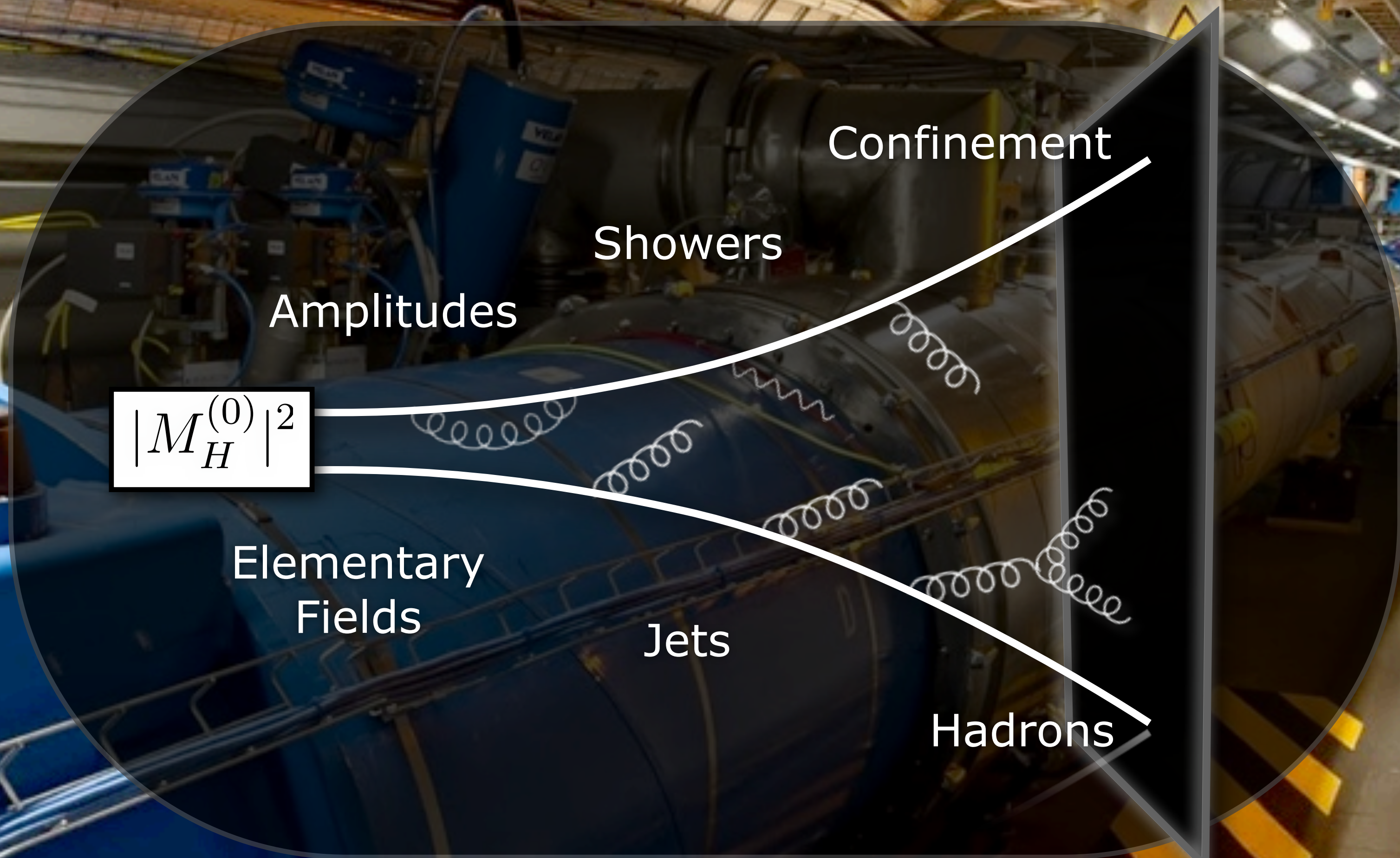
DISCOVERY Seminar, Sep 27 2012, NBI, Copenhagen

Solving the LHC



Peter Skands
(CERN TH)

Why?

July 4th 2012: "Higgs-like" stuff at CERN

+ huge amount of other physics studies:

# of journal papers:
144 ATLAS, 116 CMS, 51 LHCb, 27 ALICE

Some of these are already, or will ultimately be, **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: a new formalism for highly accurate collider-physics predictions, and future perspectives

How?

Fixed Order Perturbation Theory:

Problem: limited orders

Parton Showers:

Problem: limited precision

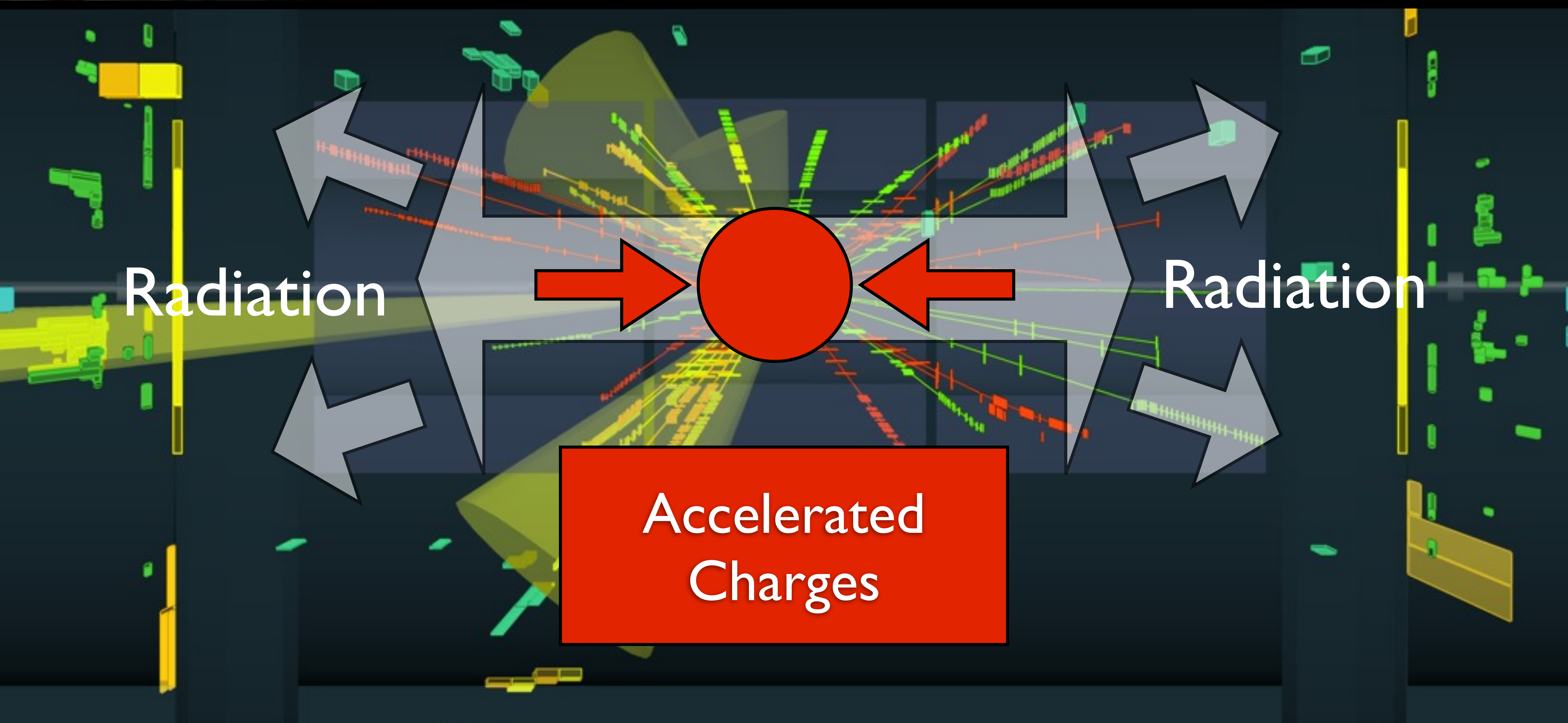
"Matching": Best of both Worlds?

Problem: stitched together, slow

Markovian Perturbation Theory

→ Infinite orders, high precision, fast

Bremsstrahlung



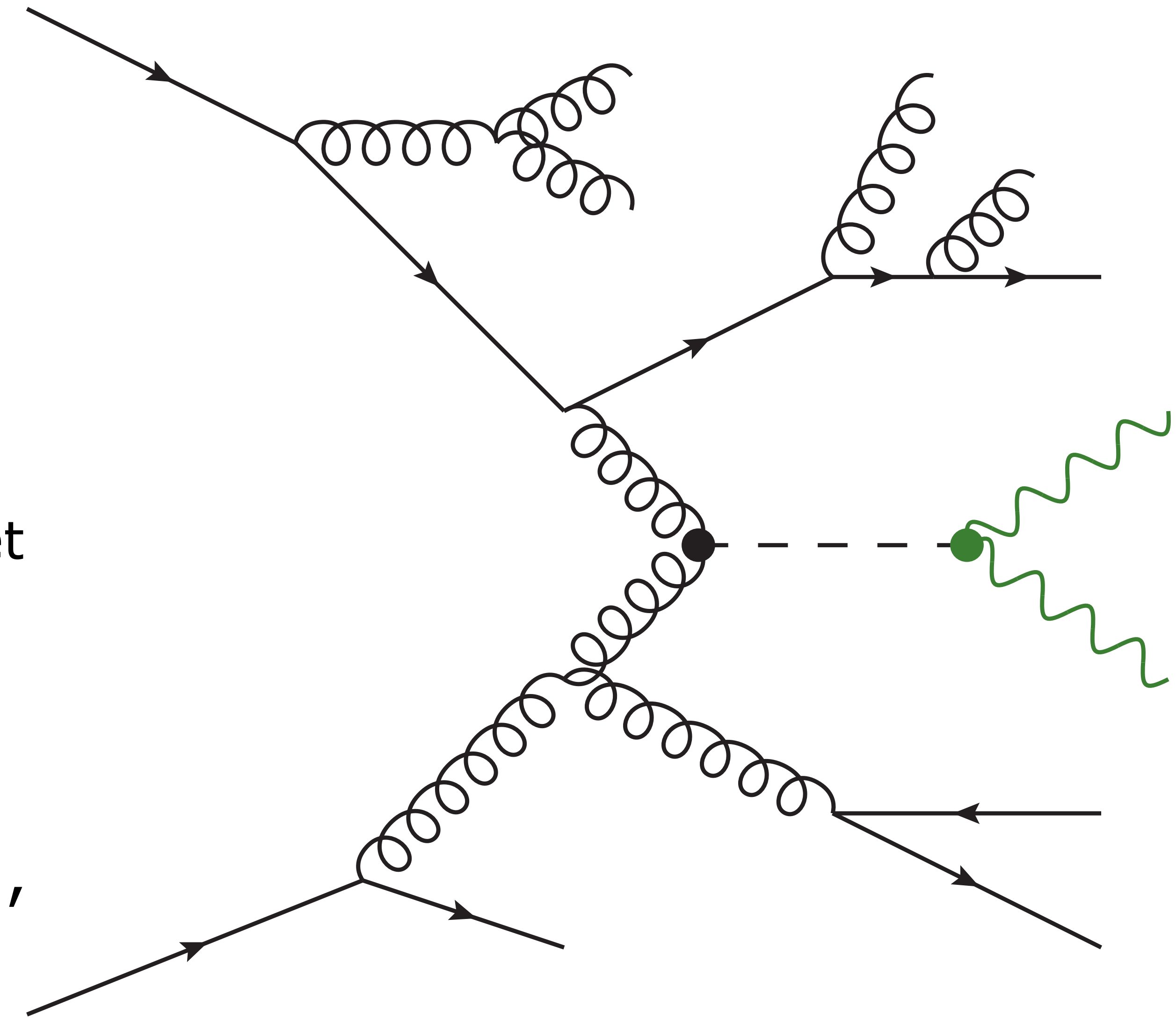
The harder they get kicked, the harder the fluctations that continue to become strahlung

Bremsstrahlung

Most bremsstrahlung is emitted by particles that are almost 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 N, N+1, N+2, etc …

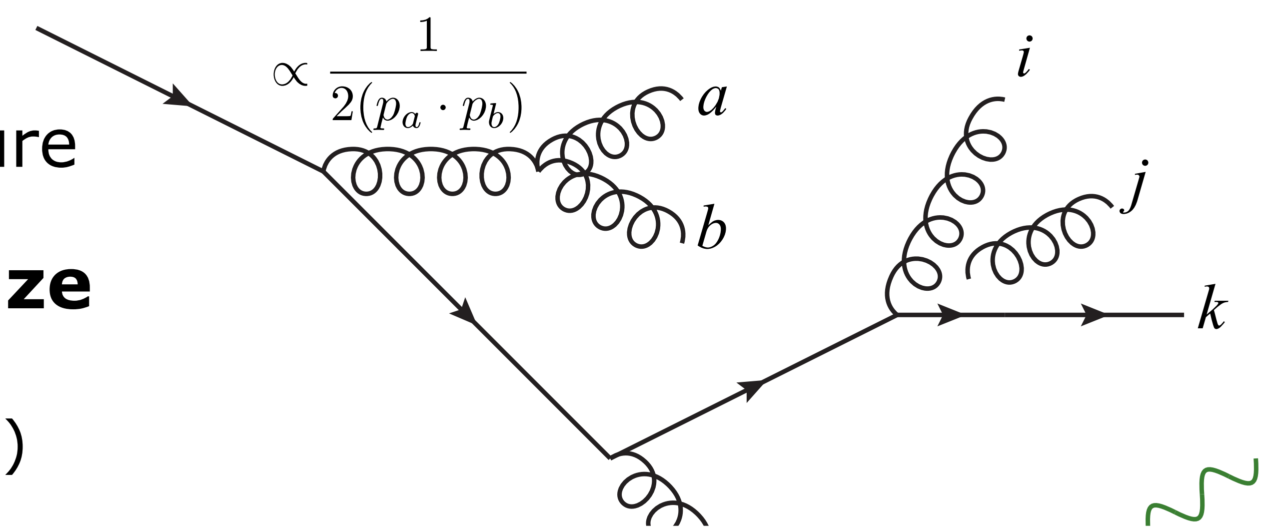


Jets = Fractals

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

Most bremsstrahlung is driven by Divergent propagators → simple structure

Gauge amplitudes factorize in singular limits (→ universal *"conformal"* or *"fractal"* structure)



Partons ab → collinear:

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

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

Gluon j → soft:

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

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

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

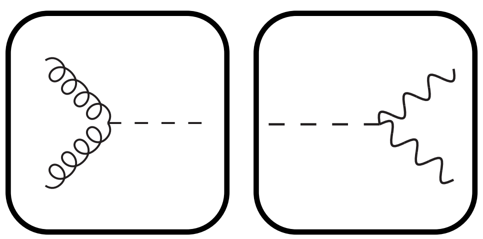
Can apply this many times → nested factorizations

Divide and Conquer

Factorization → Split the problem into many (nested) pieces

+ Quantum mechanics → Probabilities → Random Numbers

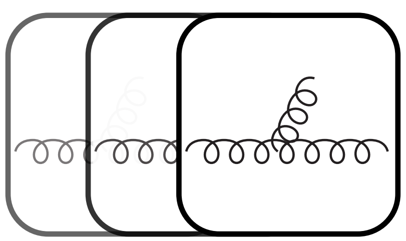
$$\mathcal{P}_{\mathrm{event}} = \mathcal{P}_{\mathrm{hard}} \otimes \mathcal{P}_{\mathrm{dec}} \otimes \mathcal{P}_{\mathrm{ISR}} \otimes \mathcal{P}_{\mathrm{FSR}} \otimes \mathcal{P}_{\mathrm{MPI}} \otimes \mathcal{P}_{\mathrm{Had}} \otimes \ldots$$



Hard Process & Decays:

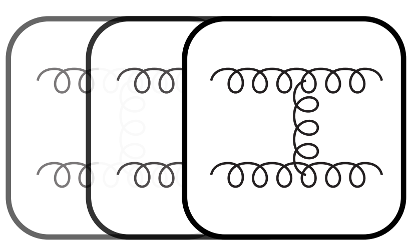
Use (N)LO matrix elements

→ Sets "hard" resolution scale for process: Q_{MAX}



ISR & FSR (Initial & Final-State Radiation):

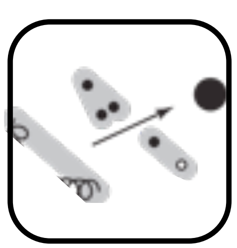
Altarelli-Parisi equations → differential evolution, dP/dQ^2, as function of resolution scale; run from Q_{MAX} to ~ 1 GeV (More later)



MPI (Multi-Parton Interactions)

Additional (soft) parton-parton interactions: LO matrix elements

→ Additional (soft) "Underlying-Event" activity (Not the topic for today)



Hadronization

Non-perturbative model of color-singlet parton systems → hadrons

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"

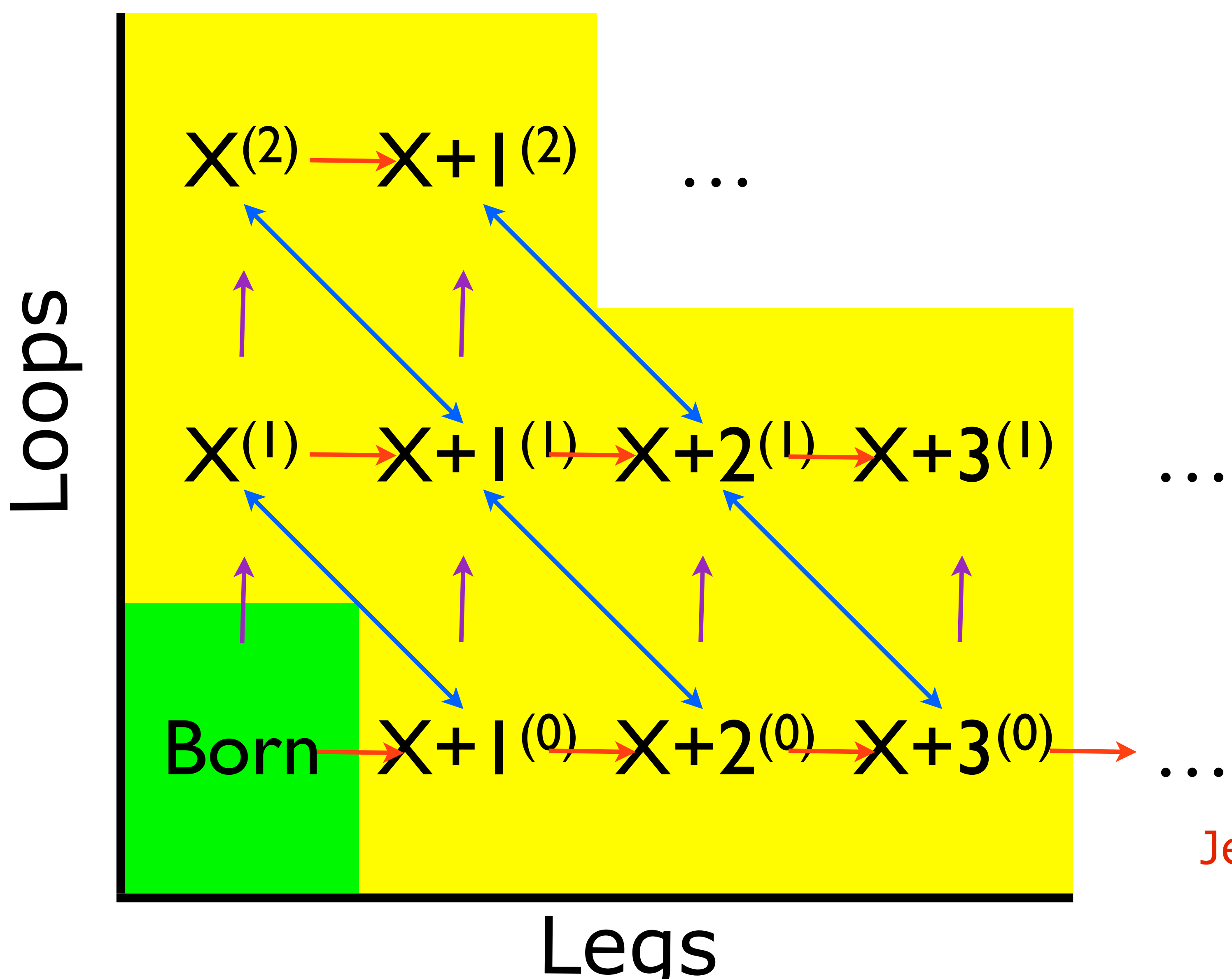
$$\frac{N_F(t)}{N_F(t_0)} \;=\; \Delta_F(t_0,t) \;=\; \exp\left(- \int \frac{\mathrm{d}\sigma_{F+1}}{\mathrm{d}\sigma_F} \right)$$

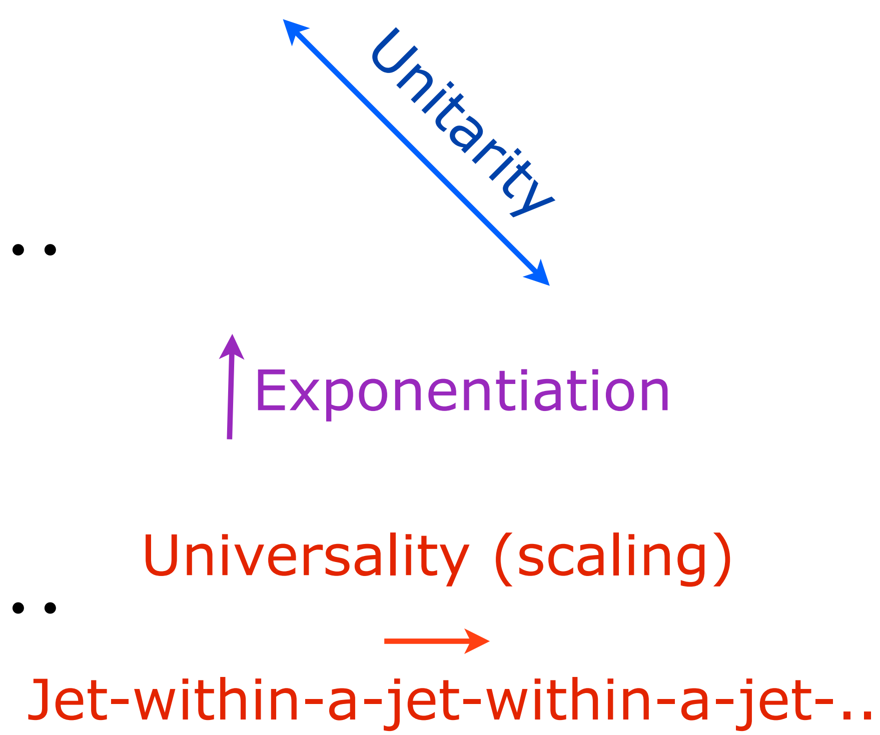
= *Approximation to Loop Corrections*

Bootstrapped Perturbation Theory

→ All Orders (resummed)

Born
+ Shower





But ≠ full QCD! Only LL Approximation.

→ Jack of All Orders, Master of None?

Good Algorithm(s) → Dominant all-orders structures

But what about all these unphysical choices?

- Renormalization Scales (for each power of α_s)
- The choice of shower evolution "time" ~ Factorization Scale(s)
- The radiation/antenna/splitting functions (finite terms arbitrary)
- The phase space map ("recoils", $d\Phi_{n+1}/d\Phi_n$)
- The infrared cutoff contour (hadronization cutoff)

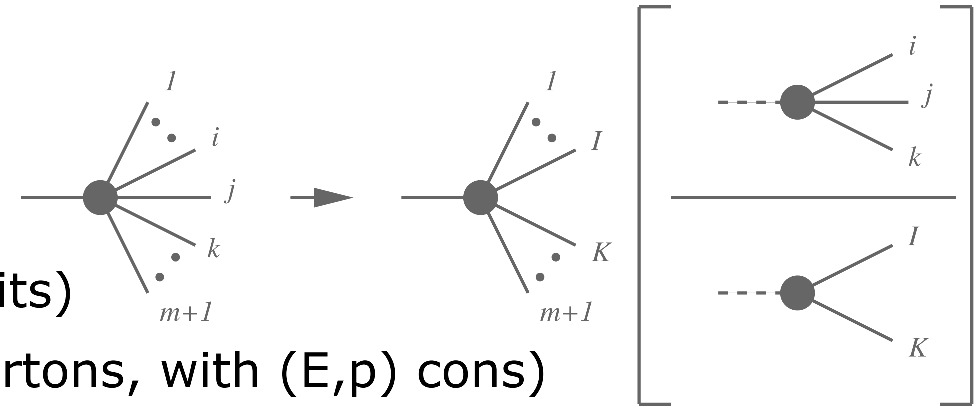
Nature does not depend on them → vary to estimate uncertainties
Problem: existing approaches vary only one or two of these choices

1. Systematic Variations → Comprehensive Theory Uncertainty Estimates

→

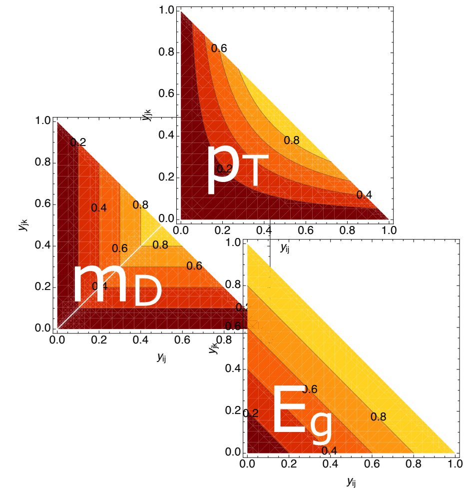
2. Higher-Order Corrections → Systematic Reduction of Uncertainties

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)

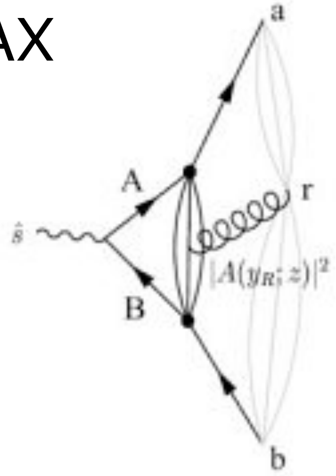


Resolution Time

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 $\kappa_{3\rightarrow 2}$
Special cases: ARIADNE, Kosower, + massive generalizations

vincia.hepforge.org

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 corrections, which would be finite everywhere?

Answer:

Used to be no.

(Though first order worked out in the eighties (Sjöstrand), expansions rapidly became too complicated)

For multileg amplitudes, people then resorted to slicing up phase space (fixed-order amplitude goes *here*, shower goes *there*), generated many different cookbook recipes and much bookkeeping

Solution: $(MC)^2$

"Higher-Order Corrections To Timelike Jets"
GeeKS: 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

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

Solution: $(MC)^2$: Monte-Carlo Markov Chain

Markovian Antenna Showers (VINCIA)
→ Number of generated terms grows like N
+ extremely simple expansions

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 Born level

$$|M_F|^2$$

Generate "shower" emission

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

Correct to Matrix Element

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

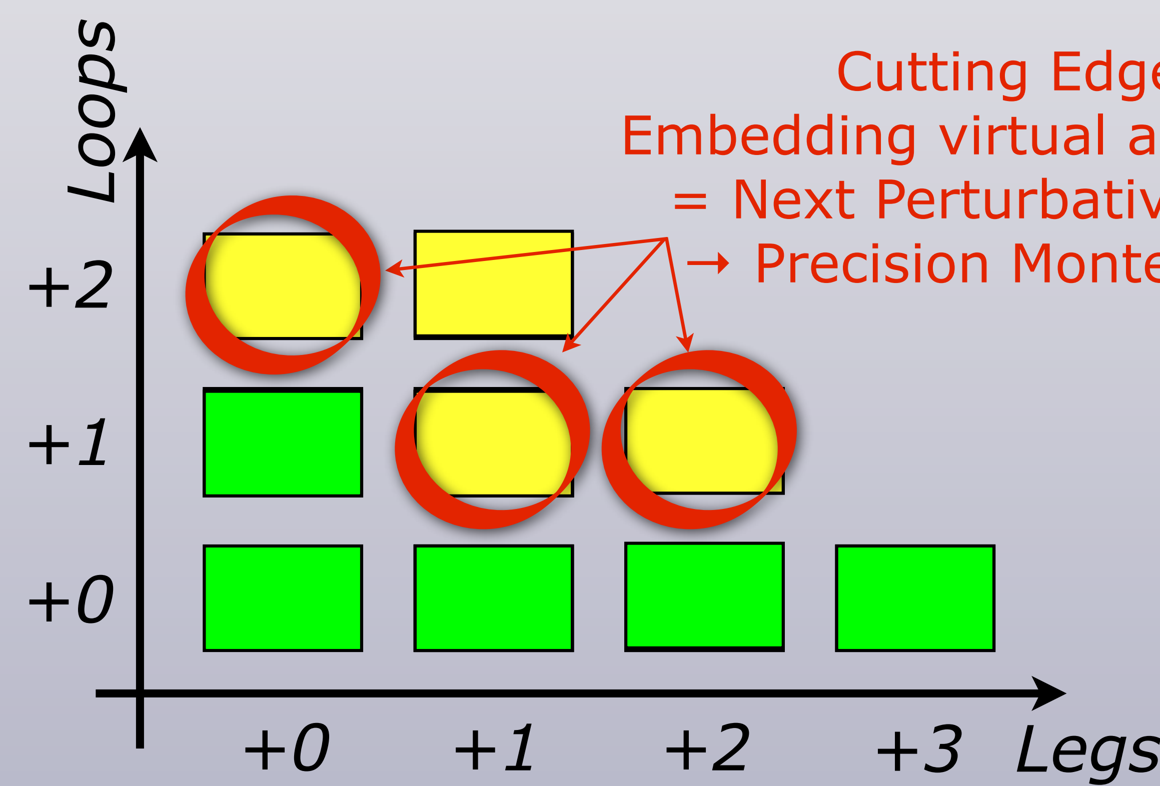
Unitarity of Shower

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

Correct to Matrix Element

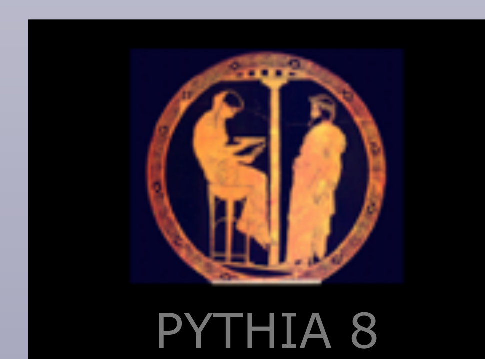
$$|M_F|^2 \to |M_F|^2 + 2\mathrm{Re}[M_F^1 M_F^0] + \int \mathrm{Real}$$

Repeat



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

+



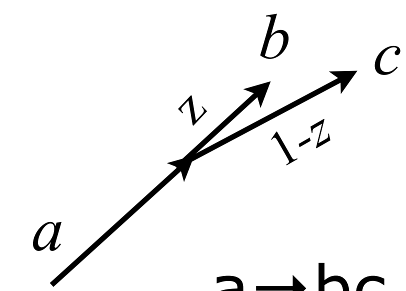
"Higher-Order Corrections To Timelike Jets"
GeeKS: Giele, Kosower, Skands, PRD 84 (2011) 054003

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

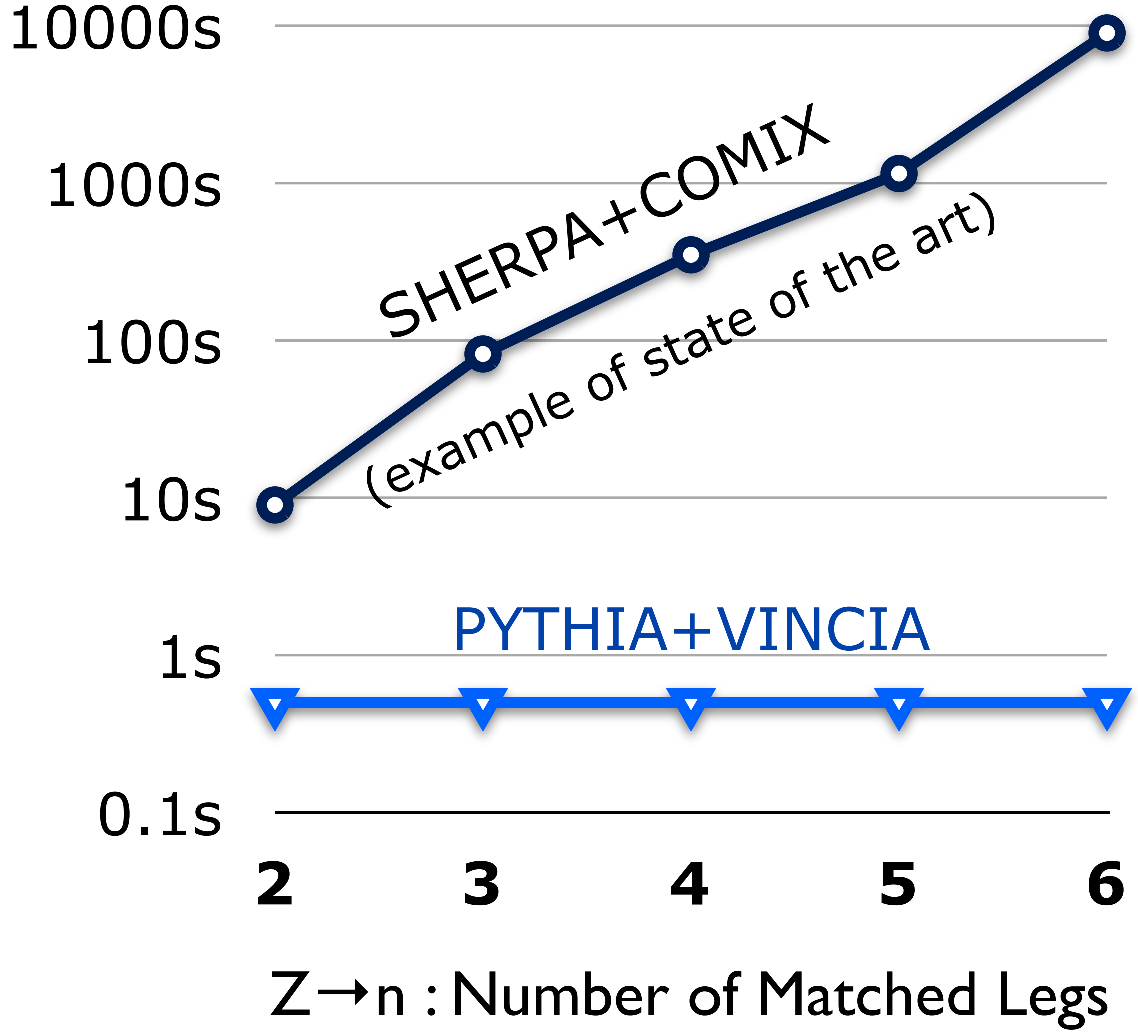
→ Can trace helicities through shower

→ Eliminates contribution from unphysical helicity configurations

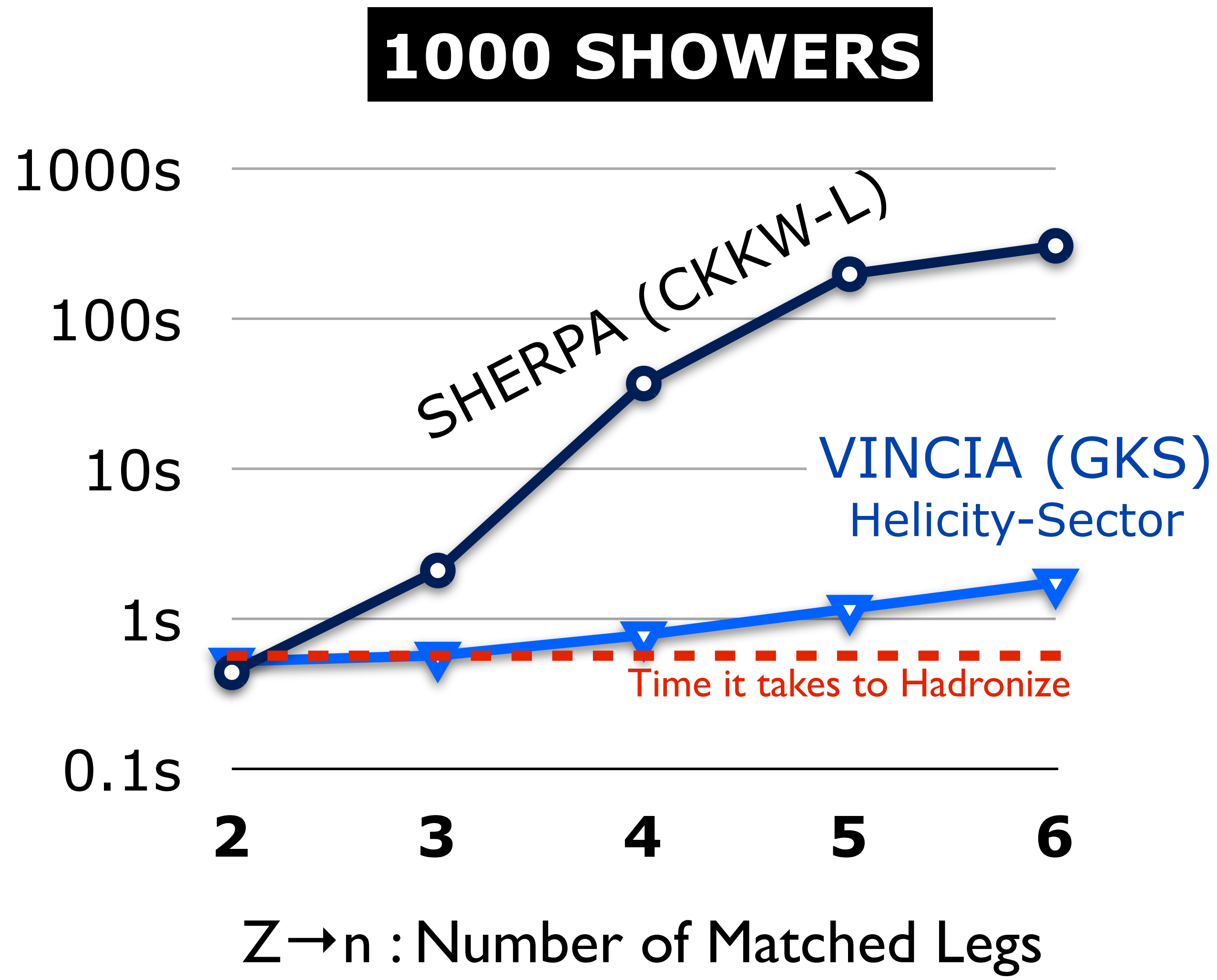
→ Can match to individual helicity amplitudes rather than helicity sum
→ Fast! (gets rid of another factor 2^N)

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)

Loop Corrections

Giele, Kosower, Skands, Phys.Rev. D78 (2008) 014026

Pedagogical Example: $Z^0 \to q\bar{q}$ First Order (~POWHEG)

Fixed Order: Exclusive 2-jet rate (2 and only 2 jets), at Q = Q_{had}

$$= |M_0^0|^2 \left(1 + \frac{2\,\mathrm{Re}[M_0^0 M_0^{1*}]}{|M_0^0|^2} + \int_0^{Q^2_{\mathrm{had}}} \mathrm{d}\Phi_{\mathrm{ant}}\; g_s^2\, \mathcal{C}\; A_{g/q\bar{q}} \right) = \frac{|M_1^0|^2}{|M_0^0|^2}$$

Born — Virtual — Unresolved Real

(MC)²: Exclusive 2-jet rate (2 and only 2 jets), at Q = Q_{had}

$$|M_0^0|^2\; \Delta(s, Q^2_{\mathrm{had}}) \;=\; |M_0^0|^2 \left(1 - \int_{Q^2_{\mathrm{had}}}^{s} \mathrm{d}\Phi_{\mathrm{ant}}\; g_s^2\, \mathcal{C}\; A_{g/q\bar{q}} + \mathcal{O}(\alpha_s^2) \right)$$

Born — Sudakov — Approximate Virtual + Unresolved Real

NLO Correction: Subtract and correct by difference

$$\frac{2\,\mathrm{Re}[M_0^0 M_0^{1*}]}{|M_0^0|^2} = \frac{\alpha_s}{2\pi}\, 2C_F\, \left(2 I_{q\bar{q}}(\epsilon, \mu^2/m_Z^2) - 4\right)$$

$$\int_0^s \mathrm{d}\Phi_{\mathrm{ant}}\; 2C_F\; g_s^2\; A_{g/q\bar{q}} = \frac{\alpha_s}{2\pi}\, 2C_F\, \left(-2 I_{q\bar{q}}(\epsilon, \mu^2/m_Z^2) + \frac{19}{4}\right)$$

$$\Big\}\quad |M_0^0|^2 \to \left(1 + \frac{\alpha_s}{\pi}\right) |M_0^0|^2$$

IR Singularity Operator

Ongoing work, with E. Laenen & L. Hartgring (NIKHEF)

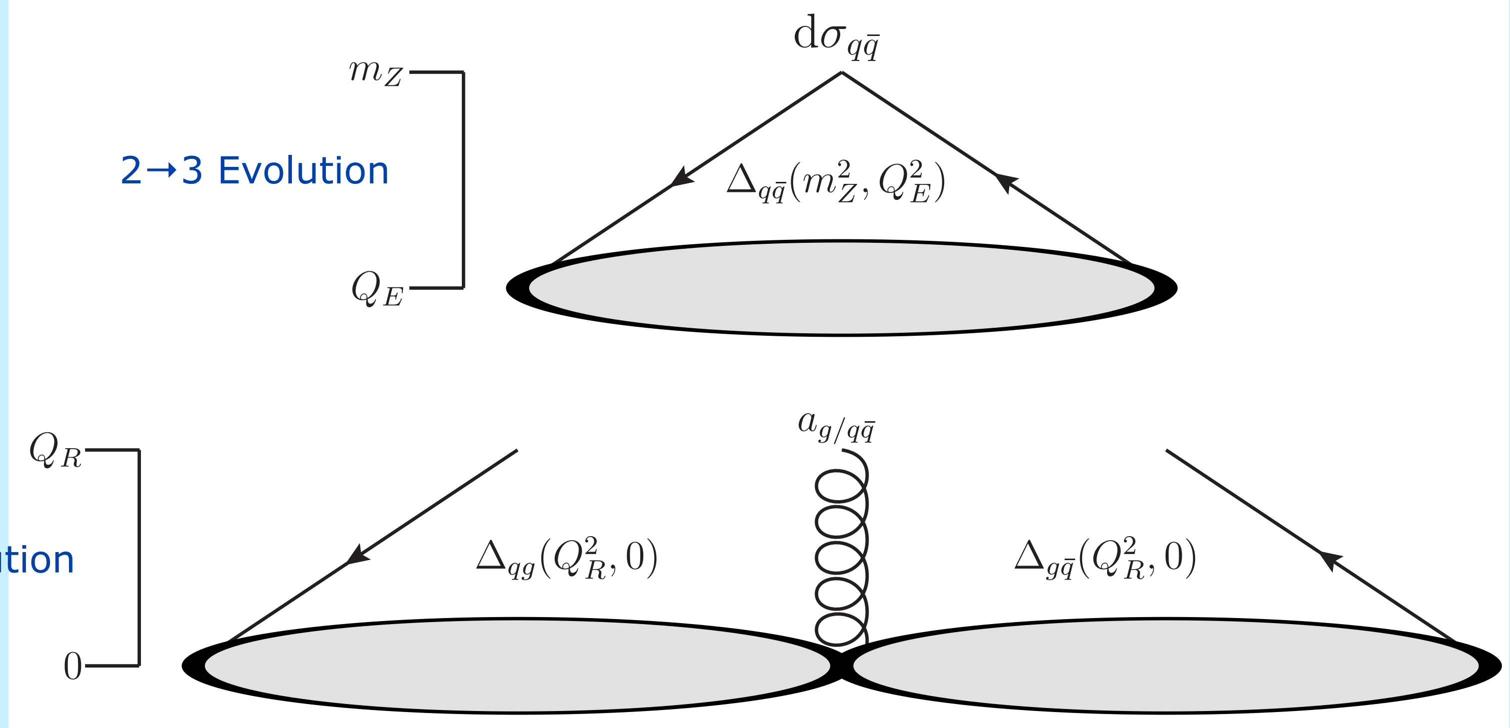
Getting Serious: second order

Fixed Order: Exclusive 3-jet rate (3 and only 3 jets), at Q = Q$_{\mathrm{had}}$

$$\mathrm{Exact} \;\rightarrow\; |M_1^0|^2 \;+\; 2\,\mathrm{Re}[M_1^0 M_1^{1*}] \;+\; \int_0^{Q^2_{\mathrm{had}}} \frac{\mathrm{d}\Phi_2}{\mathrm{d}\Phi_1}|M_2^0|^2$$

Born — Virtual — Unresolved Real

(MC)^2:



$$\mathrm{Approximate} \;\rightarrow\; (1+V_0)\;|M_1^0|^2\;\Delta_2(m_Z^2, Q_1^2)\;\Delta_3(Q_{R1}^2, Q_{\mathrm{had}}^2)\;,$$

$V_0 = \alpha_s/\pi$ — μ_R — 2→3 Evolution — 3→4 Evolution

Loop Corrections

Ongoing work, with E. Laenen & L. Hartgring (NIKHEF)

NLO Correction: Subtract and correct by difference

$$
\begin{aligned}
V_{1Z}(q,g,\bar{q}) \;=\; & \left[\frac{2\,\mathrm{Re}[M_1^0 M_1^{1*}]}{|M_1^0|^2}\right]^{\mathrm{LC}} - \frac{\alpha_s}{\pi} - \frac{\alpha_s}{2\pi}\left(\frac{11N_C - 2n_F}{6}\right)\ln\left(\frac{\mu_{\mathrm{ME}}^2}{\mu_{\mathrm{PS}}^2}\right) \\
& + \frac{\alpha_s C_A}{2\pi}\left[-2I_{qg}^{(1)}(\epsilon,\mu^2/s_{qg}) - 2I_{qg}^{(1)}(\epsilon,\mu^2/s_{g\bar{q}}) + \frac{34}{3}\right] \\
& + \frac{\alpha_s n_F}{2\pi}\left[-2I_{qg,F}^{(1)}(\epsilon,\mu^2/s_{qg}) - 2I_{g\bar{q},F}^{(1)}(\epsilon,\mu^2/s_{qg}) - 1\right] \\
& + \frac{\alpha_s C_A}{2\pi}\left[8\pi^2\int_{Q_1^2}^{m_Z^2} \mathrm{d}\Phi_{\mathrm{ant}}\, A_{g/q\bar{q}}^{\mathrm{std}} + 8\pi^2\int_{Q_1^2}^{m_Z^2}\mathrm{d}\Phi_{\mathrm{ant}}\,\delta A_{g/q\bar{q}}\right. \\
& \left. - \sum_{j=1}^{2} 8\pi^2\int_0^{s_j}\mathrm{d}\Phi_{\mathrm{ant}}\,(1-O_{Ej})\,A_{g/qg}^{\mathrm{std}} + \sum_{j=1}^{2}8\pi^2\int_0^{s_j}\mathrm{d}\Phi_{\mathrm{ant}}\,\delta A_{g/qg}\right] \\
& + \frac{\alpha_s n_F}{2\pi}\left[-\sum_{j=1}^{2}8\pi^2\int_0^{s_j}\mathrm{d}\Phi_{\mathrm{ant}}(1-O_{Sj})\,P_{Aj}\,A_{\bar{q}/qg}^{\mathrm{std}} + \sum_{j=1}^{2}8\pi^2\int_0^{s_j}\mathrm{d}\Phi_{\mathrm{ant}}\,\delta A_{\bar{q}/qg}\right. \\
& \left. -\frac{1}{6}\,\frac{s_{qg}-s_{g\bar{q}}}{s_{qg}+s_{g\bar{q}}}\ln\left(\frac{s_{qg}}{s_{g\bar{q}}}\right)\right], \qquad (72)
\end{aligned}
$$

V_0

μ_R

Gluon Emission IR Singularity

Gluon Splitting IR Singularity

2→3 Sudakov Logs

Q_1 = 3-parton Resolution Scale

3→4 Emit

O_{Ej} = Gluon-Emission Ordering Function

δA = LO Matching Terms

3→4 Sudakov Logs

3→4 Split

O_{Sj} = Gluon-Splitting Ordering Function

Loop Corrections

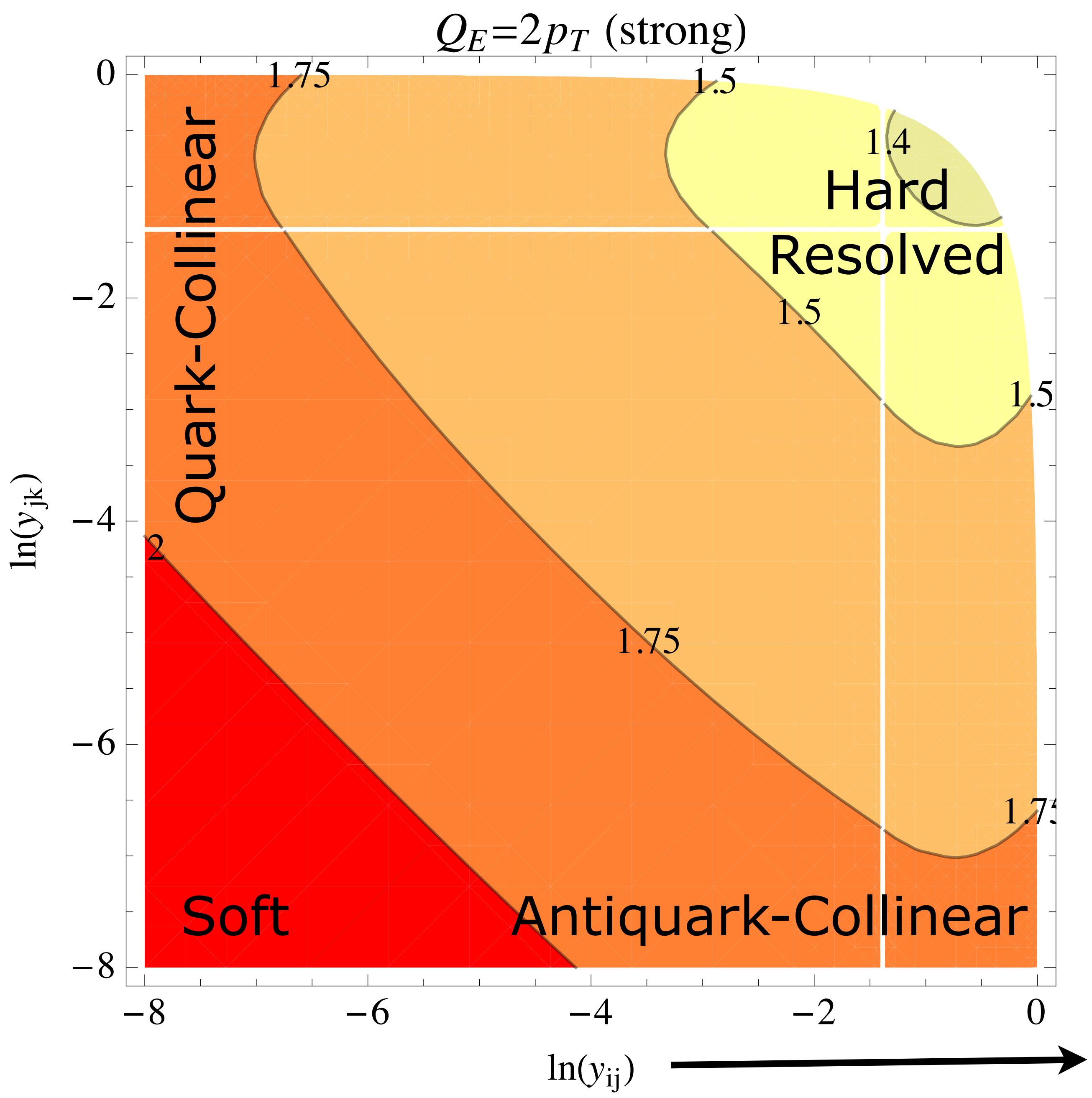
Ongoing work, with E. Laenen & L. Hartgring (NIKHEF)

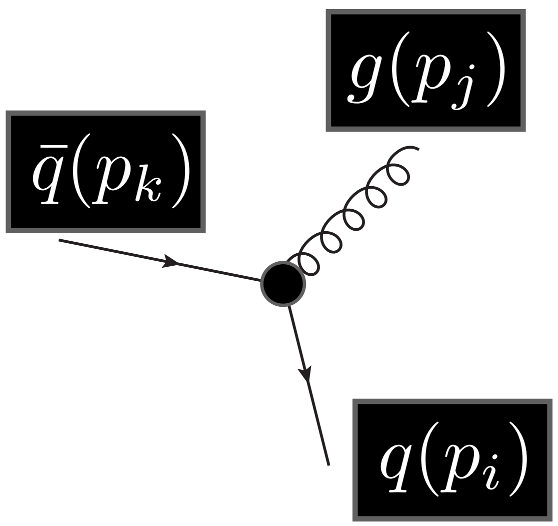
(MC)^2 : NLO Z → 2 → 3 Jets + Markov Shower

Size of NLO Correction:
over 3-parton Phase Space

Markov Evolution in:
Transverse Momentum

Parameters:
$\alpha_S(M_Z) = 0.12$
$\mu_R = m_Z$
$\Lambda_{QCD} = \Lambda_{MS}$





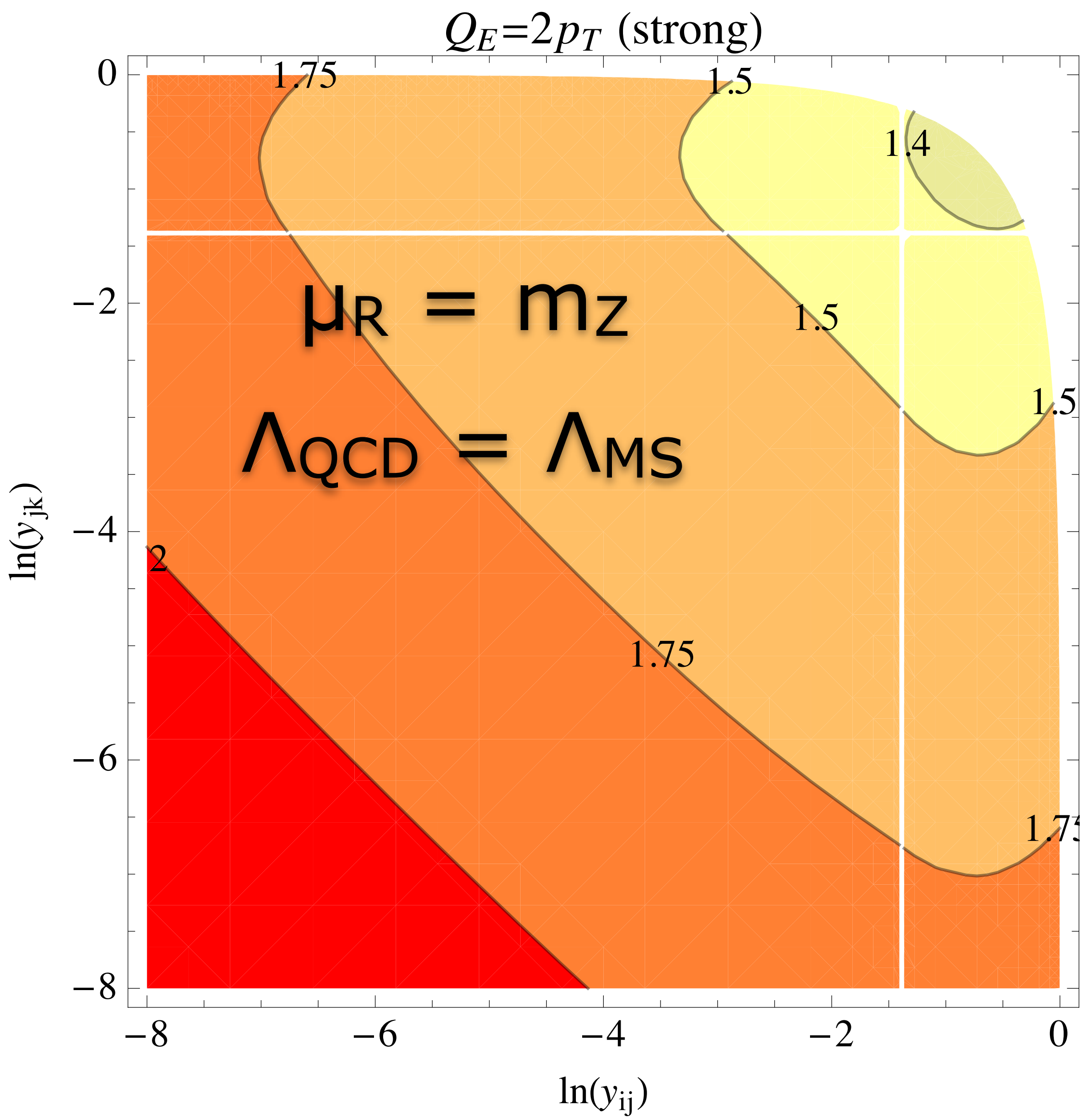
Scaled Invariants

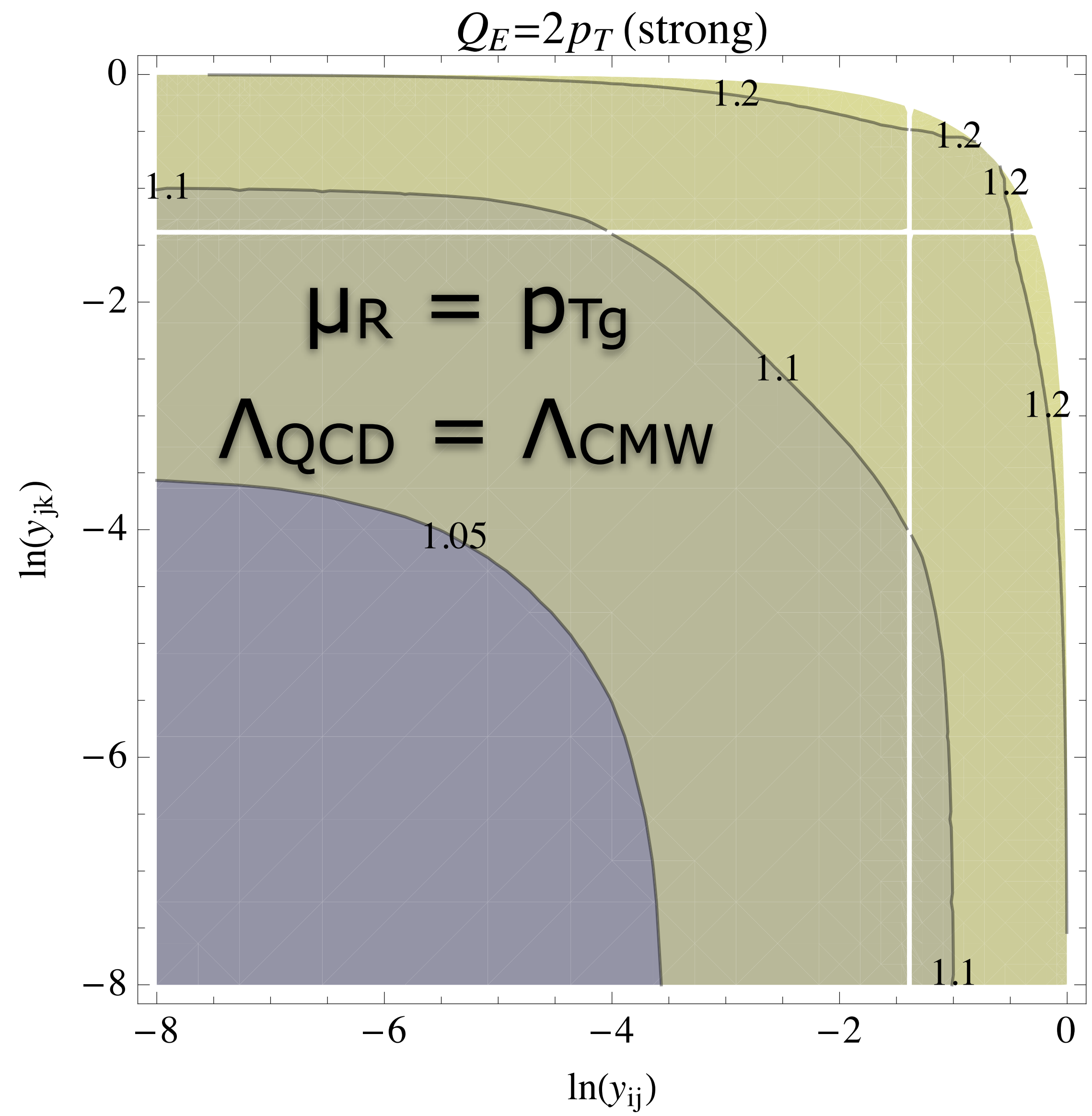
$$y_{ij} = \frac{(p_i \cdot p_j)}{M_Z^2}$$

→ 0 when i||j
& when E_j → 0

Ongoing work, with E. Laenen & L. Hartgring (NIKHEF)

The choice of μ_R



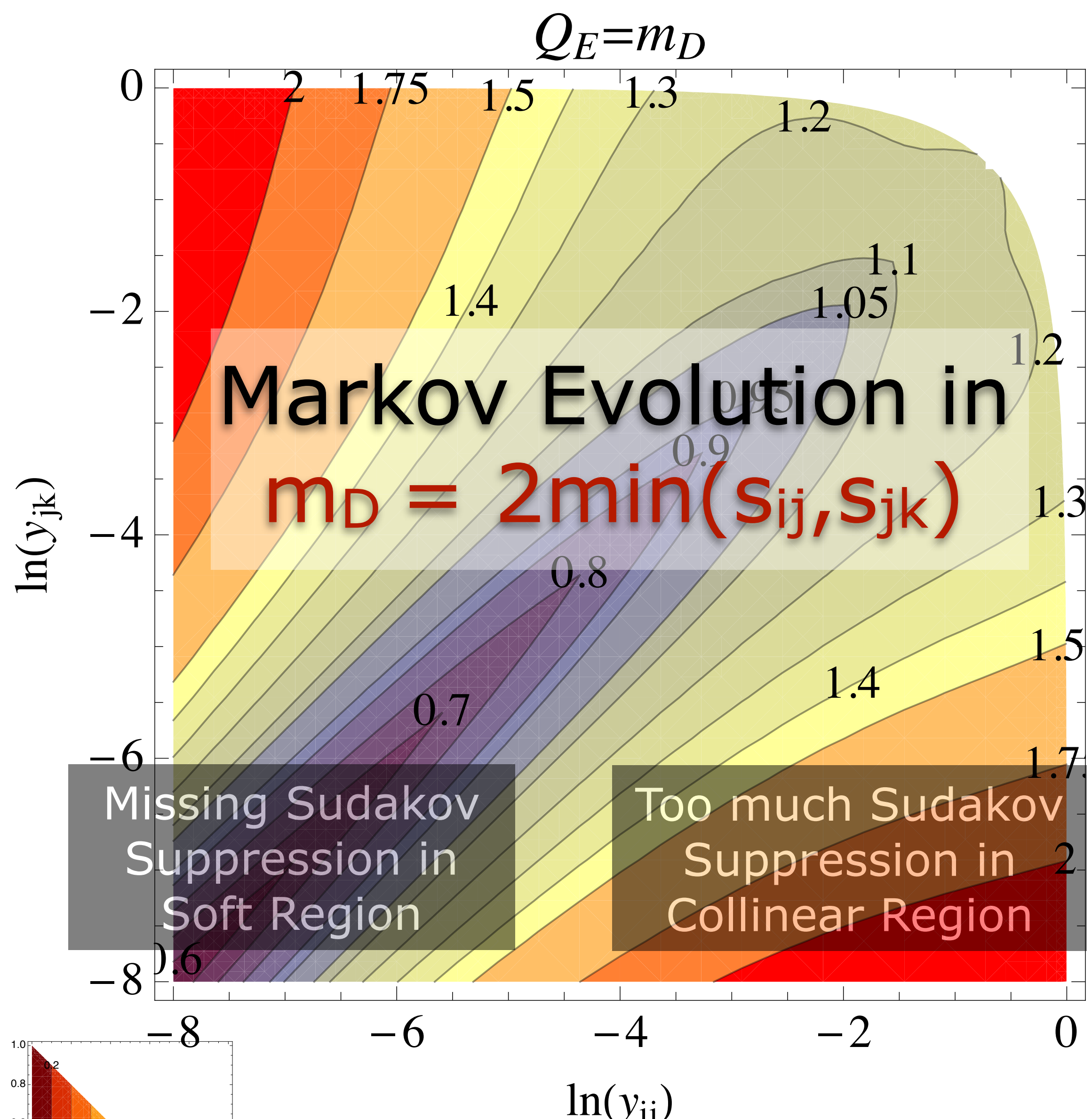


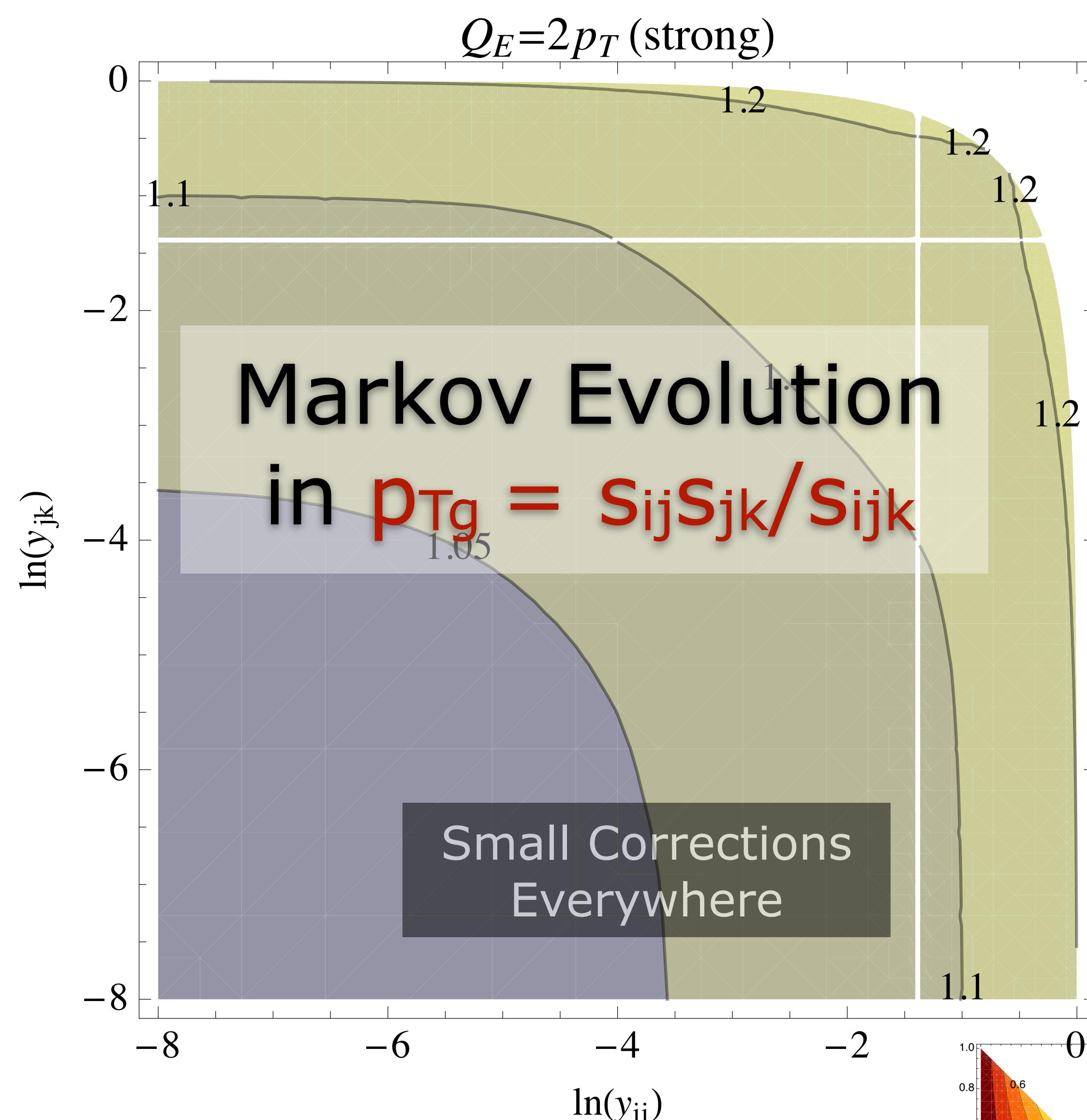
Markov Evolution in: Transverse Momentum, $\alpha_S(M_Z)$ = 0.12

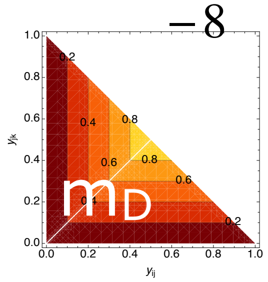
Loop Corrections

Ongoing work, with E. Laenen & L. Hartgring (NIKHEF)

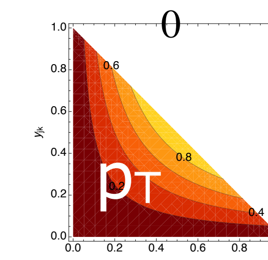
The choice of evolution variable (Q)







Parameters: $\alpha_S(M_Z) = 0.12$, $\mu_R = p_{Tg}$, $\Lambda_{QCD} = \Lambda_{CMW}$



Future Directions

1. Publish 3 papers (~ a couple of months: helicities, NLO multileg, ISR)

2. Apply these corrections to a broader class of processes, including ISR → LHC phenomenology

3. Automate correction procedure, via interfaces to BlackHat, MadLoop, … (for the LO corrections, we currently use MadGraph)

4. Recycle formalism to derive unitary all-orders second-order corrections to antenna showers (e.g., the one I just showed could be applied to *any* qq→qgq branching, anywhere in the shower) → higher-logarithmic shower resummations

Uncertainties

No calculation is more precise than the reliability of its uncertainty estimate → aim for full assessment of TH uncertainties.

Doing Variations

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

Traditional Approach:

Run calculation $1_{\text{central}} + 2N_{\text{variations}}$ = **slow**

Another use for simple analytical expansions?

For each event, can compute *probability this event would have resulted under alternative conditions*

$$P_2 = \frac{\alpha_{s2} a_2}{\alpha_{s1} a_1} P_1$$

+ ***Unitarity***: also recompute no-evolution probabilities

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

VINCIA: **= fast, automatic**

Central weights = 1

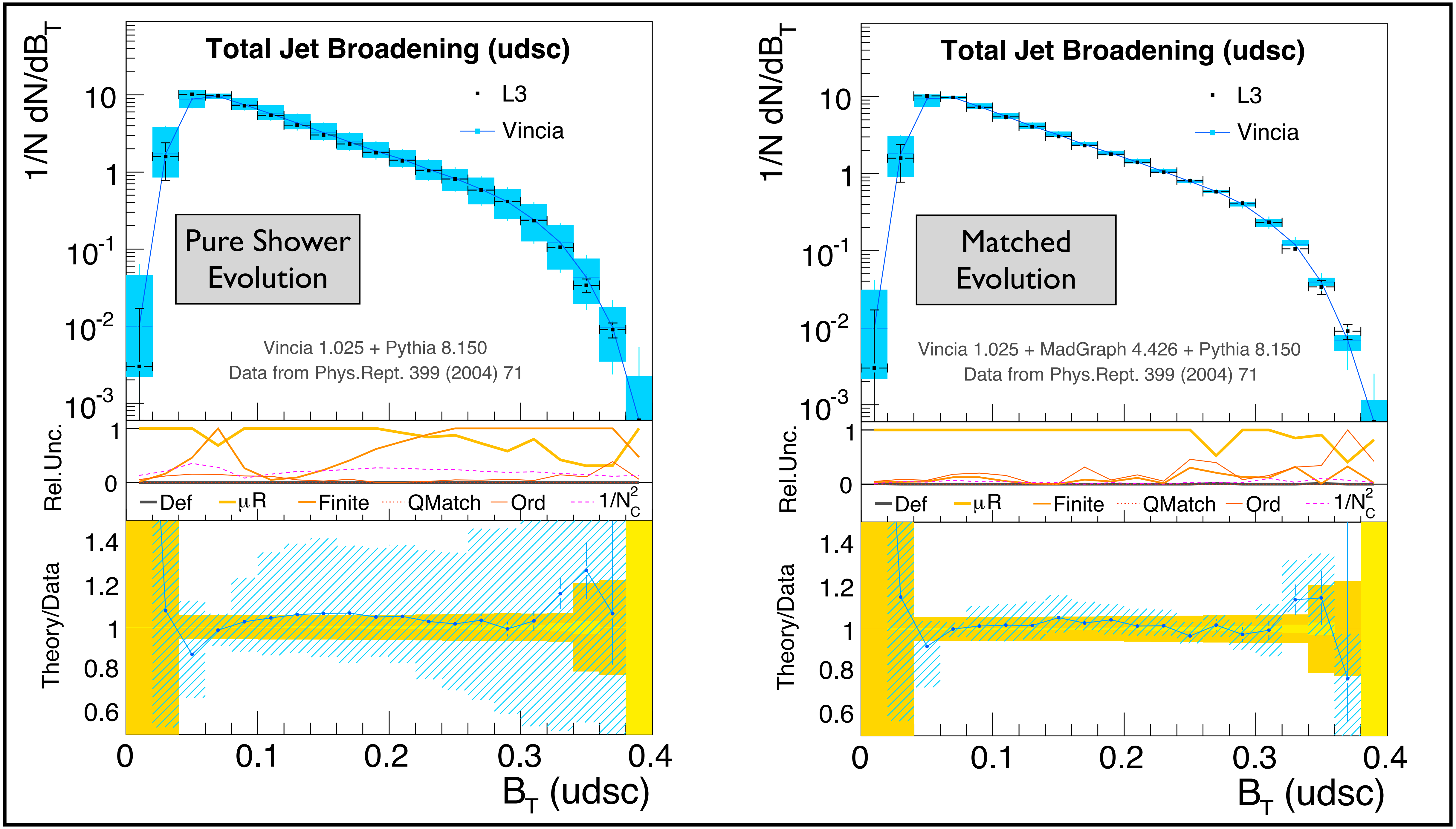
+ N sets of alternative weights = **variations** (all with <w>=1)

→ For every configuration/event, calculation tells how sure it is

Bonus: events only have to be hadronized & detector-simulated ONCE!

Quantifying Precision

Example of Physical Observable: **Before** (left) and **After** (right) Matching



Jet Broadening = LEP event-shape variable, measures “fatness” of jets

+ Interfaced to PYTHIA

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. Z. Skands
   Published in: JHEP 0605:026,2006 (arXiv: hep-ph/0603175)

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

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

Development partially financed via MC*net*, EU ITN, renewed (Tuesday!) for 4 more years (3.7 MEUR)

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 (in our case Scientific Linux) on *any* machine: Exact replica of our normal working environment

Factorization of IT and Science parts: *nice!*

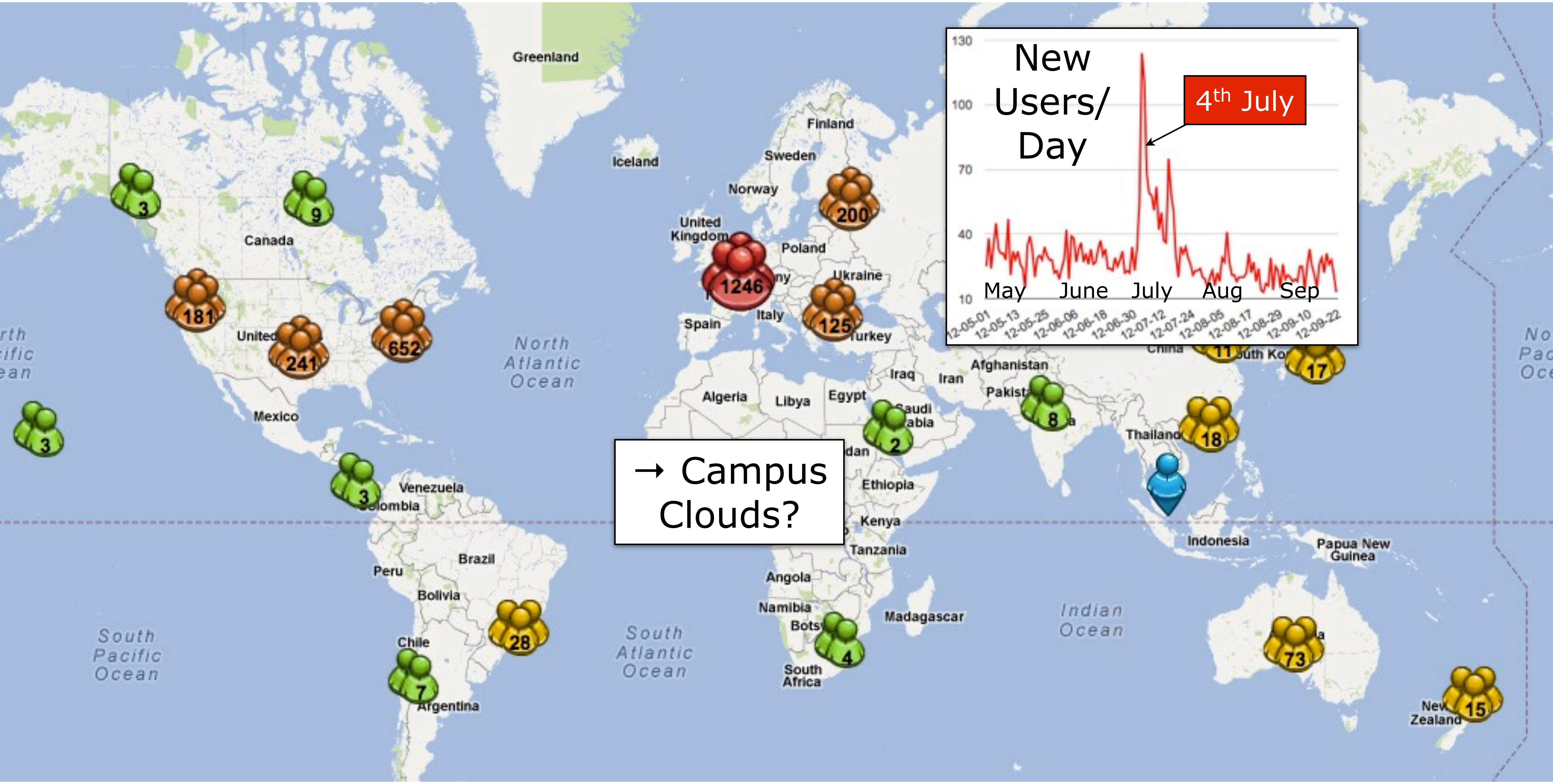
Infrastructure; Sending Jobs and Retrieving output

Based on BOINC platform for volunteer clouds (but can also use other distributed computing resources)

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

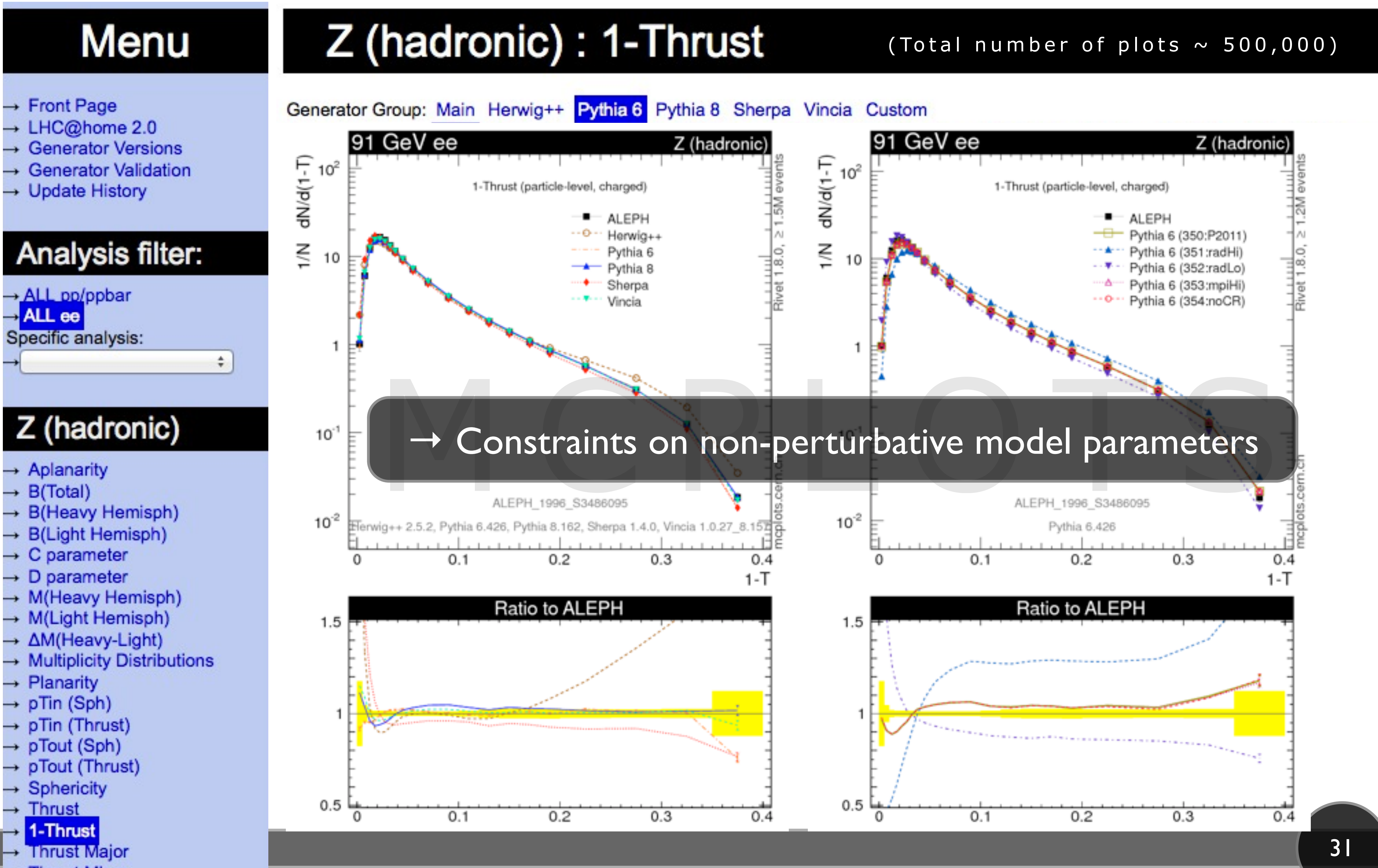
http://lhcathome2.cern.ch/test4theory/

Last 24 Hours: 2853 machines



Next Big Project (EU ICT): **Citizen Cyberlab** (3.4M€), kickoff in November …

Results → mcplots.cern.ch



→ Constraints on non-perturbative model parameters

Beyond Perturbation Theory

Better pQCD → Better non-perturbative constraints

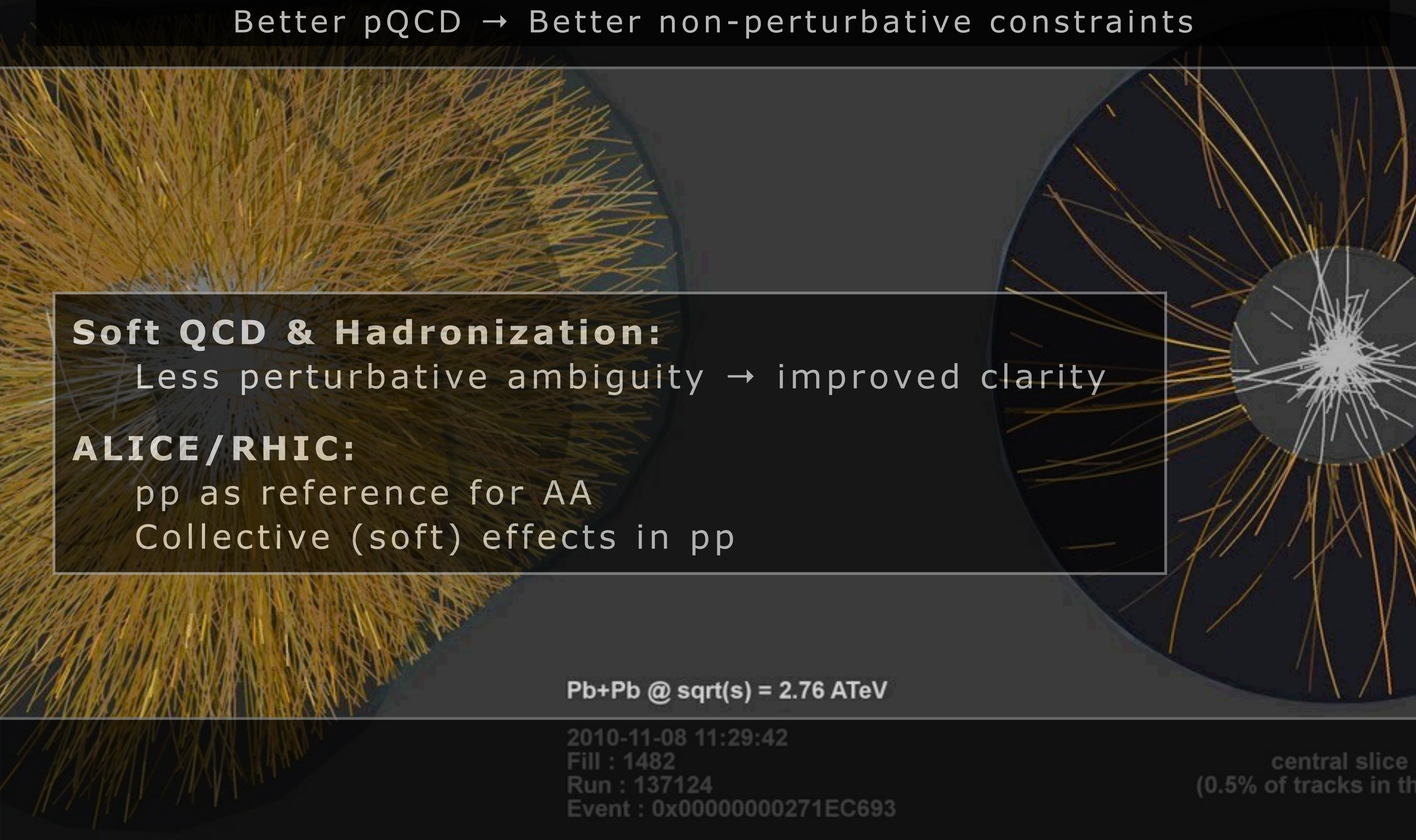
Soft QCD & Hadronization:

Less perturbative ambiguity → improved clarity

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:

New efficient formalism to embed higher-order amplitudes within shower resummations (VINCIA)

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: min-bias, multiplicities, ID particles, correlations, shapes, you name it … *(THANK YOU to the experiments!)*

New ideas (dualities, hydro, …) still in their infancy; but there *are* new ideas! (heavy-ion collisions offers complementary testing ground)

"Solving the LHC" is both interesting and rewarding

Key to high precision → max information

See also 2012 edition of *Review of Particle Physics* (PDG), section on "Monte Carlo Event Generators", by P. Nason & PS.

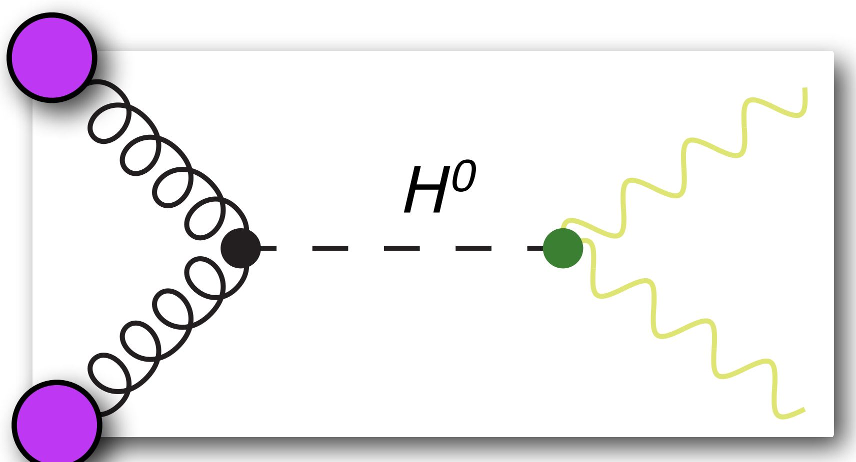
Theory and Practice

Example: The Higgs diphoton signal

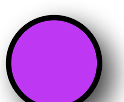
THEORY

Perturbation around zero coupling

Truncate at lowest non-vanishing order



Improve by computing quantum corrections, order by order



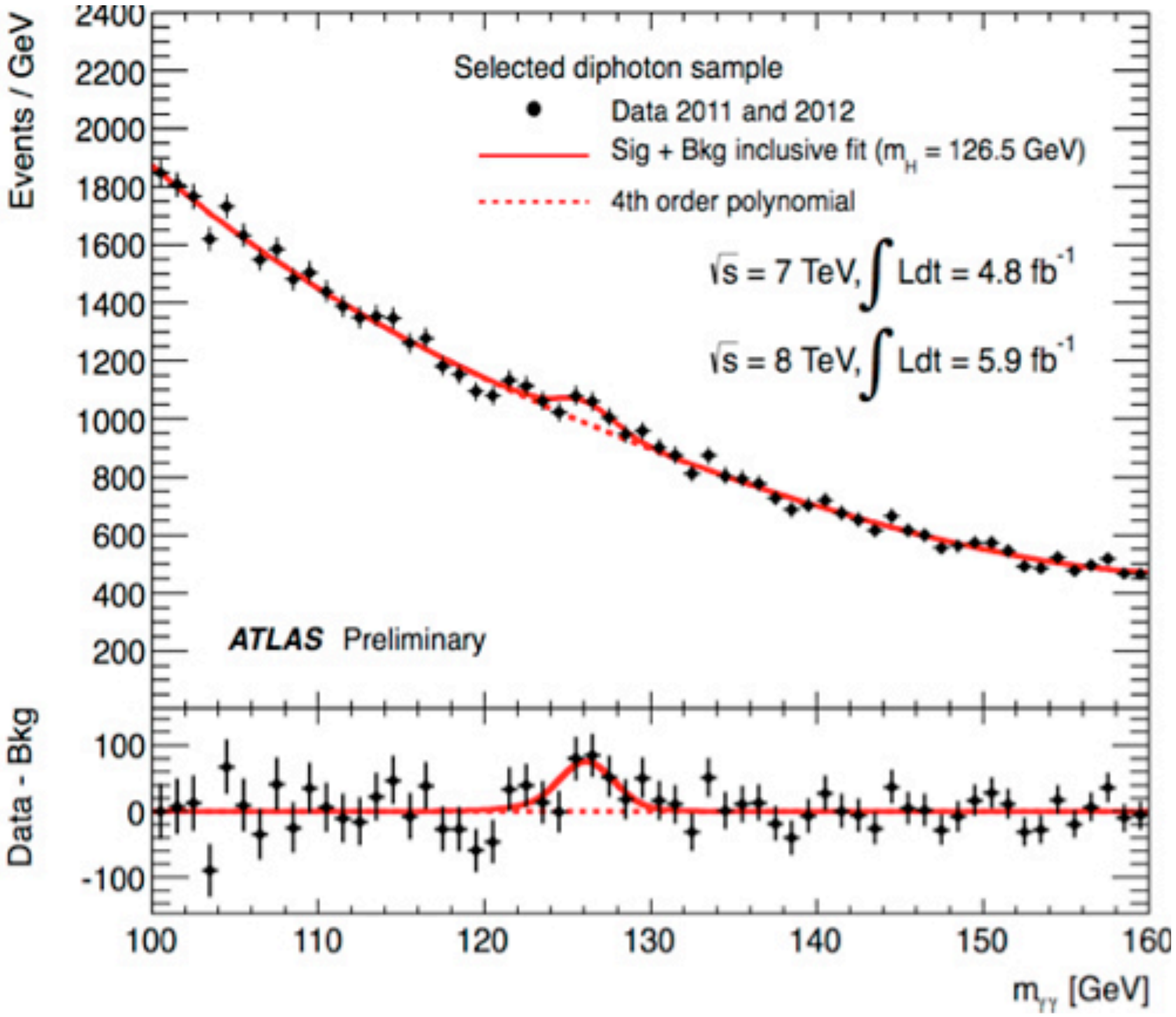
How many gluons (of given energy) are there in the proton?

(not calculable perturbatively, obtained from fits to data)

Experiment (ATLAS 2011 + 2012)

Photon pairs: invariant mass

(in context of search for $H^0 \to \gamma\gamma$)

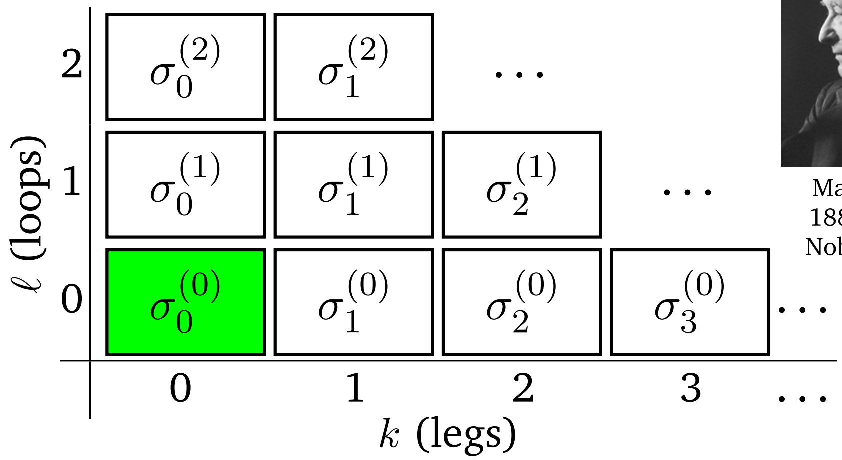


Fixed Order: Recap

Improve by computing quantum corrections, order by order

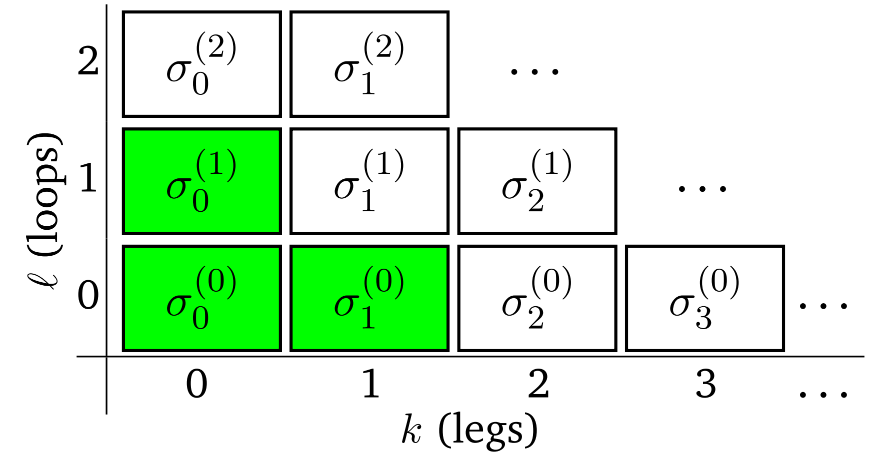
(from PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389)

Leading Order



Max Born, 1882-1970 Nobel 1954

Next-to-Leading Order



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

→ 1/ϵ² + 1/ϵ + Finite

→ -1/ϵ² - 1/ϵ + Finite

The Subtraction Idea

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

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

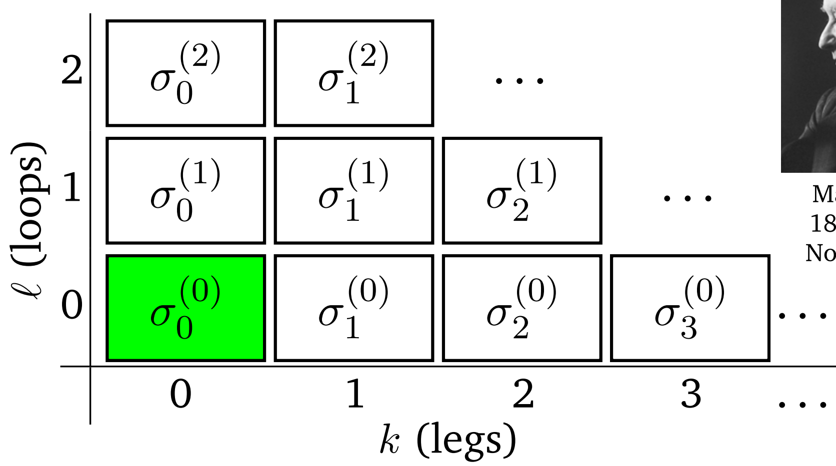
Universal "Subtraction Terms" (will return to later)

Fixed Order: Recap

Improve by computing quantum corrections, order by order

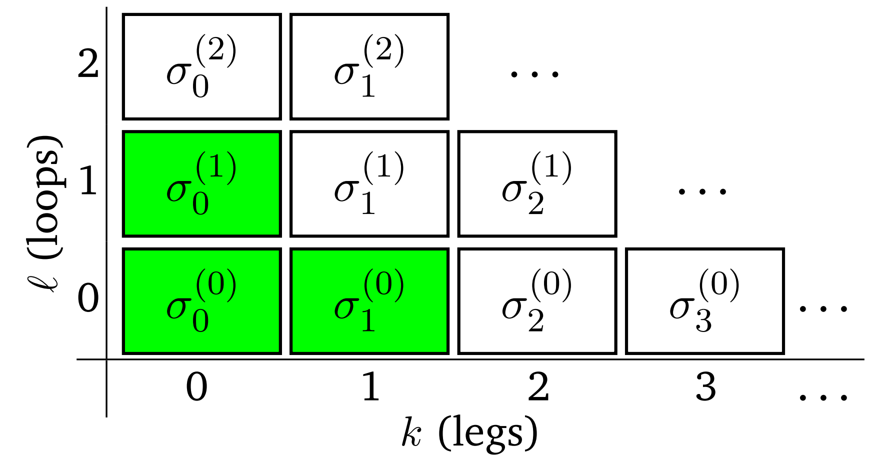
(from PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389)

Leading Order

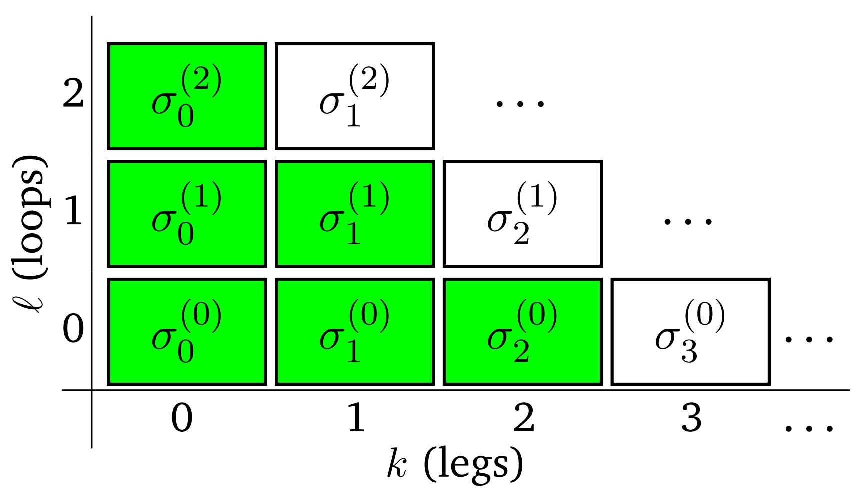


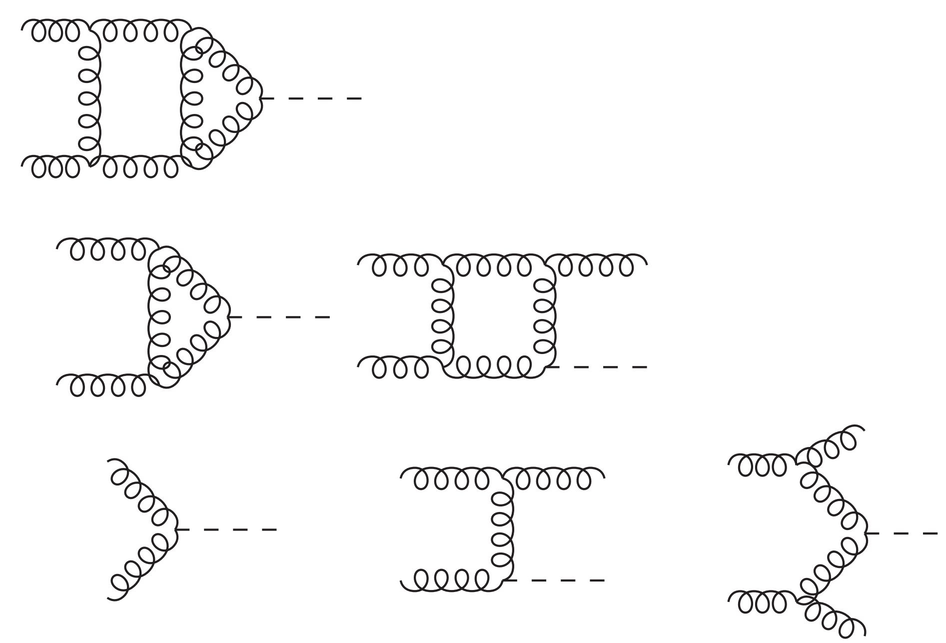
Max Born,
1882-1970
Nobel 1954

Next-to-Leading Order



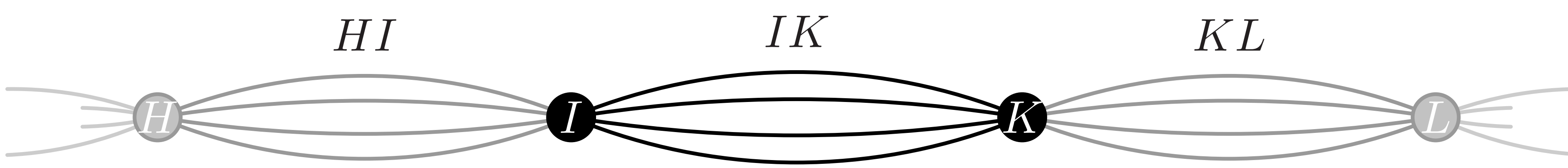
State of the Art: NNLO





Shower Types

Traditional vs Coherent vs Global vs Sector vs Dipole



	$\text{Coll}(I)$	$\text{Soft}(IK)$
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. (Θ_I and Θ_K represent angular vetos with respect to partons I and K, respectively, and Θ_{IK} represents a sector phase-space veto, see text.)

Global Antennae

$\times$	$\frac{1}{y_{ij}y_{jk}}$	$\frac{1}{y_{ij}}$	$\frac{1}{y_{jk}}$	$\frac{y_{jk}}{y_{ij}}$	$\frac{y_{ij}}{y_{jk}}$	$\frac{y_{jk}^2}{y_{ij}}$	$\frac{y_{ij}^2}{y_{jk}}$	1	y_{ij}	y_{jk}
$q\bar{q} \to qg\bar{q}$										
$++ \to +++$	1	0	0	0	0	0	0	0	0	0
$++ \to +-+$	1	-2	-2	1	1	0	0	2	0	0
$+- \to ++-$	1	0	-2	0	1	0	0	0	0	0
$+- \to +--$	1	-2	0	1	0	0	0	0	0	0
$qg \to qgg$										
$++ \to +++$	1	0	$-\alpha+1$	0	$2\alpha-2$	0	0	0	0	0
$++ \to +-+$	1	-2	-3	1	3	0	-1	3	0	0
$+- \to ++-$	1	0	-3	0	3	0	-1	0	0	0
$+- \to +--$	1	-2	$-\alpha+1$	1	$2\alpha-2$	0	0	0	0	0
$gg \to ggg$										
$++ \to +++$	1	$-\alpha+1$	$-\alpha+1$	$2\alpha-2$	$2\alpha-2$	0	0	0	0	0
$++ \to +-+$	1	-3	-3	3	3	-1	-1	3	1	1
$+- \to ++-$	1	$-\alpha+1$	-3	$2\alpha-2$	3	0	-1	0	0	0
$+- \to +--$	1	-3	$-\alpha+1$	3	$2\alpha-2$	-1	0	0	0	0
$qg \to q\bar{q}'q'$										
$++ \to ++-$	0	0	0	0	0	0	$\frac{1}{2}$	0	0	0
$++ \to +-+$	0	0	$\frac{1}{2}$	0	-1	0	$\frac{1}{2}$	0	0	0
$+- \to ++-$	0	0	$\frac{1}{2}$	0	-1	0	$\frac{1}{2}$	0	0	0
$+- \to +--$	0	0	0	0	0	0	$\frac{1}{2}$	0	0	0
$gg \to g\bar{q}q$										
$++ \to ++-$	0	0	0	0	0	0	$\frac{1}{2}$	0	0	0
$++ \to +-+$	0	0	$\frac{1}{2}$	0	-1	0	$\frac{1}{2}$	0	0	0
$+- \to ++-$	0	0	$\frac{1}{2}$	0	-1	0	$\frac{1}{2}$	0	0	0
$+- \to +-+$	0	0	0	0	0	0	$\frac{1}{2}$	0	0	0

Sector Antennae

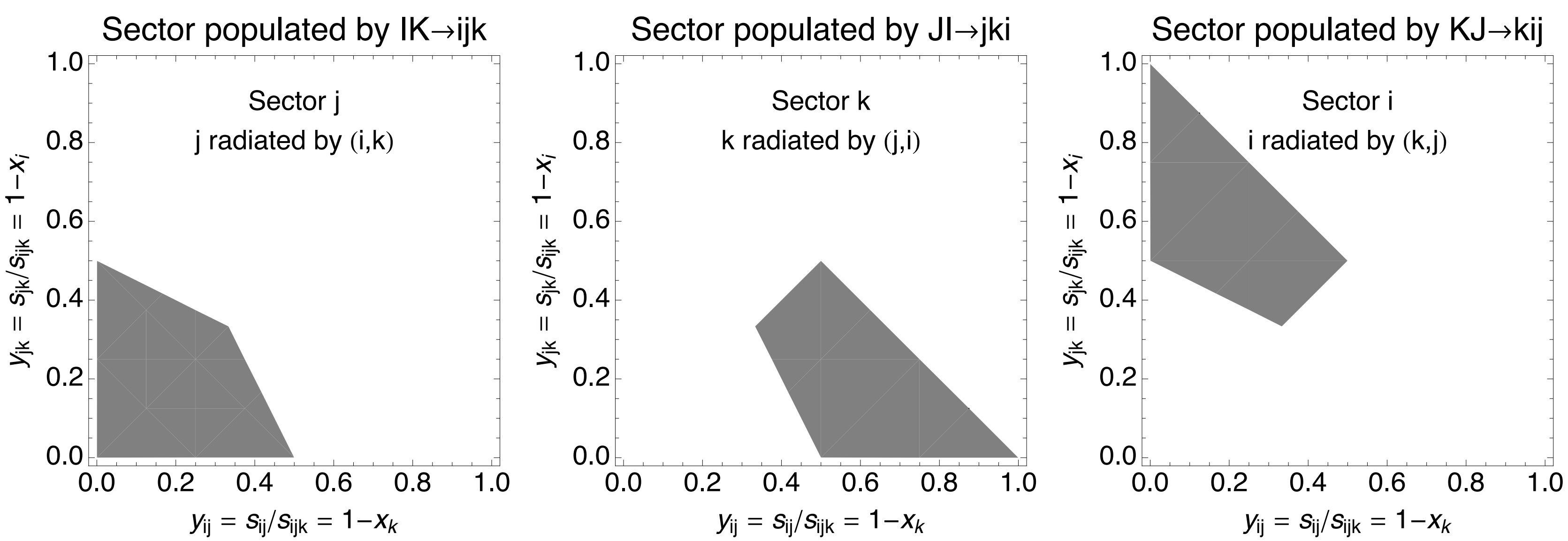
Global

$$\bar{a}^{\mathrm{gl}}_{g/qg}(p_i,p_j,p_k) \overset{s_{jk}\to 0}{\longrightarrow} \frac{1}{s_{jk}}\left(P_{gg\to G}(z) - \frac{2z}{1-z} - z(1-z)\right)$$

→ P(z) = Sum over two neigboring antennae

Sector

Only a single term in each phase space point



→ Full P(z) must be contained in every antenna

$$\begin{aligned}\bar{a}^{\mathrm{sct}}_{j/IK}(y_{ij},y_{jk}) = \bar{a}^{\mathrm{gl}}_{j/IK}(y_{ij},y_{jk}) \; &+ \; \delta_{Ig}\delta_{H_K H_k}\left\{\delta_{H_I H_i}\delta_{H_I H_j}\left(\frac{1+y_{jk}+y_{jk}^2}{y_{ij}}\right)\right.\\ &+ \; \left.\delta_{H_I H_j}\left(\frac{1}{y_{ij}(1-y_{jk})} - \frac{1+y_{jk}+y_{jk}^2}{y_{ij}}\right)\right\}\\ &+ \; \delta_{Kg}\delta_{H_I H_i}\left\{\delta_{H_I H_j}\delta_{H_K H_k}\left(\frac{1+y_{ij}+y_{ij}^2}{y_{jk}}\right)\right.\\ &+ \; \left.\delta_{H_K H_j}\left(\frac{1}{y_{jk}(1-y_{ij})} - \frac{1+y_{ij}+y_{ij}^2}{y_{jk}}\right)\right\}\end{aligned}$$

Sector = Global + additional collinear terms
(from "neighboring" antenna)

The Denominator

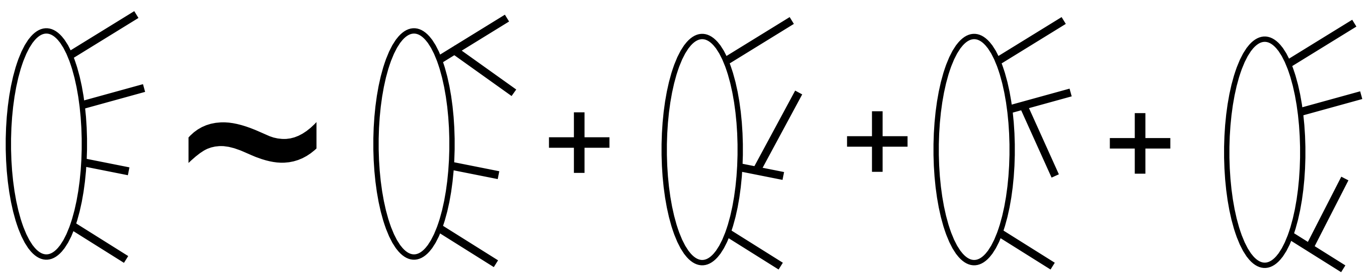
$$a_i \rightarrow \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2}$$

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

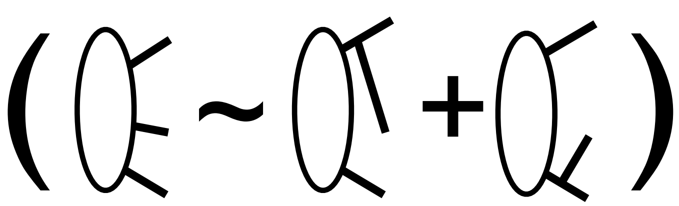
Existing parton showers are *not* really Markov Chains

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

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



j = 2
→ 4 terms



j = 1
→ 2 terms

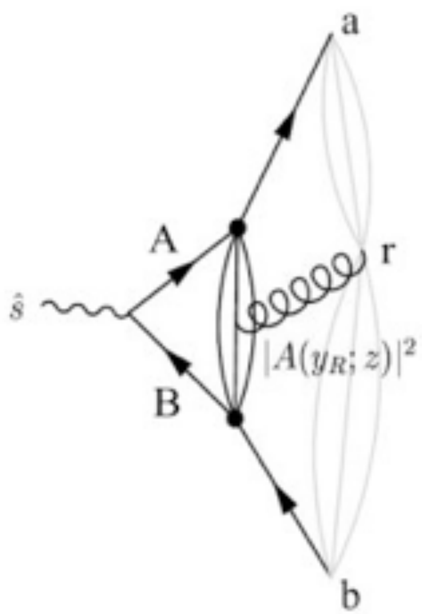
Parton- (or Catani-Seymour) Shower:
After 2 branchings: 8 terms
After 3 branchings: 48 terms
After 4 branchings: 384 terms

(+ 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! → 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*

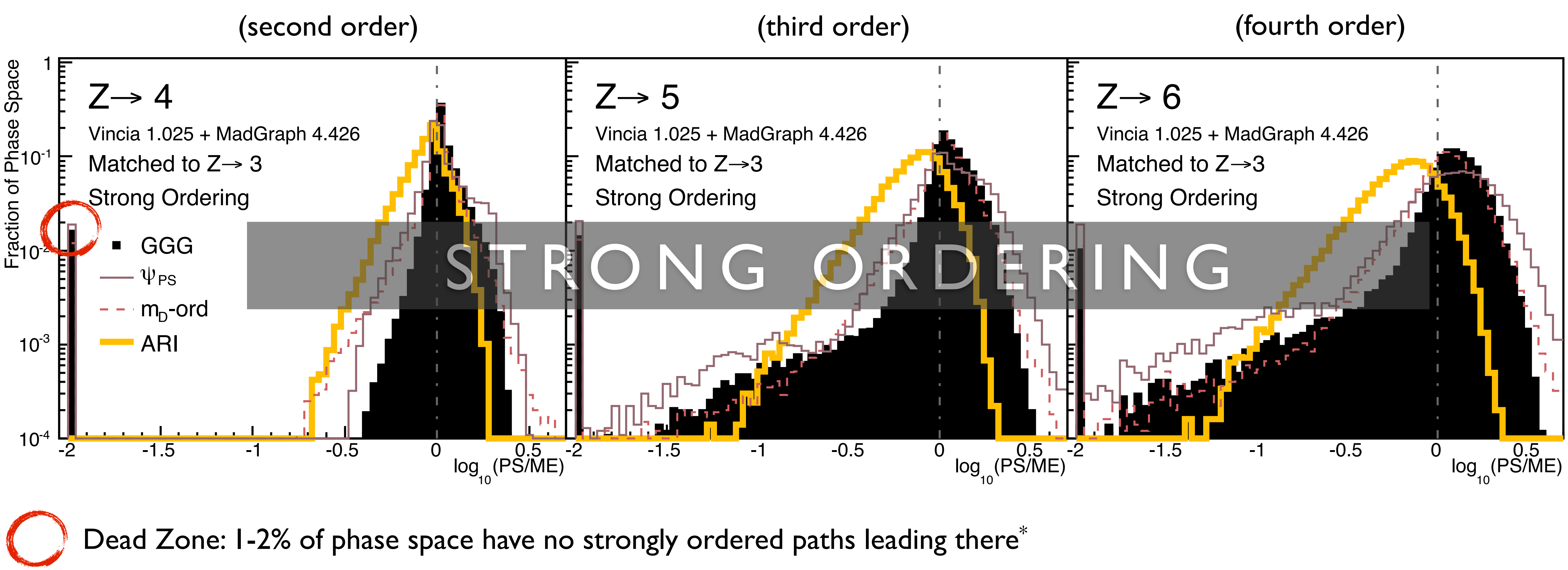
Approximations

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 **Log_{10}(PS/ME)**



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

Generate Branchings *without* imposing strong ordering

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

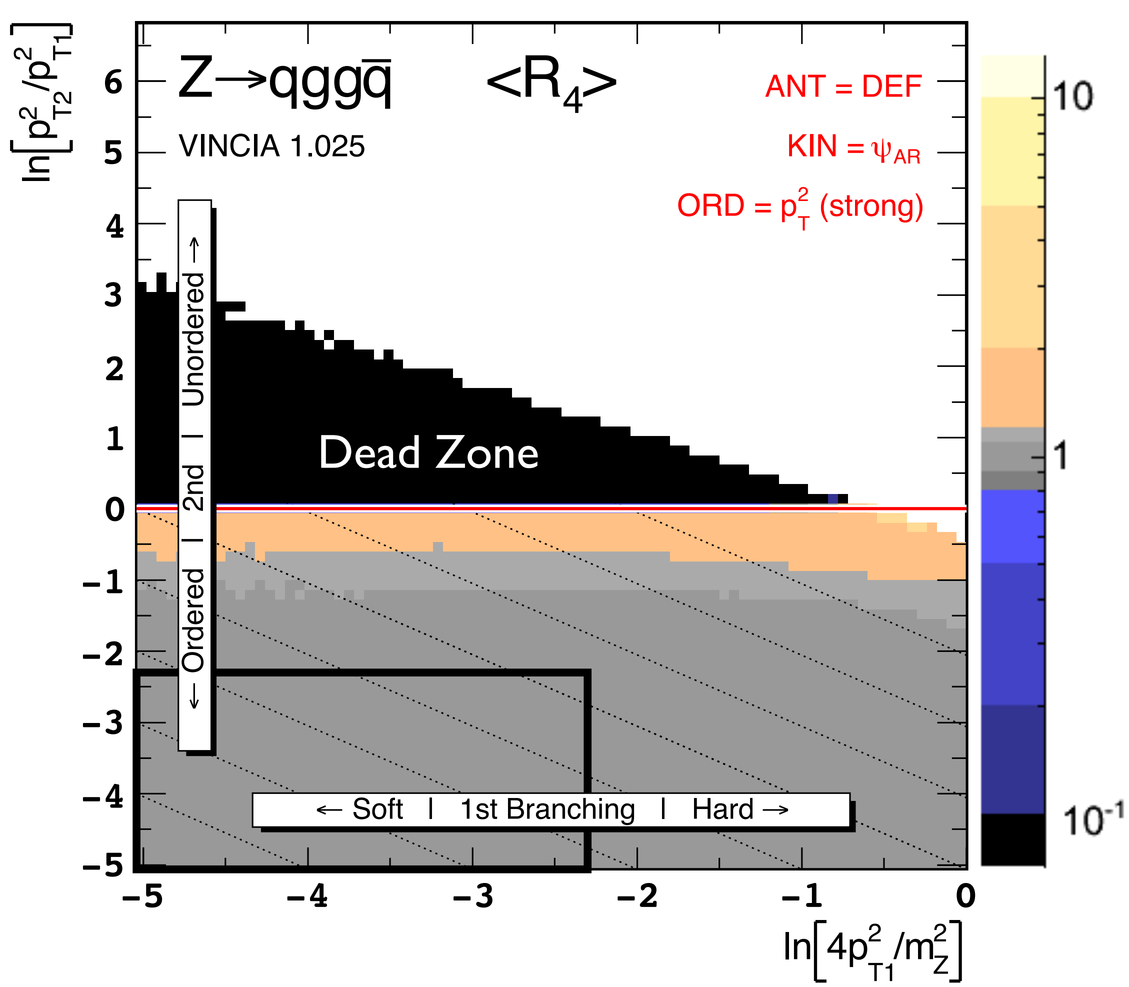
Overcounting removed by matching

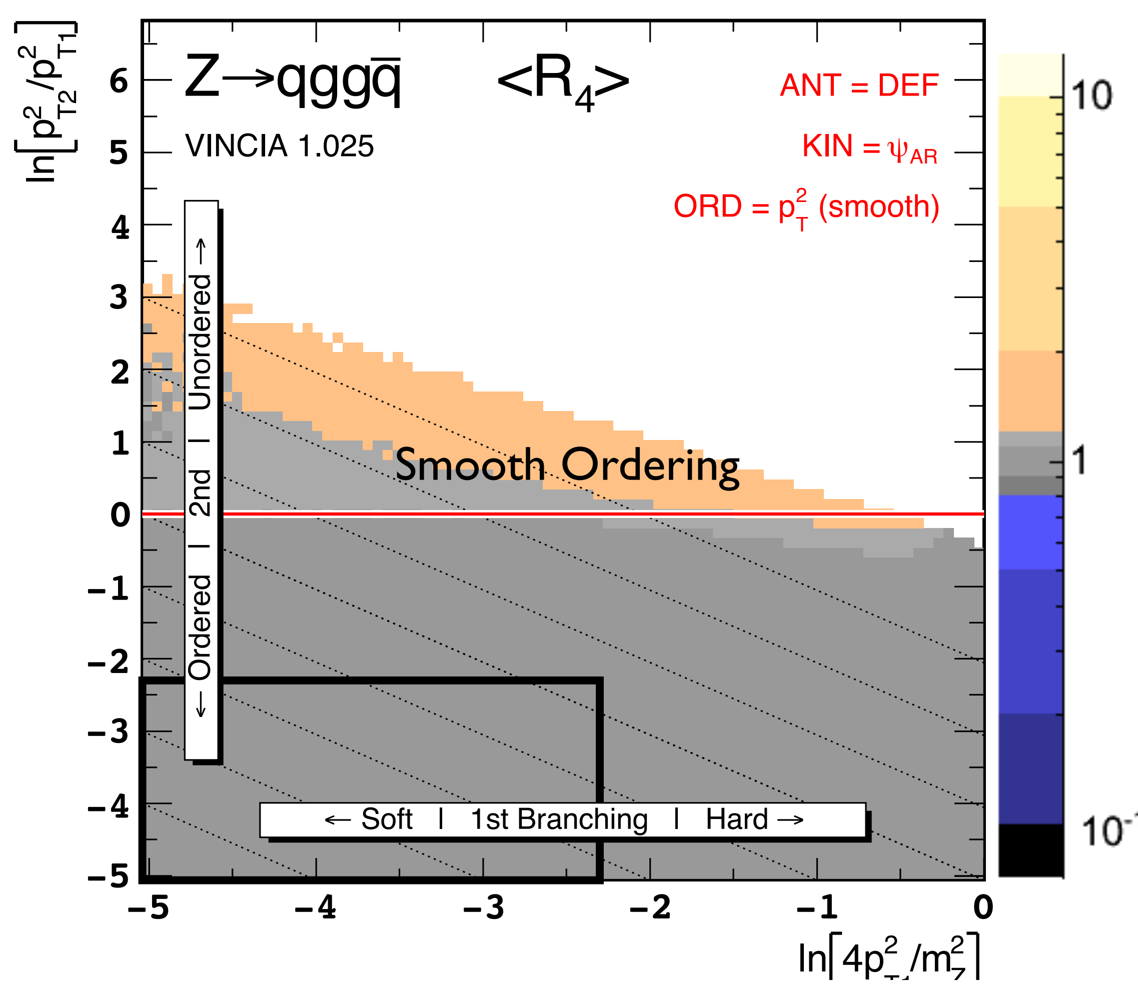
+ smooth ordering beyond matched multiplicities

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

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

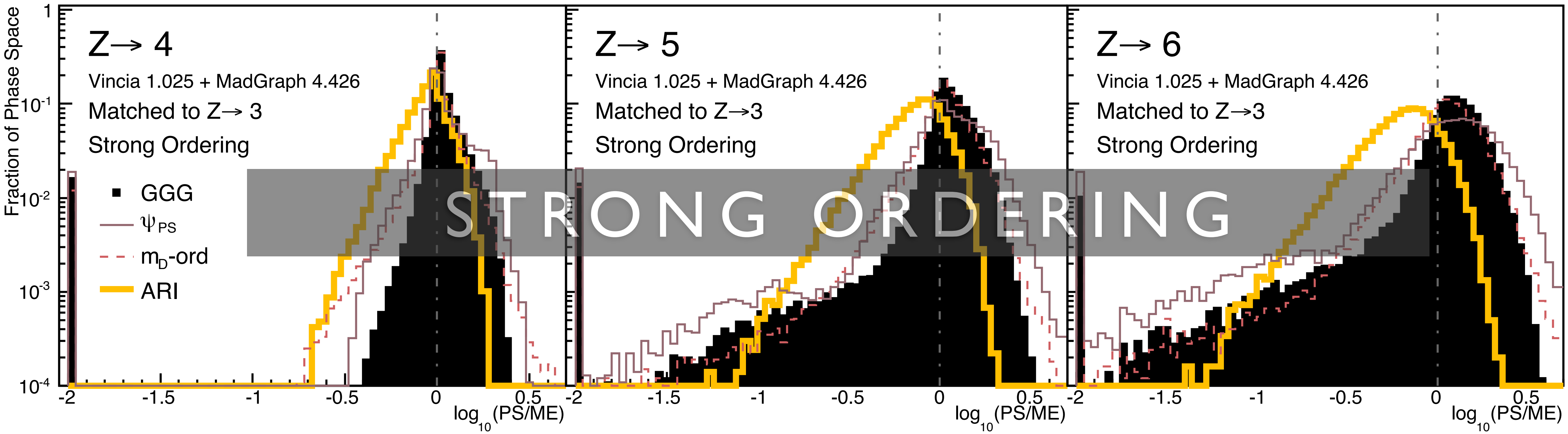
$p_\perp^2$ current branching



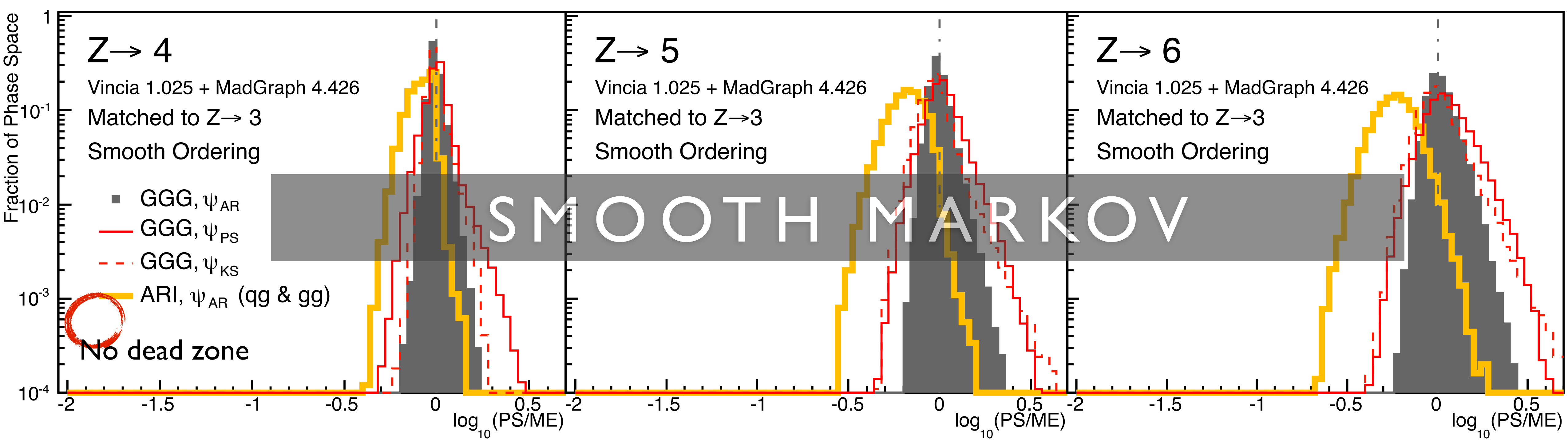


→ Better Approximations

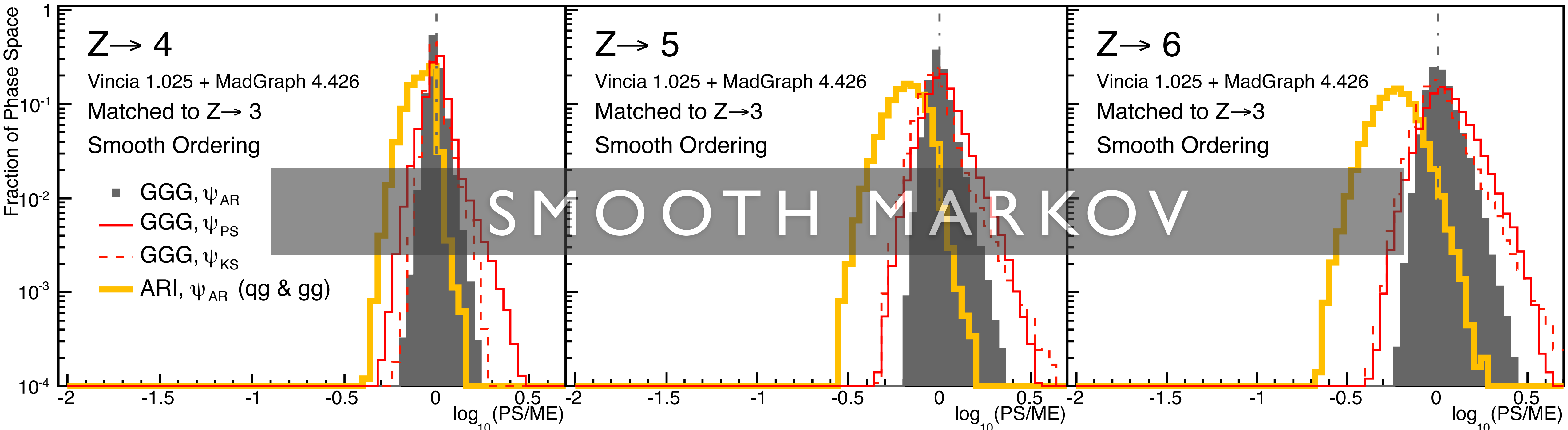
Distribution of **$Log_{10}(PS_{LO}/ME_{LO})$** (inverse ~ matching coefficient)



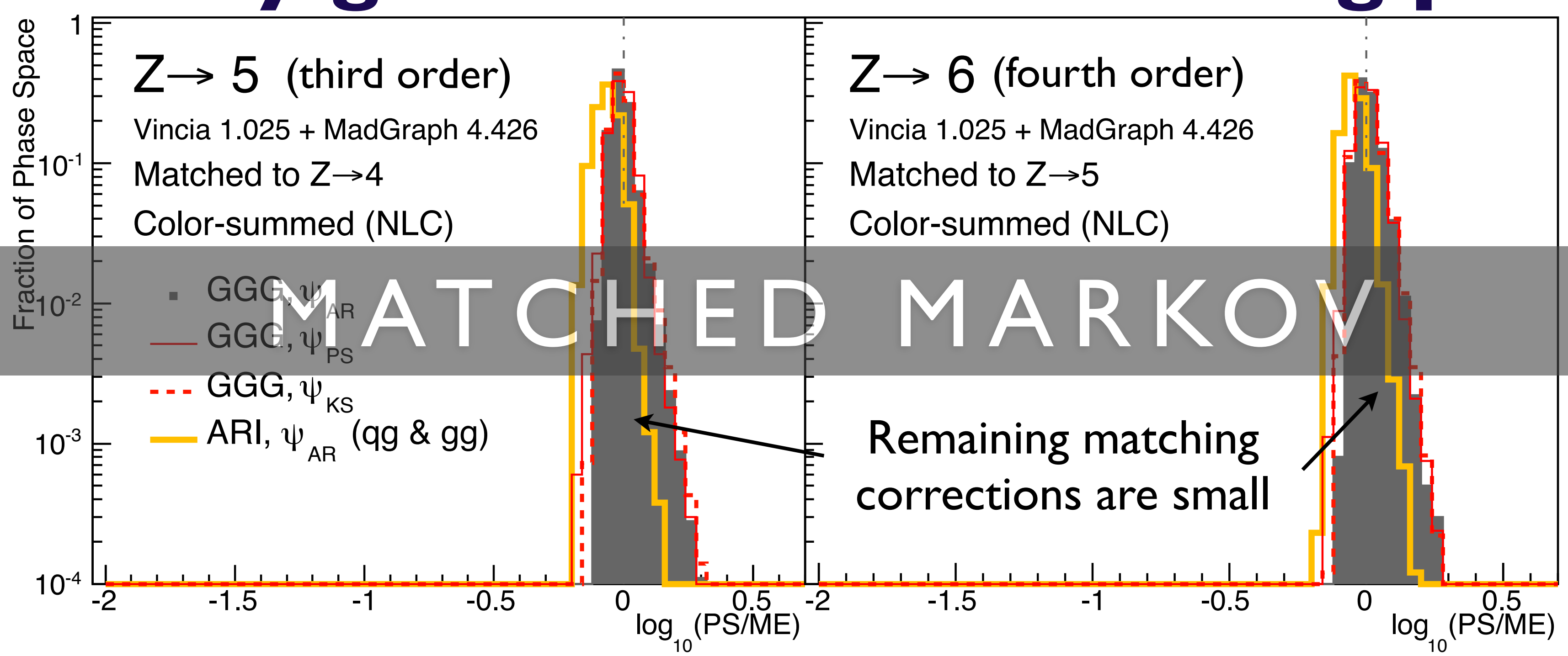
Leading Order, Leading Color, Flat phase-space scan, over **all of phase space** (no matching scale)



+ Matching (+ full colour)

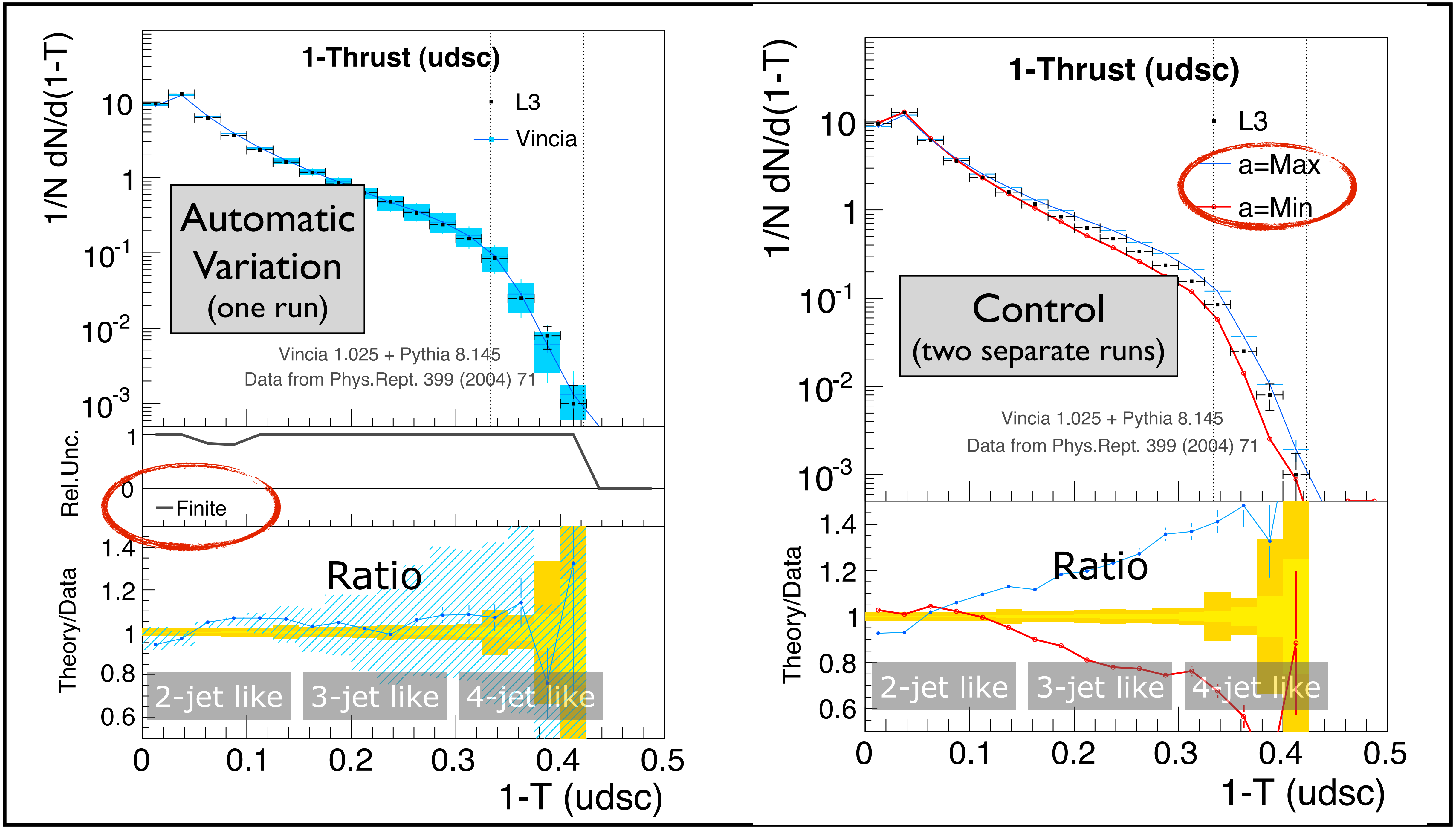


→ A very good all-orders starting point



Example: Non-Singular Terms

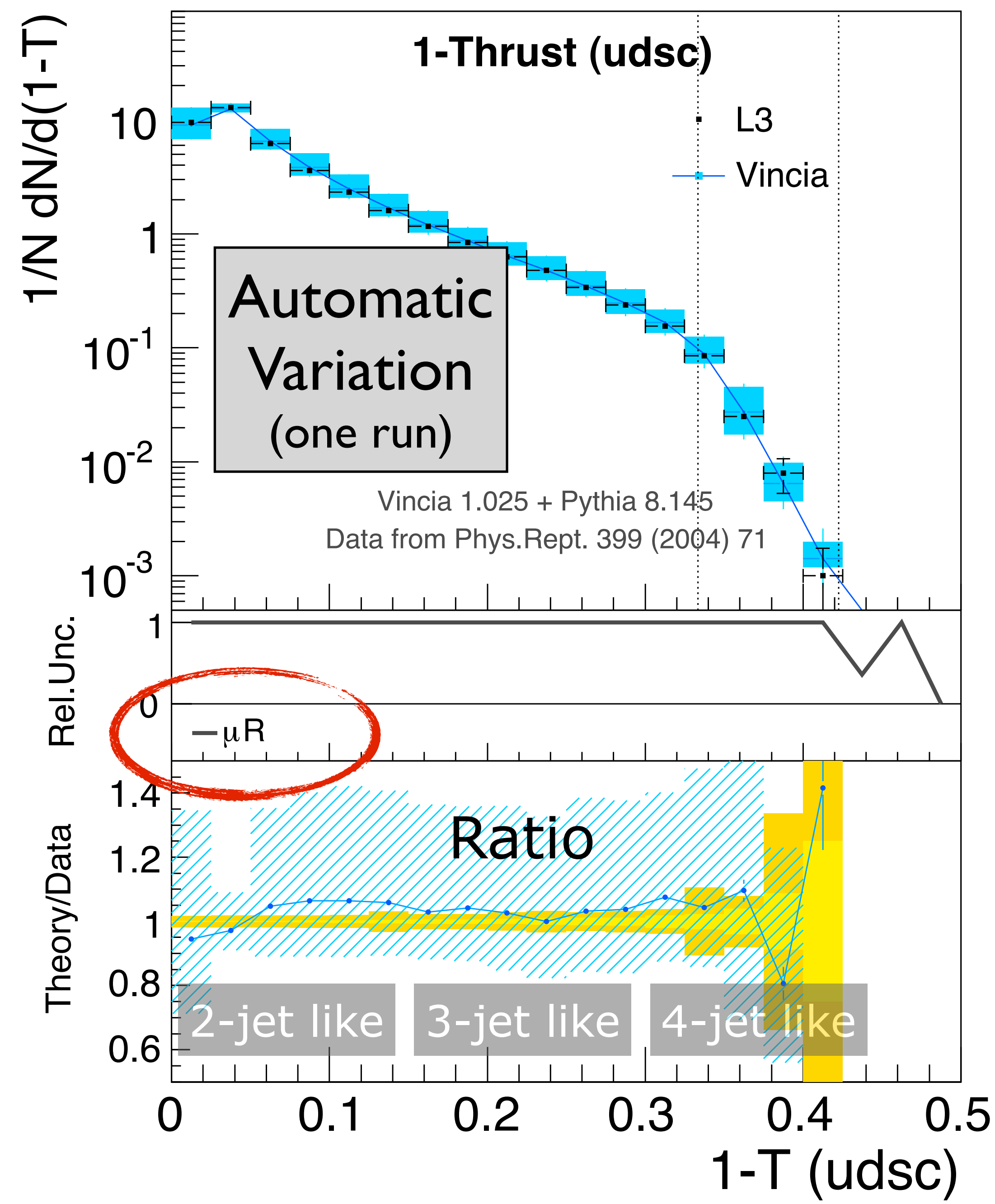
Giele, Kosower, Skands, PRD 84 (2011) 054003

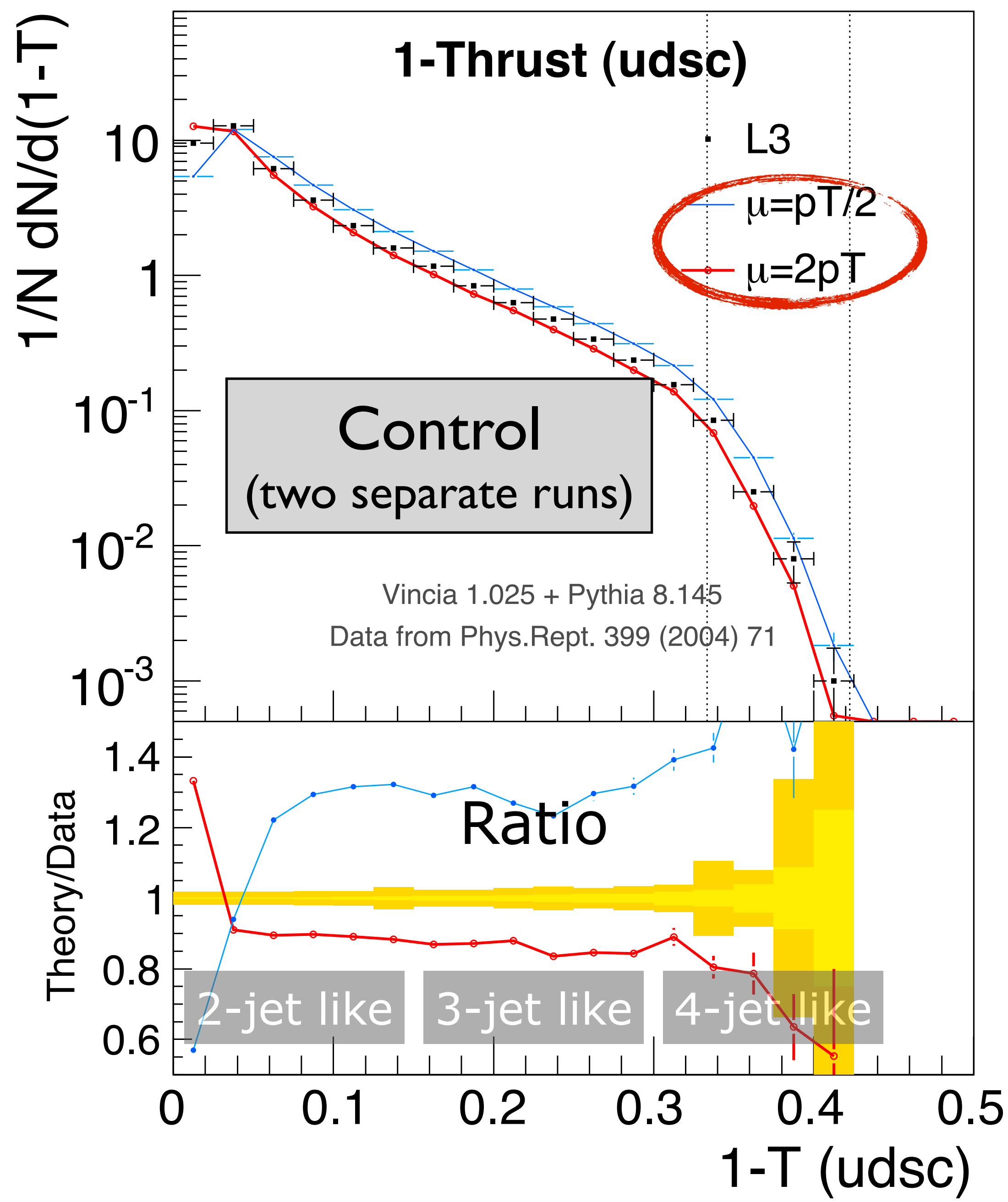


Thrust = LEP event-shape variable, goes from 0 (pencil) to 0.5 (hedgehog)

Example: μR

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





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

IR Singularity Operators

Gehrmann, Gehrmann-de Ridder, Glover, JHEP 0509 (2005) 056

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

$$X^0_{ijk} = S_{ijk,IK} \frac{|\mathcal{M}^0_{ijk}|^2}{|\mathcal{M}^0_{IK}|^2}$$

$$A^0_3(1_q, 3_g, 2_{\bar{q}}) = \frac{1}{s_{123}} \left(\frac{s_{13}}{s_{23}} + \frac{s_{23}}{s_{13}} + 2\frac{s_{12}s_{123}}{s_{13}s_{23}} \right)$$

Integrated antenna

$$\mathcal{P}oles\left(\mathcal{A}^0_3(s_{123})\right) = -2\mathbf{I}^{(1)}_{q\bar{q}}\left(\epsilon, s_{123}\right)$$

$$\mathcal{F}inite\left(\mathcal{A}^0_3(s_{123})\right) = \frac{19}{4} \,.$$

$$\mathcal{X}^0_{ijk}(s_{ijk}) = \left(8\pi^2 \left(4\pi\right)^{-\epsilon} e^{\epsilon\gamma}\right) \int \mathrm{d}\Phi_{X_{ijk}} \, X^0_{ijk}.$$

Singularity Operators

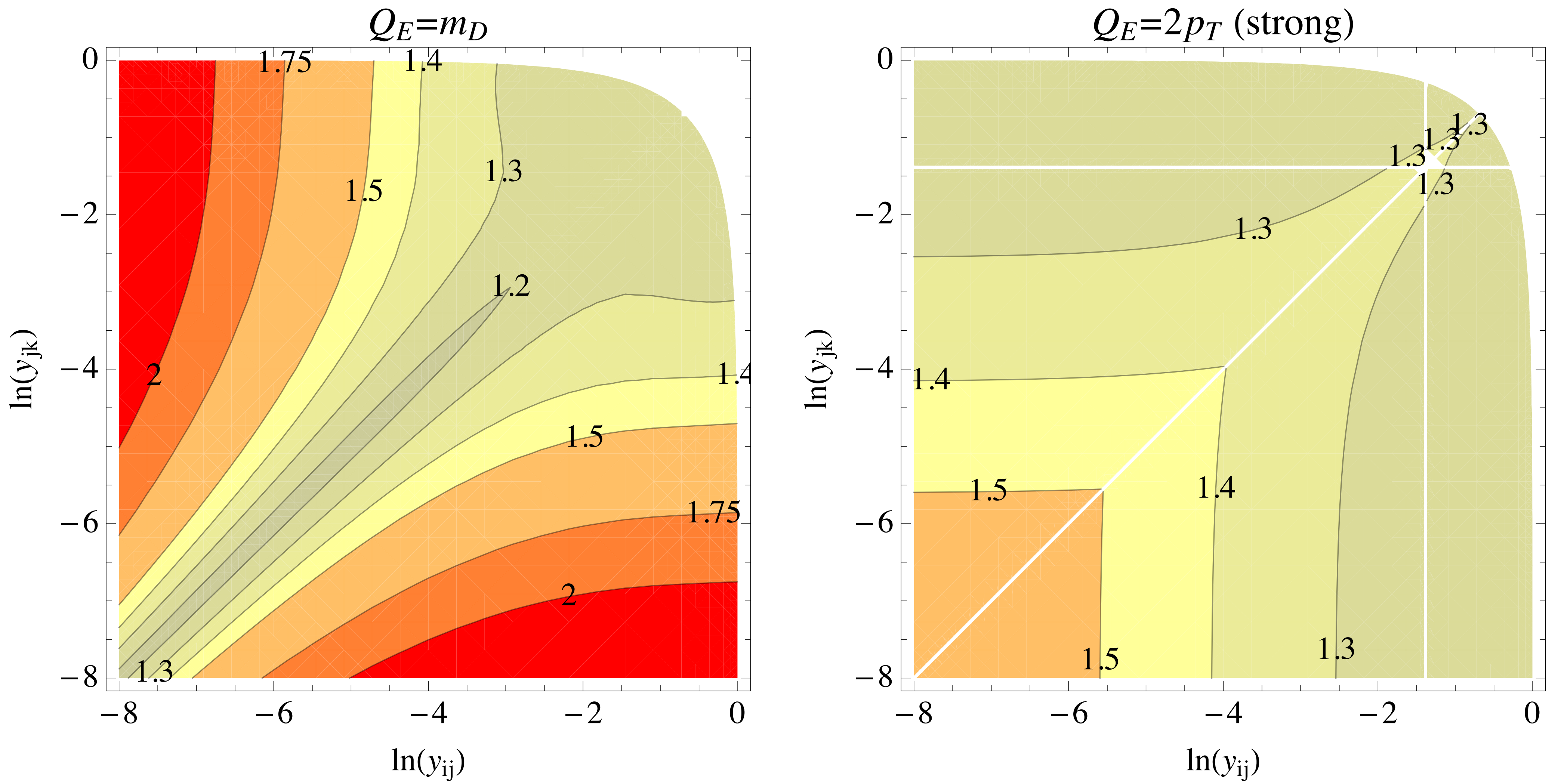
$$\mathbf{I}^{(1)}_{q\bar{q}}\left(\epsilon, \mu^2/s_{q\bar{q}}\right) = -\frac{e^{\epsilon\gamma}}{2\Gamma\left(1-\epsilon\right)} \left[\frac{1}{\epsilon^2} + \frac{3}{2\epsilon}\right] \mathrm{Re}\left(-\frac{\mu^2}{s_{q\bar{q}}}\right)^{\epsilon}$$

$$\mathbf{I}^{(1)}_{qg}\left(\epsilon, \mu^2/s_{qg}\right) = -\frac{e^{\epsilon\gamma}}{2\Gamma\left(1-\epsilon\right)} \left[\frac{1}{\epsilon^2} + \frac{5}{3\epsilon}\right] \mathrm{Re}\left(-\frac{\mu^2}{s_{qg}}\right)^{\epsilon}$$ for qg→qgg

$$\mathbf{I}^{(1)}_{qg,F}\left(\epsilon, \mu^2/s_{qg}\right) = \frac{e^{\epsilon\gamma}}{2\Gamma\left(1-\epsilon\right)} \frac{1}{6\epsilon} \mathrm{Re}\left(-\frac{\mu^2}{s_{qg}}\right)^{\epsilon}$$ for qg→qq’q’

The choice of evolution variable (Q)

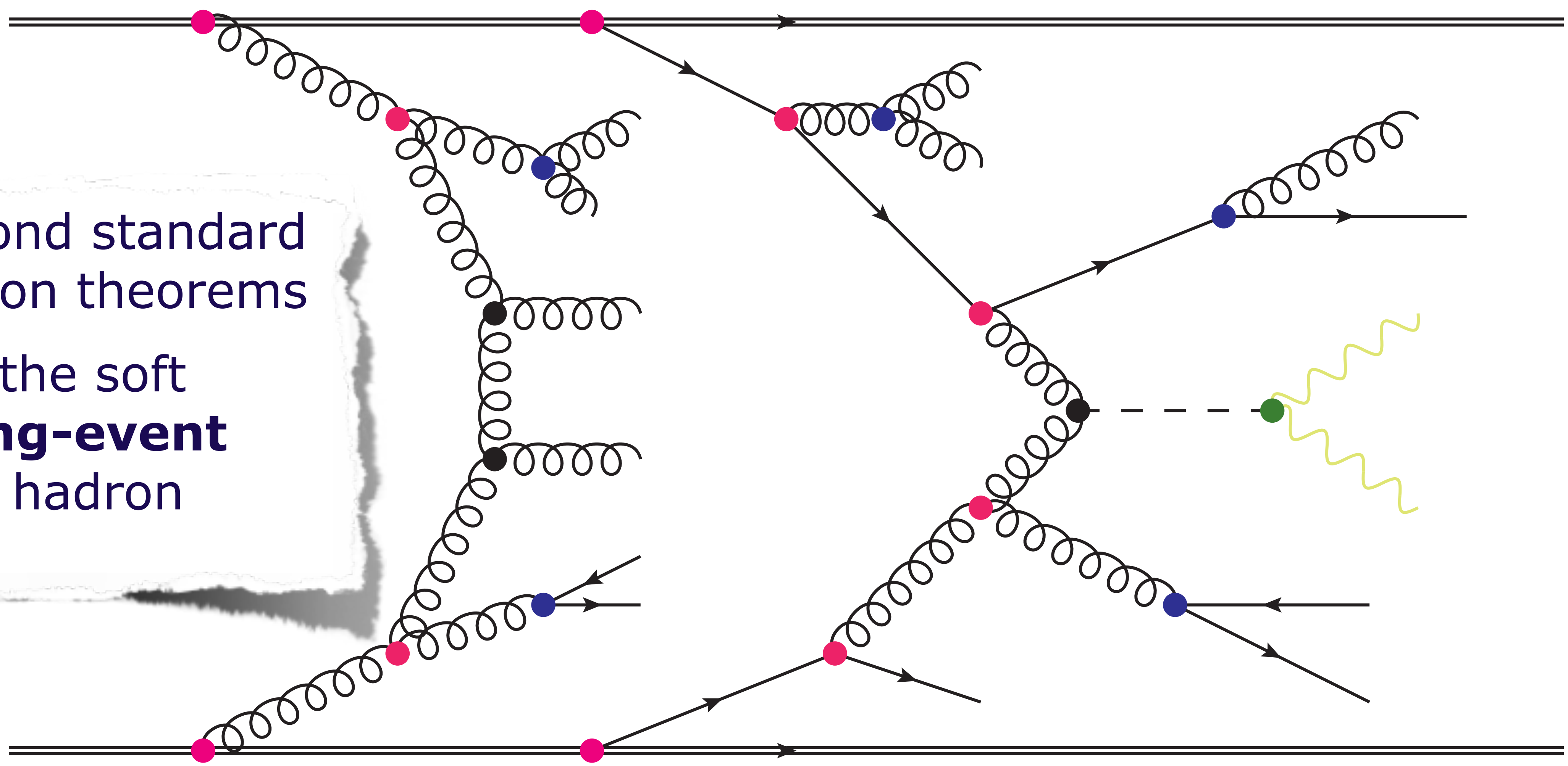
Variation with $\mu_R = m_D = 2\min(s_{ij}, s_{jk})$



Parameters: $\alpha_S(M_Z) = 0.12$, $\Lambda_{QCD} = \Lambda_{CMW}$

Additional Sources of Particle Production

Hadrons are composite → possibility of *Multiple Parton-Parton Interactions (+ their showers)*



Goes beyond standard factorization theorems

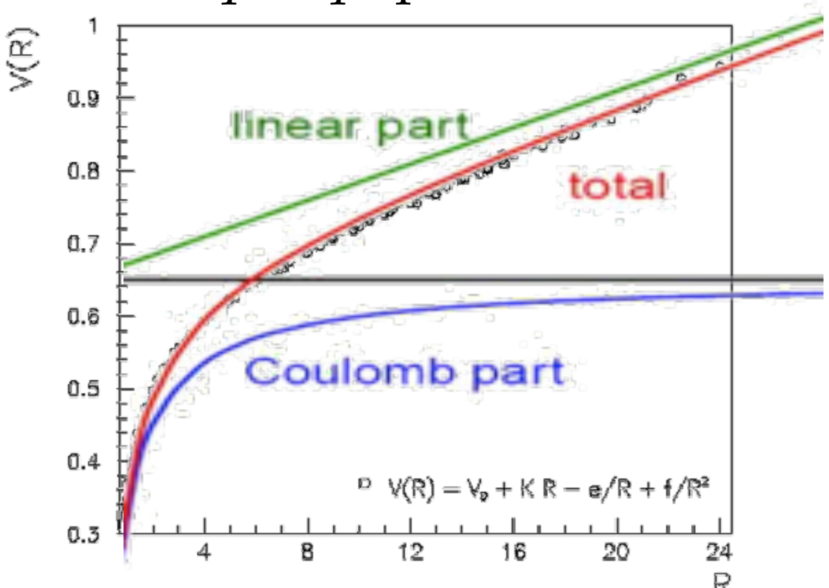
Builds up the soft **underlying-event** activity in hadron collisions

Many recent developments, on *factorization, multi-parton PDFs, cross sections, interaction models, color flow, etc*. But not the topic for today

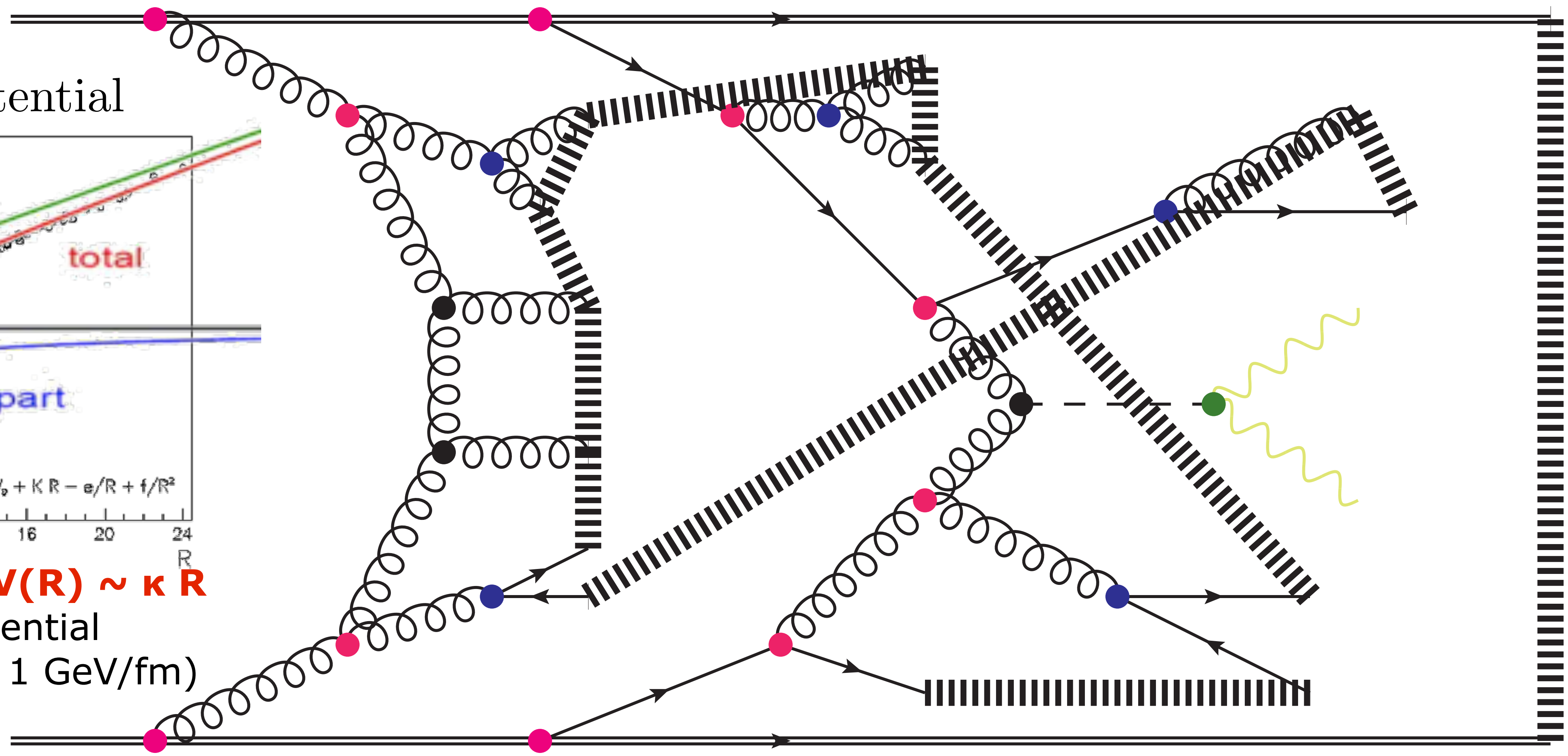
Hadronization

- A set of **colored** partons resolved at a scale of ~ 1 GeV (the perturbative cutoff) → set of **color-neutral** hadronic states.

$q - \bar{q}$ potential



Long Distances: **V(R) ~ κ R**
= String Potential
(with tension κ ~ 1 GeV/fm)



➡ Model as 1+1 dimensional (classical) string
+ breaks via quantum tunneling

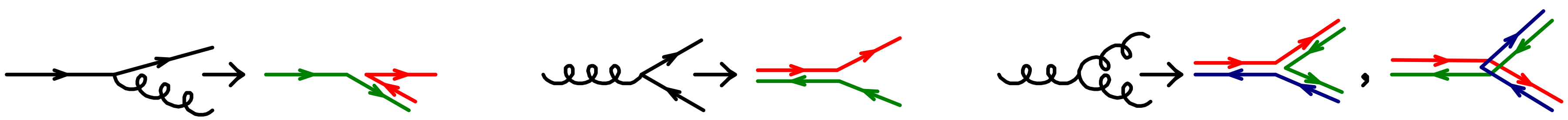
} **"Lund Model"**

(Color Flow in MC Models)

"Planar Limit"

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

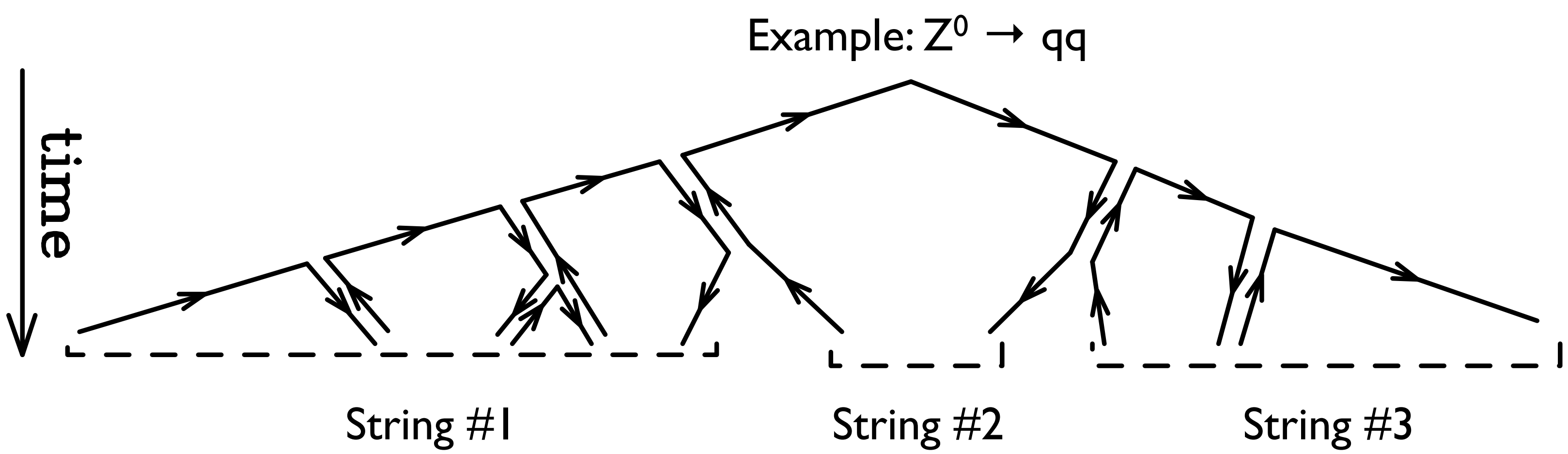
Rules for color flow:



*) 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

The problem:

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

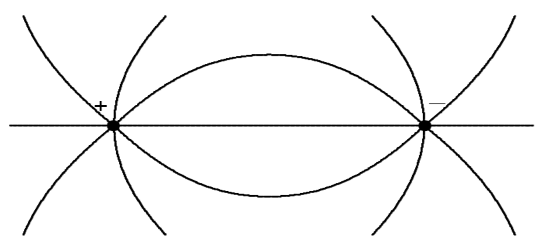
MC models do this in three steps

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

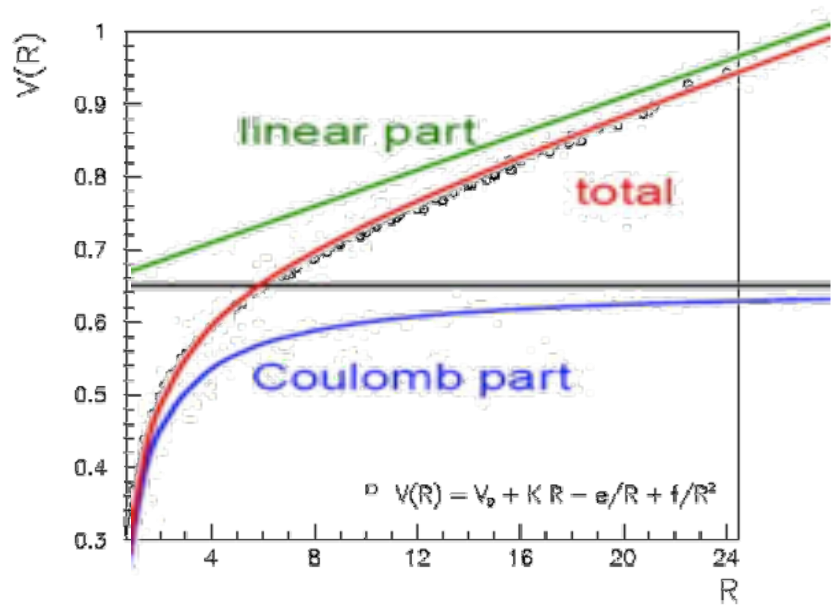
Distance Scales ~ 10^{-15} m = 1 fermi

From Partons to Strings

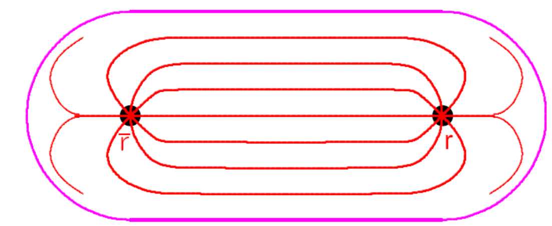
Short Distances ~ pQCD



Partons



Long Distances ~ Linear Confinement



Strings (Flux Tubes), Hadrons

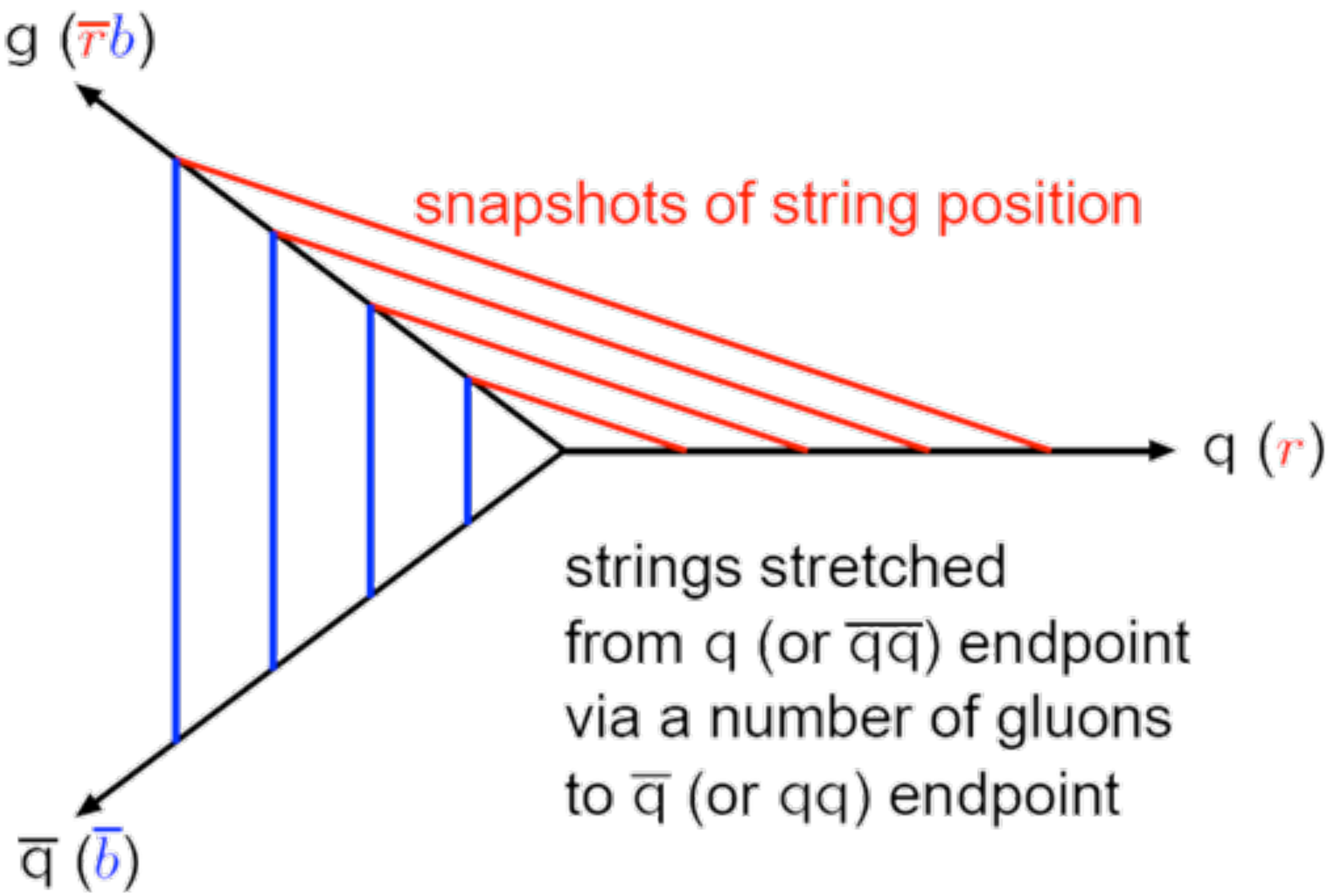
$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$

- **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**



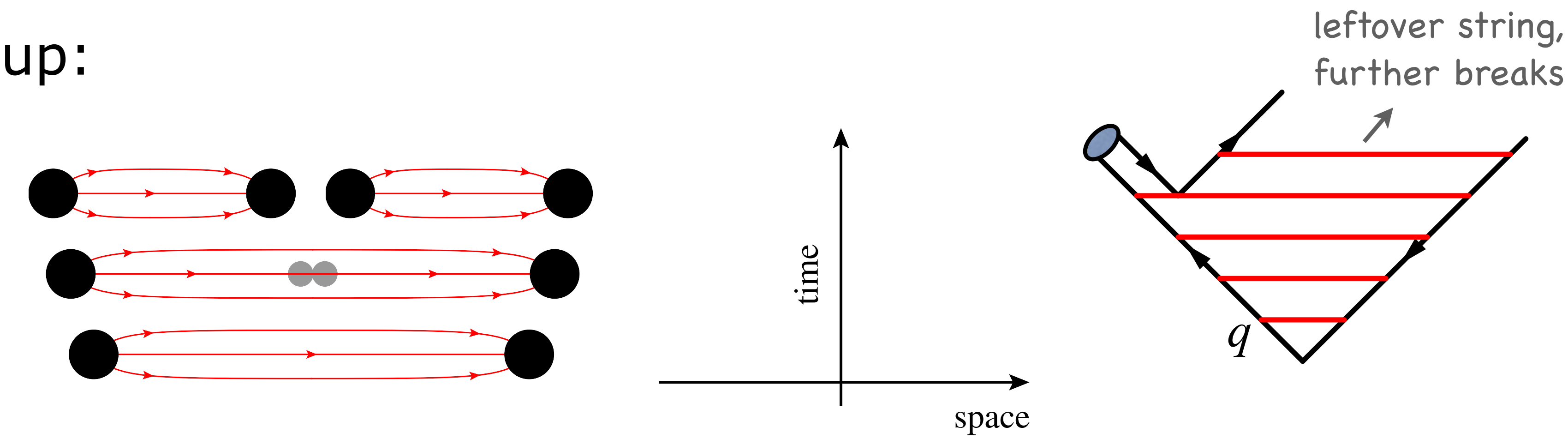
Gluon = kink on string, carrying energy and momentum

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: