CTEQ - Introduction to Monte Carlo

Lecture 3

MPI, Hadronization, and Non-perturbative Effects

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Overview

- lecture 1 - introduction and Monte Carlo techniques
- lecture 2 - matrix elements and parton showers
- **lecture 3 - multi-parton interactions, hadronization, and non-perturbative effects**

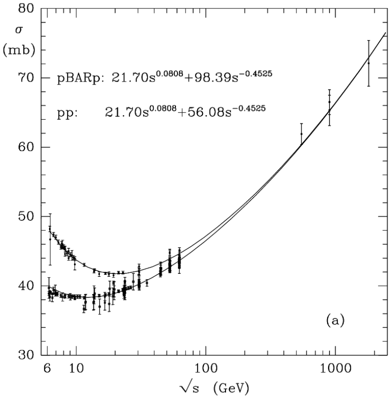
Soft Physics

- most measurements focus on hard processes, *e.g.* high mass dijet events
- soft QCD interactions occur in addition to hard processes
- events with only soft QCD are important for understanding QCD
- most events at the LHC are soft QCD $\rightarrow$ minimum-bias events
- minimum-bias events require some detector activity
- no-bias events do not and randomly sample beam crossings
- from a theory perspective, minimum bias is sometimes taken as no bias

Total Cross Section

- use Donnachie-Landshoff parameterized Regge fit
- first term is Pomeron, second is Reggeon

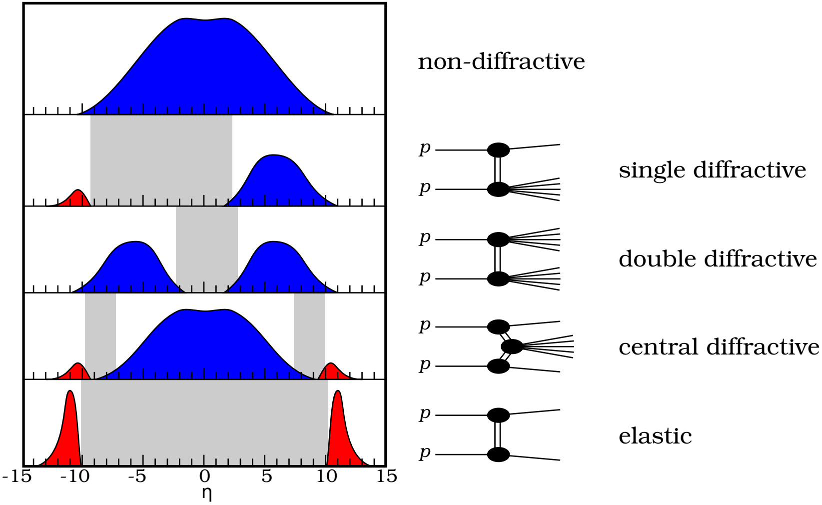
$$\sigma_{\text{tot}}(s) = (21.70 s^{0.0808} + 56.08 s^{-0.425}) \text{ mb}$$



- $\sigma_{\text{tot}}(14 \text{ TeV}) = 101.5$ mb

Event Classification

- event classification different between experiment and theory



Non-diffractive Cross Section

$$\sigma_{\text{tot}}(s) = \sigma_{\text{inel}}(s) + \sigma_{\text{el}}(s)$$
$$\sigma_{\text{el}}(s) = \frac{\sigma^2_{\text{tot}}(s)}{16\pi(5 + 4s^{0.0808})}$$

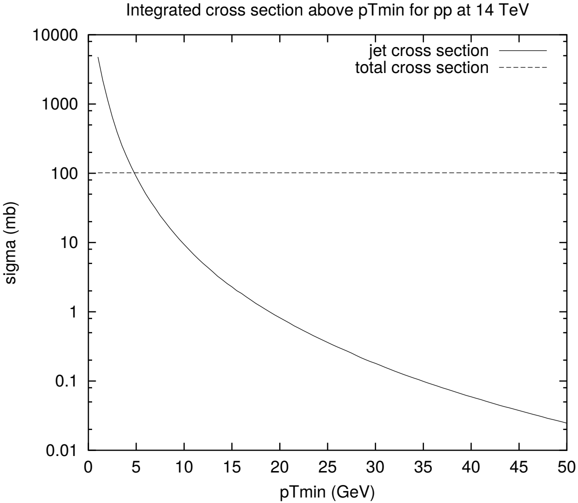
- relate σ_{tot} to σ_{el} via optical theorem and asymptotic behavior
- write non-diffractive cross section in terms of known inelastic and diffractive cross sections

$$\sigma_{\text{inel}}(s) = \sigma_{\text{ND}}(s) + 2\sigma_{\text{SD}}(s) + \sigma_{\text{DD}}(s) + \sigma_{\text{CD}}(s)$$
$$\Rightarrow \sigma_{\text{ND}}(s) = \sigma_{\text{inel}}(s) - 2\sigma_{\text{SD}}(s) + \sigma_{\text{DD}}(s) + \sigma_{\text{CD}}(s)$$

- minimum bias is primarily non-diffractive (with some double diffractive)

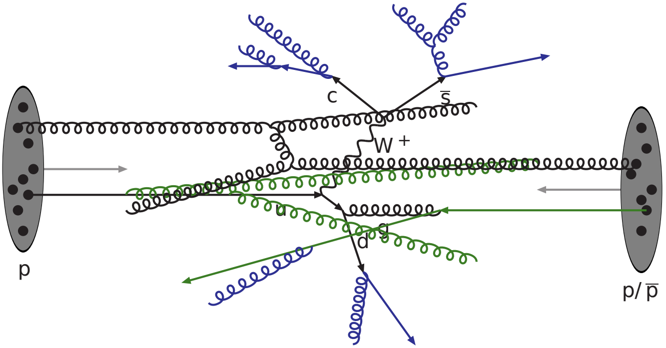
Modeling Minimum Bias

- from last lecture, QCD t-channel gluon-exchange cross sections diverge as $1/p_T^4$ for $\hat{t} \to 0$
- these processes will dominate minimum bias production



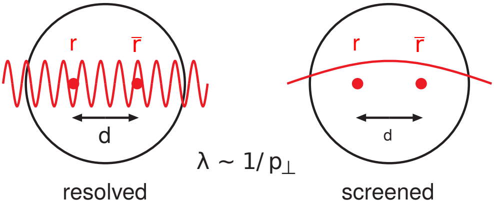
Modeling Minimum Bias

- QCD $2 \to 2$ jet cross section exceeds σ_{tot}
- interpret as multiple parton interactions (MPI) per event
- recast problem: number of MPI diverges, not cross section



Color Screening

- low p_{T} perturbative QCD not valid, q/g not asymptotic states
- assume some type of color screening in proton



- introduce smooth damping factor

$$\left(\frac{p_{\mathrm{T}}^4}{p_{\mathrm{T}0}^2 + p_{\mathrm{T}}^2}\right)\left(\frac{\alpha_s(p_{\mathrm{T}0}^2 + p_{\mathrm{T}}^2)^2}{\alpha_s(p_{\mathrm{T}}^2)}\right)$$

- allow $p_{\mathrm{T}0}$ to vary as a function of energy

$$p_{\mathrm{T}0}(\sqrt{s}) = p_{\mathrm{T}0}(E_0)\left(\frac{\sqrt{s}}{E_0}\right)^{\theta}$$

Multi-parton Interactions

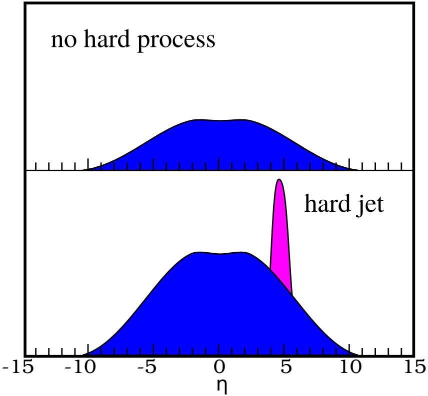
- regulated $\sigma_{2\to2}$ is finite
- assuming independent interactions, number of MPI can be estimated

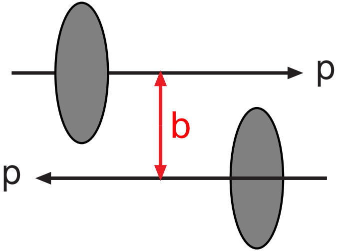
$$\langle n_{\mathrm{MPI}}\rangle \sigma_{\mathrm{ND}} = \sigma_{2\to2}$$
$$\Rightarrow \langle n_{\mathrm{MPI}}\rangle = \frac{\sigma_{2\to2}}{\sigma_{\mathrm{ND}}}$$

- can now write MPI probability
$$\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_{\mathrm{T}}} = \frac{1}{\sigma_{\mathrm{ND}}}\frac{\mathrm{d}\sigma_{2\to2}}{\mathrm{d}p_{\mathrm{T}}} \exp\left(-\int_{p_{\mathrm{T}}}^{p_{\mathrm{T}\,i-1}} \frac{1}{\sigma_{\mathrm{ND}}}\frac{\mathrm{d}\sigma_{2\to2}}{\mathrm{d}p'_{\mathrm{T}}}\mathrm{d}p'_{\mathrm{T}}\right)$$
- use veto algorithm to generate subsequent MPI

Some Complications

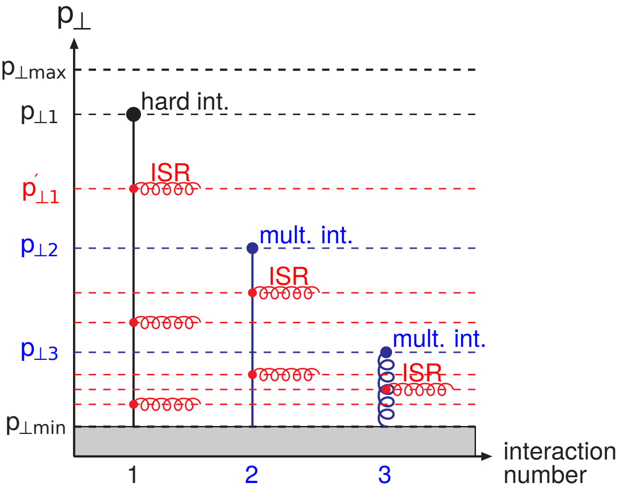
- MPI are not actually independent
- modify PDFs after MPI selected, include flavor conservation
- consider proton impact parameter
- hard process → more underlying event (pedestal effect)





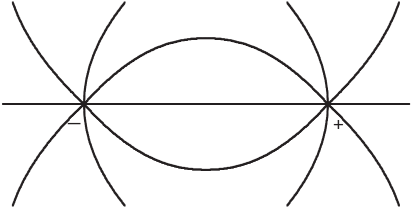
Putting it Together

- with p_T ordered parton shower, interleave ISR, FSR, and MPI

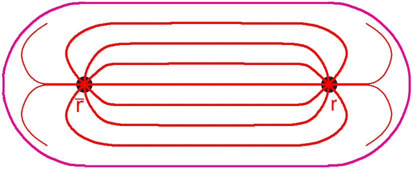


Field Lines

- QED field lines extend to infinity

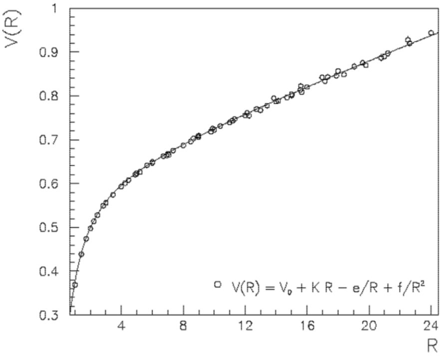


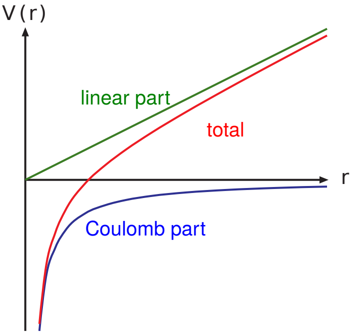
- QCD field lines compressed into strings



QCD Potential

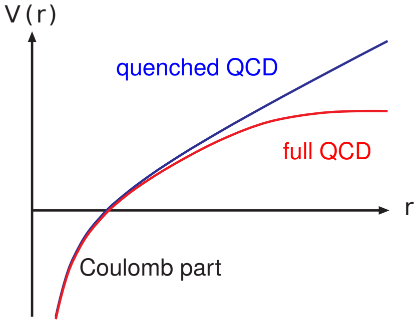
- quenched lattice QCD demonstrates linear confinement





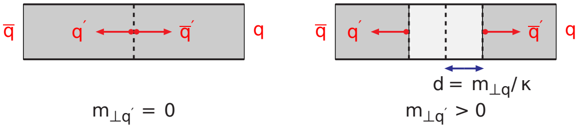
QCD Potential

- reality might not be quite so nice ...
- a non-quenched lattice measurement would be nice!



String Breaks

- each break is described by quantum tunneling
- only consider linear term



$$\mathcal{P} \propto \exp\left(\frac{-\pi m_{\mathrm{T}q}^2}{\kappa}\right)$$

$$m_{\mathrm{T}}^2 = p_{\mathrm{T}}^2 + m^2$$

$$\rightarrow \mathcal{P} \propto \exp\left(\frac{-\pi p_{\mathrm{T}}^2}{\kappa}\right) \exp\left(\frac{-m_q^2}{\kappa}\right)$$

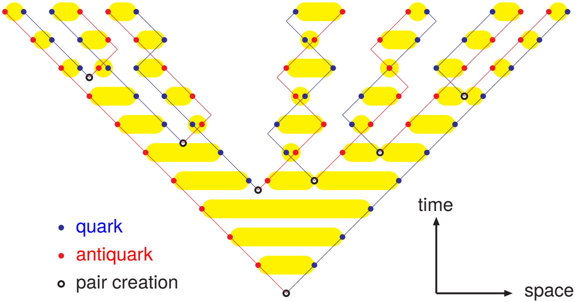
- common Gaussian p_{T} distribution for all breaks
- heavy quark production suppressed
  $u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11}$
- baryons produced via diquark breaks

String Model

1. randomly select side of string for break
2. select flavor of produced hadron
3. perform string break, sample p_{T}
4. sample remaining momentum of the string, z

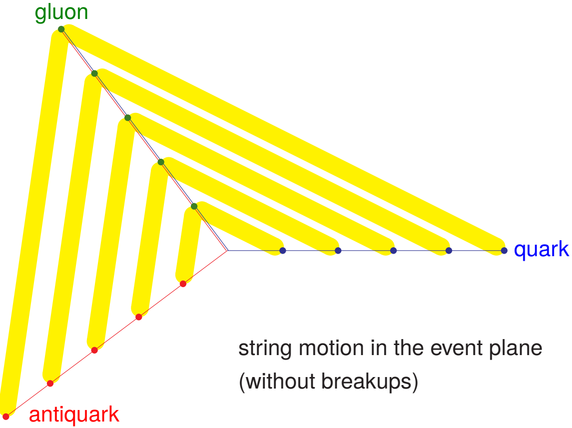
$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-b\frac{m_{\mathrm{T}}^2}{z}\right)$$

5. return to 1 until no remaining string momentum



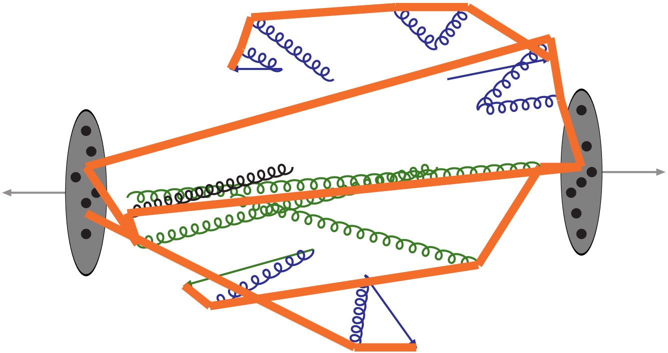
String Kinks

- more complex topologies exist (attached gluons, gluon-gluon, junctions, *etc.*)
- gluons on string provide a kink, modifying the kinematics

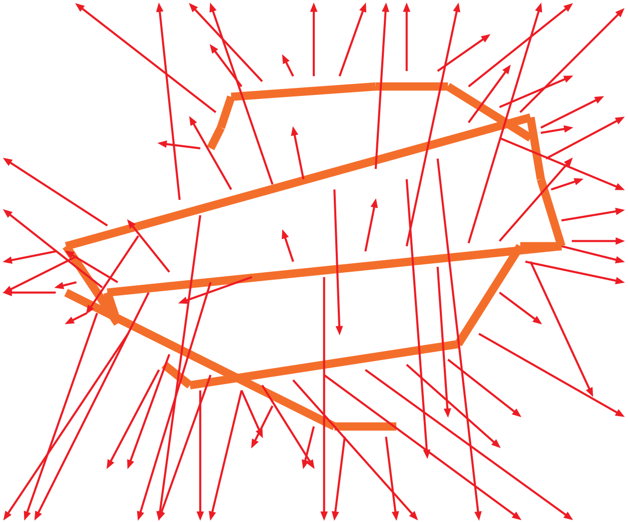


string motion in the event plane
(without breakups)

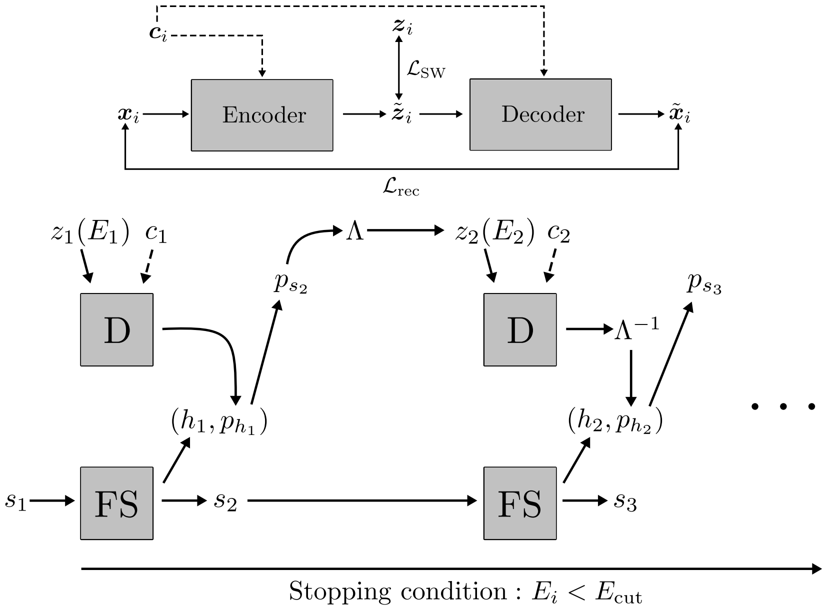
Strings in an Event



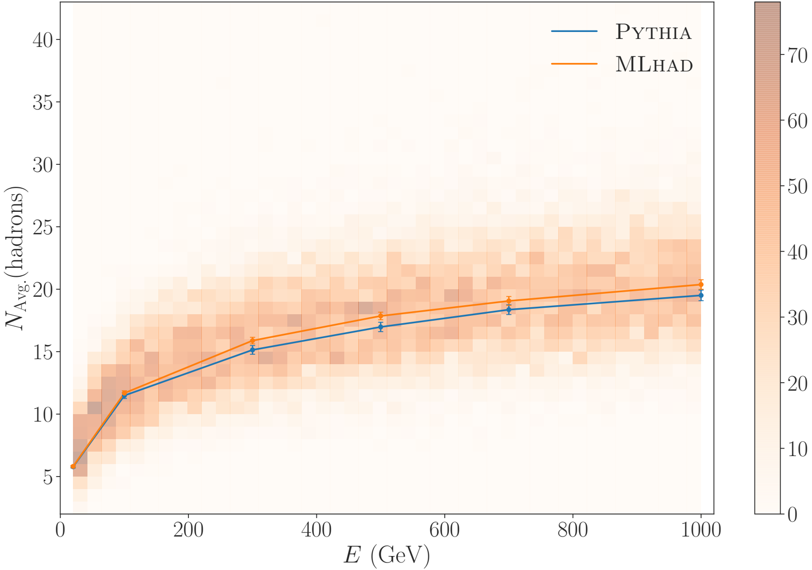
Hadrons in an Event



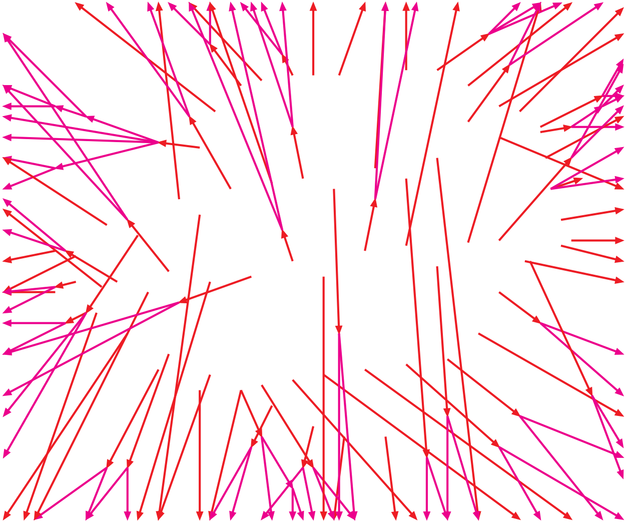
Machine Learning Hadronization



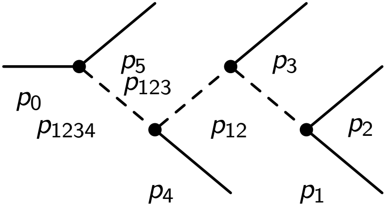
Machine Learning Hadronization



Decays of Hadrons



Phase-Space Generation



- m-generator
- two-body decays through intermediate masses

$$\mathrm{d}\Phi_2(q_0, q_1, q_2) = \left(\frac{1}{(2\pi)^2 2^2}\right) \delta(q_0 - q_1 - q_2) \frac{\mathrm{d}\vec{q}_1}{E_1} \frac{\mathrm{d}\vec{q}_2}{E_2}$$

$$\mathrm{d}\Phi_3(q_0, q_1, q_2, q_3) = \left(\frac{2}{\pi}\right) \mathrm{d}\Phi_2(q_0, q_{12}, q_3)\, m_{12} \mathrm{d}m_{12}\, \mathrm{d}\Phi_2(q_{12}, q_1, q_2)$$

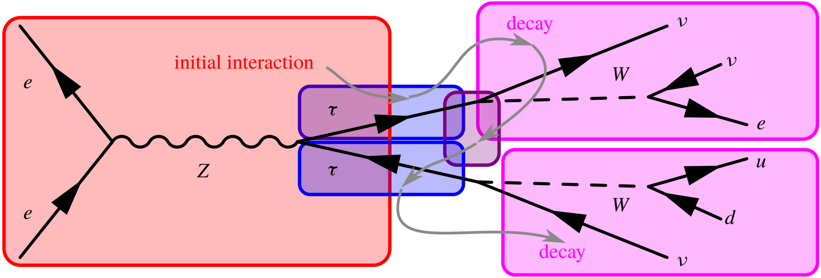
- weight by $\mathcal{M}$ for the phase-space point

Spin Correlations

- $D \equiv$ decay matrix for each particle, $D_{\text{initial}} = \mathbb{1}$
- $\mathcal{M} \equiv$ matrix element, $\rho \equiv$ density matrix

1. calculate $\mathcal{M}$ for the initial interaction
2. find ρ for an outgoing particle using the interaction $\mathcal{M}$ and D's of the remaining outgoing particles
3. decay the particle using its $\mathcal{M}$, ρ, and the D's of its decay products
4. repeat 2 - 3 until all decay products are stable.
5. calculate D for the particle
6. go up a decay and perform 2 - 5 on the undecayed particles
7. Repeat 2 - 6 until all particles are decayed

Spin Correlations



❷ $\rho^{j}_{\lambda_j \lambda'_j} = \rho^{1}_{\kappa_1 \kappa'_1} \rho^{2}_{\kappa_2 \kappa'_2} \mathcal{M}_{\kappa_1 \kappa_2; \lambda_1 \ldots \lambda_n} \mathcal{M}^{*}_{\kappa'_1 \kappa'_2; \lambda'_1 \ldots \lambda'_n} \prod_{k \neq j} D^{k}_{\lambda_k \lambda'_k}$

❸ $\mathcal{W}_{\mathrm{decay}} = \rho_{\lambda_0 \lambda'_0} \mathcal{M}_{\lambda_0; \lambda_1 \ldots \lambda_n} \mathcal{M}^{*}_{\lambda'_0; \lambda'_1 \ldots \lambda'_n} \prod_{k=1,n} D^{k}_{\lambda_k \lambda'_k}$

❺ $D_{\lambda_0 \lambda'_0} = \mathcal{M}_{\lambda_0; \lambda_1 \ldots \lambda_n} \mathcal{M}^{*}_{\lambda'_0; \lambda'_1 \ldots \lambda'_n} \prod_{l=1,n} D^{l}_{\lambda_l \lambda'_l}$

Forming Deuterons

- how do deuterons form?
- first guess, coalesce proton-neutron pairs into deuteron

1. make all possible *pn* combinations
2. randomize ordering of combinations
3. calculate k for each *pn* combination in COM frame

$$k = \sqrt{(\vec{p}_p - \vec{p}_n)^2}$$

4. if $k < c_0$ combine *pn* combination into deuteron

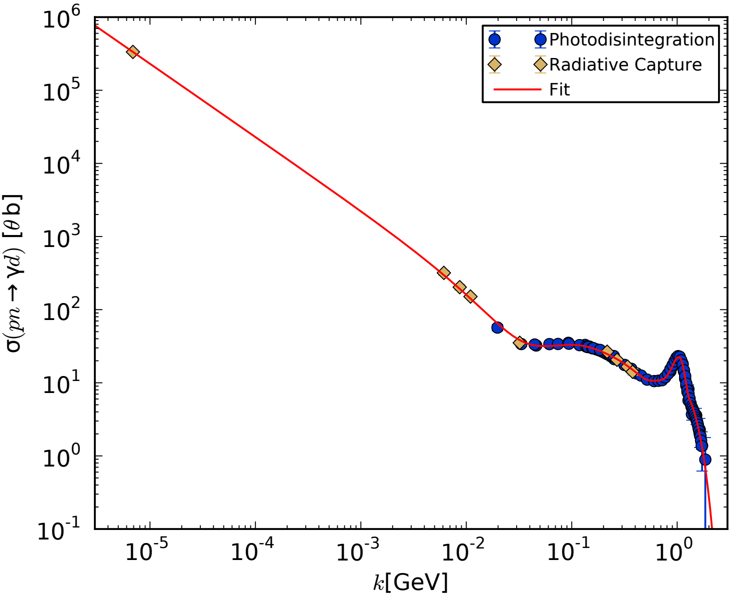
A More Sophisticated Model

- does not describe LHC data particularly well
- assumes uniform cross section in k
- does not handle energy-momentum conservation
- neglects other production channels

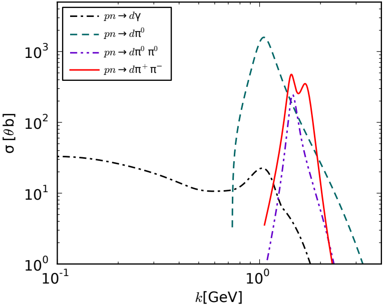
- next try, include all $2 \to n$ production, differential in k (Dal-Raklev model)

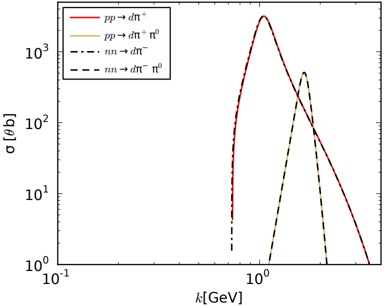
- $pn \to \gamma D$
- $pn \to \pi^0 D$
- $pn \to \pi^- \pi^+ D$
- $pn \to \pi^0 \pi^0 D$
- $pp \to \pi^+ D$
- $nn \to \pi^- D$
- $pp \to \pi^+ \pi^0 D$
- $nn \to \pi^- \pi^0 D$

Cross Sections from Data



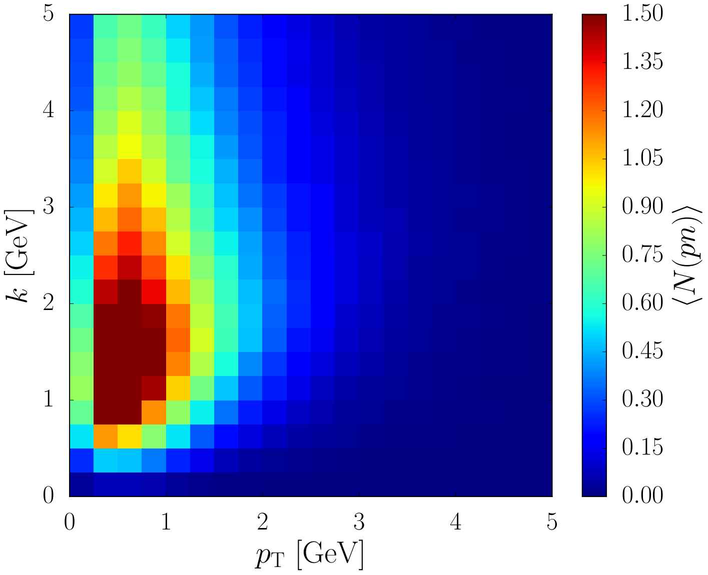
Cross Section Fits



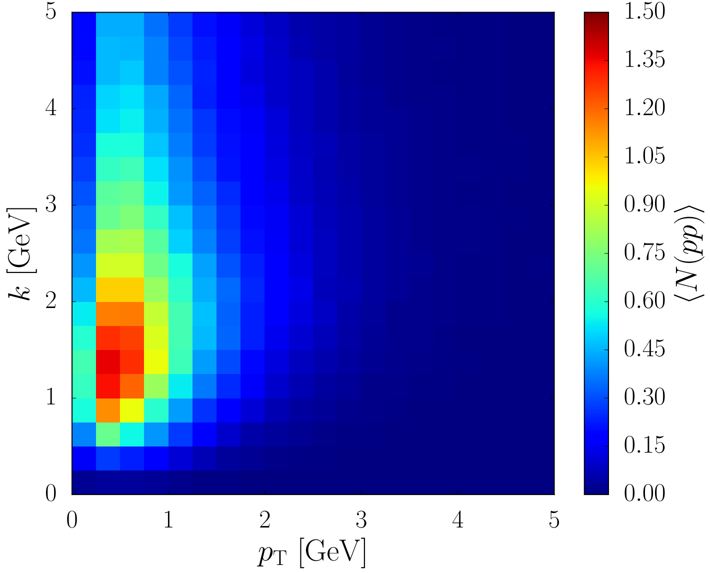


- all the cross sections are parameterized with relatively simple functions

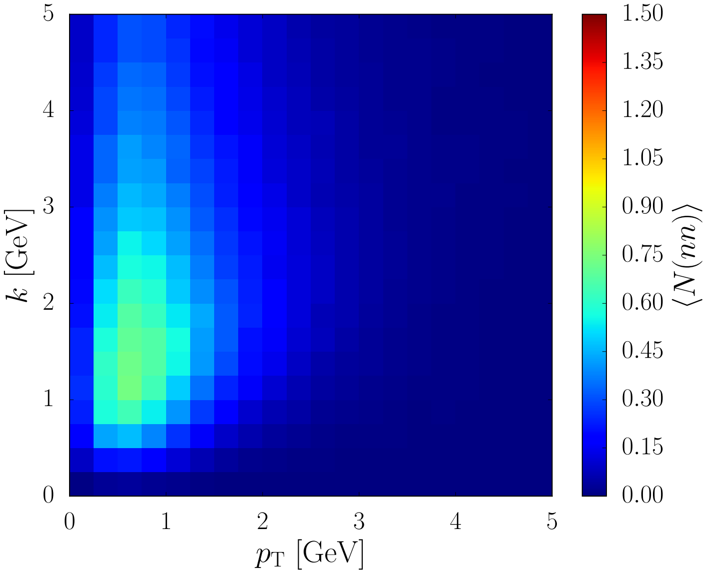
Possible Combinations



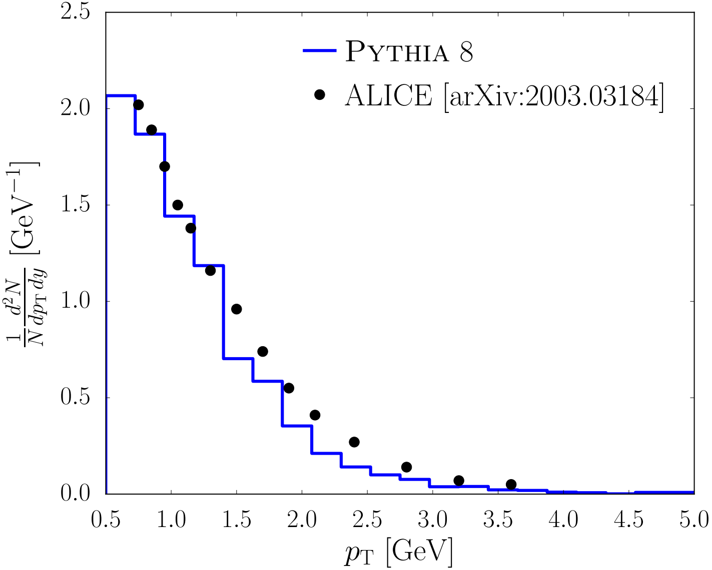
Possible Combinations



Possible Combinations



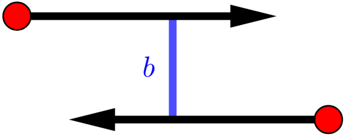
Does it Work?

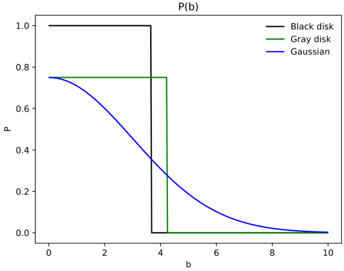


Pythia 8
ALICE [arXiv:2003.03184]
$\frac{1}{N}\frac{d^2N}{dp_T\,dy}$ [GeV^{-1}]
p_T [GeV]
0.0
0.5
1.0
1.5
2.0
2.5
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

Spacetime Picture

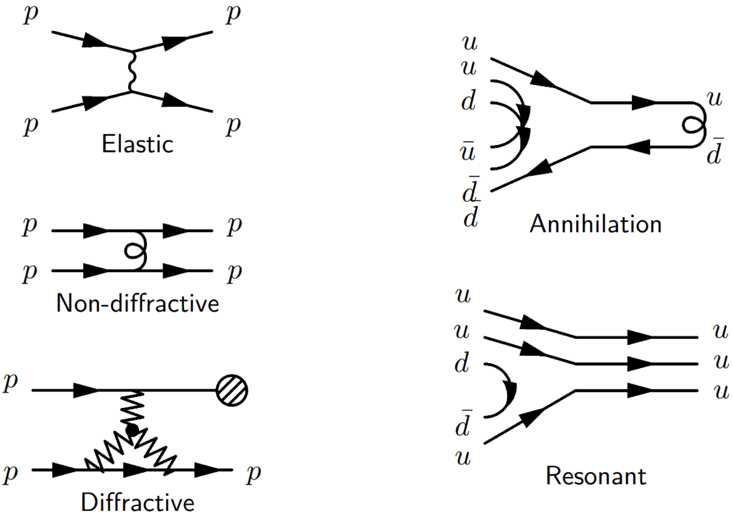
- coalescence model only in momentum space
- if we have full spacetime picture of event, then can consider this instead
- hadronic rescattering occurs when to hadrons pass closely in spacetime





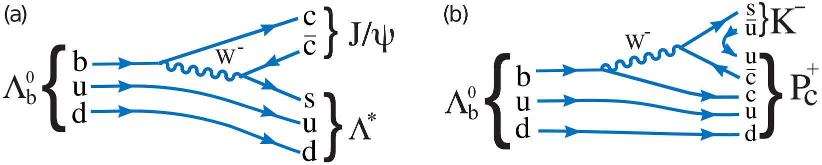
Hadronic Rescattering

- just like soft partonic QCD, we have similar interactions



Exotic Hadrons

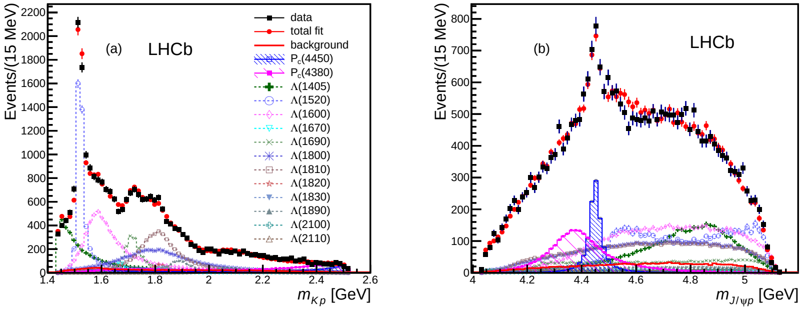
- LHCb set out to measure $\Lambda_b^0 \to J/\psi[\to \mu\mu]\Lambda^*[K^- p^+]$
- saw some unexpected structure



- nature of decay indicates five-quark states
- $P_c(4312)^+, P_c(4440)^+, P_c(4457)^+$

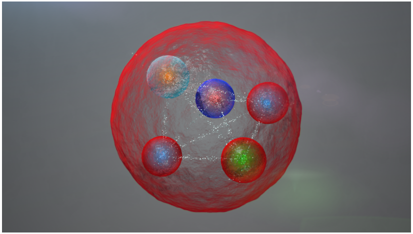
Show Me the Data!

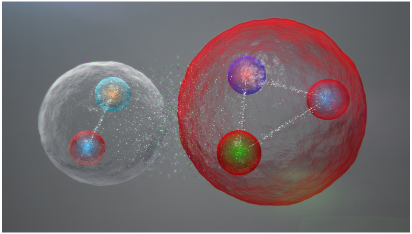
- can look at different final state combinations $J/\psi K^- p^+$
- expect Λ^* resonance in $K^- p^+$
- do not expect resonance in $J/\psi p^+$



Exotic Models

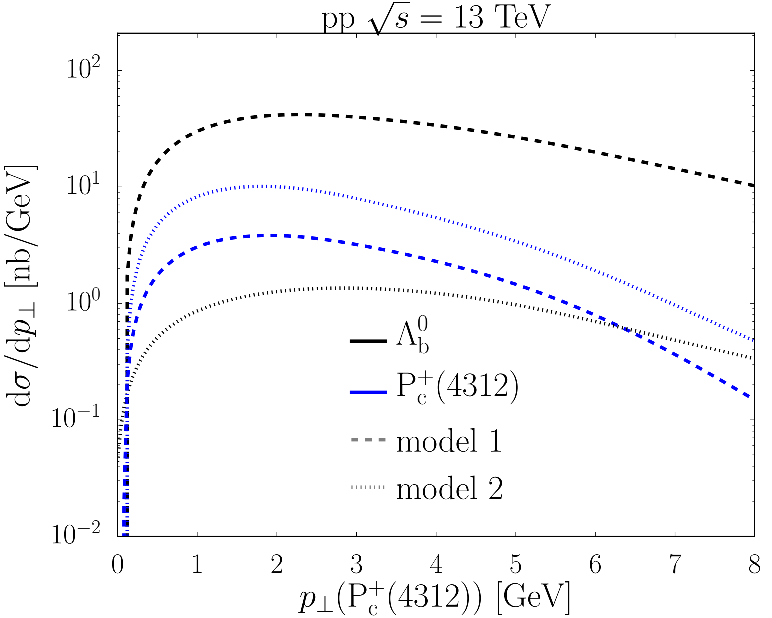
- how do we model the pentaquarks?





- can consider either tightly bound, or more like molecular state
- possible $\Sigma_c^* \bar{D}^0$ or $\Sigma_c^* \bar{D}^{*0}$ molecular states
- can pentaquarks form outside of decays?
- try hadronic rescattering!

A Prediction



Summary

- multi-parton interactions can be added via veto algorithm with parton shower
- string model gives a relatively good description of hadronization
- naive decays just require phase space
- including spin correlations and proper structure much more complicated
- once we have a full event, we can make a number of interesting predictions

1. connect perturbative and non-perturbative regimes
2. provide complete events with final state particles
3. robustly perform high-dimension integrals