Aspen Winter Conference 2009 – The Year of the Ox

(towards)

Theoretical Understanding of Quantum Chromodynamics at Hadron Colliders

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Overview

Disclaimer: gory details not possible in 25 mins!

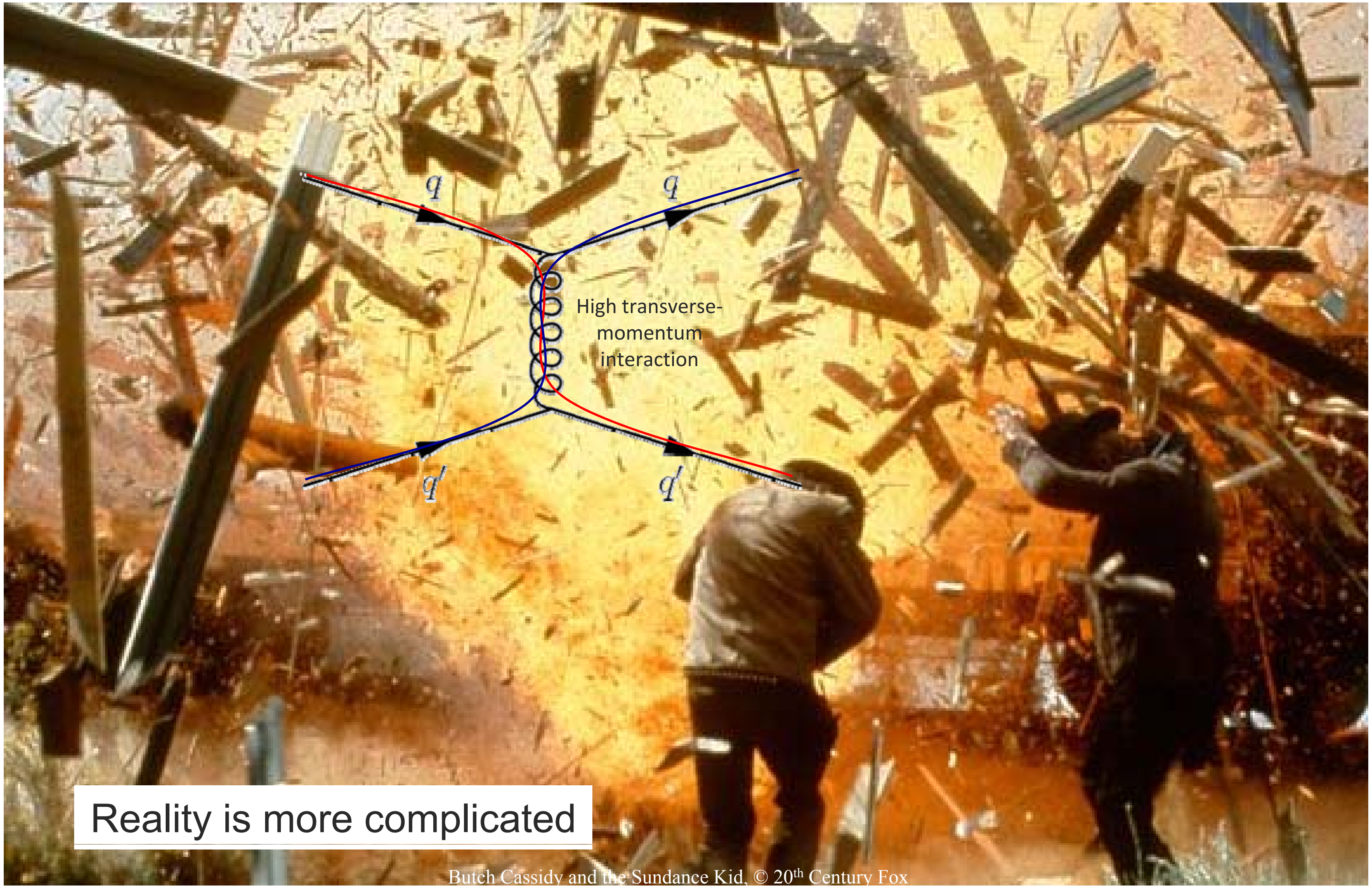
► Calculating Collider Observables

- Three Ways to High Precision

► The Road to High Precision for Everyone

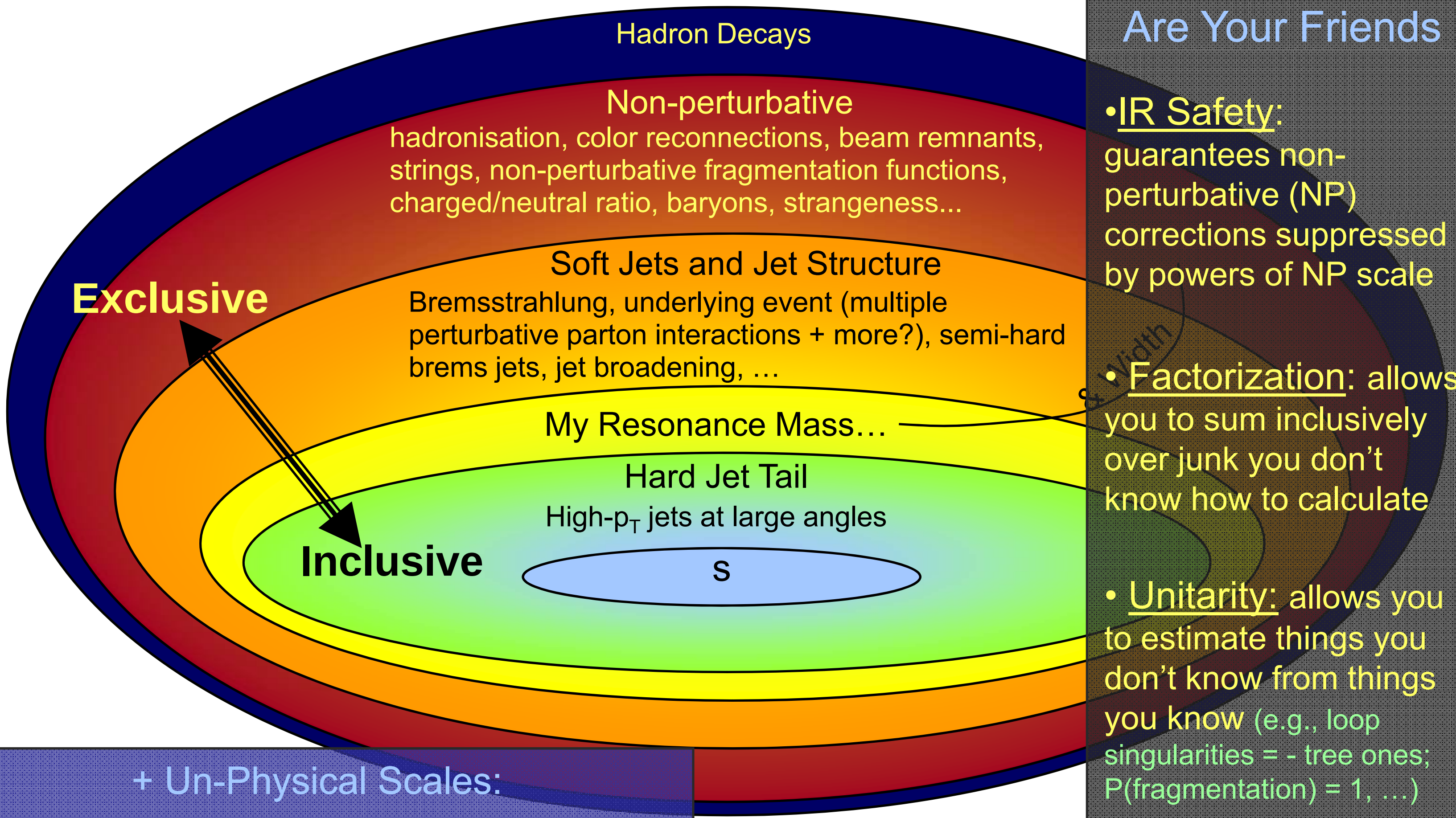
- What we want
  - High precision: model constraints + window to higher scales
- What we got
- How to get what we want
  - No alternative: **solve QCD**

Calculating Collider Observables



Factorization, Infrared Safety, and Unitarity

- ► Not the title of a book you'd read?



These Things Are Your Friends

- **IR Safety**: guarantees non-perturbative (NP) corrections suppressed by powers of NP scale
- **Factorization**: allows you to sum inclusively over junk you don't know how to calculate
- **Unitarity:** allows you to estimate things you don't know from things you know (e.g., loop singularities = - tree ones; P(fragmentation) = 1, …)

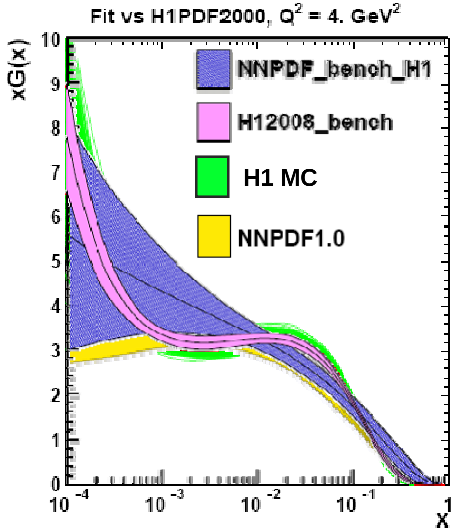
+ Un-Physical Scales:

- Q_F , Q_R : Factorization(s) & Renormalization(s)
- Q_E : Evolution(s)

The Way of the Chicken

► Who needs QCD? I'll use leptons

- Sum inclusively over all QCD
  - Leptons almost IR safe by definition
  - WIMP-type DM, Z', EWSB → may get some leptons
- Beams = hadrons for next decade (RHIC / Tevatron / LHC)
  - At least need **well-understood PDFs**
  - High precision = **higher orders** → enter QCD
- Isolation → indirect sensitivity to dirt
- Fakes → indirect sensitivity to dirt
- Not everything gives leptons
  - Need to be a lucky chicken …



Summary of Hera-LHC Workshop: Parton Distributions
Ball et al; Feltesse, Glazov, Radescu; 0901.2504 [hep-ph]

► The unlucky chicken

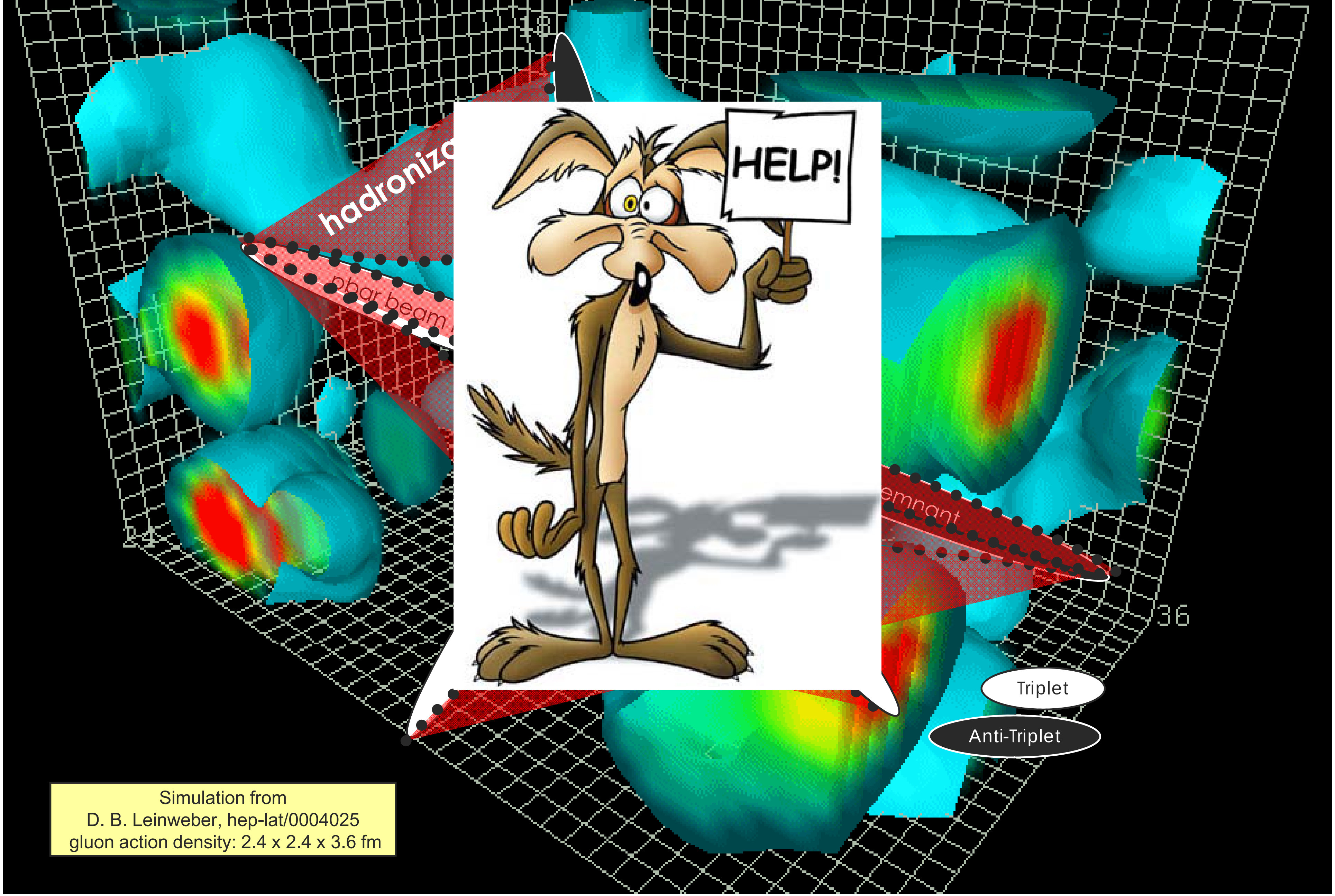
- Put all its eggs in one basket and didn't solve QCD

The Way of the Fox

▶ I'll use semi-inclusive observables

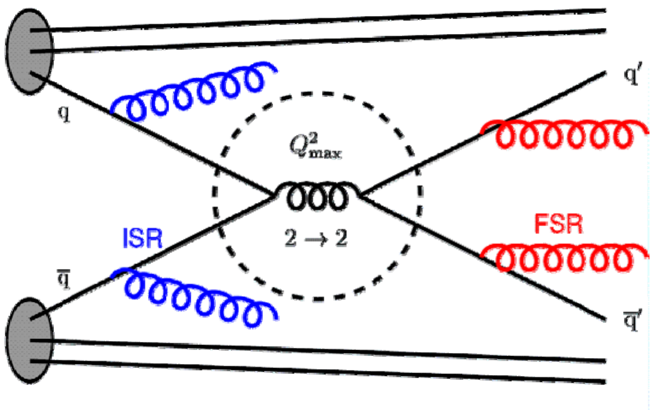
- Sum inclusively over the worst parts of QCD
  - Still need to be friends with IR safety → **jet algs**
  - **FASTJET** Cacciari, Salam, Soyez: JHEP 0804(2008)063
    Cone → "anti-kT" ~ IR safe cone
- Beams = hadrons for next decade (RHIC / Tevatron / LHC)
  - Still need **well-understood PDFs**
  - High precision = **more higher orders → more QCD**
- Large hierarchies (s, m_1, m_2, p_{Tjet1}, p_{Tjet2}, …) → Careful !
  - **Huge enhancements** caused by leaps towards classical limit
  - Perturbative series "blows up" → cannot truncate at any fixed order
  - For 600 GeV particles, **a 100 GeV jet can be "soft"** ← Alwall, de Visscher, Maltoni: JHEP 0902(2009)017
  - Use infinite-order **approximations** = parton showers
    - Only "LL" → not highly precise + only good when **everything** is hierarchical
    - Need to combine with explicit matrix elements → **matching** (more later)
    - Still, non-factorizable + non-pert corrections set an **ultimate** limit

Now Hadronize This



Simulation from
D. B. Leinweber, hep-lat/0004025
gluon action density: 2.4 x 2.4 x 3.6 fm

The Way of the Ox



- ► Calculate Everything: **solve QCD** → requires compromise
  - Improve Born-level perturbation theory, by including the 'most significant' corrections → complete events → any observable you want

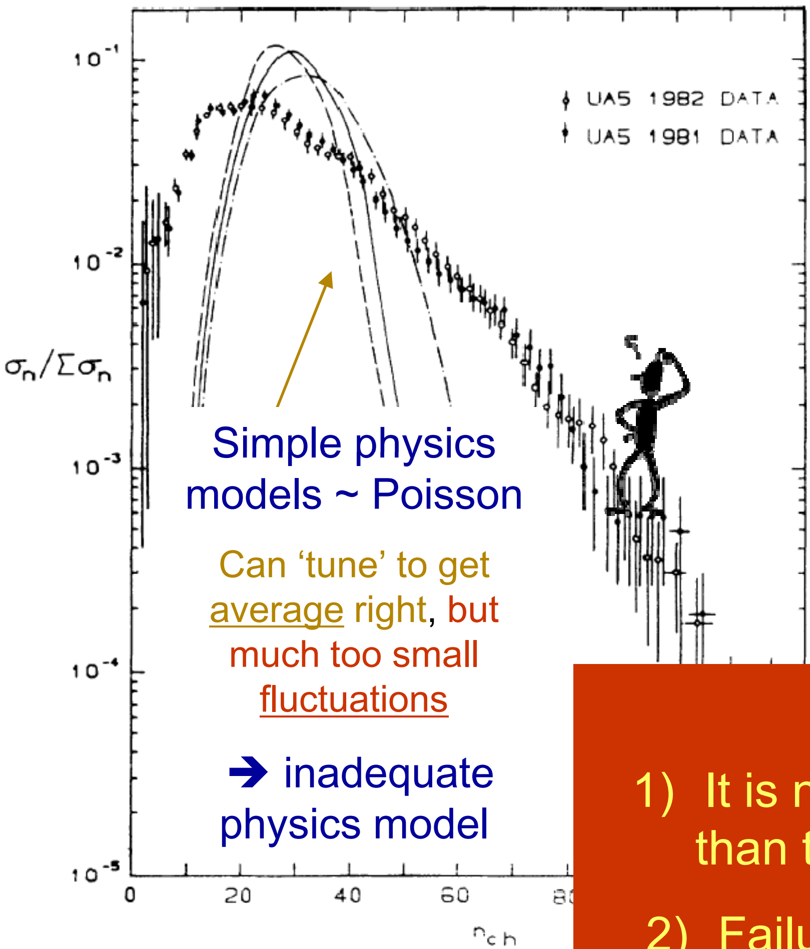
1. Parton Showers		*1. Soft/Collinear Logarithms*
2. Matching	roughly	*2. Finite Terms, "K"-factors*
3. Hadronisation		*3. Power Corrections (more if not IR safe)*
4. The Underlying Event		*4. ?*

(+ many other ingredients: resonance decays, beam remnants, Bose-Einstein, …)

Asking for complete events is a tall order …

Classic Example: Number of tracks

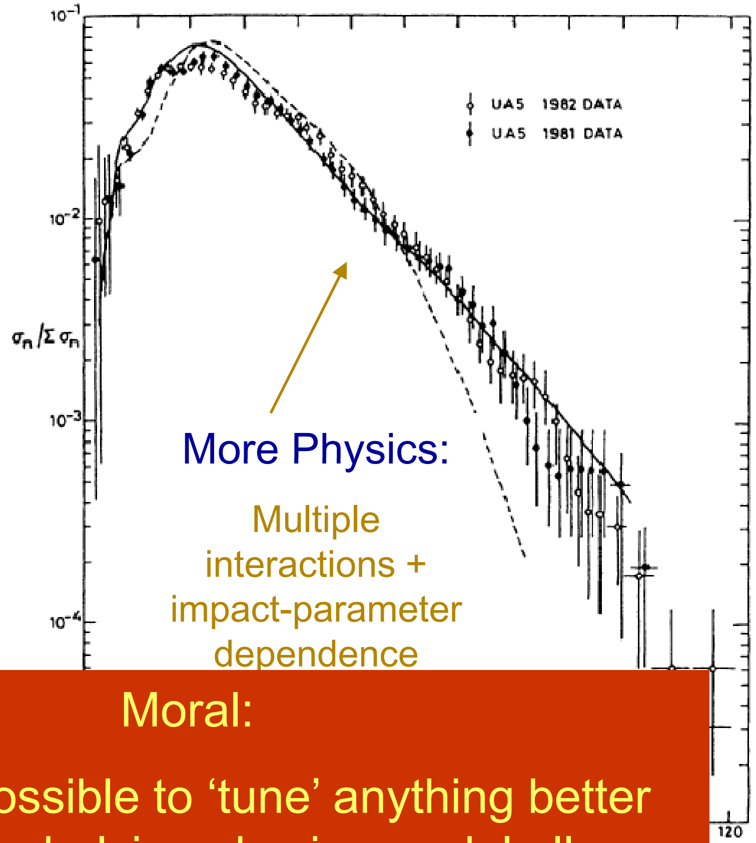
UA5 @ 540 GeV, single pp, charged multiplicity in minimum-bias events



Simple physics models ~ Poisson

Can 'tune' to get average right, but much too small fluctuations

➔ inadequate physics model



More Physics:

Multiple interactions + impact-parameter dependence

FIG. 3. Charged-multiplicity distributio
results (Ref. 32) vs simple models: dashed l
cluding hard scatterings, dash-dotted also in
final-state radiation.

eV, UA5
riable im-
tribution;

Moral:

1) It is not possible to 'tune' anything better than the underlying physics model allows
2) Failure of a physically motivated model usually points to more physics (interesting)
3) Failure of a fit not as interesting

What We Want & What We Got

PS: Parton Shower (LL)
LL: Leading Log (∞ order)
LO: Leading Order

► Generate Events, Evaluate Observables

- SM benchmarks: **(N)NLO**
  - **Mostly: K×LO + LO** jets up to matched order + PS jets
  - [MC@NLO, POWHEG: **NLO** + PS jets (no further matching)]
- SM + jets, BSM (+ jets): **(N)LO**
  - **Generic** NLO/NNLO matching now being discussed
  - Lavesson, Lönnblad: JHEP 0812(2008)070
  - Giele, Kosower, PS: PRD78(2008)014026
- NLL resummations of multiple emissions
  - LL showers with array of "NLL effects"
  - NLLJET: e^+e^-: Kato and Munehisa, CPC64(1991)67
- Theory of the Underlying Event (will return to later)
  - Phenomenological Models
  - Multiple Parton Interactions
- Systematically improvable non-perturbative models
  - (Includes non-perturbative BSM, e.g., hidden-valley)
  - Phenomenological Models
  - Non-interacting Clusters ↔ Strings
- Complete Evaluation of Remaining Uncertainties
  - Monte Carlos with Uncertainty Bands
  - "Herwig ÷ Pythia" (+ MAX/MIN)

The Matching Game

- ► $[X]_{ME}$ + shower **already** contains $\text{sing}_{LL}\{\,[X + n\text{ jet}]_{ME}\,\}$
  - So we really just missed some finite bits, not the entire ME!
  - Adding full $[X + n\text{ jet}]_{ME}$ = overkill➔ LL singular terms would be double-counted

Solution 1: **“Additive” (most widespread)**

Seymour, CPC90(1995)95
+ many more recent …

- Work out the difference and correct by *that amount*
- ➔ add compensating $[X + n\text{ jet}]_{ME}$ events, with double-counting subtracted out

$$w_n = [X + n\text{ jet}]_{ME} - \text{Shower}\{w_{n-1,2,3,..}\}$$

  - **WITH phase space cuts (“matching scale”): Herwig, CKKW, MLM, ARIADNE**
  - **WITHOUT phase space cuts: MC@NLO (but only 1 jet + has negative weights)**

Solution 2: **“Multiplicative”**

Sjöstrand, Bengtsson : Nuc Phys B289(1987)810; PLB185(1987)435
+ one or two more recent …

- Work out the ratio between PS and ME ➔ multiply PS by that ratio (< 1 if PS > ME)

$$P_n = [X + n\text{ jet}]_{ME} \,/\, \text{Shower}\{[X+n-1\text{ jet}]_{ME}\}$$

- Positive weights, auto-unweighting, no matching scale, exponentiates, **idiot proof**
  - **At LO: Pythia (only 1 jet but has positive weights)**
  - **At NLO: POWHEG (only 1 jet but has positive weights)**
  - **VINCIA/GeNeVa: generalized to multijets, now aiming for NNLO (+ NLL) (+ uncertainty bands)**

NLO with Addition

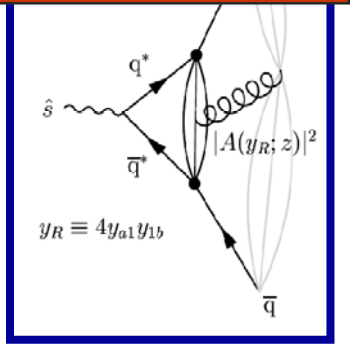
Multiplication at this order
➔ α, β = 0 (POWHEG)

- First Order Shower expansion

PS

$$\int \mathrm{d}\Phi_2\, |M_2^{(0)}|^2 \int_{Q^2_{\rm had}}^{s} \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2}\, A_{q\bar{q}}(\ldots)\, \delta\left(\mathcal{O} - \mathcal{O}(\{p\}_3)\right)$$

Unitarity of shower ➔ 3-parton real = ÷ 2-parton "virtual"



- 3-parton real correction ($A_3 = |M_3|^2/|M_2|^2$ + finite terms; α, β)

$$w_3^{(R)} = |M_3^{(0)}|^2 - \left(A_3^0(\ldots) + \frac{4\pi\alpha_s \hat{C}_F}{s}\left(\alpha + \beta\frac{s_{ar}+s_{rb}}{s}\right)\right)|M_2^{(0)}|^2$$

$$= -\frac{4\pi\alpha_s \hat{C}_F}{s}\left(\alpha + \beta\frac{s_{ar}+s_{rb}}{s}\right)|M_2^{(0)}|^2 \quad \Rightarrow$$

Finite terms cancel in 3-parton O

- 2-parton virtual correction (same example)

$$w_2^{(V)} = 2\mathrm{Re}\left[M_2^{(1)} M_2^{(0)*}\right] + |M_2^{(0)}|^2 \int_0^s \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2} A_{q\bar{q}}(\ldots) + \int_0^{Q^2_{\rm had}} \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2}\, w_3^{(R)}$$

$$= \frac{\alpha_s \hat{C}_F}{2\pi}\left(2I^{(1)}_{q\bar{q}}(\epsilon,s) - 4 - 2I^{(1)}_{q\bar{q}}(\epsilon,s) + \frac{19 + \alpha + \frac{2}{3}\beta}{4}\right)|M_2^{(0)}|^2$$

$$= \frac{\alpha_s}{\pi}\left(1 + \frac{1}{3}\left(\alpha + \frac{2}{3}\beta\right)\right)|M_2^{(0)}|^2 \quad \Rightarrow$$

Finite terms cancel in 2-parton O (normalization)

Controlling the Calculation

- In a matched shower calculation, there are many dependencies on things not traditionally found in matrix-element calculations:

- The final answer will depend on:
  - The choice of shower evolution "time"
  - The splitting functions (finite terms not fixed)
  - The phase space map ("recoils", $d\Phi_{n+1}/d\Phi_n$)
  - The renormalization scheme (vertex-by-vertex argument of α_s)
  - The infrared cutoff contour (hadronization cutoff)
  - Matching prescription and matching scales

Variations →	Matching to MEs (& N^nLL?) →
Comprehensive uncertainty estimates	Reduced Dependence
(showers with uncertainty bands)	(systematic reduction of uncertainty)

VINCIA

VIRTUAL NUMERICAL COLLIDER WITH INTERLEAVED ANTENNAE

Gustafson, PLB175(1986)453; Lönnblad (ARIADNE), CPC71(1992)15.
Azimov, Dokshitzer, Khoze, Troyan, PLB165B(1985)147
Kosower PRD57(1998)5410; Campbell,Cullen,Glover EPJC9(1999)245

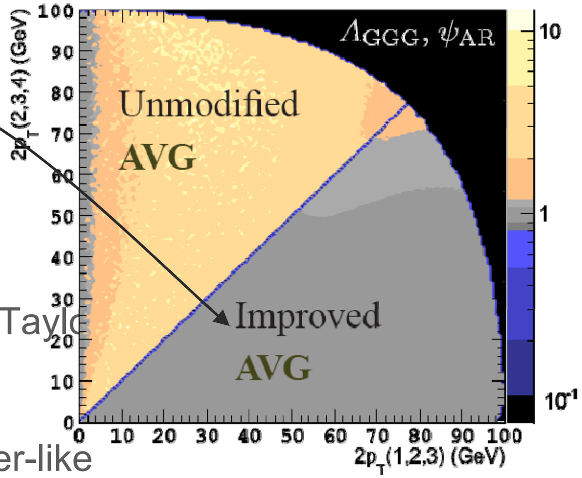
► Based on Dipole-Antennae

- Shower off color-connected pairs of partons
- Plug-in to PYTHIA 8 (C++)

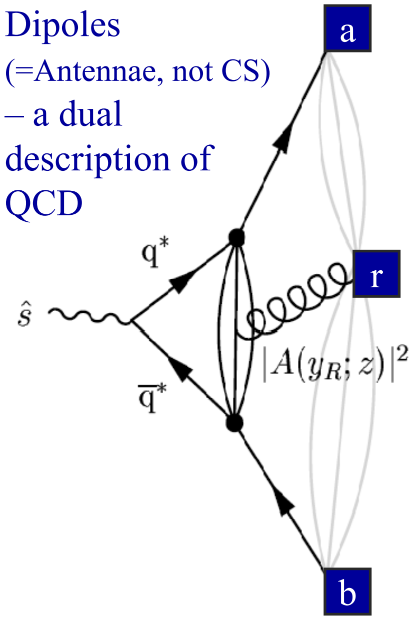
► So far:

- Choice of evolution time:
  - pT-ordering
  - Dipole-mass-ordering
  - Thrust-ordering
- Splitting functions
  - QCD + arbitrary finite terms (Taylo
- Phase space map
  - Antenna-like or Parton-shower-like
- Renormalization scheme (μ_R = {evolution scale, p_T, s, 2-loop, …})
- Infrared cutoff contour (hadronization cutoff)
  - Same options as for evolution time, but independent of time → universal choice

Comparison of pure shower to **second-order** matrix elements



Dipoles (=Antennae, not CS) – a dual description of QCD

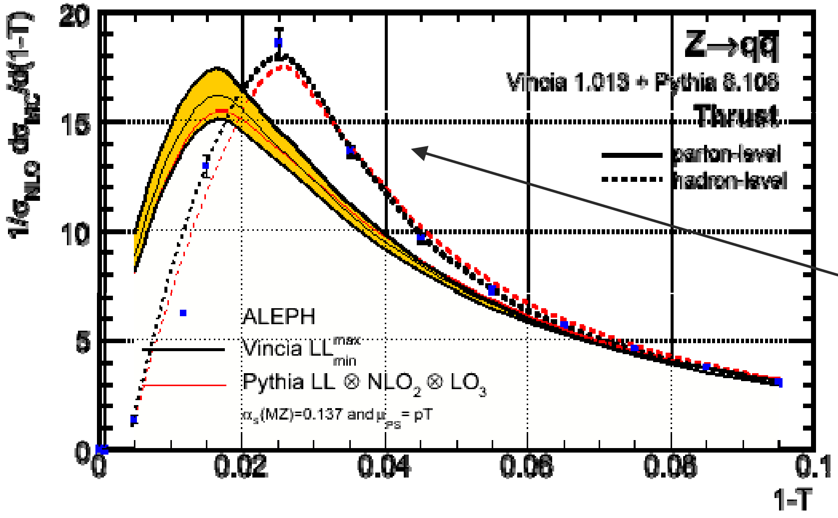


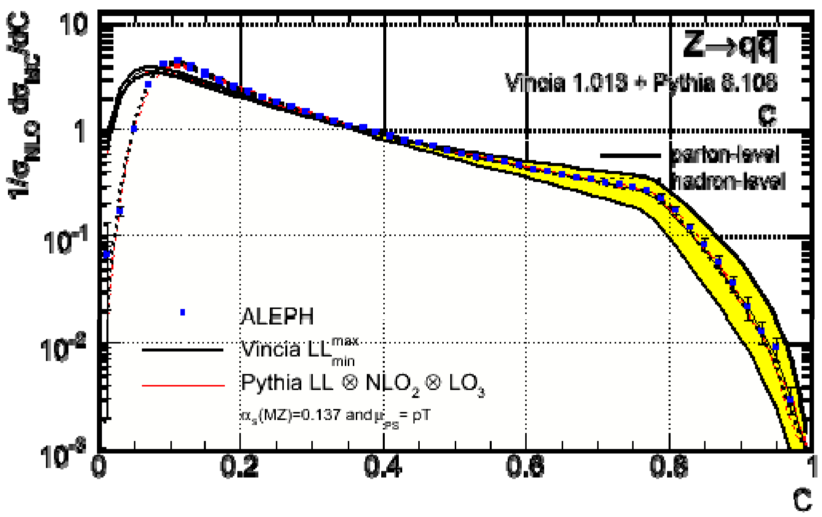
PS: ask about Dokshitzer-Marchesini, please … ☺

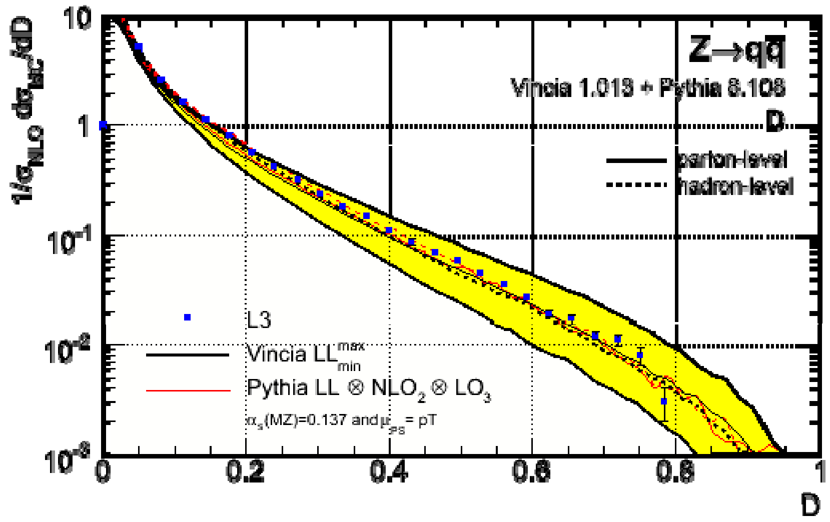
Giele, Kosower, PS: PRD78(2008)014026 + Les Houches 'NLM' 2007

VINCIA in Action

VIRTUAL NUMERICAL COLLIDER WITH INTERLEAVED ANTENNAE







- Can vary
  - evolution variable, kinematics maps, radiation functions, renormalization choice, matching strategy (here just varying splitting functions)
- At Pure LL,
  - can definitely see a non-perturbative correction, but hard to precisely constrain it

Giele, Kosower, PS : PRD78(2008)014026 + Les Houches ‘NLM’ 2007

VINCIA in Action

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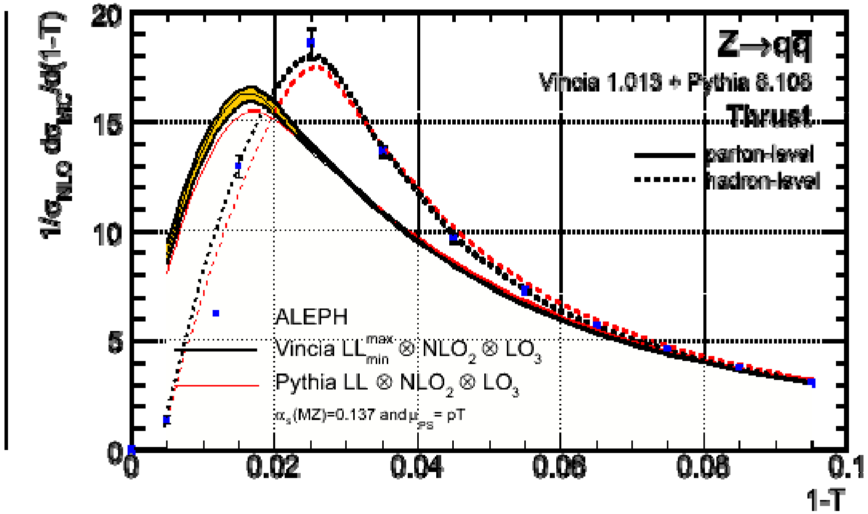

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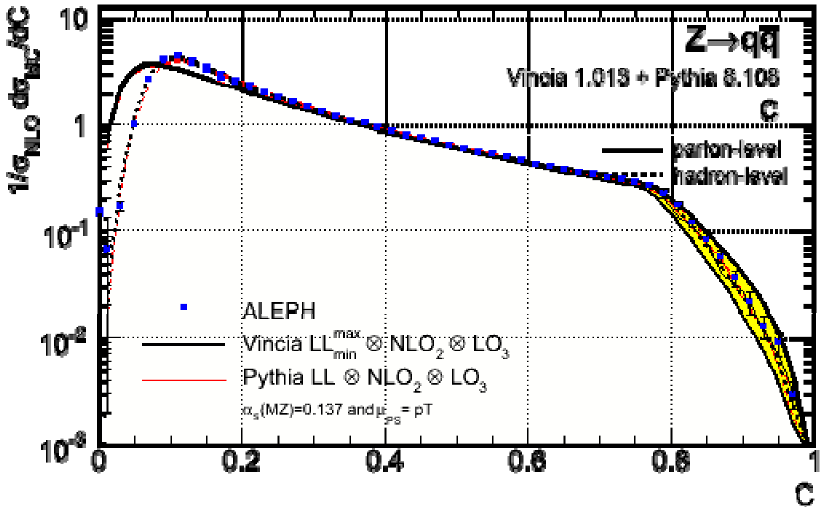

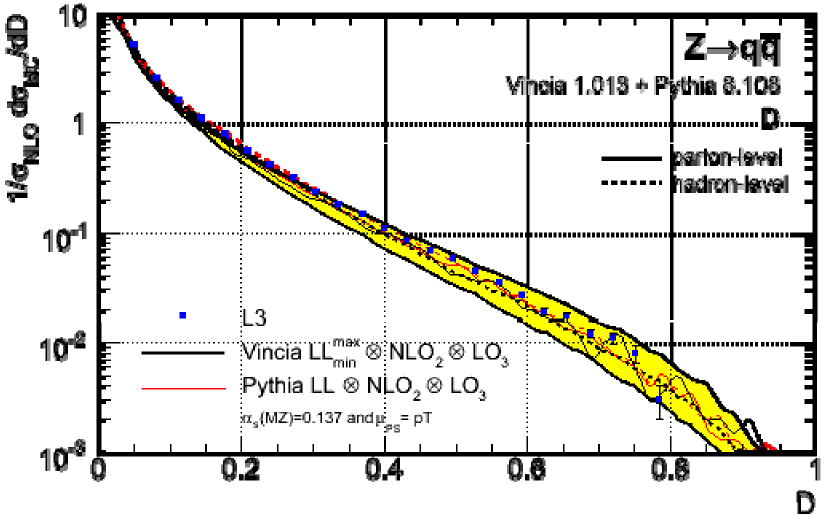

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VINCIA in Action

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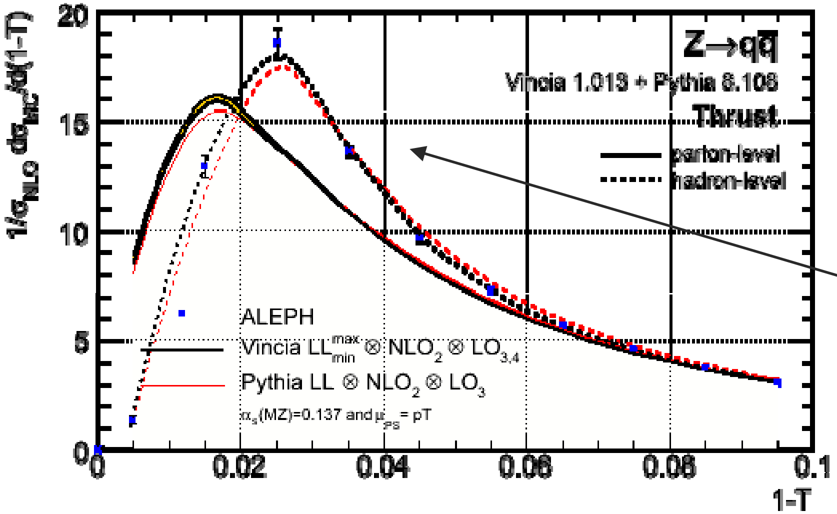
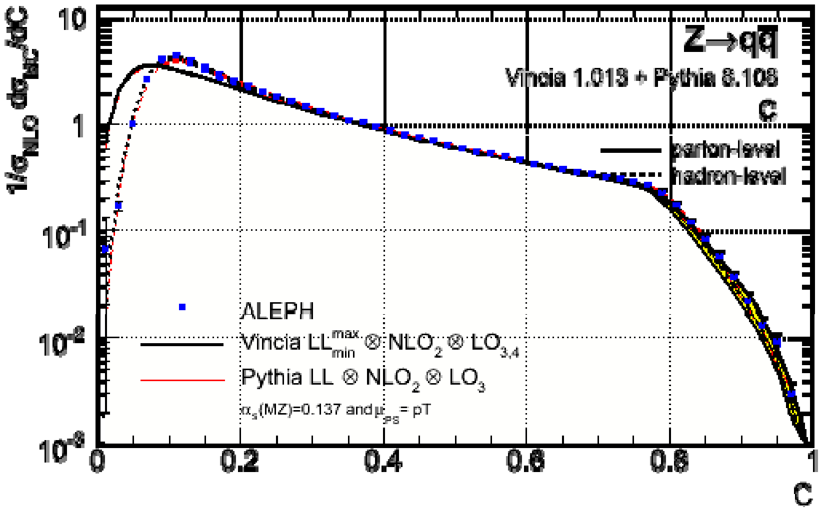
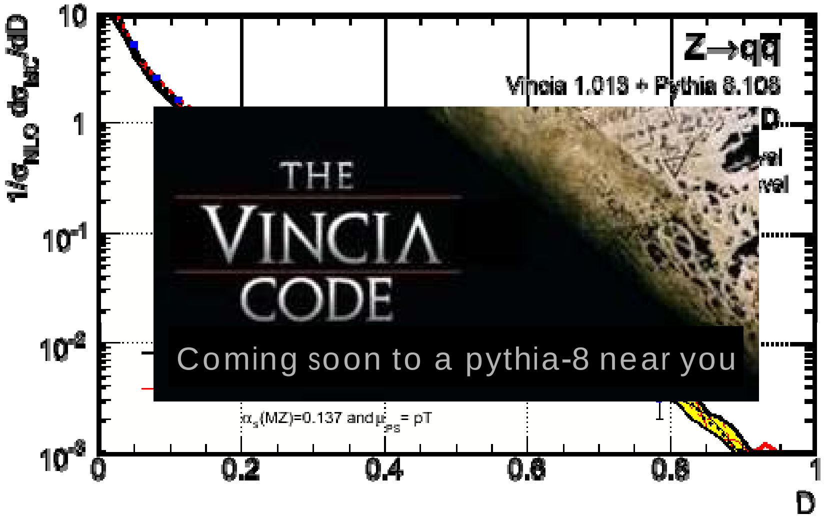


- ▶ Can vary
  - evolution variable, kinematics maps, radiation functions, renormalization choice, matching strategy (here just varying splitting functions)
- ▶ After 2nd order matching
  - ➔ Non-pert part can be precisely constrained.

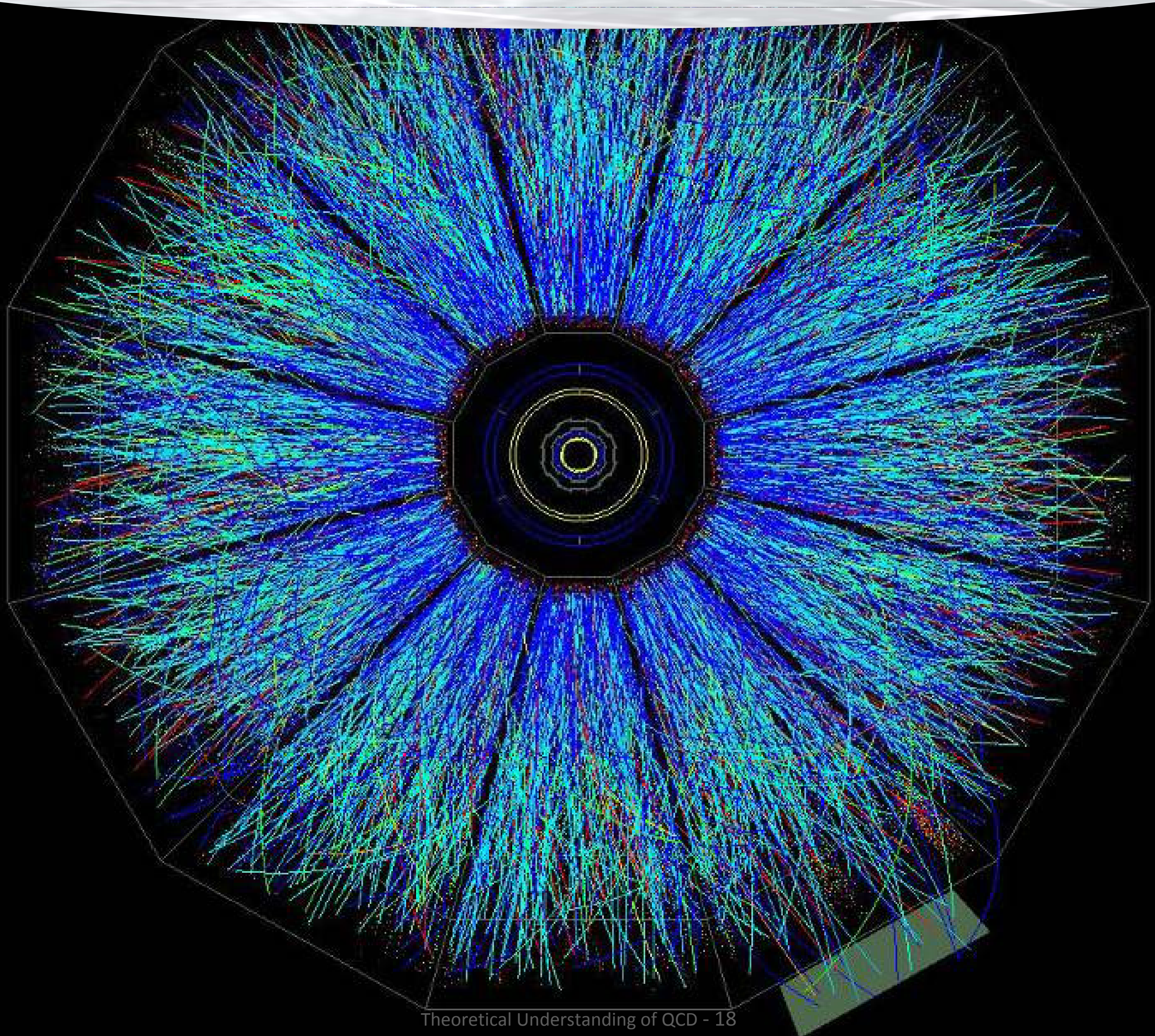
(will need 2nd order logs as well for full variation)





Giele, Kosower, PS : PRD78(2008)014026 + Les Houches 'NLM' 2007

The Underlying Event



Particle Production

- ▶ Starting point: matrix element + parton shower
  - hard parton-parton scattering
    - (normally 2→2 in MC)
  - + bremsstrahlung associated with it
    - ➔ 2→n in (improved) LL approximation

▶ But hadrons are not elementary

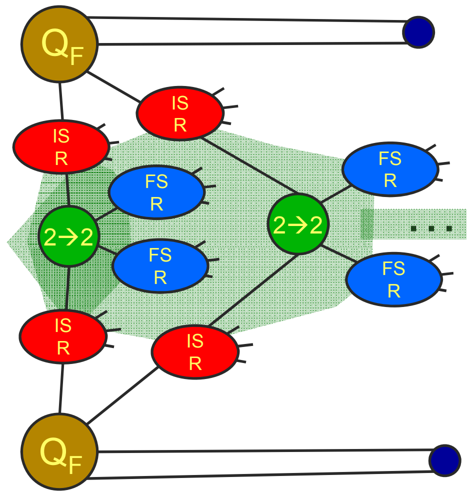
▶ + QCD diverges at low p_T

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

e.g. 4→4, 3→ 3, 3→2

▶ No factorization theorem

➔ Herwig++, Pythia, Sherpa: MPI models



Note:

Can take

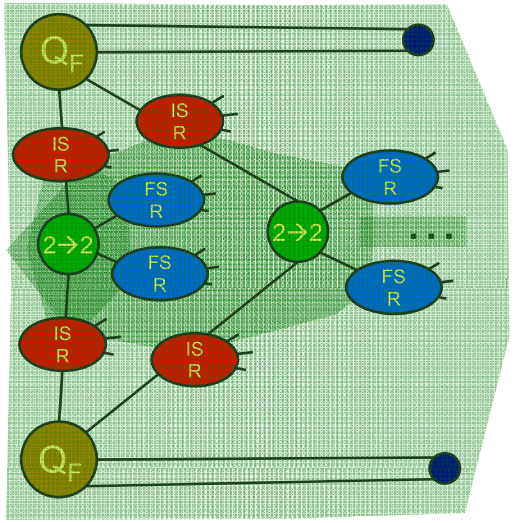
$Q_F \gg \Lambda_{QCD}$

Additional Sources of Particle Production

$Q_F >> \Lambda_{QCD}$

ME+ISR/FSR

+ perturbative MPI



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

+

Stuff at

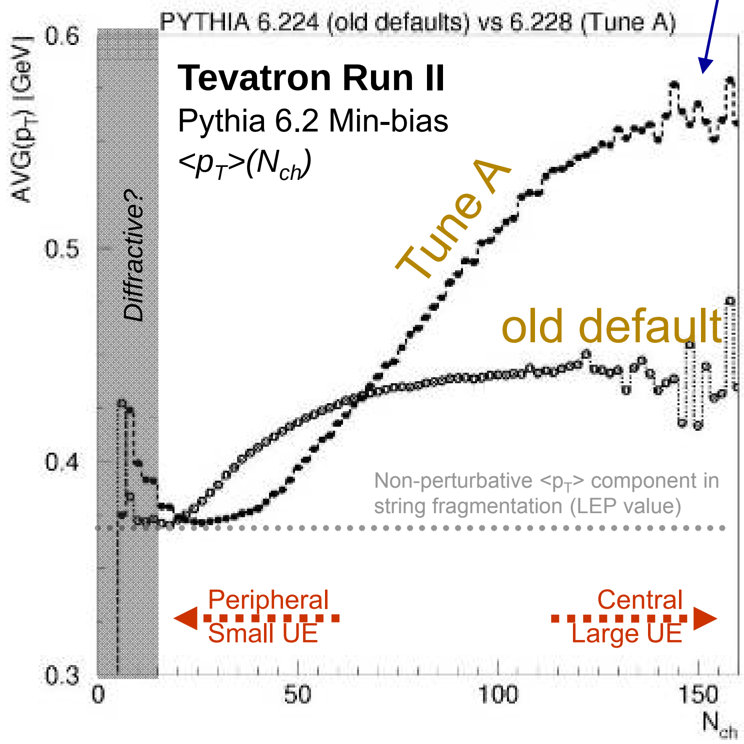
$Q_F \sim \Lambda_{QCD}$

- Hadronization
- Remnants from the incoming beams
- Additional (non-perturbative / collective) phenomena?
  - Bose-Einstein Correlations
  - Non-perturbative gluon exchanges / color reconnections ?
  - String-string interactions / collective multi-string effects ?
  - “Plasma” effects?
  - Interactions with “background” vacuum, remnants, or active medium?

Underlying Event and Color

- Min-bias data at Tevatron showed a surprise
  - Charged particle pT spectra were highly correlated with event multiplicity: **not expected**
  - For his 'Tune A', Rick Field noted that a high correlation in color space between the different MPI partons could account for the behavior
  - But needed ~ 100% correlation. So far not explained
  - Virtually all 'tunes' now employ these more 'extreme' correlations
    - But existing models too crude to access detailed physics
  - What is their origin? Why are they needed?

Not only more (charged particles), but each one is harder



Successful models: string interactions (area law)

PS & D. Wicke : EPJC52(2007)133 ; J. Rathsman : PLB452(1999)364

Conclusions

- QCD Phenomenology is in a state of impressive activity
  - Increasing move from educated guesses to precision science
  - Better matrix element calculators+integrators (+ more user-friendly)
  - Improved parton showers and improved matching
  - Developments in underlying events / minimum bias, towards a theory?
  - Upgrades of hadronization and decays
  - I believe the aim is set: NNLO + NLO multileg + NLL shower MC's
    - To improve further, will need theoretical foundation for UE and hadronization
- Early LHC Physics: theory
  - At 14 TeV, everything is interesting
  - Even if not a dinner Chez Maxim, rediscovering the Standard Model is much more than bread and butter
  - Real possibilities for real surprises
  - It is both essential, and I hope possible, to ensure timely discussions on "non-classified" data, such as min-bias, dijets, Drell-Yan, etc → allow rapid improvements in QCD modeling (beyond simple retunes) after startup

Additional Slides

(Bremsstrahlung Example: SUSY @ LHC)

- ► Naively, brems suppressed by $\alpha_s \sim 0.1$
  - Truncate at fixed order = LO, NLO, …
  - However, if ME >> 1 → can't truncate!

$$\frac{1}{\sigma}\frac{d^2\sigma}{dx_1 dx_2} = \frac{2\alpha_s}{3\pi}\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

- ► Example: SUSY pair production at 14 TeV, with MSUSY ~ 600 GeV

LHC - sps1a - m~600 GeV — Plehn, Rainwater, PS PLB645(2007)217

FIXED ORDER pQCD	σ_{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	σ_{0j}	4.83	5.65	0.286	0.502	1.30
inclusive X + 1 "jet" →	σ_{1j}	2.89	2.74	0.136	0.145	0.73
inclusive X + 2 "jets" →	σ_{2j}	1.09	0.85	0.049	0.039	0.26
$p_{T,j} >$ 50 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
	σ_{1j}	5.90	5.37	0.283	0.285	1.50
	σ_{2j}	4.17	3.18	0.179	0.117	1.21

(Computed with SUSY-MadGraph)

Cross section for 1 or more 50-GeV jets larger than total σ, obviously non-sensical

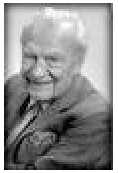
- Conclusion: 100 GeV can be "soft" at the LHC
  - Matrix Element (fixed order) expansion breaks completely down at 50 GeV
  - With decay jets of order 50 GeV, this is important to understand and control

→ Alwall, de Visscher, Maltoni: JHEP 0902(2009)017

Monte Carlo at Fixed Order

High-dimensional problem (phase space)

d≥5 ➔ Monte Carlo integration



"Monte Carlo": N. Metropolis, first Monte Carlo calculation on ENIAC (1948), basic idea goes back to Enrico Fermi

"Experimental" distribution of observable $\mathcal{O}$ in production of X:

Fixed Order (all orders)

$$\frac{d\sigma}{d\mathcal{O}}\Big|_{\mathrm{ME}} = \sum_{k=0} \int d\Phi_{X+k} \left|\sum_{\ell=0} M^{(\ell)}_{X+k}\right|^2 \delta(\mathcal{O} - \mathcal{O}(\{p\}_{X+k}))$$

k : legs

ℓ : loops

{p} : momenta

Note 1: For k larger than a few, need to be quite clever in phase space sampling

Note 2: For $k+\ell > 0$, need to be careful in arranging for real-virtual cancellations

Principal virtues

1. Stochastic error $O(\mathcal{N}^{-1/2})$ independent of dimension
2. Full (perturbative) quantum treatment at each order
3. (KLN theorem: finite answer at each (complete) order)

Z→4 Matching by multiplication

- **Starting point:**
  - LL shower w/ large coupling and large finite terms to generate “trial” branchings (“sufficiently” large to over-estimate the full ME).
  - Accept branching $[i]$ with a probability

$$\mathcal{P}^{[i]}(\{p\}_4) = \frac{\alpha_s(\mu_{\mathrm{ps}}^{[i]}) A_3^{[i]}(\{p\}_4)}{\hat{\alpha}_s \hat{A}_3^{[i]}(\{p\}_4)} + \frac{\alpha_s^2(\mu_{\mathrm{me}})}{\hat{\alpha}_s}\left(\frac{A_4^0(\{p\}_4) - \sum_{[j]\in 4\to 3} A_3^{[j]}(\{p\}_4)\, A_3^{[\hat{j}]}(\{\hat{p}\}_3^{[j]})}{\sum_{[j]\in 4\to 3}\alpha_s(\mu_{\mathrm{ps}}^{[j]})\hat{A}_3^{[j]}(\{p\}_4)\, A_3^{[\hat{j}]}(\{\hat{p}\}_3^{[j]})}\right)$$

Sjöstrand-Bengtsson term

2nd order matching term (with 1st order subtracted out)

- **Each point in 4-parton phase space then receives a contribution**

$$\begin{aligned}&\hat{\alpha}_s\alpha_s(\mu_{\mathrm{ps}}^{[qg]})\hat{A}_3^{[qg]}(\{p\}_4)A_3^{[q\bar{q}]}(\{\hat{p}^{[qg]}\}_3)\mathcal{P}^{[qg]} + \hat{\alpha}_s\alpha_s(\mu_{\mathrm{ps}}^{[g\bar{q}]})\hat{A}_3^{[g\bar{q}]}(\{p\}_4)A_3^{[q\bar{q}]}(\{\hat{p}^{[g\bar{q}]}\}_3)\mathcal{P}^{[g\bar{q}]}\\ &= \alpha_s^2(\mu_{\mathrm{me}})A_4^0(\{p\}_4)\end{aligned}$$

(If you think this looks deceptively easy, you are right)

Note: to maintain positivity for subleading colour, need to match across 4 events, 2 representing one color ordering, and 2 for the other ordering

The Z→3 1-loop term

- Second order matching term for 3 partons

$$w_3^{(V)} = 2\mathrm{Re}\left[M_3^{(1)}M_3^{(0)*}\right] + |M_3^{(0)}|^2 \left(\int_0^s \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2}\left(A_{qg}S_{qg} + A_{g\bar{q}}S_{g\bar{q}}\right)\right) + \int_0^{Q^2_{\mathrm{had}}} \frac{\mathrm{d}\Phi_4}{\mathrm{d}\Phi_3}\, w_4^{(R)}$$
$$-w_2^{(V)}A_{q\bar{q}}S_{q\bar{q}} + |M_3^{(0)}|^2\left(\delta_\alpha + \int_{Q^2_{E3}}^s \frac{\mathrm{d}\Phi_3'}{\mathrm{d}\Phi_2}\left(A_{q\bar{q}}S_{q\bar{q}} - (1 - Q^2_{E3}/Q^2_{E4})\left(A_{qg}S_{qg} + A_{g\bar{q}}S_{g\bar{q}}\right)\right)\right)$$

- Additive (S=1) → Ordinary NLO subtraction + shower leftovers
  - Shower off $w_2^{(V)}$
  - "Coherence" term: difference between 2- and 3-parton (power-suppressed) evolution above Q_{E3}. Explicit Q_E-dependence cancellation.
  - δ_α: Difference between alpha used in shower ($\mu = p_T$) and alpha used for matching → Explicit scale choice cancellation
  - Integral over $w_4^{(R)}$ in IR region still contains NLL divergences → regulate
  - Logs not resummed, so remaining (NLL) logs in $w_3^{(R)}$ also need to be regulated
- Multiplicative : S = (1+…) → Modified NLO subtraction + shower leftovers
  - A*S contains all logs from tree-level → $w_4^{(R)}$ finite.
  - Any remaining logs in $w_3^{(V)}$ cancel against NNLO → NLL resummation if put back in S

(Why Perturbative MPI?)

► **Analogue**: Resummation of multiple bremsstrahlung emissions

- Divergent σ for one emission (X + jet, fixed-order)

➔Finite σ for divergent number of jets (X + jets, infinite-order)

- N(jets) rendered finite by finite perturbative resolution = parton shower cutoff

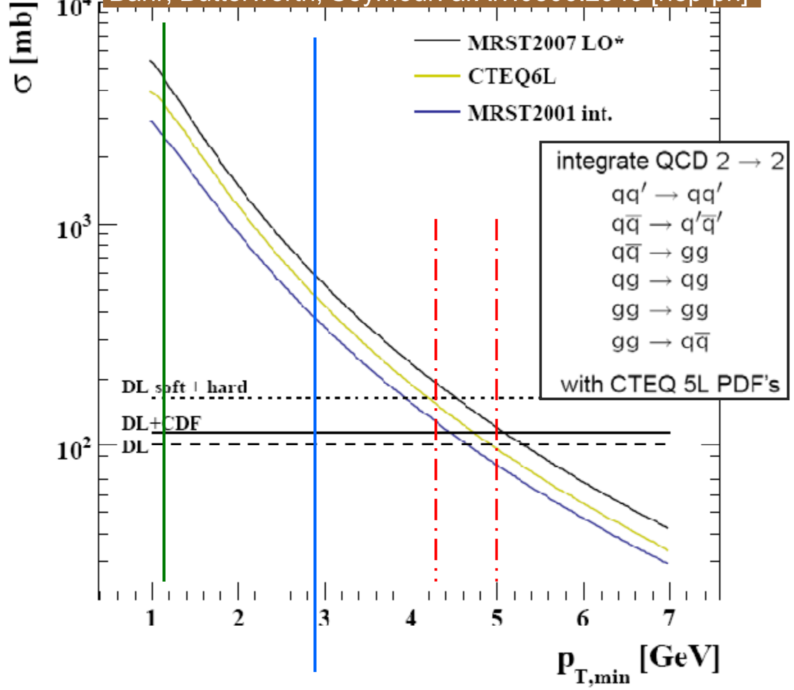
►(Resummation of) **Multiple Perturbative Interactions**

•Divergent σ for one interaction (fixed-order)

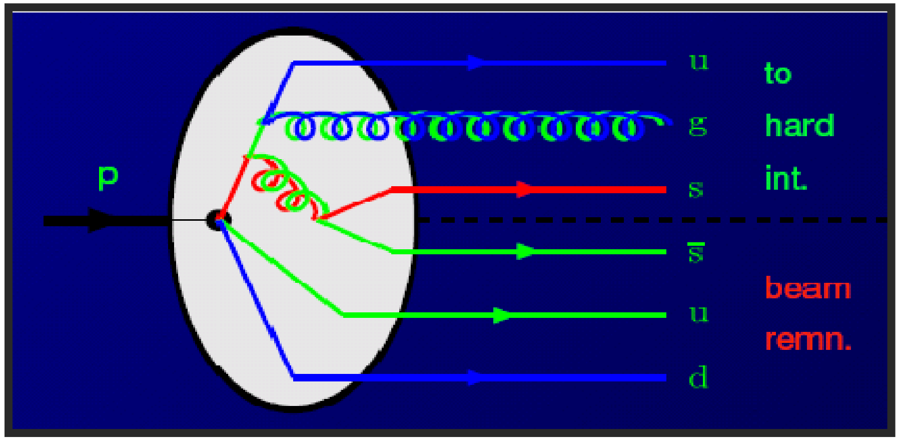
➔Finite σ for divergent number of interactions (infinite-order)

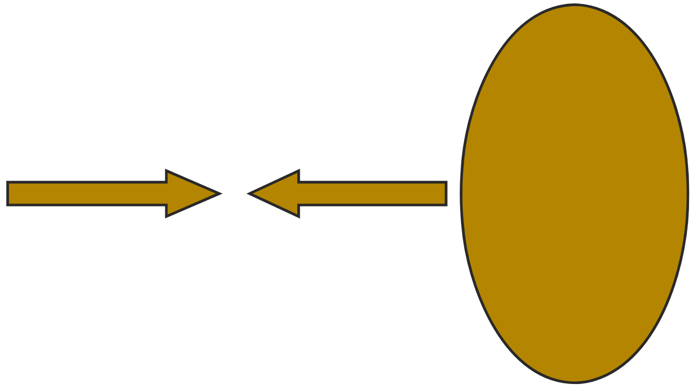
- N(jets) rendered finite by finite perturbative resolution = color-screening cutoff (E_{cm}-dependent, but large uncert)

Bahr, Butterworth, Seymour: arXiv:0806.2949 [hep-ph]



What’s the problem?





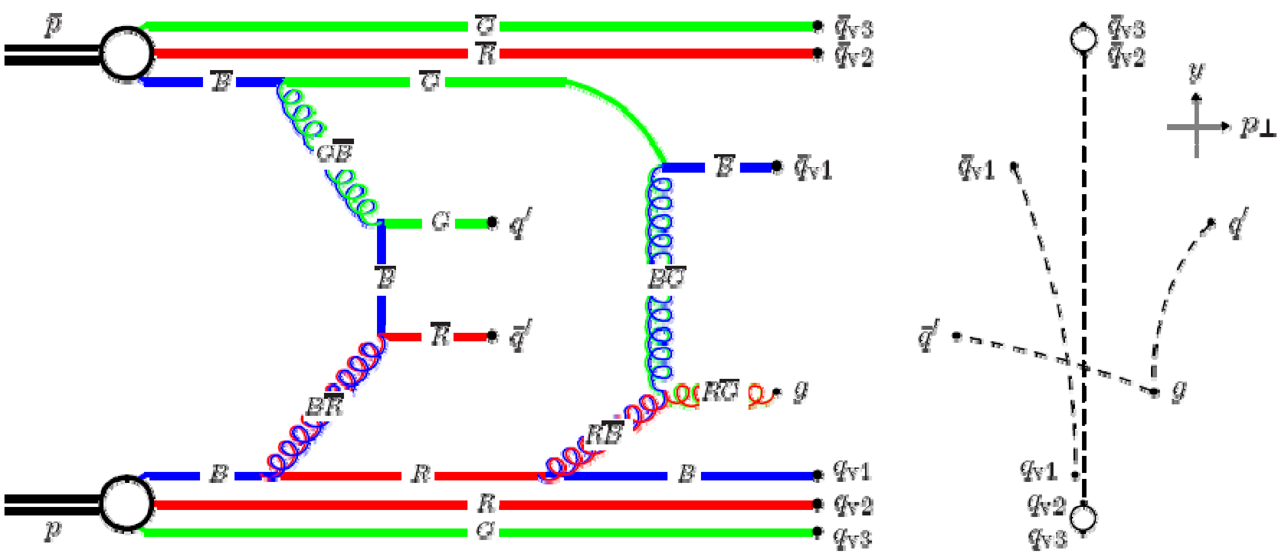
How are the initiators and remnant partons correllated?

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

Underlying Event and Color

► The colour flow determines the hadronizing string topology

- Each MPI, even when soft, is a color spark
- Final distributions <u>crucially</u> depend on color space



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

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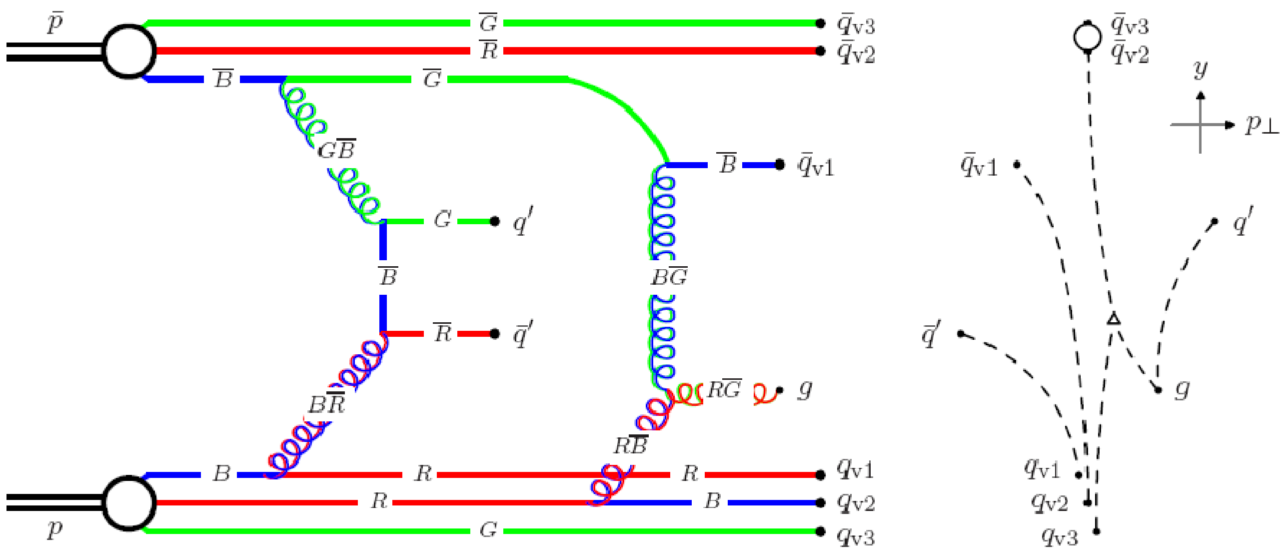

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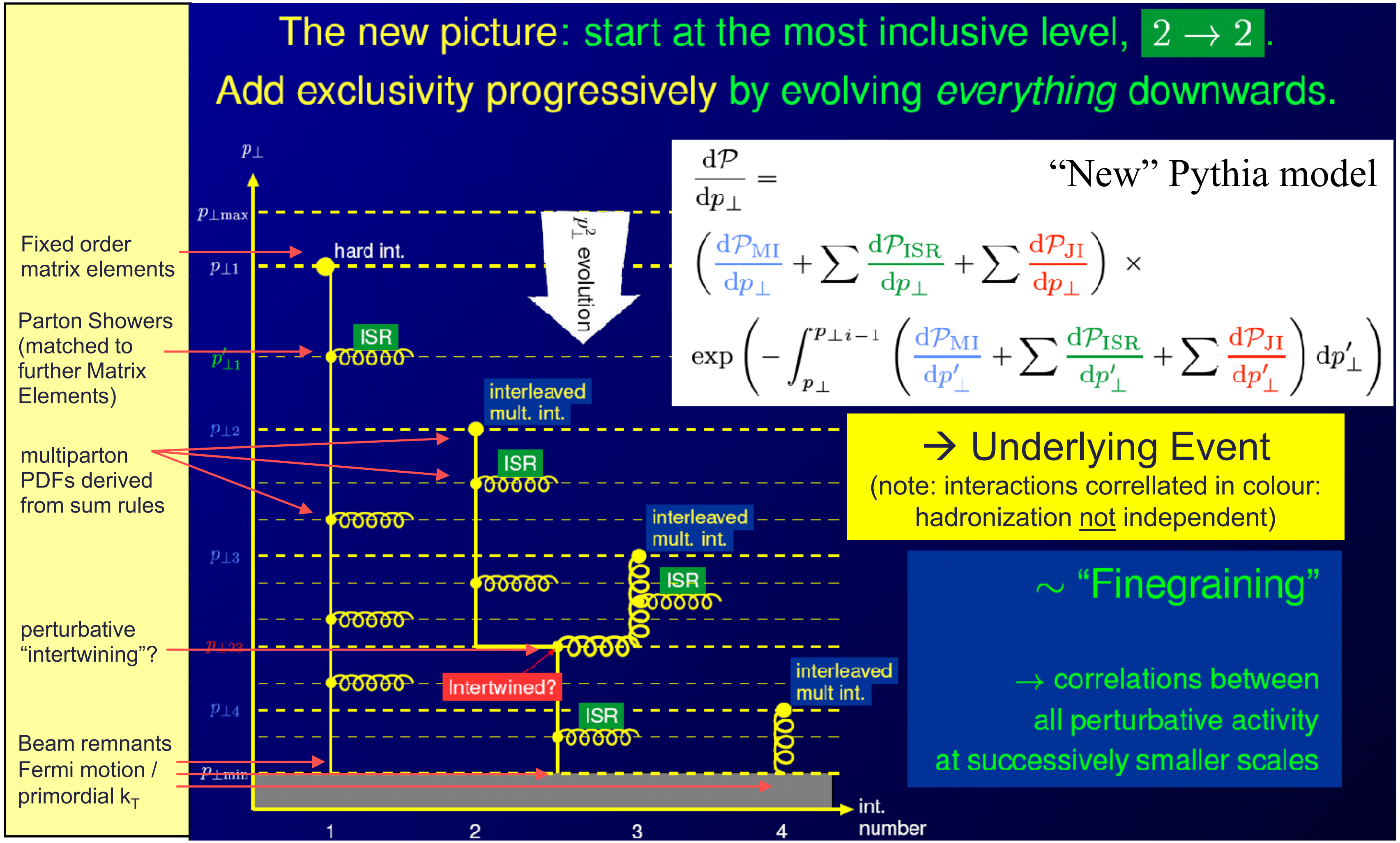
The Interleaved Idea



Sjöstrand & PS : JHEP03(2004)053, EPJC39(2005)129