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The Underlying Event in hadronic collisions

QCD at Colliders
18/01/2007

Outline

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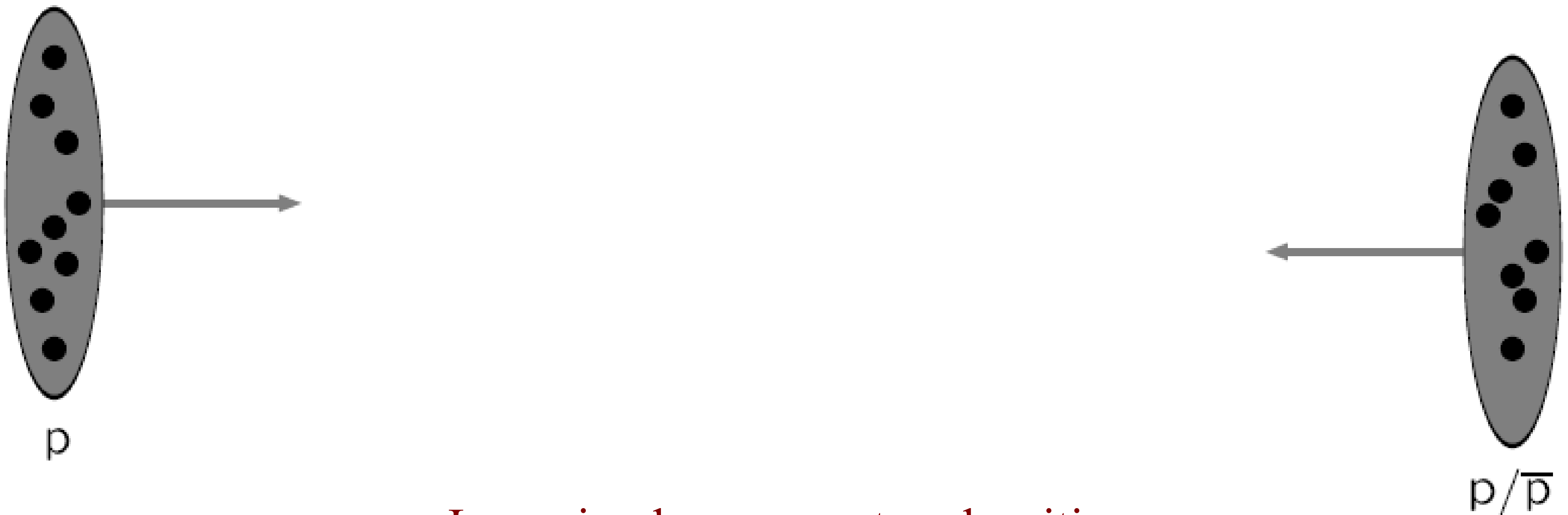
A. What is the "Underlying Event" (UE)?

B. Components of the UE:
Theoretical Treatment and MC Generators

C. The UE at the Tevatron and the LHC
(eventually, some colorful plots.)

A. What is the UE? (1)

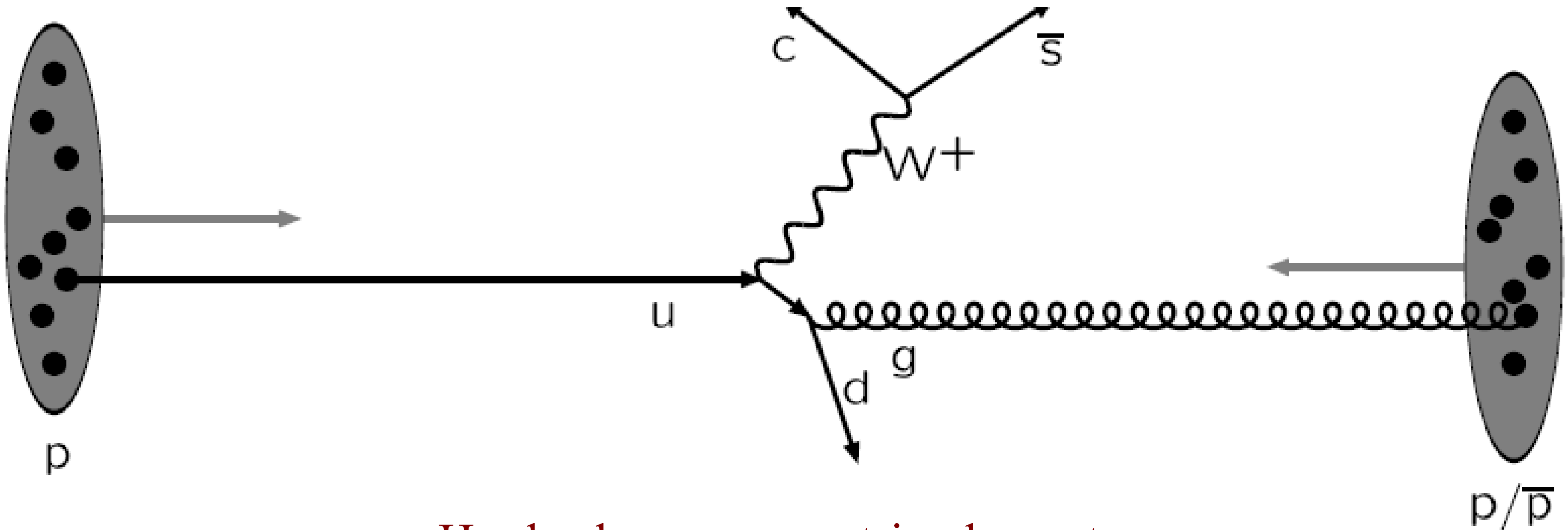
- Consider a hadronic collision (not to scale):



Incoming beams: parton densities

The following plots are based upon: T. Sjöstrand, "Theory of Hadronic Collisions"

A. What is the UE? (2)



Hard subprocess: matrix elements,
Resonance decays (correlated to hard process)

A. What is the UE? (3)

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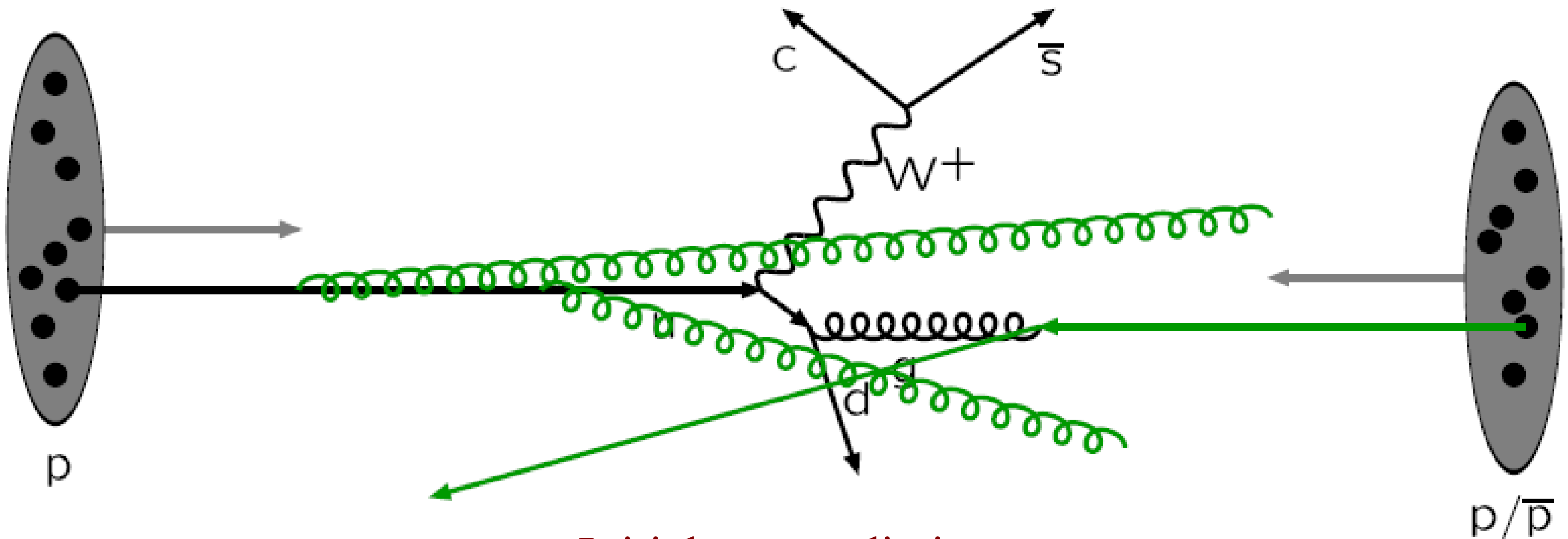
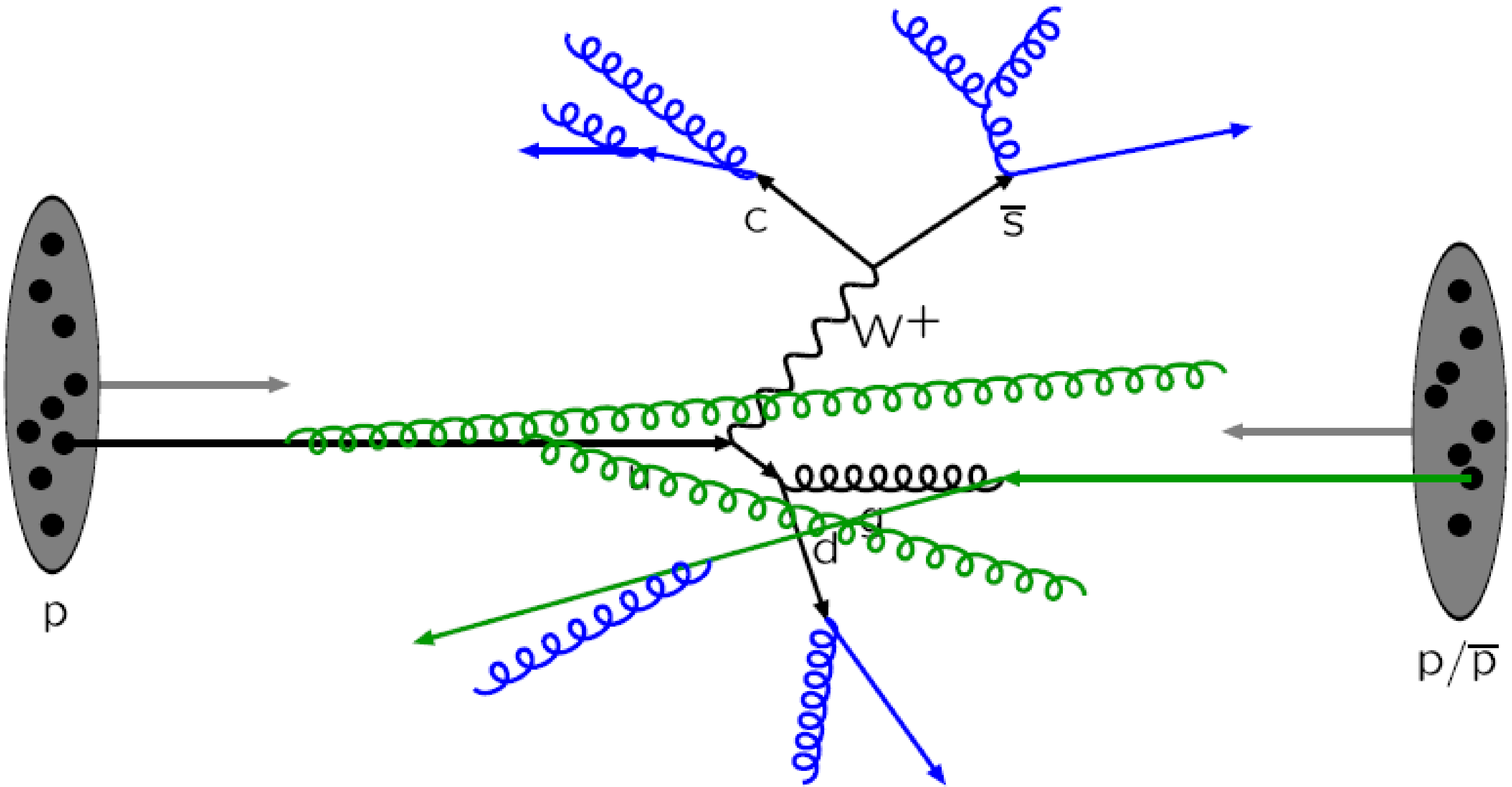


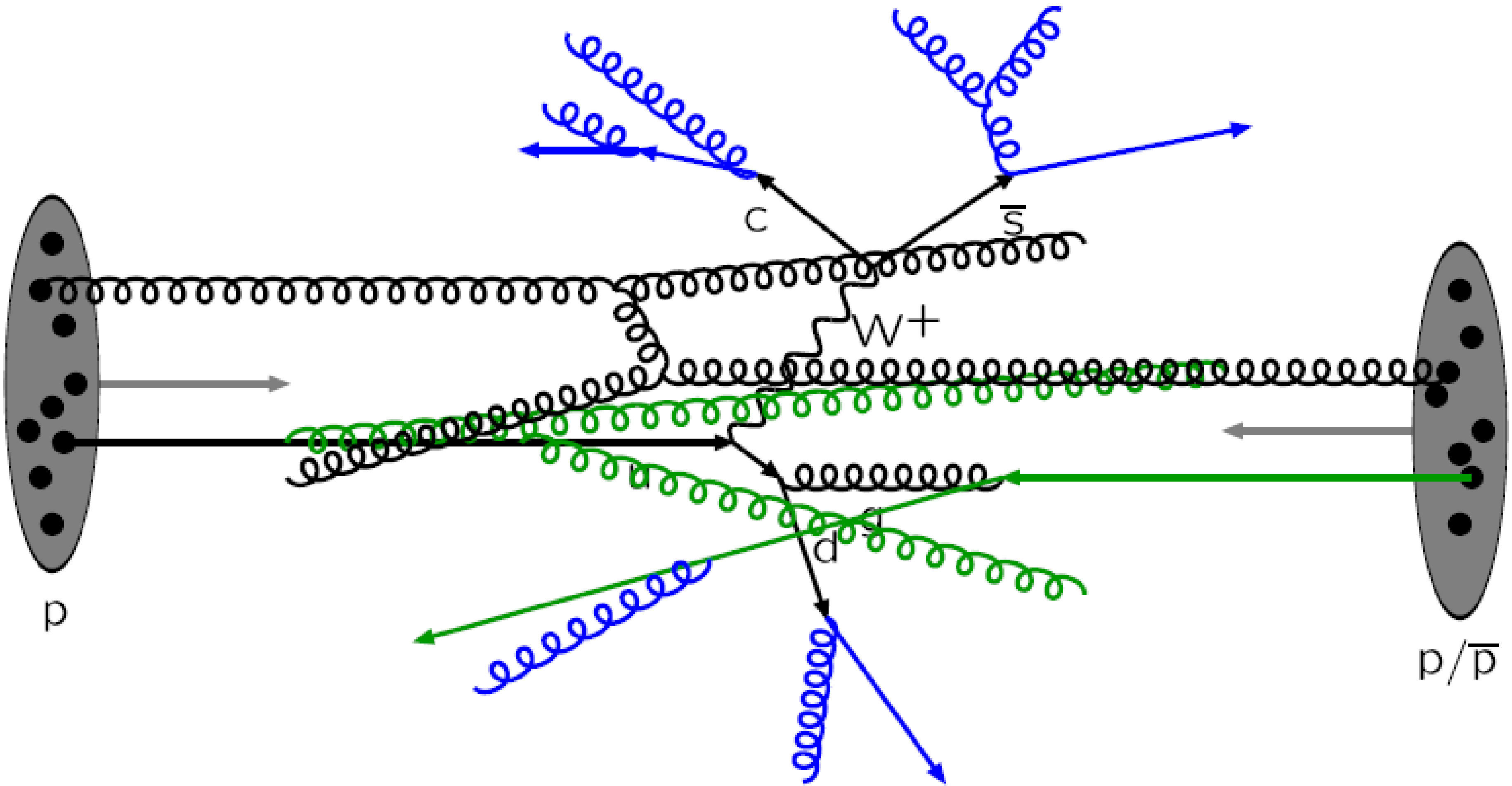
Initial state radiation

A. What is the UE? (4)



Final State Radiation

A. What is the UE? (5)



Multiple parton-parton Interactions...

A. What is the UE? (6)

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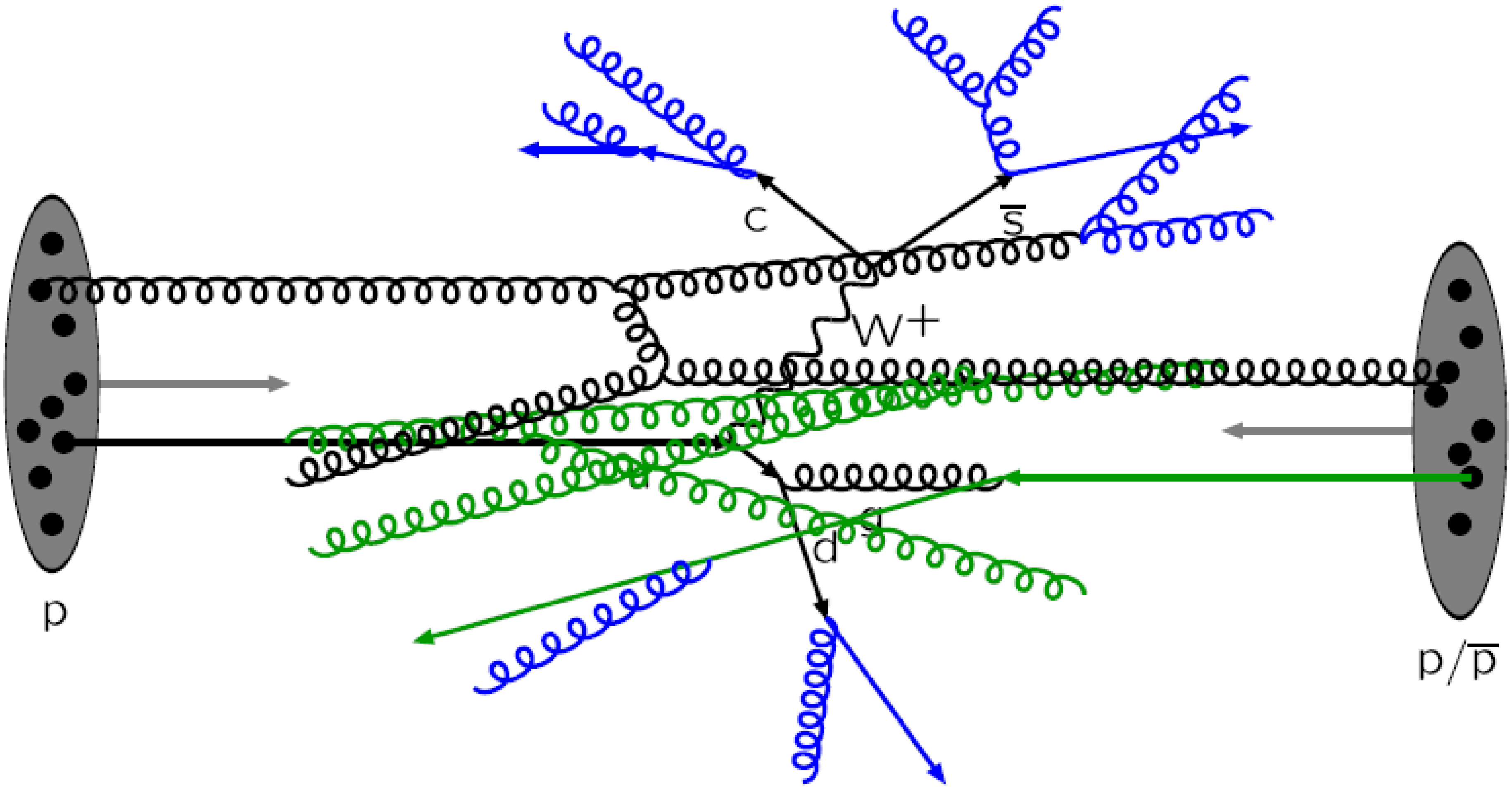
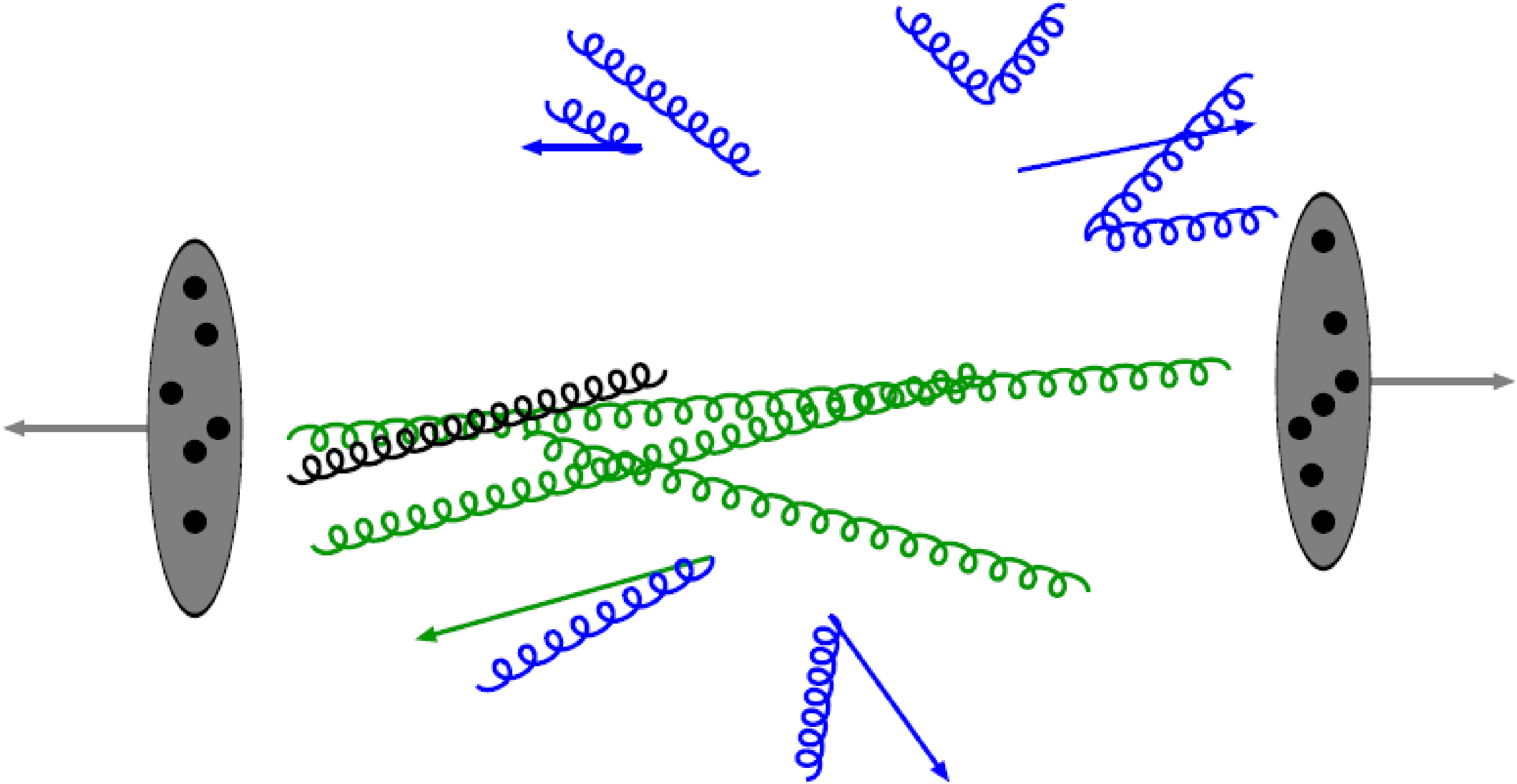


Multiple parton-parton interactions...
...with their ISR/FSR

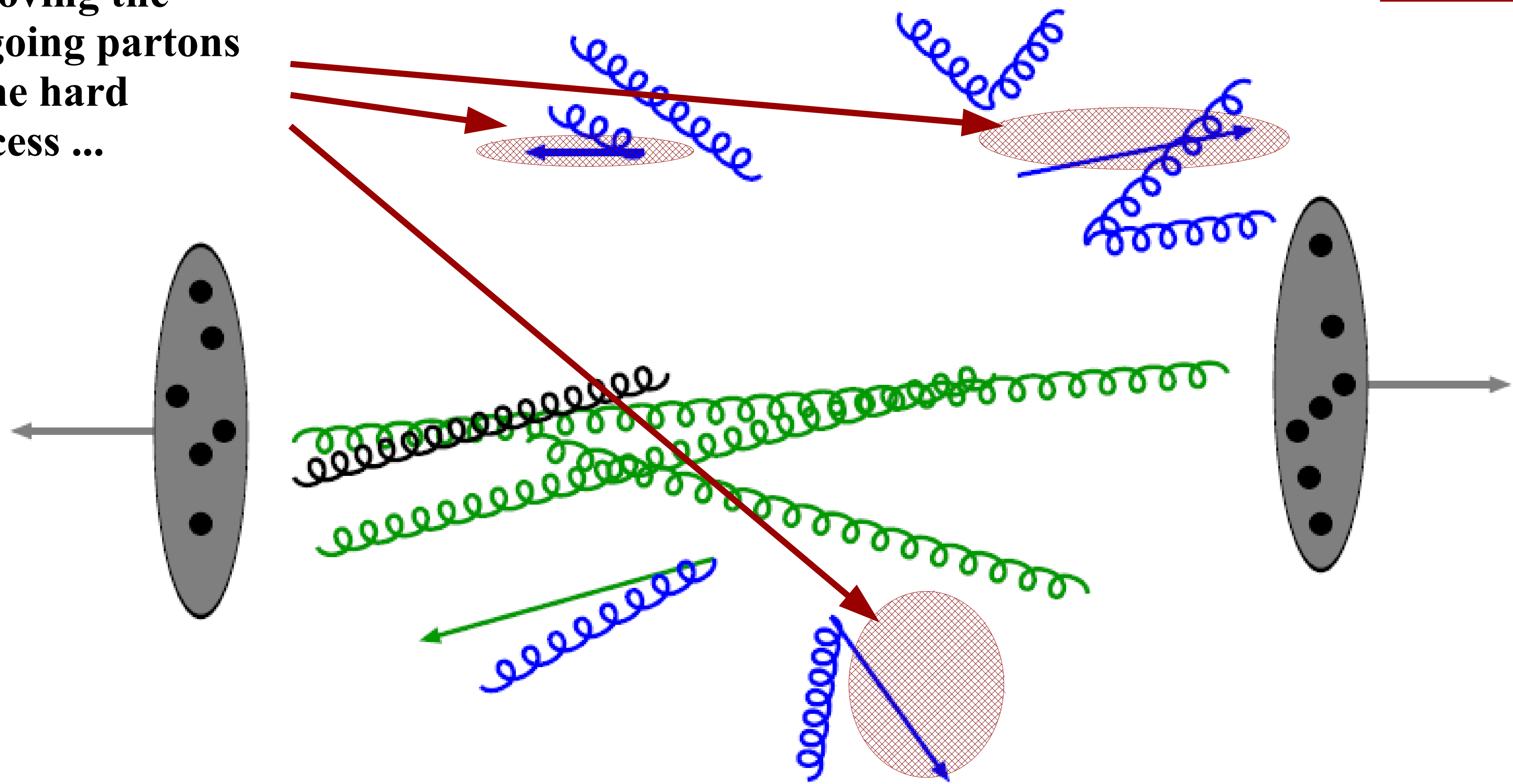
A. What is the UE? (7)



Beam remnants and other outgoing partons

A. What is the UE? (8)

removing the outgoing partons of the hard process ...

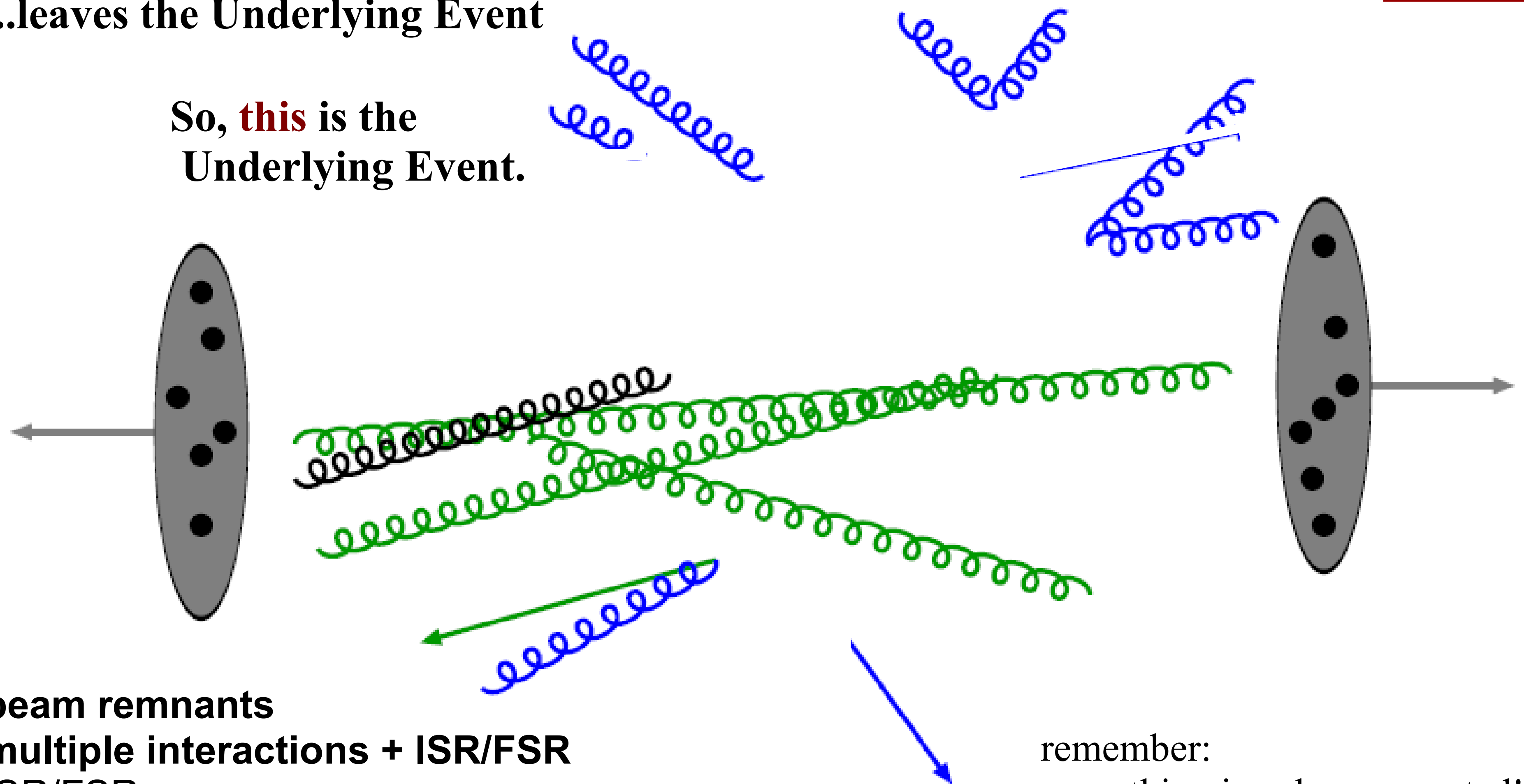


Beam remnants and other outgoing partons

A. What is the UE? (9)

...leaves the Underlying Event

So, this is the Underlying Event.



beam remnants
multiple interactions + ISR/FSR
ISR/FSR
+ pile-up
+ cavern background noise
(depending on your definition)

remember:
everything is color-connected!

B. Components of the UE

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- (ISR/FSR)
- Beam Remnants
- Multiple Interactions
- Pile-Up
- (Noise)

In this definition, the UE is
“everything except of the LO process”
subtracting the UE is thus
- convenient if you are a theorist
- fatal if you are an experimentalist (how to measure the “LO process”?)

Beam Remnants

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- **each incoming particle** may leave behind a **beam remnant** (part of the hadron that does not take active part in the ISR or hard scatter)

- even without further interactions, they are **color-connected** to the rest of the event. Consider a **proton beam**:
  - **iniator quark u or d** (normally a valence quark):
    $\rightarrow$ ud or uu-**diquark** in a color antitriplet state
  - **initiator gluon**:
    $\rightarrow$ **uud** in a color octet state (can be seen as a color triplet quark+color antitriplet diquark, e.g. u and ud)
  - **sea quark initiator**, e.g. s:
    $\rightarrow$ **uudsbar** four-quark state (can be seen as a meson+diquark)
  - **sea antiquark initator**, e.g. sbar:
    $\rightarrow$ **uuds** (can be seen as baryon+quark)

- connected also via **momentum conservation** (incl. **primordial p_T**)

Beam Remnants (2)

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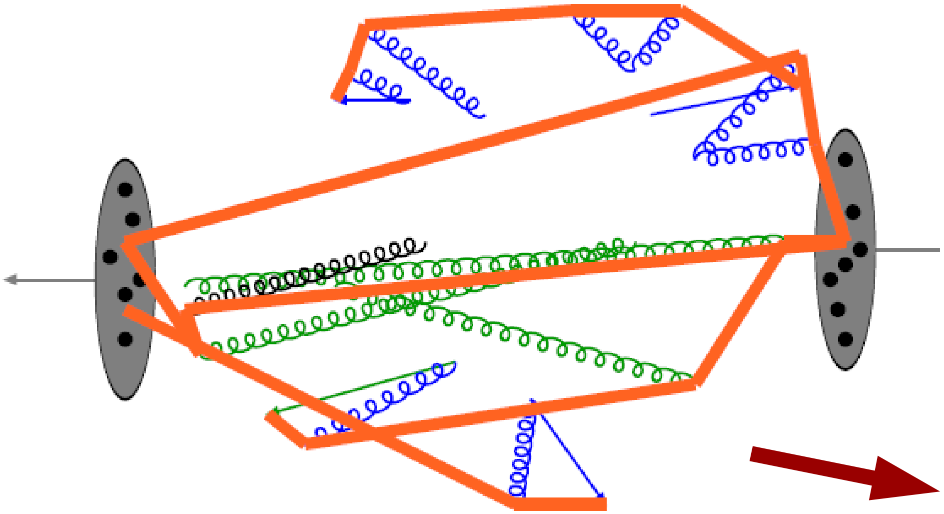
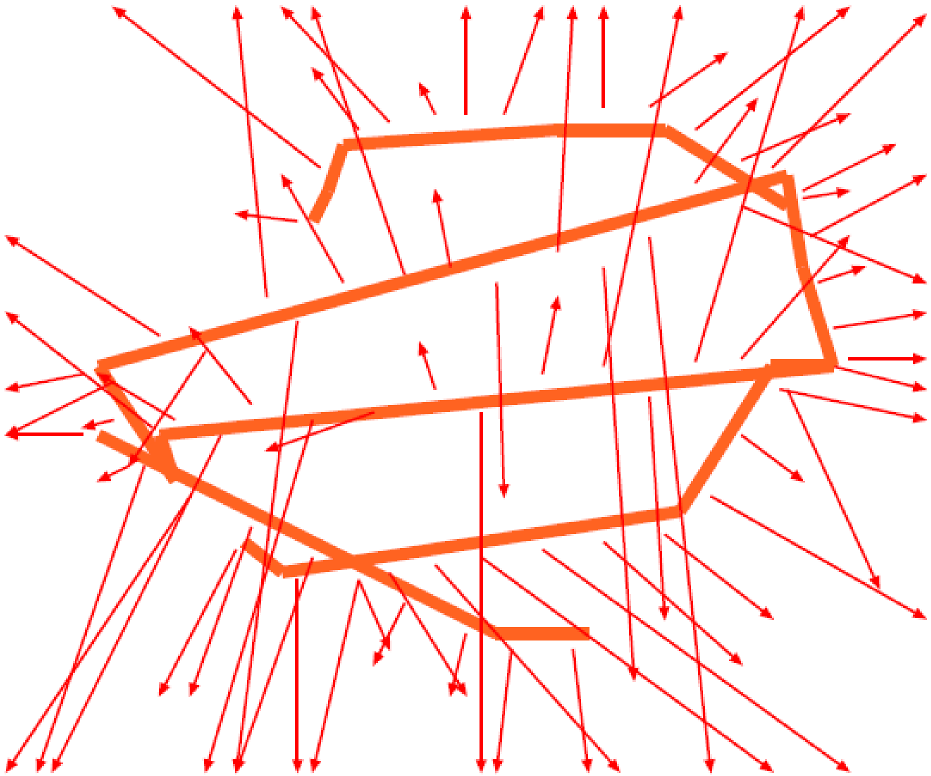


everything is connected by **color confinement** (not to scale!)



in the Pythia-Model, strings between color-connected objects **fragment to primary hadrons**

Multiple Interactions (MI)

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- **several parton pairs** can undergo (semi-)hard **interactions** in an event
- data from CDF suggests that MI indeed take place. Still:
- “In the full event generation process, probably no other area is as **poorly understood** as this one” [Pythia Manual] (1)
- together with the hard scatter in an event, mainly soft scatters take place.
  => **non-pertubative region** (remember the running of the coupling?)
  the usual pdf+matrix element approach can't be applied (2)
- (1) + (2): need for **phenomenological models in event generators**

Multiple Interactions (2)

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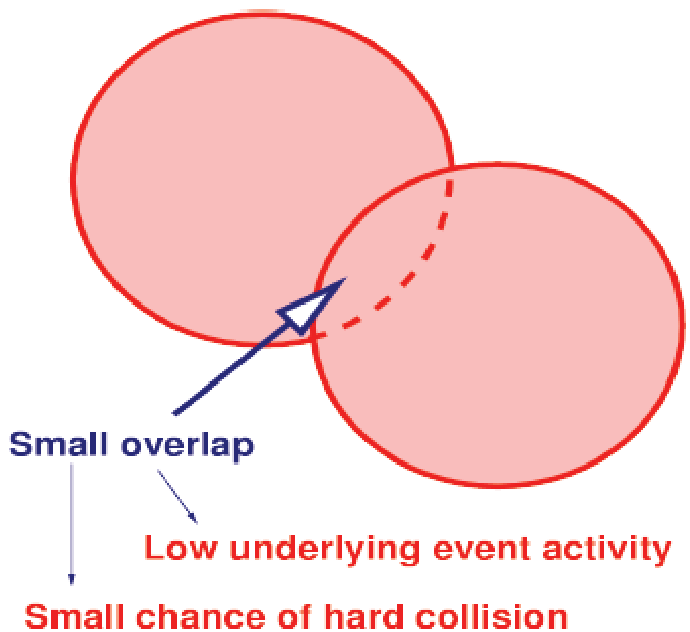
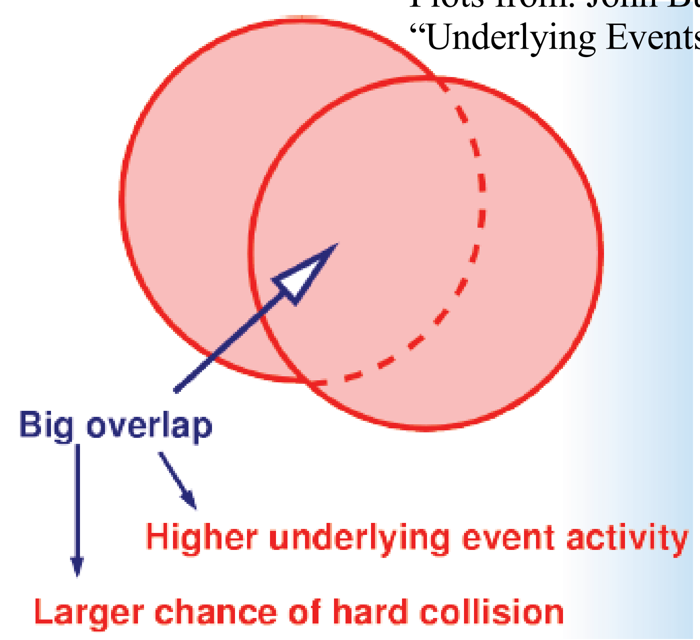
- The number of interactions per event <n> depends on **impact parameter b, matter distributions** inside hadrons are introduced.
- (1) Events with a hard scatter are more likely for small b.
  (2) <n> increases for small b.
  (1)+(2): **events with a hard scatter** have **more underlying activity** than
  typical minimum-bias events!

Plots from: John Butterworth, "Underlying Events"





MI in Pythia

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- The **hard-scatter cross section** $\frac{d\sigma}{dp_T^2}$ is extended to low p_T
- Since it **diverges for $p_T \rightarrow 0$**, a **cut-off parameter $p_{T,min}$** is introduced as a regularisation. $p_{T,min}$: O(1 GeV), and $\sim s^{0.08}$
- The **total hard-scatter cross section** above $p_{T,min}$ for a given b is then

$$\sigma_{hard}(p_{T,min}) = \int_{p_{T,min}^2}^{s/4} \frac{d\sigma}{dp_T^2} dp_T^2$$

- This parton-parton cross section is then compared to the total hadronic cross section σ_{nd}, leading to **$\langle n \rangle = \sigma_{nd} / \sigma_{hard}$**.
  n is then assumed to be Poisson-distributed
- **$p_{T,min}$ is matched to experimental data** & extrapolated to LHC energies

MI in Pythia (2)

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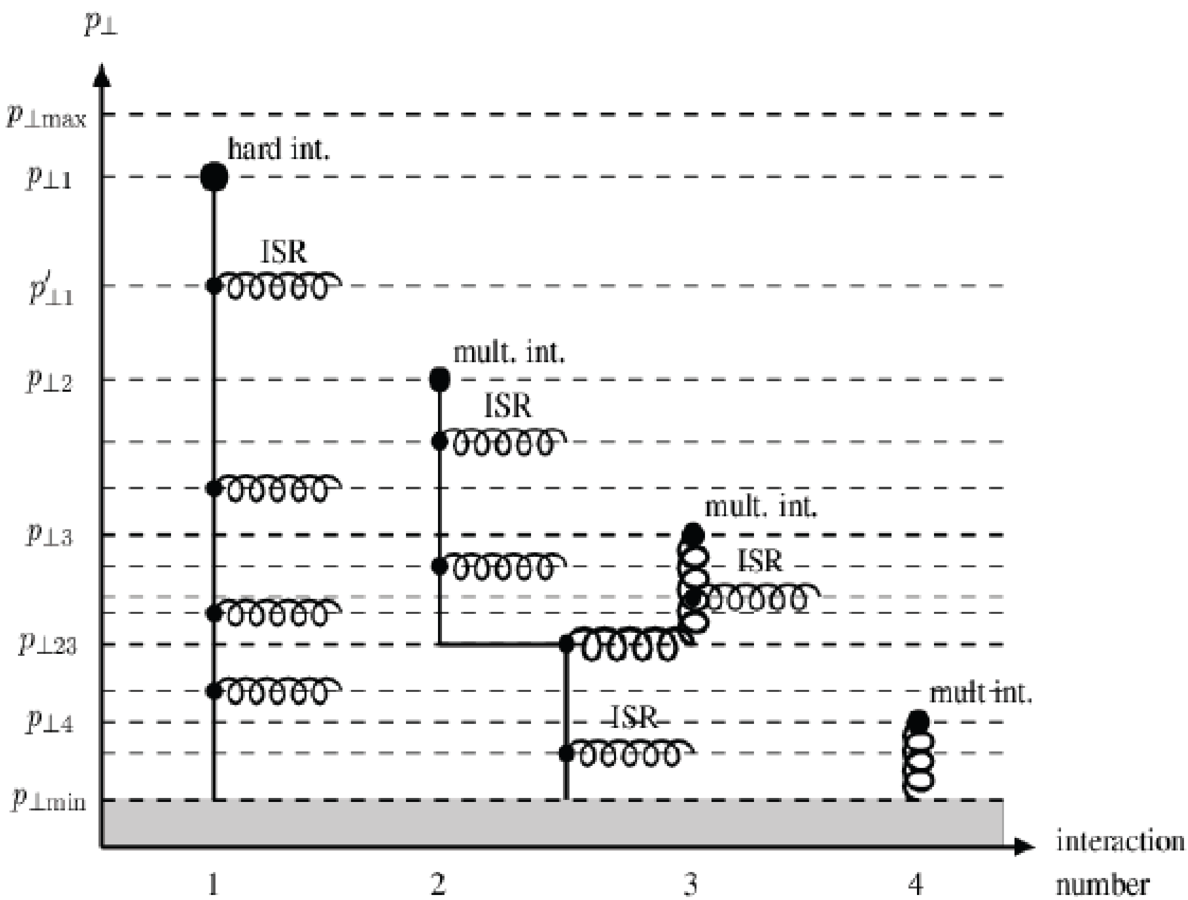
- In an event with MI, Pythia imposes an ordering:
  All **interactions are simulated in decreasing order of p_T**.
  The procedure is similar to the parton-shower model.

- For the first (and hardest) scatter, ordinary **pdf:s** are used
  They are then **subsequently adjusted depending on the preceeding x values and flavours** chosen.
  - when a valence quark is kicked out, the pdf of this flavour is rescaled
  - for a sea quark, the corresponding antiquark distribution is inserted

- For each interaction, the **ISR/FSR** machineries are used
  in the newest model, ISR is p_T-ordered over *all* interactions

remarks:
- 3 different Pythia UE models exist, and I simplified and mixed all of them for pedagogical reasons :-)
- the color reconnection mechanism has to be adjusted for MI to match data

MI in Pythia (3)



MI in HERWIG (JIMMY)

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- also assumed **Poisson-distributed <n>** for given impact parameter b
- **total cross section** for interactions with **n scatters of type a** is given by the parton cross section, the pdfs and the **overlap function A(b)**:

$$\sigma_n = \int \mathrm{d}^2 b \, \frac{(A(b)\sigma_{\mathrm{a}})^n}{n!} \, \mathrm{e}^{-A(b)\sigma_{\mathrm{a}}}$$

- assumes that the x and b-distributions of the parton are independent
- the overlap function depends on the matter distribution in the hadron

- For each scatter type a, $\boldsymbol{\sigma_{n,a}/\sigma_{total,a}}$ gives the **probability that n scatters of type a occur**. Thus those n scatters are generated, without rescaling the pdfs (like in Pythia).
- Simple model, compared to Pythia

Pile-Up

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- In high-luminosity colliders, **more than one hadron per beam may interact per bunch crossing**

- Other (semi-hard) interactions thus provide a background to rare events

- **Procedure for MC generators**:

  - produce n (~Poisson distributed around <n>) minimum-bias events, potentially with a seperate collision vertex
  - add them to the event record of the hard scatter

C. The UE at Tevatron & LHC

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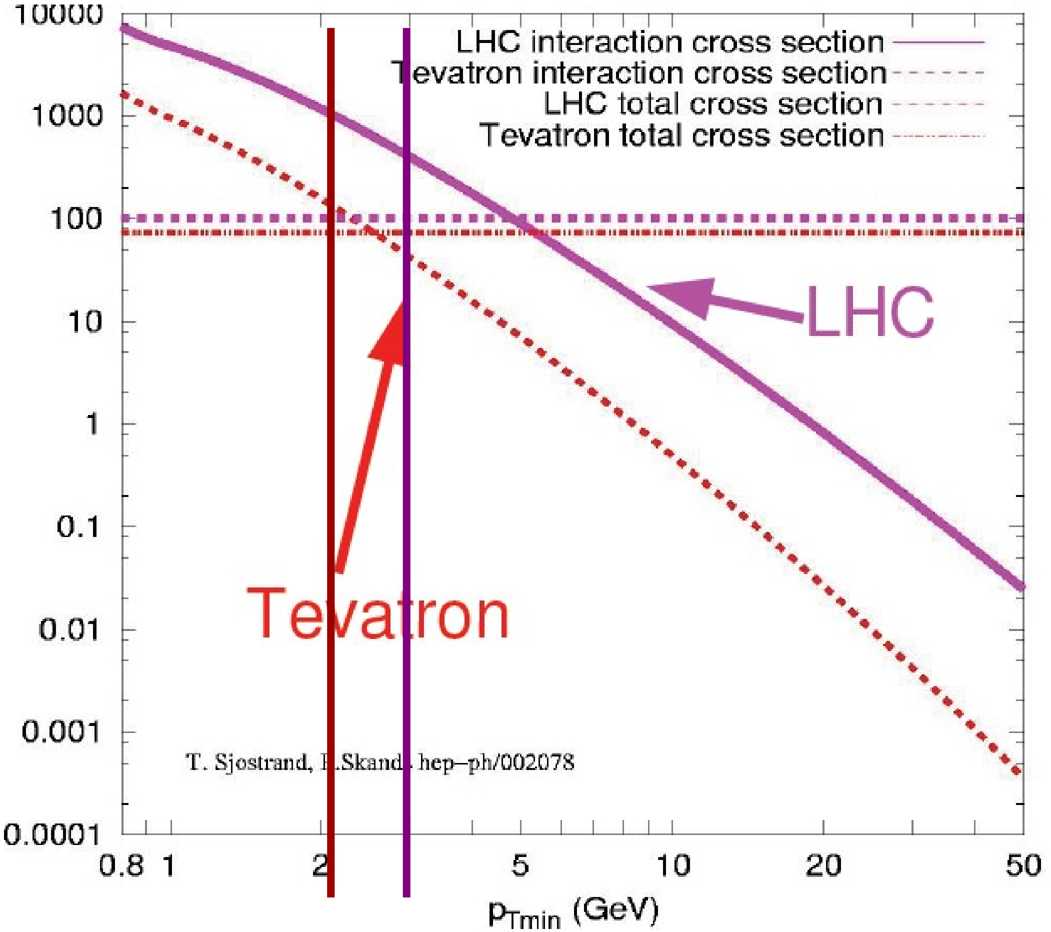

2.1 (Tevatron) 2.9 (LHC)

with the regularisation cut-off $p_{T,min}$ chosen in Pythia, the **average number of (semi)hard interactions** per events is

- **5 for the LHC**
- 2 for the Tevatron

(average over all b!)

Evidence for MI from CDF

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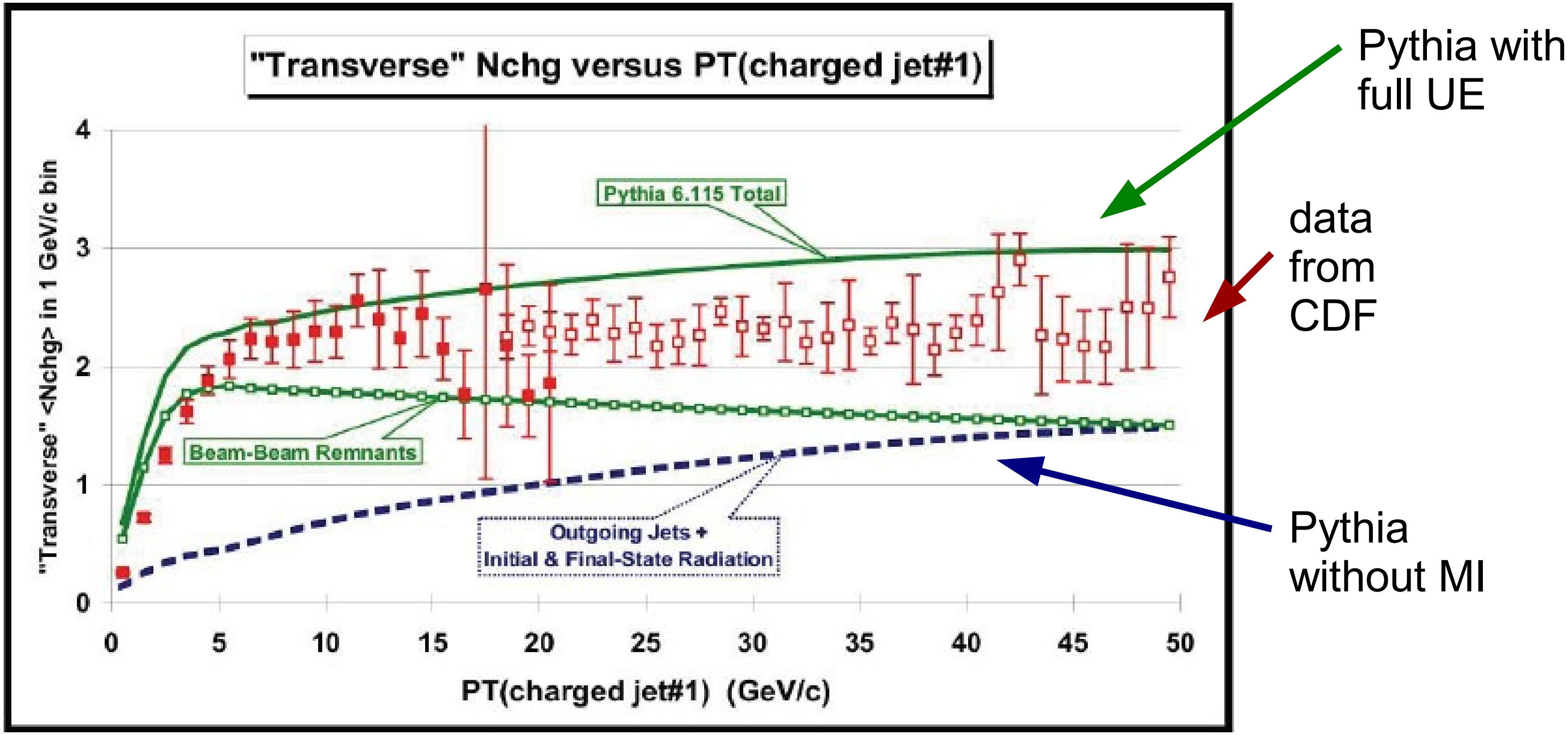
CDF coll. PRD 65, 092002 (2002)



Multiplicity distribution in region transverse to the jet can only be described by adding multiple interactions (remnant-remnant-interaction)

Pythia MI parameters for the LHC

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PYTHIA6.214 - tuned	
ISUB: 11,12,13,28,53,68 94,95,96	QCD $2 \to 2$ partonic scattering + non-diffractive + double diffractive
MSTP(51)=7	CTEQ5L - selected p.d.f.
MSTP(81)=1	multiple interactions
MSTP(82)=4	complex scenario + double Gaussian matter distribution
PARP(82)=1.8	$p_{t_{min}}$ parameter
PARP(84)=0.5	core radius: 50% of the hadronic radius
PARP(89)=1.0	energy scale (TeV) used to calculate $p_{t_{min}}$
PARP(90)=0.16	power of the energy dependence of $p_{t_{min}}$

free parameters for the multiple interactions in Pythia:

- $\mathbf{p_{T,min}}$
- **matter distribution** within the hadron

(for the complex scenario; additionally: simple & intermediate model)

MC Predictions for the LHC

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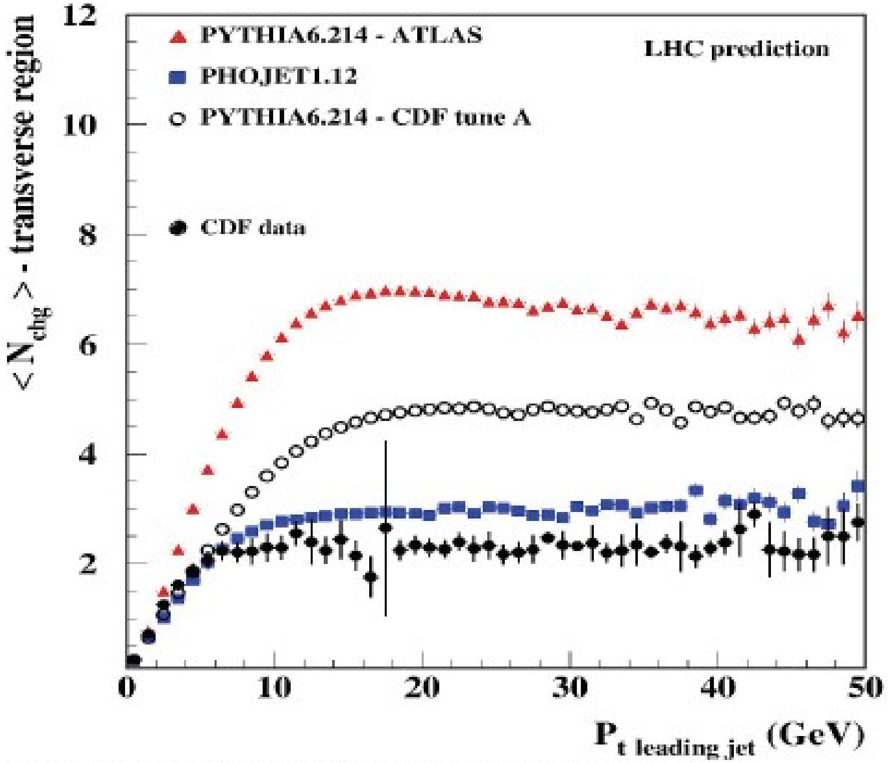
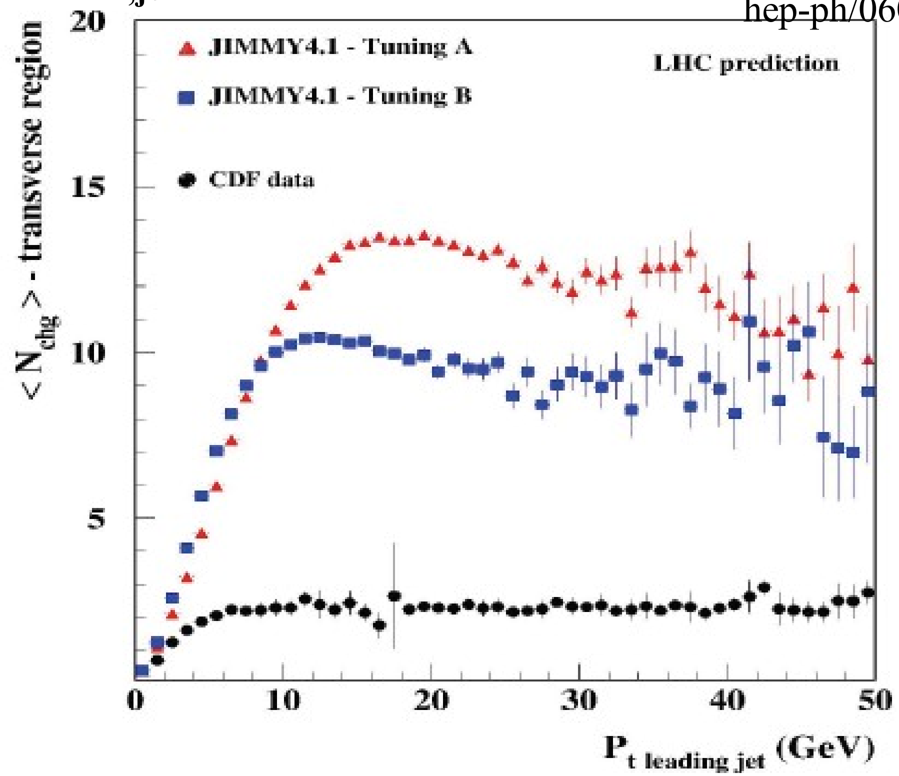
number of charged particles "transverse" to leading jet as function $p_{T,jet1}$.

C. Buttar et al, HERA – LHC workshop proceedings, hep-ph/0601012



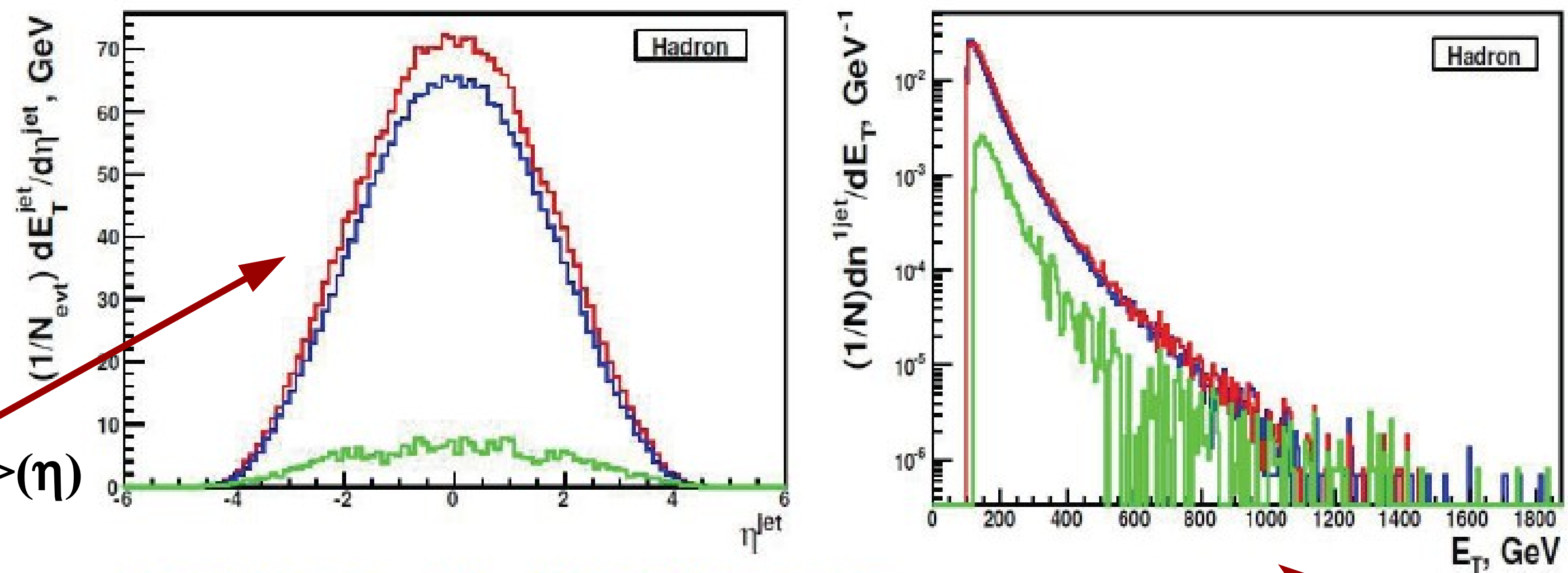


Approach for LHC: **Extrapolate Hera/Tevatron data to LHC energies**
Results are **very different for different models**!
The underlying event will be one of the first things investigated with early data.

The UE contribution to jets
(LHC prediction)

SHERPA: $E_T > 100\,\mathrm{GeV}, |\eta| < 5$

P. Starovoitov, T. Carli
HERA-LHC WS, June 2006



~ $<E_T>(\eta)$

Hard Scale, HS+UE, Difference

leading jet-E_T-distribution

The **UE contributes 10-30% to the number of jets**, even at large E_T!

Summary

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- **Underlying Event**: "everything except for the leading order process of interest"
  - ISR/FSR
  - Multiple Interactions
  - beam remnants
  - pile-up, noise, ...
- **little theoretical understanding**/experimental data about MI and beam remnants => several **phenomenogical models** available
- importance of UE increases with $\sqrt{s}$
- **large UE-contributions** e.g. to jet-distributions **predicted for the LHC** (but the prediction depend strongly on the chosen model!)