# Event Simulation for the Large Hadron Collider

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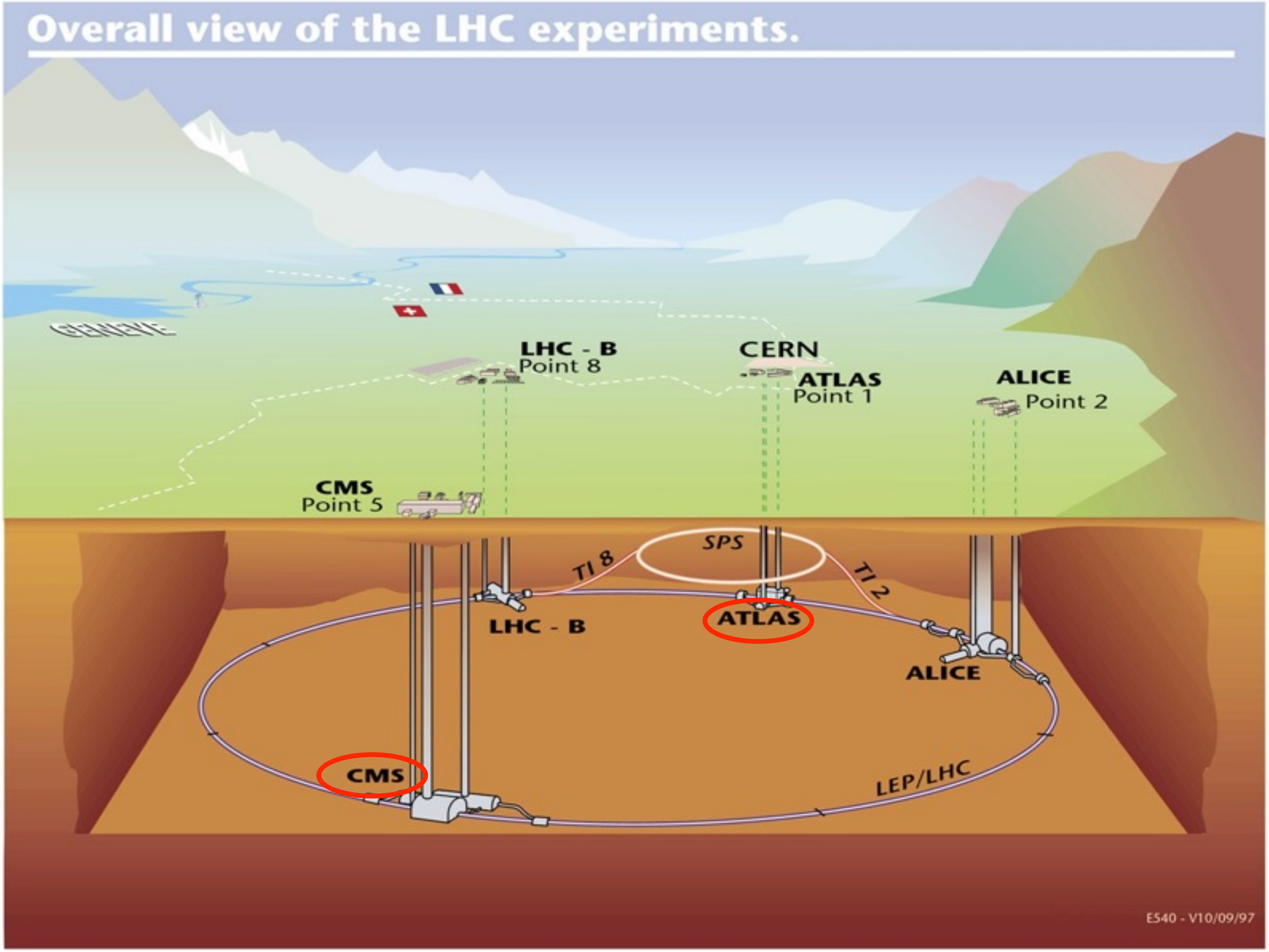
# Event Simulation for the Large Hadron Collider

- Monte Carlo event generation:
  - theoretical status and limitations
- Recent improvements:
  - perturbative and non-perturbative
- Overview of results:
  - W, Z, top, Higgs, … (+jets)

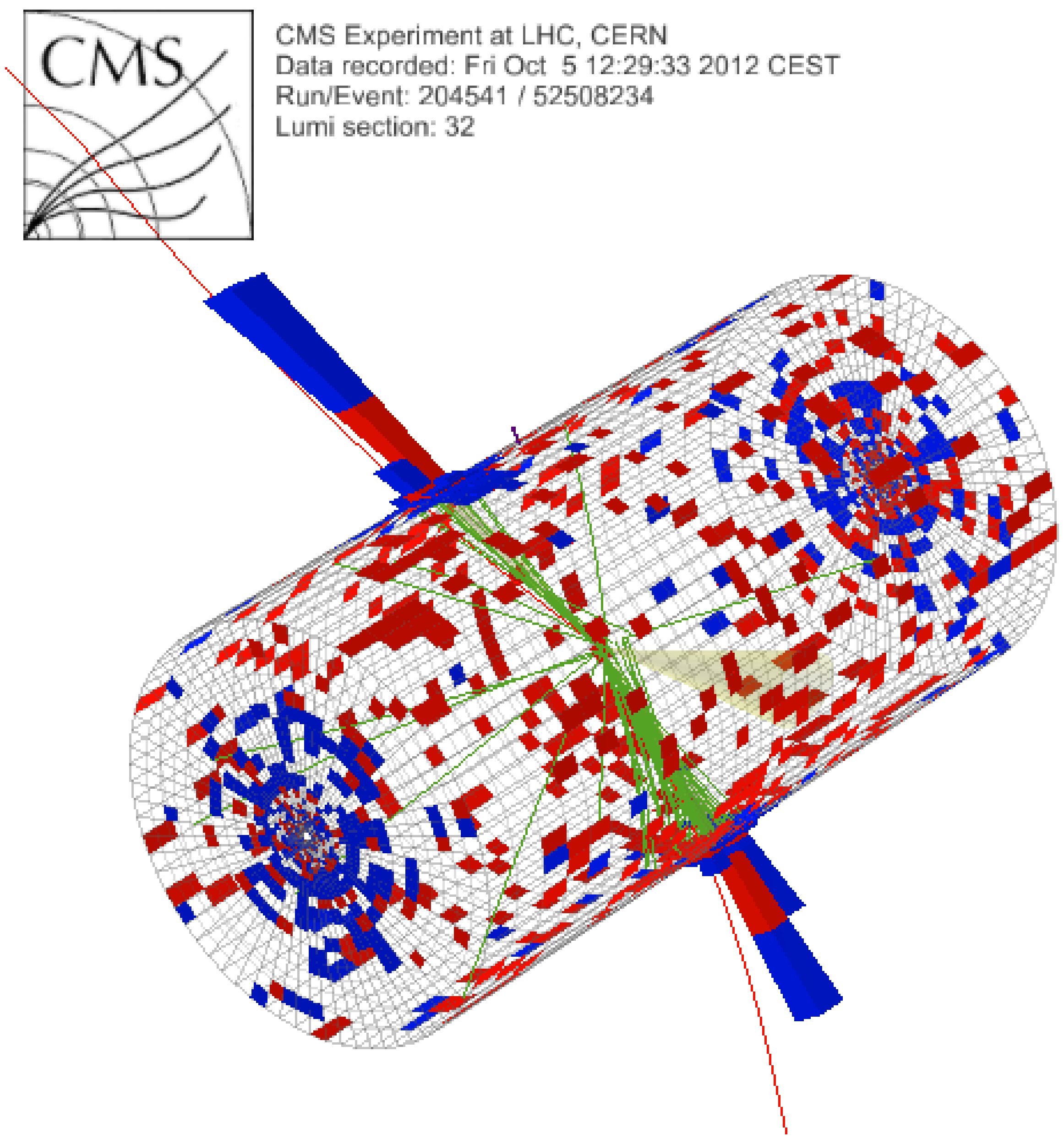
# Monte Carlo Event Generation

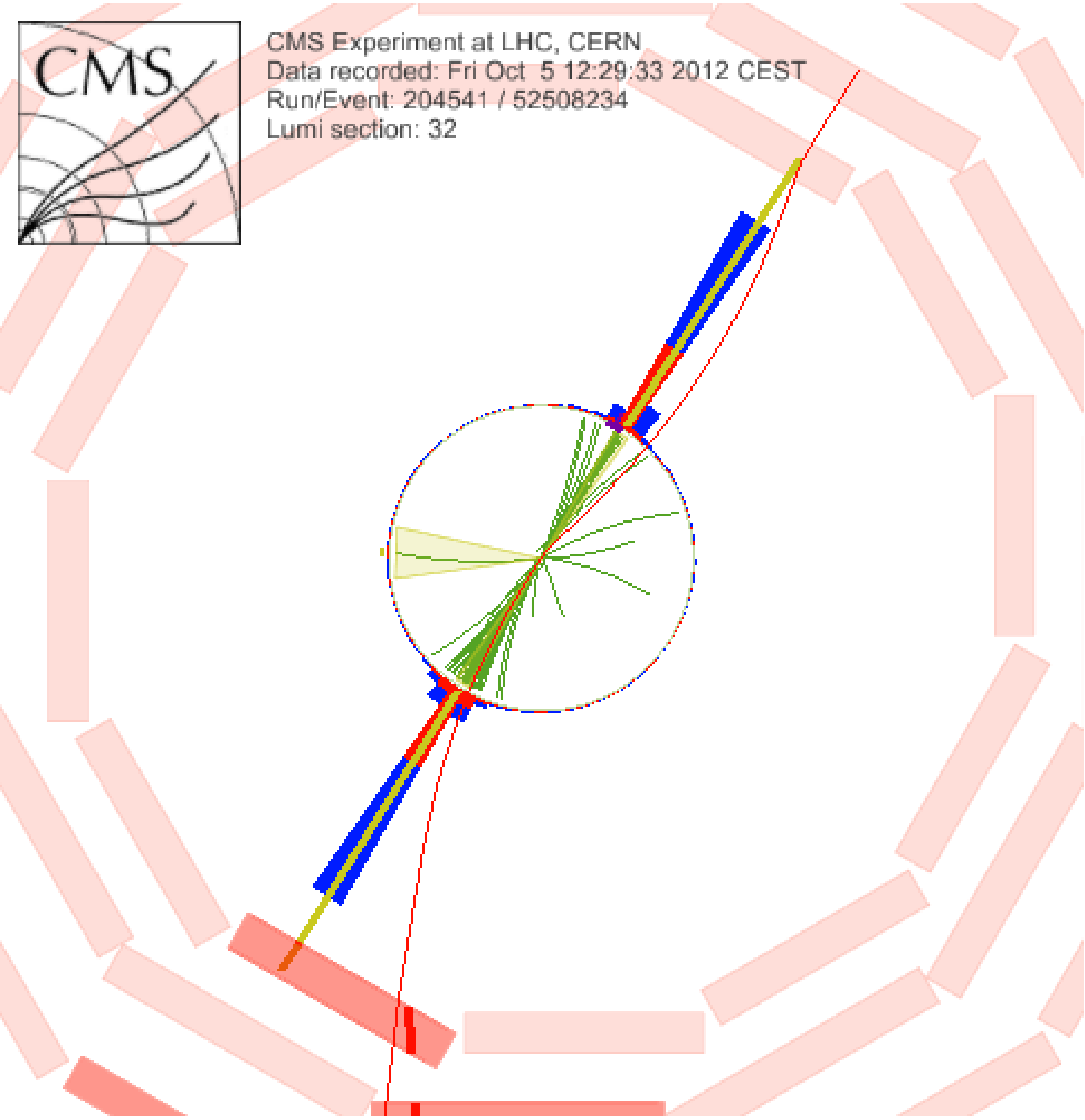
# Monte Carlo Event Generation

- Aim is to produce simulated (particle-level) datasets like those from real collider events
  - i.e. lists of particle identities, momenta, ...
  - simulate quantum effects by (pseudo)random numbers
- Essential for:
  - Designing new experiments and data analyses
  - Correcting for detector and selection effects
  - Testing the Standard Model and measuring its parameters
  - Estimating new signals and their backgrounds


Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
E540 - V10/09/97

# A high-mass dijet event

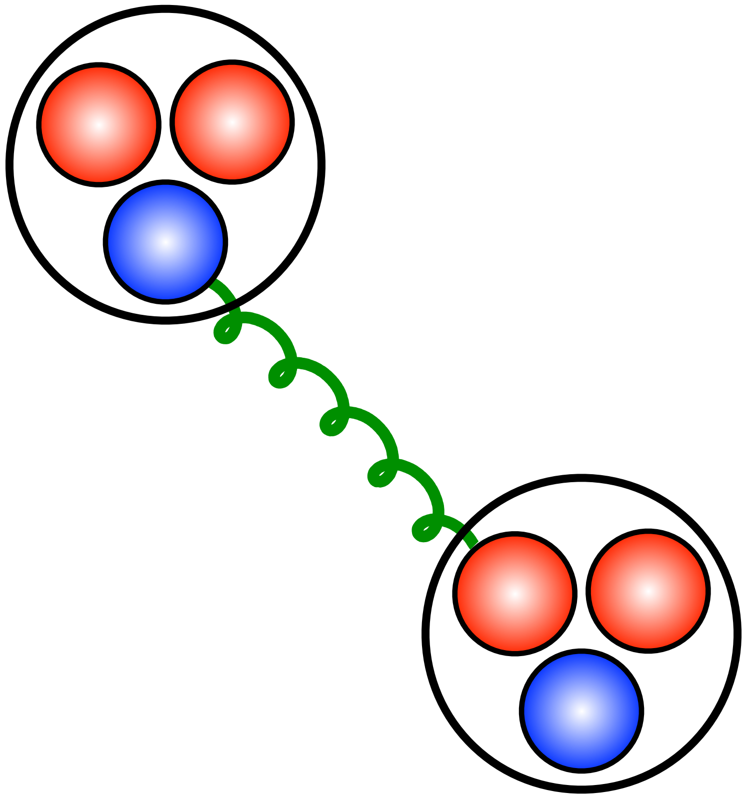



- $M_{jj}$ = 5.15 TeV

CMS PAS EXO-12-059

# LHC Dijet



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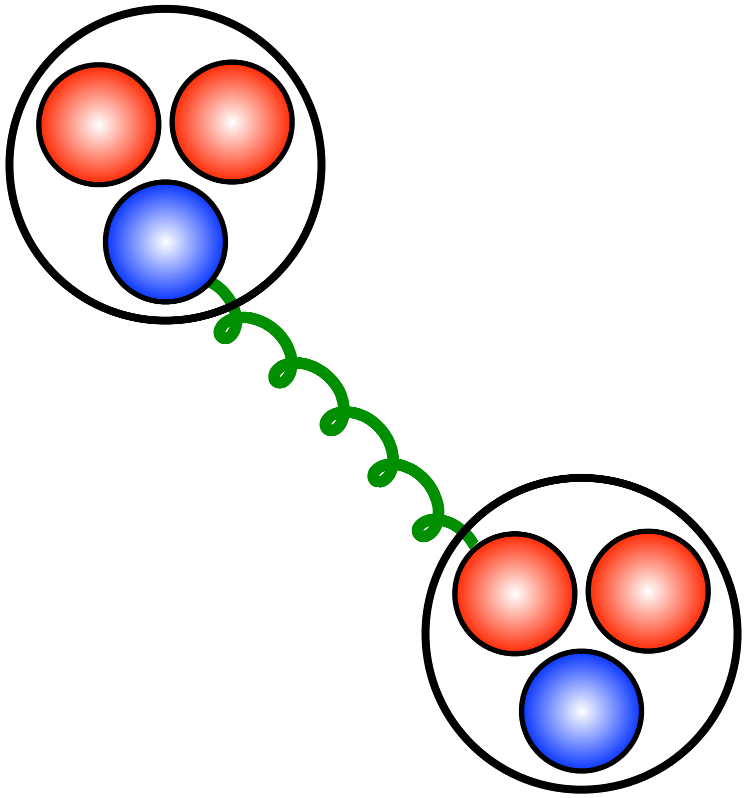

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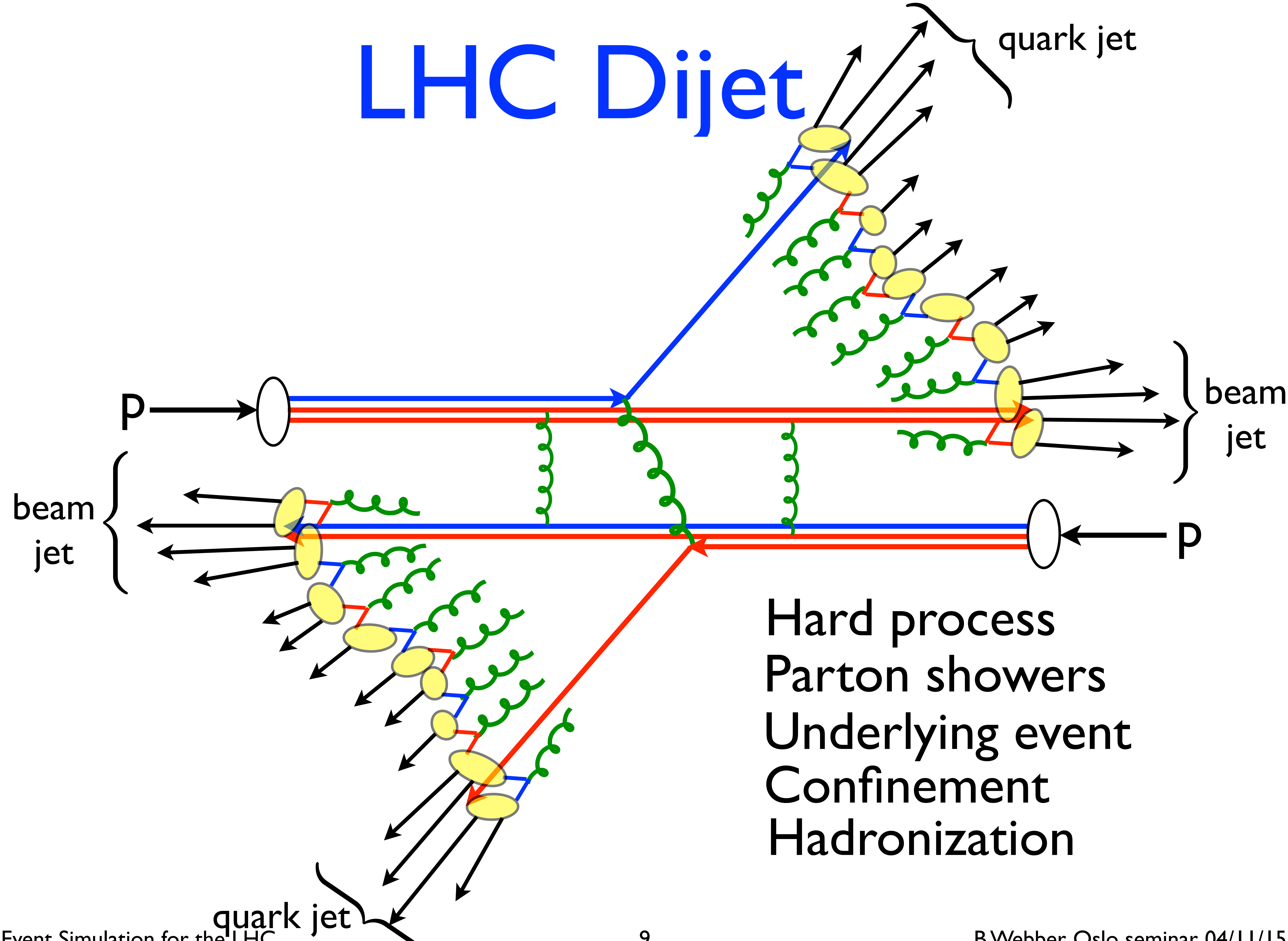
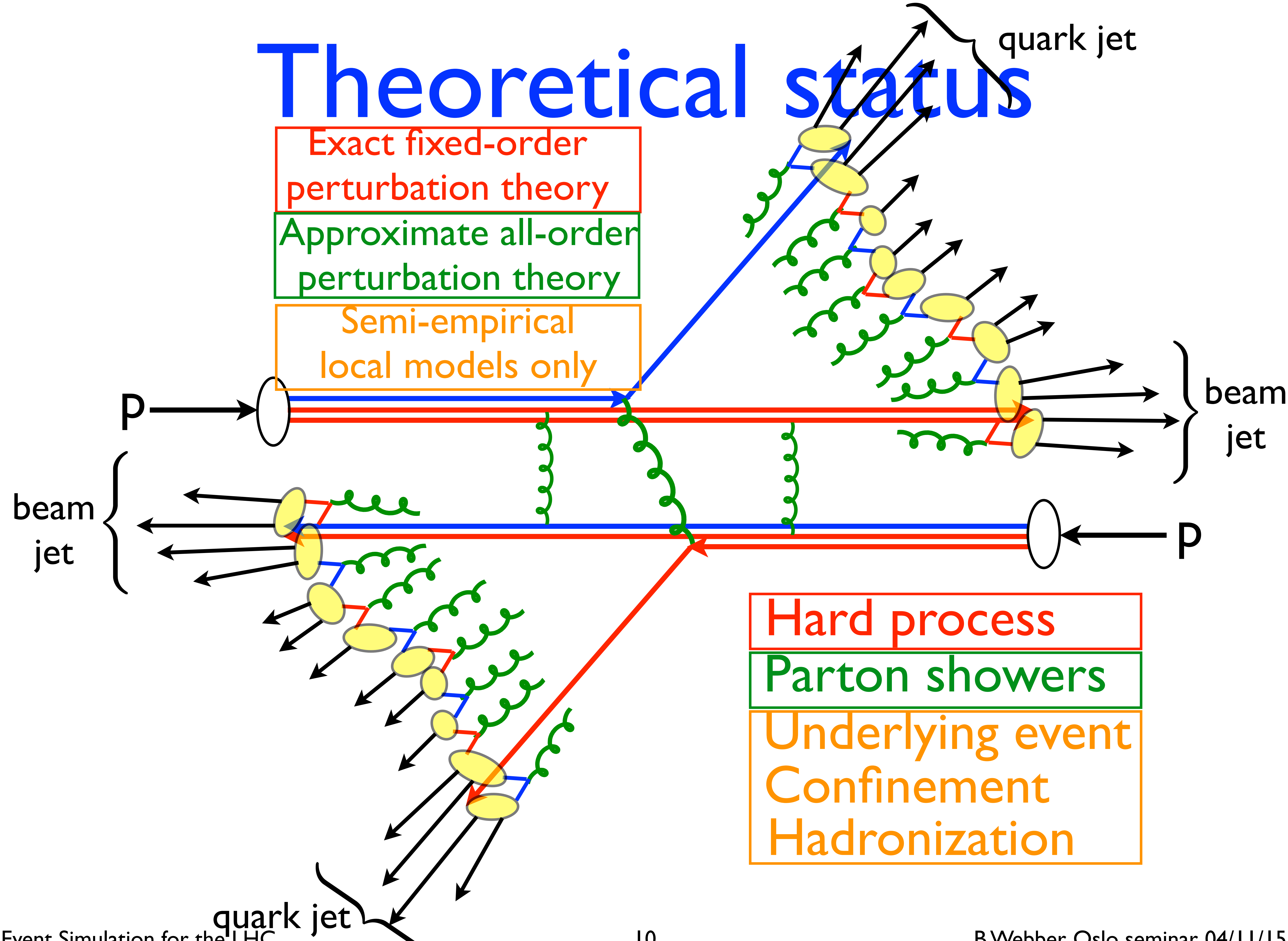



Hard process
Parton showers
Underlying event
Confinement
Hadronization

# Theoretical status



# QCD Factorization

$$\sigma_{pp\to X}(E_{pp}^2) = \int_0^1 \underbrace{dx_1\, dx_2}_{\text{momentum fractions}}\, \underbrace{f_i(x_1,\mu^2)\, f_j(x_2,\mu^2)}_{\text{parton distributions at scale } \mu^2}\, \underbrace{\hat{\sigma}_{ij\to X}(x_1 x_2 E_{pp}^2, \mu^2)}_{\text{hard process cross section}}$$

momentum fractions

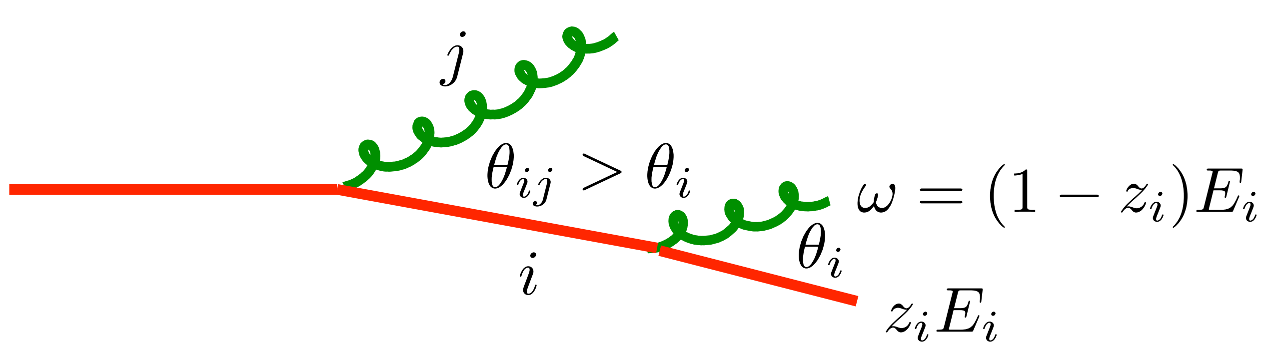
parton distributions at scale $\mu^2$

hard process cross section

- Jet formation and underlying event take place over a much longer time scale, with unit probability
- Hence they cannot affect the cross section
- Scale dependences of parton distributions and hard process cross section are perturbatively calculable, and cancel order by order

# Parton Shower Approximation

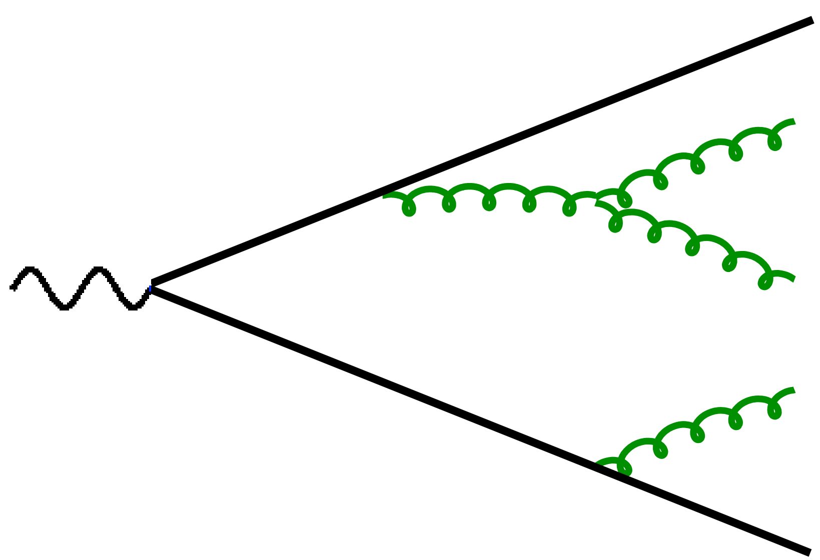
- Keep only most singular parts of QCD matrix elements:
- Collinear $$d\sigma_{n+1} \approx \frac{\alpha_S}{2\pi}\sum_i P_{ii}(z_i,\phi_i)\,dz_i\,\frac{d\xi_i}{\xi_i}\frac{d\phi_i}{2\pi}d\sigma_n \qquad \xi_i = 1-\cos\theta_i$$
- Soft $$\begin{aligned} d\sigma_{n+1} &\approx \frac{\alpha_S}{2\pi}\sum_{i,j}(-\mathbf{T}_i\cdot\mathbf{T}_j)\frac{p_i\cdot p_j}{p_i\cdot k\,p_j\cdot k}\omega\,d\omega\,d\xi_i\,\frac{d\phi_i}{2\pi}d\sigma_n \\ &= \frac{\alpha_S}{2\pi}\sum_{i,j}(-\mathbf{T}_i\cdot\mathbf{T}_j)\frac{\xi_{ij}}{\xi_i\,\xi_j}\frac{d\omega}{\omega}d\xi_i\,\frac{d\phi_i}{2\pi}d\sigma_n \\ &\approx \frac{\alpha_S}{2\pi}\sum_{i,j}(-\mathbf{T}_i\cdot\mathbf{T}_j)\,\Theta(\xi_{ij}-\xi_i)\frac{d\omega}{\omega}\frac{d\xi_i}{\xi_i}d\sigma_n \end{aligned}$$




→ Angular-ordered parton shower (or dipoles)

# Hadronization Models

- In parton shower, relative transverse momenta evolve from a high scale Q towards lower values
- At a scale near $\Lambda_{QCD}$~200 MeV, perturbation theory breaks down and hadrons are formed
- Before that, at scales $Q_0$ ~ few x $\Lambda_{QCD}$, there is universal preconfinement of colour
- Colour, flavour and momentum flows are only locally redistributed by hadronization



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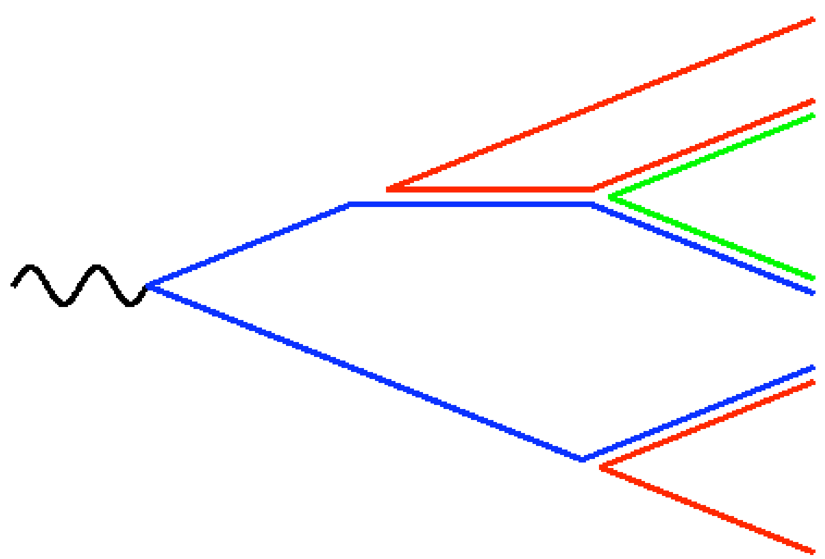

# String Hadronization Model

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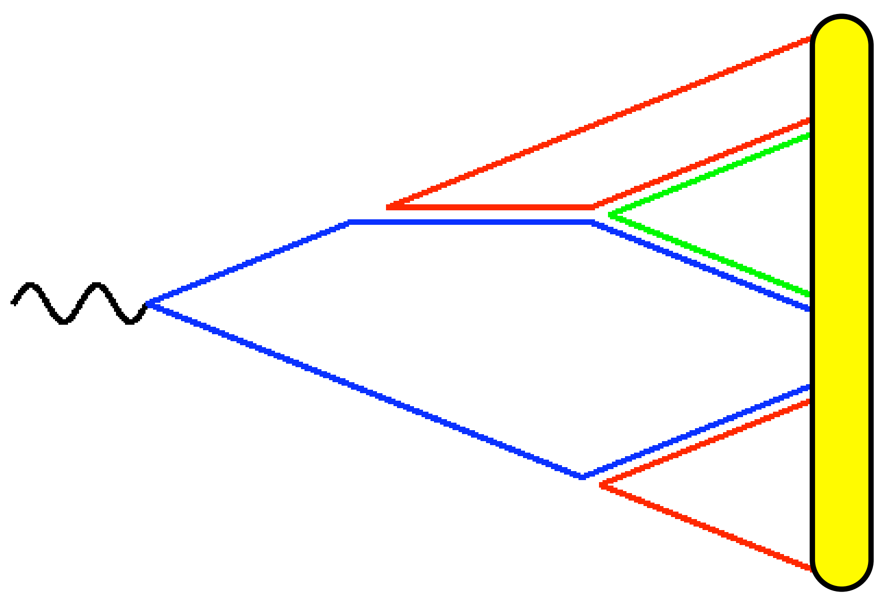
- Colour flow dictates how to connect hadronic string (width ~ few x $\Lambda_{QCD}$) with shower



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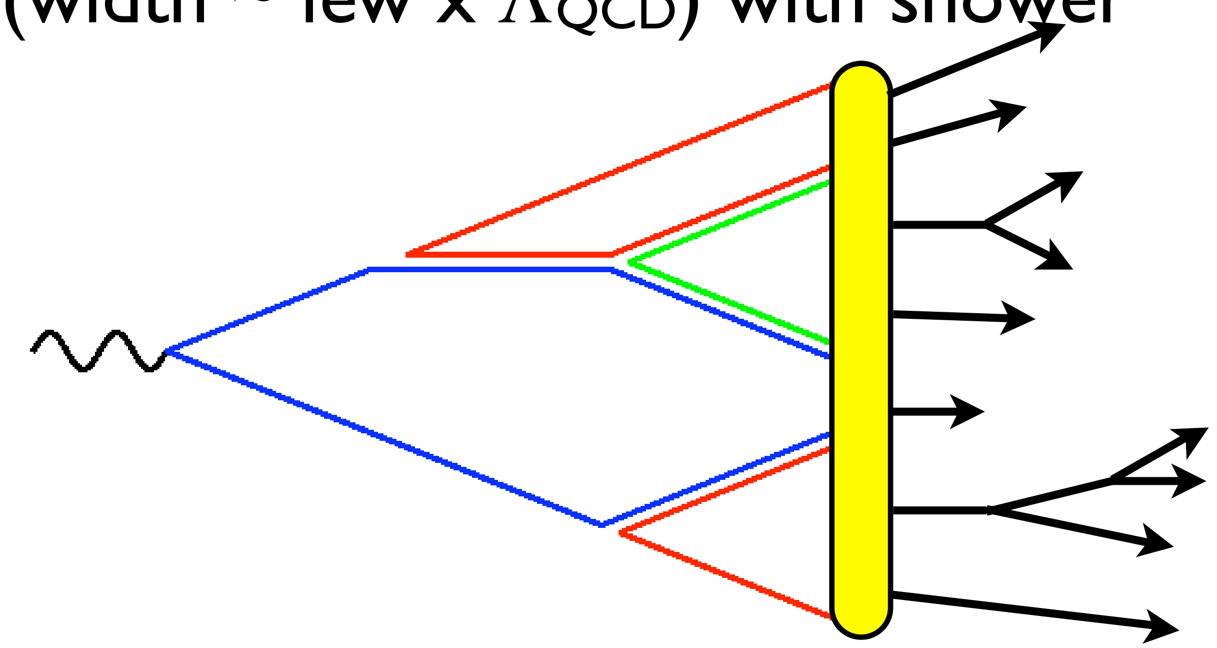

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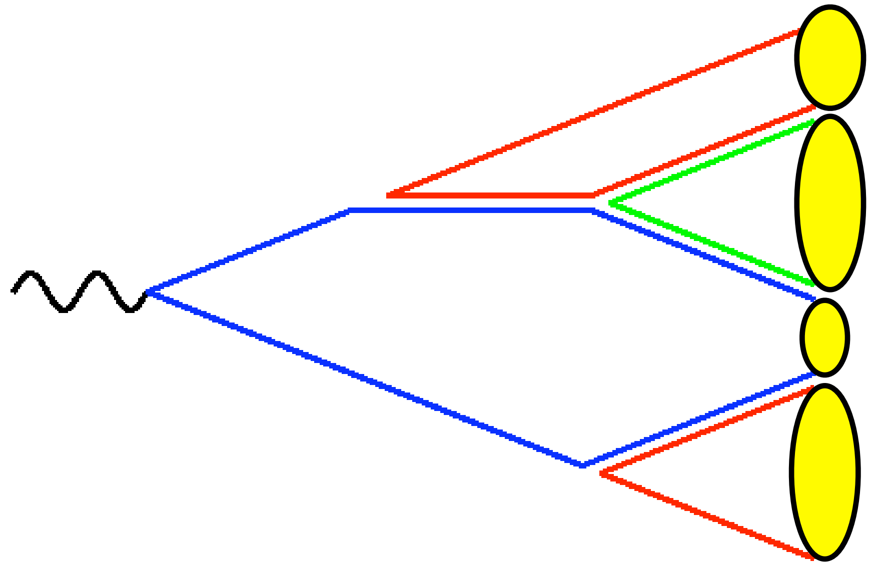
- Decay of preconfined clusters provides a direct basis for hadronization



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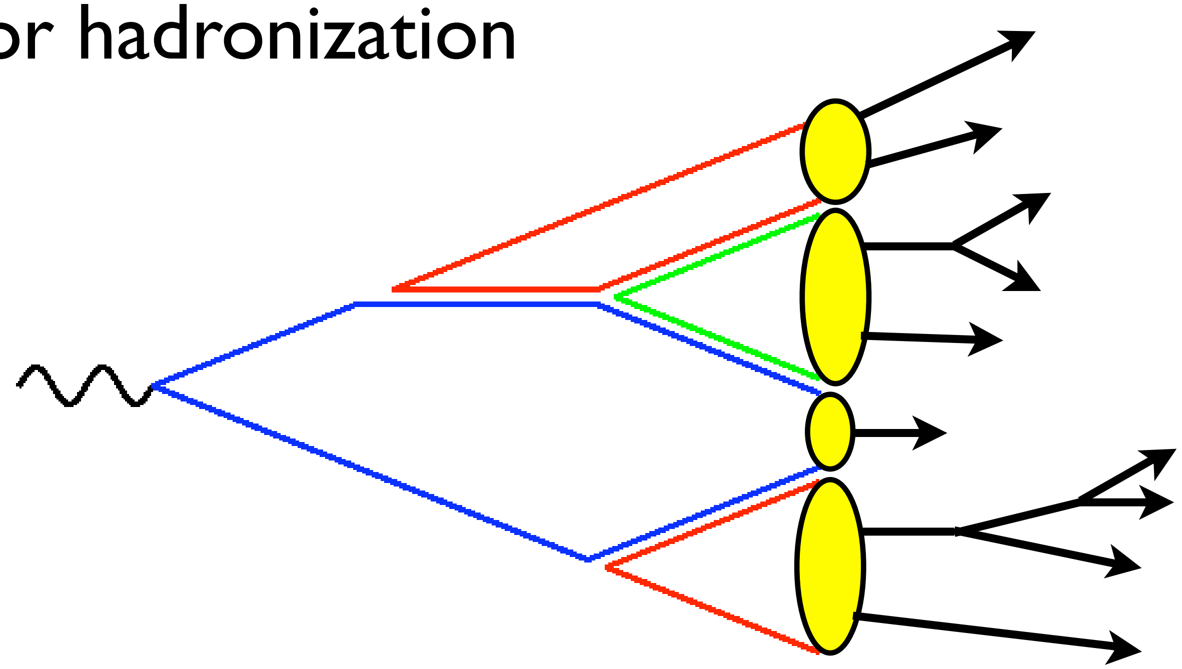

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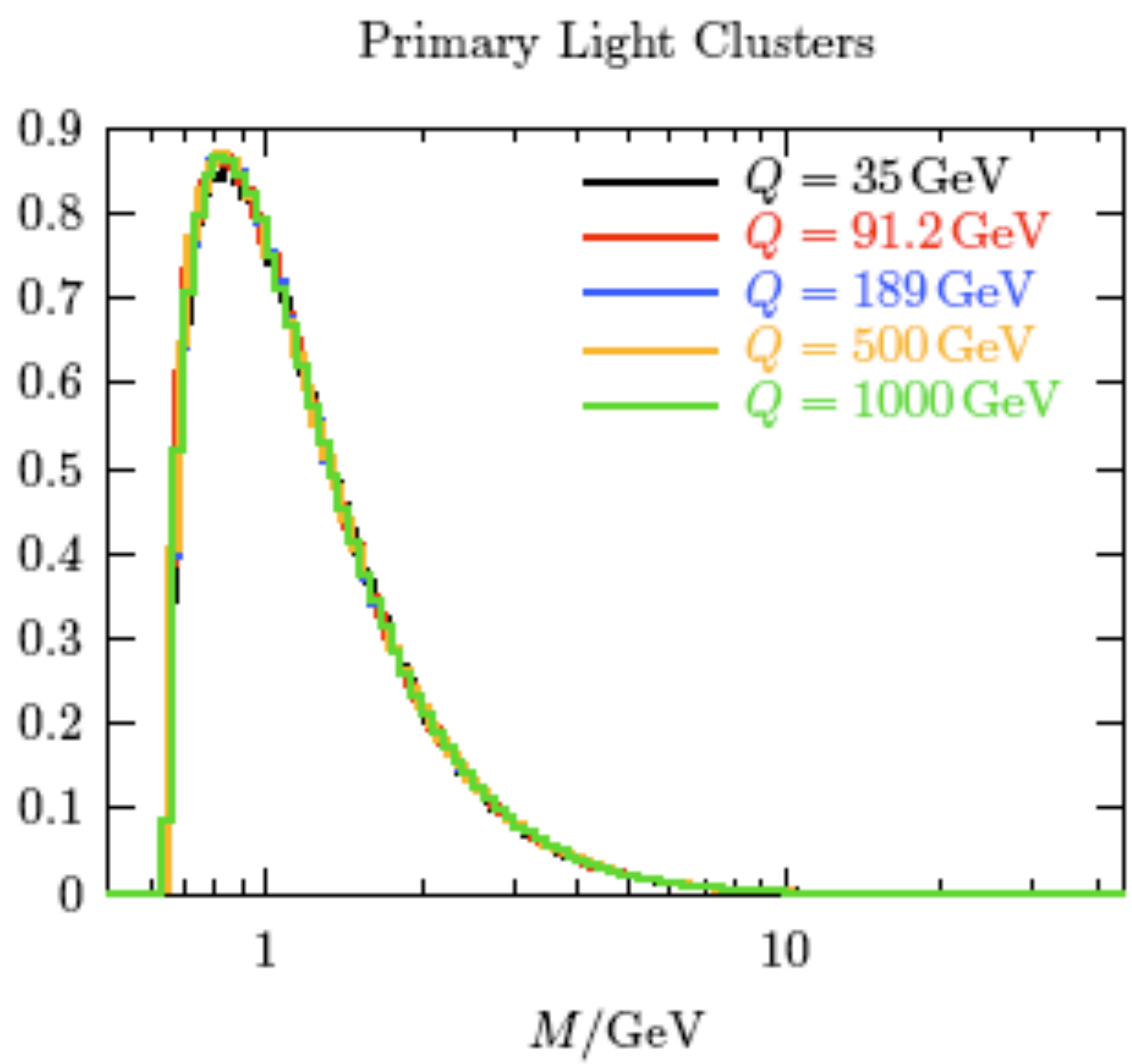
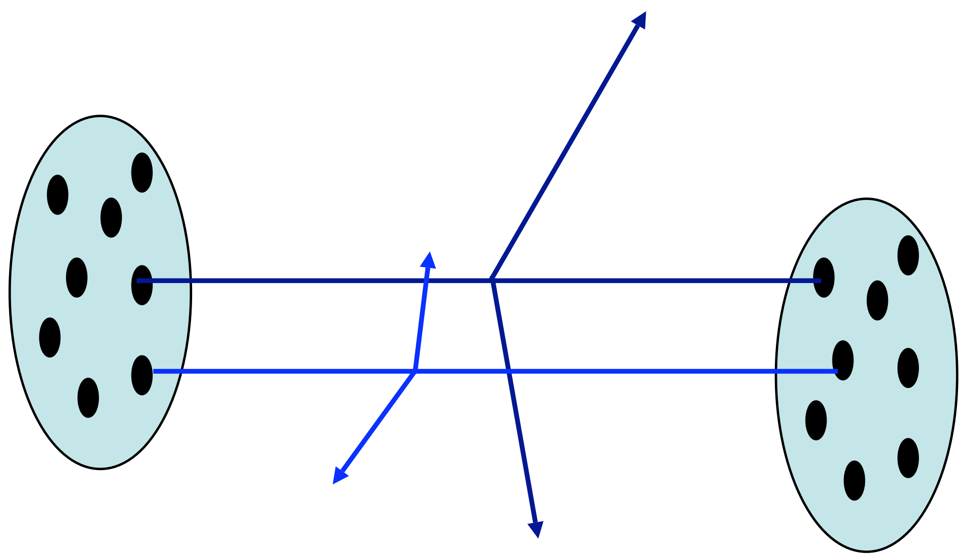



- Mass distribution of preconfined clusters is universal
- Phase-space decay model for most clusters
- High-mass tail decays anisotropically (string-like)

# Hadronization Status

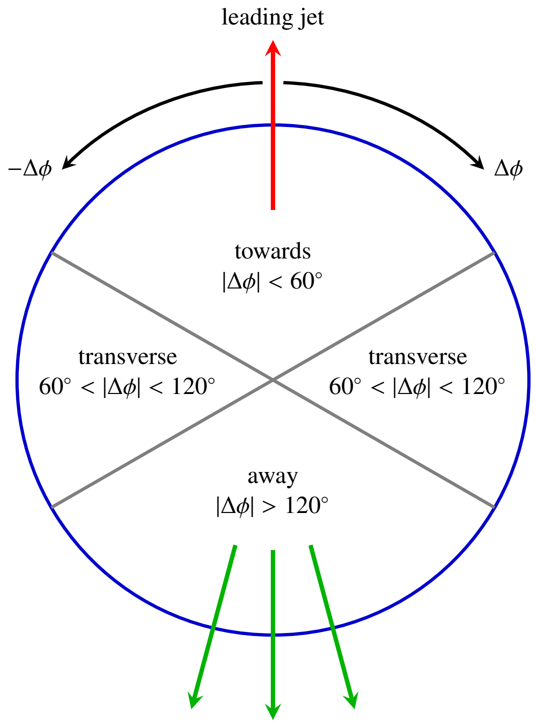
- No fundamental progress since 1980s
  - Available non-perturbative methods (lattice, AdS/QCD, ...) are inapplicable
- Less important in some respects in LHC era
  - Jets, leptons and photons are observed objects, not hadrons
- But still important for detector effects
  - Jet response, heavy-flavour tagging, lepton and photon isolation, ...

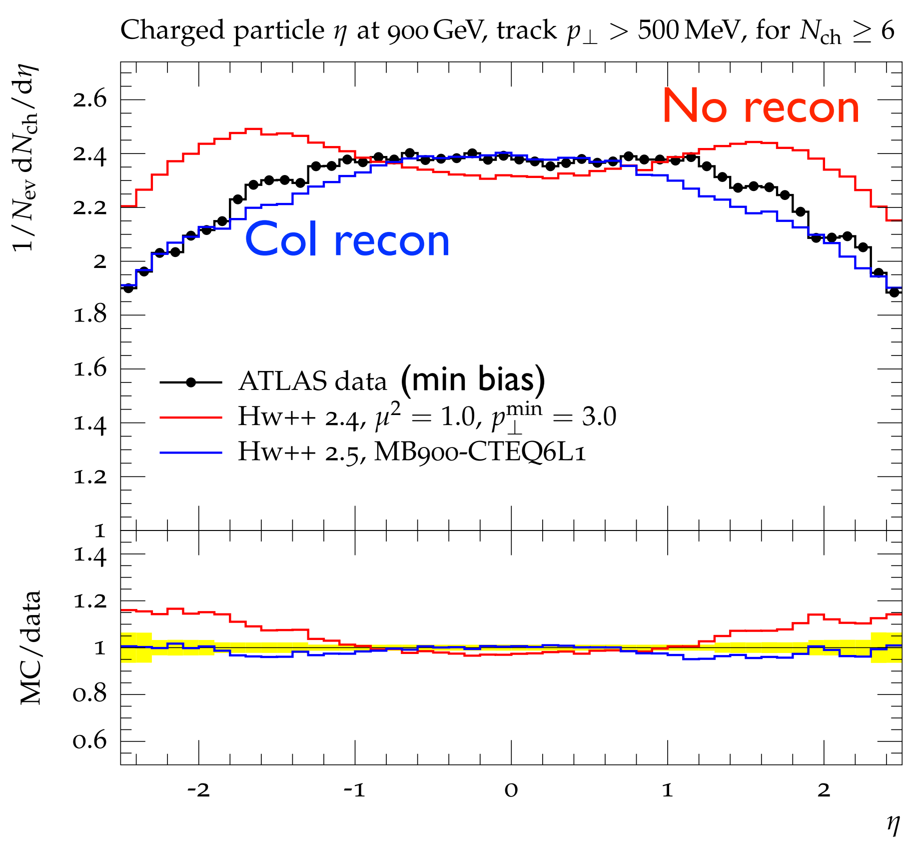
# Underlying Event

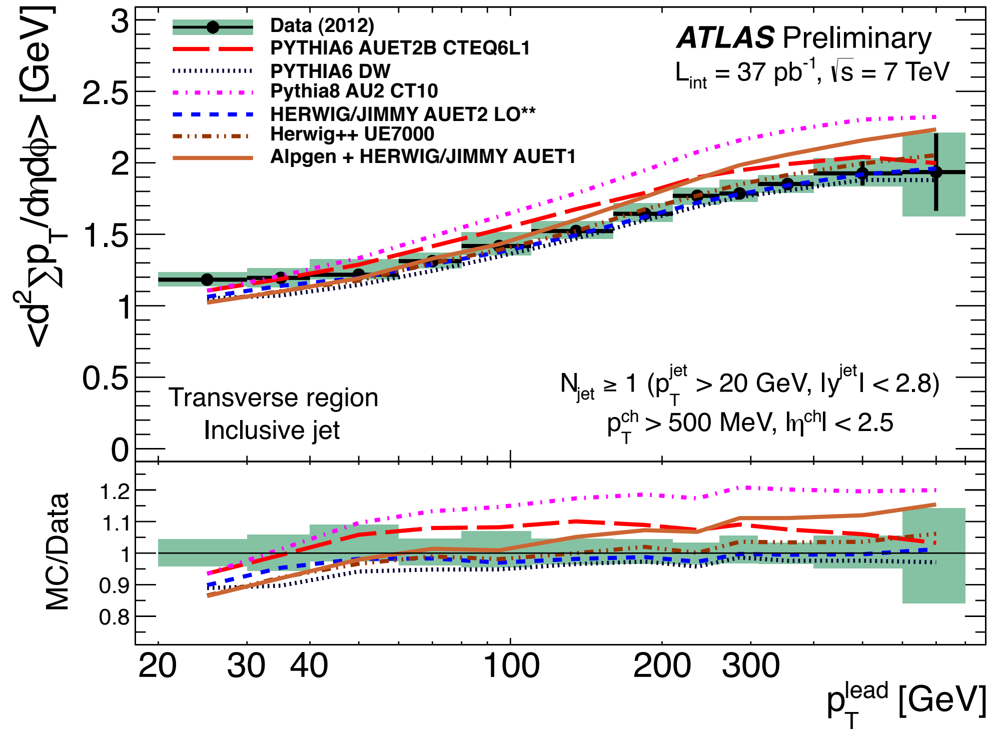


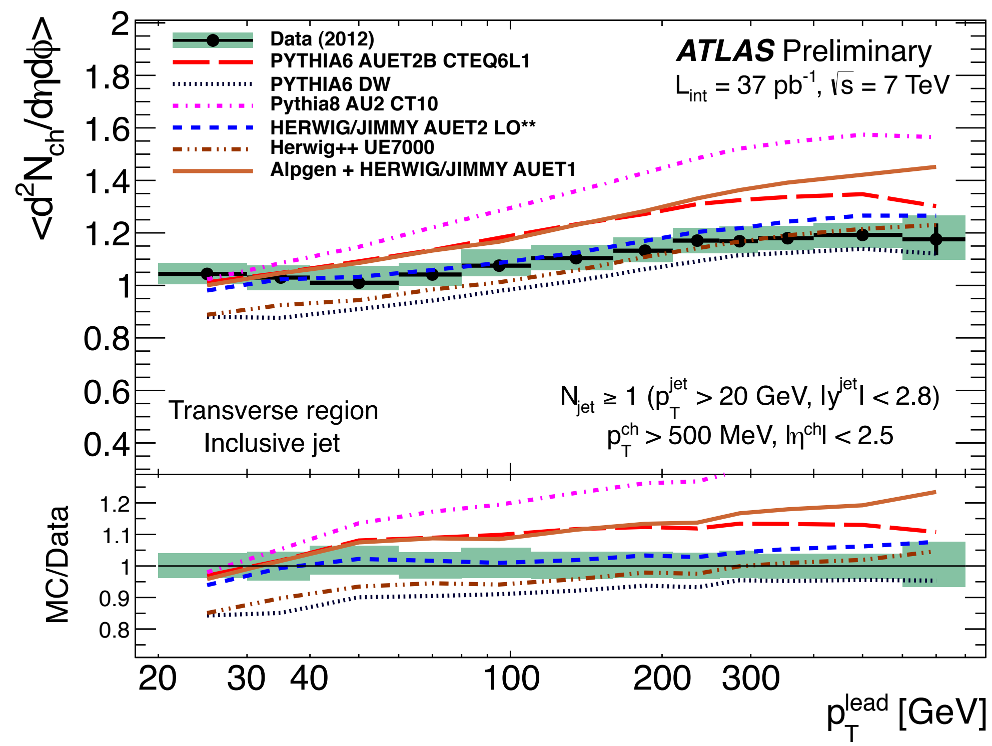
- Multiple parton interactions in same collision
  - Depends on density profile of proton
- Assume QCD 2-to-2 secondary collisions
  - Need cutoff at low $p_T$
- Need to model colour flow
  - Colour reconnections are necessary

# Underlying Event



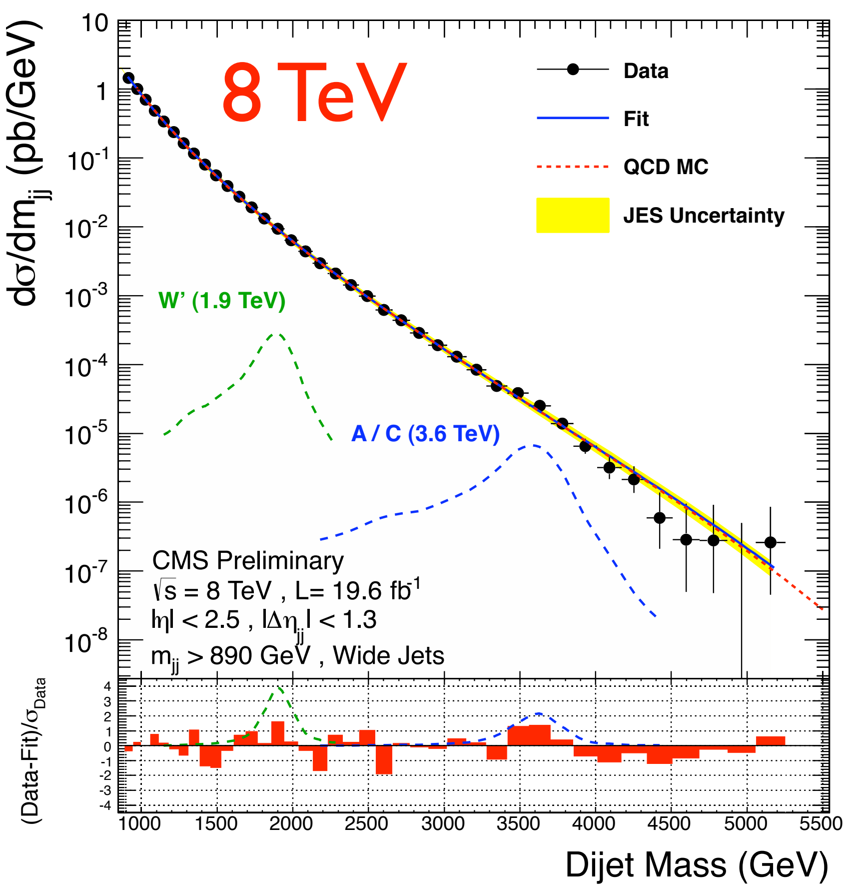



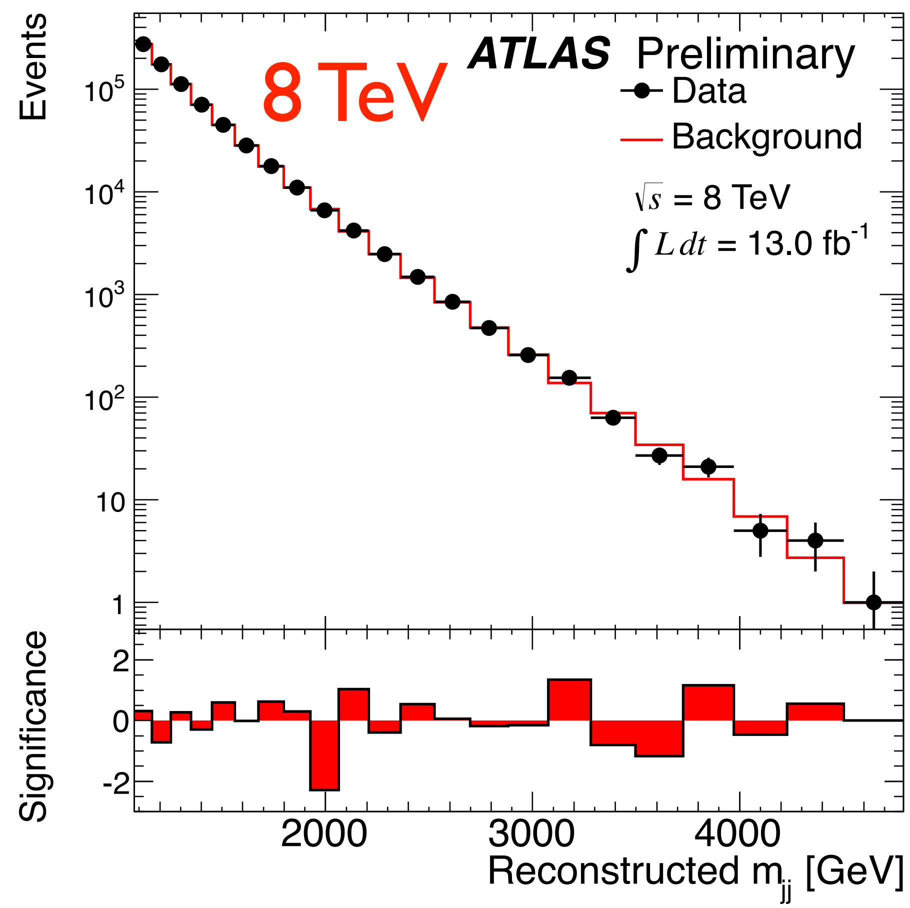

Gieseke, Röhr, Siódmok, arXiv:1206.2205

ATLAS CONF-2012-164

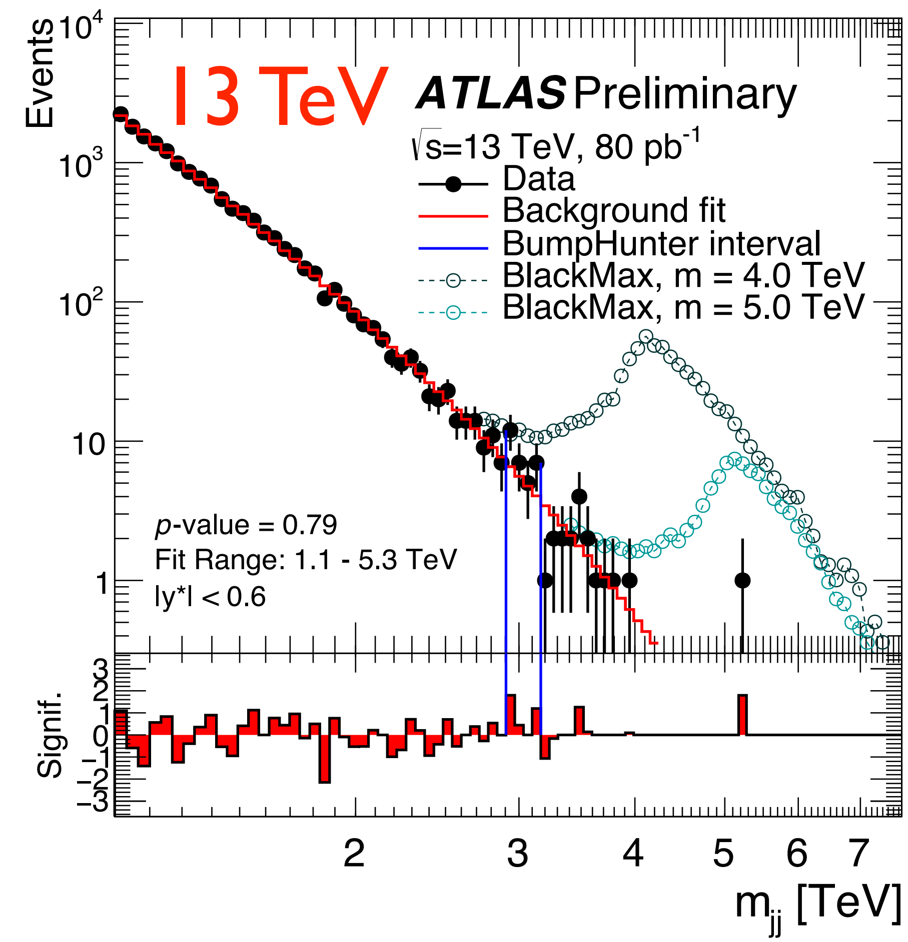
# Dijet Mass Distribution




CMS PAS EXO-12-059



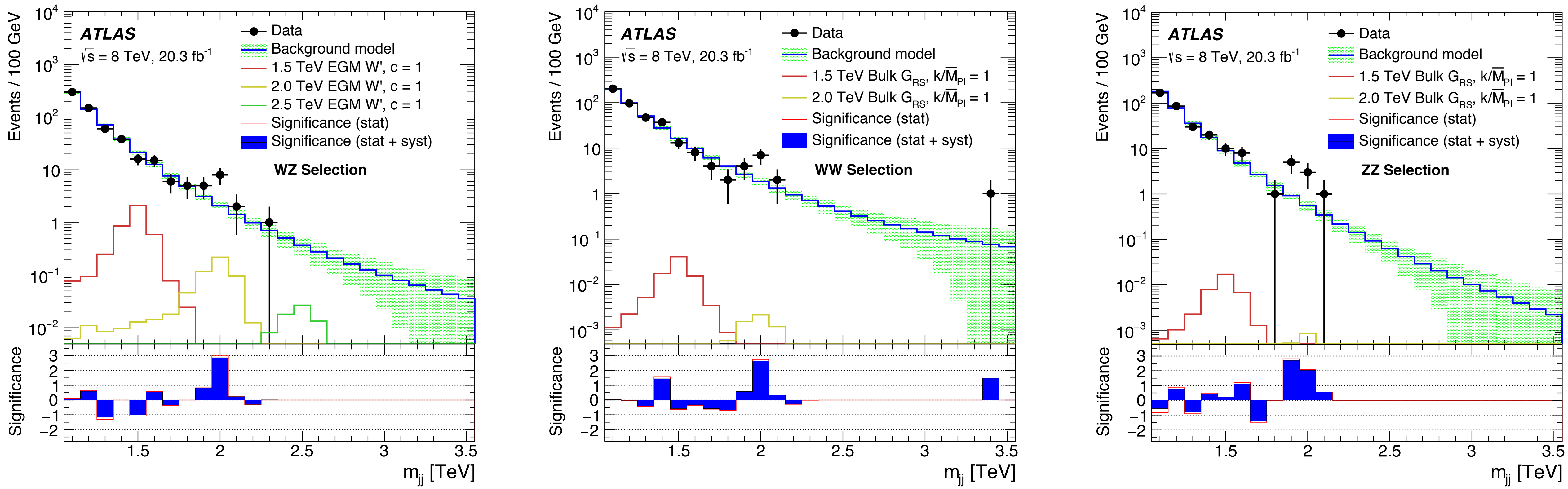

ATLAS CONF-2012-148




ATLAS CONF-2015-042

- No significant deviation from Standard Model (yet)
- But …

# Diboson selection




ATLAS, arXiv:1506.00962

- Each jet selected for hadronic W or Z decay
- WZ, WW and ZZ selections overlap

# MC Event Generators

- **HERWIG** http://projects.hepforge.org/herwig/
  - Angular-ordered parton shower, cluster hadronization
  - v6 Fortran; Herwig++
- **PYTHIA** http://www.thep.lu.se/~torbjorn/Pythia.html
  - Dipole-type parton shower, string hadronization
  - v6 Fortran; v8 C++
- **SHERPA** http://projects.hepforge.org/sherpa/
  - Dipole-type parton shower, cluster hadronization
  - C++

"General-purpose event generators for LHC physics",
A Buckley et al., arXiv:1101.2599, Phys. Rept. 504(2011)145

# Other relevant software

## (with apologies for omissions)

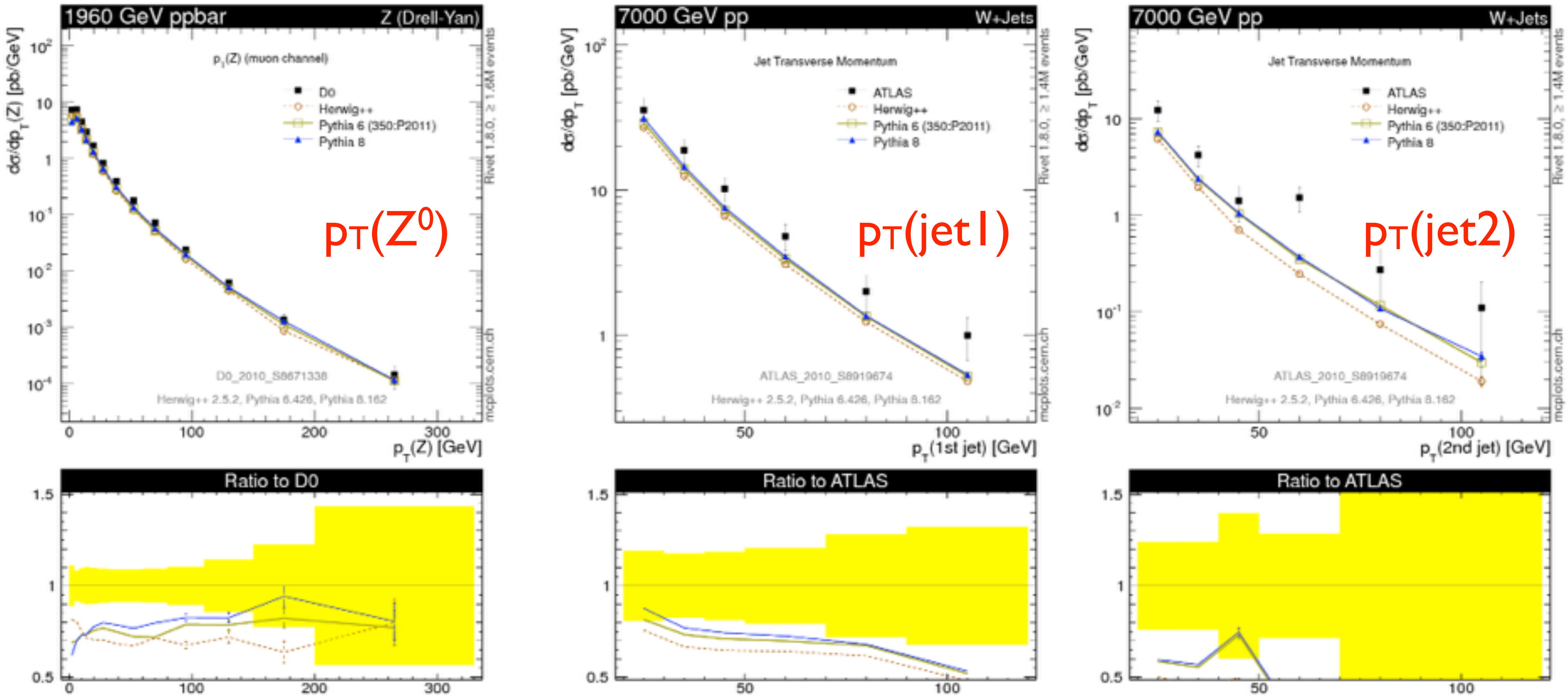
- Other event/shower generators: PhoJet, Ariadne, Dipsy, Cascade, Vincia
- Matrix-element generators: MadGraph/MadEvent, CompHep, CalcHep, Helac, Whizard, Sherpa, GoSam, aMC@NLO
- Matrix element libraries: AlpGen, POWHEG BOX, MCFM, NLOjet++, VBFNLO, BlackHat, Rocket
- Special BSM scenarios: Prospino, Charybdis, TrueNoir
- Mass spectra and decays: SOFTSUSY, SPHENO, HDecay, SDecay
- Feynman rule generators: FeynRules
- PDF libraries: LHAPDF
- Resummed ($p_\perp$) spectra: ResBos
- Approximate loops: LoopSim
- Jet finders: anti-$k_\perp$ and FastJet
- Analysis packages: Rivet, Professor, MCPLOTS
- Detector simulation: GEANT, Delphes
- Constraints (from cosmology etc): DarkSUSY, MicrOmegas
- Standards: PDF identity codes, LHA, LHEF, SLHA, Binoth LHA, HepMC

Sjöstrand, Nobel Symposium, May 2013

# Parton Shower Monte Carlo

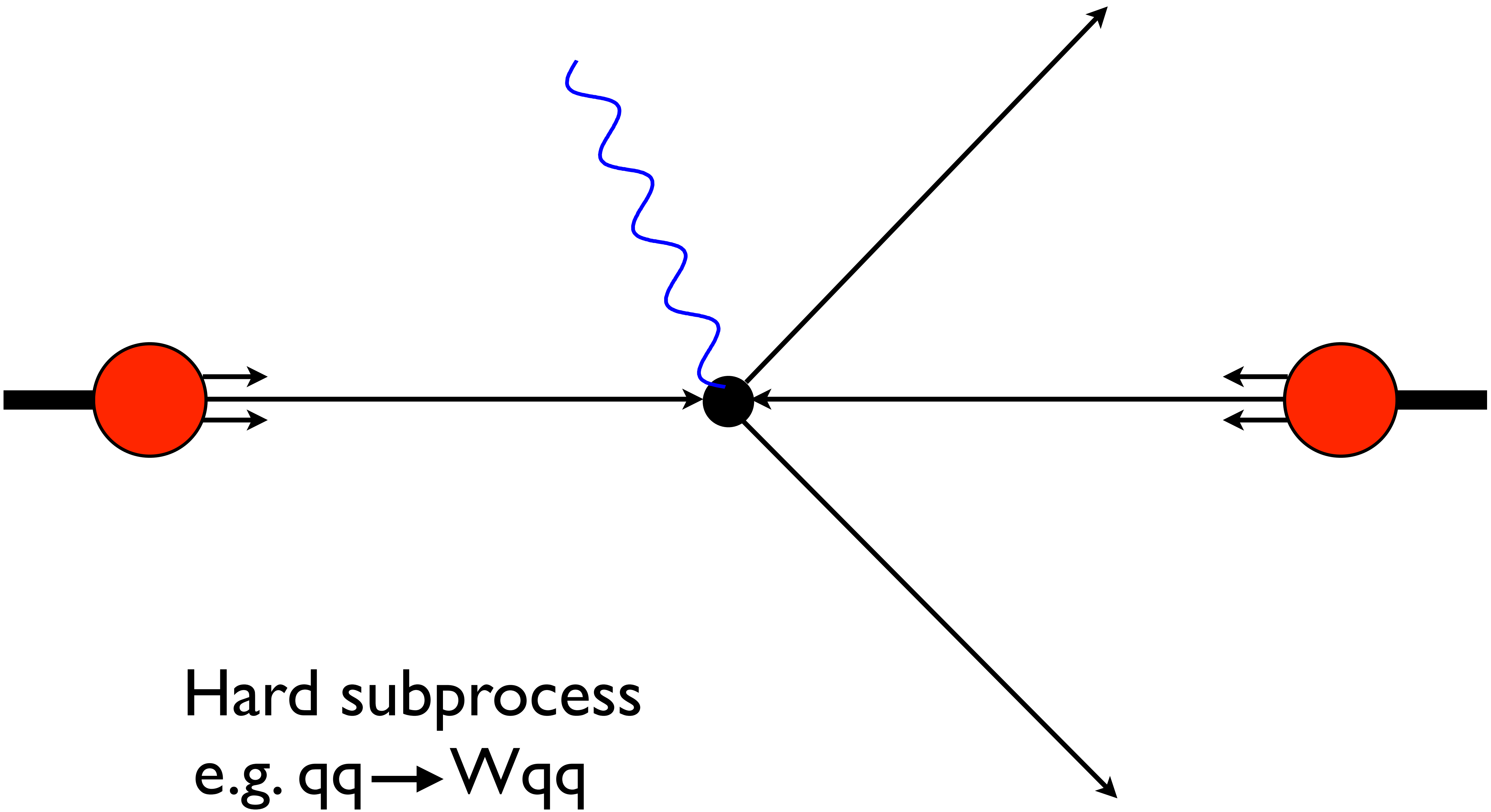
http://mcplots.cern.ch/

- Hard subprocess: $q\bar{q} \to Z^0/W^\pm$



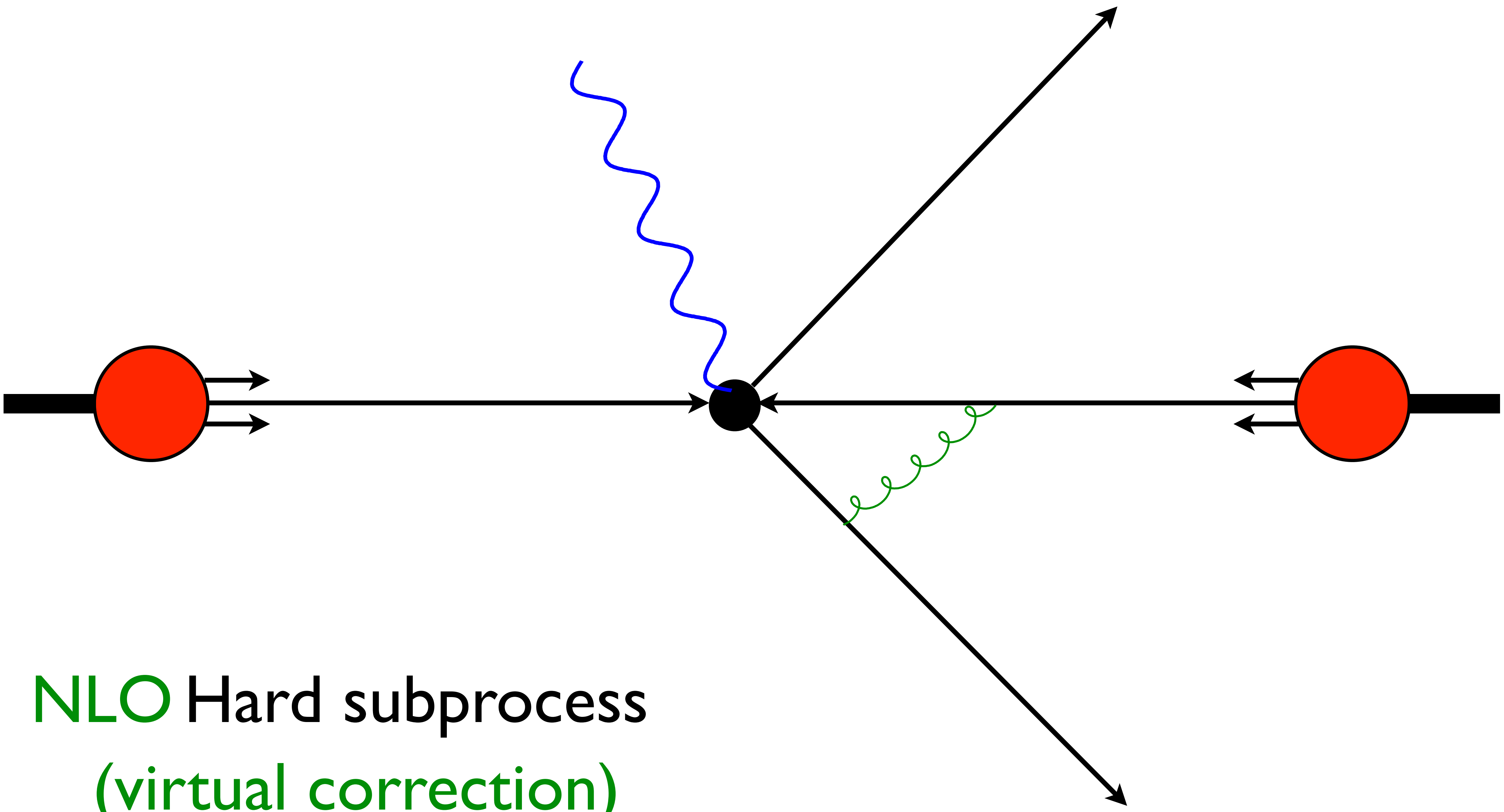

- Leading-order (LO) normalization ➡ need next-to-LO (NLO)
- Worse for high $p_T$ and/or extra jets ➡ need multijet merging

# Improving Event Simulation



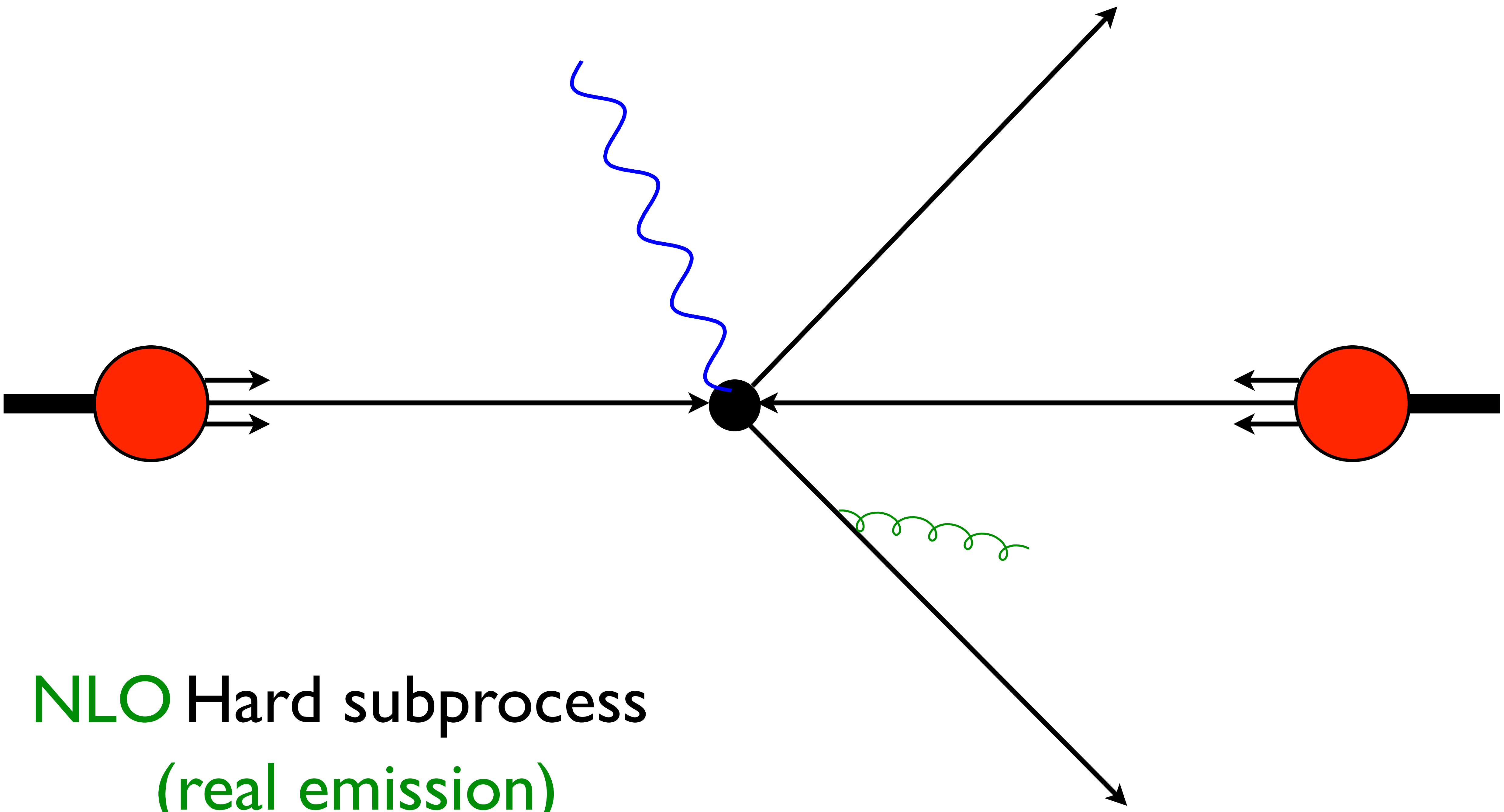
Hard subprocess
e.g. qq → Wqq

# Improving Event Simulation



NLO Hard subprocess
(virtual correction)

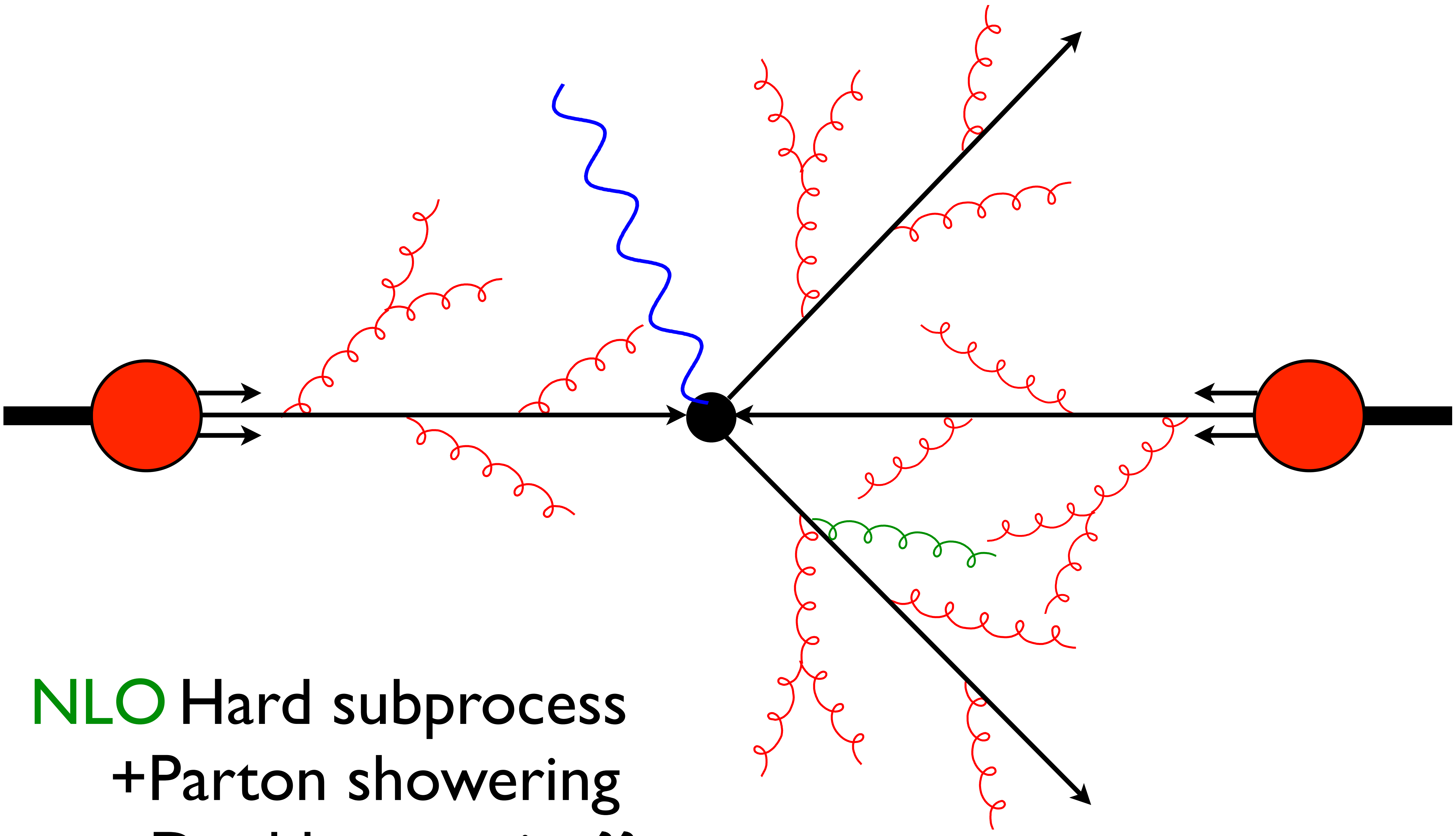
# Improving Event Simulation



NLO Hard subprocess

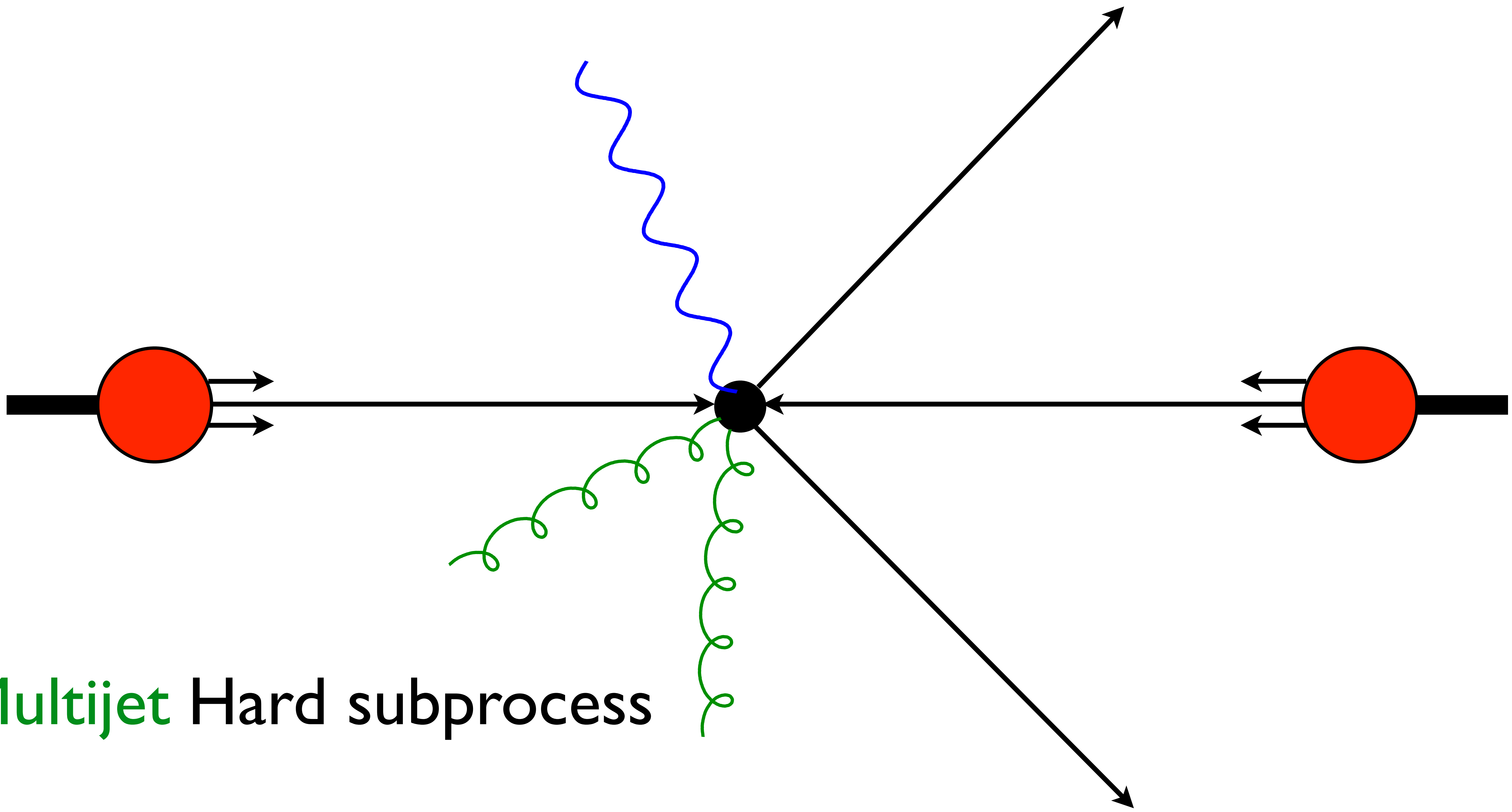
(real emission)

# Improving Event Simulation



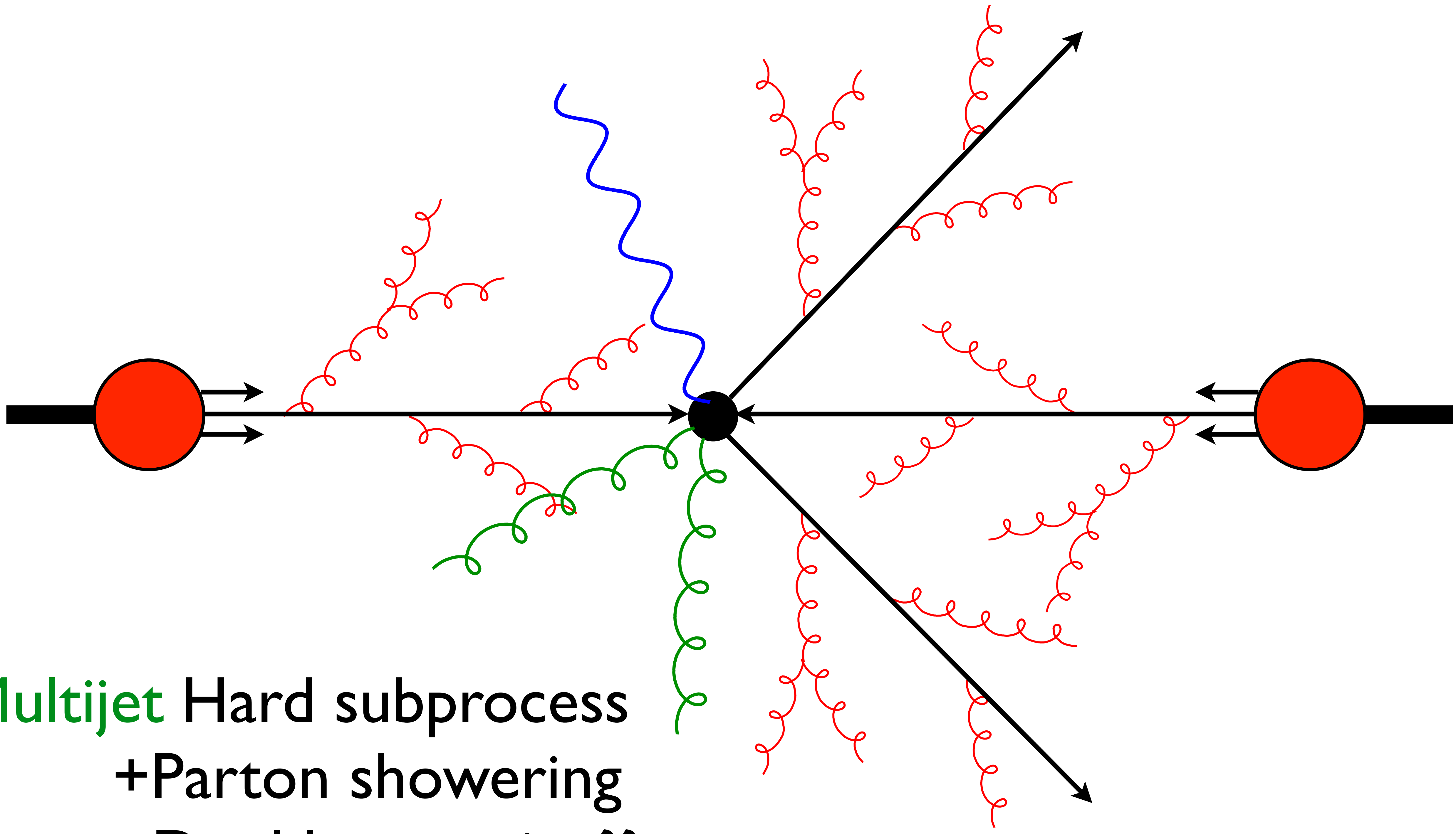
NLO Hard subprocess
+Parton showering
= Double counting??

# Improving Event Simulation



Multijet Hard subprocess

# Improving Event Simulation



Multijet Hard subprocess
+Parton showering
= Double counting??

# Matching & Merging

- Two rather different objectives:
- Matching parton showers to NLO matrix elements, without double counting
  - MC@NLO — Frixione, BW, 2002
  - POWHEG — Nason, 2004
- Merging parton showers with LO n-jet matrix elements, minimizing jet resolution dependence
  - CKKW — Catani, Krauss, Kühn, BW, 2001
  - Dipole — Lönnblad, 2001
  - MLM merging — Mangano, 2002

# MC@NLO matching

S Frixione & BW, JHEP 06(2002)029

- Compute parton shower contributions (real and virtual) at NLO
  - Generator-dependent
- Subtract these from exact NLO
  - Cancels divergences of exact NLO!
- Generate modified no-emission (LO+virtual) and real-emission hard process configurations
  - Some may have negative weight
- Pass these through parton shower etc.
  - Only shower-generated terms beyond NLO

# MC@NLO matching

S Frixione & BW, JHEP 06(2002)029

finite virtual → $V$; divergent → $\sum_i C_i$, $R$

$$d\sigma_{NLO} = \left[B(\Phi_B) + V(\Phi_B) - \int \sum_i C_i(\Phi_B, \Phi_R)\, d\Phi_R\right] d\Phi_B + R(\Phi_B, \Phi_R)\, d\Phi_B\, d\Phi_R$$

$$\equiv \left[B + V - \int C\, d\Phi_R\right] d\Phi_B + R\, d\Phi_B\, d\Phi_R$$

$$d\sigma_{MC} = B(\Phi_B)\, d\Phi_B \left[\Delta_{MC}(0) + \frac{R_{MC}(\Phi_B, \Phi_R)}{B(\Phi_B)} \Delta_{MC}(k_T(\Phi_B, \Phi_R))\, d\Phi_R\right]$$

$$\equiv B\, d\Phi_B\, [\Delta_{MC}(0) + (R_{MC}/B)\, \Delta_{MC}(k_T)\, d\Phi_R]$$

$$d\sigma_{MC@NLO} = \left[B + V + \int (R_{MC} - C)\, d\Phi_R\right] d\Phi_B\, [\Delta_{MC}(0) + (R_{MC}/B)\, \Delta_{MC}(k_T)\, d\Phi_R]$$
$$+ (R - R_{MC})\, \Delta_{MC}(k_T)\, d\Phi_B\, d\Phi_R$$

finite $\gtrless 0$ → $\int (R_{MC} - C)\, d\Phi_R$, $(R - R_{MC})$

MC starting from no emission → $\Delta_{MC}(0)$

MC starting from one emission → $d\Phi_B\, d\Phi_R$

- Expanding gives NLO result

# POWHEG matching

P Nason, JHEP 11(2004)040

- POsitive Weight Hardest Emission Generator
- Use exact real-emission matrix element to generate hardest (highest relative $p_T$) emission configurations
  - No-emission probability implicitly modified
  - (Almost) eliminates negative weights
  - Some uncontrolled terms generated beyond NLO
- Pass configurations through parton shower etc

# POWHEG matching

P Nason, JHEP 11(2004)040

$$d\sigma_{\rm MC} = B(\Phi_B)\, d\Phi_B \left[\Delta_{\rm MC}(0) + \frac{R_{\rm MC}(\Phi_B,\Phi_R)}{B(\Phi_B)}\,\Delta_{\rm MC}(k_T(\Phi_B,\Phi_R))\, d\Phi_R\right]$$

$$d\sigma_{\rm PH} = \overline{B}(\Phi_B)\, d\Phi_B \left[\Delta_R(0) + \frac{R(\Phi_B,\Phi_R)}{B(\Phi_B)}\,\Delta_R(k_T(\Phi_B,\Phi_R))\, d\Phi_R\right]$$

$$\overline{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int\left[R(\Phi_B,\Phi_R) - \sum_i C_i(\Phi_B,\Phi_R)\right] d\Phi_R$$

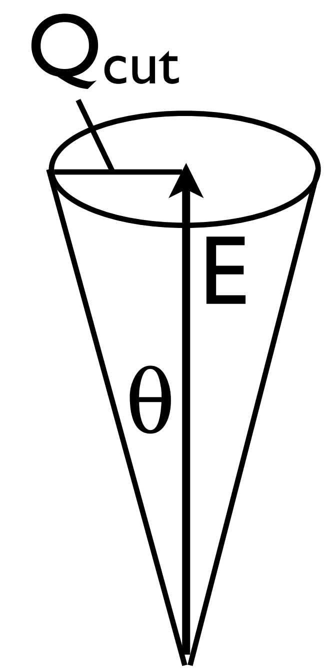
$$\Delta_R(p_T) = \exp\left[-\int d\Phi_R\, \frac{R(\Phi_B,\Phi_R)}{B(\Phi_B)}\,\theta\left(k_T(\Phi_B,\Phi_R) - p_T\right)\right]$$

- NLO with (almost) no negative weights
- High $p_T$ always enhanced by $K = \overline{B}/B = 1 + \mathcal{O}(\alpha_S)$

arbitrary NNLO

# Multijet Merging

- Objective: merge LO n-jet matrix elements* with parton showers such that:
  - Multijet rates for jet resolution > $Q_{cut}$ are correct to LO (up to $N_{max}$)
  - Shower generates jet structure below $Q_{cut}$ (and jets above $N_{max}$)
  - Leading (and next) $Q_{cut}$ dependence cancels




* ALPGEN or MadGraph, $n \lesssim N_{max}$

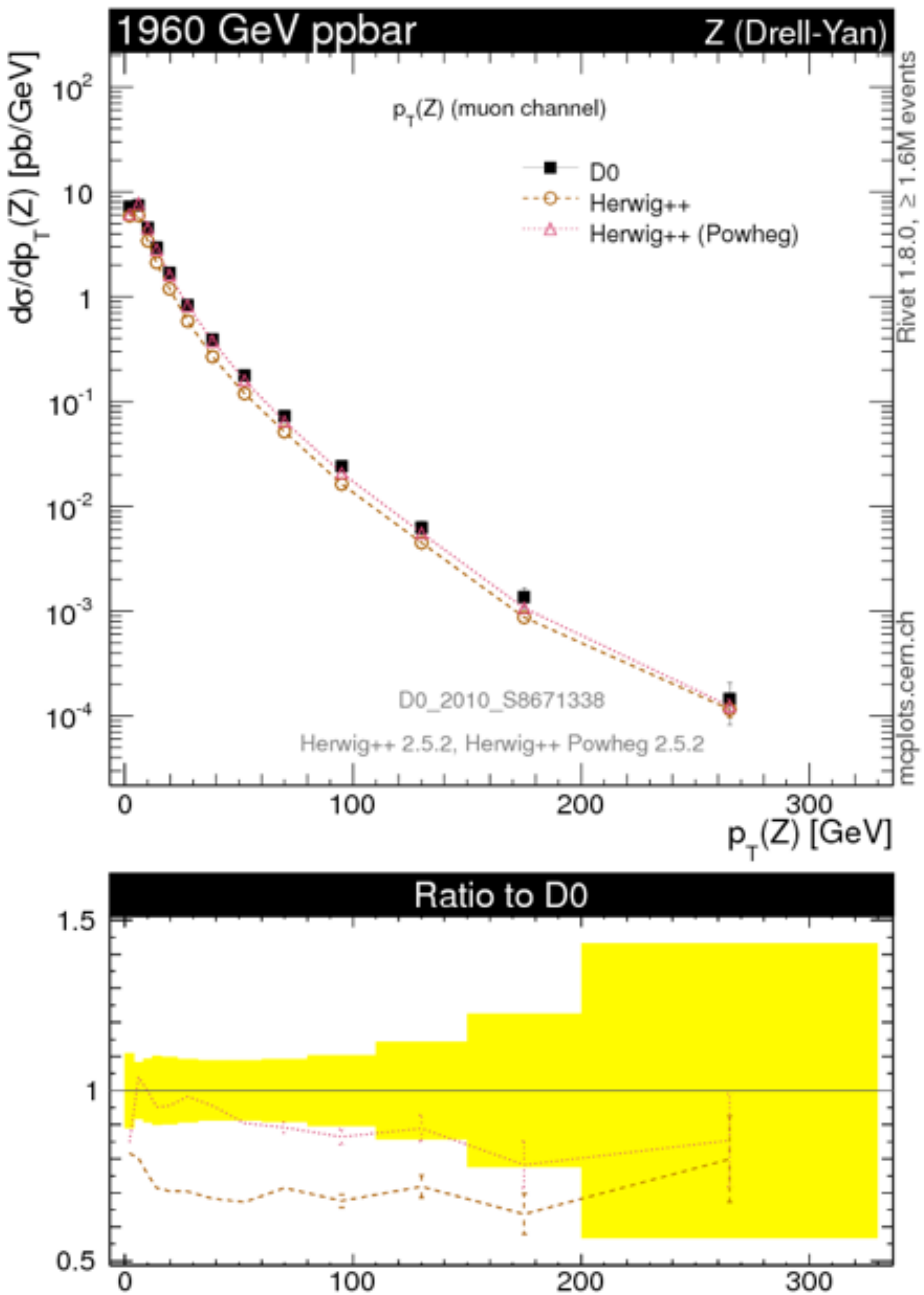
CKKW: Catani et al., JHEP 11(2001)063

-L: Lonnblad, JHEP 05(2002)063

MLM: Mangano et al., NP B632(2002)343

# Vector boson production

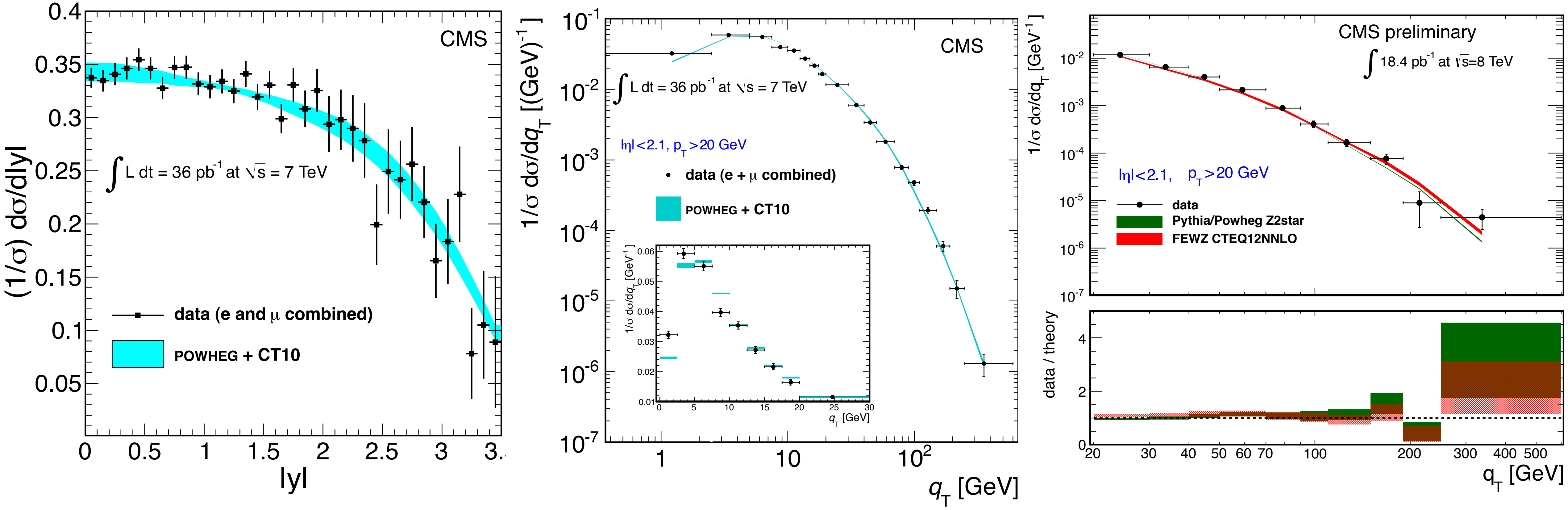
# $Z^0$ at 2 TeV (Tevatron)




http://mcplots.cern.ch/

- Absolute normalization: LO too low
- POWHEG agrees with rate and distribution

# $Z^0$ at 7,8 TeV (LHC Run 1)

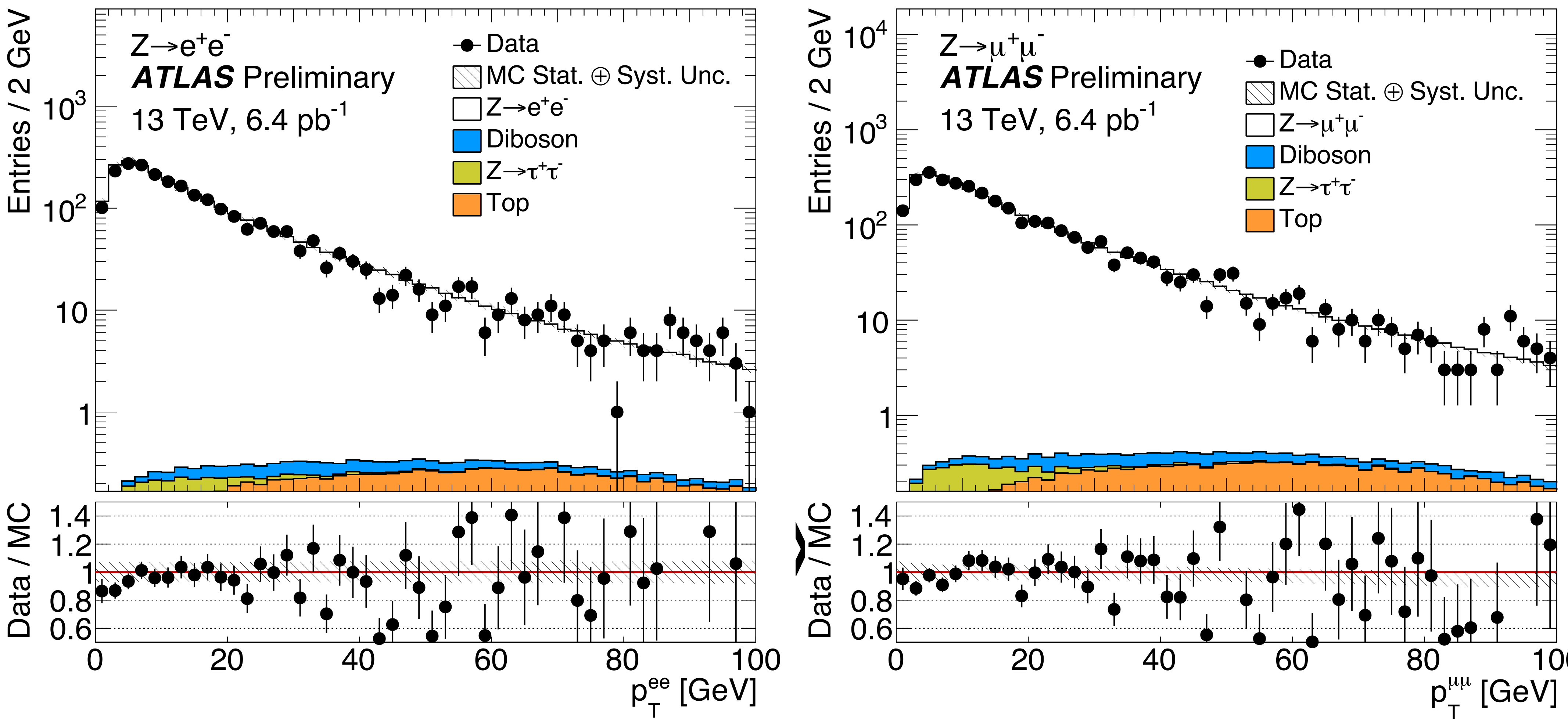



CMS, PRD85(2012)032002

CMS PAS SMP-12-025

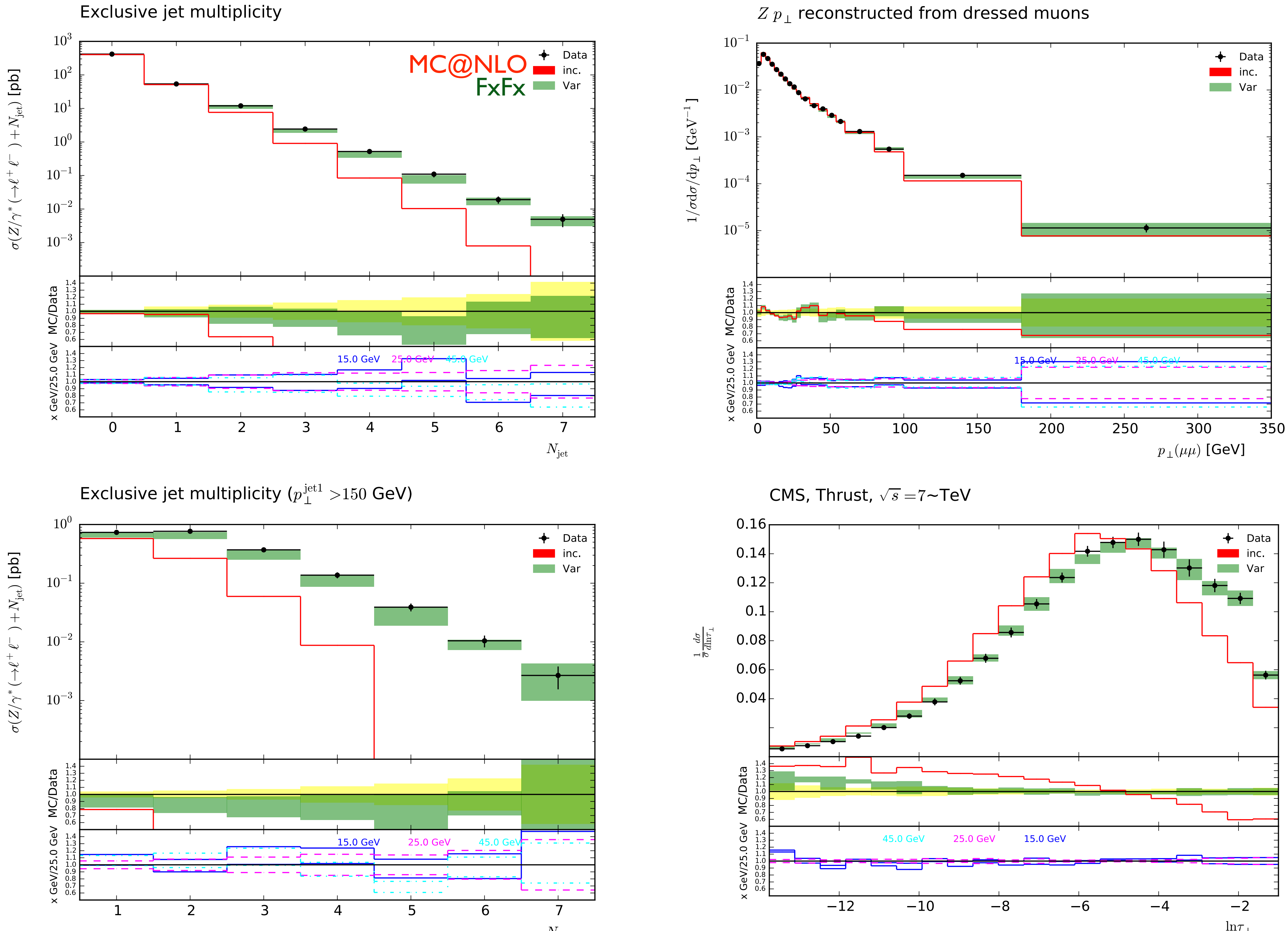
- Normalized to data
- Rapidity $y=\log[(E+p_L)/(E-p_L)]/2$
- POWHEG agrees with distribution (and NNLO)

# $Z^0$ at 13 TeV (LHC Run 2)




- Normalized to data again
- So far, good agreement

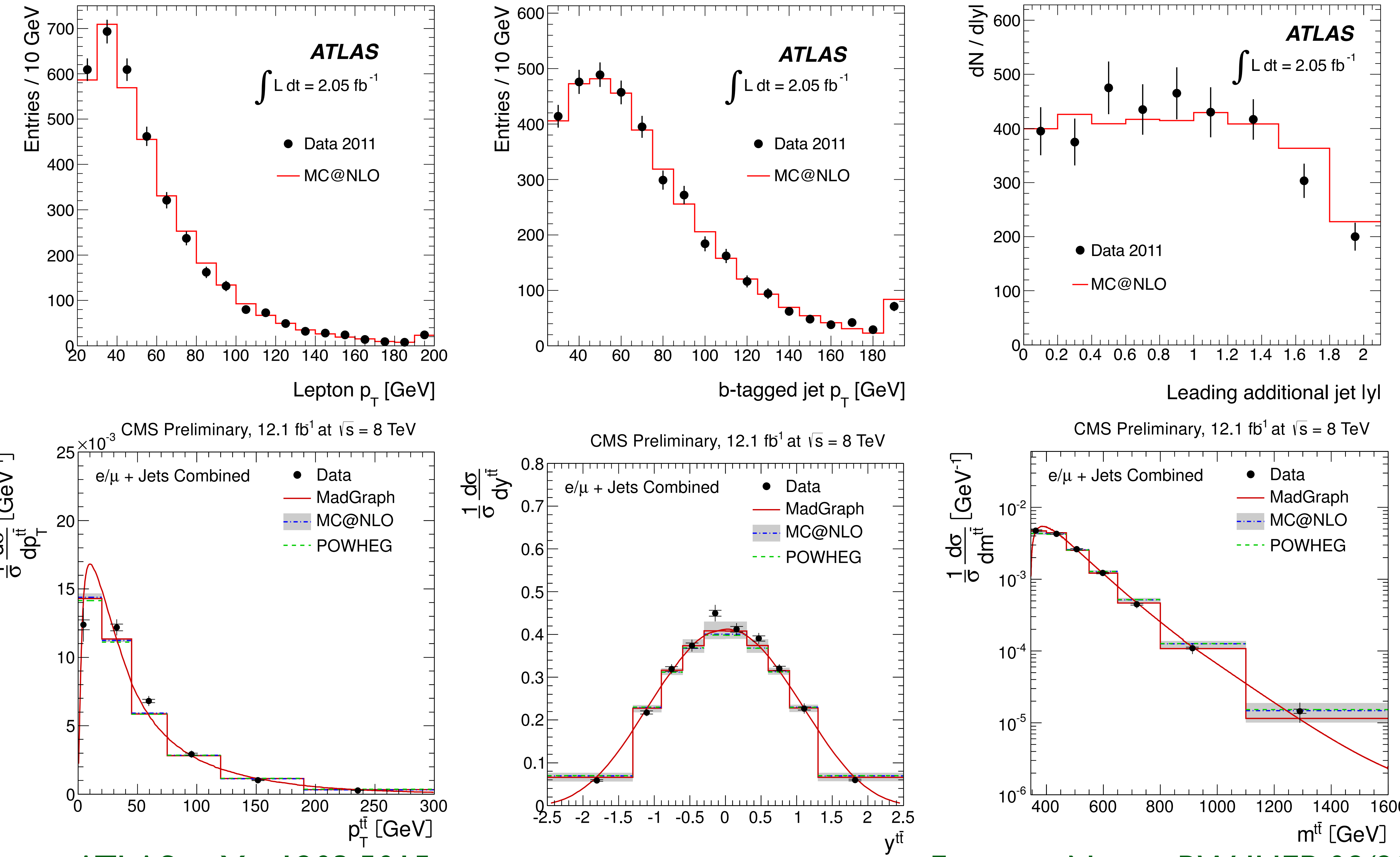
# Combined matching+merging




Frederix, Frixione, Papaefstathiou, Prestel, Torrielli, arXiv:1511.00847 (today!)

# Top quark pair production

# Top quark distributions




ATLAS, arXiv:1203.5015

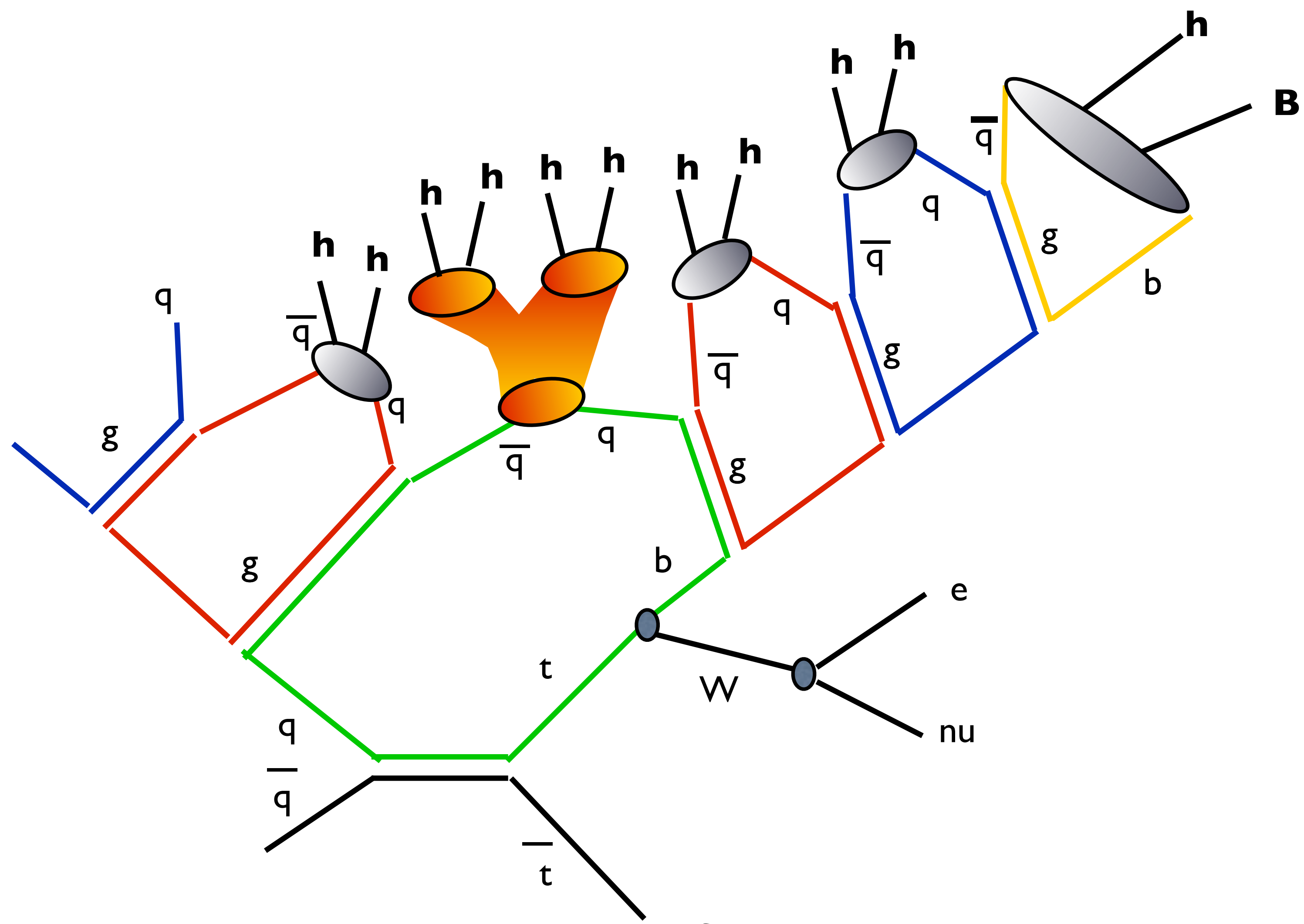
CMS PAS TOP-12-027

Frixione, Nason, BW, JHEP 08(2003)007

Alioli, Nason, Oleari, Re, JHEP 06(2010)043

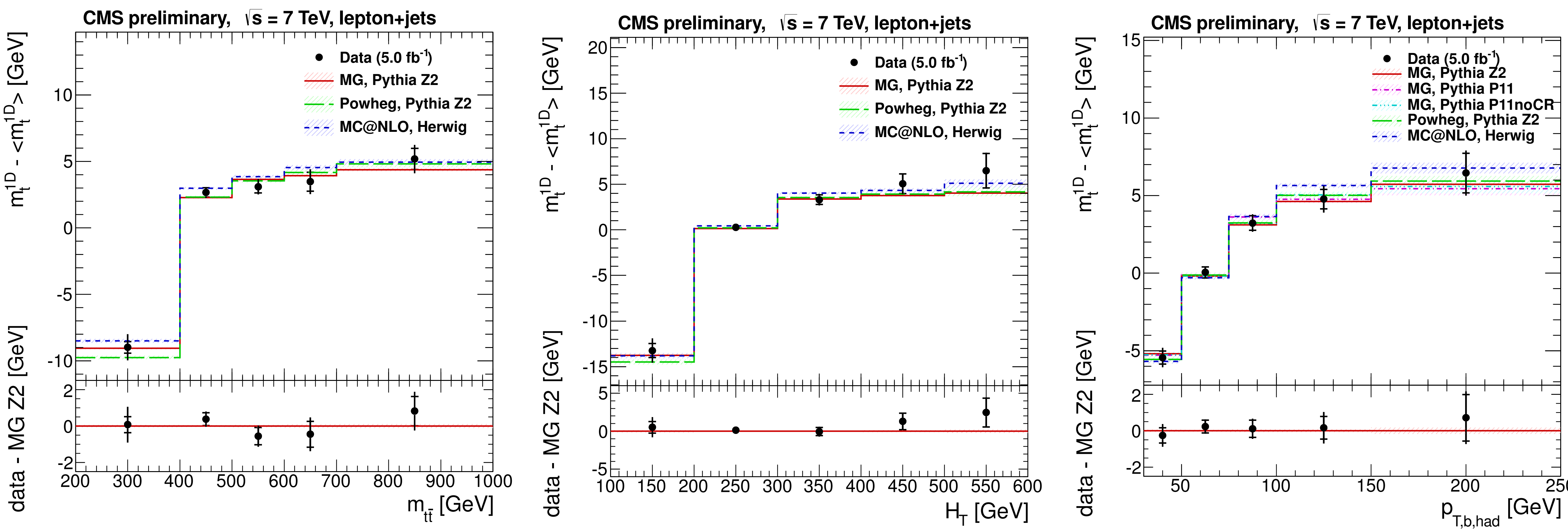
# Top mass & hadronization

Mangano, Top LHC WG, July 2012




- Top decay linked to rest of event
- Reconstructed 'top mass' depends on kinematics
- Top mass has non-perturbative ambiguity

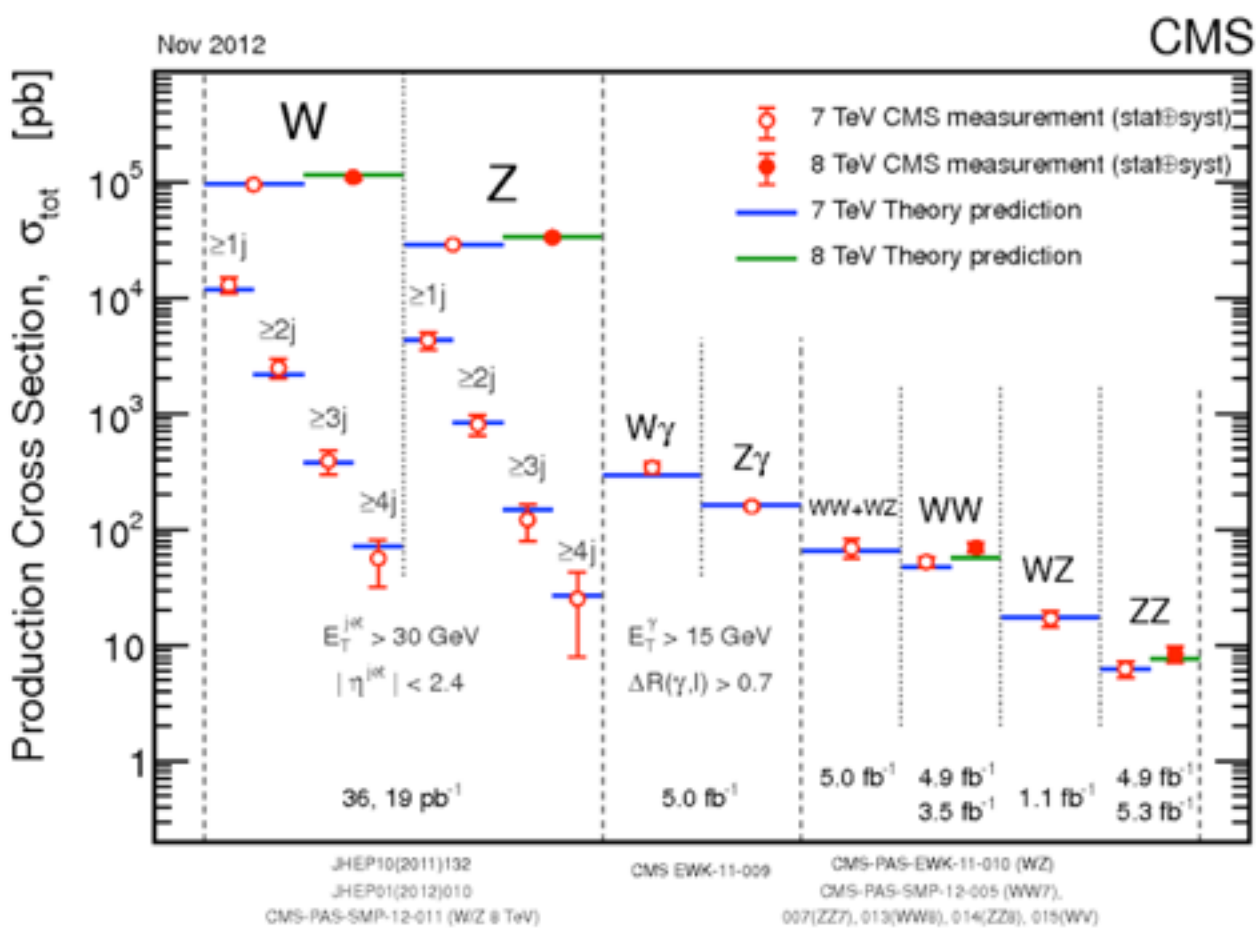
# Top mass & kinematics

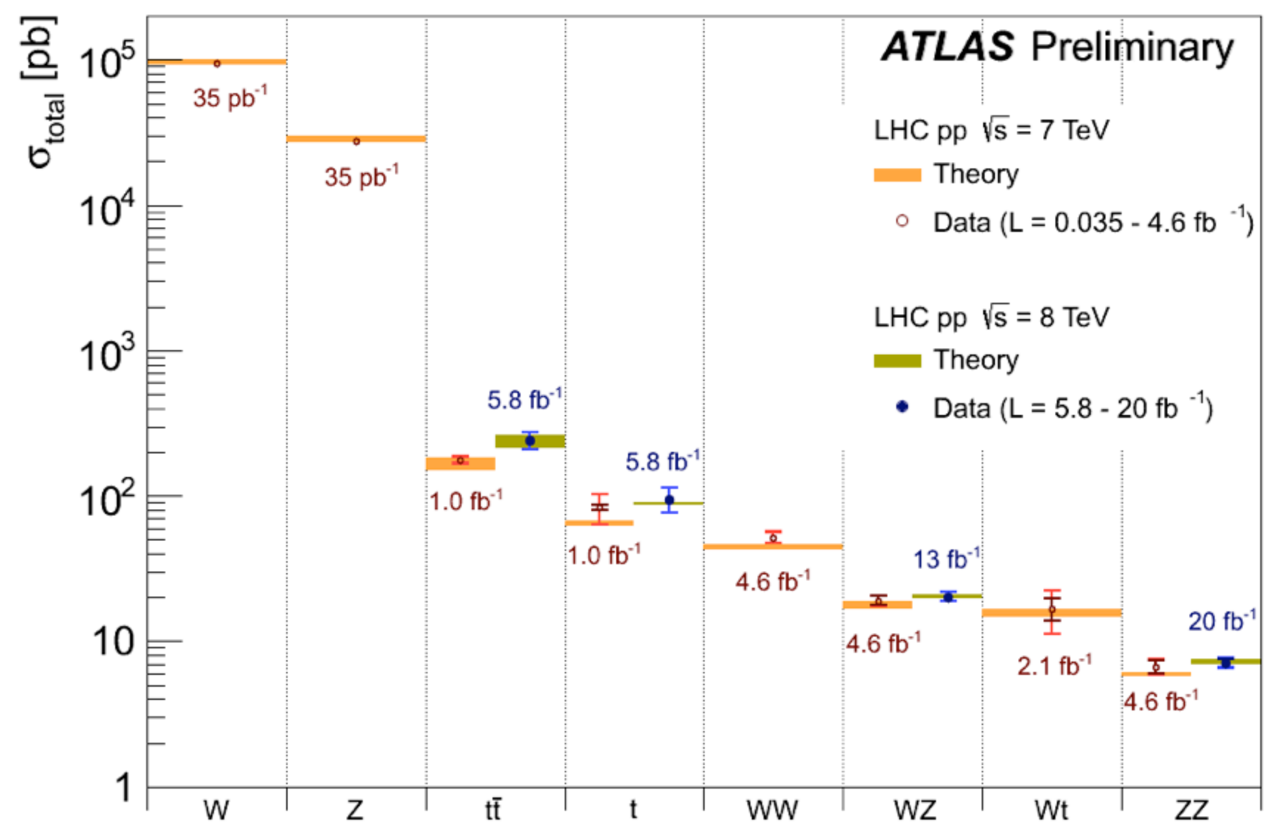



CMS PAS TOP-12-029

- Reconstructed top mass depends on kinematics
- But different generators track data well with a common input mass

# LHC Cross Section Summary

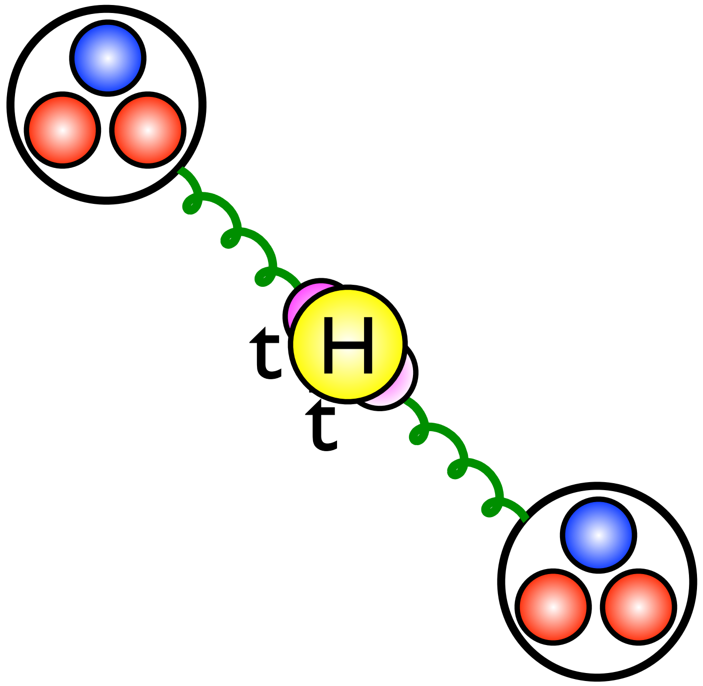


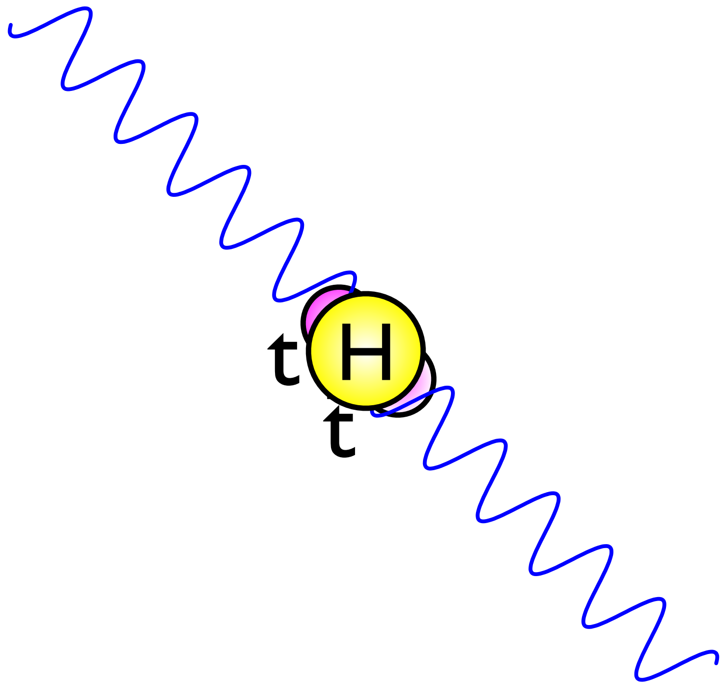

- Surprisingly good agreement
- No firm evidence of non-Standard-Model phenomena (in Run 1)

# Higgs boson production

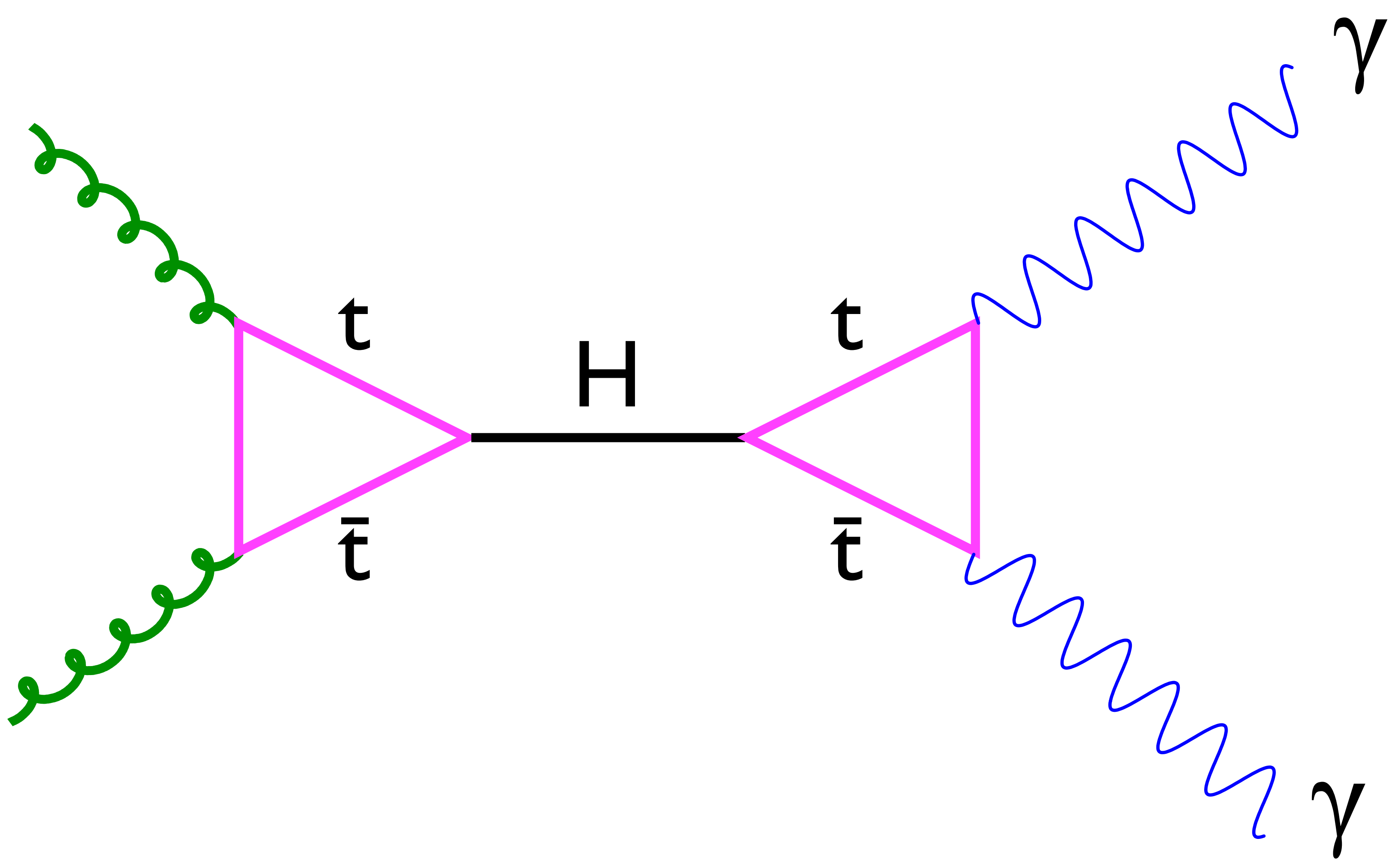
# Higgs Production by Gluon Fusion



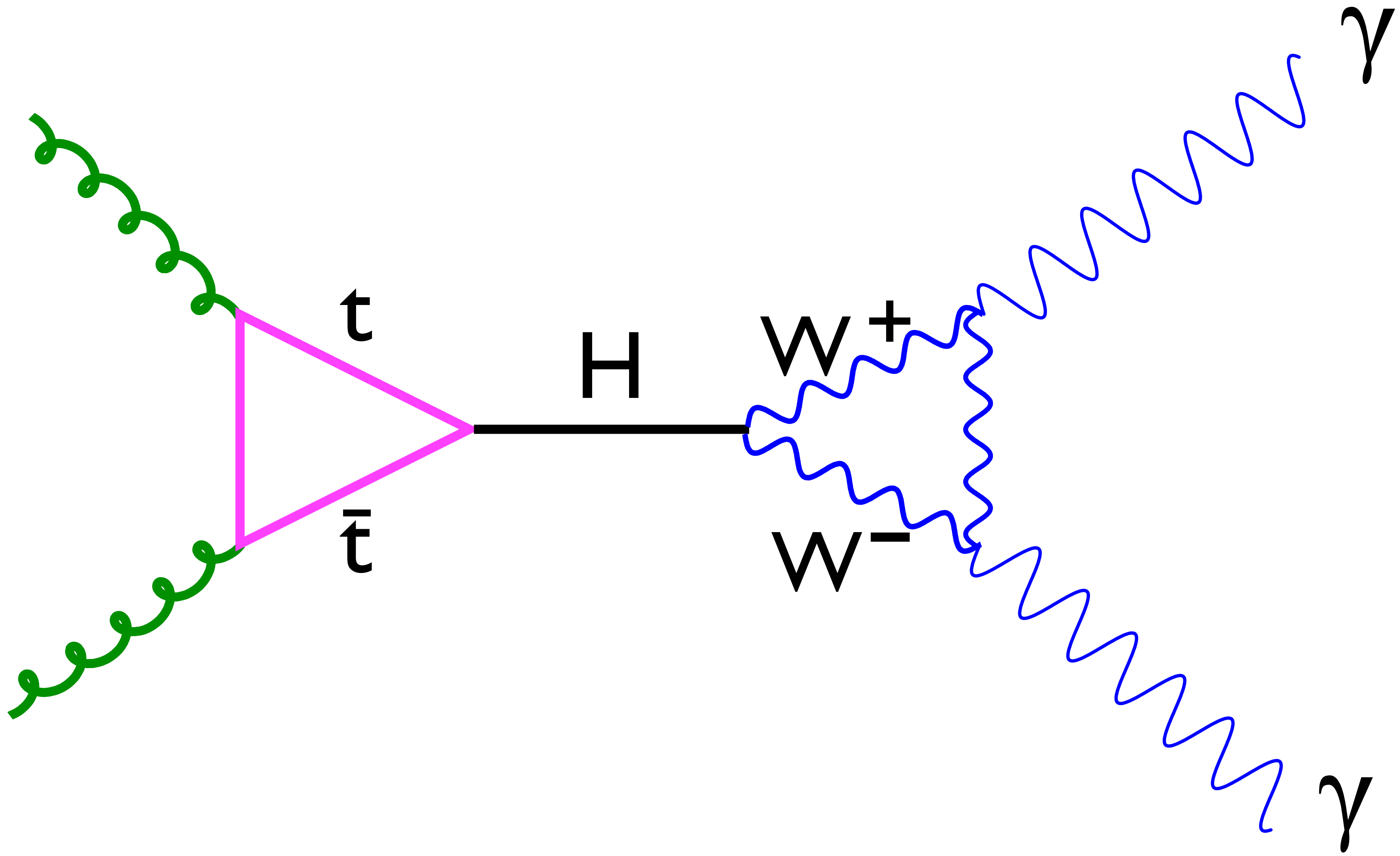
# Higgs Production by Gluon Fusion



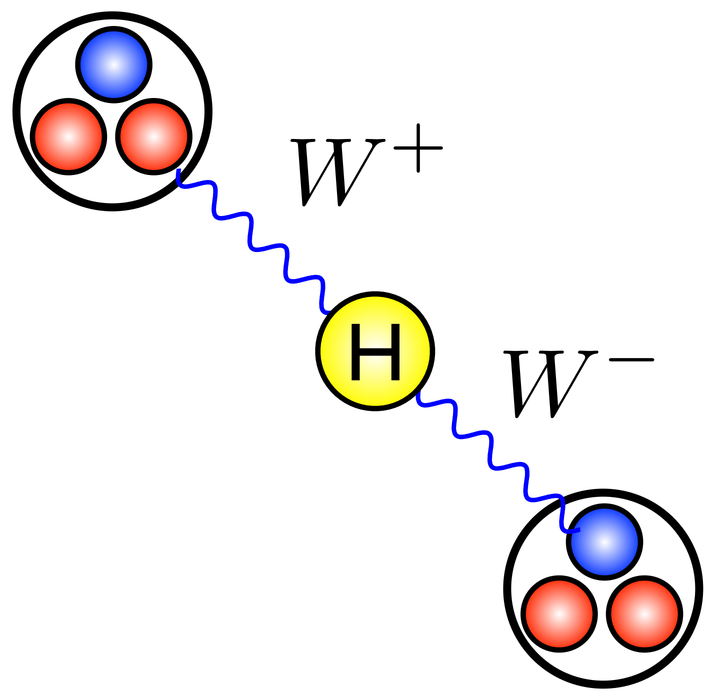
# Higgs Production by Gluon Fusion



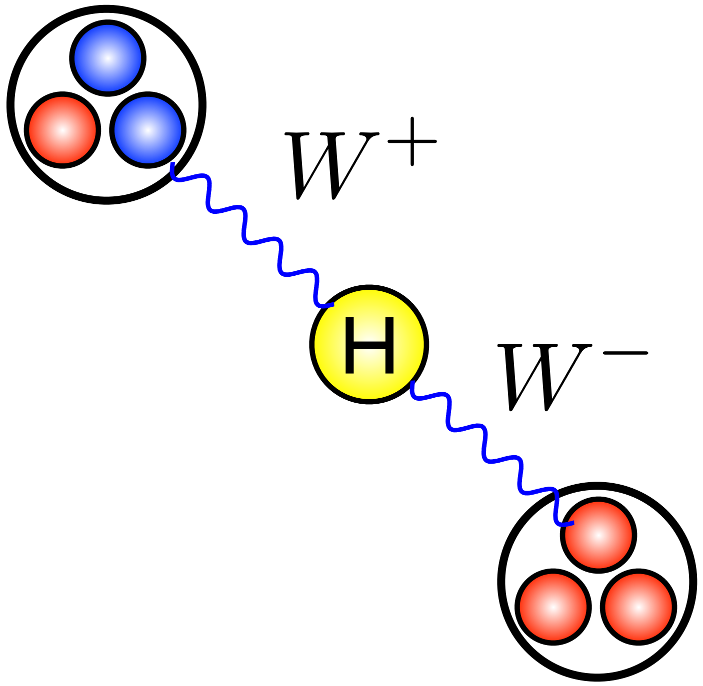
# Higgs Production by Gluon Fusion



# Higgs Production by Vector Boson Fusion



# Higgs Production by Vector Boson Fusion



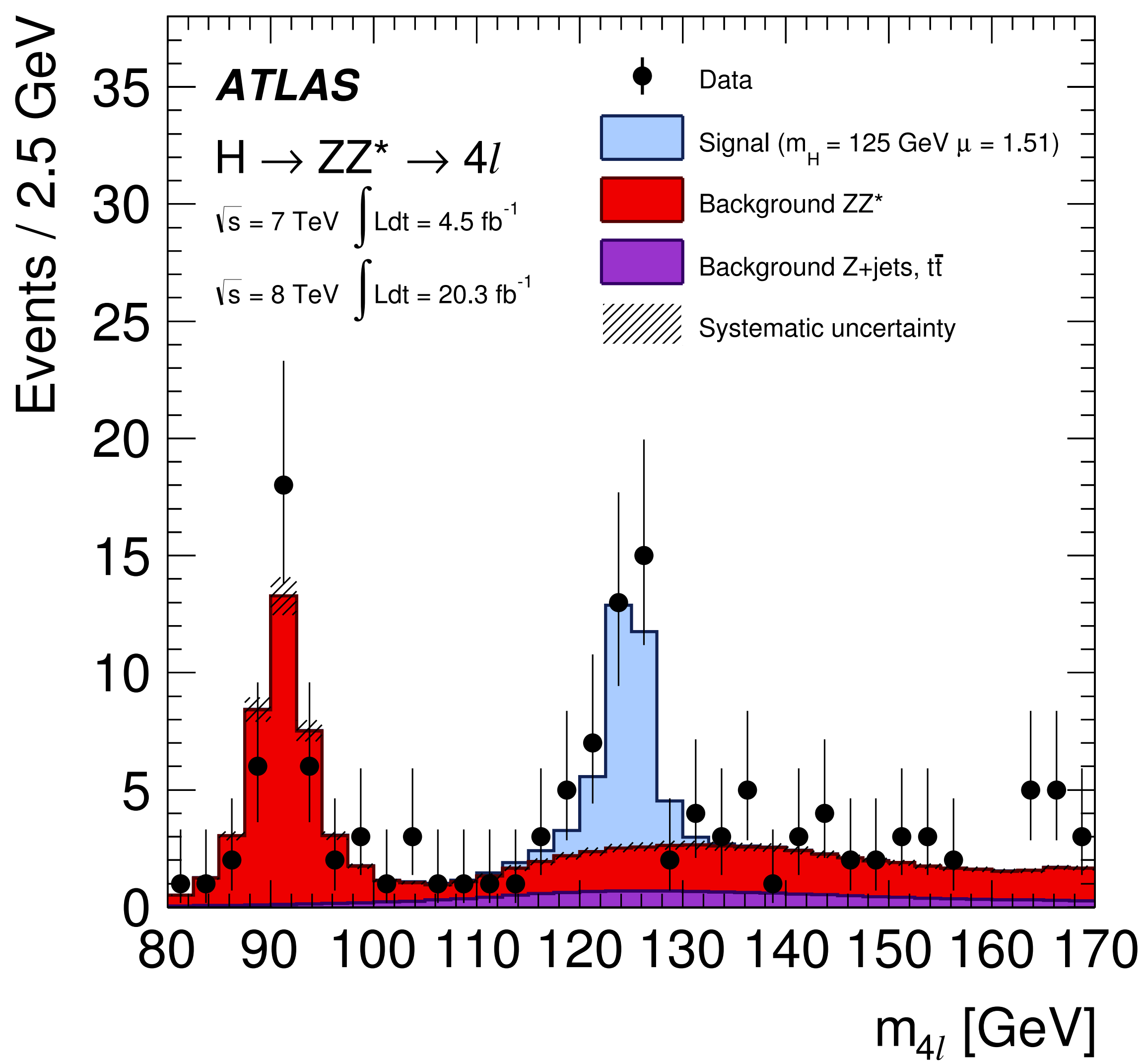

- Forward jets
- Few central jets
- Central jet veto increases S/B

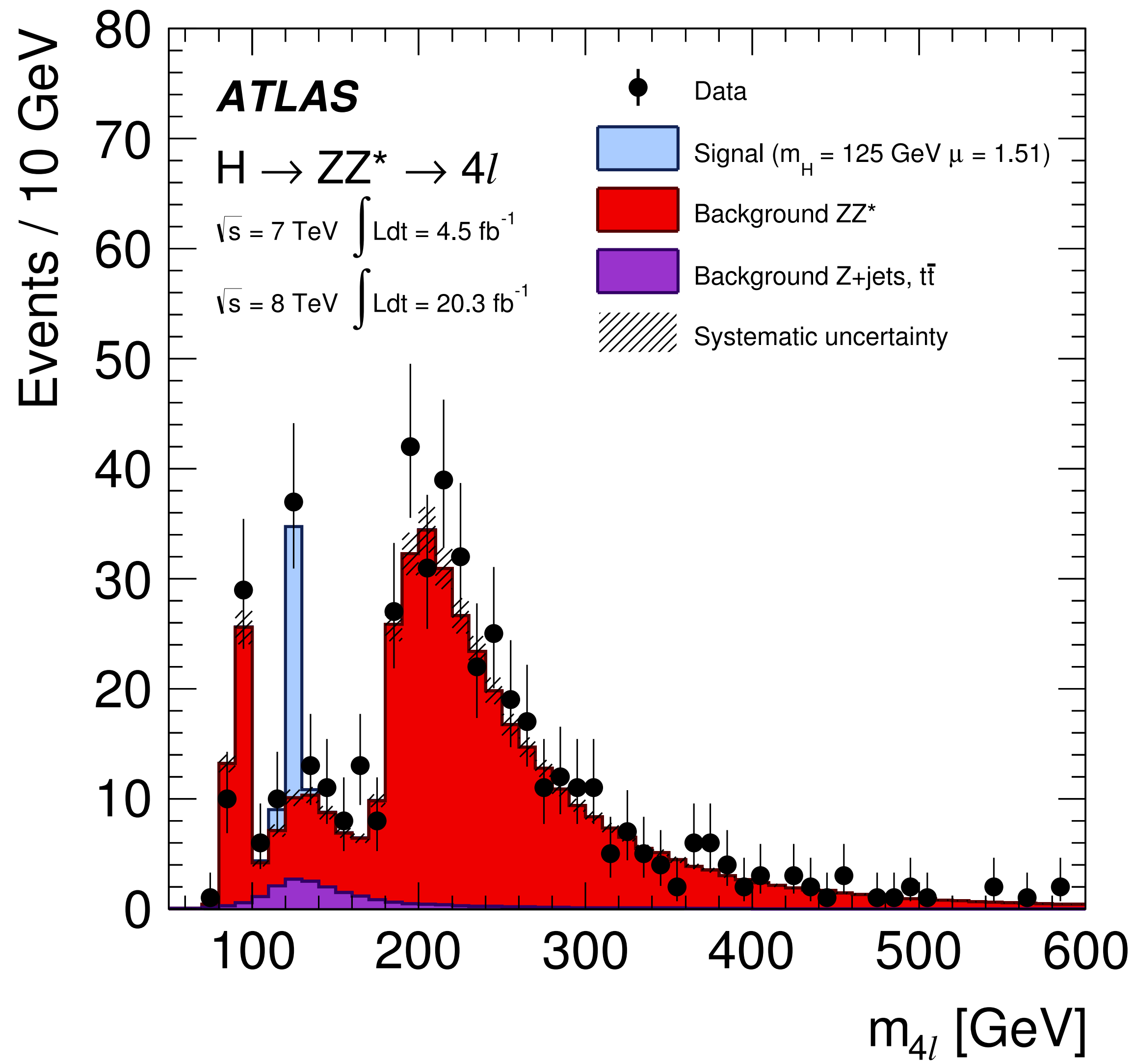
# Higgs Signal and Background Simulation

| Process | Generator |
|---|---|
| ggF, VBF | POWHEG [57, 58]+PYTHIA |
| $WH, ZH, t\bar{t}H$ | PYTHIA |
| $W$+jets, $Z/\gamma^*$+jets | ALPGEN [59]+HERWIG |
| $t\bar{t}, tW, tb$ | MC@NLO [60]+HERWIG |
| $tqb$ | AcerMC [61]+PYTHIA |
| $q\bar{q} \to WW$ | MC@NLO+HERWIG |
| $gg \to WW$ | gg2WW [62]+HERWIG |
| $q\bar{q} \to ZZ$ | POWHEG [63]+PYTHIA |
| $gg \to ZZ$ | gg2ZZ [64]+HERWIG |
| $WZ$ | MadGraph+PYTHIA, HERWIG |
| $W\gamma$+jets | ALPGEN+HERWIG |
| $W\gamma^*$ [65] | MadGraph+PYTHIA |
| $q\bar{q}/gg \to \gamma\gamma$ | SHERPA |

Discovery paper: ATLAS, Phys.Lett.B716(2012)1

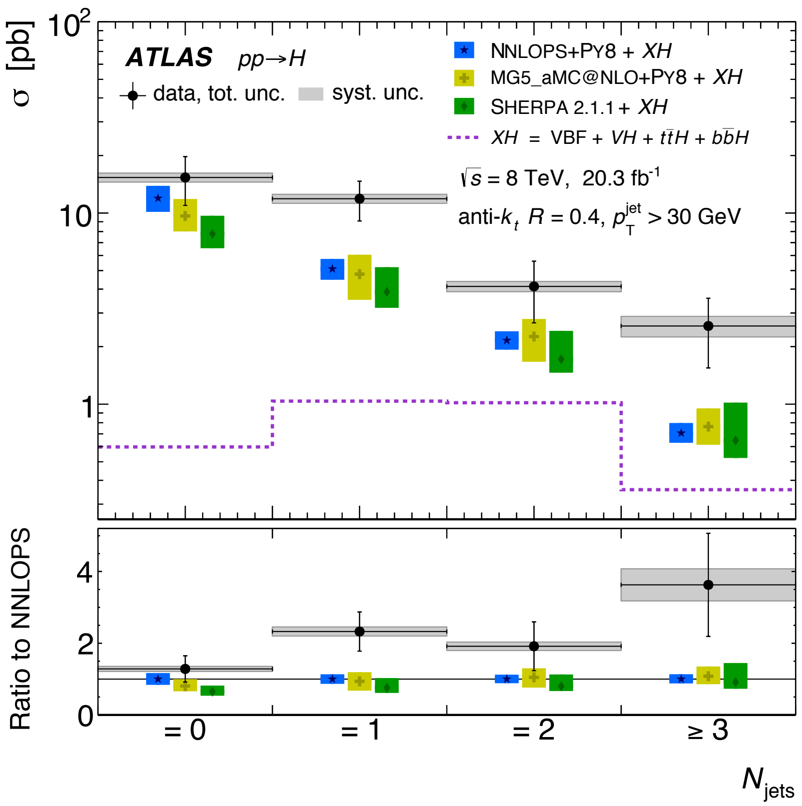
# Higgs→4 leptons Signal and Background



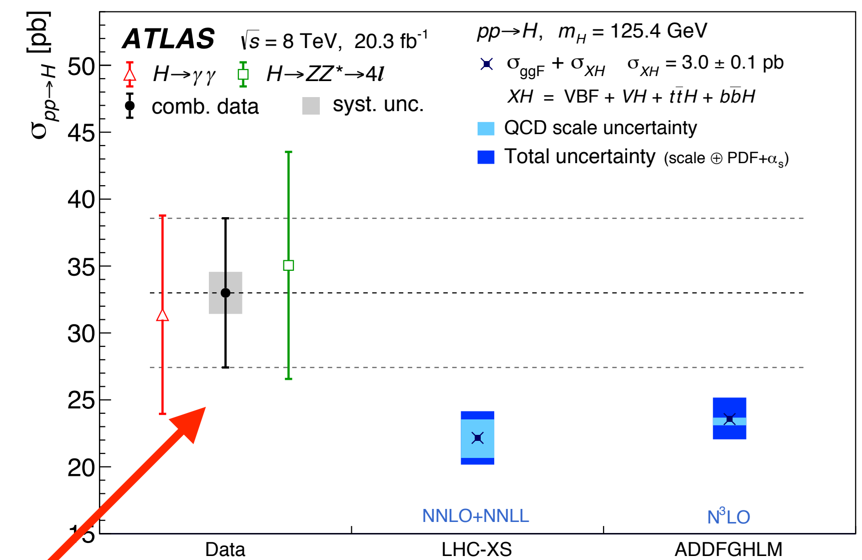




ATLAS, Phys.Rev.D91(2015)012006

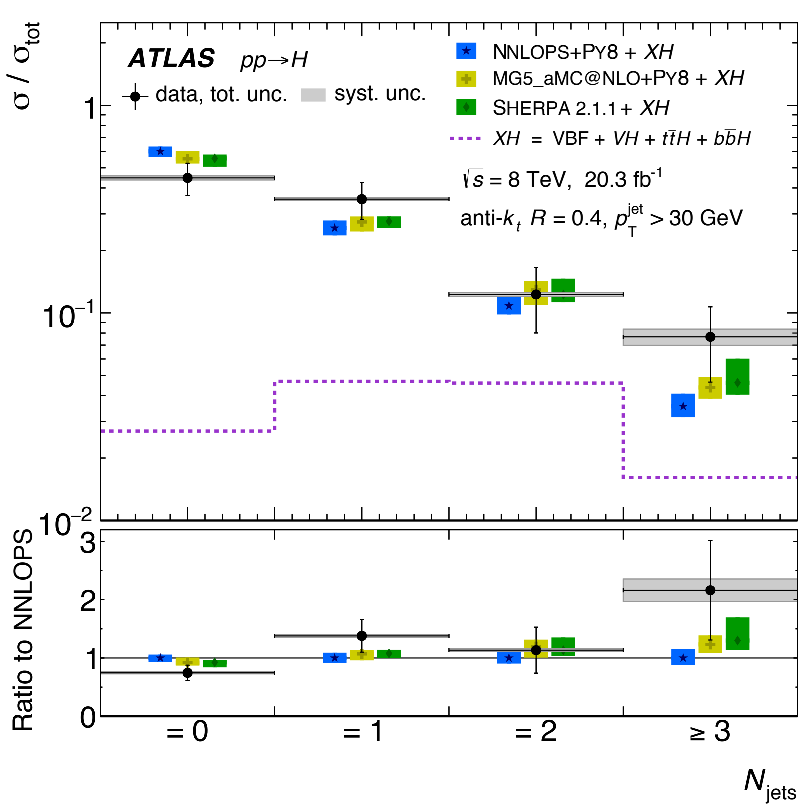
# Higgs + Multijets Rates




| Monte Carlo event generators | |
|---|---|
| SHERPA 2.1.1 [36, 37] | $H + 0, 1, 2$ jets @NLO [i,j] |
| MG5_aMC@NLO [38, 39] | $H + 0, 1, 2$ jets @NLO [i,k,l] |
| POWHEG NNLOPS [40, 41] | $\mathrm{NNLO}_{\geq 0j}$, $\mathrm{NLO}_{\geq 1j}$ [e,l,m] |



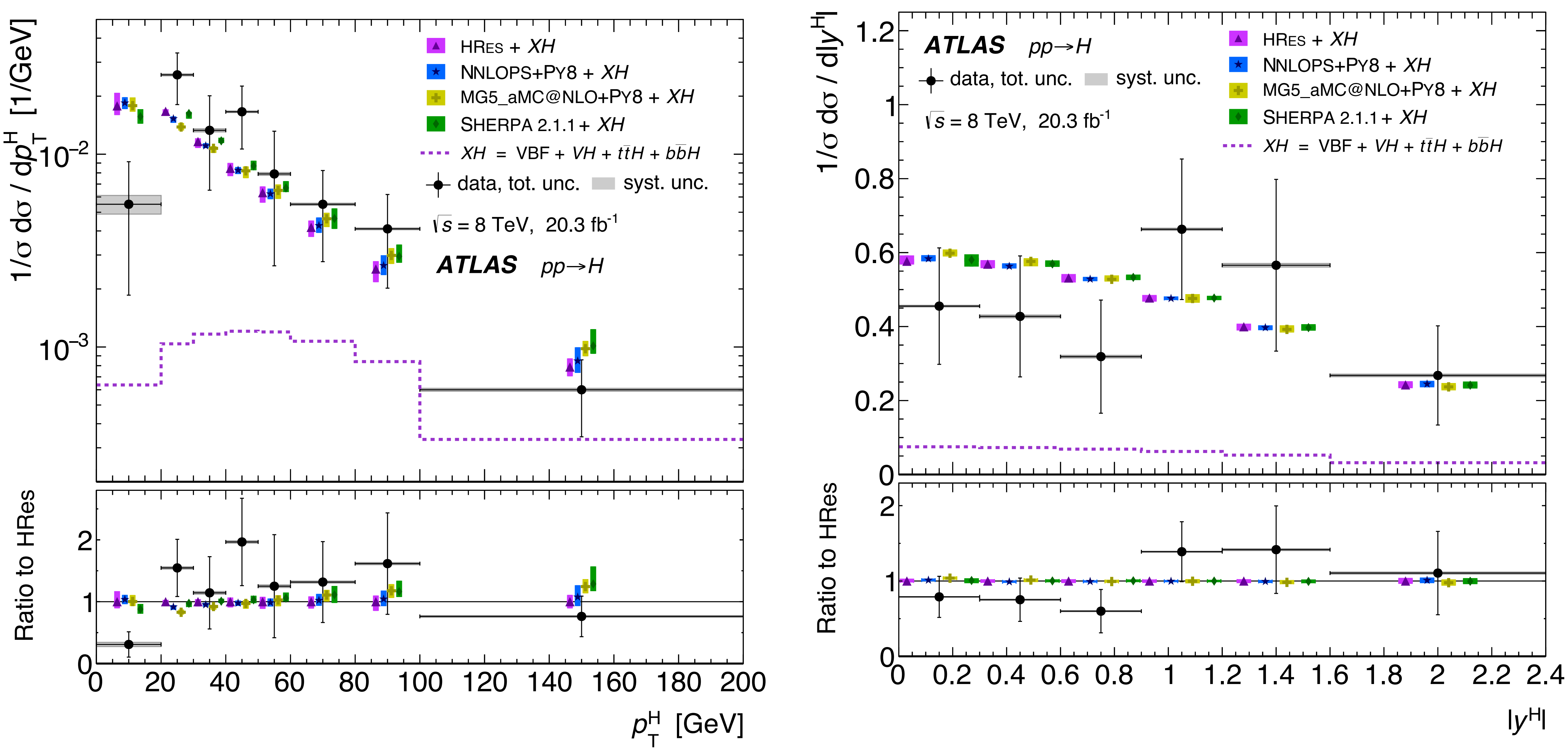

- pp→H cross section is larger than predicted




- <u>Relative</u> rates are as predicted

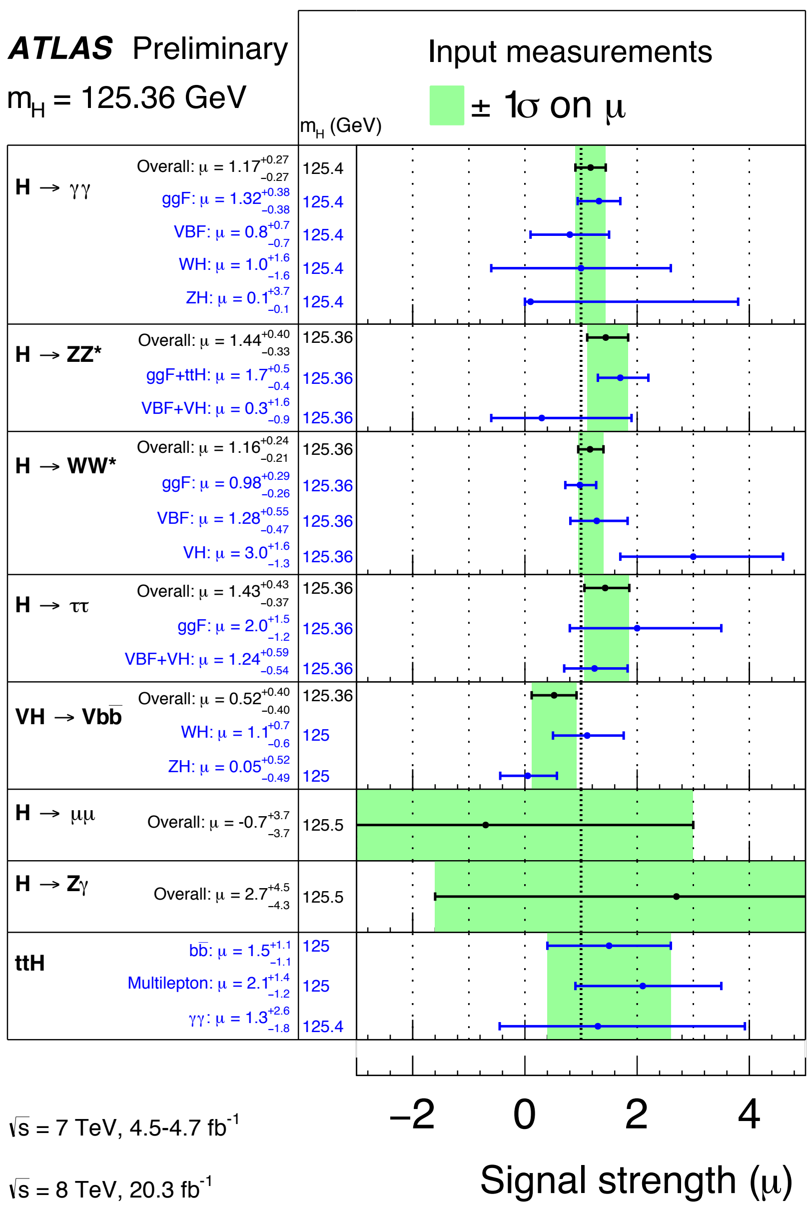
ATLAS, Phys.Rev.Lett.115(2015)091801

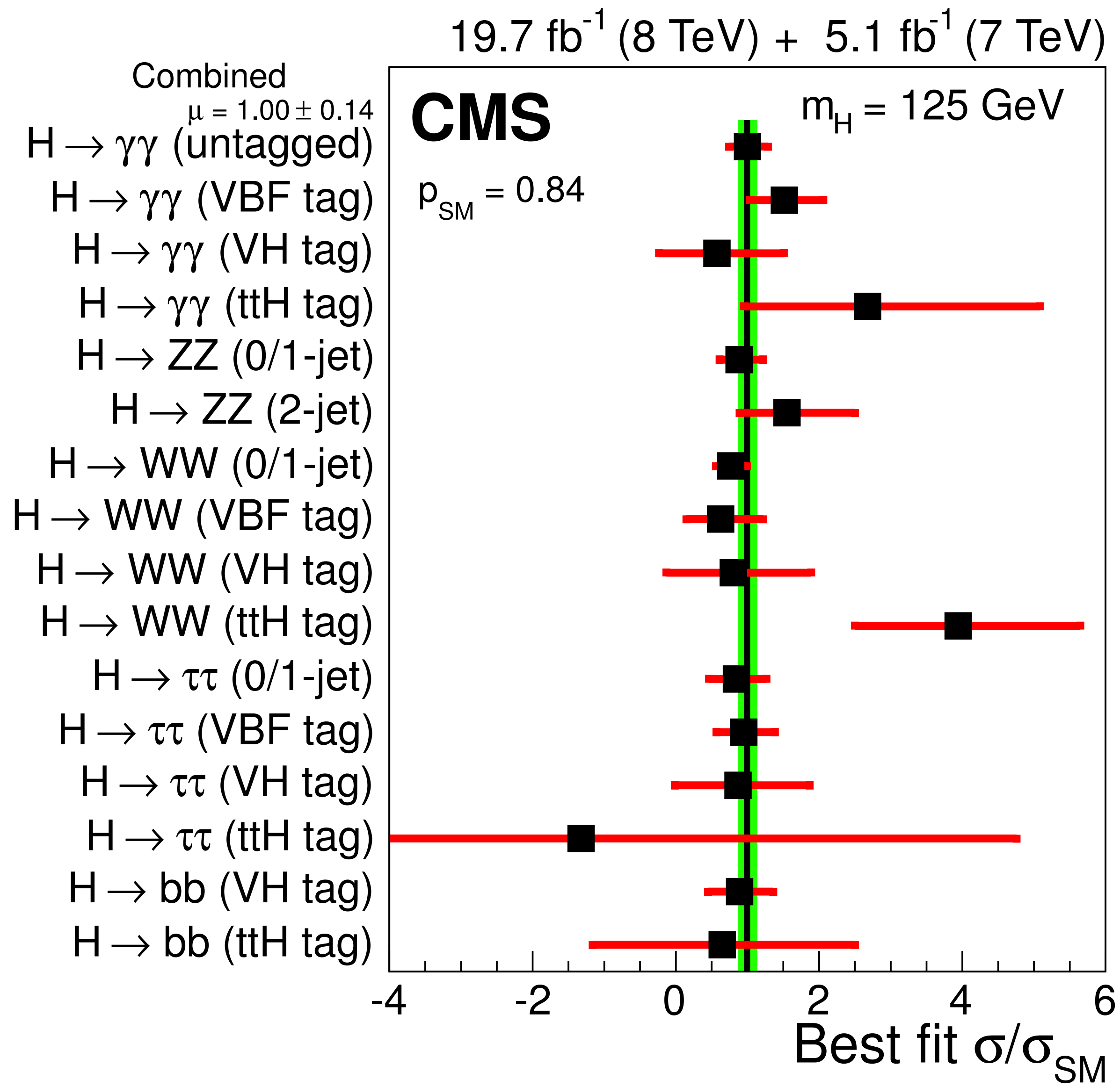
# Higgs Differential Distributions




ATLAS, Phys.Rev.Lett.115(2015)091801

# Higgs Decays




- No sign of deviations from Standard Model

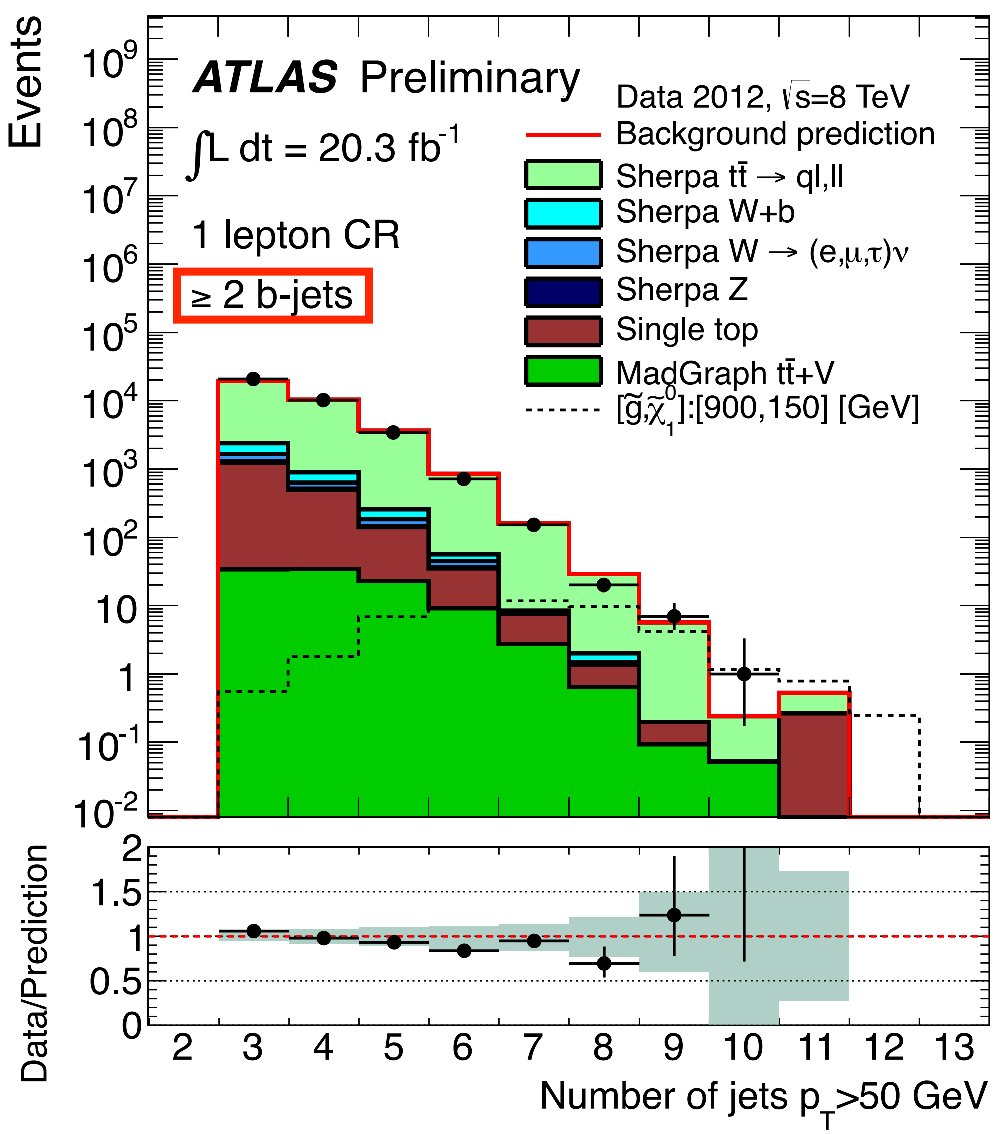
# Beyond Standard Model Simulation

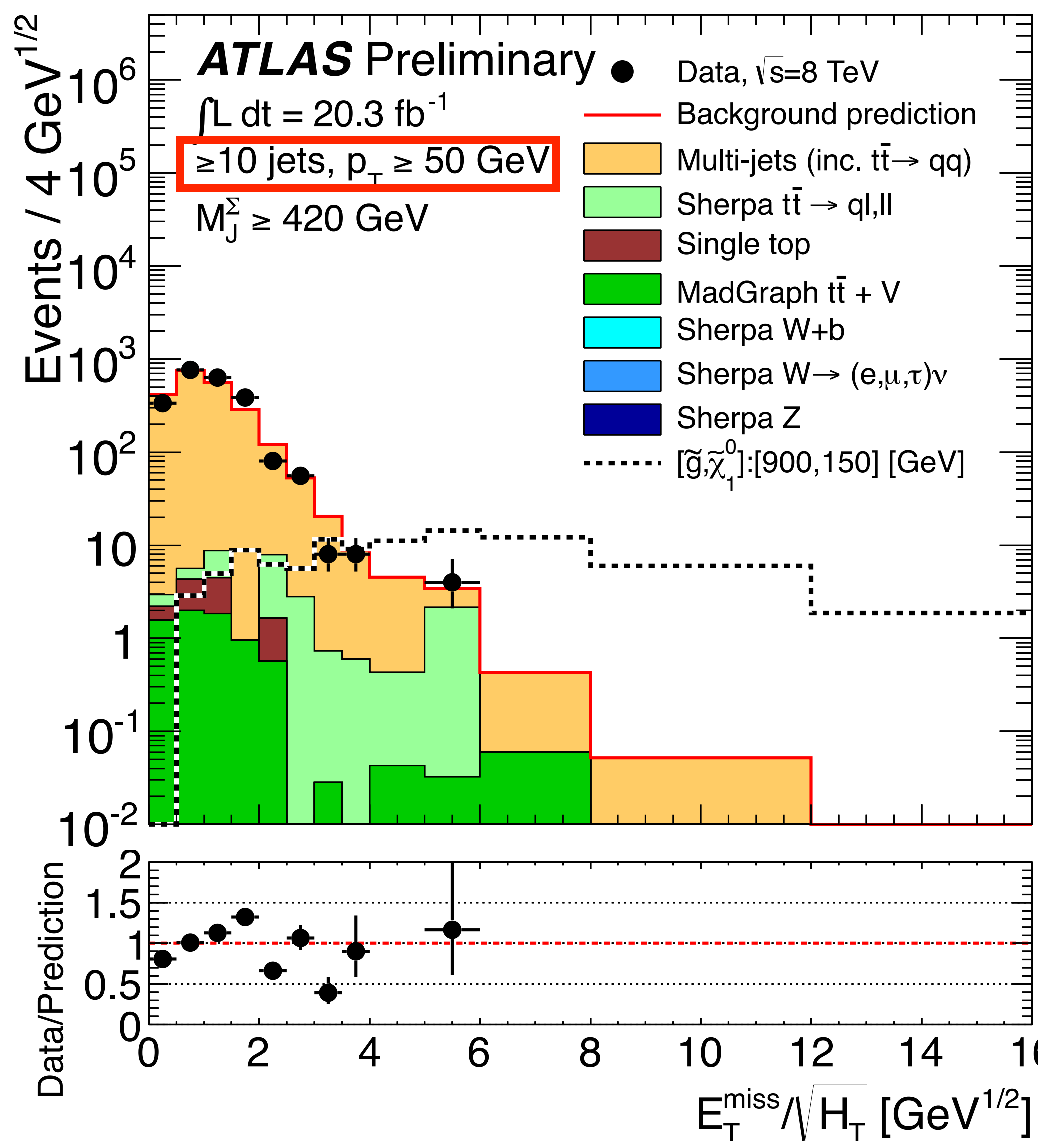
# BSM Simulation

- Main generators have some BSM models built in
  - Pythia 6 has the most models
  - Herwig++ has careful treatment of SUSY spin correlations and off-shell effects
- Trend is now towards external matrix element generators: FeynRules + MadGraph, ...
- QCD corrections and matching/merging still needed

# Searching for new signals

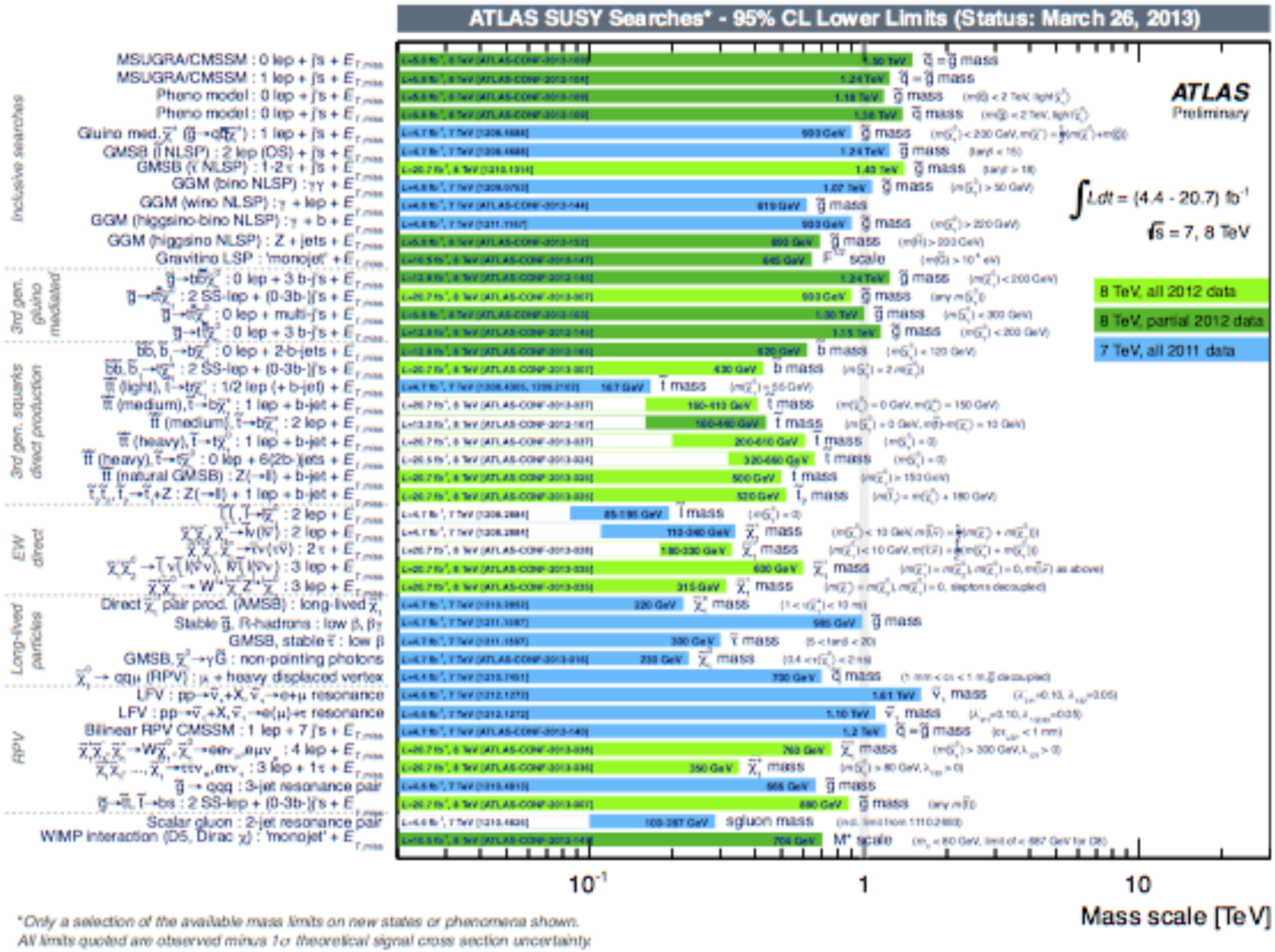
ATLAS CONF-2013-054



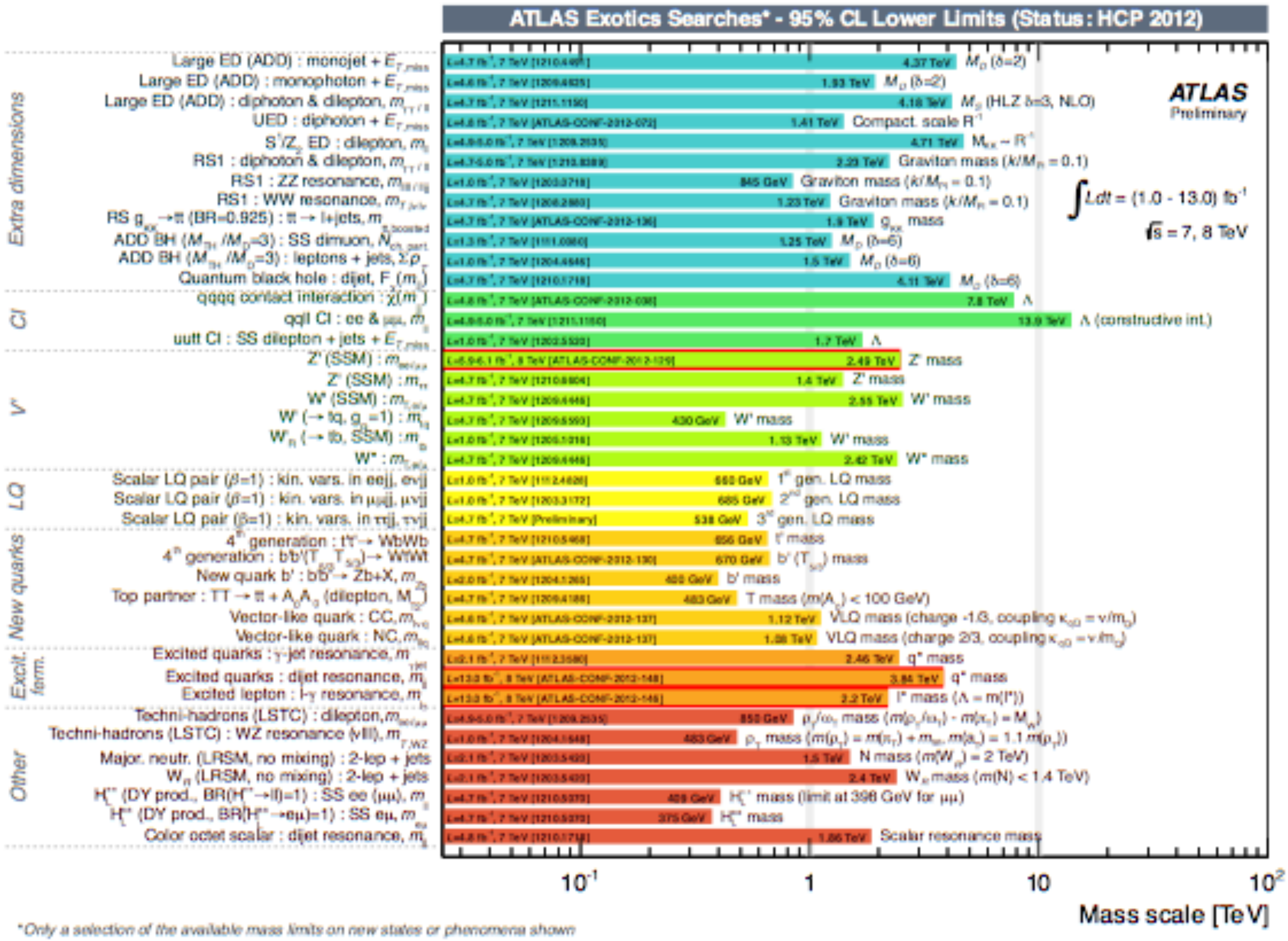




- Dashed = Herwig++ $\tilde{g}\tilde{g},\ \tilde{g} \rightarrow t + \bar{t} + \tilde{\chi}_1^0$
- Background: mostly Sherpa LO multijet merging

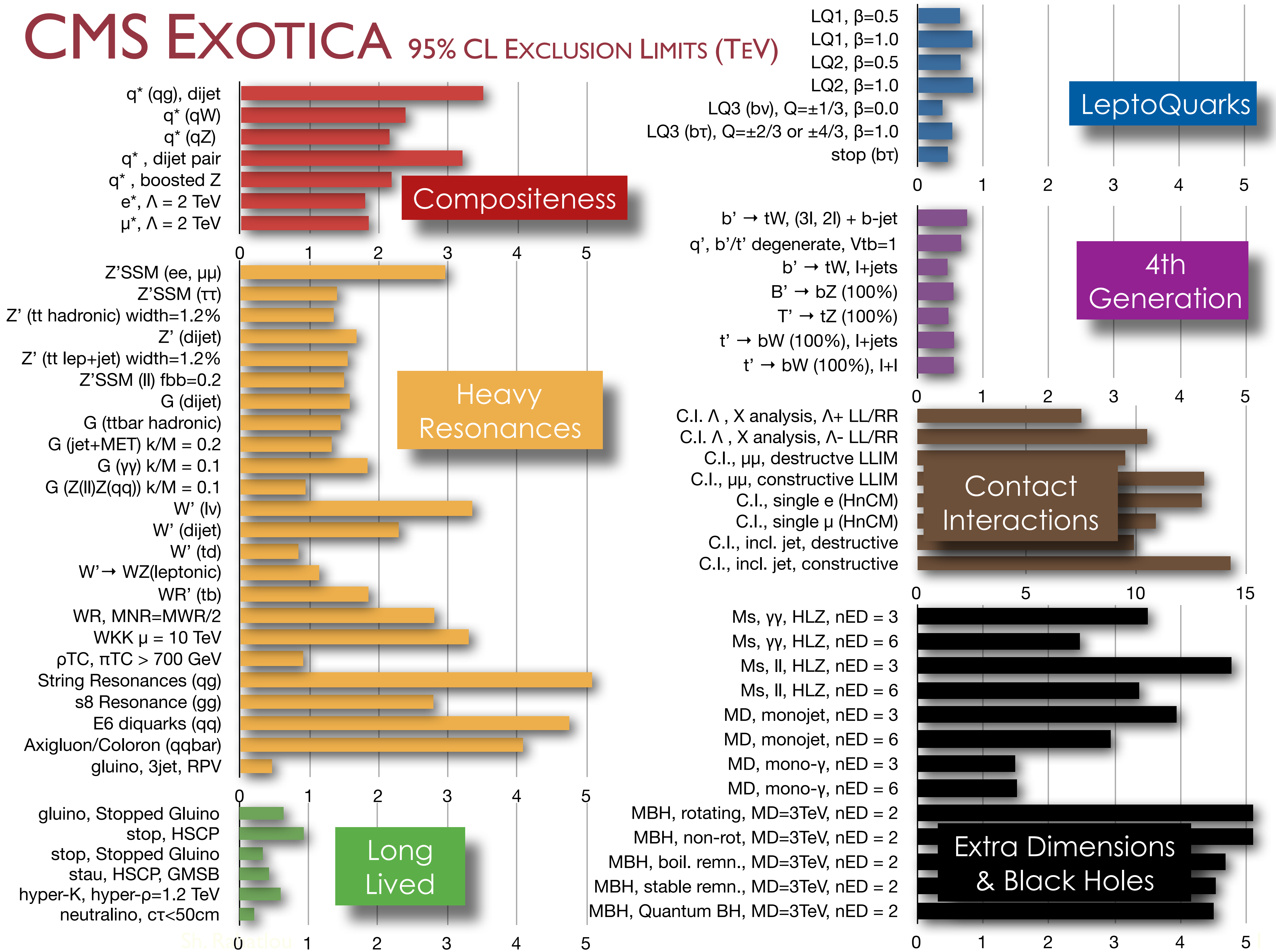
# ATLAS SUSY Search



# ATLAS Exotica Search



# CMS Exotica Search



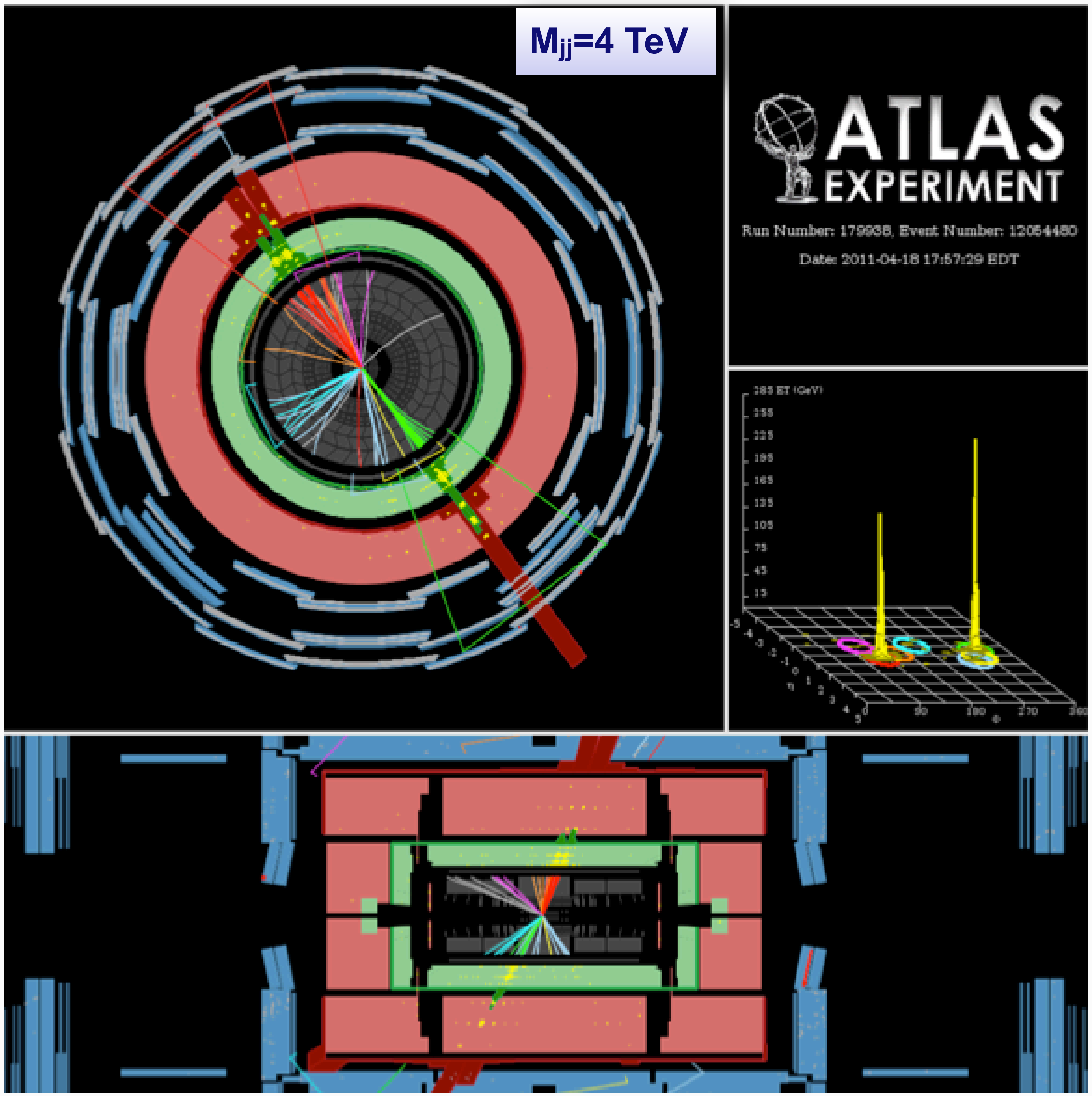
# Conclusions and Prospects

- Standard Model has (so far) been spectacularly confirmed at the LHC
- Monte Carlo event generation of (SM and BSM) signals and backgrounds plays a big part
- Matched NLO and merged multi-jet generators have proved essential
    - Automation and NLO merging in progress
    - NNLO much more challenging
- Still plenty of scope for new discoveries!

# Thanks for listening!

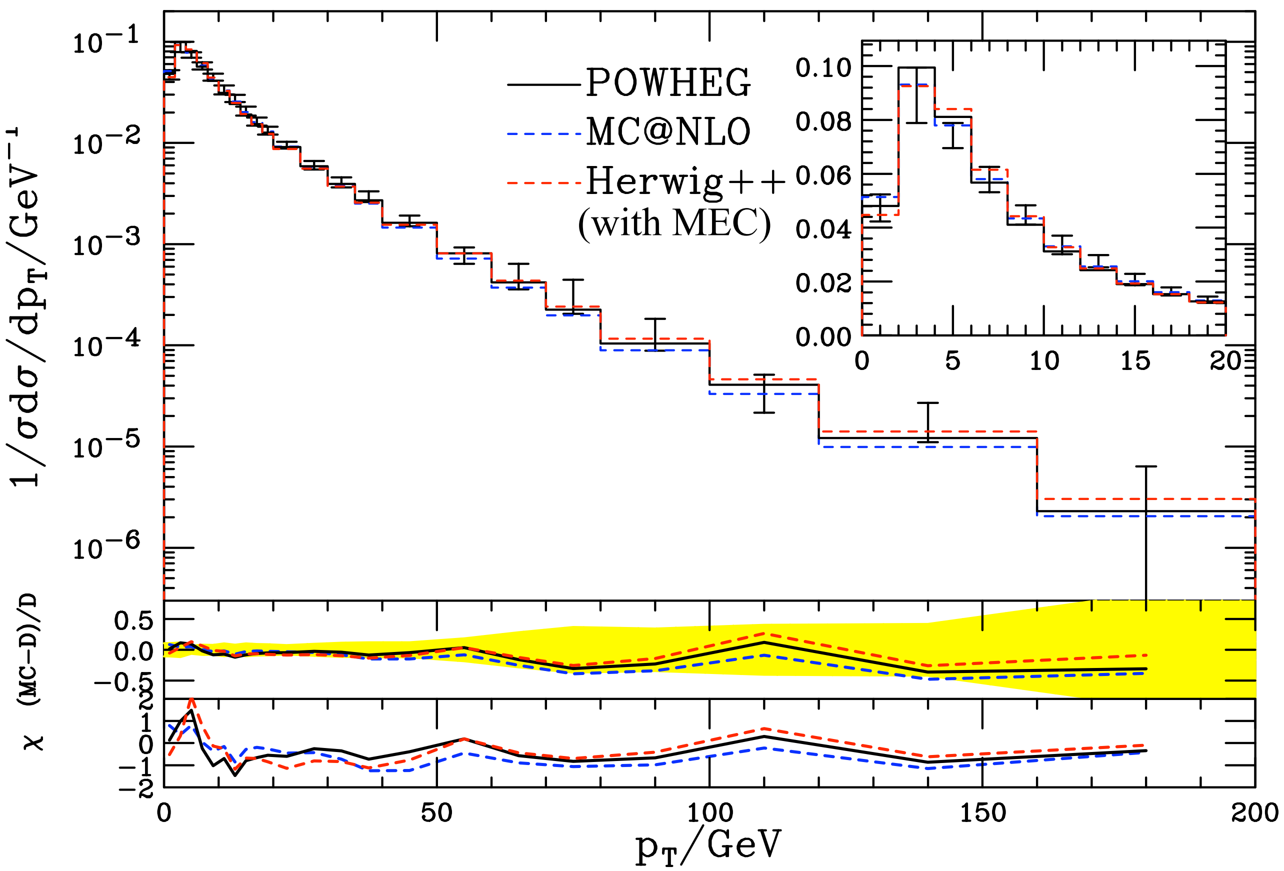
# Backup

# A high-mass dijet event

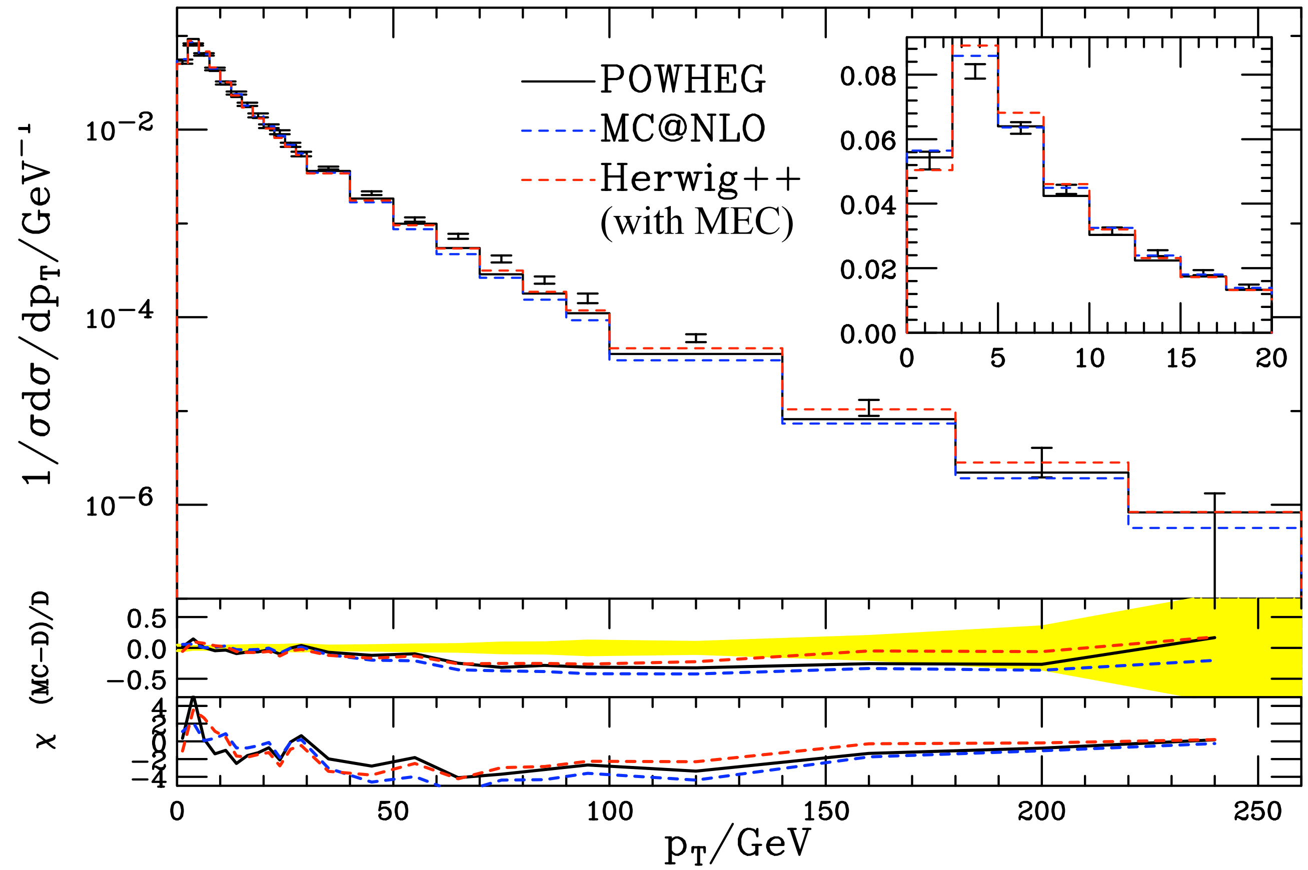


# W & $Z^0$ at Tevatron

D0 Run I: W




D0 Run II: $Z^0$

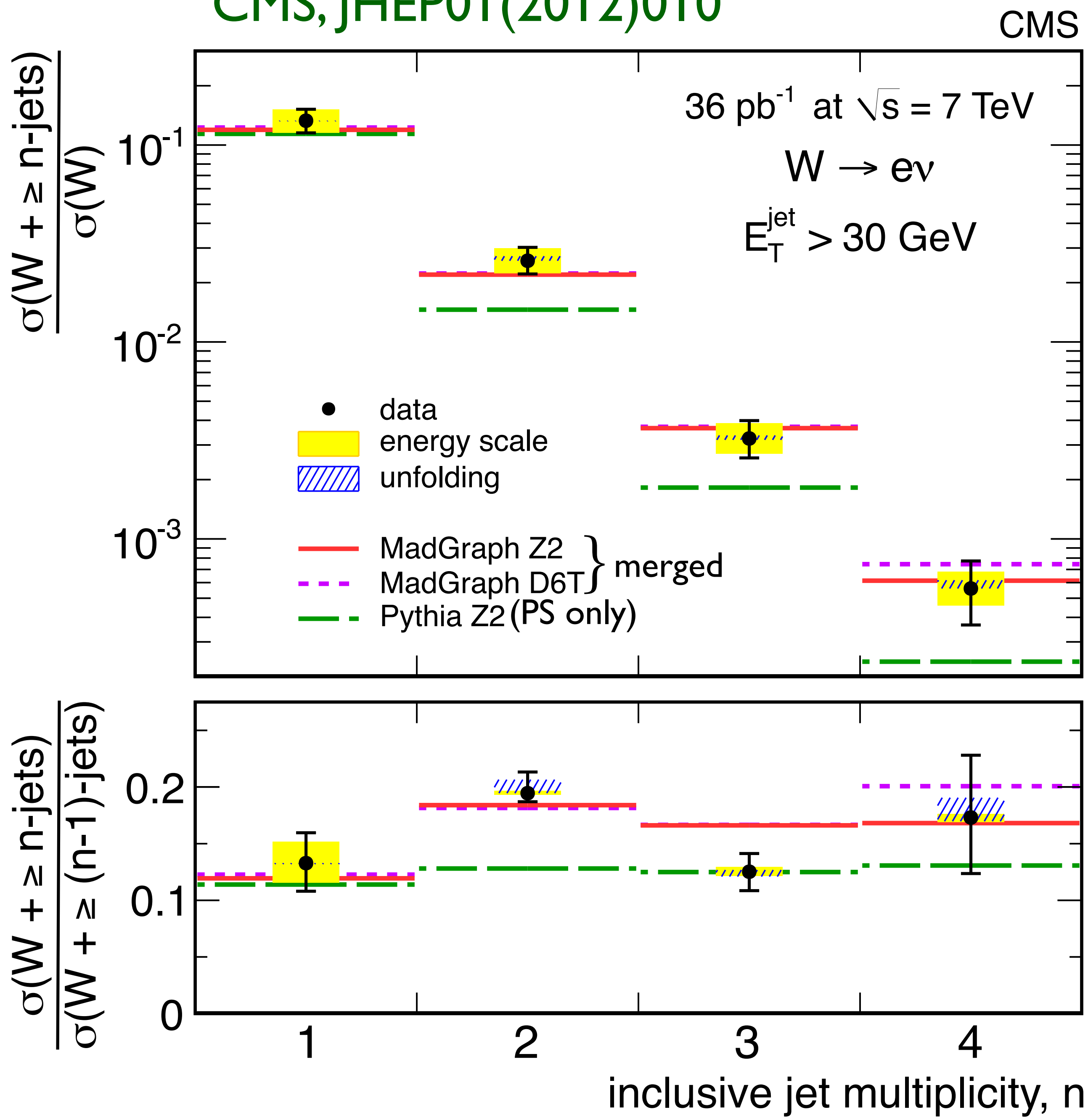



- Herwig++ includes W/Z+jet (MEC)
- All agree (tuned) at Tevatron
- Normalized to data

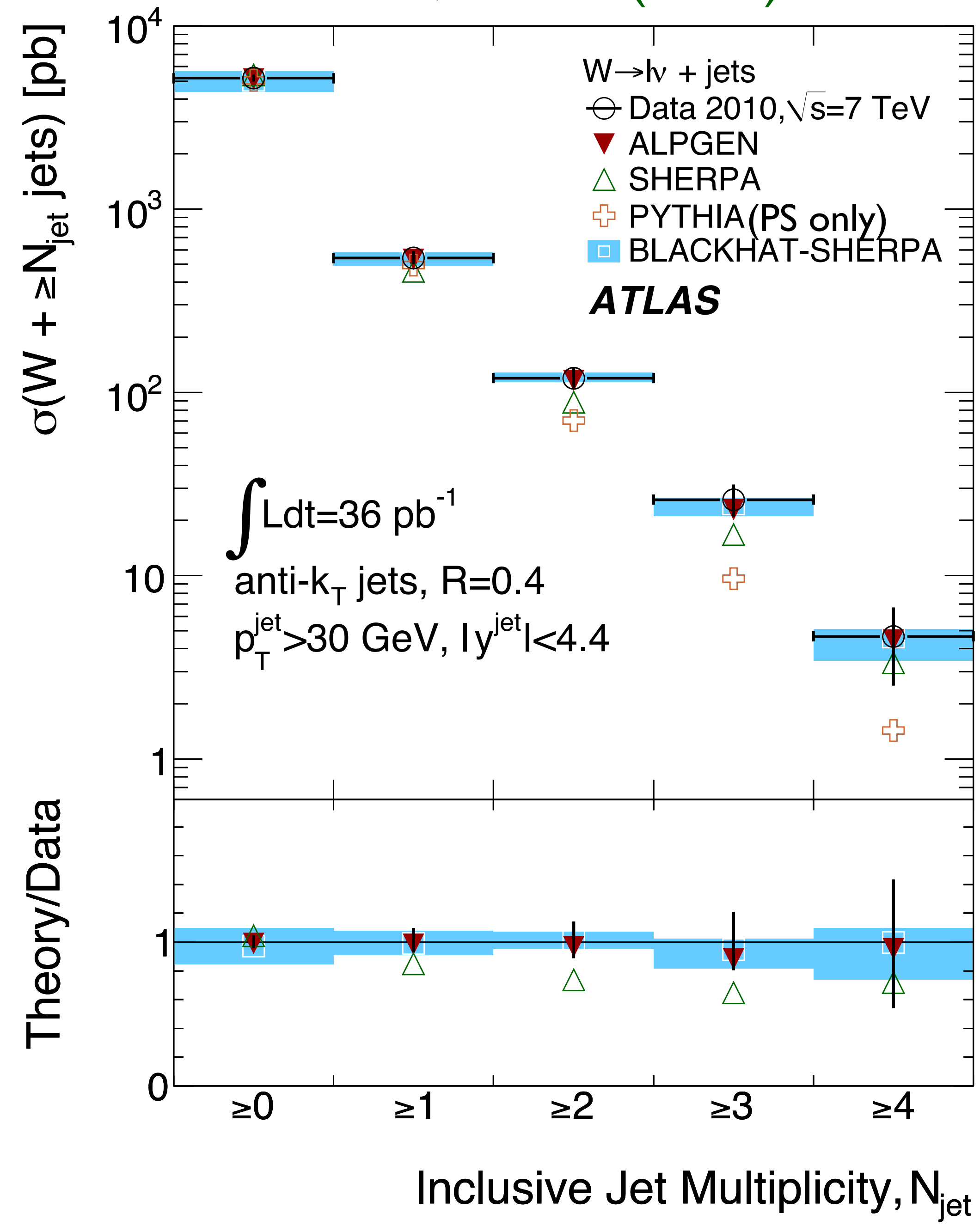
Hamilton, Richardson, Tully JHEP10(2008)015

# W+jets at LHC

CMS, JHEP01(2012)010

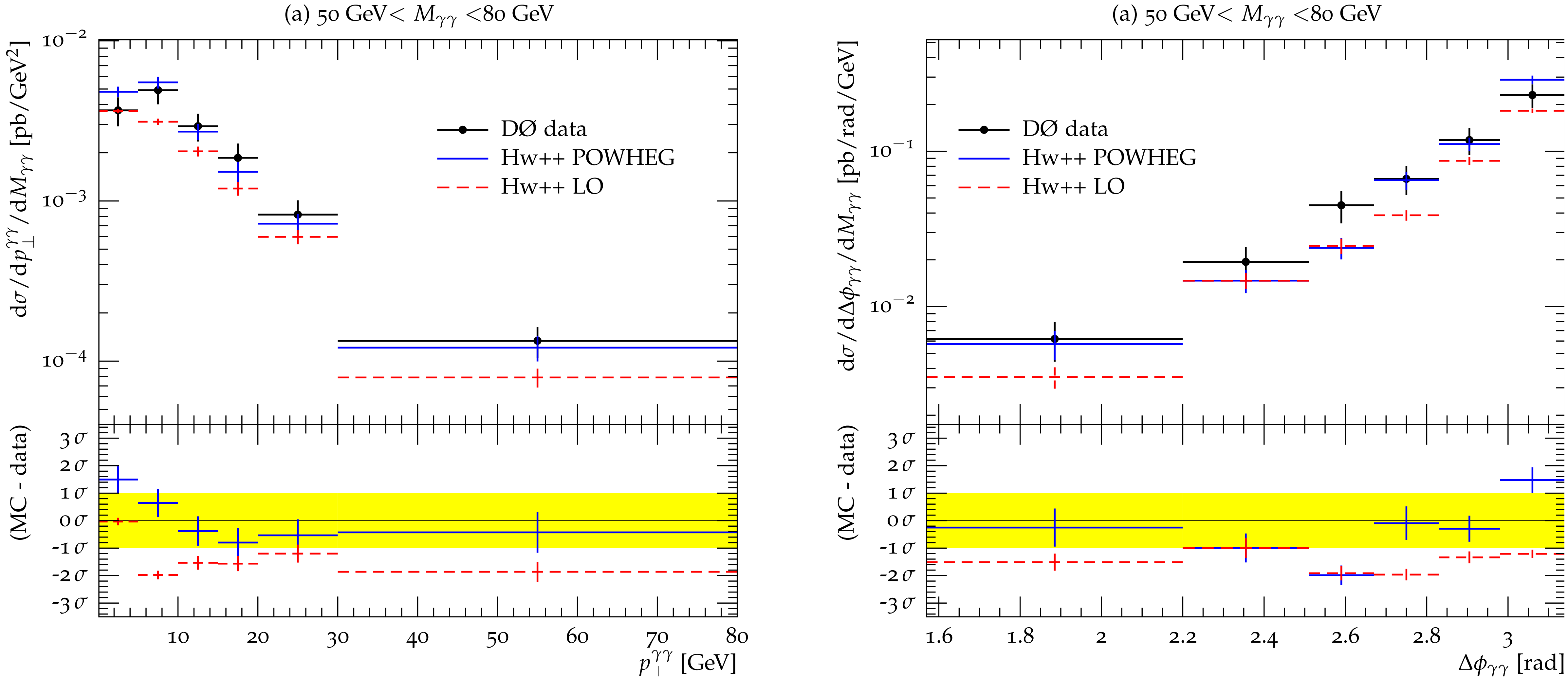



ATLAS, PRD85(2012)092002




- Very good agreement with predictions from merged simulations, while parton shower alone starts to fail for $n_{jet} \geq 2$

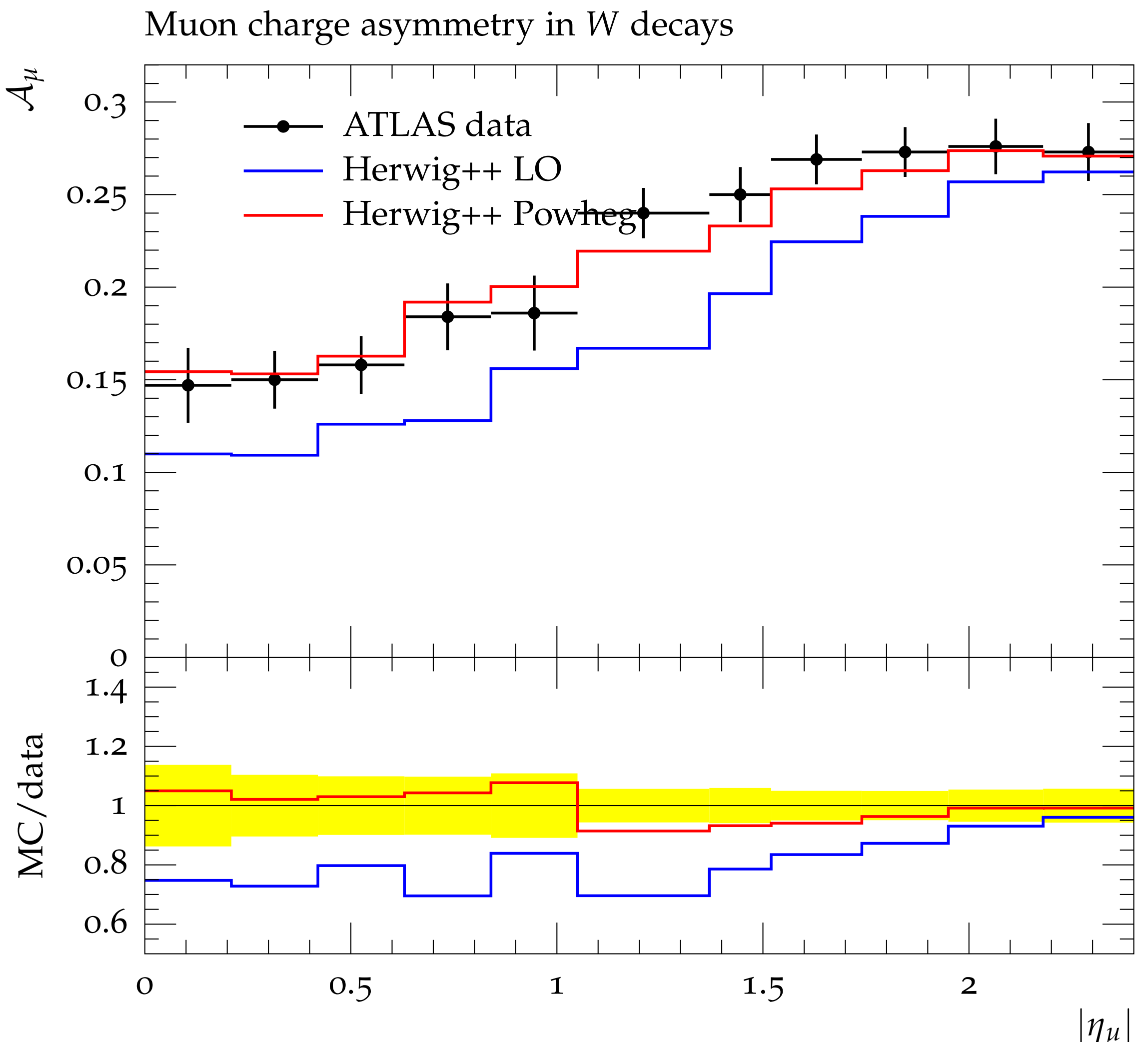
# γγ at Tevatron

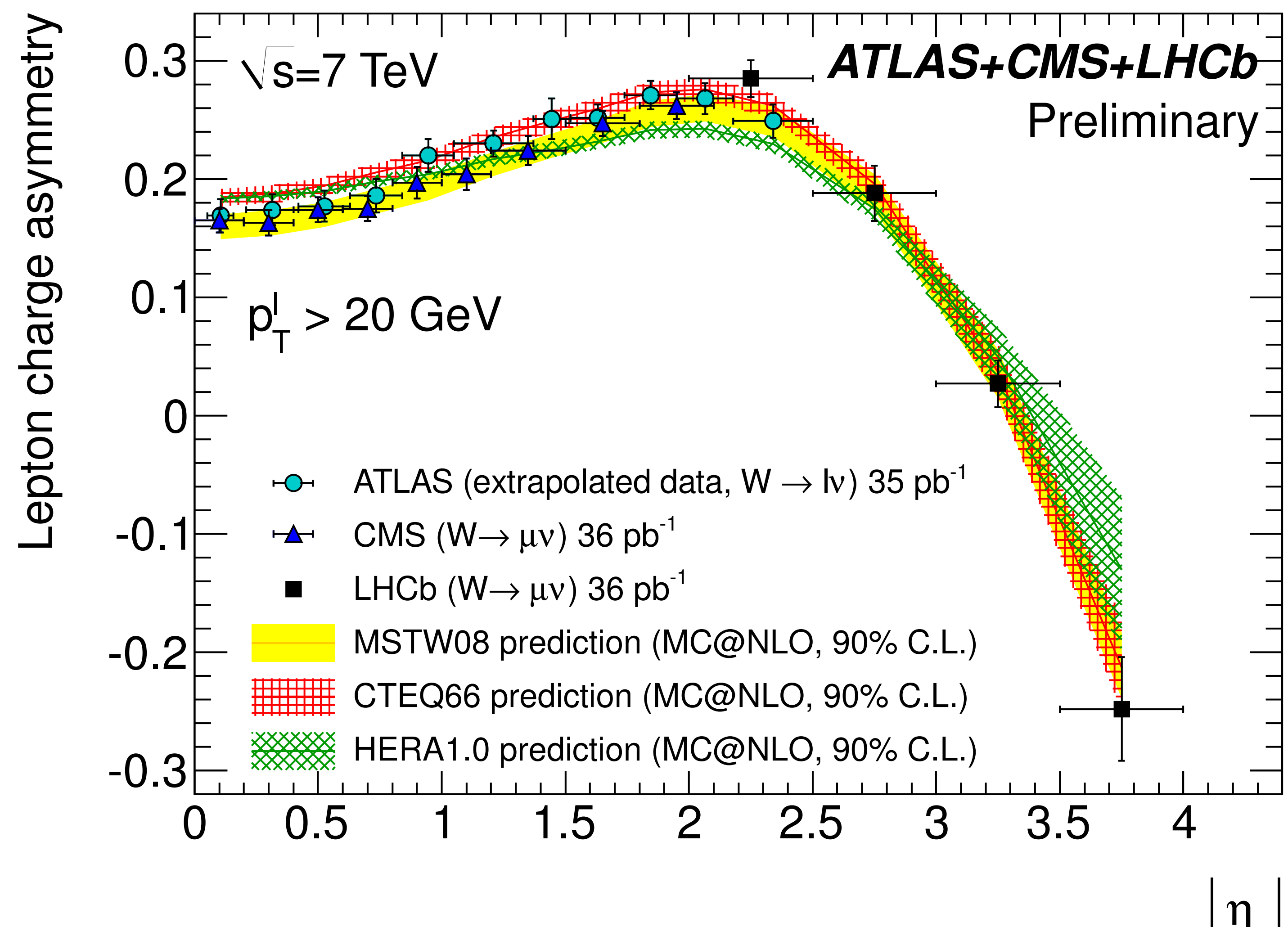



- Absolute normalization ➡ LO too low
- POWHEG agrees with rate and distribution
- At LHC, important background for Higgs search

D'Errico & Richardson, JHEP02(2012)130

# W asymmetry at LHC



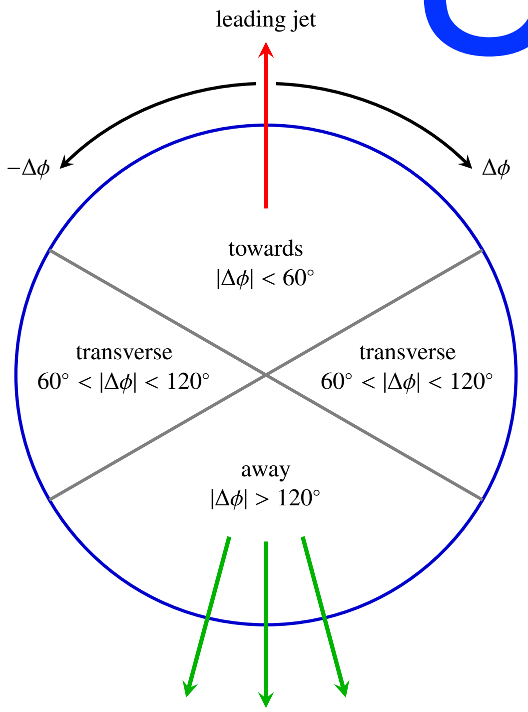

$$A_\mu = \frac{N(\mu^+) - N(\mu^-)}{N(\mu^+) + N(\mu^-)} \qquad \eta_\mu = \log\tan(\theta_\mu/2)$$

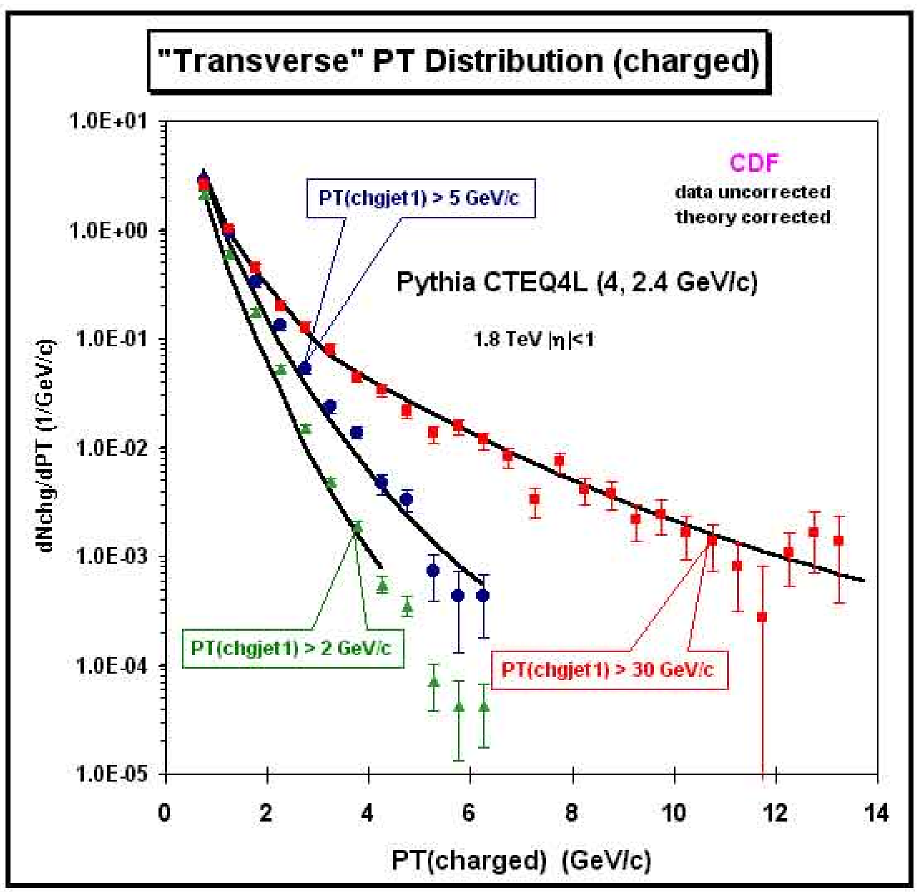
ATLAS-CONF-1211-129

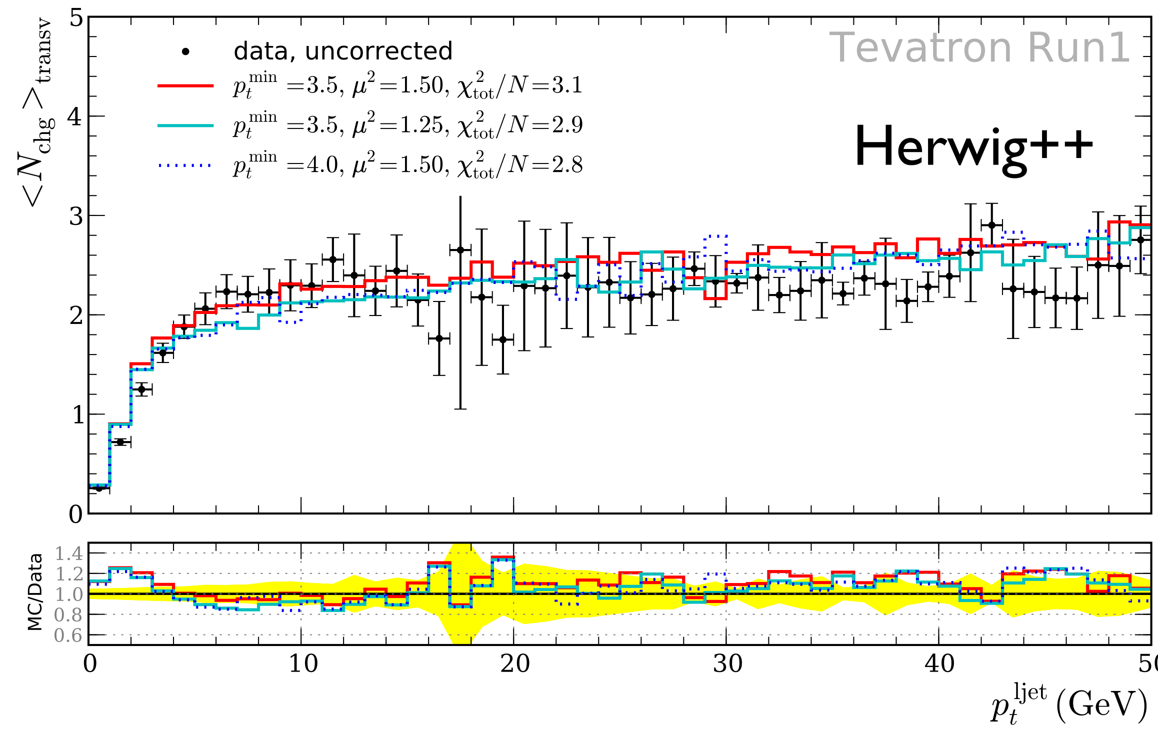
- Asymmetry probes parton distributions

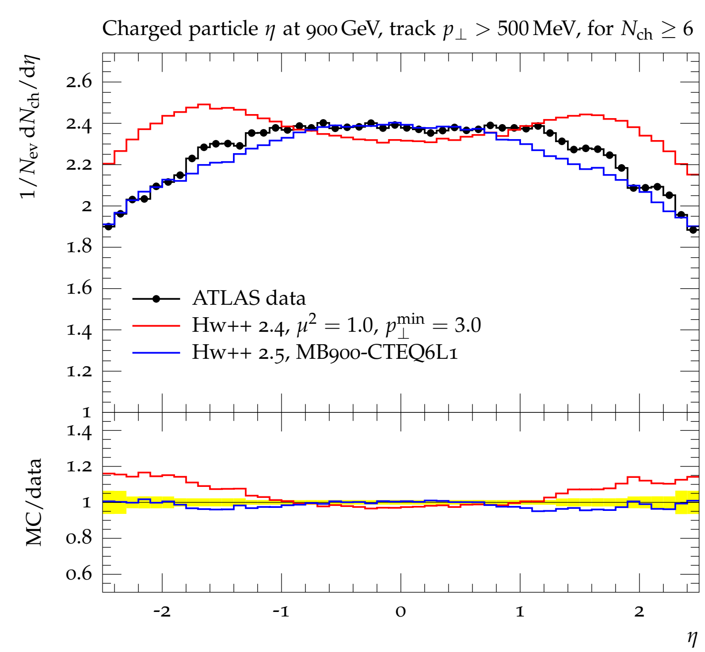
$$u\bar{d} \to W^+ \to \mu^+\nu_\mu \quad \textbf{vs} \quad d\bar{u} \to W^- \to \mu^-\bar{\nu}_\mu$$

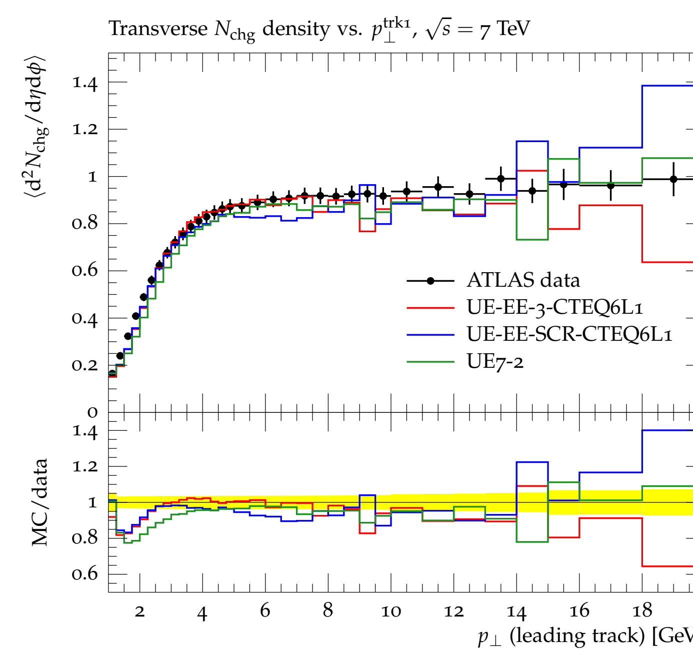
# Underlying Event



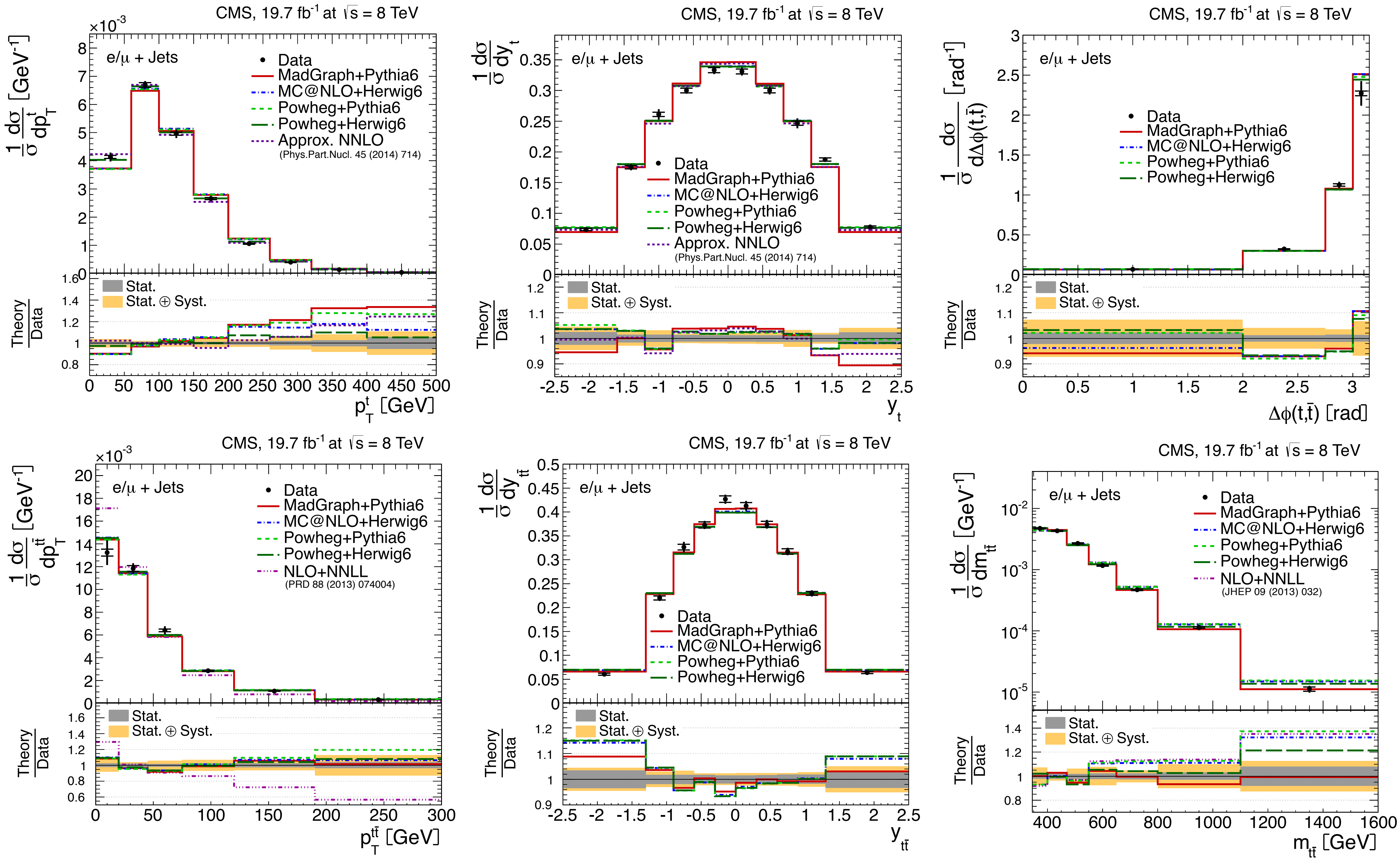




ATLAS PRD83(2011)112001

Gieseke, Röhr, Siódmok, arXiv:1206.2205

# Top pairs at 8 TeV



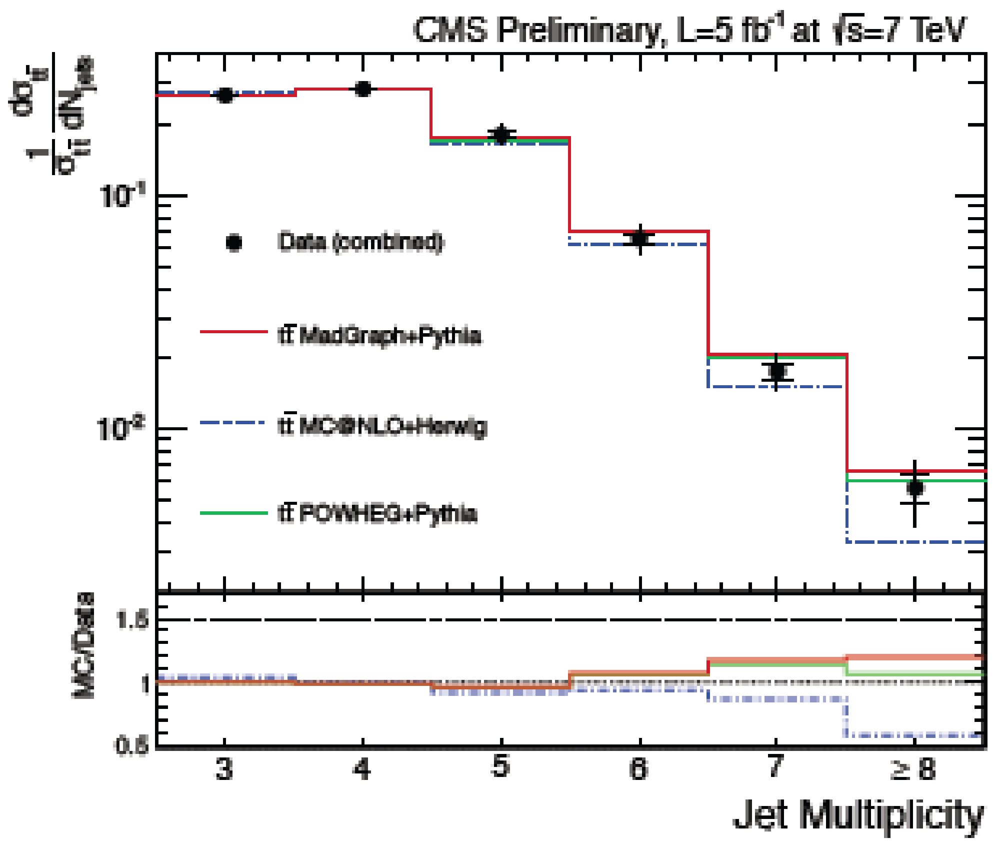

CMS, 1505.04480

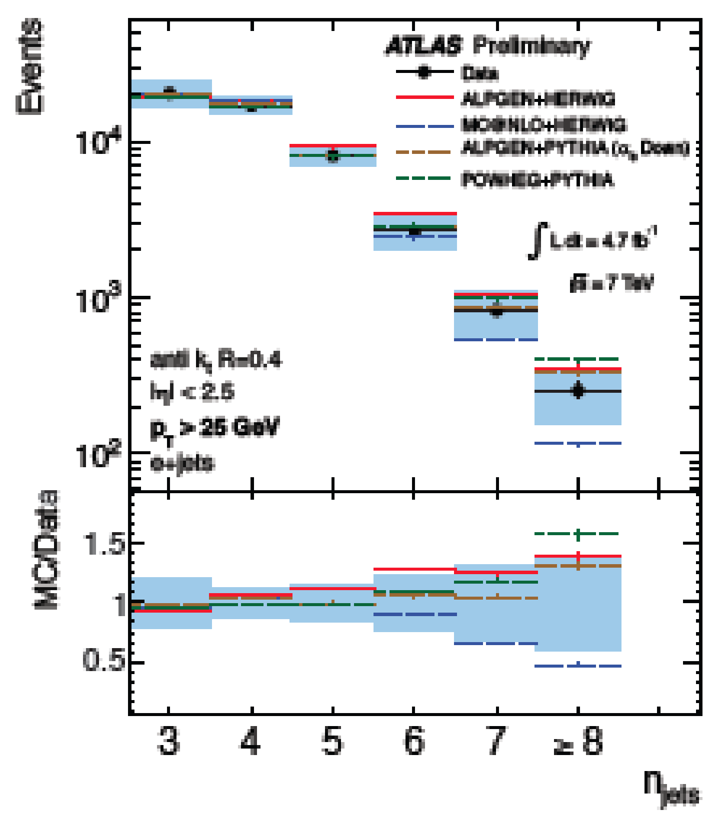
# Top+jets

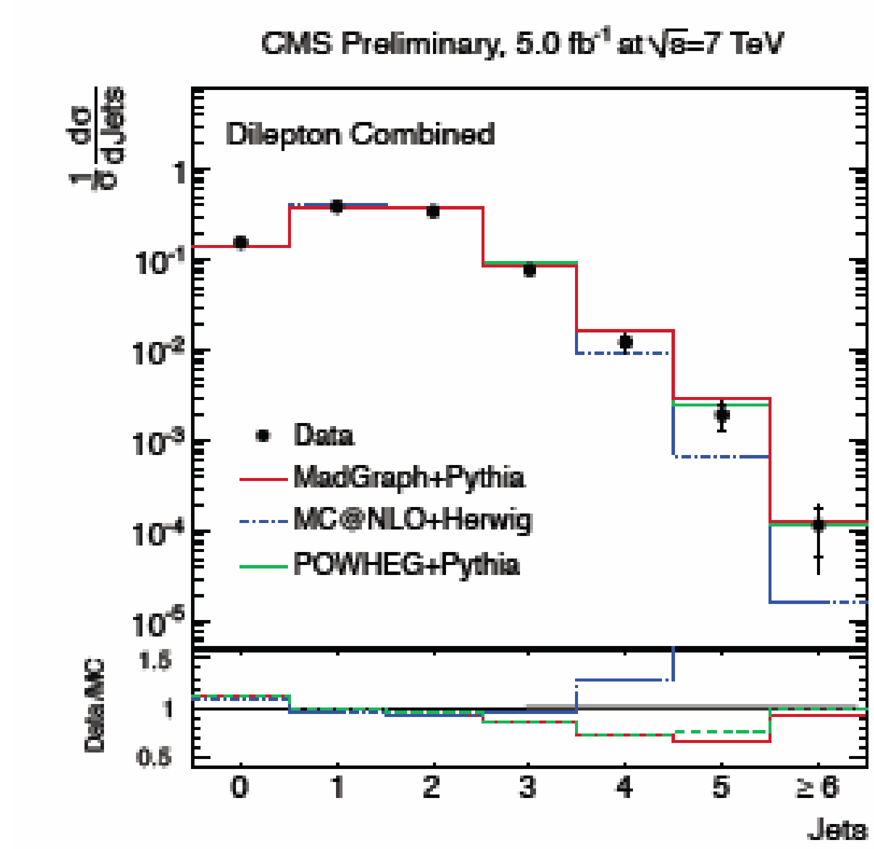
**CMS PAS TOP-12-018** (l+jets)
**ATLAS-CONF-2012-155** (l+jets)

$$\frac{1}{\sigma}\frac{d\sigma(N_{jets})}{dN_{jets}}$$

**CMS PAS TOP-12-023** (dilepton)



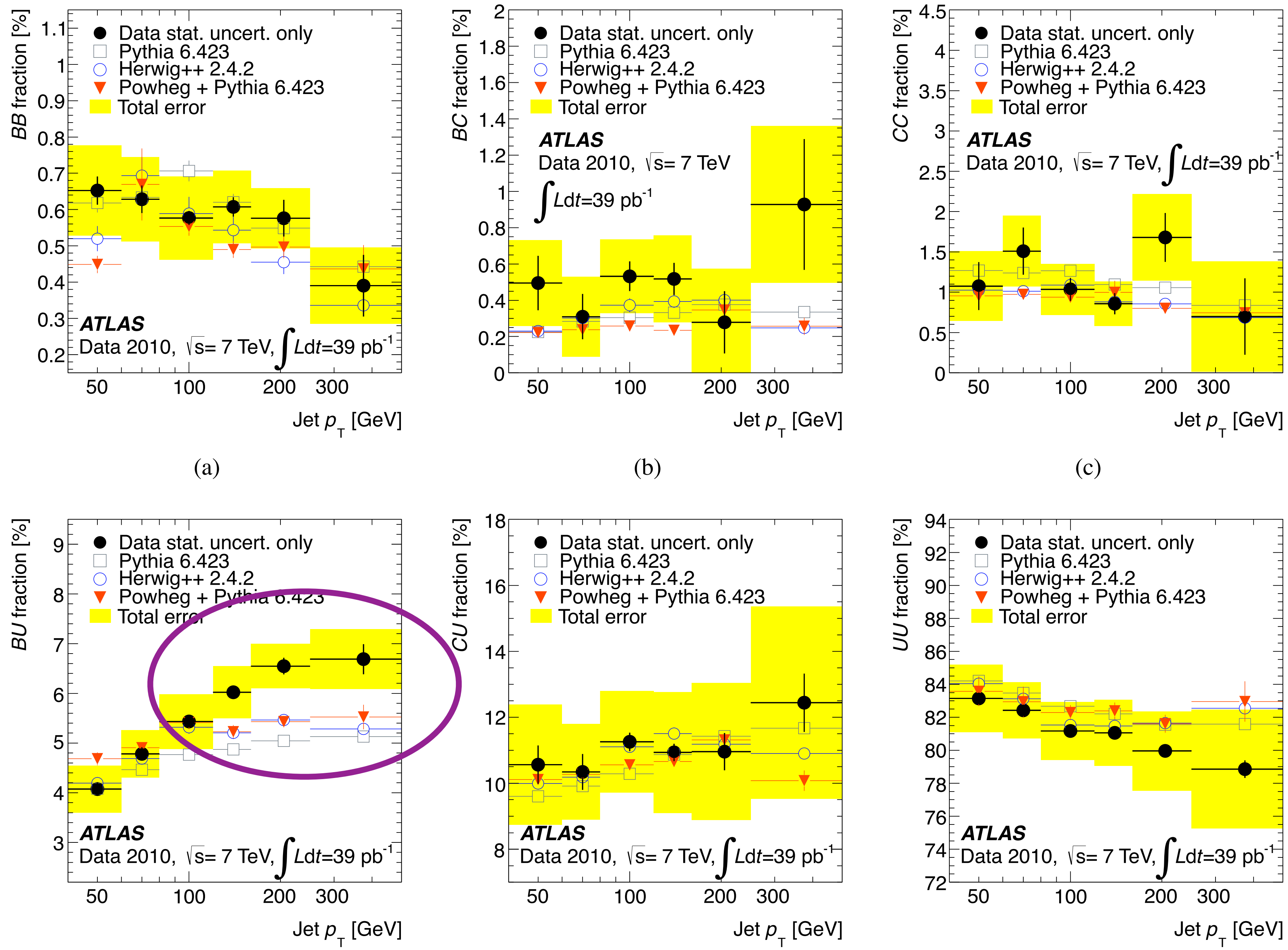




- Matched NLO not adequate for >2 extra jets
- Merged multijets better there (for dσ/σ)

# But all is not perfect ...

- Dijet flavours versus jet $p_T$

ATLAS, arXiv:1210.0441




- Interesting excess of (single) b quark jets

# Automatic NLO matching

- MC@NLO-type
  - MadGraph5_aMC@NLO (MadLoop5)

    Alwall et al., 1405.0301
  - Sherpa+OpenLoops

    Höche et al., 1111.1220; 1201.5882
  - Herwig++ Matchbox+OpenLoops/GoSam

    Plätzer, Gieseke, 1109.6256; Bellm et al., 1310.6877
- POWHEG-type

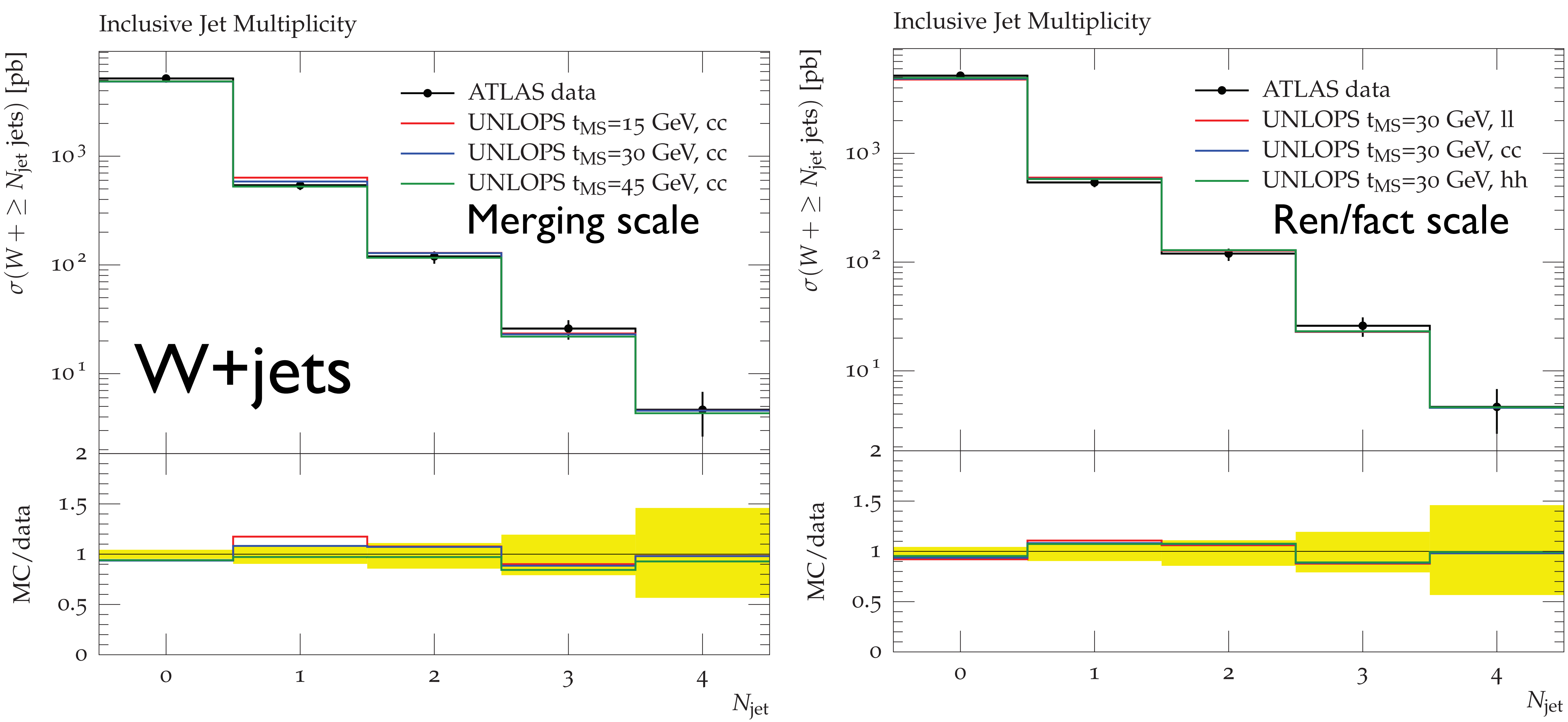
# Combined matching+merging

- NLO calculations generally refer to inclusive cross sections e.g. $\sigma(W+\geq n \text{ jets})$
- Multijet merging does not preserve them, because of mismatch between exact real-emission and approximate (Sudakov) virtual corrections
- When correcting this mismatch, one can simultaneously upgrade them to NLO
- There remains the issue of merging scale dependence beyond NLO (large logs)

# Combined matching+merging

- Many competing schemes (pp, under development)
  - MEPS@NLO (SHERPA)
  - FxFx (aMC@NLO) Frederix & Frixione, arXiv:1209.6215
  - UNLOPS (Pythia 8) Lönnblad & Prestel, arXiv:1211.7278
  - MatchBox (Herwig++) Plätzer, arXiv:1211.5467
  - MiNLO (POWHEG) Hamilton et al., arXiv:1212.4504
  - GENEVA Alioli, Bauer et al., arXiv:1212.4504
- Some key ideas in LoopSim Rubin, Salam & Sapeta, JHEP1009, 084

# Combined matching+merging




UNLOPS: Lönnblad & Prestel, arXiv:1211.7278

- Scale dependences almost eliminated

# MEPS@NLO

- W+0,1,2 jets at NLO
- W+3,4 jets at LO

Höche et al., 1207.5030

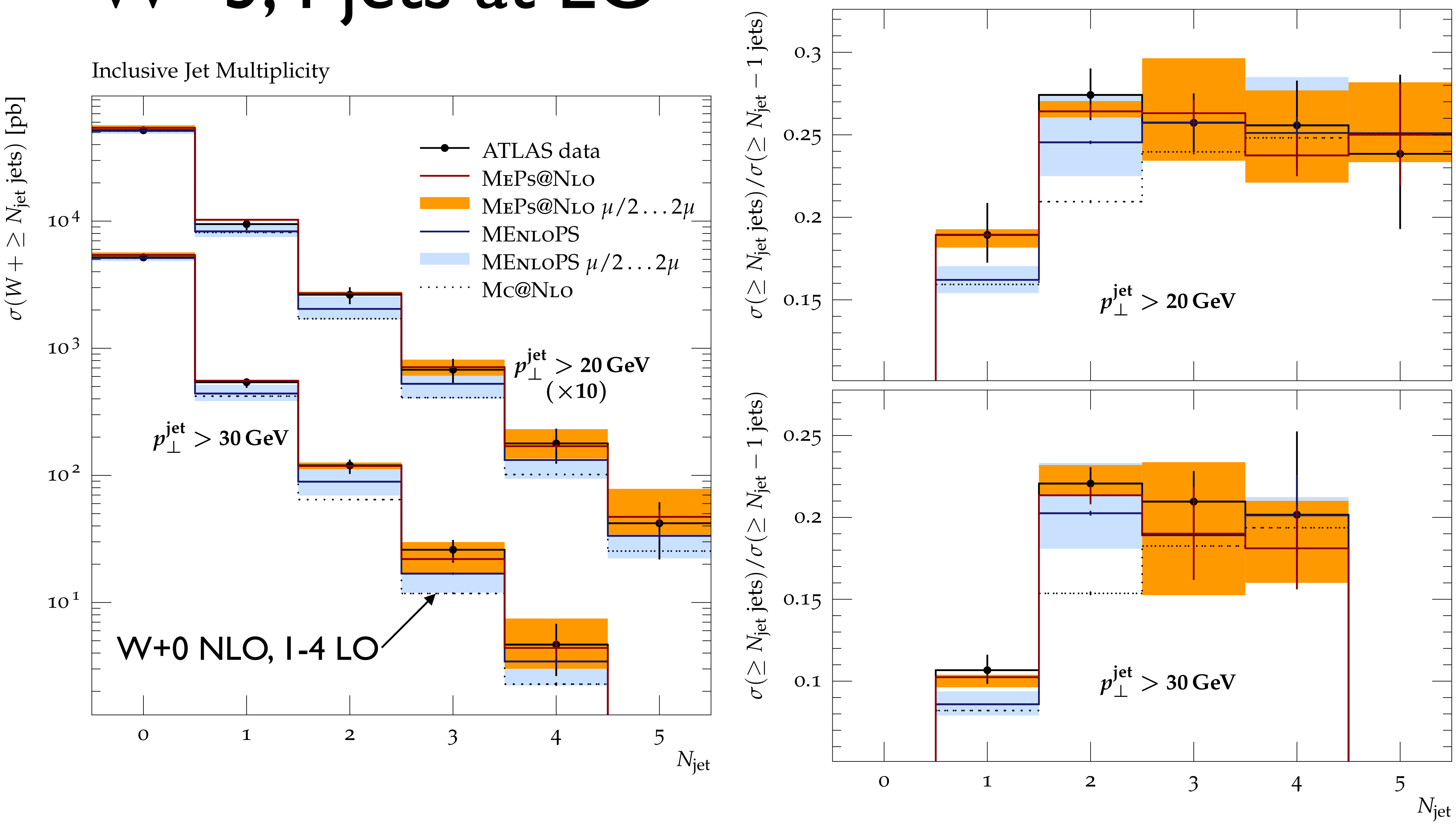


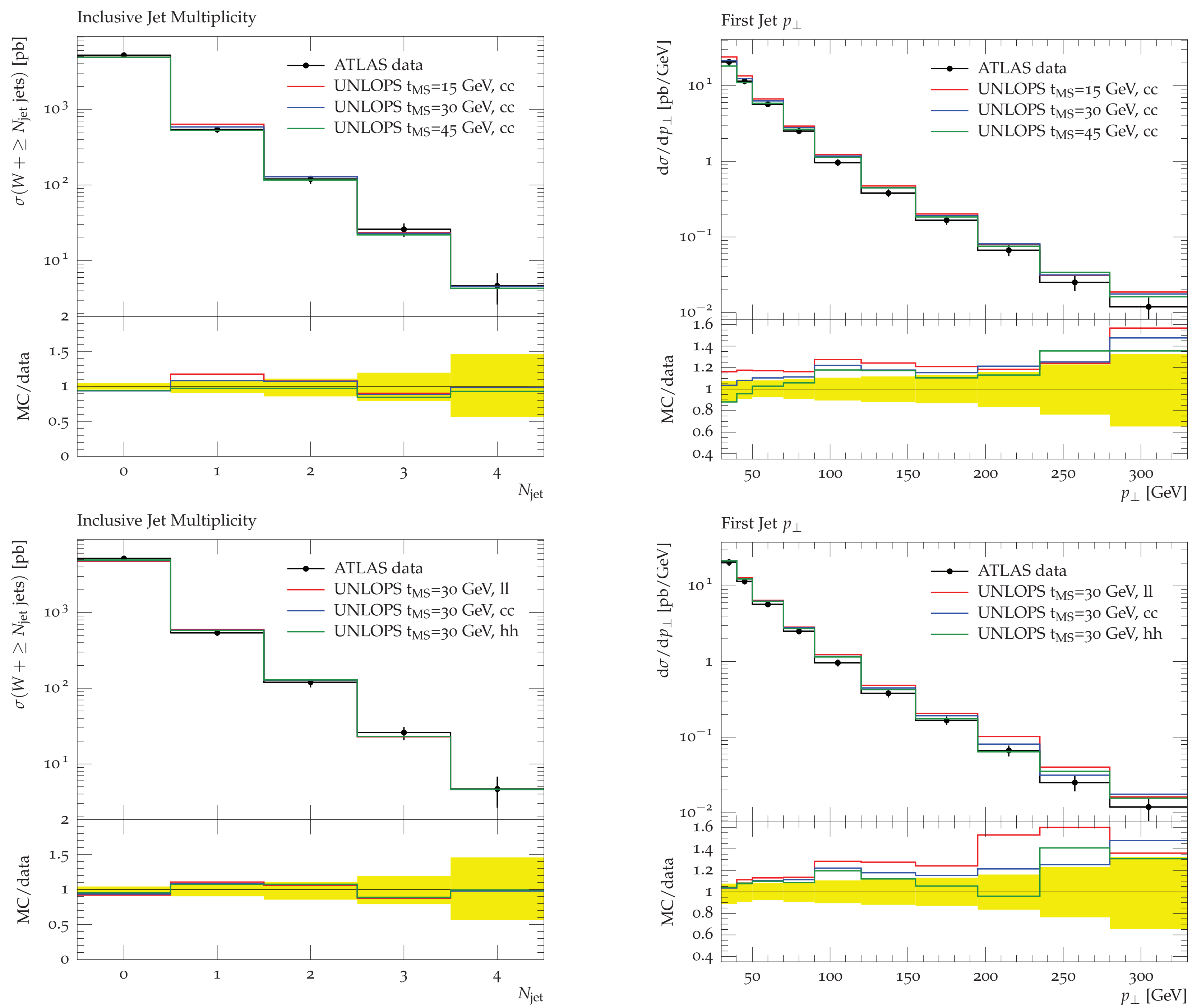

**Figure 1:** Cross section as a function of the inclusive jet multiplicity (left) and their ratios (right) in $W$+jets events measured by ATLAS [50].

# UNLOPS merging

- Merging scale dependence

Lönnblad, Prestel, 1211.7278

- Renorm'n/ factor'n scale dependence



# NNLO matching

- Fully inclusive NNLO, one extra jet NLO
- So far, limited to Drell-Yan & Higgs production (DY/H)
  - MiNLO-NNLOPS

    Hamilton et al., 1309.0017, 1407.3773
  - UN$^2$LOPS

    Höche, Li, Prestel, 1405.3607, 1407.3773

# Achievable Precision?

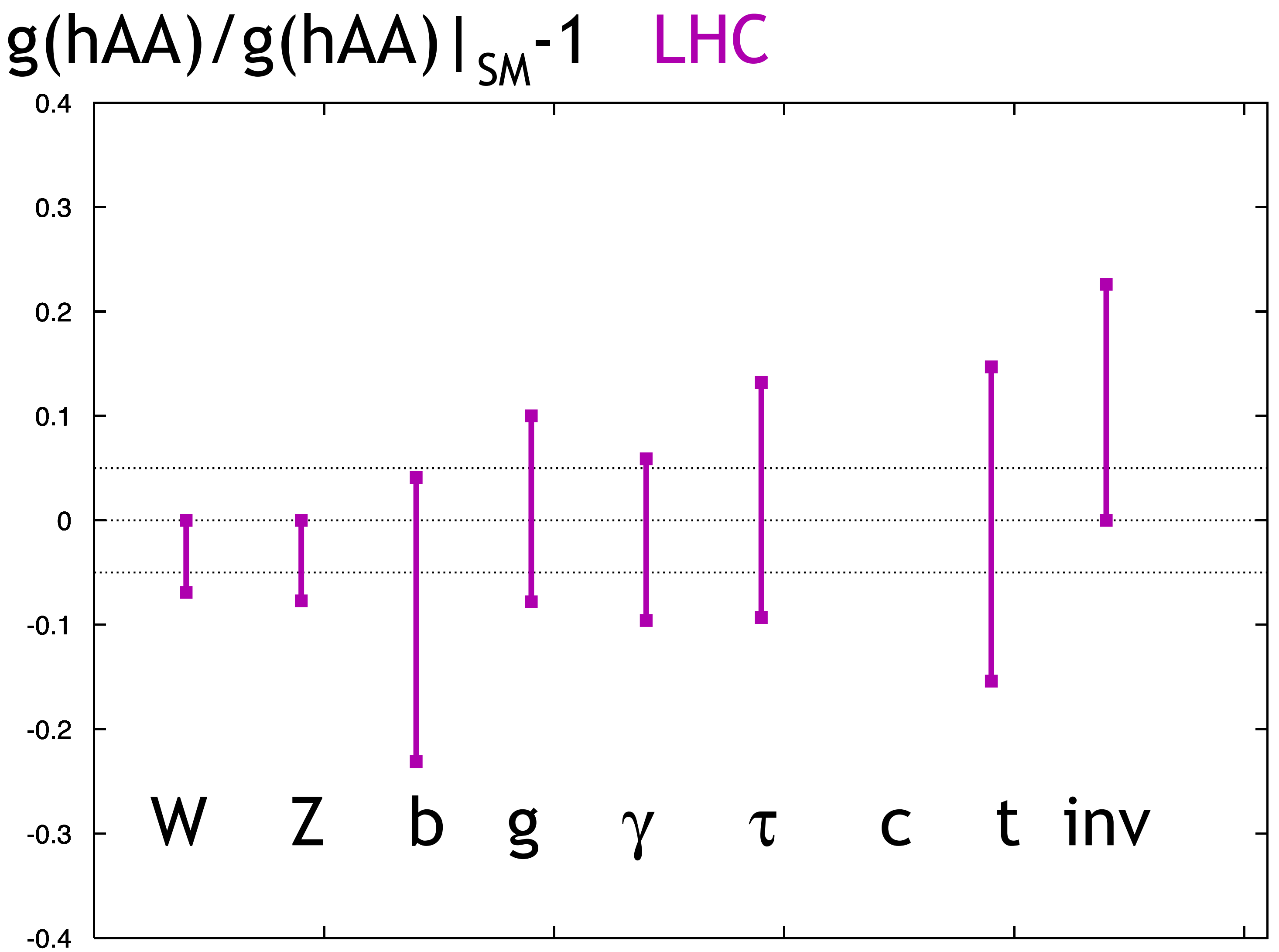



Figure 1: Capabilities of LHC for model-independent measurements of Higgs boson couplings. The plot shows 1 $\sigma$ confidence intervals for LHC at 14 TeV with 300 fb$^{-1}$. No error is estimated for $g(hcc)$. The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

M Peskin, arXiv:1207.2516

# Achievable Precision?

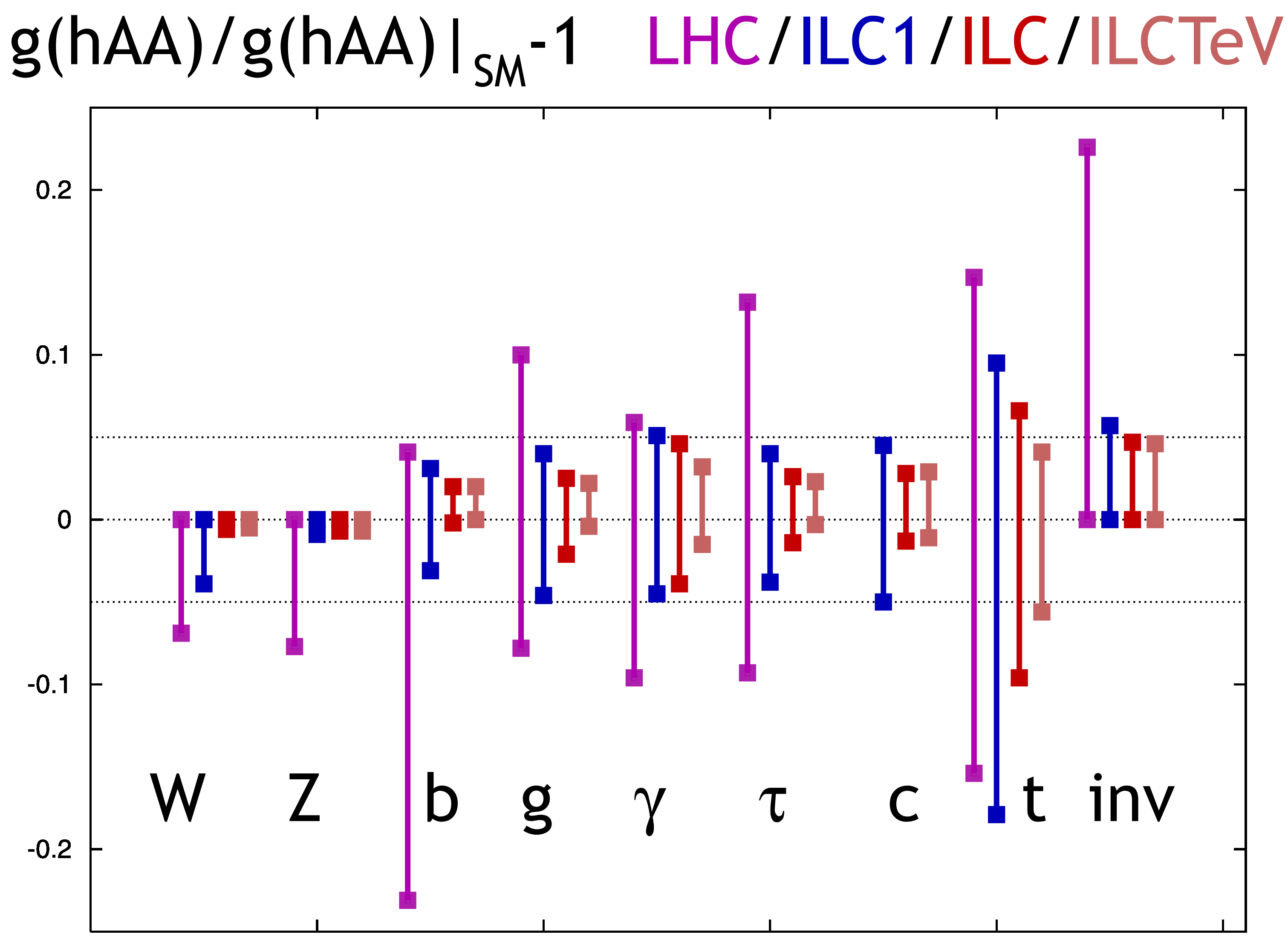



Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 $\sigma$ confidence intervals for LHC at 14 TeV with 300 $fb^{-1}$, for ILC at 250 GeV and 250 $fb^{-1}$ ('ILC1'), for the full ILC program up to 500 GeV with 500 $fb^{-1}$ ('ILC'), and for a program with 1000 $fb^{-1}$ for an upgraded ILC at 1 TeV ('ILCTeV'). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

M Peskin, arXiv:1207.2516