# Monte Carlo simulation of QCD radiation

Mike Seymour
University of Manchester

Giuseppe Marchesini Memorial Meeting
Galileo Galilei Institute for Theoretical Physics
May 19th 2017

# Introduction: Pino and Monte Carlo

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1984

Simulation of QCD Jets
Including Soft
Gluon Interference
**Nucl. Phys. B238 (1984) 1**
(959 citations)

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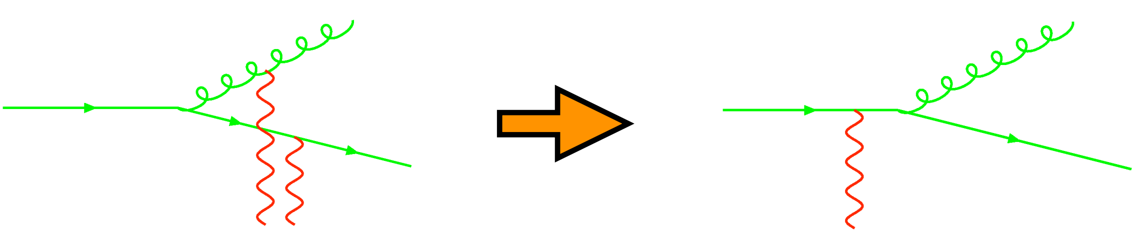

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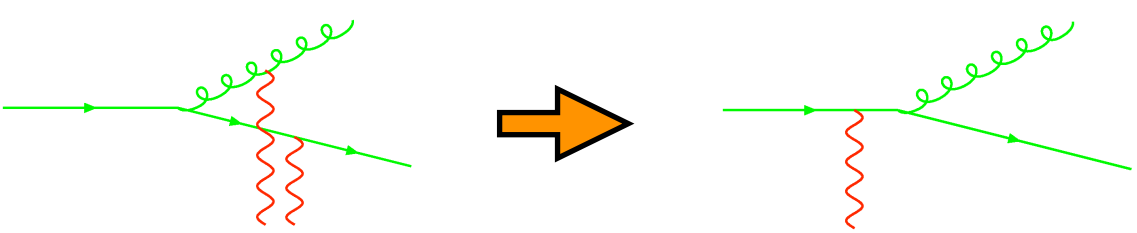

**EARWIG**

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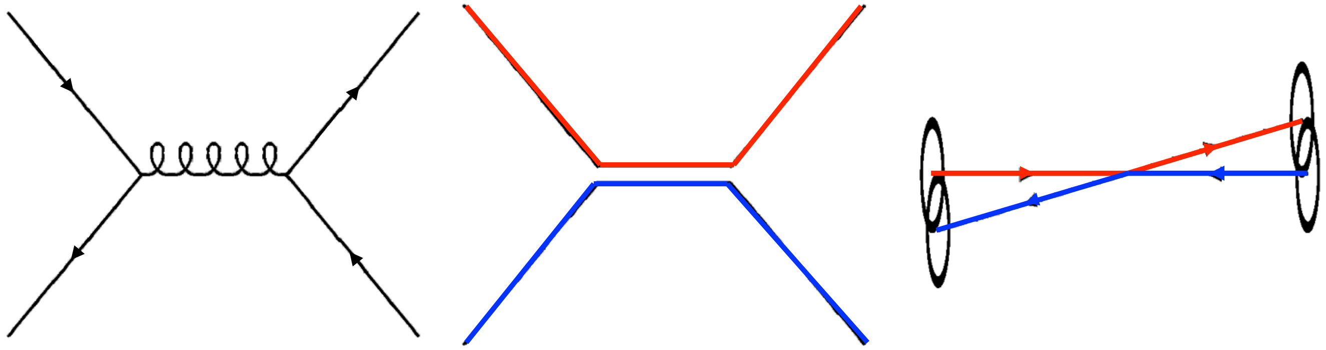
**Nucl. Phys. B310 (1988) 461**
(1042 citations)



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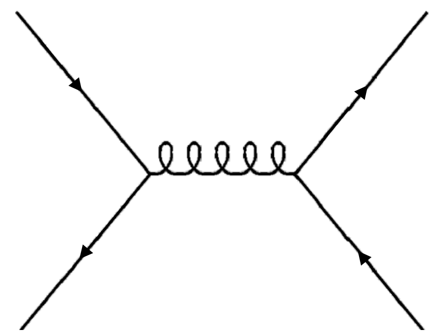

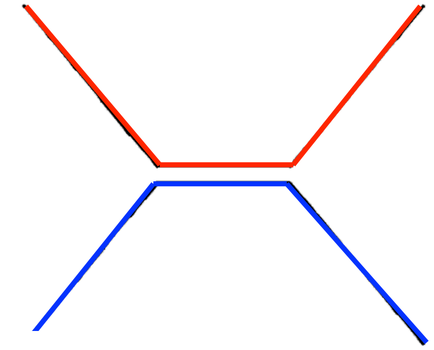

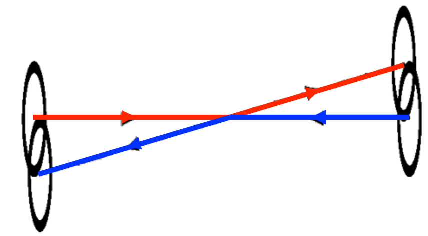

Associated Transverse Energy in Hadronic Jet Production
**Phys. Rev. D38 (1988) 3419**
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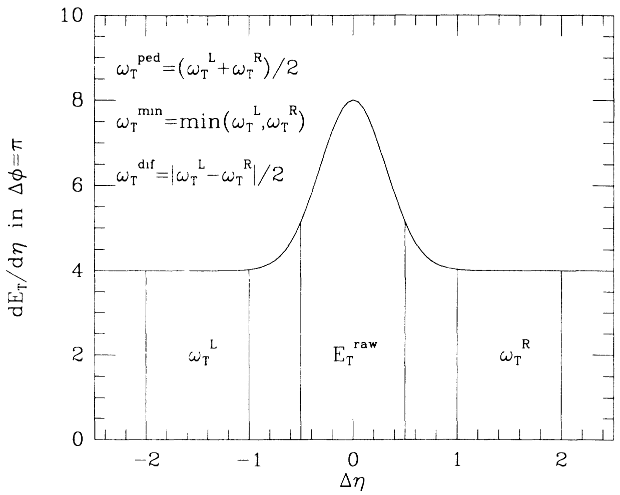


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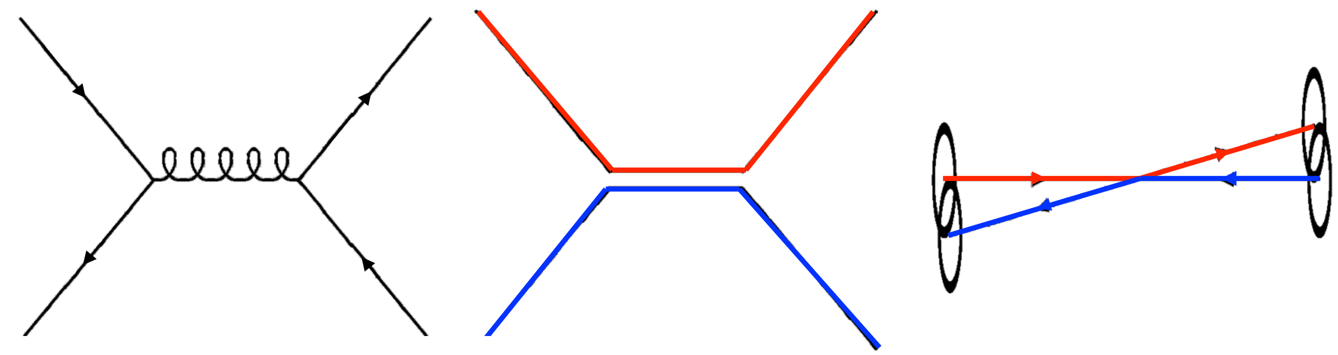
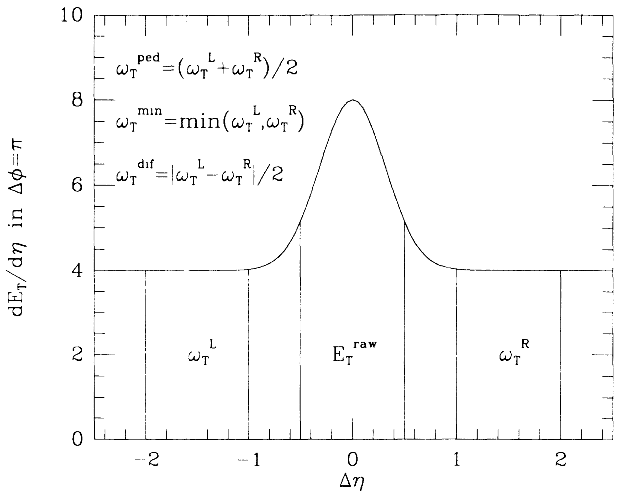
**EARWIG**

**HERWIG**
v3.0





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Simulation of QCD Coherence in Heavy Quark Production and Decay
**Nucl. Phys. B330 (1990) 261**
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**EARWIG**

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**EARWIG** (1984)

**HERWIG** v3.0 (1988)

**HERWIG** v4.0 (1989)

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1984 | 1988 | 1989 | 1991

QCD coherent branching and semi-inclusive processes at large x (**CMW**)
**Nucl. Phys. B349 (1991) 635**
(326 citations)

$$\Lambda_{MC} = \exp\left(\frac{67 - 3\pi^2 - 10N_f/3}{2(33 - 2N_f)}\right)\Lambda_{\overline{MS}}$$

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**EARWIG**

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**HERWIG** v5.1

# Introduction: Pino and Monte Carlo

1984 1988 1989 1991 2001

**EARWIG**

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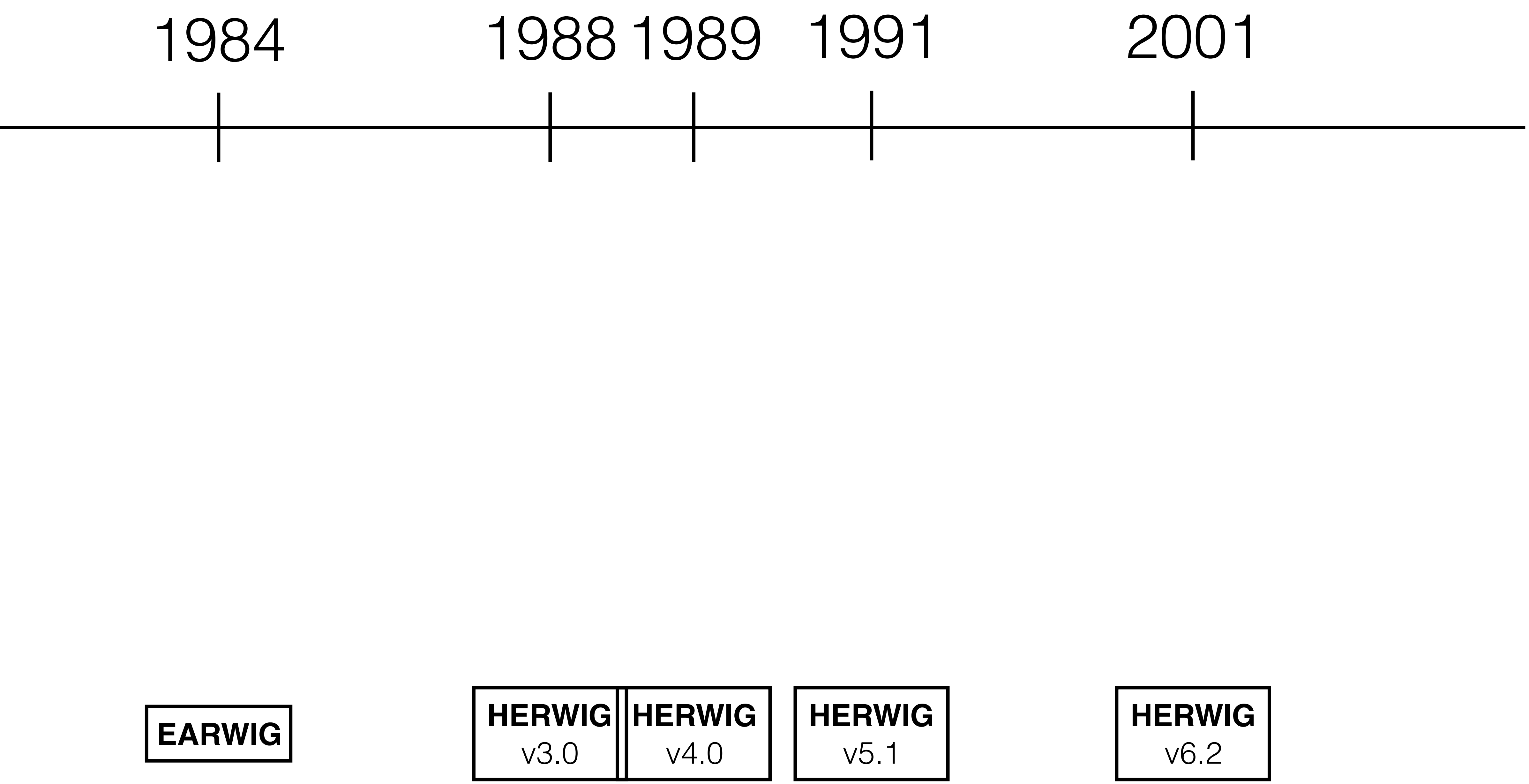

# Introduction: Pino and Monte Carlo

1984 1988 1989 1991 2001 2002

**EARWIG**

**HERWIG** v3.0

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**HERWIG** v5.1

**HERWIG** v6.2

# Introduction: Pino and Monte Carlo

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|---|---|---|---|---|---|
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# Introduction: Pino and Monte Carlo

1984 — EARWIG

1988 — **HERWIG** v3.0

1989 — **HERWIG** v4.0

1991 — **HERWIG** v5.1

2001 — **HERWIG** v6.2

2002 — **HERWIG** v6.5

2008 — Monte Carlo and large angle gluon radiation **JHEP 0903 (2009) 117** (17 citations)

# Introduction: Pino and Monte Carlo

| 1984 | 1988 | 1989 | 1991 | 2001 | 2002 | 2008 |
|---|---|---|---|---|---|---|
| EARWIG | HERWIG v3.0 | HERWIG v4.0 | HERWIG v5.1 | HERWIG v6.2 | HERWIG v6.5 | |

# Introduction: Pino, Monte Carlo and Me

| 1984 | 1988 | 1989 | 1991 | 2001 | 2002 | 2008 |
|---|---|---|---|---|---|---|
| **EARWIG** | **HERWIG** v3.0 | **HERWIG** v4.0 | **HERWIG** v5.1 | **HERWIG** v6.2 | **HERWIG** v6.5 | |

# Introduction: Pino, Monte Carlo and Me

1990

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**HERWIG** v4.5

**EARWIG**

**HERWIG** v3.0

**HERWIG** v4.0

**HERWIG** v5.1

**HERWIG** v6.2

**HERWIG** v6.5

# Introduction: Pino, Monte Carlo and Me

1990 1994

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PNPI Winter School
Gatchina

**HERWIG**
v4.5

**EARWIG**

**HERWIG**
v3.0

**HERWIG**
v4.0

**HERWIG**
v5.1

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v6.2

**HERWIG**
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# Introduction: Pino, Monte Carlo and Me

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Matrix-Element Corrections to
Parton Shower Algorithms
**Comp. Phys. Comm. 90 (1995) 95**
(160 citations)

**HERWIG**
v4.5

**EARWIG**

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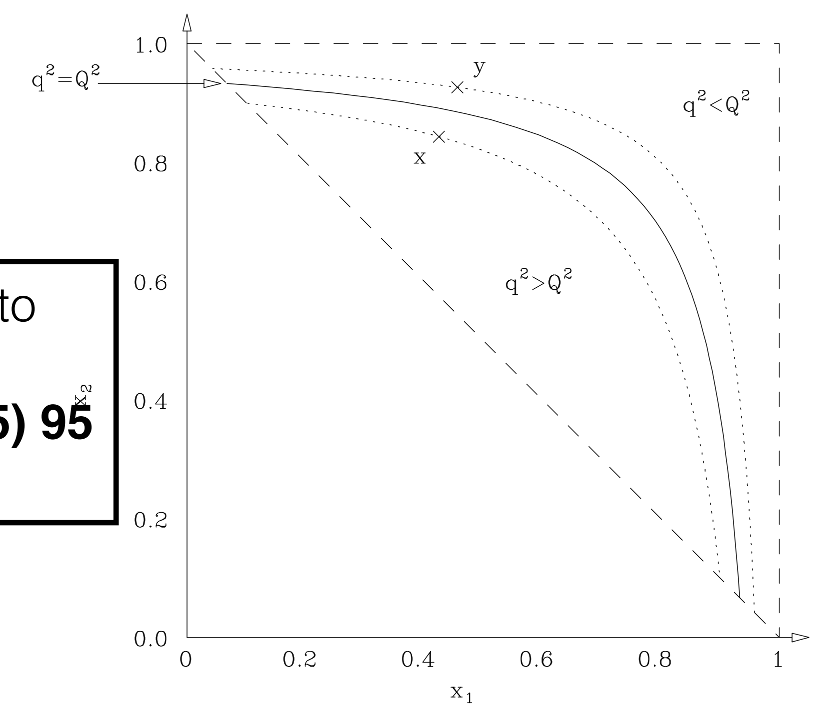


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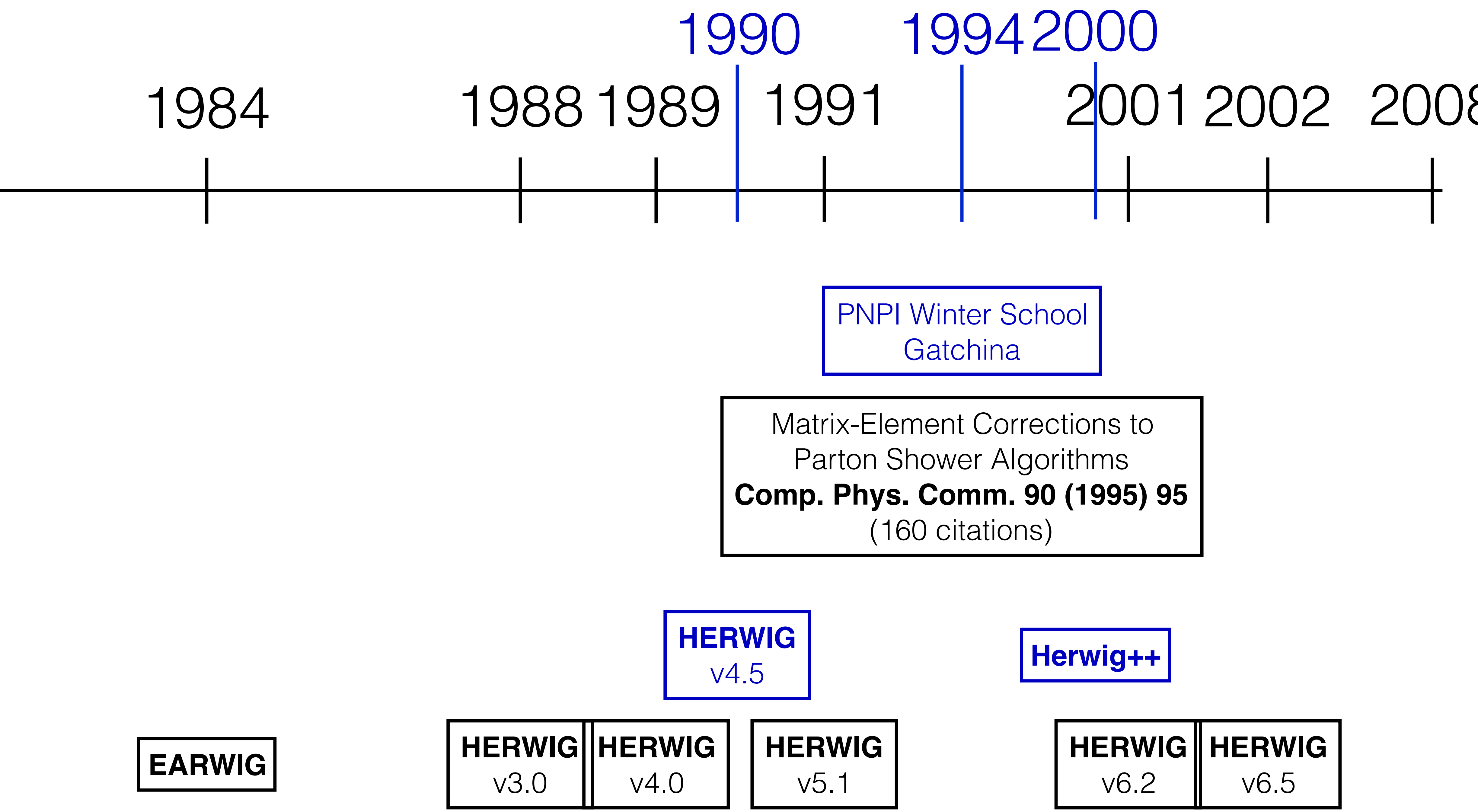
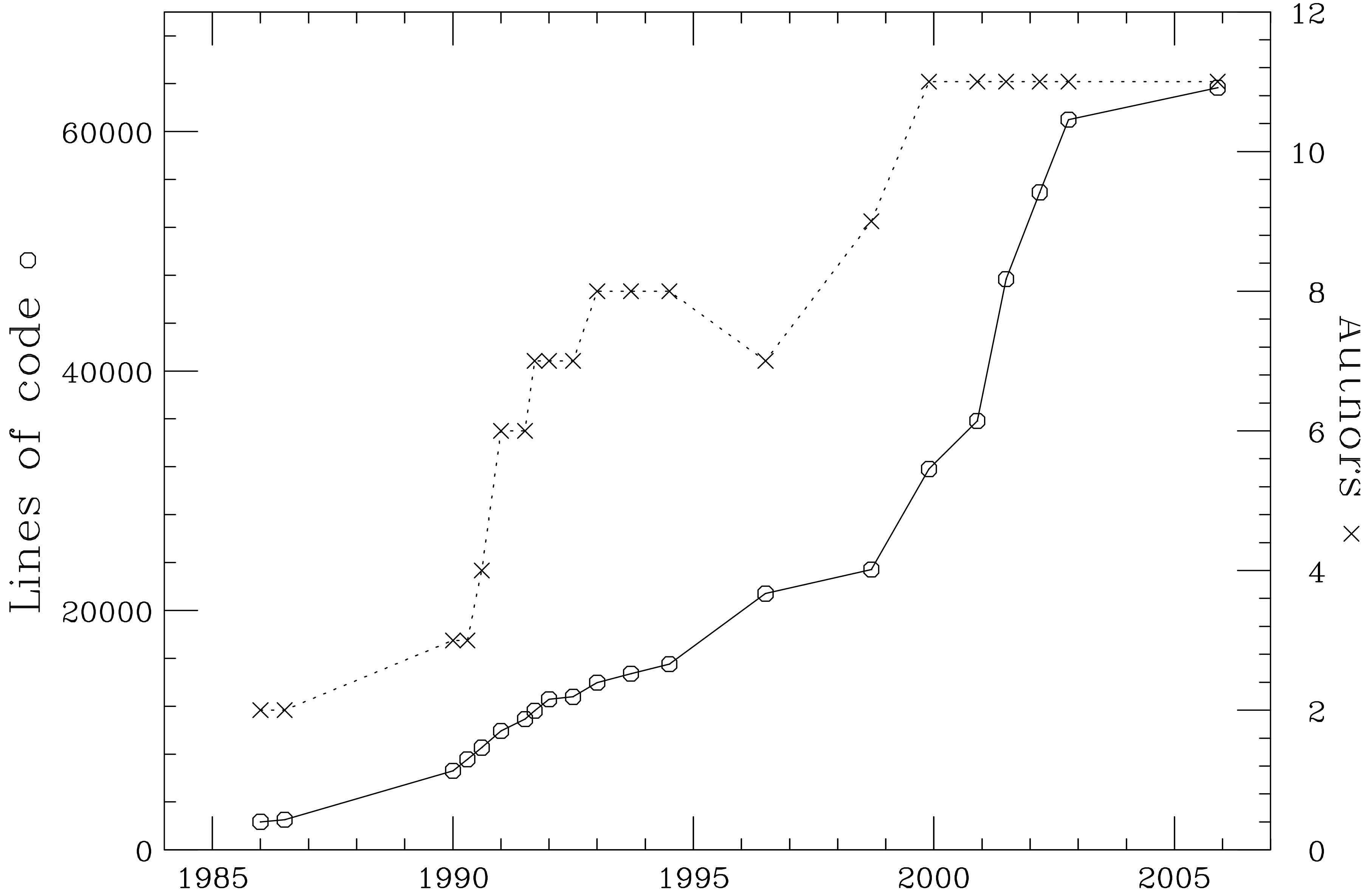


# Introduction: From HERWIG to Herwig++ and back again to Herwig



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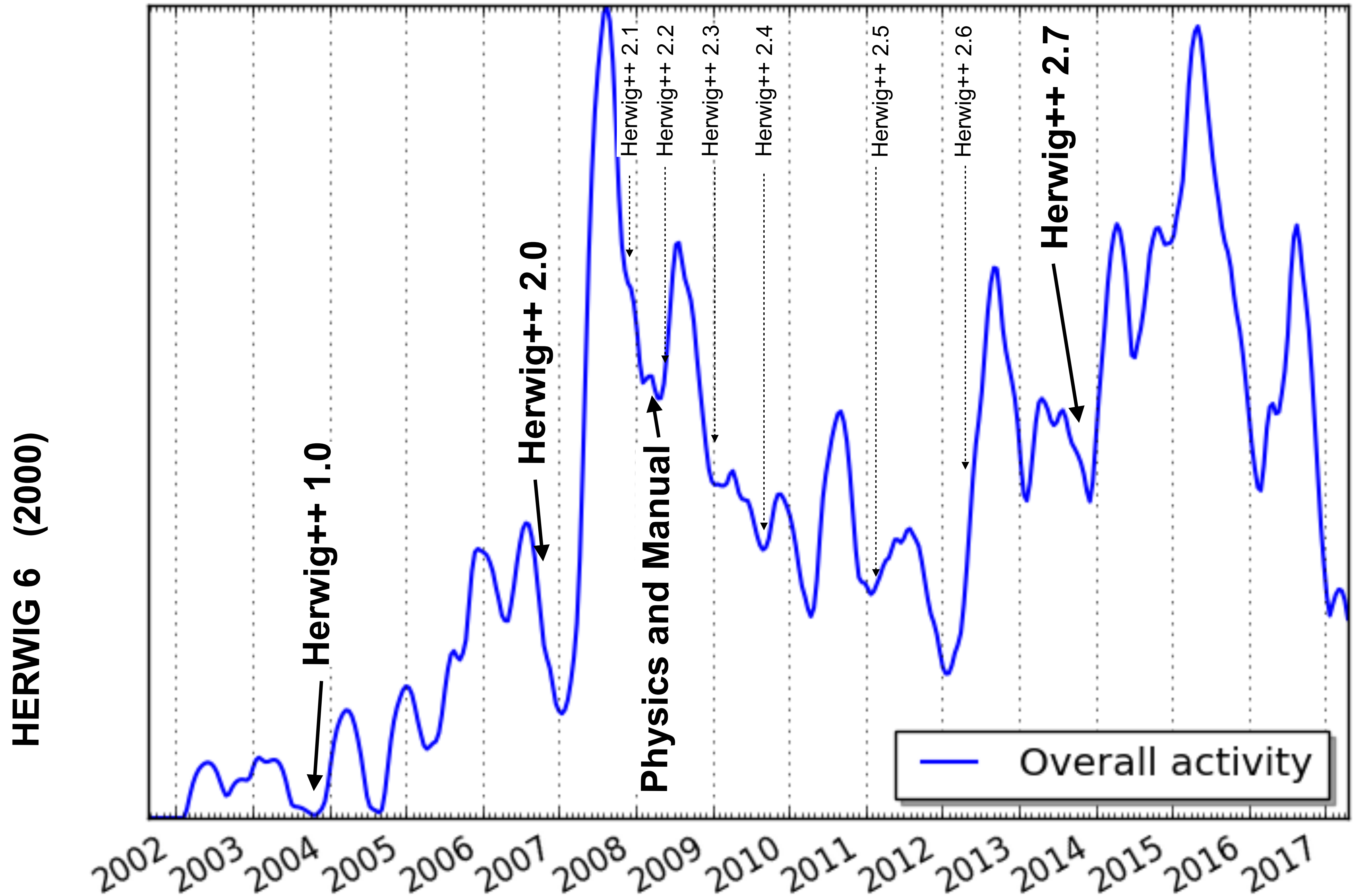

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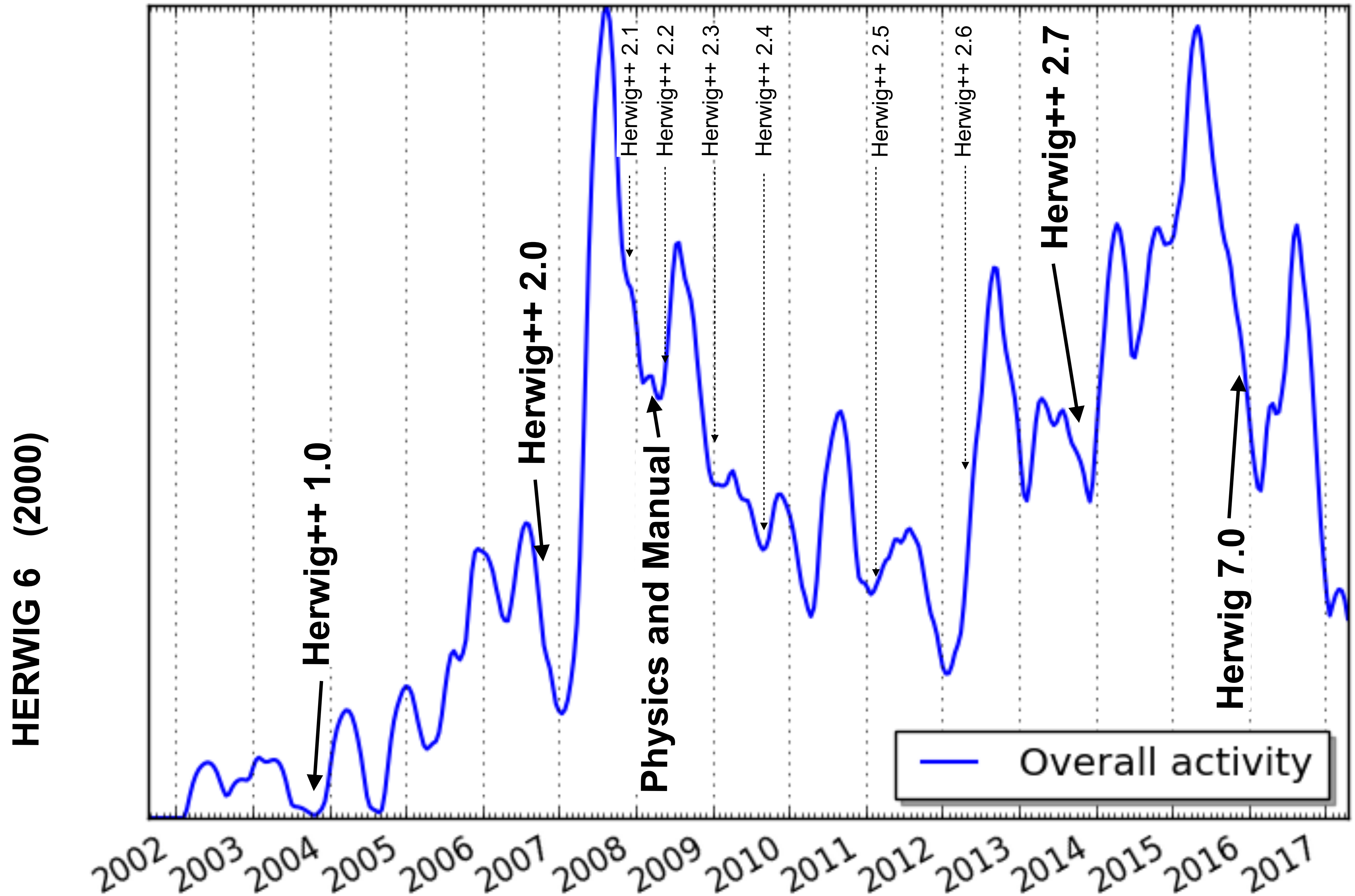

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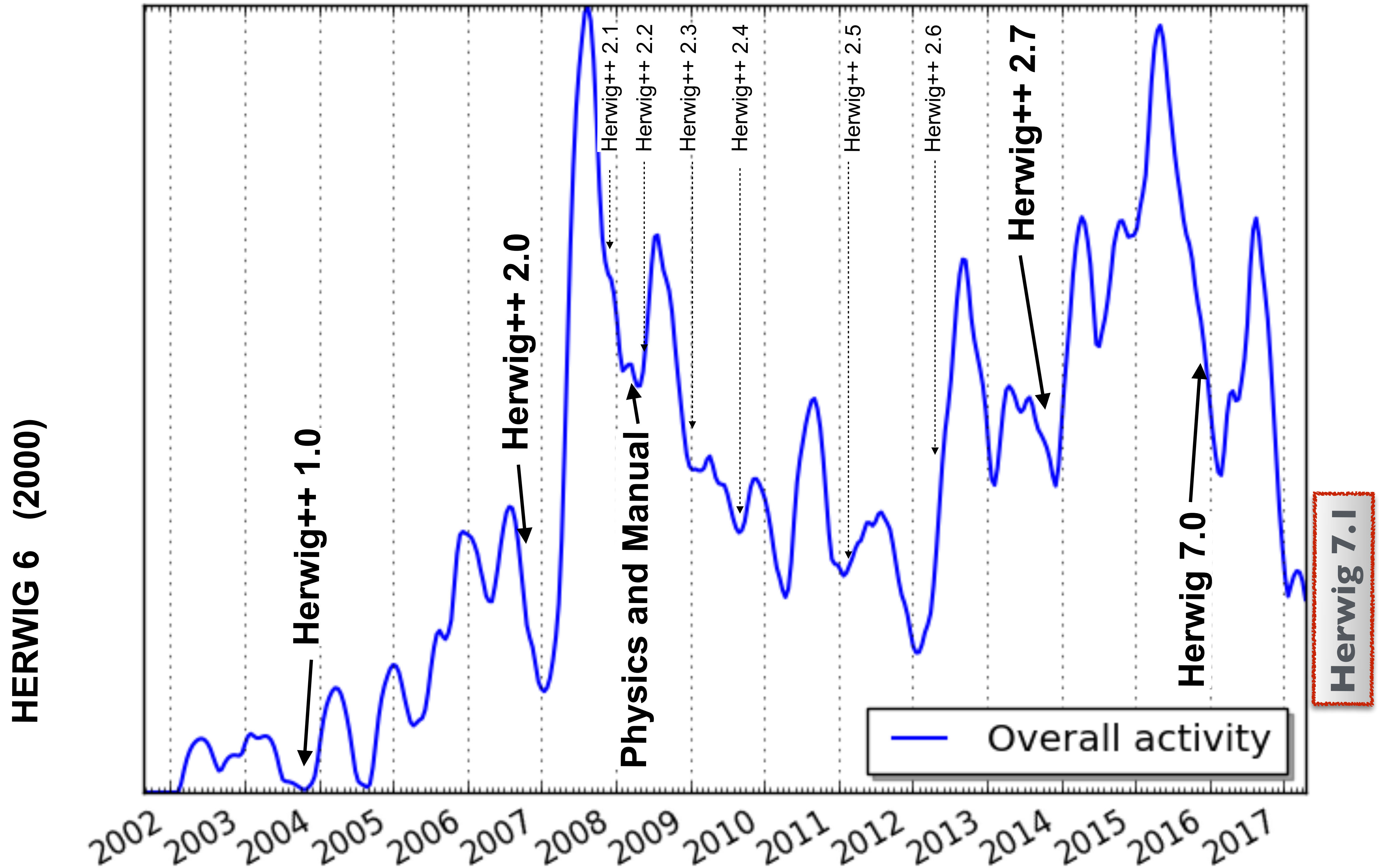

# Herwig7: Matching and Merging

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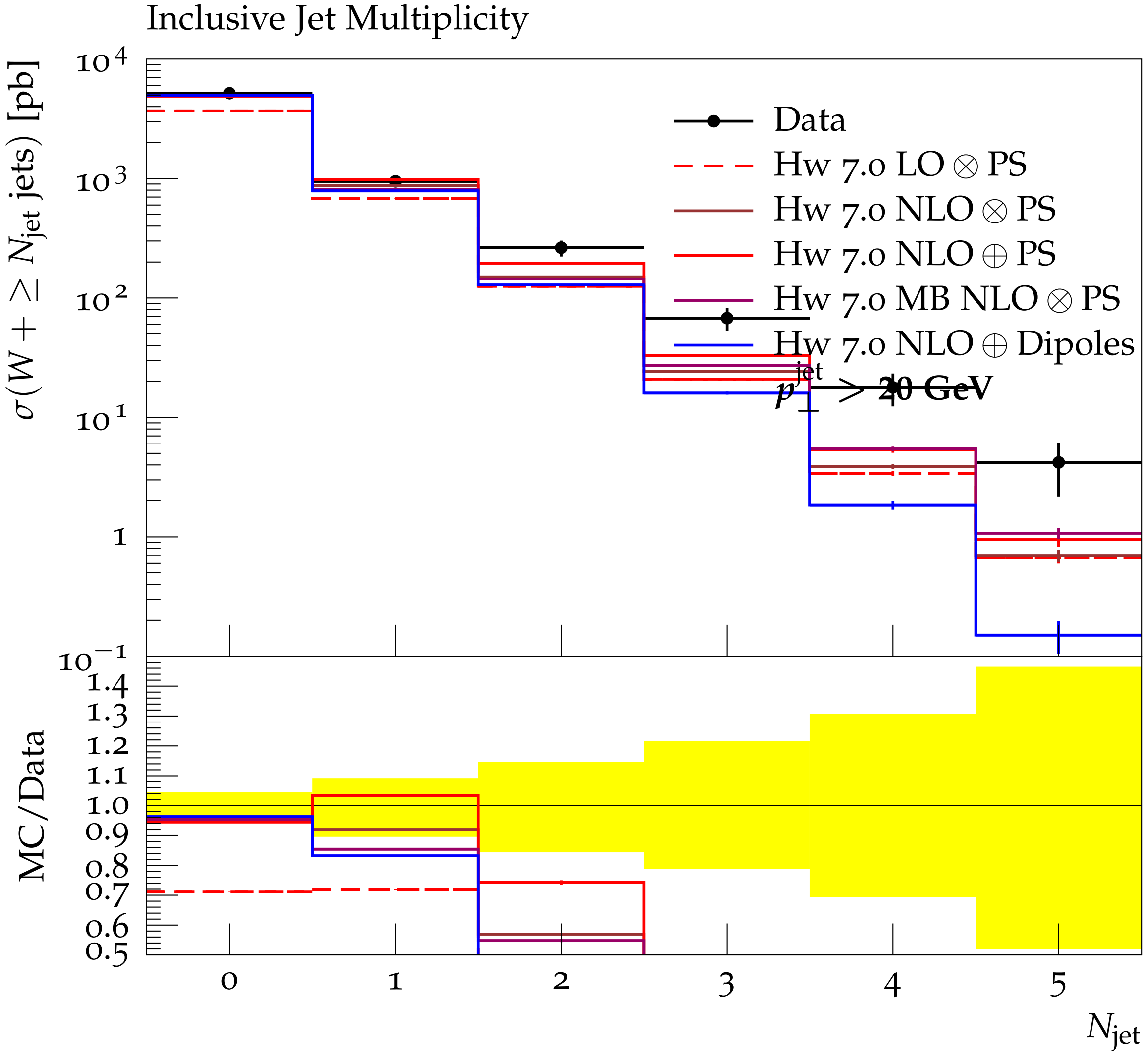
- Herwig 7.0 (December 3rd 2015)
  - Automated generation of NLO cross sections
  - Automated MC@NLO-like or POWHEG-like matching to parton shower or dipole shower

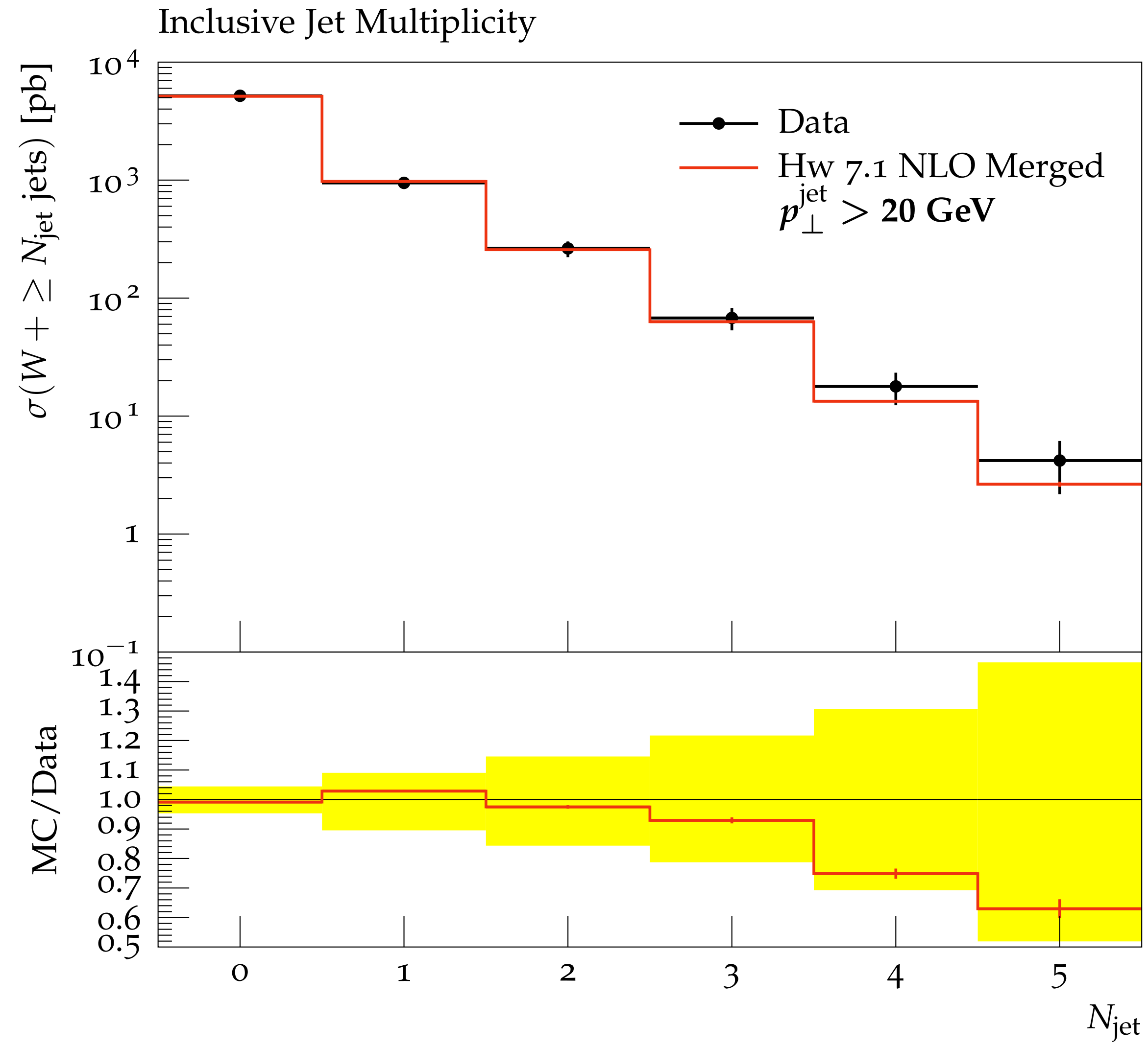
# Herwig7: Matching and Merging

- Herwig 7.0 (December 3rd 2015)
  - Automated generation of NLO cross sections
  - Automated MC@NLO-like or POWHEG-like matching to parton shower or dipole shower
- Herwig 7.1 (May 19th 2017)
  - Multi-jet merging of NLO matched cross sections
  - New model for soft interactions and diffraction

# Motivation

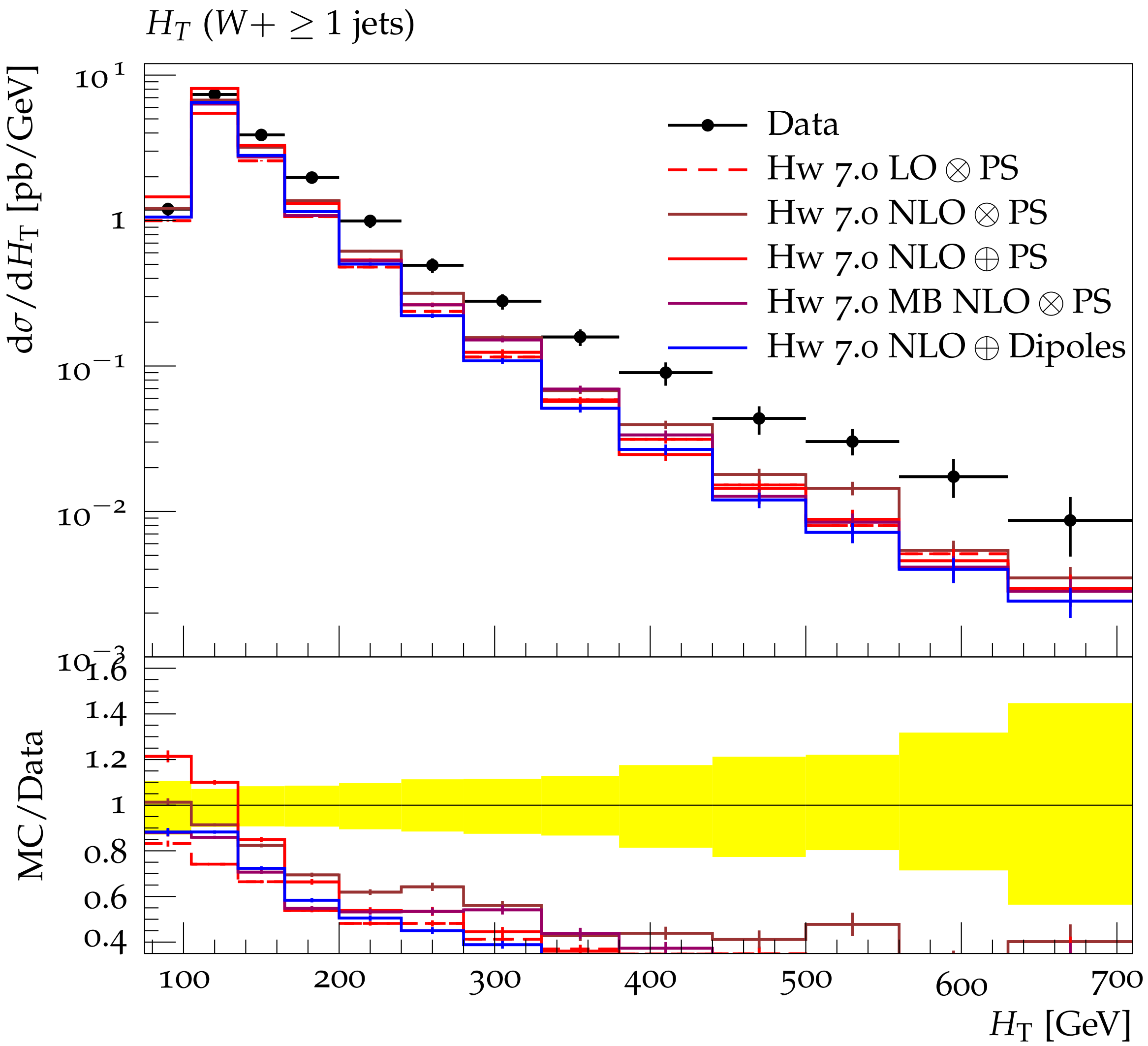


Inclusive Jet Multiplicity
Data
Hw 7.0 LO ⊗ PS
Hw 7.0 NLO ⊗ PS
Hw 7.0 NLO ⊕ PS
Hw 7.0 MB NLO ⊗ PS
Hw 7.0 NLO ⊕ Dipoles
$p_\perp^{jet} > 20$ GeV
$\sigma(W + \geq N_{jet}$ jets) [pb]
MC/Data
$N_{jet}$

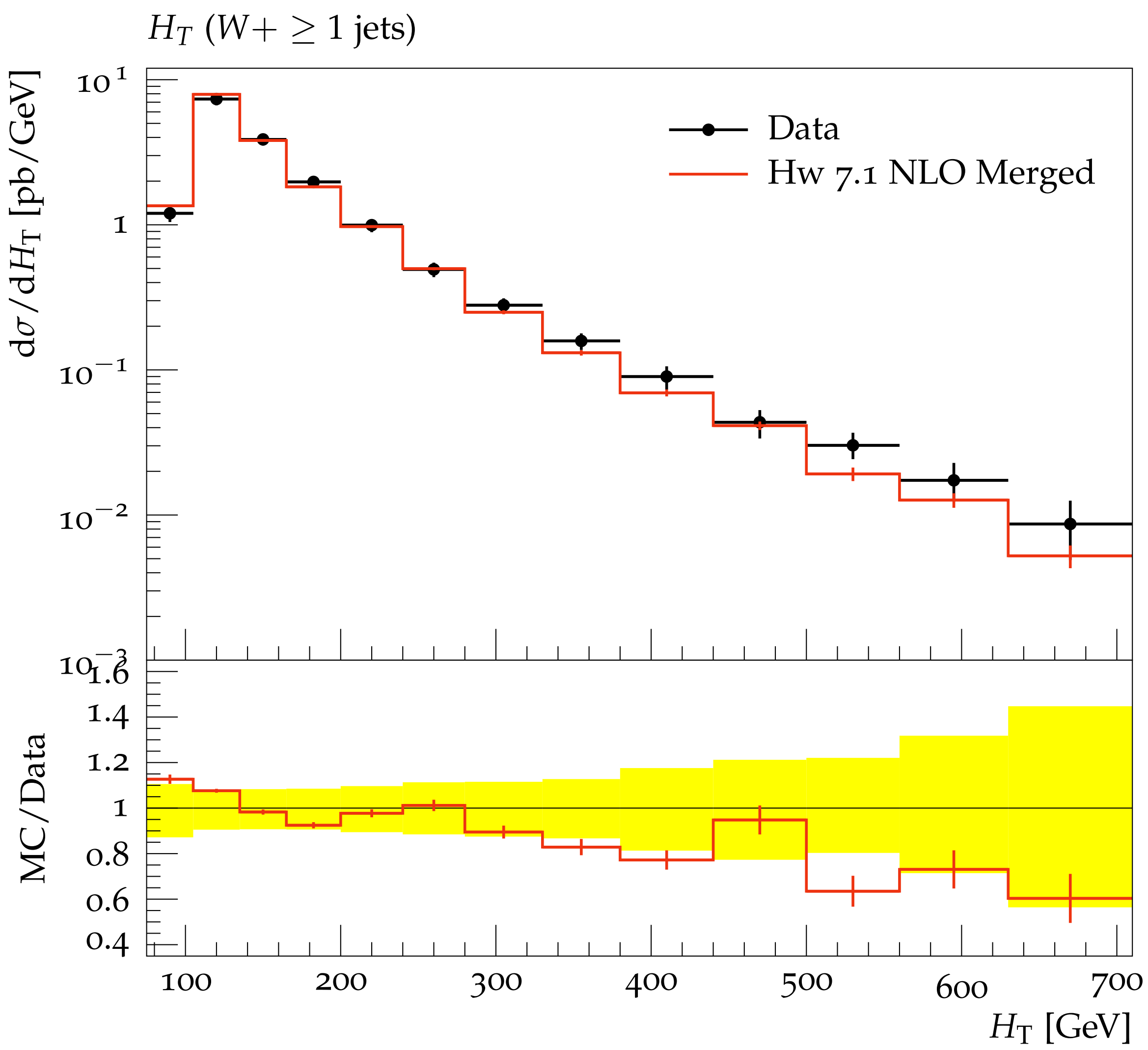



Inclusive Jet Multiplicity
Data
Hw 7.1 NLO Merged
$p_\perp^{jet} > 20$ GeV
$\sigma(W + \geq N_{jet}$ jets) [pb]
MC/Data
$N_{jet}$

# Motivation



$H_T$ ($W+ \geq 1$ jets)
Data
Hw 7.0 LO ⊗ PS
Hw 7.0 NLO ⊗ PS
Hw 7.0 NLO ⊕ PS
Hw 7.0 MB NLO ⊗ PS
Hw 7.0 NLO ⊕ Dipoles
dσ/d$H_T$ [pb/GeV]
MC/Data
$H_T$ [GeV]

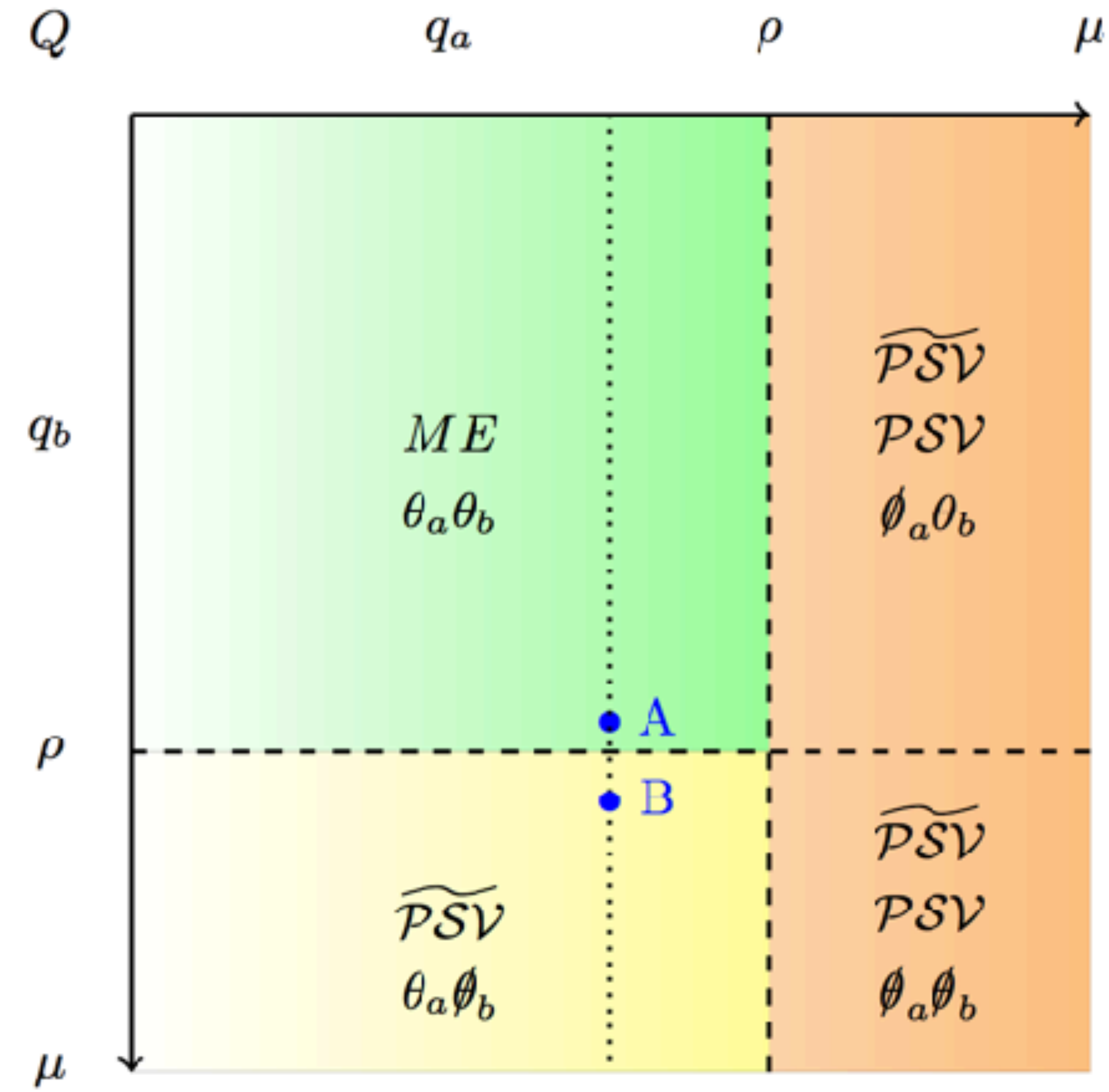
$H_T$ ($W+ \geq 1$ jets)
Data
Hw 7.1 NLO Merged
dσ/d$H_T$ [pb/GeV]
MC/Data
$H_T$ [GeV]

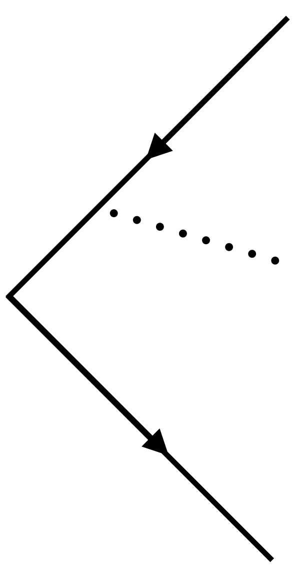
# Merging

Basic Idea:
Divide the phase space into ME and PS regions.

$$\mathcal{PS}_\mu[u(\phi_n, Q)] = \widetilde{\mathcal{PSV}}_\mu[\widetilde{\mathcal{PS}}_\rho[u(\phi_n, Q)]]$$

Overlapping phase spaces produce dead regions if not treated properly.



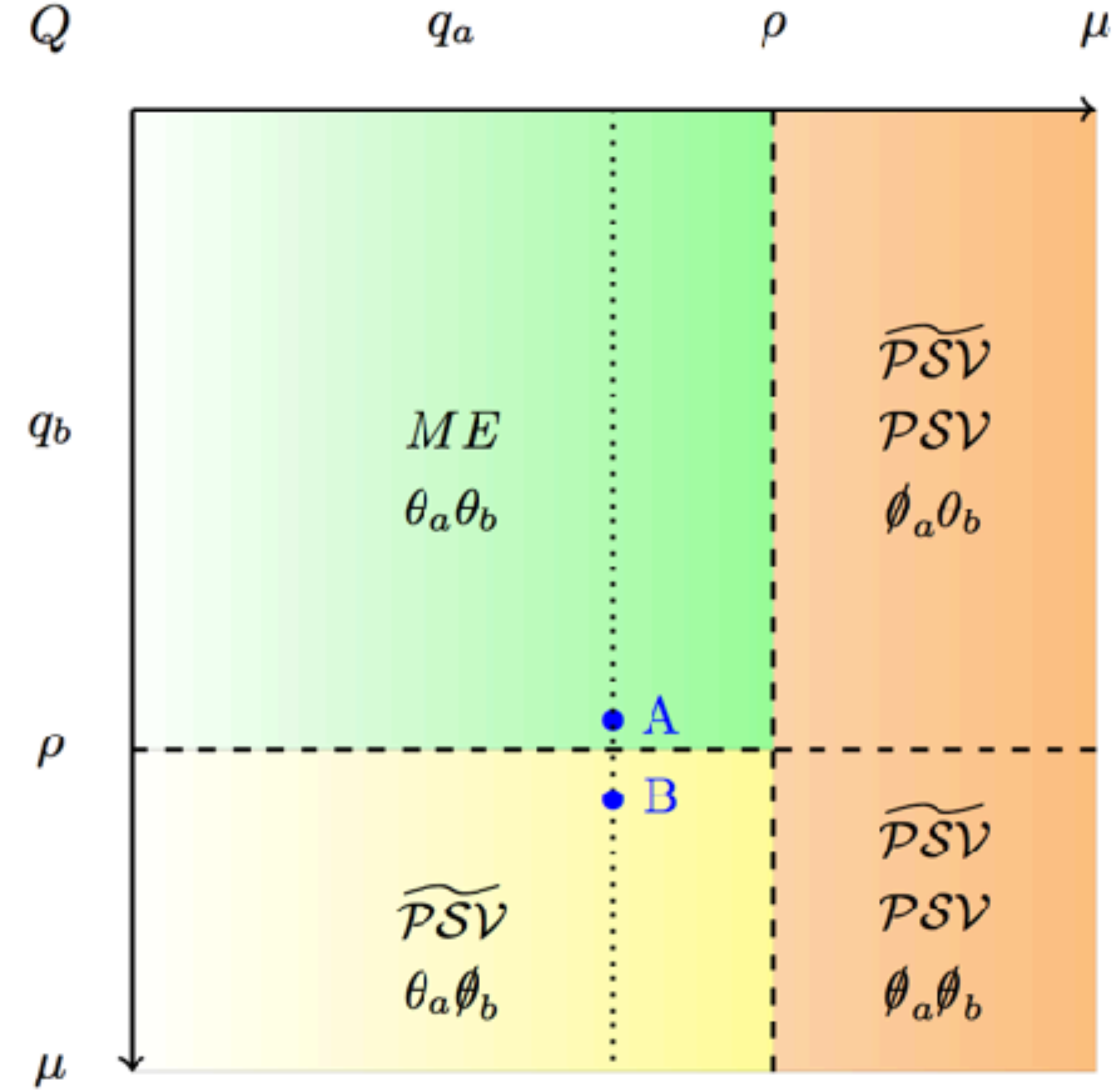



Simple example:

- Start with two kernels with overlapping phase spaces.
- ME region defined by clustering algorithm.
- Both scales $q_a$ and $q_b$ must be above merging scale
- Assume emission in shower region from kernel $P_a$
- Simple veto PS would produce point A but not B

# Merging

$$\mathcal{PS}_\mu[u(\phi_n,Q)] = \widetilde{\mathcal{PSV}}_\mu[\widetilde{\mathcal{PS}}_\rho[u(\phi_n,Q)]]$$




Now replace $\widetilde{\mathcal{PS}}_\rho[u(\phi_n,Q)]$
with expressions from the ME calculation
weighted with shower history:

$$w_I^k = \sum_\alpha \frac{w_{C,\alpha}^k}{\sum_s w_{C,\beta}^k} \frac{\alpha_S(q_k)}{\alpha_S(\mu_R)} \cdot \underbrace{\frac{f_k^{(1,2)}(\eta_{k-1},q_{k-1})}{f_k^{(1,2)}(\eta_{k-1},q_k)} \Pi^{(1,2)}(q_{k-1}|q_k)}_{\approx \Delta(q_{k-1}|q_k)} \prod_f \Delta(q_{k-1}|q_k)$$

# Merging

$$d\sigma_n u(\phi_n, q_n) w_H^n - \int_\rho^{q_n} dq \sum_\alpha \frac{w_{C,\alpha}}{\sum_\beta w_{C,\beta}} u(\phi_n^\alpha, q_n^\alpha) d\sigma_{n+1} w_H^{n+1}$$

$$+ d\sigma_{n+1} u(\phi_{n+1}, q_{n+1}) w_H^{n+1}$$

Unitarized LO and NLO merging now adds and subtracts the same parts. Here only if the cluster history is produced.

In order to add NLO corrections the history and the additional emissions need to be expanded to order $\alpha_S$ in the ME and the PS region

$$d\sigma_n u(\phi_n, q_n) \left. \frac{\partial w_H^n}{\partial \alpha_S} \right| - \int_\rho^{q_n} dq \sum_\alpha \frac{w_{C,\alpha}}{\sum_\beta w_{C,\beta}} u(\phi_n^\alpha, q_n^\alpha) d\sigma_{n+1}$$

$$+ d\sigma_{n+1} u(\phi_{n+1}, q_{n+1})$$

# Merging

For example $$\prod_i \frac{\alpha_S(q_i)}{\alpha_S(\mu)} = 1 - \sum_i b_0 \frac{\alpha_S(\mu)}{\pi} \log\left(\frac{q_i}{\mu}\right) + \mathcal{O}(\alpha_S^2)$$

Together with LO weights the expansion needs to produce the form

$$d\sigma_n^B (1 + \mathcal{O}(\alpha_S^2))$$

but e.g.

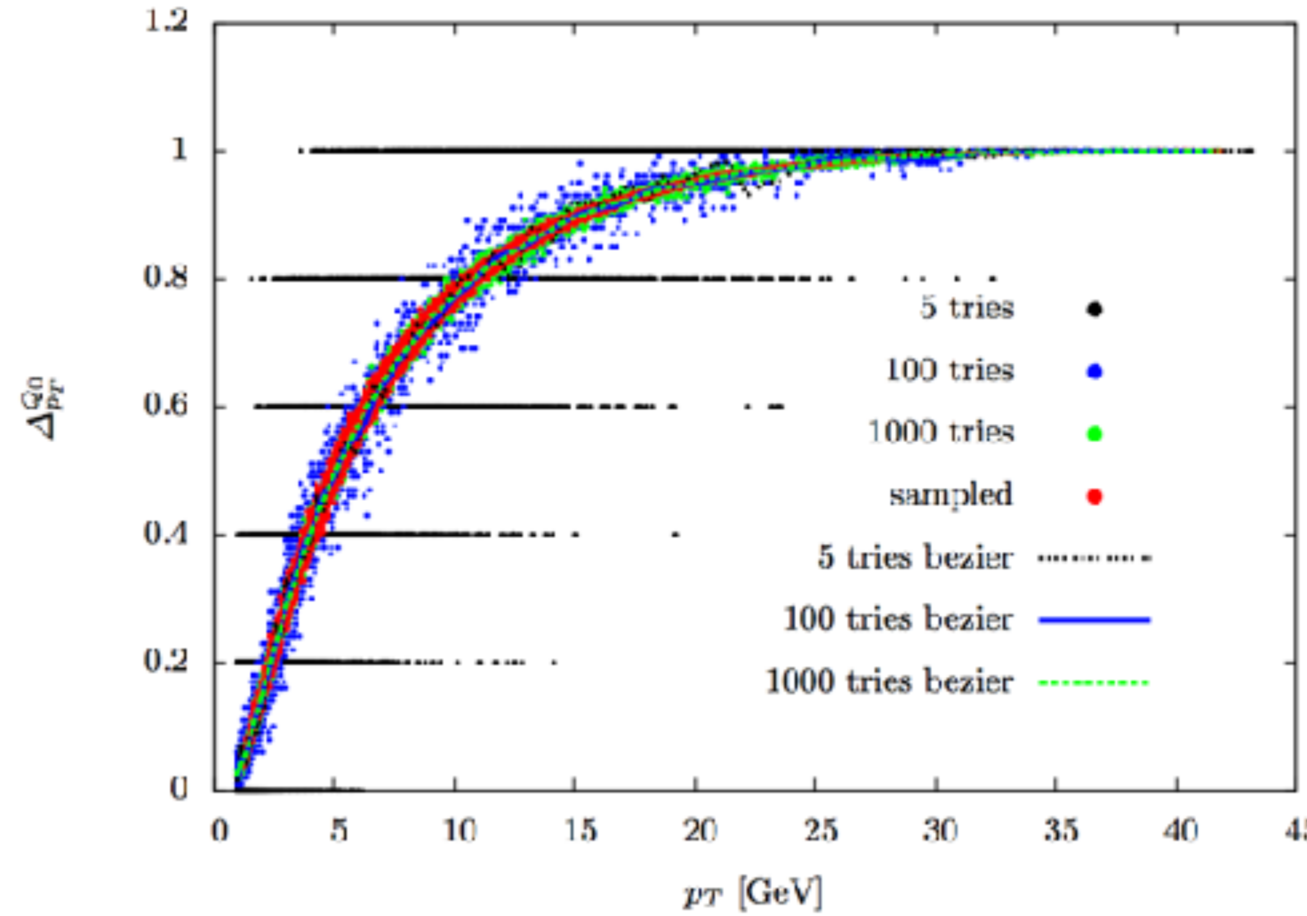
$$d\sigma_n^B \prod_i \left( \left[ 1 - \sum_X \alpha_S w^i_{\partial_X} \right] \prod_X w^i_X \right) \quad \text{and} \quad d\sigma_n^B \prod_i \left( \left[ \prod_X w^i_X - \sum_X \alpha_S w^i_{\partial_X} \right] \right)$$

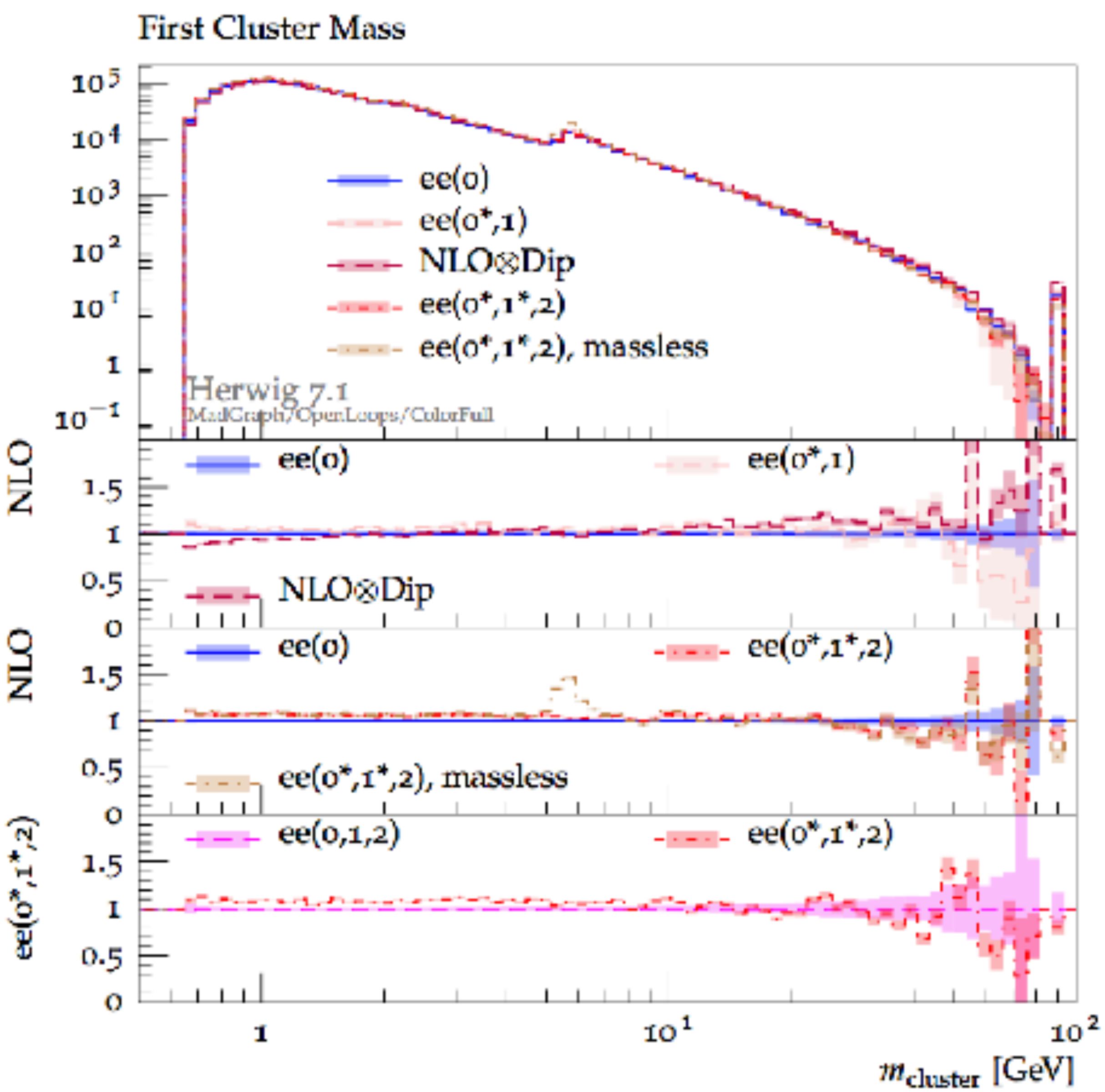
both fulfil the criterion above.

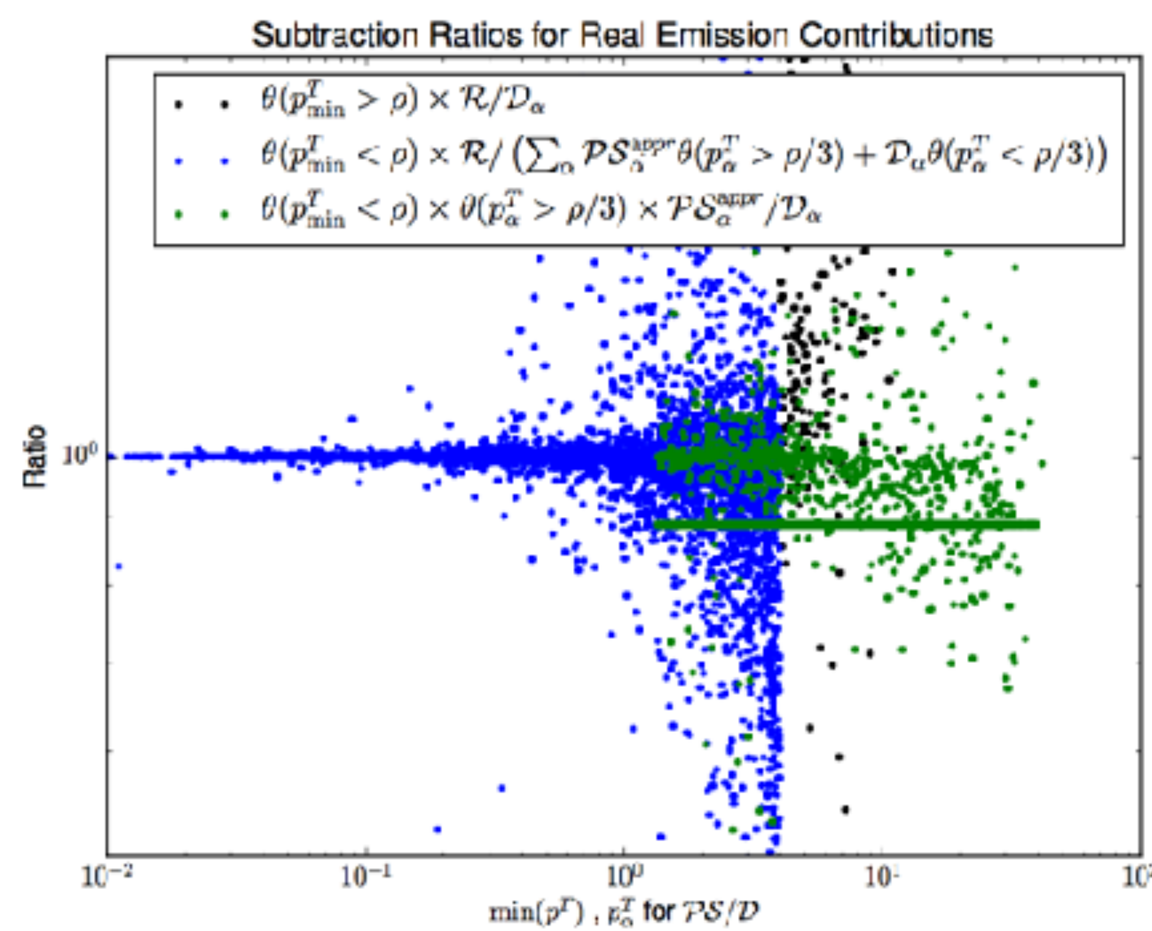
Can be used as uncertainty as difference tests higher orders.

# Sanity Checks

- Sudakov sampling
- Subtraction plots
- Cluster mass spectra



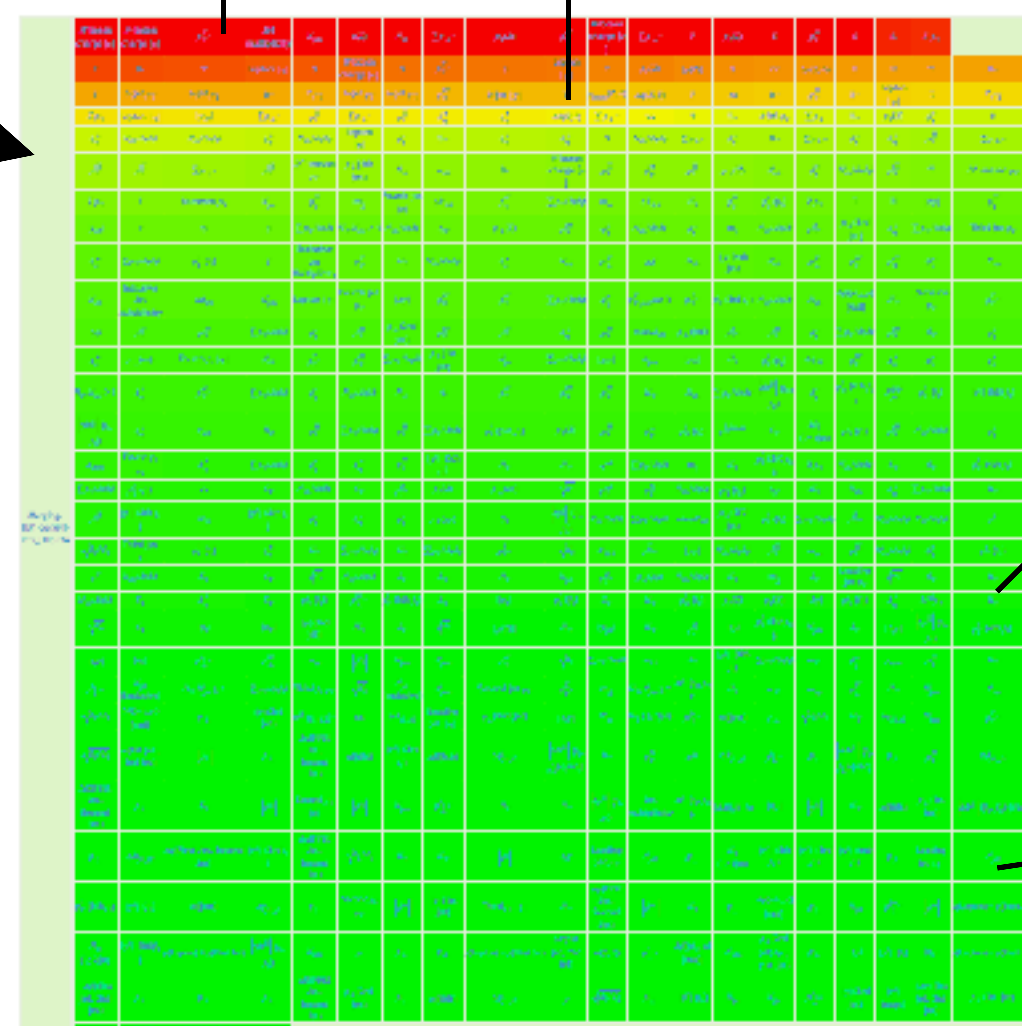
# Herwig 7.1 - Release Status / Testing

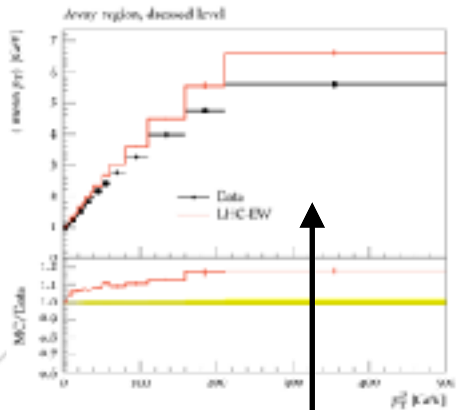
Currently ~20000 observables

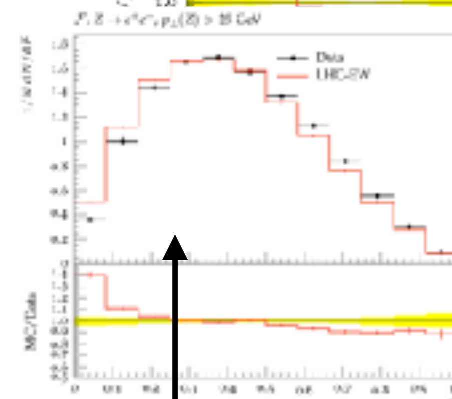
Need a way to structurally filter results.

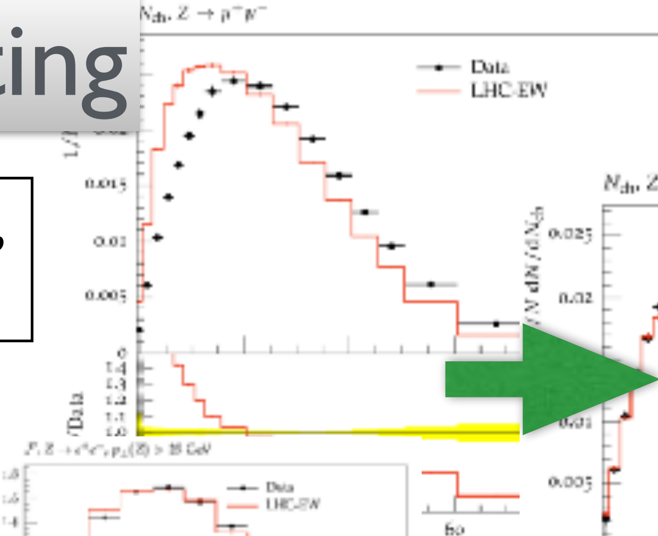
JB, S. Webster, P. Richardson

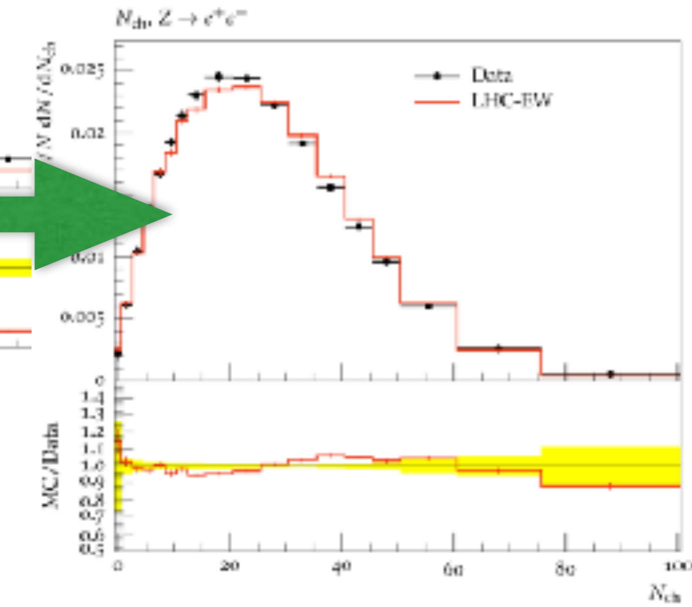
| Revisions | BFactory | TVT-Photon | LHC-EW | LHC-Photon | DIS-NoME | LHC-Jets | LEP | SppS | TVT-WZ | TVT-Jets | DIS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Merging-H71-corMPI-RES | --- | --- | 0.1[illegible] | --- | --- | 0.35 | --- | --- | --- | --- | --- |
| MB-QT-H71-5B-RES | --- | --- | 1.65 | --- | --- | 0.41 | 0.71 | --- | [illegible] | 0.57 | 5.38 |
| POW-QT-H71-0B-RES | --- | --- | --- | --- | --- | --- | 0.76 | --- | 1.48 | --- | 1.37 |
| MB-POW-QT-H71-0B-RES | --- | --- | --- | --- | --- | --- | 1.04 | --- | --- | --- | 3.40 |
| LD-H71-0B-RES | 0.84 | 0.87 | 1.33 | 0.81 | 0.86 | 0.82 | 0.80 | 0.67 | 1.83 | 0.76 | 1.43 |
| POW-QT-H71-5B-RES | --- | --- | 2.07 | --- | --- | 0.57 | 0.71 | --- | 0.72 | 0.53 | 1.13 |
| MB-QT-H71-0B-RES | --- | --- | --- | --- | --- | --- | 0.82 | --- | --- | --- | 3.57 |
| LD-H70-RES | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| LD-H71-5B-RES | 0.99 | 0.87 | 1.11 | 0.80 | 1.22 | 0.85 | 0.69 | 0.68 | 0.94 | 0.86 | 1.25 |
| MB-POW-QT-H71-5B-RES | --- | --- | 2.07 | --- | --- | 0.57 | 1.04 | --- | 0.81 | 0.53 | 5.77 |
| Merging-H71-RES | --- | --- | 0.15 | --- | --- | 0.35 | 0.94 | --- | 0.67 | 0.89 | 2.14 |

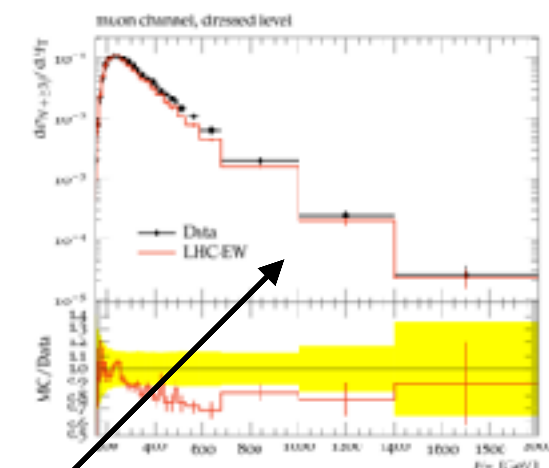


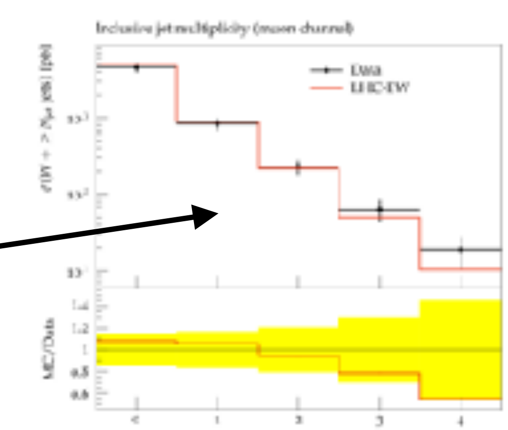


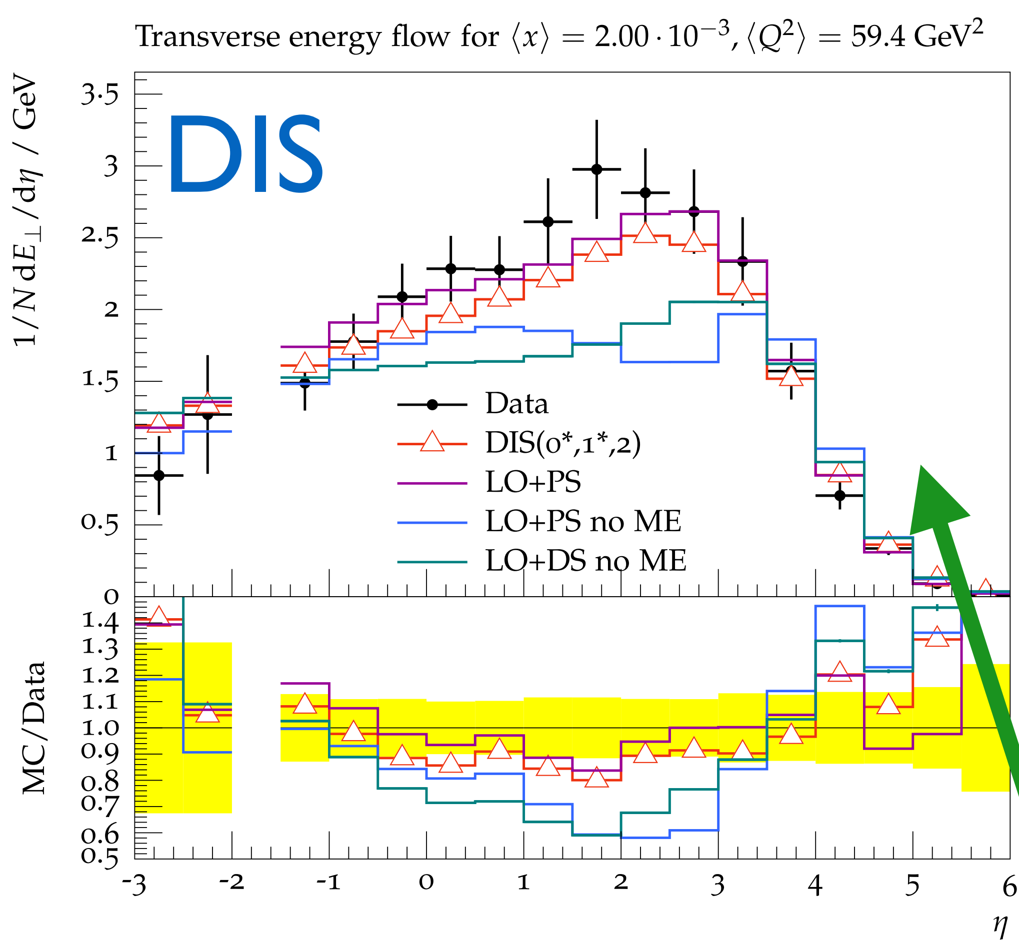



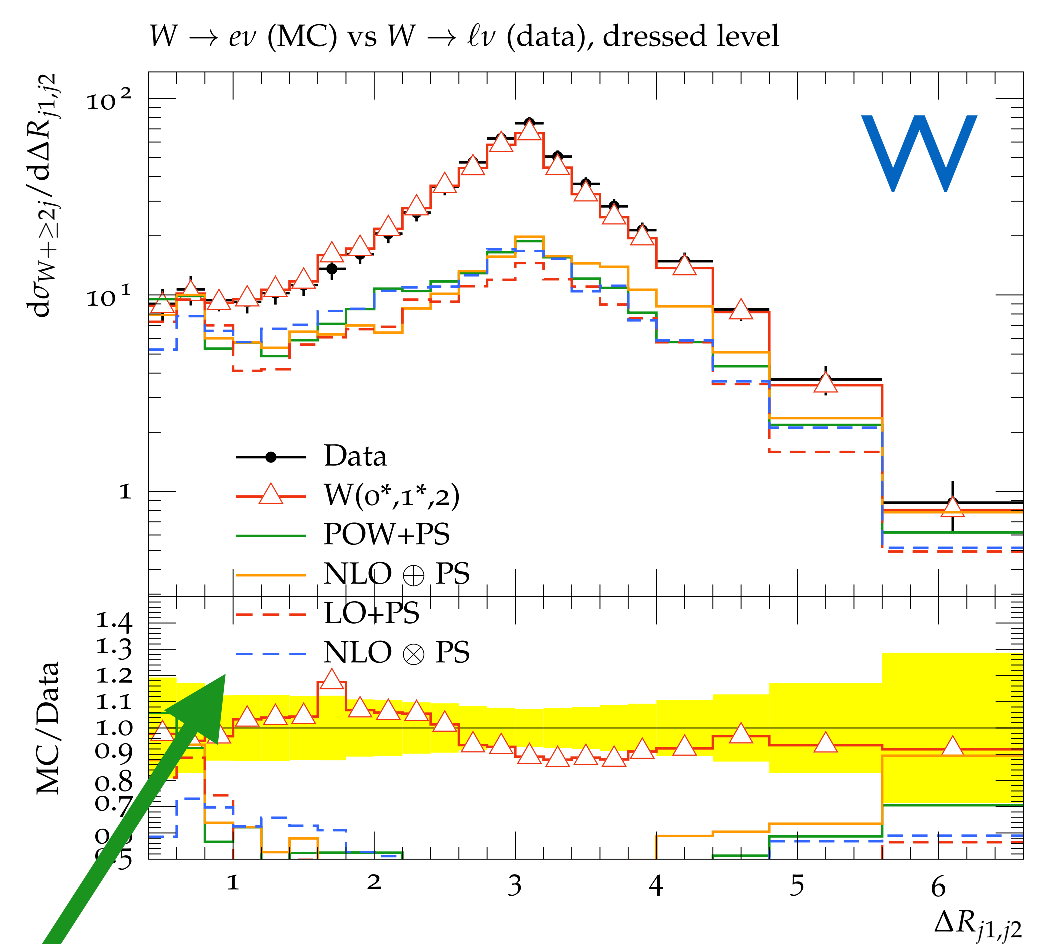



# Test Results



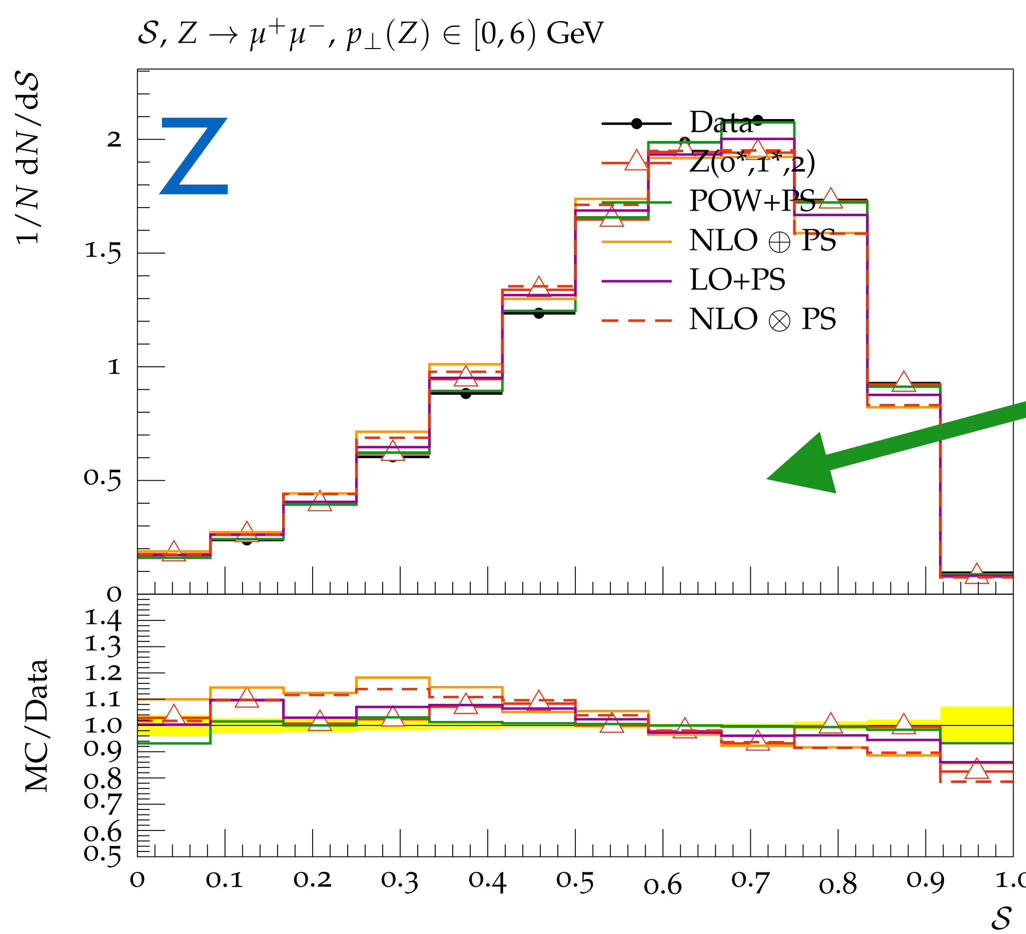

One tune to rule them all…

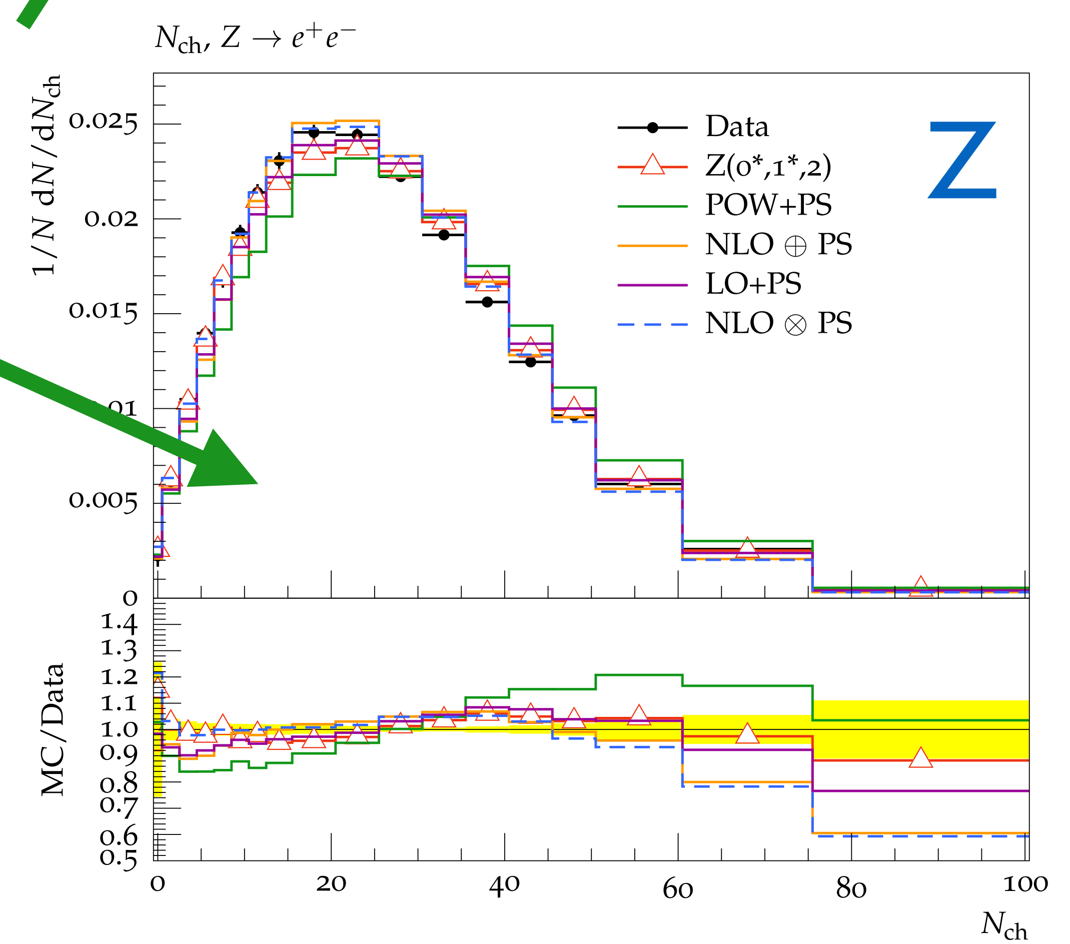
LEP is fine

DIS tested

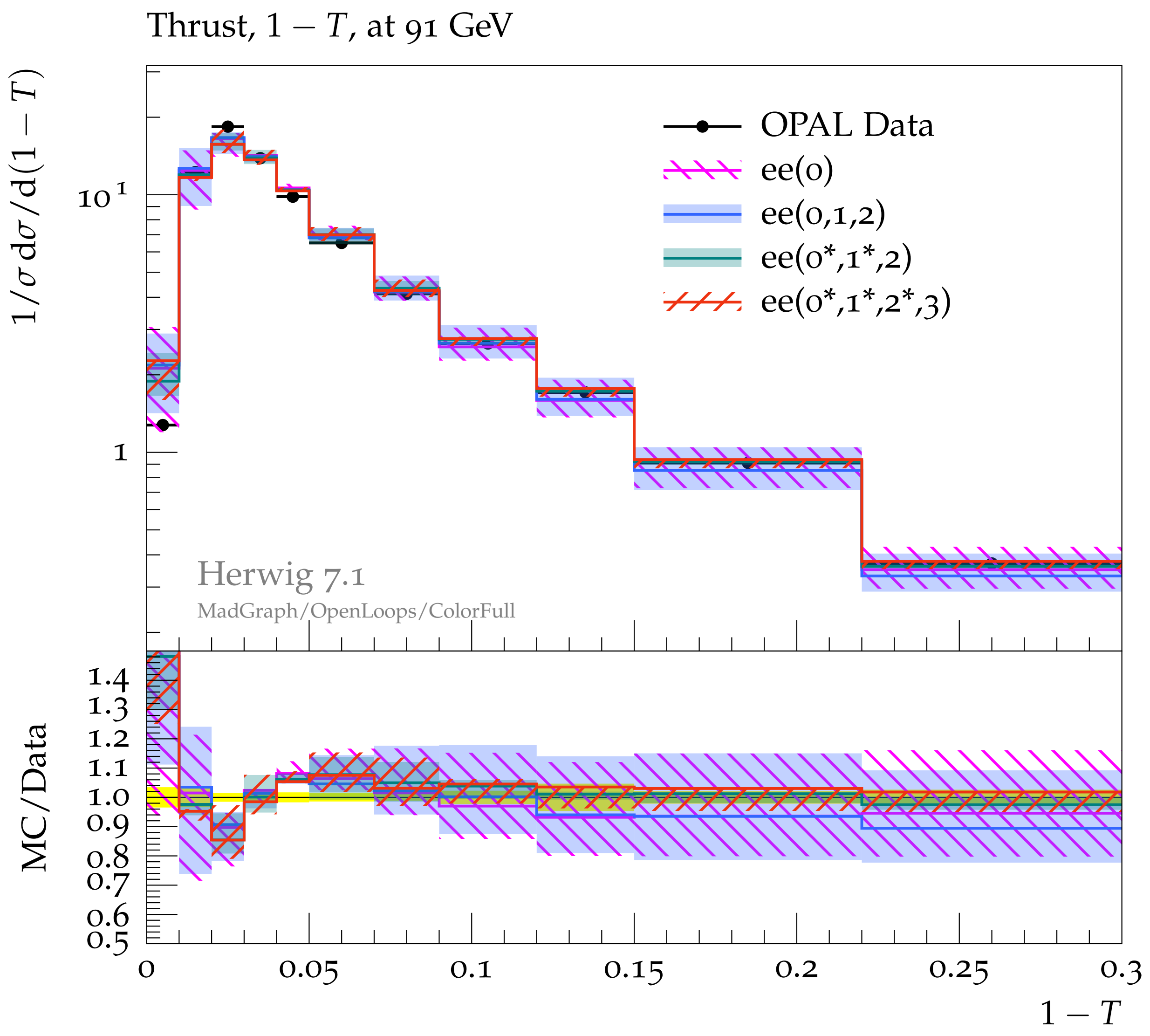
DY hard emissions

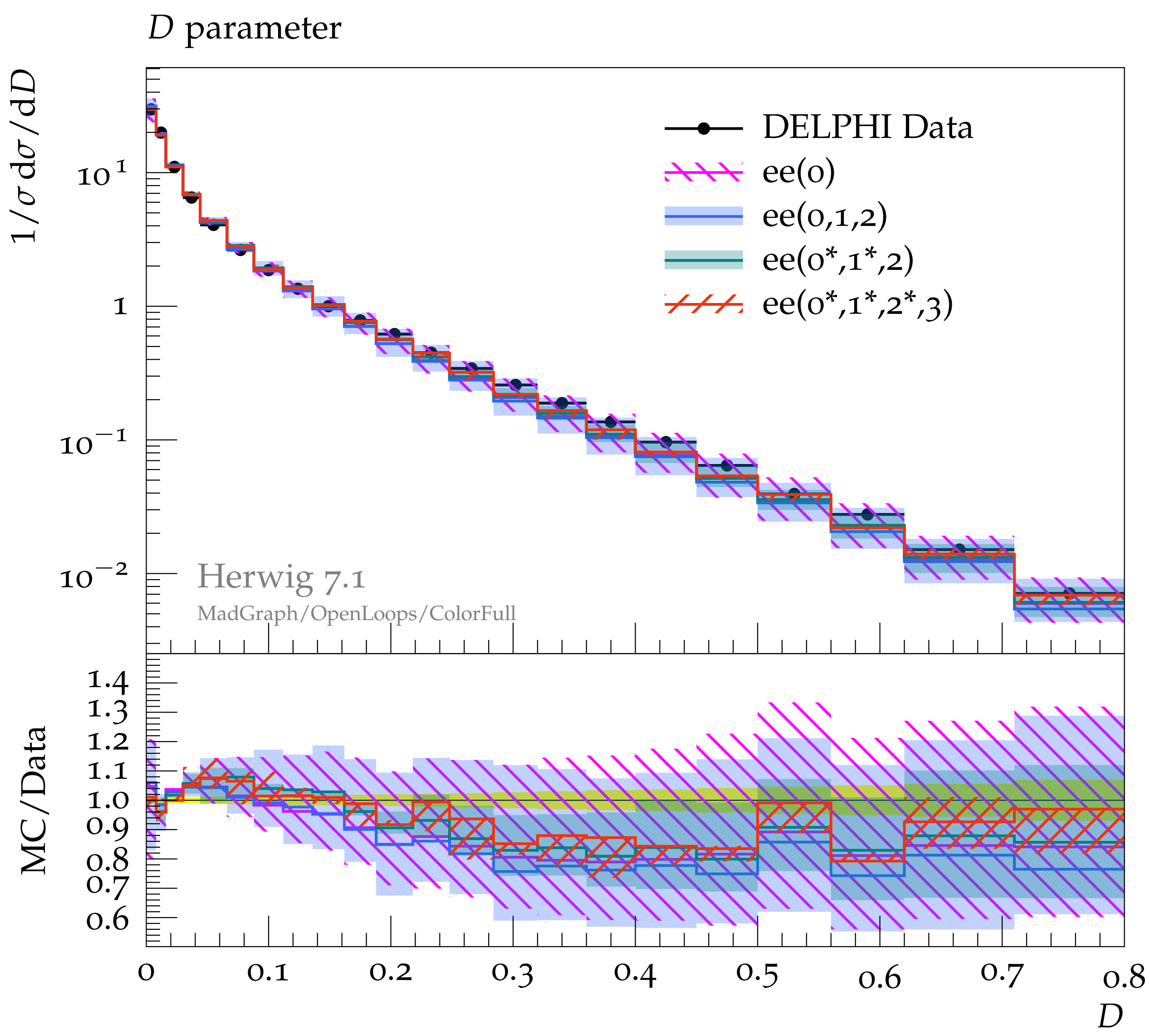
Interplay with MPI needs testing



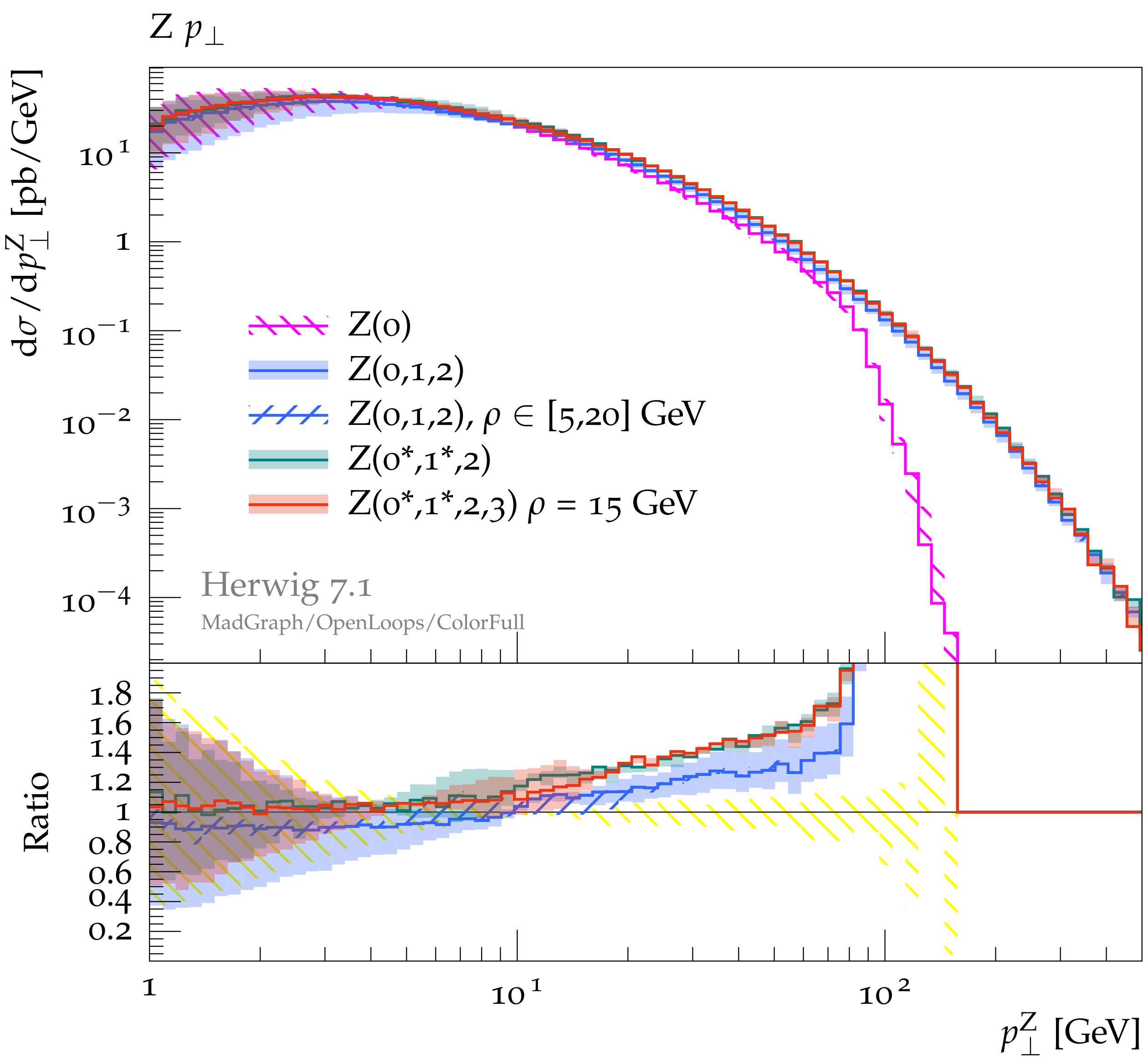
# Results: e+e- annihilation

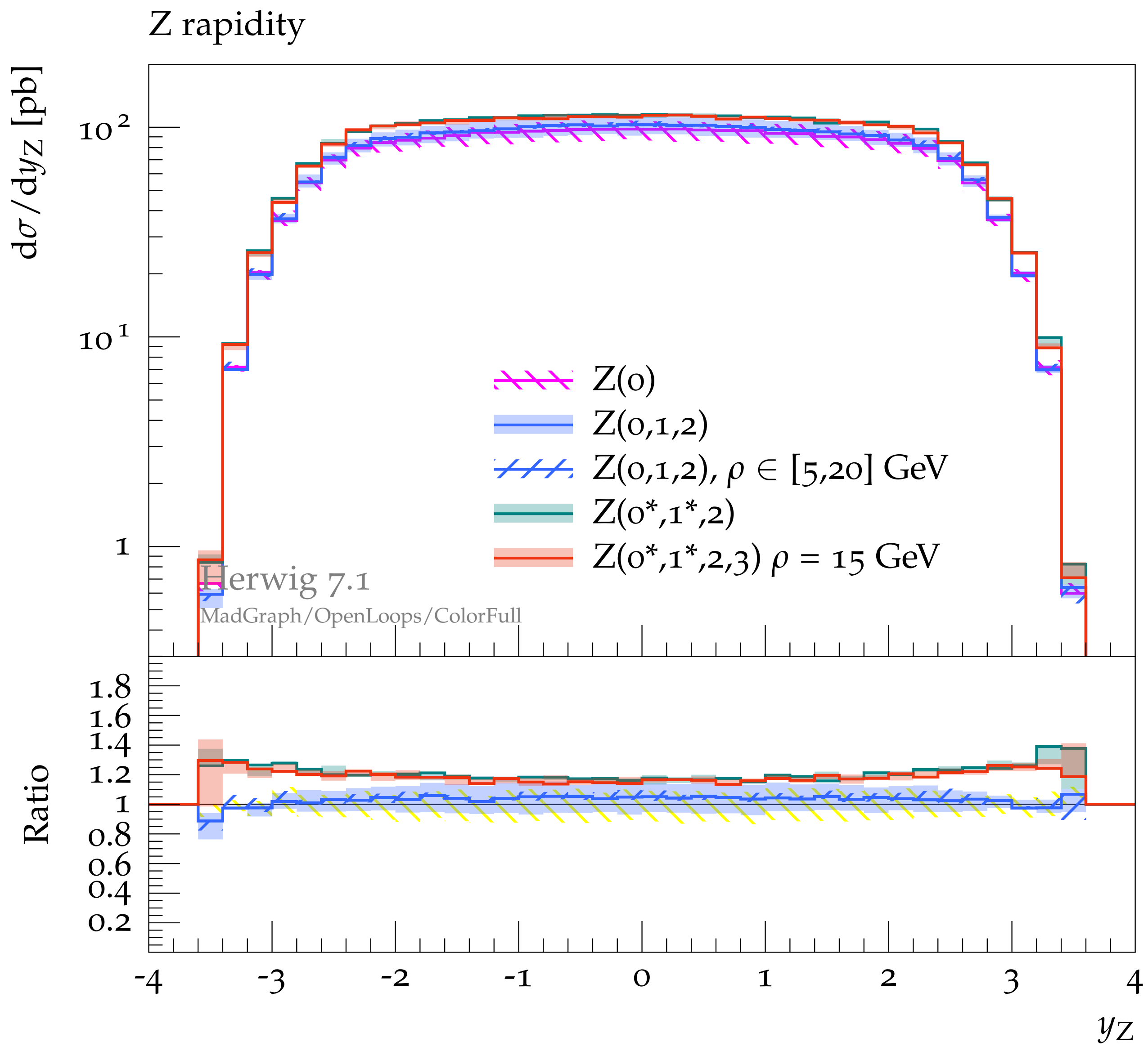


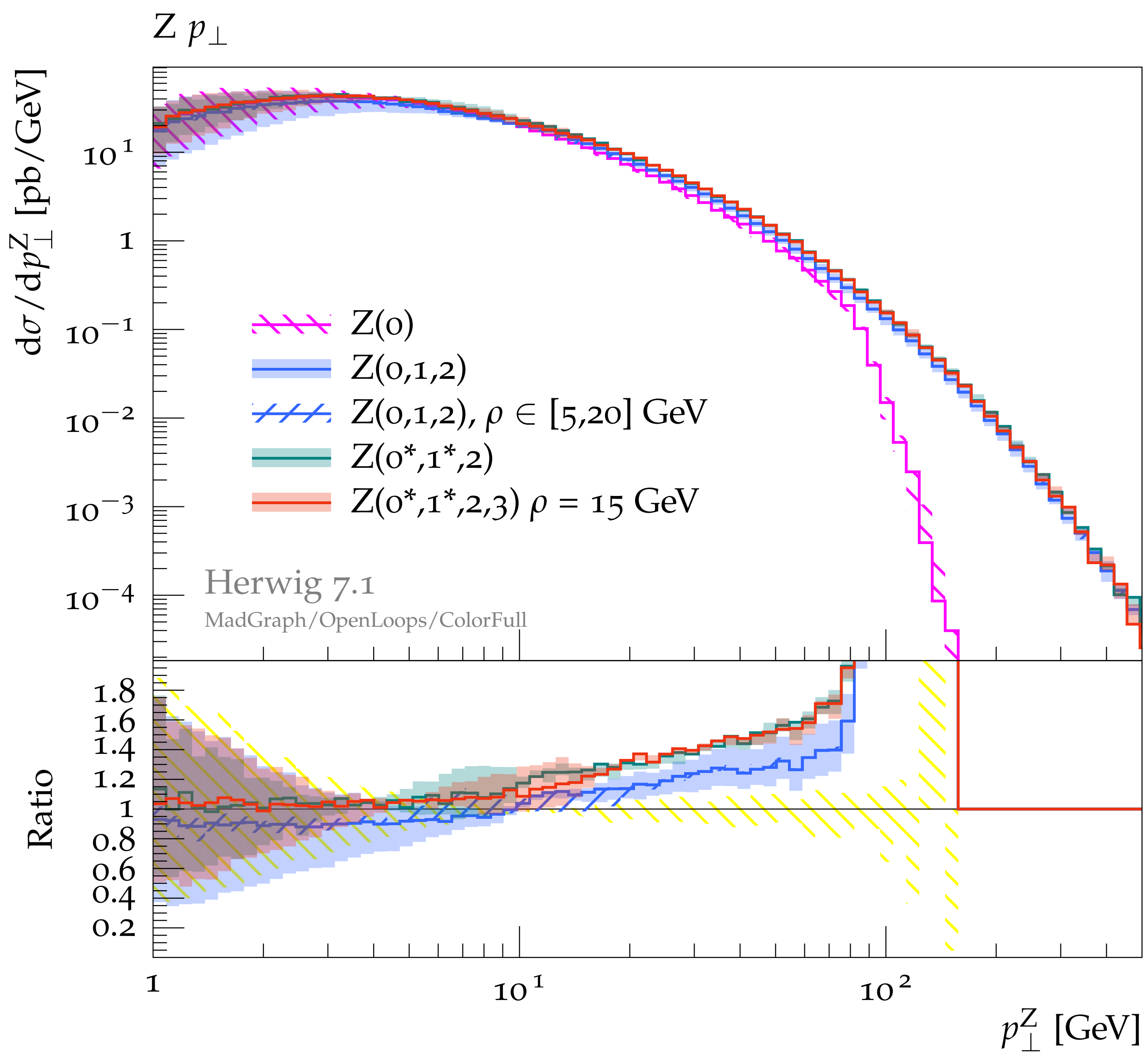

Mike Seymour
MC sim of QCD radiation

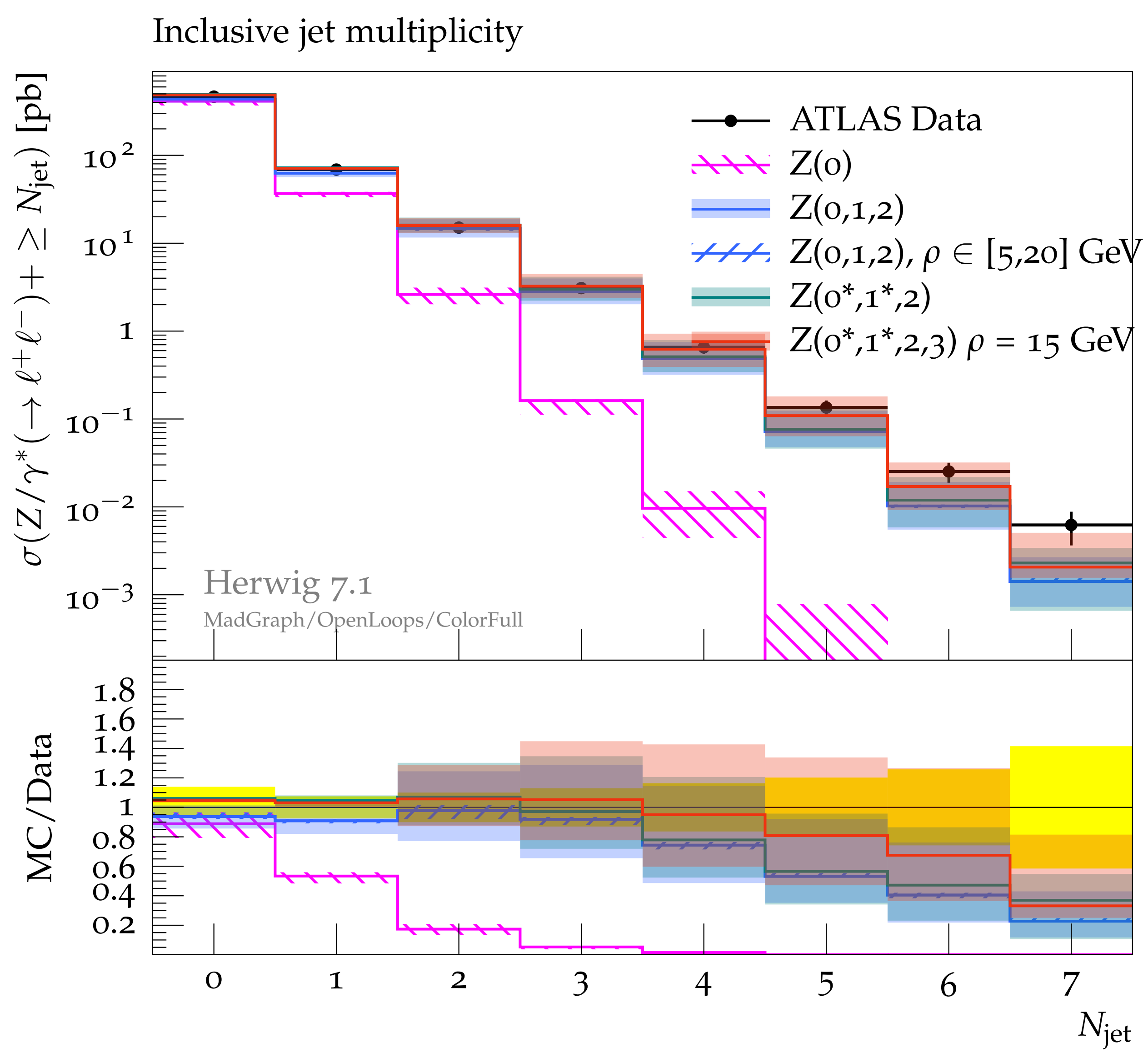
# Results: LHC Z+jets



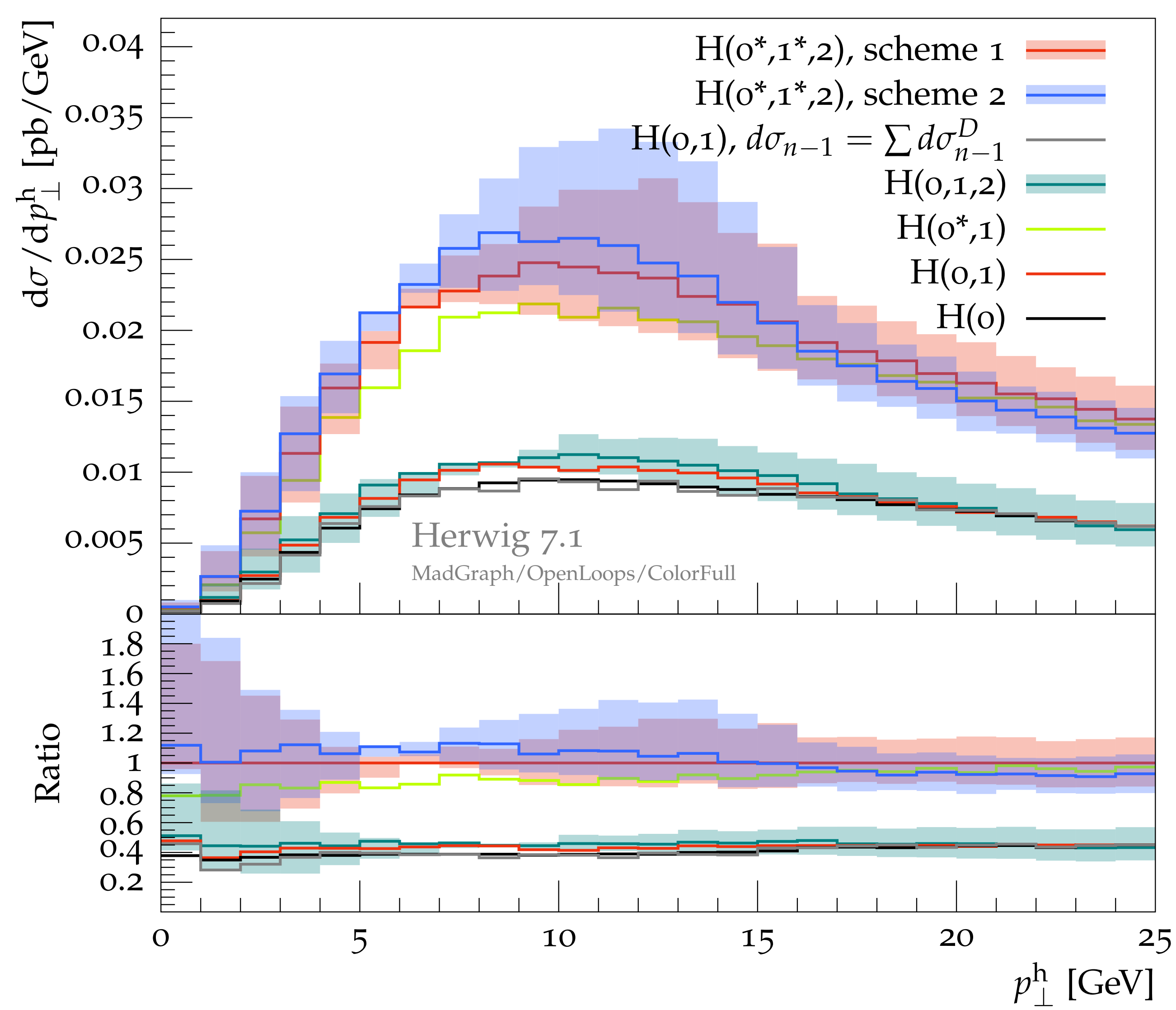



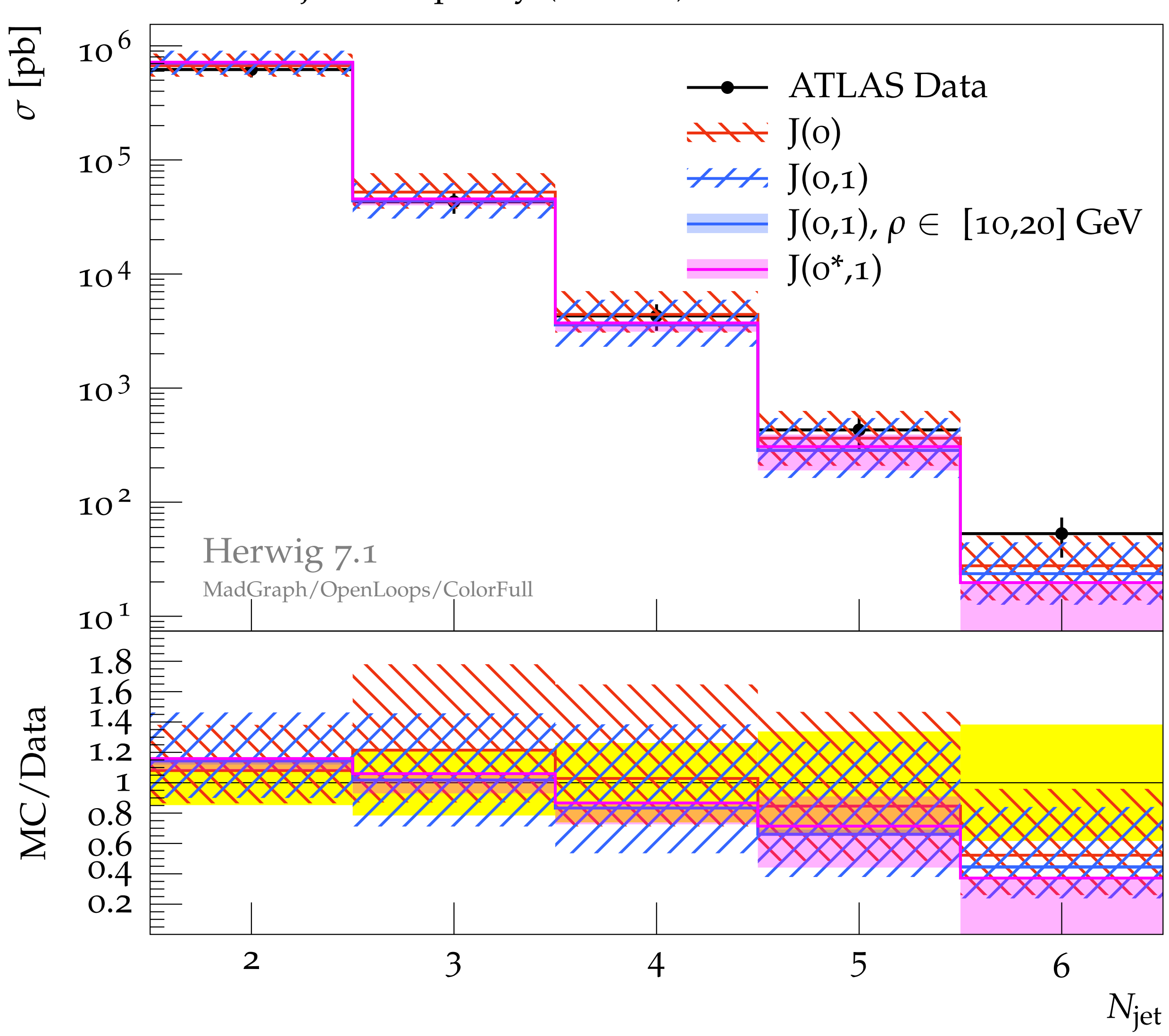
# Results: LHC Z+jets



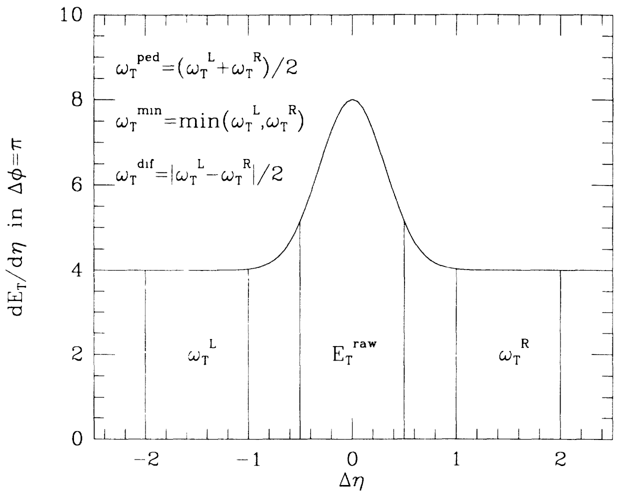



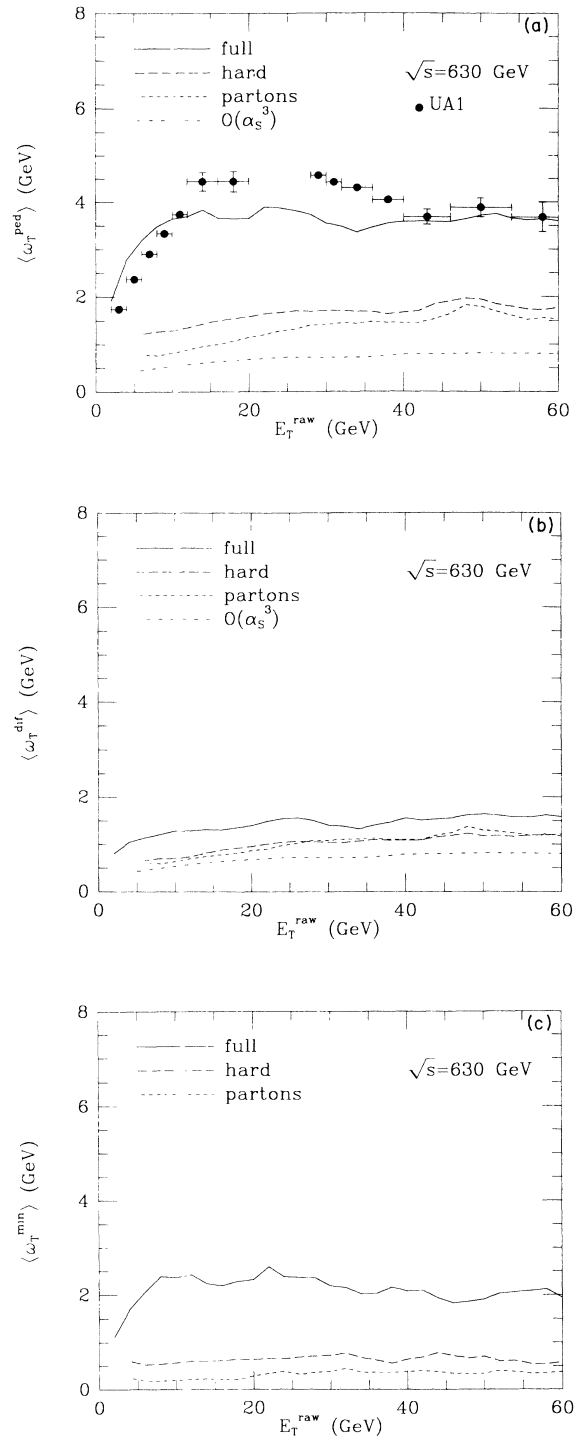
# Results: LHC Higgs+jets



# Herwig7: Soft Interactions and Diffraction




Associated Transverse Energy in Hadronic Jet Production
G. Marchesini and B.R. Webber
**Phys. Rev. D38 (1988) 3419**

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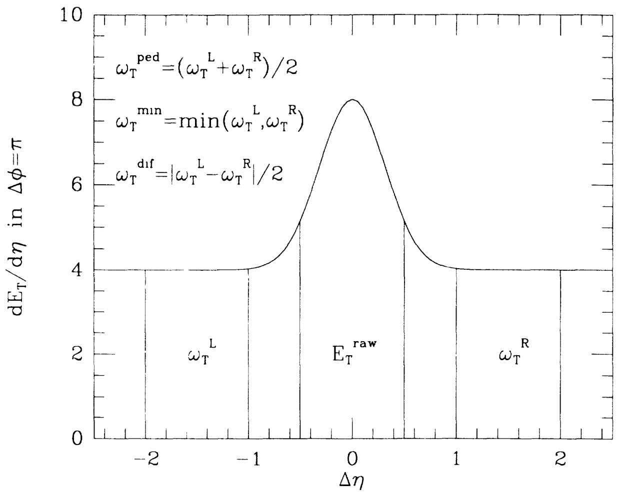


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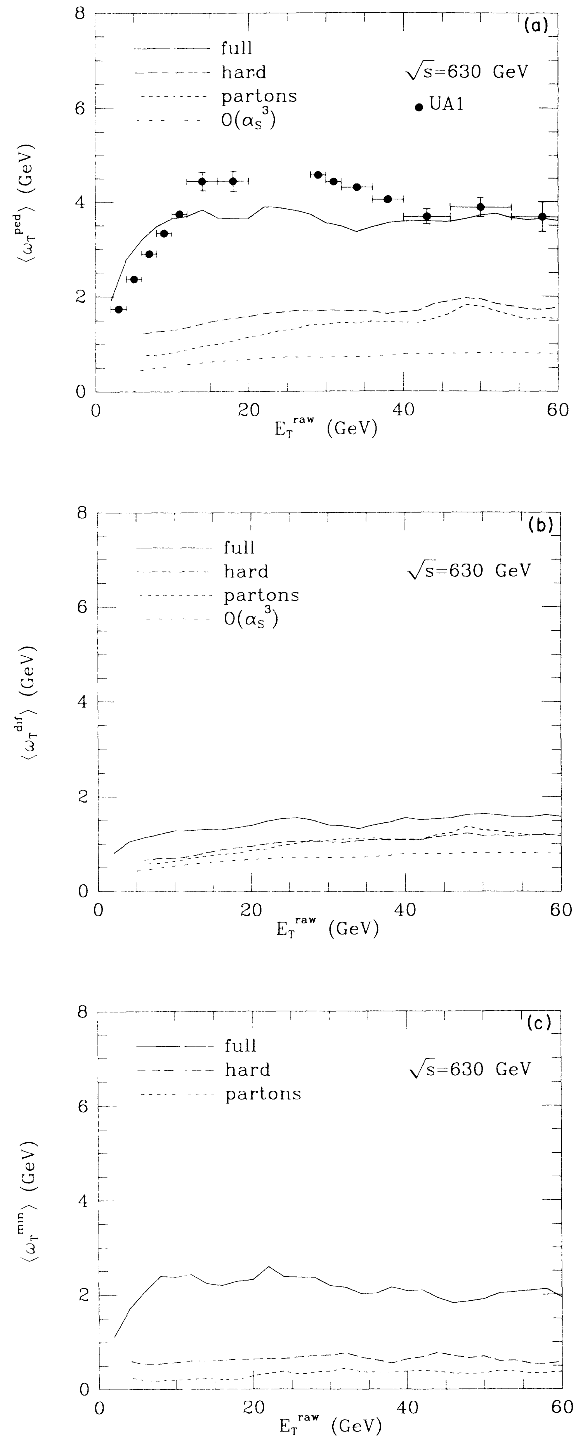
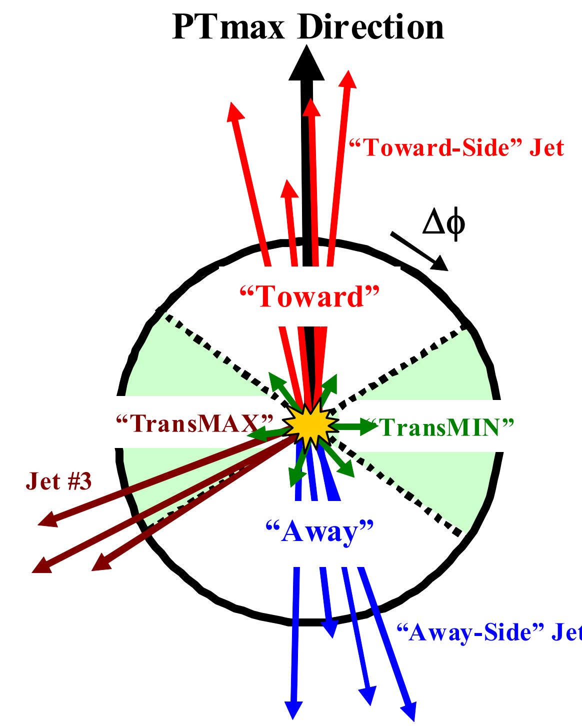



Rick Field/CDF/CMS
~2000



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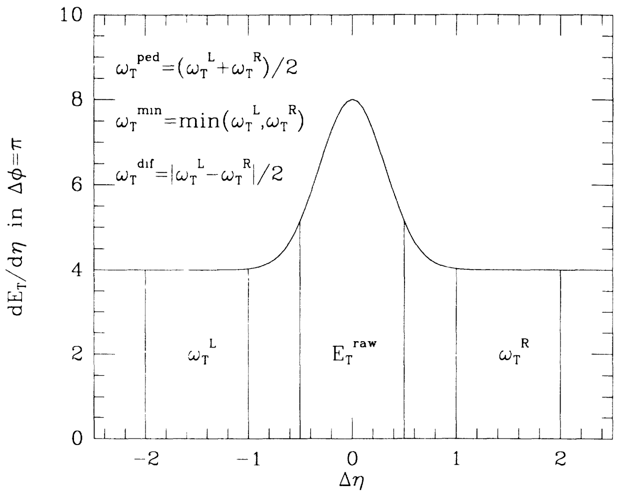


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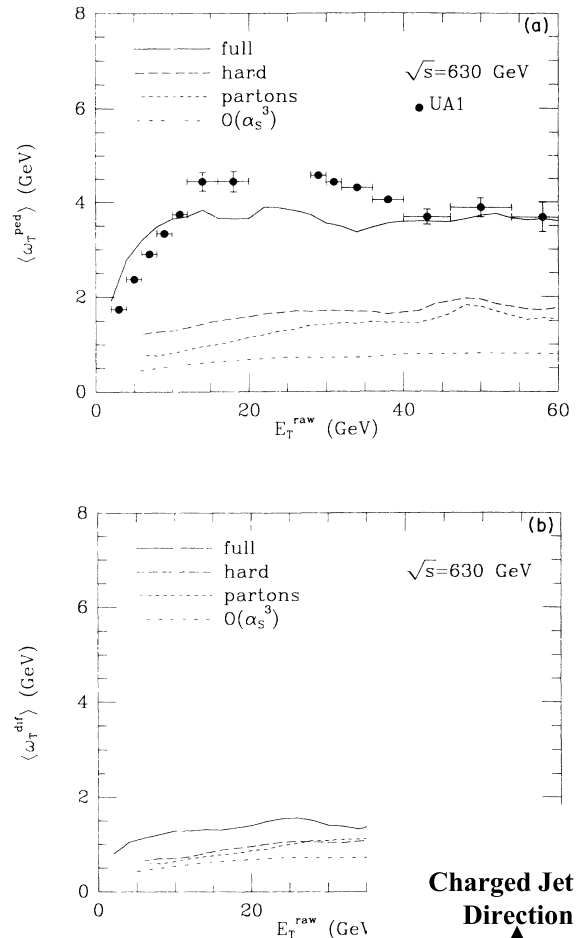
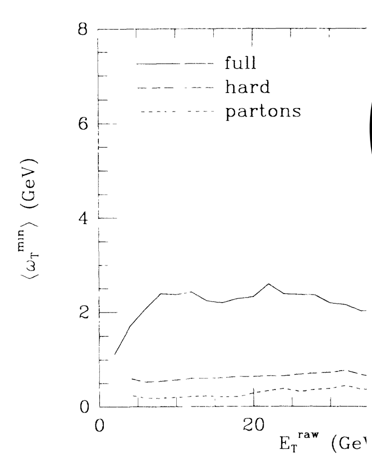
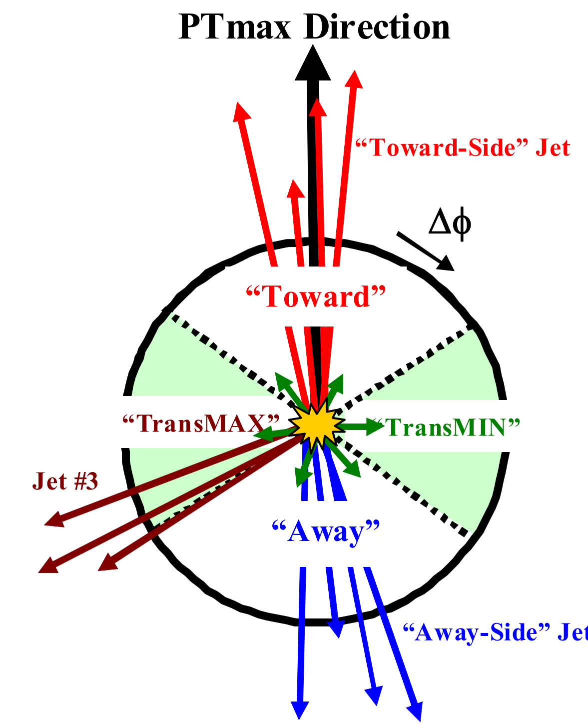
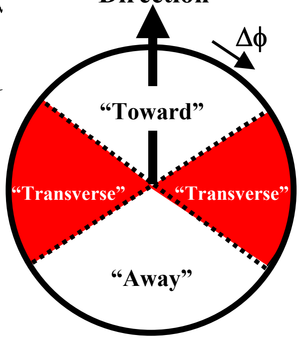
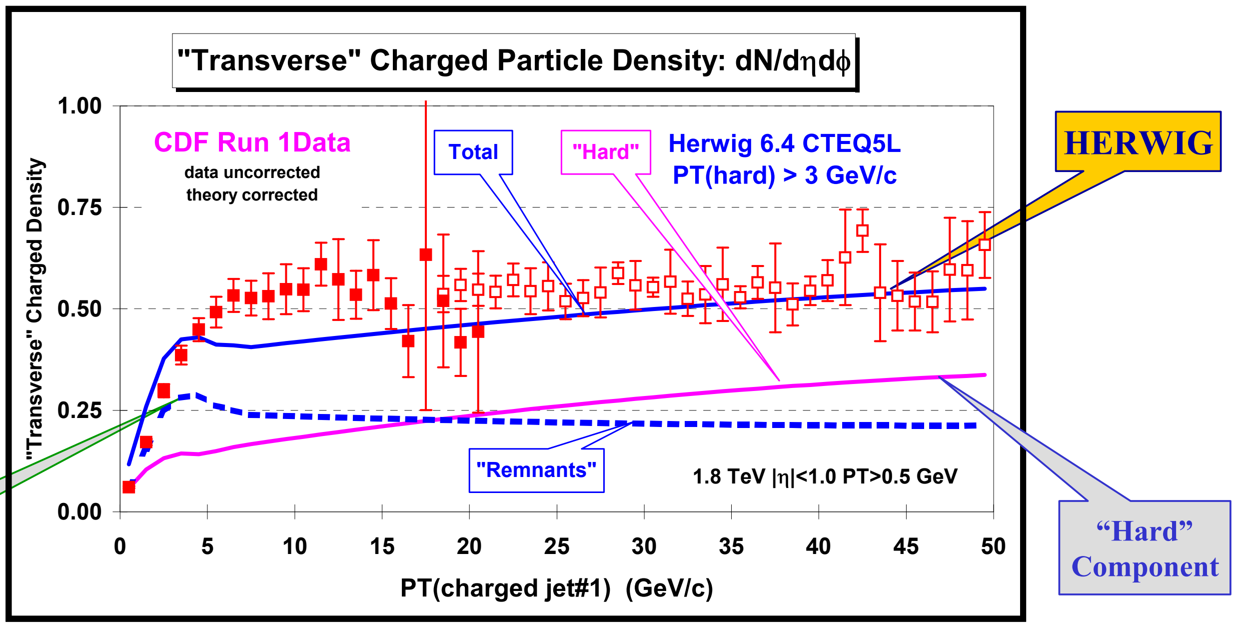



Rick Field/CDF/CMS ~2000



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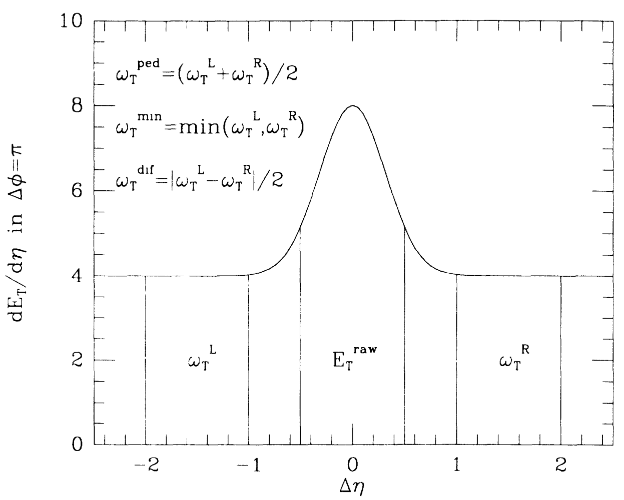


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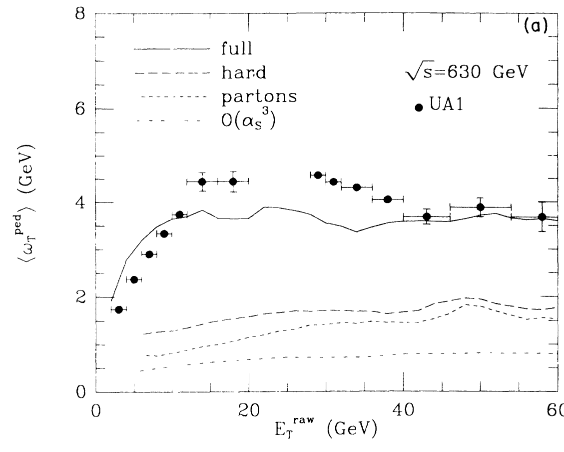
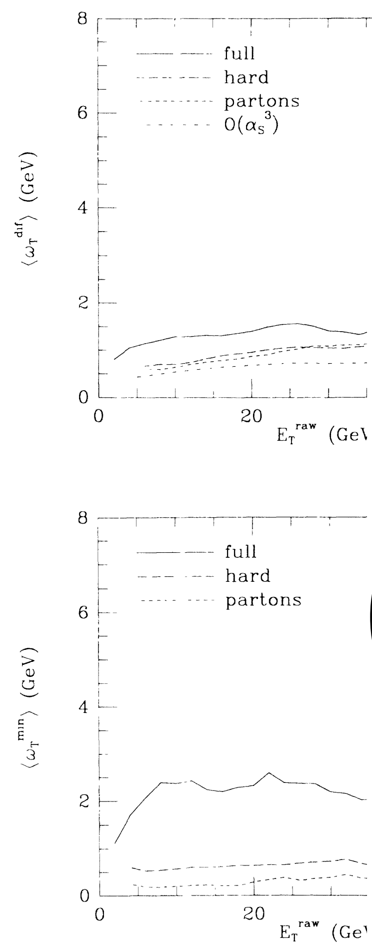
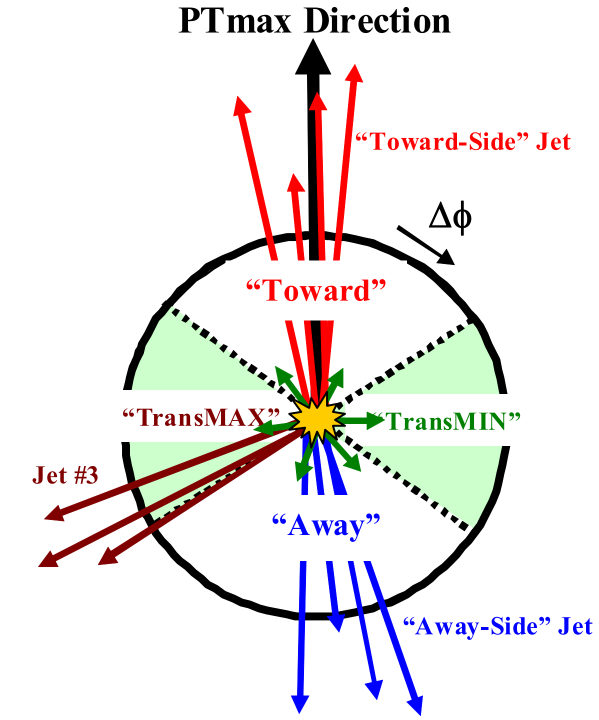
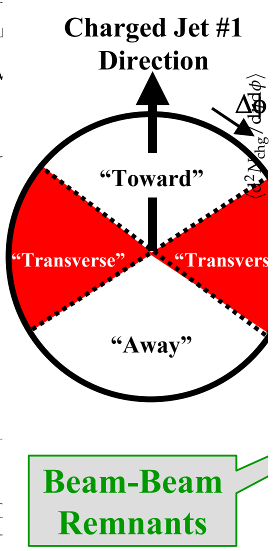
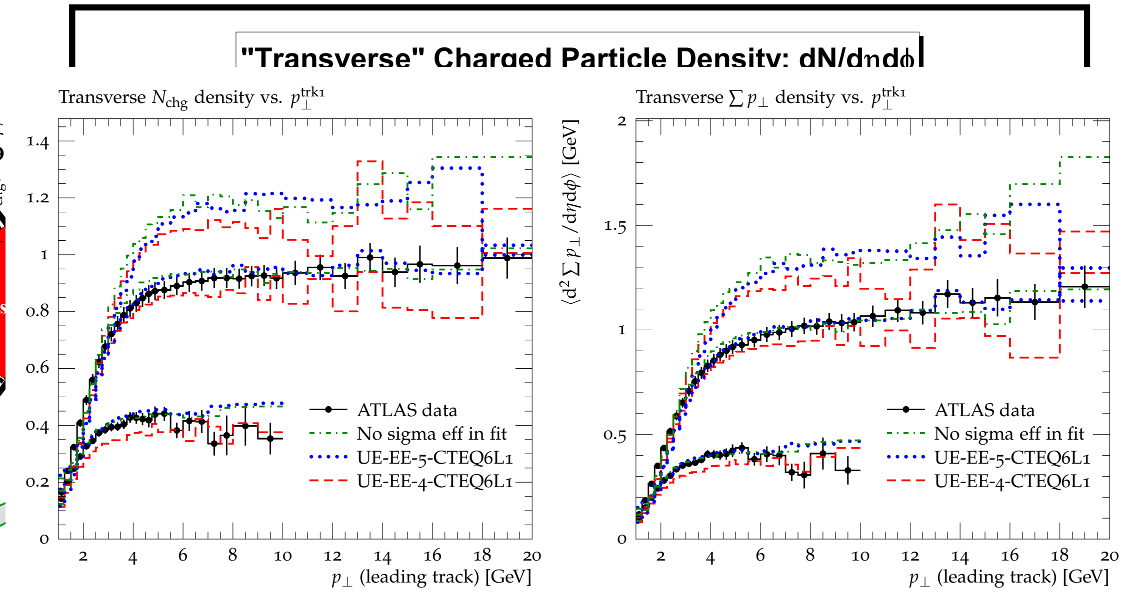



Rick Field/CDF/CMS
~2000

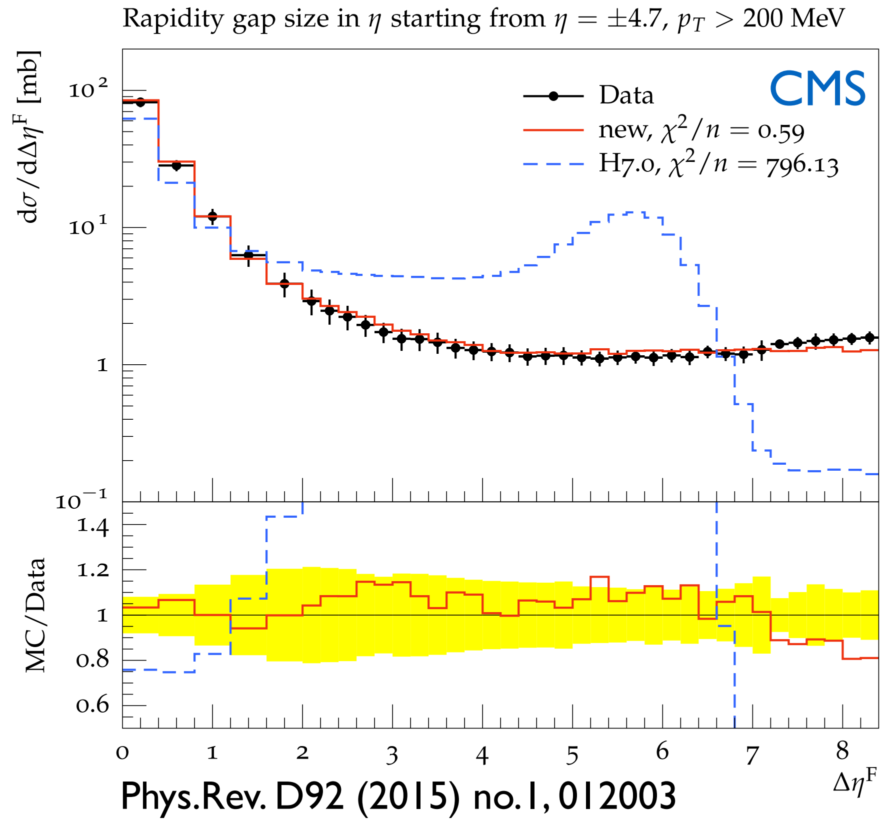


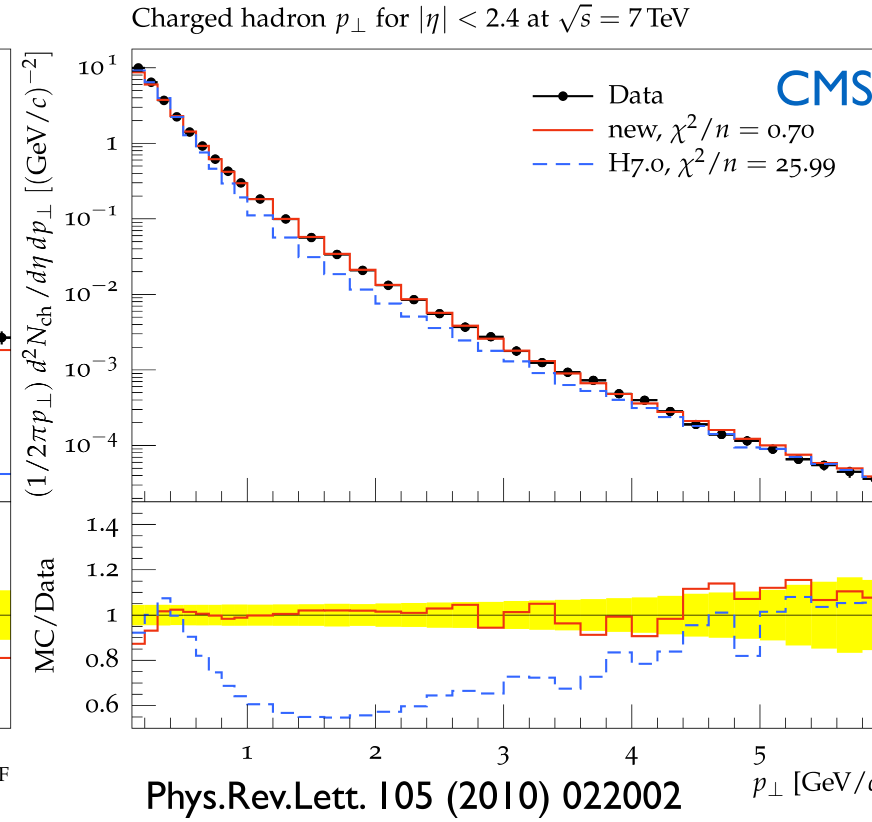




MHS & A. Siódmok
**JHEP 1310 (2013) 113**

# Herwig 7.1




Phys.Rev. D92 (2015) no.1, 012003

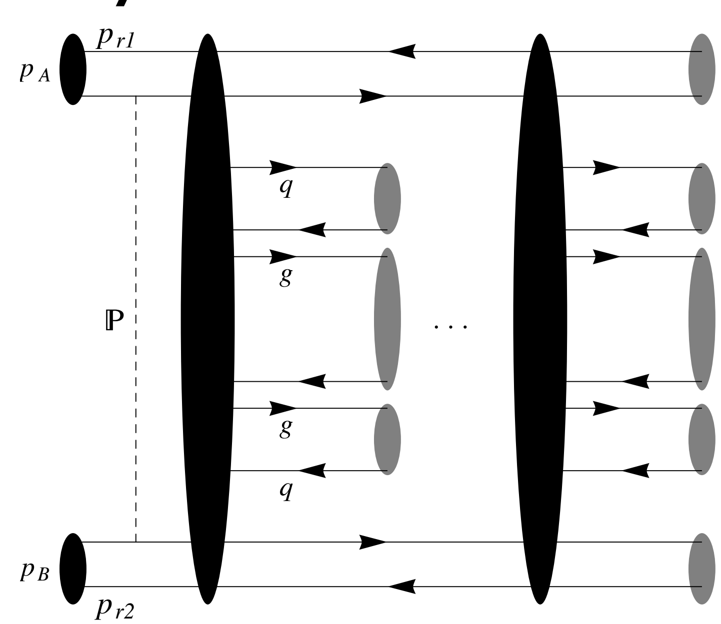


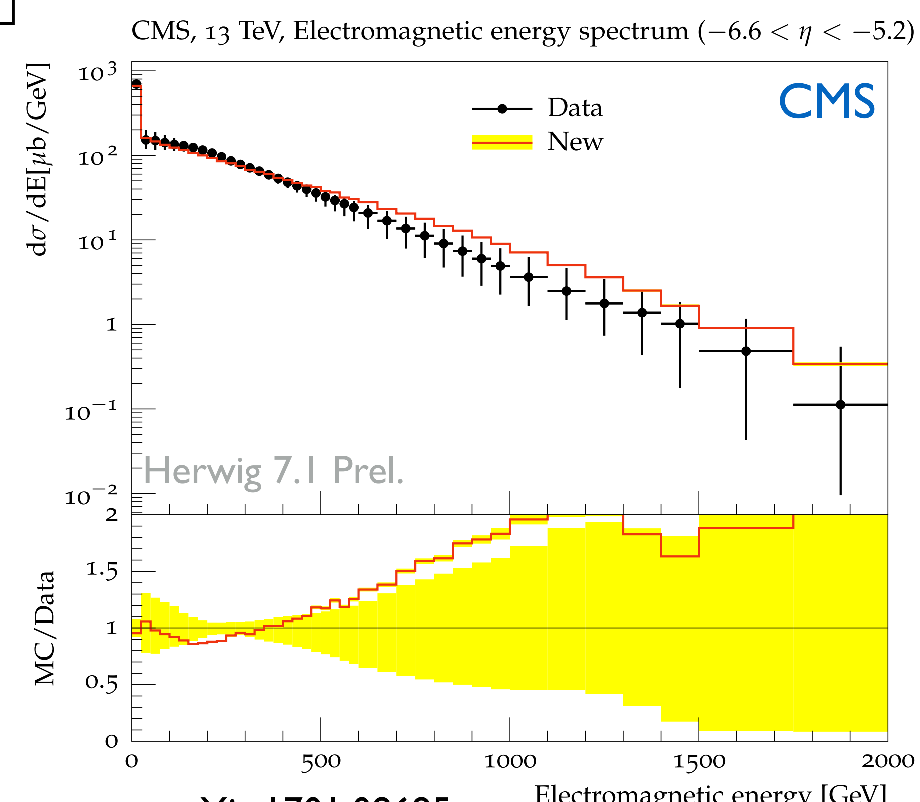

Phys.Rev.Lett. 105 (2010) 022002

Eur.Phys.J. C77 (2017) no.3, 156

S. Gieseke, F. Loshaj, P. Kirchgaeßer

- Ladders produce partons flat in rapidity
- Adding SD and DD for Plateau
- Motivated by Regge Theory
- Tuned to MinBias data
- New default Model




arXiv:1701.08695

# Summary: Thank you Pino!

For a remarkable partnership,
with a legacy that is thriving