LUND UNIVERSITY

Academic Training Lectures
CERN
4, 5, **6**, 7 April 2005

Monte Carlo Generators for the LHC

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CERN and Lund University

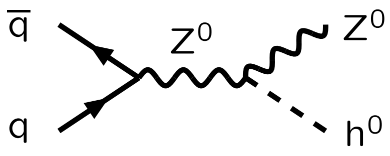
1. (Monday) Introduction and Overview; Matrix Elements
2. (Tuesday) Parton Showers; Matching Issues
3. **(today) Multiple Interactions and Beam Remnants**
4. (Thursday) Hadronization and Decays; Summary and Outlook

Event Physics Overview

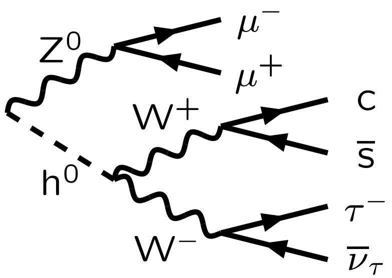
Repetition: from the "simple" to the "complex",
or from "calculable" at large virtualities to "modelled" at small

Matrix elements (ME):

1) Hard subprocess:
$|\mathcal{M}|^2$, Breit-Wigners,
parton densities.

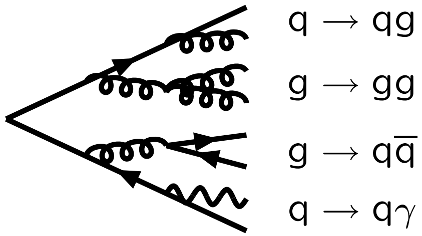


2) Resonance decays:
includes correlations.

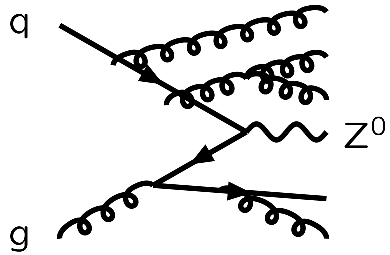


Parton Showers (PS):

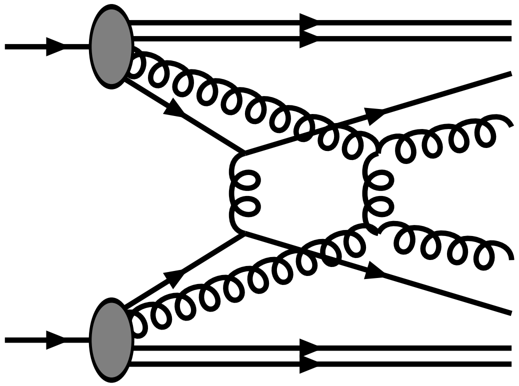
3) Final-state parton showers.



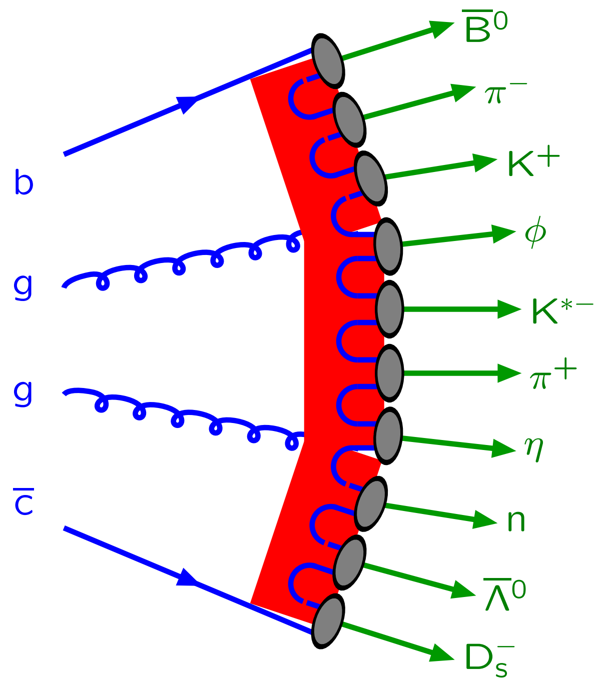
4) Initial-state parton showers.



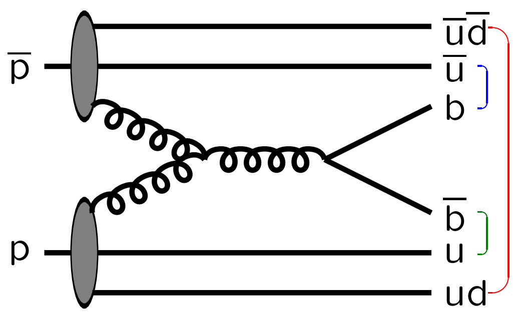
5) Multiple parton–parton interactions.



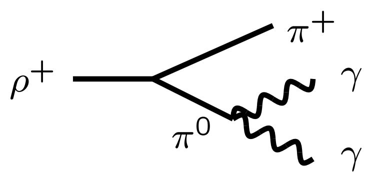
7) Hadronization



6) Beam remnants, with colour connections.



8) Ordinary decays: hadronic, τ, charm, . . .

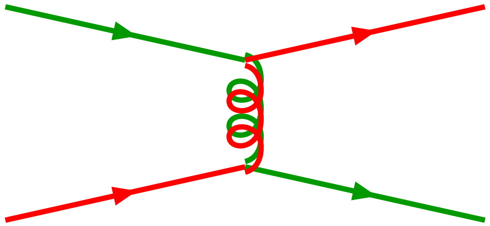


5) + 6) = Underlying Event

What is multiple interactions?

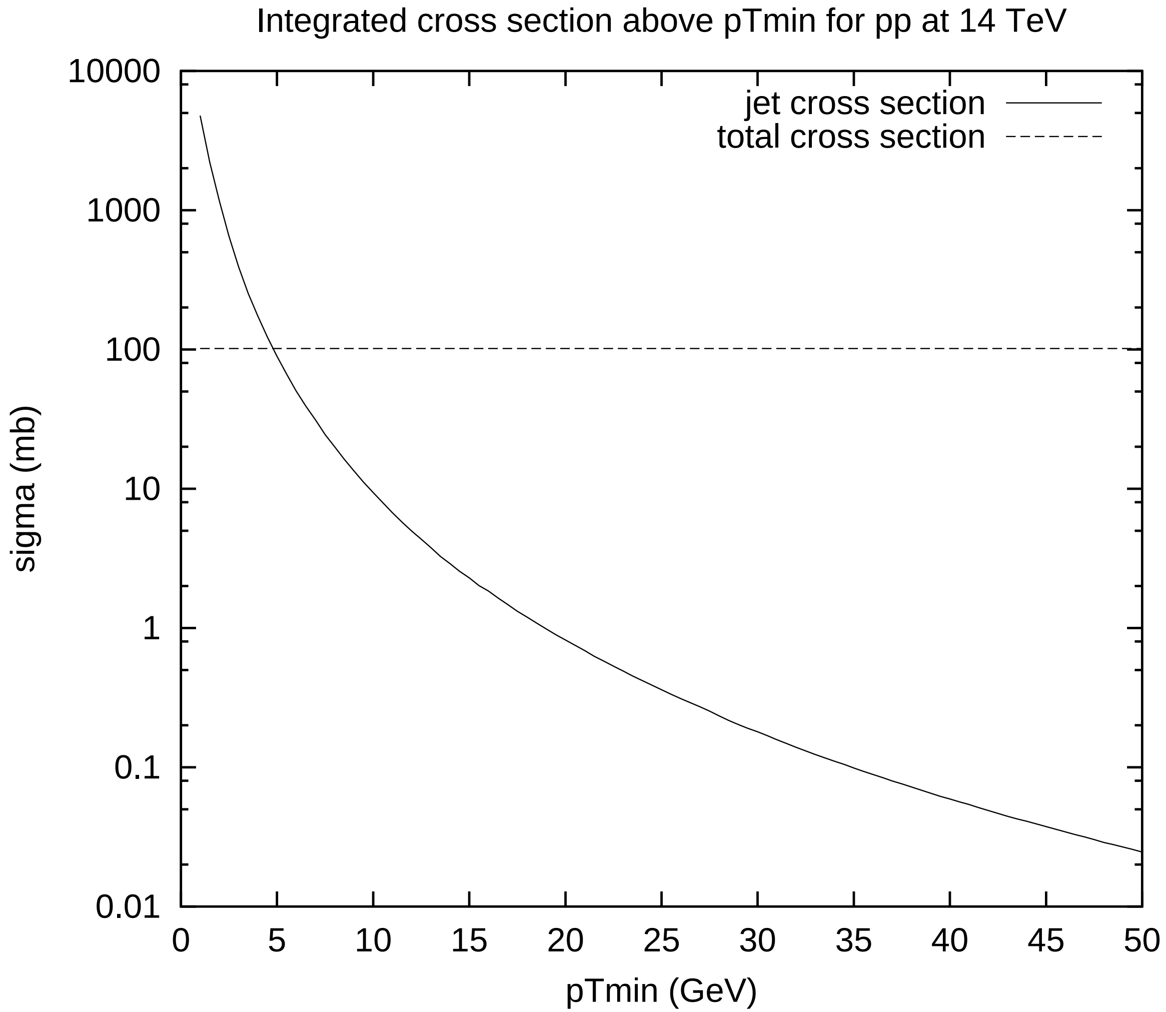
Cross section for $2 \to 2$ interactions is dominated by t-channel gluon exchange, so diverges like $\mathrm{d}\sigma/\mathrm{d}p_\perp^2 \approx 1/p_\perp^4$ for $p_\perp \to 0$.

integrate QCD $2 \to 2$



$\mathrm{qq}' \to \mathrm{qq}'$
$\mathrm{q\overline{q}} \to \mathrm{q'\overline{q}'}$
$\mathrm{q\overline{q}} \to \mathrm{gg}$
$\mathrm{qg} \to \mathrm{qg}$
$\mathrm{gg} \to \mathrm{gg}$
$\mathrm{gg} \to \mathrm{q\overline{q}}$

with CTEQ 5L PDF's



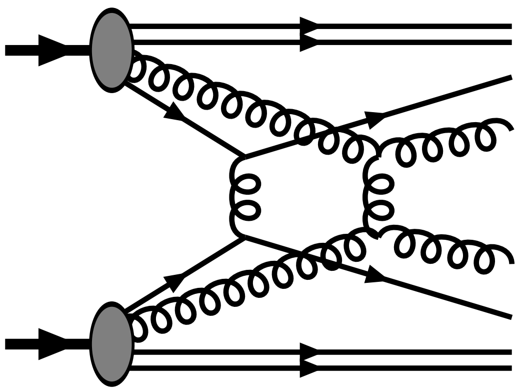
So $\sigma_{\text{int}}(p_{\perp\text{min}}) > \sigma_{\text{tot}}$ for $p_{\perp\text{min}} \lesssim 5$ GeV

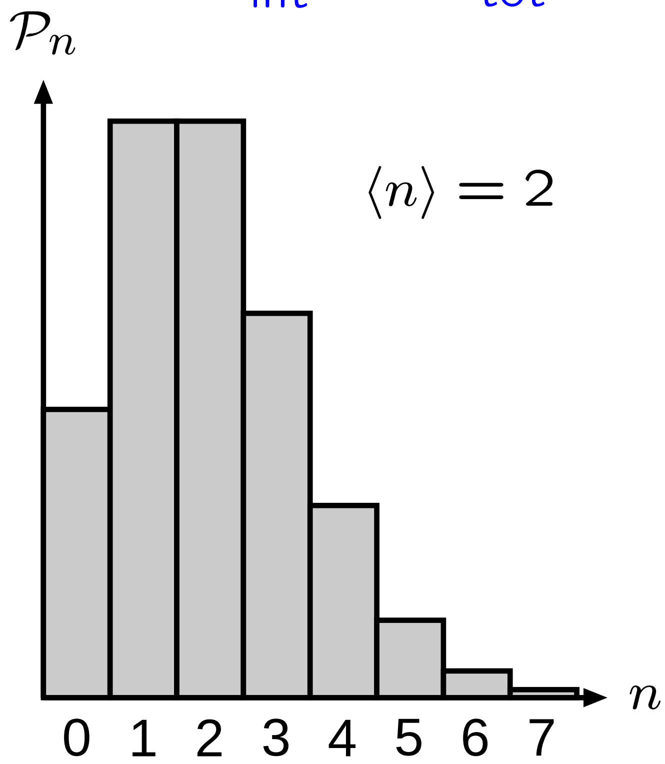
Half a solution: many interactions per event

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

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

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





If interactions occur independently

then **Poissonian statistics**

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

but energy–momentum conservation

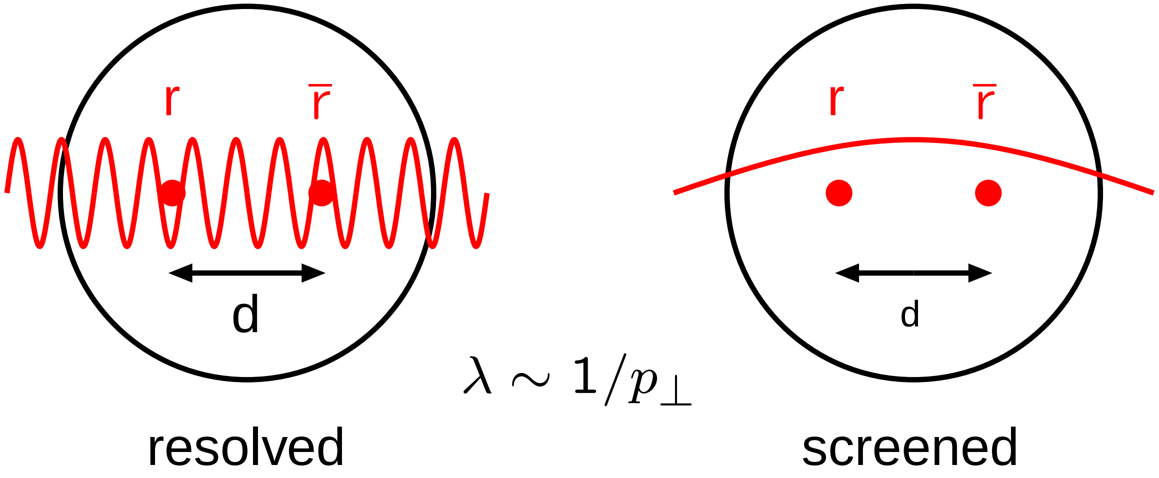
$\Rightarrow$ large n suppressed

Other half of solution:
perturbative QCD not valid at small $p_\perp$ since q, g not asymptotic states (confinement!).

Naively breakdown at

$$p_{\perp\min} \simeq \frac{\hbar}{r_\mathrm{p}} \approx \frac{0.2\ \mathrm{GeV}\cdot\mathrm{fm}}{0.7\ \mathrm{fm}} \approx 0.3\ \mathrm{GeV} \simeq \Lambda_\mathrm{QCD}$$

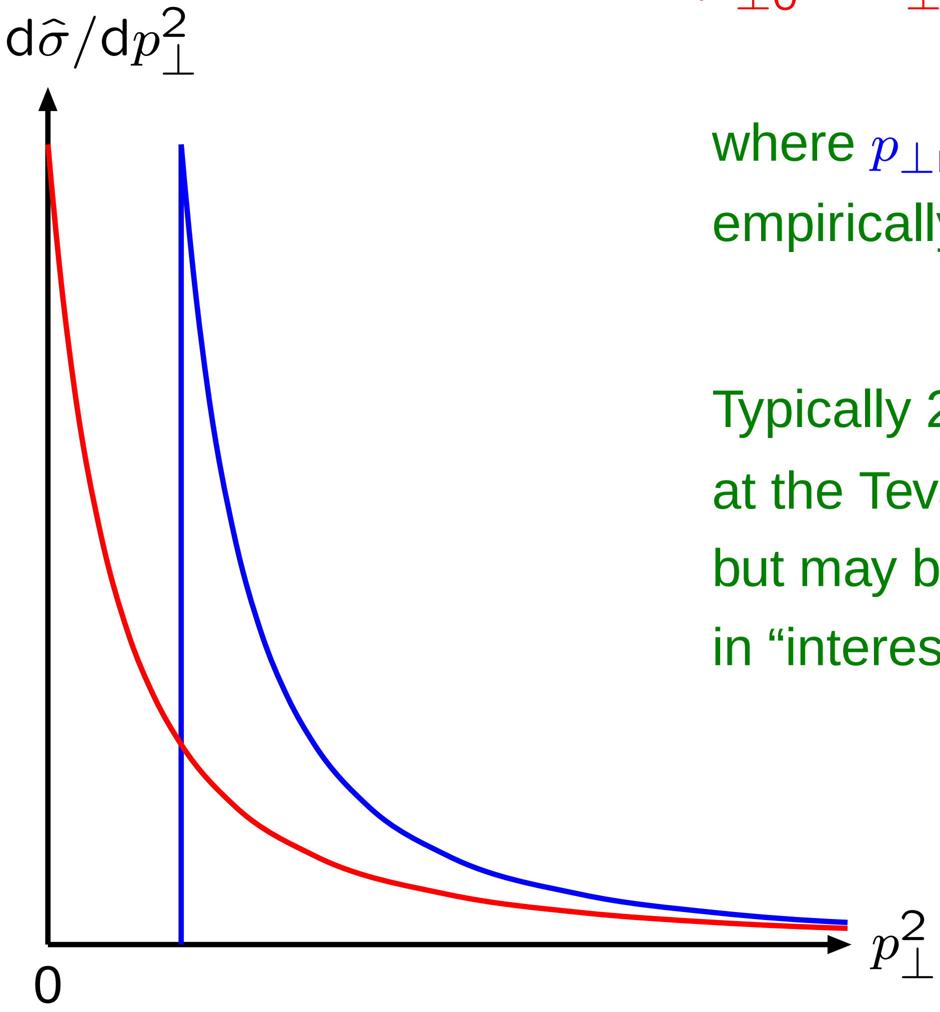
…but better replace r_p by (unknown) colour screening length d in hadron



so modify

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4}\,\theta\left(p_\perp - p_{\perp\mathrm{min}}\right) \quad \text{(simpler)}$$

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



where $p_{\perp\mathrm{min}}$ 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 $p_{\perp\mathrm{min}}$ main free parameter
- Is only a model for nondiffractive events, i.e. for $\sigma_{\mathrm{nd}} \simeq (2/3)\sigma_{\mathrm{tot}}$
- Average number of interactions is $\langle n \rangle = \sigma_{\mathrm{int}}(p_{\perp\mathrm{min}})/\sigma_{\mathrm{nd}}$
- 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 $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > \ldots$ by "Sudakov" trick (what happens "first"?)

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

- Momentum conservation in PDF's $\Rightarrow$ $\mathcal{P}_n$ narrower than Poissonian
- Simplify after first interaction: only gg or $\mathrm{q}\overline{\mathrm{q}}$ 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"):

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

  where $r_2 \neq r_1$ represents "hot spots"

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

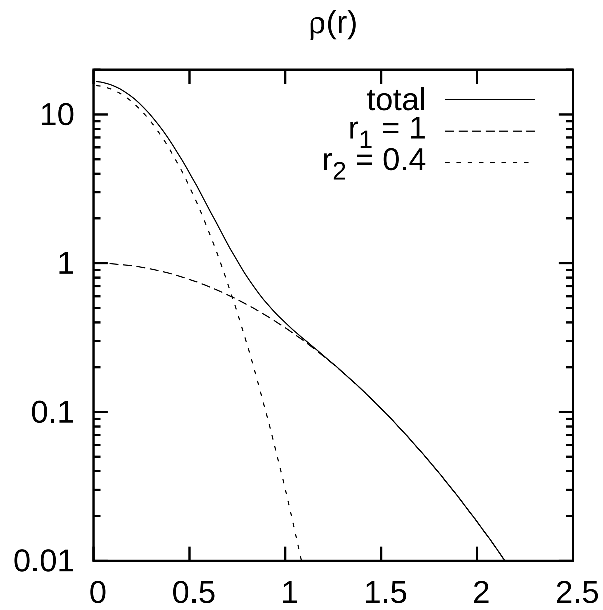
$$\mathcal{O}(b) = \int \mathrm{d}^3\mathbf{x}\,\mathrm{d}t\;\rho_{1,\mathrm{matter}}^{\mathrm{boosted}}(\mathbf{x},t)\rho_{2,\mathrm{matter}}^{\mathrm{boosted}}(\mathbf{x},t)$$

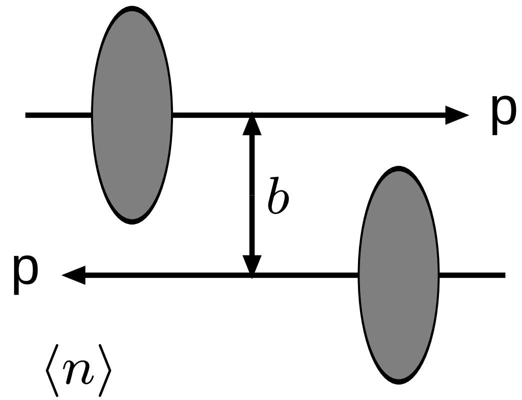
- Average activity at b proportional to $\mathcal{O}(b)$

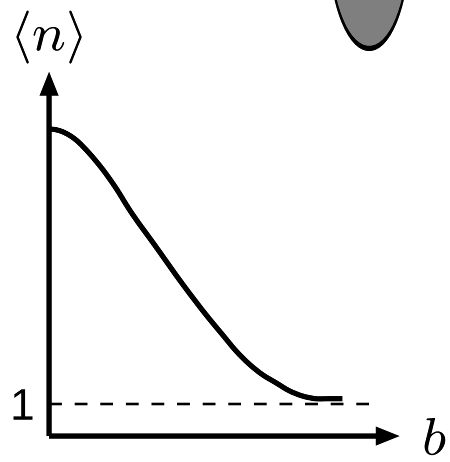
  $\Rightarrow$ central collisions normally more active

  $\Rightarrow$ $\mathcal{P}_n$ broader than Poissonian

- More time-consuming $(b, p_\perp)$ generation
- Need for simplifications remains

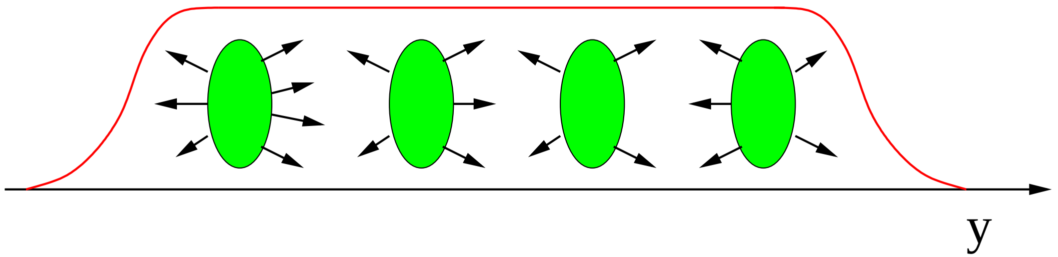






(3) HERWIG

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" $\approx p_\perp \to 0$ limit of multiple interactions
- extended also to "hard" interactions similarly to PYTHIA

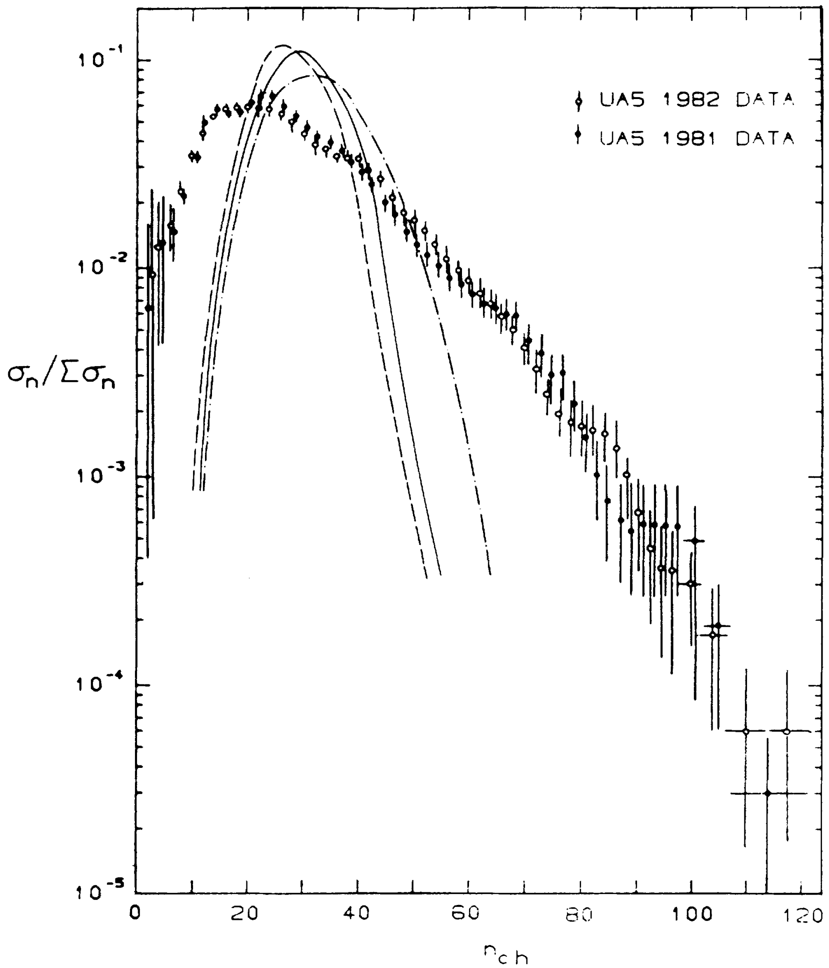


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

without multiple interactions

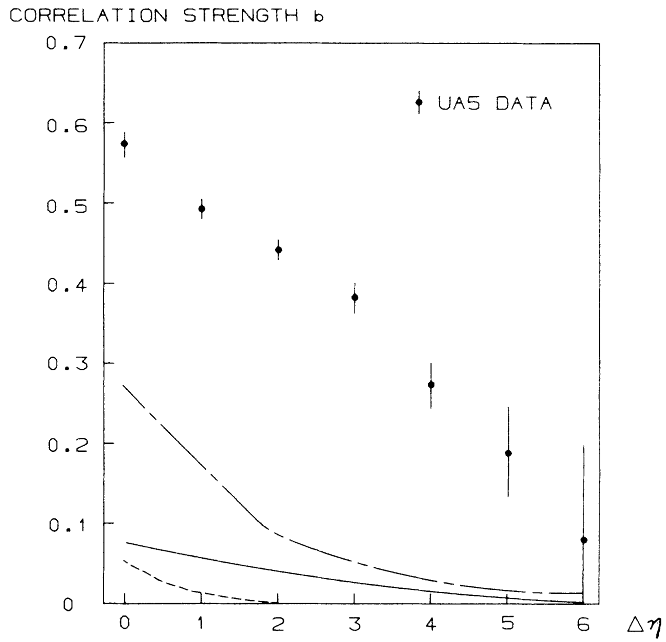


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

with multiple interactions

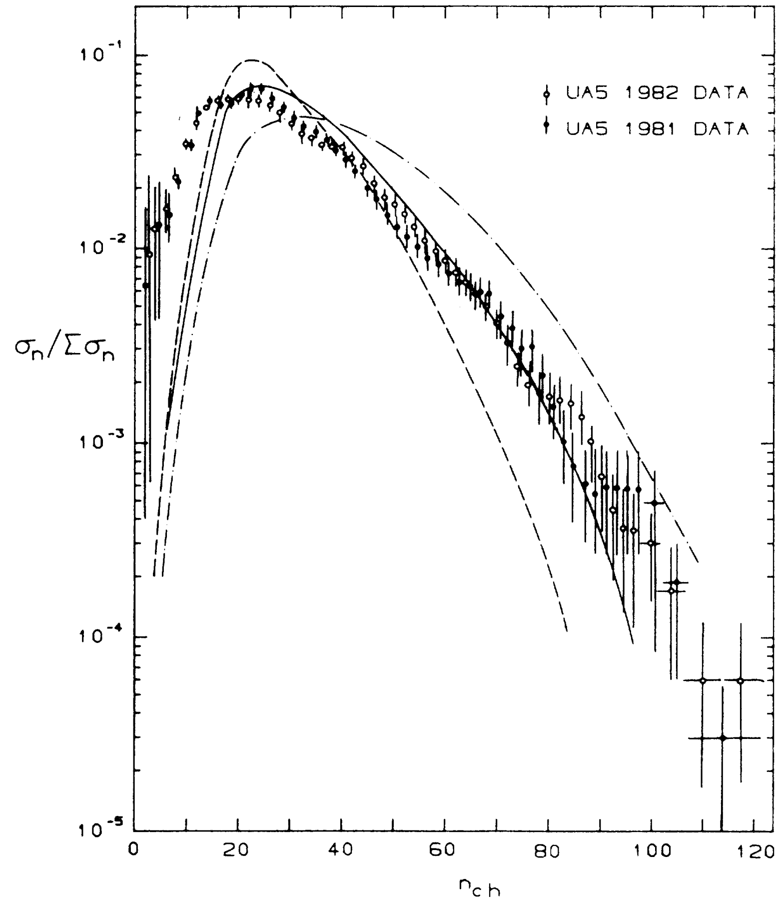


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min}=2.0$ GeV; solid line, $p_{T\min}=1.6$ GeV; dashed-dotted line, $p_{T\min}=1.2$ GeV.

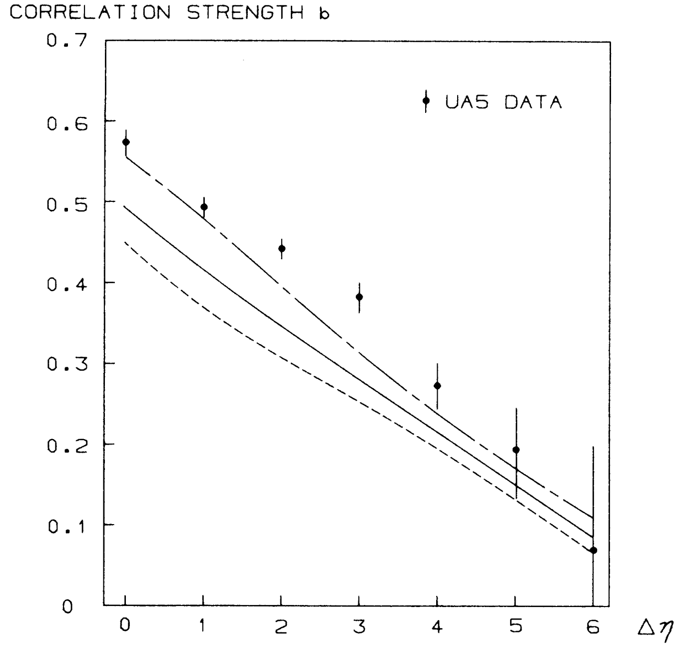


FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

Evidence for multiple interactions

- Width of multiplicity distribution: UA5, E735
  (previous slides)

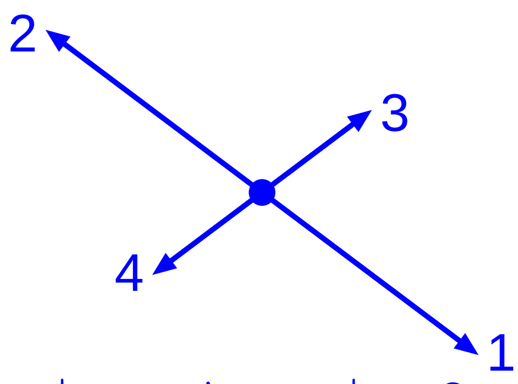
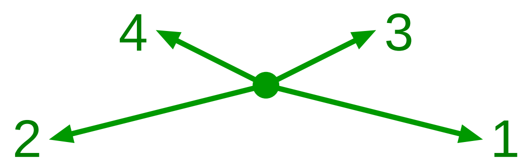
- Forward–backward correlations: UA5
  (previous slides)

- 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

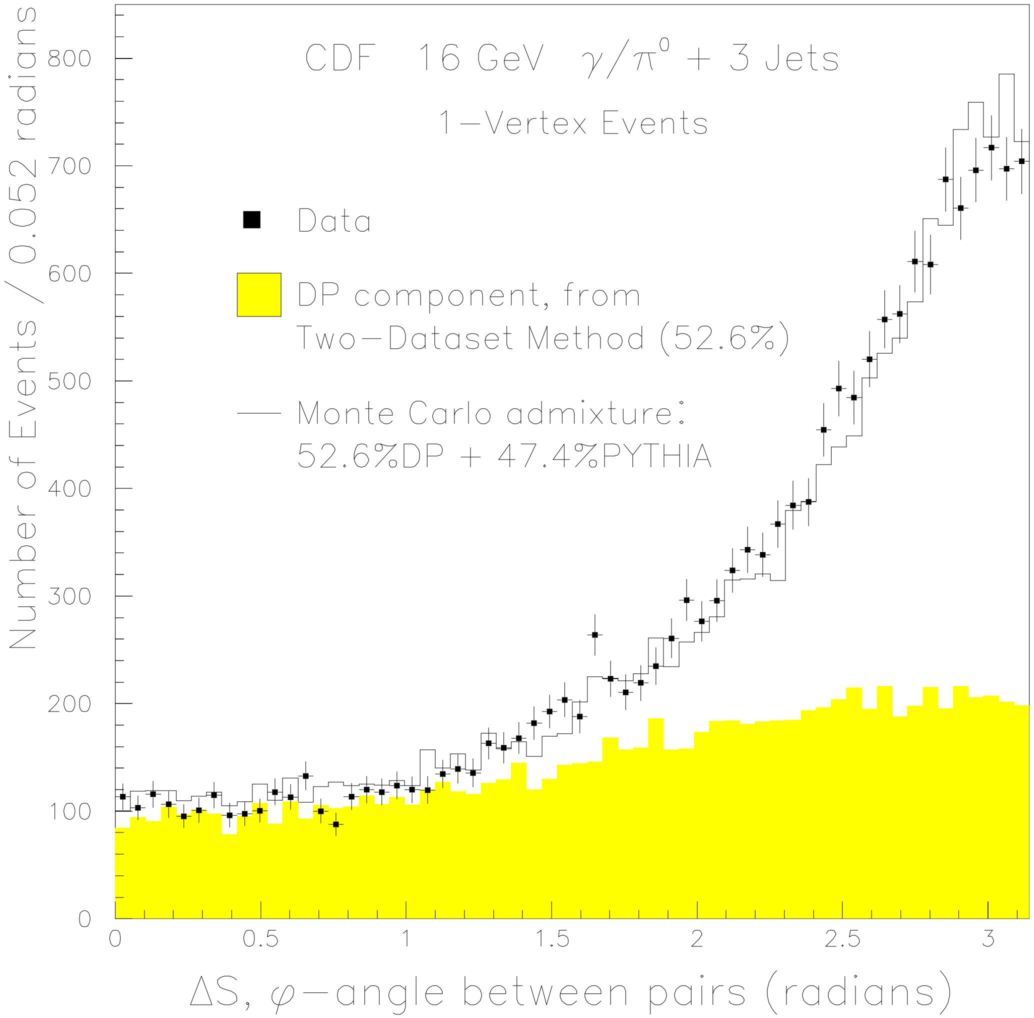
- Direct observation: AFS, (UA2,) CDF

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

Double Parton Scattering	Double BremsStrahlung
	
$\lvert\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}\rvert \approx 0$	$\lvert\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}\rvert \gg 0$
$\lvert\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}\rvert \approx 0$	$\lvert\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}\rvert \gg 0$
$\mathrm{d}\sigma/\mathrm{d}\varphi$ flat	$\mathrm{d}\sigma/\mathrm{d}\varphi$ 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

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

Strong enhancement relative to naive expectations!

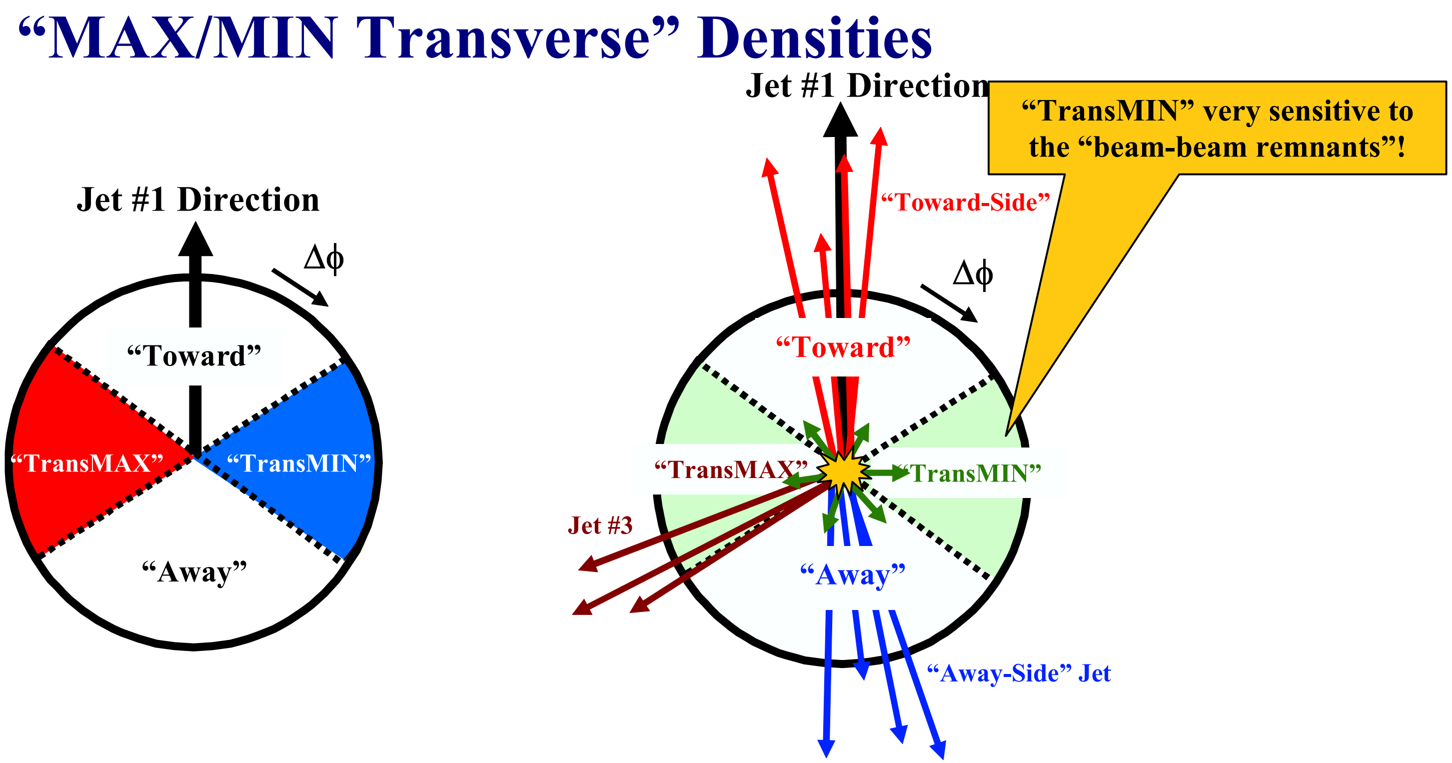
• Jet pedestal effect: UA1, H1, CDF

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.

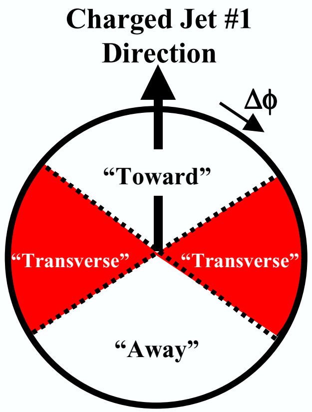
Centrality effect saturates at $p_{\perp\mathrm{hard}} \sim 10$ GeV.

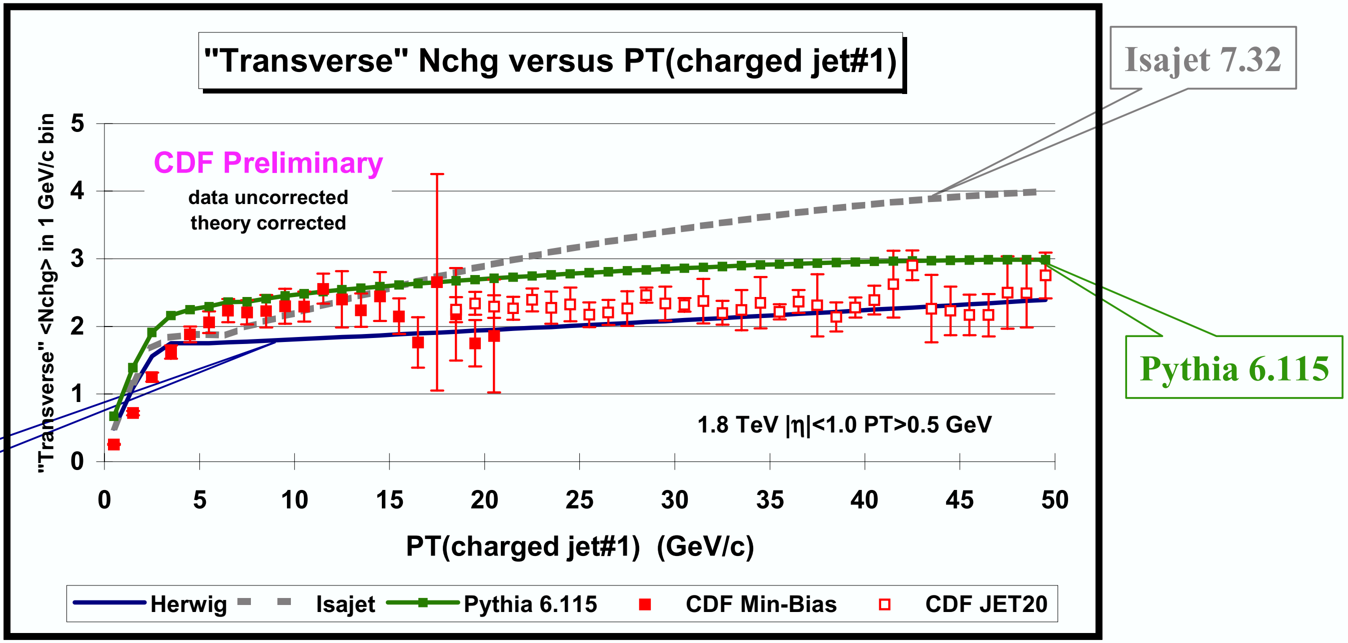
Studied in detail by Rick Field, comparing with CDF data:



- **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(chgjet#1)





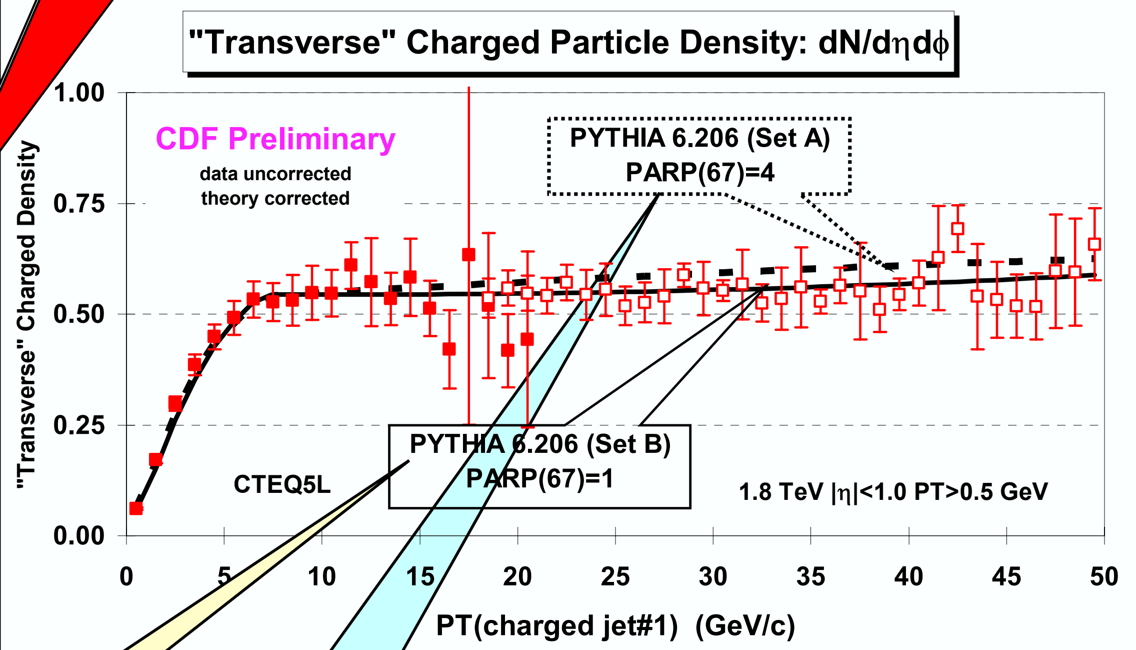
- Plot shows the **“Transverse” <Nchg> versus P_T(chgjet#1)** compared to the the QCD hard scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115 (**default parameters with P_T(hard)>3 GeV/c**).
- Only charged particles with $|\eta| < 1$ and $P_T > 0.5$ GeV are included and the QCD Monte-Carlo 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

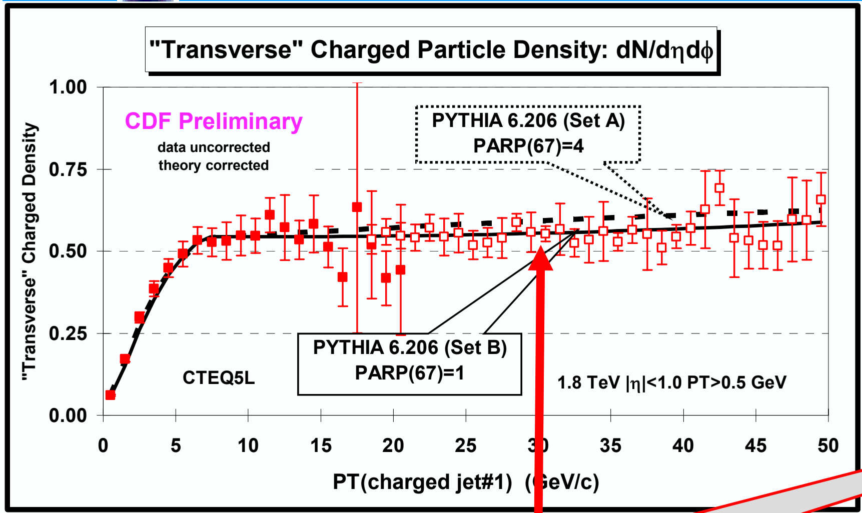


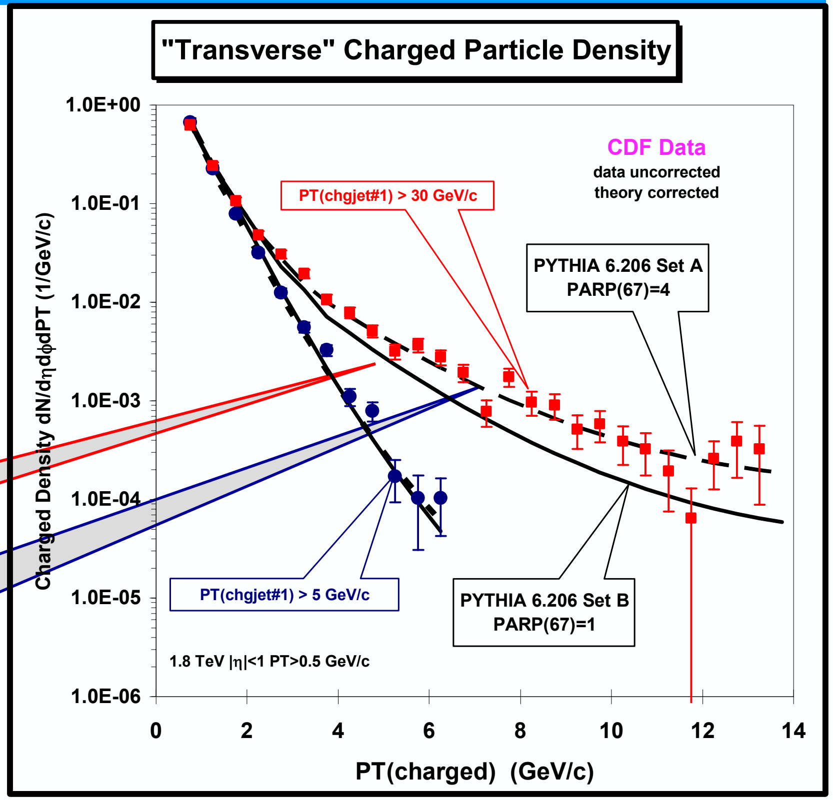
Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

Tuned PYTHIA 6.206 "Transverse" P_T Distribution





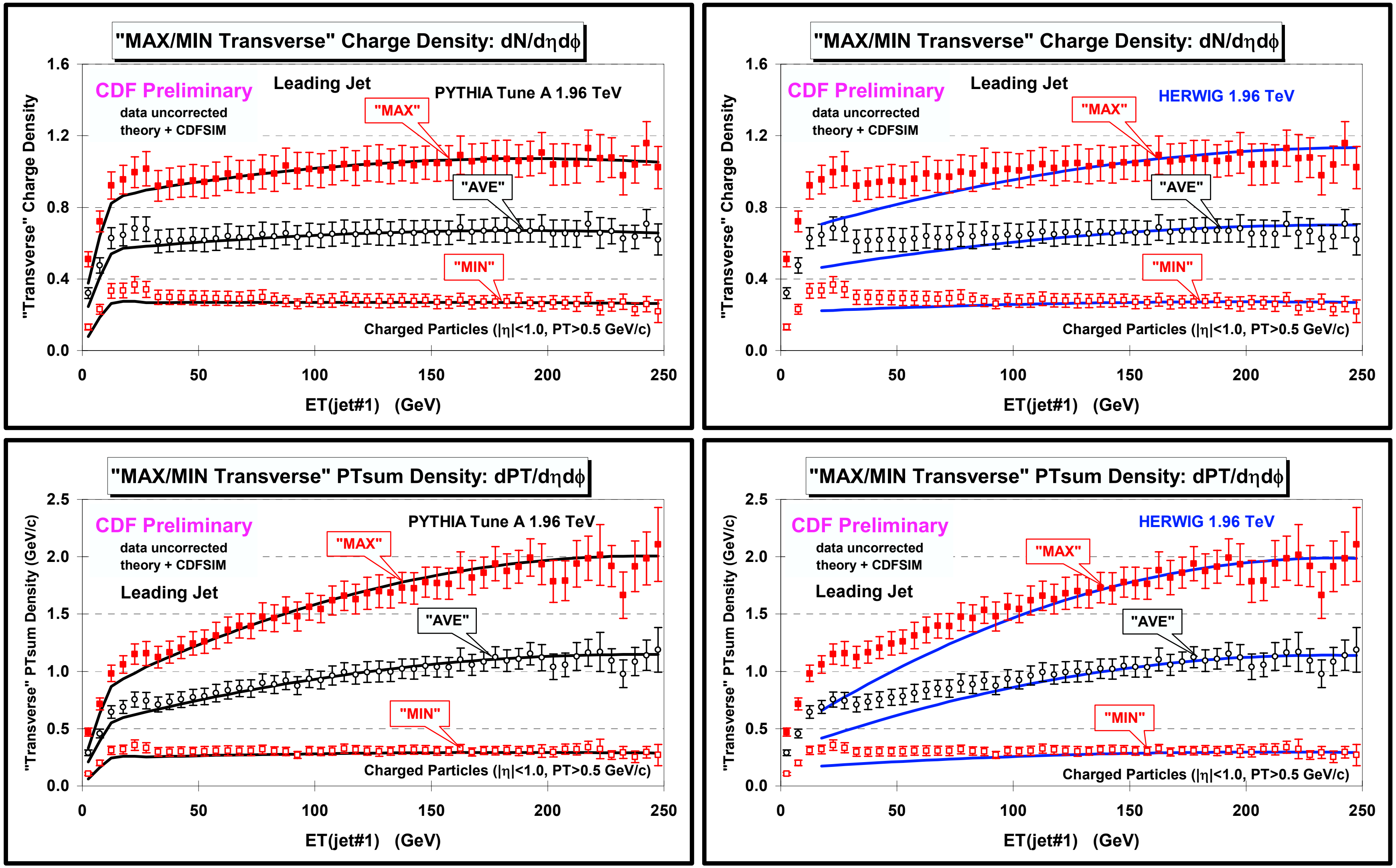
P_T(charged jet#1) > 30 GeV/c

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

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

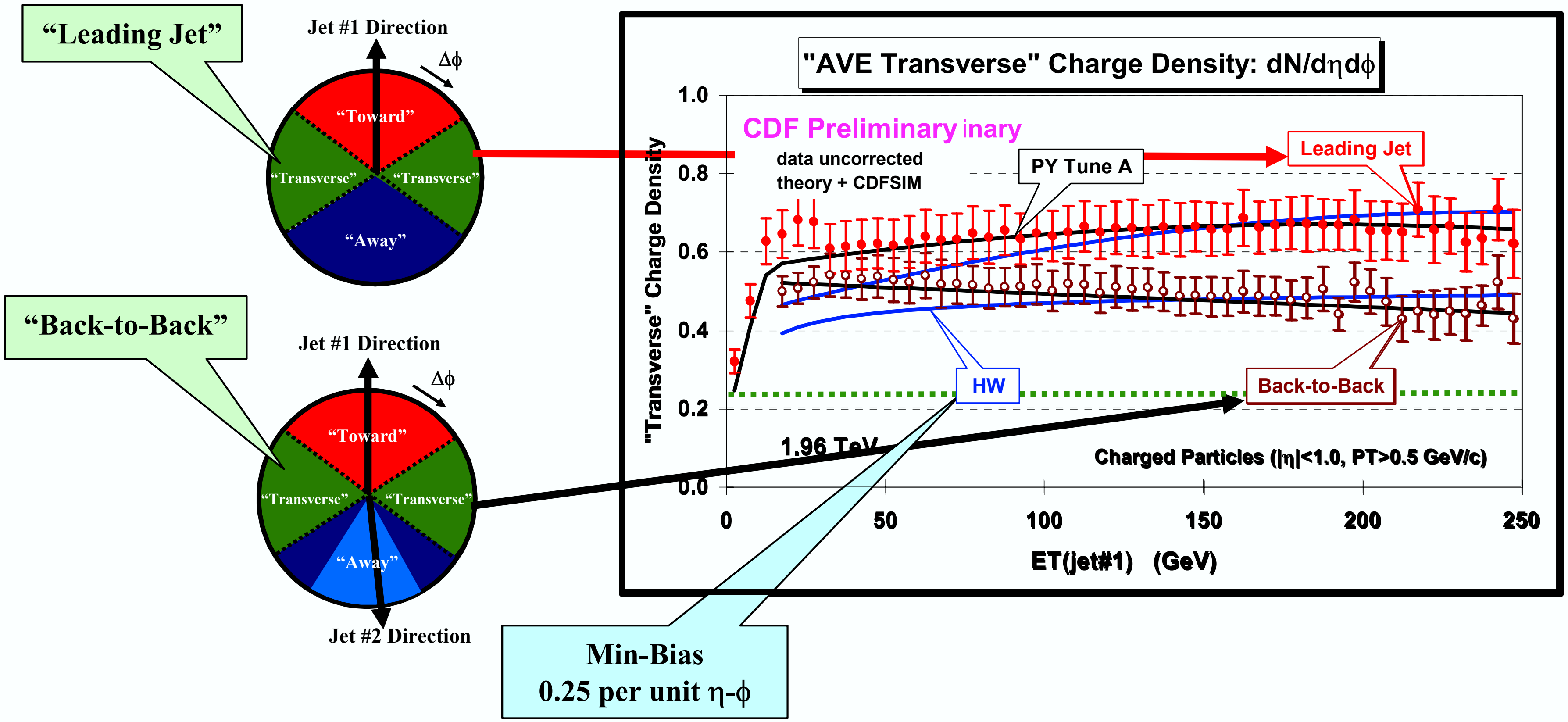
Leading Jet: "MAX & MIN Transverse" Densities

PYTHIA Tune A HERWIG



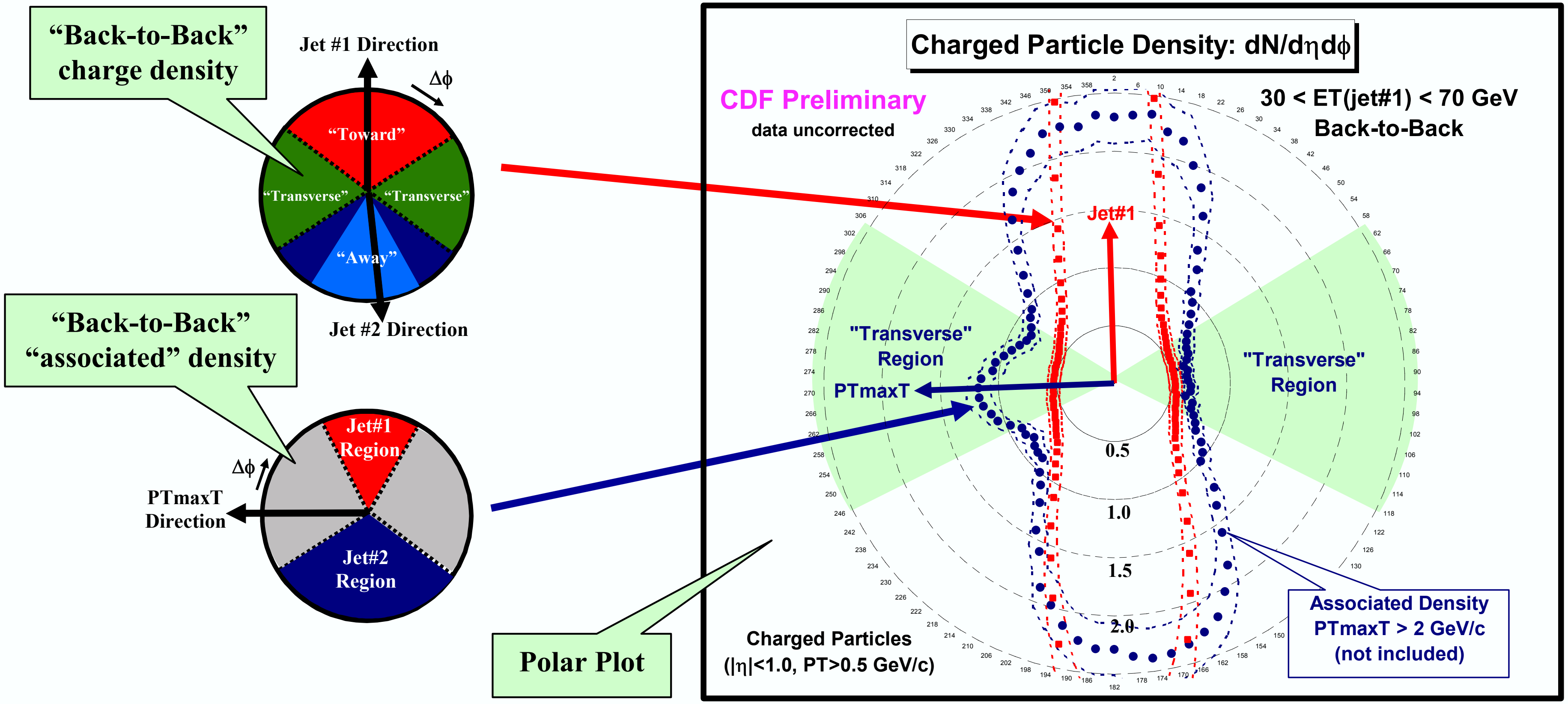
Charged particle density and PTsum density for "leading jet" events versus E_T(jet#1) for PYTHIA Tune A and HERWIG.

"Transverse" Charge Density versus E_T(jet#1)



- Shows the **average charged particle density**, $dN_{chg}/d\eta d\phi$, in the **"transverse" region** (p_T > 0.5 GeV/c, $|\eta| < 1$) versus E_T(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

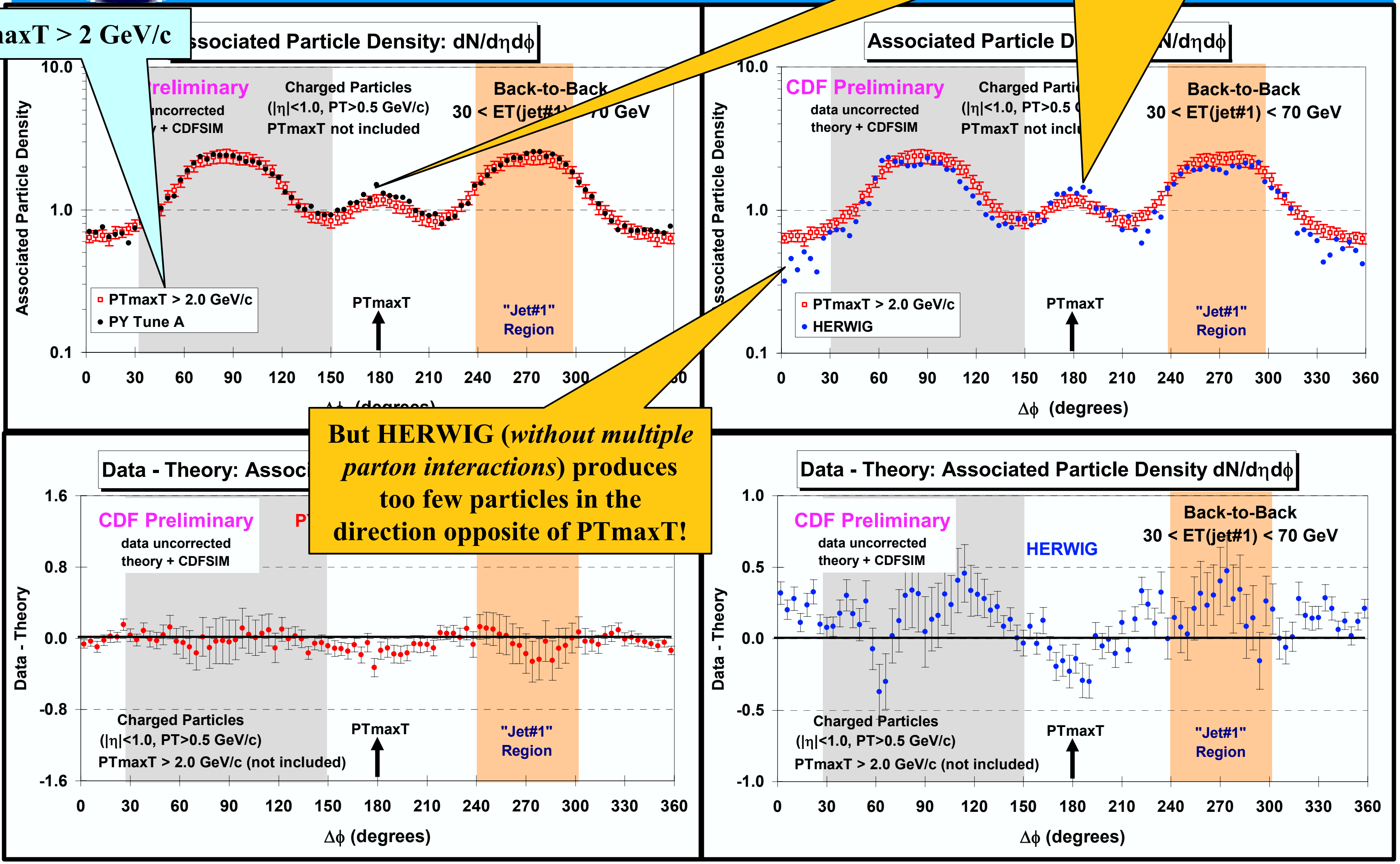


- Shows the **Δϕ dependence of the "associated" charged particle density**, dNchg/dηdϕ, $p_T > 0.5$ GeV/c, |η| < 1, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180°) and the charged particle density, dNchg/dηdϕ, $p_T > 0.5$ GeV/c, |η| < 1, relative to jet#1 (rotated to 270°) for "back-to-back events" with 30 < E_T(jet#1) < 70 GeV.

"Associated" Charge De... PYTHIA Tune A vs HER...

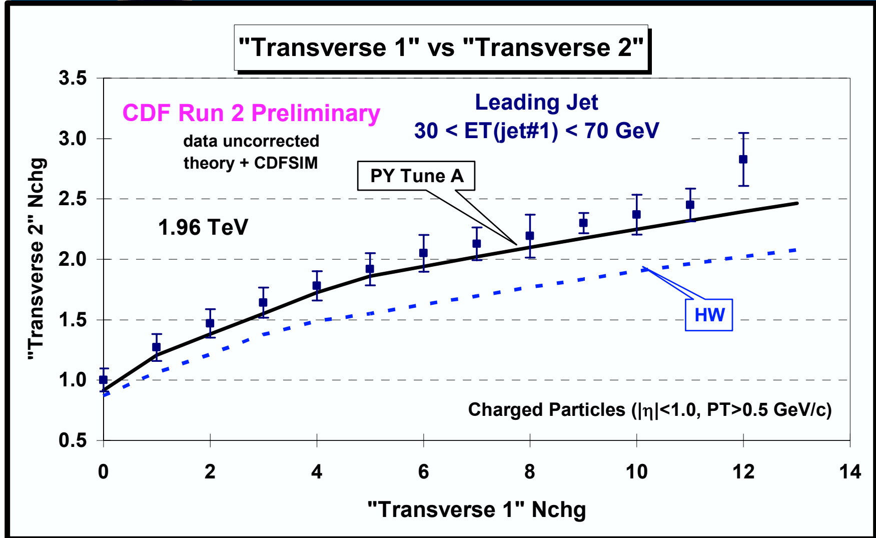
For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too many "associated" particles in the direction of PTmaxT!

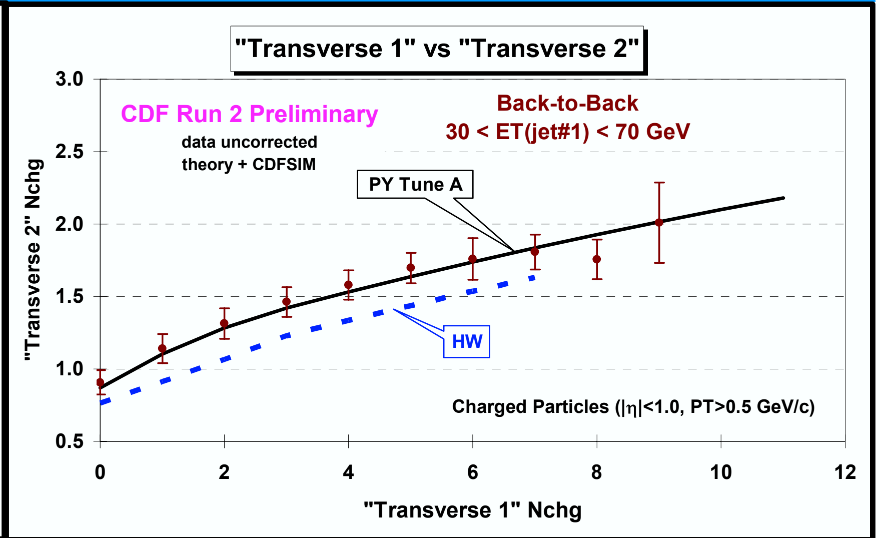
PTmaxT > 2 GeV/c

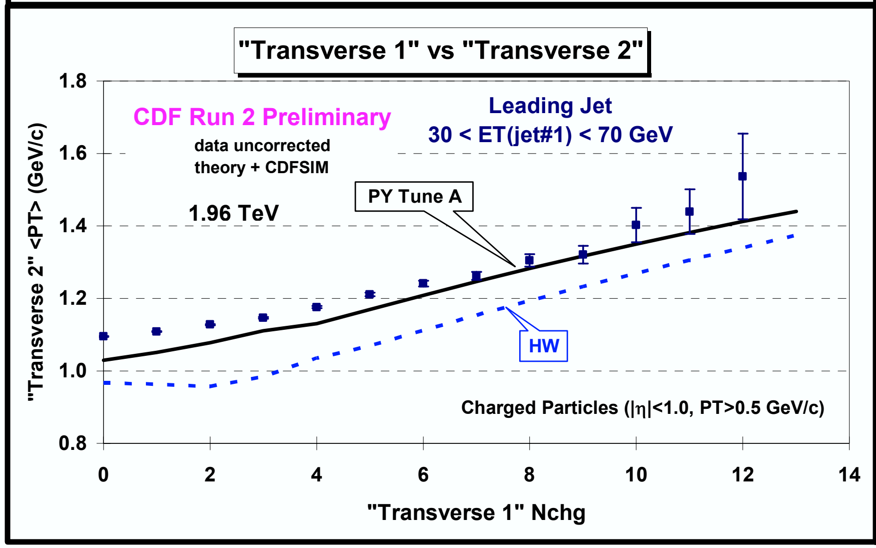


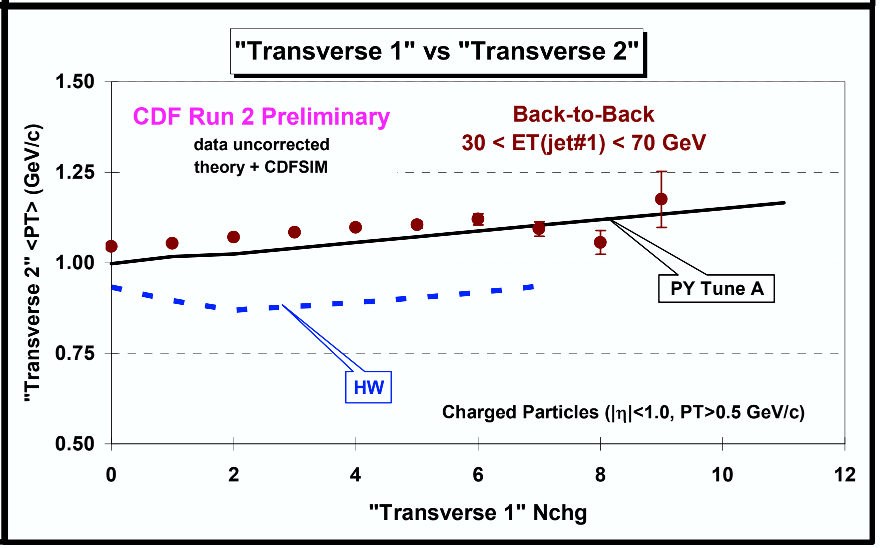
But HERWIG (*without multiple parton interactions*) produces too few particles in the direction opposite of PTmaxT!

"Transverse 1" Region vs "Transverse 2" Region

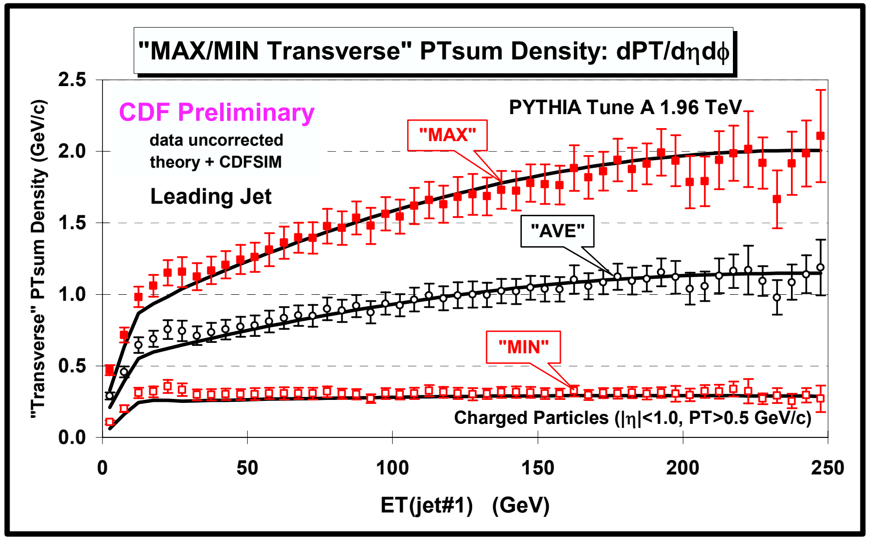


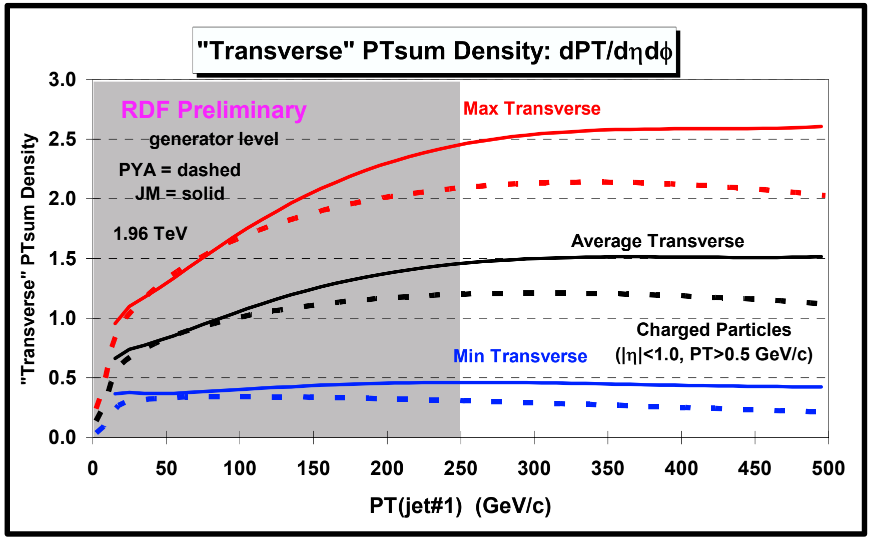






PYTHIA Tune A vs JIMMY: "Transverse Region"

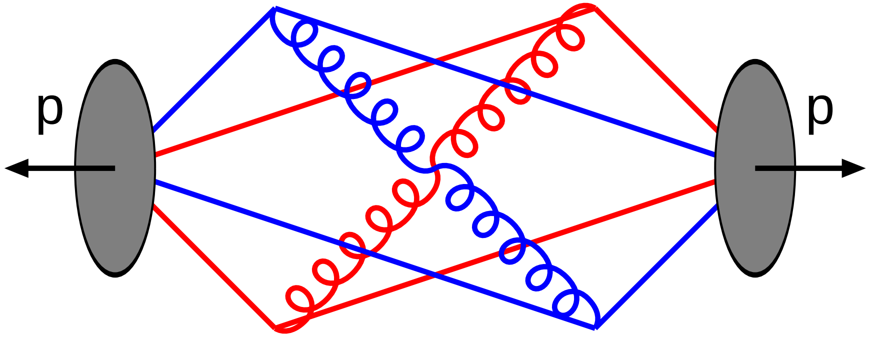




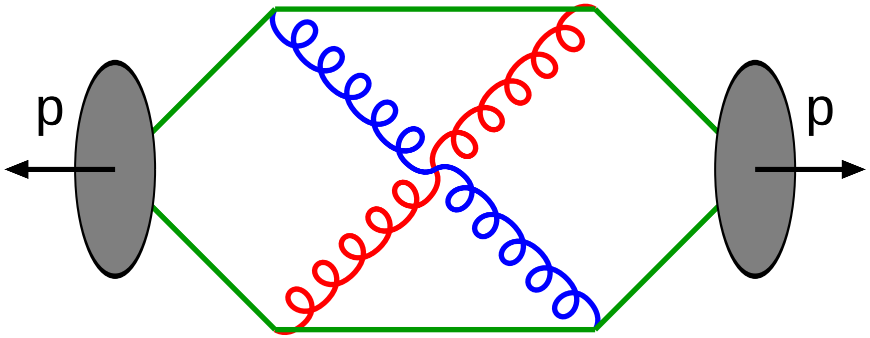
- **(*left*) Run 2 data for charged *scalar* PTsum density (|η|<1, p_T>0.5 GeV/c) in the MAX/MIN/AVE "transverse" region versus P_T(jet#1) compared with PYTHIA Tune A (*after CDFSIM*).**
- **(*right*) Shows the generator level predictions of PYTHIA Tune A (*dashed*) and JIMMY ($P_T$min=1.8 GeV/c) for charged *scalar* PTsum density (|η|<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

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



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



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

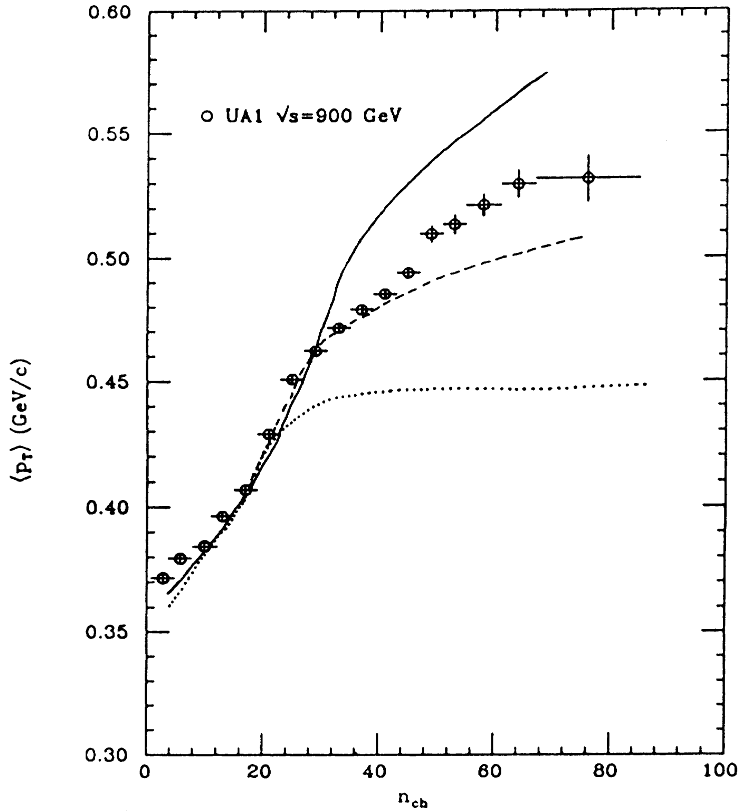
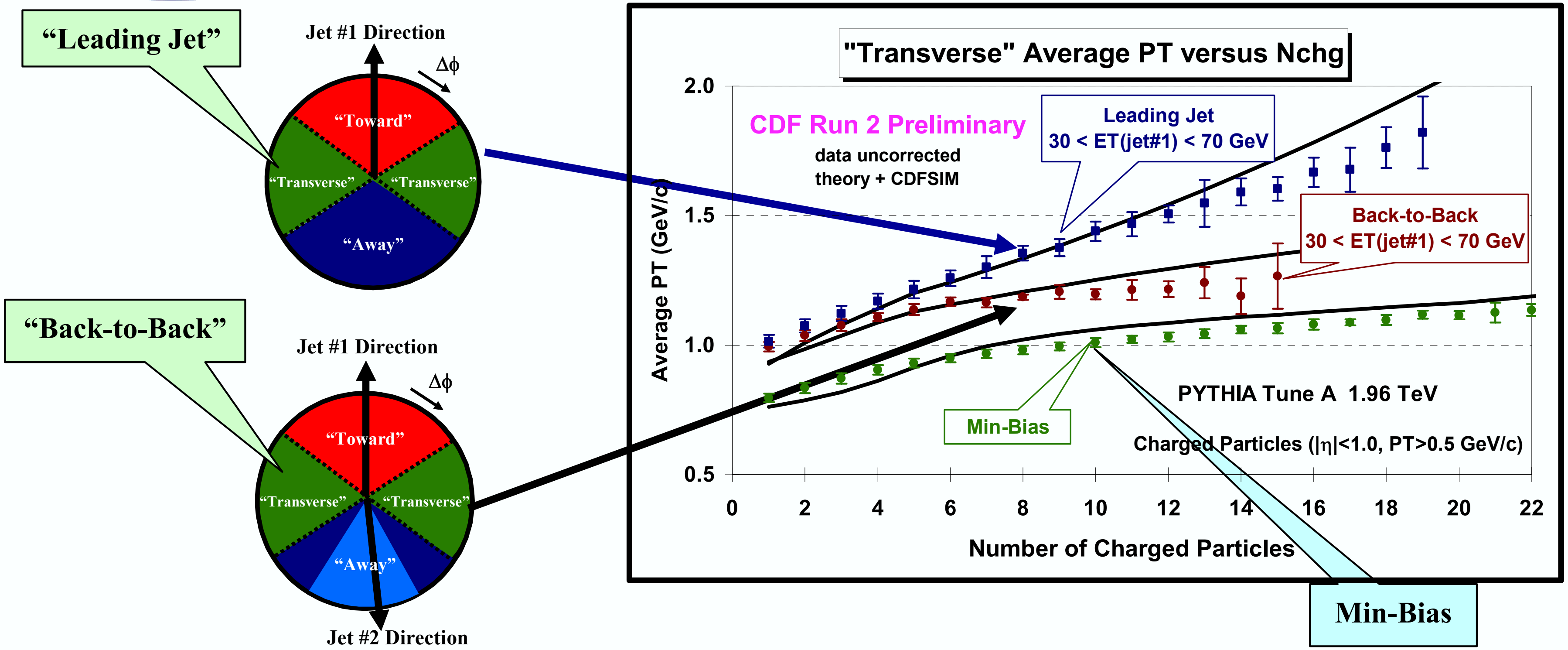


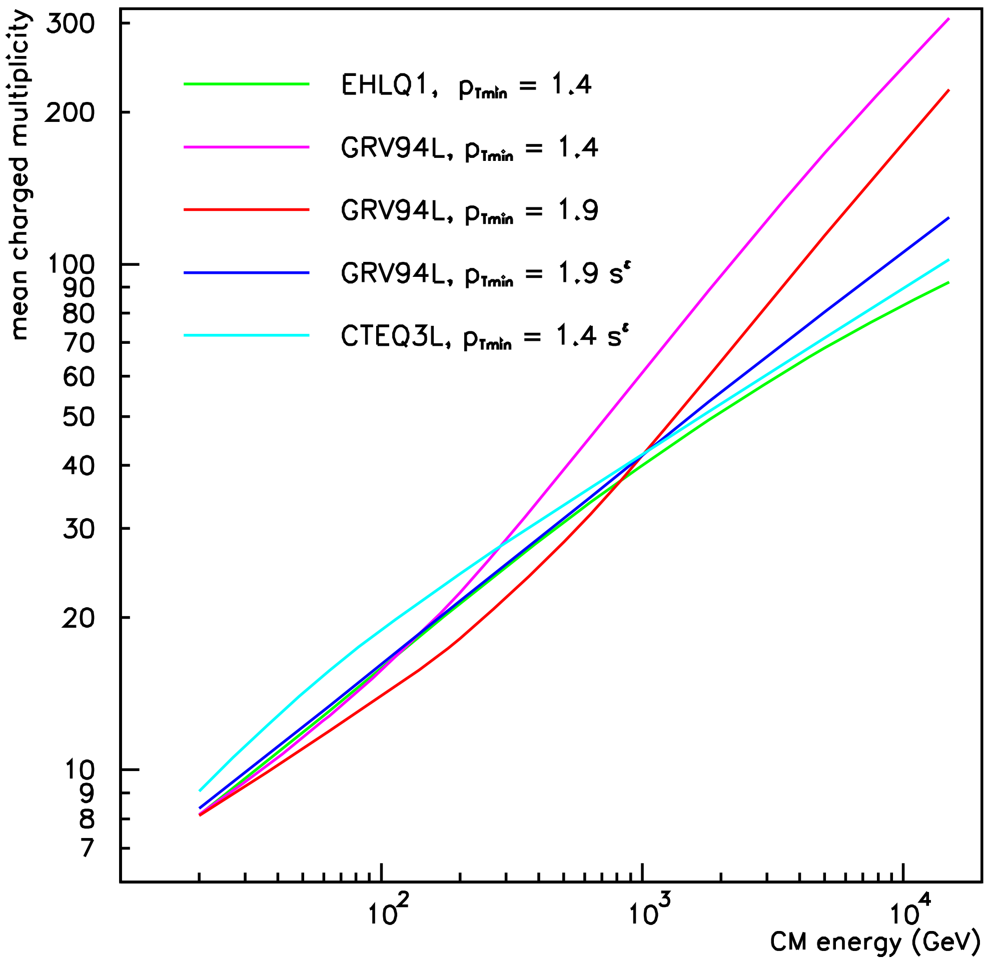
FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings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

"Transverse" <p_T> versus "Transverse" Nchg



- Look at the <p_T> of particles in the "transverse" region (p_T > 0.5 GeV/c, |η| < 1) versus the number of particles in the "transverse" region: <p_T> vs Nchg.
- Shows <p_T> versus Nchg in the "transverse" region (p_T > 0.5 GeV/c, |η| < 1) for "Leading Jet" and "Back-to-Back" events with 30 < E_T(jet#1) < 70 GeV compared with "min-bias" collisions.

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



Larger collision energy

$\Rightarrow$ probe parton ($\approx$ gluon) density at smaller x

$\Rightarrow$ smaller colour screening length d

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

Post-HERA PDF fits steeper at small x

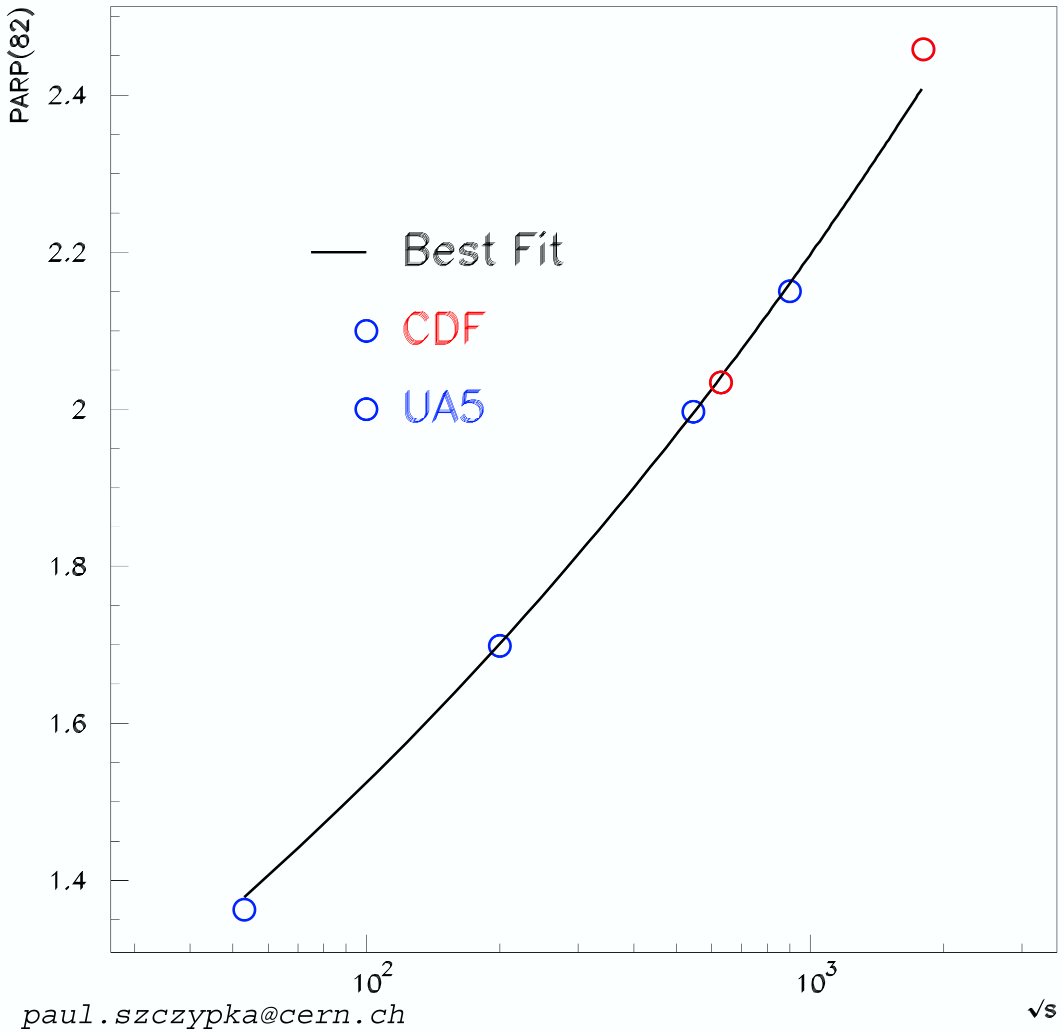
$\Rightarrow$ stronger energy dependence

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

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

Extrapolation of P_T_min I

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



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

$\varepsilon = 0.079 \pm 0.006$

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**

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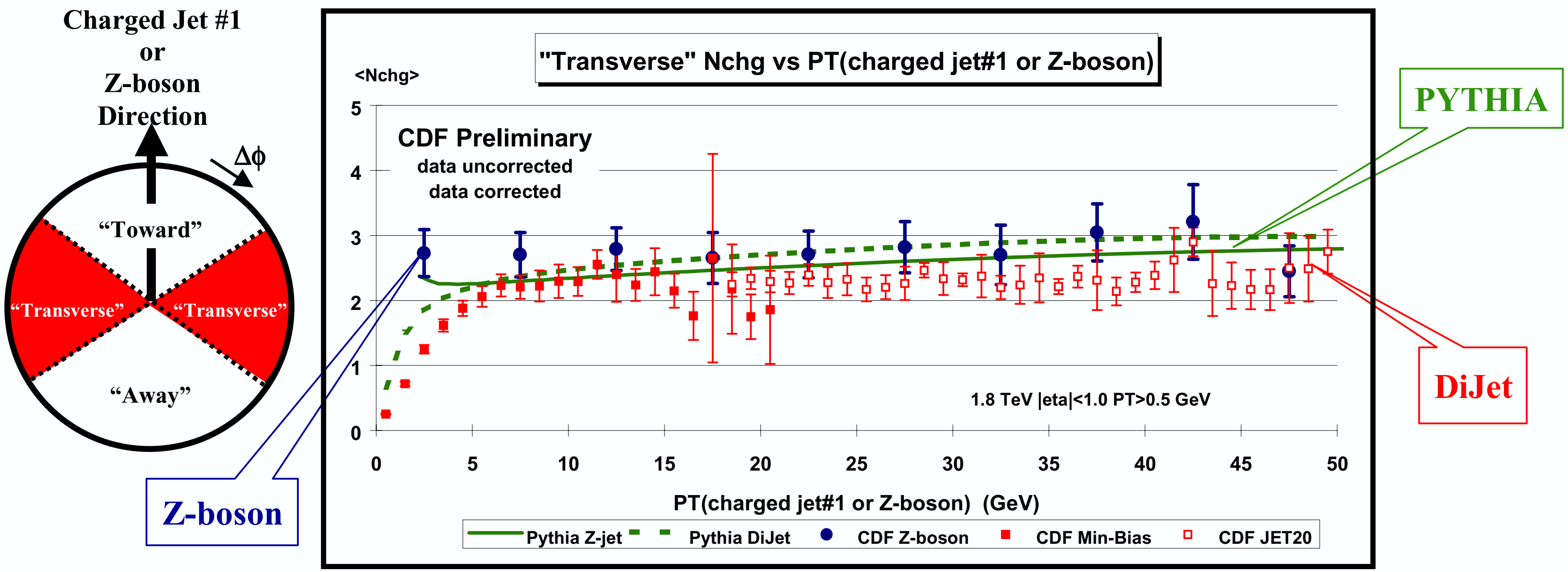
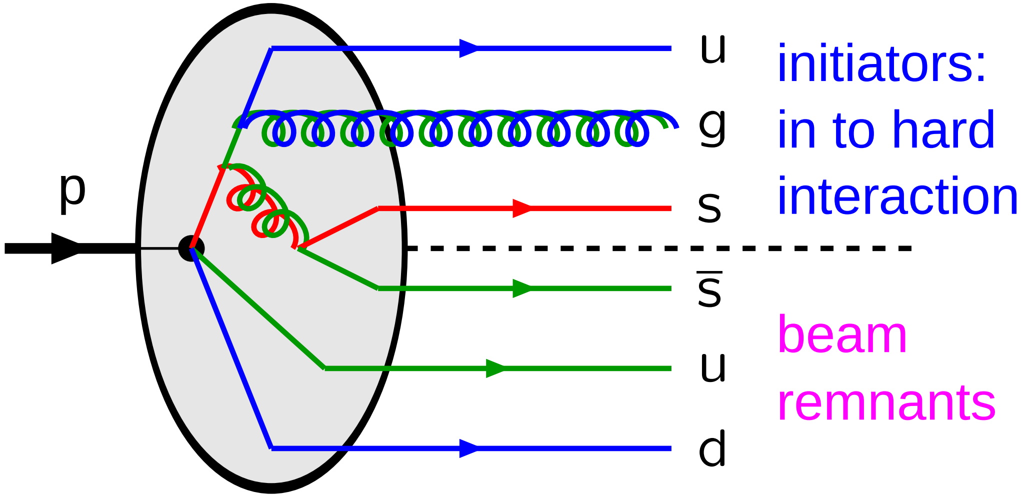
DiJet vs Z-Jet "Transverse" Nchg



- Comparison of the dijet and the Z-boson data on the average number of charged particles (P_T > 0.5 GeV, |η| <1) for the "transverse" region.
- The plot shows the QCD Monte-Carlo predictions of PYTHIA 6.115 (default parameters with P_T(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

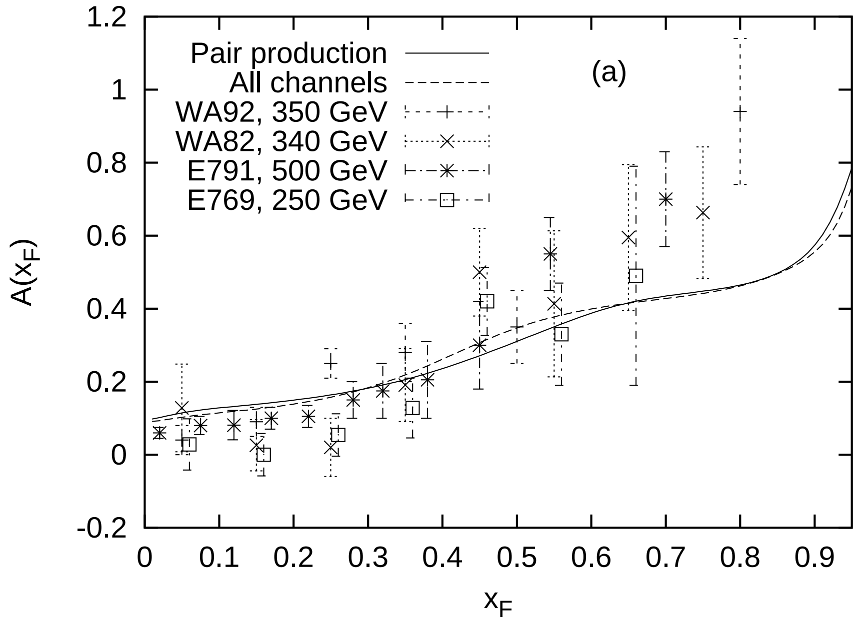
2) Introduce companion quark $\text{q}/\overline{\text{q}}$ to each kicked-out sea quark $\overline{\text{q}}/\text{q}$, with x based on assumed $\text{g} \to \text{q}\overline{\text{q}}$ splitting

3) Gluon and other sea: rescale for total momentum conservation

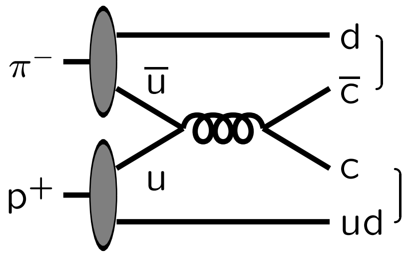
Beam remnant physics

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

$$A(x_\mathrm{F}) = \frac{\#\mathrm{D}^- - \#\mathrm{D}^+}{\#\mathrm{D}^- + \#\mathrm{D}^+}$$



(also B asymmetries at LHC, but small)

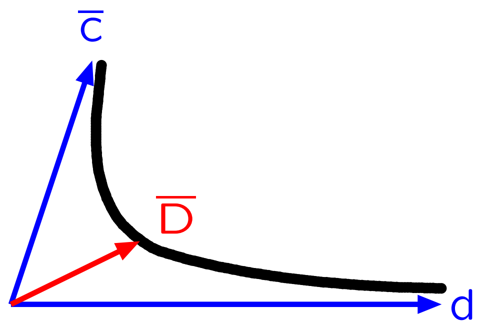


If low-mass string e.g.:

$\bar{\mathrm{c}}\mathrm{d}$: D^-, D^{*-}

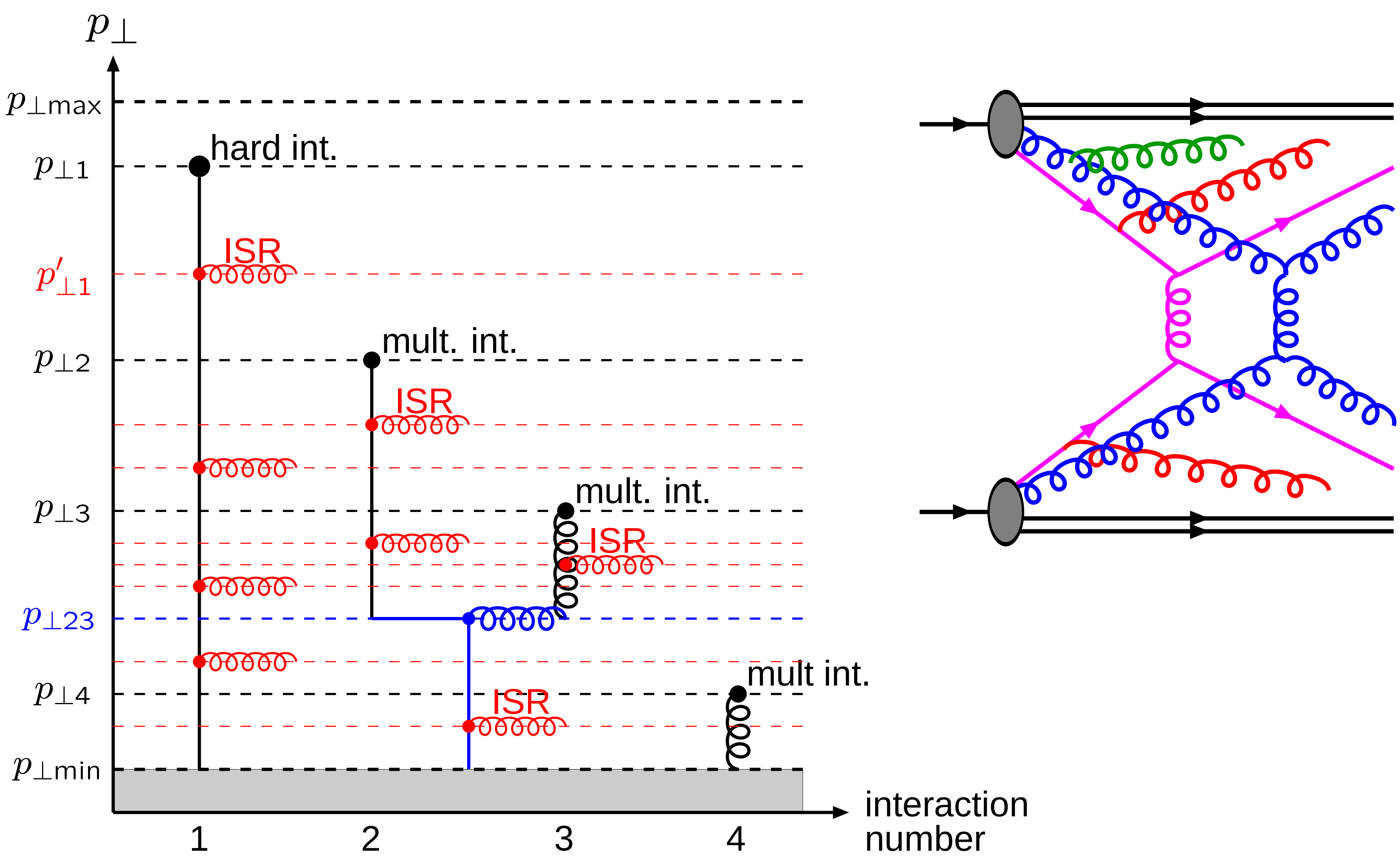
cud: Λ_c^+, Σ_c^+, Σ_c^{*+}

$\Rightarrow$ 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:

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

Evolution equation, only Initial State Radiation:

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

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

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

with ISR sum running over all previous MI

$\Rightarrow$ one interleaved sequence of MI and ISR

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

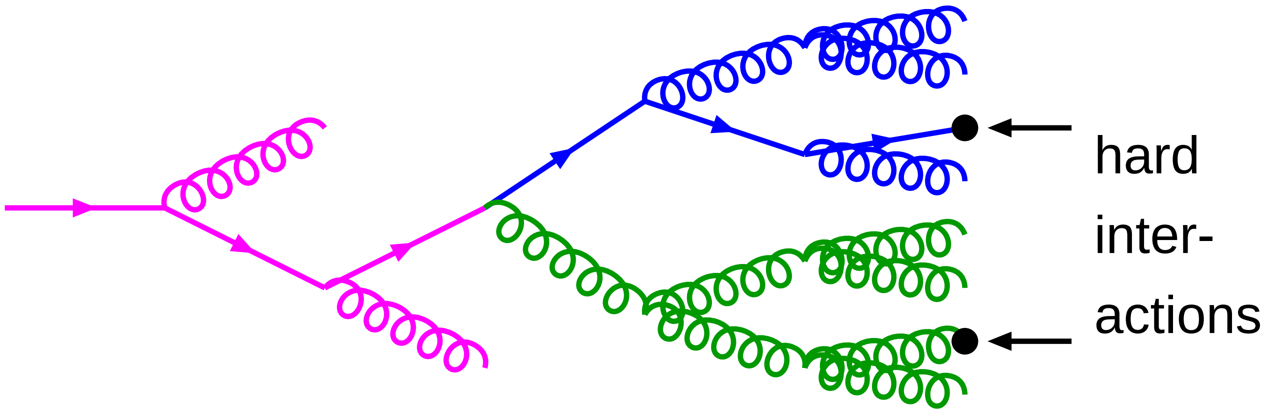
Other issues

- **Regularization procedure:**

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

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

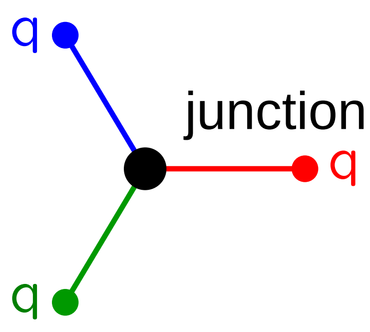
- **Intertwined interactions:**



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

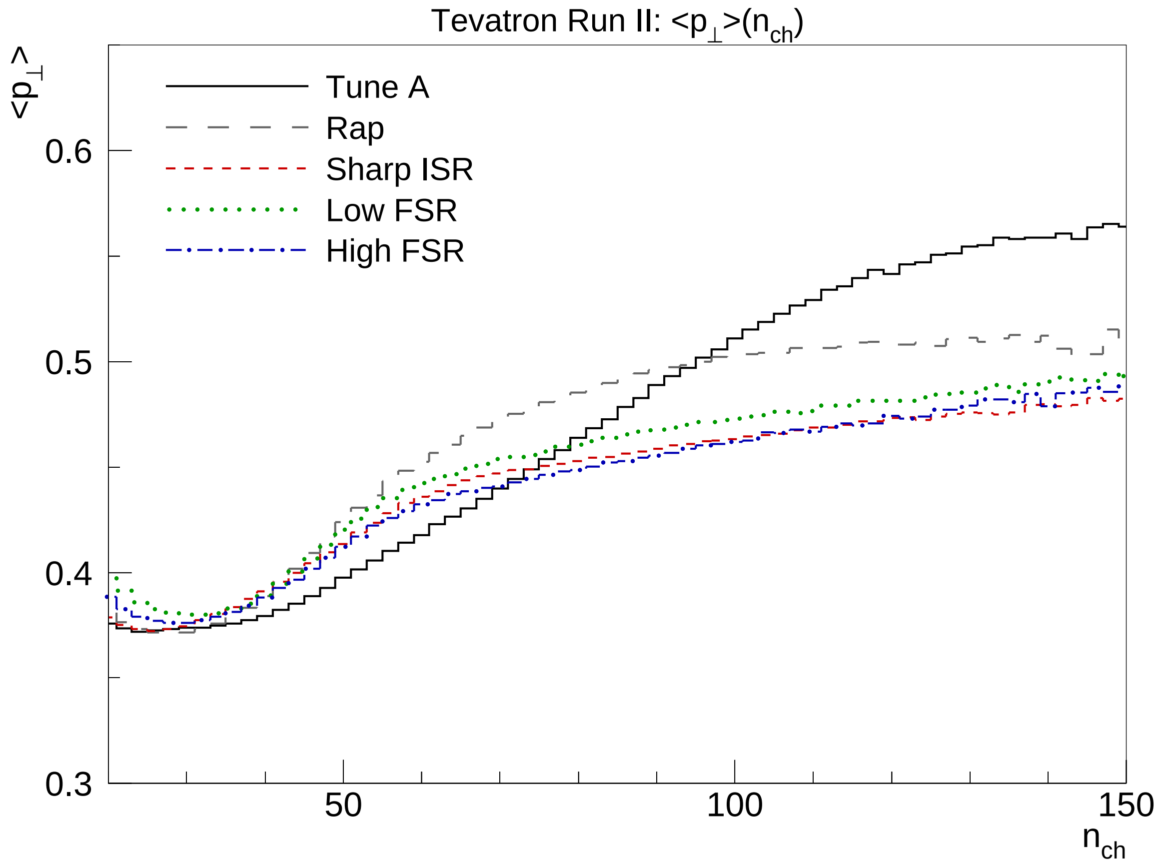
- **Where does the baryon number go?**

Junction “carries” baryon number!
Motion determined by colour flow attached to it.
Messy hadronization (but handled with model)



Data comparisons

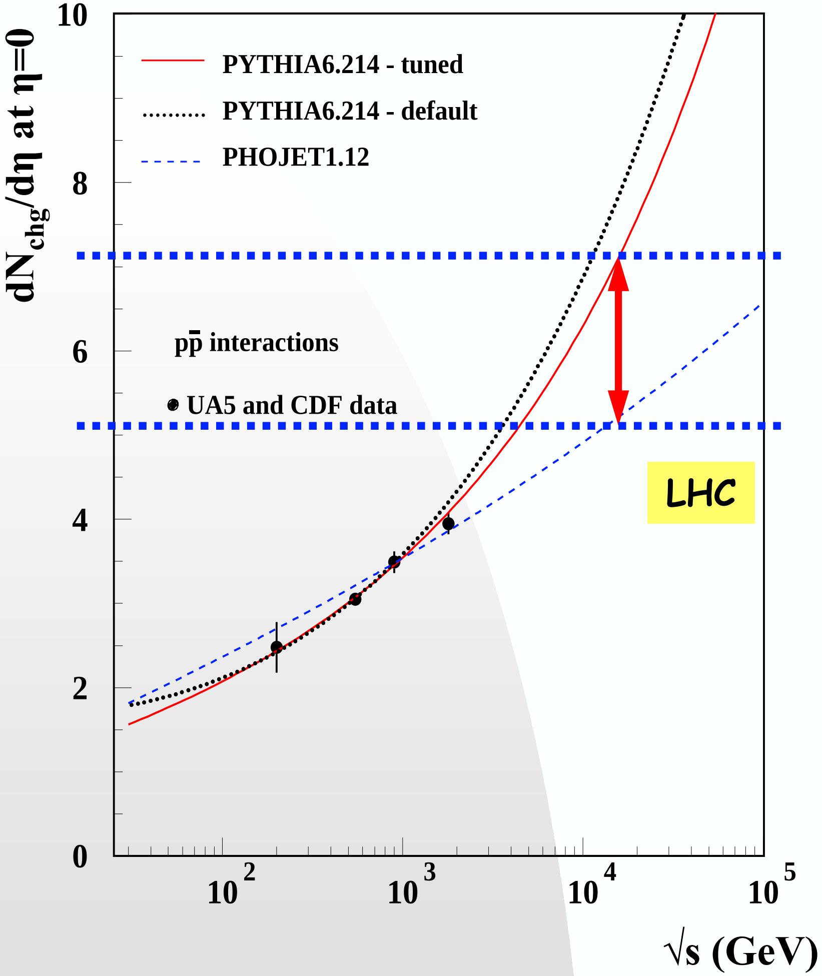
usually comparable with Tune A (for better or worse), but
still in need of good tuning and detailed tests, and . . .
. . . $\langle p_\perp \rangle (n_{\mathrm{ch}})$ problematical (need very short string!)

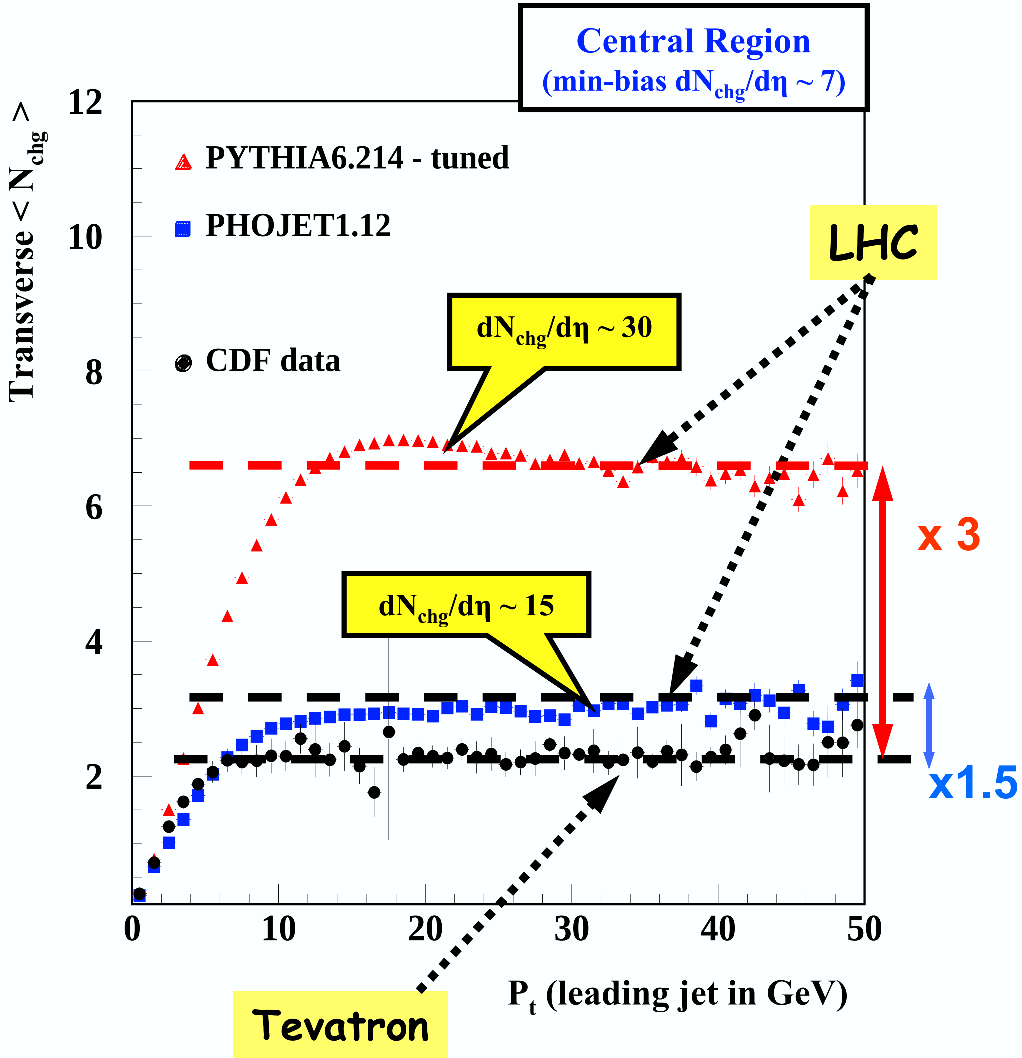


colour correlations not yet understood!

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**

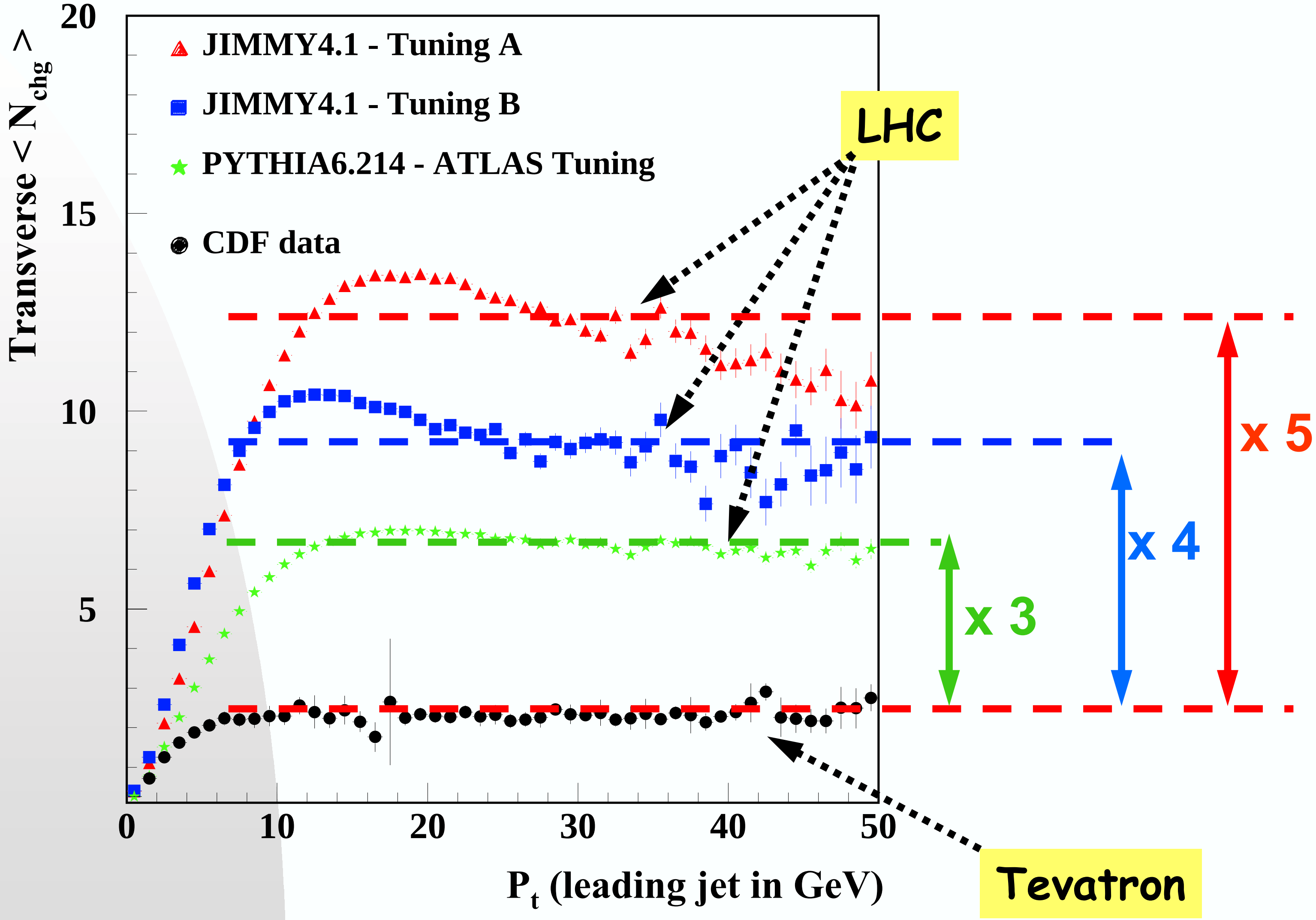
LHC predictions: pp collisions at √s = 14 TeV





- 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)



Multiple Interactions Outlook

• 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 •

⋆ $p_{\perp\mathrm{min}}/p_{\perp 0}$ 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. . . . •