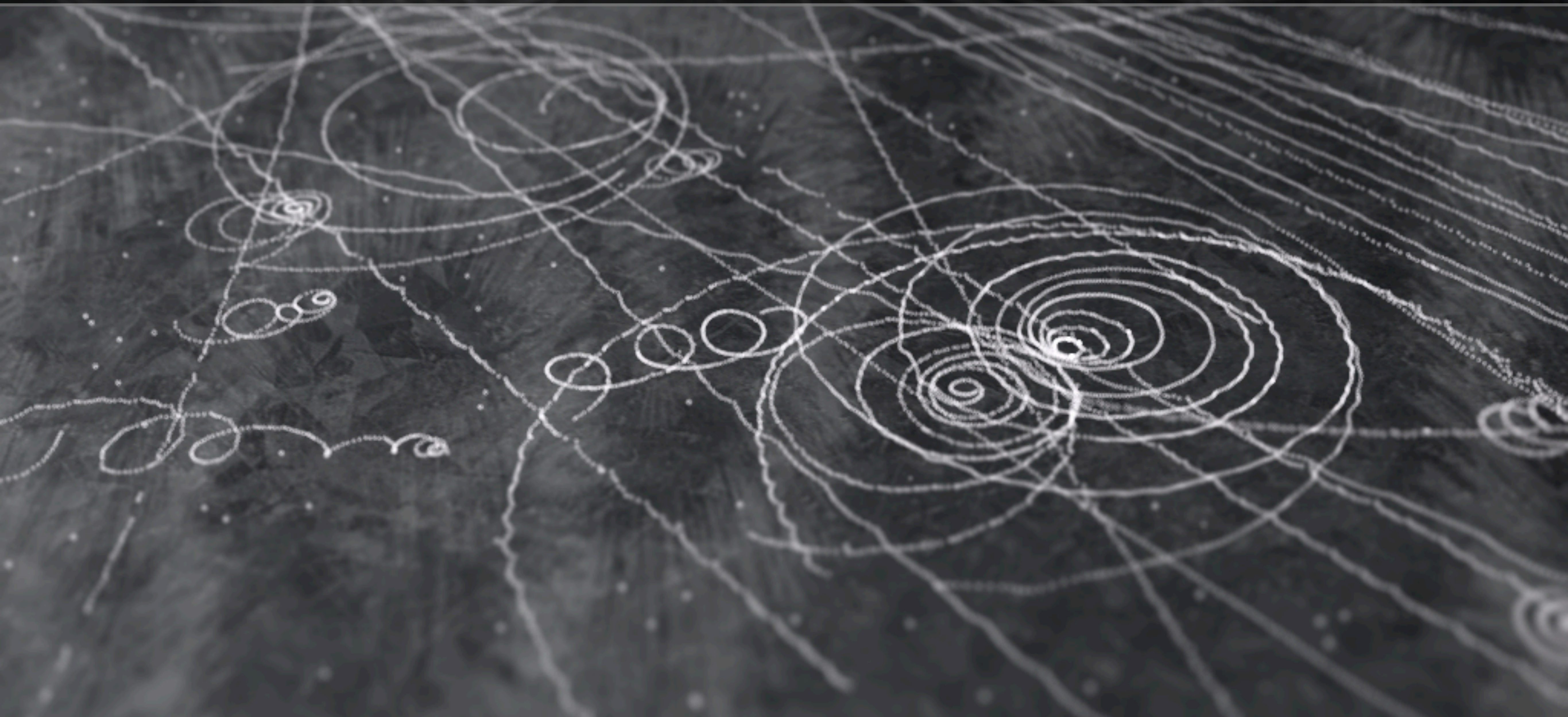
CERN ATLAS Group Meeting, Dec 20 2011, Thoiry

Modern Event Generators and Tuning Issues



Peter Skands
(CERN TH)

QCD Models

A

A) Start from pQCD. Extend towards Infrared.
HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

Elastic & Diffractive
Treated as separate class
No predictivity

Color Screening
Regularization of pQCD
Hadronization

Unitarity
Showers (ISR+FSR)
Multiple 2→2 (MPI)

Hard Process
Perturbative 2→2 (ME)
Resonance Decays

PYTHIA uses **string fragmentation**, HERWIG & SHERPA use **cluster fragmentation**

Elastic — Min-Bias — Dijets/WZ/Top/…

0 — Λ_{QCD} — 5 GeV — ∞

B

B) Start from Hadrons & Optical Theorem. Extend towards Ultraviolet.
PHOJET, DPMJET, QGSJET, SIBYLL, …

Hadrons
Optical Theorem
pp→pp

Pomerons: Diffraction
Cut Pomerons: Non-diffractive (soft)

Hard Pomeron?

Note: PHOJET & DPMJET use **string fragmentation** (from PYTHIA) → some overlap

Hard Process

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Keep in Mind:
LO×LL is doing **very well** if it gets within 10% of an IR safe quantity

Fixed-Order Matrix Elements

- **LO vs K×LO vs NLO vs ...**
- **PDF set** (& uncertainties & LO vs LO* vs NLO vs …)
- **Factorization scale**
- **Renormalization scale(s)** (& other RGE-improved couplings)

Talk by F. Siegert

Note: LO* may not be optimal compromise between LO and NLO. Alternatives under investigation.

Multi-Scale Problems

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Multi-Scale Problems (in fixed-order context)

- **Scale hierarchies** (jet scales, particle masses) → conformal enhancements
- **Renormalization scale(s)**
- **Resonance Decays** (finite widths, spin correlations,…)
- **Mass Effects**
- **Resummation Effects & Matching to Parton Showers**
- **Large Rapidities** (forward jets → high-energy limit)

Talk by F. Siegert

WARNINGS and common pitfalls:
Too low ME cutoffs, "NLO"→LO, zero widths, weird μ_R choices, inconsistent parameters when combining codes

Bremsstrahlung

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Elastic & Diffractive	Color Screening	Unitarity	Hard Process
Treated as separate class	Regularization of pQCD	Showers (ISR+FSR)	Perturbative $2\to2$ (ME)
No predictivity	Hadronization	Multiple $2\to2$ (MPI)	Resonance Decays

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FSR+ISR

- **Size of Phase Space** (matching onto ME scales)
- **Coherence** (e.g., angular ordering vs p_T-ordering vs …)
- **Renormalization Scale(s)**
- **Momentum Recoils**
- **Initial-Final connections** (e.g., FSR broadening of an ISR jet…)
- **Radiation Kernels** (e.g., DGLAP vs Dipoles/Antennae vs …)
- **Polarization Effects**

Keep in Mind:
LO×LL is doing **very well** if it gets within 10% of an IR safe quantity

Modern parton showers approximate NLL, but still large uncertainties. At least vary/tune μ_R to reflect ambiguities

Underlying Event

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Beyond single-parton factorization: expect **uncertainties > LO**

Multiple Parton Interactions

Multi-Parton PDFs & Correlations (e.g., in *x* and impact parameter)

Perturbative vs Non-Perturbative Dynamics

- Hard Scatterings ~ Rutherford with unknown K-factor
- Soft Scatterings ~ Cut Pomerons?

Showers & MPI (Interleaving, showers off MPI, intertwining, rescattering, …)

Note: crazy to require agreement between current MPI-based models and data at 5%-level or better …

Confinement

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Partonic Confinement

IR Physics.
Uncertainties guaranteed to be >> LO

- **FSR Cutoff** (~ scale of hadronization)
- **ISR Cutoff** (~ starting scale for DGLAP ISR evolution)
- **MPI Cutoff** (~ starting scale for perturbative MPI evolution)
- **Color Space** (formation of color-singlet hadronizing systems)
- **Hadronization Modeling** (clusters vs strings, fragmentation functions)

Expect worse agreement for rare phenomena (e.g., Ω). **Order-of-magnitude** may have to be accepted.

Parton/Hadron Dynamics

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IR Physics.
Uncertainties guaranteed to be >> LO

Parton/Hadron Interplay

- **Hard Diffraction** (→ diffractive jets + UE in high-mass diffraction?)
- **Soft Non-Diffractive Scattering** (incl soft diffraction)
- **Color Reconnections** (String/Cluster reinteractions)

Note: expect larger uncertainties on very soft phenomena, rapidity gaps, …

Soft QCD

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IR Physics.
Uncertainties guaranteed to be >> LO

Long-Distance Physics

- **Hadron and τ Decay Modeling**
- **Bose-Einstein Correlations**
- **Elastic Scattering**
- **Soft Diffractive Scattering**
- **Hadronic Re-interactions?** (Boltzmann gas vs hydro … ?)

Modeling Soft QCD

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PYTHIA:

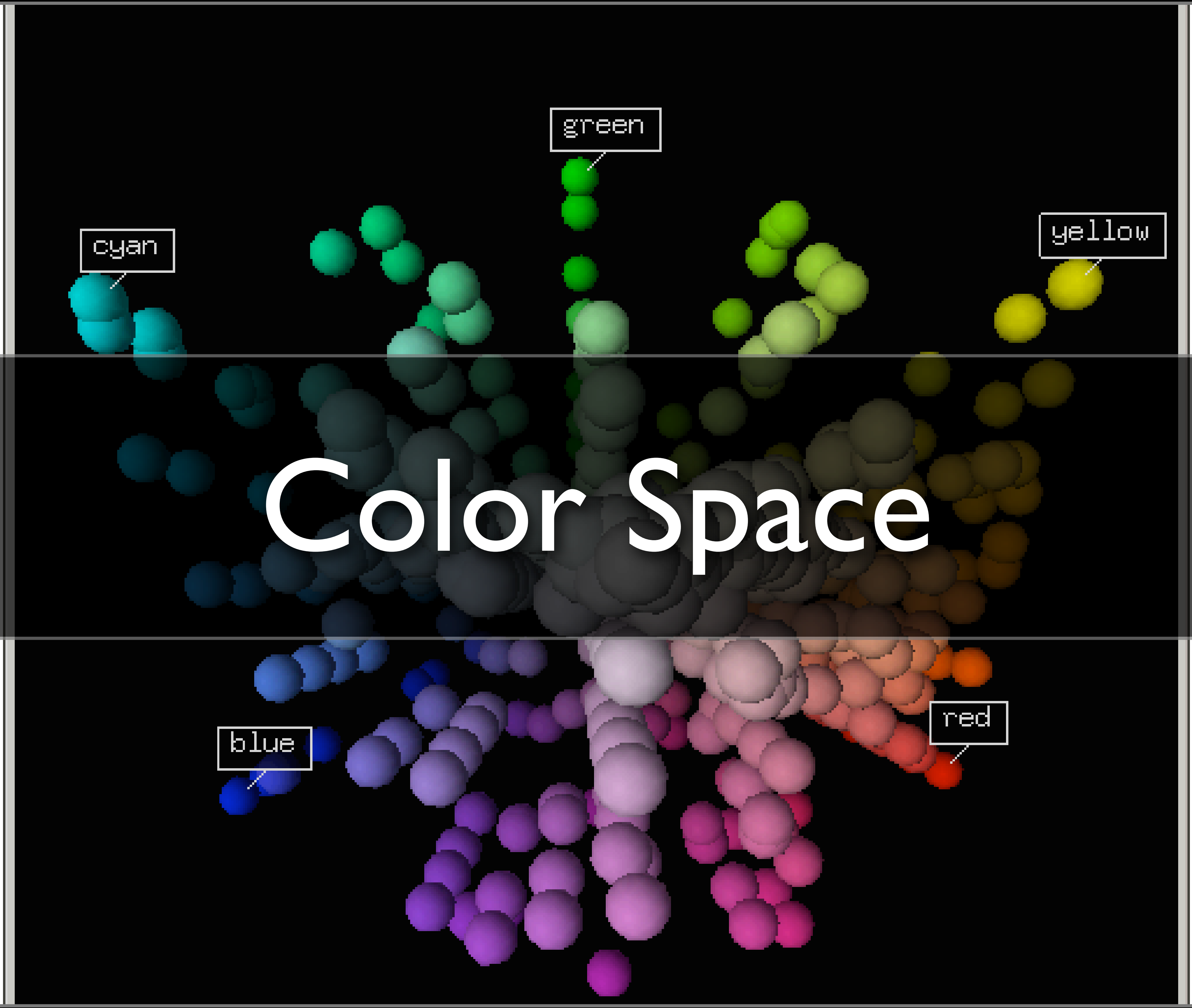
$\sigma_{INEL}(s)$: Donnachie-Landshof ($\sigma_{tot}(s)$ - $\sigma_{el}(s)$)

$\sigma_{SD,DD}(s)$: Parametrization ~ dM^2/M^2 (See next slides)

$$\sigma_{NON\text{-}DIFF}(s) = \sigma_{tot} - \sigma_{el} - \sigma_{SD} - \sigma_{DD}$$

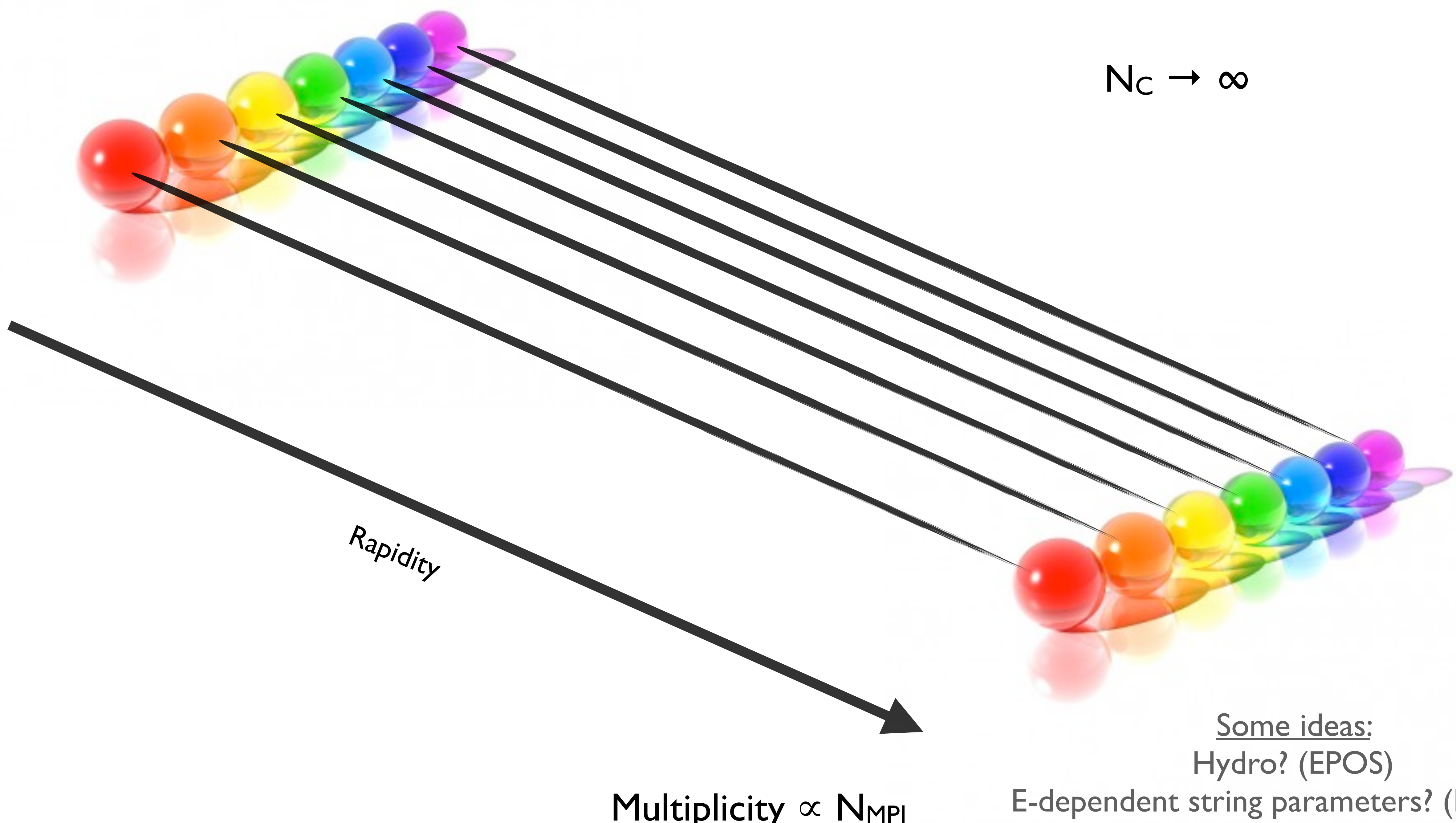
This is defined by what you choose for the others

You can adjust these, individually, if you don't like PYTHIA's def



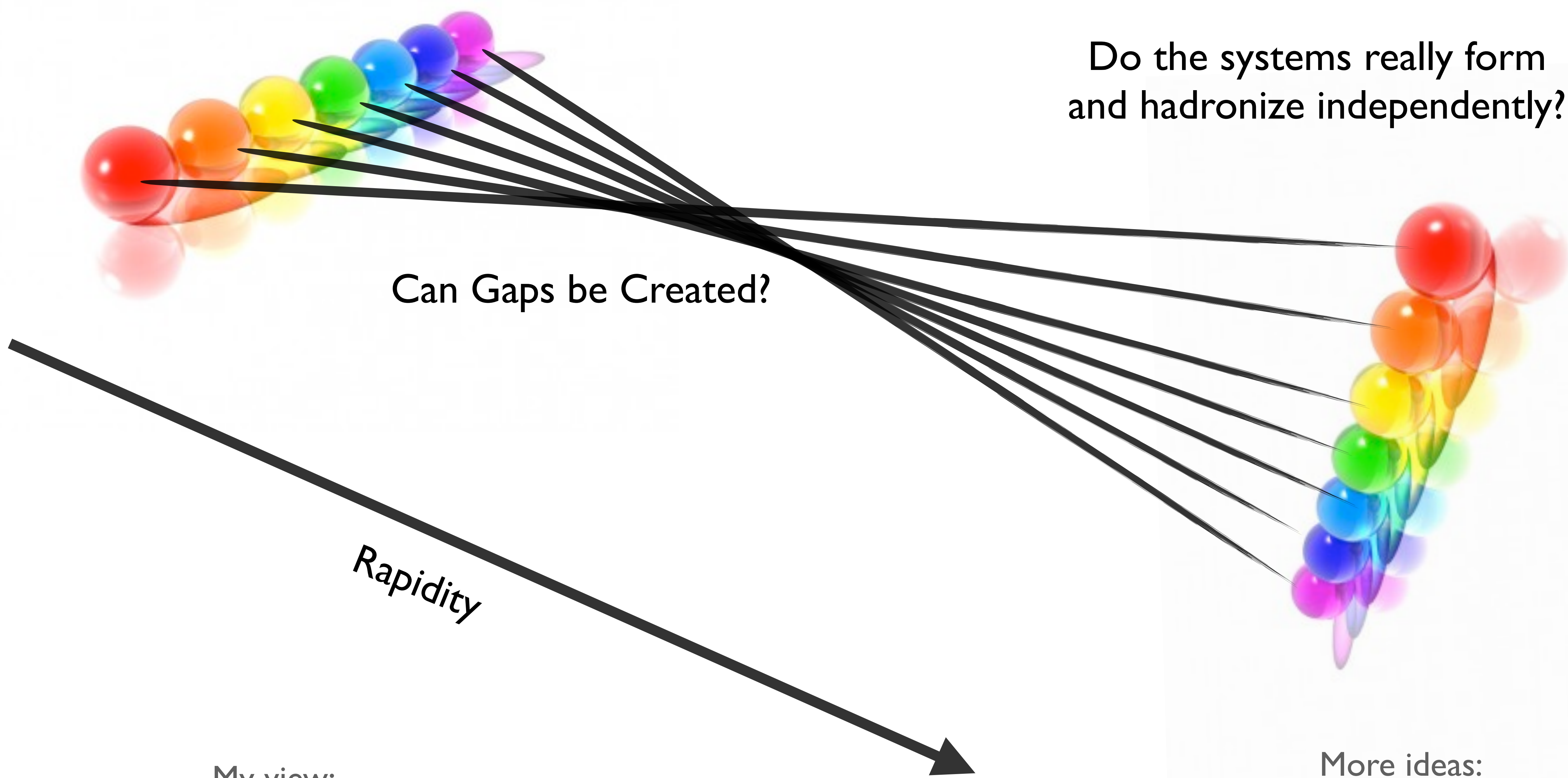
Color Space

Color Connections



Some ideas:
Hydro? (EPOS)
E-dependent string parameters? (DPMJET)
“Color Ropes”?

Color Reconnections?



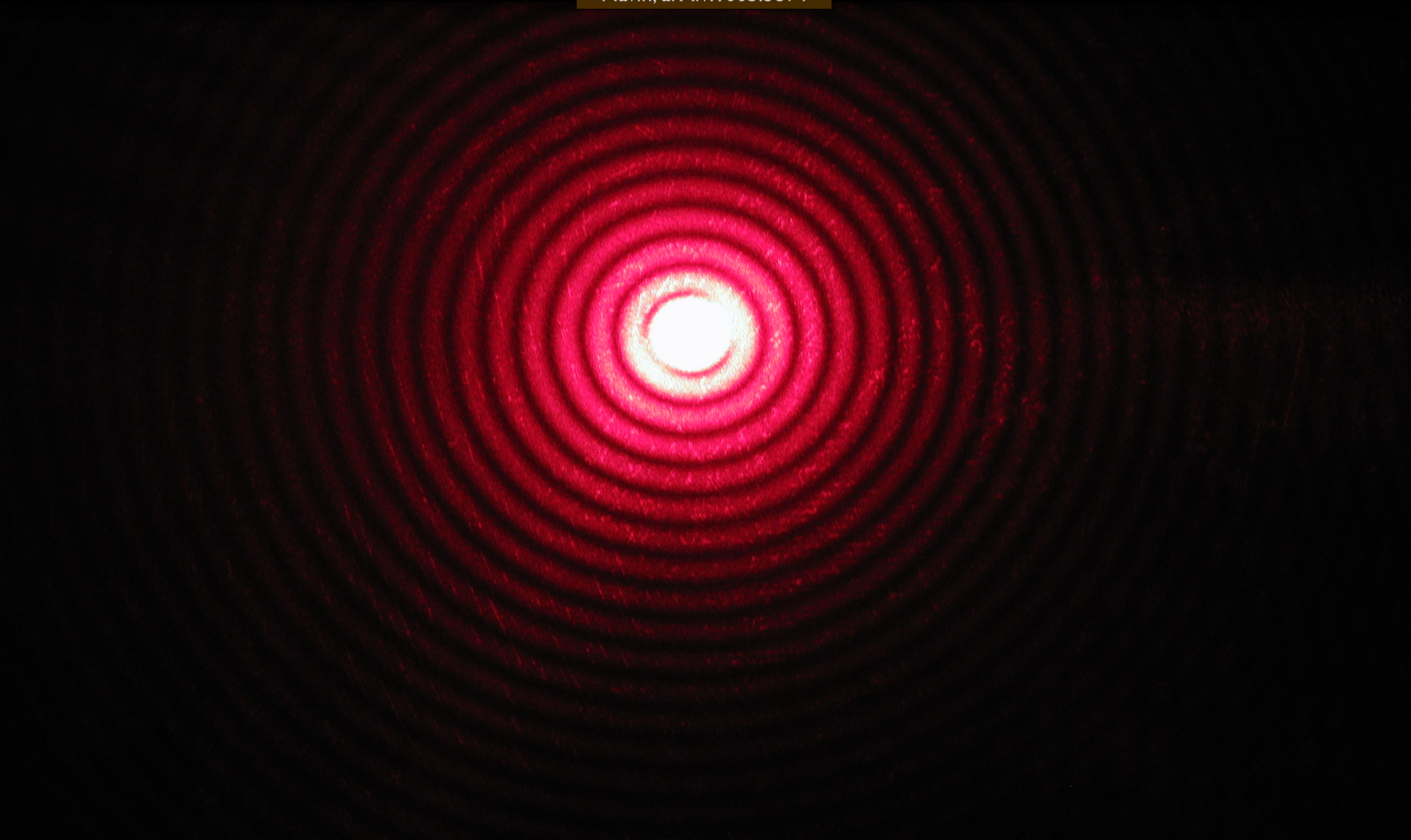
<u>My view:</u>
Universality is ok *(a string is a string)*
Problem is 3 $\neq \infty$

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

<u>More ideas:</u>
Coherent string formation?
Color reconnections?
String dynamics?

Diffraction (in PYTHIA 8)

Navin, arXiv:1005.3894



Diffraction (in PYTHIA 8)

Navin, arXiv:1005.3894

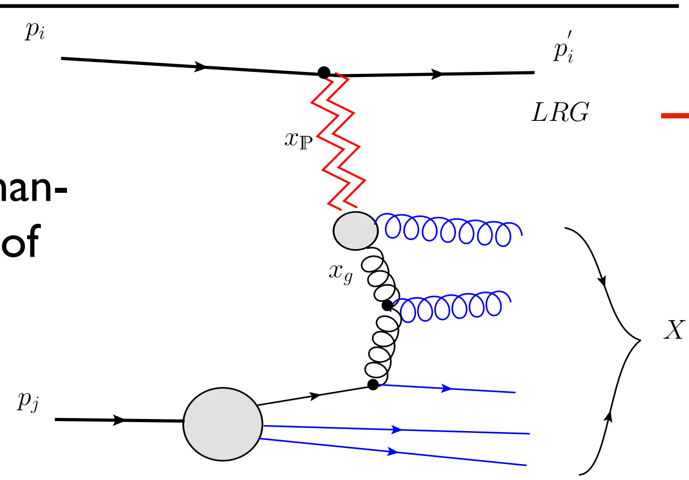
Diffractive Cross Section Formulæ:

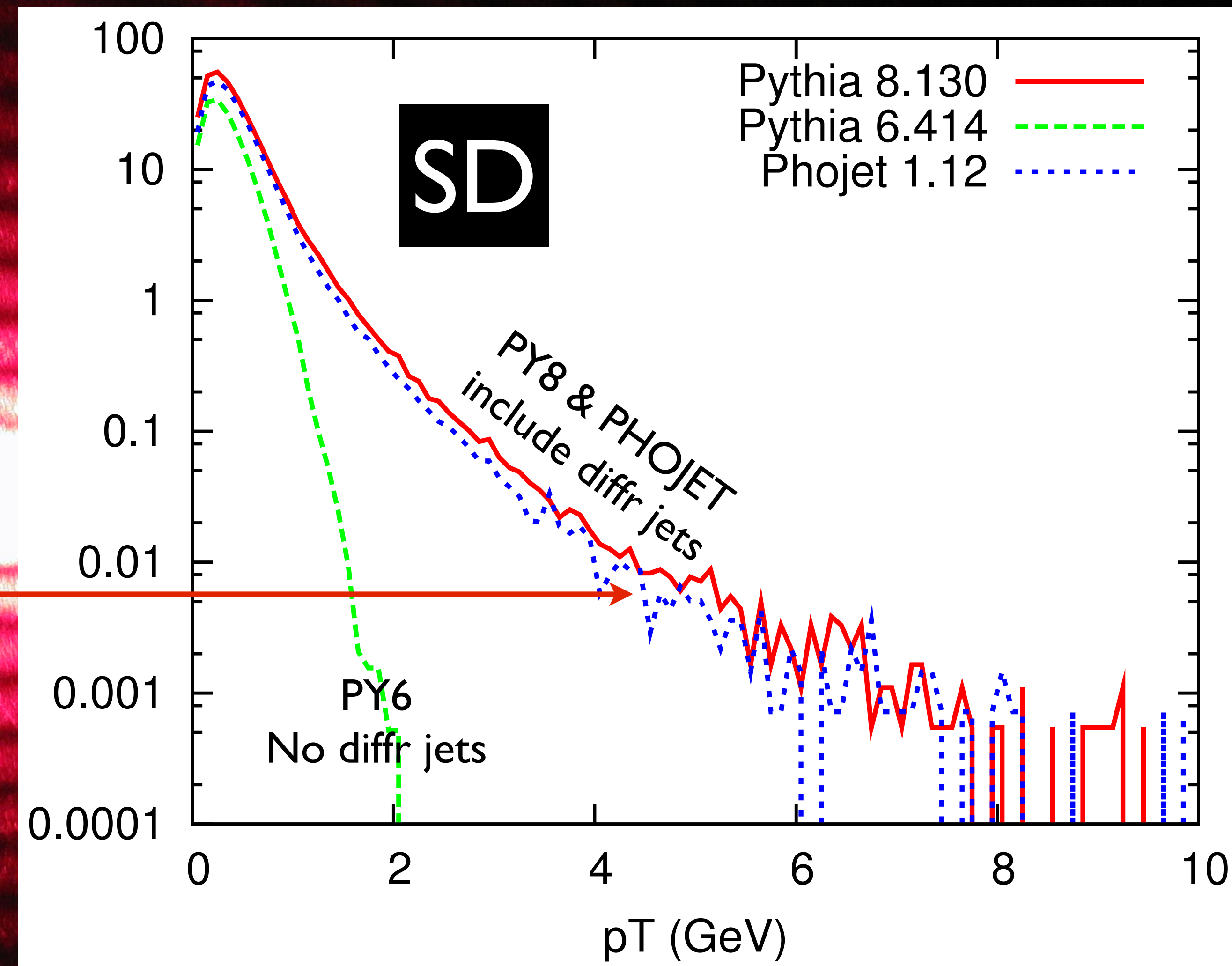
$$\frac{d\sigma_{sd(AX)}(s)}{dt\,dM^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta^2_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\,\exp(B_{sd(AX)}t)\,F_{sd}\,,$$

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

Partonic Substructure in Pomeron:

Follows the Ingelman-Schlein approach of Pompyt





PYTHIA 8

- $M_X \leq 10\,\mathrm{GeV}$: original longitudinal string description used
- $M_X > 10\,\mathrm{GeV}$: 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 $\langle n_{\mathrm{interactions}}\rangle = \sigma_{\mathrm{jet}}/\sigma_{\mathbb{P}p}$.

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

Diffraction (in PYTHIA 8)

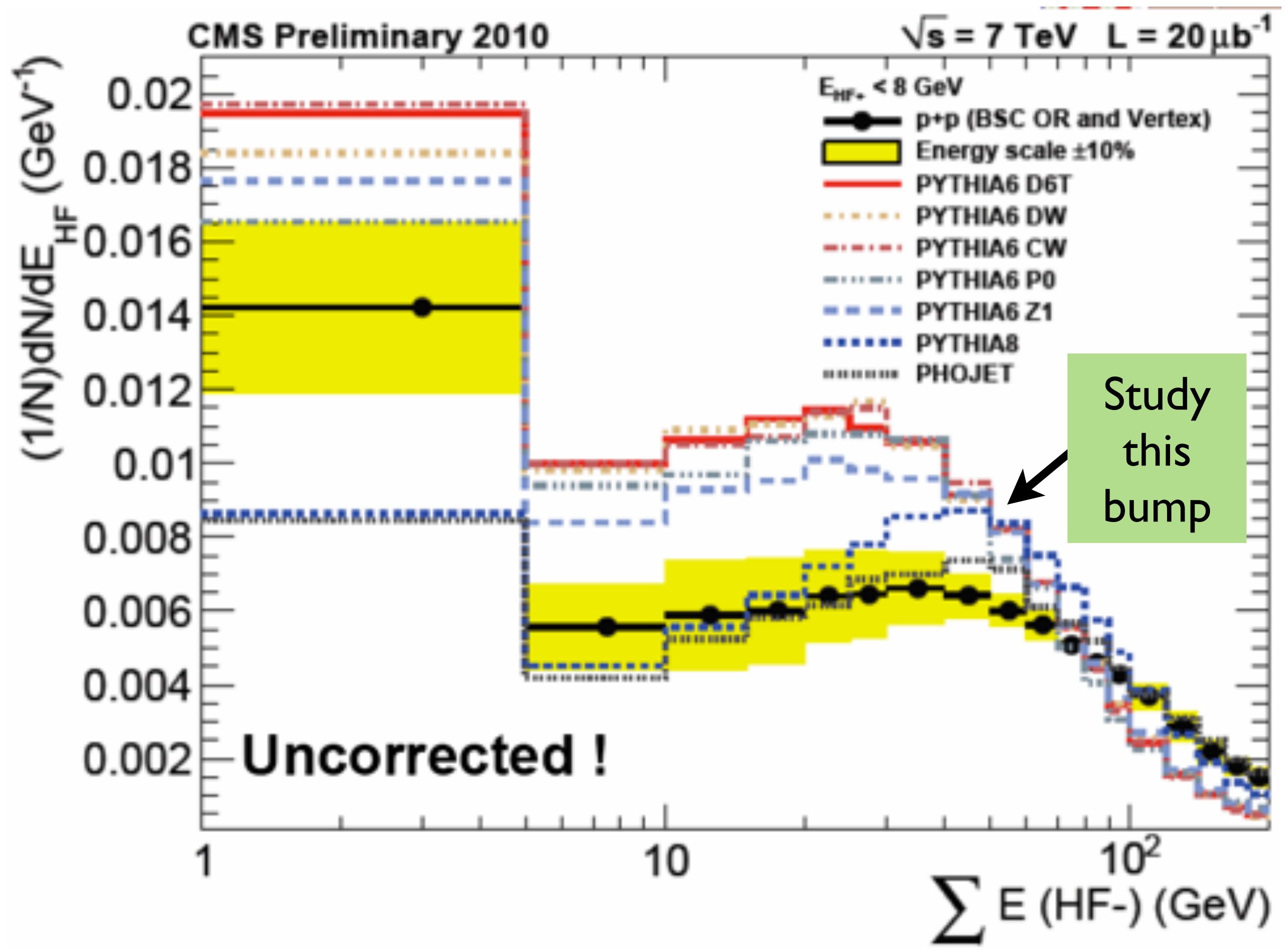
Navin, arXiv:1005.3894

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

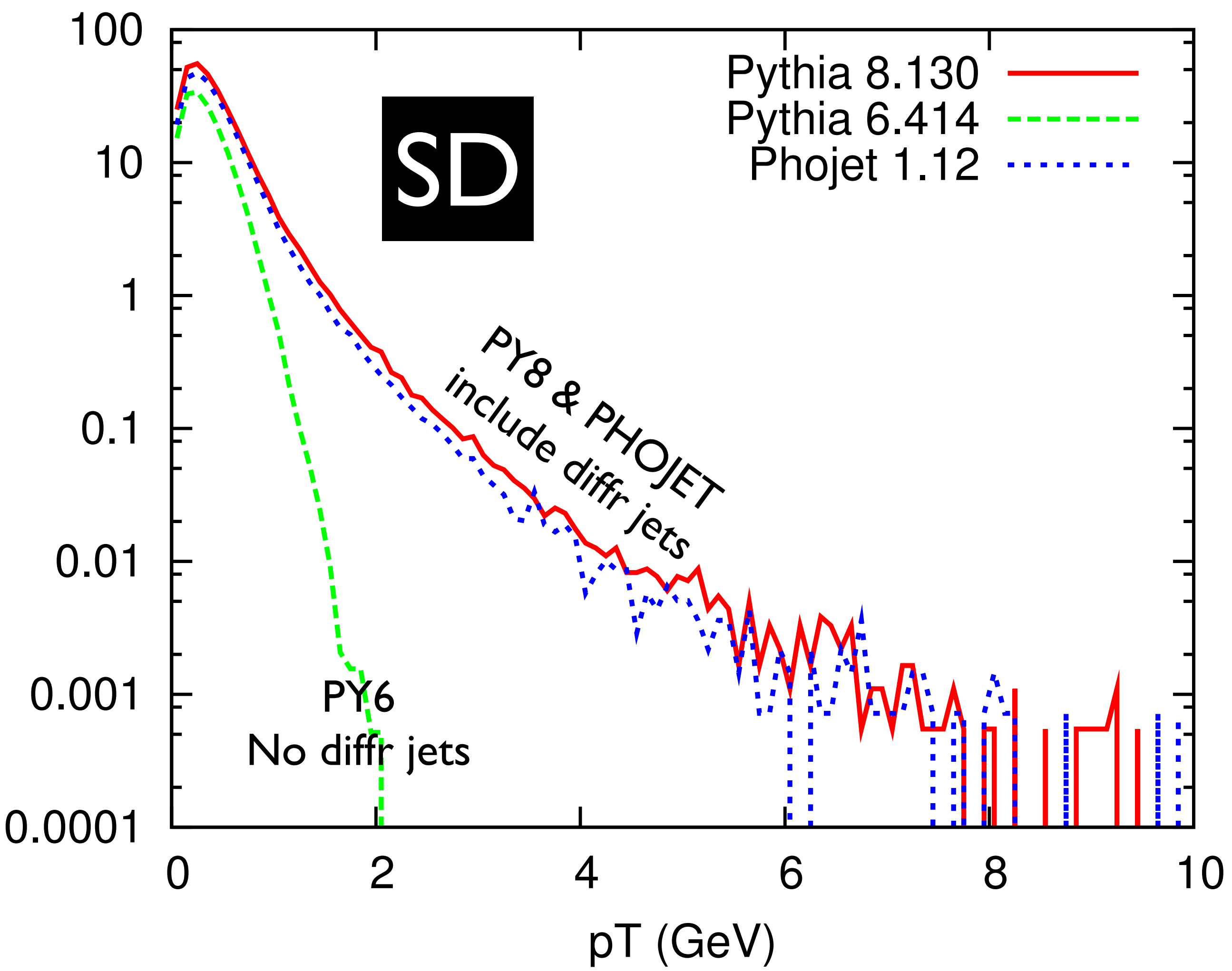
→ This component especially needs testing and tuning

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)

Consequences



Harder Spectrum in High-M Diffraction
→
More p_T generated in high-mass diffractive events
+ High-mass diffraction is likely to throw something into the observable region of calorimeters etc (bias)

+ new MPI-based UE in high-M Diffraction
→
High-Mass diffraction now has a "pedestal" relative to low-mass diffraction, similar to the case of UE in jets vs Min-Bias → further increases amount of activity (and dissipated energy) in high-mass diffractive events.

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

→ This component especially needs testing and tuning (e.g., look at n_{ch} and p_T spectra in high-mass (>10GeV) diffraction). Constrain size of "pedestal" in high-M diffraction.

Can be important if using PYTHIA to simulate pile-up!

Summary

For **most** perturbative physics

We are still at LO×(N)LL

(Lots of theoretical activity towards improving this, e.g., VINCIA)

For the time being, uncertainties ~ 10% or greater (with tuning)

Multi-scale problems → fixed order breaks down → larger uncertainties

For UE in central region

Amazing agreement with MPI-based models → right direction

Formal accuracy still lower than for hard interaction

For non-perturbative and forward UE physics

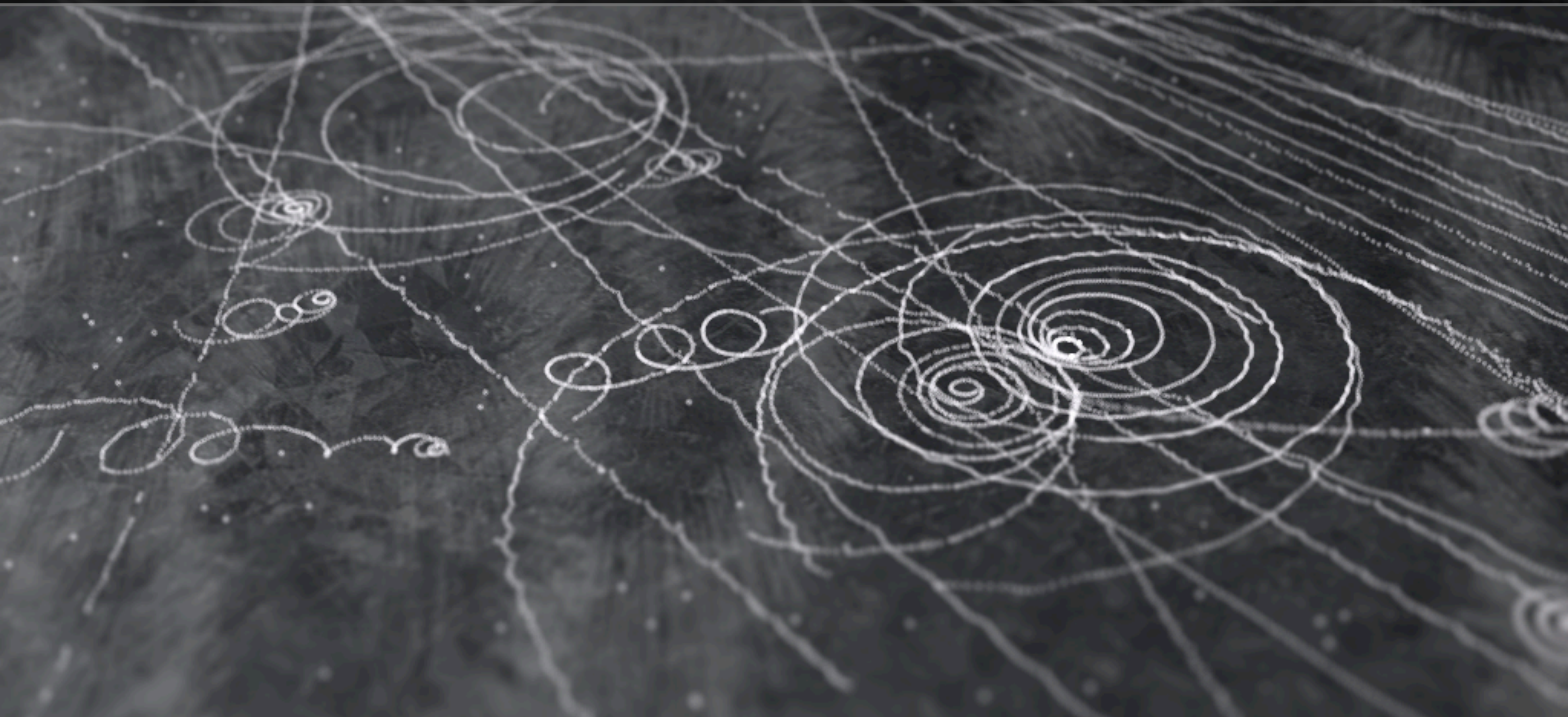
Single chain ~ well understood (LEP); baryons + rare phenomena (J/ψ, Ω, etc) tough.

Need more studies (and data) on breakup of beam remnant

Coherence not well understood for multiple chains. **Need more studies (and data)** on role of color reconnections, and on properties of (high-mass) diffraction.

New models developed in all MCs, need constraints. You have an active role to play.

Backup Slides

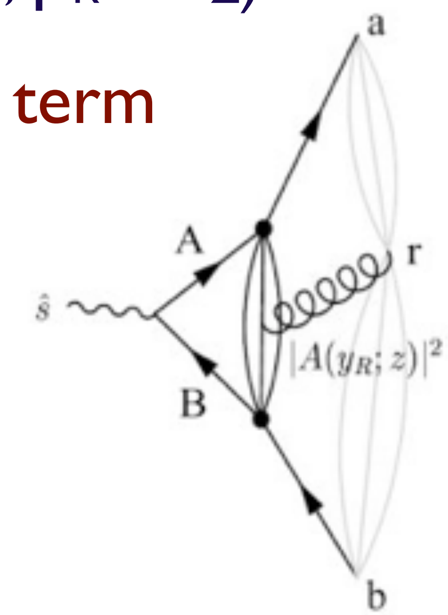


Scales: $\mu_R = p_T$ and Λ_{CMW}

Compute $e^+e^- \to 3$ 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

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



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? Anyway, we're using pT here)

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

Note: CMW not automatic in PYTHIA, has to be done by hand, by choosing effective Λ or $\alpha_s(M_Z)$ values instead of $\overline{MS}$ ones
Note 2: There are obviously still order 2 uncertainties on μ_R, but this is the background for the central choice made in showers

Interfaces to External MEs (POWHEG/SCALUP)

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

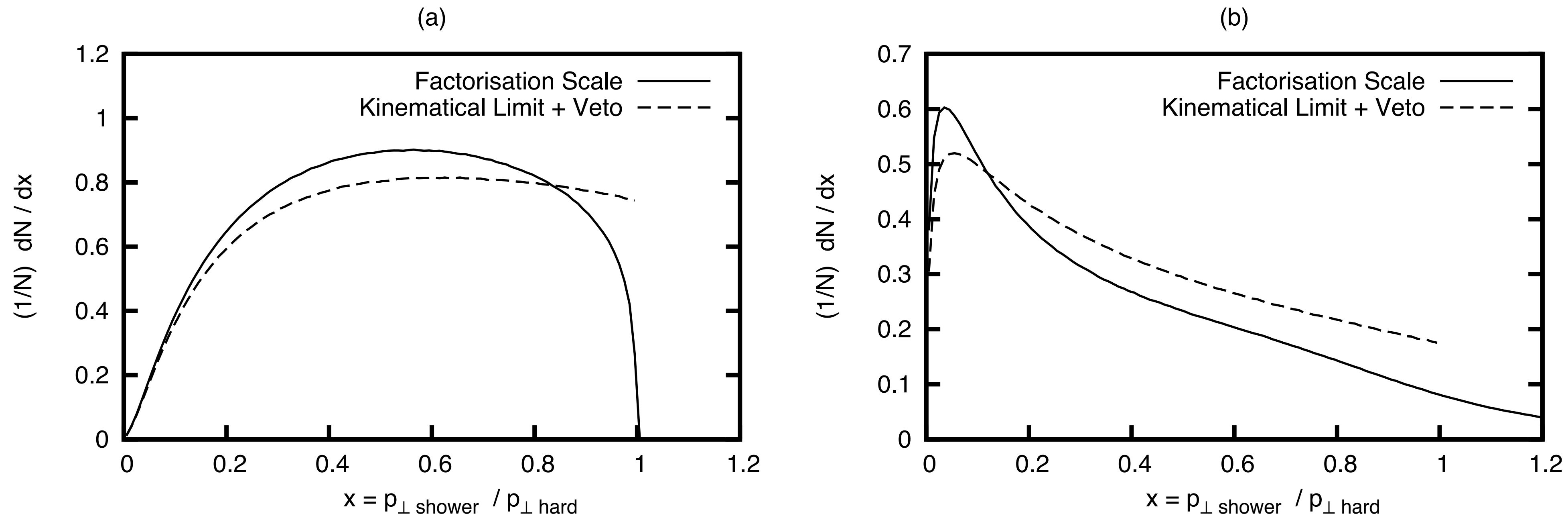
Standard Les Houches interface (LHA, LHEF) specifies startup scale SCALUP for showers, so "trivial" to interface any external program, including POWHEG.
Problem: for ISR

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

$$\int d\Phi_r \frac{R(v,r)}{B(v)} \theta(k_T(v,r) - p_T)$$

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

Interfaces to External MEs (MLM)

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

If using one code for MEs and another for showering

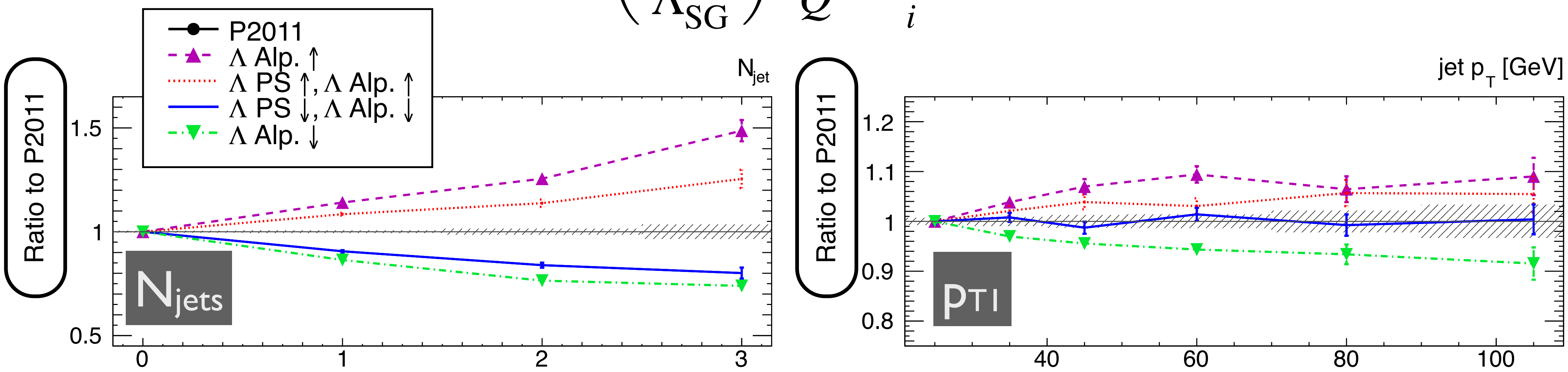
Tree-level corrections use α_s from Matrix-element Generator

Virtual corrections use α_s from Shower Generator (Sudakov)

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

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

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

Lönnblad Matching in PYTHIA 8

Lönnblad, JHEP 05 (2002) 046, similar to CKKW

Slide from S. Prestel

Get the state S_{+n} (with all partons above a cut t_{MS}) from a matrix element generator

Find all possible shower histories $(S_{+0},\rho_0),\ldots,(S_{+n},\rho_n)$

- Pick one according to the probability with which the shower would have produced it

Generate the Sudakov factor by **trial showering**

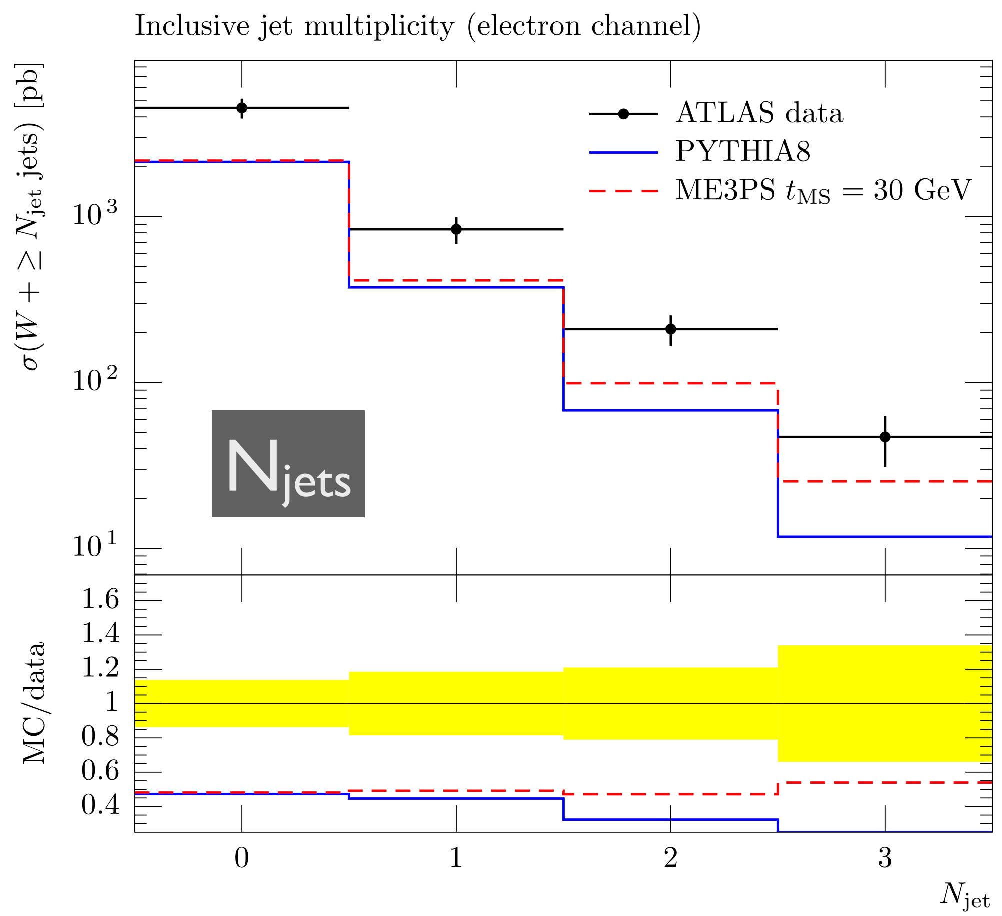
- Reweight with α_s factors and PDF factors

Start shower from **last reconstructed scale**

- If n is the highest multiplicity, continue;
- Else veto events with shower splittings above t_{MS}

Combine histograms for all MEs

→ distributions with ME+PS merging.



Now automated in PYTHIA 8 (needs ME events in LHEF format)
L. Lönnblad & S. Prestel, arXiv:1109.4829

Pythia 6: The Perugia Variations

"Tuning MC Generators: The Perugia Tunes" - PRD82 (2010) 074018

Central Tune + 9 variations

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

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	…

Tunes of PYTHIA 8 : Corke & Sjöstrand - JHEP 03 (2011) 032 & JHEP 05 (2011) 009

(Multiple Parton Interactions)

Note: will change name from "MI" to "MPI" in PYTHIA 8.160

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$\sigma_{2\to 2}(p_T) > \sigma_{tot}$ for $p_\perp \approx 5$ GeV

→ fixed-order unreliable, but pQCD still ok if resummed (unitarity)

→ Resum dijets? Yes → MPI!

Regularise cross section with $p_{\perp 0}$ as free parameter

$$\frac{d\hat{\sigma}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

with energy dependence

$$p_{\perp 0}(E_{CM}) = p_{\perp 0}^{ref} \times \left(\frac{E_{CM}}{E_{CM}^{ref}}\right)^{\epsilon}$$

MultipleInteractions:alphaSvalue	**0.135**	$\alpha_s(m_Z)$
MultipleInteractions:alphaSorder	**1**	
MultipleInteractions:Kfactor	**1.0**	
MultipleInteractions:bProfile	**3**	Gauss
MultipleInteractions:pT0Ref	**2.085**	IR reg scale at 1.8 TeV
MultipleInteractions:ecmPow	**0.19**	Energy-Scaling power of IR scale

+ see "Multiple Interactions" and "PDF selection"

+ "A Second Hard Process" (can specify 2nd interaction)

MPI 4C

(Hadronization)

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ISR and FSR cutoffs
+ String-Fragmentation Parameters

See, e.g., Buckley et al., EPJC65 (2010) 331 and Phys.Rept. 504 (2011) 145

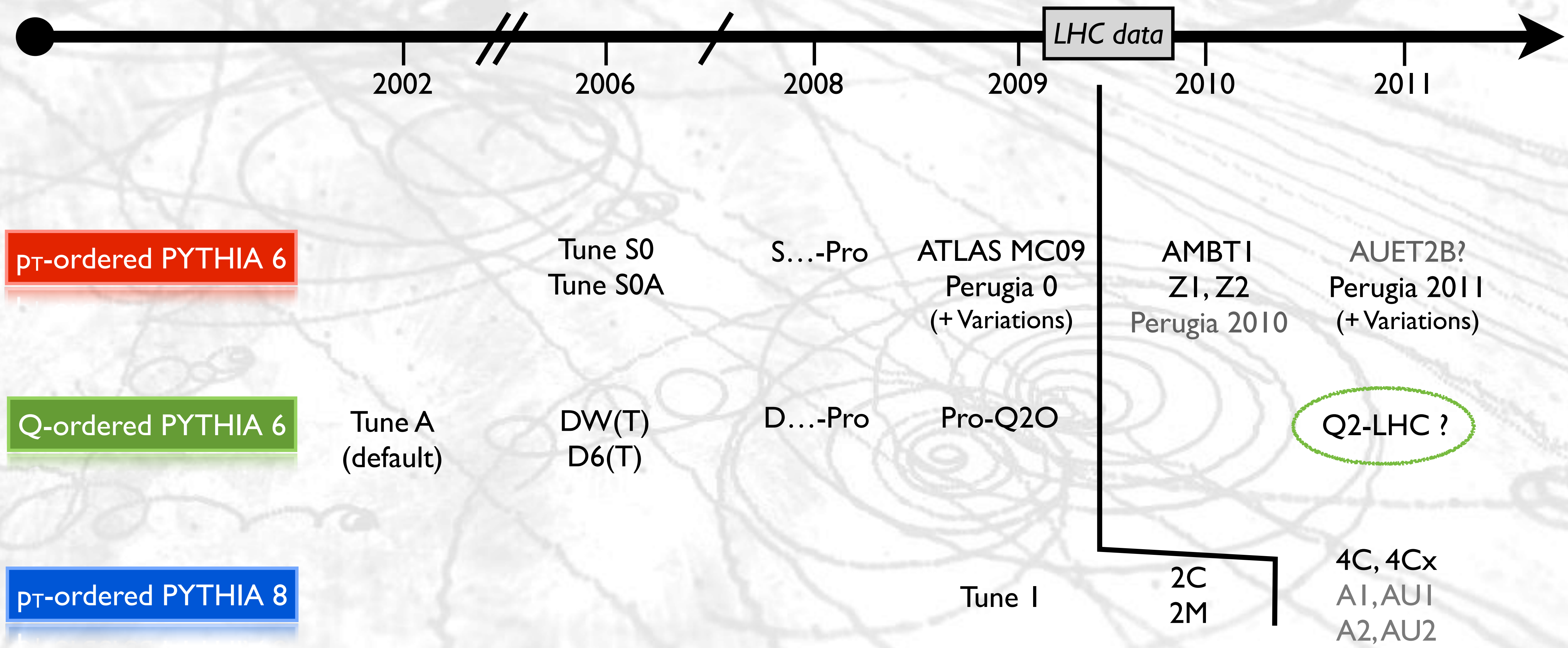
Important task: evaluate whether LEP/LHC universality holds

E.g., use universality-testing technique proposed in Schulz & PS, EPJ C71 (2011) 1644

For percent-level m_{top}, must also consider non-perturbative uncertainties

E.g., Central vs NOCR, etc, discussed in PS & Wicke, EPJ C52 (2007) 133

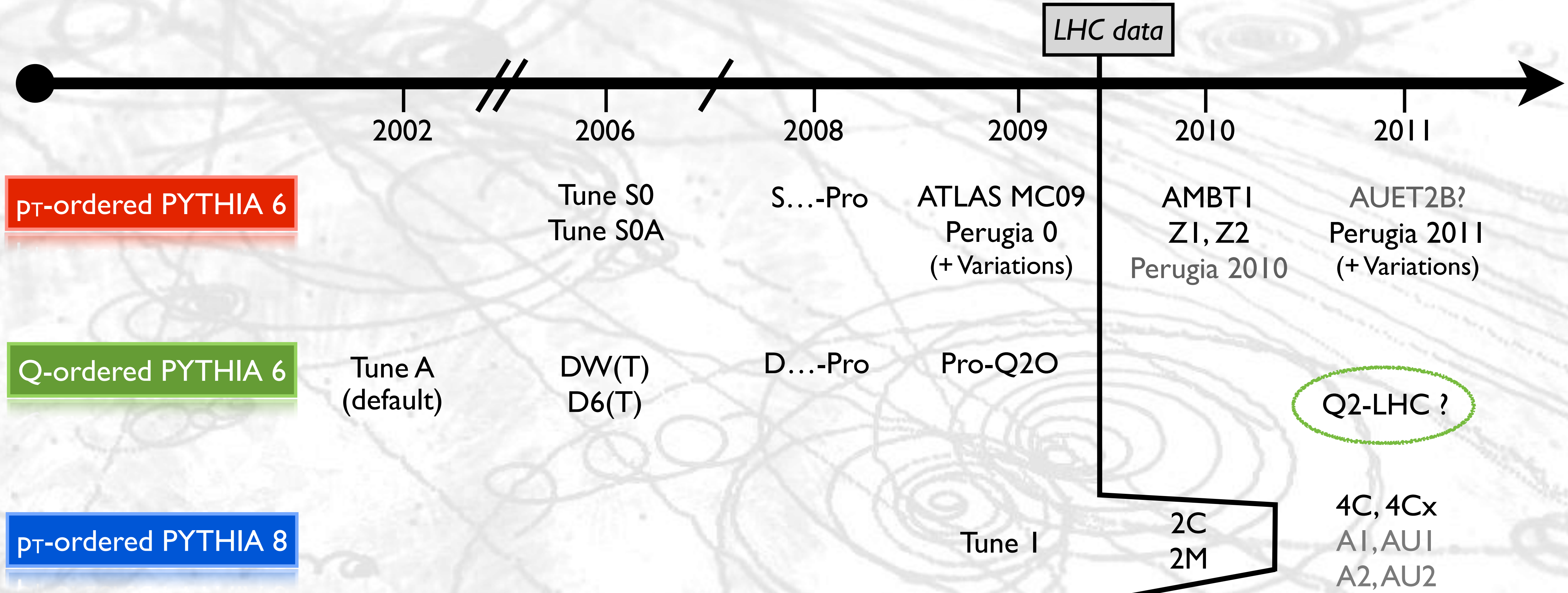
PYTHIA Models



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



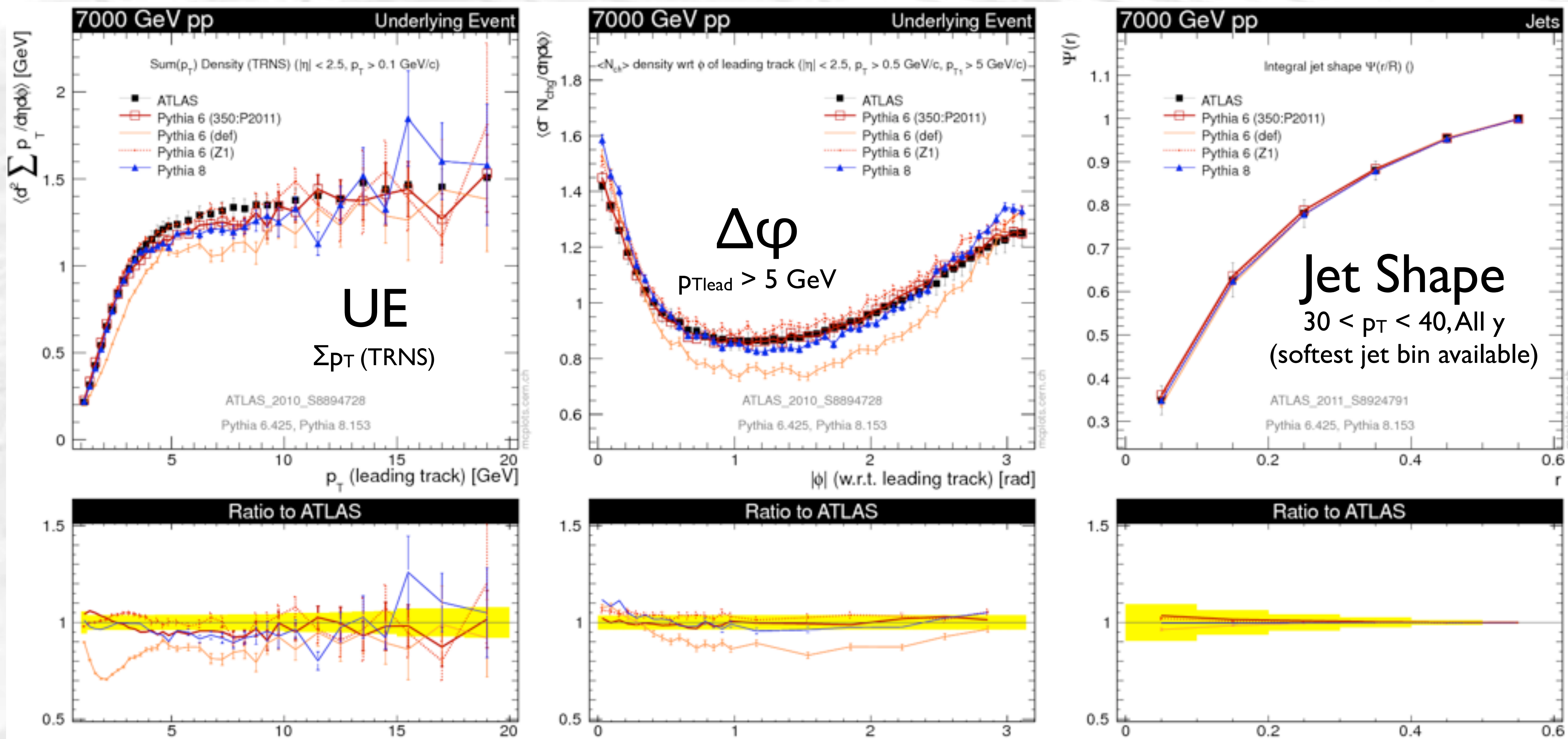
Main Data Sets included in each Tune (no guarantee that all subsets ok)

	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								✔	✔		✔

What Works*

*) if you use an up-to-date tune. Here comparing to PY6 default (~ Tune A) to show changes.

Underlying Event & Jet Shapes



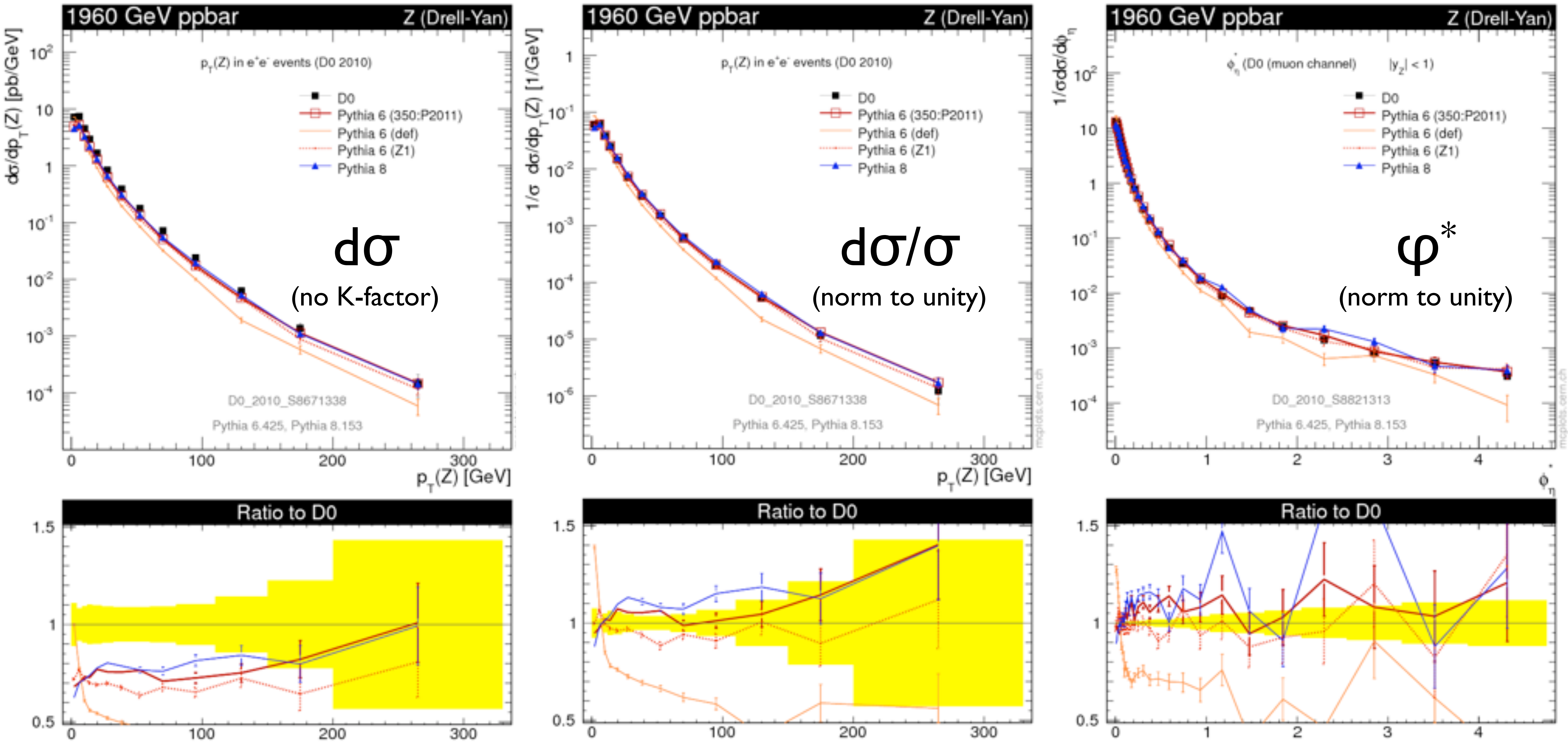
PS: yes, we **should** update the PYTHIA 6 defaults ...

What Works*

*) if you use an up-to-date tune. Here comparing to PY6 default (~ Tune A) to show changes.

Drell-Yan p_T (Normalized to Unity)

Apologies: we don't have DY measurements from LHC on the mcplots site yet



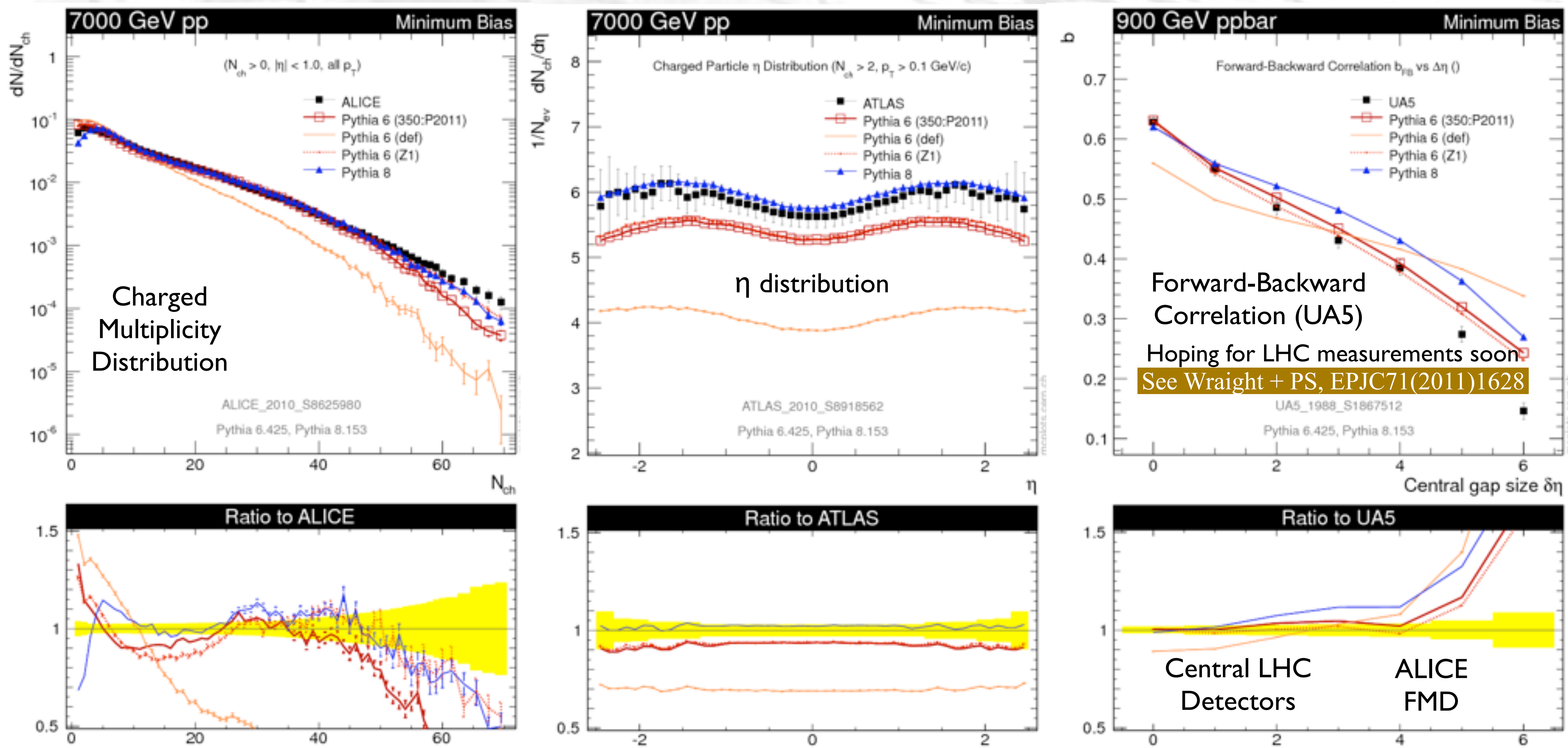
PS: yes, we **should** update the PYTHIA 6 defaults ...

What Kind of Works*

*) if you use an up-to-date tune. Here comparing to PY6 default (~ Tune A) to show changes.

Minimum-Bias Multiplicities

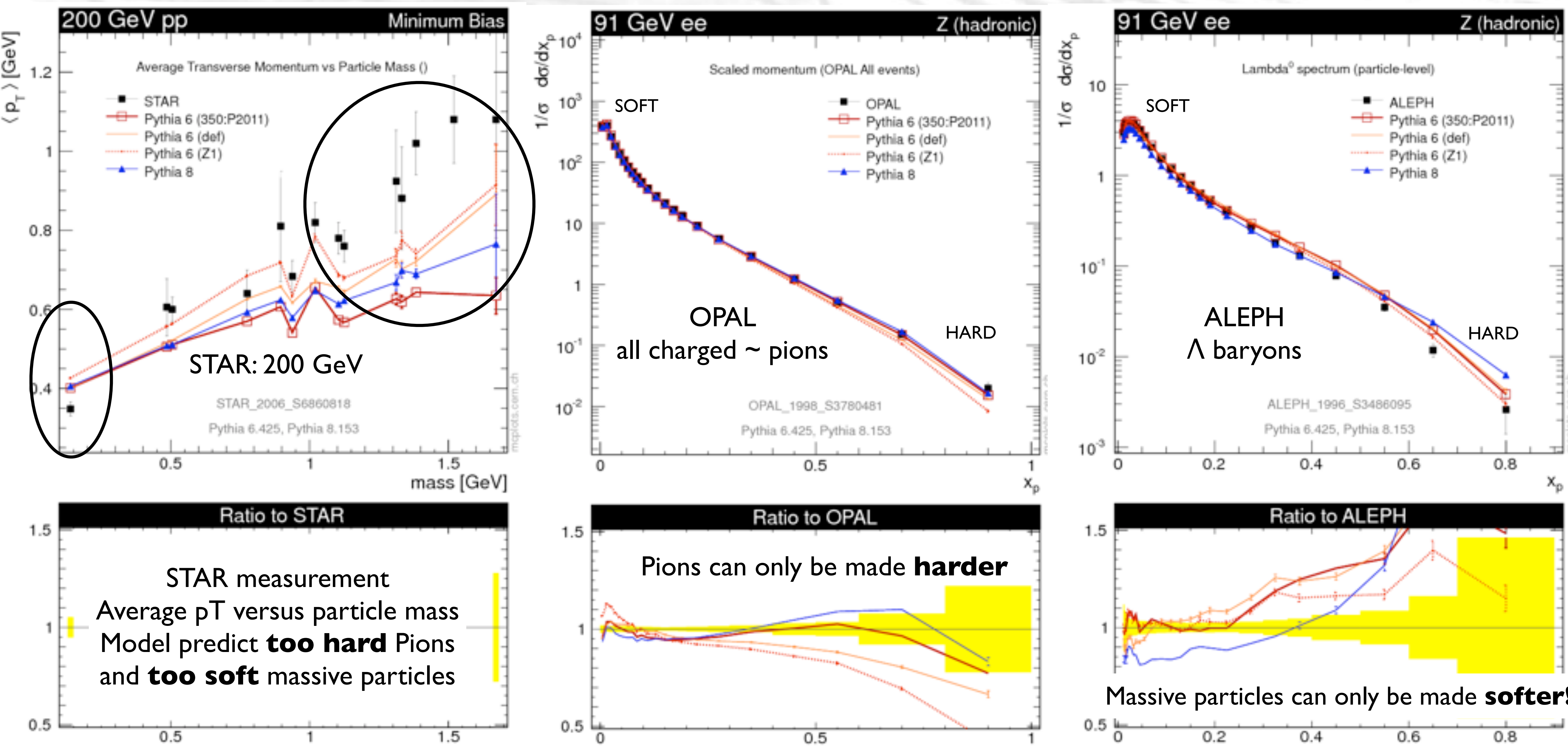
(here showing as inclusive as possible)



PS: yes, we **should** update the PYTHIA 6 defaults ...

pT Spectra / Mass Dependence

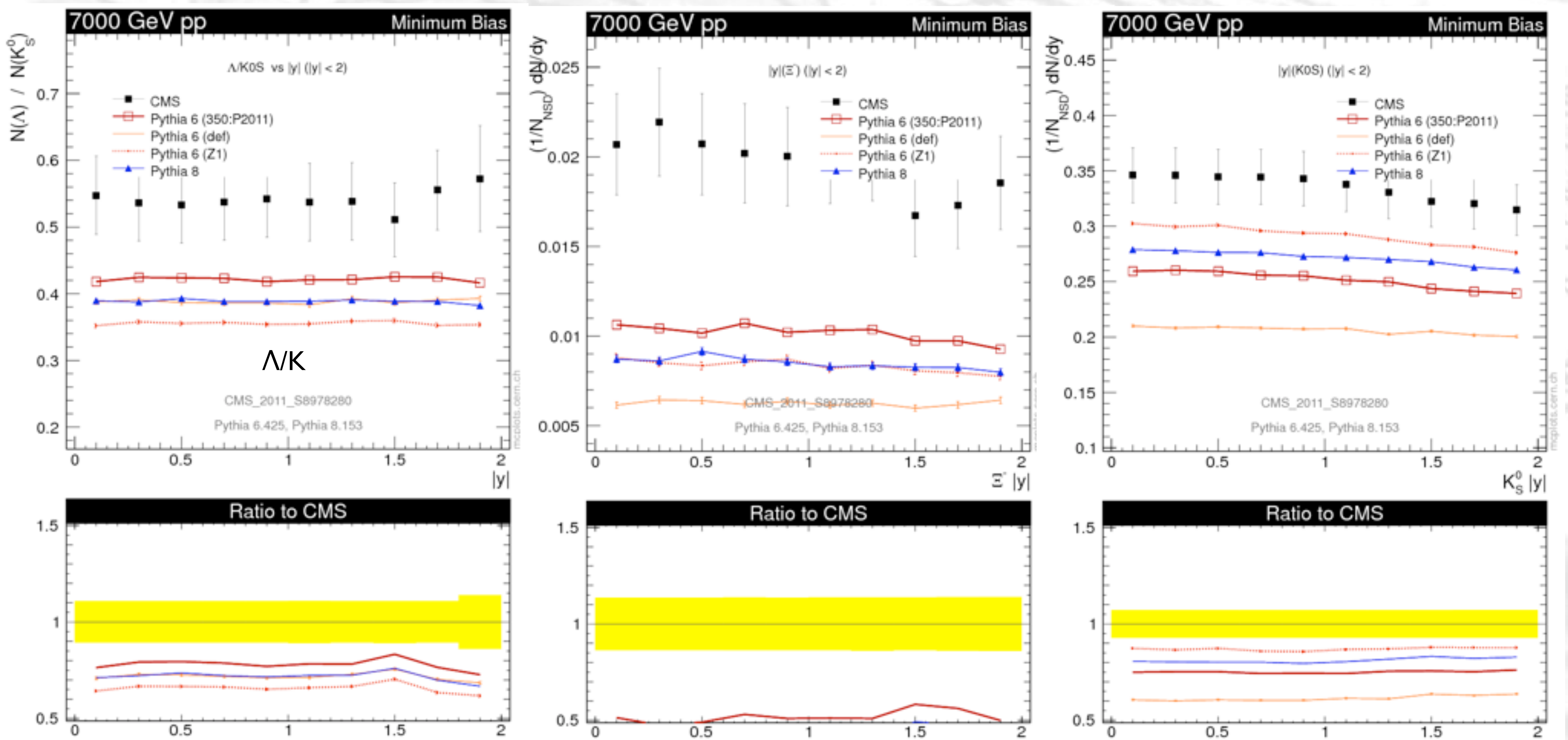
Must be compared with LEP



So: tuning problem? or physics problem? Will return on Friday

Strangeness and Baryons

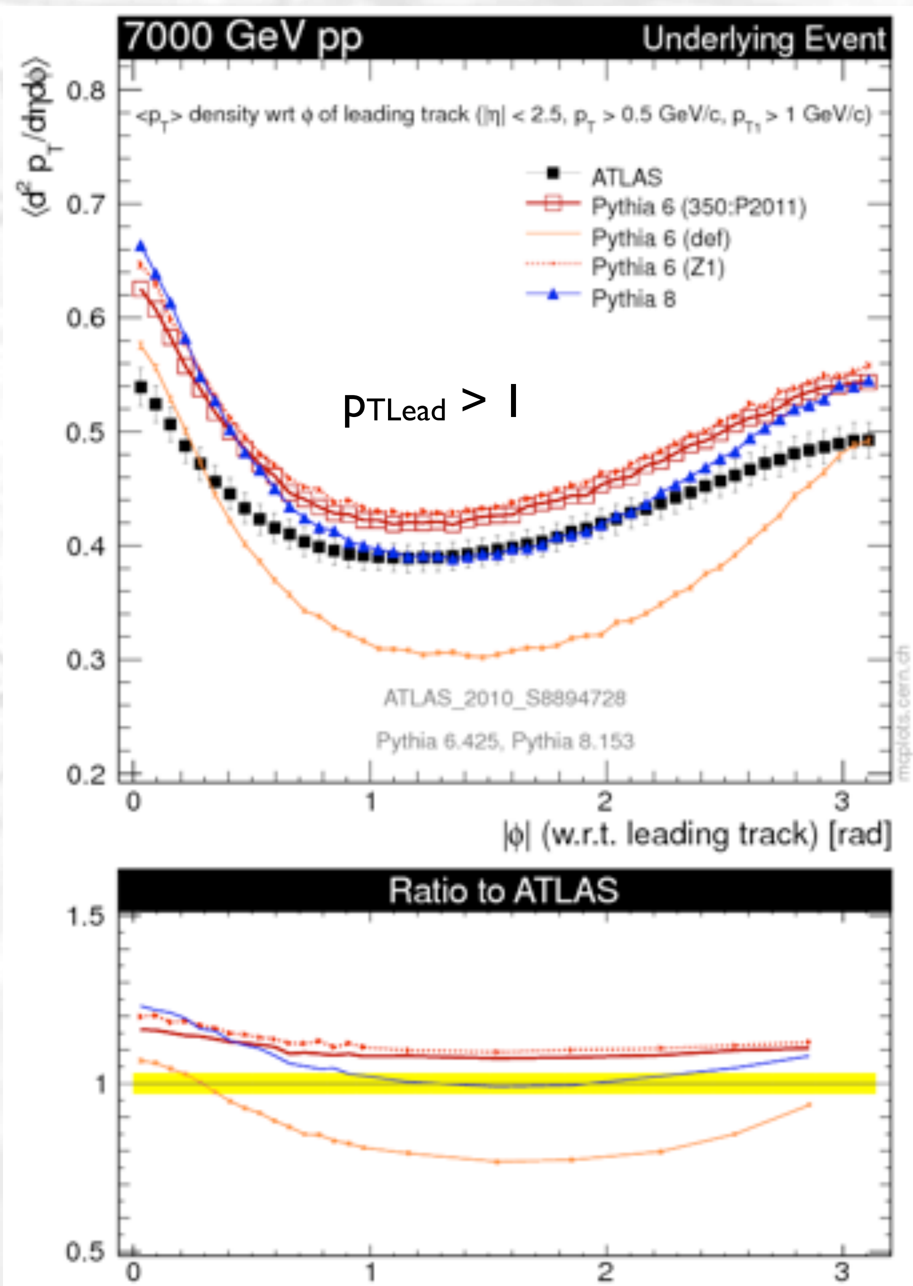
Tried to learn from early data, but still not there …



Again, quite difficult to adjust flavor parameters while remaining within LEP bounds …

Very Soft Structure

Minimum-Bias too lumpy?



Underlying Event ok?