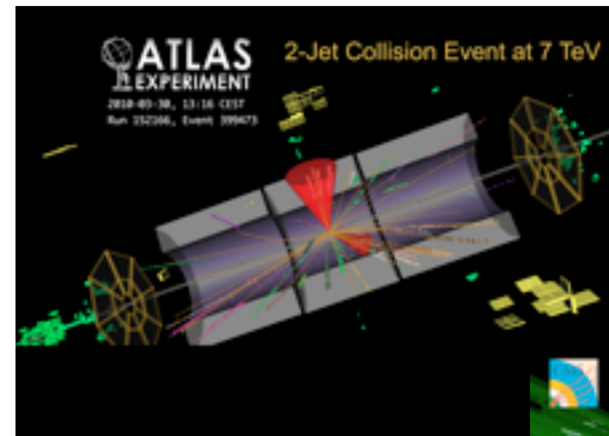
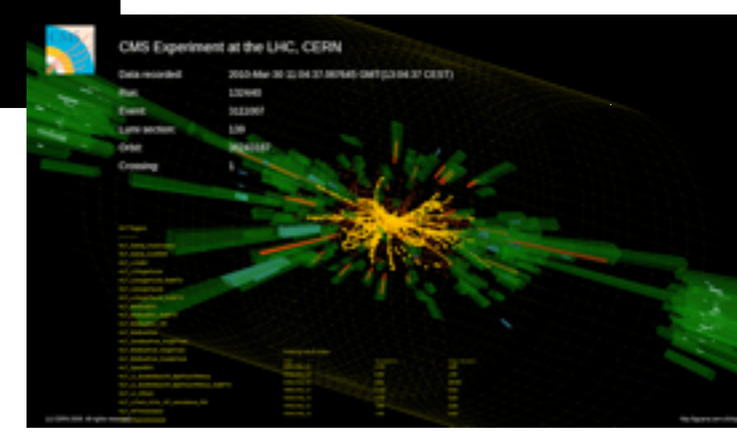
From Partons to Pions

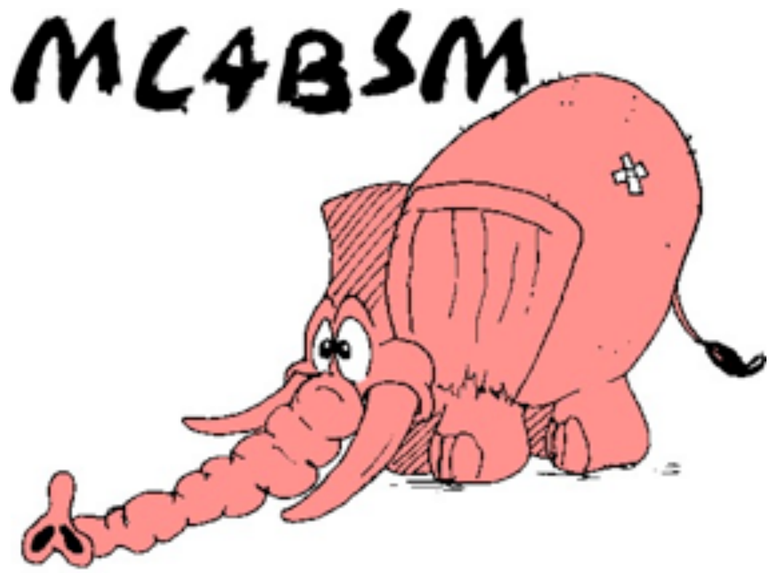
P. Z. Skands (CERN-TH)

New Physics Pipeline

Comparisons to Collider observables



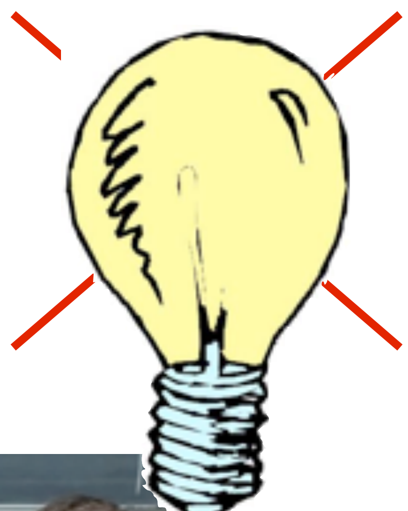




L=...

New Physics Pipeline

Comparisons to Collider observables



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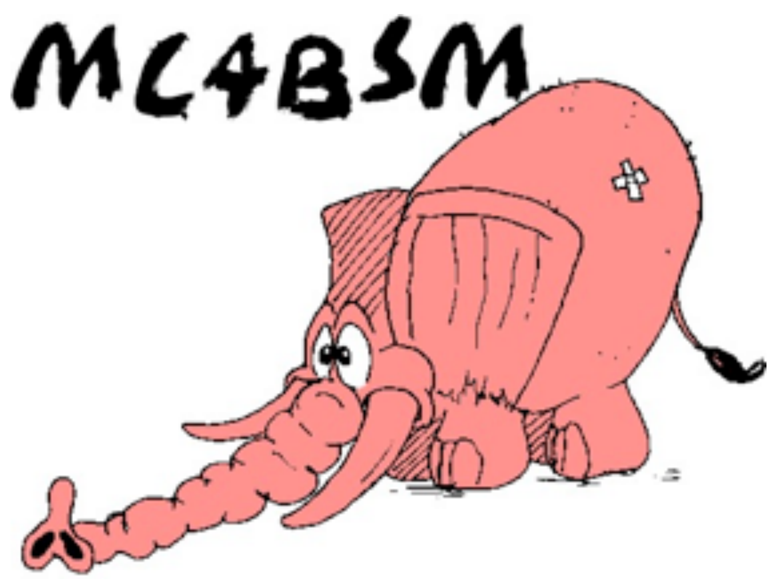
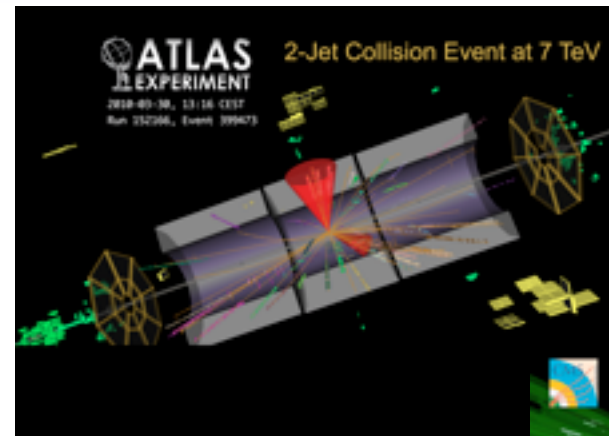
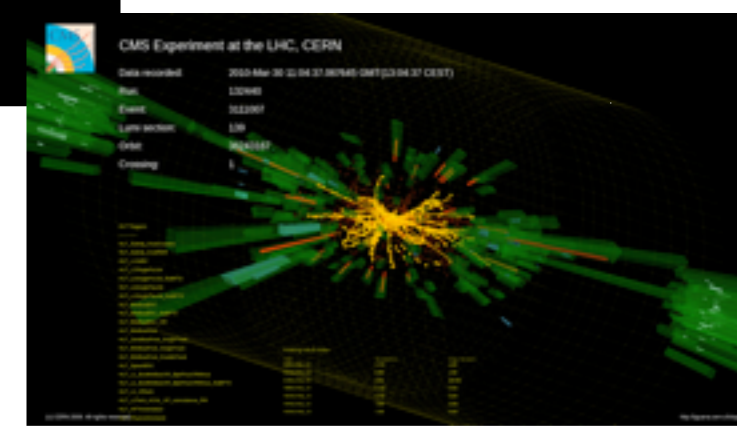


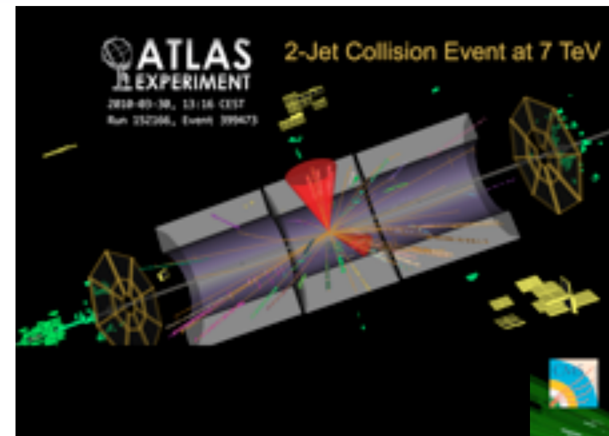


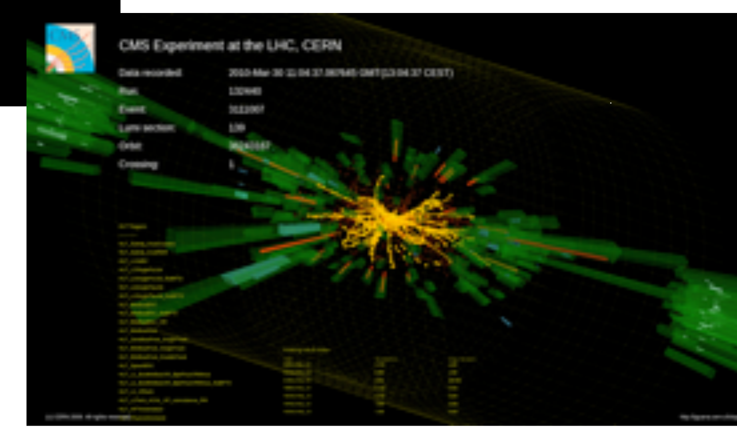


A) Model is wrong

New Physics Pipeline

Comparisons to Collider observables





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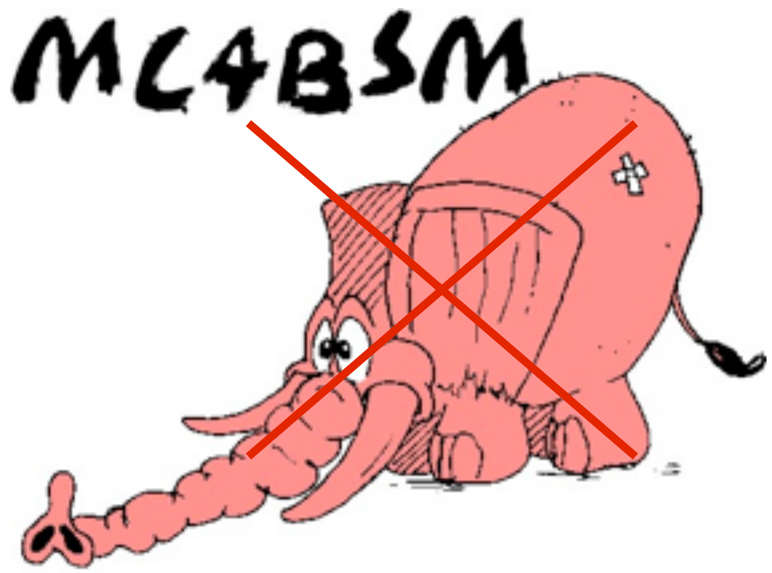


B) Monte Carlo is wrong

From Partons …

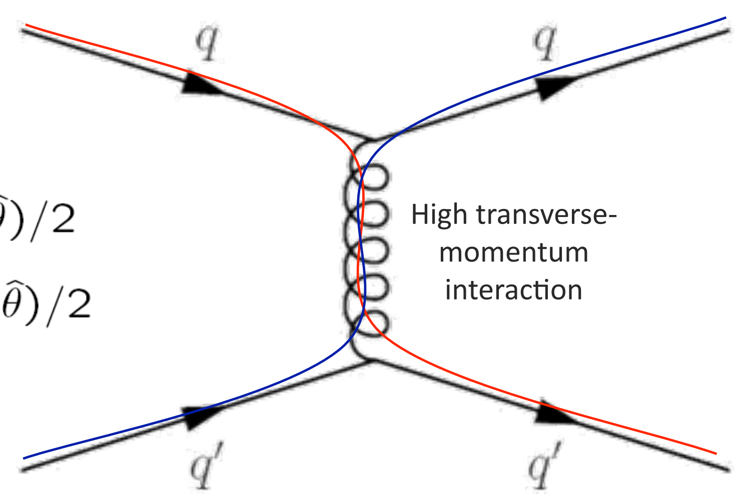
Main Tool

Lowest-Order Matrix Elements calculated in a fixed-order perturbative expansion → parton-parton scattering cross sections

L=…

$$\mathrm{qq'} \to \mathrm{qq'} \quad : \quad \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}} = \frac{\pi}{\hat{s}^2}\frac{4}{9}\alpha_{\mathrm{s}}^2\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$$

$$\hat{s} = (p_1 + p_2)^2$$
$$\hat{t} = (p_1 - p_3)^2 = -\hat{s}(1-\cos\hat{\theta})/2$$
$$\hat{u} = (p_1 - p_4)^2 = -\hat{s}(1+\cos\hat{\theta})/2$$



L → LanHEP/FeynRules → MadGraph/CompHEP/CalcHEP/… → partons

… to Pions


q
q
High transverse-
momentum
interaction
q'
q'
Reality is more complicated

Complications

LO = ***Leading Order*** and ***Totally Inclusive***

Radiative corrections

- **Additional jets** change signal topology
- **K factors** change cross sections (total *and* differential)

Complications

LO = ***Perturbative*** and ***Factorized***

Hadronization, Underlying Event,
Beam Remnants, Hadron Decays, ...

- **No major changes** to event rates or topologies
- Aparatus > 1fm away from interaction point
- Important for **calibration** and **precision**
- **Observables** should be **physical and IR safe**

The Way of the Chicken

- Who needs QCD? I'll use leptons
  - Sum inclusively over all QCD
    - Leptons almost IR safe by definition
    - WIMP-type DM, Z', EWSB → may get some leptons

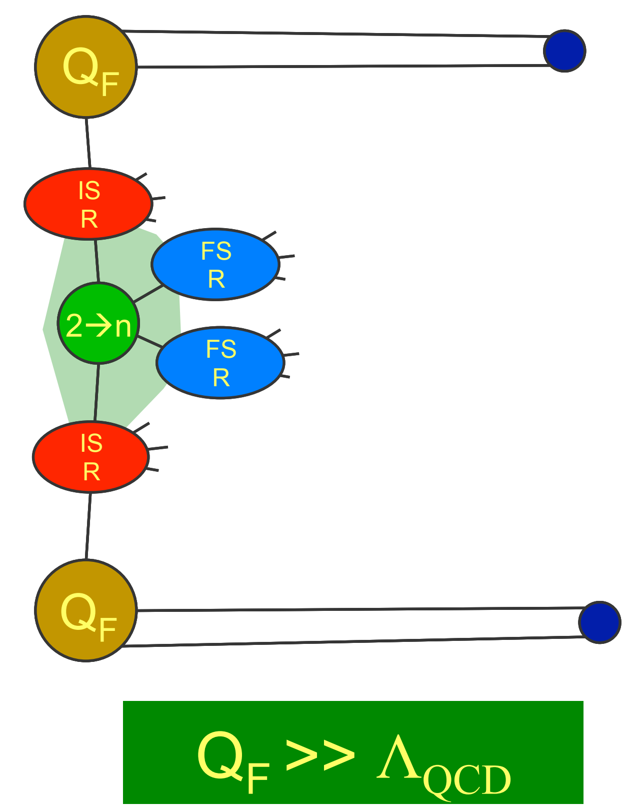
Additional Sources of Particle Production

▶ Starting point: Matrix Elements

n = a handful
+ resonance decays

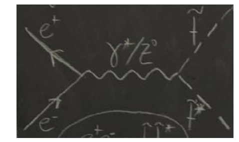
2→n hard parton scattering at (N)LO

+ Bremsstrahlung ➔ 2→∞ at (N)LL



Bremsstrahlung

"DLA" $\frac{\alpha\, s_{ab}}{s_{ai} s_{ib}}$

$$d\sigma_X = \ldots$$ 

$$d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}}$$

$$d\sigma_{X+2} \sim 2g^2 d\sigma_{X+1} \frac{ds_{a2}}{s_{a2}} \frac{ds_{2b}}{s_{2b}}$$

$$d\sigma_{X+3} \sim 2g^2 d\sigma_{X+2} \frac{ds_{a3}}{s_{a3}} \frac{ds_{3b}}{s_{3b}}$$

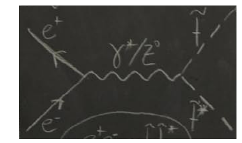
Interpretation: the structure evolves

But something's not right…

This is an approximation to inifinite-order tree-level cross sections

Bremsstrahlung

"DLA" $\frac{\alpha\, s_{ab}}{s_{ai}s_{ib}}$

$d\sigma_X = \ldots$ 

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KLN

Interpretation: the structure evolves

$\sigma_{X+1}(Q) = \sigma_{X;\mathrm{incl}} - \sigma_{X;\mathrm{excl}}(Q)$

This includes both real and virtual corrections

+ UNITARITY:

Virt = – Int(Tree) + F

(or: given a jet definition, an event has *either* 0, 1, 2, or *n* jets)

$$\begin{aligned}\sigma_{X;\mathrm{excl}} &= \sigma_X - \sigma_{X+1} \\ &= \sigma_X - \sigma_{X+1;\mathrm{excl}} - \sigma_{X+2;\mathrm{excl}} - \ldots\end{aligned}$$

Matching

- ► A (Complete Idiot's) Solution – Combine
  1. $[X]_{ME}$ + showering
  2. $[X + 1\ jet]_{ME}$ + showering
  3. …

Run generator for X (+ shower)

Run generator for X+1 (+ shower)

Run generator for … (+ shower)

Combine everything into one sample

The Matching Game

- Shower off X already contains LL part of all X+n

$$d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}}$$

- Adding back full ME for X+n would be overkill

Solution 1: "Additive" (most widespread)

Seymour, CPC90(1995)95
+ many more recent …

Add event samples, with modified weights

$w_X = |M_X|^2$ + *Shower*

$w_{X+1} = |M_{X+1}|^2 - Shower\{w_X\}$ + *Shower*

$w_{X+n} = |M_{X+n}|^2 - Shower\{w_X, w_{X+1}, \ldots, w_{X+n-1}\}$ + *Shower*

HERWIG: for X+1 @ LO (Shower = 0 in dead zone of angular-ordered shower)

MC@NLO: for X+1 @ LO and X @ NLO (note: correction can be negative)

CKKW (SHERPA & others), MLM (ALPGEN & others): for all X+n @ LO
(force Shower = 0 above "matching scale" and only match to matrix elements in that region)

The Matching Game

- Shower off X already contains LL part of all $X+n$

$$d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}}$$

- Adding back full ME for $X+n$ would be overkill

Solution 2: "Multiplicative"

One event sample

$w_X = |M_X|^2$ + *Shower*

Make a "course correction" to the shower at each order

$R_{X+1} = |M_{X+1}|^2 / Shower\{w_X\}$ + *Shower*

$R_{X+n} = |M_{X+n}|^2 / Shower\{w_{X+n-1}\}$ + *Shower*

PYTHIA: for X+1 @ LO (for color-singlet production and ~ all SM and BSM decay processes)

POWHEG: for X+1 @ LO and X @ NLO (note: positive weights)

VINCIA: for all X+n @ LO and X @ NLO (only worked out for decay processes so far)

Remaining Uncertainties

- In a (matched) shower calculation, there are many dependencies on things not traditionally found in matrix-element calculations:

- The final answer will depend on:
    - The choice of shower evolution "time"
    - The splitting functions (finite terms not fixed)
    - The phase space map ("recoils", $d\Phi_{n+1}/d\Phi_n$)
    - The renormalization scheme (vertex-by-vertex argument of α_s)
    - The infrared cutoff contour (hadronization cutoff)
    - + Matching prescription and "matching scales"

Variations →	Matching to MEs (& N^nLL?) →
Comprehensive uncertainty estimates	Reduced Dependence
(showers with uncertainty bands)	(systematic reduction of uncertainty)

Additional Sources of Particle Production

▶ Starting point: Matrix Elements + Parton Showers

n = a handful + resonance decays

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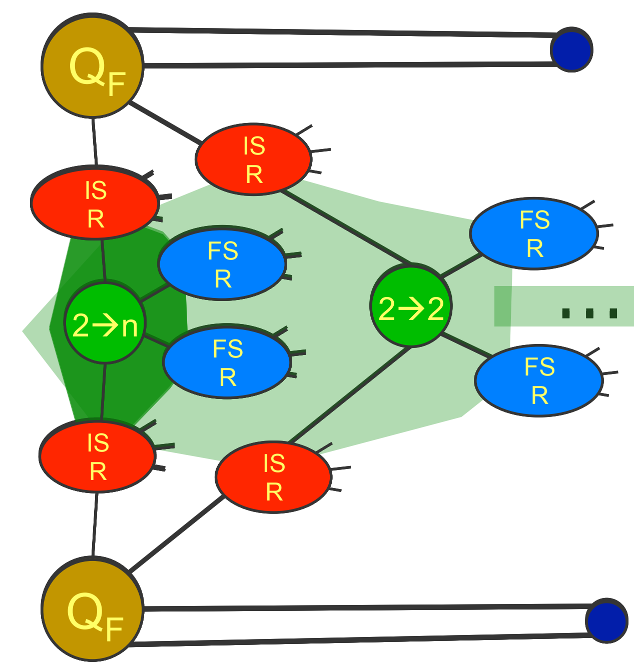


$Q_F >> \Lambda_{QCD}$

Hadrons are not elementary
+ QCD diverges at low p_T

→ multiple perturbative parton-parton interactions

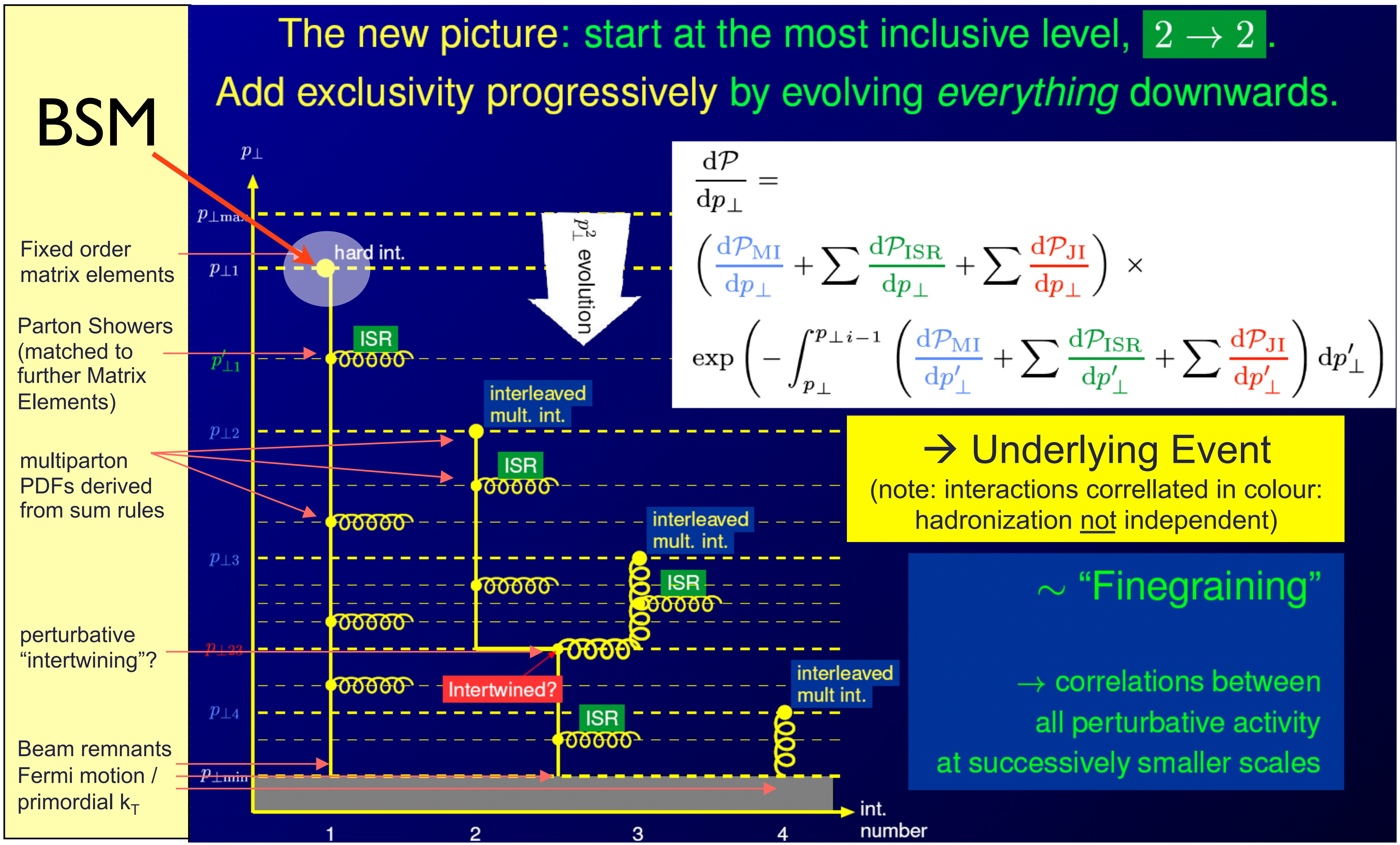
e.g. 4→4, 3→ 3, 3→2

Underlying Event has perturbative part!

▶ No factorization theorem

➔Herwig++, Pythia, Sherpa: MPI models

Underlying Event: The Interleaved Idea



Sjöstrand & PS : JHEP03(2004)053, EPJC39(2005)129

Additional Sources of Particle Production

$Q_F >> \Lambda_{QCD}$

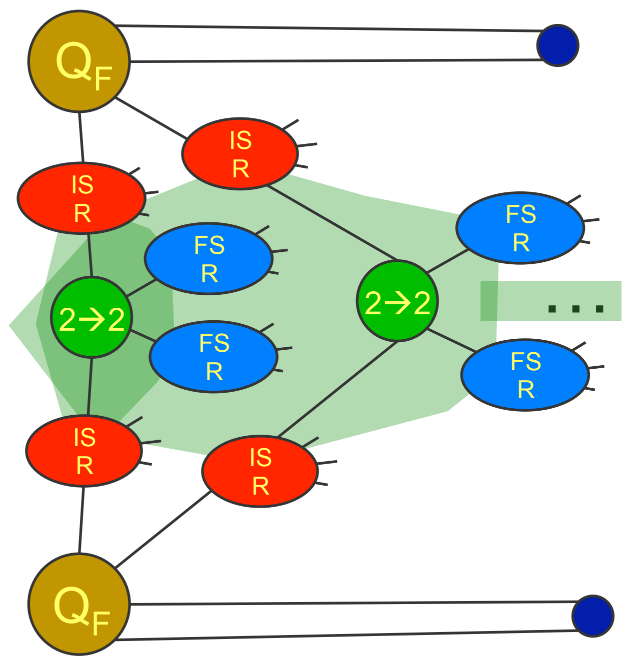
ME+ISR/FSR

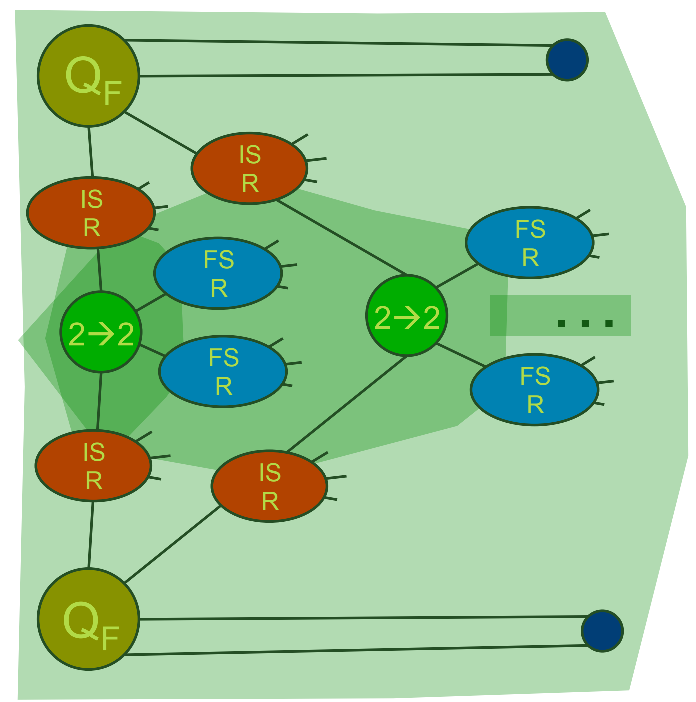
+ perturbative MPI

+

Stuff at

$Q_F \sim \Lambda_{QCD}$





Need-to-know issues for IR sensitive quantities (e.g., N_{ch})

Now Hadronize This

Simulation from
D. B. Leinweber, hep-lat/0004025
gluon action density: 2.4 x 2.4 x 3.6 fm

Hadronization

The problem:

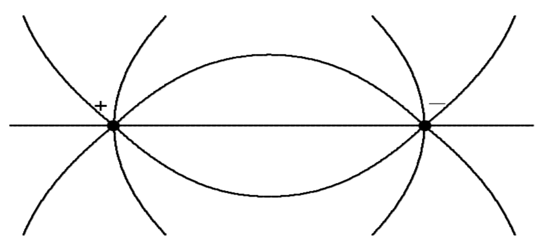
- Given a set of partons resolved at a scale of ~ 1 GeV (the shower + MPI cutoff), need a **"mapping"** from this set onto a set of on-shell colour-singlet hadronic states.
- I.e., a fully exclusive fragmentation function defined at Q_{Had} ~ 1 GeV

MC models do this in three steps

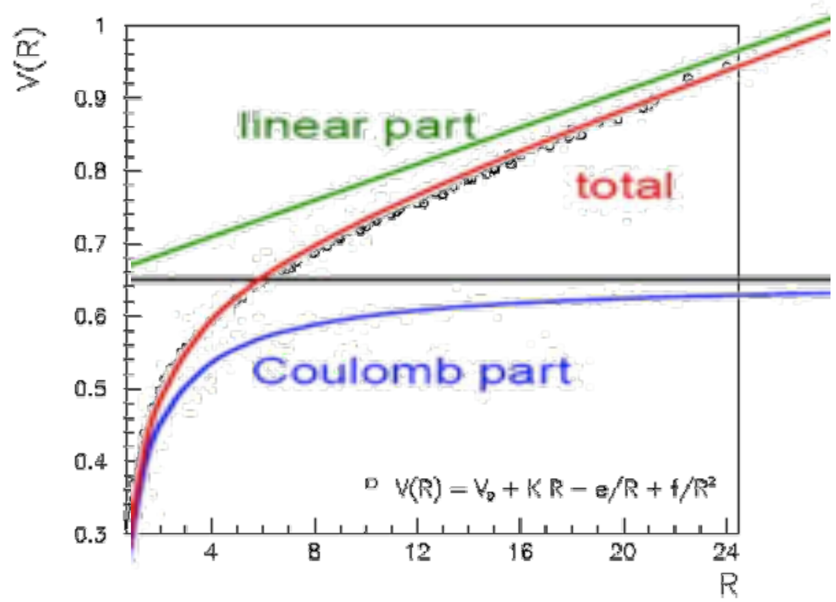
1. Map partons onto **continuum of highly excited hadronic states** *(called 'strings' or 'clusters')*
2. Iteratively map strings/clusters onto **discrete set of primary hadrons** *(string breaks / cluster splittings / cluster decays)*
3. Sequential decays into **secondary hadrons** (e.g., rho > pi pi, Lambda > n pi0, pi0 > gamma gamma, ...)

From Partons to Strings

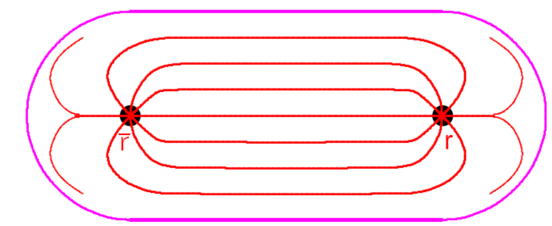
Short Distances ~ pQCD



Partons



Long Distances ~ Linear Confinement



Strings (Flux Tubes), Hadrons

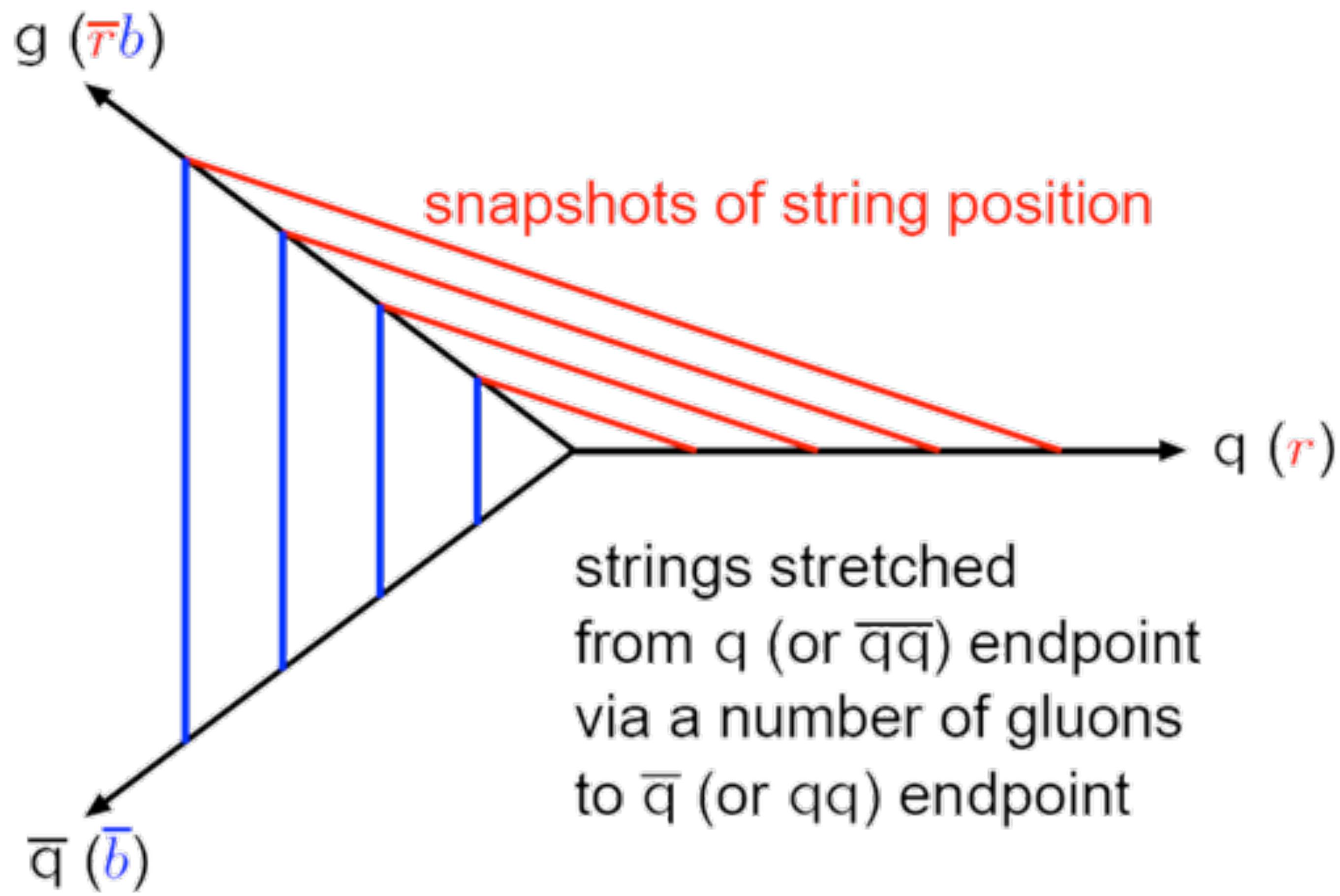
$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$

- **Motivates a model:**
  - Separation of transverse and longitudinal degrees of freedom
  - Simple description as 1+1 dimensional worldsheet – string – with Lorentz invariant formalism

The (Lund) String Model

Map:

- **Quarks** > String Endpoints
- **Gluons** > Transverse Excitations (kinks)
- Physics then in terms of string worldsheet evolving in spacetime
- Probability of string break constant per unit area > **AREA LAW**



Gluon = kink on string, carrying energy and momentum

Simple space-time picture
Details of string breaks more complicated …

Outlook

Collider Physics is witnessing rapid evolution: NLO, ME matching, tuning, showers, PDFs, interfaces …

- **Driven by demand** of high precision in complex LHC environment with huge phase space
- **Currently heavily based** on semi-classical approximations (Leading Order, Leading Log, Leading Color, …)
  - Sufficient to reach **O(10%)** precision (with hard work)

Race to Develop a Phenomenology Of Every Thing *(POET)*

- Matching to LO, NLO, NLL, … and (reliable) evaluations of remaining **perturbative uncertainties**
- Could then extract very **high precision** from inclusive measurements with confidence (high-precision frontier)

Then focus on the really hard stuff …

- For which fundamentally new ideas may be needed

A Quantum Paradigm

Whatever you do ...
Define it in terms of
Physical Observables

THEN
Extract fundamental
quantities from those
observables