LUND UNIVERSITY

CERN–Fermilab Collider School
Fermilab
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Theory of Hadronic Collisions

Part II: Phenomenology

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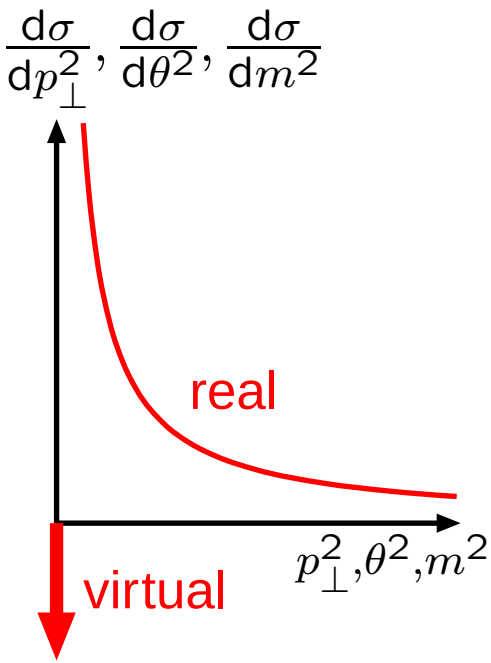
1. (yesterday) Introduction and Overview; Parton Showers
2. **(today) Matching Issues; Multiple Interactions I**
3. (on Monday) Hadronization; MI II/LHC; Generators & Conclusions

Matrix Elements vs. Parton Showers

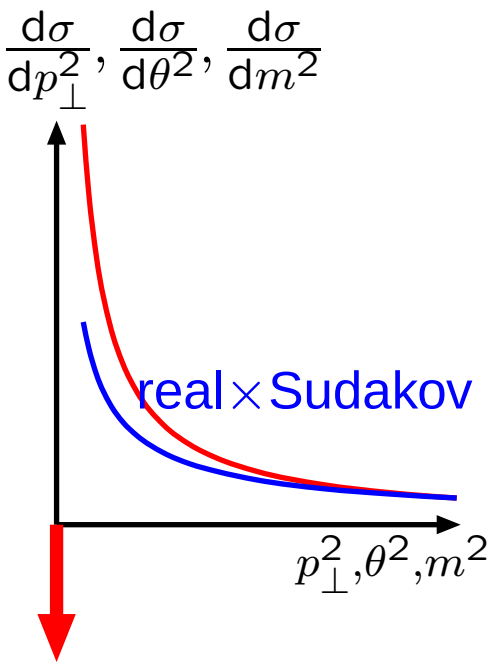
ME : Matrix Elements

- $+$ systematic expansion in α_S (‘*exact*’)
- $+$ powerful for multiparton Born level
- $+$ flexible phase space cuts
- $-$ loop calculations very tough
- $-$ negative cross section in collinear regions
  $\Rightarrow$ unpredictive jet/event structure
- $-$ *no easy match to hadronization*

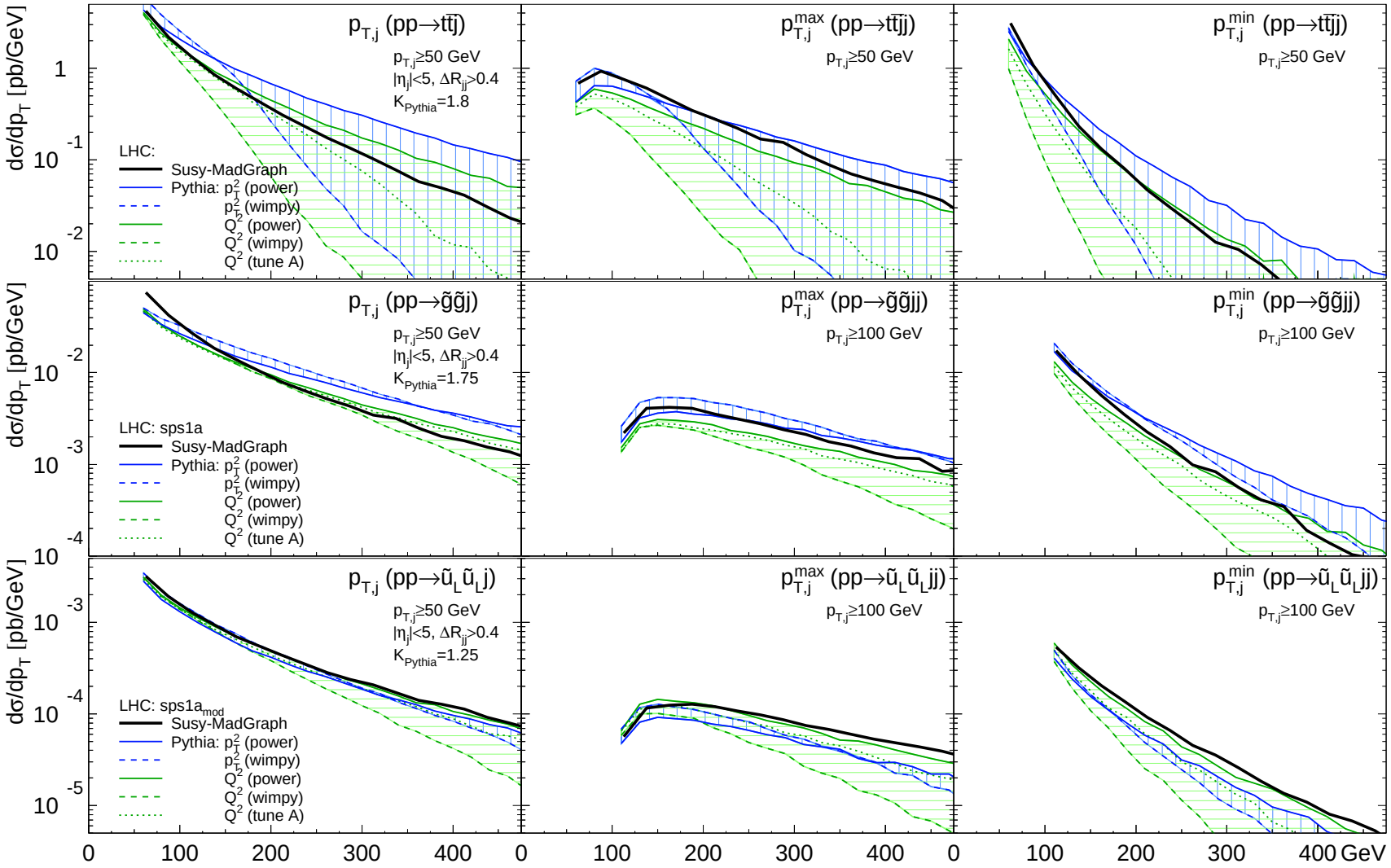


PS : Parton Showers

- $-$ approximate, to LL (or NLL)
- $-$ main topology not predetermined
  $\Rightarrow$ inefficient for exclusive states
- $+$ process-generic $\Rightarrow$ simple multiparton
- $+$ Sudakov form factors/resummation
  $\Rightarrow$ sensible jet/event structure
- $+$ *easy to match to hadronization*



$p_\perp$(1 jet) $p_\perp^{\max}$(2 jets) $p_\perp^{\min}$(2 jets)



power: $Q^2_{\max} = s$; wimpy: $Q^2_{\max} = m_\perp^2$; tune A: $Q^2_{\max} = 4m_\perp^2$

$m_{\mathrm{t}} = 175$ GeV, $m_{\tilde{\mathrm{g}}} = 608$ GeV, $m_{\tilde{\mathrm{u}}_L} = 567$ GeV

(T. Plehn, D. Rainwater, P. Skands)

Matrix Elements and Parton Showers

Recall complementary strengths:

- ME's good for well separated jets
- PS's good for structure inside jets

Marriage desirable! But how?

Problems:

- gaps in coverage?
- doublecounting of radiation?
- Sudakov?
- NLO consistency?

Much work ongoing $\Longrightarrow$ no established orthodoxy

Three main areas, in ascending order of complication:

1) Match to lowest-order nontrivial process — merging

2) Combine leading-order multiparton process — vetoed parton showers

3) Match to next-to-leading order process — MC@NLO

Merging

= cover full phase space with smooth transition ME/PS

Want to reproduce $$W^{\mathrm{ME}} = \frac{1}{\sigma(\mathrm{LO})}\,\frac{\mathrm{d}\sigma(\mathrm{LO}+\mathrm{g})}{\mathrm{d}(\mathrm{phasespace})}$$

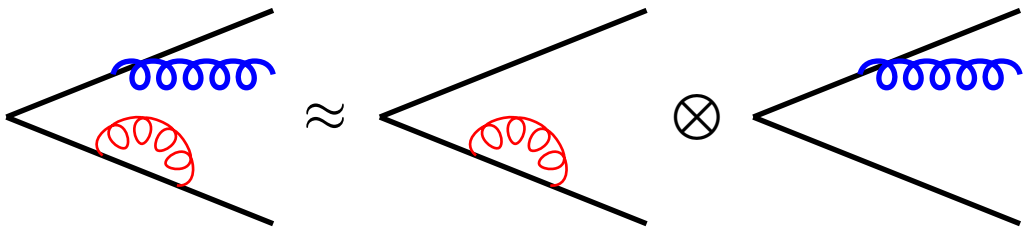
by shower generation + correction procedure

$$\overbrace{W^{\mathrm{ME}}}^{\text{wanted}} = \overbrace{W^{\mathrm{PS}}}^{\text{generated}}\ \overbrace{\frac{W^{\mathrm{ME}}}{W^{\mathrm{PS}}}}^{\text{correction}}$$

- Exponentiate ME correction by shower Sudakov form factor:

$$W^{\mathrm{PS}}_{\mathrm{actual}}(Q^2) = W^{\mathrm{ME}}(Q^2)\,\exp\left(-\int_{Q^2}^{Q^2_{\mathrm{max}}} W^{\mathrm{ME}}(Q'^2)\,\mathrm{d}Q'^2\right)$$

- Do not normalize W^{ME} to $\sigma(\mathrm{NLO})$ (error $\mathcal{O}(\alpha_s^2)$ either way)



$$\boxed{\begin{array}{ccccc} 1+\mathcal{O}(\alpha_s) & & & & \int = 1 \\ \downarrow & & & & \downarrow \\ \mathrm{d}\sigma & = & K & \sigma_0 & \mathrm{d}W^{\mathrm{PS}} \end{array}}$$

- Normally several shower histories $\Rightarrow$ $\sim$equivalent approaches

Final-State Shower Merging

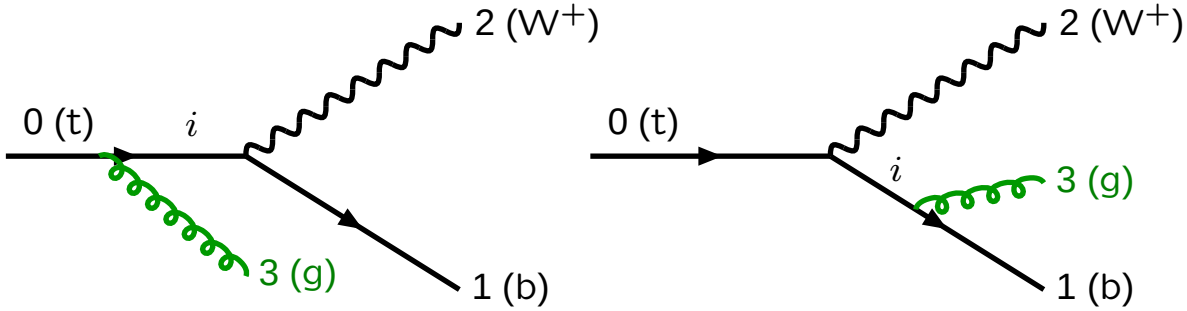
Merging with $\gamma^*/\mathrm{Z}^0 \to \mathrm{q\overline{q}g}$ for $m_\mathrm{q} = 0$ since long

(M. Bengtsson & TS, PLB185 (1987) 435, NPB289 (1987) 810)

For $m_\mathrm{q} > 0$ pick $Q_i^2 = m_i^2 - m_{i,\mathrm{onshell}}^2$ as evolution variable since

$$W^{\mathrm{ME}} = \frac{(\ldots)}{Q_1^2 Q_2^2} - \frac{(\ldots)}{Q_1^4} - \frac{(\ldots)}{Q_2^4}$$

Coloured decaying particle also radiates:



ME $\frac{1}{Q_0^2 Q_1^2}$

matches

PS $\mathrm{b} \to \mathrm{bg}$

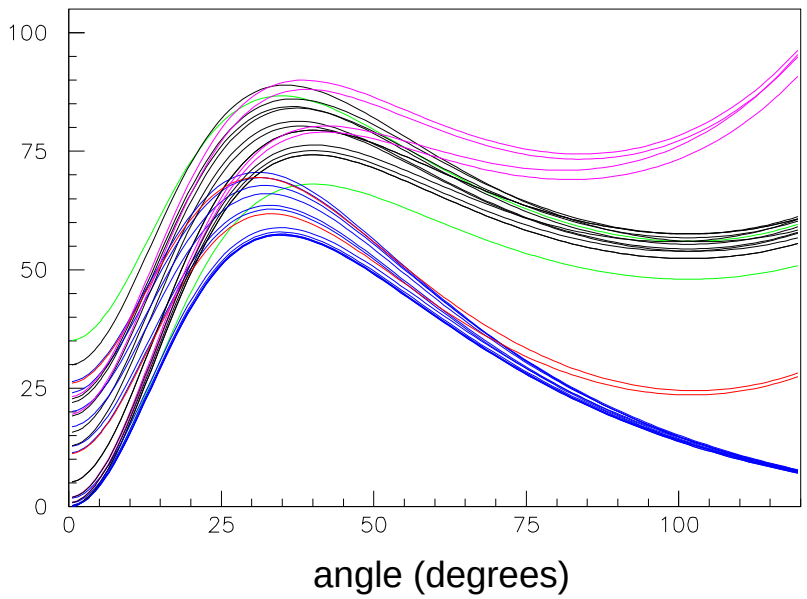
$\boxed{\Rightarrow \text{ can merge PS with generic } a \to bc\mathrm{g} \text{ ME}}$

(E. Norrbin & TS, NPB603 (2001) 297)

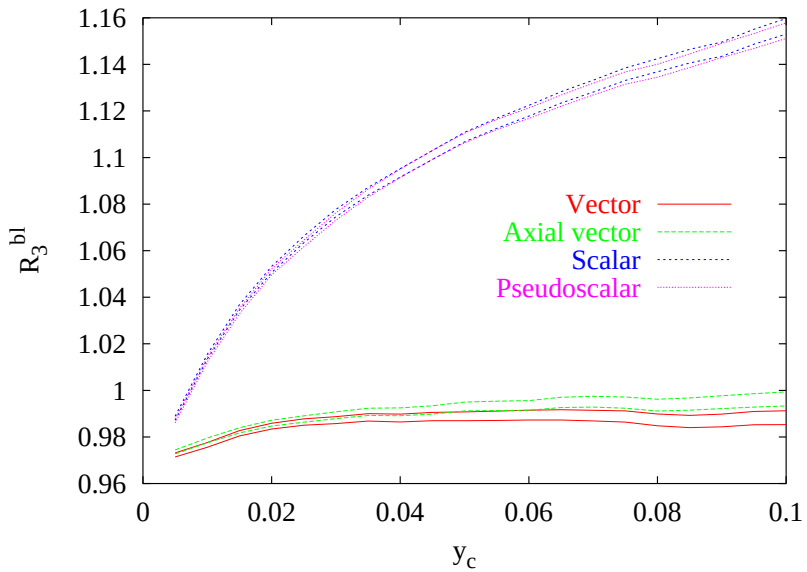
Subsequent branchings $\mathrm{q} \to \mathrm{qg}$: also matched to ME, with reduced energy of system

PYTHIA performs merging with generic FSR $a \to bcg$ ME,
in SM: $\gamma^*/Z^0/W^\pm \to q\bar{q}$, $t \to bW^+$, $H^0 \to q\bar{q}$,
and MSSM: $t \to bH^+$, $Z^0 \to \tilde{q}\bar{\tilde{q}}$, $\tilde{q} \to \tilde{q}'W^+$, $H^0 \to \tilde{q}\bar{\tilde{q}}$, $\tilde{q} \to \tilde{q}'H^+$,
$\chi \to q\bar{\tilde{q}}$, $\chi \to q\bar{\tilde{q}}$, $\tilde{q} \to q\chi$, $t \to \tilde{t}\chi$, $\tilde{g} \to q\bar{\tilde{q}}$, $\tilde{q} \to q\tilde{g}$, $t \to \tilde{t}\tilde{g}$

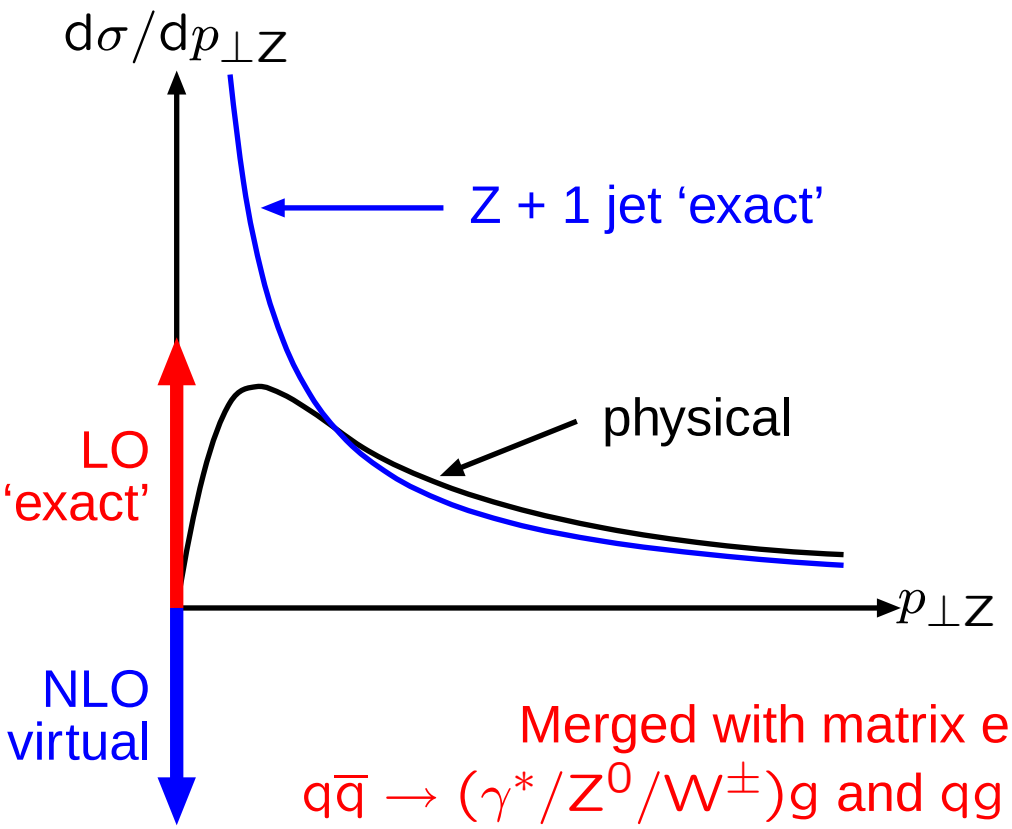
g emission for different colour, spin and parity:



$R_3^{bl}(y_c)$: mass effects in Higgs decay:



Initial-State Shower Merging



resummation:
physical $p_{\perp Z}$ spectrum

shower: ditto
+ accompanying
jets (exclusive)

Merged with matrix elements for
$q\bar{q} \to (\gamma^*/Z^0/W^\pm)g$ and $qg \to (\gamma^*/Z^0/W^\pm)q'$:
(G. Miu & TS, PLB449 (1999) 313)

$$\left(\frac{W^{\mathrm{ME}}}{W^{\mathrm{PS}}}\right)_{q\bar{q}'\to gW} = \frac{\hat{t}^2 + \hat{u}^2 + 2m_W^2\hat{s}}{\hat{s}^2 + m_W^4} \leq 1$$

$$\left(\frac{W^{\mathrm{ME}}}{W^{\mathrm{PS}}}\right)_{qg\to q'W} = \frac{\hat{s}^2 + \hat{u}^2 + 2m_W^2\hat{t}}{(\hat{s} - m_W^2)^2 + m_W^4} < 3$$

with $Q^2 = -m^2$
and $z = m_W^2/\hat{s}$

Merging in HERWIG

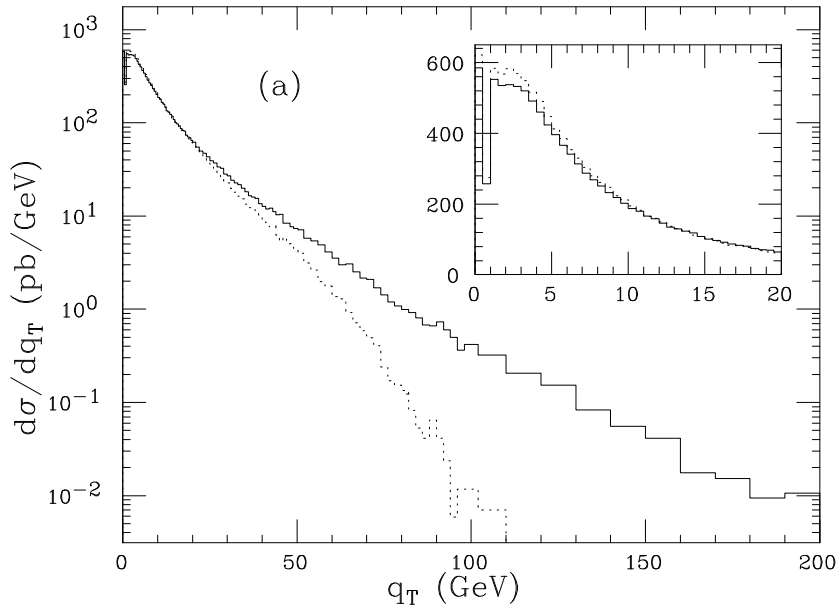
HERWIG also contains merging, for

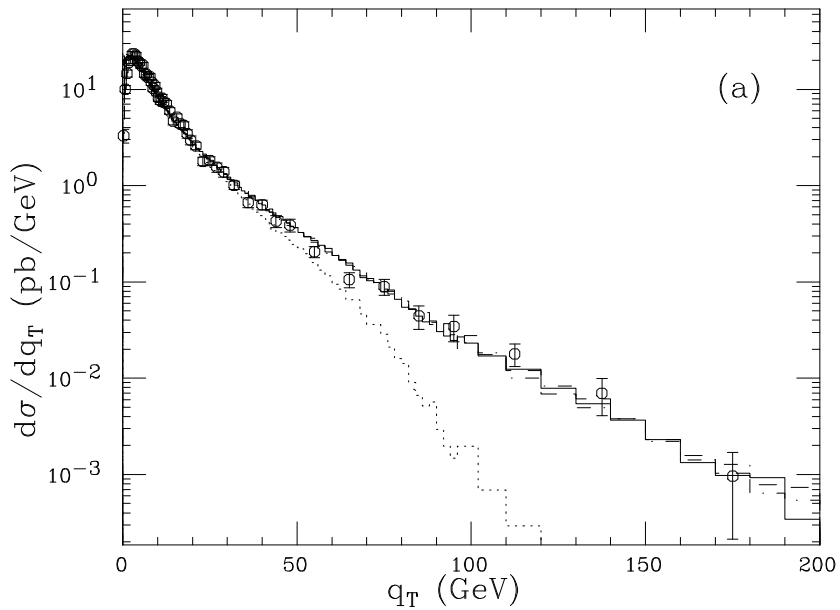
- $Z^0 \to q\bar{q}$
- $t \to bW^+$
- $q\bar{q} \to Z^0$

and some more

Special problem:
angular ordering does not cover full phase space; so
(1) fill in “dead zone” with ME
(2) apply ME correction
in allowed region

Important for agreement with data:





Vetoed Parton Showers

S. Catani, F. Krauss, R. Kuhn, B.R. Webber, JHEP 0111 (2001) 063; L. Lönnblad, JHEP0205 (2002) 046;

F. Krauss, JHEP 0208 (2002) 015; S. Mrenna, P. Richardson, JHEP0405 (2004) 040;

S. Höche et al., hep-ph/0602031

Generic method to combine ME's of several different orders
to NLL accuracy; will be a 'standard tool' in the future

Basic idea:

- consider (differential) cross sections $\sigma_0, \sigma_1, \sigma_2, \sigma_3, \ldots$,
  corresponding to a lowest-order process (e.g. W or H production),
  with more jets added to describe more complicated topologies,
  in each case to the respective leading order
- σ_i, $i \geq 1$, are divergent in soft/collinear limits
- absent virtual corrections would have ensured "detailed balance",
  i.e. an emission that adds to σ_{i+1} subtracts from σ_i
- such virtual corrections correspond (approximately)
  to the Sudakov form factors of parton showers
- so use shower routines to provide missing virtual corrections
  $\Rightarrow$ rejection of events (especially) in soft/collinear regions

Veto scheme:

1) Pick hard process, mixing according to $\sigma_0 : \sigma_1 : \sigma_2 : \ldots$,
above some ME cutoff (e.g. all $p_{\perp i} > p_{\perp 0}$, all $R_{ij} > R_0$),
with large fixed α_{s0}

2) Reconstruct imagined shower history (in different ways)

3) Weight $W_\alpha = \prod_{\text{branchings}} (\alpha_s(k_{\perp i}^2)/\alpha_{s0}) \Rightarrow$ accept/reject

CKKW-L:

4) Sudakov factor for non-emission
on all lines above ME cutoff
$W_{\text{Sud}} = \prod_{\text{“propagators”}}$
$\text{Sudakov}(k_{\perp\text{beg}}^2, k_{\perp\text{end}}^2)$

4a) CKKW : use NLL Sudakovs

4b) L: use trial showers

5) $W_{\text{Sud}} \Rightarrow$ accept/reject

6) do shower,
vetoing emissions above cutoff

MLM:

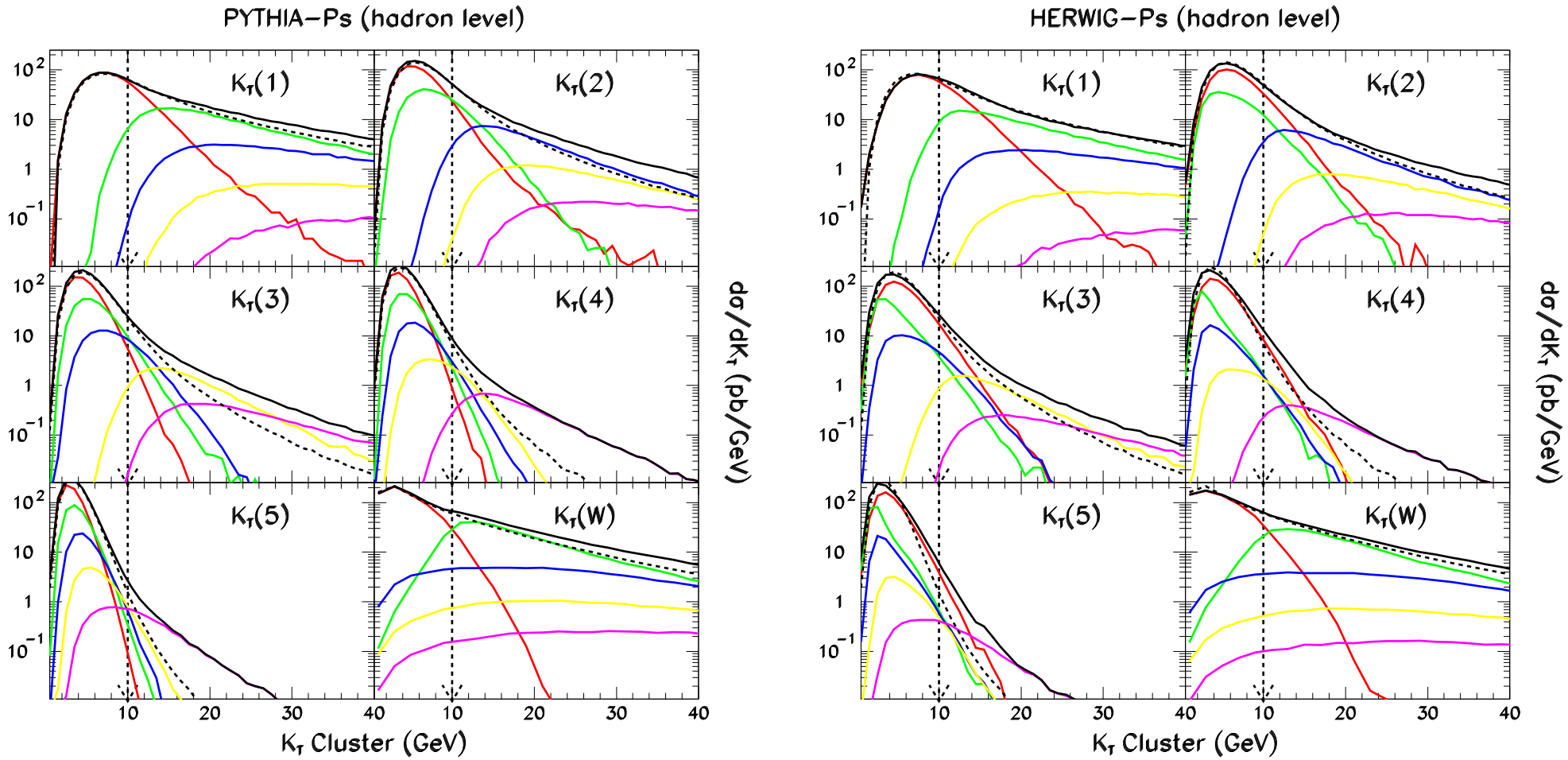
4) do parton showers

5) (cone-)cluster
showered event

6) match partons and jets

7) if all partons are matched,
and $n_{\text{jet}} = n_{\text{parton}}$,
keep the event,
else discard it

CKKW mix of $W + (0, 1, 2, 3, 4)$ partons,
hadronized and clustered to jets:



(S.Mrenna, P. Richardson)

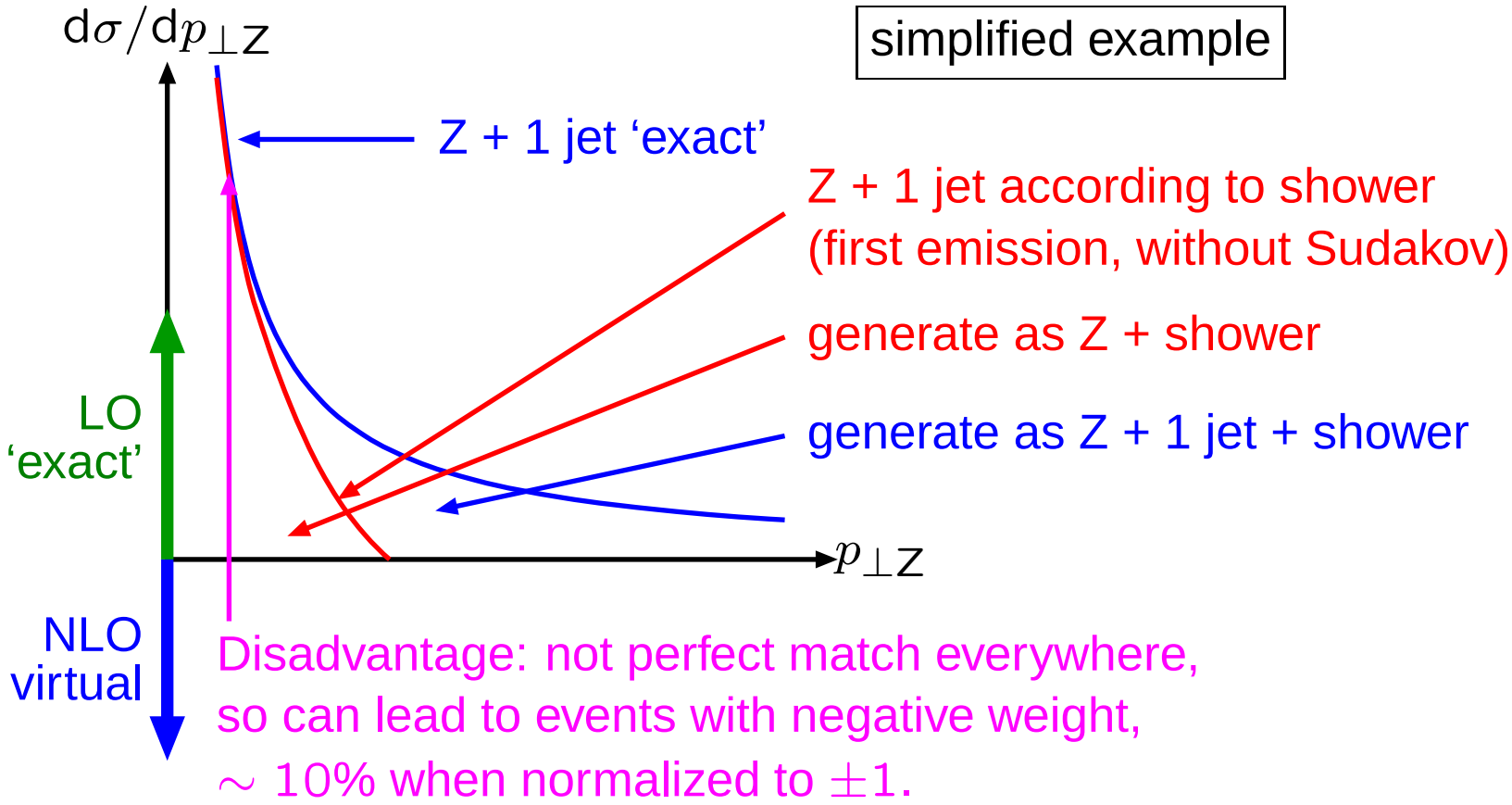
MC@NLO

Objectives:

- Total rate should be accurate to NLO.
- NLO results are obtained for all observables when (formally) expanded in powers of α_S.
- Hard emissions are treated as in the NLO computations.
- Soft/collinear emissions are treated as in shower MC.
- The matching between hard and soft emissions is smooth.
- The outcome is a set of "normal" events, that can be processed further.

Basic scheme (simplified!):

1) Calculate the NLO matrix element corrections to an n-body process (using the subtraction approach).
2) Calculate analytically (no Sudakov!) how the first shower emission off an n-body topology populates $(n+1)$-body phase space.
3) Subtract the shower expression from the $(n+1)$ ME to get the "true" $(n+1)$ events, and consider the rest of σ_{NLO} as n-body.
4) Add showers to both kinds of events.



MC@NLO in comparison:

- Superior with respect to "total" cross sections.
- Equivalent to merging for event shapes (differences higher order).
- Inferior to CKKW–L for multijet topologies.

$\Rightarrow$ pick according to current task and availability.

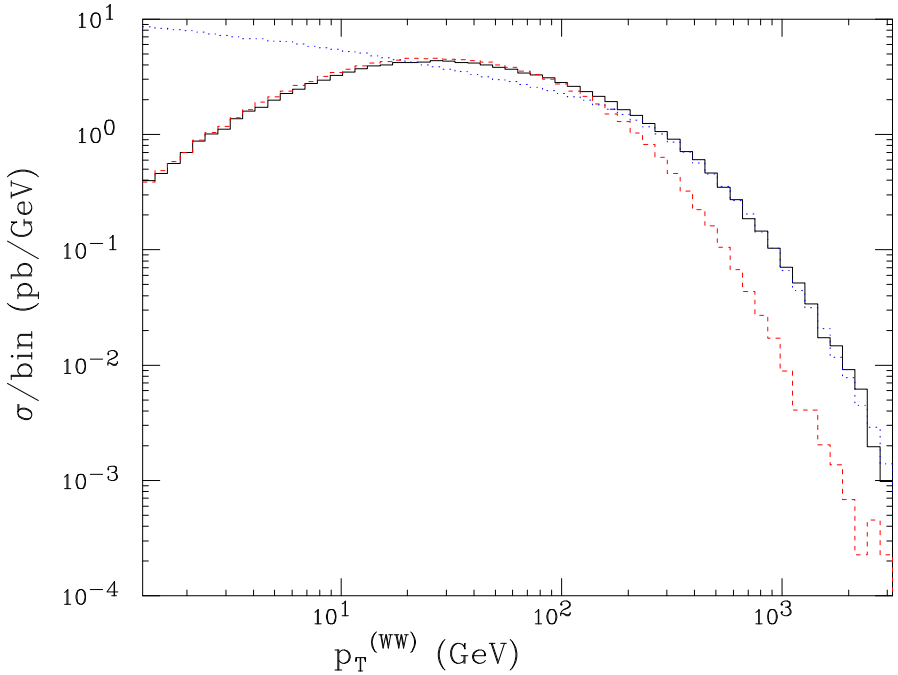
MC@NLO 2.31 [hep-ph/0402116]

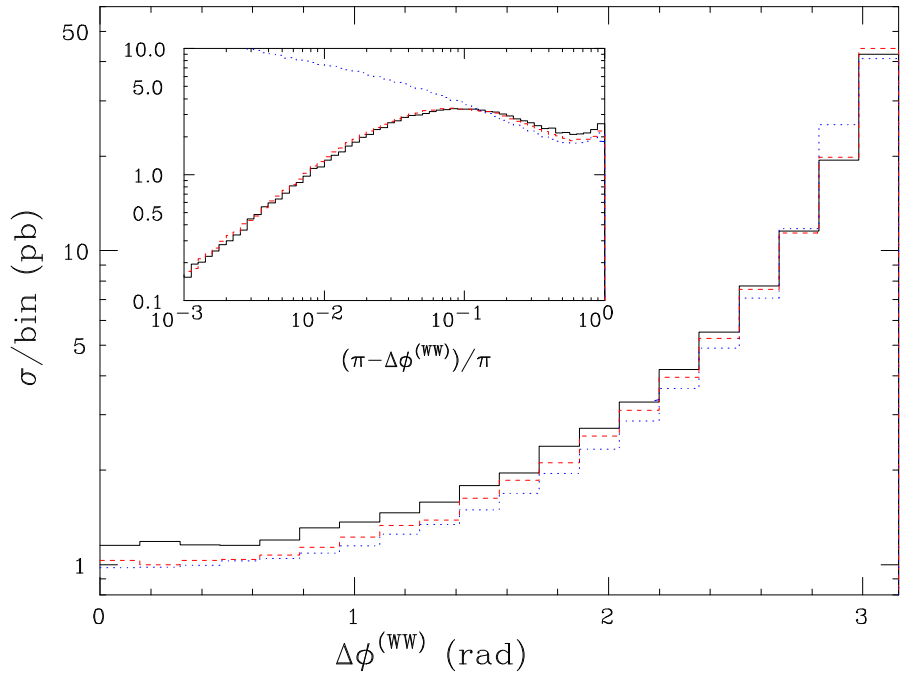
IPROC	Process
–1350–IL	$H_1 H_2 \to (Z/\gamma^* \to) l_{\rm IL} \bar{l}_{\rm IL} + X$
–1360–IL	$H_1 H_2 \to (Z \to) l_{\rm IL} \bar{l}_{\rm IL} + X$
–1370–IL	$H_1 H_2 \to (\gamma^* \to) l_{\rm IL} \bar{l}_{\rm IL} + X$
–1460–IL	$H_1 H_2 \to (W^+ \to) l^+_{\rm IL} \nu_{\rm IL} + X$
–1470–IL	$H_1 H_2 \to (W^- \to) l^-_{\rm IL} \bar{\nu}_{\rm IL} + X$
–1396	$H_1 H_2 \to \gamma^* (\to \sum_i f_i \bar{f}_i) + X$
–1397	$H_1 H_2 \to Z^0 + X$
–1497	$H_1 H_2 \to W^+ + X$
–1498	$H_1 H_2 \to W^- + X$
–1600–ID	$H_1 H_2 \to H^0 + X$
–1705	$H_1 H_2 \to b\bar{b} + X$
–1706	$H_1 H_2 \to t\bar{t} + X$
–2850	$H_1 H_2 \to W^+ W^- + X$
–2860	$H_1 H_2 \to Z^0 Z^0 + X$
–2870	$H_1 H_2 \to W^+ Z^0 + X$
–2880	$H_1 H_2 \to W^- Z^0 + X$

(Frixione, Webber)

- Works identically to HERWIG: the very same analysis routines can be used
- Reads shower initial conditions from an event file (as in ME corrections)
- Exploits Les Houches accord for process information and common blocks
- Features a self contained library of PDFs with old and new sets alike
- LHAPDF will also be implemented

W^+W^- Observables





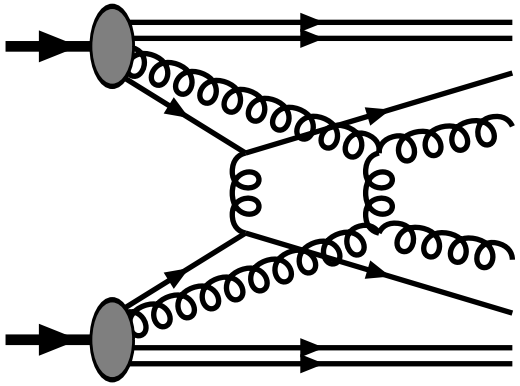
These correlations are problematic: the soft and hard emissions are both relevant. MC@NLO does well, resumming large logarithms, and yet handling the large-scale physics correctly

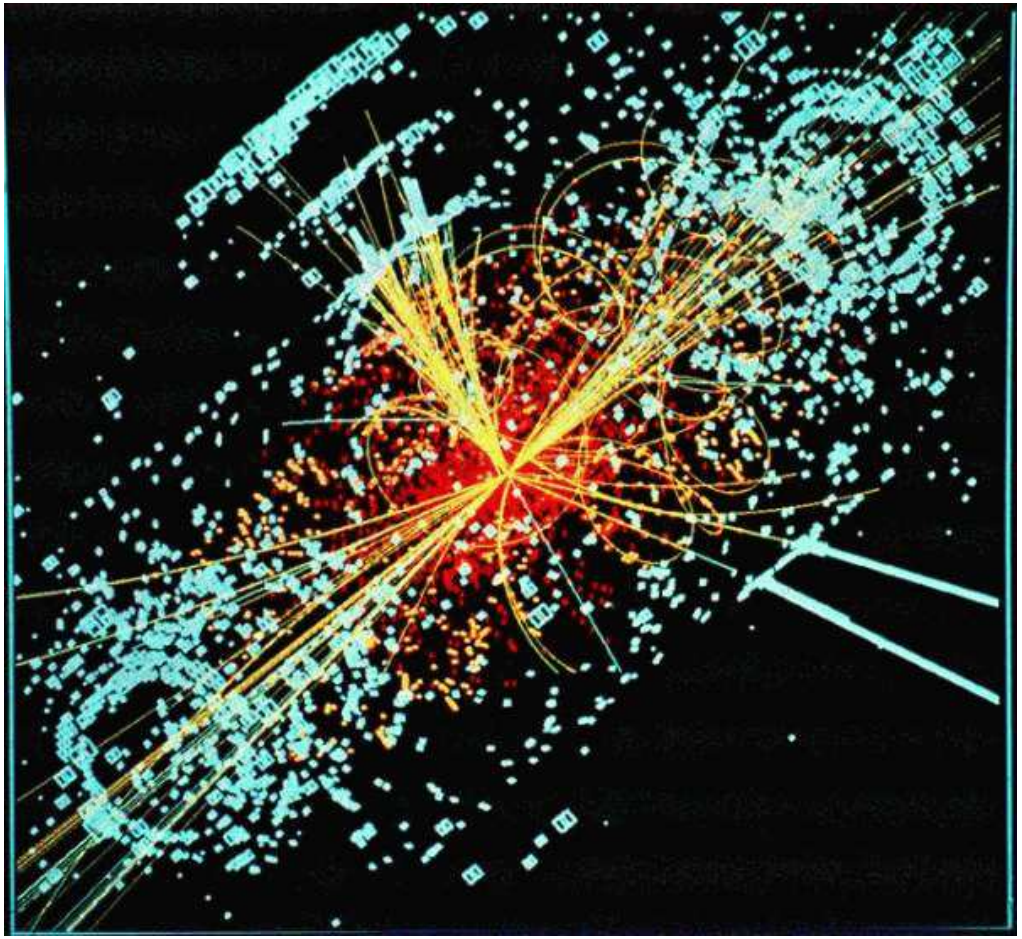
Solid: MC@NLO

Dashed: HERWIG$\times \frac{\sigma_{NLO}}{\sigma_{LO}}$

Dotted: NLO

Multiple Interactions

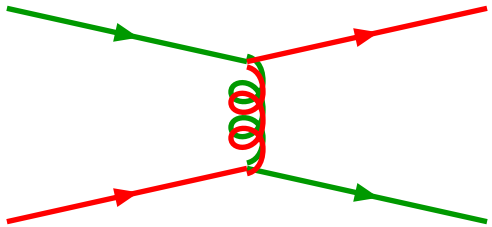




What is multiple interactions?

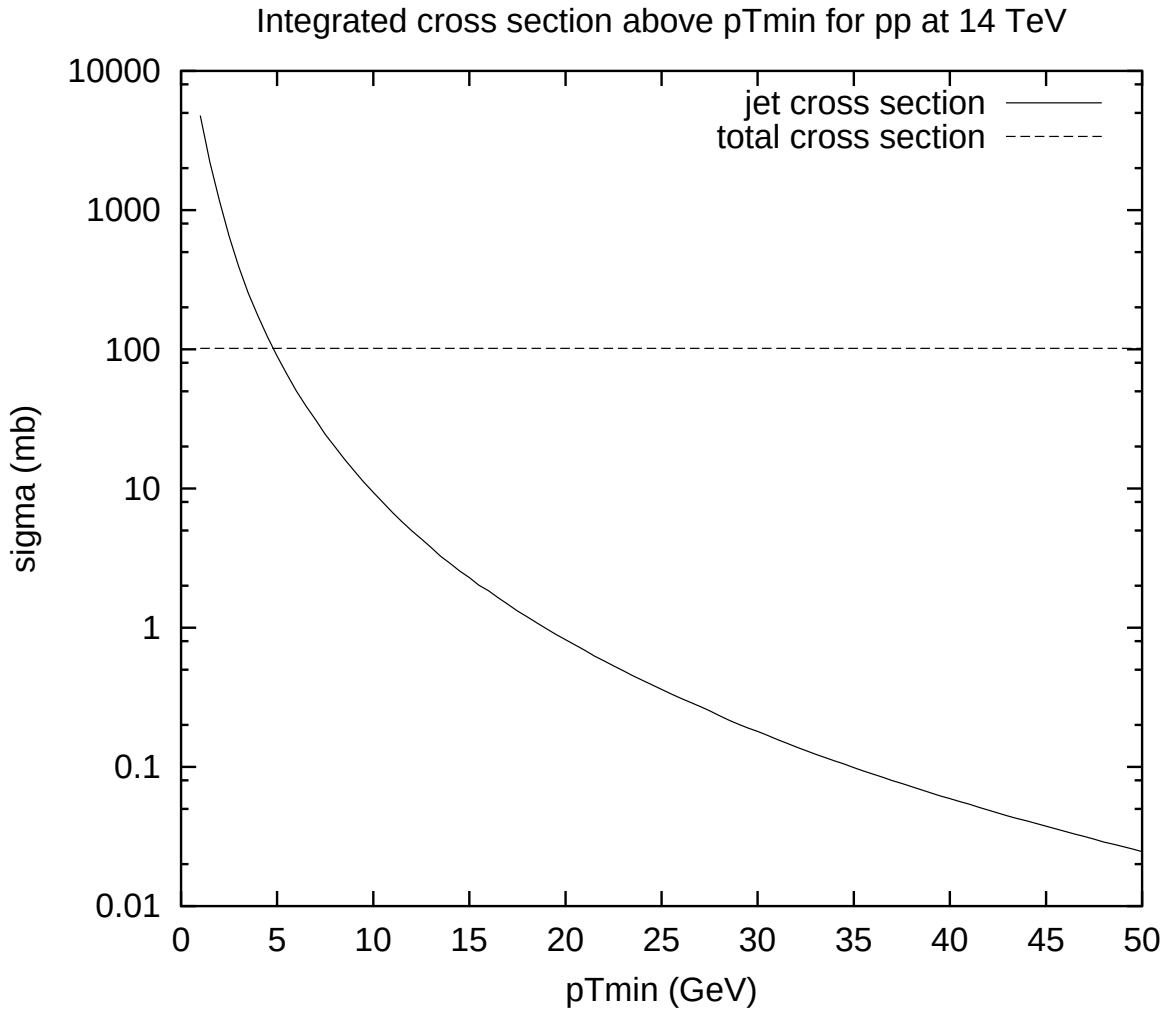
Cross section for $2 \to 2$ interactions is dominated by t-channel gluon exchange, so diverges like $\mathrm{d}\sigma/\mathrm{d}p_\perp^2 \approx 1/p_\perp^4$ for $p_\perp \to 0$.

integrate QCD $2 \to 2$



$$\mathrm{q}\mathrm{q}' \to \mathrm{q}\mathrm{q}'$$
$$\mathrm{q}\overline{\mathrm{q}} \to \mathrm{q}'\overline{\mathrm{q}}'$$
$$\mathrm{q}\overline{\mathrm{q}} \to \mathrm{g}\mathrm{g}$$
$$\mathrm{q}\mathrm{g} \to \mathrm{q}\mathrm{g}$$
$$\mathrm{g}\mathrm{g} \to \mathrm{g}\mathrm{g}$$
$$\mathrm{g}\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$$

with CTEQ 5L PDF's



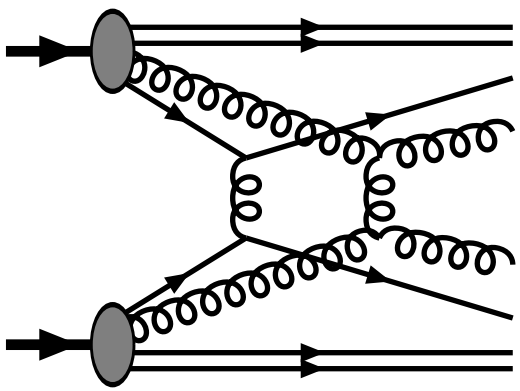
So $\sigma_{\text{int}}(p_{\perp\text{min}}) > \sigma_{\text{tot}}$ for $p_{\perp\text{min}} \lesssim 5$ GeV

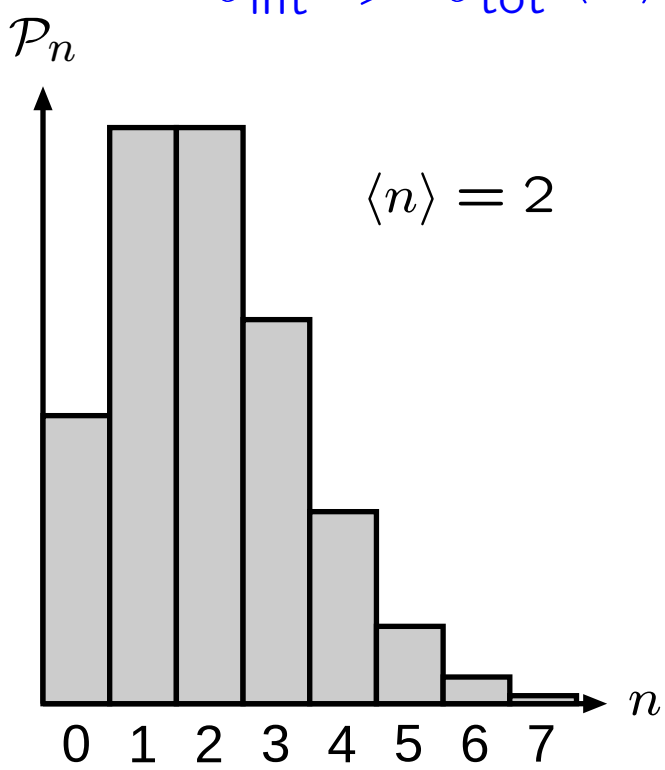
Half a solution: many interactions per event

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

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

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





If interactions occur independently

then Poissonian statistics

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

but energy–momentum conservation

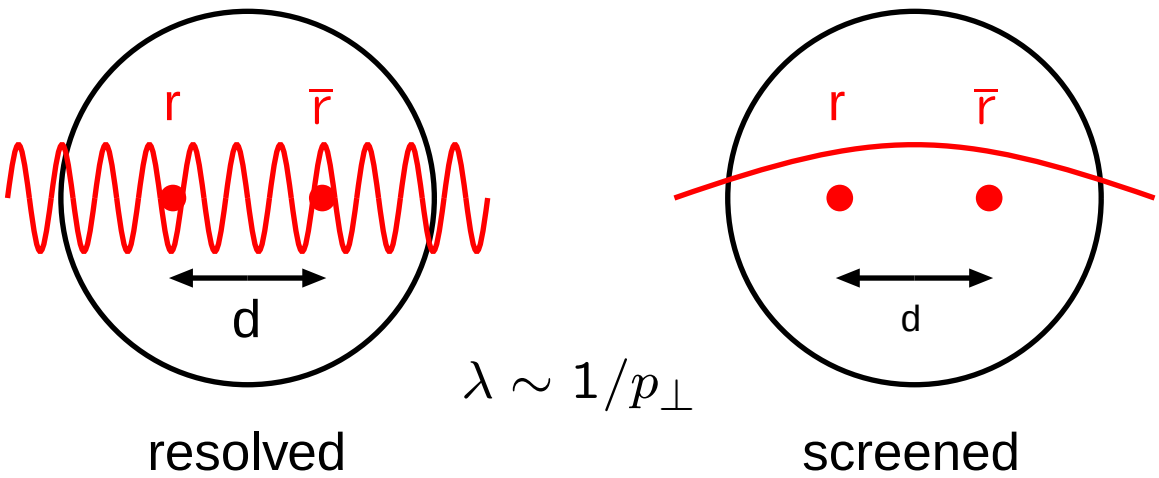
$\Rightarrow$ large n suppressed

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

Naively breakdown at

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

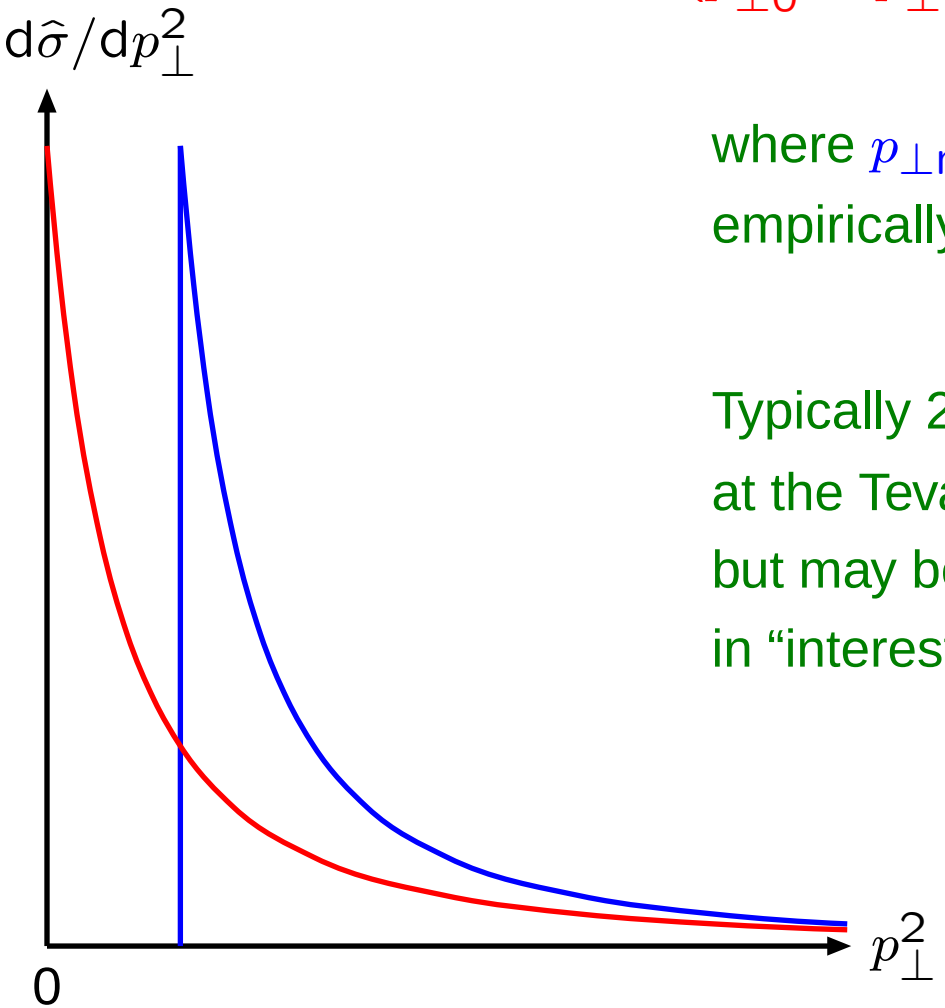
. . . but better replace r_p by (unknown) colour screening length d in hadron



so modify

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

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



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 $\mathrm{q\overline{q}}$ outgoing, no showers, ...

(2) More sophisticated scenario:

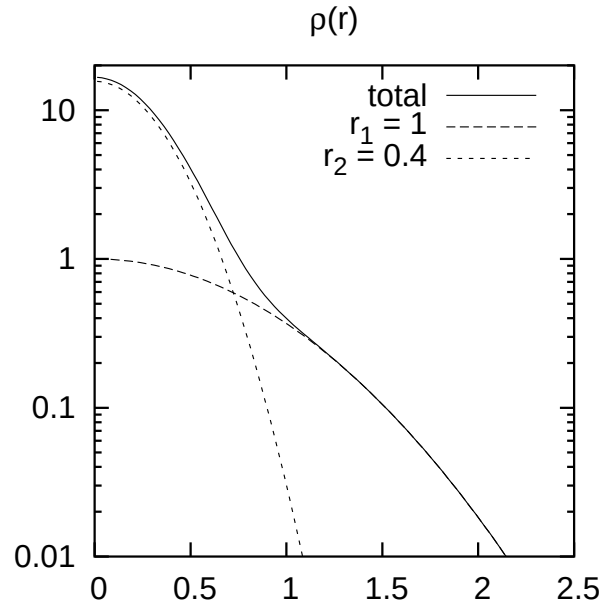
- Smooth turn-off at $p_{\perp 0}$ scale
- Require ≥ 1 interaction in an event
- Hadrons are extended,
  e.g. double Gaussian ("hot spots"):

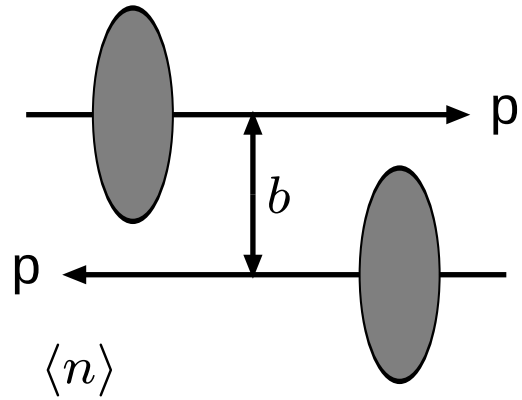
$$\rho_{\text{matter}}(r) = N_1 \exp\left(-\frac{r^2}{r_1^2}\right) + N_2 \exp\left(-\frac{r^2}{r_2^2}\right)$$

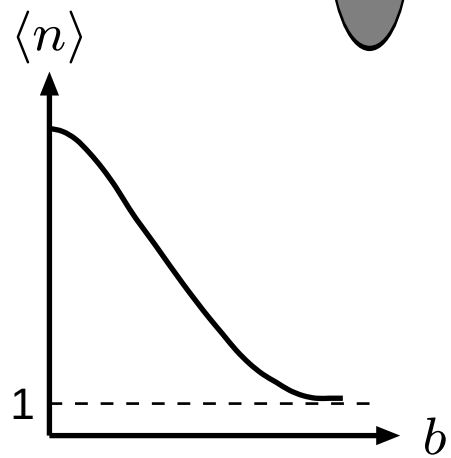
  where $r_2 \neq r_1$ represents "hot spots"
- Events are distributed in impact parameter b
- Overlap of hadrons during collision

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

- 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

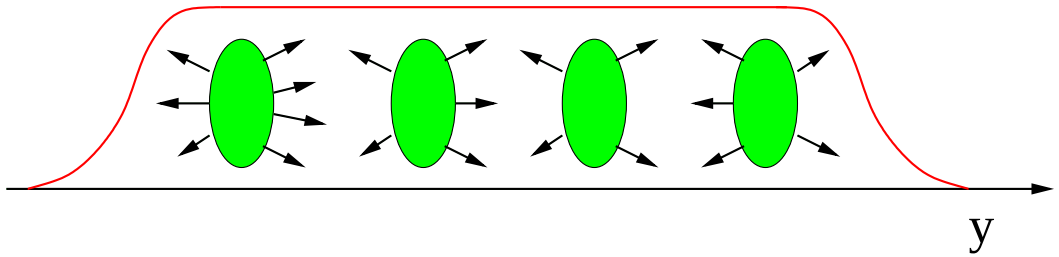






(3) HERWIG

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

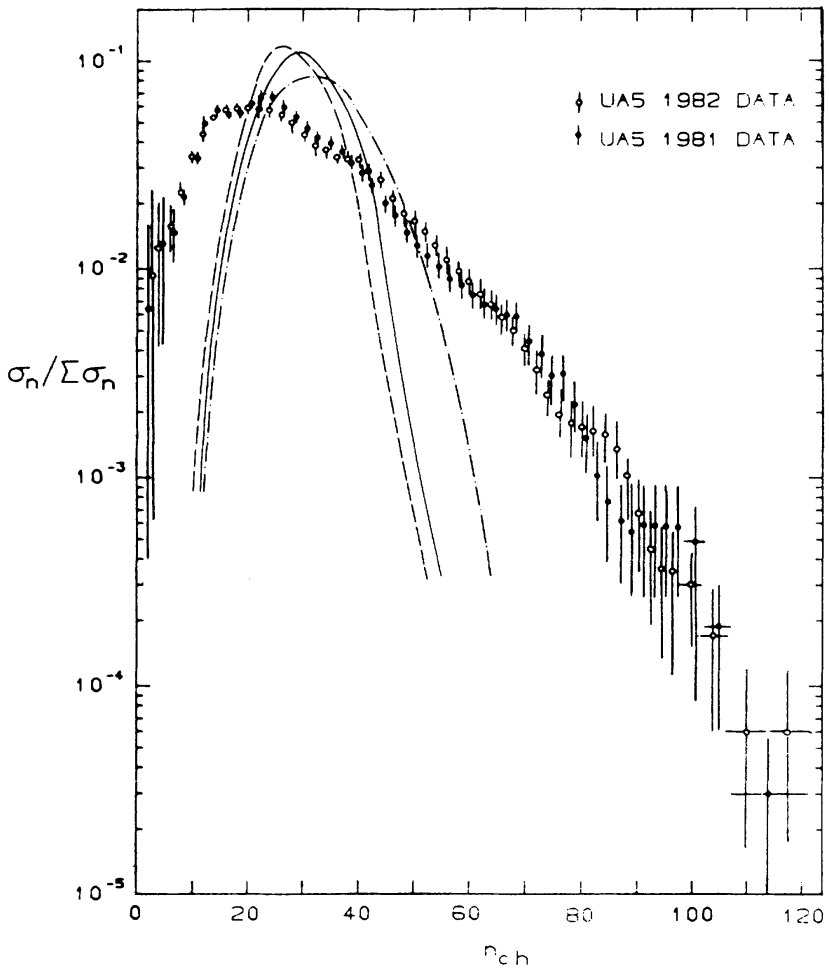


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

without multiple interactions

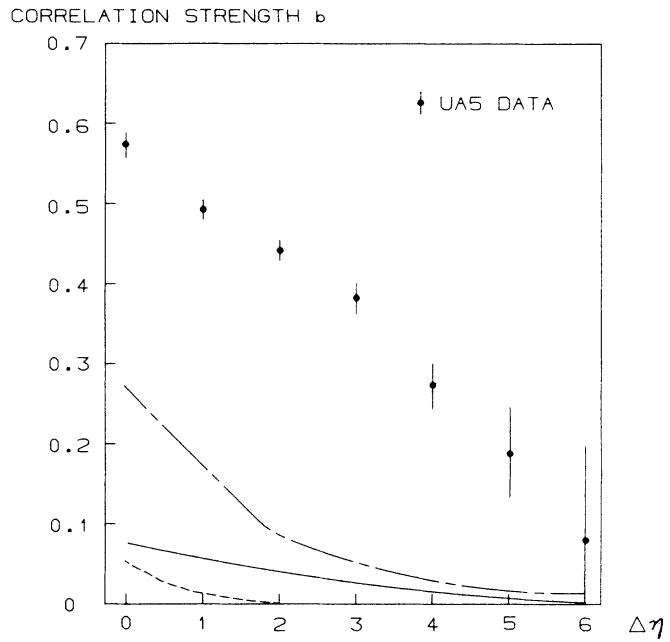


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

with multiple interactions

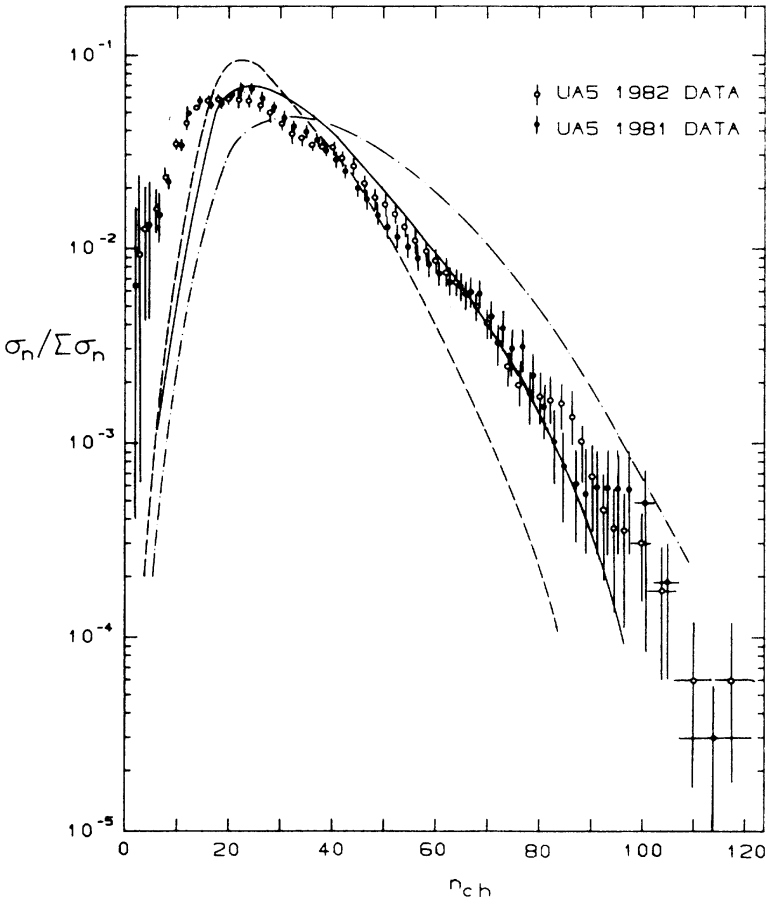


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min}=2.0$ GeV; solid line, $p_{T\min}=1.6$ GeV; dashed-dotted line, $p_{T\min}=1.2$ GeV.

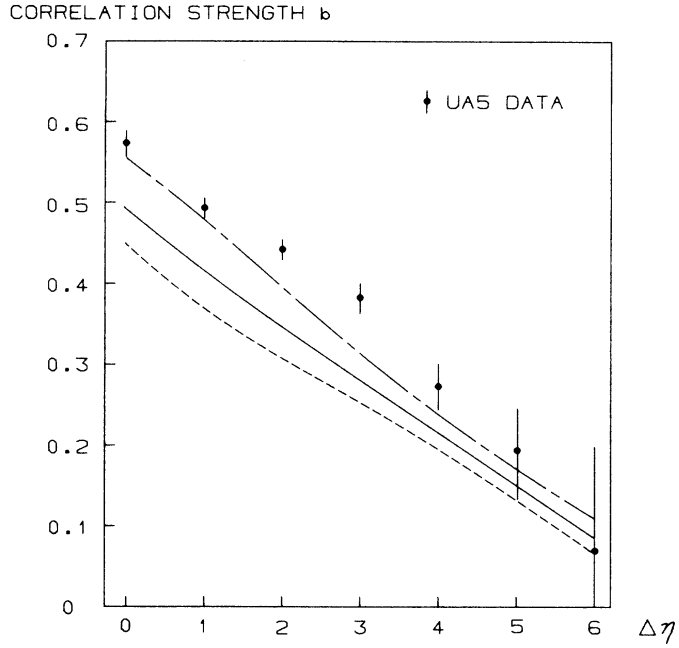


FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

Evidence for multiple interactions

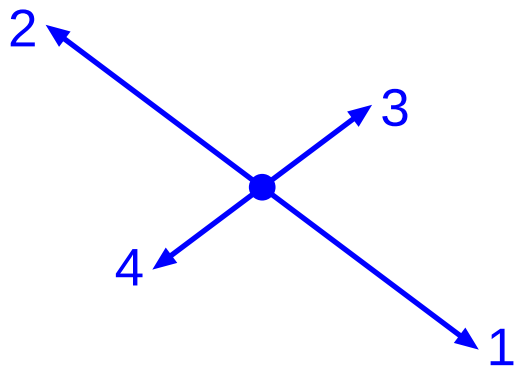
- Width of multiplicity distribution: UA5, E735
  (previous slides)
- Forward–backward correlations: UA5
  (previous slides)
- Minijet rates: UA1

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

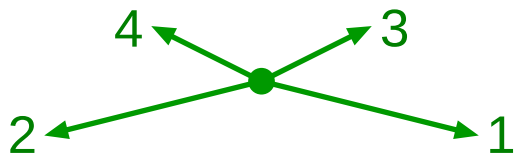


$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \approx 0$

$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \approx 0$

$\mathrm{d}\sigma/\mathrm{d}\varphi$ flat

Double BremsStrahlung



$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \gg 0$

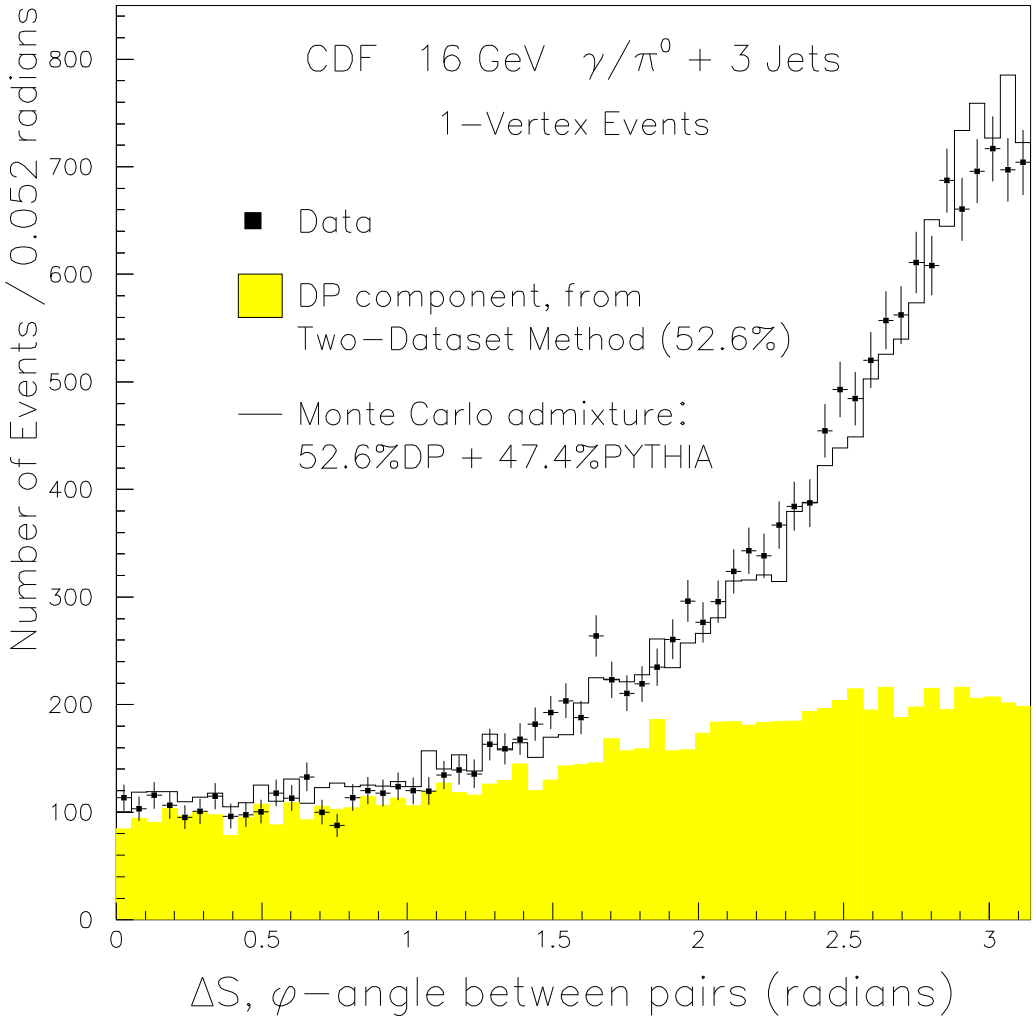
$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \gg 0$

$\mathrm{d}\sigma/\mathrm{d}\varphi$ 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

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

Strong enhancement relative to naive expectations!

• Jet pedestal effect: UA1, H1, CDF

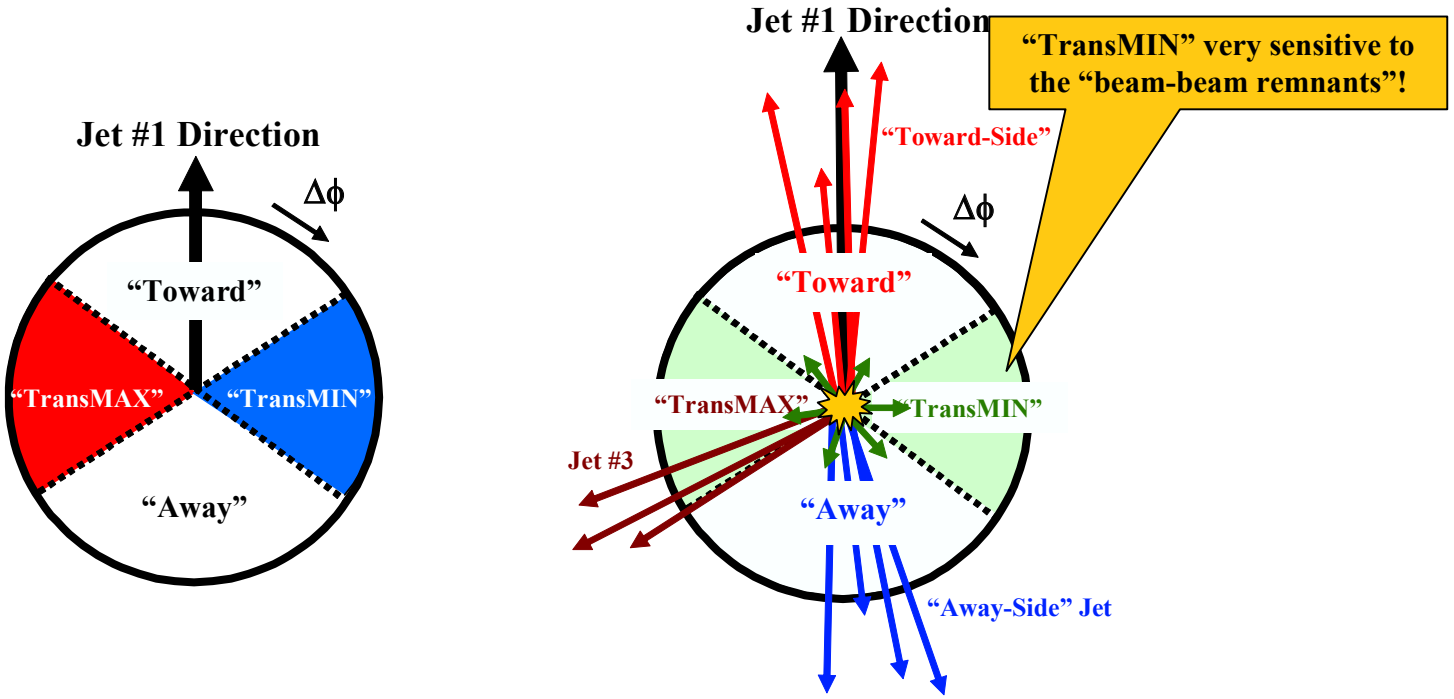
Events with hard scale (jet, $W/Z, \ldots$) have more underlying activity!

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:

"MAX/MIN Transverse" Densities



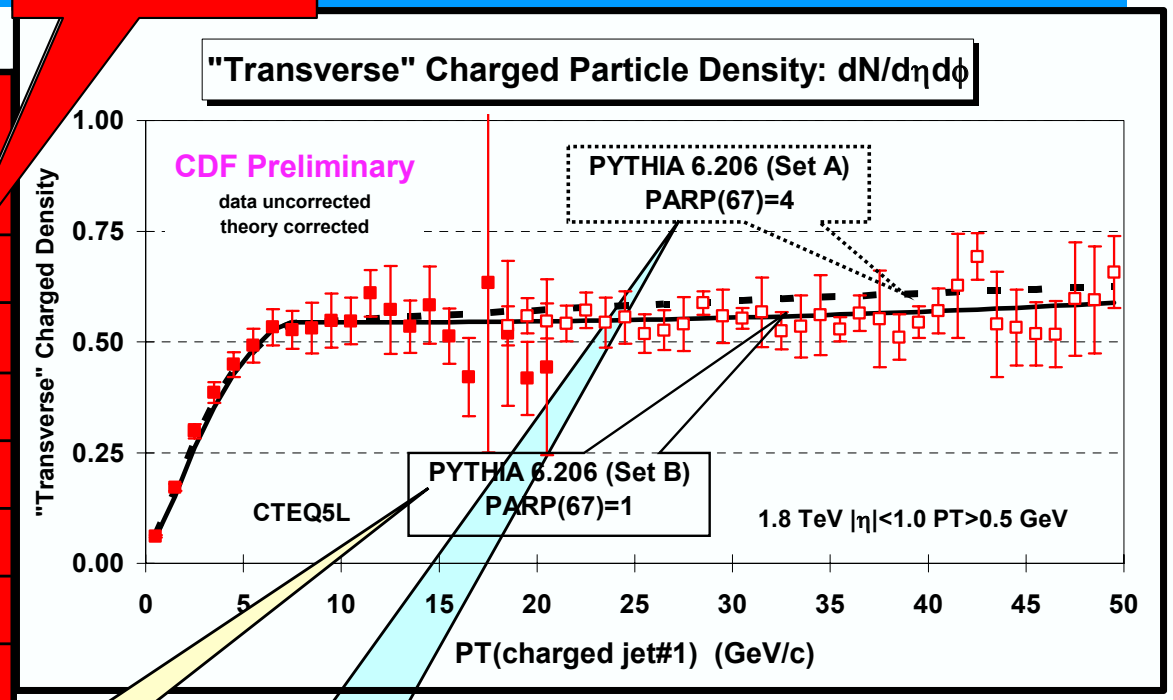
- **Define the MAX and MIN "transverse" regions on an event-by-event basis with MAX (MIN) having the largest (smallest) density.**

Tuned PYTHIA 6.206

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

Tune A CDF Run 2 Default!

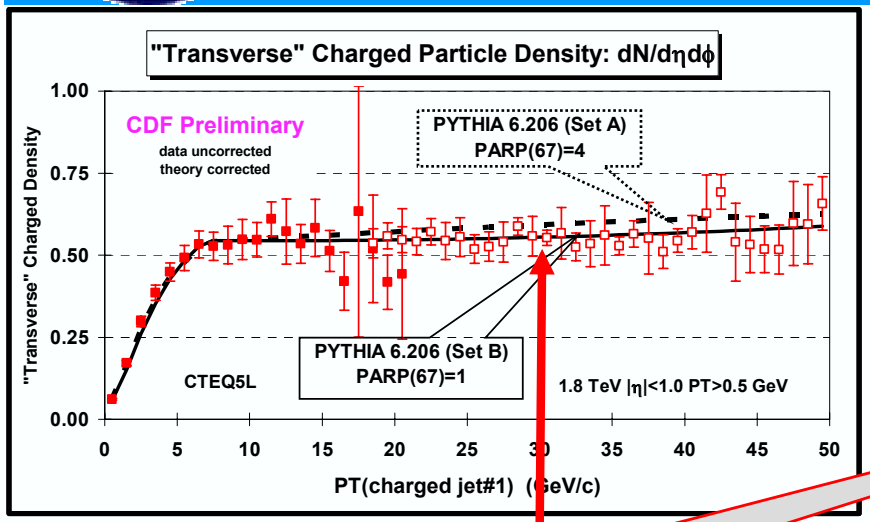


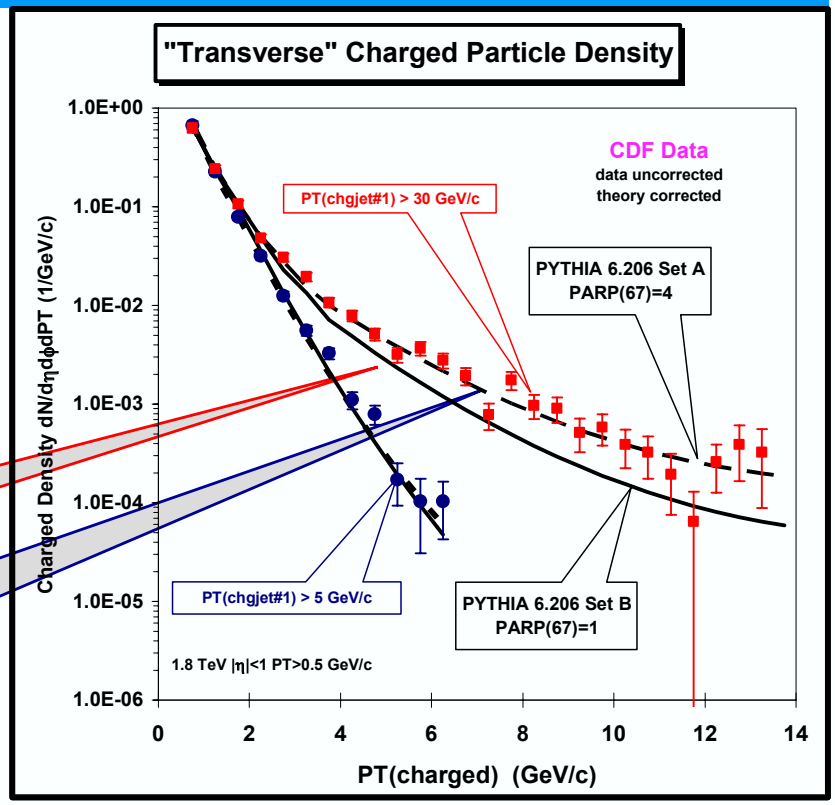
Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

Tuned PYTHIA 6.206 "Transverse" P_T Distribution





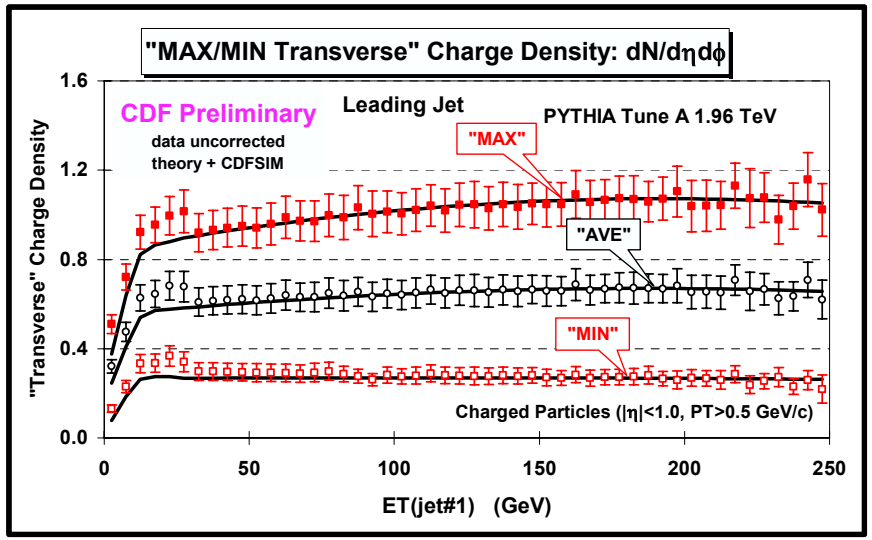
P_T(charged jet#1) > 30 GeV/c

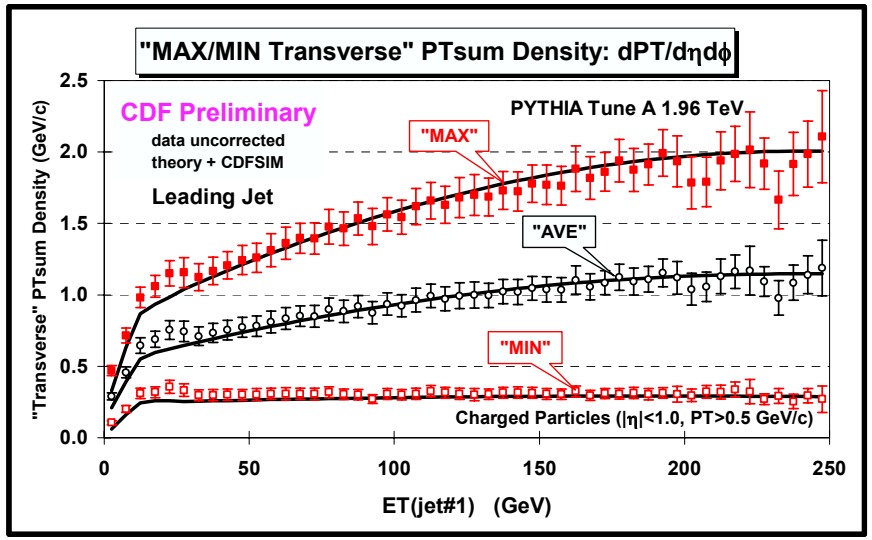
PARP(67)=4.0 (old default) is favored over PARP(67)=1.0 (new default)!

- **Compares the average "transverse" charge particle density ($|\eta|<1$, $P_T>0.5$ 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)).**

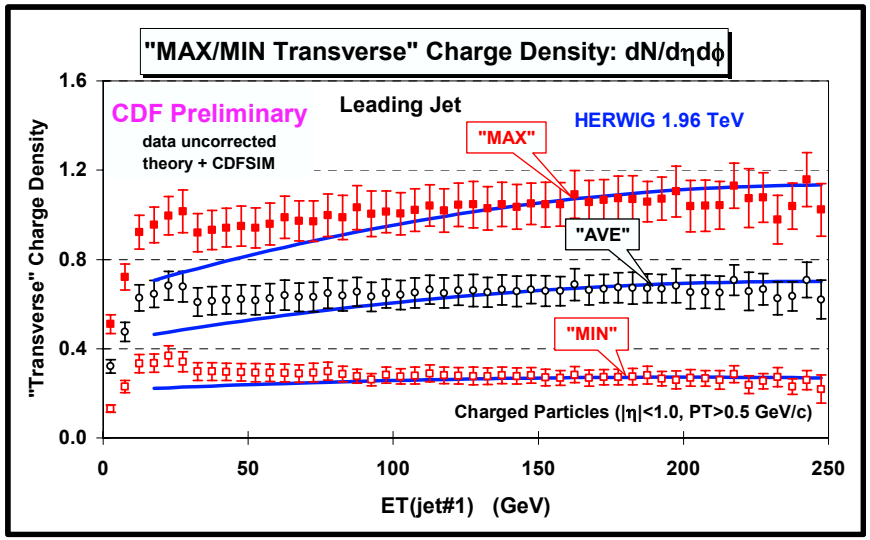
Leading Jet: "MAX & MIN Transverse" Densities

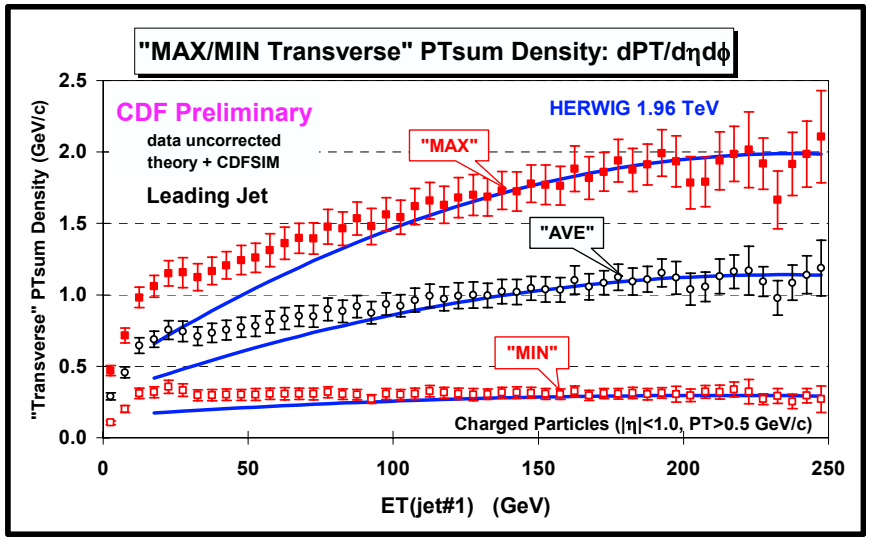
PYTHIA Tune A





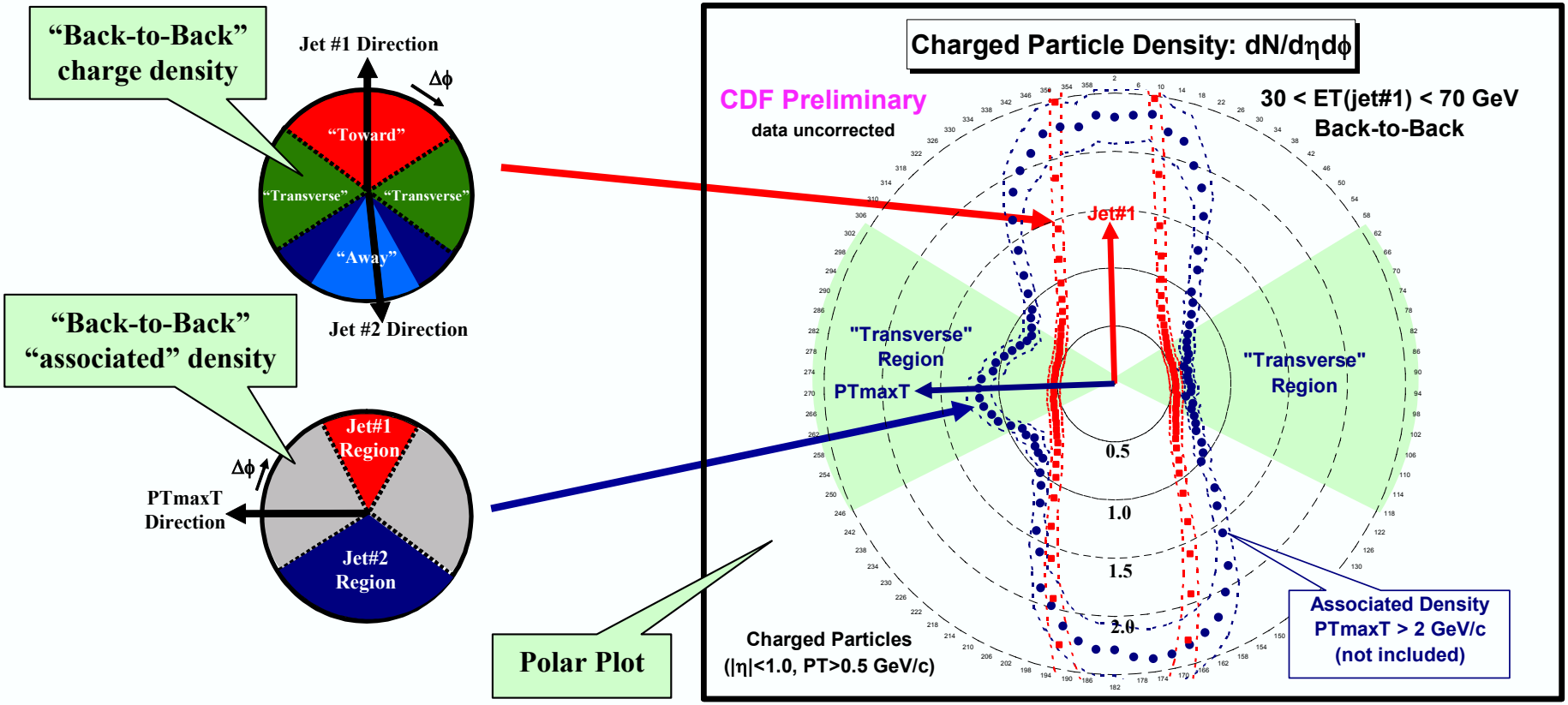
HERWIG





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

Back-to-Back "Associated" Charged Particle Densities

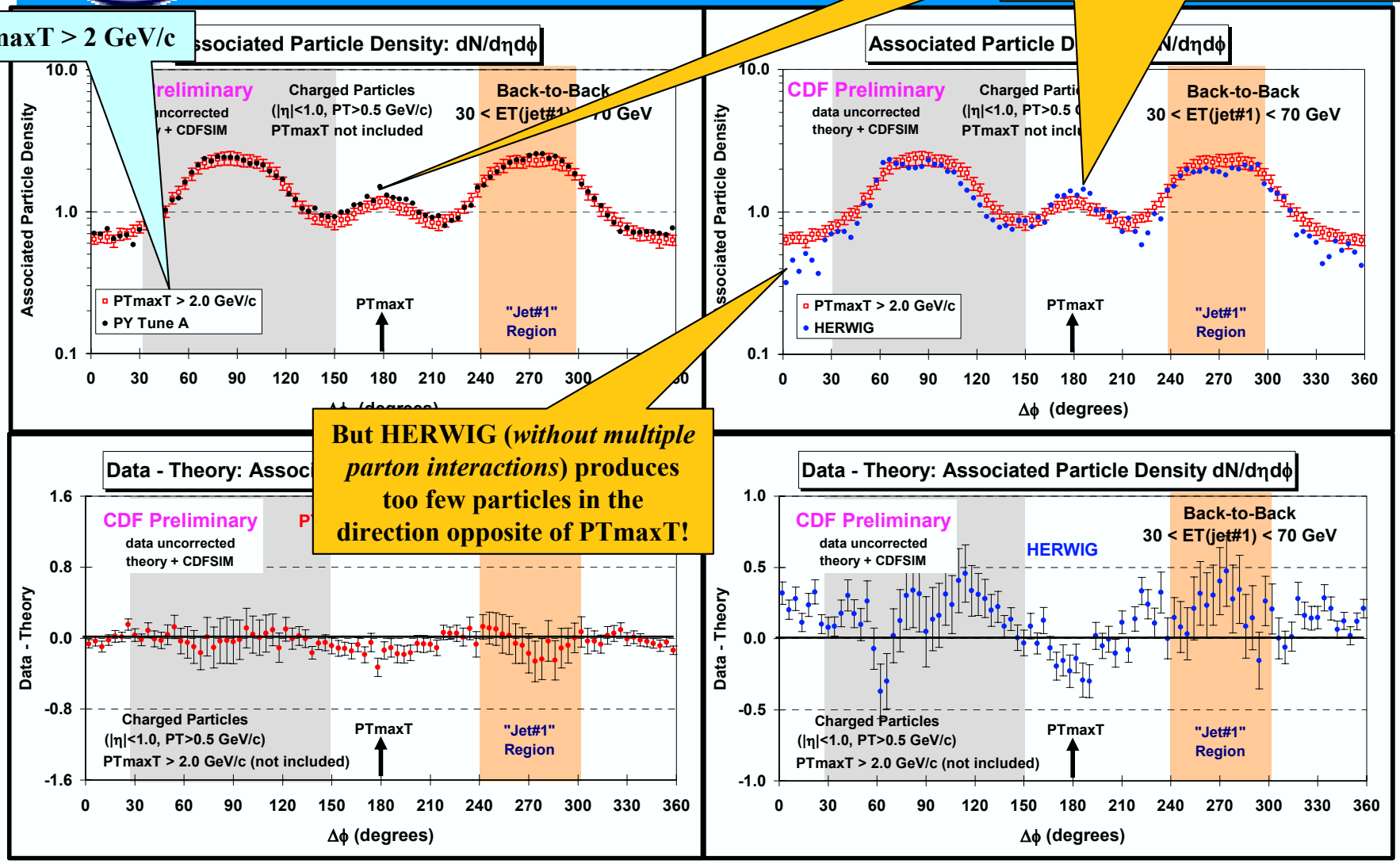


➡ **Shows the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180°) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$,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

"Associated" Charge De
PYTHIA Tune A vs HE

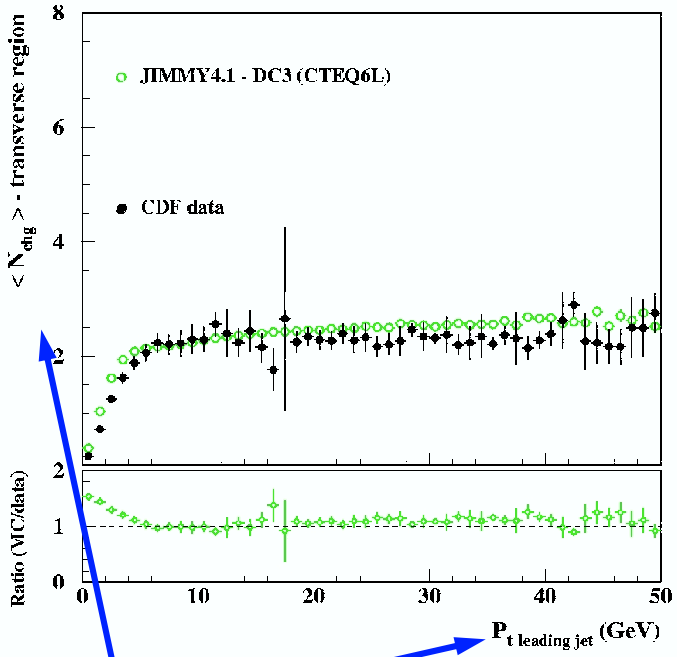
For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too many "associated" particles in the direction of PTmaxT!

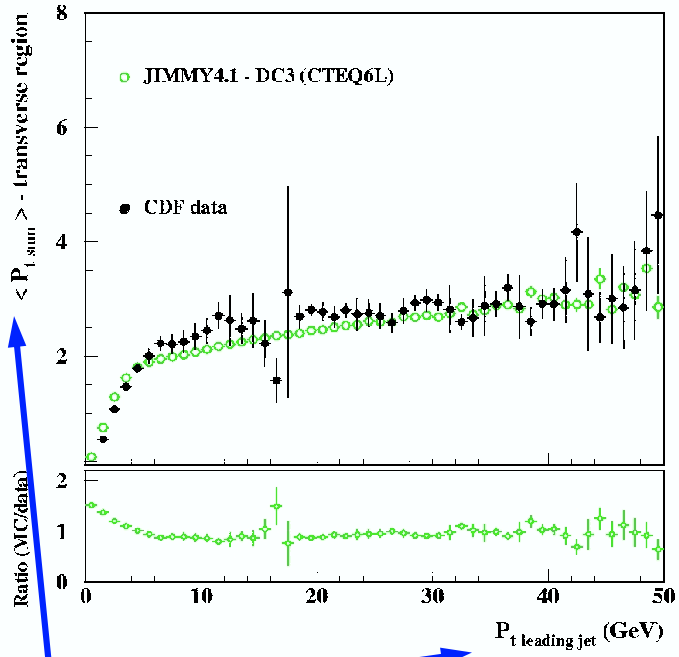
PTmaxT > 2 GeV/c



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

UE tunings: Jimmy validation using CDF data



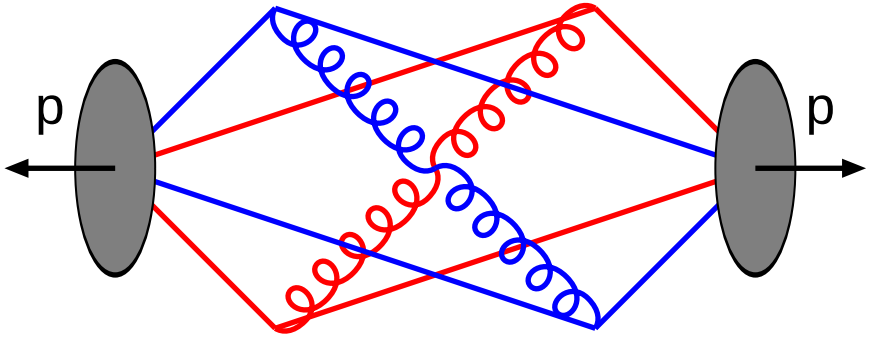


Average multiplicity of charged particles in the underlying event associated to a leading jet with $\mathbf{P_t^{ljet}}$ (GeV).

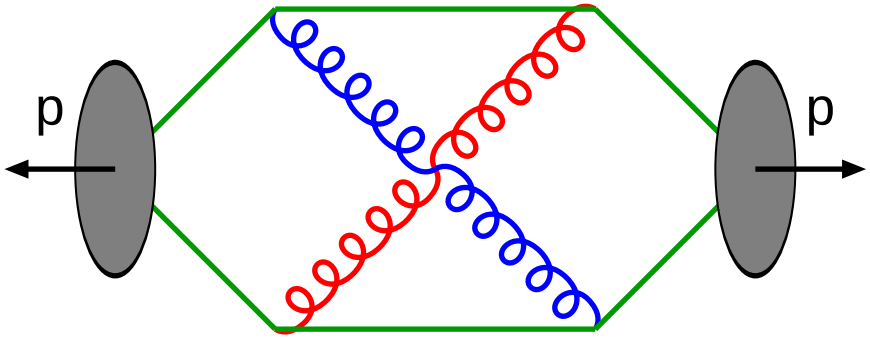
Average $\mathbf{p_T^{sum}}$ (GeV) of charged particles in the underlying event associated to a leading jet with $\mathbf{P_t^{ljet}}$ (GeV).

Colour correlations

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



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



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

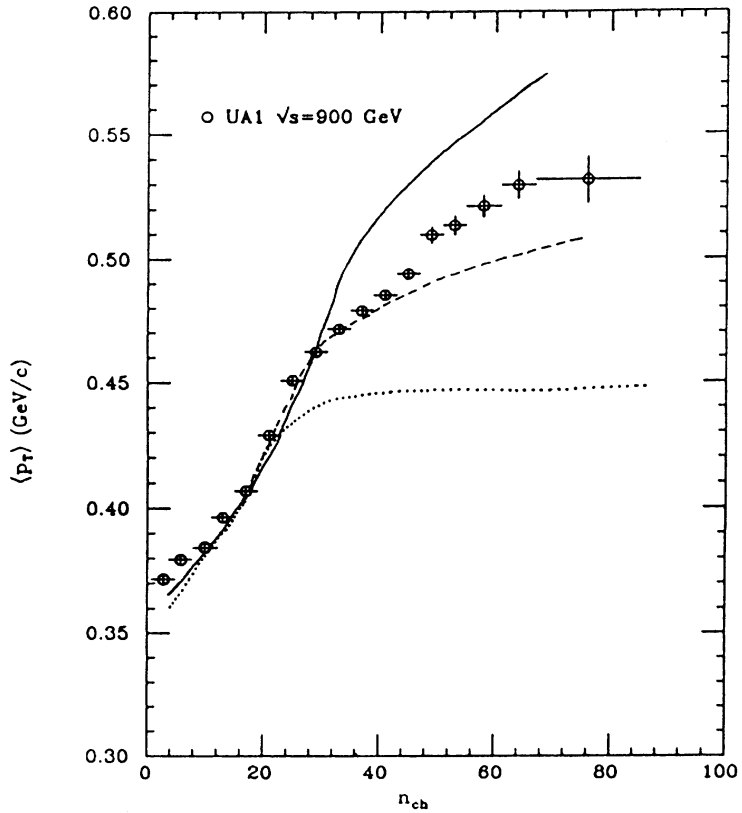
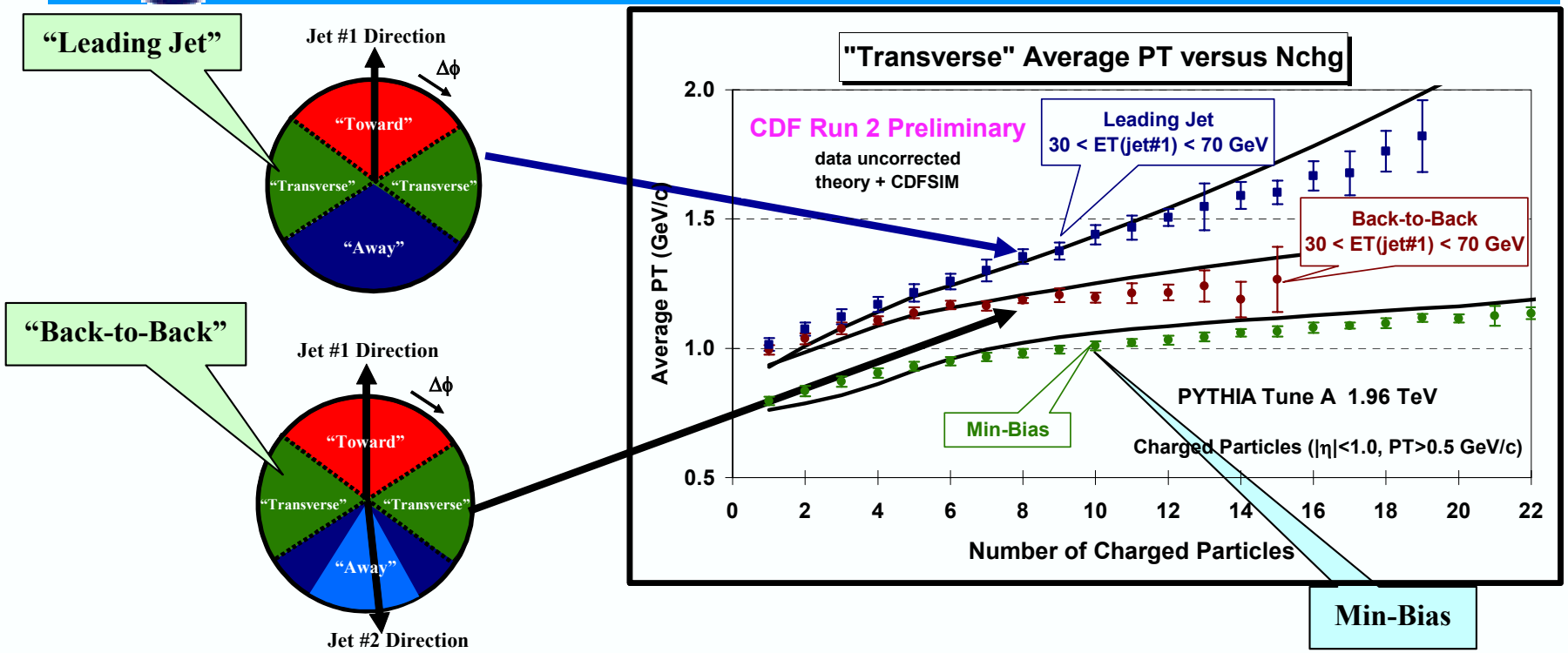


FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings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

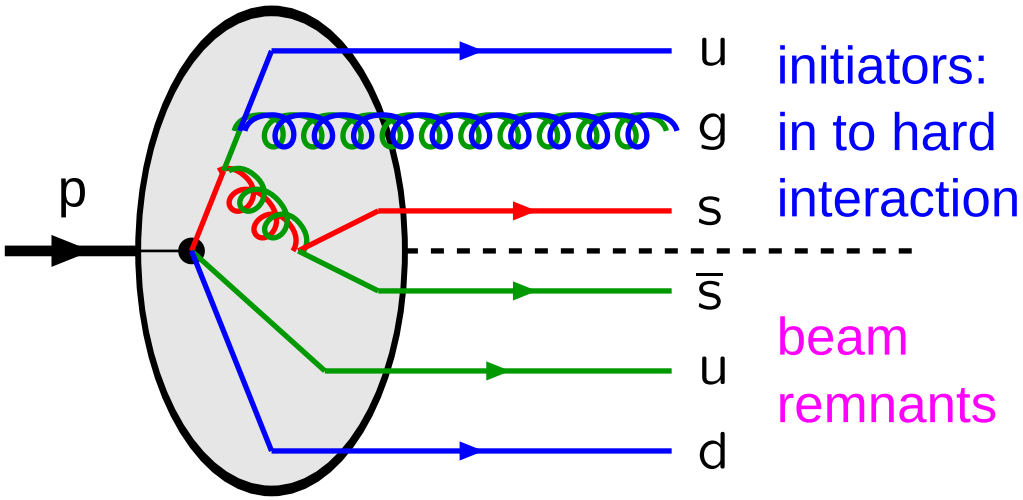
"Transverse" $\langle p_T \rangle$ versus "Transverse" Nchg



- Look at the $\langle p_T \rangle$ of particles in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus the number of particles in the "transverse" region: $\langle p_T \rangle$ vs Nchg.

- Shows $\langle p_T \rangle$ versus Nchg in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) for "Leading Jet" and "Back-to-Back" events with $30 < E_T(\text{jet}\#1) < 70$ GeV compared with "min-bias" collisions.

Initiators and Remnants



Need to assign:

- correlated flavours
- correlated $x_i = p_{zi}/p_{z\mathrm{tot}}$
- 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: $i \neq i_{\mathrm{current}}$)

1) Valence quarks: scale down by number already kicked out

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

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

Interleaved Multiple Interactions