



LUND UNIVERSITY

YETI'06–SM
IPPP, Durham, UK
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Monte Carlo Event Generators

Torbjörn Sjöstrand

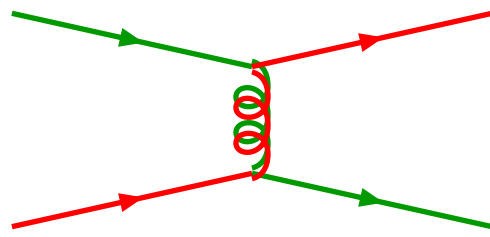
Lund University

1. (yesterday) Introduction and Overview; Monte Carlo Techniques
2. (yesterday) Matrix Elements; Parton Showers I
3. (today) Parton Showers II; Matching Issues
4. **(today) Multiple Interactions and Beam Remnants**
5. (tomorrow) Hadronization and Decays; Summary and Outlook

What is multiple interactions?

Cross section for $2 \rightarrow 2$ interactions is dominated by t -channel gluon exchange, so diverges like $d\sigma/dp_{\perp}^2 \approx 1/p_{\perp}^4$ for $p_{\perp} \rightarrow 0$.

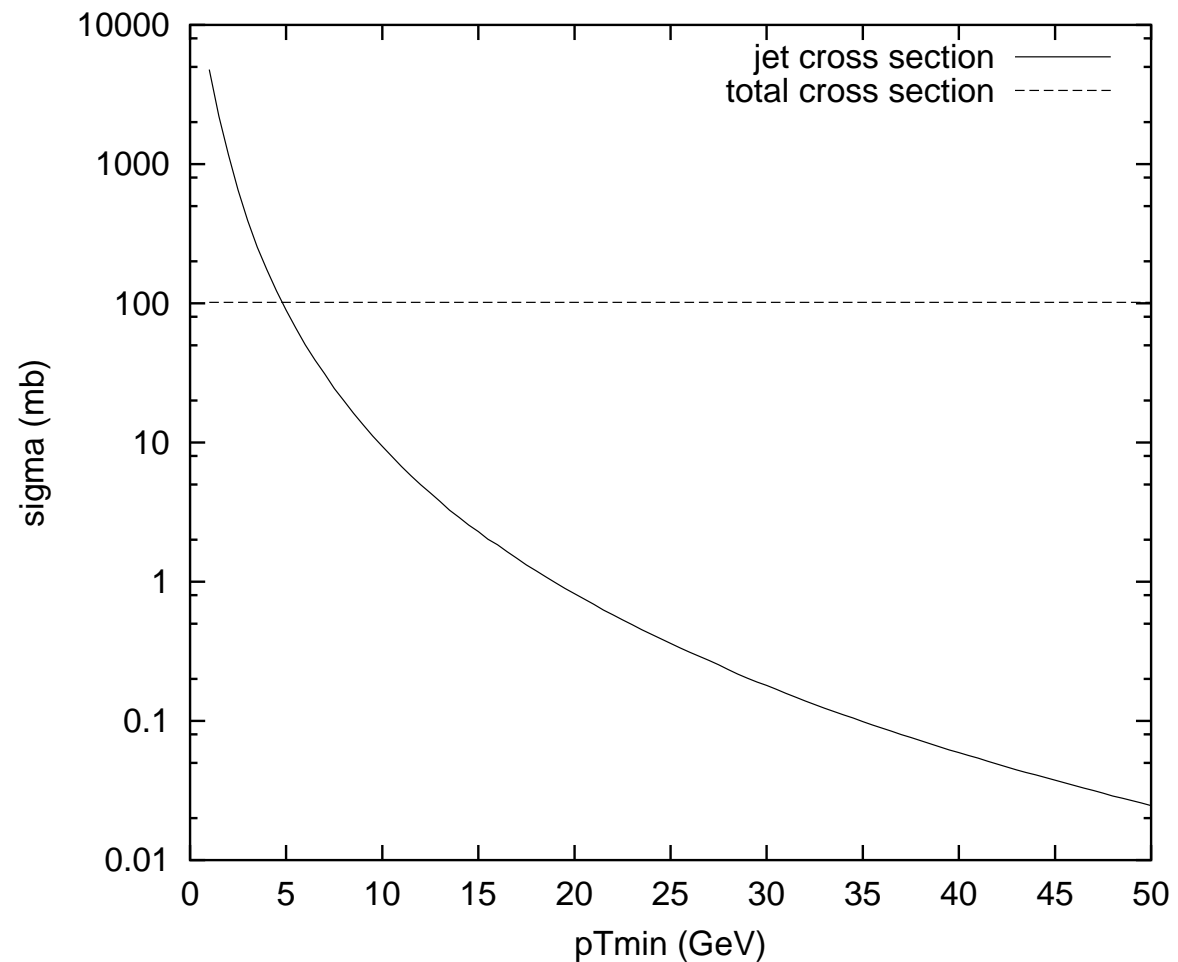
integrate QCD $2 \rightarrow 2$



$qq' \rightarrow qq'$
 $q\bar{q} \rightarrow q'\bar{q}'$
 $q\bar{q} \rightarrow gg$
 $qg \rightarrow qg$
 $gg \rightarrow gg$
 $gg \rightarrow q\bar{q}$

with CTEQ 5L PDF's

Integrated cross section above p_{Tmin} for pp at 14 TeV



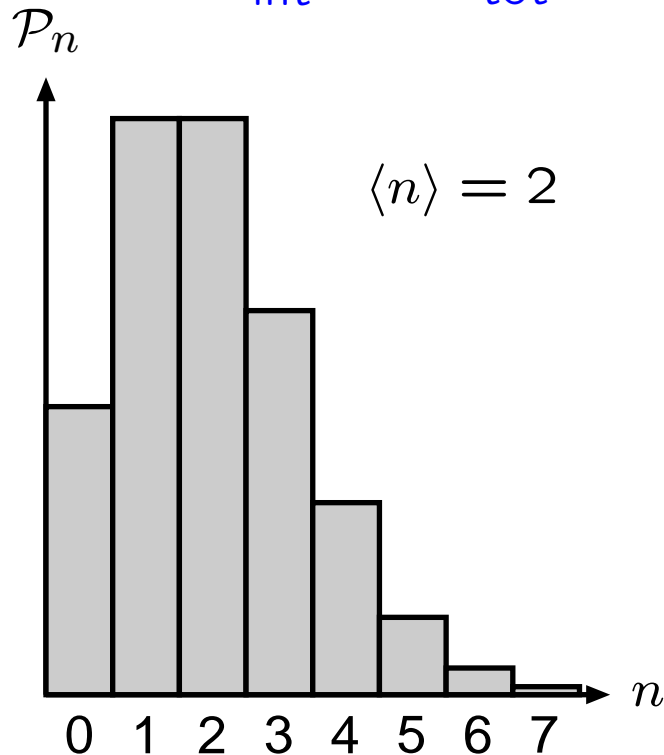
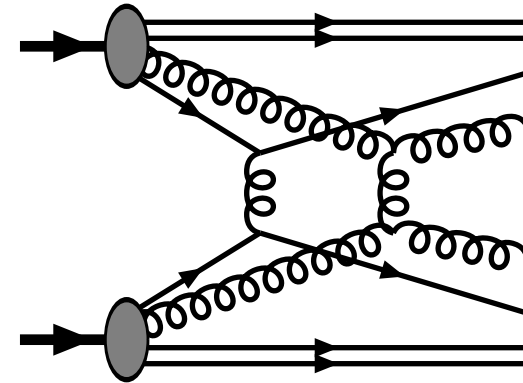
So $\sigma_{\text{int}}(p_{\perp\text{min}}) > \sigma_{\text{tot}}$ for $p_{\perp\text{min}} \lesssim 5 \text{ GeV}$

Half a solution: many interactions per event

$$\sigma_{\text{tot}} = \sum_{n=0}^{\infty} \sigma_n$$

$$\sigma_{\text{int}} = \sum_{n=0}^{\infty} n \sigma_n$$

$$\sigma_{\text{int}} > \sigma_{\text{tot}} \iff \langle n \rangle > 1$$



If interactions occur independently
then **Poissonian statistics**

$$\mathcal{P}_n = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle}$$

but energy–momentum conservation
 \Rightarrow large n suppressed

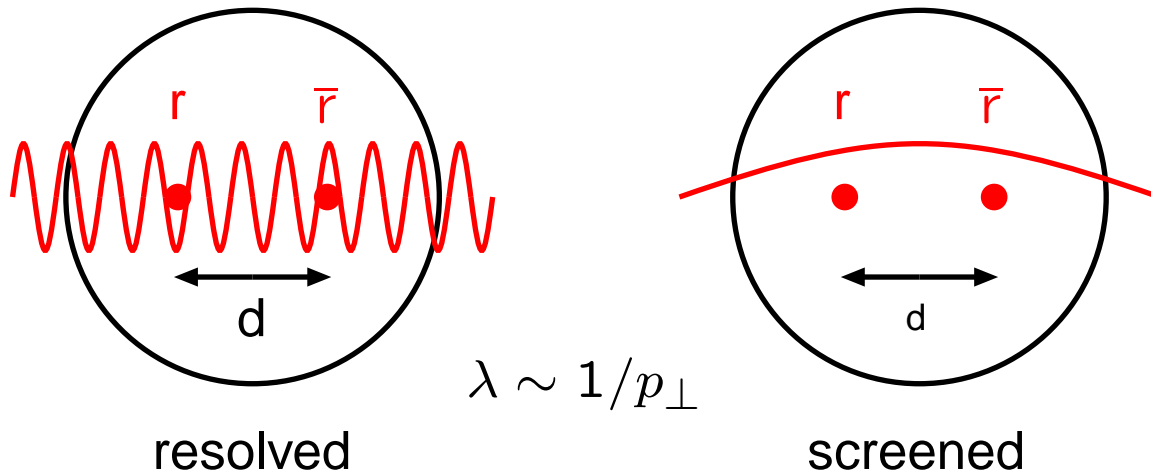
Other half of solution:

perturbative QCD not valid at small p_{\perp} since q, g not asymptotic states (confinement!).

Naively breakdown at

$$p_{\perp \text{min}} \simeq \frac{\hbar}{r_p} \approx \frac{0.2 \text{ GeV} \cdot \text{fm}}{0.7 \text{ fm}} \approx 0.3 \text{ GeV} \simeq \Lambda_{\text{QCD}}$$

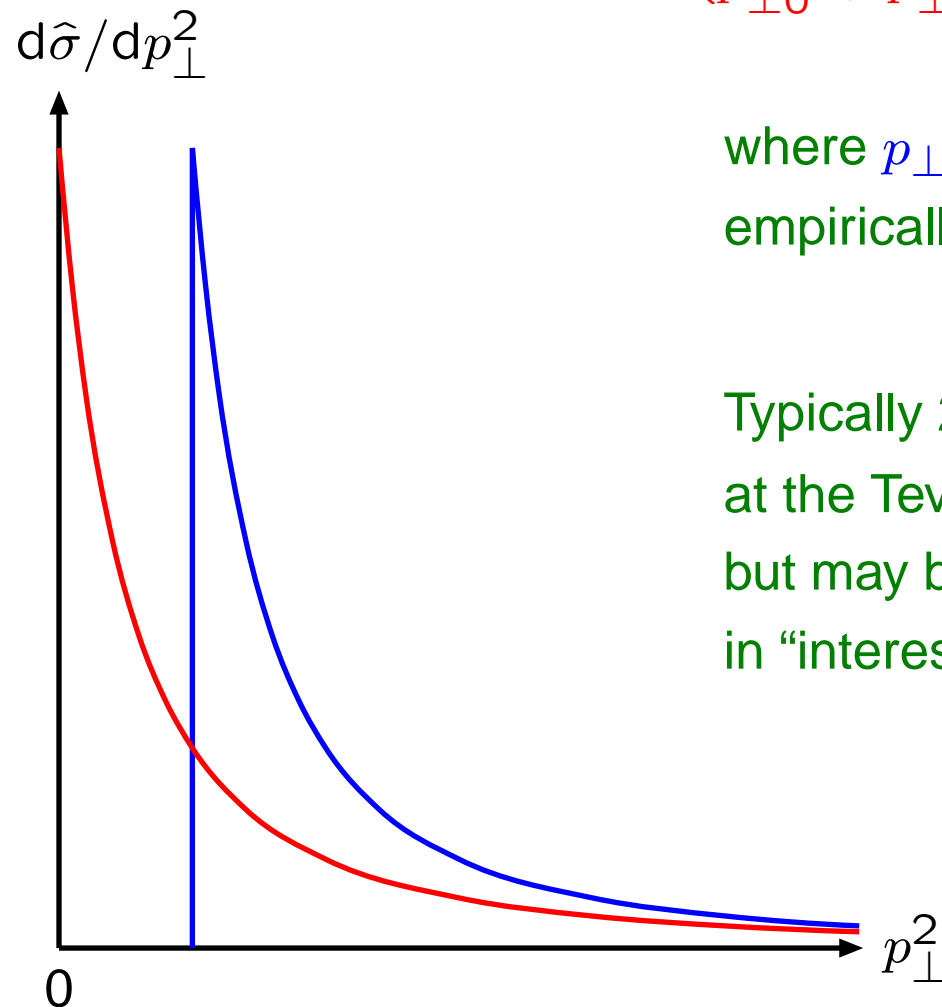
... but better replace r_p by (unknown) colour screening length d in hadron



so modify

$$\frac{d\hat{\sigma}}{dp_{\perp}^2} \propto \frac{\alpha_S^2(p_{\perp}^2)}{p_{\perp}^4} \rightarrow \frac{\alpha_S^2(p_{\perp}^2)}{p_{\perp}^4} \theta(p_{\perp} - p_{\perp\min}) \quad (\text{simpler})$$

$$\text{or} \rightarrow \frac{\alpha_S^2(p_{\perp 0}^2 + p_{\perp}^2)}{(p_{\perp 0}^2 + p_{\perp}^2)^2} \quad (\text{more physical})$$



where $p_{\perp\min}$ or $p_{\perp 0}$ are free parameters,
empirically of order **2 GeV**

Typically 2 – 3 interactions/event
at the Tevatron, 4 – 5 at the LHC,
but may be more
in “interesting” high- p_{\perp} ones.

Modelling multiple interactions

T. Sjöstrand, M. van Zijl, PRD36 (1987) 2019: first model(s)
for event properties based on perturbative multiple interactions

(1) Simple scenario:

- Sharp cut-off at $p_{\perp \min}$ main free parameter
- Is only a model for nondiffractive events, i.e. for $\sigma_{\text{nd}} \simeq (2/3)\sigma_{\text{tot}}$
- Average number of interactions is $\langle n \rangle = \sigma_{\text{int}}(p_{\perp \min})/\sigma_{\text{nd}}$
- Interactions occur almost independently, i.e.
Poissonian statistics $\mathcal{P}_n = \langle n \rangle^n e^{-\langle n \rangle} / n!$
with fraction $\mathcal{P}_0 = e^{-\langle n \rangle}$ pure low- p_{\perp} events
- Interactions generated in ordered sequence $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > \dots$
by “Sudakov” trick (what happens “first”?)

$$\frac{d\mathcal{P}}{dp_{\perp i}} = \frac{1}{\sigma_{\text{nd}}} \frac{d\sigma}{dp_{\perp}} \exp \left[- \int_{p_{\perp}}^{p_{\perp(i-1)}} \frac{1}{\sigma_{\text{nd}}} \frac{d\sigma}{dp'_{\perp}} dp'_{\perp} \right]$$

- Momentum conservation in PDF's $\Rightarrow \mathcal{P}_n$ narrower than Poissonian
- Simplify after first interaction: only gg or $q\bar{q}$ outgoing, no showers, ...

(2) More sophisticated scenario:

- Smooth turn-off at $p_{\perp 0}$ scale
- Require ≥ 1 interaction in an event
- Hadrons are extended,
e.g. double Gaussian (“hot spots”):

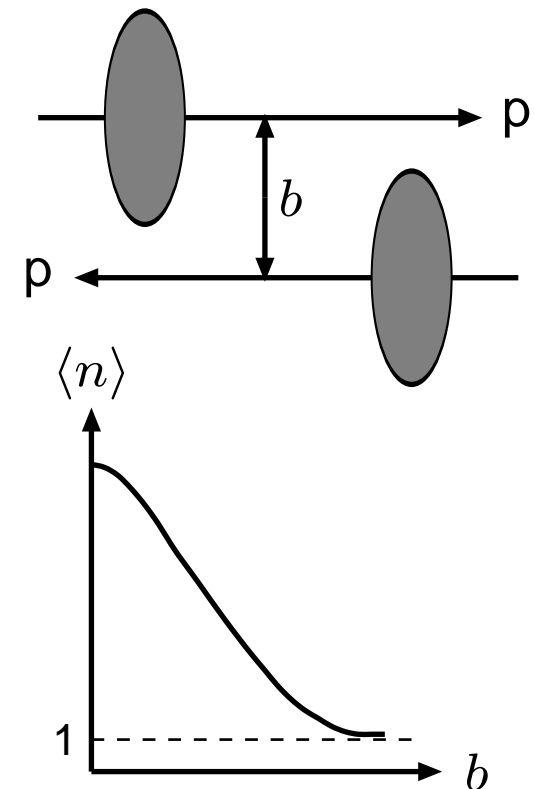
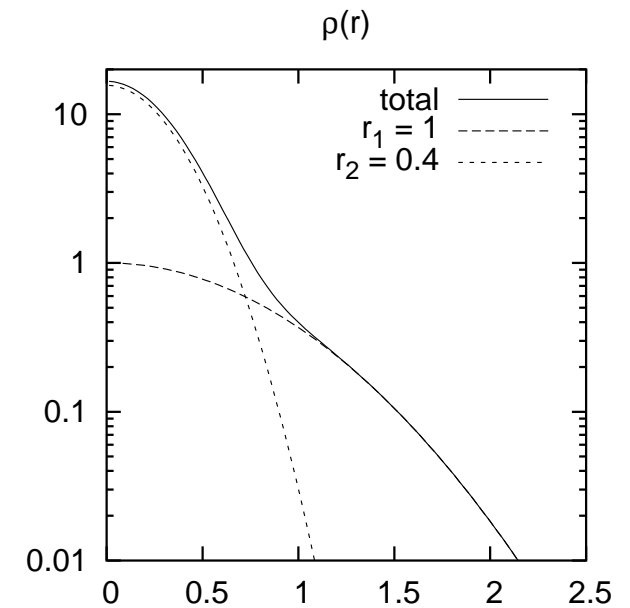
$$\rho_{\text{matter}}(r) = N_1 \exp\left(-\frac{r^2}{r_1^2}\right) + N_2 \exp\left(-\frac{r^2}{r_2^2}\right)$$

where $r_2 \neq r_1$ represents “hot spots”

- Events are distributed in impact parameter b
- Overlap of hadrons during collision

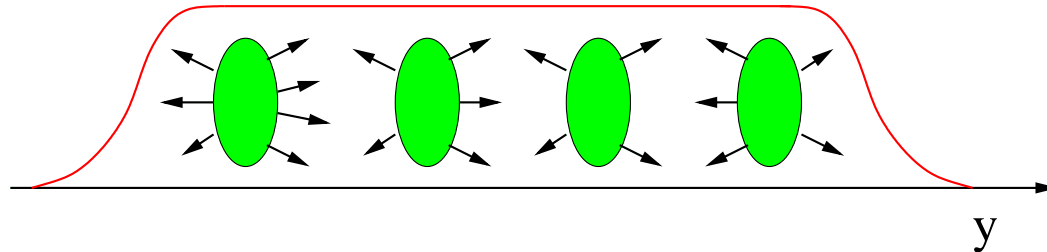
$$\mathcal{O}(b) = \int d^3\mathbf{x} dt \rho_{1,\text{matter}}^{\text{boosted}}(\mathbf{x}, t) \rho_{2,\text{matter}}^{\text{boosted}}(\mathbf{x}, t)$$

- Average activity at b proportional to $\mathcal{O}(b)$
 \Rightarrow central collisions normally more active
 $\Rightarrow \mathcal{P}_n$ broader than Poissonian
- More time-consuming (b, p_{\perp}) generation
- Need for simplifications remains



(3) HERWIG

Soft Underlying Event (SUE), based on UA5 Monte Carlo



- Distribute a (\sim negative binomial) number of clusters independently in rapidity and transverse momentum according to parametrization/extrapolation of data
- modify for overall energy/momentum/flavour conservation
- no minijets; correlations only by cluster decays

(4) Jimmy (HERWIG add-on)

- similar to **PYTHIA (2)** above; but details different
- matter profile by electromagnetic form factor
- no p_{\perp} -ordering of emissions, no rescaling of PDF: abrupt stop when (if) run out of energy

(5) Phojet/DTUjet

- comes from “historical” tradition of soft physics of “cut Pomerons” $\approx p_{\perp} \rightarrow 0$ limit of multiple interactions
- extended also to “hard” interactions similarly to PYTHIA

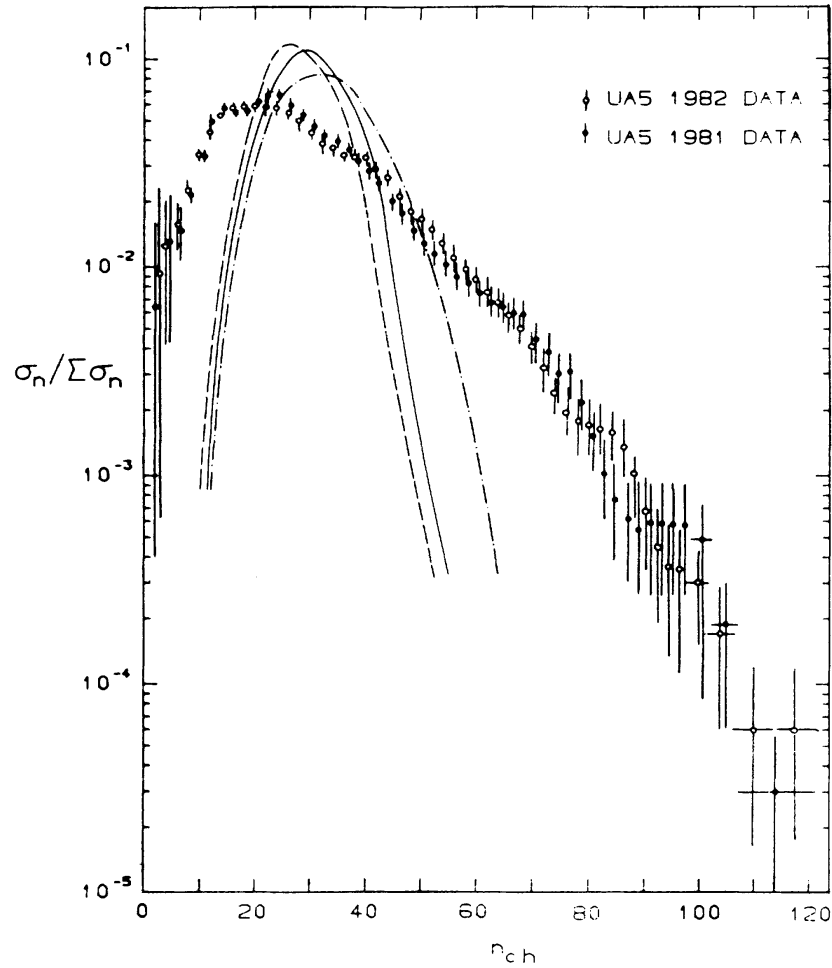


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

without multiple interactions

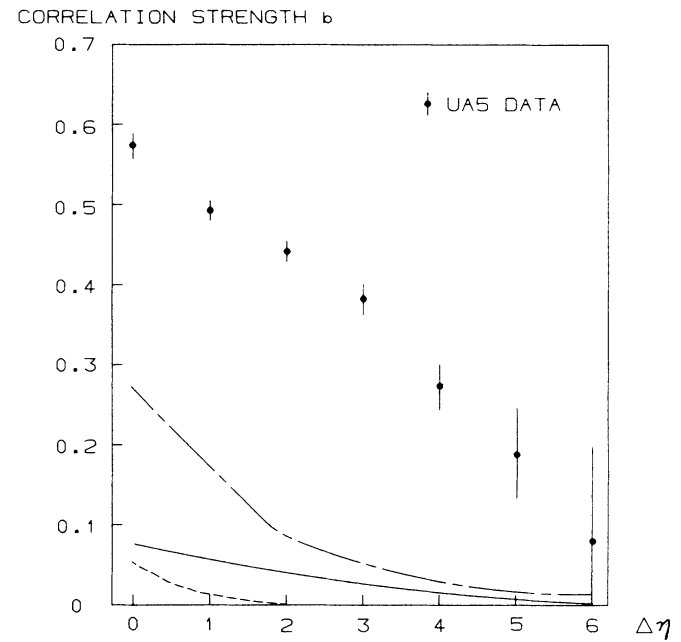


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

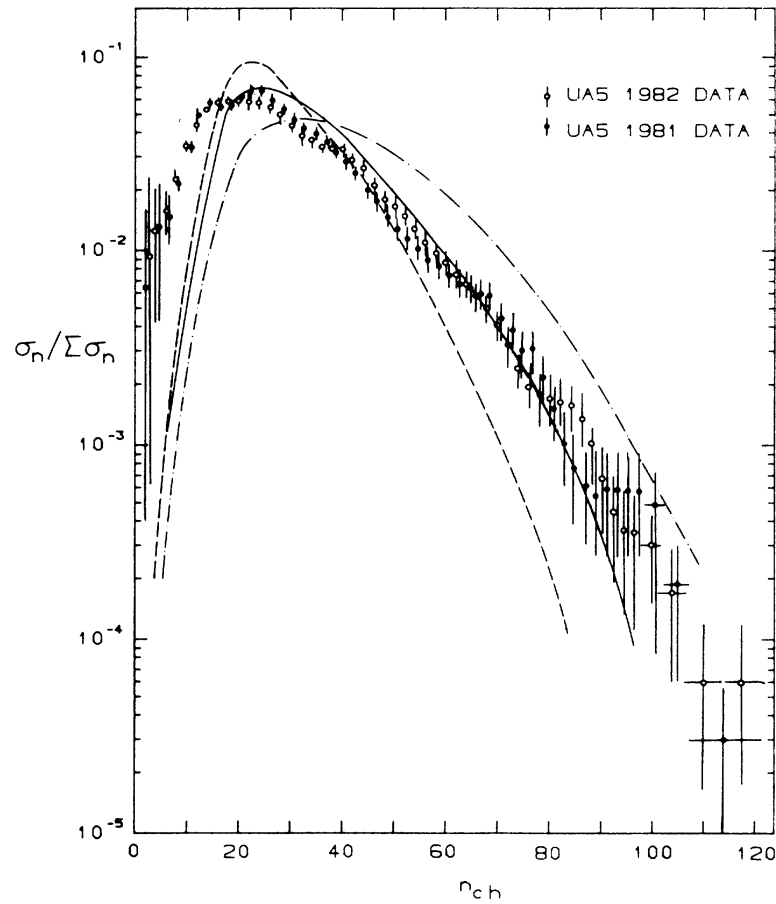


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{Tmin}=2.0$ GeV; solid line, $p_{Tmin}=1.6$ GeV; dashed-dotted line, $p_{Tmin}=1.2$ GeV.

with multiple interactions

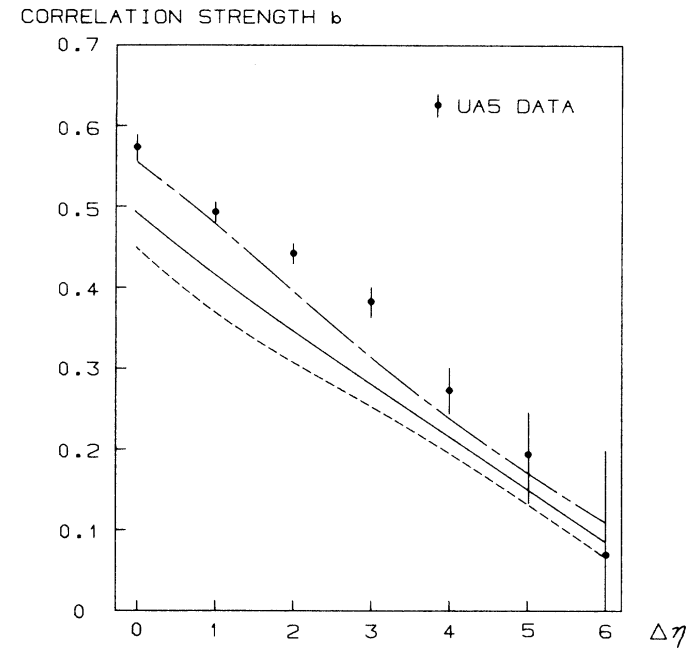


FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

Evidence for multiple interactions

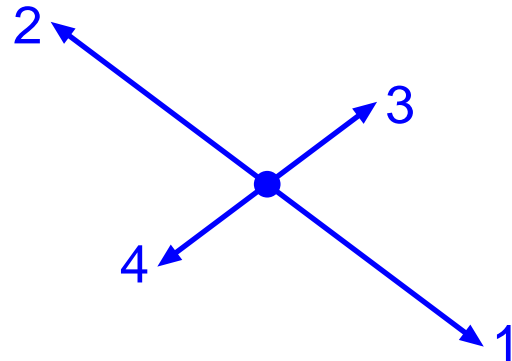
- Width of multiplicity distribution: UA5, E735
(previous slides)
- Forward–backward correlations: UA5
(previous slides)
- Minijet rates: UA1

No. jets	UA1 (%)	no MI	simple	double Gaussian
1	9.96	14.30	11.51	8.88
2	3.45	2.45	2.45	2.67
3	1.12	0.22	0.32	0.74
4	0.22	0.01	0.04	0.25
5	0.05	0.00	0.00	0.07

- Direct observation: AFS, (UA2,) CDF

Order 4 jets $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > p_{\perp 4}$ and define φ as angle between $p_{\perp 1} - p_{\perp 2}$ and $p_{\perp 3} - p_{\perp 4}$

Double Parton Scattering

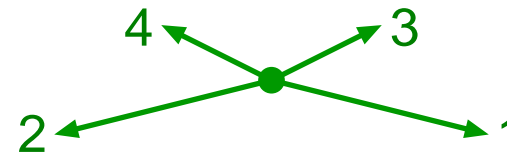


$$|p_{\perp 1} + p_{\perp 2}| \approx 0$$

$$|p_{\perp 3} + p_{\perp 4}| \approx 0$$

$d\sigma/d\varphi$ flat

Double BremsStrahlung



$$|p_{\perp 1} + p_{\perp 2}| \gg 0$$

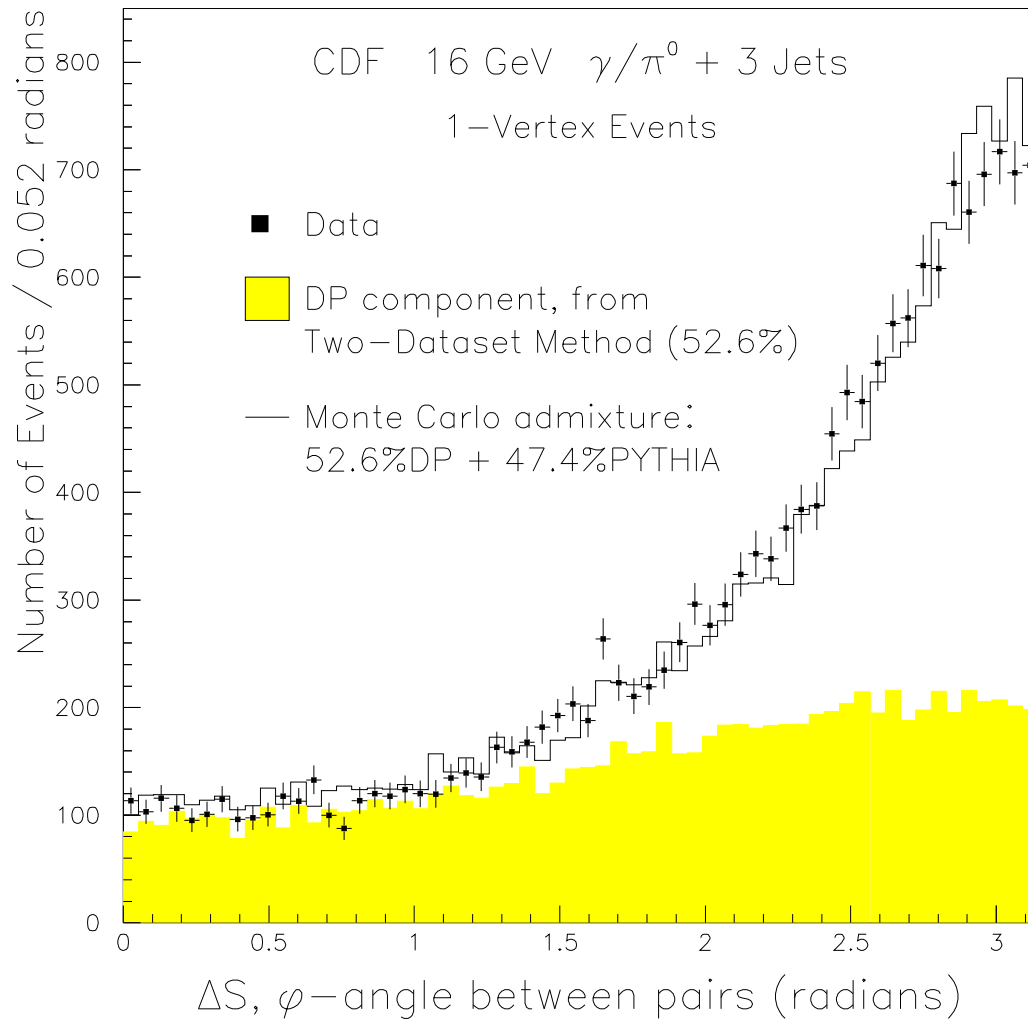
$$|p_{\perp 3} + p_{\perp 4}| \gg 0$$

$d\sigma/d\varphi$ peaked at $\varphi \approx 0$

AFS 4-jet analysis (pp at 63 GeV);

double bremsstrahlung subtracted:

observed	6	in arbitrary units
no MI	0	
simple MI	1	
double Gaussian	3.7	



CDF 3-jet + prompt photon analysis

Yellow region = double parton scattering (DPS)

The rest = PYTHIA showers

$$\sigma_{\text{DPS}} = \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \quad \text{for } A \neq B \quad \Rightarrow \quad \sigma_{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3} \text{ mb}$$

Strong enhancement relative to naive expectations!

- Jet pedestal effect: UA1, H1, CDF

Events with hard scale (jet, W/Z, ...) have more underlying activity!

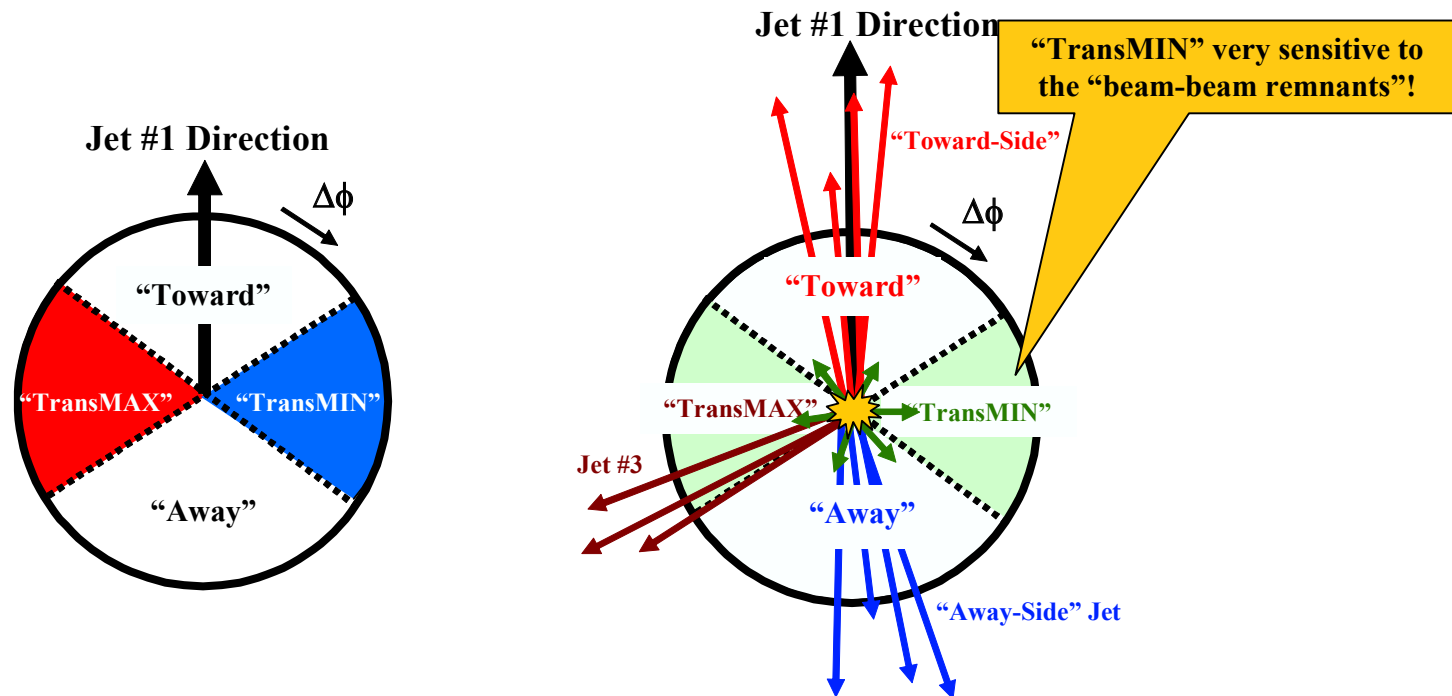
Events with n interactions have n chances that one of them is hard, so “trigger bias”: hard scale \Rightarrow central collision

\Rightarrow more interactions \Rightarrow larger underlying activity.

Centrality effect saturates at $p_{\perp\text{hard}} \sim 10$ GeV.

Studied in detail by Rick Field, comparing with CDF data:

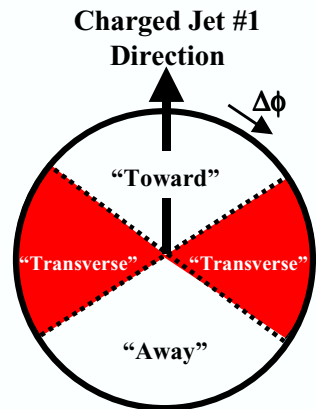
“MAX/MIN Transverse” Densities



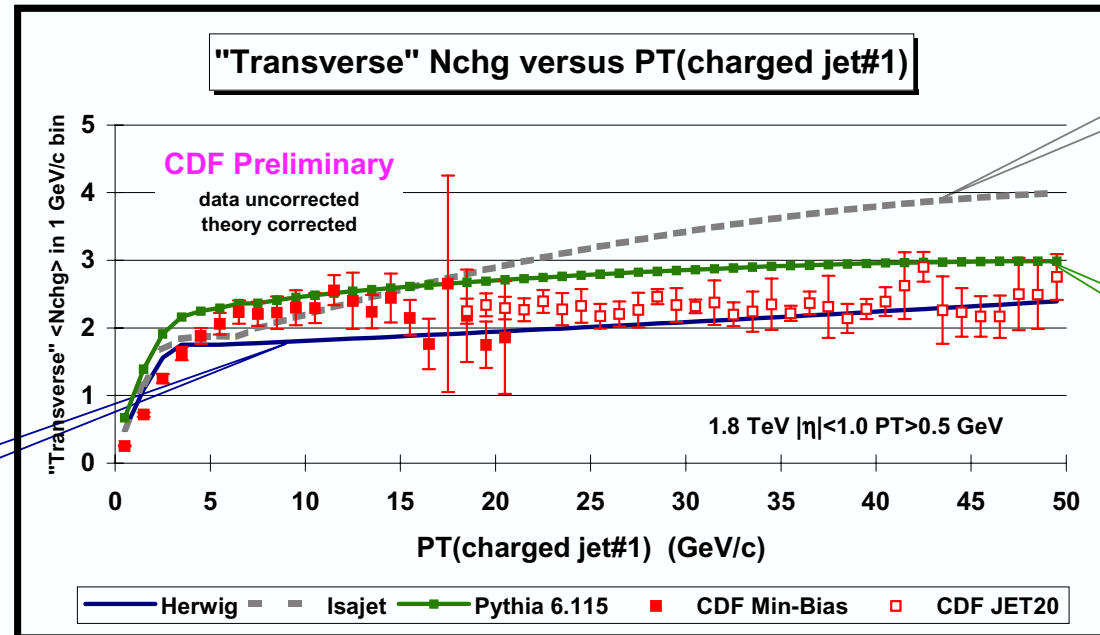
- Define the **MAX and MIN “transverse” regions** on an event-by-event basis with MAX (MIN) having the largest (smallest) density.



“Transverse” Nchg versus $P_T(\text{chgjet\#1})$



Herwig 5.9



Isajet 7.32

Pythia 6.115

- ➔ Plot shows the “Transverse” $\langle N_{\text{chg}} \rangle$ versus $P_T(\text{chgjet\#1})$ compared to the the QCD hard scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115 (default parameters with $P_T(\text{hard}) > 3$ GeV/c).
- ➔ Only charged particles with $|\eta| < 1$ and $P_T > 0.5$ GeV are included and the QCD Monte-Carlo predictions have been corrected for efficiency.



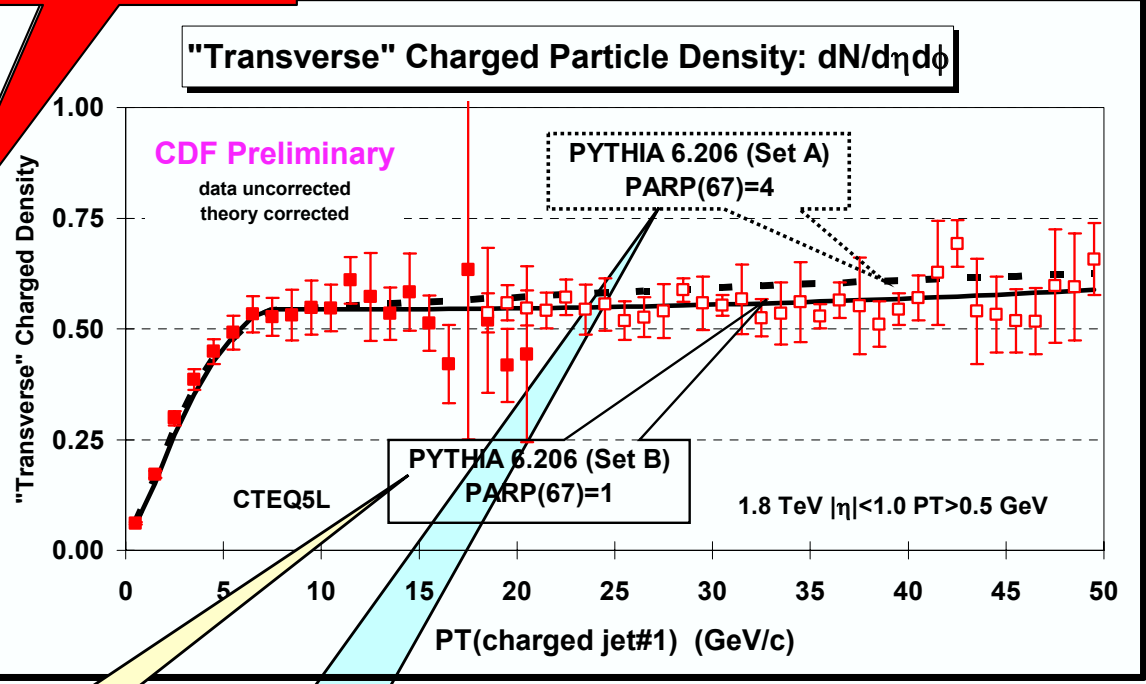
Tuned PYTHIA 6.206



**Tune A CDF
Run 2 Default!**

PYTHIA 6.206 CTEQ5L

Parameter	Tune B	Tune A
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	1.9 GeV	2.0 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	1.0	0.9
PARP(86)	1.0	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(67)	1.0	4.0



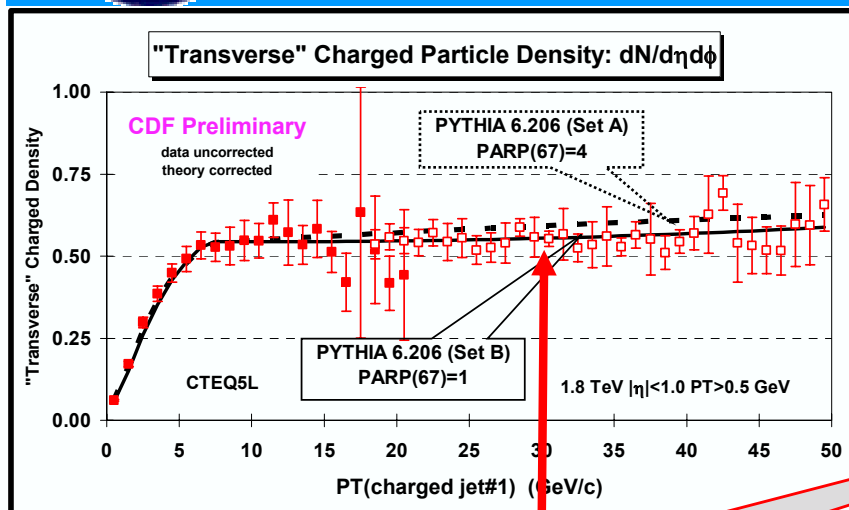
Plot shows the "Transverse" charged particle density versus $P_T(\text{chgjet}\#1)$ compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

New PYTHIA default
(less initial-state radiation)

Old PYTHIA default
(more initial-state radiation)

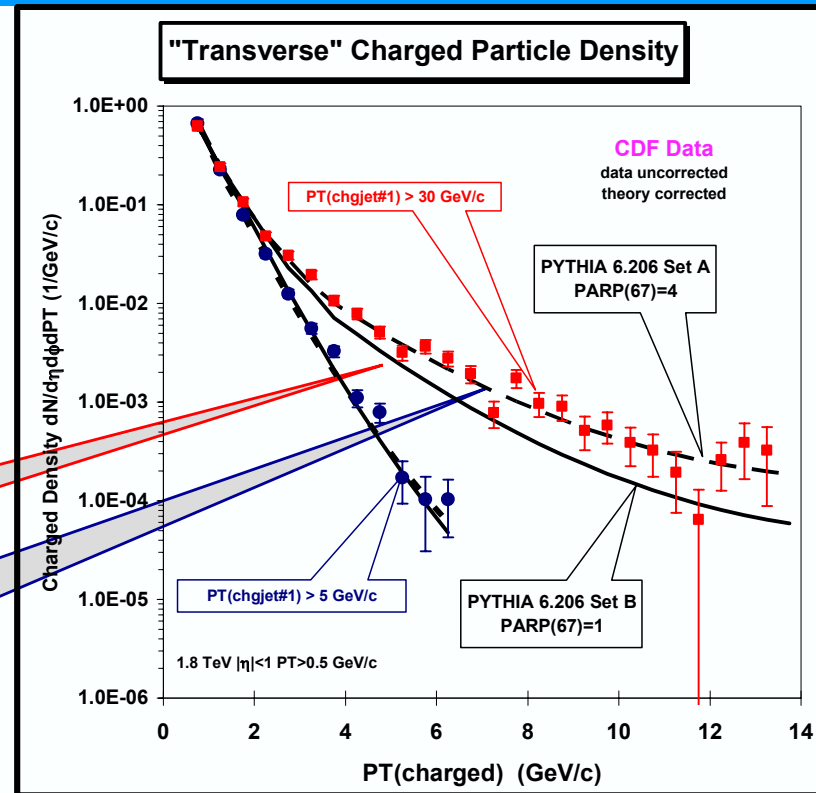


Tuned PYTHIA 6.206 "Transverse" P_T Distribution



$P_T(\text{charged jet\#1}) > 30$ GeV/c

PARP(67)=4.0 (old default) is favored over PARP(67)=1.0 (new default)!

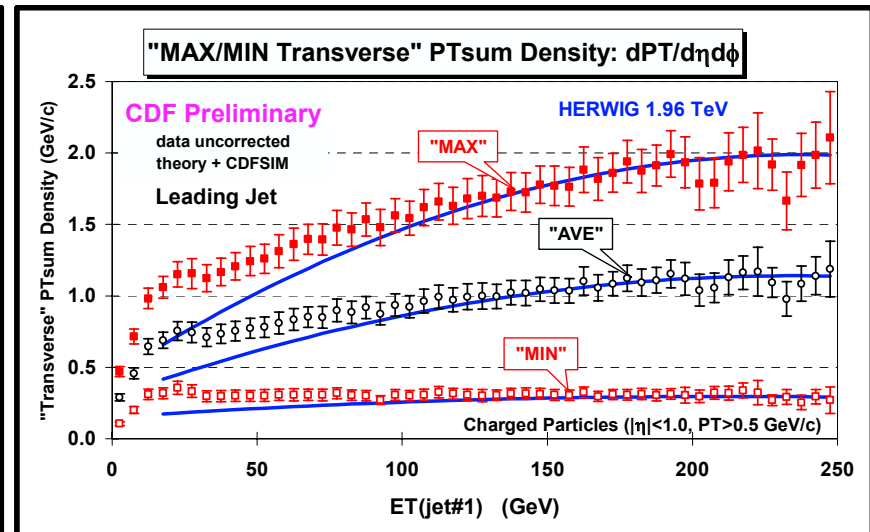
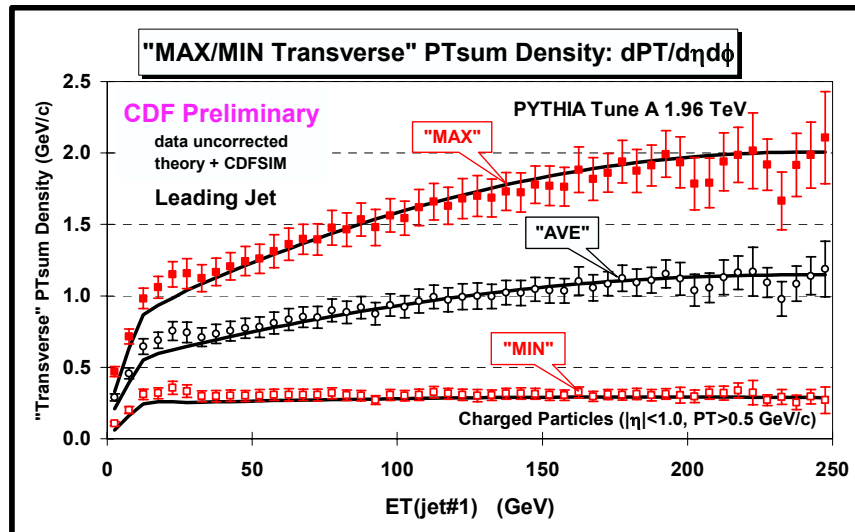
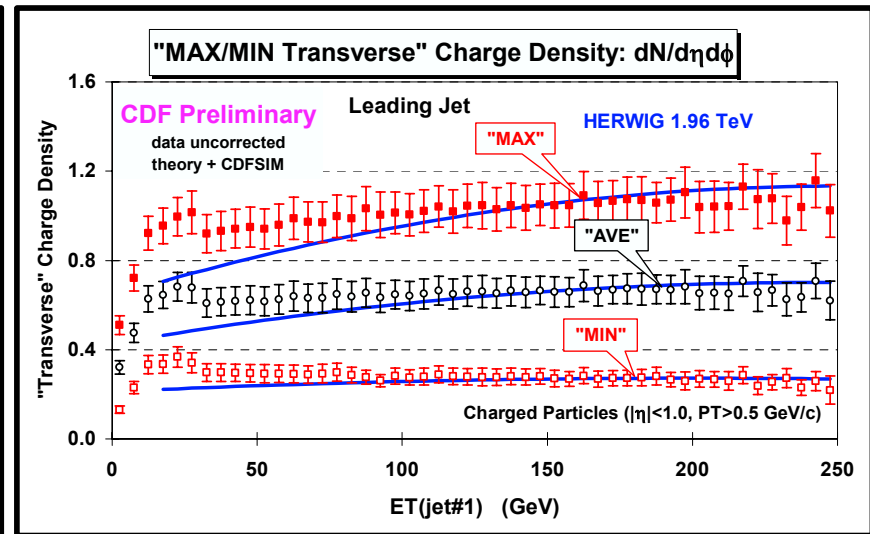
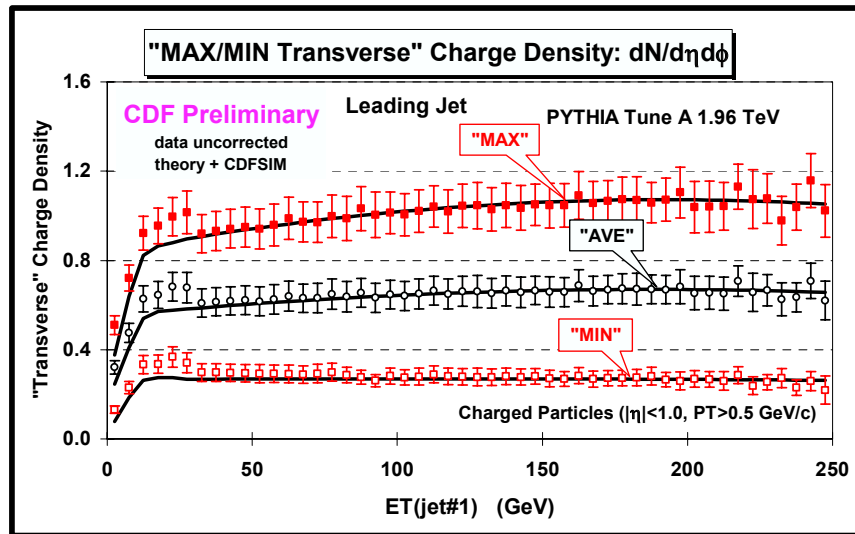


- ➔ Compares the average "transverse" charge particle density ($|\eta| < 1$, $P_T > 0.5$ GeV) versus $P_T(\text{charged jet\#1})$ and the P_T distribution of the "transverse" density, $dN_{\text{chg}}/d\eta d\phi dP_T$ with the QCD Monte-Carlo predictions of two **tuned** versions of **PYTHIA 6.206** ($P_T(\text{hard}) > 0$, CTEQ5L, **Set B** (PARP(67)=1) and **Set A** (PARP(67)=4)).

Leading Jet: "MAX & MIN Transverse" Densities

PYTHIA Tune A

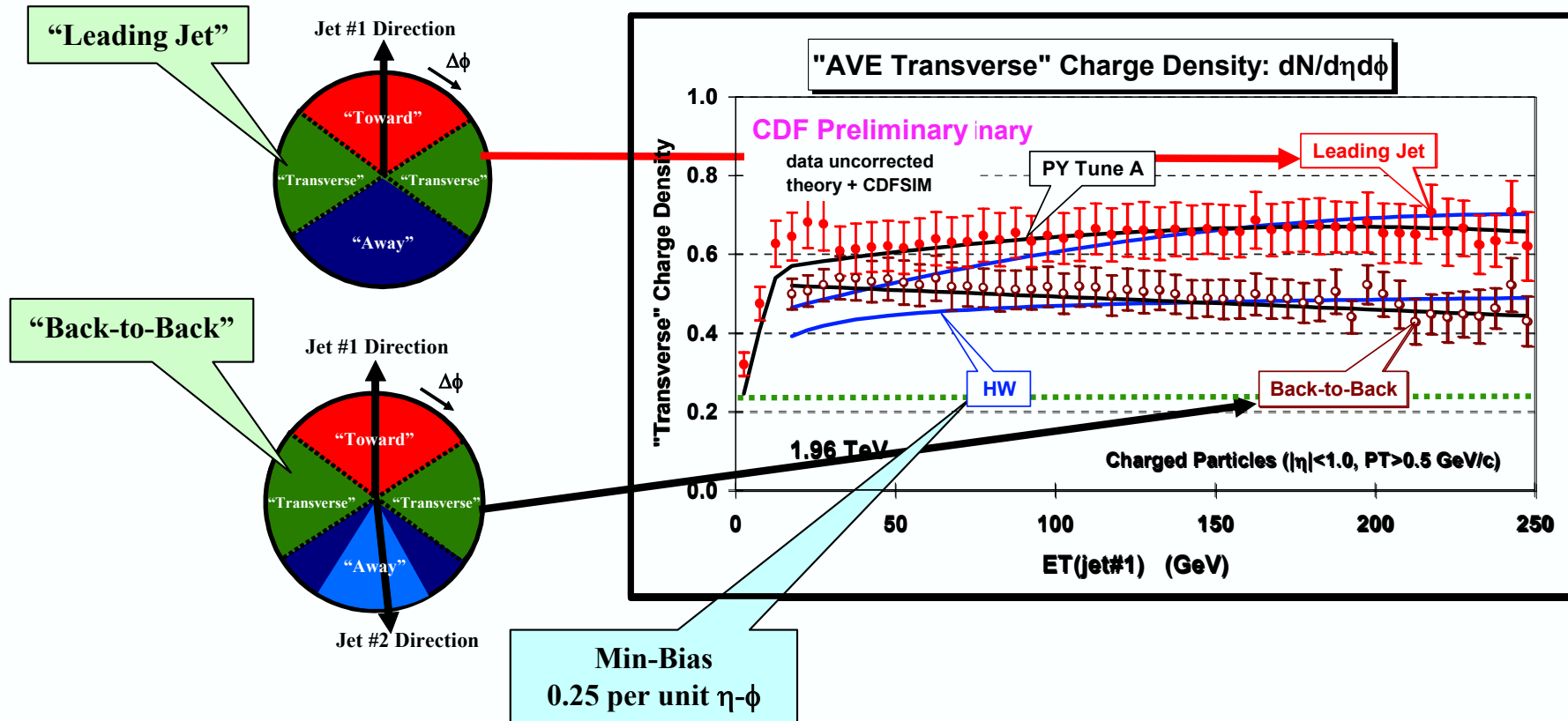
HERWIG



Charged particle density and PTsum density for "leading jet" events versus $E_T(\text{jet}\#1)$ for PYTHIA Tune A and HERWIG.



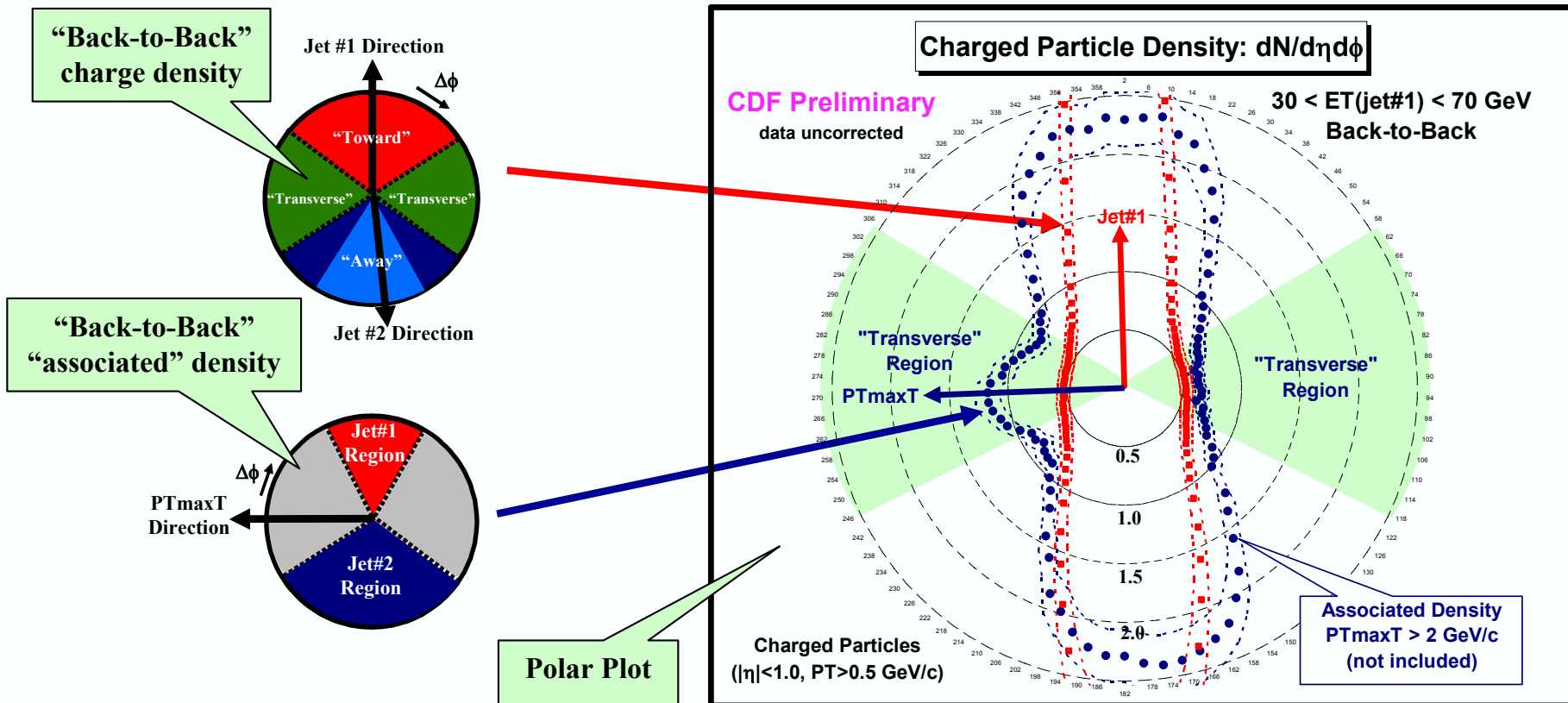
“Transverse” Charge Density versus $E_T(\text{jet}\#1)$



- ➔ Shows the **average charged particle density**, $dN_{\text{chg}}/d\eta d\phi$, in the “transverse” region ($p_T > 0.5 \text{ GeV}/c$, $|\eta| < 1$) versus $E_T(\text{jet}\#1)$ for “Leading Jet” and “Back-to-Back” events.
- ➔ Compares the (*uncorrected*) data with **PYTHIA Tune A** and **HERWIG** after CDFSIM.



Back-to-Back “Associated” Charged Particle Densities

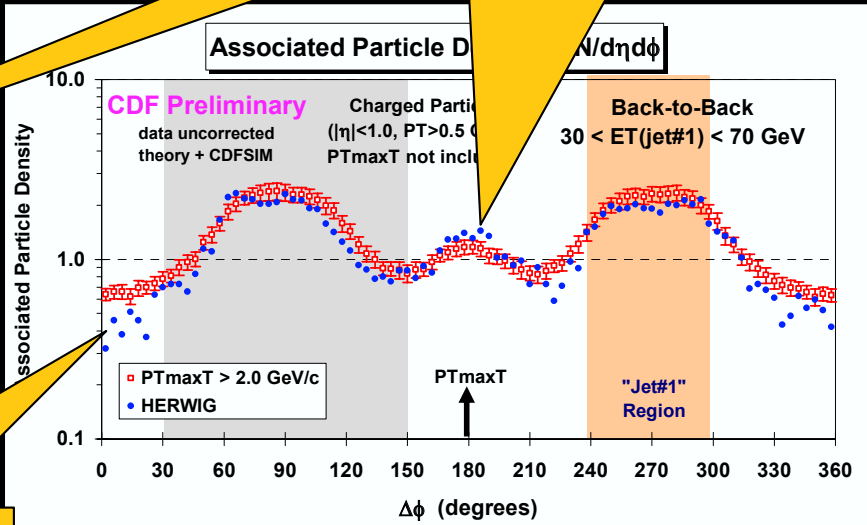
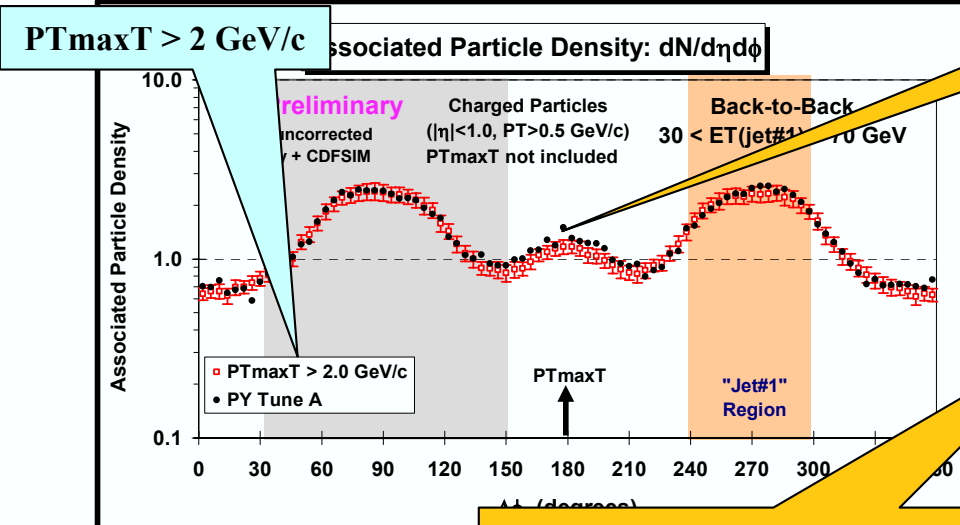


➔ Shows the $\Delta\phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, $PT_{\text{maxT}} > 2.0$ GeV/c (not including PT_{maxT}) relative to PT_{maxT} (rotated to 180°) and the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270°) for “back-to-back events” with $30 < E_T(\text{jet}\#1) < 70$ GeV.

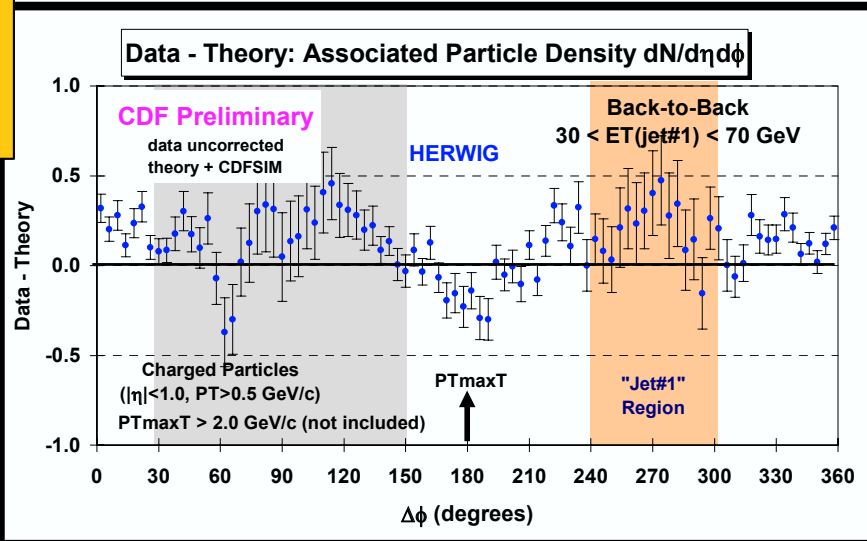
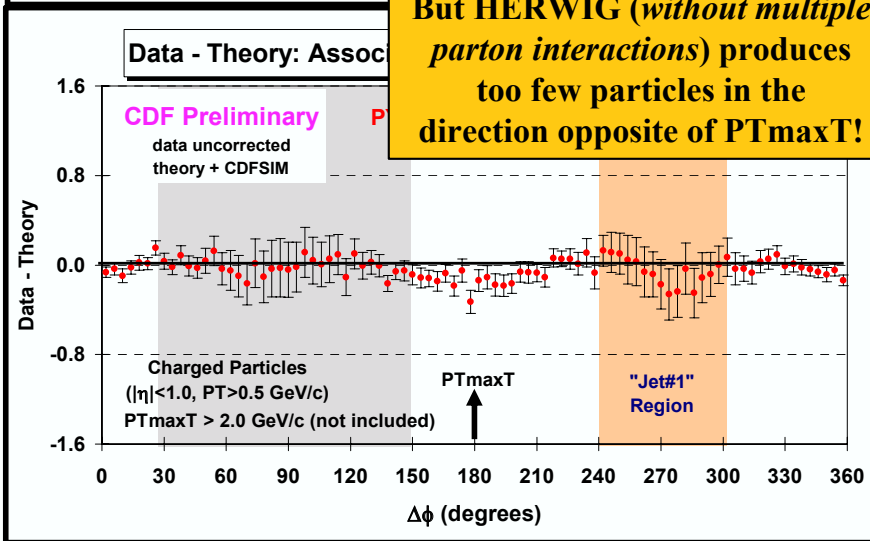


“Associated” Charge Density PYTHIA Tune A vs HERWIG

For $PT_{maxT} > 2.0$ GeV both PYTHIA and HERWIG produce slightly too many “associated” particles in the direction of PT_{maxT} !

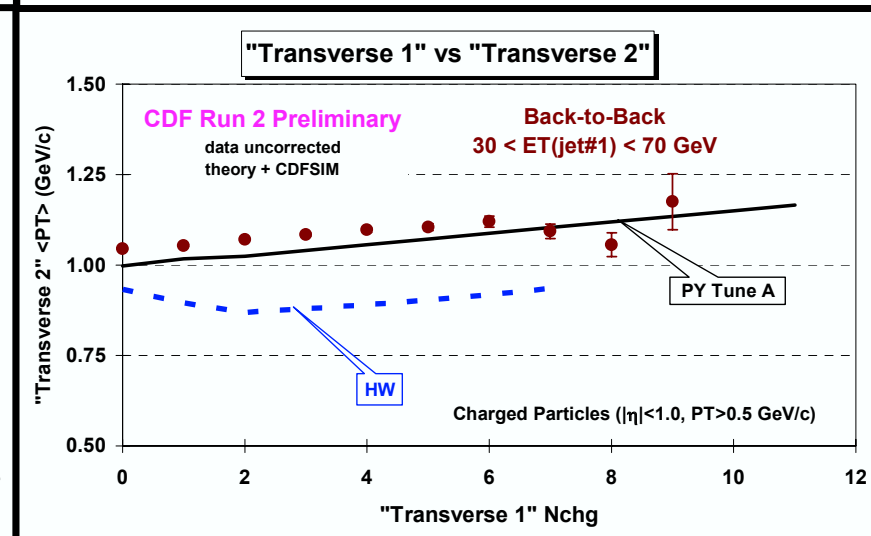
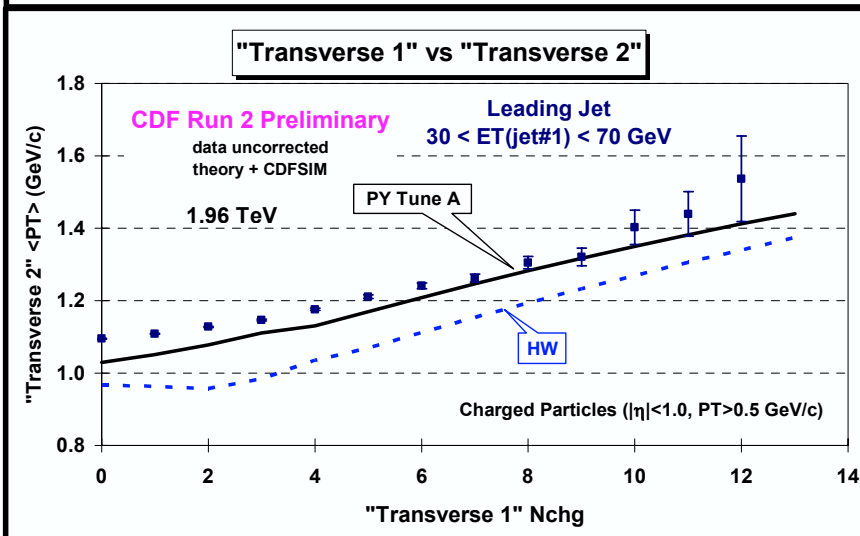
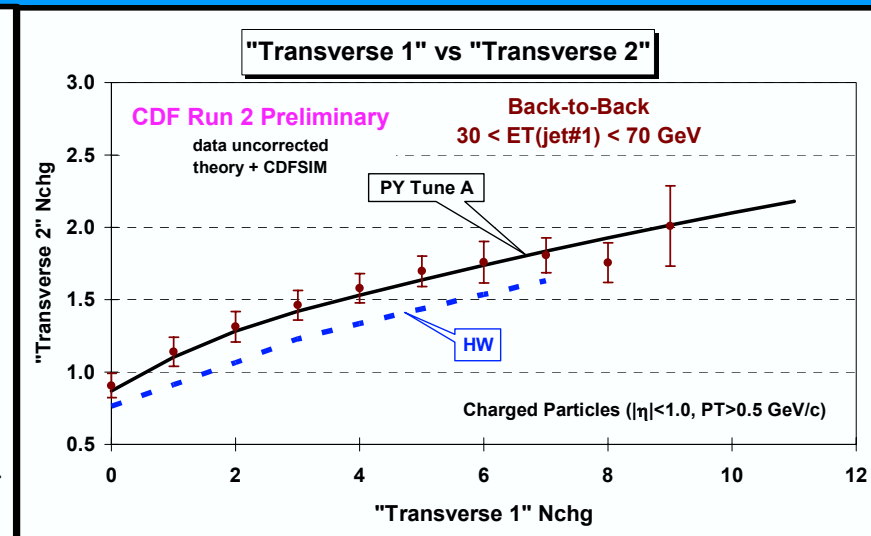
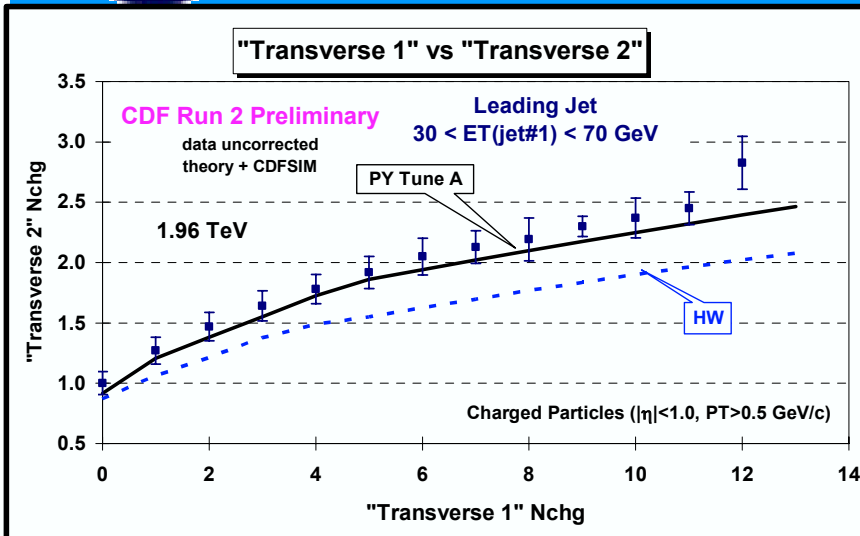


But HERWIG (without multiple parton interactions) produces too few particles in the direction opposite of PT_{maxT} !

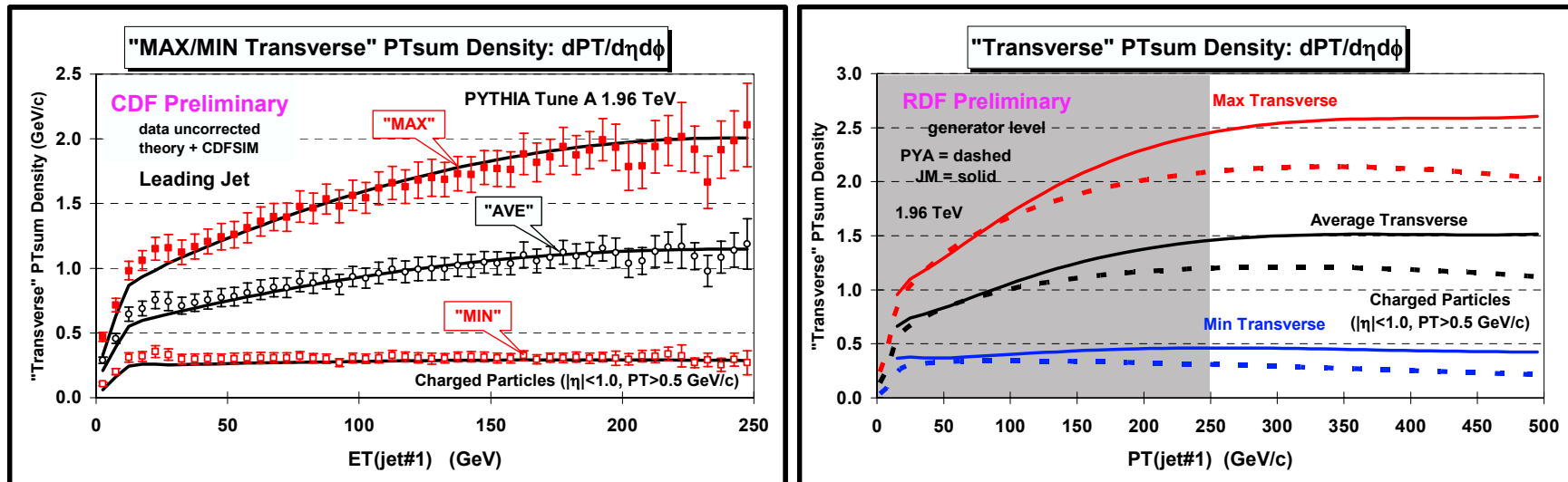




“Transverse 1” Region vs “Transverse 2” Region



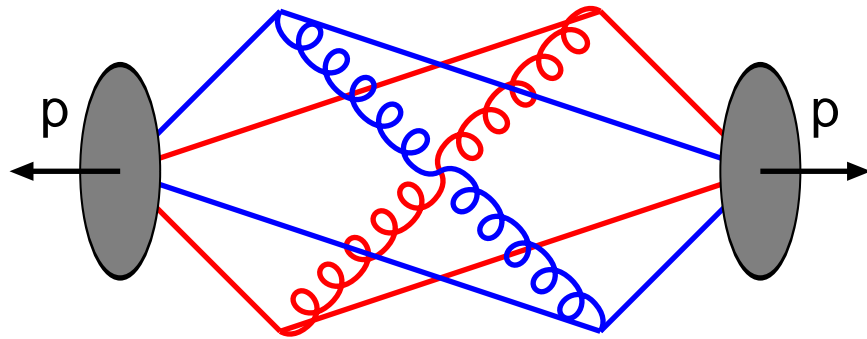
PYTHIA Tune A vs JIMMY: “Transverse Region”



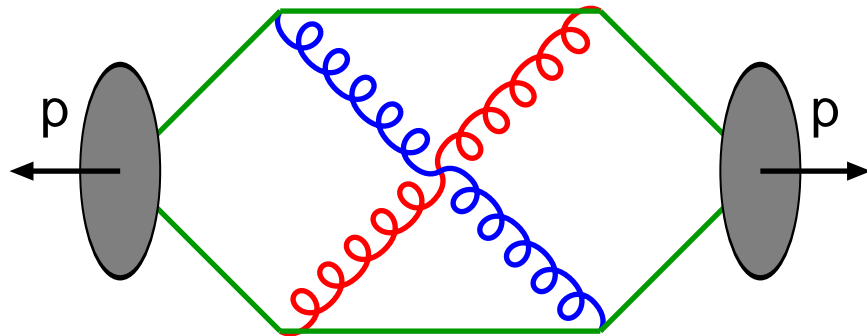
- (left) Run 2 data for charged *scalar* PTsum density ($|\eta| < 1, p_T > 0.5$ GeV/c) in the MAX/MIN/AVE “transverse” region versus $P_T(jet\#1)$ compared with PYTHIA Tune A (after CDFSIM).
- (right) Shows the generator level predictions of PYTHIA Tune A (dashed) and JIMMY ($P_{Tmin} = 1.8$ GeV/c) for charged *scalar* PTsum density ($|\eta| < 1, p_T > 0.5$ GeV/c) in the MAX/MIN/AVE “transverse” region versus $P_T(jet\#1)$.
- The tuned JIMMY now agrees with PYTHIA for $P_T(jet\#1) < 100$ GeV but produces much more activity than PYTHIA Tune A (and the data?) in the “transverse” region for $P_T(jet\#1) > 100$ GeV!

Colour correlations

$\langle p_{\perp} \rangle(n_{ch})$ is very sensitive to colour flow



long strings to remnants \Rightarrow much $n_{ch}/\text{interaction} \Rightarrow \langle p_{\perp} \rangle(n_{ch}) \sim \text{flat}$



short strings (more central) \Rightarrow less $n_{ch}/\text{interaction} \Rightarrow \langle p_{\perp} \rangle(n_{ch})$ rising

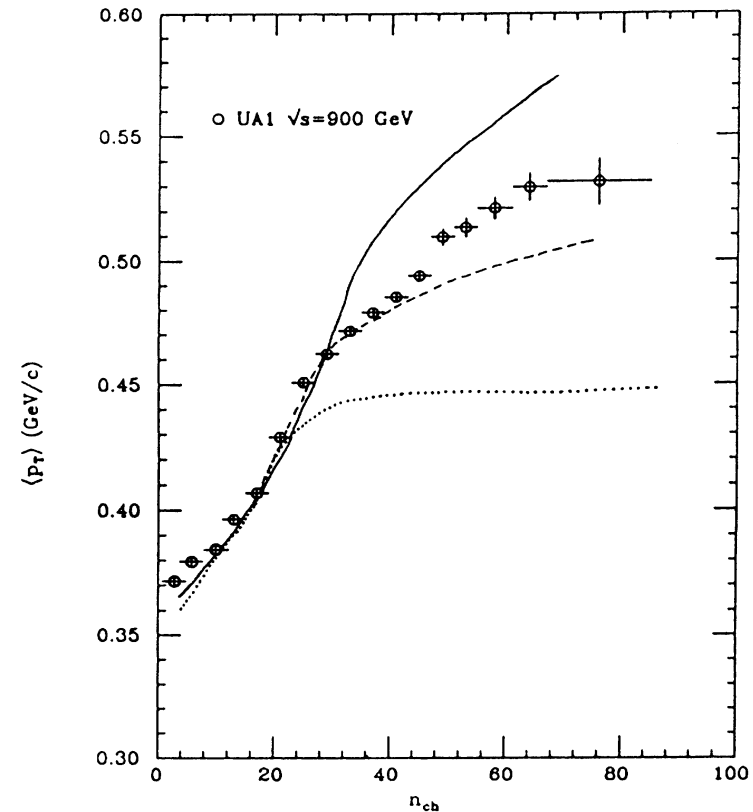
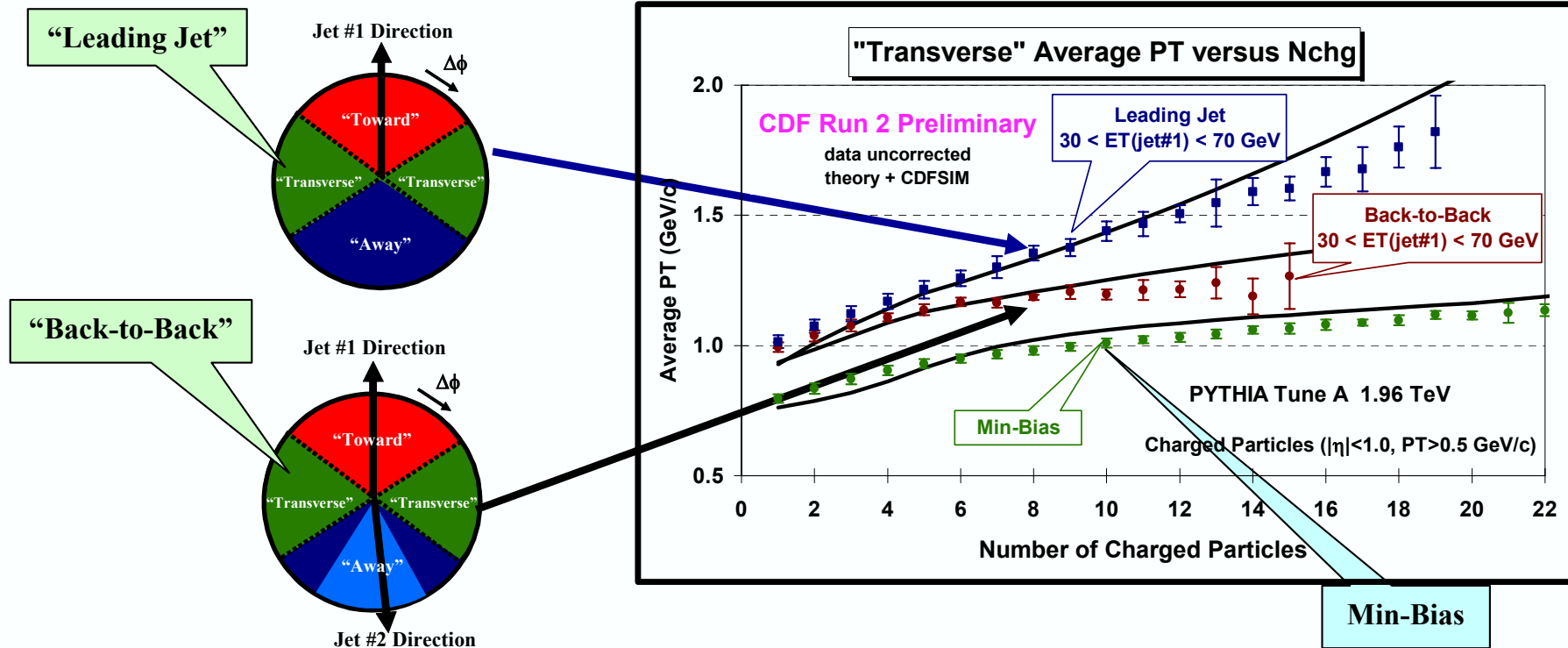


FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings only; dotted line, gg scatterings with “maximal” string length; solid line gg scatterings with “minimal” string length.

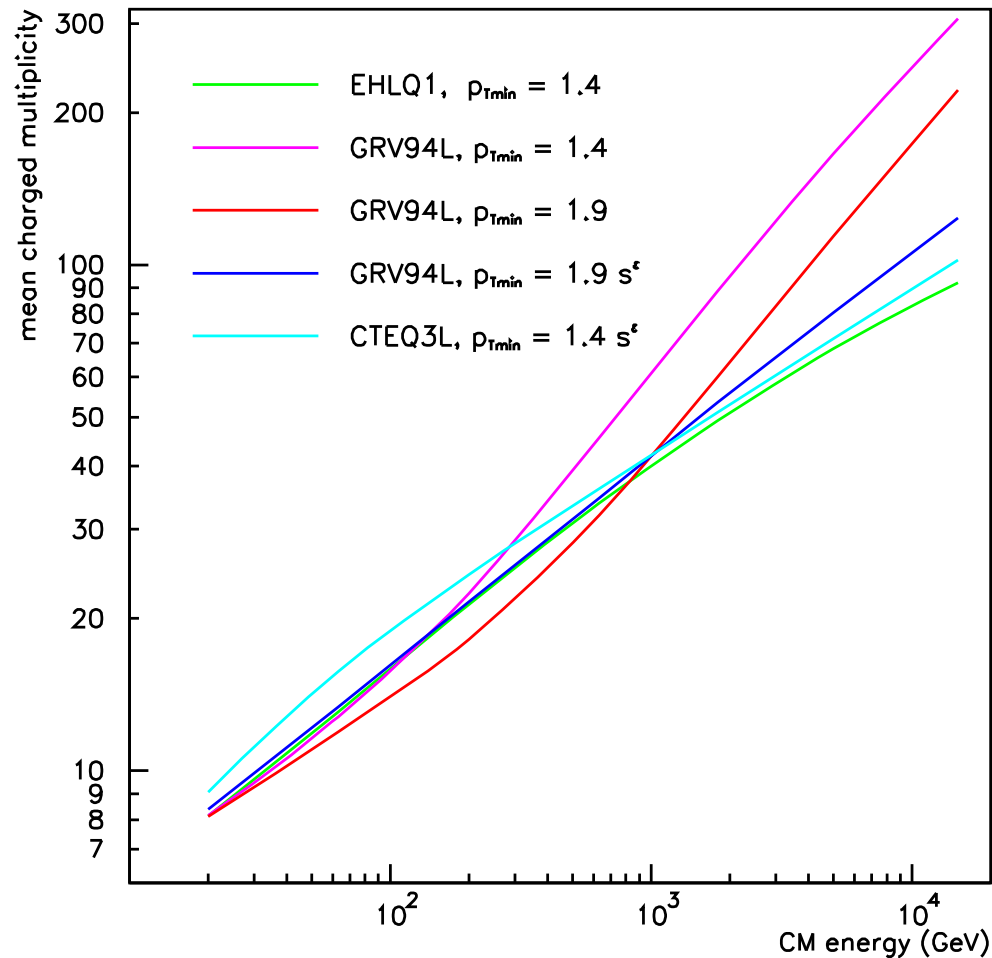


“Transverse” $\langle p_T \rangle$ versus “Transverse” N_{chg}



- ➔ Look at the $\langle p_T \rangle$ of particles in the “transverse” region ($p_T > 0.5 \text{ GeV}/c, |\eta| < 1$) versus the number of particles in the “transverse” region: $\langle p_T \rangle$ vs N_{chg} .
- ➔ Shows $\langle p_T \rangle$ versus N_{chg} in the “transverse” region ($p_T > 0.5 \text{ GeV}/c, |\eta| < 1$) for “Leading Jet” and “Back-to-Back” events with $30 < E_T(\text{jet}\#1) < 70 \text{ GeV}$ compared with “min-bias” collisions.

Energy dependence of $p_{\perp\min}$ and $p_{\perp 0}$



Larger collision energy
 \Rightarrow probe parton (\approx gluon)
 density at smaller x

\Rightarrow smaller colour
 screening length d

\Rightarrow larger $p_{\perp\min}$ or $p_{\perp 0}$

Post-HERA PDF fits
 steeper at small x

\Rightarrow stronger energy
 dependence

Current PYTHIA default (Tune A, old model), tied to CTEQ 5L, is

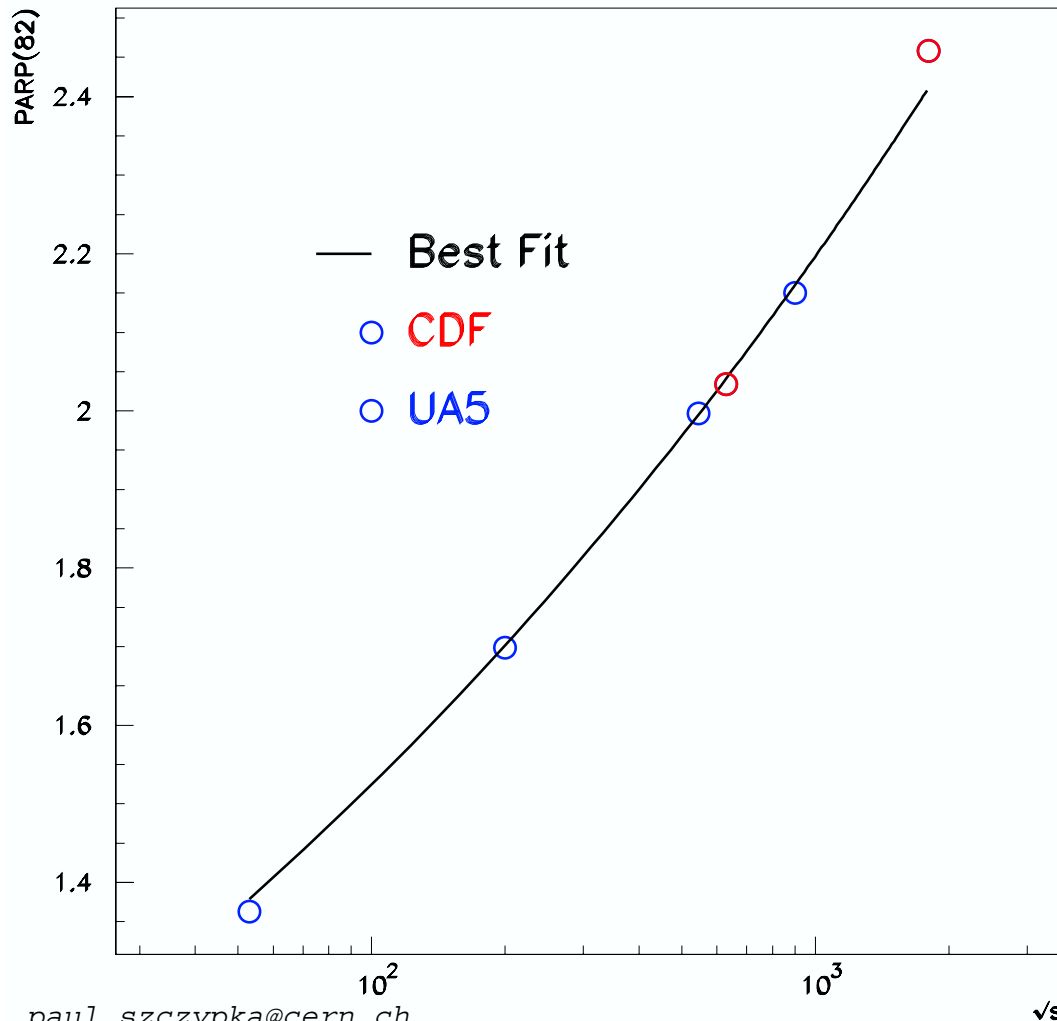
$$p_{\perp\min}(s) = 2.0 \text{ GeV} \left(\frac{s}{(1.8 \text{ TeV})^2} \right)^{0.08}$$



Extrapolation of P_{T_min} I



Fitting to: $P_{T_{min}}(\sqrt{s}) = P_{T_{min}}^{LHC} \left(\frac{\sqrt{s}}{14 \text{ TeV}} \right)^{2\epsilon}$



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$$P_{T_{Min}}^{LHC} = 3.34 \pm 0.13$$

$$\epsilon = 0.079 \pm 0.006$$

These values give:

$$\langle dN_{ch}/d\eta \rangle_{\eta=0}^{LHC} = 6.45 \pm 0.25$$

in Single-Diffractive Events

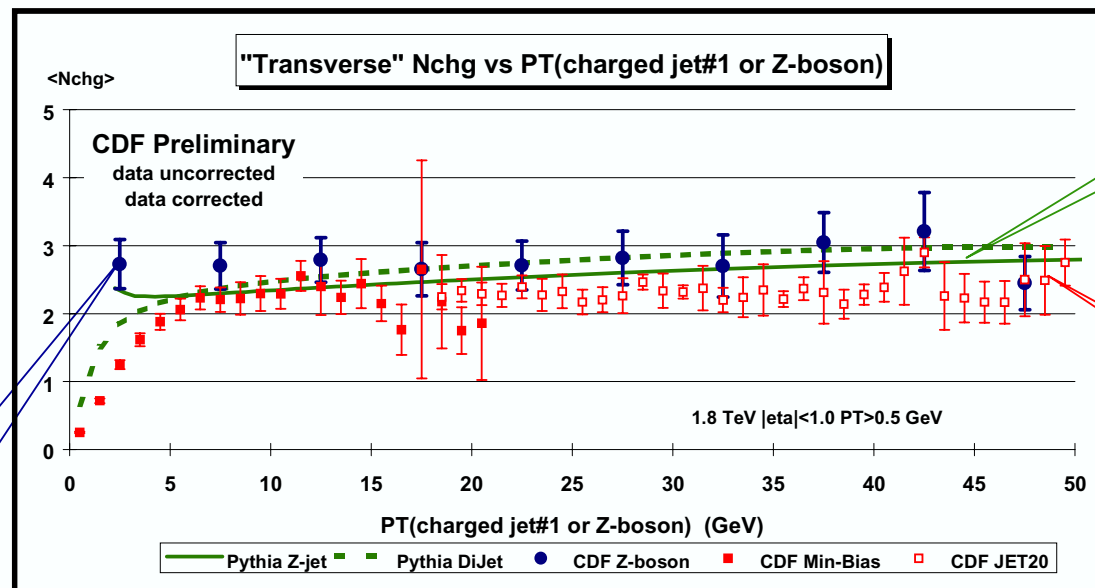
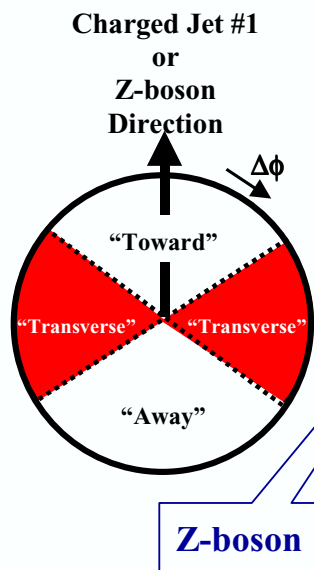
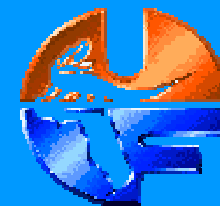
Compared to the phenomenological extrapolation of:

$$\langle dN_{ch}/d\eta \rangle_{\eta=0}^{LHC} = 6.27 \pm 0.50$$

→ **Compatible**



DiJet vs Z-Jet “Transverse” Nchg

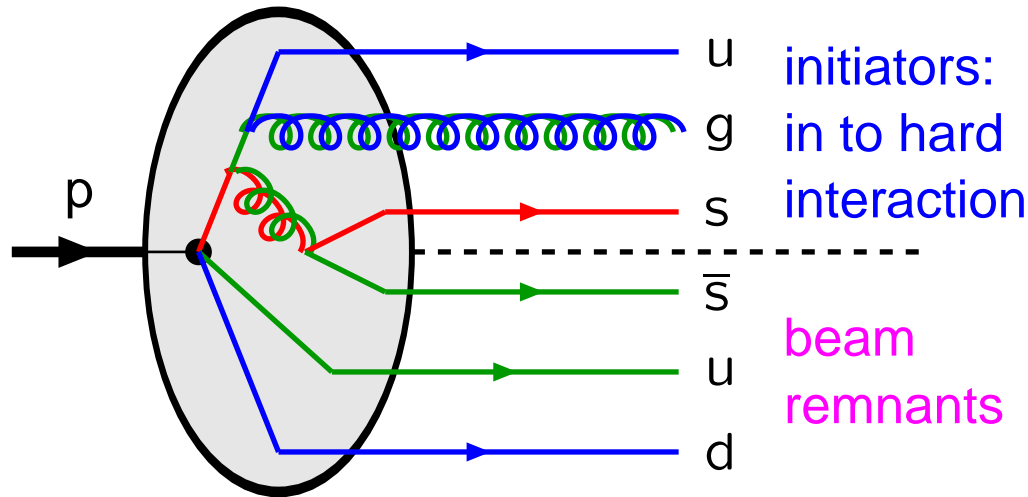


PYTHIA

DiJet

- ➔ Comparison of the **dijet** and the **Z-boson** data on the average number of charged particles ($P_T > 0.5$ GeV, $|\eta| < 1$) for the **“transverse”** region.
- ➔ The plot shows the QCD Monte-Carlo predictions of **PYTHIA 6.115** (default parameters with $P_T(\text{hard}) > 3$ GeV/c) for dijet (dashed) and “Z-jet” (solid) production.

Initiators and Remnants



Need to assign:

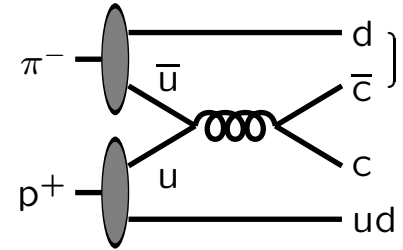
- correlated flavours
- correlated $x_i = p_{zi}/p_{z\text{tot}}$
- correlated primordial $k_{\perp i}$
- correlated colours
- correlated showers

• PDF after preceding MI/ISR activity:

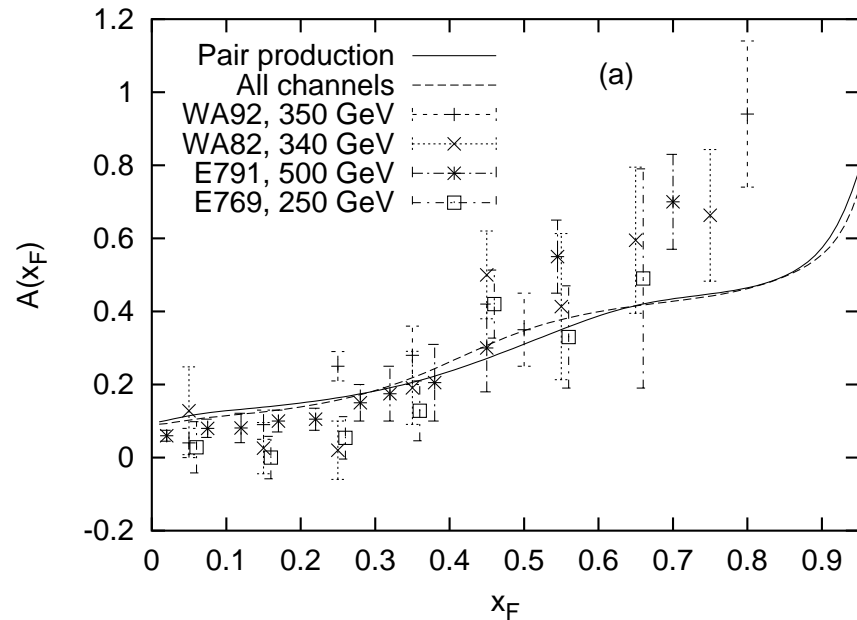
- 0) Squeeze range $0 < x < 1$ into $0 < x < 1 - \sum x_i$ (ISR: $i \neq i_{\text{current}}$)
- 1) Valence quarks: scale down by number already kicked out
- 2) Introduce companion quark q/\bar{q} to each kicked-out sea quark \bar{q}/q ,
with x based on assumed $g \rightarrow q\bar{q}$ splitting
- 3) Gluon and other sea: rescale for total momentum conservation

Beam remnant physics

Colour flow connects hard scattering to beam remnants.
 Can have consequences,
 e.g. in $\pi^- p$

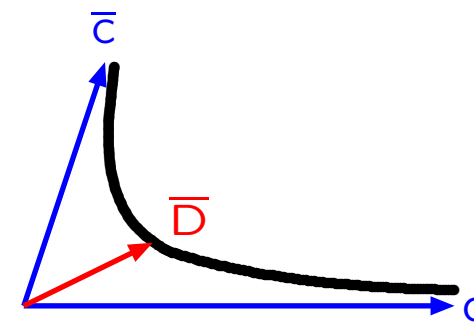


$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$



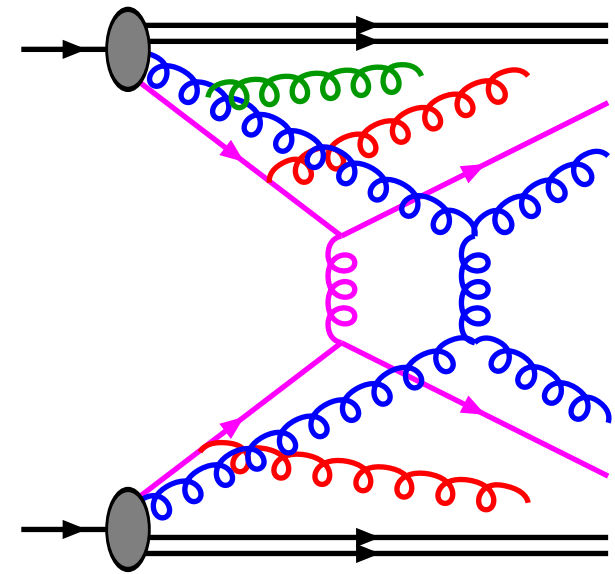
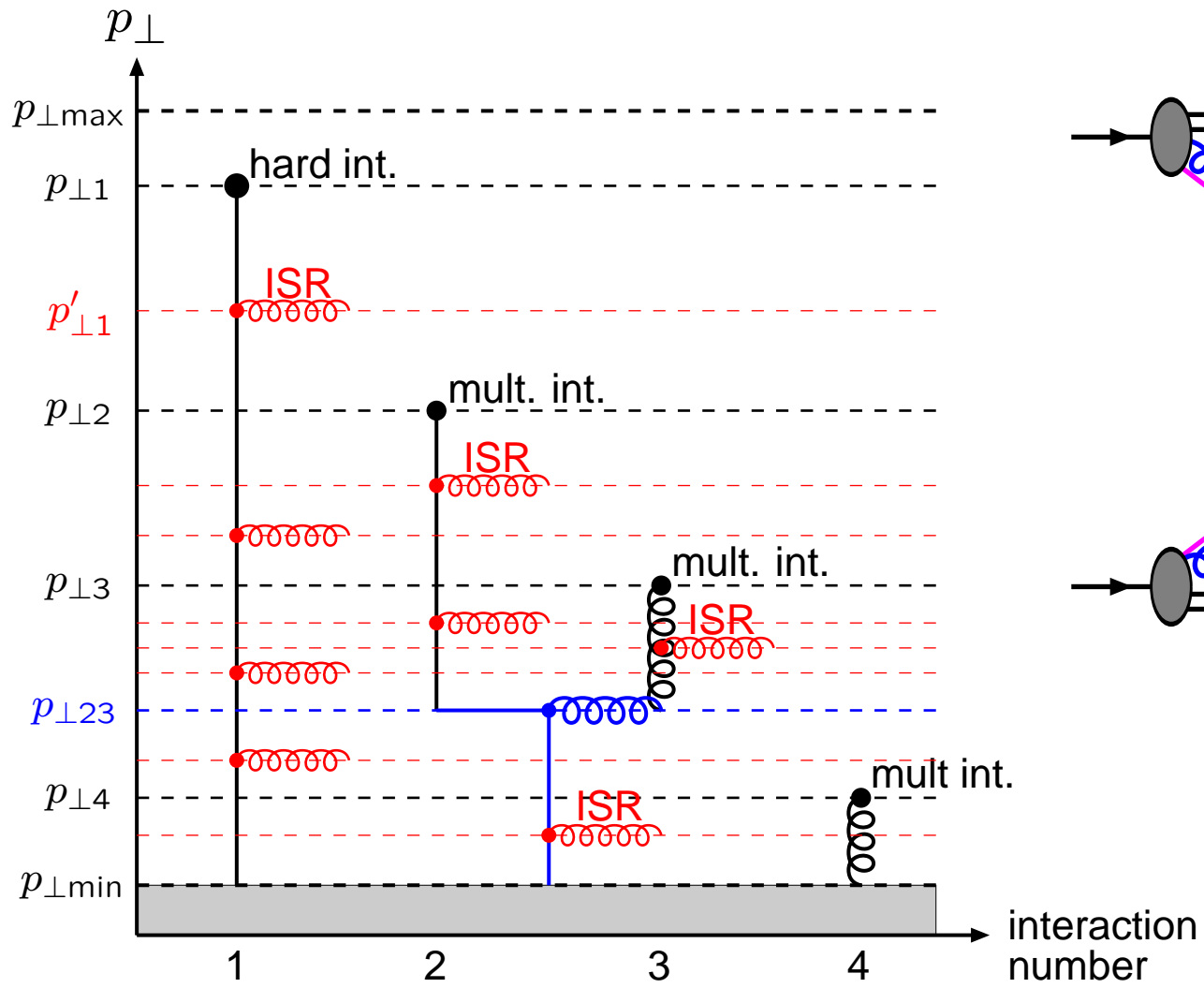
(also B asymmetries at LHC, but small)

If low-mass string e.g.:
 $\bar{c}d$: D^- , D^{*-}
 cud : Λ_c^+ , Σ_c^+ , Σ_c^{*+}
 \Rightarrow flavour asymmetries



Can give D 'drag' to
 larger x_F than c quark
 for any string mass

Interleaved Multiple Interactions



Competition

“Evolution” equation, only Multiple Interactions:

$$\frac{d\mathcal{P}}{dp_{\perp}} = \frac{d\mathcal{P}_{\text{MI}}}{dp_{\perp}} \exp\left(-\int_{p_{\perp}}^{p_{\perp i-1}} \frac{d\mathcal{P}_{\text{MI}}}{dp'_{\perp}} dp'_{\perp}\right)$$

Evolution equation, only Initial State Radiation:

$$\frac{d\mathcal{P}}{dp_{\perp}} = \frac{d\mathcal{P}_{\text{ISR}}}{dp_{\perp}} \exp\left(-\int_{p_{\perp}}^{p_{\perp i-1}} \frac{d\mathcal{P}_{\text{ISR}}}{dp'_{\perp}} dp'_{\perp}\right)$$

Evolution equation, MI + ISR, with competition for PDF and phase space:

$$\frac{d\mathcal{P}}{dp_{\perp}} = \left(\frac{d\mathcal{P}_{\text{MI}}}{dp_{\perp}} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp_{\perp}}\right) \exp\left(-\int_{p_{\perp}}^{p_{\perp i-1}} \left(\frac{d\mathcal{P}_{\text{MI}}}{dp'_{\perp}} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp'_{\perp}}\right) dp'_{\perp}\right)$$

with ISR sum running over all previous MI

⇒ one interleaved sequence of MI and ISR

FSR: no competition so not required (but nice for ME merging)

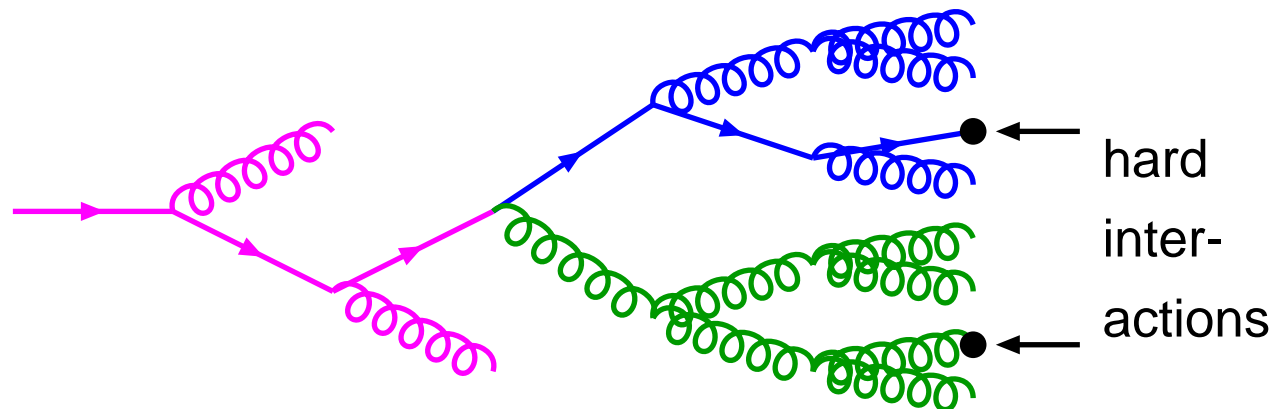
Other issues

- **Regularization procedure:**

$$\alpha_s(p_{\perp}^2) \frac{dp_{\perp}^2}{p_{\perp}^2} \rightarrow \alpha_s(p_{\perp 0}^2 + p_{\perp}^2) \frac{dp_{\perp}^2}{p_{\perp 0}^2 + p_{\perp}^2}$$

common for MI (quadratically) and ISR by colour neutralization
 $p_{\perp 0} \approx 2-3$ GeV energy-dependent

- **Intertwined interactions:**



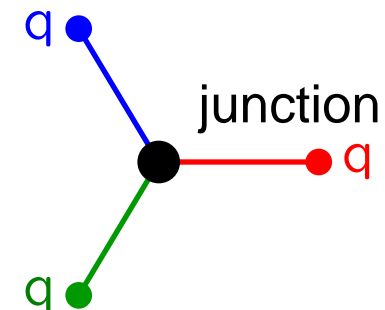
Not (yet) explicitly included, but estimated; shown not to be critical

- **Where does the baryon number go?**

Junction “carries” baryon number!

Motion determined by colour flow attached to it.

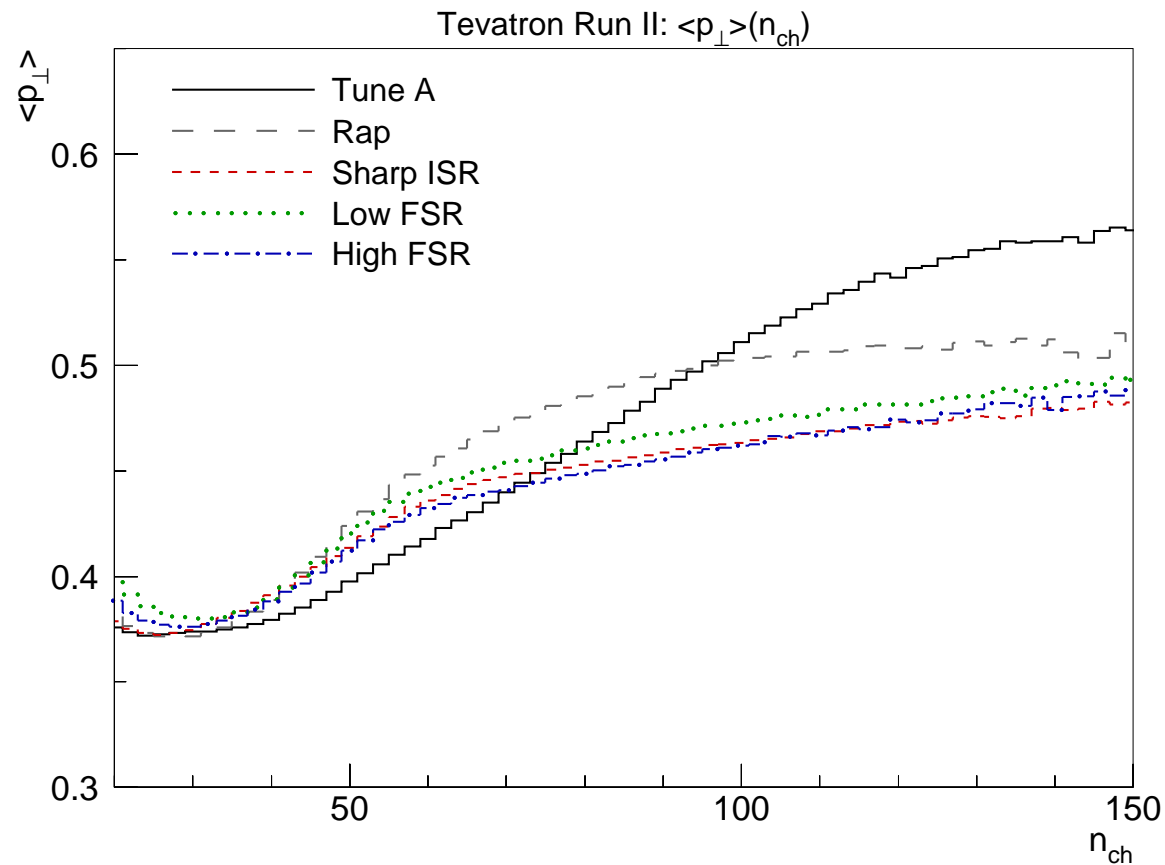
Messy hadronization (but handled with model)



Data comparisons

usually comparable with Tune A (for better or worse), but still in need of good tuning and detailed tests, and ...

... $\langle p_{\perp} \rangle(n_{ch})$ problematical (need very short string!)

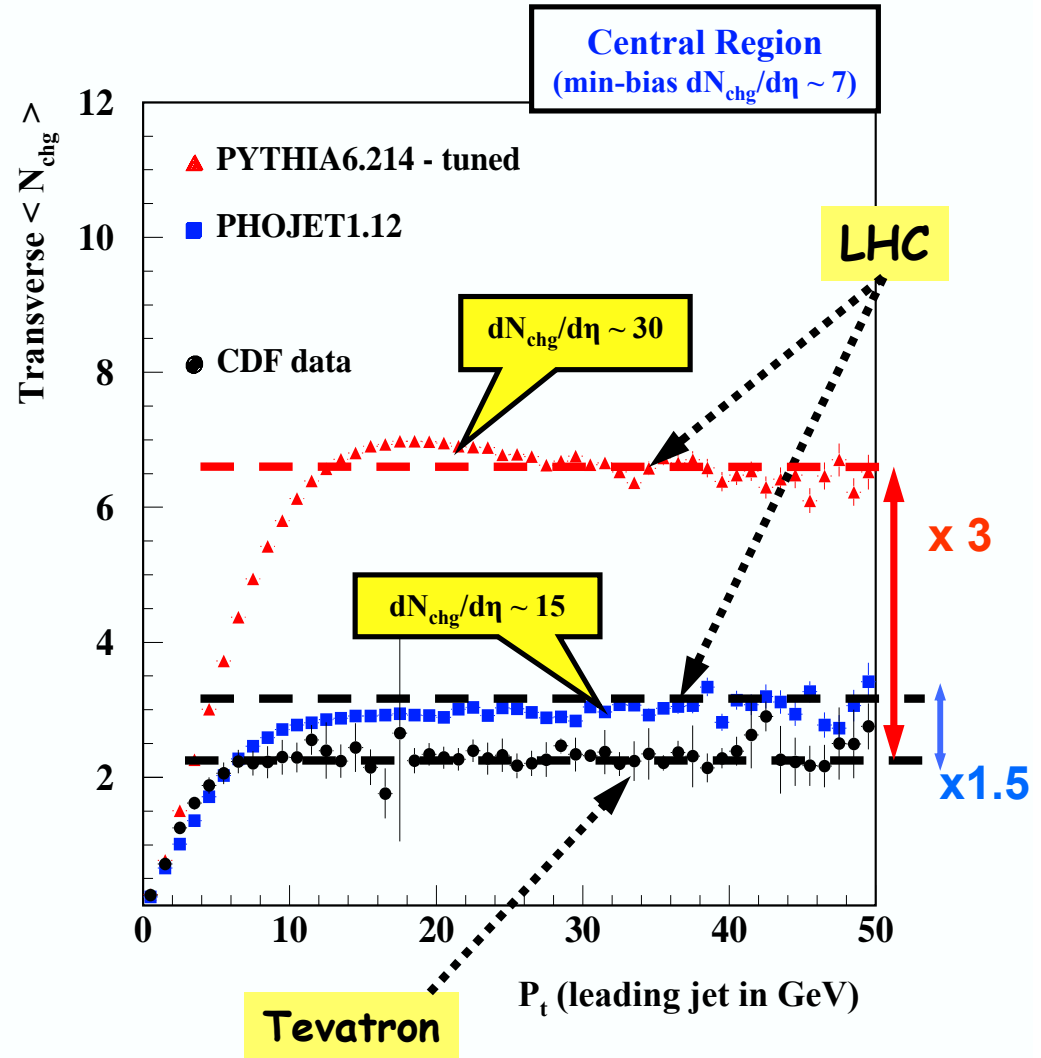
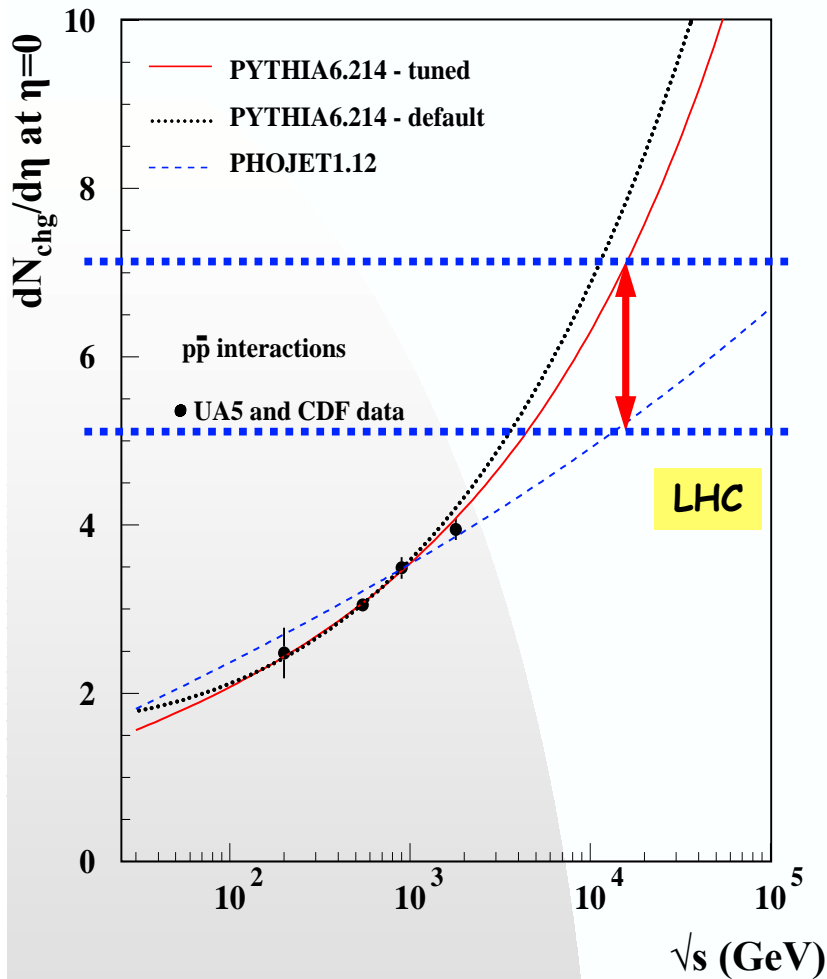


colour correlations not yet understood!

Comments	PYTHIA6.2 - Default	ATLAS – TDR (PYTHIA5.7)	CDF – Tune A (PYTHIA6.206)	PYTHIA6.214 - Tuned
Generated processes (QCD + low-pT)	Non-diffractive inelastic (MSEL=1)	Non-diffractive inelastic (MSEL=1)	Non-diffractive inelastic + double diffraction (MSEL=0, ISUB 94 and 95)	Non-diffractive + double diffraction (MSEL=0, ISUB 94 and 95)
p.d.f.	CTEQ 5L (MSTP(51)=7)	CTEQ 2L (MSTP(51)=9)	CTEQ 5L (MSTP(51)=7)	CTEQ 5L (MSTP(51)=7)
Multiple interactions models	MSTP(81) = 1 MSTP(82) = 1	MSTP(81) = 1 MSTP(82) = 4	MSTP(81) = 1 MSTP(82) = 4	MSTP(81) = 1 MSTP(82) = 4
pT min	PARP(82) = 1.9 PARP(89) = 1 TeV PARP(90) = 0.16	PARP(82) = 1.55 no energy depend.	PARP(82) = 2.0 PARP(89) = 1.8 TeV PARP(90) = 0.25	PARP(82) = 1.8 PARP(89) = 1 TeV PARP(90) = 0.16
Core radius	20% of the hadron radius (PARP(84) = 0.2)	20% of the hadron radius (PARP(84) = 0.2)	40% of the hadron radius (PARP(84) = 0.4)	50% of the hadron radius (PARP(84) = 0.5)
Gluon production mechanism	PARP(85) = 0.33 PARP(86) = 0.66	PARP(85) = 0.33 PARP(86) = 0.66	PARP(85) = 0.9 PARP(86) = 0.95	PARP(85) = 0.33 PARP(86) = 0.66
α_s and K-factors	MSTP(2) = 1 MSTP(33) = 0	MSTP(2) = 2 MSTP(33) = 3	MSTP(2) = 1 MSTP(33) = 0	MSTP(2) = 1 MSTP(33) = 0
Regulating initial state radiation	PARP(67) = 1	PARP(67) = 4	PARP(67) = 4	PARP(67) = 1



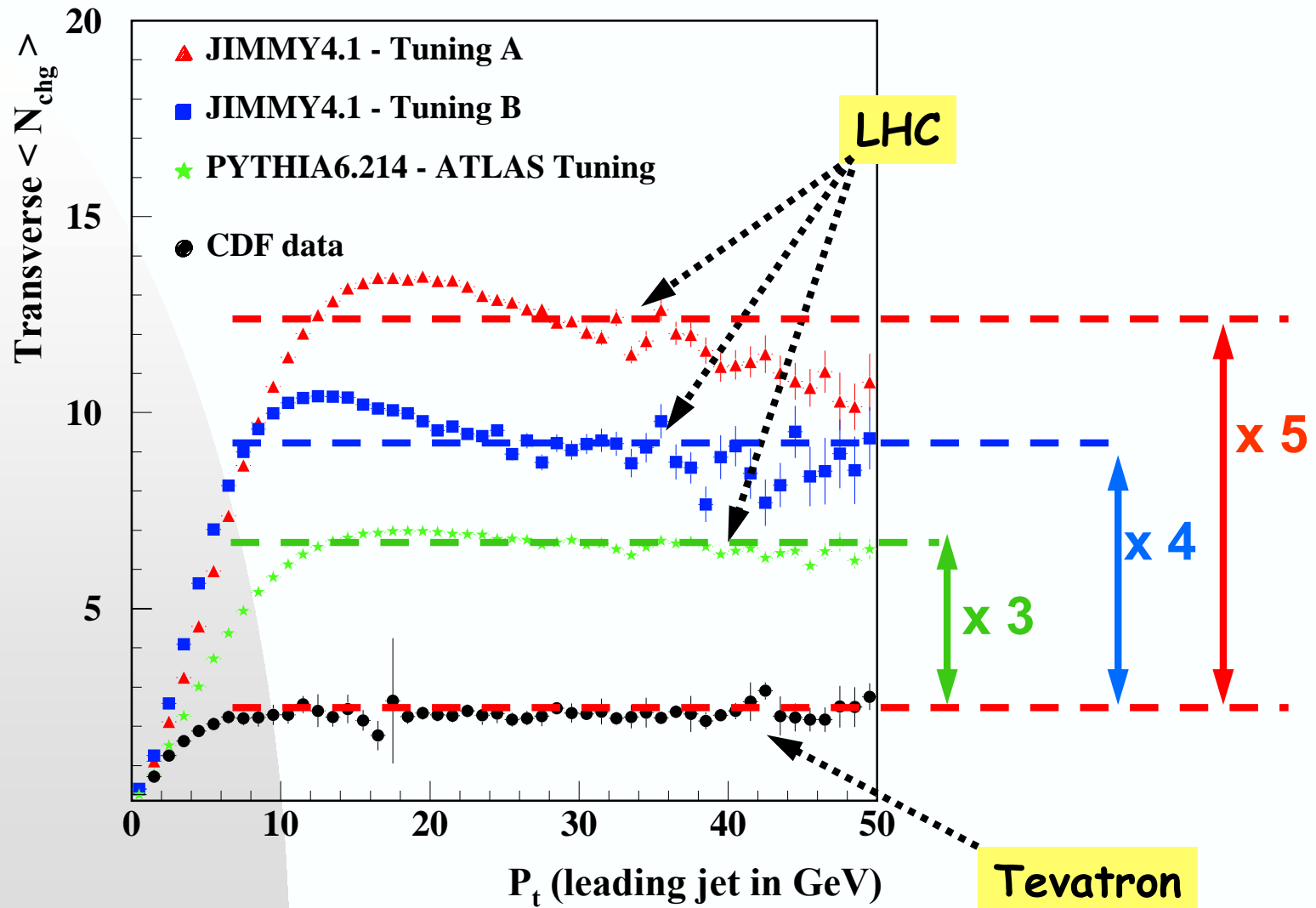
LHC predictions: pp collisions at $\sqrt{s} = 14$ TeV



- **PYTHIA** models favour $\ln^2(s)$;
- **PHOJET** suggests a $\ln(s)$ dependence.



LHC predictions: JIMMY4.1 Tunings A and B vs. PYTHIA6.214 – ATLAS Tuning (DC2)



Summary Lecture 4

- Multiple interactions concept compelling; it *has to* exist at some level. ●
 - ★ By now, **strong** direct evidence, **overwhelming** indirect evidence ★

- Understanding of multiple interactions crucial for LHC precision physics ●

- Many details uncertain ●

- ★ $p_{\perp\text{min}}/p_{\perp 0}$ cut-off ★

- ★ impact parameter picture ★

- ★ energy dependence ★

- ★ multiparton densities in incoming hadron ★

- ★ colour correlations between scatterings ★

- ★ interferences between showers ★

- ★ . . . ★

- Above physics aspects must all be present, and more? ●

If a model is simple, it is wrong!

- So stay tuned for even more complicated models in the future. . . . ●