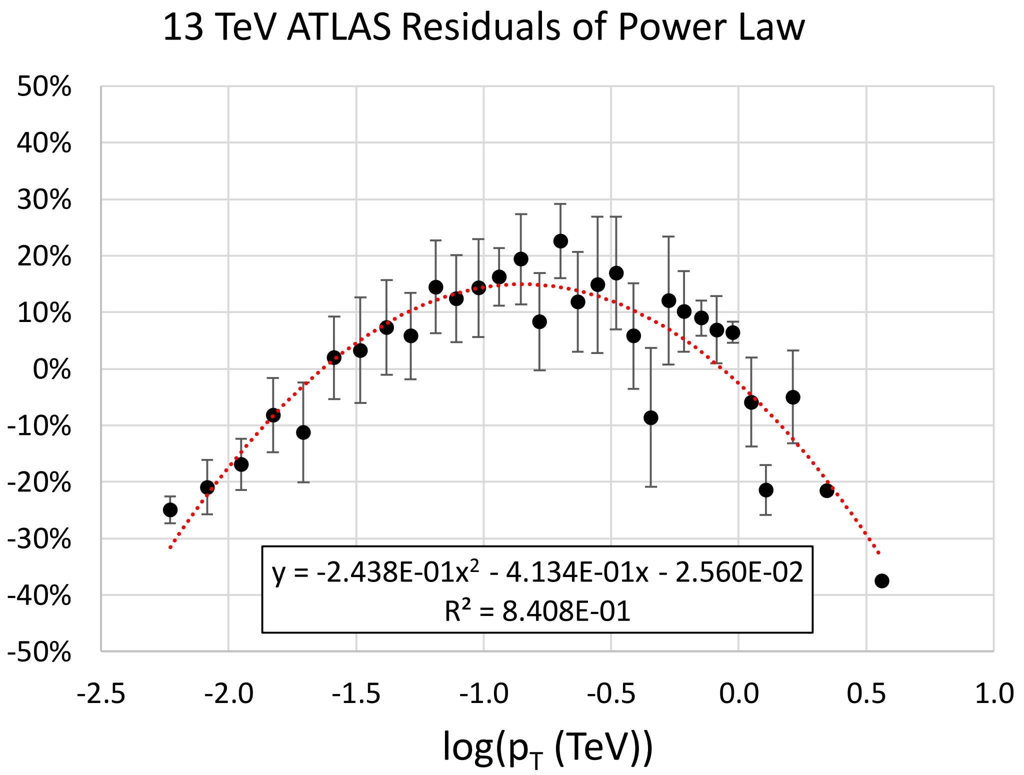
SHERPA: α =(1.895 ± 0.353)x10^{-5}
n_{pT} = 6.380 ± 0.089

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

SHERPA underestimates D

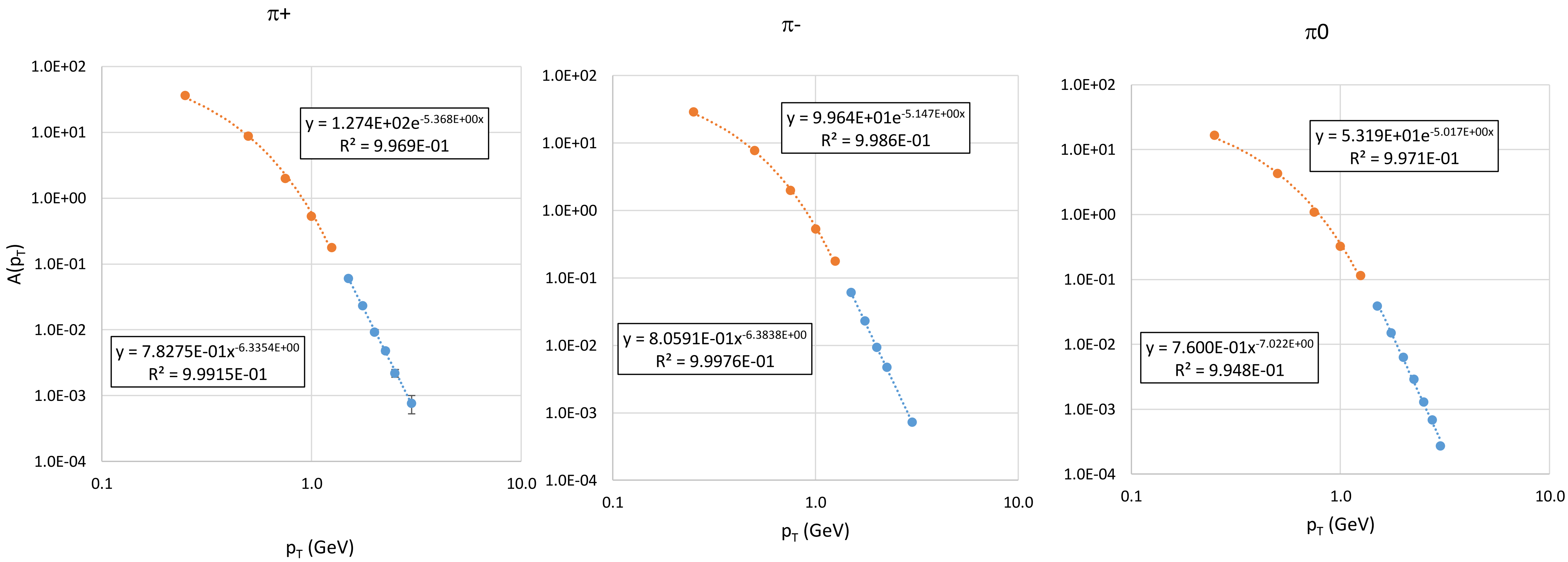
Power Law in p_T not 'Perfect'





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

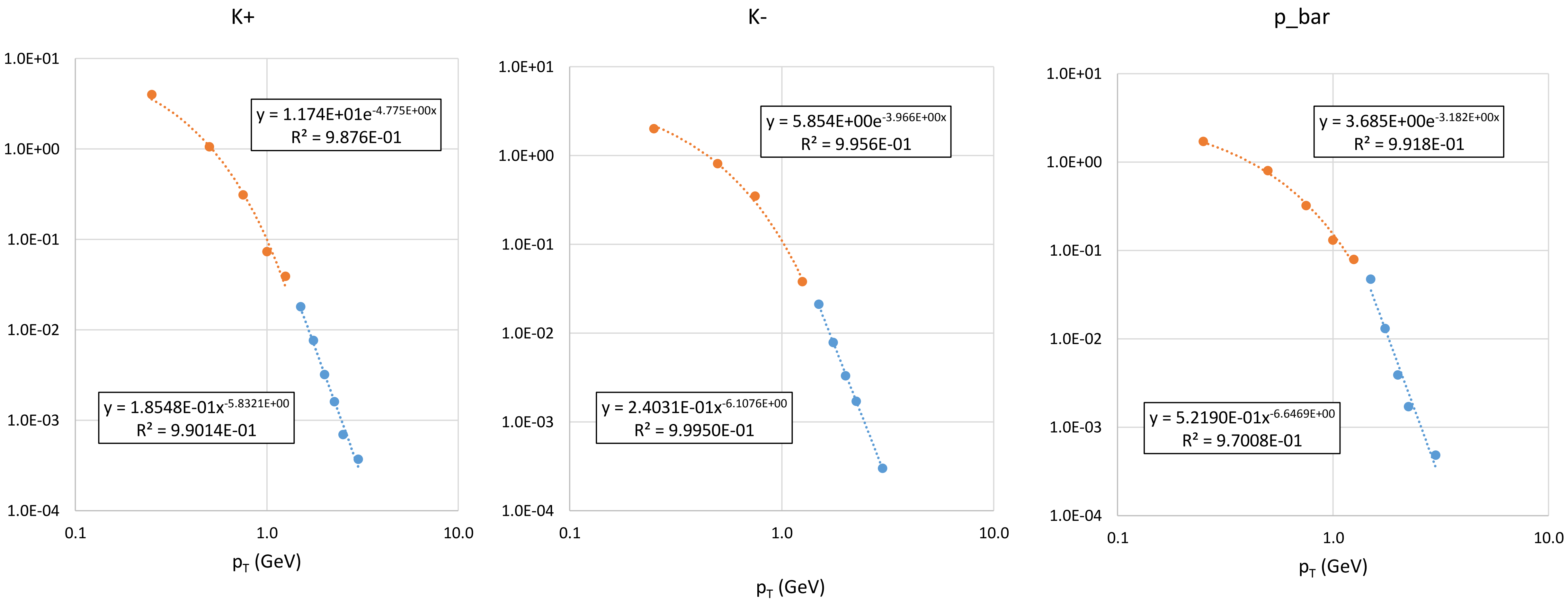
$A(p_T)$ for Single Particle Inclusive Production in p-p Collisions



p_T power law $p_T > 1.25$ GeV

$p + p \rightarrow \pi^+ + X$, ..., from F.E.T. et al. PRD 14, 1217 (1976)

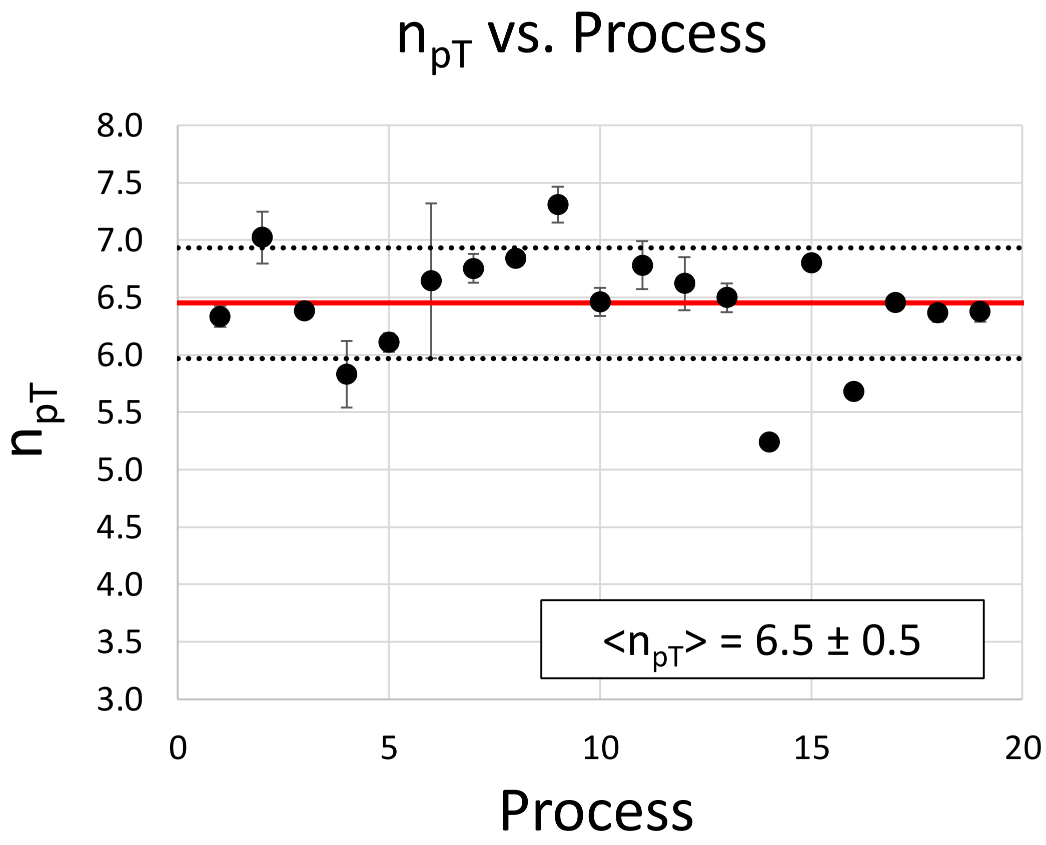
$A(p_T)$ Single Particle Inclusive Production in p-p



$p + p \rightarrow K^+ + X$ ..., from F.E.T. et al. PRD 14, 1217 (1976)

Summary of p_T Power Law using Radial Scaling

Index	Process	√s (TeV)	n_{pT}	error
1	Ref[1] π+ 10 GeV to 63 GeV (pT>1.25 GeV)	0.063	6.34	0.09
2	Ref[1] π0 10 GeV to 63 GeV (pT>1.25 GeV)	0.063	7.02	0.23
3	Ref[1] π- 10 GeV to 63 GeV (pT>1.25 GeV)	0.063	6.38	0.06
4	Ref[1] K+ 10 GeV to 63 GeV (pT>1.25 GeV)	0.063	5.83	0.29
5	Ref[1] K– 10 GeV to 63 GeV (pT>1.25 GeV)	0.063	6.11	0.08
6	Ref[1] p_bar 10 GeV to 63 GeV (pT>1.25 GeV)	0.063	6.65	0.67
7	DO: Inclusive Jets p_bar-p 1.80 TeV	1.800	6.75	0.12
8	DO: Inclusive Jets p_bar-p 1.96 TeV	1.960	6.84	0.04
9	CDF: Inclusive Jets p_bar-p 1.96 TeV	1.960	7.31	0.16
10	ATLAS: Inclusive Jets p-p 2.76 TeV	2.760	6.46	0.12
11	ATLAS: Inclusive Jets p-Pb Pb-forward 5.02 TeV	5.020	6.78	0.21
12	ATLAS: Inclusive jets p-Pb p-forward 5.02 TeV	5.020	6.62	0.23
13	ATLAS: Inclusive Jets p-p 7 TeV	7.000	6.50	0.12
14	CMS: Prompt γ	7.000	5.24	0.03
15	CMS: Inclusive Jets p-p (pT<1.95 TeV) 8 TeV	8.000	6.80	0.05
16	ATLAS: Prompt γ	8.000	5.68	0.03
17	ATLAS: Inclusive Jets p-p 13 TeV	13.000	6.46	0.04
18	CMS: Inclusive Jets p-p (pT<1.38 TeV)	13.000	6.37	0.08
19	**MC: Inclusive Jets p-p SHERPA 7 TeV**	**7.000**	**6.38**	**0.09**
	Ref[1] F. E. Taylor et al. Phys. Rev. D 14, 1217 (1976)	<npT>	6.5	0.5



n_{pT} seems ~ independent of process (γ?) over a wide range of √s and ≠ 4.

Line Counting, Higher Twists, Diquarks

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

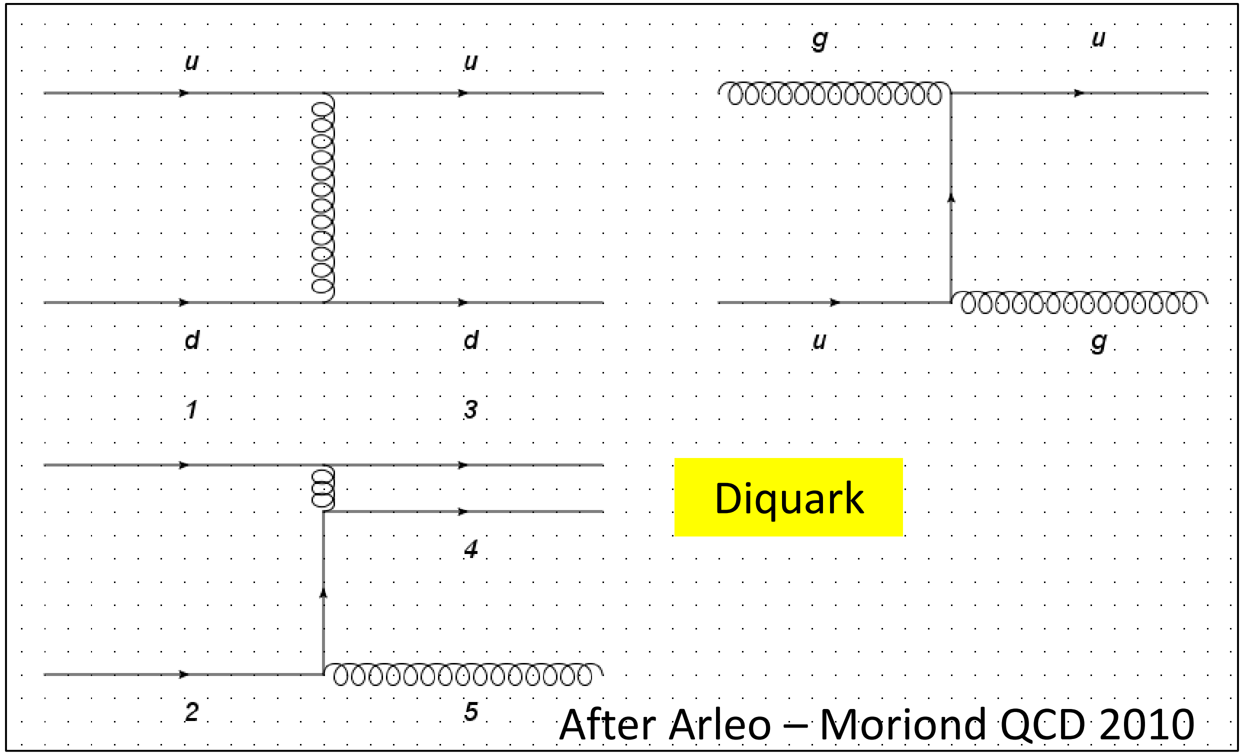
n_A = number of active fields

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

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

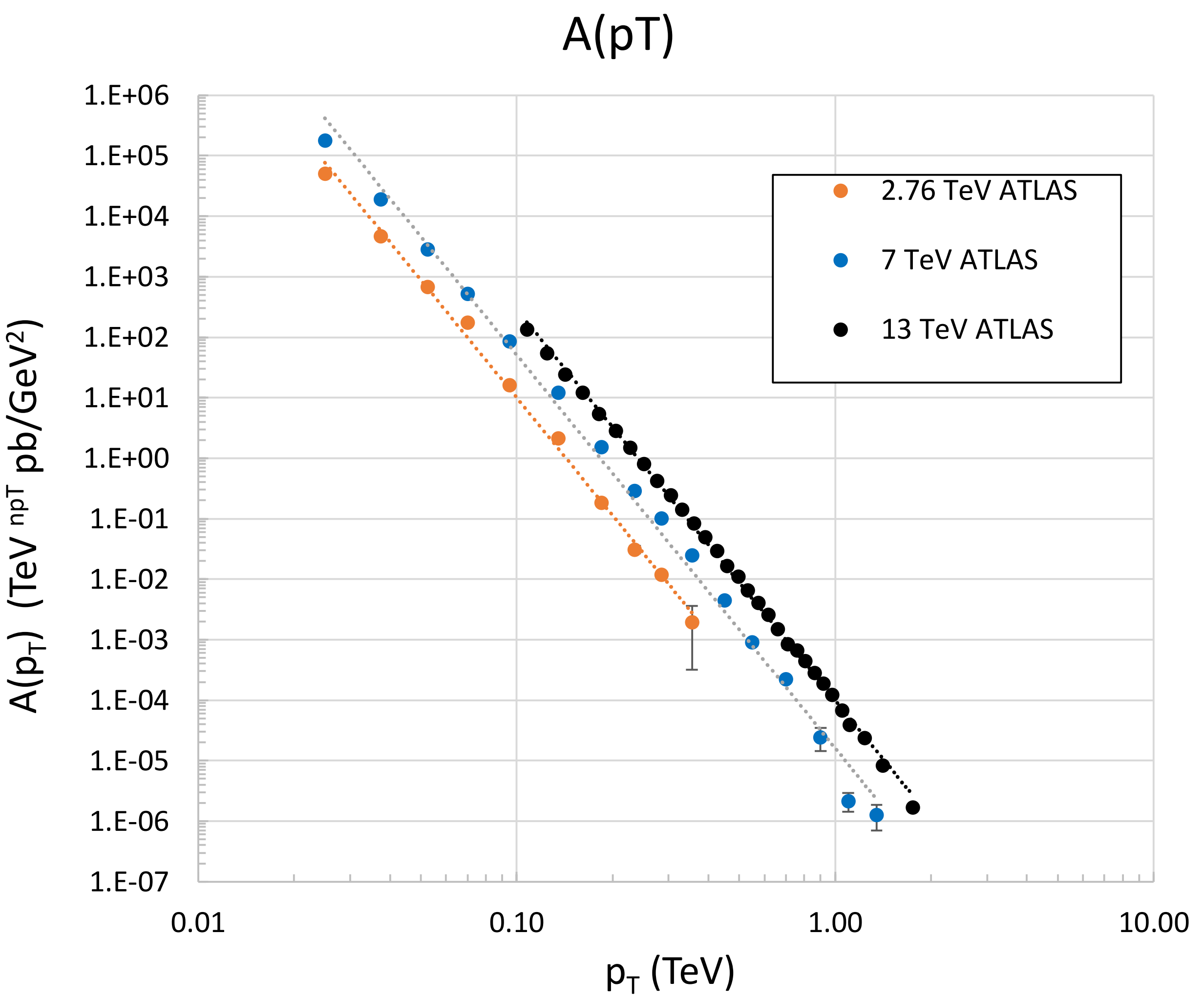
$$\frac{d^2\sigma}{p_T dp_T dy} \sim \frac{1}{p_T^6}$$

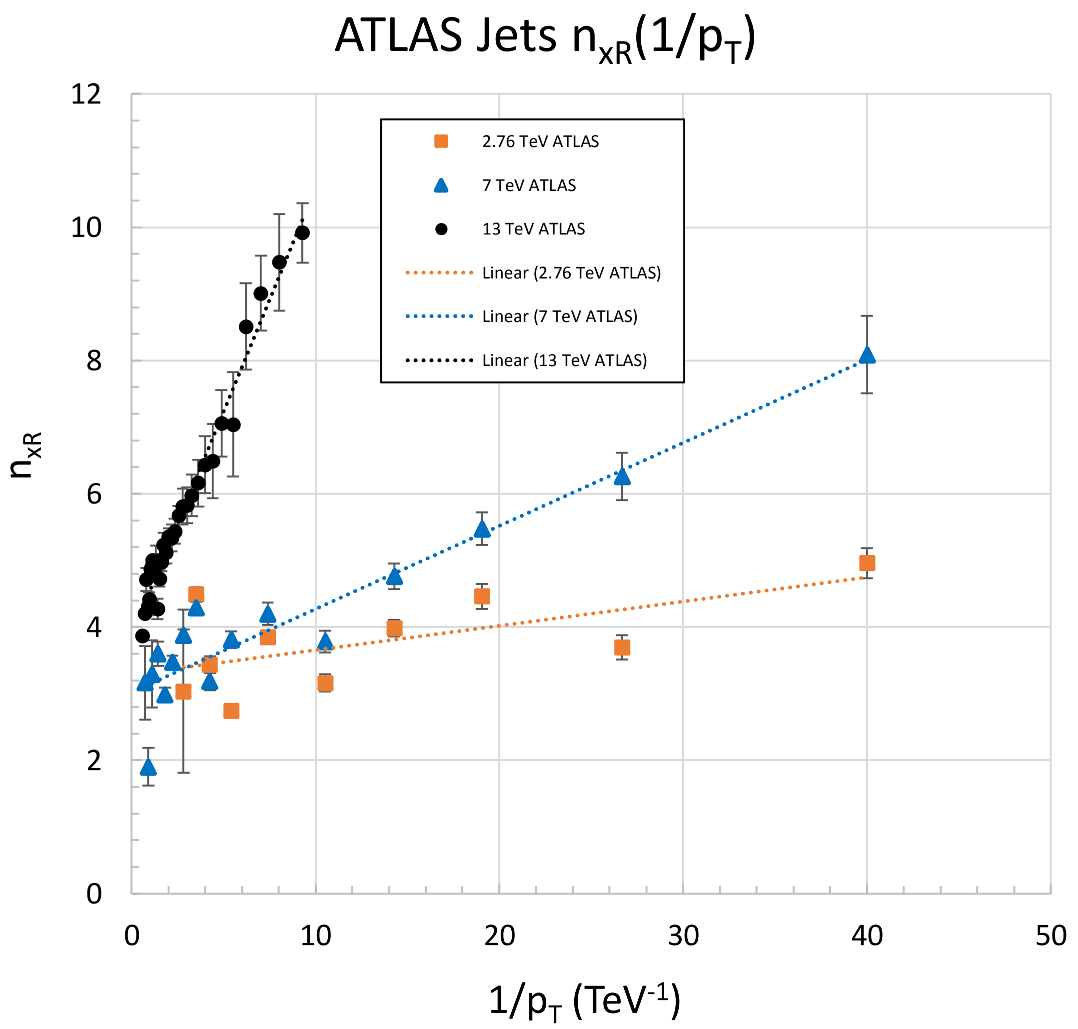
n_A = 5 2 → 3 scattering
DOMINATES $x_R \rightarrow 0$



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

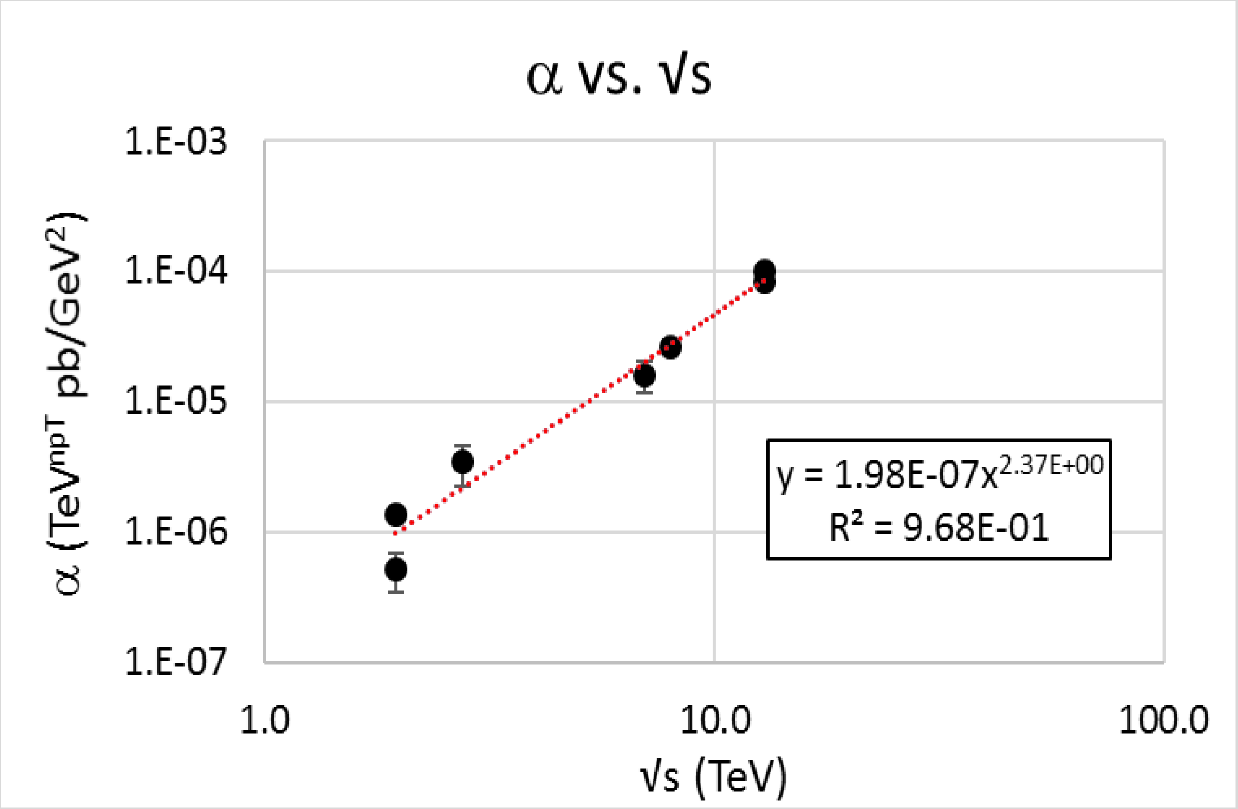
s-dependence of ATLAS Inclusive Jets

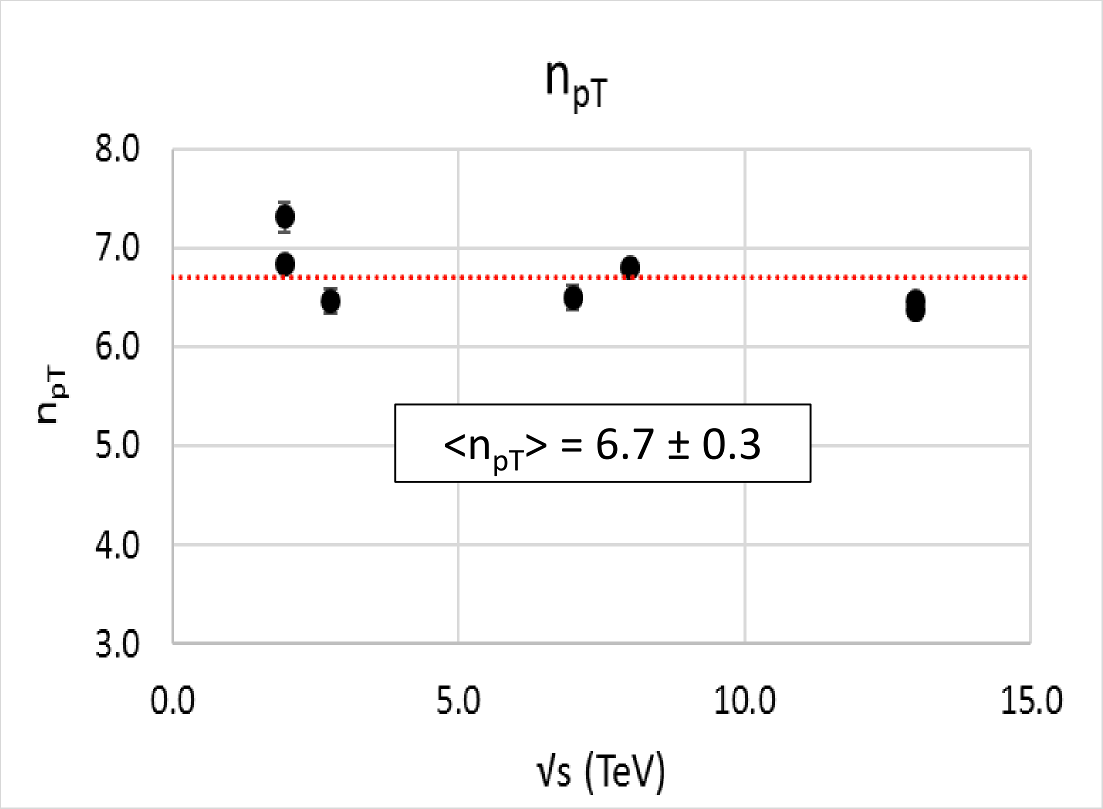




s-dependence of p_T – dependence of jets

$$A(p_T) = \frac{\alpha}{p_T^{\,n_{pT}}}$$

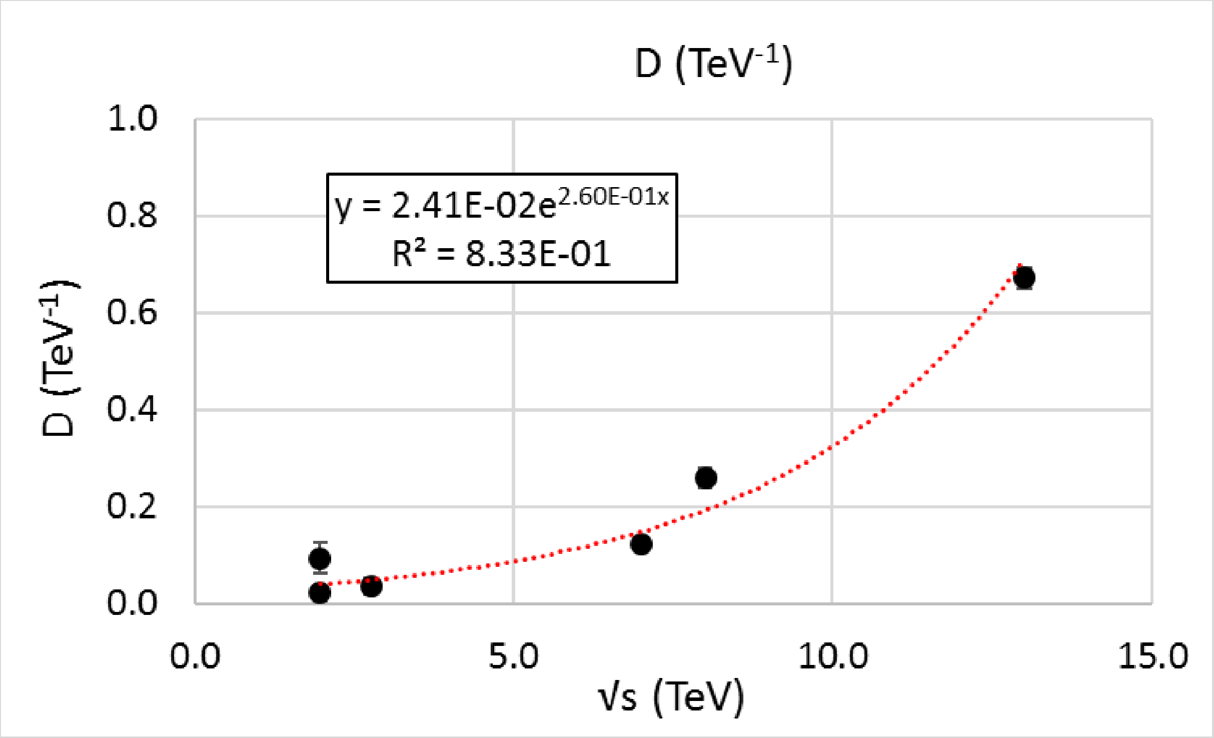


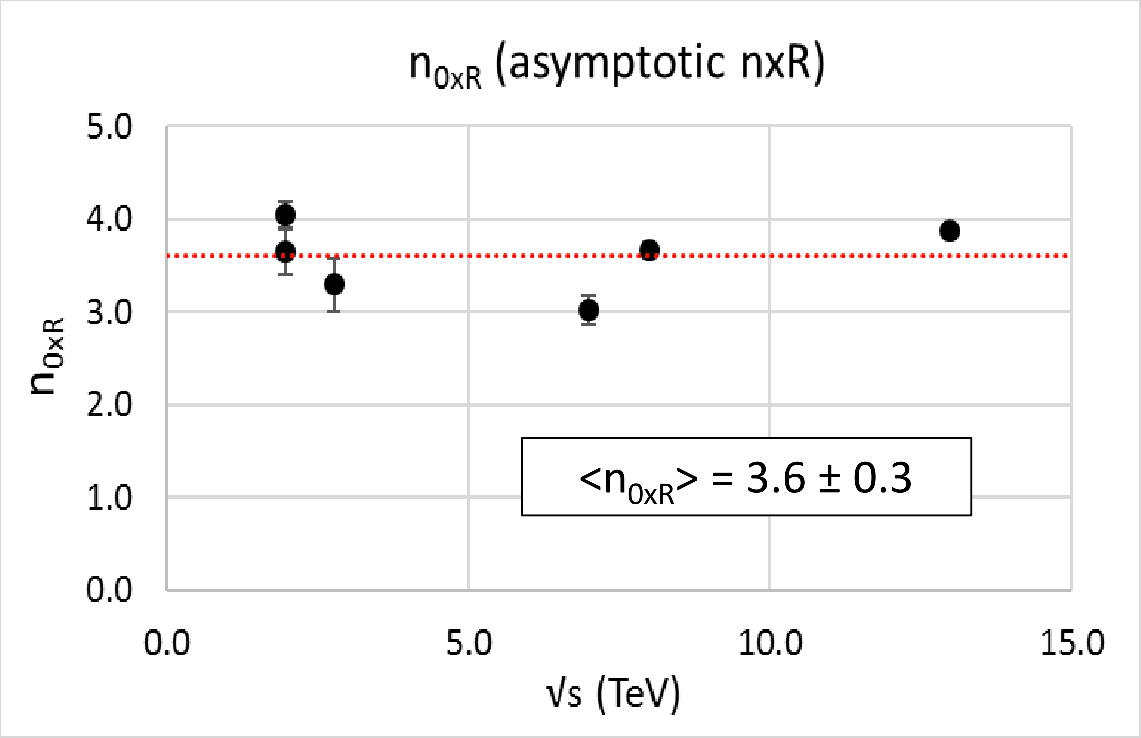


s-dependence of x_R of jets

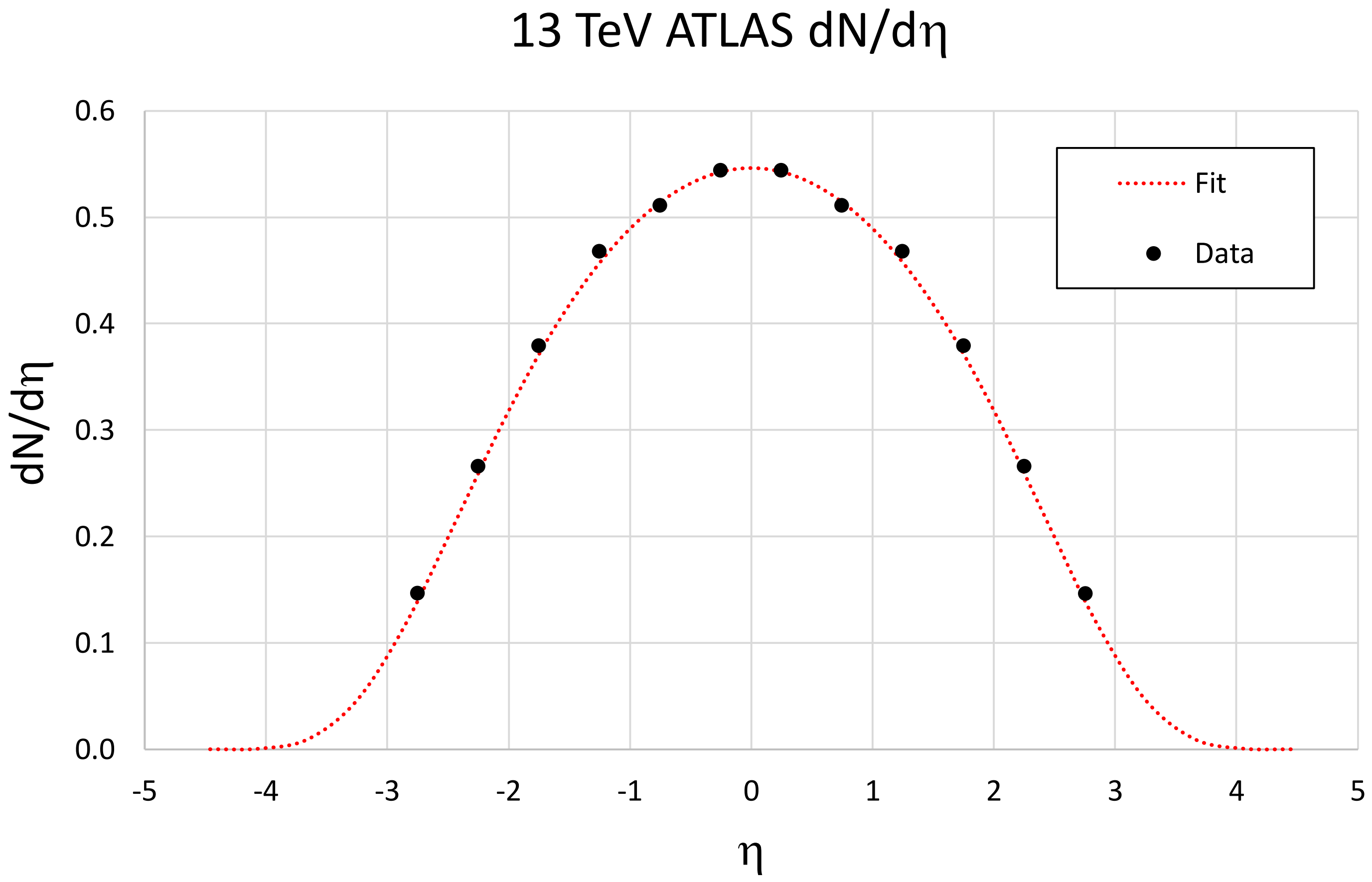
Rapid growth with √s! What will be the D value at √s = 100 TeV? Probably related to $N_{Jets}(s)$ and multiple parton scatterings.

$$(1 - x_R)^{(D/p_T + n_{0xR})}$$





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:

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

dσ/dη in Toy Model

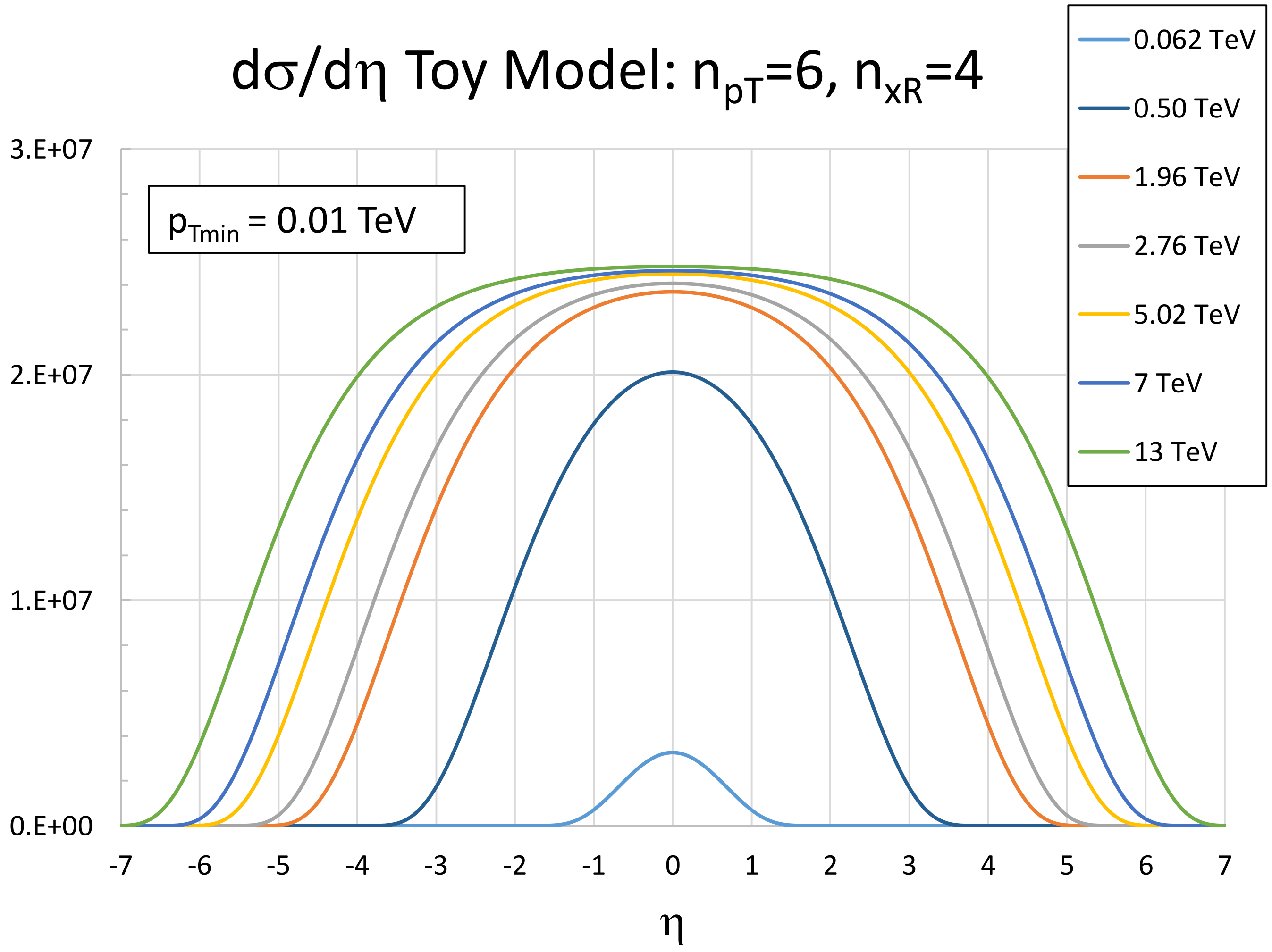
$$\frac{d\sigma}{d\eta} = \int_{p_{T\min}}^{p_{T\max}} \frac{d^2\sigma}{p_T dp_T d\eta} p_T dp_T = \int_{p_{T\min}}^{p_{T\max}} \frac{a}{p_T^{\,n_{pT}}} \left(1 - \frac{2p_T}{\sqrt{s}}\cosh(\eta)\right)^{n_{xR}} p_T dp_T$$

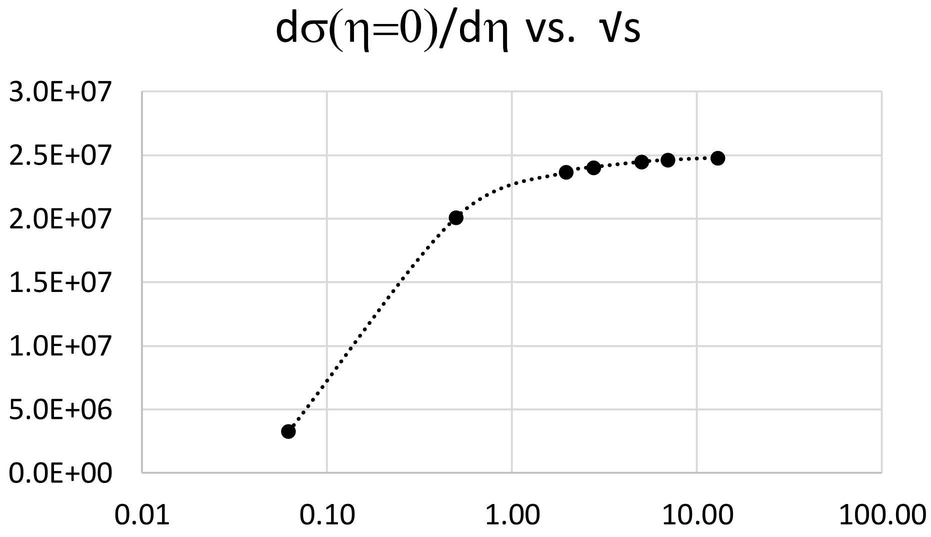
$$\frac{d\sigma\left(p_{T\min}, p_{T\max}\right)}{d\eta} = aF\left(p_{T\min}, p_{T\max}, \frac{\cosh(\eta)}{\sqrt{s}}\right)$$

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



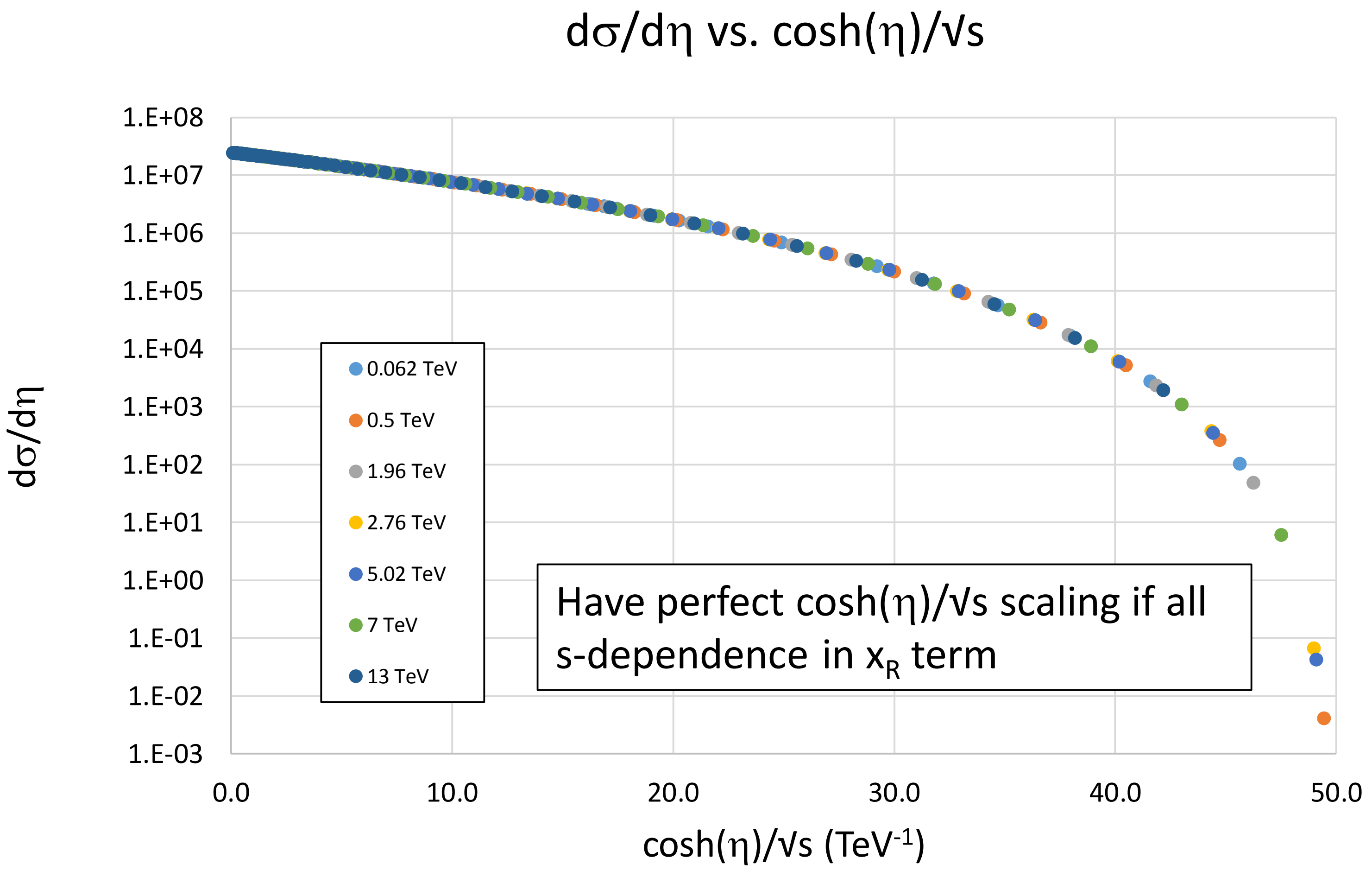


Width of plateau controlled by kinematic limit:

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

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",

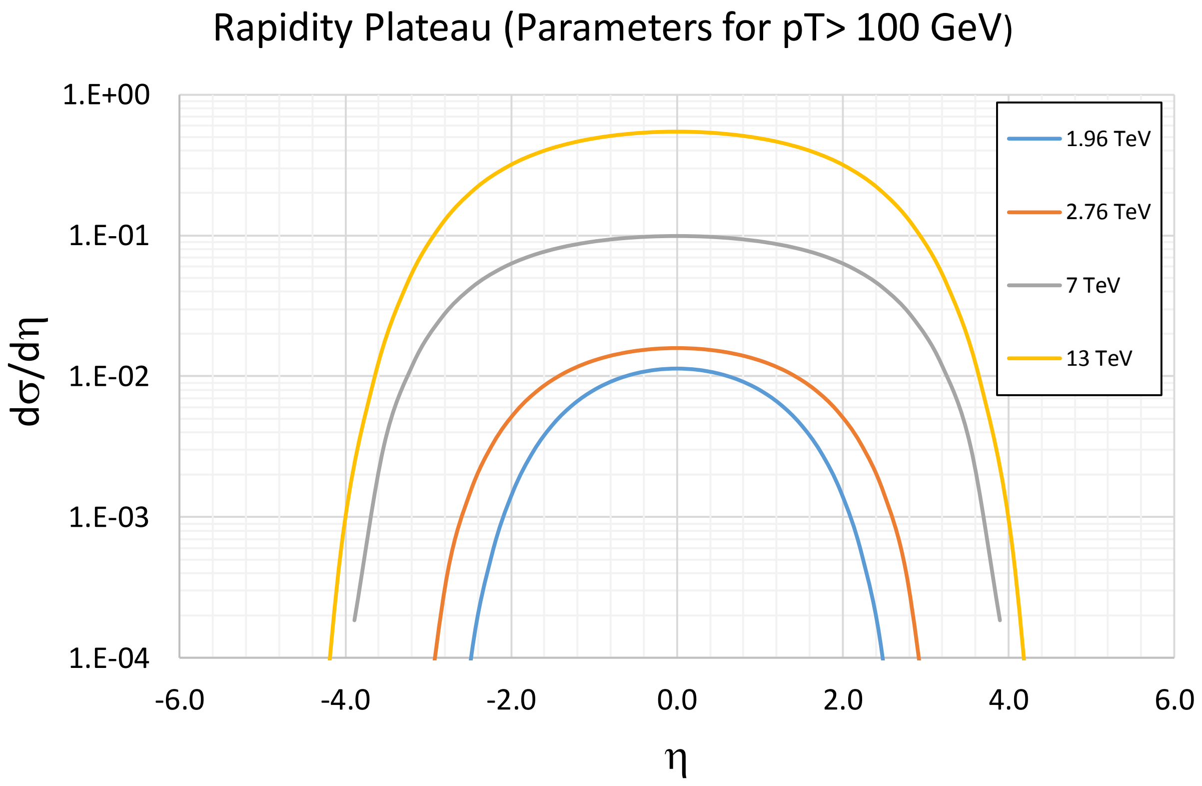
R. W. Ellsworth,

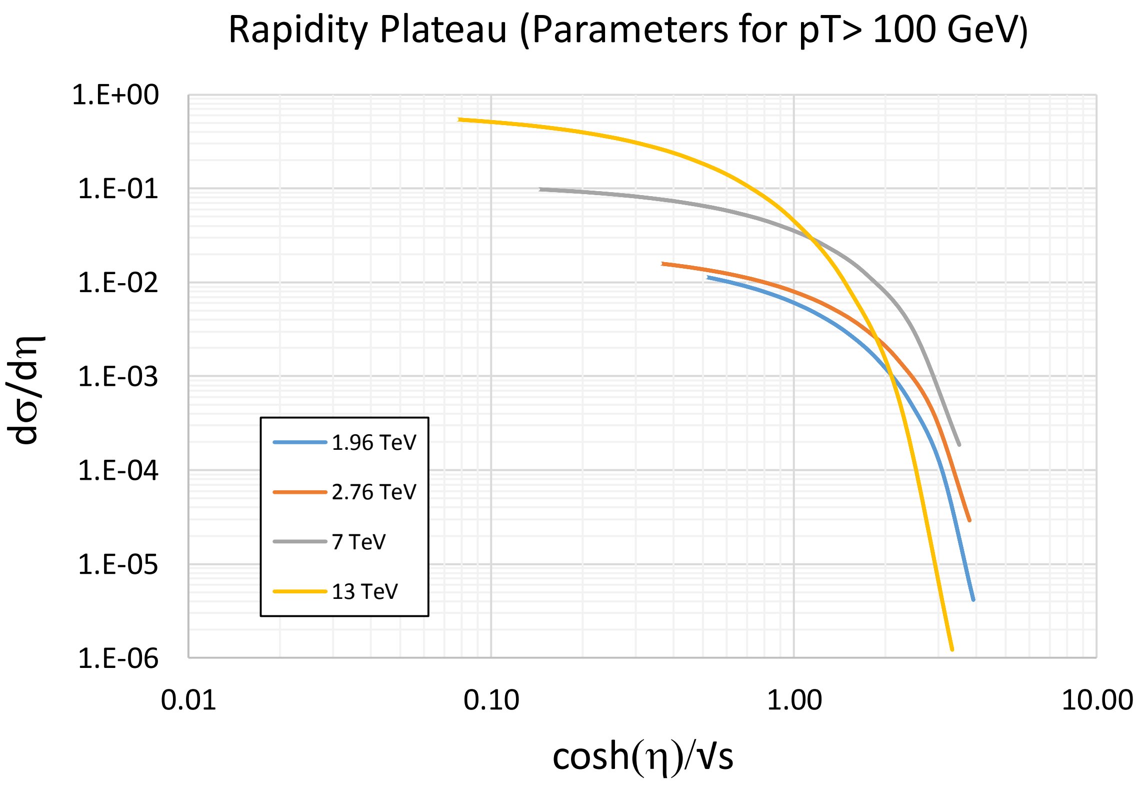
16th International Cosmic Ray Conference, Vol. 7. Published by the Institute for Cosmic Ray Research, University of Tokyo

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

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

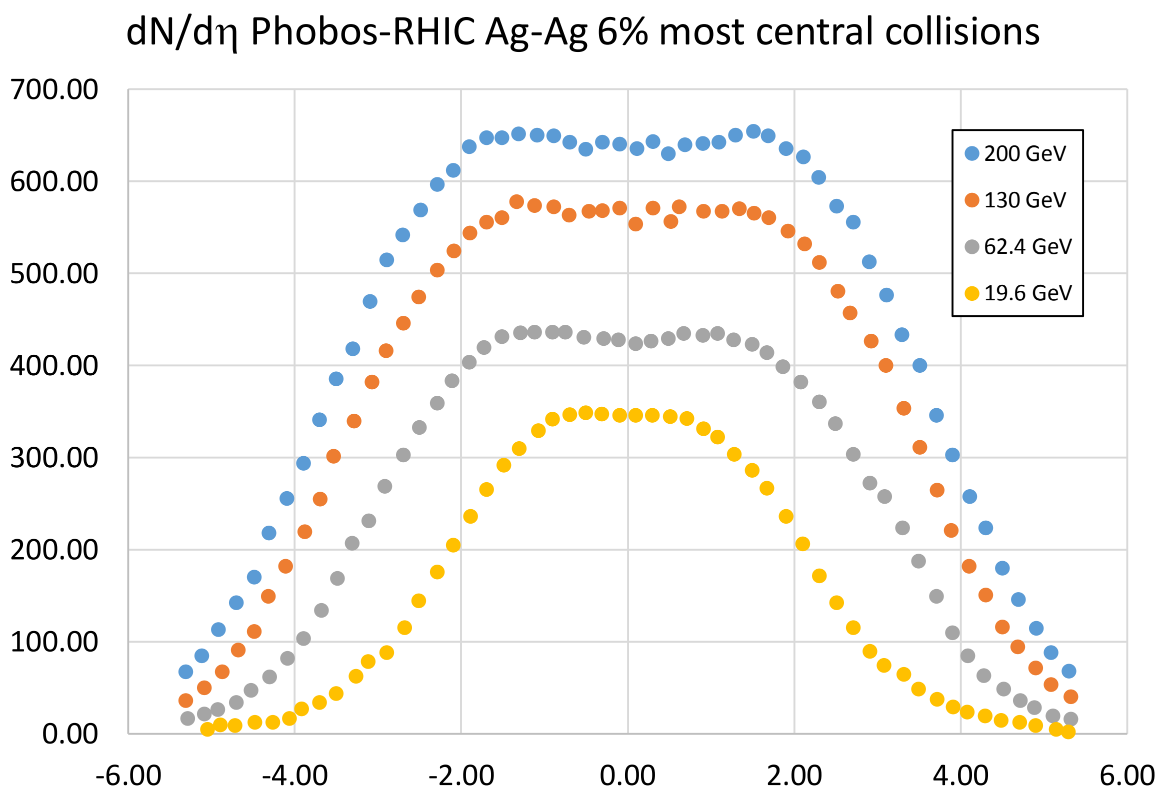


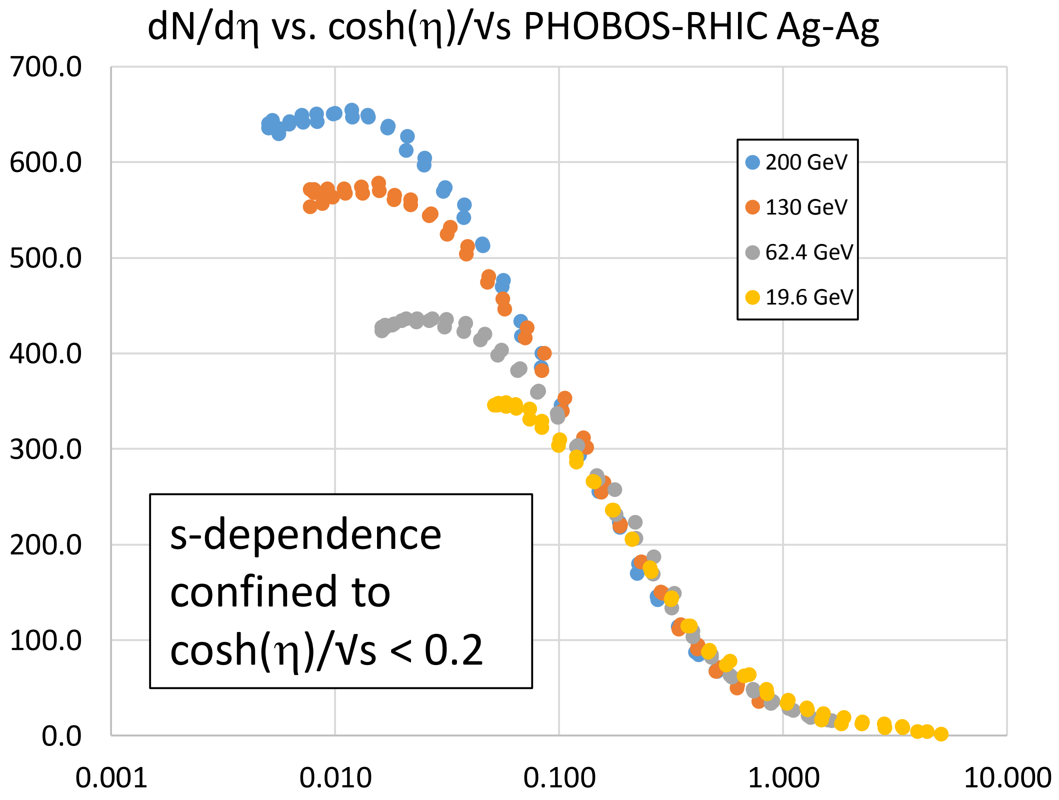


13 TeV is different because of large 'D' term for nxR = D/pT+n0xR

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.

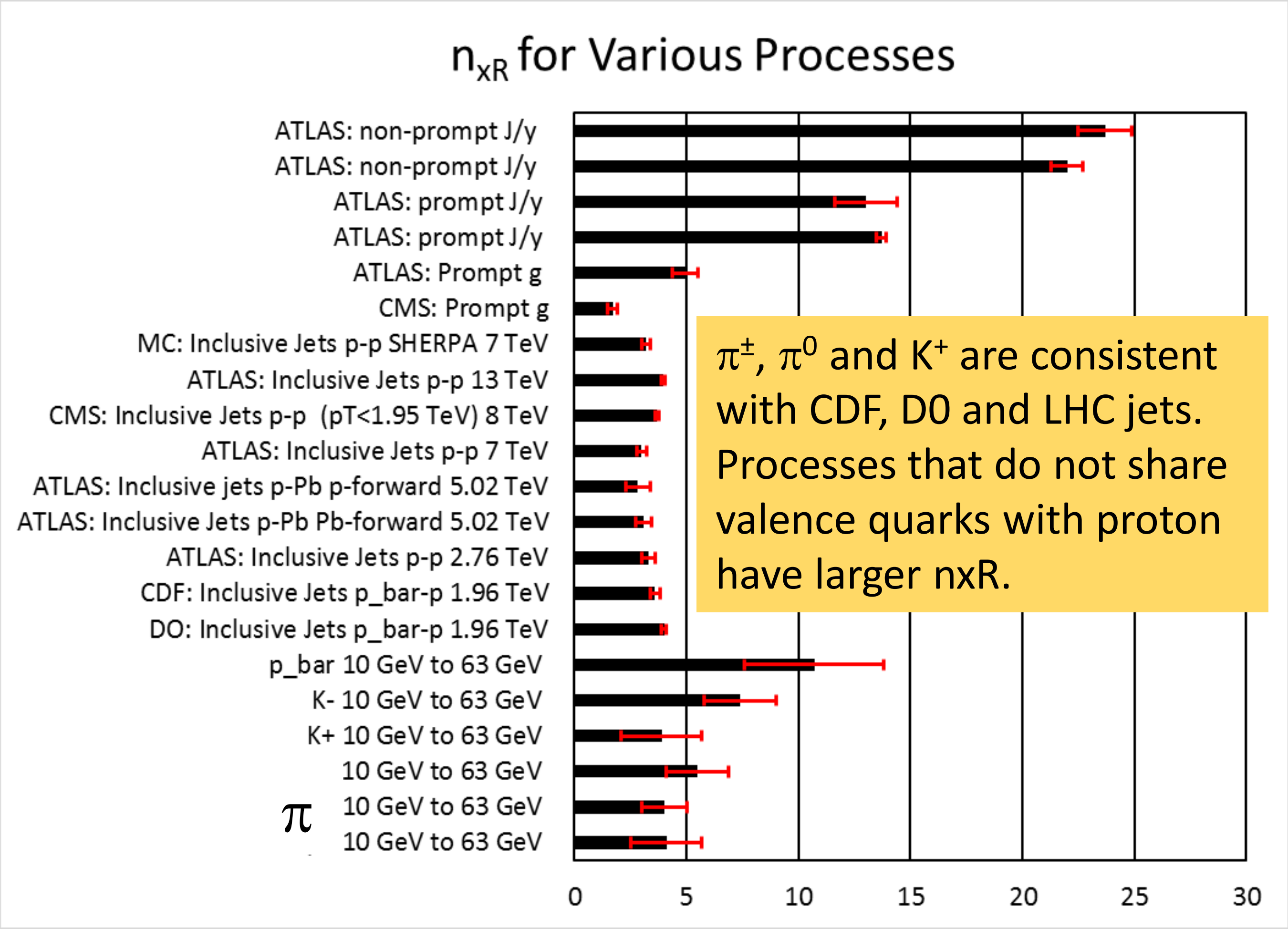
What about the x_R-Dependence

- 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.

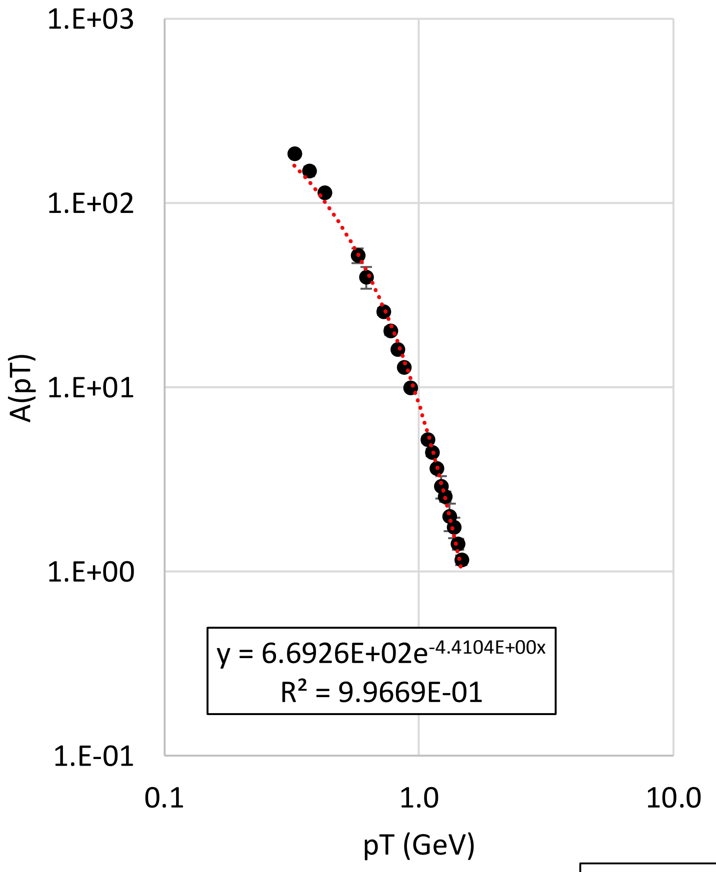
Applications of Radial Scaling

- Heavy Ions – particles and jets
  - Examine the p_T, x_R and y dependence – differences with p-p would indicate 'heavy ion physics'
    - Naively p_T dependence should be the same in p-p, p-HI and HI-HI collisions
    - n_{xR} perhaps different and would be sensitive to a different hadronization and/or jet quenching
- Inclusive Charm Production
  - Several sources of J/ψ – direct production and feed-down from bottom decays
    - Heavy quarkonium production a test of non-relativistic QCD effective field theory
    - $\psi(2S)$ essentially free from feed-down decays of higher mass quarkonium states
    - Should be able to measure the mass of parent in decay production by Λ term in p_T spectrum

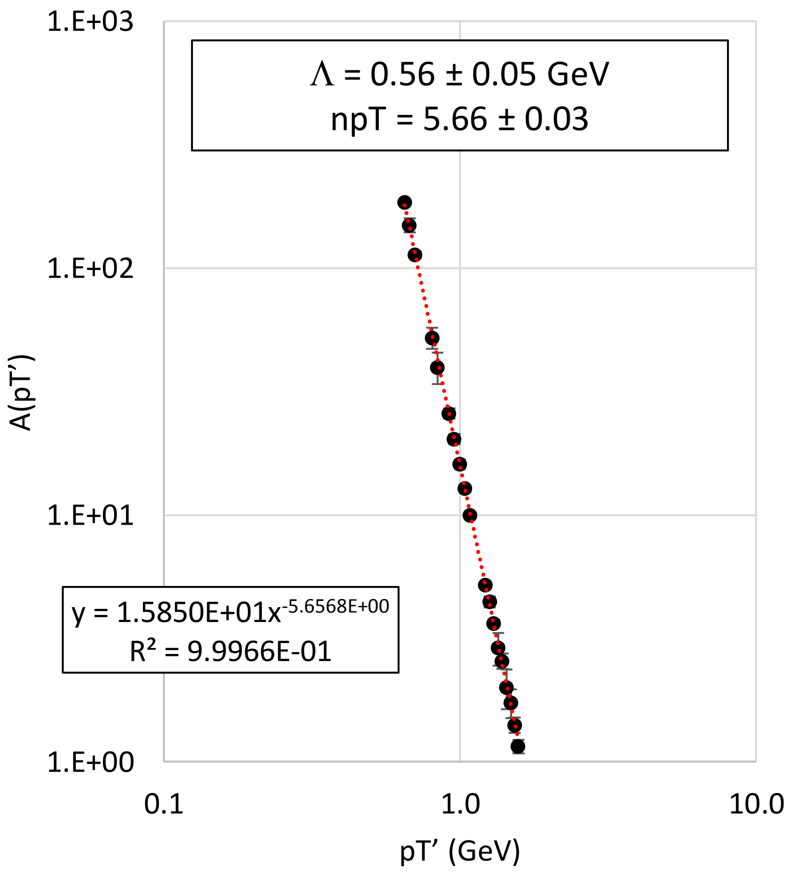
$$A(p_T) = \alpha_0 \frac{\Lambda^{n_{pT}-4}}{\left(\Lambda^2 + p_T^2\right)^{\frac{n_{pT}}{2}}}$$

BRAHMS π^+ from Ag-Ag Collisions 62.4 GeV

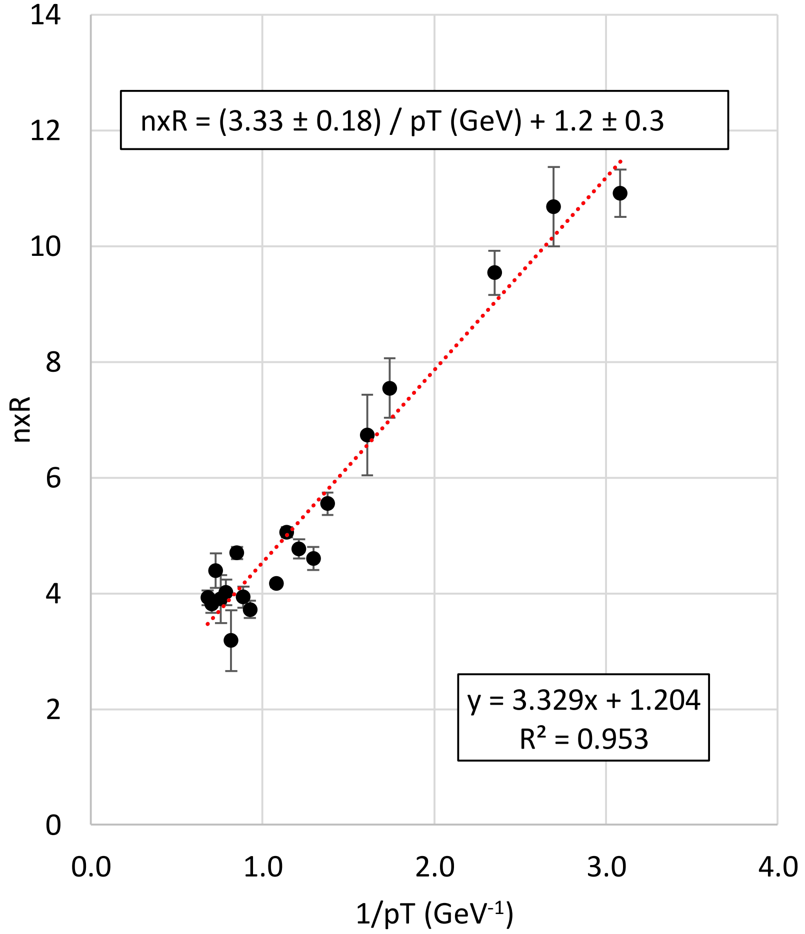
A(pT) vs. pT



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

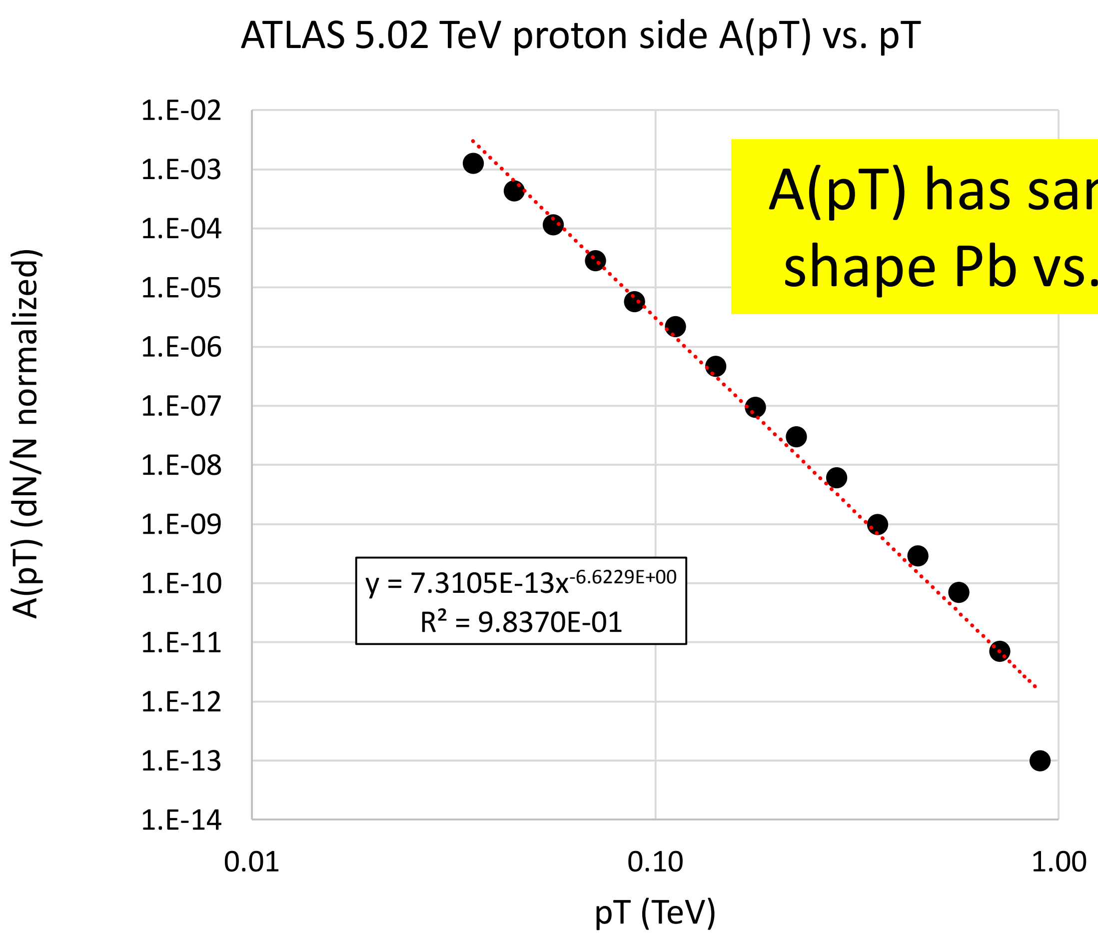


nxR(1/pT) vs. 1/pT

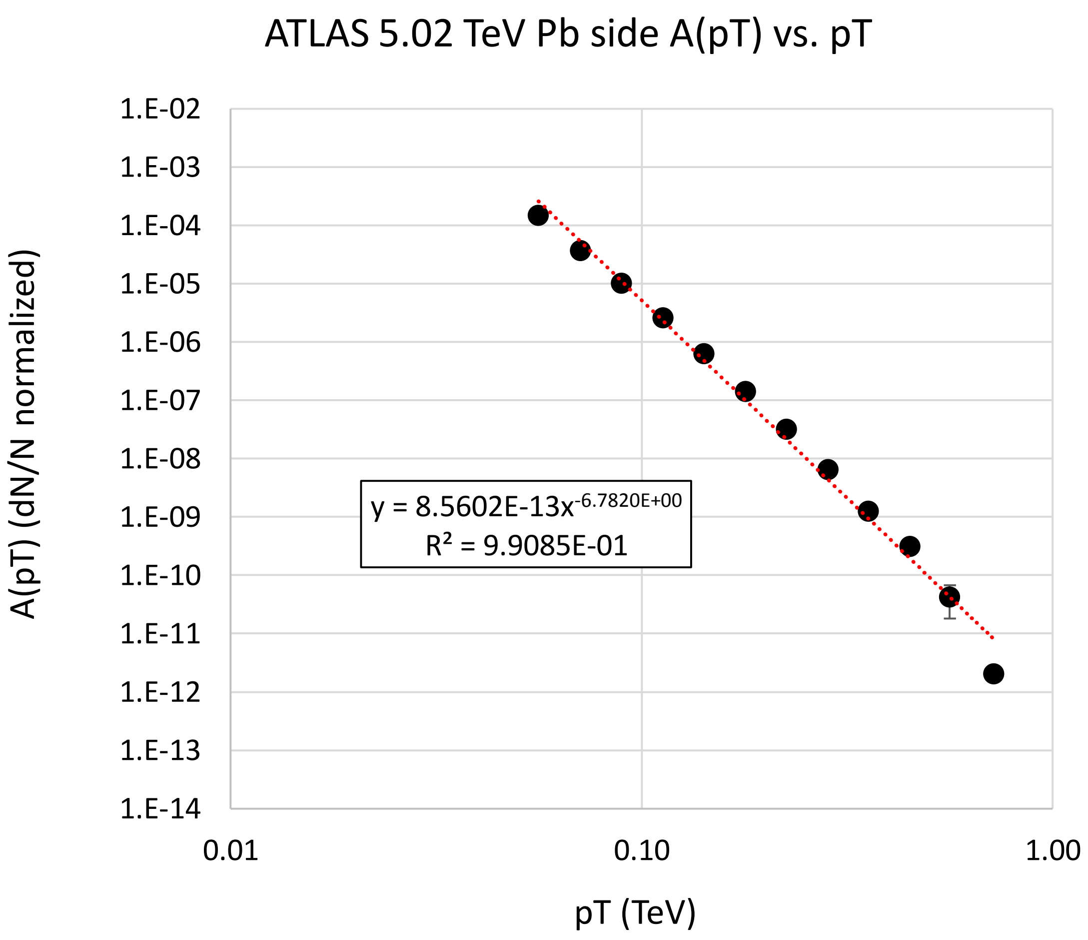


$$A(p_T) = \alpha_0 \frac{\Lambda^{n_{pT}-4}}{\left(\Lambda^2 + p_T^2\right)^{\frac{n_{pT}}{2}}}$$

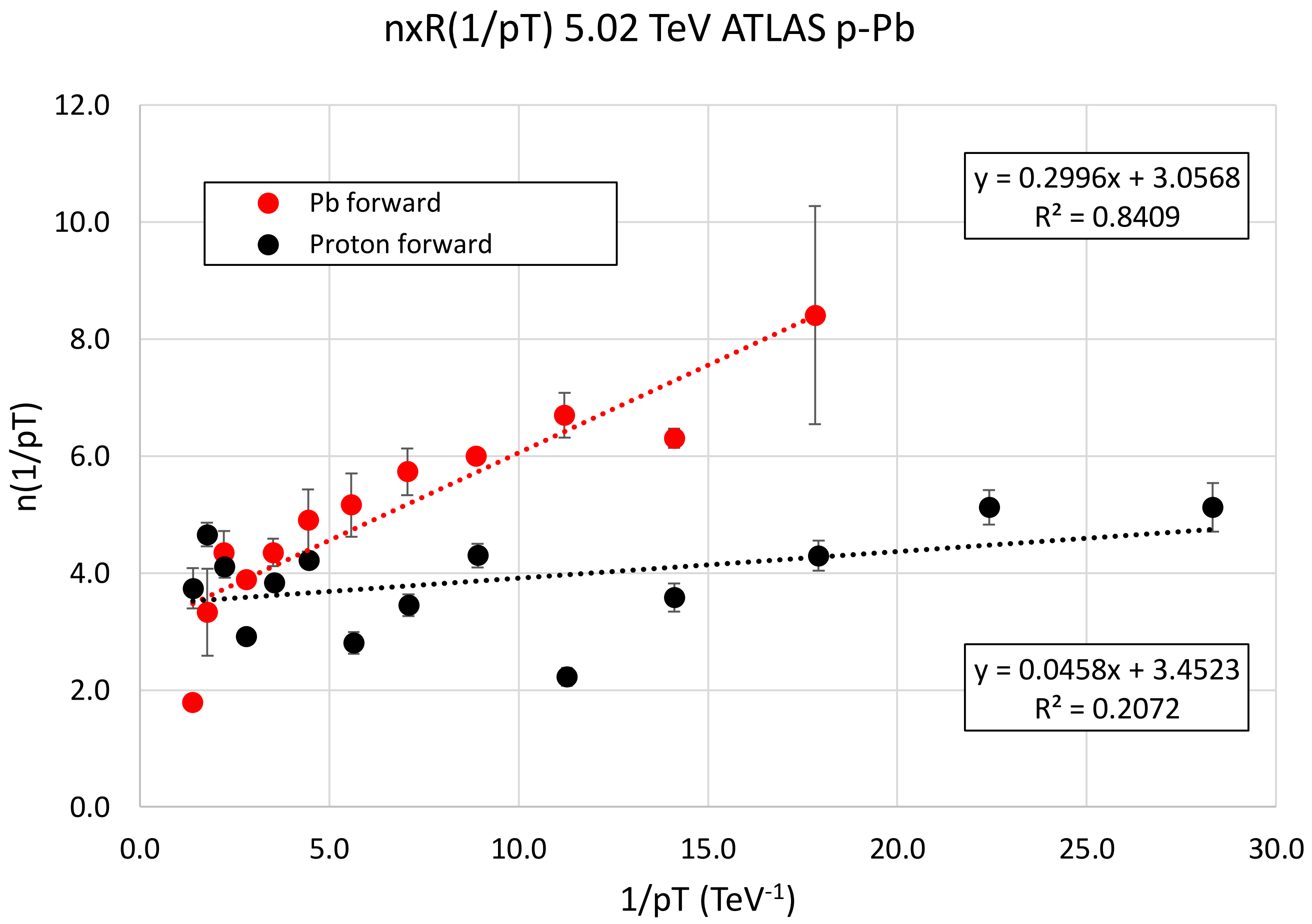
A(p_T) for 5.02 TeV p-Pb Inclusive Jets



A(pT) has same shape Pb vs. p



Evidence of Jet Quenching p-Pb Collisions



Low p_T Jets suppressed like p-p jets would be at √s = 10 TeV

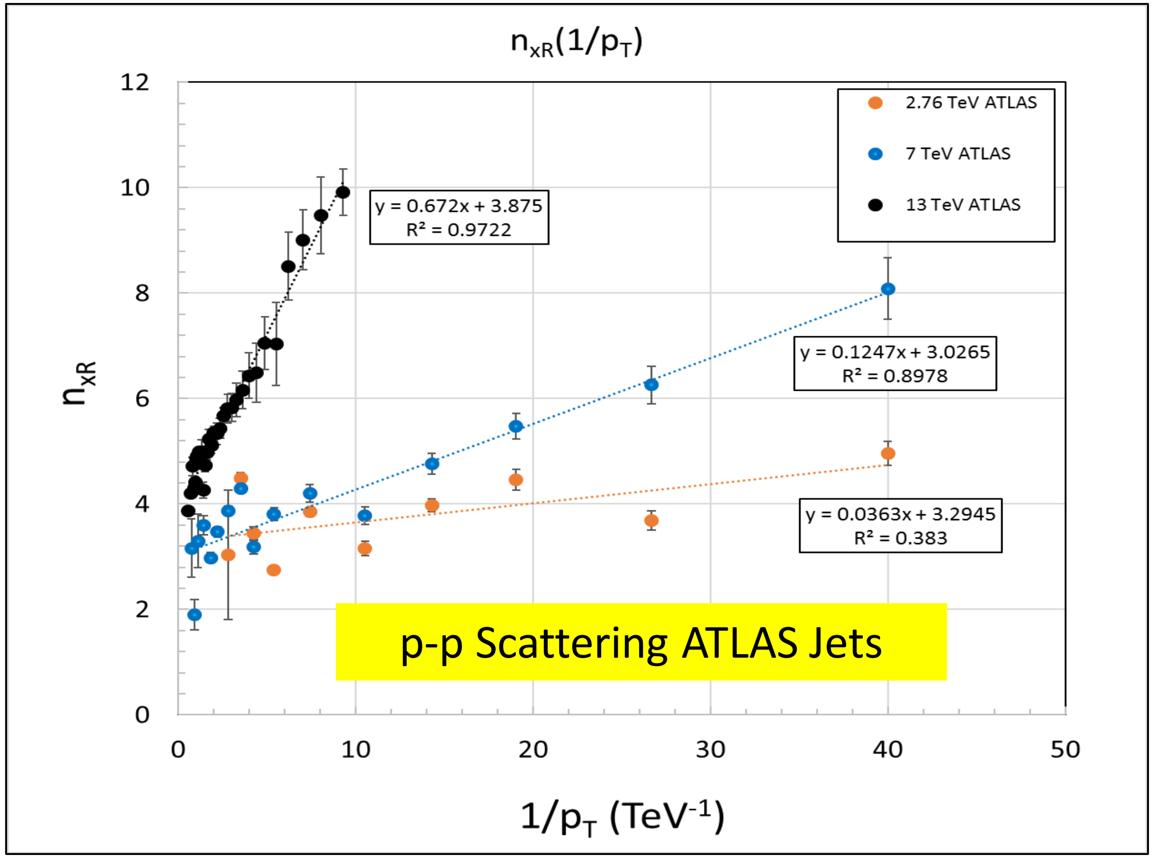
Interpretation:

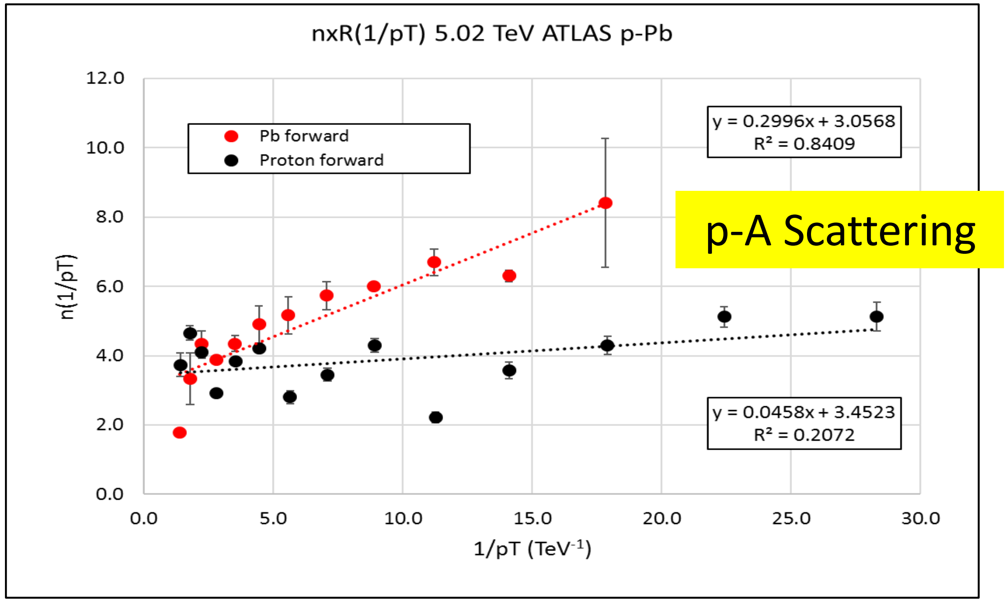
Jet co-moving with nuclear remnant undergoes multiple interactions which soften its xR dependence.

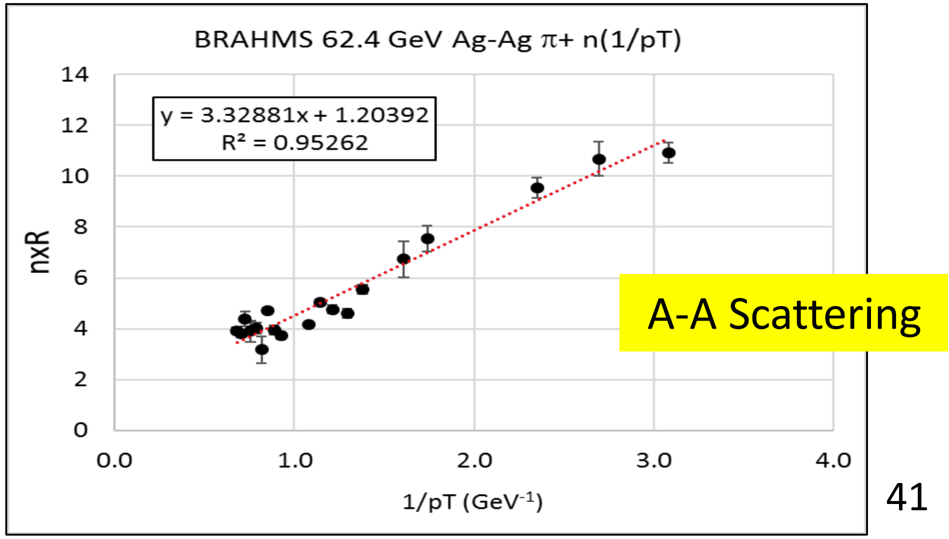
Jet co-moving with proton remnant does not experience 'extra' interactions – hence xR distribution is the same as p-p scattering.

Using p_T and x_R makes this distinction quite obvious.

p-p, p-A, A-A scattering: Analogous Behavior



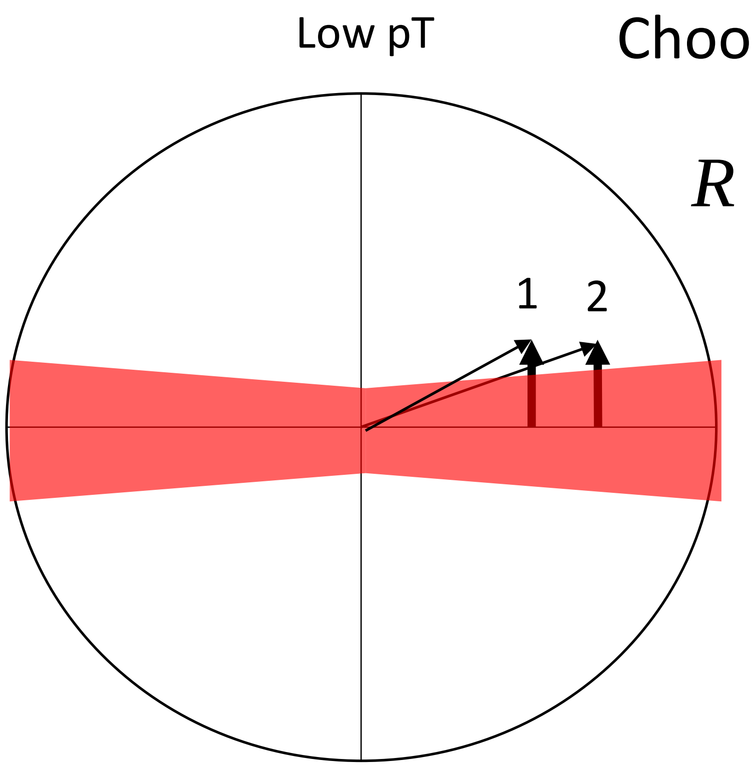




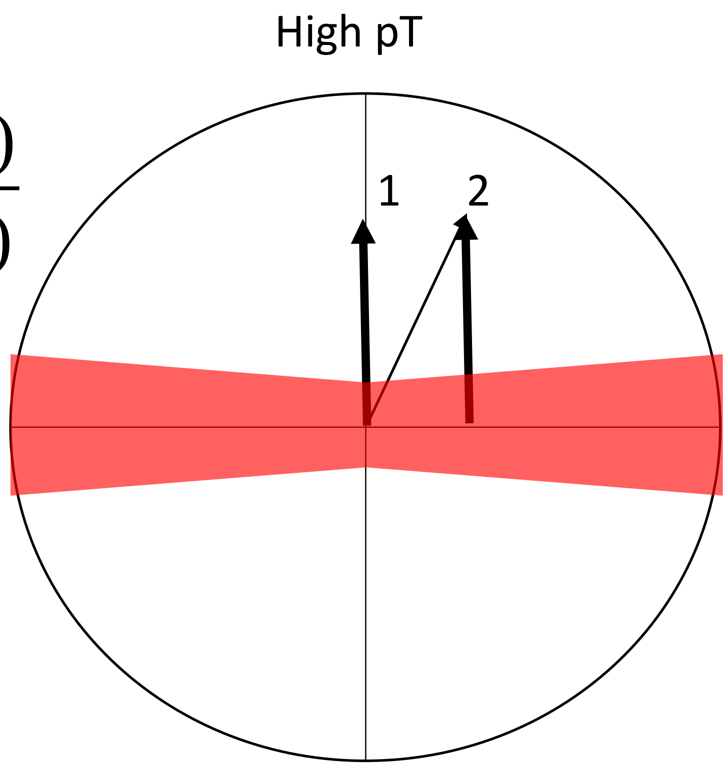
All behave: $$(1 - x_R)^{(D/p_T + n_{0\,xR})}$$

Physical Picture

Choose 4 points in phase space:



$$R = R(p_{TLow}) = R(p_{T\,High}) = \frac{(1 - x_{R2})}{(1 - x_{R1})}$$



"Beam fragmentation region"

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

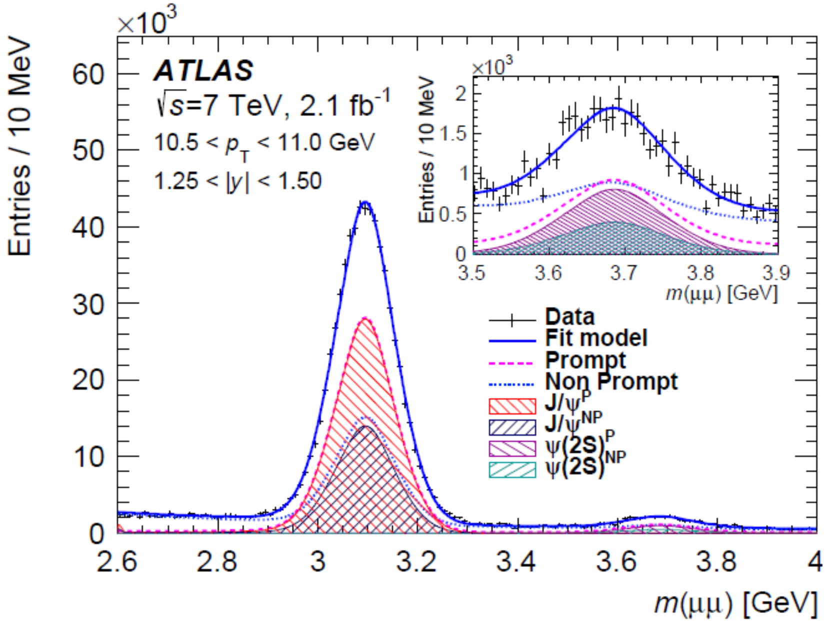
Jet quenching in both cases. Same Physics?

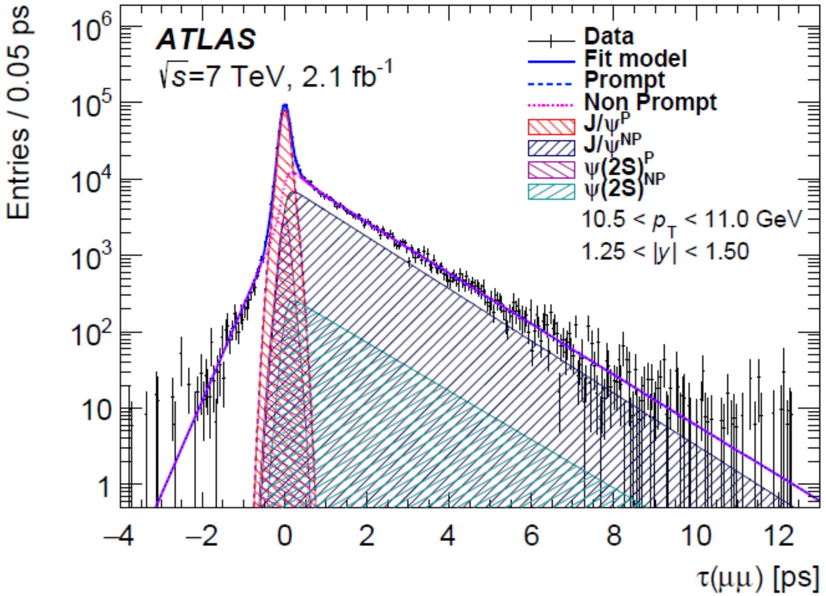
Jet strongly attenuated on approach to kinematic boundary because of large "D" term

$$R^{(D/p_{TLow}+n_{xR0})} \ll R^{(D/p_{THigh}+n_{xR0})}$$

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

CHARM Production at LHC



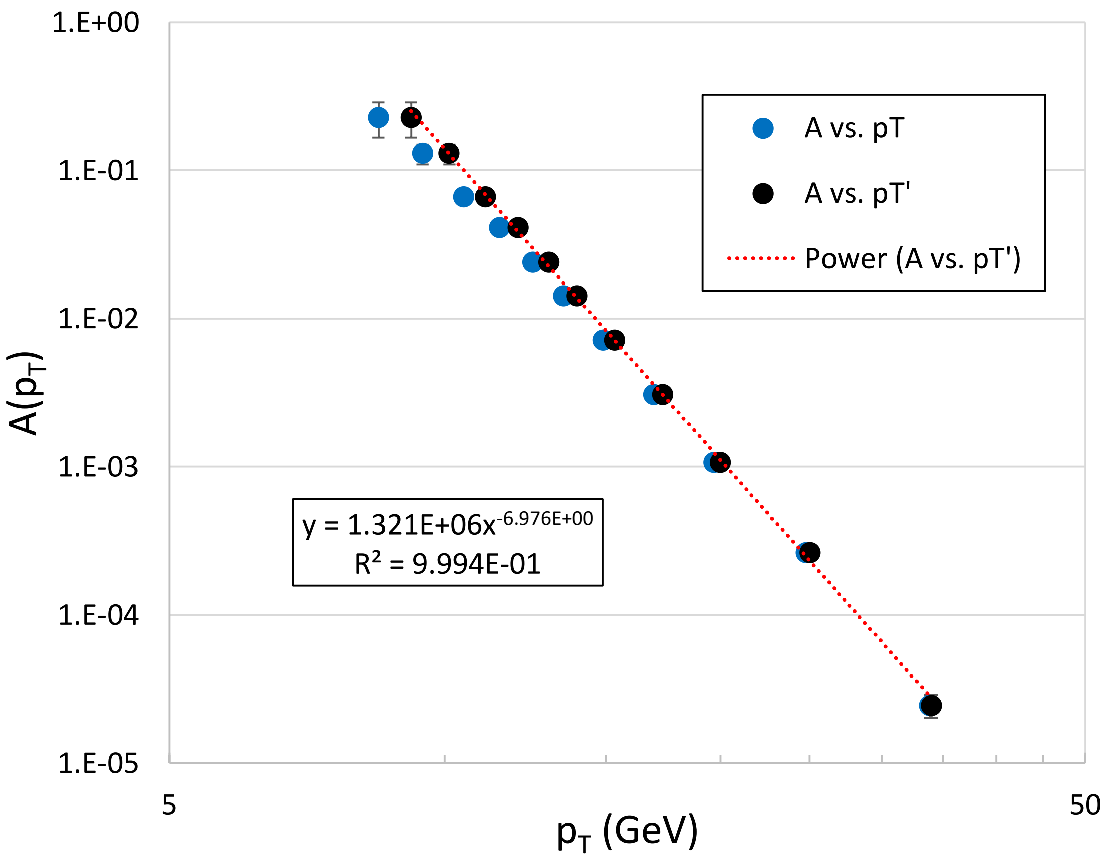


$$A(p_T) = \alpha_0 \frac{\Lambda^{n_{pT}-4}}{\left(\Lambda^2 + p_T^2\right)^{\frac{n_{pT}}{2}}}$$

- Can separate 'prompt' production – $\tau(\mu\mu) \sim 0$ from 'non-prompt' production where $\tau(\mu\mu) > 0$.
- Can separately measure J/ψ and ψ(2S).
- Can estimate the mass of the parent particle by shape of pT-spectrum at low pT.
- ATLAS, CMS and LHCb contribute but data seem inconsistent. See backups.

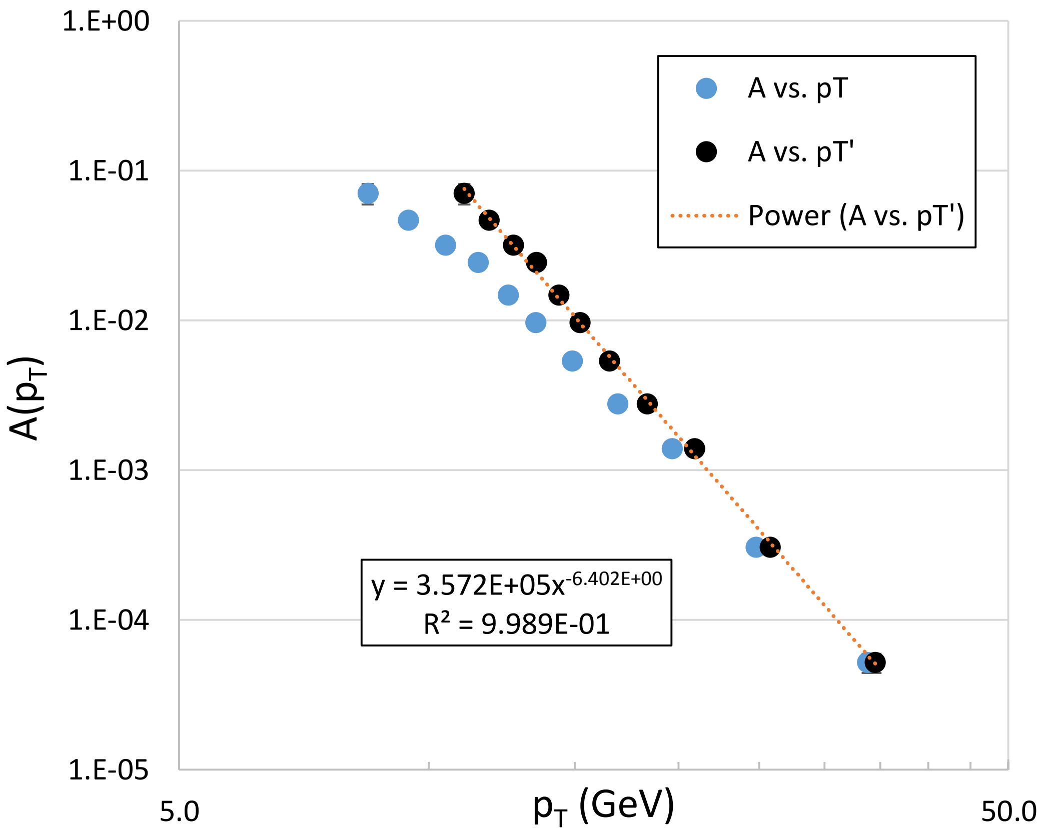
CHARM – Prompt & Non-Prompt p-p Data

ATLAS A(pT) vs. pT 5.02 TeV prompt J/Psi



$\Lambda = 3.6 \pm 0.3$ GeV

ATLAS 5.02 TeV Non-prompt J/Psi



$\Lambda = 7.1 \pm 0.9$ GeV

Summary of p_T Power Law with Form Factor

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

Form factor parameter Λ proportional the mass of the parent particle for heavy quark production in quadrature with intrinsic kT.

Index	Process	√s (TeV)	Λ(GeV)	$\sigma(\Lambda)$	npT	σ(npT)	$\langle\Lambda\rangle$	SD
1	Ref[1] π+ 10 GeV to 63 GeV	0.063	0.602	0.012	6.93	0.04	0.69	0.11
2	Ref[1] π0 10 GeV to 63 GeV	0.063	0.653	0.001	7.20	0.09		
3	Ref[1] π- 10 GeV to 63 GeV	0.063	0.607	0.003	6.86	0.03		
4	Ref[1] K+ 10 GeV to 63 GeV	0.063	0.613	0.054	6.04	0.12		
5	Ref[1] K- 10 GeV to 63 GeV	0.063	0.776	0.091	6.58	0.09		
6	Ref[1] p_bar 10 GeV to 63 GeV	0.063	0.892	0.071	6.79	0.28		
7	BRAHMS RHIC π+ Ag-Ag	0.062	0.56	0.05	5.66	0.03	0.56	0.05
8	ATLAS: prompt J/ψ	5.020	3.57	0.25	6.98	0.06	3.57	0.54
9	ATLAS: prompt J/ψ	7.000	3.25	1.20	6.68	0.03		
10	CMS: prompt J/ψ	7.000			6.68	0.05		
11	ATLAS: prompt J/ψ	8.000	3.01	1.22	6.34	0.03		
12	LHCb: prompt J/ψ	13.000	4.44	0.28	7.02	0.03		
13	ATLAS: prompt ψ(2S)	7.000	4.10	1.79	6.55	0.05	4.30	1.45
14	ATLAS: prompt ψ(2S)	8.000	4.50	1.10	6.56	0.06		
15	ATLAS: non-prompt J/ψ	5.020	7.10	0.90	6.40	0.07	6.23	1.11
16	ATLAS: non-prompt J/ψ	7.000	5.80	1.12	6.04	0.03		
17	ATLAS: non-prompt J/ψ	8.000	7.41	0.47	6.05	0.03		
18	LHCb: non-prompt J/ψ	13.000	4.62	0.24	5.72	0.05		
19	ATLAS: non-prompt ψ(2S)	7.000	4.10	2.00	5.58	0.05	7.75	3.65
20	ATLAS: non-prompt ψ(2S)	8.000	11.40	0.10	6.83	0.13		
	Ref[1] F. E. Taylor et al. Phys. Rev. D 14, 1217 (1976)			<npT>	6.5	0.5		

Intrinsic kT

ψ(2S) 3.686 GeV
BR(ψ(2S)→J/ψ(1S)) 60%

Domain of b-physics

Observations through the Prism of Radial Scaling

- Inclusive jet production at the LHC is quite similar to light quark single particle inclusive production studied > 40 years ago.
- 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: **$1/p_T^{(6.5 \pm 0.5)}$** in the limit $x_R \to 0$.
- The x_R dependence is consistent with a power law $(1-x_R)^{nxR}$, where n_{xR} is qualitatively dependent on the number of spectator quarks as well as p_T and √s at high √s. At high √s and HI collisions (Charm ?) $nx_R = D/p_T + nx_{R0}$.
- Inclusive Charm in p-p collisions has the same behavior as π^+ and jets in heavy ion collisions.
- Radial scaling determines the pseudo-rapidity plateau and provides a separation of rise of the central plateau by kinematics from pQCD by means of the scaling variable $\cosh(\eta)/\sqrt{s}$.

The p_T-dependence of jets/particles again - 3 views

- pQCD agrees with data – so why care that $1/p_T^6$ dominates rather than $1/p_T^4$:
  - The underlying paradigm of the standard model works.
  - Jets and single particles in p-p collisions are governed by the same physics.
  - But there are 10's of tuned parameters and a mound of processes contributing. How unique?
  - Is there a minimum set of parameters sufficient? Simulations are tuned to data.

- There is a diquark in the nucleon that is either intrinsic or emergent:
  - Hence the 2→3 scattering dominates to make the $1/p_T^6$ dependence.
  - Lattice QCD and Jlab proton form factor data give evidence of a diquark system inside the proton.
  - But what about single γ production where $n_{pT} \sim 5.6$?
  - How can Charm and anti-proton production also come from (exotic) diquarks?

- The 'extra' p_T powers come from p_T dependence in the fragmentation and hadronization:
  - The pT-dependence is really not a power law but something that looks like one and can be fit by a quadratic in log(pT) ~ log-normal
  - Single γ is different because there is no fragmentation and hadronization.
  - Why does this work so well – why so precocious in $\sqrt{s}$?

Summary – Radial Scaling 1974 → 2017

- A formulation is given of inclusive Jet production in p-p collisions that controls the kinematic boundary so that the underlying dynamics can be studied:

$$\frac{d^2\sigma}{dp_T^2\,dy}(s,m) = \alpha_0(s)\frac{\Lambda(s)^{n_{pT}-4}}{\left(\Lambda(s)^2+p_T^2\right)^{\frac{n_{pT}}{2}}}\left(1-\frac{2\sqrt{\left(p_T^2\cosh^2(y)\left(1+\left(m^2/p_T^2\right)\tanh^2(y)\right)+m^2\right)}}{\sqrt{s+m_{QN}^2}}\right)^{\frac{D(s)}{p_T}+n_{x_R0}}$$

generally small – except low p_T and large m production

- Can be applied to jets as well as single particle inclusive production.
- Formulation seems useful in studying heavy ion collisions.
- Surprising that such a simple idea works so well – but controlling known kinematic boundary effects would be the first thing one would do.

“To travel hopefully is a better thing than to arrive”- RLS

- In looking at LHC data I found considerable differences between experiments that claim to measure the same thing:
  - For example ATLAS, CMS and LHCb all have data on J/ψ prompt and non-prompt production. The data are not consistent – perhaps because of different acceptance corrections, etc.
  - I recommend that experiments compare data and plots and work on understanding the differences in the measurements – they may reveal new physics.
  - Small inconsistencies can be leads to better understandings.
- Many studies are of limited kinematic range – for example Z production in either a limited range of |y| or integrated over a wide range in y. Neither case is useful for determining the fine-grained systematics of the process and in comparing to other measurements.
  - Measure processes over a wide kinematic range & post cross sections on web.
- Conclusions are frequent stated as such: “Our data agree with simulations of NNLO with parton set XYZ” or “with the model given in Ref[25]”.
  - Where is the physics? Experimentalists should not be shy in interpreting results. That should encourage theorists to get it right and make it understandable.

Backup

Caveats, Disclaimers, Limitations

- The spirit of this study is to see how far a simple idea could be applied to LHC and other data without sophisticated analysis machinery in order to uncover patterns – if they exist
  - No ‘raw’ data were used – all information from the public domain
  - Excel was used for tabulation and plotting
  - Mathematica was used to determine closed-form expressions
  - When available tabulated data were used but when not available plots were scanned using ImageJ – freeware distributed by NIH. The accuracy of scanned plots is estimated to be < 1%.
  - Numerical integrations were calculated by simple sums
  - Parameter errors were underestimated – fits of power laws were performed in linearized expressions using LINEST – an Excel fitting program of the central values without systematic or statistical errors but the resultant error reflects the fluctuations of points with equal weight about the fitted form.

Parton-Parton Elastic Scattering – 2 Examples

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

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

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

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

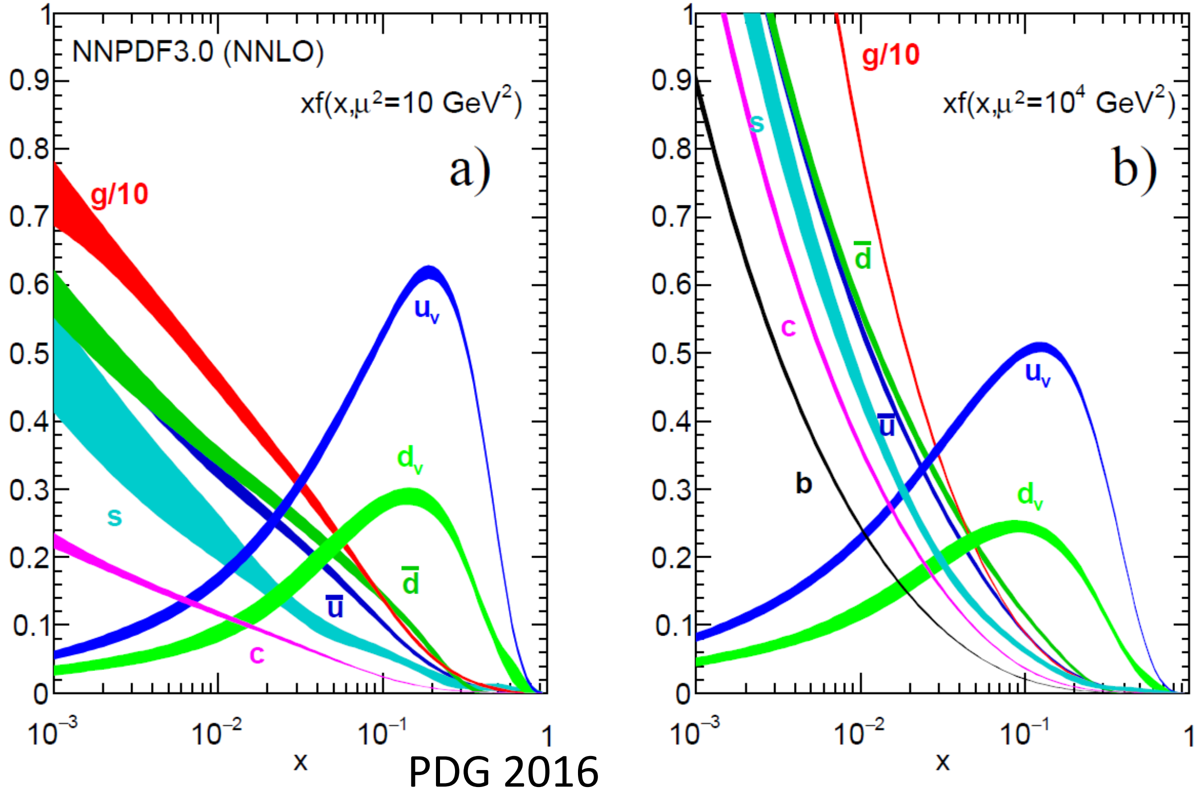
$$\cos\theta = \left(1-\frac{p_T^2}{\hat{s}}\right)^{1/2}$$

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

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

PDF and DGLAP Evolution and Splitting Functions

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

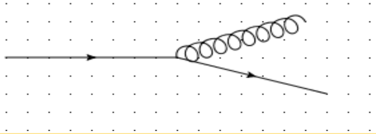


PDG 2016

DGLAP evolution and splitting functions:

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

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



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

$A(p_T)_{jets}$: Power law $1/p_T^{npT}$ or Quadratic in $\log(p_T)$?

- Power law:

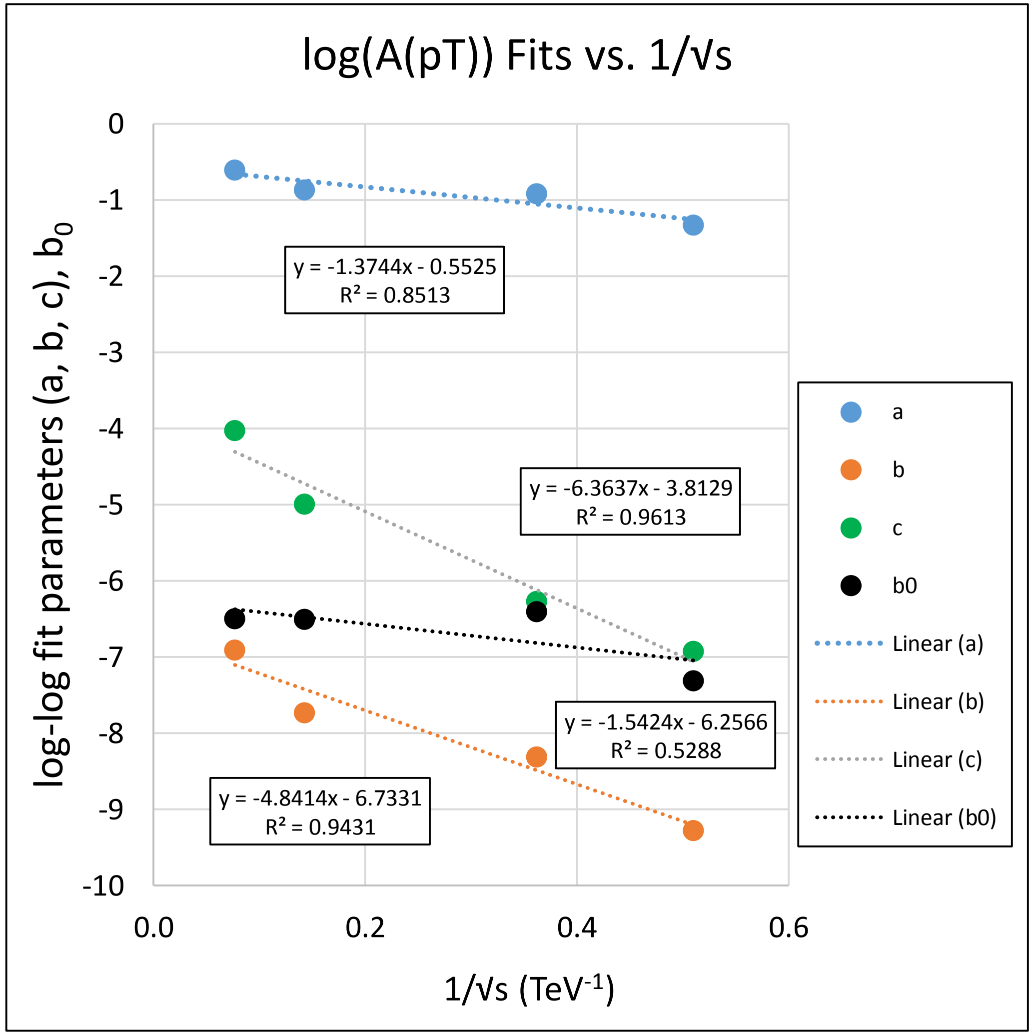
$$\log(A(p_T)) = b_0 \log(p_T) + c_0$$

- Or a quadratic in log(pT):

$$\log(A(p_T)) = a\log^2(p_T) + b\log(p_T) + c$$

log-log fits		$\log^2$	log	constant	log-alone	constant
$1/\sqrt{s}$	$\sqrt{s}$	a	b	c	b_0	c_0
0.510	1.960	-1.326	-9.275	-6.920	-7.310	-6.286
0.362	2.760	-0.914	-8.308	-6.269	-6.406	-5.463
0.143	7.000	-0.864	-7.730	-4.994	-6.499	-4.794
0.077	13.000	-0.607	-6.908	-4.021	-6.496	-4.002

- Note: $-b_0$ and $-b$ seem to converge to $n_{pT} \approx 6.5$ (no evidence of $1/p_T^4$ term)



Integrate over x_R to find p_T Dependence

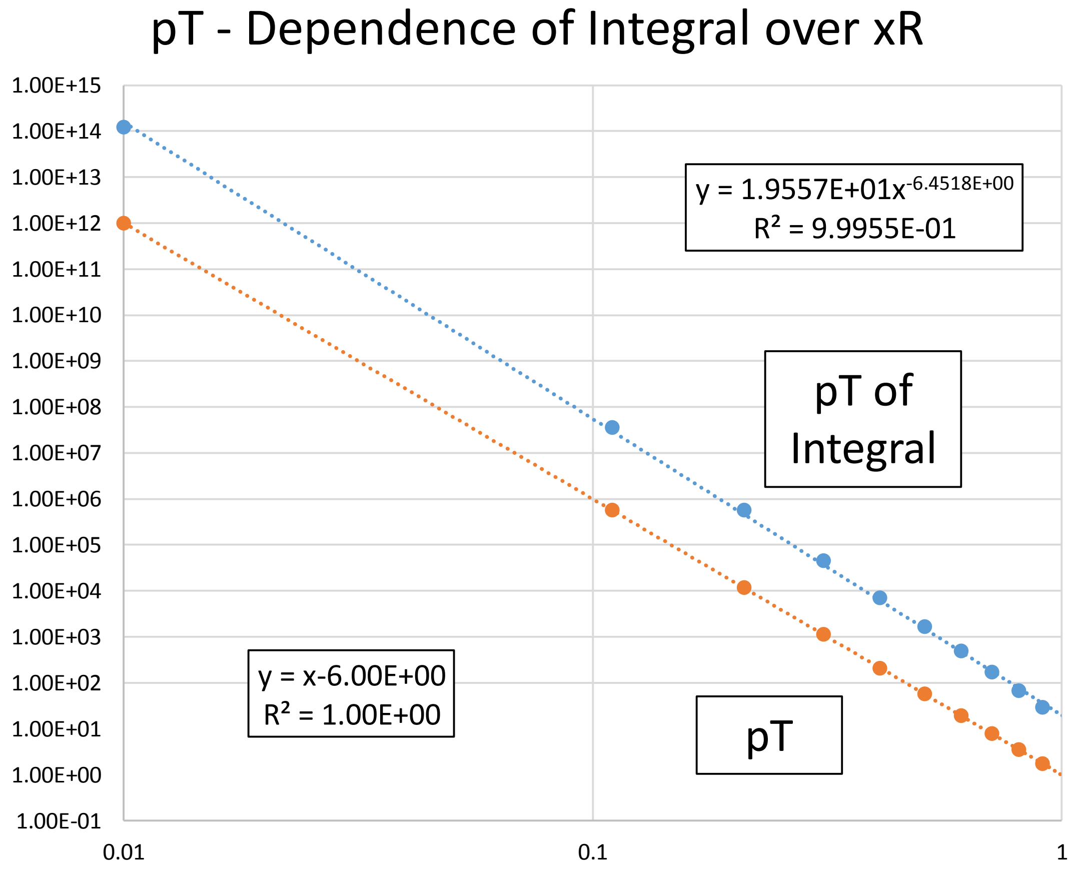
- J. Thaler suggested:

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

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

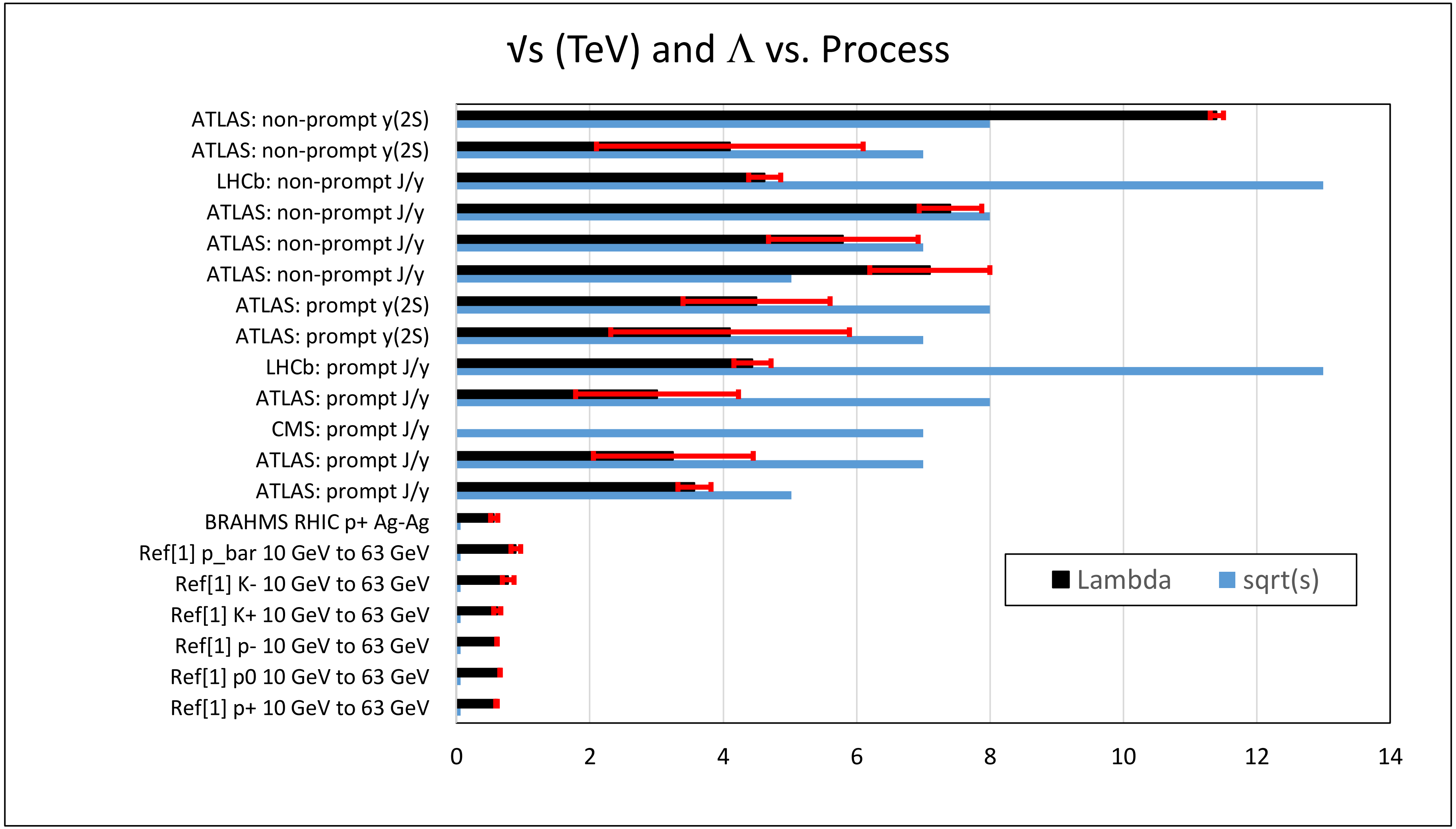
$$x_{R\min} = \frac{2p_T}{\sqrt{s}}$$

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



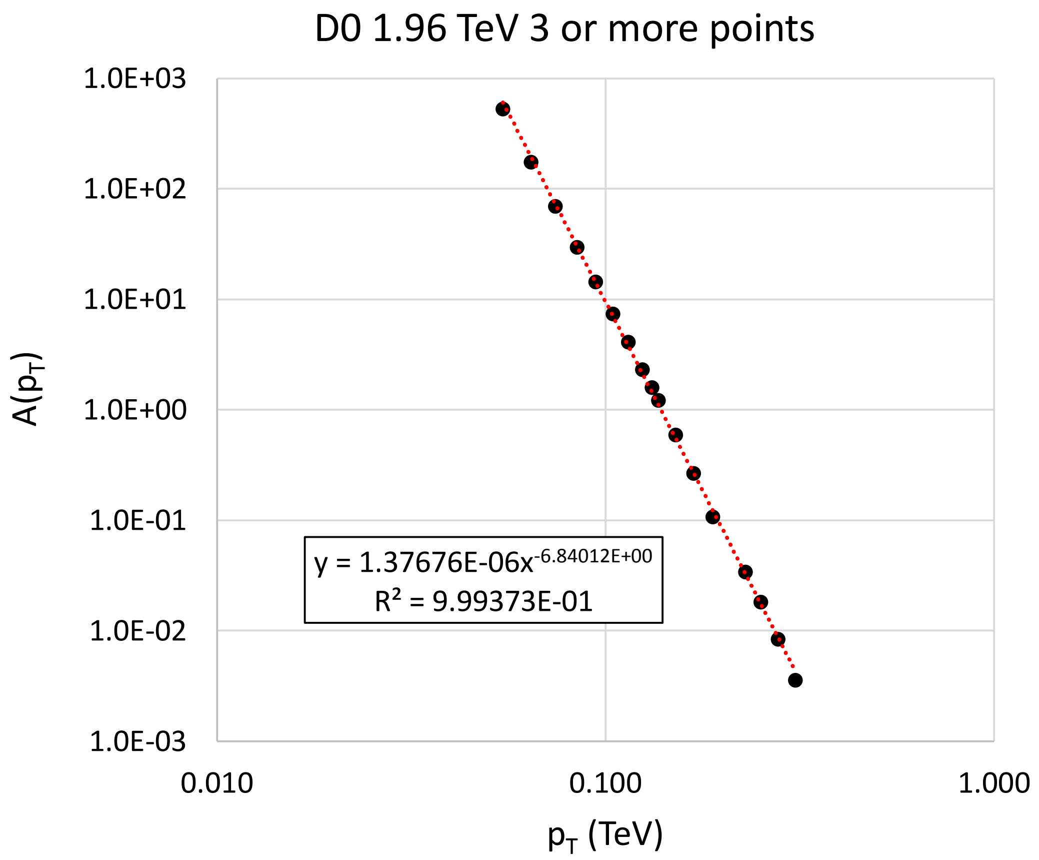
Interesting suggestion – integration can be extended to determine the moments of the "fragmentation" function $(1-x_R)^{nxR}$.

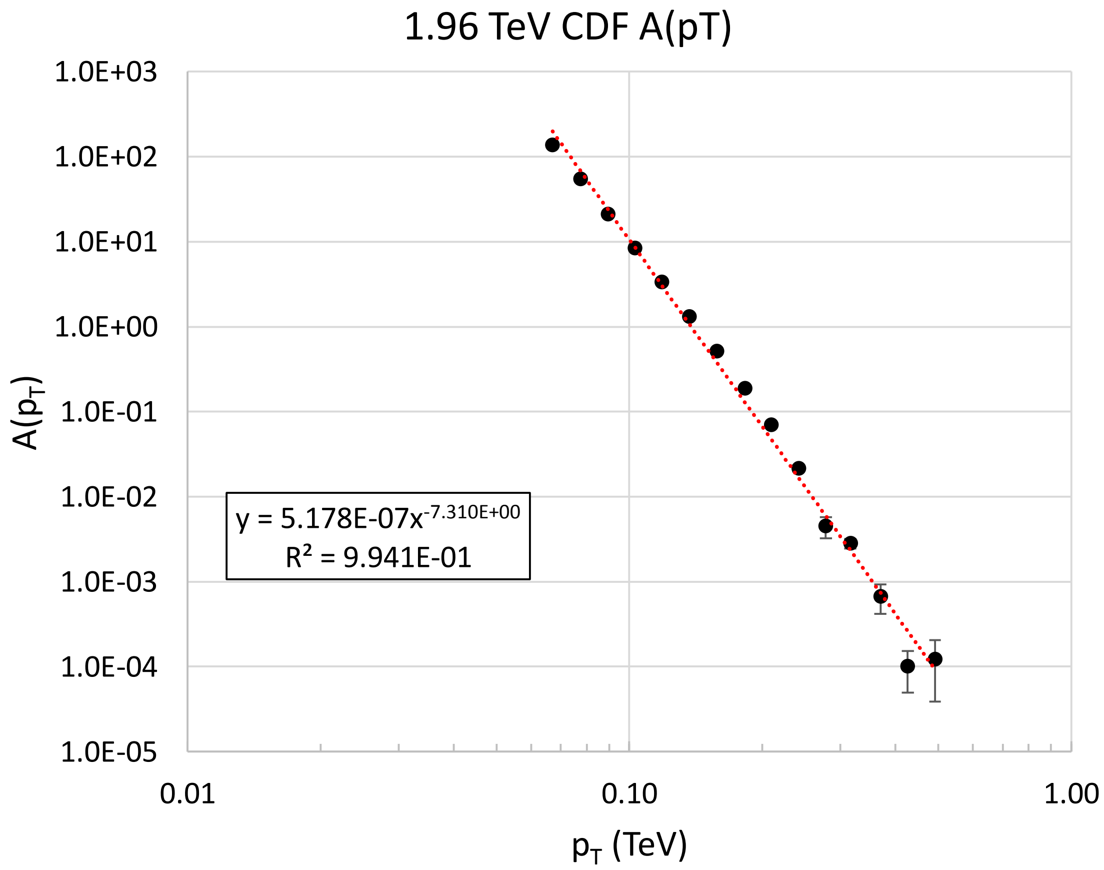
Λ vs. Process


√s (TeV) and Λ vs. Process
ATLAS: non-prompt y(2S)
ATLAS: non-prompt y(2S)
LHCb: non-prompt J/y
ATLAS: non-prompt J/y
ATLAS: non-prompt J/y
ATLAS: non-prompt J/y
ATLAS: prompt y(2S)
ATLAS: prompt y(2S)
LHCb: prompt J/y
ATLAS: prompt J/y
CMS: prompt J/y
ATLAS: prompt J/y
ATLAS: prompt J/y
BRAHMS RHIC p+ Ag-Ag
Ref[1] p_bar 10 GeV to 63 GeV
Ref[1] K- 10 GeV to 63 GeV
Ref[1] K+ 10 GeV to 63 GeV
Ref[1] p- 10 GeV to 63 GeV
Ref[1] p0 10 GeV to 63 GeV
Ref[1] p+ 10 GeV to 63 GeV
0
2
4
6
8
10
12
14
Lambda
sqrt(s)

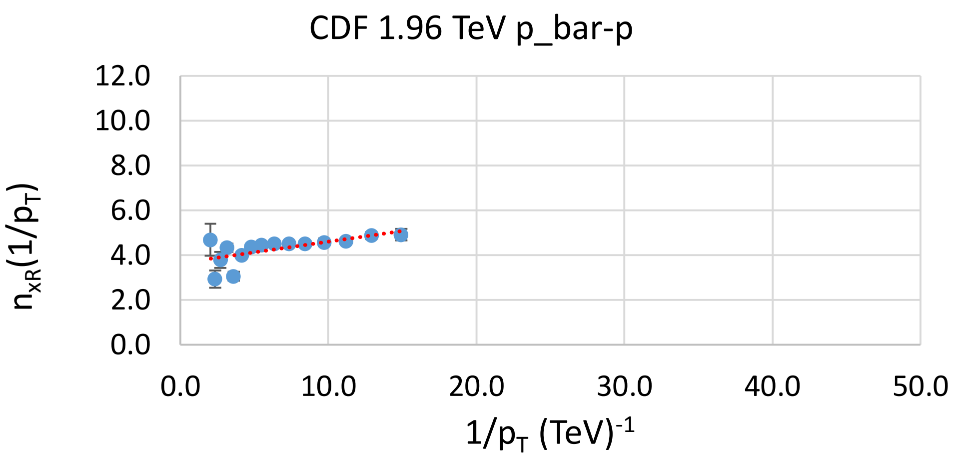
p_bar-p Inclusive Jet Production

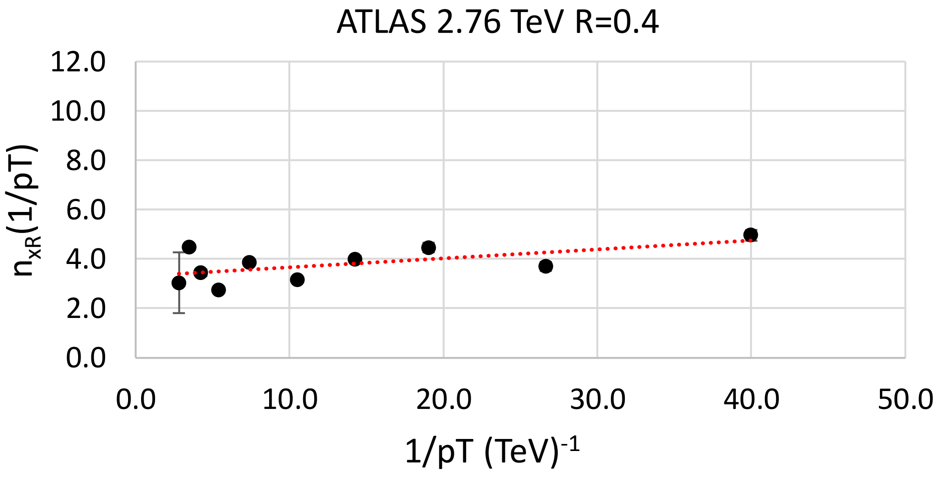
- Valence q-anti-q scattering/annihilation

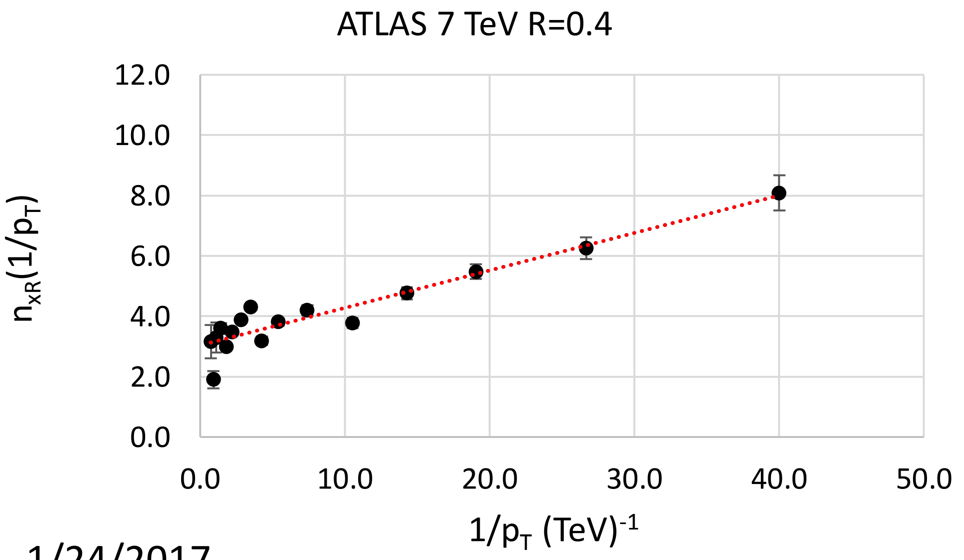


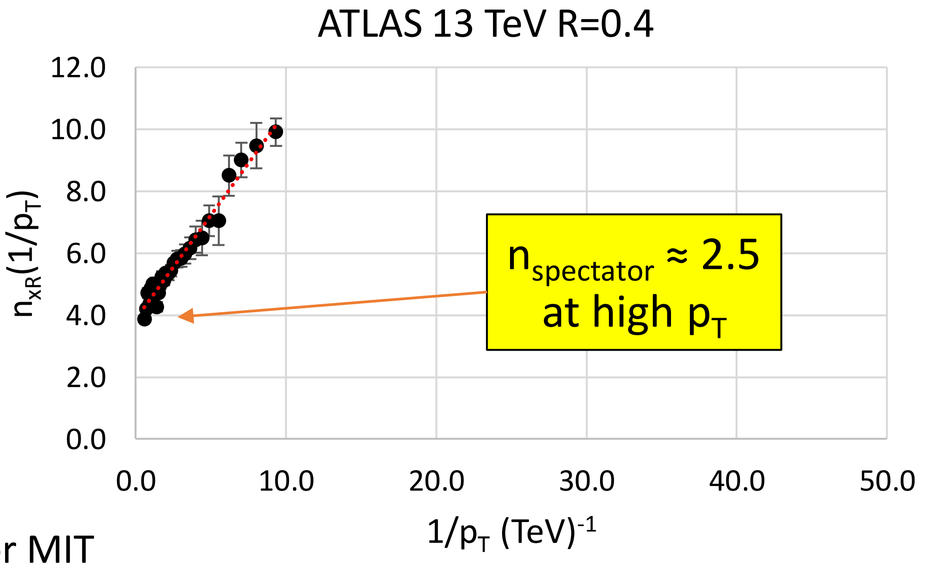


n_{xR}: Inclusive Jet Production p(p_bar)-p Scattering









s-dependence in Perfect Radial Scaling

- In perfect radial scaling entire s-dependence is in the x_R term:

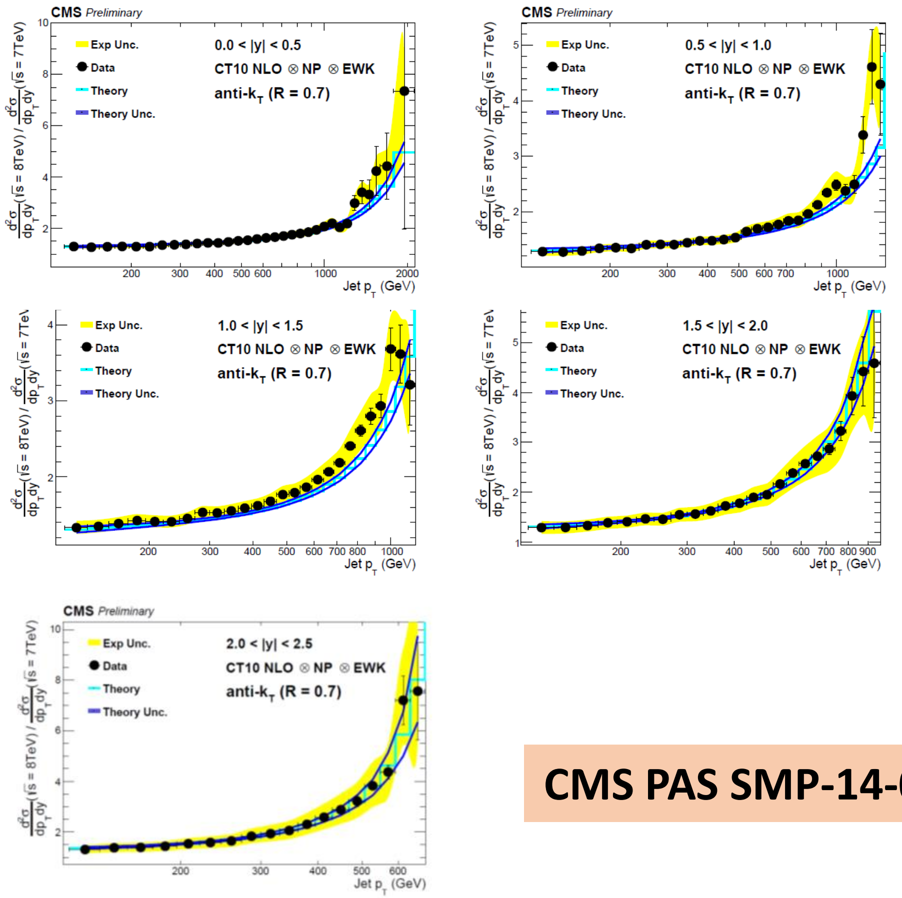
$$x_R = \frac{E}{E_{\max}} \approx \frac{2p_T \cosh(\eta)}{\sqrt{s}} \approx \frac{2p_T \cosh(y)}{\sqrt{s}} \sqrt{\left(1+\frac{m_J^2}{p_T^2}\tanh(y)\right)}$$

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

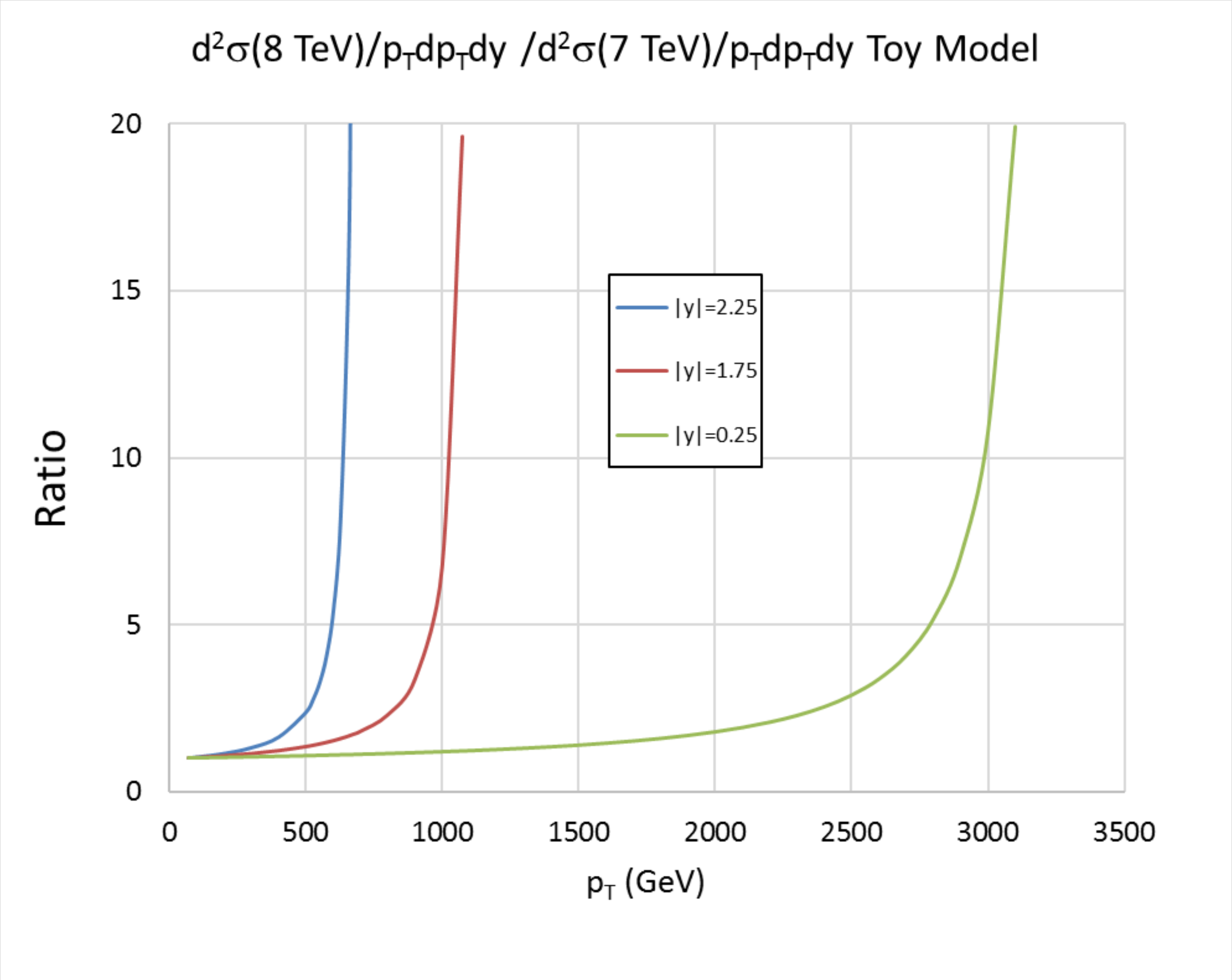
- This is roughly true for π^0 production in E63 ($10 < \sqrt{s} < 27$ GeV) but is broken by QCD evolution.
- Studying cross sections using x_R makes QCD evolution clear since radial scaling controls kinematic boundary.

An Example of x_R-dependence near Kinematic Boundary

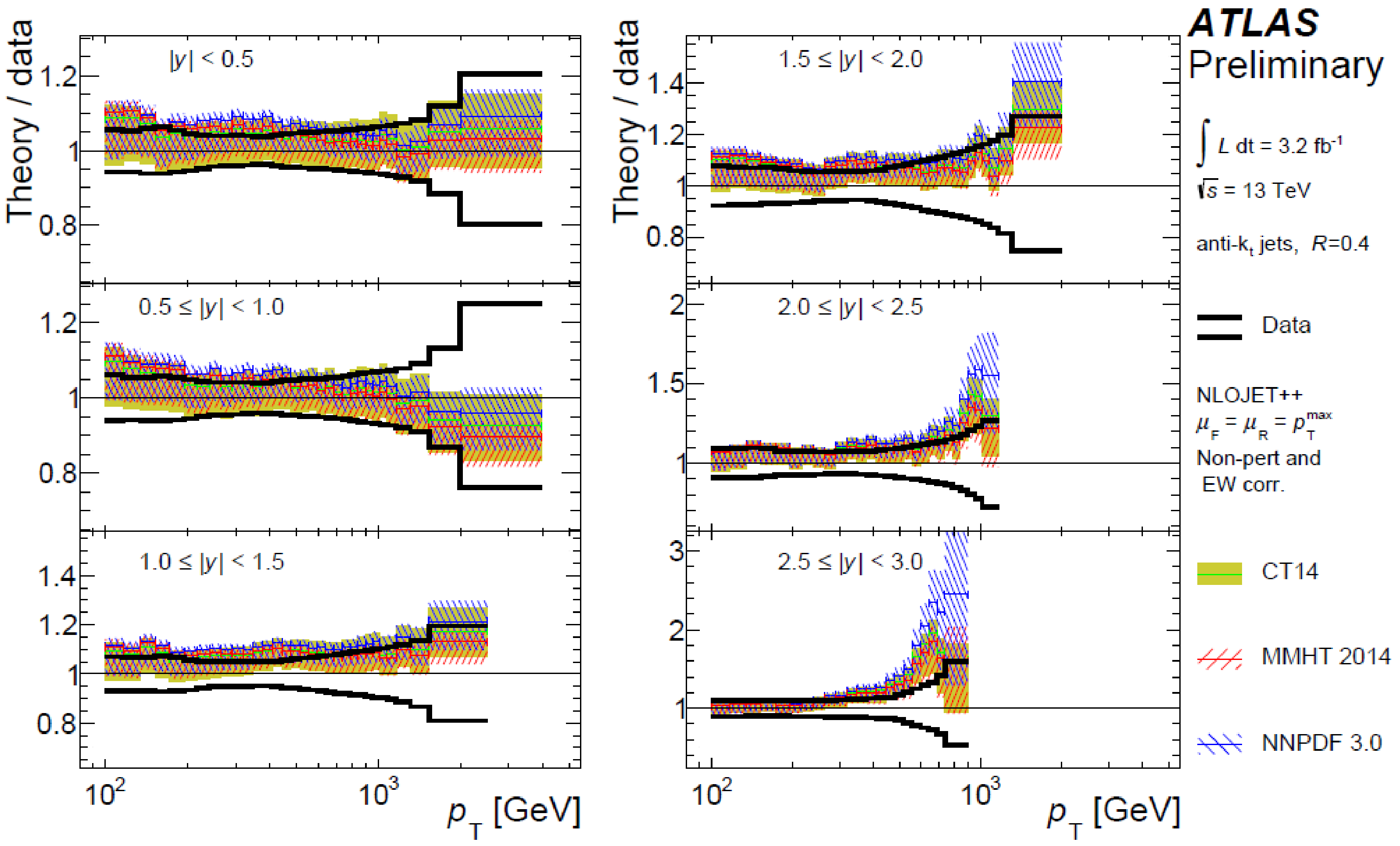
- CMS Inclusive Jets 8 TeV / 7 TeV



CMS PAS SMP-14-001

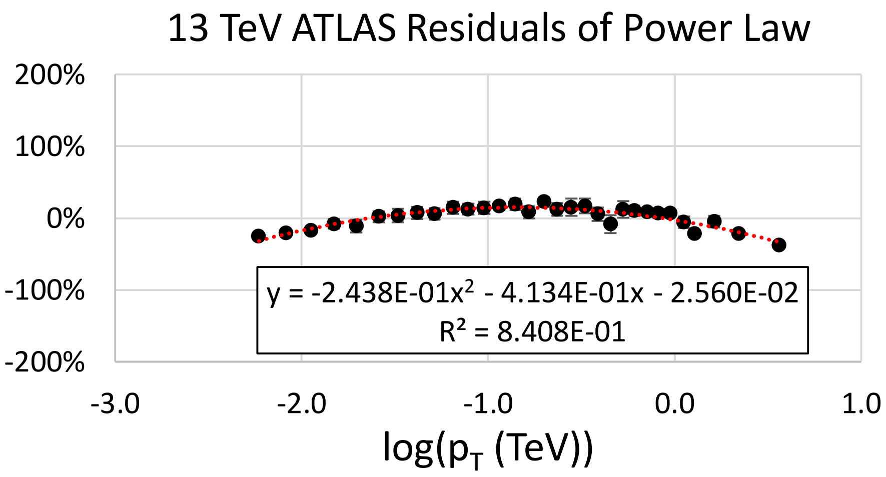


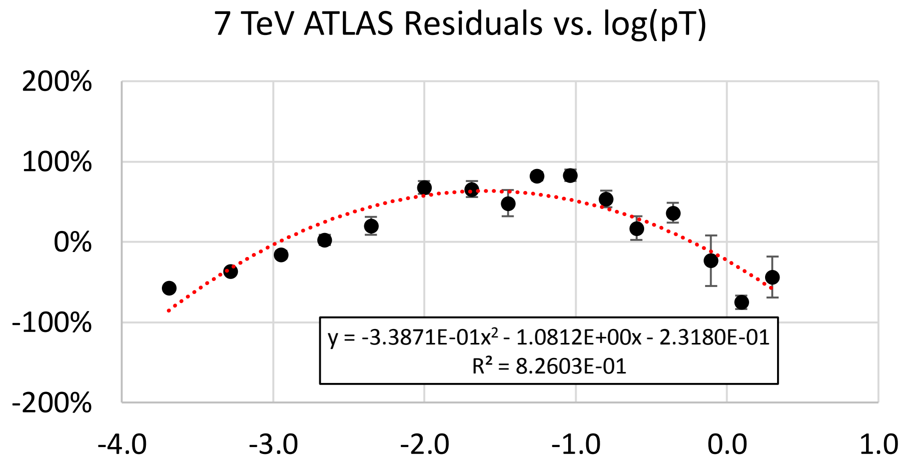
ATLAS 13 TeV Jets - Comparisons of Theory(Simulation) with Data

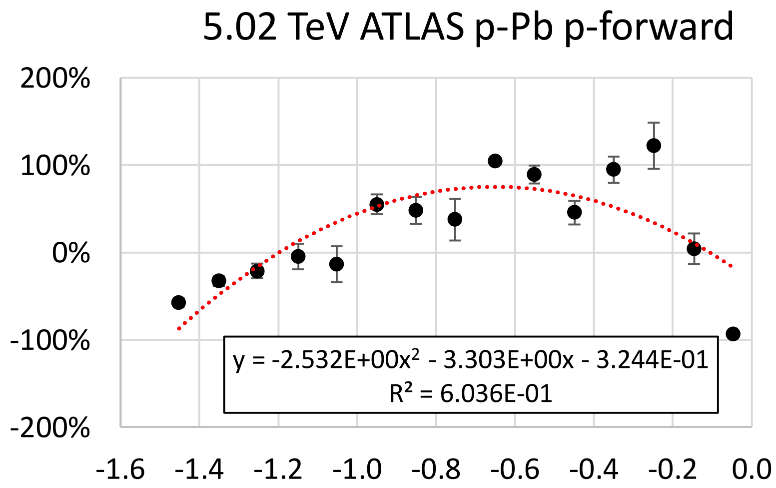


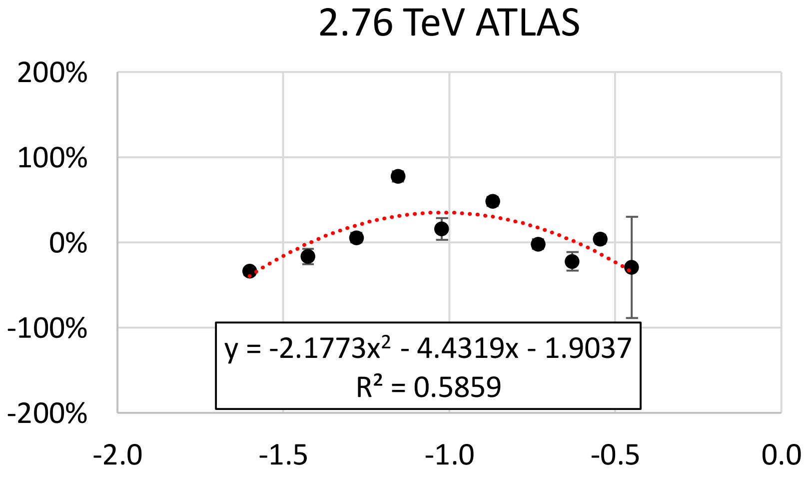
Agreement generally good over most of the y-region except at high rapidity.

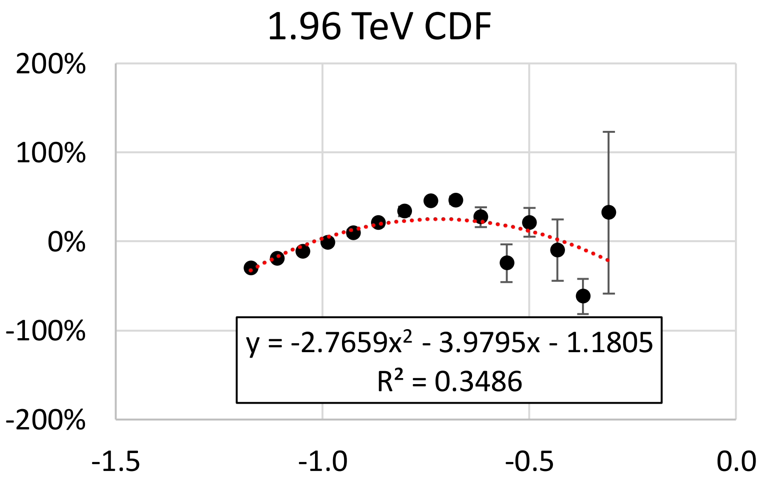
Deviations from p_T Power Law



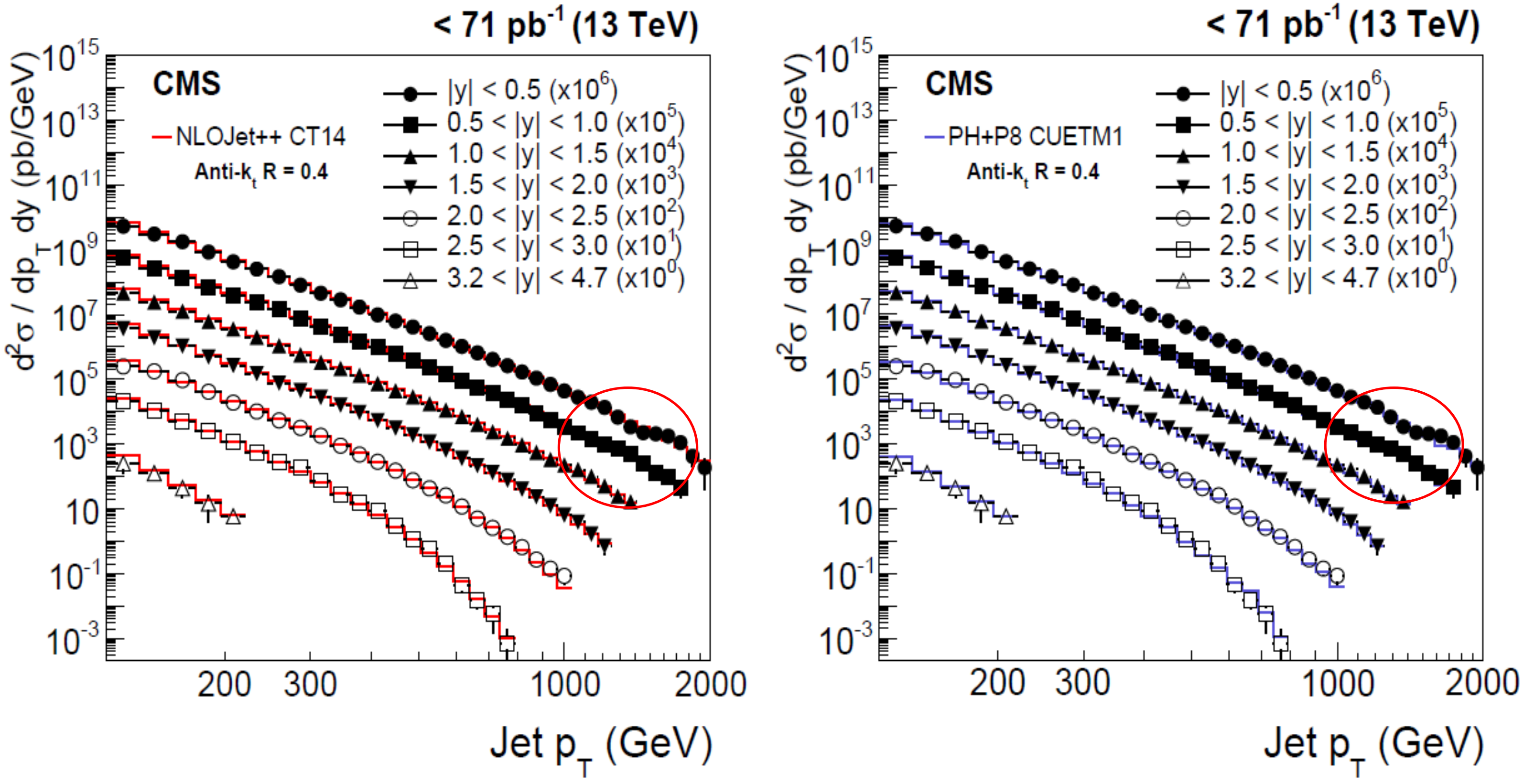








13 TeV CMS Inclusive Jets R=0.4

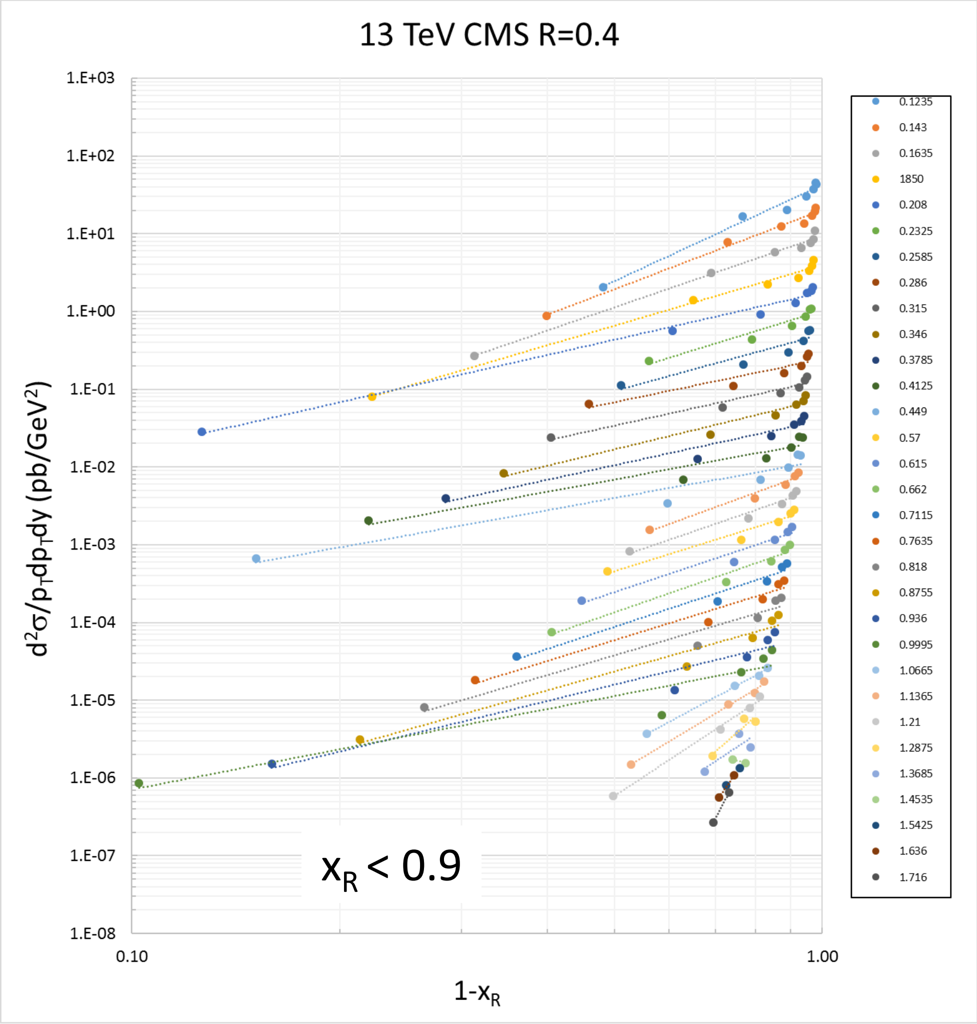


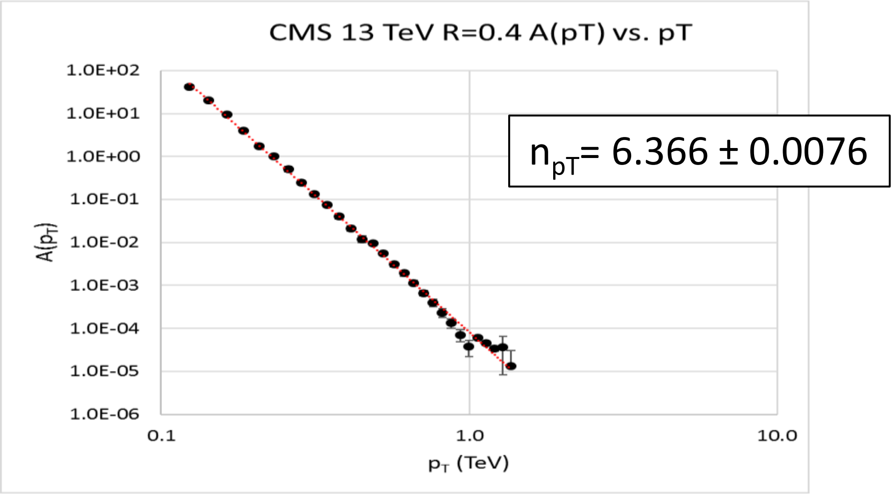
- Compared to Theory
- LHS: NLOJET++ based on the CT14 PDF (similar to ATLAS)
- RHS: POWHEG(PH) + PYTHIA8 (P8)
- Data set quite similar to the 13 TeV ATLAS inclusive jets

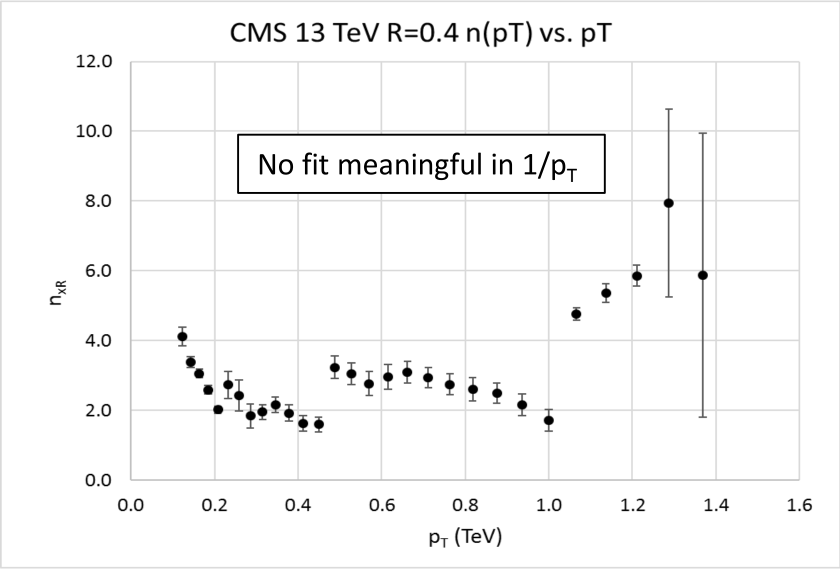
arXiv:1605.04436v2 [hep-ex] 13 Aug. 2016
https://hepdata.net/record/ins1459051
Eur.Phys.J. C76 (2016) 451, 2016 Khachatryan, et al.

13 TeV CMS Inclusive Jets

https://hepdata.net/record/ins1459051
Eur.Phys.J. C76 (2016) 451, 2016 Khachatryan, et al.





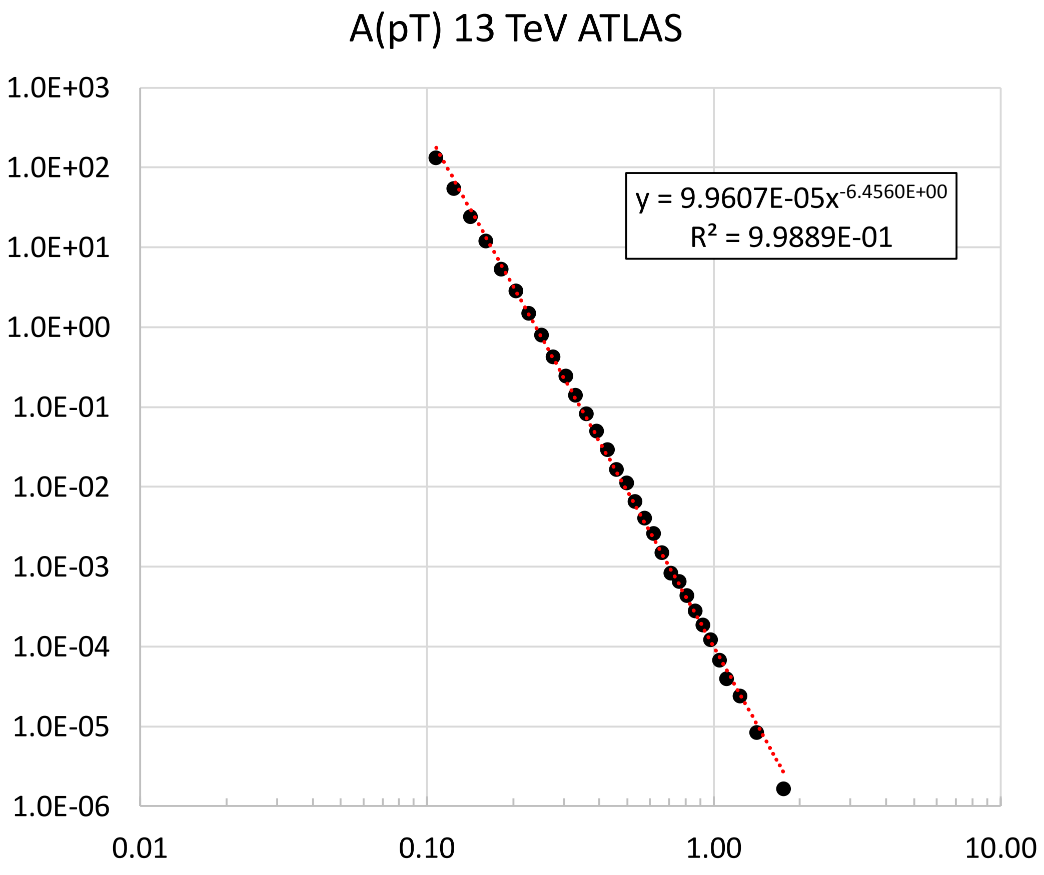


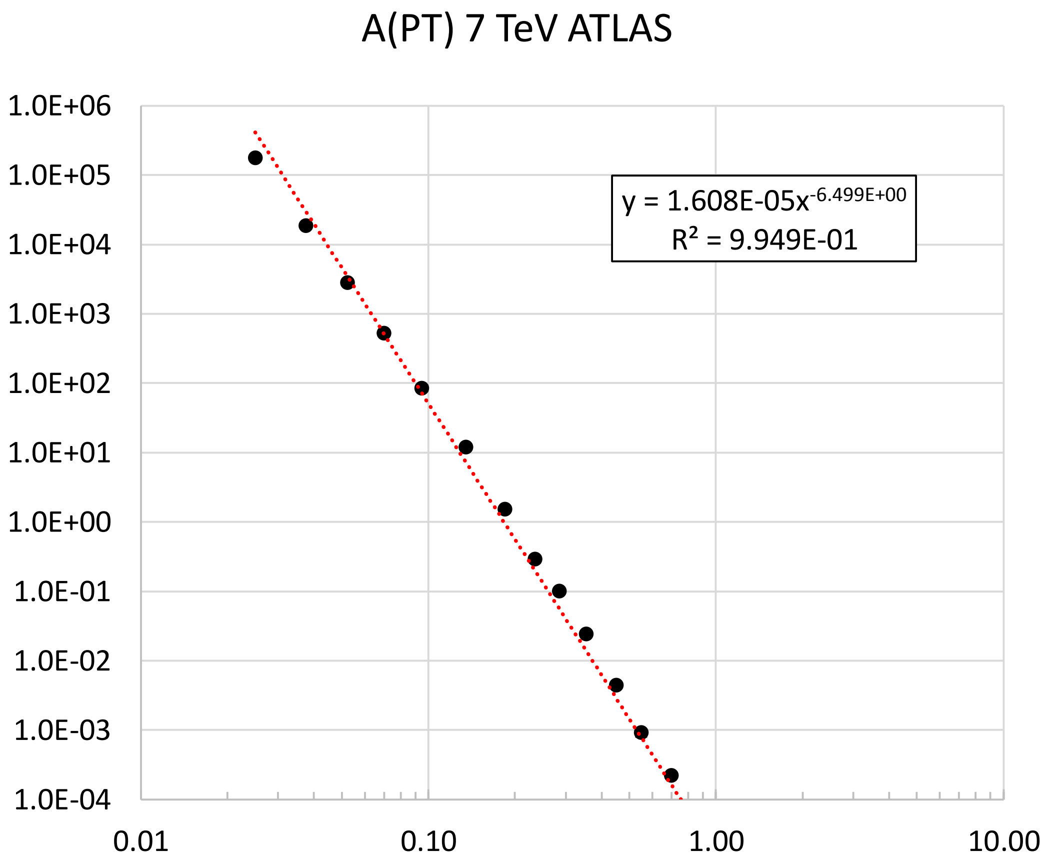
CMS jet reconstruction seems to have large uncorrected systematic errors – OR power law in (1-xR) not a good model

s-dependence – CDF, D0, ATLAS, CMS

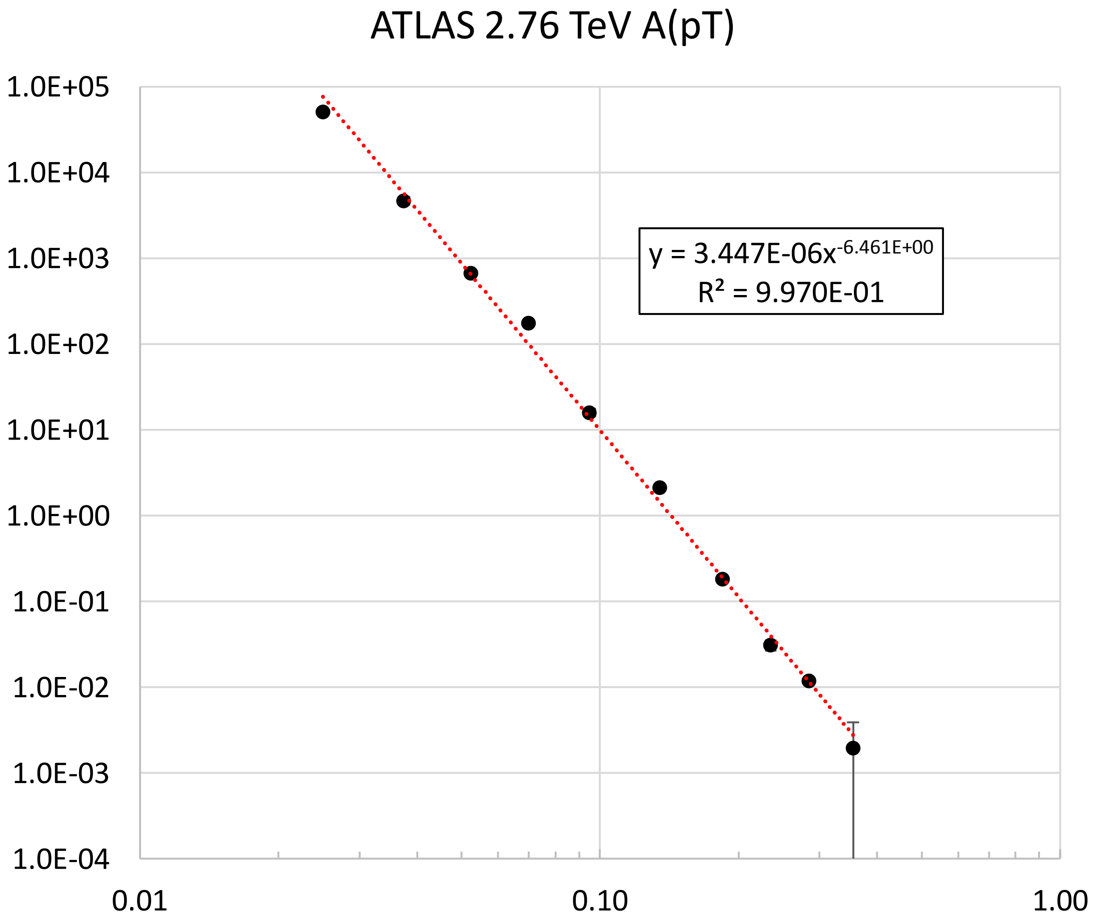
Process	√s	α (TeV^{npT} pb/GeV^2)	error	n_{pT}	error	D (TeV^{-1})	error	n_{xR}	error
Inclusive Jets p_bar-p CDF	1.960	5.178E-07	1.694E-07	7.310	0.156	0.094	0.031	3.647	0.241
Inclusive Jets p_bar-p D0	1.960	1.377E-06	1.262E-07	6.840	0.044	0.022	0.015	4.048	0.142
Inclusive Jets p-p ATLAS R=0.4	2.760	3.447E-06	1.194E-06	6.461	0.124	0.036	0.016	3.295	0.288
Inclusive Jets p-p ATLAS R=0.4	7.000	1.608E-05	4.342E-06	6.499	0.125	0.125	0.011	3.027	0.157
Inclusive Jets p-p CMS R=0.7	8.000	2.650E-05	1.580E-06	6.804	0.051	0.260	0.021	3.666	0.092
Inclusive Jets p-p CMS R=0.4	13.000	8.256E-05	6.270E-06	6.366	0.076	No fit		No fit	
Inclusive Jets ATLAS p-p R=0.4	13.000	9.961E-05	4.386E-06	6.456	0.040	0.672	0.021	3.875	0.077

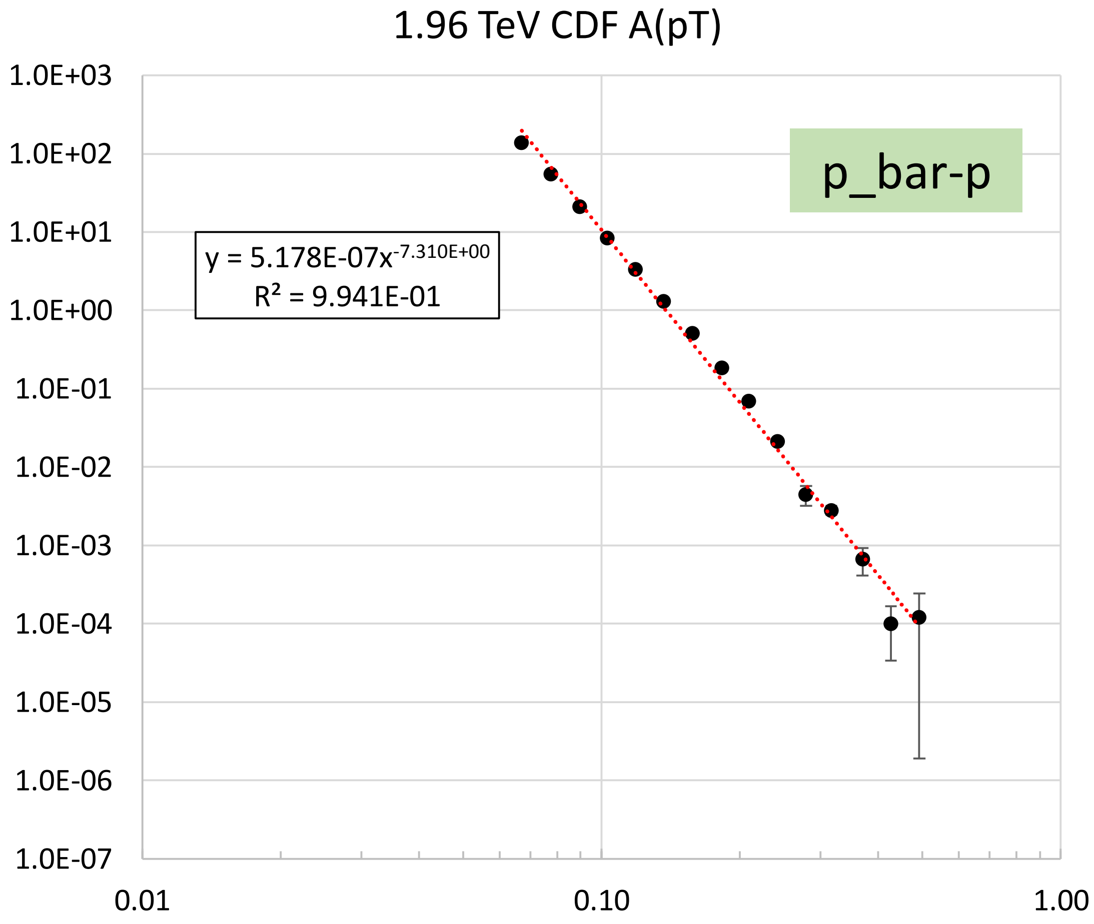
Compilation of $A(p_T)$ for Various Jet Studies





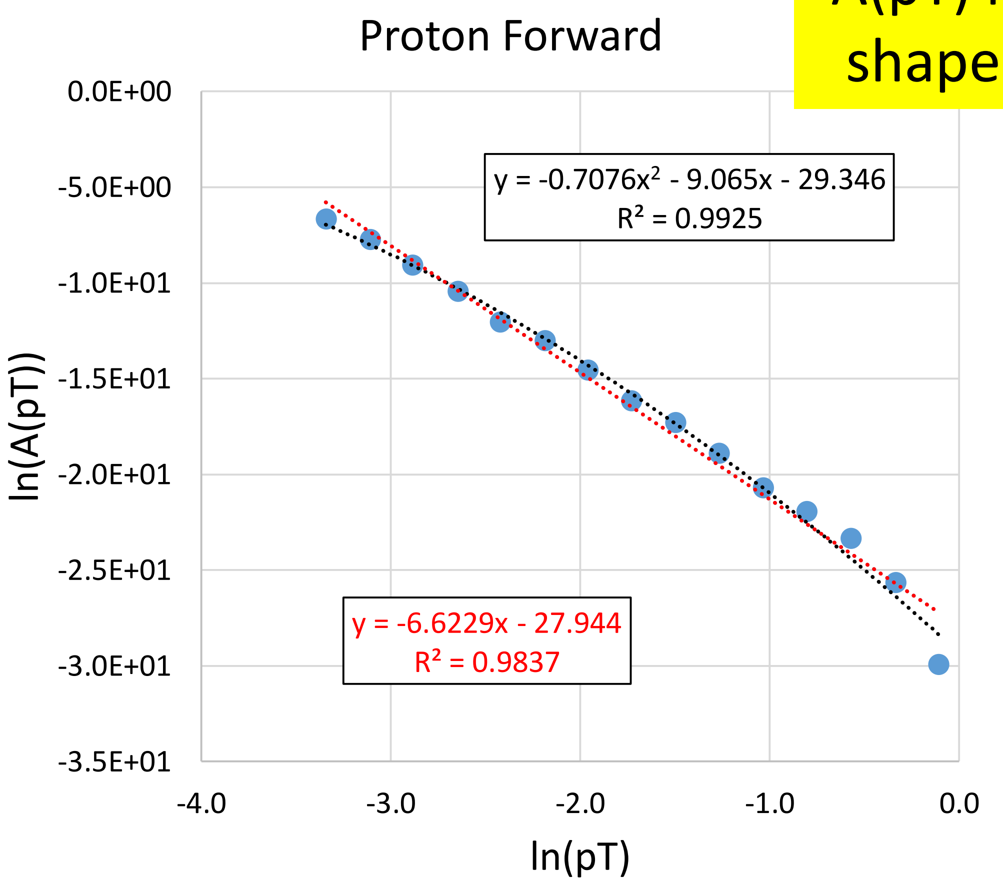
Compilation of $A(p_T)$ for Various Jet Studies -2

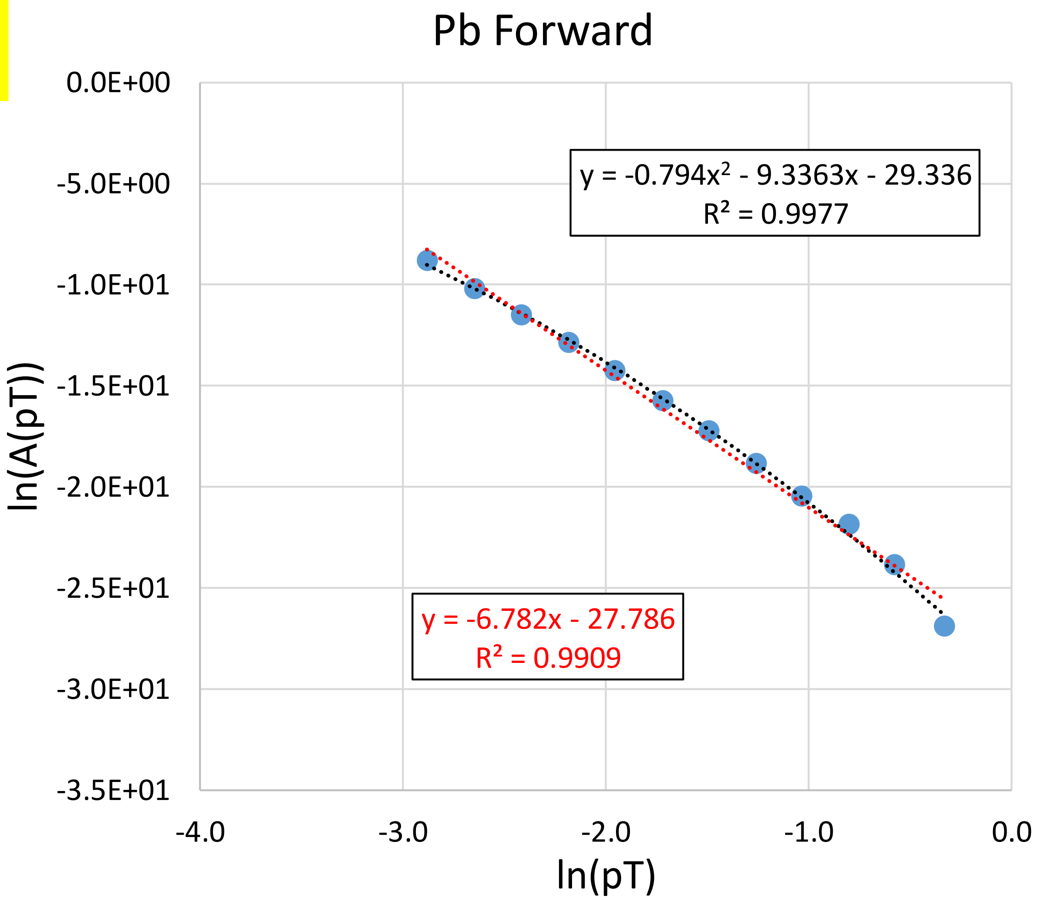




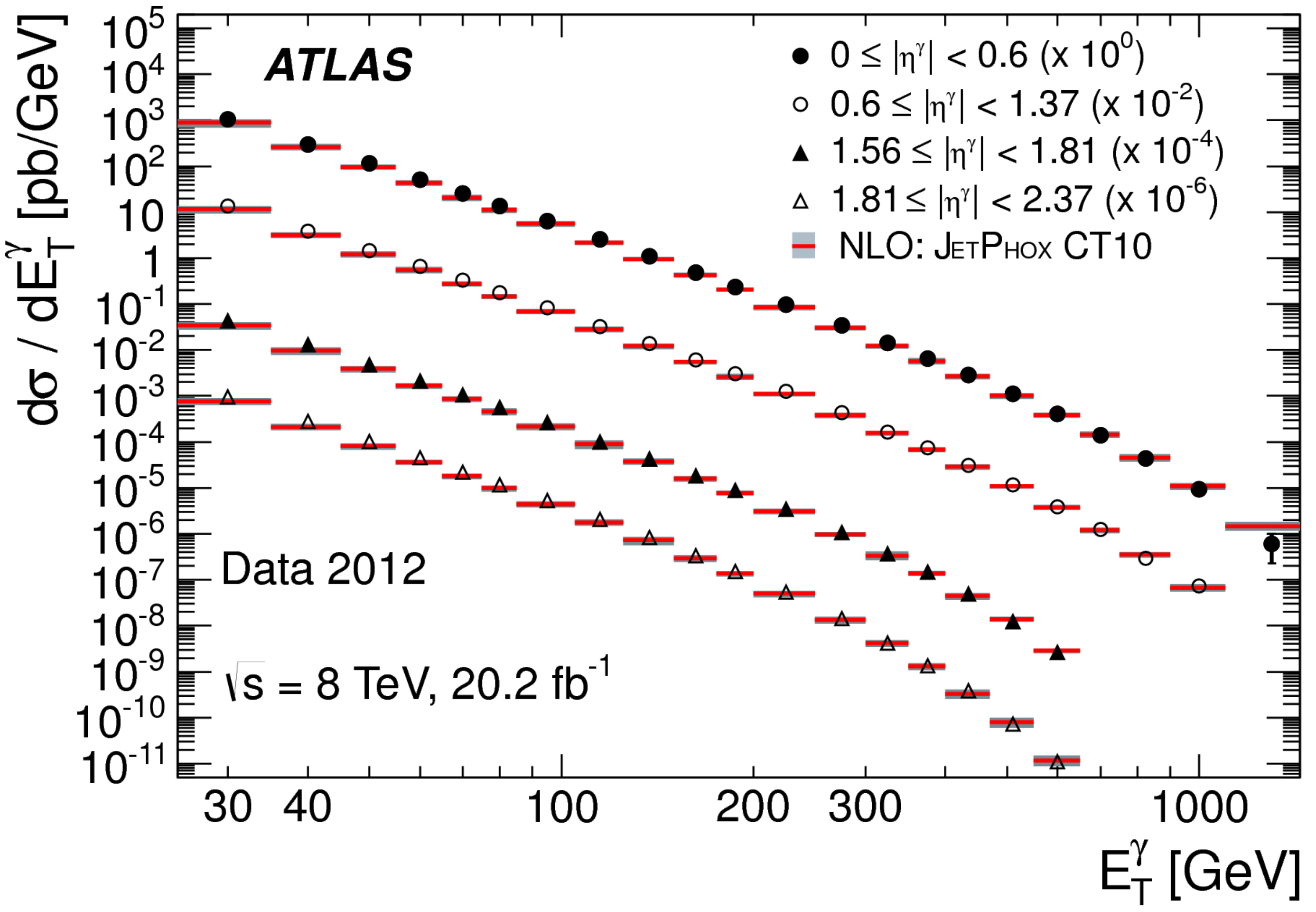
$A(p_T)$ for 5.02 TeV p-Pb Inclusive Jets

A(pT) has same shape Pb vs. p





Prompt γ Production ATLAS 8 TeV

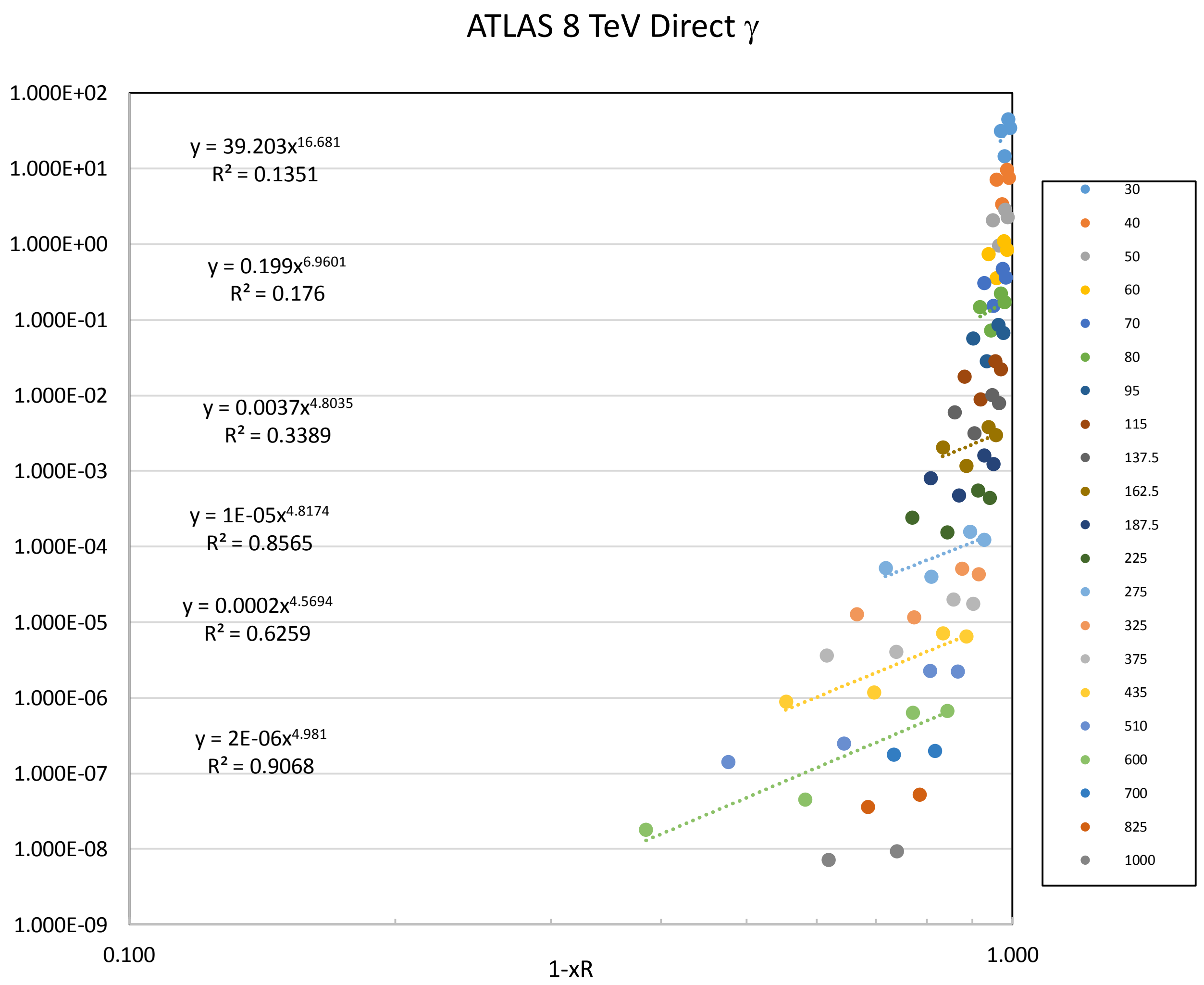


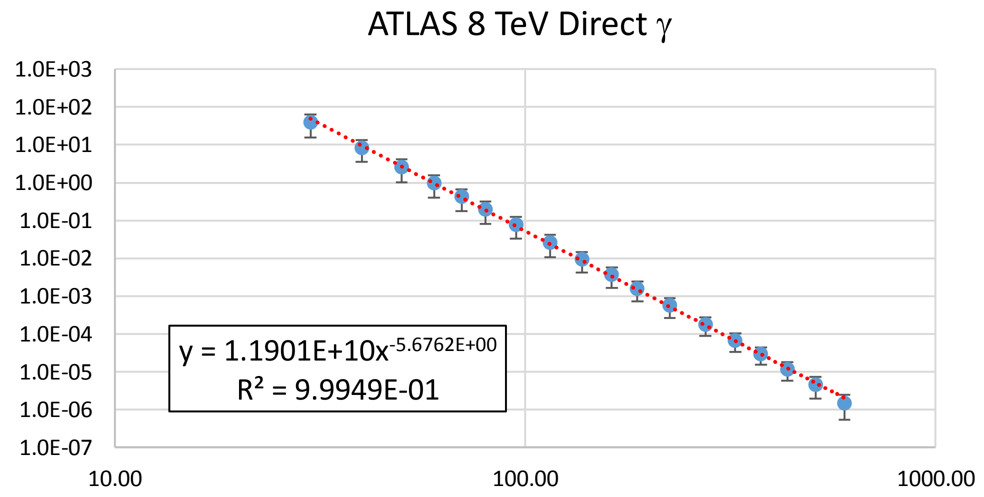
arXiv:1609.03825v1 [hep-ex] 13 Sep 2016 Michal Svatos, On behalf of the ATLAS Collaboration

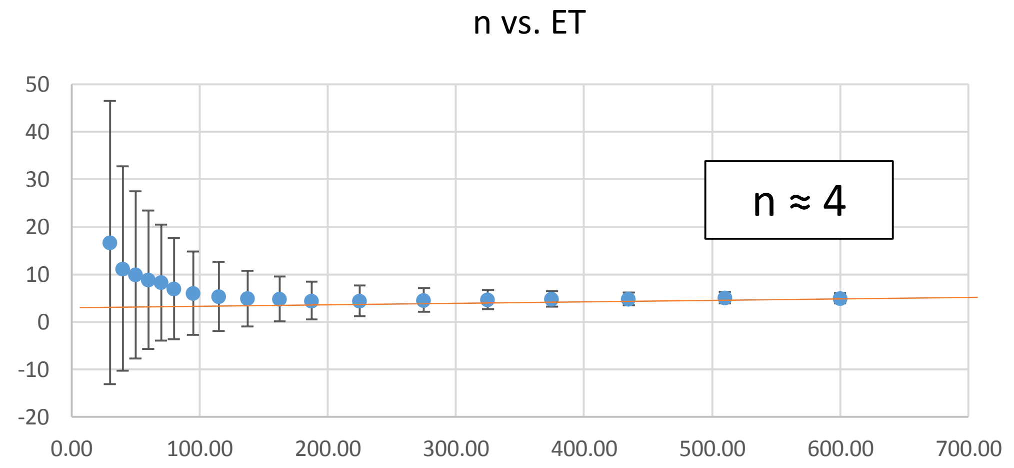
Single photons are separated from background by an isolation cut. In a cone R=0.4 the $E_{Tiso} < 4.8$ GeV + 4.2×10^{-3} $E_{T\gamma}$

Prompt photons are either from direct sources of the primordial scattering or from parton bremsstrahlung.

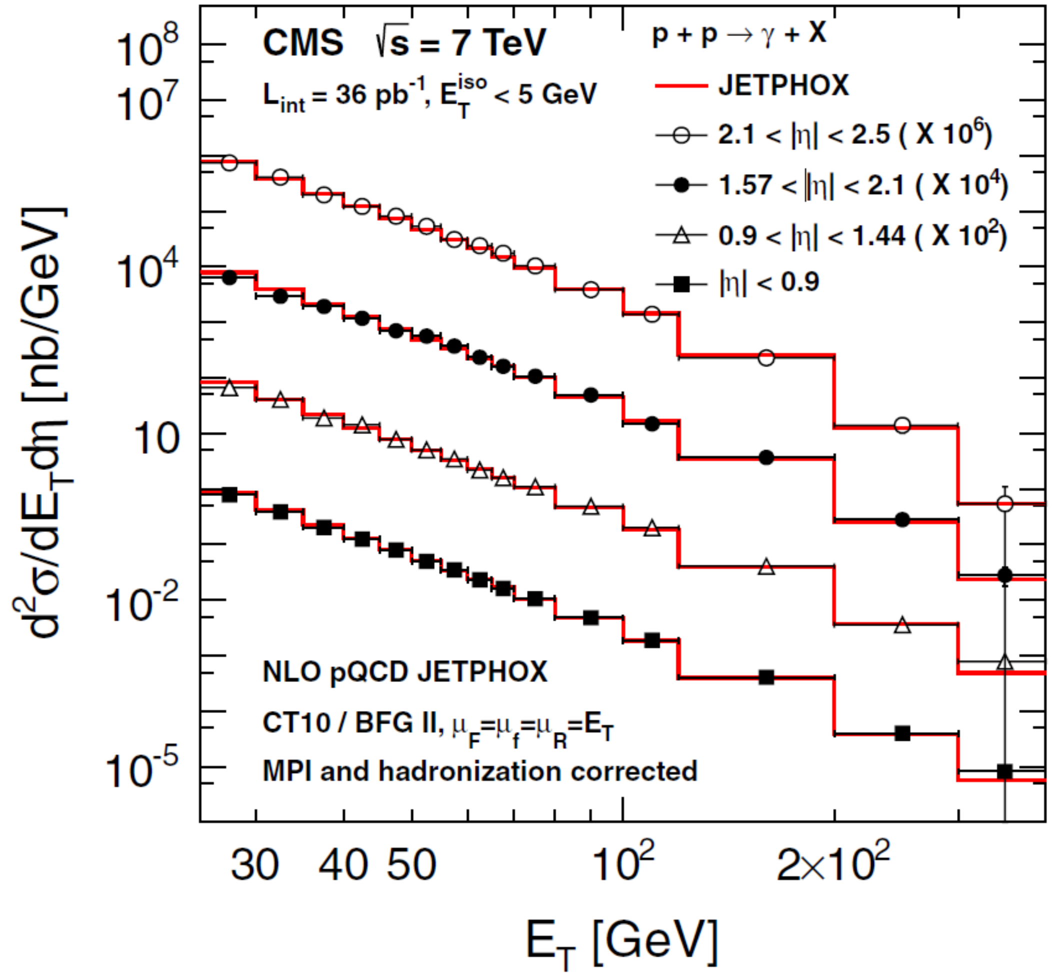
Prompt γ Production ATLAS 8 TeV







Isolated Prompt γ Production CMS 7 TeV



S. Chatrchyan et al.
PHYSICAL REVIEW D 84, 052011 (2011)

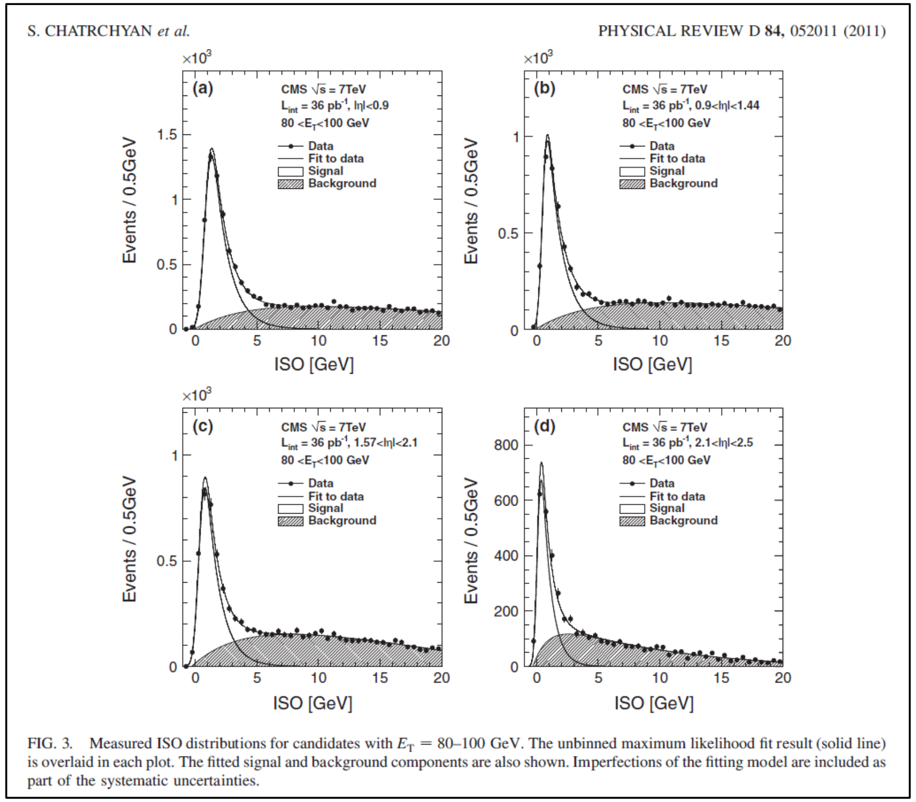
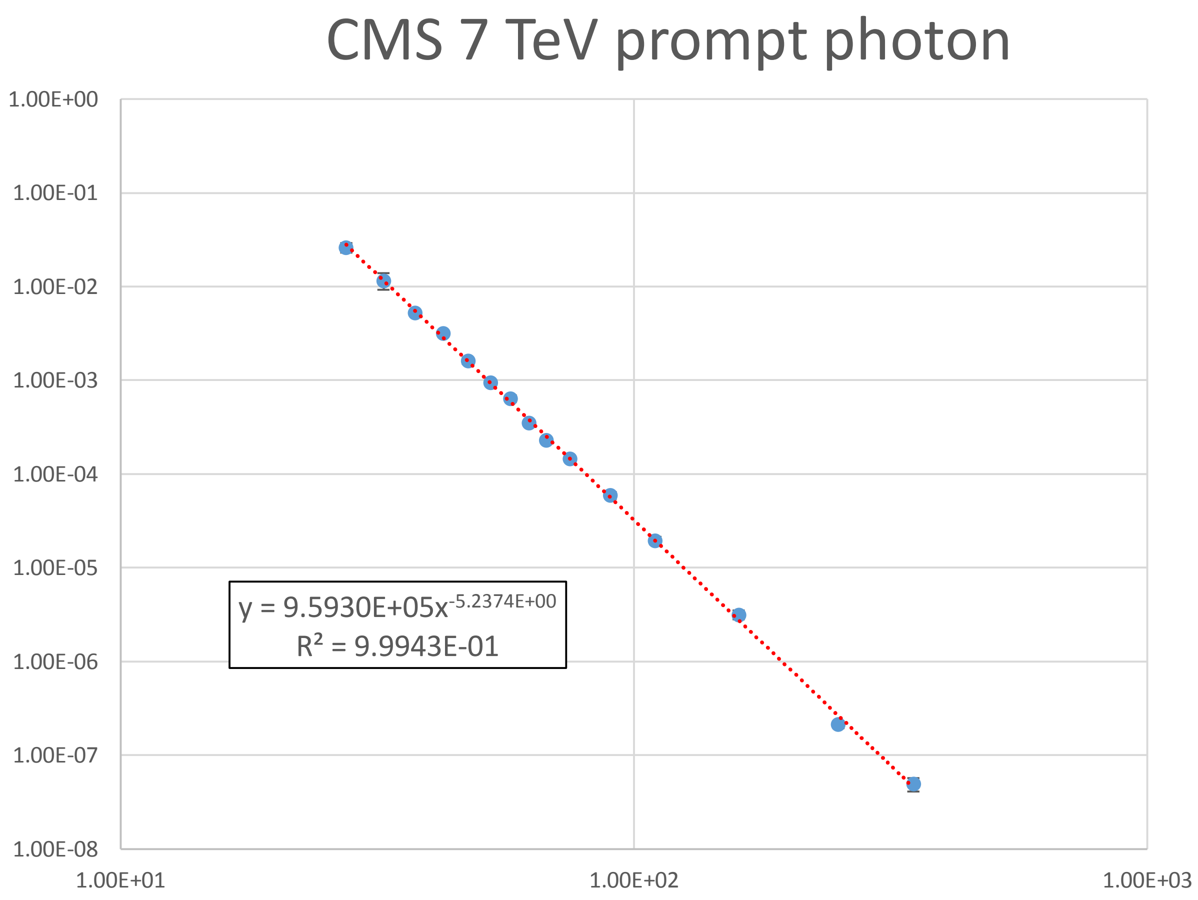
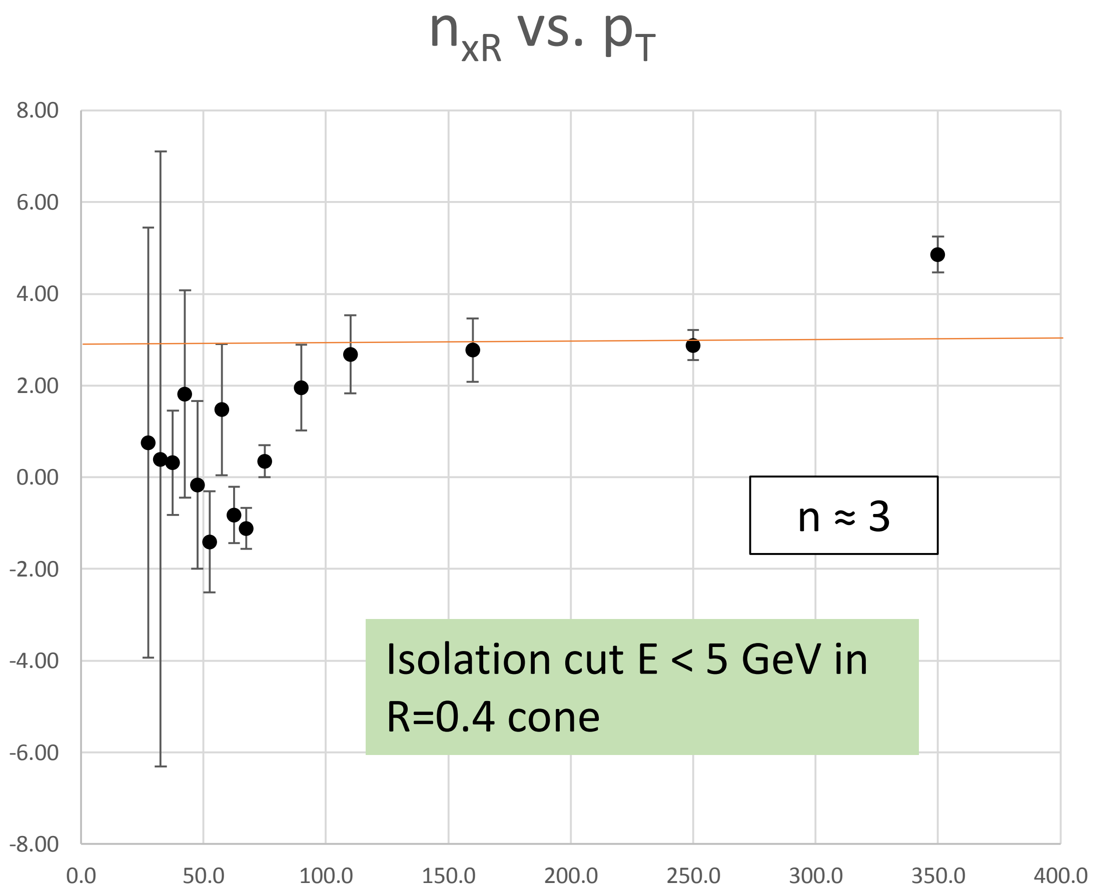


FIG. 3. Measured ISO distributions for candidates with E_T = 80–100 GeV. The unbinned maximum likelihood fit result (solid line) is overlaid in each plot. The fitted signal and background components are also shown. Imperfections of the fitting model are included as part of the systematic uncertainties.

Isolated Prompt γ Production CMS 7 TeV





n_{xR}: Inclusive Jet Production p-p Scattering (1976)

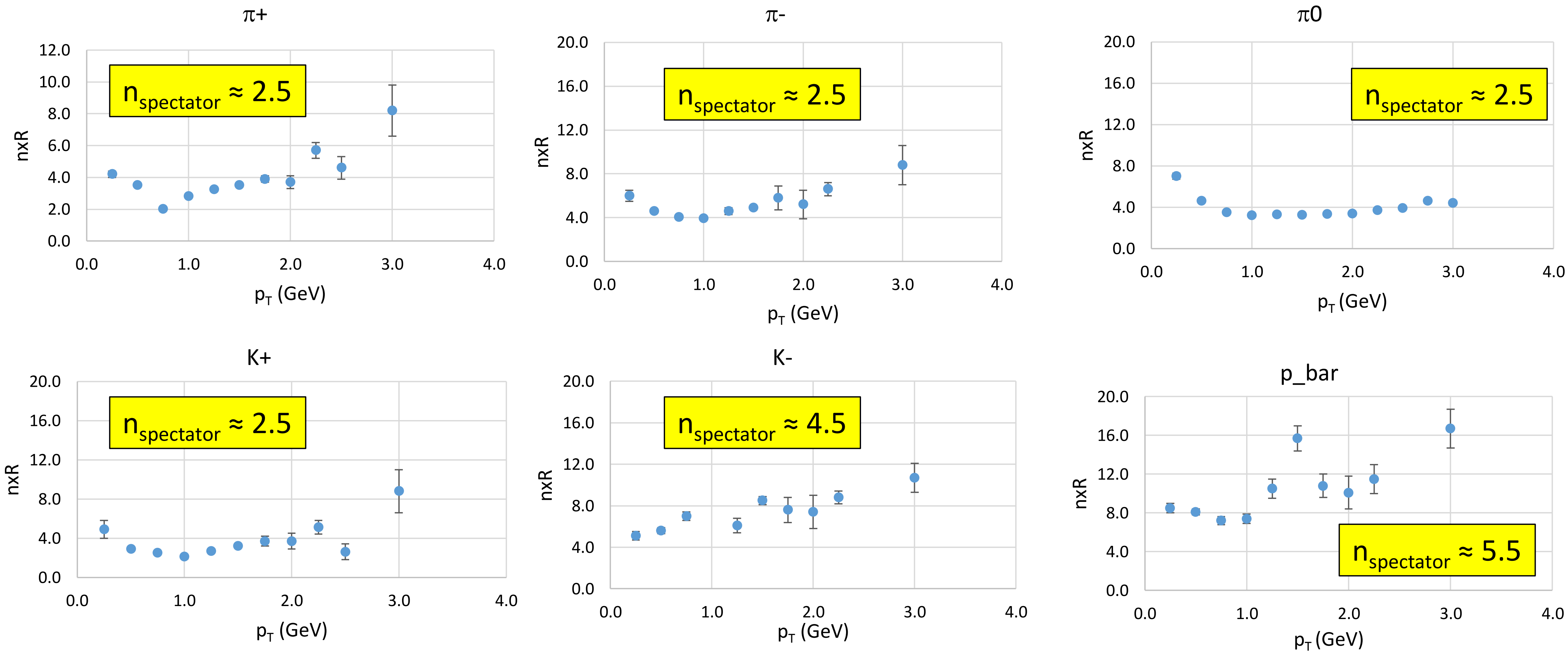


Table of $(1-x_R)$ Powers

Index	Process	√s (TeV)	nxR	error	<nxR>	nxR0
1	π+ 10 GeV to 63 GeV	0.063	4.1	1.6		
2	π0 10 GeV to 63 GeV	0.063	4.0	1.0		
3	π- 10 GeV to 63 GeV	0.063	5.5	1.4		
4	K+ 10 GeV to 63 GeV	0.063	3.9	1.8		
5	K- 10 GeV to 63 GeV	0.063	7.4	1.6		
6	p_bar 10 GeV to 63 GeV	0.063	10.7	3.1		
7	DO: Inclusive Jets p_bar-p 1.96 TeV	1.960	4.0	0.1		
8	CDF: Inclusive Jets p_bar-p 1.96 TeV	1.960	3.6	0.2		
9	ATLAS: Inclusive Jets p-p 2.76 TeV	2.760	3.3	0.3		
10	ATLAS: Inclusive Jets p-Pb Pb-forward 5.02 TeV	5.020	3.1	0.4		
11	ATLAS: Inclusive jets p-Pb p-forward 5.02 TeV	5.020	2.8	0.6		
12	ATLAS: Inclusive Jets p-p 7 TeV	7.000	3.0	0.2		
13	CMS: Inclusive Jets p-p (pT<1.95 TeV) 8 TeV	8.000	3.7	0.1		
14	ATLAS: Inclusive Jets p-p 13 TeV	13.000	4.0	0.1		
15	MC: Inclusive Jets p-p SHERPA 7 TeV	7.000	3.2	0.2		
16	CMS: Prompt γ	7.000	1.7	0.2		
17	ATLAS: Prompt γ	8.000	4.9	0.6		
18	ATLAS: prompt J/ψ	5.020	13.7	0.2		
19	ATLAS: prompt J/ψ	7.000	13.0	1.4		
20	ATLAS: non-prompt J/ψ	5.020	22.0	0.7		
21	ATLAS: non-prompt J/ψ	7.000	23.7	1.2		

y vs. η 13 TeV Jets

- ATLAS 13 TeV jets used y-bins. Thus to determine x_R one has to know the jet mass, m_J; but m_J has been integrated out in the data analyzed.

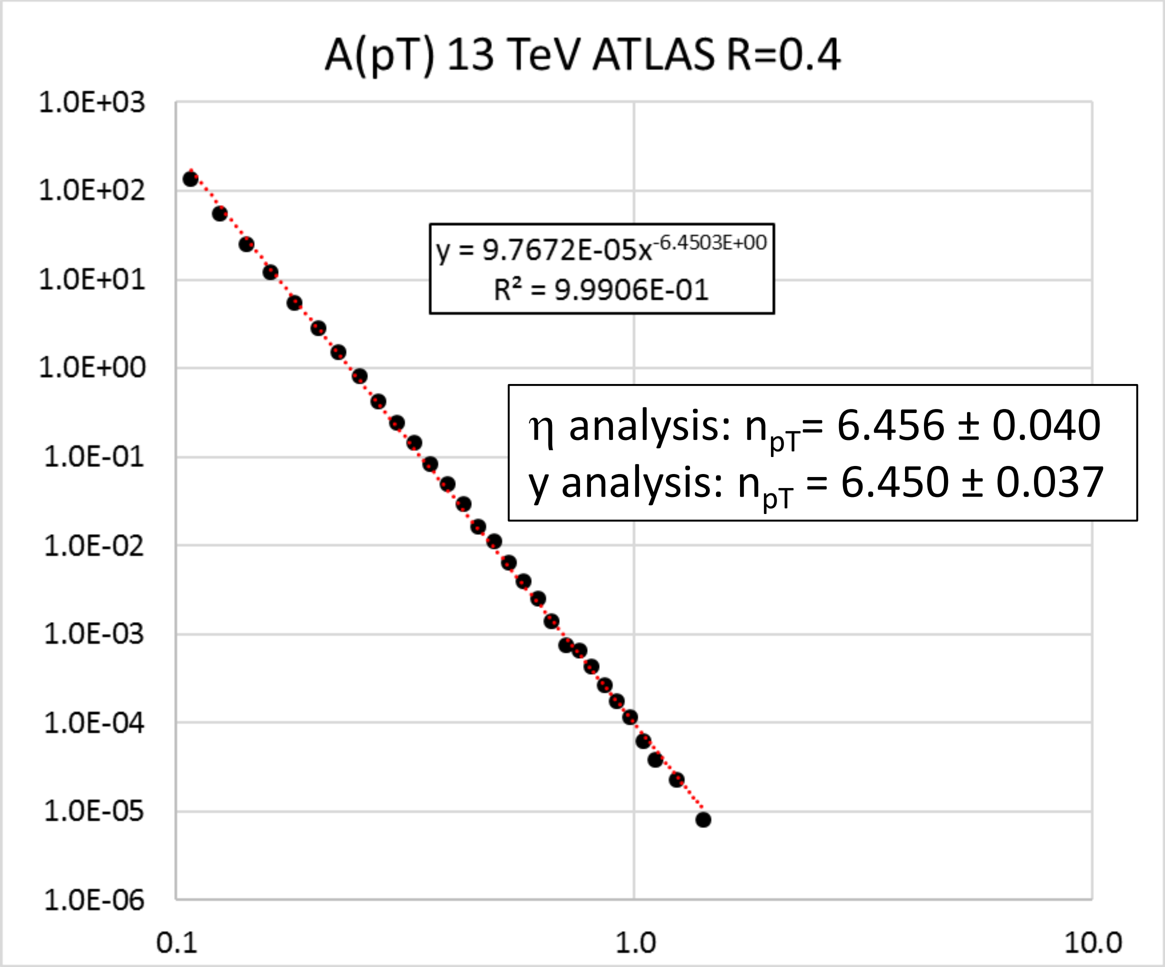
$$m_J^2 = (\Sigma\, p_i)^2$$

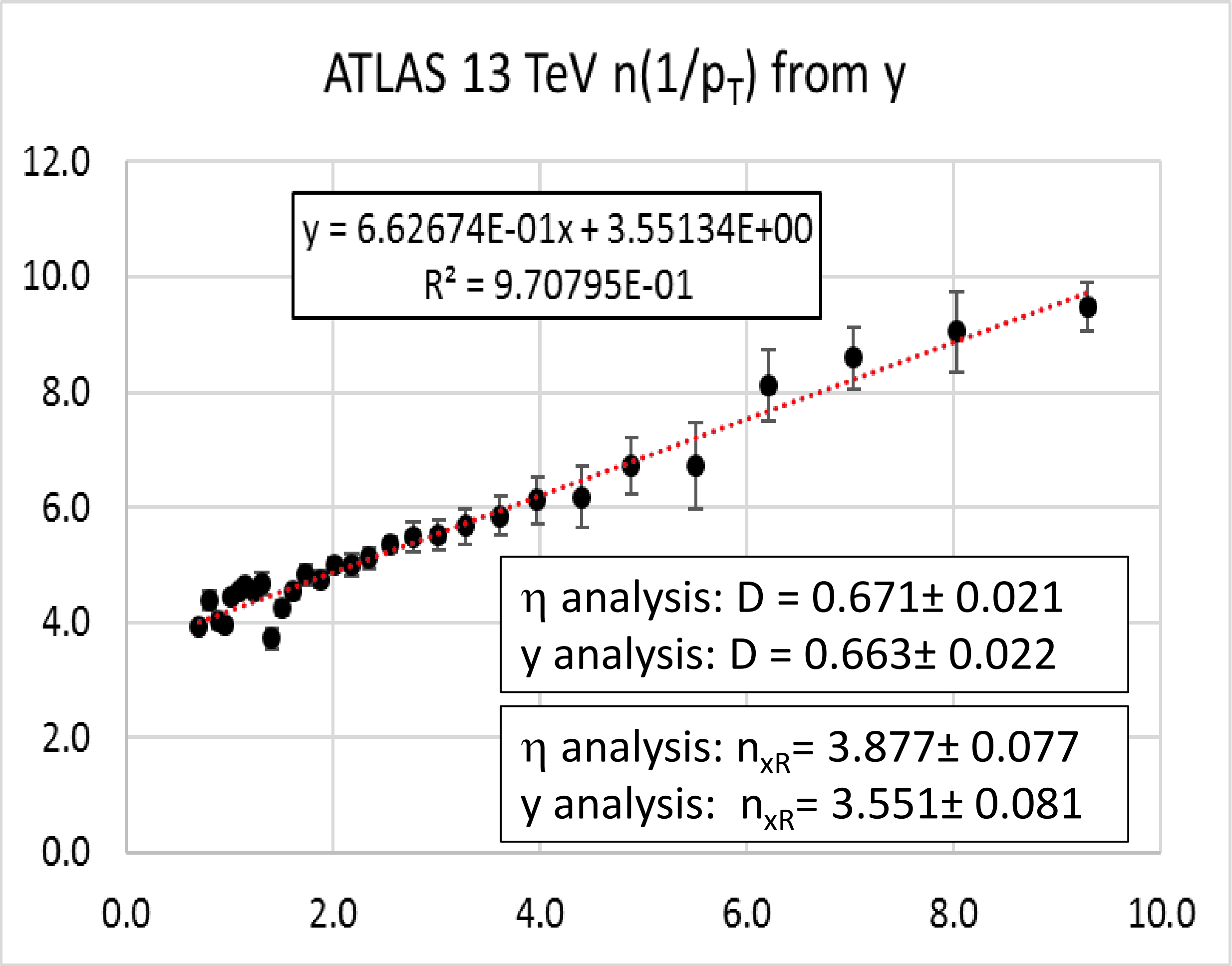
$$\frac{1}{\sin(\theta)} = \cosh(y)\left[1 + \frac{m_J^2}{p_T^2}\tanh^2(y)\right]^{1/2} = \cosh(\eta)$$

- The jet mass can be bounded by $m_J/p_T < R/\sqrt{2} = 0.28$ (Kolodrubetz, et al. arXiv:1605.08038v1) for R=0.4.

Analyzing 13 TeV Jets with y

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



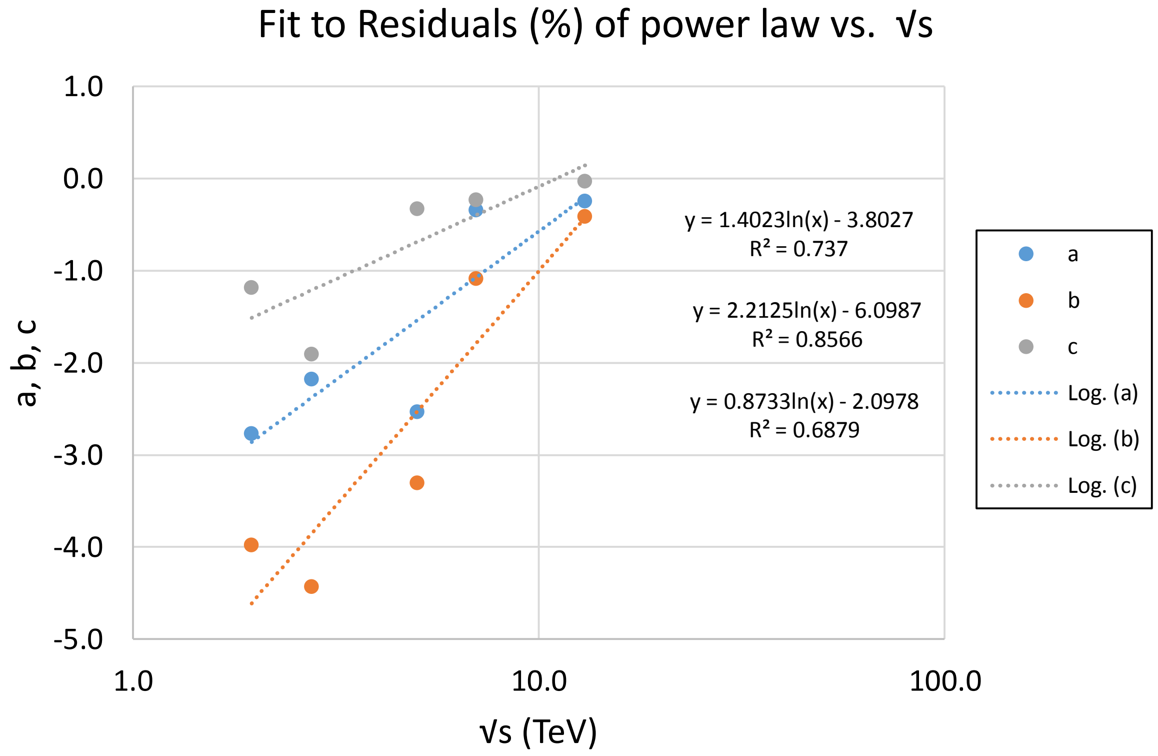


Quadratic fit parameters of residual fits

- Fit parameters vs. √s

$$\frac{A(p_T) - Afit(p_T)}{Afit(p_T)} = a\log(p_T)^2 + b\log(p_T) + c$$

√s (TeV)	a	b	c
1.960	-2.766	-3.979	-1.181
2.760	-2.177	-4.432	-1.904
5.020	-2.532	-3.303	-0.324
7.000	-0.339	-1.081	-0.232
13.000	-0.244	-0.413	-0.026

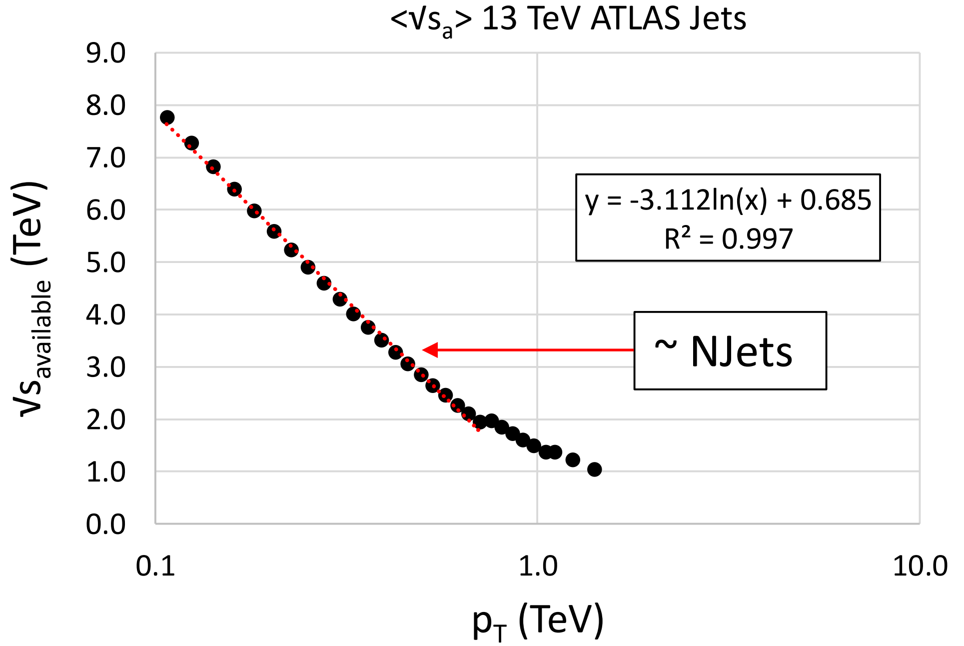


Rescaling √s to √s* to $\sqrt{s_a}$

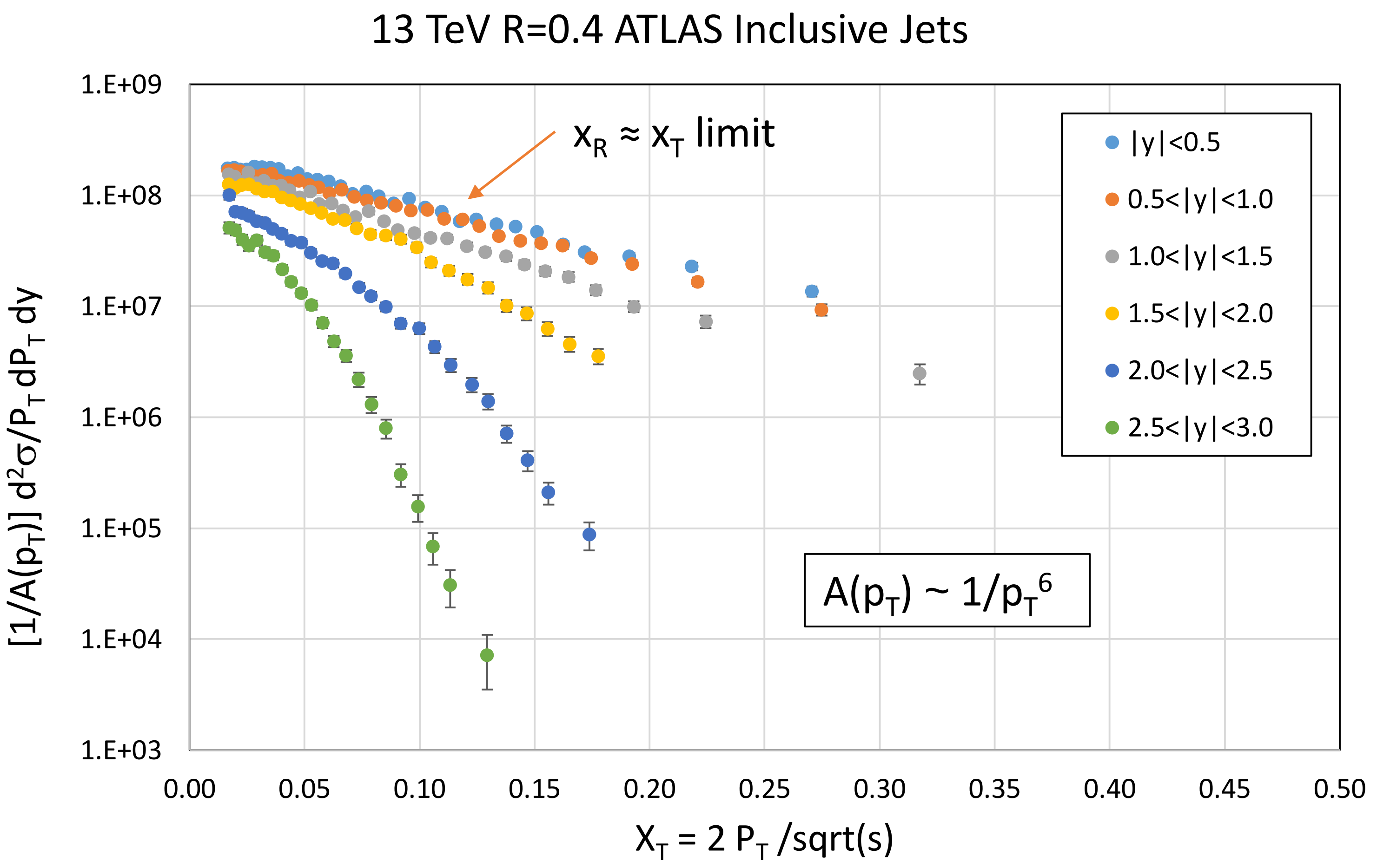
- Interpret the strong $1/p_T$ dependence in 13 TeV n_{xR} as caused by a ‘drain’ in √s available for primary collision. Force $(1-x_R)^4$ behavior to find effective √s*. ISR, FSR or multiple parton interactions would lead to N_{Jet} increasing. The ‘available’ $\sqrt{s_a}$ is given by:

$$\sqrt{s^*} = 2p_T\cosh(\eta)\left[1-\left(1-\frac{2p_T\cosh(\eta)}{\sqrt{s}}\right)^{\frac{\left((D/p_T)-n0_{xR}\right)}{4}}\right]^{-1}$$

$$\sqrt{s_a} = \sqrt{s} - \sqrt{s^*}$$



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 $F(x_T,\theta) = F(x_R)$

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

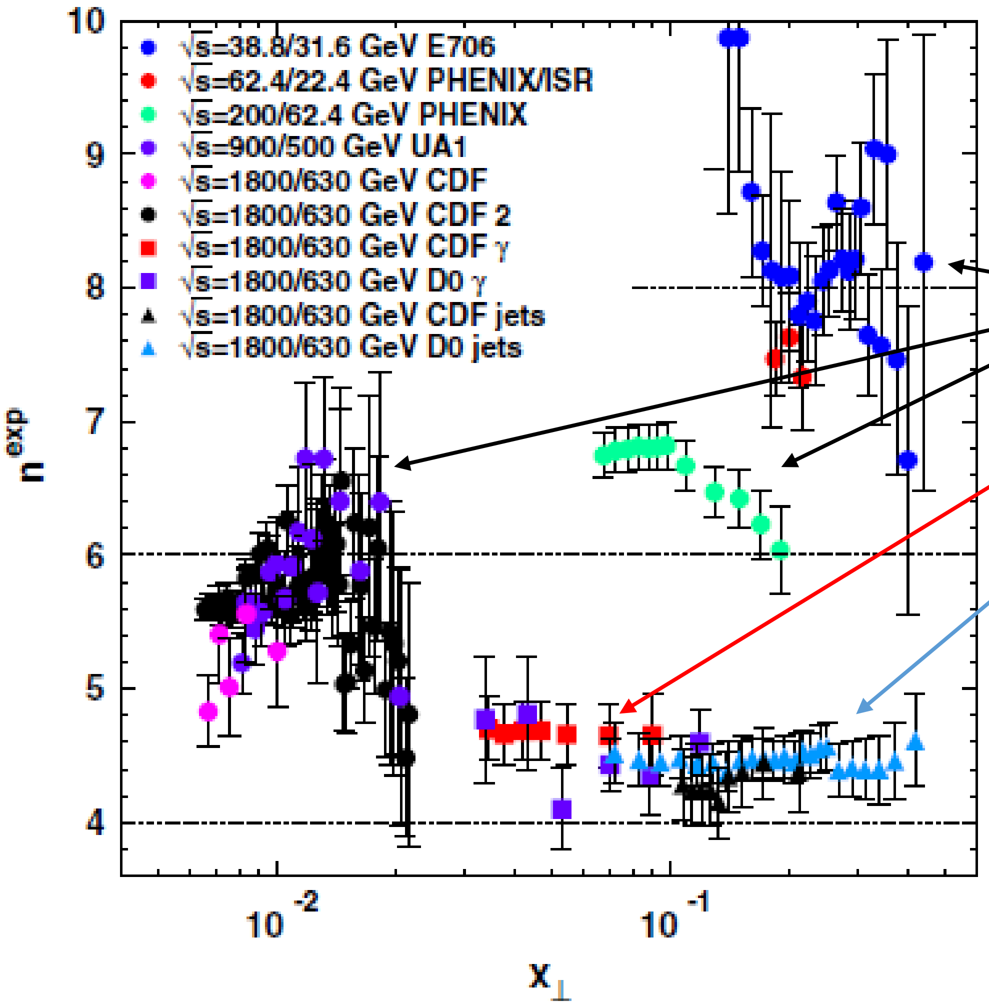
Using x_T to Determine n_{eff} - replication of analysis

- Assume

$$
\begin{cases}
\sigma = E\dfrac{d^3\sigma}{dp^3} = \dfrac{1}{p_T^{neff}} F(x_T,\theta) \\
p_T = \dfrac{\sqrt{s}}{2} x_T \\
\ln\left(\dfrac{\sigma_1}{\sigma_2}\right) = -n_{eff}\ln\left(\dfrac{\sqrt{s_1}}{\sqrt{s_2}}\right) + \ln\left(\dfrac{F(x_T,\theta_1)}{F(x_T,\theta_2)}\right) \\
n_{eff} = \dfrac{-\ln\left(\sigma_1/\sigma_2\right)}{\ln\left(\sqrt{s_1}/\sqrt{s_2}\right)} + \dfrac{\ln\left(F(x_T,\theta_1)/F(x_T,\theta_2)\right)}{\ln\left(\sqrt{s_1}/\sqrt{s_2}\right)} = \dfrac{-\ln\left(\sigma_1/\sigma_2\right)}{\ln\left(\sqrt{s_1}/\sqrt{s_2}\right)} + \dfrac{\ln\left(F(x_{R1})/F(x_{R2})\right)}{\ln\left(\sqrt{s_1}/\sqrt{s_2}\right)}
\end{cases}
$$

- Neglect the ‘F’ term:

Arleo - continued



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

$h^{\pm}/\pi^0$ – circles

γ – squares

Jets – triangles

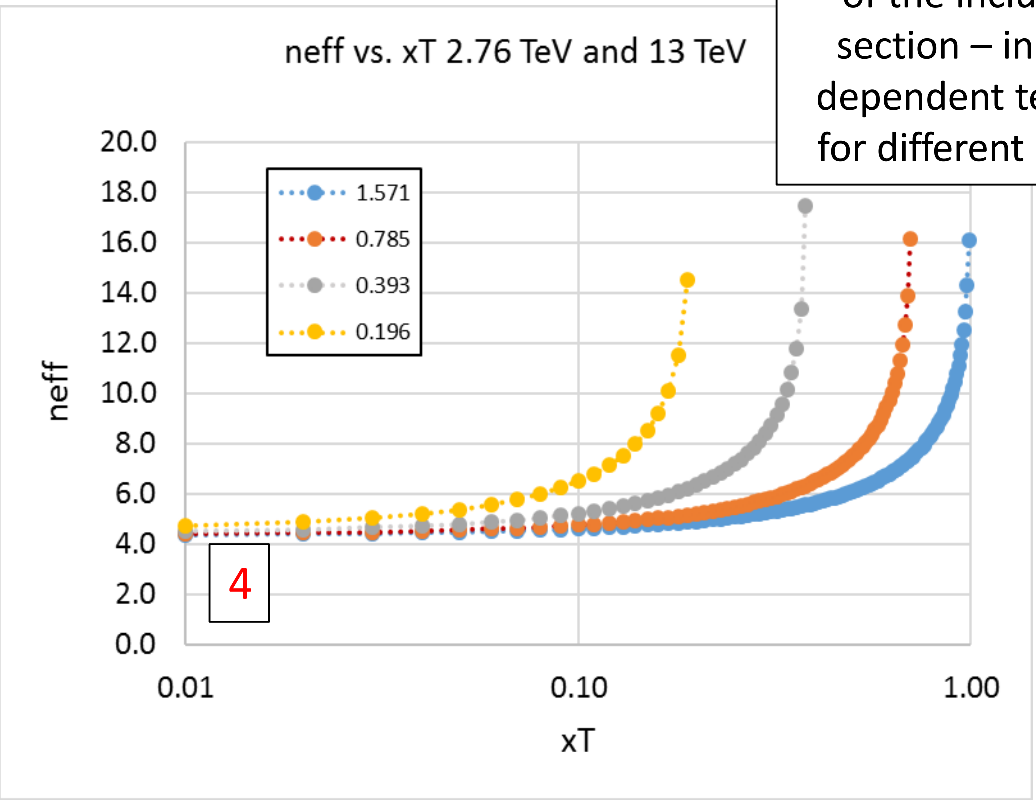
n^{exp} determined in a two component model by variation in x_T and p_T for two values of √s.

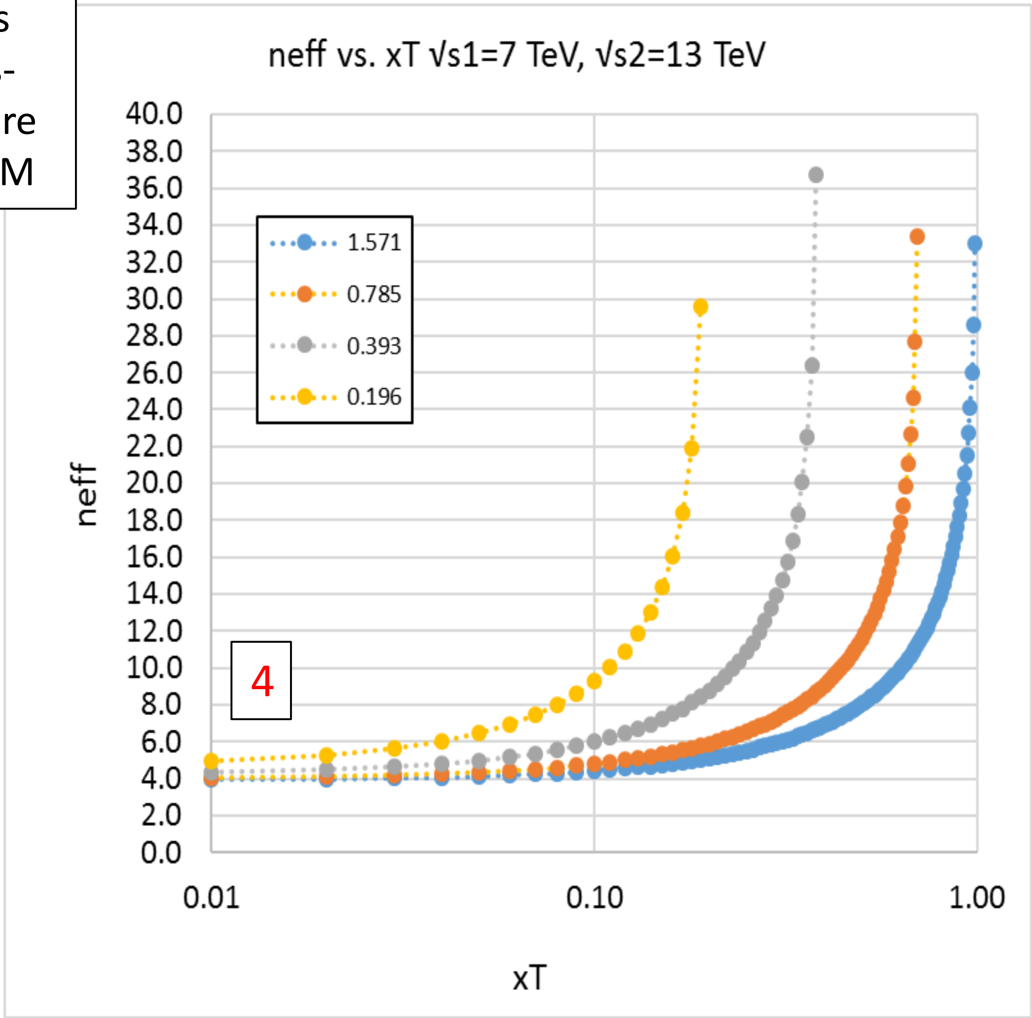
The x_R analysis finds power of p_T independent of process within errors: $n_{pT} = 6.5 \pm 0.4$

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

n_{eff} without correction term using ATLAS Jet Fits

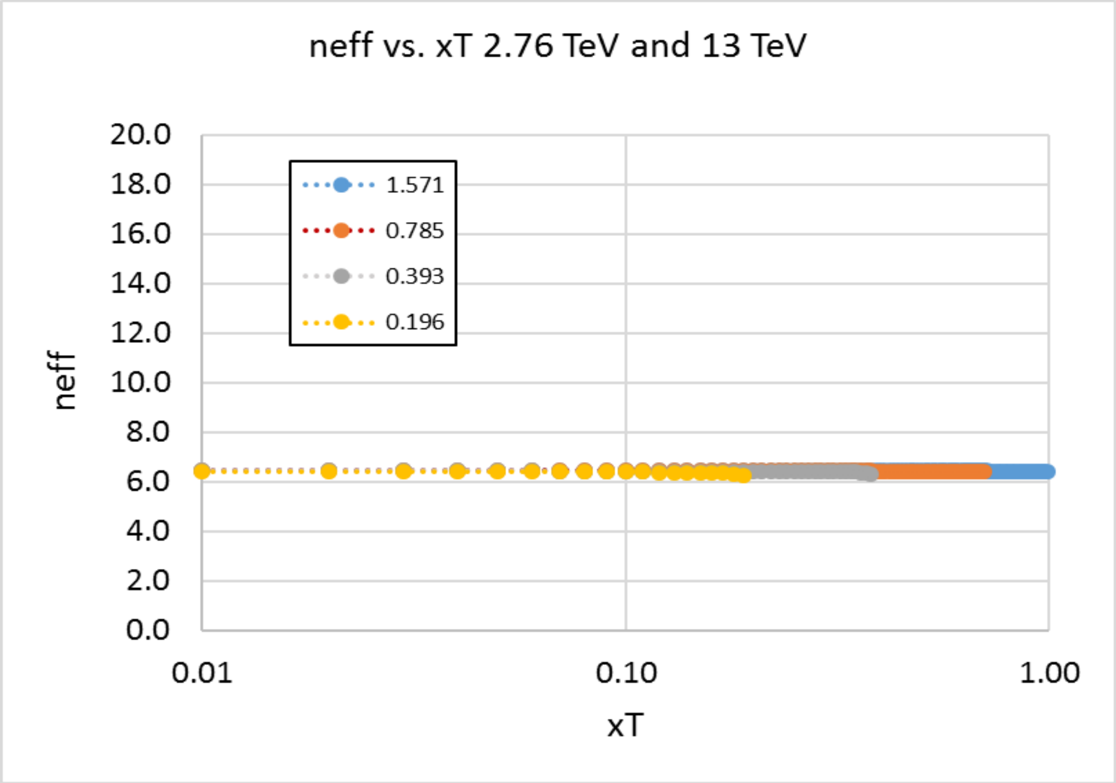
Use the full parameterization of the inclusive Jet cross section – including the s-dependent terms. Plots are for different angles in COM



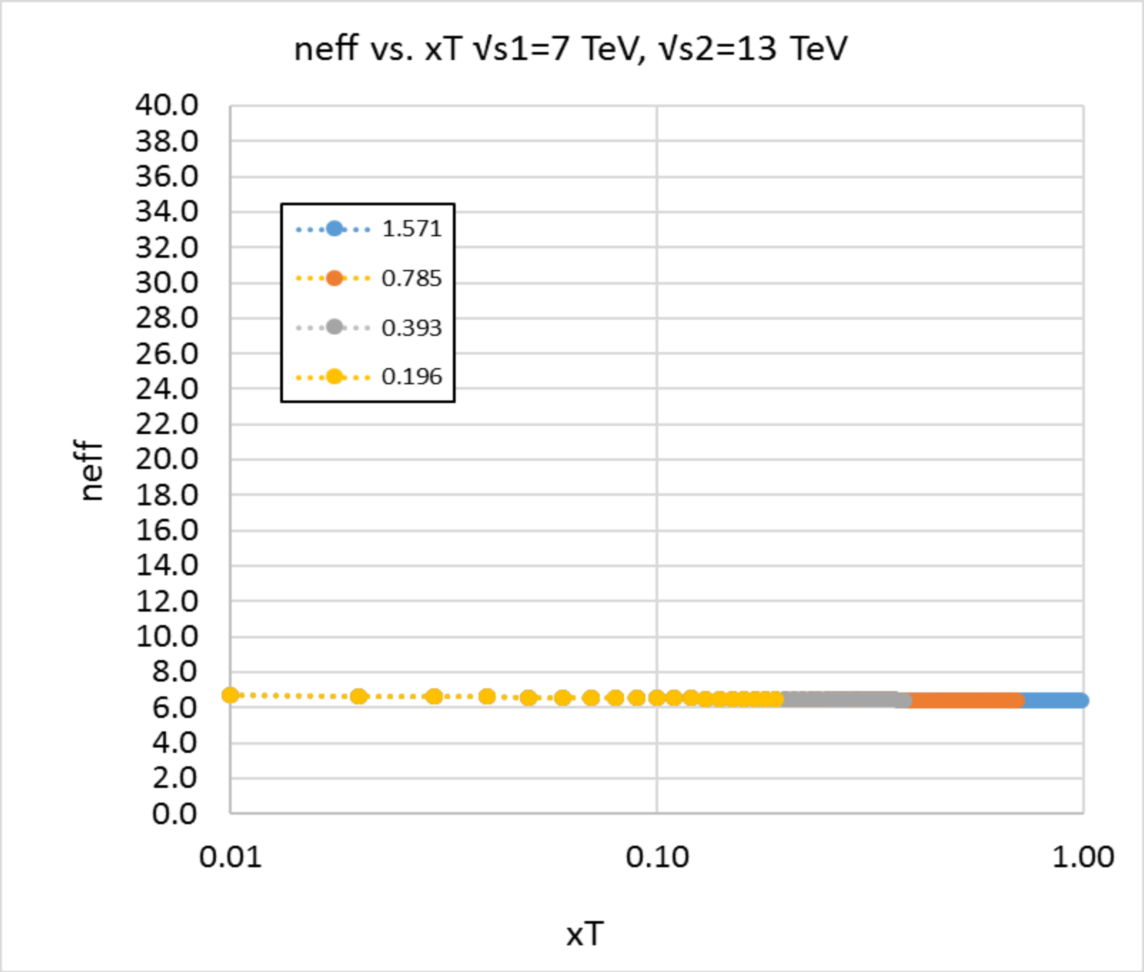


Find n_{eff} -> 4 as x_T -> 0

n_{eff} with the F-correction term



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



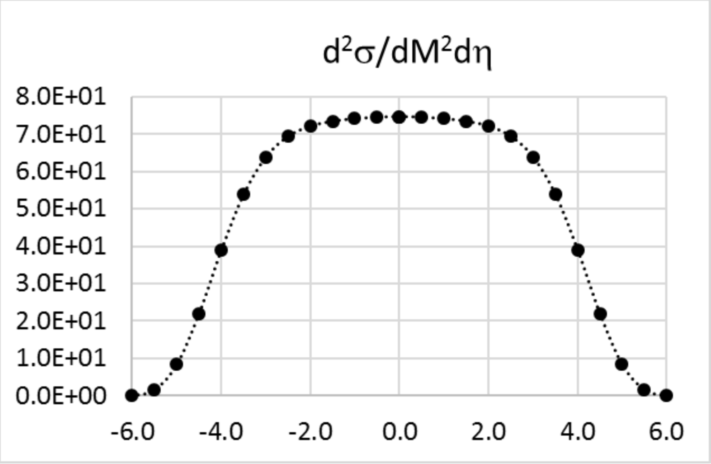
The 'Drell-Yan' Limit

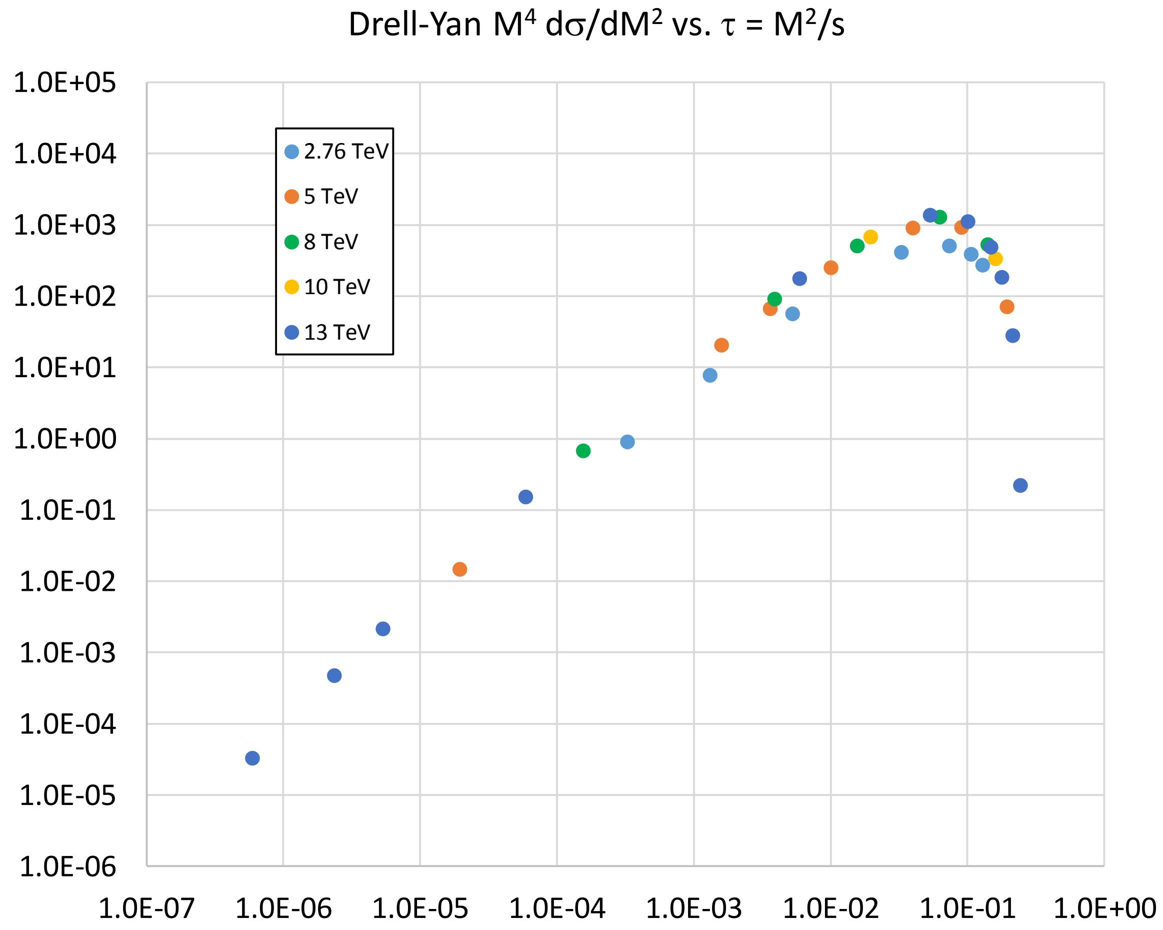
Computed for p_{Tmin} = 0.01 TeV:

$$M^4 \frac{d\sigma}{dM^2} = M^4 \iint \left(\frac{d}{dM^2} \right) \frac{d^2\sigma}{dp_T^2 dy} dp_T dy$$

Typical point calculation with Λ = Quad(√s) :

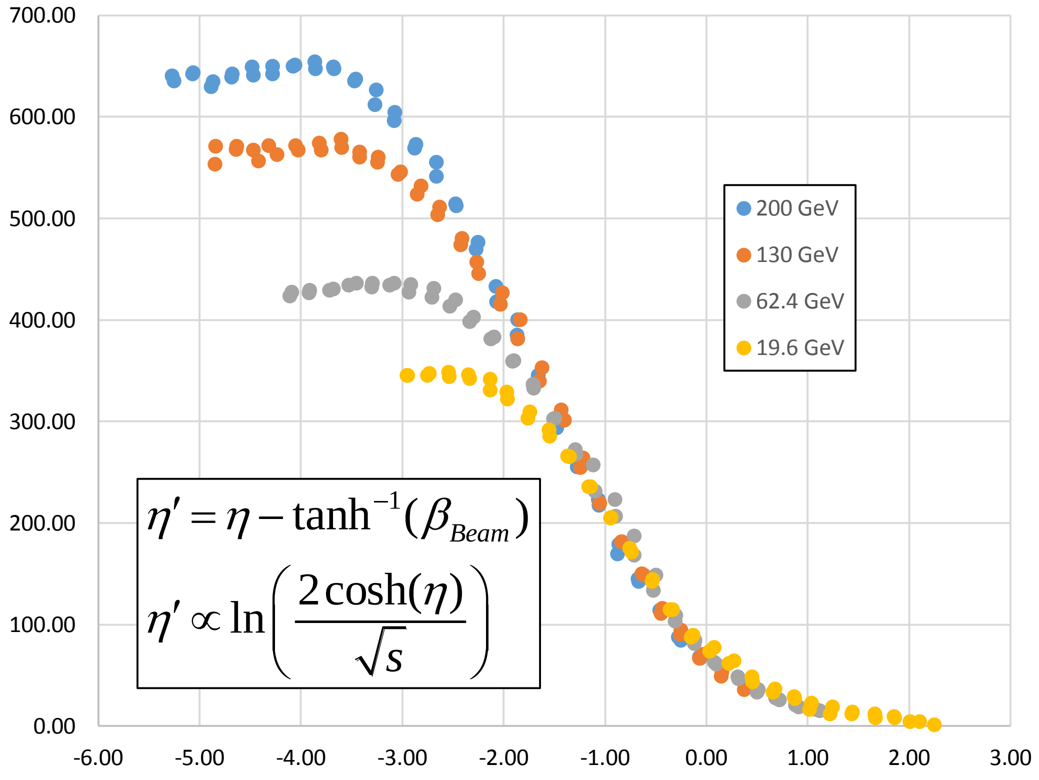
√s (TeV)	M (TeV)	τ	σ
7.00	0.9900	2.0002E-02	6.2735E+02
Λ (TeV)	0.0350	pTmin (TeV)	0.010



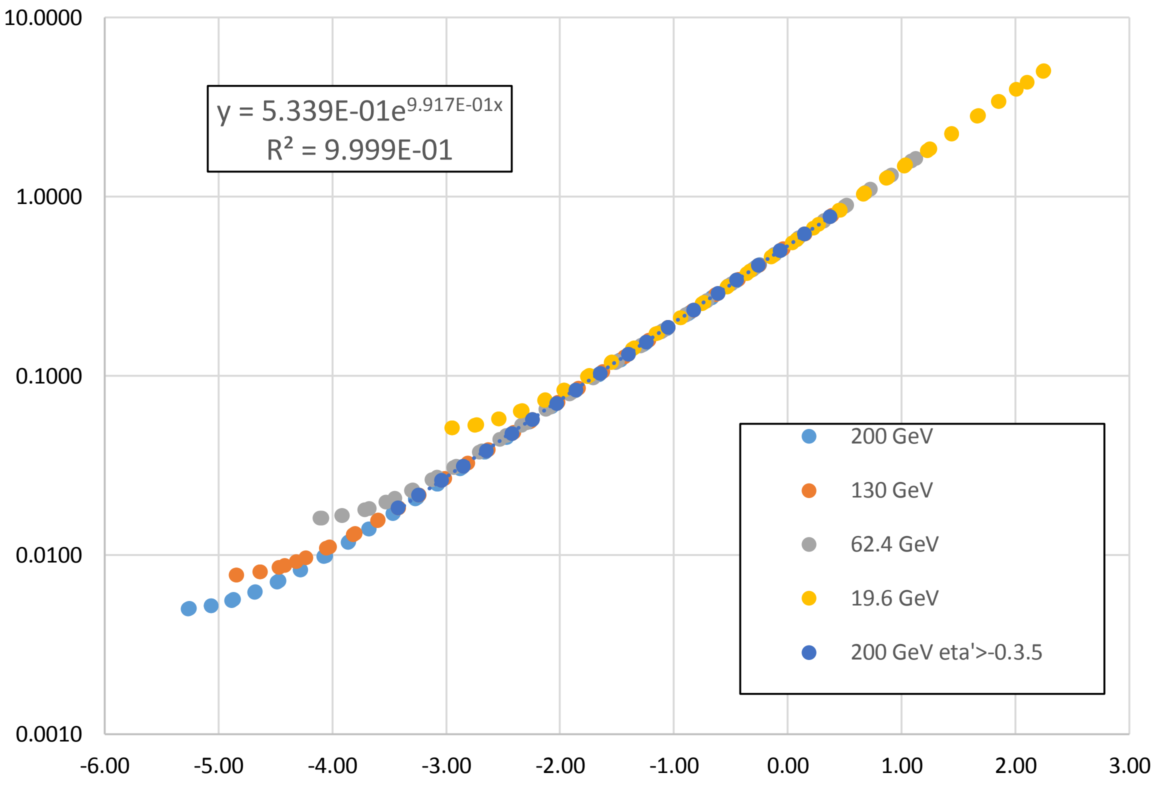


PHOBOS η’ Scaling vs. cosh(η)/√s

dN/dη vs. η'



η' vs. cosh(η)/√s



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

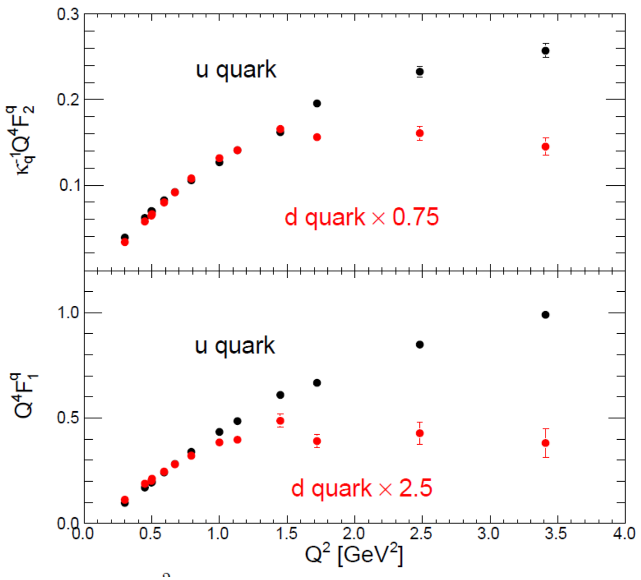
Jorge Segovia

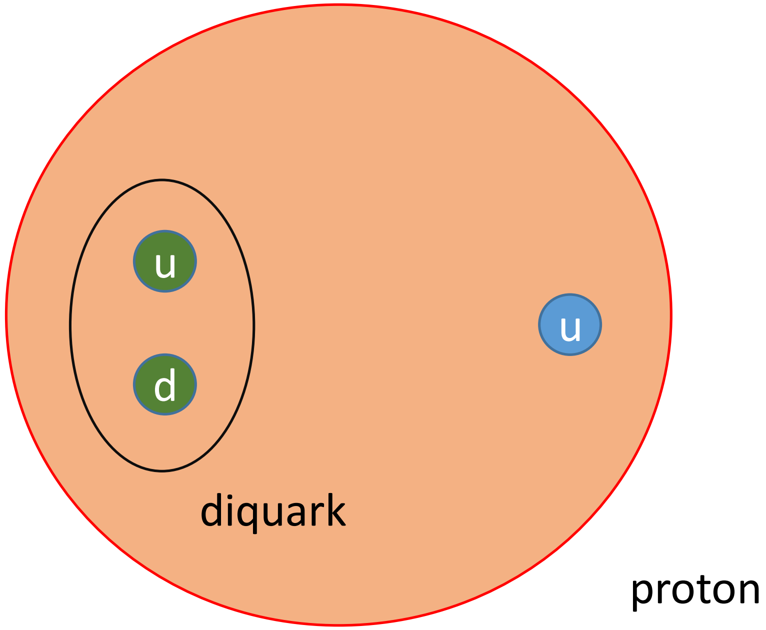
EPJ Web of Conferences 113, 05025 (2016)

Hadron Systematics and Emergent Diquarks

Alexander Selema and Frank Wilczek

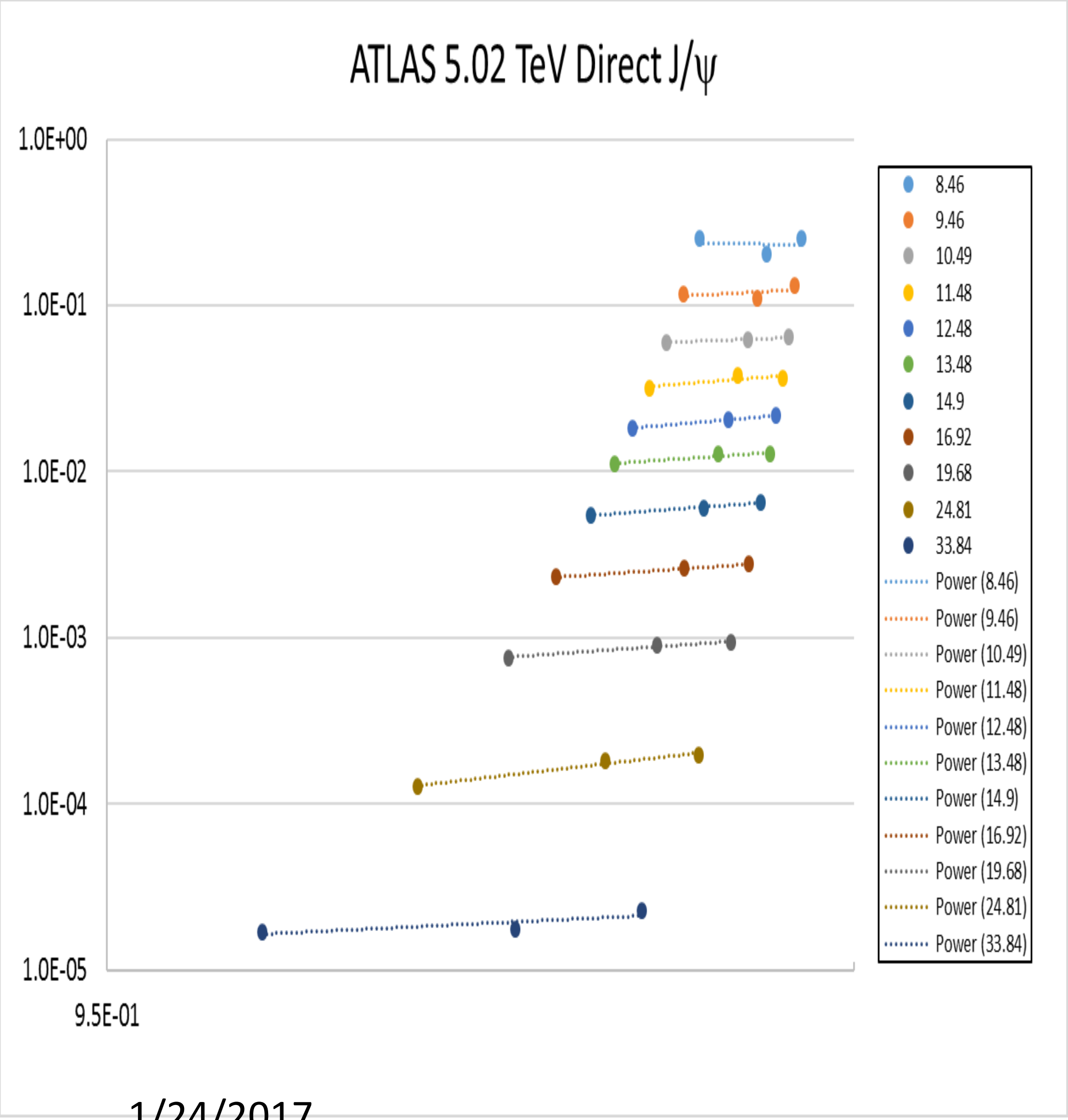
arXiv:hep-ph/0602128v1 14 Feb 2006

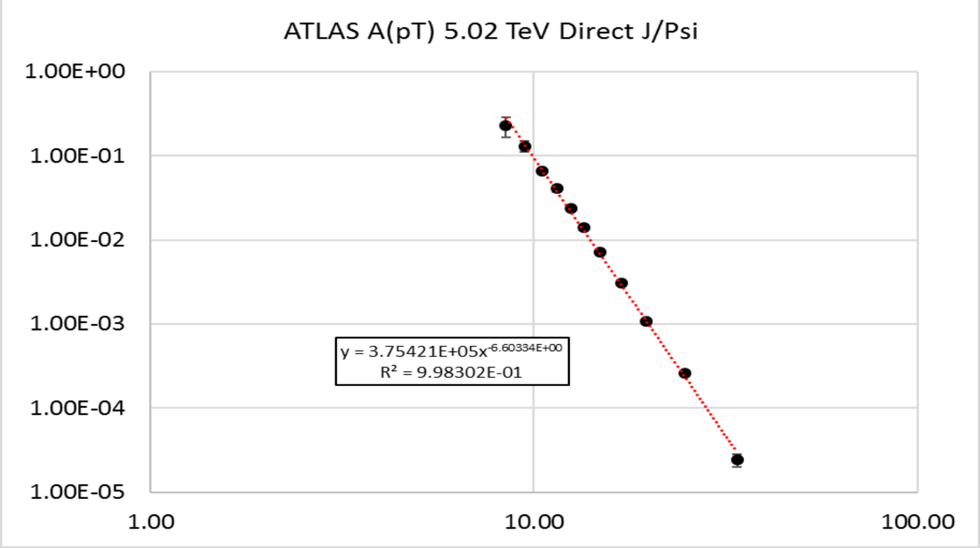


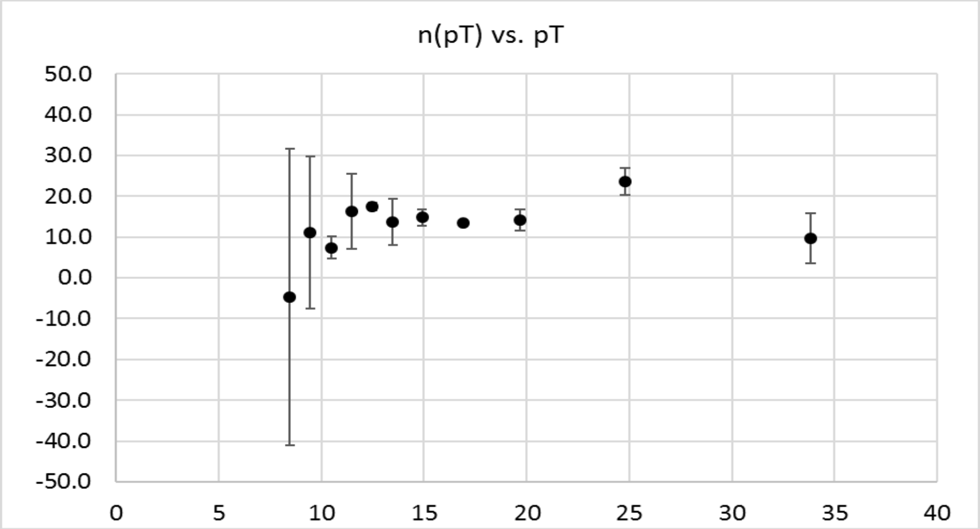


Cates, et al. conclude that d-quark contribution to the proton form-factor appears to be suppressed from no-diquark assumption.

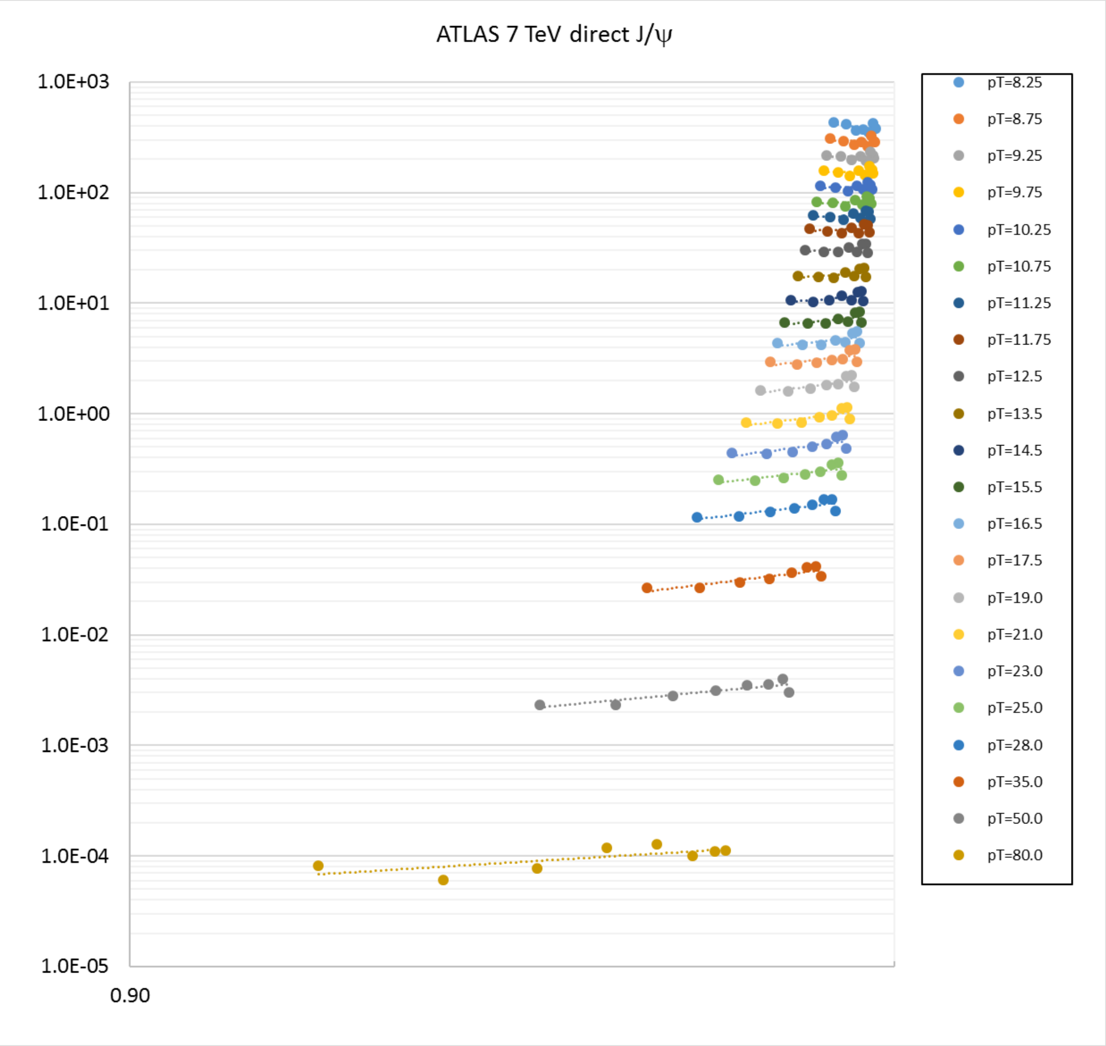
ATLAS 5.02 TeV Direct Λ = 0

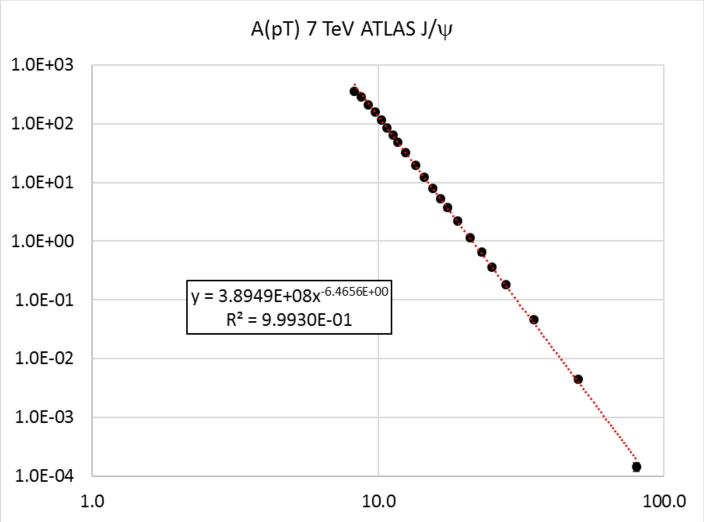


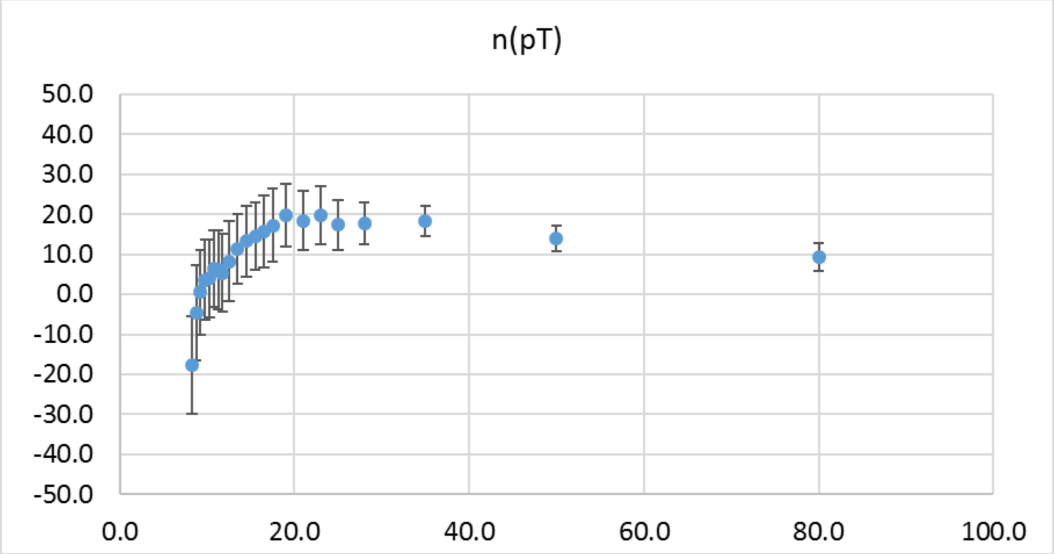




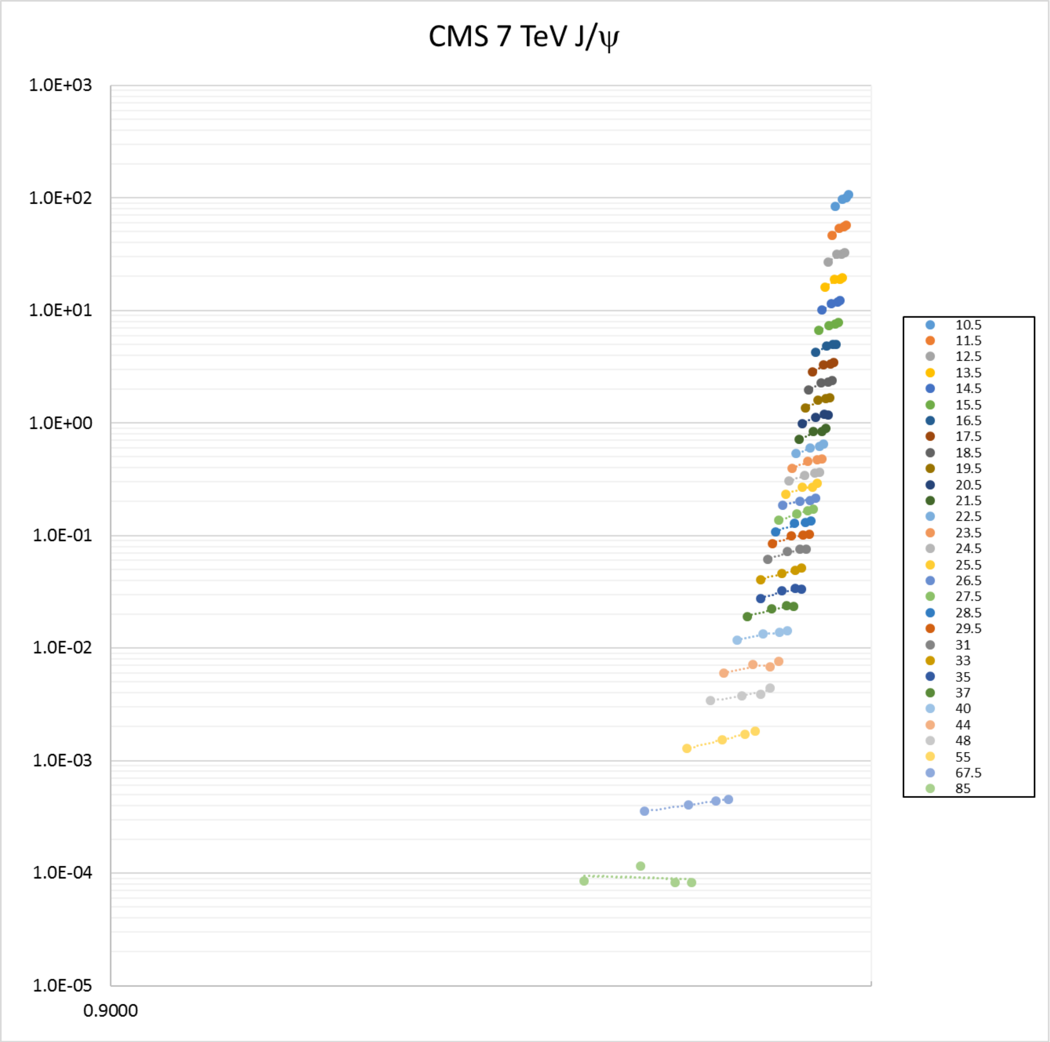
ATLAS 7 TeV Direct Λ = 0

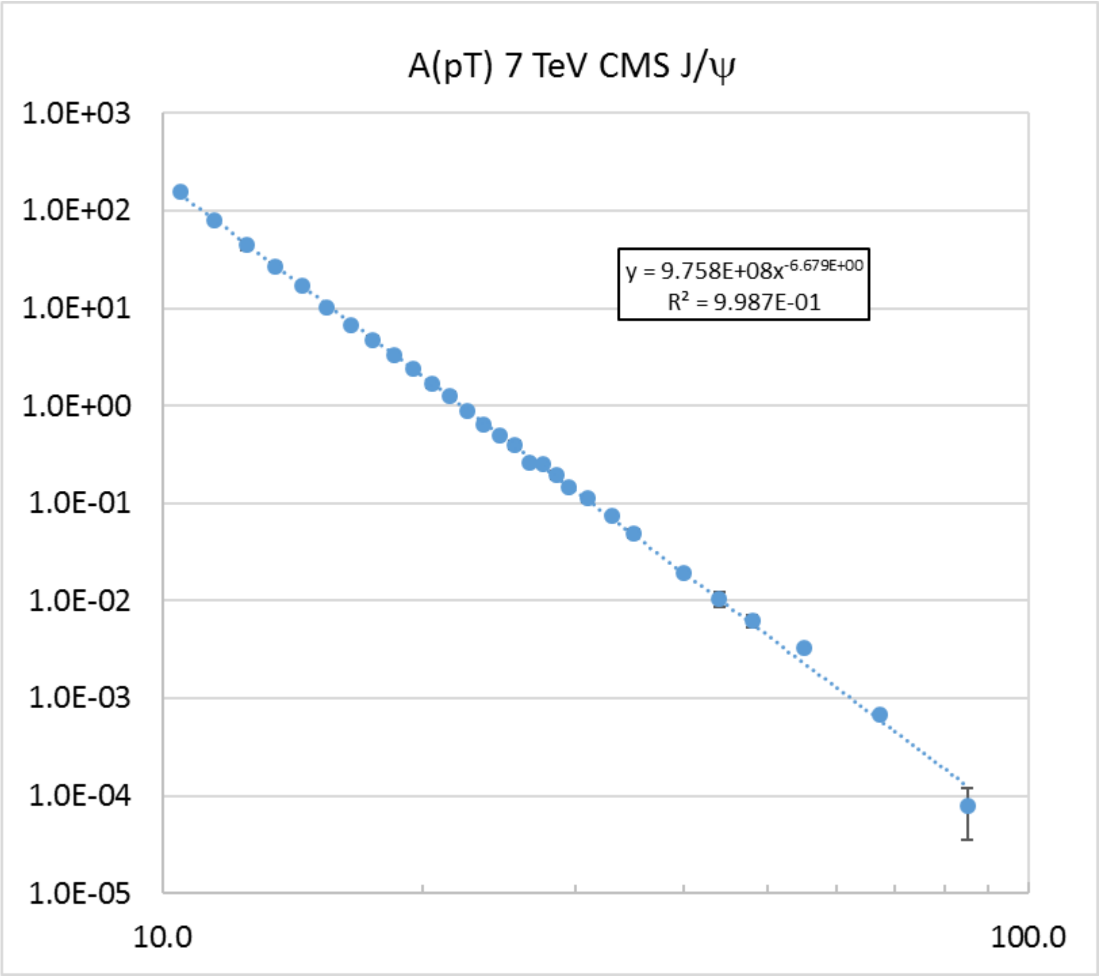




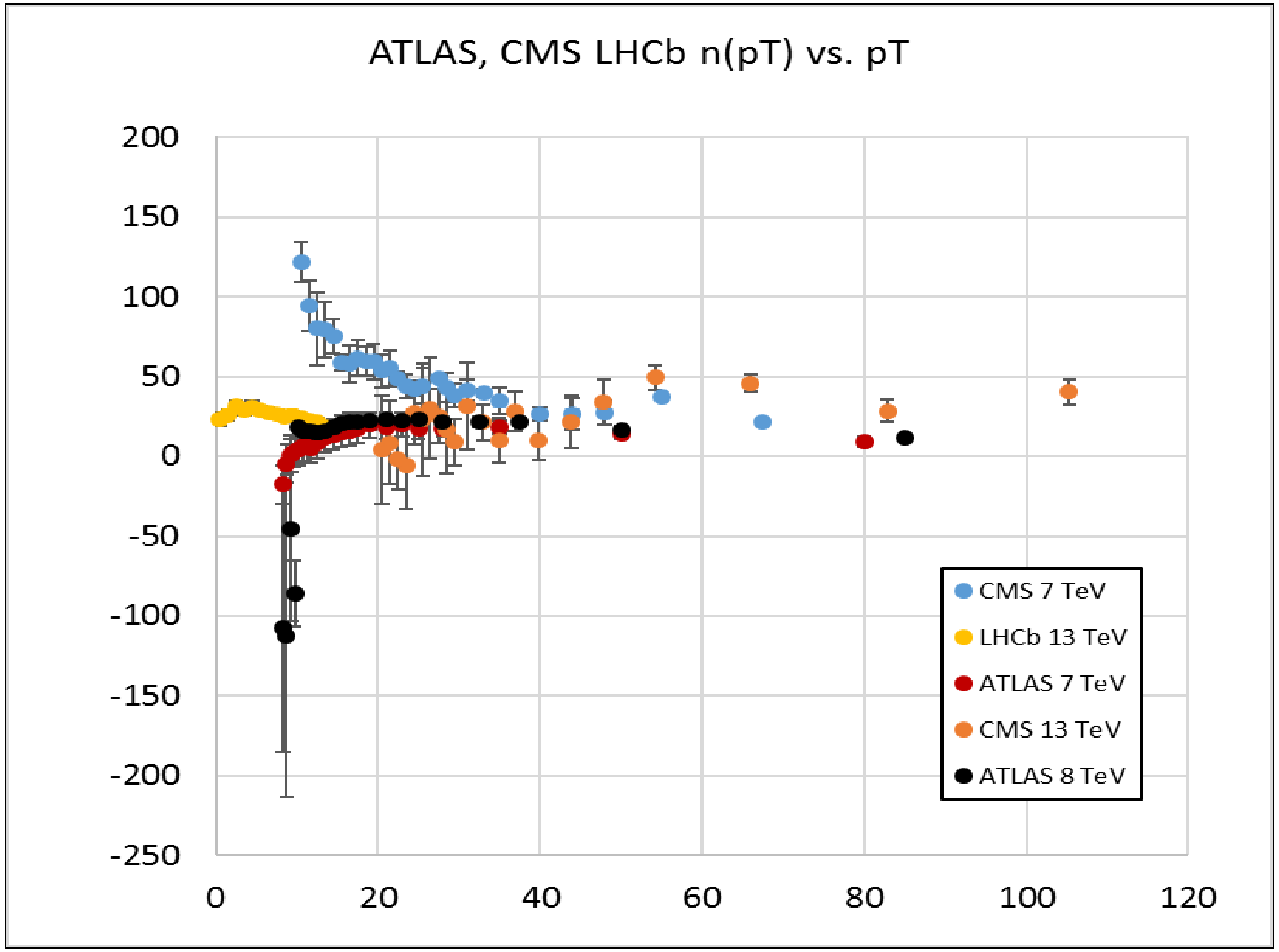


7 TeV CMS Prompt Λ = 0

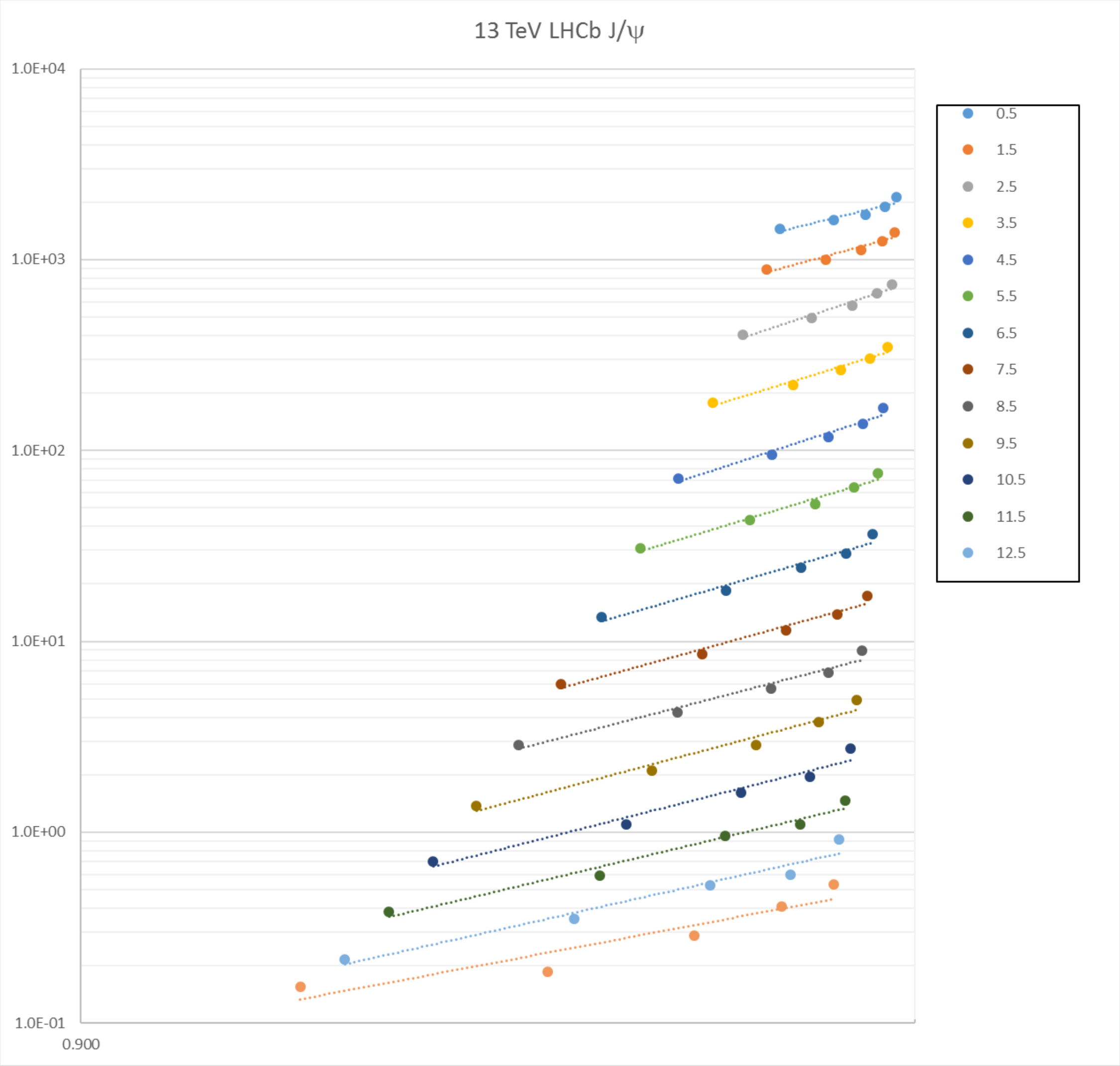


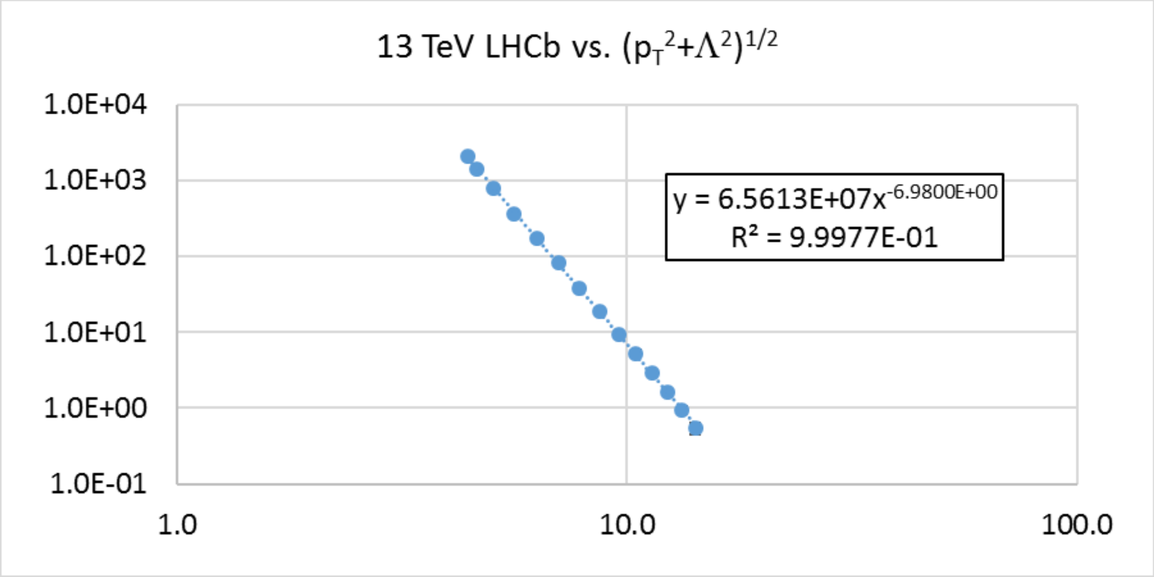


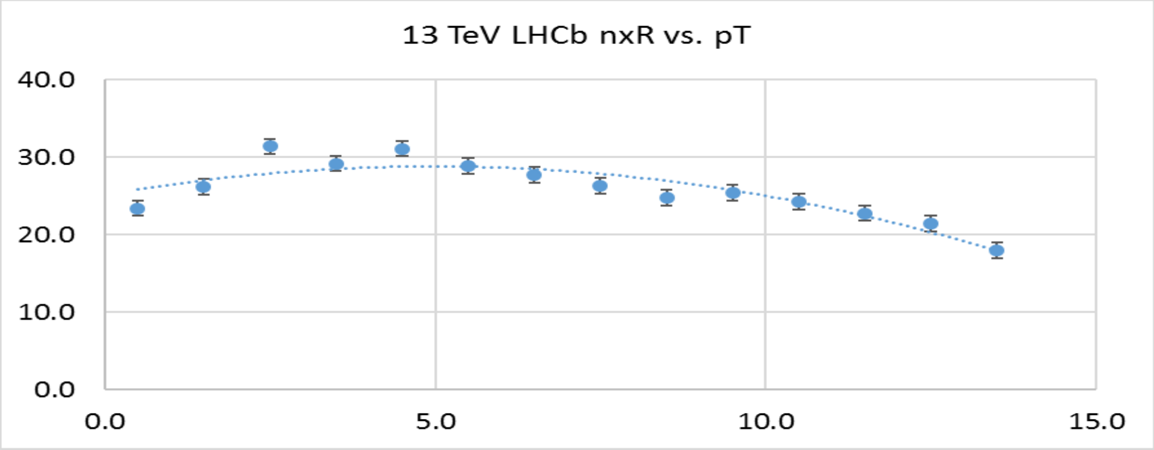
J/Psi-comparison of $(1-x_R)$ Power



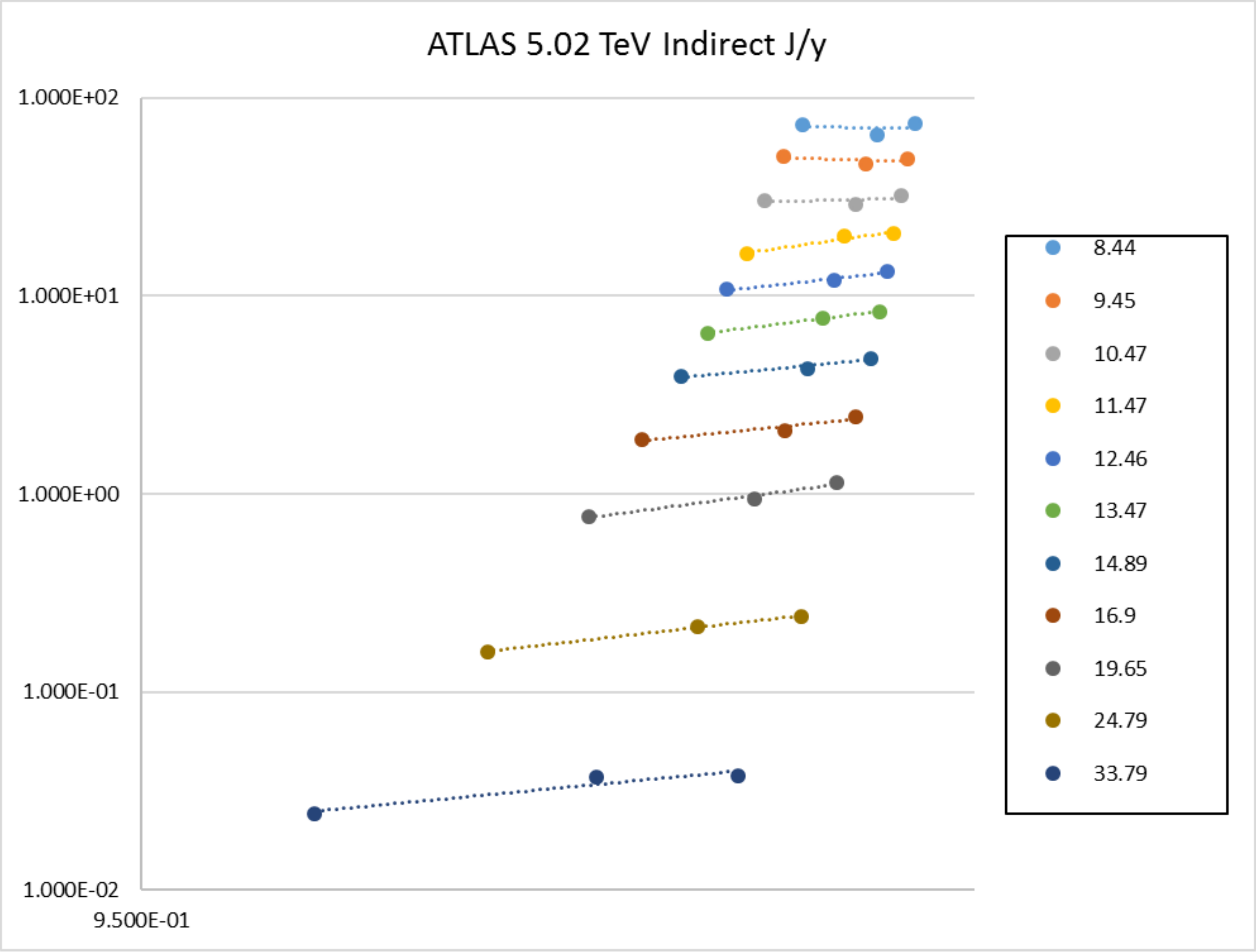
13 TeV LHCb Direct $\Lambda = 4.4 \pm 0.4$ GeV

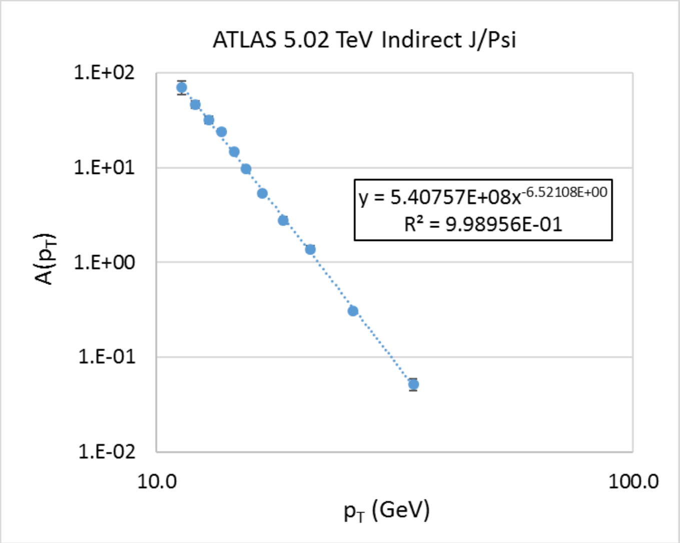


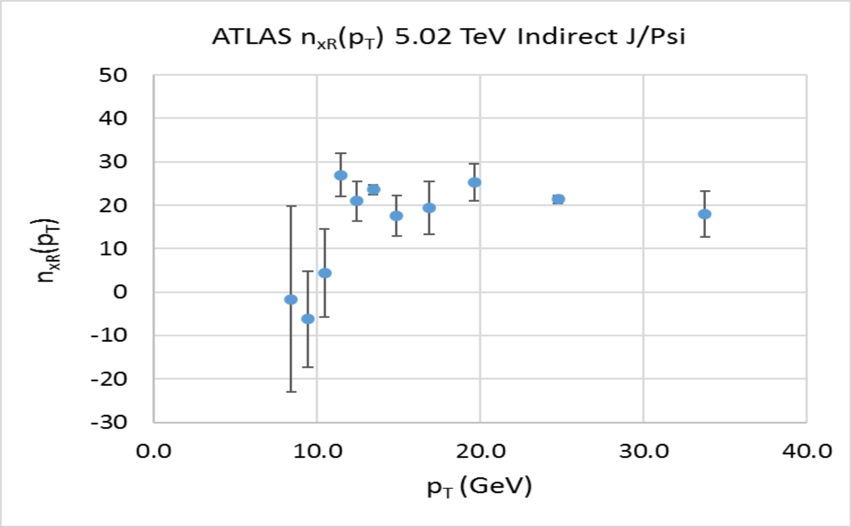




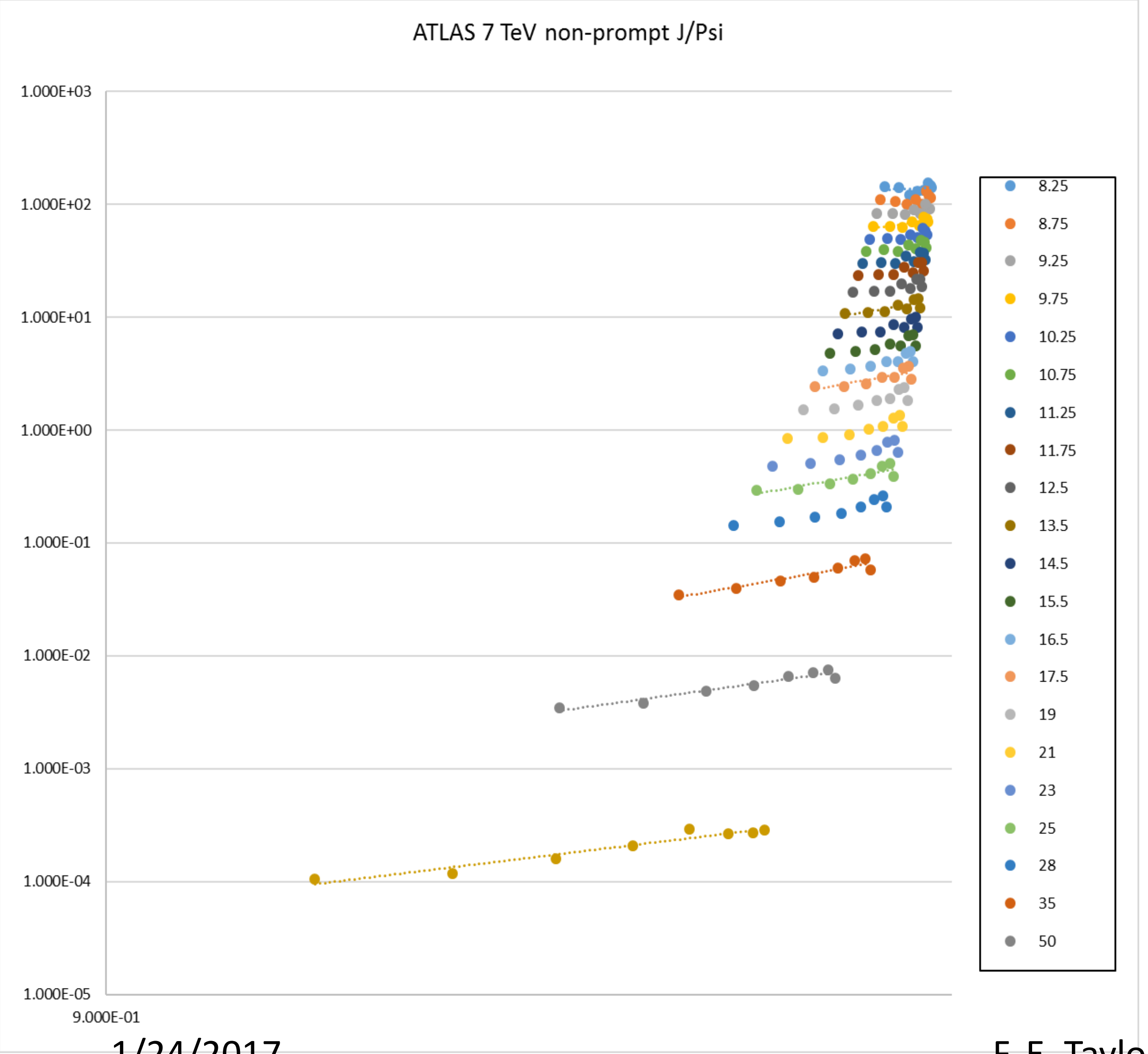
ATLAS 5.02 J/Psi Decay Λ=7.1 ± 1.5 GeV

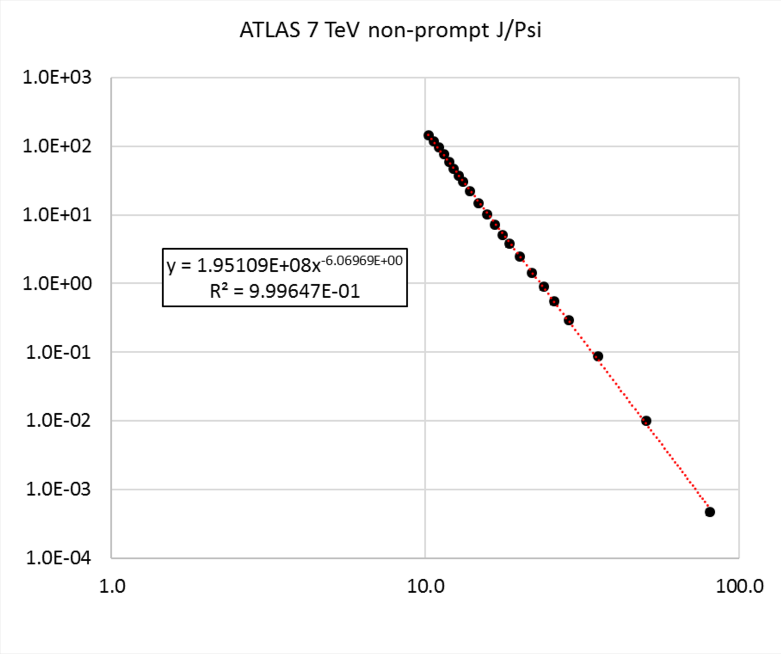


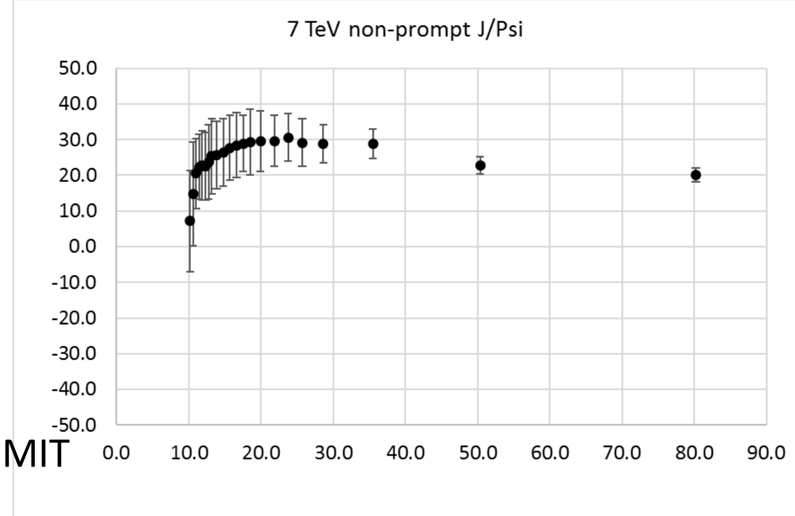




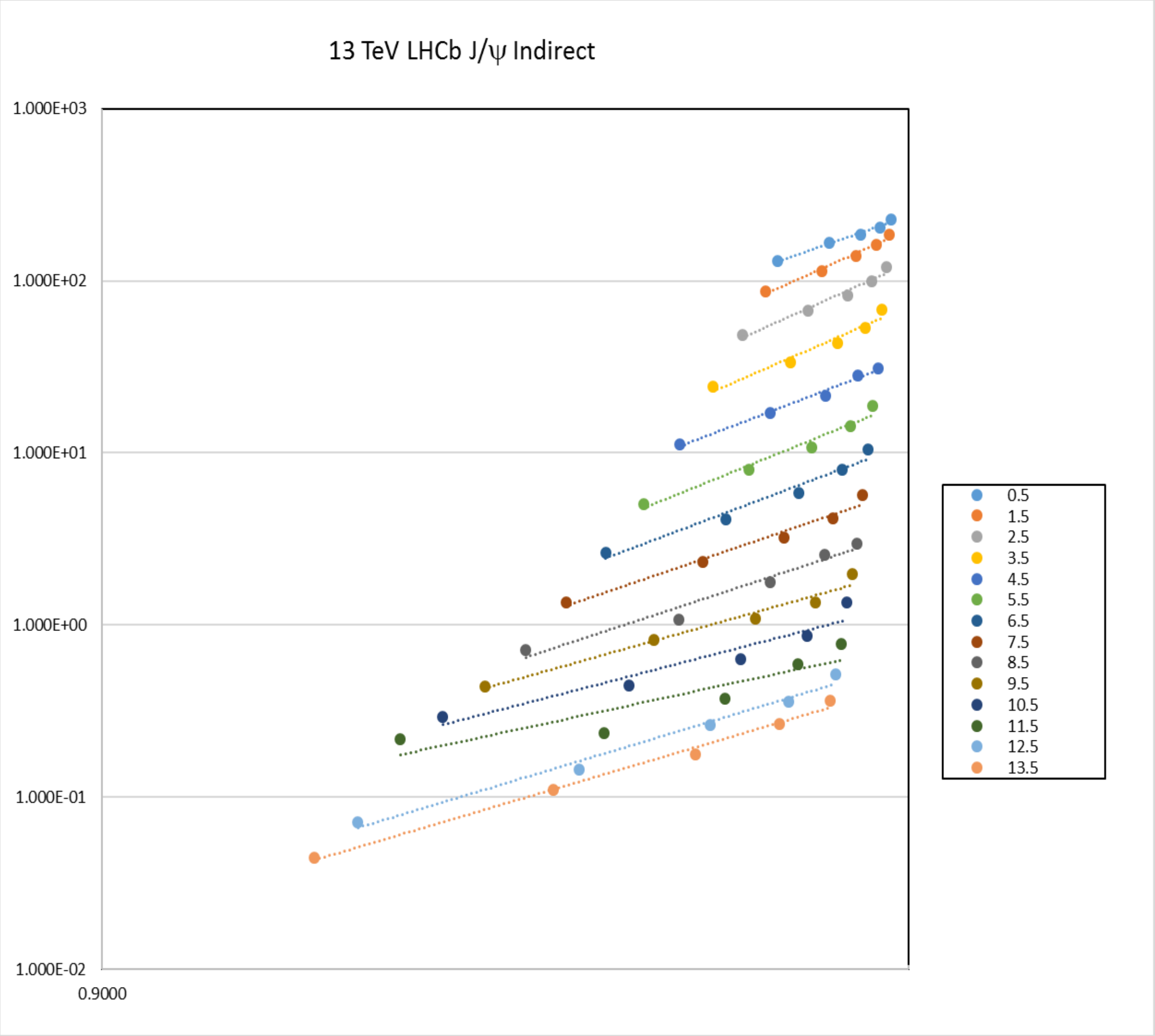
ATLAS 7 TeV Decay $\Lambda = 5.8 \pm 1.6$ GeV

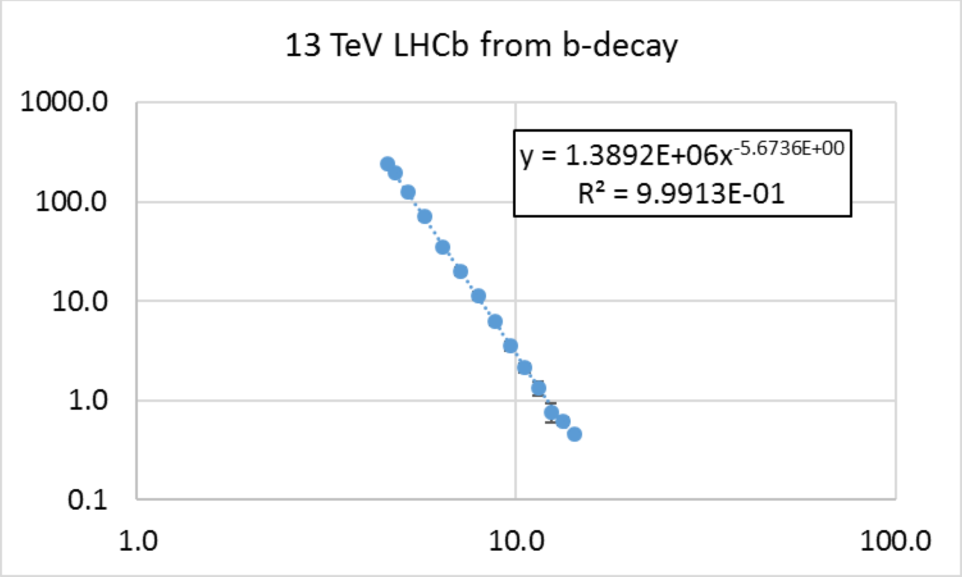


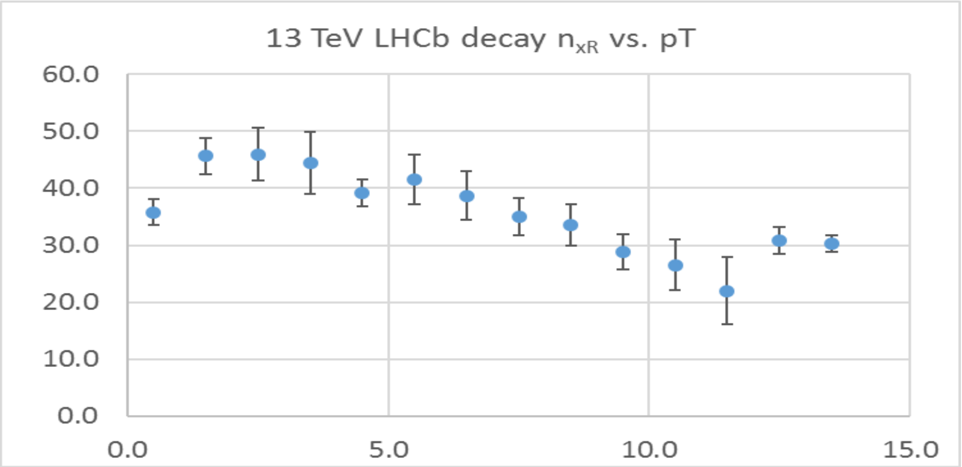




13 TeV LHCb Decay $\Lambda = 4.6 \pm 0.3$ GeV

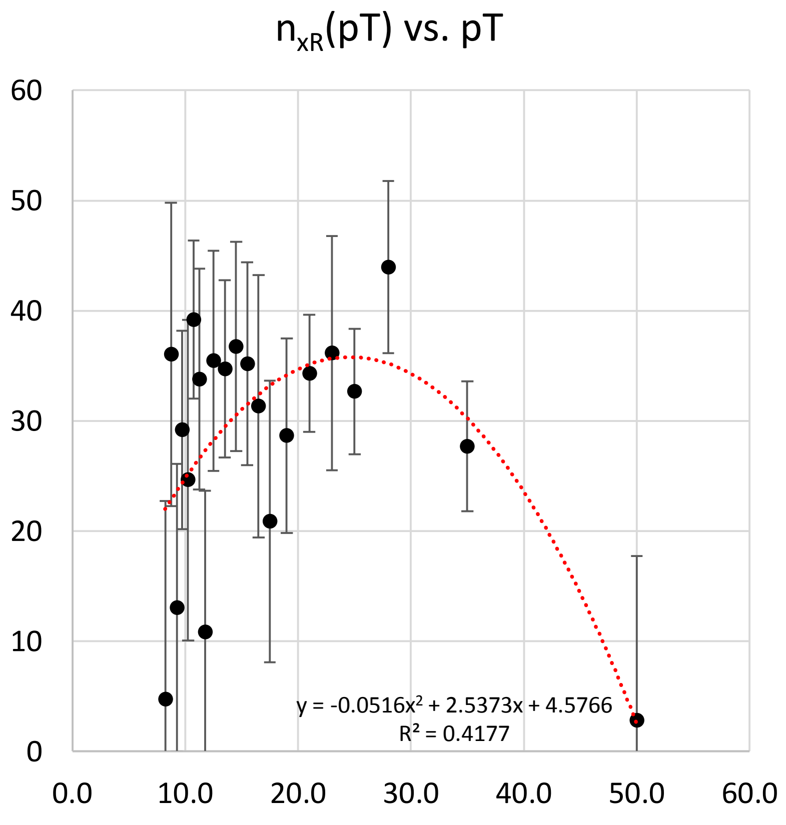




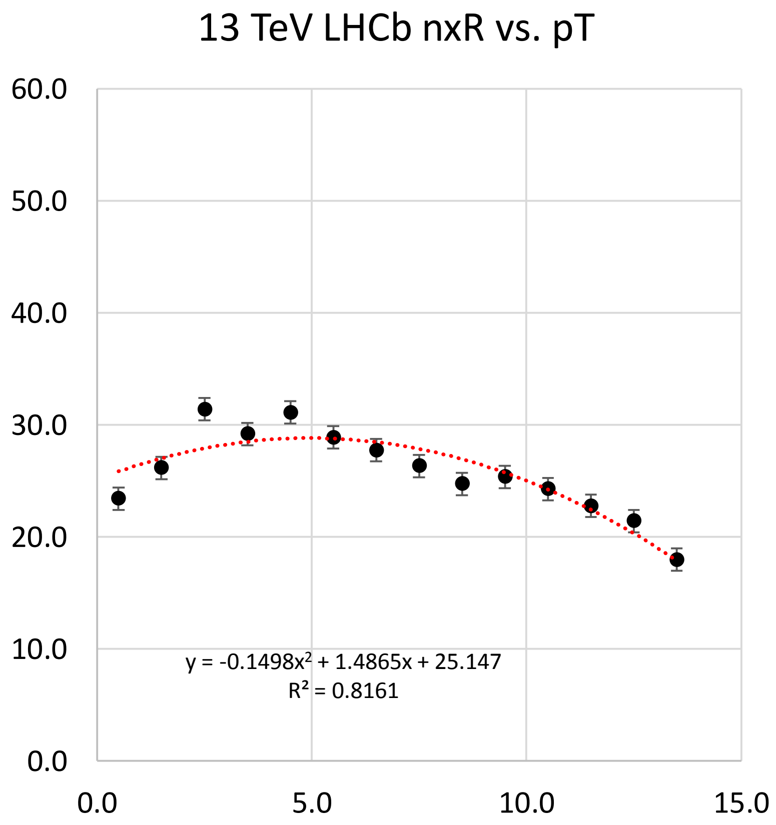


CHARM n_{xR}

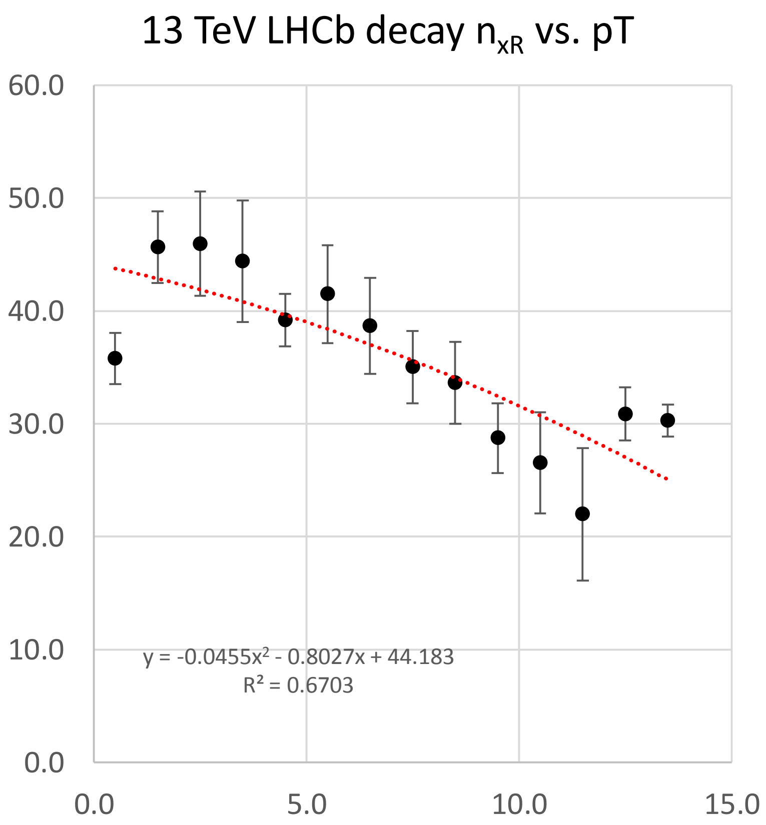
CHARM ψ(2S) 7 TeV ATLAS



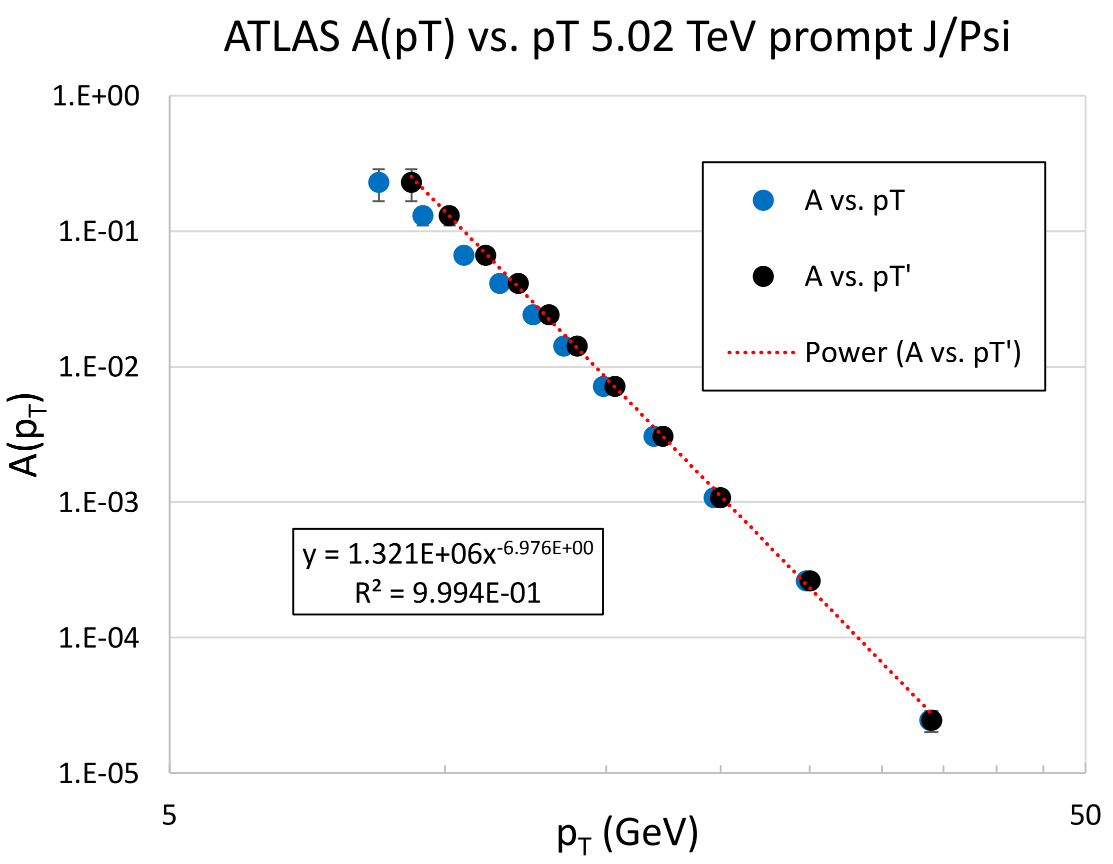
LHCb 13 TeV 'Direct' J/ψ

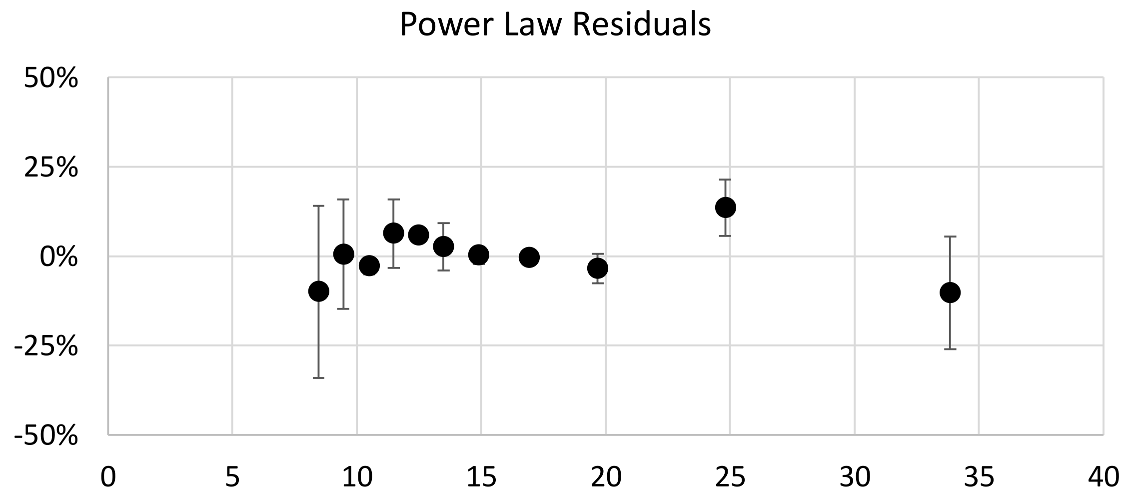


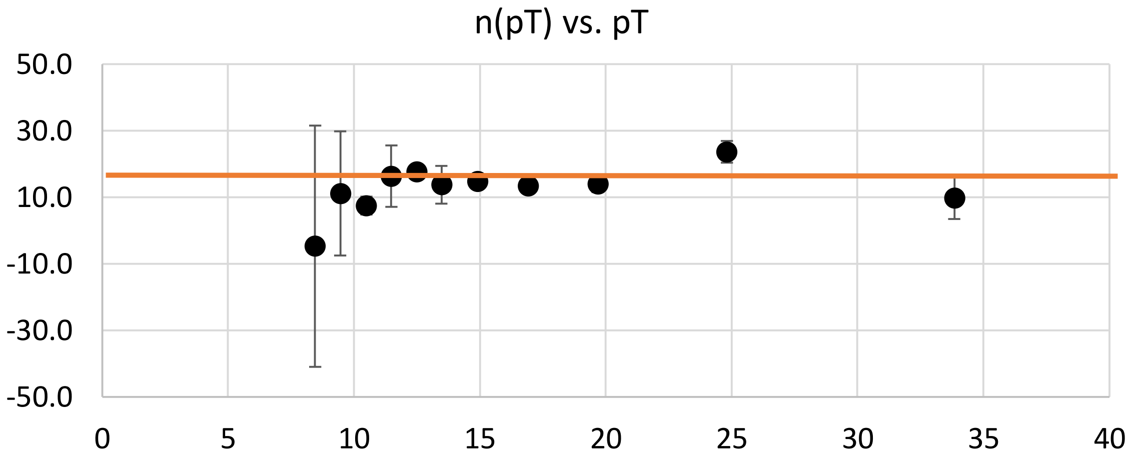
13 TeV LHCb Decay



CHARM – Directly Produced $\Lambda = 3.6 \pm 0.3$ GeV

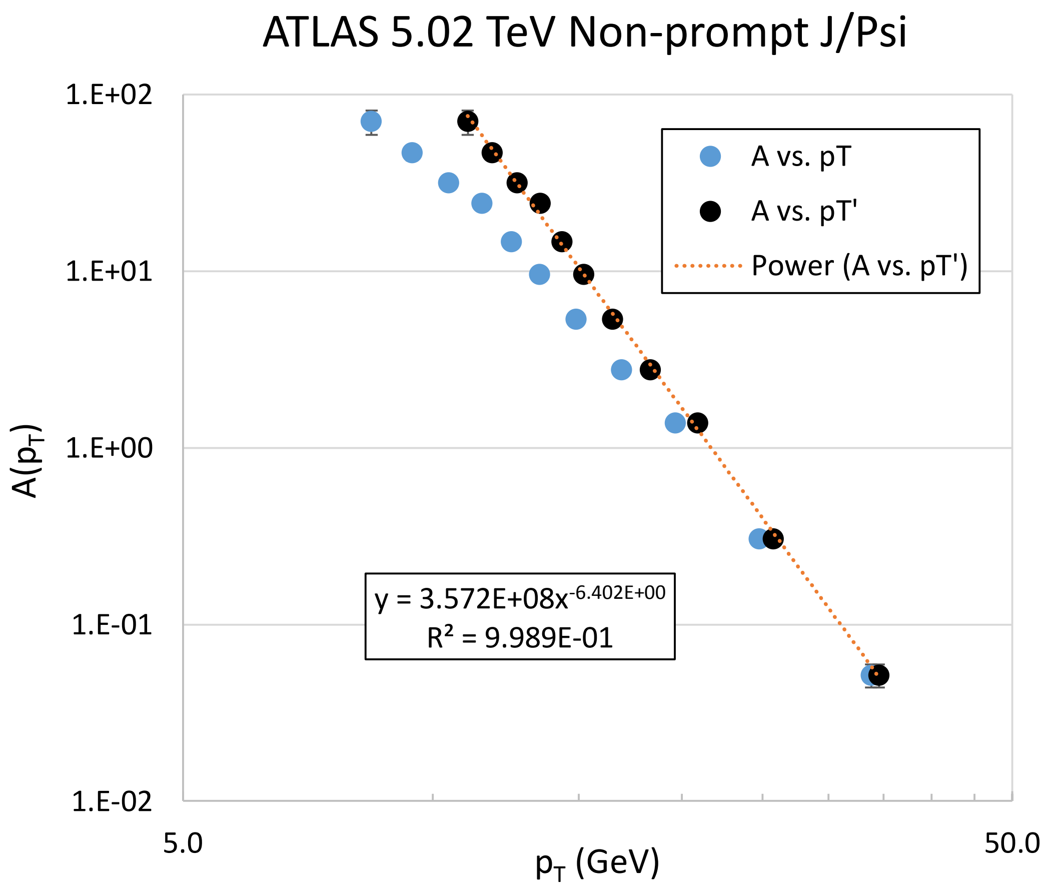






$$A(p_T) = \alpha_0 \frac{\Lambda^{n_{pT}-4}}{\left(\Lambda^2 + p_T^2\right)^{\frac{n_{pT}}{2}}}$$

CHARM from b-decay Λ=7.1 ± 0.9 GeV



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