Monte Carlo Tutorial

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Shimla, India
11 Dec 2017

Monte Carlo Tutorials

Welcome to the Monte Carlo tutorial session.

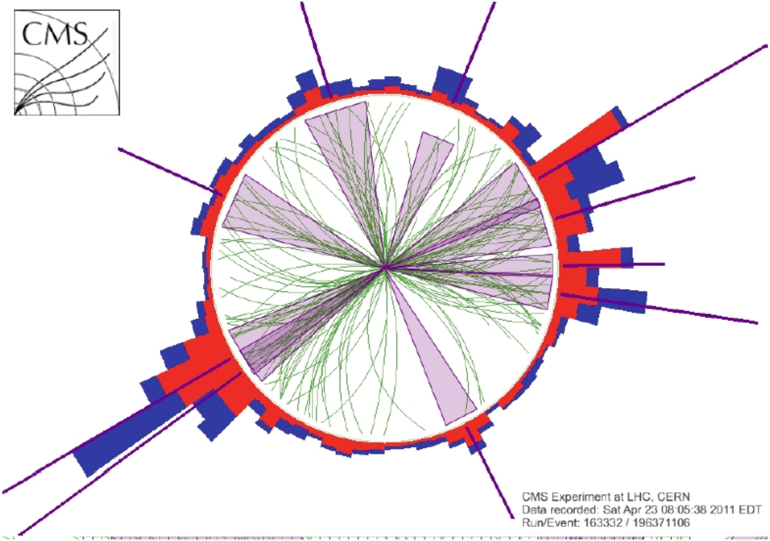
1 Lecture on Monte Carlos and MPI (SG) $\sim 1\,$h

2 Lecture on Rivet, ideas and coding (Deepak Kar) $\sim 1\,$h

3 Hands-on tutorial on Herwig (and Pythia?) $\sim 1\,$h

4 Hands-on tutorial on Rivet analyses implementation
and runs with Herwig and/or Pythia $\sim 1\,$h

Motivation



[CMS 2011]

pp Event Generator

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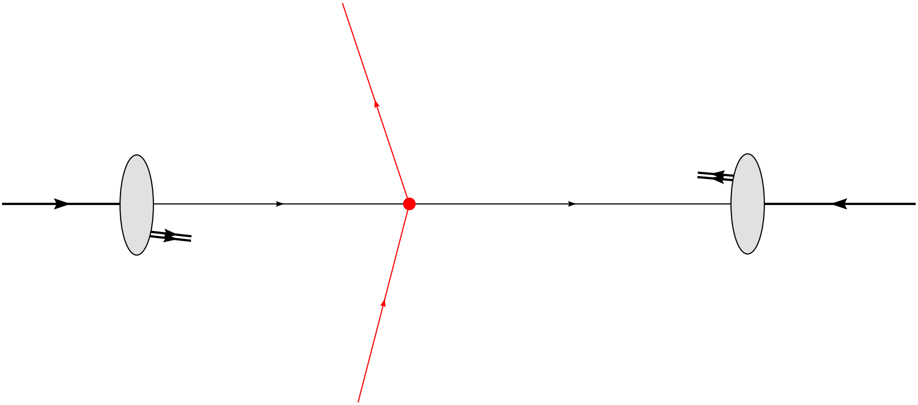

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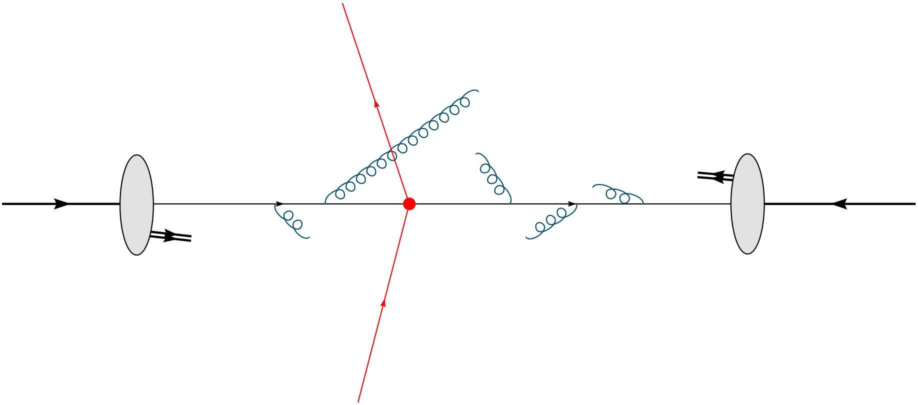

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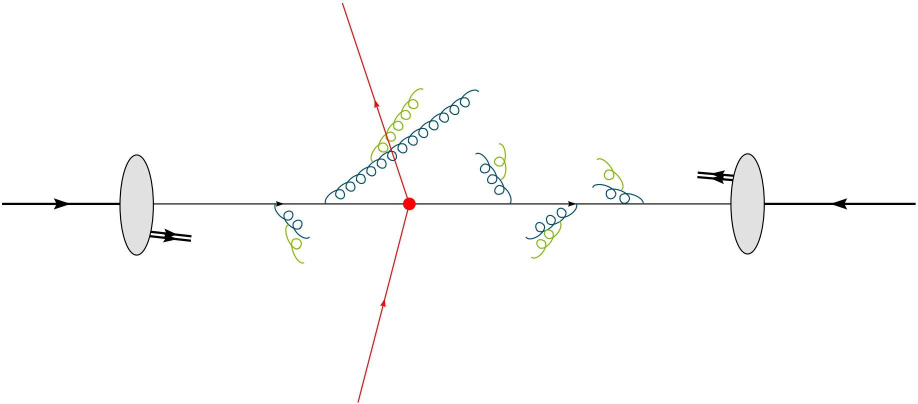

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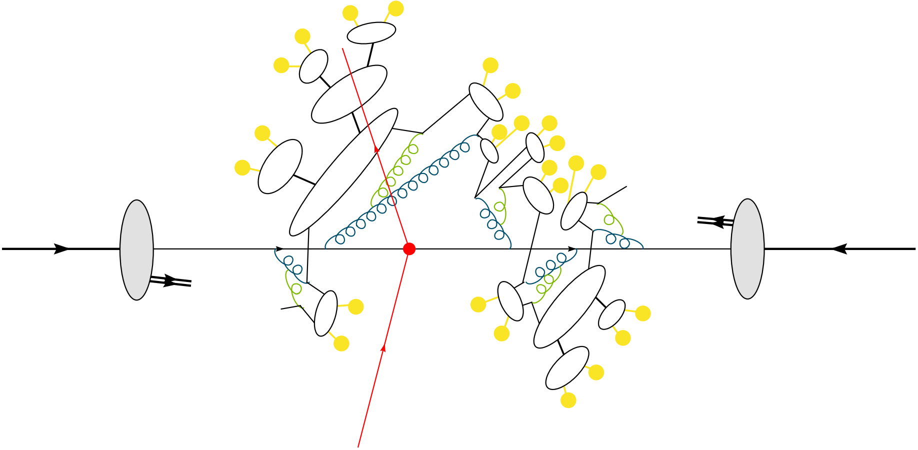

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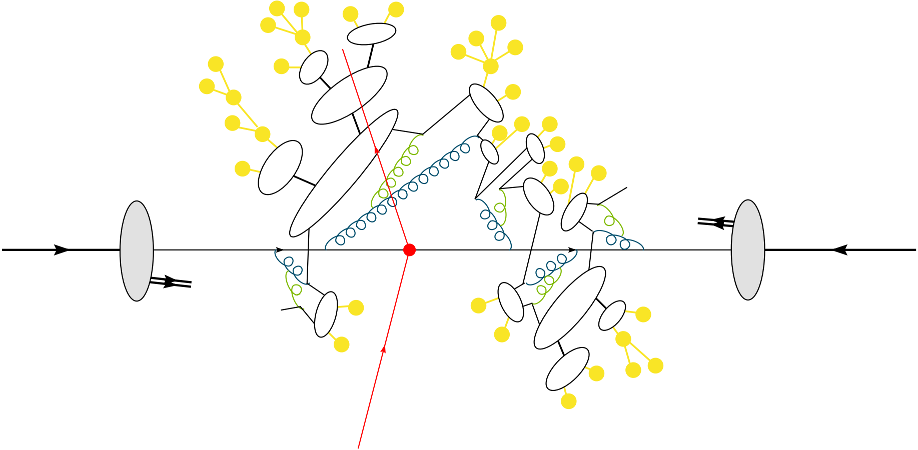

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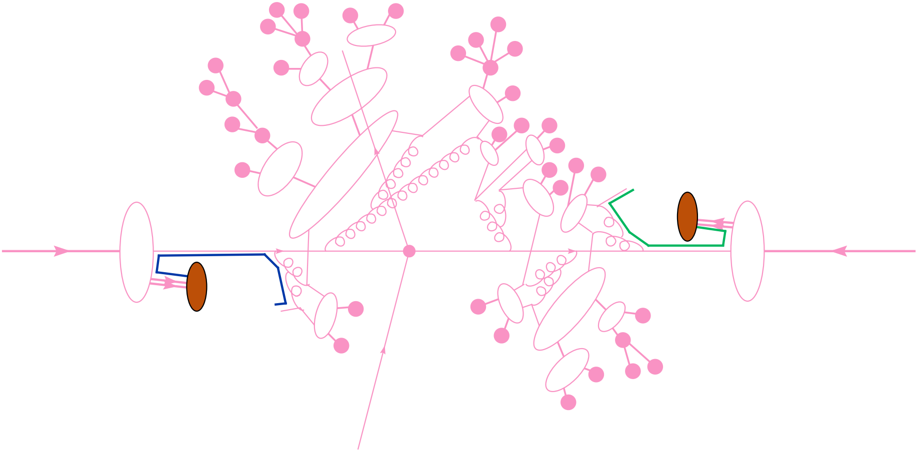

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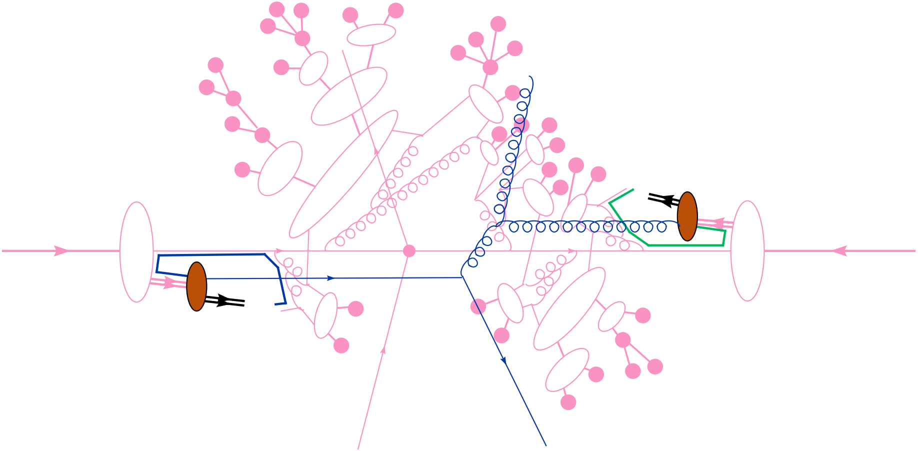

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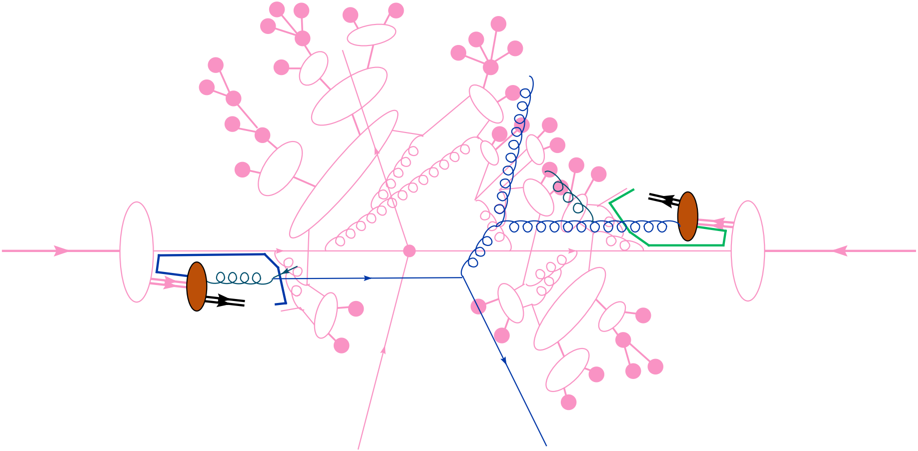

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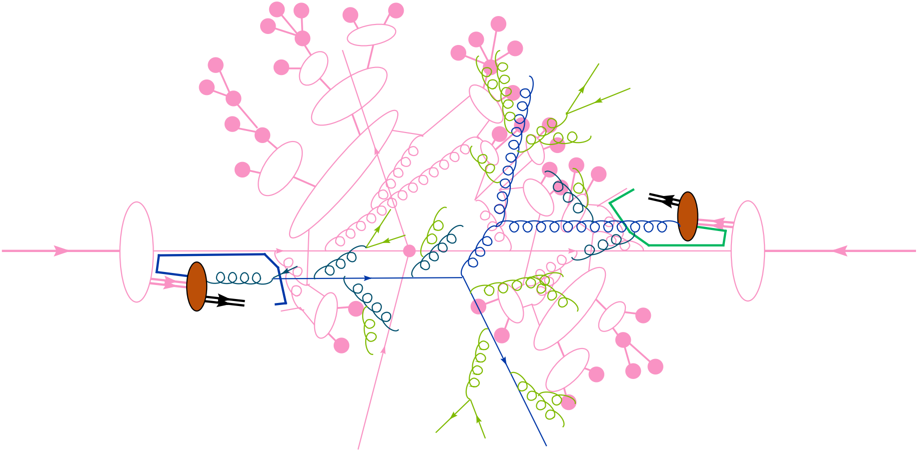

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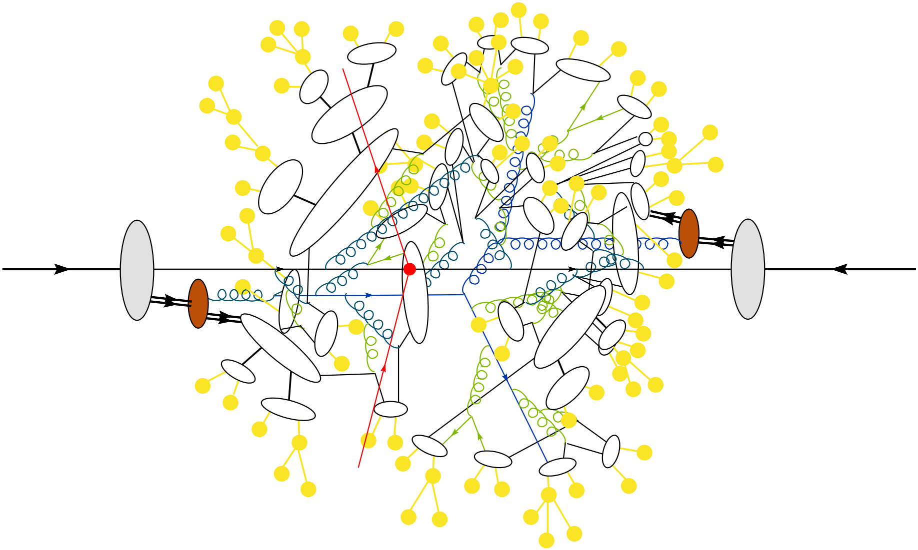

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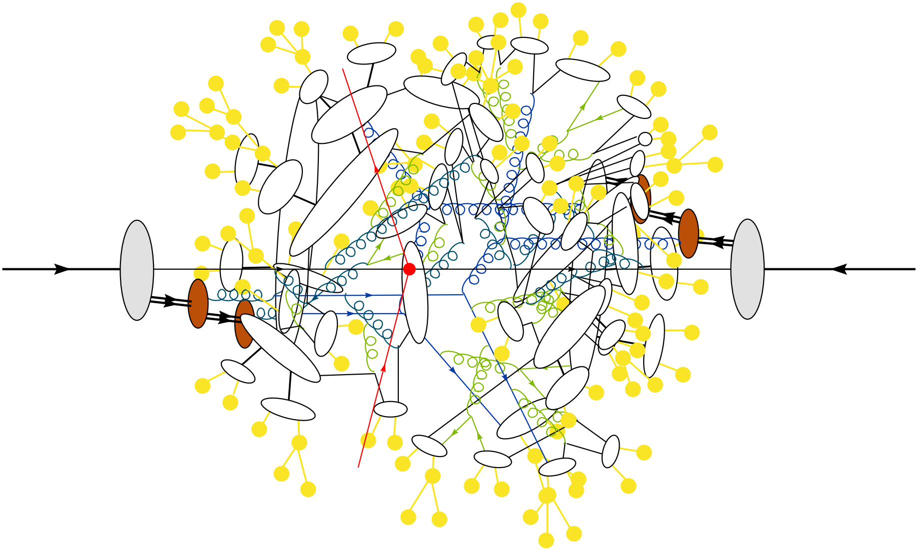


Divide and conquer

Partonic cross section from Feynman diagrams

$$d\sigma = d\sigma_{\rm hard} dP(\text{partons} \to \text{hadrons})$$

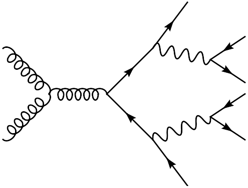
$$\begin{aligned} dP(\text{partons} \to \text{hadrons}) = \; & dP(\text{resonance decays}) && [\Gamma > Q_0] \\ & \times dP(\text{parton shower}) && [\text{TeV} \to Q_0] \\ & \times dP(\text{hadronisation}) && [\sim Q_0] \\ & \times dP(\text{hadronic decays}) && [O(\text{MeV})] \end{aligned}$$

Underlying event from multiple partonic interactions

$$d\sigma \longleftarrow d\sigma(\text{QCD } 2 \to 2)$$

Matrix elements

- Perturbation theory/Feynman diagrams give us (fairly accurate) final states for a few number of legs ($O(1)$).



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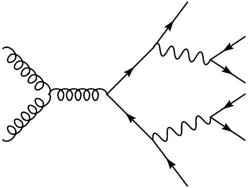

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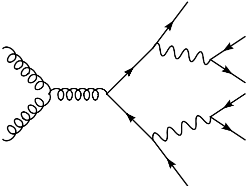


- OK for very inclusive observables.
- Starting point for further simulation.
- Want exclusive final state at the LHC ($O(100)$).
- Want arbitrary cuts.
- $\rightarrow$ use Monte Carlo methods.

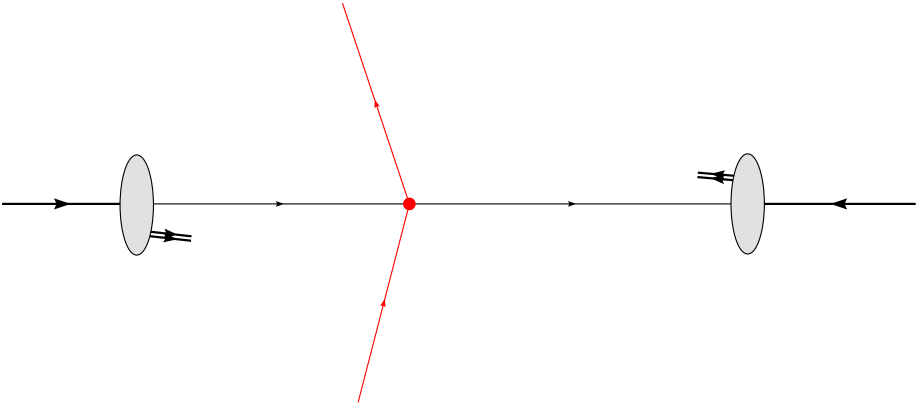
Matrix elements

Where do we get (LO) $|M|^2$ from?

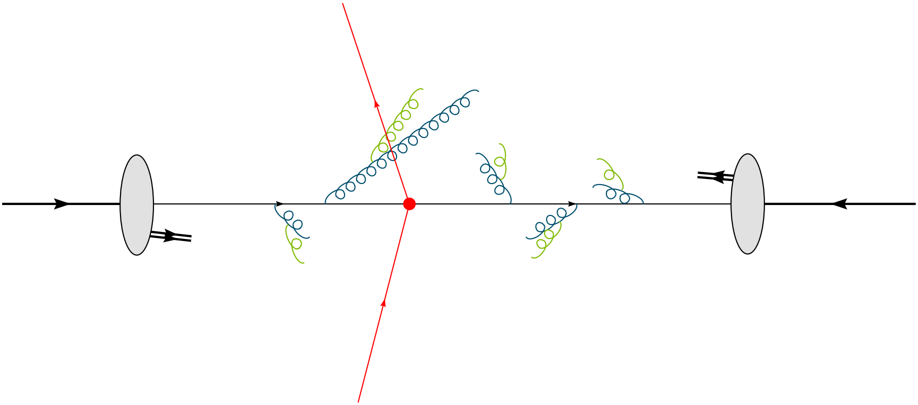
- Most/important simple processes (SM) are 'built in'.
- Calculate yourself (≤ 3 particles in final state).
- Matrix element generators:
  - MadGraph/MadEvent
  - Comix/AMEGIC (part of Sherpa)
  - HELAC/PHEGAS
  - Whizard
  - CalcHEP/CompHEP
  - OpenLoops
  - GoSam
  - …

  generate code or event files that can be further processed.
- $\rightarrow$ UFO/FeynRules interface to ME generators.

Hard matrix element



Hard matrix element → parton showers



Parton showers

Quarks and gluons in final state, pointlike.

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- Know short distance (short time) fluctuations from matrix element/Feynman diagrams: $Q \sim$ few GeV to O(TeV).

- Measure hadronic final states, long distance effects, $Q_0 \sim 1\,\text{GeV}$.

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Dominated by large logs, terms

$$\alpha_S^n \log^{2n} \frac{Q}{Q_0} \sim 1\ .$$

Generated from emissions *ordered* in Q.

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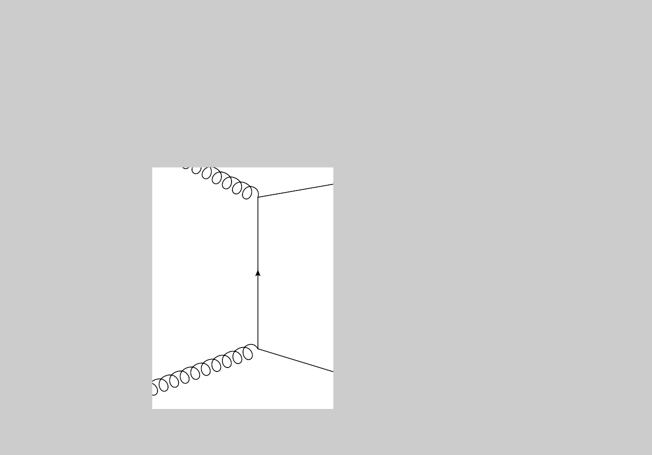
Dominated by large logs, terms

$$\alpha_S^n \log^{2n} \frac{Q}{Q_0} \sim 1 \ .$$

Generated from emissions *ordered* in Q.
Soft and/or collinear emissions.

ME approximated by parton cascade

Evolution in scale, typically $Q \sim 1\,\text{TeV}$ down to $Q \sim 1\,\text{GeV}$.



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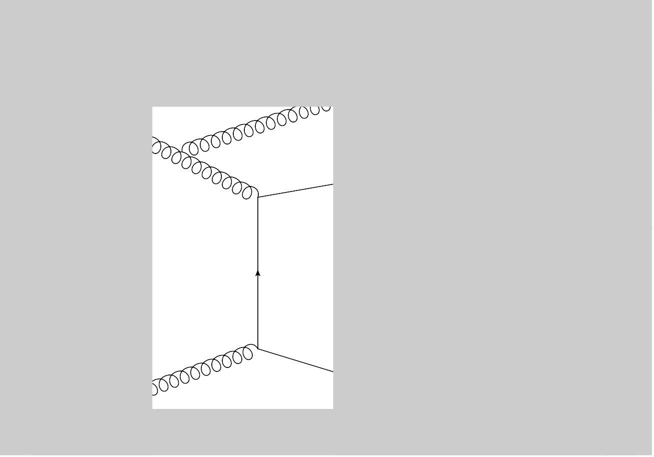

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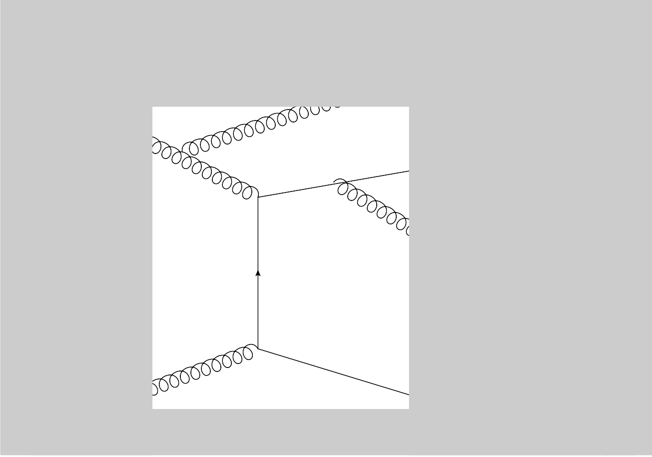

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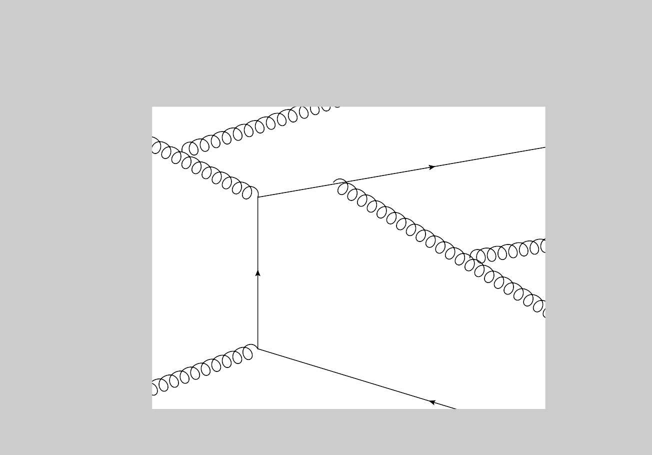

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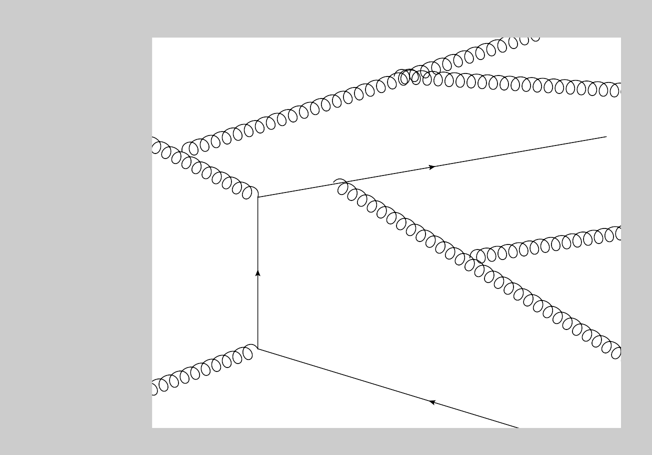
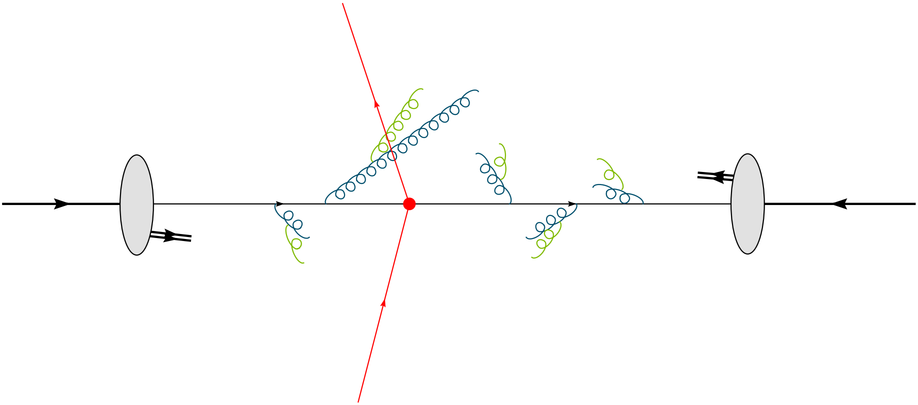
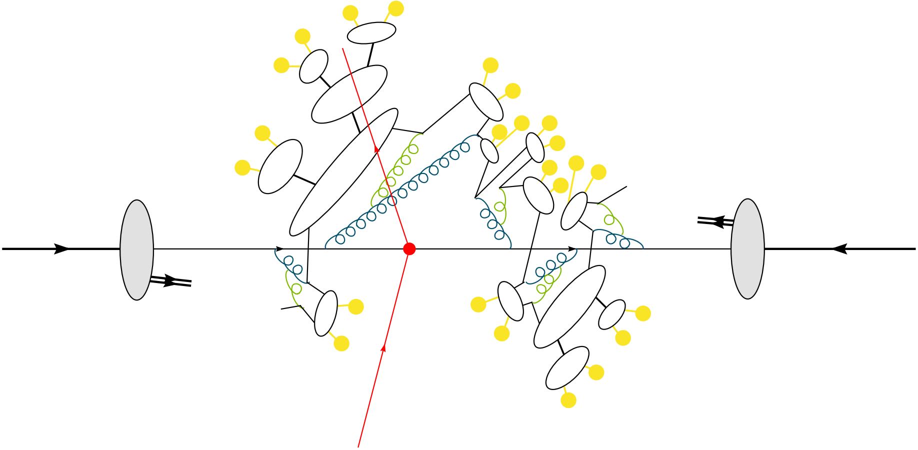


Parton shower



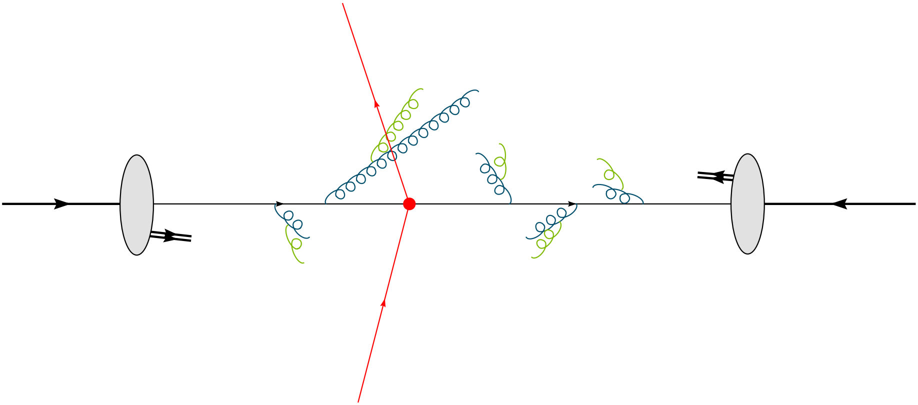
Parton shower ⟶ hadrons



Parton shower $\longrightarrow$ hadrons

- Parton shower terminated at t_0 = lower end of PT.
- Can't measure quarks and gluons.
- Degrees of freedom in the detector are hadrons.
- Need a description of confinement.

Cluster hadronization



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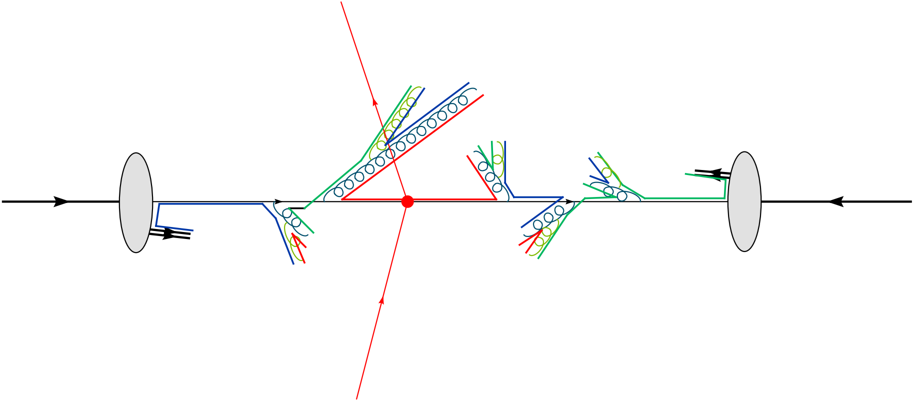

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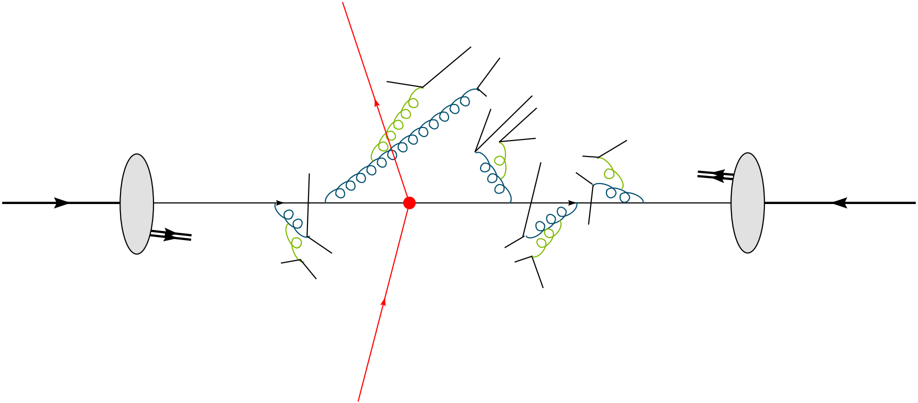

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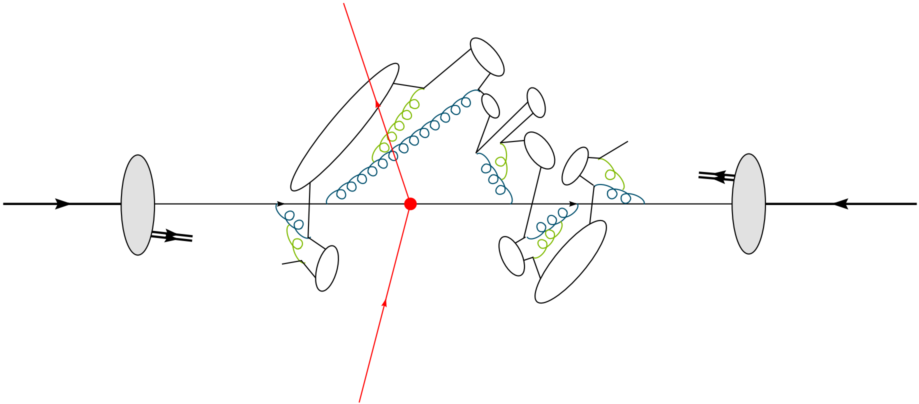

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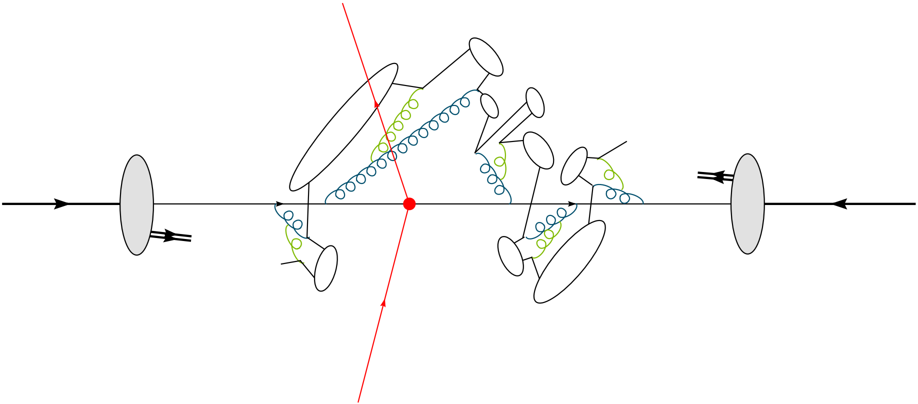

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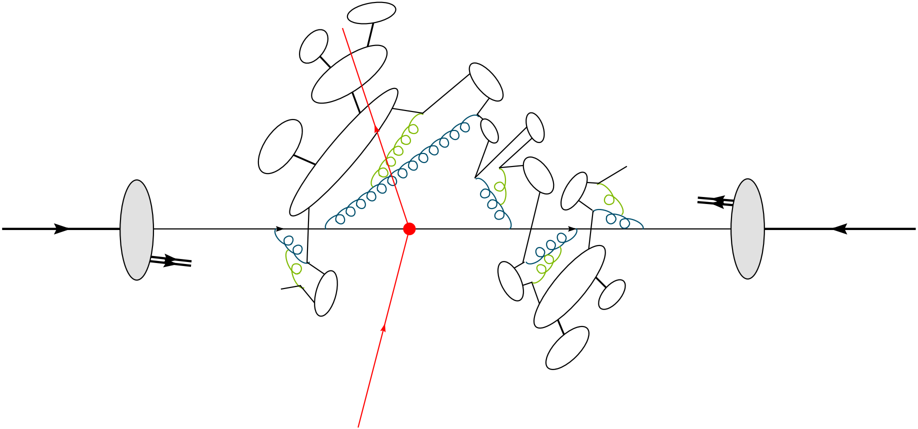

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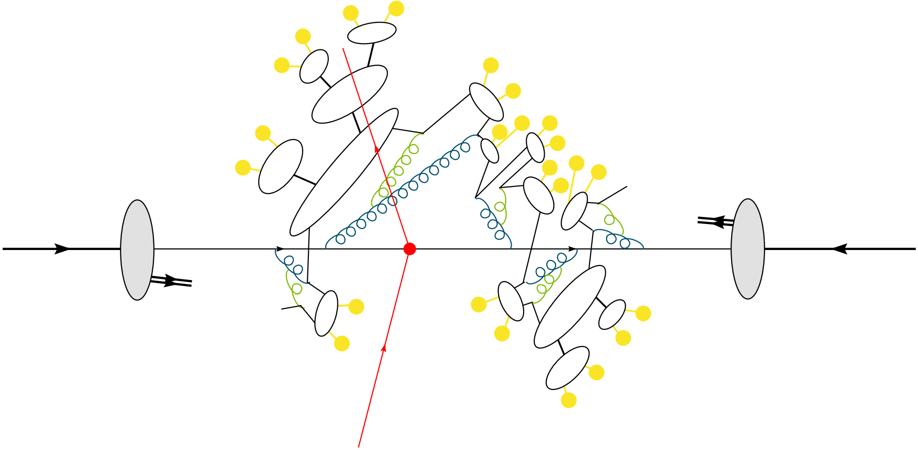

Hadronization

- Only string and cluster models used in recent MC programs.
- Strings developed from non–perturbative perspective, improved by parton shower.
- Cluster model started mostly on perturbative side, improved by string like cluster fission.

Hadronic decays

Many aspects:

$$
\begin{aligned}
B^{*0} \to \gamma B^0 & \\
\hookrightarrow \bar{B}^0 & \\
\hookrightarrow e^- \bar{\nu}_e D^{*+} & \\
\hookrightarrow \pi^+ D^0 & \\
\hookrightarrow K^- \rho^+ & \\
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EM decay.

Hadronic decays

Many aspects:

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Weak mixing.

Hadronic decays

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Strong decay.

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Weak decay, ρ^+ mass smeared.

Hadronic decays

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ρ^+ polarized, angular correlations.

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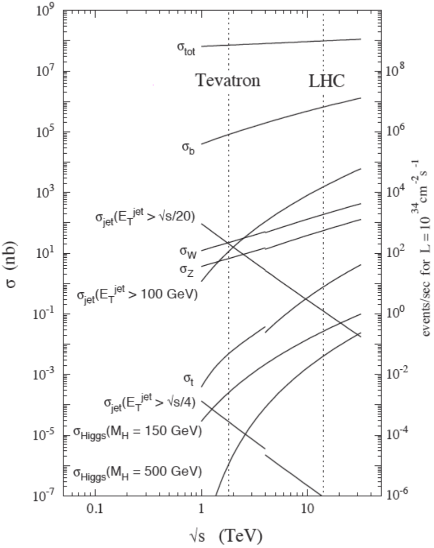
$$

Dalitz decay, m_{ee} peaked.

Min Bias/Underlying event in data

Collider cross sections

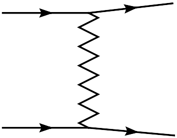


Collider cross sections

$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \underbrace{\sigma_{\text{SD}} + \overbrace{\sigma_{\text{DD}}}_{\sigma_{\text{Diff}}} + \underbrace{\sigma_{\text{soft}} + \sigma_{\text{hard}}}_{\sigma_{\text{ND}}}}^{\sigma_{\text{NSD}}}$$

What is the Underlying event?

$$\sigma_{\text{tot}} = \color{red}{\sigma_{\text{el}}} + \sigma_{\text{SD}} + \overbrace{\sigma_{\text{DD}} + \underbrace{(\sigma_{\text{soft}} + \sigma_{\text{hard}})}_{\sigma_{\text{ND}}}}^{\sigma_{\text{NSD}}}$$



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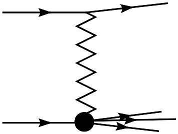

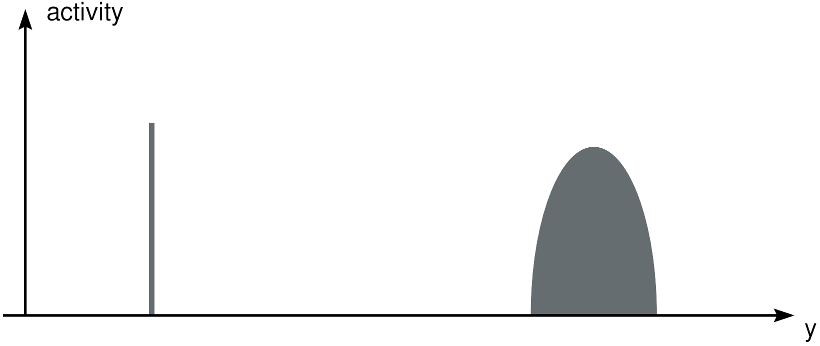

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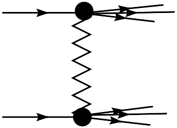

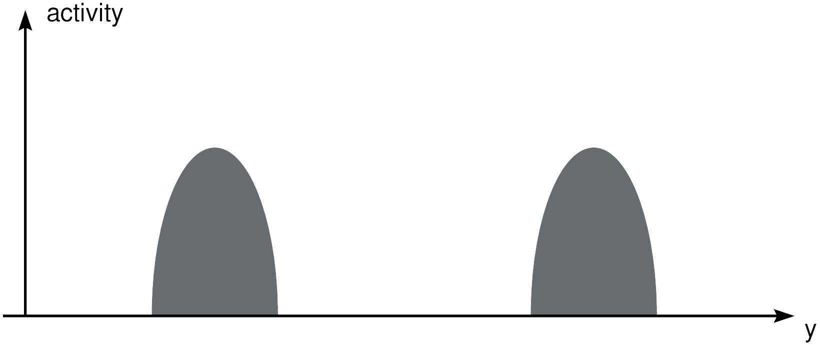

double diffractive

What is the Underlying event?

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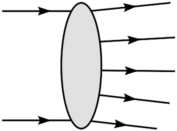

(multiple/soft) interactions

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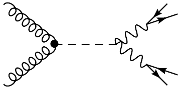

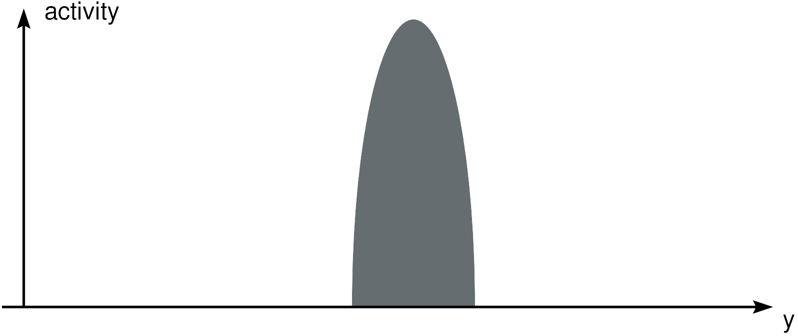

hard scattering

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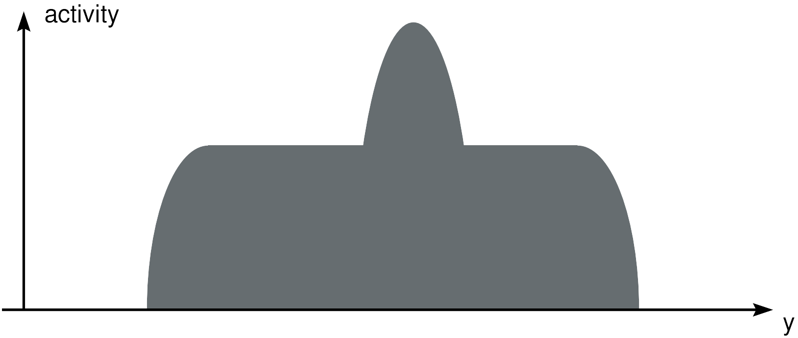

hard scattering + underlying event

What is the Underlying event?

"Everything except the process of interest."

- Experimentalist: "includes parton showers etc."
- MC author: "everything on top of primary hard process."

The Underlying event (UE) is everywhere in the detector.

- Cannot select UE
- May spoil measurements.
- What characteristics?
- Hard?
- Soft?

Why should I learn about it?

- UE comes with every event.
- Can't trigger/select it away.
- Gives additional tracks and calorimeter hits, in the same cells as your signal.
- Jet energy scale determination.
- Important systematic error.
- Jets where your signal shouldn't give any (VBF).

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- Zero bias
  - *Every* event in a perfect 4π detector.

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- Hard scattering
  - Very selective trigger
  - BUT accompanied by soft stuff $\to$ underlying event.

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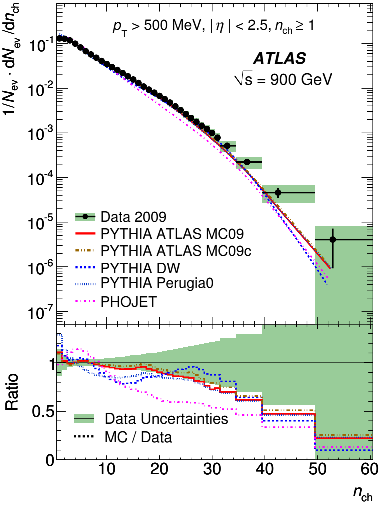
  - $\rightarrow$ with some minimum $p_\perp$.
  - Often want non–single–diffractive
- Hard scattering
  - Very selective trigger
  - BUT accompanied by soft stuff $\rightarrow$ underlying event.

Physics in MB and UE very similar.

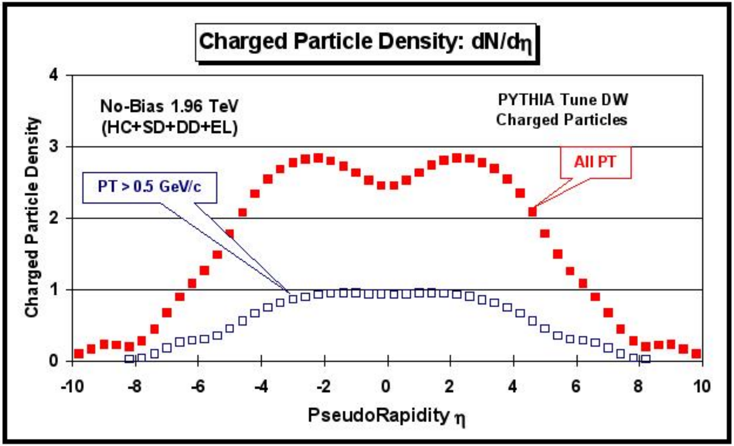
Charakteristics of MB events

N_{ch}



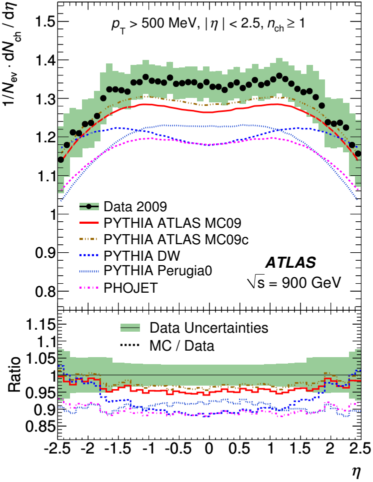
Charakteristics of MB events

$dN/d\eta$ Zero bias vs min bias (Tevatron)



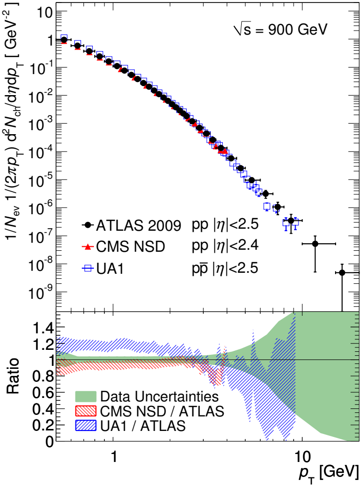
Charakteristics of MB events

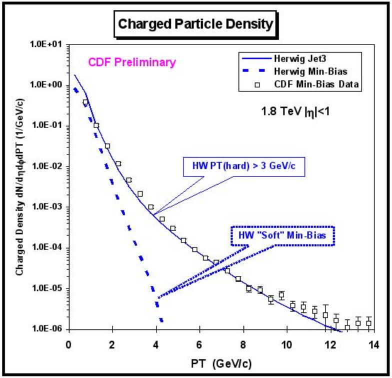
$dN/d\eta$ ATLAS



Charakteristics of MB events

$p_\perp$ spectra of all particles





Charakteristics of MB events

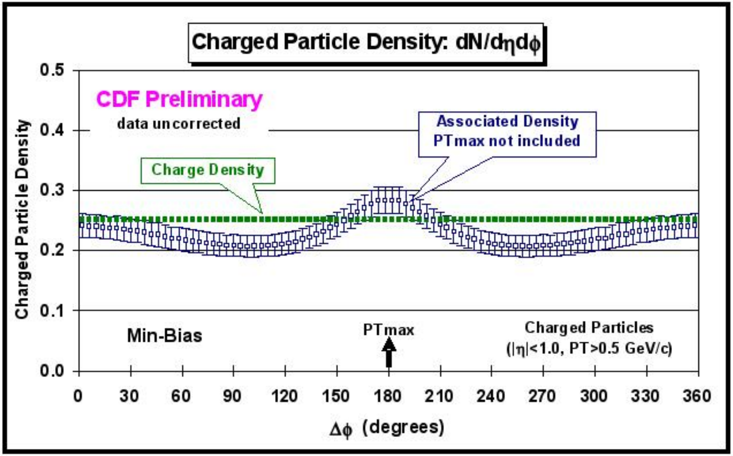
- Inclusive quantities have to be correct, of course.
- Already show, that soft component is important in modelling.

Charakteristics of MB events

- Inclusive quantities have to be correct, of course.
- Already show, that soft component is important in modelling.
- Don't tell much about morphology of event.
- $\rightarrow$ look at distributions inside detector.
- $\rightarrow$ leading particles.

Azimuthal distributions

Measure $\Delta\phi$ relative to leading particle/jet/track.



Azimuthal distributions

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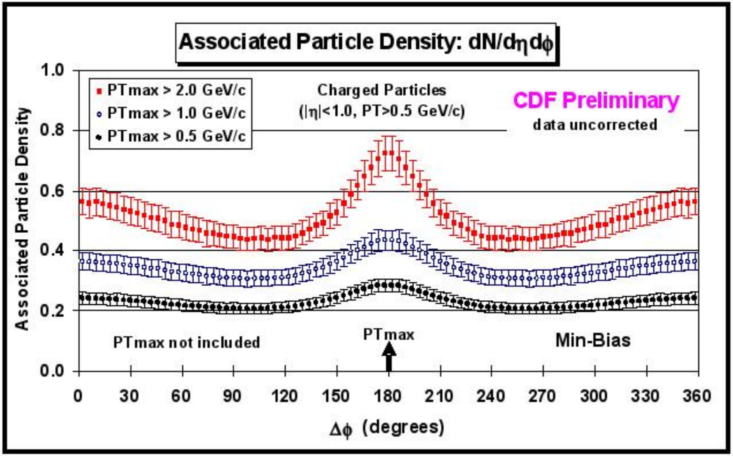


Azimuthal distributions

Observation:

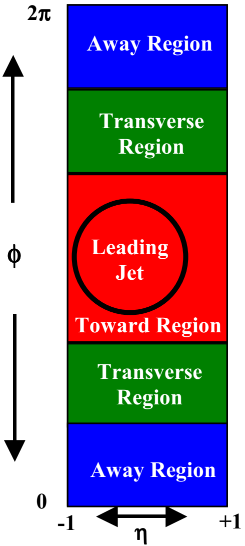
- Events not flat. Have 'leading object'.
- Harder leading object:
  - $\rightarrow$ harder recoil.
  - $\rightarrow$ more activity everywhere, also transverse.

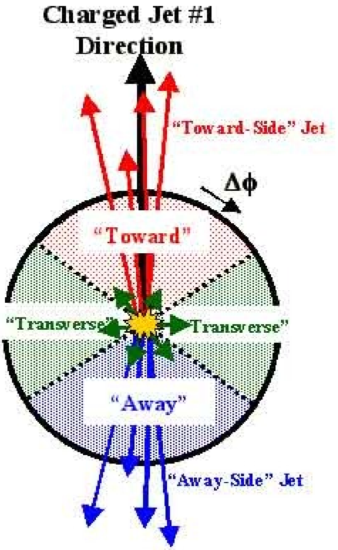
Trigger: The harder leading object, the more jets are inclusively just below this threshold (pedestal effect).

Closer look at transverse region!

"Rick Field analysis".

Towards, away, transverse

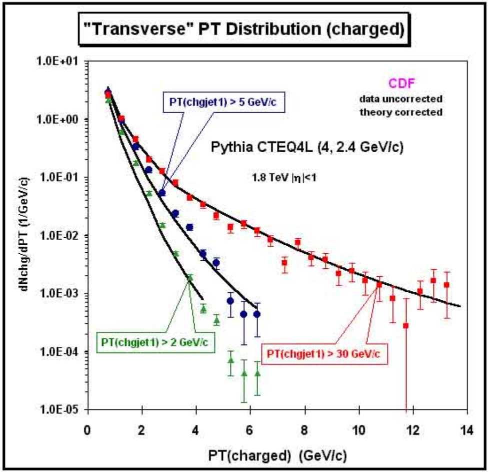




Measurements of the UE: separate from hard bit of event.

- How big is the 'activity' in the different regions?
- How does it depend on the leading object?
- If UE is really *underlying*,
  should decouple from leading event.

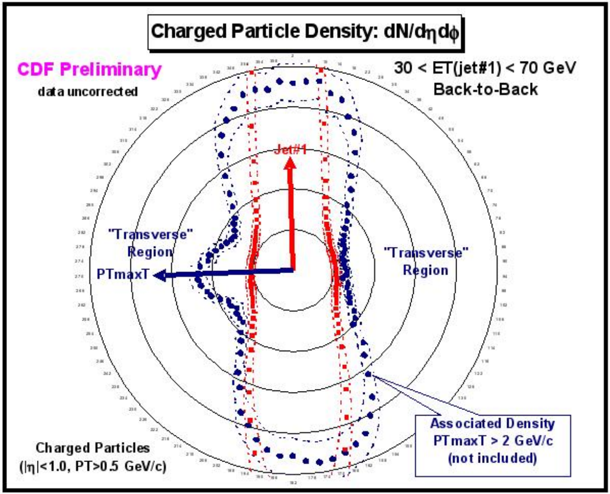
Spectrum in transverse region



Not only average important. The UE has a jetty substructure!

More azimuthal distributions

Now select the hardest of the two transverse regions only (TransMAX): associated distribution:



More azimuthal distributions

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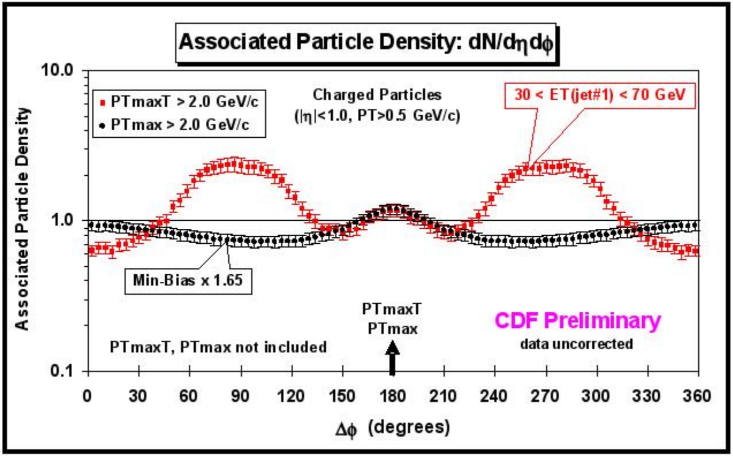


Birth of 3rd jet ∼ leading jet in MinBias

Towards modelling

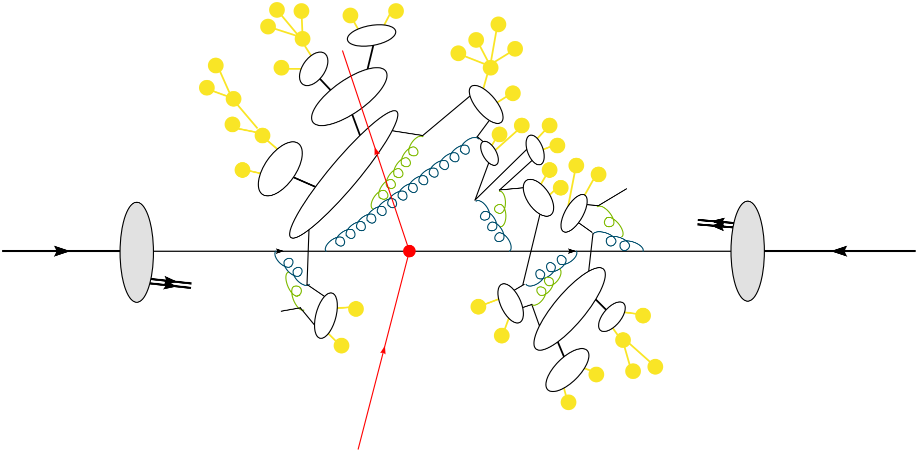
- Leading jet in Minimum bias $\sim$ 3rd jet in back–to–back sample.
- UE and MB really seem to reflect the same physics.
- Hard component important.
- Hard jets not sufficient
  (but well described $\to$ D0 dijet angular decorrelation).

Hard jets in the UE via multiple interactions?

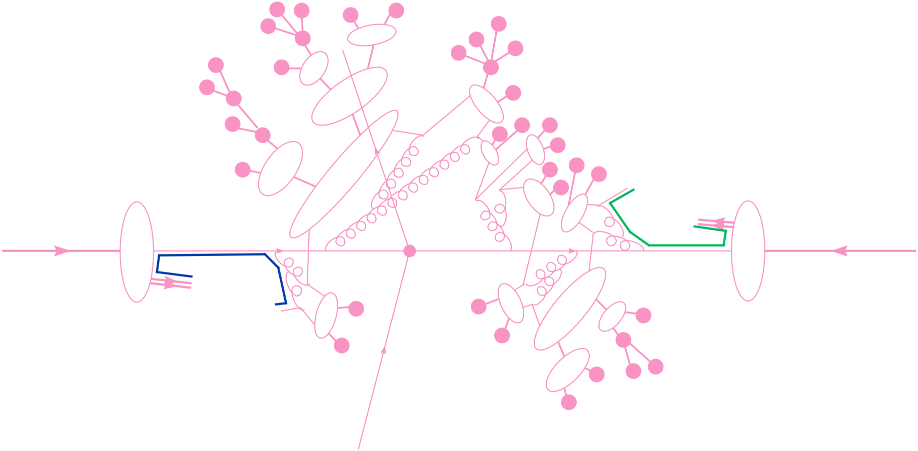
- Additional Partonic $2 \to 2$ interactions (MPI).
- No correlation with hard event.

Multiple Partonic Interactions in Herwig

pp Event Generator



pp Event Generator



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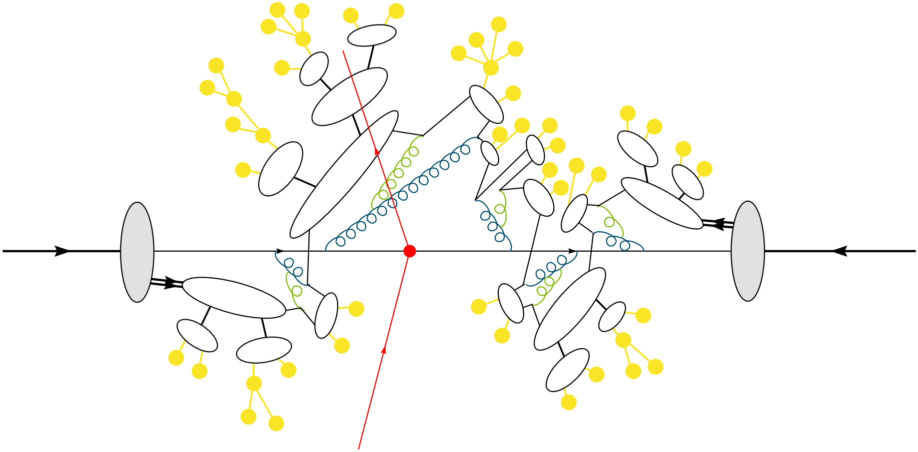
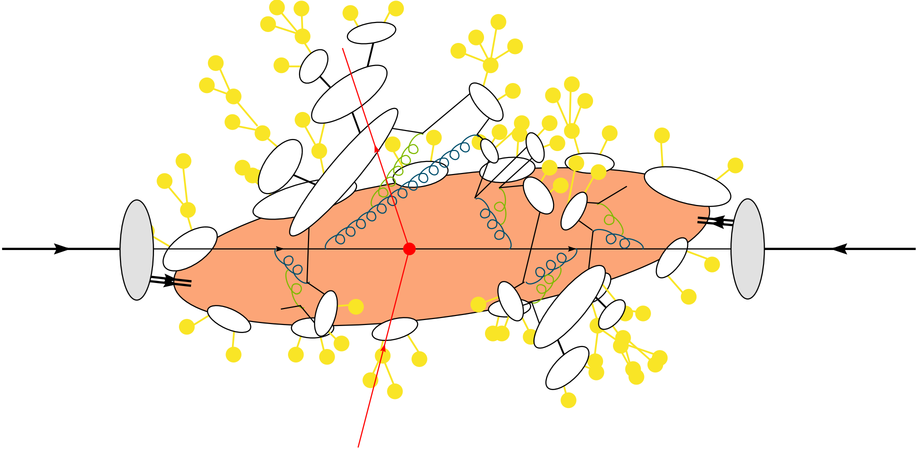


No UE model

Just remnant clusters

- Simplest model?
- Connects loose colour ends and produces some N_{ch}.
- No extra transverse energy.
- Fails.

pp Event Generator



UA5 model

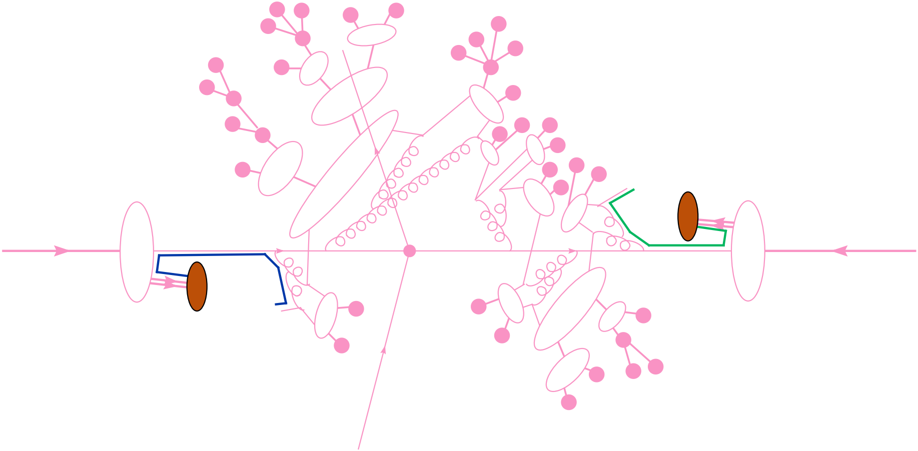
UA5 model

- Produce $\langle n \rangle$ extra clusters, flat in y, with soft $p_\perp$ sprectrum.
- Included from Herwig++ 2.0. [Herwig++, hep-ph/0609306]
- Little predictive power.
- Only gets averages right, not large (and interesting!) fluctiations $\rightarrow$ mini jets.
- Was default in fHerwig. Superseded by `JIMMY`.

[JM Butterworth, JR Forshaw, MH Seymour, ZP C72 637 (1996)]

Similar to new soft physics model

pp Event Generator



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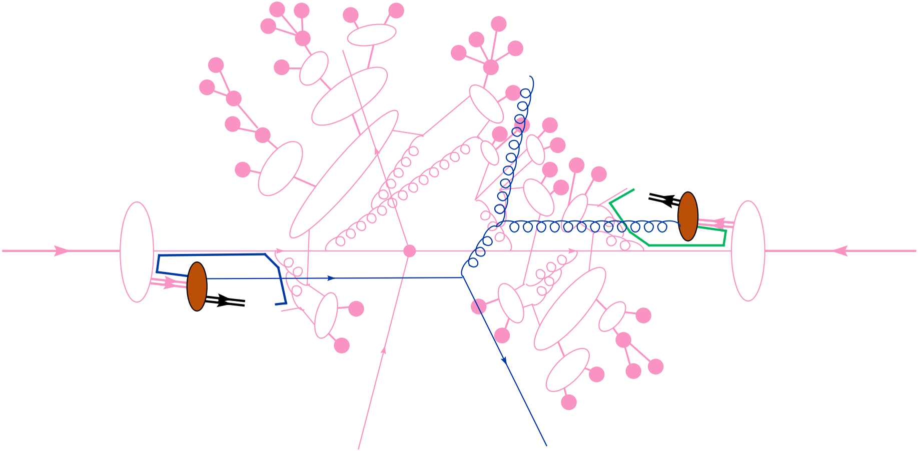

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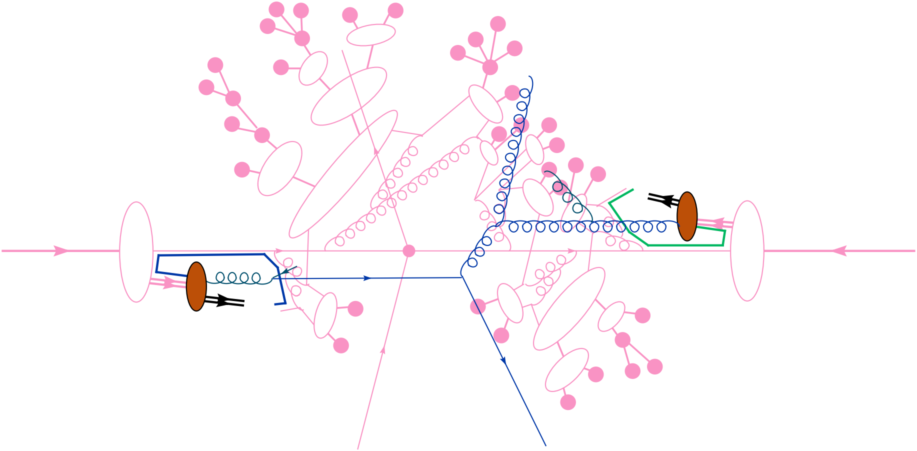

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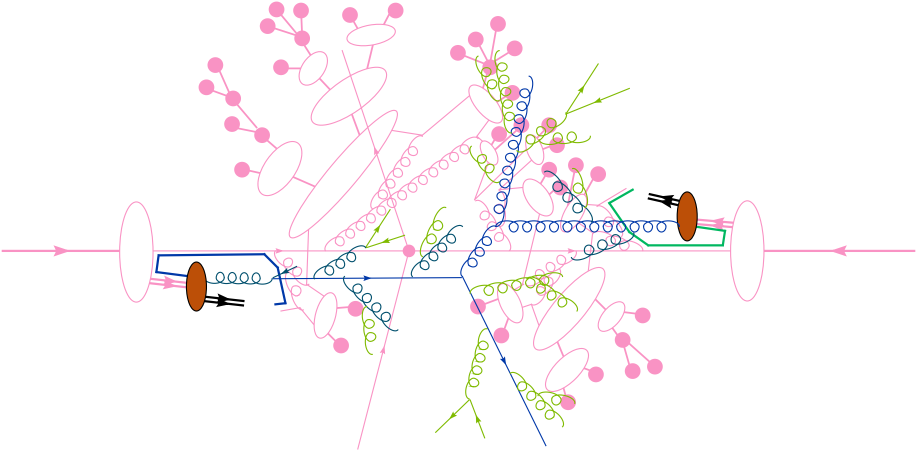

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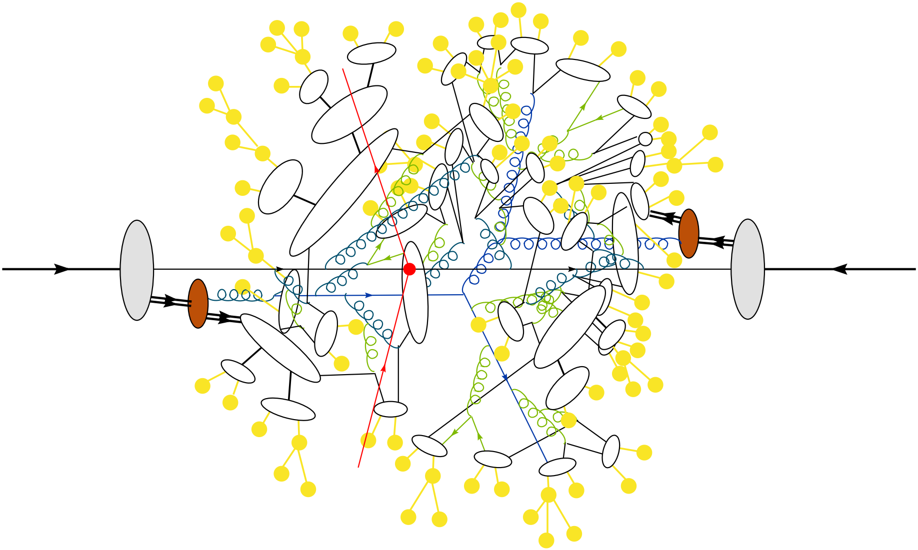

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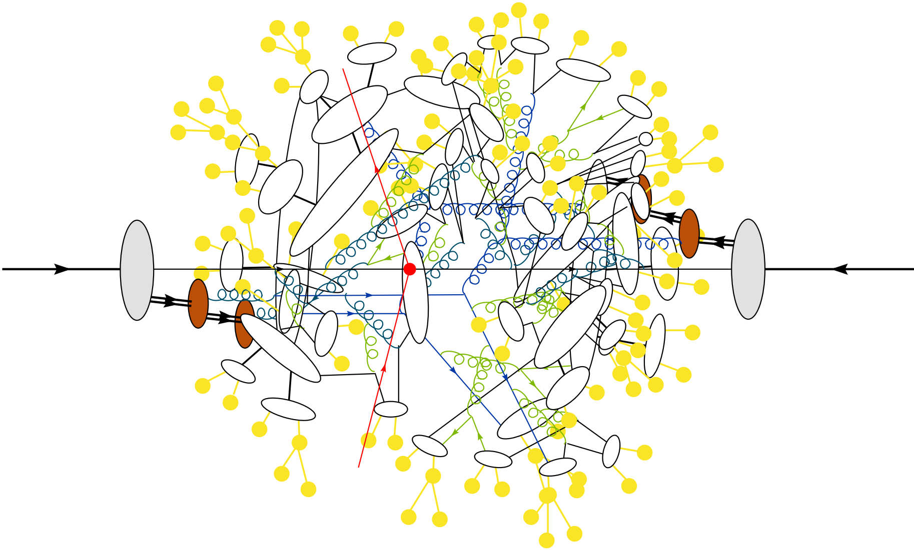
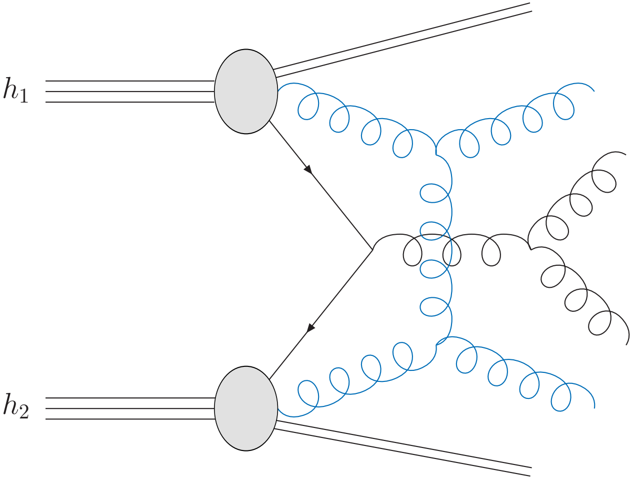


Eikonal model basics

Mulitple hard interactions (MPI)



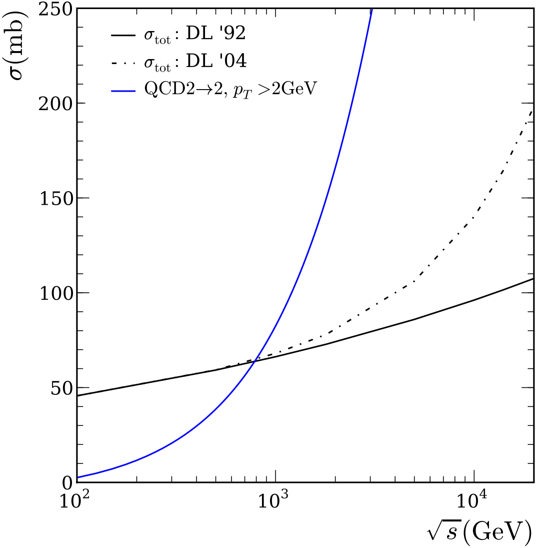
Eikonal model basics

Starting point: hard inclusive jet cross section.

$$\sigma^{\rm inc}(s;p_t^{\rm min}) = \sum_{i,j} \int_{{p_t^{\rm min}}^2} {\rm d}p_t^2 f_{i/h_1}(x_1,\mu^2) \otimes \frac{{\rm d}\hat{\sigma}_{i,j}}{{\rm d}p_t^2} \otimes f_{j/h_2}(x_2,\mu^2)\,,$$

$\sigma^{\rm inc} > \sigma_{\rm tot}$ eventually (for moderately small $p_t^{\rm min}$).

Eikonal model basics



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$\sigma^{\rm inc} > \sigma_{\rm tot}$ eventually (for moderately small $p_t^{\rm min}$).

Interpretation: $\sigma^{\rm inc}$ counts *all* partonic scatters that happen during a single *pp* collision $\Rightarrow$ more than a single interaction.

$$\sigma^{\rm inc} = \bar{n}\sigma_{\rm inel}\,.$$

Eikonal model basics

Use eikonal approximation (= independent scatters). Leads to Poisson distribution of number m of additional scatters,

$$P_m(\vec{b},s) = \frac{\bar{n}(\vec{b},s)^m}{m!} \mathrm{e}^{-\bar{n}(\vec{b},s)} \ .$$

Then we get σ_{inel}:

$$\sigma_{\mathrm{inel}} = \int \mathrm{d}^2\vec{b} \sum_{m=1}^{\infty} P_m(\vec{b},s) = \int \mathrm{d}^2\vec{b} \left(1 - \mathrm{e}^{-\bar{n}(\vec{b},s)}\right) \ .$$

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Cf. σ_{inel} from scattering theory in eikonal approx. with scattering amplitude $a(\vec{b},s) = \frac{1}{2i}(\mathrm{e}^{-\chi(\vec{b},s)} - 1)$

$$\sigma_{\mathrm{inel}} = \int \mathrm{d}^2\vec{b} \left(1 - \mathrm{e}^{-2\chi(\vec{b},s)}\right) \qquad \Rightarrow \qquad \chi(\vec{b},s) = \frac{1}{2}\bar{n}(\vec{b},s) \, .$$

$\chi(\vec{b},s)$ is called *eikonal* function.

Eikonal model basics

Calculation of $\bar{n}(\vec{b},s)$ from parton model assumptions:

$$\bar{n}(\vec{b},s) = L_{\text{partons}}(x_1,x_2,\vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$

$$= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$

$$\times D_{i/A}(x_1,p_t^2,|\vec{b}'|) D_{j/B}(x_2,p_t^2,|\vec{b}-\vec{b}'|)$$

Eikonal model basics

Calculation of $\bar{n}(\vec{b},s)$ from parton model assumptions:

$$
\begin{aligned}
\bar{n}(\vec{b},s) &= L_{\rm partons}(x_1,x_2,\vec{b}) \otimes \sum_{ij} \int {\rm d}p_t^2 \frac{{\rm d}\hat{\sigma}_{ij}}{{\rm d}p_t^2} \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int {\rm d}x_1 {\rm d}x_2 \int {\rm d}^2\vec{b}' \int {\rm d}p_t^2 \frac{{\rm d}\hat{\sigma}_{ij}}{{\rm d}p_t^2} \\
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&\quad \times f_{i/A}(x_1,p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2,p_t^2) G_B(|\vec{b}-\vec{b}'|) \\
&= A(\vec{b}) \sigma^{\rm inc}(s;p_t^{\rm min}) \ .
\end{aligned}
$$

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$$\times f_{i/A}(x_1,p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2,p_t^2) G_B(|\vec{b}-\vec{b}'|)$$

$$= A(\vec{b}) \sigma^{\text{inc}}(s;p_t^{\text{min}}) \ .$$

$$\Rightarrow \quad \chi(\vec{b},s) = \tfrac{1}{2}\bar{n}(\vec{b},s) = \tfrac{1}{2}A(\vec{b})\sigma^{\text{inc}}(s;p_t^{\text{min}}) \ .$$

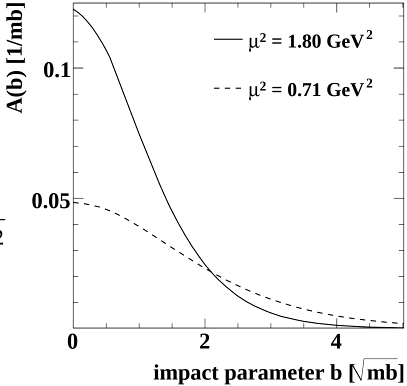
Overlap function

$$A(b) = \int \mathrm{d}^2\vec{b}' G_A(|\vec{b}'|) G_B(|\vec{b} - \vec{b}'|)$$

$G(\vec{b})$ from electromagnetic FF:

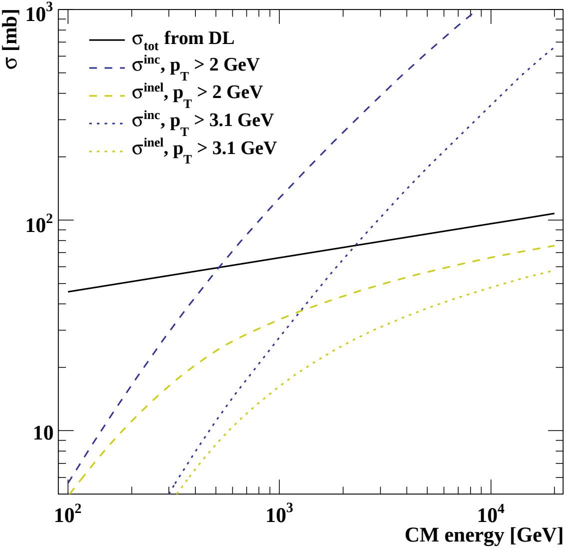
$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{\mathrm{d}^2\vec{k}}{(2\pi)^2} \frac{\mathrm{e}^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

But μ^2 *not fixed* to the *electromagnetic* $0.71\,\mathrm{GeV}^2$.
Free for colour charges.



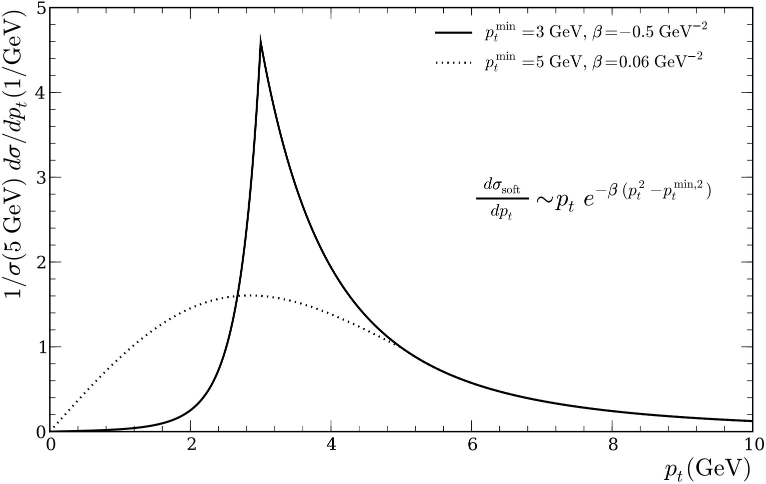
$\Rightarrow$ Two main parameters: $\mu^2, p_t^{\min}$.

Unitarized cross sections



Extending into the soft region

Continuation of the differential cross section into the soft region $p_t < p_t^{\min}$ (here: p_t integral kept fixed)



Hot Spot model

Fix the two parameters μ_{soft} and $\sigma_{\text{soft}}^{\text{inc}}$ in

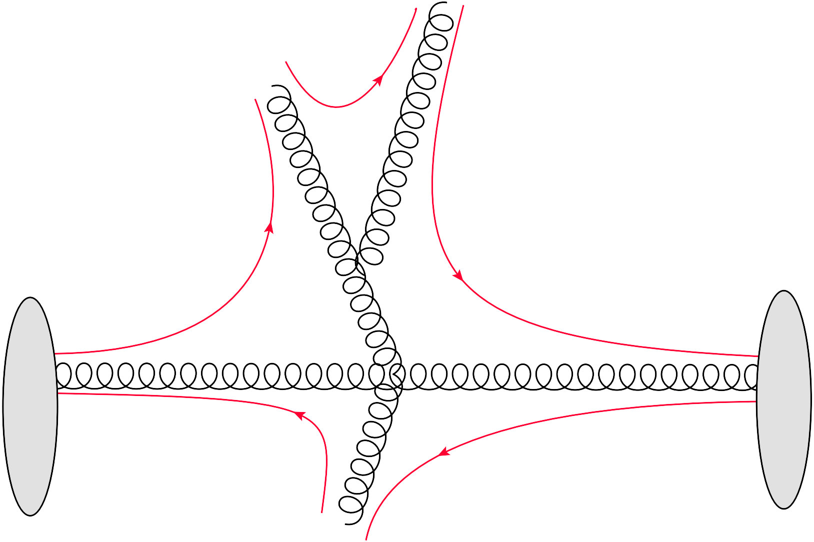
$$\chi_{\text{tot}}(\vec{b},s) = \frac{1}{2}\left(A(\vec{b};\mu)\sigma^{\text{inc}}\text{hard}(s;p_t^{\text{min}}) + A(\vec{b};\mu_{\text{soft}})\sigma_{\text{soft}}^{\text{inc}}\right)$$

from two constraints. Require simultaneous description of σ_{tot} and b_{el} (measured/well predicted),

$$\sigma_{\text{tot}}(s) \stackrel{!}{=} 2\int \mathrm{d}^2\vec{b}\left(1-\mathrm{e}^{-\chi_{\text{tot}}(\vec{b},s)}\right) ,$$

$$b_{\text{el}}(s) \stackrel{!}{=} \int \mathrm{d}^2\vec{b}\,\frac{b^2}{\sigma_{\text{tot}}}\left(1-\mathrm{e}^{-\chi_{\text{tot}}(\vec{b},s)}\right) .$$

Colour Reconnection — idea



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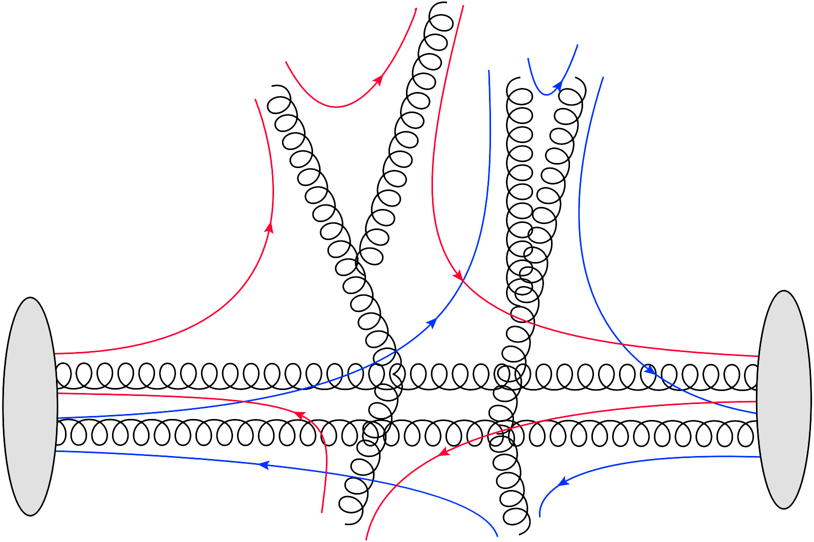

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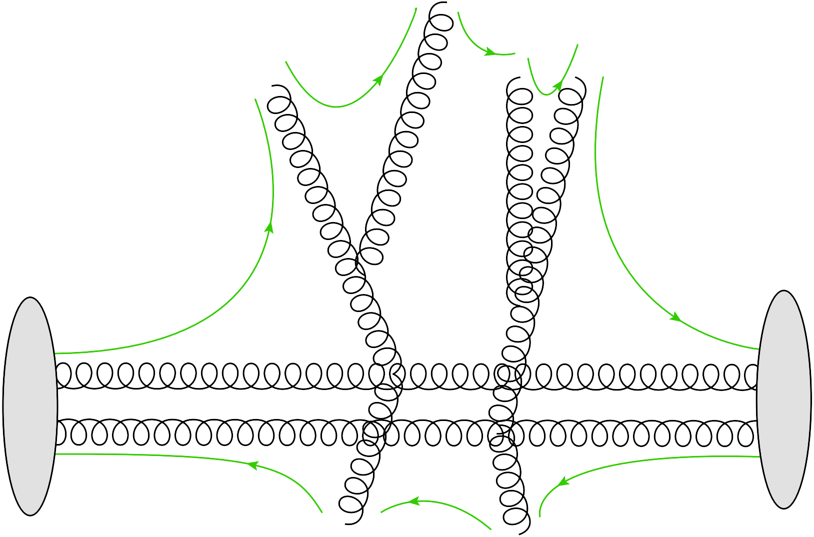
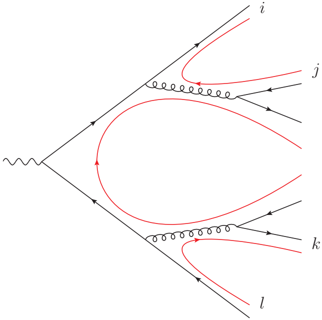


Colour reconnection (CR) in Herwig



Extend cluster hadronization:

- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs

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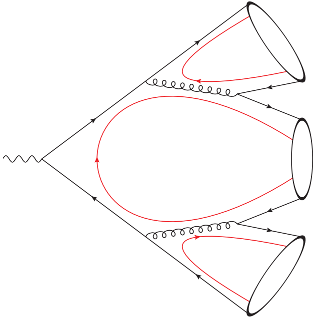

Extend cluster hadronization:

- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs
- $\rightarrow$ *clusters*

[SG, C. Röhr, A. Siodmok, EPJ C72 (2012) 2225]

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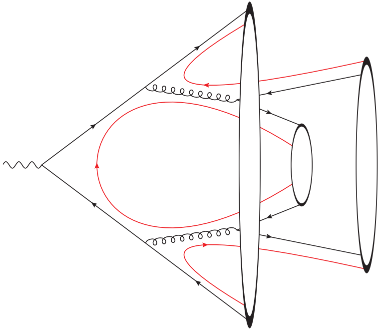

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- → *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$

[SG, C. Röhr, A. Siodmok, EPJ C72 (2012) 2225]

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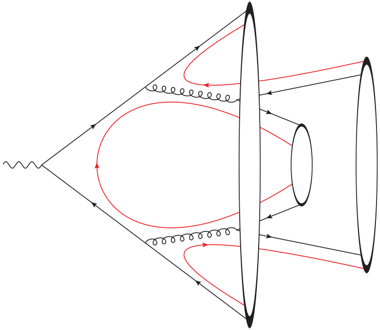

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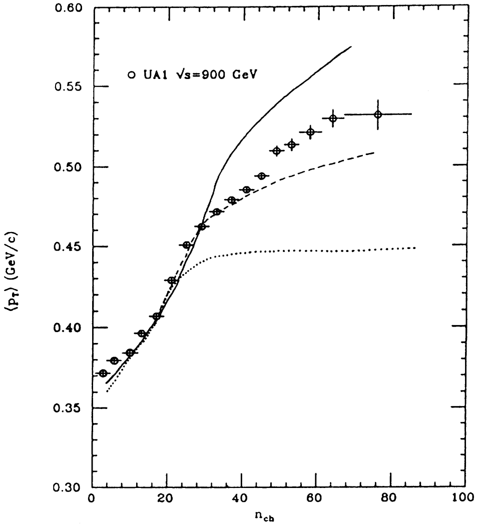
- Allow CR if the cluster mass decreases,

$$M_{il} + M_{kj} < M_{ij} + M_{kl},$$

- Accept alternative clustering with probability p_{reco} (model parameter) $\Rightarrow$ this allows to switch on CR smoothly
- Alternative *Statistical CR* (Metropolis)

[SG, C. Röhr, A. Siodmok, EPJ C72 (2012) 2225]

Colour reconnections



- Sensitivity to CR already known since UA1.
- (From Sjöstrand / van Zijl)

MPI in Herwig

Semihard MPI

- Default from Herwig++ 2.1. [Herwig++, 0711.3137]
- Multiple hard interactions, $p_t \geq p_t^{\min}$. [Bähr, SG, Seymour, JHEP 0807:076]
- pQCD $2 \to 2$.
- Similar to `JIMMY`.
- Good description of harder UE data ("plateau").

MPI in Herwig

Soft MPI

- Default from Herwig++ 2.3. [Herwig++, 0812.0529]
- Extension to soft interactions $p_t < p_t^{\text{min}}$.
- Theoretical work with simplest possible extension.
  [Bähr, Butterworth, Seymour, JHEP 0901:065]
- "Hot Spot" model. [Bähr, Butterworth, SG, Seymour, 0905.4671]

Recent developments in Herwig

First implementation of soft scattering

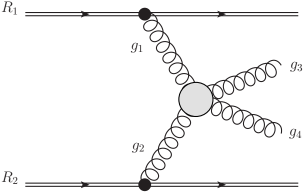
Soft gluon production with soft $p_t < p_t^{\min}$ spectrum.

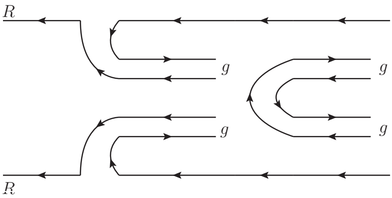
Colour structure important. Two extreme cases possible.

Sensitivity to parameter

$$\texttt{colourDisrupt} = P(\text{disrupt colour lines})$$

Long colour lines appear when swapping outgoing gluons.



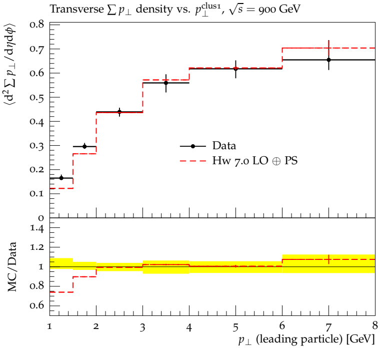


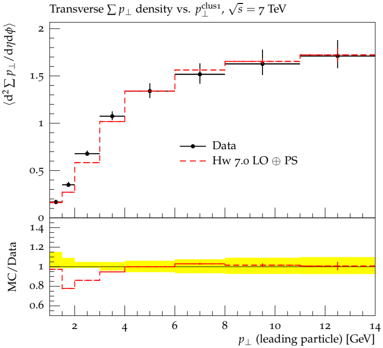
Colour reconnections applied!

So far at the LHC

Soft model is extension of MPI model for Underlying Event and *harder* aspects of Min Bias events.
Herwig 7.0 at 900 GeV and 7 TeV:

[ATLAS, Eur.Phys.J. C71 (2011) 1636]



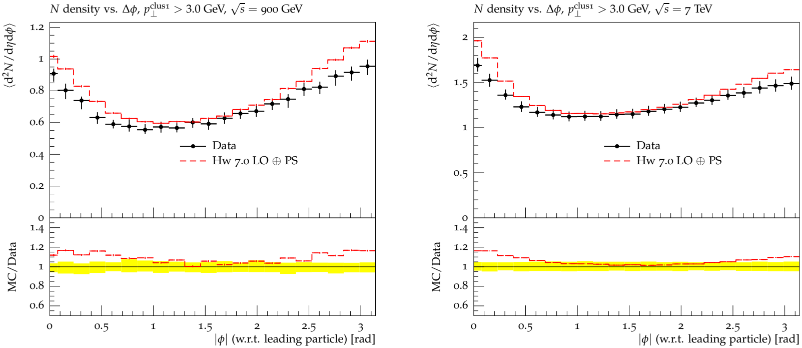


Still reasonably well for moderately soft particles.

So far at the LHC

Soft model is extension of MPI model for Underlying Event and *harder* aspects of Min Bias events.
Herwig 7.0 at 900 GeV and 7 TeV:

[ATLAS, Eur.Phys.J. C71 (2011) 1636]

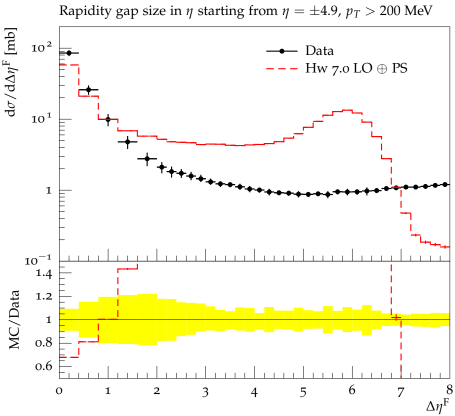


Still reasonably well for moderately soft particles.

The bump

A clear case of abusing a model for the hard UE in forward/diffractive final states…

[ATLAS, Eur.Phys.J. C72 (2012) 1926]



Bump is artefact. No Diffraction. Poor modeling of soft interactions. Colour assignment ad hoc.

Newer developments

Challenge accepted.

- Model for diffractive final states.
- Model for soft particle production.

[SG, F. Loshaj, P. Kirchgaeßer, EPJ C77 (2017) 156]

- New baryon production mechanisms.

[SG, P. Kirchgaeßer, S. Plätzer, arXiv 10/2017]

Diffraction as part of minimum bias simulation

Diffractive final states directly modeled.

Not embedded in MPI approach via cuts through triple pomeron vertices. Therefore change in constraint

$$x\sigma_{\rm tot}(s) \stackrel{!}{=} 2\int {\rm d}^2\vec{b}\left(1-{\rm e}^{-\chi_{\rm tot}(\vec{b},s)}\right)\ ,$$

where

$$x \approx 1 - \frac{\sigma_{\rm diff}}{\sigma_{\rm tot}} \approx 75\%\ .$$

In min-bias simulation: every event is either

- diffractive, directly modeled from *pp* initial state.
- non-diffractive, modeled in the MPI picture, parton level.

Diffractive final states

Strictly low mass diffraction only. Allow M^2 large nonetheless.

M^2 power-like, t exponential (Regge).

$$pp \to \text{(baryonic cluster)} + p\ .$$

Hadronic content from cluster fission/decay $C \to hh\ldots$
Cluster may be quite light. If very light, use directly

$$pp \to \Delta + p\ .$$

Also double diffraction implemented.

$$pp \to \text{(cluster)} + \text{(cluster)} \qquad pp \to \Delta + \Delta\ .$$

Technically: new MEs for diffractive processes set up.

Model for soft particle production in Herwig

Reproduce core properties of soft particle production.

"flat in rapidity", "narrow in p_t".

Main idea: "soft interaction = cut pomeron = particle ladder".

N_{soft} from MPI model = #ladders.

Clusters produced via colour connected quarks and gluons.

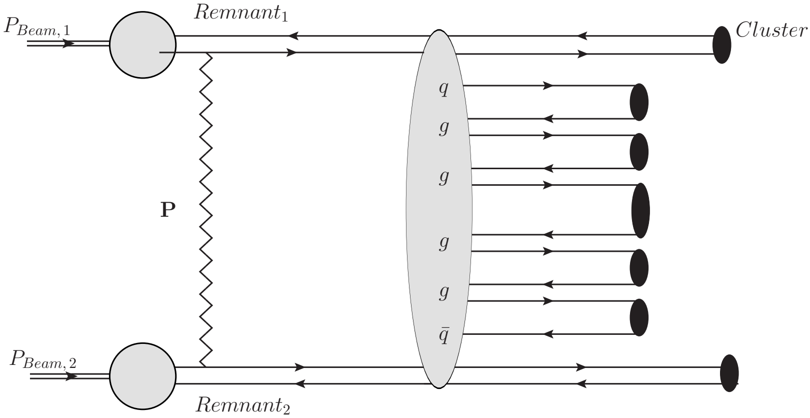
Adopt to soft interactions in Herwig via remnant decays.

Soft particle production model in Herwig

- #ladders = N_{soft} (MPI).
- N particles from Poissonian, width $\langle N \rangle$.
  Model parameter $1/\ln C \equiv n_{\text{ladder}} \to$ tuned.
- x_i smeared around $\langle x \rangle$ (calculated).
- $p_\perp$ from Gaussian acc to soft MPI model.
- particles are q, g, see figure.
  Symmetrically produced from both remnants.
- Colour connections between neighboured particles.

Soft particle production model in Herwig

Single soft ladder with MinBias initiating process.



Further hard/soft MPI scatters possible.

Parameters and tuning

Diffraction plus MPI incl new soft model.

Diffractive cross sections adjusted to data.

Tuning to Min Bias data: $\eta, p_\perp$ for various $N_{\rm ch}$, $\langle p_\perp \rangle (N_{\rm ch})$.

Usual MPI parameters

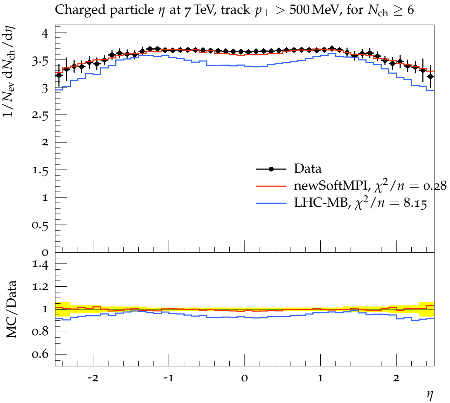
$$(p_{\perp,0}^{\rm min}, b) \to p_\perp^{\rm min}(\sqrt{s}), \quad \mu^2, \quad p_{\rm reco} \ .$$

One additional parameter

$$n_{\rm ladder} \ .$$

Tuned results

ATLAS Min Bias 7 TeV. [ATLAS, New.J.Phys. 13 (2011) 053033]

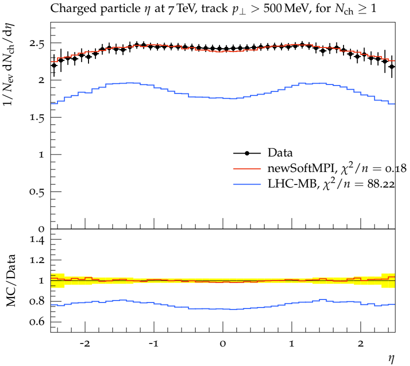


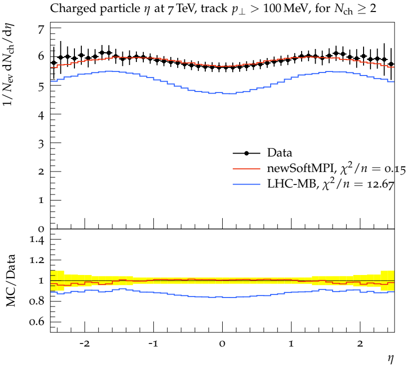
Similar to previous results, “harder part of Min Bias”.

Tuned results

ATLAS Min Bias 7 TeV.

[ATLAS, New.J.Phys. 13 (2011) 053033]



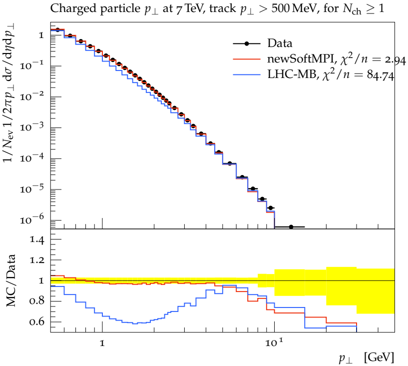


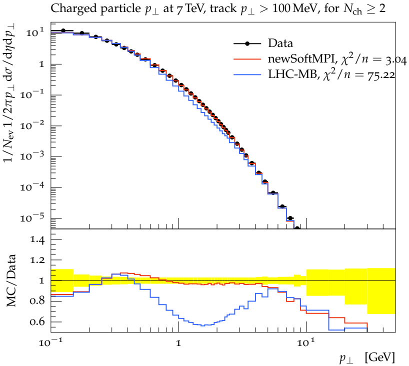
Also soft rates well described.

Tuned results

ATLAS Min Bias 7 TeV.

[ATLAS, New.J.Phys. 13 (2011) 053033]

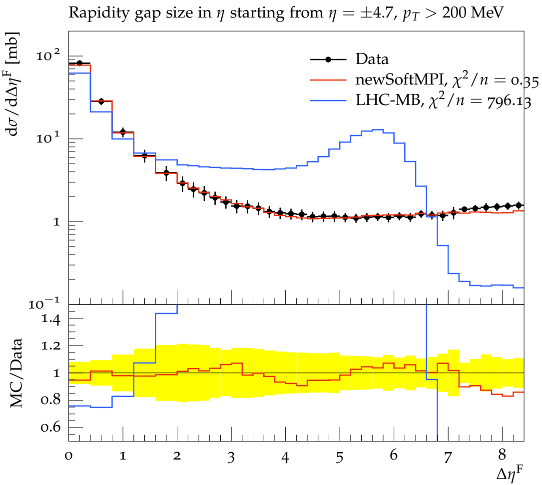




Tails? Still within 1σ.

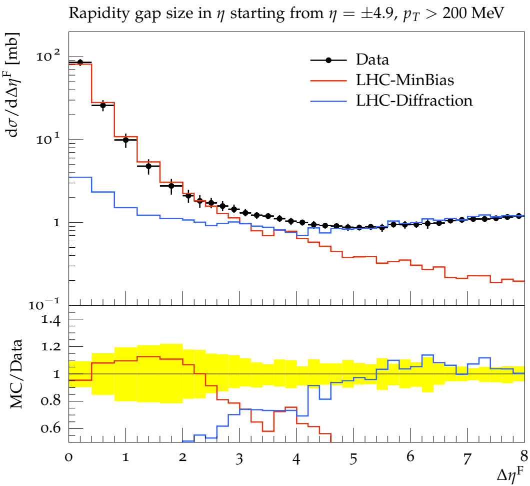
The bump plot, $\Delta\eta_F$

[CMS, PRD 92 (2015) 012003]



Individual contributions to $\Delta\eta_F$

[ATLAS, Eur.Phys.J. C72 (2012) 1926]



Baryons

[SG, P. Kirchgaeßer, S. Plätzer, 1710.10906]

Modelling of baryon production:

- Thus far, not considered in particular
- Take a lot of energy as mass, at once
- More baryons $\rightarrow$ less charge

Ideas for improvement:

- Colour reconnection
- non-perturbative $g \rightarrow s\bar{s}$ splitting in cluster formation, re-tune gluon mass vs strange mass (constituent masses).

[talk of P. Kirchgaeßer, Wednesday 9am]

MPI Summary

- MPI (with colour reconnections) currently model of choice.
- Describes averages *and* fluctuations.
- Not always universal, but all models tunable.
- soft component needed for MB modelling.
- Constraints from inclusive cross sections.
- Different emphasis on hard/soft modelling between generators.
- Many details still only models.

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