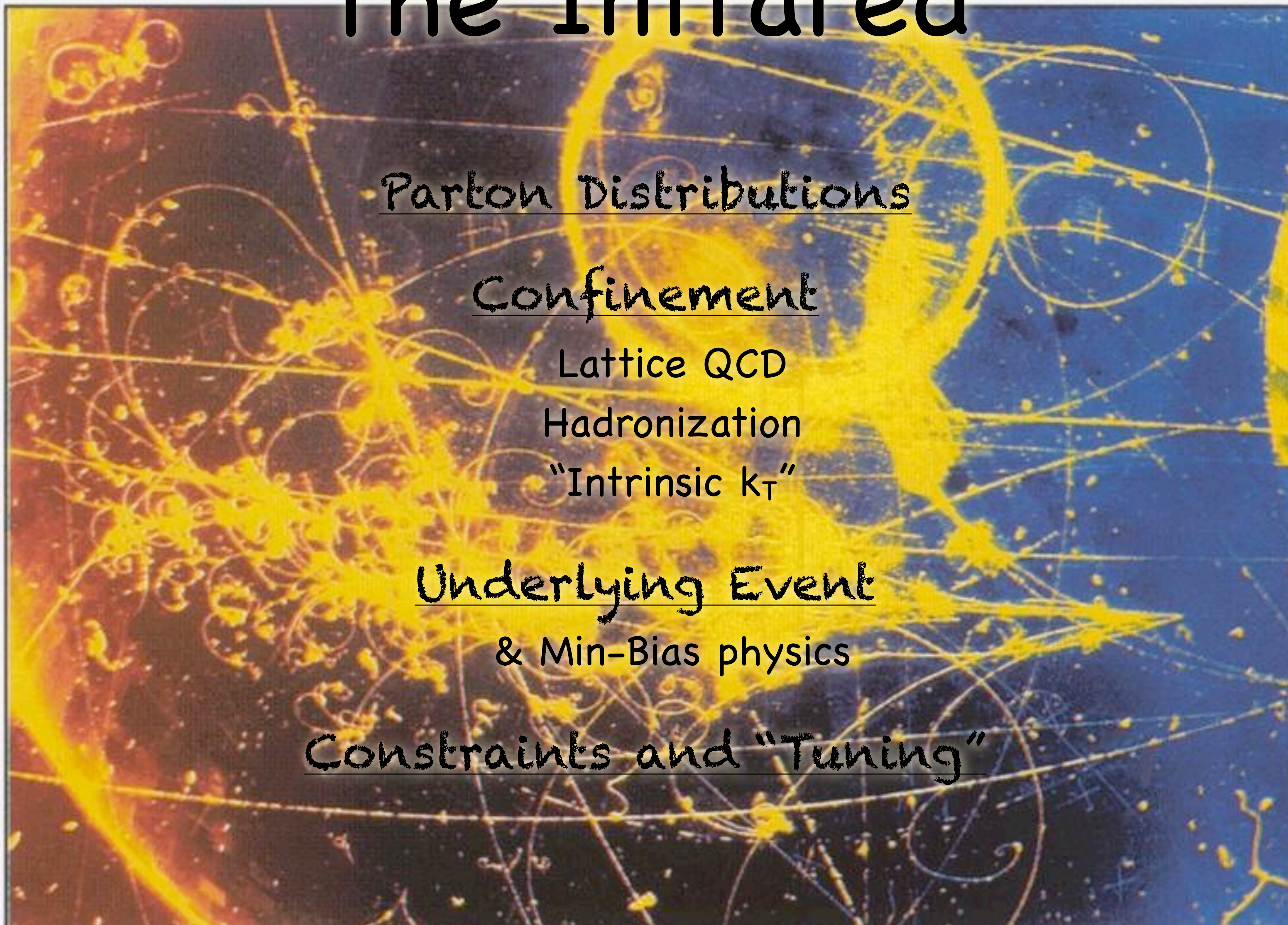
The Infrared



Parton Distributions

Confinement

Lattice QCD

Hadronization

"Intrinsic k_T"

Underlying Event

& Min-Bias physics

Constraints and "Tuning"

P. Skands - QCD Lecture 3

Parton Densities

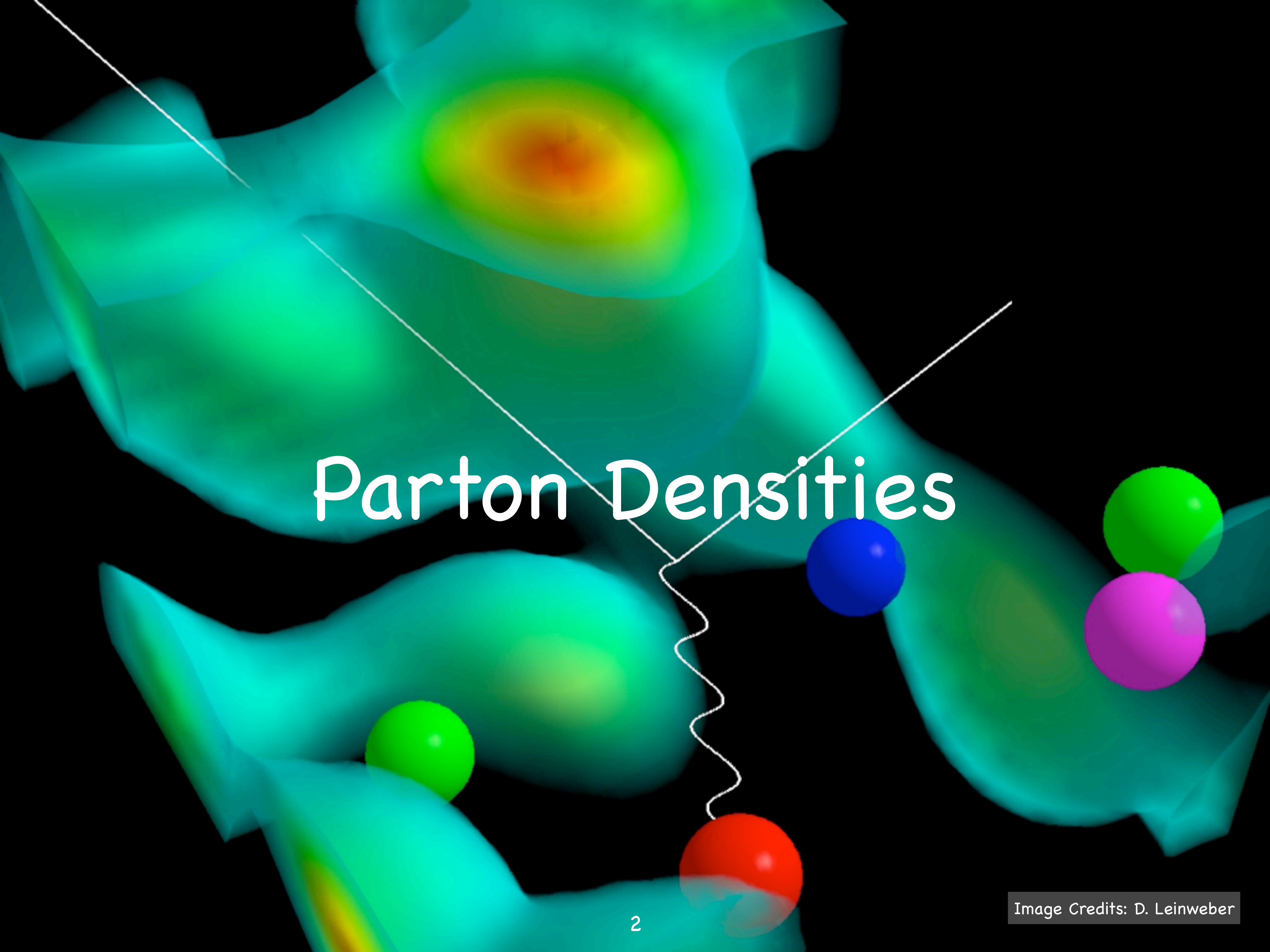
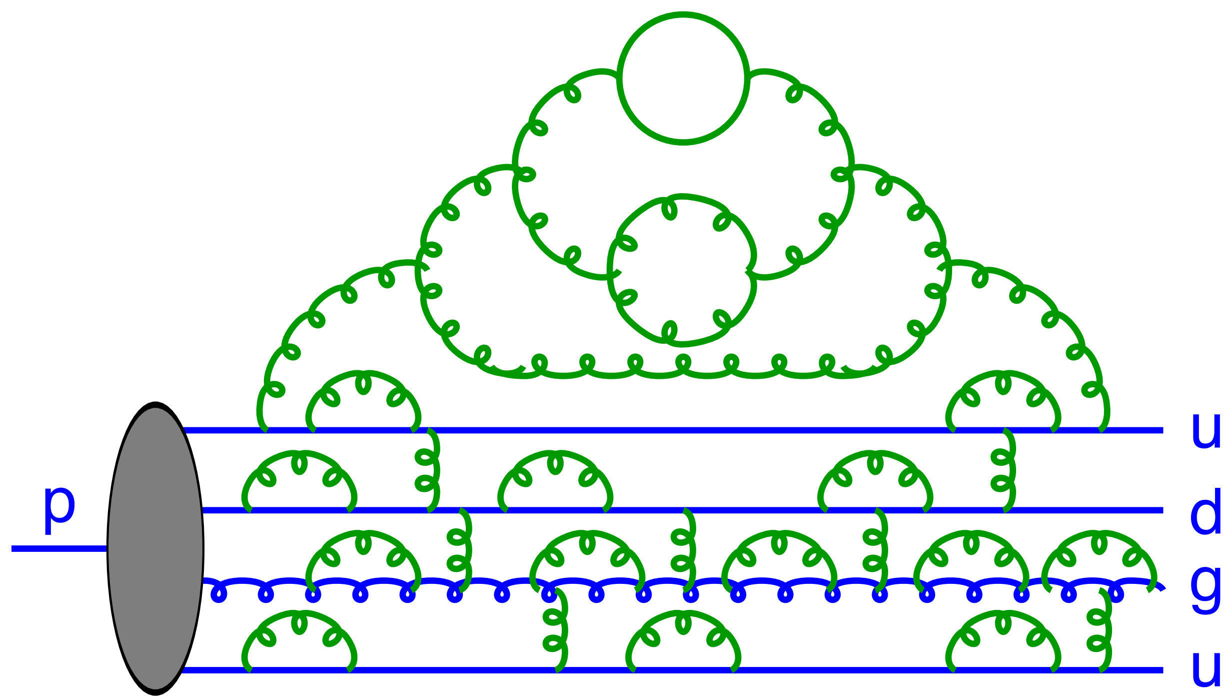


Image Credits: D. Leinweber

Parton Densities

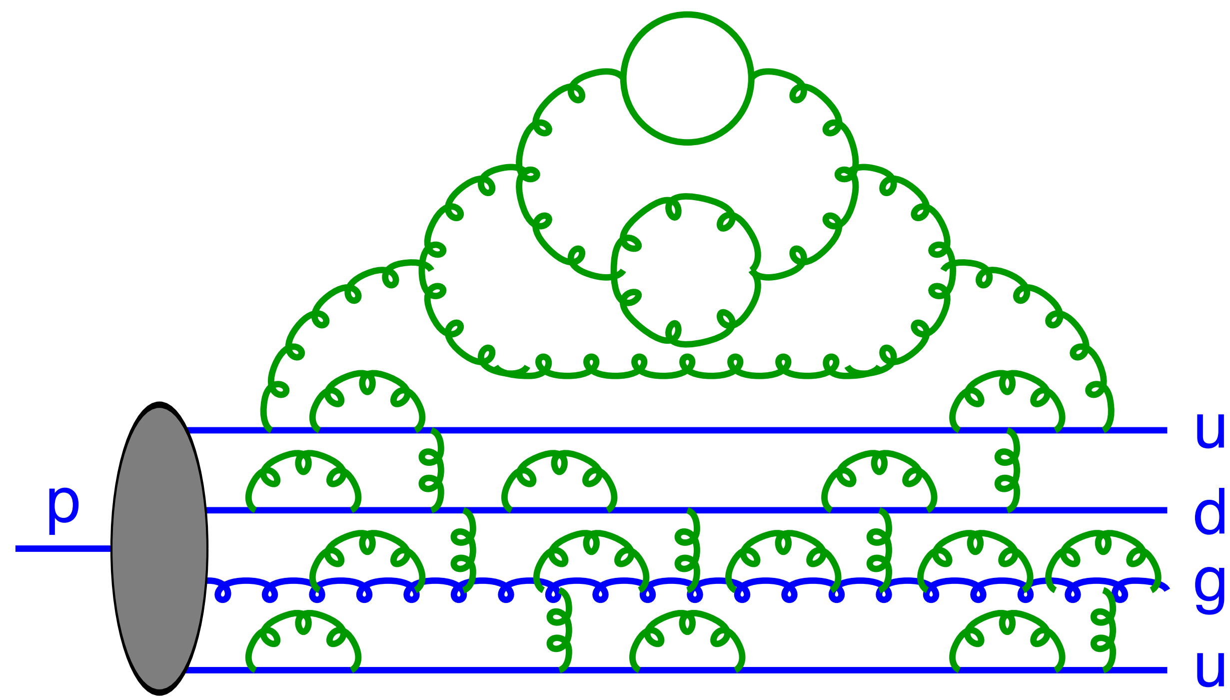
Hadrons are composite, with time-dependent structure:



Slide from T. Sjöstrand

Parton Densities

Hadrons are composite, with time-dependent structure:



$f_i(x, Q^2)$ = number density of partons i
at momentum fraction x and probing scale Q^2.

Linguistics (example):

$$F_2(x, Q^2) = \sum_i e_i^2 \, x f_i(x, Q^2)$$

structure function parton distributions

Slide from T. Sjöstrand

Parton Densities

$\vec{p}_j = x \vec{P}_{proton}$

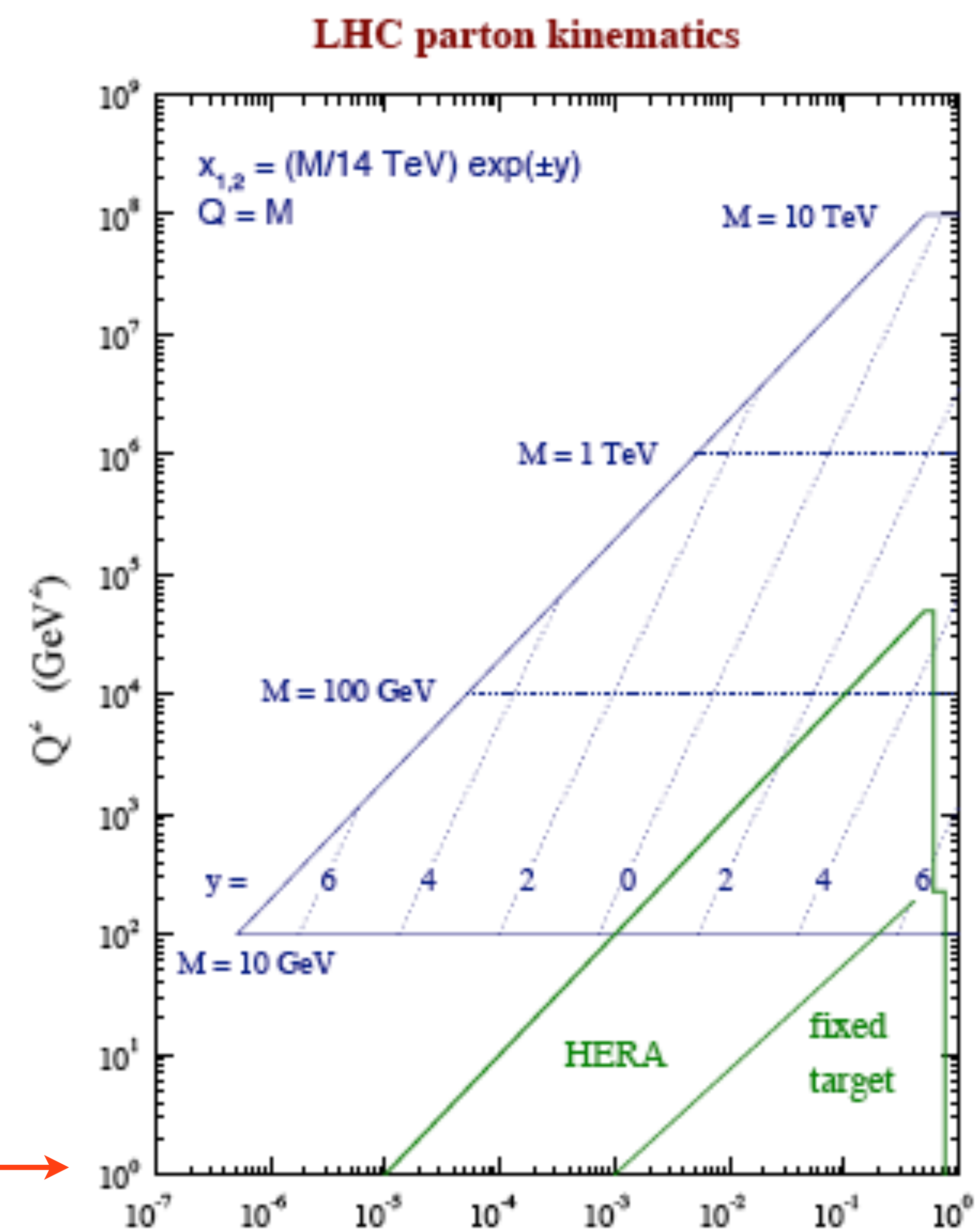
$f_a(x_a, Q_i^2)$ Parton distribution functions (PDF)

- sum over long-wavelength histories leading to a with x_a at the scale Q_i^2 (ISR)

Absolute normalization unknown (non-pert)
→ fit to measurements at small $Q^2 \approx m_{proton}$

m_{proton} →

LHC kinematics

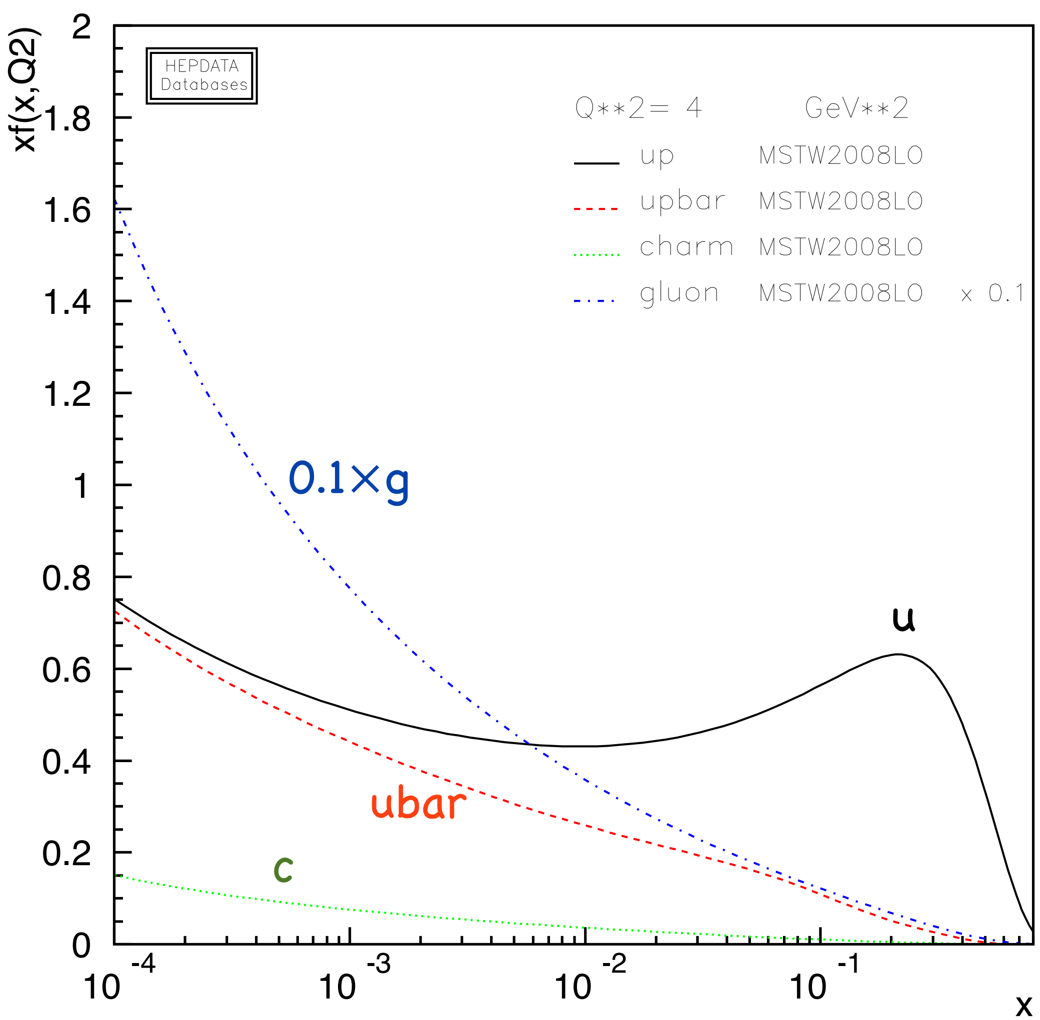


Evolution in Q^2 by DGLAP

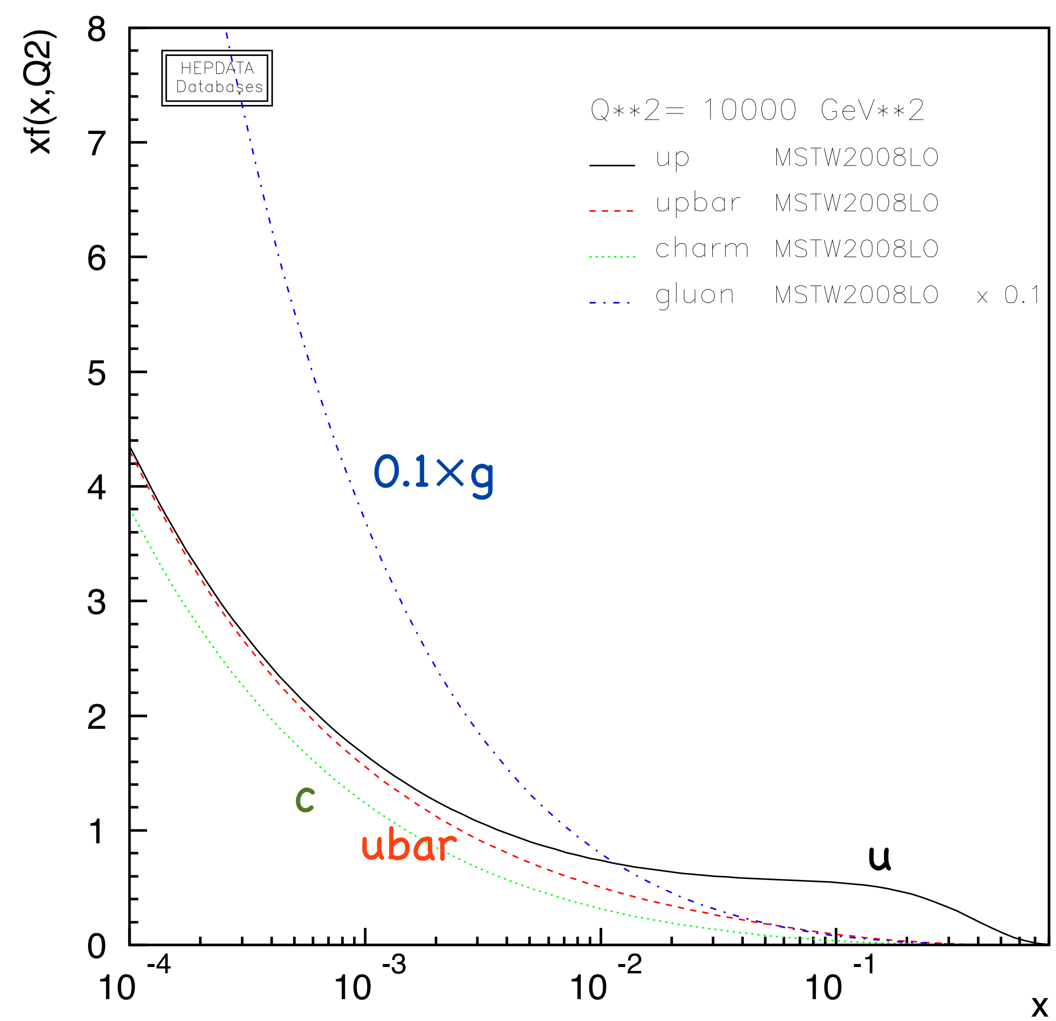
(Dokshitzer-Gribov-Lipatov-Altarelli-Parisi)

$$\frac{\mathrm{d} f_b(x,Q^2)}{\mathrm{d}(\ln Q^2)} = \sum_a \int_x^1 \frac{\mathrm{d}z}{z} f_a(x',Q^2) \frac{\alpha_S}{2\pi} P_{a\to bc}\left(z = \frac{x}{x'}\right)$$

$Q^2 = (2\ \mathrm{GeV})^2$

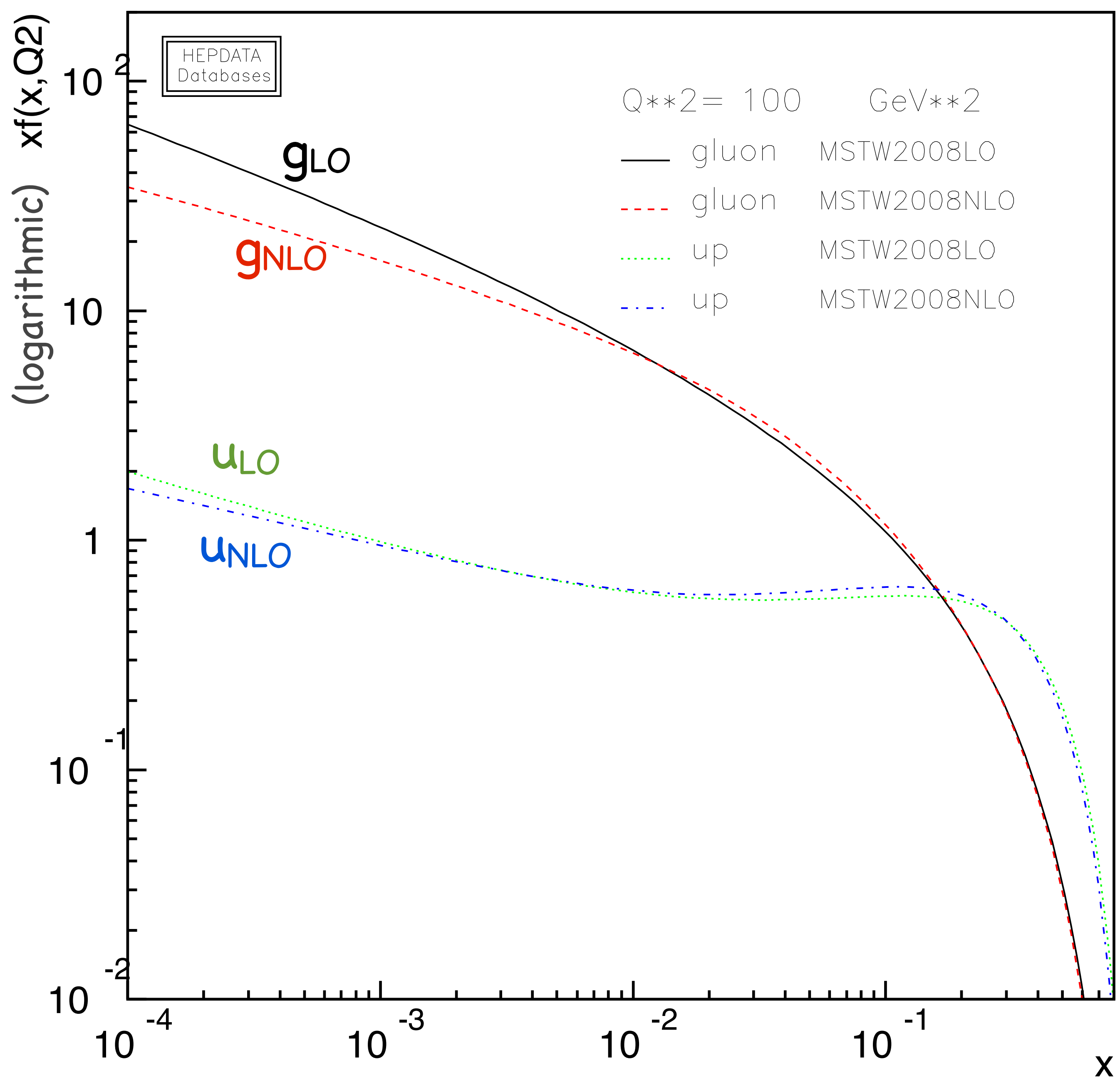


$Q^2 = (100\ \mathrm{GeV})^2$



LO vs NLO

$Q^2 = (10\ \text{GeV})^2$



NLO matrix elements contain low-x singularities beyond DGLAP (→ enhancement)

→ need less low-x PDFs

(+ momentum conservation
→ more partons at high x
→ larger cross sections)

Important to use the right PDFs with the right Matrix Elements

PDF Uncertainties

Much debate recently on PDF errors

Attempt to propagate experimental errors properly → 68% CL

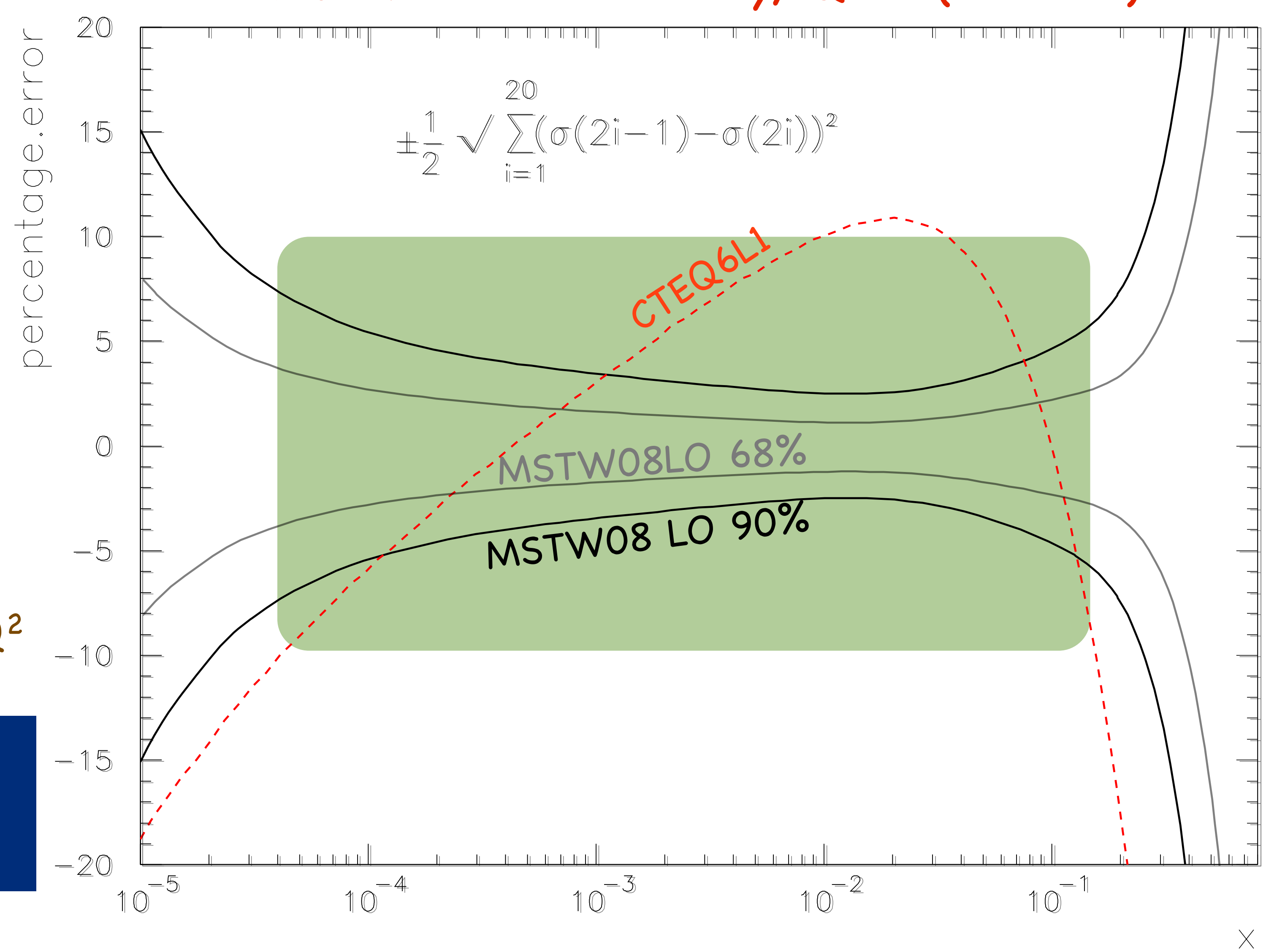
But "tensions" between different badly compatible data sets → ... ?

→ 90%, something else?

+ unknown uncertainty from starting parametrization at low Q^2

Still, good to ≈ 10% even for LO gluon in $10^{-4} < x < 10^{-1}$
(bigger errors at lower Q^2)

Gluon PDF uncertainty, $Q^2 = (10\ \mathrm{GeV})^2$



Neural Nets, LO*, MC PDFs, …

Neural Net PDFs

Attempt to use an unbiased starting parametrization represented by a neural net fitting function

LO*, LO**, MC PDFs, … : "Optimize"

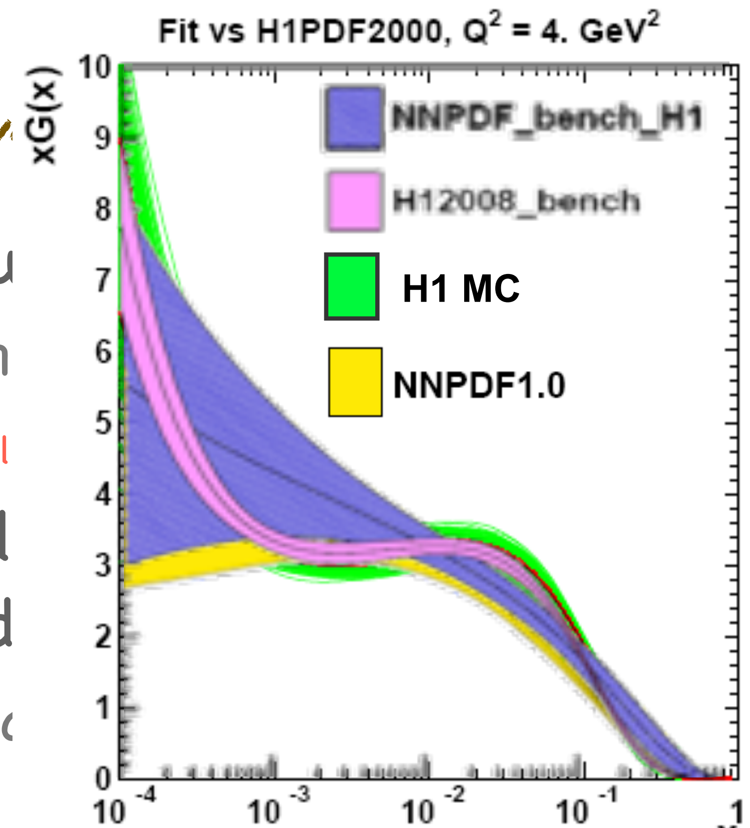
→ LO* allows ≈ 10% violation of momentu

→ Accommodate more low-x glue while main

→ Cross sections "closer" to NLO [but still

→ MC PDFs, like LO**, attempt to parallel actual evolution equations as implemented

E.g., using the α_s choices, physical phase spa



PDFs is a rapidly evolving field → important to keep up to date

→ Reliability of your results and uncertainties

(more in MC lecture …)

Confinement

Local Parton-Hadron Duality

Hadronization / Fragmentation

"Intrinsic $k_\perp$"

Image Credits: Yeimaya [flickr]

QCD in the Infrared

What we know

Asymptotic Freedom ✓

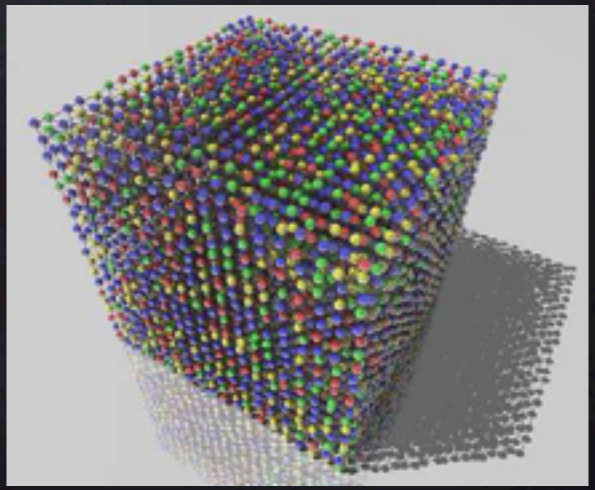
Gauge invariance ✓

C, P, T invariance ✓

Lorentz invariance ✓

Causality ✓

Lattice QCD ...



Lattice QCD

Spacetime

Approximated by

4D (Euclidean) box of points

- Similar to crystal lattice (with imaginary time) 3fm/c ≈ 10 yoctoseconds

Symmetries

- Full Lorentz → Hypercubic
- But gauge invariance ok ✓

"Discretization Errors" → 0

- in limit of infinitely small lattice spacing, a

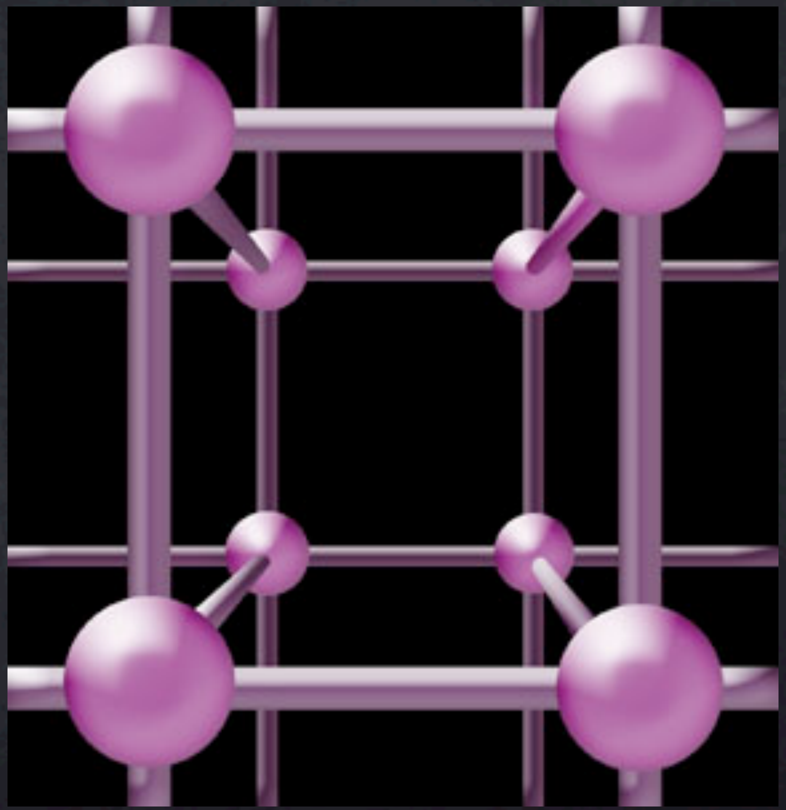


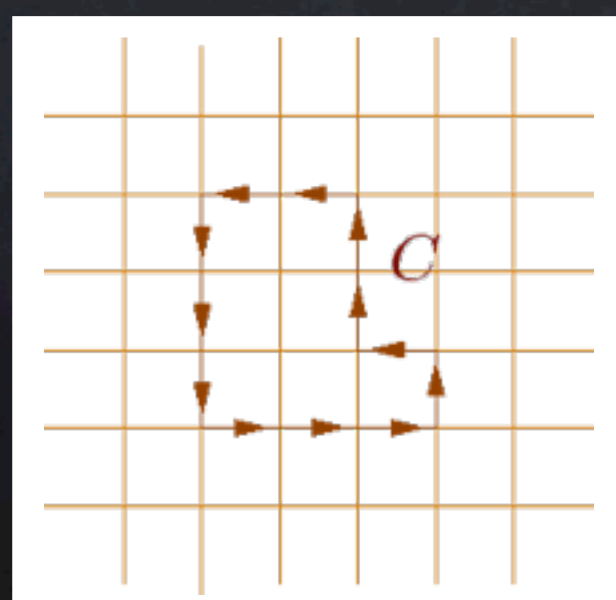
Image Credits: I. McVicar, CERN Courier

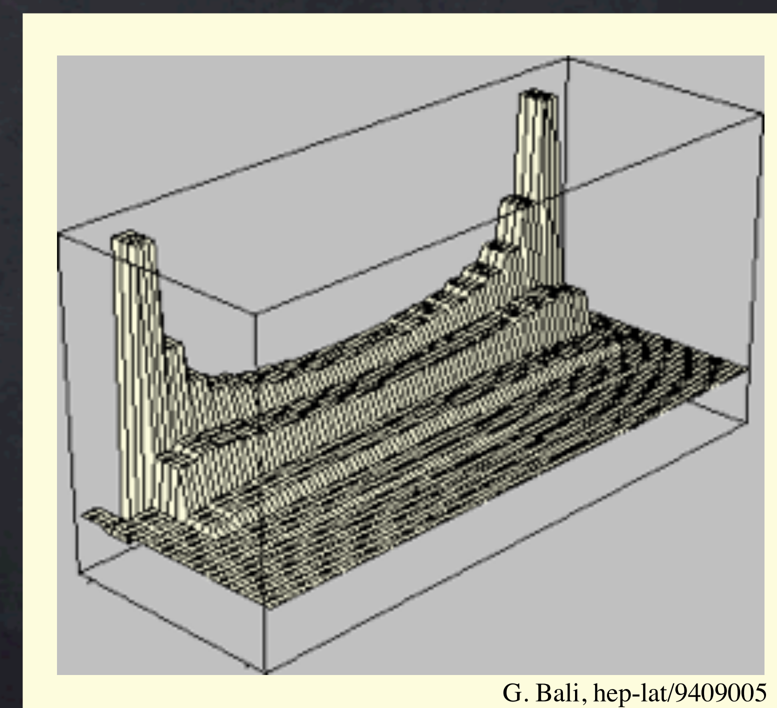
Solve QCD

Direct computation of Path Integral

Probability of field configuration {U}

$$\{U\} : e^{-S[U]}$$

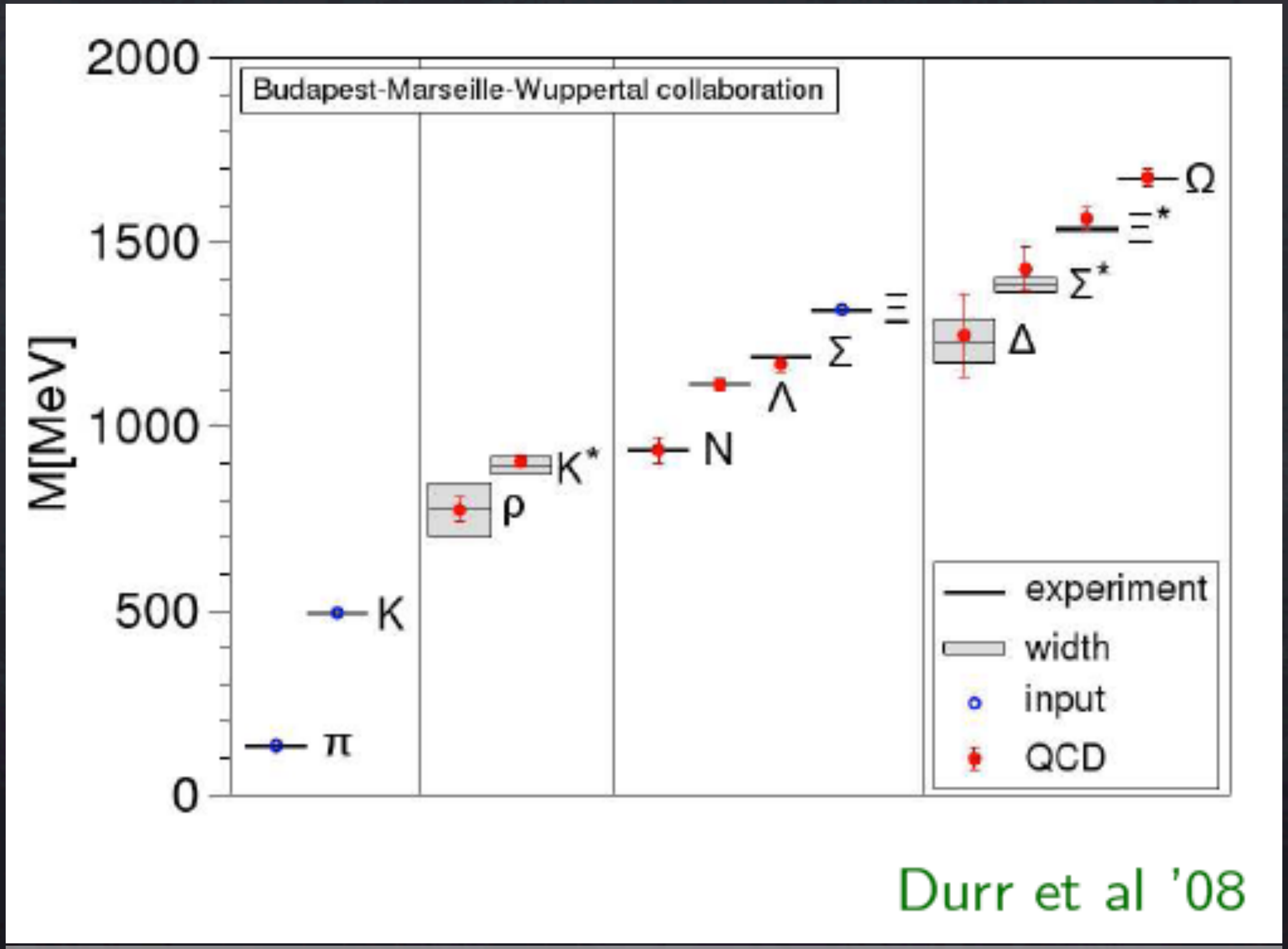




Separation of two static color charges by 22 lattice spacings

Example: Lattice Hadron Masses

Compute Hadron Spectrum (Given m_π and m_K as inputs)



Example by G. Salam

Why not Lattice for LHC?

To "resolve" a hard LHC collision

$$\underline{\text{Lattice spacing:}}\ \frac{1}{14\ \text{TeV}} \sim 10^{-5}\ \text{fm}$$

To include hadronization

Proper time $t \sim \frac{1}{0.5\ \text{GeV}} \sim 0.4\ \text{fm}/c$ × Lorentz Boost Factor

Boost factor at LHC ≈ 10^4

→ would need ≈ 4000 fm to fit entire collision

→ 10^{34} lattice points in total

Biggest lattices today are 64×64×64×128 ≈ 10^7

→ one or a few hadrons at a time

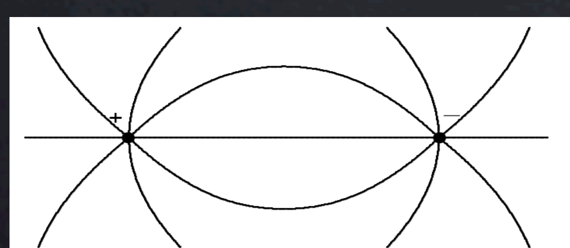
Linear Confinement

"Quenched" QCD

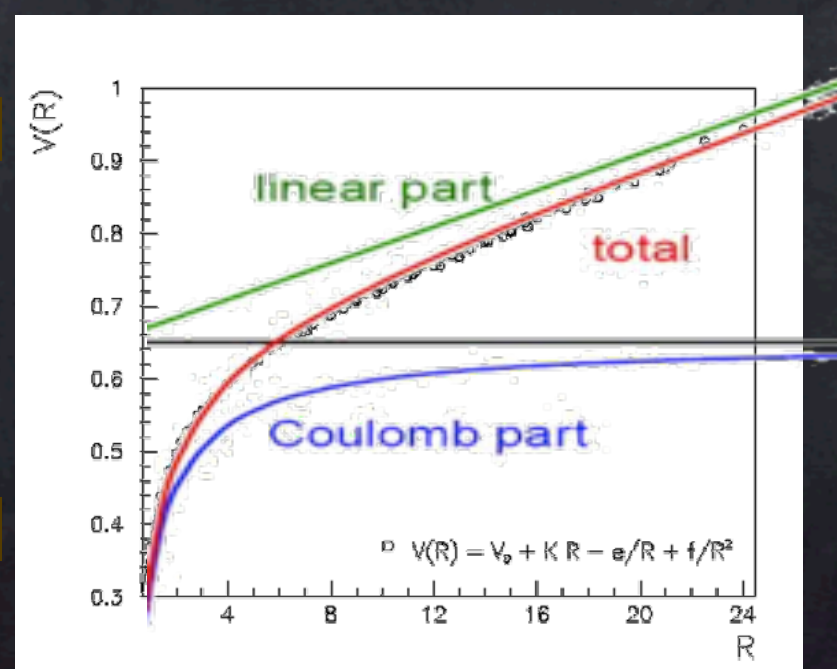
Look at the gluon field between two quarks

= Static quark sources plus dynamic gluon field (no g→qq)

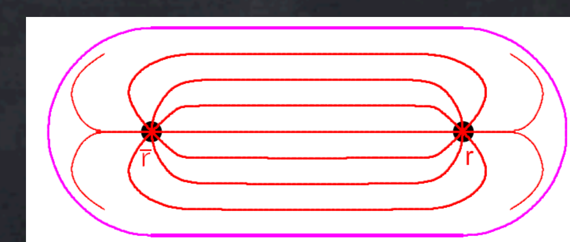
Short Distances ~ pQCD



Partons



Long Distances ~ Linear Confinement



Strings (Flux Tubes), Hadrons

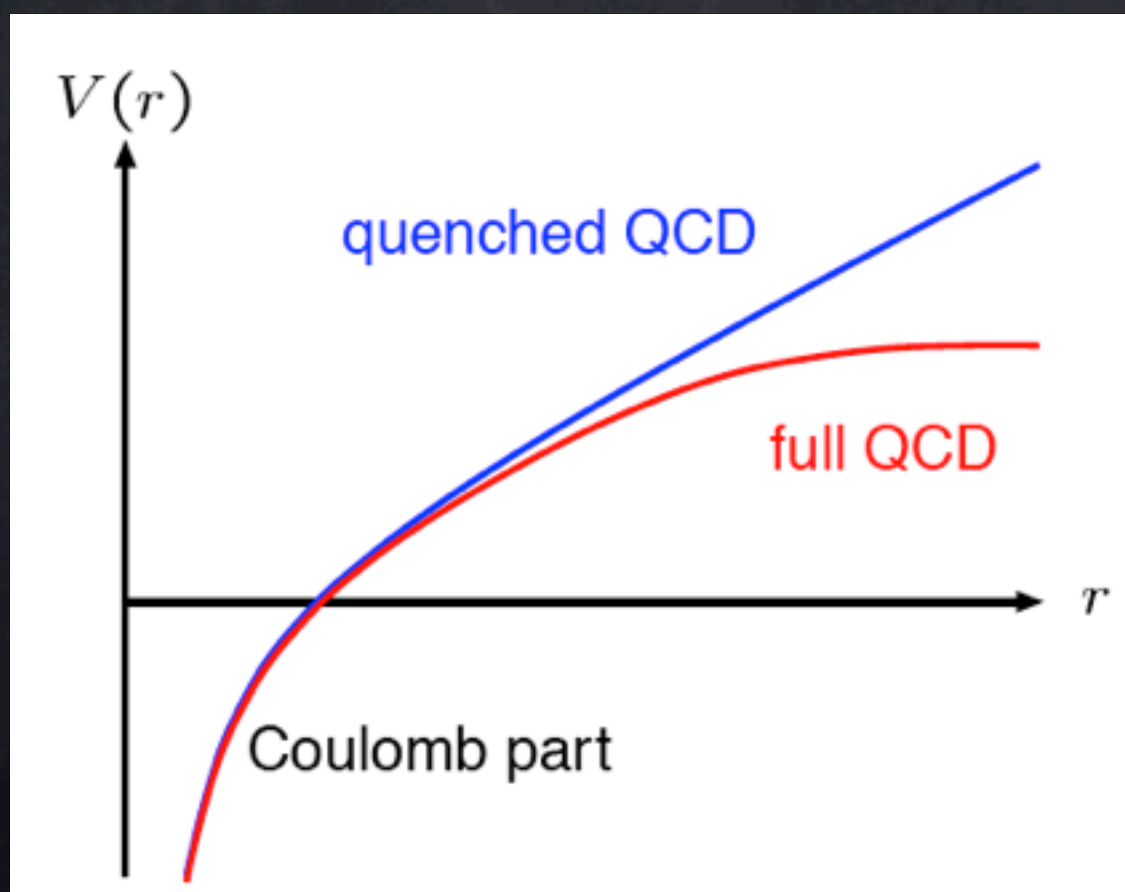
$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$

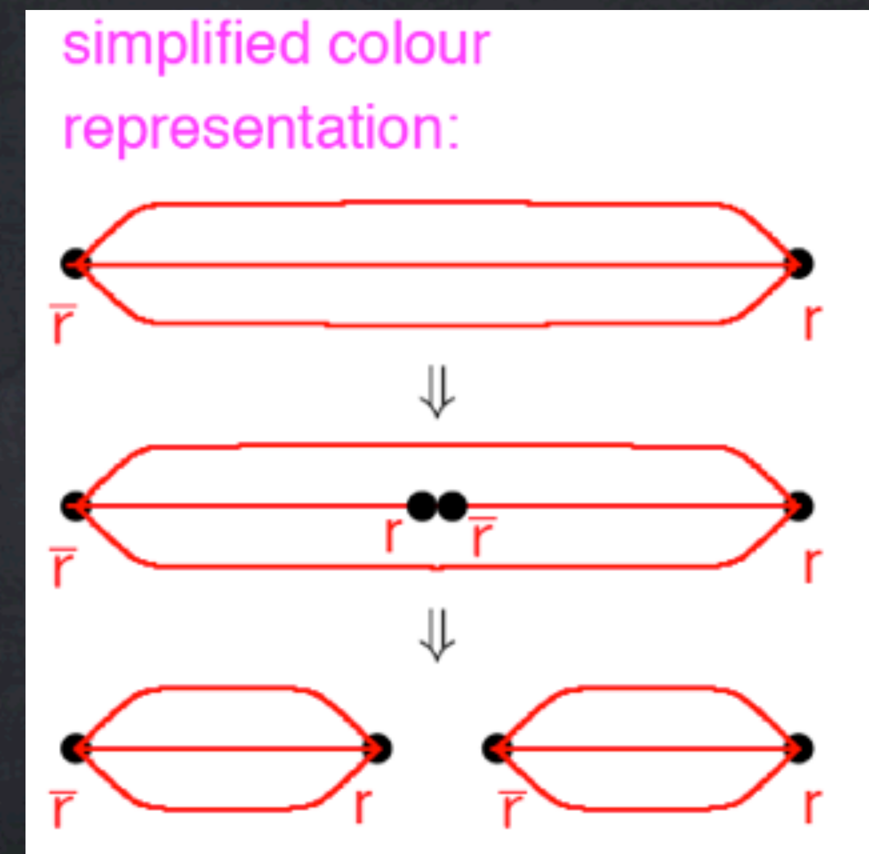
Illustrations by T. Sjöstrand

Real World?

In unquenched QCD

g→qq → The strings would break





From here on: Models

Illustrations by T. Sjöstrand

Local Parton-Hadron Duality

Hard Line

Each perturbative parton (at very low Q^2)

≈ one hadron in full picture

THIS IS AWFULLY WRONG!

(although some success describing incl spectra)

Soft Line (closer to the truth?)

Partons in perturbative calculations

≈ hadronic jets in full picture

THIS IS STILL PRETTY WRONG!

(although corrections power-suppressed if jets IR safe)

And yet you still find both of these pictures in modern papers

Today,

Hard Line → pQCD × FFs

Soft line → IR safety

What's wrong?

LPHD ≈ Independent Fragmentation (I.F.)

Universal fragmentation of a parton into hadrons

But duh!

The point of confinement is that partons are colored

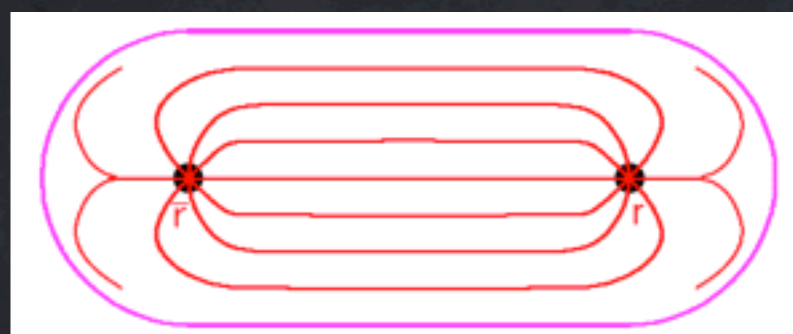
Hadronization = the process of color neutralization

I.e, the one question NOT addressed by LPHD or I.F.

→ fundamentally misguided to think about independent fragmentation of individual partons

The String Model

Linear Confinement



Describe as classical (1+1 dimensional) string

(i.e., ignore Coulomb)

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

→ The (Lund) String Model

Change degrees of freedom: two opposite charges moving apart → one Lorentz invariant string (piece)

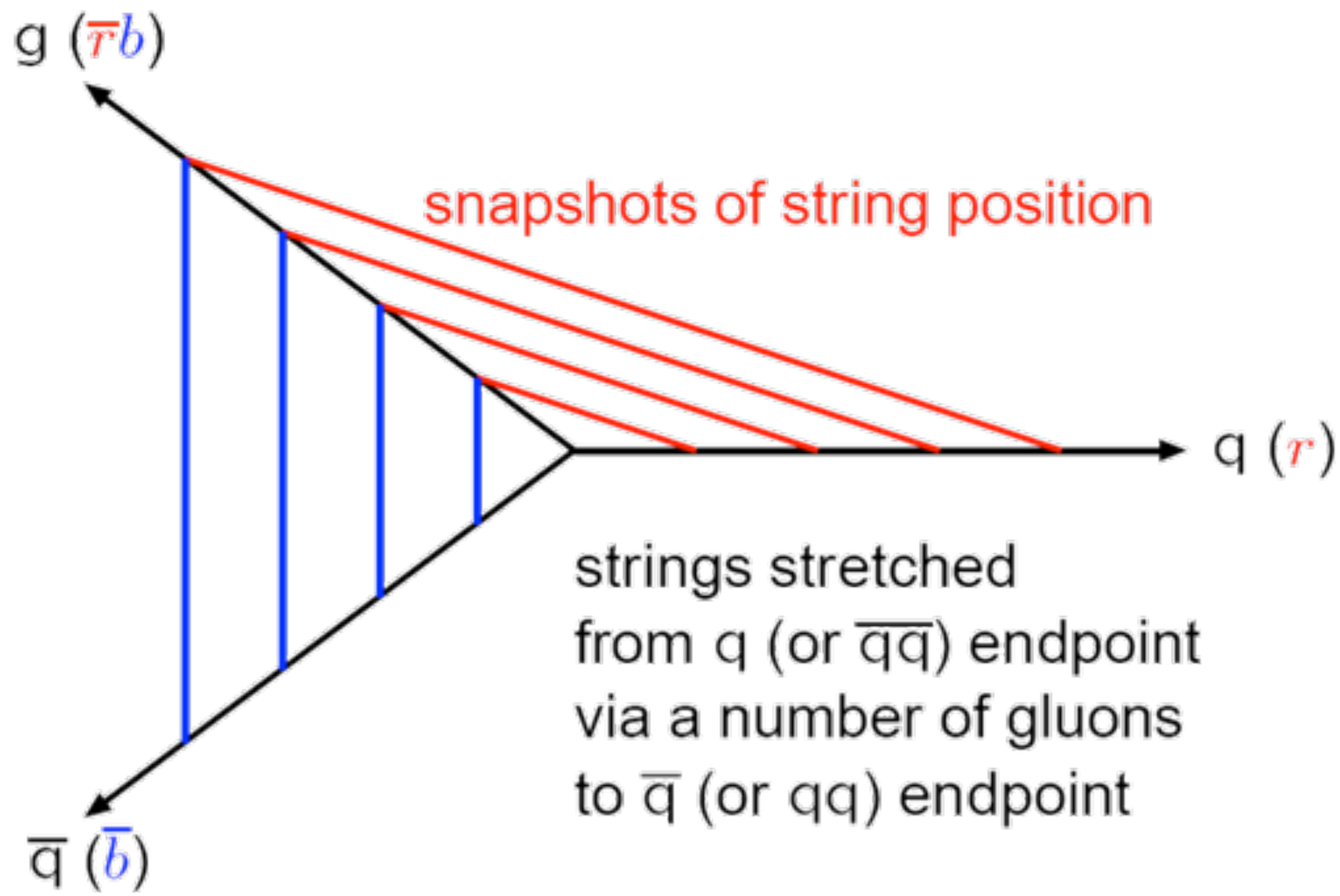
Classical string theory → string motion in spacetime

Illustrations by T. Sjöstrand

The Lund String

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

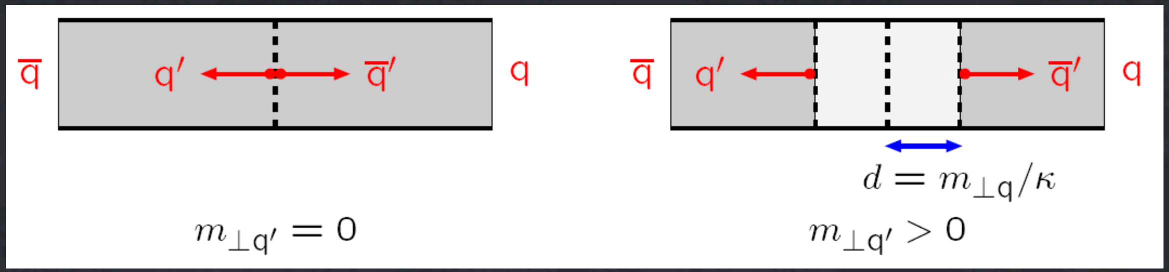
Simple space-time picture + no separate params for g jets
Details of string breaks more complicated …

Illustrations by T. Sjöstrand

String Breaks

String Breaks

Modeled by tunneling



$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp q}^2}{\kappa}\right) = \exp\left(-\frac{\pi p_{\perp q}^2}{\kappa}\right)\exp\left(-\frac{\pi m_q^2}{\kappa}\right)$$

1) common Gaussian $p_\perp$ spectrum

2) suppression of heavy quarks $u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11}$

3) diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production

Also depends on:

spins, hadron multiplets, hadronic wave functions, phase space, ... → (much) more complicated → many parameters

→ Not calulable, must be constrained by data → 'tuning'

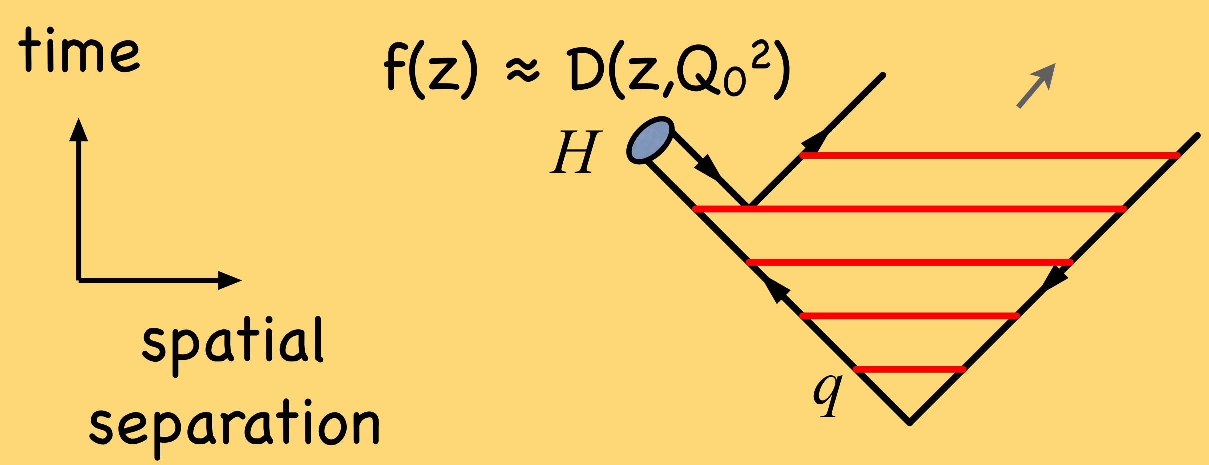
Illustrations by T. Sjöstrand

String Breaks → Hadrons

Having selected a hadron flavor

How much momentum does it take?

Spacetime Picture



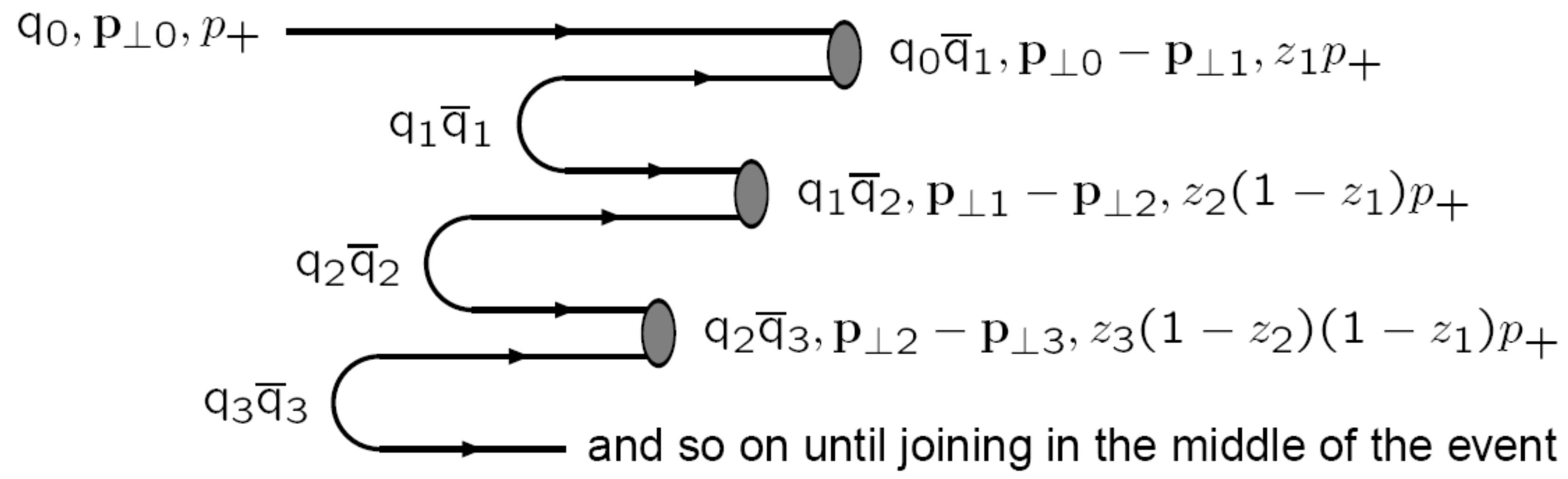
$$P_H = z\, p_q$$

(lightcone momenta)

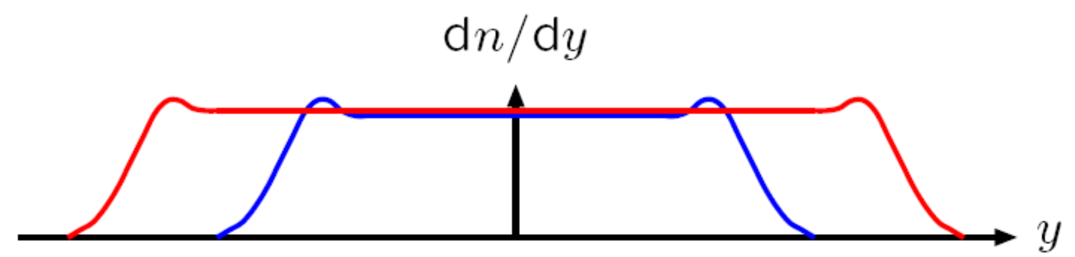
It takes a fraction z, determined by the fragmentation function, $f(z,Q_0^2)$

More String Breaks

Iterative Ansatz



Scaling in lightcone $p_\pm = E \pm p_z$ (for $q\overline{q}$ system along z axis) implies flat central rapidity plateau + some endpoint effects:

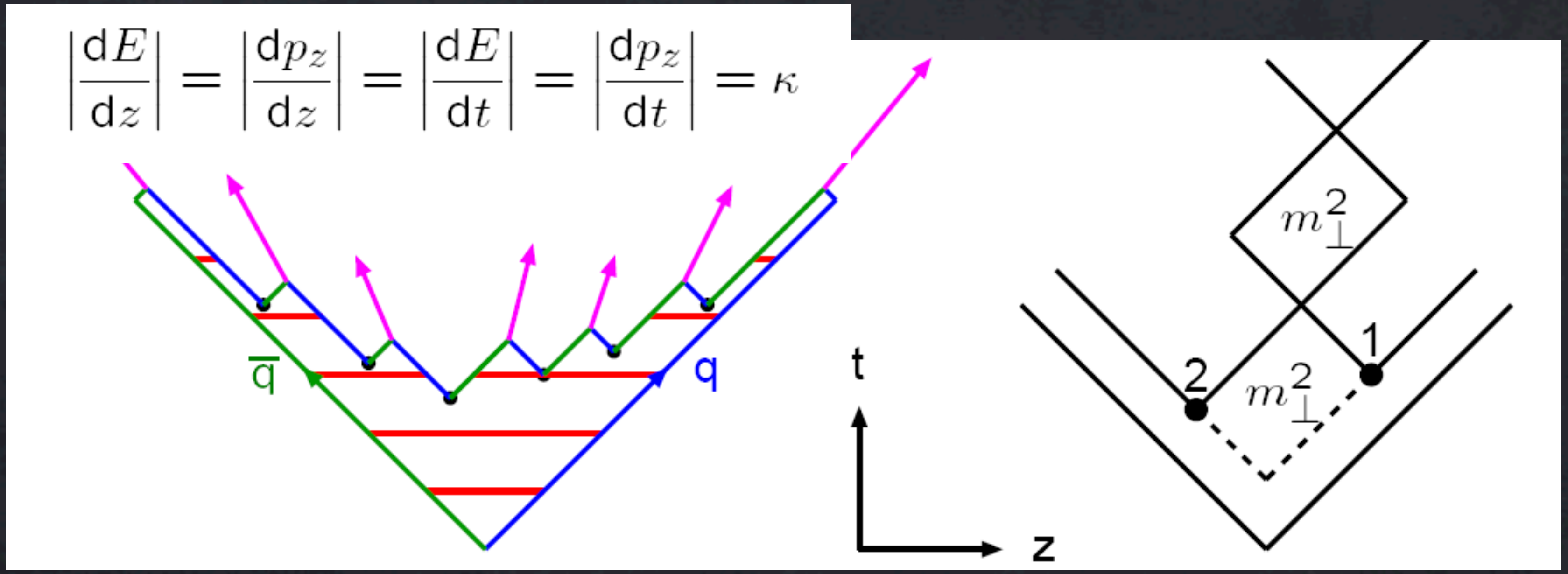


$\langle n_{ch} \rangle \approx c_0 + c_1 \ln E_{cm}$, $\sim$ Poissonian multiplicity distribution

Illustrations by T. Sjöstrand

→ Hadrons

Repeat for large system → Lund Model



Note: string breaks causally disconnected

→ can proceed in arbitrary order (left-right, right-left, in-out, …)

→ Justifies iterative ansatz (useful for MC implementation)

Illustrations by T. Sjöstrand

Causality

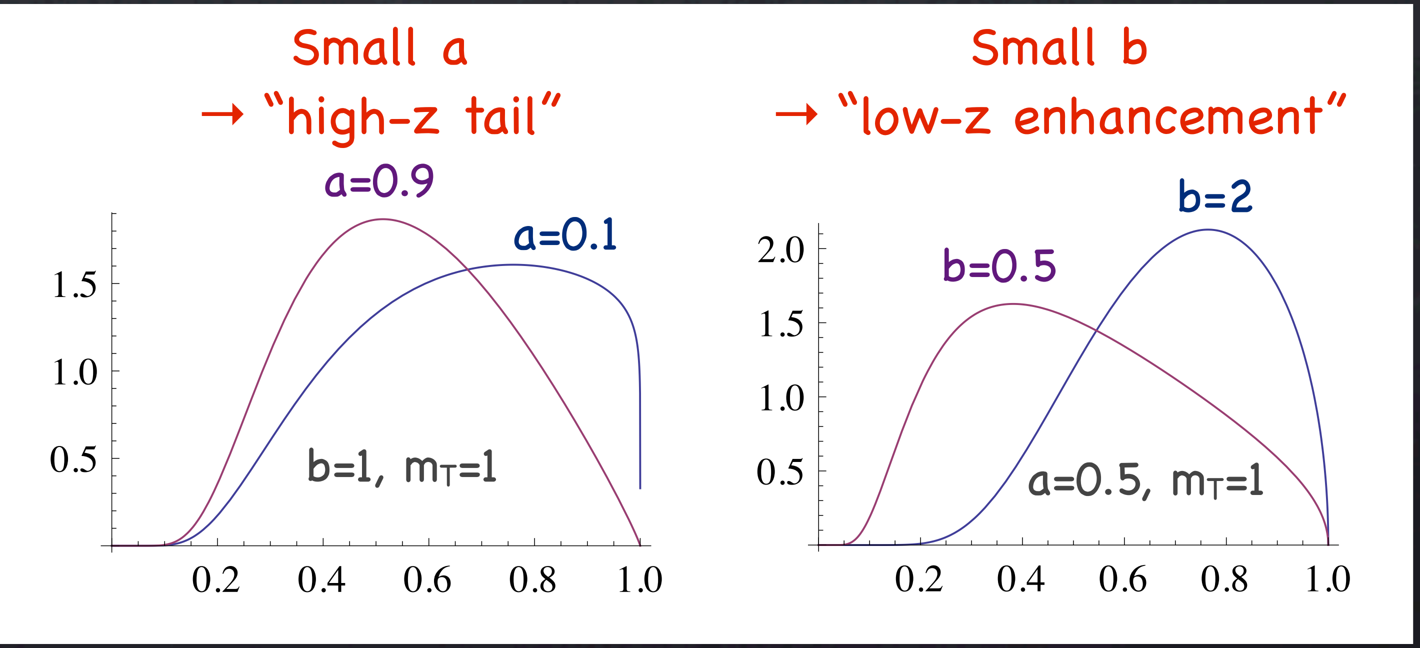
Note: string breaks causally disconnected

→ can proceed in arbitrary order (left-right, right-left, in-out, ...)

→ Justifies iterative ansatz (useful for MC implementation)

Also constrains form of fragmentation function!

(Left-Right Symmetry)



⇒ Lund symmetric fragmentation function

$$f(z) \propto (1-z)^a \exp(-b m_\perp^2/z)/z$$

Alternative: The Cluster Model

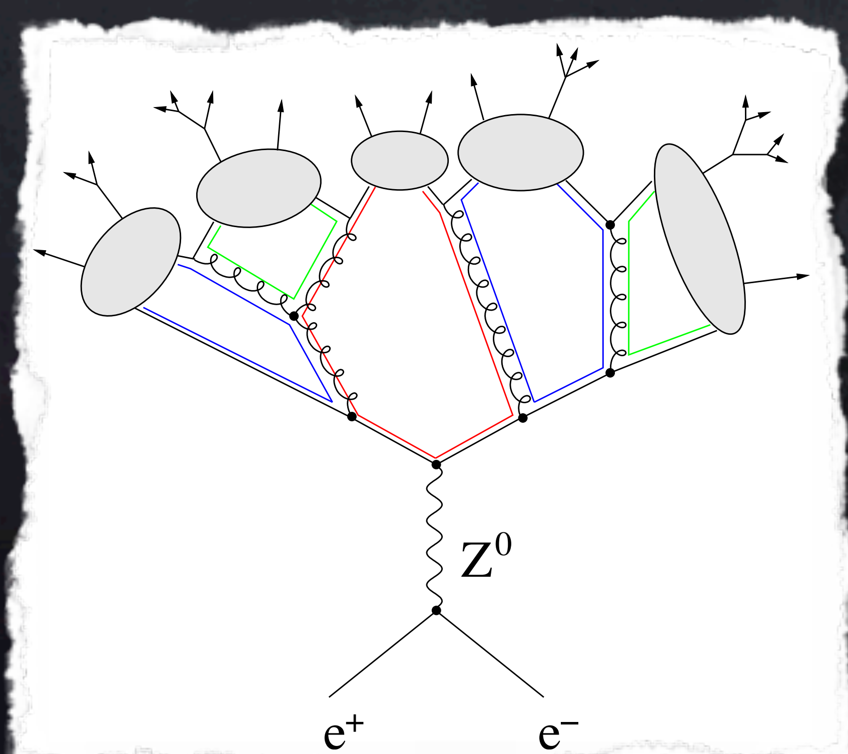
"Preconfinement"

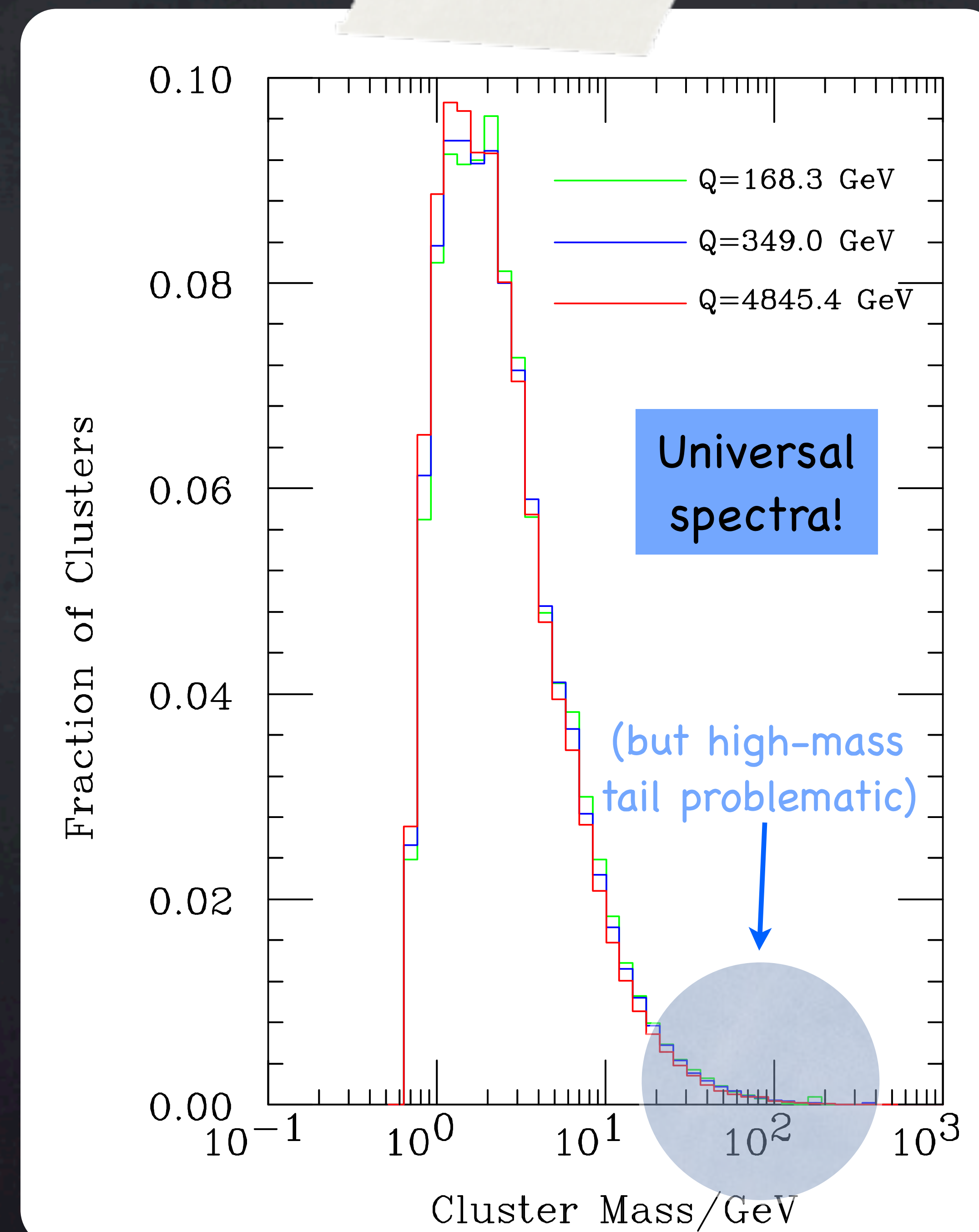
Force $g \to q\bar{q}$ splittings at Q_0

→ high-mass $q\bar{q}$ "clusters"

Isotropic 2-body decays to hadrons

according to PS ≈ $(2s_1+1)(2s_2+1)(p^*/m)$





Underlying Event

Nomenclature → what is what?

Perturbative? Or not?

(What) can we learn about it from Minimum-Bias?

What about diffraction?

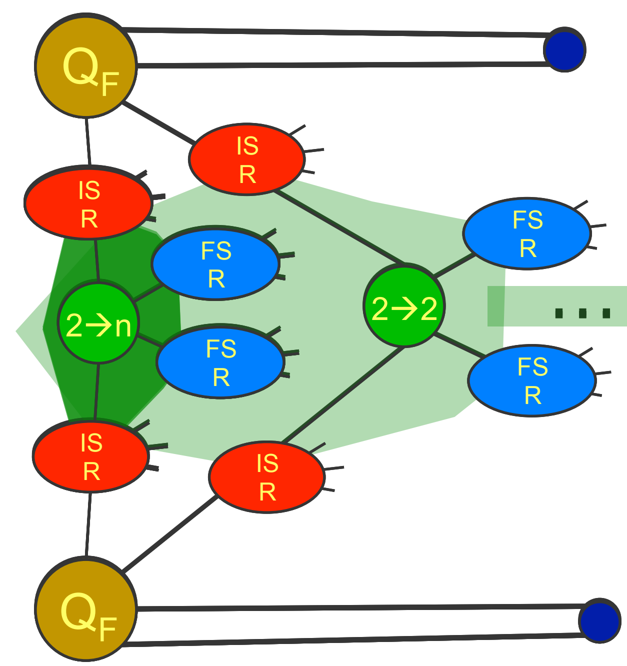
Additional Sources of Particle Production

- Starting point: Matrix Elements + Parton Showers

n = a handful + resonance decays

2→n hard parton scattering at (N)LO

+ Bremsstrahlung ➔ 2→∞ at (N)LL



$Q_F >> \Lambda_{QCD}$

Hadrons are not elementary
+ QCD diverges at low p_T

→ multiple <u>perturbative</u> parton-parton interactions

e.g. 4→4, 3→ 3, 3→2

Underlying Event has perturbative part!

- No factorization theorem

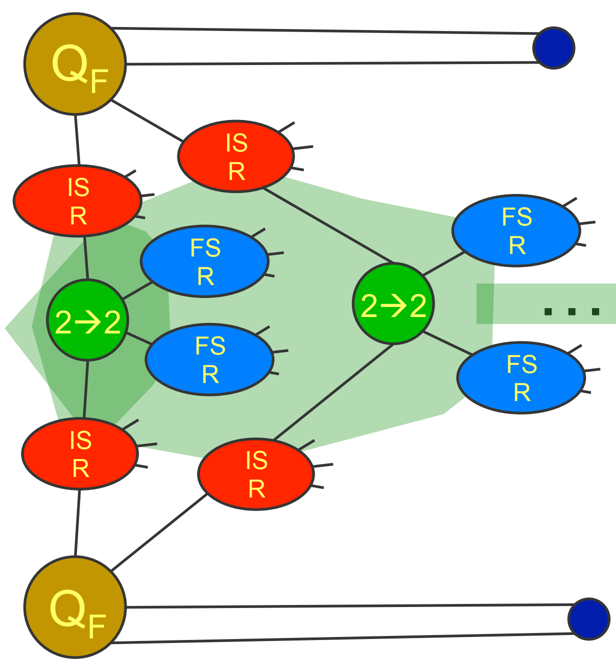
➔Herwig++, Pythia, Sherpa: MPI models

Additional Sources of Particle Production

$Q_F >> \Lambda_{QCD}$

ME+ISR/FSR

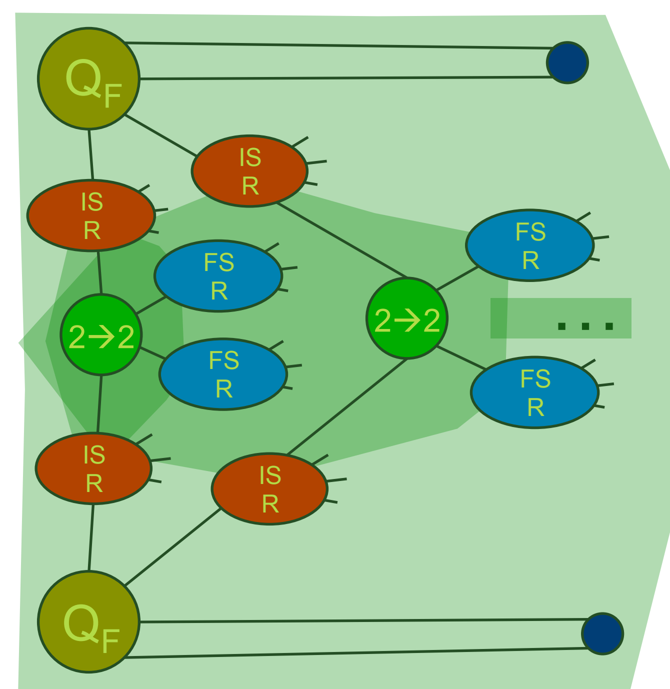
+ perturbative MPI



+

Stuff at

$Q_F \sim \Lambda_{QCD}$



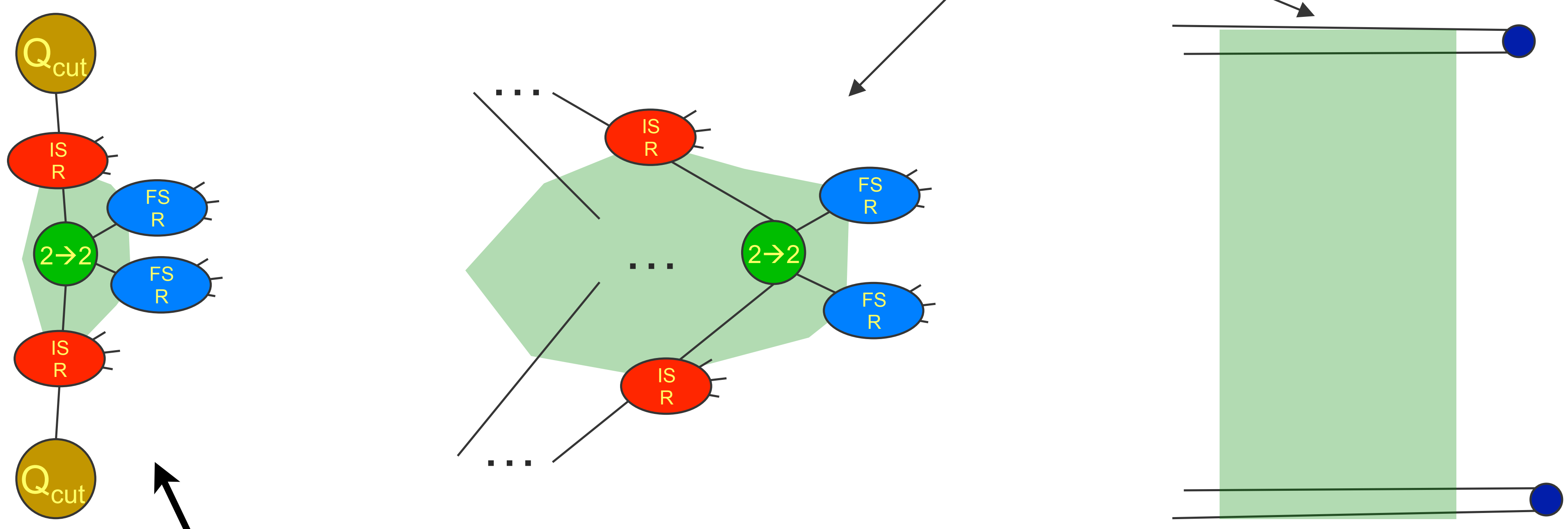
Need-to-know issues for IR sensitive quantities (e.g., N_{ch})

What is What?

See also **Tevatron-for-LHC Report of the QCD Working Group, hep-ph/0610012**

- ▶ Many nomenclatures being used.
  - Not without ambiguity. I use:

Some freedom in how much particle production is ascribed to each: "hard" vs "soft" models



Primary Interaction

(~ trigger)

Multiple Parton Interactions (MPI)

Beam Remnants

Underlying Event (UE)

Inelastic, non-diffractive

Note: each is colored → Not possible to separate cleanly at hadron level anyway

What is Minimum-Bias?

The 'average' hadron-hadron collision

(TH) Reference laboratory for testing QCD models with almost unlimited statistics

(EXP) Benchmark for Luminosity Measurements

The HARDEST physics process to study

Non-perturbative physics (no "hard trigger scale")

→ still don't have exact solutions

(PHENO) Important testing ground for new models

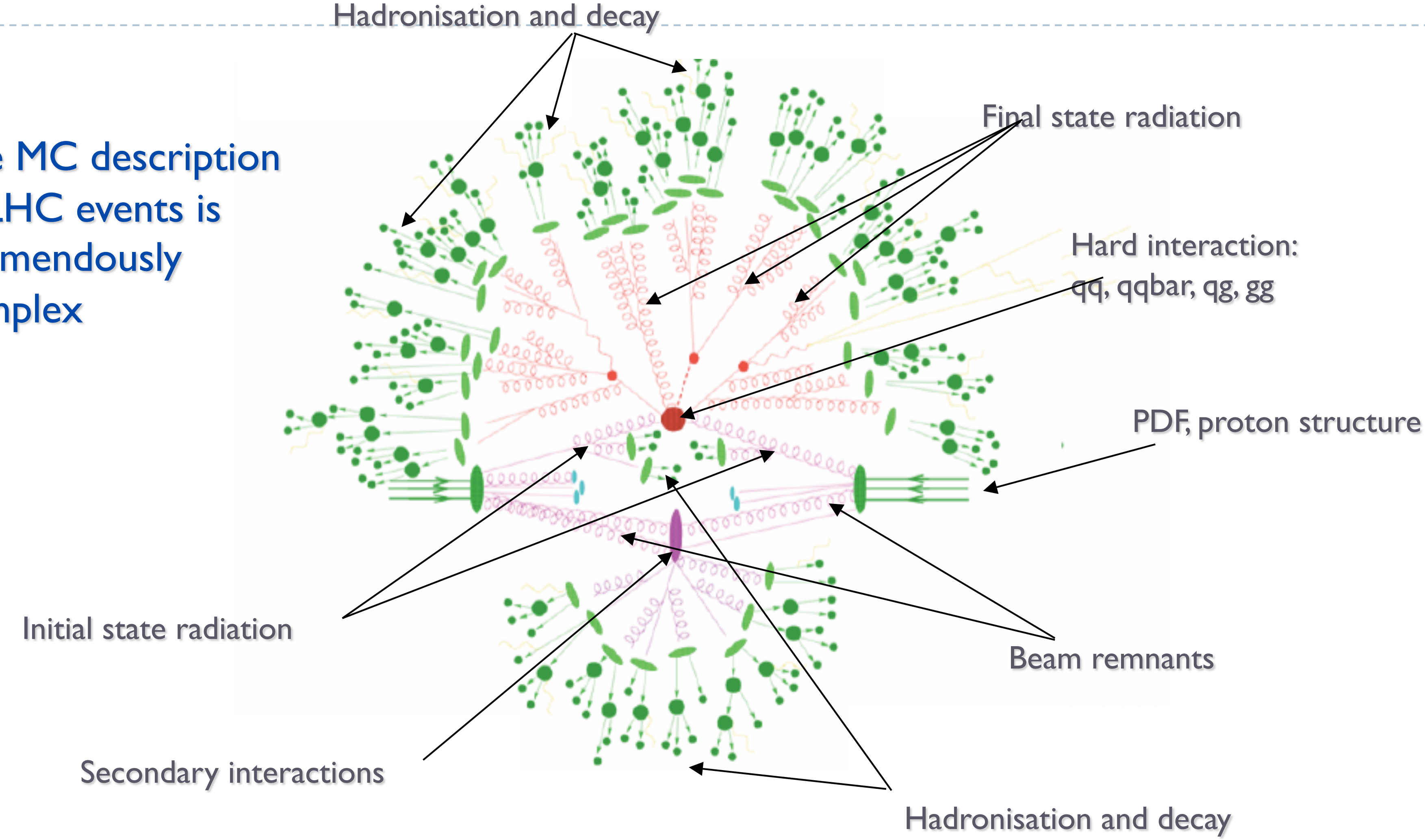
→ Constraints & Feedback to high-pT studies

Tails → Study evolution from soft gook to hard events

Dissecting Minimum-Bias

A lab for testing theory models and detector performance with high statistics

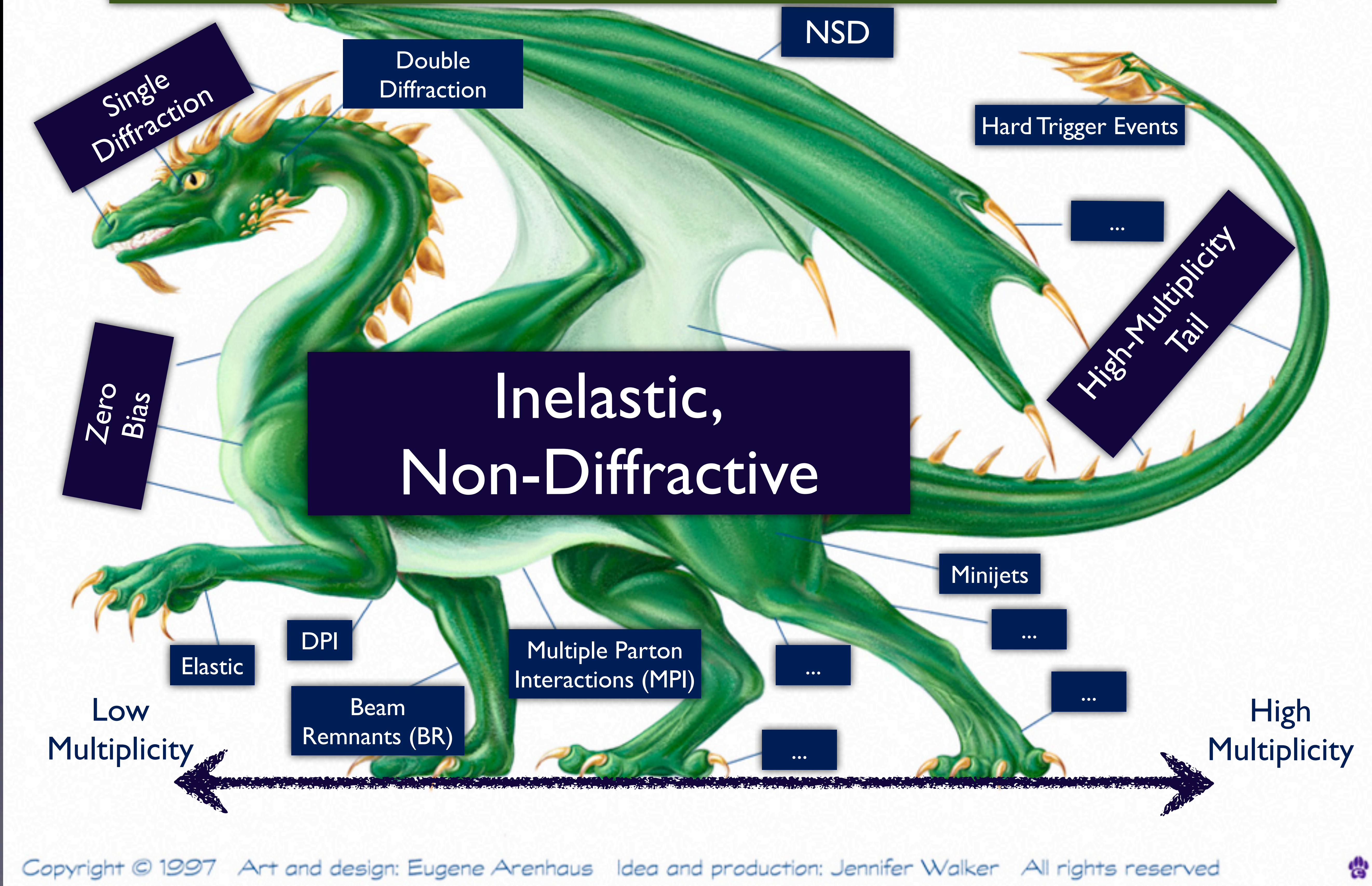
The MC description of LHC events is tremendously complex



This is a schematization to be able to cut down the problem in pieces and model them in a different way. The "pieces" are correlated !

(slide from F. Cossutti (CMS), 7th MCnet Annual Meeting, January 2010)

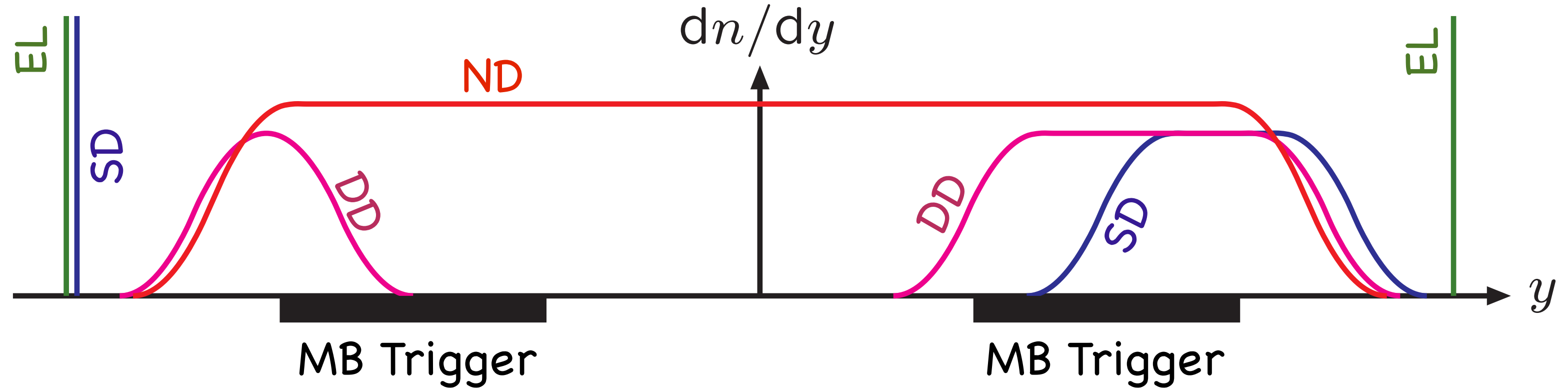
Dissecting Minimum-Bias



What is Minimum-Bias?

$$= \left(\sigma_{\text{elastic}} + \sigma_{\text{single-diffractive}} + \sigma_{\text{double-diffractive}} + \cdots + \sigma_{\text{non-diffractive}}\right) \times \varepsilon_{\text{MB-trigger}}$$

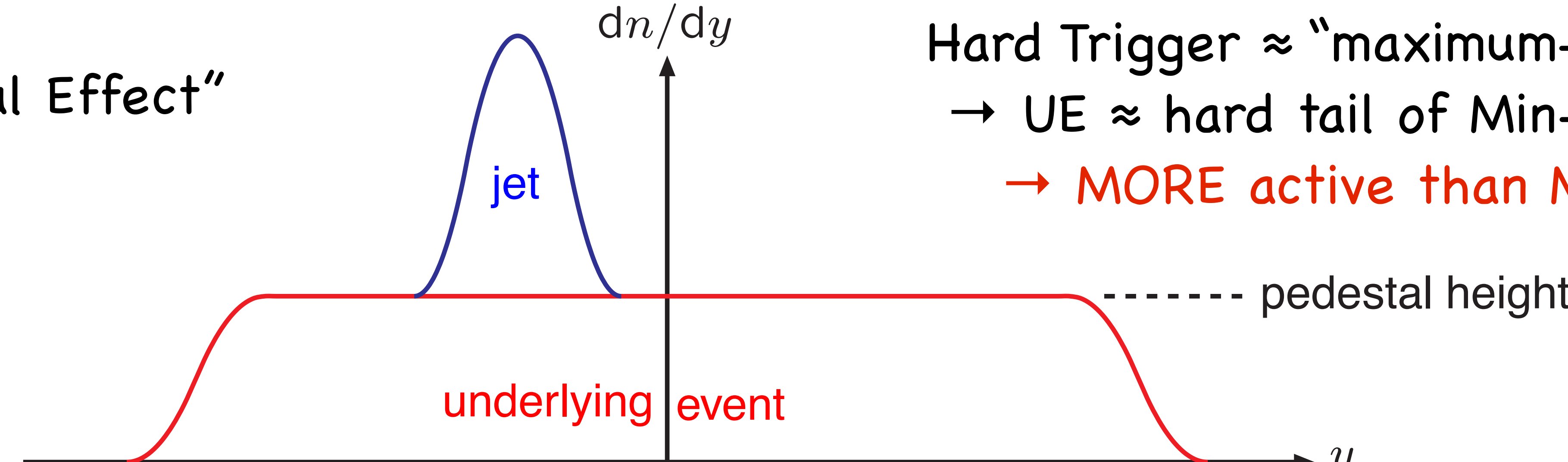
$\sigma_{\text{tot}} =$



reality: $\sigma_{\text{min-bias}} \approx \sigma_{\text{non-diffractive}} + \sigma_{\text{double-diffractive}} \approx 2/3 \times \sigma_{\text{tot}}$

What is Underlying Event?

"Pedestal Effect"



Hard Trigger ≈ "maximum-bias"

→ UE ≈ hard tail of Min-Bias

→ MORE active than MB

Illustrations by T. Sjöstrand

Multiple Parton Interactions?
(M.P.I.)

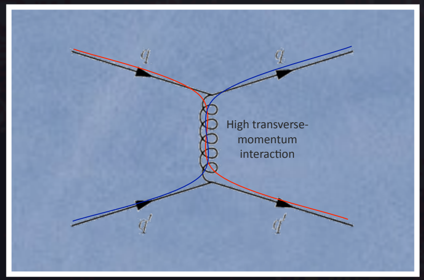
QCD

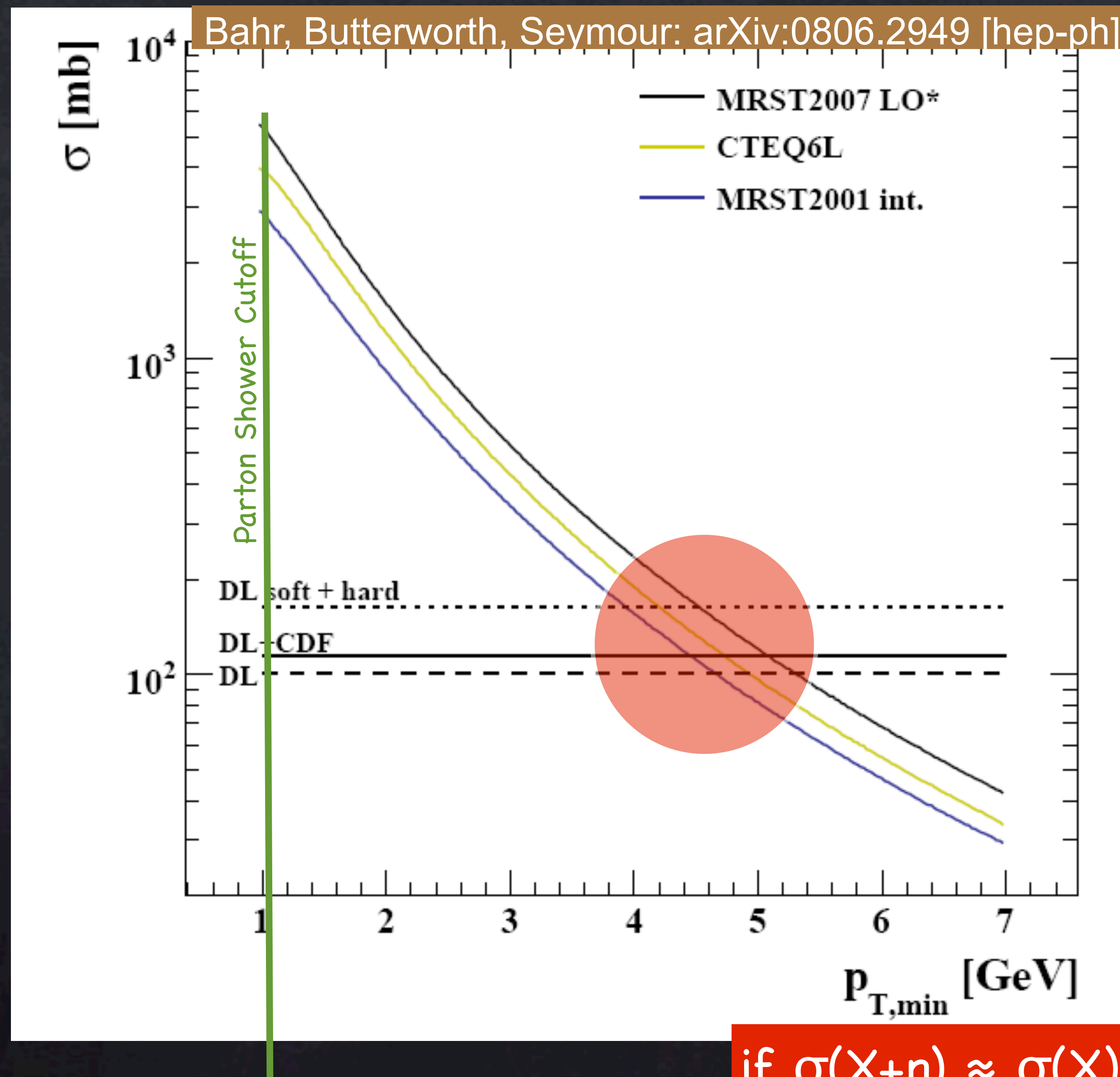
2→2

= Sum of

$qq' \to qq'$
$q\bar{q} \to q'\bar{q}'$
$q\bar{q} \to gg$
$qg \to qg$
$gg \to gg$
$gg \to q\bar{q}$

≈ Rutherford
(t-channel gluon)





Becomes larger than total pp cross section?

At $p_\perp \approx 5$ GeV

if $\sigma(X+n) \approx \sigma(X)$ you got a problem
fixed-order truncation not reliable

$\sigma_{\text{parton-parton}} > \sigma_{\text{proton-proton}}$

What does $\sigma_{\text{parton-parton}}$ count?

$$\frac{d\sigma_{2j}}{dp_\perp^2} = \sum_{i,j,k} \int dx_1 \int dx_2 \int d\hat{t}\; f_i(x_1,\mu_F^2)\, f_j(x_2,\mu_F^2)\, \frac{d\hat{\sigma}_{ij\to kl}}{d\hat{t}}\, \delta\left(p_\perp^2 - \frac{\hat{t}\hat{u}}{\hat{s}}\right) \propto \frac{1}{p_{\perp\min}^2}$$

(neglecting pdf dependence and α_s running)

Inclusive number of PARTON-PARTON interactions

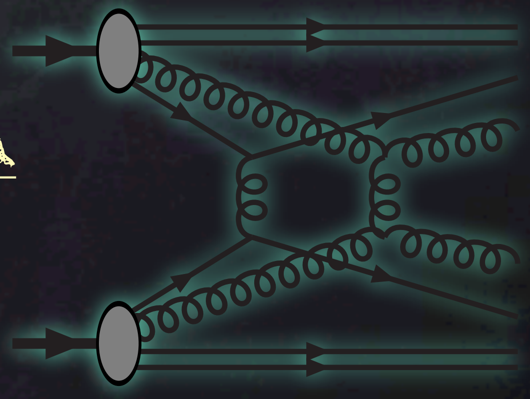
What does $\sigma_{\text{proton-proton}}$ count?

Inclusive number of PROTON-PROTON interactions

→ **Each proton-proton collision**

has many parton-parton interactions

→ underlying event



How many?

Naively $\langle n_{2\to2}(p_{\perp\min})\rangle = \dfrac{\sigma_{2\to2}(p_{\perp\min})}{\sigma_{\text{tot}}}$

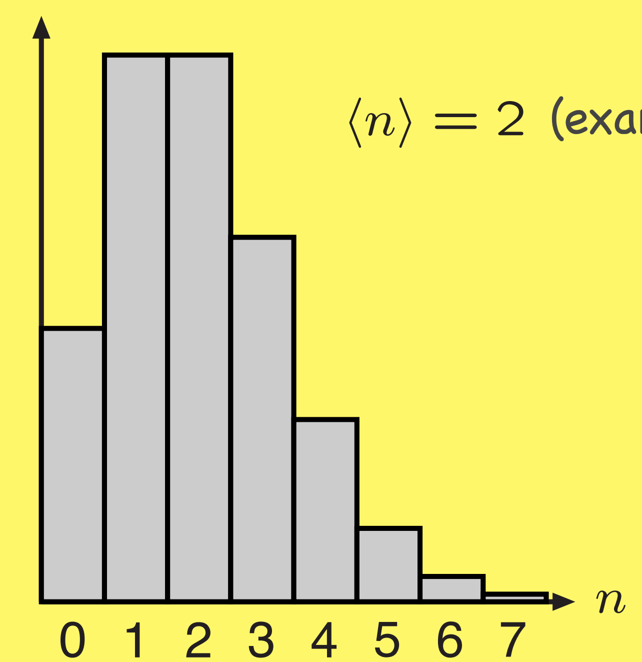
Interactions independent (naive factorization) → Poisson

$$\sigma_{\text{tot}} = \sum_{n=0}^{\infty} \sigma_n$$

$$\sigma_{\text{int}} = \sum_{n=0}^{\infty} n\,\sigma_n$$

$$\sigma_{\text{int}} > \sigma_{\text{tot}} \Longleftrightarrow \langle n\rangle > 1$$

$\mathcal{P}_n$



$$\mathcal{P}_n = \frac{\langle n\rangle^n}{n!}\, e^{-\langle n\rangle}$$

Real Life

Momentum conservation suppresses high-n tail

+ physical correlations

→ not simple product

Naive Factorization

Often used for simplicity

(i.e., assuming corrections are small / suppressed)

CDF Collaboration, Phys. Rev. Lett. 79 (1997) 584

Measurement of Double Parton Scattering in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ Tev

The double parton scattering (DP) process [1], in which two parton-parton hard scatterings take place within one $\overline{p}p$ collision, can provide information on both the distribution of partons within the proton and on possible parton-parton correlations, topics difficult to address within the framework of perturbative QCD. The cross section for DP comprised of scatterings A and B is written

$$\sigma_{\mathrm{DP}} \equiv \frac{\sigma_A \sigma_B}{\sigma_{\mathrm{eff}}}, \tag{1}$$

with a process-independent parameter σ_{eff} [2–5]. This expression assumes that the number of parton-parton interactions per collision is distributed according to Poisson statistics [6], and that the two scatterings are distinguishable [7]. Previous DP measurements have come

$\sigma_{\mathrm{eff}} \approx$ "first moment" of multiple parton interaction distributions
First rough characterization of MPI

But careful, σ_{eff} not valid / meaningful beyond factorized approximation!

Always report <u>physical observables</u> together with extracted quantities

MPI and Min-Bias

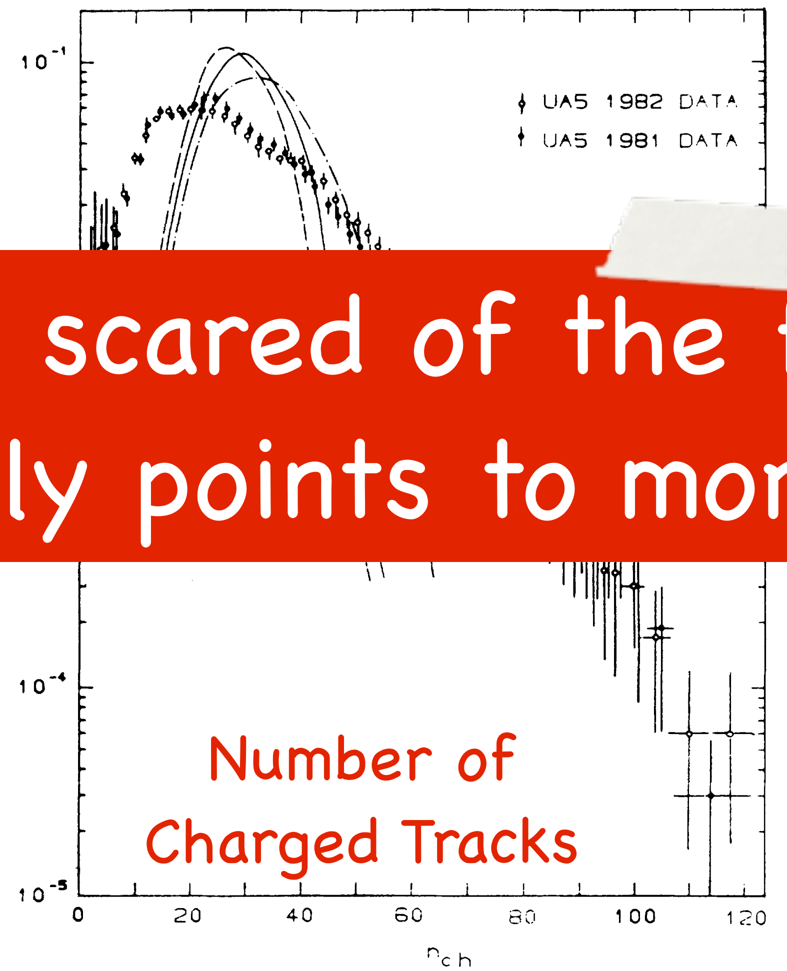


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

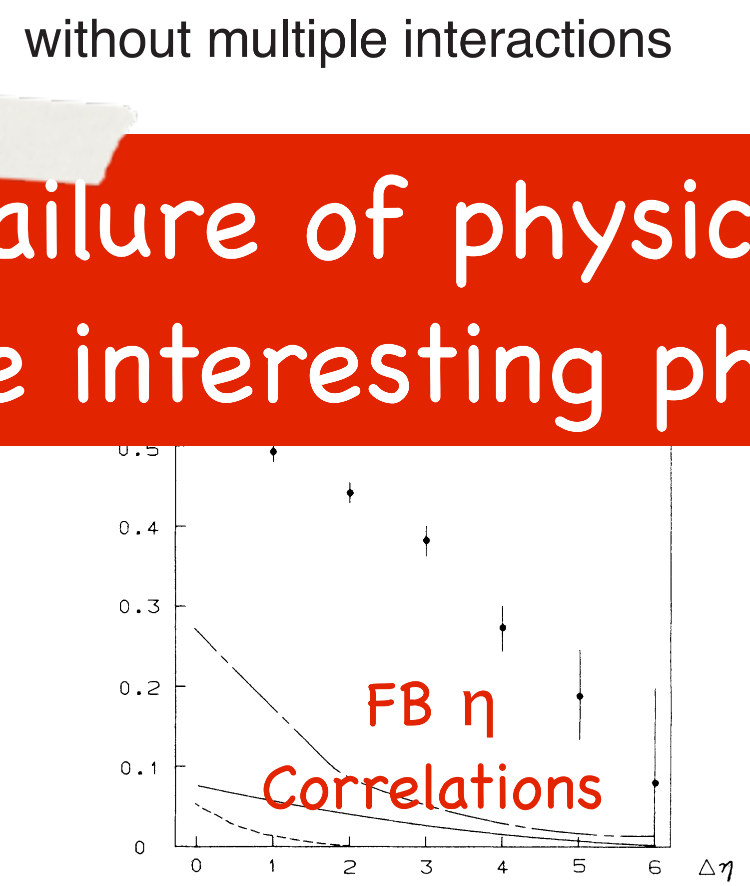


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

Do not be scared of the failure of physical models
Usually points to more interesting physics

Sjöstrand & v. Zijl, Phys.Rev.D36(1987)2019

MPI and Min-Bias

with multiple interactions

MPI also generate a "UE" in Min-Bias itself!

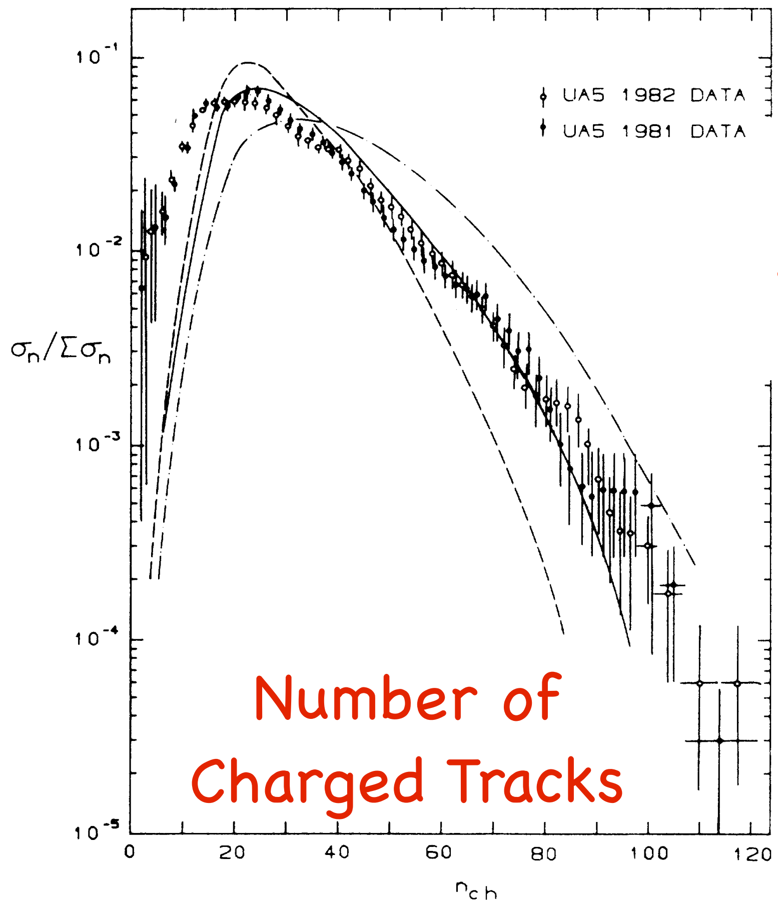


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min}=2.0$ GeV; solid line, $p_{T\min}=1.6$ GeV; dashed-dotted line, $p_{T\min}=1.2$ GeV.

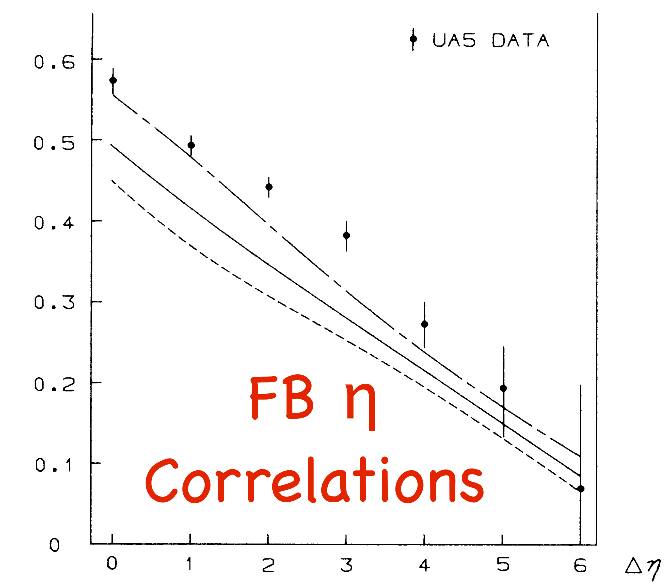
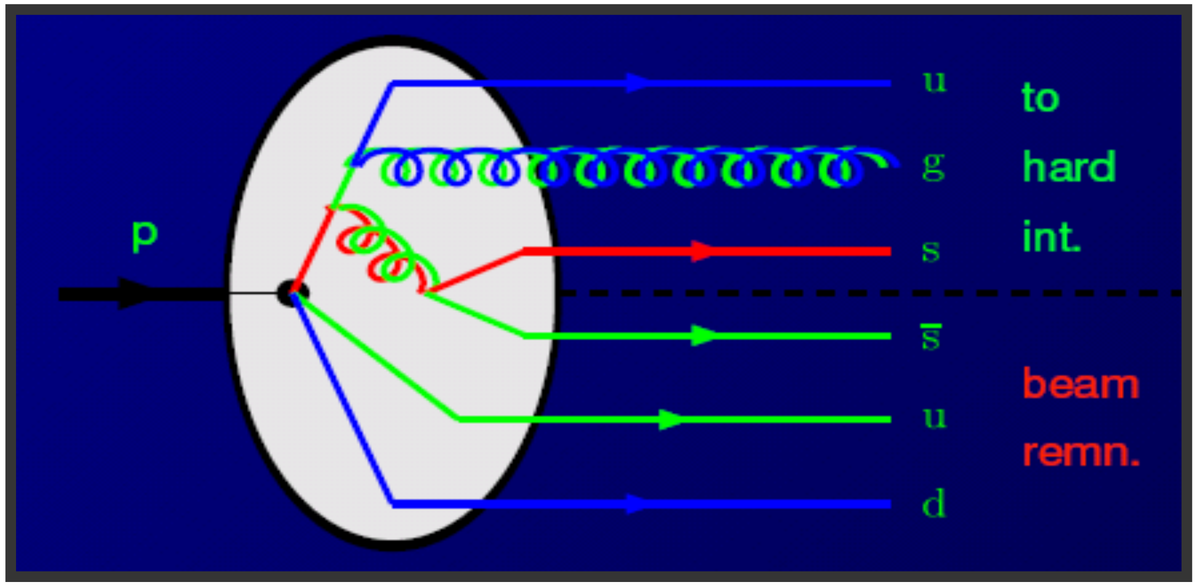
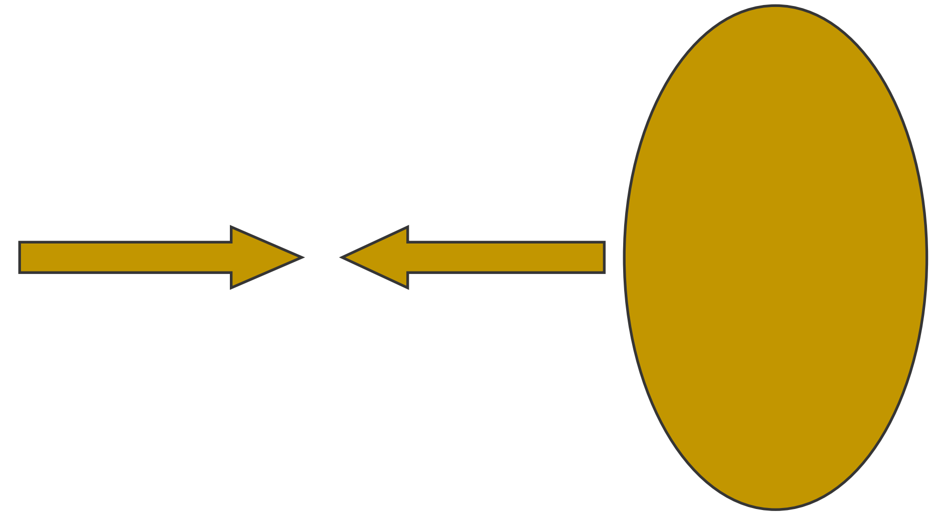


FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

Sjöstrand & v. Zijl, Phys.Rev.D36(1987)2019

Multi-Parton PDFs



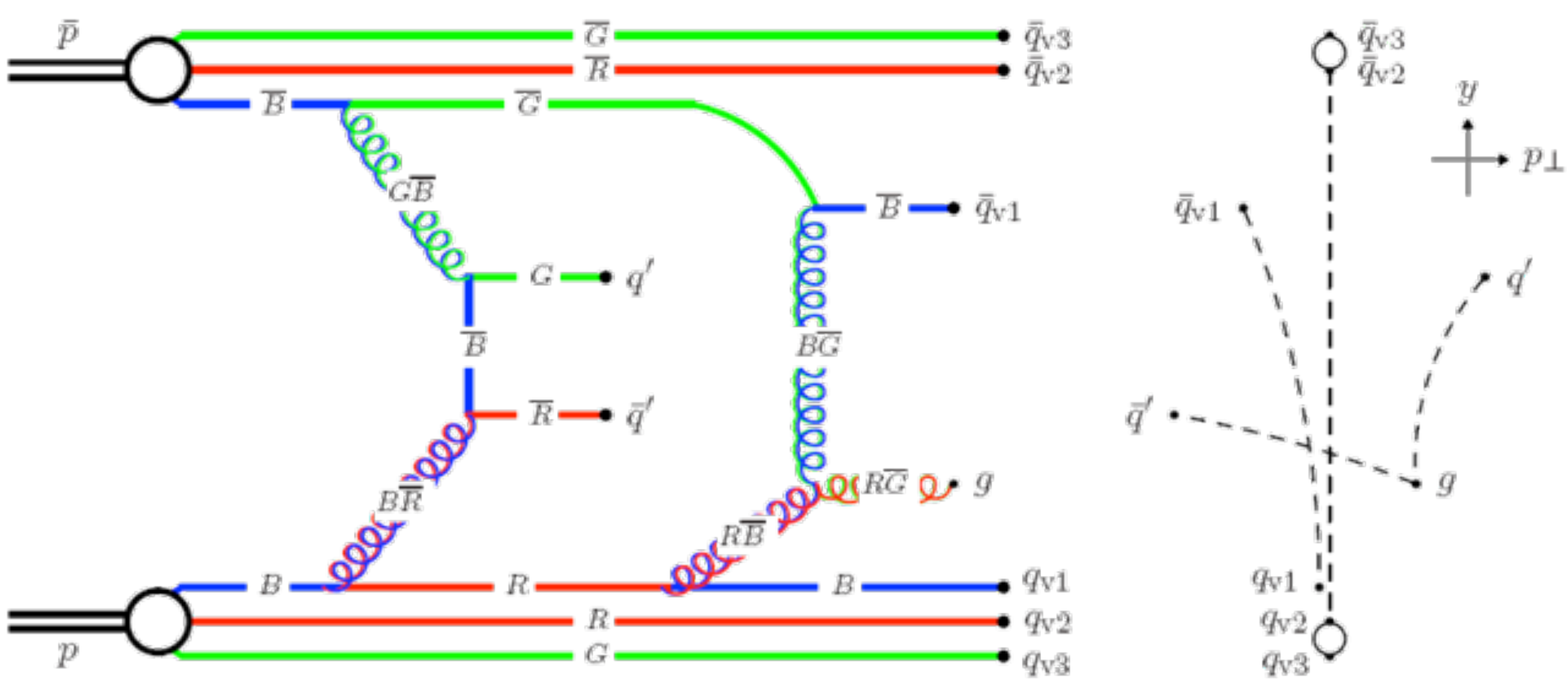


How are the initiators and remnant partons correllated?

- in impact parameter?
- in flavour?
- in x (longitudinal momentum)?
- in k_T (transverse momentum)?
- in colour (→ string topologies!)
- What does the beam remnant look like?
- (How) are the showers correlated / intertwined?

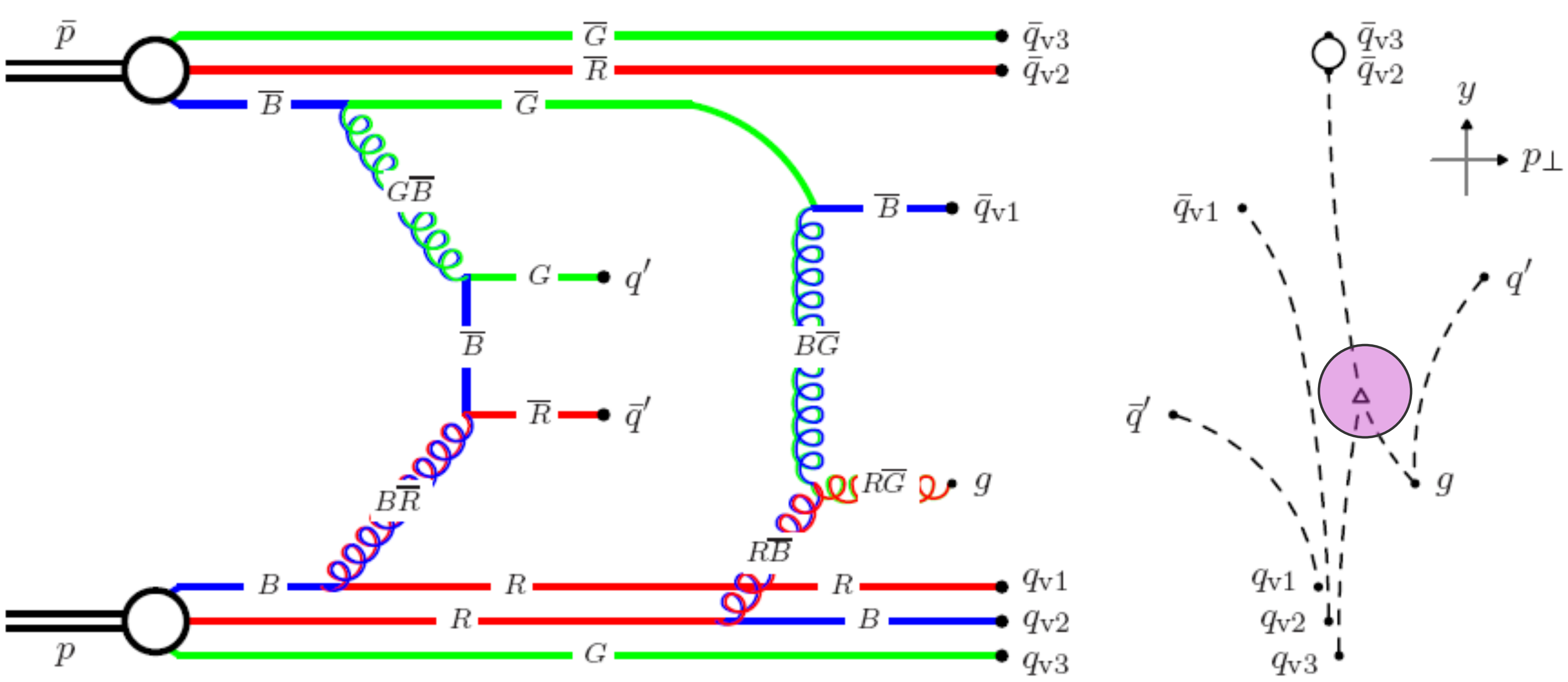
Colour and the UE

- The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions crucially depend on color space



Colour and the UE

- The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions crucially depend on color space

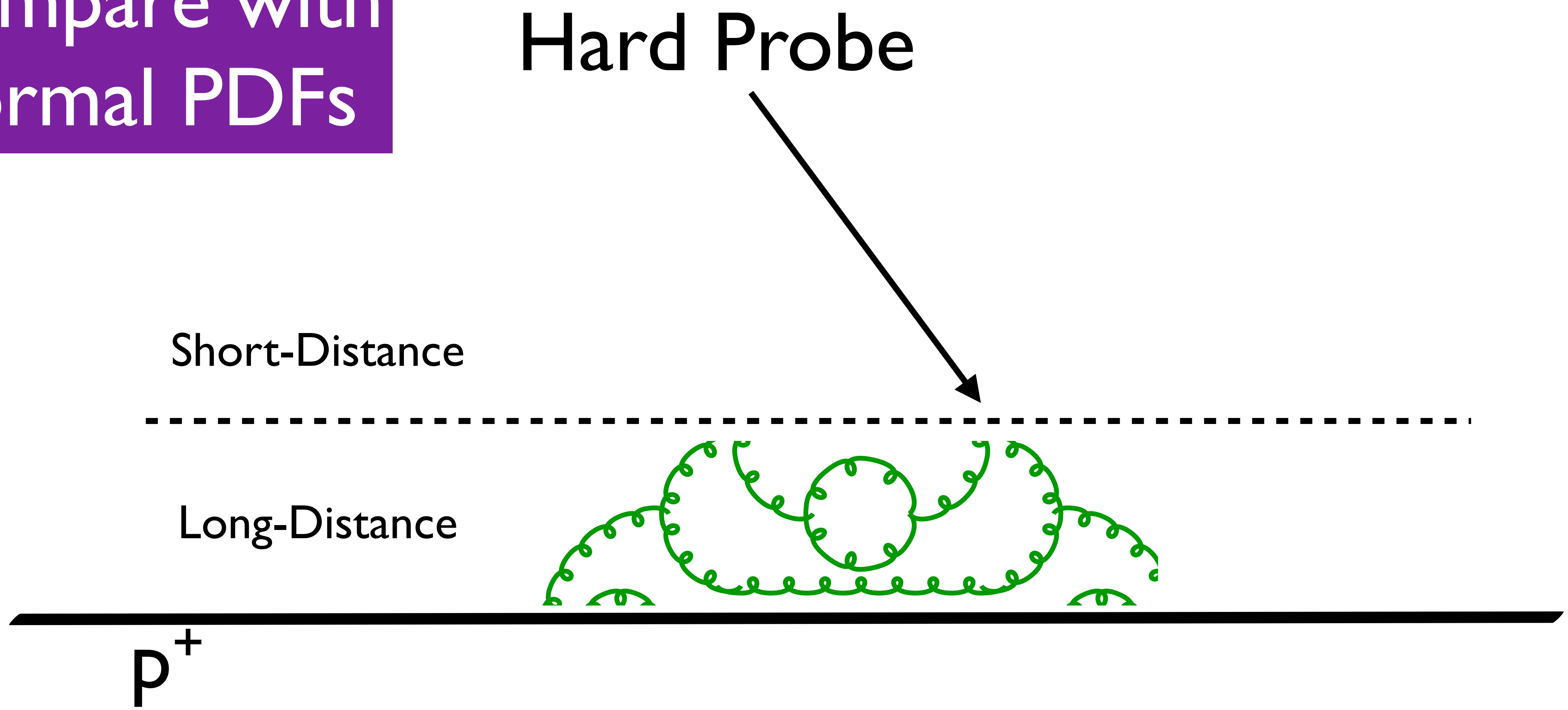


Note: this just color **connections**, then there may be color **reconnections** too

(+ Diffraction)

"Intuitive picture"

Compare with normal PDFs

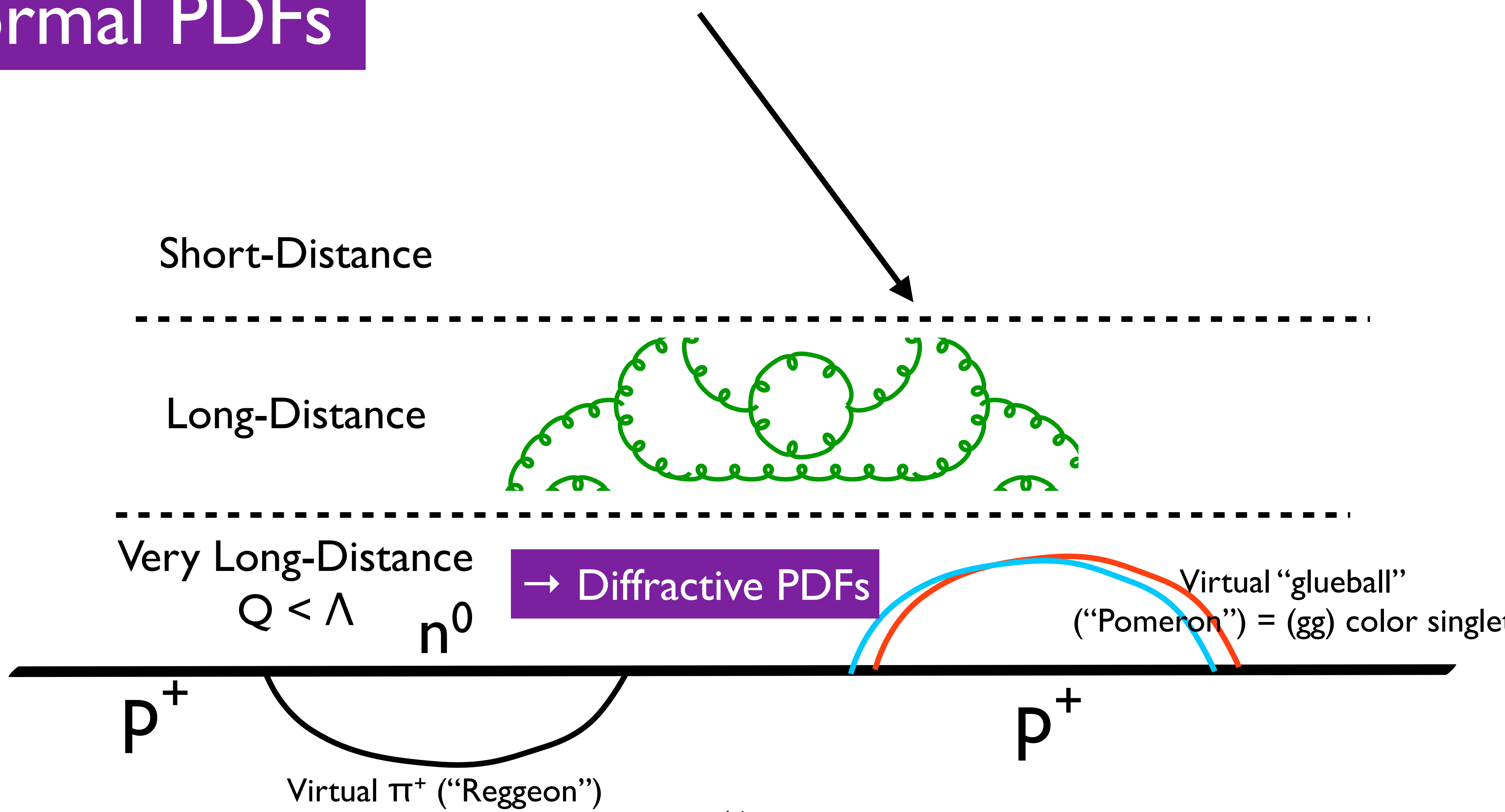


(+ Diffraction)

"Intuitive picture"

Compare with normal PDFs

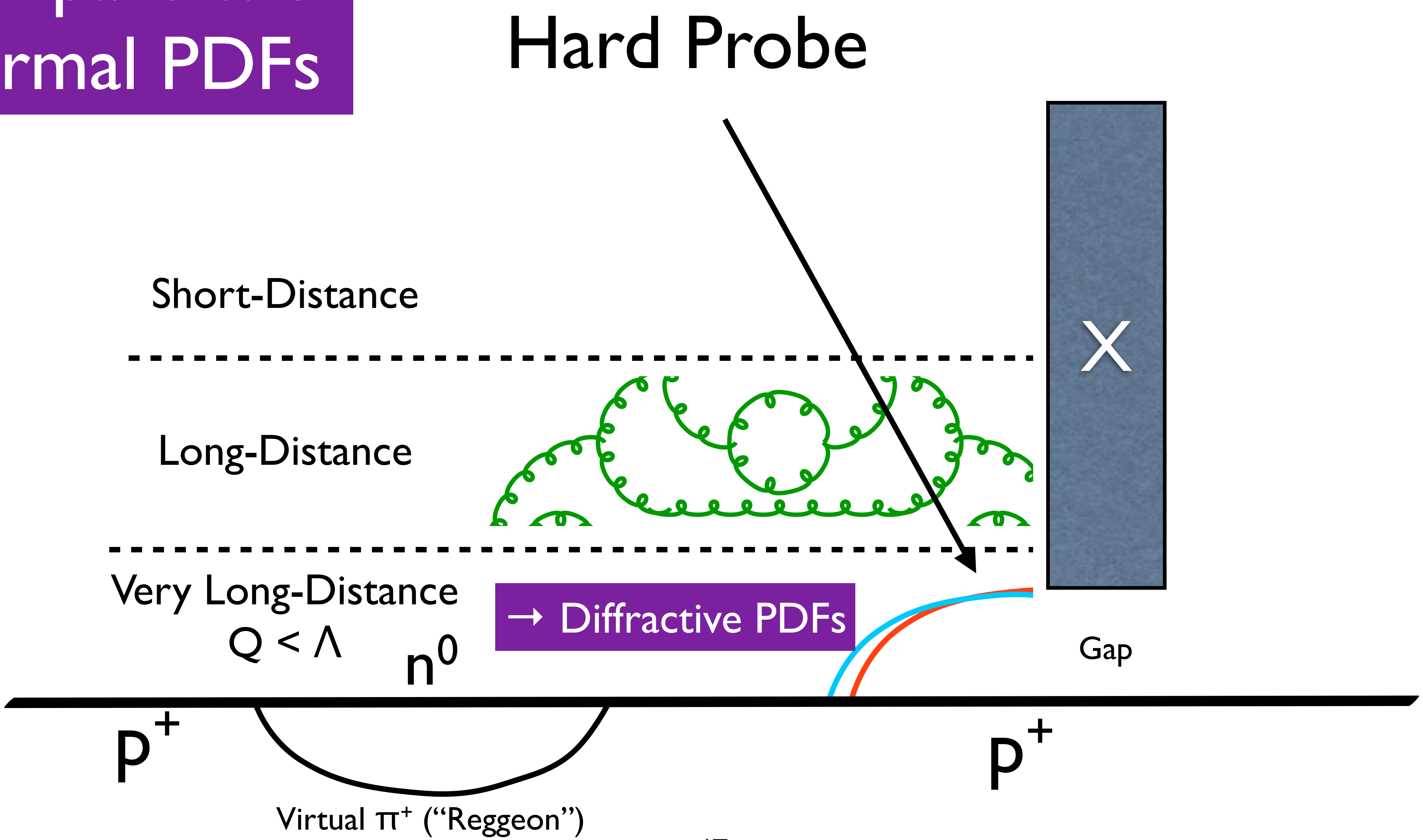
Hard Probe



(+ Diffraction)

"Intuitive picture"

Compare with normal PDFs



The Hard Tail

More about MC models in Lecture 4

Alright, but ...

If it's really multi-PARTON interactions – as opposed to just some additional soft gook – we should be able to see a tail of HARD partonic scattering!

Multiple (mini)jets

Already observed
(E.g., AFS, CDF, D0) → σ_{eff}

Even Double Drell-Yan?

Will be searched for at LHC

Infrared Summary

Parton Densities

= Our beams!

Well constrained central fits at NLO and NNLO

Learning about precision issues: uncertainties, parametrization dependence, scheme dependence, mutually inconsistent data sets, ...

Learning about 'tuning'/optimization of LO sets

"Arbitrariness" from vice to virtue?

LO*: allow (small) violations of momentum sum rule?

PDFs optimized for use with MC generators

Use approximate generator 'scheme' for evolution → formalize?

Still a developing field → developments yet to come!

Infrared Summary

Fragmentation

Still an unsulved puzzle

→ Emergent degrees of freedom

Phenomenological models build on fundamental symmetries, perturbative limits, and lattice inputs

Much more sophisticated than simple fits

Still, probably unreasonable to ask for better than 10% precision on main IR quantities (e.g., number of tracks, proton/pion ratio, ...), and worse in tails.

LHC → important checks in situ (+ it's fun!)

Underlying Event

Minimum-Bias

High-Statistics reference laboratory ('the LEP of hadron colliders')

Ideal for studies of non-pQCD properties

Including Fragmentation, diffraction, beam remnant blowup, ...

Again, 10% precision is probably the best we can do

Model power = simultaneous description of many observables

Underlying Event

Pedestal effect: more active than minimum-bias

Dominating model: multiple parton interactions

Beware large fluctuations

+ Phenomenology → Theory?