Dissecting Soft Radiation with Factorization.

Frank Tackmann

Deutsches Elektronen-Synchrotron

LHC Physics Discussion
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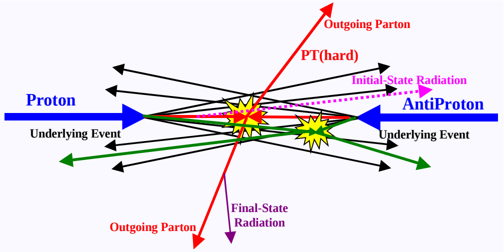
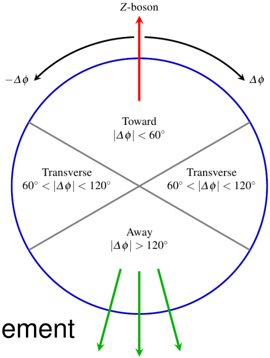
work with Iain Stewart and Wouter Waalewijn
(arXiv:1405.6722)

What is the “Underlying Event”?





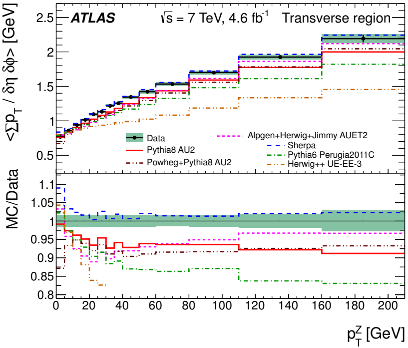
Answers you might get, depending on who you ask

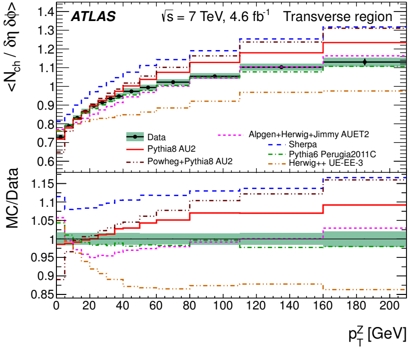
- Everything which is not the hard partonic matrix element
- All soft radiation underlying the hard scattering
- All particles not coming from primary hard process
- Monte Carlo: (soft) multiparton interactions (MPI)

Current approach

- Measure charged particle and energy densities in transverse regions
- Use these to tune Monte Carlo models (ISR, FSR, MPI, ...)

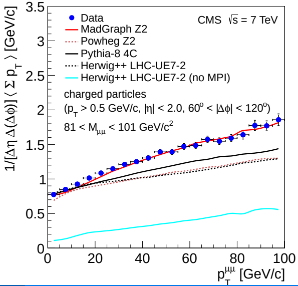
Transverse Region in Drell-Yan.





[ATLAS 1409.3433, CMS 1204.1411]

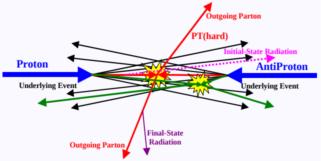
- MPI models in MC seem to produce too soft/too many particles
- Part of “UE activity” is due to primary and not-so-soft radiation
  (well known, same is seen in jet production)



What is the “Underlying Event”?

Better question to ask:

What are the contributions from various soft effects to a given observable?



We want to distinguish contributions from

- Soft ISR: Perturbative soft radiation from primary partons
- Hadronization: Nonperturbative soft radiation
- MPI: soft radiation not associated with primary interaction

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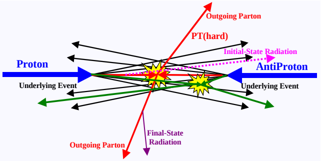

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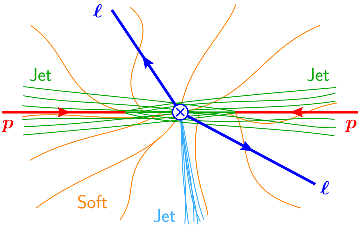
Consider an observable which

- is directly sensitive to soft effects
- corresponds to a well-defined hard process
- we understand well enough with factorization to make predictions

$\Rightarrow$ Consider jet mass spectrum in exclusive Z+jet and H+jet events

Jet Mass Spectrum in V+Jet.



- Require jet with $p_T^J \geq 200\,\mathrm{GeV}$
- Veto additional jets with $p_T^J > 50\,\mathrm{GeV}$
  (jet-veto effect essentially drops out for normalized spectrum)

Jet mass spectrum can be factorized for $m_J \ll p_T^J$ (without MPI)
[Jouttenus, Stewart, FT, Waalewijn]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_J^2} = \sum_\kappa H_\kappa \,(I \otimes f)^2 \int \mathrm{d}k_s \, J_{q,g}(m_J^2 - 2p_T^J k_s)\, S_\kappa(k_s)$$

where each function has a field-theoretic definition (in SCET)

Hard function H_κ: partonic process κ: $qg \to Zq$, $q\bar{q} \to Zg$, $gg \to Hg$
Beam function $I \otimes f$: collinear energetic ISR plus PDFs

Jet function $J_{q,g}$: collinear energetic FSR
Soft function $S_\kappa(k_s)$: primary soft radiation (ISR, FSR, pert. and nonpert.)

Soft Function Factorization.

Convolution of J and S determines shape of jet mass spectrum

$$\frac{d\sigma}{dm_J^2} \sim \int dk_s\, J_{q,g}(m_J^2 - 2p_T^J\, k_s)\, S_\kappa(k_s)$$

Soft function can be factorized further

$$S_\kappa(k_s) = \int dk\, \underbrace{S_\kappa^{\rm pert}(k_s - k)}_{\text{pert. soft ISR \& FSR}}\quad \underbrace{F_\kappa(k)}_{\text{nonpert. hadronization}}$$

For $k_s \gg k \sim \Lambda_{\rm QCD}$ can expand in moments

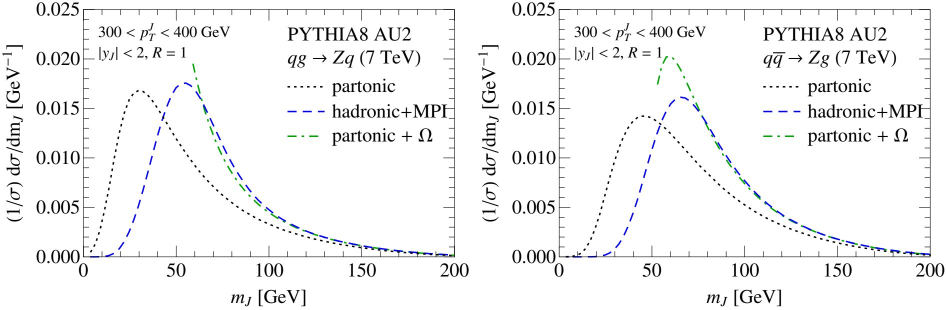
$$F_\kappa(k) = \delta(k) + \Omega_\kappa\, \delta'(k) + \cdots$$

$$\Rightarrow \qquad S_\kappa(k_s) = S_\kappa^{\rm pert}(k_s - \Omega_\kappa) + \cdots$$

For $m_J^2 \gg p_T^J \Lambda_{\rm QCD}$ (tail of the spectrum) expect nonpert. corrections to shift the jet mass

$$m_J^2 = (m_J^2)^{\rm pert} + 2p_T^J\, \Omega_\kappa$$

Jet Mass Spectrum in Pythia8.



Remarkably well satisfied by Pythia's hadronization *and also* MPI

- Tail reproduced by $m_J^2 \to m_J^2 + 2p_T^J\,\Omega$ (with $\Omega \simeq 2.5\,\mathrm{GeV}$)

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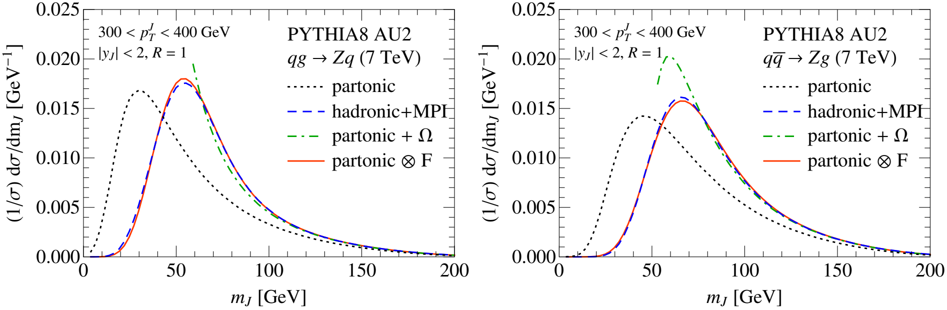

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- Tail reproduced by $m_J^2 \to m_J^2 + 2p_T^J\,\Omega$ (with $\Omega \simeq 2.5\,\mathrm{GeV}$)
- Even more general $\dfrac{d\sigma}{dm_J^2} \to \displaystyle\int dk\, \frac{d\sigma^{\text{partonic}}}{dm_J^2}(m_J^2 - 2p_T^J\,k)\, F(k)$

⇒ Apparent degeneracy between hadronization and MPI
(not too surprising: MPI populates jet with constant background of soft particles)

Jet Mass Moment.

Consider the 1st moment of the normalized jet mass spectrum, which tracks the shift in the spectrum

$$M_1 = \frac{1}{\sigma} \int \mathrm{d}m_J^2 \, m_J^2 \, \frac{\mathrm{d}\sigma}{\mathrm{d}m_J^2}$$

- Factorization predicts

$$M_1 = M_{1\,\kappa}^{\mathrm{pert}}(p_T^J, y_J, R) \,+\, 2p_T^J \, \Omega_\kappa(R) \qquad (+\,\mathrm{MPI})$$

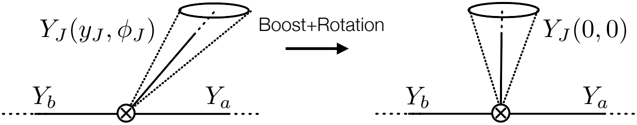
- Monte Carlo can be parametrized as

$$M_1 = M_{1\,\kappa}^{\mathrm{partonic}}(p_T^J, y_J, R) \,+\, 2p_T^J \, \Omega_\kappa^{\mathrm{had}}(R) \,+\, 2p_T^J \, \Upsilon_\kappa^{\mathrm{MPI}}(R)$$

We will compare to

- Pythia8 with AU2-MSTW2008LO and 4C tunes
- Herwig++ 2.7 with default UE-EE-5-MRST tune

Hadronization from Factorization.



Nonperturbative matrix element of Wilson lines Y_i

$$\Omega_\kappa(R) = \langle 0 | Y_J^\dagger(y_J, \phi_J) Y_b^\dagger Y_a^\dagger \, M(y_J, \phi_J, R) \, Y_a Y_b Y_J(y_J, \phi_J) | 0 \rangle$$

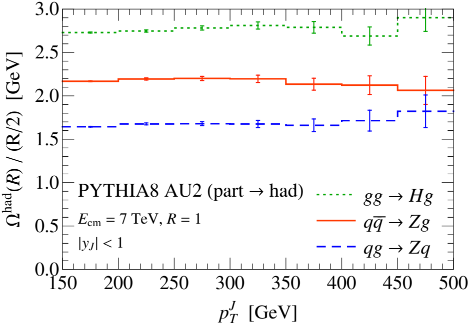
- Depends on partonic channel κ via color representation of Y_i
- Independent of p_T^J (by definition) and y_J, ϕ_J (shown by boosting)

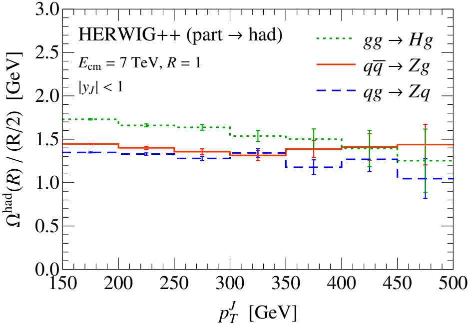
Can be expanded in powers of R

$$\Omega_\kappa(R) = \frac{R}{2}\,\Omega_{q,g}^{(1)} + \frac{R^3}{8}\,\Omega_\kappa^{(3)} + \frac{R^5}{32}\,\Omega_\kappa^{(5)} + \cdots$$

- Only odd powers of $R/2$ (to all orders)
- Leading $\Omega_{q,g}^{(1)}$ is universal for quark and gluon initiated jets
  - $\Omega_q^{(1)}$ is the same that appears in 1-jettiness (thrust) in DIS

Hadronization in Monte Carlo.

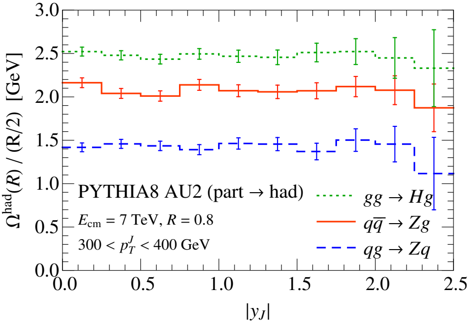


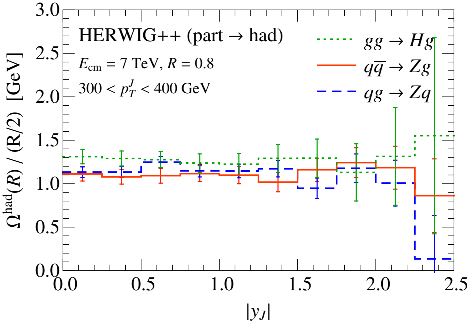


Agrees with factorization predictions (very well in Pythia, not as well in Herwig)

- independence of p_T^J

Hadronization in Monte Carlo.

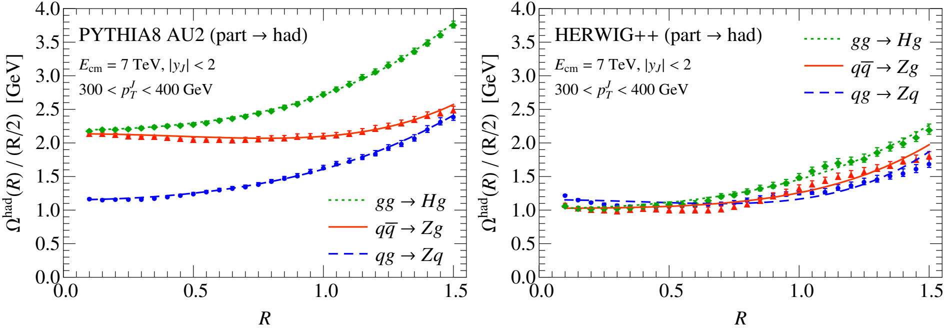




Agrees with factorization predictions (very well in Pythia, not as well in Herwig)

- independence of p_T^J
- independence of y_J

Hadronization in Monte Carlo.



Agrees with factorization predictions (very well in Pythia, not as well in Herwig)

- independence of p_T^J
- independence of y_J
- R dependence starts linear (better fit with odd powers at large R)
- quark/gluon universality in limit of small R

⇒ Channel dependence very different between Pythia and Herwig

Primary Soft ISR.

Kinematics and dimensional analysis imply $M_{1\,\kappa}^{\rm pert} \sim (p_T^J R)^2$

$$\frac{M_{1\,\kappa}^{\rm pert}}{2p_T^J} \sim p_T^J\, R^{2-\gamma_\kappa} + p_T^J\, R^4$$

- $\gamma_\kappa \propto \alpha_s > 0$ due to resummation effects

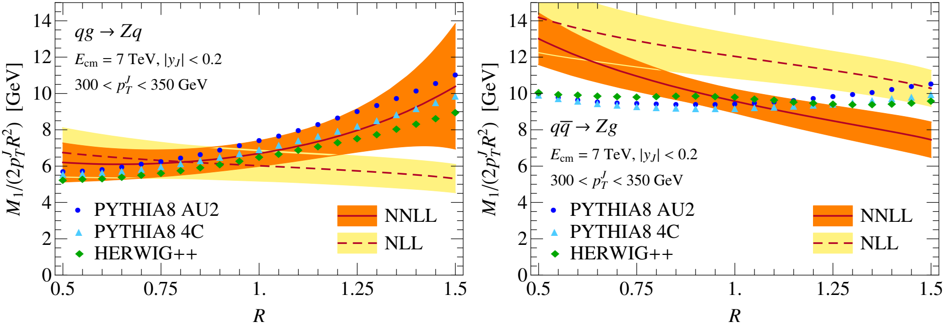
R^4 contribution arises from soft ISR

$$S_\kappa^{\rm pert}(k_s) \supset \frac{\alpha_s C_\kappa}{\pi}\, R^2\, \frac{1}{k_s}$$

- Interference between two beams, formally enters at $\mathcal{O}(\alpha_s)$ and NNLL
- Color factor depends on channel

κ	C_κ
$gq \to Zq$	$C_A/2 = +3/2$
$q\bar{q} \to Zg$	$C_F - C_A/2 = -1/6$
$gg \to Hg$	$C_A/2 = +3/2$

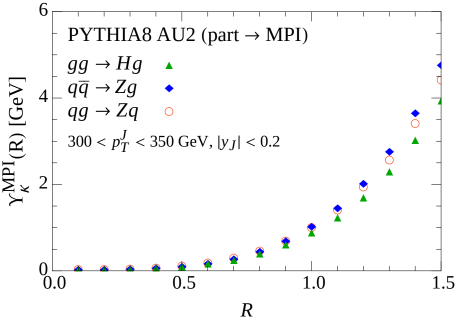
Partonic Contribution in Monte Carlo.



Partonic contribution in MC very well described by

$$\frac{M_{1\,\kappa}^{\text{partonic}}}{2p_T^J} = c_2^\kappa(p_T^J, y_J)\,R^{2-\gamma_\kappa} + c_4^\kappa(p_T^J, y_J)\,R^4$$

- Soft ISR modelled by radiation pattern from both initial and final showers
  - Good agreement for $qg \to Zq$ (not as good for $gg \to Hg$)
  - MCs do not reproduce negative interference for $q\bar{q} \to Zg$



MPI almost channel independent and with perfect R^4 behavior

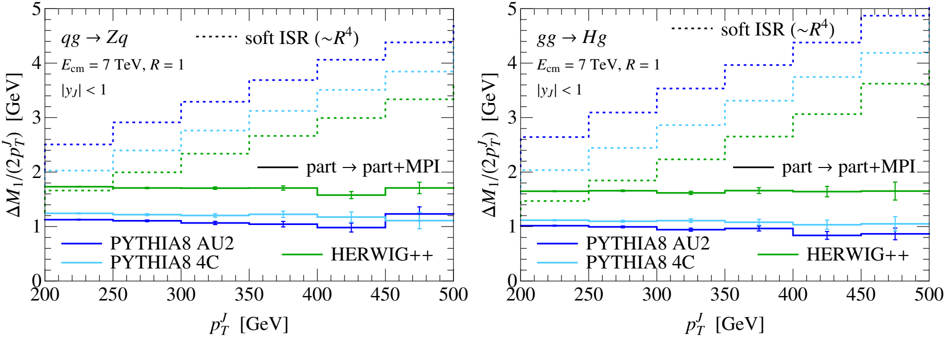
- Like soft ISR, it populates jet with a constant background of soft particles
  - Expect same R^4 scaling
- Essentially independent of primary hard process
  - Expect channel independence, and also p_T^J, y_J independence

⇒ Can in principle distinguish different "UE-like" R^4 contributions

Soft ISR vs. MPI.

Compare

- Soft ISR: fitted R^4 contribution in partonic results (dotted)
- Effect from turning on MPI (solid)



Ambiguity between MPI and soft ISR in Monte Carlos

- Different MCs/tunes compensate more/less soft ISR with less/more MPI

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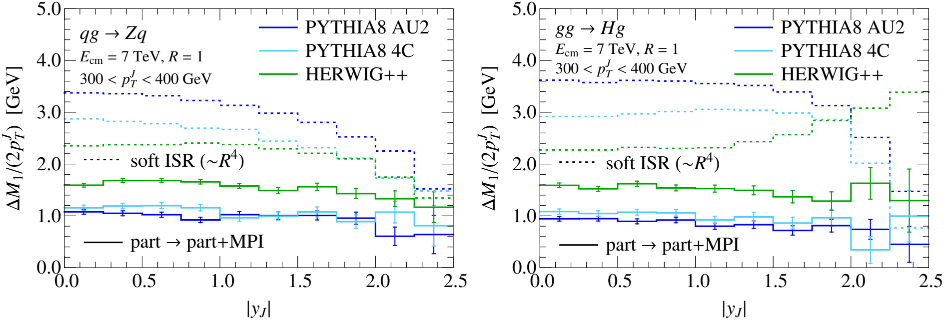

Ambiguity between MPI and soft ISR in Monte Carlos

- Different MCs/tunes compensate more/less soft ISR with less/more MPI
- Different y_J dependence of soft ISR in Pythia and Herwig

Summary.

$$\frac{M_1}{2p_T^J} \sim \underbrace{c_2^\kappa(p_T^J, y_J)\, R^{2-\gamma_\kappa}}_{\text{leading pert.}} + \underbrace{c_4^\kappa(p_T^J, y_J)\, R^4}_{\text{soft ISR}} + \underbrace{\frac{R}{2}\Omega_{q,g}^{(1)} + \frac{R^3}{8}\cdots}_{\text{hadronization}} + \underbrace{R^4}_{\text{MPI}}$$

Jet-mass spectrum and in particular its 1st moment as a function of jet radius R allows to separate physically distinct sources of soft effects

- Hadronization (nonpert. soft)
- Primary soft ISR interference
- Soft MPI

Allows a 3-way comparison between

- Properties that can be predicted from QCD by factorization
- MC models
- Measurements

$\Rightarrow$ Try to measure $M_1(R)$ for different p_T^J, y_J, and partonic channels