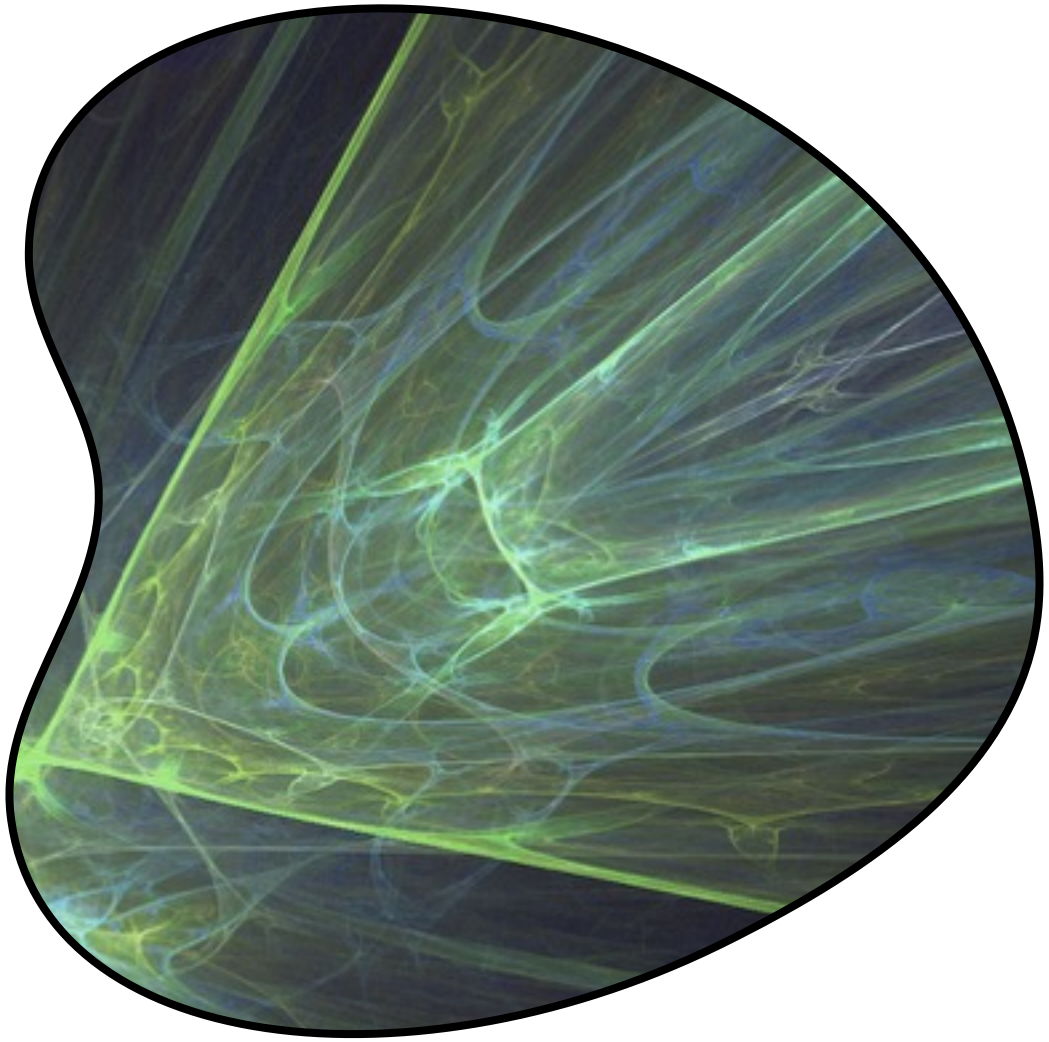
Parton-shower & hadronisation uncertainties in top physics
How can we do better?

Peter Skands (Monash University)

Parton Showers
Hadronisation
Underlying Event
Physics & Uncertainties
How can we help you?
How can you help us?



CMS Workshop on Top Physics with 100 fb^{-1}
November 2016

ANCORA · IMPARO

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Parton Showers & Hadronisation

Fragmentation (of a hard parton into a jet of hadrons)

Parton Showers ⟷ **Perturbative** QCD

Purpose: compute the effect of (any number of) perturbative QCD emissions / branchings - on any final-state observable

Between the **hard-process scale,** Q_F, and Q_{Had} ~1 GeV

- Starting Point: fixed-order **matrix elements** (at scale Q_F)
- End Result: **multi-parton state**, resolved at scale ~ Q_{Had}

Hadronisation ⟷ **Non-Perturbative** QCD

Purpose: compute the effect on final-state observables of the transition from partons to hadrons

- Starting Point: parton-shower final state, resolved at scale ~ Q_{Had}
- End Result: stable (long-lived) hadrons → GEANT

Must model confinement (strings/clusters), hadron decays, **+ what else?**

What about the **Underlying Event**? **Colour Reconnections**? …

Disclaimer

This discussion is as much a chance for me to catch up with what you're doing, as a chance to provide my input

- I have not been following top physics closely in the last few years. May not be fully up to date on all aspects, especially experimental developments.

State of the art for precision MC calculations nowadays is matching & merging (@NLO). Not my main area of expertise, but will attempt to comment where relevant

- Focus on **Parton Showers**
- **Hadronisation** (incl Colour Reconnections)
- **Underlying Event**

What can we learn from top?

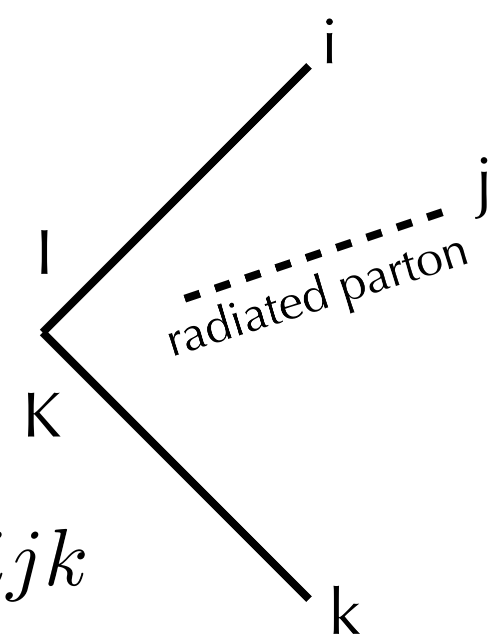
How can we improve for top?

Parton Shower Basics

PS kernels generate approximations to QCD matrix elements

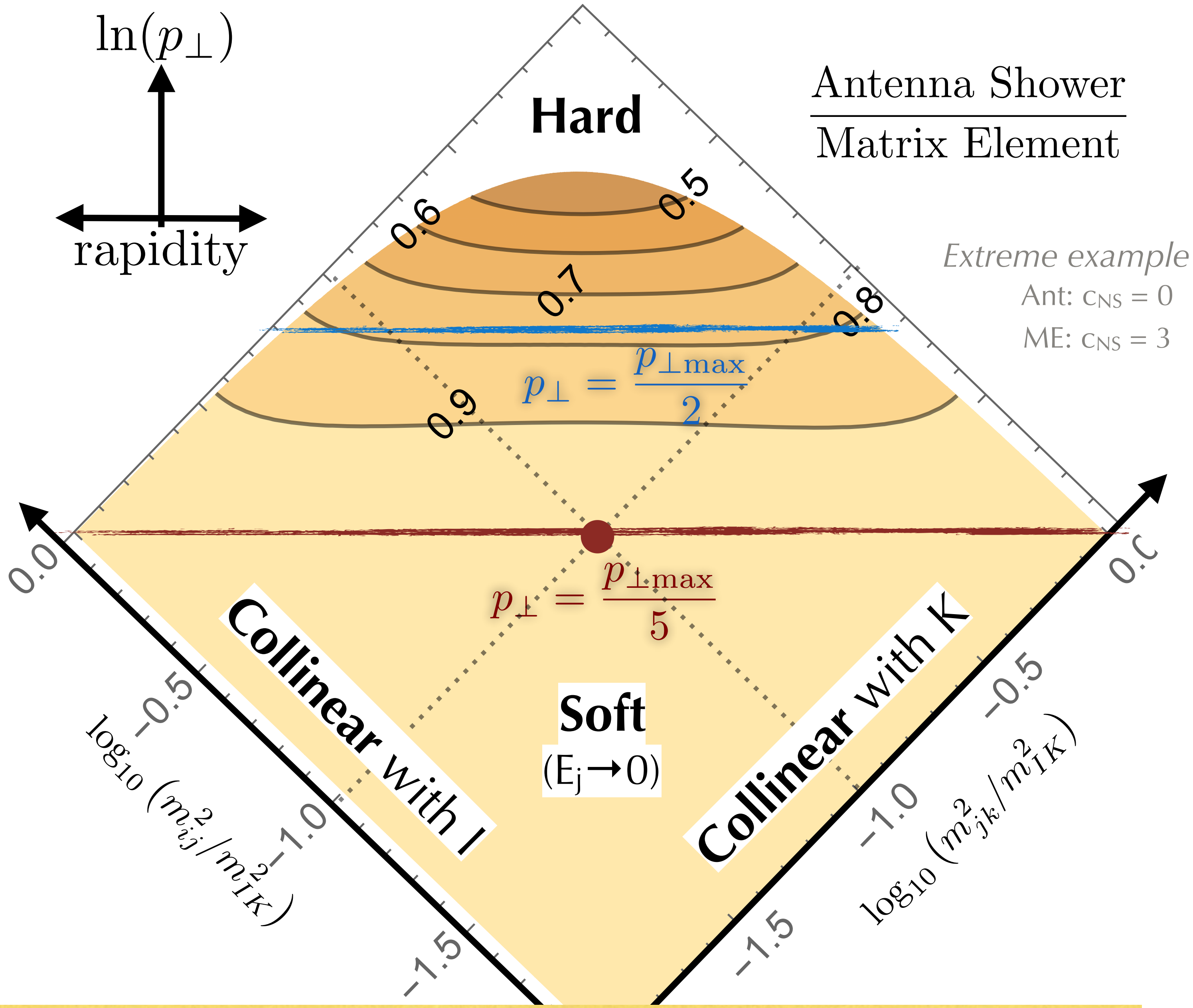
- Exact in the collinear limits (DGLAP)
- Soft limits also captured by *coherent* showers

E.g., QCD dipole:



$$IK \to ijk$$

LO: Dipole Phase Space



On a log-log plot of invariant masses (or $\ln(p_T)$ vs rapidity) the (LO) emission density is ~ constant. Shower kernels agree with matrix elements except for very hard emissions.

Shower Ambiguities & Uncertainties

Expect differences mainly at **subleading** levels

→ Interested in observables & constraints that can probe **higher-order** / **subleading** aspects of shower evolutions

[Precision Substructure, Multi-parton & initial-final coherence, Scaling (violation), Multiple-emission (compressed) hierarchies]

Certainly needed for **future** high-precision showers!

The final states generated by a shower algorithm will depend

1. The choice of perturbative evolution variable(s) $t^{[i]}$. ← Ordering & Evolution-scale choices
2. The choice of phase-space mapping $\mathrm{d}\Phi^{[i]}_{n+1}/\mathrm{d}\Phi_n$. ← Recoils, kinematics
3. The choice of radiation functions a_i, as a function of the phase-space variables. ← Non-singular terms, Reparametrizations, Subleading Colour
4. The choice of renormalization scale function μ_R.

main focus (for now) → (items 3 and 4)

(5. Choices of starting and ending scales. (matching to hard process and to hadronisation) ← Phase-space limits / suppressions for hard radiation and choice of hadronization scale)

Estimating the uncertainties of **Parton Showers**

Note: several (very) recent papers on this topic, by essentially all the main general-purpose MC groups.

Useful for understanding issues, recommendations, efficient MC

(+ each group uses slightly different language)

Alternative weights for each event
(Original Proposal for VINCIA arXiv:1102.2126)

Herwig

Benchmark Studies: arXiv:1605.01338

Automated Shower Uncertainties: arXiv:1605.08256 — μ_R, μ_F, PDFs

Pythia

Baseline Tune in 8.2: Monash Tune: arXiv:1404.5630

Automated Shower Uncertainties: arXiv:1605.08352 — μ_R, $\pm$ finite

Sherpa

Automated Shower Uncertainties: arXiv:1606.08753 — μ_R, μ_F, PDFs

Automated Variations

In all cases: still only a partial set, but at least a beginning → Feedback!

Our Reference Processes

Dijets

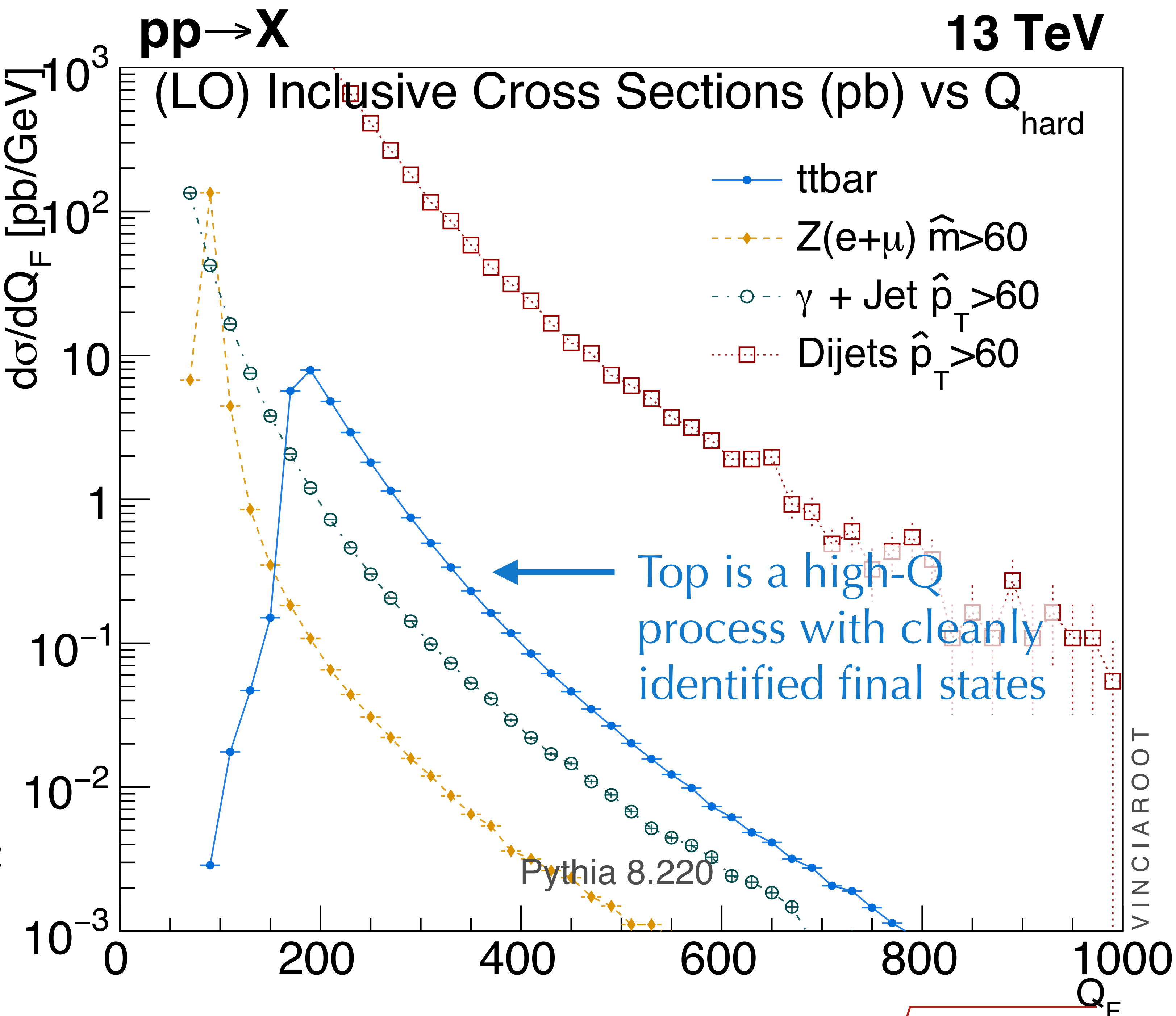
- Jet Shapes
- Substructure
- Azimuth Decorr.

Gamma+Jet

- JES Calibration

Drell-Yan

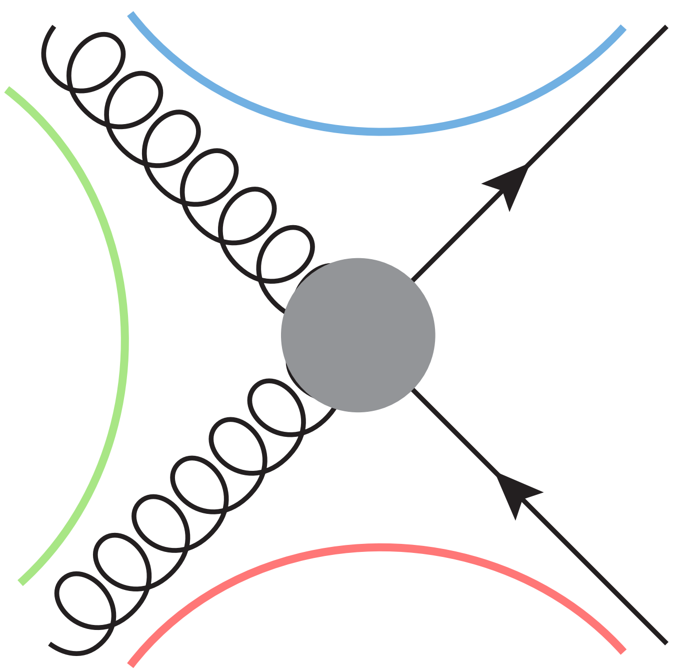
- ISR with well-defined Q_F scale
- Off resonance: extend to higher Q^2



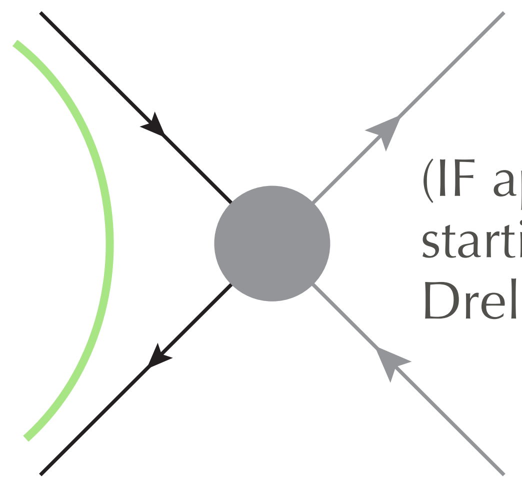
Scales in PYTHIA: **Drell-Yan:** $Q_F = \hat{m}$ **2→2 :** $Q_F = m_\perp = \sqrt{p_\perp^2 + m^2}$

Top: Production

Importantly, top production involves Initial-Final colour flows

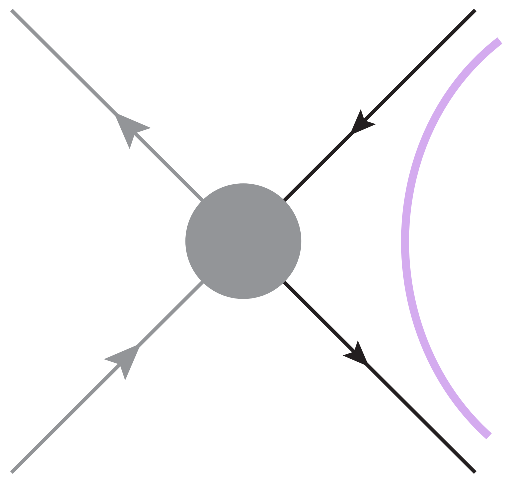


Not present in main ISR shower constraint: Drell-Yan



(IF appears starting from Drell-Yan + Jet)

Not present in main FSR shower constraint: LEP



Expect strong dependence on top boosts

- **At threshold**: no radiation from tops (only initial-state ends active)
- **At high boosts**: soft & quasi-collinear enhancements from tops
- IF present in γ+Jet and Dijets as well (without mass/boost effect)

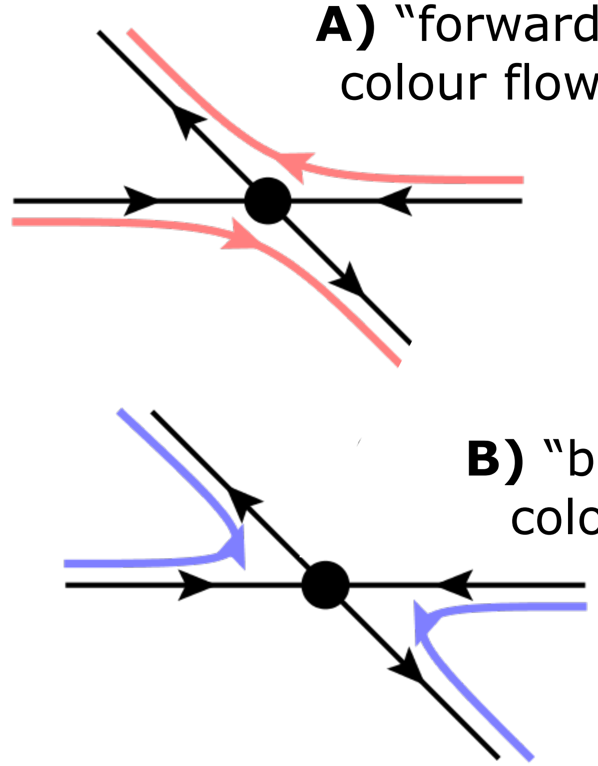
ttbar Jet Pull Angle: ATLAS_2015_I1376945

Some consequences of IF colour flow

Example: quark-quark scattering in hadron collisions

Consider one specific phase-space point (eg scattering at 45°)

2 possible colour flows: **A** and **B**



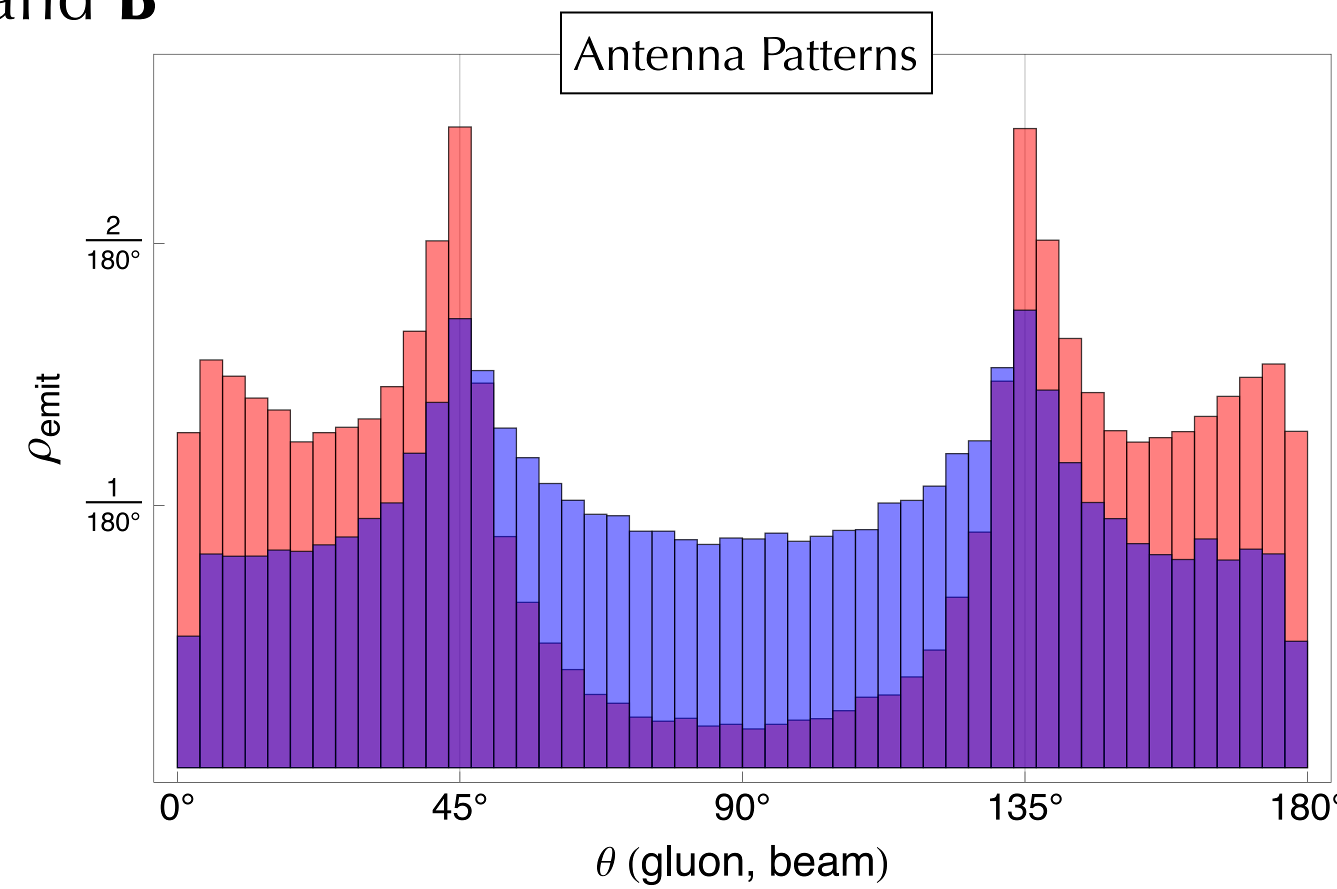


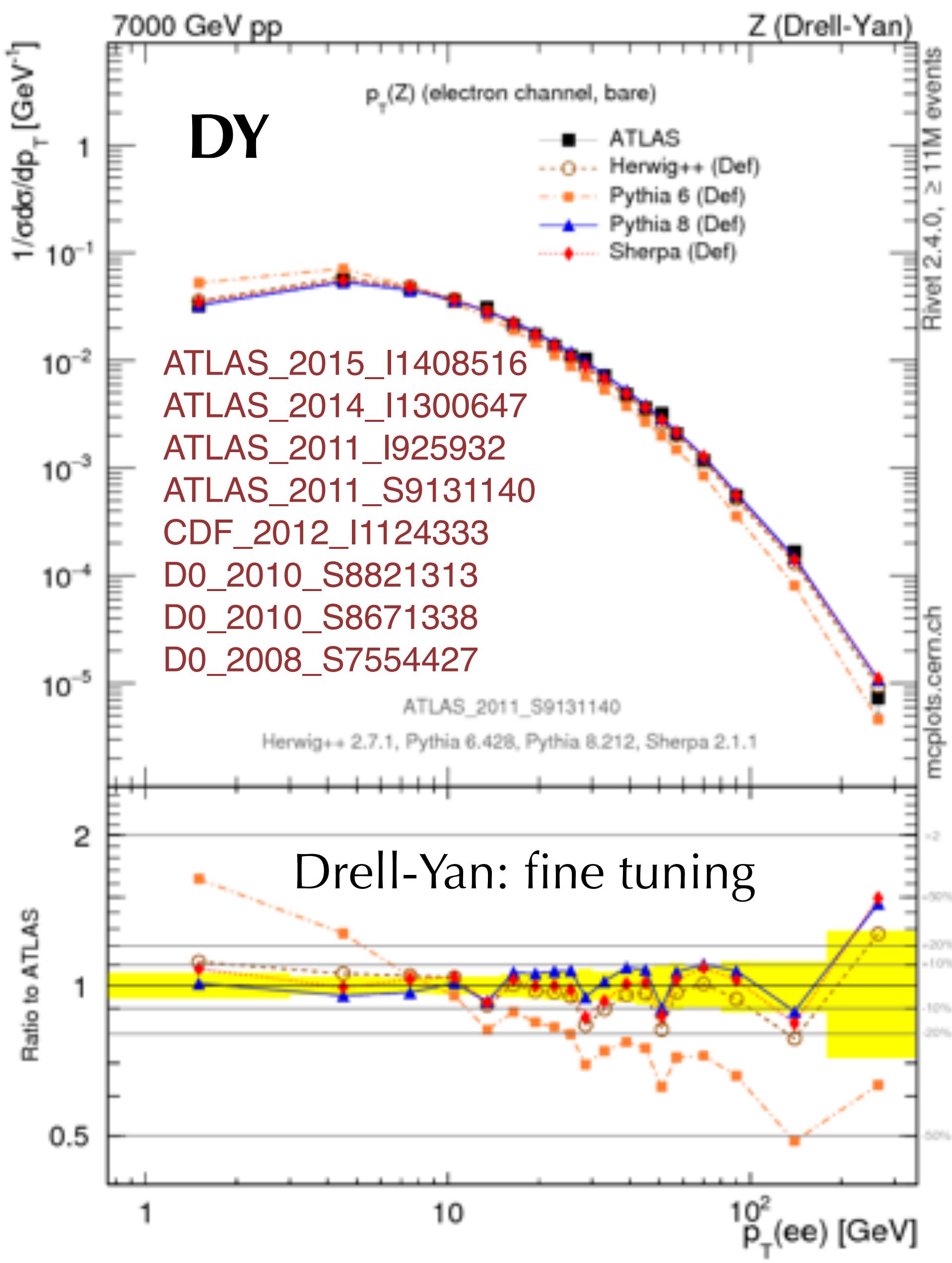
Figure 4: Angular distribution of the first gluon emission in $qq \to qq$ scattering at 45°, for the two different color flows. The light (red) histogram shows the emission density for the forward flow, and the dark (blue) histogram shows the emission density for the backward flow.

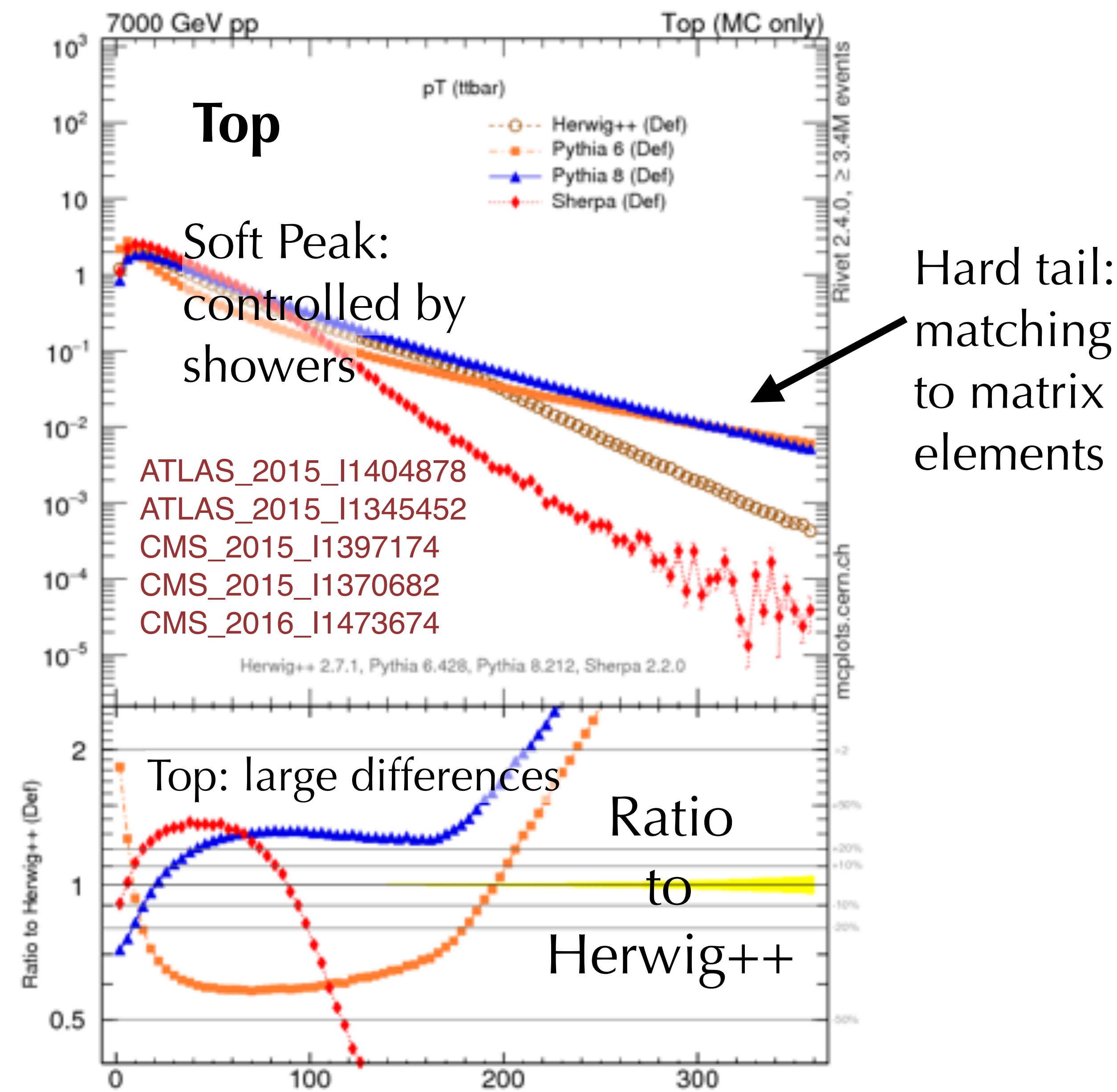
Kinematics (e.g., Mandelstam variables) are identical. The only difference is the colour-flow assignment.

PS: coherence also influences the Tevatron top-quark forward-backward asymmetry: see PS, Webber, Winter, JHEP 1207(2012)151

p_T(ttbar) (& related measurements)

Tests initial-state side of radiation in association with production, similarly to p_T(dilepton) in Drell-Yan

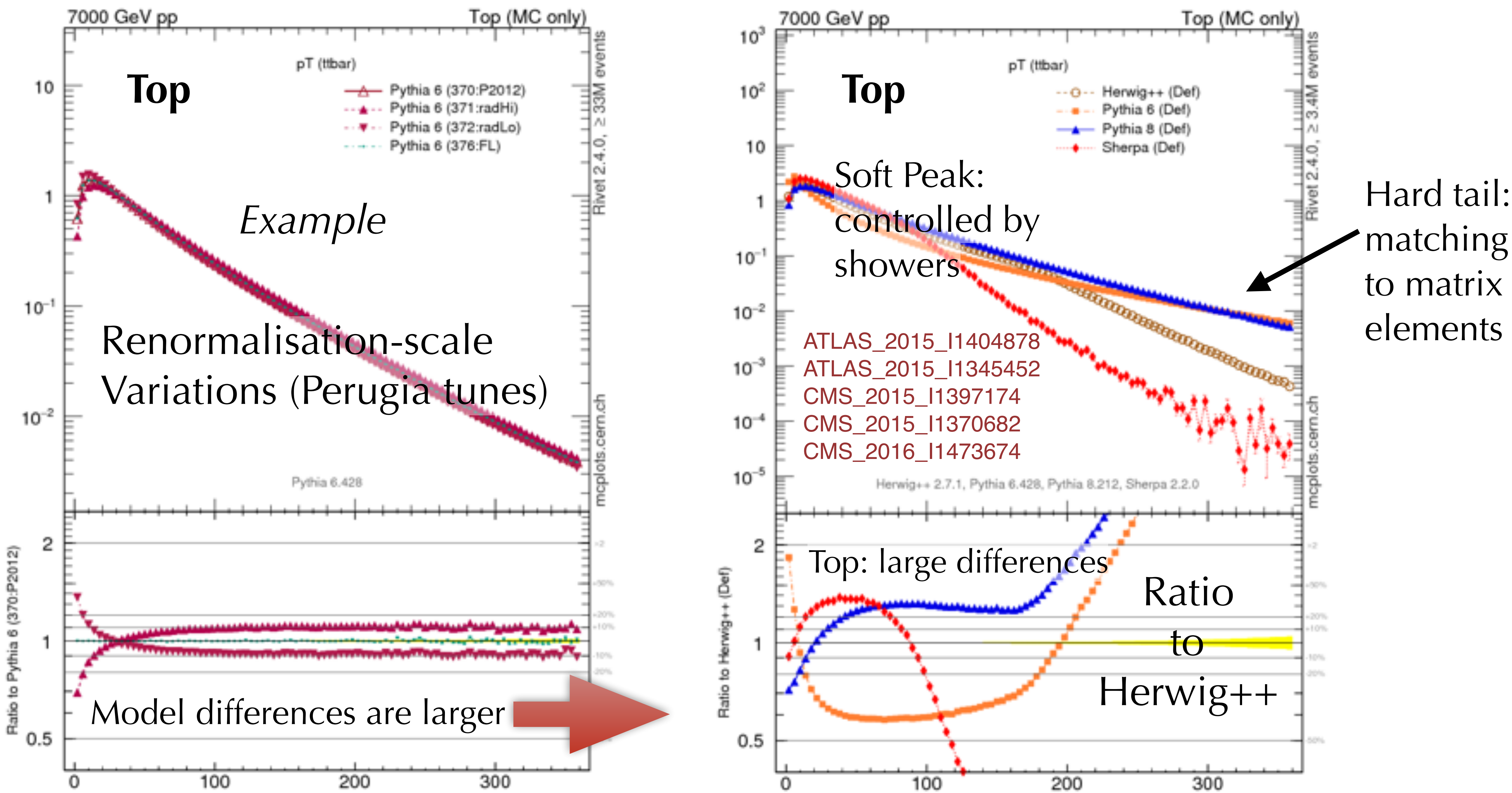




Would be nice to get these top measurements onto mcplots.cern.ch

Uncertainties

Tests initial-state side of radiation in association with production, similarly to p_T(dilepton) in Drell-Yan



Would be nice to get these top measurements onto mcplots.cern.ch

What causes these differences?

Suspect significant differences from alphaStrong choices (both central values and scales);

Could be (has been?) checked/validated

Treatment of Phase Space (and coherence conditions) for Initial-Final dipoles; e.g., PYTHIA 8 currently has "non-coherent" starting condition for QCD processes

See e.g., arXiv:1205.1466

Matching to hard region ⟷ soft region via unitarity

See e.g., arXiv:1003.2384

Recoil Strategies

Model differences should ideally be reduced/resolved by showers beyond LL

… work in progress. In short term: **constraints + pheno + tuning**

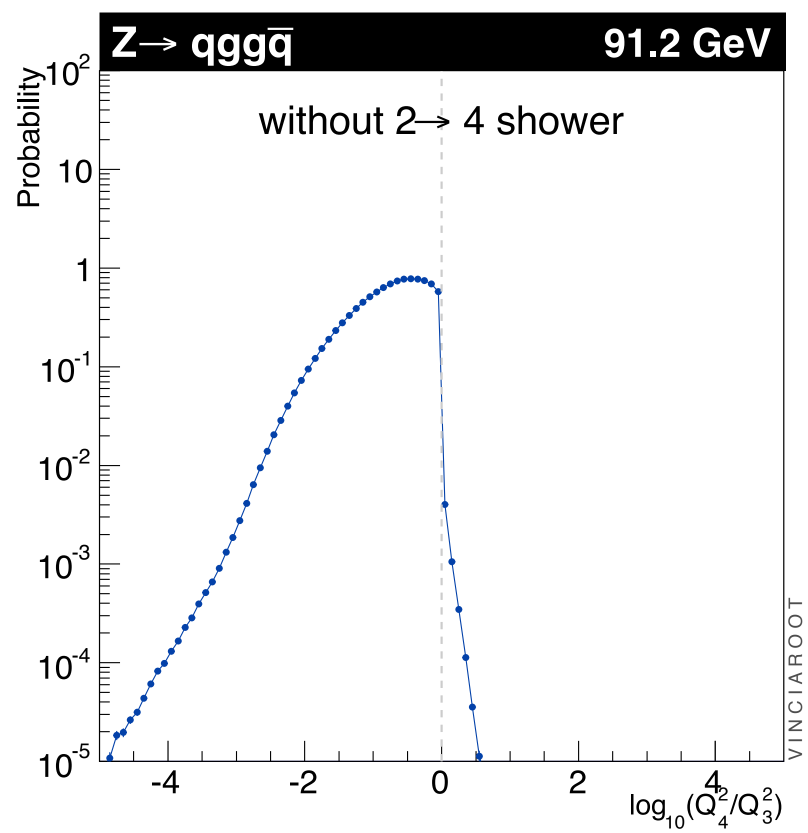
(The Future of Showers: a preview!)

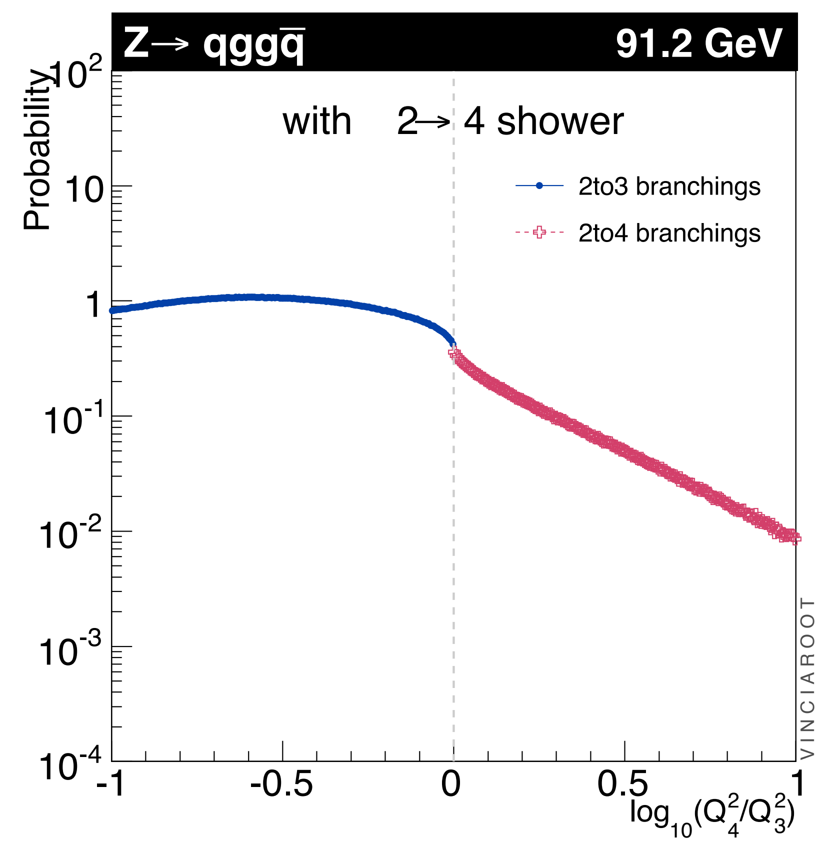
Last week on arXiv: 1611.00013

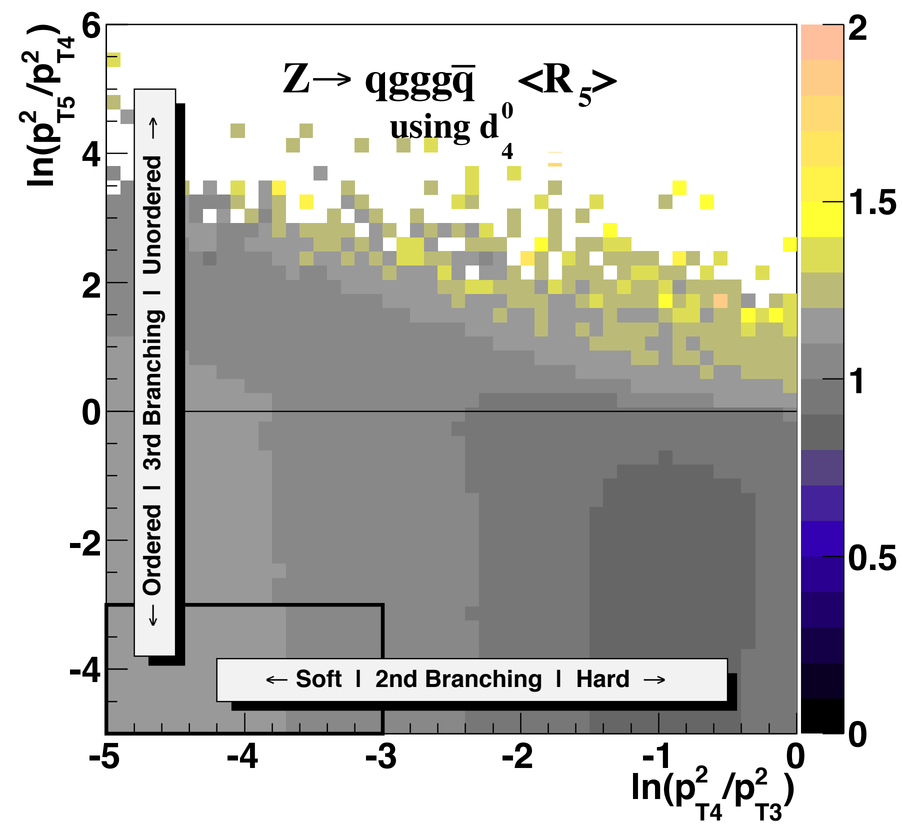
H. T. Li & PS "A framework for second-order parton showers"

Combine O(α_s^2)-corrected 2→3 branchings for "ordered" shower emissions with direct 2→4 branchings for "unordered" ones, evolved in a common p_T measure → 2nd-order Sudakovs

Still at proof-of-concept level, but looks encouraging





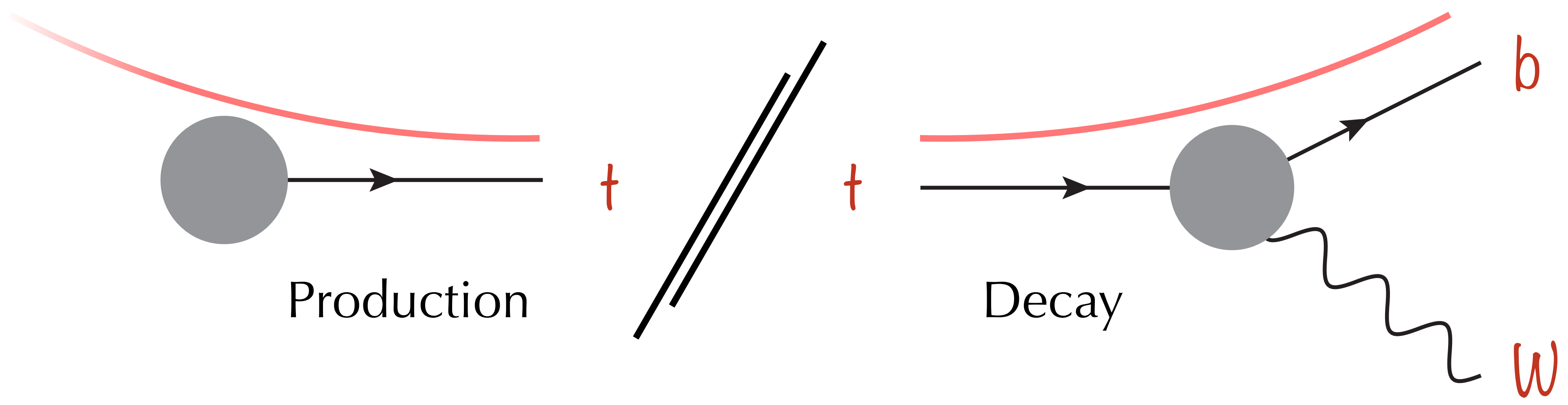


See also Hartgring, Laenen, PS: arXiv:1303.4974

Top Decay

Unique: decay of a (very) massive coloured particle

Will be the go-to reference case for a lot of BSM cases



Is use of narrow-width approximation justified?

(Some ME generators allow to go beyond)

Expect cross talk for scales below Γ_{top} ~ 1.5 GeV; essentially no **perturbative** overlap

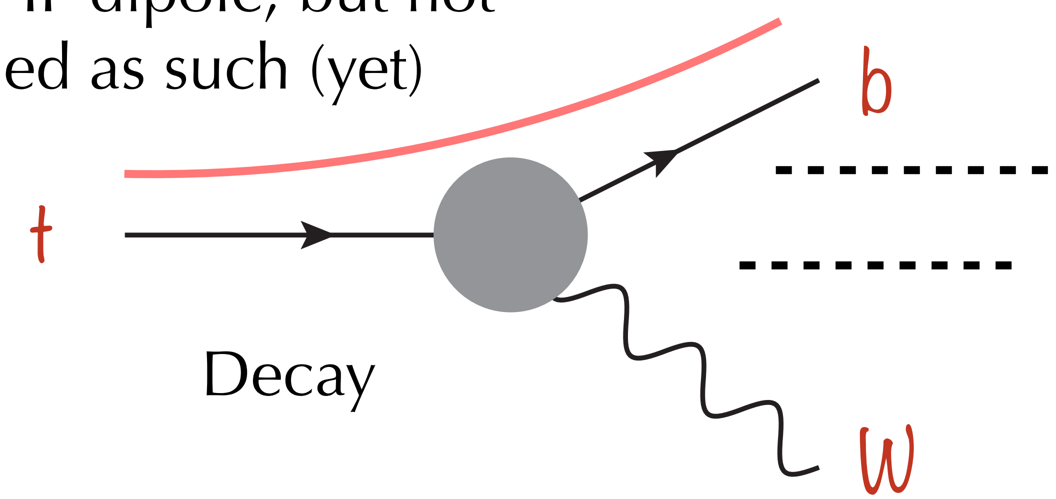
Keep in mind though, that in a generator like PYTHIA, we also average over the polarisations in the intermediate step, so any ttbar spin correlations are washed out

Top Decay

Unique: decay of a (very) massive coloured particle

Will be the go-to reference case for a lot of BSM cases

This can be seen as a different kind of IF dipole, but not modelled as such (yet)



In PYTHIA, the b end of a fictitious bW dipole emits; equivalent to IF setup for first emission but not for subsequent ones

Importantly, this preserves bW invariant mass (i.e., top Breit-Wigner)
But would expect recoil effects wrong/exaggerated to some extent inside the b-gluon-W system. *Develop experimental / in-situ cross checks of structure?*

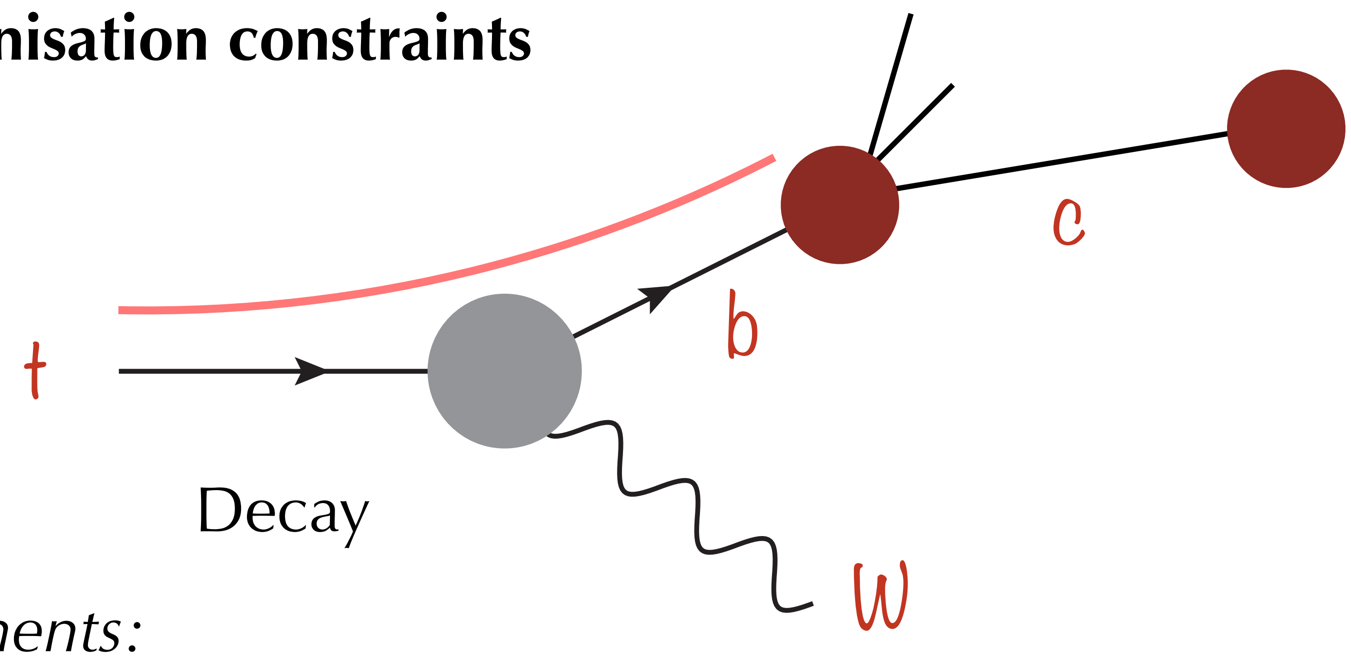
Solution: now working (with S. Mrenna) on an antenna-based (IF) model for radiation in decays of massive resonances. But this will take time.

Top Decay

Unique: decay of a (very) massive coloured particle

Will be the go-to reference case for a lot of BSM cases

B hadronisation constraints

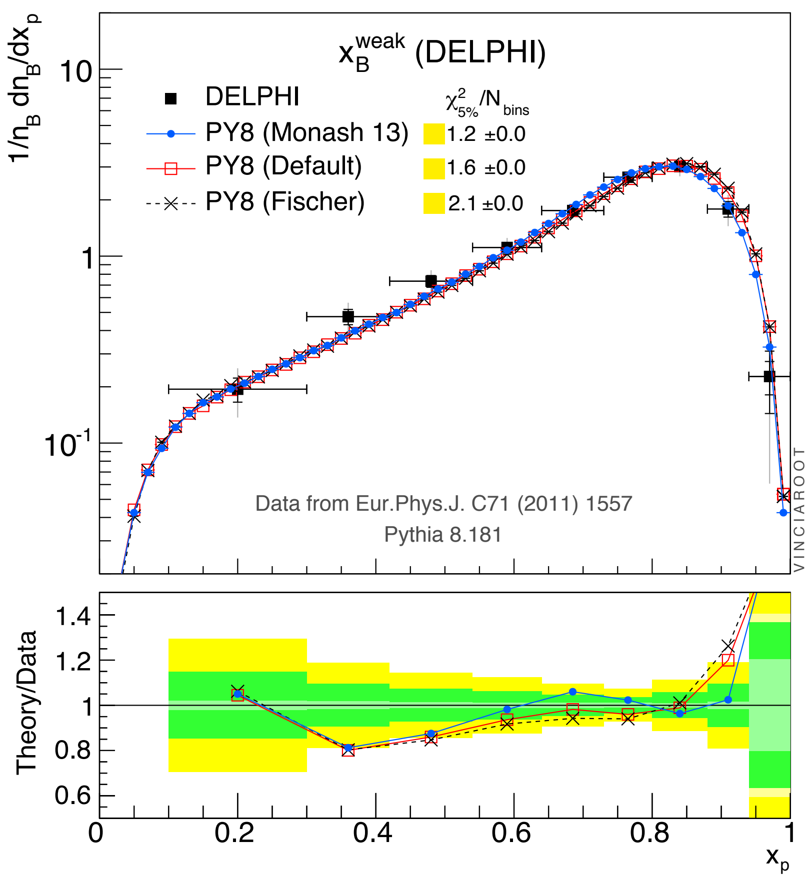


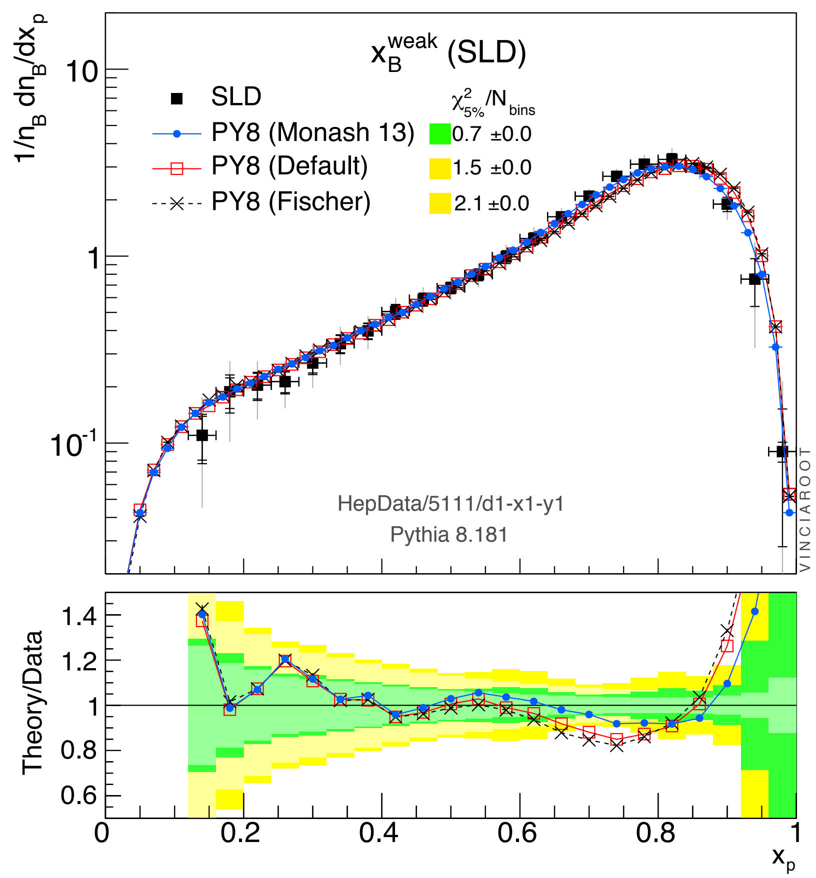
My comments:

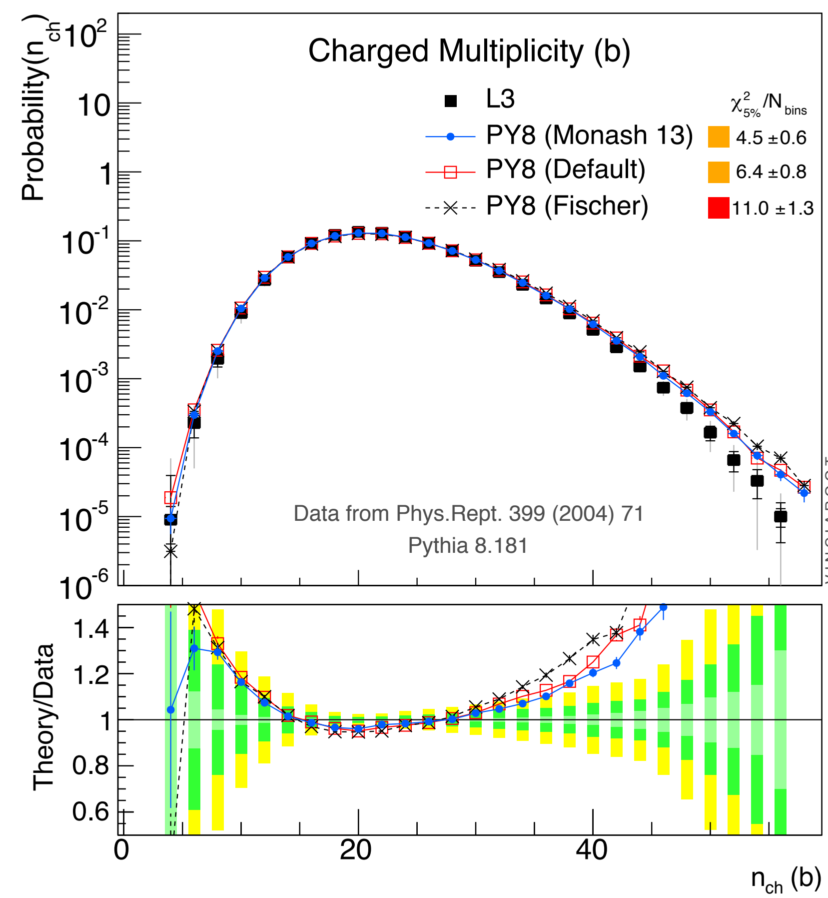
- **b fragmentation** in principle well constrained by LEP & SLD measurements; some tension between the two, may now have been resolved? Rivet 2.5.2 update includes : OPAL_2003_I599181 "Inclusive analysis of the b quark fragmentation function in Z decays" & modified DELPHI_2011_I890503, but have not yet propagated to tunes : should be checked)
- In pp, the b quark is connected to the initial state, and is embedded in the UE (is lifetime + boost from top enough to escape (most of) CR? Compare with incl b jets?)

Example: Monash Tune @ LEP

Slight tension between SLD and DELPHI on E(B)/E(jet)







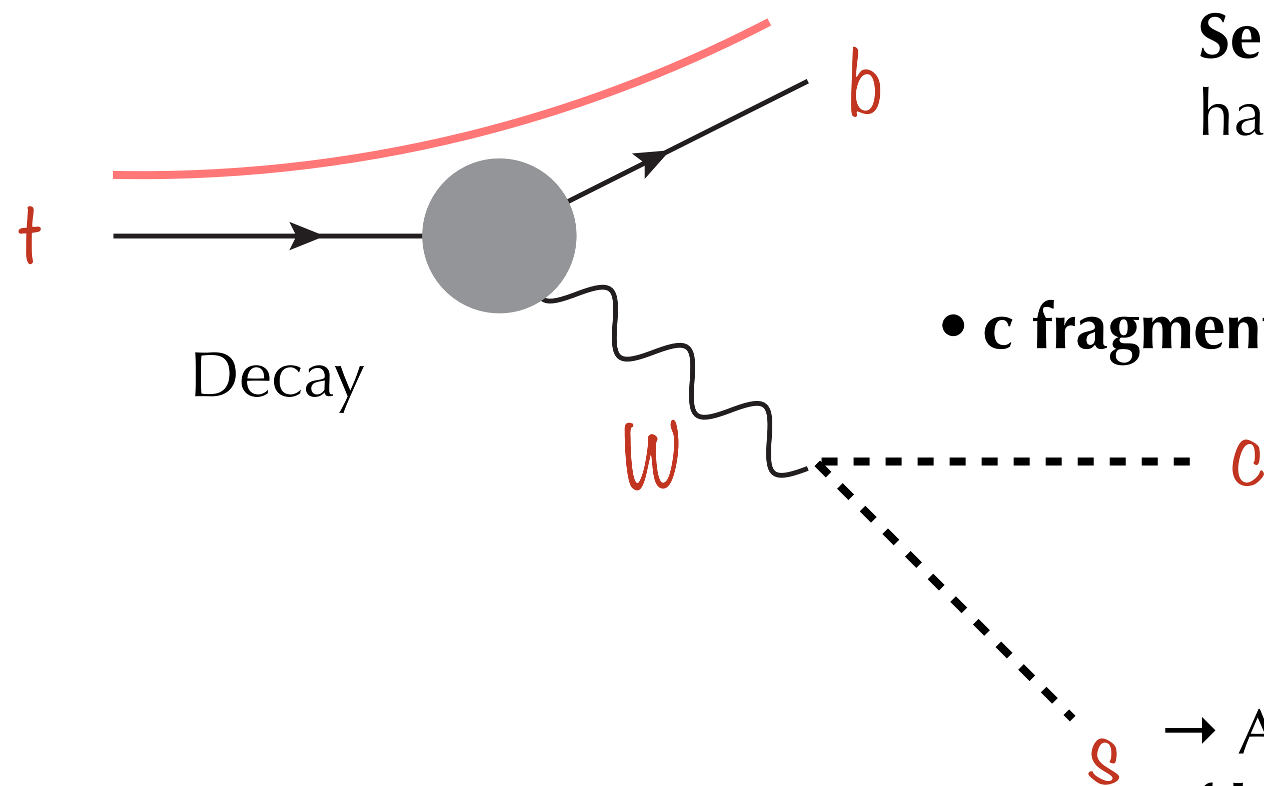
Controlled by fragmentation r_b parameter
(in addition to flavour-blind fragmentation parameters)
Could use the RIVET plots to define b-specific N.P. variations

Track multiplicity in b jets appears to have a tail to too high multiplicities

Is this observed at LHC as well?

Top Decay

Further possibilities for hadronisation studies in top



Semileptonic (or fully hadronic) **ttbar events**

- **c fragmentation** poorly constrained

Tag charm in W ?

→ Also clean source of **leading strange**

In-situ reference constraints on fragmentation of hard strange quarks

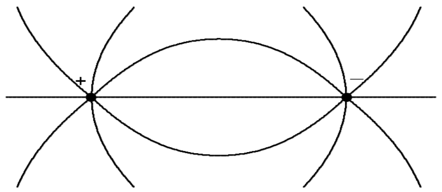
Connects with hadronisation, which is looking **strange** at LHC …

Quark-Antiquark Potential

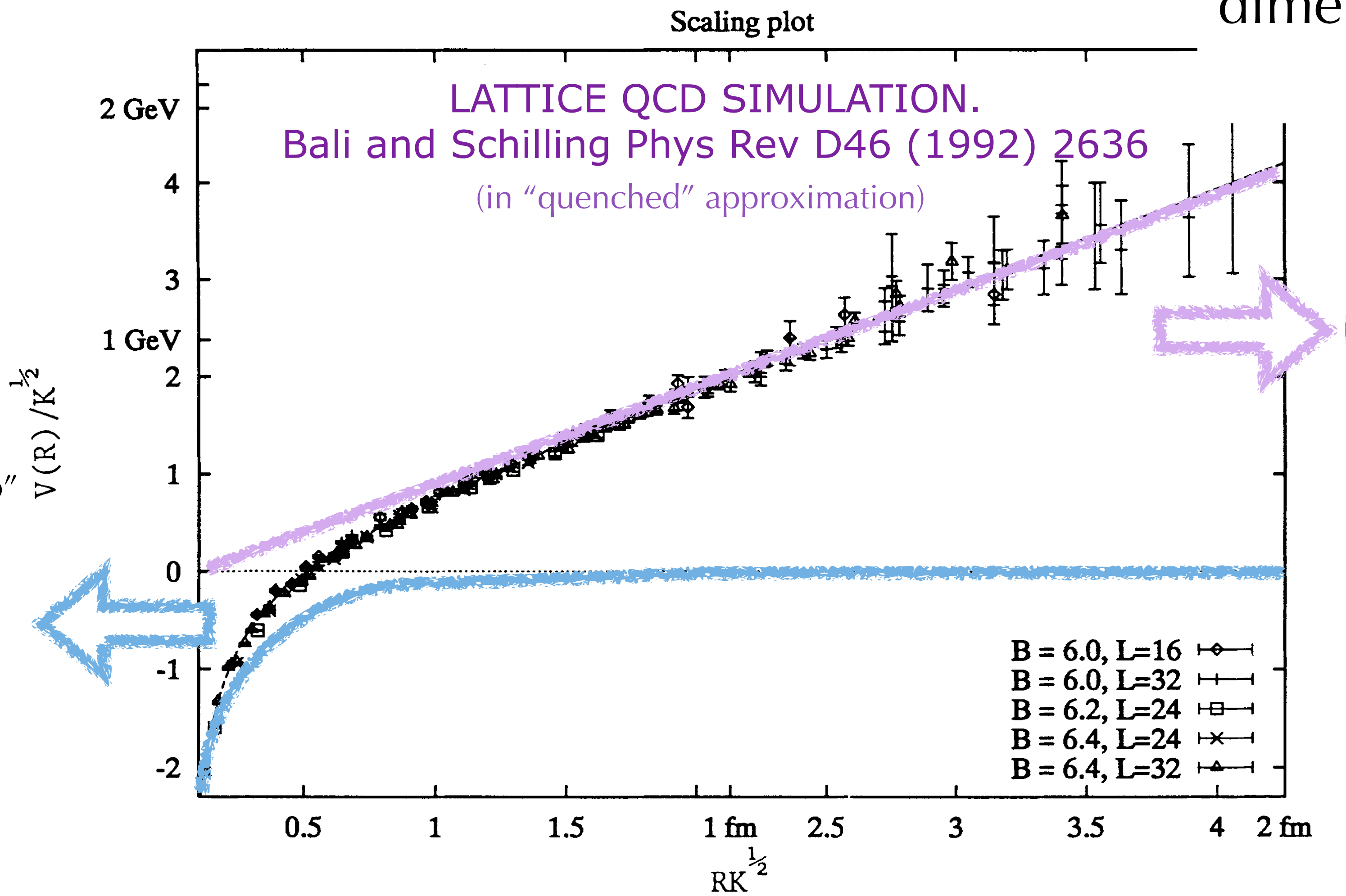
As function of separation distance

PYTHIA's main feature: **the Lund model** (1+1 dimensional "string")

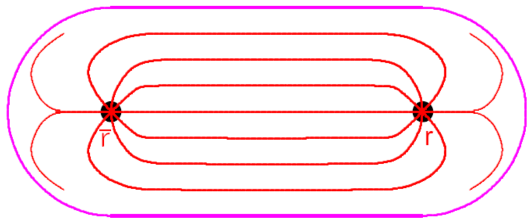
Short Distances ~ "Coulomb"



"Free" Partons



Long Distances ~ Linear Potential



"Confined" Partons
(a.k.a. Hadrons)

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

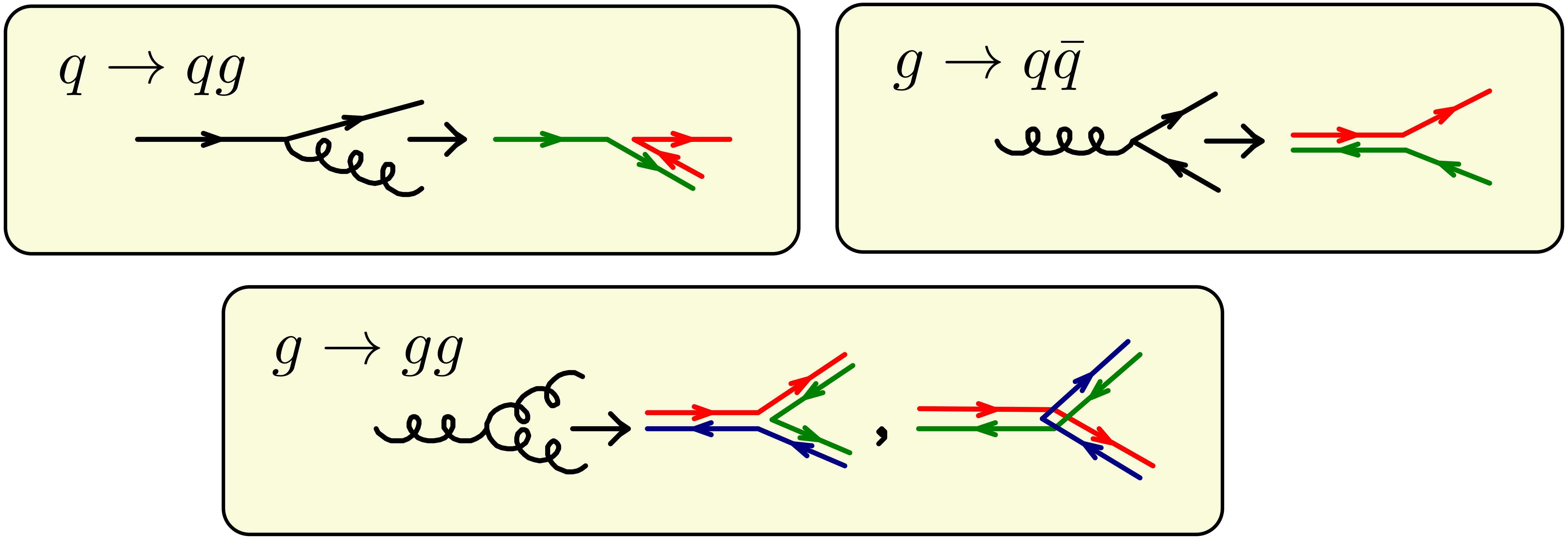
~ Force required to lift a 16-ton truck

Which Charges? Colour Flow

After the parton shower finishes, there can be lots of partons, $\mathcal{O}$(10-100). The main question is therefore:

Between which partons do confining potentials arise?

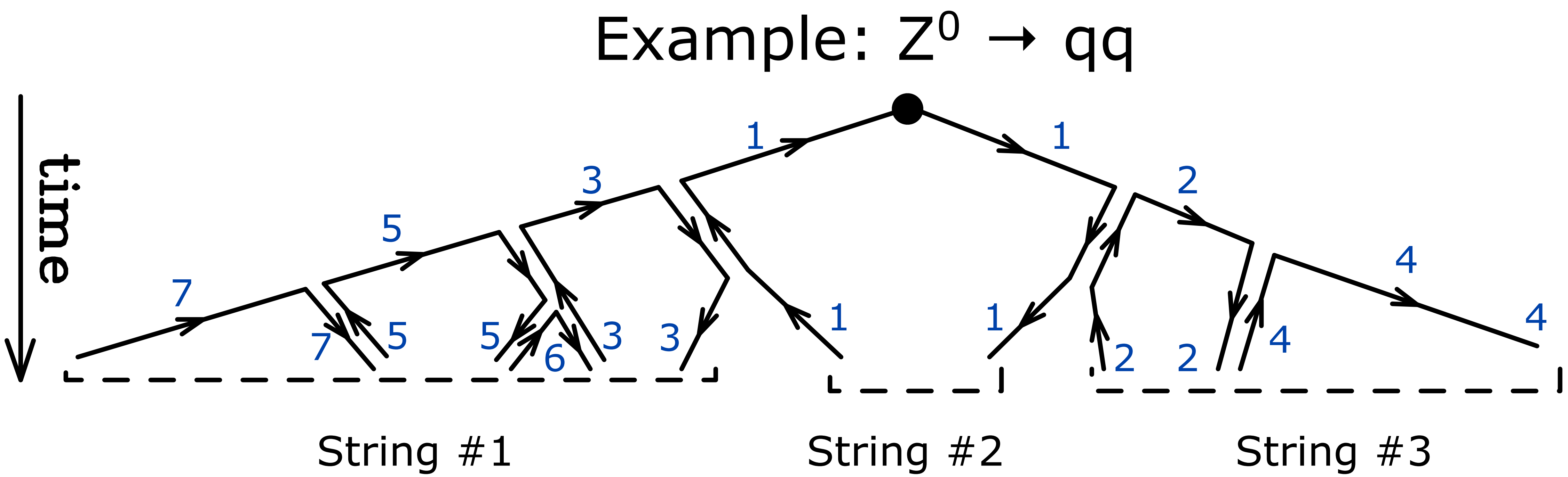
MC generators use a simple set of rules for colour flow, based on large-N_C limit (valid to ~ $1/N_C^2$ ~ 10%) G. 't Hooft, Nucl.Phys. B72 (1974) 461.



Illustrations from: Nason & Skands, PDG Review on *MC Event Generators*, 2014

Colour Flow

For an entire Cascade



For a single fragmenting system:

Coherence of pQCD cascades (angular ordering or boosted dipoles/antennae)

→ not much "overlap" between strings

→ Leading-colour approximation pretty good

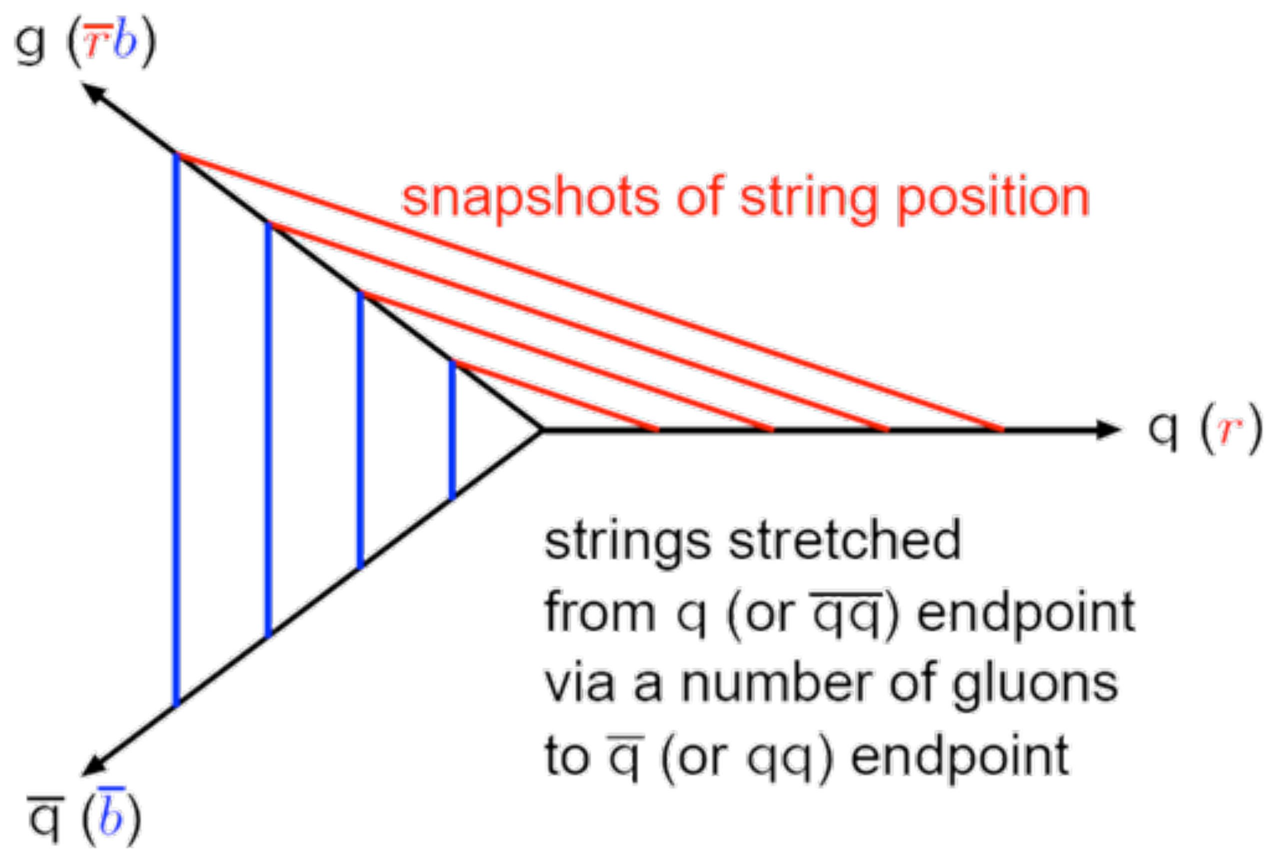
(The trouble at LHC: MPI & ISR → many such systems; overlapping)

The (Lund) String Model

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

Map:

- **Quarks** → String Endpoints
- **Gluons** → Transverse Excitations (kinks)
- Physics then in terms of string worldsheet evolving in spacetime
- Probability of string break (by quantum tunneling) constant per unit area → ***AREA LAW***



Gluon = kink on string, carrying energy and momentum

→ **STRING EFFECT**

Simple space-time picture

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

Colour Confusion ?

Next-to-simplest: 2 string systems

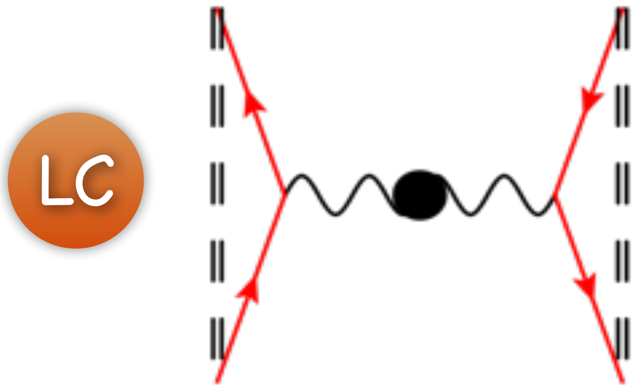
Several studies at LEP2 (ee → WW → 4 jets)

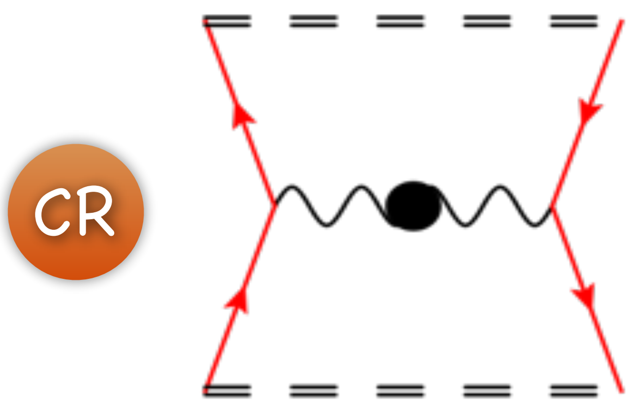
CR implied a non-perturbative uncertainty on the W mass measurement, $\Delta M_W \sim 40$ MeV

CR strength best fit ~ 10% ~ $1/N_C^2$

But in WW, overlaps are expected to be suppressed by kinematics, and there are “only” two strings;

In pp, MPI can create (many) more … ?



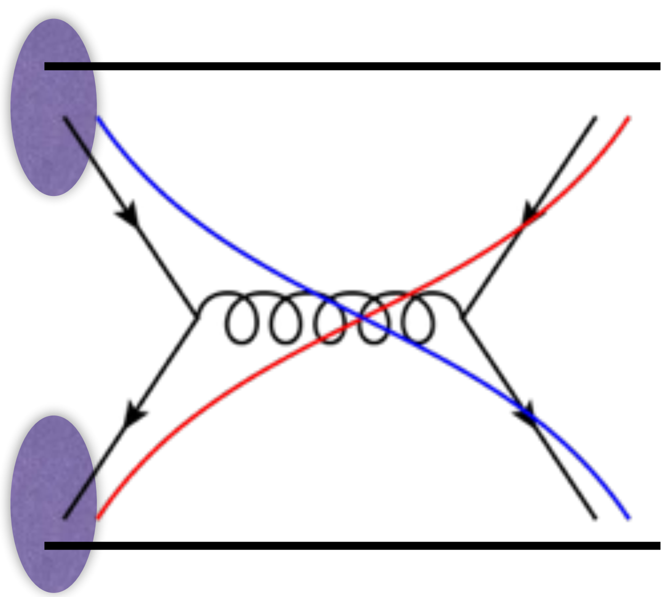


Proton-Proton (LHC)

A lot more colour kicked around (& also colour in initial state)

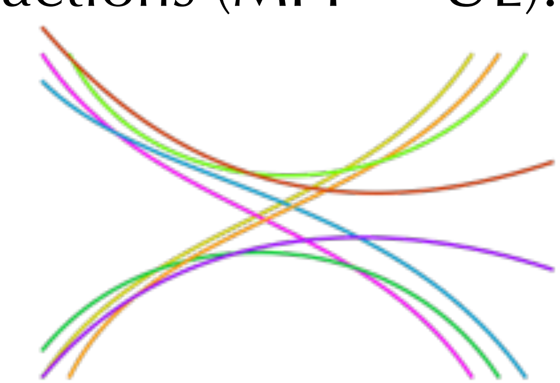
Include “Beam Remnants”

Still might look relatively simple, to begin with



(+baryon beam remnants → “string junctions”)

With *several* parton-parton interactions (MPI → UE):



How to make sense of the colour structure?

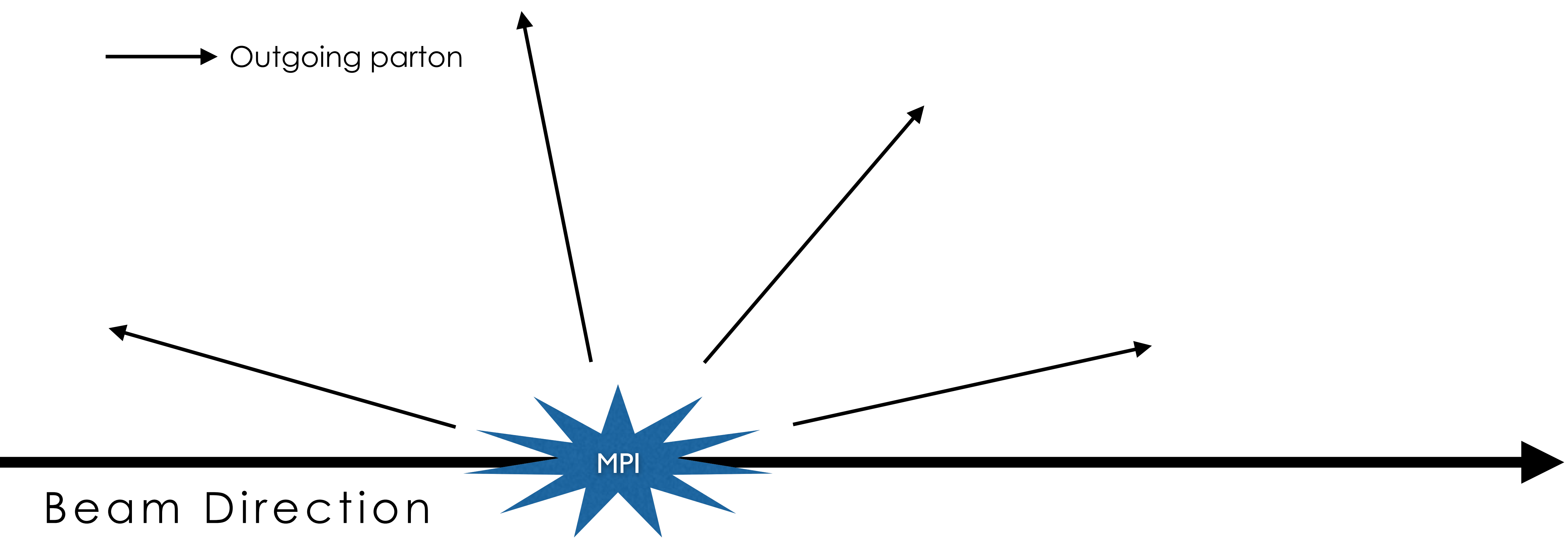
Overviews of recent models: arXiv:1507.02091 , arXiv:1603.05298

String-fragmentation of junctions: Sjöstrand & Skands **NPB 659 (2003) 243**; CR with junctions: Christiansen & Skands **JHEP 1508 (2015) 003**

Colour: What's the Problem?

(including **MPI:** Multiple Parton-Parton Interactions ~ the "underlying event")

Without Colour Reconnections
Each MPI hadronizes **independently** of all others

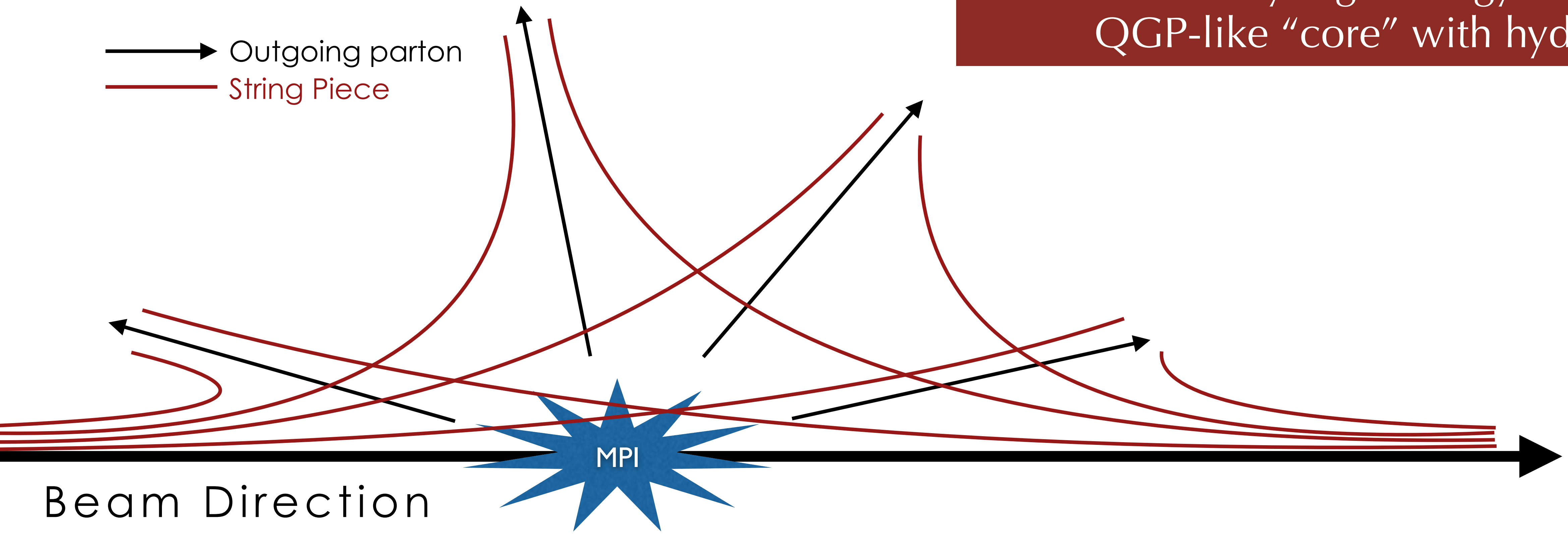


Colour: What's the Problem?

(including **MPI:** Multiple Parton-Parton Interactions ~ the "underlying event")

Without Colour Reconnections
Each MPI hadronizes **independently** of all others

So many strings in so little space
If true → Very high energy densities
QGP-like "core" with hydro?



→ Thermal? E.g., EPOS

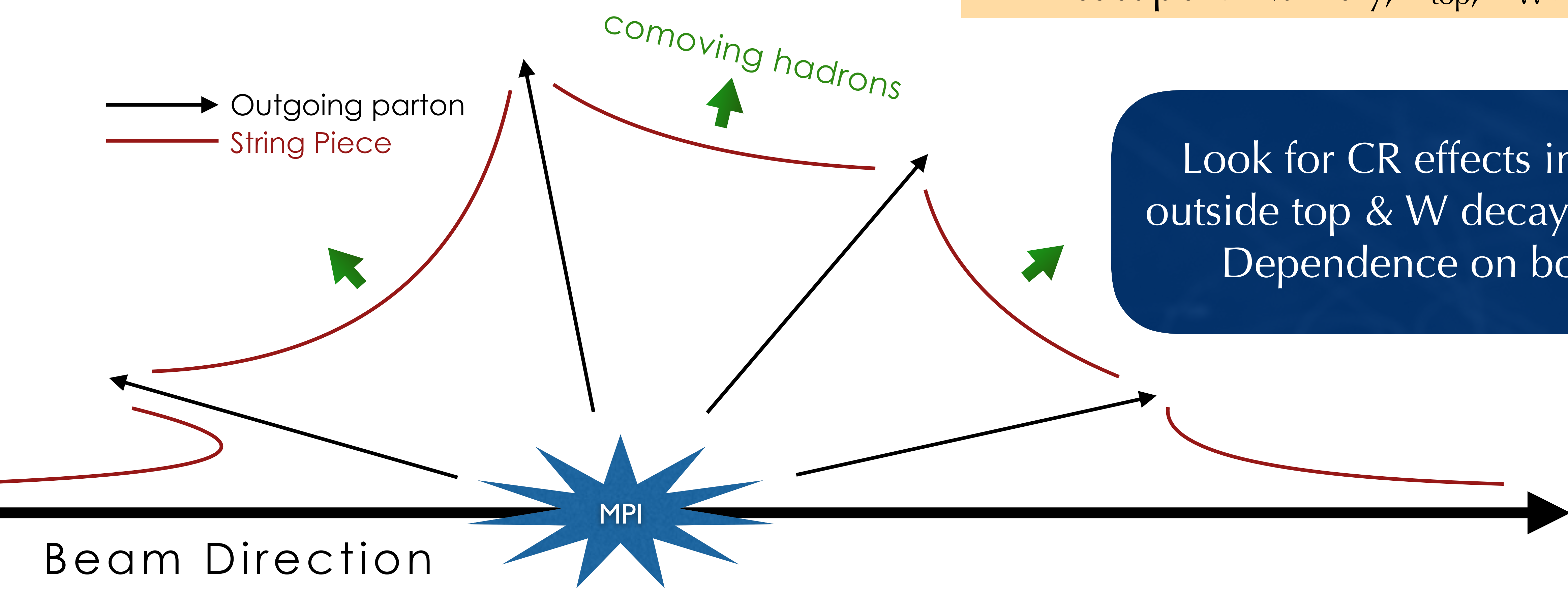
Colour Reconnections

(including **MPI:** Multiple Parton-Parton Interactions ~ the “underlying event”)

With Colour Reconnections
MPI hadronize **collectively**

See also Ortiz et al., Phys.Rev.Lett. 111 (2013) 4, 042001

Do long-lived or highly boosted particles “escape”? Naively, Γ_{top}, $\Gamma_W > \Lambda_{QCD}$



Look for CR effects inside vs outside top & W decay systems? Dependence on boosts?

String-Length Minimisation E.g., PYTHIA, HERWIG

Or Thermal? E.g., EPOS

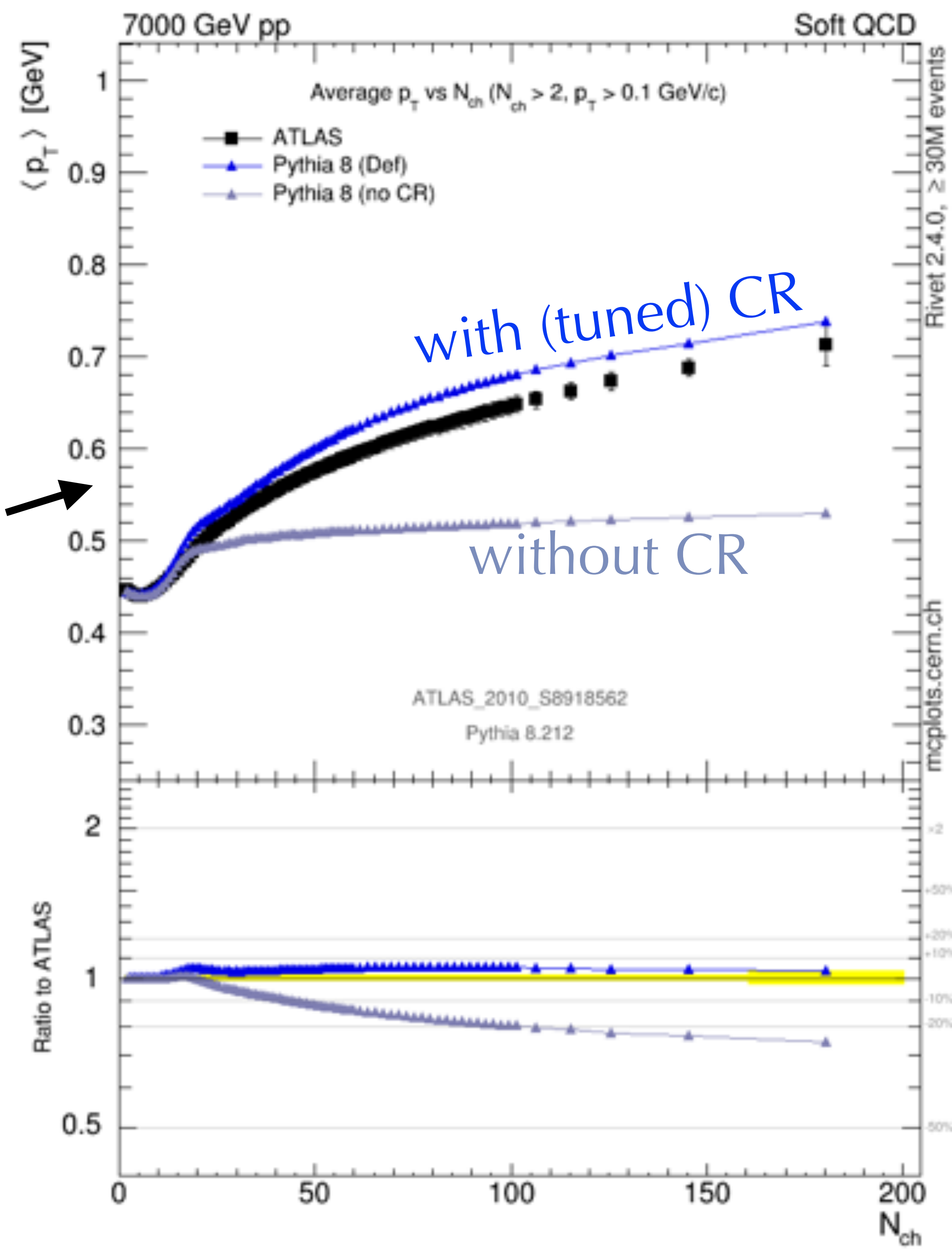
Or Higher String Tension? E.g., DIPSY rope

What do we see in pp collisions?

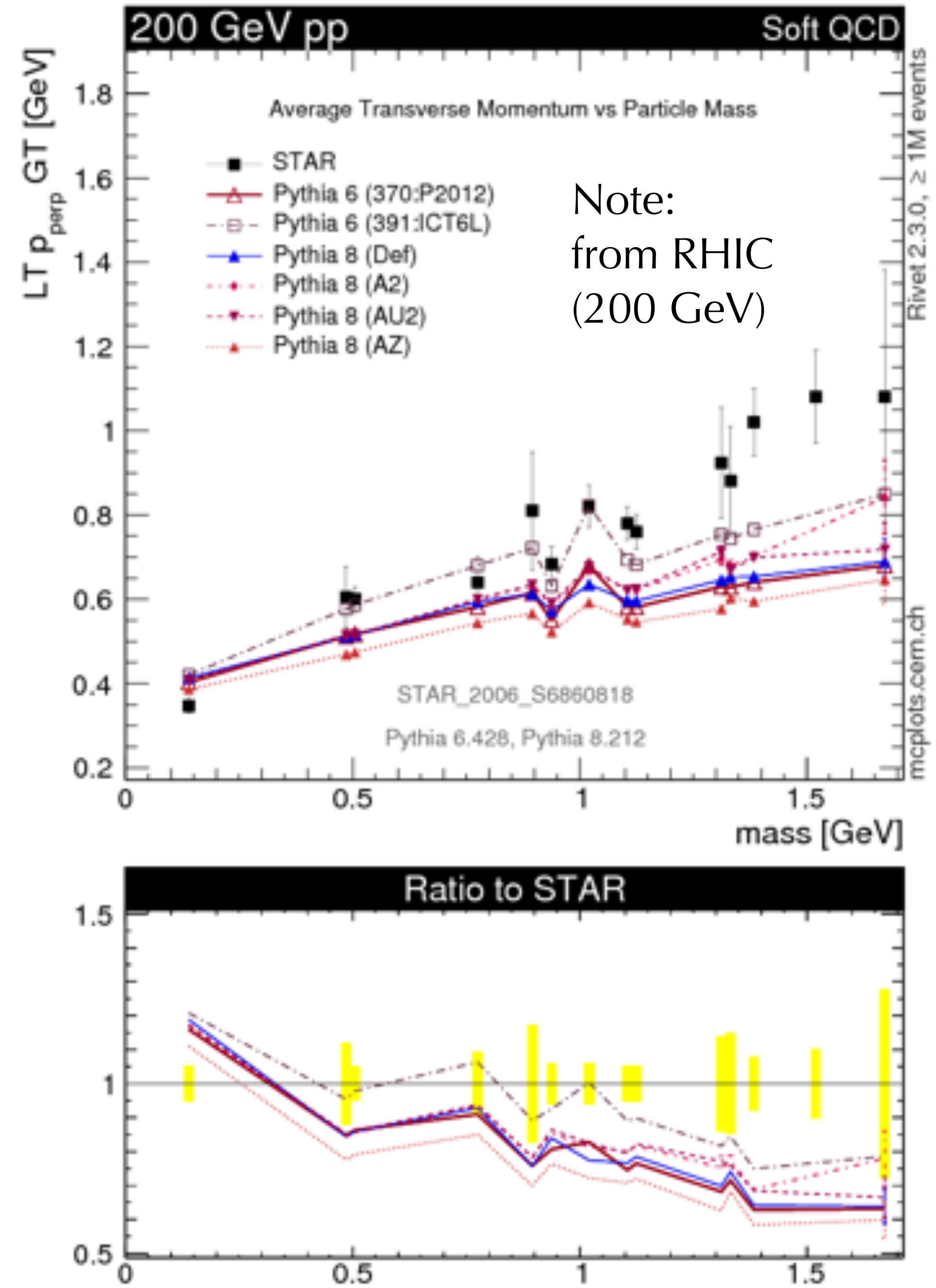
Plots from mcplots.cern.ch

'New Look'

<pT> vs Number of Particles



<pT> vs Particle Mass

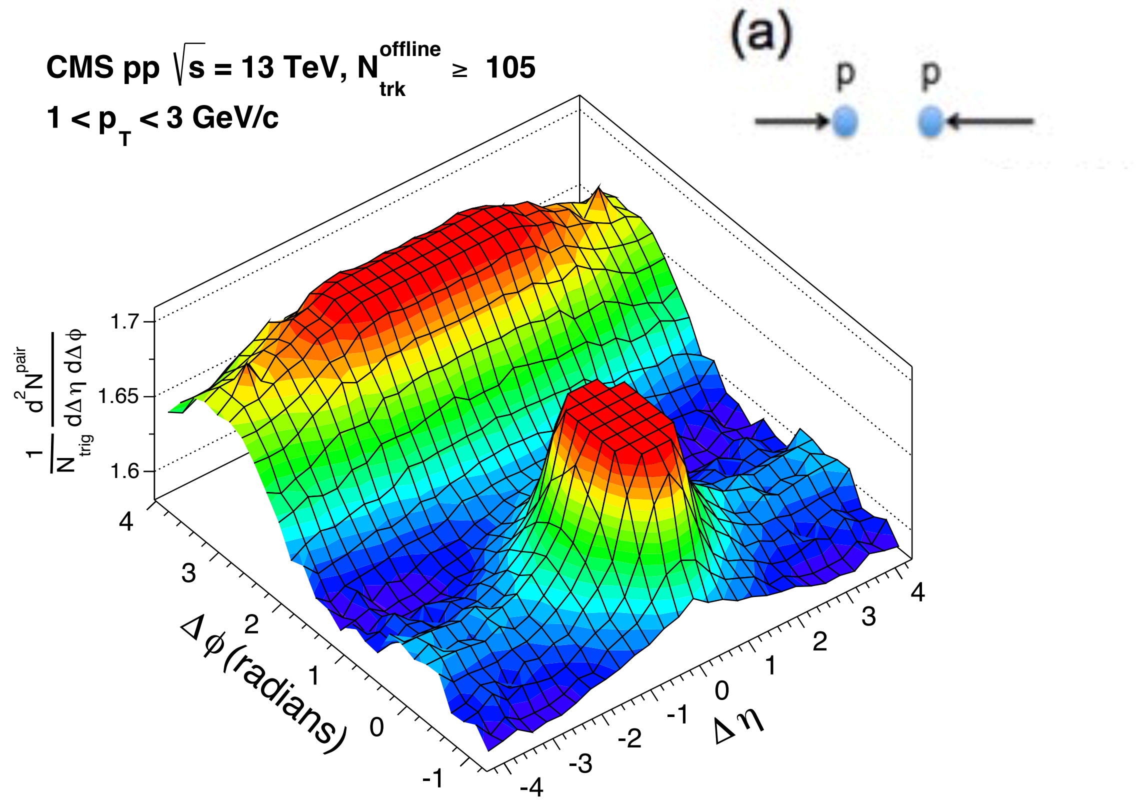


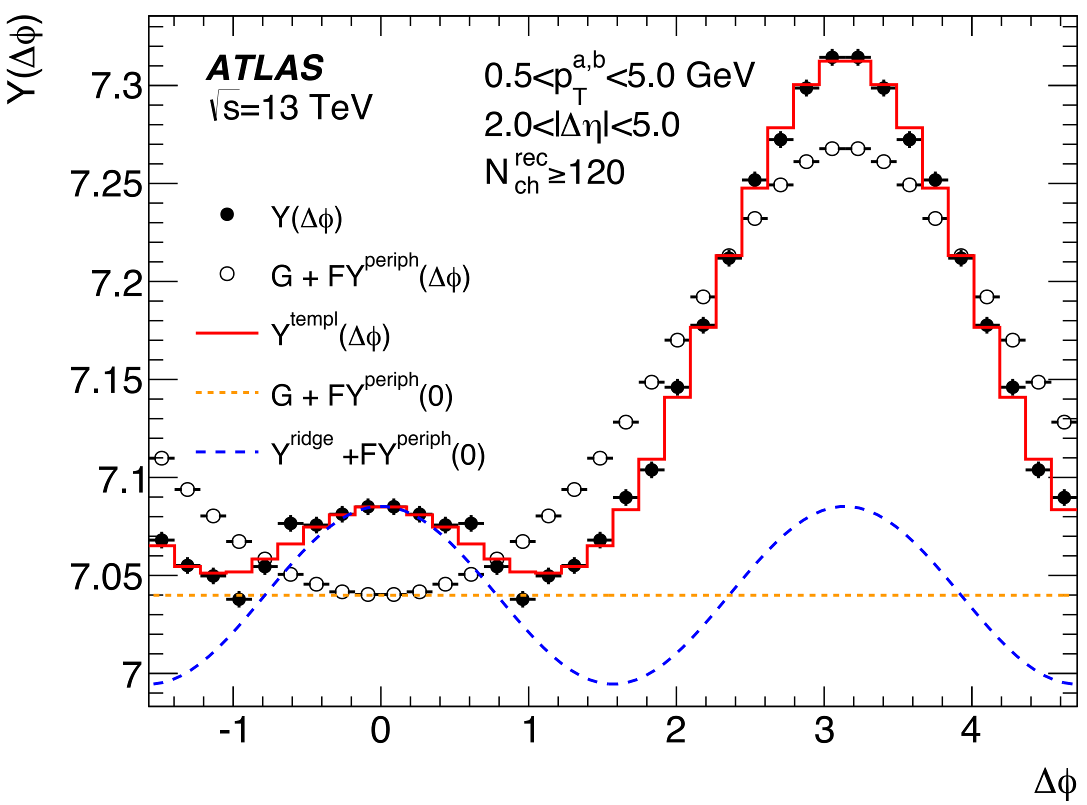
Average pT **increases** with particle multiplicity and (faster than predicted) with particle mass

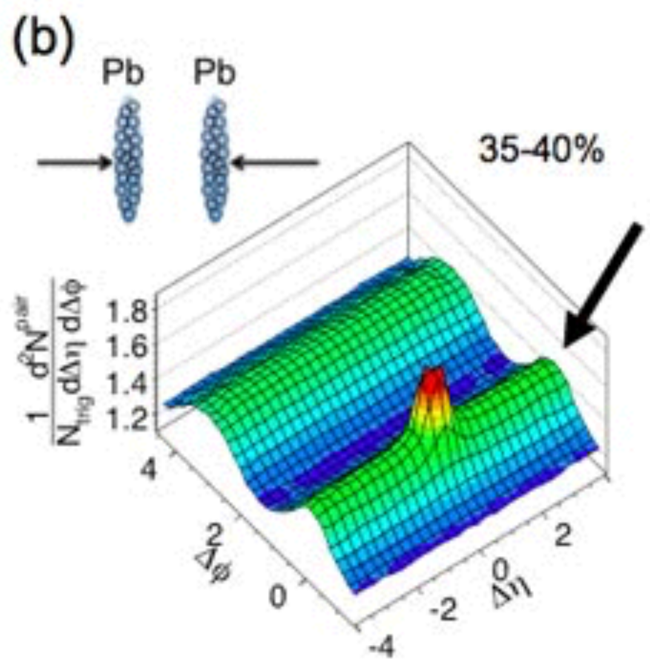
The "CMS Ridge"

[CMS PRL 116(2016)172302][ATLAS PRL 116(2016)172301]

High-Multiplicity pp collisions

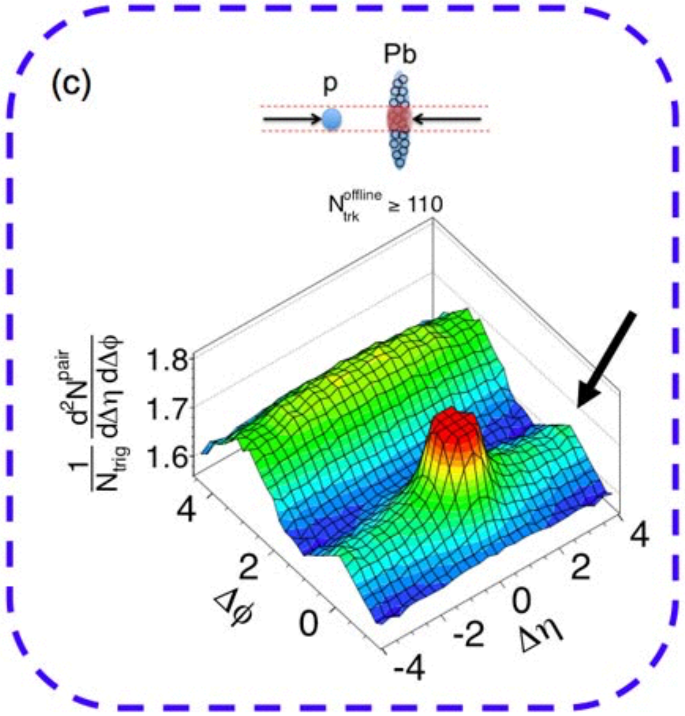






← Reminiscent of the (much stronger) ridge seen in HI collisions.

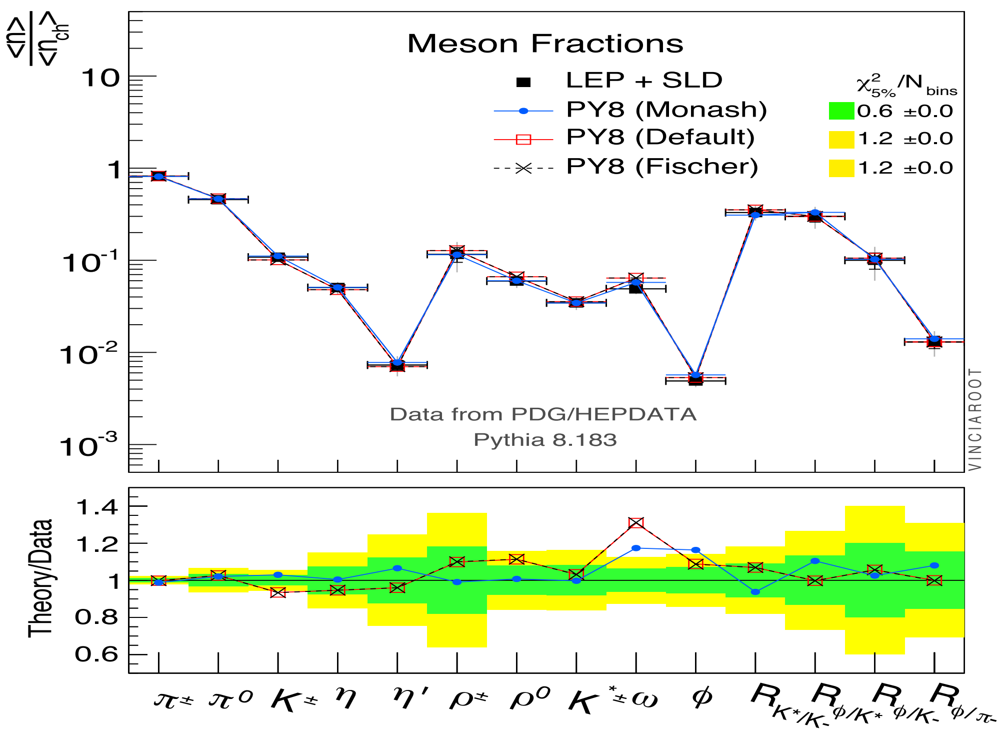
Surprisingly strong also in proton-Lead →

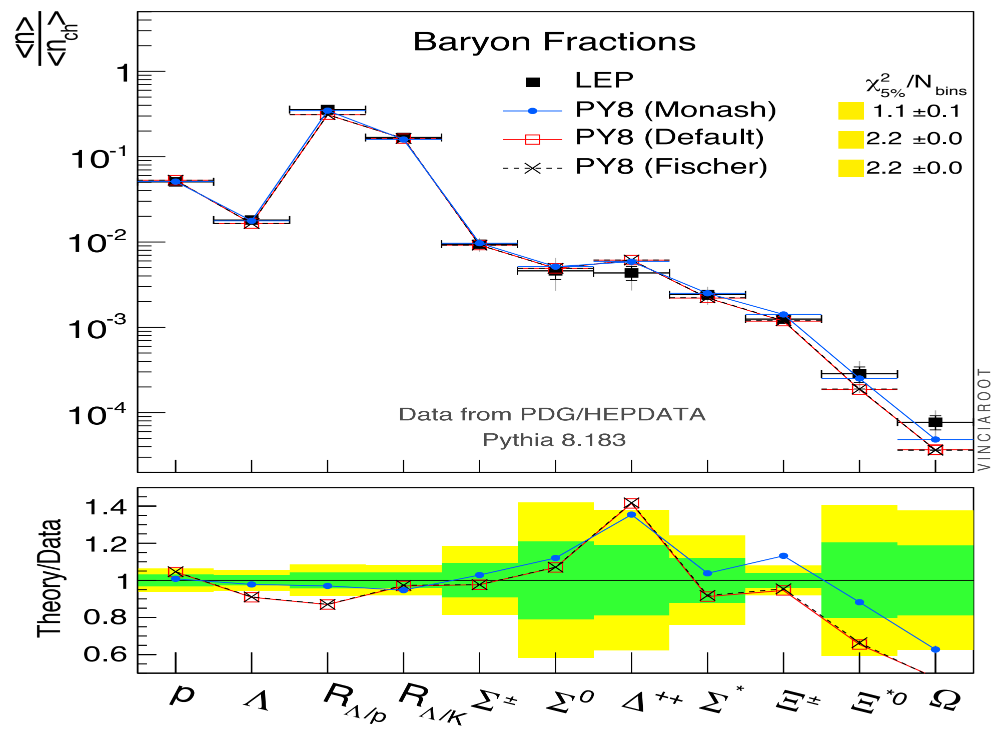


Back to Strangeness

Plots from the Monash tune paper
Eur.Phys.J. C74 (2014) no.8, 3024

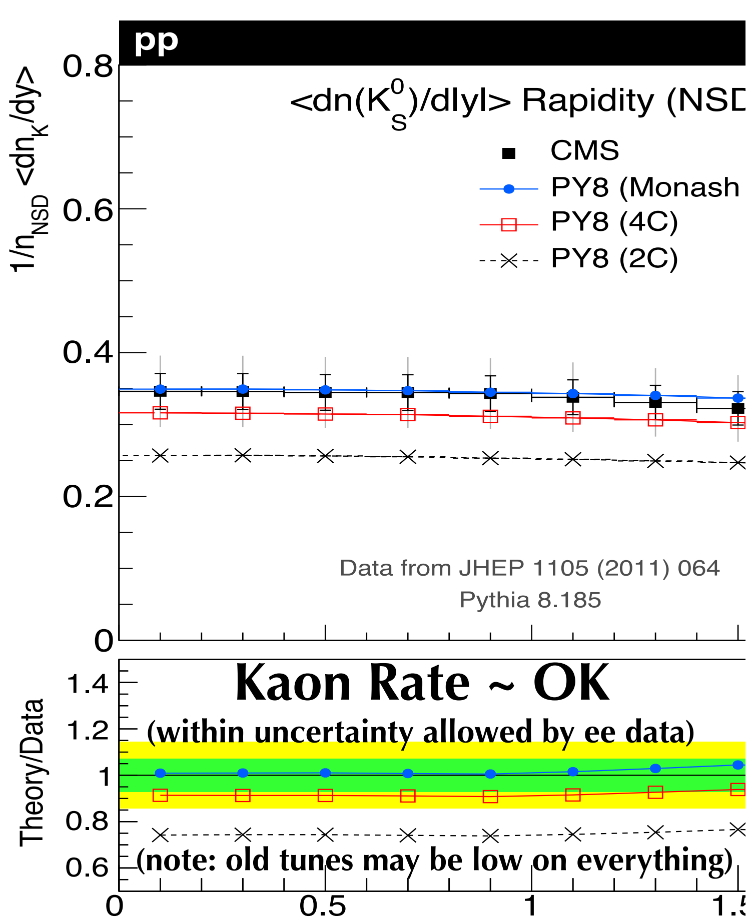
Z Decays

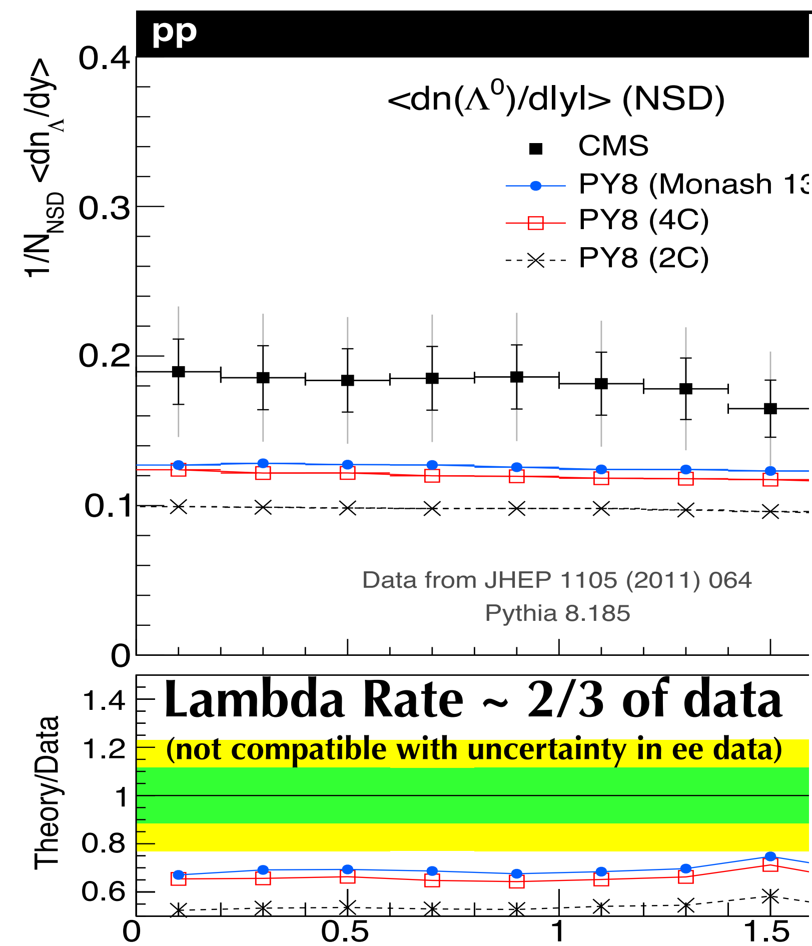


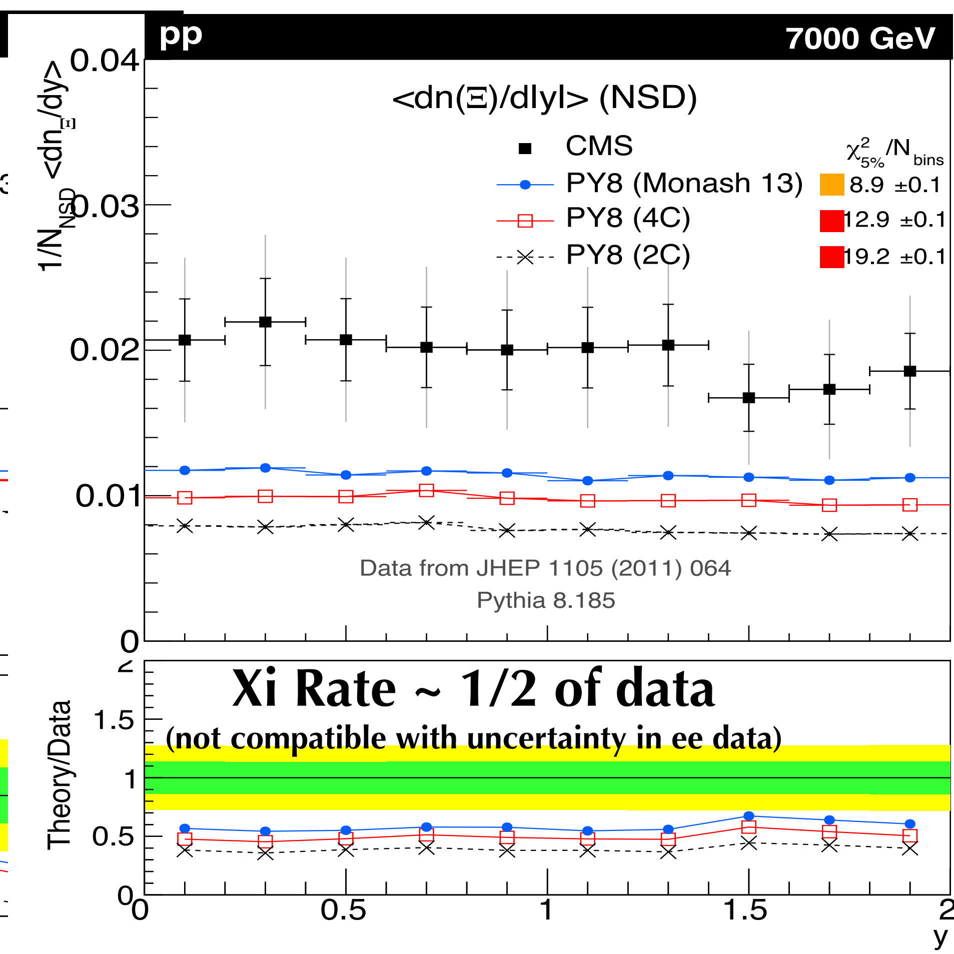


This is the data used to tune the models

CMS

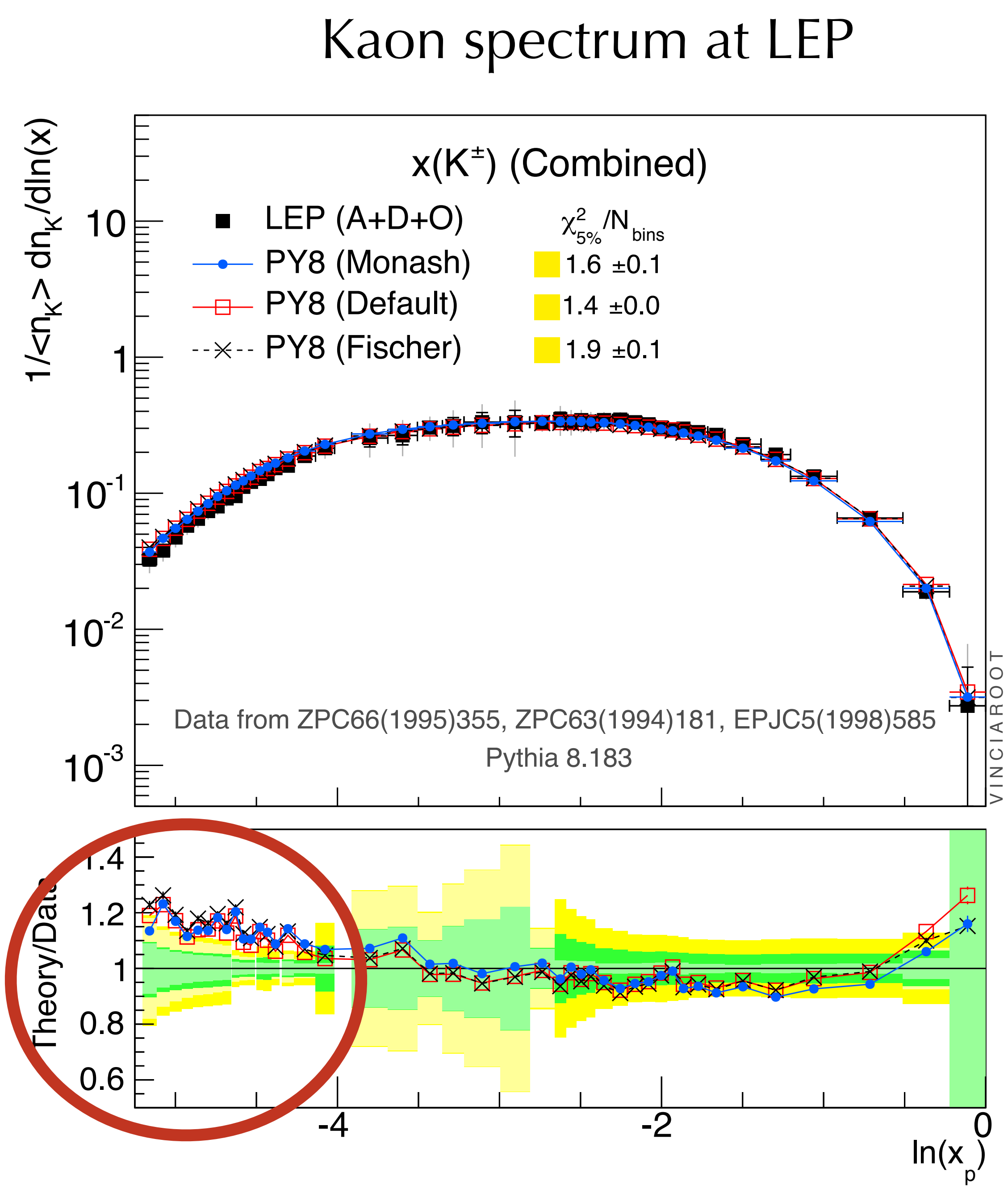


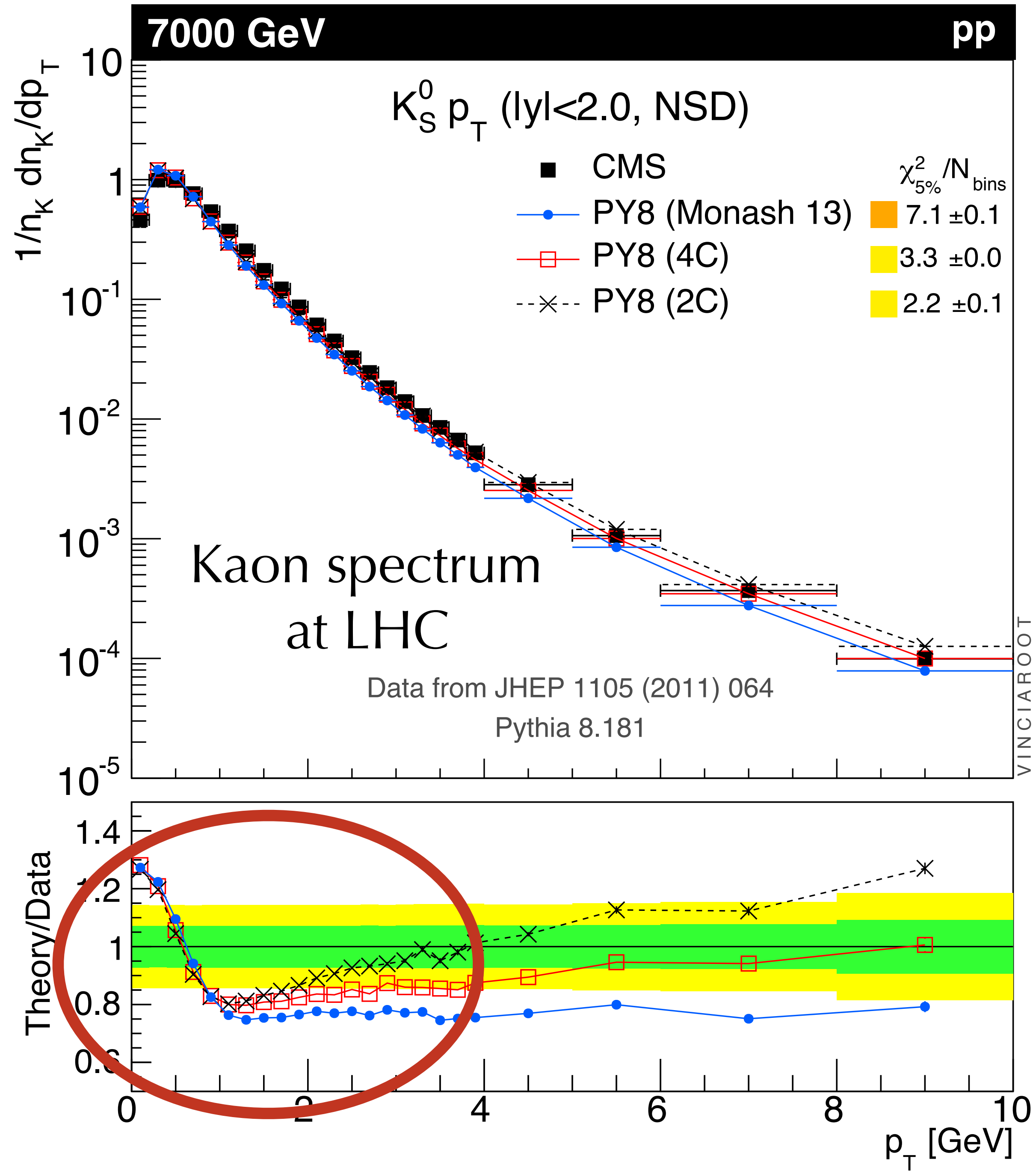




Plots from the Monash tune paper
Eur.Phys.J. C74 (2014) no.8, 3024

Note: rates normalised to unity now



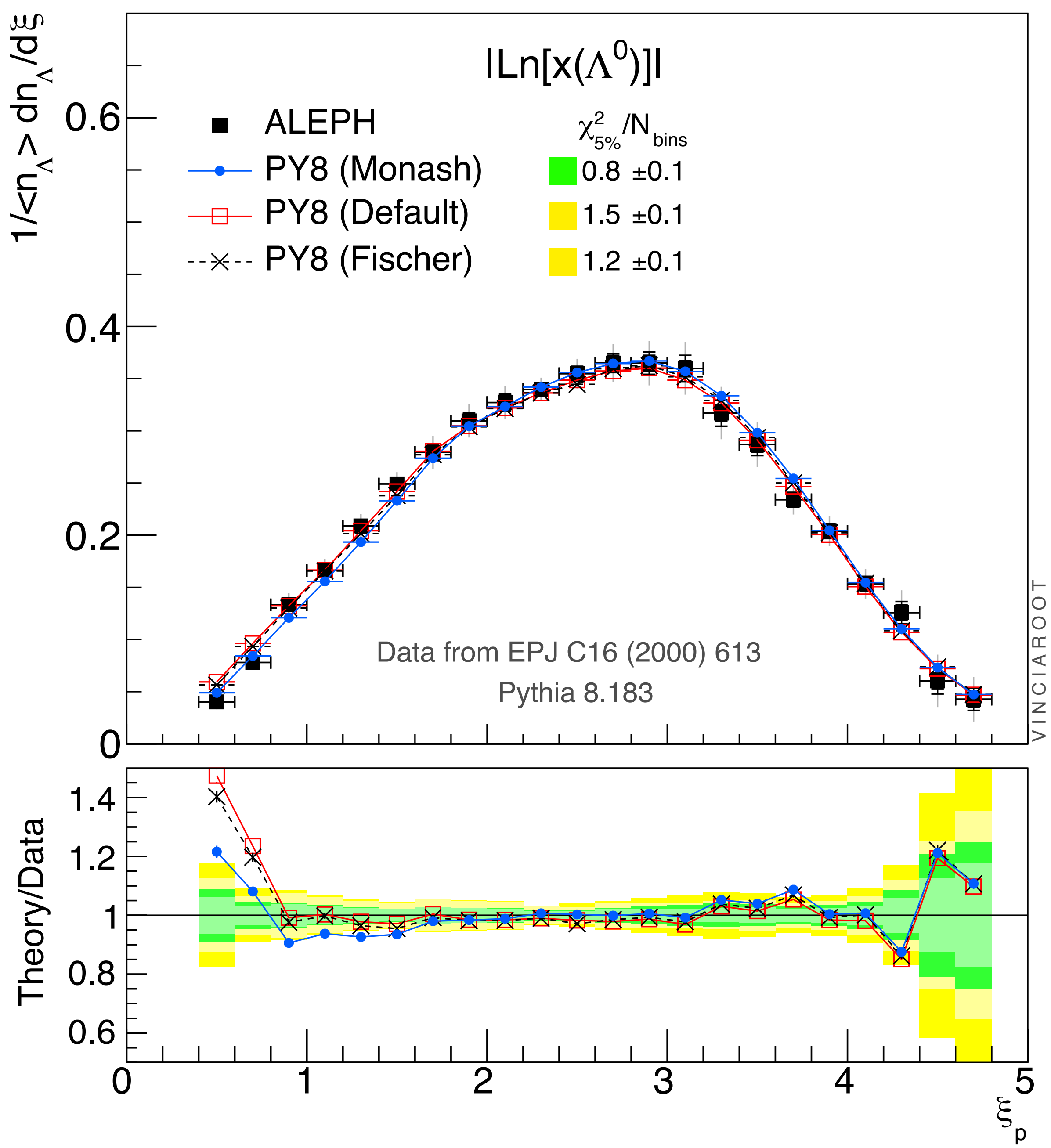


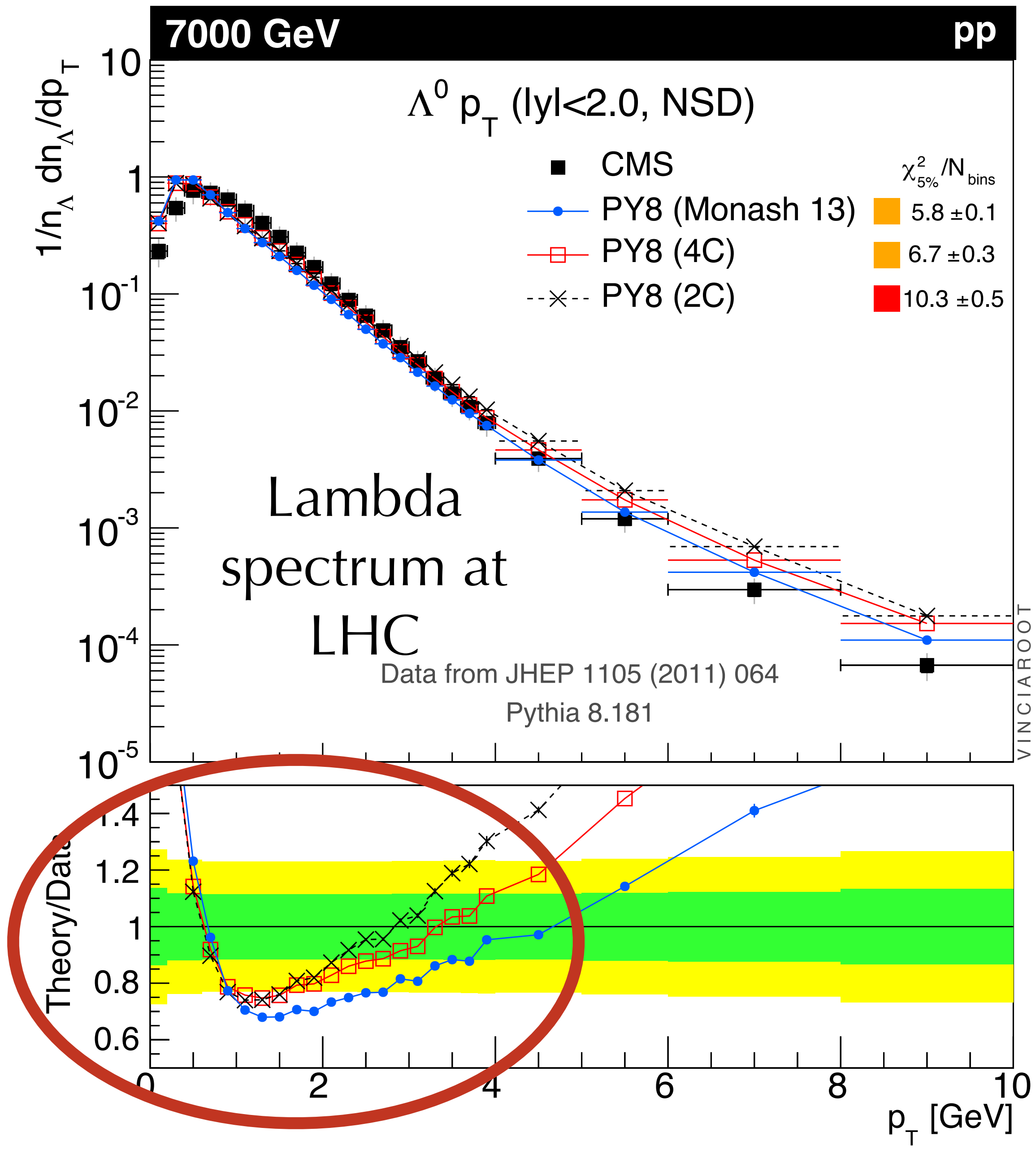
(+ Several measurements by ALICE, LHCb)

Plots from the Monash tune paper
Eur.Phys.J. C74 (2014) no.8, 3024

Note: rates normalised to unity now

Lambda spectrum at LEP



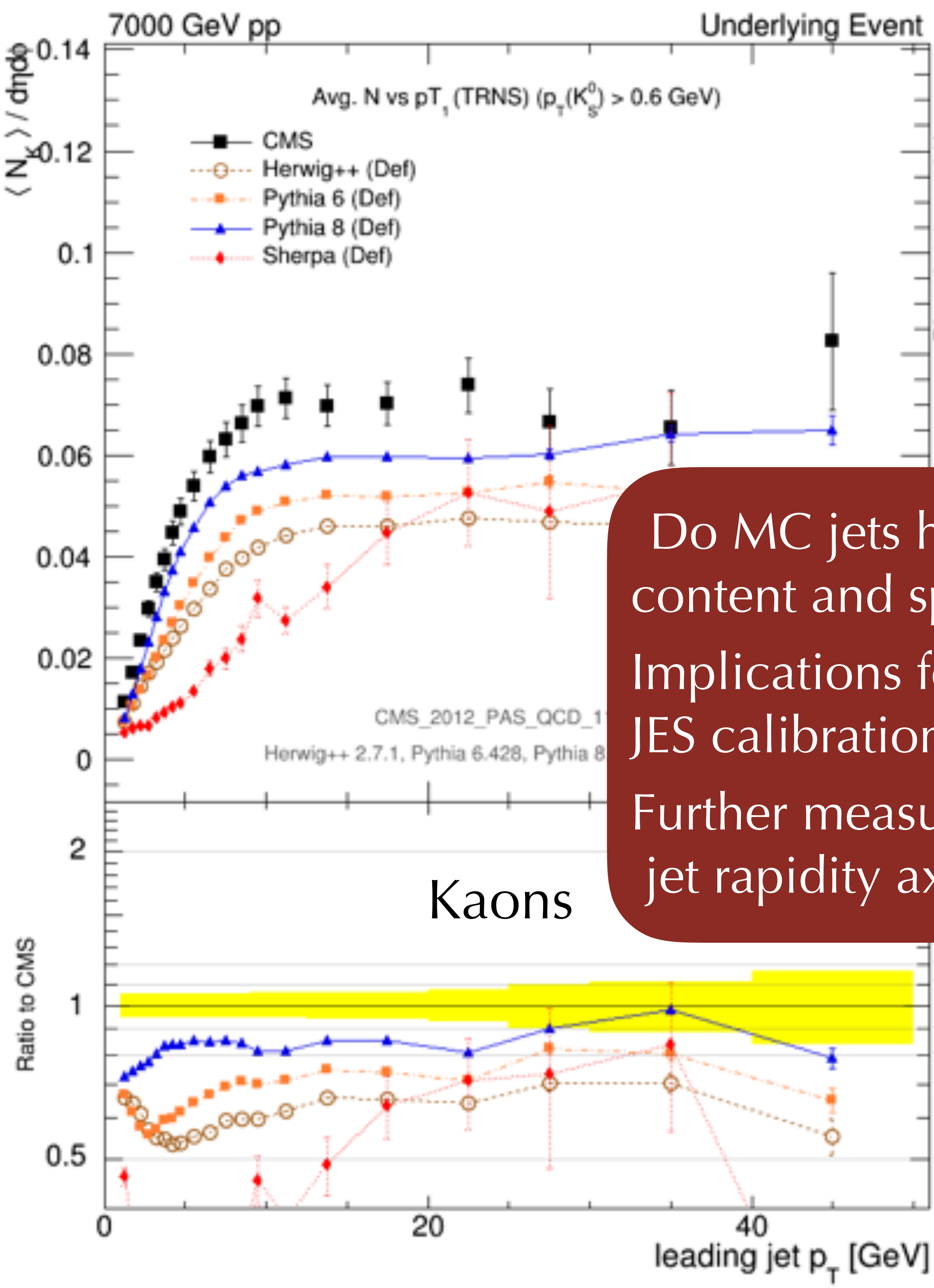


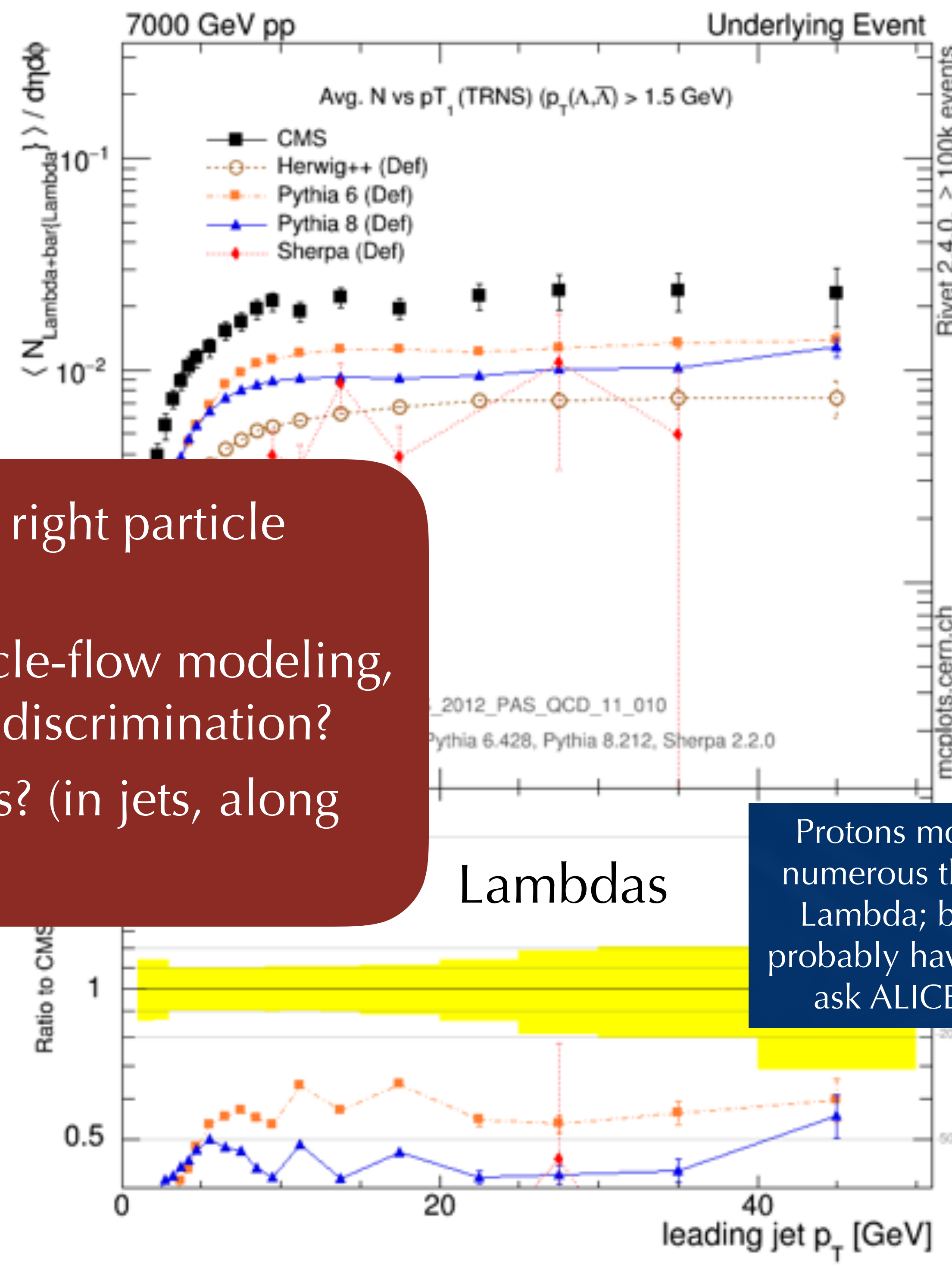
(+ Several measurements by ALICE, LHCb)

CMS: Strangeness in the Underlying Event

Plots from mcplots.cern.ch

Effect also present in UE *(note: effect enhanced by p_T cuts, cf spectra)*





Do MC jets have the right particle content and spectra?

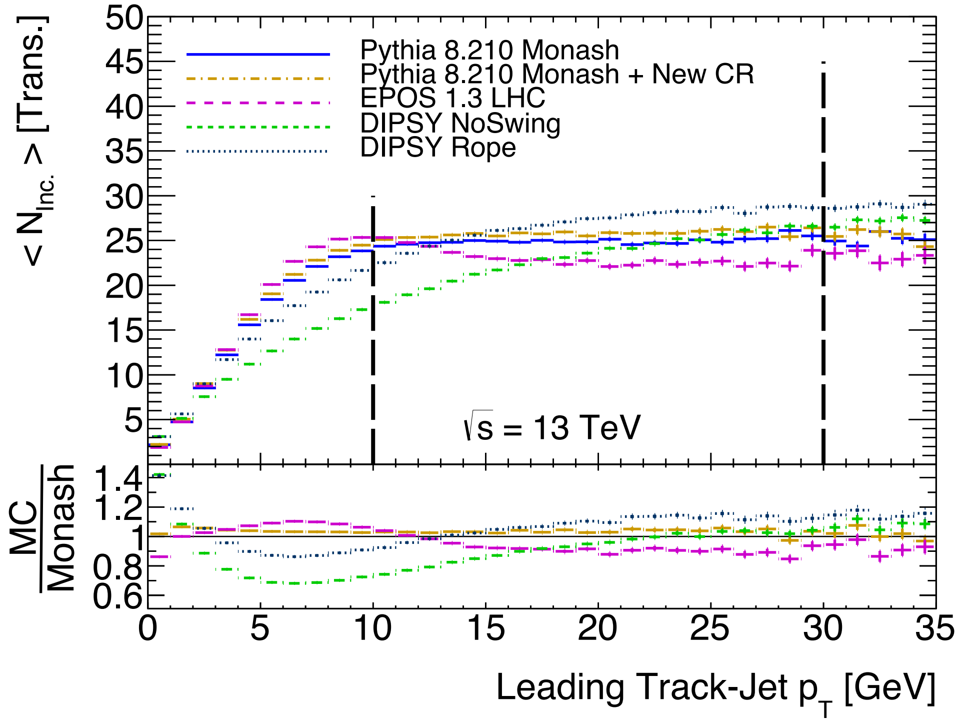
Implications for particle-flow modeling, JES calibrations, Q/G discrimination?

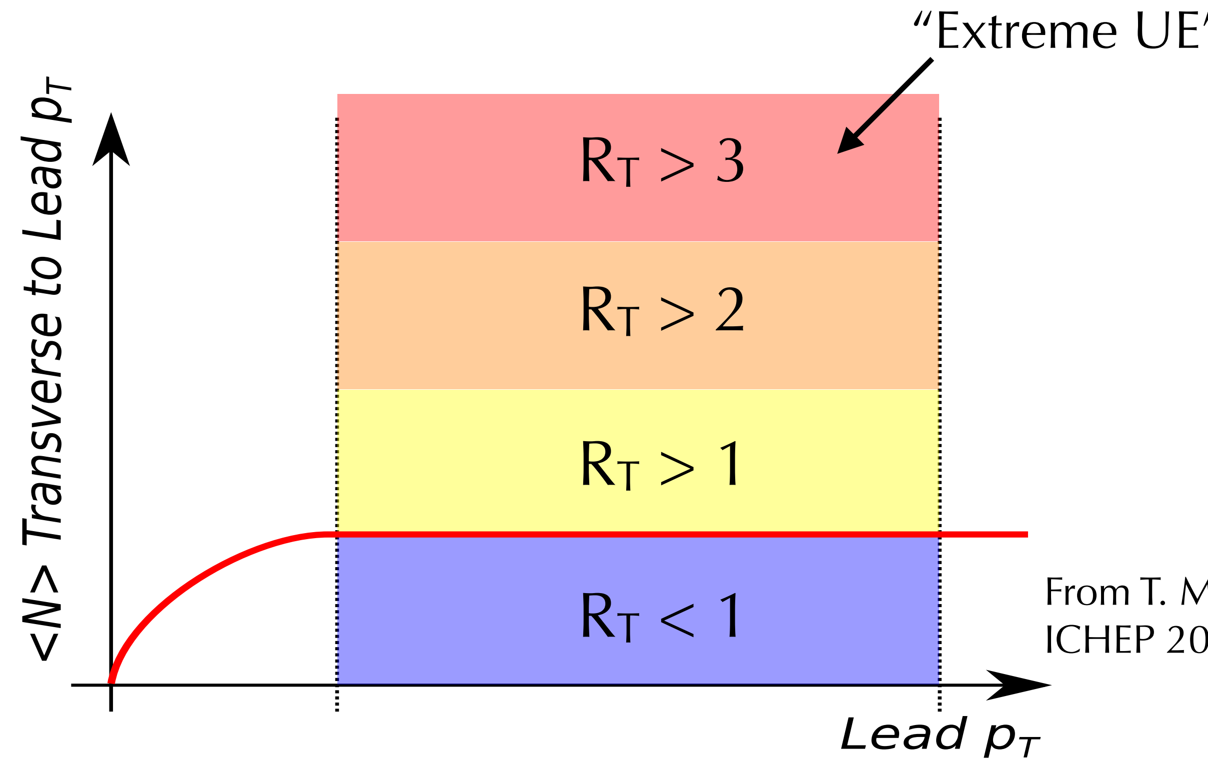
Further measurements? (in jets, along jet rapidity axis, …)

Protons more numerous than Lambda; but probably have to ask ALICE?

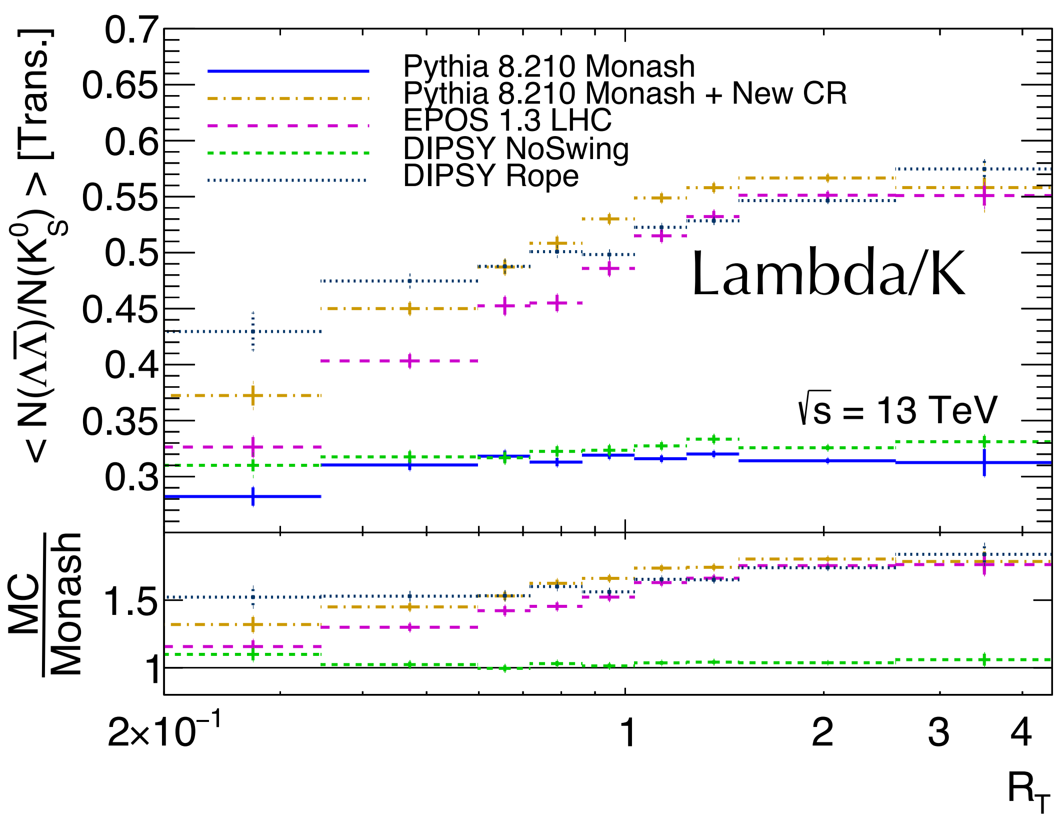
→ Extensions of CMS UE Study?

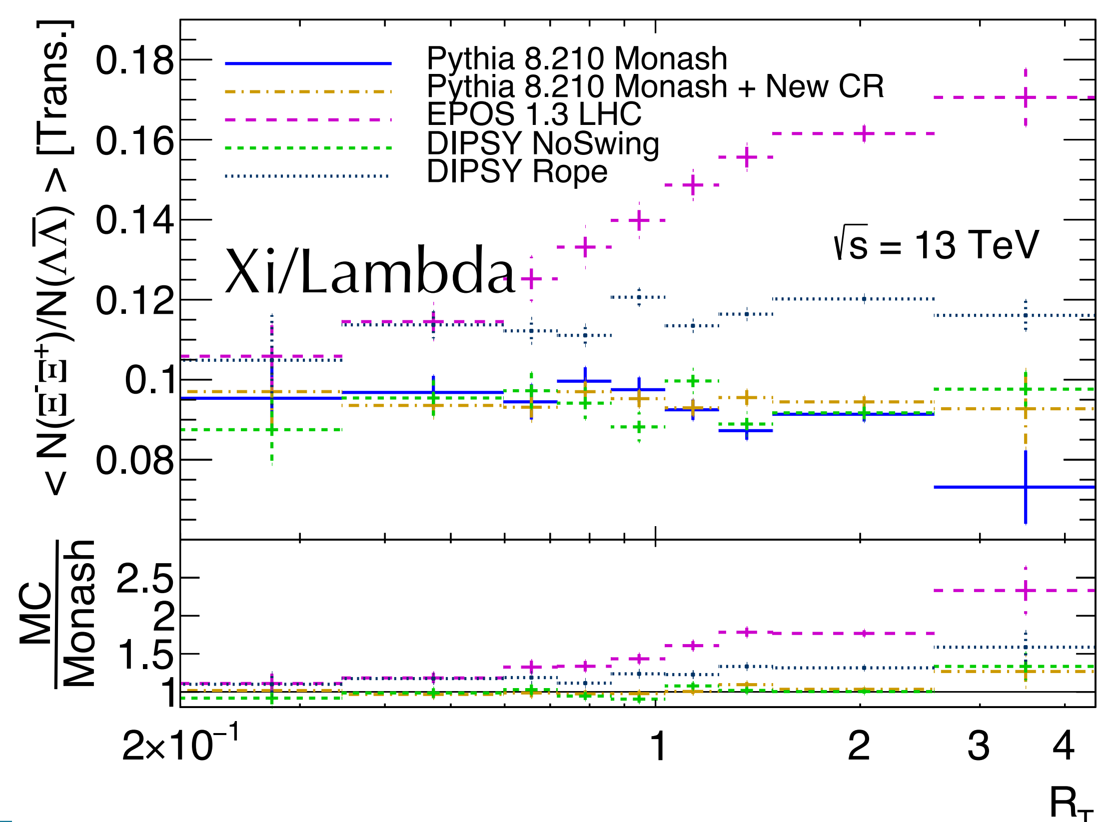
Probing Collective Effects in Hadronisation with the Extremes of the Underlying Event
T. Martin, P. Skands, S. Farrington, Eur.Phys.J. C76 (2016) no.5, 299



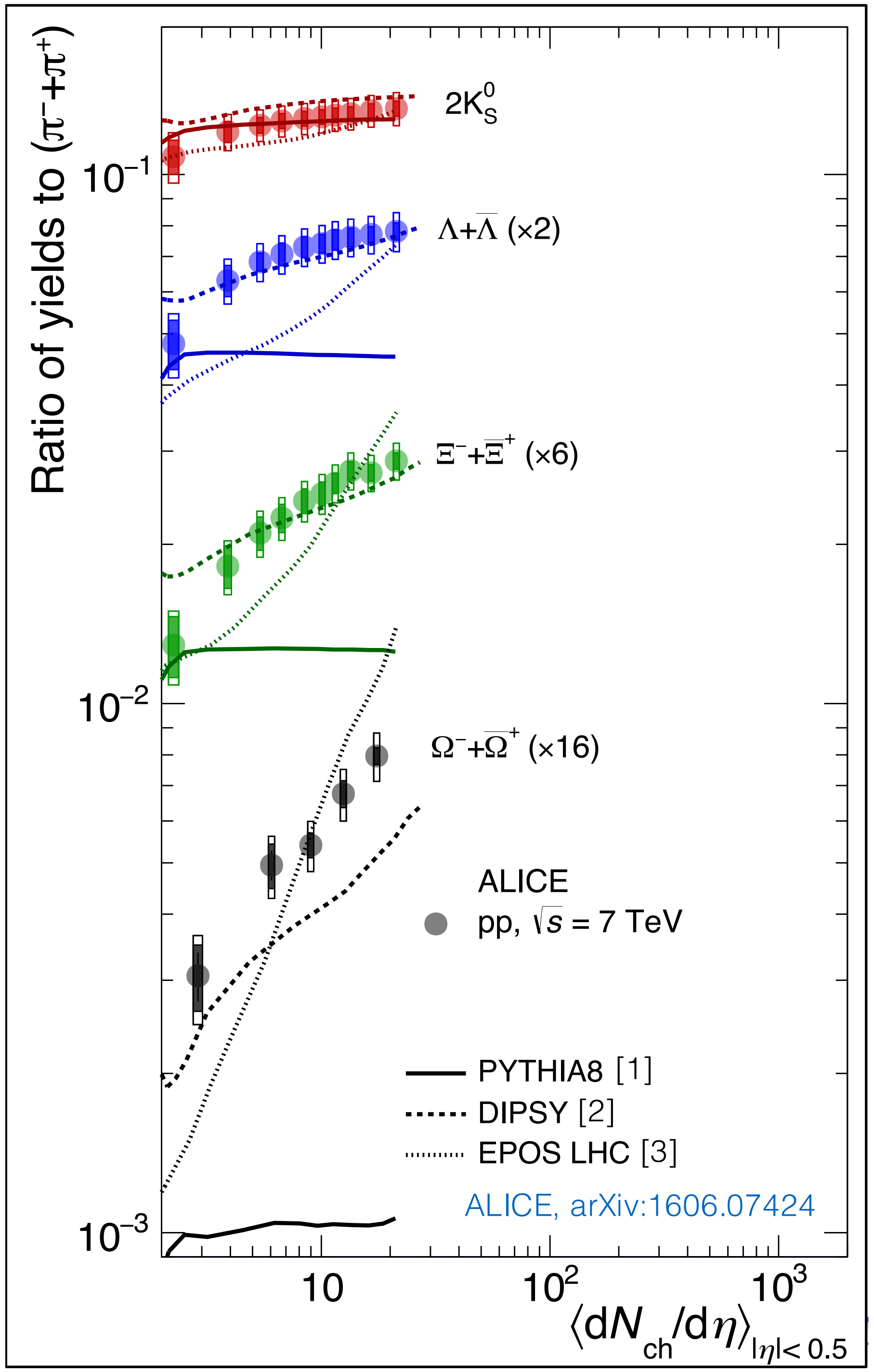


From T. Martin, ICHEP 2016





The main ICHEP 2016 "Discovery" ?



D.D. Chinellato – 38th International Conference on High Energy Physics

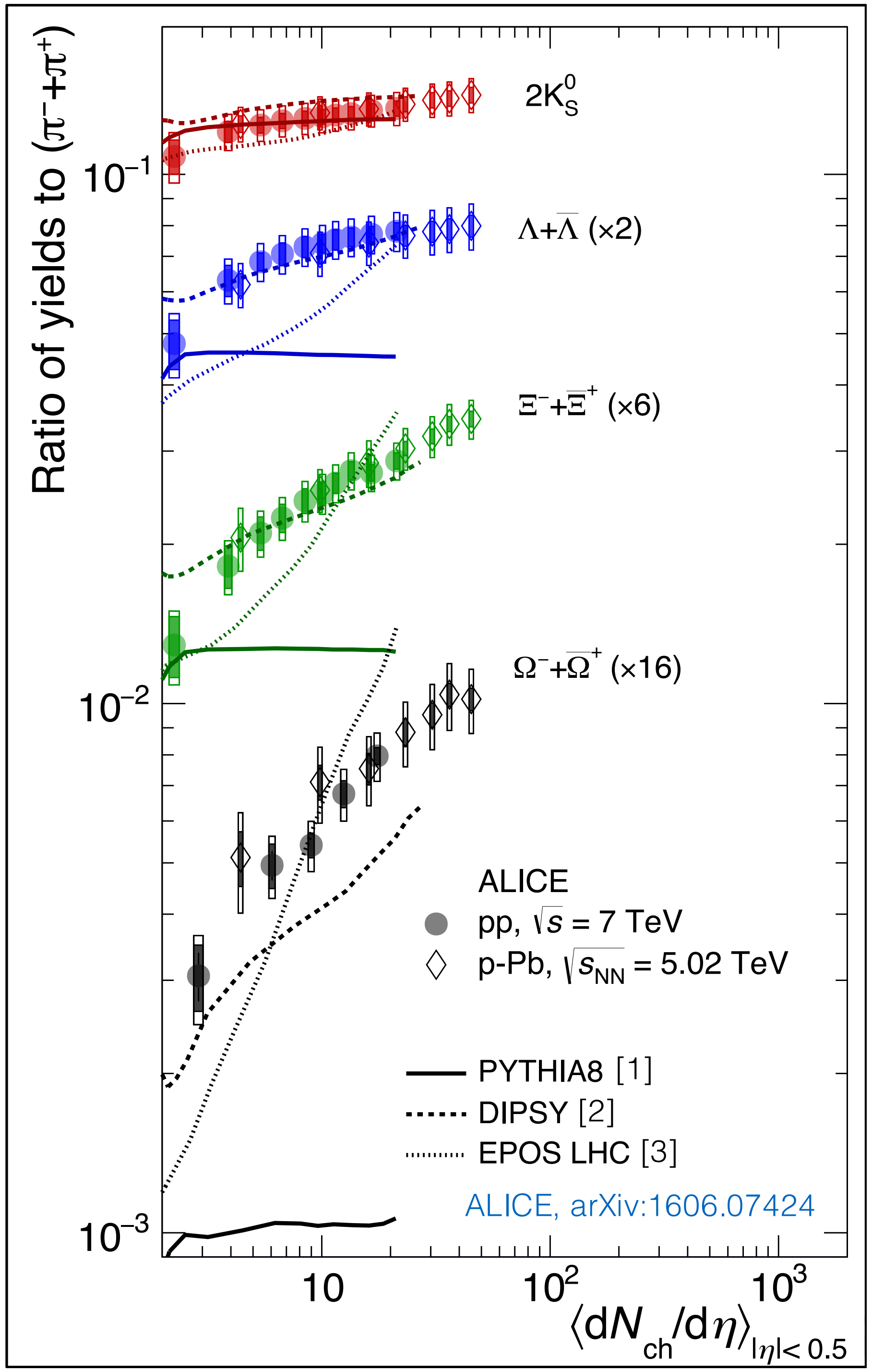
A clear enhancement of strangeness with (pp) event multiplicity is observed

- Especially for multi-strange baryons
- No corresponding enhancement for protons → this really must be a strangeness effect
- Cross-check measurements of the phi meson are now underway

Jet universality: jets at LHC modelled the same as jets at LEP

- Flat line ! (cf PYTHIA)
- DIPSY includes "colour ropes"
- EPOS includes hydrodynamic "core"

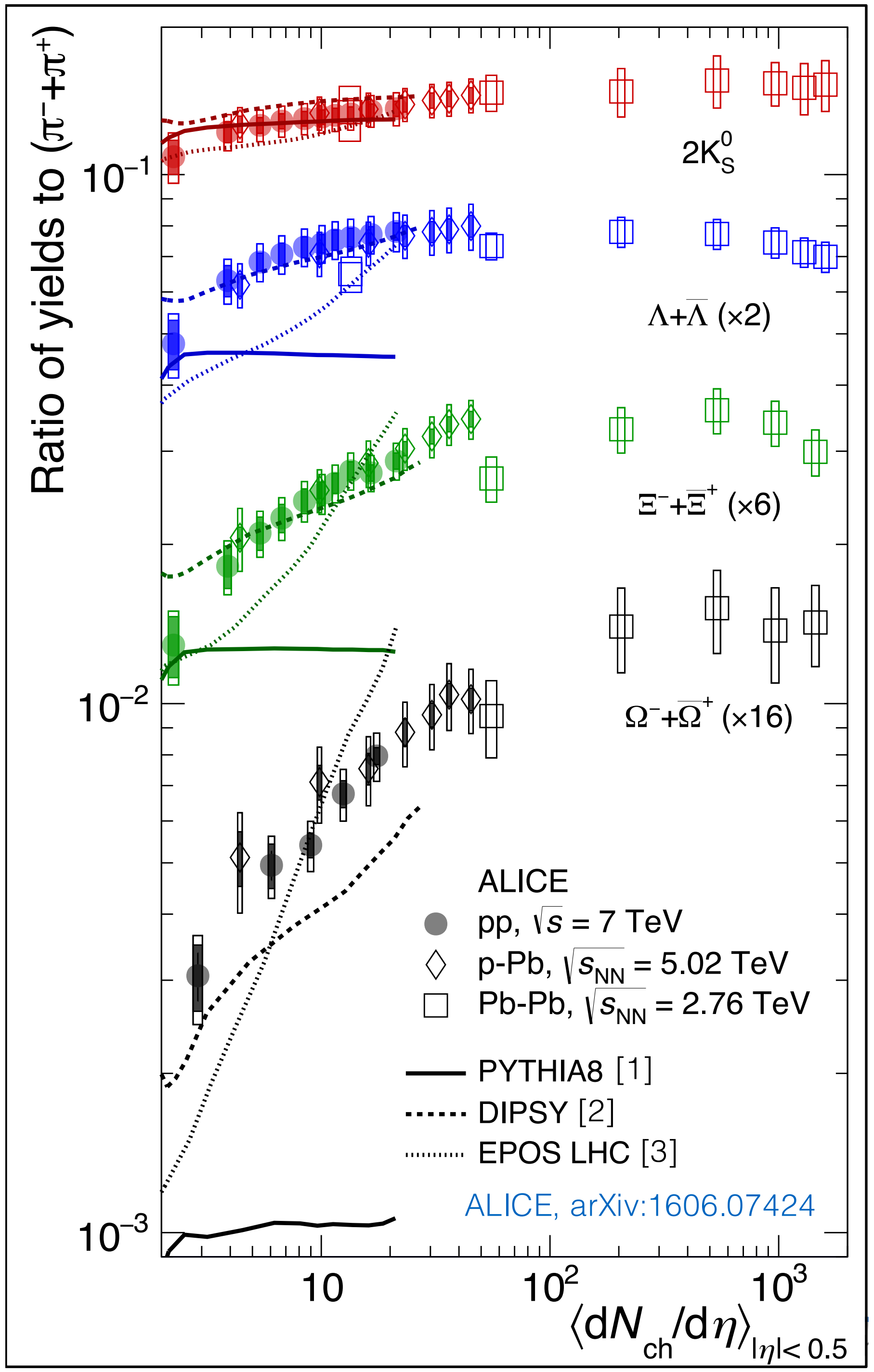
The Plot Thickens



D.D. Chinellato – 38th International Conference on High Energy Physics

Looks like the effect, whatever it is, continues smoothly into p-Pb

The Plot Thickens



D.D. Chinellato – 38th International Conference on High Energy Physics

Looks like the effect, whatever it is, continues smoothly into p-Pb

… and into Pb-Pb!

Looks like jet universality and hadronisation in pp is up for revision.

Is it thermal? Stringy? Both?

Collective? Flowy? …

High-p_T processes (like dijets, Drell-Yan, top), should correspond to (very) high-multiplicity.

Do you see this?

In top jets? the UE? the W jets?