Stefano Frixione

Monte Carlos

MC4BSM-8, Daejeon, 19/5/2014

Plan

- Basics of Monte Carlos
- Recent progress (in the perturbative part)
- Outlook

I shall only have time to review mainstream stuff
(apologies to those left out)

Why bother?

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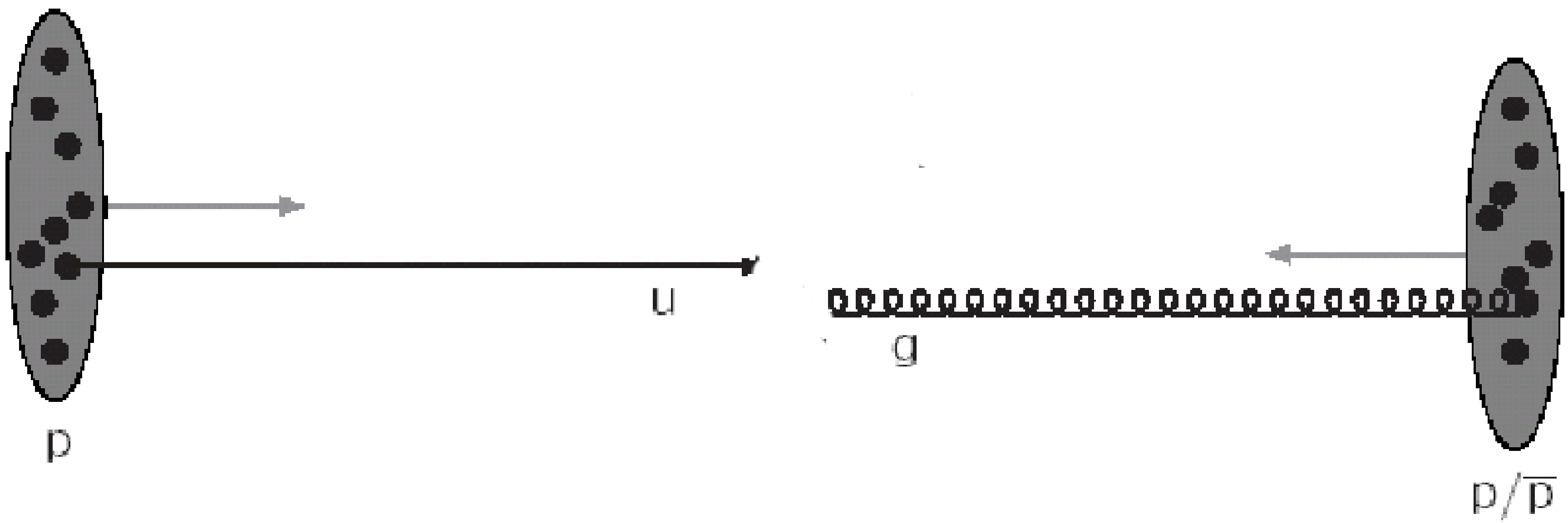
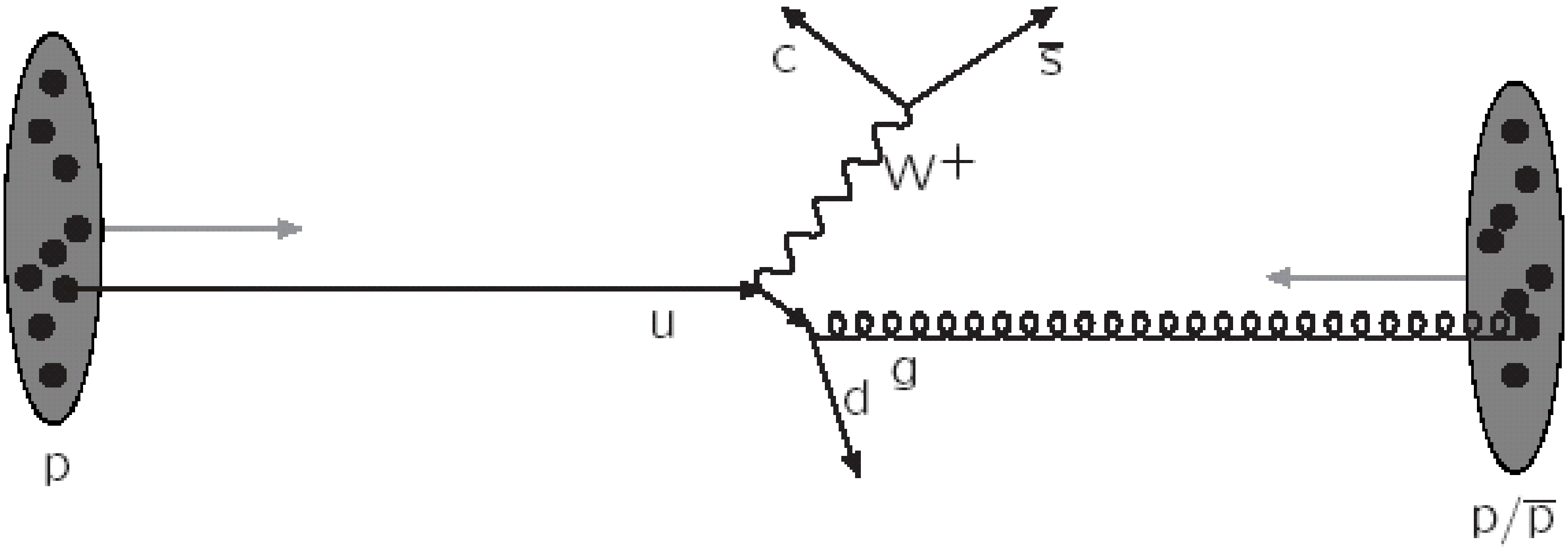
- By far the best way to model the events emerging from LHC detectors, at the same time allowing an intuitive understanding of complicated processes
- May play (have played) a much more significant role in discoveries and exclusions than in the past
- Because a lot of work went into them in the past few years, resulting in very significant progress (e.g., now MCs are quite good at predictions, and not only at postdictions)

Plot: T. Sjöstrand



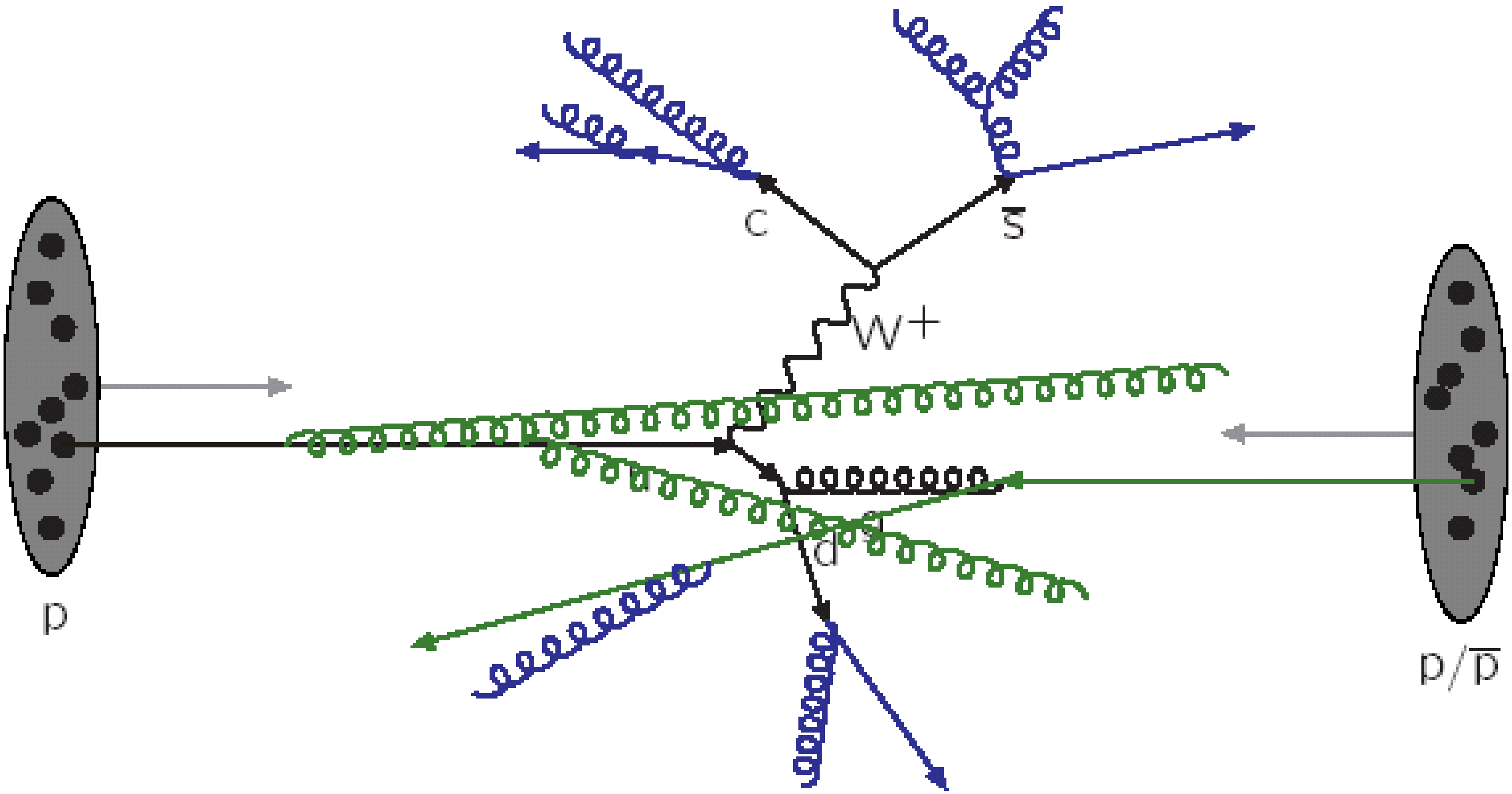
0. Pull out one parton from each of the incoming hadrons
(use PDFs to choose flavour and x)

Plot: T. Sjöstrand



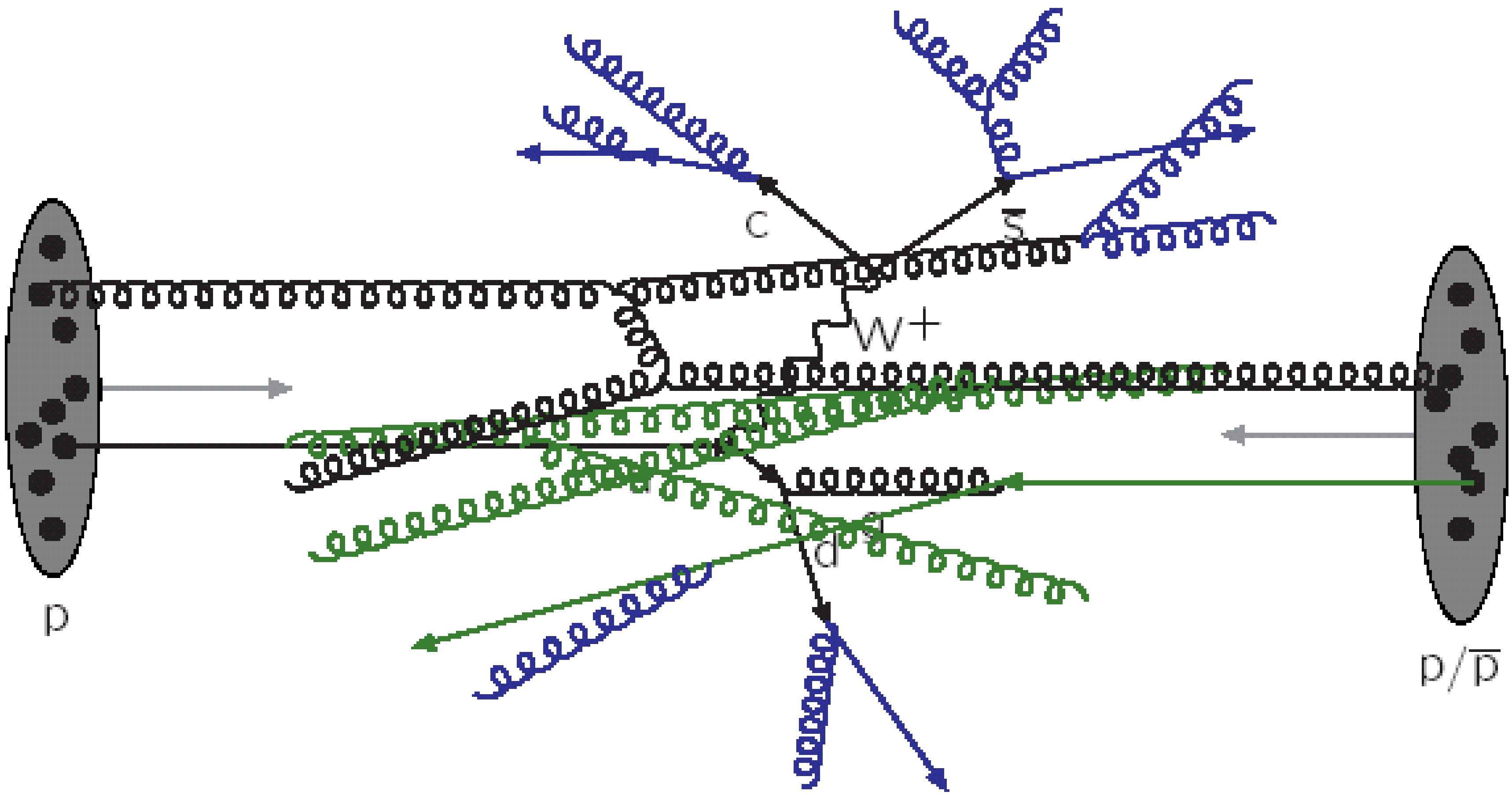
1. Make them collide and produce *large-p_T stuff*
(Hard Subprocess)

Plot: T. Sjöstrand



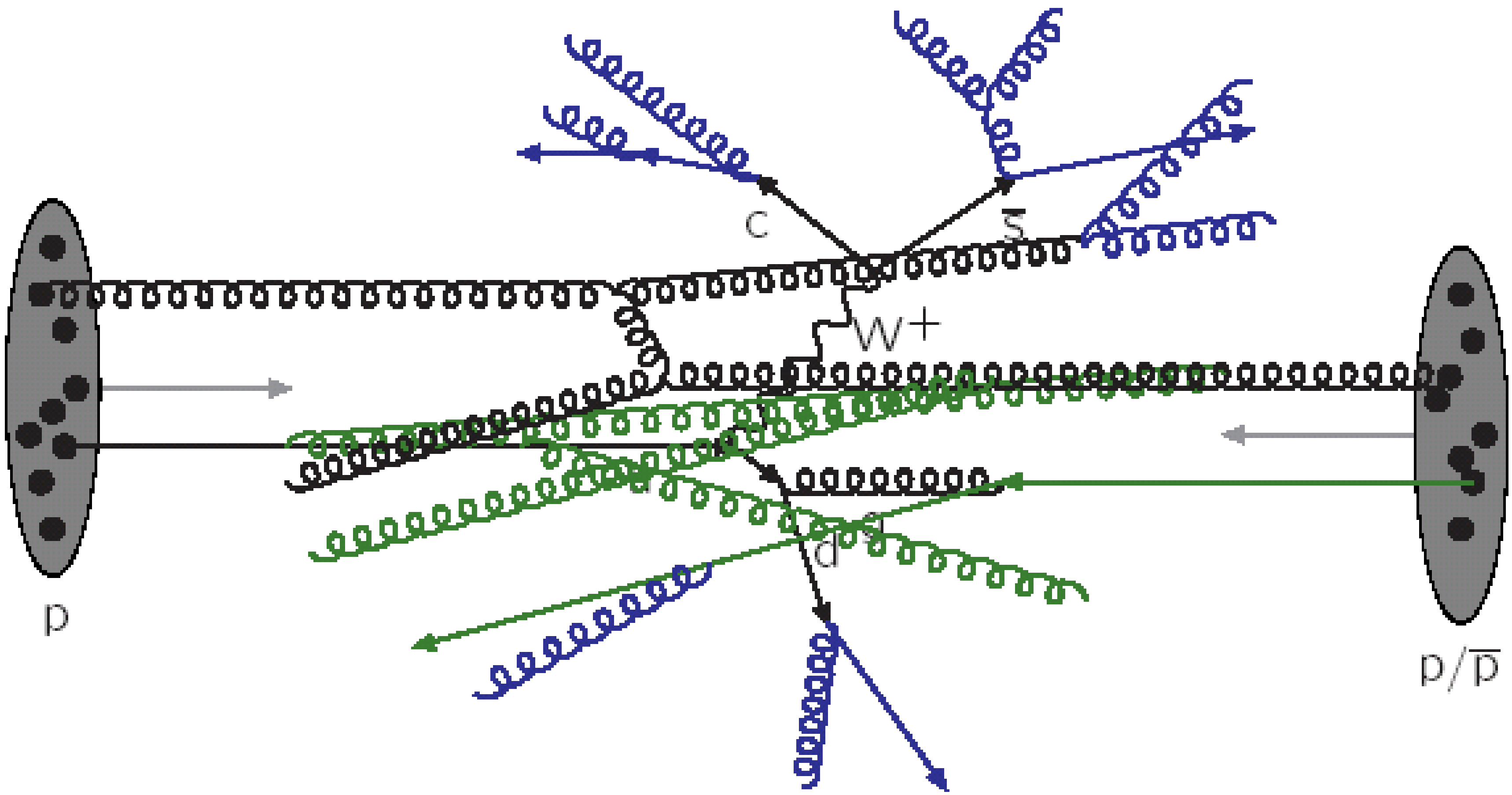
2. Let quarks and gluons emit other quarks and gluons (Parton Shower)

Plot: T. Sjöstrand



3. Other partons may undergo the same fate *at smaller* p_T*'s*
(MPI + beam remnants ≡ Underlying Event)

Plot: T. Sjöstrand



4. Convert quarks and gluons into physical hadrons (Hadronization)

1. Hard process. Very well understood, fully perturbative with no approximations (traditionally, at the LO only)

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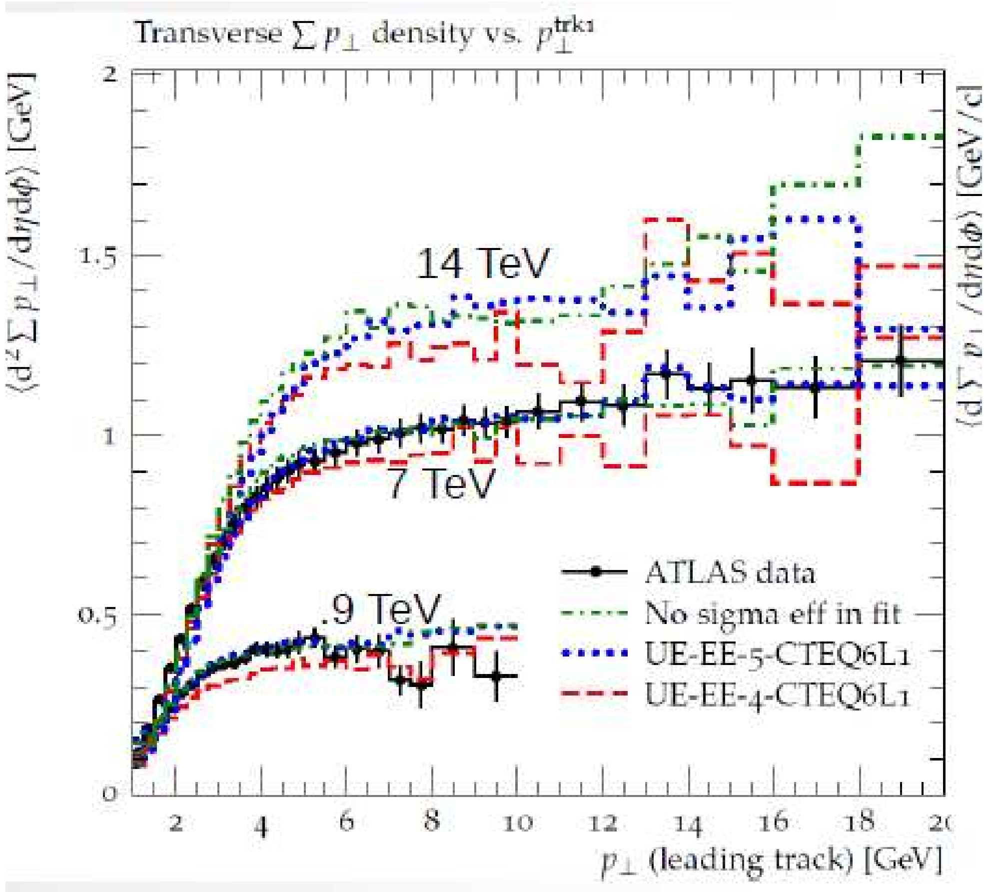
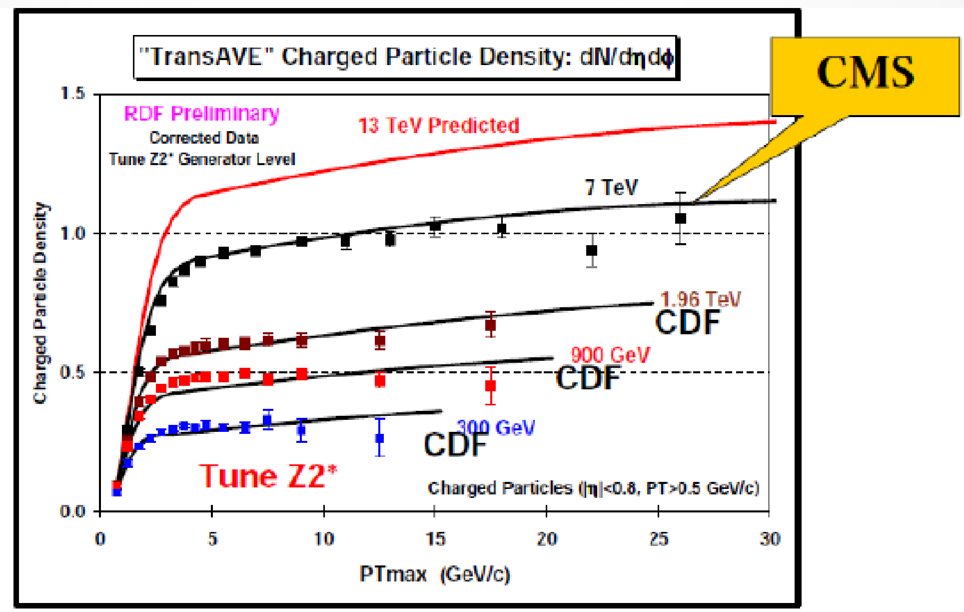
3. Underlying Event. Poorly understood. Performances at the LHC are however better than previously thought

UEs (HW++ and PY8)

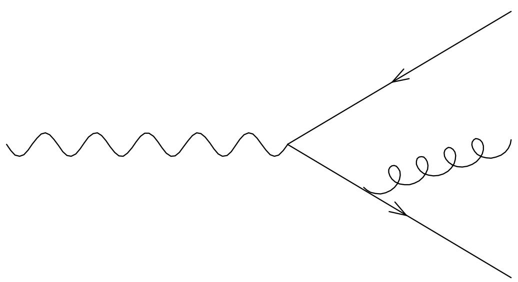




- Accepted wisdom: MPIs are necessary to describe well UE

Parton Showers

- Each emission in a shower is based on a collinear approximation; collinear emissions factorize and can be easily iterated



Master equation to be iterated:

$$d\sigma_{q\bar{q}g} \xrightarrow{t\to 0} d\sigma_{q\bar{q}} \times \frac{\alpha_S}{2\pi}\frac{dt}{t}P_{qq}(z)dz\frac{d\varphi}{2\pi}$$

- As long as $E_q \simeq E_g \gg \Lambda_{\mathrm{QCD}}$

$$t = Q^2, \qquad t = \theta^2 E^2, \qquad t = p_T^2$$

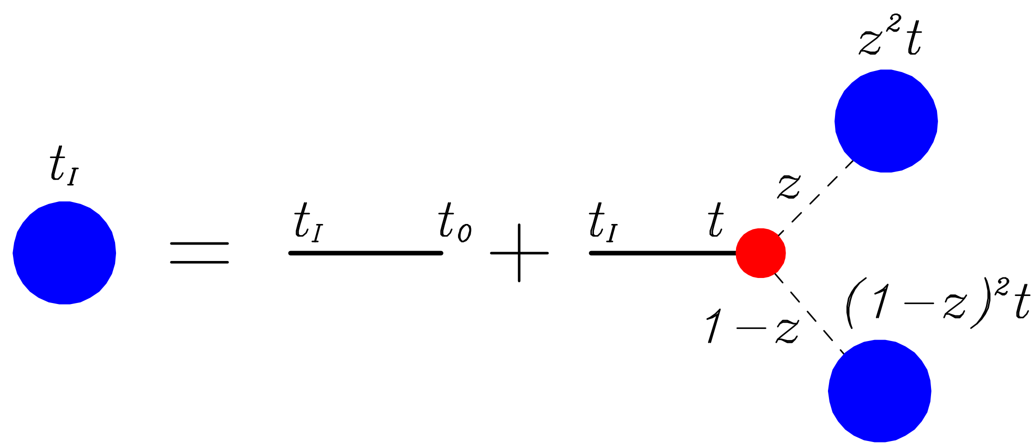
are equivalent (and similarly for z: energy, momentum, light cone fraction)

- Choices of shower variables are *not equivalent* in the soft region ($E_g \ll E_q$). Perturbative QCD theorems (Mueller) prescribe to use angles to respect colour coherence. In practice, pQCD deficiencies may be compensated by the non-perturbative part (mostly hadronization)

Collect all "shower histories" (i.e. kinematic configurations weighted with their probabilities) into a generating functional. This obeys:

$$\mathcal{F}(t_I) = \Delta(t_I, t_0) + \int_{t_0}^{t_I} \frac{dt}{t} \Delta(t_I, t) \int dz \frac{\alpha_S}{2\pi} P(z) \mathcal{F}((1-z)^2 t) \mathcal{F}(z^2 t)$$

with e.g. $t = \theta^2 E^2$ (angular ordering). Parton types understood



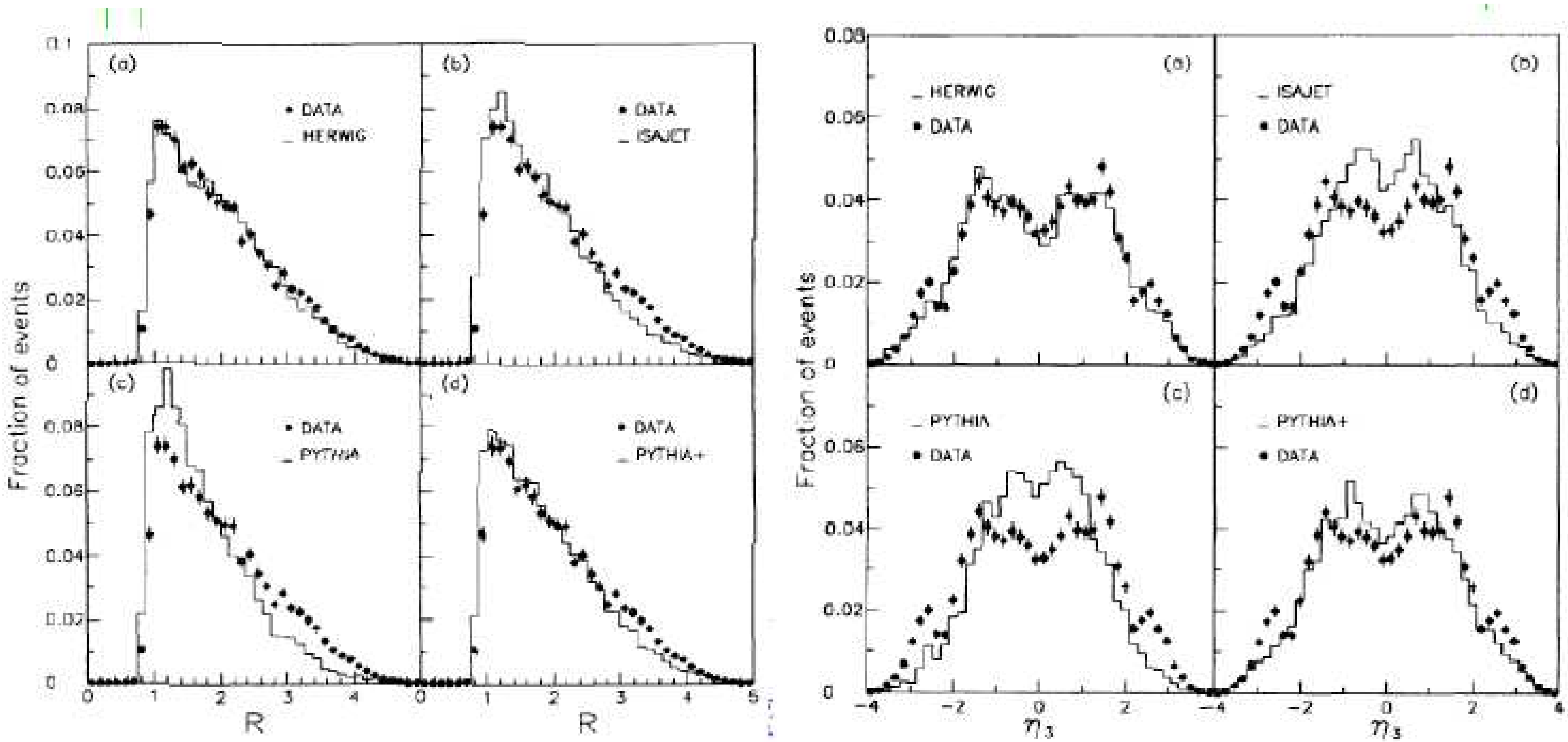
By imposing unitarity one gets

$$1 = \Delta(t_I, t_0) + \int_{t_0}^{t_I} \frac{dt}{t} \Delta(t_I, t) \int dz \frac{\alpha_S}{2\pi} P(z)$$

from which one solves for the Sudakov

$$\Delta(t_I, t_0) = \exp\left(- \int_{t_0}^{t_I} \frac{dt}{t} \int dz \frac{\alpha_S}{2\pi} P(z) \right)$$

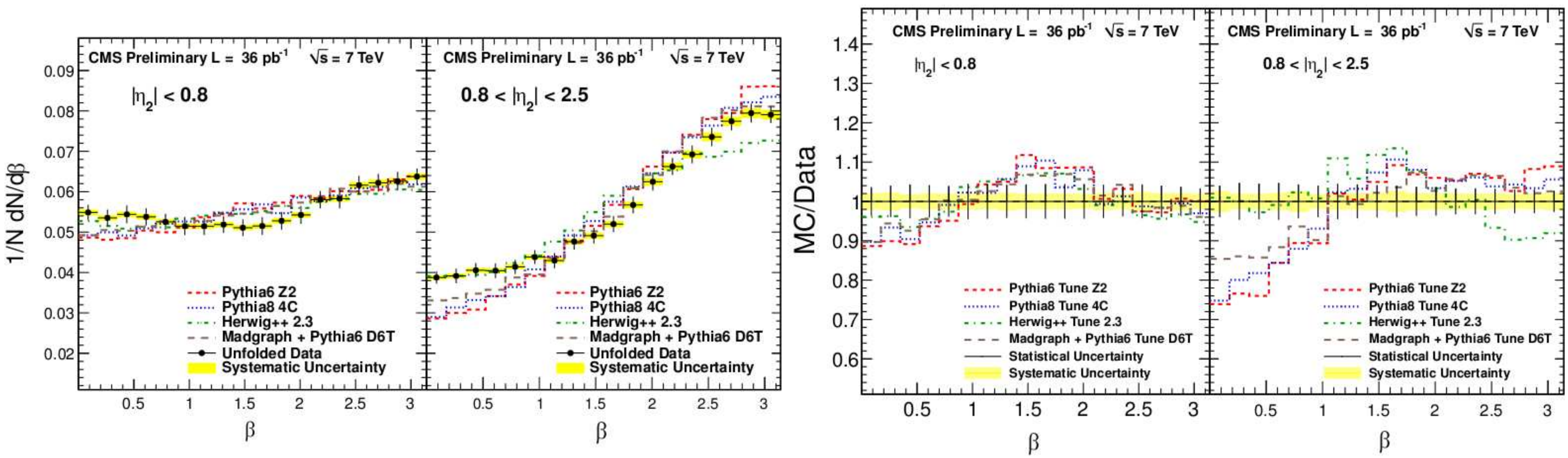
Coherence (or lack of it)



3-jet correlations @CDF. $E_{T1} > 110$ GeV, $E_{T3} > 10$ GeV, $R \equiv R_{23}$

- Forcing coherence is not equivalent to built it in. But a clever hadronization model may compensates for perturbative deficiencies

With newer jet data the message doesn't change



$$\beta = |\mathrm{atan}_2\,(\Delta\phi_{23}, \Delta\eta_{23})|,\ \Delta\eta_{23} = \mathrm{sign}(\eta_2)\,(\eta_3 - \eta_2)$$

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QCD vs QED: angular ordered + cluster hadr

Hard process (matrix element)

Find colour partners

Intra-quark radiation suppressed in QCD. Cluster hadronization will respect this pattern (thanks to preconfinement)

QCD vs QED: virtuality ordered + string hadr

Hard process (matrix element)

The pattern of radiation is identical in the two cases. Enter string hadronization.

Find colour partners

In QCD, string hadronization will pull hadrons in the $q\bar{q}$ cone apart, thus recovering what was achieved at the perturbative level by an angular-ordered shower

- There are two main schools of thought in the event generator community.

PYTHIA	HERWIG
Hadrons are produced by hadronization. You must get the nonperturbative dynamics right.	Get the perturbative physics right and any hadronization model will be good enough
Better data has required improvements to the perturbative simulation.	Better data has required changes to the cluster model to make it more string-like.

- There ain't no such thing as a good parameter-free description.

As summarised by Peter Richardson (with whom I agree, at least on this matter)

- Rather than starting from the collinear limit and then incorporate soft behaviour, start from the soft limit (Colour Dipole Model; Andersson, Gustafson, Lönnblad)

- This replaces a $1 \to 2$ picture with a $2 \to 3$ one

- Not quite what is done is newer dipole approaches, where typically one distinguishes a radiator from a spectator (as in Catani-Seymour NLO subtraction)

Recap of the good old days

HERWIG	PYTHIA/SHERPA	ARIADNE (CDM)
$t \simeq angle$	$t = virtuality$	$t = p_T^2$
hardest not first	hardest first	hardest first
coherent	coherence forced	coherent
dead zones	no dead zones	no dead zones
ISR easy	ISR easy	ISR difficult
kinematics: difficult	kinematics: easy	kinematics: easy
cluster hadr	string/cluster hadr	string hadr

- Now $\longrightarrow$ HW++: θ-ordered; Pythia6/8, SHERPA: p_T-ordered; HW++, PY8, SHERPA: CS dipoles; Vincia: dipoles

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(C. Darwin, closing statement of The Origin of Species, 1859)

The mechanism that drives evolution is chance

(sometimes someone has an idea),

but beauty and wonderfulness are the results of death

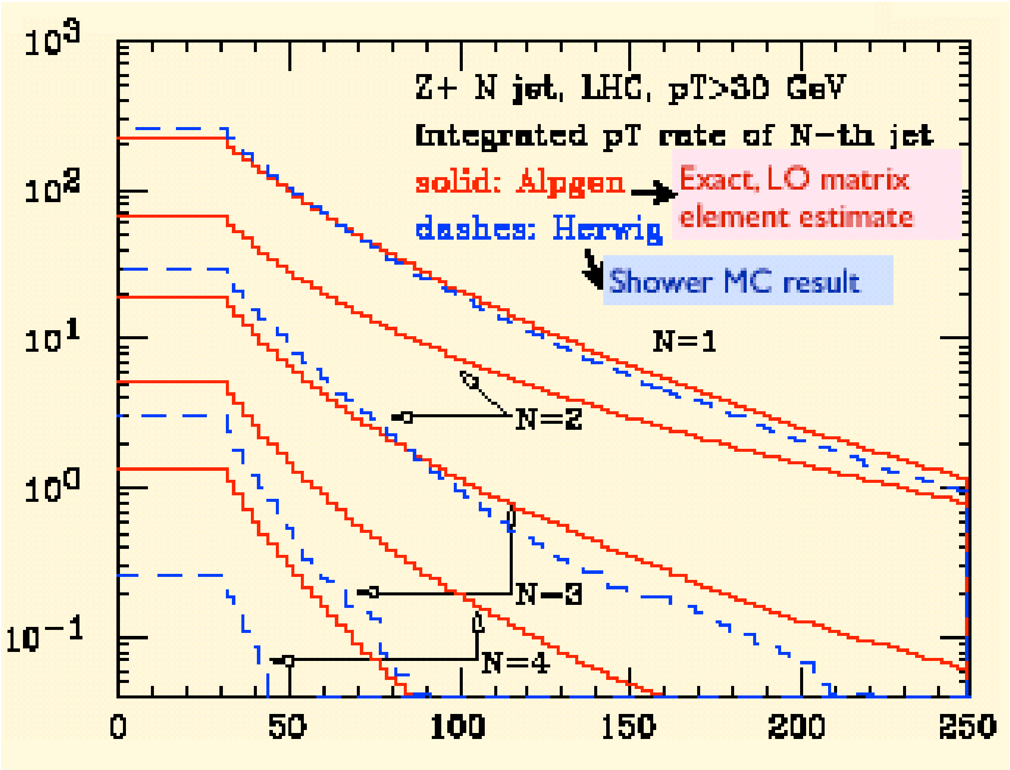
(someone [else?] has to prove that idea wrong)

The more precise a prediction, the easier is to prove it wrong

The most significant theoretical progress lately has been made on the best-understood component of MCs: the perturbative part.
This has driven a massive increase in predictive power and precision

There are compelling phenomenological motivations as well $\longrightarrow$

Plot: M. Mangano



LHC physics is a multi-jet physics

New-physics signal may easily have 5-10 jets (e.g. fully hadronic SUSY Higgs, $T \to tW$, heavy sparticle pair production, little Higgs, ...)

- MCs are simply unable to reliably simulate these multi-jet events
- The reason behind this failure is obvious. The parton shower is inherently collinear. The probability associated with well-separated final-state particles is largely underestimated

How to improve (perturbatively) Monte Carlos?

The key issue is to go beyond the collinear approximation

$\Longrightarrow$ use exact matrix elements of order higher than leading

Which ones?

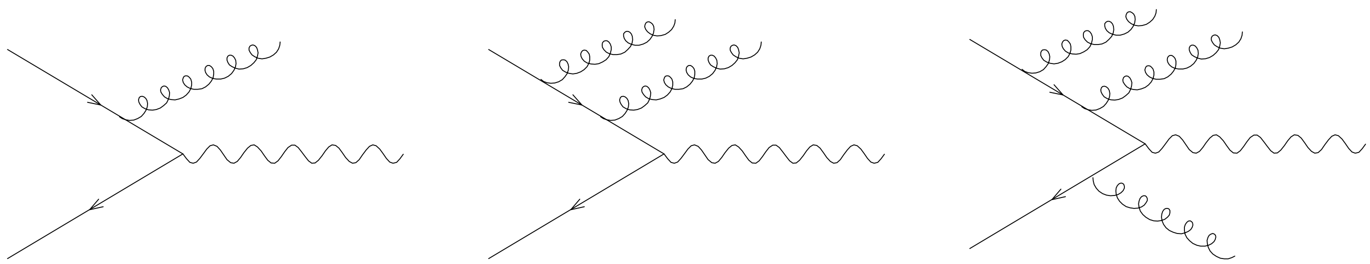
There are two possible choices, that lead to two vastly different strategies:

- Matrix Element Corrections $\longrightarrow$ tree level
- NLO+PS $\longrightarrow$ tree level and loop

- Since 2012, we have been learning to combine these two approaches

Matrix Element Corrections

Compute (exactly) as many as possible real emission diagrams before starting the shower. Example: W production



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Problems

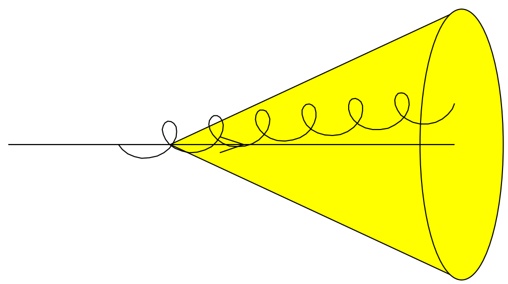
- Double counting (the shower can generate the same diagrams)
- The diagrams are divergent

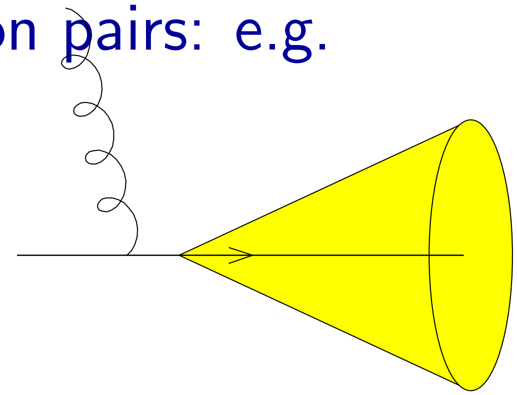
Solutions

⟶ Catani, Krauss, Kuhn, Webber (2001), Lönnblad (2002), Mangano (2005) (CKKW, SMPR, CKKW-L, MLM); Hoeche, Krauss, Schumann, Siegert (2009), Hamilton, Richardson, Tully (2009), Lönnblad, Prestel (2011, UMEPS)

What all solutions have in common

- Separate PS- from ME-dominated kinematics regions. This is done by "measuring" the hardness of each parton pairs: e.g.





Soft $\Longrightarrow$ use PS   Hard $\Longrightarrow$ use ME's

- This removes double counting (and divergencies in ME's), but it introduces an unphysical bias, upon which physical predictions depend

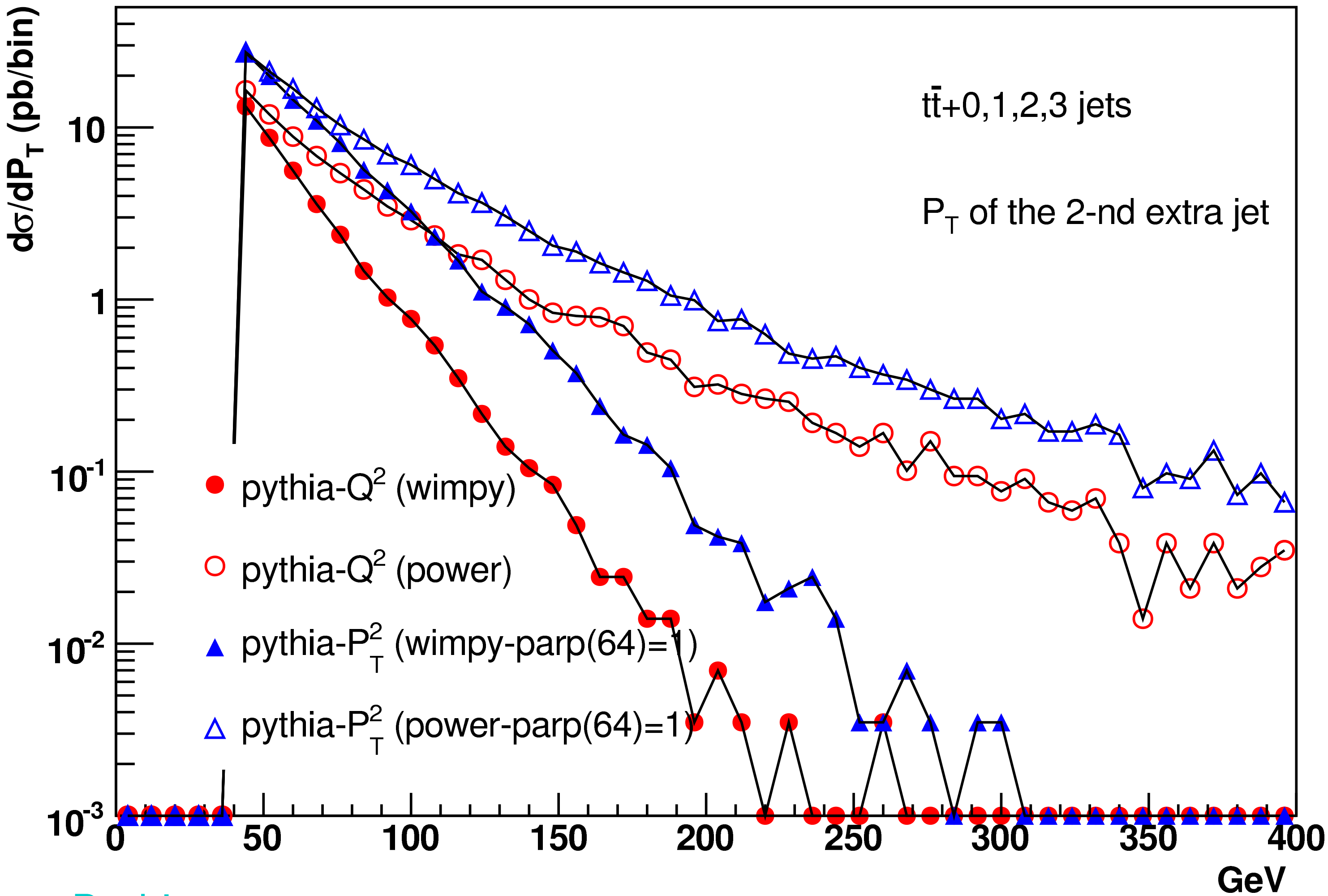
- The bias is removed by *at least one* of the following operations

  Modify ME's (through reweighting)

  Choose suitable PS initial conditions (depend on kinematics)

  Forbid emissions/Reject events in the shower phase

Matching at work: before matching

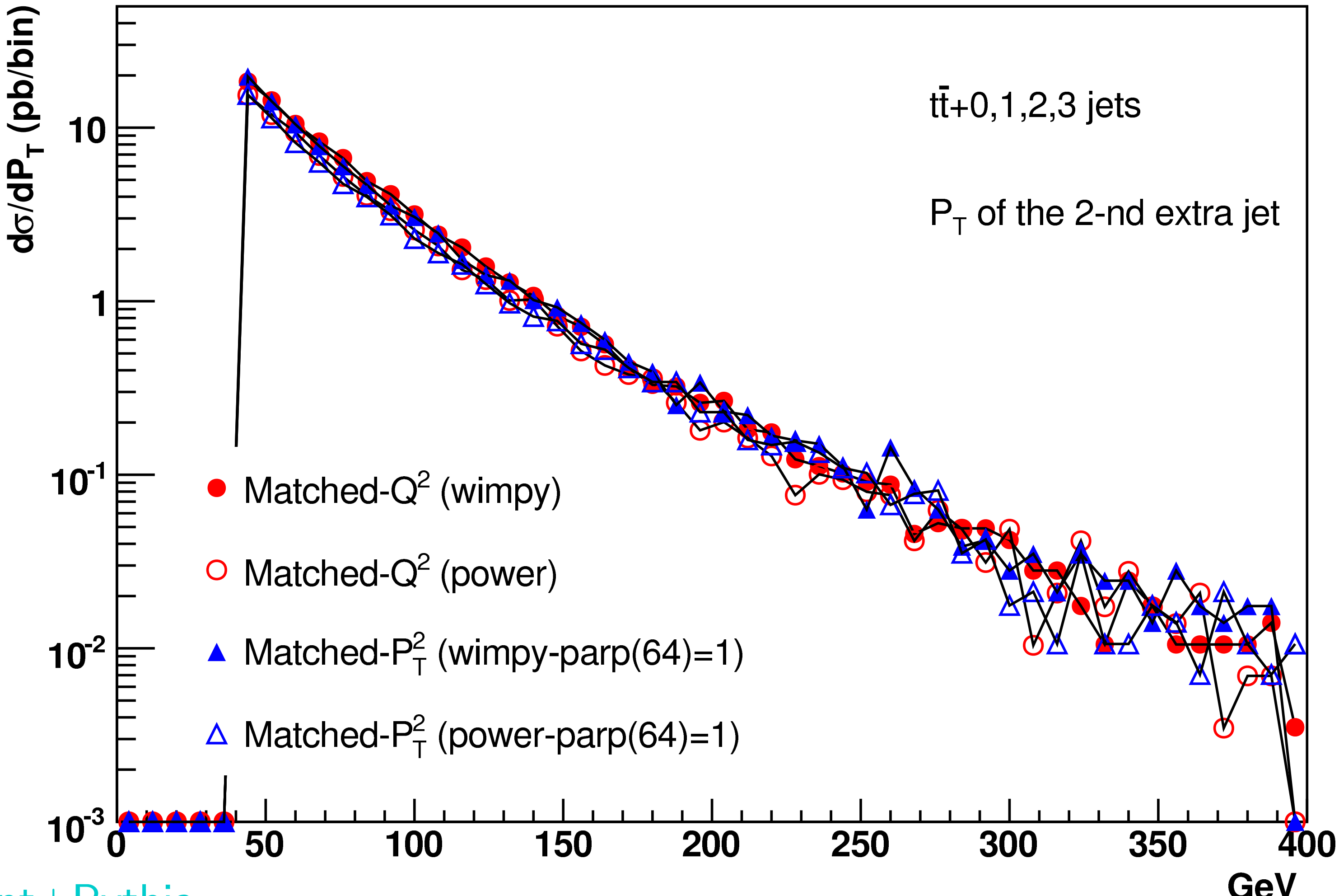


MadEvent+Pythia

OK if you want to fit data, useless to have an idea of how data *will* look like

In other words, good at postdictions, but no predictive power

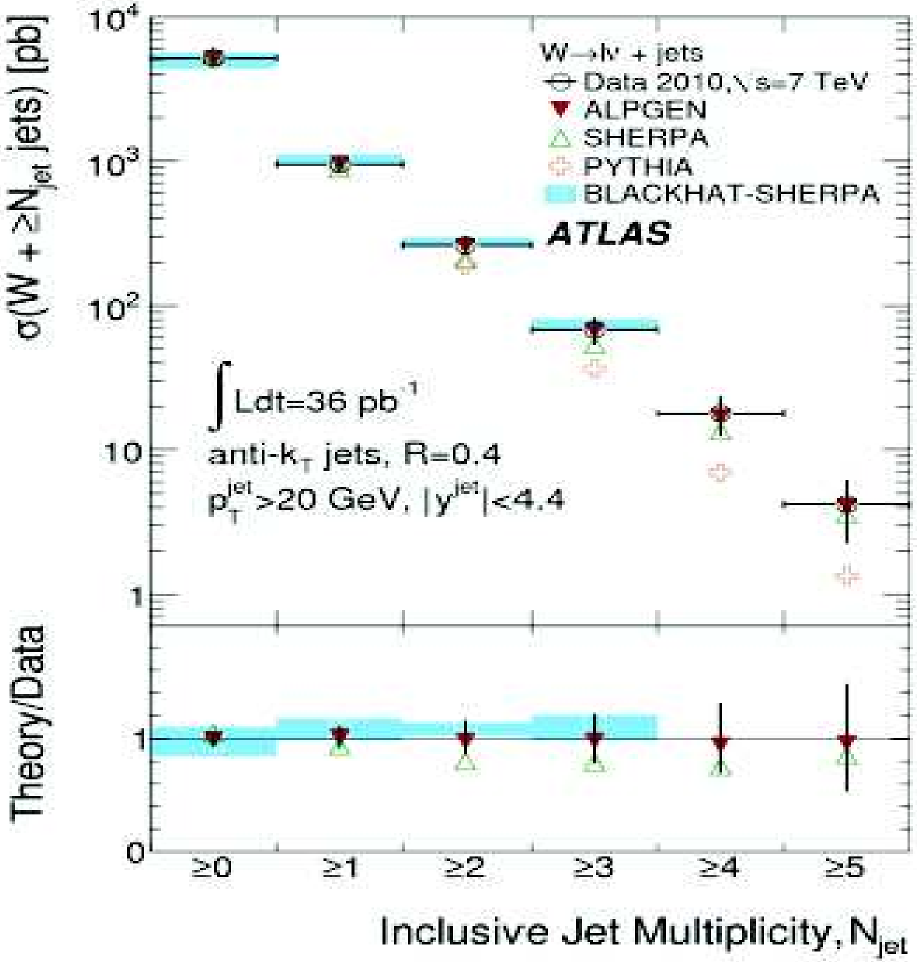
Matching at work: after matching

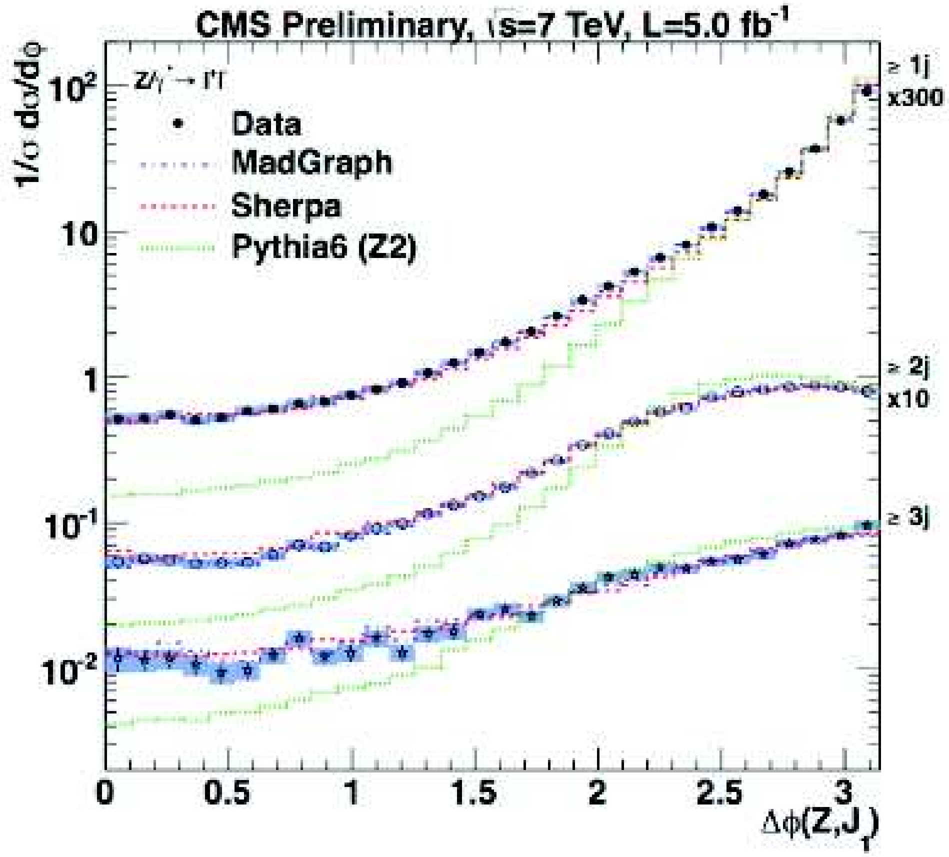


MadEvent+Pythia

A simple reason for this: the physics is right (no collinear approximation used outside the collinear regions)

Comparisons to data





Once the overall normalization is fixed (i.e., one parameter) one obtains a very satisfactory description

MEC: what to take home

Substantial progress made in the past few years. Main consequence: multi-jet backgrounds not a matter of science fiction any longer

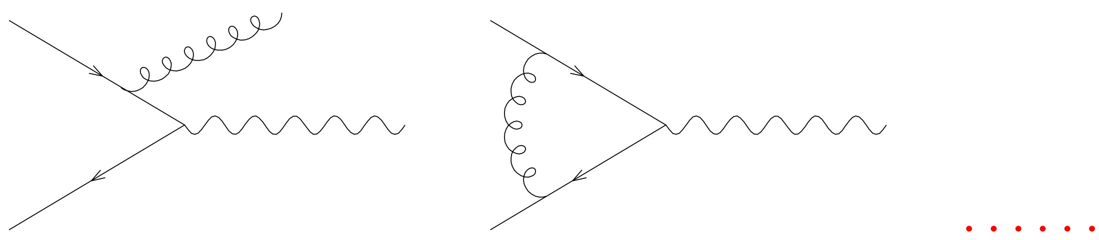
- Never forget to check the merging systematics
- Tuning to data is strongly recommended, and anyhow necessary to figure out the correct normalization: these are LO QCD computation!
- These procedures have been thoroughly tested for $W/Z+$jets. For other processes, or peculiar observables, systematics can be (much?) larger. Compare predictions from different codes

The use of standalone PYTHIA/HERWIG for multi-jet physics cannot be excused any longer. That's the stone age

NLO+PS

Compute all the NLO diagrams (and only those) before starting the shower.

Example: W production



Problems

- Double counting (the shower can generate *some of* the same diagrams)
- The diagrams are divergent

Solutions

$\longrightarrow$ MC@NLO (Frixione, Webber, 2002), POWHEG (Nason, 2004)

Construction of MC@NLO

$$\mathcal{F}_{\text{MC@NLO}} = \mathcal{F}^{(2\to n+1)}\, d\sigma^{(\mathbb{H})}_{\rm MC@NLO} + \mathcal{F}^{(2\to n)}\, d\sigma^{(\mathbb{S})}_{\rm MC@NLO}$$

with the two *finite* short-distance cross sections

$$d\sigma^{(\mathbb{H})}_{\rm MC@NLO} = d\phi_{n+1}\left(\mathcal{M}^{(r)}(\phi_{n+1}) - \mathcal{M}^{(\text{MC})}(\phi_{n+1})\right)$$

$$d\sigma^{(\mathbb{S})}_{\rm MC@NLO} = \int_{+1} d\phi_{n+1}\left(\mathcal{M}^{(b+v+rem)}(\phi_n) - \mathcal{M}^{(c.t.)}(\phi_{n+1}) + \mathcal{M}^{(\text{MC})}(\phi_{n+1})\right)$$

that feature the *MC subtraction terms*

$$\mathcal{M}^{(\text{MC})} = \mathcal{F}^{(2\to n)}\mathcal{M}^{(b)} + \mathcal{O}(\alpha_S^2\alpha_S^b)$$

MC subtraction terms are process independent, by MC-dependent
(i.e., those for matching with Herwig and Pythia are different)

Construction of POWHEG

Use the exact phase-space factorization $d\phi_{n+1} = d\phi_n d\phi_r$, and construct

$$\overline{\mathcal{M}}^{(b)}(\phi_n) = \mathcal{M}^{(b+v+rem)}(\phi_n) + \int d\phi_r \left[\mathcal{M}^{(r)}(\phi_{n+1}) - \mathcal{M}^{(c.t.)}(\phi_{n+1})\right]$$

For a *given* p_T, define the (process-dependent) *vetoed* Sudakov

$$\Delta_R(t_I, t_0; p_T) = \exp\left[-\int_{t_0}^{t_I} d\phi'_r \frac{\mathcal{M}^{(r)}}{\mathcal{M}^{(b)}} \Theta(k_T(\phi'_r) - p_T)\right]$$

The short-distance cross section is:

$$d\sigma_{\text{POWHEG}} = d\phi_n \overline{\mathcal{M}}^{(b)}(\phi_n)\left[\Delta_R(t_I, t_0; 0) + \Delta_R(t_I, t_0; k_T(\phi_r)) \frac{\mathcal{M}^{(r)}(\phi_{n+1})}{\mathcal{M}^{(b)}(\phi_n)} d\phi_r\right]$$

- First term ($\mathbb{S}$-type events) strongly suppressed
- $k_T(\phi_r)$ will play the role of hardest emission so far ($\mathbb{H}$-type events)

Attaching (angular-ordered) showers

- One wants the matrix-element-generated p_T to be the hardest
  $\Longrightarrow$ veto emissions harder than p_T during shower

- But this screws up colour coherence

Colour coherence can be restored at the price of a more involved structure

$$\mathcal{F}_{\text{POWHEG}}[t_I; p_T] \quad = \quad \Delta(t_I, t_0) + \int_{t_0}^{t_I} \frac{dt}{t} \int dz \Delta_R(t_I, t; p_T) \frac{\alpha_S}{2\pi} P(z) \times \mathcal{F}_{\text{V}}((1-z)^2 t; p_T)\, \mathcal{F}_{\text{V}}(z^2 t; p_T)\, \mathcal{F}_{\text{VT}}(t_I, t; p_T)$$

- $\mathcal{F}_{\text{V}}(t; p_T)$ are *vetoed* showers. Evolve down to t_0, with all emissions constrained to have a transverse momentum smaller than p_T

- $\mathcal{F}_{\text{VT}}(t_I, t; p_T)$ are *vetoed-truncated* showers. Evolve from t_I down to t (i.e., *not* t_0) along the hardest line. On top of that, they are vetoed

To reduce the impact of the exponentiation of the full real matrix element, one introduces the following variant

$$d\sigma^{(\mathrm{damp})}_{\mathrm{POWHEG}} = d\phi_n \overline{\mathcal{M}}^{(b)}_S \left\{ \Delta^S_R \frac{\mathcal{M}^{(r)}_S}{\mathcal{M}^{(b)}} + \mathcal{M}^{(r)}_F \right\} d\phi_r$$

with:

$$\mathcal{M}^{(r)} = \mathcal{M}^{(r)}_S + \mathcal{M}^{(r)}_F = F(p_T)\mathcal{M}^{(r)} + (1 - F(p_T))\mathcal{M}^{(r)}$$

$$(1 - F(p_T))\mathcal{M}^{(r)} \longrightarrow \text{finite} \qquad p_T \longrightarrow 0$$

To maintain the NLO accuracy, one must define:

$$\overline{\mathcal{M}}^{(b)}_S = \overline{\mathcal{M}}^{(b)} \left(\mathcal{M}^{(r)} \longrightarrow \mathcal{M}^{(r)}_S \right) \qquad \Delta^S_R = \Delta_R \left(\mathcal{M}^{(r)} \longrightarrow \mathcal{M}^{(r)}_S \right)$$

Features

$\mathrm{MC@NLO} = \mathrm{POWHEG} + \mathcal{O}(\alpha_S^2 \alpha_S^b) + \mathrm{logs}$ (with or without damp)

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- The differences of matrix-element origin are due to
  - Exponentiation of real matrix elements in POWHEG
  - Use of $\overline{\mathcal{M}}^{(b)}$, which "moves" the $p_T = 0$ K factor to $p_T > 0$ *before* showering

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These differences are generally small (for inclusive variables at least), but tests done only for "simple" processes. $gg \to H$ is a spectacular counterexample

- MEC is a *merging* scheme

$$(X + 0j + \mathrm{PS}) + (X + 1j + \mathrm{PS}) + (X + 2j + \mathrm{PS})\ldots$$

- NLO+PS is a *matching* scheme

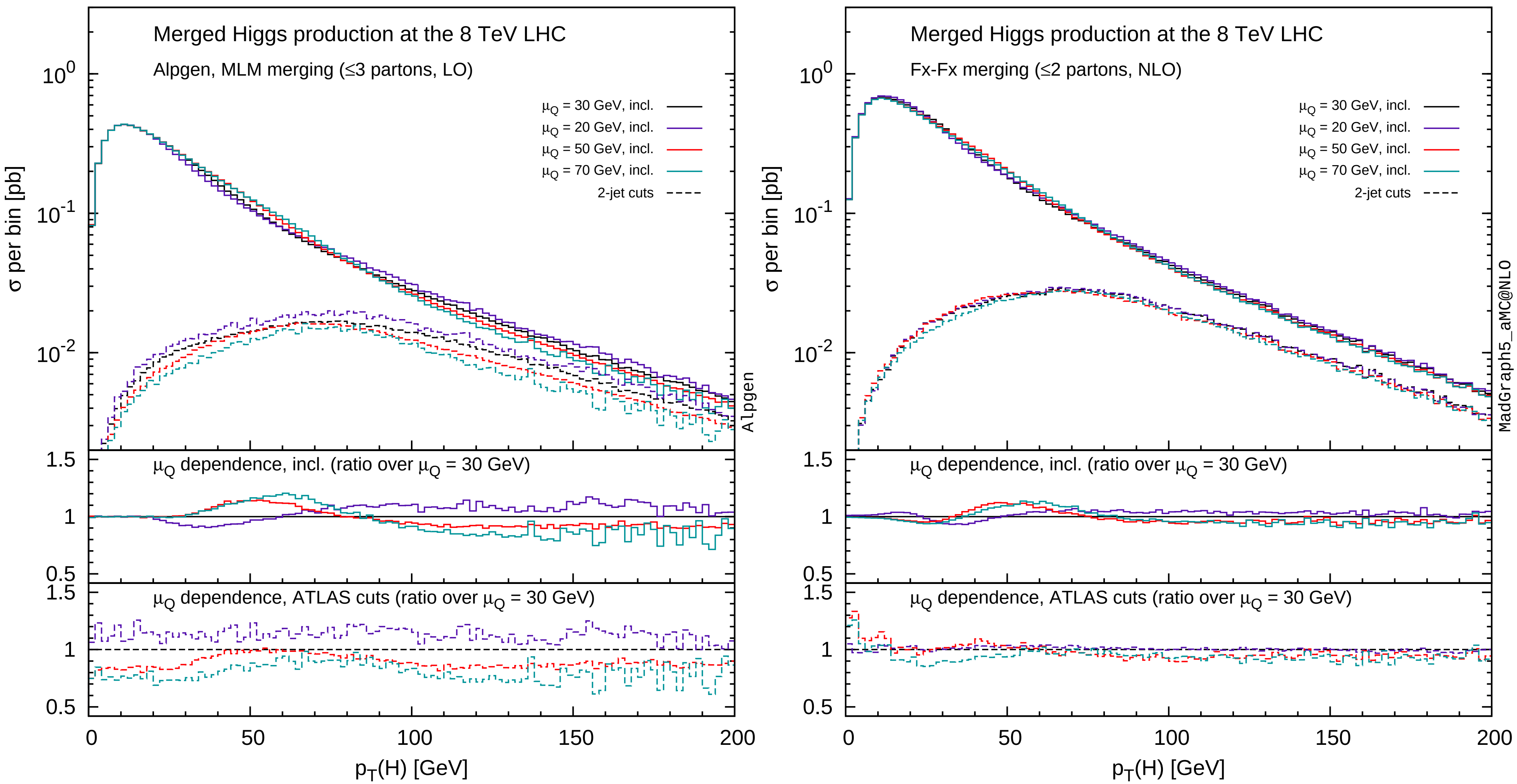
$$\{[X + kj] + [X + (k+1)j]\} + \mathrm{PS} \qquad k \text{ given}$$

We can now combine the two, by promoting all individual samples of the first line to NLO accuracy. Technically rather non trivial

Hoeche, Krauss, Schonherr, Siegert (Sherpa); Frederix, Frixione (FxFx, embedded in MadGraph5_aMC@NLO); Lönnblad, Prestel (UNLOPS with Pythia8); Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi (GENEVA); Plätzer (HW++)

Very new (≥ 2012). No systematic comparison among different approaches

Merging: LO ⟶ NLO



Left: LO (Alpgen). Right: FxFx (MadGraph5_aMC@NLO)

Conclusions and outlook

- We have new showers
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Future directions

- NLO: apply what we have done to BSM – it's no extra work
- Invest more resources in understanding soft physics
- Further perturbative progress (NNLO+PS, NLL showers) is on the (far) horizon