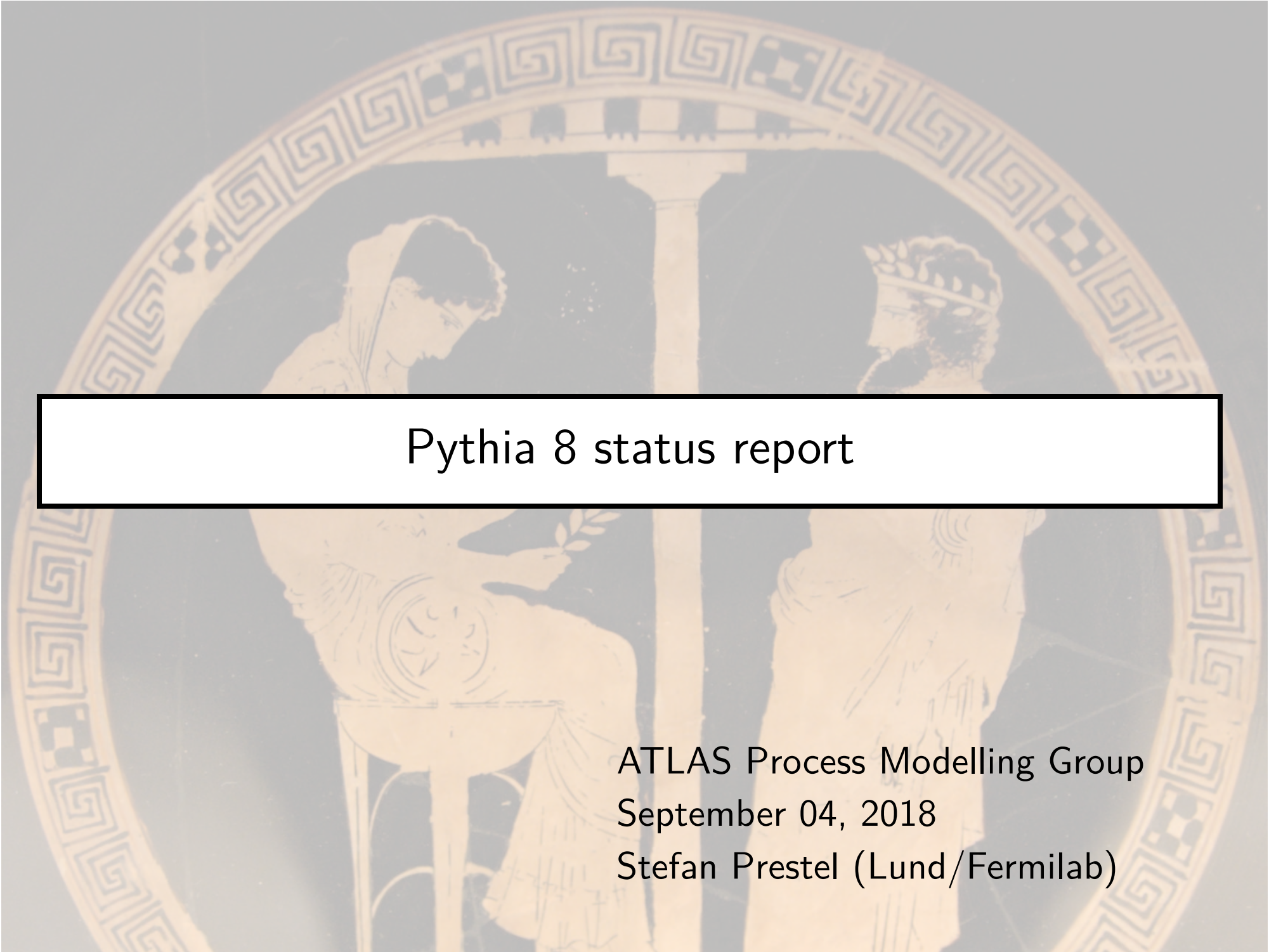


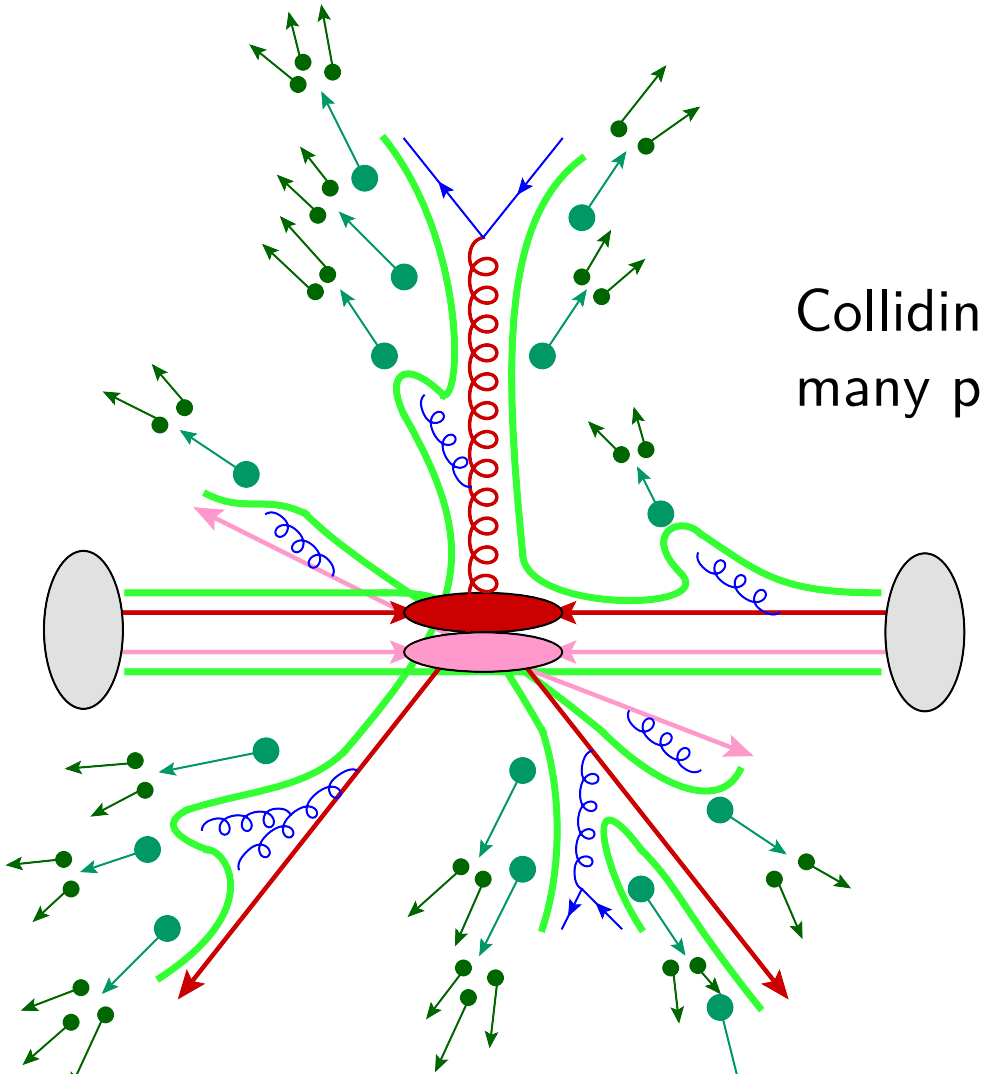
Pythia 8 status report

ATLAS Process Modelling Group

September 04, 2018

Stefan Prestel (Lund/Fermilab)

Accurate pseudodata from theory tools $\rightarrow$ better analyses of backgrounds, better analyses of signals



Colliding composite objects kick-starts many processes:

hard scattering

radiation cascade

multiparton interactions

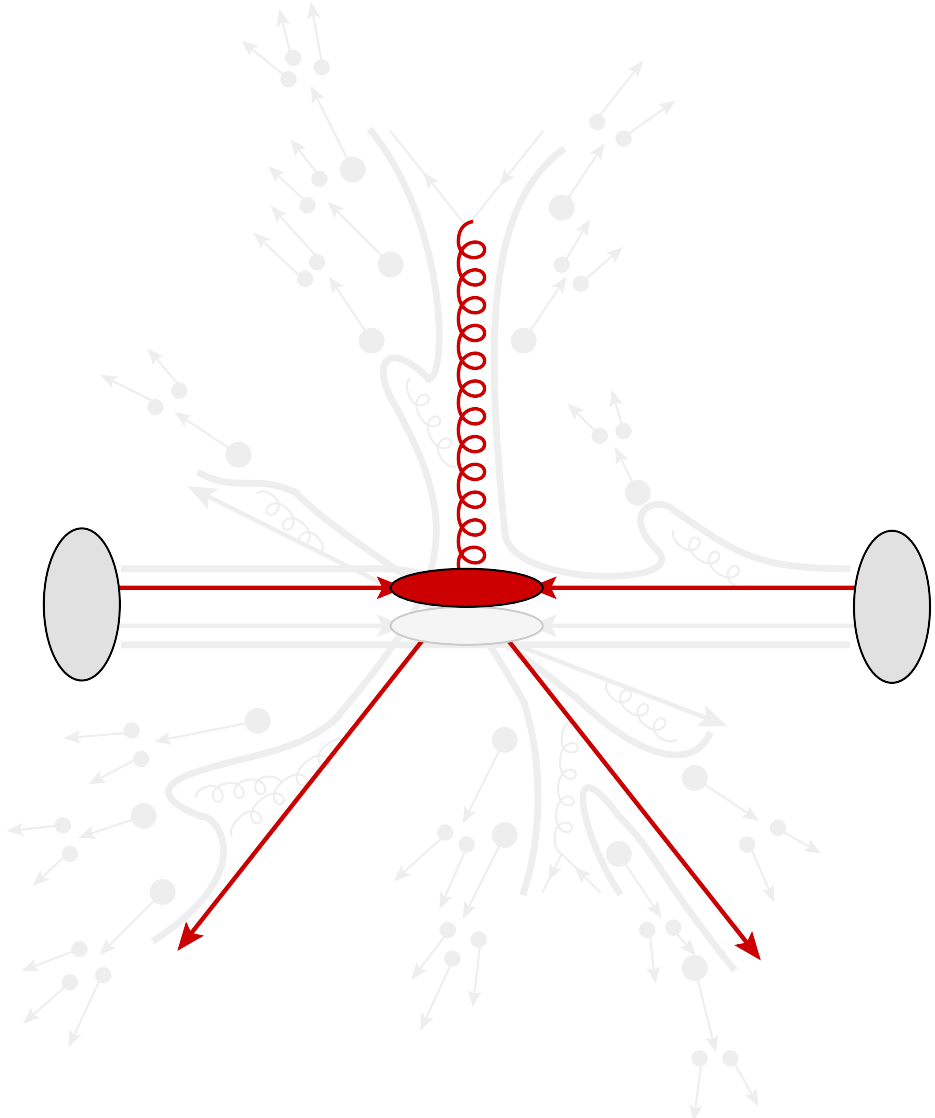
hadronization and decay

Beams	ee, ep, pp, γx, pA, AA, DM
Hard scattering	Core library of internal processes, otherwise from external tools. NLO+PS matching/merging with both aMC@NLO and POWHEG-BOX processes.
Parton shower	Three alternative models: Default (w/ and w/o dipole recoil), Vincia and Dire plugins.
Multiparton interactions	Regularised secondary $2 \to 2$ SM scatterings, interleaved with shower evolution.
Soft physics	Regge-based diffraction and cross section models
Fragmentation	String hadronization with Schwinger-based or thermal transition probabilities.

PYTHIA8 convenience features: "Automatic" PS uncertainties

PYTHIA8 news: PS developments, improved elastic & diffractive cross sections, heavy ions and photons

I) Hard scattering



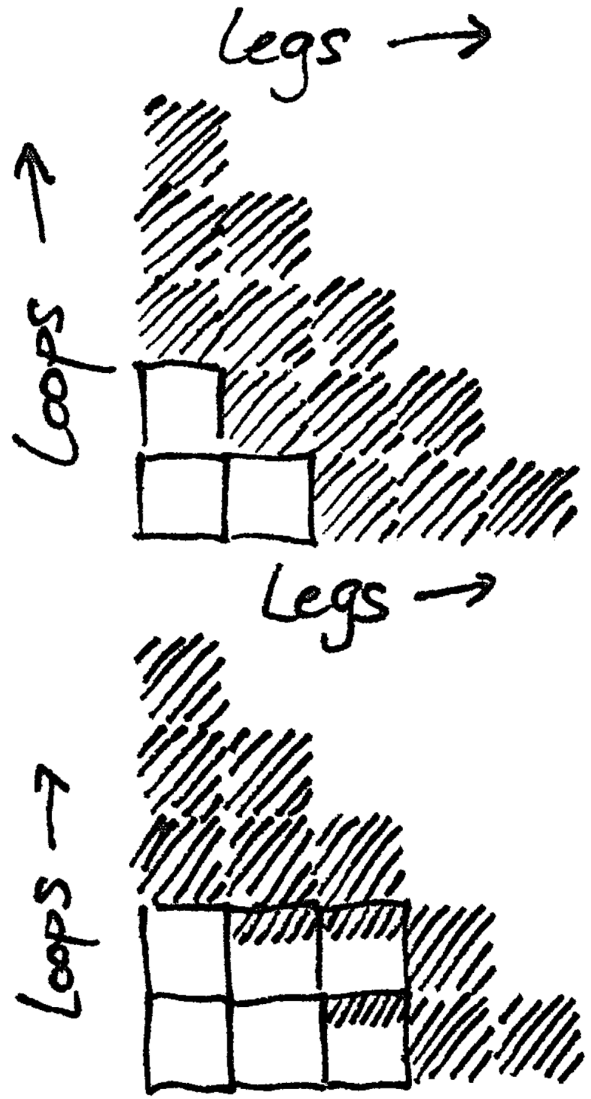
Domain of fixed-order and precision calculations. Big community effort, including POWHEG-BOX, MADGRAPH, aMC@NLO & Pythia.

Philosophy: Combine multi-jet calculations with each other and with subsequent shower for maximal accuracy.

Matching: Combine $\{n, n+1\}$-parton states with shower. Overlap handled by subtraction. Increase precision of inclusive n-parton observables to NLO.

Merging: Combine $\{n, n+1, \ldots, n+m\}$-parton states with shower. Overlap handled by cuts & vetoes.

NLO merging: Same as merging, but with some overlap handled by subtraction. NLO precision of inclusive $n+i$-parton observables for well-separated $n+i$ jets.



Matching & merging: Availability through Pythia + friends

Matching

through POWHEG-BOX: works with Pythia shower variations.
through aMC@NLO: requires global recoil for first emission.

Merging

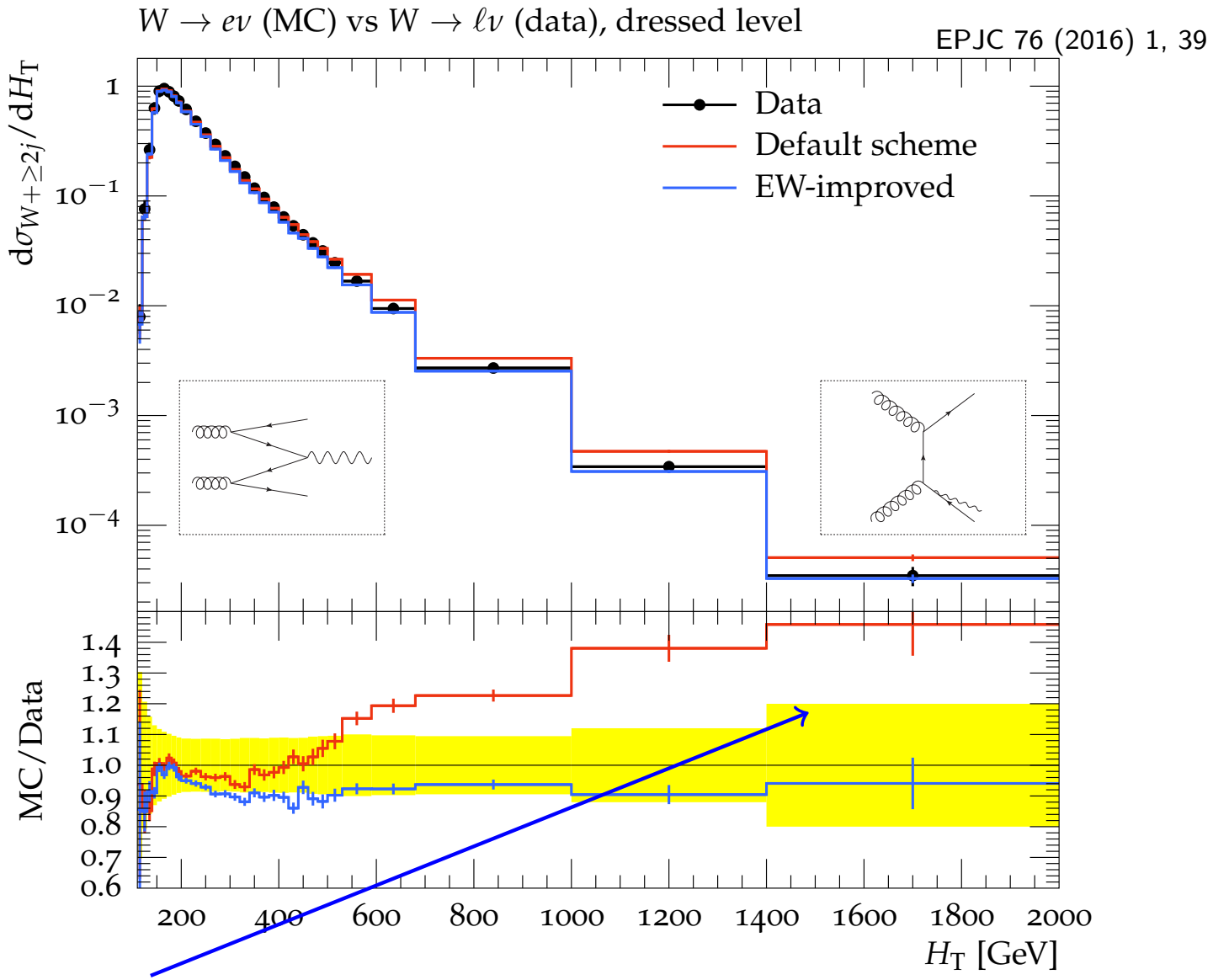
CKKW-L: default in ATLAS. Partially combined with EW corrections. Currently not working with shower variations.
MLM: not clear if can work with shower variations.
FxFx: more heavily used since more streamlined on aMC-side. not clear if can work with shower variations.
UNLOPS: implementation in ATLAS underway. Currently not working with shower variations.

Other

Default Pythia often includes matrix element corrections for 1st splittings.
Vincia plugin contains iterated ME corrections as alternative to merging.

...you probably have more than I do.

Cautionary tales...

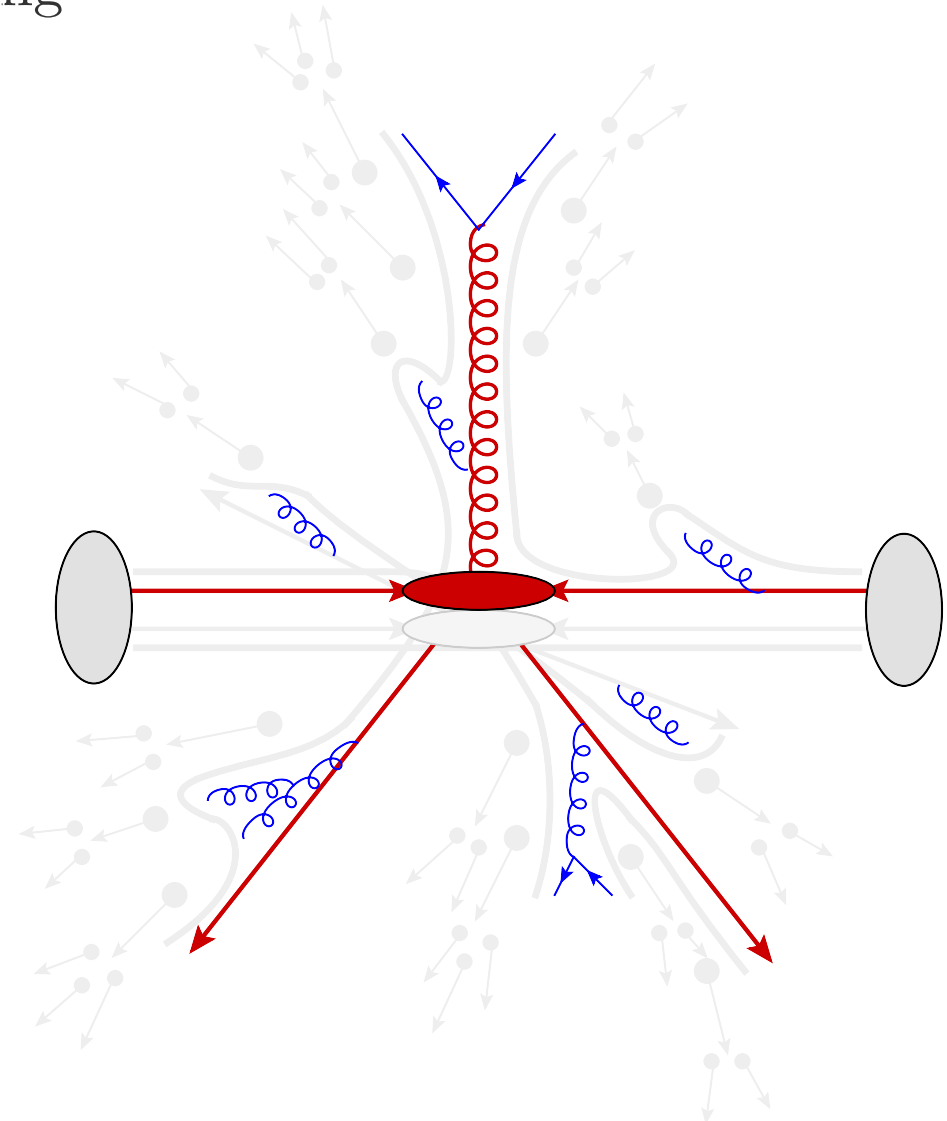


Higher-orders for QCD- and EW corrections very different!

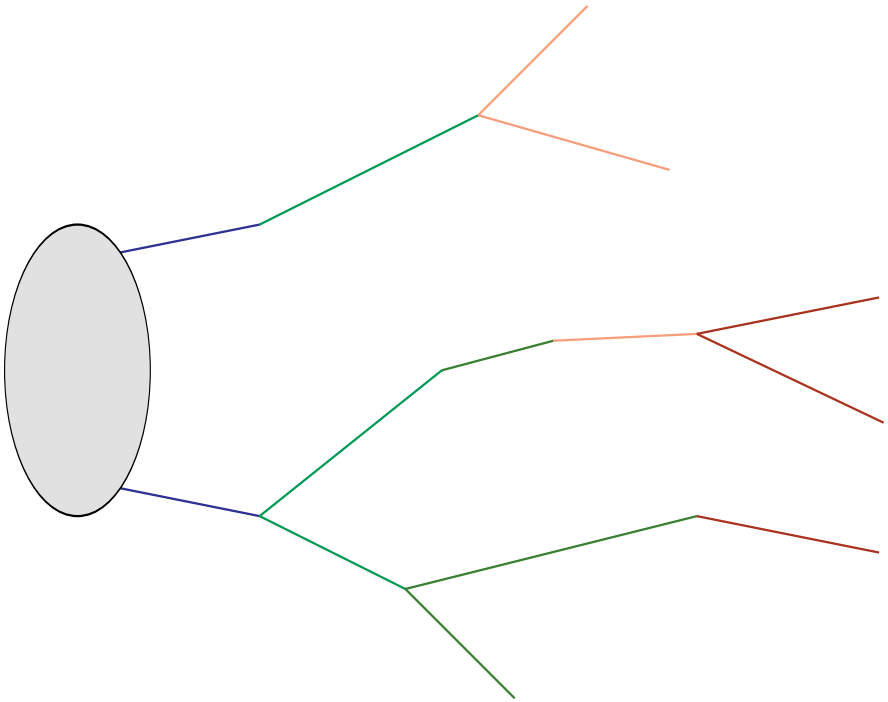
Be holistic when e.g. choosing scales (`Merging:allowWeakClustering = on`)

Matching/Merging Questions or Discussion?

II) Parton showering



Crucial part of physics modeling, as required for jet structure and evolution. NLO+PS only as good as the PS



Showers "dress" partons with radiation by iteratively generating branchings.

Each generated *exclusive* state is a solution to an evolution equation.

Summed semi-inclusively, this solution recovers DGLAP evolution.

Summed fully inclusively, the input cross section is not changed.

These boundary conditions do not determine the cascade completely
$\rightarrow$ different choices beyond simplest leading terms allowed
(ordering/radiation functions/phase space mapping)

Shower options for Pythia

Current default

◇ Improved DGLAP evolution in $p_\perp$
◇ ME corrections for 1st splitting.
◇ QCD, QED, EW, hidden valley
◇ Extensive tuning expertise.

Default with new recoil

◇ Improved DGLAP QCD evol^n in $p_\perp$.
◇ Improved (dipole) recoil for DIS/VBF-like processes.
◇ No realistic tune yet.

Vincia plugin

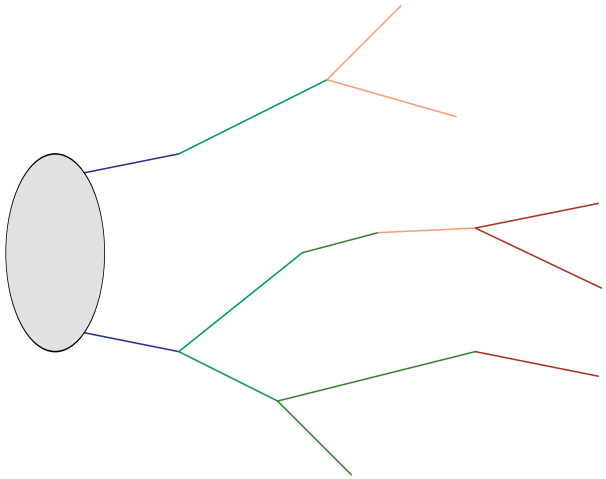
◇ Soft/collinear QCD evolution in 1/eikonal
◇ Implements iterated LO matrix element corrections.
◇ Detailed handcrafted tune.

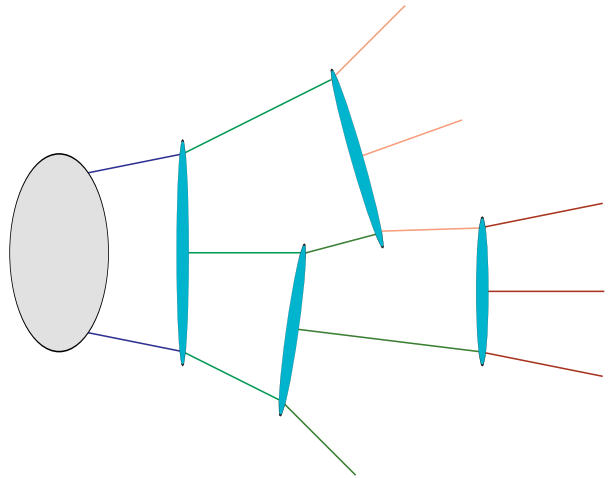
Dire plugin

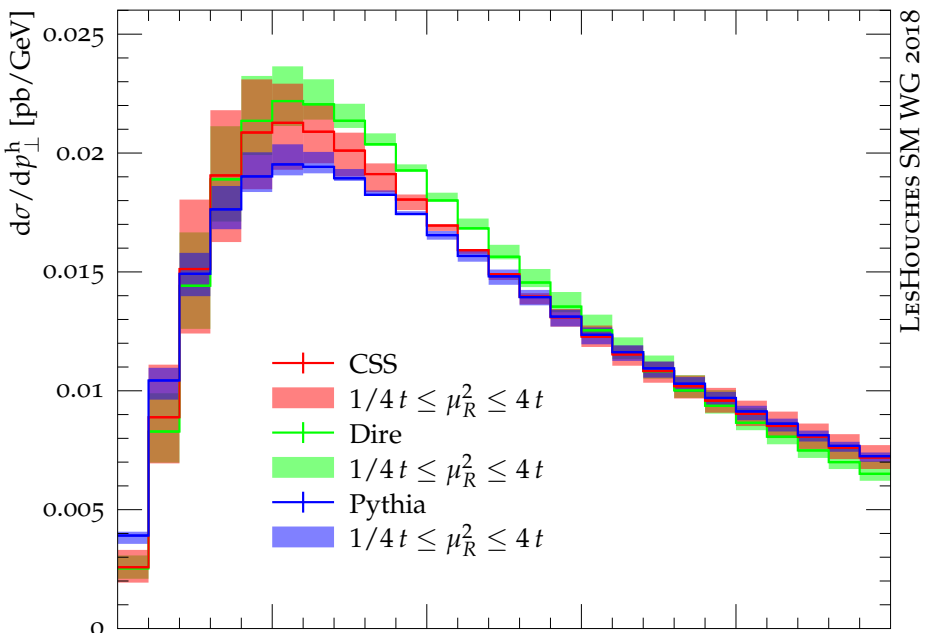
◇ Soft/collinear QCD evolution in 1/eikonal
◇ Implements NLO corrections to evolution.
◇ Simple (LO) Professor tune.

Differences between parton shower options

arXiv:1803.07977 (LH proceedings 2017)







Theory of default and plugins differs

. . . in ordering

. . . in radiation functions

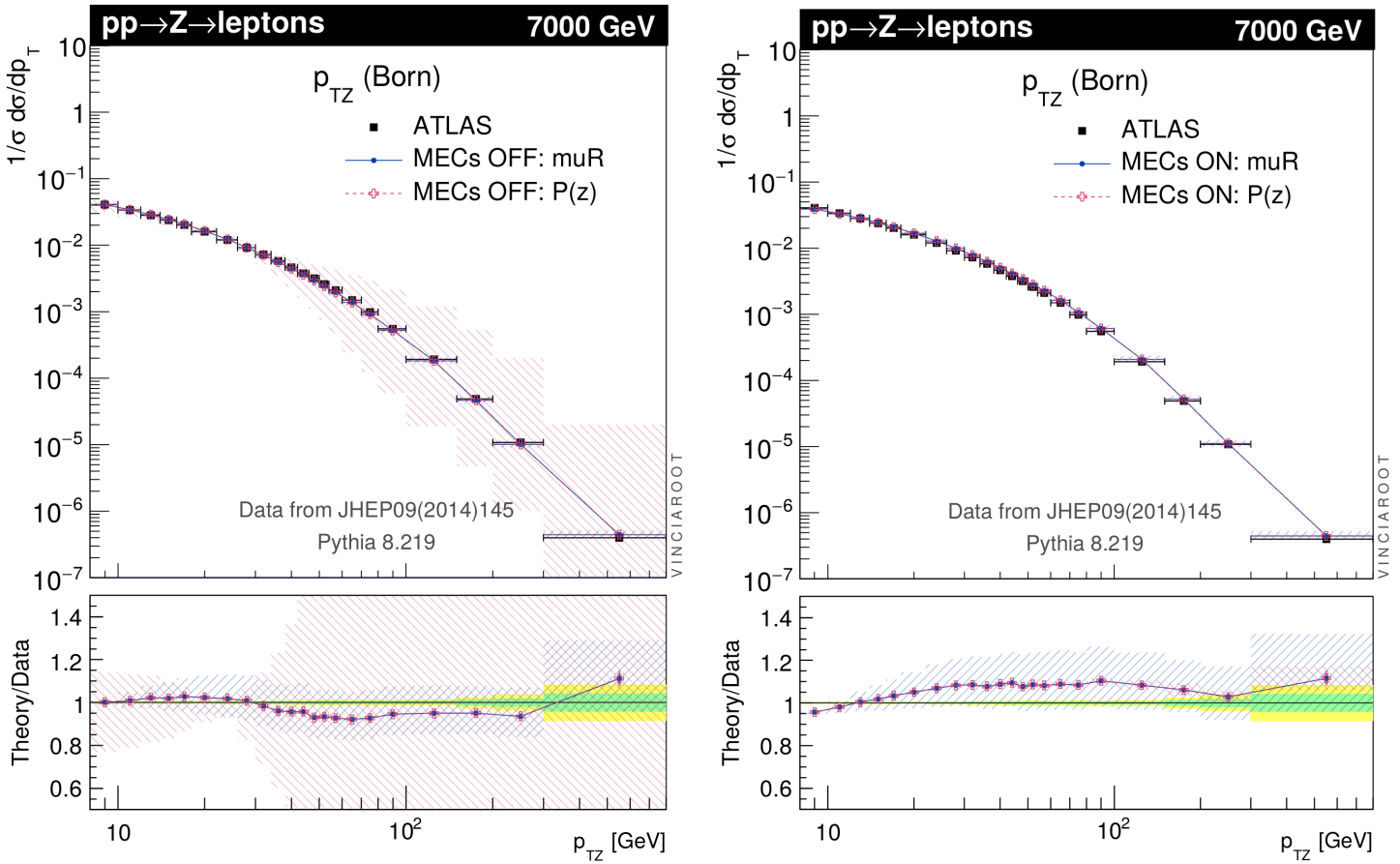
. . . in treatment of coherence.

leading to visible differences.

Shower plugins further handle on uncertainty for shower-sensitive observables (jet substructure...)

Shower variations in PYTHIA

arXiv:1605.08352



PYTHIA allows `UncertaintyBands:doVariations = on` for automatic variations of

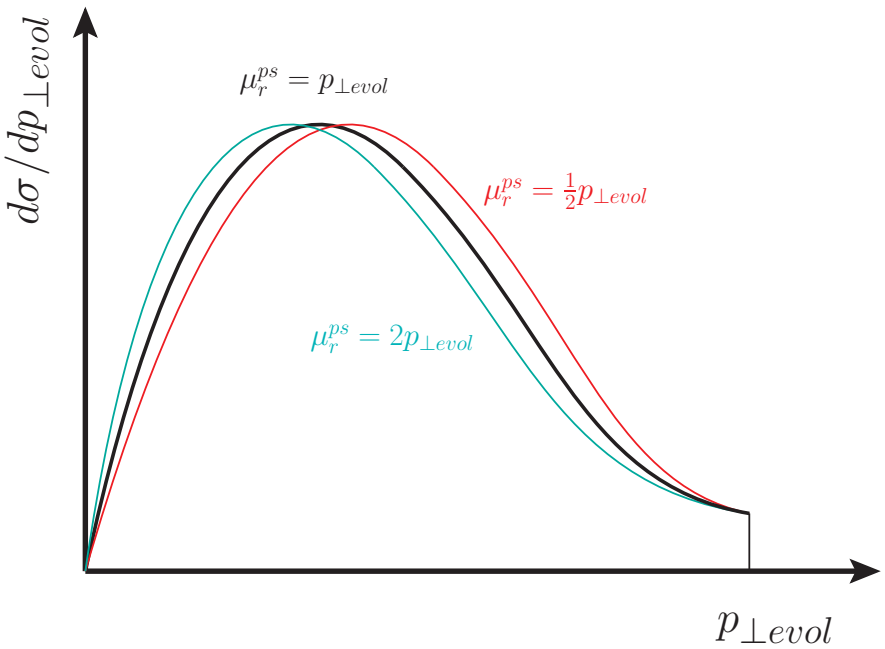
- ◇ μ_r in shower (`fsr:muRfac=0.5 isr:muRfac=0.5`…)
- ◇ finite pieces of splitting kernels (`fsr:cNS=2.0 isr:cNS=-2.0`…)
- ◇ PDF members in shower (e.g. `isr:PDF:plus, isr:PDF:minus`…)

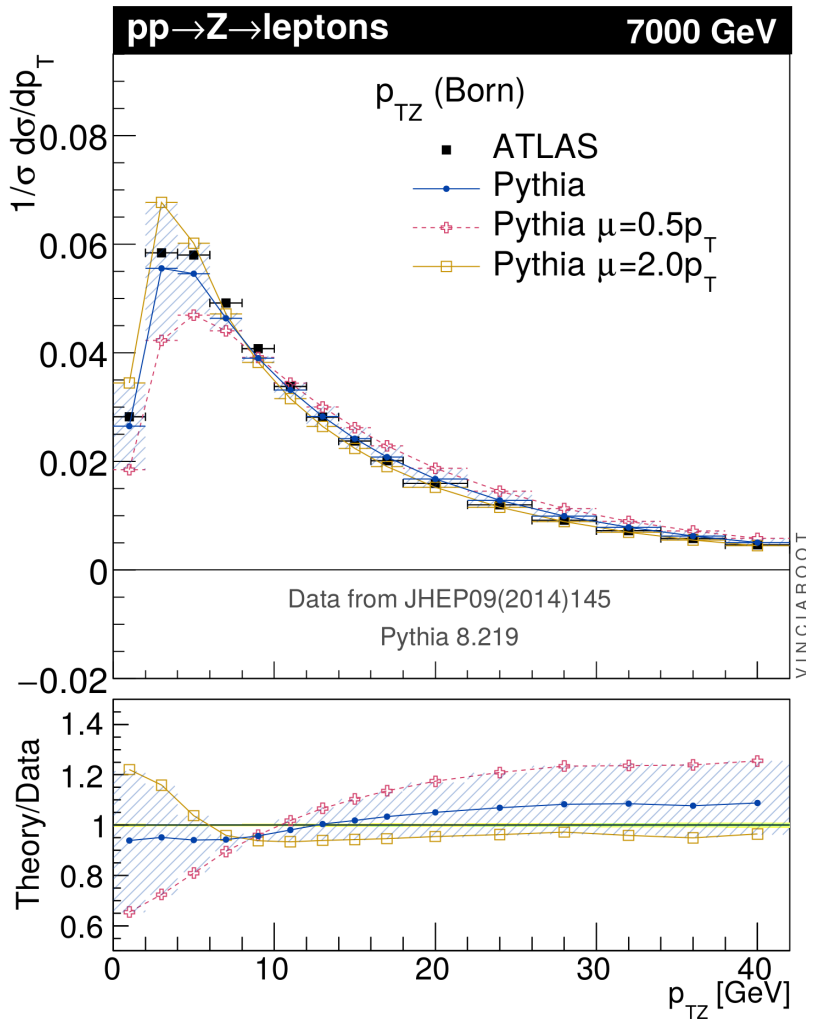
VINCIA includes `vincia24.cc` as illustration (slightly different syntax)
DIRE includes `dire03.cc` as illustration (syntax slightly different)

Peculiarities when varying μ_q^{PS} and μ_r^{PS}

arXiv:1605.08352

$\mu_{r/q}^{PS}$ variations will often yield regions with vanishing uncertainty band.
This is expected from "shower unitarity" (area under curve = inclusive x-section)

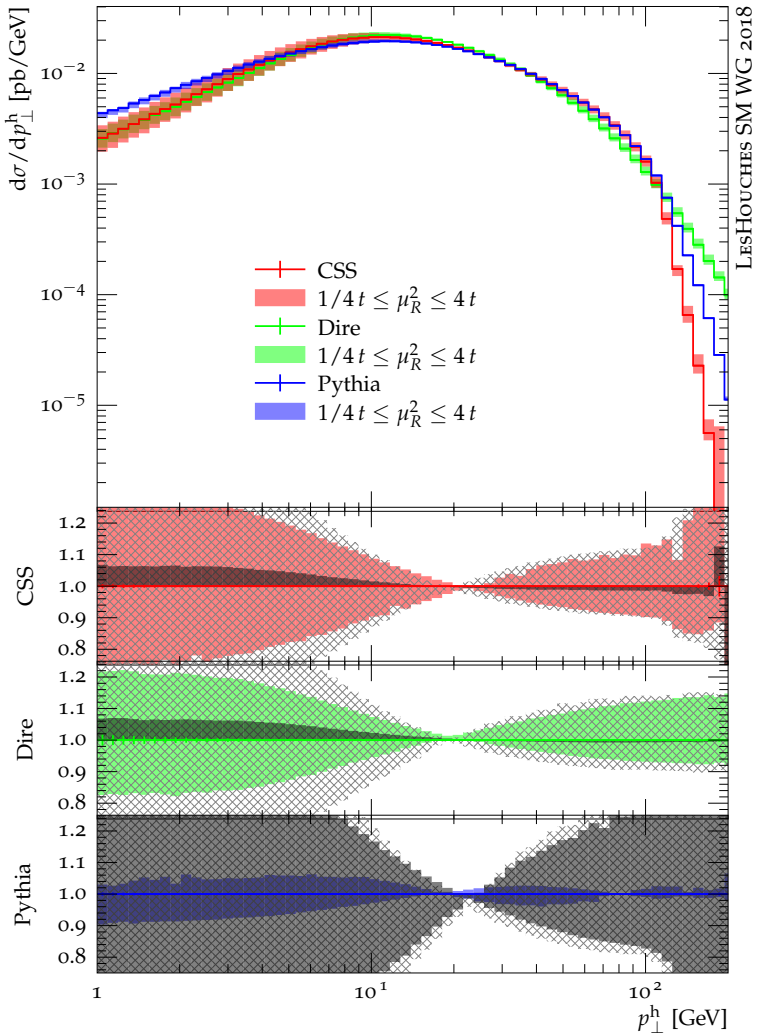




PDF variations can "fill in" some regions.

Parton shower variations with compensation terms

arXiv:1803.07977 (LH proceedings 2017)



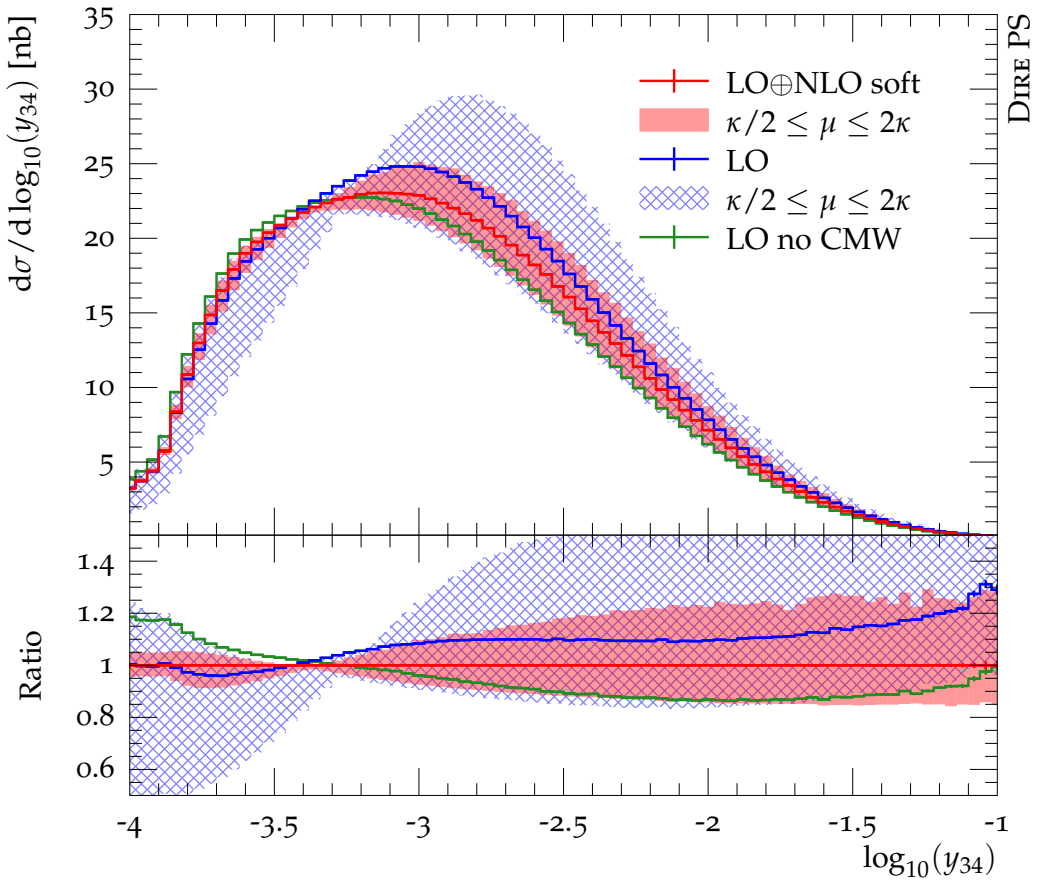
PS includes many improvements beyond leading-order, that might be nice to retain when performing variations

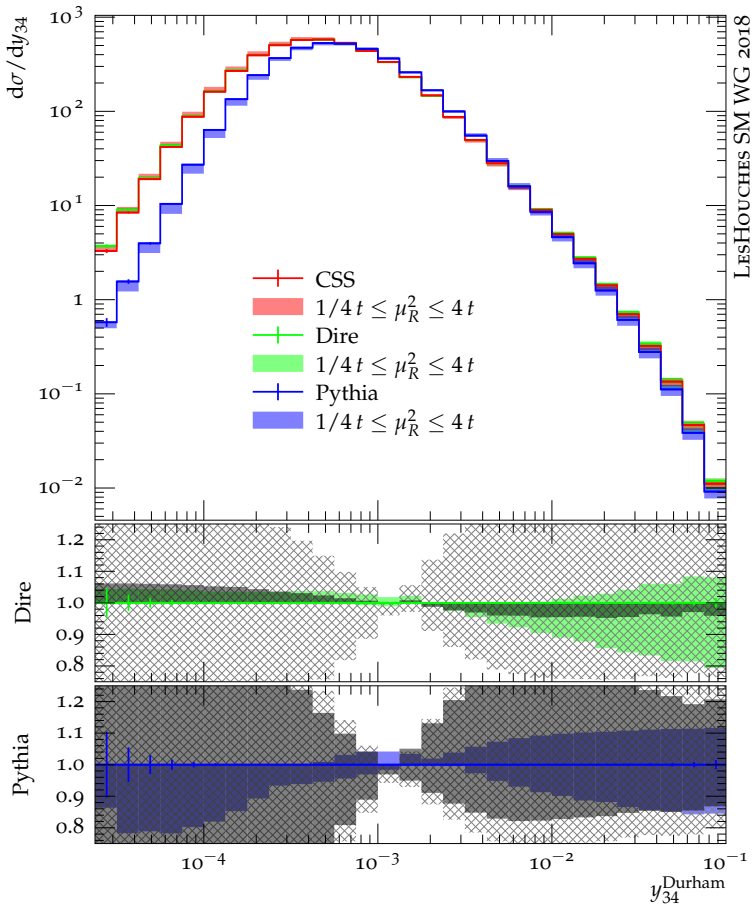
$\rightarrow$ Introduce compensating terms.

Drastic reduction realistic?

(Almost) complete NLO shower vs. uncertainty estimates

arXiv:1805.03757 (S. Höche, F. Dulat, SP)

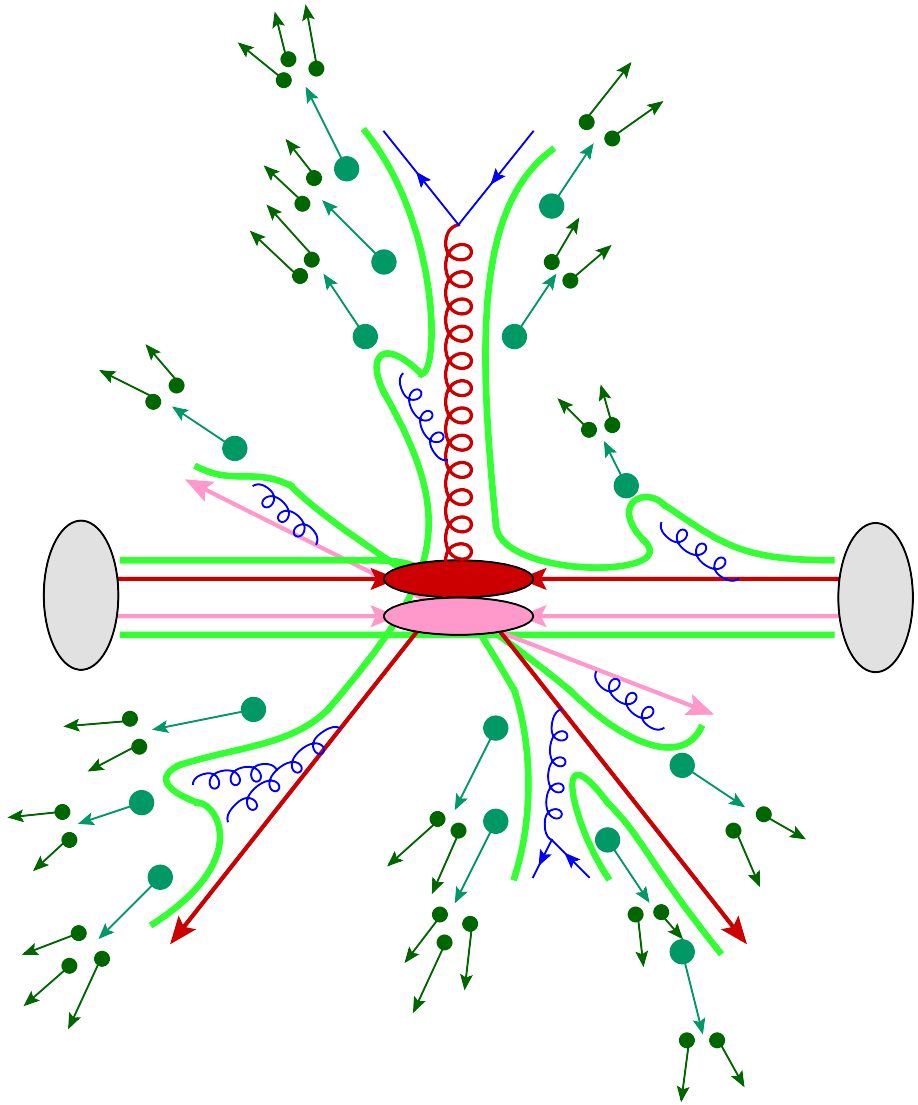




→ Reduced uncertainty in NLO calculations.
"Compensated" LO scale variation attempts give much too small & distorted band.

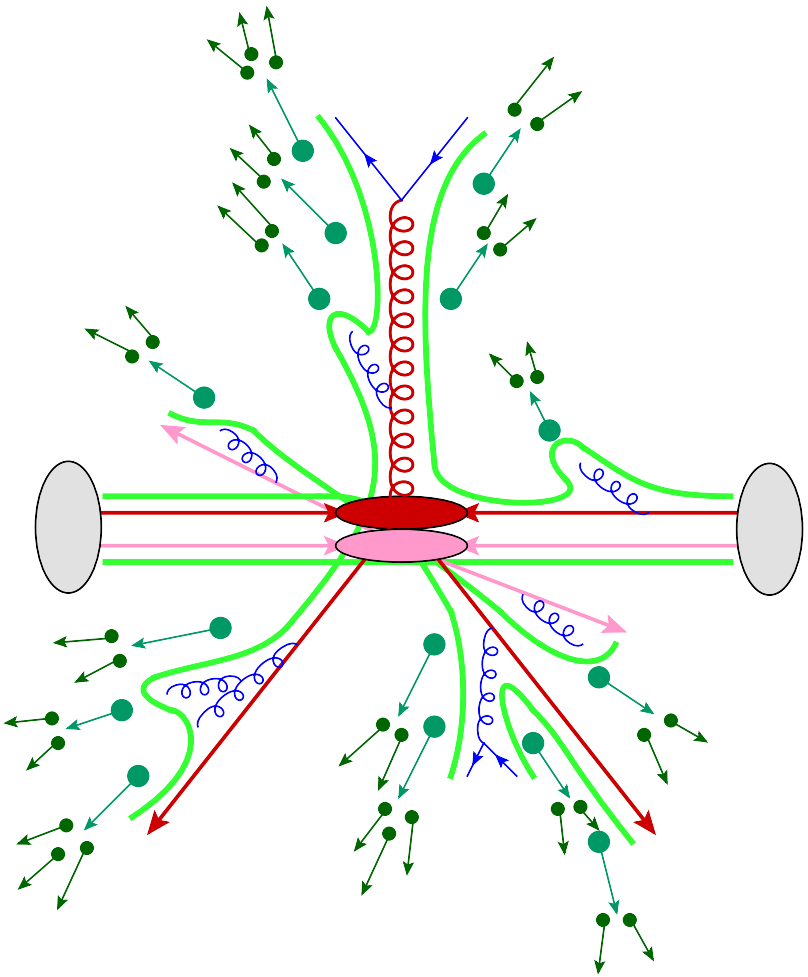
Parton shower Questions or Discussion?

III) Tuning



A collision is more than "just" perturbative QCD. Heuristic models needed to fill the gaps. Inherent parameters need to be extracted from data $\rightarrow$ Tuning.

Correlations between pQCD and soft/non-perturbative modelling



Uncertainties:

Short-distance cross section:

μ_r^H, μ_f^H, PDF^H, α_s^H

Parton shower:

μ_q^{PS}, μ_r^{PS}, μ_f^{PS}, μ_{cut}^{PS}, PDF^{PS}, α_s^{PS}

Multiple interactions:

μ_q^{MPI}, PDF^{MPI}, α_s^{MPI} ...

...correlated with:

μ_f^H with shower starting scale

μ_f^H, PDF^H with MPI

μ_q^{PS}/μ_f^H and $\text{PDF}^{PS}/\text{PDF}^H$

μ_r^{PS}/μ_r^H and α_s^{PS}/α_s^H for NLO+PS

μ_{cut}^{PS} with "string $p_\perp$" & "primordial $k_\perp$"

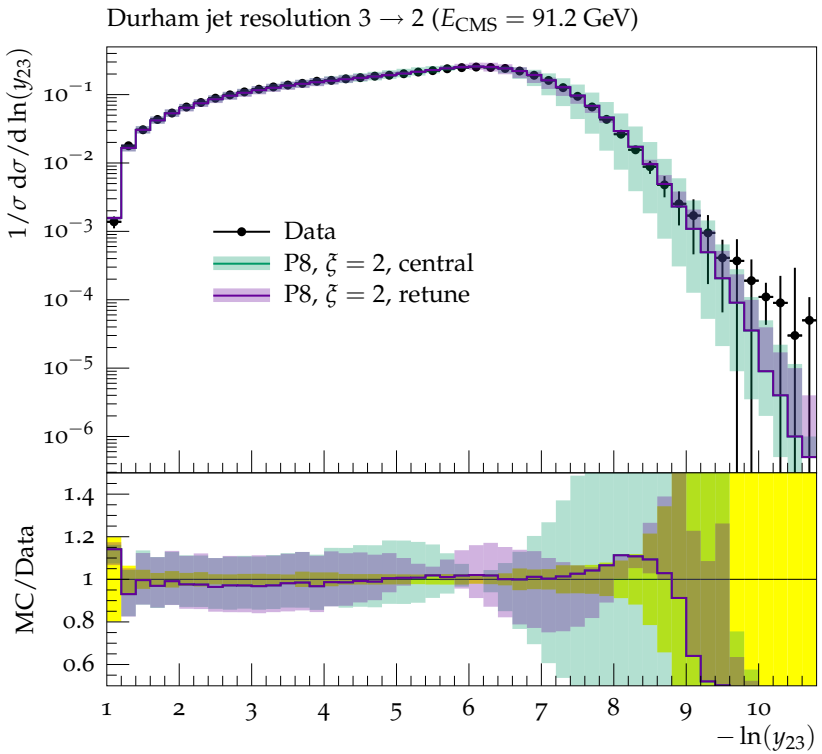
α_s^{MPI} and α_s^{PS}

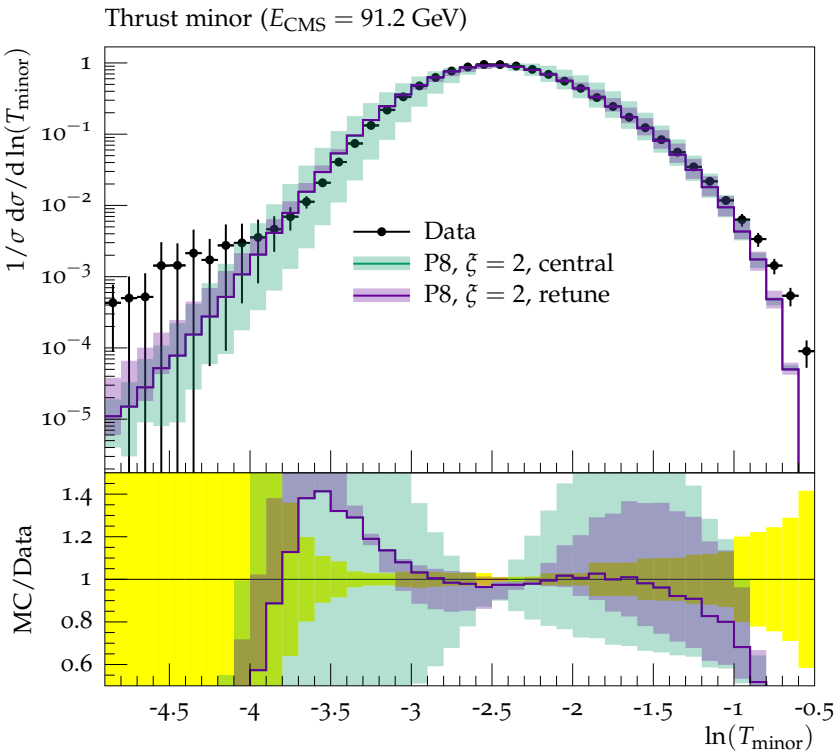
α_s^{MPI} and "string tension"

Tough to describe all phenomena, let alone with satisfactory uncertainty.

Tuning and correlations

arXiv:1803.07977 (LH proceedings 2017)





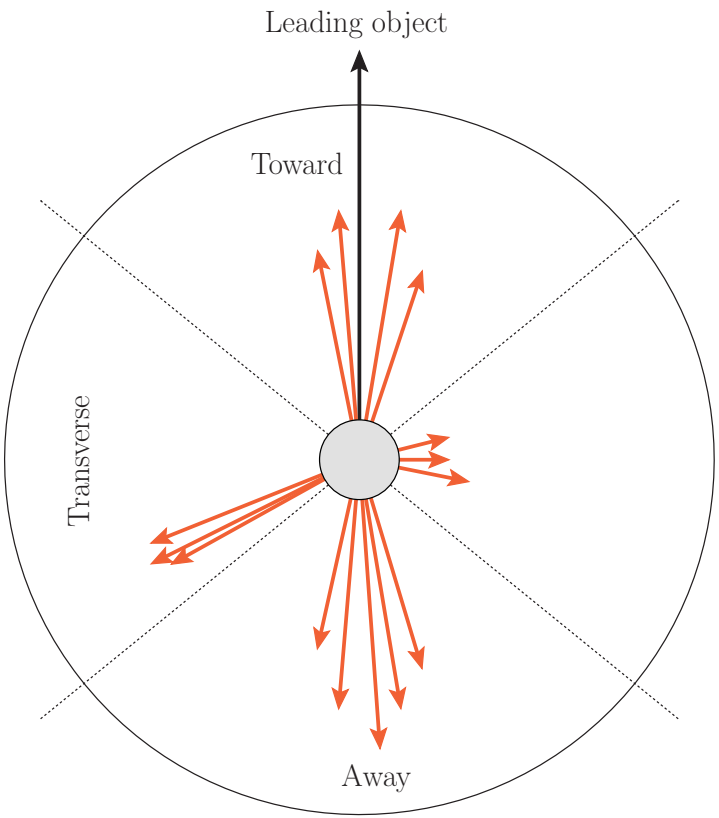
Naively, would want to tune *only* soft/NP parameters using "specialized" observables ($n_{ch}, n_{\pi,K}\ldots$ scaled momentum). But NP models are very sensitive to *perturbative input* state. ⇒ Soft/NP & perturbative parameters very correlated!

Also, "perturbative" observables can have NP regions as well. Should perturbative variations degrade the accuracy there? ⇒ One tune per variation?

Results of joint tune/scale variation seem reasonable at LEP. Run once per variation :(

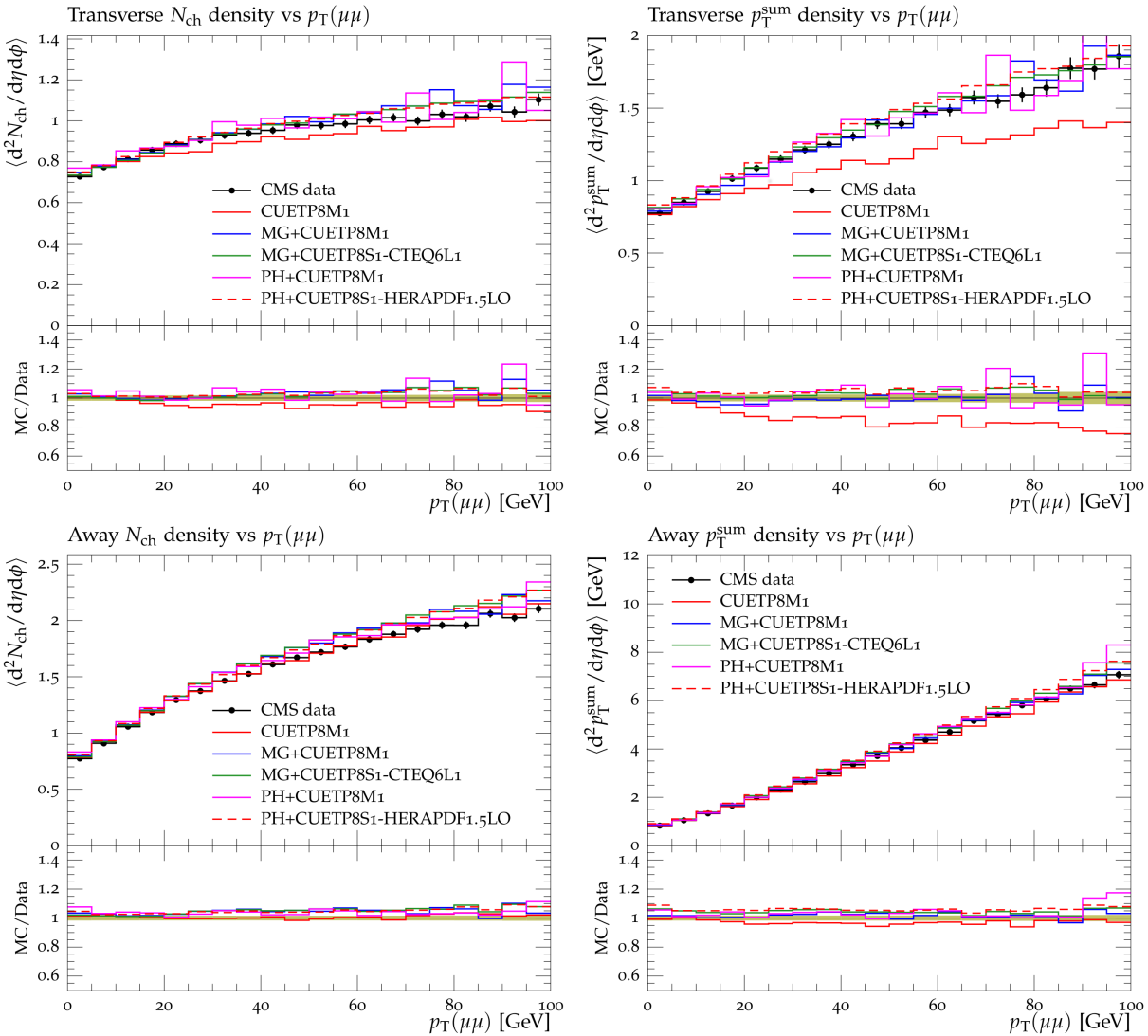
Scattering composite objects adds more complexity:
Underlying event, modelled by *multiparton interactions*

As for fragmentation, fit MPI on "specialized" measurements (charged multiplicities, divided into MPI-sensitive and MPI-insensitive regions)



Fitting MPI → Tuning perturbative physics?

Plot from arXiv:1512.00815



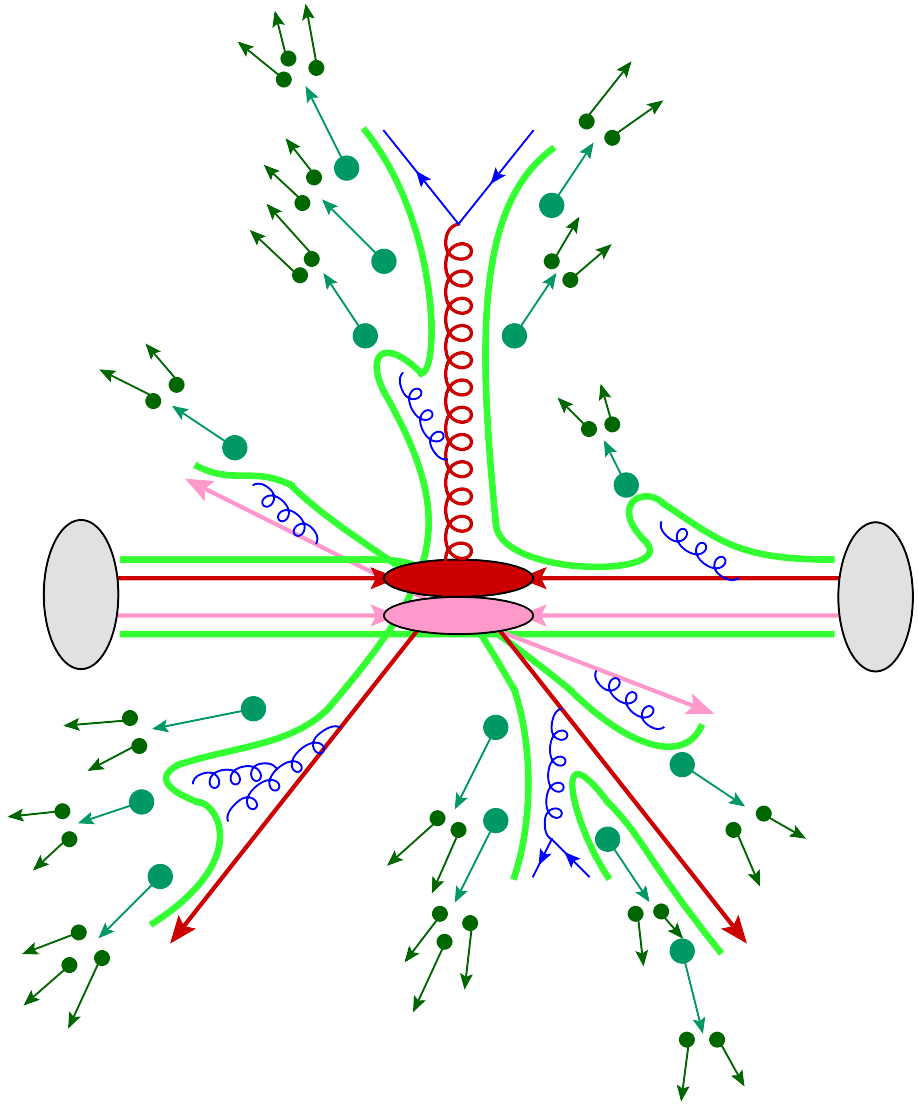
Hard QCD has considerable impact on tailored MPI observables!

But no generator/merging allows consistent transition

Minimum Bias → Dijets with UE → Multijets with UE.

Tuning Questions or Discussion?

IV) Semi-soft and non-perturbative effects

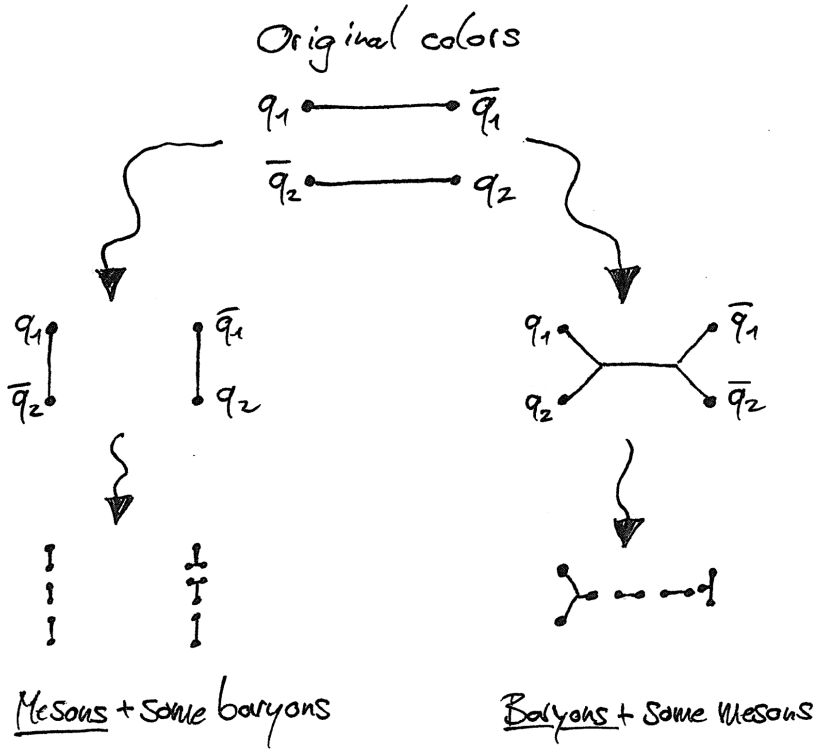


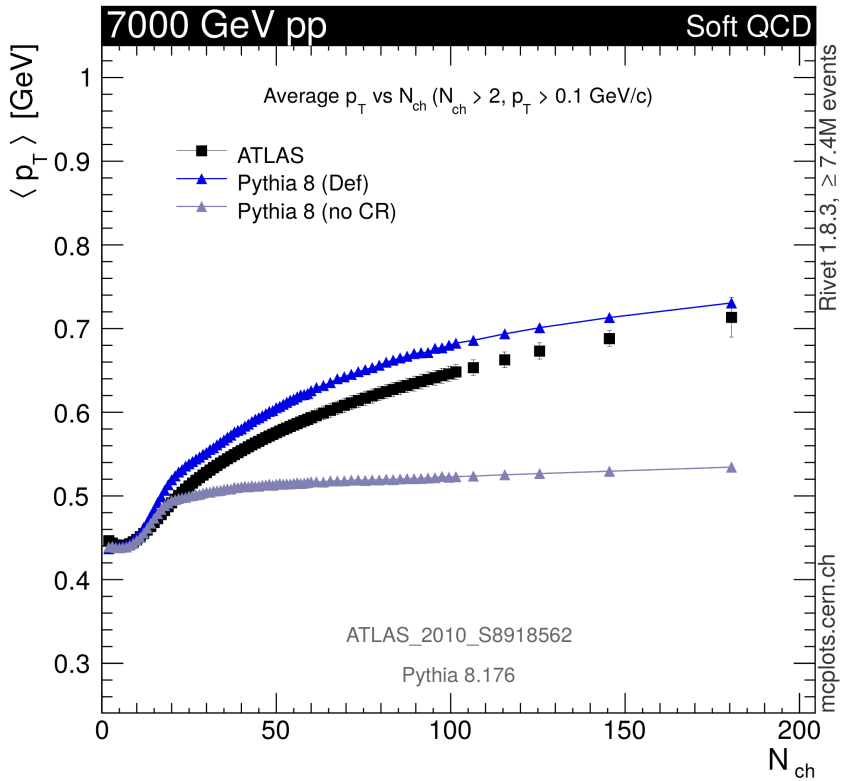
Non-perturbative models needed to describe the bulk of cross sections at LHC and beyond & offer exciting insights into emergent phenomena.

Color reconnection

Illustrative plot from arXiv:1505.01681

Many overlapping QCD interactions → collective behavior from color rearrangement:





→ Reconnection necessary to describe data.
New model of `arXiv:1505.01681` emphasizes SU(3) selection rules to arrange input color states for string hadronization. Feedback welcome!

NP processes: Total, elastic and diffractive cross-sections

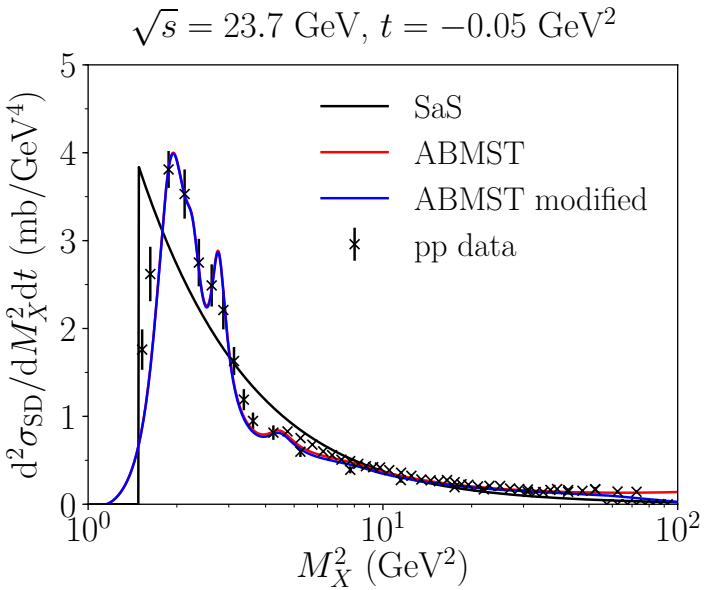
Plots from arXiv:1804.10373

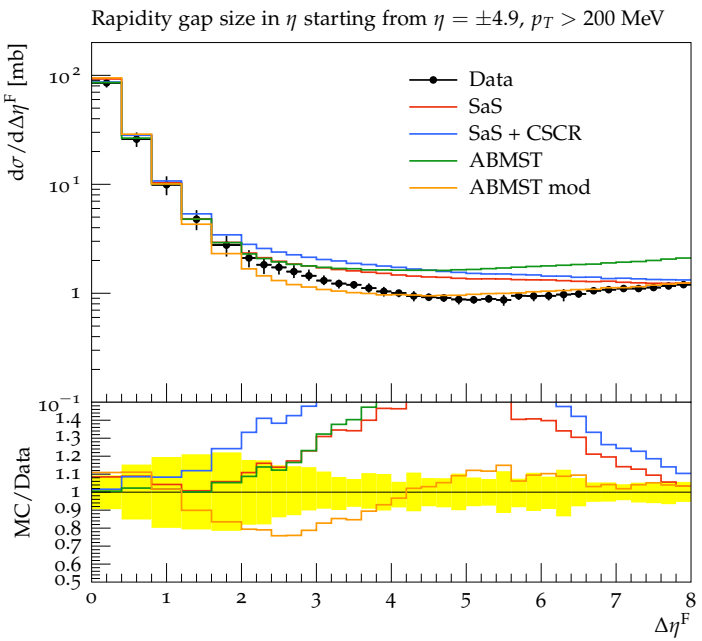
Accurate modelling of complete scattering cross section crucial to understand Min-Bias & UE, and hence jet profiles + pile-up.

Difficult to describe all LHC data w/ old single Pomeron exchange model.
⇒ Total + elastic σ updated to two modern parametrizations w/ ≥ 4 exchanges.

Also need to dissect σ into diffractive and non-diffractive parts to describe scatterings with (partially) intact p-beams.
⇒ Unification of soft & hard diffraction.

Ready for serious use + feedback from experimental bird's-eye view welcome!

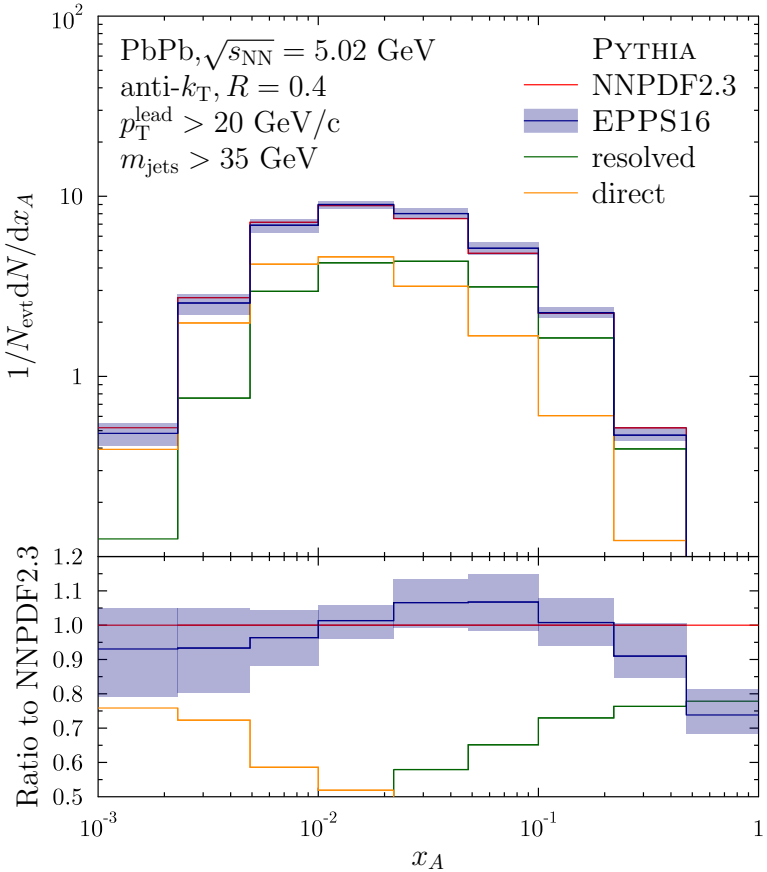


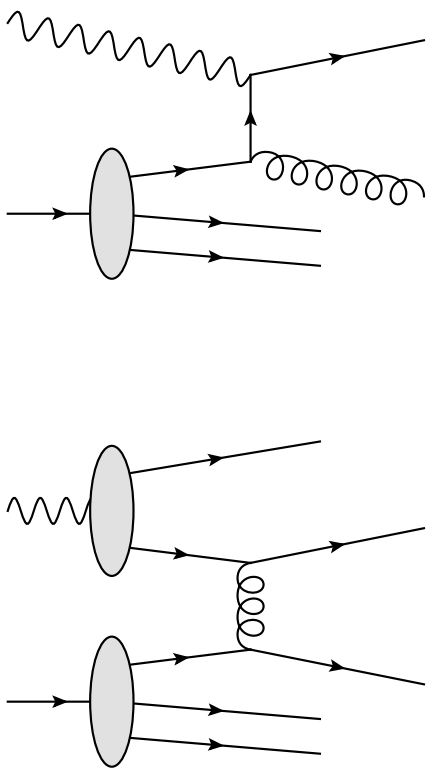


NP processes: Ultra-peripheral collisions

Figures by I. Helenius, arXiv:1510.05900, arXiv:1806.07326

In ultra-peripheral pA or AA collisions, colliding photons can also have non-perturbative structure & illuminate nuclear PDFs.





PYTHIA implementation ready to use for measurements at pp LHC, e.g. dijets in UPC. Sample usage, see `main70.cc`. **Feedback welcome!**

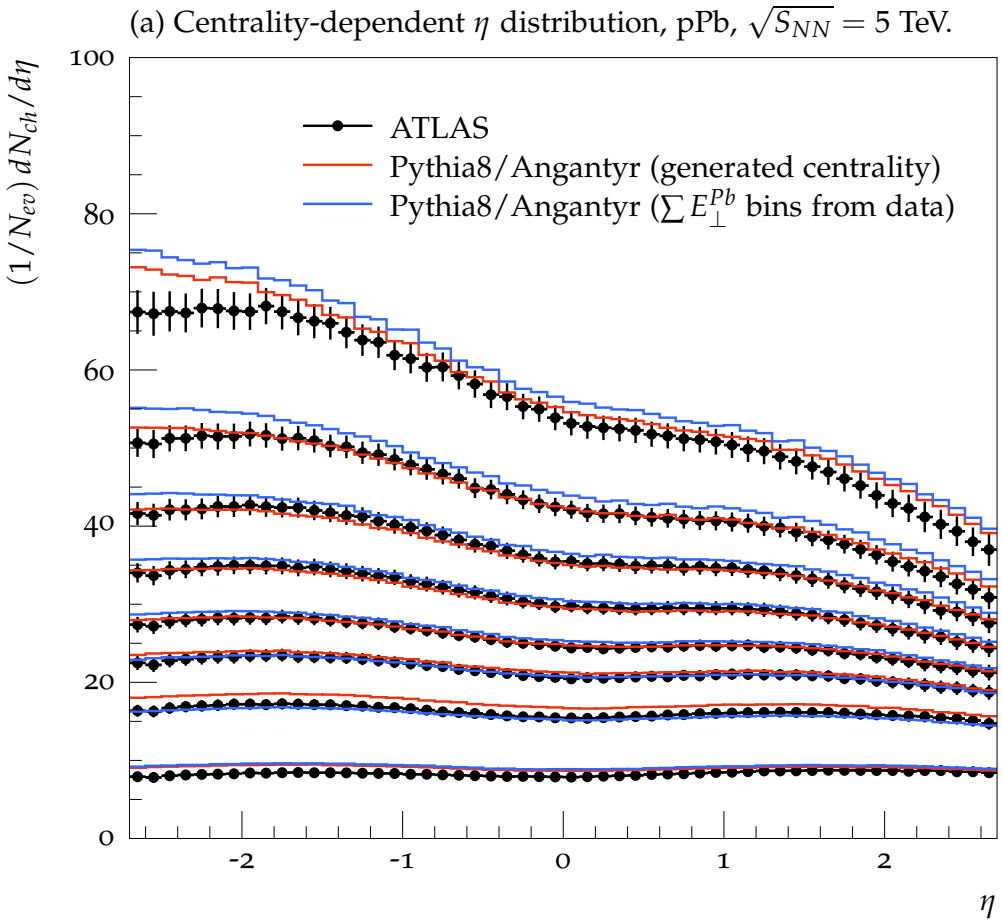
arxiv:1806.10820

High-multiplicity (MinBias) pp collisions already suggest extreme QCD behavior. How does that relate to the state of matter in heavy ion collisions?

pA and AA collisions included through ANGANTYR model:

- Gives complete event-by-event final state of nucleon-nucleon subcollisions and of total collision
- Includes event-by-event fluctuations of nucleon wavefunctions.

Pythia ready for pA and AA collisions (see `main112.cc` and `main113.cc`)

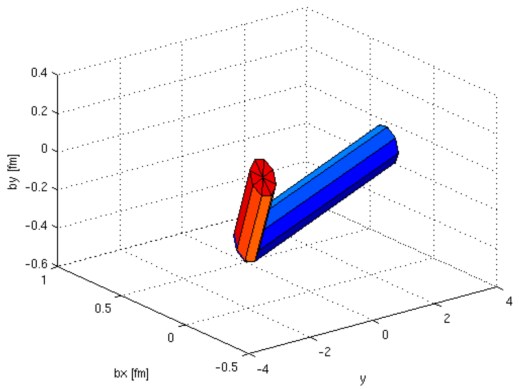


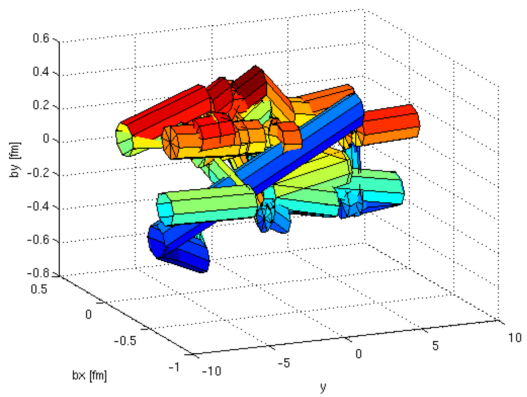
Collective effects

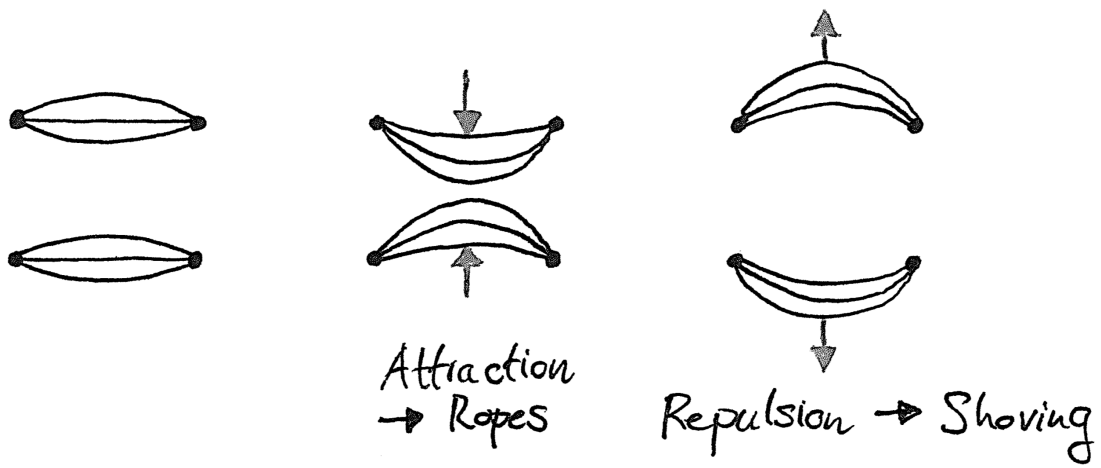
Collisions at LHC are packed densely with color.

CR mimics collective effects, but not dynamics.

Model string interactions
$\rightarrow$ Microscopic model of collectivity!

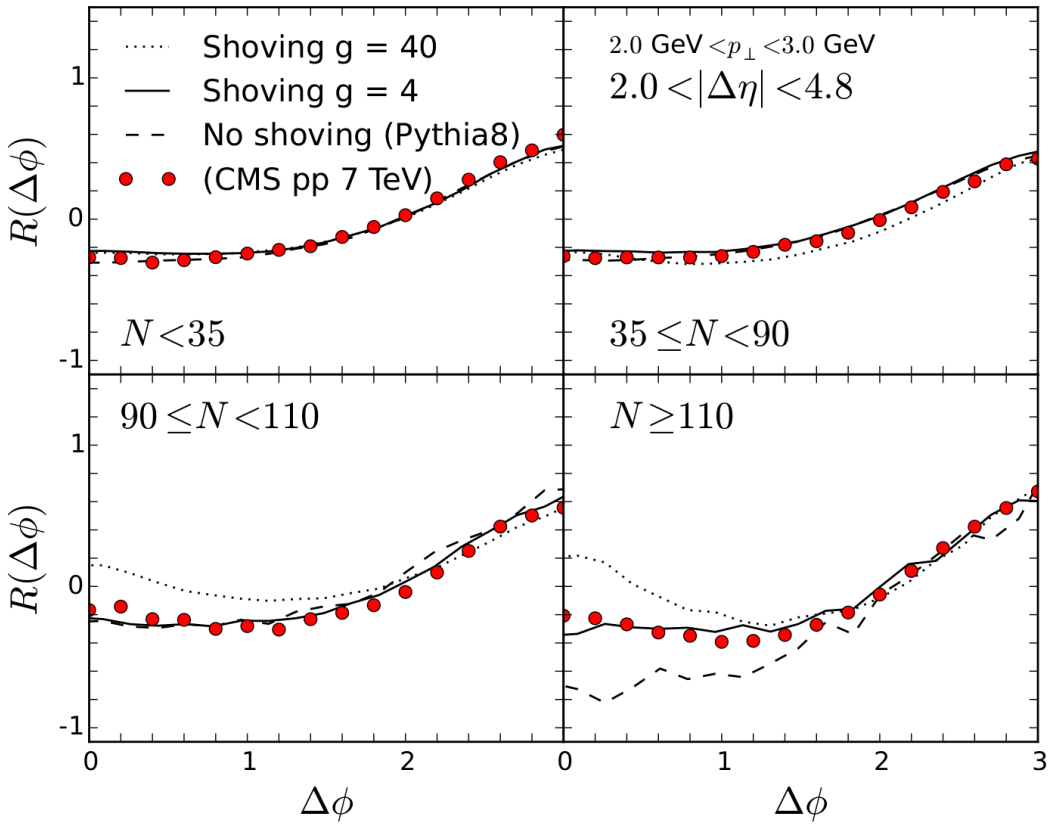






Collective effects

Plots from arXiv:1710.09725



In 2010, CMS measured long-range azimuthal multiplicity correlations. Repulsive string interactions can reproduce the "ridge" in CMS pp data with only one parameter on top of PYTHIA.

IV) Plans

Perturbative side:

- Consistently combine shower variations and merging
- Implement matching/merging for Vincia and Dire
- Improve shower evolution beyond leading color/order (Vincia & Dire)
- Include Vincia & Dire as core Pythia functionality

Non-perturbative side:

- Unified photo-production and diffractive framework
- Extend spacetime picture of hadronization
- Combine “ropes” with heavy-ion modelling

V) Summary

- Pythia contains sophisticated matching/merging facilities for **fixed-order** calculations.
  No real news – need to understand uncertainties & correlation with showers and tuning. Need to consolidate UNLOPS functionality in ATHENA!
- Renewed interested in advanced **parton shower** models:
  Vincia, Dire, improvements to default shower. Global assessment of new models necessary. Use for jet (sub)structure encouraged.
- Significant expansion in **non-perturbative physics**:
  Better diffraction, new photo-production processes, new heavy ion interactions. Need feedback from experiment!