# Underlying Events

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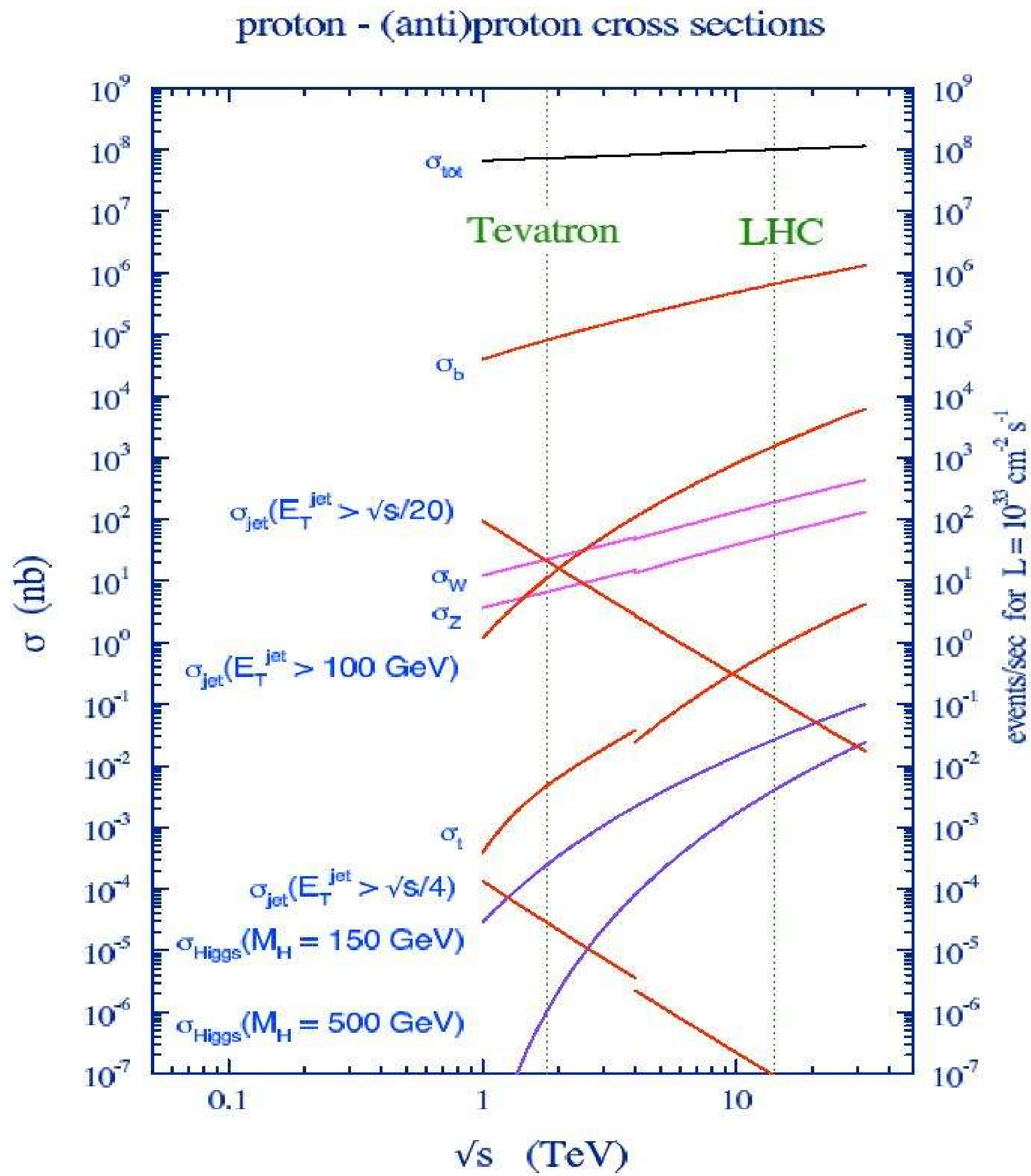
Wilhelm and Else Heraeus-Seminar on “New Event Generators for Particle Physics Experiments”

*Dresden 4-6 Jan 2006*

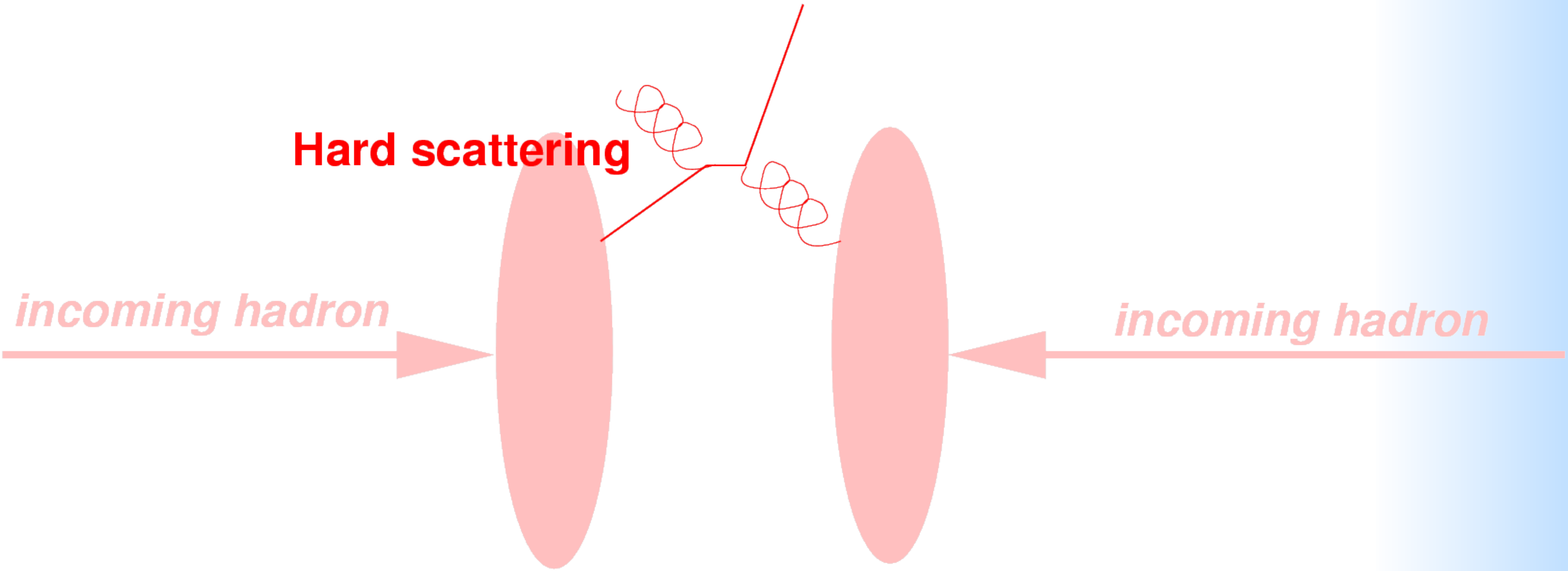
- What is the “underlying event” and why worry?
- Relating “minimum bias” and  “underlying event”
- Models on the market
- Where might we go from here?

# What is it and why worry?

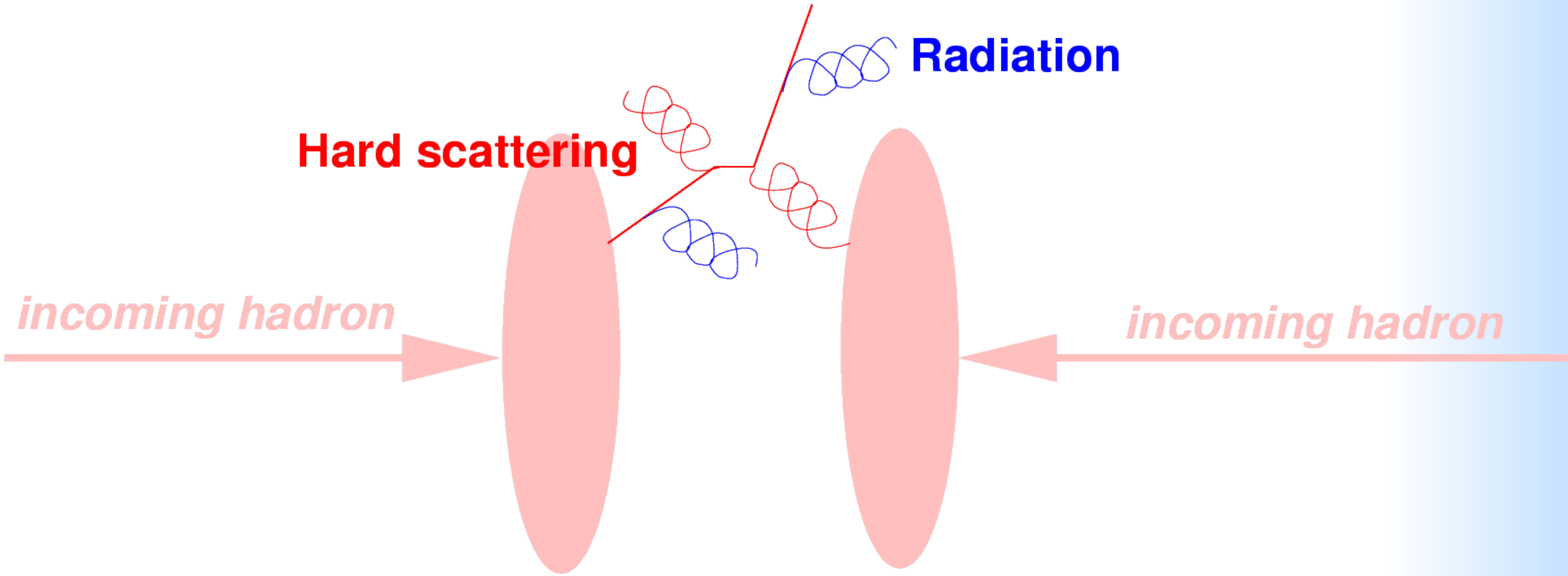



- Used to the idea that the “interesting” (high transverse momentum, high mass...) events are often quite a small fraction of the total number of collisions.

- Even in a given observed collision there will be several physical processes taking place in addition to the “interesting” process.



Hard scattering
incoming hadron
incoming hadron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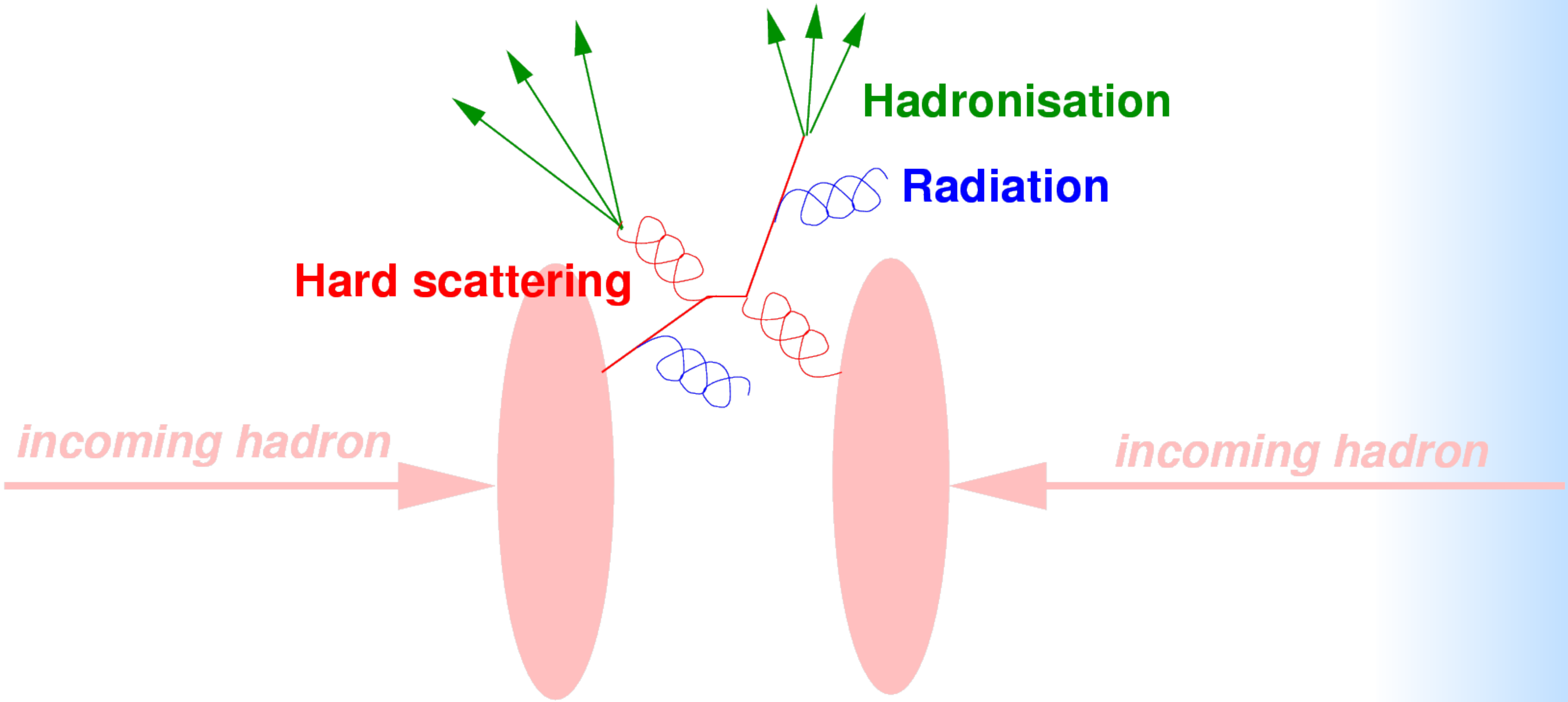
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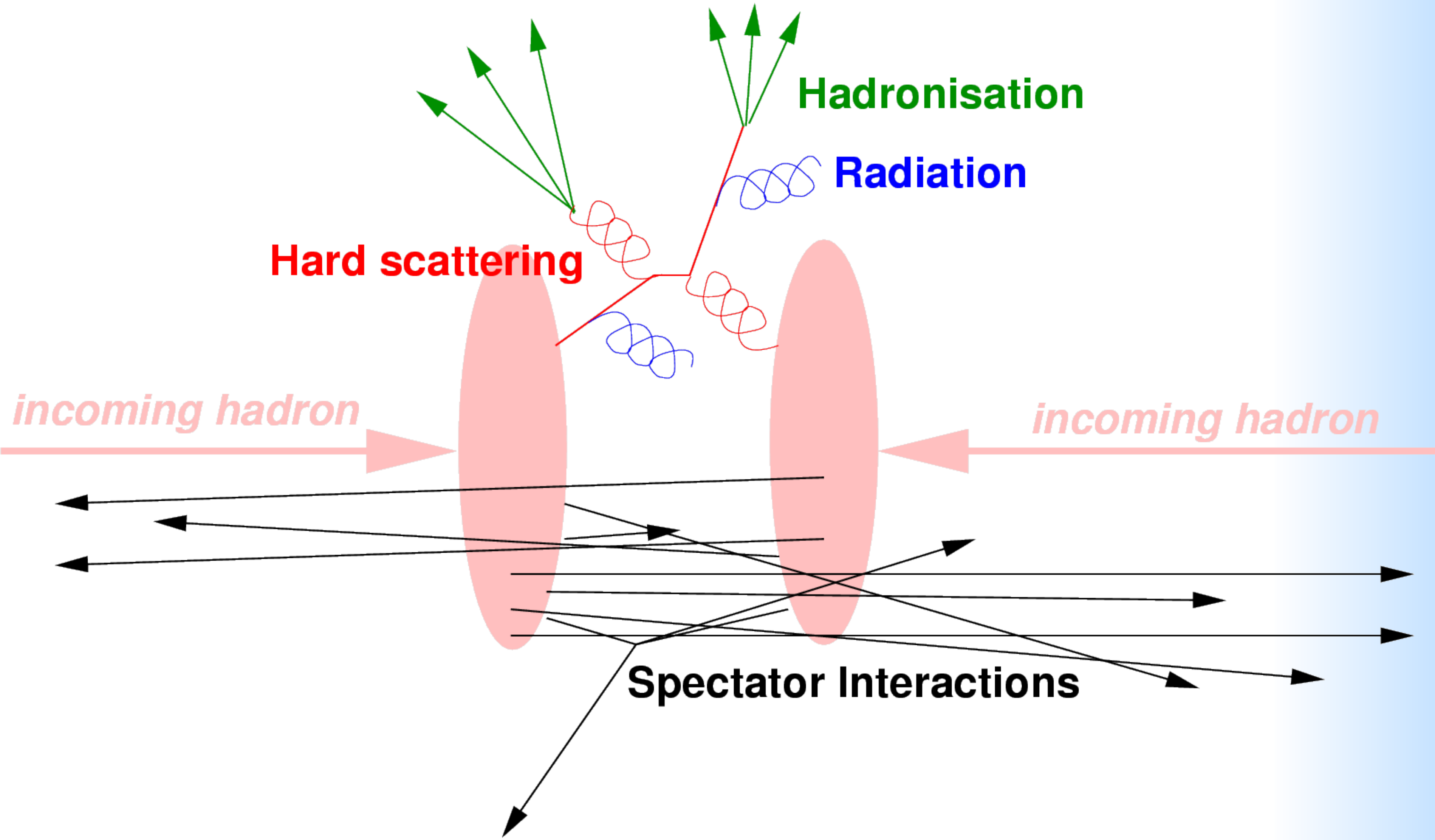
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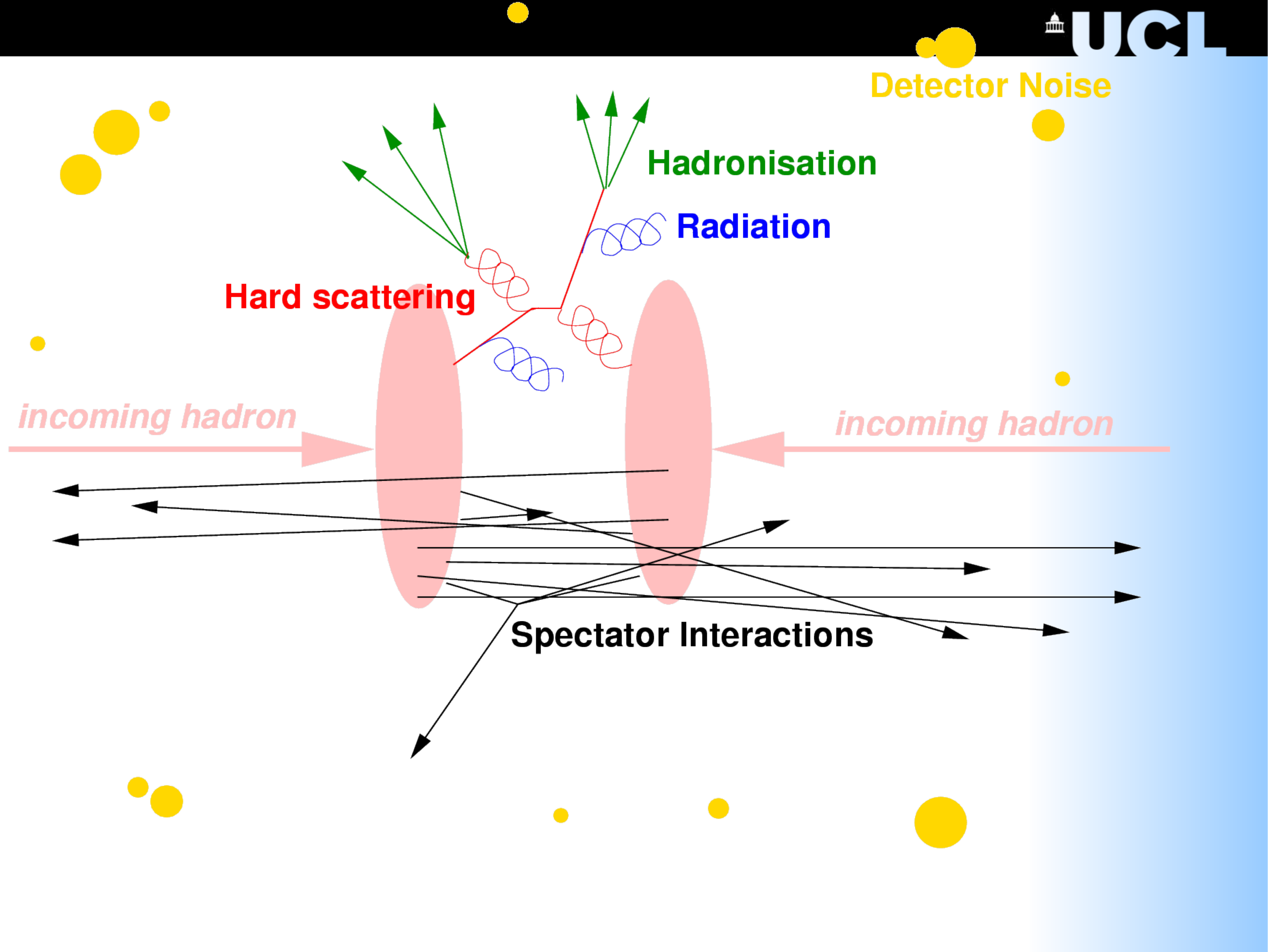
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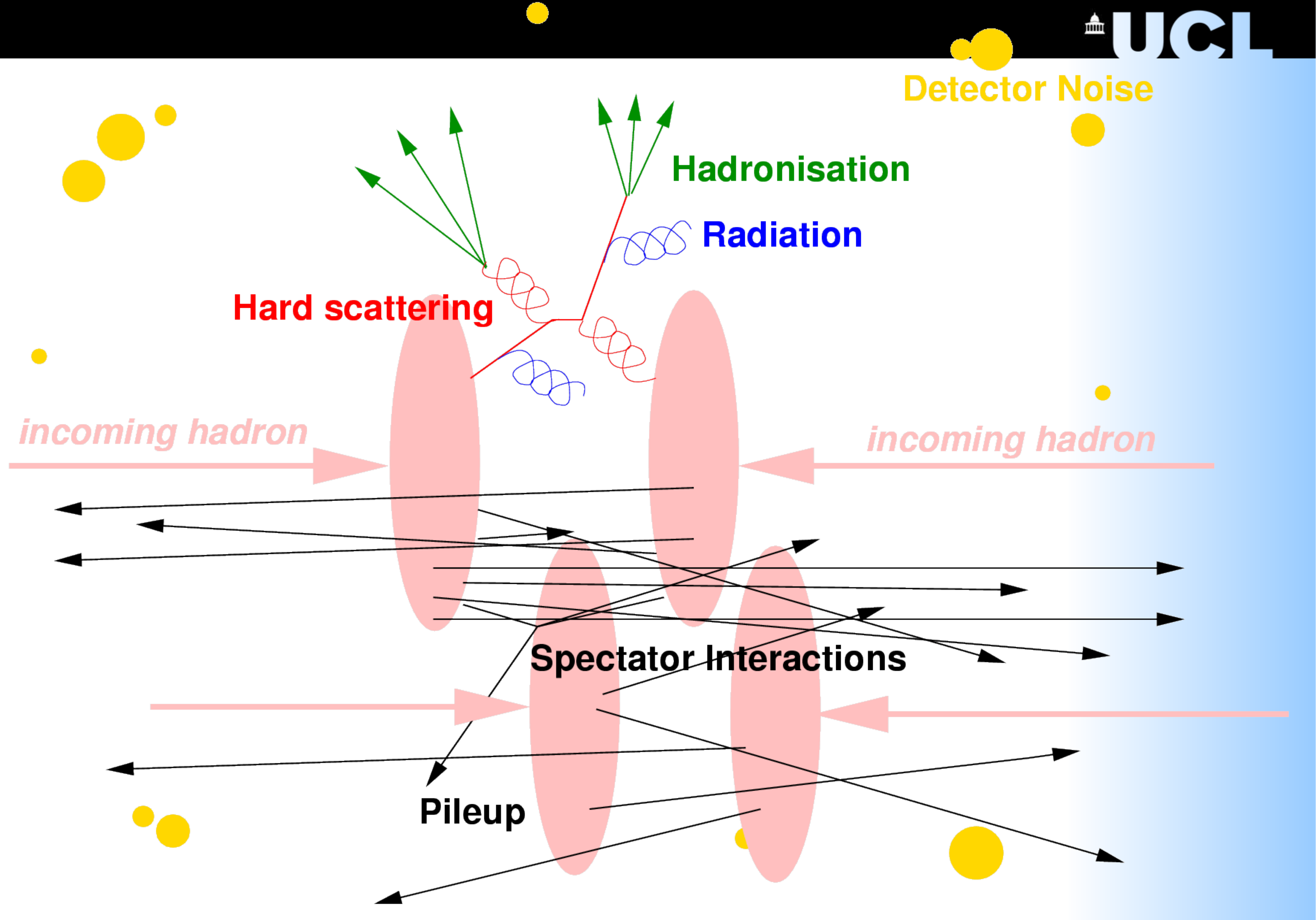

Detector Noise
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Pileup

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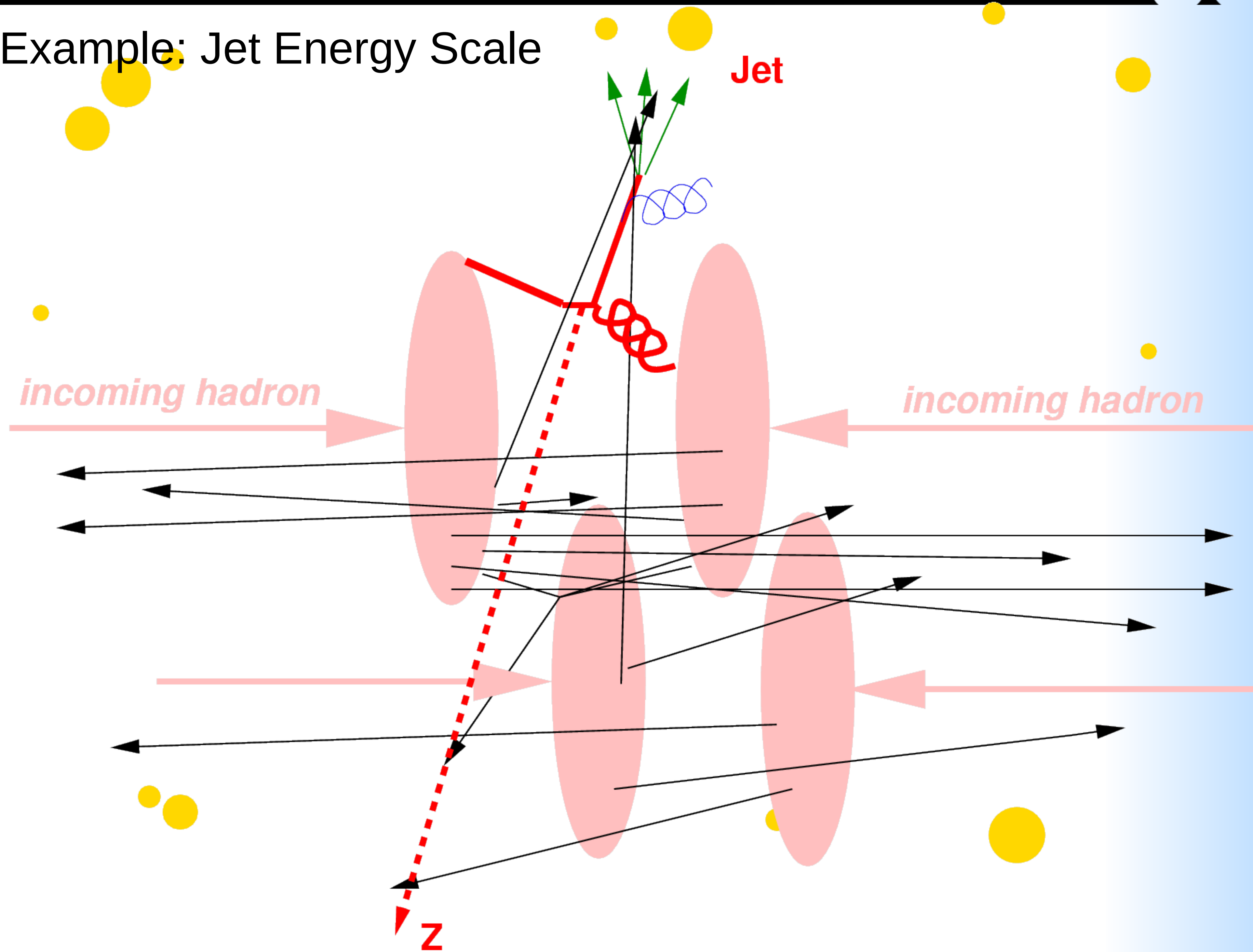
  - the need to measure more exclusive quantities
- Examples:

# Example: Jet Energy Scale

- Leptonic energy scale typically much better known than the hadronic/jet energy scale.
- To determine response to hadronic jets, typically look for well measured leptonic processes (e.g. Z -> e+e-) and balance leptons against jets.
- This balance is affected by the environment of the event.

# Example: Jet Energy Scale




Effects of the Underlying Event

# Example: Multijet selection

- Missing $E_T$ + lepton + jets: common signature for beyond the standard model physics (SUSY etc) as well as for top studies, Higgs searches.
- Extra jets can be produced by QCD radiation, spectator interactions and pileup.
- Low $E_T$ jets can have their $E_T$ boosted.

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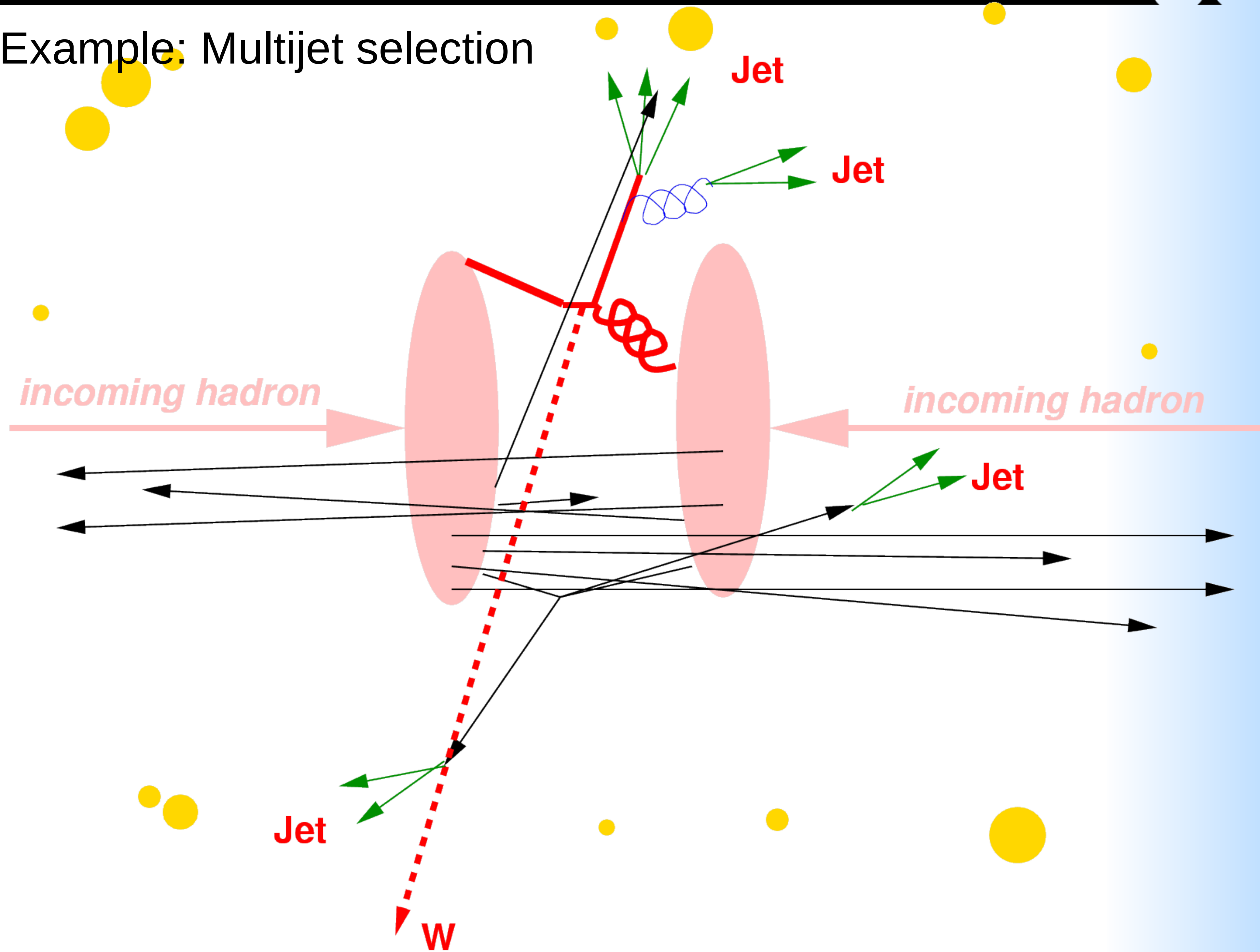
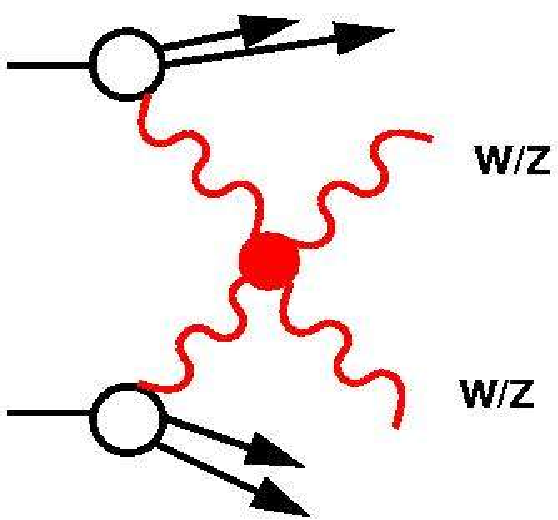
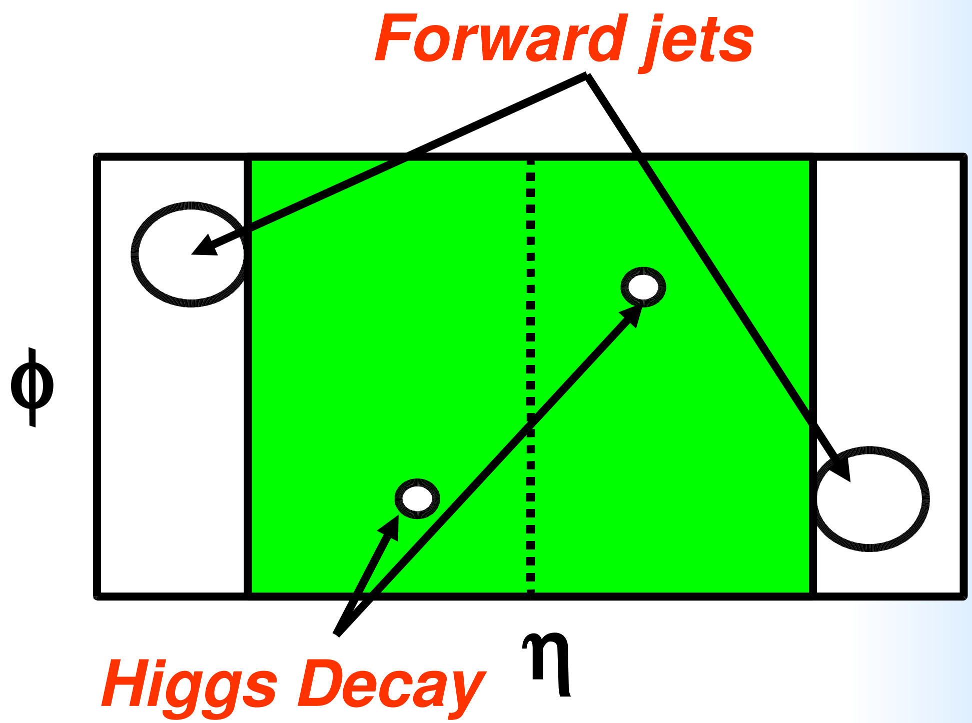



Effects of the Underlying Event

# Example: Minijet veto

- In some processes there is no colour exchange between the protons.
- Suppression of QCD radiation in the event;
  - Important signature for reducing backgrounds.
- No suppression in activity from spectator interactions or pileup.



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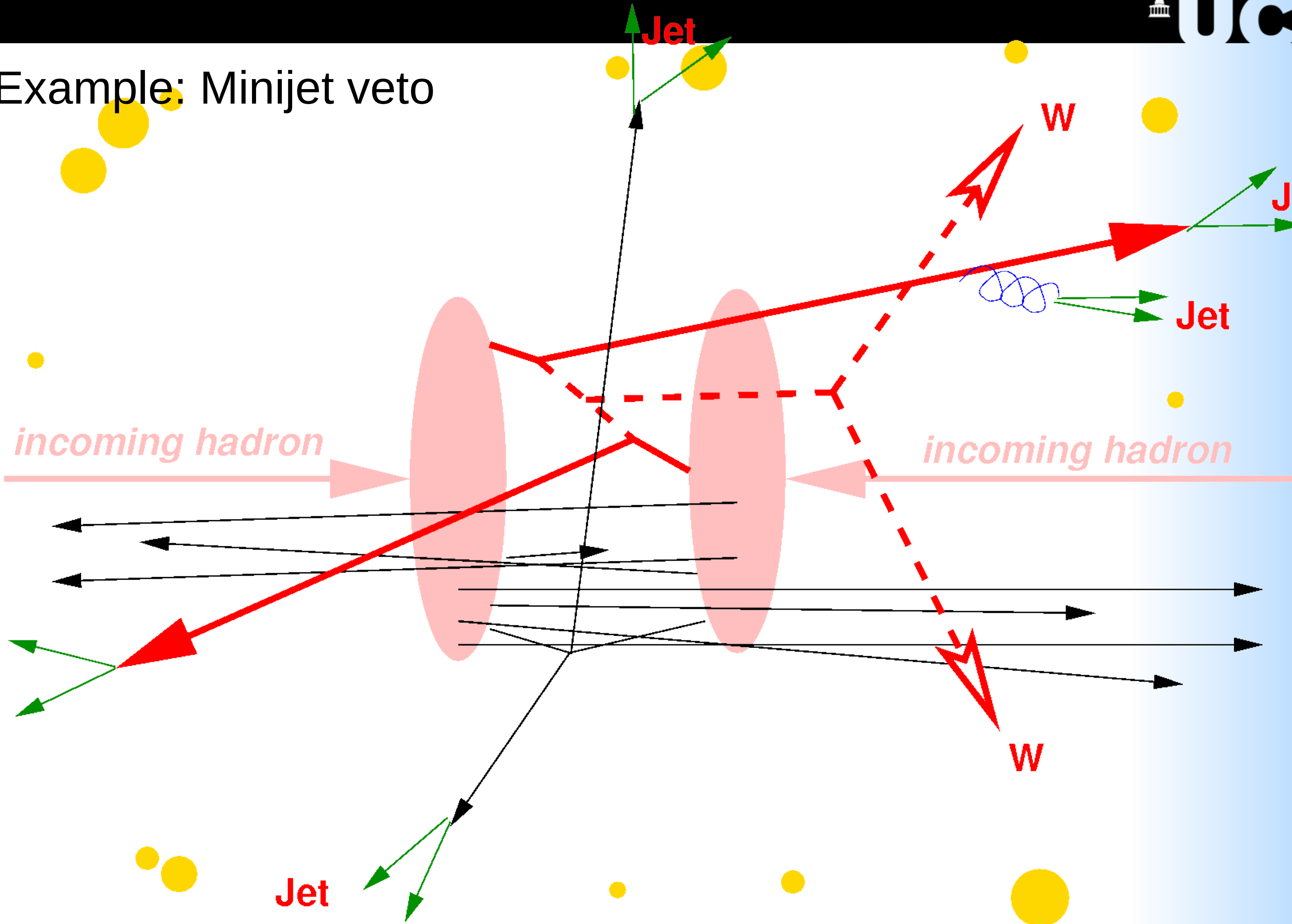

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- What is the best definition of the Underlying Event?

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- *Leads to very model-dependent measurements with poor accuracy and limited shelf-life.*

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- *Good, but ties the measurement to a particular underlying event model.*

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- *Now most commonly used... recommended!*

- A real “event” is pileup, noise, hadrons from spectator interactions, from QCD and QED radiation and from the hard matrix element.
- The least model-dependent measurement possible is the hadronic final state from a given collision. *Producing this is the main job of an experiment!*
- This includes particles from the “interesting” process, and particles from spectator interactions.
- The second of these should be referred to as the “underlying event”. It may need to be estimated in order to measure and interpret the data. *Producing this estimate is the main job of the models discussed here!*

# Modeling the Underlying Event

Collect potentially useful physical ideas

- May be hard (*i.e.* contain high $p_T$ scatters) or soft.
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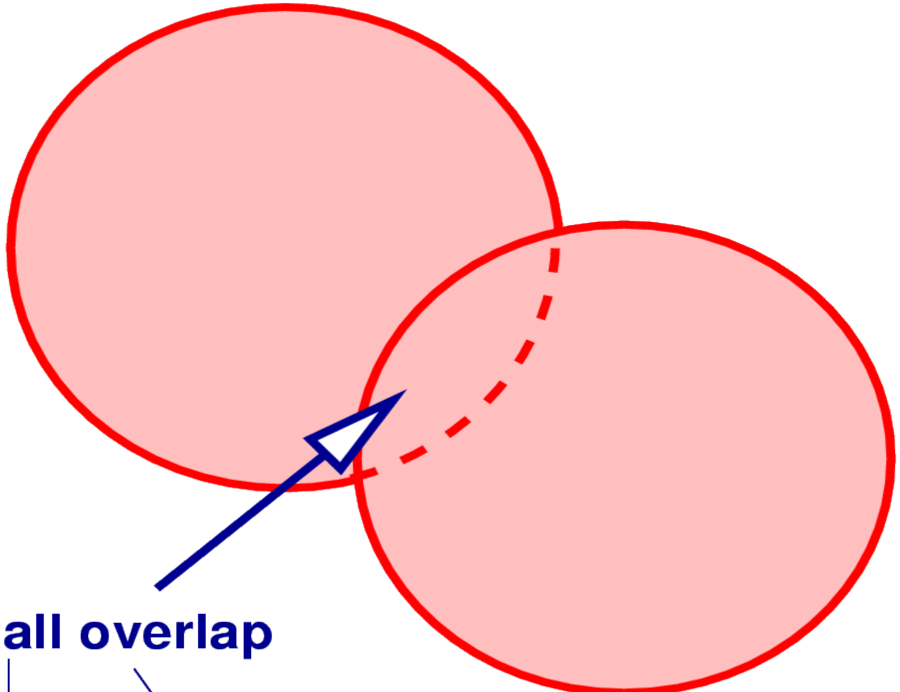
- Expect impact parameter (b) dependence.
  - Therefore need some assumption about the b distribution of matter, and its relation to the x distribution.
  - Will not simply be the equivalent of a minimum bias event "underneath" the process of interest – correlations are very significant.



**Small overlap**

**Low underlying event activity**

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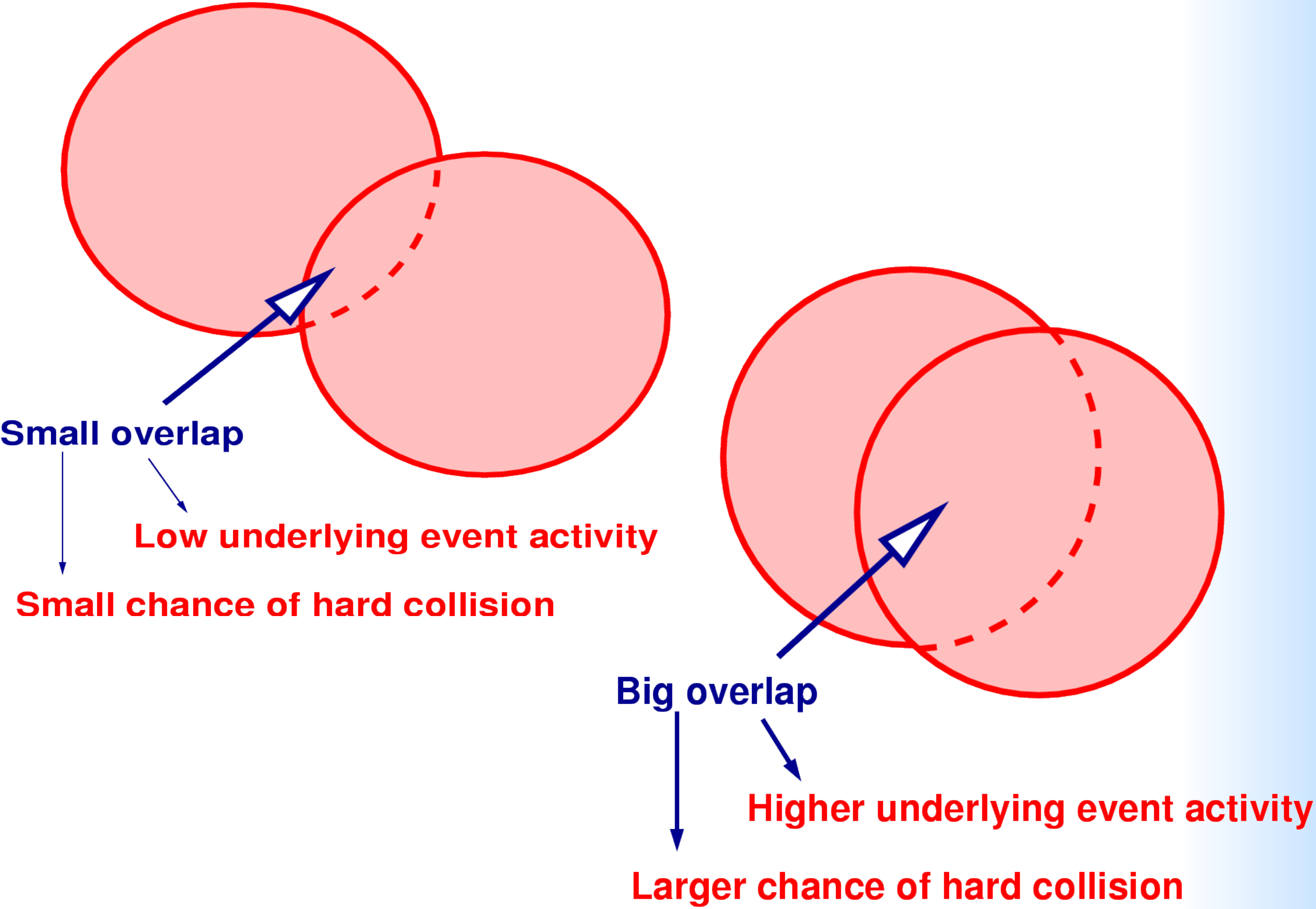
Small overlap
Low underlying event activity
Small chance of hard collision
Big overlap
Higher underlying event activity
Larger chance of hard collision

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- Forward particle production – rescattering/absorption; leading protons and neutrons.
- Related to survival probability for rapidity gaps – incoherent remnant interactions fill the gap.

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- A single particle-particle (i.e. proton-proton) interaction.

# Zero and Minimum Bias Events

- Average event (zero or minimum bias) has low transverse energy, low multiplicity.
- Several zero bias events will accompany every triggered event at LHC at $10^{34}$ $cm^{-2}s^{-1}$.
- Can be measured experimentally at some level using random triggers at low luminosity.
- Modeling them at some level is still necessary
- They can be used to test some of the physics ideas used in underlying event models.

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  - HERWIG (JIMMY) (JMB, Forshaw, Seymour)
- Soft "partonic" scatters matched to hard 2->2 scatters
  - PYTHIA (several options) (Sjostrand & van Zijl, Sjostrand &Skands), PHOJET (Engel), now SHERPA.

# HERWIG Soft Underlying Event

- Parameterisation of UA5 inelastic charged multiplicity distribution (i.e. minimum bias)
  - Exponentially falling $p_T$ distribution, flat rapidity distribution.
- No dependence on parton densities.
- Tunable (see HERWIG 6 manual for details), but lack of an underlying physical model makes extrapolation (e.g. to high energies) extremely suspect.
- Cannot include correlations.
- High $p_T$ tail presumably double-counts a hard component

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- Either way, something has gone wrong with the physical assumption that each hadron-hadron event has at most one parton-parton scatter.

- Solution: assume Poisson statistics and either
  - the total cross section from Regge fits *(PHOJET, all PYTHIA models)*, or
  - something about the matter distribution in the proton *(JIMMY, and PYTHIA complex models)*
- Eikonalise the cross section.
- Plenty of other details to be considered, as usual...

# Multiparton Interactions in PYTHIA

Sjostrand and van Zijl, 1987

- Mean number of scatters per event = σ(dijet)/ σ(nd)
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- Multiplicity distribution from Poisson statistics
  - No impact parameter dependence in simple model.
- Various options for matching hard scatters to soft "gluon-gluon" scatters
  - hard cutoff or smooth turnoff below some $p_T$.

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- Parton density q(x) is rescaled to $q(x/(1-\Sigma x_i))$ after i collisions
  - Forces conservation of momentum!
  - Implies a time ordering of scatters, hardest first.
  - Should change the initial dijet cross section.

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- All secondary scatters are gg->gg or gg-> qqbar
- Parton showering only done for the hardest scatter.

- "Complex" model operates as the simple one except that a matter distribution as a function of impact parameter is used to introduce an impact parameter dependence.
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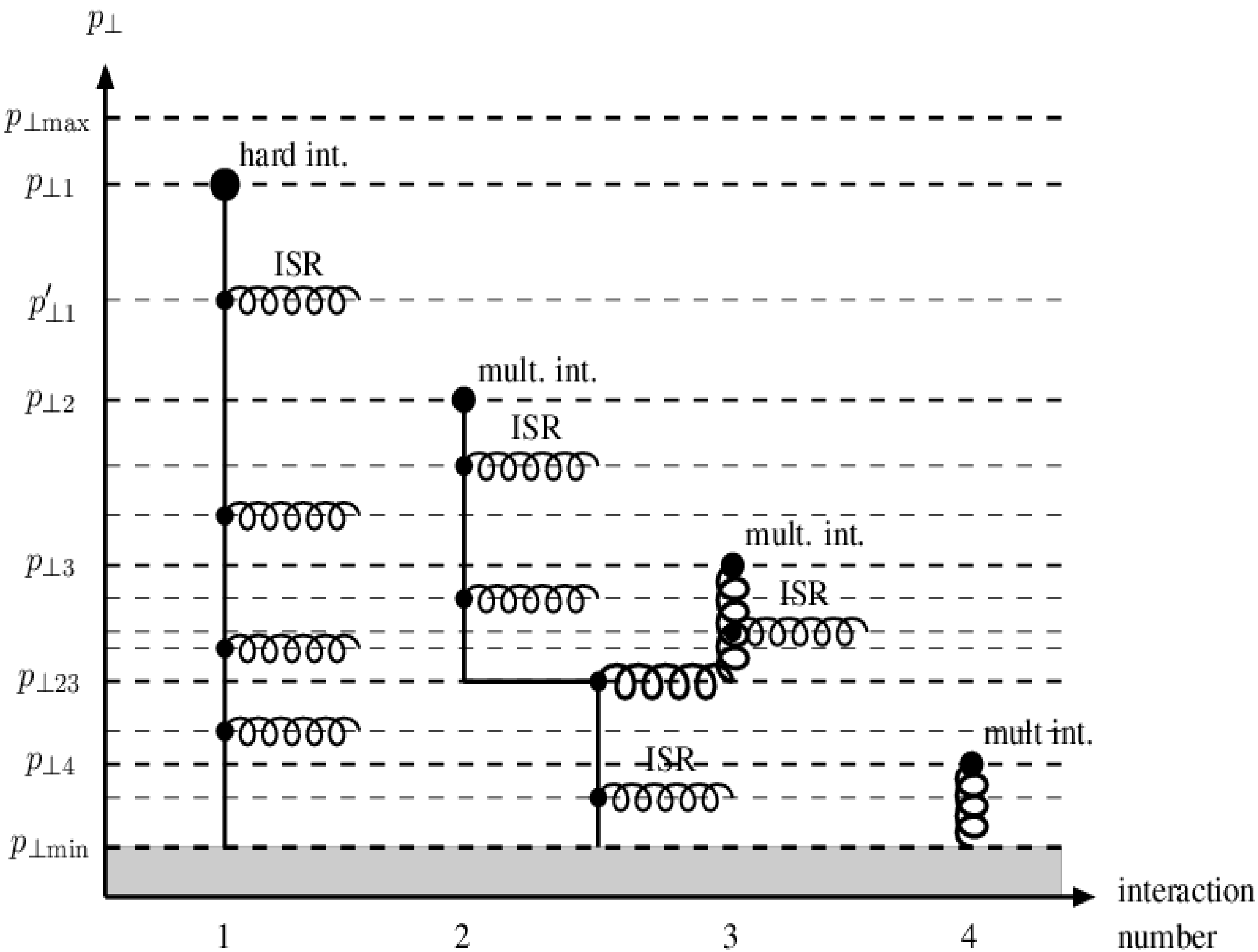
  - Enhances correlations and fluctuations (as required by data)
- Does not work for photon-proton or photon-photon
- Both simple and complex models work for minimum bias as well as for underlying event

# PYTHIA new model

Sjostrand and Skands 2003

- Motivated by the desire to allow more realistic colour and flavour structure for scatters.
  - Not just the momentum, but the flavour content of the remnant is adjusted as each scatter removes a parton.
  - Initial and final state QCD radiation now included for all scatters.
  - Backward evolution for initial state radiation, and generation of secondary scatters, both use these modified PDFs.
  - Multiple interactions can share a common ancestor even above $p_T$ cut off.

# PYTHIA New Model



# JIMMY's Eikonal Model

- All scatters treated on an equal footing.
  - For fixed impact parameter (b) all scatters are independent (flavour and momentum*).
  - Parton showering back to an initiaor parton at the shower cutoff scale is carried out for all scatters.
  - * if a scatter evolves back to an x which would violate energy momentum conservation, it is vetoed and tried again. If it keeps failing, no more scatters are generated and the eikonal is modified accordingly.

- Total cross section for events with n scatters of a given type (e.g. type **a**) is calculated from the parton cross sections, the PDF and the eikonal formalism.

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

*A(b)* is the area overlap function

  - *A(b)*, the area overlap function, is calculated on the assumption that the matter distribution is the fourier transform of the electromagnetic form factor.
  - Also implicit assumption that the x and b distributions of the parton densities are independent.

- This formula is used to derive the probability that an event has exactly **n** scatters, given that is has at least one.
  - Pretabulated at the start of a JIMMY run.
  - Correlations and fluctuations are included, without generating an event-by-event impact parameter.

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  - Pretabulated at the start of a JIMMY run.
  - Correlations and fluctuations are included, without generating an event-by-event impact parameter.
- The total cross section for events having at least one scatter of type **a** is modified (unitarised) by the program at the end of a run based on the actual number of multiple-scattering events which occurred.

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- Initiator parton can be a photon, thus dynamically generating the “anomalous” component.
- No rescaling of PDFs – probes lower x values than PYTHIA.
- No energy dependence of $p_T$ cut off.

# Practical Problems with JIMMY's Simple Eikonal Model

- Event type **a** is QCD 2->2 scattering (the only implemented process in JIMMY), typically we want to see the effect of low $p_T$ multiple scatters on a high $p_T$ rare event. To get the low $p_T$ multiple scatters, PTMIN must be set low, which is very inefficient.

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- Would also like to see the effect of QCD multiple scatters on other rare processes (type **b**).

- To calculate the probability of an event having n scatters of type **a** and **m** of type **b**, the formula is:

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

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- Or, if **m** is a subset of **n** (e.g. The higher $p_T$ scatters)

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

- To tabulate such results at the start requires prior knowledge of the cross section for **b** as well as **a** and is very awkward to do exactly.

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- Work in the approximation that the chance of >1 scatter of type **b** is negligible.
- Probability of n scatters of type **a** and at least one of type **b** is:

JIMMY

$$P(n|m \geq 1) = \frac{\int \mathrm{d}^2 b \, \frac{(A(b)\sigma_{\mathrm{a}})^n}{n!} \, \mathrm{e}^{-A(b)\sigma_{\mathrm{a}}} \left(1 - \mathrm{e}^{-A(b)\sigma_{\mathrm{b}}}\right)}{\int \mathrm{d}^2 b \, (1 - \mathrm{e}^{-A(b)\sigma_{\mathrm{b}}})}, \qquad n \geq 0$$

Since $\sigma_{\mathrm{b}}$ is small, we can expand the exponentials and obtain

$$P(n|m \geq 1) \approx \int \mathrm{d}^2 b \, A(b) \, \frac{(A(b)\sigma_{\mathrm{a}})^n}{n!} \, \mathrm{e}^{-A(b)\sigma_{\mathrm{a}}}, \qquad n \geq 0.$$

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  - If a scatter of type a is also of type **b**, reject the **m**$^{th}$ type b scatter with probability 1/(**m+1)**
- Continuous at the boundary between **a** and **b**, correct to first order in $\sigma$(b).

# Multiple Interactions in PHOJET

Engel

- Both soft and hard scatters treated together (separated by a $p_T$ cut).

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- Used extensively in photon-hadron & photon-photon events as well as hadron-hadron.
- Not a general purpose MC.

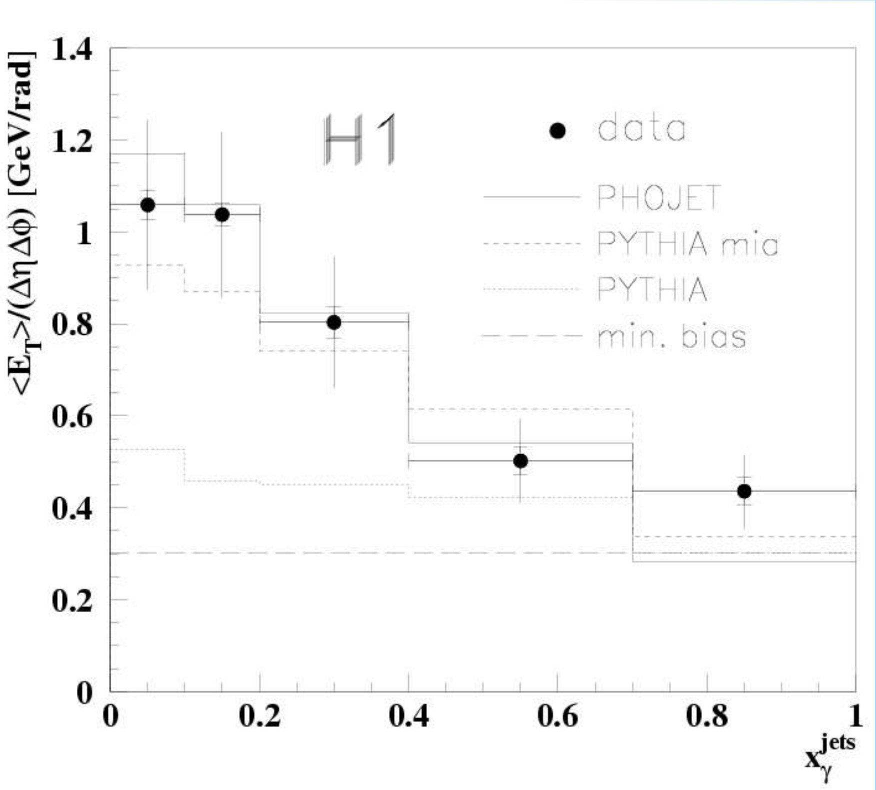
# Underlying Events in new generators: my guesses...

- SHERPA
  - Implementation of PYTHIA simple model. New model planned.
- HERWIG++
  - Planned implementation of JIMMY+soft matching (Borozan & Seymour)
- PYTHIA 7
  - Could use whatever HERWIG++ has via ThePEG
- PYTHIA 8
  - Presumably will contain implementation of existing PYTHIA models.

# So what to trust?

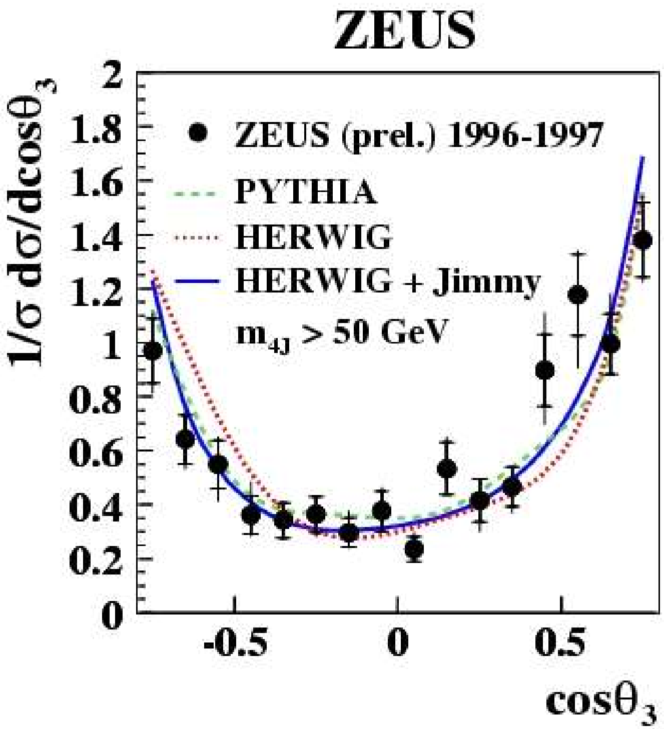
- There is fairly convincing evidence from UA5, Tevatron and HERA that multiparton interactions take place. Certainly these are the only models which have the power to describe the data.

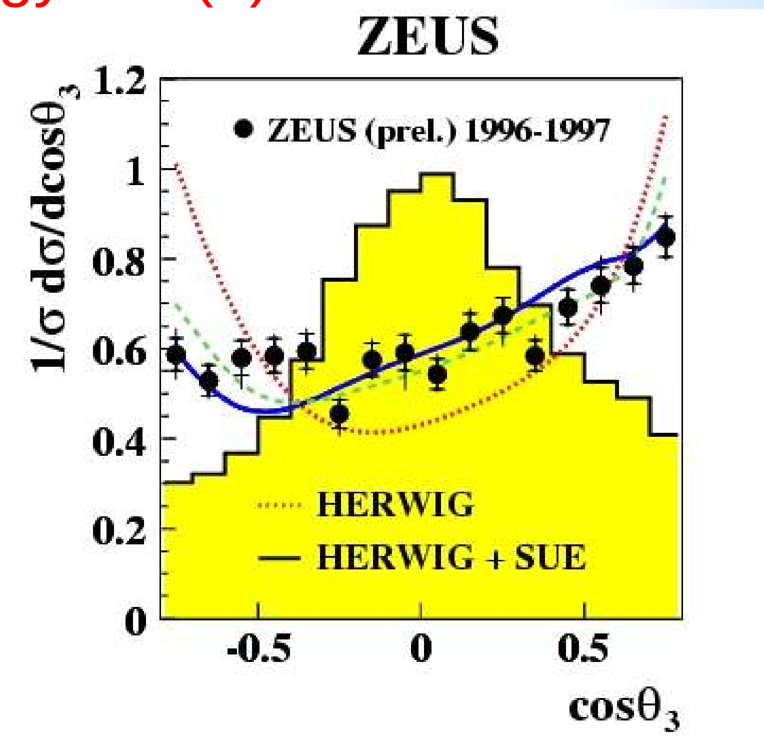
e.g. Energy flow outside jets in resolved photon only modelled by MI models...



# Four-jet cross sections

Photoproduction, jet transverse energy > 6 (5) GeV.

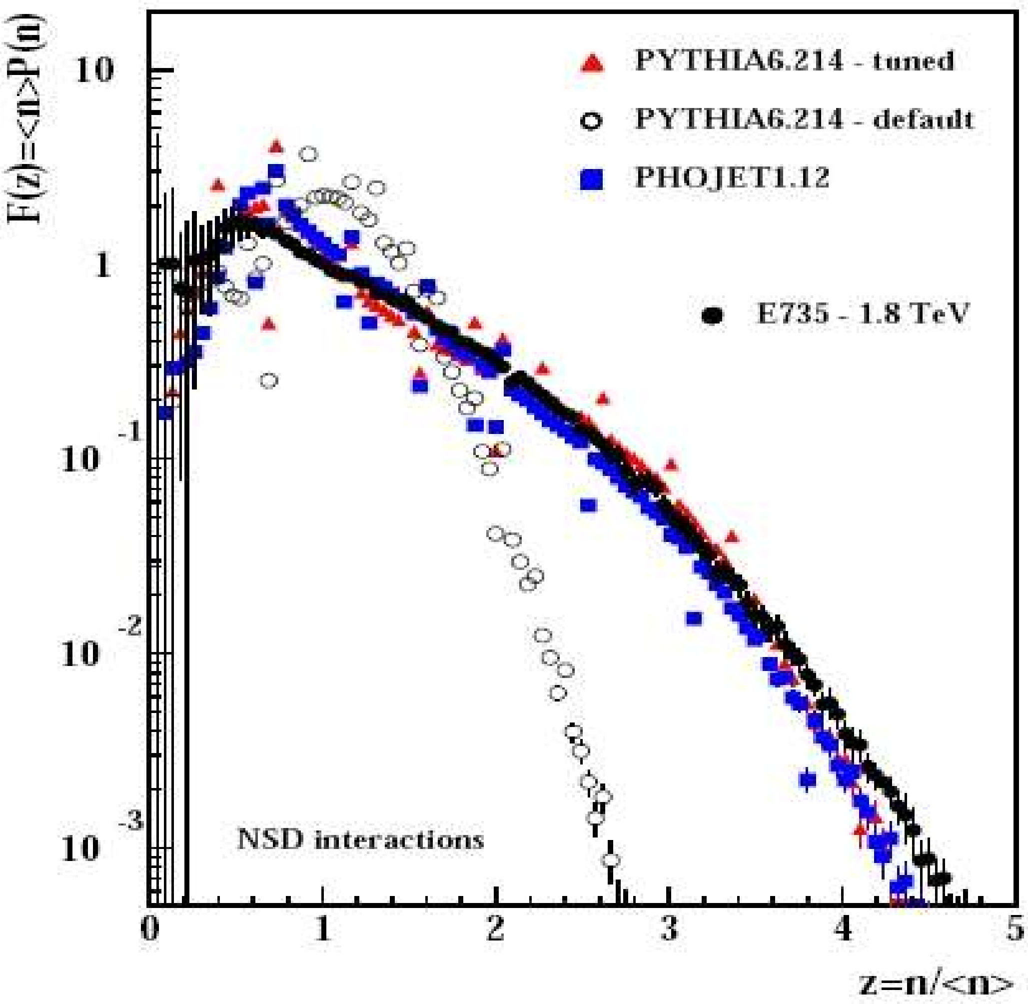



Four jet Mass > 50 GeV. QCD (LO+PS) doing well.

No mass cut. Need something else. Multiparton interaction models are favoured.

# Key distributions for tuning models




UA5 “KNO” distribution – sensitive to correlations/fluctuations

*(ATLAS: Moraes, Buttar, Dawson)*

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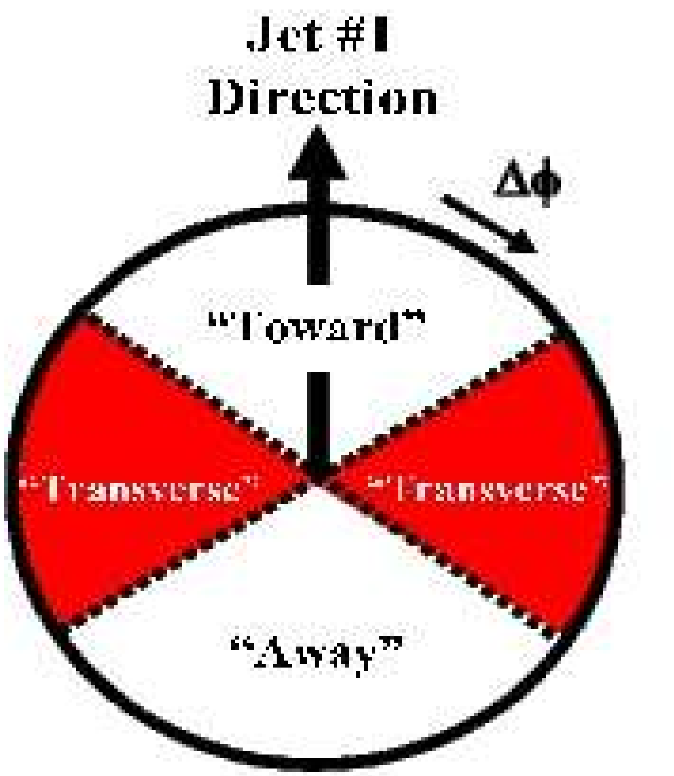
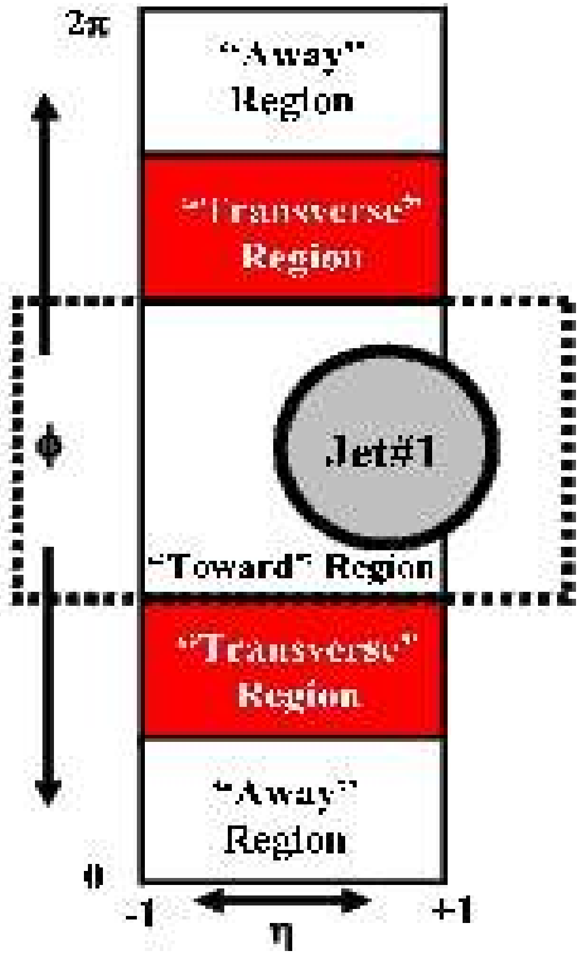
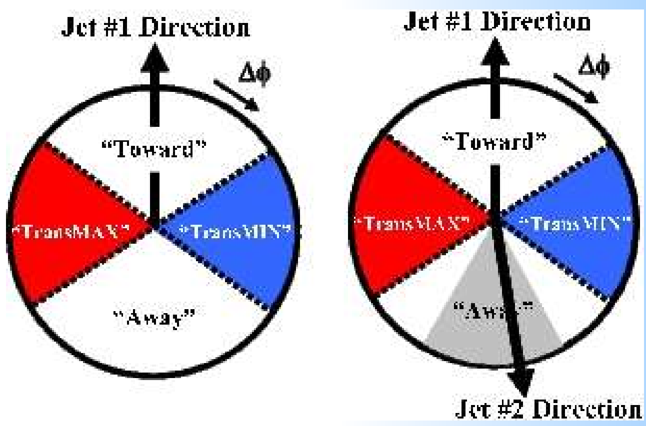



Particle and energy flow in regions defined w.r.t. leading jet or in djet systems.

*CDF: R. Field et al*



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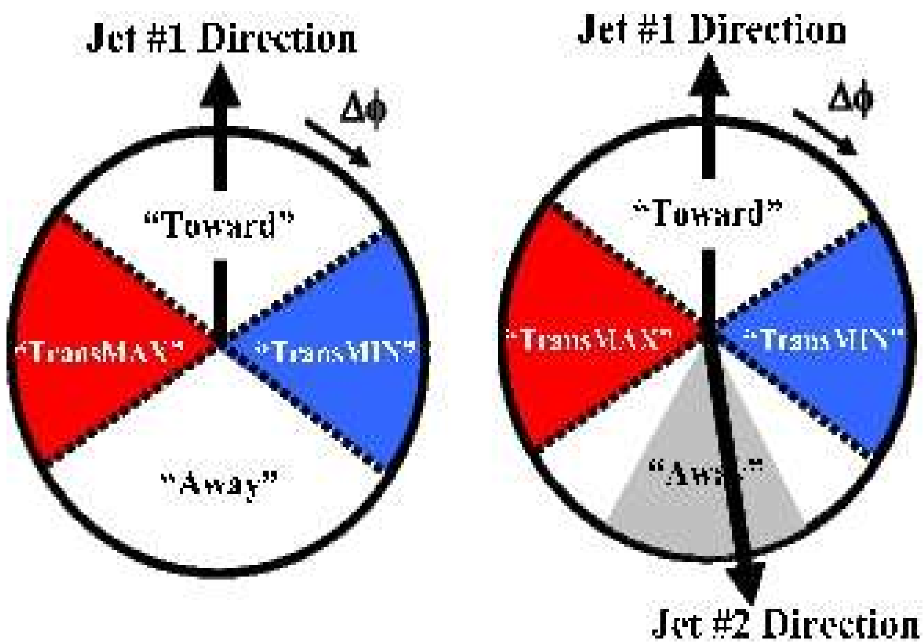
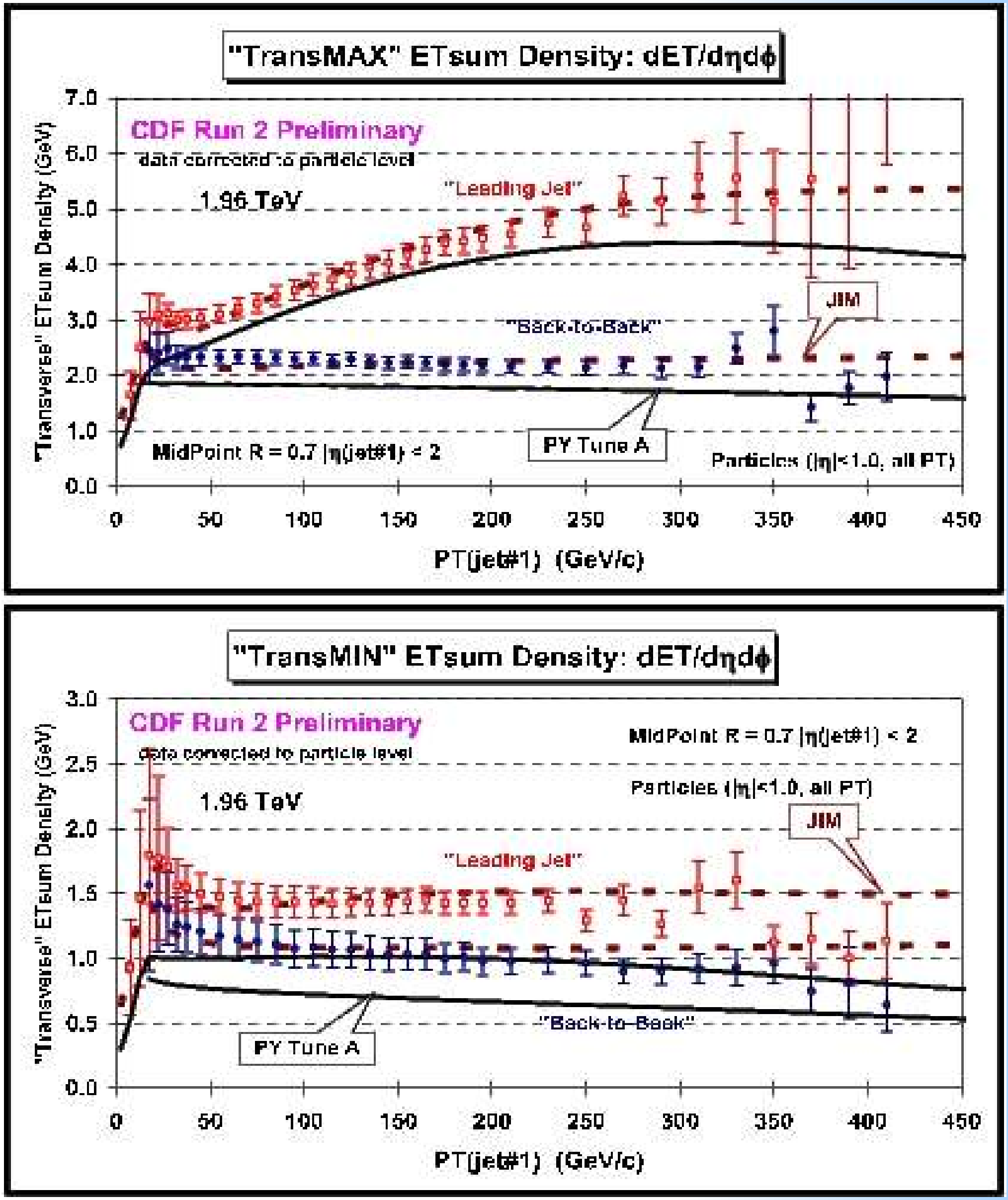
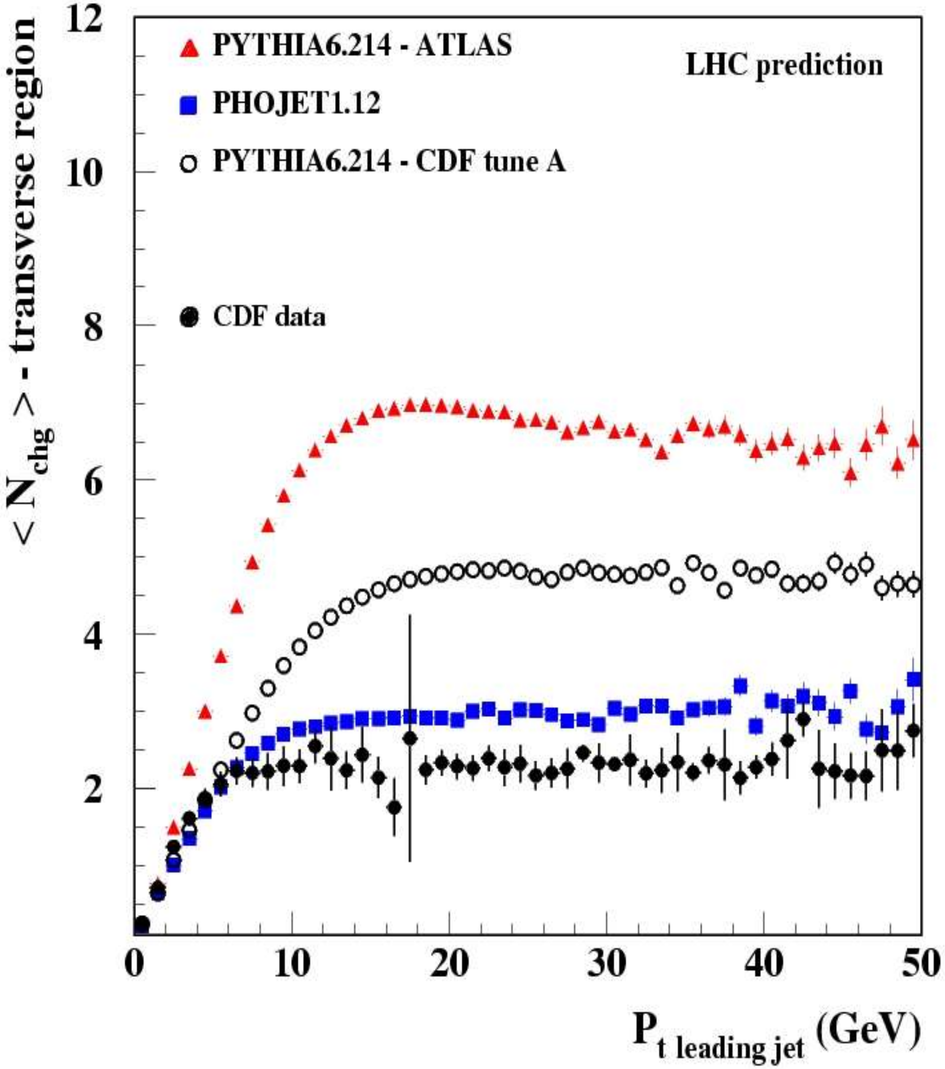
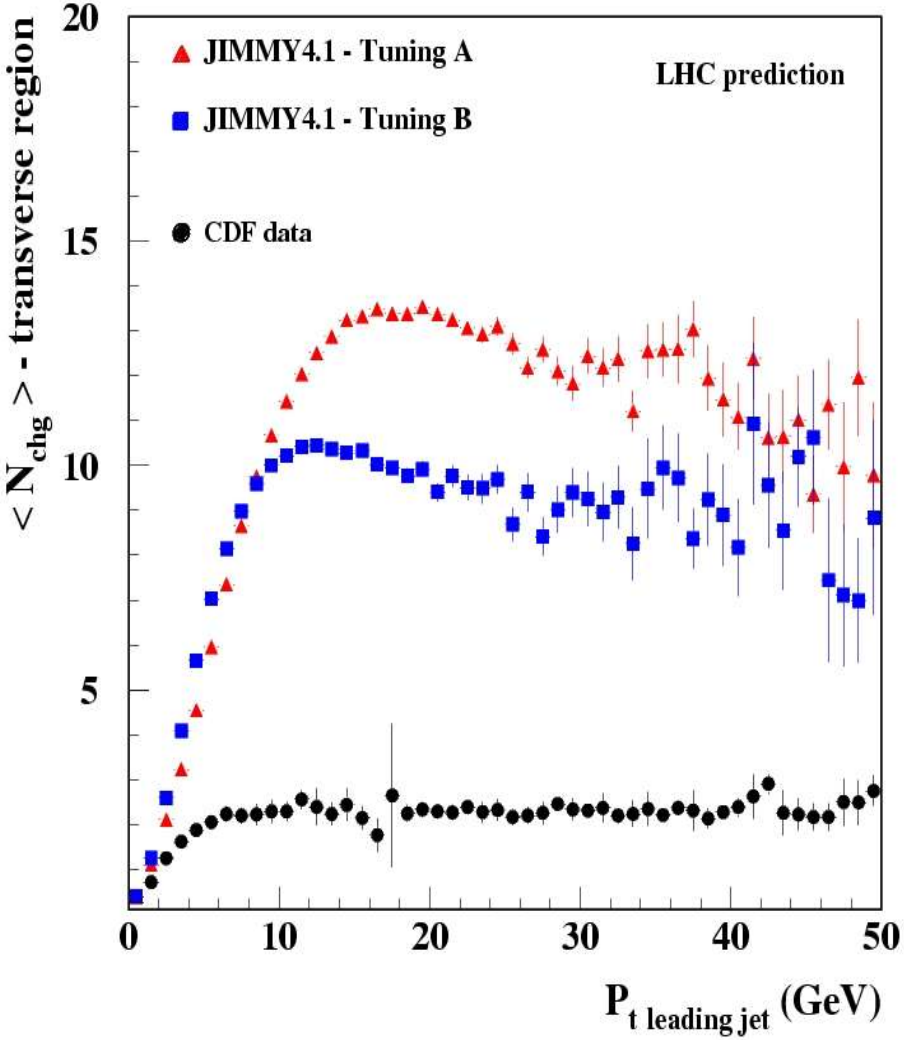


# Extrapolation uncertainties still large



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- Parton distribution
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  - Smaller, denser proton means more scatters
- Minimum transverse momentum of hard scatters
  - Sets the minimum x probed for a given centre-of-mass energy
  - May have energy dependence itself?

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- Low x PDFs and saturation.
  - The multiparton interaction rate at LHC is sensitive to $x < 10^{-7}$
- Off-diagonal PDFs and confinement
  - Probability of pulling two partons out of the proton at different x's.

# Summary

- Underlying events affect, to a greater or lesser extent, everything measured at hadron colliders*.

* and even some at lepton colliders!

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- Any complete simulation program must have options for simulating the underlying event.

# URLs

- PYTHIA
  - http://www.thep.lu.se/~Torbjorn/Pythia.html
- HERWIG/JIMMY
  - http://hepforge.cedar.ac.uk/fherwig
- PHOJET
  - http://www-ik.fzk.de/~engel/phojet.html