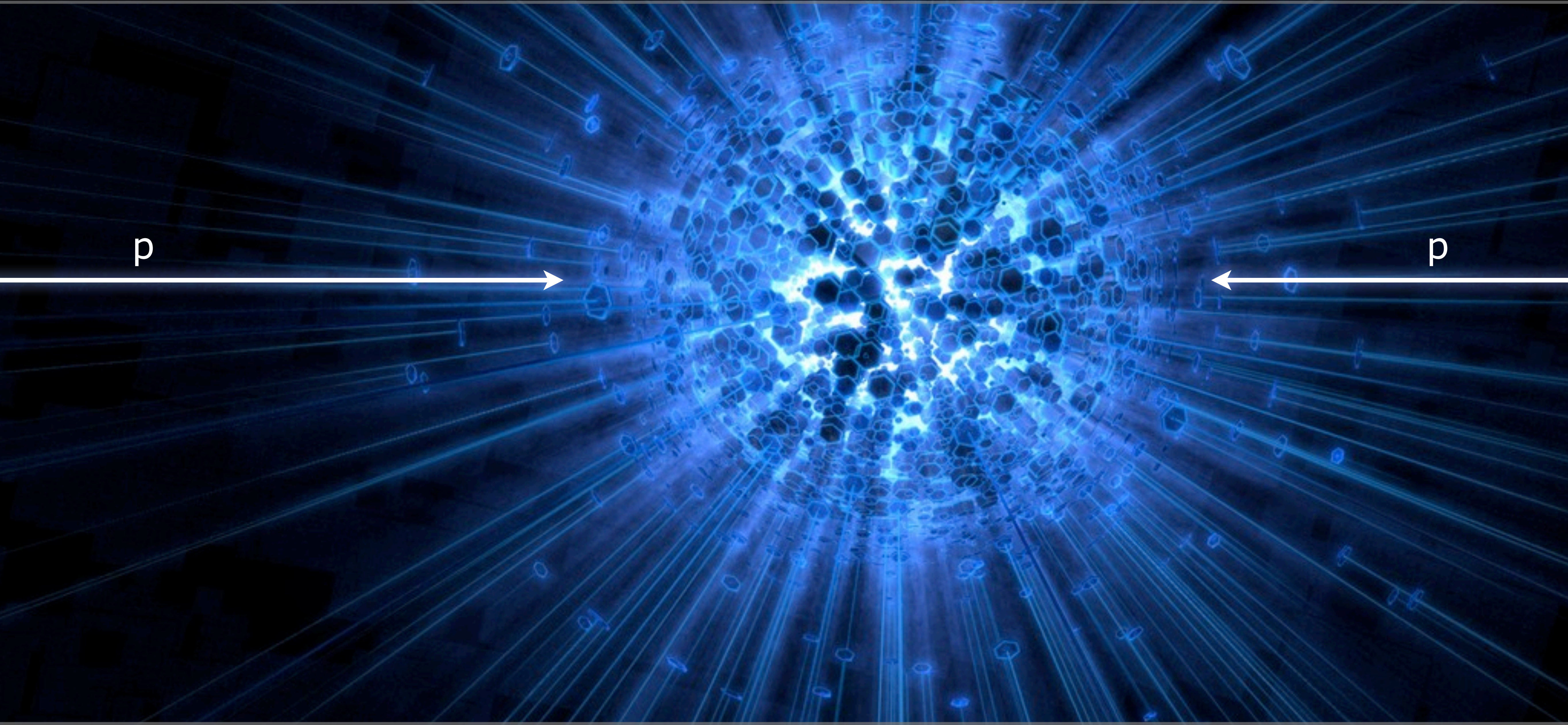
Physics Colloquium, Nov 28 2012, Monash U, Melbourne

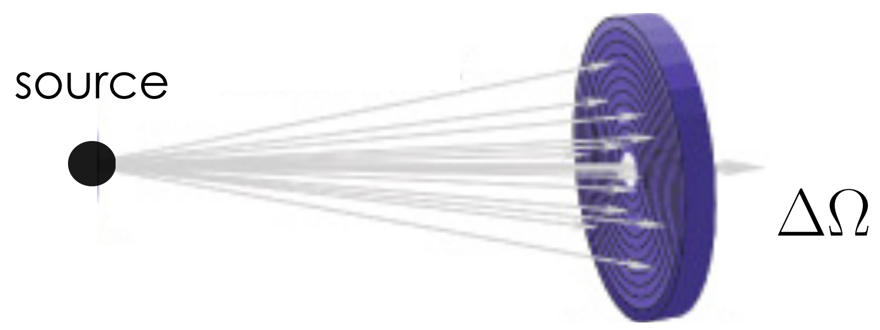
# Virtual Colliders




Peter Skands
CERN Theoretical Physics

# Introduction

## Scattering Experiments




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

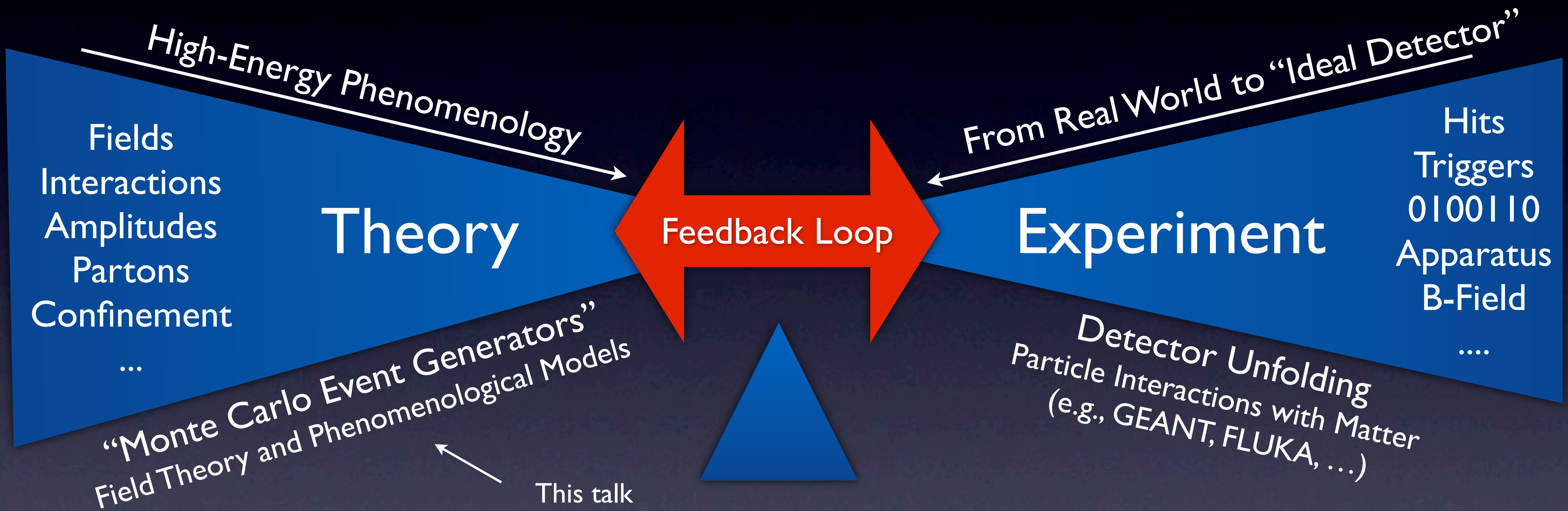
→ Integrate differential cross sections over specific phase-space regions

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
Only physical observables are well-defined and meaningful

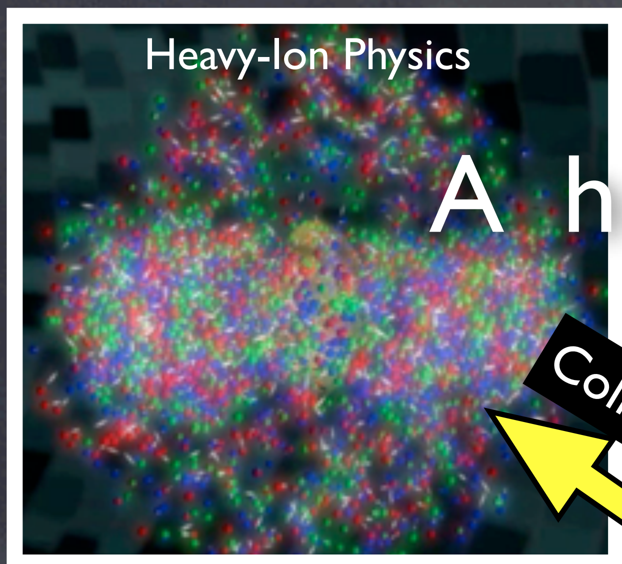
# Why virtual colliders?
# The Problem of Measurement

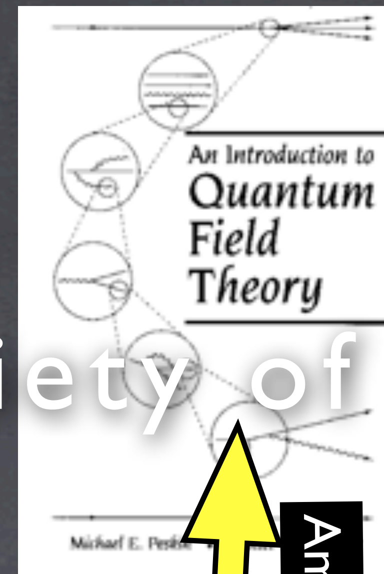


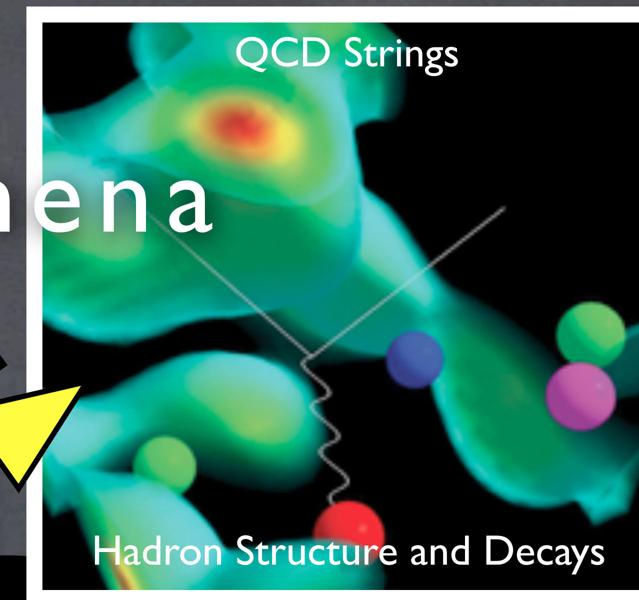

Theory: Need predictions for "physical observables" (Bohr would agree)

Experiment: Need simulated events to optimize detectors and measurements

# A huge variety of phenomena




Collective Effects

Amplitudes

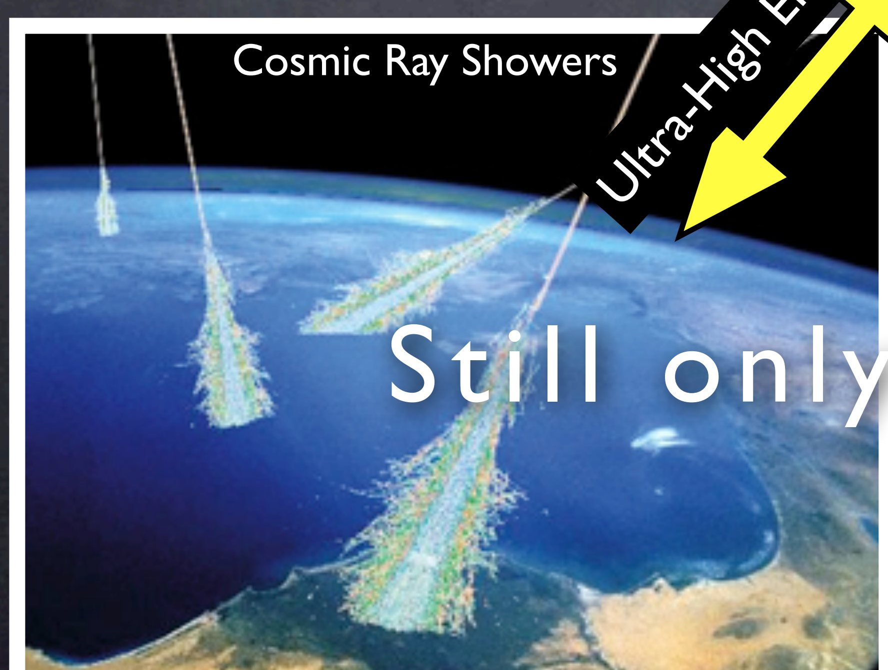
Confinement

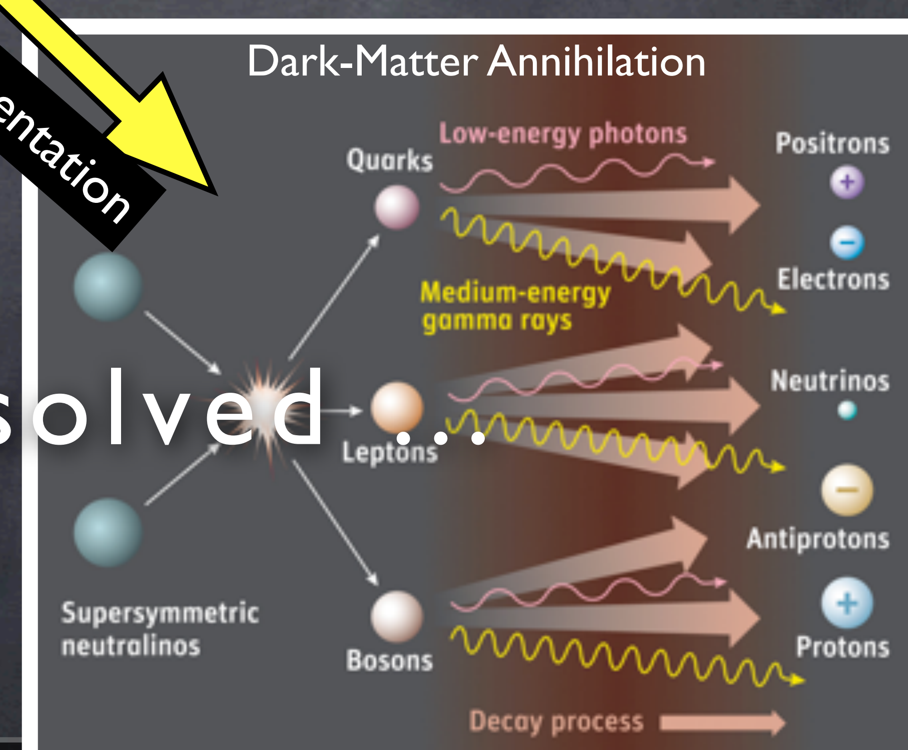
THEORY

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

Ultra-High Energies

Fragmentation




Still only partially solved...

# … and of course the Higgs


+ other physics studies:

# of journal papers so far:
183 ATLAS, 183 CMS, 67 LHCb, 36 ALICE, + …

Some of these studies are already **theory limited**

**Precision = Clarity**, in our vision of the Terascale

Searching towards lower cross sections, the game gets harder

+ Intense scrutiny (after discovery) requires high precision

Theory task: invest in precision

**This talk:** how we (attempt to) solve the LHC, and how we plan to get better at it

# How?

## **Fixed-order** perturbative Quantum Field Theory:

**Good**: full quantum treatment, order by order

**Problems**: can only really do first few orders; computationally slow; converges badly (or not at all) in classical limits

## **Infinite-order** semi-classical approximations

**Good**: universal; computationally fast; classical correspondence is guaranteed

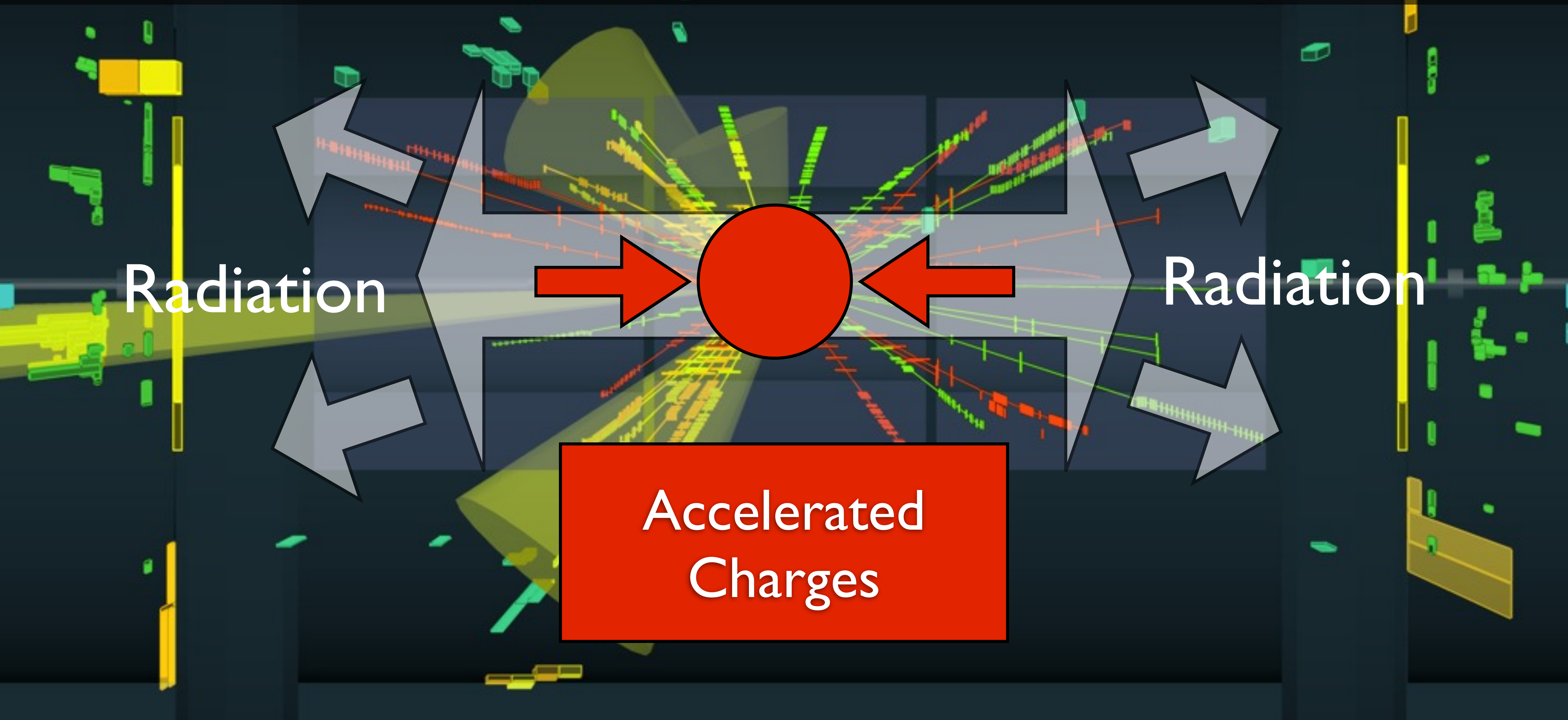
**Problems**: limited precision; misses interference effects

## **"Matching"**: Best of both Worlds?

**Good**: QFT for first few orders + semi-classical for the rest

**Problems**: cobbled together; computationally slow; divergences → room for improvement

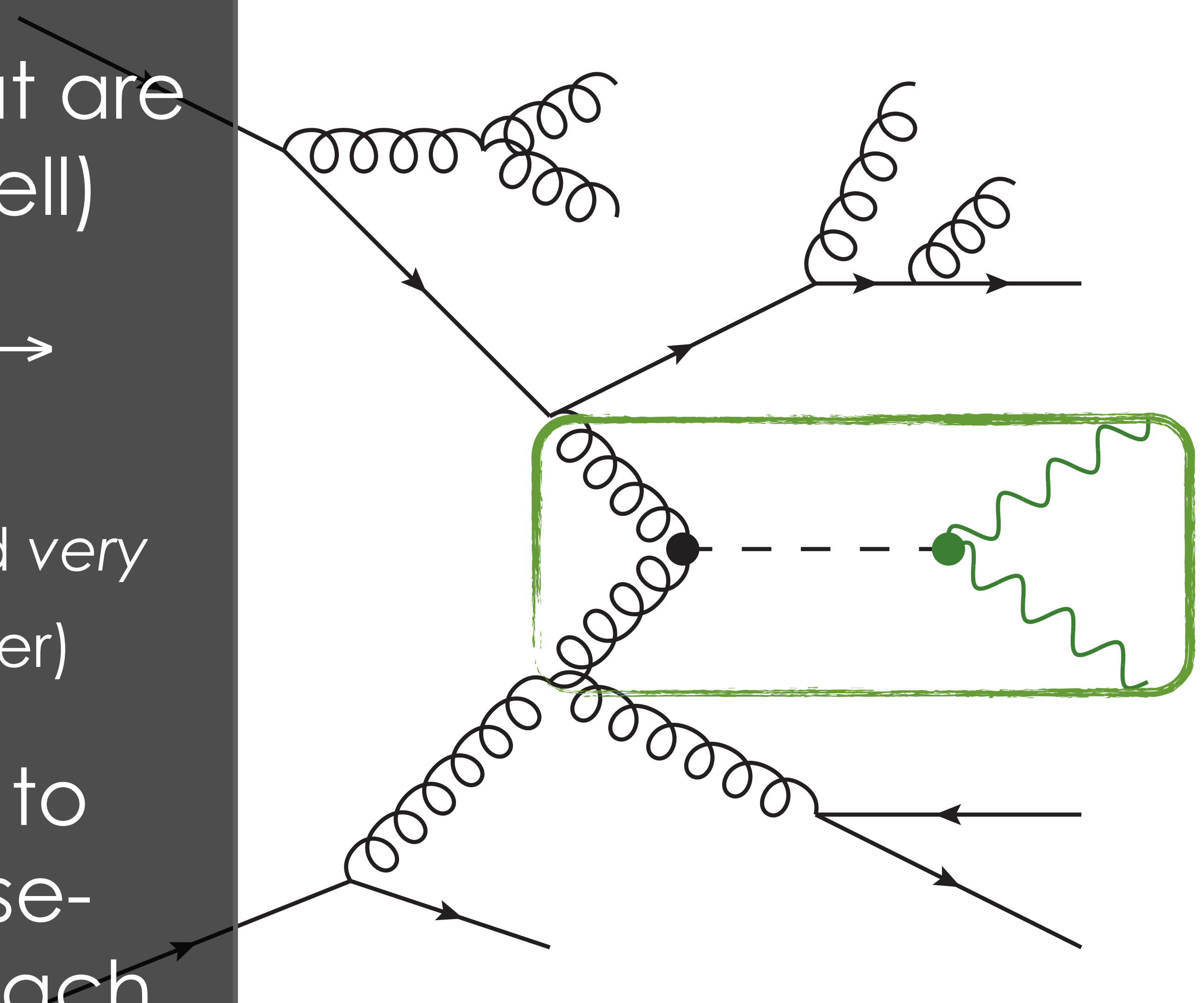
# The Problem of Bremsstrahlung




The harder they get kicked, the harder the fluctations that continue to become strahlung

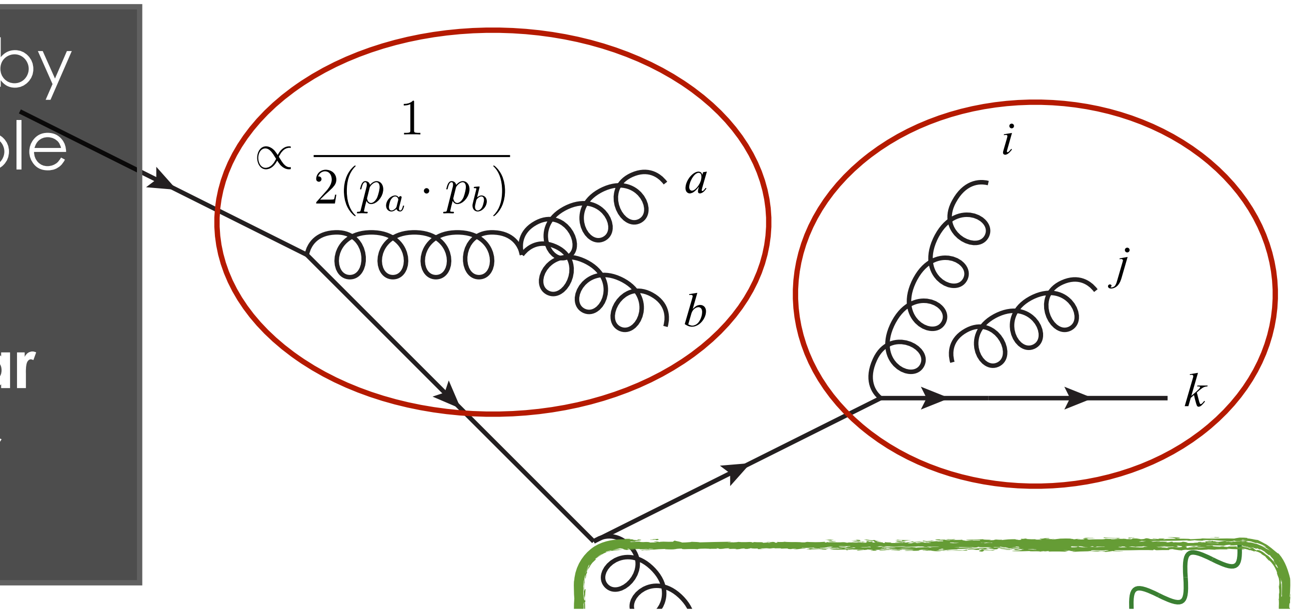
# Bremsstrahlung

- **Most bremsstrahlung** is emitted by particles that are almost classical (=on shell)
- **Divergent propagators** → Bad fixed-order convergence (would need *very high* orders to get reliable answer)
- Would be **infinitely slow** to carry out separate phase-space integrations for each and every order



# Jets = Fractals

- **Most bremsstrahlung** is driven by divergent propagators → simple structure
- **Amplitudes factorize in singular limits** (→ universal "conformal" or "fractal" structure)




Partons ab → "collinear":

P(z) = Altarelli-Parisi splitting kernels, with z = energy fraction = $E_a/(E_a+E_b)$

$$|\mathcal{M}_{F+1}(\ldots,a,b,\ldots)|^2 \overset{a||b}{\rightarrow} g_s^2 \mathcal{C} \frac{P(z)}{2(p_a \cdot p_b)} |\mathcal{M}_F(\ldots,a+b,\ldots)|^2$$

Gluon j → "soft":

Coherence → Parton j really emitted by (i,k) "colour antenna"

$$|\mathcal{M}_{F+1}(\ldots,i,j,k\ldots)|^2 \overset{j_g \rightarrow 0}{\rightarrow} g_s^2 \mathcal{C} \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |\mathcal{M}_F(\ldots,i,k,\ldots)|^2$$

+ scaling violation: $g_s^2 \rightarrow 4\pi\alpha_s(Q^2)$

Can apply this many times → nested factorizations

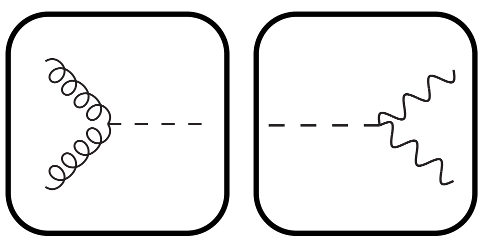
See: PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

# Divide and Conquer

**Factorization** → Split the problem into many (nested) pieces

+ Quantum mechanics → Probabilities → Random Numbers (Monte Carlo)

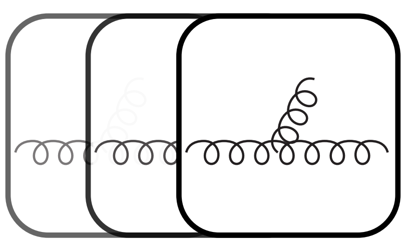
$$\mathcal{P}_{\mathrm{event}} = \mathcal{P}_{\mathrm{Hard}} \otimes \mathcal{P}_{\mathrm{Dec}} \otimes \mathcal{P}_{\mathrm{Brems}} \otimes \mathcal{P}_{\mathrm{Hadr}} \otimes \ldots$$



**Hard Process & Decays:**

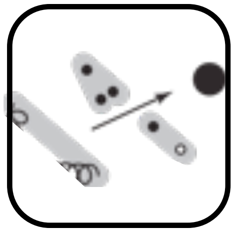
Use fixed-order amplitudes

→ Also defines fundamental resolution scale for process: $Q_{\mathrm{MAX}}$



**Bremsstrahlung:**

Semi-classical evolution equations → differential perturbative evolution, $dP/dQ^2$, as function of resolution scale; run from $Q_{\mathrm{MAX}}$ to $Q_{\mathrm{CONFINEMENT}}$ ~ 1 GeV (More later)



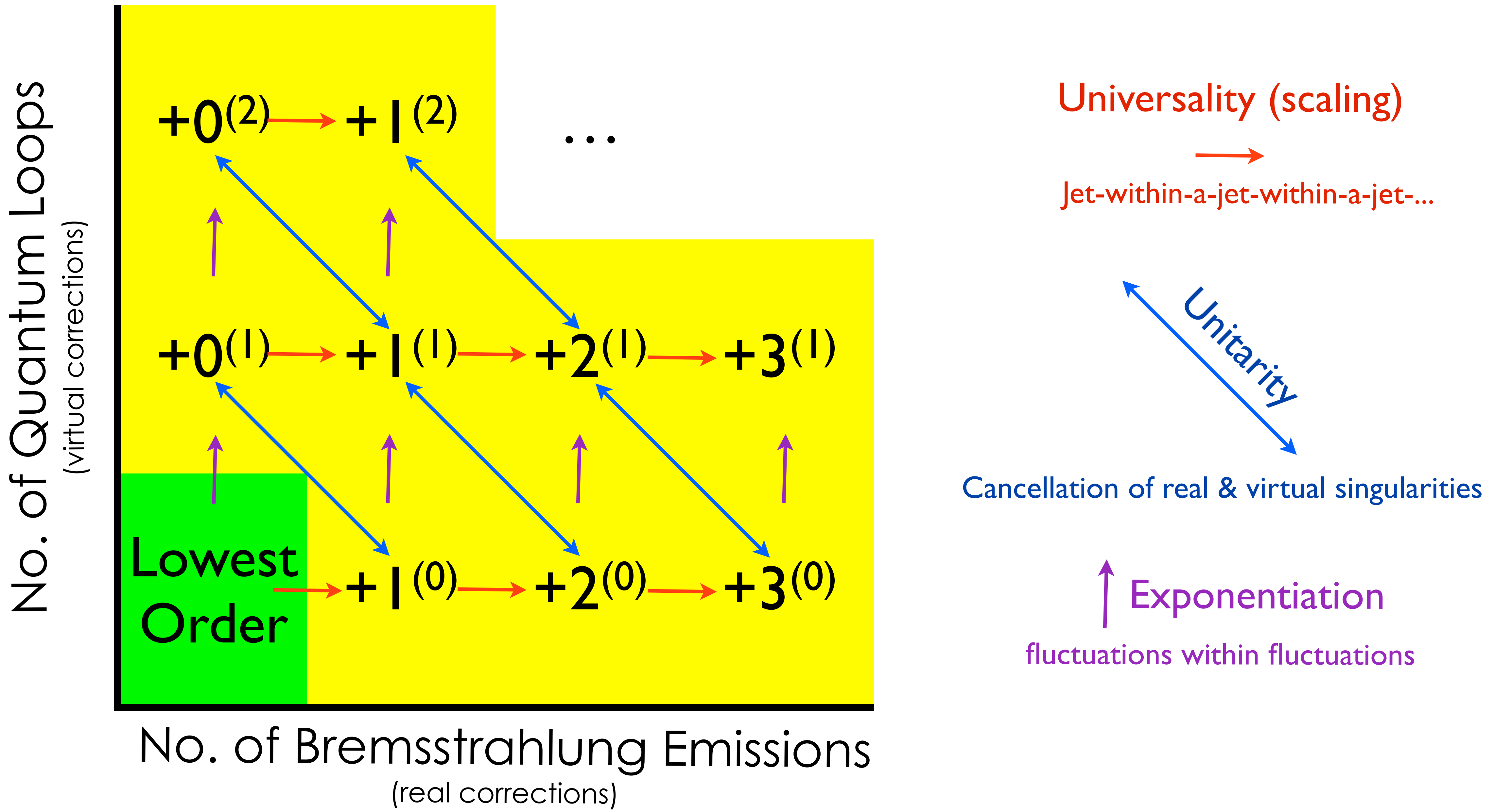
**Hadronization**

Non-perturbative model of transition from coloured partons to colour-neutral hadrons (confinement): at $Q_{\mathrm{CONFINEMENT}}$

# Bootstrapped Perturbation Theory

Start from an **arbitrary lowest-order** process (green = QFT amplitude squared)

**Parton showers** generate the bremsstrahlung terms of the rest of the perturbative series (yellow = fractal with scaling violation)



# Jack of All Orders, Master of None?

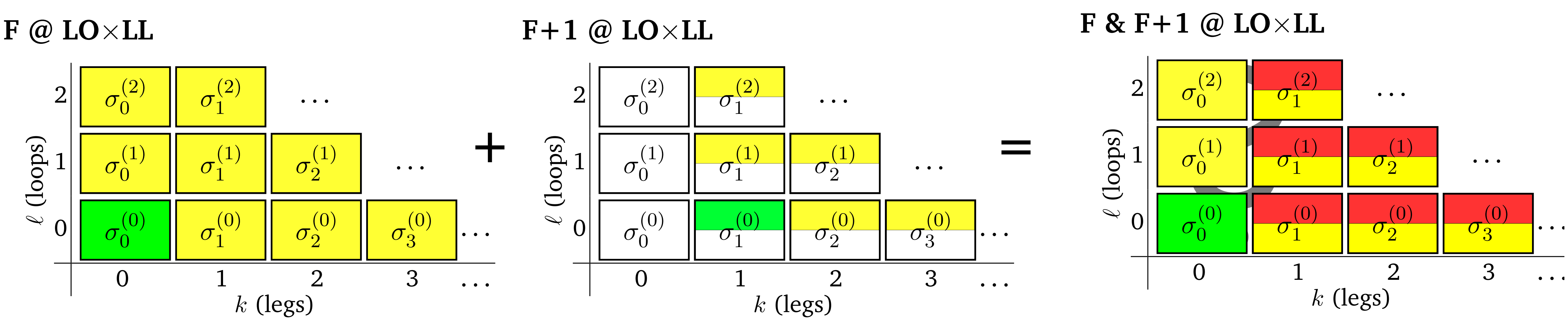
## Nice to have all-orders solution

But it is only exact in the singular (soft & collinear) limits

→ gets the bulk of bremsstrahlung corrections right, but fails equally spectacularly: for hard wide-angle radiation: **visible, extra jets**

… which is exactly where fixed-order calculations work!

## So combine them!

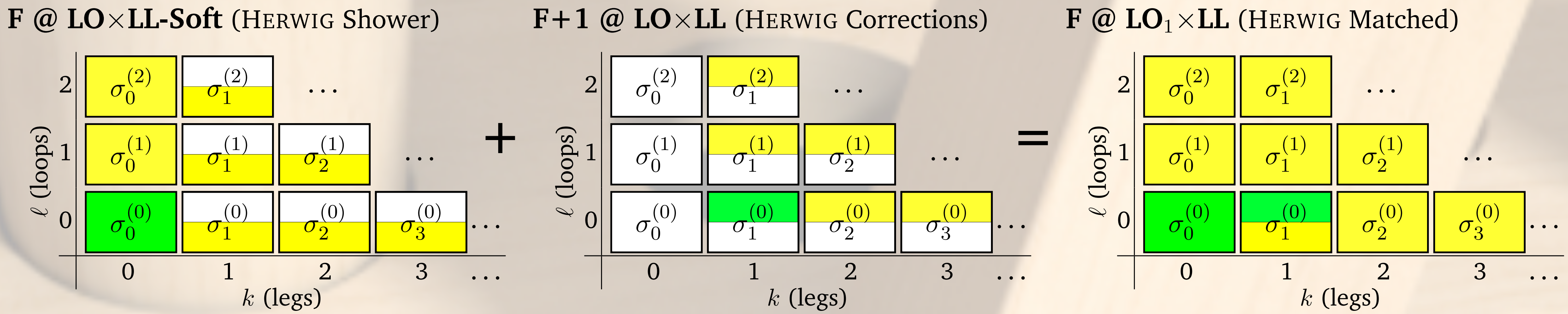



See: PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

**FAIL!**

# The Problem of Matching

- **First emission**: "the HERWIG correction"
  - Use the fact that the specific HERWIG parton shower has a "dead zone" for hard wide-angle radiation




- **Arbitrary emissions**: the "CKKW" prescription

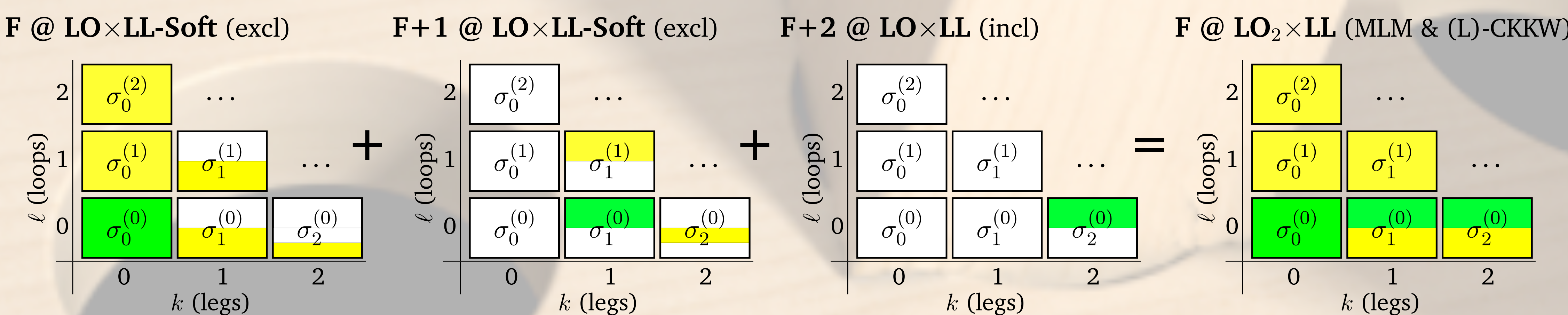



Image Credits: istockphoto

# The "CKKW" Prescription

## Start from a set of fixed-order calculations

Separate Phase-Space Integrations

$$\sigma_F^{\text{inc}} \qquad \sigma_{F+1}^{\text{inc}}(Q_{\text{cut}}) \qquad \sigma_{F+2}^{\text{inc}}(Q_{\text{cut}})$$

Wish to add showers while eliminating Double Counting:
Transform inclusive cross sections, for "X or more", to exclusive ones, for "X and only X"

Jet Algorithm → Recluster back to F → "fake" brems history
Attach shower-like resummation factors to each vertex and internal line

$$\sigma_{F+1}^{\text{exc}}(Q_{F+1}) \qquad \sigma_{F+2}^{\text{exc}}(Q_{F+2})$$

Attach shower-like resummation factors on external lines

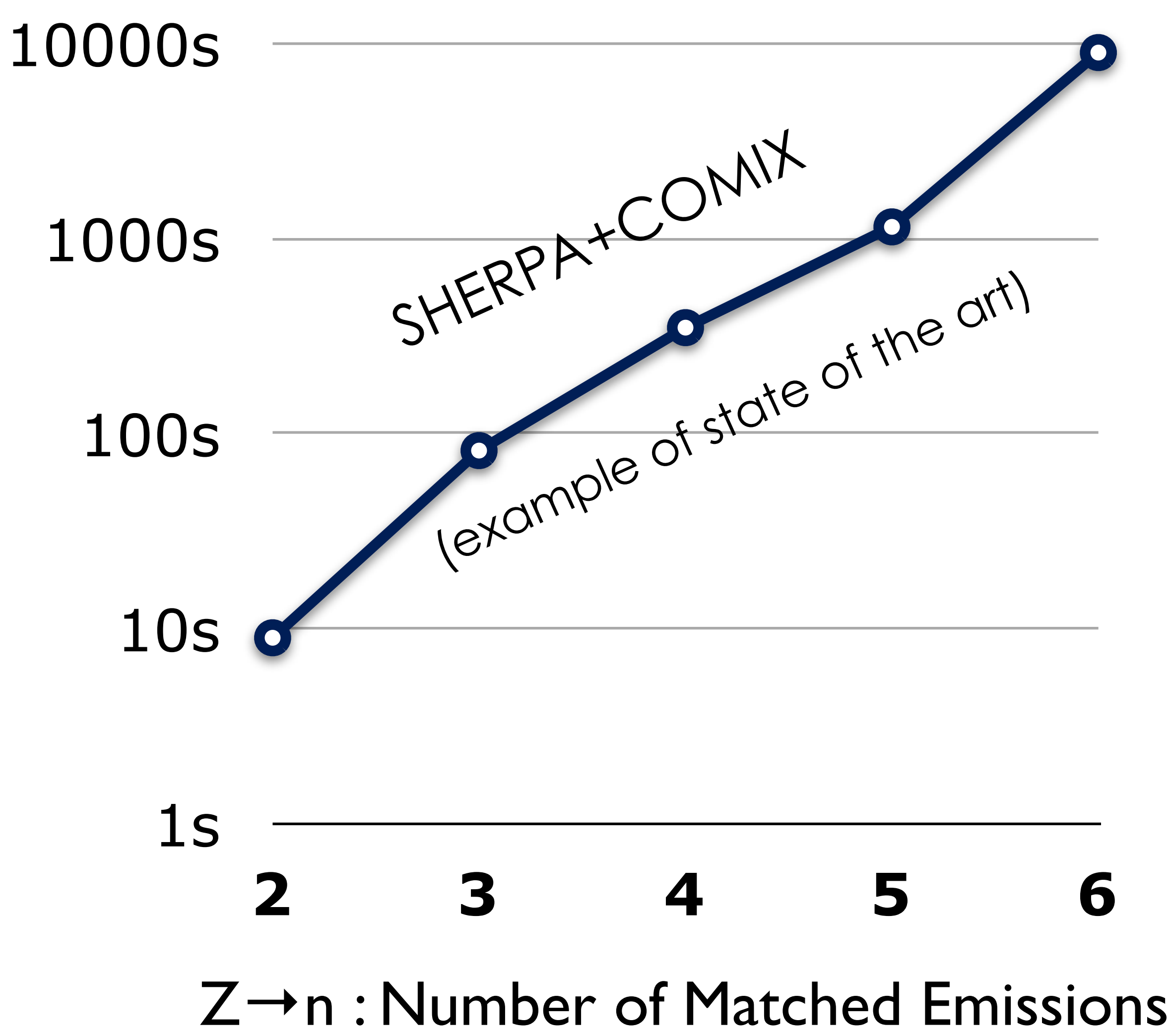
$$\sigma_F^{\text{exc}}(Q_{\text{cut}}) \qquad \sigma_{F+1}^{\text{exc}}(Q_{\text{cut}})$$

Now add a genuine parton shower → remaining evolution down to confinement scale

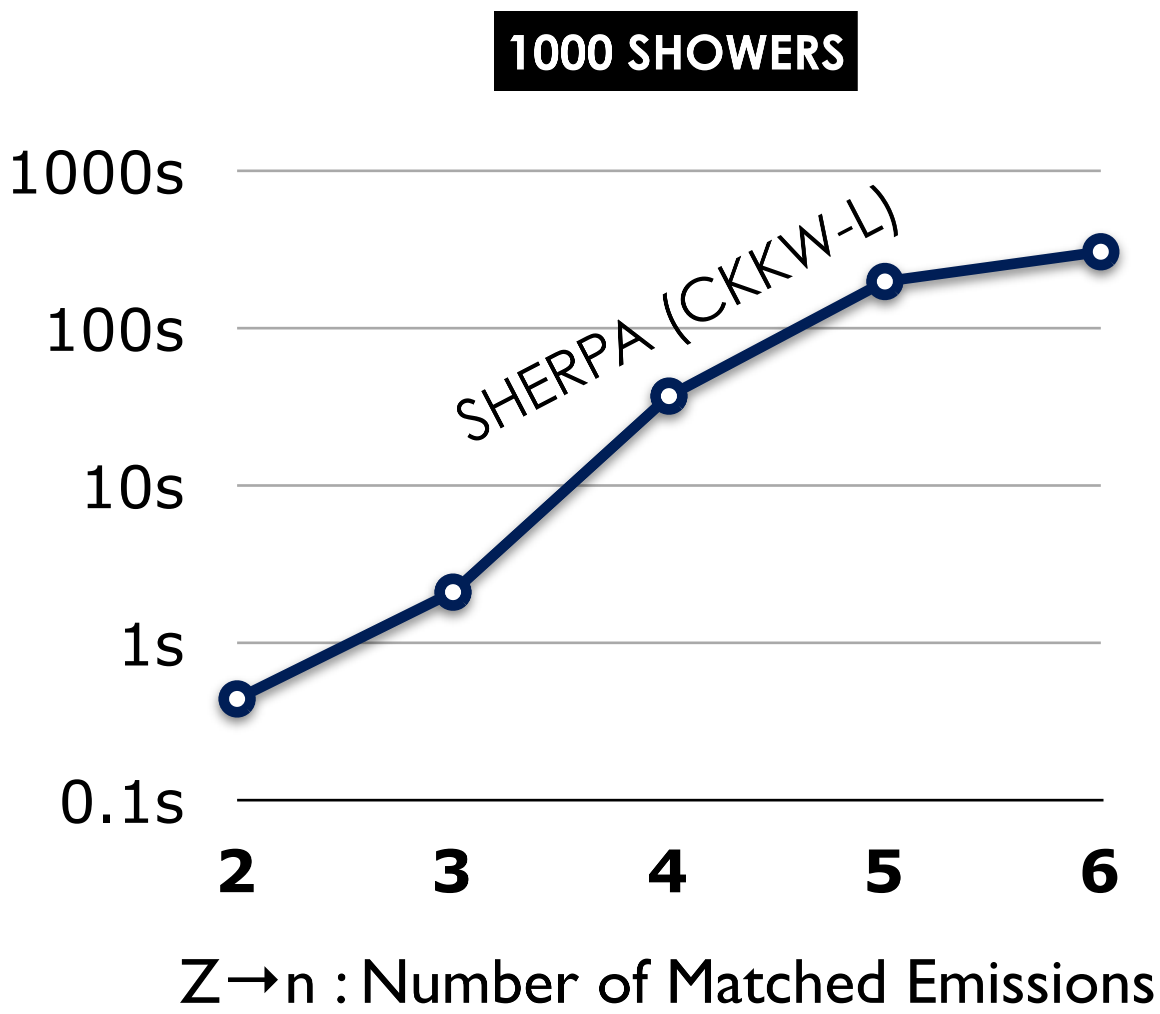
Start from $Q_{\text{cut}}$ | Start from $Q_{F+2}$

# The Cost

1. Initialization time
(to pre-compute cross sections and warm up phase-space grids)




2. Time to generate 1000 events
(Z → partons, fully showered & matched. No hadronization.)




Z→udscb ; Hadronization OFF ; ISR OFF ; udsc MASSLESS ; b MASSIVE ; $E_{CM}$ = 91.2 GeV ; $Q_{match}$ = 5 GeV
SHERPA 1.4.0 (+COMIX) ; PYTHIA 8.1.65 ; VINCIA 1.0.29 (+MADGRAPH 4.4.26) ;
gcc/gfortran v 4.7.1 -O2 ; single 3.06 GHz core (4GB RAM)

# Changing Paradigm

## Ask:

*Is it possible to use the all-orders structure that the shower so nicely generates for us, as a substrate, a stratification, on top of which fixed-order amplitudes could be interpreted as finite corrections?*

## Answer:

Used to be no.

First order worked out in the 80$^{s}$ (Sjöstrand, the PYTHIA correction), but beyond that, the expansions became too complicated

People then resorted to slicing up phase space (fixed-order amplitude goes *here*, shower goes *there*) → previous slides

# Markovian Evolution

"Higher-Order Corrections To Timelike Jets"
Giele, Kosower, Skands, PRD 84 (2011) 054003

- **Idea:**
  - Start from quasi-conformal all-orders structure (approximate)
  - Impose exact higher orders as finite corrections
  - Truncate at fixed scale (rather than fixed order)
  - Bonus: low-scale partonic events → can be hadronized
- **Problems:**
  - Traditional parton showers are history-dependent (non-Markovian)
  - → Number of generated terms grows like $2^N N!$
  - + Highly complicated expansions
- **Solution:**
  - Markovian Antenna Showers (VINCIA)
  - → Number of generated terms grows like N
  - self-correcting + simple expansions

Traditional Parton Shower:
After 2 branchings: 8 terms
After 3 branchings: 48 terms
After 4 branchings: 384 terms

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

# New: Markovian pQCD*

*) pQCD : perturbative QCD

Start at Lowest Order

$$|M_F|^2$$

Generate "shower" emission

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

Correct to Matrix Element

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

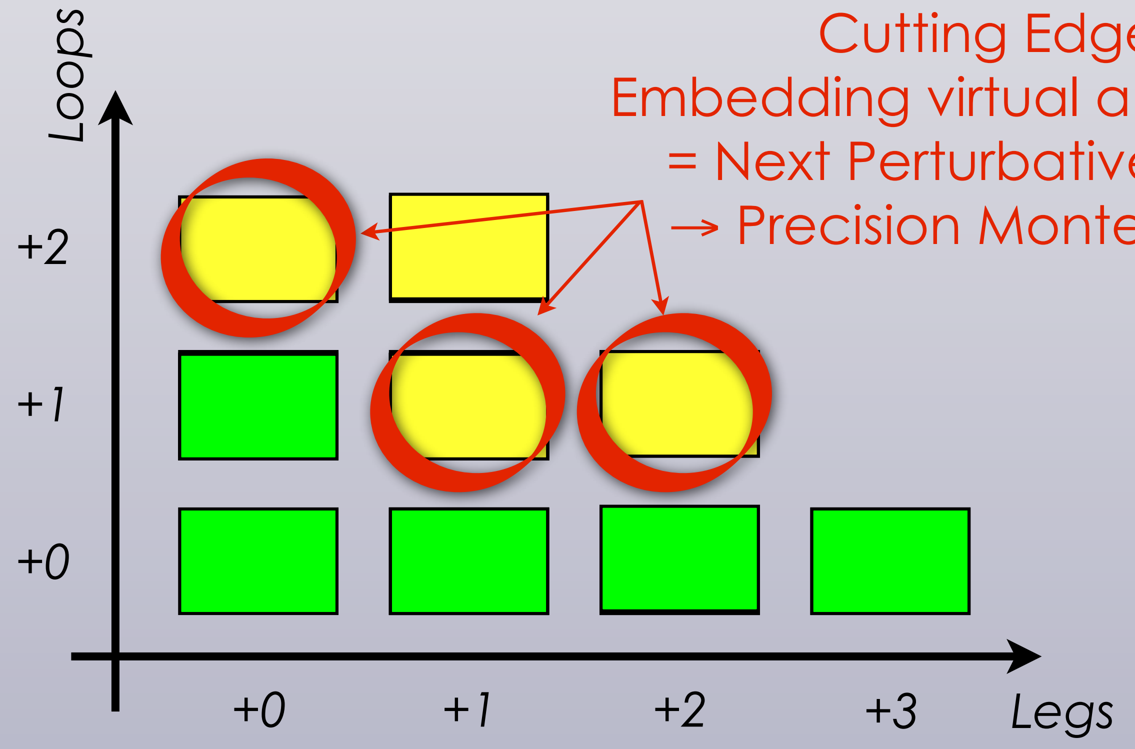
Unitarity of Shower

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

Correct to Matrix Element

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

Repeat

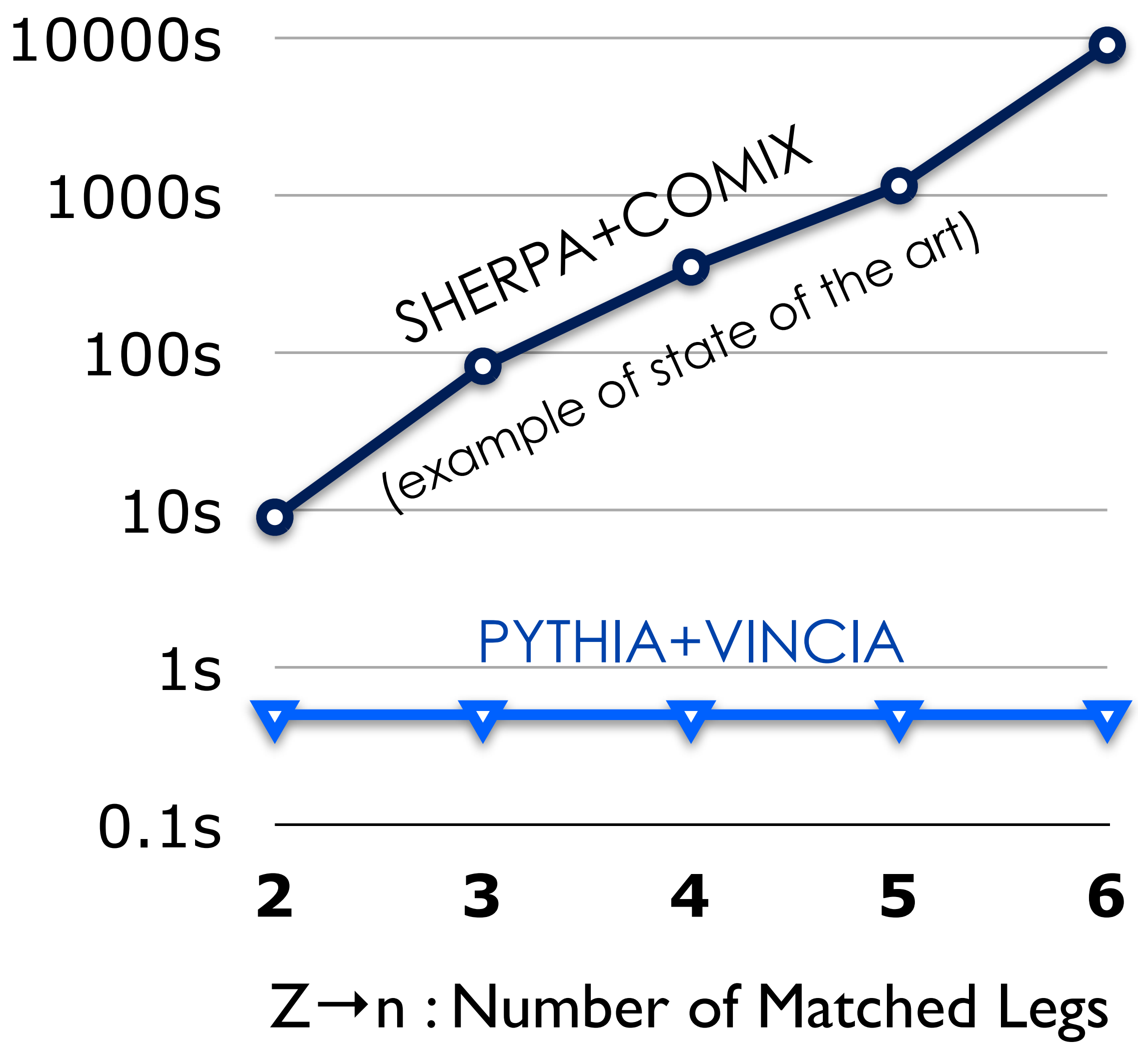



Cutting Edge:
Embedding virtual amplitudes
= Next Perturbative Order
→ Precision Monte Carlos

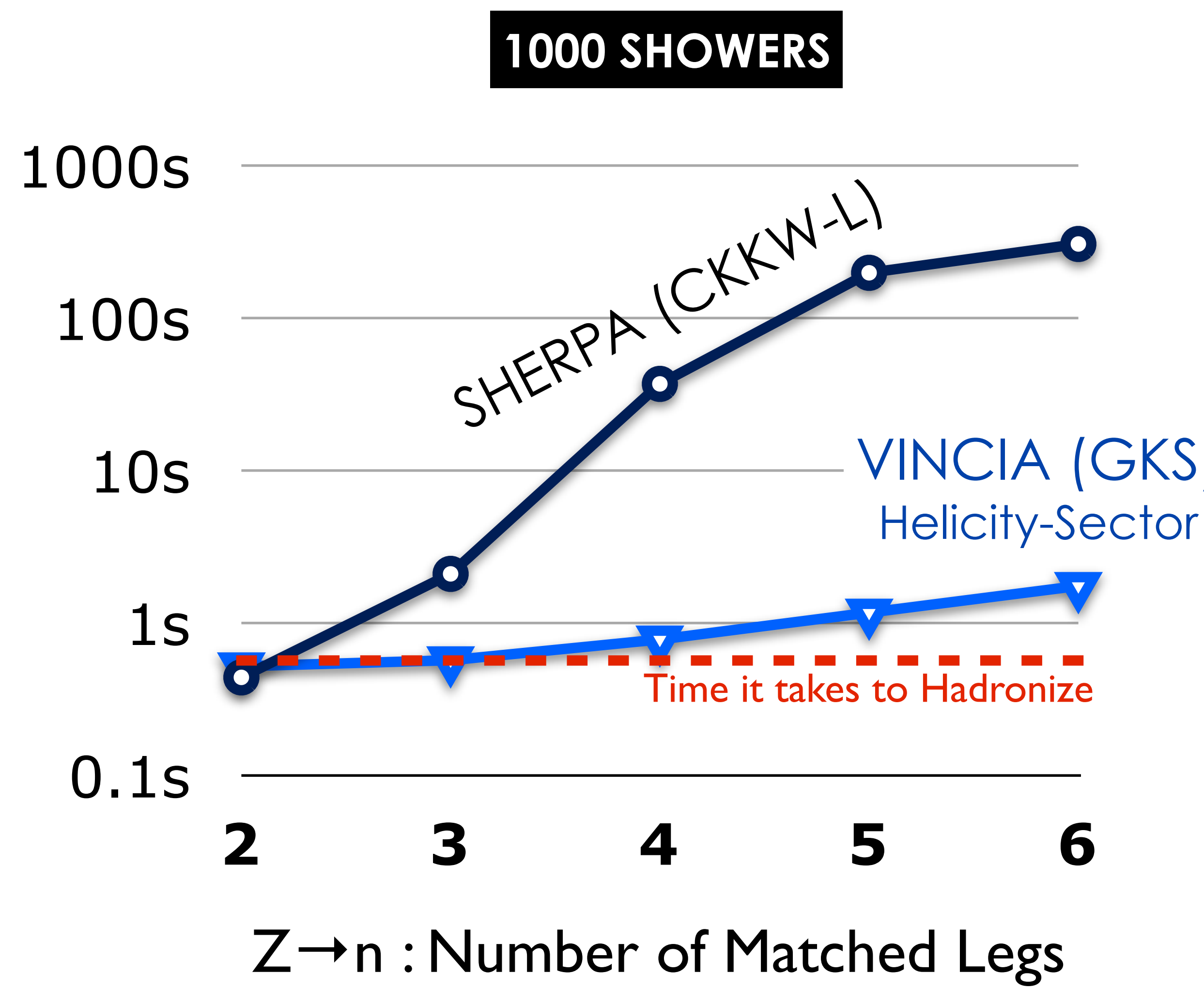

"Higher-Order Corrections To Timelike Jets"
GeeKS: Giele, Kosower, Skands, PRD 84 (2011) 054003


# Speed

**1. Initialization time**
(to pre-compute cross sections and warm up phase-space grids)




**2. Time to generate 1000 events**
(Z → partons, fully showered & matched. No hadronization.)




Z→udscb ; Hadronization OFF ; ISR OFF ; udsc MASSLESS ; b MASSIVE ; $E_{CM}$ = 91.2 GeV ; $Q_{match}$ = 5 GeV
SHERPA 1.4.0 (+COMIX) ; PYTHIA 8.1.65 ; VINCIA 1.0.29 (+MADGRAPH 4.4.26) ;
gcc/gfortran v 4.7.1 -O2 ; single 3.06 GHz core (4GB RAM)

# + Interfaced to PYTHIA

**General-purpose "virtual collider"** *(begun in 1978, main author: T. Sjöstrand)*

**Physics Processes**, mainly for $e^+e^-$ and $pp/p\bar{p}$ beams

- Standard Model: Quarks, gluons, photons, Higgs, W & Z boson(s); + Decays
- Supersymmetry + Generic Beyond-the-Standard-Model: N. Desai & P. Skands, arXiv:1109.5852
- + New gauge forces, More Higgses, Compositeness, 4th Gen, Hidden-Valley, …

**(Parton Showers) and Underlying Event**

- $P_T$-ordered showers & multiple-parton interactions: Sjöstrand & Skands, Eur.Phys.J. C39 (2005) 129
- + more recent improvements: Corke & Sjöstrand, JHEP 01 (2010) 035; Eur.Phys.J. C69 (2010) 1

**Hadronization: Lund String**

- Org "Lund" (Q-Qbar) string: Andersson, Camb.Monogr.Part.Phys.Nucl.Phys.Cosmol. 7 (1997) 1
- + "Junction" ($Q_R Q_G Q_B$) strings: Sjöstrand & Skands, Nucl.Phys. B659 (2003) 243; JHEP 0403 (2004) 053

**Soft QCD:** Minimum-bias, color reconnections, Bose-Einstein, diffraction, …

- Color Reconnection: Skands & Wicke, EPJC52 (2007) 133
- Bose-Einstein: Lönnblad, Sjöstrand, EPJC2 (1998) 165
- Diffraction: Navin, arXiv:1005.3894
- LHC "Perugia" Tunes: Skands, PRD82 (2010) 074018

Topcites Home 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2007 2008 2009 2010

**The 100 most highly cited papers during 2010 in the hep-ph archive**

1. **PYTHIA 6.4 Physics and Manual**
   By T. Sjostrand, S. Mrenna, P. Skands
   Published in: JHEP 0605:026,2006 (arXiv: hep-ph/0603175)

**Now → PYTHIA 8:**
Sjöstrand, Mrenna, Skands, CPC 178 (2008) 852

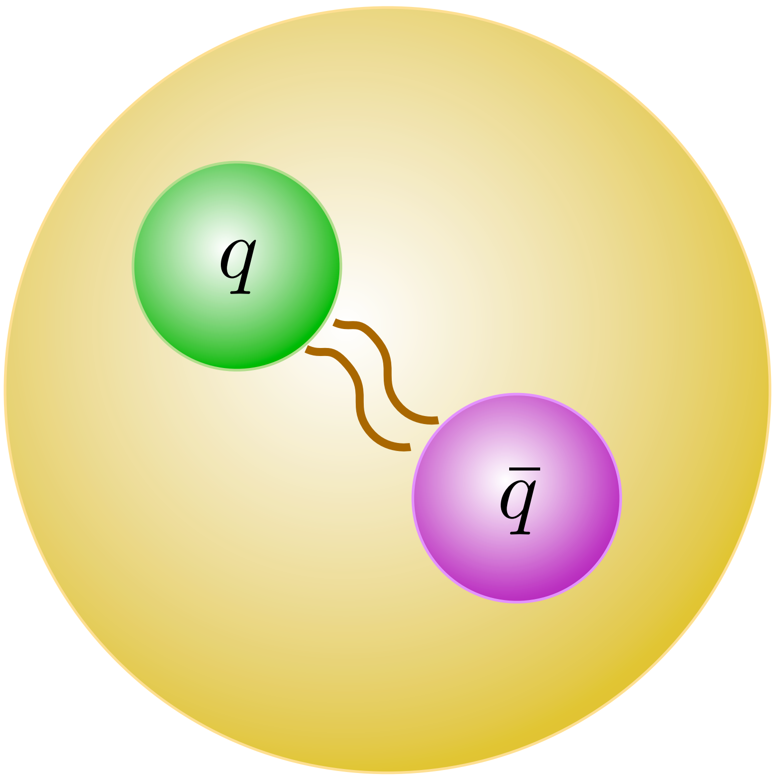
# Confinement

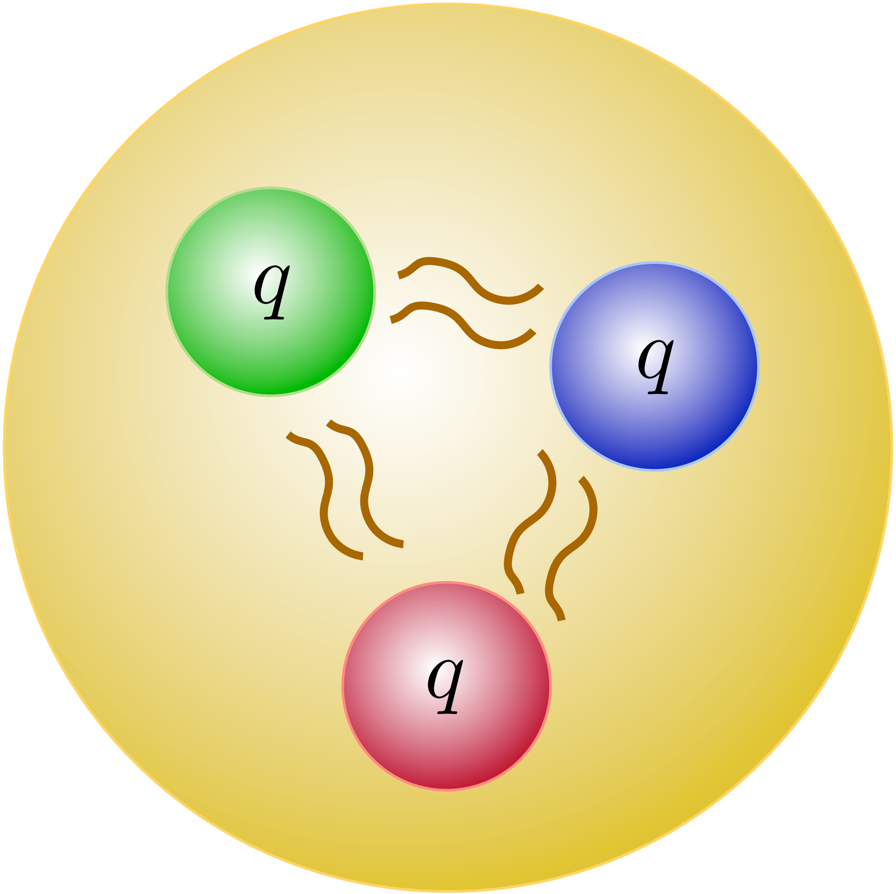
## We don't see quarks and gluons …

**Mesons**

*Quark-Antiquark Bound States*

$\pi^0, \pi^\pm, K^0, K^\pm, \eta, \ldots$




**Baryons**

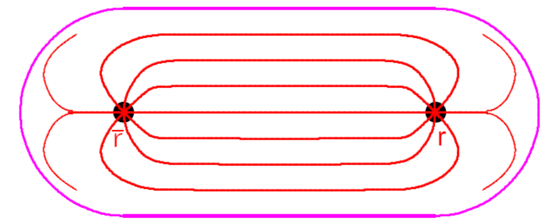
*Quark-Quark-Quark Bound States*

$p^\pm, n^0, \Lambda^0, \ldots$

# Linear Confinement

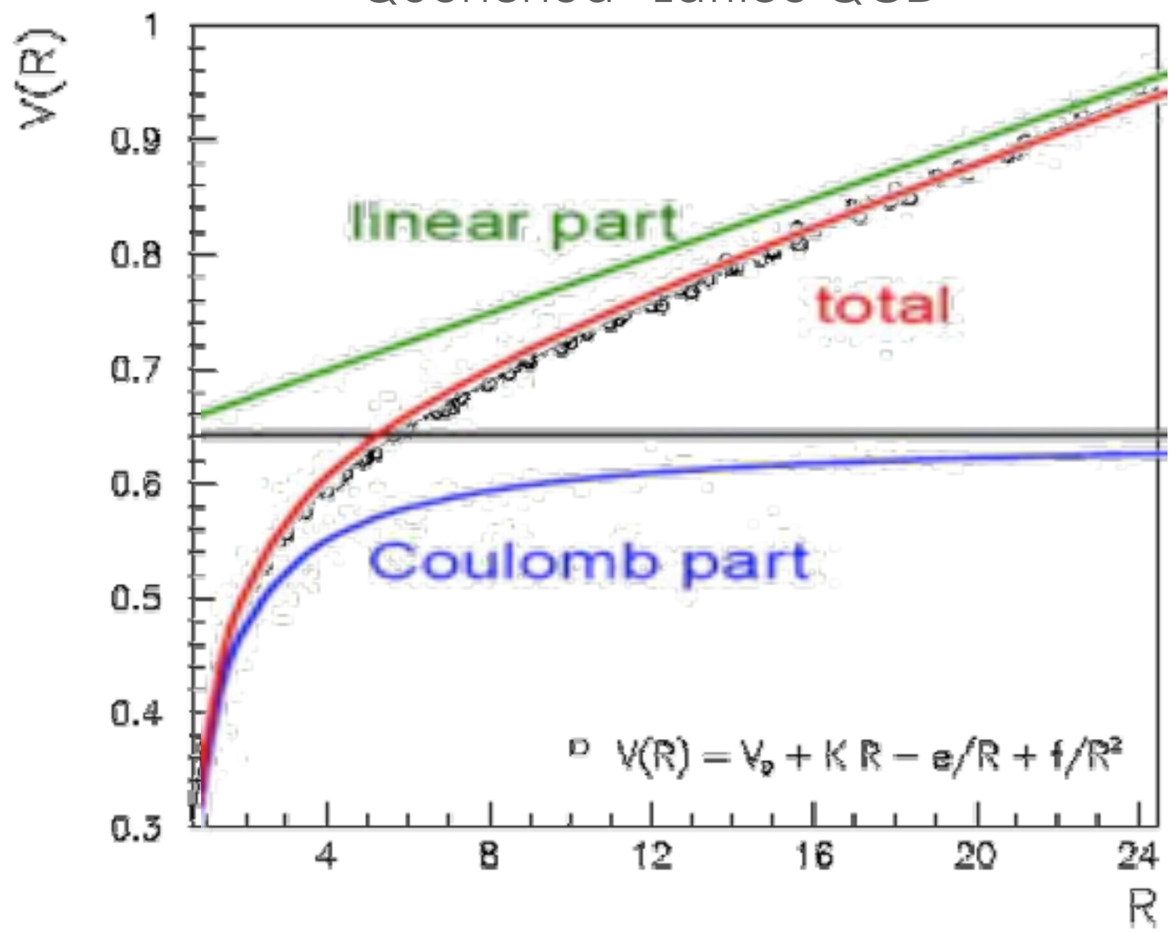
**Lattice QCD:** Potential between a quark and an antiquark as function of distance, R

Long Distances ~ Linear Confinement

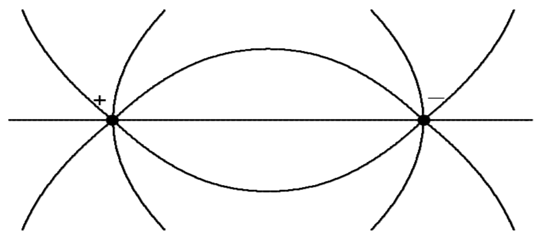


Hadrons

"Quenched" Lattice QCD




Short Distances ~ pQCD

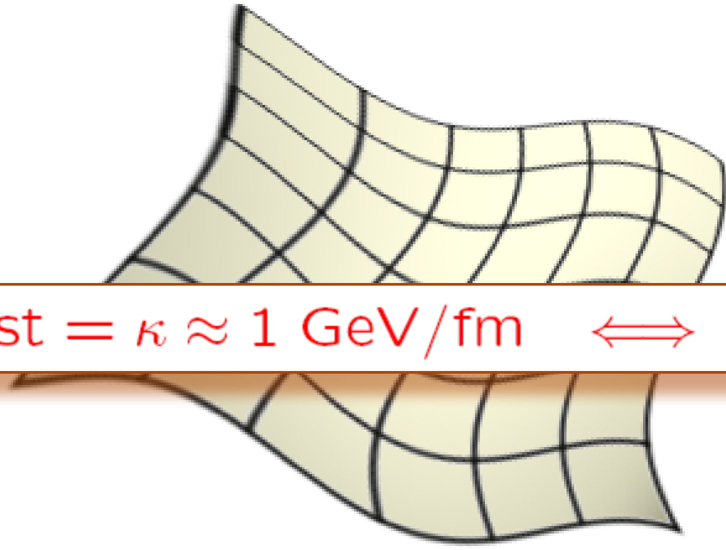


Partons

What physical system has a linear potential?

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

# From Partons to Strings



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

## Motivates a model:

Model: assume the color field collapses into a (infinitely) narrow flux tube of uniform energy density $\varkappa \sim 1$ GeV / fm

→ Relativistic 1+1 dimensional worldsheet – string

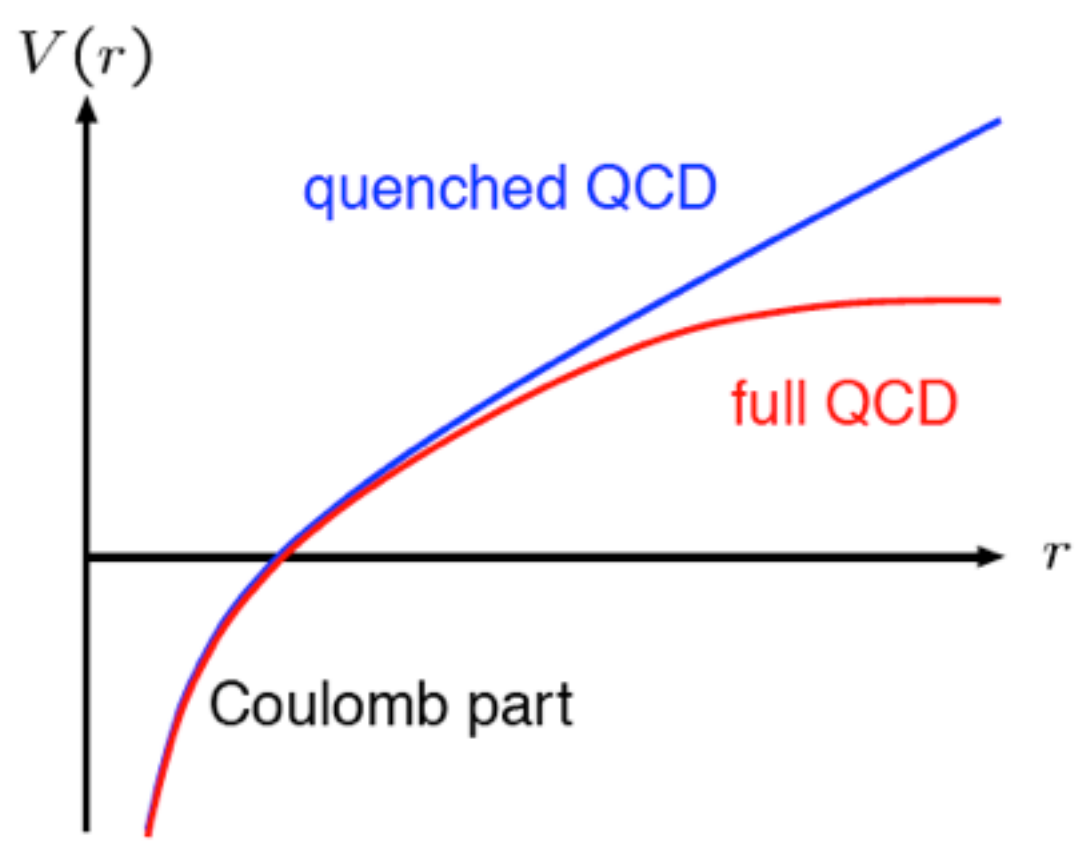
***Lund String Model of Hadronization***

Pedagogical Review: B. Andersson, *The Lund model.* Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol., 1997.

# String Breaks

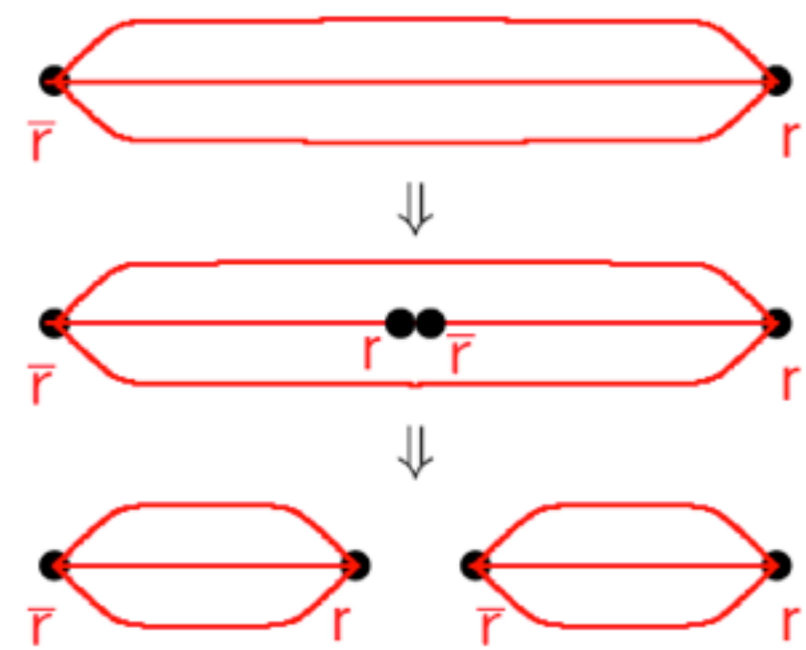
## In "unquenched" QCD

g→qq → The strings would break




String Breaks
(via Quantum Tunneling)

simplified colour representation



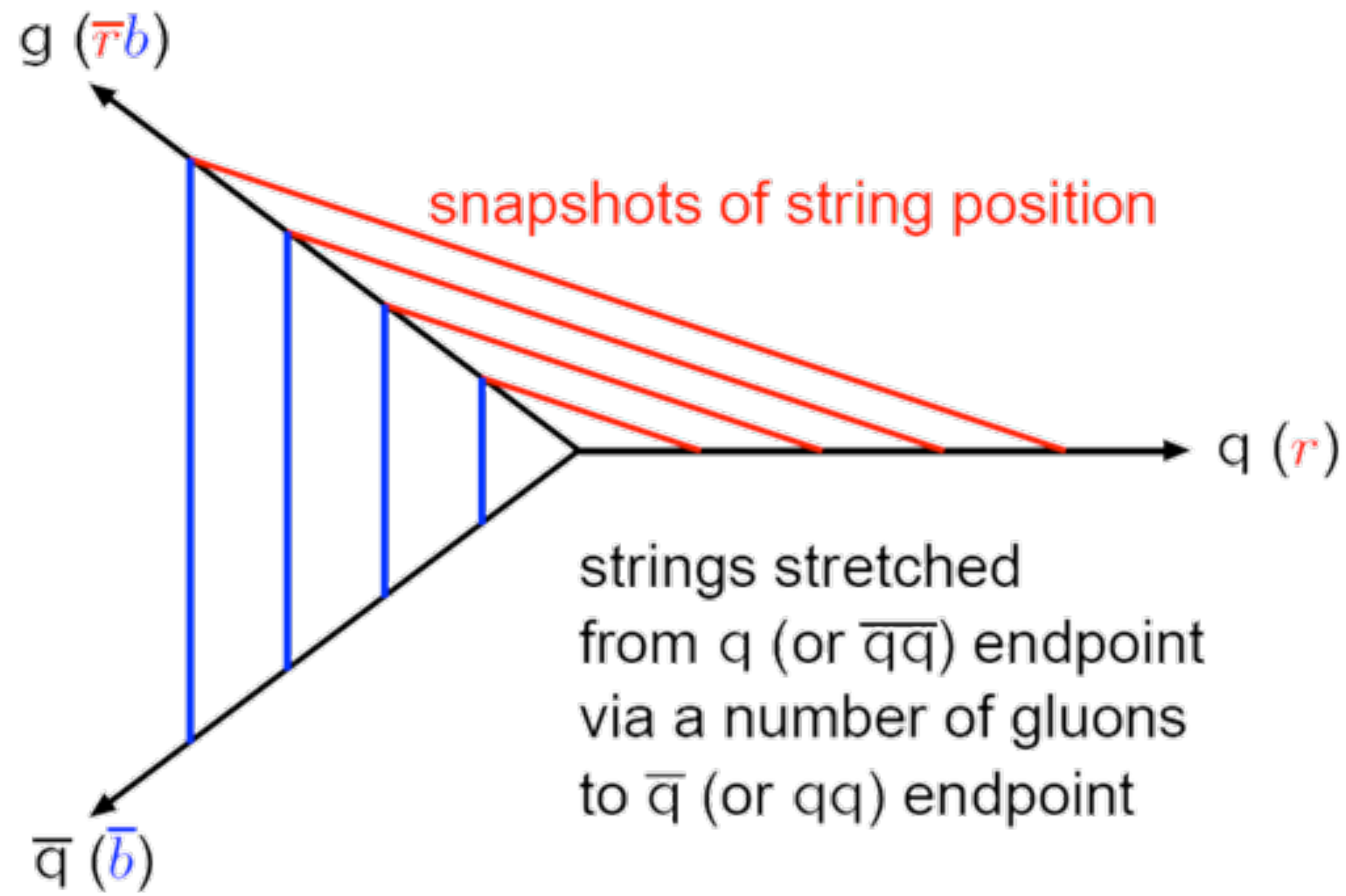

$$\mathcal{P} \propto \exp\left(\frac{-m_q^2 - p_{\perp q}^2}{\kappa}\right)$$

Illustrations by T. Sjöstrand

# 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 (by quantum tunneling) constant per unit area → **AREA LAW**




Gluon = kink on string, carrying energy and momentum

Simple space-time picture
Details of string breaks more complicated

# Hadronization: Summary

**The problem:**

Given a set of **coloured** partons resolved at a scale of ~ 1 GeV, need a (physical) mapping to a new set of degrees of freedom = **colour-neutral** hadronic states.

**Numerical models** do this in three steps

1. Map partons onto endpoints/kinks of **continuum of strings** ~ highly excited hadronic states *(evolves as string worldsheet)*
2. Iteratively map strings/clusters onto **discrete set of primary hadrons** *(string breaks, via quantum tunneling)*
3. Sequential decays into **secondary hadrons** (e.g., $\rho \to \pi\pi$ , $\Lambda^0 \to n\pi^0$, $\pi^0 \to \gamma\gamma$, ...)

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

# Theory ↔ Data

## Global Comparisons

Thousands of measurements

Different energies, acceptance regions, and observable defs

Different generators & versions, with different setups

LEP
Tevatron
SLC
LHC
ISR
HERA
SPS
RHIC

Quite technical
Quite tedious
→
Ask ~~someone~~ else
everyone

LHC@home 2.0
TEST4THEORY

B. Segal,
P. Skands,
J. Blomer,
P. Buncic,
F. Grey,
A. Haratyunyan,
A. Karneyeu,
D. Lombrana-Gonzalez,
M. Marquina

6,500 Volunteers

Over 500 billion simulated collision events

# LHC@Home 2.0 - Test4Theory

**Idea: ship volunteers a virtual atom smasher**
(to help do high-energy theory simulations)

Runs when computer is idle. Sleeps when user is working.

**Problem:** Lots of different machines, architectures

(tedious, technical)

Use Virtualization (CernVM) → provides standardized computing environment on *any* machine (in our case Scientific Linux)

→ replica of our normal working environment. Factorization of IT and Science

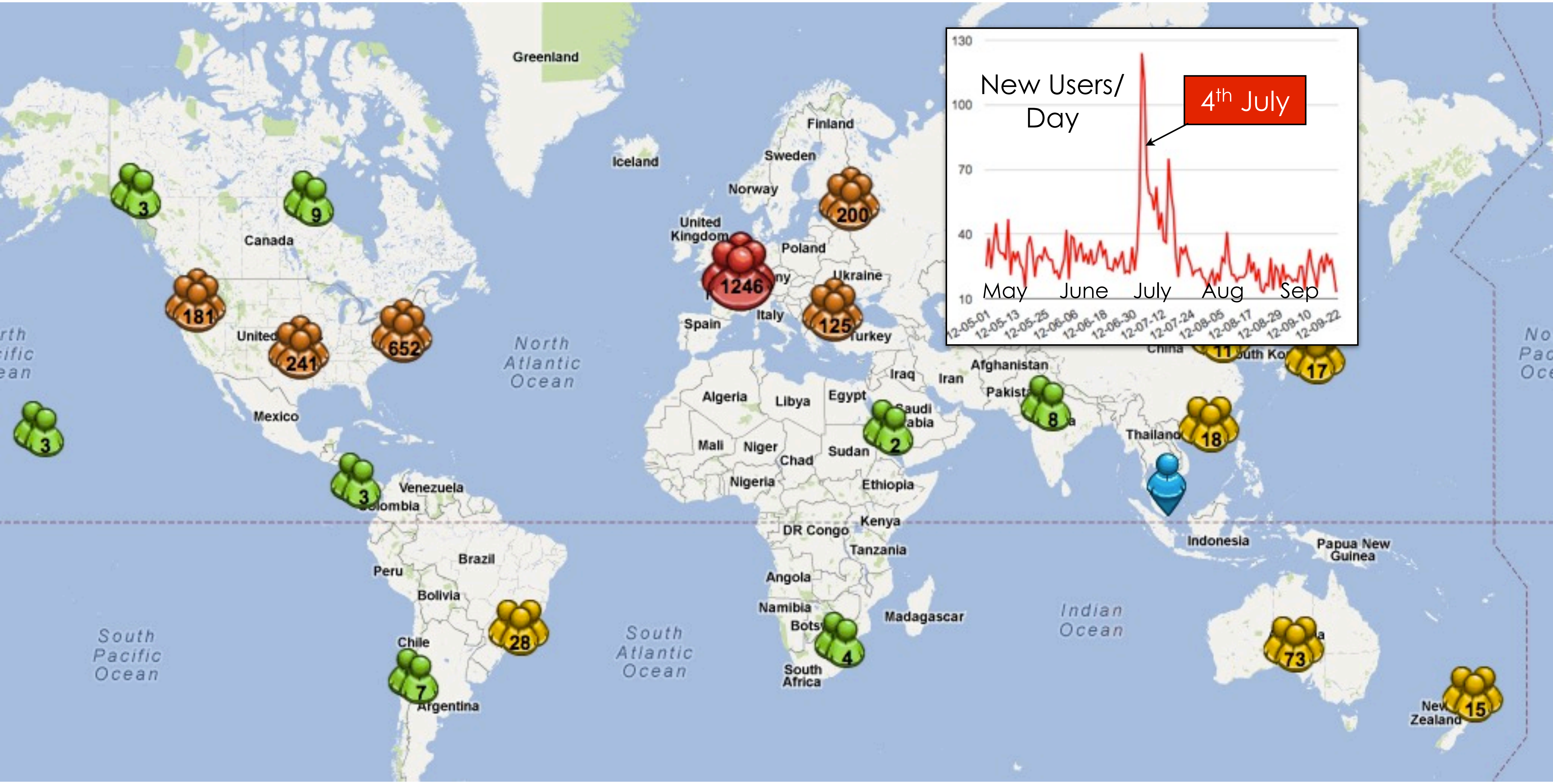
**Infrastructure;** Sending Jobs and Retrieving output

Based on BOINC platform for volunteer clouds (but can also use other distributed computing resources, like GRID or traditional farms)

New aspect: virtualization, never previously done for a volunteer cloud

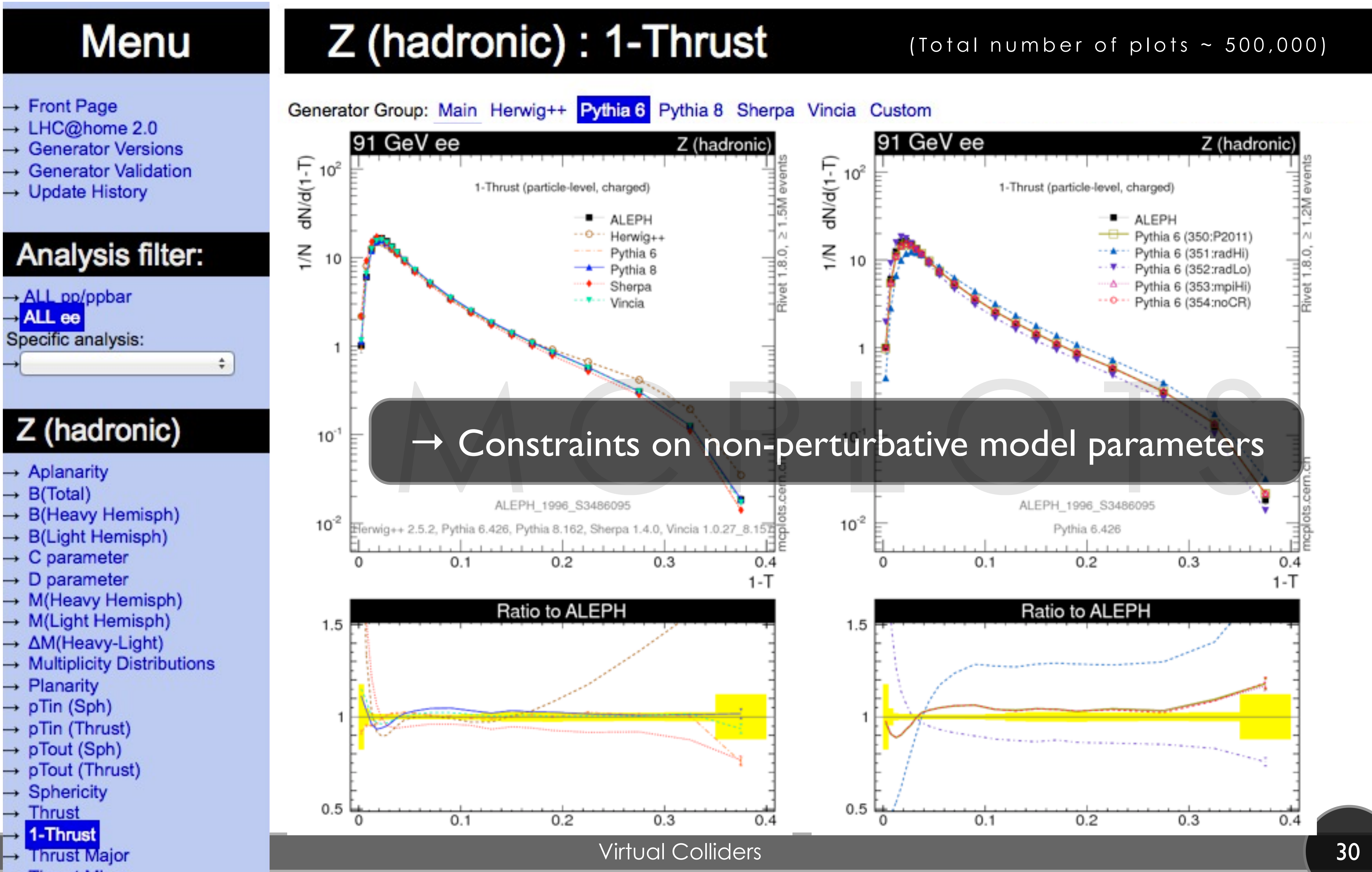
http://lhcathome2.cern.ch/test4theory/

# Last 24 Hours: 2853 machines




Next Big Project : **Citizen Cyberlab** (3.4M€), interact with simulations to learn physics, just started …

# Results → mcplots.cern.ch




→ Constraints on non-perturbative model parameters

# Beyond Perturbation Theory

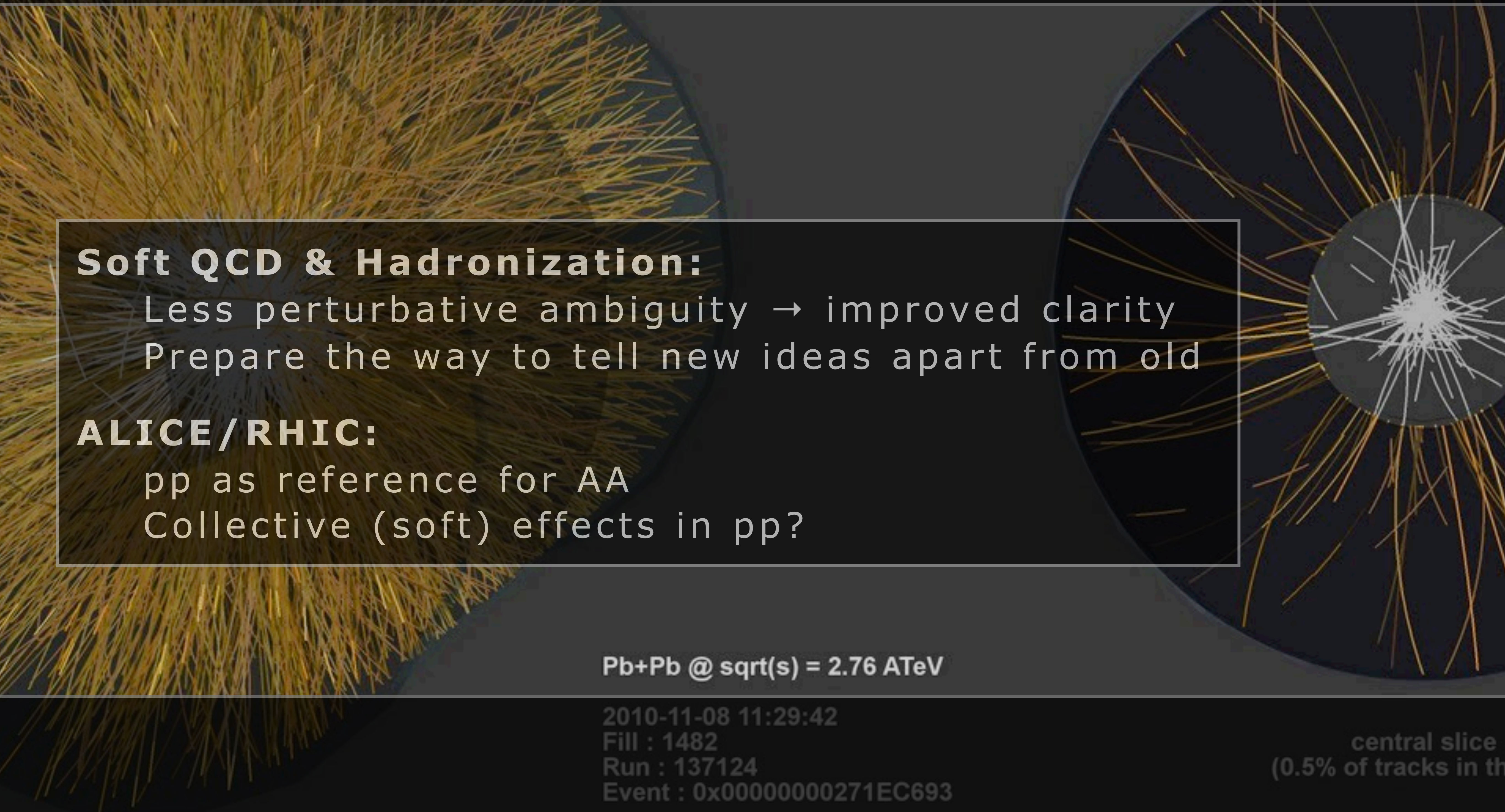
Better pQCD → Better non-perturbative constraints

**Soft QCD & Hadronization:**

- Less perturbative ambiguity → improved clarity
- Prepare the way to tell new ideas apart from old

**ALICE/RHIC:**

- pp as reference for AA
- Collective (soft) effects in pp?



# Beyond Colliders?

Other uses for a high-precision fragmentation model

**Dark-matter annihilation:**
Photon & particle spectra

**Cosmic Rays:**
Extrapolations to ultra-high energies

ISS, March 28, 2012
Aurora and sunrise over Ireland & the UK

# Summary

**QCD phenomenology is witnessing a rapid evolution:**

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

**Non-perturbative QCD** is still hard

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

Lots of input from LHC *(THANK YOU to the experiments!)*

**"Solving the LHC"** is both interesting and rewarding

New ideas needed and welcome on both perturbative and non-perturbative sides → many opportunities for theory-experiment interplay

Key to high precision → max information about the Terascale

# The Strong Coupling

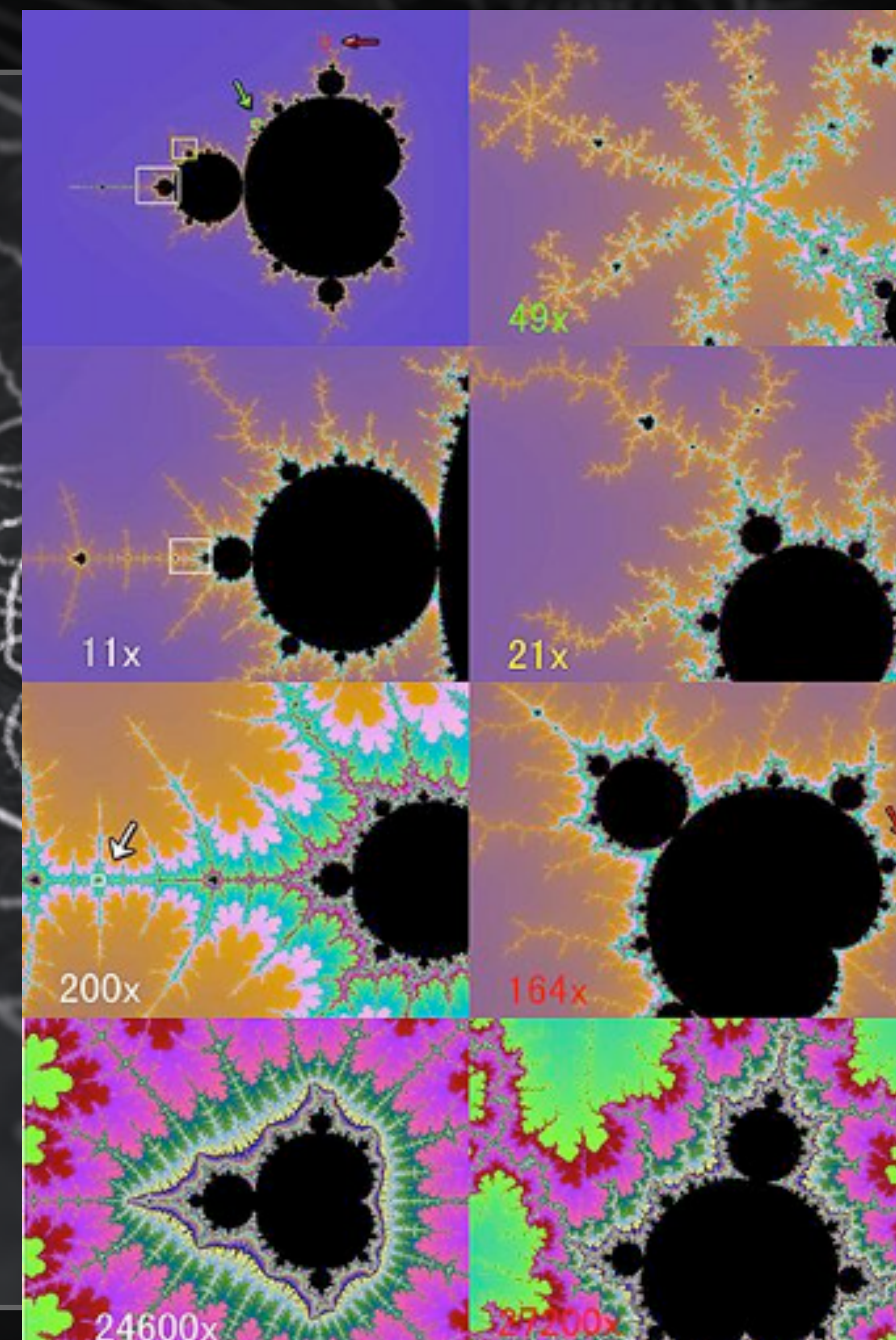
Bjorken scaling

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 didn't "run", this would be absolutely true (e.g., N=4 Supersymmetric Yang-Mills)

As it is, $\alpha_s$ only runs slowly (logarithmically) → can still gain insight from fractal analogy



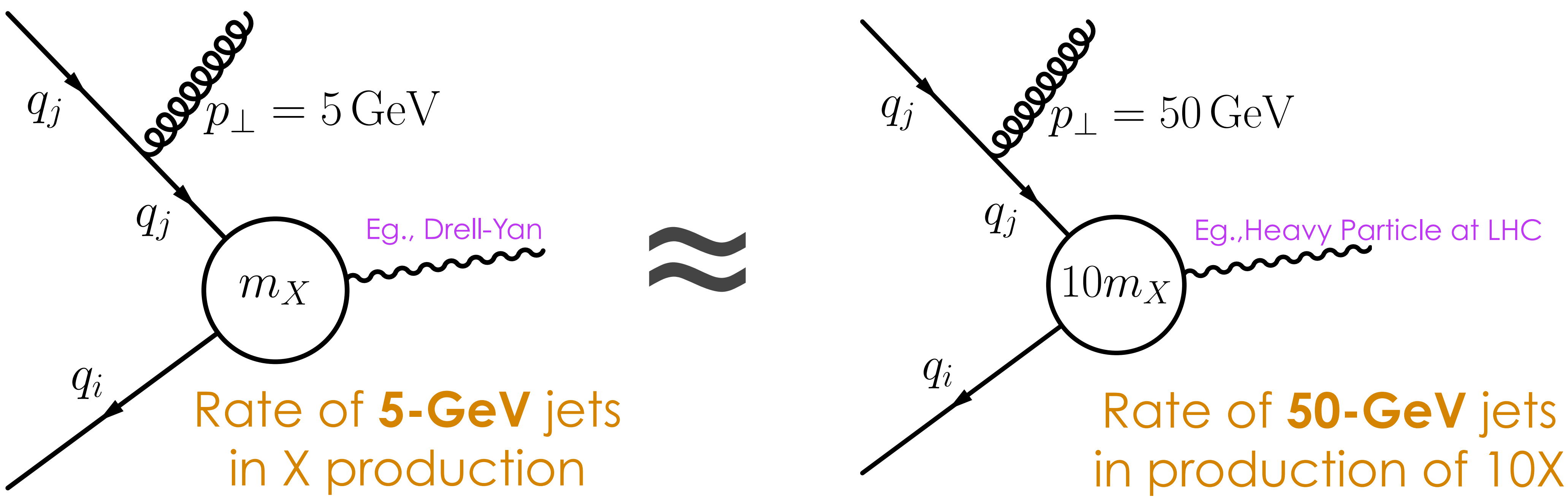

Note: I use the terms "conformal" and "scale invariant" interchangeably

Strictly speaking, conformal (angle-preserving) symmetry is more restrictive than just scale invariance

But examples of scale-invariant field theories that are not conformal are rare (eg 6D noncritical self-dual string theory)

## Bremsstrahlung

Rate of bremsstrahlung jets mainly depends on the RATIO of the jet $p_T$ to the "hard scale"



# Conformal QCD in Action

## Naively, QCD radiation suppressed by $\alpha_s \approx 0.1$

Truncate at fixed order = LO, NLO, …

But beware the jet-within-a-jet-within-a-jet …

**Example:** 100 GeV can be "soft" at the LHC

SUSY pair production at 14 TeV, with $M_{SUSY} \approx 600$ GeV

LHC - sps1a - m~600 GeV

Plehn, Rainwater, PS PLB645(2007)217

| FIXED ORDER pQCD | $\sigma_{tot}$ [pb] | $\tilde{g}\tilde{g}$ | $\tilde{u}_L\tilde{g}$ | $\tilde{u}_L\tilde{u}_L^*$ | $\tilde{u}_L\tilde{u}_L$ | $TT$ |
|---|---|---|---|---|---|---|
| $p_{T,j} >$ 100 GeV | $\sigma_{0j}$ | 4.83 | 5.65 | 0.286 | 0.502 | 1.30 |
| inclusive X + 1 "jet" → | $\sigma_{1j}$ | 2.89 | 2.74 | 0.136 | 0.145 | 0.73 |
| inclusive X + 2 "jets" → | $\sigma_{2j}$ | 1.09 | 0.85 | 0.049 | 0.039 | 0.26 |
| $p_{T,j} >$ 50 GeV | $\sigma_{0j}$ | 4.83 | 5.65 | 0.286 | 0.502 | 1.30 |
| | $\sigma_{1j}$ | 5.90 | 5.37 | 0.283 | 0.285 | 1.50 |
| | $\sigma_{2j}$ | 4.17 | 3.18 | 0.179 | 0.117 | 1.21 |

(Computed with SUSY-MadGraph)

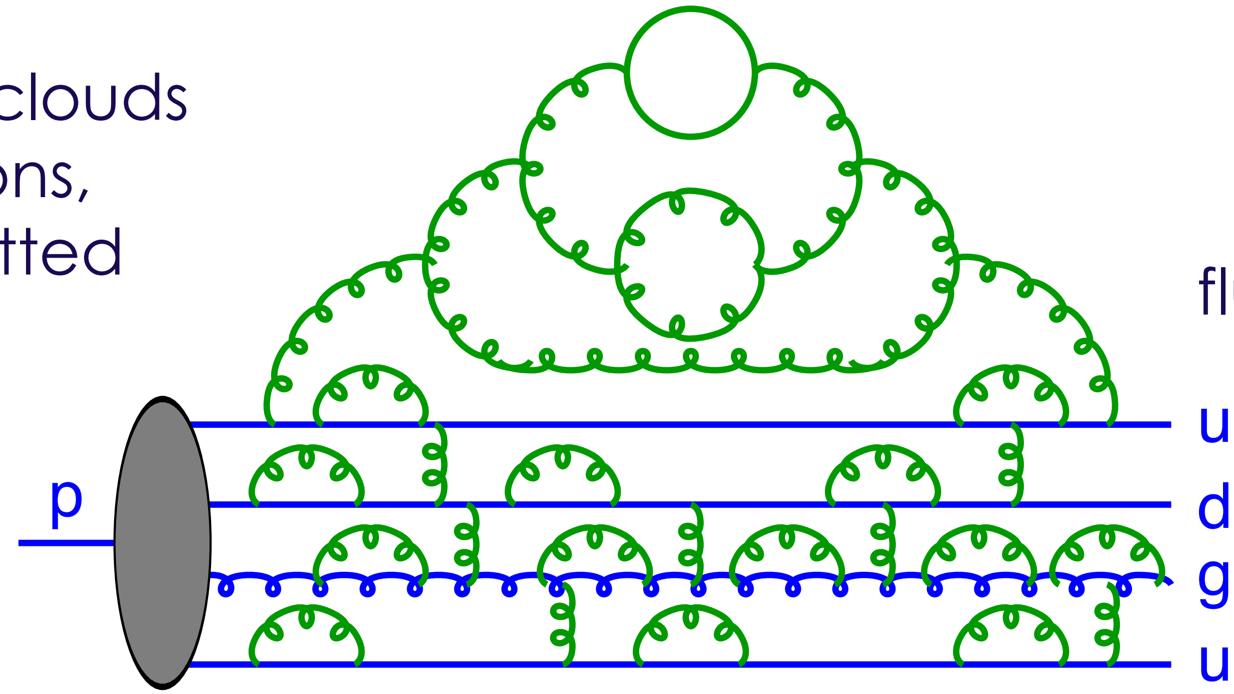
σ for X + jets much larger than naive estimate

σ for 50 GeV jets ≈ larger than total cross section → not under control

# (Parton Distributions)

Hadrons are composite, with time-dependent structure:

Partons within clouds of further partons, constantly emitted and absorbed




For hadron to remain intact, virtualities $k^2 < M_h^2$

High-virtuality fluctuations suppresed by powers of

$$\frac{\alpha_s M_h^2}{k^2}$$

$M_h$ : mass of hadron

$k^2$ : virtuality of fluctuation

→ Lifetime of fluctuations ~ $1/M_h$

Hard incoming probe interacts over much shorter time scale ~ $1/Q$

On that timescale, partons ~ frozen

Hard scattering knows nothing of the target hadron apart from the fact that it contained the struck parton

Illustration from T. Sjöstrand

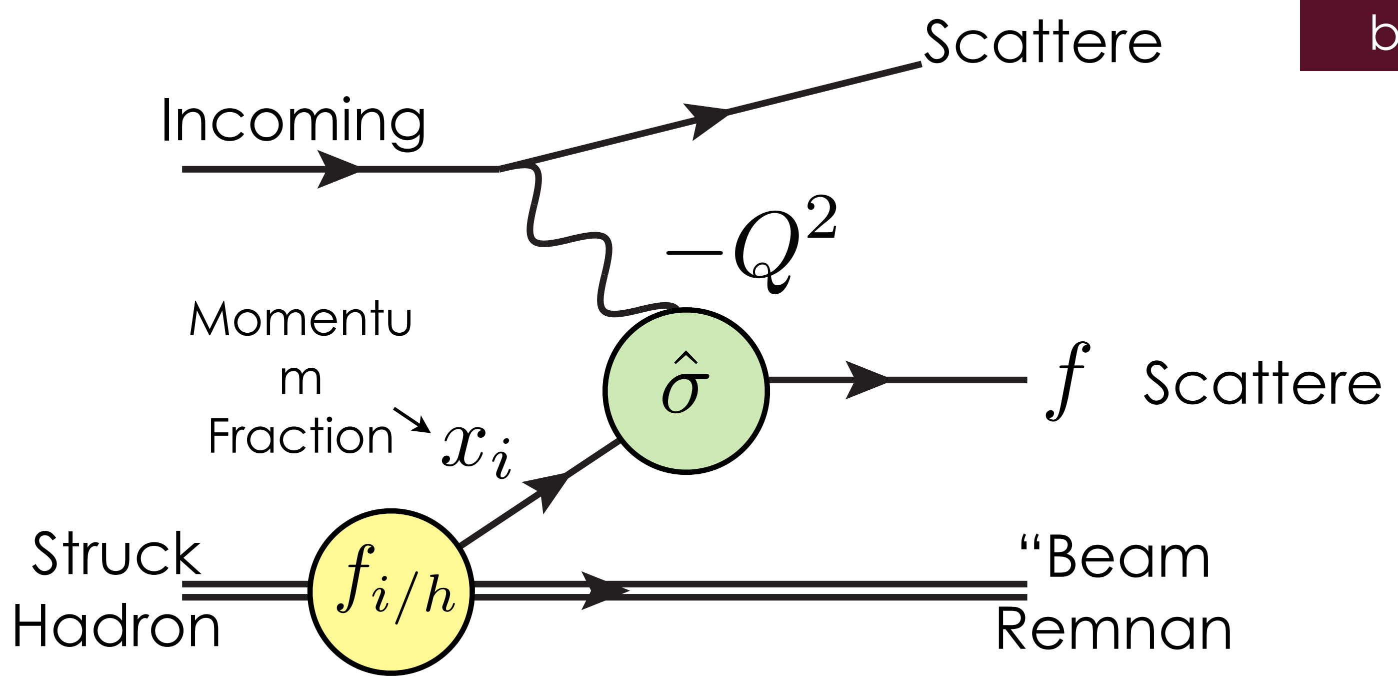
# (Factorization Theorem)

See also electron-nucleon scattering in lectures by K. Assamagan

## Example: DIS (Collins, Soper, 1987)

Deep Inelastic Scattering (DIS)

(By "deep",




→ We really can write the cross section in factorized

$$\sigma^{\ell h} = \sum_i \sum_f \int dx_i \int d\Phi_f \, f_{i/h}(x_i, Q_F^2) \, \frac{d\hat{\sigma}^{\ell i \to f}(x_i, \Phi_f, Q_F^2)}{dx_i \, d\Phi_f}$$

Sum over Initial (i) and final (f) parton flavors

$\Phi_f$ = Final-state phase space

$f_{i/h}$ = PDFs Universal Constrained by fits to data

Differential partonic Hard-scattering Matrix Element(s)

# Last Ingredient: Loops

PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

**Unitarity** (KLN):

Singular structure at loop level must be equal and opposite to tree level

Kinoshita-Lee-Nauenberg:

Loop = – Int(Tree) + F

*Neglect F → Leading-Logarithmic (LL) Approximation*

→ **Virtual (loop) correction:**

$$2\mathrm{Re}[\mathcal{M}_F^{(0)}\mathcal{M}_F^{(1)*}] \; = \; -g_s^2\, N_C \left|\mathcal{M}_F^{(0)}\right|^2 \int \frac{\mathrm{d}s_{ij}\,\mathrm{d}s_{jk}}{16\pi^2 s_{ijk}} \left( \frac{2s_{ik}}{s_{ij}s_{jk}} \; + \; \text{less singular terms} \right)$$

**Realized by Event *evolution*** in Q = fractal scale (virtuality, $p_T$, formation time, …)

Resolution scale
$t = \ln(Q^2)$

$$\frac{\mathrm{d}N_F(t)}{dt} = -\frac{\mathrm{d}\sigma_{F+1}}{\mathrm{d}\sigma_F} N_F(t)$$

= *Approximation to Real Emissions*

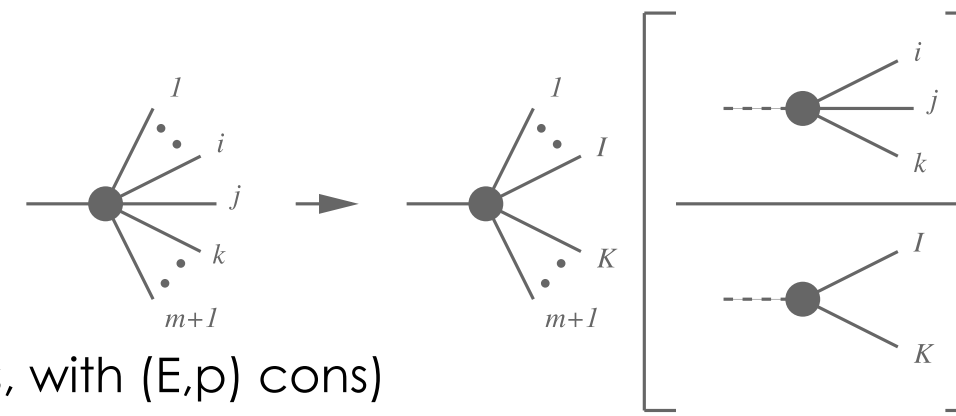
Probability to remain "unbranched" from $t_0$ to t
→ The "Sudakov Factor"

$$\frac{N_F(t)}{N_F(t_0)} = \Delta_F(t_0,t) = \exp\left(-\int \frac{\mathrm{d}\sigma_{F+1}}{\mathrm{d}\sigma_F}\right)$$

= *Approximation to Loop Corrections*

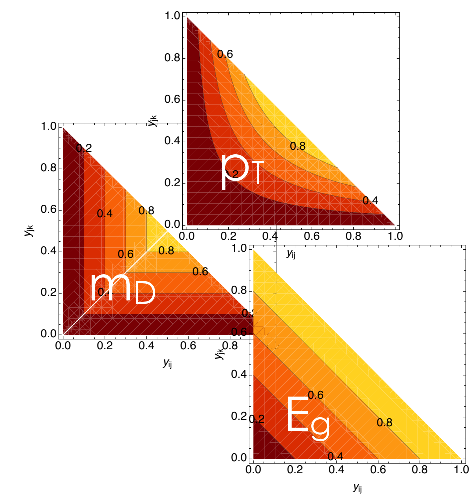
Virtual Numerical Collider with Interleaved Antennae
Written as a Plug-in to PYTHIA 8
C++ (~20,000 lines)

Giele, Kosower, Skands, PRD 78 (2008) 014026, PRD 84 (2011) 054003
Gehrmann-de Ridder, Ritzmann, Skands, PRD 85 (2012) 014013




## Based on antenna factorization

- of Amplitudes (exact in both soft and collinear limits)
- of Phase Space (LIPS : 2 on-shell → 3 on-shell partons, with (E,p) cons)




**Resolution Time**

Infinite family of continuously deformable $Q_E$

Special cases: transverse momentum, invariant mass, energy

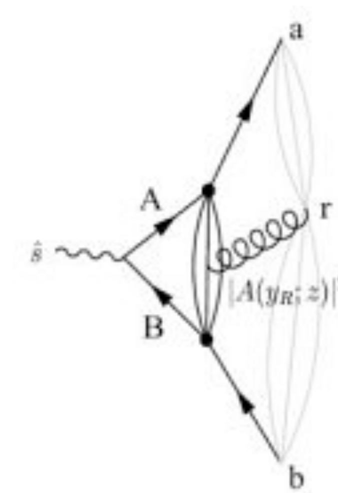
+ Improvements for hard 2→4: "smooth ordering"

**Radiation functions**

Written as Laurent-series with arbitrary coefficients, $ant_i$

Special cases for non-singular terms: Gehrmann-Glover, MIN, MAX

+ Massive antenna functions for massive fermions $(c,b,t)$




**Kinematics maps**

Formalism derived for infinitely deformable $\varkappa_{3\to2}$

Special cases: ARIADNE, Kosower, + massive generalizations

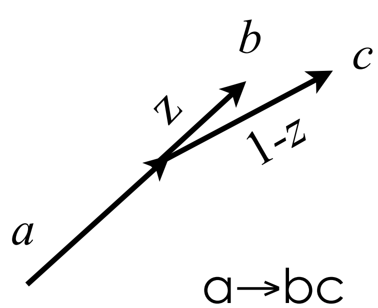
vincia.hepforge.org

# Helicities

Larkoski, Peskin, PRD 81 (2010) 054010
+ Ongoing, with A. Larkoski (MIT) & J. Lopez-Villarejo (CERN)

**Traditional parton showers** use the standard Altarelli-Parisi kernels, P(z) = helicity sums/averages over:

| $P(z)$ | $++$ | $-+$ | $+-$ | $--$ |
|---|---|---|---|---|
| $g_+ \to gg:$ | $1/z(1-z)$ | $(1-z)^3/z$ | $z^3/(1-z)$ | $0$ |
| $g_+ \to q\bar{q}:$ | - | $(1-z)^2$ | $z^2$ | - |
| $q_+ \to qg:$ | $1/(1-z)$ | - | $z^2/(1-z)$ | - |
| $q_+ \to gq:$ | $1/z$ | $(1-z)^2/z$ | - | - |



a→bc

**Generalize** these objects to dipole-antennae

E.g.,

$$q\bar{q} \to qg\bar{q}$$

$++ \to +++$ MHV

$++ \to +-+$ NMHV

$+- \to ++-$ P-wave

$+- \to +--$ P-wave

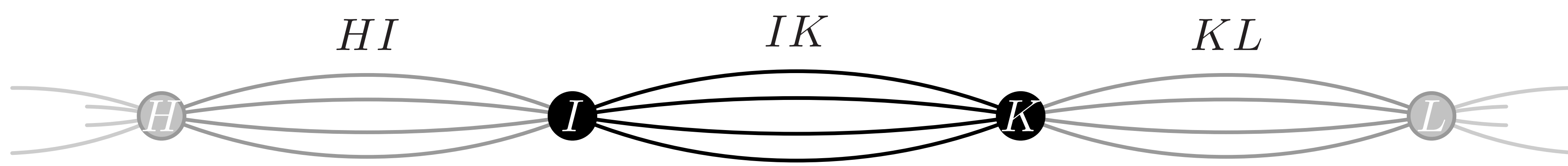
→ Can trace helicities through shower

→ Eliminates contribution from unphysical helicity configurations

→ Can match to individual helicity amplitudes rather than helicity sum
→ Fast! (gets rid of another factor $2^N$)

# Shower Types

Traditional vs Coherent vs Global vs Sector vs Dipole




| | Coll($I$) | Soft($IK$) |
|---|---|---|
| *Parton Shower (DGLAP)* | $a_I$ | $a_I + a_K$ |
| *Coherent Parton Shower (*HERWIG *[12,40],* PYTHIA6 *[11])* | $\Theta_I a_I$ | $\Theta_I a_I + \Theta_K a_K$ |
| *Global Dipole-Antenna (*ARIADNE *[17], GGG [36], WK [32],* VINCIA*)* | $a_{IK} + a_{HI}$ | $a_{IK}$ |
| *Sector Dipole-Antenna (LP [41],* VINCIA*)* | $\Theta_{IK} a_{IK} + \Theta_{HI} a_{HI}$ | $a_{IK}$ |
| *Partitioned-Dipole Shower (SK [23], NS [42], DTW [24],* PYTHIA8 *[38],* SHERPA*)* | $a_{I,K} + a_{I,H}$ | $a_{I,K} + a_{K,I}$ |

Figure 2: Schematic overview of how the full collinear singularity of parton $I$ and the soft singularity of the $IK$ pair, respectively, originate in different shower types. ($\Theta_I$ and $\Theta_K$ represent angular vetos with respect to partons $I$ and $K$, respectively, and $\Theta_{IK}$ represents a sector phase-space veto, see text.)

# The Denominator

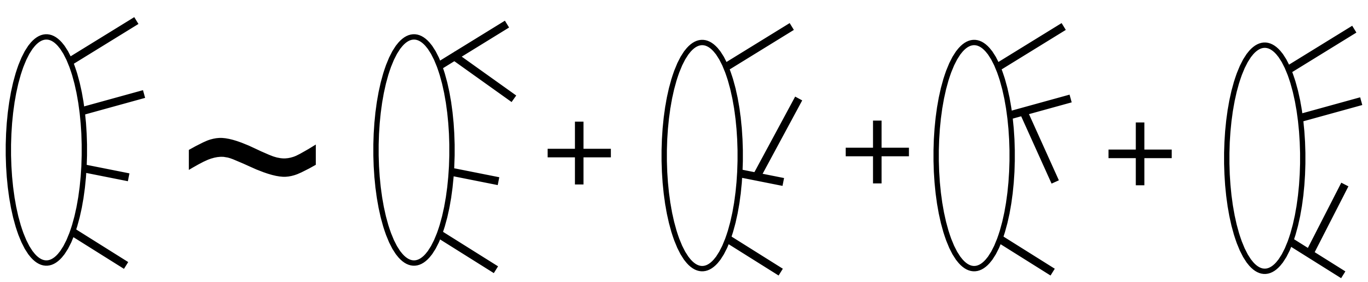
$$a_i \rightarrow \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2}$$

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

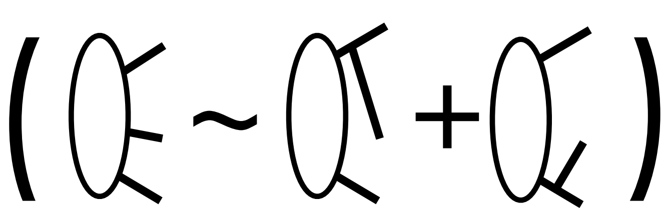
Existing parton showers are *not* really Markov Chains

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

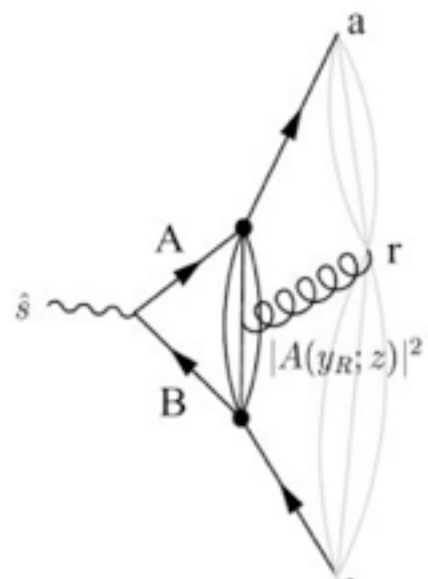
*(+ parton showers have complicated and/or frame-dependent phase-space mappings, especially at the multi-parton level)*

# Matched Markovian Antenna Showers

**Antenna showers:** one term per parton *pair*

**$2^n n! \rightarrow n!$**

*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! → 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*

# Effective 2→4

## Generate Branchings *without* imposing strong ordering

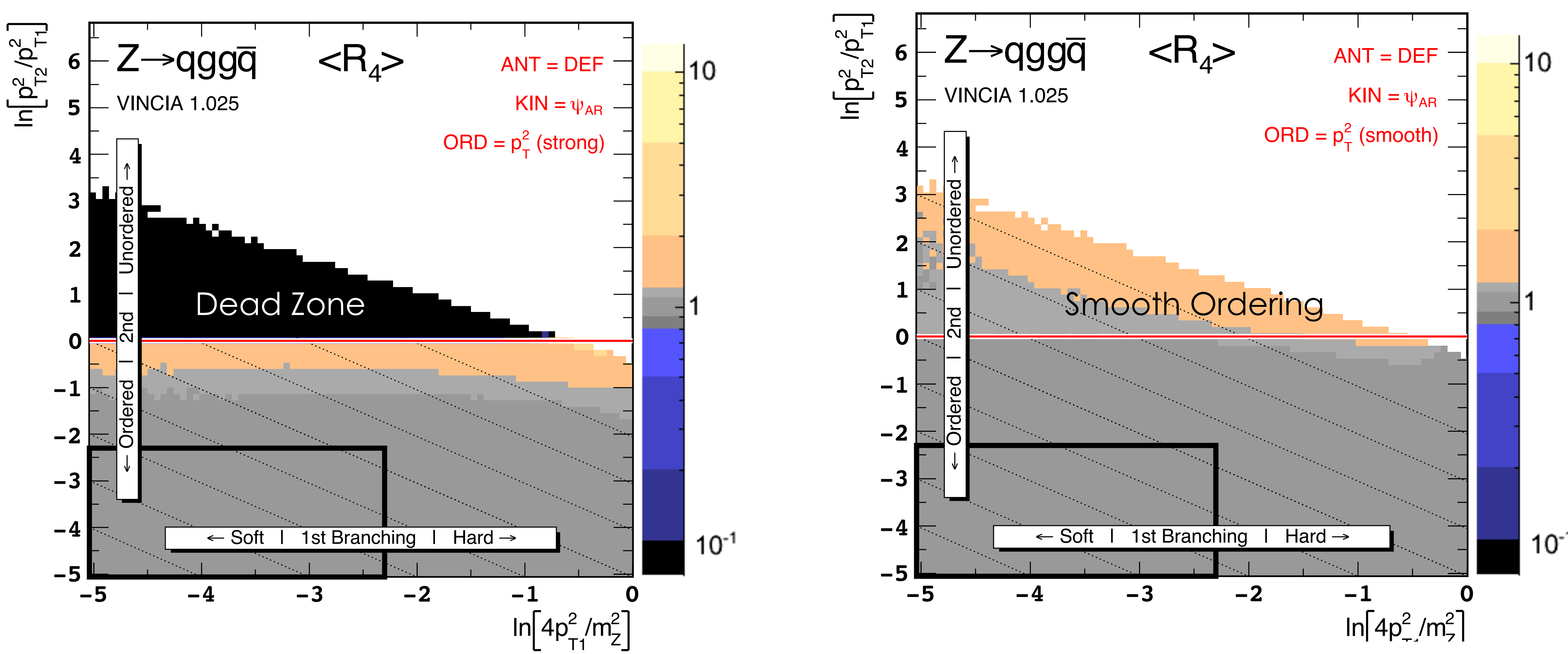
At each step, each dipole allowed to fill its entire phase space

Overcounting removed by matching

+ smooth ordering beyond matched multiplicities

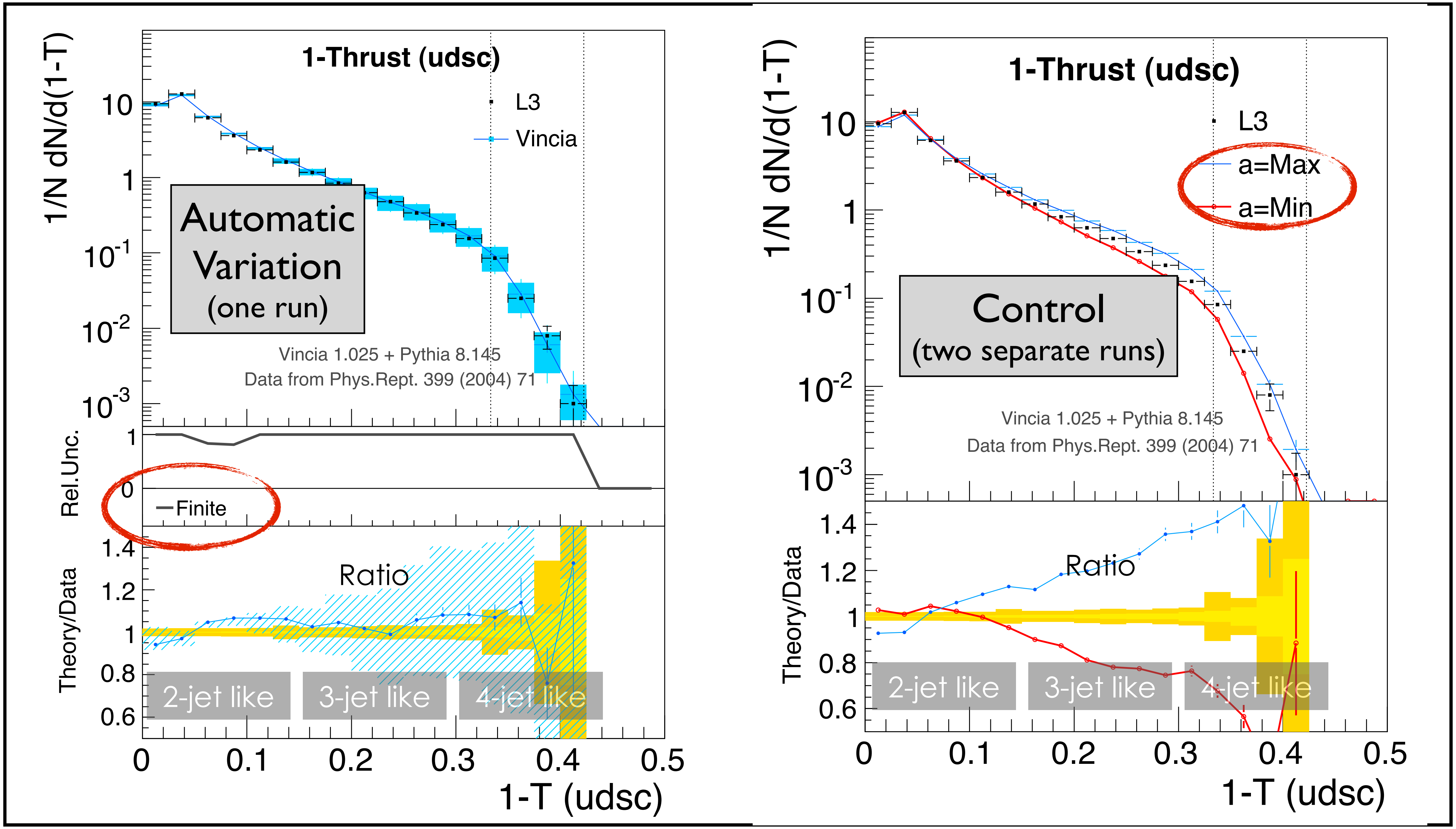
$$\frac{\hat{p}_\perp^2}{\hat{p}_\perp^2 + p_\perp^2} P_{\mathrm{LL}}$$

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



# Example: Non-Singular Terms

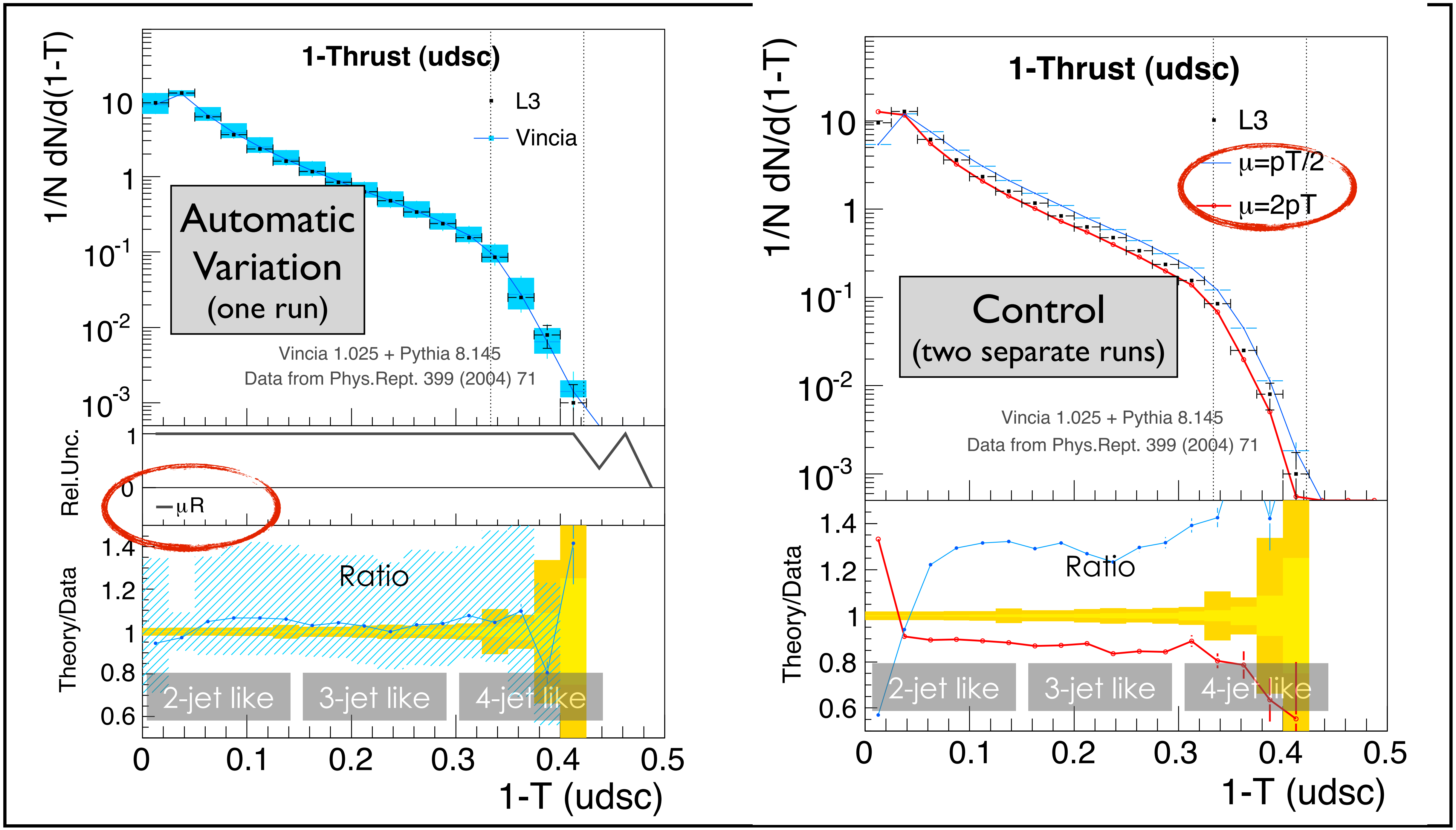
Giele, Kosower, Skands, PRD 84 (2011) 054003




**Thrust** = LEP event-shape variable, goes from 0 (pencil) to 0.5 (hedgehog)

# Example: μR

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




**Thrust** = LEP event-shape variable, goes from 0 (pencil) to 0.5 (hedgehog)

# Fixed Order: Recap

**Improve by** computing quantum corrections, order by order

(from PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389)

F (

### Leading Order

| $\ell$ (loops) \ $k$ (legs) | 0 | 1 | 2 | 3 | ... |
|---|---|---|---|---|---|
| 2 | $\sigma_0^{(2)}$ | $\sigma_1^{(2)}$ | ... | | |
| 1 | $\sigma_0^{(1)}$ | $\sigma_1^{(1)}$ | $\sigma_2^{(1)}$ | ... | |
| 0 | $\sigma_0^{(0)}$ | $\sigma_1^{(0)}$ | $\sigma_2^{(0)}$ | $\sigma_3^{(0)}$ | ... |

Max Born, 1882-1970 Nobel 1954

### Next-to-Leading Order

| $\ell$ (loops) \ $k$ (legs) | 0 | 1 | 2 | 3 | ... |
|---|---|---|---|---|---|
| 2 | $\sigma_0^{(2)}$ | $\sigma_1^{(2)}$ | ... | | |
| 1 | $\sigma_0^{(1)}$ | $\sigma_1^{(1)}$ | $\sigma_2^{(1)}$ | ... | |
| 0 | $\sigma_0^{(0)}$ | $\sigma_1^{(0)}$ | $\sigma_2^{(0)}$ | $\sigma_3^{(0)}$ | ... |

$$\sigma^{\rm NLO} = \sigma^{\rm Born} + \int \mathrm{d}\Phi_{F+1} \left|\mathcal{M}^{(0)}_{F+1}\right|^2 + \int \mathrm{d}\Phi_F\, 2\mathrm{Re}\left[\mathcal{M}^{(1)}_F \mathcal{M}^{(0)*}_F\right]$$

→ $1/\epsilon^2 + 1/\epsilon$ + Finite

→ $-1/\epsilon^2 - 1/\epsilon$ + Finite

**The Subtraction Idea**

$$= \sigma^{\rm Born} + \underbrace{\int \mathrm{d}\Phi_{F+1} \left(|\mathcal{M}^{(0)}_{F+1}|^2 - \mathrm{d}\sigma_S^{\rm NLO}\right)}_{\text{Finite by Universality}}$$

$$+ \underbrace{\int \mathrm{d}\Phi_F\; 2\mathrm{Re}[\mathcal{M}^{(1)}_F \mathcal{M}^{(0)*}_F] + \int \mathrm{d}\Phi_{F+1}\, \mathrm{d}\sigma_S^{\rm NLO}}_{\text{Finite by KLN}} .$$

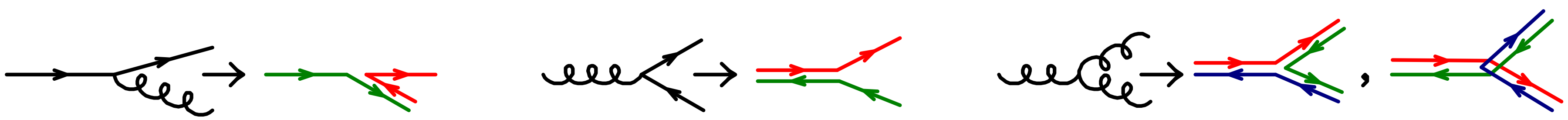
Universal "Subtraction Terms" (will return to later)

# (Color Flow in MC Models)

## "Planar Limit"

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

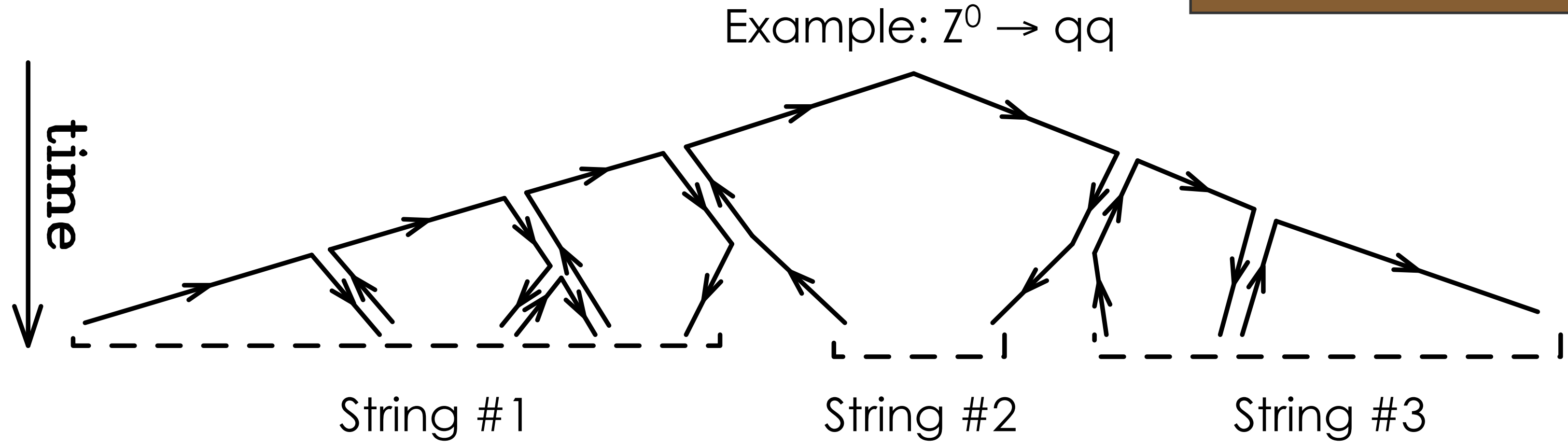
Rules for color flow:



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

## For an entire cascade:

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



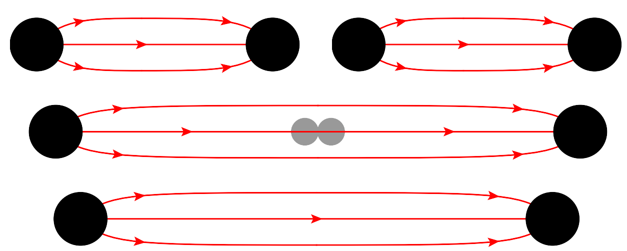

Coherence of pQCD cascades → not much "overlap" between strings

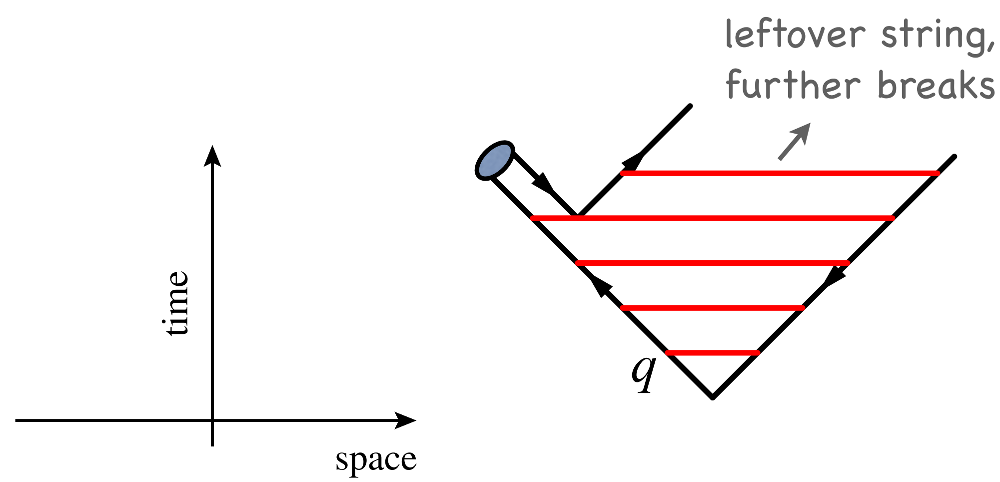
→ planar approx pretty good

LEP measurements in WW confirm this (at least to order 10% ~ $1/N_C^2$ )

# 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: