JETSCAPE Winter School 2018

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Monte Carlo implementation of QCD processes

MCnet LUND UNIVERSITY Vetenskapsrådet Discovery centre for particle physics

LHC physics is QCD

- Incoming hadrons: Parton Distributions
- Outgoing hadrons: Hadronization
- Hard Process: Perturbative matrix elements
- + parton showers, beam remnants, multiparton interactions...

A good review article is (still): 1101.2599
https://particle.wiki is an emerging living ressource – feel free to join

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- On top of this a nuclear structure is added...
- ...inspired by pre-QCD and QCD theory.

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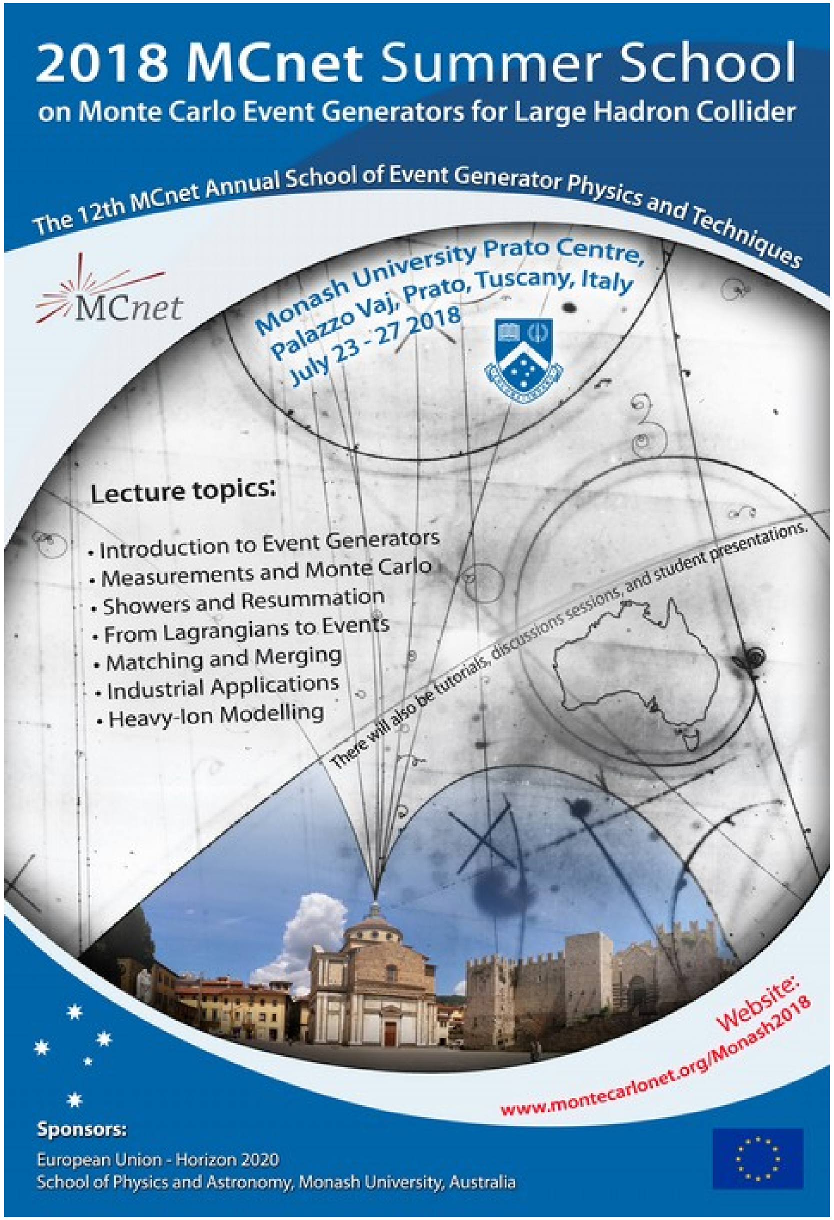
This lecture; Soft QCD

- The basic structure of an MC event.
- Multiparton Interactions.
- Final state parton shower.
- String Hadronization.
- Colour reconnection.
- From pp to pA and AA.

A whole school about this!



The structure of a pp event

Figure by T. Sjöstrand

Incoming hadrons – Parton Distribution Functions (PDFs), fitted to DIS data.

Based on Pythia 8.2: 1410.3012

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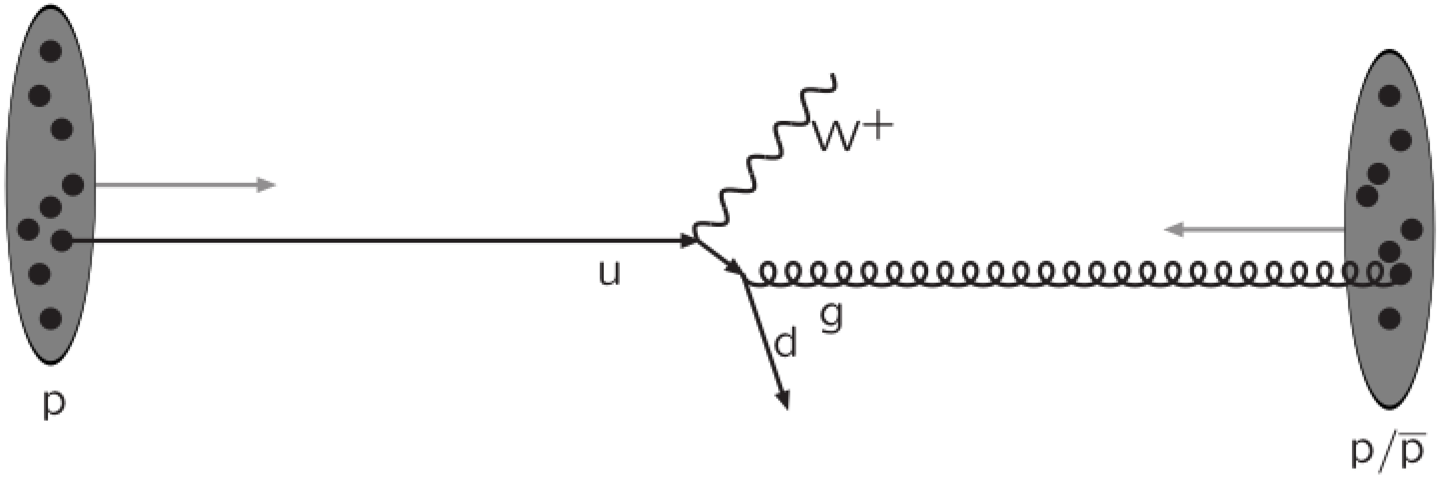
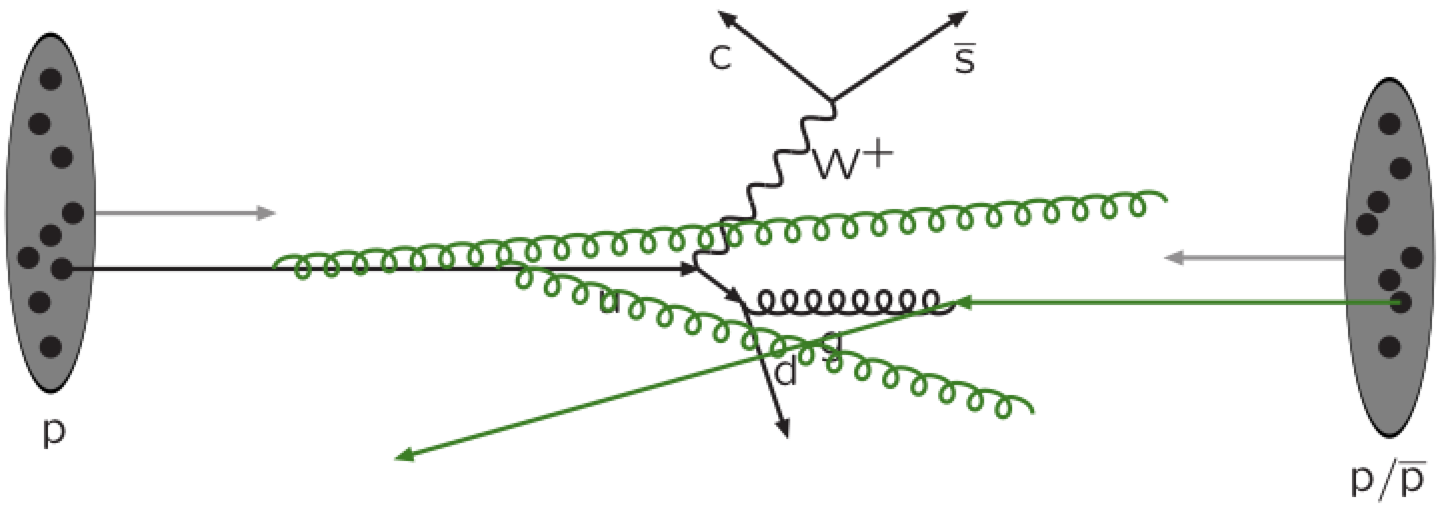


Hard scattering – matrix element

The structure of a pp event

Figure by T. Sjöstrand



Immediate resonance decay and initial state radiation (parton shower)

The structure of a pp event

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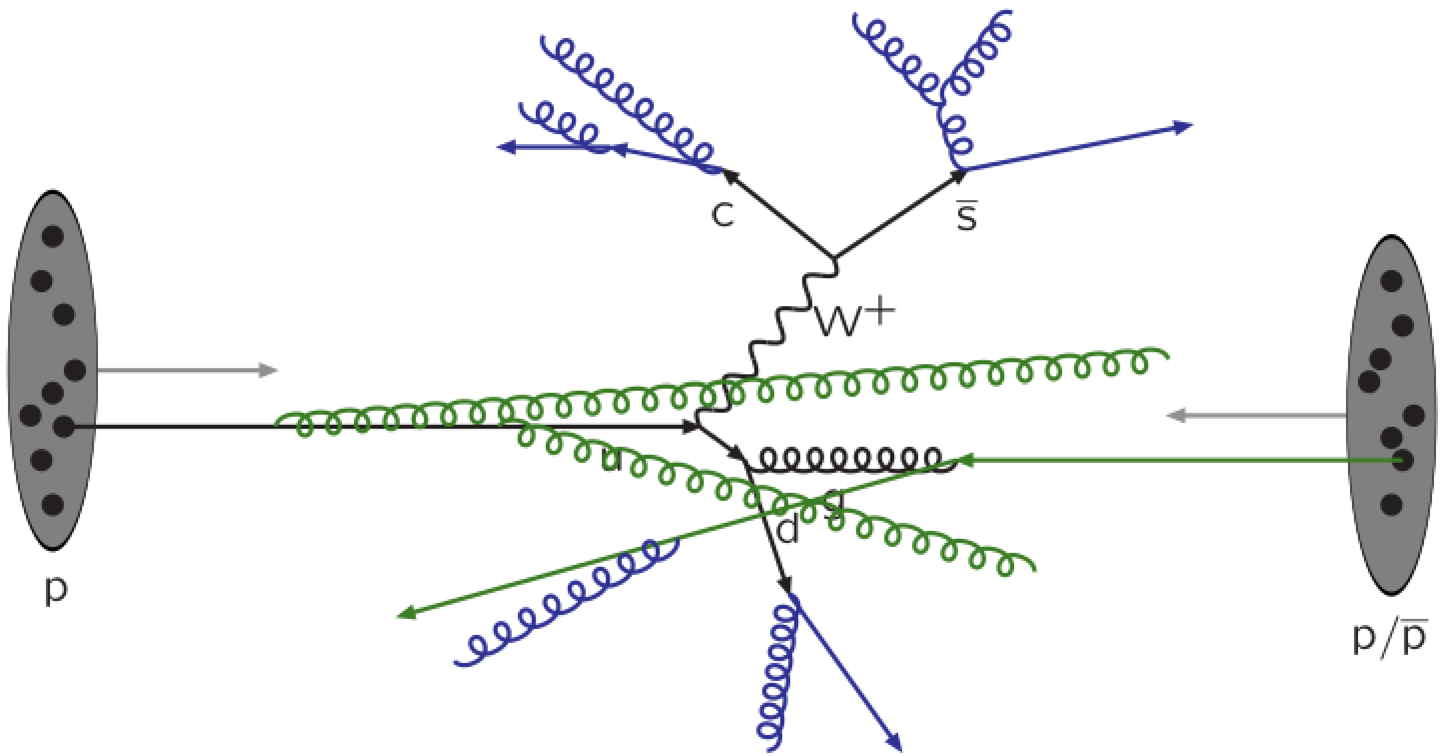
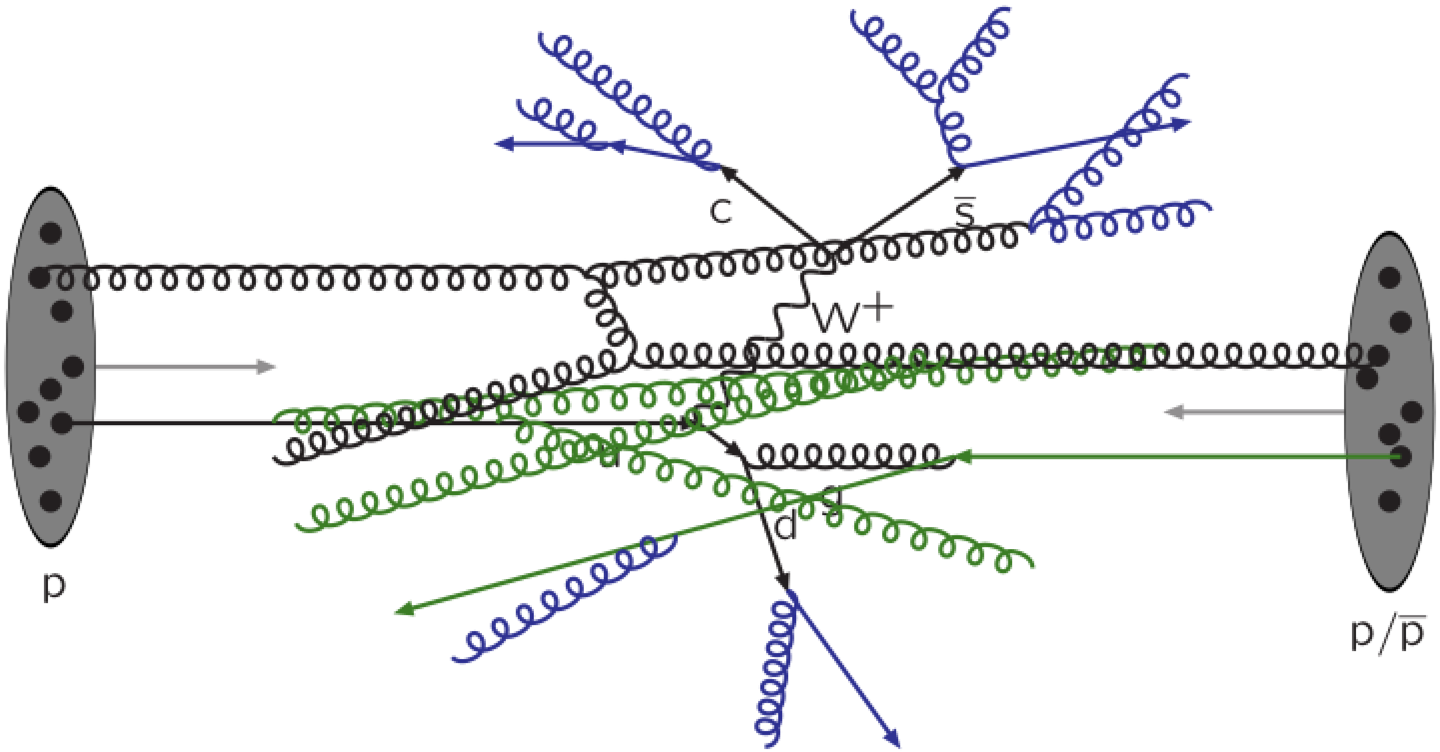


Parton Shower – radiation from produced particles in final state.

The structure of a pp event

Figure by T. Sjöstrand



Multiple partonic interactions (MPIs) with accompanying radiation.

The structure of a pp event

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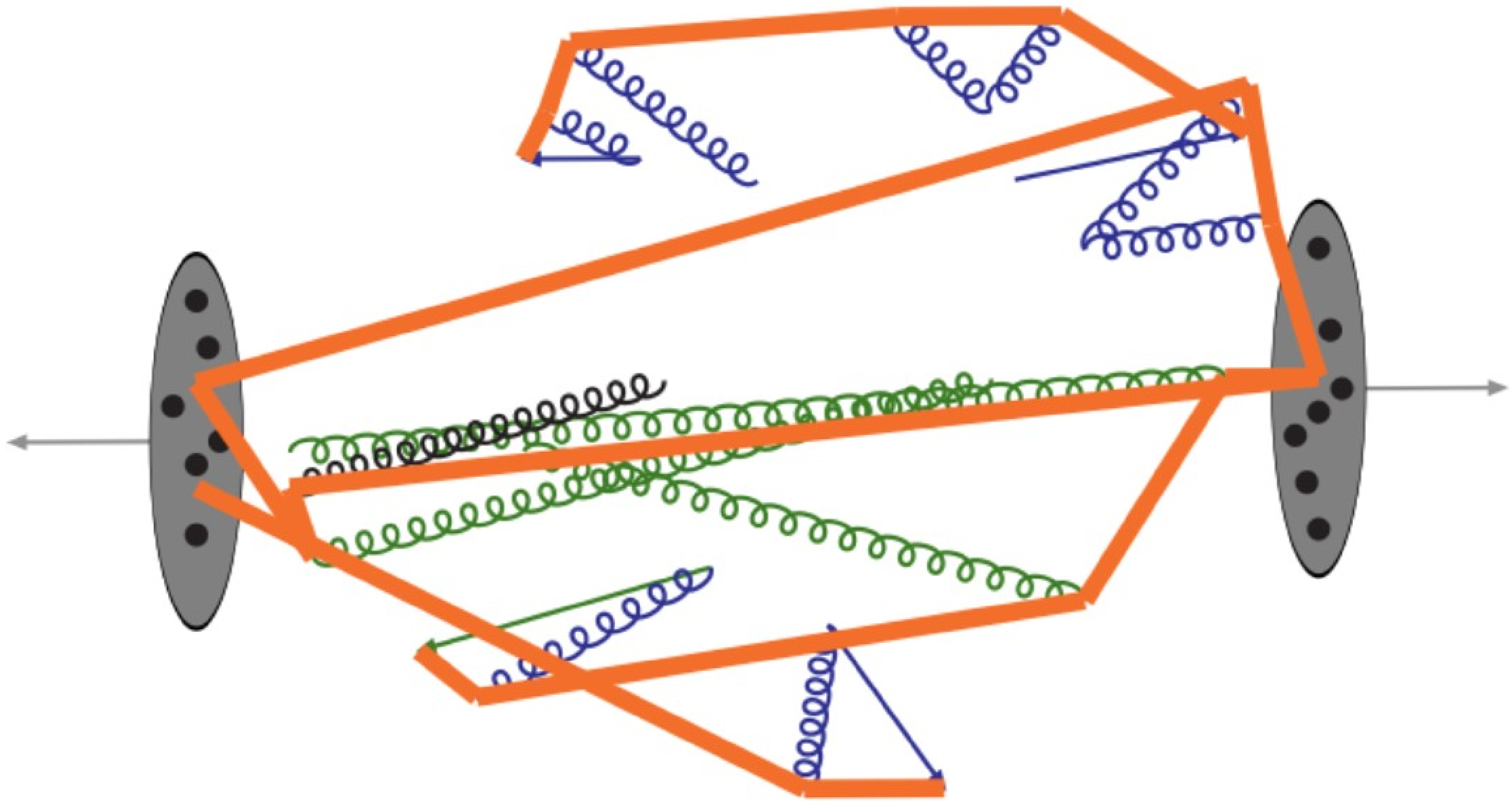
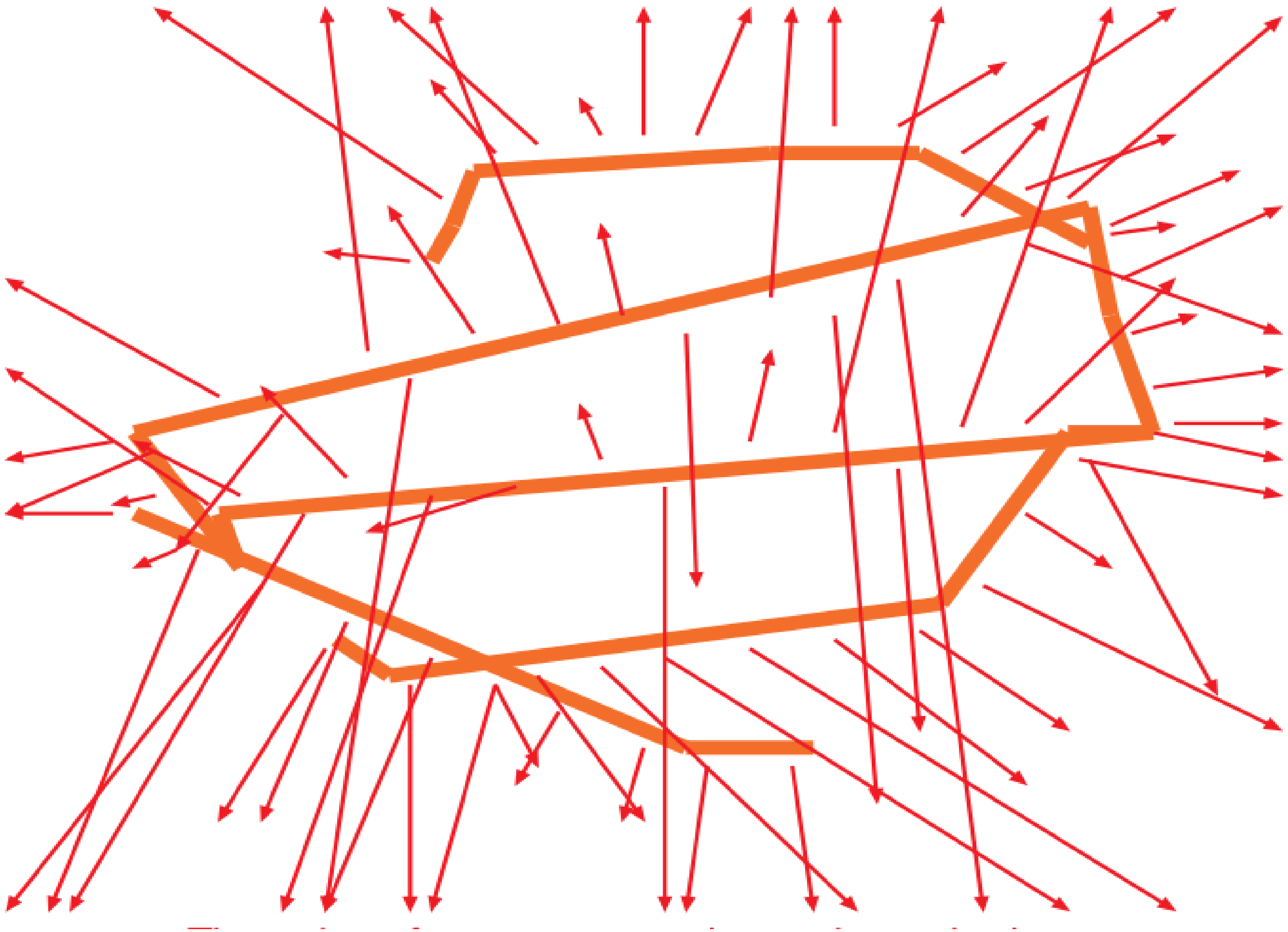


Formation of *strings* due to colour confinement

The structure of a pp event

Figure by T. Sjöstrand



Fragmentation/Hadronization of strings into (primary) hadrons + subsequent decays

Output must look like data

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- Goal: Full, exclusive final state events.

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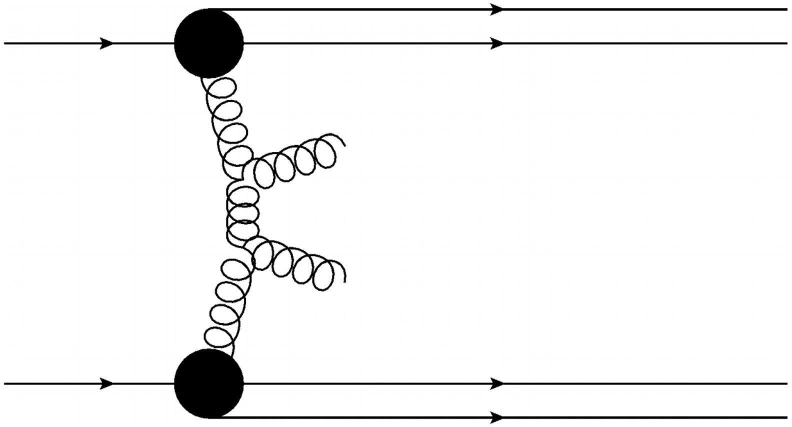
- Goal: Full, exclusive final state events.
- Experimental reality: ~10s-100s of final state partons not calculable with matrix elements.
- Transition partons → hadrons require non-perturbate *models.*
- Focus of this lecture:
  - A QCD MPI event; hard interactions, FS shower and hadronization.
  - Stacking of events to get heavy ion collisions.

Multiparton Interactions

- We consider a pure QCD event.
- All hard sub-collisions with 2→2 ME.
- Regularized with screening parameter.



$$\frac{d\sigma_{2\to2}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_\perp^2+p_{\perp 0}^2)}{(p_\perp^2+p_{\perp 0}^2)^2}.$$

Data tells us: $p_{\perp,0} \approx \frac{1}{d_{screen}} \approx 2\ \mathrm{GeV}$

Sjöstrand and van Zijl: Phys. Rev. D 36, 2019
Sjöstrand and Skands: hep-ph/0408302

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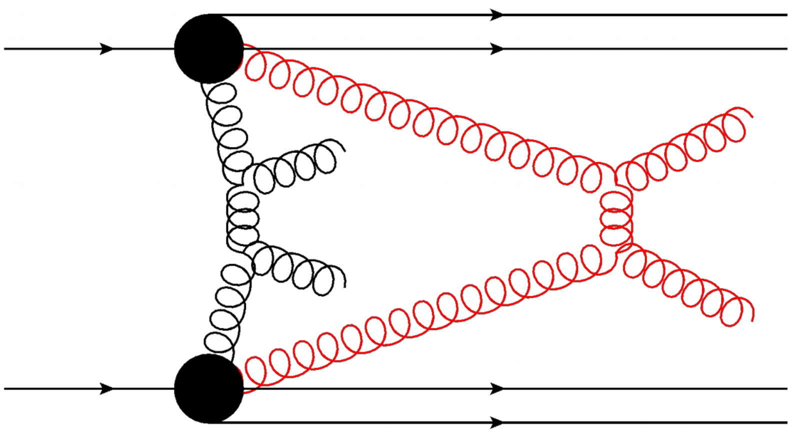


$$\frac{d\sigma_{2\to 2}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_\perp^2 + p_{\perp 0}^2)}{(p_\perp^2 + p_{\perp 0}^2)^2}.$$

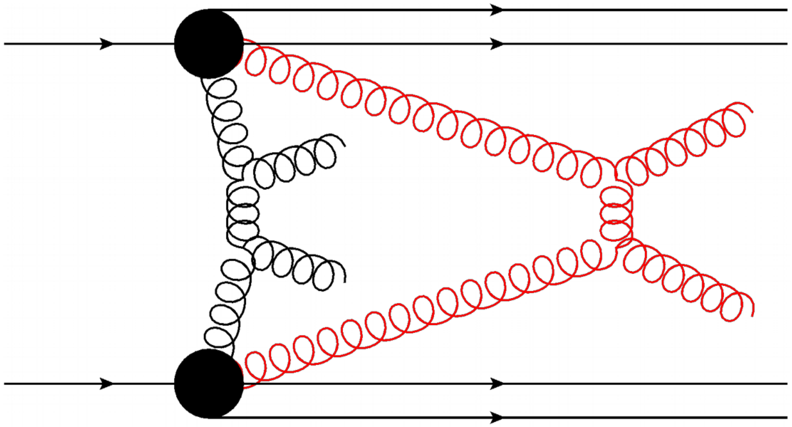
$$\mathcal{P}(p_\perp = p_{\perp i}) =$$

$$\frac{1}{\sigma_{nd}} \frac{d\sigma_{2\to 2}}{dp_\perp} \exp\left[-\int_{p_\perp}^{p_{\perp i-1}} \frac{1}{\sigma_{nd}} \frac{d\sigma}{dp'_\perp} dp'_\perp\right]$$

- Multiple emissions ordered in transverse momentum

Multiparton Interactions

- Proton structure parametrized in PDFs.
- PDFs rescaled after each emission...
- + momentum conservation → Narrower than Poissonian.



Multiparton Interactions

- Proton structure parametrized in PDFs + ISR.
- PDFs rescaled after each emission...
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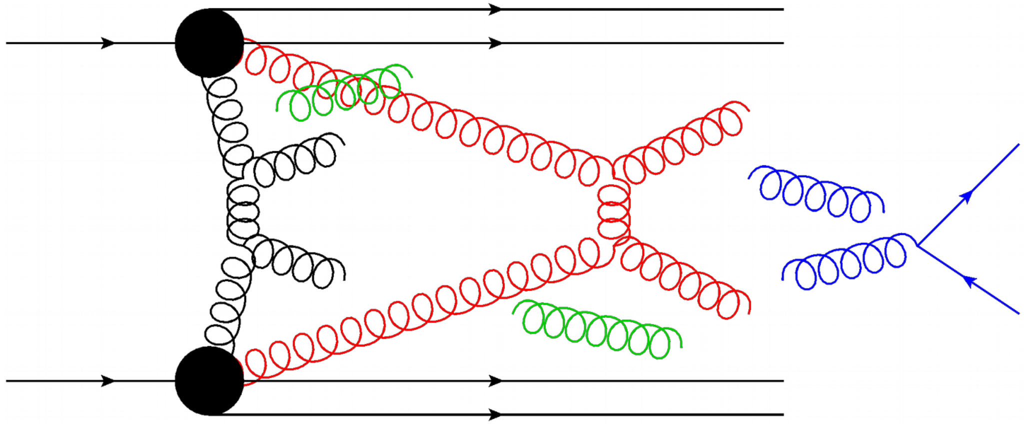

- Will treat parton radiation for the simpler case of Final State Radiation.

Final state shower

- Not feasible to calculate more than a few emissions with diagrams.
- Solution: Let successive emissions happen independently and *iterate* the process.
- *Approximates* tree-level ME by product of splitting functions.
- *Necessary* to produce jet structures.
- Remember: Experiments measure jets. And

  a jet is not a parton

Dipole radiation

- Modern parton showers use *dipole radiation* to account for coherence effects.
- Briefly study the case: $Z \to q\bar{q} + g$

Gustafson and Pettersson: Nucl. Phys. B306 (1988) 746
Lönnblad: Comput. Phys. Commun. 71 (1992) 15–3

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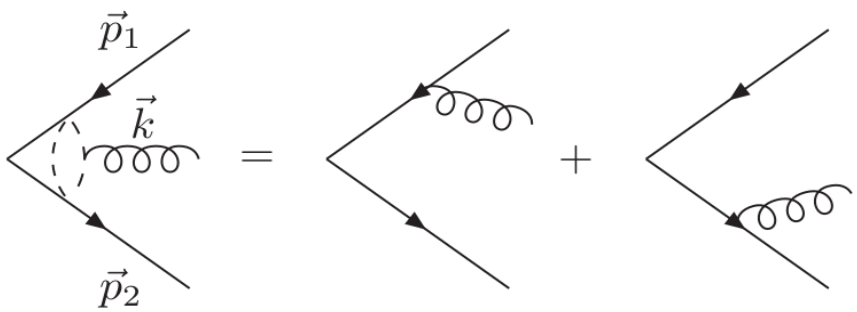
$$\frac{|\mathcal{M}_{q\bar{q}g}|^2}{|\mathcal{M}_{q\bar{q}}|^2} \propto \frac{\vec{p_1} \cdot \vec{p_2}}{(\vec{p_1} \cdot \vec{k})(\vec{p_2} \cdot \vec{k})}$$



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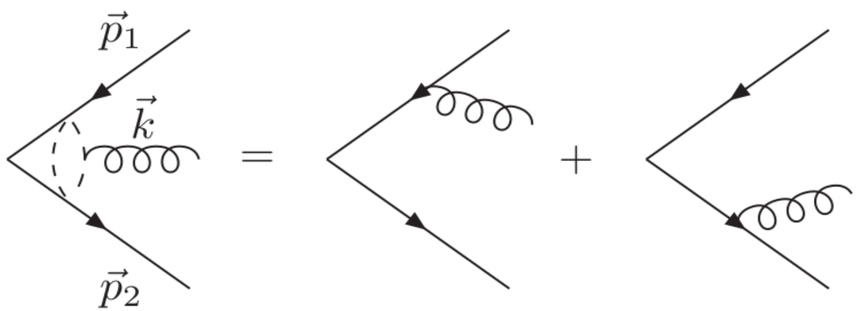

- Implies *angular ordering* – emission only allowed inside the cone

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Iterating the emissions

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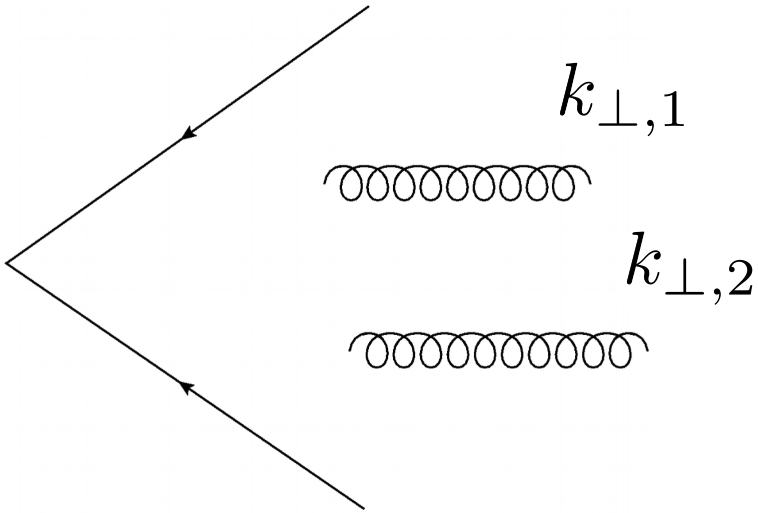

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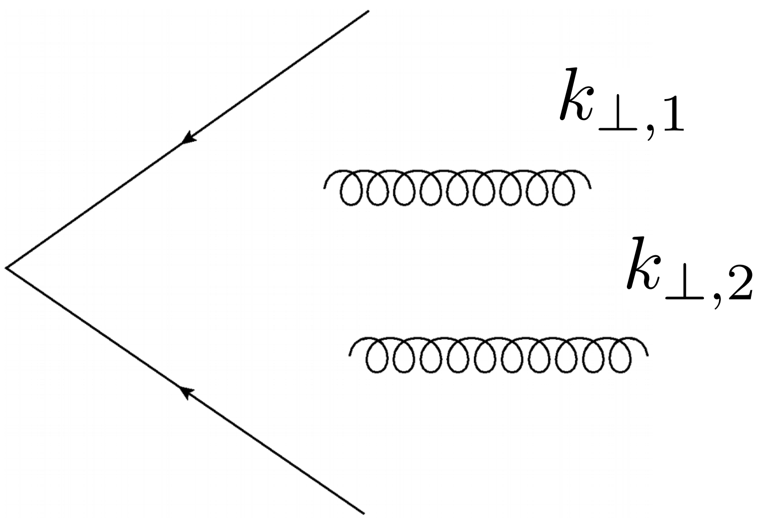

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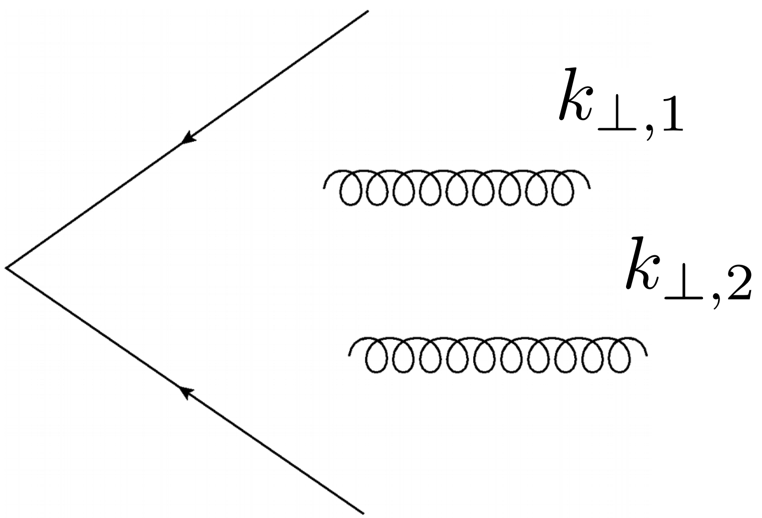
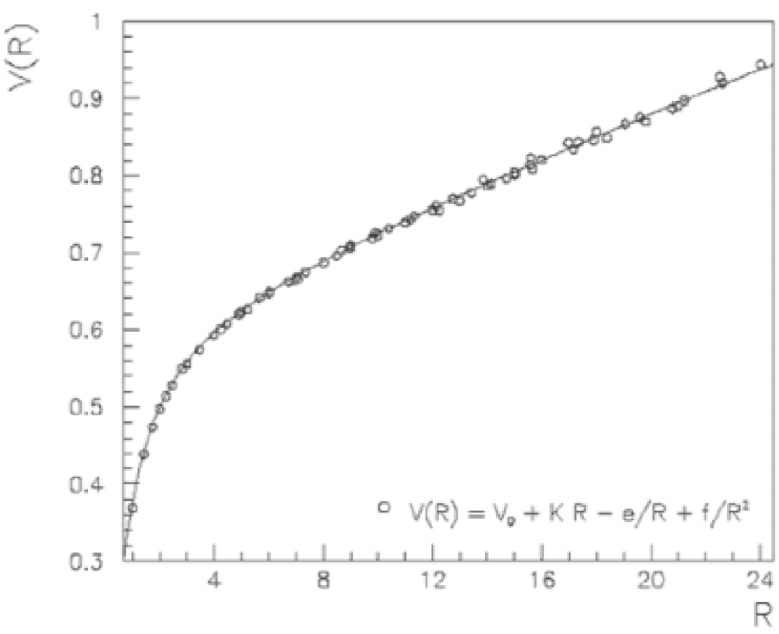


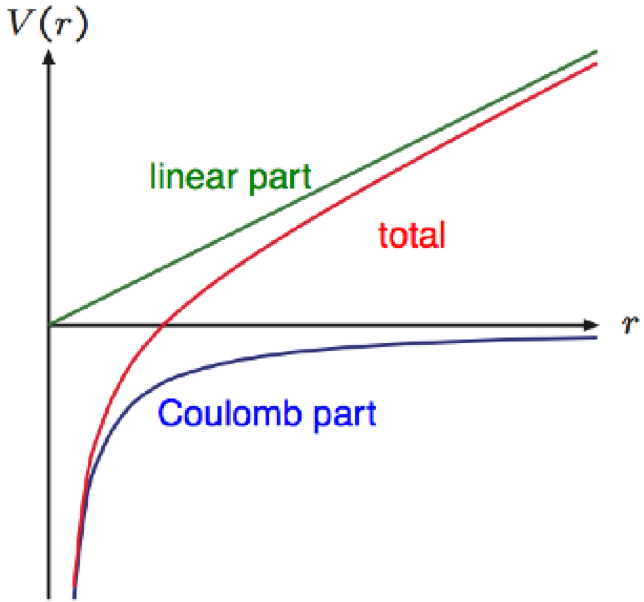
- If times well separated: Treat as independent emissions.
- If not: Independent dipole picture breaks down.

- Soft + collinear radiation: good!
- Several hard jets: bad!

Hadronization

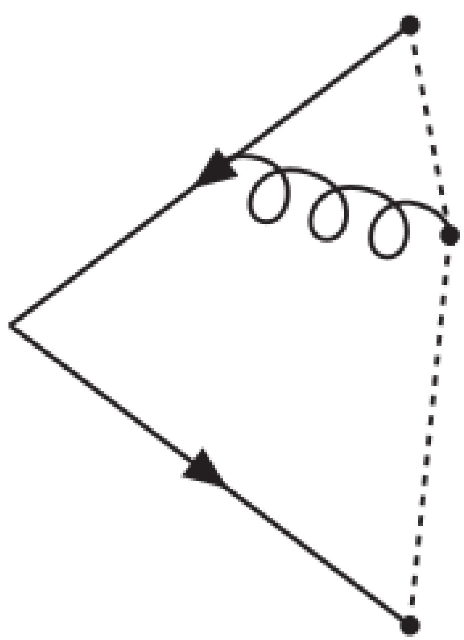
- The dipole FS shower picture translates nicely into *strings* spanned between colour charges.
- Linear confinement potential $V(r) = \kappa r$
- Not perturbative – but still QCD.





The Lund String

- Confining colour fields = strings with $\kappa \approx 1\ \mathrm{GeV/fm}$
- Potential energy builds up – string breaks when energetically favorable.



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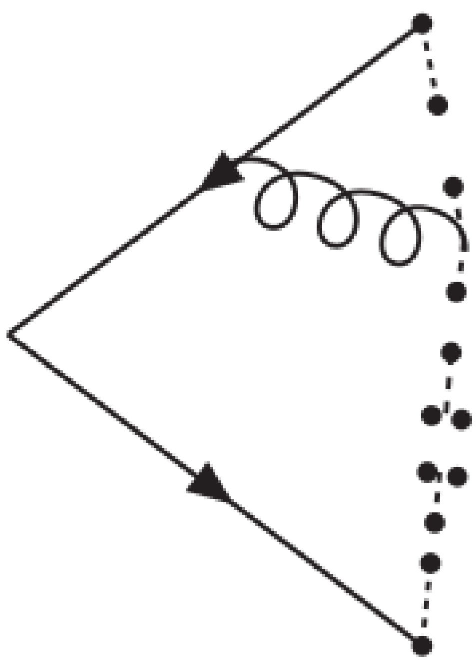

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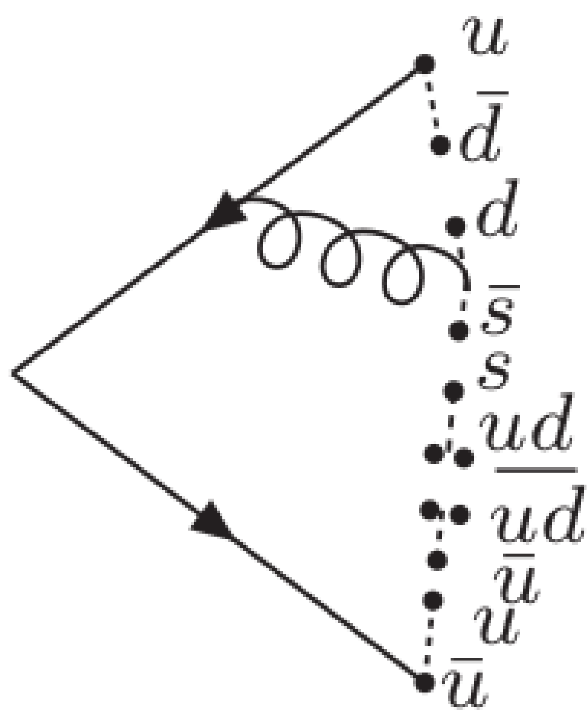

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Tunneling mechanism

- String breaks through tunneling mechanism (so-called Schwinger equation).

$$\frac{d\mathcal{P}}{dp_\perp} \propto \kappa \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$$

- Selection of mass and transverse momentum factorizes.
- Suppression of heavier types are then *eg.*

$$\rho = \frac{\mathcal{P}_s}{\mathcal{P}_u} = \exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right)$$

Longitudinal momentum

- Breakups are causally disconnected – we can start iteration anywhere on the string.
- Lund string choice: Outside in.
- Starting from either end should produce same result. This symmetry gives the fragmentation function:

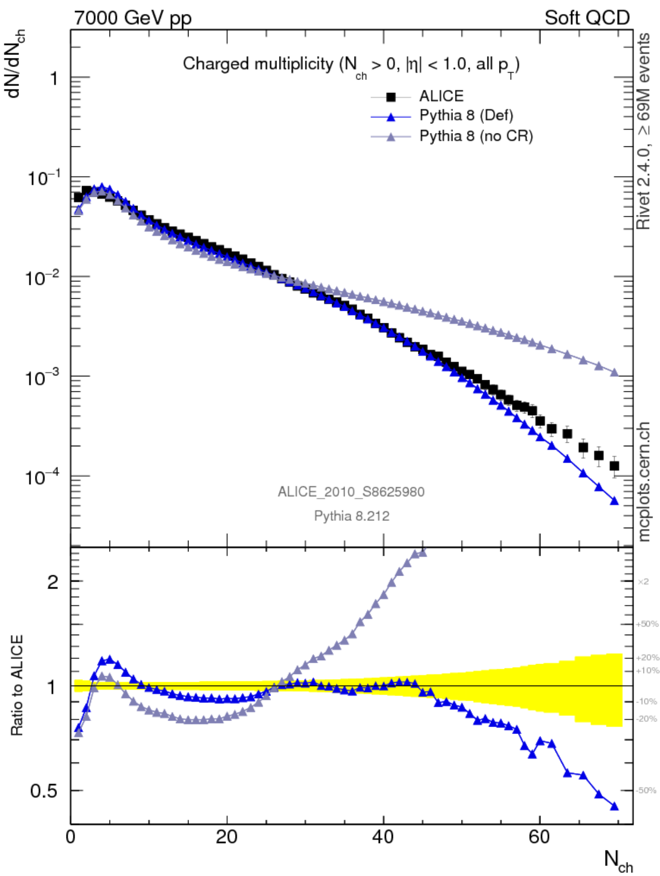
$$f(z) \propto z^{-1}(1-z)^a \exp\left(-\frac{bm_\perp^2}{z}\right)$$

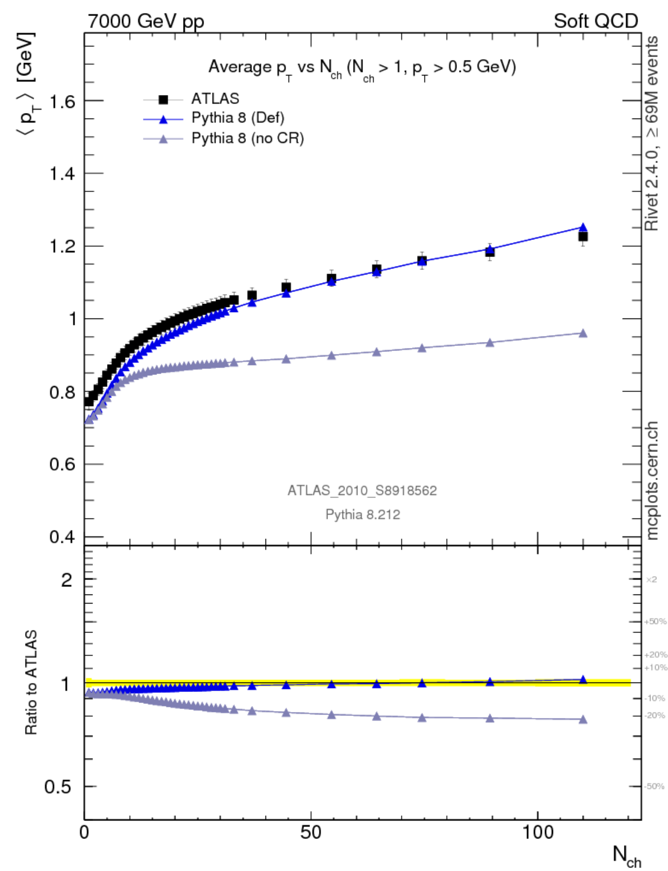
Parameters

- One obtains many (O(10)) model parameters.
- Philosophy is:
  - Tune all parameters to LEP data.
  - Fixed parameters predicts pp data.
  - A tune = a set of parameters valid for all collision systems at all energies.
  - Don’t be afraid of parameters!
  - ...but worry about “special tunes”.

Colour Reconnection

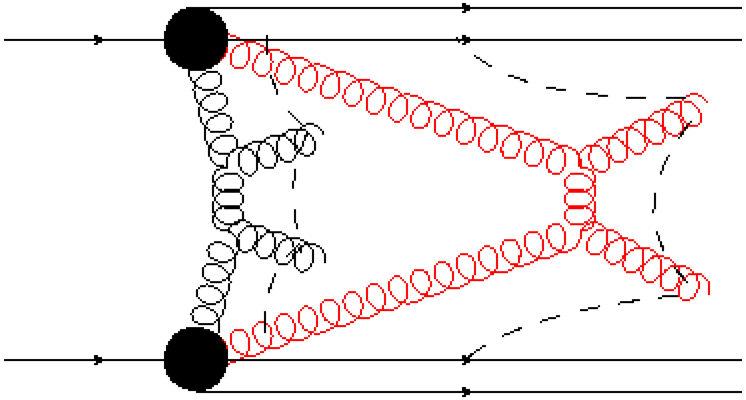
- PS + String: good description of LEP data (see *eg.* 1404.5630).
- For pp we need Colour Reconnection.





Colours and strings

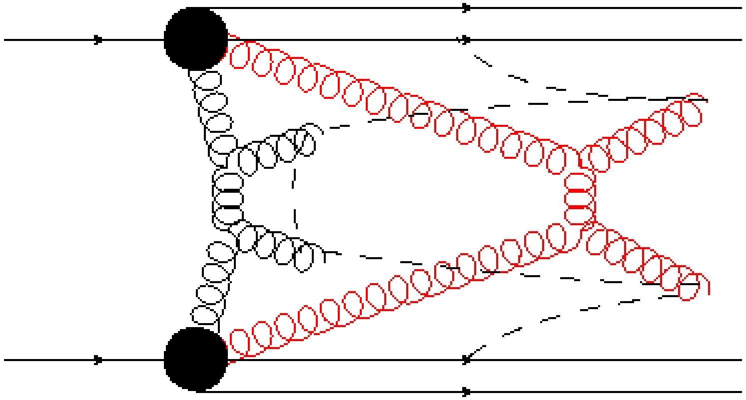
- Without CR all MPIs hadronize independently.



- So many strings – so little space!
- Colour configuration set in shower limit.

Colours and strings

- CR introduces neccesary “collectivity”.
- Reduced string length = reduced multiplicity.



- Colour coherence added *a posteriori.*
- Only necessary because shower in imperfect.

Pythia default CR

- Pythia CR is rather *ad hoc*, but it “works”.
- Probability for two MPI systems to join is:

$$\mathcal{P} = \frac{(\gamma p_{\perp 0})^2}{(\gamma p_{\perp 0}^2 + p_{\perp}^2)}$$

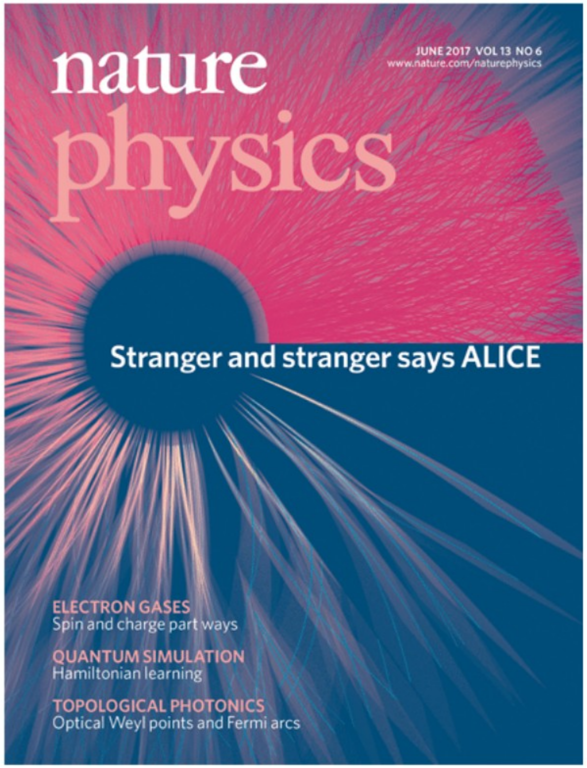
- The actual merged topology is decided by minimizing ~potential energy.

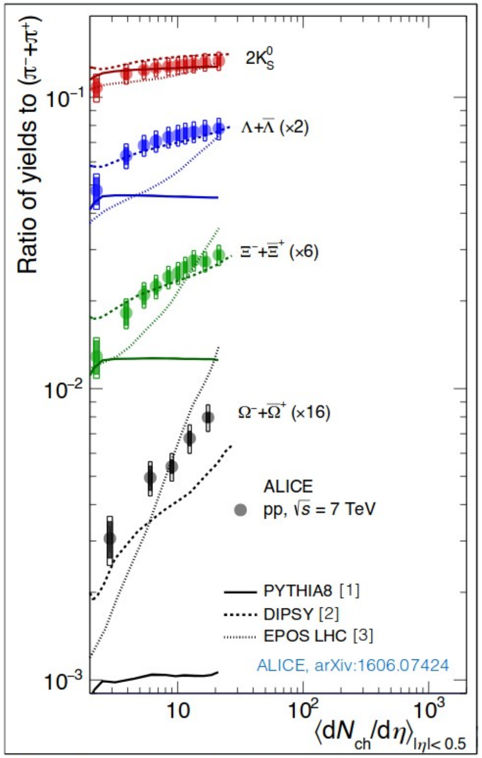
$$\lambda = \sum_{dipoles} \log(1 + \sqrt{2} E/m_0)$$

Best reference: Pythia 6 manual: hep-ph/0603175

But there is more...

- CR only gets multiplicities, more involved models exist.





D.D. Chinellato – 38th International Conference on High Energy Physics

- This will be covered in my WS talk.

From pp to AA

- We have now covered the journey from matrix element calculations to exclusive final states.
- At the same time we have covered the journey from LEP to LHC MC generator phenomenology.
- Now: How to apply MPIs to an AA collision: The “Angantyr” framework in Pythia8.

CB, Gustafson, Lönnblad: 1607.04434

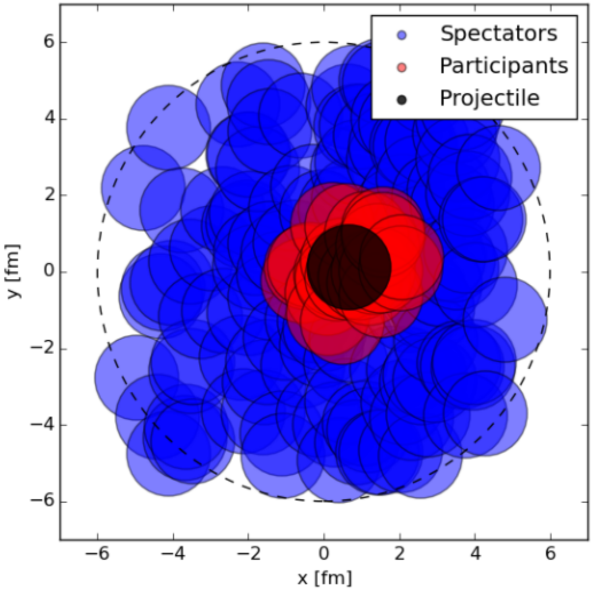
It (mostly) comes down to geometry

- Heavy ions in Pythia is based on a Glauber picture.
- Nucleons “wounded” in impact parameter space.

$$\Im(A_{el}) = \frac{1}{2}(|A_{el}|^2 + P_{abs}); T \equiv -iA_{el} \Rightarrow$$

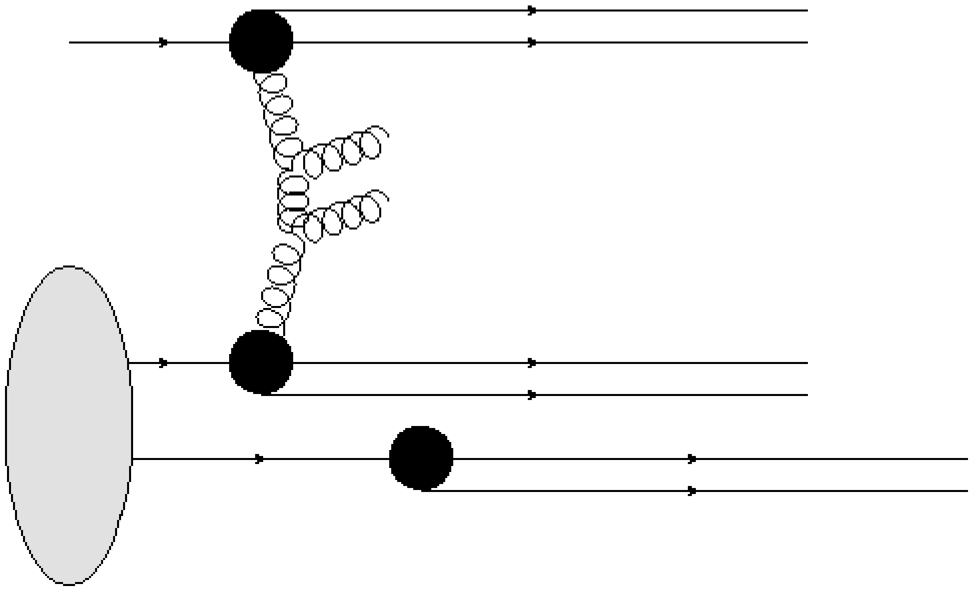
$$\frac{d\sigma_{el}}{d^2b} = \langle T(b) \rangle^2, \frac{d\sigma_{tot}}{d^2b} = 2\langle T(b) \rangle$$

$$\frac{d\sigma_{abs}}{d^2b} = 2\langle T(b) \rangle - \langle T(b) \rangle^2$$



Parton level stacking

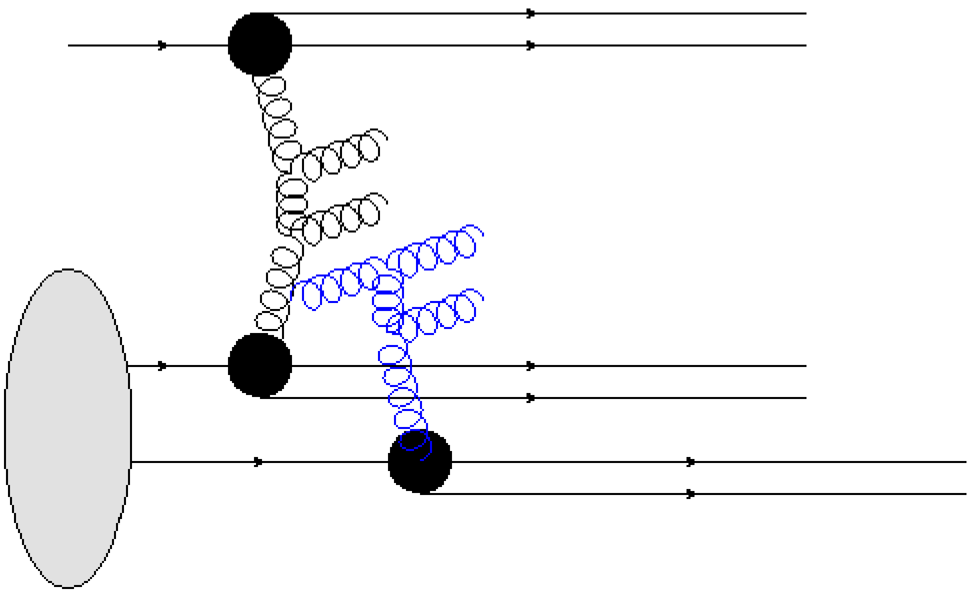
- MPI structure similar but different from pp.
- Simplest possible is identical to pp.



- CR and hadronization as usual.
- The spectator is just added to the beam

Adding another nucleon

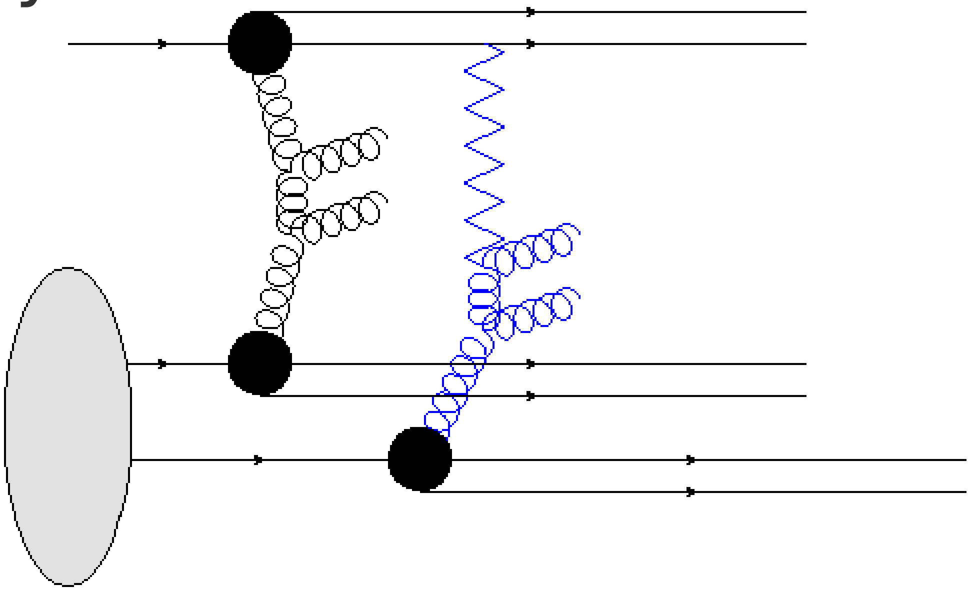
- Keeping CR/proton structure in mind, another wounded nucleon should look like this.
- More activity near A-side gives more mult.



- Difficult to obtain directly by stacking.

...so we cheat.

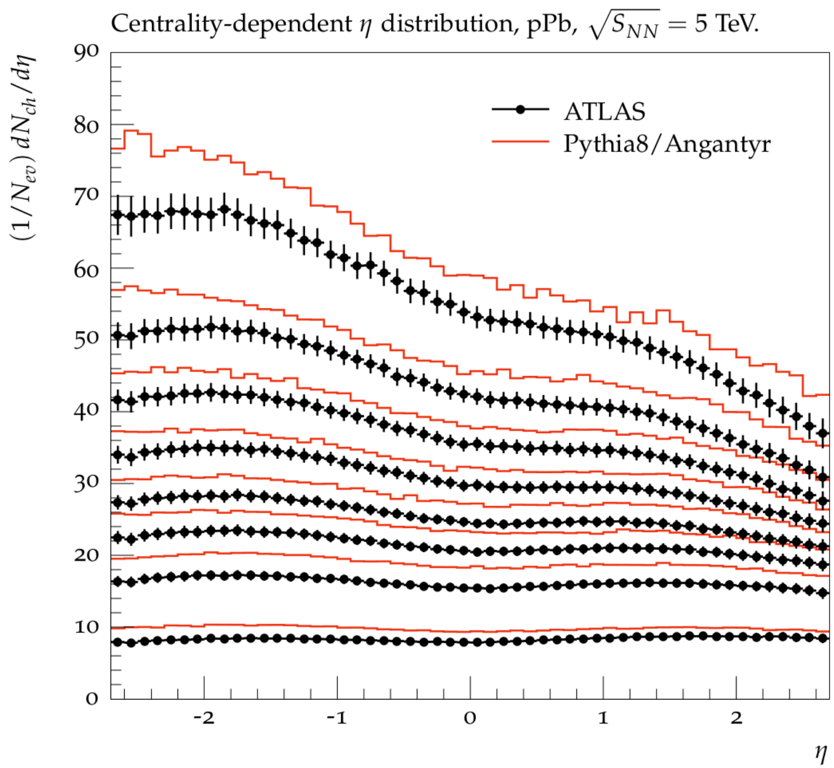
- Looks like a normal event + SD event.
- Pro: We can do CR and hadronization separately – also for AA.

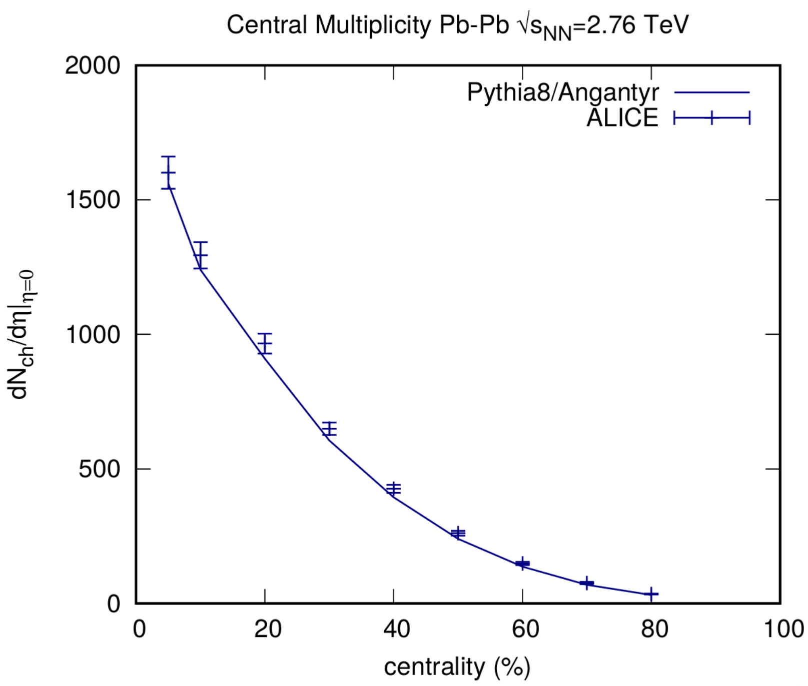


- Con: The colour singlet is not really a Pomeron.

Works quite well

- Works well for multiplicity in pA and AA.
- User can add signal processes.
- Highly customizable – users can add models.





Summary

- QCD is everywhere in MC event generators.
- Overview of: Parton shower + CR + string.
- Parton shower + string is good enough for LEP. Both are needed for full, exclusive predictions.
- MPIs and CR must be added for LHC.
- Some “collectivity” explained by CR – more on Friday.
- Extensions of MPI models to pA and AA are available. Built on Glauber picture.