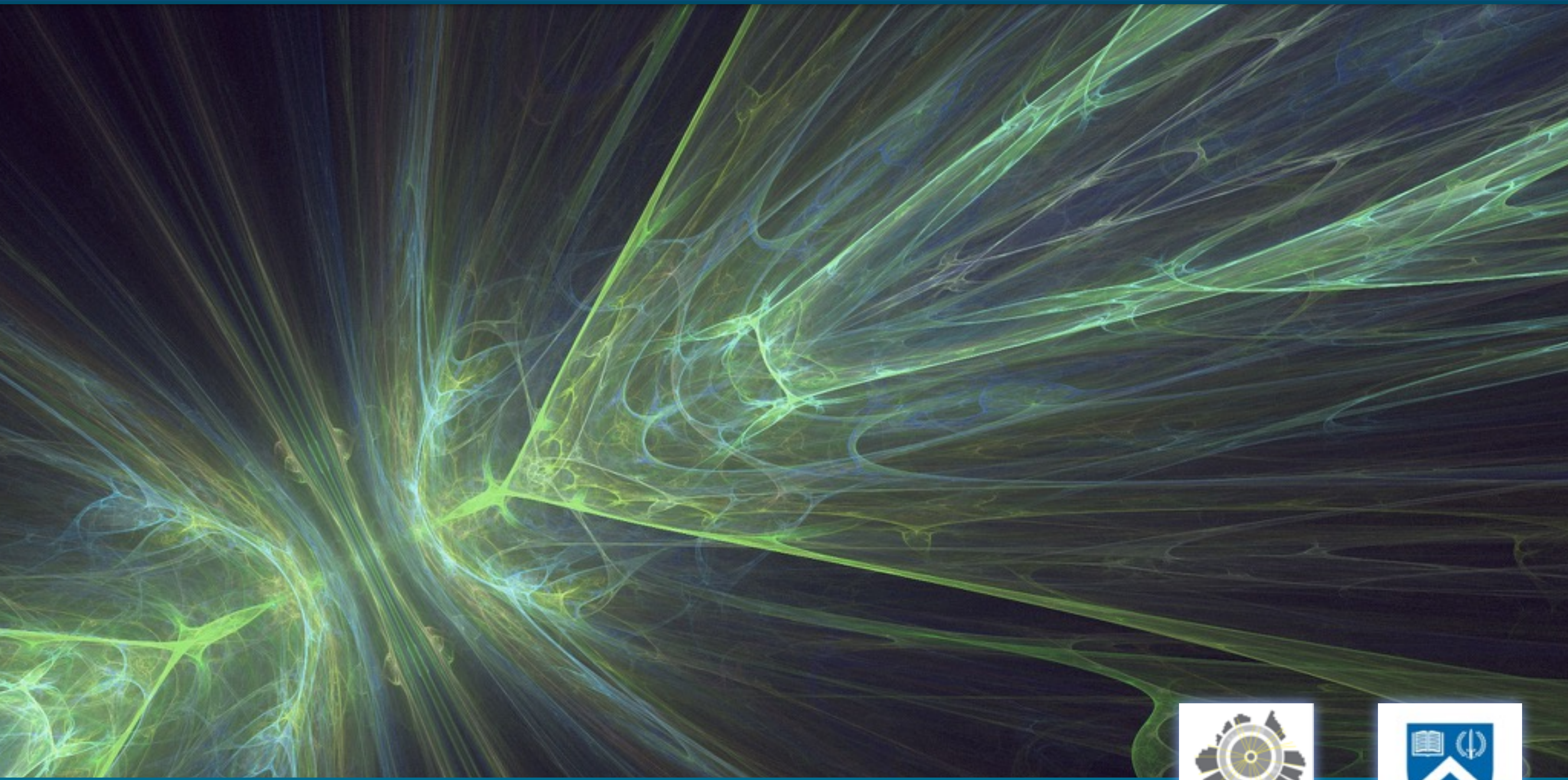
Understanding Hadronisation at PP Colliders

Peter Skands (Monash University)



Fermilab LPC - Topic of the Week
August 2016

Monte Carlos and Fragmentation

Monte Carlo generators aim to give **fully exclusive descriptions of collider final states** - within and beyond the Standard Model

Including effects of initial- and final-state radiation (ISR & FSR showers)

+ (Sequential) Resonance decays (top quarks, Z/W/H bosons, & BSM)

+ Soft physics: Underlying Event, Hadronisation, Decays, Beam Remnants

Explicit modelling of QCD dynamics ⟷ comparison to measurements

E.g., MC models were crucial to establish "string effect" in early 80s

Extensively used to design/optimise analyses (& planning future ones)

Study observables, sensitivities, effects of cuts, detector efficiencies, derive correction factors, extract fundamental parameters, cross sections, …

Lund String Model has probably been the most successful hadronisation model over the last 30 years.

This talk: it is beginning to show some interesting failures at LHC

Impact on hadronisation corrections for high-p_T analyses?

See, e.g., MCnet review arXiv:1101.2599, or TASI lectures arXiv:1207.2389

QCD is more than a (fixed-order) expansion in α_s

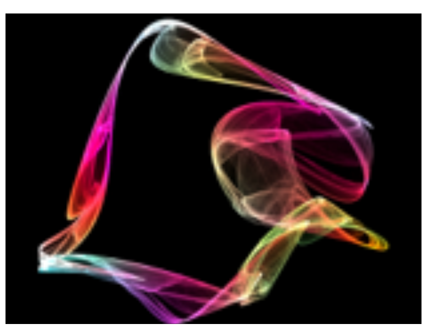
Challenges Beyond Fixed Order: *"Emergent Phenomena"*

Fractal Structures: scale Invariance of massless Lagrangian → jets-within-jets-within-jets (& loops-within-loops-within-loops)

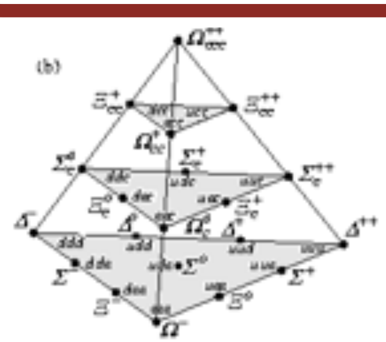
Confinement (win $1,000,000 if you can prove)

most of my research

Jets (perturbative QCD, initial- and final-state radiation)
⟷ QFT amplitude structures, factorisation & unitarity
⟷ Precision jet (structure) studies, calibrations.



Strings (strong gluon fields) ⟷ quantum-classical correspondence. String physics. String breaks. Dynamics of hadronisation phase transition. Hadronisation corrections.

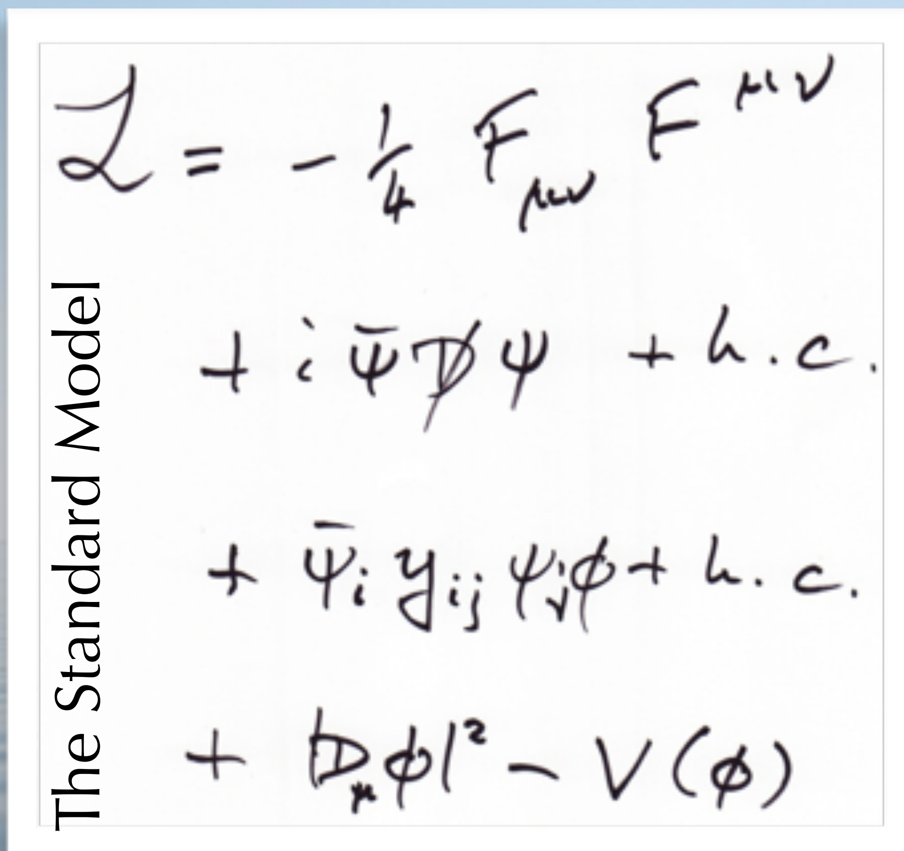


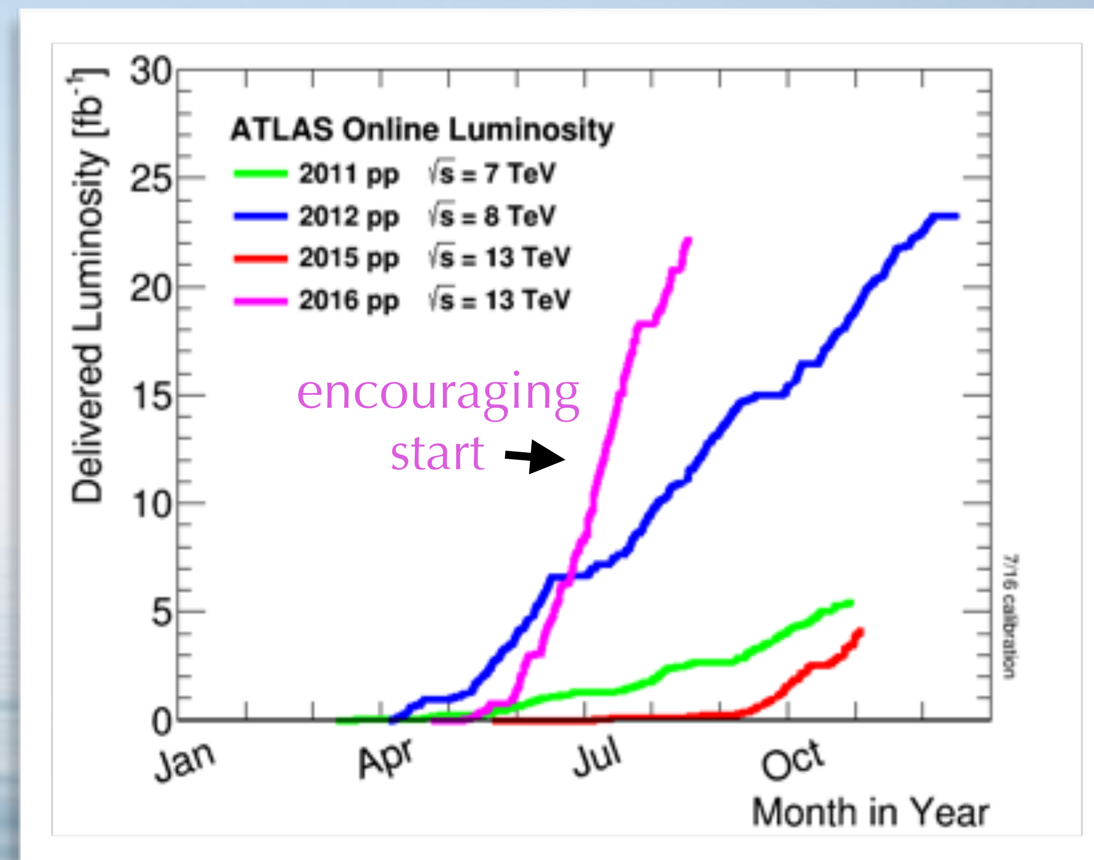
Hadrons ⟷ Spectroscopy (incl excited and exotic states), lattice QCD, (rare) decays, mixing, light nuclei. Hadron beams → multiparton interactions, diffraction, …

Ulterior Motives for Studying QCD

There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy

Shakespeare, Hamlet.





We strongly suspect there is more to (particle) physics

… but are still looking for *deviations* from the Standard Model

Accurate modelling of QCD → **improve searches & precision**

The Phenomenology Pipeline

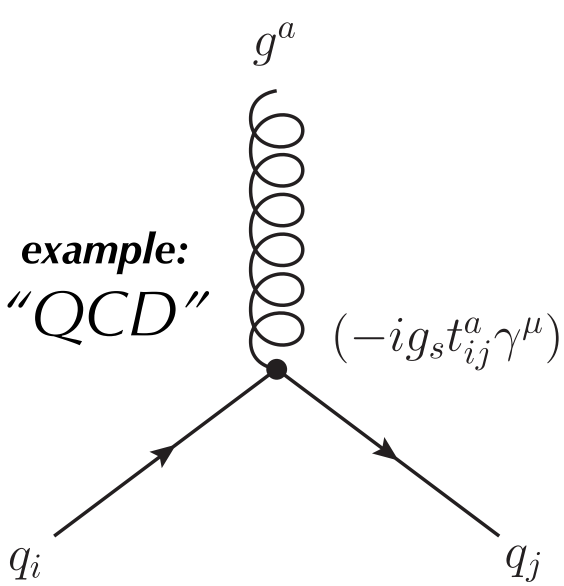
The Pipeline looks something like this:

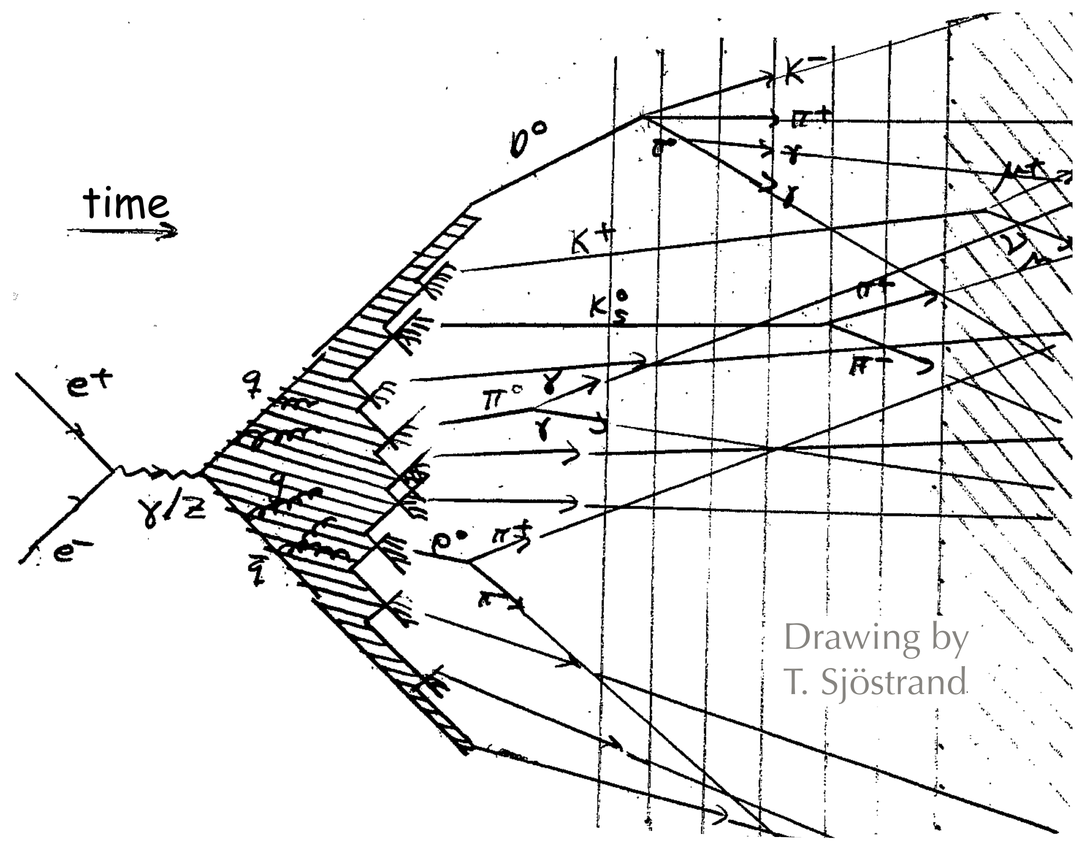
THEORY → Model → **PHENOMENOLOGY** (Calculations, Observables) → **EXPERIMENT**

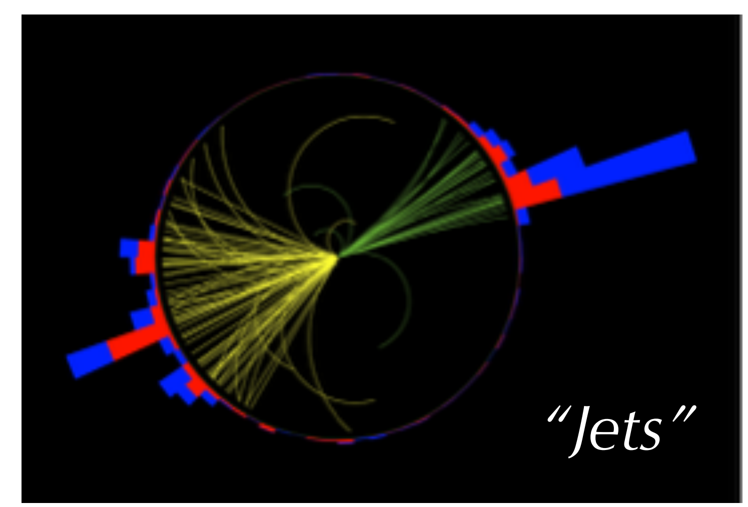
Planning
Design
R&D
Hardware
Triggers
…

Analyses

example:
"QCD"







Corrections
Systematics

Exclusions
Hints
Evidence
Discoveries
Surprises

← **INTERPRETATION** ← Measurements

Validate/Falsify Models
Constrain Free Parameters

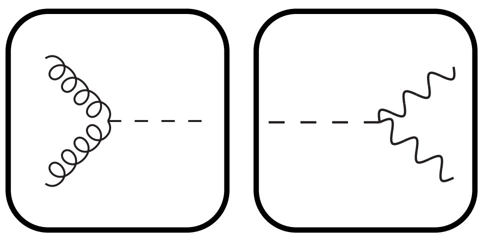
Statistical Tests

Monte Carlo Event Generators

Factorization → Split the problem into many (nested) pieces

+ Quantum mechanics → Probabilities → Random Numbers

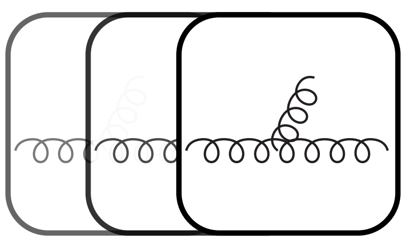
$$\mathcal{P}_{\mathrm{event}} = \mathcal{P}_{\mathrm{hard}} \otimes \mathcal{P}_{\mathrm{dec}} \otimes \mathcal{P}_{\mathrm{ISR}} \otimes \mathcal{P}_{\mathrm{FSR}} \otimes \mathcal{P}_{\mathrm{MPI}} \otimes \mathcal{P}_{\mathrm{Had}} \otimes \ldots$$



Hard Process & Decays:

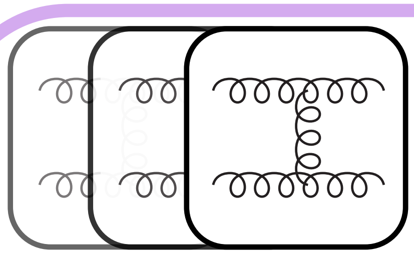
Use process-specific (N)LO matrix elements

→ Sets "hard" resolution scale for process: Q_{MAX}



ISR & FSR (Initial & Final-State Radiation):

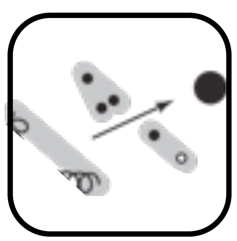
Universal DGLAP equations → differential evolution, dP/dQ^2, as function of resolution scale; run from Q_{MAX} to $Q_{\mathrm{Confinement}} \sim 1$ GeV



MPI (Multi-Parton Interactions)

Additional (soft) parton-parton interactions: LO matrix elements

→ Additional (soft) "Underlying-Event" activity



Hadronization

Non-perturbative model of color-singlet parton systems → hadrons

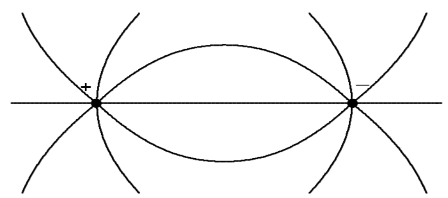
Hadronisation – What do we know?

Quark-Antiquark Potential

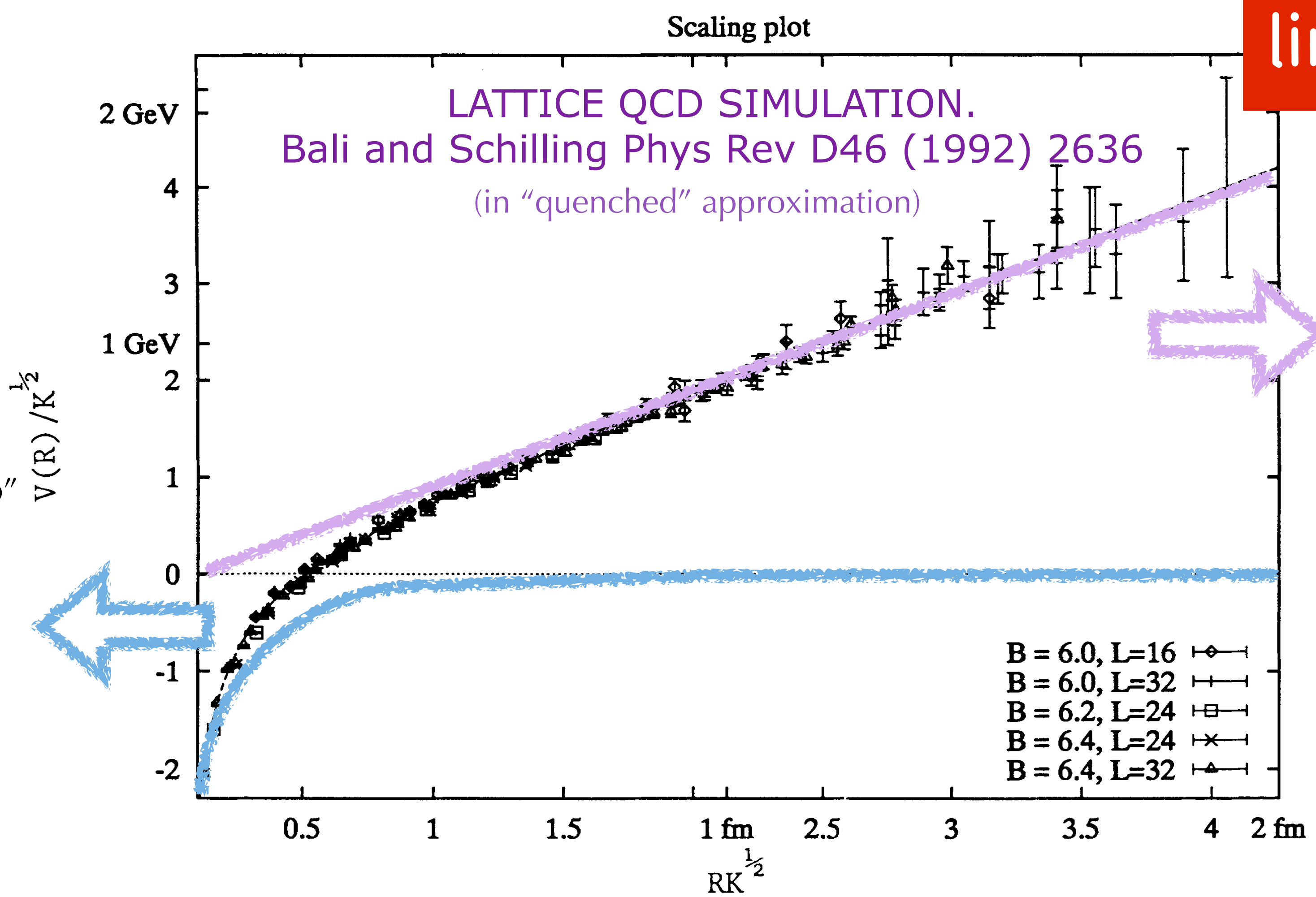
As function of separation distance

What physical system has a linear potential?

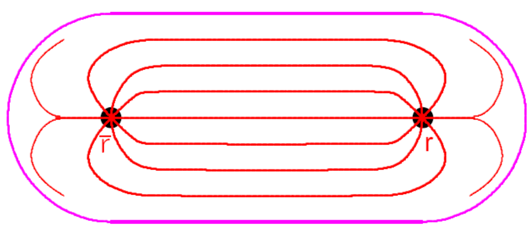
Short Distances ~ "Coulomb"



"Free" Partons



Long Distances ~ Linear Potential



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

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

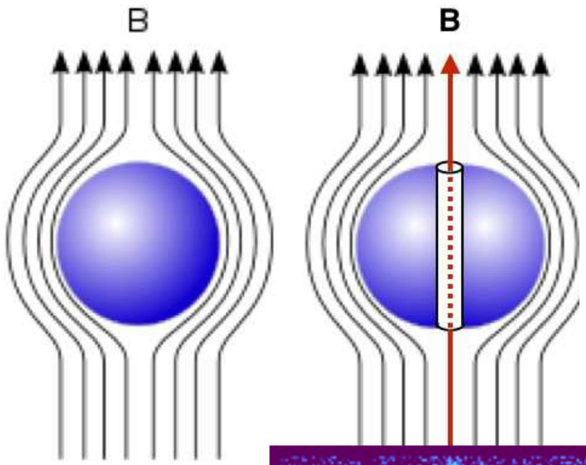
~ Force required to lift a 16-ton truck

A Brief History of Vortex Lines

1911: Discover of superconductivity (K. Onnes)

1933: Discovery of **flux expulsion** (Meissner & Ochsenfeld)

Penetration depth : λ (distance over which field decays by 1/e)



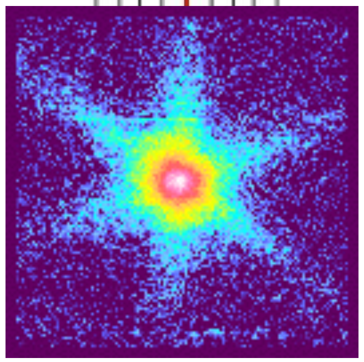
1957: **Vortex Lines** (Abrikosov) (in Type II SC)

Swirling supercurrents produce a non-SC "core"

Core size : ξ (aka "coherence length"; exp decay outside core)

Flux Quantisation: each core carries a single unit of flux

Type II if core size small $\xi < \sqrt{2}\lambda$ (otherwise Type I)



1960^{s} - 1970^{s}: "Dual models" for strong force

Regge Theory: massless endpoints on rotating relativistic strings

Nielsen-Olesen: Higgs-type Lagrangians → vortex lines ⟷ Nambu strings

Advent of SM (QCD) → string models refocus on gravity (& EW cosmic strings)

1974: Artru & Mennessier, "String model and multiproduction"

Ca 1980: Andersson, Gustafson, Sjöstrand, *et al*: **the Lund String Model**

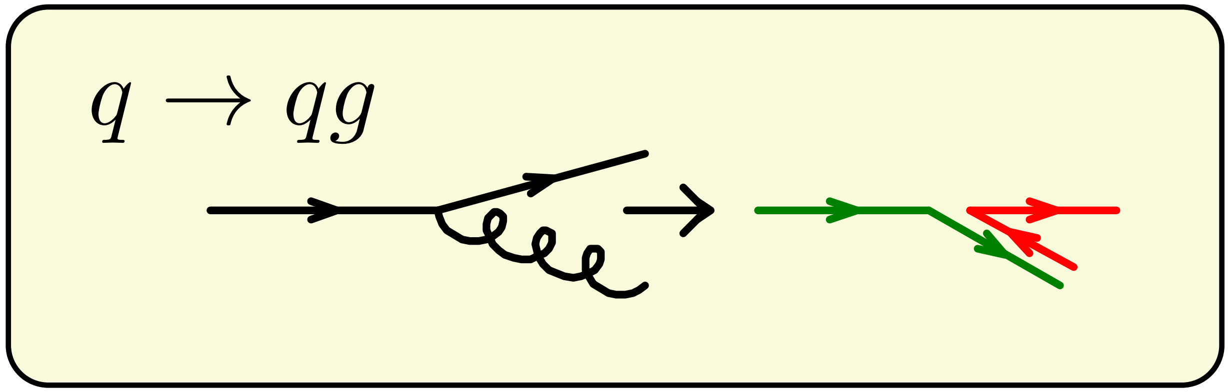
Which Charges? Colour Flow

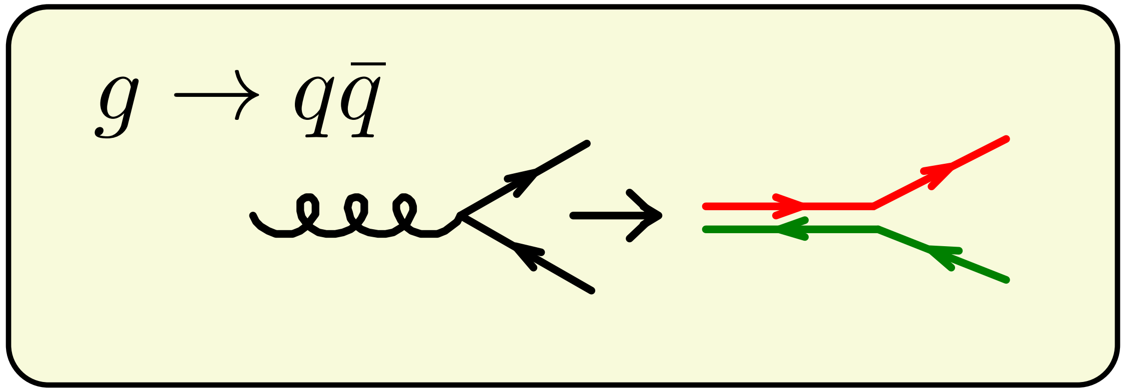
After the parton shower finishes, there can be lots of partons, $\mathcal{O}$(10-100). The main question is therefore:

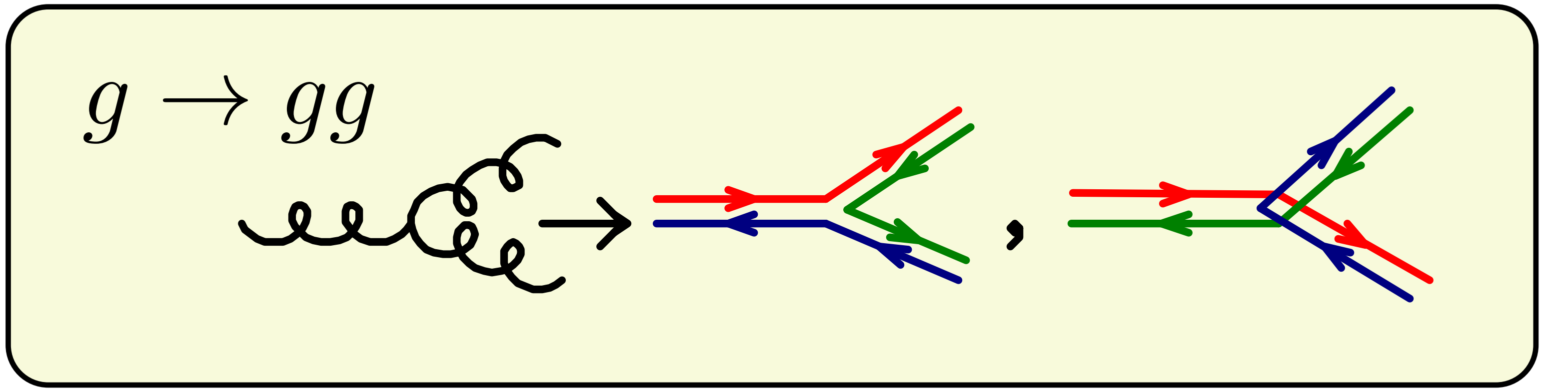
Between which partons do confining potentials arise?

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.



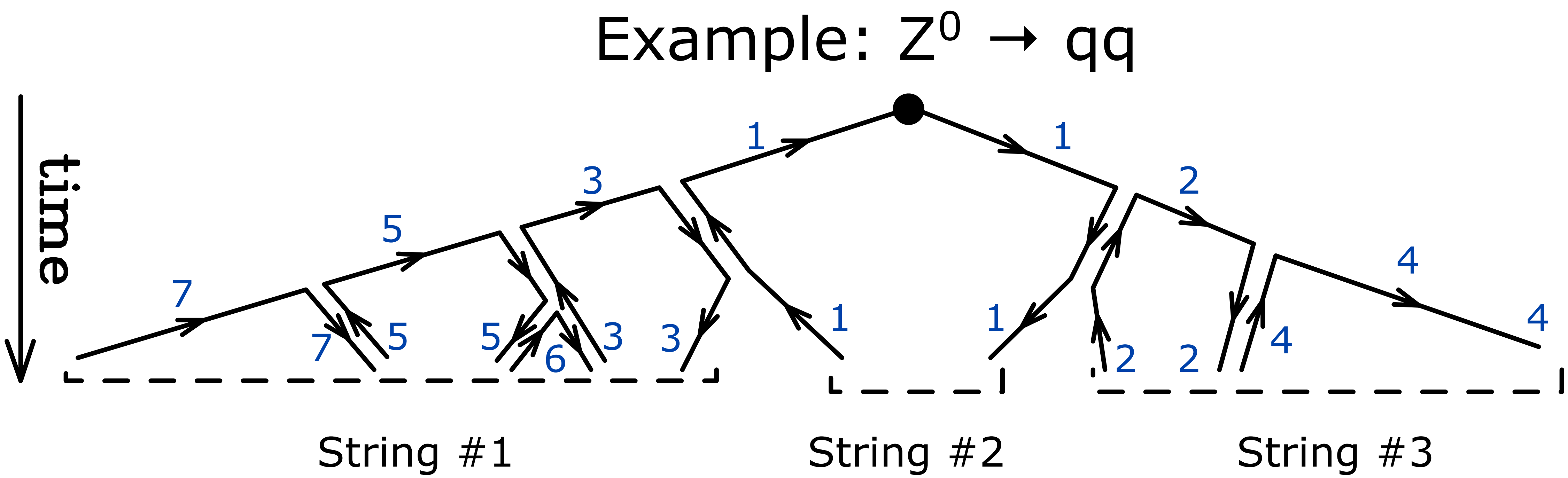




Illustrations from: Nason & Skands, PDG Review on *MC Event Generators*, 2014

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

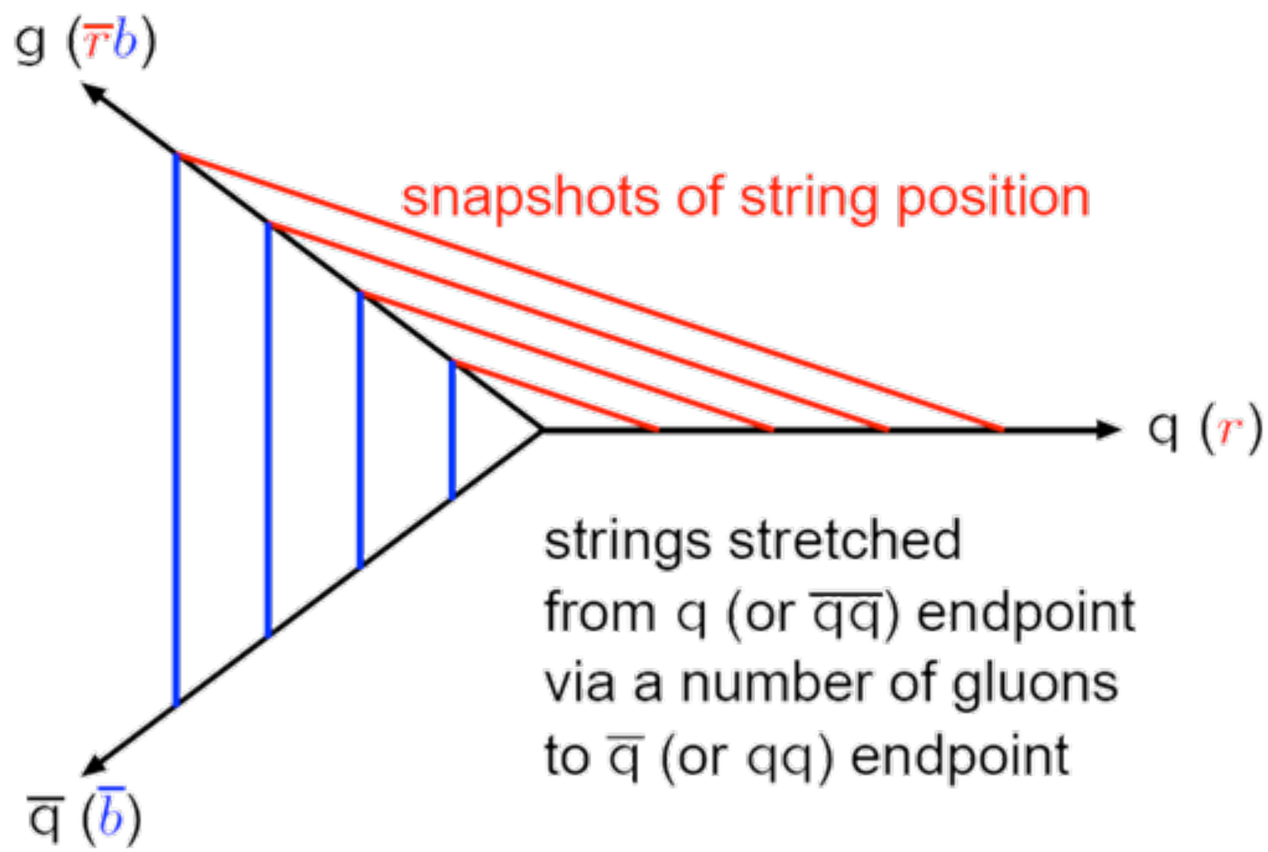
(The trouble at LHC: MPI & ISR → many such systems; overlapping)

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**

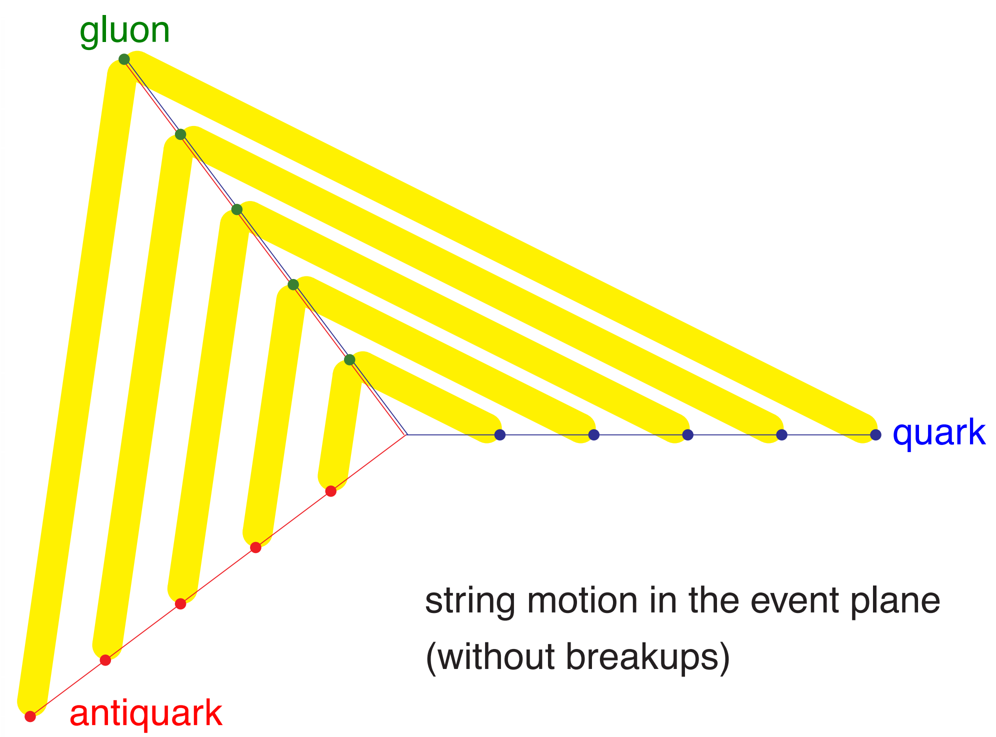
Simple space-time picture

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

Differences Between Quark and Gluon Jets

Example of Recent Studies

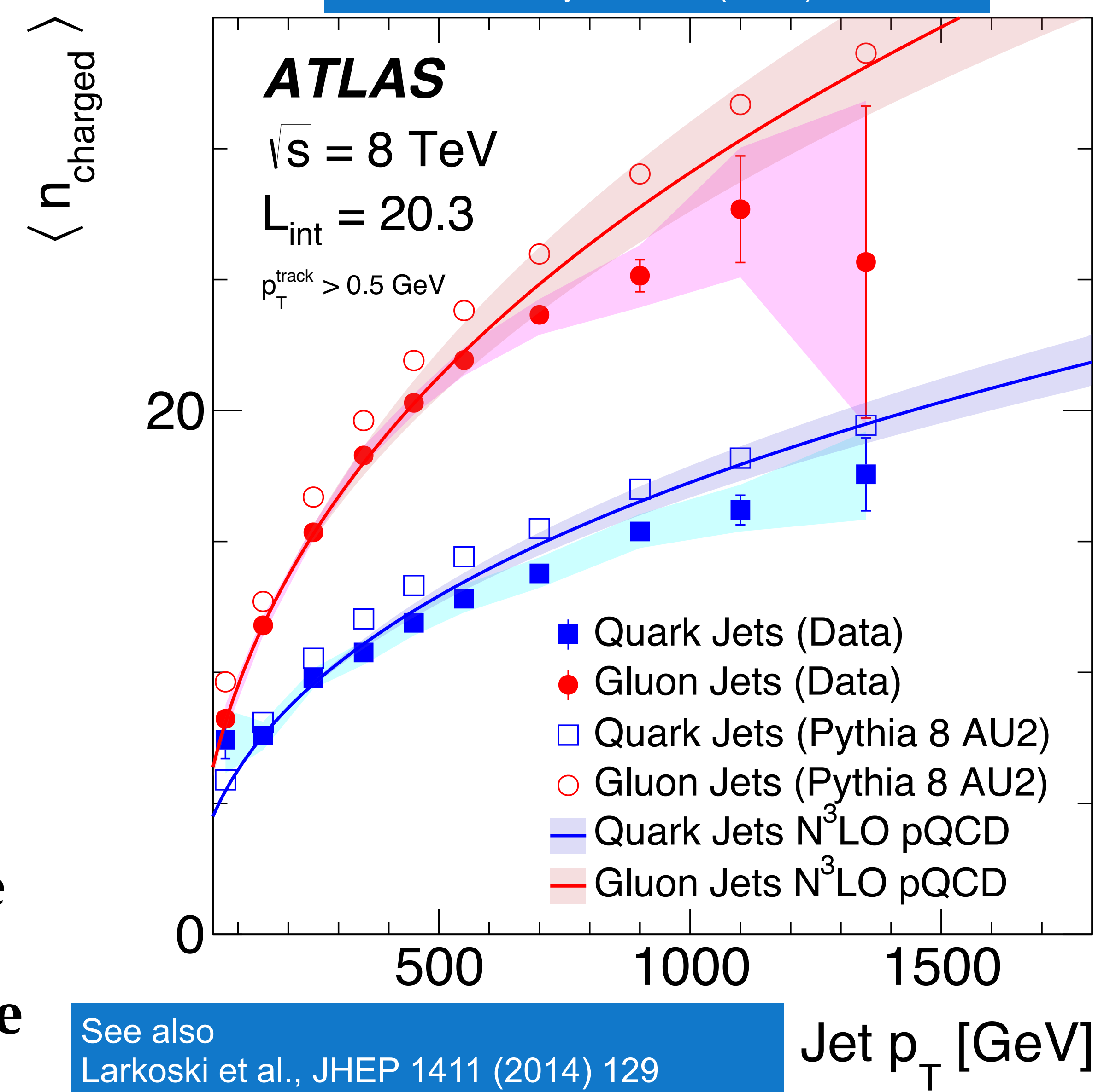
Gluon connected to two string pieces



Each quark connected to one string piece

→ expect factor 2 ~ C_A/C_F larger particle multiplicity in gluon jets vs quark jets

ATLAS, Eur.Phys.J. C76 (2016) no.6, 322



See also
Larkoski et al., JHEP 1411 (2014) 129
Thaler et al., Les Houches, arXiv:1605.04692

Can be important for discriminating new-physics signals (decays to quarks vs decays to gluons, vs composition of background and bremsstrahlung combinatorics)

The Effects of Hadronisation

Generally, expect few-hundred MeV shifts by hadronisation

Corrections to IR safe observables are "power corrections"

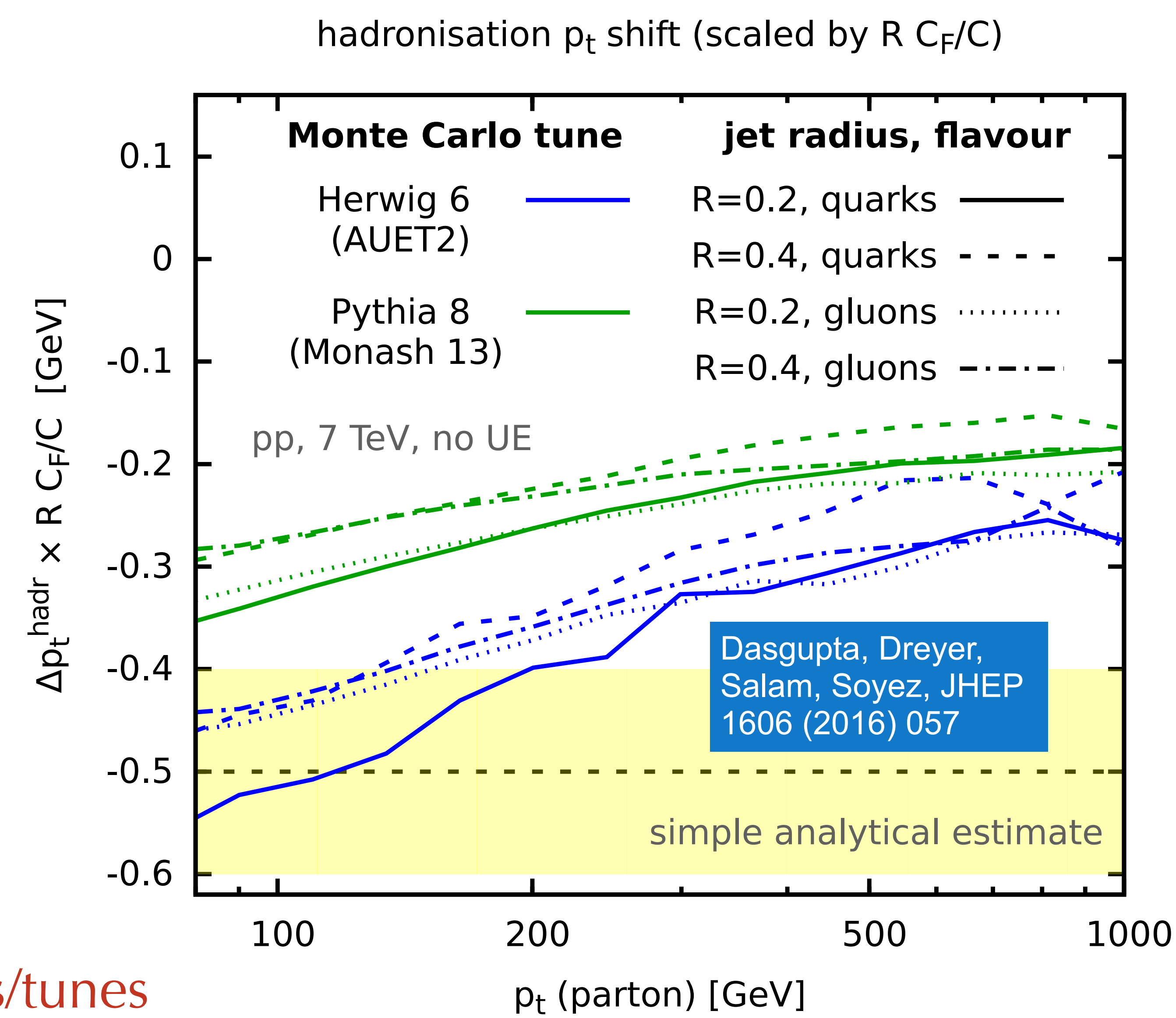
$$\propto \Lambda^2_{\rm QCD}/Q^2_{\rm OBS}$$

Corrections for jets of radius $R = \Delta\eta \times \Delta\phi$

$$\propto 1/R$$

See
Korchemsky, Sterman, NPB 437 (1995) 415
Seymour, NPB 513 (1998) 269
Dasgupta, Magnea, Salam, JHEP 0802 (2008) 055

Simple analytical estimate
→ ~ 0.5 GeV / R correction from hadronisation
(scaled by colour factor)



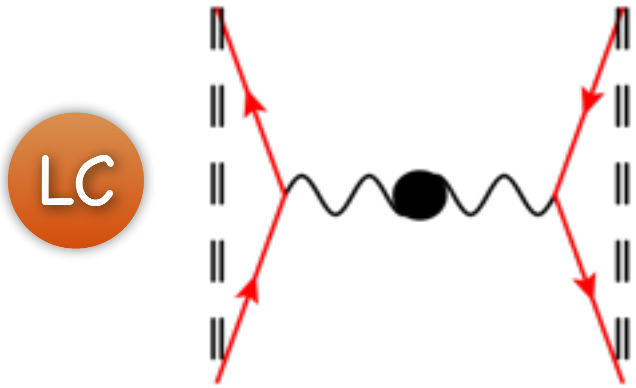
Significant differences between codes/tunes
→ **important to pin down with precise QCD hadronisation measurements at LHC**

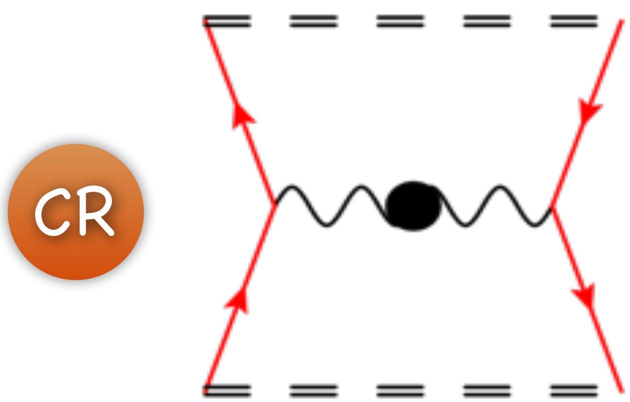
LES HOUCHES STUDY (ARXIV:1605.04692): Q/G CAN BE HIGHLY AFFECTED BY COLOUR RECONNECTIONS

Colour Confusion ?

Next-to-simplest: 2 string systems

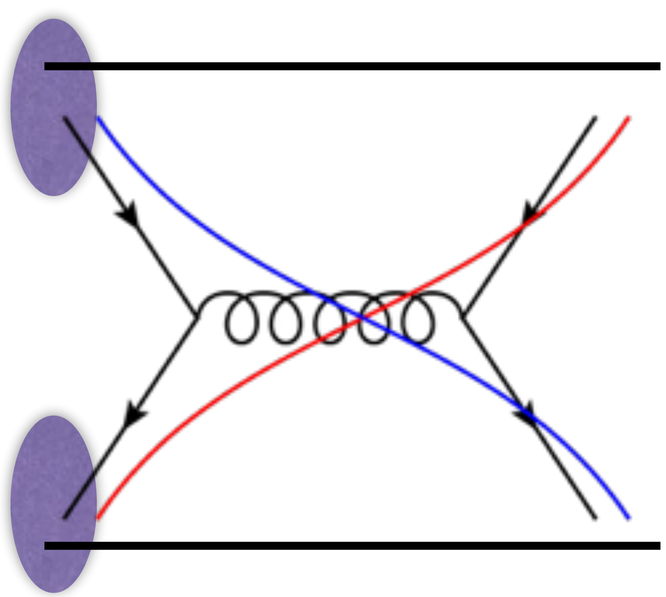
- Several studies at LEP2 (ee → WW → 4 jets)
  - CR implied a non-perturbative uncertainty on the W mass measurement, $\Delta M_W \sim 40$ MeV
- CR strength best fit ~ 10% ~ $1/N_C^2$
- But in WW, overlaps are expected to be suppressed by kinematics, and there are “only” two strings;
- In pp, MPI can create (many) more … ?



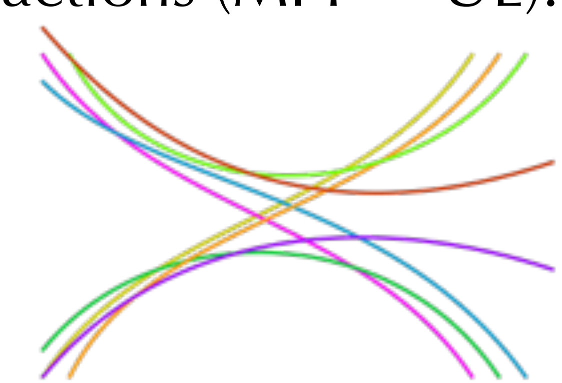


Proton-Proton (LHC)

- A lot more colour kicked around (& also colour in initial state)
- Include “Beam Remnants”
- Still might look relatively simple, to begin with



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

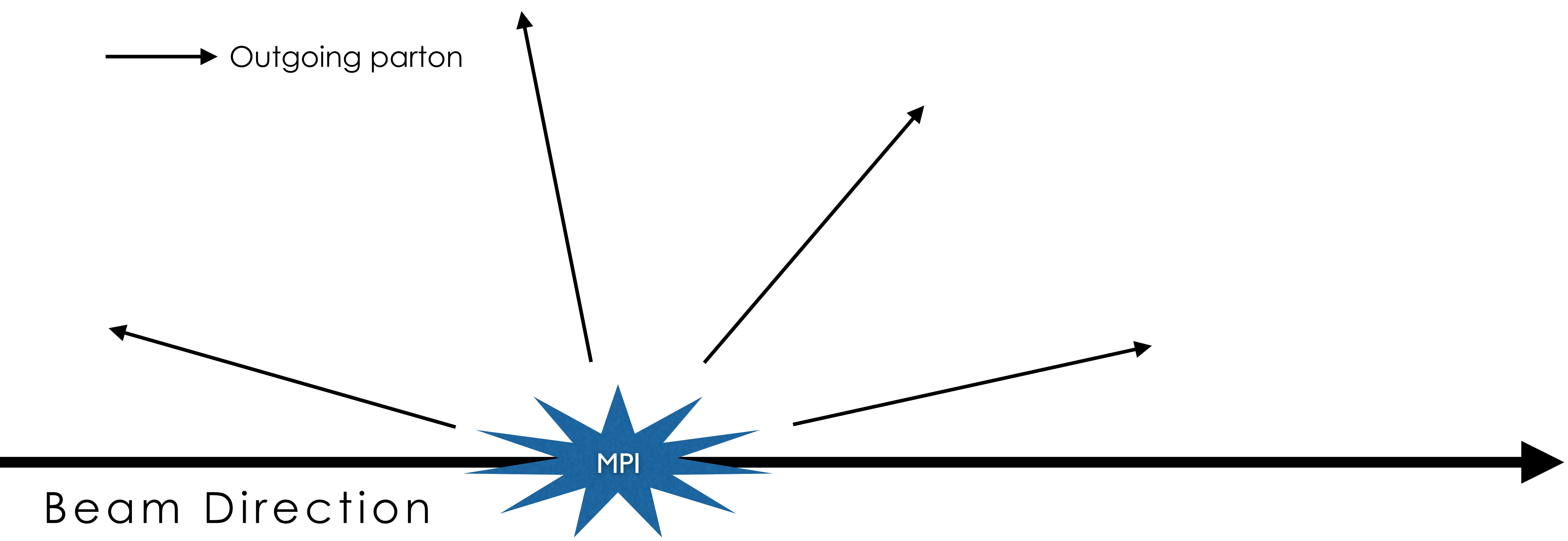
(+baryon beam remnants → “string junctions”)

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

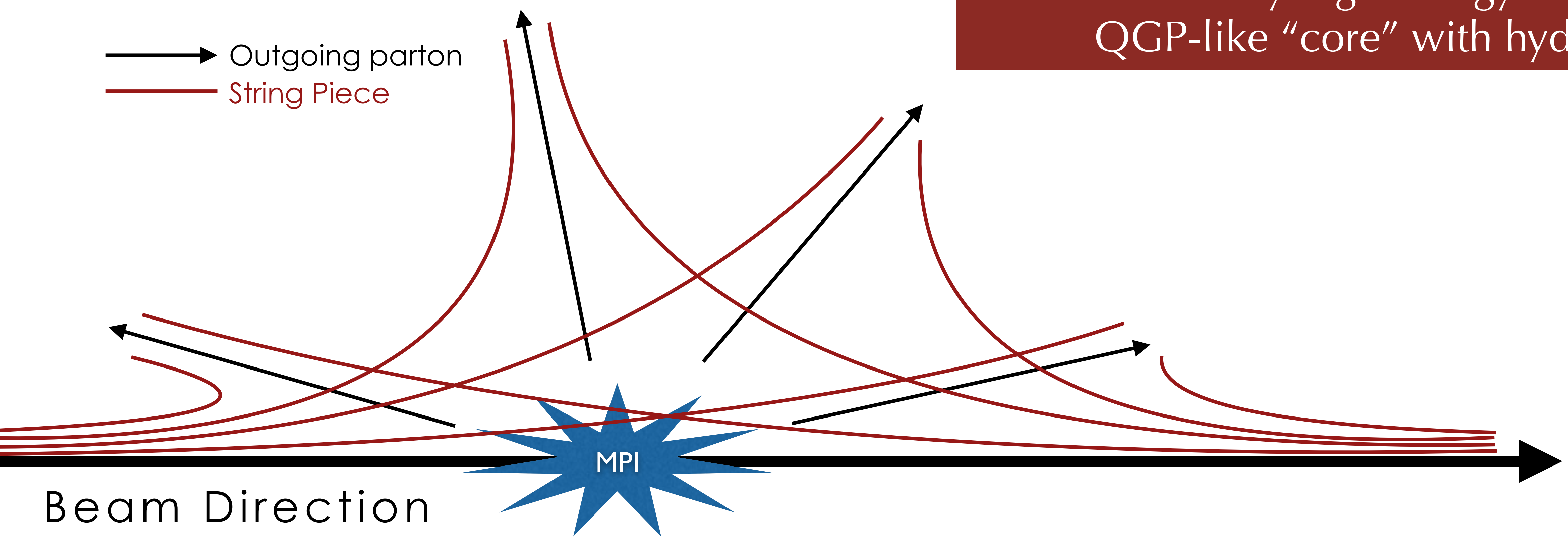


Colour: What's the Problem?

(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

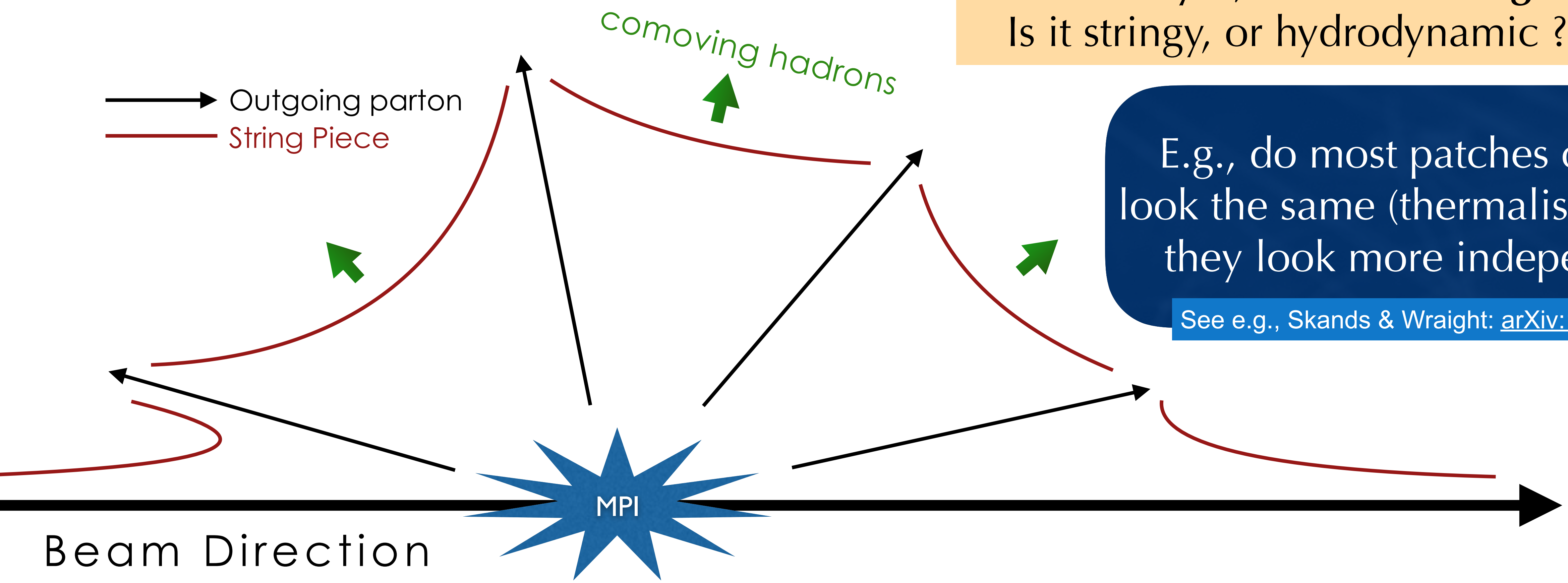
Colour Reconnections

(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

Highly interesting theory questions now.
Is there collective flow in pp?
If yes, what is its origin?
Is it stringy, or hydrodynamic ? (or …?)



E.g., do most patches of event look the same (thermalised?) or do they look more independent?

See e.g., Skands & Wraight: arXiv:1101.5215

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

Or Thermal? E.g., EPOS

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

What do we see?

submicron particles dispersed in superfluid 4He

Visualisation by: Fonda, Meichle, Ouellette, Hormoz, Lathrop, PNAS 111(2014)4707

http://www.pnas.org/content/suppl/2014/03/20/1312536110.DCSupplemental

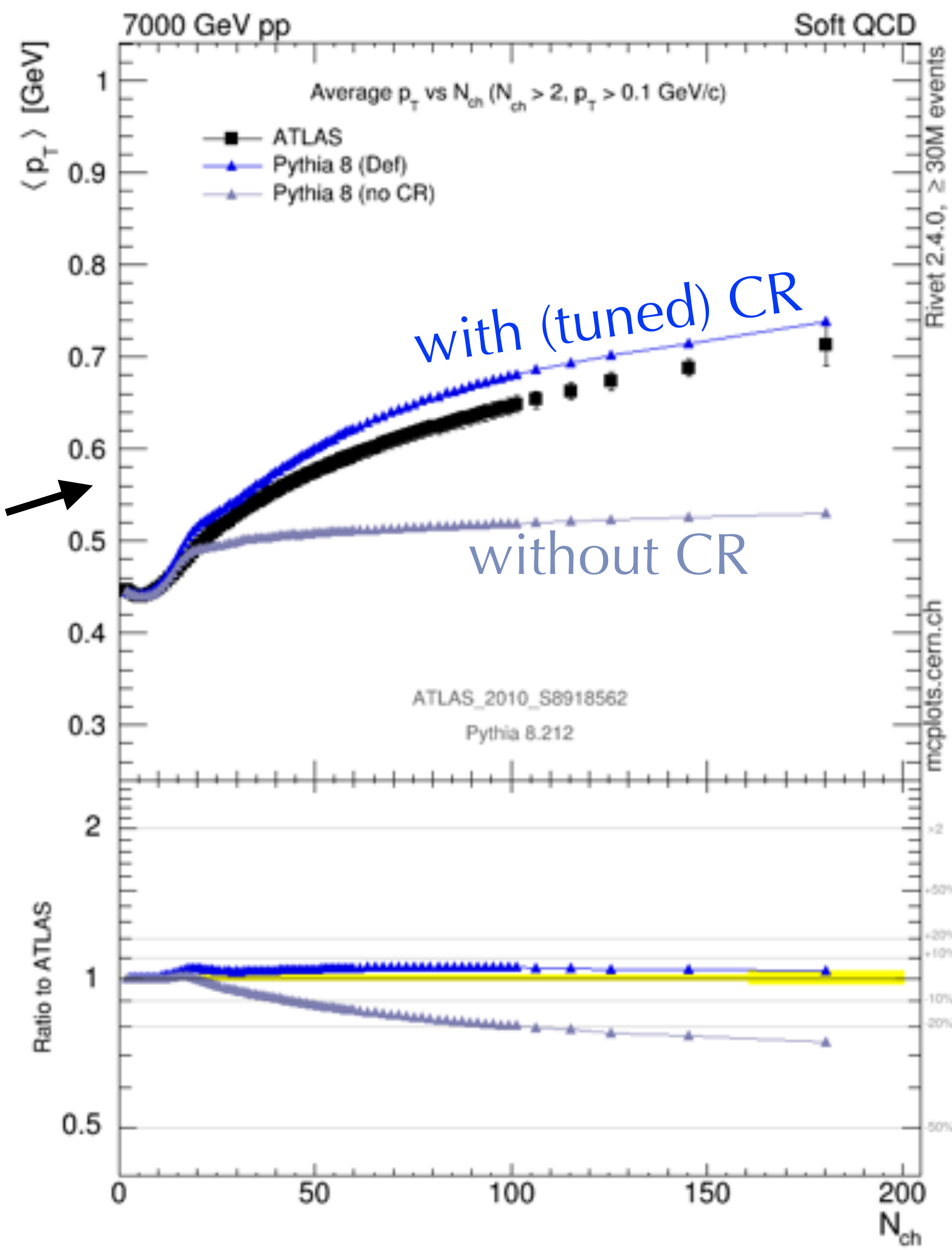
"Direct observation of Kelvin waves excited by quantized vortex reconnection"

What do we see in pp collisions?

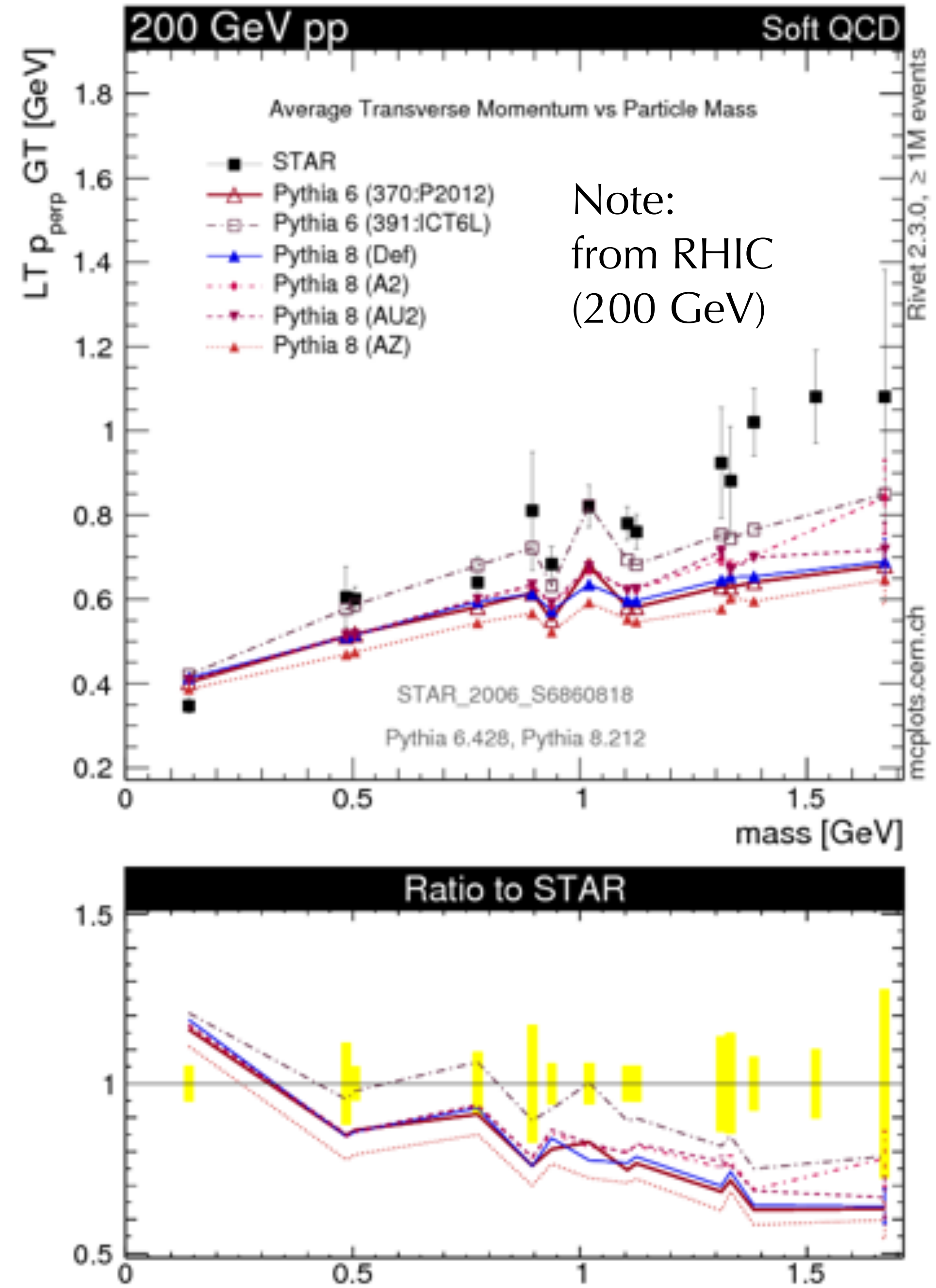
Plots from mcplots.cern.ch

'New Look'

<pT> vs Number of Particles



<pT> vs Particle Mass

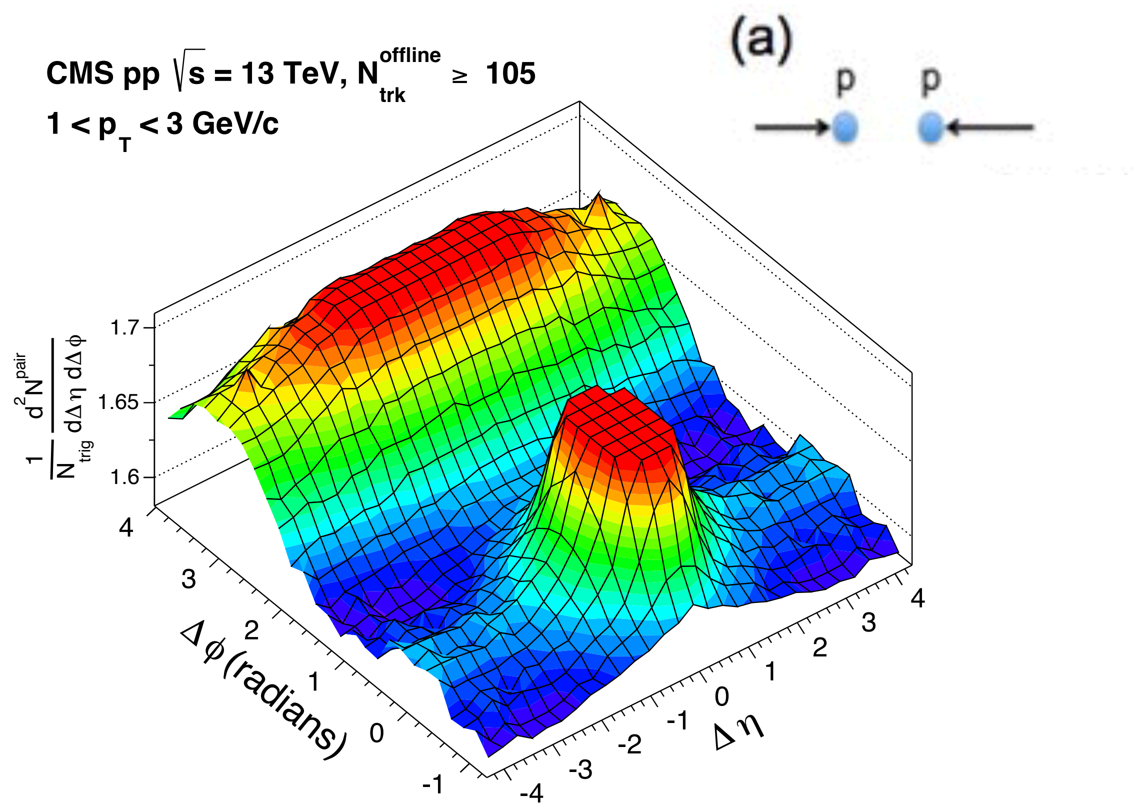


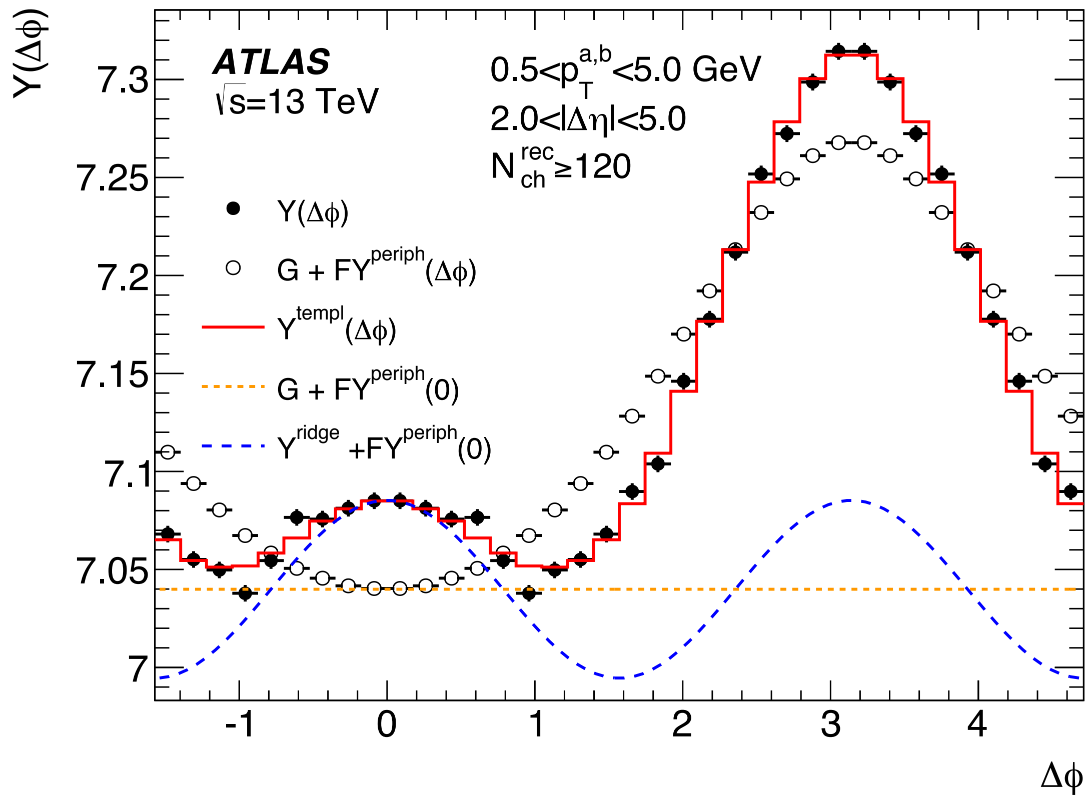
Average pT **increases** with particle multiplicity and (faster than predicted) with particle mass

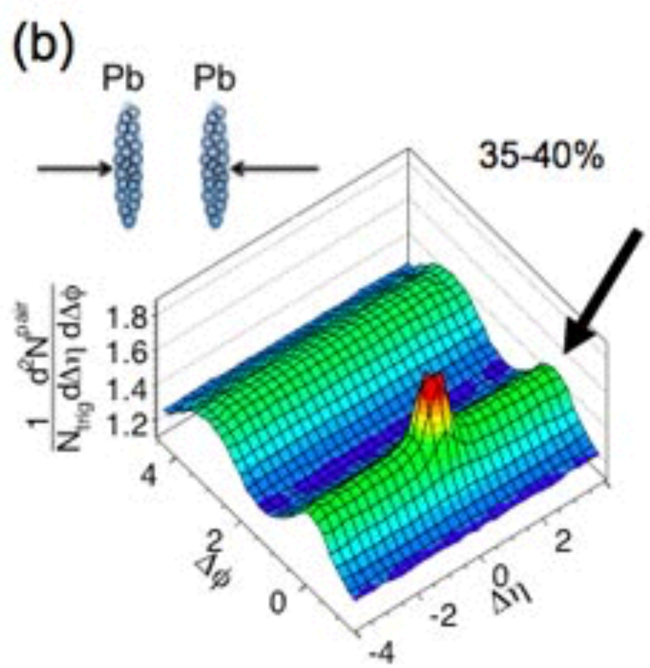
The "CMS Ridge"

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

High-Multiplicity pp collisions

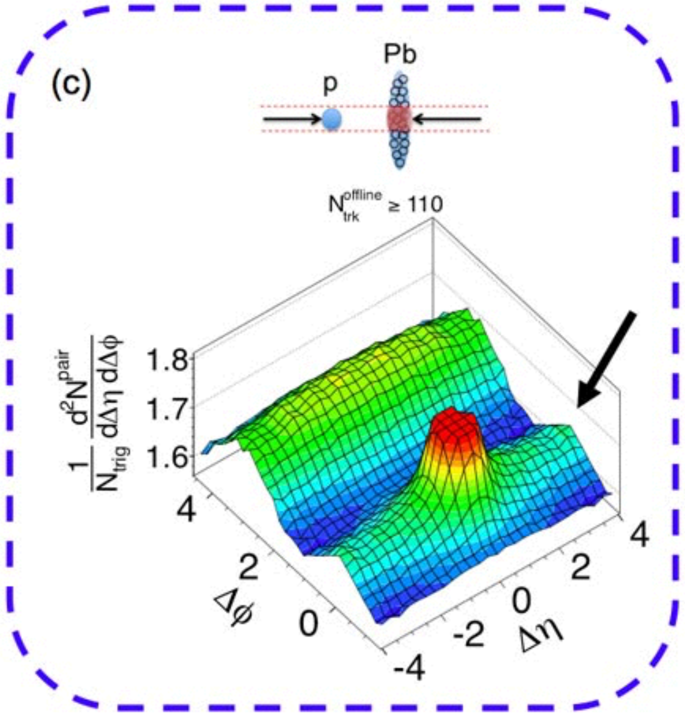






← Reminiscent of the (much stronger) ridge seen in HI collisions.

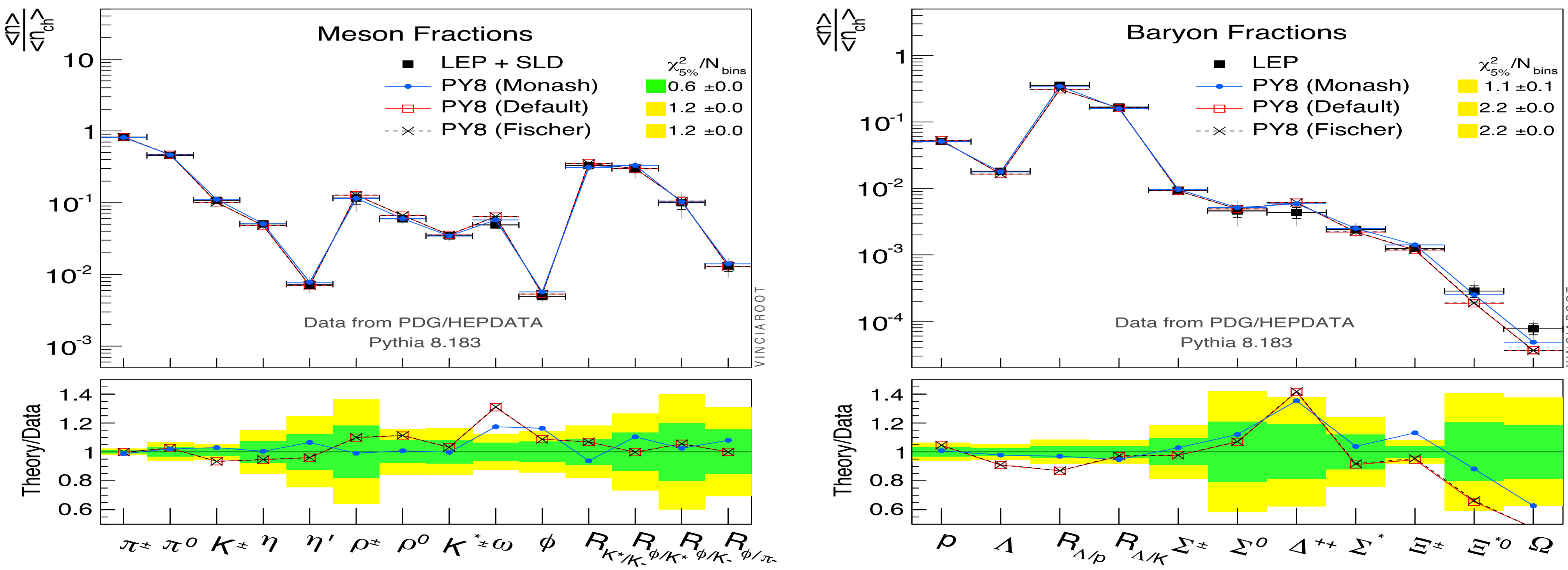
Surprisingly strong → also in proton-Lead



Strangeness

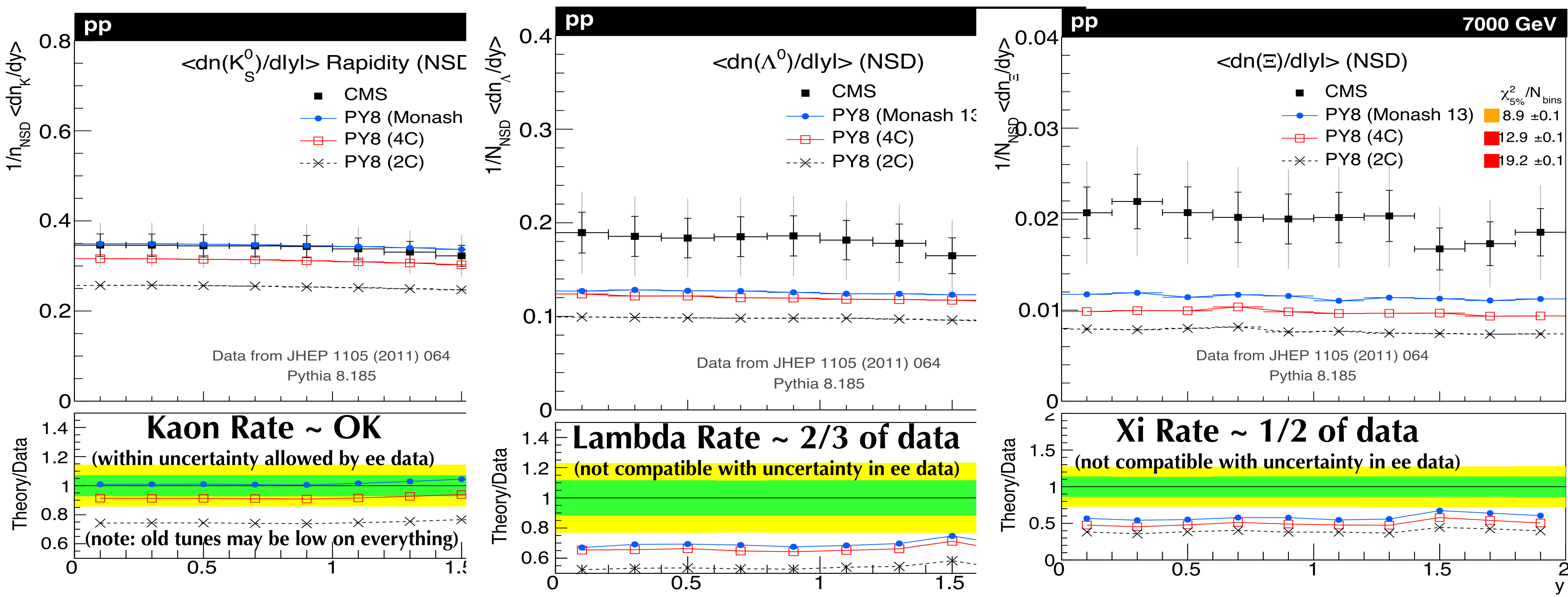
Plots from the Monash tune paper
Eur.Phys.J. C74 (2014) no.8, 3024

Z Decays



This is the data used to tune the models

CMS

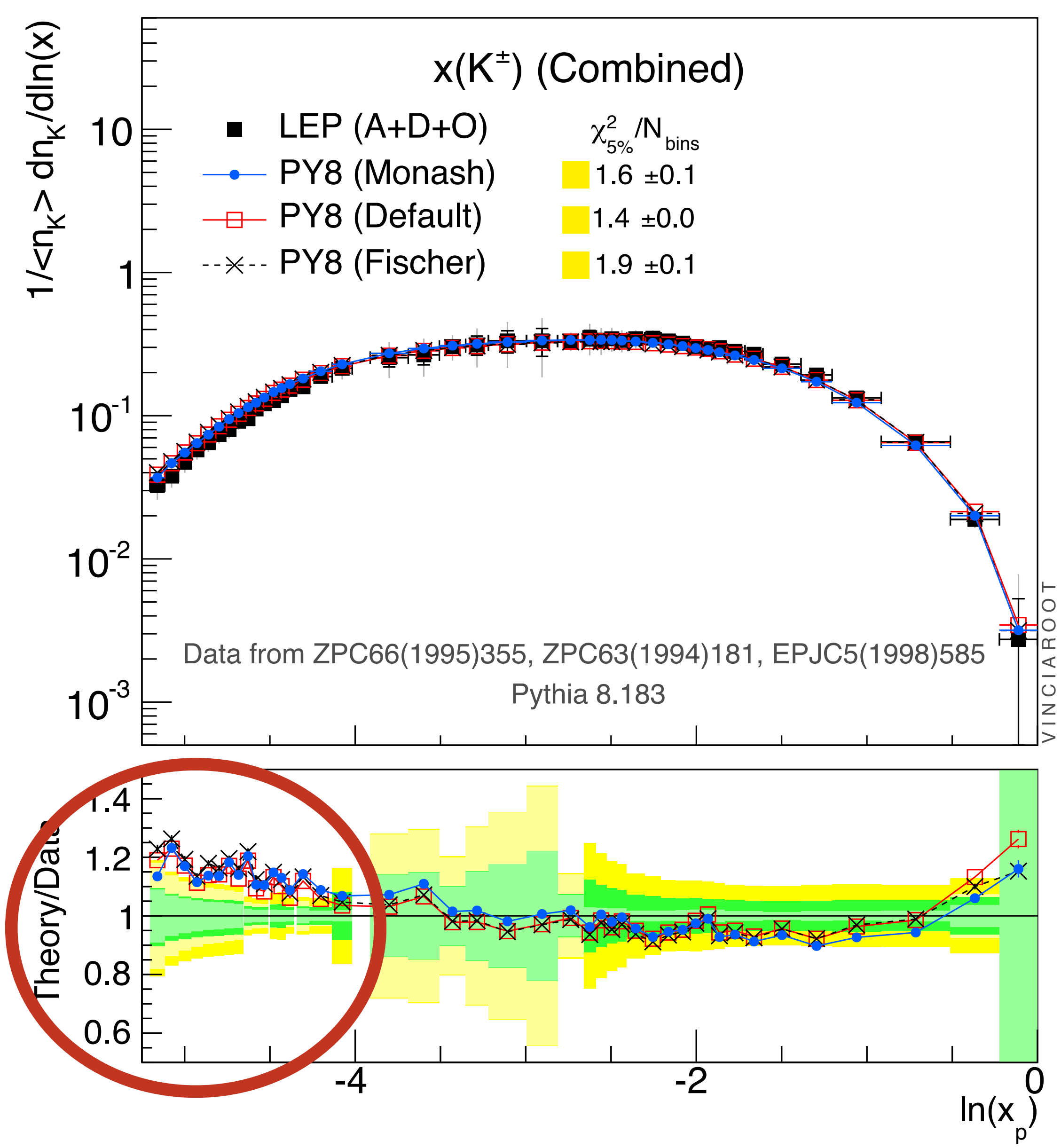


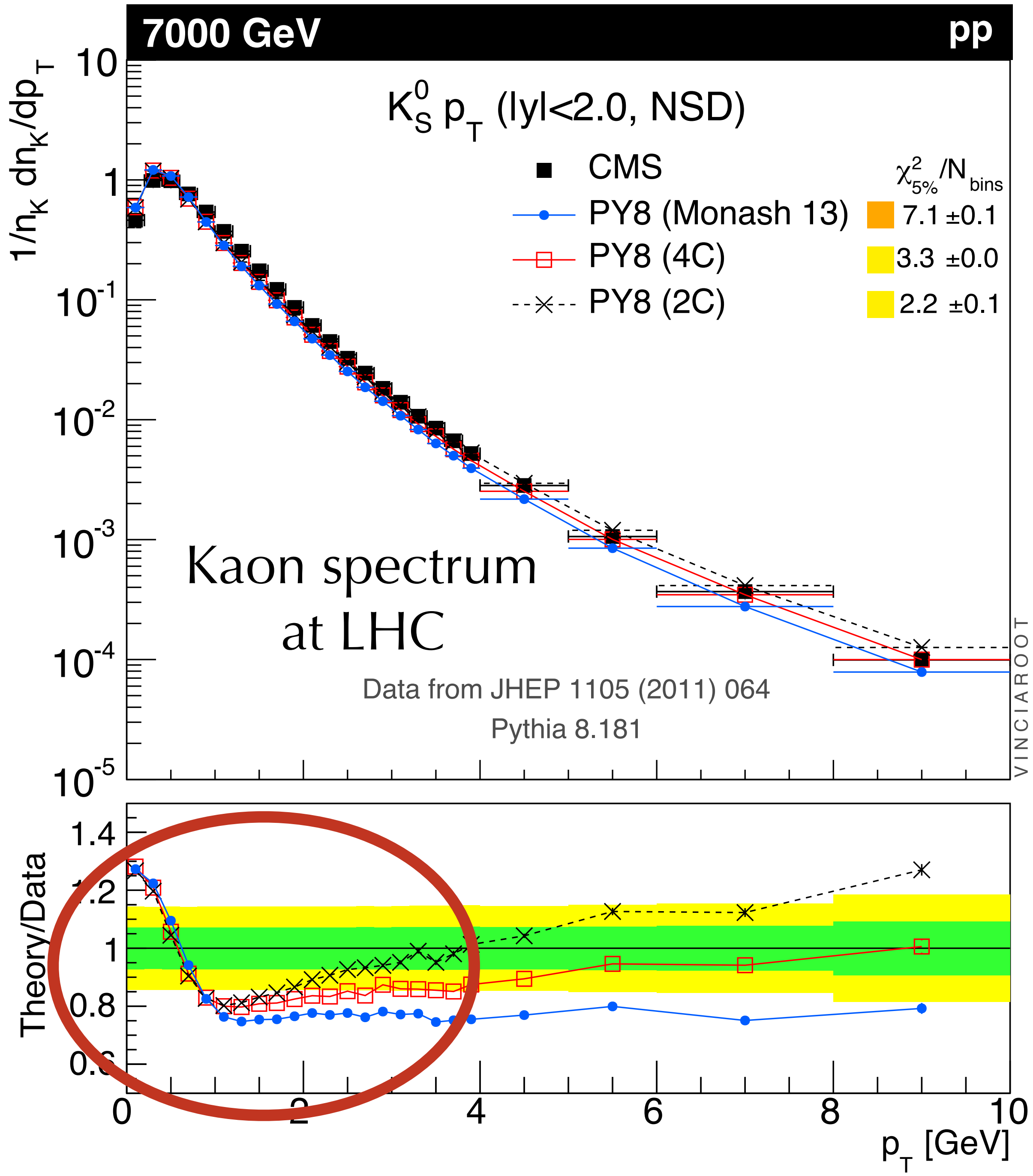
Strangeness Spectra

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

Note: rates normalised to unity now

Kaon spectrum at LEP





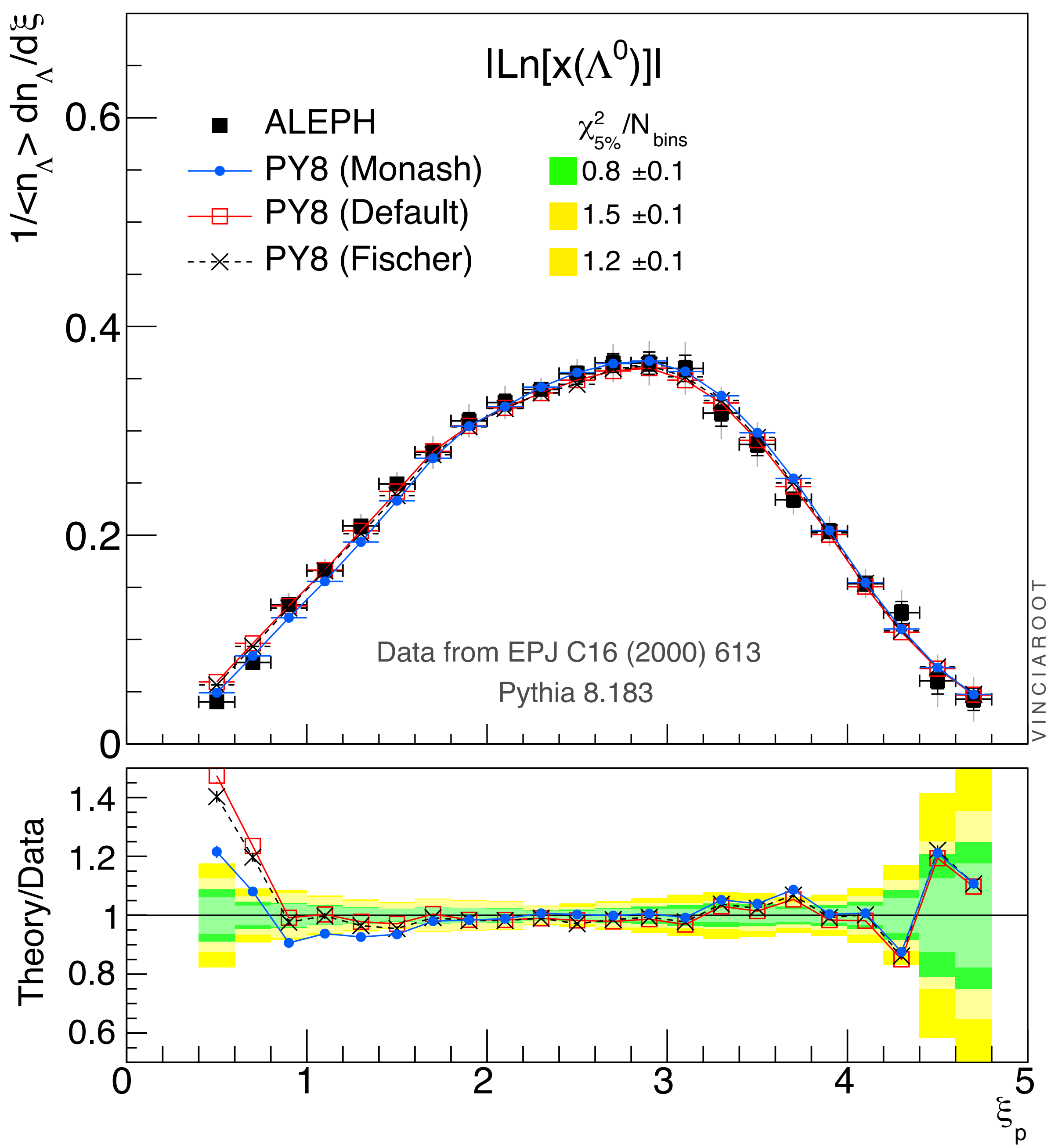
(+ Several measurements by ALICE, LHCb)

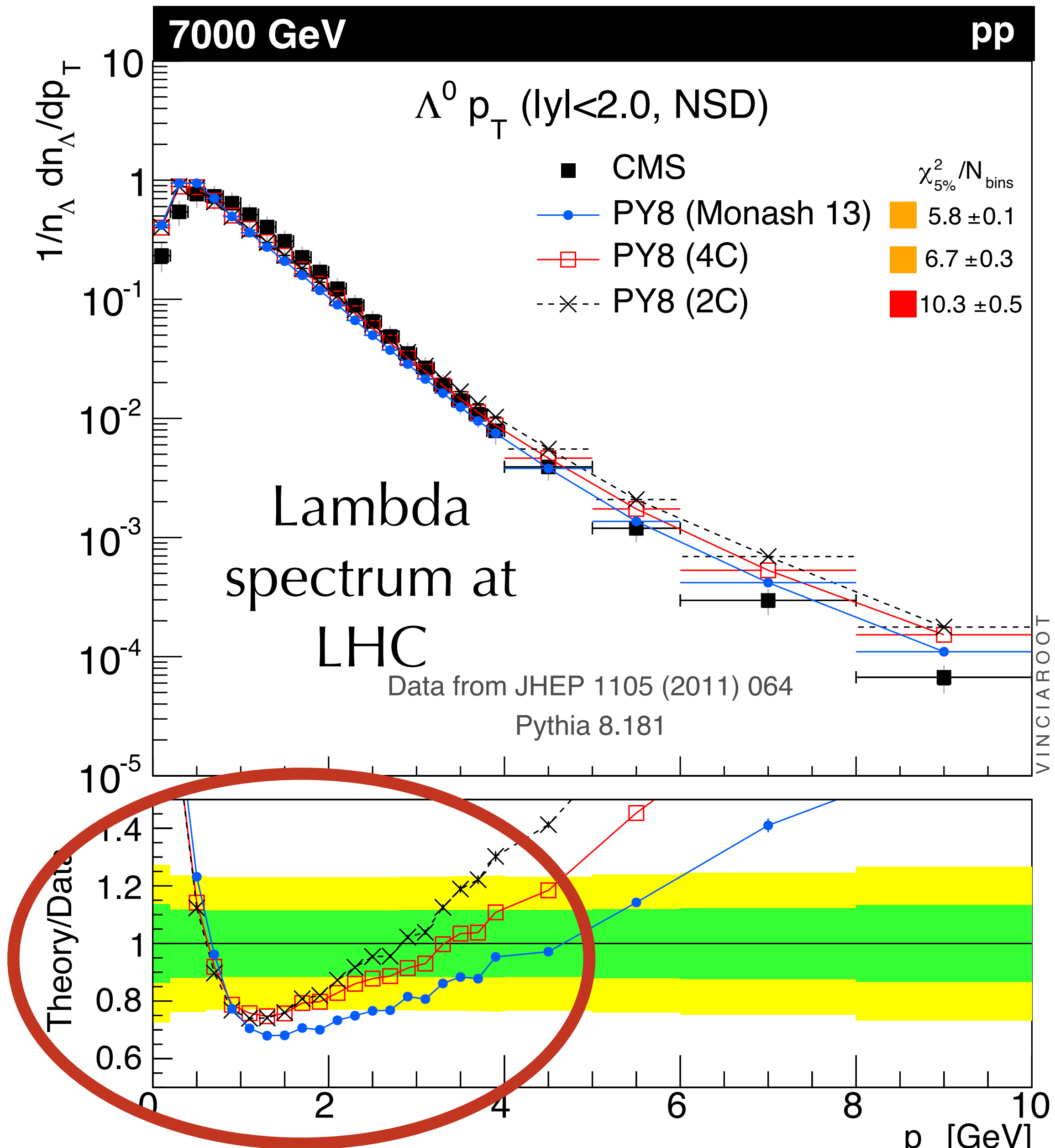
Strangeness Spectra

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

Note: rates normalised to unity now

Lambda spectrum at LEP



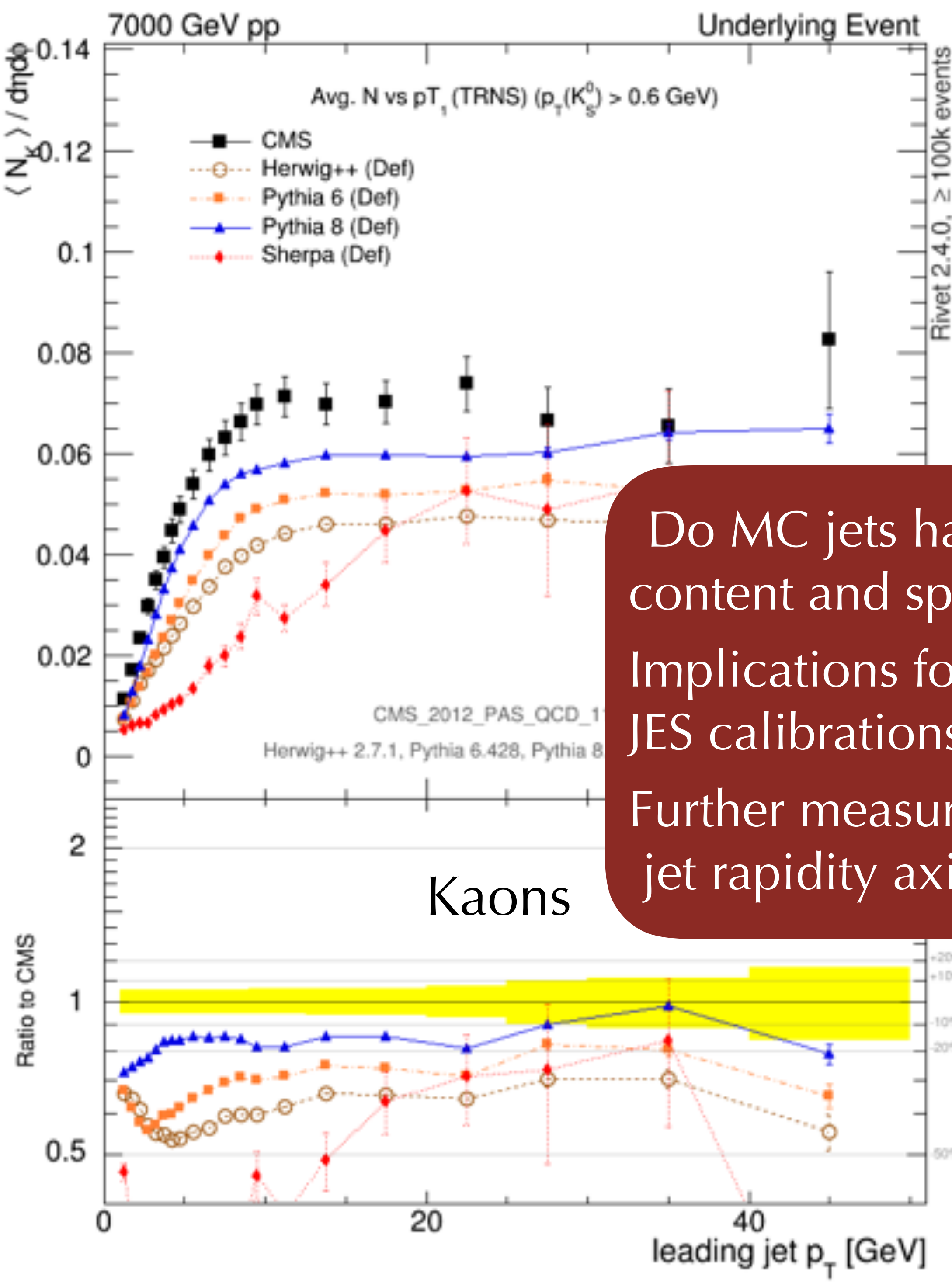


(+ Several measurements by ALICE, LHCb)

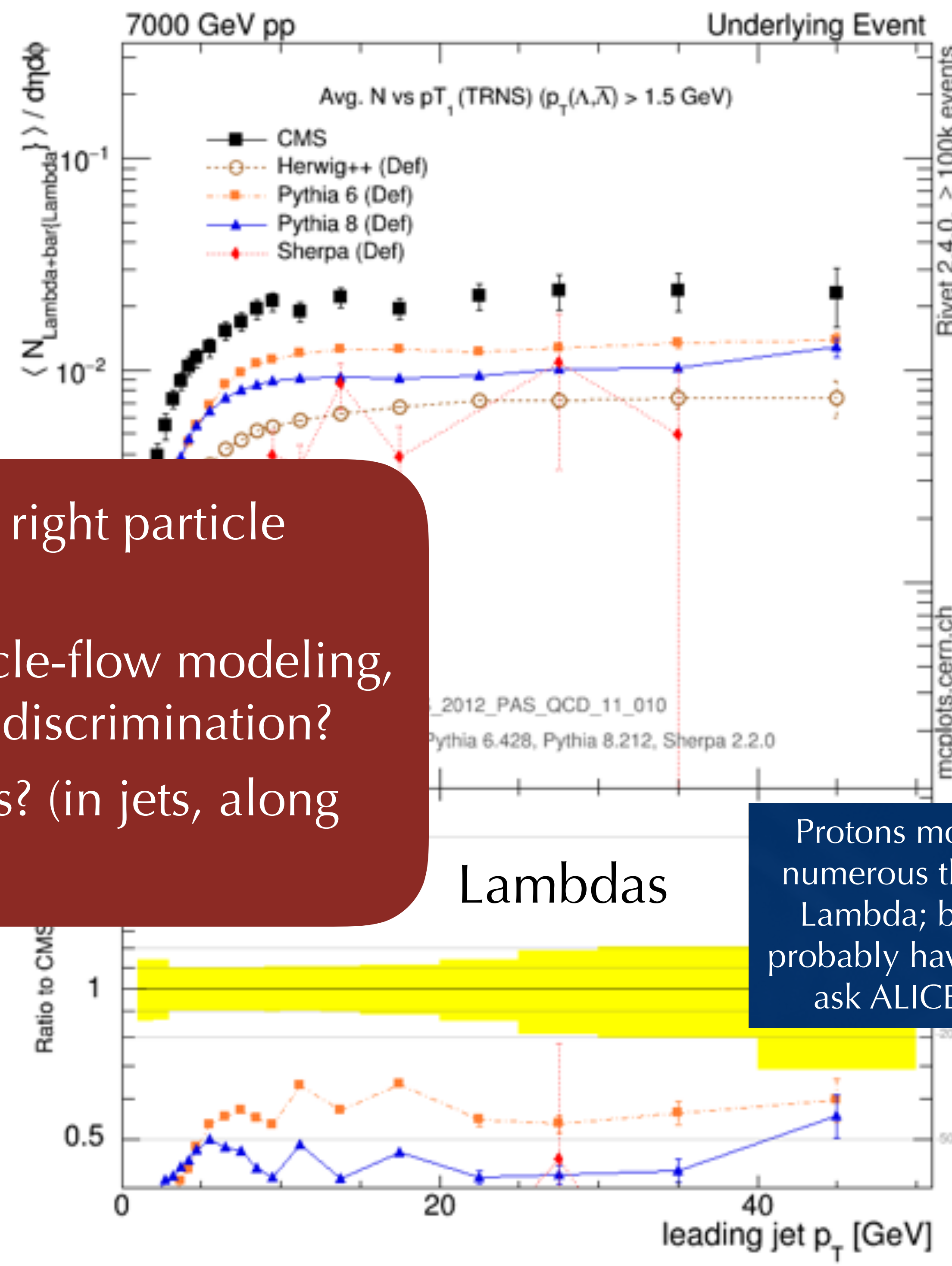
CMS: Strangeness in the Underlying Event

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

Plots from mcplots.cern.ch



Kaons



Lambdas

Do MC jets have the right particle content and spectra?

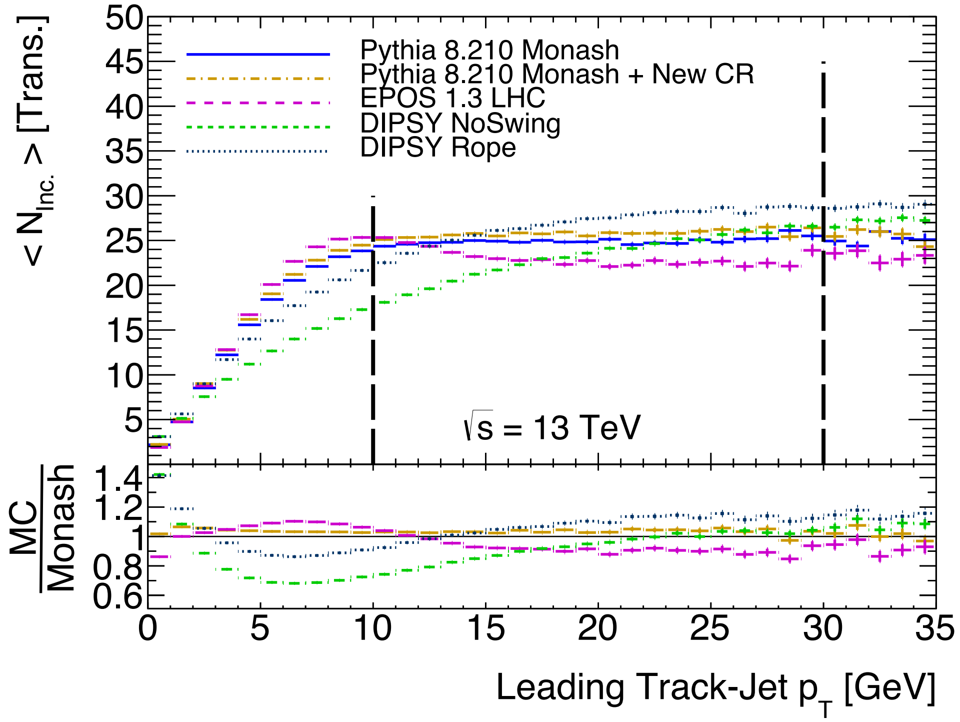
Implications for particle-flow modeling, JES calibrations, Q/G discrimination?

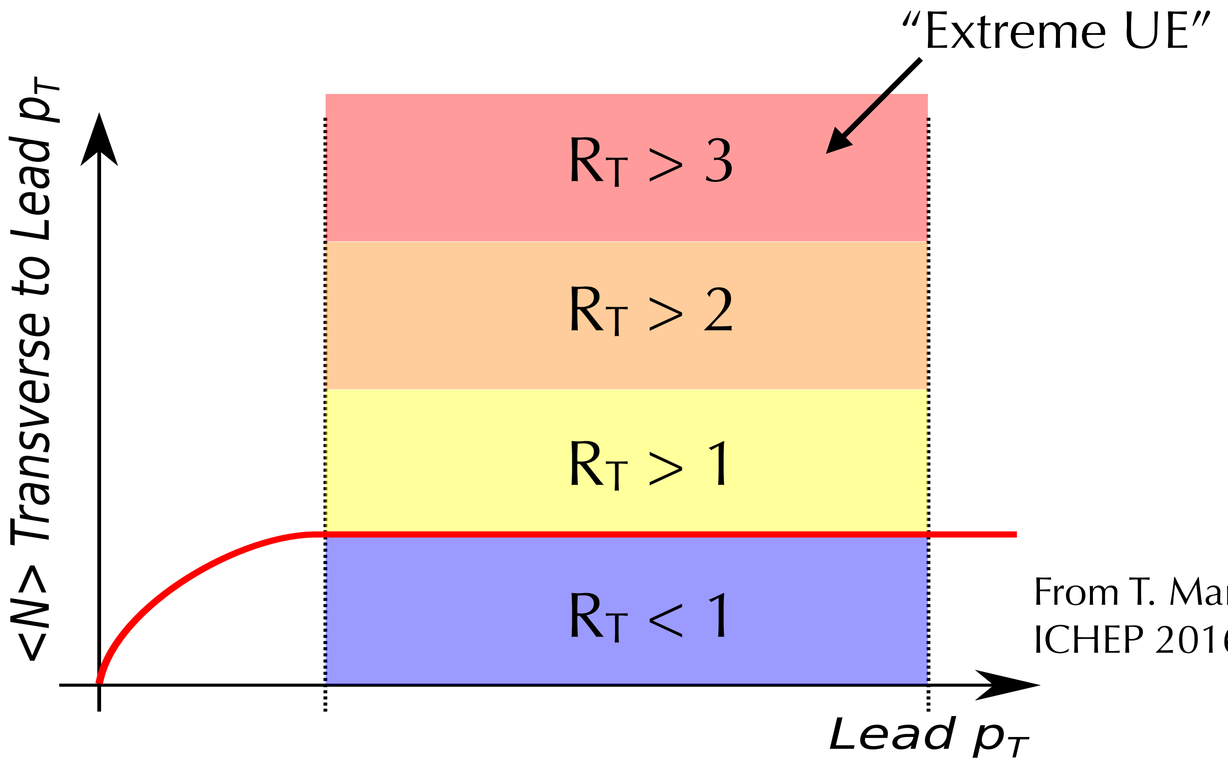
Further measurements? (in jets, along jet rapidity axis, …)

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

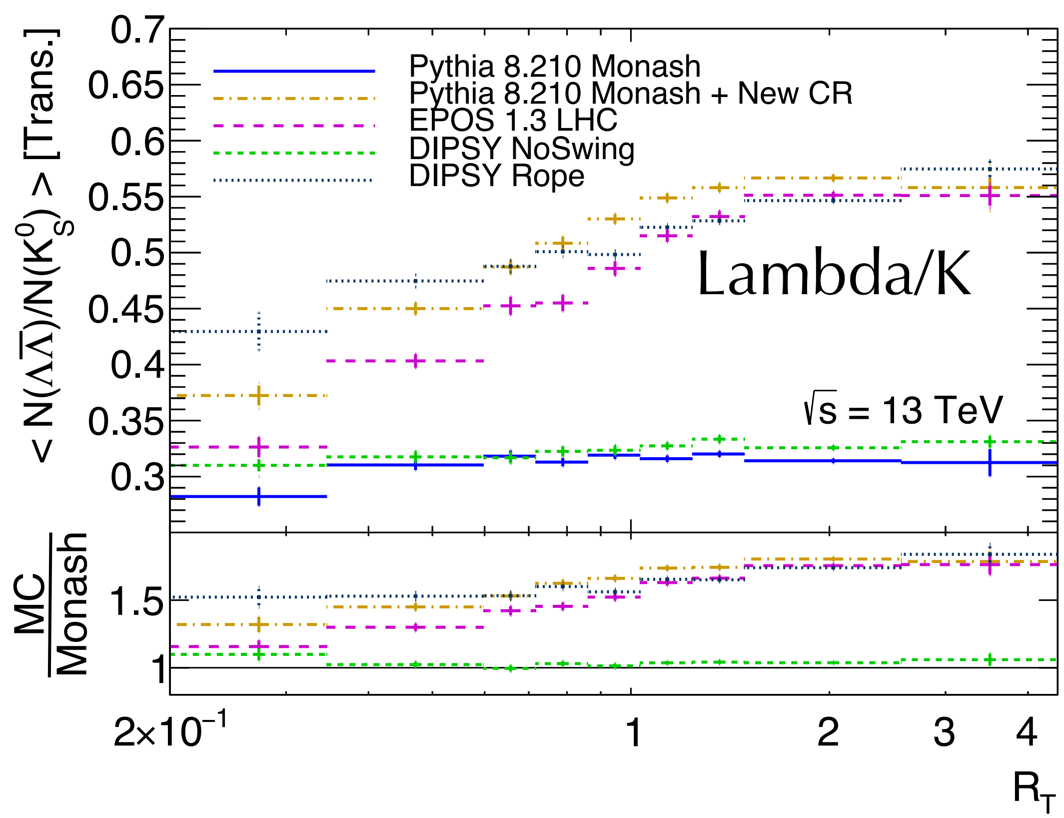
→ Extensions of CMS UE Study?

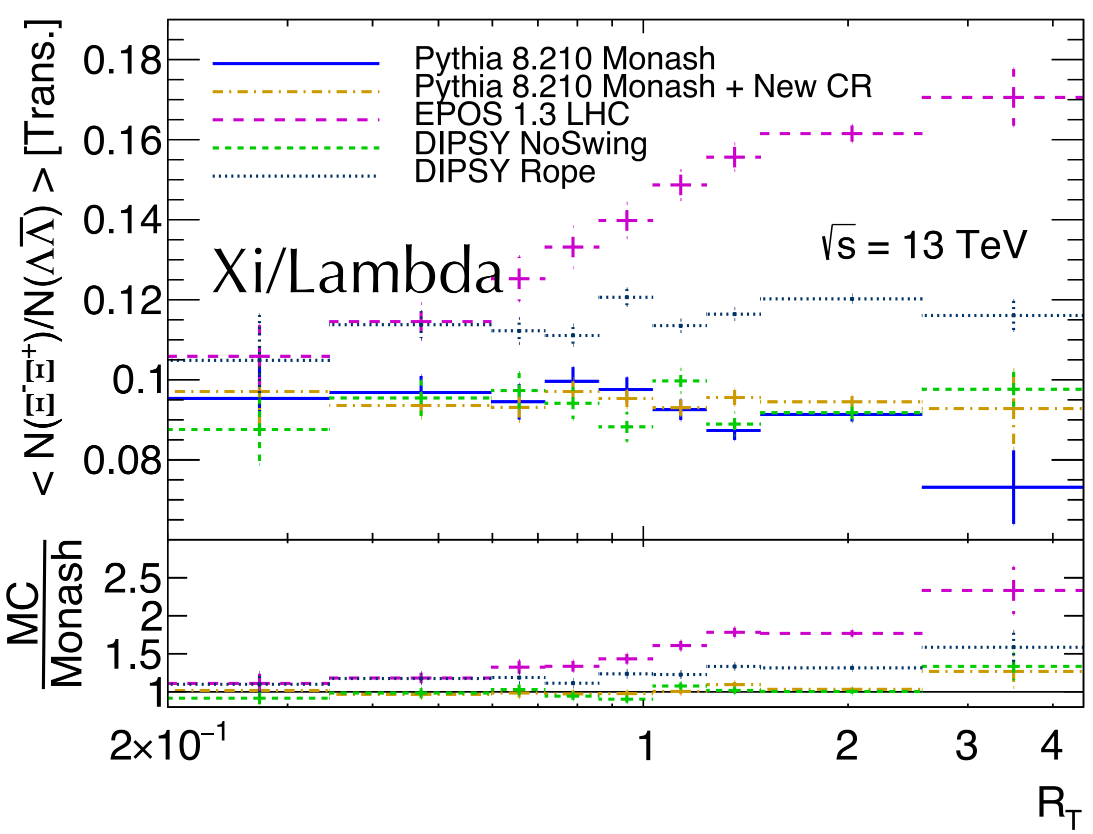
Probing Collective Effects in Hadronisation with the Extremes of the Underlying Event
T. Martin, P. Skands, S. Farrington, Eur.Phys.J. C76 (2016) no.5, 299



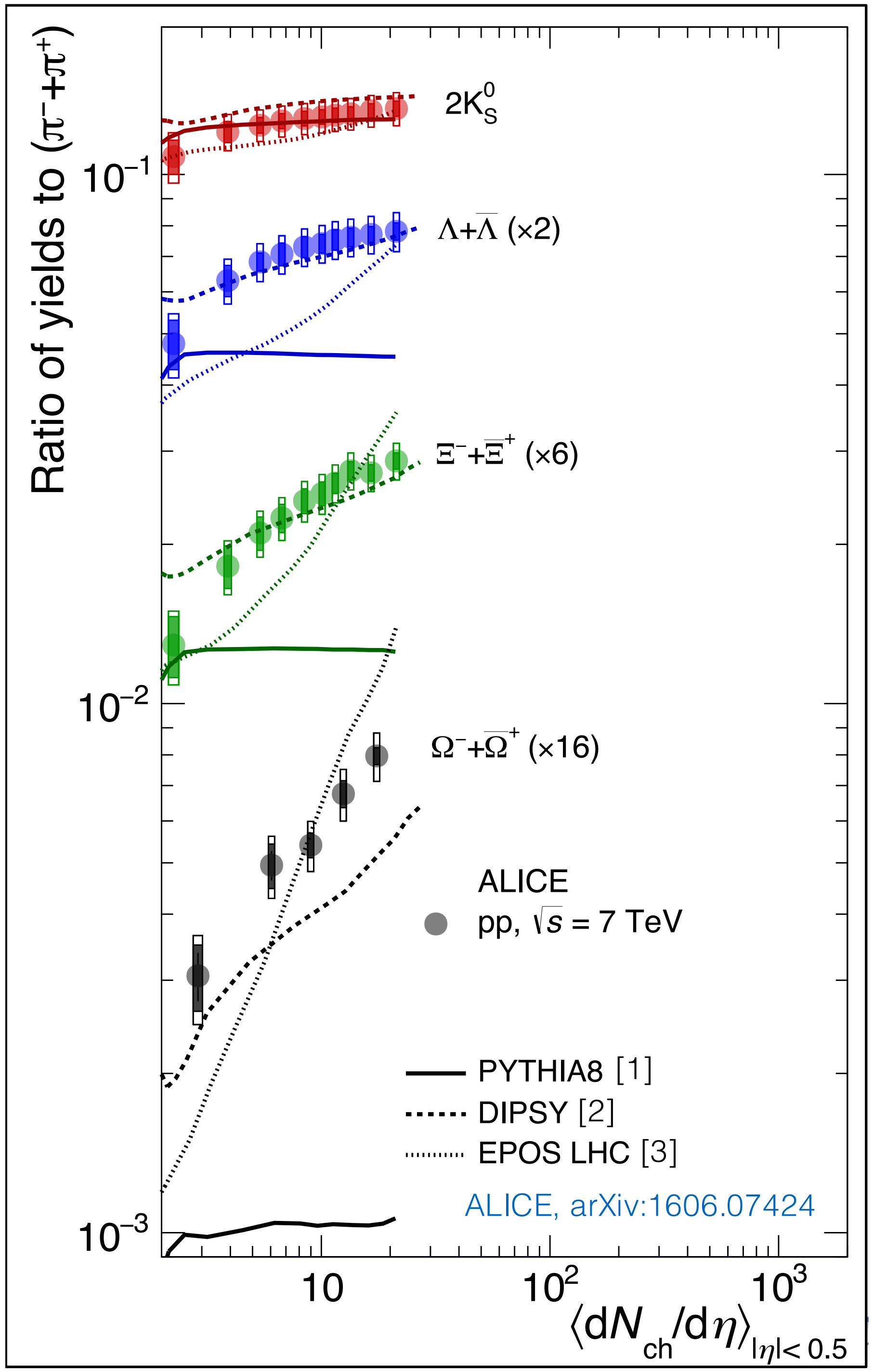


From T. Martin, ICHEP 2016





Recent news from ALICE (ICHEP 2016)



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

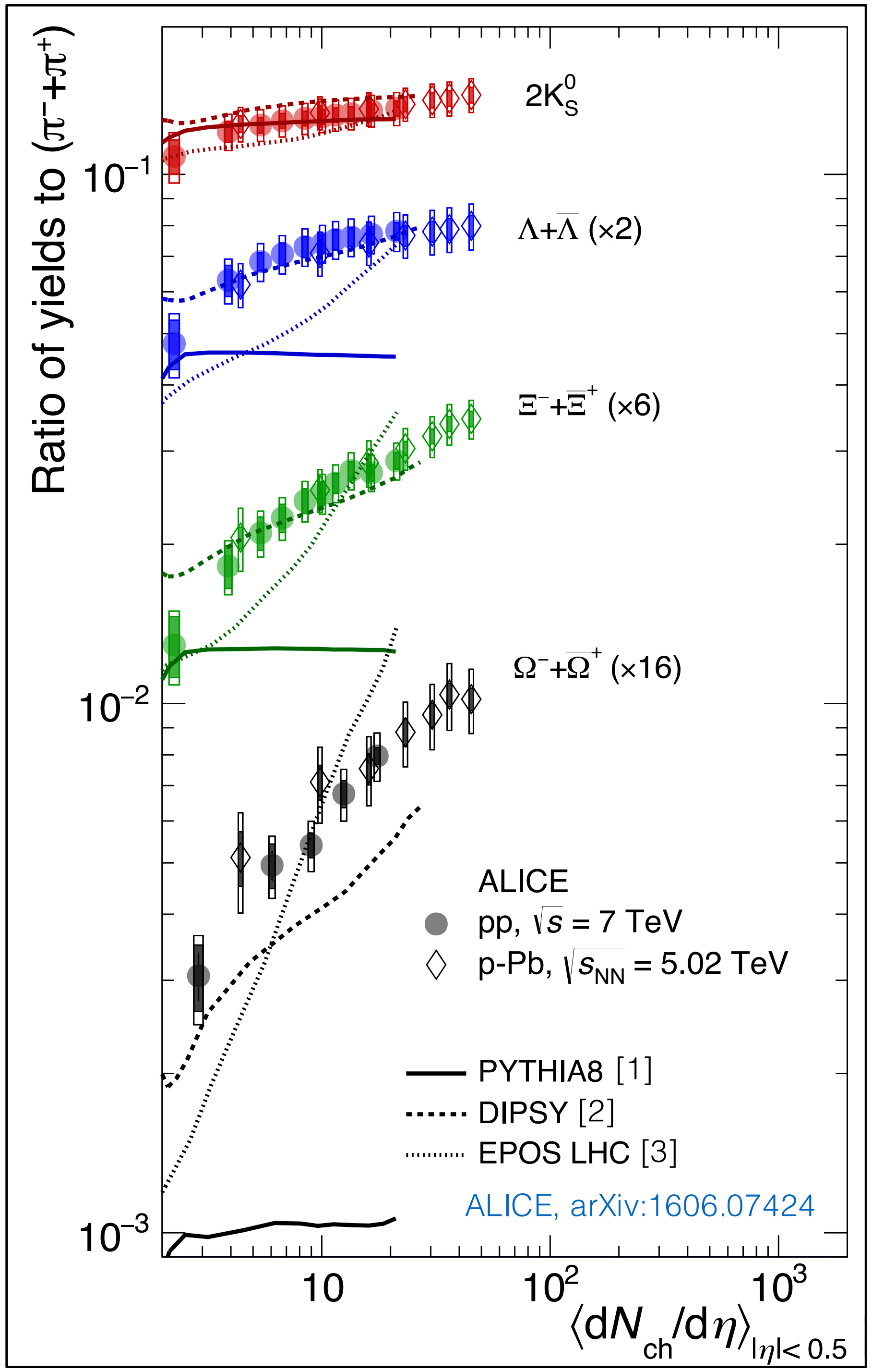
A clear enhancement of strangeness with (pp) event multiplicity is observed

- 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



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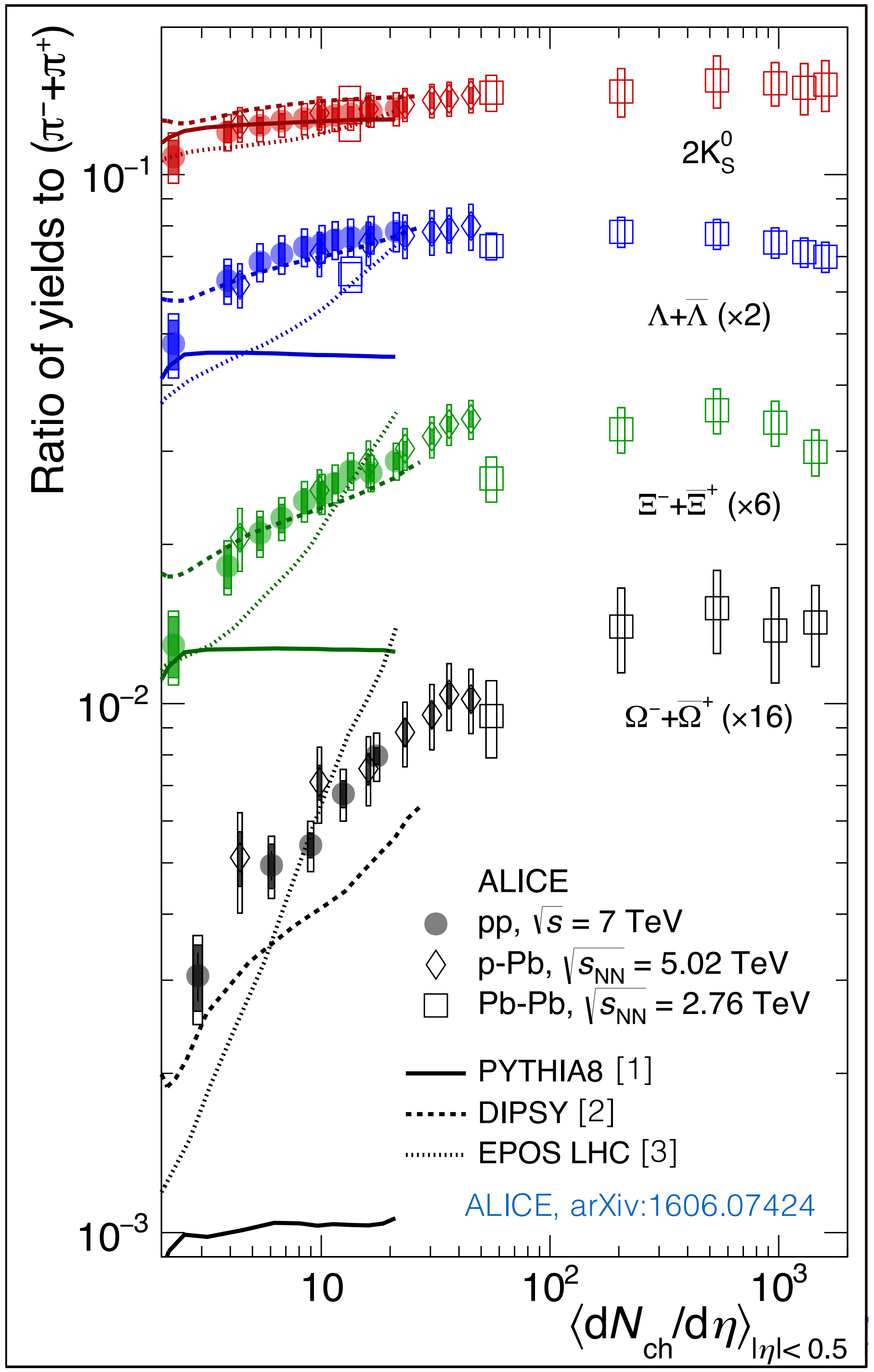
Looks like the effect, whatever it is, continues smoothly into p-Pb

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 !

Unexpected.

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

Is it thermal? Stringy? Both?

Collective? Flowy? …

Physics must explain smooth transition to heavy ions. No abrupt "phase transition" seen in these observables

Summary

Higgs-type Lagrangians → Vortex Lines → String Models

Remain our best bet at modelling hadronisation in QCD

High-multiplicity & high-p_T triggered events: large amounts of colour kicked around: soft event structure appears to require (at least) going beyond Leading Colour → *Colour Reconnections (CR)*

Beyond CR, it now appears that **the effective QCD scale is *increasing***

What are the ***dynamics*** of pp / multi-string environments?

Phenomenology: Modern revisions of the Lund string model

What measurements can be performed to shed more light?

Possible to get more information from **lattice?** Multi-string systems?

By the way (advertisement):

Did you know you can get automated shower-uncertainty weights ?

Automated Parton-Shower Uncertainties in PYTHIA 8 Mrenna & Skands, arXiv:1605.08352

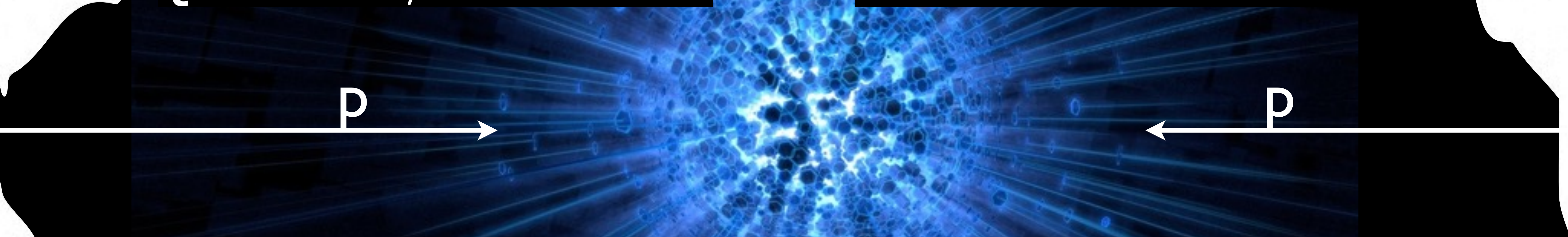
Similar capabilities in HERWIG++, SHERPA, VINCIA

Bellm, Plätzer, Richardson, Siodmok, Webster 1605.08256 | Bothmann, Schönherr, Schumann 1606.08753 | Giele, Kosower, Skands PRD84 (2011) 054003

New research at Monash

Precision LHC phenomenology
PYTHIA & VINCIA
NLO Event Generators
QCD strings, hadronisation

Support LHC **experiments**, **astro-particle** community, and **Future** accelerators
+Outreach and Citizen Science



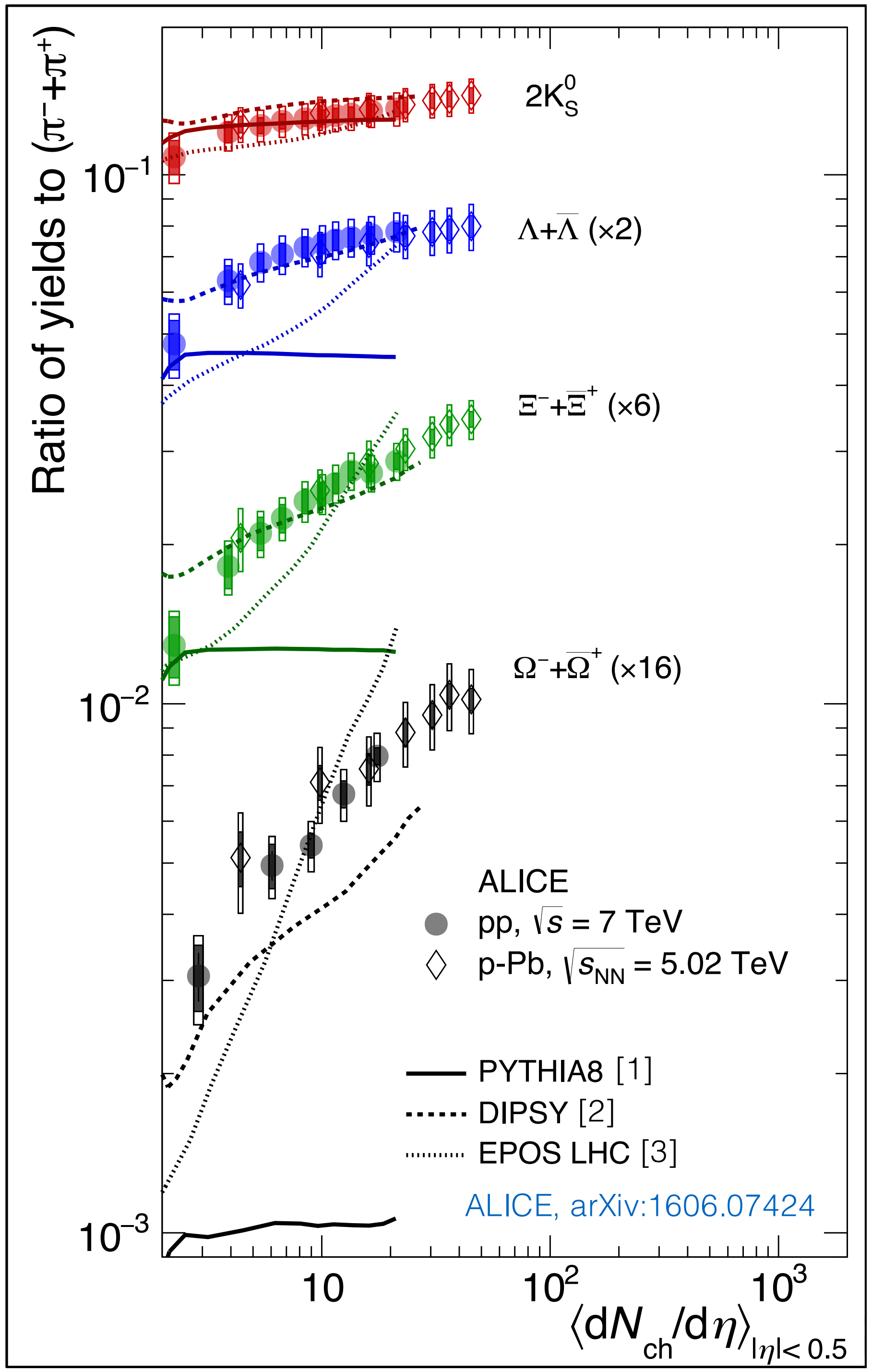
+ Partnerships: Warwick Alliance, MCnet, CoEPP

New joint research program with Warwick ATLAS, on developing and testing advanced colllider-QCD models. **Opportunities for PhD students** based at Monash + exchange to UK/CERN.

See: arXiv:1603.05298

MC*net* is an EU Marie Curie Training Network (ITN) on MC generators for LHC (Herwig, Pythia, Sherpa). ***Funded for Horizon 2020!*** Starting in 2017 with Monash an associate partner

No Enhancement for Protons



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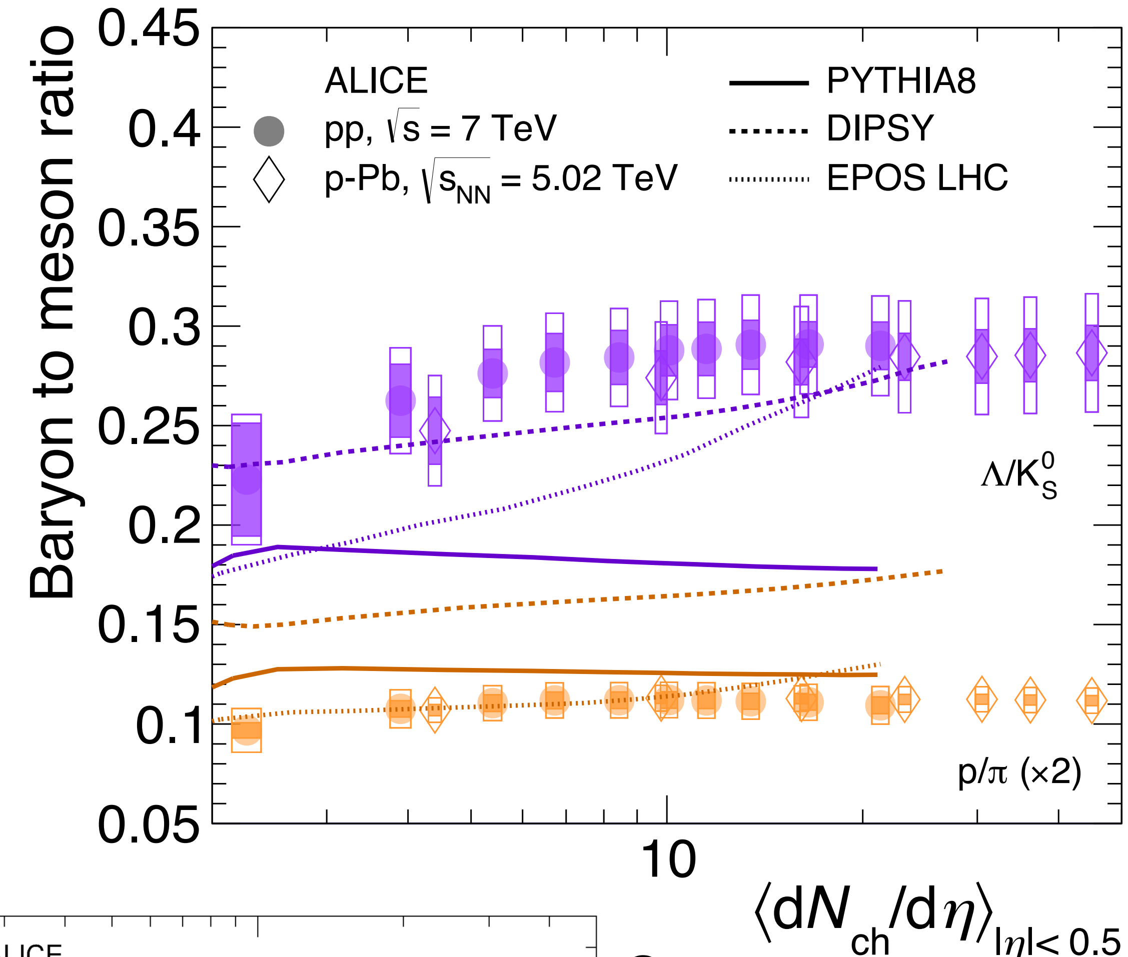
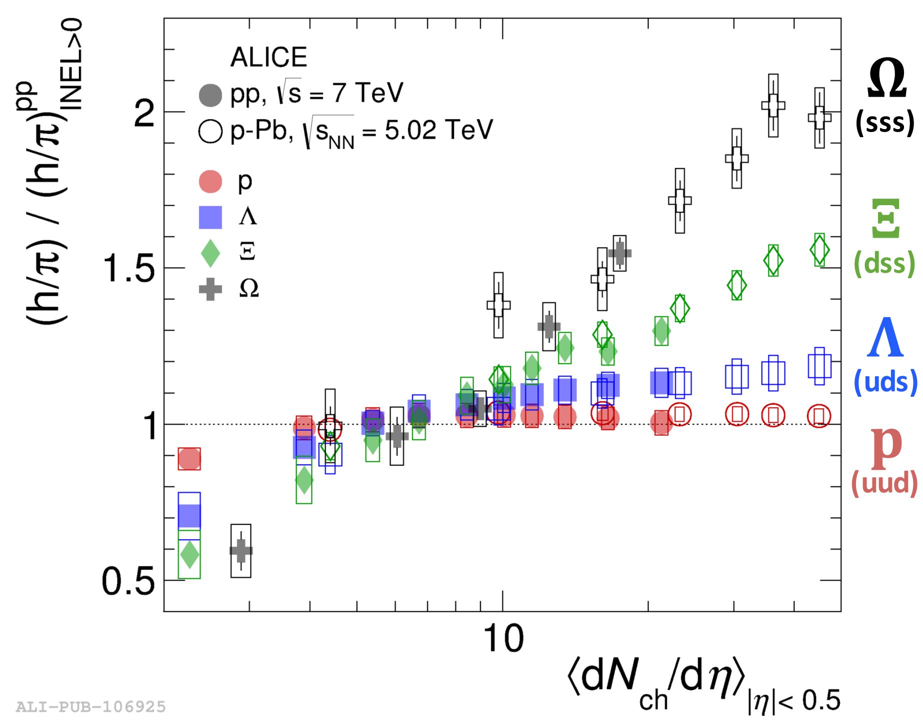
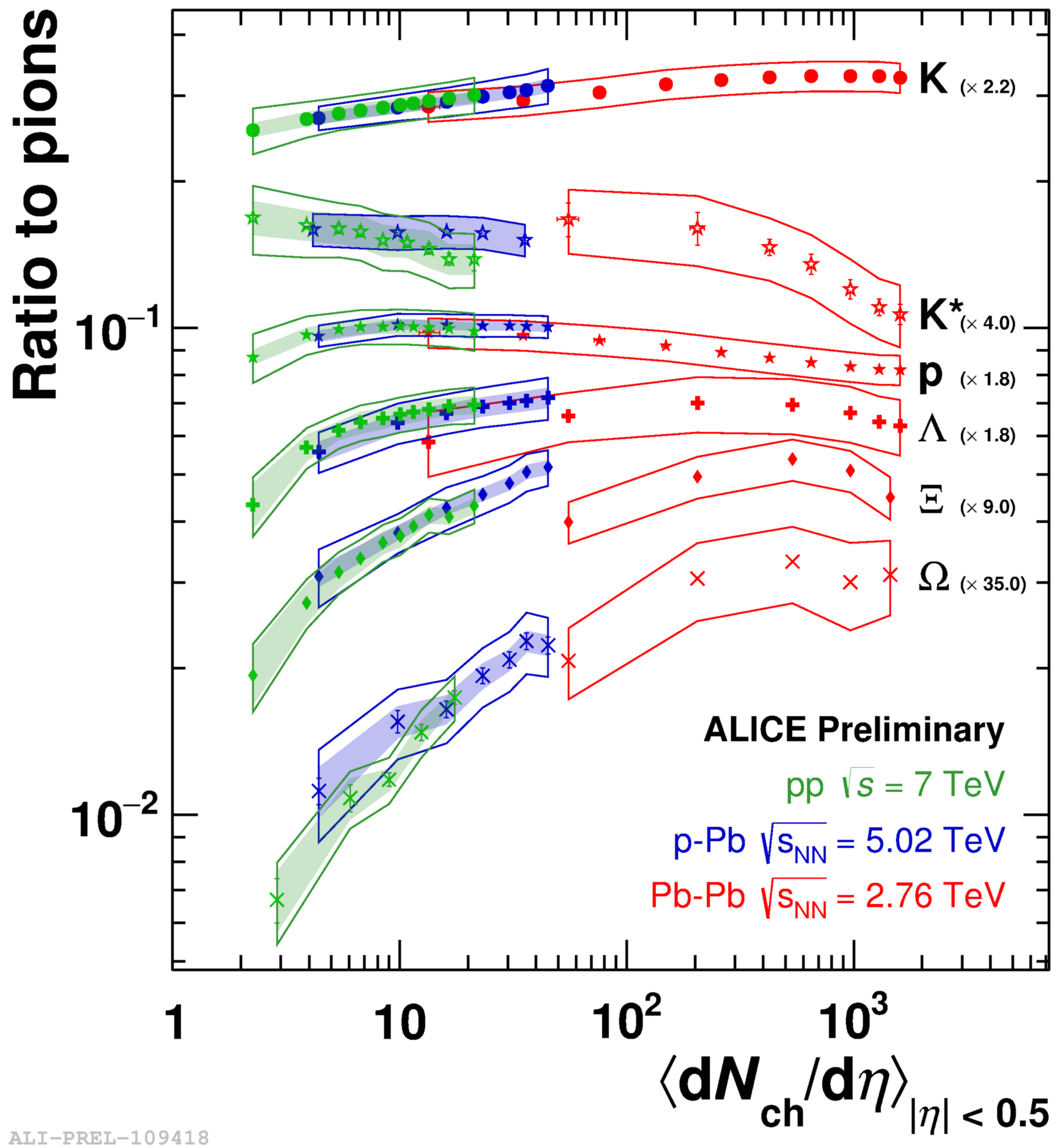




All on the same plot

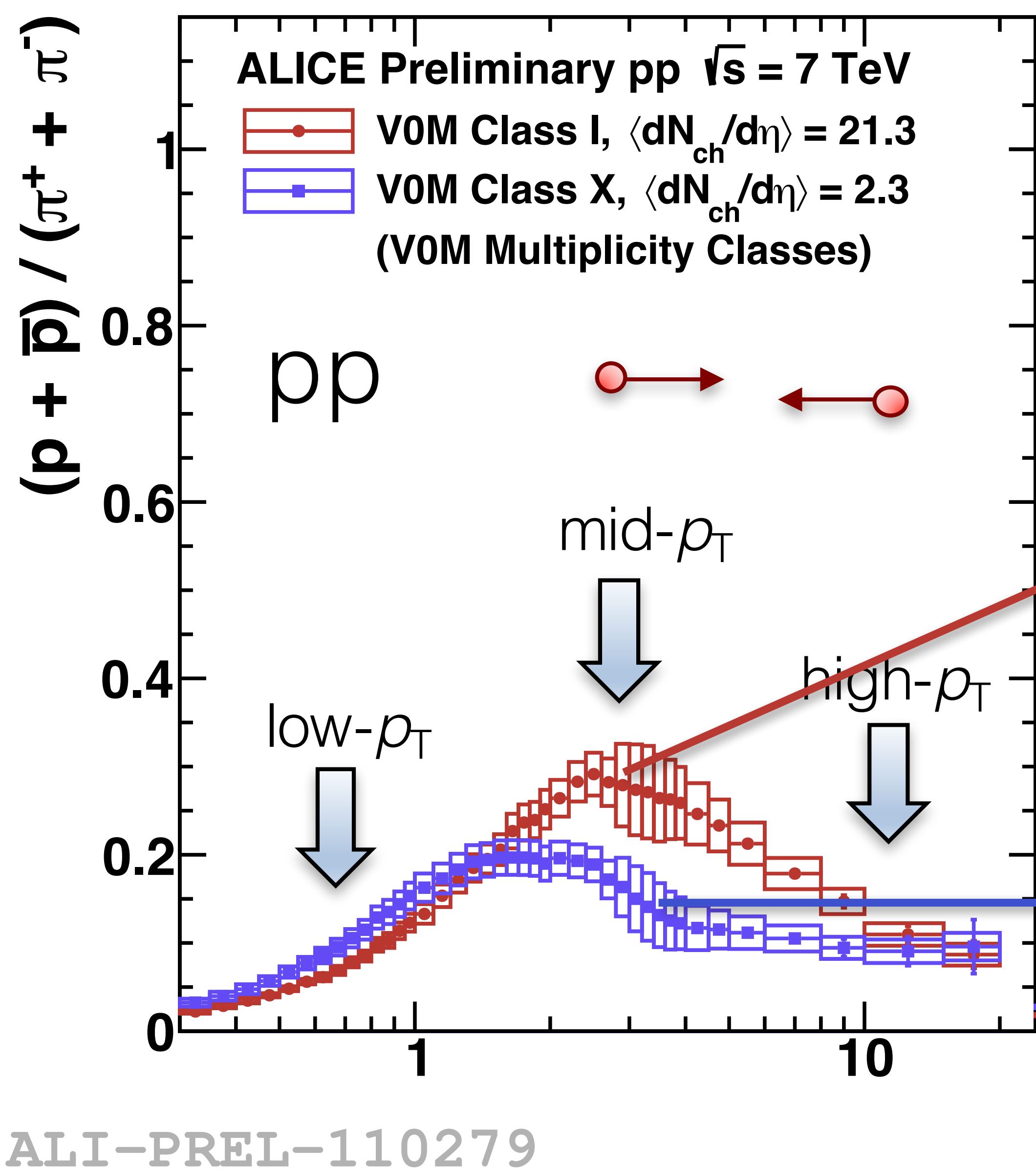
Including K* and protons

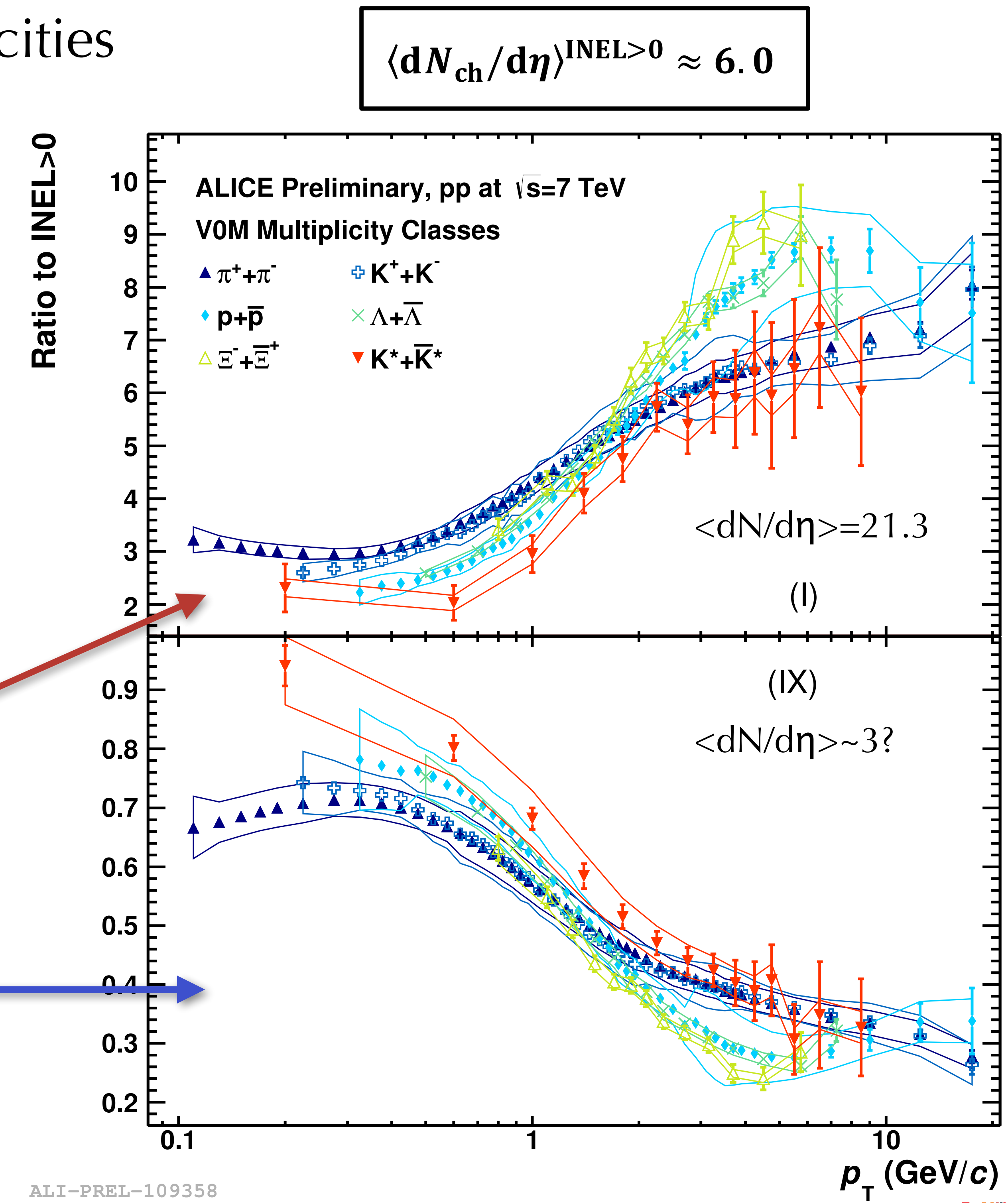


p_T Dependence

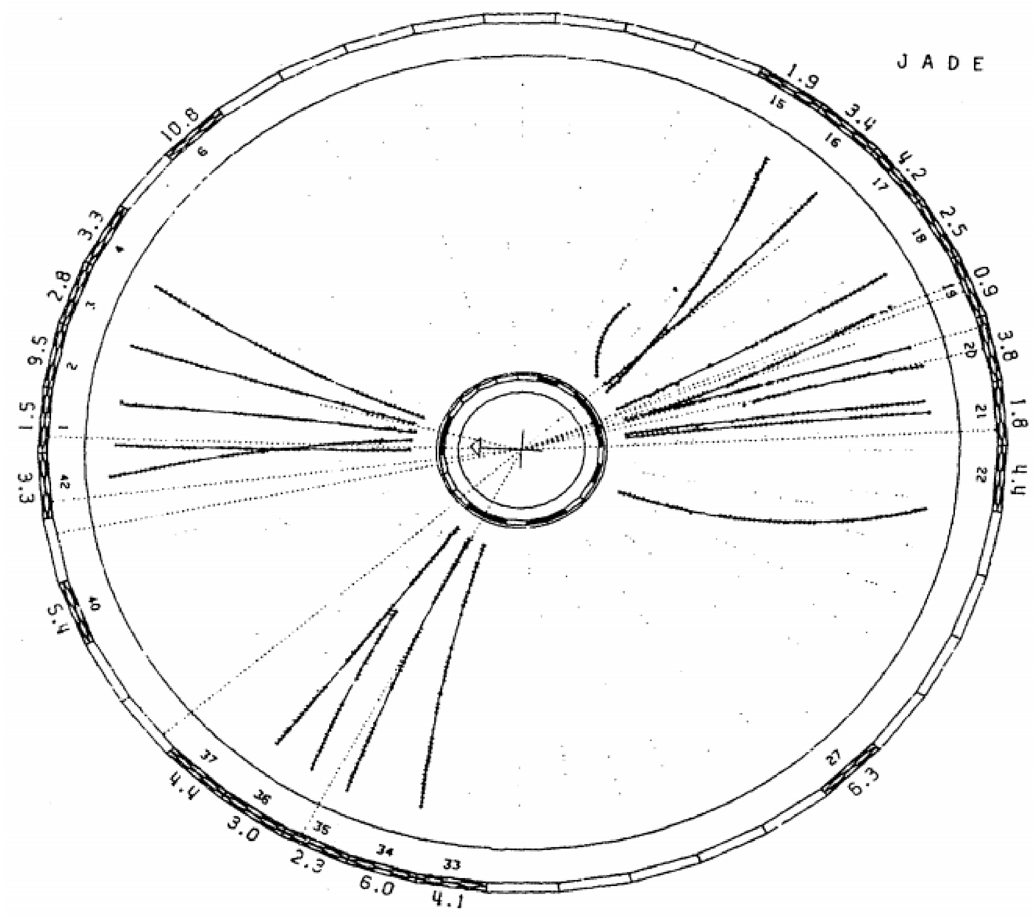
Spectra become harder at high multiplicities

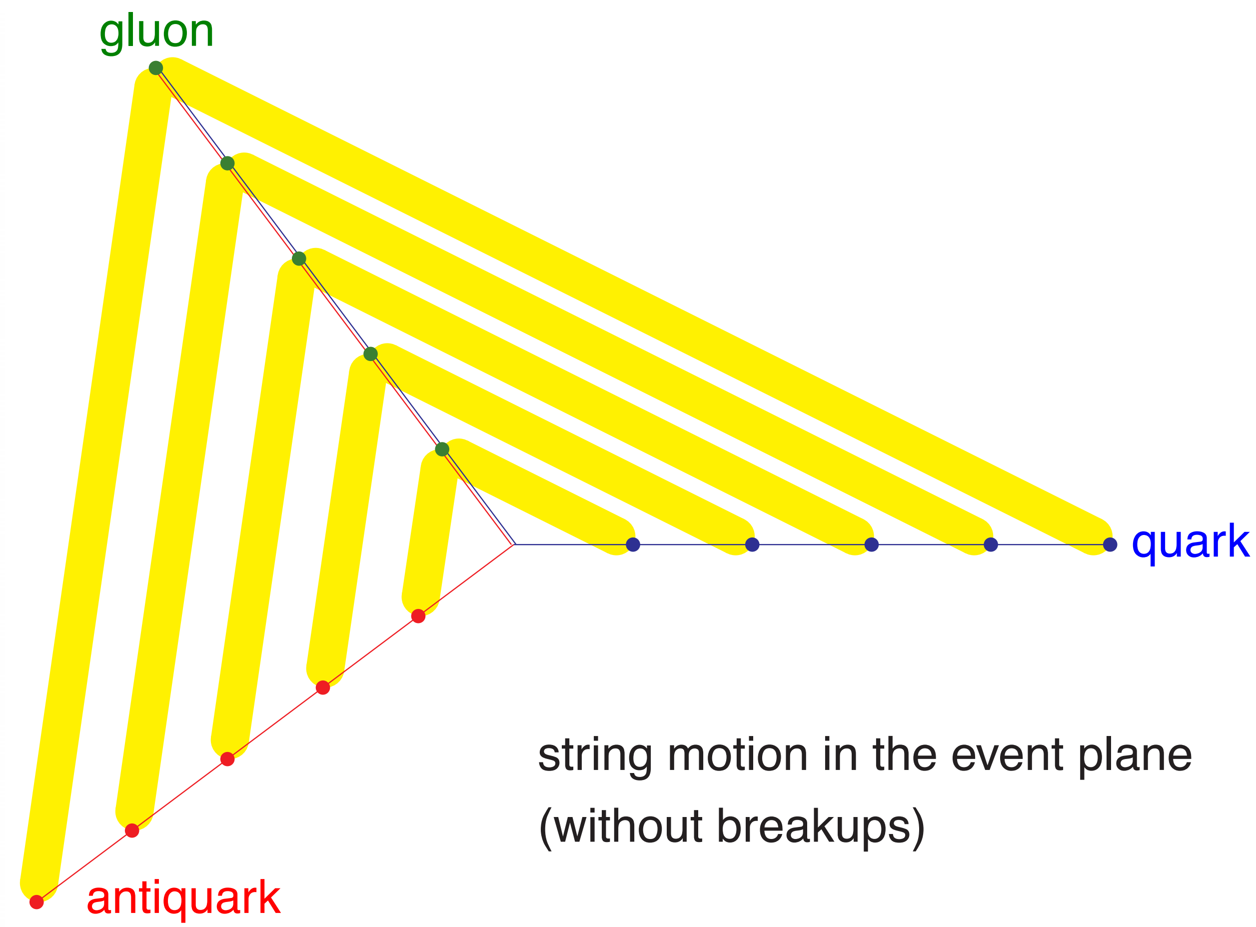
More pronounced for baryons than mesons





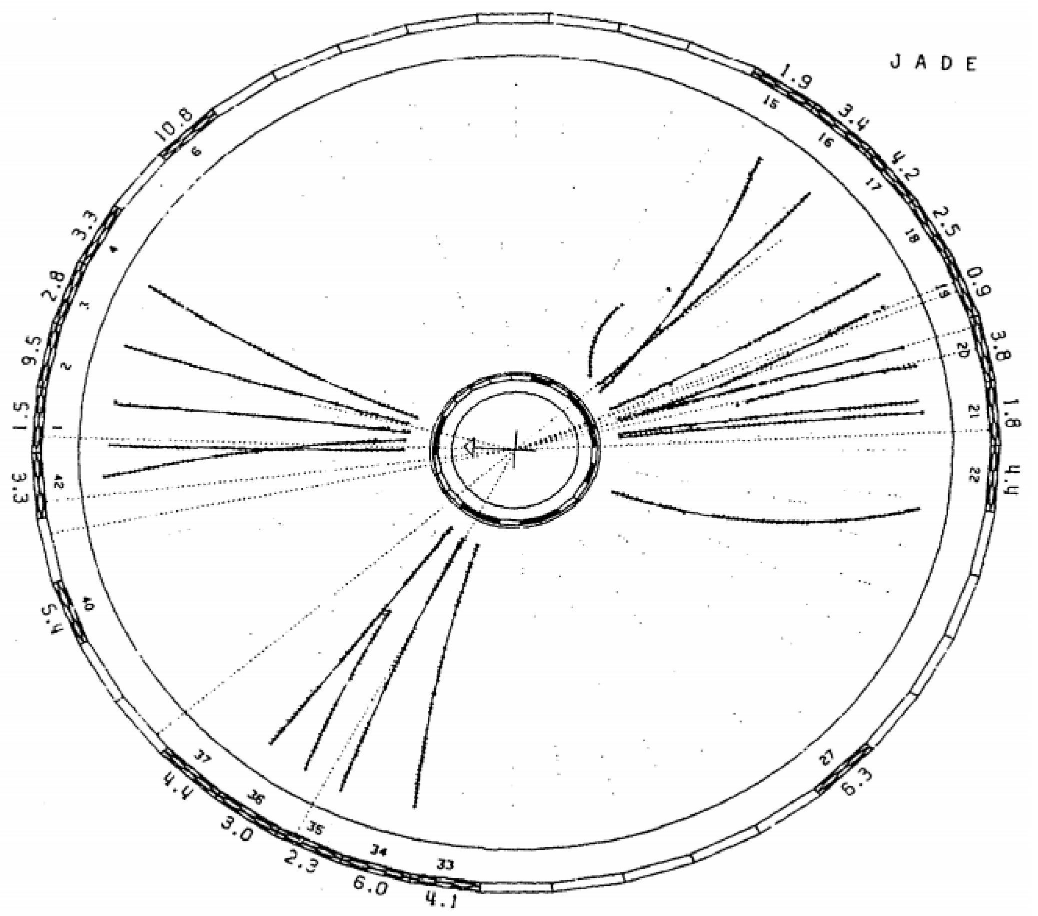
1980: string (colour coherence) effect

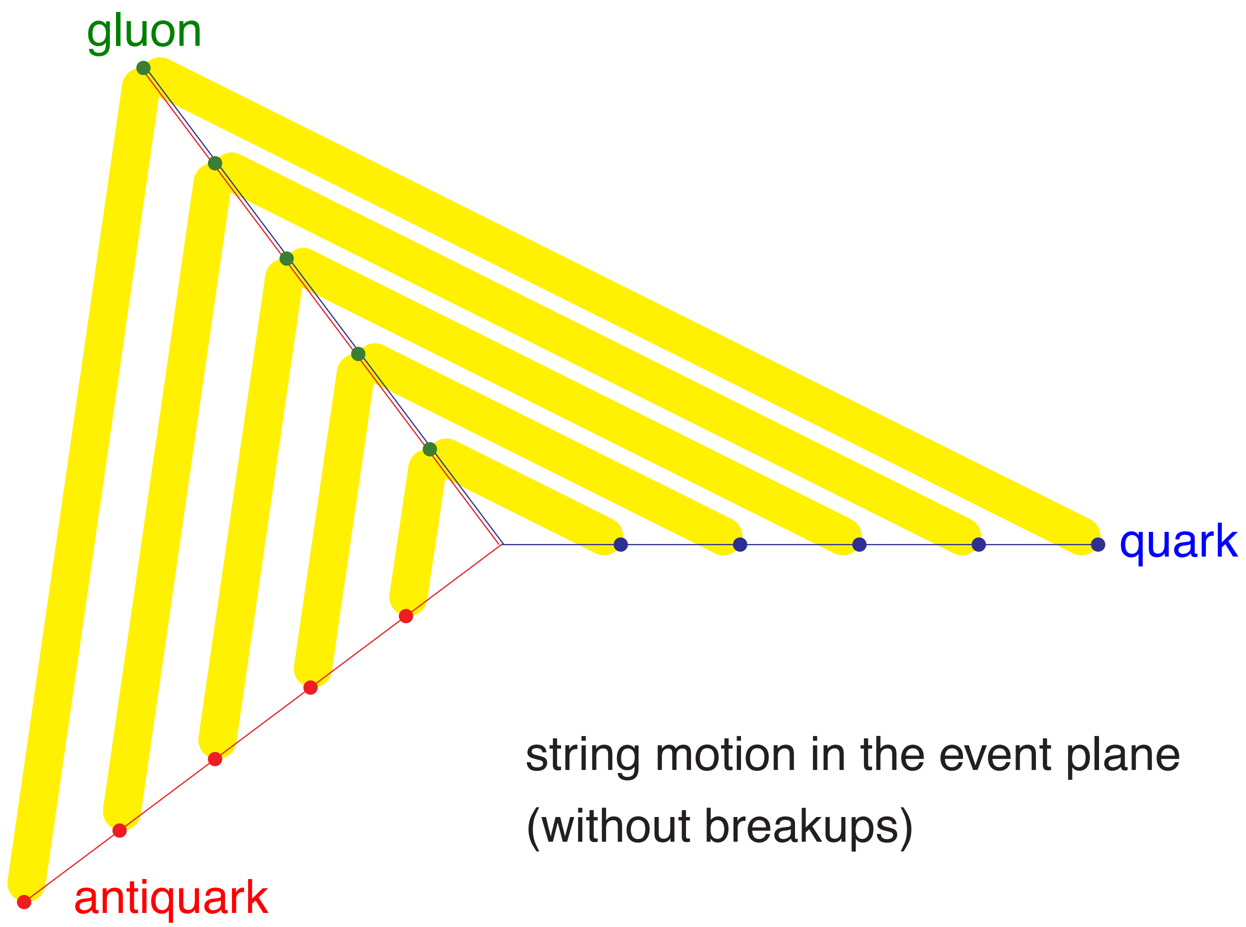


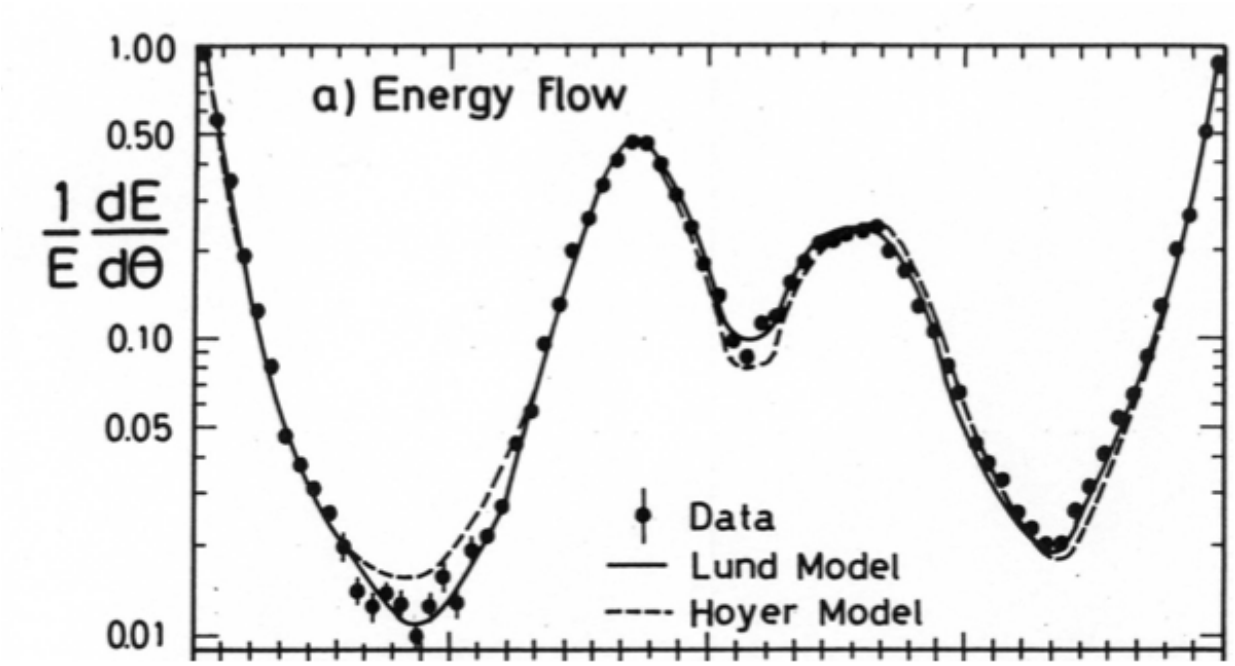


string motion in the event plane
(without breakups)

1980: string (colour coherence) effect







Predicted unique event structure; inside & between jets.

Confirmed first by JADE 1980.

Generator crucial to sell physics!

(today: PS, M&M, MPI, . . .)

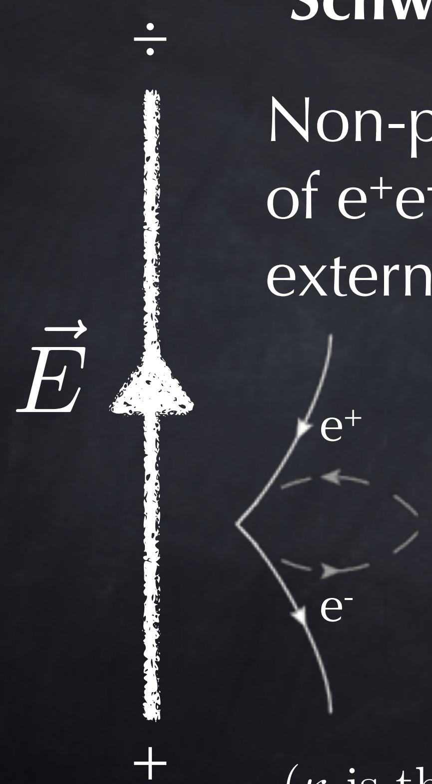
String Breaks

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

In “unquenched” QCD

g→qq → The strings will break

Schwinger Effect



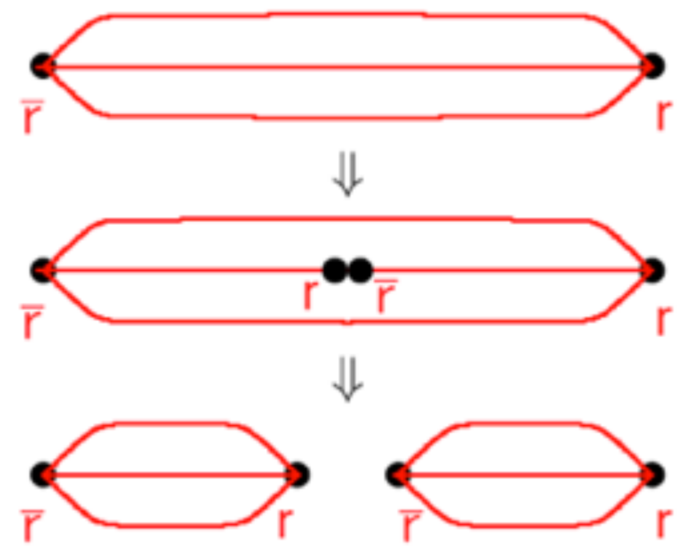
Non-perturbative creation of e^+e^- pairs in a strong external Electric field

Probability from Tunneling Factor

$$\mathcal{P} \propto \exp\left(\frac{-m^2 - p_\perp^2}{\kappa/\pi}\right)$$

(κ is the string tension equivalent)

String Breaks
by Tunneling (Schwinger Type)



→ Gaussian p_T spectrum
Heavier quarks suppressed. Prob(q=d,u,s,c) ≈ 1 : 1 : 0.2 : 10^{-11}

- Breakup vertices causally disconnected → order is irrelevant → iterative algorithm

String Breaks

In QCD, strings can (and do) break!

(In superconductors, would require magnetic monopoles)

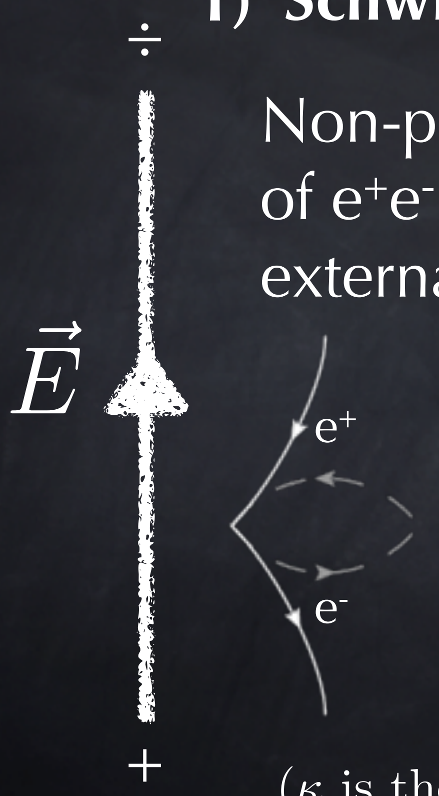
In QCD, the roles of electric and magnetic are reversed

Quarks (and antiquarks) are "chromoelectric monopoles"

There are at least two possible analogies ~ tunneling:

CANONICAL

1) Schwinger Effect



Non-perturbative creation of e^+e^- pairs in a strong external Electric field

Probability from Tunneling Factor

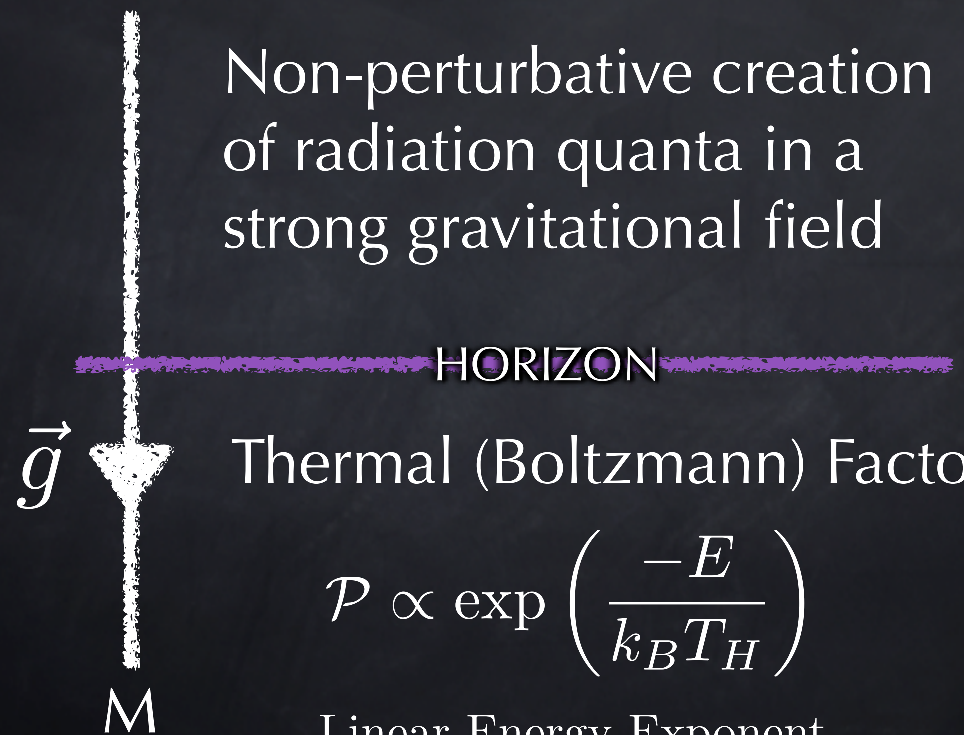
$$\mathcal{P} \propto \exp\left(\frac{-m^2 - p_\perp^2}{\kappa/\pi}\right)$$

(κ is the string tension equivalent)

ALTERNATIVE?

2) Hawking Radiation

Non-perturbative creation of radiation quanta in a strong gravitational field



Thermal (Boltzmann) Factor

$$\mathcal{P} \propto \exp\left(\frac{-E}{k_B T_H}\right)$$

Linear Energy Exponent

What are "Colour Reconnections"?

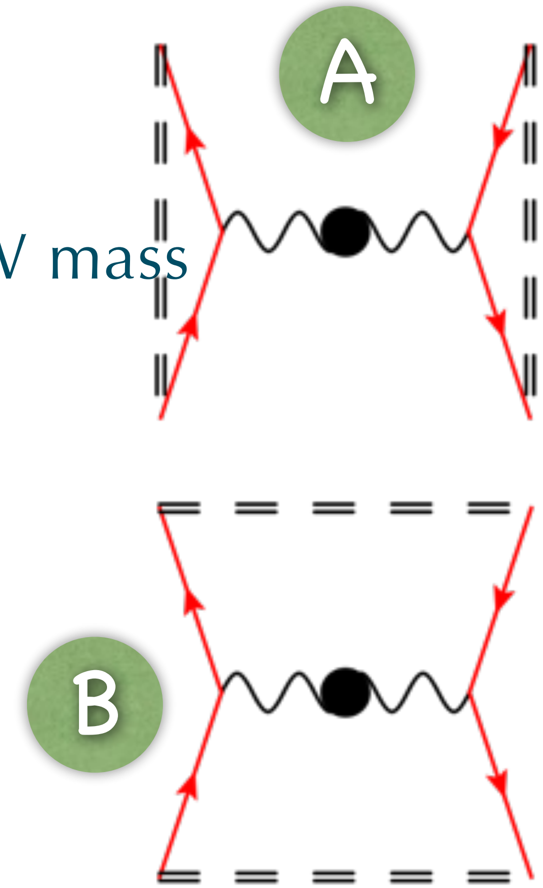
Simple example: $e^+e^- \to W^+W^- \to \text{hadrons}$

Intensely studied at LEP2.

CR implied a non-perturbative uncertainty on the W mass measurement, ΔMW ~ 40 MeV

CR constrained to ~ 10% ~ 1/NC2

Simple two-string system. What about pp?



Several modelling attempts

Based on "just" minimising the string action

String interactions (Khoze, Sjostrand)

Generalized Area Law (Rathsman et al.)

Colour Annealing (Skands et al.)

Gluon Move Model (Sjostrand et al.)

More recently: SU(3)$_C$ group multiplet weights

Dipole Swing (Lonnblad et al.); Colour Ropes (Bierlich et al.)

String Formation Beyond Leading Colour (Skands et al.)

$$\begin{aligned} 3\otimes\bar{3} &= 8\oplus 1 \\ 3\otimes 3 &= 6\oplus\bar{3} \\ 3\otimes 8 &= 15\oplus 6\oplus 3 \\ 8\otimes 8 &= 27\oplus 10\oplus\overline{10}\oplus 8\oplus 8\oplus 1 \end{aligned}$$

See Christiansen & Skands and references therein, **JHEP 1508 (2015) 003**