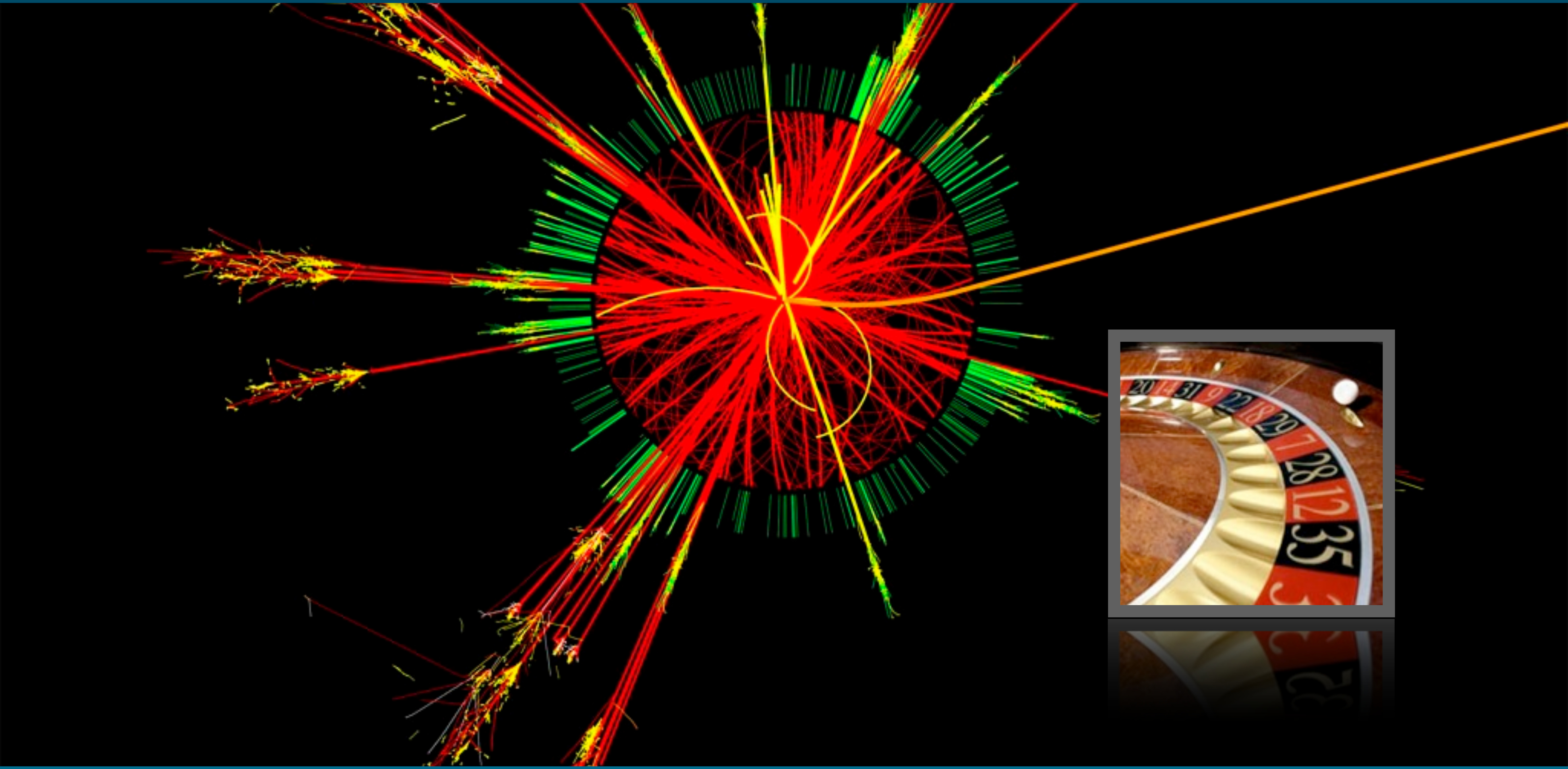
Event Generator Physics

Peter Skands (CERN Theoretical Physics Dept)



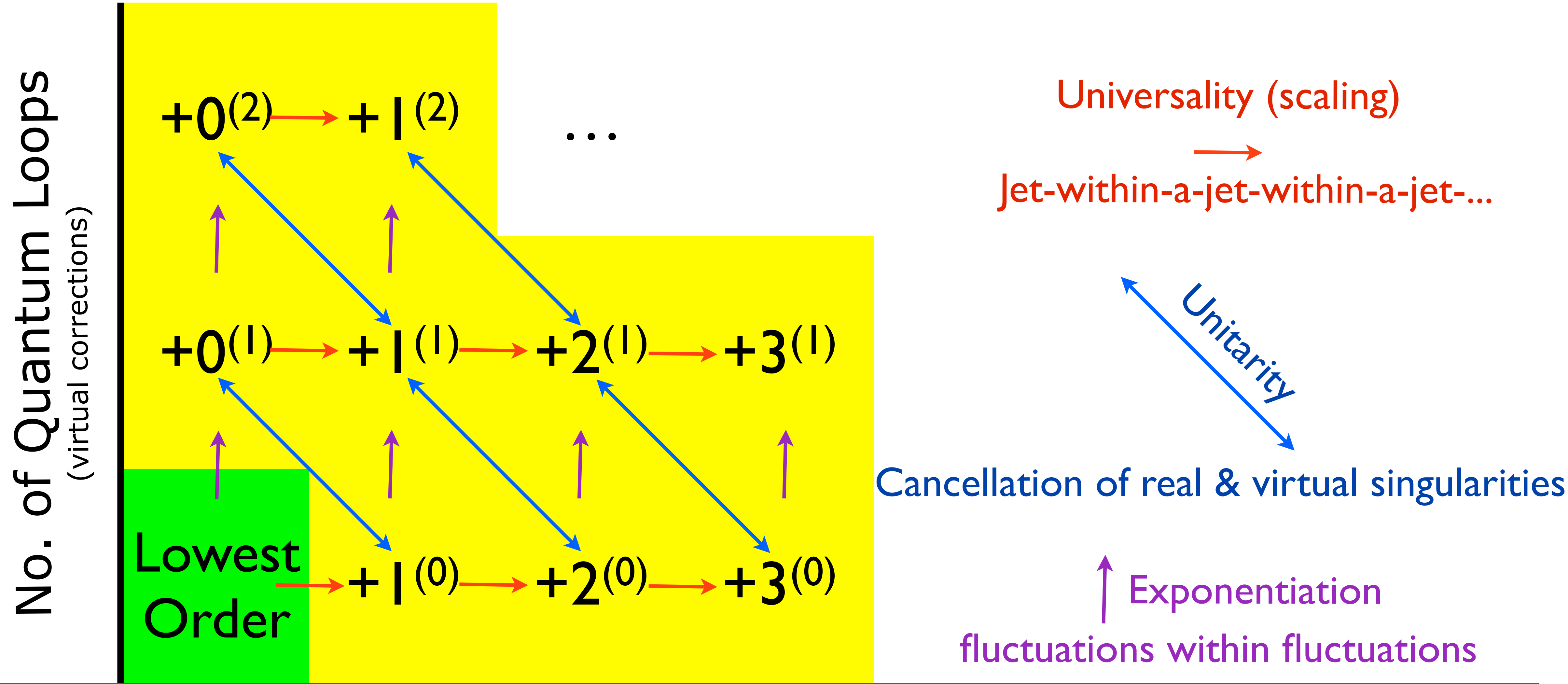
Ecole Joliot Curie
Frejus, France, September - October 2013

Lecture 2 / 2

Recap:
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 (approximate infinite-order resummation)



But ≠ full QCD! Only LL Approximation

(real corrections)

Recap: Perturbative Ambiguities

The final states generated by a shower algorithm will depend on

1. The choice of perturbative evolution variable(s) $t^{[i]}$. ← Ordering & Evolution-scale choices
2. The choice of phase-space mapping $\mathrm{d}\Phi_{n+1}^{[i]}/\mathrm{d}\Phi_n$. ← Recoils, kinematics
3. The choice of radiation functions a_i, as a function of the phase-space variables. ← Non-singular terms, Reparametrizations, Subleading Colour
4. The choice of renormalization scale function μ_R.
5. Choices of starting and ending scales. ← Phase-space limits / suppressions for hard radiation and choice of hadronization scale

→ gives us additional handles for uncertainty estimates, beyond just μ_R
+ ambiguities can be reduced by including more pQCD → matching!

Jack of All Orders, Master of None?

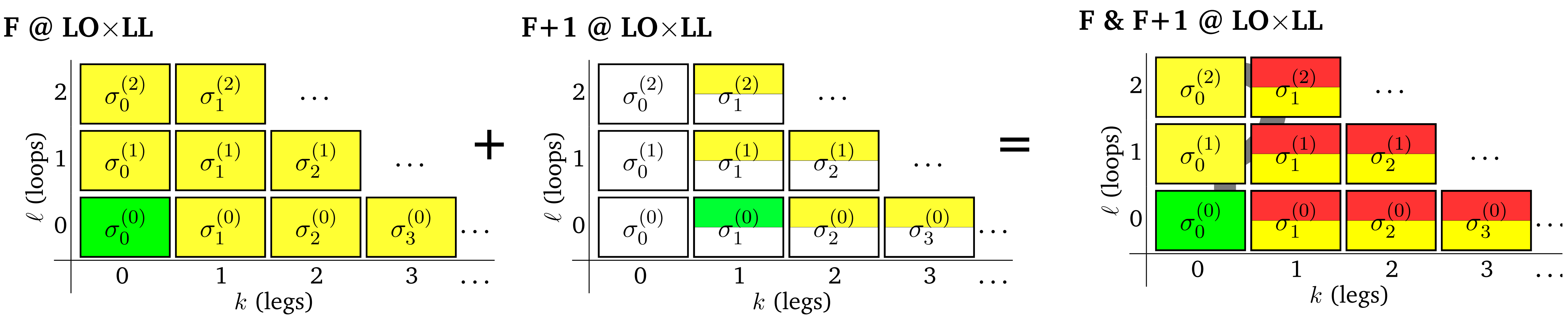
Nice to have all-orders solution

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!



FAIL!

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

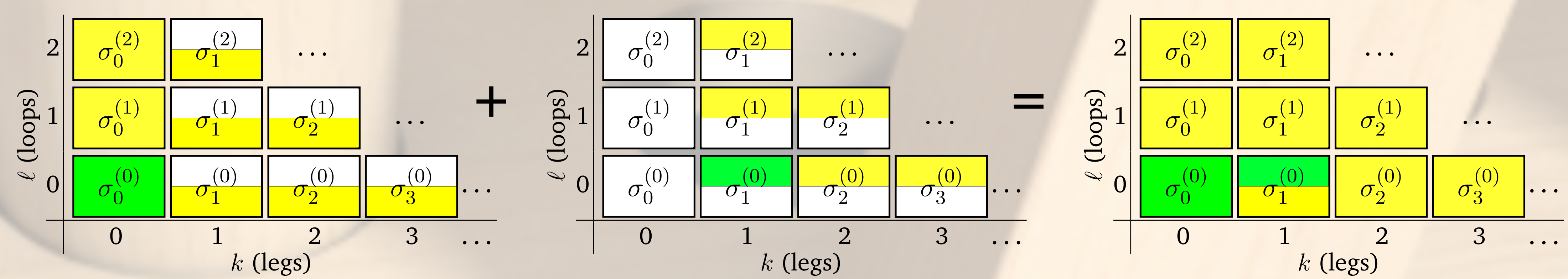
Matching 1: Slicing

Examples: MLM, CKKW, CKKW-L

First emission: "the HERWIG correction"

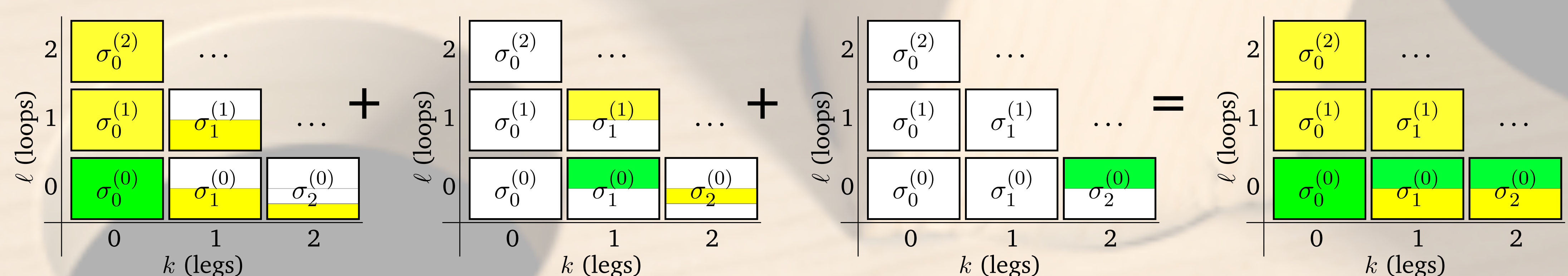
Use the fact that the angular-ordered HERWIG parton shower has a "dead zone" for hard wide-angle radiation (Seymour, 1995)

F @ LO×LL-Soft (HERWIG Shower) **F+1 @ LO×LL** (HERWIG Corrections) **F @ LO$_1$×LL** (HERWIG Matched)



Many emissions: the MLM & CKKW-L prescriptions

F @ LO×LL-Soft (excl) **F+1 @ LO×LL-Soft** (excl) **F+2 @ LO×LL** (incl) **F @ LO$_2$×LL** (MLM & (L)-CKKW)



(CKKW & Lönnblad, 2001) (Mangano, 2002) (+many more recent; see Alwall et al., EPJC53(2008)473)

Image Credits: istockphoto

The "CKKW" Prescription

Catani, Krauss, Kuhn, Webber, JHEP11(2001)063
Lönnblad, JHEP05(2002)046

Start from a set of fixed-order MEs

Separate Phase-Space Integrations

σ_F^{inc} $\sigma_{F+1}^{\mathrm{inc}}(Q_{\mathrm{cut}})$ $\sigma_{F+2}^{\mathrm{inc}}(Q_{\mathrm{cut}})$

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 (CKKW) → Recluster back to F → "fake" brems history
Or use statistical showers (Lönnblad), now done in all implementations
Reweight each internal line by shower Sudakov factor & each vertex by $\alpha_s(\mu_{PS})$

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

Reweight each external line by shower Sudakov factor

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

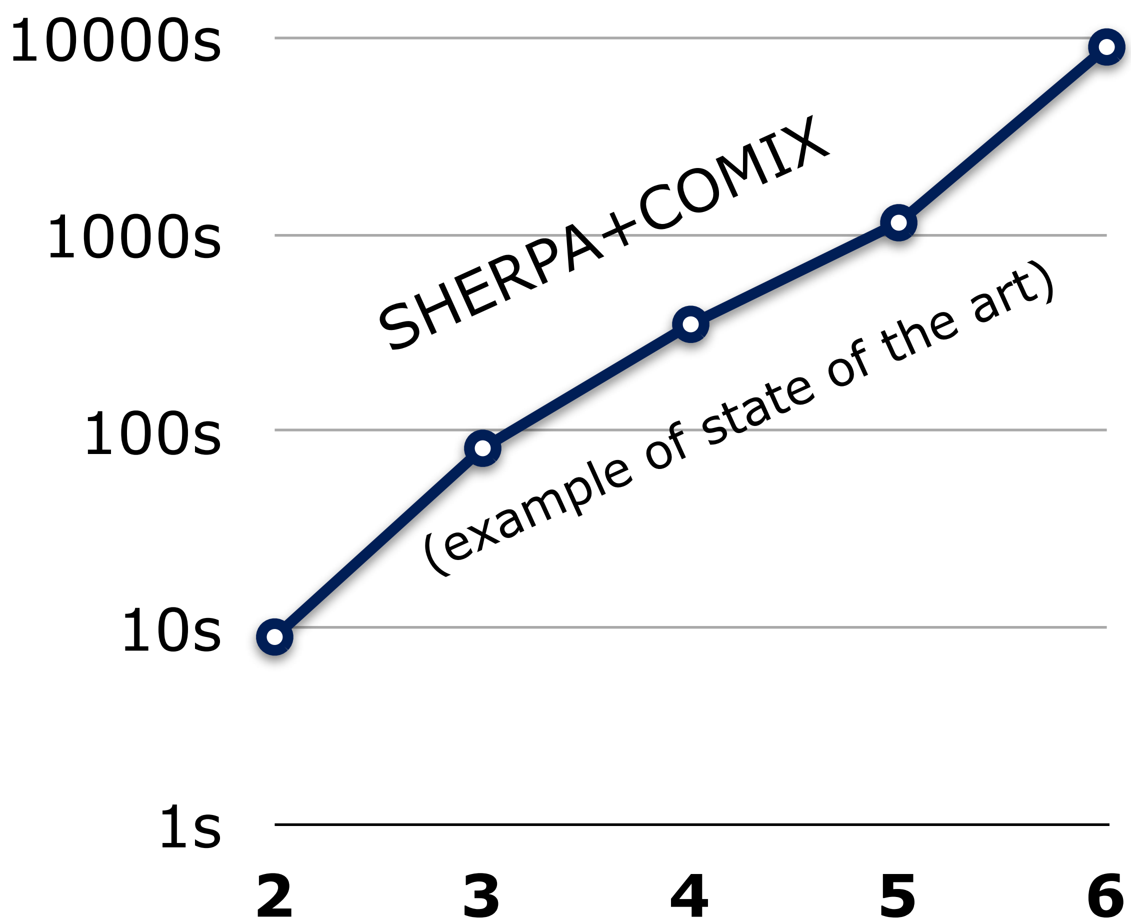
Now add a genuine parton shower → remaining evolution down to confinement scale

Start from Q_{cut}

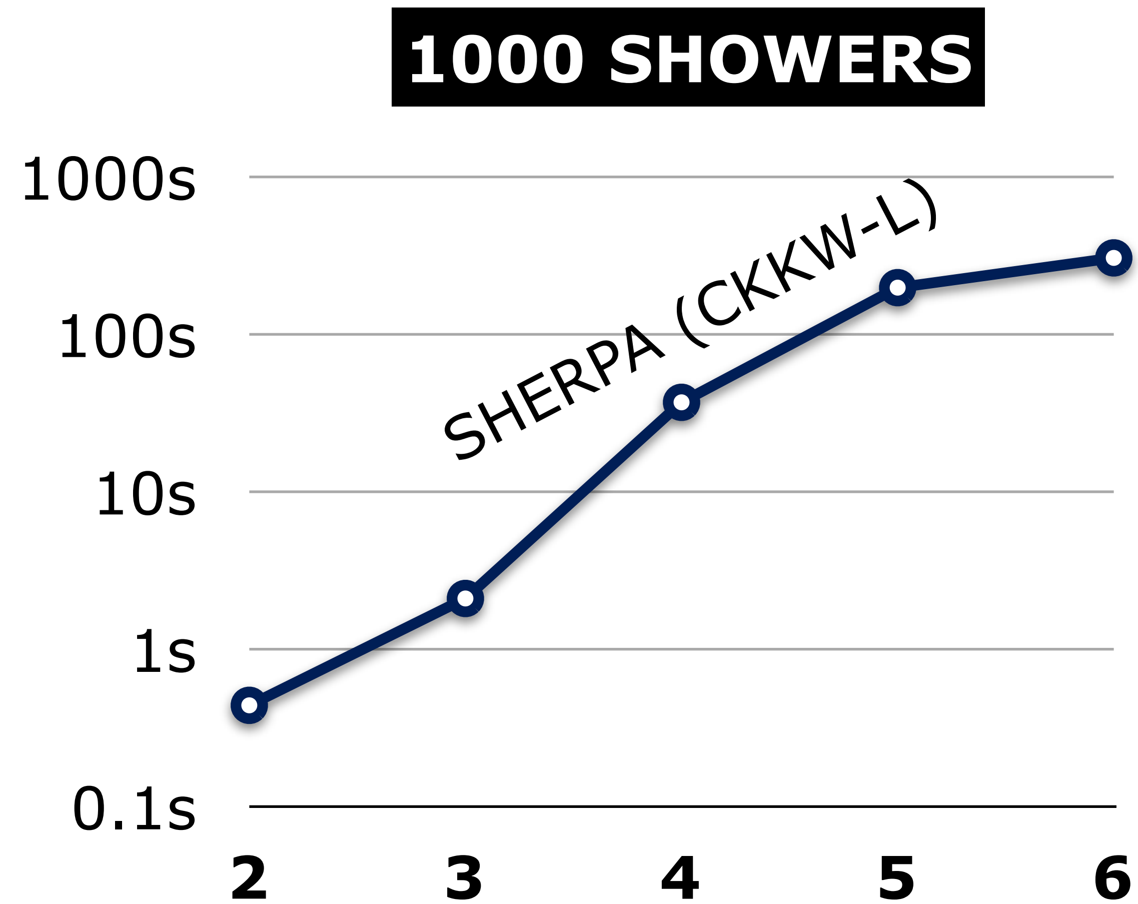
Start from Q_{F+2}

Slicing: 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)

Matching: Classic Example

W + Jets

Important at the LHC

Consider $\sigma(W+n_{jets})$

Pure PYTHIA (shower)

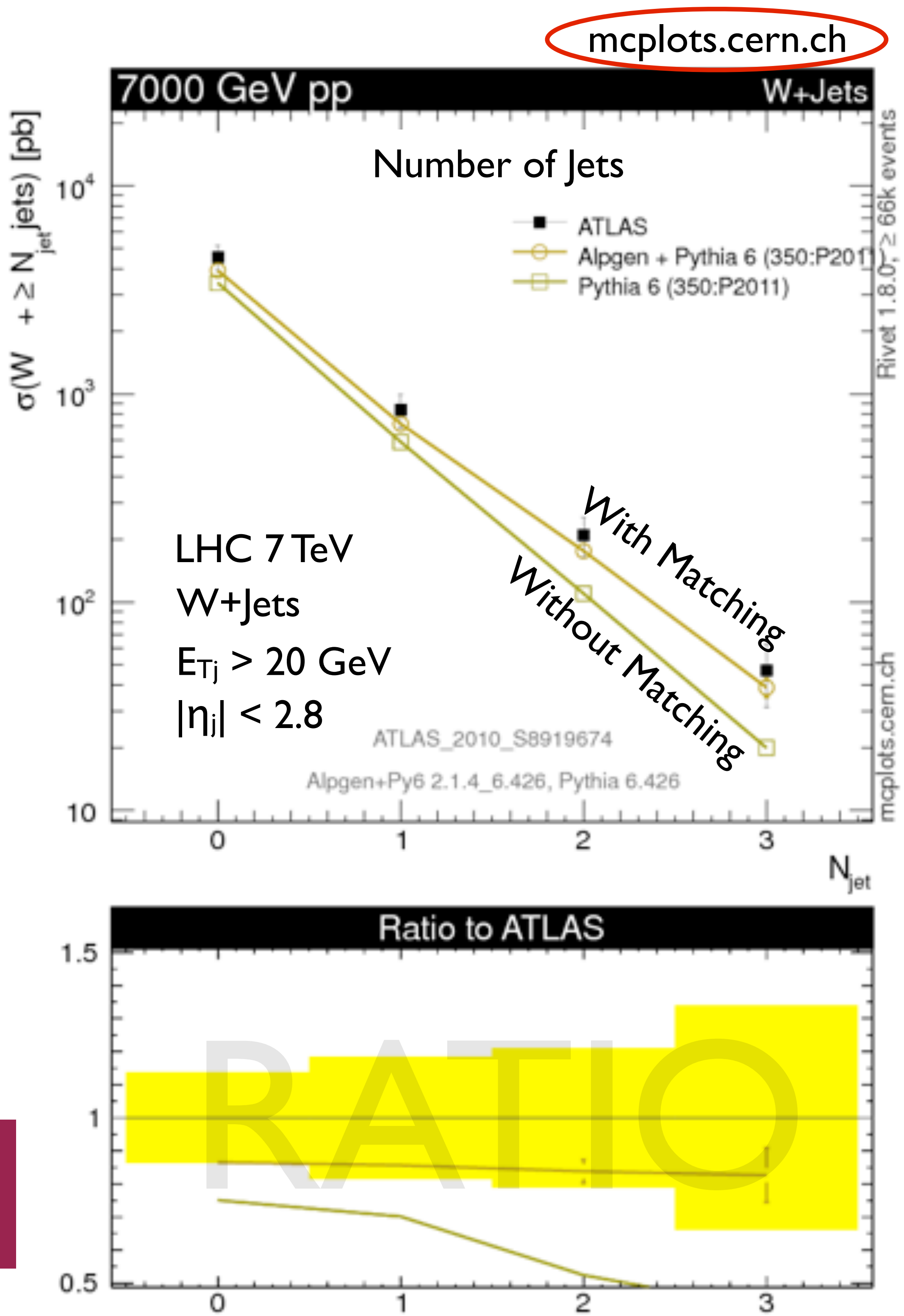
(includes LO matching for $n_{jet} \leq 1$, more later)

Shower for $n_{jet} \geq 2$

ALPGEN+PYTHIA (MLM)

Includes LO matching for $n_{jet} \leq 3$

Note: but the cross-section normalization is still only LO!



(Counter-Example)

QCD Multi-Jets:

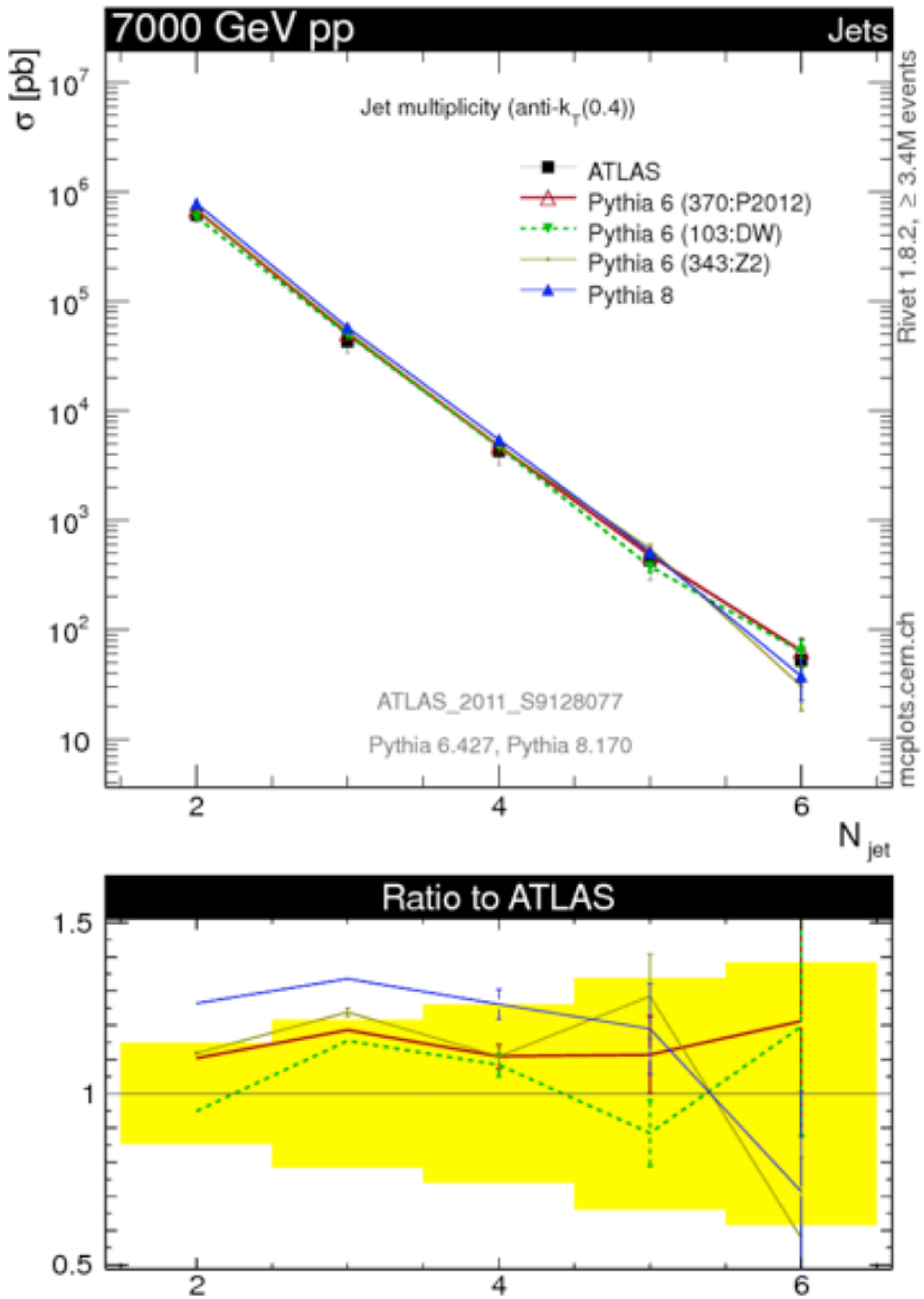
Even at 6 jets, there is almost always at least one strongly ordered path

→ showers work!

(In W+jets, that is not the case)

→ Matching not always needed.

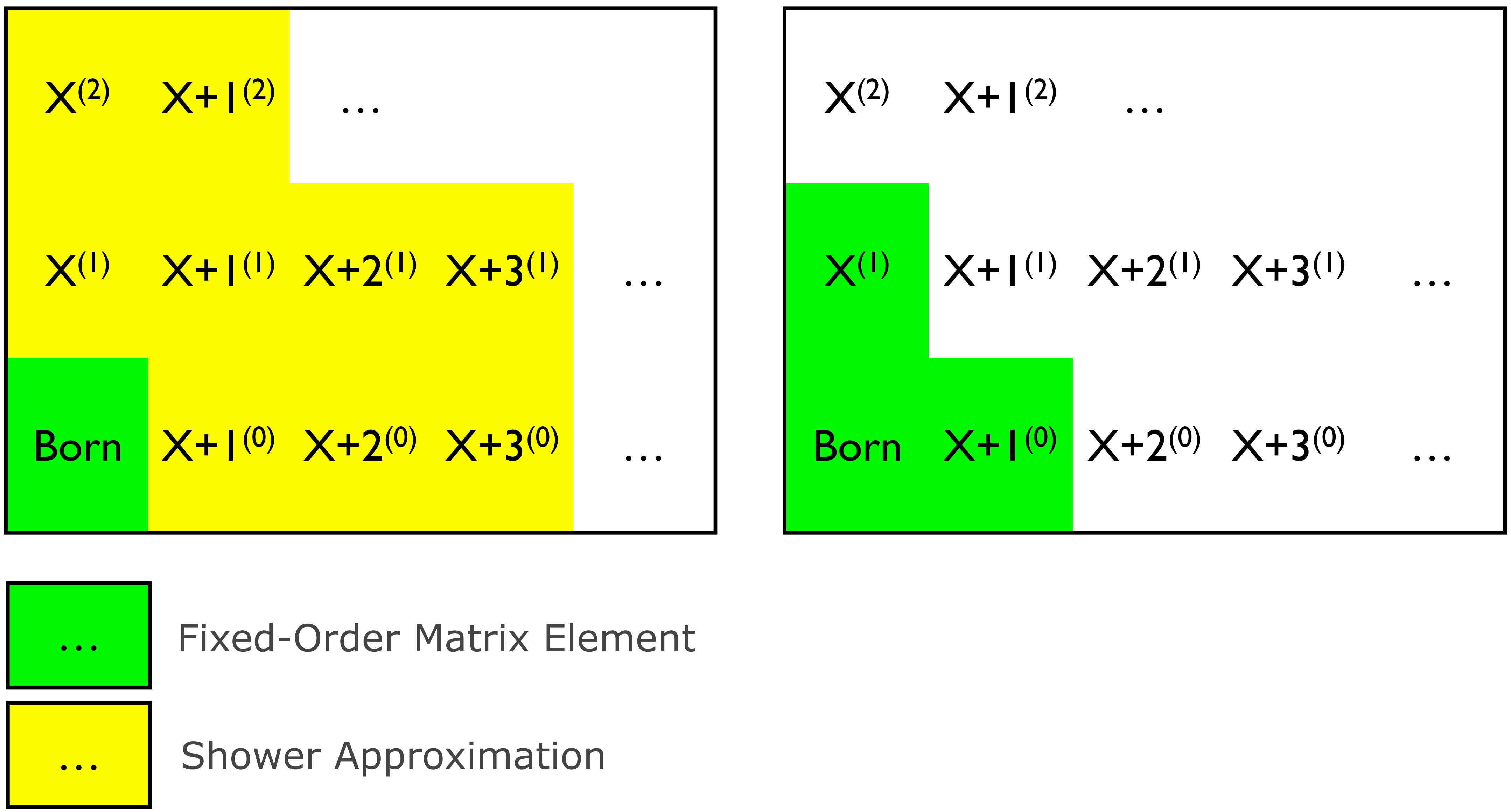
But note that spin correlations between the jets are still absent in the shower treatment



Matching 2: Subtraction

Examples: MC@NLO, aMC@NLO

LO × Shower   NLO



Matching 2: Subtraction

Examples: MC@NLO, aMC@NLO

LO × Shower

$X^{(2)}$	$X+1^{(2)}$	…		
$X^{(1)}$	$X+1^{(1)}$	$X+2^{(1)}$	$X+3^{(1)}$	…
Born	$X+1^{(0)}$	$X+2^{(0)}$	$X+3^{(0)}$	…

… Fixed-Order Matrix Element

… Shower Approximation

NLO - Shower$_{NLO}$

$X^{(2)}$	$X+1^{(2)}$	…		
$X^{(1)}$	$X+1^{(1)}$	$X+2^{(1)}$	$X+3^{(1)}$	…
Born	$X+1^{(0)}$	$X+2^{(0)}$	$X+3^{(0)}$	…

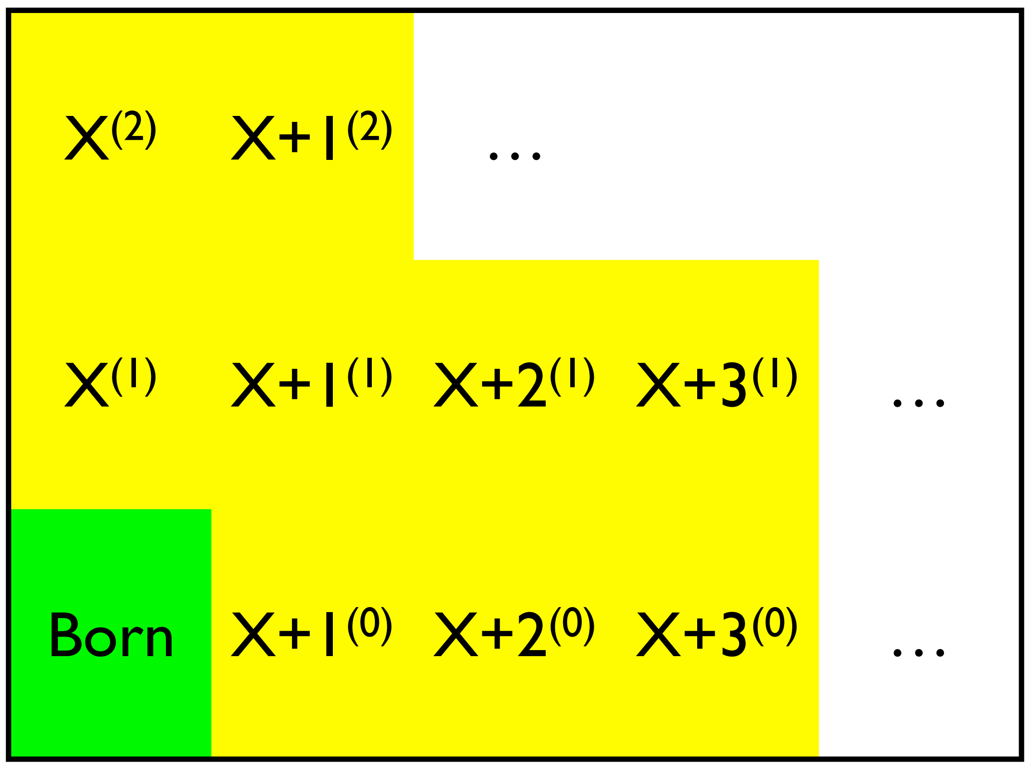
Expand shower approximation to NLO analytically, then subtract:

… Fixed-Order ME minus Shower Approximation (NOTE: can be < 0!)

Matching 2: Subtraction

Examples: MC@NLO, aMC@NLO

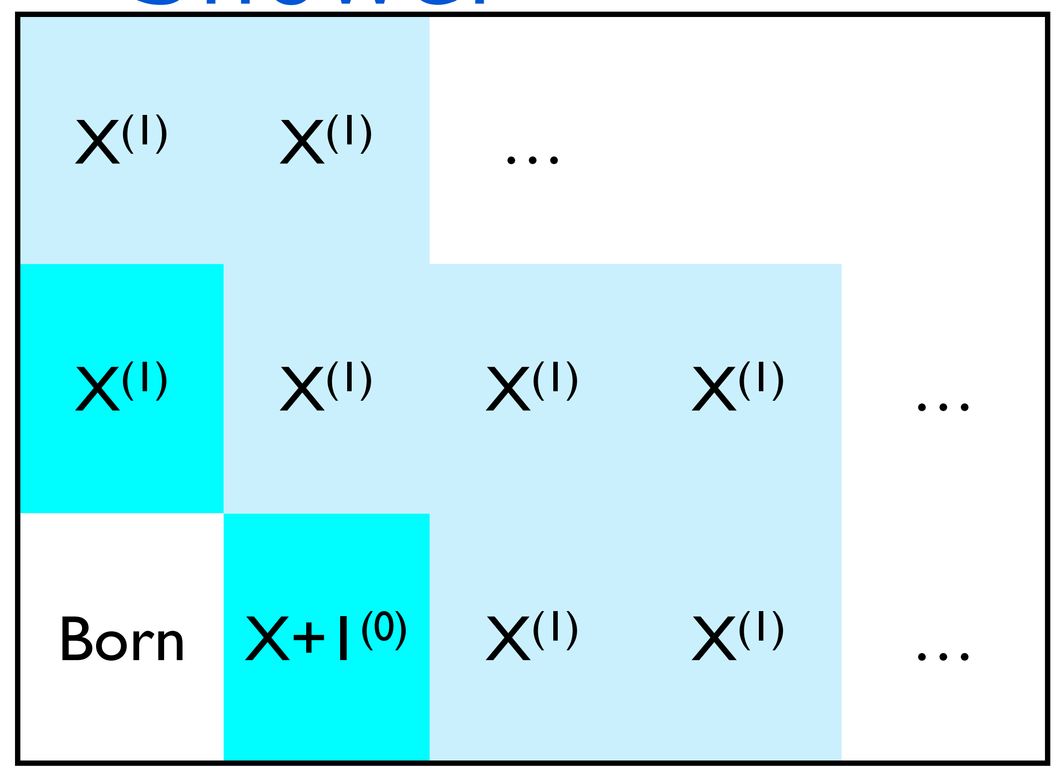
LO × Shower



... Fixed-Order Matrix Element

... Shower Approximation

(NLO - Shower$_{\mathrm{NLO}}$) × Shower



... Fixed-Order ME minus Shower Approximation (NOTE: can be < 0!)

... Subleading corrections generated by shower off subtracted ME

Matching 2: Subtraction

Examples: MC@NLO, aMC@NLO

Combine → MC@NLO

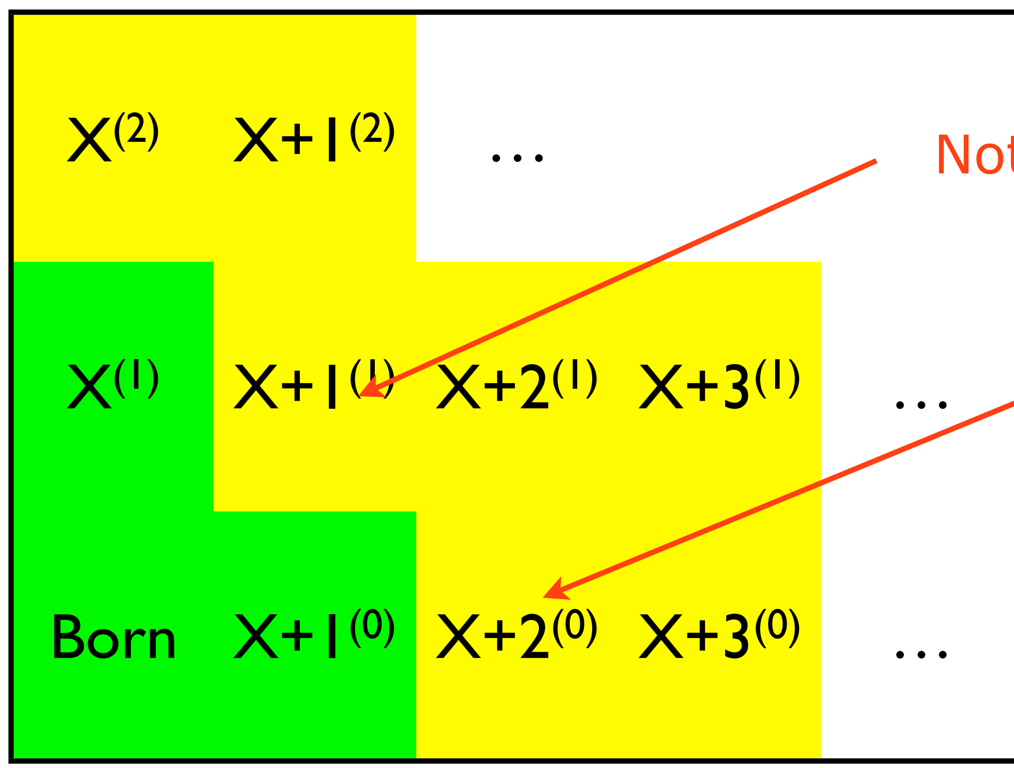
Frixione, Webber, JHEP 0206 (2002) 029

Consistent NLO + parton shower (though correction events can have w<0)

Recently, has been almost fully automated in aMC@NLO

Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli, JHEP 1202 (2012) 048

NLO: for X inclusive
LO for X+1
LL: for everything else



Note 1: NOT NLO for X+1

Note 2: Multijet tree-level matching still superior for X+2

NB: w < 0 are a problem because they kill efficiency:
Extreme example: 1000 positive-weight - 999 negative-weight events → statistical precision of 1 event, for 2000 generated (for comparison, normal MC@NLO has ~ 10% neg-weights)

Matching 3: ME Corrections

Standard Paradigm:

Have ME for X, X+1,…, X+n;

Want to combine and add showers → "The Soft Stuff"

Double counting, IR divergences, multiscale logs

Works pretty well at low multiplicities

Still, only corrected for "hard" scales; Soft still pure LL.

At high multiplicities:

Efficiency problems: slowdown from need to compute and generate phase space from $d\sigma_{X+n}$, and from unweighting (efficiency also reduced by negative weights, if present)

Scale hierarchies: smaller single-scale phase-space region

Powers of alphaS pile up

Better Starting Point: a QCD fractal?

(shameless VINCIA promo)

(plug-in to PYTHIA 8 for ME-improved final-state showers, uses helicity matrix elements from MadGraph)

Interleaved Paradigm:

Have shower; want to improve it using ME for X, X+1, …, X+n.

Interpret all-orders shower structure as a trial distribution

Quasi-scale-invariant: intrinsically multi-scale (resums logs)

Unitary: automatically unweighted (& IR divergences → multiplicities)

More precise expressions imprinted via veto algorithm: ME corrections at LO, NLO, … → soft *and* hard corrections

No additional phase-space generator or σ_{X+n} calculations → **fast**

Automated Theory Uncertainties

For each event: vector of output weights (central value = 1)

+ Uncertainty variations. Faster than N separate samples; only one sample to analyse, pass through detector simulations, etc.

LO: Giele, Kosower, Skands, PRD84(2011)054003 **NLO:** Hartgring, Laenen, Skands, arXiv:1303.4974

Matching 3: ME Corrections

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

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

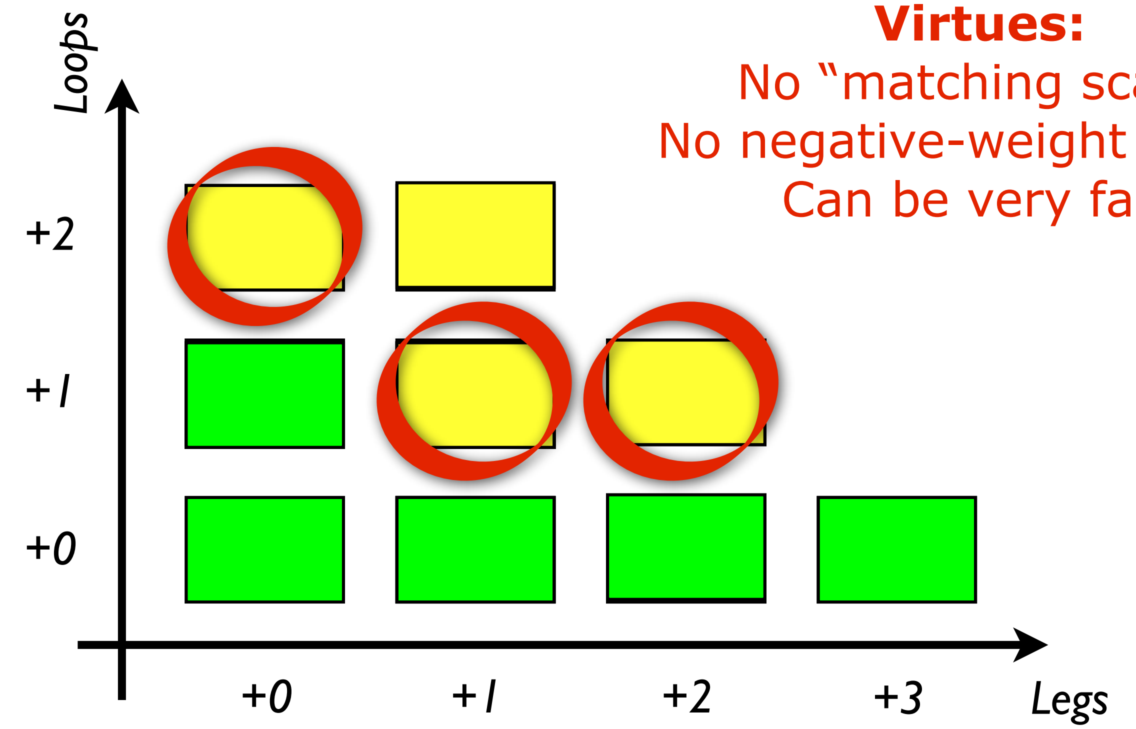
Correct to Matrix Element

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

Repeat

Illustrations from: PS, TASI Lectures, arXiv:1207.2389

Examples: PYTHIA, POWHEG, VINCIA



Virtues:
No "matching scale"
No negative-weight events
Can be very fast

First Order

PYTHIA: LO_1 corrections to most SM and BSM decay processes, and for pp → Z/W/H (Sjöstrand 1987)

POWHEG (& POWHEG BOX): LO_1 + NLO_0 corrections for generic processes (Frixione, Nason, Oleari, 2007)

Multileg NLO:

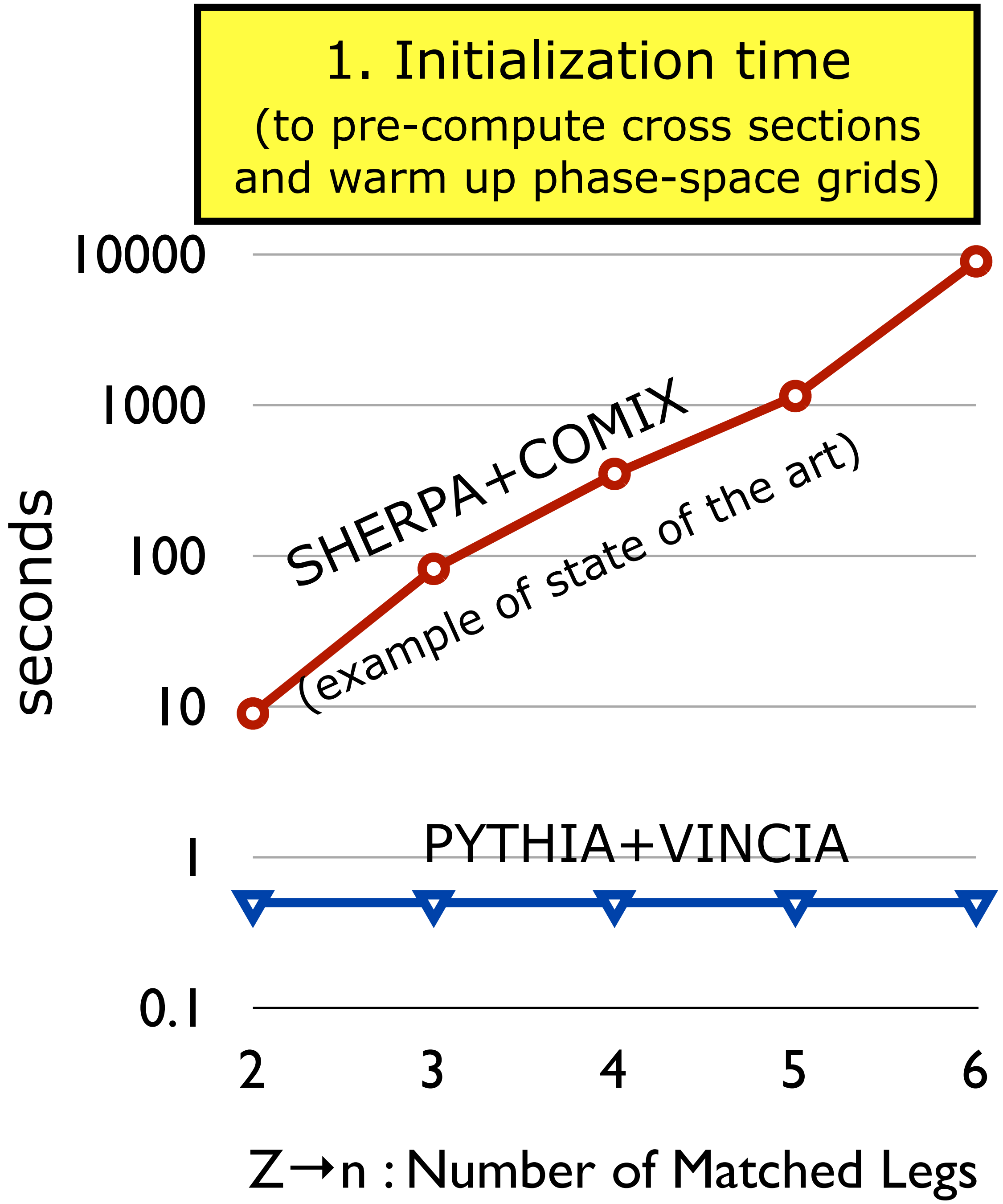
VINCIA: $LO_{1,2,3,4}$ + $NLO_{0,1}$ (shower plugin to PYTHIA 8; formalism for pp soon to appear) (see previous slide)

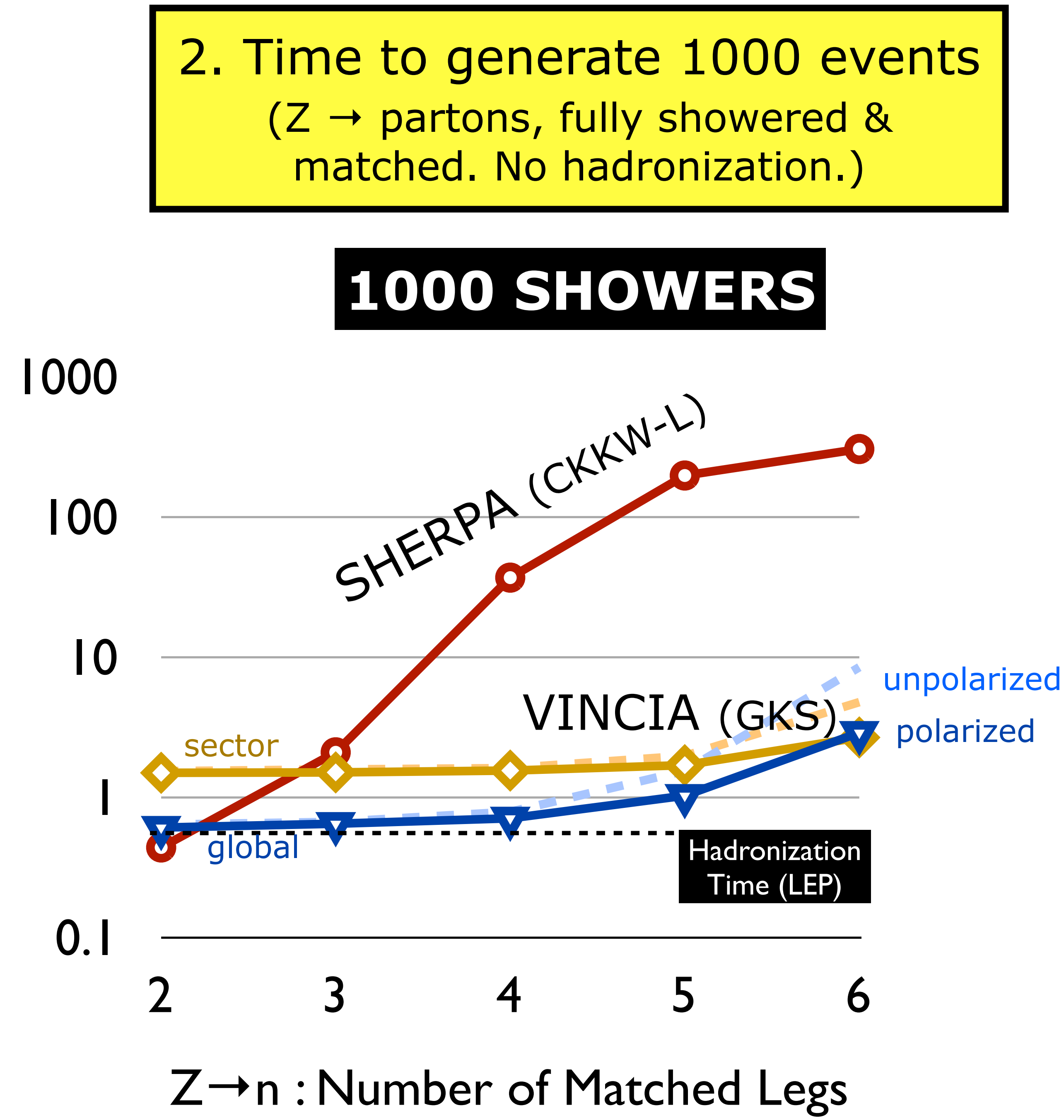
MiNLO-merged POWHEG: $LO_{1,2}$ + $NLO_{0,1}$ for pp → Z/W/H

UNLOPS: for generic processes (in PYTHIA 8, based on POWHEG input) (Lönnblad & Prestel, 2013)

Speed

Larkoski, Lopez-Villarejo, Skands, PRD 87 (2013) 054033





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gcc/gfortran v 4.7.1 -O2 ; single 3.06 GHz core (4GB RAM)

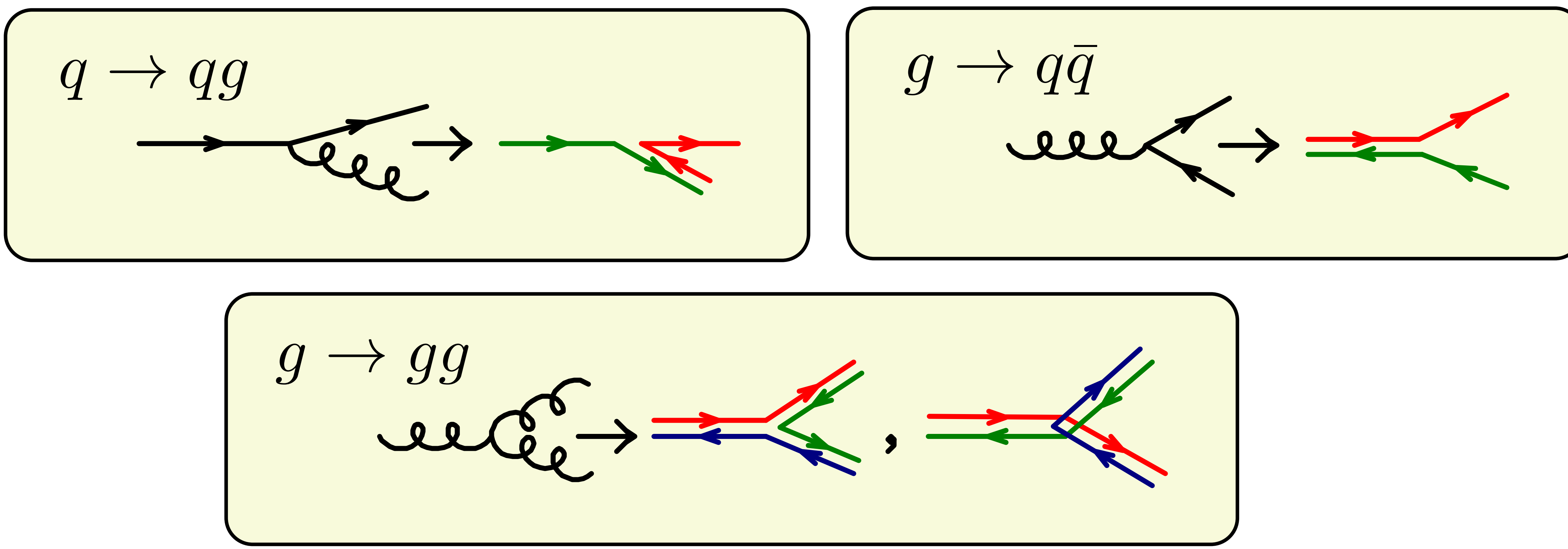
Hadronization

& tuning

Color Flow

Between which partons do confining potentials arise?

Set of simple rules for color flow, based on large-N_C limit



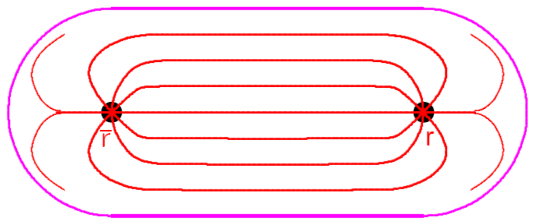
(Never Twice Same Color: true up to $O(1/N_C^2)$)

Illustrations from: P.Nason & P.S., PDG Review on *MC Event Generators*, 2012

Confinement

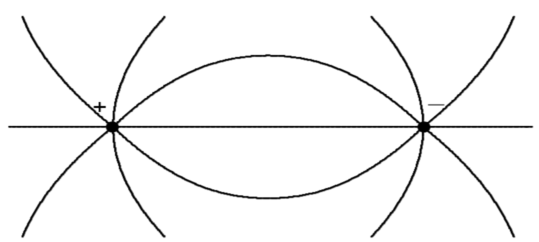
Potential between a quark and an antiquark as function of distance, R

Long Distances ~ Linear Potential

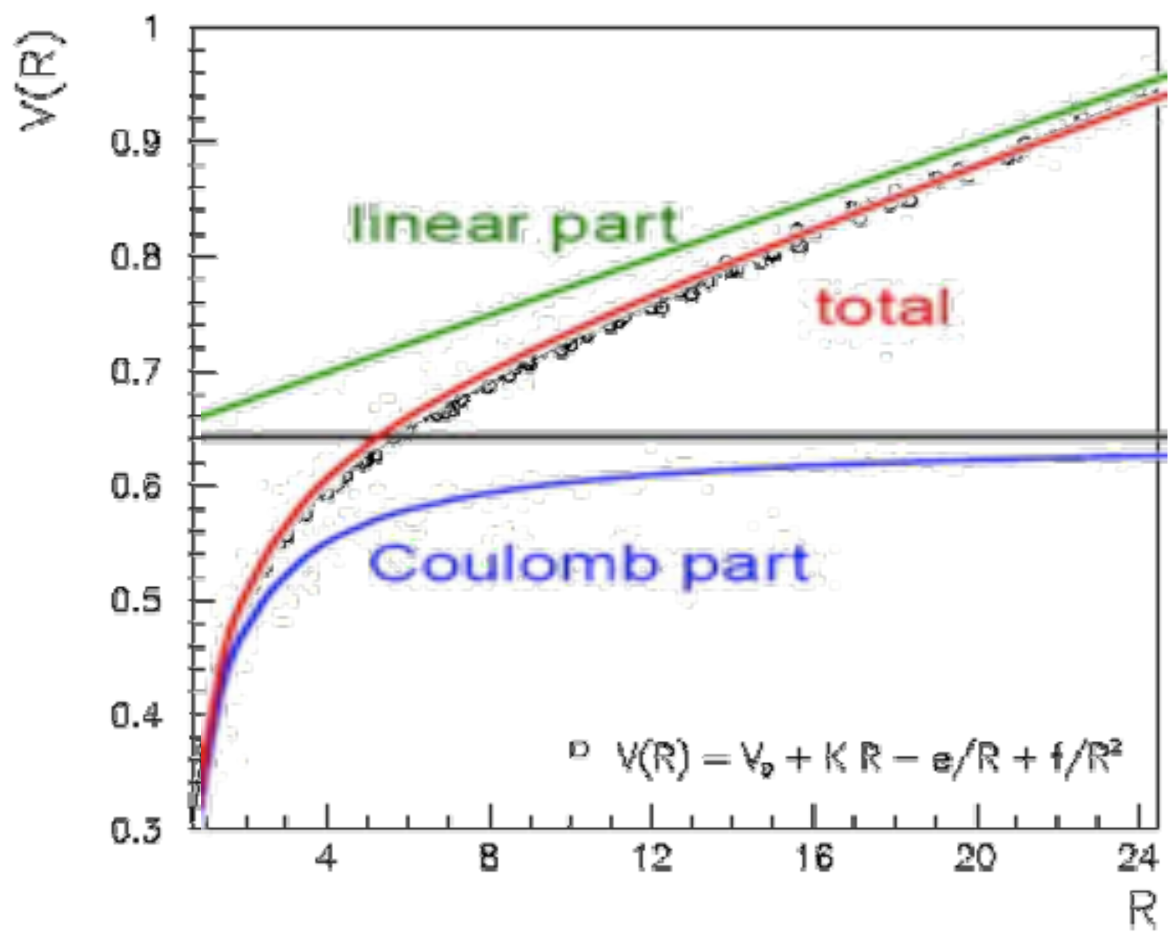


Quarks (and gluons) confined inside hadrons

Short Distances ~ "Coulomb"



Partons



What physical system has a linear potential?

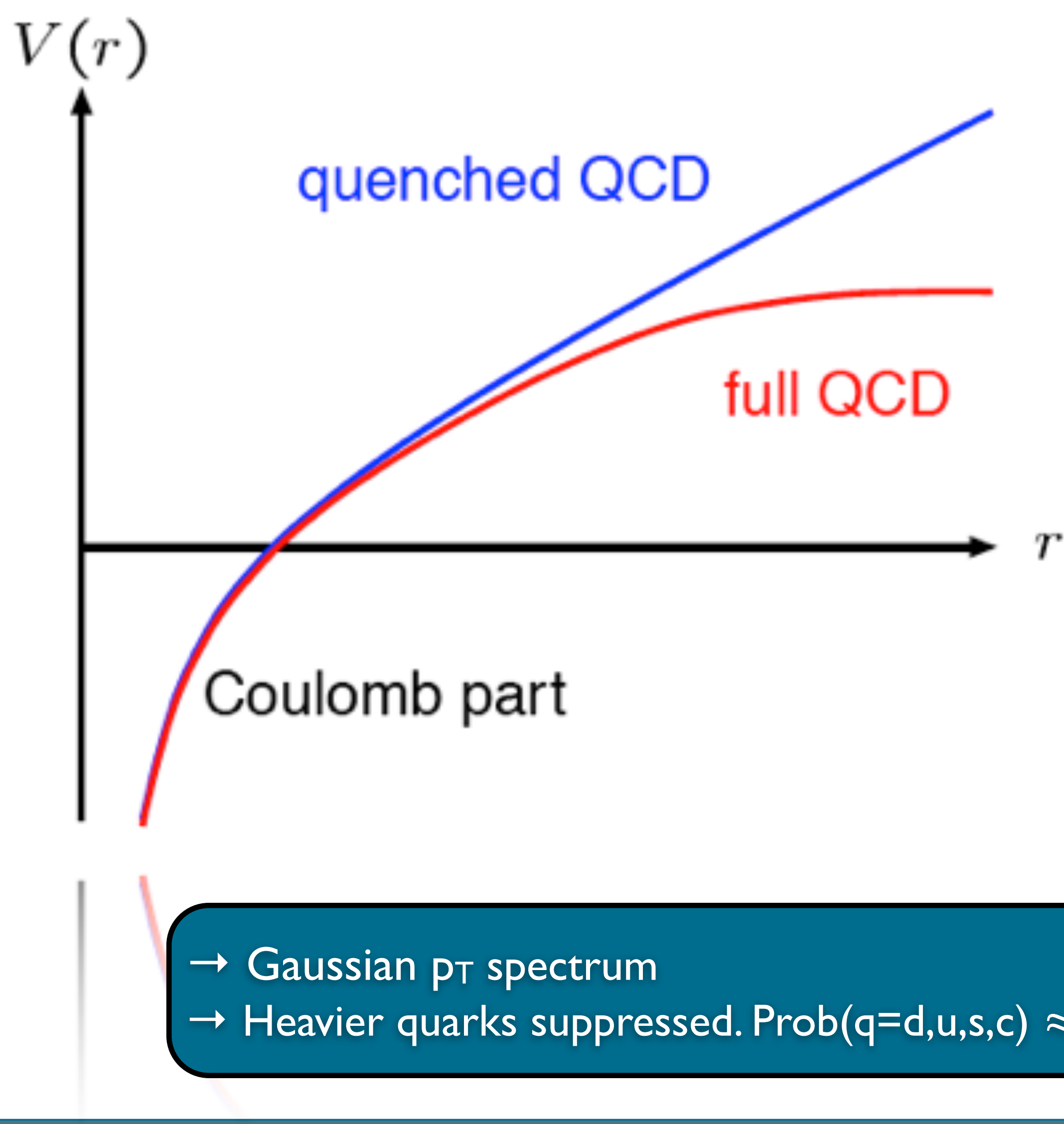
$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$

~ Force required to lift a 16-ton truck

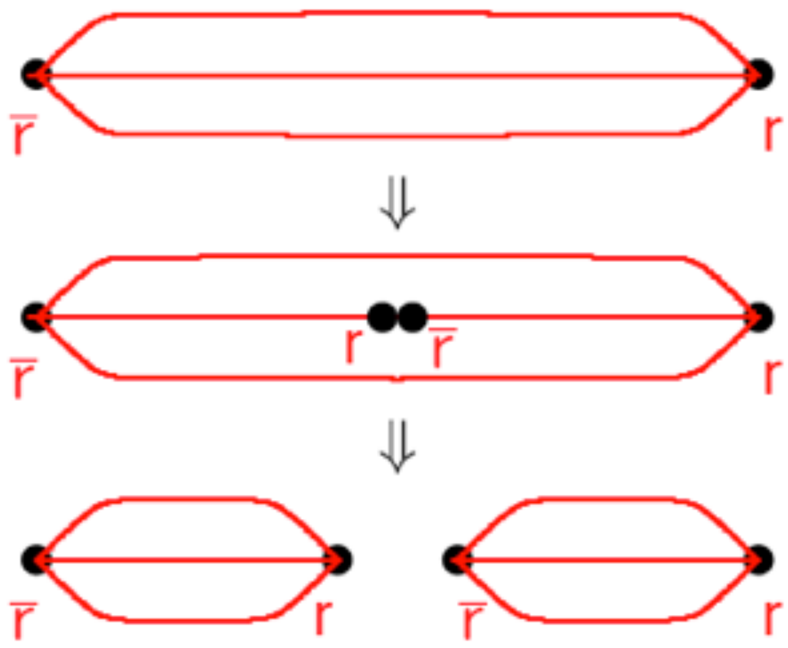
String Breaks

In "unquenched" QCD

g→qq → The strings would break



String Breaks:
via Quantum Tunneling



(simplified colour representation)

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

→ Gaussian p_T spectrum
→ Heavier quarks suppressed. Prob(q=d,u,s,c) ≈ 1 : 1 : 0.2 : 10^{-11}

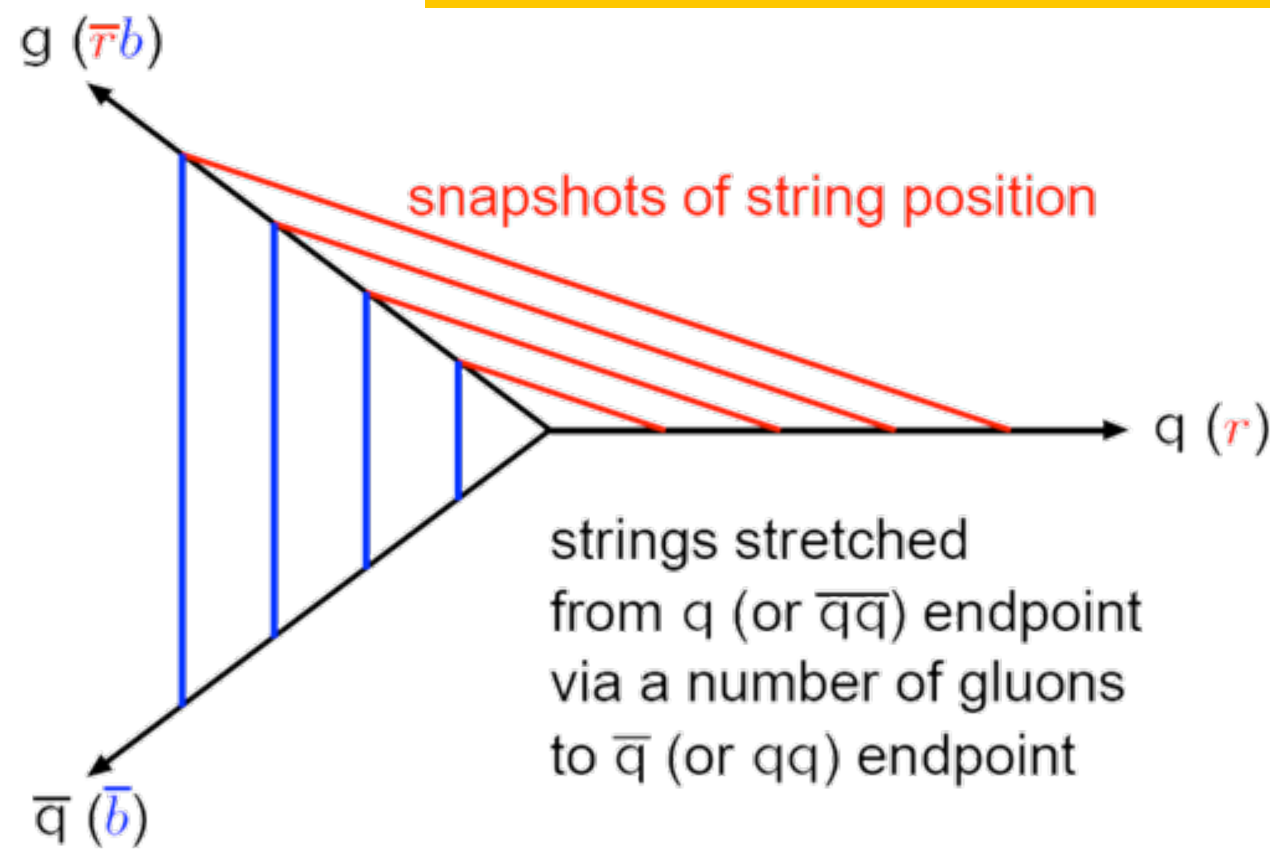
Illustrations by T. Sjöstrand

The (Lund) String Model

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

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**



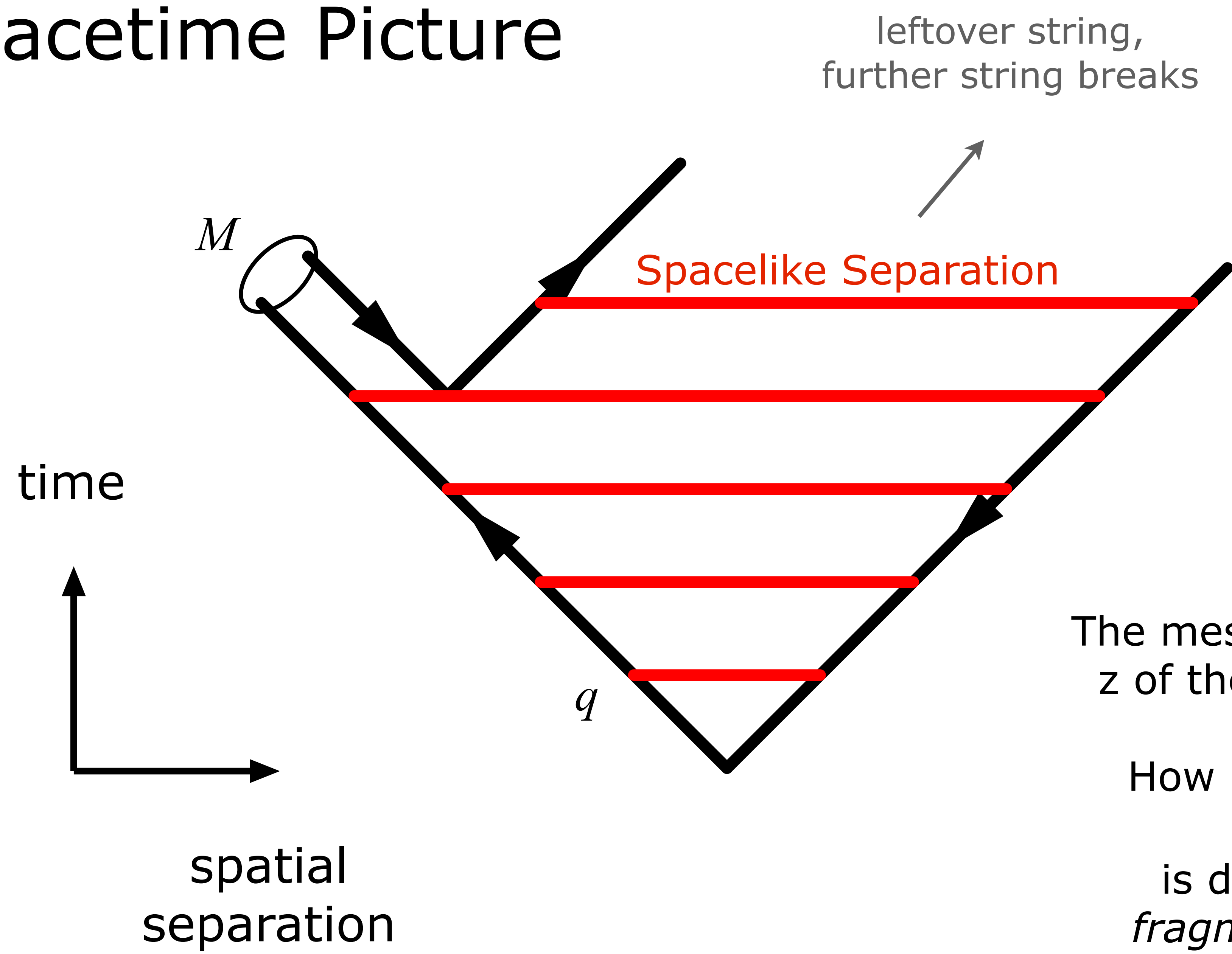
Gluon = kink on string, carrying energy and momentum

Simple space-time picture

Details of string breaks more complicated (e.g., baryons, spin multiplets)

Fragmentation Function

Spacetime Picture



The meson M takes a fraction z of the quark momentum,

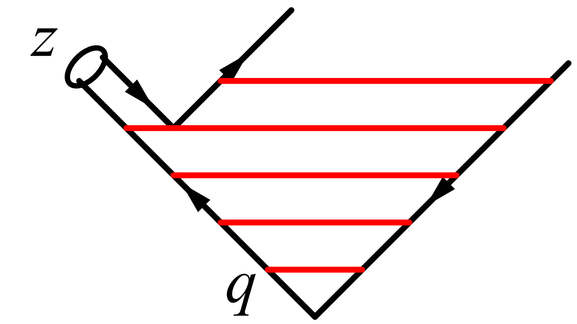
How big that fraction is,
$z \in [0,1]$,
is determined by the *fragmentation function*,
$f(z,Q_0^2)$

Left-Right Symmetry

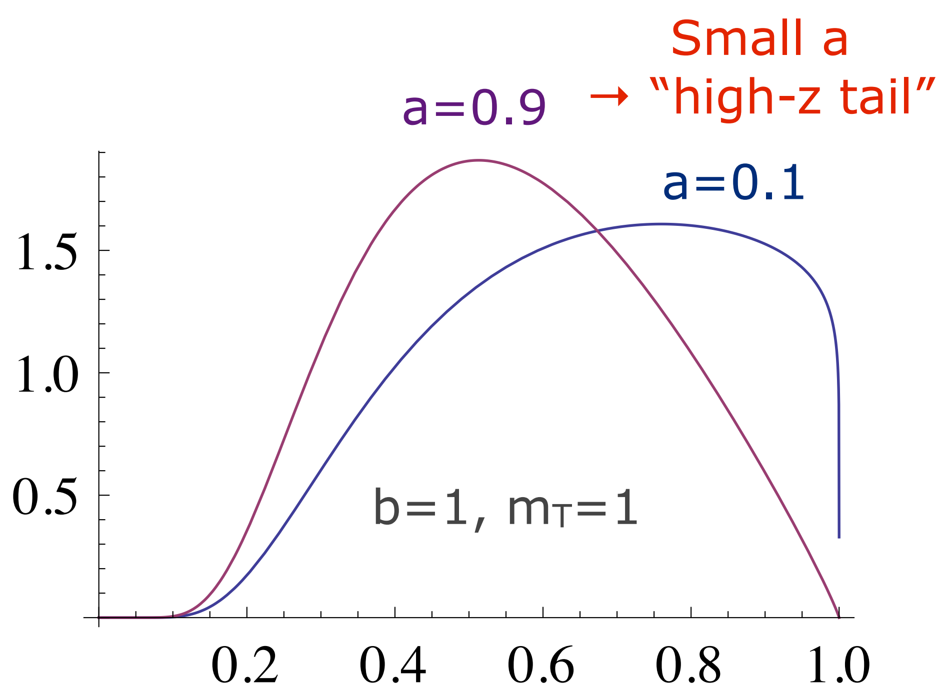
Causality → Left-Right Symmetry

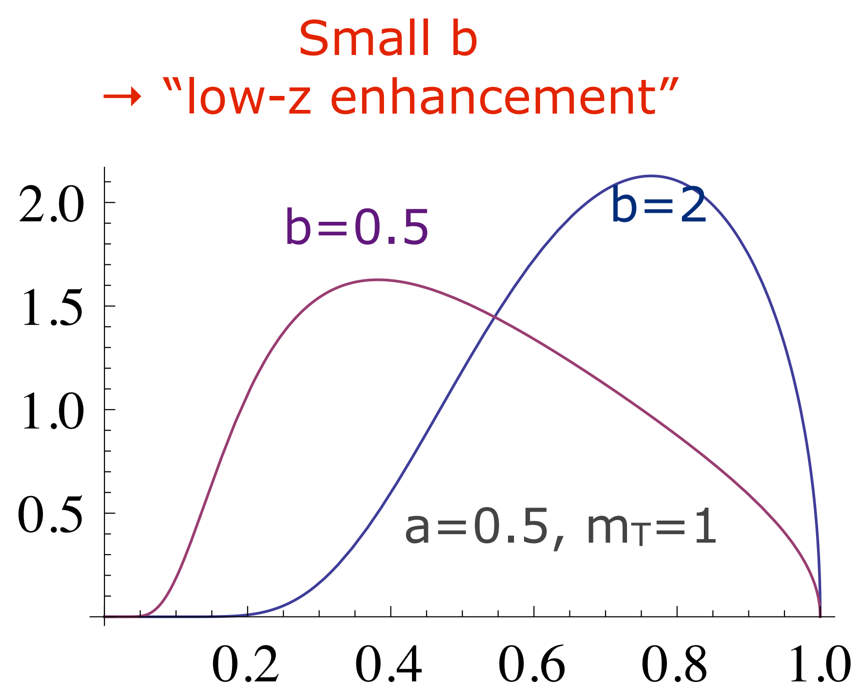
→ Constrains form of fragmentation function!

→ Lund Symmetric Fragmentation Function



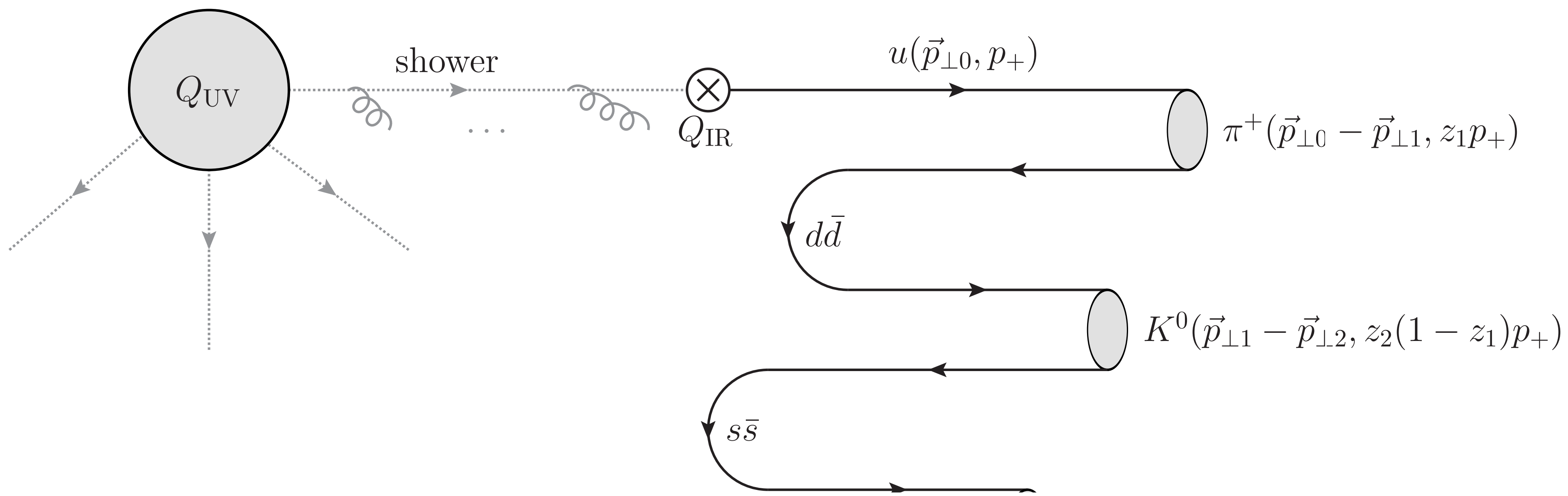
$$f\ z\ \propto \frac{1}{z}\ 1-z\ ^{a}\ \left(-\frac{b\ m_h^2\ \ p_{\perp h}^2}{z}\right)$$



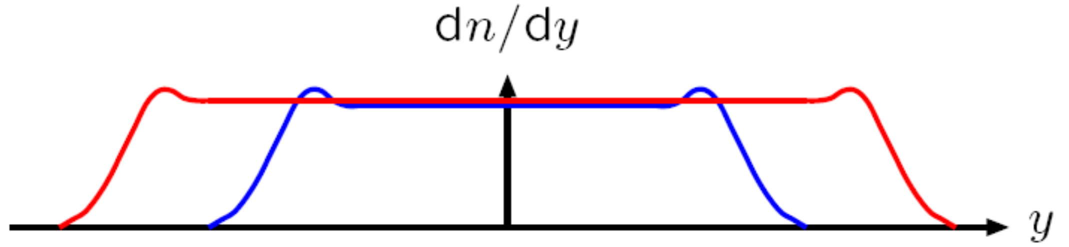


Iterative String Breaks

Causality → May iterate from outside-in



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



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

Illustration by T. Sjöstrand

Alternative: The Cluster Model

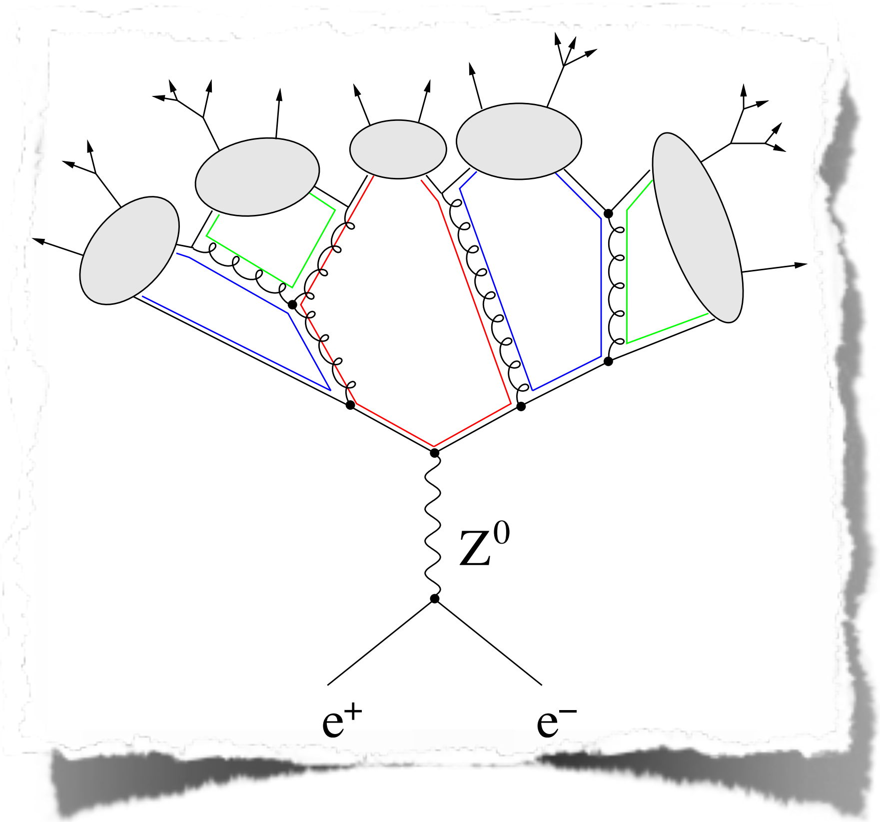
"Preconfinement"

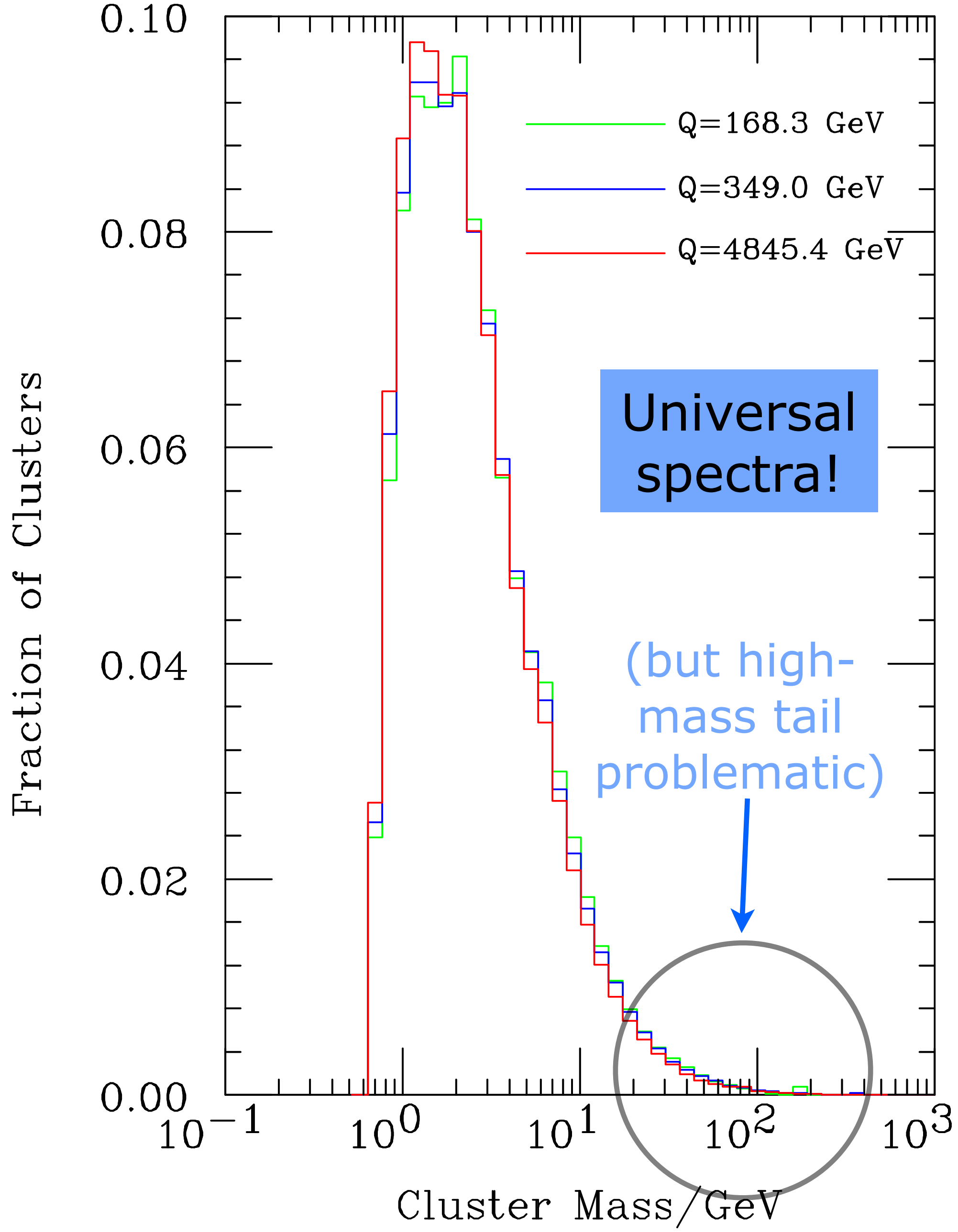
+ Force g→qq splittings at Q_0

→ high-mass q-qbar "clusters"

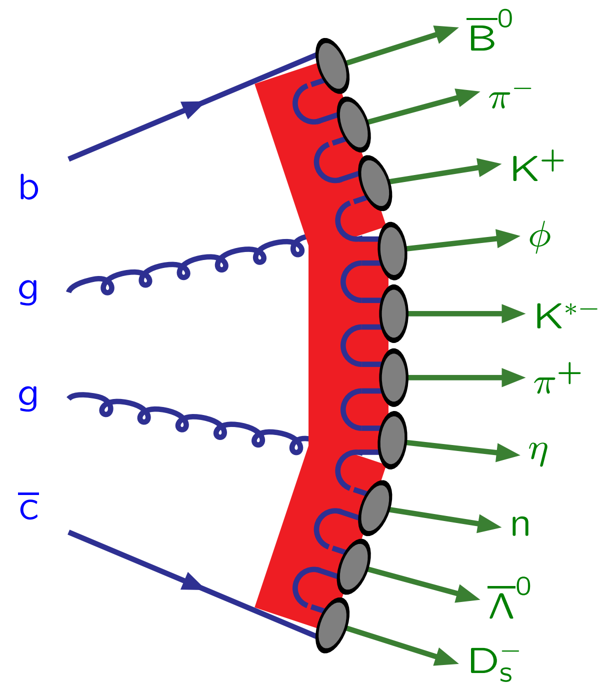
Isotropic 2-body decays to hadrons

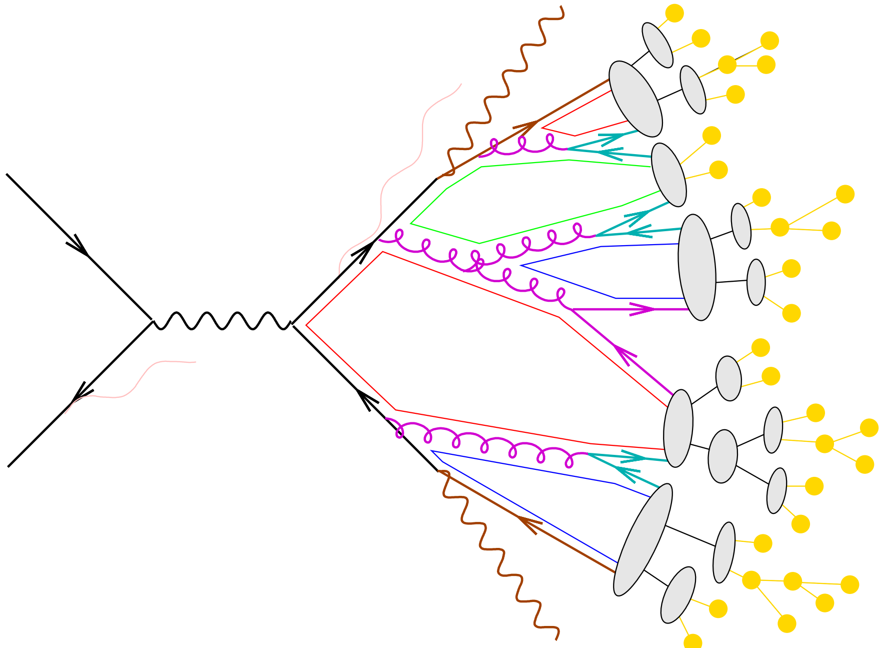
according to PS ≈ $(2s_1+1)(2s_2+1)(p^*/m)$





Strings and Clusters





program	PYTHIA	HERWIG (&SHERPA)
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

Small strings → clusters. Large clusters → strings

Tuning

Theory

Experiment

Adjust this to agree with this

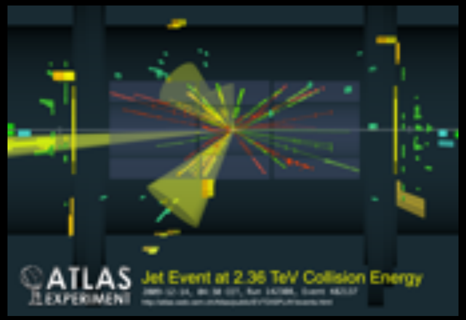
→ Science

In Practice

VINCIA

PYTHIA

...



"Virtual Colliders"
= Simulation Codes

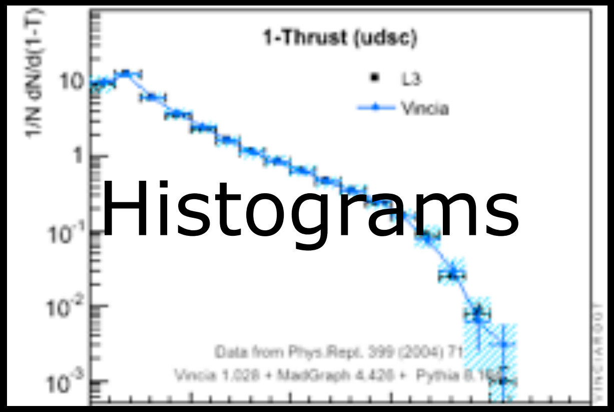
Particle Physics Models, Algorithms, …

→ Simulated Particle Collisions

Real Universe
→ Experiments & Data

Particle Accelerators, Detectors, and Statistical Analyses

→ Published Measurements



What is Tuning?

FSR pQCD Parameters

$\alpha_s(m_Z)$

The value of the strong coupling at the Z pole

Governs overall amount of radiation

α_s Running

Renormalization Scheme and Scale for α_s

1- vs 2-loop running, MSbar / CMW scheme, $\mu_R \sim p_T^2$

Matching

Additional Matrix Elements included?

At tree level / one-loop level? Using what scheme?

Subleading Logs

Ordering variable, coherence treatment, effective $1\rightarrow3$ (or $2\rightarrow4$), recoil strategy, …

Branching Kinematics (z definitions, local vs global momentum conservation), hard parton starting scales / phase-space cutoffs, masses, non-singular terms, …

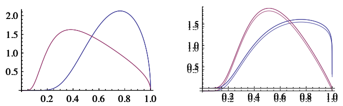
String Tuning

Main IR Parameters

Longitudinal FF = f(z)

Lund Symmetric Fragmentation Function

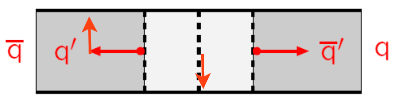
The a and b parameters



pT in string breaks

Scale of string breaking process

IR cutoff and $\langle p_T \rangle$ in string breaks



Meson Multiplets

Mesons

Strangeness suppression, Vector/Pseudoscalar, η, η′, …

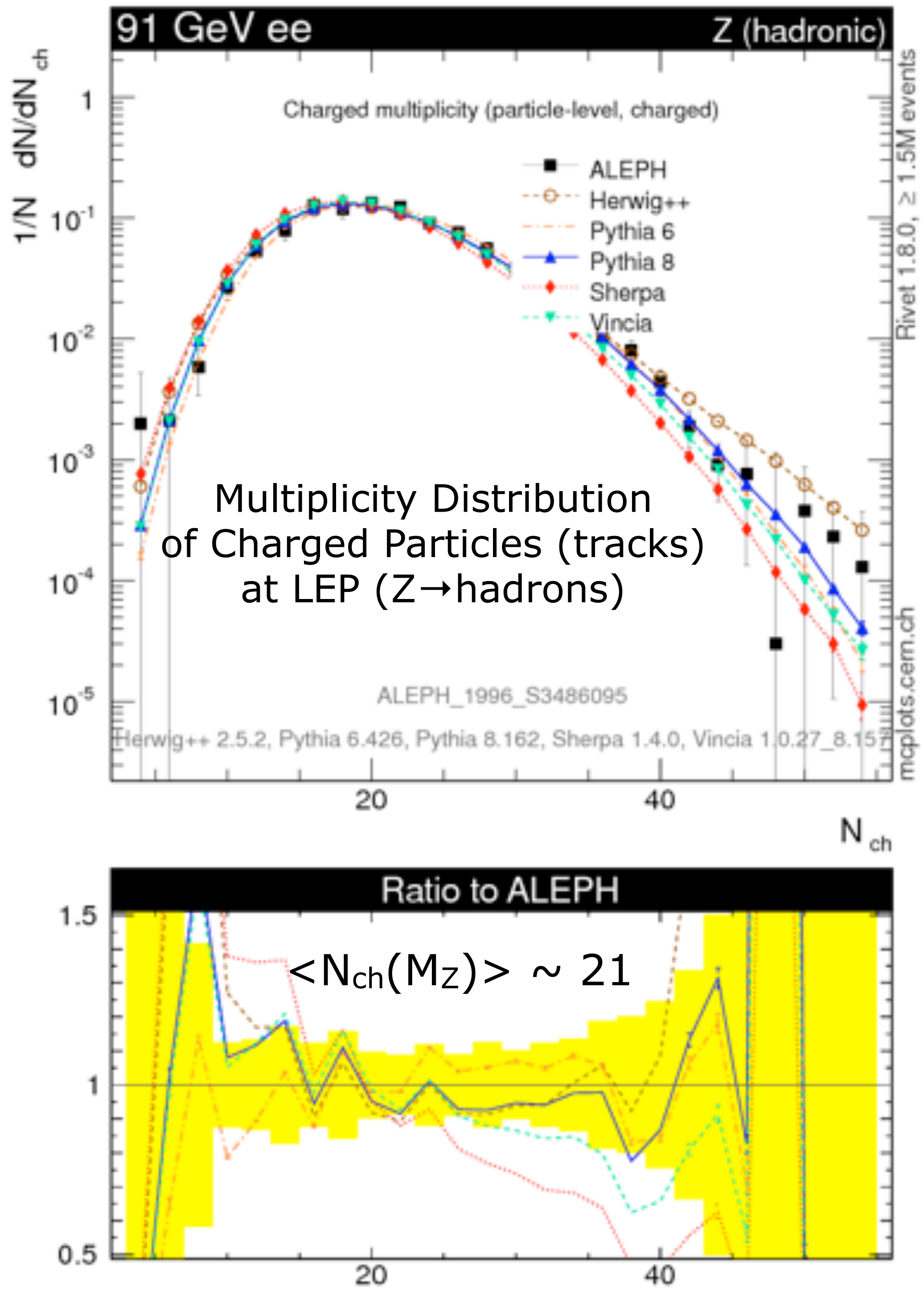
Baryon Multiplets

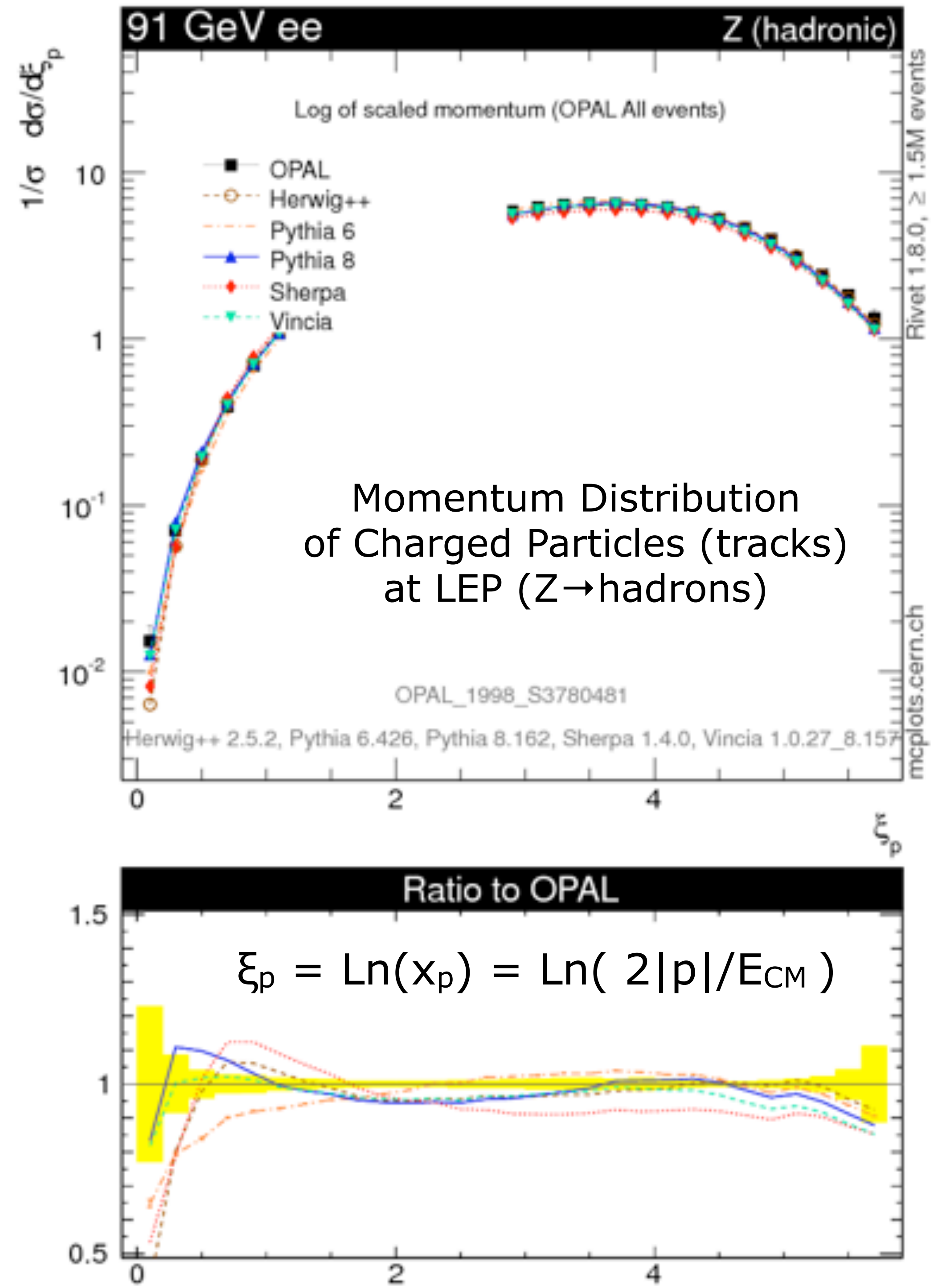
Baryons

Diquarks, Decuplet vs Octet, popcorn, junctions, … ?

Fragmentation Tuning

Note: use infrared-**unsafe** observables - sensitive to hadronization (example)



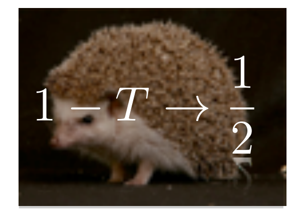


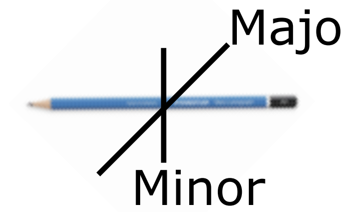
Need IR Corrections?

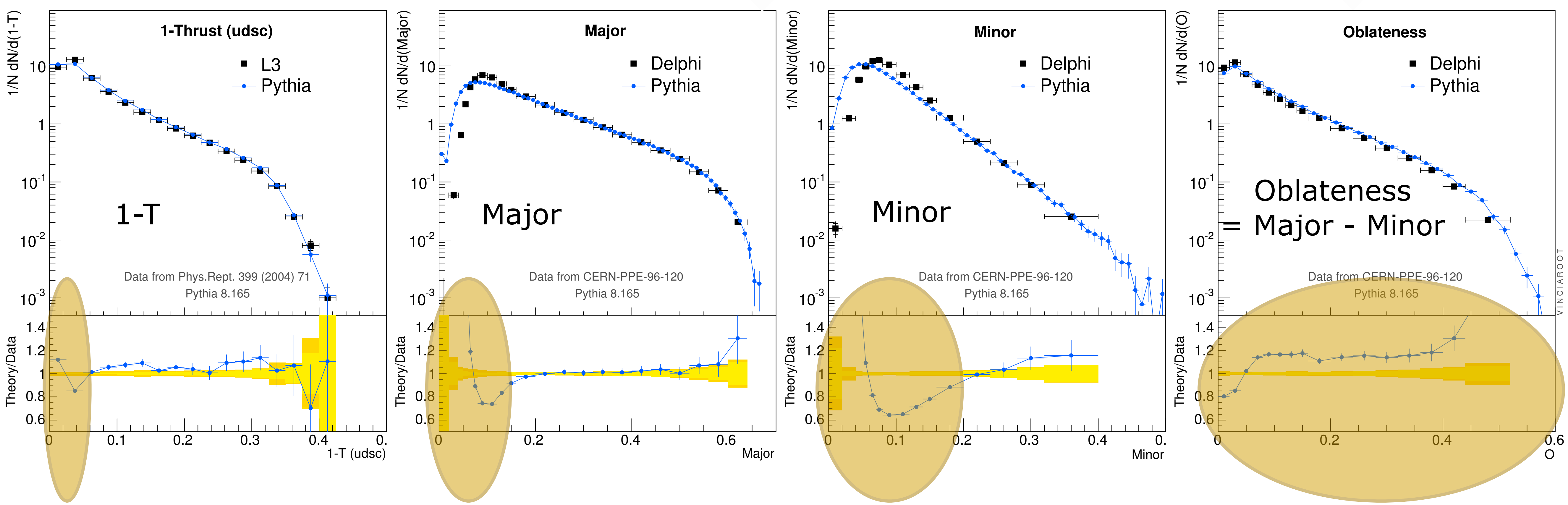
PYTHIA 8 (hadronization off) **vs LEP: Thrust**

$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p_i} \cdot \vec{n}|}{\sum_i |\vec{p_i}|} \right)$$

$1 - T \to 0$







Significant Discrepancies (>10%)

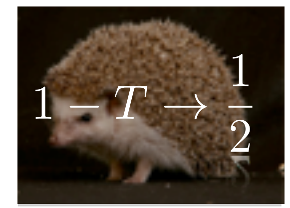
for T < 0.05, Major < 0.15, Minor < 0.2, and for all values of Oblateness

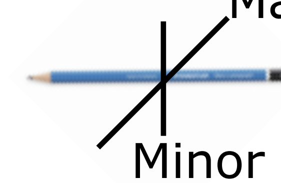
Need IR Corrections?

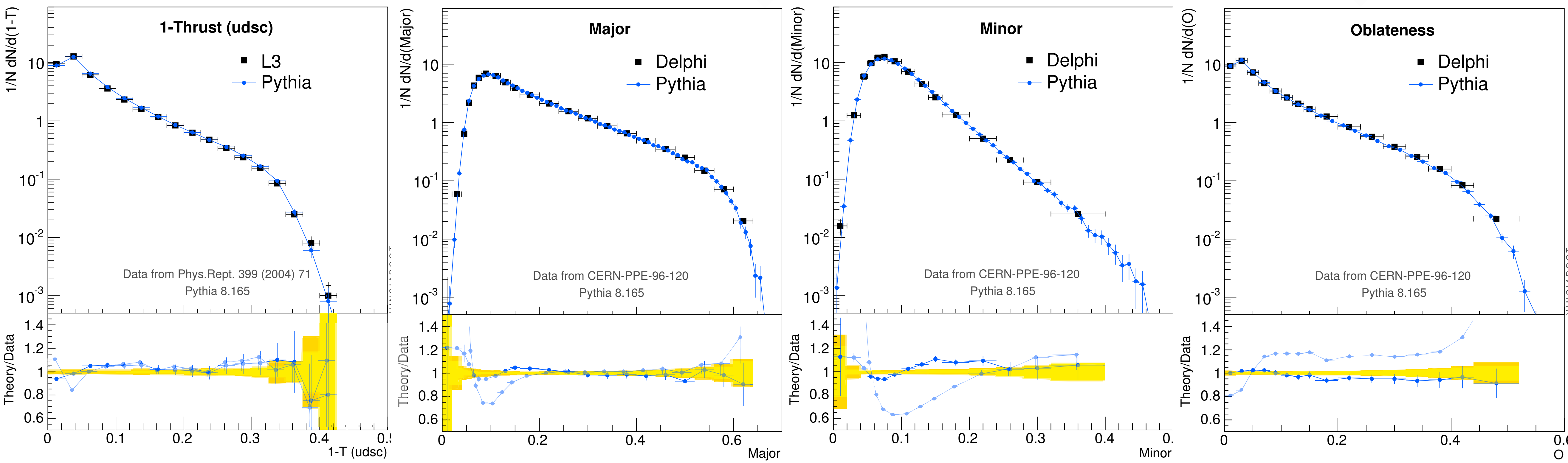
PYTHIA 8 (hadronization on) vs LEP: Thrust

$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p_i} \cdot \vec{n}|}{\sum_i |\vec{p_i}|} \right)$$

$1 - T \to 0$







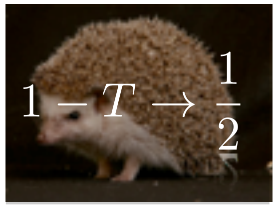
Note: Value of Strong coupling is
$\alpha_s(M_Z) = 0.14$

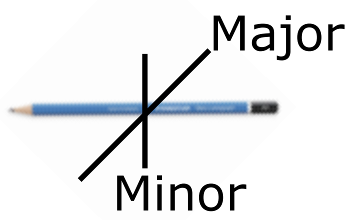
Value of Strong Coupling

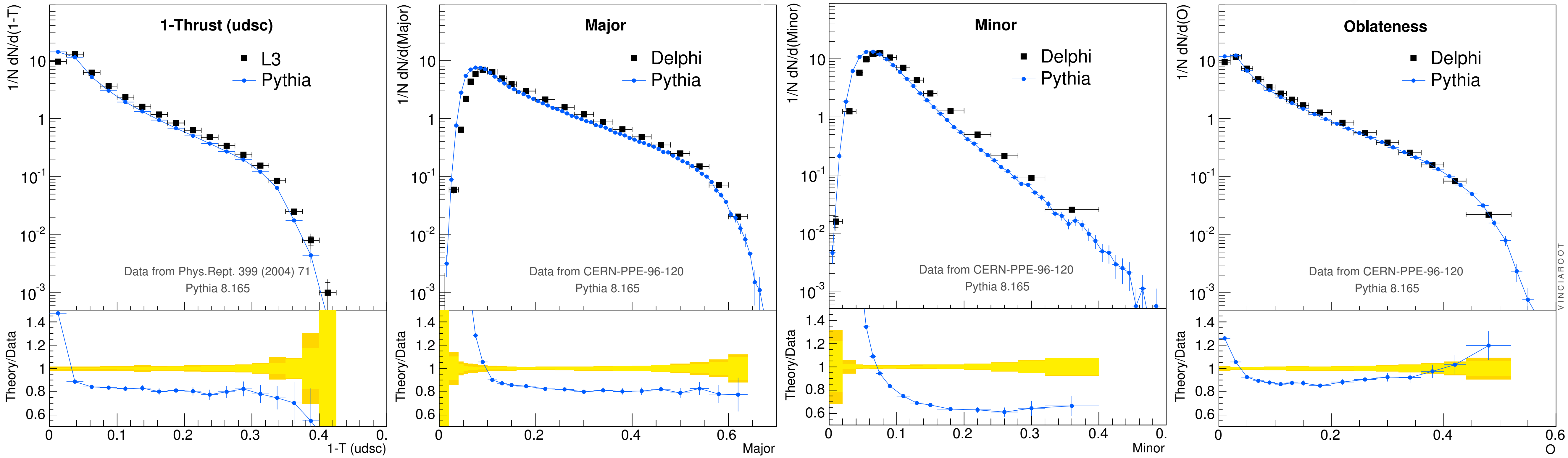
PYTHIA 8 (hadronization on) vs LEP: Thrust

$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p_i} \cdot \vec{n}|}{\sum_i |\vec{p_i}|} \right)$$

$1 - T \to 0$







Note: Value of Strong coupling is
$\alpha_s(M_Z) = 0.12$

Wait … is this Crazy?

Best result

Obtained with $\alpha_s(M_Z) \approx 0.14$

$\neq$ World Average = 0.1176 ± 0.0020

Value of α_s depends on the order and scheme

MC ≈ Leading Order + LL resummation

Other leading-Order extractions of $\alpha_s \approx 0.13 - 0.14$

Effective scheme interpreted as "CMW" → 0.13;

2-loop running → 0.127; NLO → 0.12 ?

Not so crazy

Tune/measure even pQCD parameters with the actual generator.

Sanity check = consistency with other determinations at a similar formal order, within the uncertainty at that order (including a CMW-like scheme redefinition to go to 'MC scheme')

Improve → Matching at LO and NLO

Sneak Preview:

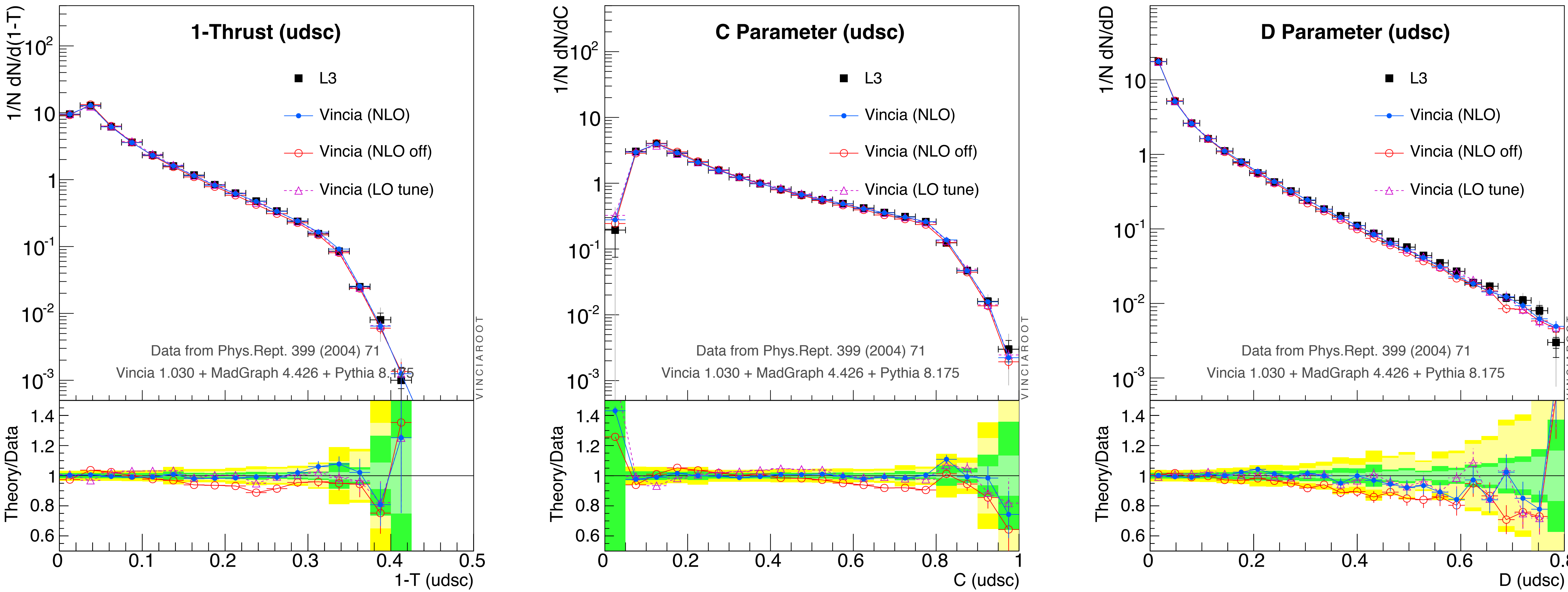
Multijet NLO Corrections with VINCIA

Hartgring, Laenen, Skands, arXiv:1303.4974

First LEP tune with NLO 3-jet corrections

LO tune: $\alpha_s(M_Z) = 0.139$ (1-loop running, MSbar)

NLO tune: $\alpha_s(M_Z) = 0.122$ (2-loop running, CMW)



Summary

Hard Wide-Angle Radiation: Matching

Slicing (Q_{cut}) : MLM, CKKW, CKKW-L

Subtraction (w<0) : MC@NLO

ME Corrections : PYTHIA, POWHEG, VINCIA

Next big steps:

Combining multileg NLO corrections with parton showers
It's perturbation theory = we should be able to solve it. Expect this for next run of LHC.
Improving the intrinsic accuracy of showers? NLL, NLC, … ?

Non-perturbative physics

Is still hard. String model remains best bet, but ~ 30 years old by now. Ripe for a revolution?

Many things omitted:

Random-number theory, Underlying Event, BSM, B Physics, Beam Remnants, Elastic and Diffractive Scattering, Heavy Ions, ...

See also: MCnet Review (long): Phys.Rept. 504 (2011) 145-233 and/or PDG Review on Monte Carlo Event Generators, and/or PS, TASI Lectures (short): arXiv:1207.2389

MCnet Studentships

MCnet projects:

- PYTHIA (+ VINCIA)
- HERWIG
- SHERPA
- MadGraph
- Ariadne (+ DIPSY)
- Cedar (Rivet/Professor)

Activities include

- summer schools (2014: Manchester?)
- short-term studentships
- graduate students
- postdocs
- meetings (open/closed)

Monte Carlo

training studentships

3-6 month fully funded studentships for current PhD students at one of the MCnet nodes. An excellent opportunity to really understand and improve the Monte Carlos you use!

Application rounds every 3 months.

MCnet

funded by: MARIE CURIE ACTIONS

for details go to:
www.montecarlonet.org

Come to Australia

p

p

Establishing a new group in **Melbourne**

Working on **PYTHIA** & **VINCIA**

NLO Event Generators

Precision LHC **phenomenology & soft physics**

Support LHC **experiments**, **astro-particle** community, and **future** accelerators

Outreach and Citizen Science

ANCORA · IMPARO

Oct 2014
→ Monash University
Melbourne, Australia

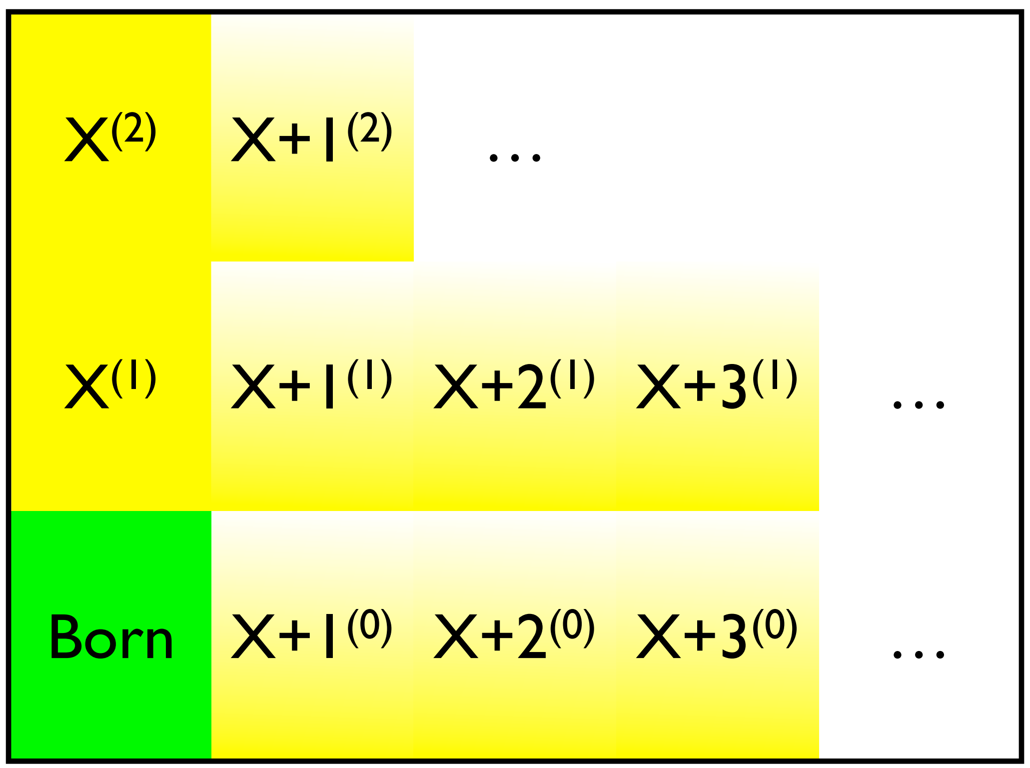
Slicing

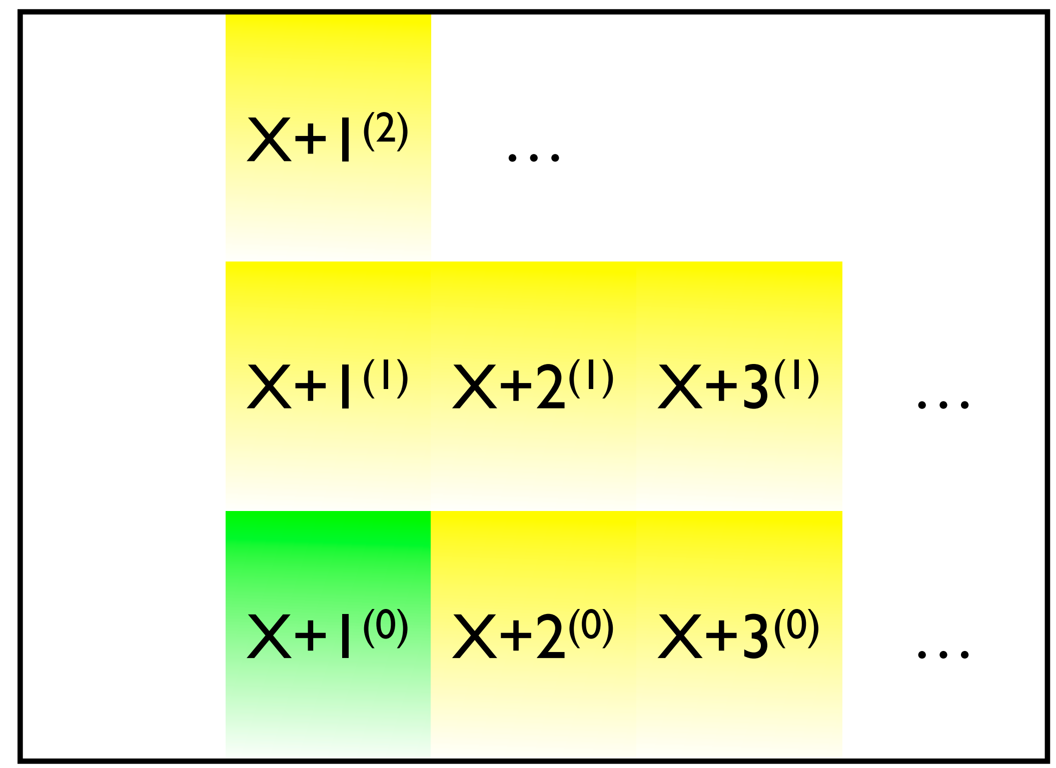
Examples: MLM, CKKW, CKKW-L

LO$_0$ × **PS**$_{(pT>pTcut)}$ + **LO$_1$**$_{(pT1>pTcut)}$ × **PS**$_{(pT<pT1)}$

Std: veto shower above some p_{Tcut}

Highest n: veto shower above p_{Tn}





… Fixed-Order Matrix Element

… Shower Approximation

… Fixed-Order ME above p_T cut & nothing below

Illustrations from: PS, TASI Lectures, arXiv:1207.2389

Slicing

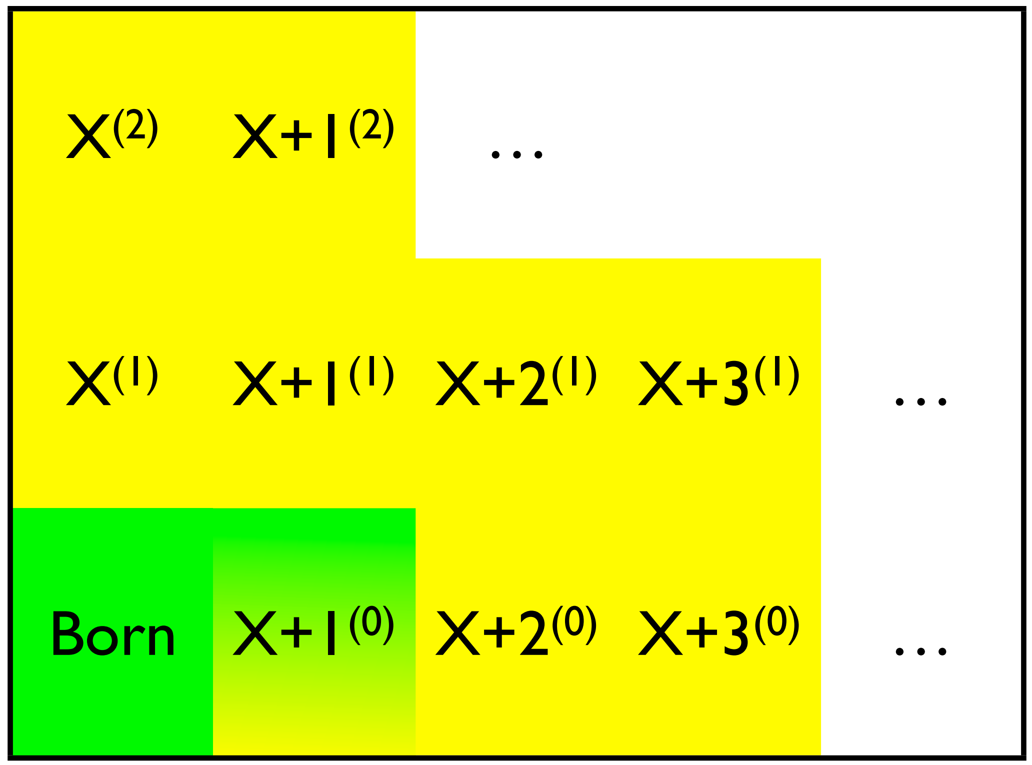
Examples: MLM, CKKW, CKKW-L

$\mathbf{LO_0} \times \mathbf{PS}_{(pT>pTcut)}$ + $\mathbf{LO_1}_{(pT1>pTcut)} \times \mathbf{PS}_{(pT<pT1)}$

Std: veto shower above p_{Tcut}

Highest n: veto shower above p_{Tn}

X+1 now LO correct for hard radiation and still LL correct for soft



+ Generalizes to arbitrary numbers of jets (at LO)

Much work on extensions to NLO

... Fixed-Order Matrix Element

... Shower Approximation

... Fixed-Order ME above p_T cut & nothing below

... Fixed-Order ME above p_T cut & Shower Approximation below

Illustrations from: PS, TASI Lectures, arXiv:1207.2389