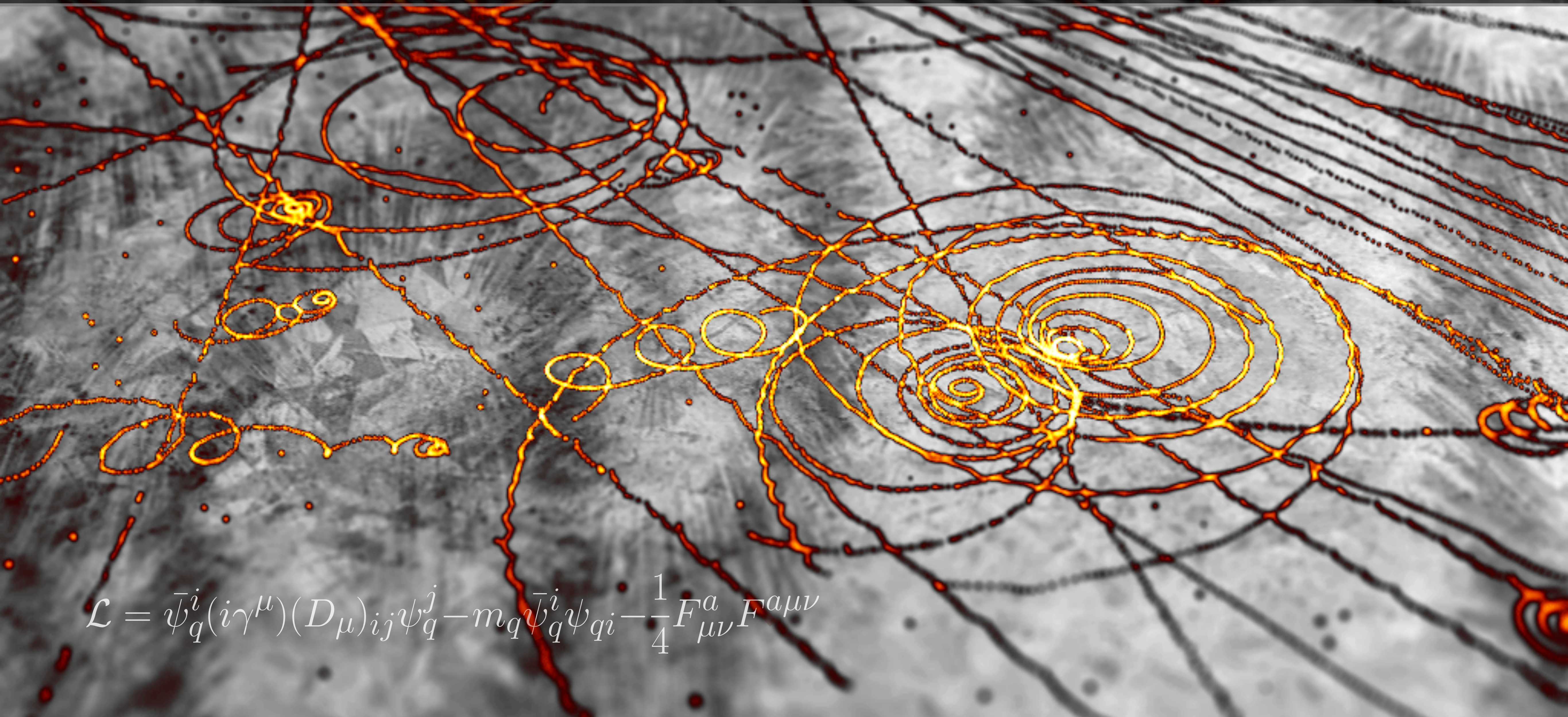
Standard Model Physics, Copenhagen, April 2012

Soft Physics Models



$$\mathcal{L} = \bar{\psi}^i_q (i\gamma^\mu)(D_\mu)_{ij}\psi^j_q - m_q \bar{\psi}^i_q \psi_{qi} - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$$

Peter Skands (CERN)

Many plots from **mcplots.cern.ch** - with A. Karneyeu, D. Konstantinov, S. Prestel, A. Pytel (+ funding from LPCC)

From Partons to Pions

General-Purpose Monte Carlo models

Start from pQCD *(still mostly LO)*. Extend towards Infrared.

HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

Elastic & Diffractive | *Direction of this talk* | *Hard Physics*

Elastic | Min-Bias | Jets/W/Z/H/Top/…

0 | Λ_{QCD} | 5 GeV | ∞

Elastic & Diffractive
Treated as separate class
Little predictivity

Color Screening
Regularization of pQCD
Hadronization

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

Hard Process
Perturbative 2→2 (ME)
Resonance Decays

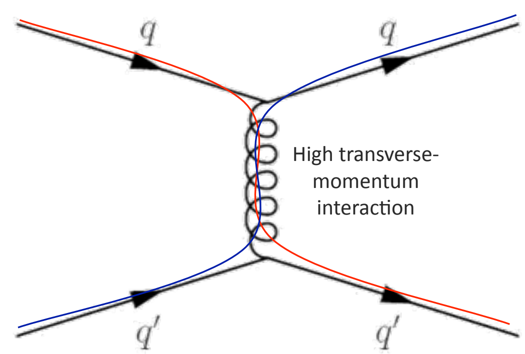
PYTHIA uses **string fragmentation**,
HERWIG, SHERPA use **cluster fragmentation**

(N)LL

(N)LO Matching

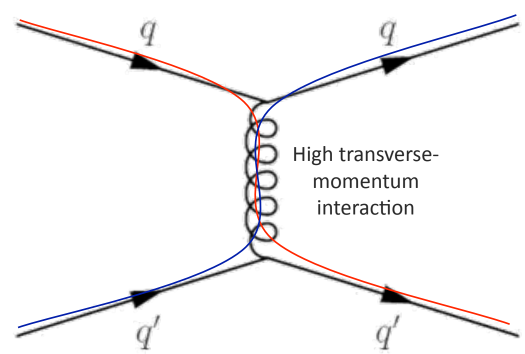
(Also possible to start from non-perturbative QCD (via optical theorem) and extend towards UV)
E.g., PHOJET, DPMJET, QGSJET, SIBYLL, … (But will not cover here)

Factorization



Factorization

Factorization
+ Infrared Safety

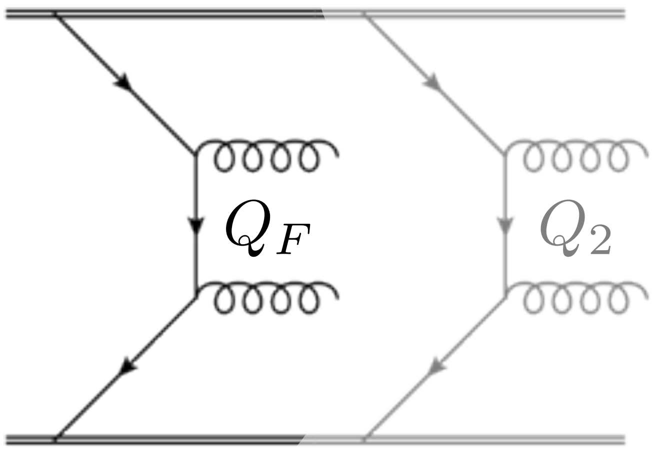


Perturbative Tools

Factorization: Subdivide Calculation

Multiple Parton Interactions go beyond existing theorems → perturbative short-distance physics in Underlying Event

→ Generalize factorization to MPI



Perturbative Tools

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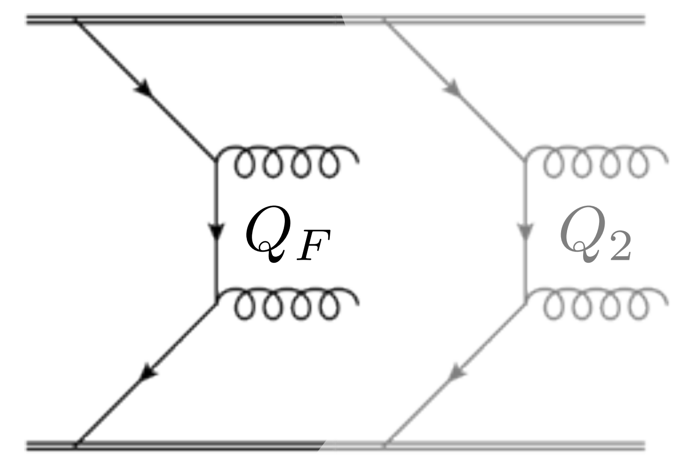


Infrared* Safety

*Soft and Collinear

$$\text{Corrections} \quad \propto \quad \frac{Q_{\mathrm{IR}}^2}{Q_{\mathrm{UV}}^2}$$

… in minimum-bias, we typically do not have a hard scale ($Q_{UV} \sim Q_{IR}$), wherefore *all* observables depend significantly on IR physics …

Combining IR safe + IR sensitive observables → stereo vision:

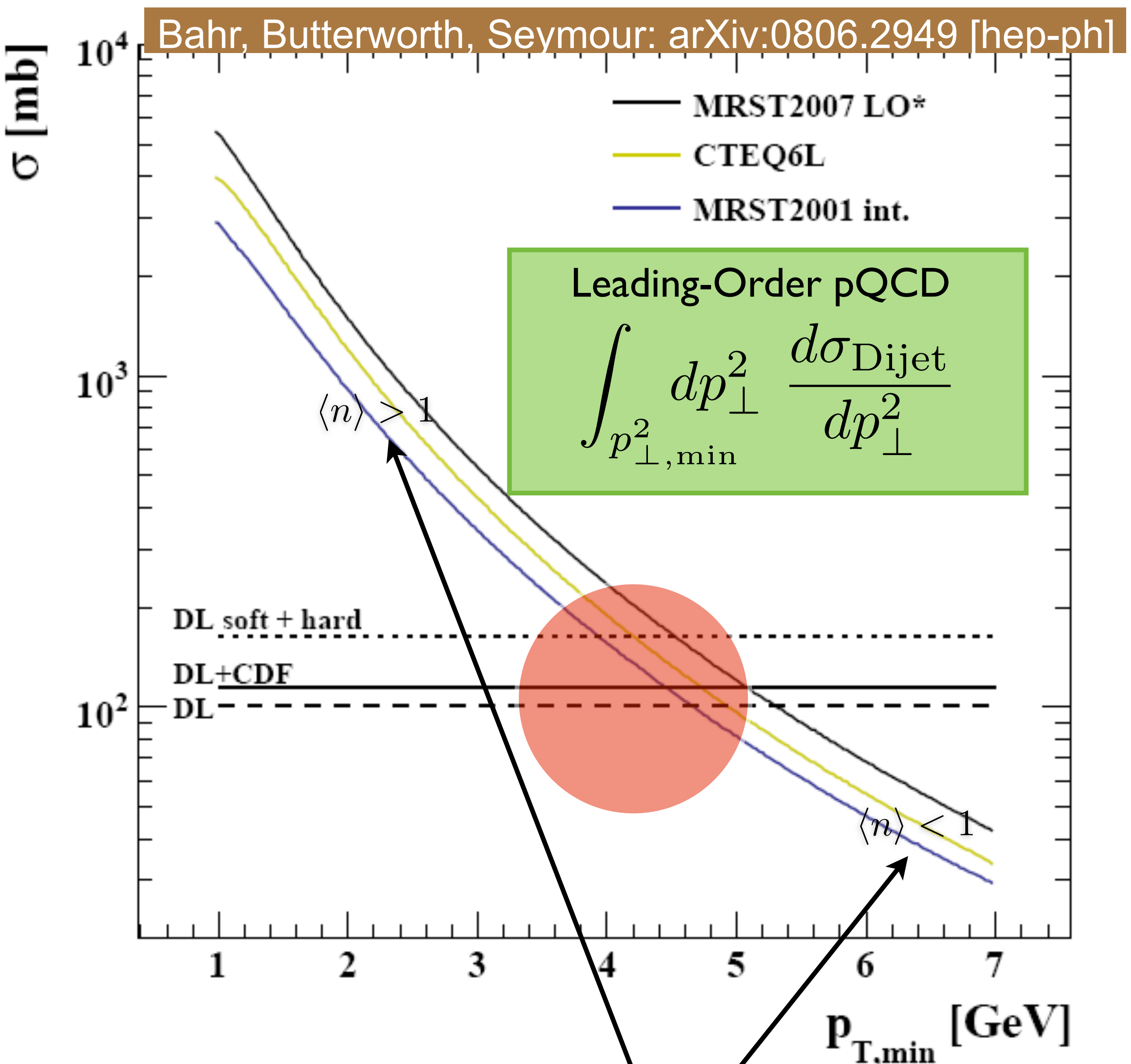
IR safe → overall energy flow/correlations

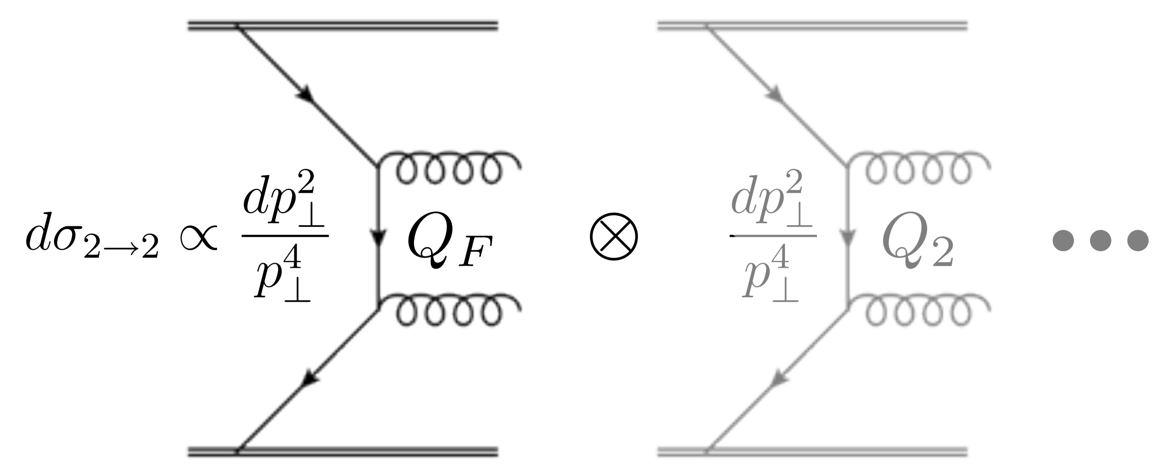
IR sensitive → spectra and correlations of individual particles/tracks.

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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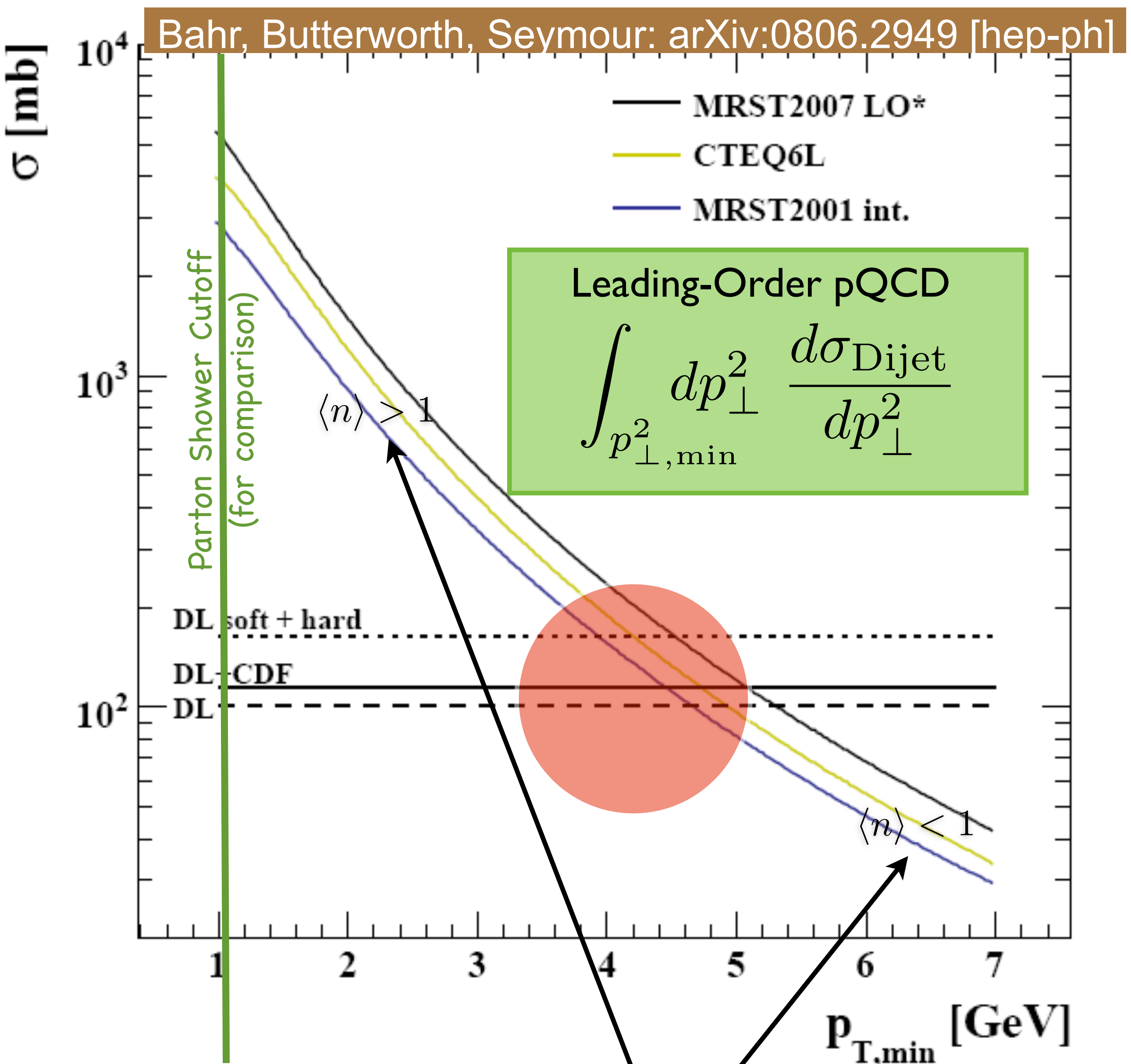

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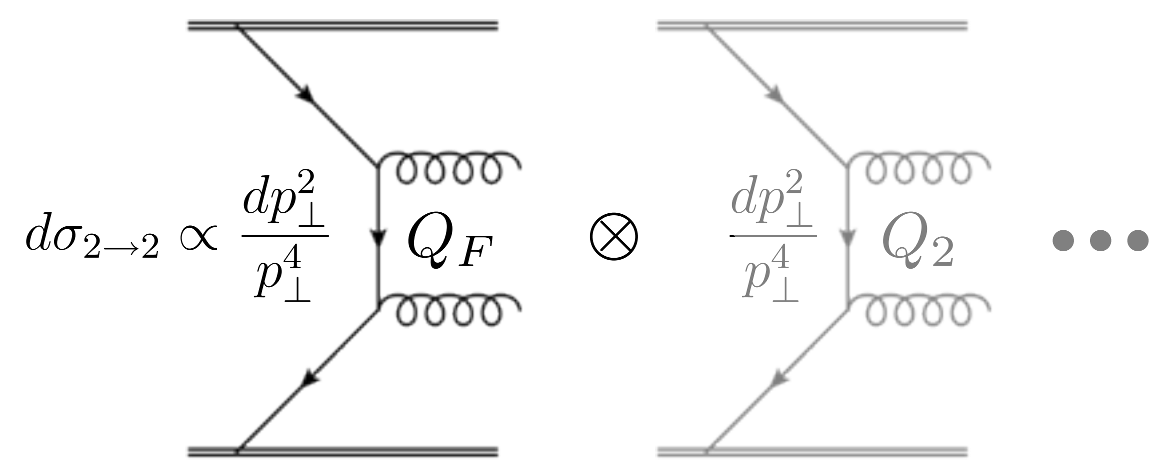

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1: A Simple Model

The minimal model incorporating single-parton factorization, perturbative unitarity, and energy-and-momentum conservation

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

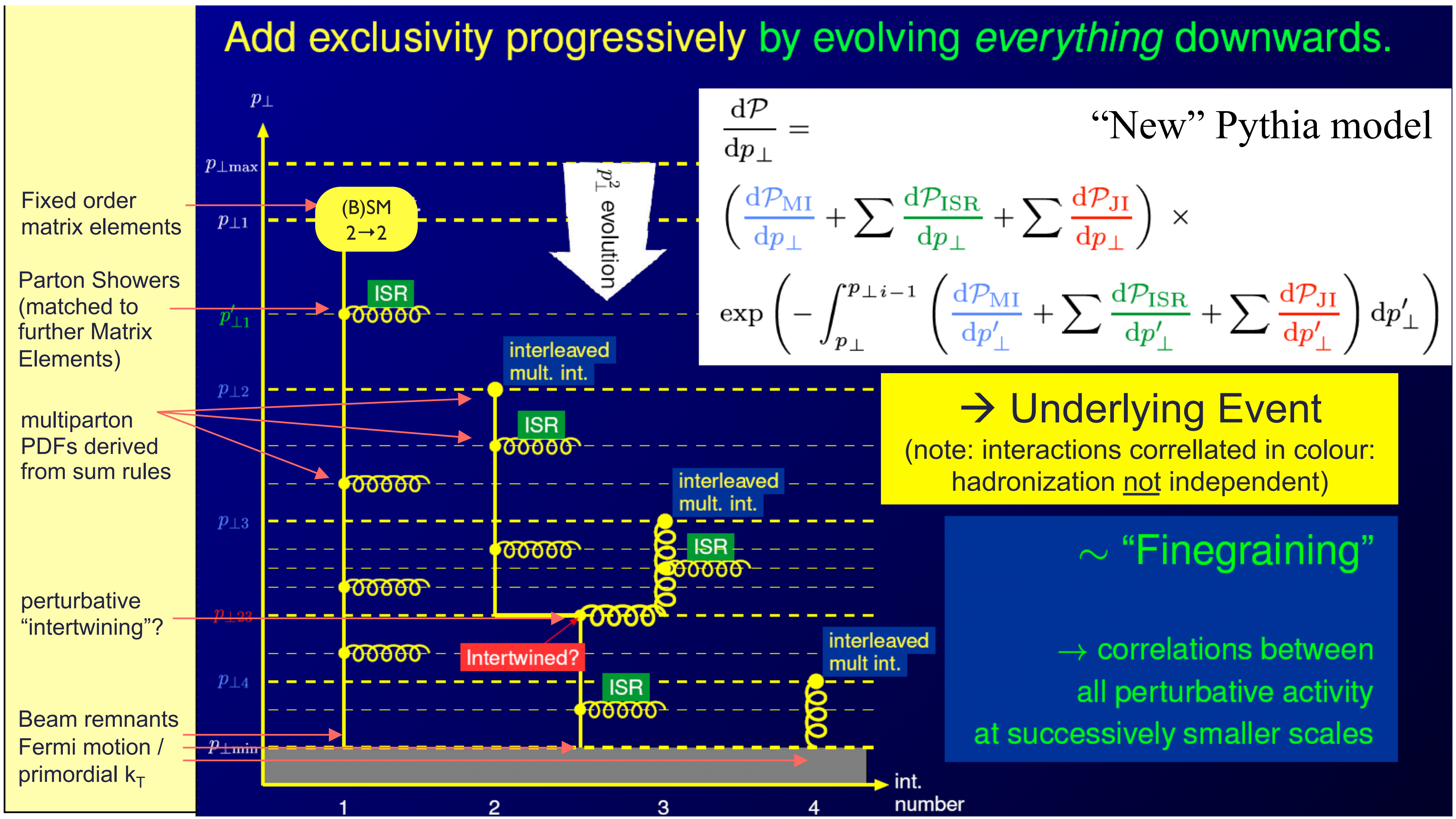
Parton-Parton Cross Section Hadron-Hadron Cross Section

1. Choose $p_{T\min}$ cutoff
   = main tuning parameter
2. Interpret $<n>(p_{T\min})$ as mean of Poisson distribution
   Equivalent to assuming all parton-parton interactions equivalent and independent ~ each take an instantaneous "snapshot" of the proton
3. Generate n parton-parton interactions (pQCD 2→2)
   Veto if total beam momentum exceeded → overall (E,p) cons
4. Add impact-parameter dependence → $<n> = <n>(b)$
   Assume factorization of transverse and longitudinal d.o.f., → PDFs : $f(x,b) = f(x)g(b)$ — Ordinary CTEQ, MSTW, NNPDF, …
   b distribution ∝ EM form factor → **JIMMY model** Butterworth, Forshaw, Seymour Z.Phys. C72 (1996) 637
   Constant of proportionality = second main tuning parameter
5. Add separate class of "soft" (zero-p_T) interactions representing interactions with $p_T < p_{T\min}$ and require $\sigma_{\text{soft}} + \sigma_{\text{hard}} = \sigma_{\text{tot}}$
   → **Herwig++ model** Bähr et al, arXiv:0905.4671

2: Interleaved Evolution

Equivalent to 1 at lowest order, but can include correlated evolution + generalizes "perturbative resolution" to higher twist

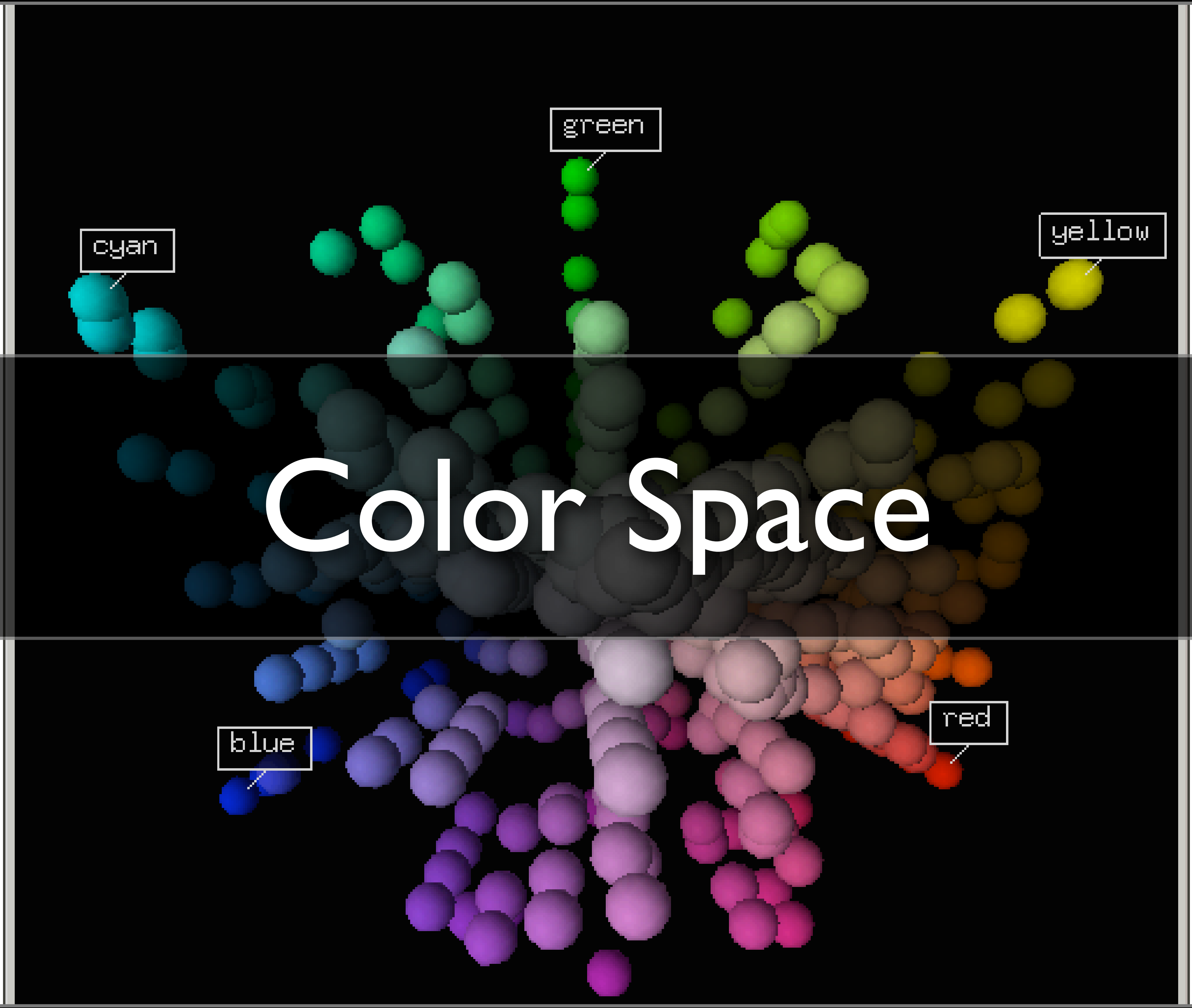
Sjöstrand, P.S., JHEP 0403 (2004) 053; EPJ C39 (2005) 129



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

+ KMR model (see talk by K. Zapp)

Color Space

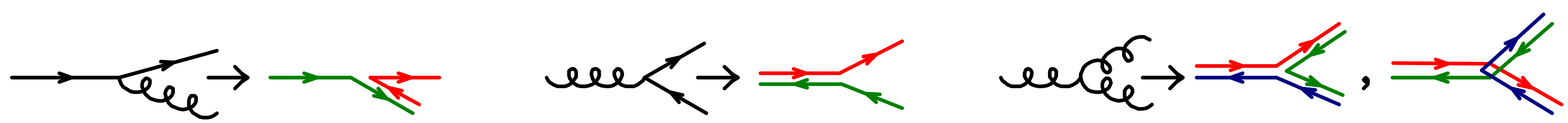


Color Flow in MC Models

"Planar Limit"

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

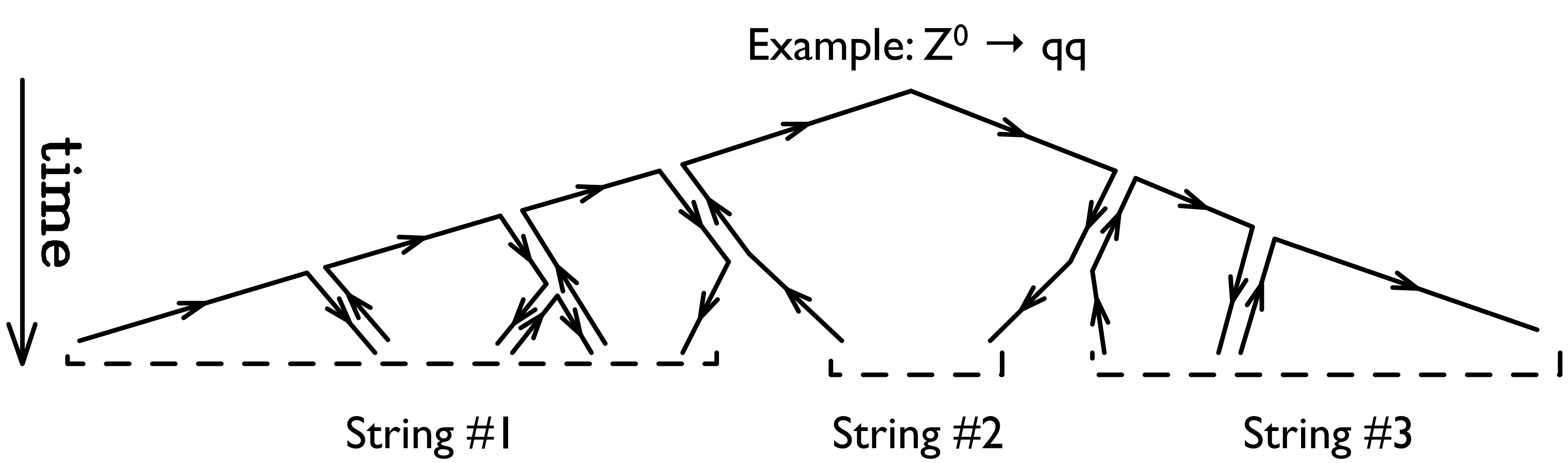
Rules for color flow:



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

For an entire cascade:

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



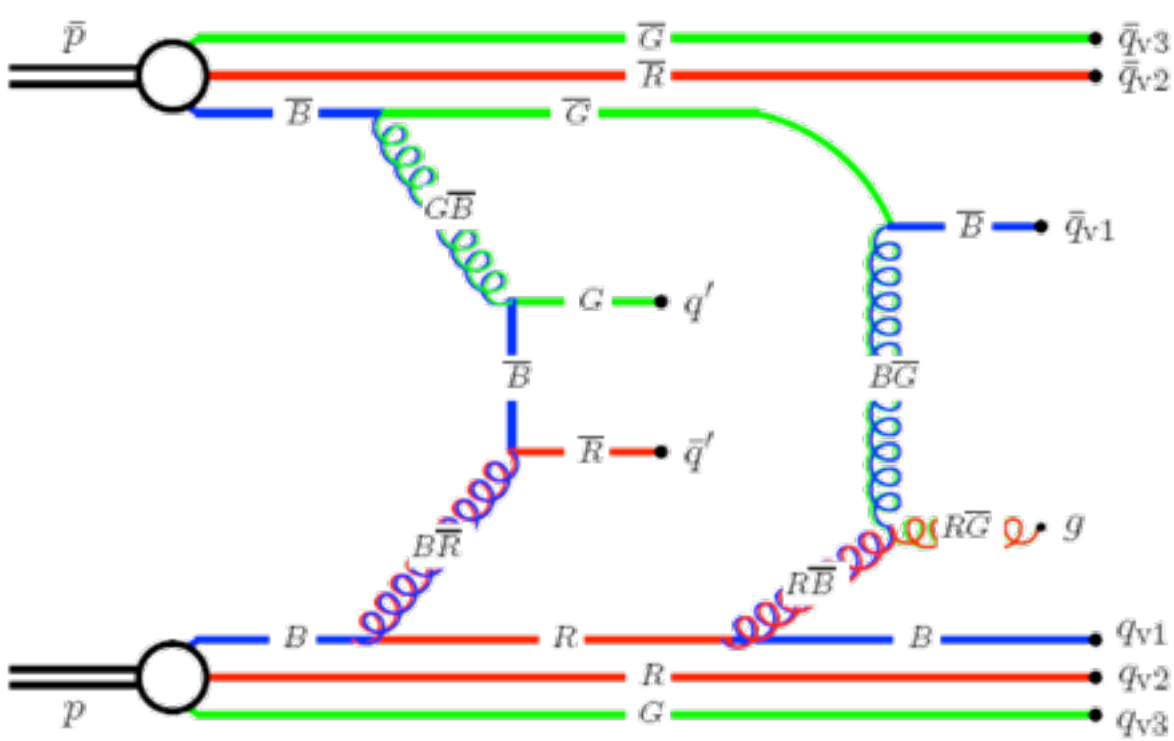
Coherence of pQCD cascades → not much "overlap" between strings
→ planar approx pretty good
LEP measurements in WW confirm this (at least to order 10% ~ $1/N_c^2$)

Color Connections

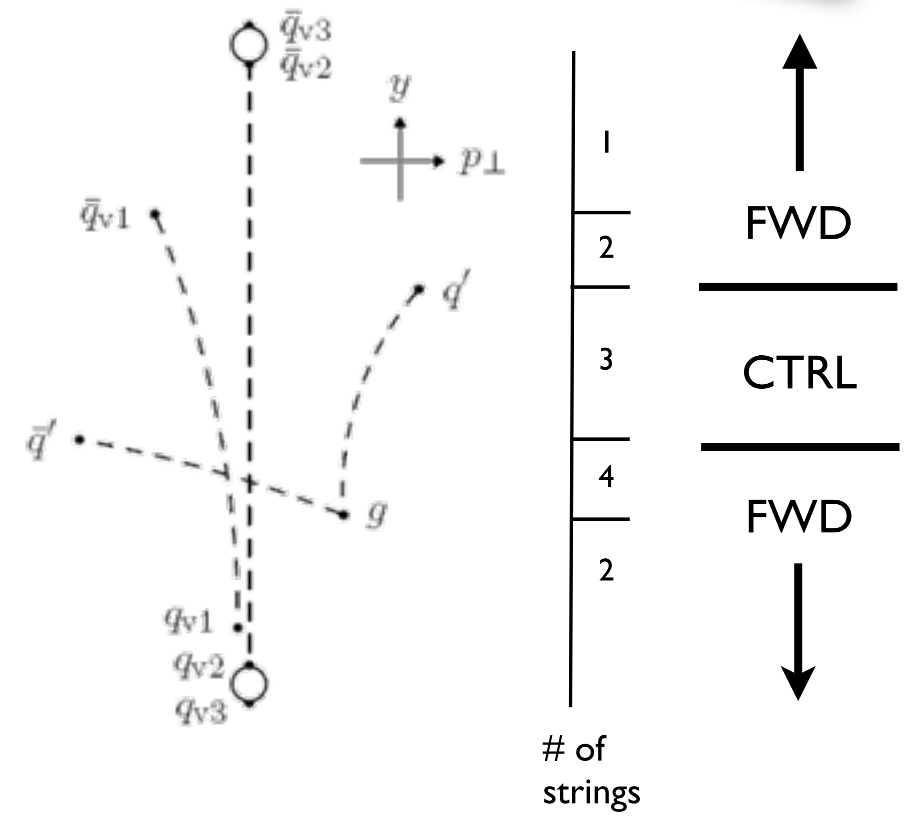
Each MPI (or cut Pomeron) exchanges color between the beams

- ► The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions crucially depend on color space

Different models make different ansätze



Sjöstrand & PS, JHEP 03(2004)053



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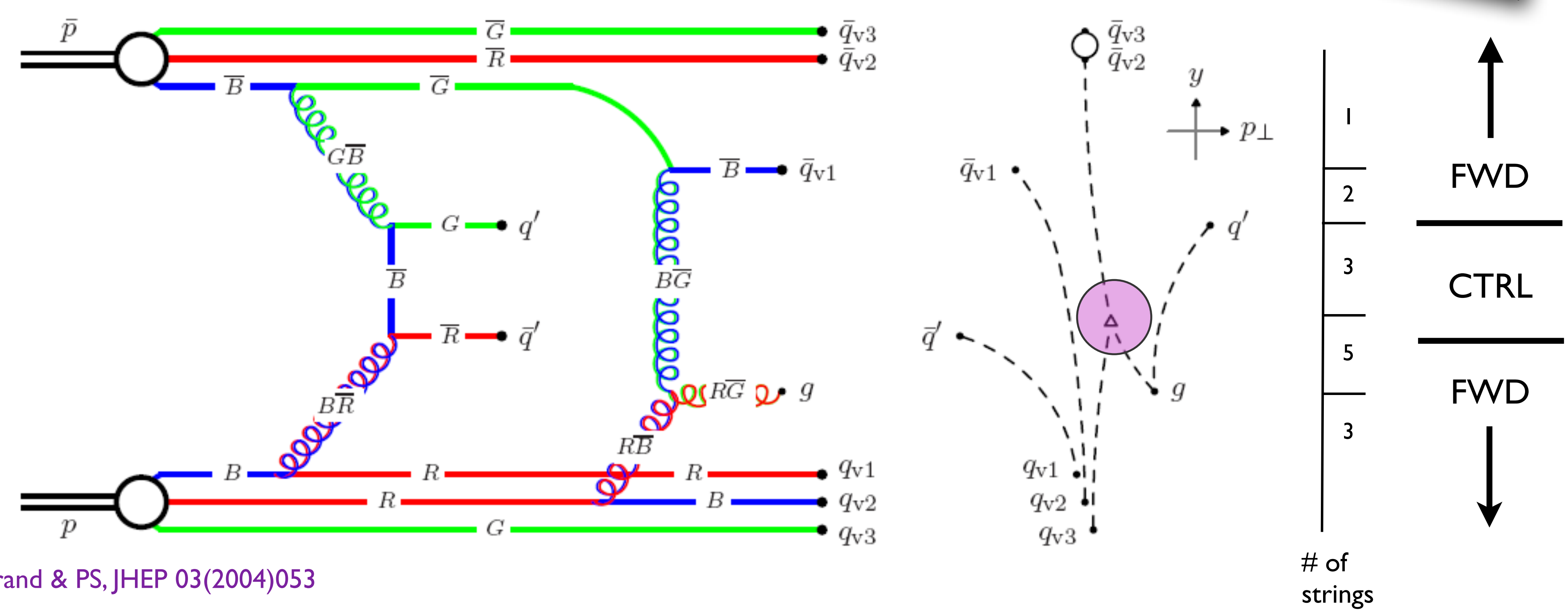

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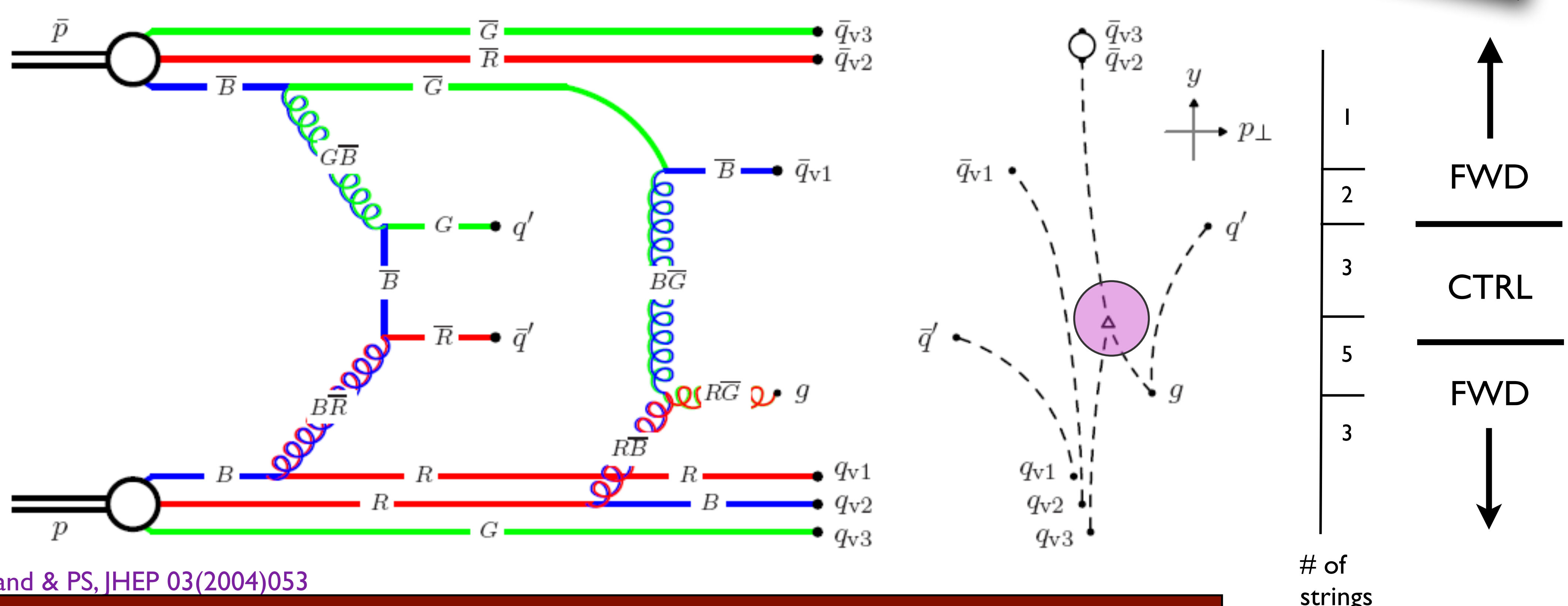


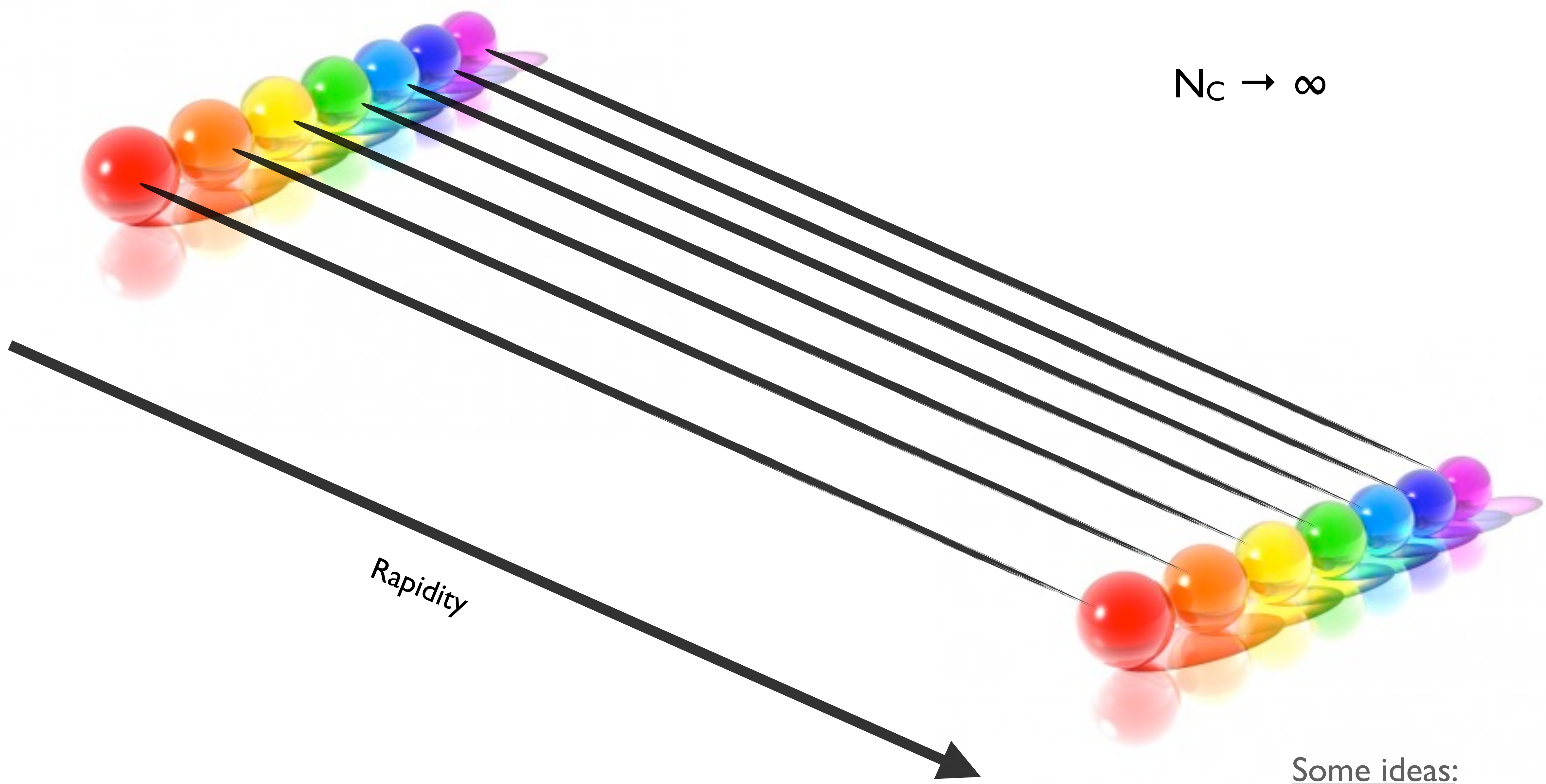
Sjöstrand & PS, JHEP 03(2004)053

Forward region (and forward-backward + forward-central **correlations**) sensitive to beam-remnant break-up!

Color Connections

Better theory models needed

$N_C \to \infty$



Multiplicity $\propto N_{MPI}$

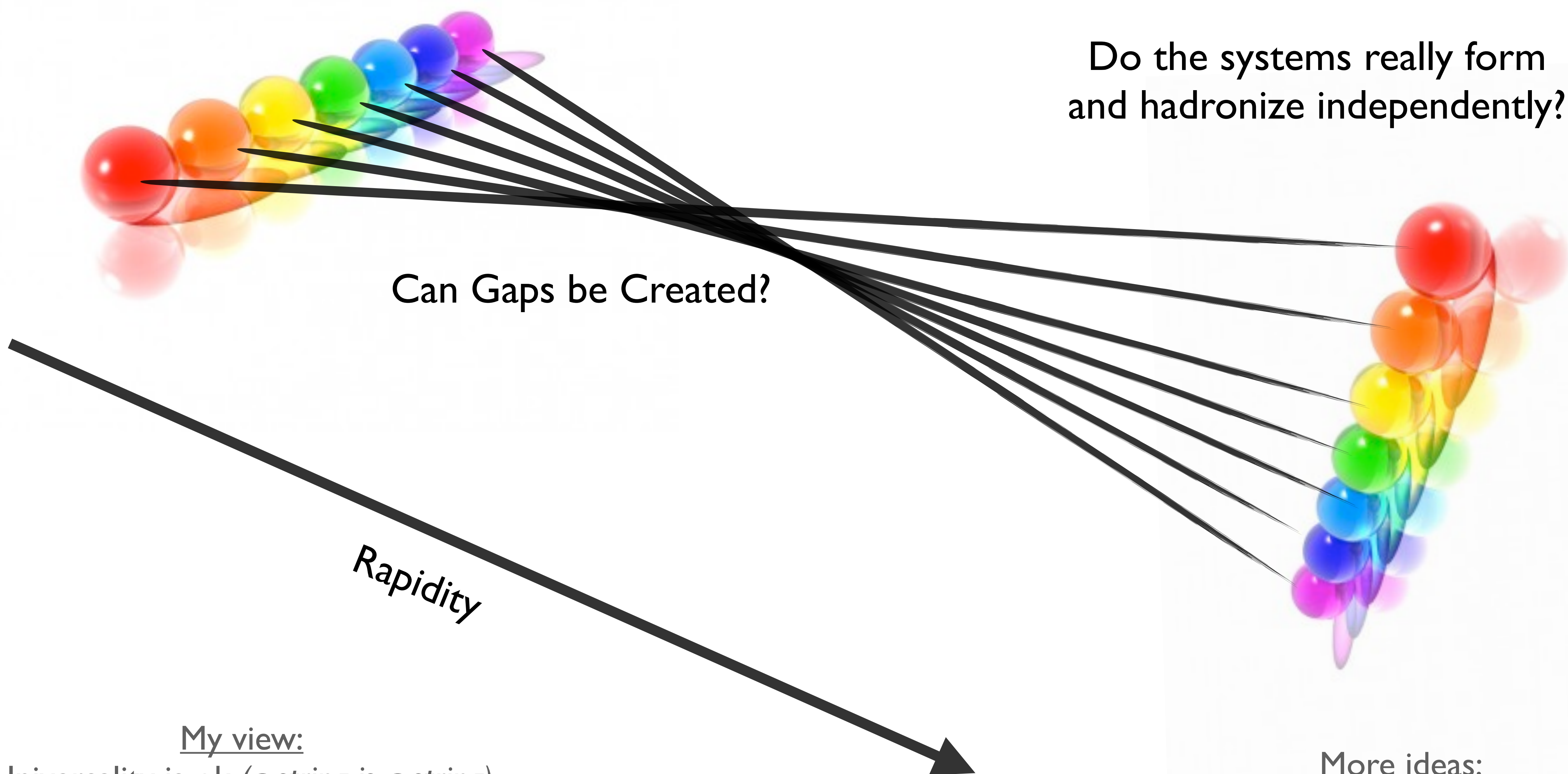
<u>Some ideas:</u>
Hydro? (EPOS)
E-dependent string parameters? (DPMJET)
"Color Ropes"?

Color Reconnections?

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

Better theory models needed

Do the systems really form
and hadronize independently?



<u>My view:</u>
Universality is ok *(a string is a string)*
Problem is $3 \neq \infty$
Use String Area Law to govern
collapse of color wavefunction

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

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

Color Reconnections?

E.g.,
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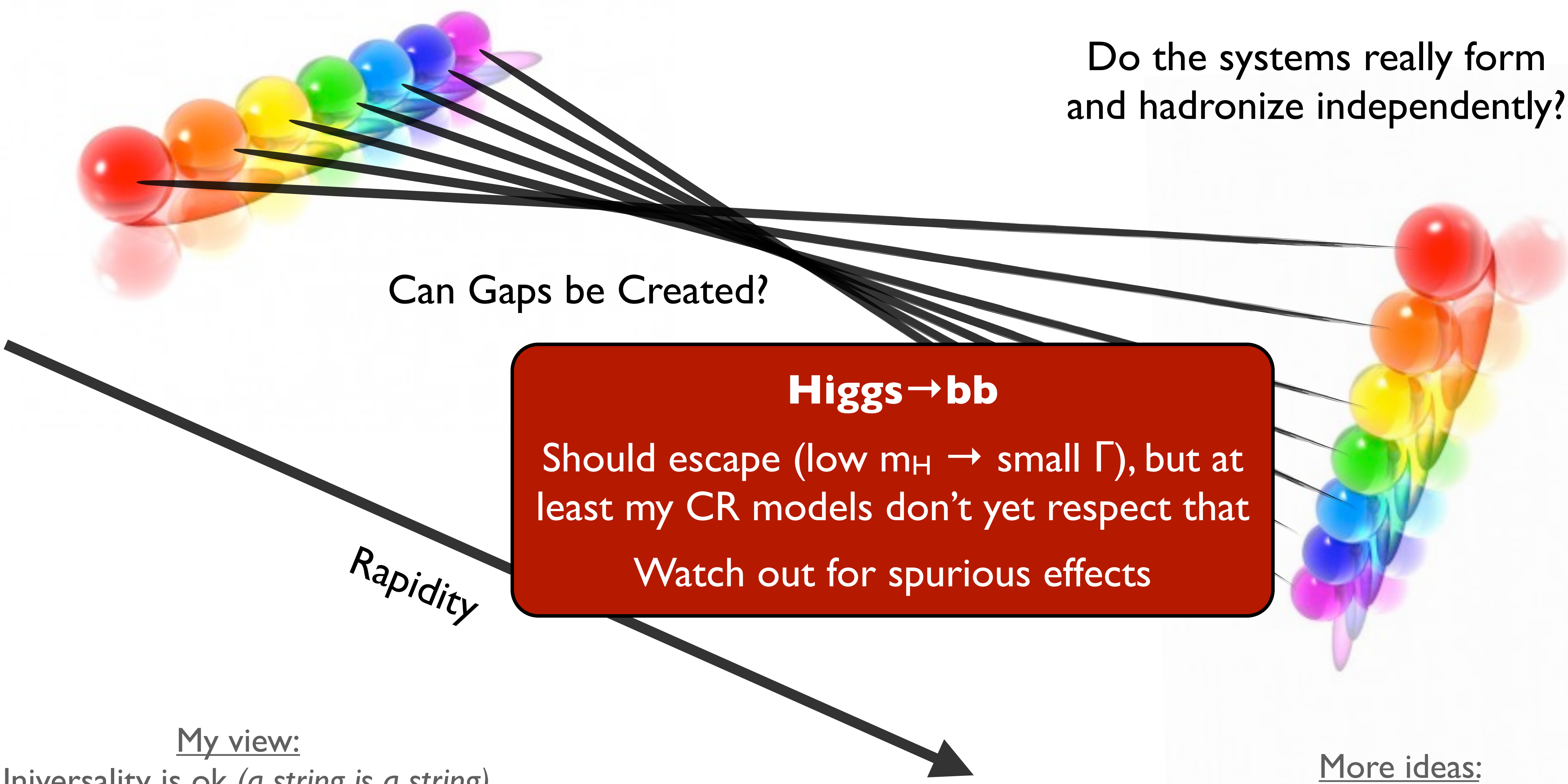

Higgs→bb

Should escape (low m_H → small Γ), but at least my CR models don't yet respect that

Watch out for spurious effects

My view:
Universality is ok *(a string is a string)*
Problem is $3 \neq \infty$
Use String Area Law to govern collapse of color wavefunction

Multiplicity $\overset{<}{\cancel{\propto}}$ N_{MPI}

More ideas:
Coherent string formation?
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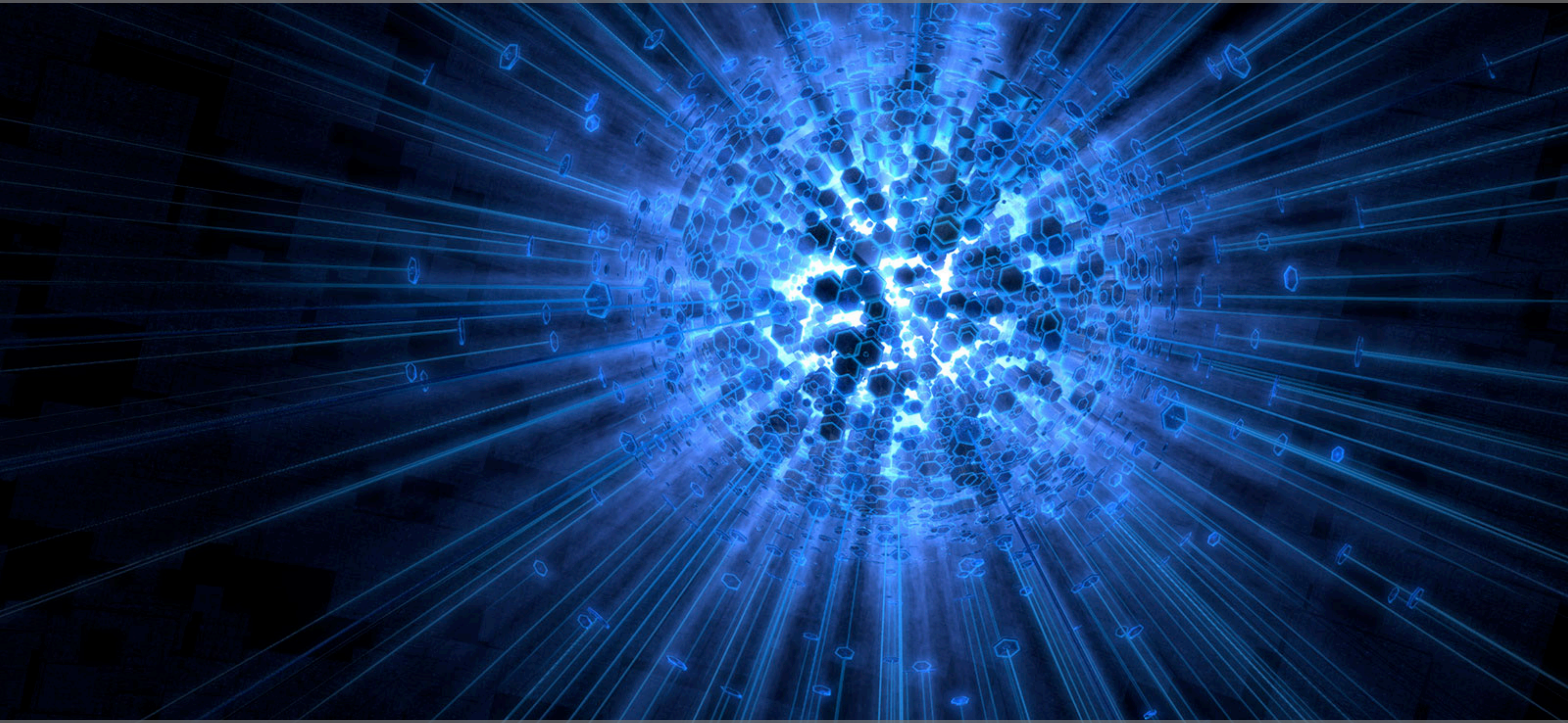
String dynamics?

Data



Data

http://lhcathome2.cern.ch/

Apples to Apples

$\sigma_{tot} \approx$		EXPERIMENT		THEORY MODELS
ELASTIC	$pp \to pp$	QED+QCD	~	(*QED = ∞)
SINGLE DIFFRACTION	$pp \to p + gap + X$	Gap = observable	≠	Small gaps suppressed but not zero
DOUBLE DIFFRACTION	$pp \to X + gap + X$	Gap = observable	≠	Small gaps suppressed but not zero
INELASTIC NON-DIFFRACTIVE	$pp \to X$ *(no gap)*	Gap = observable	≠	Large gaps suppressed but not zero

(+ multi-gap diffraction)

Apples to Apples

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(+ multi-gap diffraction)

Amplitudes
Monte Carlo
Parton Showers
Multiple Interactions
Strings
Diffraction
Collective Effects
Hadron Decays
...

Theory

Feedback Loop

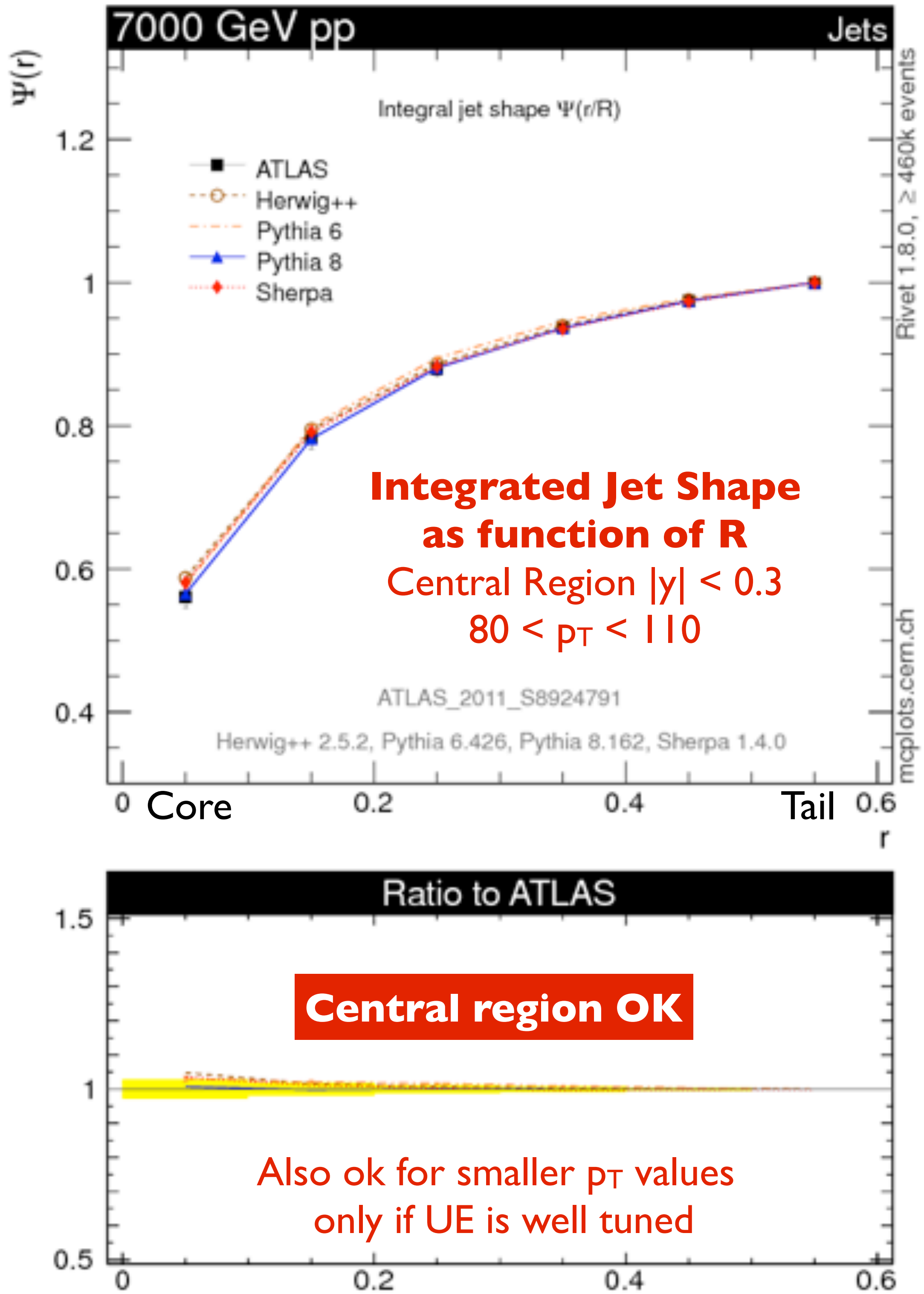
Experiment

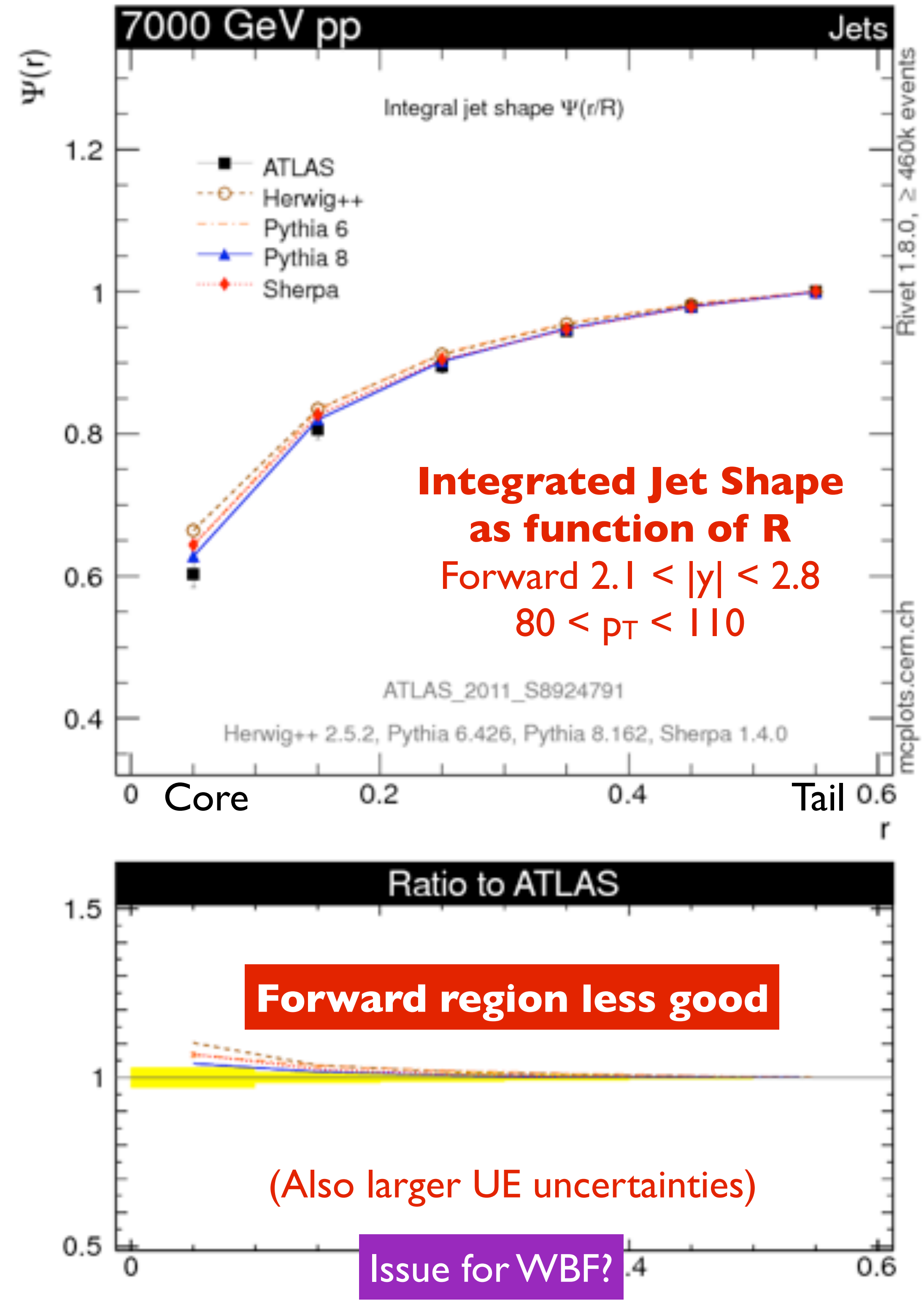
Hits
Trigger
B-Field
GEANT
0100110
Acceptance
Cuts
....

Theory worked out to
Hadron Level
with acceptance cuts
(~ detector-independent)

Measurements corrected to
Hadron Level
with acceptance cuts
(~ model-independent)

FSR: Jet Shapes



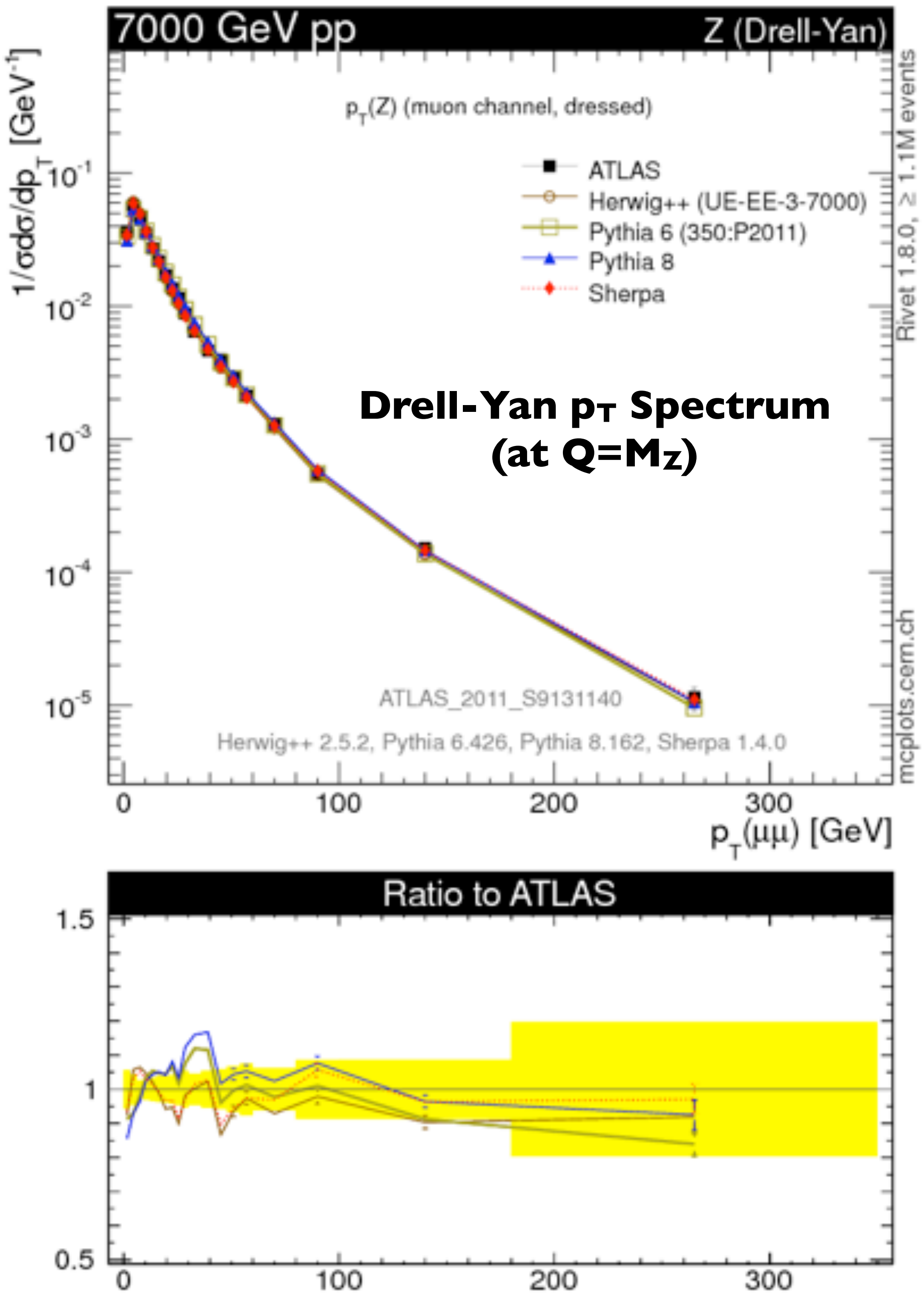


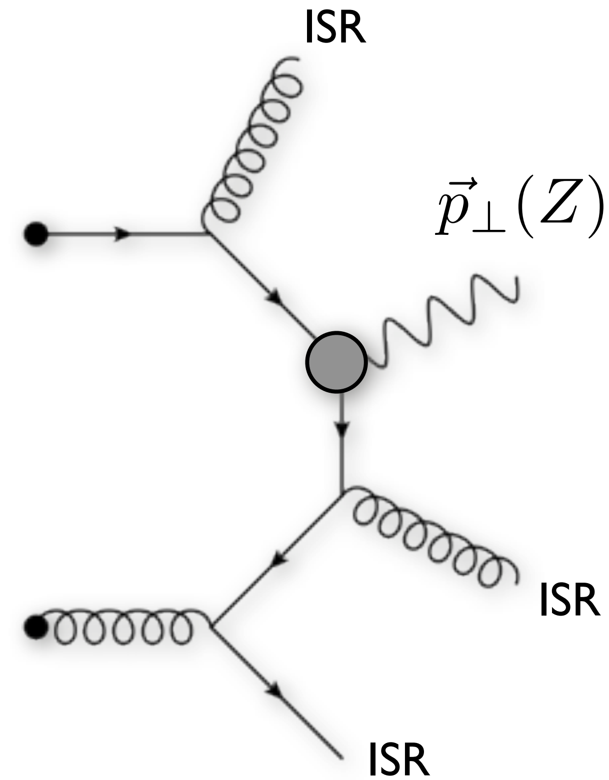
Plots from mcplots.cern.ch

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

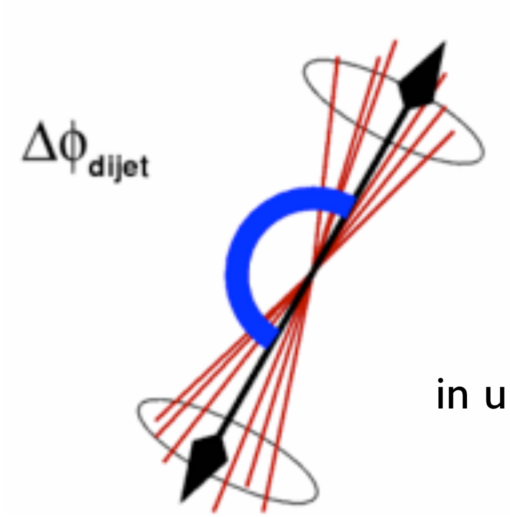
1. α_s renormalization scale choice
2. Recoil strategy (color dipoles vs global vs …)
3. FSR off ISR (ISR jet broadening)

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)

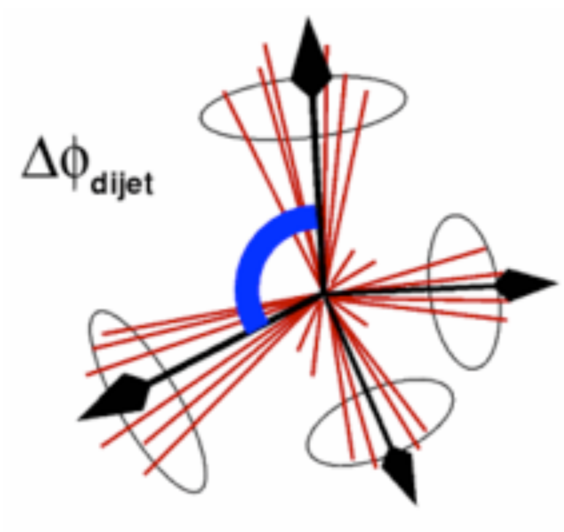
Plots from mcplots.cern.ch

ISR: Dijet Decorrelation



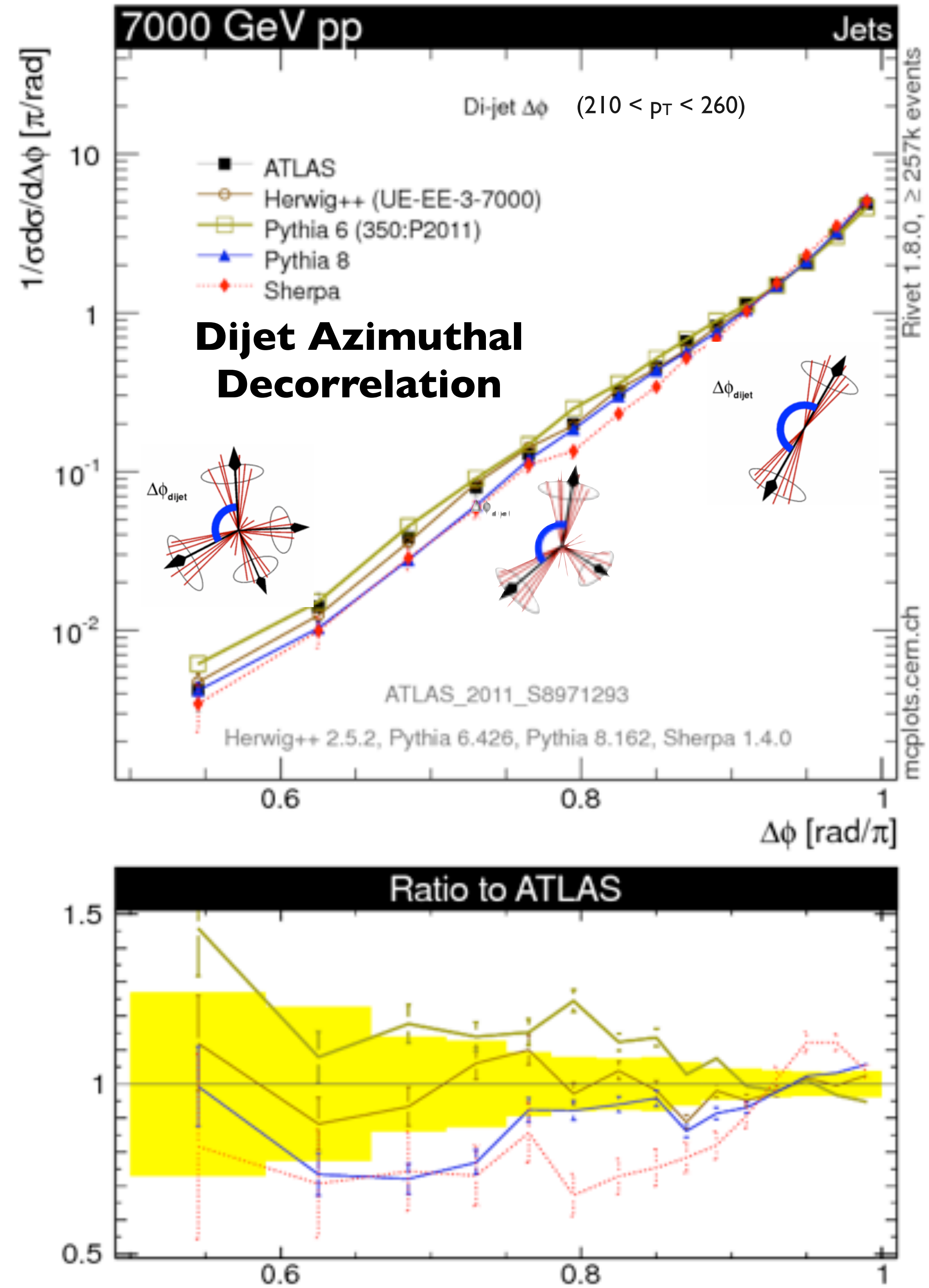
~ 1

in units of 180 degrees



$\sim ½$

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



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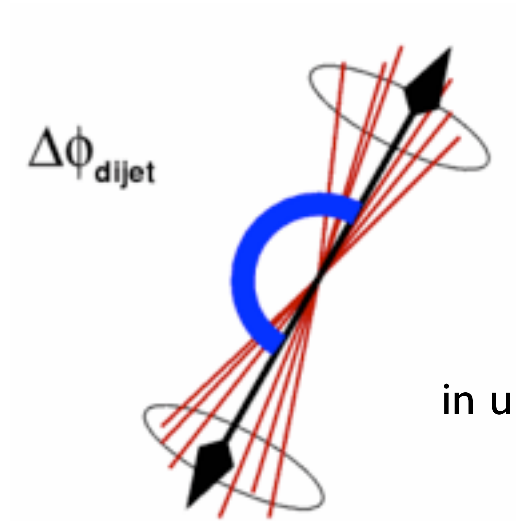
ISR: Dijet Decorrelation



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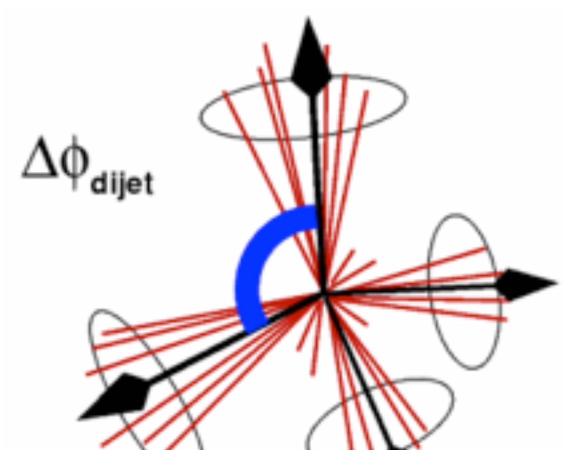
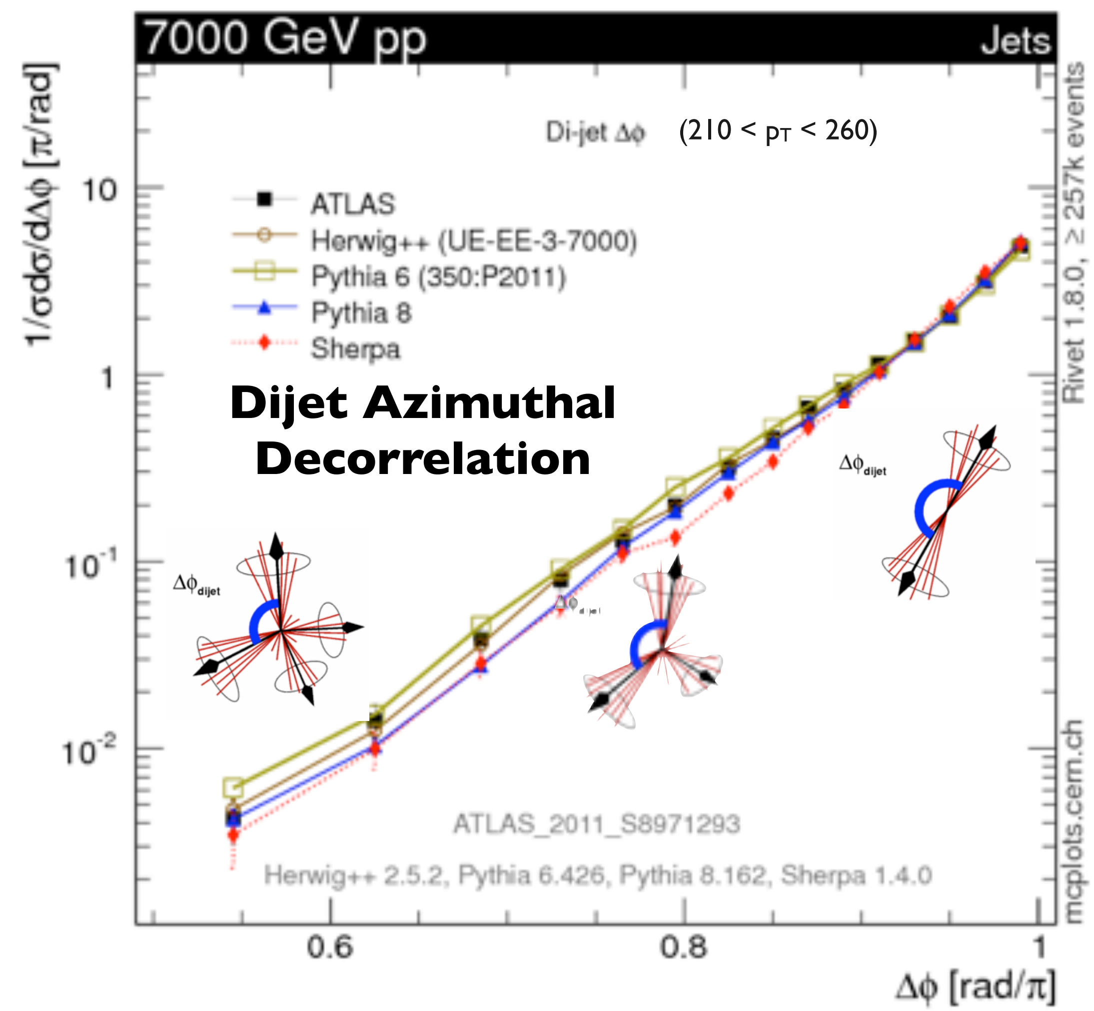


$\sim \frac{1}{2}$

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)*

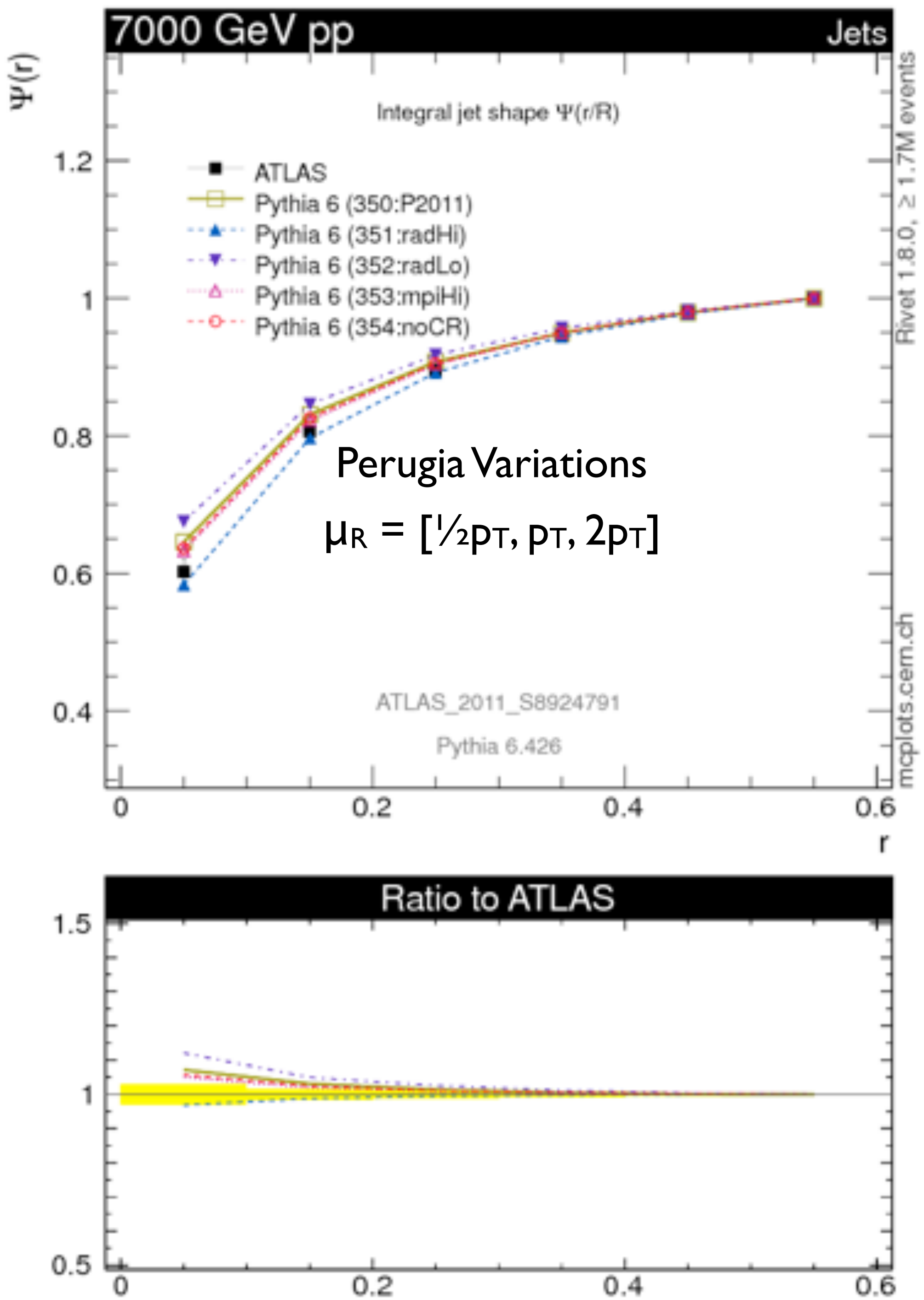
Room for improvement: Quantification of *uncertainties* is still more art than science.

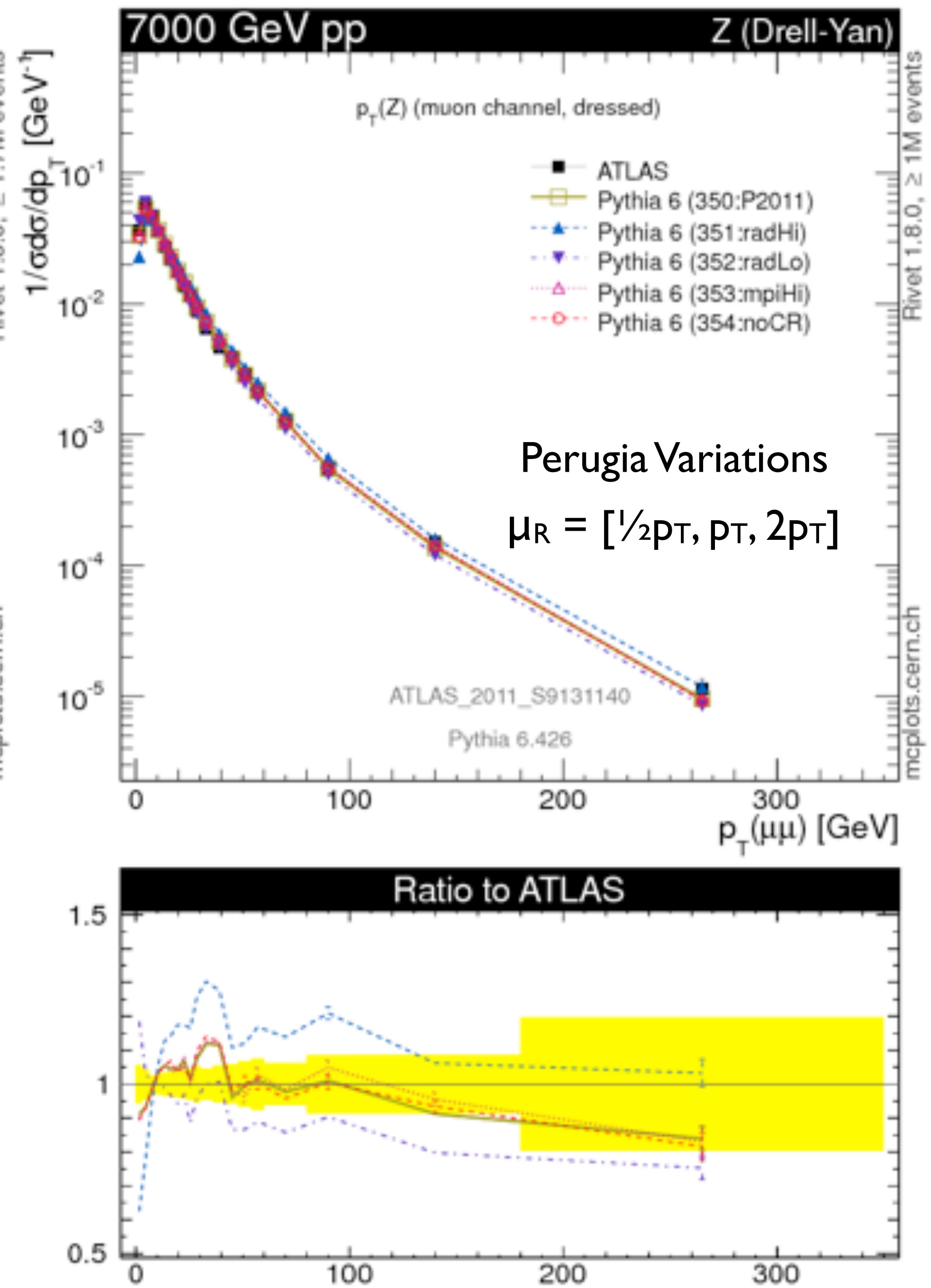
Cutting Edge: multi-jet matching at NLO and systematic NLL showering

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



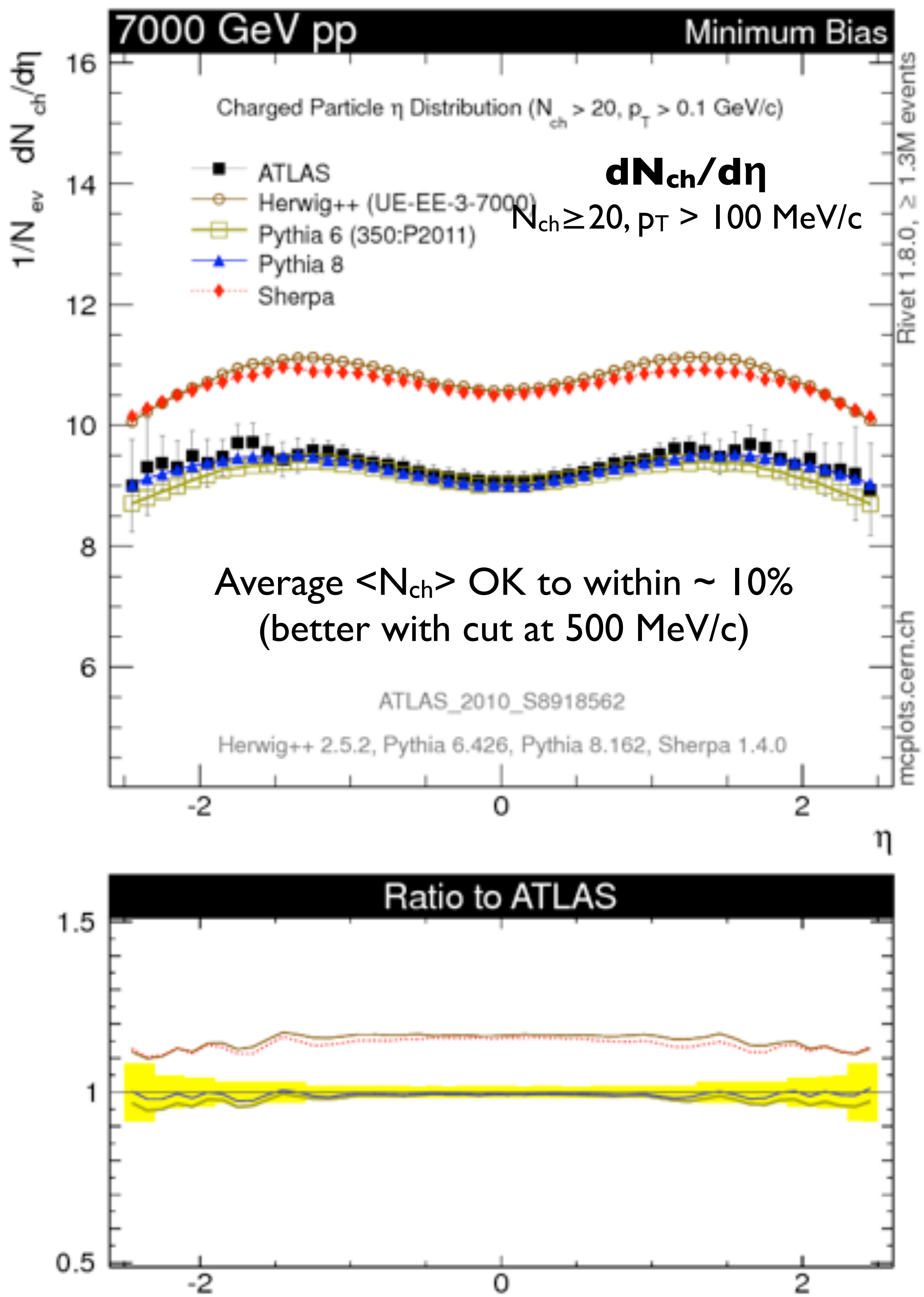


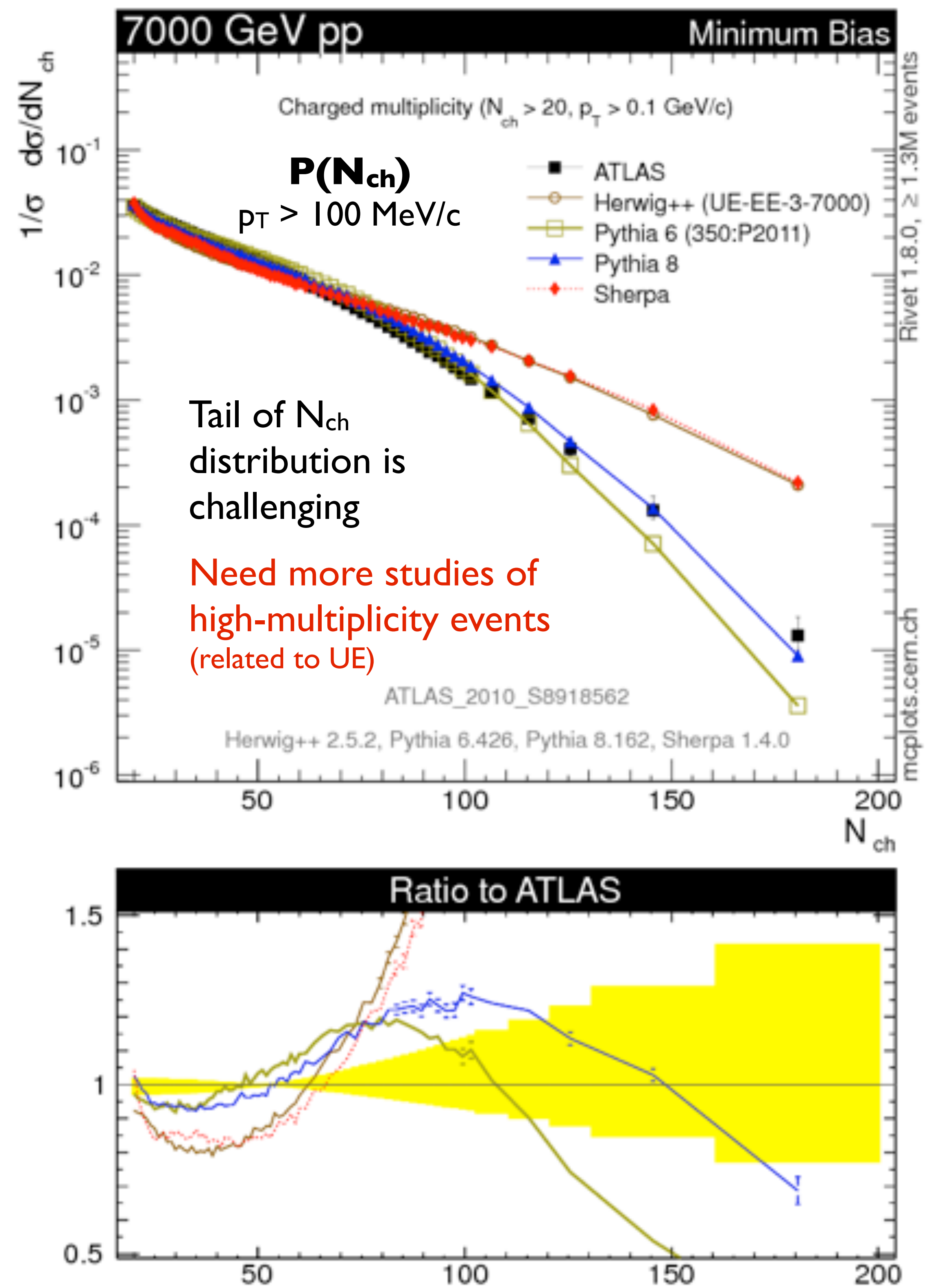
+ Similar variations for PDFs (CTEQ vs MSTW) Amount of MPI, Color reconnections, Energy scaling

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

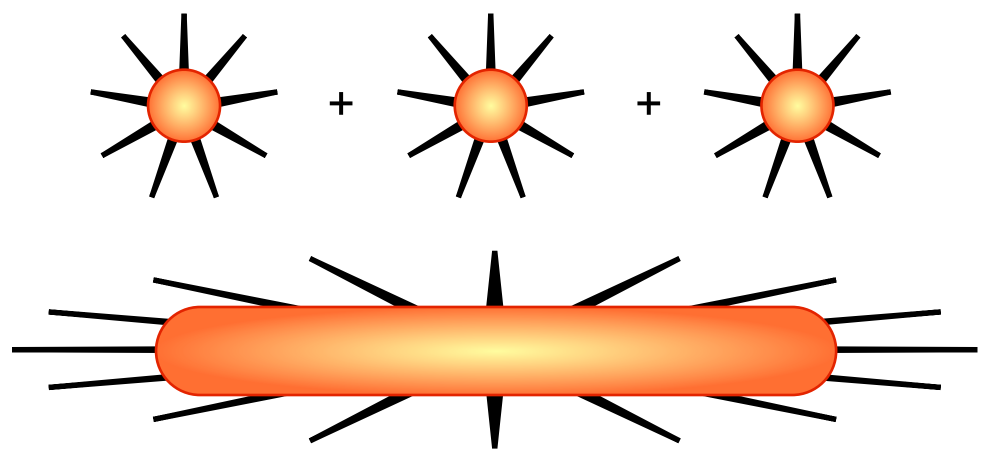
Plots from mcplots.cern.ch

Inclusive Particles





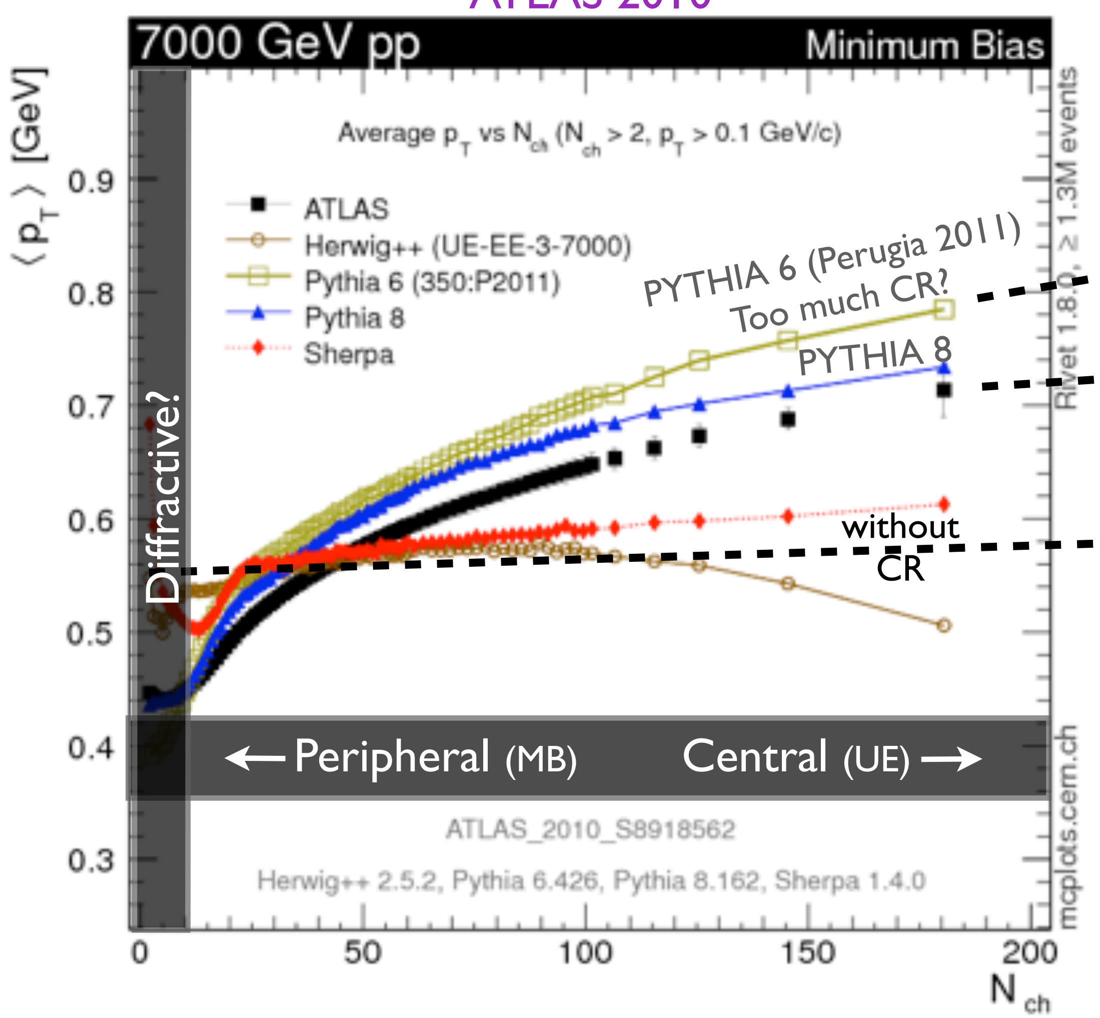
$\langle p_T \rangle$ vs N_{ch}



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

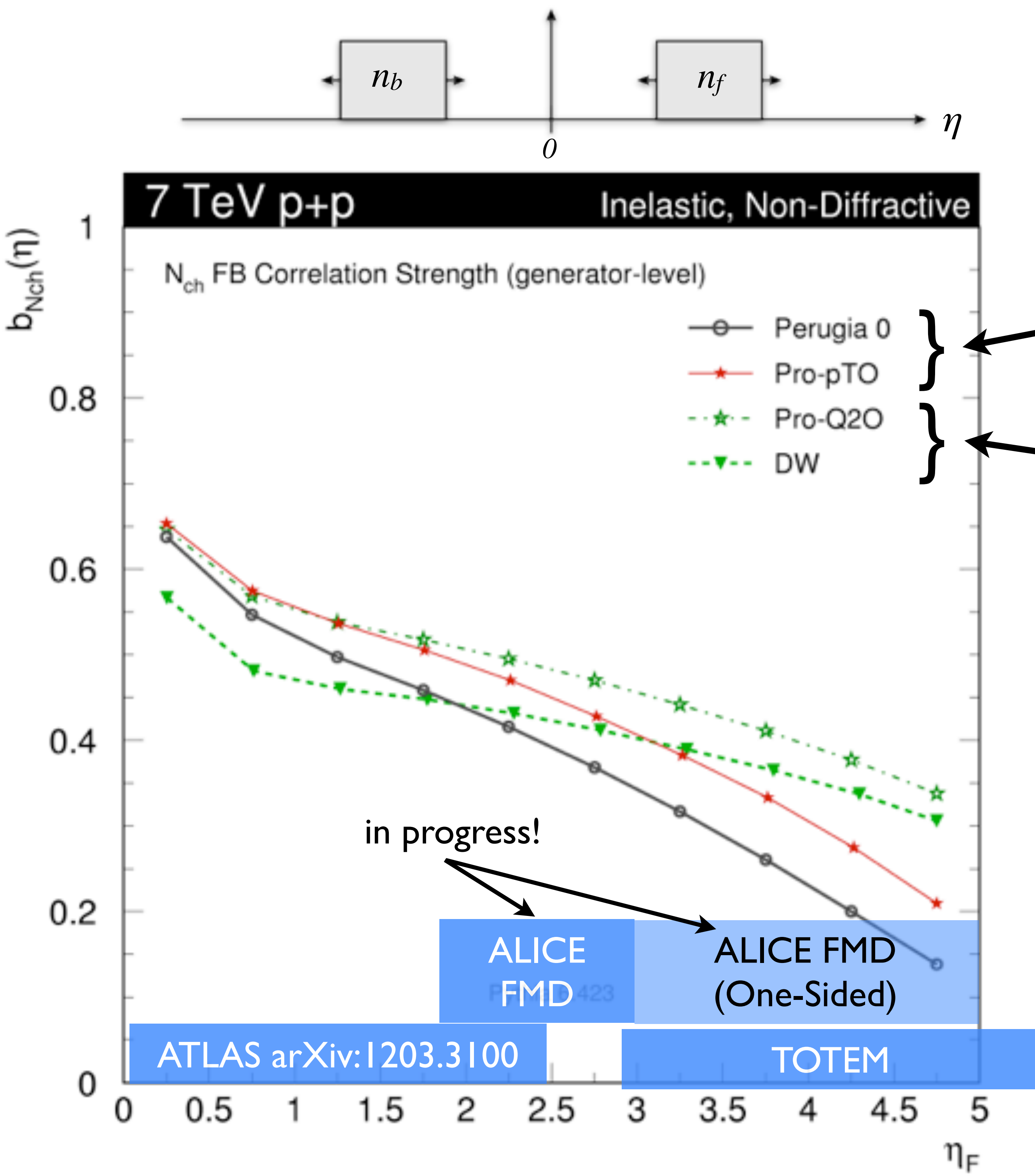
~ OK?

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

Forward-Backward Correlation



$$b = \frac{\sigma(n_b, n_f)}{\sigma(n_b)\sigma(n_f)} = \frac{\langle n_b n_f \rangle - \langle n_f \rangle^2}{\langle n_f^2 \rangle - \langle n_f \rangle^2}$$

Few MPI (each gives more multiplicity)
→ **Low** long-distance Correlations

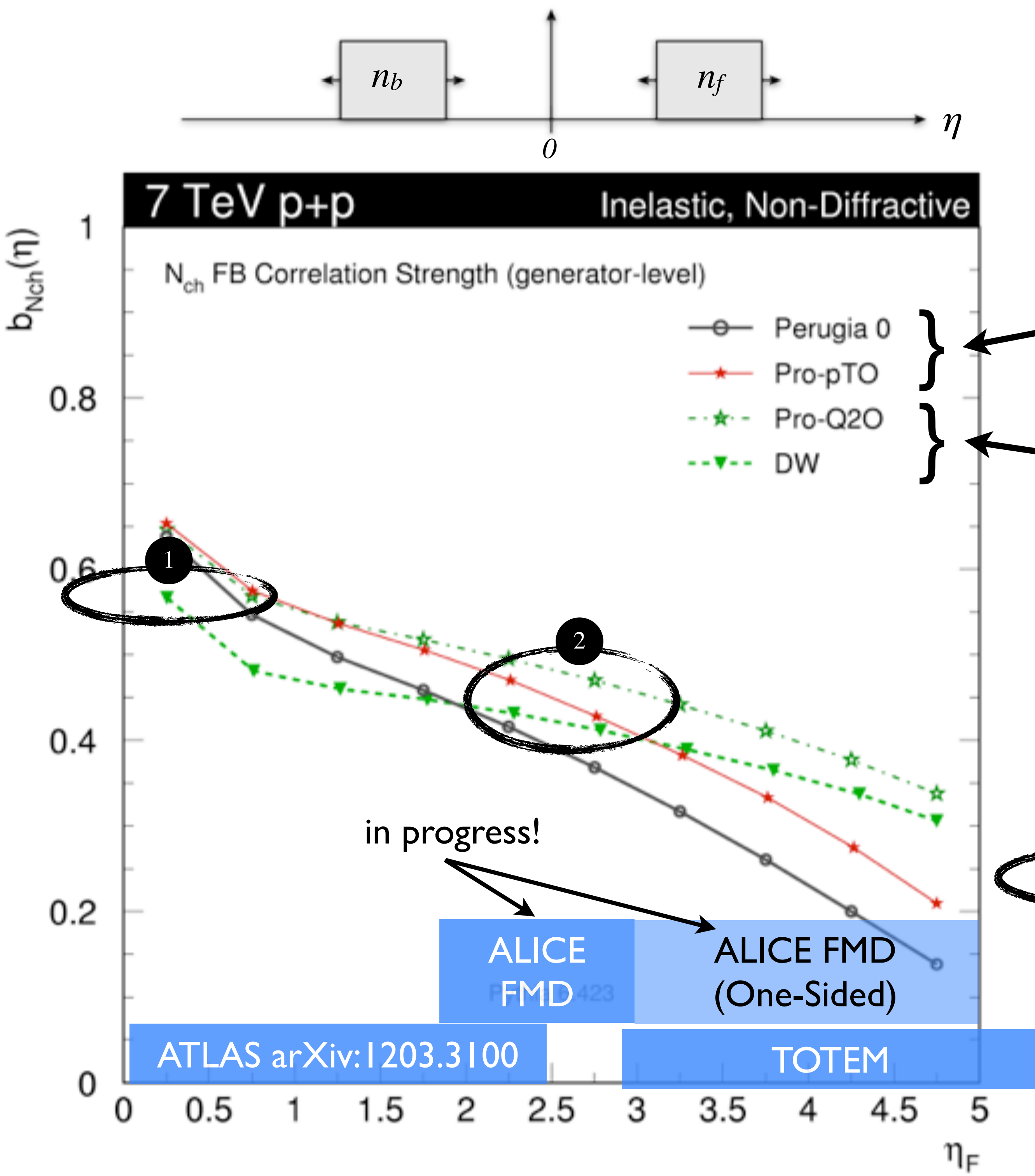
Lots of MPI (each gives little multiplicity)
→ **High** long-distance Correlations

Note: must use **multiplicity distribution** as cross-check

Diffraction → uncorrelated fluctuations
→ expect to see higher correlation in diff-suppressed samples than in diff-enhanced ones
(e.g., by placing cuts on number of central tracks?)

Additional plots in P.S., arXiv:0803.0678 ;
Wraight & P.S.: EPJ C71 (2011) 1628 ;
ATLAS arXiv: 1203.3100 [hep-ex]

Forward-Backward Correlation



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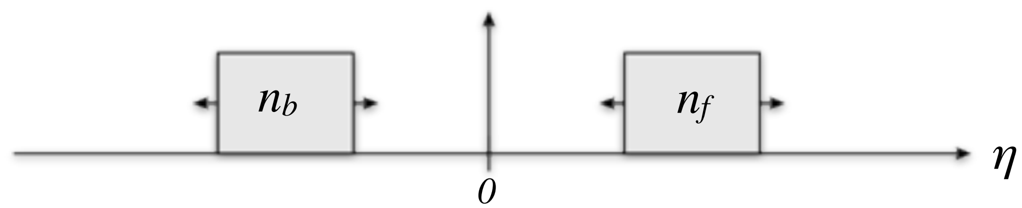
1

2

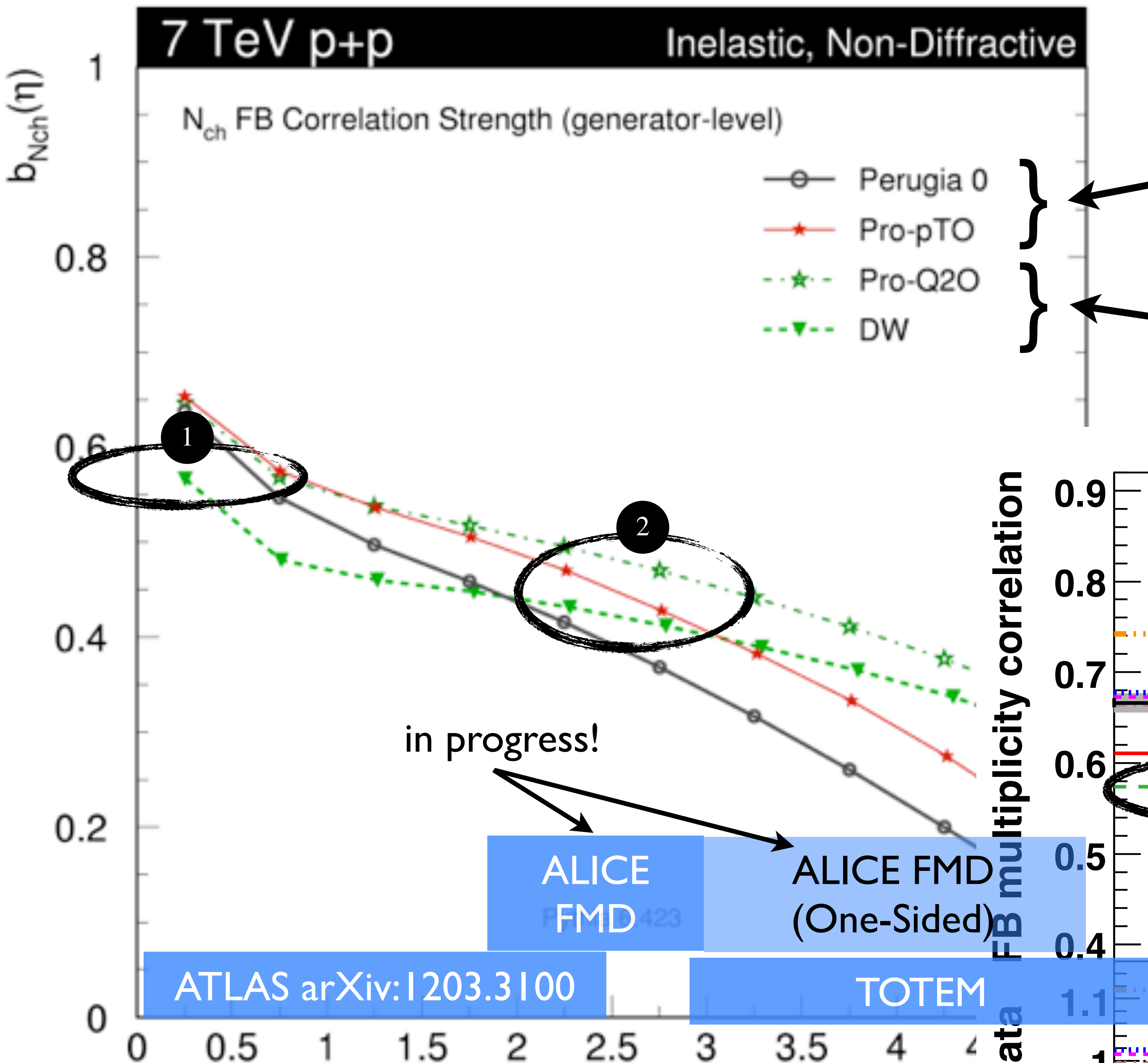
Diffraction → uncorrelated fluctuations
→ expect to see higher correlation in diff-suppressed samples than in diff-enhanced ones
(e.g., by placing cuts on number of central tracks?)

Additional plots in P.S., arXiv:0803.0678 ;
Wraight & P.S.: EPJ C71 (2011) 1628 ;
ATLAS arXiv: 1203.3100 [hep-ex]

Forward-Backward Correlation

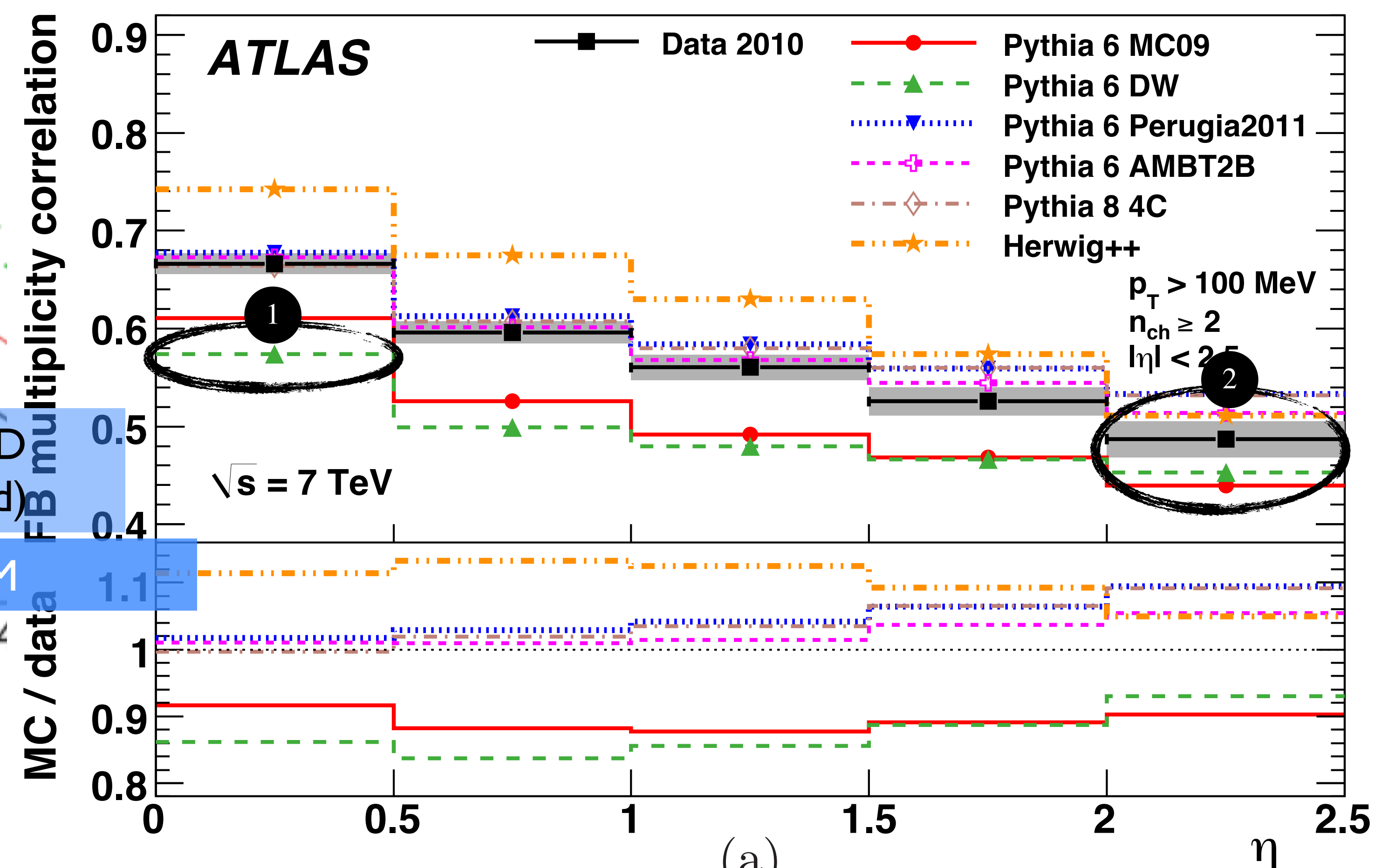


$$b = \frac{\sigma(n_b, n_f)}{\sigma(n_b)\sigma(n_f)} = \frac{\langle n_b n_f \rangle - \langle n_f \rangle^2}{\langle n_f^2 \rangle - \langle n_f \rangle^2}$$



Few MPI (each gives more multiplicity)
→ **Low** long-distance Correlations

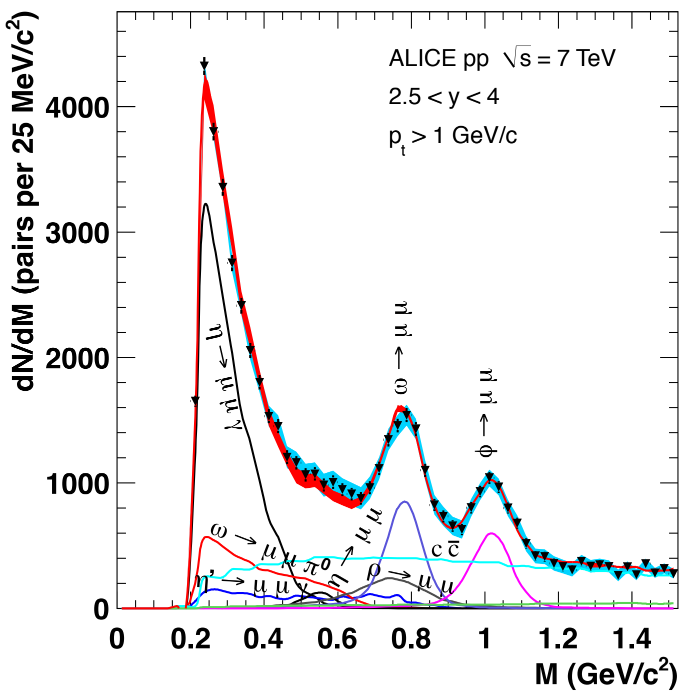
Lots of MPI (each gives little multiplicity)
→ **High** long-distance Correlations



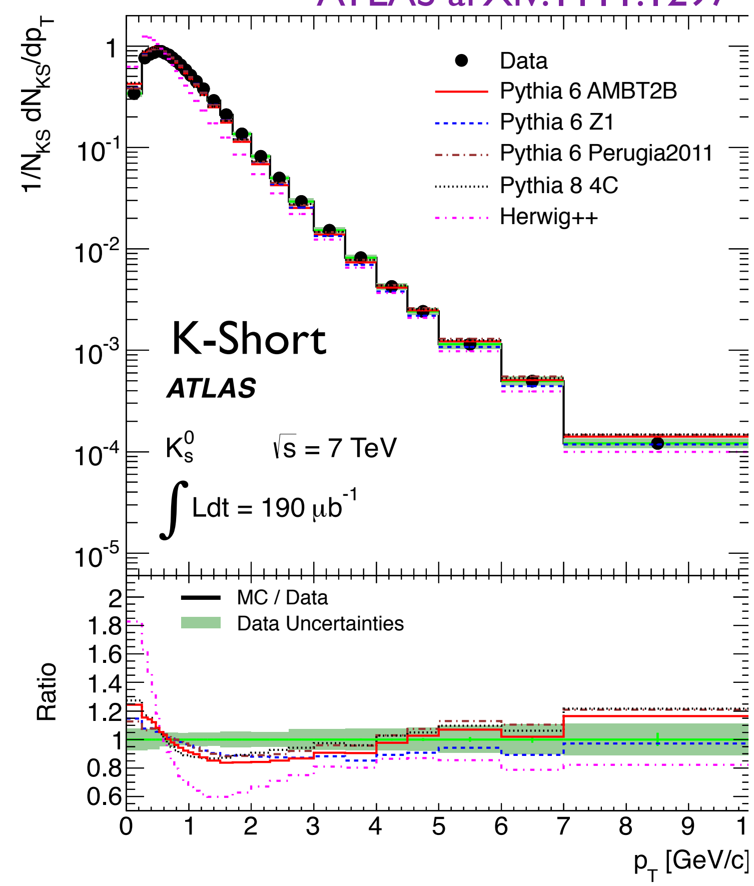
Additional plots in P.S., arXiv:0803.0678 ;
Wraight & P.S.: EPJ C71 (2011) 1628 ;
ATLAS arXiv: 1203.3100 [hep-ex]

Identified Particles

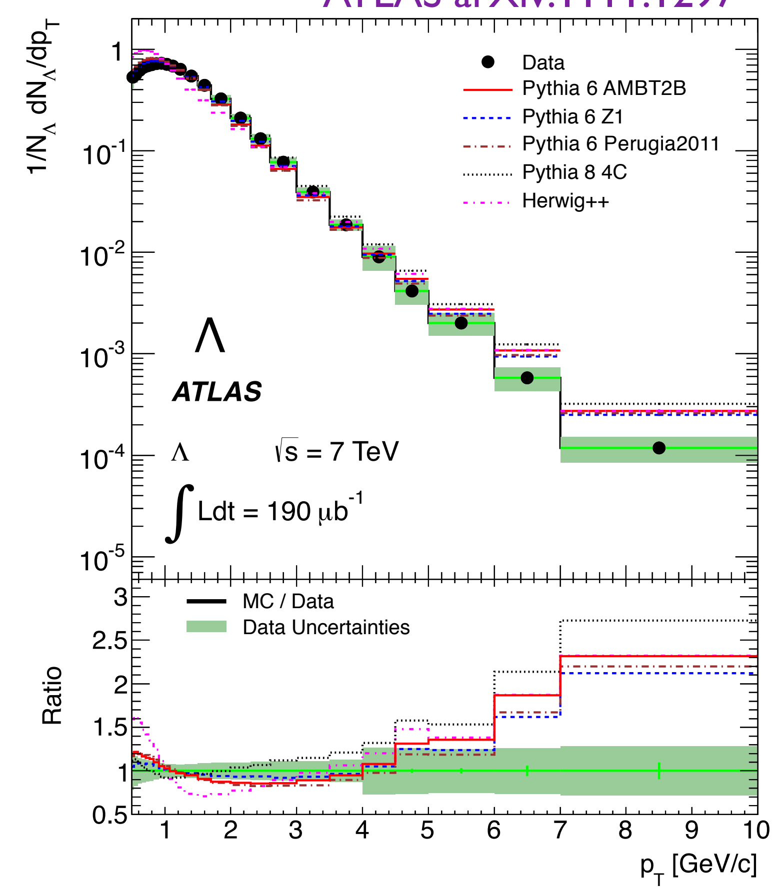
ALICE arXiv:1112.2222



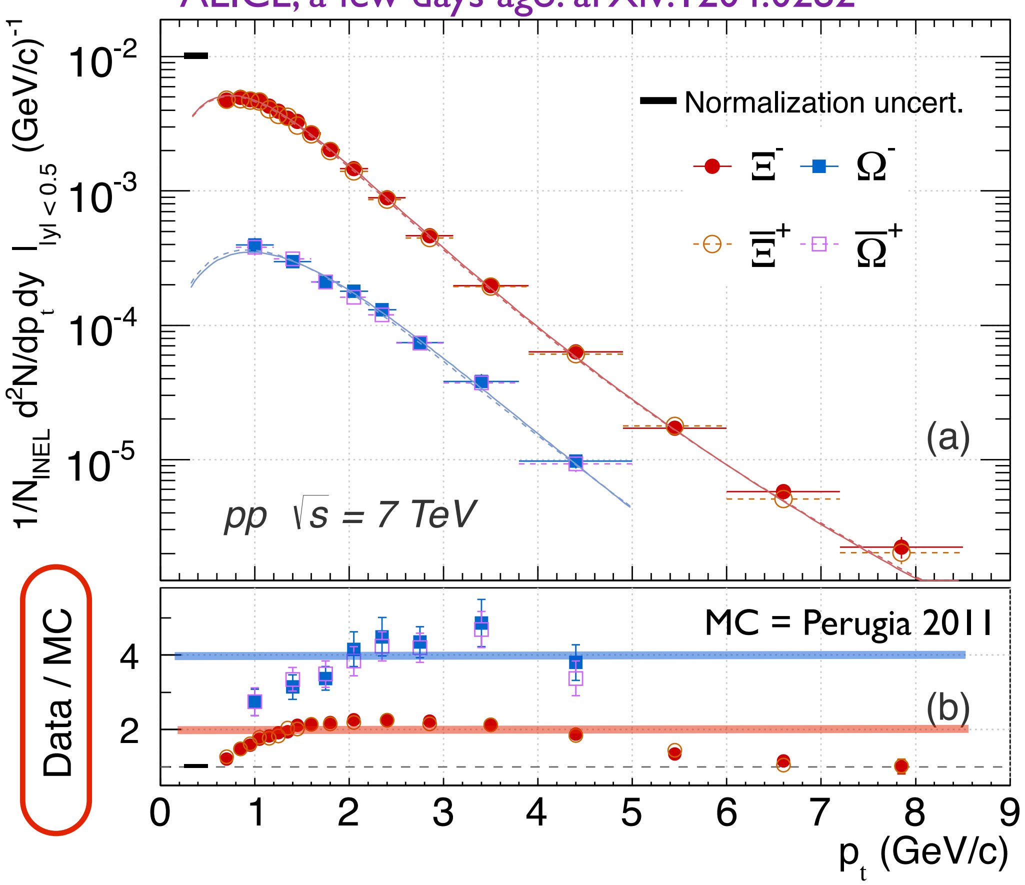
ATLAS arXiv:1111.1297



ATLAS arXiv:1111.1297



ALICE, a few days ago: arXiv:1204.0282

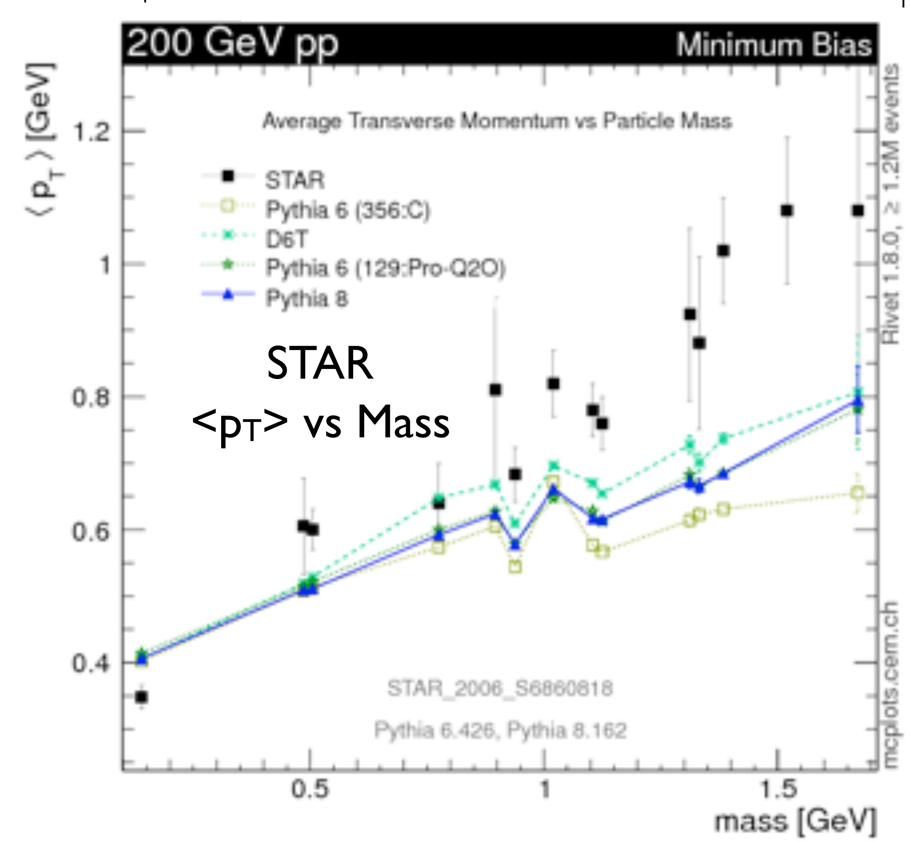


Wrong Mass Dependence?

(even *after* we tried to adjust LEP yields)

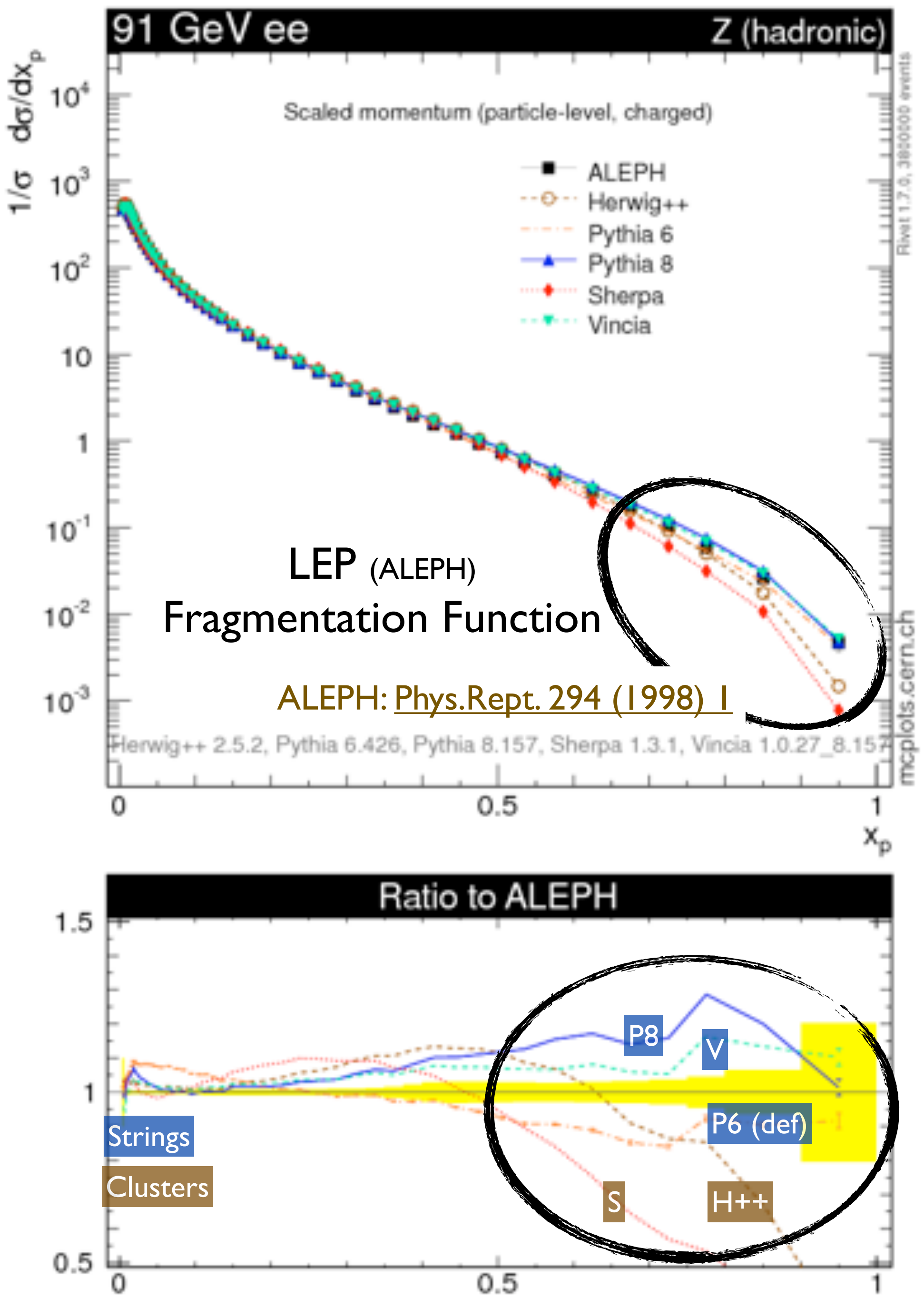
Especially at intermediate $p_T \sim 1$-4 GeV

Question: how to reconcile ee and pp data?



Extreme Fragmentation

How often does an entire jet fragment into **a single/isolated particle?** (can produce dangerous fakes)
Controlled by the behavior of the fragmentation function at z→1. Deep Sudakov region, very tough to model.
Intrinsically suppressed in cluster models. But even good string tunes probably not very reliable.



Plots from mcplots.cern.ch

Extreme Fragmentation

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Controlled by the behavior of the fragmentation function at $z \to 1$. Deep Sudakov region, very tough to model.
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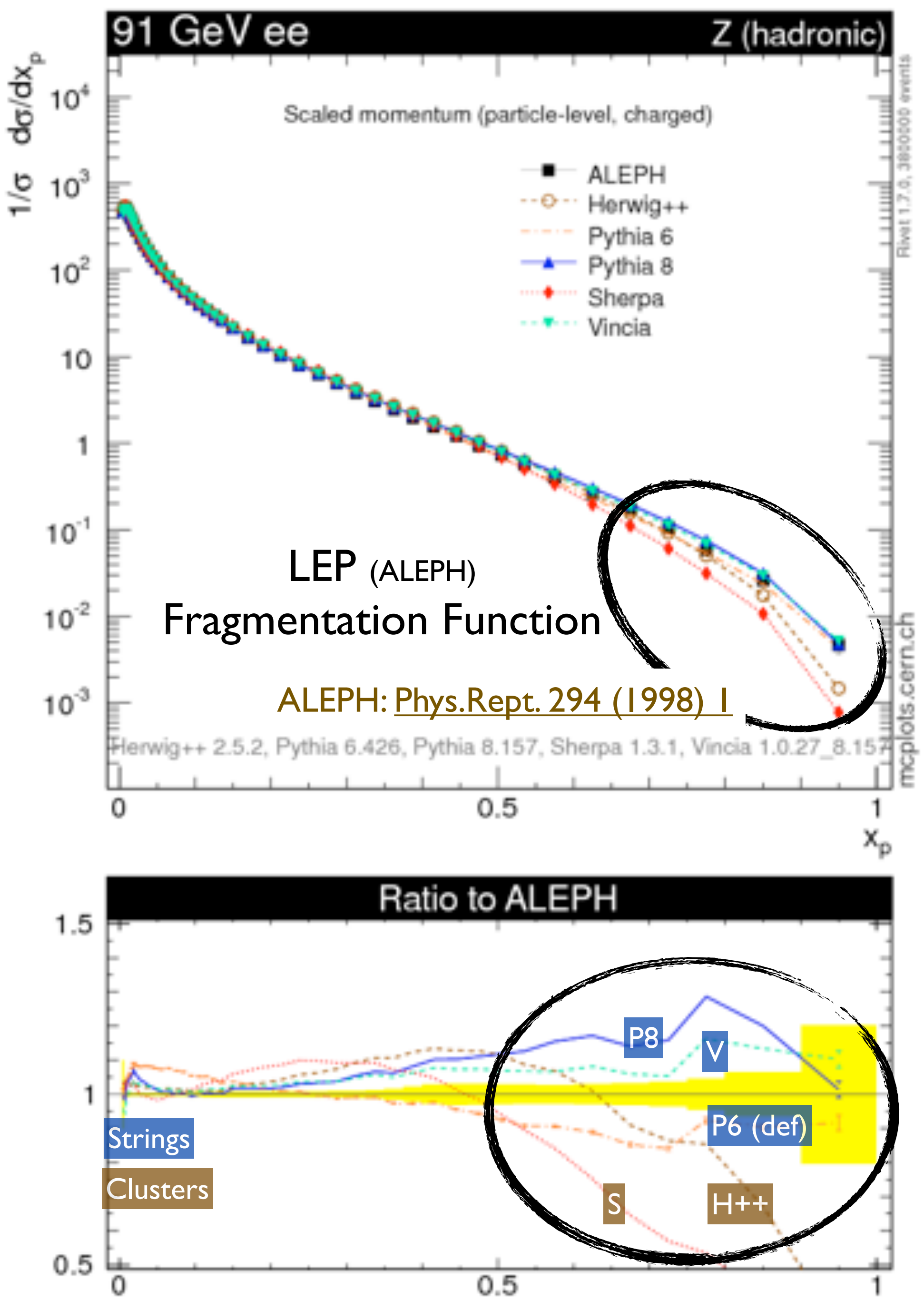

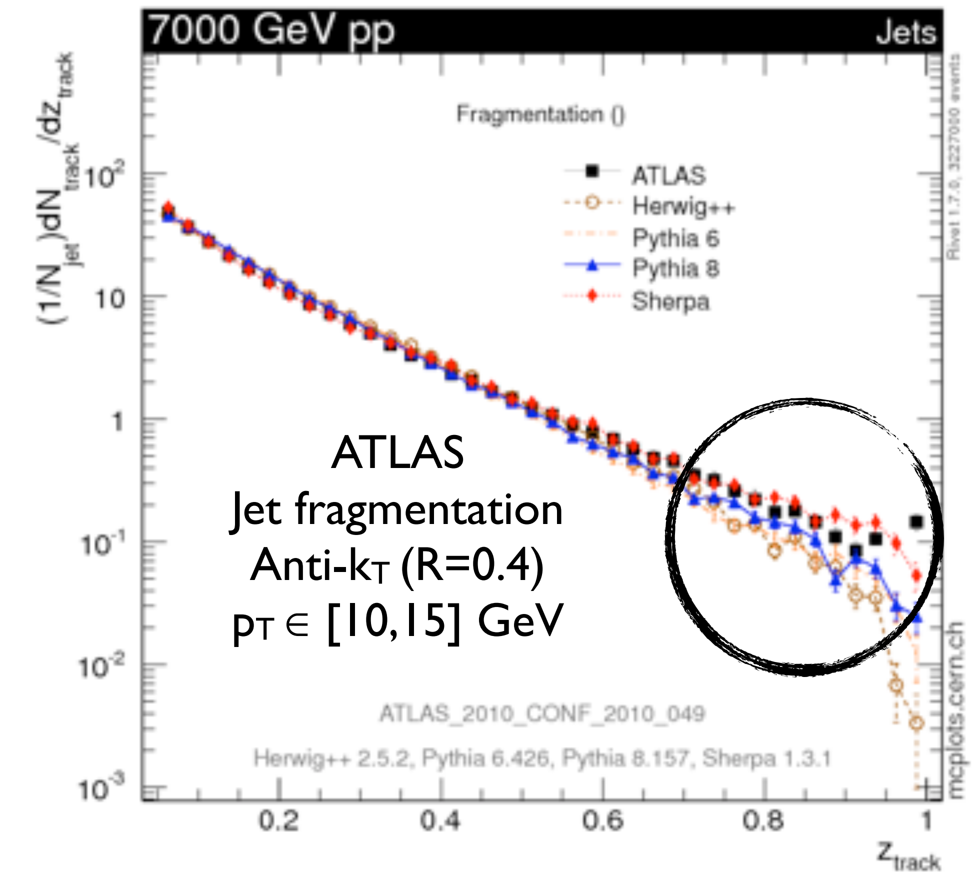

Pattern changes in pp jets

(though here only *inside* jets, and jets only at 10-15 GeV)

Needs to be studied in more detail if MC models to be used in $z \to 1$ region

Plots from mcplots.cern.ch

Pile-Up

= additional zero-bias interactions

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→WW H→γγ? (E.g., γγ 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)

Summary

IR Safe & Underlying Event: ok (for high-p_T physics)

If in doubt check **mcplots.cern.ch** ISR: include Z, top, jj, jγ, vetos (EXP) & Higgs (TH)

LO+LL still mandates rigorous uncertainty estimates. Don't trust anything.

Next pQCD Revolution: Multi-jet matching at NLO + NLL showering

Pile-Up: Mismodeling can impact E_{Tmiss} (and isolation?) estimates

No hard scale → more challenging for pQCD-based models (only PYTHIA and PHOJET so far include diffraction. HERWIG++ and SHERPA models on their way)

Especially soft & diffractive aspects need more study/constraints/modeling

Other Modeling & Tuning Aspects

Color Reconnections: coherence not well understood *between* MPI chains. Can alter IR sensitive properties*.

+ Other collective effects? (*like* Flow, Bose-Einstein effects, other higher-twist?)

Hadronization: depends on color connections.

Extreme tails ($z \to 1$) already difficult at LEP, important to check in situ (not just in min-bias)

Several pieces of evidence point to non-trivial behaviour of identified-particle spectra

*Sometimes unintentionally

Backup Slides

Diffraction (in PYTHIA 8)

Navin, arXiv:1005.3894

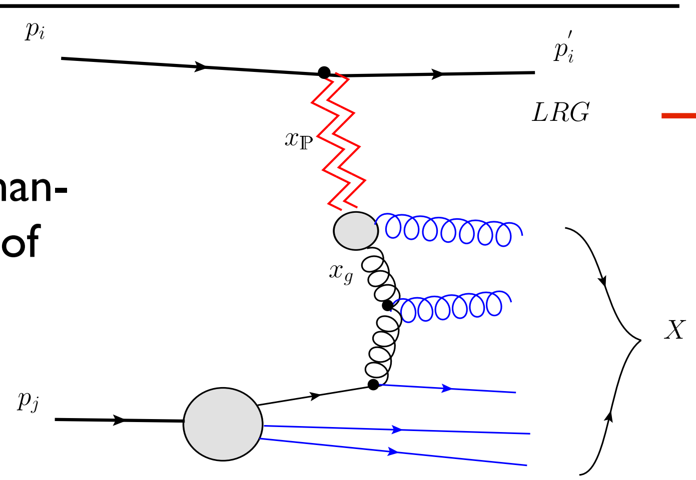
Diffractive Cross Section Formulæ:

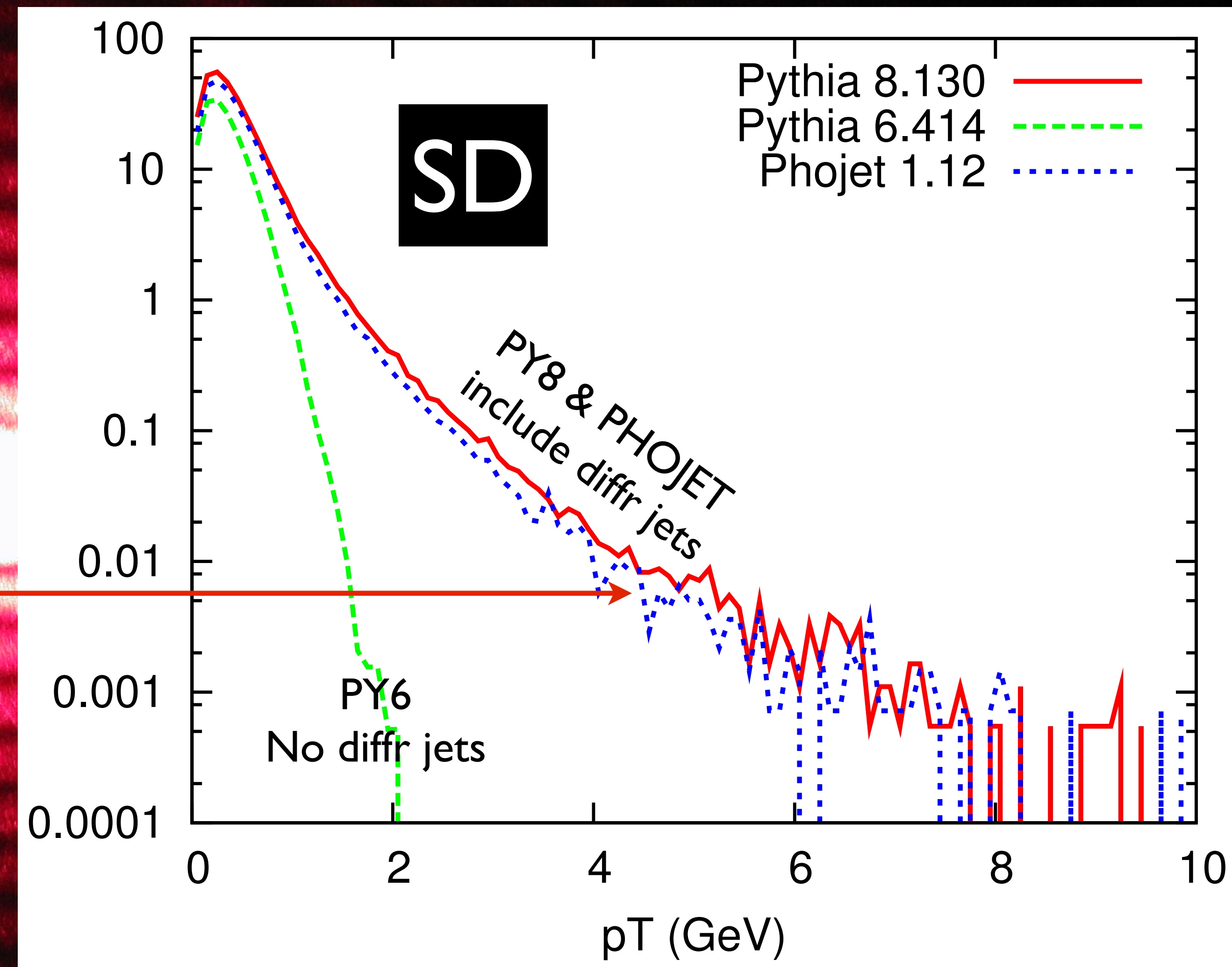
$$\frac{\mathrm{d}\sigma_{\mathrm{sd}(AX)}(s)}{\mathrm{d}t\,\mathrm{d}M^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta^2_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\,\exp(B_{\mathrm{sd}(AX)}t)\,F_{\mathrm{sd}}\,,$$

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

Partonic Substructure in Pomeron:

Follows the Ingelman-Schlein approach of Pompyt





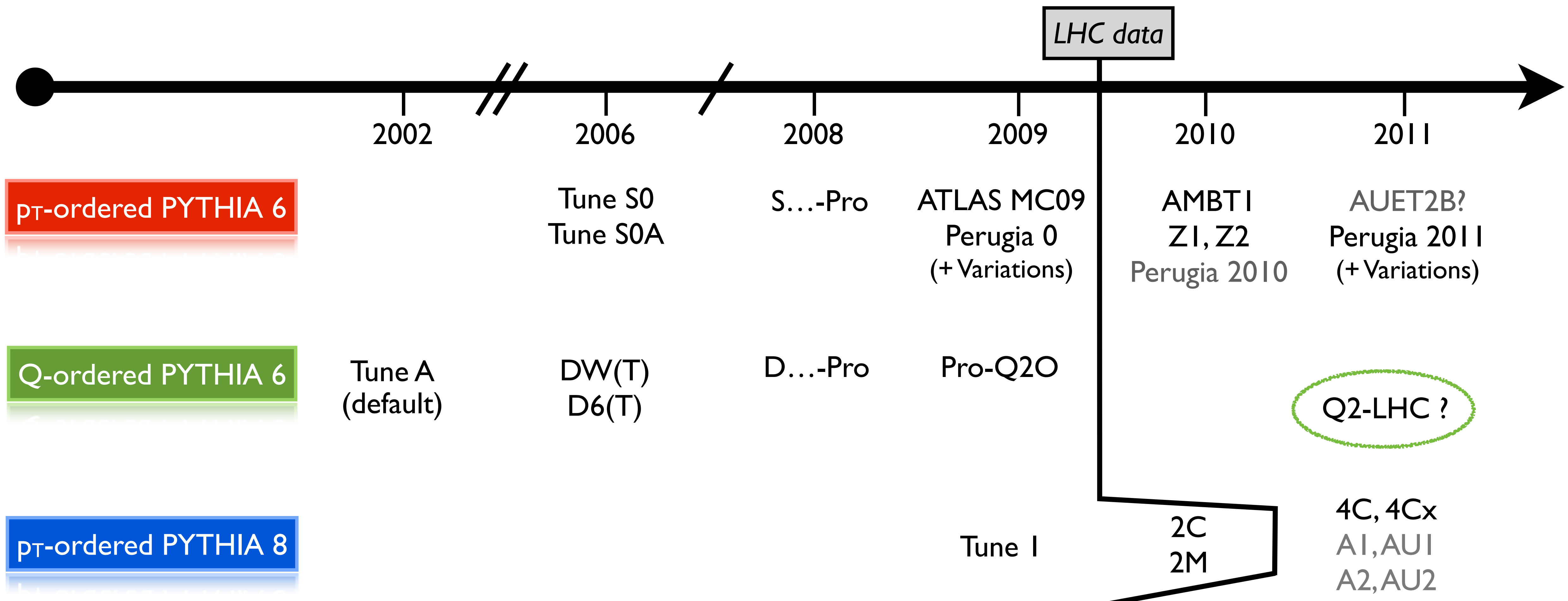
- $M_X \leq 10\,\mathrm{GeV}$: original longitudinal string description used
- $M_X > 10\,\mathrm{GeV}$: new perturbative description used (incl full MPI+showers for $\mathbb{P}$p system)

PYTHIA 8

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

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

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								✔	✔		✔

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

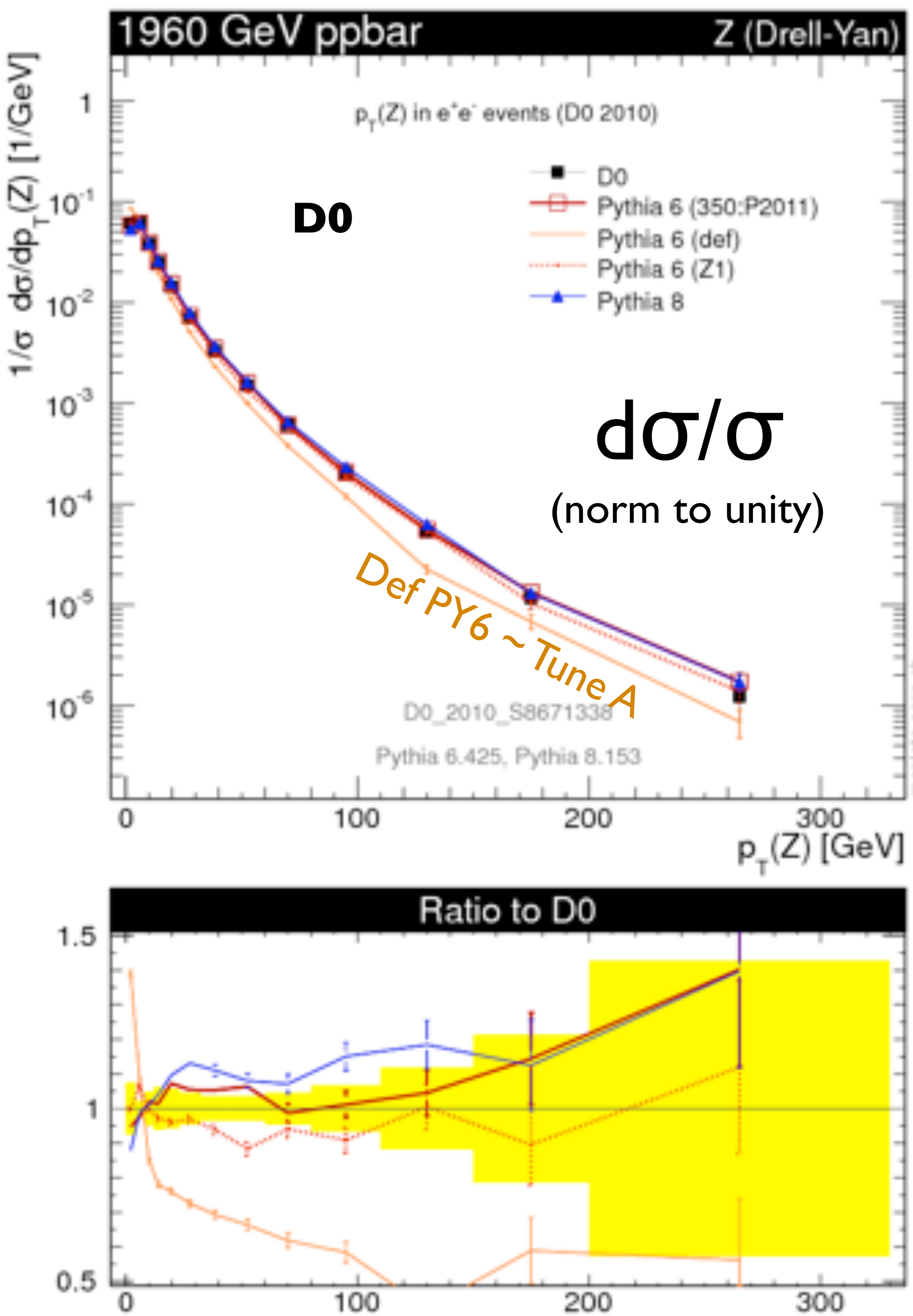
(350)	Perugia 2011	Central Perugia 2011 tune (CTEQ5L)	
(351)	Perugia 2011 radHi	Variation using $\alpha_s(\frac{1}{2}p_\perp)$ for ISR and FSR	Harder radiation
(352)	Perugia 2011 radLo	Variation using $\alpha_s(2p_\perp)$ for ISR and FSR	Softer radiation
(353)	Perugia 2011 mpiHi	Variation using $\Lambda_{\mathrm{QCD}} = 0.26\,\mathrm{GeV}$ 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

(Important test: Drell-Yan p_T spectrum)



ATLAS: arXiv:1107.2381
CMS: arXiv:1110.4973

$qq \to Z$

Oldest Tevatron tunes fail
(e.g., default Pythia 6, Tune A)

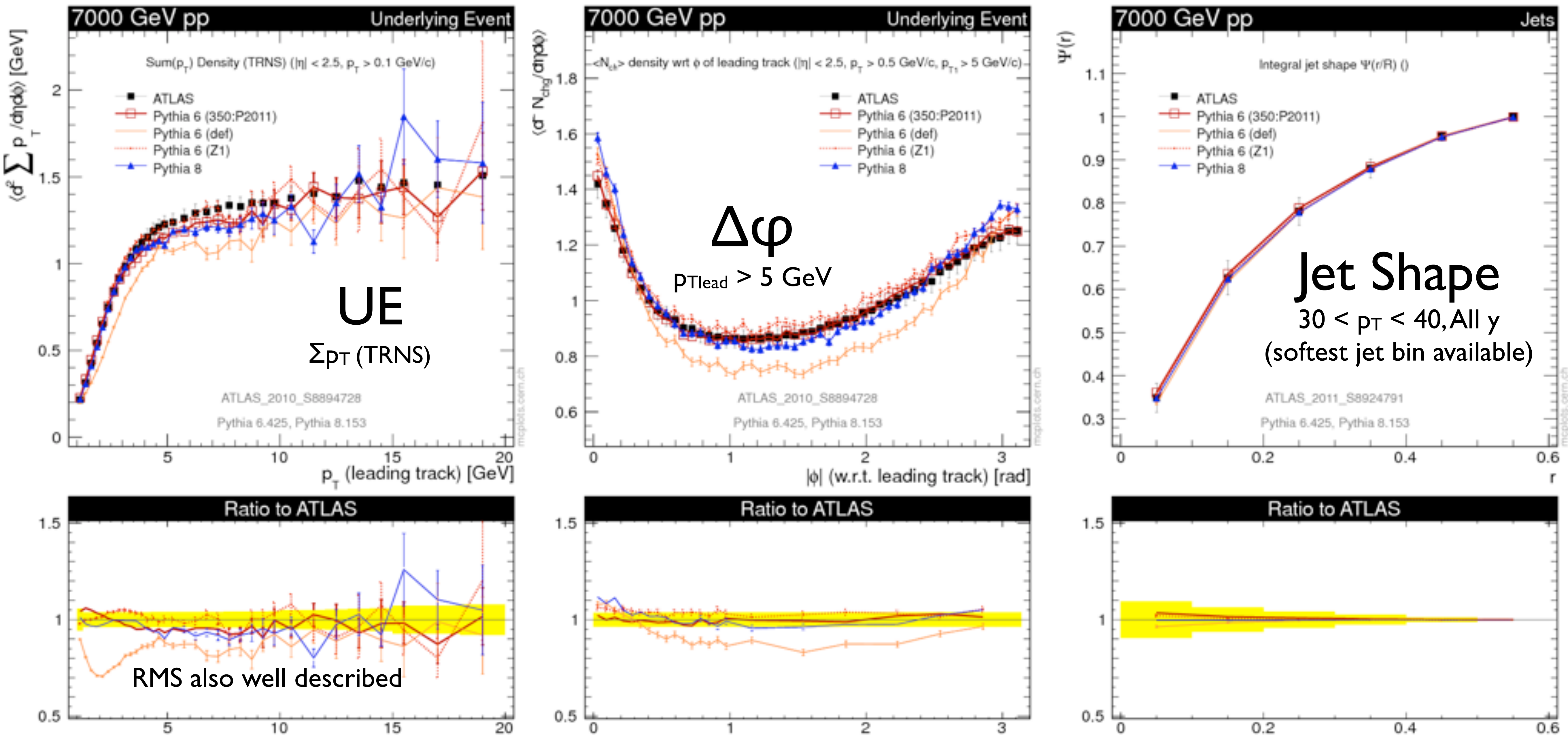
Basically all other models (including more recent Pythia ones) do fine.

$gg \to$ Higgs

Need additional cross-checks sensitive to gg-initiated processes:

Dijets with $2p_T \sim m_H \sim$ acceptable
+ $p_T(tt)$ in top events
(though note: different color structures)

(Underlying Event Tuning)



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

Plots from mcplots.cern.ch