The PYTHIA Event Generator

Peter Skands
(CERN)

LHC is a QCD Machine

Hard processes initiated by partons (quarks & gluons)

- Associated with initial-state QCD corrections
- Underlying event by QCD mechanisms (MPI, color flow)
- Extra QCD jets, isolation, fakes → all sensitive to QCD corrections

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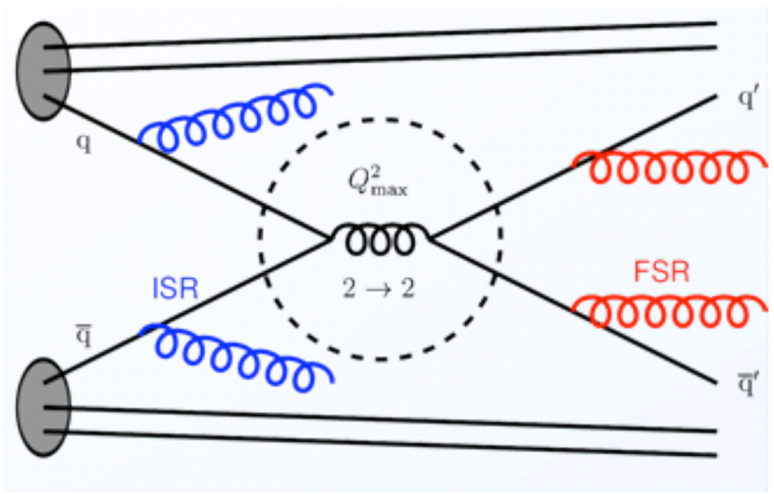
Even in BSM scenarios, production of new colored states often favored

- Squarks, gluinos, KK gluons, excited quarks, …
- + extra QCD jets …

Monte Carlo Generators



Calculate Everything ≈ solve QCD → requires compromise!

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

Existing Approaches

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

PYTHIA anno 1978

(then called JETSET)

LU TP 78-18
November, 1978

A Monte Carlo Program for Quark Jet Generation

T. Sjöstrand, B. Söderberg

A Monte Carlo computer program is presented, that simulates the fragmentation of a fast parton into a jet of mesons. It uses an iterative scaling scheme and is compatible with the jet model of Field and Feynman.

Note: Field-Feynman was an early fragmentation model
Now superseded by the String (in PYTHIA) and
Cluster (in HERWIG & SHERPA) models.

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```
      SUBROUTINE JETGEN(N)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /PAR/ PUD, PS1, SIGMA, CX2, EBEG, WFIN, IFLBEG
      COMMON /DATA1/ MESO(9,2), CMIX(6,2), PMAS(19)
      IFLSGN=(10-IFLBEG)/5
      W=2.*EBEG
      I=0
      IPD=0
C 1 FLAVOUR AND PT FOR FIRST QUARK
      IFL1=IABS(IFLBEG)
      PT1=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI1=6.2832*RANF(0)
      PX1=PT1*COS(PHI1)
      PY1=PT1*SIN(PHI1)
  100 I=I+1
C 2 FLAVOUR AND PT FOR NEXT ANTIQUARK
      IFL2=1+INT(RANF(0)/PUD)
      PT2=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI2=6.2832*RANF(0)
      PX2=PT2*COS(PHI2)
      PY2=PT2*SIN(PHI2)
C 3 MESON FORMED, SPIN ADDED AND FLAVOUR MIXED
      K(I,1)=MESO(3*(IFL1-1)+IFL2,IFLSGN)
      ISPIN=INT(PS1+RANF(0))
      K(I,2)=1+9*ISPIN+K(I,1)
      IF(K(I,1).LE.6) GOTO 110
      TMIX=RANF(0)
      KM=K(I,1)-6+3*ISPIN
      K(I,2)=8+9*ISPIN+INT(TMIX+CMIX(KM,1))+INT(TMIX+CMIX(KM,2))
C 4 MESON MASS FROM TABLE, PT FROM CONSTITUENTS
  110 P(I,5)=PMAS(K(I,2))
      P(I,1)=PX1+PX2
      P(I,2)=PY1+PY2
      PMTS=P(I,1)**2+P(I,2)**2+P(I,5)**2
C 5 RANDOM CHOICE OF X=(E+PZ)MESON/(E+PZ)AVAILABLE GIVES E AND PZ
      X=RANF(0)
      IF(RANF(0).LT.CX2) X=1.-X**(1./3.)
      P(I,3)=(X*W-PMTS/(X*W))/2.
      P(I,4)=(X*W+PMTS/(X*W))/2.
C 6 IF UNSTABLE, DECAY CHAIN INTO STABLE PARTICLES
  120 IPD=IPD+1
      IF(K(IPD,2).GE.8) CALL DECAY(IPD,I)
      IF(IPD.LT.I.AND.I.LE.96) GOTO 120
C 7 FLAVOUR AND PT OF QUARK FORMED IN PAIR WITH ANTIQUARK ABOVE
      IFL1=IFL2
      PX1=-PX2
      PY1=-PY2
C 8 IF ENOUGH E+PZ LEFT, GO TO 2
      W=(1.-X)*W
      IF(W.GT.WFIN.AND.I.LE.95) GOTO 100
      N=I
      RETURN
      END
```

PYTHIA anno 2012

(now called PYTHIA 8)

LU TP 07-28 (CPC 178 (2008) 852)
October, 2007

A Brief Introduction to PYTHIA 8.1

T. Sjöstrand, S. Mrenna, P. Skands

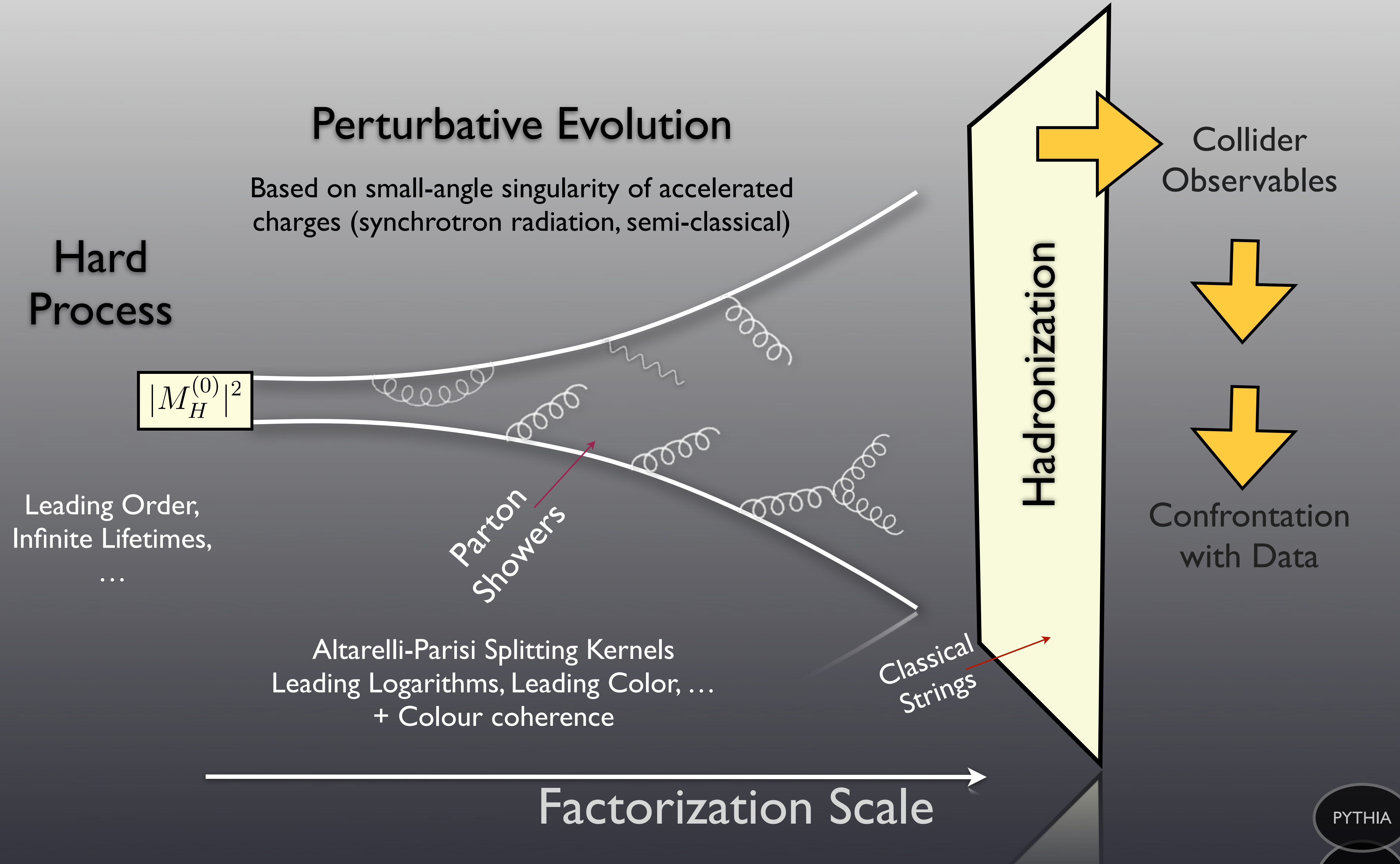
The Pythia program is a standard tool for the generation of high-energy collisions, comprising a coherent set of physics models for the evolution from a few-body hard process to a complex multihadronic final state. It contains a library of hard processes and models for initial- and final-state parton showers, multiple parton-parton interactions, beam remnants, string fragmentation and particle decays. It also has a set of utilities and interfaces to external programs. […]

~ 80,000 lines of C++

What a modern MC generator has inside:

- Hard Processes (internal, semi-internal, or via Les Houches events)
- BSM (internal or via interfaces)
- PDFs (internal or via interfaces)
- Showers (internal or inherited)
- Multiple parton interactions
- Beam Remnants
- String Fragmentation
- Decays (internal or via interfaces)
- Examples and Tutorial
- Online HTML / PHP Manual
- Utilities and interfaces to external programs

(Traditional) Monte Carlo Generators



PYTHIA 8

Ambition

Cleaner code

More user-friendly

Easy **interfacing**

Physics Improvements

Current Status

Ready and tuned to LHC data

Better interfaces to (B)SM generators via LHEF and semi-internal processes

Improved shower model + interfaces to CKKW-L, POWHEG, and VINCIA

Team Members

- Stefan Ask
- Richard Corke
- Stephen Mrenna
- Stefan Prestel
- Torbjorn Sjostrand
- Peter Skands

Contributors

- Bertrand Bellenot
- Lisa Carloni
- Tomas Kasemets
- Mikhail Kirsanov
- Ben Lloyd
- Marc Montull
- Sparsh Navin
- MSTW, CTEQ, H1: PDFs
- DELPHI, LHCb: D/B BRs
- + several bug reports & fixes

Hard Physics

Standard Model

almost all $2 \to 1$, $2 \to 2$

A few $2 \to 3$

BSM: a bit of everything

(see documentation)

Perturbative Resonance Decays

- Angular correlations often included (on a process-by-process basis - no generic formalism)
- User implementations *(semi-internal resonance)*

Hard Processes

Hard Physics

Standard Model

almost all 2→1, 2→2

A few 2→3

BSM: a bit of everything *(see documentation)*

External Input

Les Houches Accord and LHEF *(e.g., from MadGraph, CalcHEP, AlpGen,…)*

User implementations *(semi-internal process)*

Inheriting from PYTHIA's 2→2 base class, then modify to suit you

(+ automated in MadGraph 5)

Perturbative Resonance Decays

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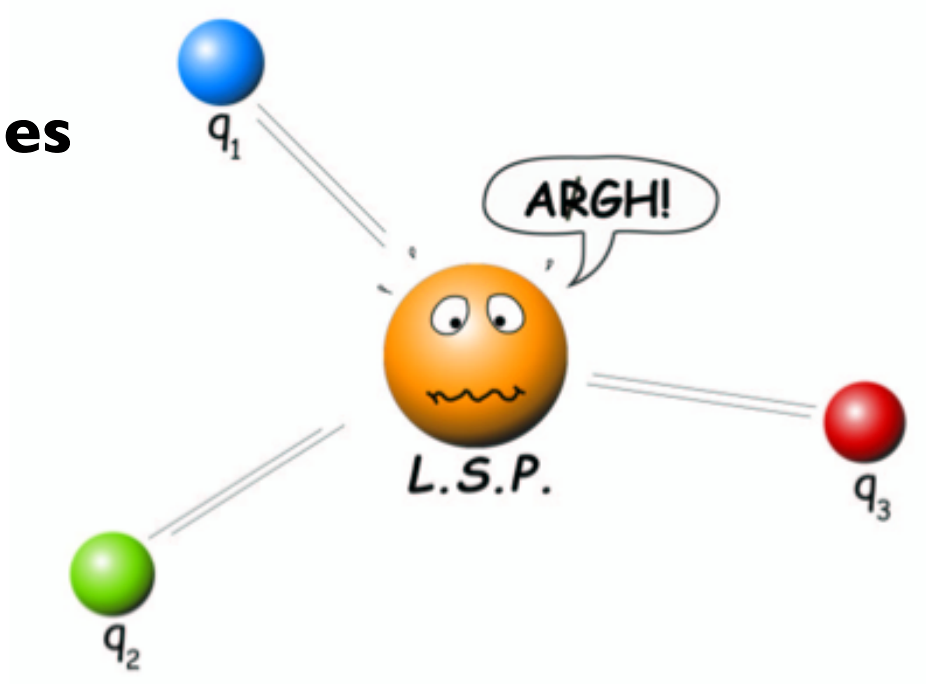
Exotic Colors

Color Epsilon Topologies

Example: RPV SUSY

$$W_{\mathrm{BNV}} = \lambda''_{ijk}\epsilon_{abc}\overline{U}_{ia}\overline{D}_{jb}\overline{D}_{kc}$$

$$\Longrightarrow\ qq \to \tilde{t}^* \to qq$$
$$\Longrightarrow\ \chi^0 \to qqq$$



PYTHIA

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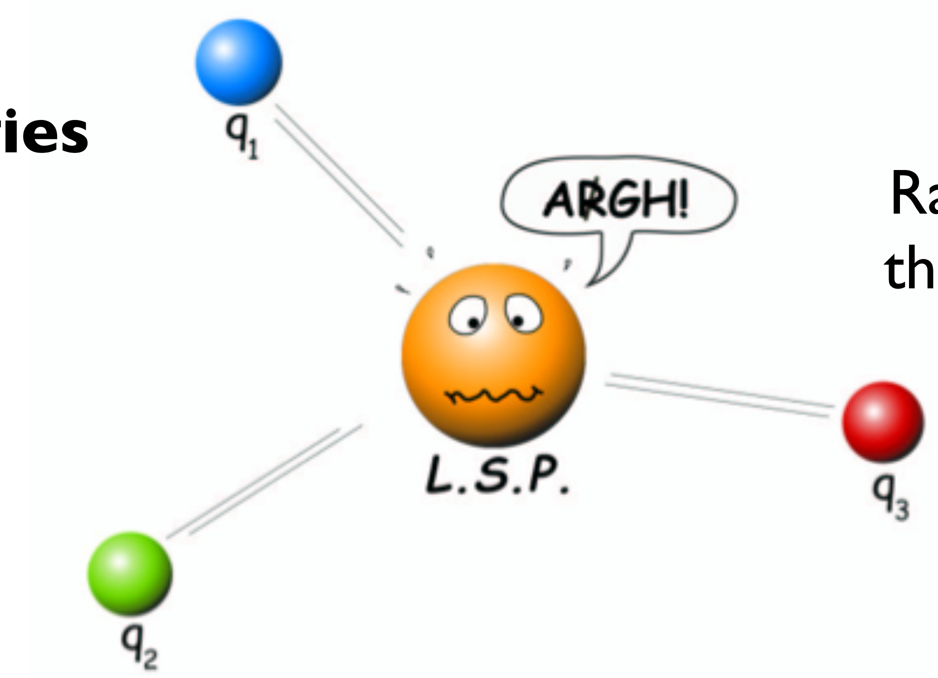

Dipole Showers:

Radiation pattern obtained as if three radiating dipoles, but with half normal strength

N. Desai & PS, arXiv:1109.5852.

(+Sextets → two dipoles)

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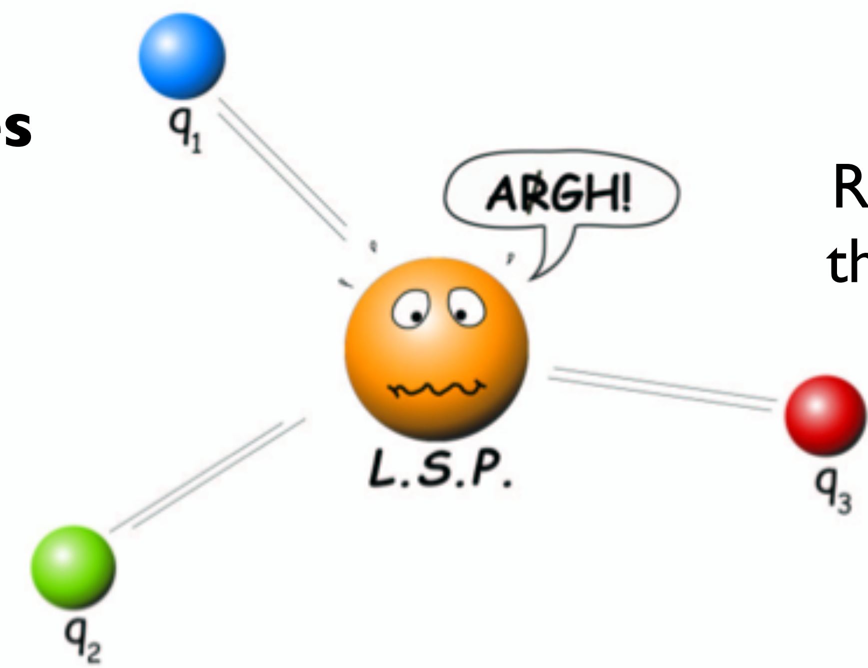

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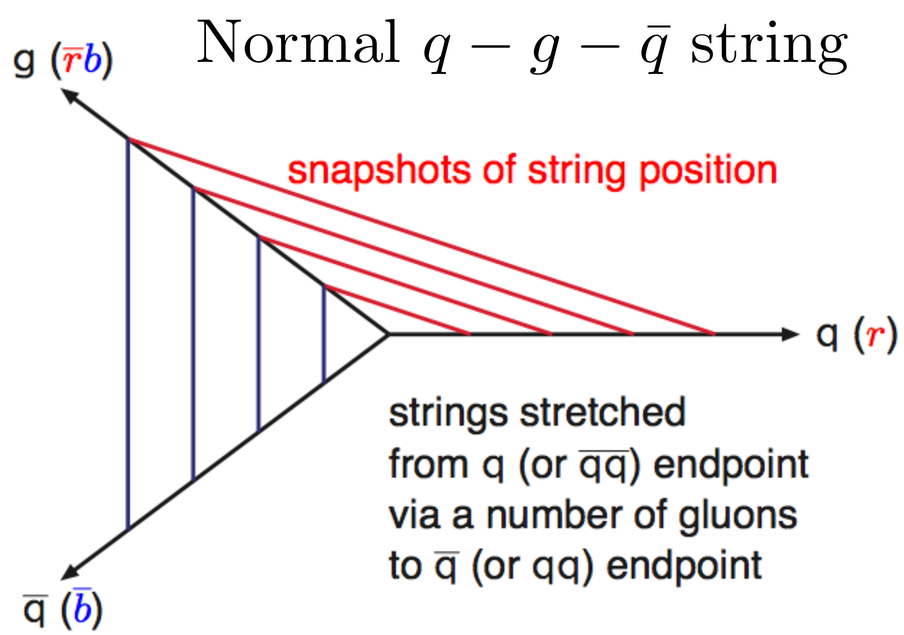

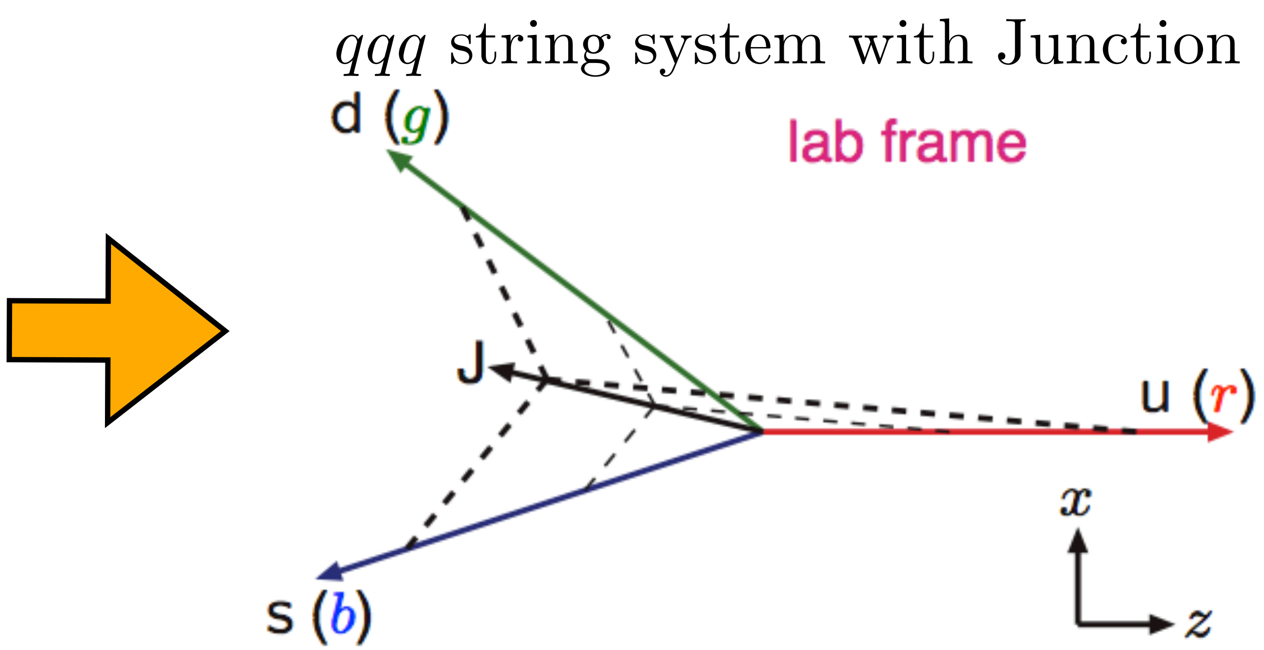

T. Sjöstrand & PS, Nucl. Phys. B659 (2003) 243

PYTHIA

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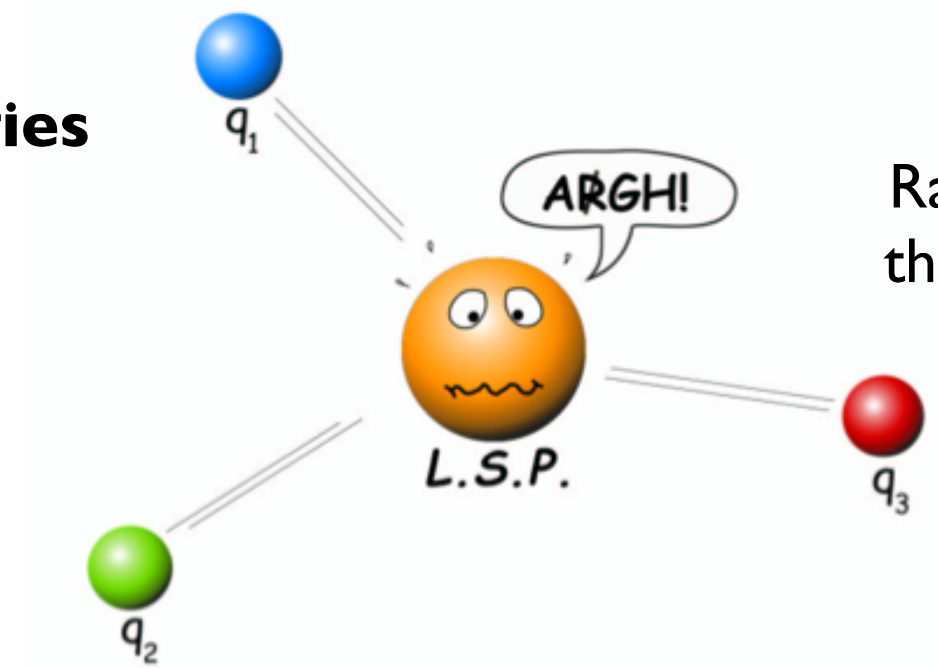

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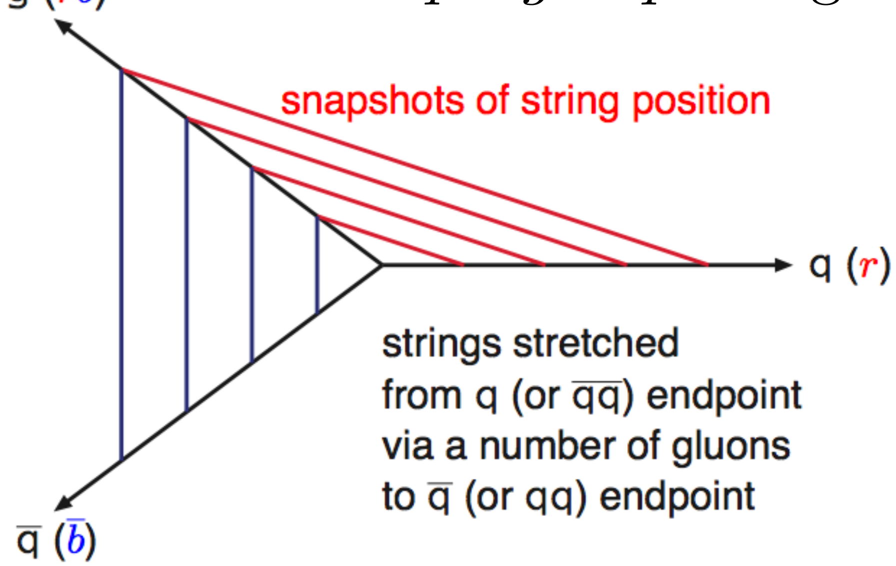
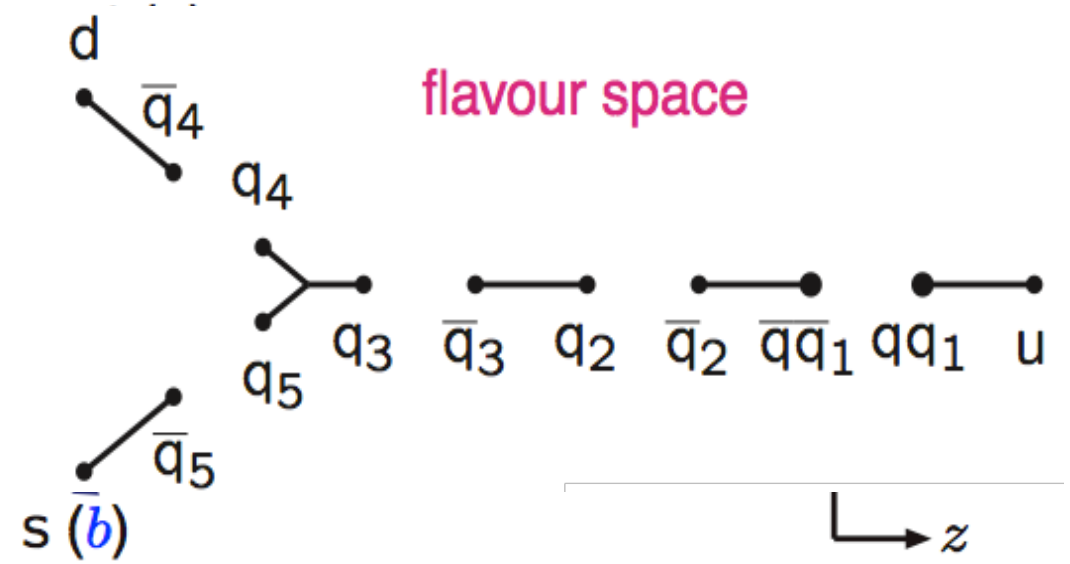
Normal $q - g - \bar{q}$ string



qqq string system with Junction



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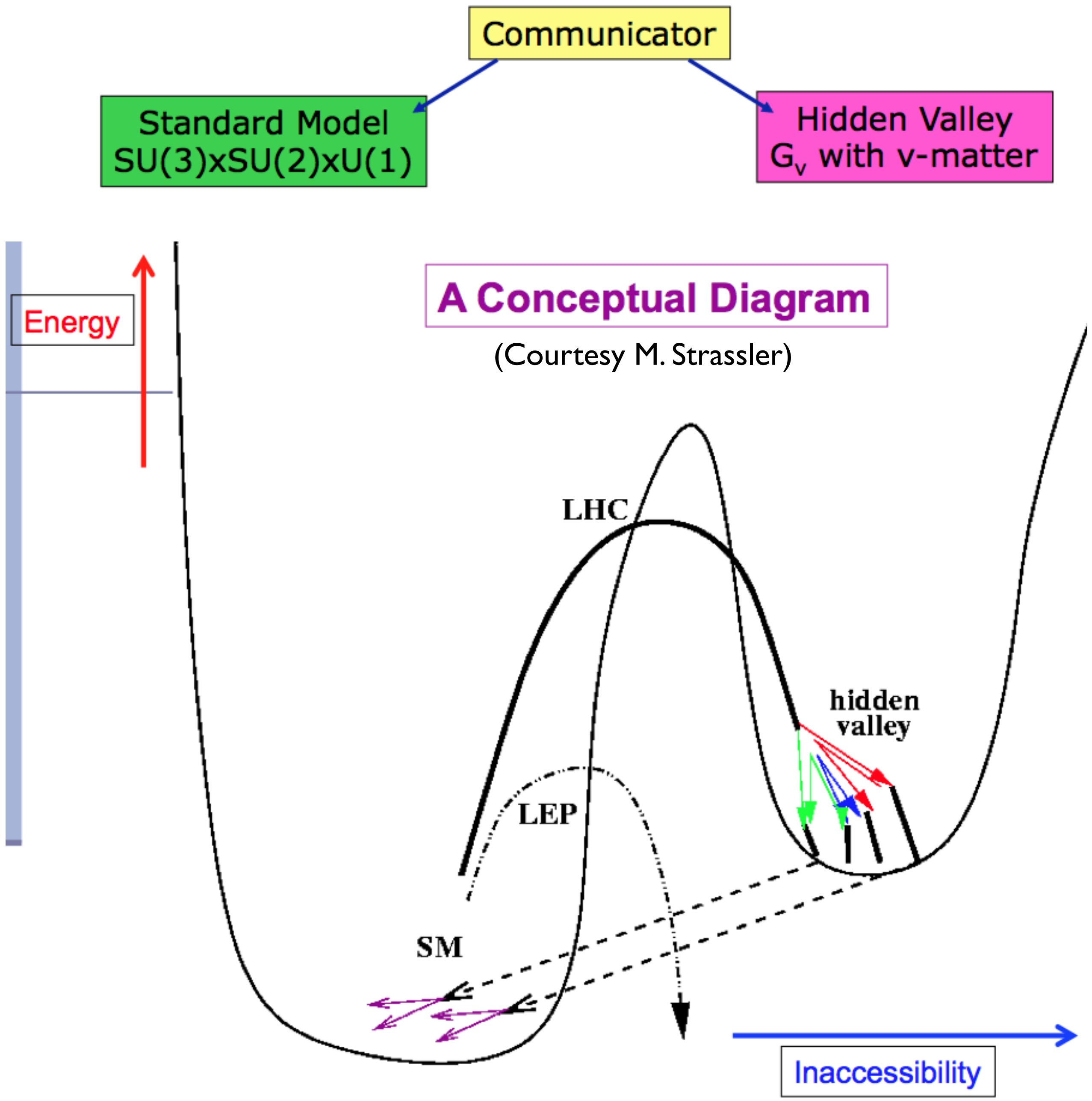
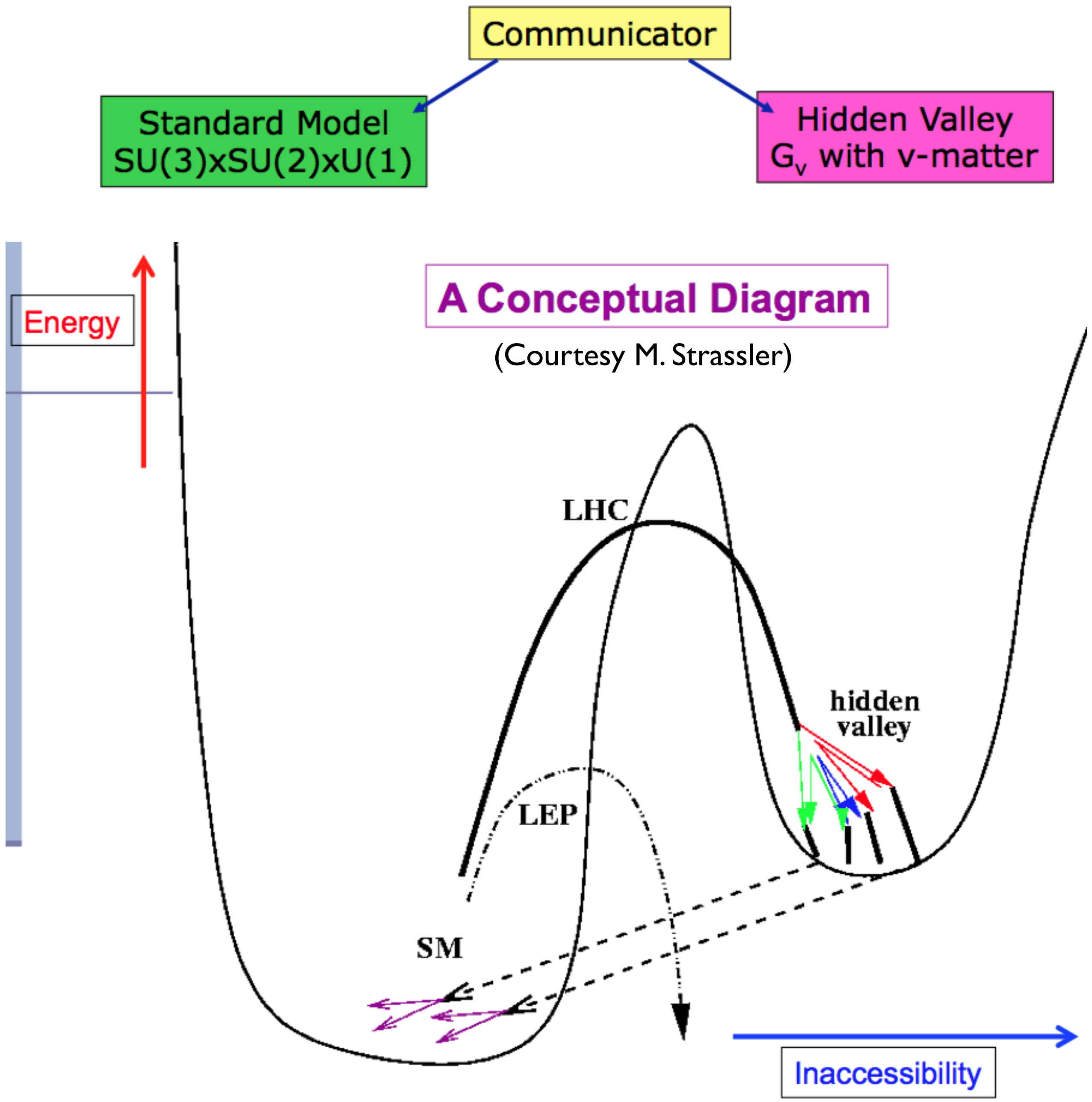
PYTHIA

Hidden Valleys



Models only interesting if they can give observable consequences at the LHC!

Hidden Valleys



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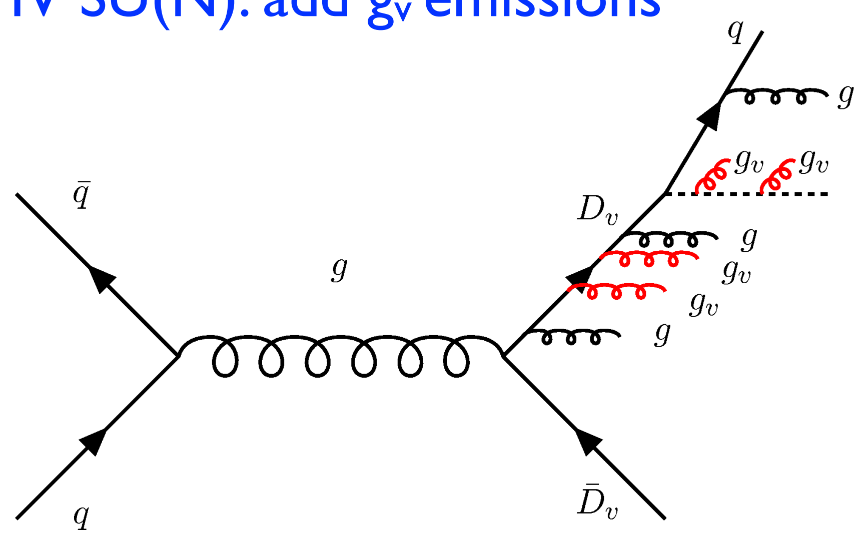
Carloni, Rathsman, Sjöstrand, JHEP 1104 (2011) 091

Interleaved shower in QCD, QED and HV sectors:

- HV U(1): add γ_v emissions
- HV SU(N): add g_v emissions



HV particles may remain invisible, or

- Broken U(1): $\gamma_v \to$ lepton pairs
- SU(N): hadronization in hidden sector, with full string fragmentation setup. For now assumed mass-degenerate.

Flavor Off-diagonal: stable & invisible
Flavor Diagonal, can decay back to SM

Resummation and Matching

Parton Distributions

- Internal *(faster than LHAPDF)*
  - *CTEQ + MSTW LO, plus a few NLO*
  - *MSTW LO*, LO**, CTEQ CT09MC*
- Interface to LHAPDF **[T. Kasemets, arXiv:1002.4376]**
- Can use separate PDFs for hard scattering and UE *(to 'stay tuned')*

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Showers

- Transverse-momentum ordered ISR & FSR *(new: fully interleaved)*
  - *Includes QCD and QED*
  - *Dipole-style recoils (partly new)*
  - *Improved high-$p_\perp$ behavior* **[R. Corke]**

PYTHIA

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Matrix-Element Matching

Automatic first-order matching for most gluon-emission processes in resonance decays, e.g.,:

$Z \to qq \to qqg$,

$t \to bW \to bWg$,

$H \to bb \to bbg$, …

Automatic first-order matching for internal 2→1 color-singlet processes, e.g.:

$pp \to H/Z/W/Z'/W'$+jet

More to come …

Interface to AlpGen, MadGraph, … via Les Houches Accords

PYTHIA

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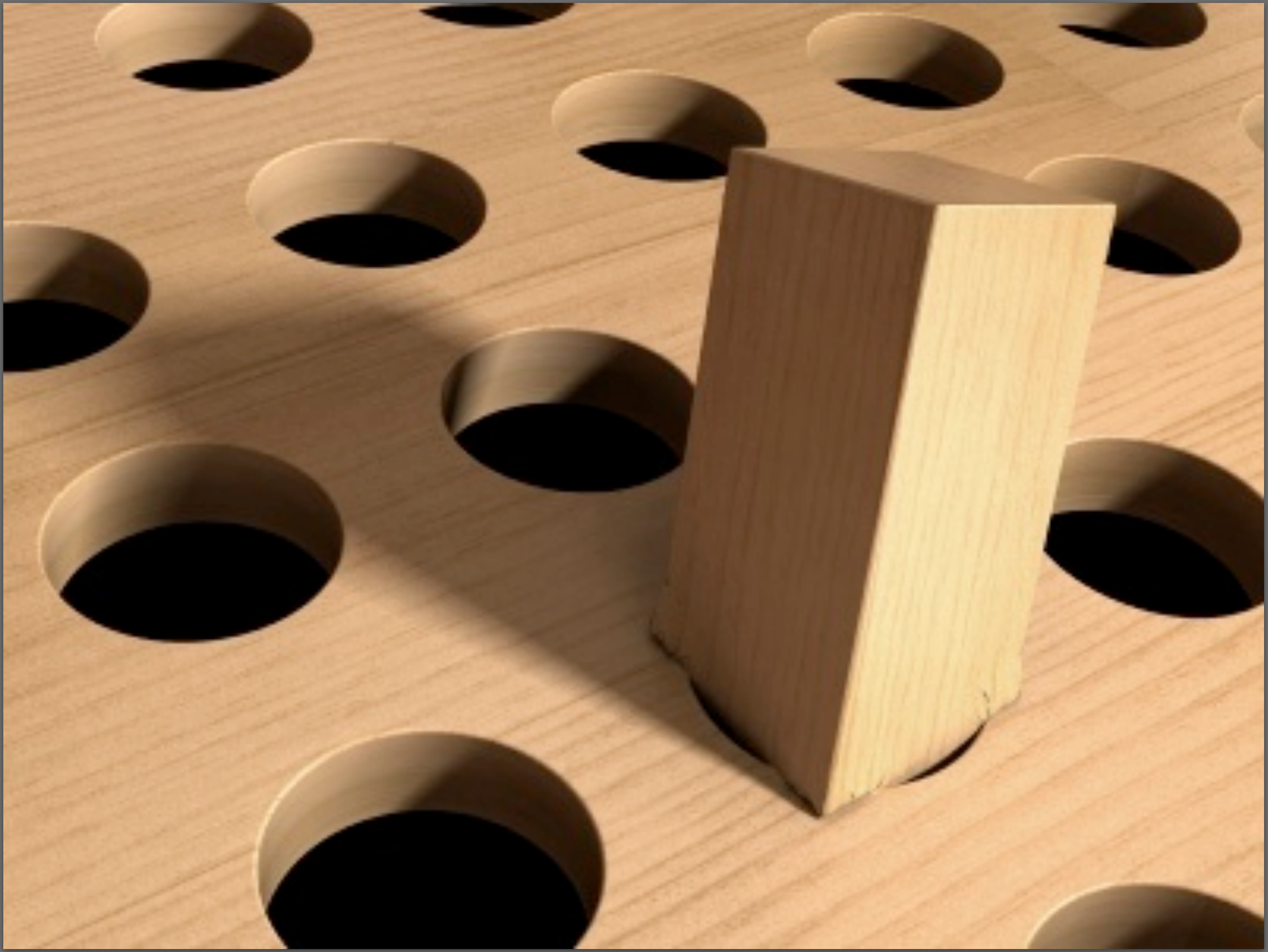
Matched Showers: Interface to VINCIA (new showers + matching) **[PS]**

Matching

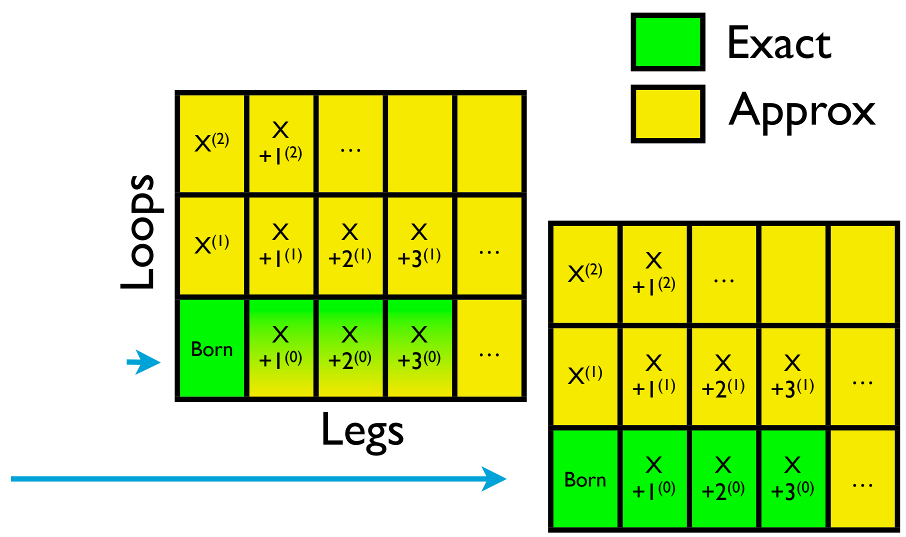


Cures

Tree-Level Matrix Elements

PHASE-SPACE SLICING *(a.k.a. CKKW, MLM, …)*

UNITARITY *(a.k.a. merging, PYTHIA, VINCIA, …)*



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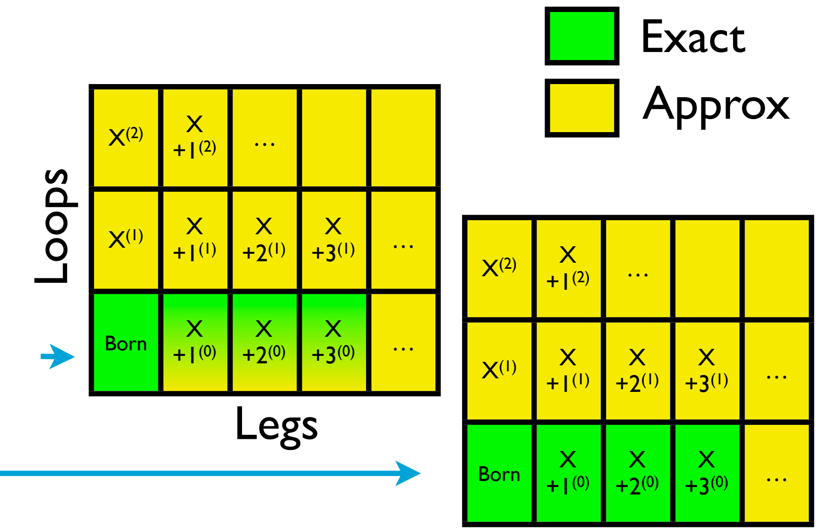

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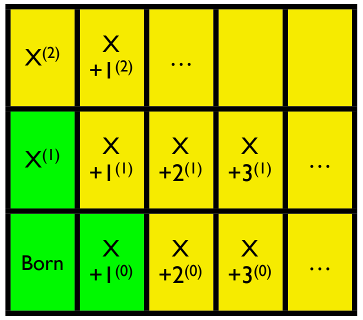
NLO Matrix Elements



SUBTRACTION *(a.k.a. MC@NLO)*

UNITARITY + SUBTRACTION *(a.k.a. POWHEG,VINCIA)*

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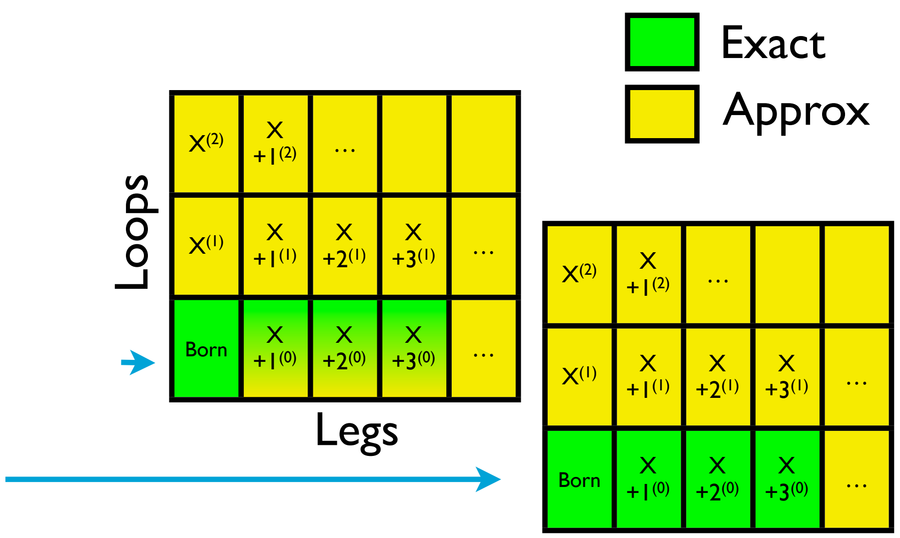

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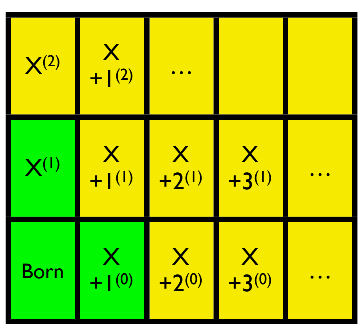
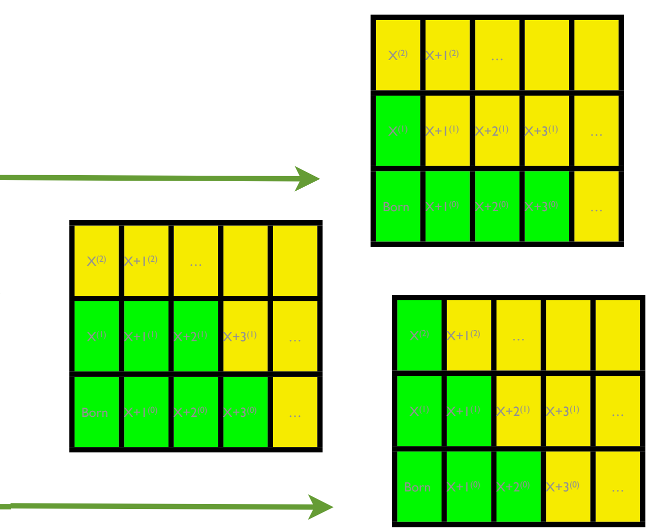


+ WORK IN PROGRESS …

NLO + multileg tree-level matrix elements

NLO multileg matching

Matching at NNLO



Matching in PYTHIA 8

Internal: merging (correcting first shower emissions)

Tree-level matrix elements

CKKW-L: via Les Houches files L. Lönnblad & S. Prestel, JHEP 1203 (2012) 019

MLM: Work started on Alpgen interface **[R. Corke]**

NLO matrix elements

POWHEG: done for ISR (via LHEF). In progress for FSR **[R. Corke]**

MC@NLO: in progress **[S. Frixione, P. Torrielli]**

(Already available for virtuality-ordered Pythia 6)

+ Interface to VINCIA: Markovian pQCD …

(uses matrix elements from Madgraph to drive evolution)

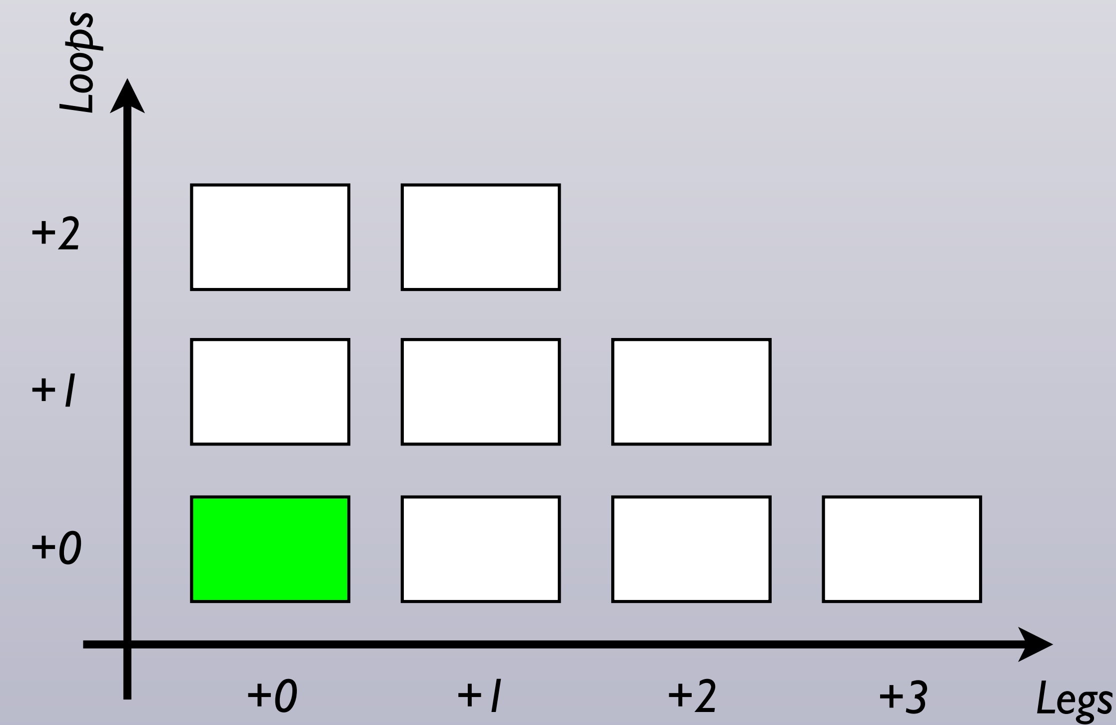
VINCIA: Markovian pQCD*

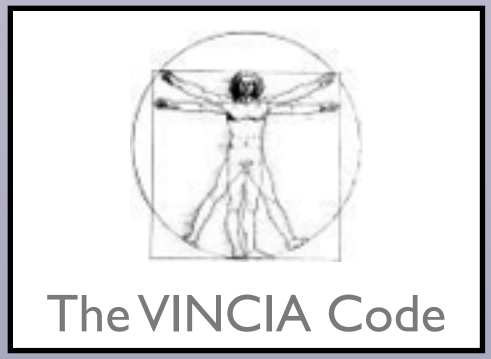
Note: still only worked out for FSR. ISR in progress **[M. Ritzmann]**

*) pQCD : perturbative QCD

Start at Born level

$$|M_F|^2$$





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VINCIA: Giele, Kosower, Skands, PRD78(2008)014026 & PRD84(2011)054003
+ ongoing work with M. Ritzmann, E. Laenen, L. Hartgring, A. Larkoski, J. Lopez-Villarejo

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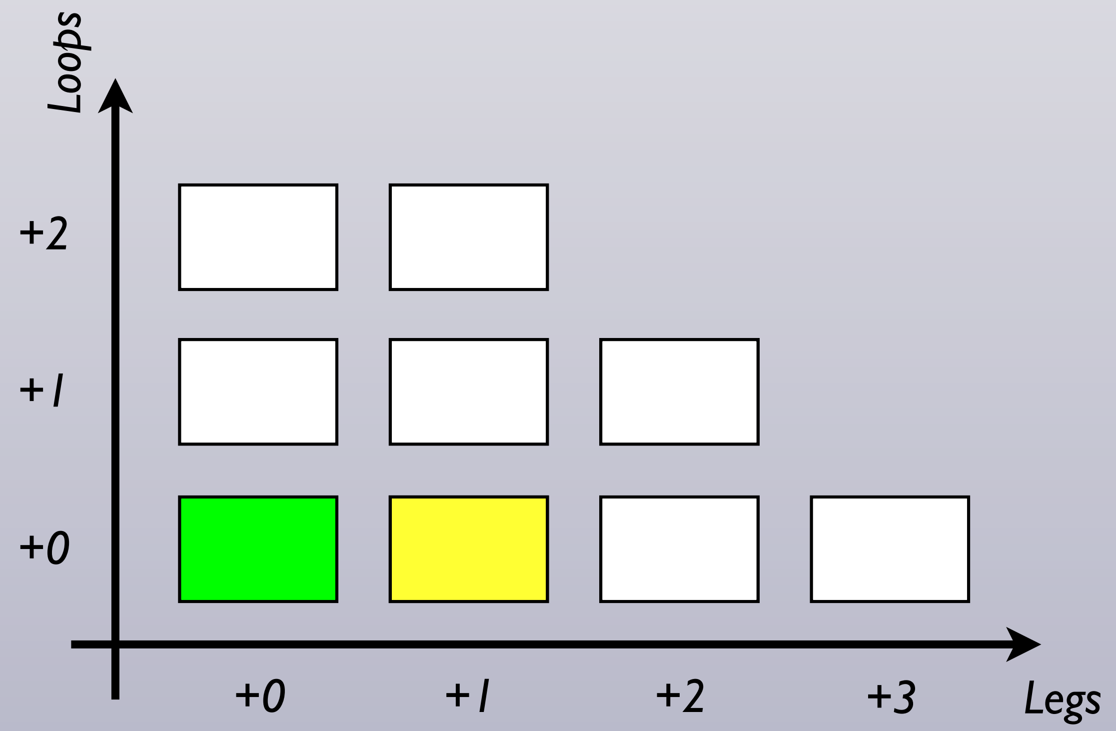
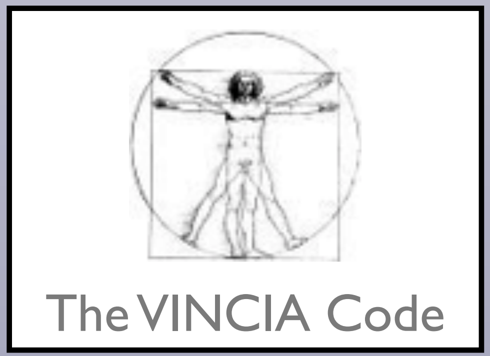
Generate "shower" emission

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





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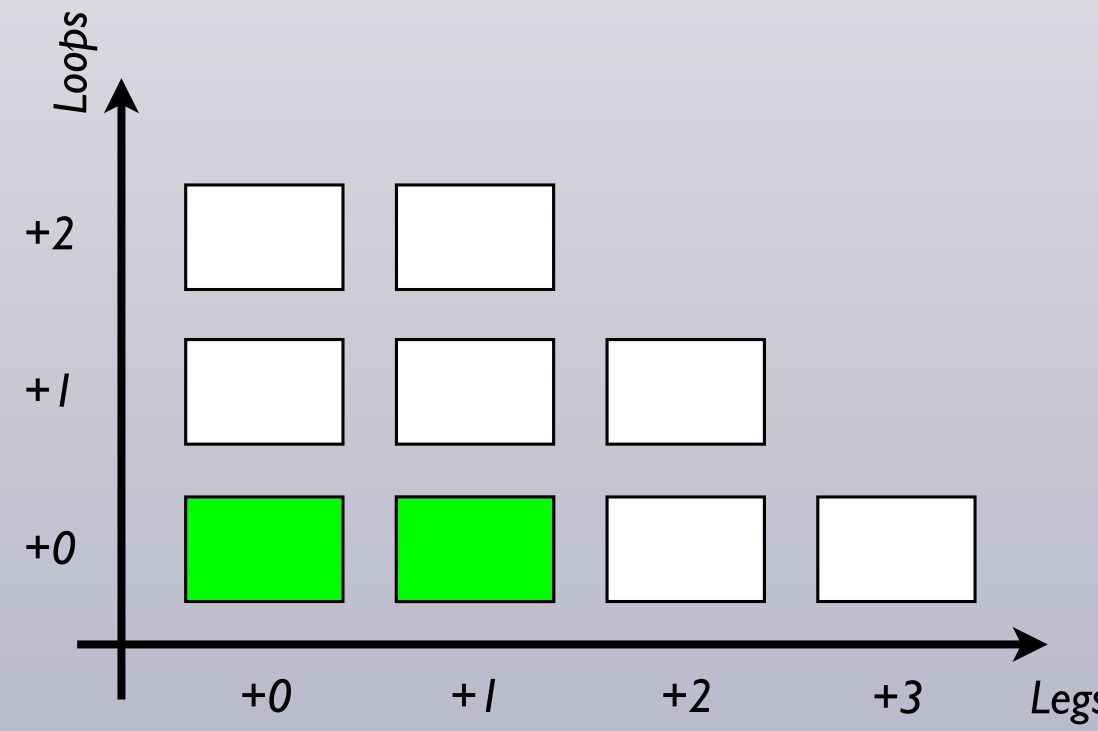
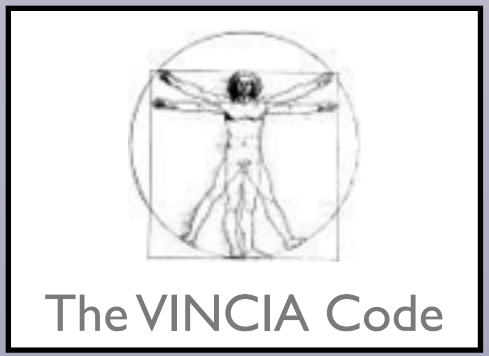
Correct to Matrix Element

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





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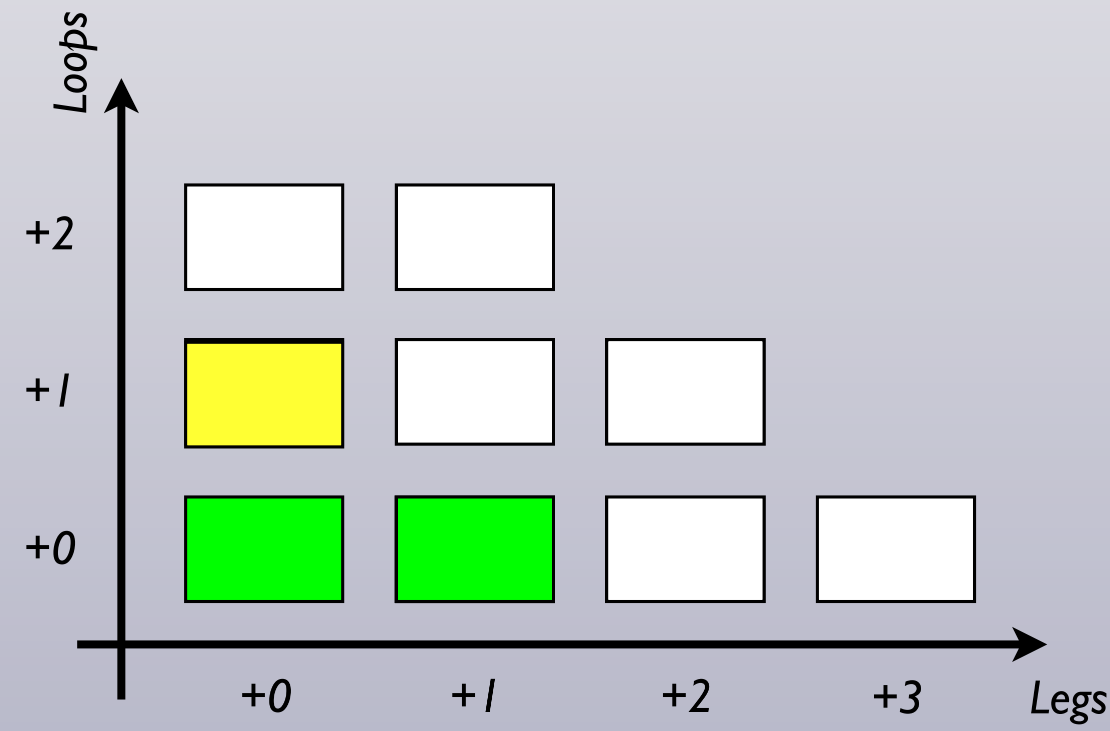
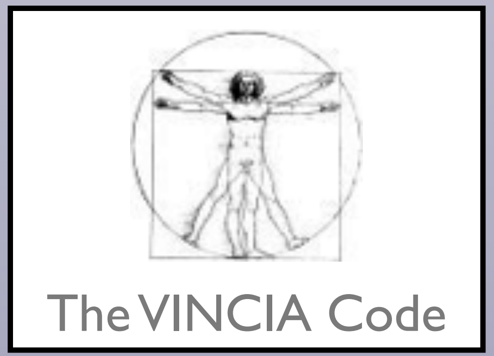
Unitarity of Shower

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





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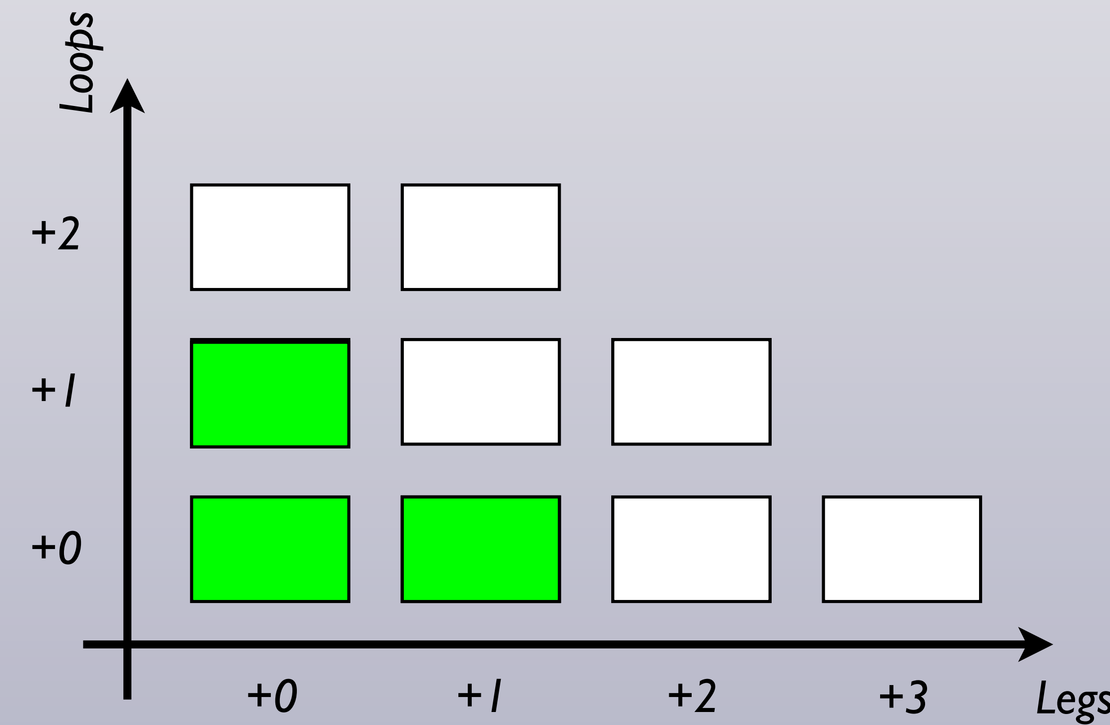

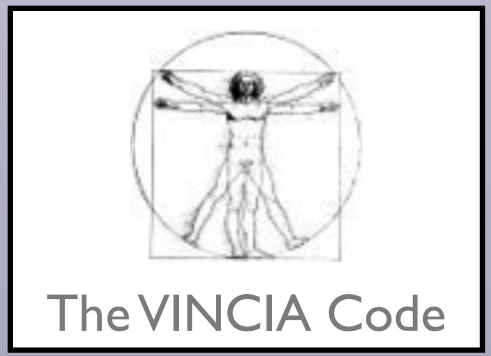

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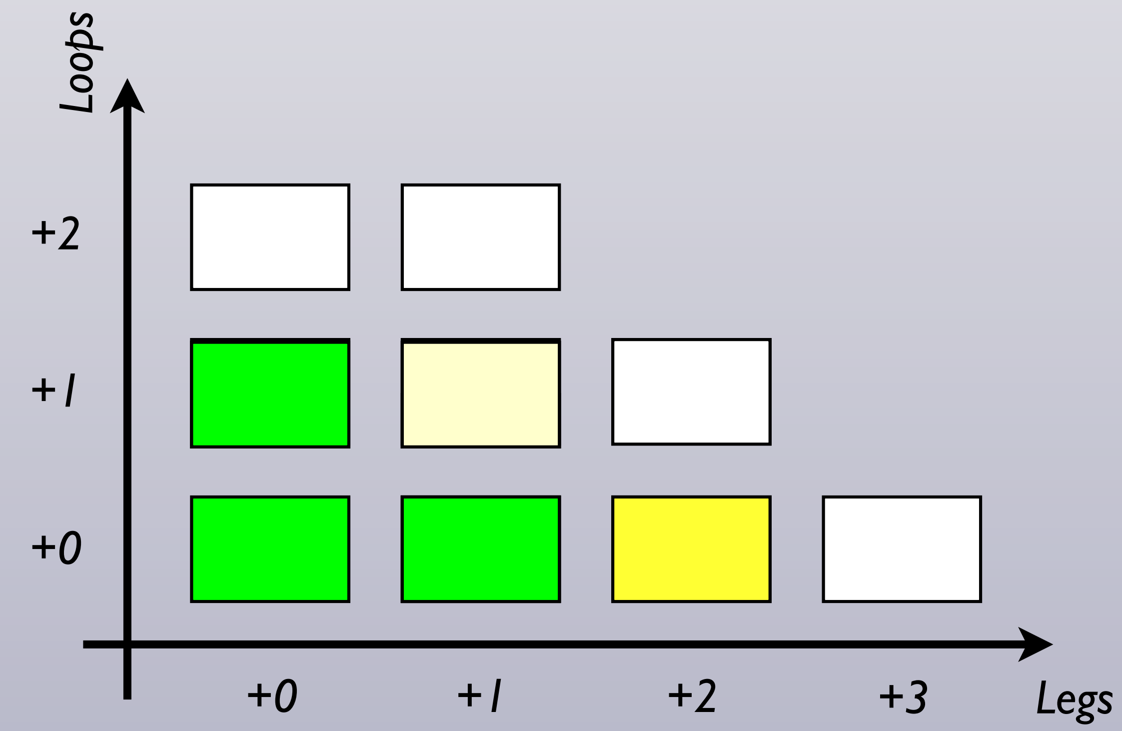

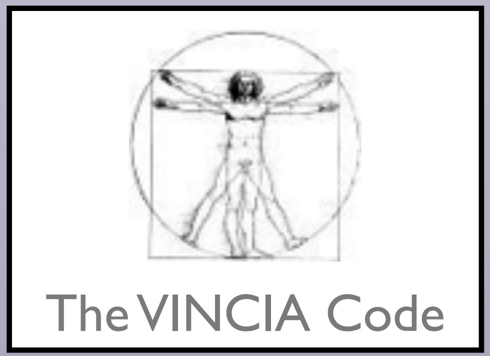

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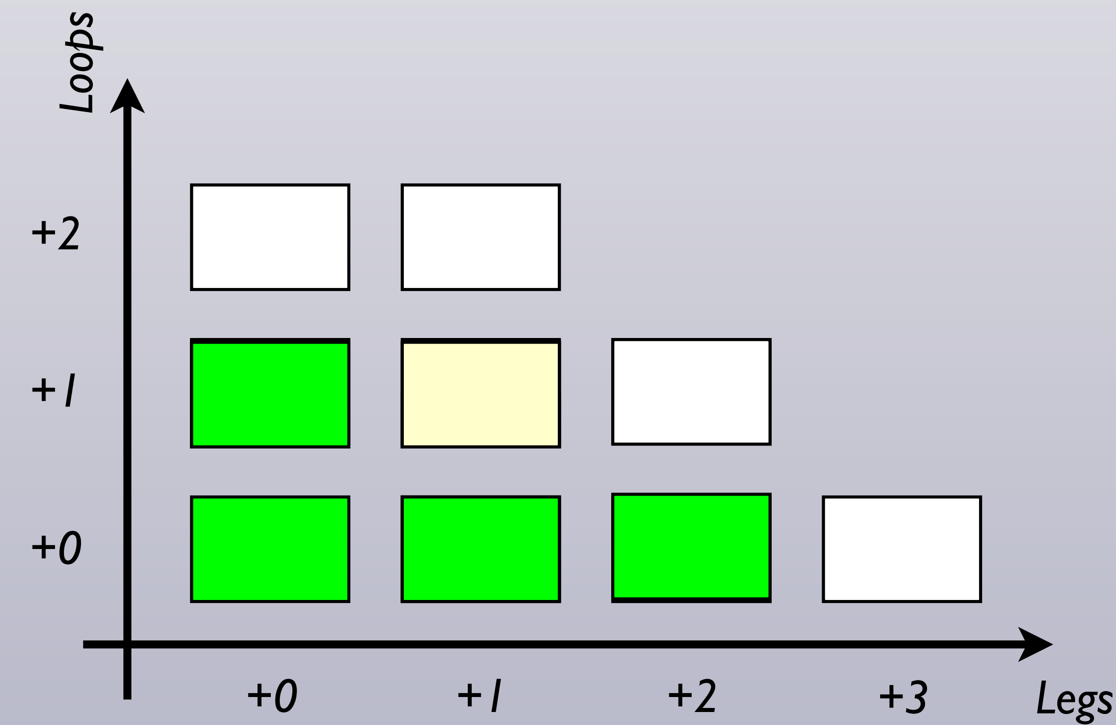

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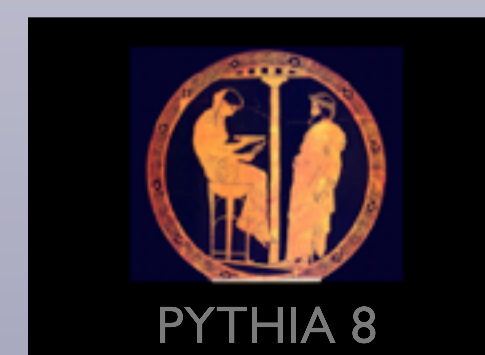

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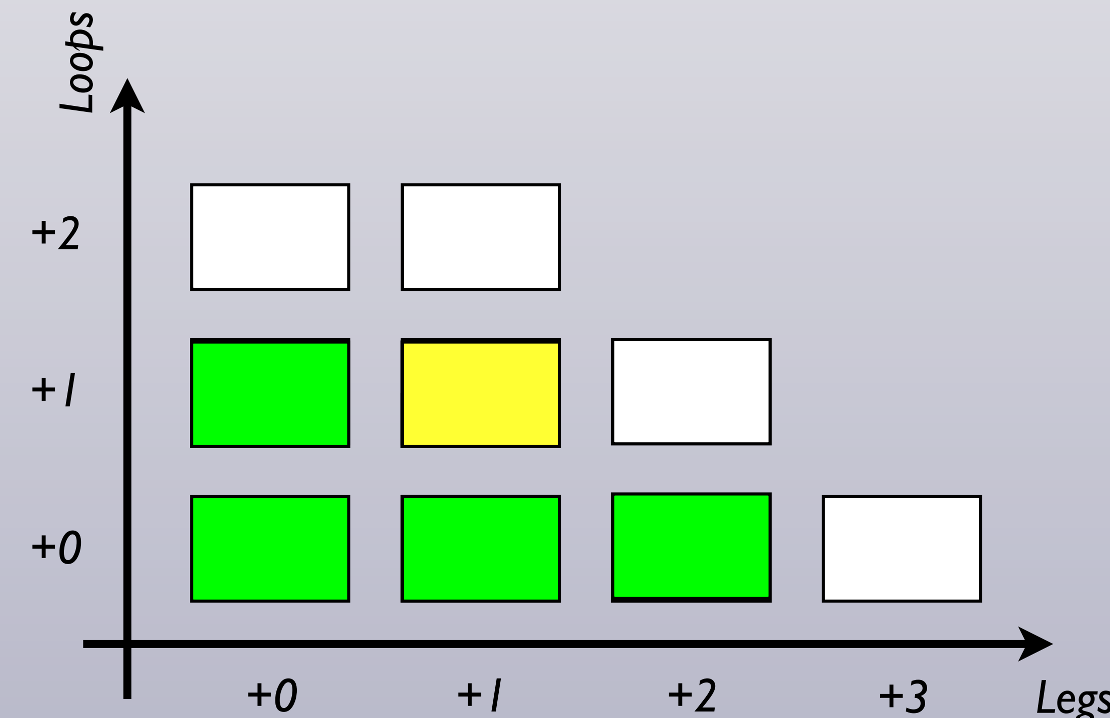

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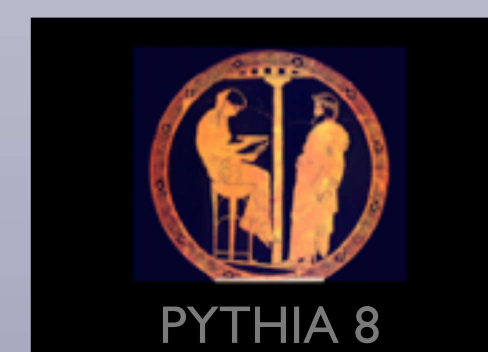

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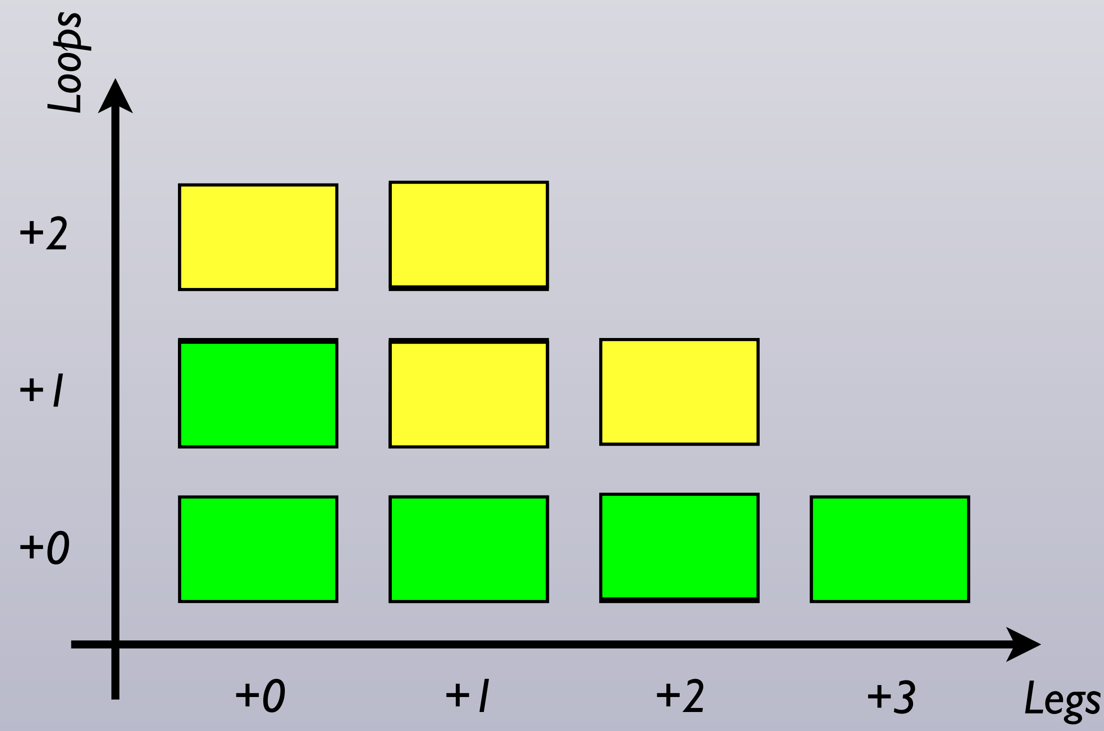

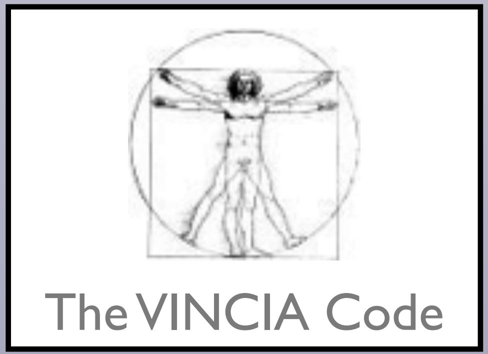

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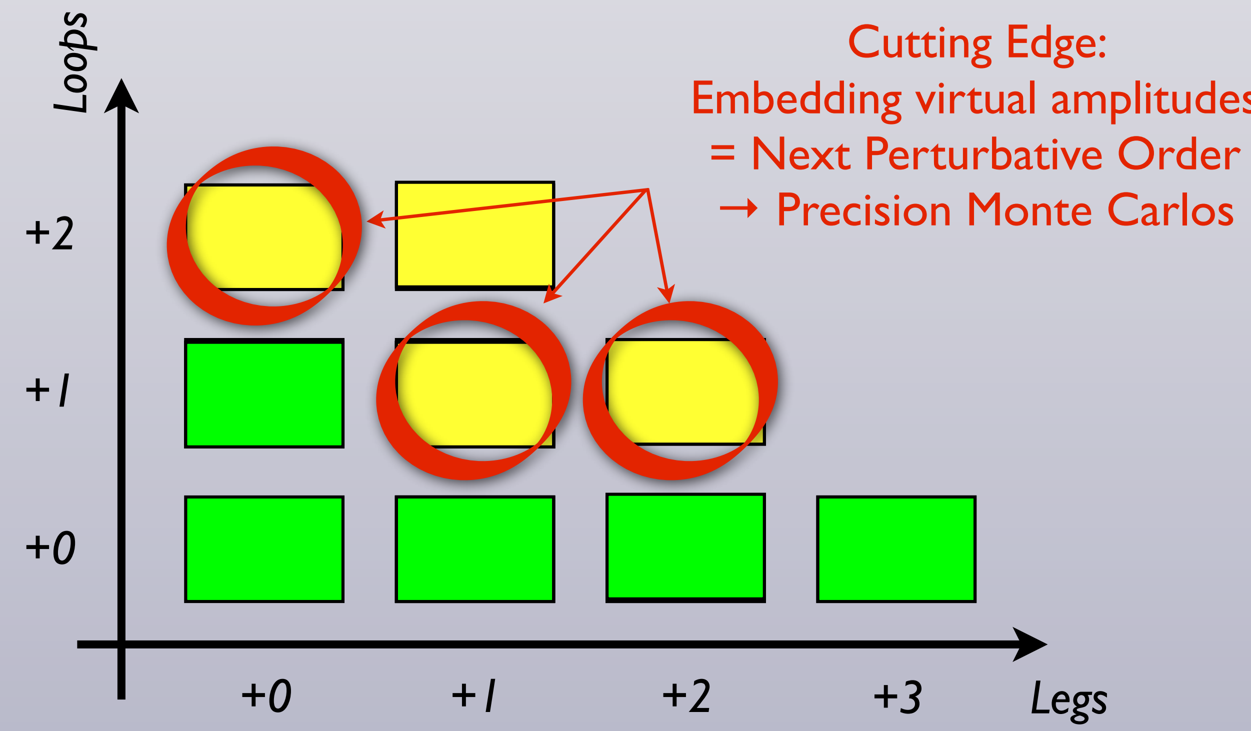

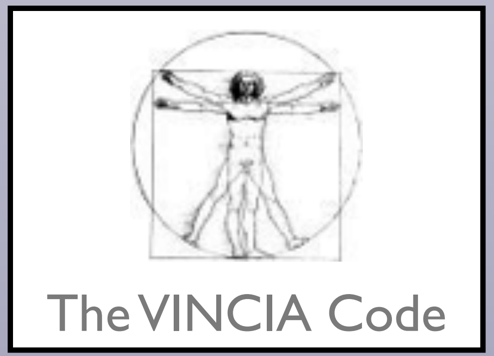

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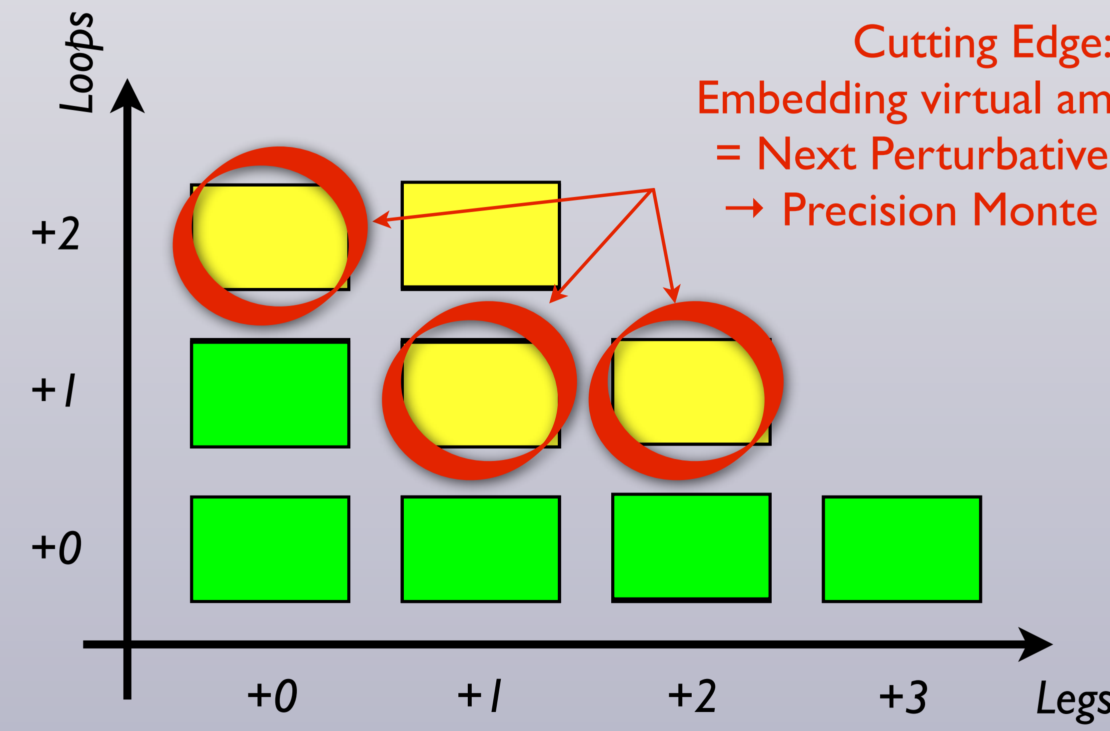
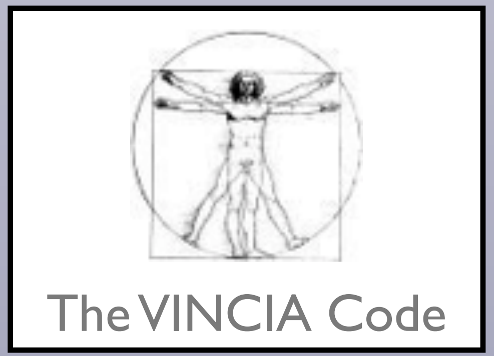


Cutting Edge:
Embedding virtual amplitudes
= Next Perturbative Order
→ Precision Monte Carlos



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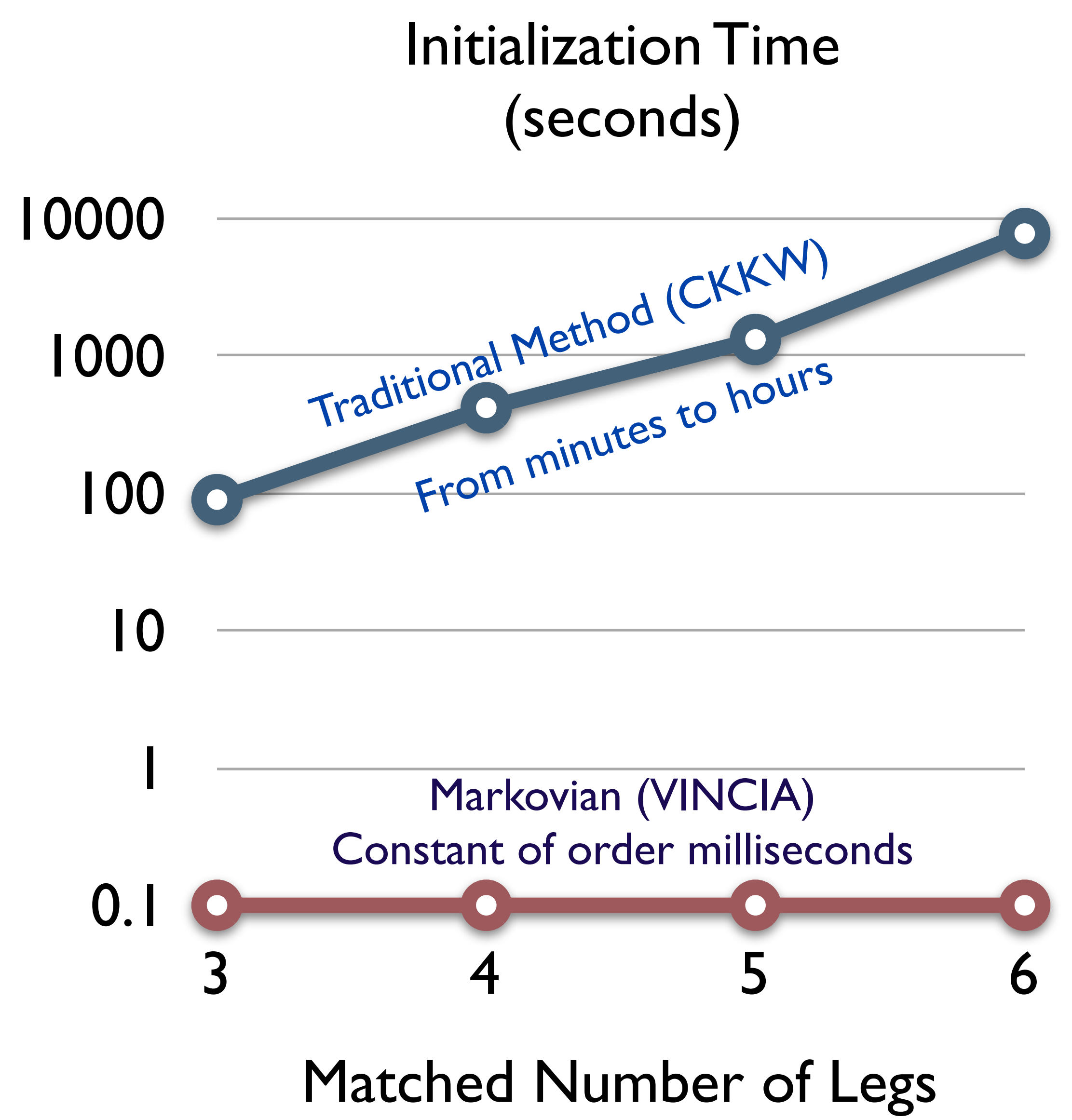
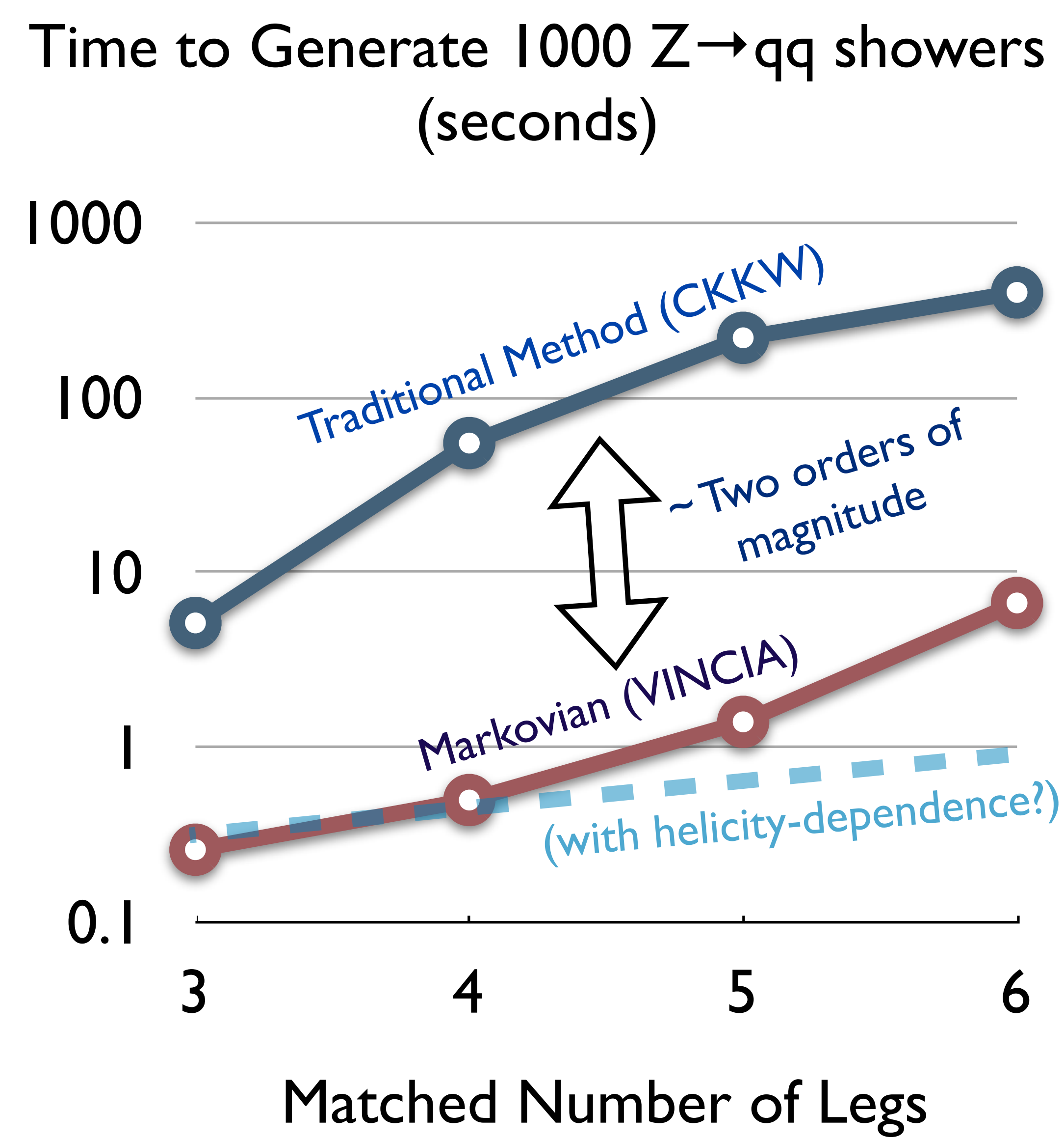
Note: other teams working on alternative strategies
Perturbation theory is solvable → expect improvements

Markov + Unitarity = SPEED

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





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

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

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

Soft QCD

Underlying-Event and Minimum-Bias

Multiple parton–parton interactions

Multi-parton PDFs constructed from (flavor and momentum) sum rules

Interleaved evolution in $p_\perp$ (partly new)

New: *Rescattering* ***[R. Corke]***

Beam remnants colour-connected to interacting systems, with String junctions

Defaults tuned to LHC (tune 4C)

Improved model of diffraction

Diffractive jet production ***[S. Navin]***

Output: Interface to HEPMC included

PYTHIA

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Hadronization

- String fragmentation
  - *Lund fragmentation function for (u,d,s) + Bowler for heavy quarks (c,b)*
- Hadron and Particle decays
  - *Usually isotropic, or:*
  - ***New**: Polarized τ decays*
  - *User decays (DecayHandler)*
  - *Link to external packages*
    - EVTGEN for B decays
    - TAUOLA for τ decays
- Bose-Einstein effects
  - *Two-particle model (off by default)*

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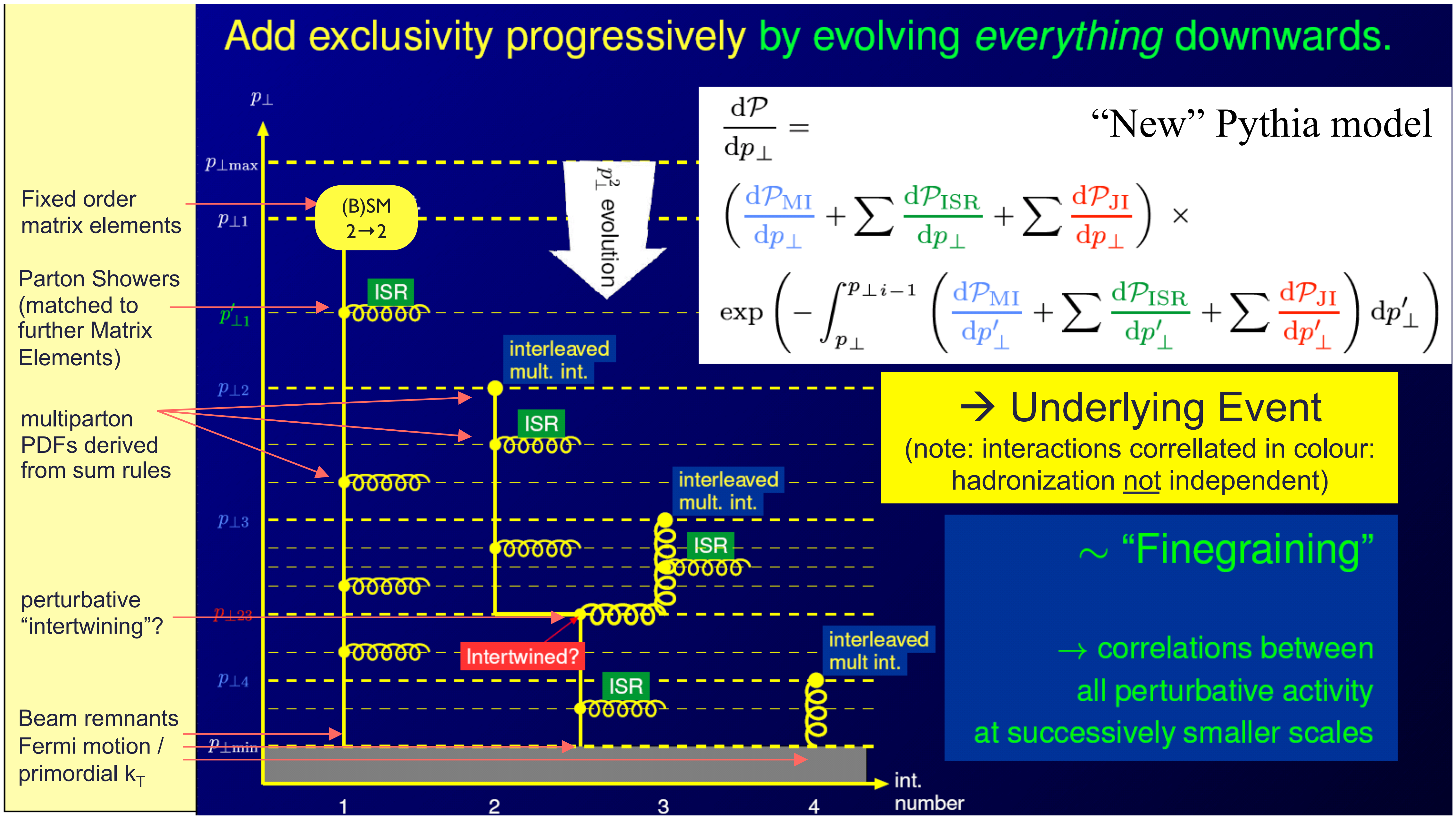
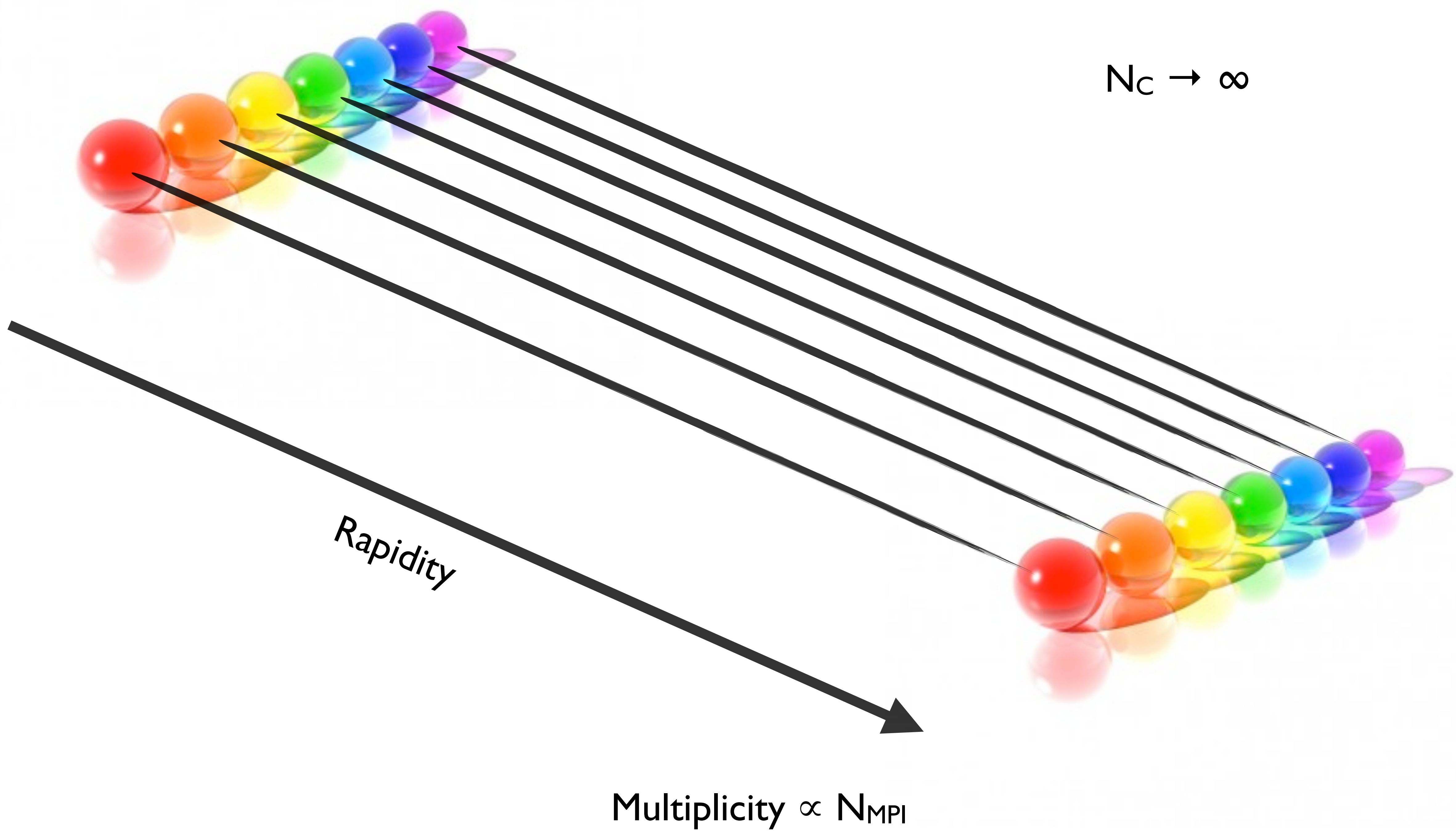
Interleaved Evolution

Sjöstrand, PS, JHEP 0403 (2004) 053; EPJ C39 (2005) 129
Corke, Sjöstrand, JHEP 1103 (2011) 032



+ (x,b) correlations Corke, Sjöstrand JHEP 1105 (2011) 009

Color Connections



Color Reconnections?

E.g.,
…
Generalized Area Law (Rathsman: Phys. Lett. B452 (1999) 364)
Color Annealing (P.S., Wicke: Eur. Phys. J. C52 (2007) 133)
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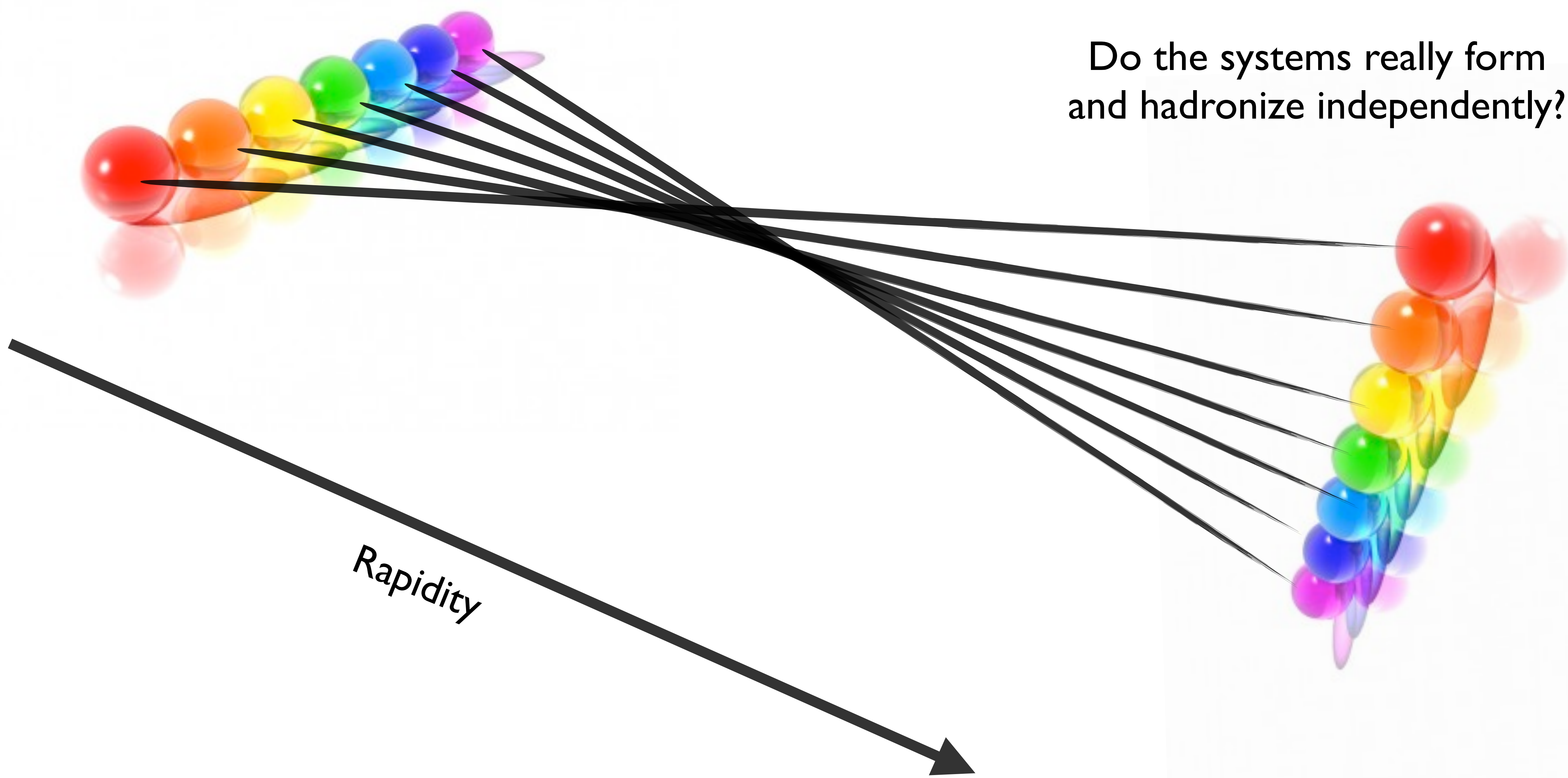
…

Better theory models needed

Do the systems really form
and hadronize independently?



Multiplicity $\overset{<}{\not\propto}$ N_{MPI}

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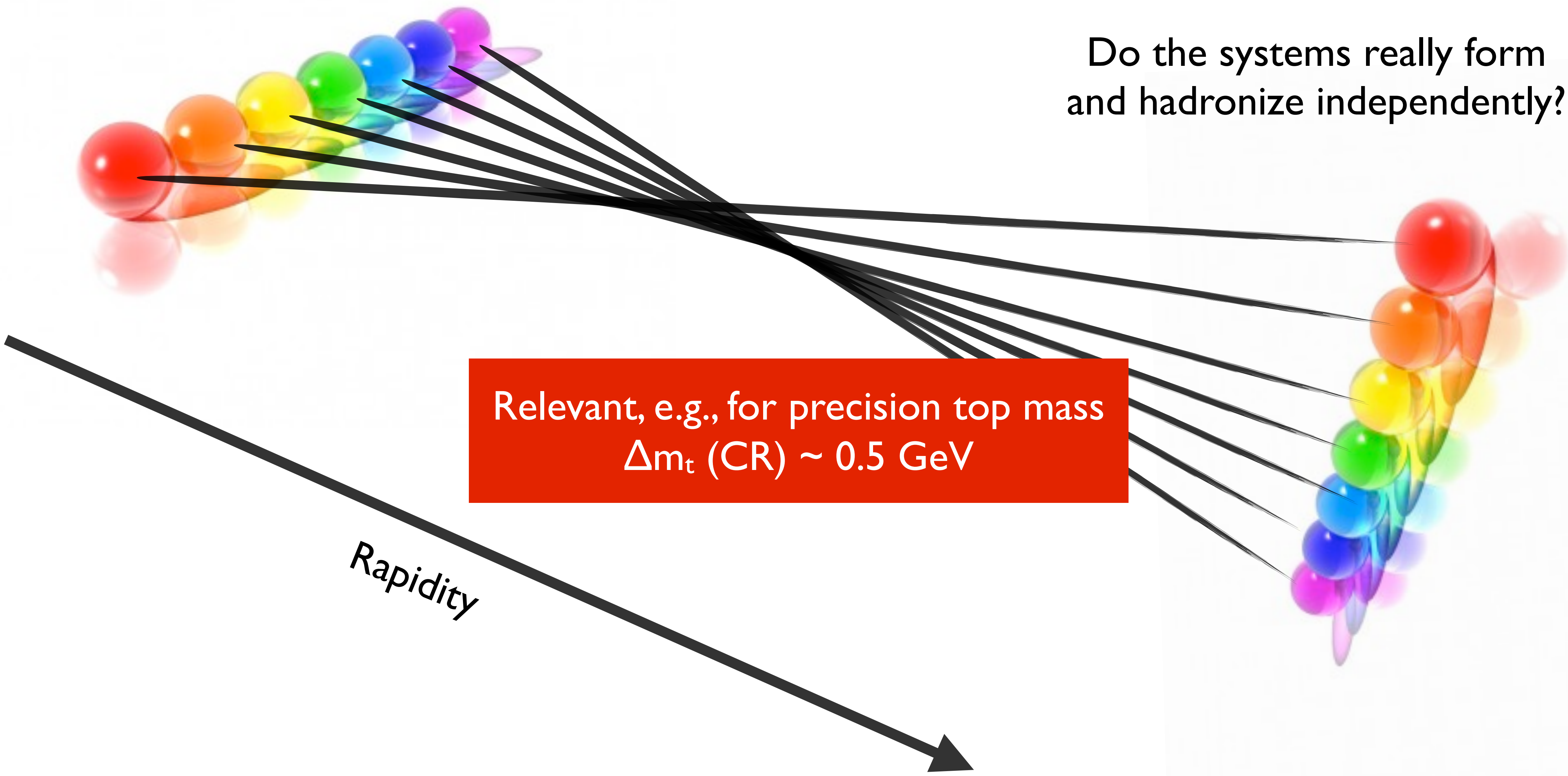

Relevant, e.g., for precision top mass
Δm_t (CR) ~ 0.5 GeV

Multiplicity $\overset{<}{\not\propto}$ N_{MPI}

Pythia 6: The Perugia Variations

Central Tune + 9 variations

Note: no variation of hadronization parameters! (sorry, ten was already a lot)

PS, PRD82 (2010) 074018

Perugia 2011 Tune Set

(350)	Perugia 2011	Central Perugia 2011 tune (CTEQ5L)	
(351)	Perugia 2011 radHi	Variation using $\alpha_s(\frac{1}{2}p_\perp)$ for ISR and FSR	Harder radiation
(352)	Perugia 2011 radLo	Variation using $\alpha_s(2p_\perp)$ for ISR and FSR	Softer radiation
(353)	Perugia 2011 mpiHi	Variation using $\Lambda_{\mathrm{QCD}} = 0.26\,\mathrm{GeV}$ also for MPI	UE more "jetty"
(354)	Perugia 2011 noCR	Variation without color reconnections	Softer hadrons
(355)	Perugia 2011 M	Variation using MRST LO** PDFs	UE more "jetty"
(356)	Perugia 2011 C	Variation using CTEQ 6L1 PDFs	Recommended
(357)	Perugia 2011 T16	Variation using PARP(90)=0.16 scaling away from 7 TeV	
(358)	Perugia 2011 T32	Variation using PARP(90)=0.32 scaling away from 7 TeV	
(359)	Perugia 2011 Tevatron	Variation optimized for Tevatron	~ low at LHC

Can be obtained in standalone Pythia from 6.4.25+

MSTP(5) = 350	MSTP(5) = 351	MSTP(5) = 352	MSTP(5) = …
Perugia 2011	Perugia 2011 radHi	Perugia 2011 radLo	…

PYTHIA

Summary

PYTHIA 6 is still going strong (sigh)

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No longer actively developed

F77 interfaces not very flexible, outmoded.

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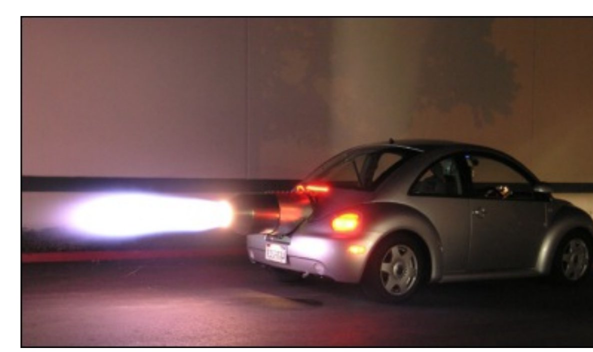

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Backup Slides

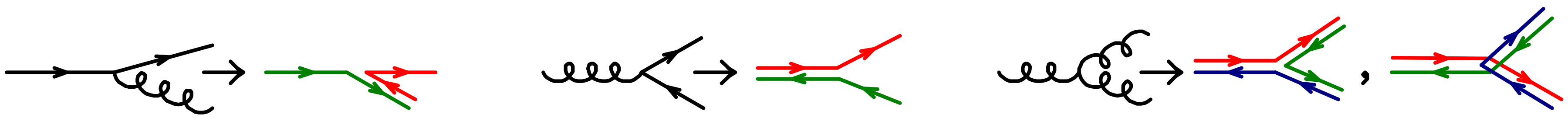
Color Flow in MC Models

"Planar Limit"

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

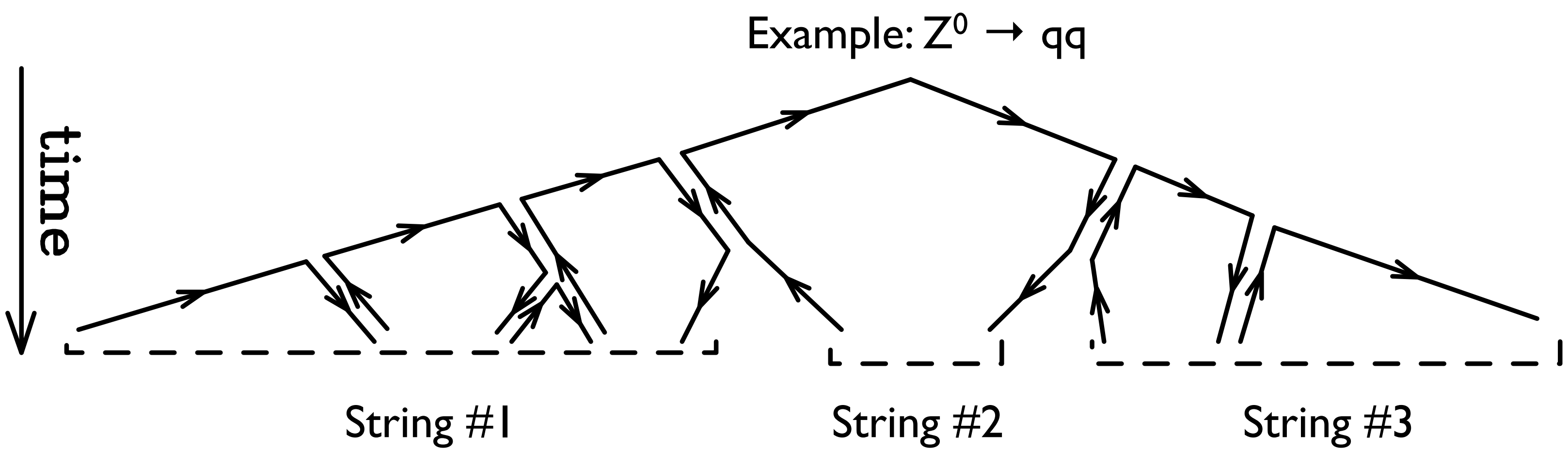
*) except as reflected by the implementation of QCD coherence effects in the Monte Carlos via angular or dipole ordering

Rules for color flow:



For an entire cascade:

Illustrations from: P.Nason & P.S., 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% ~ $1/N_c^2$)

Interfaces to External MEs (POWHEG/SCALUP)

Slide from T. Sjöstrand, TH-LPCC workshop, August 2011, CERN

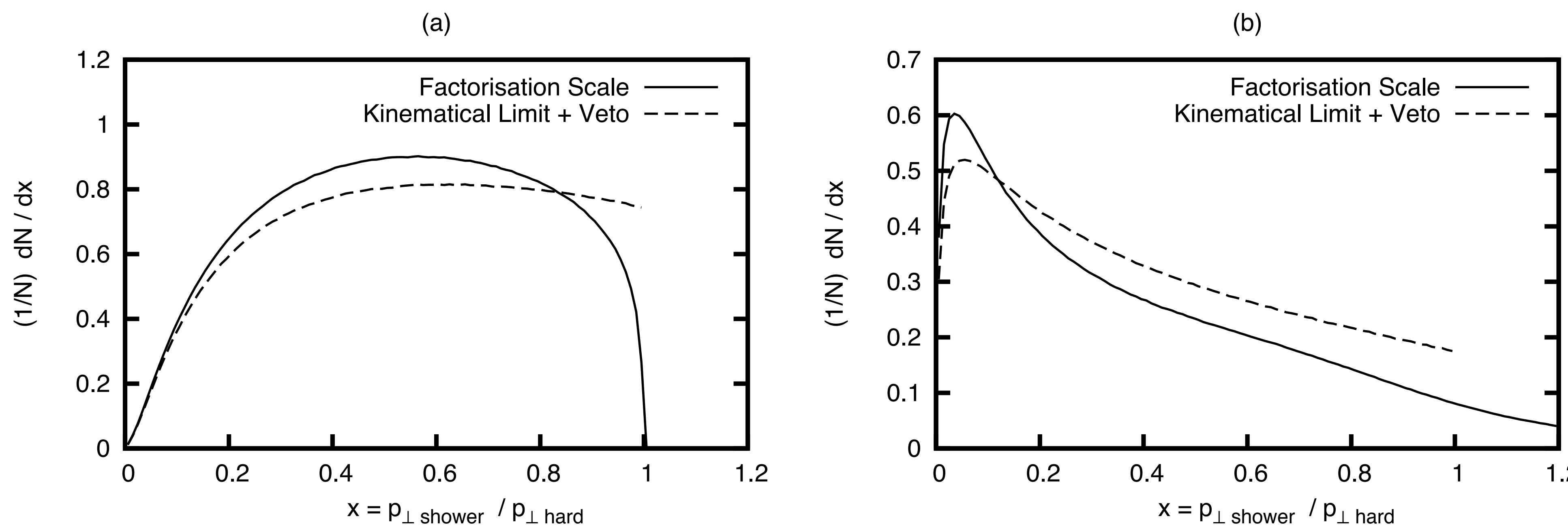
Standard Les Houches interface (LHA, LHEF) specifies startup scale `SCALUP` for showers, so "trivial" to interface any external program, including POWHEG.
Problem: for ISR

$$p_\perp^2 = p_{\perp\mathrm{evol}}^2 - \frac{p_{\perp\mathrm{evol}}^4}{p_{\perp\mathrm{evol,max}}^2}$$

$\int d\Phi_r \frac{R(v,r)}{B(v)} \theta(k_\mathrm{T}(v,r) - p_\mathrm{T})$

not needed if shower ordered in p_T?

i.e. $p_\perp$ decreases for $\theta^* > 90^\circ$ but $p_{\perp\mathrm{evol}}$ monotonously increasing.
Solution: run "power" shower but kill emissions above the hardest one, by POWHEG's definition.



Available for ISR-dominated, coming for QCD jets with FSR issues.

in PYTHIA 8

Note: Other things that may differ in comparisons: PDFs (NLO vs LO), Scale Choices

PYTHIA

Interfaces to External MEs (MLM)

B. Cooper et al., arXiv:1109.5295 [hep-ph]

If using one code for MEs and another for showering

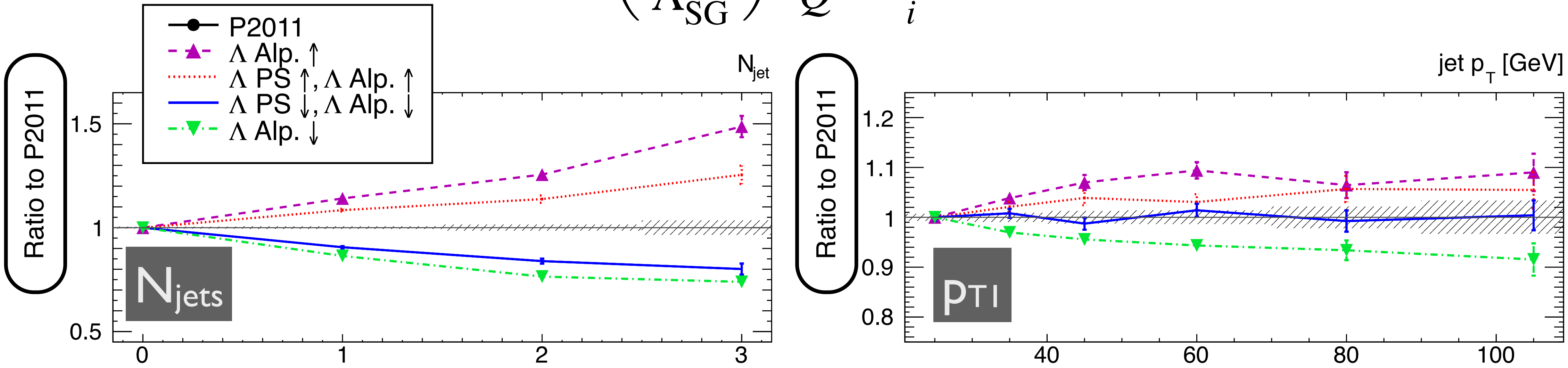
Tree-level corrections use α_s from Matrix-element Generator

Virtual corrections use α_s from Shower Generator (Sudakov)

Mismatch if the two do not use same Λ_{QCD} or $\alpha_s(m_Z)$

$$\alpha_s^2 \, b_0 \ln\left(\frac{\Lambda^2_{\rm MG}}{\Lambda^2_{\rm SG}}\right) \frac{dQ^2}{Q^2} \sum_i P_i(z) \, |M_F|^2 \, .$$

note: running **order** also has a (subleading) effect



AlpGen: can set xlclu = Λ_{QCD} since v.2.14 (default remains to inherit from PDF)
Pythia 6: set common PARP(61)=PARP(72)=PARP(81) = Λ_{QCD} in Perugia 2011 tunes
Pythia 8: use TimeShower:alphaSvalue and SpaceShower:alphaSvalue

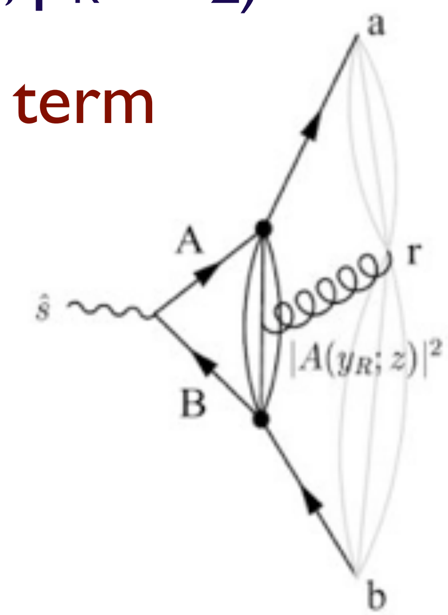
Scales: pT and CMW

Compute $e^+e^- \rightarrow 3$ jets, for arbitrary choice of μ_R (e.g., $\mu_R = m_Z$)

One-loop correction $2\mathrm{Re}[M^0 M^{1*}]$ includes a universal $O(\alpha_s^2)$ term from integrating quark loops over all of phase space

$$n_f \ A_3^0 \left(\ln\left(\frac{s_{23}}{\mu_R^2}\right) + \ln\left(\frac{s_{13}}{\mu_R^2}\right) \right)$$

+ gluon loops



Proportional to the β function (b_0).

Can be absorbed by using $\mu_R^4 = s_{13}\, s_{23} = p_T^2\, s$. (~ "BLM")

In an ordered shower, quark (and gluon) loops restricted by strong-ordering condition → modified to

$\mu_R = p_T$ (but depends on ordering variable?)

Additional logs induced by gluon loops can be absorbed by replacing Λ^{MS} by $\Lambda^{MC} \sim 1.5\ \Lambda^{MS}$ (with mild dependence on number of flavors)

Catani, Marchesini, Webber, NPB349 (1991) 635

There are obviously still order 2 uncertainties on μ_R, but this is the background for the central choice made in showers

Tuning

1. Fragmentation Tuning

Perturbative: jet radiation, jet broadening, jet structure

Non-perturbative: hadronization modeling & parameters

2. Initial-State Tuning

Perturbative: initial-state radiation, initial-final interference

Non-perturbative: PDFs, primordial k_T

3. Underlying-Event & Min-Bias Tuning

Perturbative: Multi-parton interactions, rescattering

Non-perturbative: Multi-parton PDFs, Beam Remnant fragmentation, Color (re)connections, collective effects, impact parameter dependence, …

PYTHIA Models

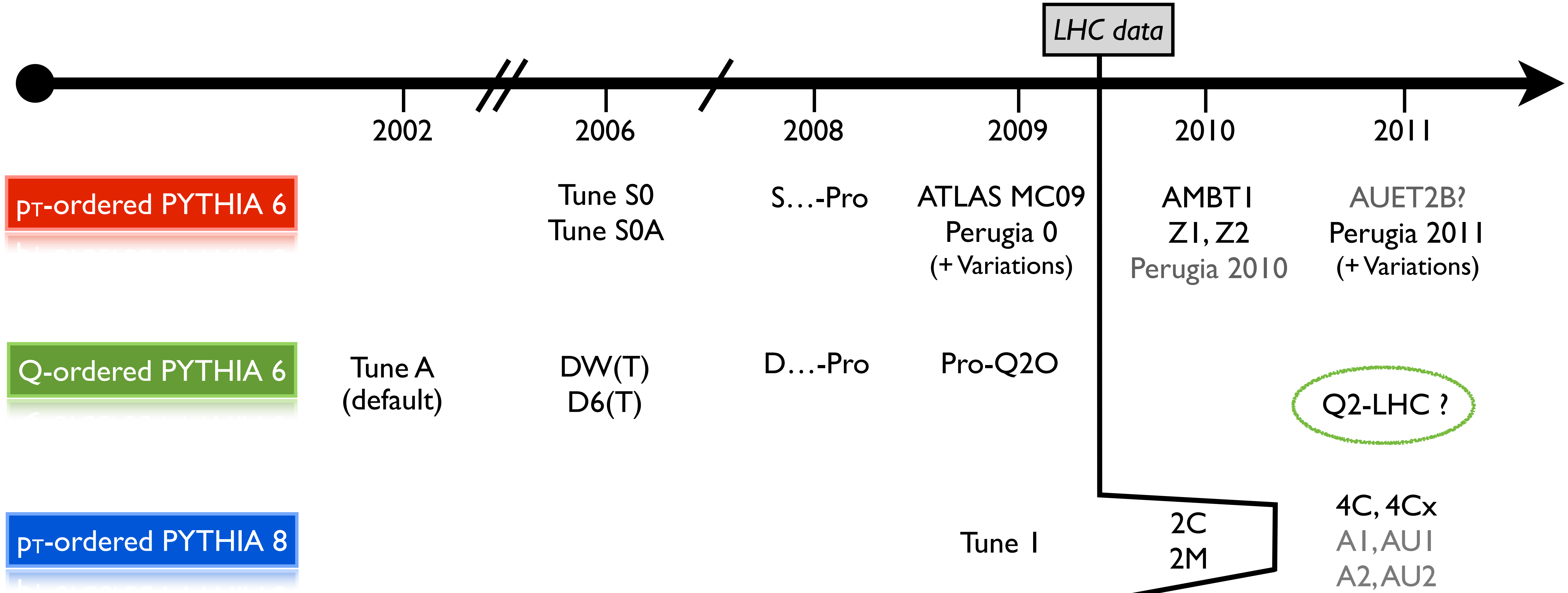
LHC data (starting between 2009 and 2010)

	2002	2006	2008	2009	2010	2011
pT-ordered PYTHIA 6		Tune S0 Tune S0A	S…-Pro	ATLAS MC09 Perugia 0 (+ Variations)	AMBT1 Z1, Z2 Perugia 2010	AUET2B? Perugia 2011 (+ Variations)
Q-ordered PYTHIA 6	Tune A (default)	DW(T) D6(T)	D…-Pro	Pro-Q2O		Q2-LHC ?
pT-ordered PYTHIA 8				Tune 1	2C 2M	4C, 4Cx A1, AU1 A2, AU2

Note: tunes differ significantly in which data sets they include

- LEP fragmentation parameters
- Level of Underlying Event & Minimum-bias Tails
- Soft part of Drell-Yan p_T spectrum

PYTHIA Models



Main Data Sets included in each Tune (no guarantee that all subsets ok)

	A	DW, D6, …	S0, S0A	MC09(c)	Pro-…, Perugia 0, Tune 1, 2C, 2M	AMBT1	Perugia 2010	Perugia 2011	Z1, Z2	4C, 4Cx	AUET2B, A2, AU2
LEP					✔		✔	✔		✔	✔
TeV MB			✔	✔	✔		✔	✔		(✔)	?
TeV UE	✔	✔		✔	✔		✔	✔		(✔)	✔?
TeV DY		✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
LHC MB						✔	✔	✔		✔	?
LHC UE								✔	✔		✔

Example: pQCD Shower Tuning

Main 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 αs

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

Matching

Additional Matrix Elements included?

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

Subleading Logs

Ordering variable, coherence treatment, effective $1\to3$ (or $2\to4$), recoil strategy, etc

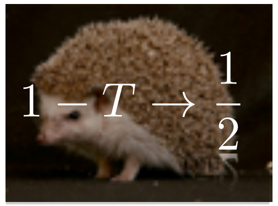
PYTHIA

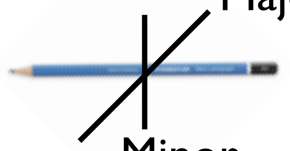
Need IR Corrections?

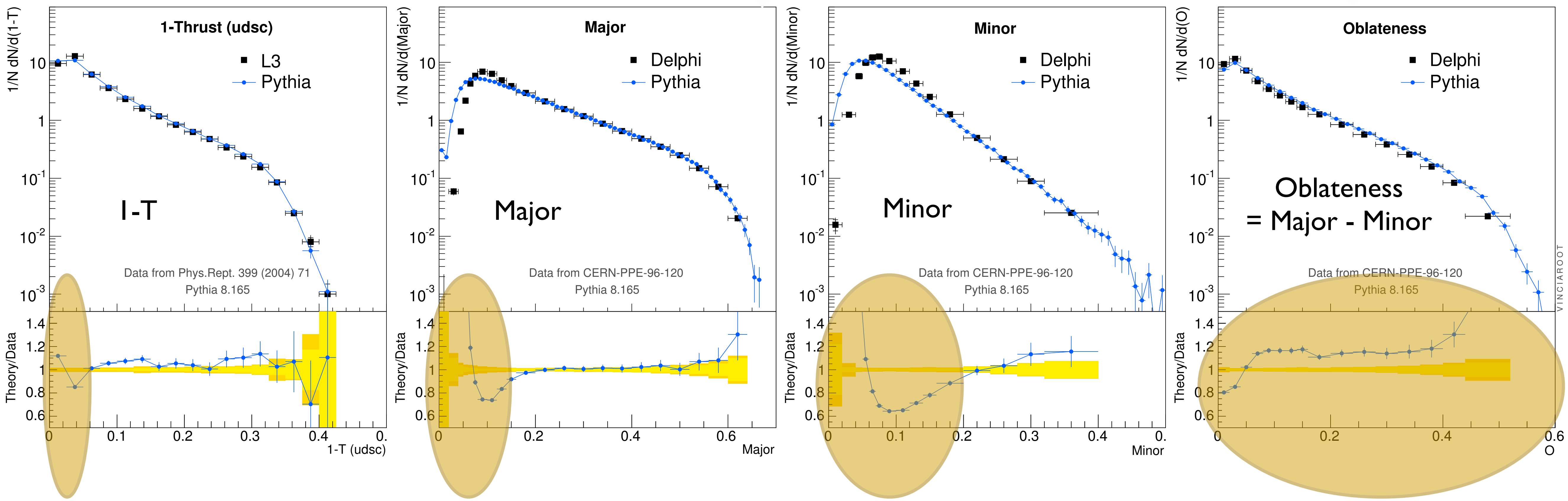
PYTHIA 8 (hadronization off) **vs LEP: Thrust**

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

$1 - T \rightarrow 0$







Significant Discrepancies (>10%)

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

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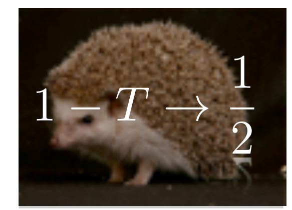

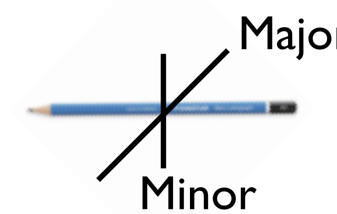

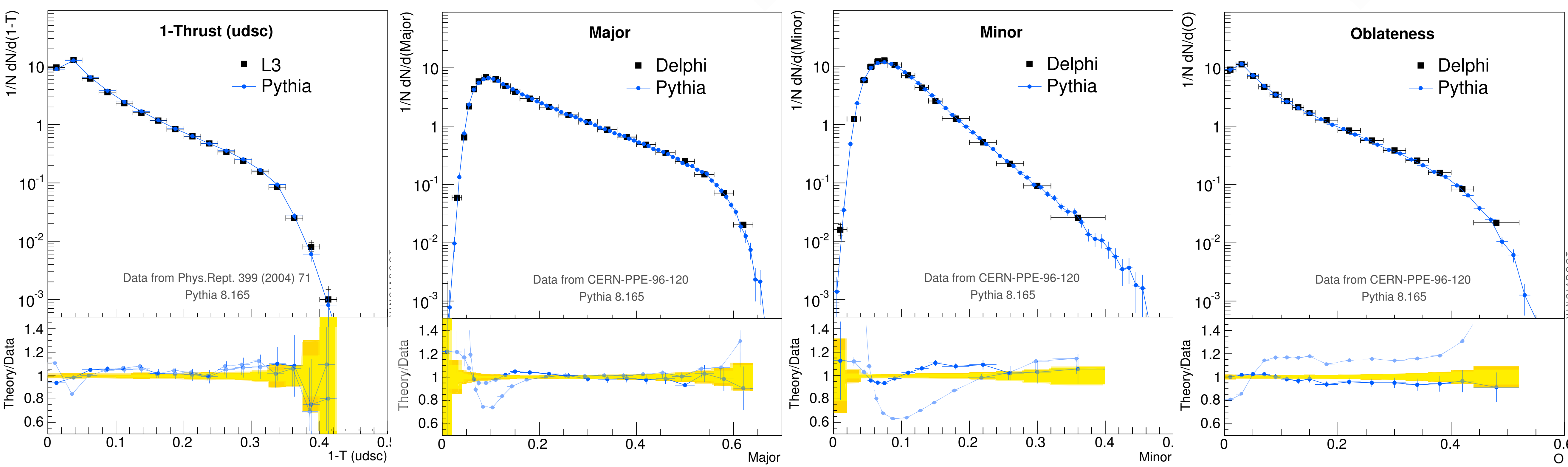

Need IR Corrections?

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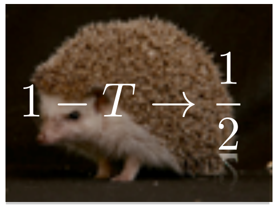

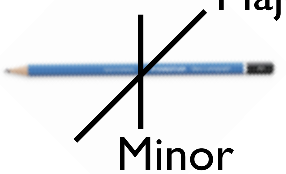

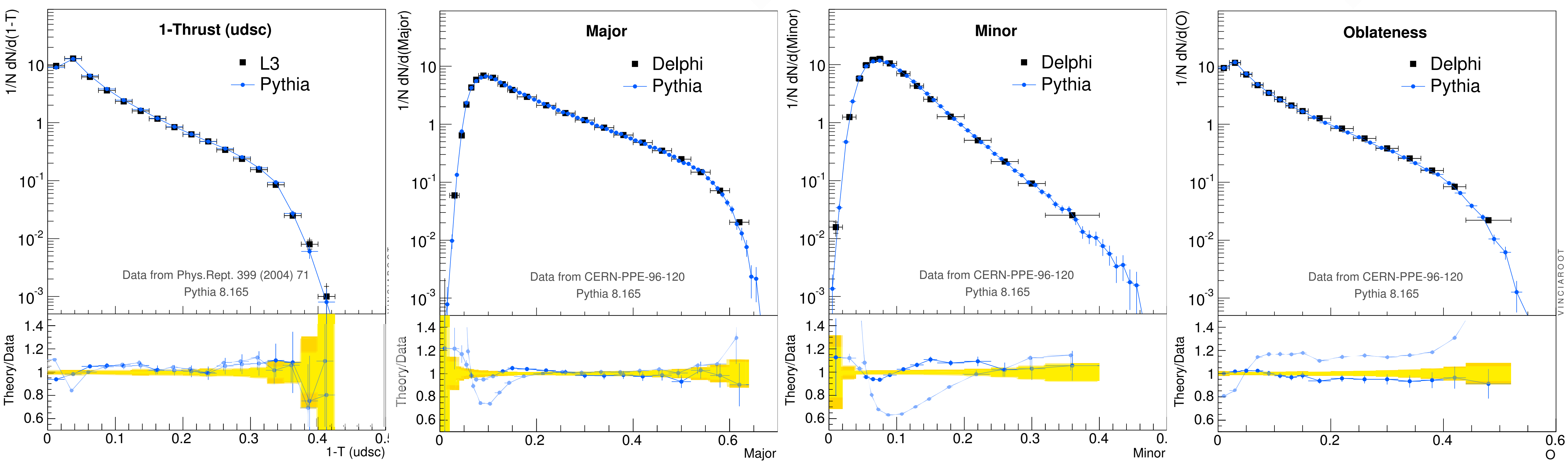

Note: Value of Strong coupling is
$\alpha_s(M_Z) = 0.14$

PYTHIA

Value of Strong Coupling

PYTHIA 8 (hadronization on) vs LEP: Thrust

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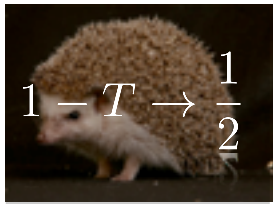
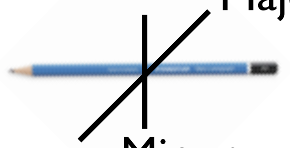
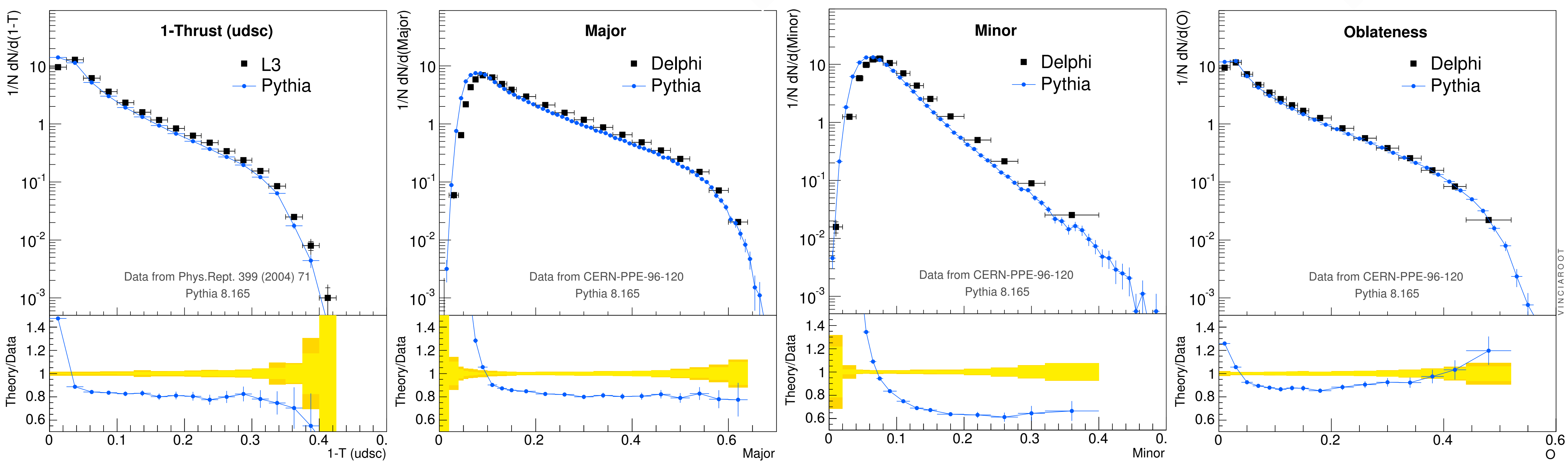
$1 - T \rightarrow 0$







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

PYTHIA

Wait … is this Crazy?

PYTHIA

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Best result

Obtained with $\alpha_s(M_Z) \approx 0.14 \neq$ World Average = 0.1176 ± 0.0020

PYTHIA

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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 ?

PYTHIA

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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')

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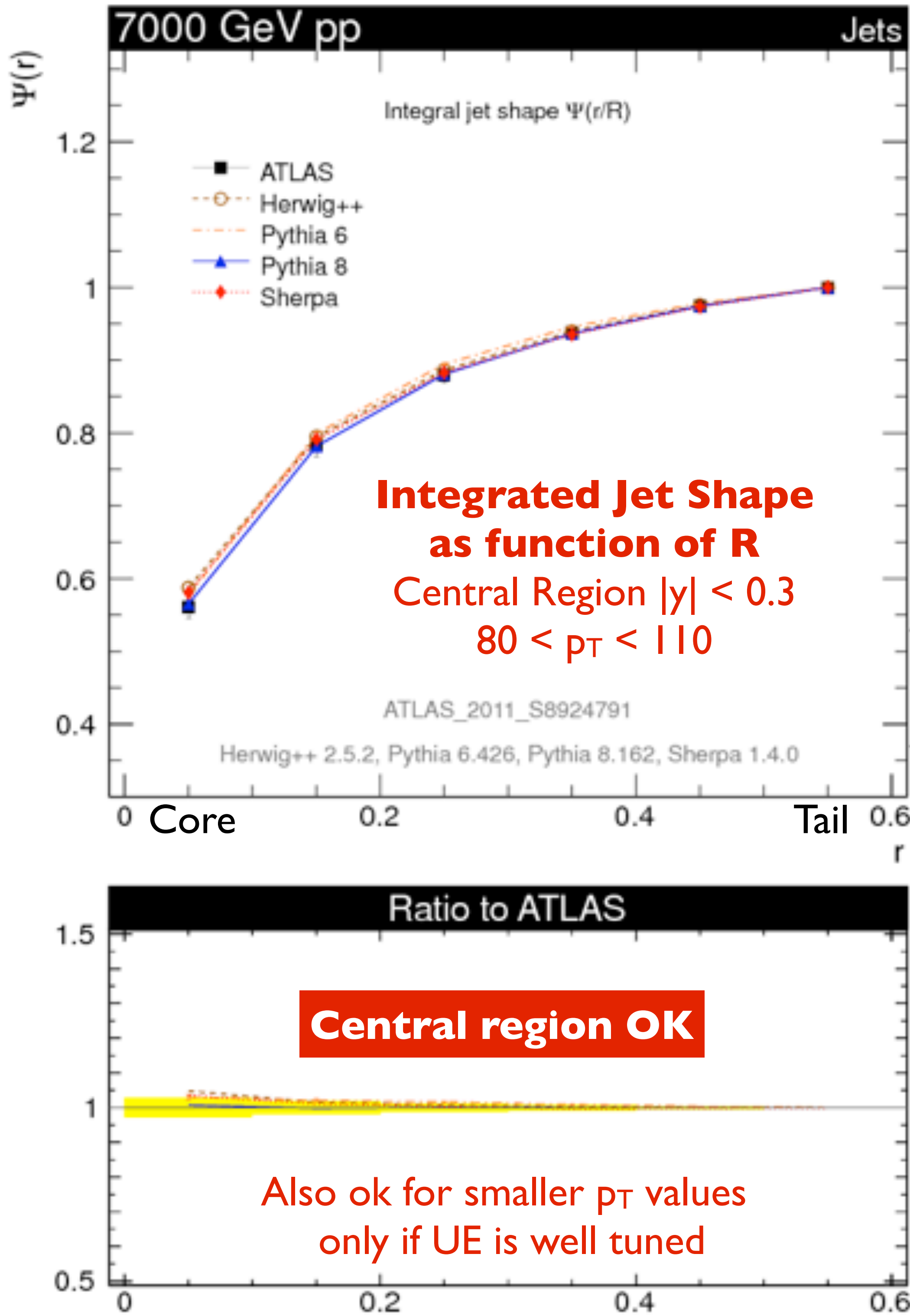
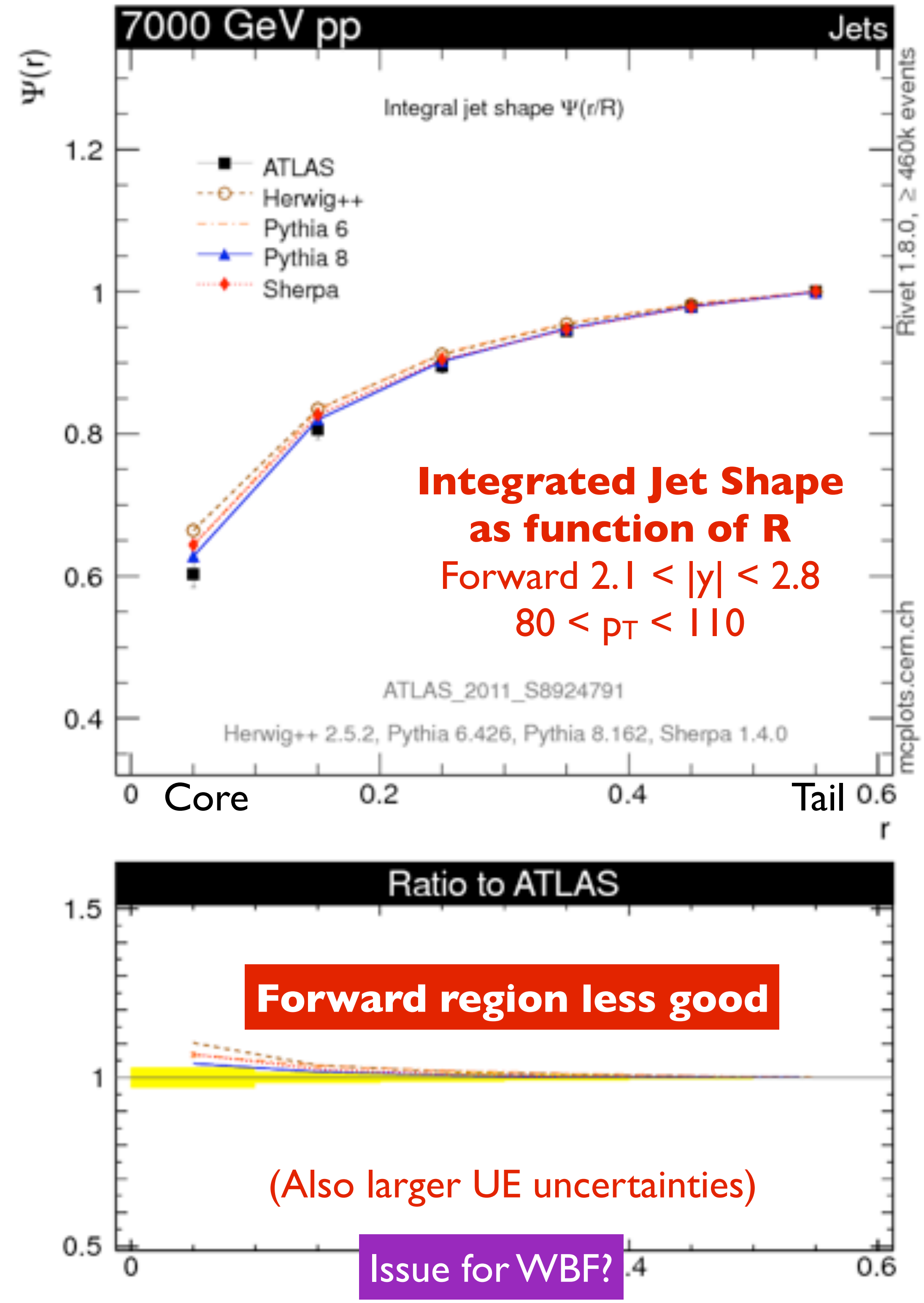
Improve → Matching at LO and NLO
Non-perturbative → Lecture on IR

PYTHIA

FSR: Jet Shapes



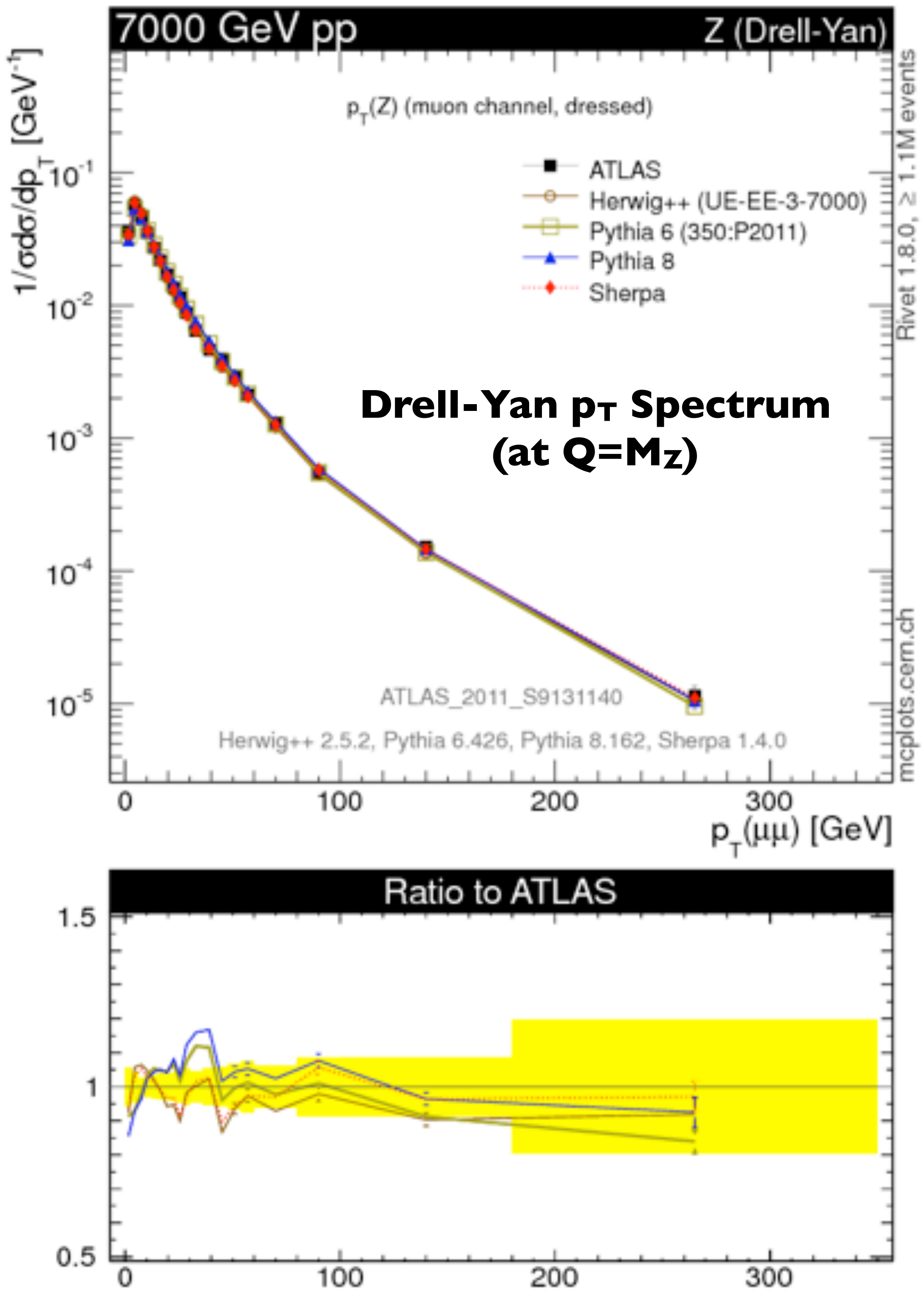


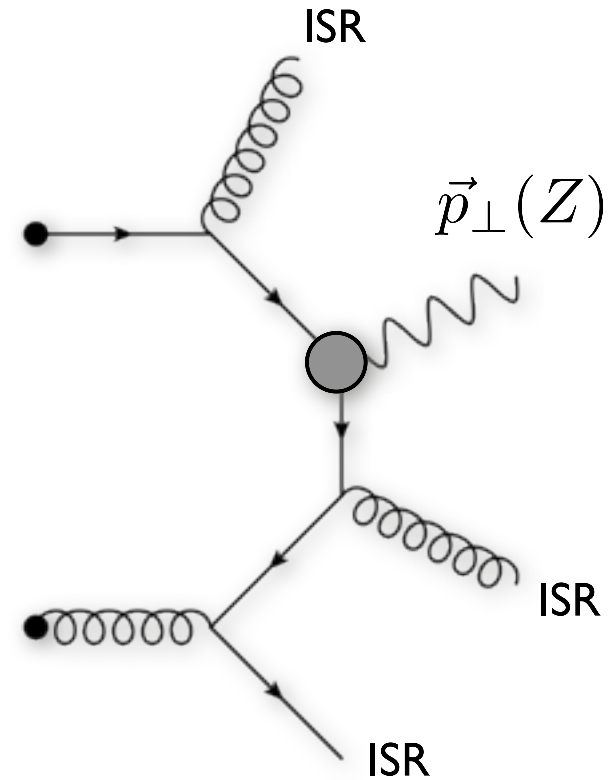
Plots from mcplots.cern.ch

ISR*: Drell-Yan p_T

ATLAS: arXiv:1107.2381
CMS: arXiv:1110.4973

*From Quarks, at $Q=M_Z$





$$\vec{p}_\perp(Z) \sim \sum_{j \in jets} \vec{p}_\perp(j)$$

Particularly sensitive to

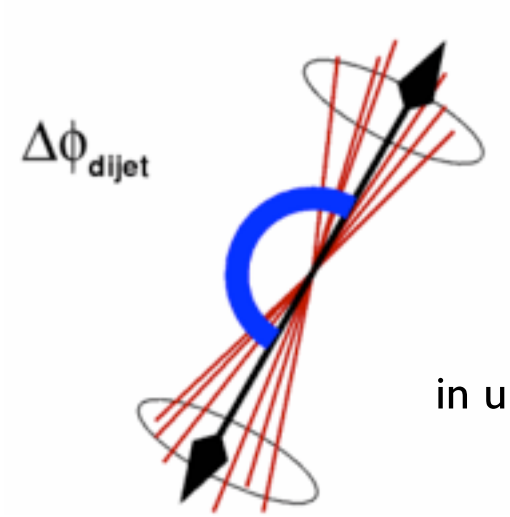
1. α_s renormalization scale choice
2. Recoil strategy (color dipoles vs global vs …)
3. FSR off ISR (ISR jet broadening)

Non-trivial result that modern GPMC shower models all reproduce it ~ correctly

Note: old PYTHIA 6 model (Tune A) did not give correct distribution, except with extreme μ_R choice (DW, D6, Pro-Q20)

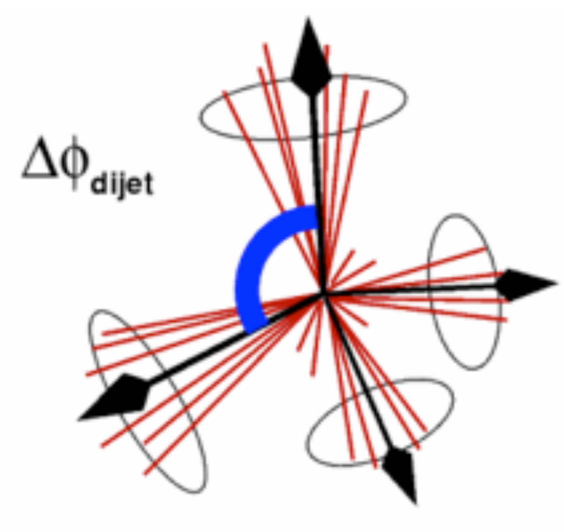
Plots from mcplots.cern.ch

ISR: Dijet Decorrelation



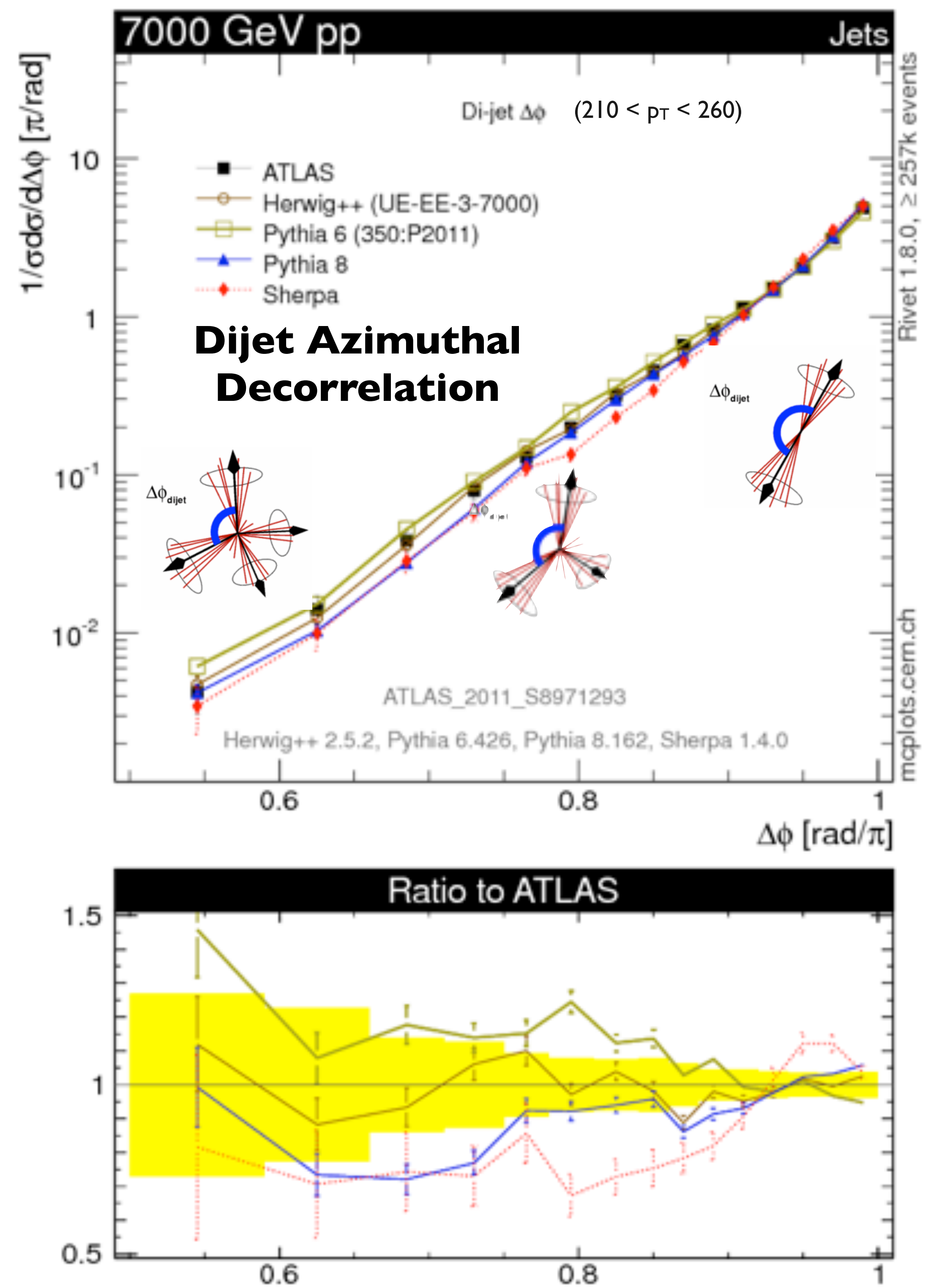
~ 1

in units of 180 degrees



$\sim \frac{1}{2}$

ATLAS Phys.Rev.Lett. 106 (2011) 172002



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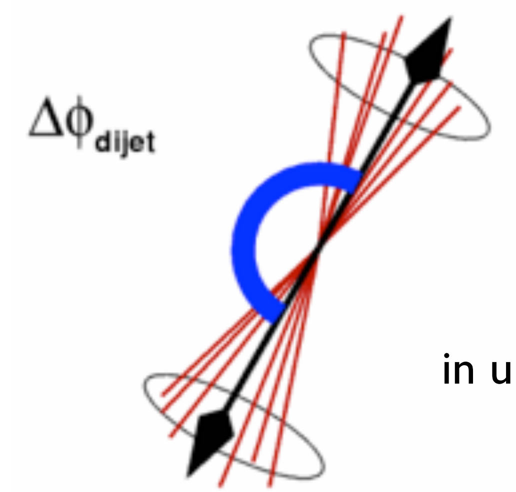
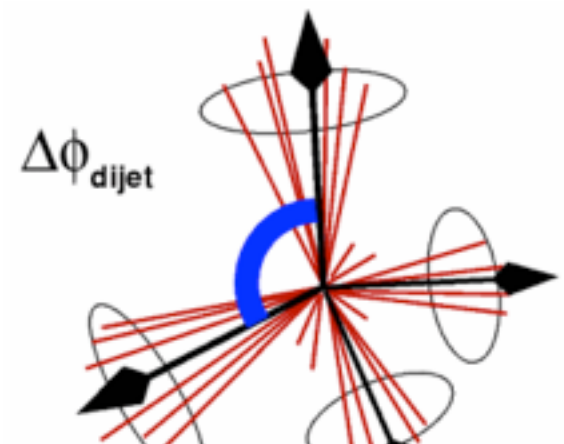


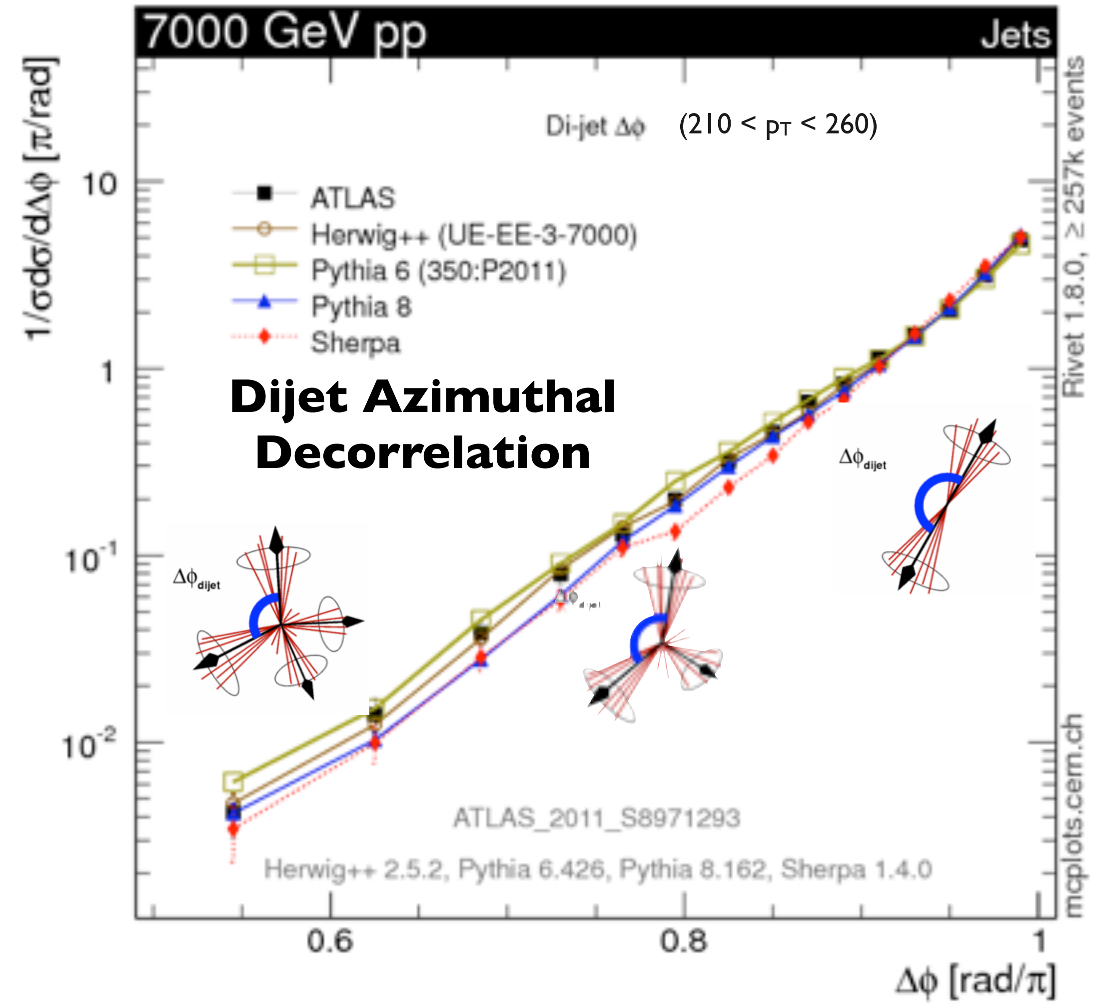
~ 1

in units of 180 degrees



~ ½

ATLAS Phys.Rev.Lett. 106 (2011) 172002



IR Safe Summary (ISR/FSR)**:**

LO + showers *generally* in good *O(20%)* agreement with LHC *(modulo bad tunes, pathological cases)*

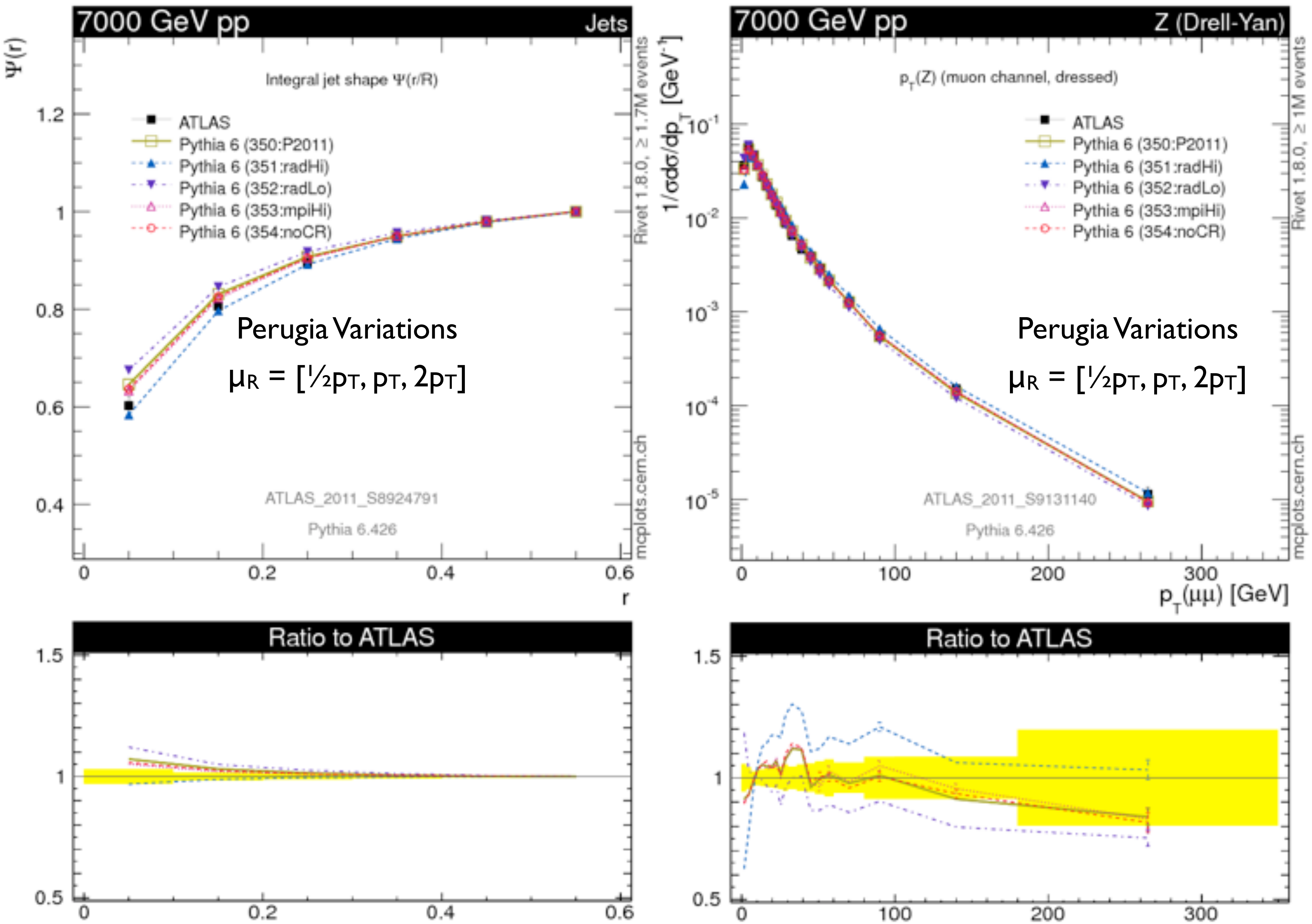
Room for improvement: Quantification of *uncertainties* is still more art than science.

Cutting Edge: multi-jet matching at NLO and systematic NLL showering

Bottom Line: perturbation theory is solvable. Expect progress.

Uncertainties

Buckley et al. (Professor) *"Systematic Event Generator Tuning for LHC"*, EPJC65 (2010) 331
P.S. *"Tuning MC Event Generators: The Perugia Tunes"*, PRD82 (2010) 074018
Schulz, P.S. *"Energy Scaling of Minimum-Bias Tunes"*, EPJC71 (2011) 1644
Giele, Kosower, P.S. *"Higher-Order Corrections to Timelike Jets"*, PRD84 (2011) 054003



Variation of μ_R here done for ISR + FSR together (theoretically consistent, but may not be most conservative?)

+ Similar variations for PDFs (CTEQ vs MSTW) Amount of MPI, Color reconnections, Energy scaling

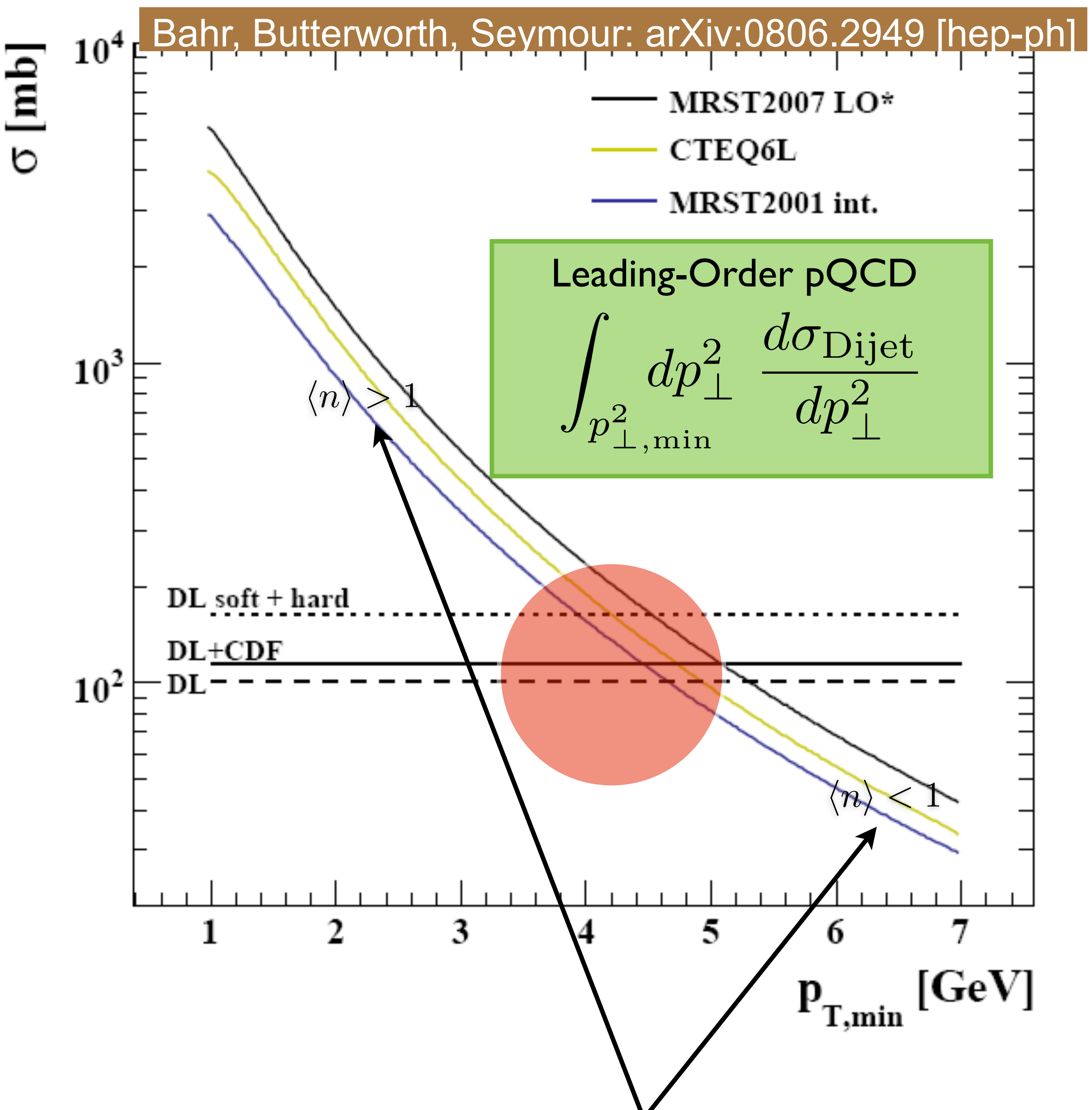
+ Variations of Fragmentation parameters (IR sensitive) on the way

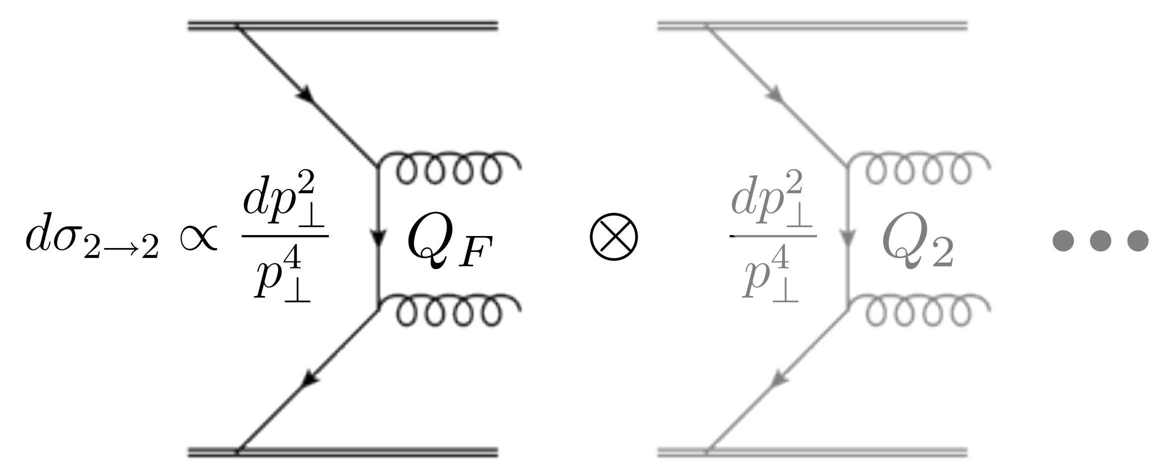
Plots from mcplots.cern.ch

Multiple Interactions

= Allow several parton-parton interactions per hadron-hadron collision. Requires extended factorization ansatz.

Earliest MC model ("old" PYTHIA 6 model)
Sjöstrand, van Zijl PRD36 (1987) 2019





Lesson from bremsstrahlung in pQCD: divergences → fixed-order breaks down
Perturbation theory still ok, with resummation (unitarity)

→ Resum dijets?
Yes → MPI!

$$\sigma_{2\to 2}(p_{\perp\min}) = \langle n \rangle (p_{\perp\min})\ \sigma_{\mathrm{tot}}$$

Parton-Parton Cross Section | Hadron-Hadron Cross Section

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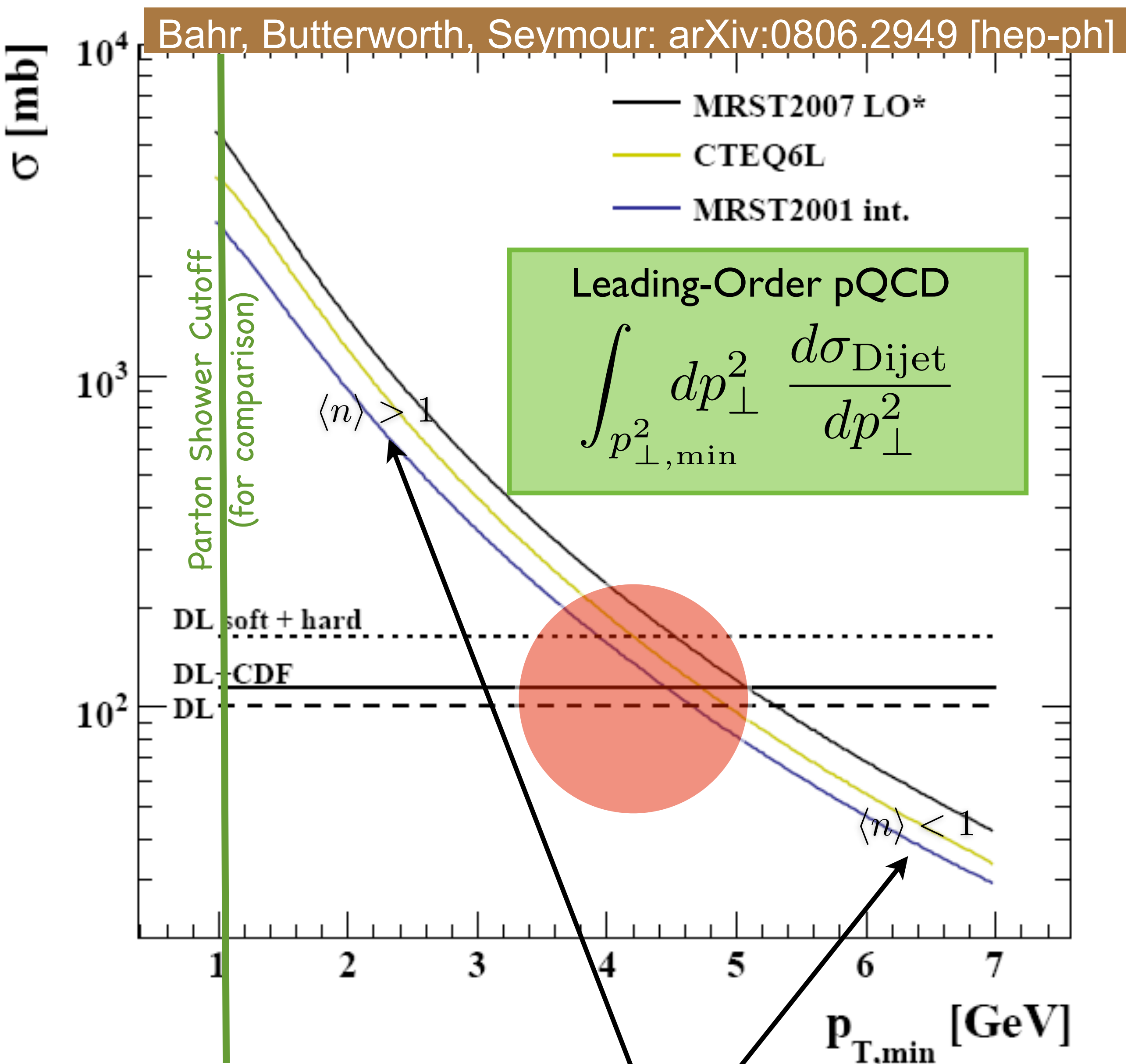
= Allow several parton-parton interactions per hadron-hadron collision. Requires extended factorization ansatz.



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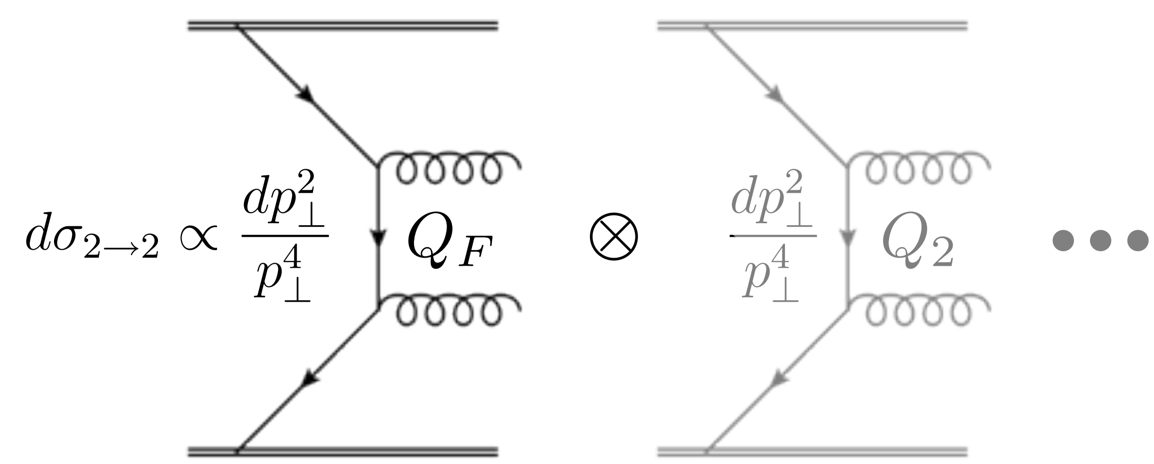

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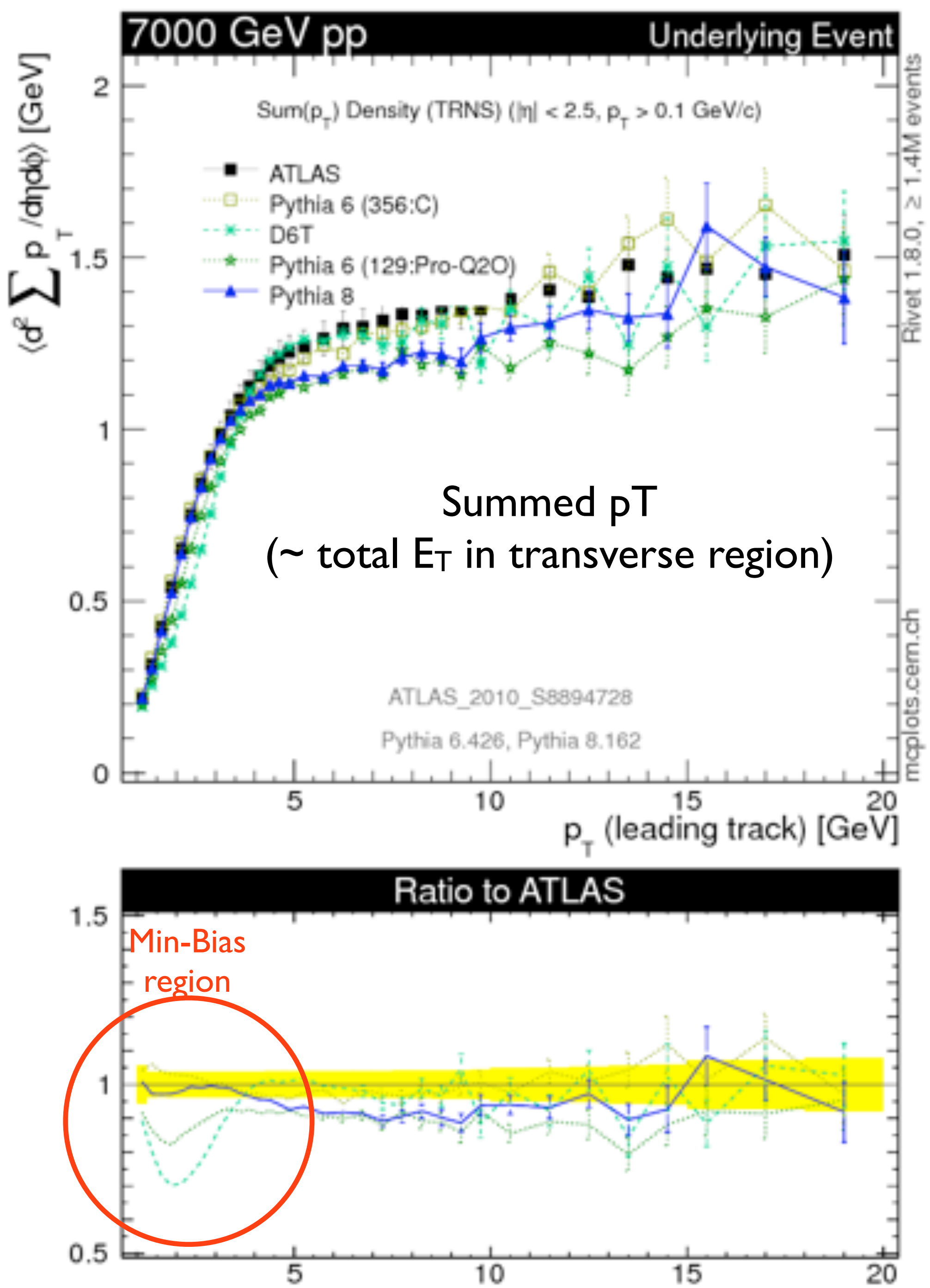
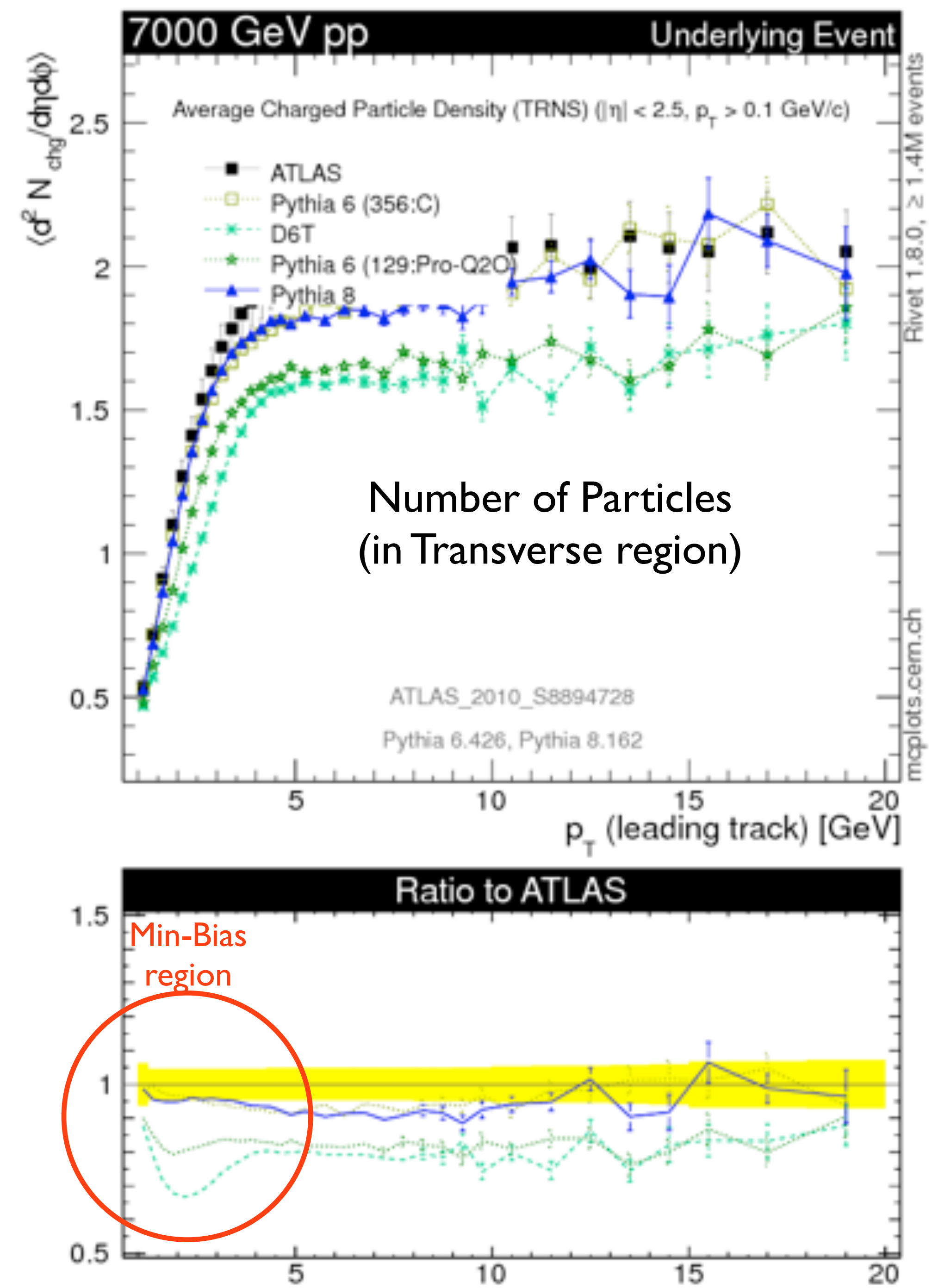
Parton-Parton Cross Section — Hadron-Hadron Cross Section

Underlying Event

Note: the UE is more active than Min-Bias, which is more active than Pile-Up



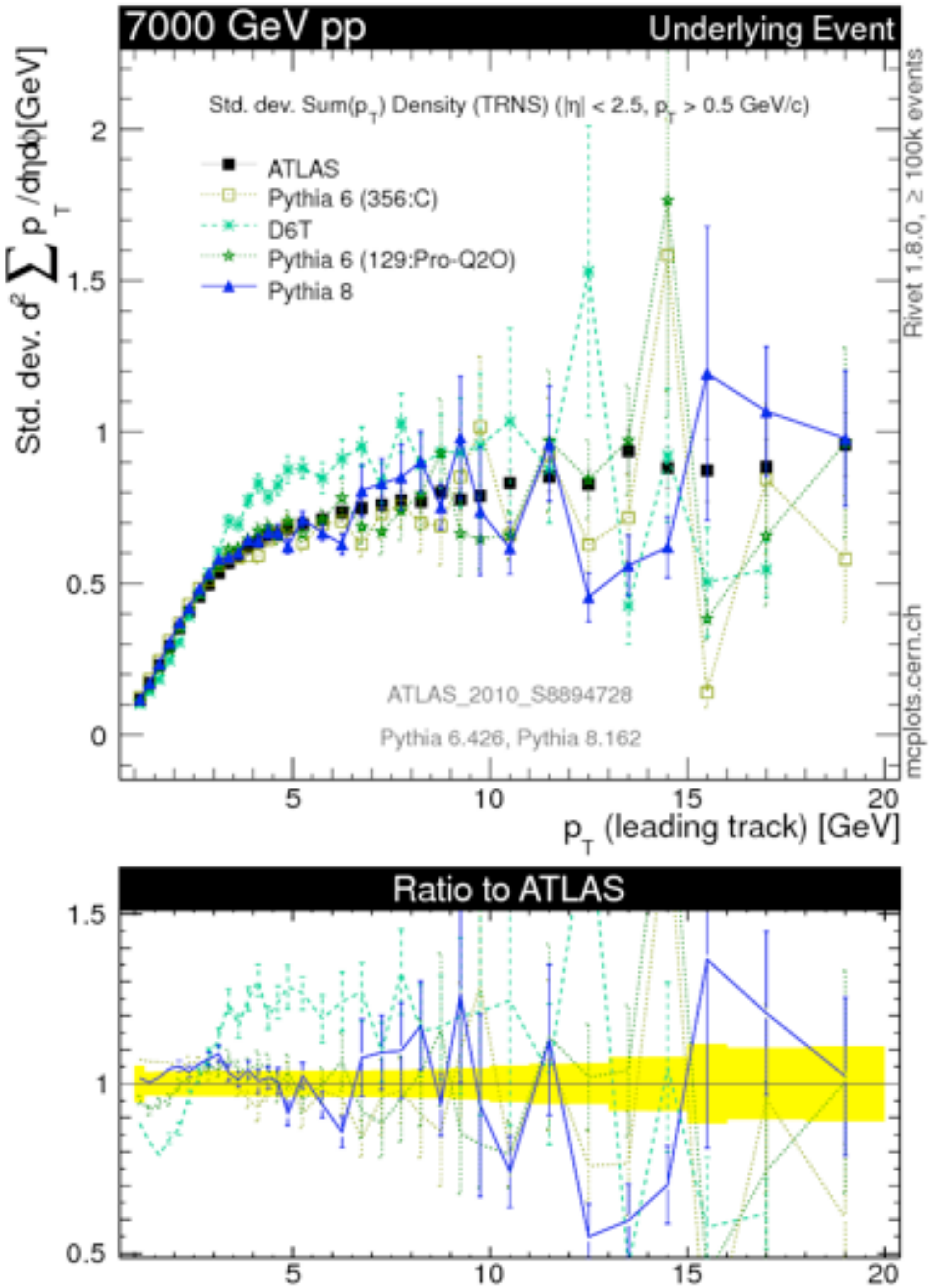


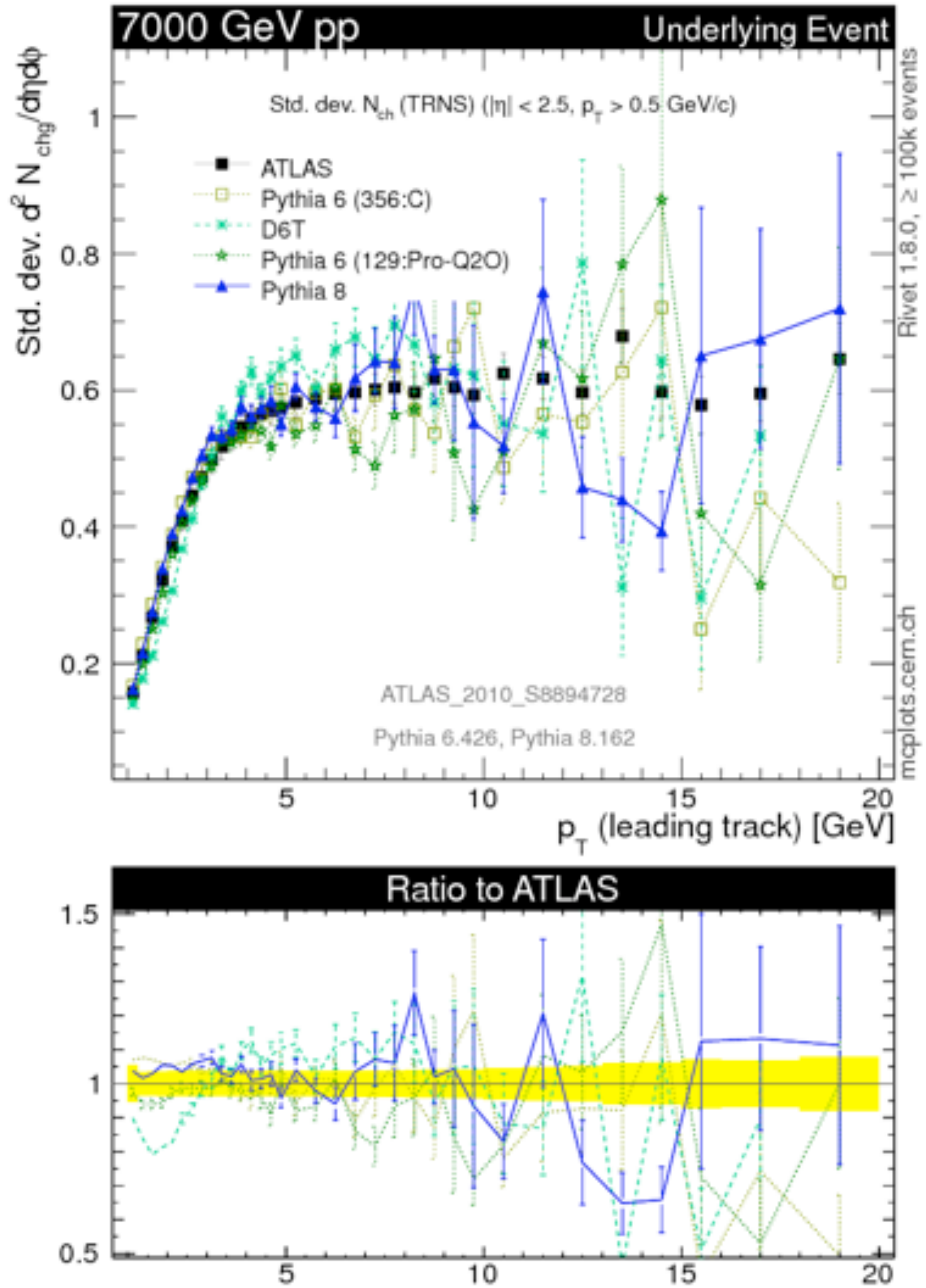
PYTHIA 8 a bit too low?

Q2-ordered tunes (D6T and Pro-Q20) have the right energy, but it's distributed on too few particles → momentum spectra too hard

Underlying Event: RMS

Measures the event-by-event FLUCTUATIONS of the Underlying Event



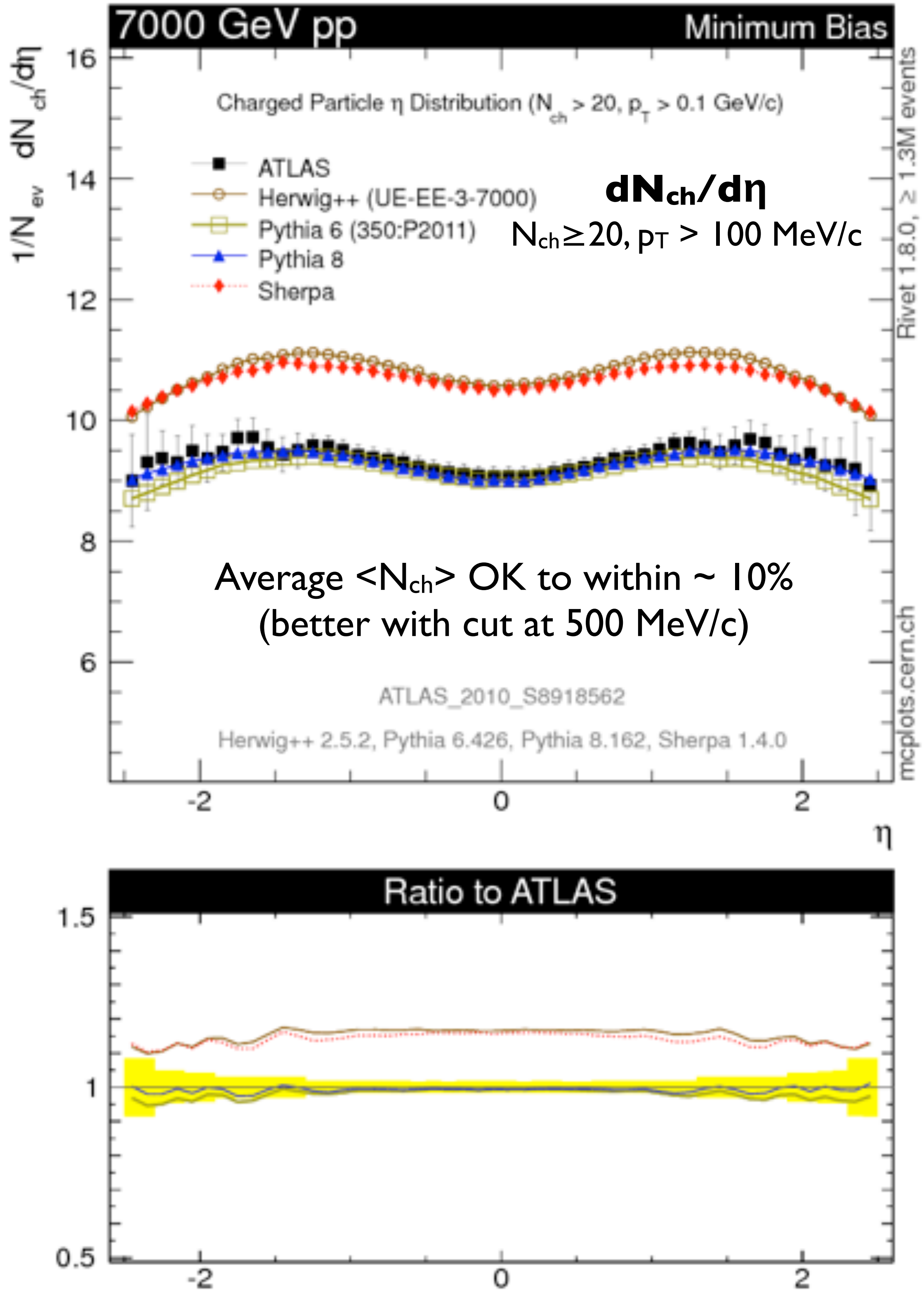


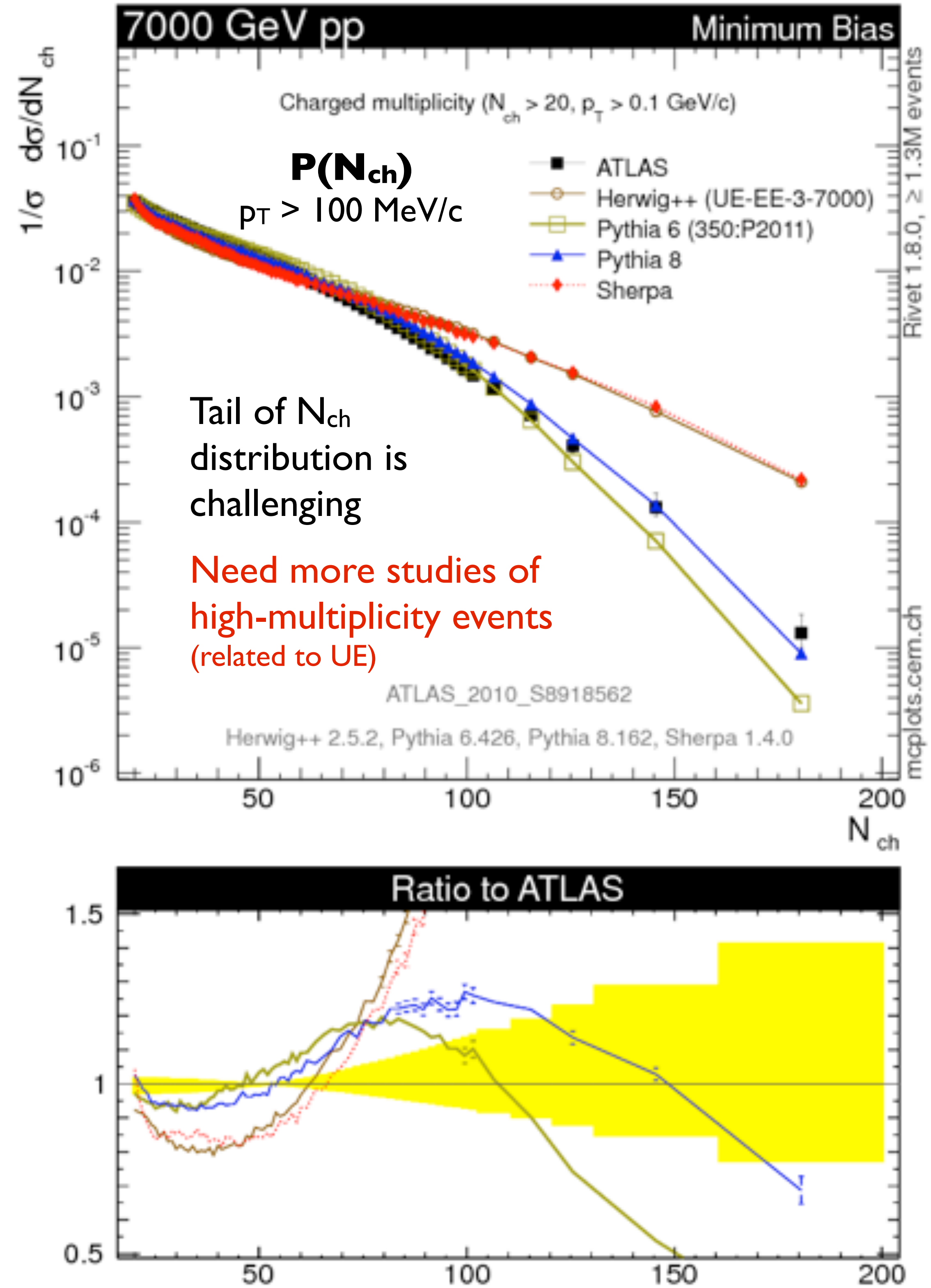
Never previously measured. Not used for tuning.

All in all Amazing agreement

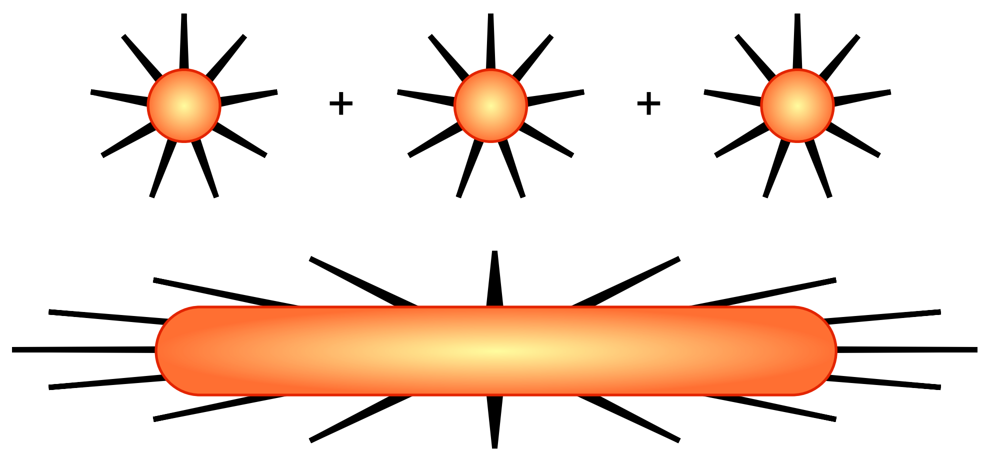
D6T has too large RMS

Min-Bias: Inclusive Particles





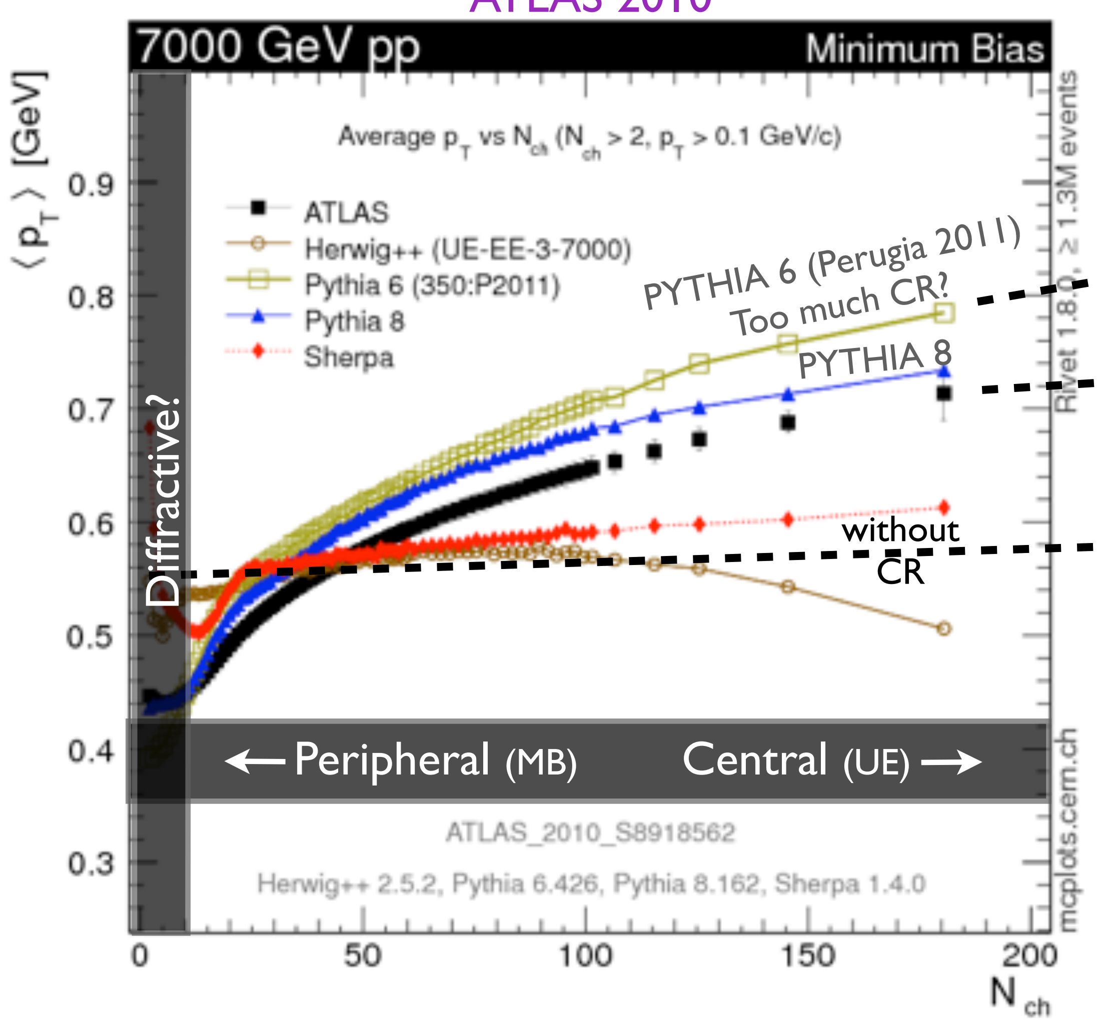
Min-Bias: $\langle p_T \rangle$ vs N_{ch}



Independent Particle Production:
→ **averages stay the same**

Color Correlations / Jets / Collective effects:
→ **average rises**

ATLAS 2010



Extrapolation to high multiplicity ~ UE

Average particles slightly too hard
→ Too much energy, or energy distributed on too few particles

~ OK?

Average particles slightly too soft
→ Too little energy, or energy distributed on too many particles

Evolution of other distributions with N_{ch} also interesting: e.g., $\langle p_T \rangle(N_{ch})$ for identified particles, strangeness & baryon ratios, 2P correlations, …

Plots from mcplots.cern.ch

Diffraction in PYTHIA 6

Diffractive Cross Section Formulæ:

$$\frac{d\sigma_{sd(AX)}(s)}{dt\,dM^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta_{A\mathbb{P}}^2\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\,\exp(B_{sd(AX)}t)\,F_{sd}\,,$$

$$\frac{d\sigma_{dd}(s)}{dt\,dM_1^2\,dM_2^2} = \frac{g_{3\mathbb{P}}^2}{16\pi}\,\beta_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M_1^2}\,\frac{1}{M_2^2}\,\exp(B_{dd}t)\,F_{dd}\,.$$

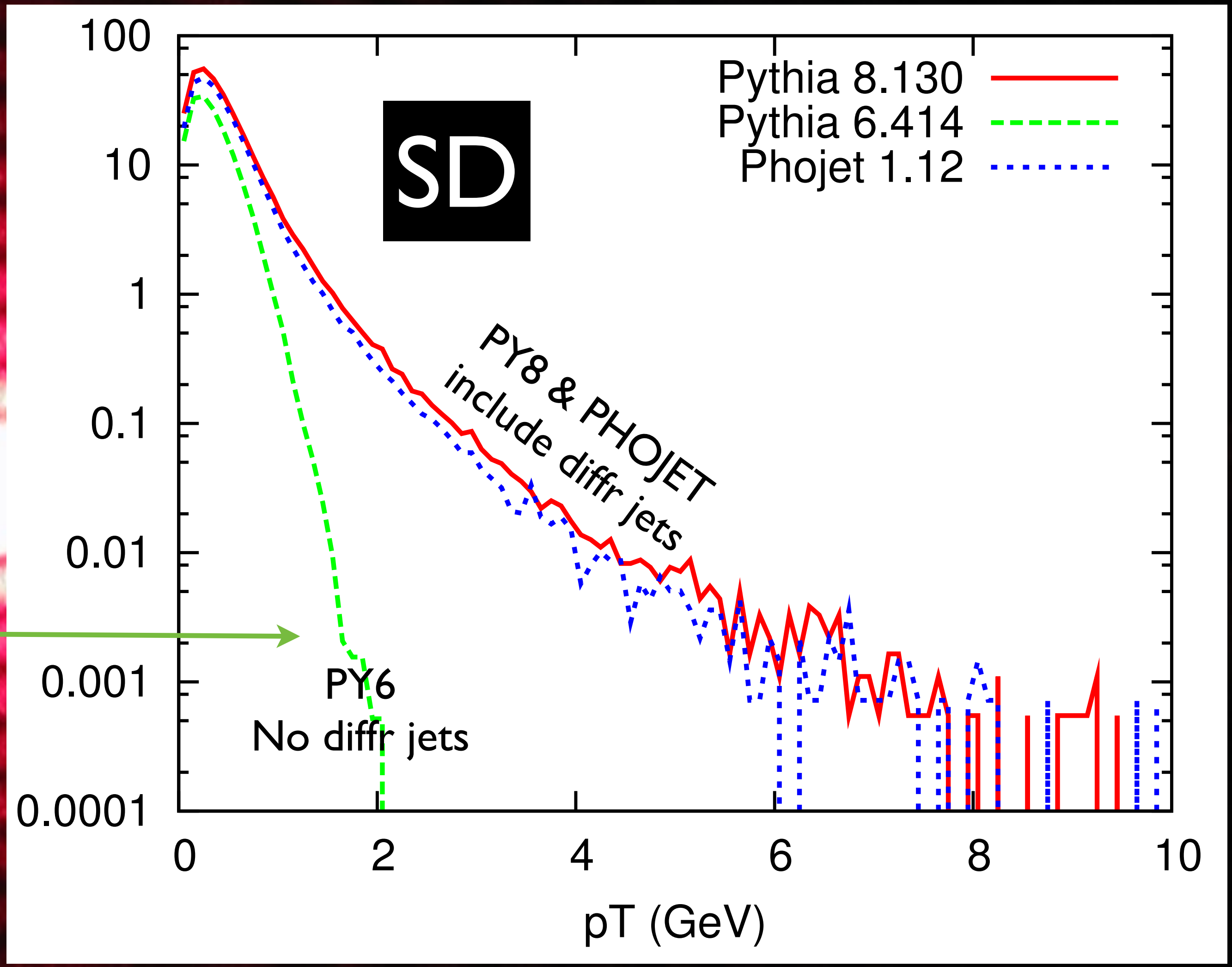
Spectra:

$2\,m_{pi} < M_D < 1$ GeV: 2-body decay

$M_D > 1$ GeV : string fragmentation

Partonic Substructure in Pomeron:

Only in POMPYT addon (P. Bruni, A. Edin, G. Ingelman) ► high-p_T "jetty" diffraction absent



Very soft spectra without POMPYT

Status: Supported, but not actively developed

Diffraction in PYTHIA 8

Navin, arXiv:1005.3894

Diffractive Cross Section Formulæ:

$$\frac{d\sigma_{sd(AX)}(s)}{dt\,dM^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta_{A\mathbb{P}}^2\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\,\exp(B_{sd(AX)}t)\,F_{sd}\,,$$

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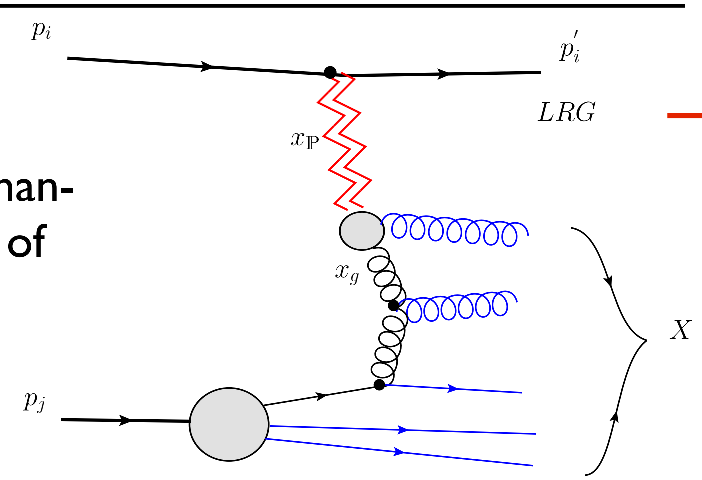
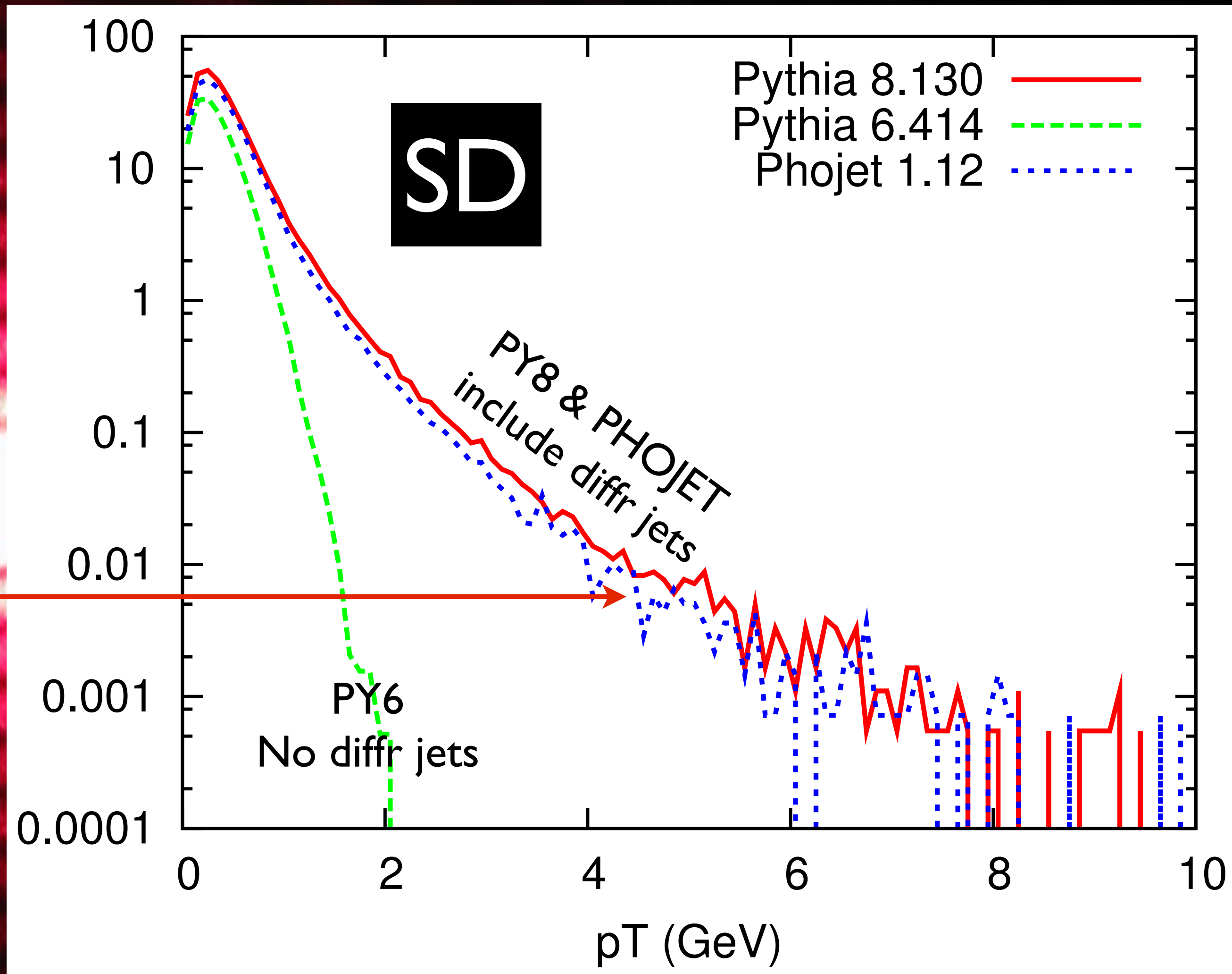
Partonic Substructure in Pomeron:

Follows the Ingelman-Schlein approach of Pompyt





PYTHIA 8

- $M_X \leq 10\,\text{GeV}$: original longitudinal string description used
- $M_X > 10\,\text{GeV}$: new perturbative description used (incl full MPI+showers for $\mathbb{P}$p system)

Choice between 5 Pomeron PDFs. Free parameter $\sigma_{\mathbb{P}p}$ needed to fix $\langle n_{\text{interactions}}\rangle = \sigma_{\text{jet}}/\sigma_{\mathbb{P}p}$.

Framework needs testing and tuning, e.g. of $\sigma_{\mathbb{P}p}$.

PYTHIA

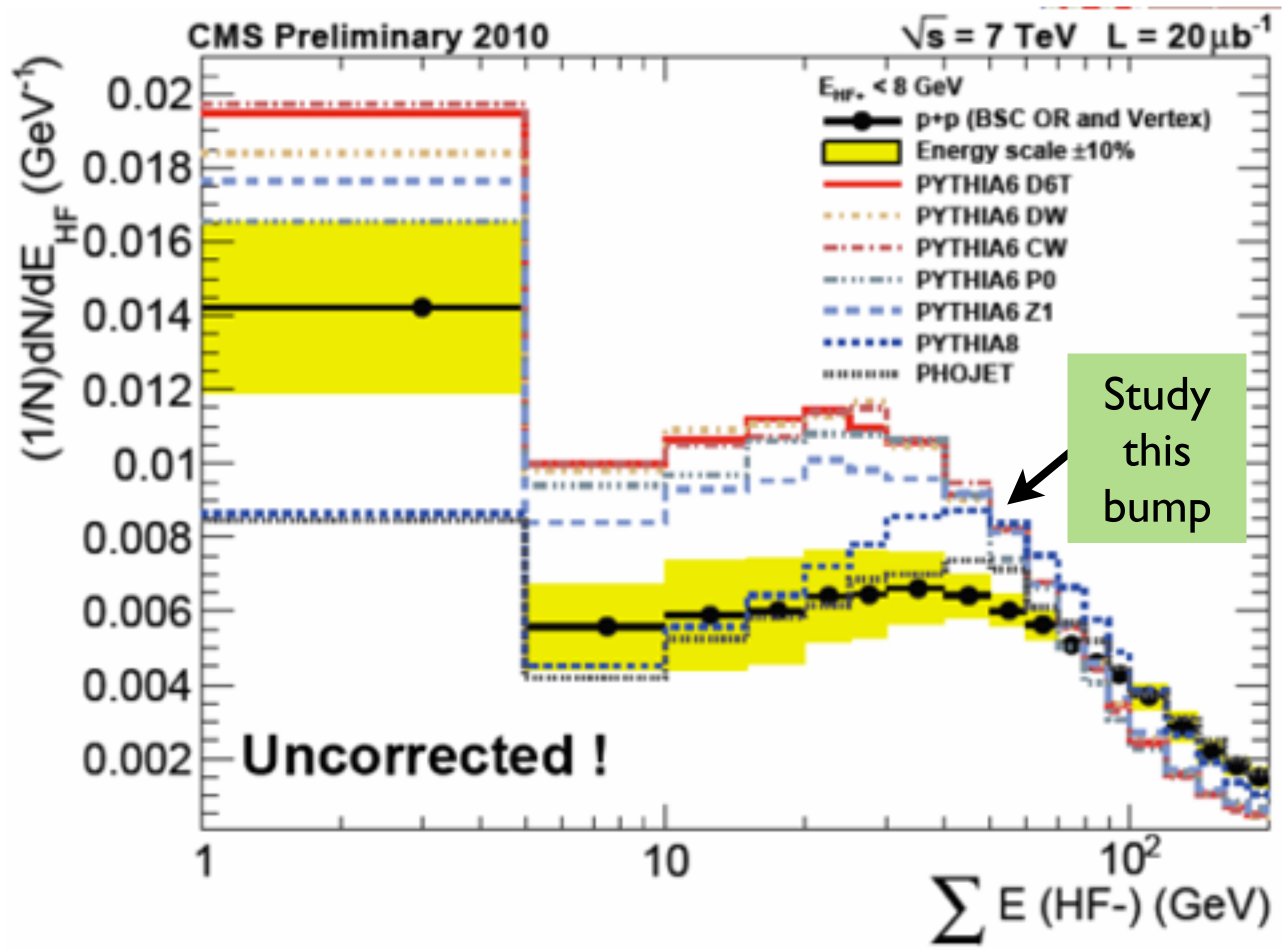
Diffraction

Framework needs testing and tuning

E.g., interplay between non-diffractive and diffractive components

+ LEP tuning used directly for diffractive modeling

Hadronization preceded by shower at LEP, but not in diffraction → dedicated diffraction tuning of fragmentation pars?



+ Little experience with new PYTHIA 8 MPI component in high-mass diffractive events

→ This component especially needs testing and tuning

E.g., look at n_{ch} and p_T spectra in high-mass (>10GeV) diffraction

(Not important for UE as such, but **can be important if using PYTHIA to simulate pile-up!)**

$\sigma_{\mathbb{P}p}$ determines level of UE in high-mass diffraction through $\langle n_{MPI} \rangle = \sigma_{jet}/\sigma_{\mathbb{P}p}$. (Larger $\sigma_{\mathbb{P}p}$ → smaller UE)

Pile-Up

= additional zero-bias interactions (contain more diffraction than ordinary min-bias)

Processes with *no hard scale*:

Larger uncertainties → Good UE does *not* guarantee good pile-up.

Error of 50% on a soft component → not bad.

Multiply it by 60 Pile-Up interactions → bad!

Calibration & filtering

Good at recovering jet calibration (with loss of resolution),

But missing energy and isolation sensitive to modeling.

$H \to WW$ $H \to \gamma\gamma$? (E.g., $\gamma\gamma$ studies by ATLAS, CMS, CDF, D0)

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Models

MC models so far: problems describing both MB & UE simultaneously
→ Consider using dedicated MB/diffraction model for pile-up

(UE/MB tension may be resolved in 2012 (eg. studies by R. Field), but for now must live with it)

Experimentalists advised to use unbiased data for PU (when possible)