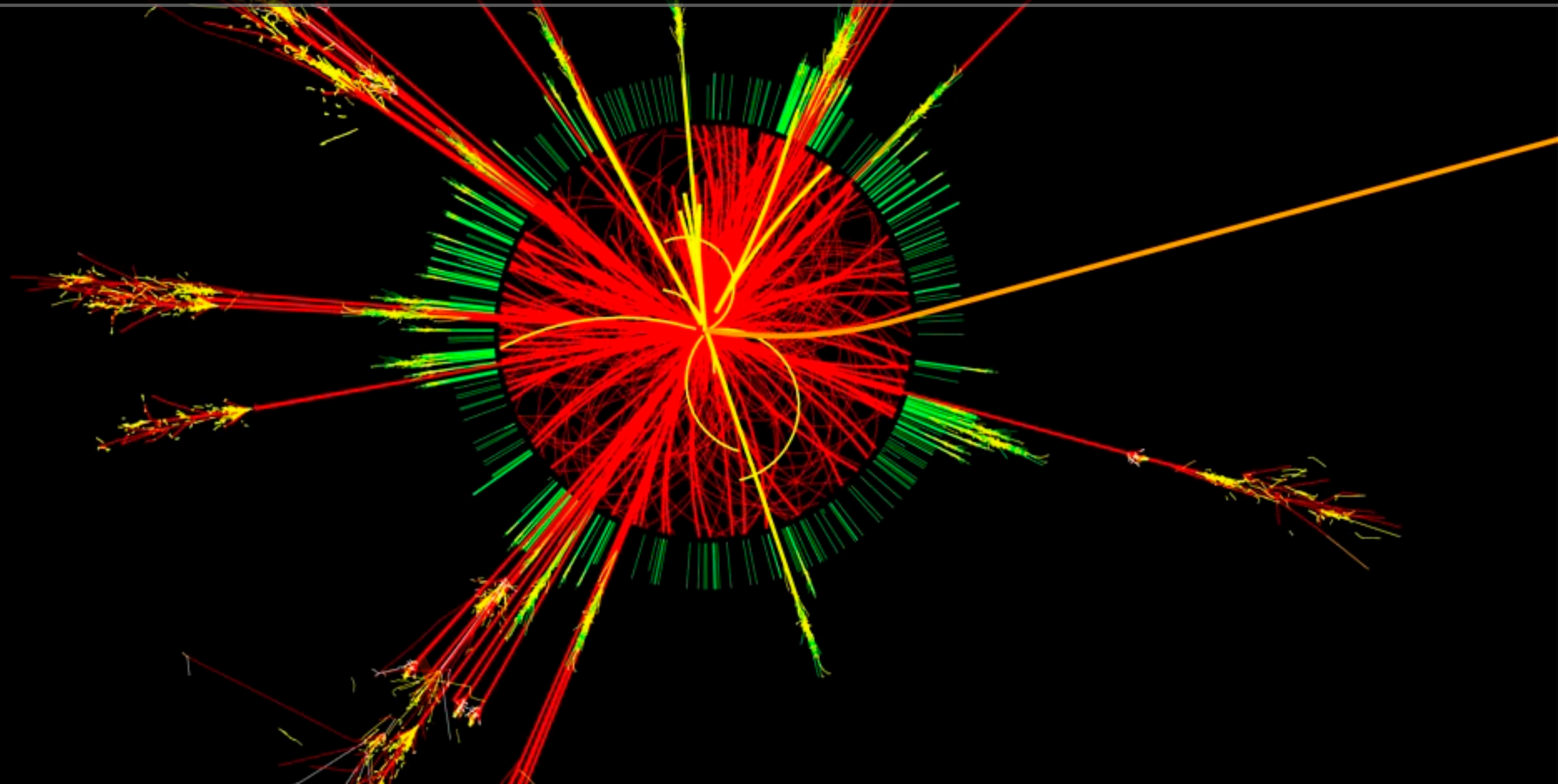
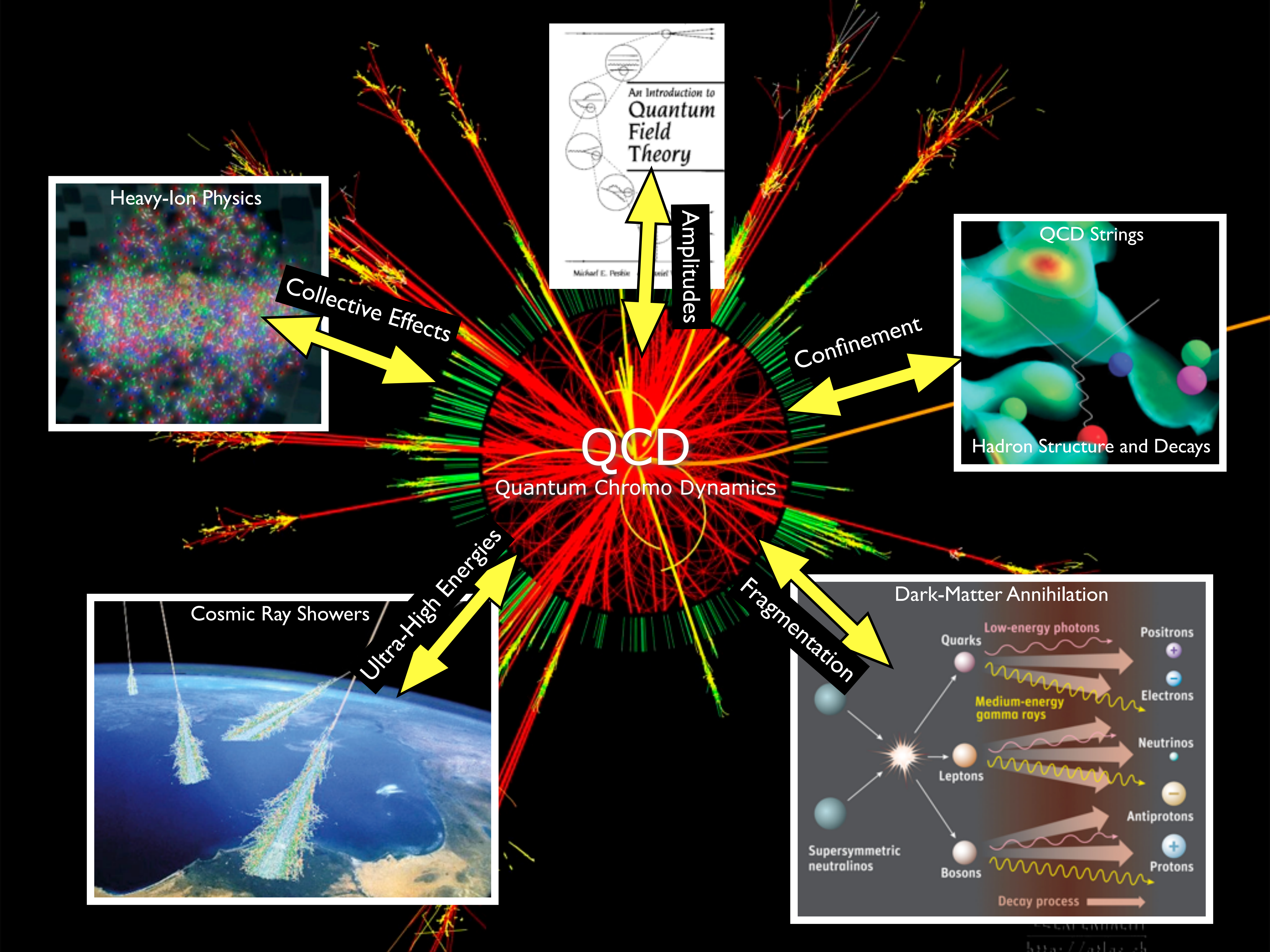
Center for Particle Physics Phenomenology, Odense, May 2012

QCD in the Era of the LHC

Theory and Practice



Peter Skands (CERN)


QCD
Quantum Chromo Dynamics
Heavy-Ion Physics
Collective Effects
An Introduction to
Quantum
Field
Theory
Michael E. Peskin
Amplitudes
QCD Strings
Confinement
Hadron Structure and Decays
Cosmic Ray Showers
Ultra-High Energies
Fragmentation
Dark-Matter Annihilation
Quarks
Low-energy photons
Positrons
Electrons
Medium-energy
gamma rays
Neutrinos
Leptons
Antiprotons
Supersymmetric
neutralinos
Bosons
Protons
Decay process

The Large Hadron Collider

Apr 5 2012 at 00:38 CEST: LHC shift crew declared 'stable beams' for physics data taking at 8 TeV

- Huge investment in resources and manpower
- Journal Publications: 85 ATLAS, 80 CMS, 25 LHCb, 22 ALICE

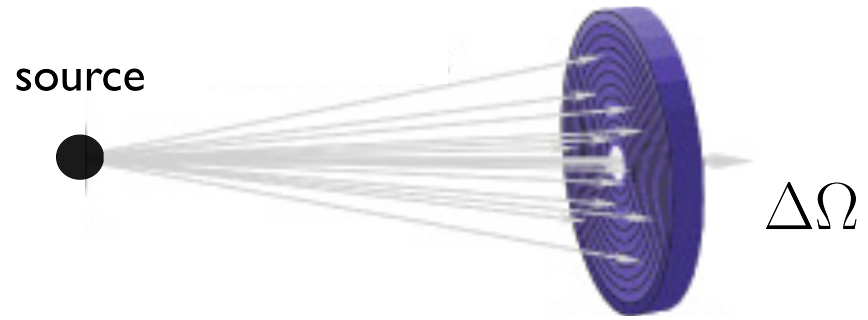
Searches for new physics still inconclusive

- Searching towards lower cross sections, the game gets harder
- + Intense scrutiny (after discovery) requires high precision

Theory task: invest in precision

This talk: to give an idea of how we (attempt to) solve QCD, and future developments

Scattering Experiments



LHC detector
Cosmic-Ray detector
Neutrino detector
X-ray telescope
…

→ Integrate differential cross sections over specific phase-space regions

Predicted number of counts
= integral over solid angle

$$N_{\mathrm{count}}(\Delta\Omega) \propto \int_{\Delta\Omega} \mathrm{d}\Omega \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}$$

In particle physics:
Integrate over all quantum histories

THEORY

$$\mathcal{L} = \bar{\psi}^i_q (i\gamma^\mu)(D_\mu)_{ij}\psi^j_q - m_q \bar{\psi}^i_q \psi_{qi} - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$$

→ colour-octet gauge bosons: gluons

+ (in SM): colour-triplet fermions: quarks

Free parameters = quark masses and value of α_s

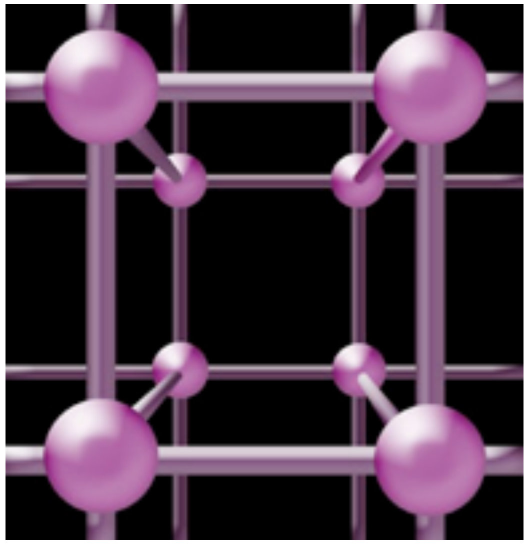
THEORY

$$\mathcal{L} = \bar{\psi}_q^i (i\gamma^\mu)(D_\mu)_{ij}\psi_q^j - m_q \bar{\psi}_q^i \psi_{qi} - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}$$

"Nothing"
Gluon action density: 2.4x2.4x3.6 fm
QCD Lattice simulation from
D. B. Leinweber, hep-lat/0004025

Why not Lattice for LHC?

To "resolve" a hard LHC collision



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

To include hadronization

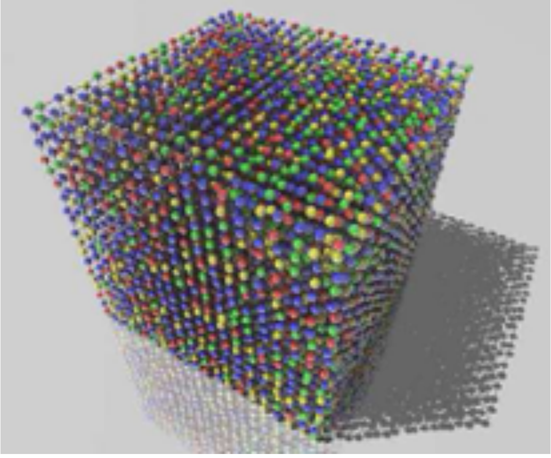
Proper time $t \sim \frac{1}{0.5\ \text{GeV}} \sim 0.4\ \text{fm}/c$ × Lorentz Boost Factor

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



Lattice → one or a few hadrons at a time

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

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
  - Beams = hadrons for next decade (RHIC / Tevatron / LHC)
    - At least need well-understood PDFs
    - High precision = higher orders → enter QCD (and more QED)
  - Isolation → indirect sensitivity to QCD
  - Fakes → indirect sensitivity to QCD
  - Not everything gives leptons
    - Need to be a lucky chicken …
- ► The unlucky chicken
  - Put all its eggs in one basket and didn't solve QCD

Monte Carlo

A Monte Carlo technique: is any technique making use of random numbers to solve a problem

Convergence:

Calculus: {A} converges to B
if an n exists for which
$|A_{i>n} - B| < \varepsilon$, for any $\varepsilon > 0$

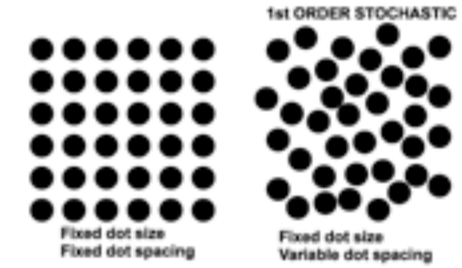
Monte Carlo: {A} converges to B
if n exists for which
the probability for
$|A_{i>n} - B| < \varepsilon$, for any $\varepsilon > 0$,
is > P, for any P[0<P<1]

"This risk, that convergence is only given with a certain probability, is inherent in Monte Carlo calculations and is the reason why this technique was named after the world's most famous gambling casino. Indeed, the name is doubly appropriate because the style of gambling in the Monte Carlo casino, not to be confused with the noisy and tasteless gambling houses of Las Vegas, is serious and sophisticated."

F. James, "Monte Carlo theory and practice", Rept. Prog. Phys. 43 (1980) 1145

Convergence

MC convergence is Stochastic!

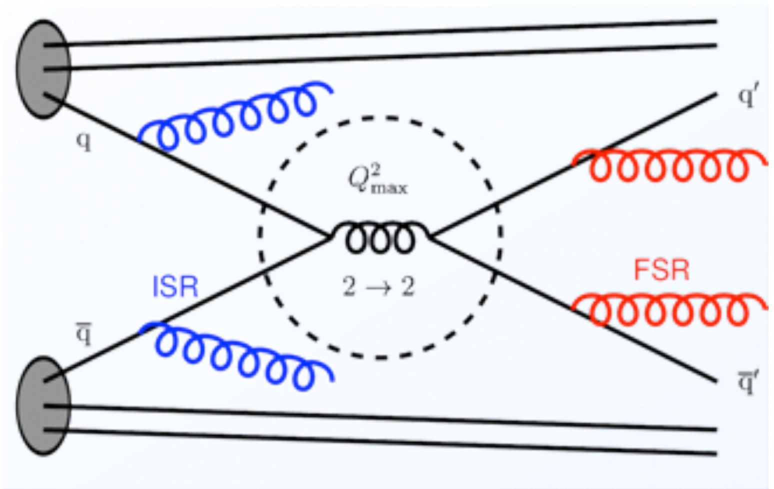


$\frac{1}{\sqrt{n}}$ in <u>any</u> dimension

Uncertainty (after n function evaluations)	n_{eval} / bin	Approx Conv. Rate (in 1D)	Approx Conv. Rate (in D dim)
Trapezoidal Rule (2-point)	2^D	$1/n^2$	$1/n^{2/D}$
Simpson's Rule (3-point)	3^D	$1/n^4$	$1/n^{4/D}$
… m-point (Gauss rule)	m^D	$1/n^{2m-1}$	$1/n^{(2m-1)/D}$
Monte Carlo	1	$1/n^{1/2}$	$1/n^{1/2}$

\+ many ways to optimize: stratification, adaptation, ...
\+ gives "events" → iterative solutions,
\+ interfaces to detector simulation & propagation codes

Monte Carlo Generators



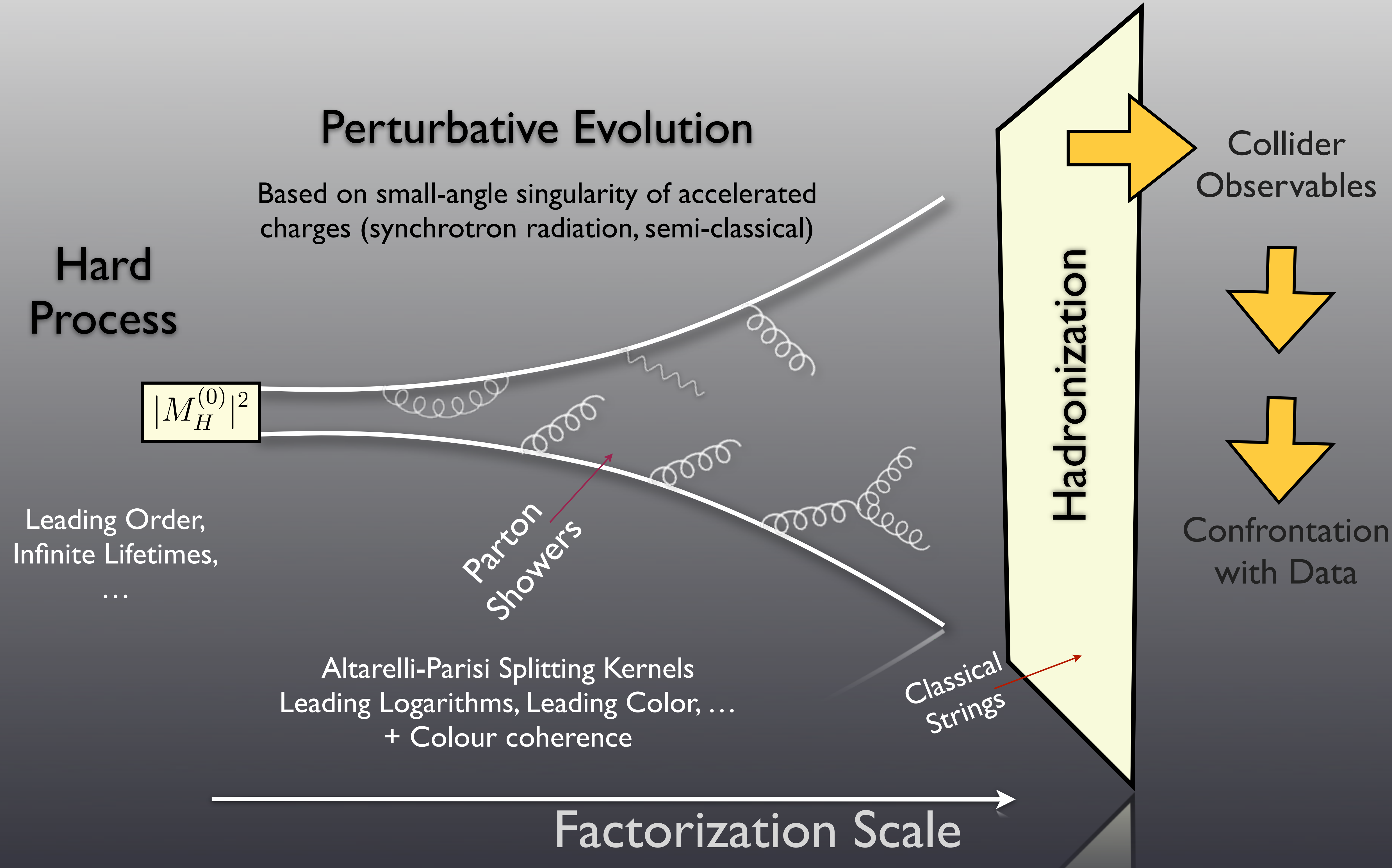
Calculate Everything ≈ solve QCD → requires compromise!

Improve lowest-order perturbation theory,
by including the 'most significant' corrections
→ complete events (can evaluate any observable you want)

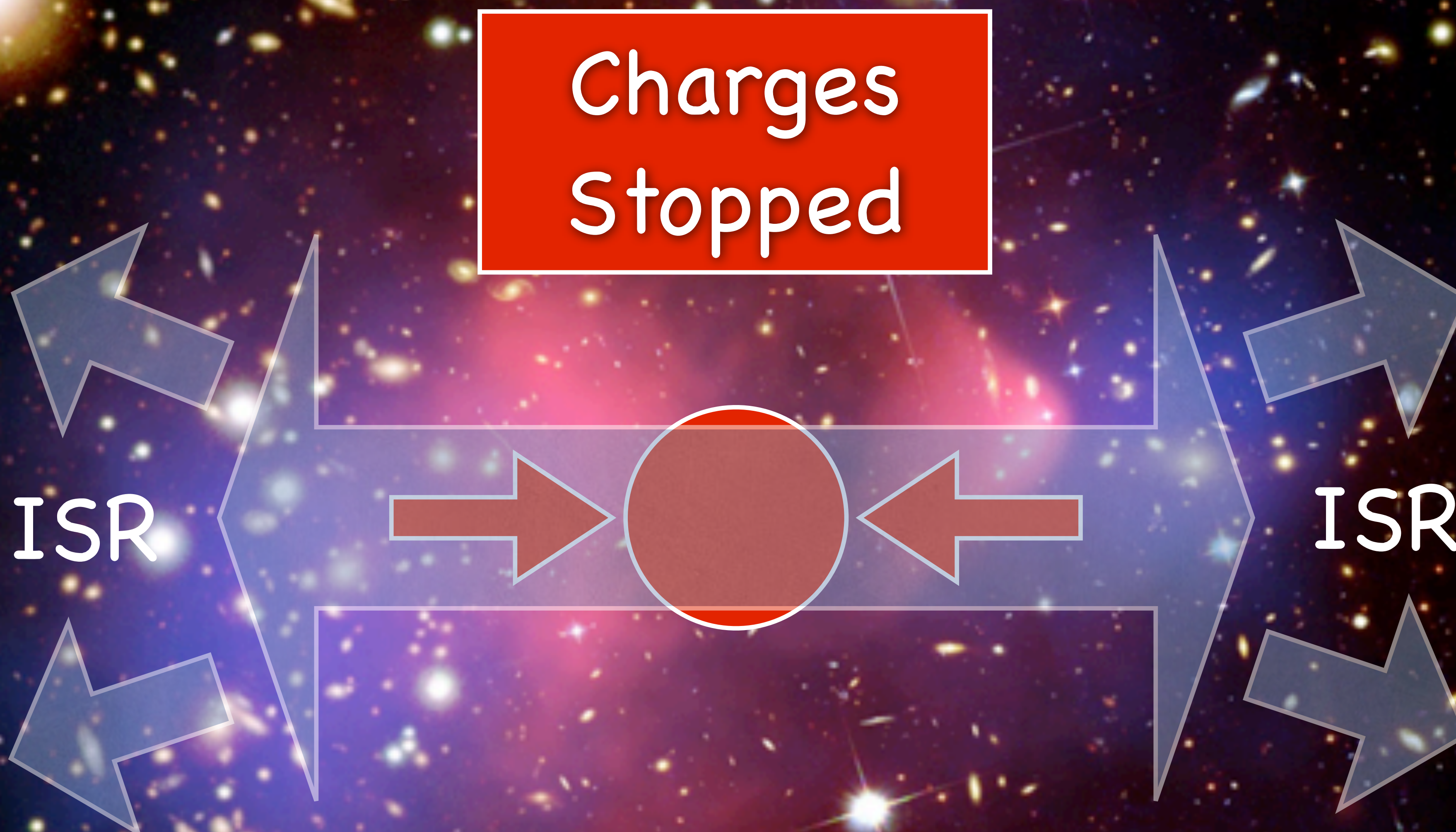
Existing Approaches

PYTHIA : Successor to JETSET (begun in 1978). Originated in hadronization studies: Lund String.
HERWIG : Successor to EARWIG (begun in 1984). Originated in coherence studies: angular ordering.
SHERPA : Begun in 2000. Originated in "matching" of matrix elements to showers: CKKW.
+ MORE SPECIALIZED: ALPGEN, MADGRAPH, ARIADNE, VINCIA, WHIZARD, MC@NLO, POWHEG, …

(Traditional) Monte Carlo Generators



Perturbative Evolution: Bremsstrahlung



The harder they stop, the harder the fluctations that continue to become strahlung

The Strong Coupling

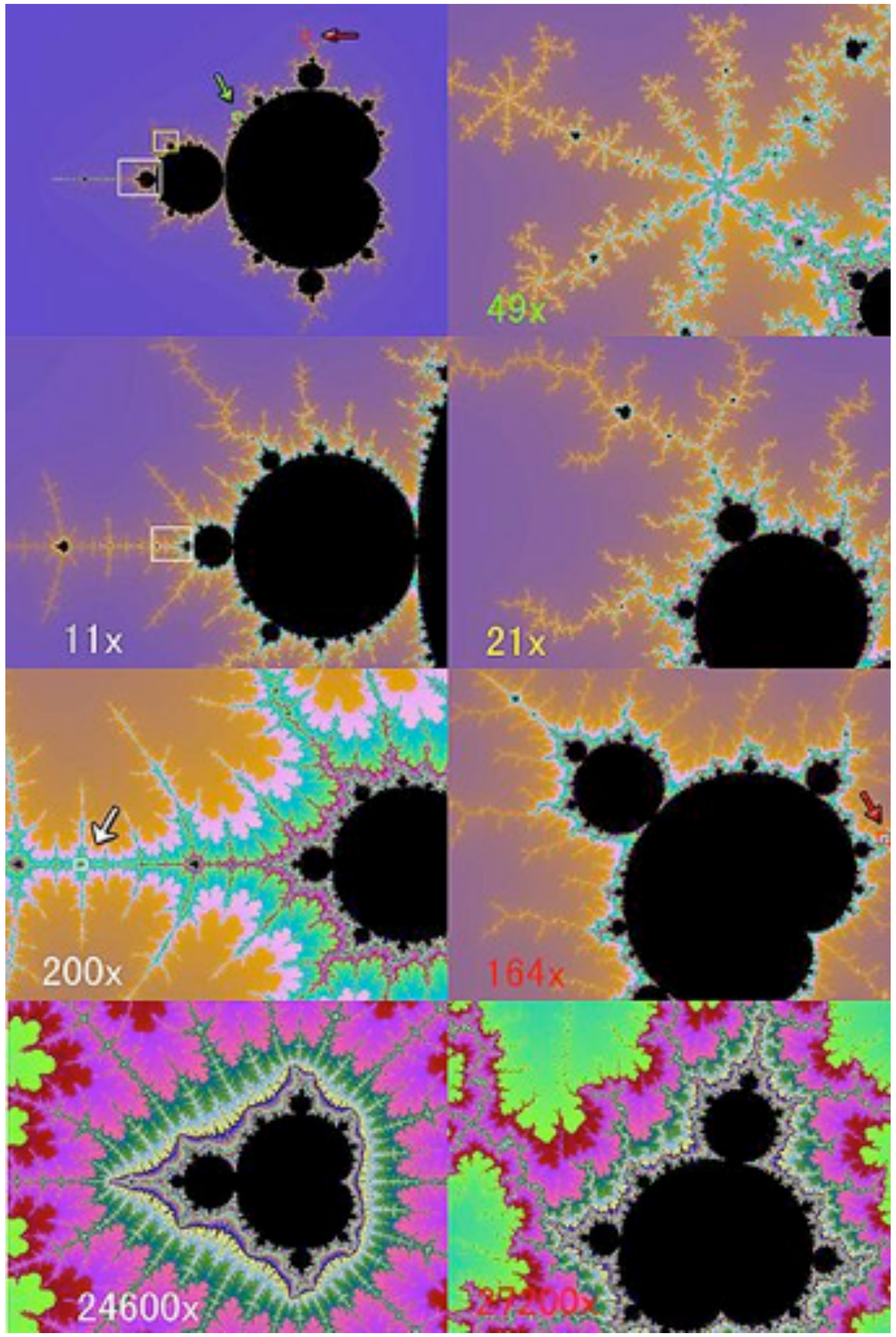
Bjorken scaling

To first approximation, QCD is SCALE INVARIANT (a.k.a. conformal)

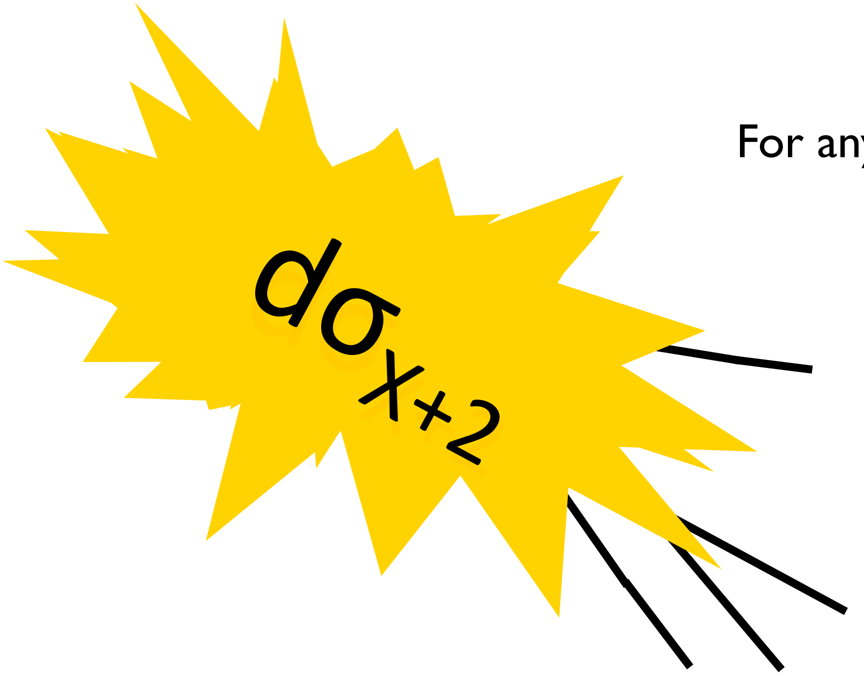
A jet inside a jet inside a jet inside a jet …

If the strong coupling did not "run", this would be absolutely true (e.g., N=4 Supersymmetric Yang-Mills)

As it is, the coupling only runs slowly (logarithmically) at high energies → can still gain insight from fractal analogy



Bremsstrahlung



For any basic process $d\sigma_X$ = ✓ (calculated process by process)

$$d\sigma_{X+1} \sim N_C 2 g_s^2 \frac{ds_{i1}}{s_{i1}} \frac{ds_{1j}}{s_{1j}} d\sigma_X \quad ✓$$

$$d\sigma_{X+2} \sim N_C 2 g_s^2 \frac{ds_{i2}}{s_{i2}} \frac{ds_{2j}}{s_{2j}} d\sigma_{X+1} \quad ✓$$

$$d\sigma_{X+3} \sim N_C 2 g_s^2 \frac{ds_{i3}}{s_{i3}} \frac{ds_{3j}}{s_{3j}} d\sigma_{X+2} \quad \ldots$$

This gives an approximation to infinite-order tree-level cross sections (here "double-log approximation: DLA")

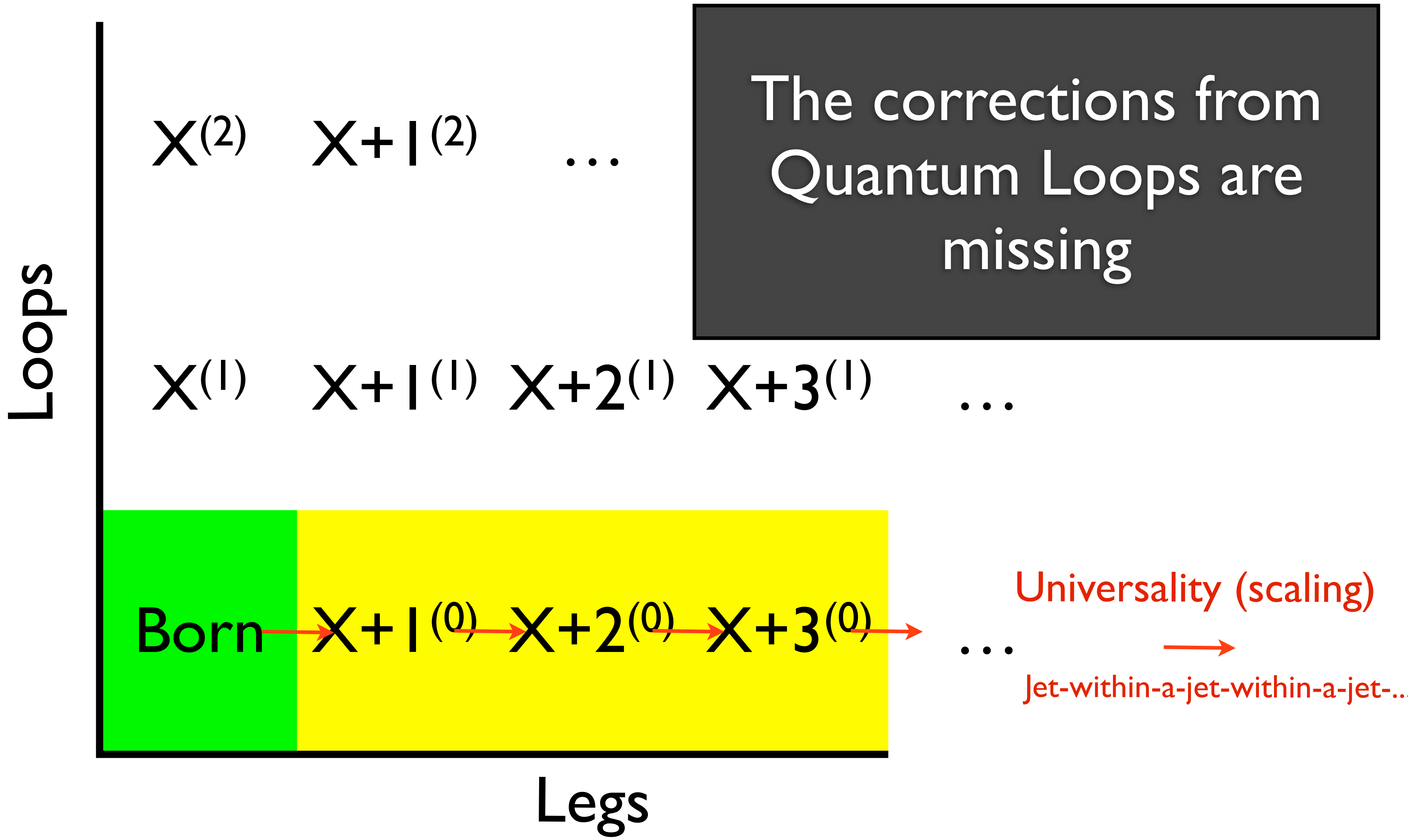
(Running coupling and a few more subleading singular terms can also be included → MLLA, NLL, …)

But something is not right …

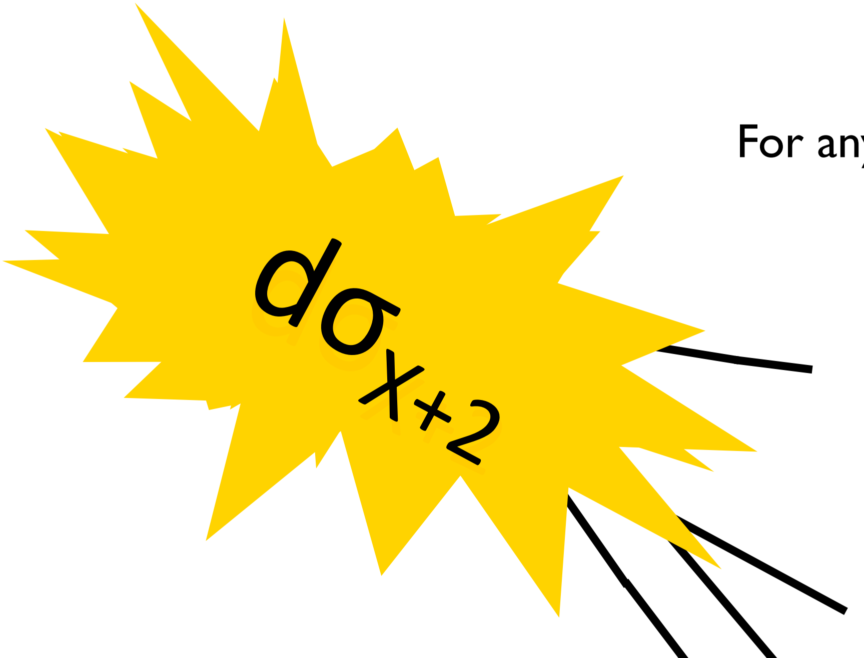
Total cross section would be infinite …

Loops and Legs

Coefficients of the Perturbative Series



Unitarity



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$$d\sigma_{X+2} \sim N_C 2 g_s^2 \frac{ds_{i2}}{s_{i2}} \frac{ds_{2j}}{s_{2j}} d\sigma_{X+1} \quad \ldots$$

Unitarity

Kinoshita-Lee-Nauenberg:

Loop = – Int(Tree) + F

Neglect F → Leading-Logarithmic (LL) Approximation

Imposed by Event *evolution*:

When (X) branches to (X+1):
Gain one (X+1). Loose one (X).

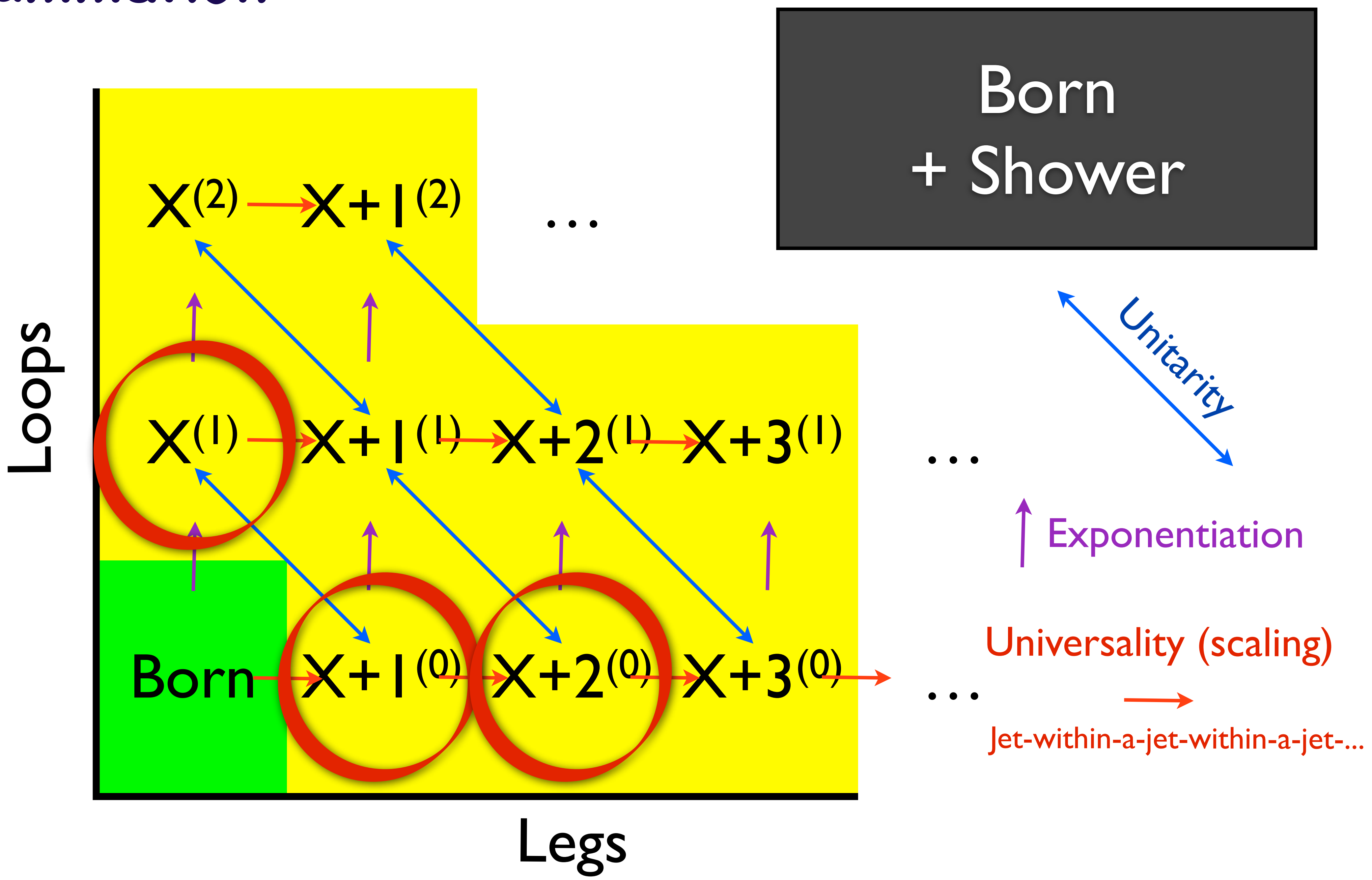
→ *evolution equation with kernel* $\frac{d\sigma_{X+1}}{d\sigma_X}$

Evolve in some measure of *resolution*
~ virtuality, energy, … ~ fractal scale

→ includes both real (tree) and virtual (loop) corrections

Bootstrapped Perturbation Theory

Resummation



New: Markovian pQCD*

*)pQCD : perturbative QCD

Start at Born level

$$|M_F|^2$$

Generate "shower" emission

$$|M_{F+1}|^2 \overset{LL}{\sim} \sum_{i \in \mathrm{ant}} a_i \; |M_F|^2$$

Correct to Matrix Element

$$a_i \to \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2} a_i$$

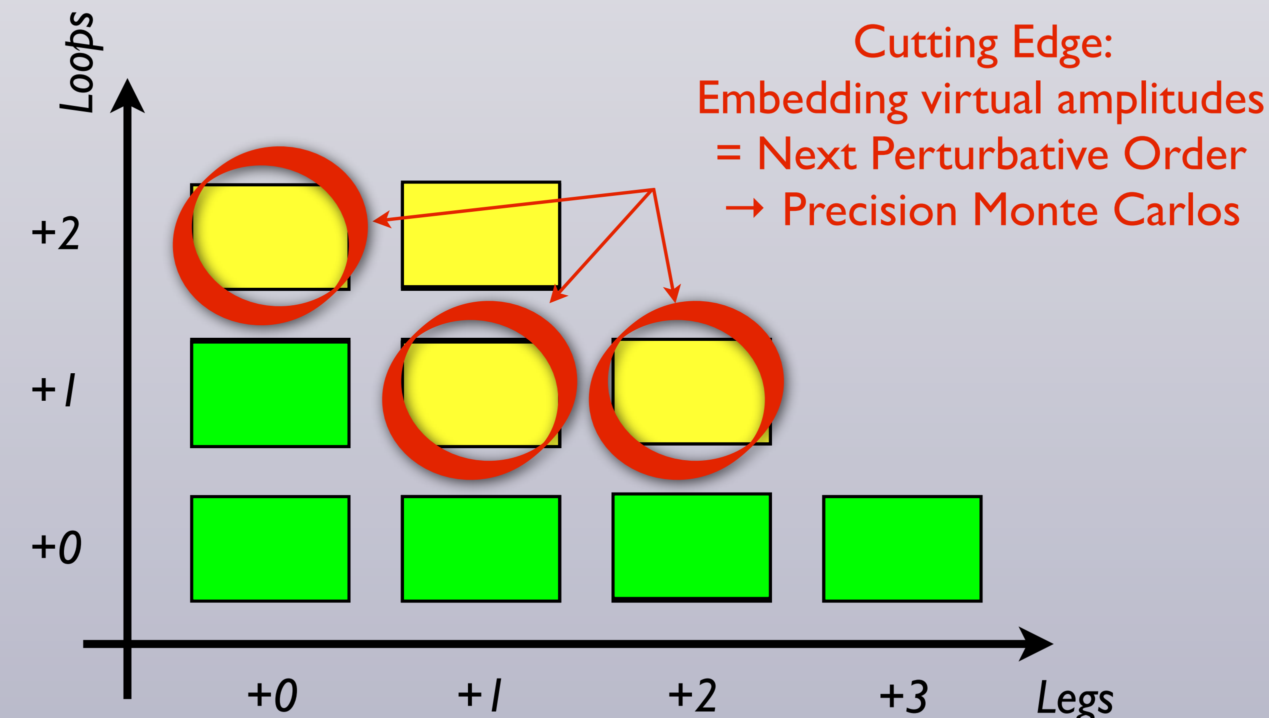
Unitarity of Shower

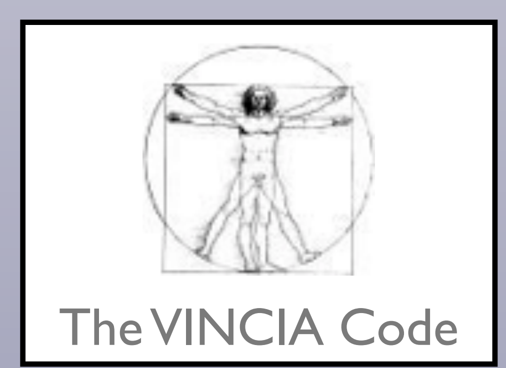
$$\mathrm{Virtual} = - \int \mathrm{Real}$$

Correct to Matrix Element

$$|M_F|^2 \to |M_F|^2 + 2\mathrm{Re}[M_F^1 M_F^0] + \int \mathrm{Real}$$

Repeat





+

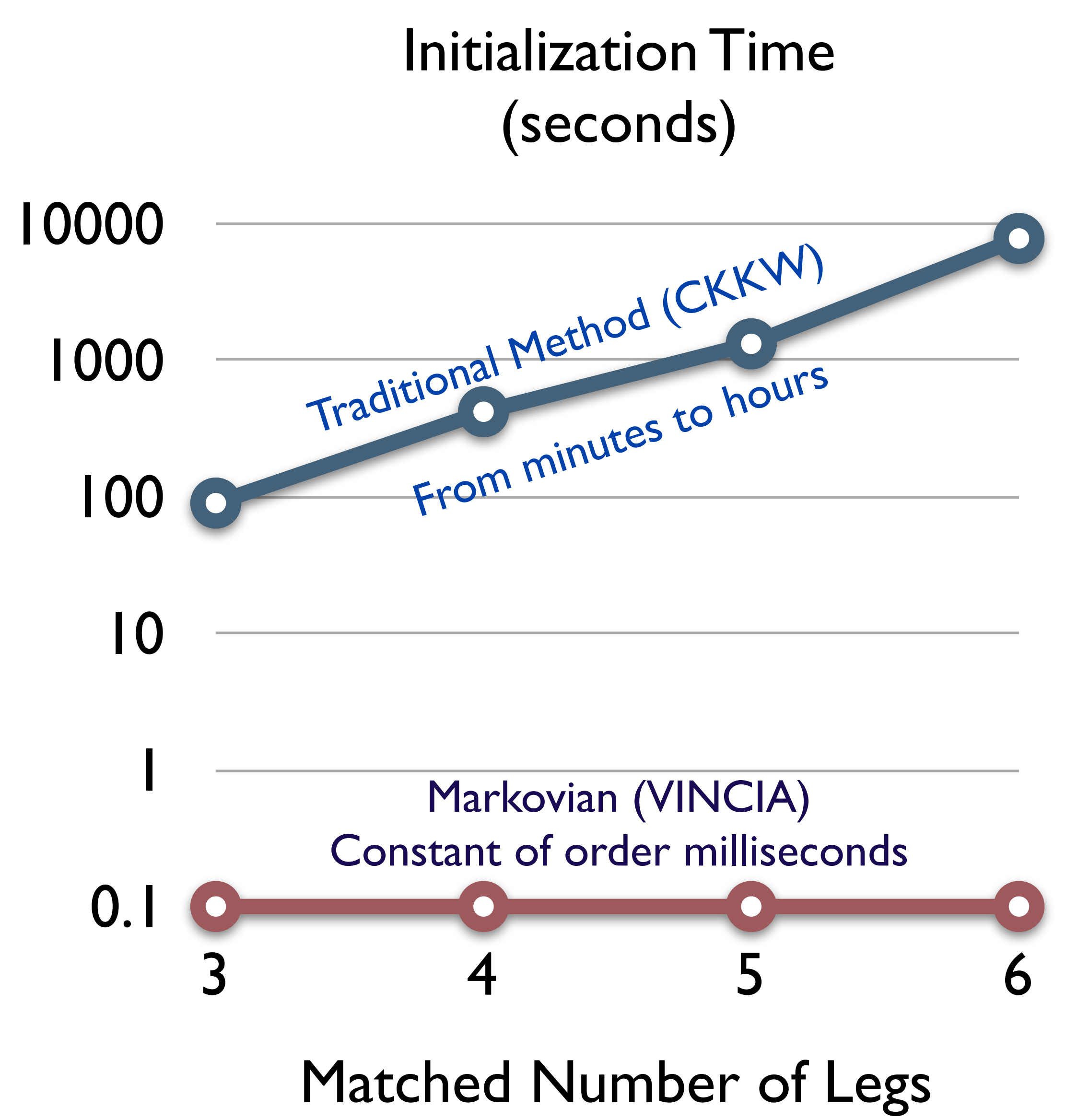
VINCIA: Giele, Kosower, Skands, PRD78(2008)014026 & PRD84(2011)054003
+ ongoing work with M. Ritzmann, E. Laenen, L. Hartgring, A. Larkoski, J. Lopez-Villarejo
PYTHIA: Sjöstrand, Mrenna, Skands, JHEP 0605 (2006) 026 & CPC 178 (2008) 852

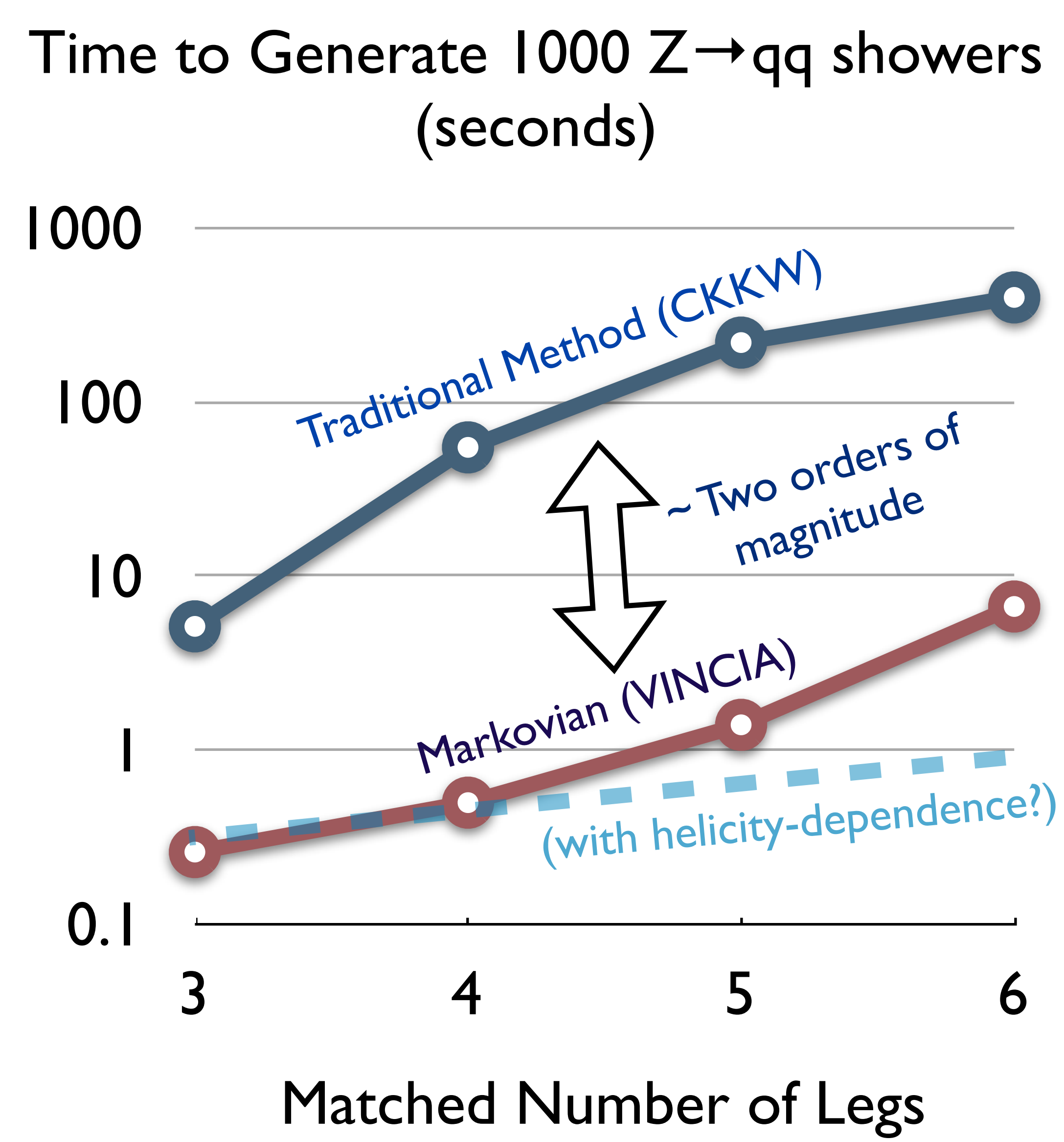
Note: other teams working on alternative strategies with similar goals
Perturbation theory is solvable → expect improvements

SPEED

Efficient Matching with Sector Showers
J. Lopez-Villarejo & PS : JHEP 1111 (2011) 150

(Why we believe Markov + unitarity is the method of choice for complex problems)





$Z \to qq$ *(q=udscb)* + shower. Matched and unweighted. Hadronization off

gfortran/g++ with gcc v.4.4 -O2 on single 3.06 GHz processor with 4GB memory

Generator Versions: Pythia 6.425 *(Perugia 2011 tune)*, Pythia 8.150, Sherpa 1.3.0, Vincia 1.026 *(without uncertainty bands, NLL/NLC=OFF)*

Uncertainties

A result is only as good as its uncertainty

Normal procedure:

Run MC 2N+1 times (for central + N up/down variations)

Takes 2N+1 times as long

+ uncorrelated statistical fluctuations

Instead: *Automate & do everything in one run*

All events have central weight = 1

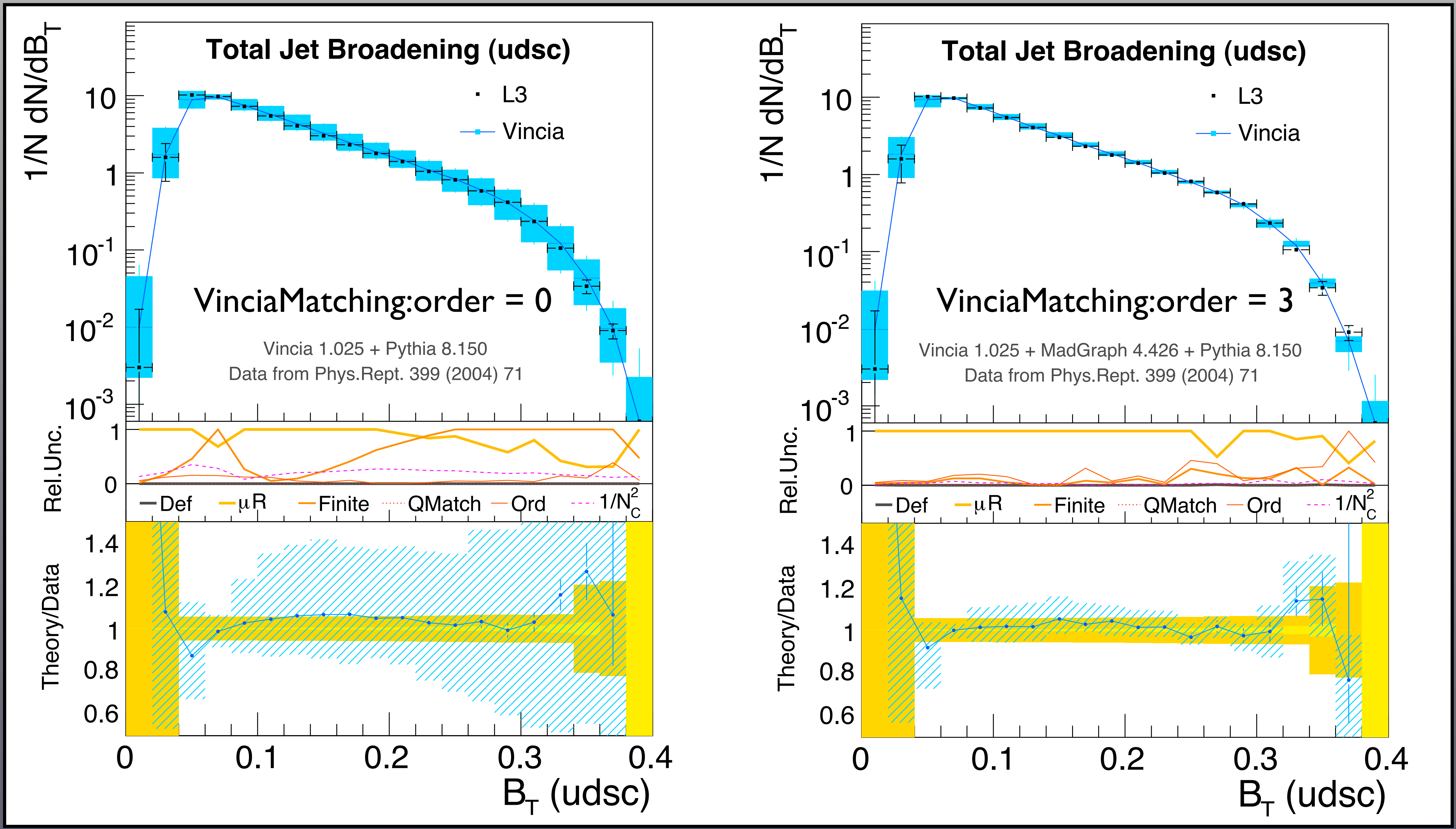
Compute *unitary* alternative weights on the fly

→ *sets of alternative weights representing variations (all with <w>=1)*

Same events, so only have to be hadronized/detector-simulated ONCE!

→ Used to provide automatic Theory Uncertainty Bands in VINCIA

Quantifying Precision



Note: VINCIA so far only developed for final-state radiation (fragmentation)
Initial State under development, to follow this autumn

Hadronization

The problem:

- Given a set of partons resolved at a scale of ~ 1 GeV (the perturbative cutoff), need a **"mapping"** from this set onto a set of on-shell colour-singlet (i.e., confined) hadronic states.

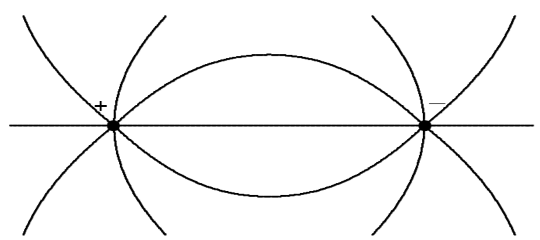
MC models do this in three steps

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., $\rho > \pi\ \pi$, $\Lambda^0 > n\ \pi^0$, $\pi^0 > \gamma\gamma$, ...)

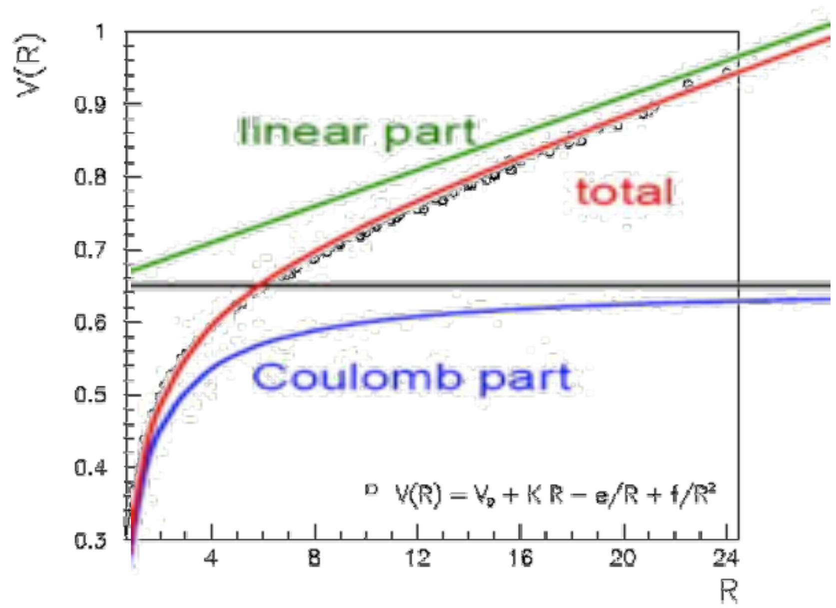
Distance Scales ~ 10^{-15} m = 1 fermi

From Partons to Strings

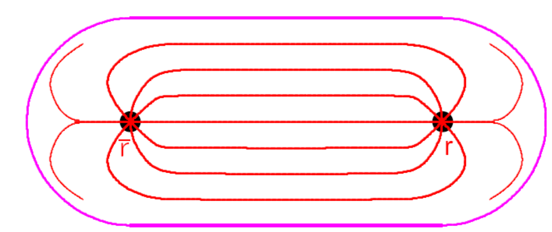
Short Distances ~ pQCD



Partons



Long Distances ~ Linear Confinement



Strings (Flux Tubes), Hadrons

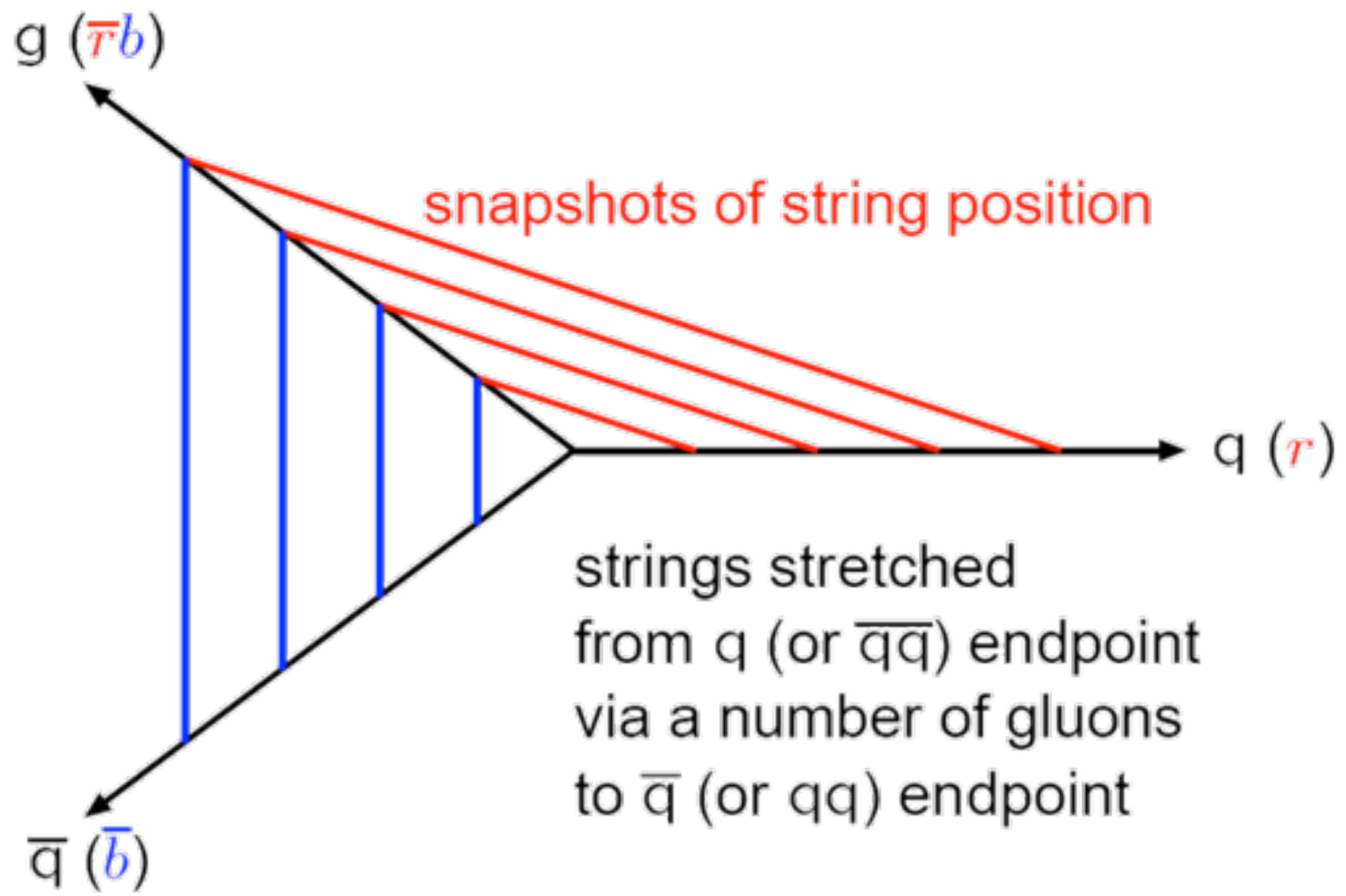
$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$

- **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**

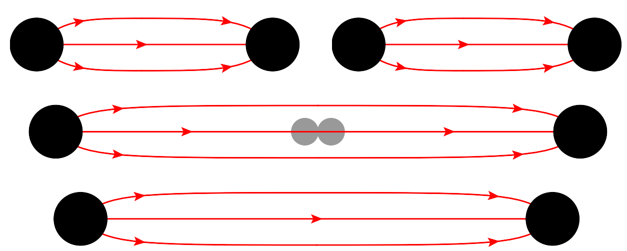


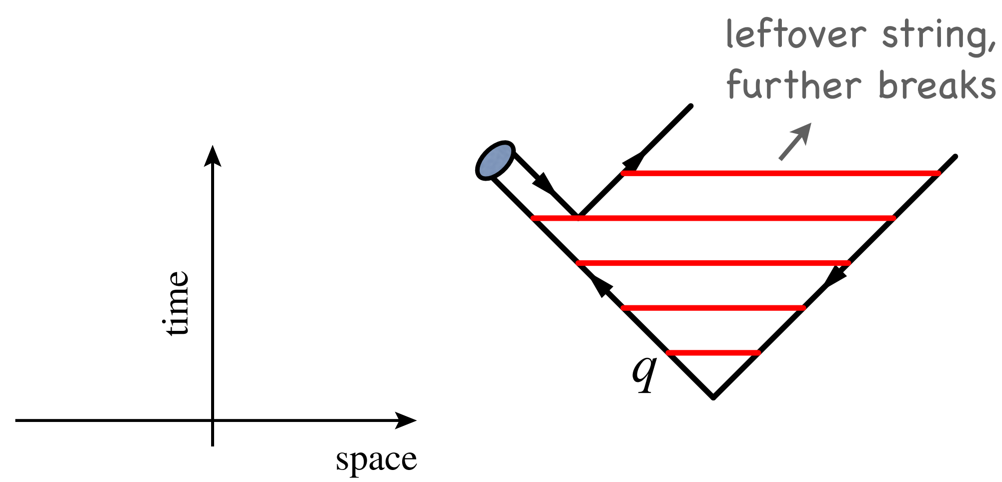
Gluon = kink on string, carrying energy and momentum

Simple space-time picture
Details of string breaks more complicated → tuning

Hadronization

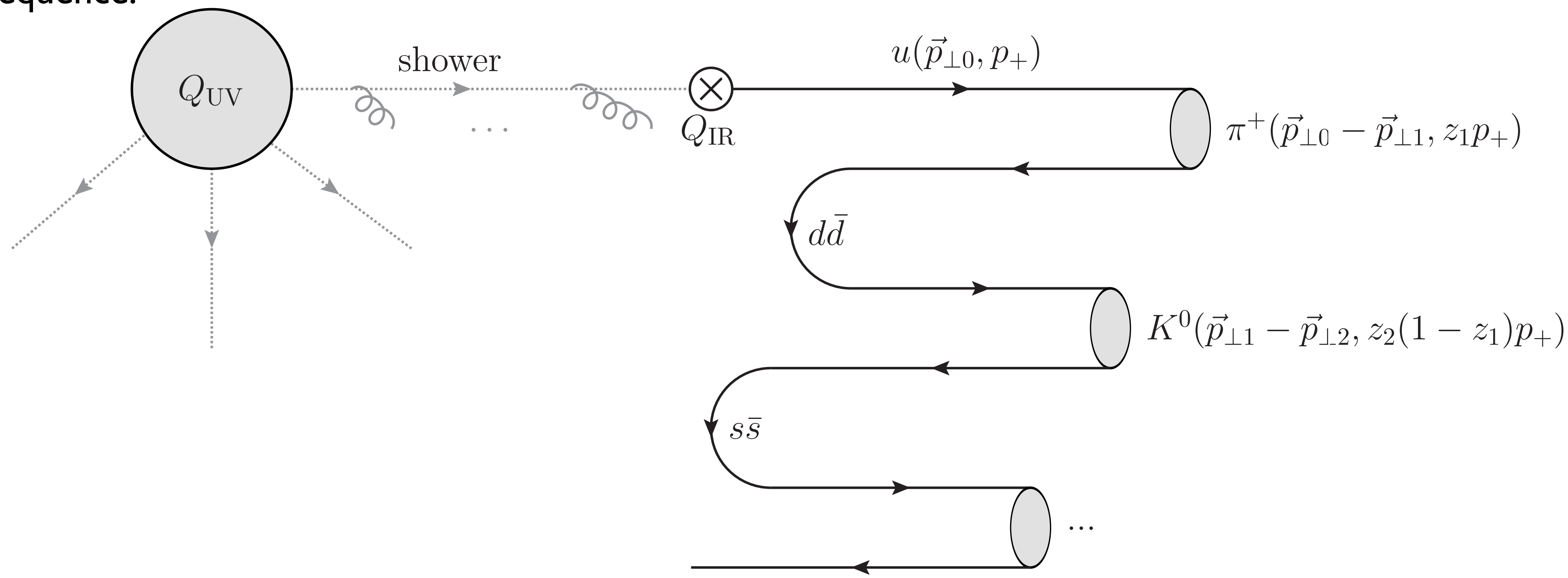
One Breakup:





Area → Law	$\text{Prob}(m_q^2, p_{\perp q}^2) \propto \exp\left(\frac{-\pi m_q^2}{\kappa}\right) \exp\left(\frac{-\pi p_{\perp q}^2}{\kappa}\right)$	Causality → Lund FF	$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{b\,(m_h^2 + p_{\perp h}^2)}{z}\right)$

Iterated Sequence:



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Number of connected Volunteers Worldwide: 4919
Number of generated events so far: 322.5 billion

Conclusions

QCD phenomenology is witnessing a rapid evolution:

Dipole/antenna shower models, (N)LO matching, better interfaces/tuning, …

New techniques developed to compute complex QCD amplitudes (e.g., unitarity), and to embed these within shower resummations (VINCIA)

Driven by demand of **high precision** for LHC environment

Will automatically benefit other communities, like astro-particle and heavy-ion

Non-perturbative QCD is still hard

Lund string model remains best bet, but ~ 30 years old

Lots of input from LHC: total cross sections, min-bias, multiplicities, ID particles, correlations, shapes, you name it … *(THANK YOU to the experiments!)*

New ideas (like AdS/QCD, hydro, ...) still in their infancy; but there *are* new ideas!

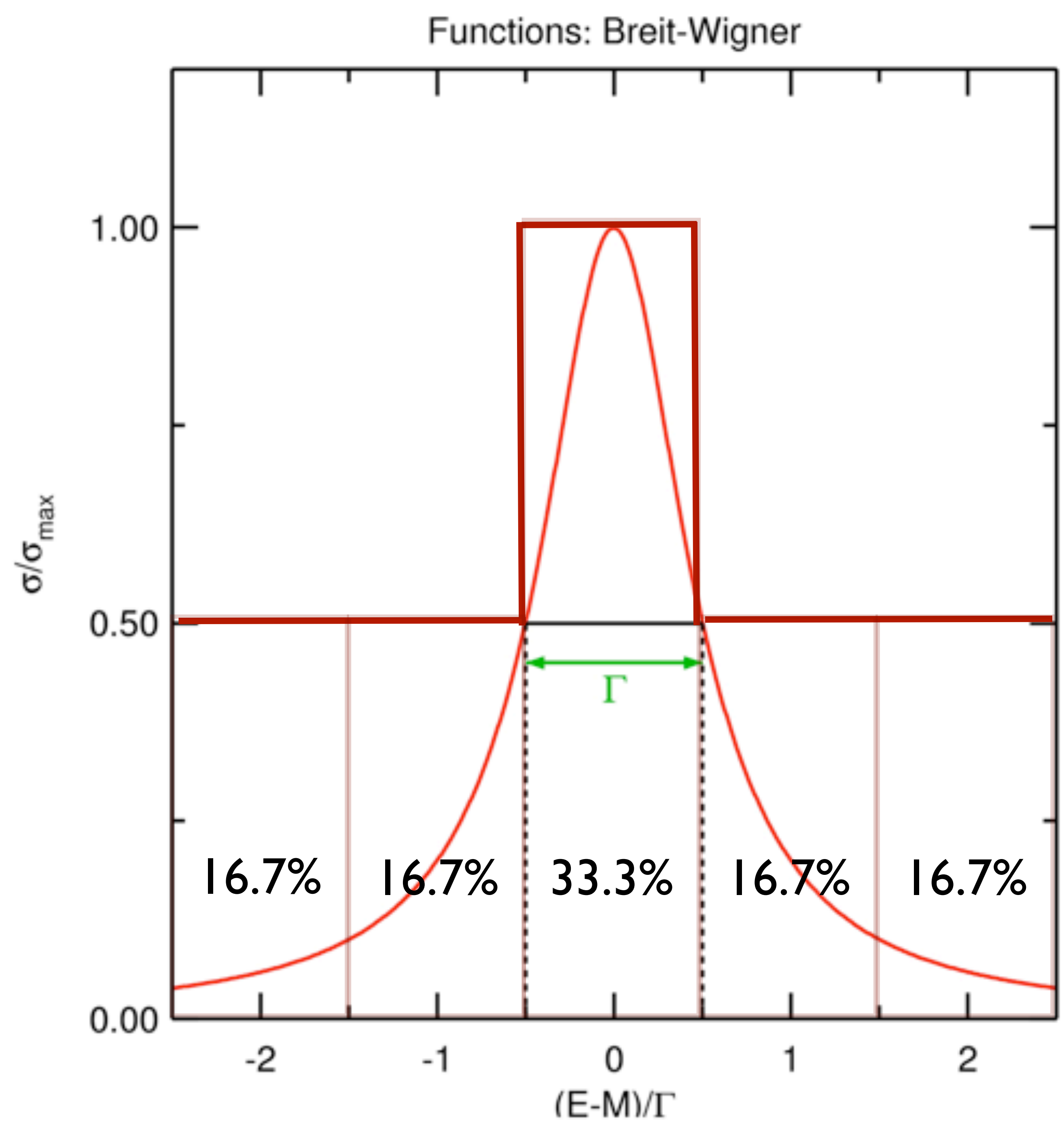
"Solving the LHC" is both interesting and rewarding

The key to high precision → maximum information about *ALL OTHER* physics...

Want more information? 2012 edition of *Review of Particle Physics* (PDG) will include a new Section, on "Monte Carlo Event Generators", by P. Nason & PS.

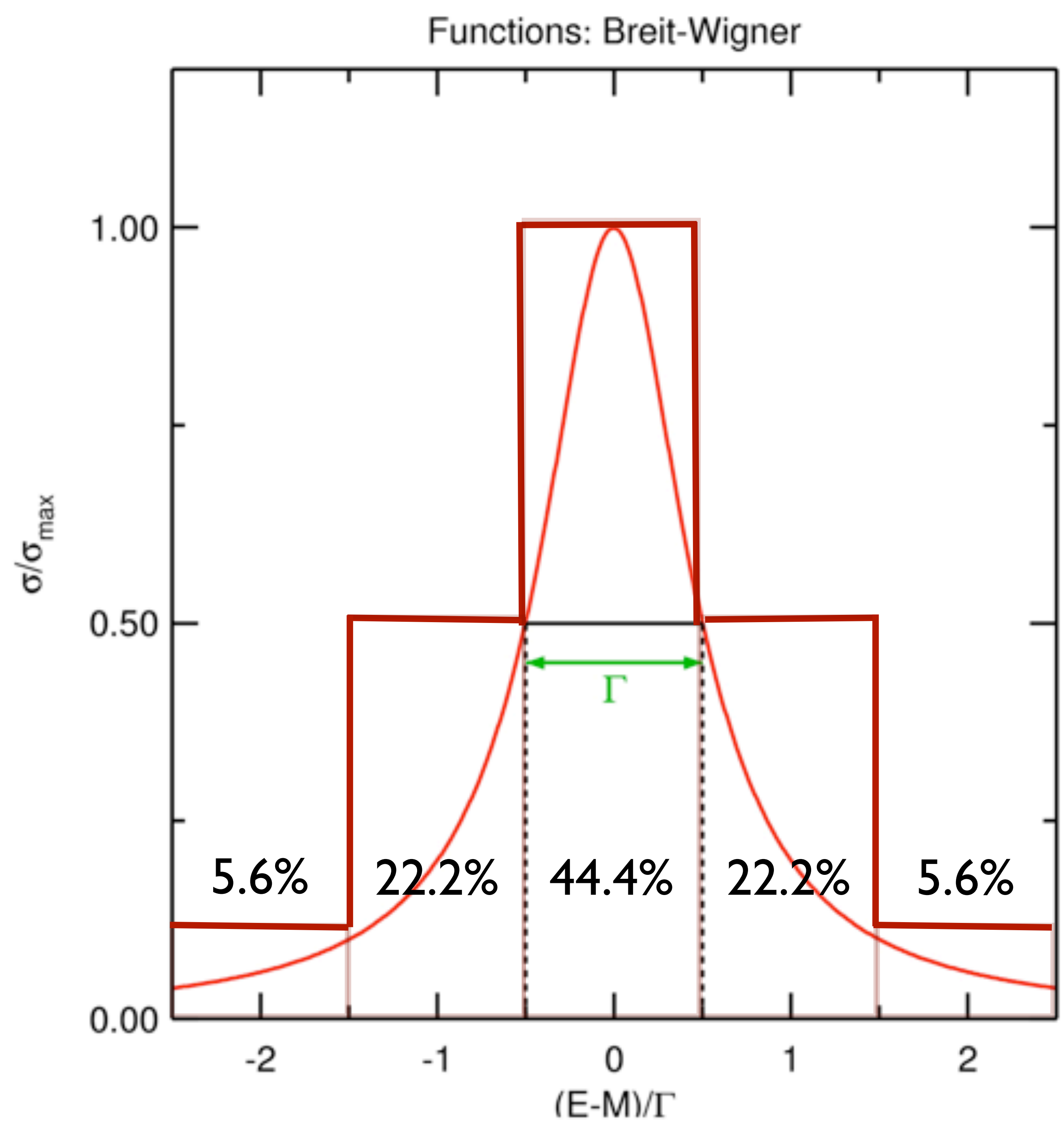
Backup Slides

Stratified Sampling



→ make it twice as likely to throw points in the peak
→ faster convergence for same number of function evaluations

Adaptive Sampling

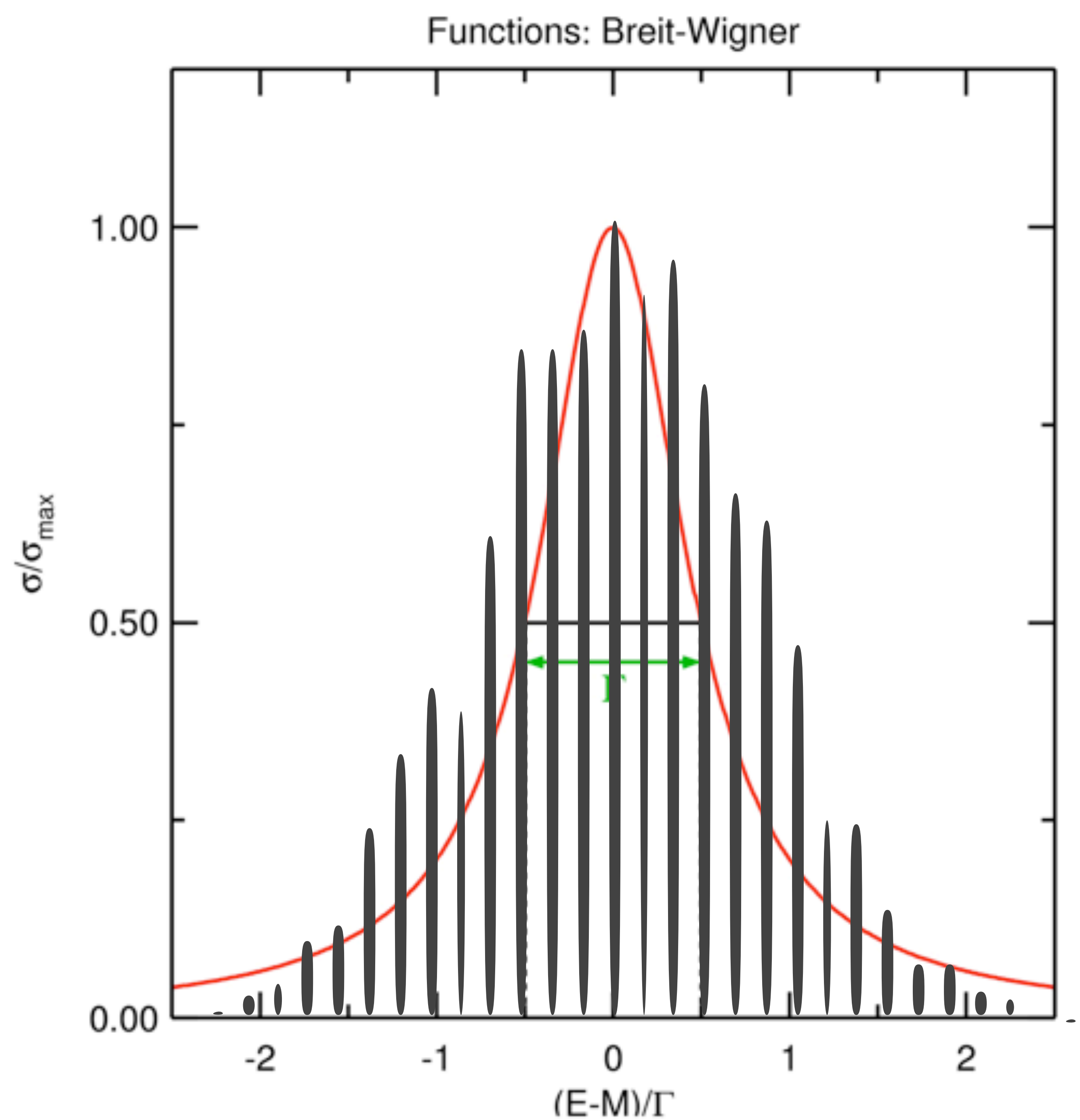


→ can even design algorithms that do this automatically as they run

→ Adaptive sampling

Importance Sampling

E.g., VEGAS algorithm, by G. Lepage



→ or throw points according to some smooth peaked function for which you have, or can construct, a random number generator (here: Gauss)

Why does this work?

1. **You are inputting knowledge:** obviously need to know where the peaks are to begin with … **(say you know, e.g., the location and width of a resonance)**

2. **Stratified sampling** increases efficiency by combining n-point quadrature with the MC method, with further gains from adaptation

3. **Importance sampling:**

$$\int_a^b f(x)\mathrm{d}x = \int_a^b \frac{f(x)}{g(x)}\mathrm{d}G(x)$$

Effectively does flat MC with changed integration variables

Fast convergence if $f(x)/g(x) \approx 1$

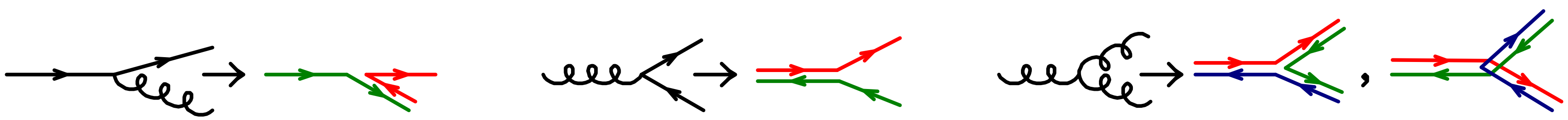
(Color Flow in MC Models)

"Planar Limit"

Equivalent to $N_C \to \infty$: no color interference*

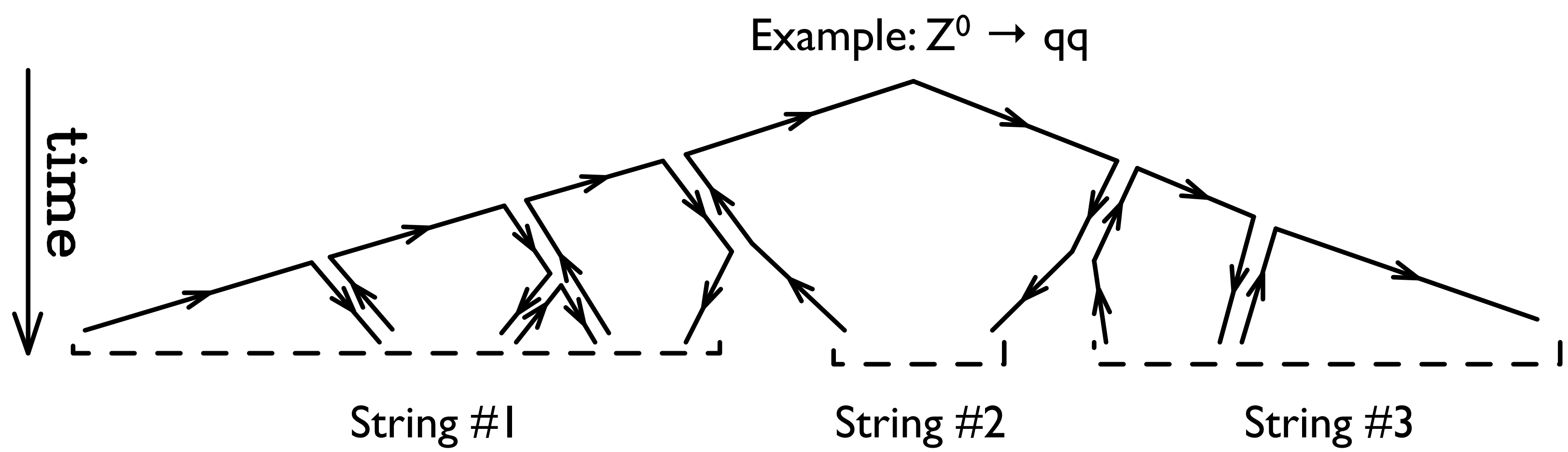
*) except as reflected by the implementation of QCD coherence effects in the Monte Carlos via angular or dipole ordering

Rules for color flow:



For an entire cascade:

Illustrations from: Nason + PS, PDG Review on *MC Event Generators*, 2012



Coherence of pQCD cascades → not much "overlap" between strings
→ planar approx pretty good
LEP measurements in WW confirm this (at least to order 10% ~ $1/N_c^2$)

The Denominator

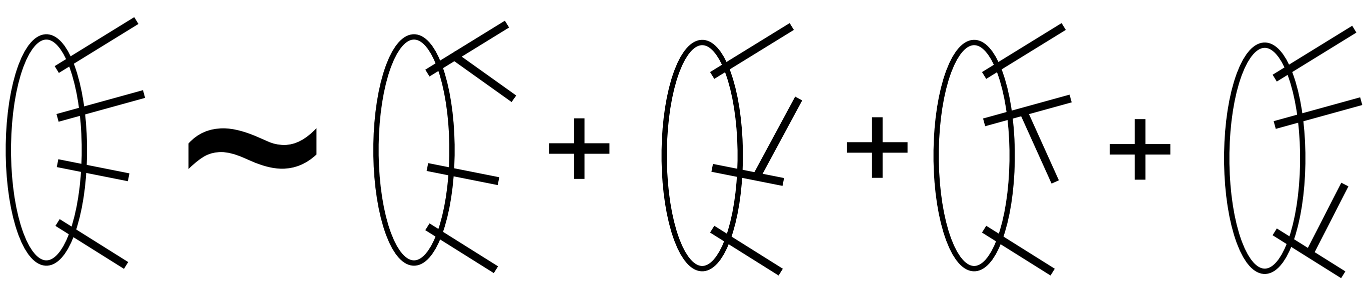
$$a_i \rightarrow \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2}$$

In a traditional parton shower, you would face the following problem:

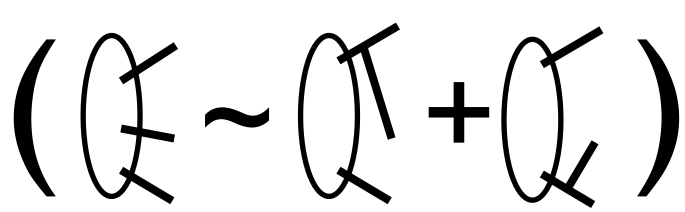
Existing parton showers are *not* really Markov Chains

Further evolution (restart scale) depends on which branching happened last → proliferation of terms

Number of histories contributing to n^{th} branching $\propto$ **$2^n n!$**



j = 2
→ 4 terms



j = 1
→ 2 terms

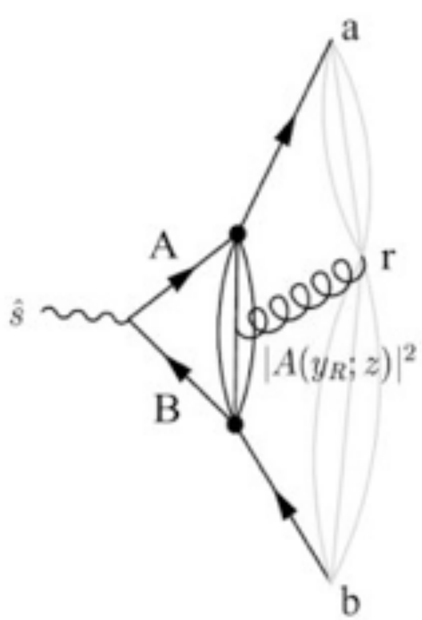
Parton- (or Catani-Seymour) Shower:
After 2 branchings: 8 terms
After 3 branchings: 48 terms
After 4 branchings: 384 terms

(+ parton showers have complicated and/or frame-dependent phase-space mappings, especially at the multi-parton level)

Matched Markovian Antenna Showers

Antenna showers: one term per parton *pair* **$2^n n! \to n!$**

Giele, Kosower, Skands, PRD 84 (2011) 054003



(+ generic Lorentz-invariant and on-shell phase-space factorization)

+ Change "shower restart" to Markov criterion:

Given an *n*-parton configuration, "ordering" scale is

$$Q_{ord} = \min(Q_{E1}, Q_{E2}, ..., Q_{En})$$

Unique restart scale, independently of how it was produced

+ Matching: $n! \to n$

Given an *n*-parton configuration, its phase space weight is:

$|M_n|^2$: *Unique weight, independently of how it was produced*

Matched Markovian Antenna Shower:
After 2 branchings: 2 terms
After 3 branchings: 3 terms
After 4 branchings: 4 terms

Parton- (or Catani-Seymour) Shower:
After 2 branchings: 8 terms
After 3 branchings: 48 terms
After 4 branchings: 384 terms

\+ **Sector** antennae *Larkosi, Peskin, Phys.Rev. D81 (2010) 054010*

→ 1 term at *any* order *Lopez-Villarejo, Skands, JHEP 1111 (2011) 150*

Approximations

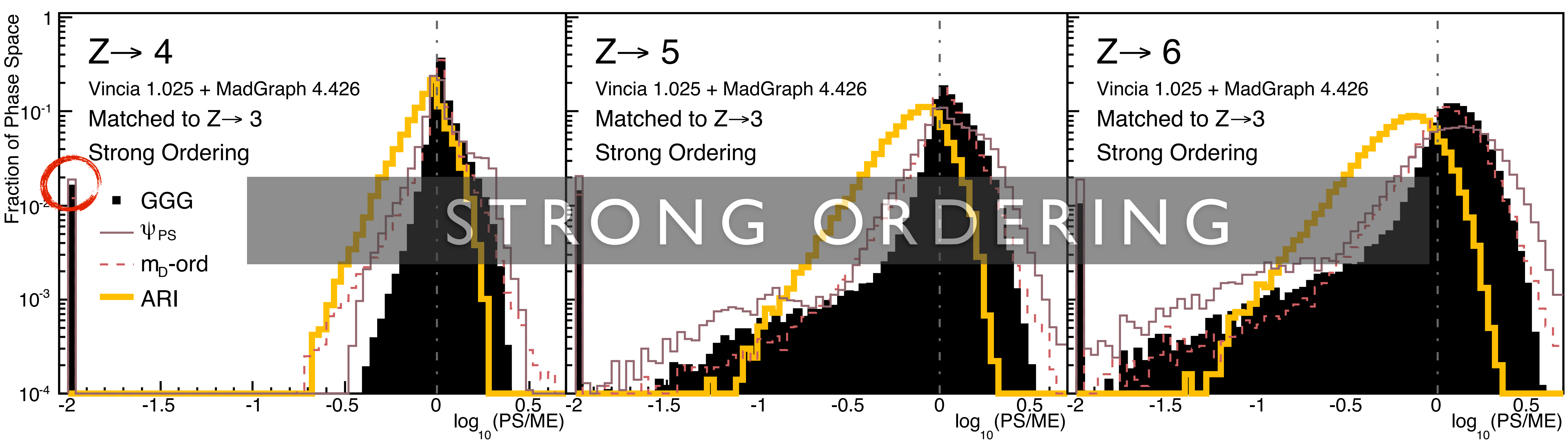
Q: How well do showers do?

Exp: Compare to data. Difficult to interpret; all-orders cocktail including hadronization, tuning, uncertainties, etc

Th: Compare products of splitting functions to full tree-level matrix elements

Plot distribution of **$\mathbf{Log_{10}}$(PS/ME)**

(second order) (third order) (fourth order)



Dead Zone: 1-2% of phase space have no strongly ordered paths leading there*

*fine from strict LL point of view: those points correspond to "unordered" non-log-enhanced configurations

2→4

Generate Branchings *without* imposing strong ordering

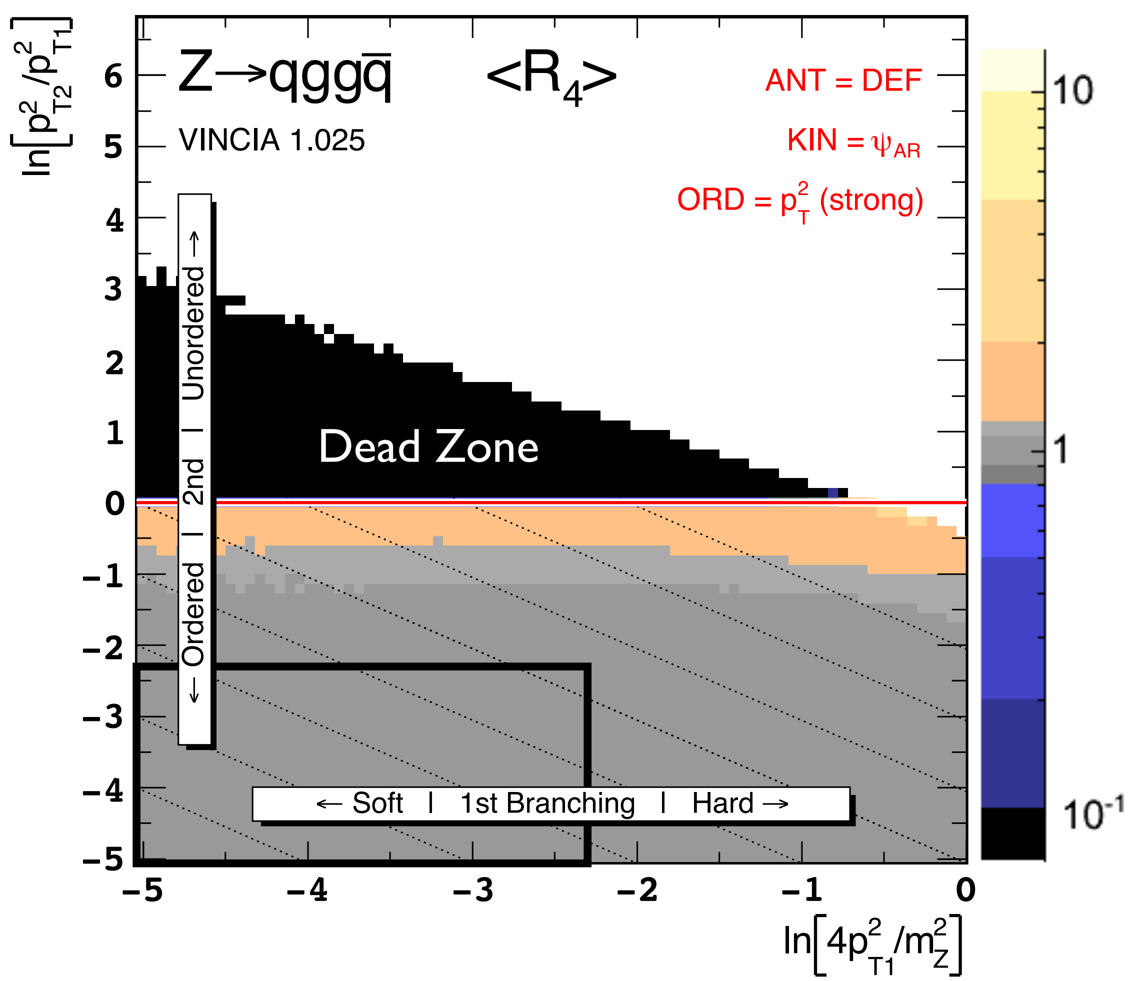
At each step, each dipole allowed to fill its entire phase space

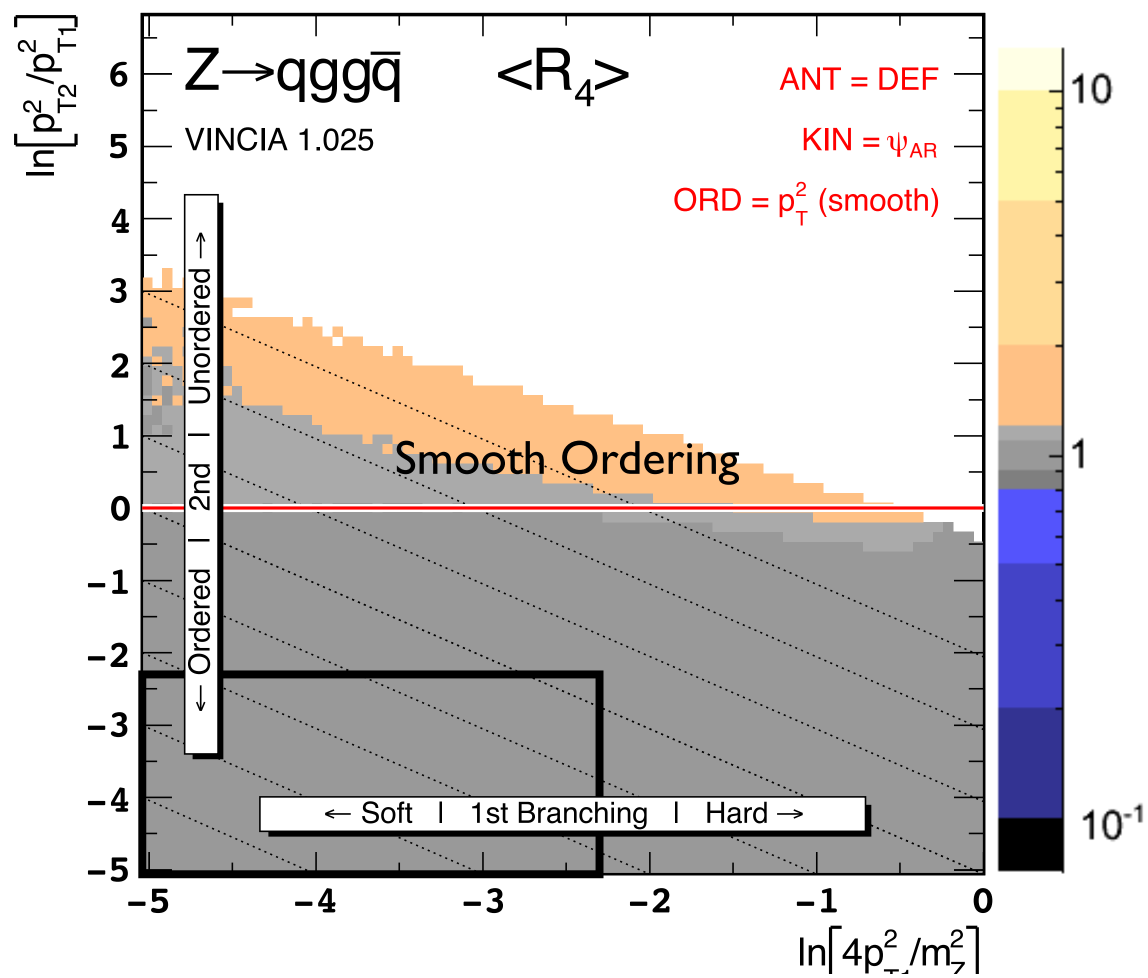
Overcounting removed by matching

+ smooth ordering beyond matched multiplicities

$$\frac{\hat{p}_\perp^2}{\hat{p}_\perp^2 + p_\perp^2} P_{\rm LL}$$

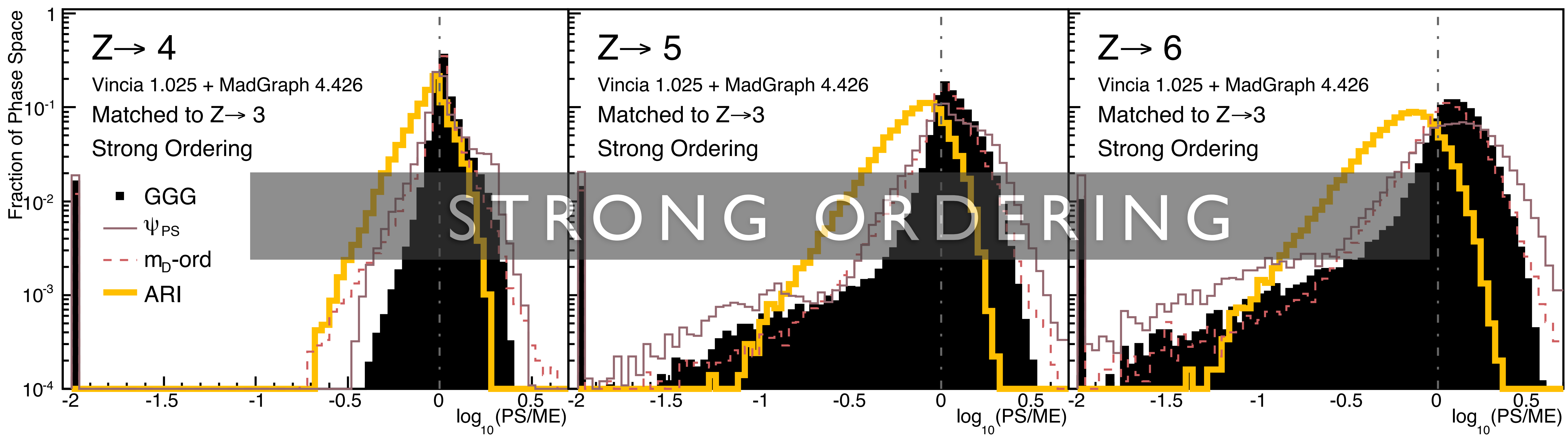
$\hat{p}_\perp^2$ last branching
$p_\perp^2$ current branching



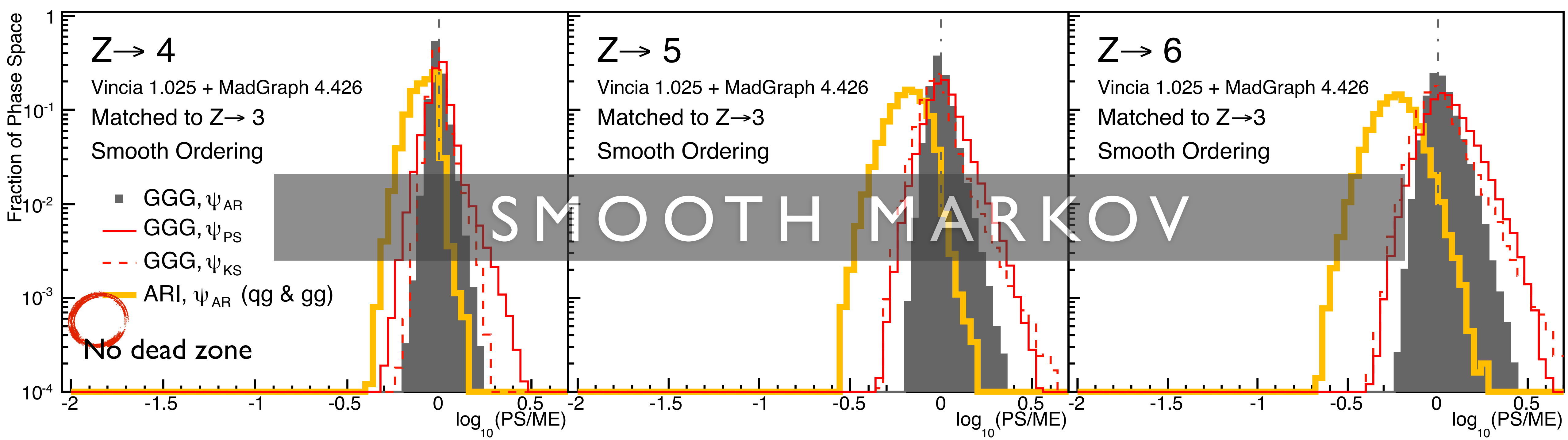


→ Better Approximations

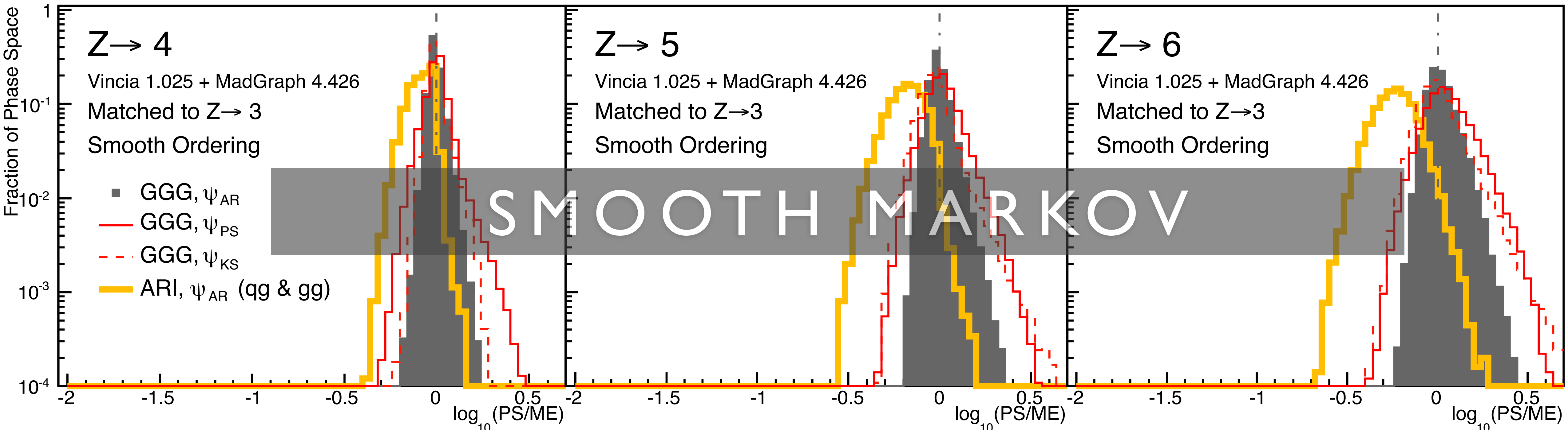
Distribution of **Log$_{10}$(PS$_{LO}$/ME$_{LO}$)** (inverse ~ matching coefficient)



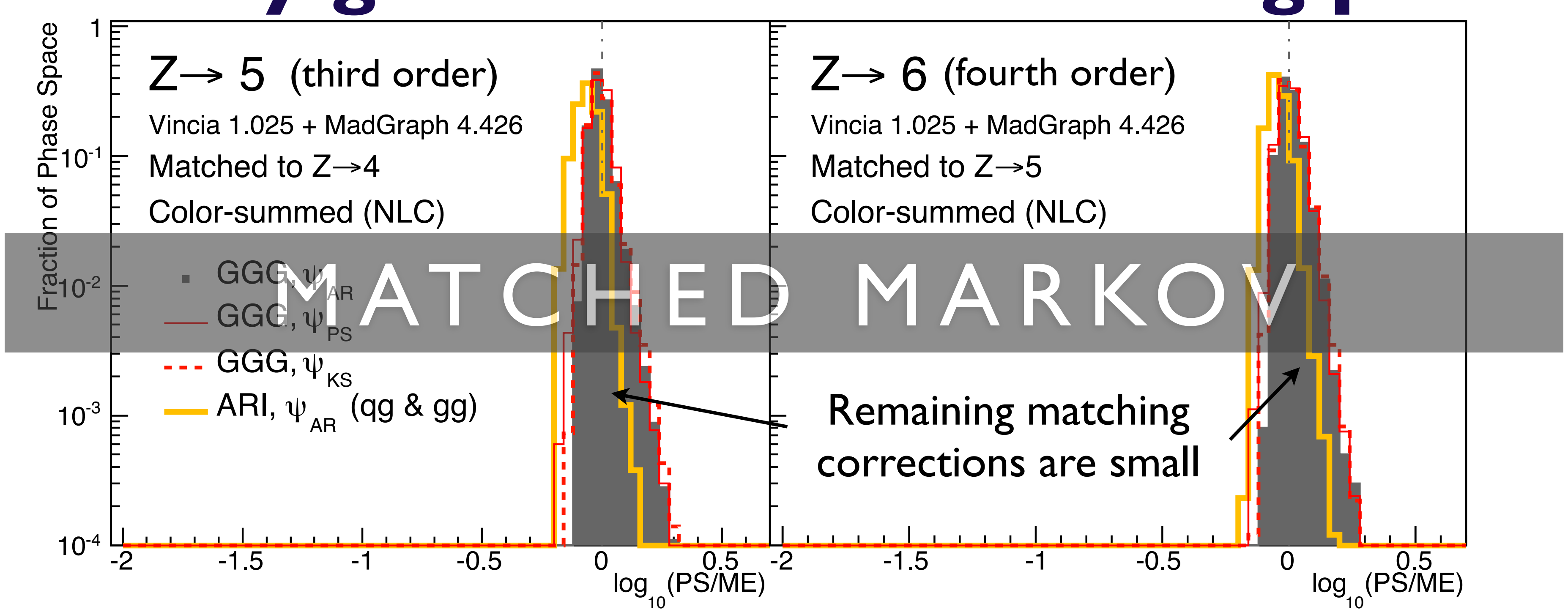
Leading Order, Leading Color, Flat phase-space scan, over **all of phase space** (no matching scale)



+ Matching (+ full colour)



→ **A very good all-orders starting point**



Uncertainties

For each branching, recompute weight for:

- Different renormalization scales
- Different antenna functions
- Different ordering criteria
- Different subleading-color treatments

	Weight
Nominal	1
Variation	$P_2 = \frac{\alpha_{s2} a_2}{\alpha_{s1} a_1} P_1$

+ Matching

Differences explicitly matched out

(Up to matched orders)

(Can in principle also include variations of matching scheme…)

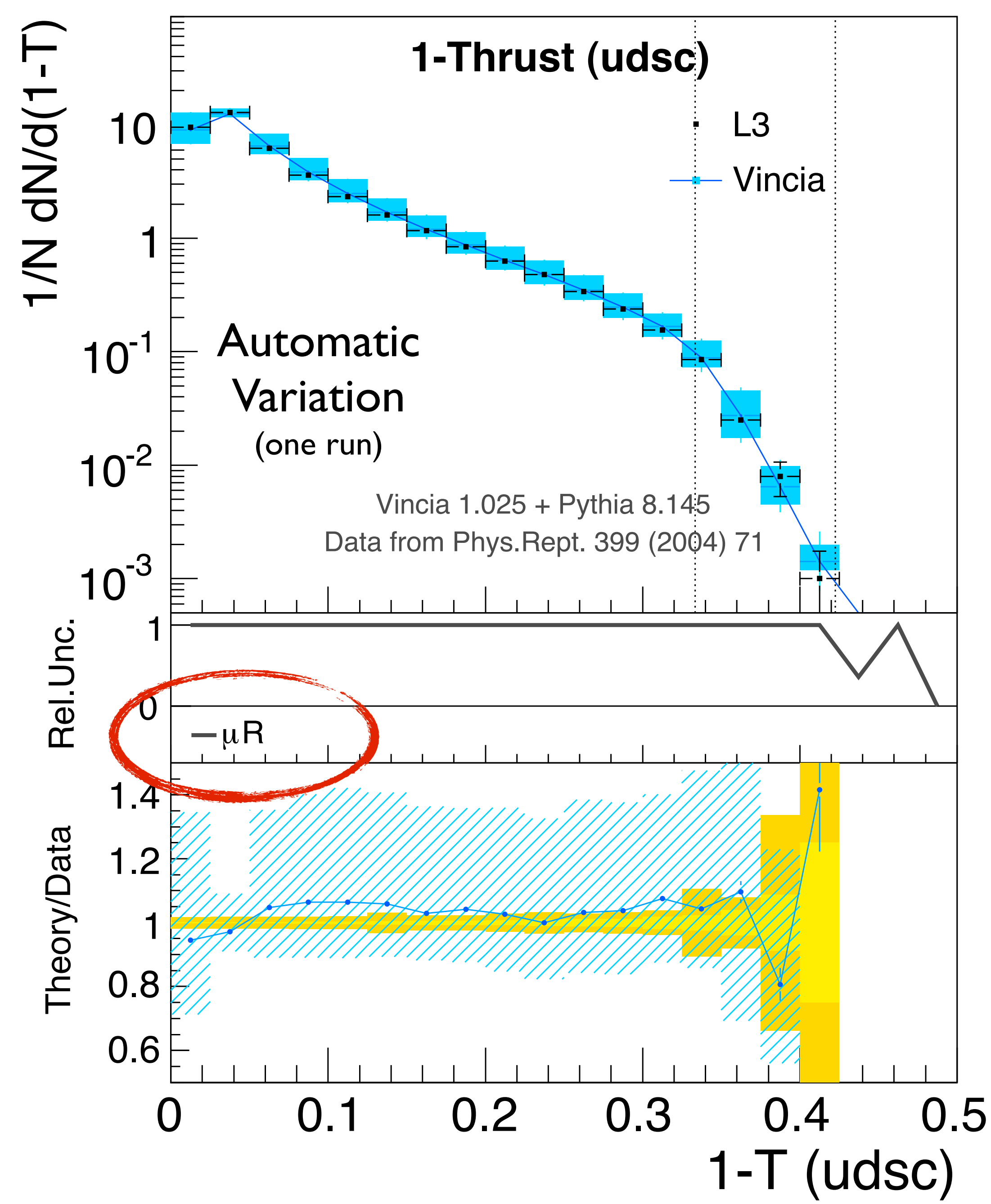
+ Unitarity

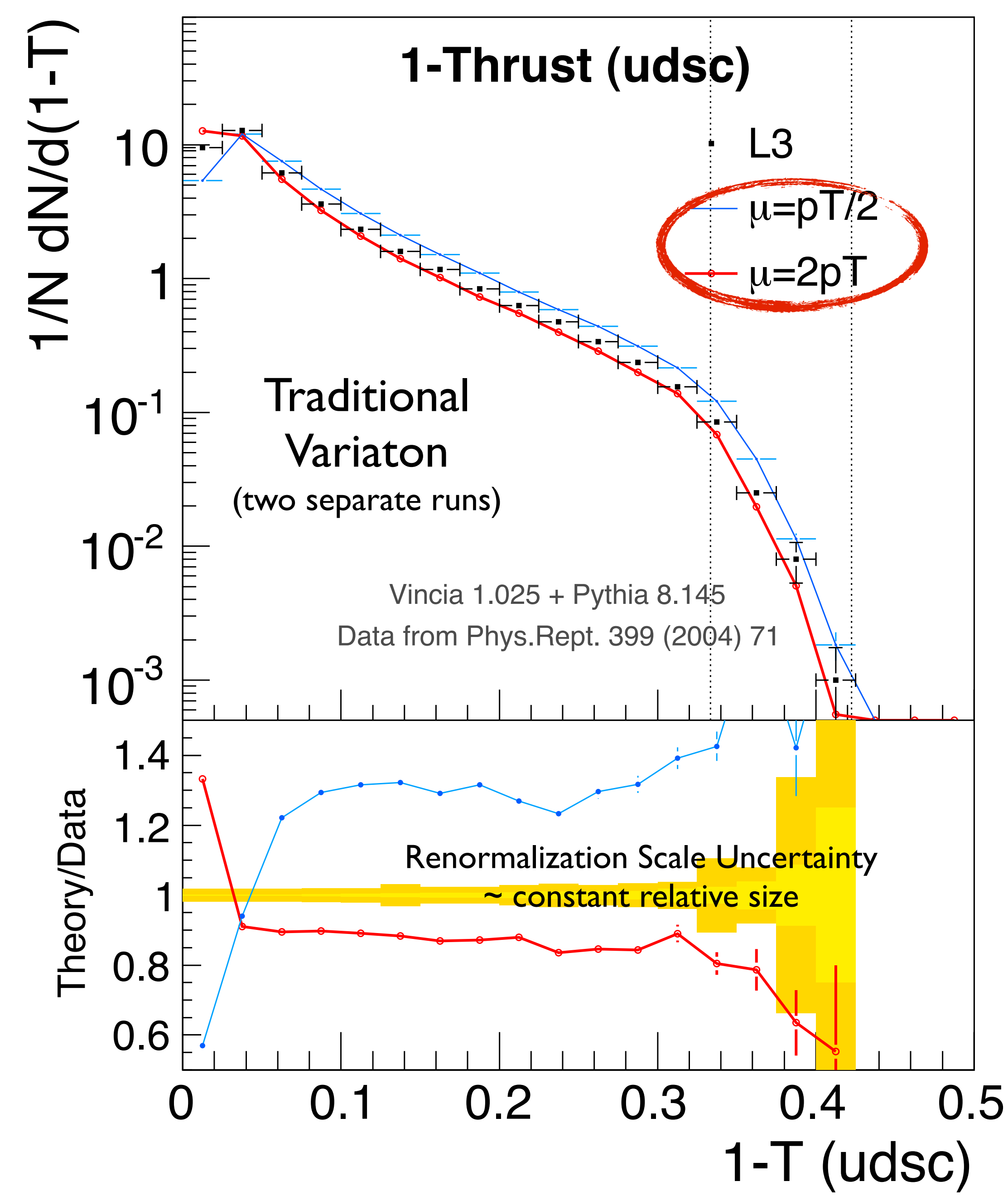
For each *failed* branching:

$$P_{2;\mathrm{no}} = 1 - P_2 = 1 - \frac{\alpha_{s2} a_2}{\alpha_{s1} a_1} P_1$$

Automatic Uncertainties

Vincia:uncertaintyBands = on

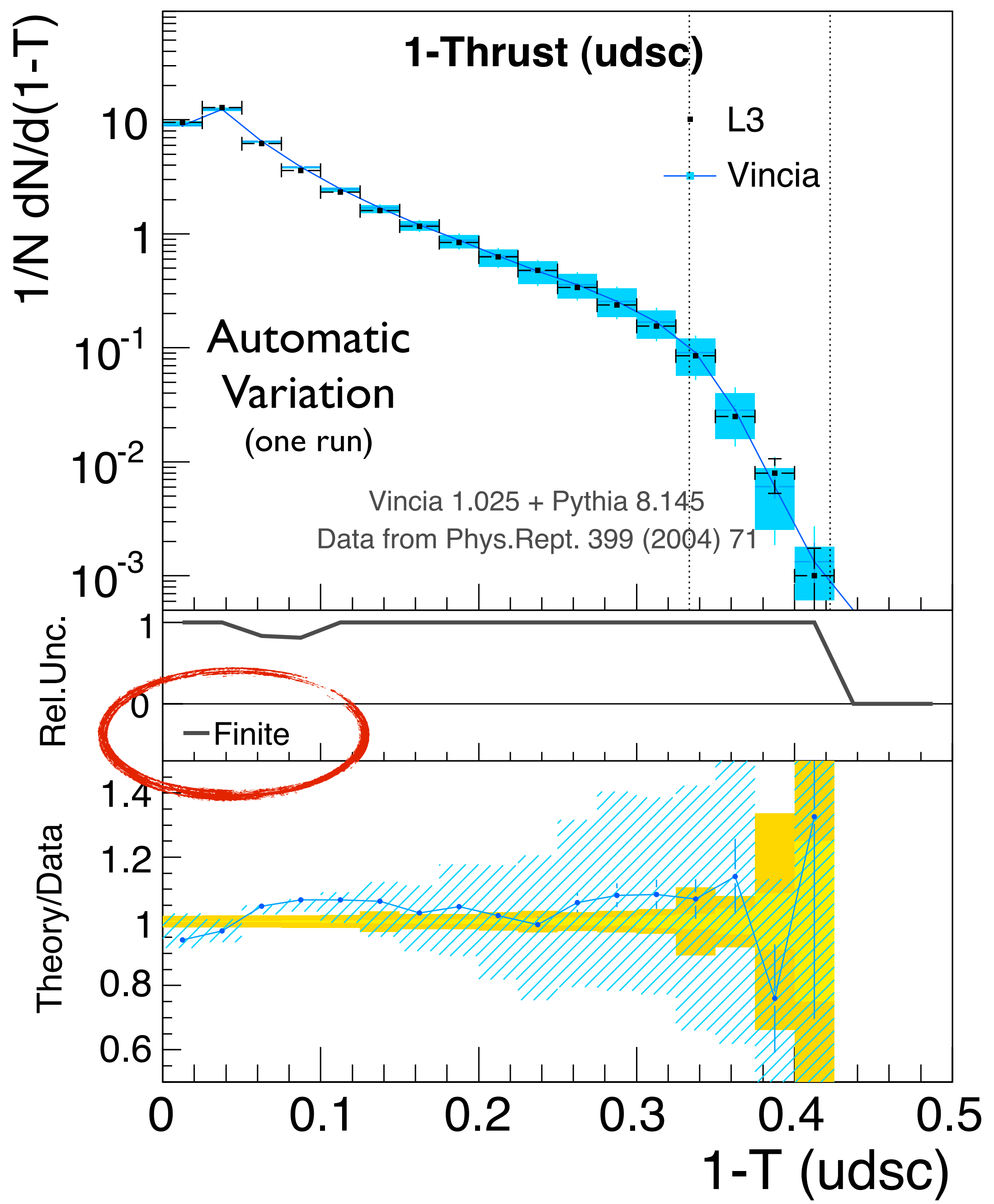


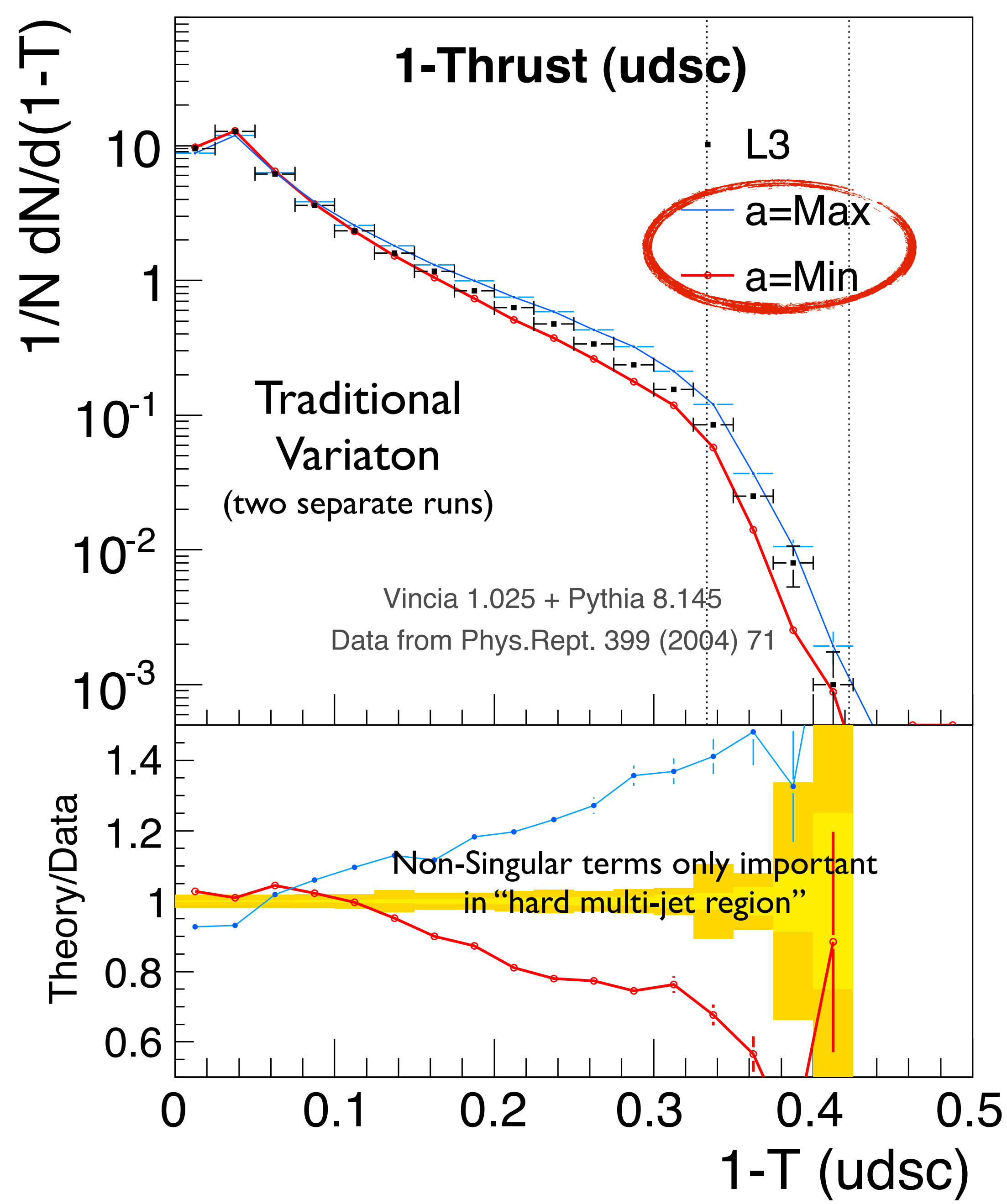


Variation of renormalization scale (no matching)

Automatic Uncertainties

Vincia:uncertaintyBands = on





Variation of "finite terms" (no matching)