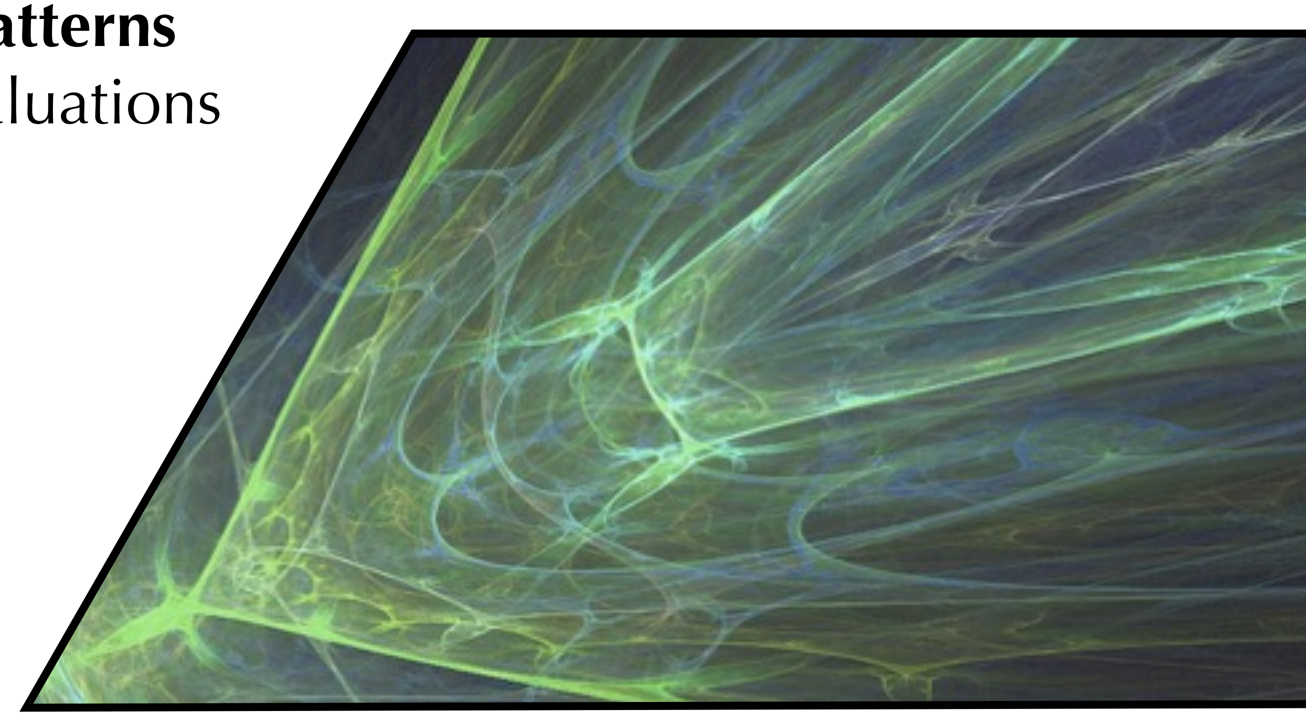
VINCIA for Hadron Colliders

Peter Skands (Monash University)

QCD showers based on 2 → 3 antenna patterns
+ (automated) perturbative uncertainty evaluations
+ matrix-element corrections



a plug-in to PYTHIA 8.2
http://vincia.hepforge.org

VINCIA 1.x for e^+e^- colliders
→ **VINCIA 2.0 for pp**

ICHEP 2016 - Chicago

Based on Fischer, Prestel, Ritzmann, Skands - arXiv:1605.06142

Monte Carlos and Fragmentation

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

Explicit modelling of QCD dynamics ⟷ comparison to measurements

Famous example: MC crucial to establish "string effect" in early 80s

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

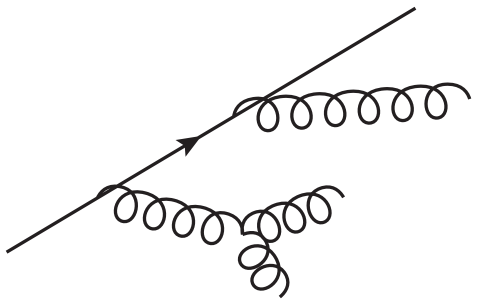
Study observables, sensitivities, effects of cuts, detector efficiencies, …

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, …

Parton Showers are based on (iterated) 1→2 splittings



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

Starting point is "Leading-Logarithmic" resummation

+ QCD coherence by "angular ordering" (or "dipoles")

+ Imposing (E,p) conservation → recoil effects ("local" or "global")

+ $|M|^2$ matching, running couplings, spin correlations, …

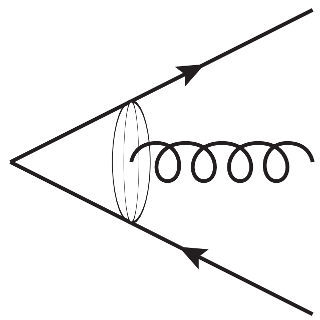
See, e.g., MCnet review arXiv:1101.2599, or TASI lectures arXiv:1207.2389

VINCIA is an **Antenna Shower**

Virtual **N**umerical **C**ollider with **I**nterleaved **A**ntennae (For FSR, identical to **CDM: colour dipole model**)

Splittings are fundamentally 2→3 *(+ we are now working on 2→4)*

Each colour **antenna** undergoes a sequence of splittings



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

Antenna radiation functions & phase-space factorisations

Collinear Limits → **DGLAP kernels** (→ collinear factorisation)

Soft Limits → **Eikonal factors** (→ Leading-Colour coherence)

2→3 phase-space maps = **exact, on-shell factorisations of the (n+1)/n-parton phase spaces** (→ Lorentz invariant, p_μ conserving, and valid over all of phase space - not just in limits)

+ Non-perturbative limit of colour dipoles/antennae → **string pieces** → natural matching onto (string) hadronisation models

Roots in Lund ~ mid-80s: Gustafson, Petterson NPB306(1988)746, …

What's new in our approach? (e.g., not in ARIADNE)

+ Iterated MECs: matrix-element corrections (since v1.x)

+ Backwards antenna evolution for ISR (new in v2.0)

+ Automated uncertainty bands/weights (& runtime ROOT displays)

New: Hadron Collisions

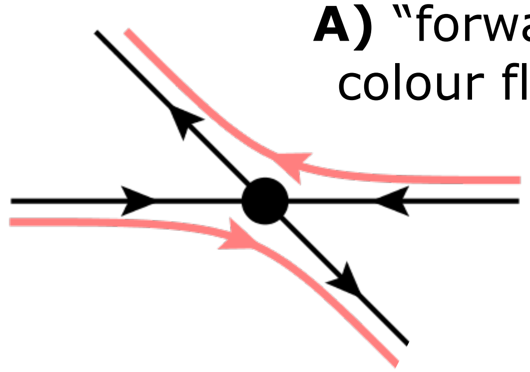
Example taken from: Ritzmann, Kosower, Skands, PLB718 (2013) 1345

Example: quark-quark scattering in hadron collisions

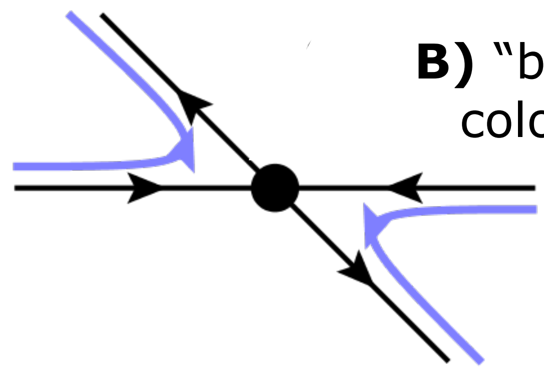
Consider one specific phase-space point (eg scattering at 45^o)

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

A) "forward" colour flow



B) "backward" colour flow



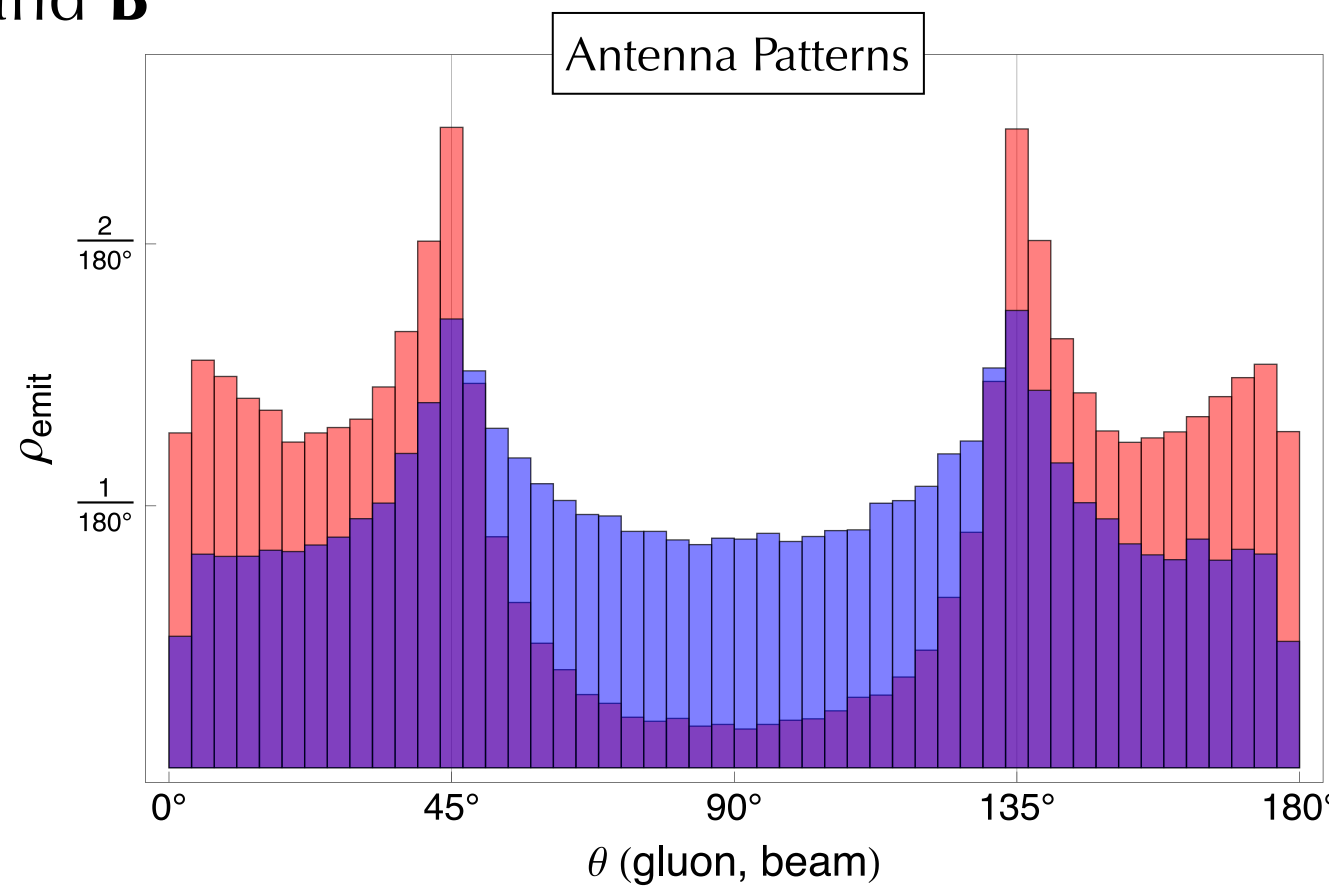


Figure 4: Angular distribution of the first gluon emission in $qq \to qq$ scattering at 45°, for the two different color flows. The light (red) histogram shows the emission density for the forward flow, and the dark (blue) histogram shows the emission density for the backward flow.

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

VINCIA: Markovian pQCD*

Essentially, an iterative version of MECs / POWHEG

*) pQCD : perturbative QCD

Repeat

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

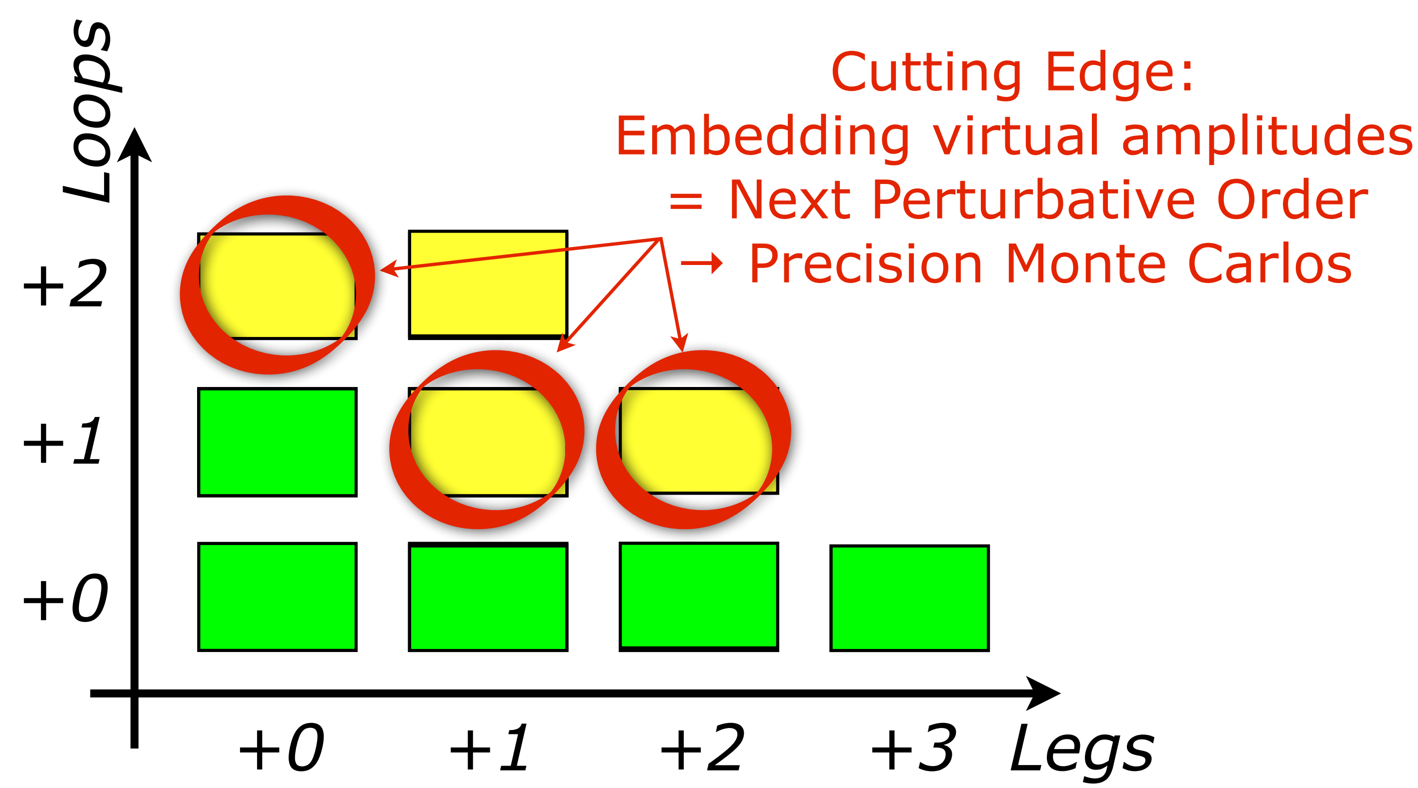
$$a_i \to \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2} a_i$$

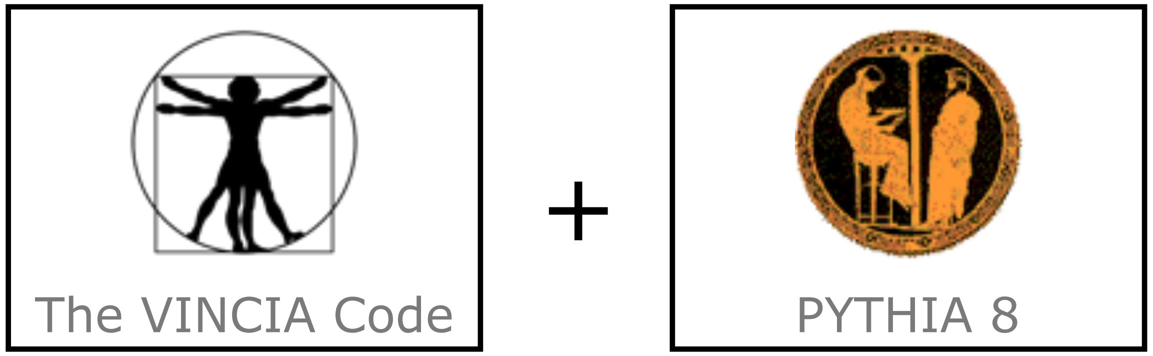
Unitarity of Shower

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

Correct to Matrix Element

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





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

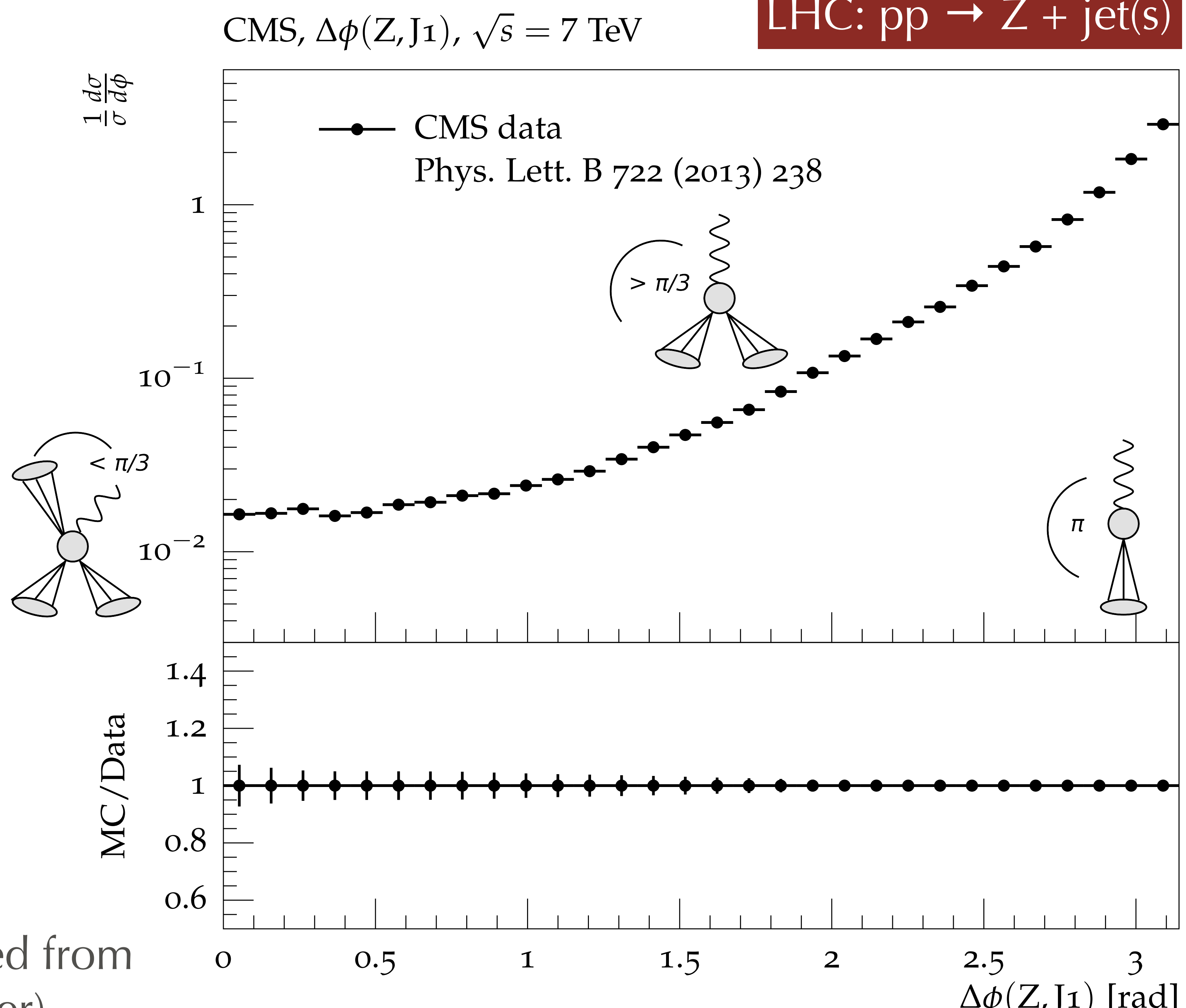
"An Introduction to PYTHIA 8.2"
Sjöstrand et al., Comput.Phys.Commun. 191 (2015) 159

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

(slides adapted from Nadine Fischer)

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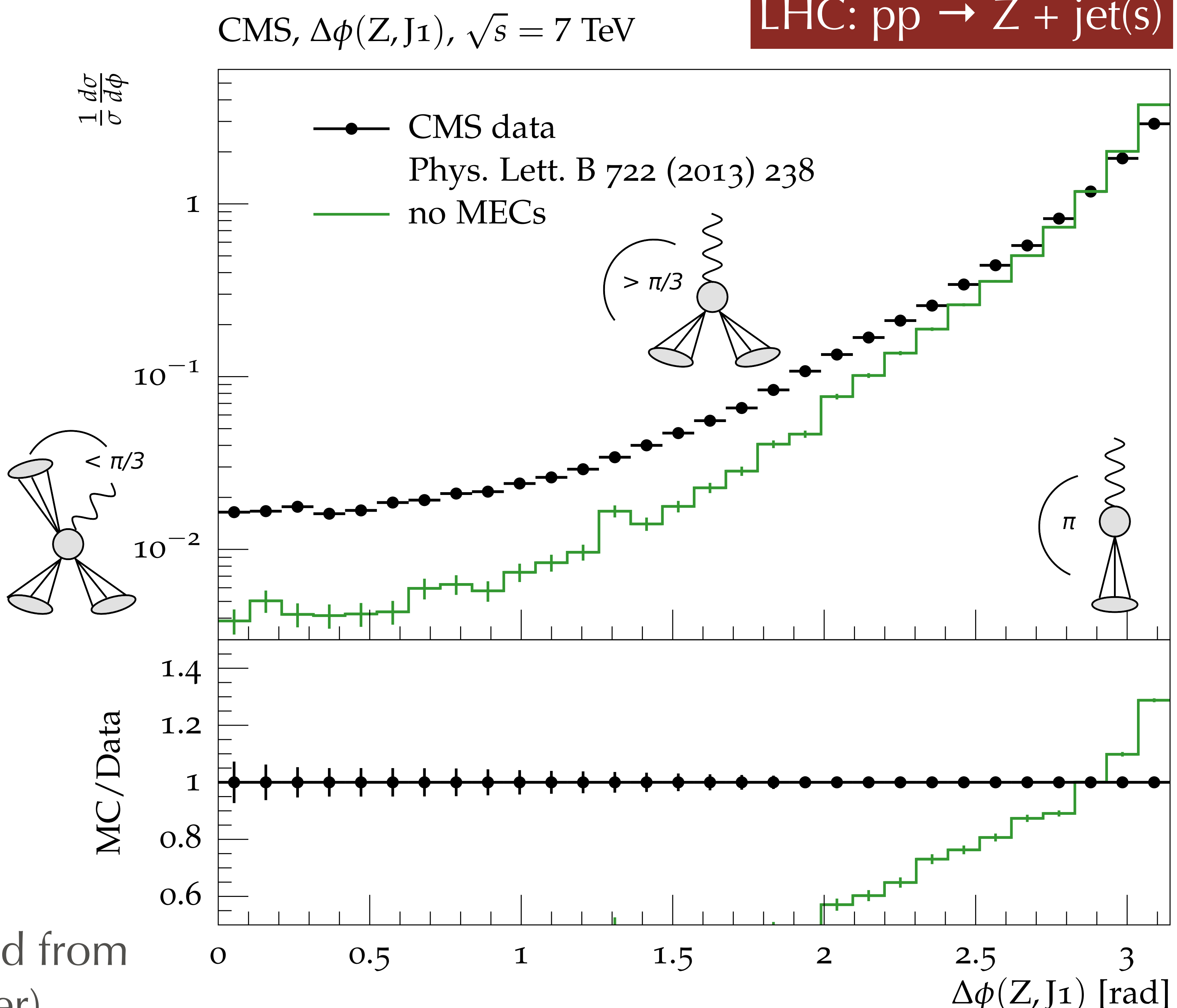

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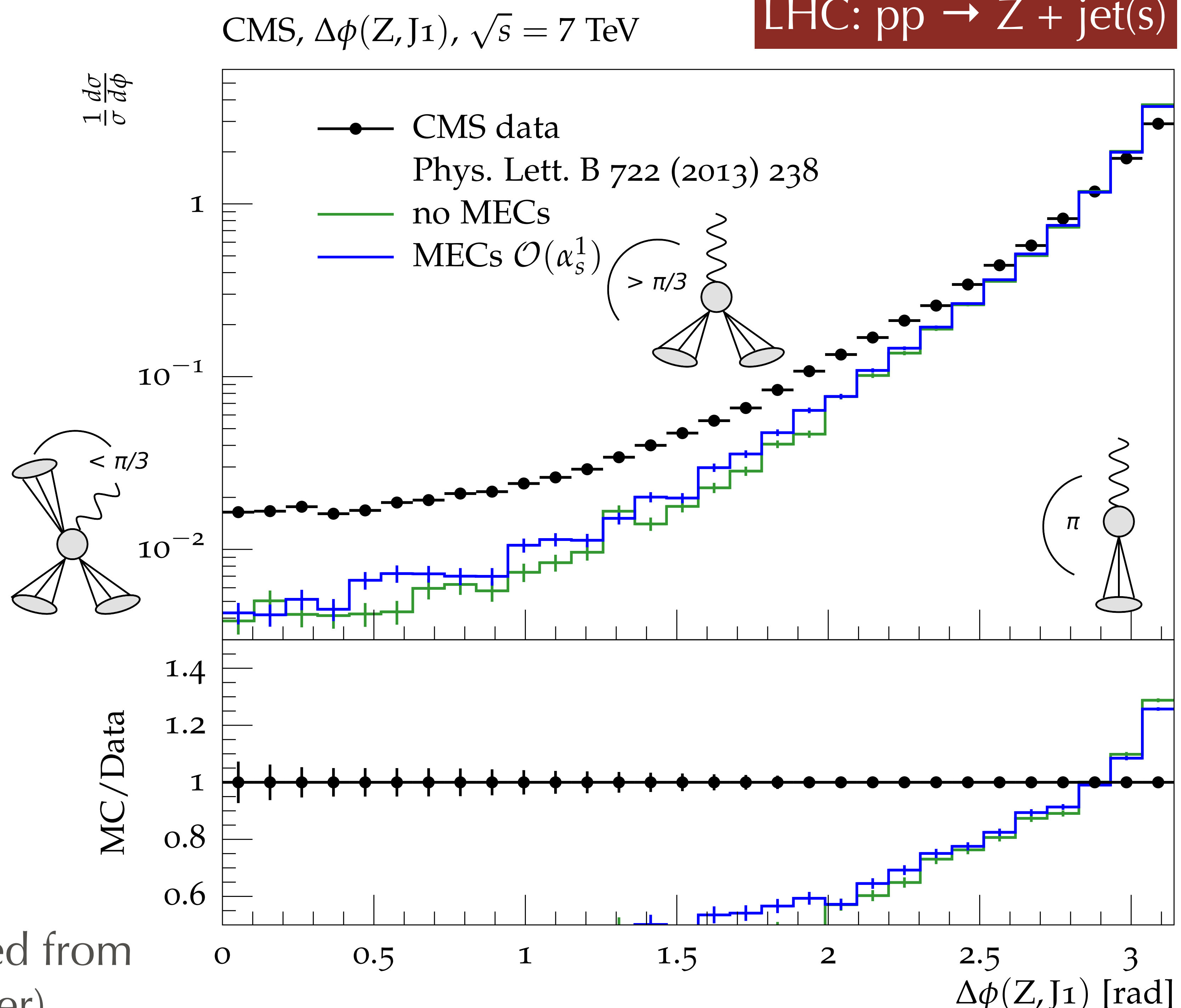

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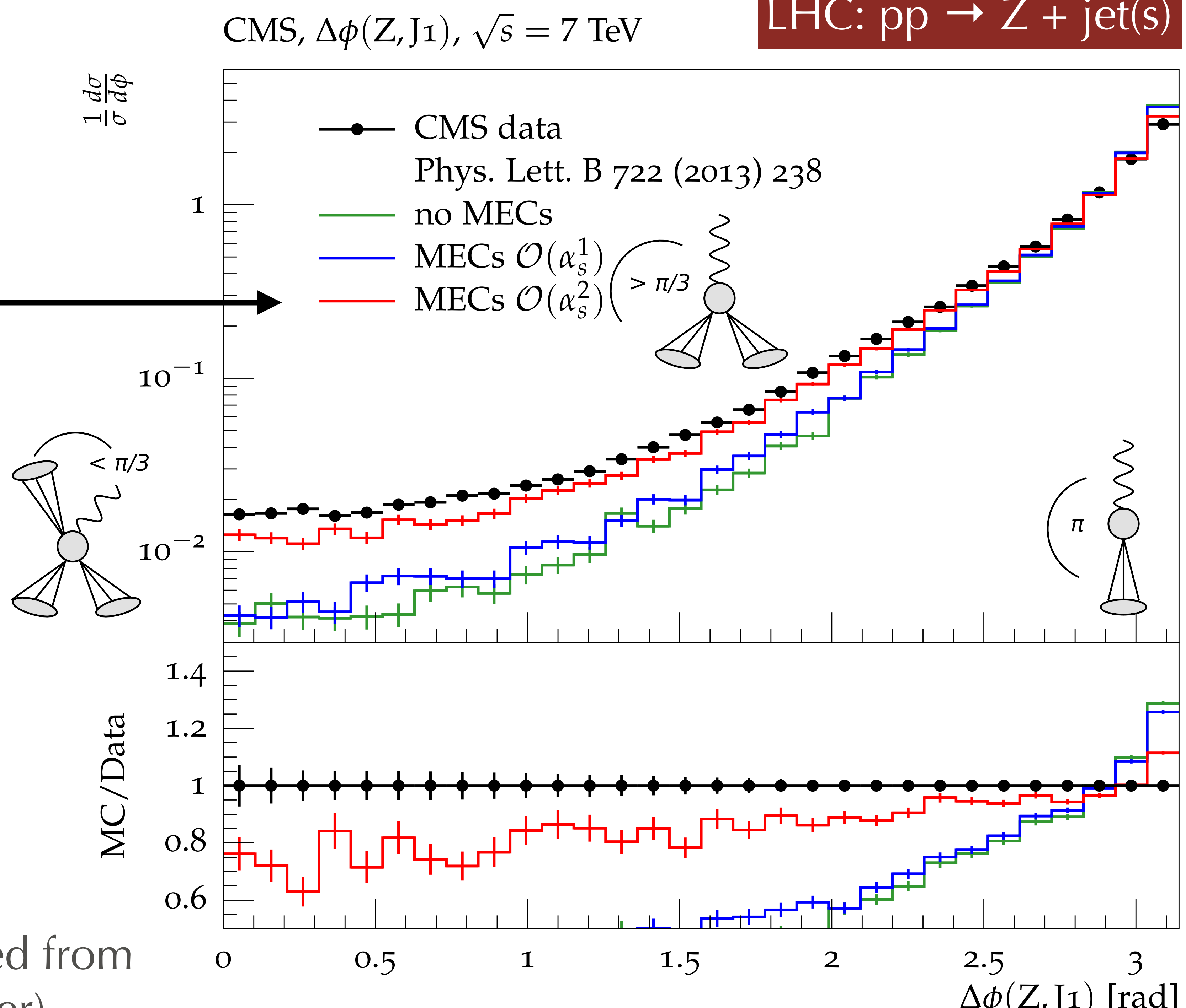
Never done before for hadron collisions



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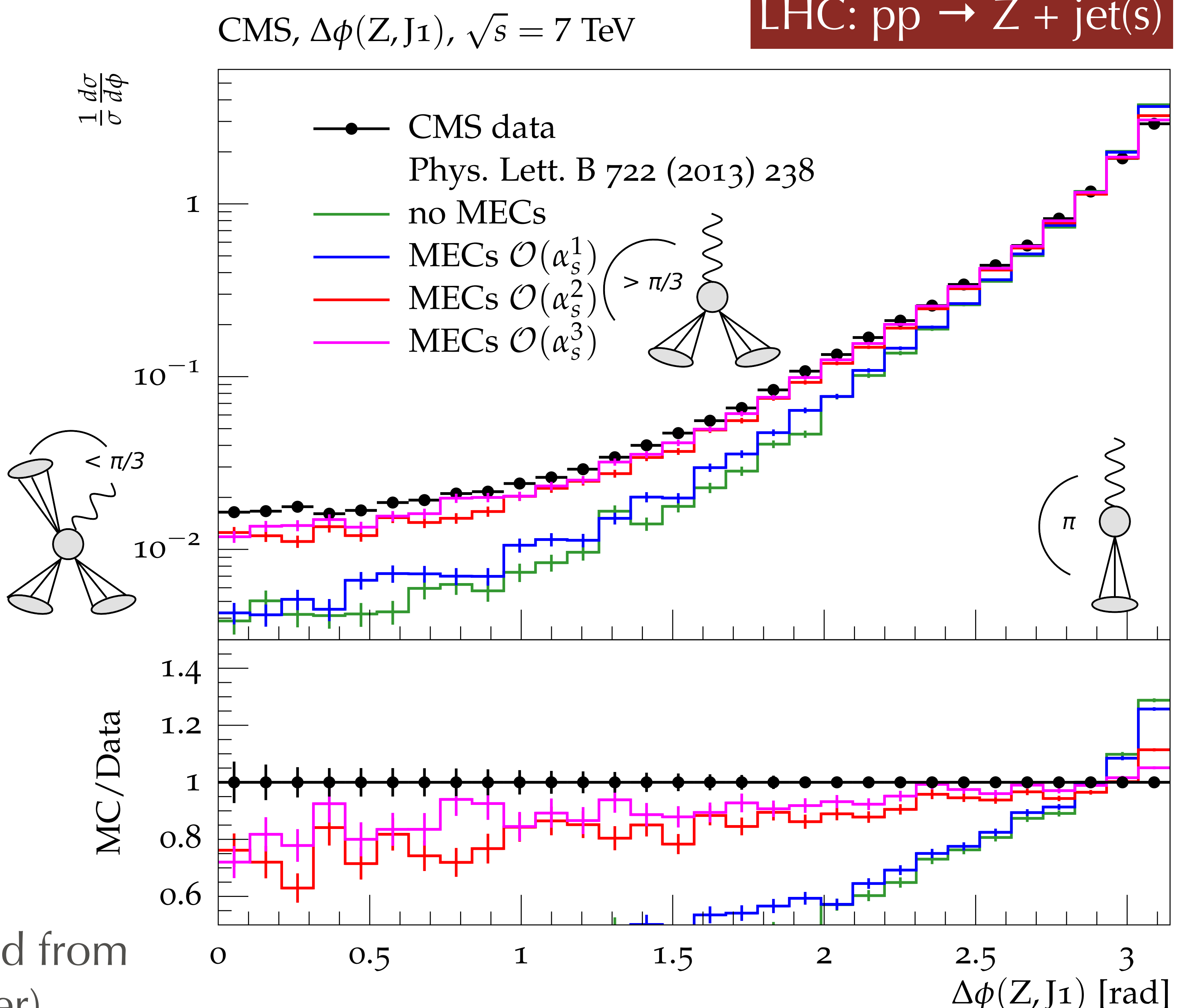

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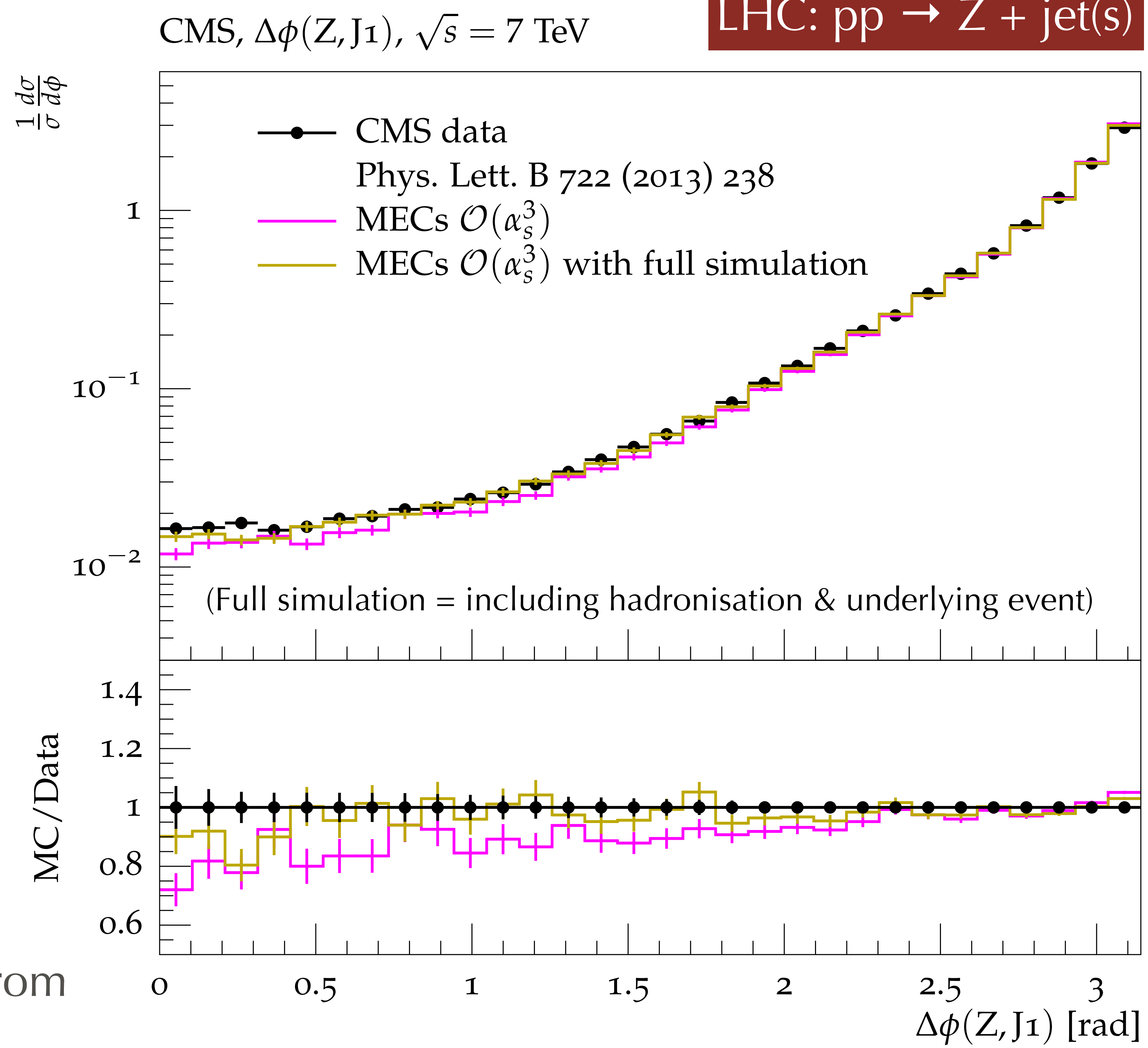


Angle between Z and the hardest jet

Full writeup:
Fischer, Prestel, Ritzmann, Skands
arXiv: 1605.06142

(slides adapted from Nadine Fischer)

Precision ⇨ Shower Uncertainties

Perturbative QCD is an asymptotic series

Truncate at LO, NLO, … → attempt to estimate possible size of remaining terms chiefly by scale variations (e.g., μ_R, μ_F)

- Reasoning ~ All-orders answer independent of these scales, hence variation at calculated order → minimal remainder

Resummations (incl showers) are all-orders calculations

Main question remains: *what is the possible size of terms beyond the precision of the algorithm/calculation?*

The answer computed by a shower algorithm depends on:

- Scale Choices for each branching (μ_R, μ_F)
- Radiation functions (beyond universal pole structure)
- Starting and Ending Scales
- Choice of resolution measure / evolution variable
- Kinematics Maps / Recoil Strategies
- Treatment of coherence, subleading colour, spin correlations, …

Can we impose constraints?

If not, *vary* …

Automated Shower Uncertainty Bands/Weights

Giele, Kosower, Skands PRD84 (2011) 054003 + hadron collisions FPRS 1605.06142 + explicit all-orders proof in Mrenna, Skands 1605.08352

Idea: perform a shower with nominal settings

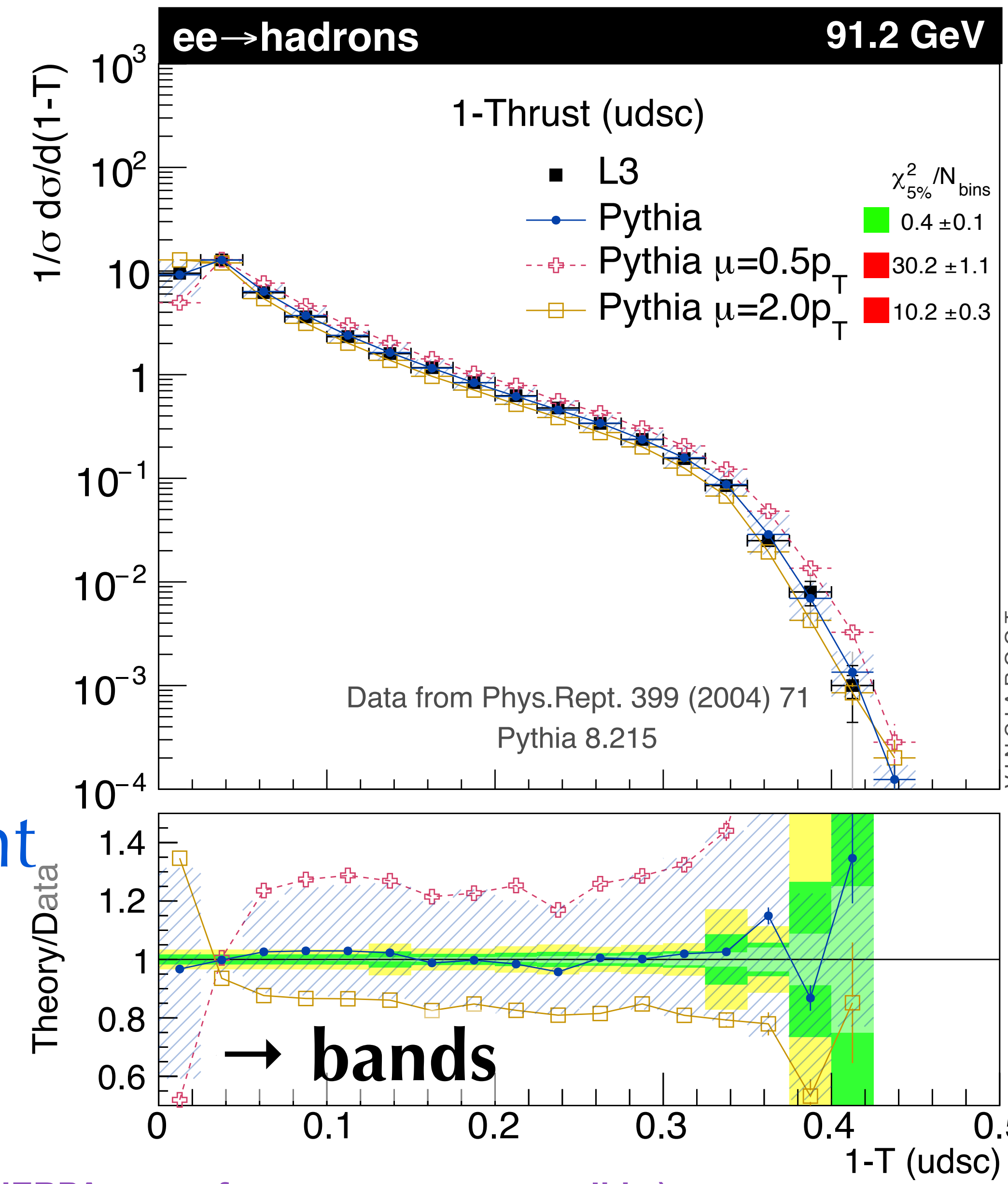
Ask: what would the probability of obtaining this event have been with **different choices** of μ_R, radiation kernels, … ?

Easy to calculate **reweighting factors**

In MC accept/reject algorithm:

∀ *Accepted Branchings:*
$$R'_{\rm acc}(t) = \frac{P'_{\rm acc}(t)}{P_{\rm acc}(t)}$$

∀ *Rejected Branchings:*
$$R'_{\rm rej}(t) = \frac{1 - P'_{\rm acc}(t)}{1 - P_{\rm acc}(t)}$$



Output: **vector of weights** for each event

One for the nominal settings

+ Alternative weights for each variation

(note: analogous functionality also recently developed for PYTHIA 8, HERWIG++, SHERPA, see references on summary slide)

VINCIA 2.0 : Summary

Virtual Numerical Collider with Interleaved Antennae

new! Fischer, Prestel, Ritzmann, Skands - arXiv:1605.06142

FSR + ISR shower Monte Carlo based on **QCD Antennae**

Splittings regarded as fundamentally 2 → 3 (instead of 1 → 2)

with (LC) coherent radiation patterns (antenna functions):

Collinear Limits → DGLAP kernels

Soft Limits → Soft Eikonals

Implemented as a simple plug-in to **PYTHIA 8**

with similar HTML manual, example programs, etc

+ **LO Matrix-Element Corrections** (with MEs from MadGraph)

For Z/W/H→jets & pp→jets to $O(\alpha_s^4)$; pp→Z/W/H + jets to $O(\alpha_s^3)$

Automated Uncertainty Bands/Weights

First proposed (&implemented) for VINCIA — Giele, Kosower, Skands PRD84 (2011) 054003

Now also in PYTHIA 8, HERWIG, SHERPA

Mrenna, Skands 1605.08352
Bellm, Plätzer, Richardson, Siodmok, Webster 1605.08256
Bothmann, Schönherr, Schumann 1606.08753

(+ VinciaROOT runtime displays for easy visual checks/plots)

vincia.hepforge.org

The Phenomenology Pipeline

Calculations

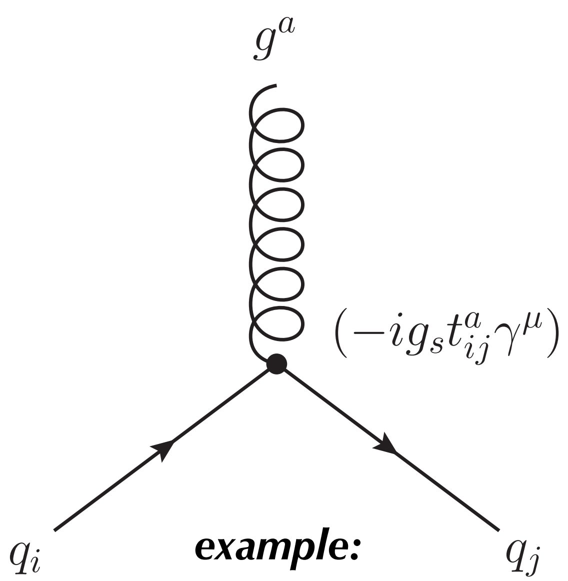
Model

Observables

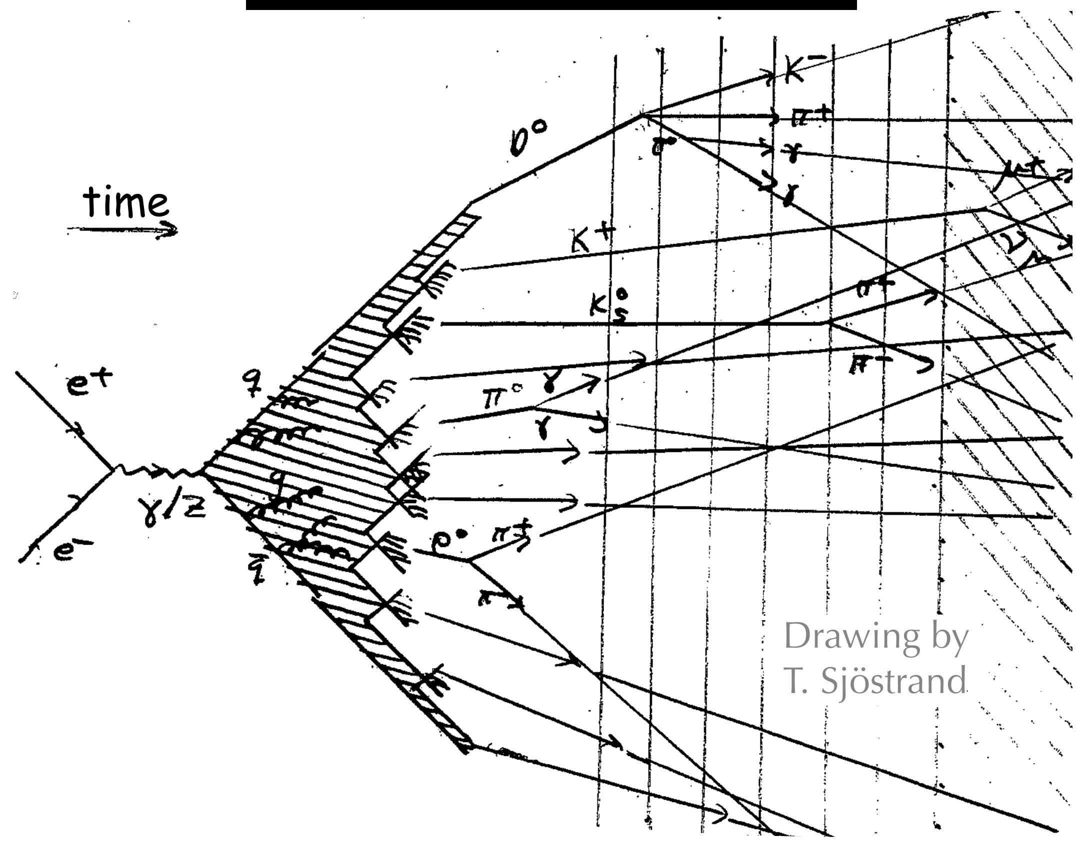
THEORY → **PHENOMENOLOGY** → **EXPERIMENT**

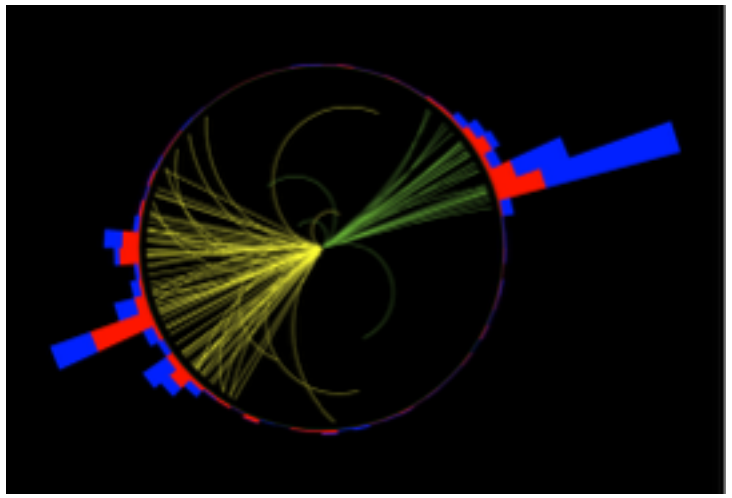
Planning
Design
R&D
Hardware
Triggers
…

Analyses



example:
QCD





"Jets"

Exclusions
Hints
Evidence
Discoveries
Surprises

← **INTERPRETATION** ←

Corrections
Systematics

Statistical Tests

Measurements

Validate/Falsify Models
Constrain Free Parameters

Matrix-Element Corrections

Exploit freedom to choose non-singular terms

Bengtsson, Sjöstrand, PLB 185 (1987) 435

Modify parton shower to use process-dependent radiation functions for first emission → absorb real correction

$$\text{Parton Shower } \frac{P(z)}{Q^2} \to \frac{P'(z)}{Q^2} = \frac{P(z)}{Q^2} \underbrace{\frac{|M_{n+1}|^2}{\sum_i P_i(z)/Q_i^2 |M_n|^2}}_{\text{MEC}}$$

(suppressing α_s and Jacobian factors)

Process-dependent MEC → P′ different for each process

Done in PYTHIA for all SM decays and many BSM ones

Norrbin, Sjöstrand, NPB 603 (2001) 297

Based on systematic classification of spin/colour structures

Also used to account for mass effects, and for a few 2→2 procs

Difficult to generalise beyond 1st emission *(= 1st-order MECs)*

Parton-shower expansions complicated & can have "dead zones"

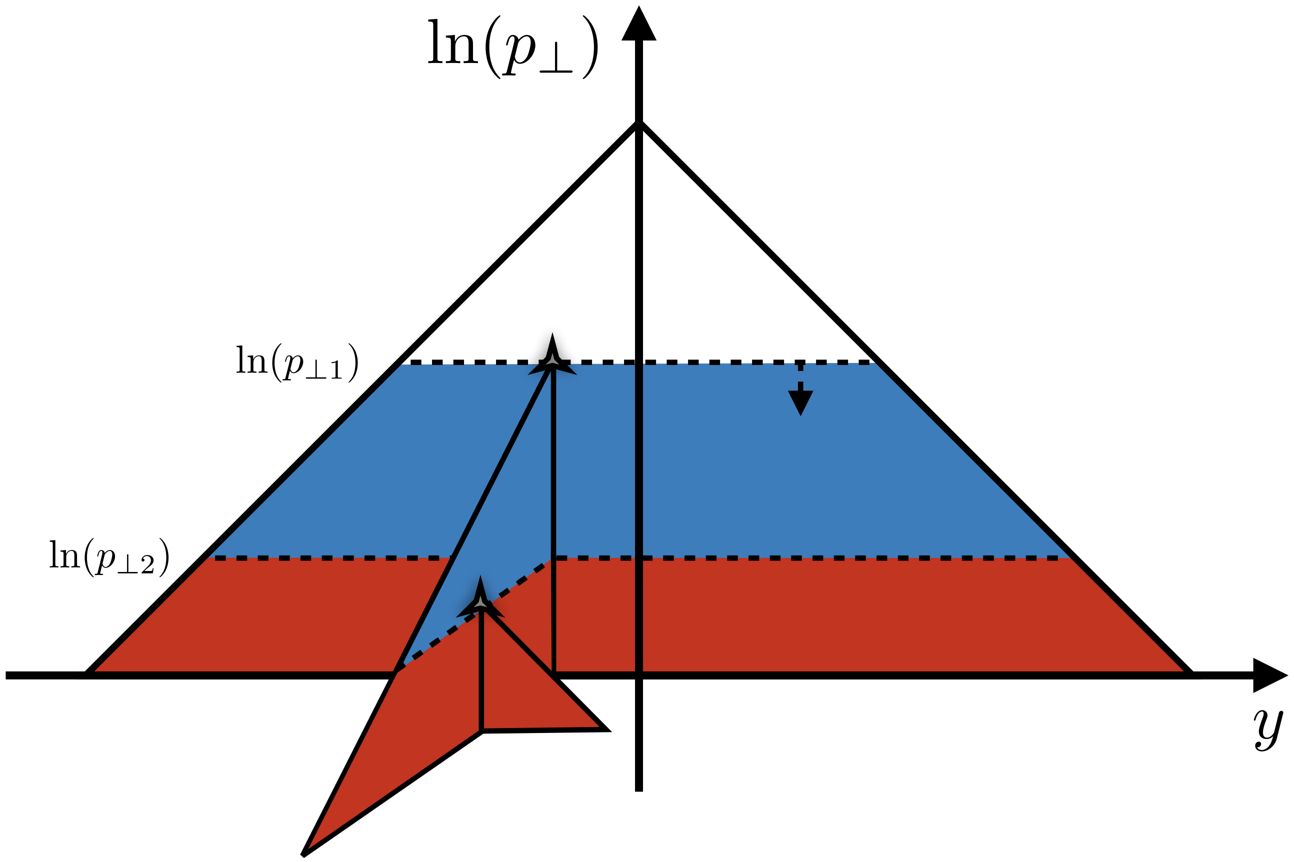
First achieved in VINCIA, by changing from parton showers to "Markovian Antenna Showers"

Giele, Kosower, Skands, PRD 84 (2011) 054003

Now extended to hadron collisions

Fischer et al, arXiv:1605.06142

Strong Ordering



Smooth Ordering