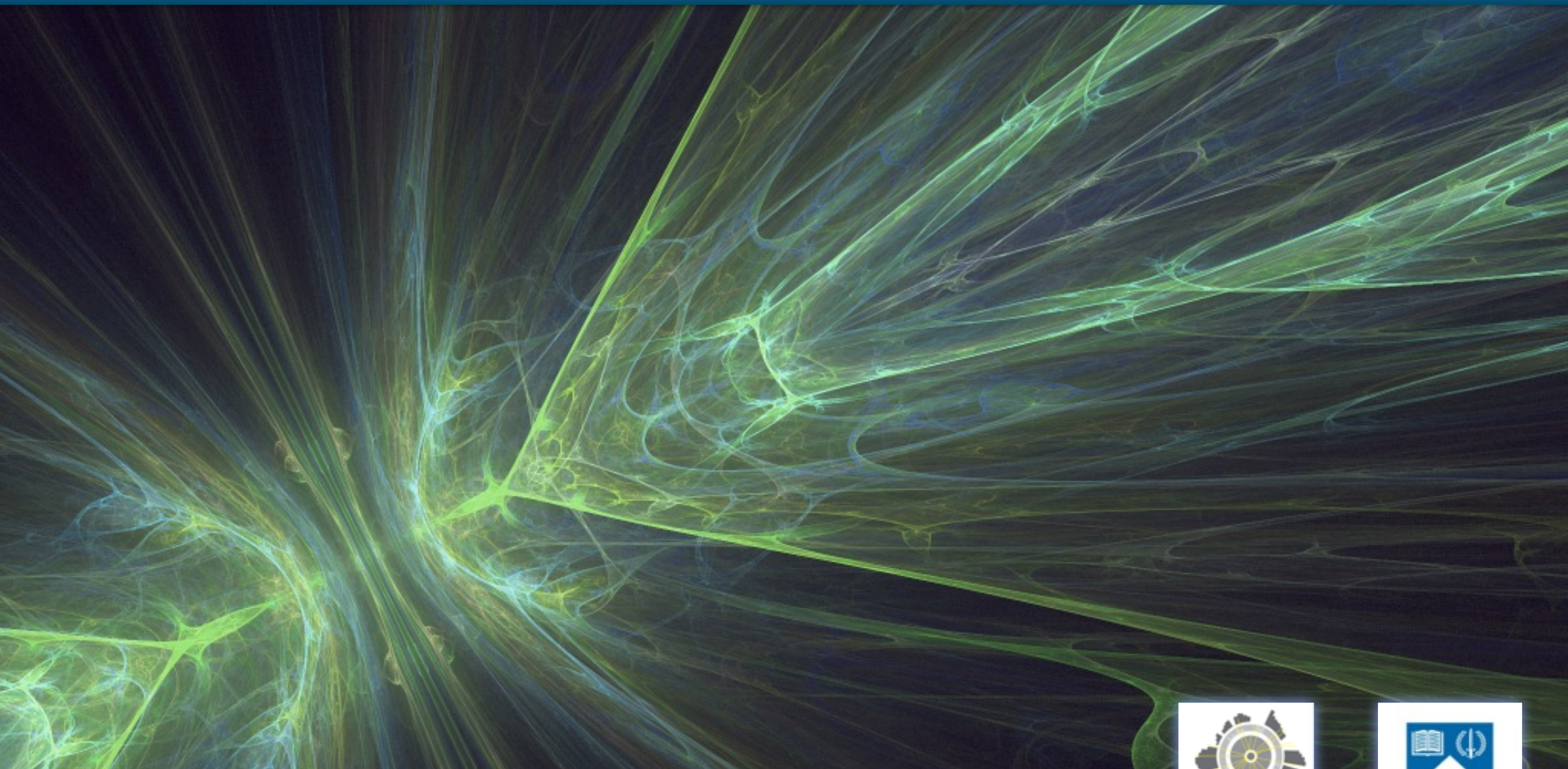
Fractals, Strings, and Particle Collisions

Peter Skands (Monash University)



Physics Colloquium, Adelaide University
May 6, 2016

THE THEORY OF QUARKS AND GLUONS; THE STRONG NUCLEAR FORCE

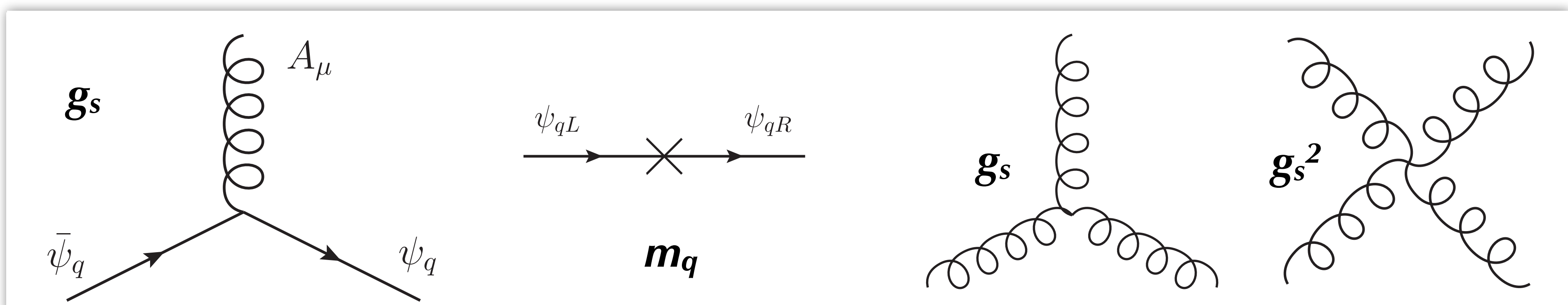
The **elementary** interactions are encoded in the **Lagrangian**

QFT → Feynman Diagrams → Perturbative Expansions (in α_s)

$g_s^2 = 4\pi\alpha_s$

THE BASIC ELEMENTS OF QCD: QUARKS AND GLUONS

$$\psi_q^j = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}$$



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

$$D_{\mu ij} = \delta_{ij}\partial_\mu - i g_s T_{ij}^a A_\mu^a$$

Gauge Covariant Derivative: makes *L* invariant under $SU(3)_C$ rotations of ψ_q

m_q: Quark Mass Terms (Higgs + QCD condensates)

Gluon-Field Kinetic Terms and Self-Interactions

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f^{abc} A_\mu^b A_\nu^c$$

More than just a (fixed-order perturbative) expansion in α_s

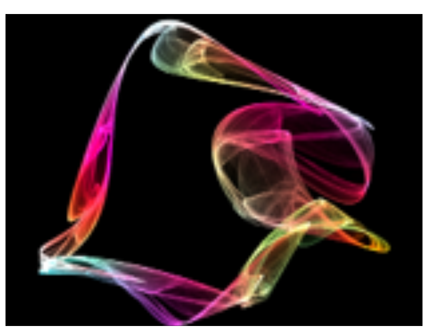
Two sources of fascinating multi-particle structures

Scale Invariance (apparent from the massless Lagrangian)

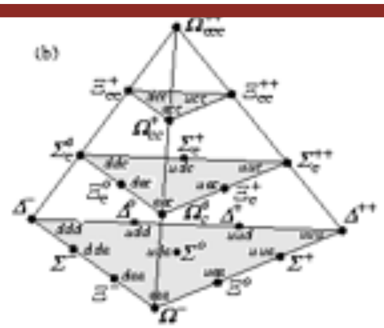
Confinement (win $1,000,000 if you can prove)

most of my research

Jets (the fractal of perturbative QCD) ↔ amplitude structures in quantum field theory ↔ factorisation & unitarity. Precision jet (structure) studies.



Strings (strong gluon fields) ↔ quantum-classical correspondence. String physics. String breaks. Dynamics of hadronization phase transition.



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.

The Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Run 2 now underway …
Almost twice the energy *(13 TeV vs 8 TeV)*
Higher intensities … *(at least until last Friday)*

\+ … … … ?

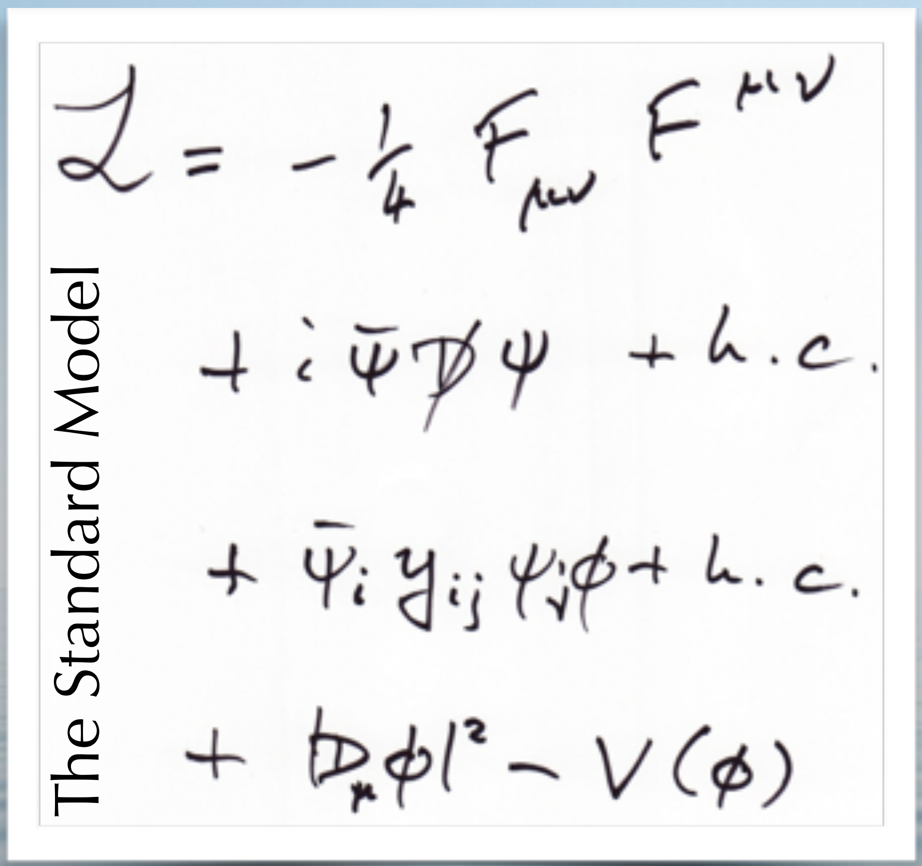
LHC Run 1: still no explicit "new physics"

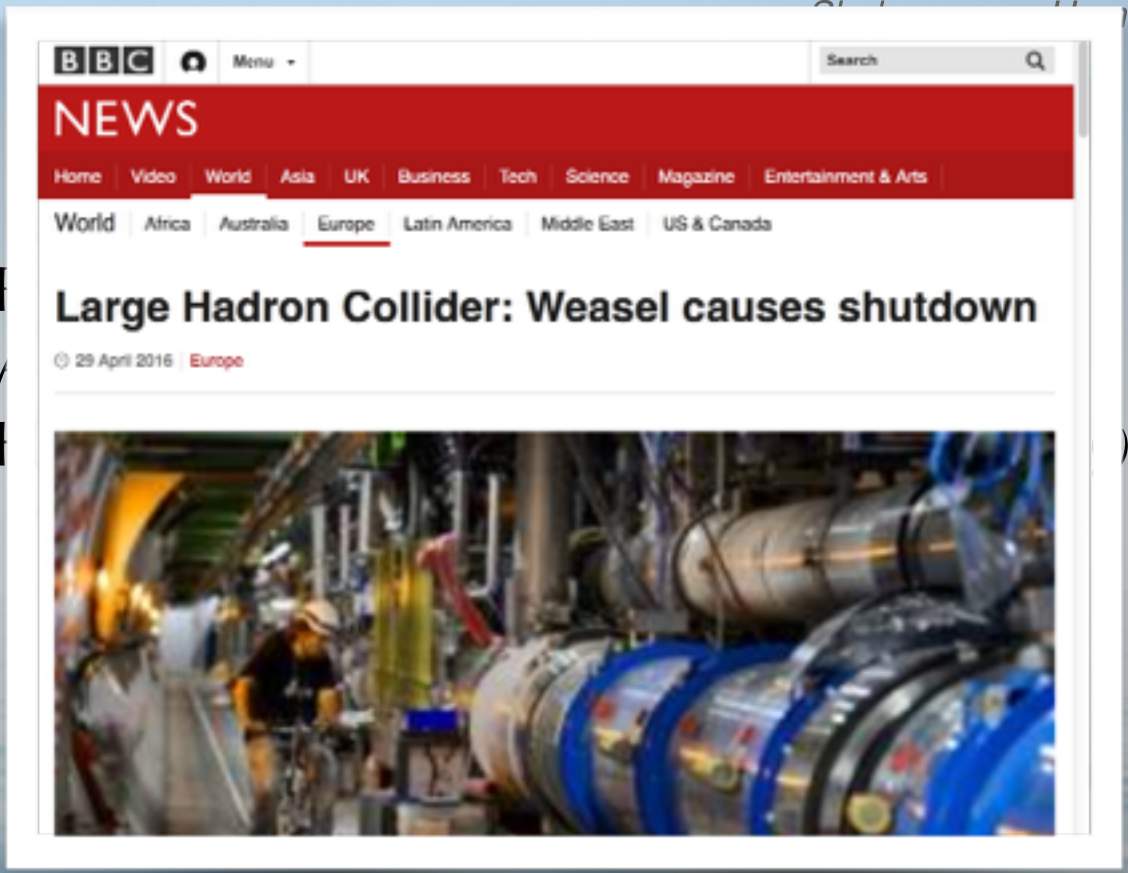
→ we're still looking for *deviations* from SM

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

Ulterior Motives for Studying QCD

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





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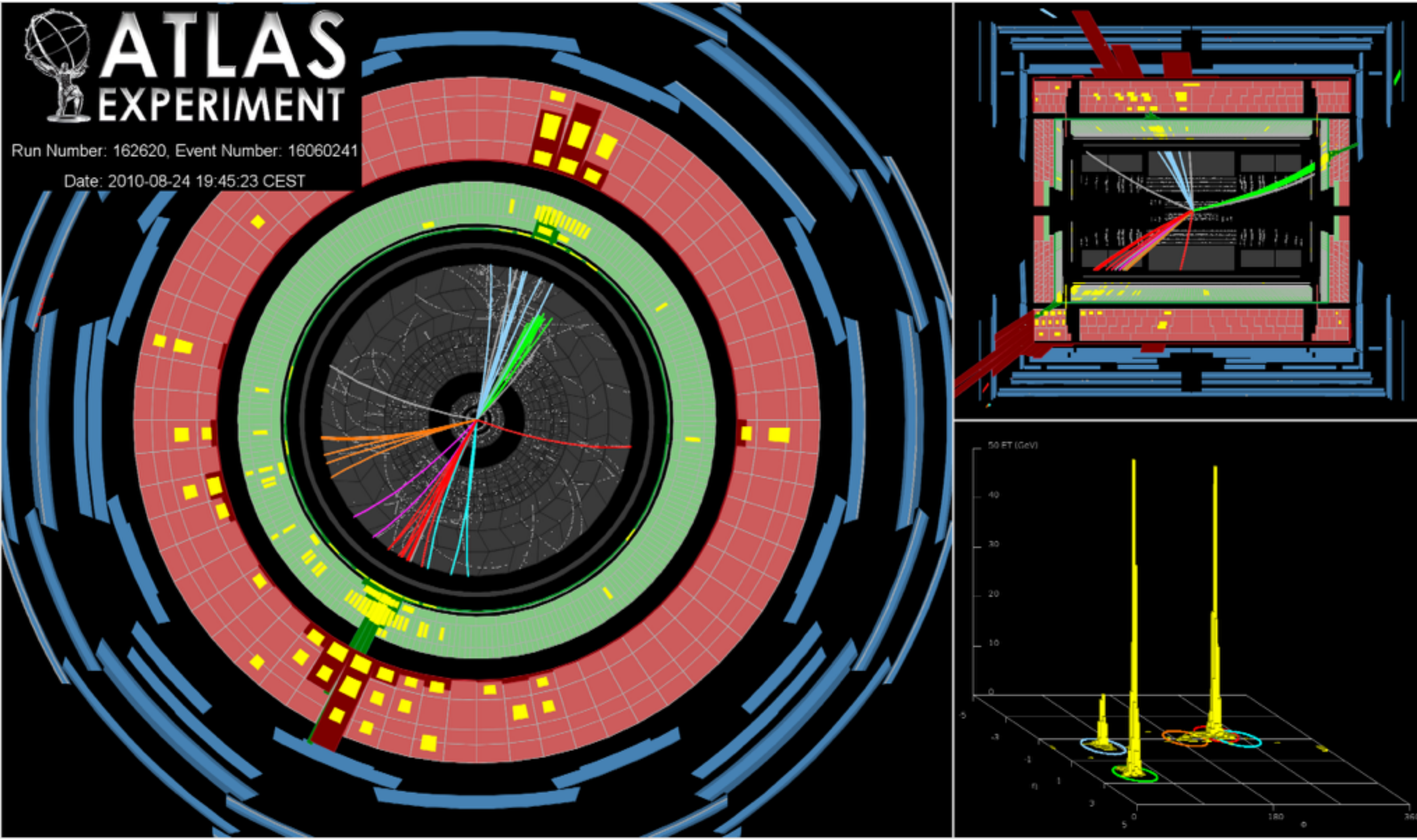


- 1st jet: p_T = 520 GeV, η = -1.4, ϕ = -2.0
- 2nd jet: p_T = 460 GeV, η = 2.2, ϕ = 1.0
- 3rd jet: p_T = 130 GeV, η = -0.3, ϕ = 1.2
- 4th jet: p_T = 50 GeV, η = -1.0, ϕ = -2.9

QCD in the Ultraviolet

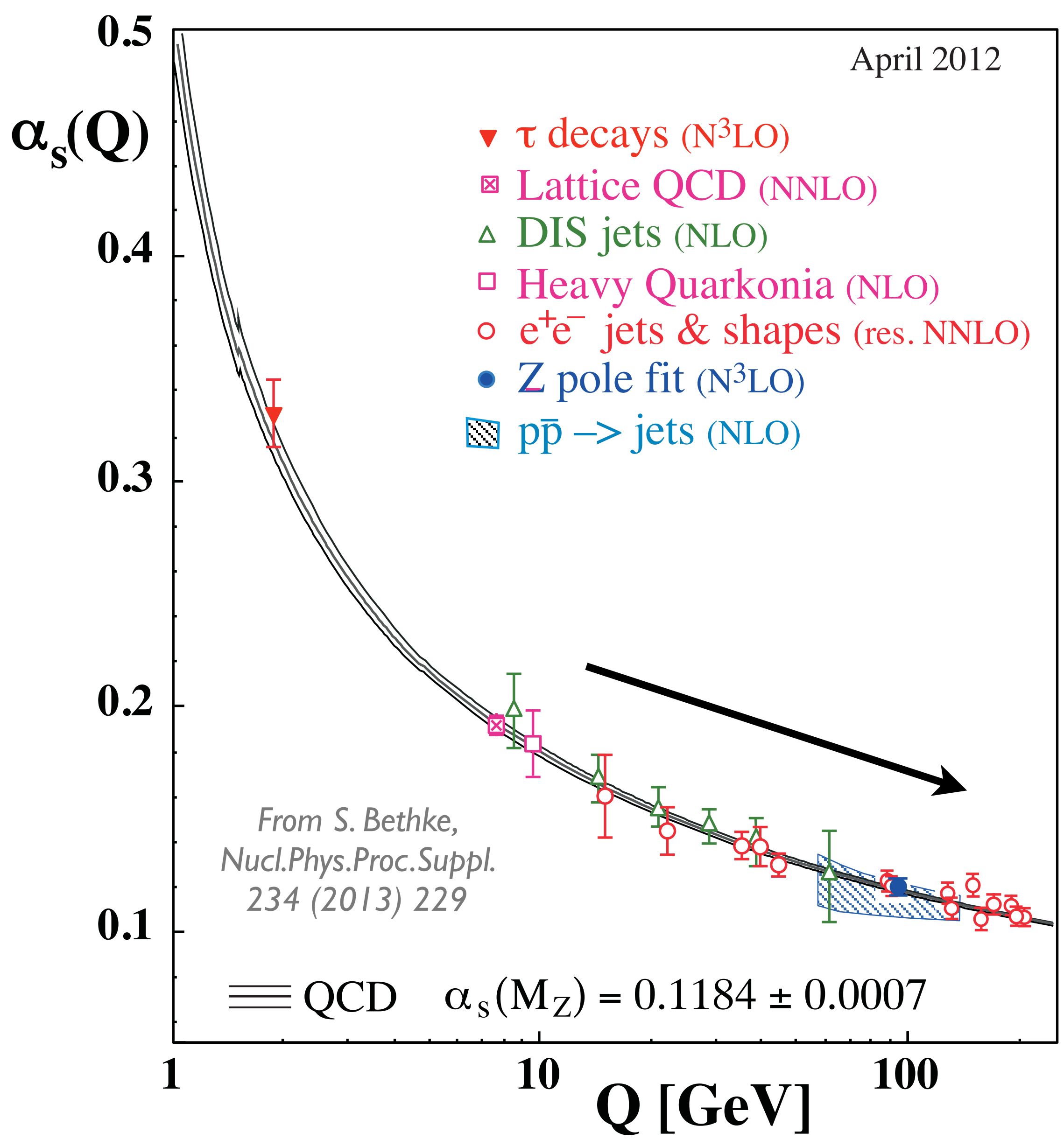
The "running" of α_s:

$$Q^2 \frac{\partial \alpha_s}{\partial Q^2} = -\alpha_s^2 (b_0 + b_1 \alpha_s + b_2 \alpha_s^2 + \ldots) \; ,$$

$$b_0 = \frac{11 C_A - 2 n_f}{12\pi}$$

C_A=3 for SU(3)

$$b_1 = \frac{17 C_A^2 - 5 C_A n_f - 3 C_F n_f}{24\pi^2} = \frac{153 - 19 n_f}{24\pi^2} \quad b_2 = \frac{2857 - 5033 n_f + 325 n_f^2}{128\pi^3} \quad b_3 = \mathrm{known}$$



Full symbols are results based on N3LO QCD, open circles are based on NNLO, open triangles and squares on NLO QCD. The cross-filled square is based on lattice QCD.

At high scales Q >> 1 GeV

Coupling $\alpha_s(Q) \ll 1$

Perturbation theory in α_s should be **reliable**: LO, NLO, NNLO, …

E.g., in event shown on previous slide:

- 1st jet: p_T = 520 GeV
- 2nd jet: p_T = 460 GeV
- 3rd jet: p_T = 130 GeV
- 4th jet: p_T = 50 GeV

The Infrared Strikes Back

Naively, QCD radiation suppressed by $\alpha_s \approx 0.1$

Truncate at fixed order = LO, NLO, …

E.g., $\sigma(X+\text{jet})/\sigma(X) \propto \alpha_s$

Example: Pair production of SUSY particles at LHC_{14}, with $M_{SUSY} \approx 600$ GeV

LHC - sps1a - m~600 GeV   Plehn, Rainwater, PS PLB645(2007)217

FIXED ORDER pQCD	σ_{tot}[pb]	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$	$\tilde{u}_L\tilde{u}_L^*$	$\tilde{u}_L\tilde{u}_L$	TT
$p_{T,j} >$ 100 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
inclusive **X + 1 “jet”** →	σ_{1j}	2.89	2.74	0.136	0.145	0.73
inclusive **X + 2 “jets”** →	σ_{2j}	1.09	0.85	0.049	0.039	0.26
$p_{T,j} >$ 50 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
	σ_{1j}	5.90	5.37	0.283	0.285	1.50
	σ_{2j}	4.17	3.18	0.179	0.117	1.21

(Computed with SUSY-MadGraph)

σ for X + jets much larger than naive estimate

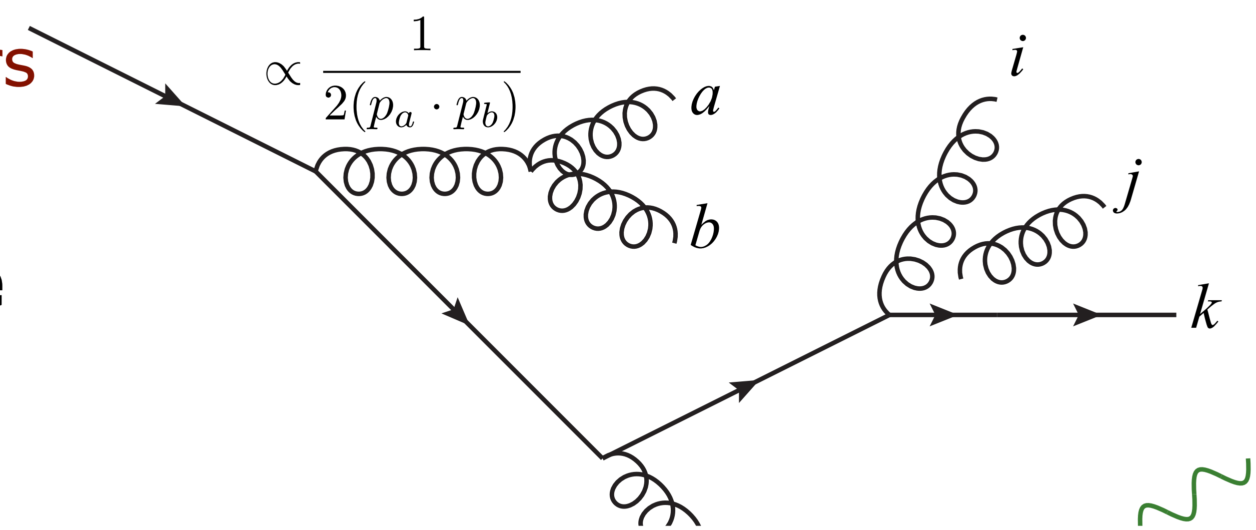
$\sigma_{50} \sim \sigma_{tot}$ tells us that there will “always” be a ~ 50-GeV jet “inside” a 600-GeV process

All the scales are high, Q >>1 GeV, so perturbation theory **should** be OK …

Jets have fractal substructure

see PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

Most bremsstrahlung is driven by divergent propagators → simple structure



Gauge amplitudes factorize in singular limits (→ universal *"conformal"* or *"fractal"* structure)

Partons ab → collinear:

P(z) = Altarelli-Parisi splitting kernels, with z = $E_a/(E_a+E_b)$

$$|\mathcal{M}_{F+1}(\ldots,a,b,\ldots)|^2 \overset{a||b}{\to} g_s^2 \mathcal{C} \frac{P(z)}{2(p_a \cdot p_b)} |\mathcal{M}_F(\ldots,a+b,\ldots)|^2$$

Gluon j → soft:

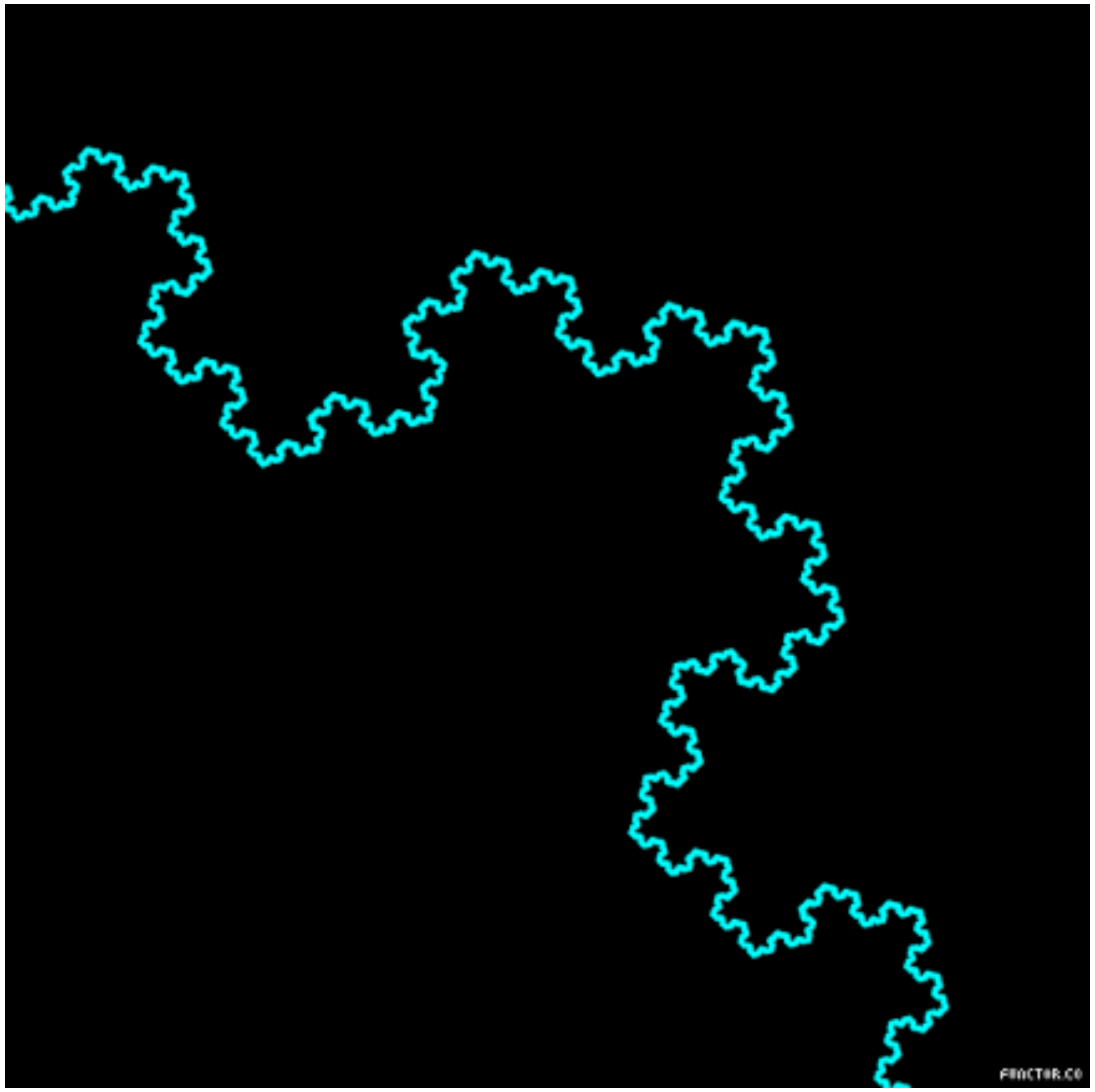
Coherence → Parton j really emitted by (i,k) "antenna"

$$|\mathcal{M}_{F+1}(\ldots,i,j,k\ldots)|^2 \overset{j_g\to 0}{\to} g_s^2 \mathcal{C} \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |\mathcal{M}_F(\ldots,i,k,\ldots)|^2$$

+ scaling violation: $g_s^2 \to 4\pi\alpha_s(Q^2)$

Jets have fractal substructure

Can apply this many times → nested factorizations → iteratively build up fractal structure



Can be cast as a differential **evolution** in the resolution scale, $dProb/dQ^2$

It's a ***quantum*** fractal: P is **probability** to resolve another jet as we decrease the scale

Eventually, it becomes more unlikely **not** to resolve a jet, than to resolve one

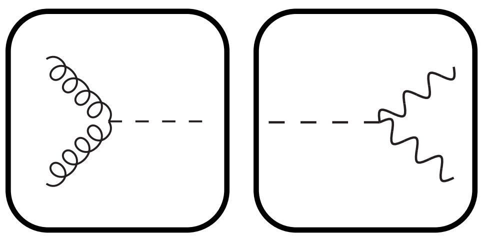
That's what the X+jet cross sections were trying to tell us earlier: $\sigma(X+jet) > \sigma(X)$

Monte Carlo Event Generators: Divide and Conquer

Factorization → Split the problem into many (nested) pieces

+ Quantum mechanics → Probabilities → Random Numbers

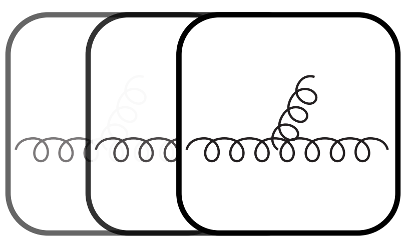
$$\mathcal{P}_{\mathrm{event}} = \mathcal{P}_{\mathrm{hard}} \otimes \mathcal{P}_{\mathrm{dec}} \otimes \mathcal{P}_{\mathrm{ISR}} \otimes \mathcal{P}_{\mathrm{FSR}} \otimes \mathcal{P}_{\mathrm{MPI}} \otimes \mathcal{P}_{\mathrm{Had}} \otimes \ldots$$



Hard Process & Decays:

Use process-specific (N)LO matrix elements

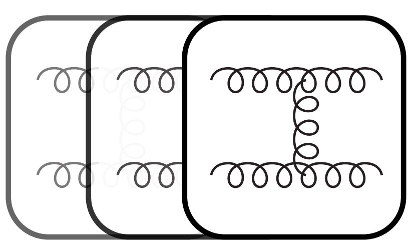
→ Sets "hard" resolution scale for process: Q_{MAX}



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

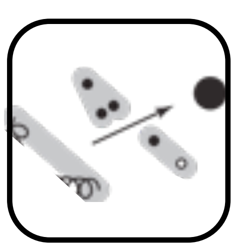
(More later)



MPI (Multi-Parton Interactions)

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

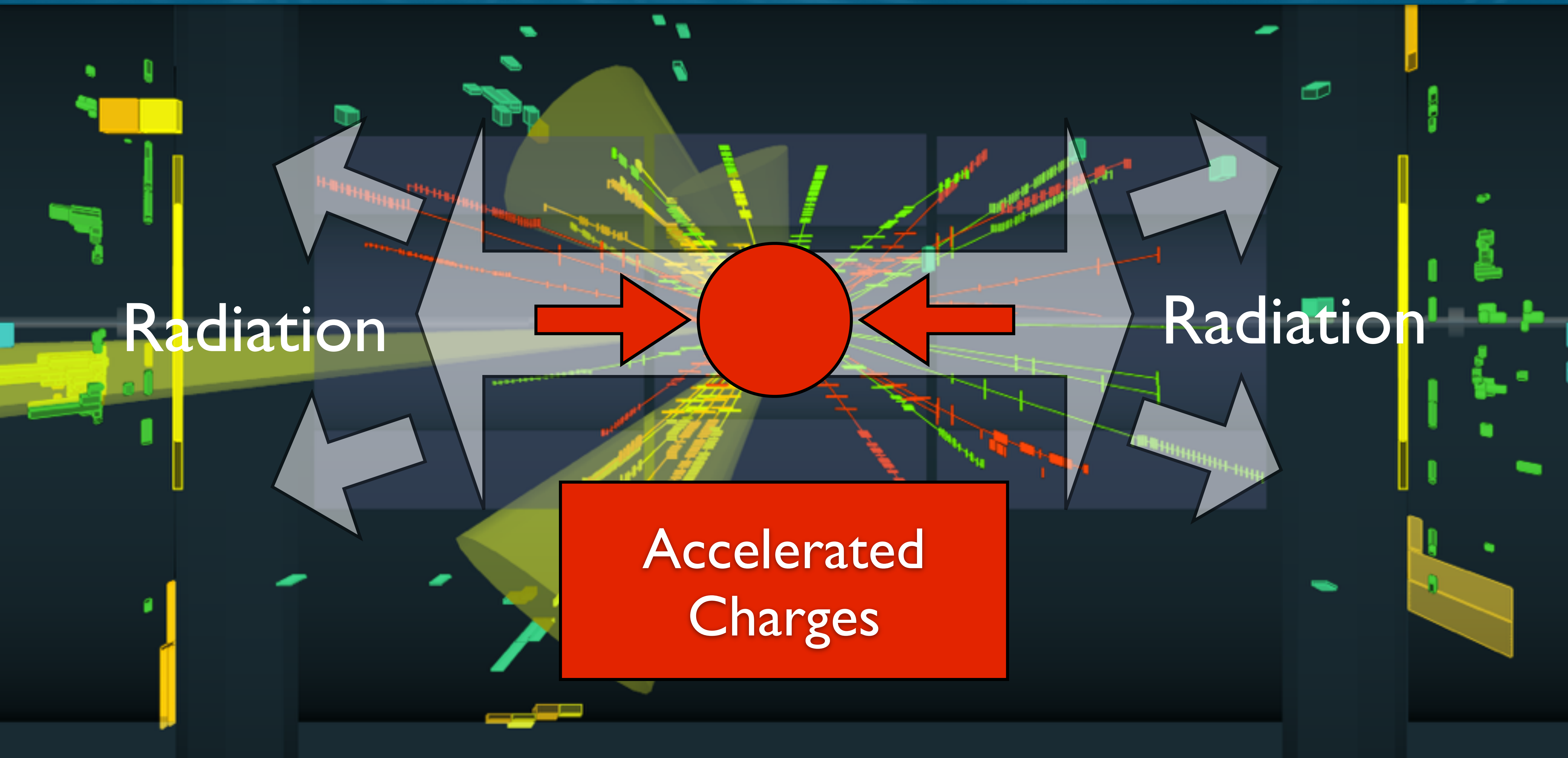
→ Additional (soft) "Underlying-Event" activity (Not the topic for today)



Hadronization

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

This is just the physics of Bremsstrahlung

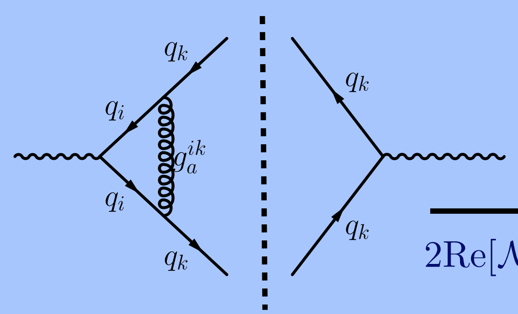


The harder they get kicked, the harder the fluctations that continue to become strahlung see PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

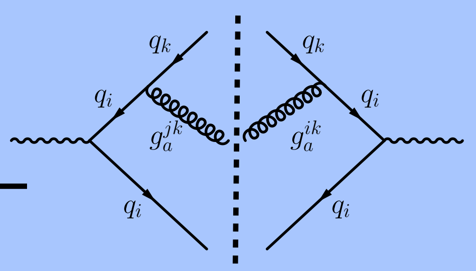
Unitarity: sum(probability) = 1

Kinoshita-Lee-Nauenberg:

(sum over degenerate quantum states = finite: infinities must cancel!)



$$\xrightarrow[2\mathrm{Re}[\mathcal{M}^{(1)}\mathcal{M}^{(0)*}]]{} \mathrm{Loop} = -\int \mathrm{Tree} + F \xleftarrow[\left|\mathcal{M}^{(0)}_{+1}\right|^2]{}$$



Neglect non-singular piece, F → "Leading-Logarithmic" (LL) Approximation

→ Can also include loops-within-loops-within-loops …

→ Bootstrap for approximate All-Orders Quantum Corrections!

Parton Showers: reformulation of pQCD corrections as gain-loss diff eq.

Iterative (Markov-Chain) evolution algorithm, based on universality and unitarity

With evolution kernel ~ $\frac{|\mathcal{M}_{n+1}|^2}{|\mathcal{M}_n|^2}$ (or soft/collinear approx thereof)

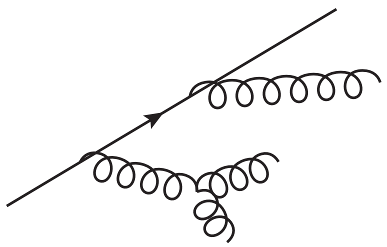
Generate explicit fractal structure across all scales (via Monte Carlo Simulation)

Evolve in some measure of *resolution* ~ hardness, virtuality, 1/time … ~ fractal scale

+ account for scaling violation via quark masses and $g_s^2 \to 4\pi\alpha_s(Q^2)$

Our Research

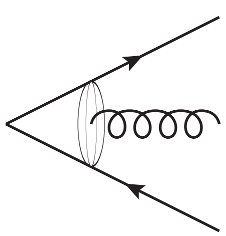
Parton Showers are based on 1→2 splittings



E.g., **PYTHIA** (also HERWIG, SHERPA)

- I.e., each **parton** undergoes a sequence of splittings
  - Dipole coherence effects can be included via “angular ordering” or via “dipole radiation functions” (~dipole partitioned into 2 monopole terms)
  - Recoil effects needed to impose (E,p) conservation (“local” or “global”)

At Monash, we develop an **Antenna Shower**, in which splittings are fundamentally 2→3 (+ working on 2→4…)



E.g., **VINCIA**
(also ARIADNE)

- Each colour **dipole/antenna** undergoes a sequence of splittings
  - + Intrinsically includes dipole coherence (leading N_C)
  - + Lorentz invariance and explicit local (E,p) conservation
  - + The non-perturbative limit of a colour dipole is a string piece
    - **Roots in Lund ~ mid-80ies: Gustafson & Petterson, Nucl.Phys. B306 (1988) 746**

- What’s new in our approach?
  - Higher-order perturbative effects can be introduced via calculable corrections in an elegant and very efficient way
  - + Writing a genuine antenna shower also for the initial state evolution

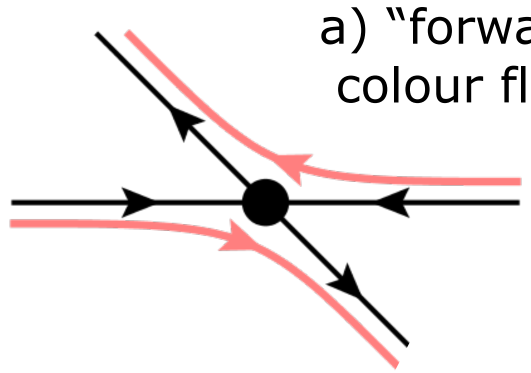
New: Hadron Collisions

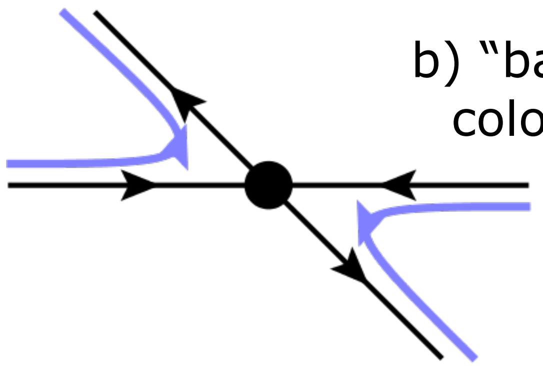
Example taken from: Ritzmann, Kosower, PS, PLB718 (2013) 1345

Example: quark-quark scattering in hadron collisions

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

2 possible colour flows: a and b





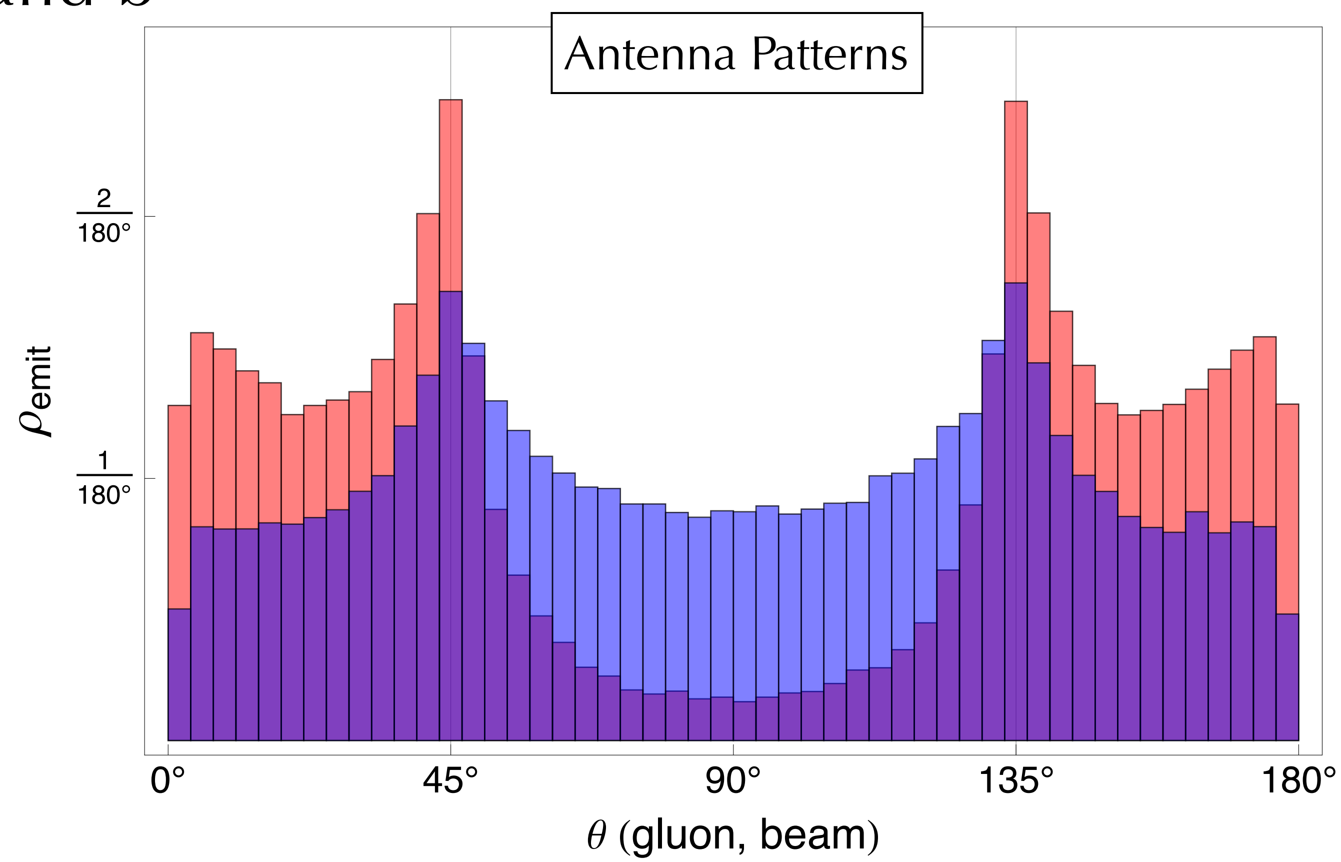


Figure 4: Angular distribution of the first gluon emission in $qq \to qq$ scattering at 45°, for the two different color flows. The light (red) histogram shows the emission density for the forward flow, and the dark (blue) histogram shows the emission density for the backward flow.

April 2016
First public release
of Vincia 2.0 (LHC)
(restricted to massless QCD)

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

VINCIA: Markovian pQCD*

Virtual Numerical Collider with Interleaved Antennae

*) pQCD : perturbative QCD

Start at Born level

$$|M_F|^2$$

Generate "shower" emission

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

Correct to Matrix Element

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

Unitarity of Shower

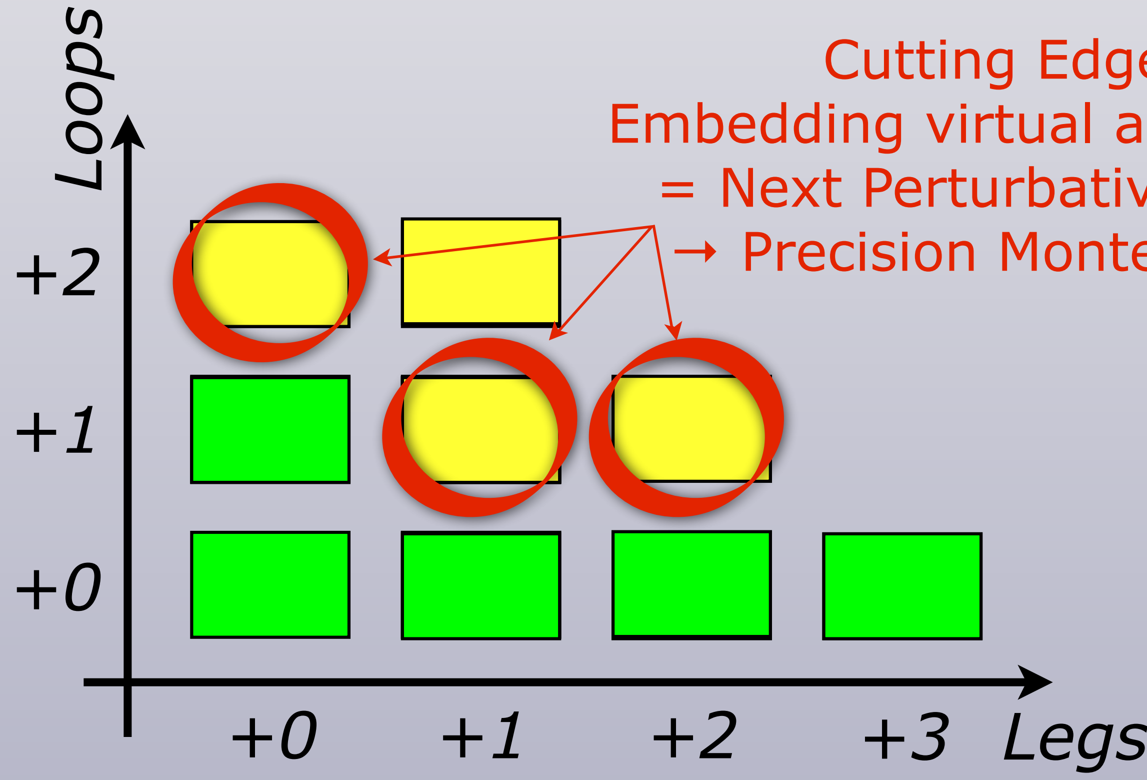
$$\mathrm{Virtual} = -\int \mathrm{Real}$$

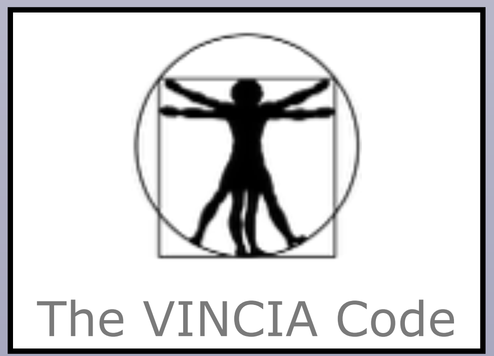
Correct to Matrix Element

$$|M_F|^2 \to |M_F|^2 + 2\mathrm{Re}[M_F^1 M_F^0] + \int \mathrm{Real}$$

Repeat

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





+

"Higher-Order Corrections To Timelike Jets"
GeeKS: Giele, Kosower, Skands, PRD 84 (2011) 054003

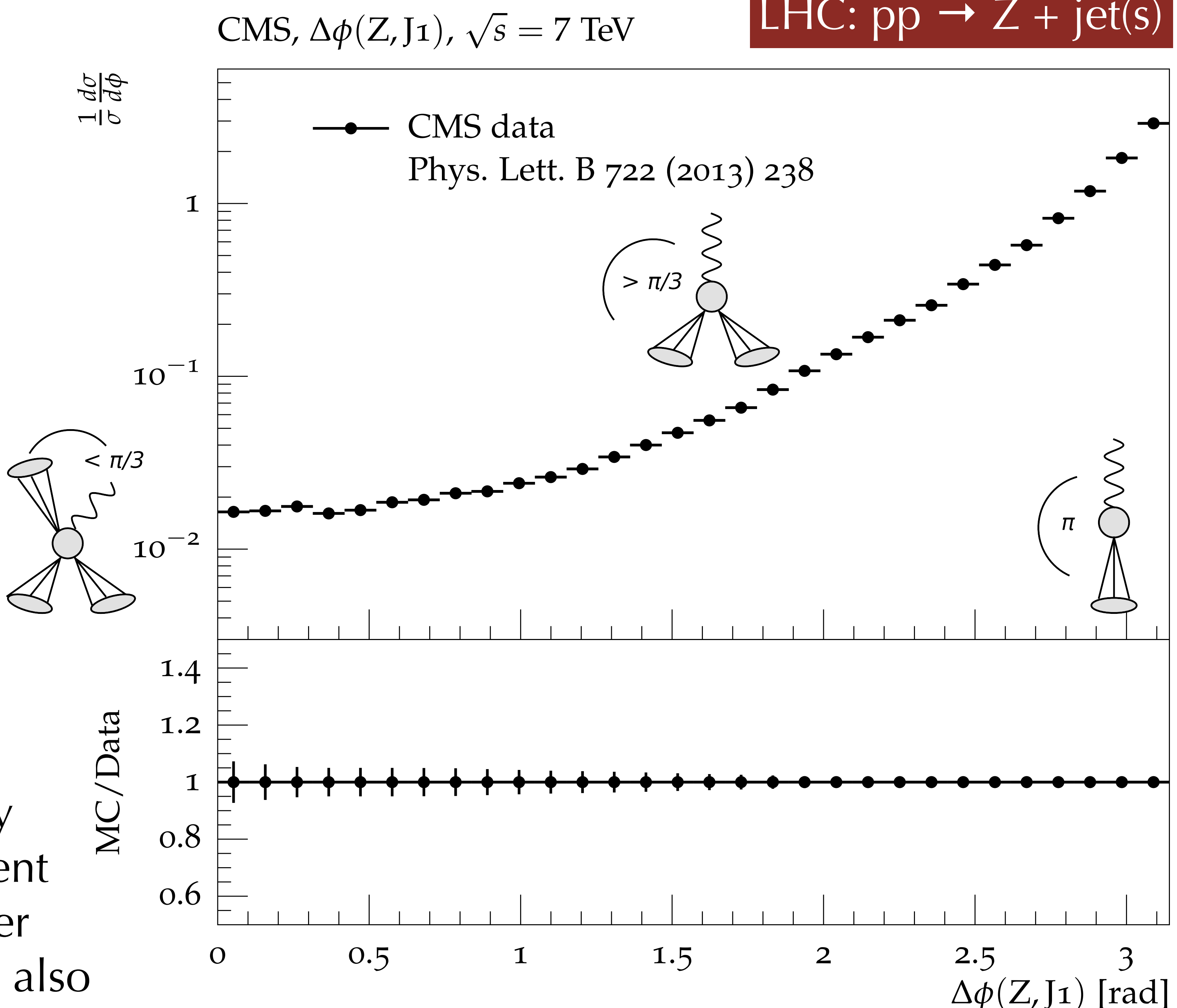
"An Introduction to PYTHIA 8.2"
Sjöstrand et al., Comput.Phys.Commun. 191 (2015) 159

Matrix-Element Corrections for ISR

NEW!

Predictions made with publicly available VINCIA 2.0.01 (vincia.hepforge.org) + PYTHIA 8 + MADGRAPH 4

LHC: pp → Z + jet(s)



Angle between Z and the hardest jet

Work done by my PhD student Nadine Fischer (from whom I also stole these slides)

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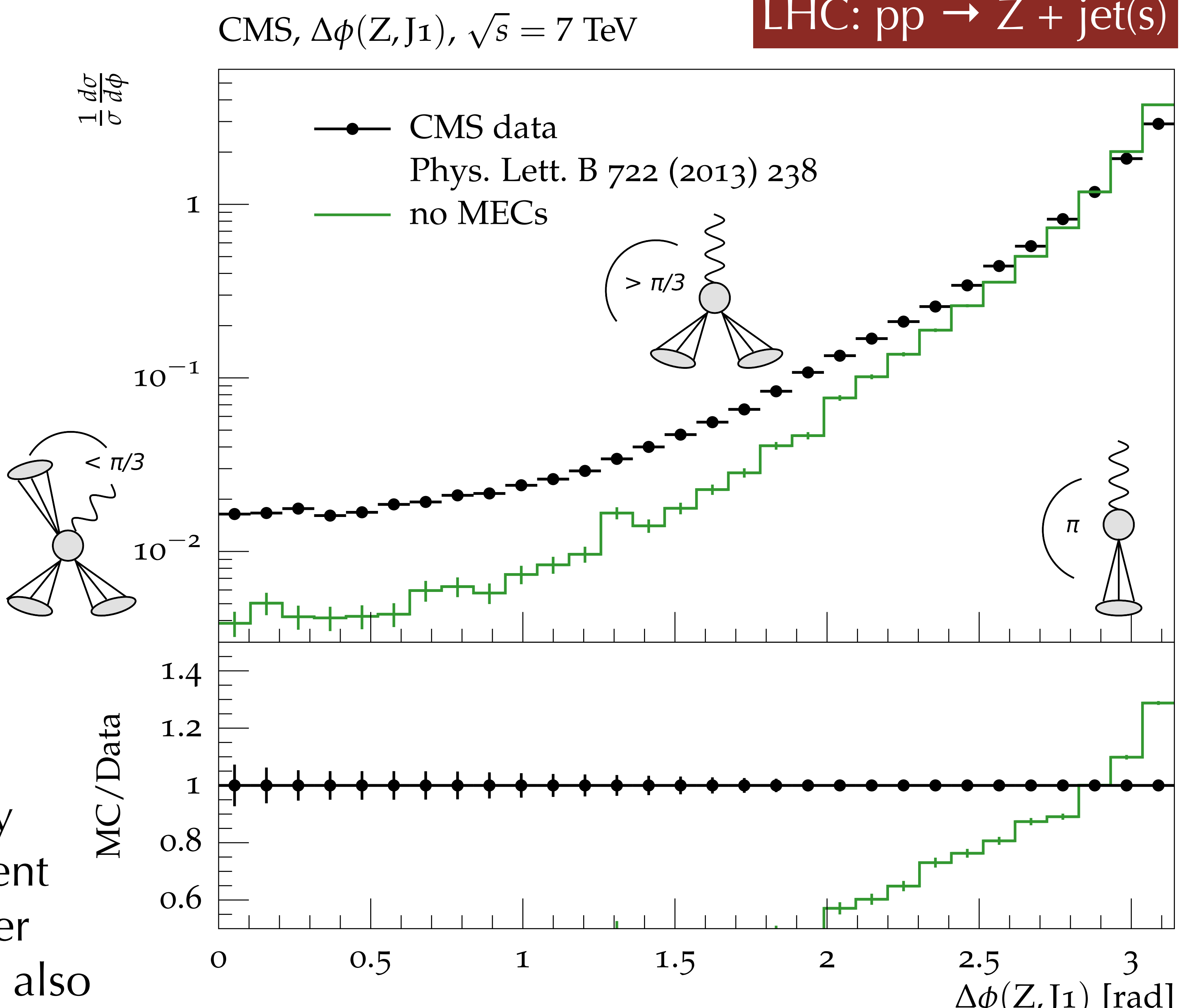

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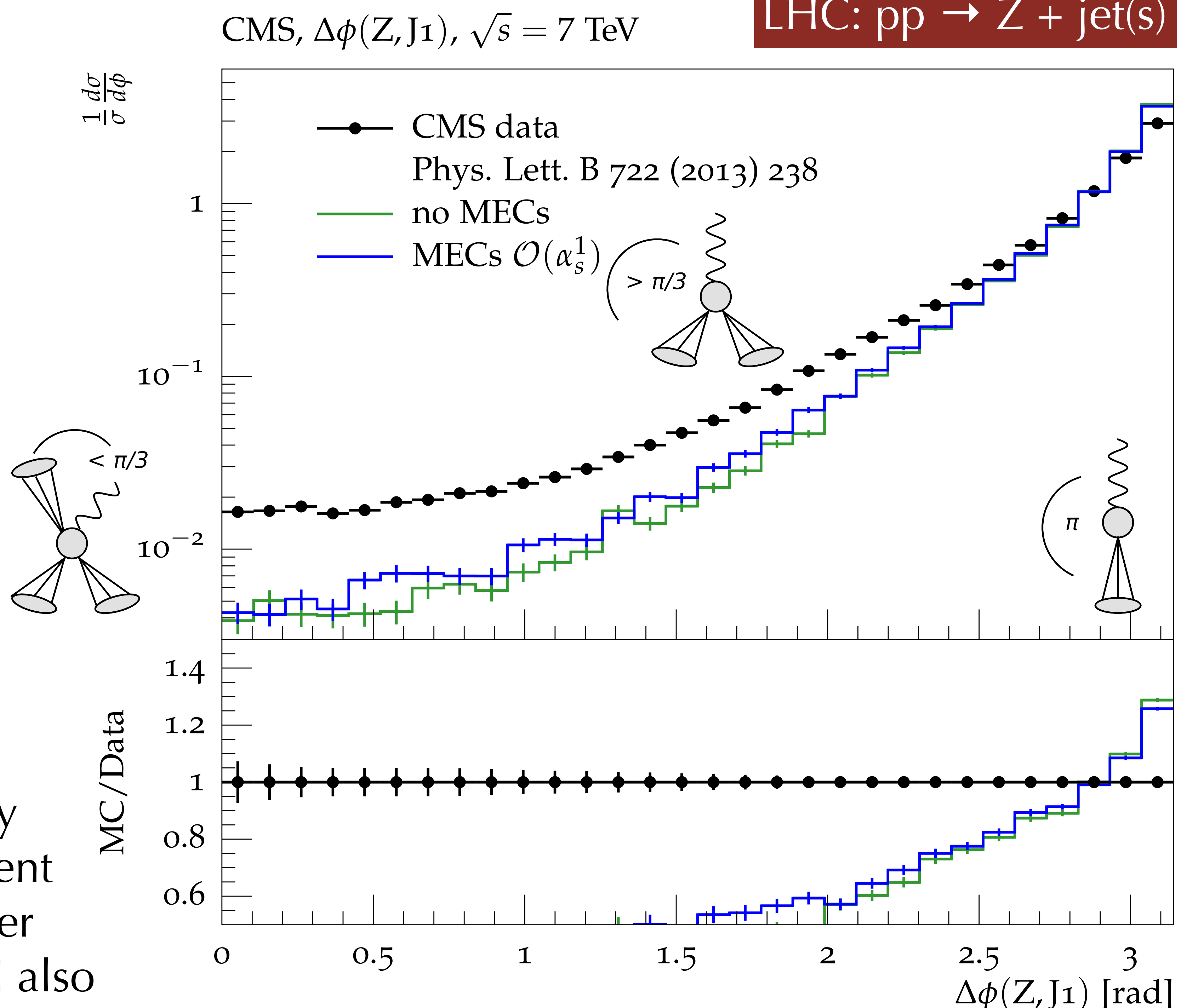

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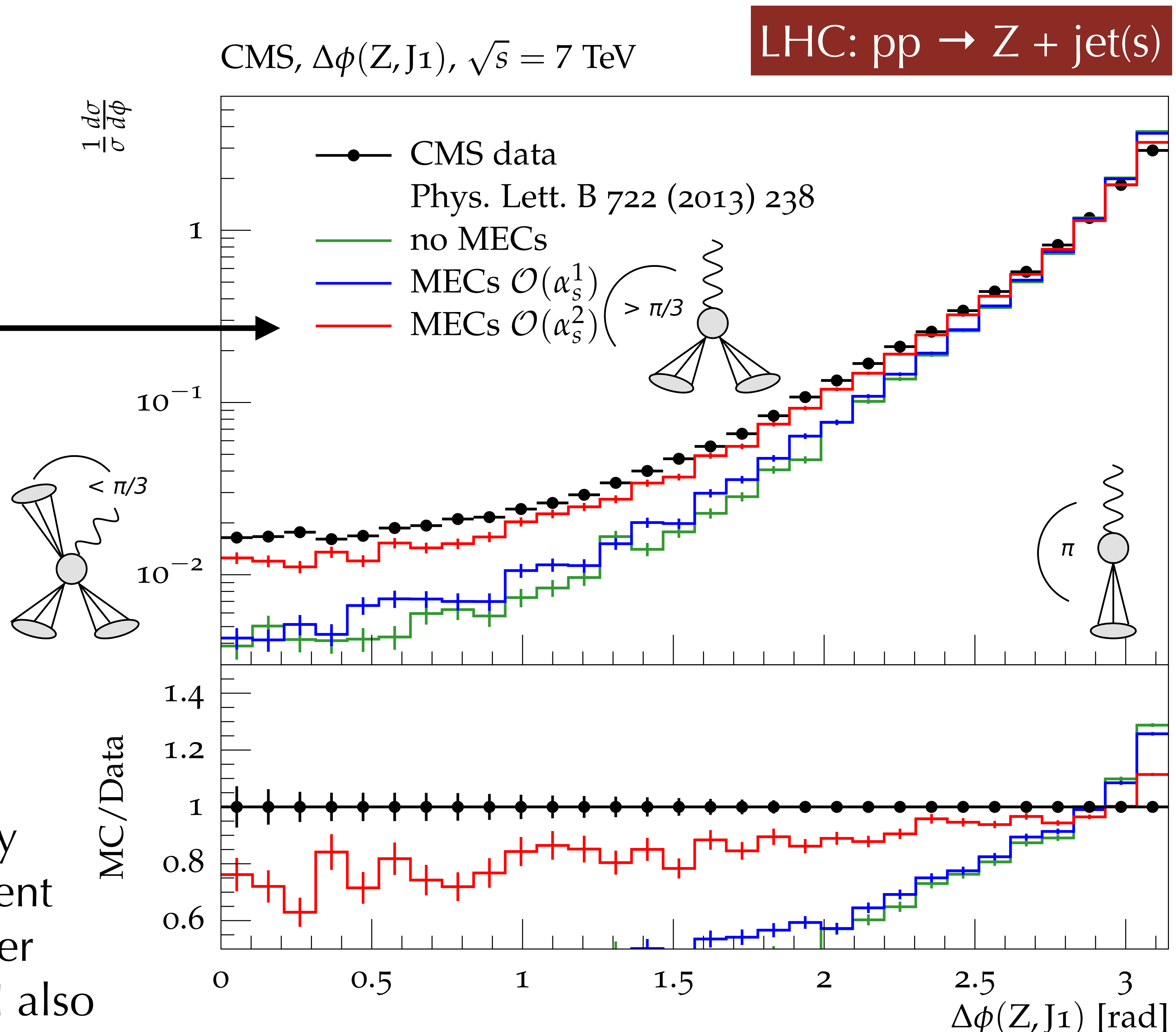
Never done before for hadron collisions



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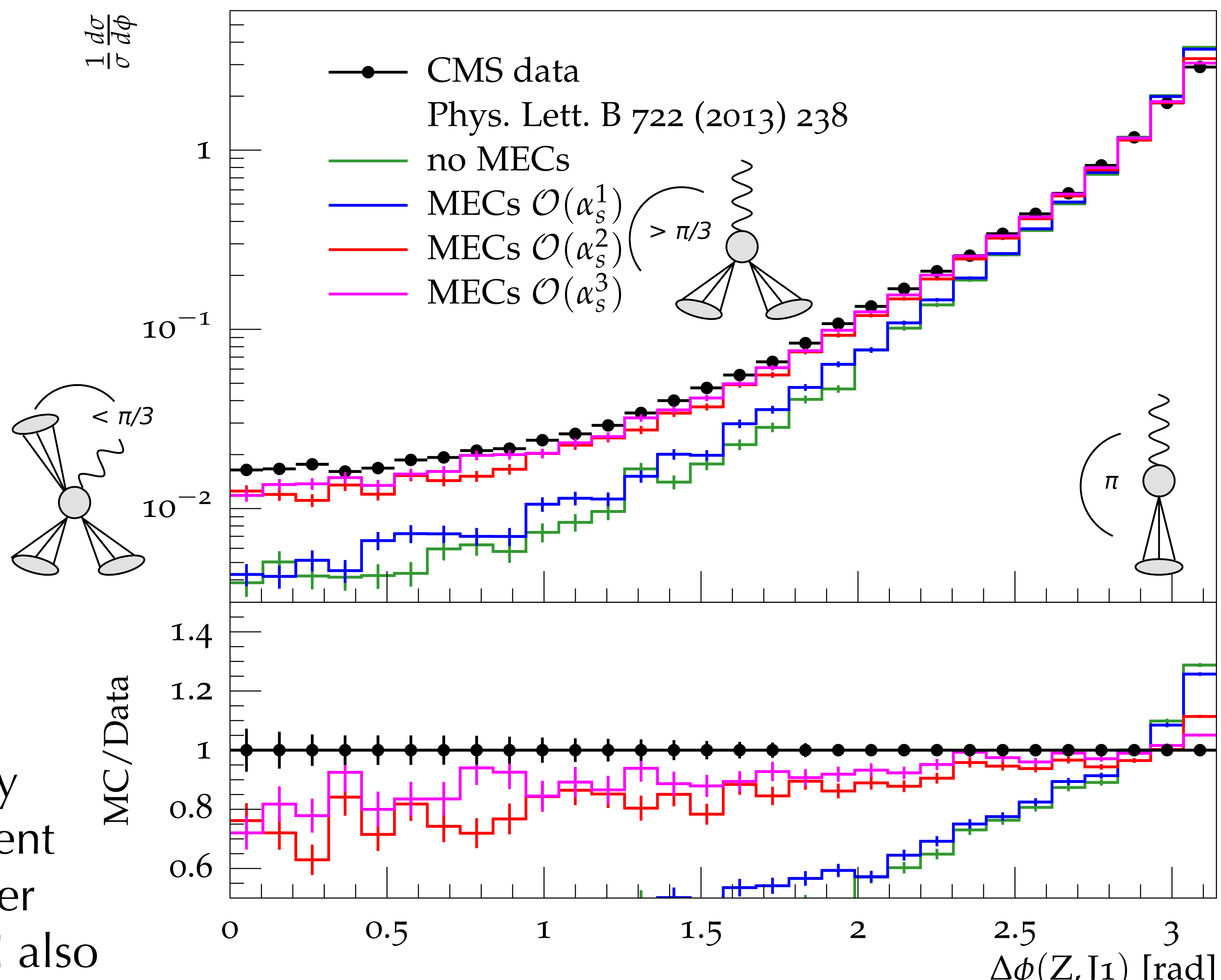

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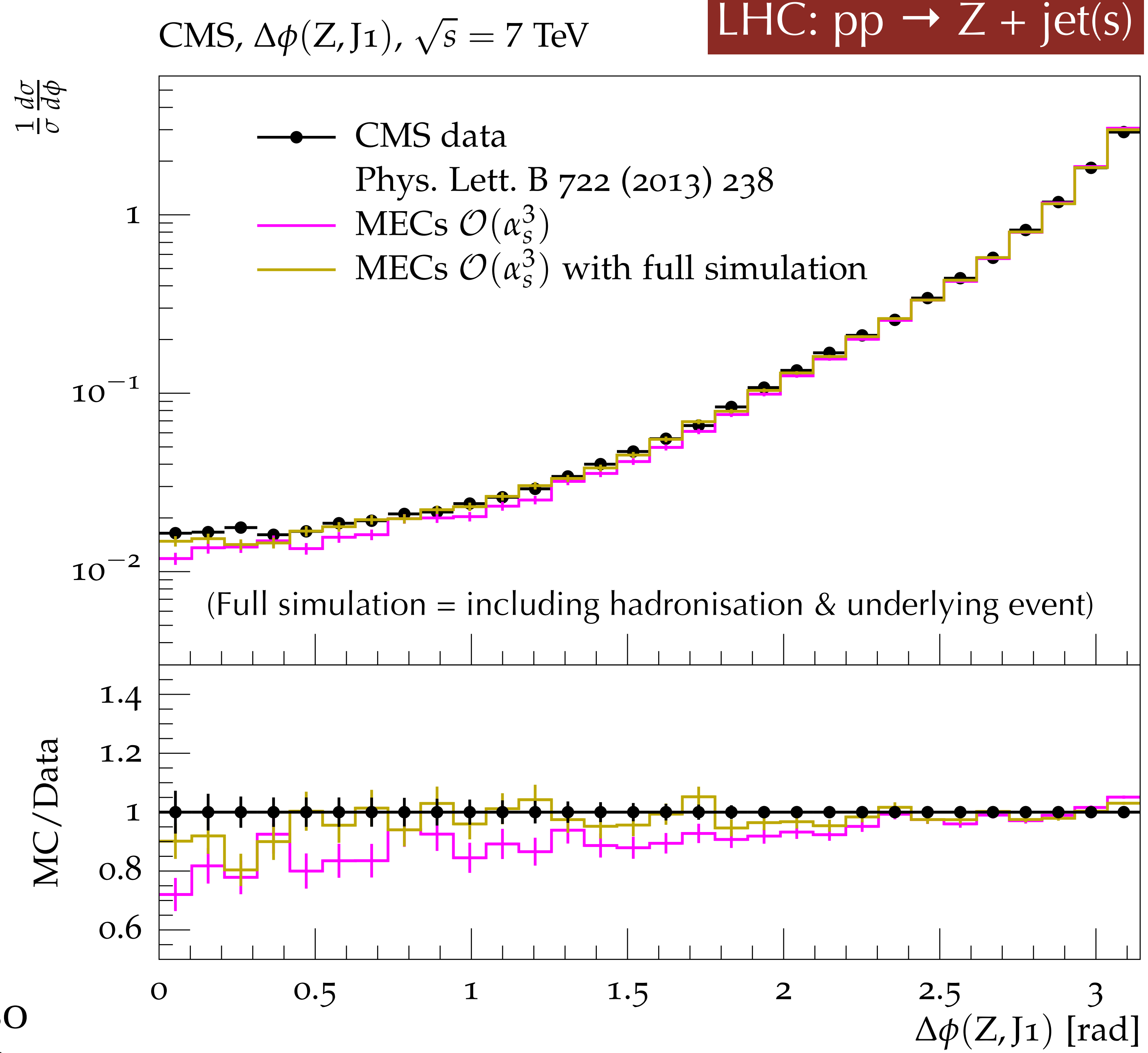


Angle between Z and the hardest jet

Full writeup now in final draft ➜ expect on arXiv in ~ 1-2 weeks.

Work done by my PhD student Nadine Fischer (from whom I also stole these slides)

+ Future Applications (why other people care)

Example: The Top Quark

Heaviest known elementary particle:
$m_t \sim 187\ u$ ($\sim m_{Au}$)

Lifetime: 10^{-24} s

Complicated decay chains:

$$t \to bW^+ \qquad \bar{t} \to \bar{b}W^-$$

$$W \to \{q\bar{q}', \ell\nu\}$$

quarks → jets
b-quarks → b-jets

$$m_t^2 \approx (p_b + p_{W^+})^2$$
$$\approx (p_{b-\mathrm{jet}} + p_{q-\mathrm{jet}} + p_{\bar{q}-\mathrm{jet}})^2$$

Accurate jet energy calibrations → m_t

Analogously for any process / measurement involving coloured partons

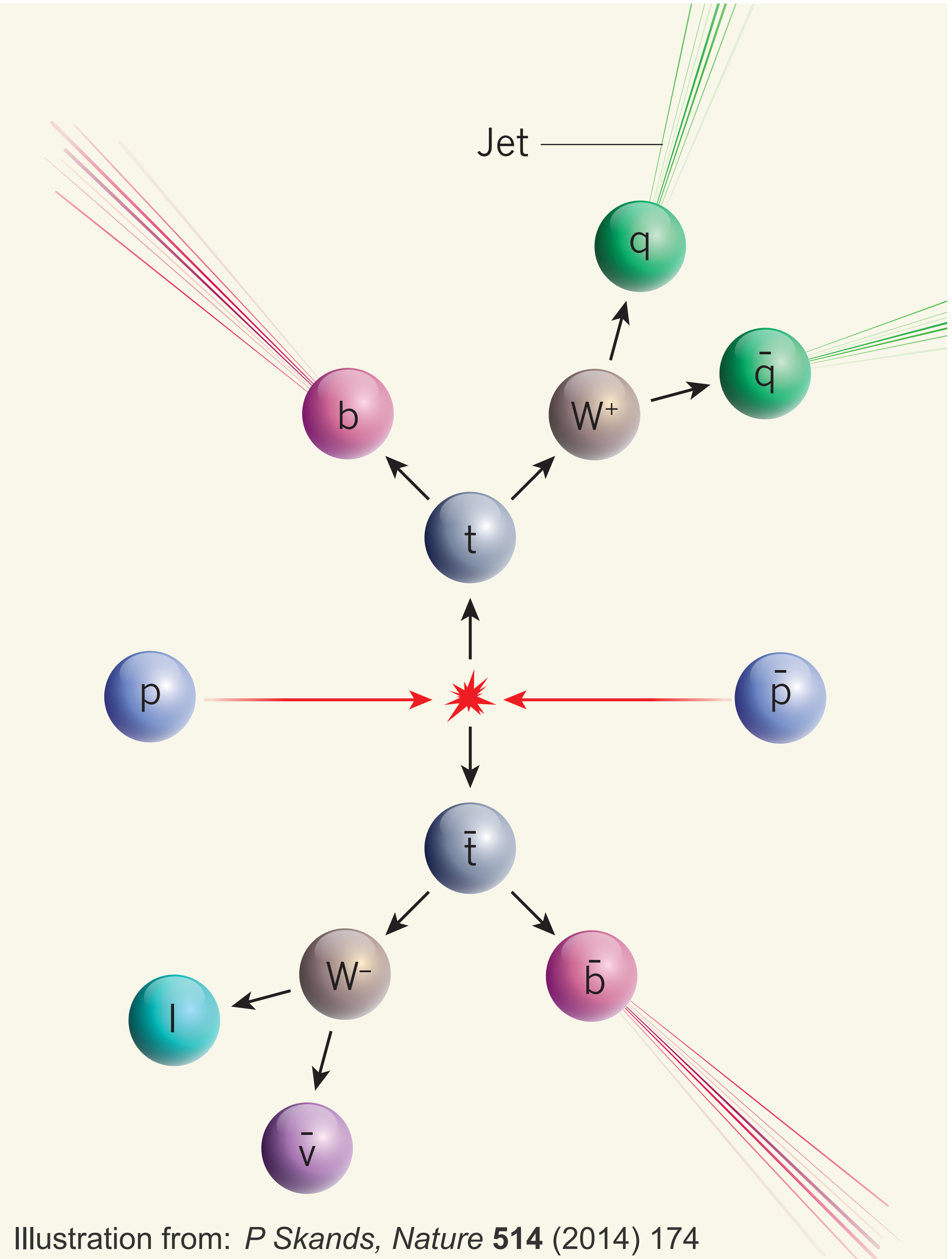


Illustration from: *P Skands, Nature* **514** (2014) 174

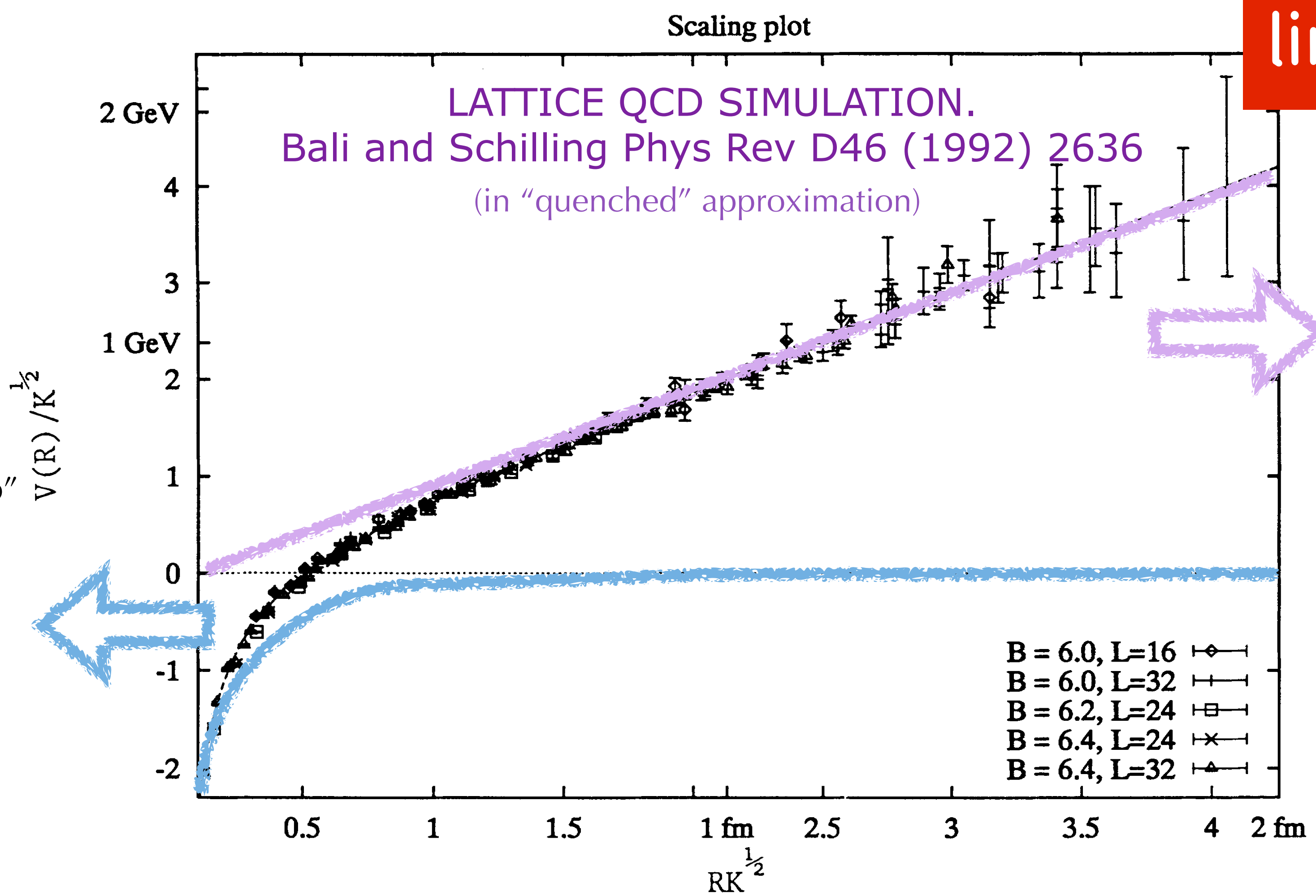
Decays of **coloured massive particles** is the most important remaining step

The Ultimate Limit: Wavelengths > 10^{-15} m

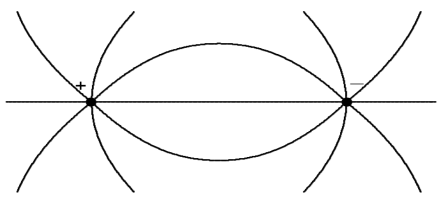
Quark-Antiquark Potential

As function of separation distance

What physical system has a linear potential?

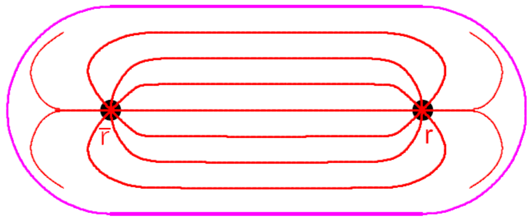


Short Distances ~ "Coulomb"



"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

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:

String Breaks

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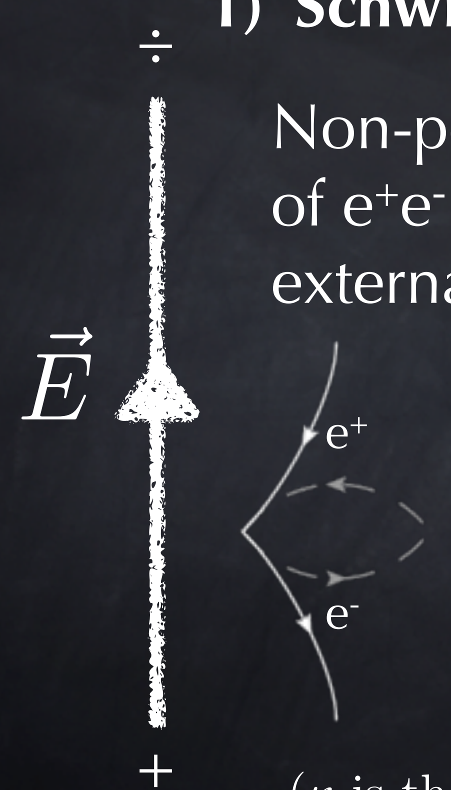
There are at least two possible analogies ~ tunneling:

CANONICAL

1) Schwinger Effect



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

Probability from Tunneling Factor

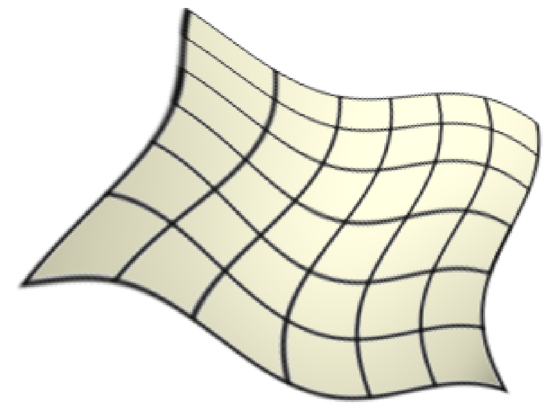
$$\mathcal{P} \propto \exp\left(\frac{-m^2 - p_\perp^2}{\kappa/\pi}\right)$$

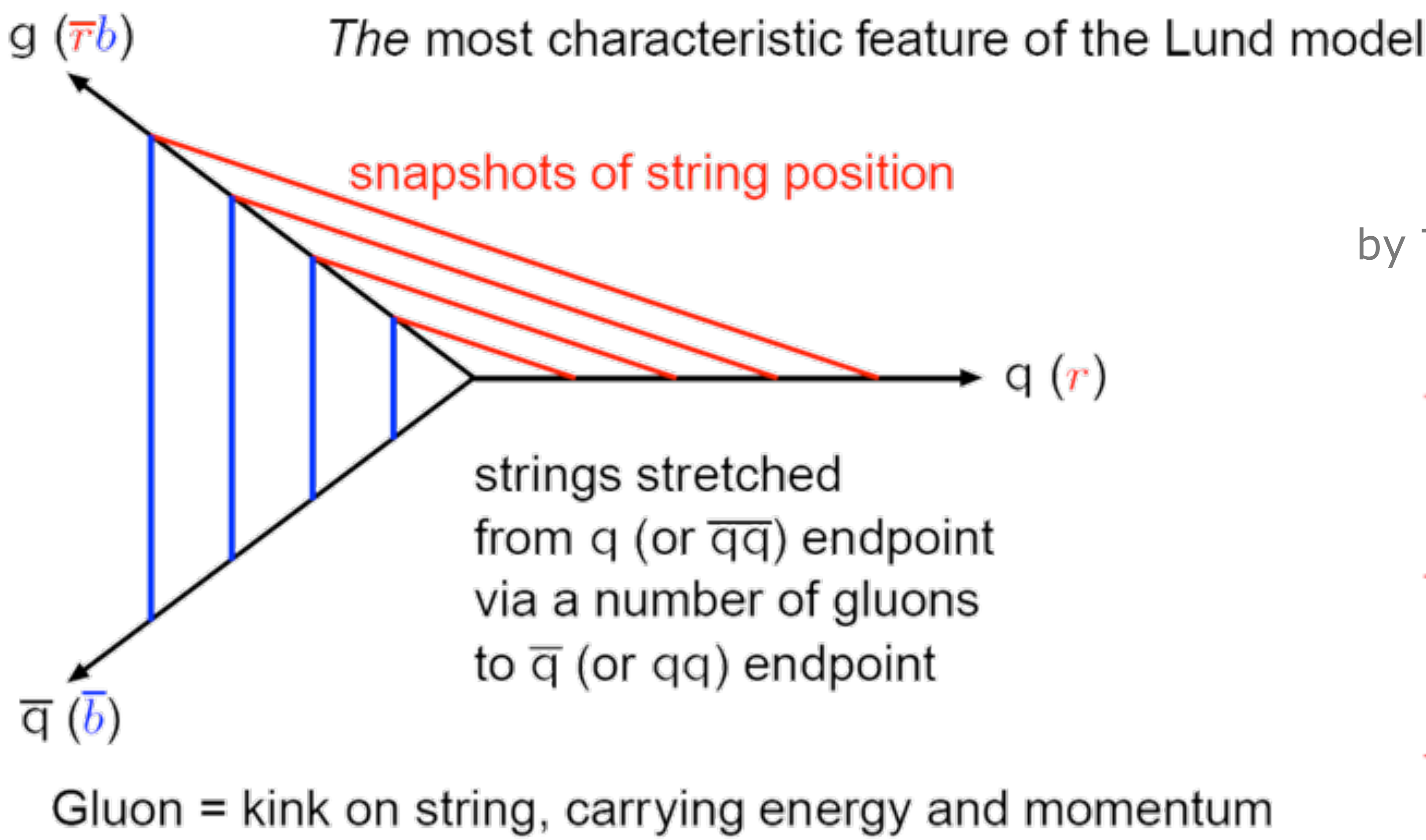
(κ is the string tension equivalent)

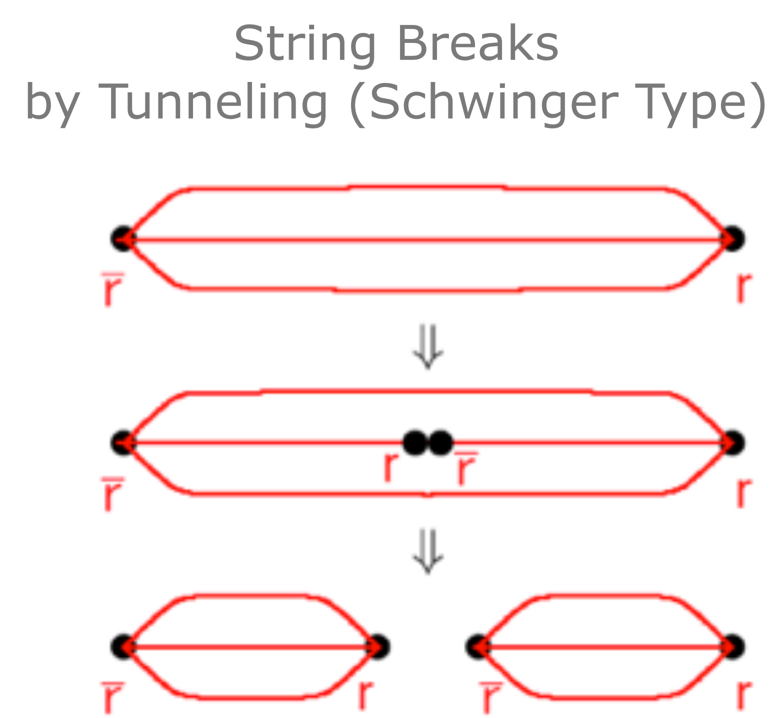
ALTERNATIVE?

The “Lund” String

- **Quarks** → String Endpoints
- **Gluons** → Transverse Excitations (kinks)





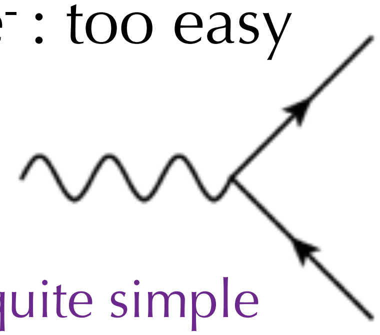


- Probability of string break constant per unit area → **AREA LAW**
- Breakup vertices causally disconnected → order is irrelevant → iterative algorithm

Colour Confusion

Between which partons do confining potentials arise?

e^+e^- : too easy



(still quite simple even after including bremsstrahlung etc.)

At e^+e^- colliders (eg LEP) : generally good agreement between **measured** particle spectra and **models** based on parton/antenna showers + strings

Basically a single **3-3bar** system, very close to the original lattice studies motivating the string model.

(+ extensions to WW reasonable to ~$O(1/N_c^2)$)

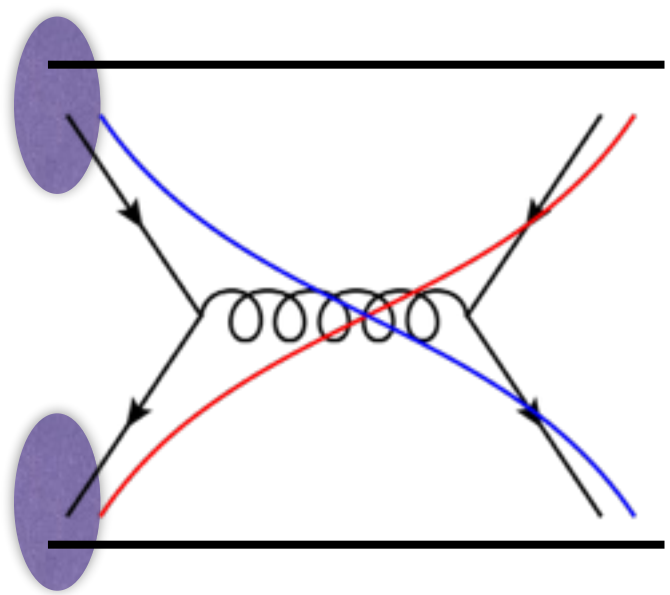
→ re-use same models as input for LHC (universality) ?

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")

String-fragmentation of junctions: Sjöstrand & Skands **Nucl.Phys. B659 (2003) 243**

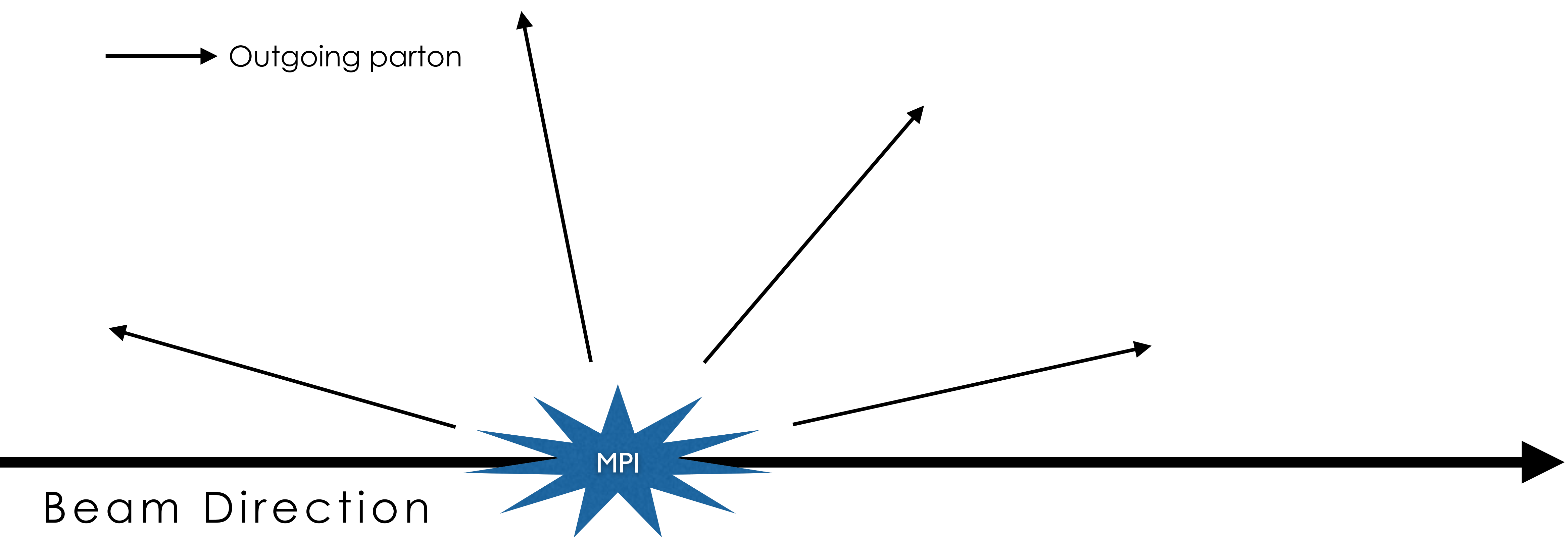
But no law against *several* parton-parton interactions

In fact, can easily be shown to happen frequently
Included in all (modern) Monte Carlo models
But how to make sense of the colour structure?

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")

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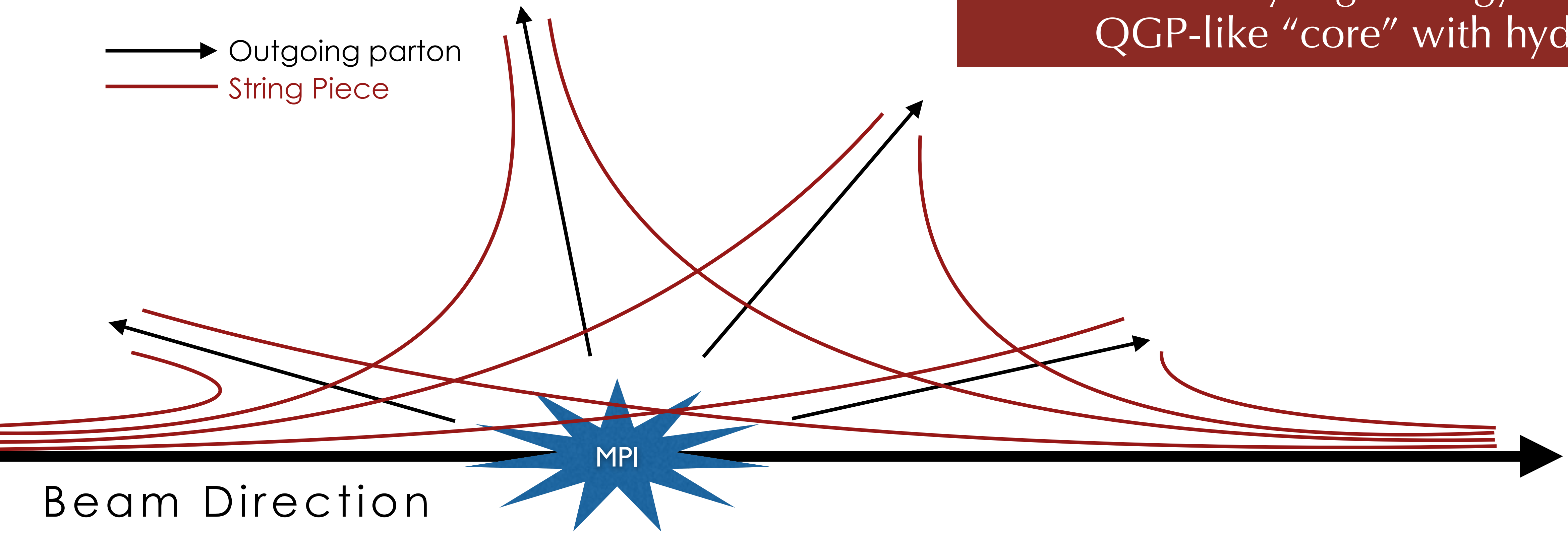
So many strings in so little space
If true → Very high energy densities
QGP-like "core" with hydro?



→ Thermal? E.g., EPOS

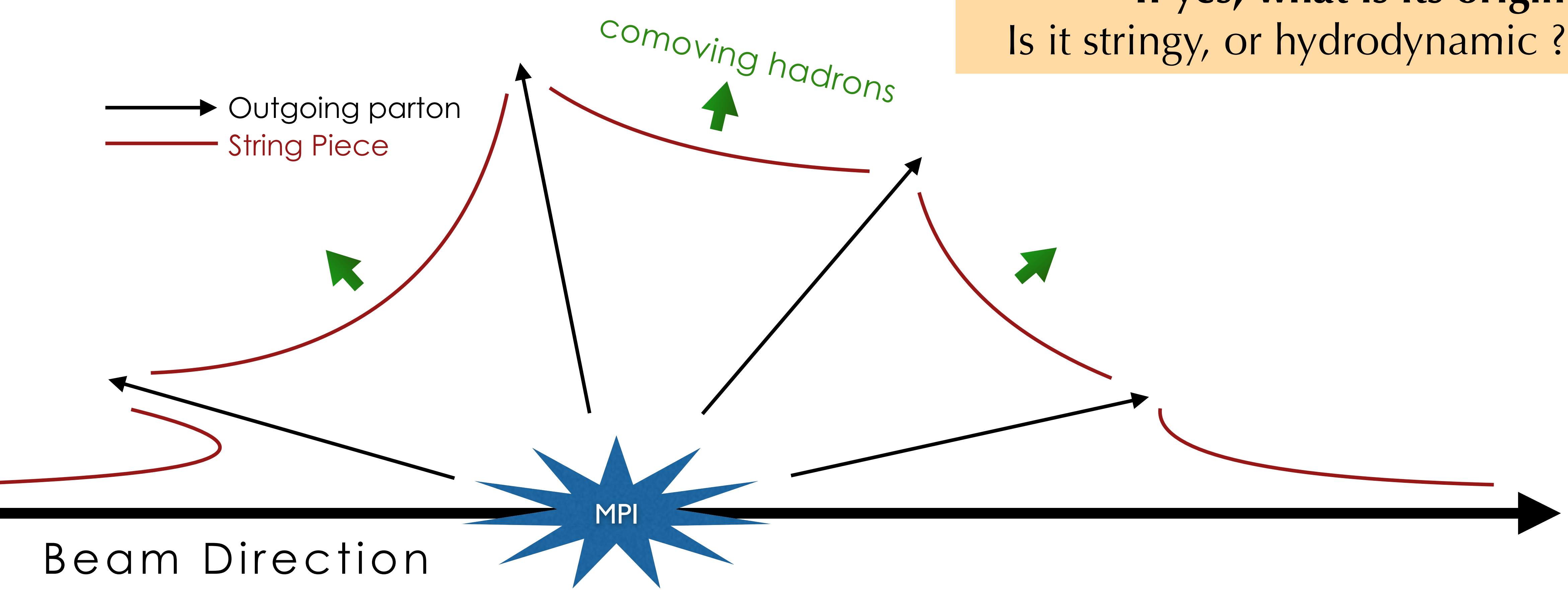
Colour Reconnections

(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? Or not?
If yes, what is its origin?
Is it stringy, or hydrodynamic ? (or …?)



String-Length Minimisation E.g., PYTHIA, HERWIG   Or Thermal? E.g., EPOS
Or Higher String Tension? E.g., DIPSY rope

What are "Colour Reconnections"?

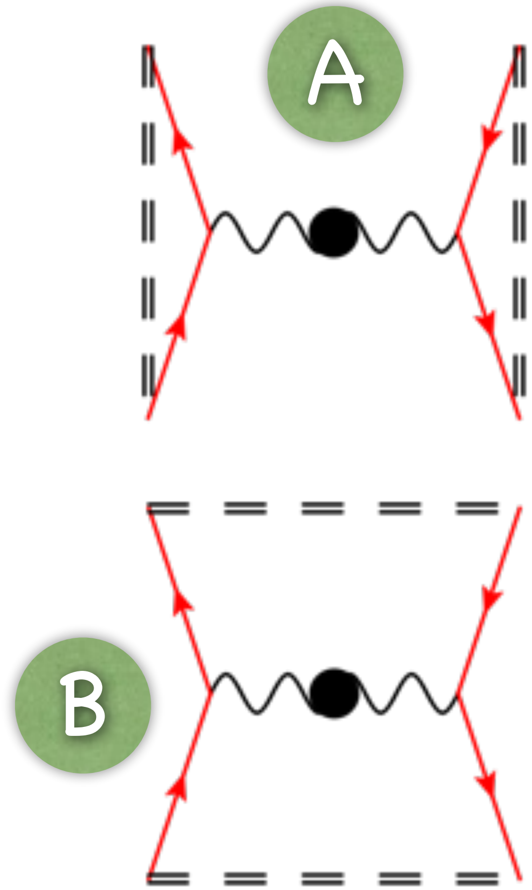
Simple example: $e^+e^- \to W^+W^- \to \text{hadrons}$

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.)
- String Formation Beyond Leading Colour (Skands et al.)

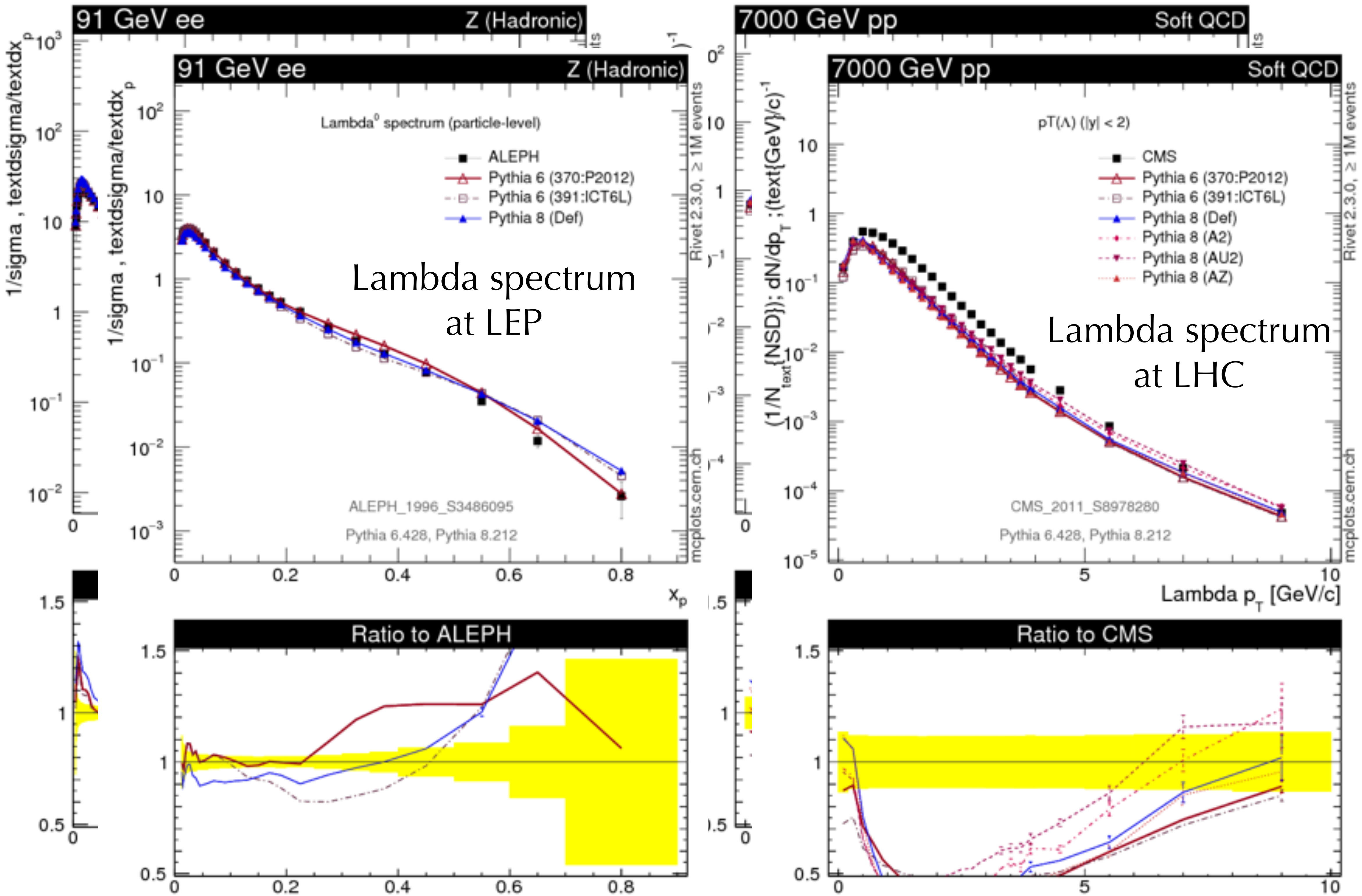
$$
\begin{aligned}
3 \otimes \bar{3} &= 8 \oplus 1 \\
3 \otimes 3 &= 6 \oplus \bar{3} \\
3 \otimes 8 &= 15 \oplus 6 \oplus 3 \\
8 \otimes 8 &= 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1
\end{aligned}
$$

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

What do we see?

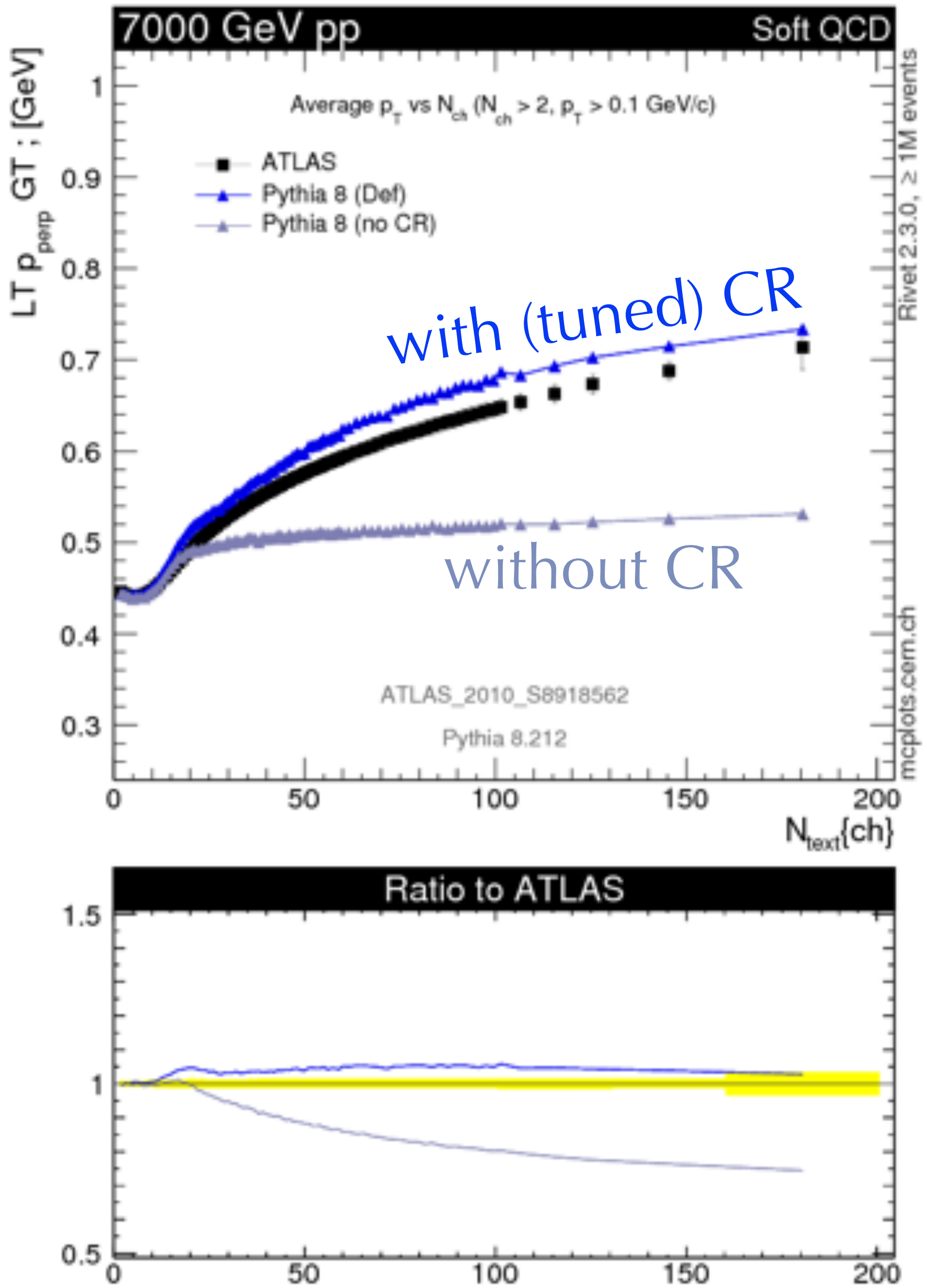
Plots from mcplots.cern.ch (powered by LHC@home)

Skands et al., **Eur.Phys.J. C74 (2014) 2714**

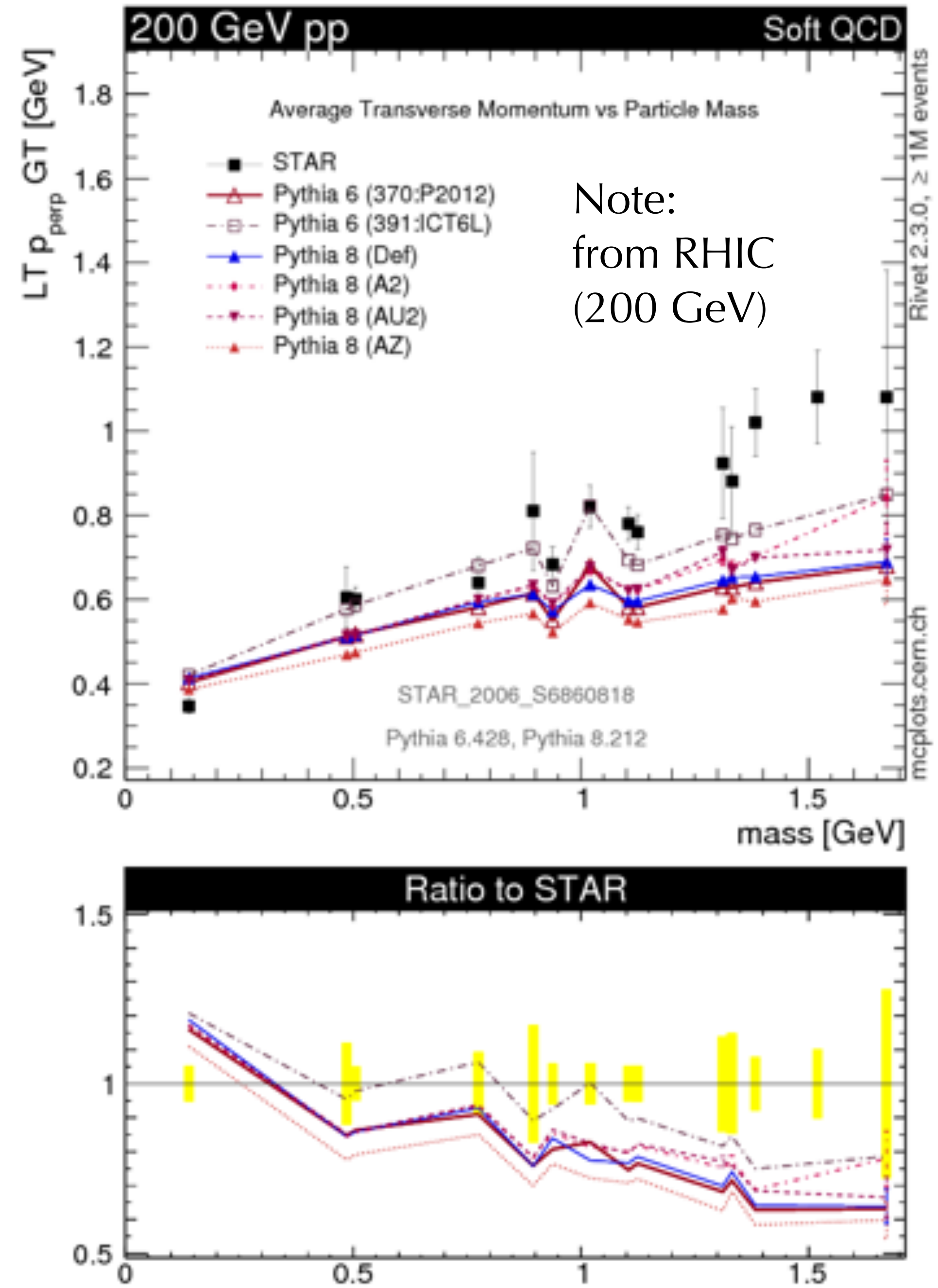


What do we see?

<pT> vs Number of Particles



<pT> vs Particle Mass



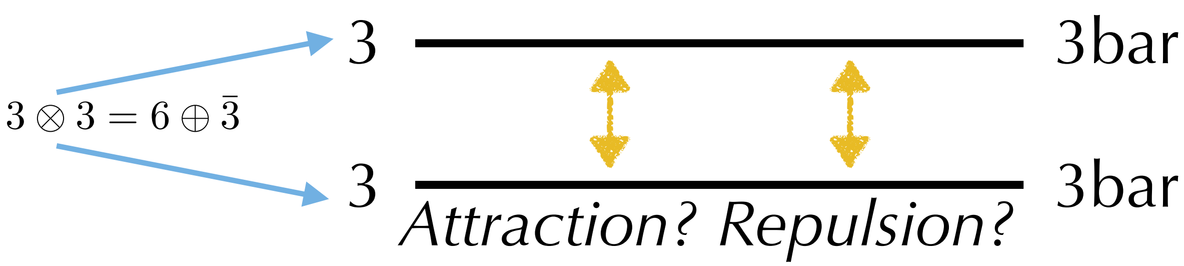
Average pT increases with particle multiplicity and (faster than predicted) with particle mass

Fundamental Questions

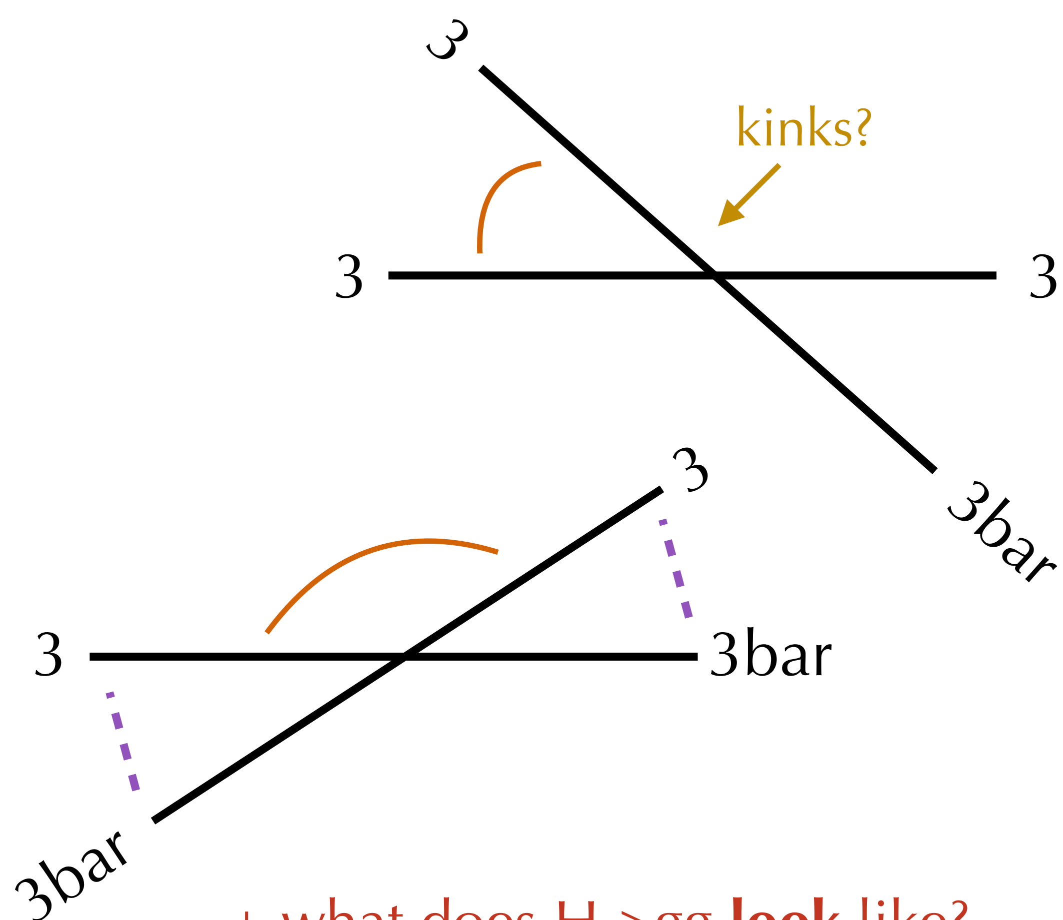
(Reflections upon yesterday's curry dinner …)

Multiple Strings: String ***interactions***?

Like Type I Superconductor?
Like Type II Superconductor?
Something else?



Potential between two triplets:
antitriplet is attractive (diquarks); sextet is repulsive
We can treat anti-triplet via CR → junction-junction structure
But we do nothing for the sextet



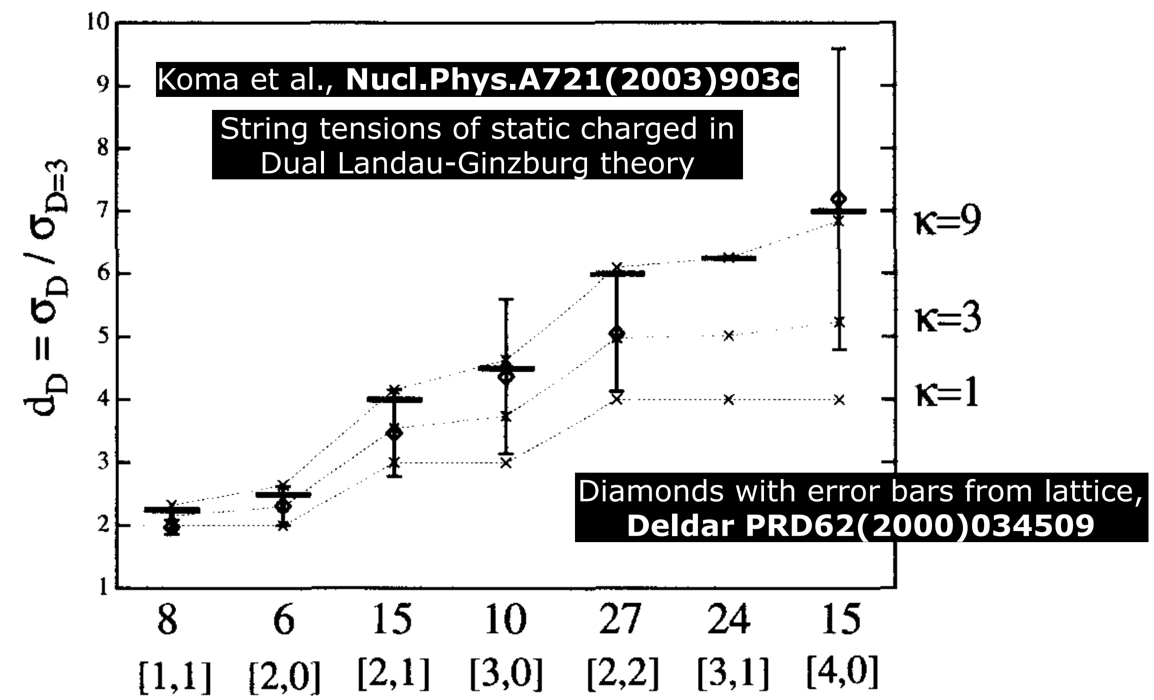


Figure 1. The ratios of the string tensions of flux tubes for various SU(3) representations, $d_D = \sigma_D/\sigma_3$ for the GL parameters $\kappa = 1$, 3 and 9 (represented by crosses, each case connected by lines to guide the eye). The ratios of eigenvalues of the quadratic Casimir operators are shown as black bars. For comparison the lattice data of Ref. [2] are also plotted (diamonds with error bars). Boldface numbers and brackets $[p, q]$ denote the dimension and the Dynkin indices of each representation D, respectively

+ what does H->gg **look** like?
One "fat" string, or two?

+ Newer results from Cardoso, Cardoso, Bicudo seem to support Casimir scaling (Type II): **arXiv:1102.1542**

Quo Vadis?

All sights are on **Run 2 of the LHC**

- Next order of precision for jet rates and structure
  - Aid precision measurements and enhance discovery reach
  - Vast multi-jet phase spaces to explore with LHC
  - Merging and MHV corrections (S. Prestel, A. Lifson, N. Fischer)
  - Beyond the Leading-Logarithmic approximation (with post doc Hai Tao Li)
- \+ systematic and automated theory uncertainties
  - Part of being precise is knowing **how** precise. Our job to give an answer.
  - **Automated uncertainty bands in both VINCIA and PYTHIA 8** (Mrenna+Skands)

Strings

- Understand the physics of colour reconnections
- What are the ***dynamics*** of multi-string environments?
- **Phenomenology**: Modern revisions of the Lund string model
- What measurements are crucial to shed more light?
- Possible to get more information from lattice? Multi-string systems?

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

p

p

+ 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*

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