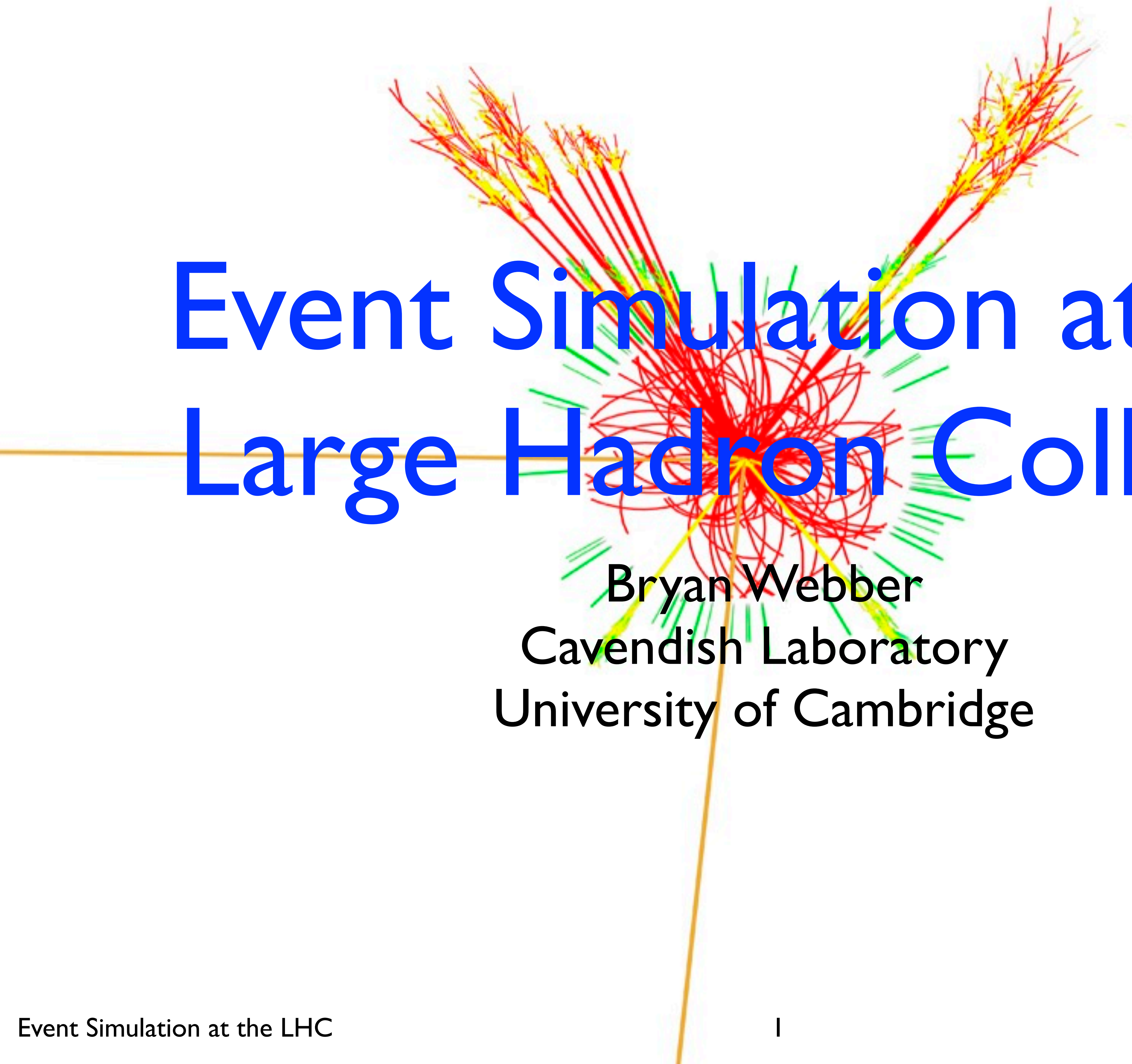


Event Simulation at the Large Hadron Collider

Bryan Webber
Cavendish Laboratory
University of Cambridge

Event Simulation at the Large Hadron Collider

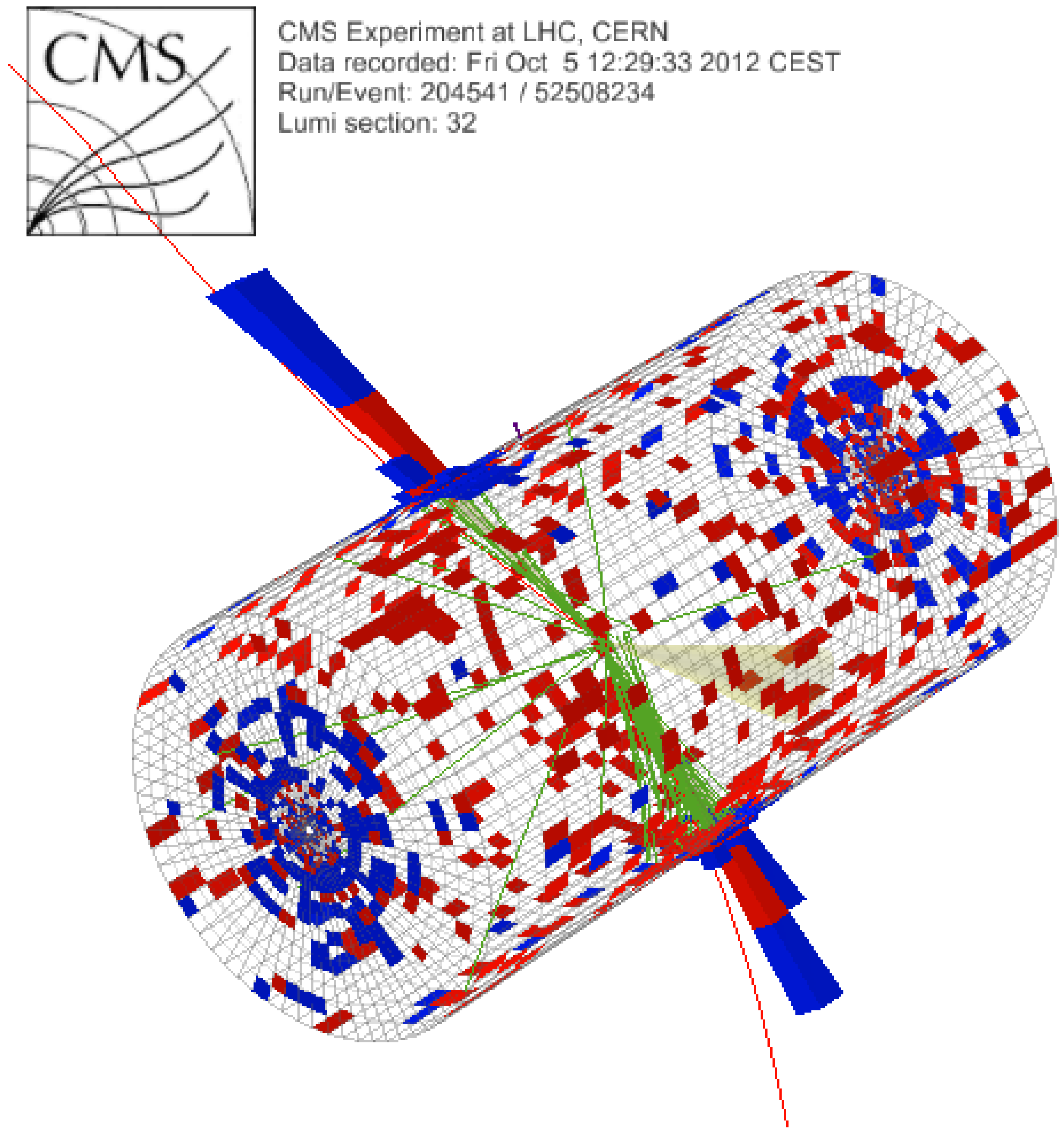
- Monte Carlo event generation:
  - theoretical status and limitations
- Recent improvements:
  - perturbative and non-perturbative
- Overview of results:
  - W, Z, top, Higgs, BSM (+jets)

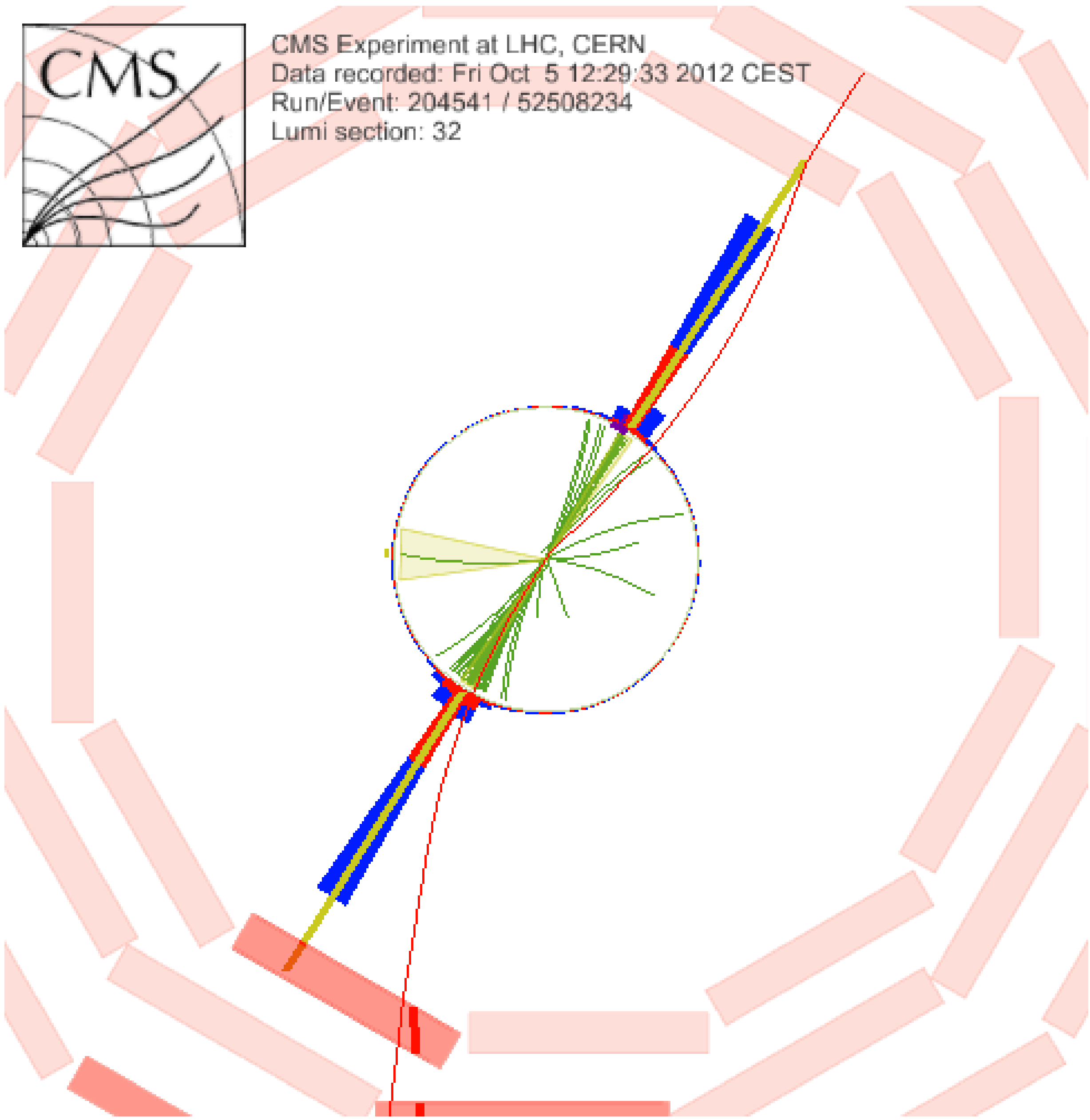
Monte Carlo Event Generation

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 SM and measuring its parameters
  - Estimating new signals and their backgrounds

A high-mass dijet event



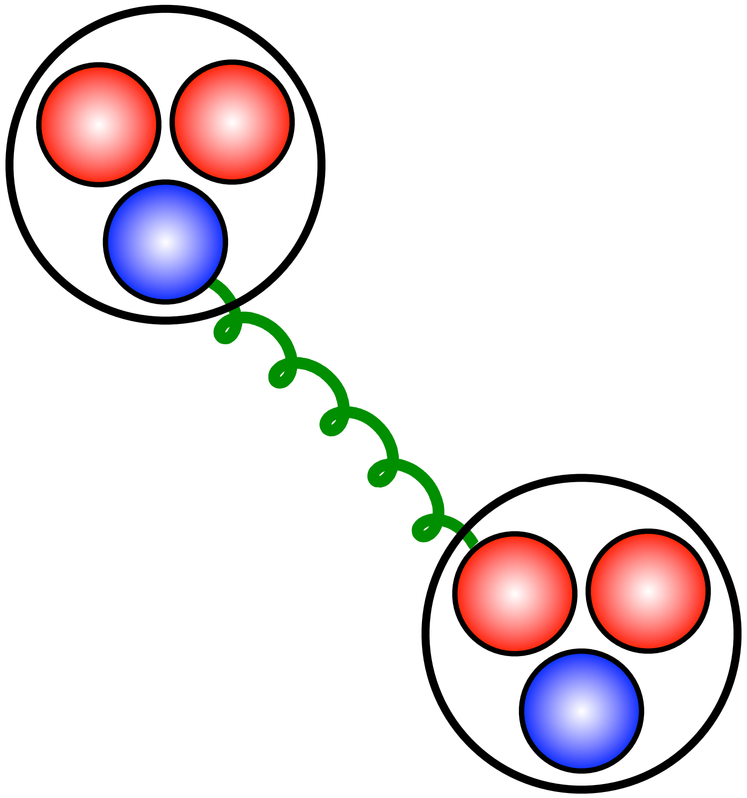


- M_{jj} = 5.15 TeV

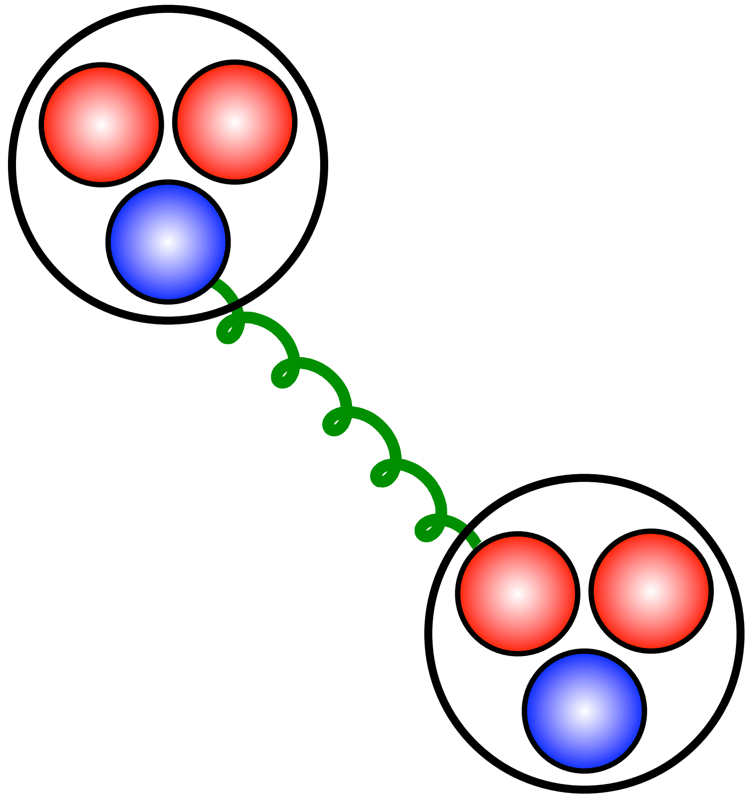
CMS PAS EXO-12-059

LHC Dijet

LHC Dijet



LHC Dijet



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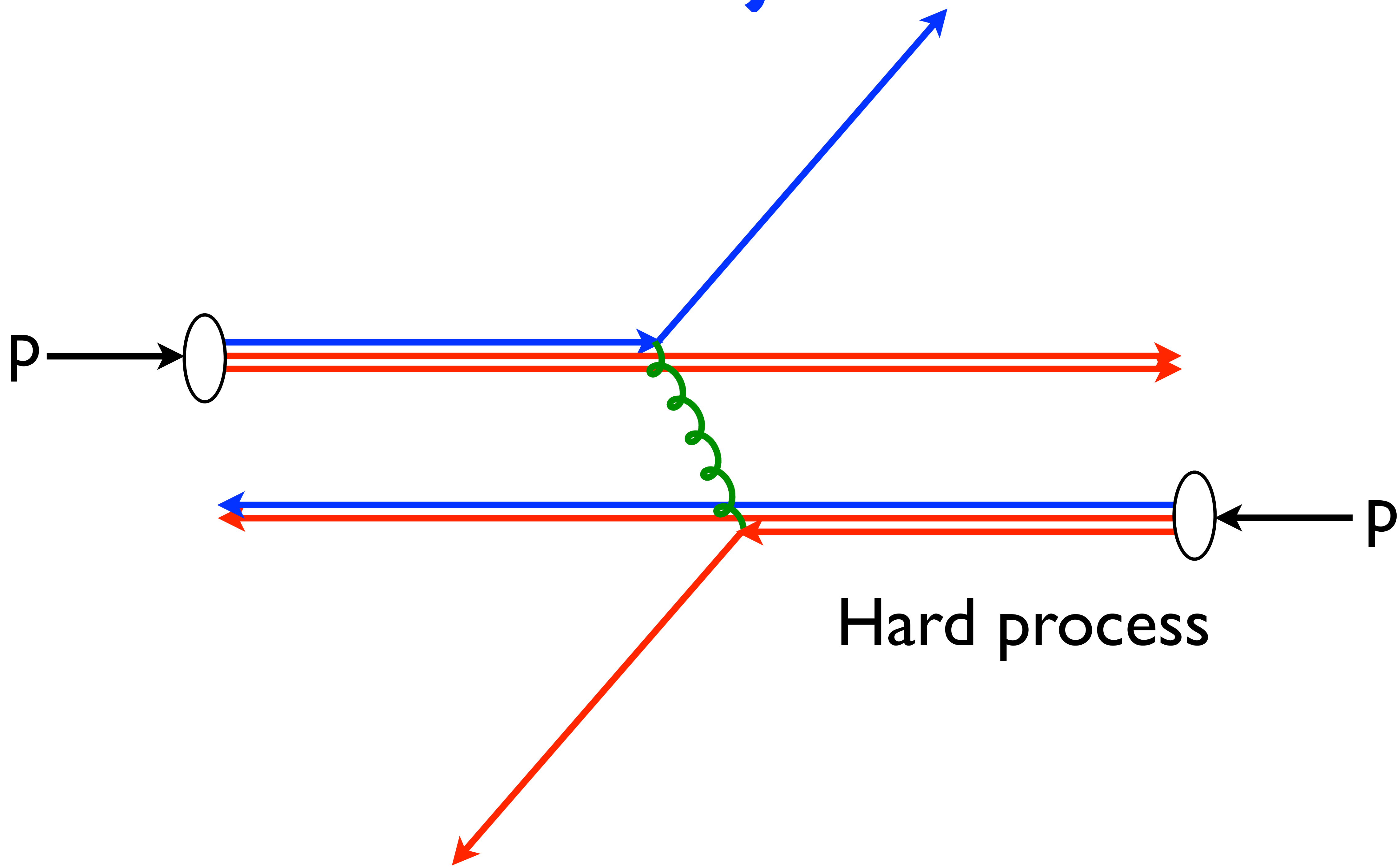

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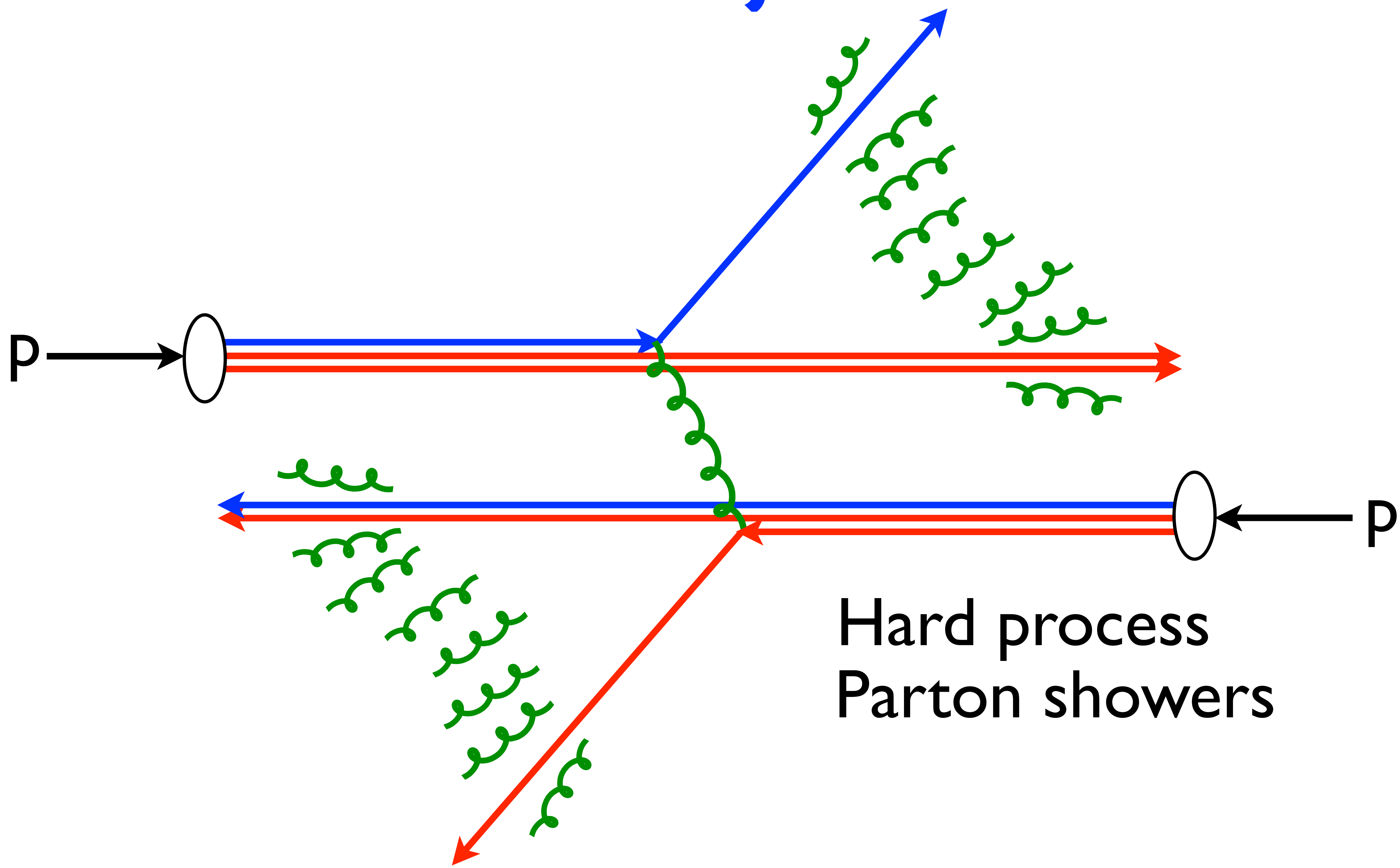

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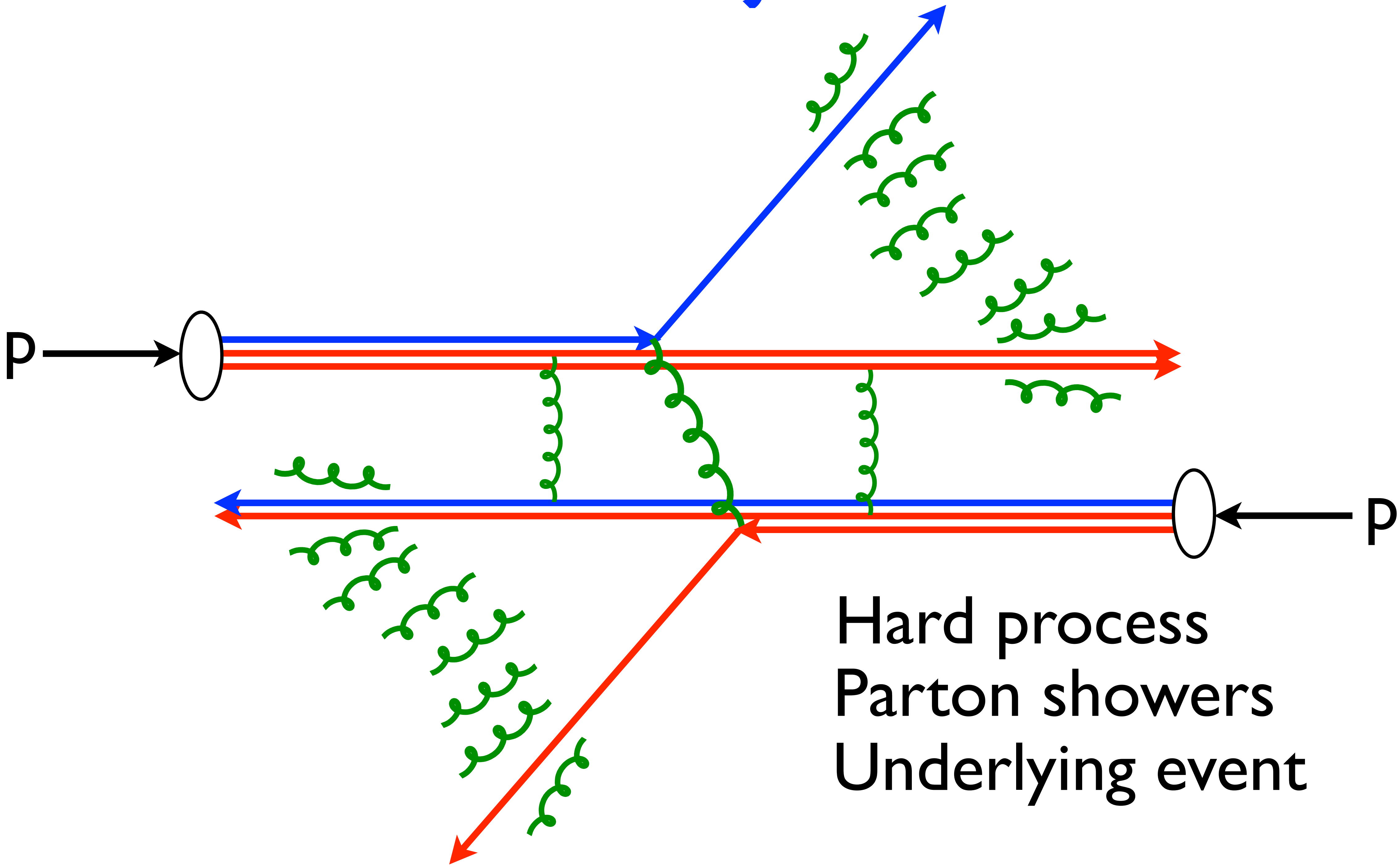
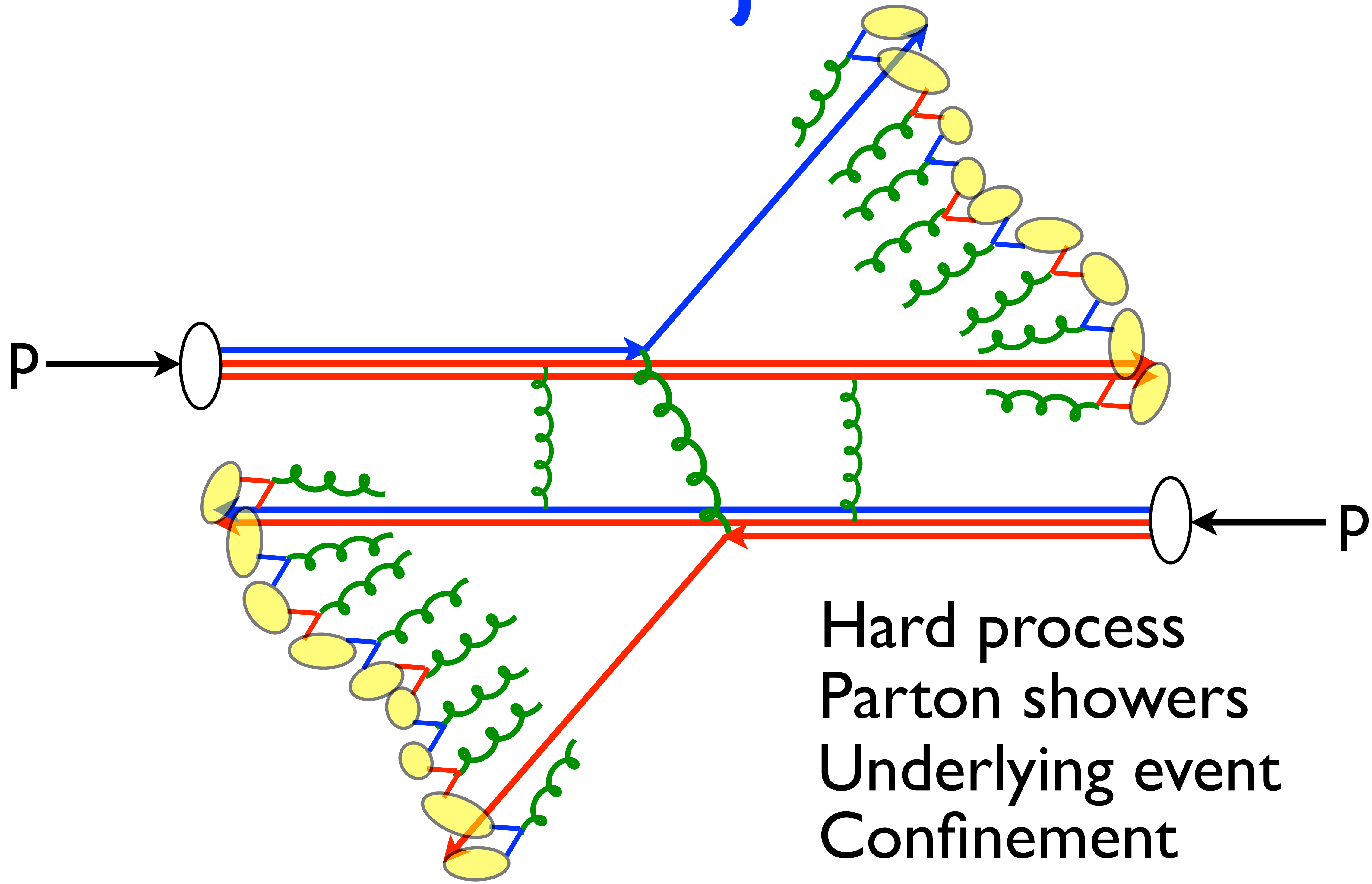


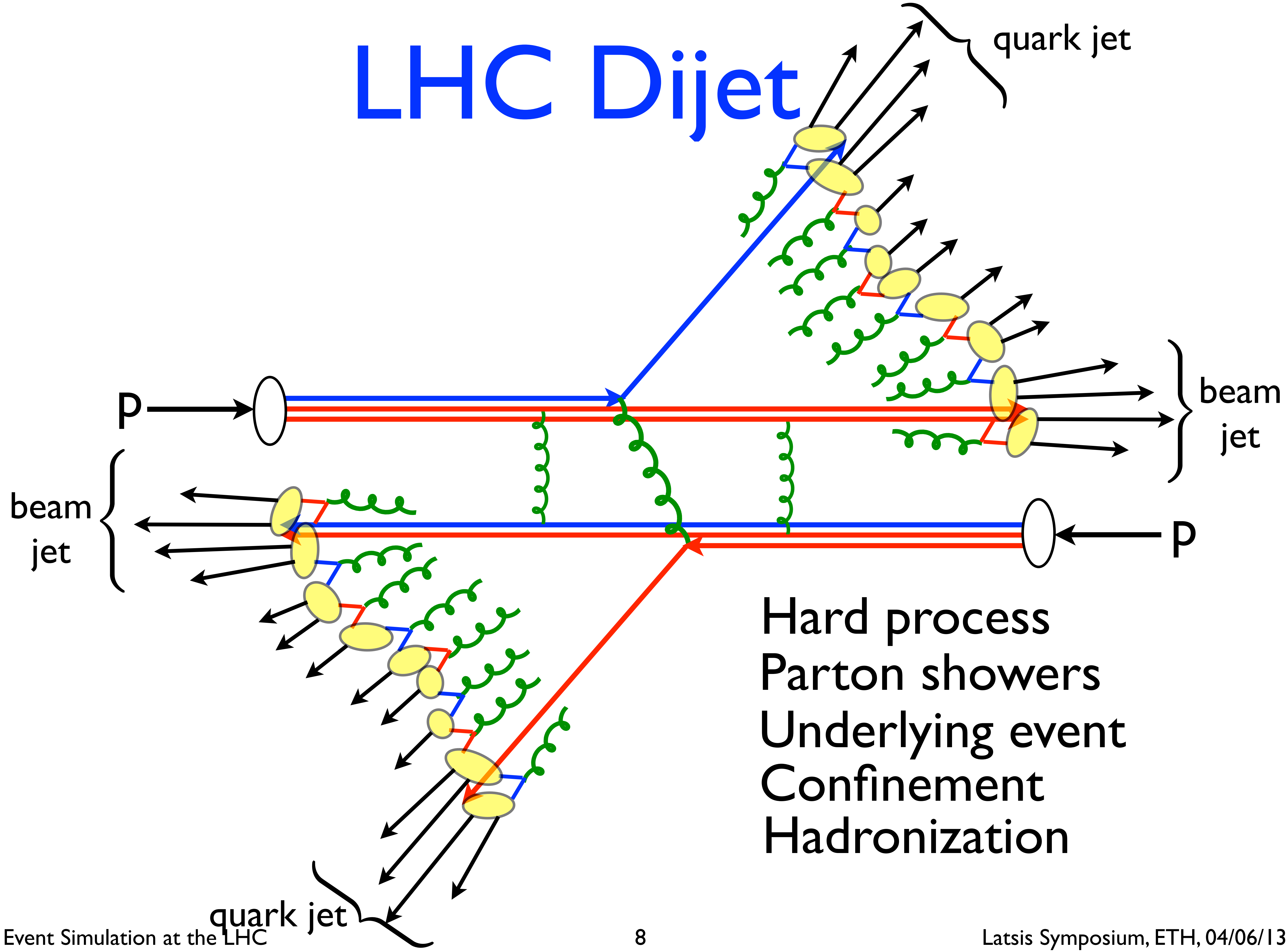
Hard process
Parton showers
Underlying event

LHC Dijet



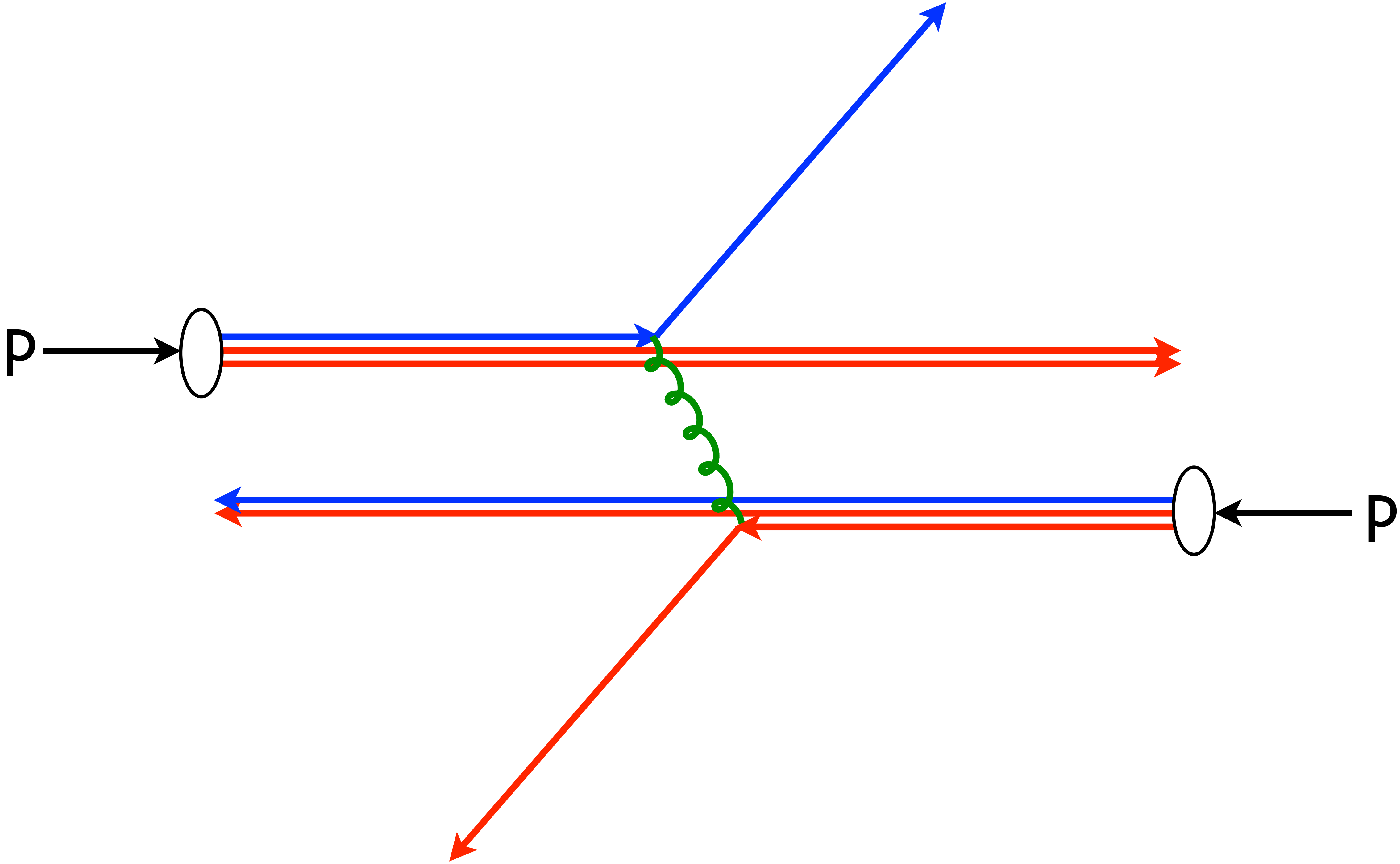
Hard process
Parton showers
Underlying event
Confinement

LHC Dijet

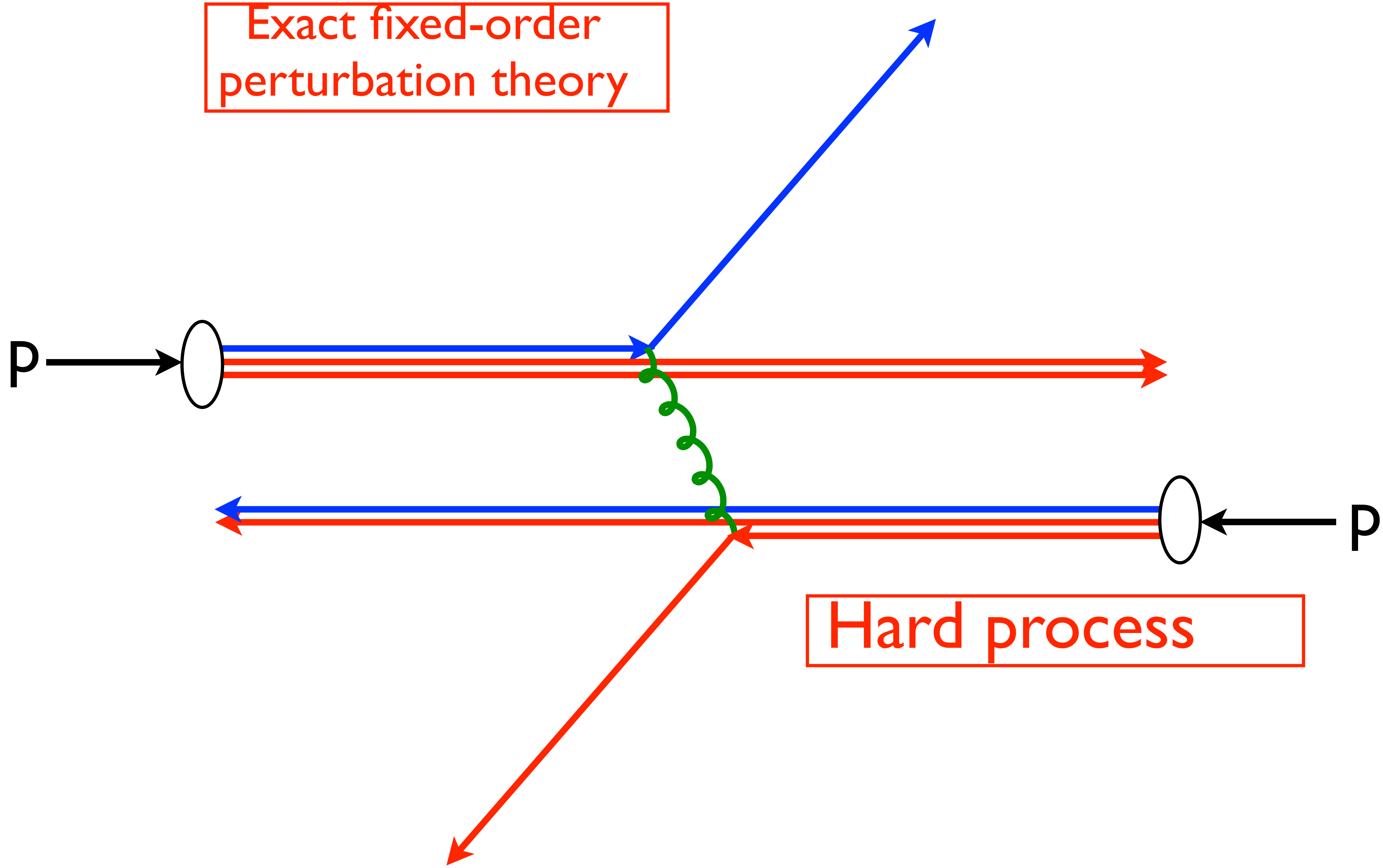


Hard process
Parton showers
Underlying event
Confinement
Hadronization

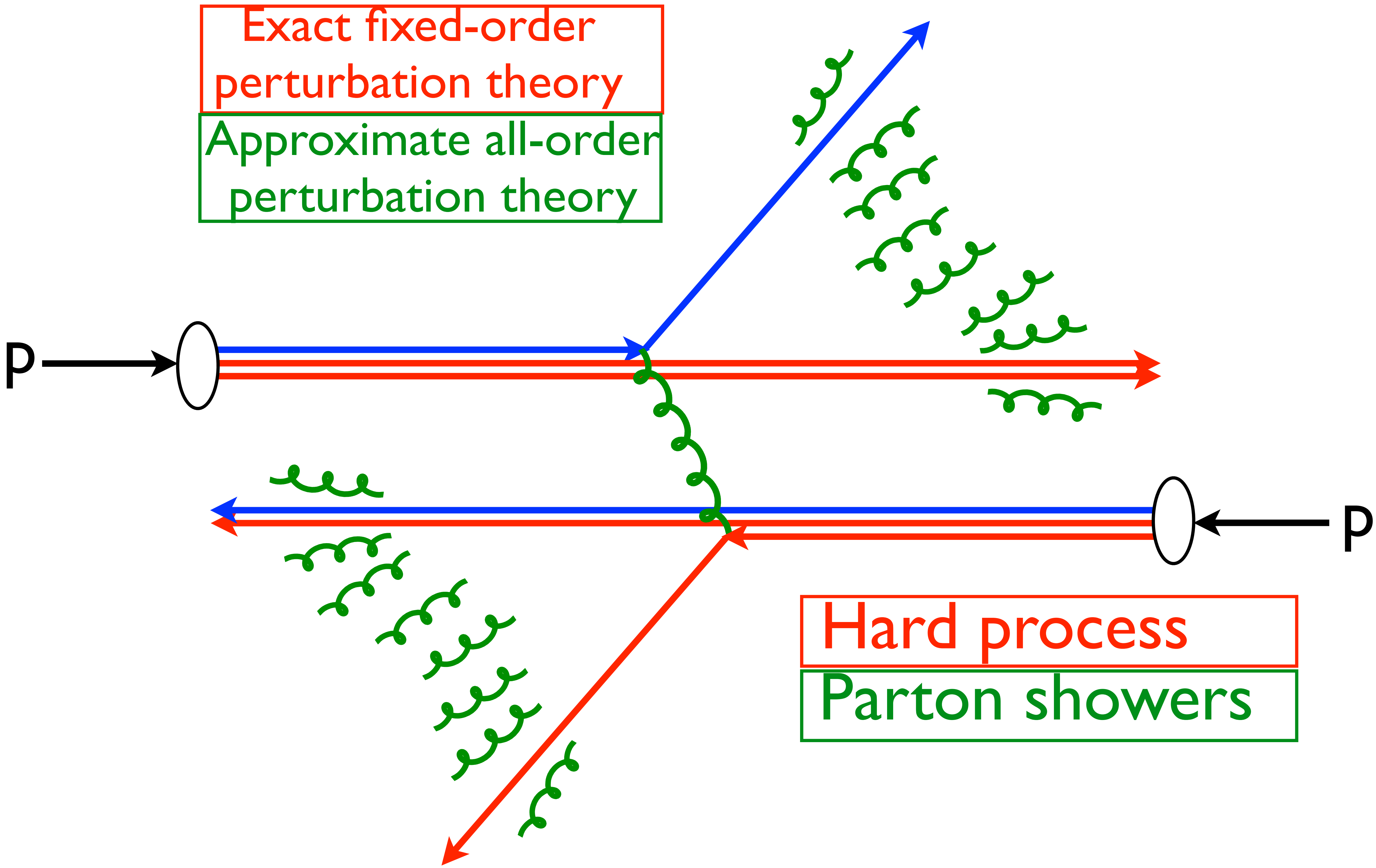
Theoretical status



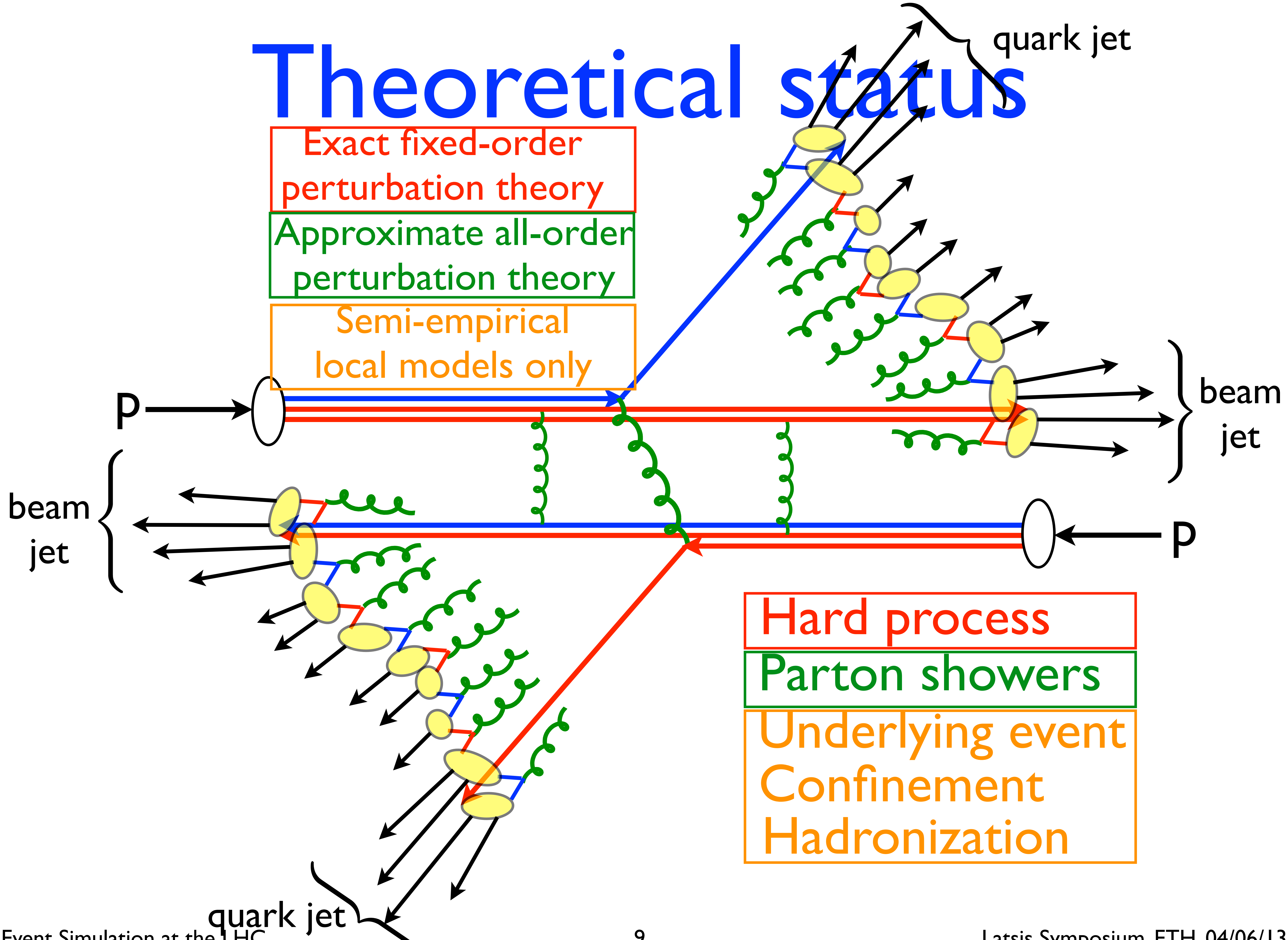
Theoretical status



Theoretical status



Theoretical status



QCD Factorization

$$\sigma_{pp\to X}(E_{pp}^2) = \int_0^1 dx_1\, dx_2\, f_i(x_1,\mu^2)\, f_j(x_2,\mu^2)\, \hat{\sigma}_{ij\to X}(x_1 x_2 E_{pp}^2,\mu^2)$$

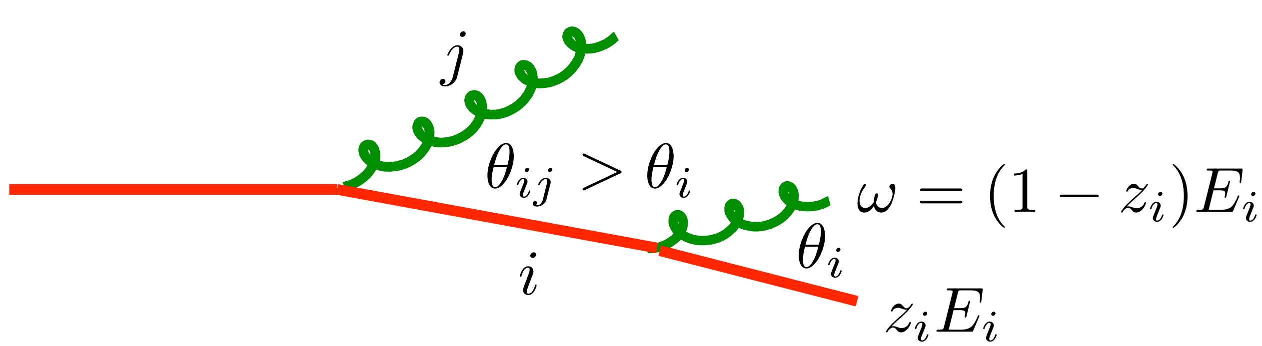
momentum fractions ($dx_1\, dx_2$) — parton distributions at scale μ^2 ($f_i(x_1,\mu^2)\, f_j(x_2,\mu^2)$) — hard process cross section ($\hat{\sigma}_{ij\to X}(x_1 x_2 E_{pp}^2,\mu^2)$)

- 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

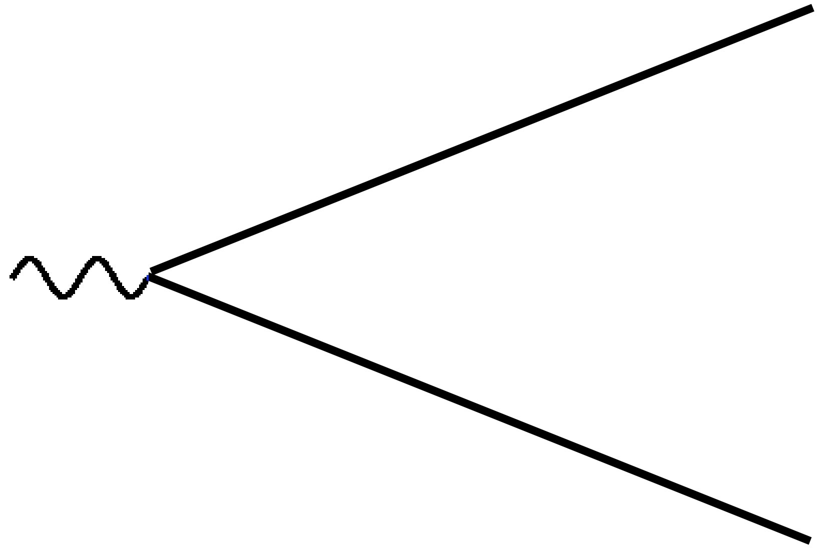
$$
\begin{aligned}
d\sigma_{n+1} &\approx \frac{\alpha_S}{2\pi} \sum_{i,j} (-\mathbf{T}_i \cdot \mathbf{T}_j) \frac{p_i \cdot p_j}{p_i \cdot k\, p_j \cdot k} \omega\, d\omega\, d\xi_i \frac{d\phi_i}{2\pi} d\sigma_n \\
&= \frac{\alpha_S}{2\pi} \sum_{i,j} (-\mathbf{T}_i \cdot \mathbf{T}_j) \frac{\xi_{ij}}{\xi_i\, \xi_j} \frac{d\omega}{\omega} d\xi_i \frac{d\phi_i}{2\pi} d\sigma_n \\
&\approx \frac{\alpha_S}{2\pi} \sum_{i,j} (-\mathbf{T}_i \cdot \mathbf{T}_j)\, \Theta(\xi_{ij} - \xi_i) \frac{d\omega}{\omega} \frac{d\xi_i}{\xi_i} d\sigma_n
\end{aligned}
$$



➡ 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 Λ_{QCD}~200 MeV, perturbation theory breaks down and hadrons are formed
- Before that, at scales Q_0 ~ few x Λ_{QCD}, there is universal preconfinement of colour
- Colour, flavour and momentum flows are only locally redistributed by hadronization



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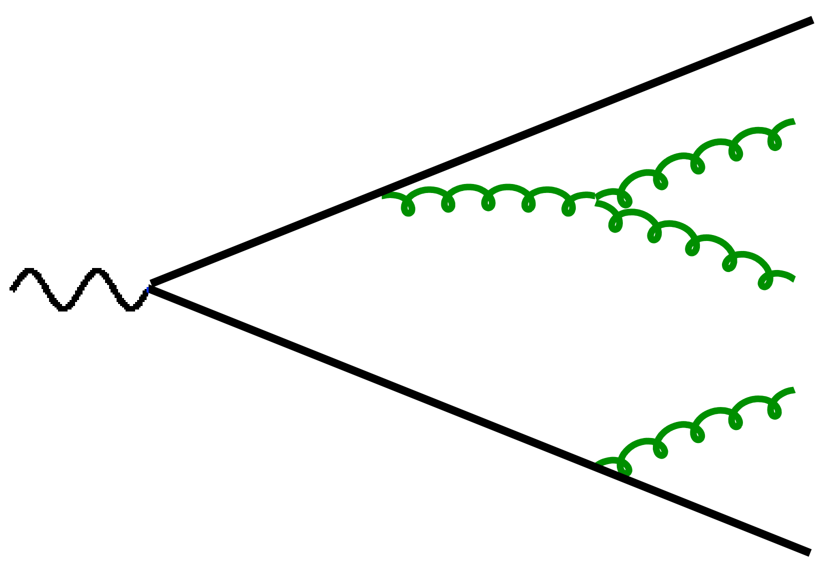

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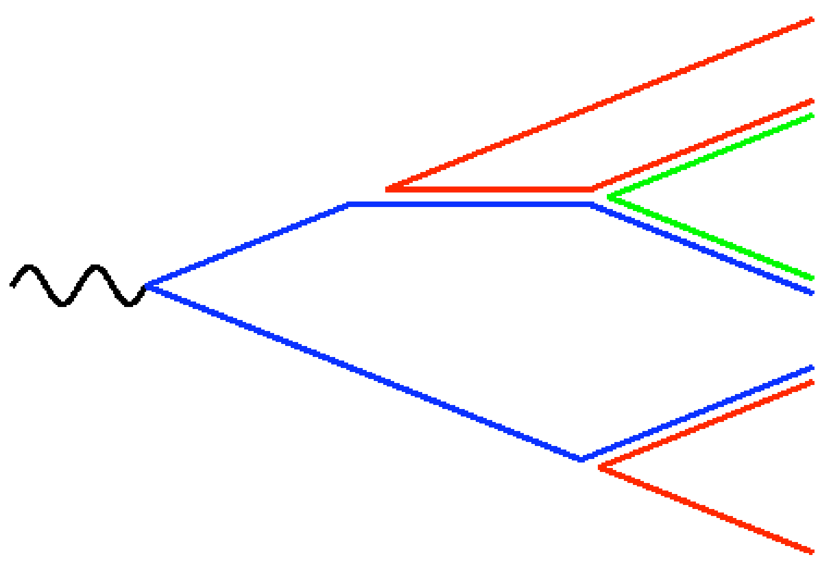

String Hadronization Model

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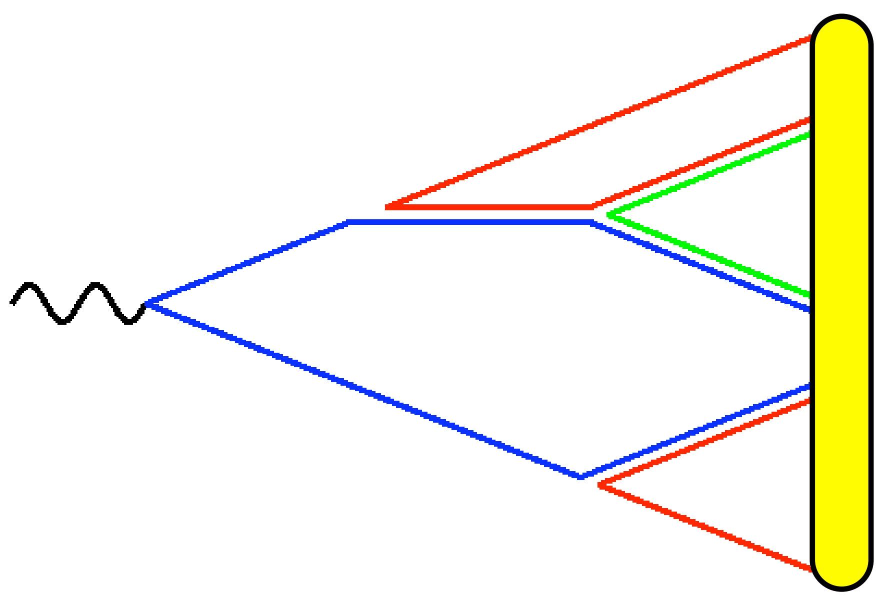

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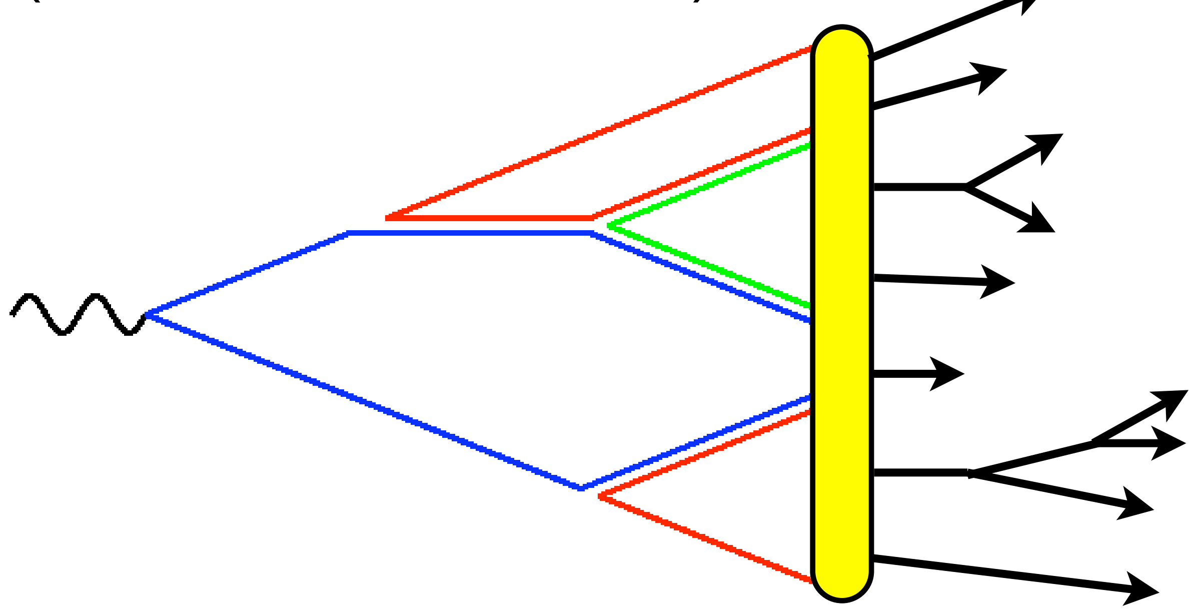

Cluster Hadronization Model

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- At a scale near Λ_{QCD}~200 MeV, perturbation theory breaks down and hadrons are formed
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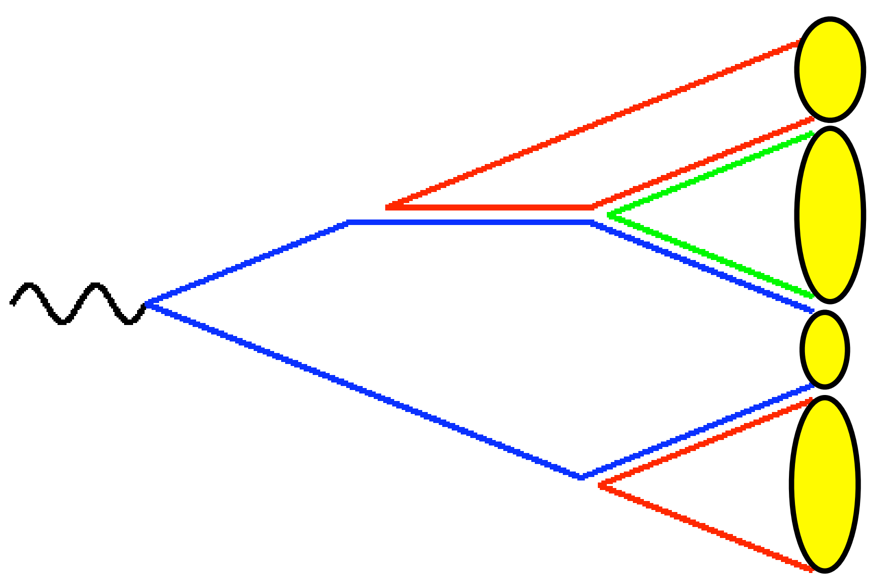
- Decay of preconfined clusters provides a direct basis for hadronization



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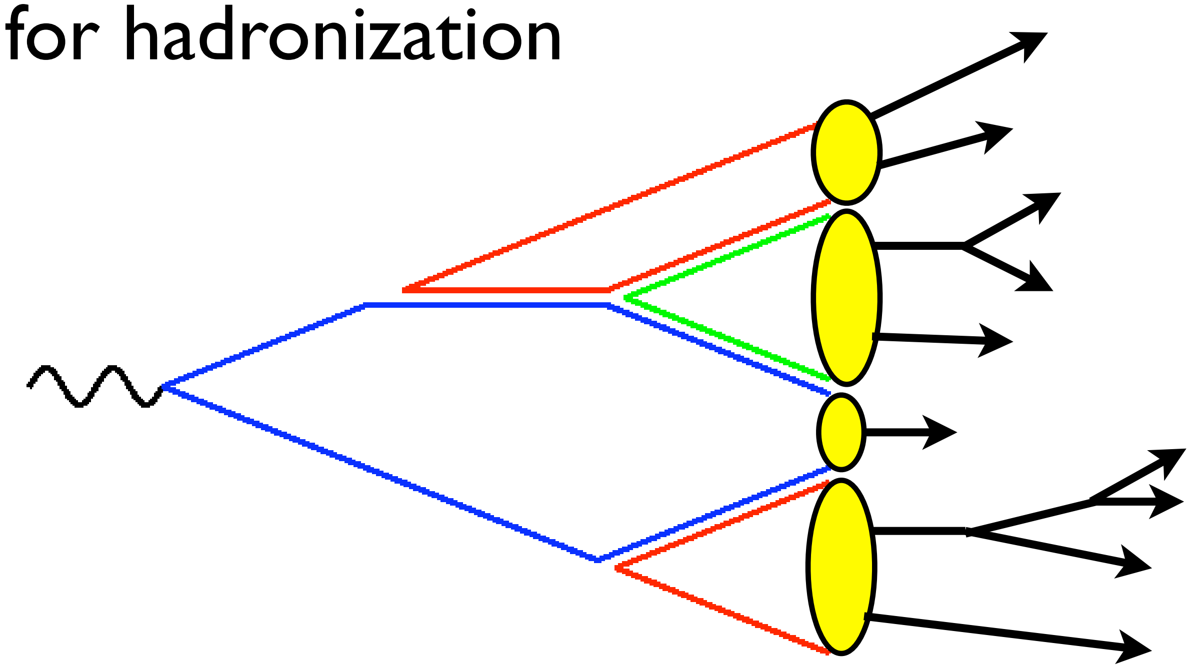
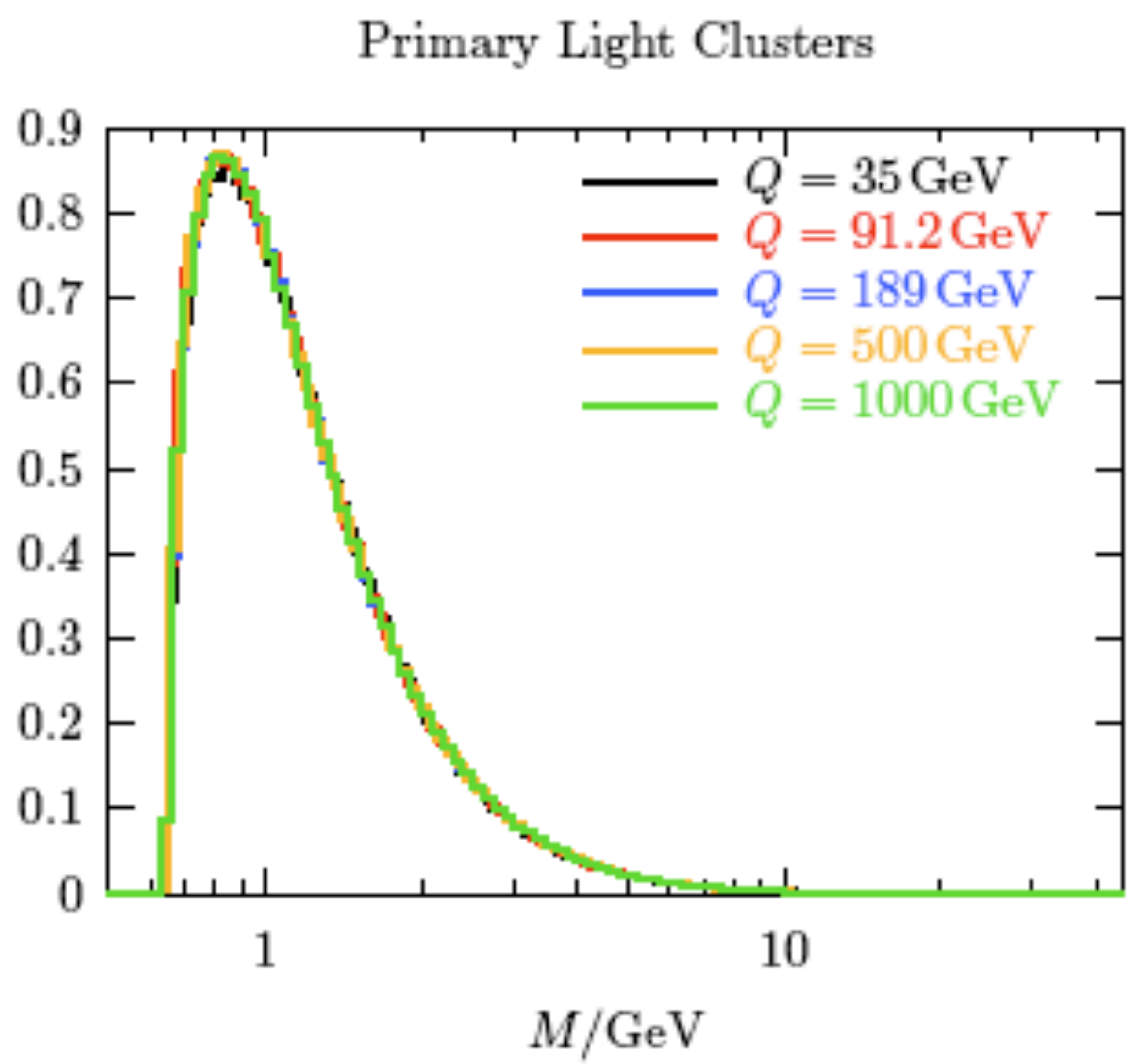


Cluster Hadronization Model

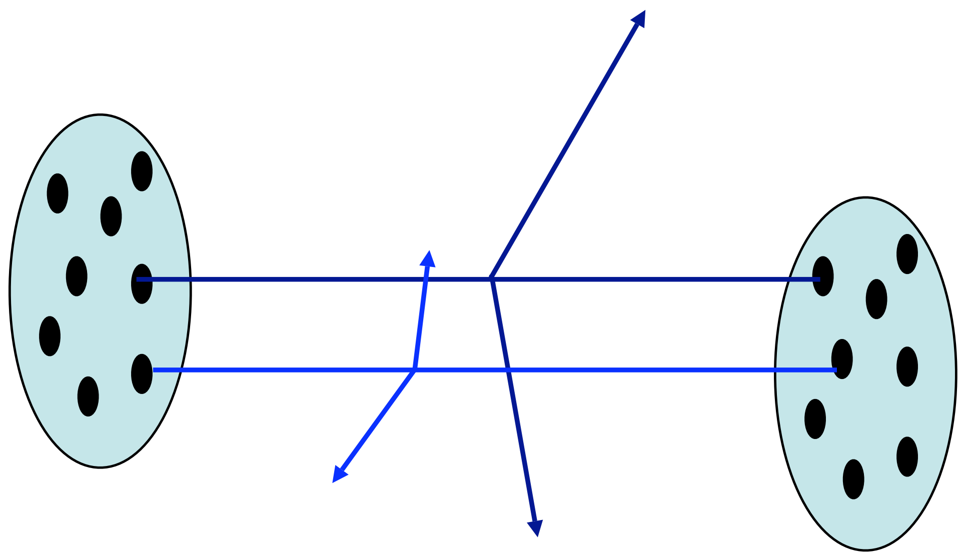


- Mass distribution of preconfined clusters is universal
- Phase-space decay model for most clusters
- High-mass tail decays anisotropically (string-like)

Hadronization Status

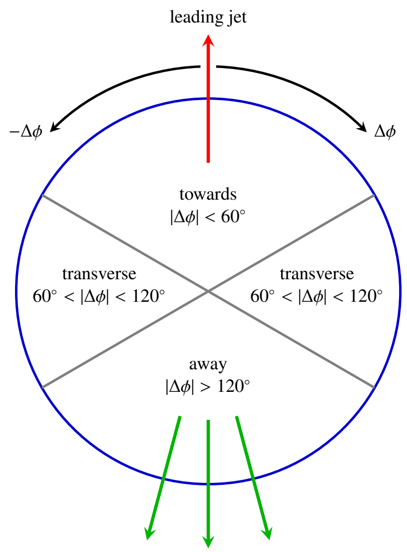
- No fundamental progress since 1980s
  - Available non-perturbative methods (lattice, AdS/QCD, ...) are inapplicable
- Less important in some respects in LHC era
  - Jets, leptons and photons are observed objects, not hadrons
- But still important for detector effects
  - Jet response, heavy-flavour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

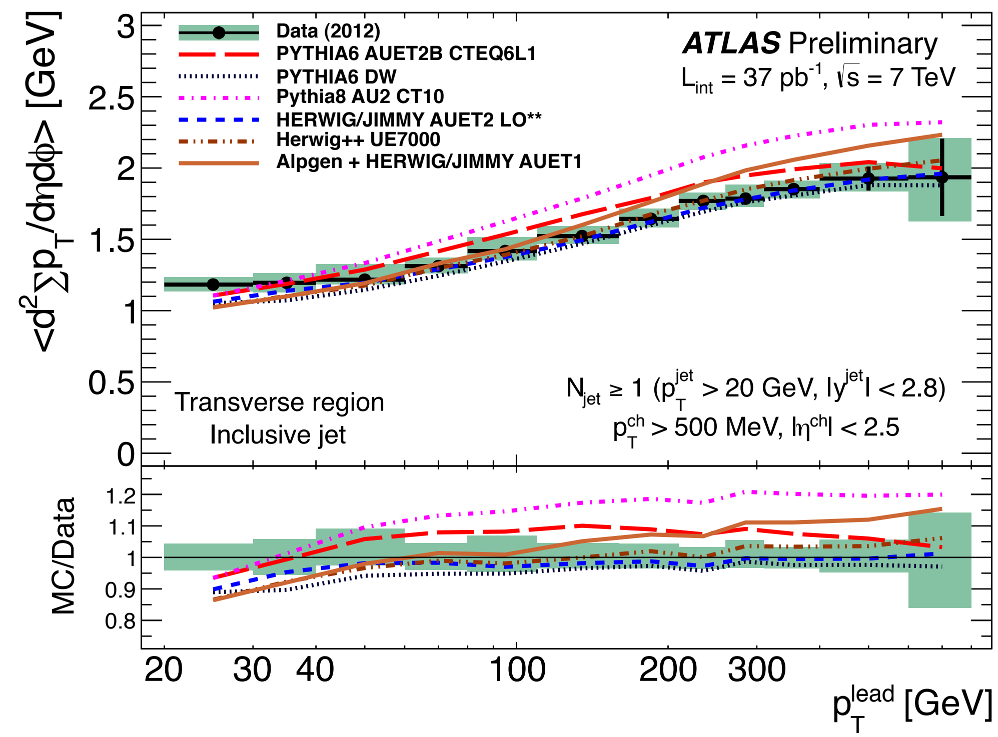
Underlying Event

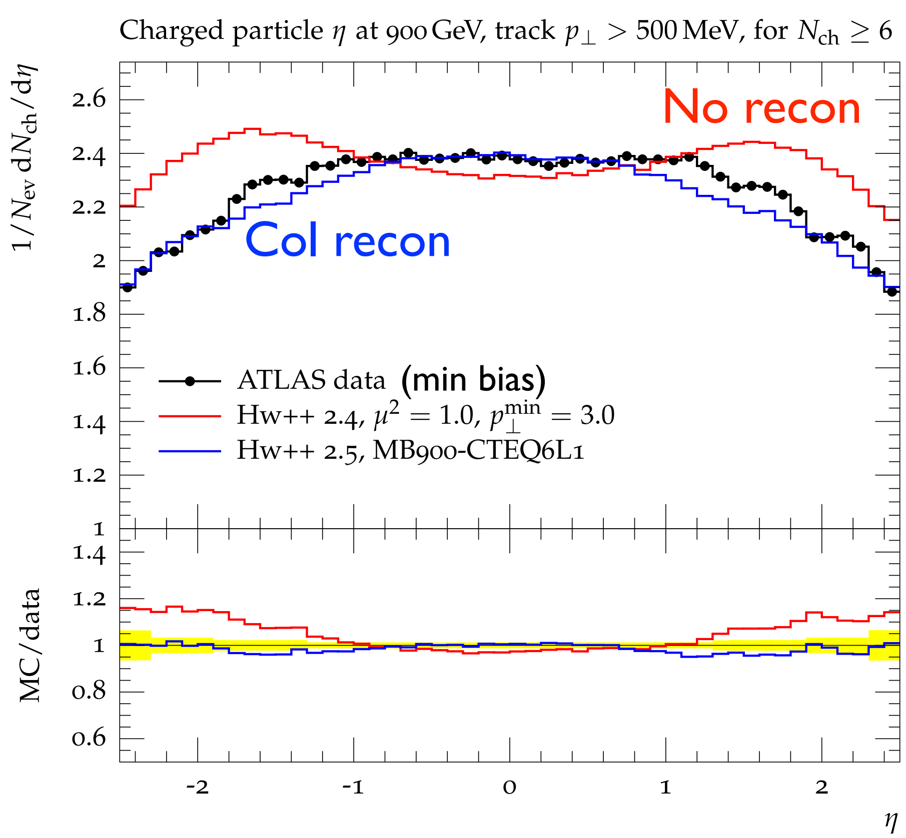


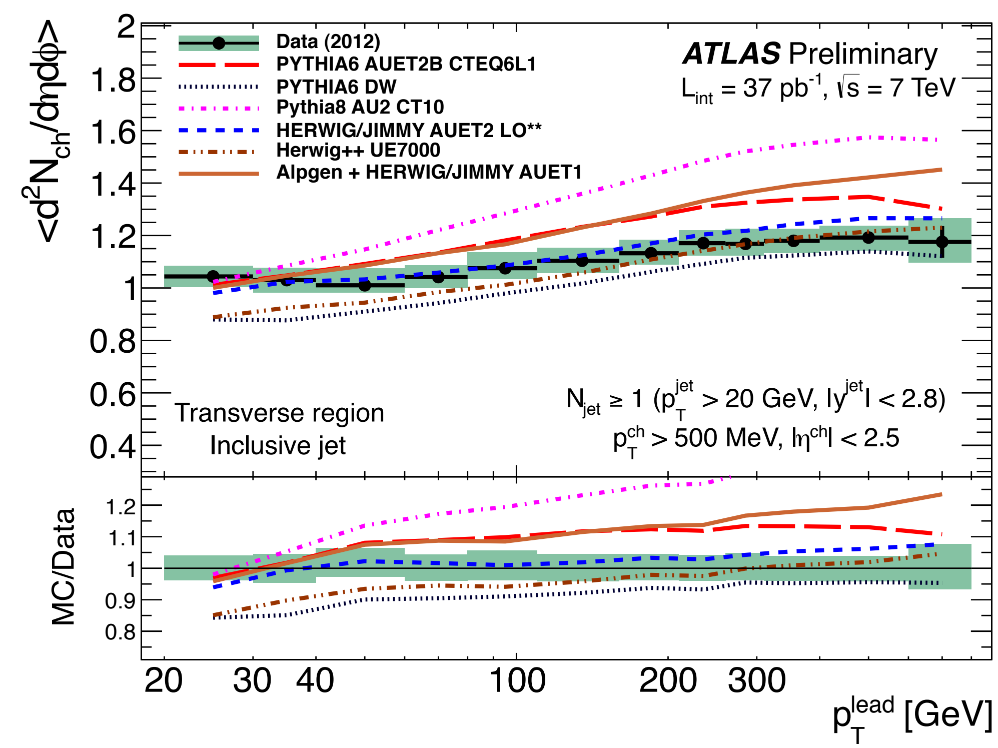
- Multiple parton interactions in same collision
  - Depends on density profile of proton
- Assume QCD 2-to-2 secondary collisions
  - Need cutoff at low p_T
- Need to model colour flow
  - Colour reconnections are necessary

Underlying Event





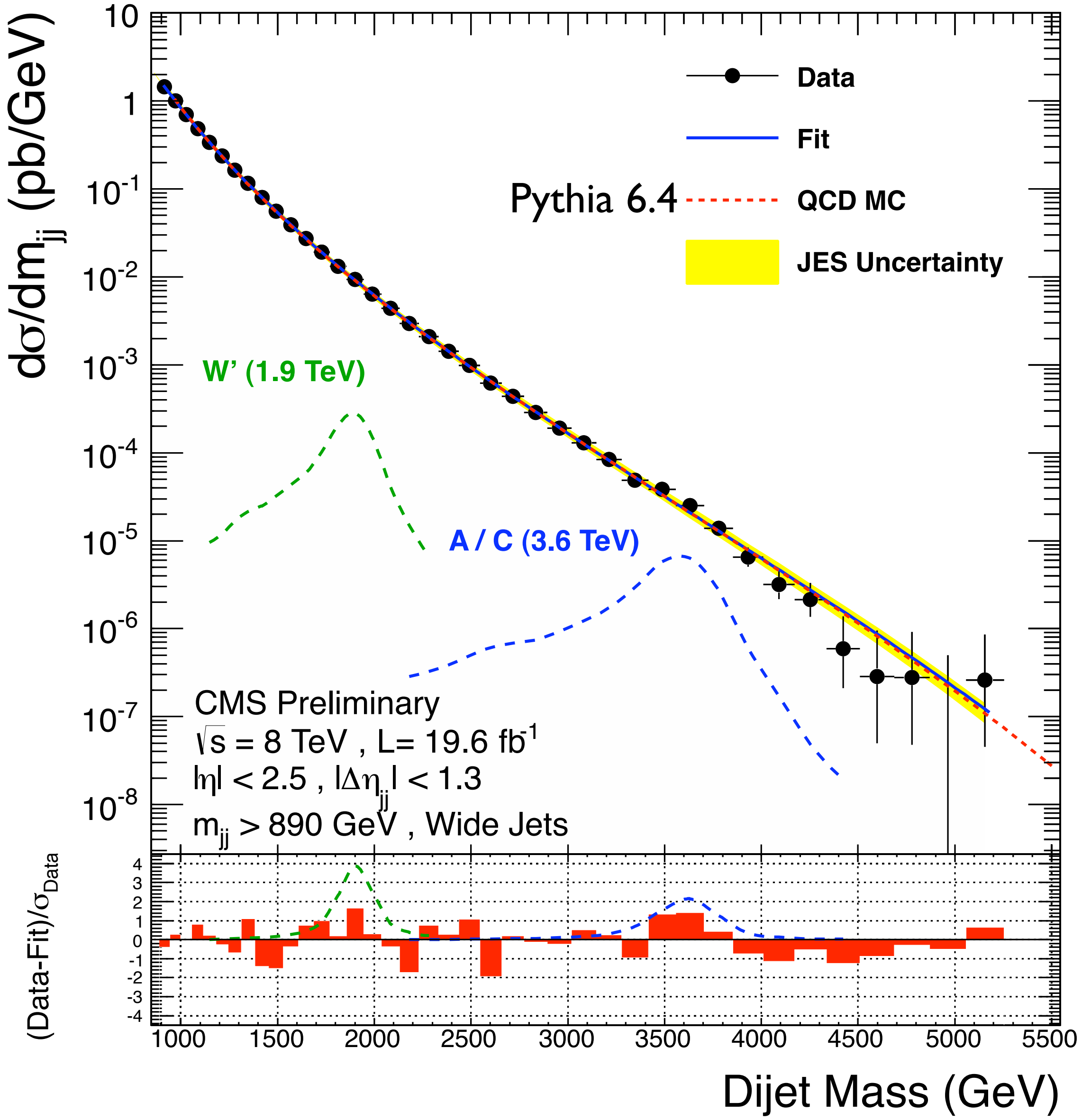




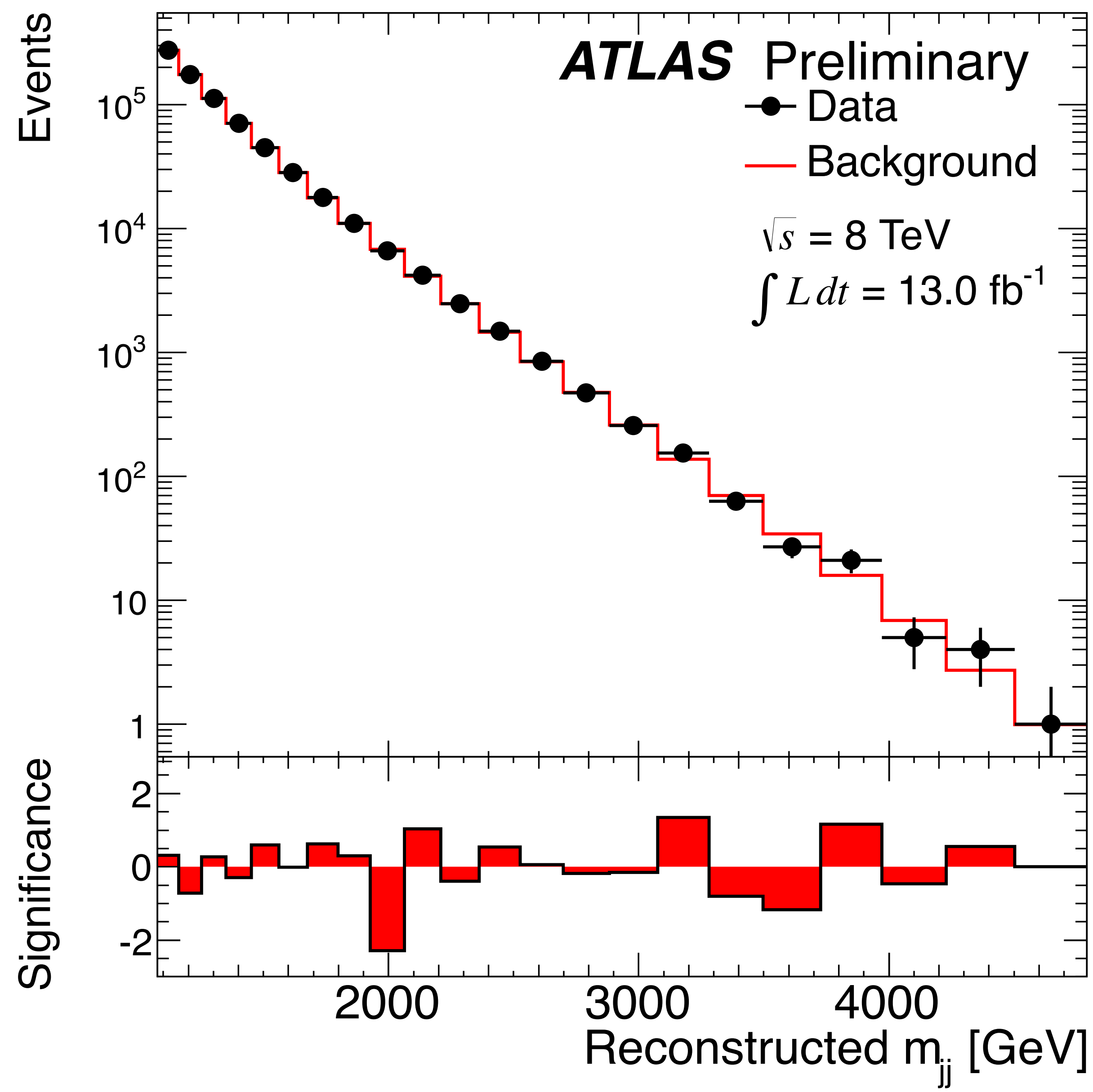
Gieseke, Röhr, Siódmok, arXiv:1206.2205

ATLAS CONF-2012-164

Dijet Mass Distribution



CMS PAS EXO-12-059



ATLAS CONF-2012-148

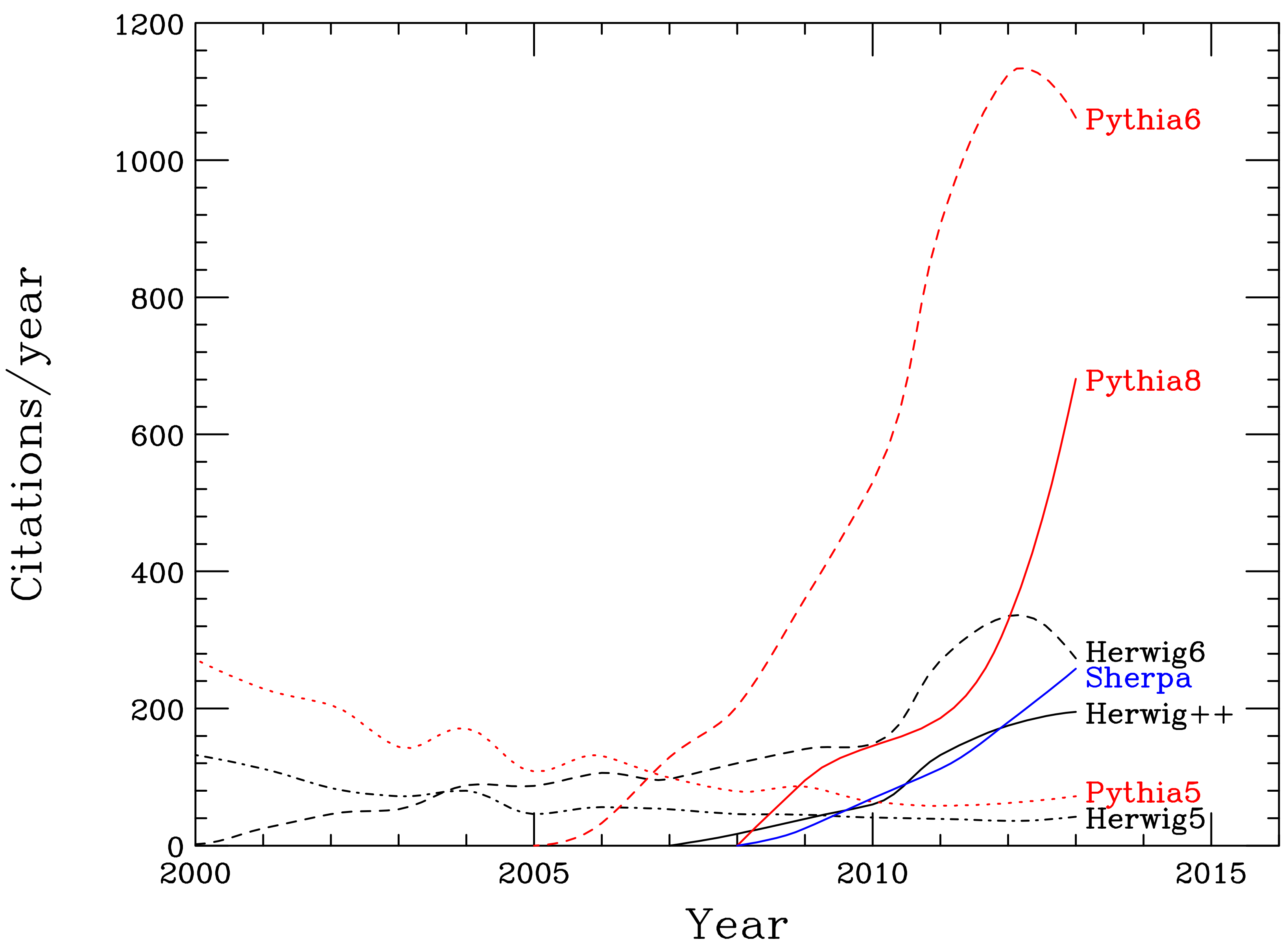
- No sign of deviation from Standard Model (yet)

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

Generator Citations



- Most-cited article only for each version
- 2013 is extrapolation (Jan to mid-May x3)

Other relevant software

(with apologies for omissions)

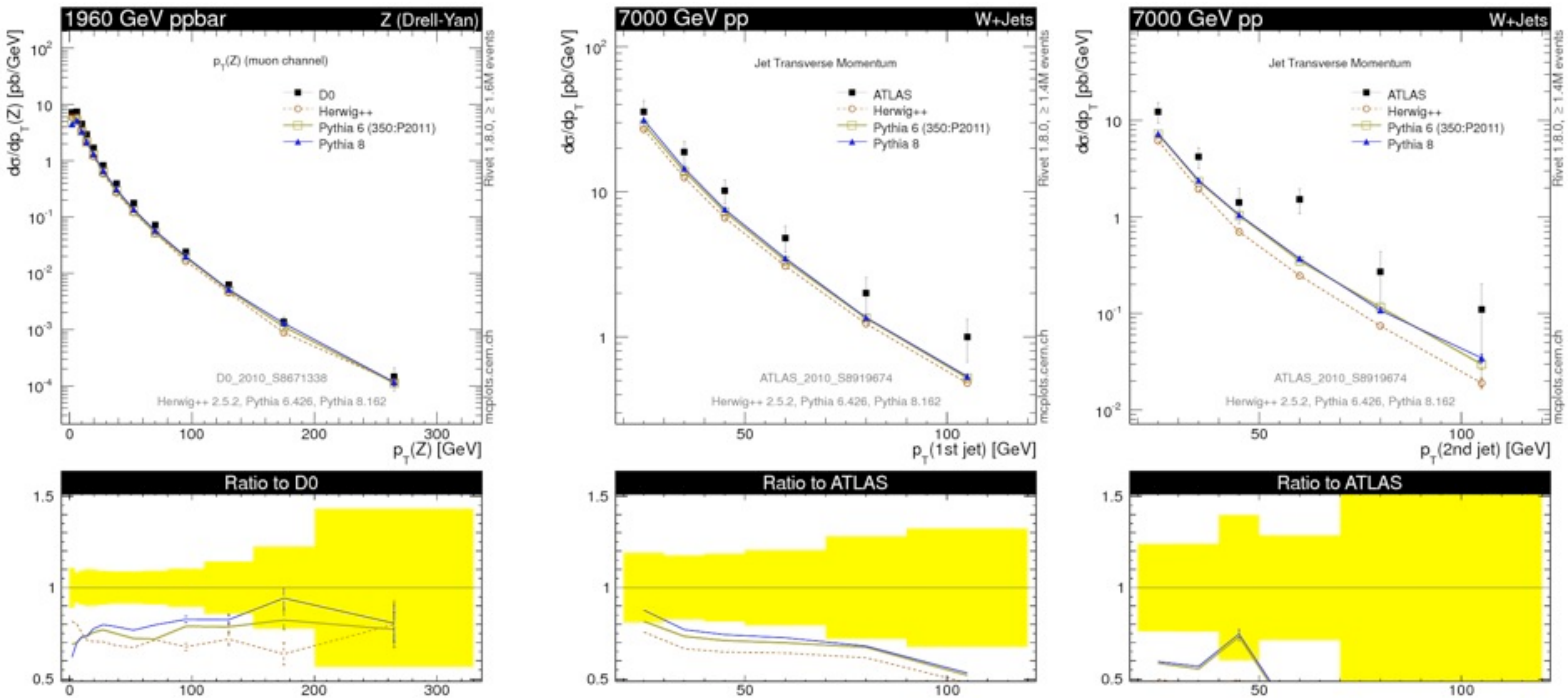
- Other event/shower generators: PhoJet, Ariadne, Dipsy, Cascade, Vincia
- Matrix-element generators: MadGraph/MadEvent, CompHep, CalcHep, Helac, Whizard, Sherpa, GoSam, aMC@NLO
- Matrix element libraries: AlpGen, POWHEG BOX, MCFM, NLOjet++, VBFNLO, BlackHat, Rocket
- Special BSM scenarios: Prospino, 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

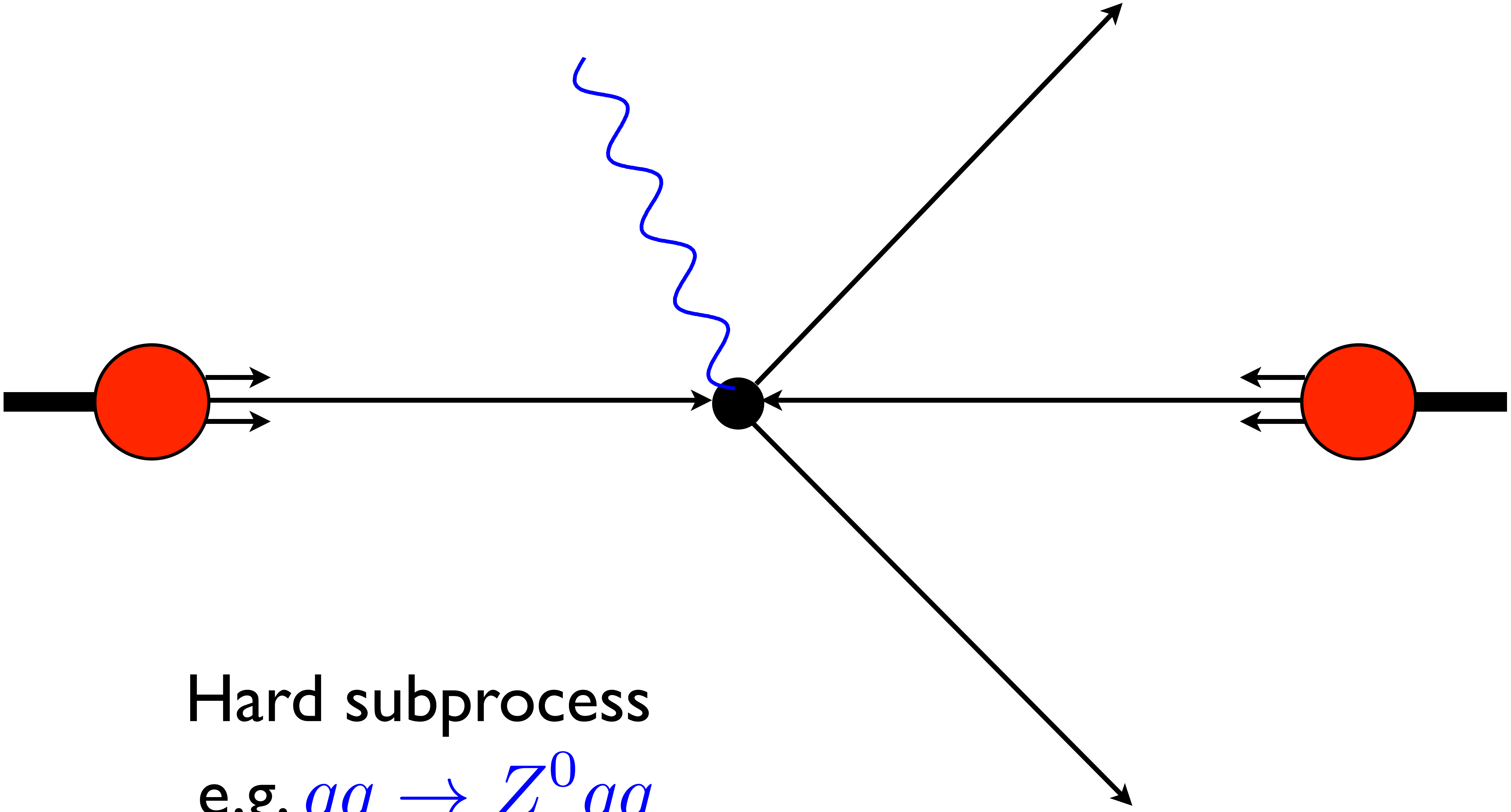
- Hard subprocess: $q\bar{q} \to Z^0/W^\pm$

http://mcplots.cern.ch/



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

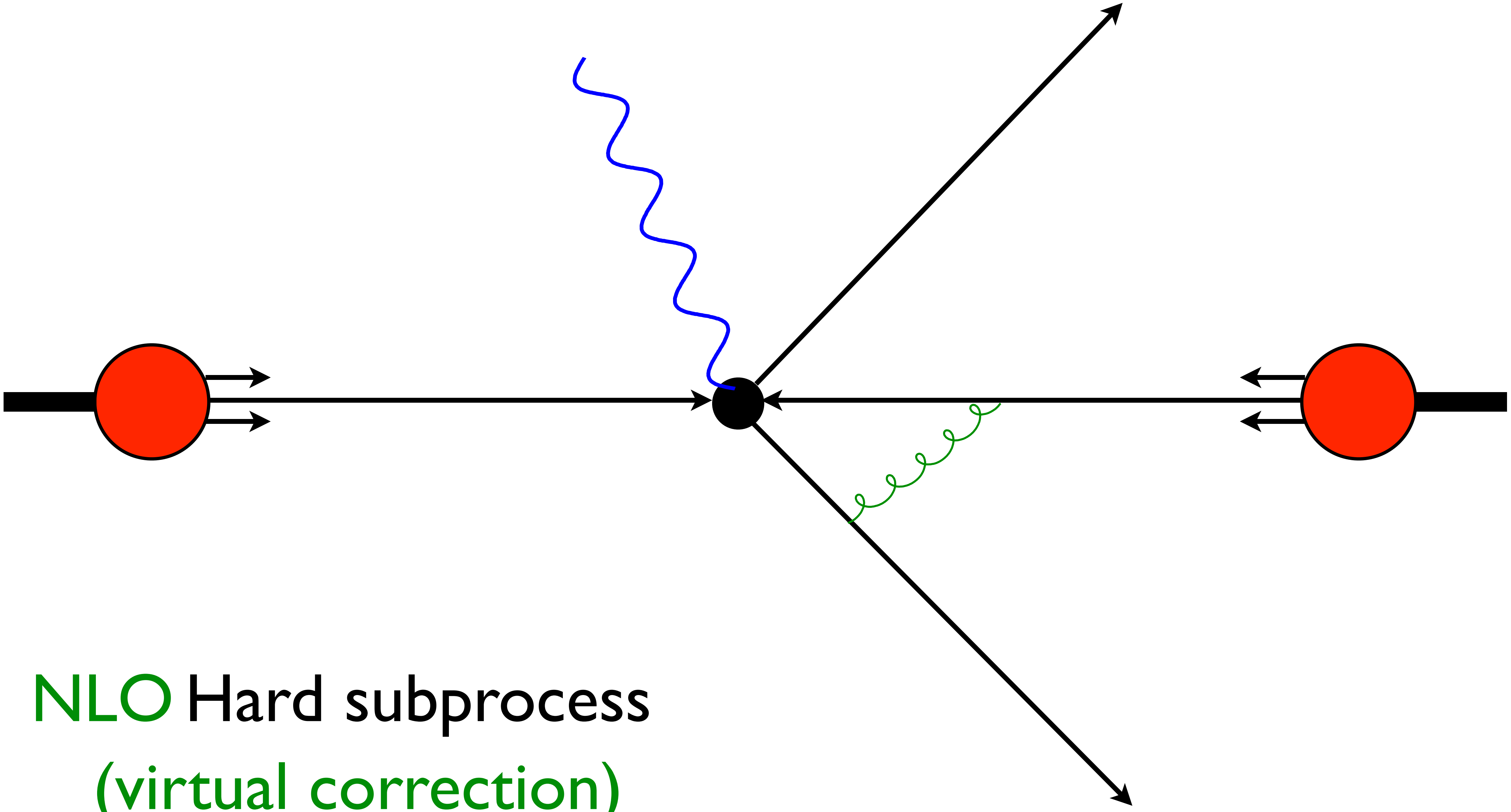
Improving Event Simulation



Hard subprocess

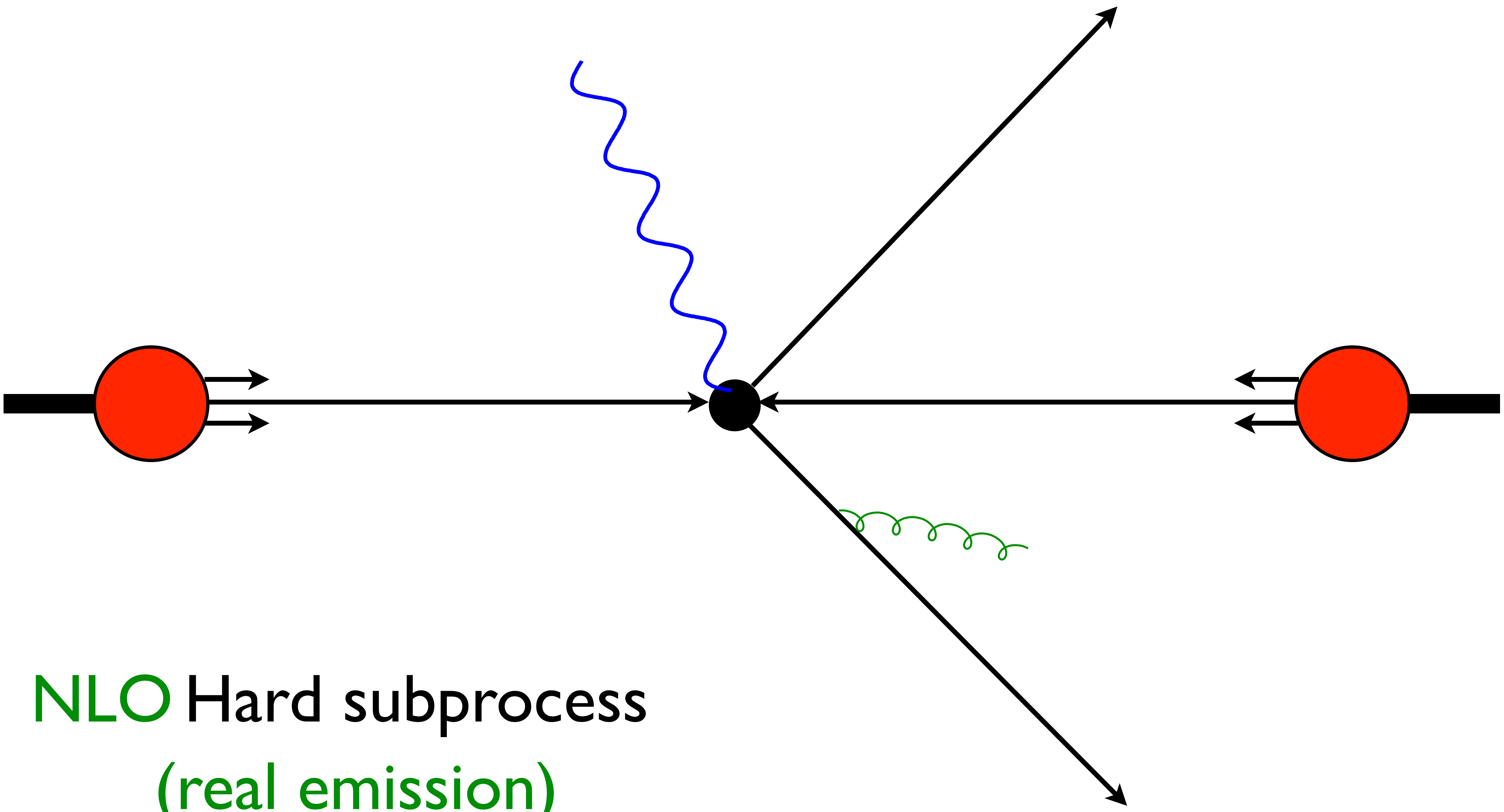
e.g. $qq \to Z^0 qq$

Improving Event Simulation



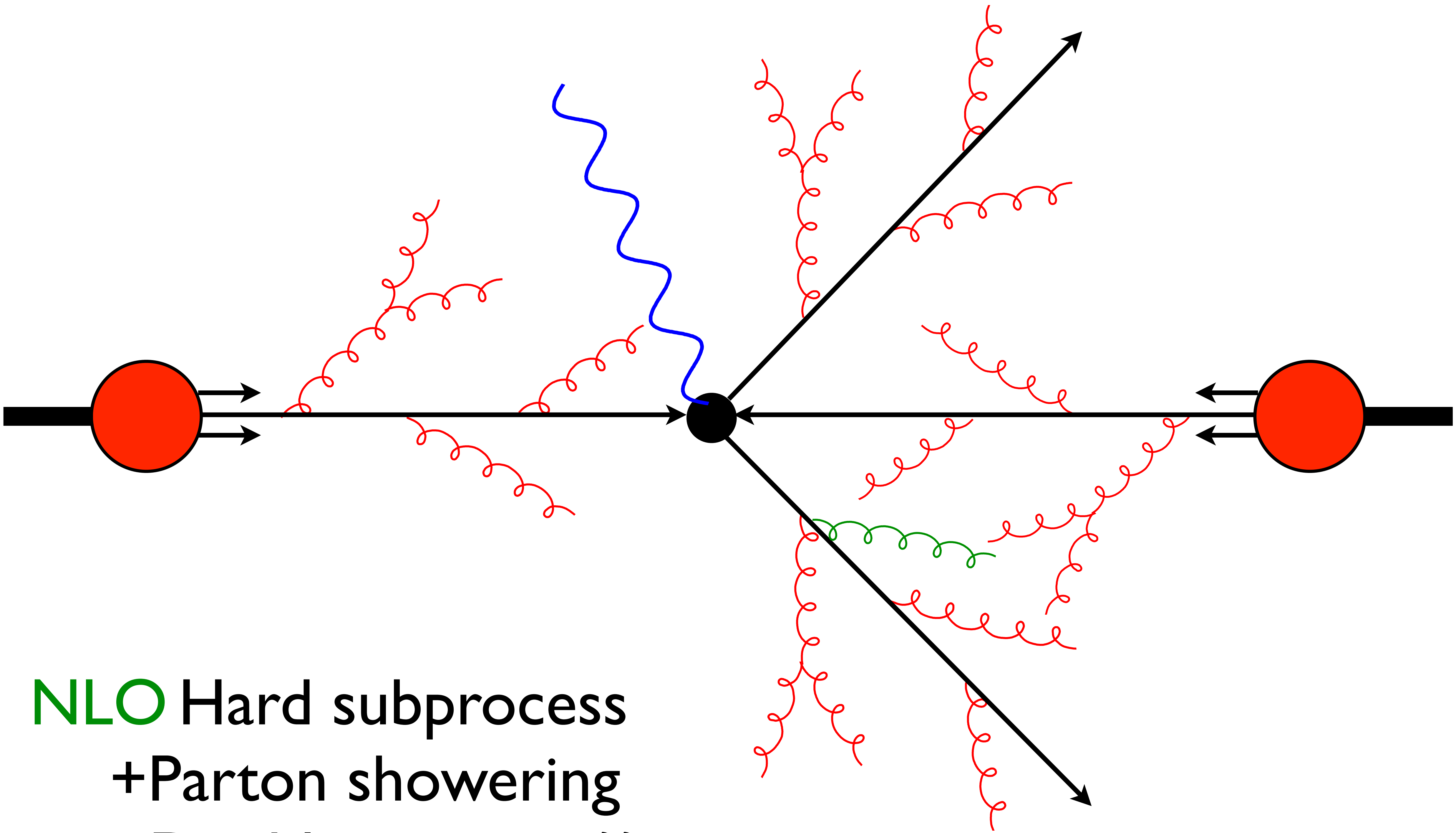
NLO Hard subprocess
(virtual correction)

Improving Event Simulation



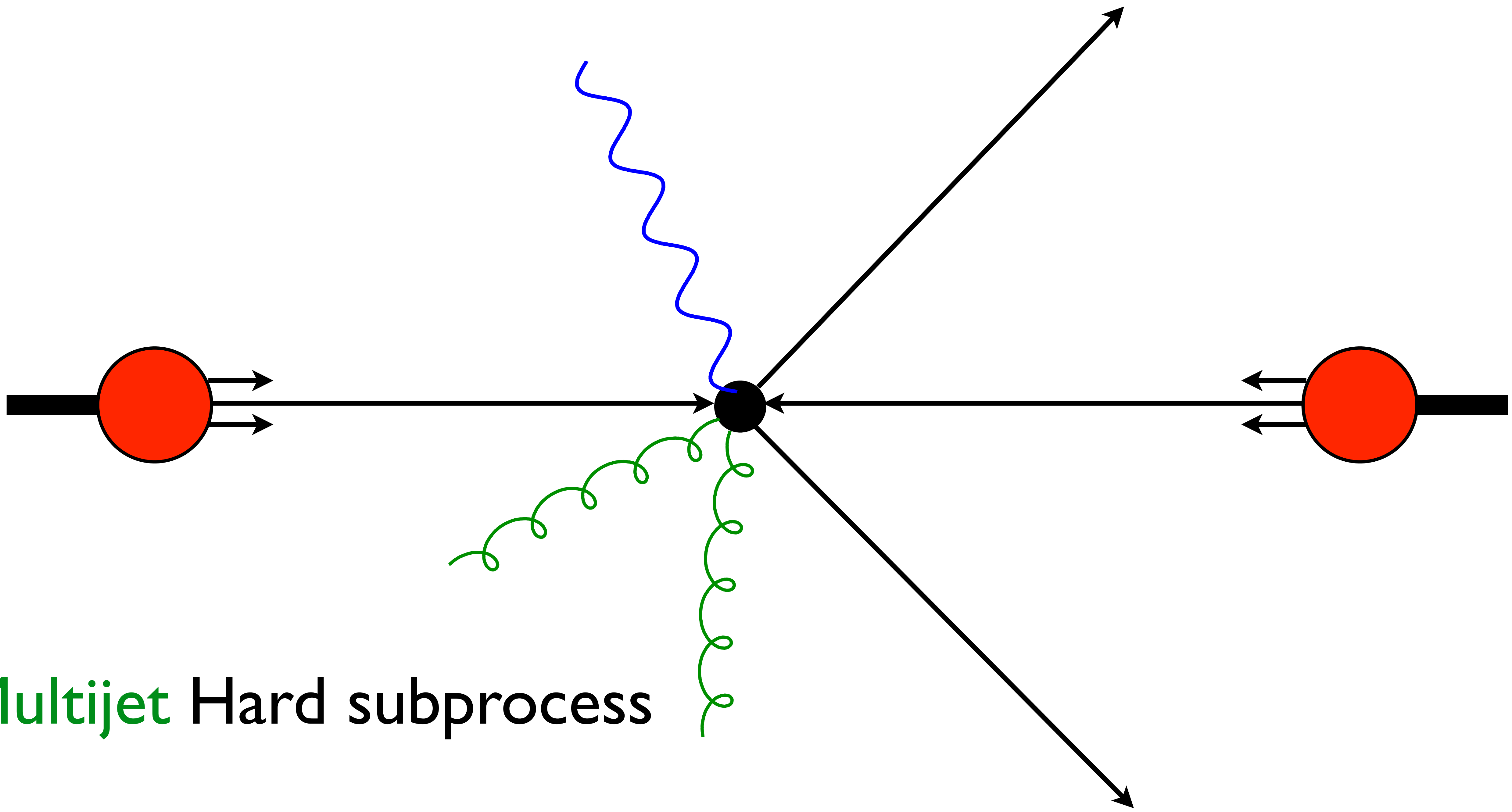
NLO Hard subprocess
(real emission)

Improving Event Simulation



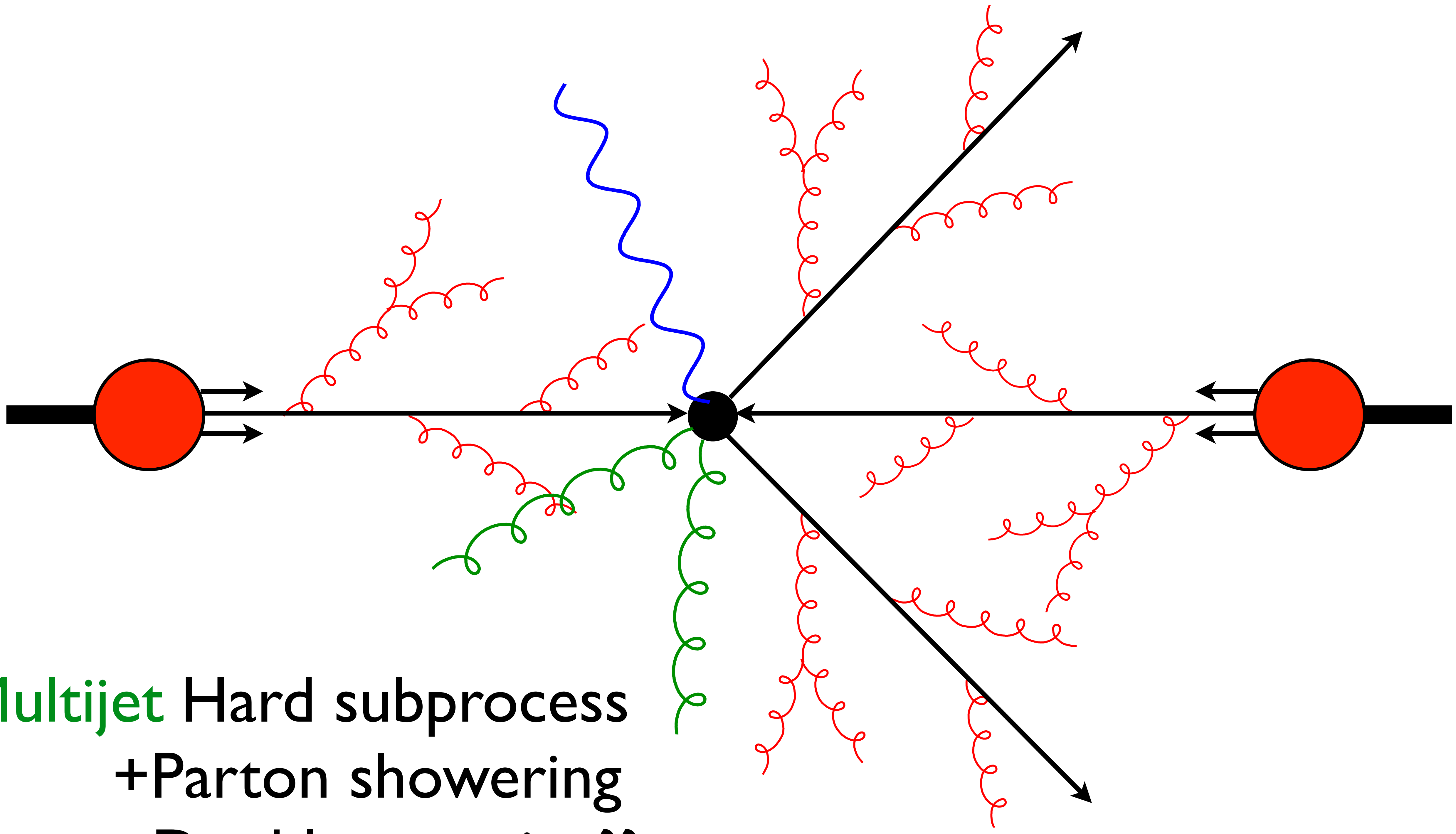
NLO Hard subprocess
+Parton showering
= Double counting??

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 — divergent

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

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

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

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

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

finite $\gtrless 0$

MC starting from no emission

MC starting from one emission

- 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

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

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

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

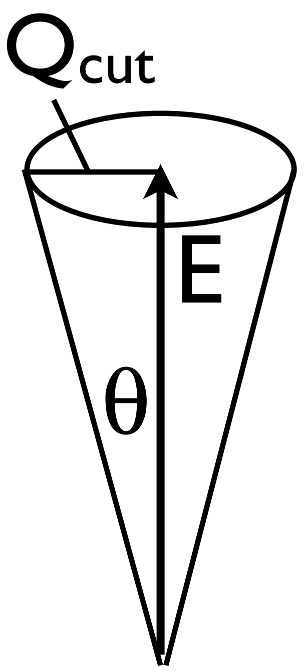
$$\Delta_R(p_T) = \exp\left[-\int d\Phi_R \frac{R(\Phi_B, \Phi_R)}{B(\Phi_B)} \theta(k_T(\Phi_B, \Phi_R) - p_T)\right]$$

- 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, $n \leq N_{max}$

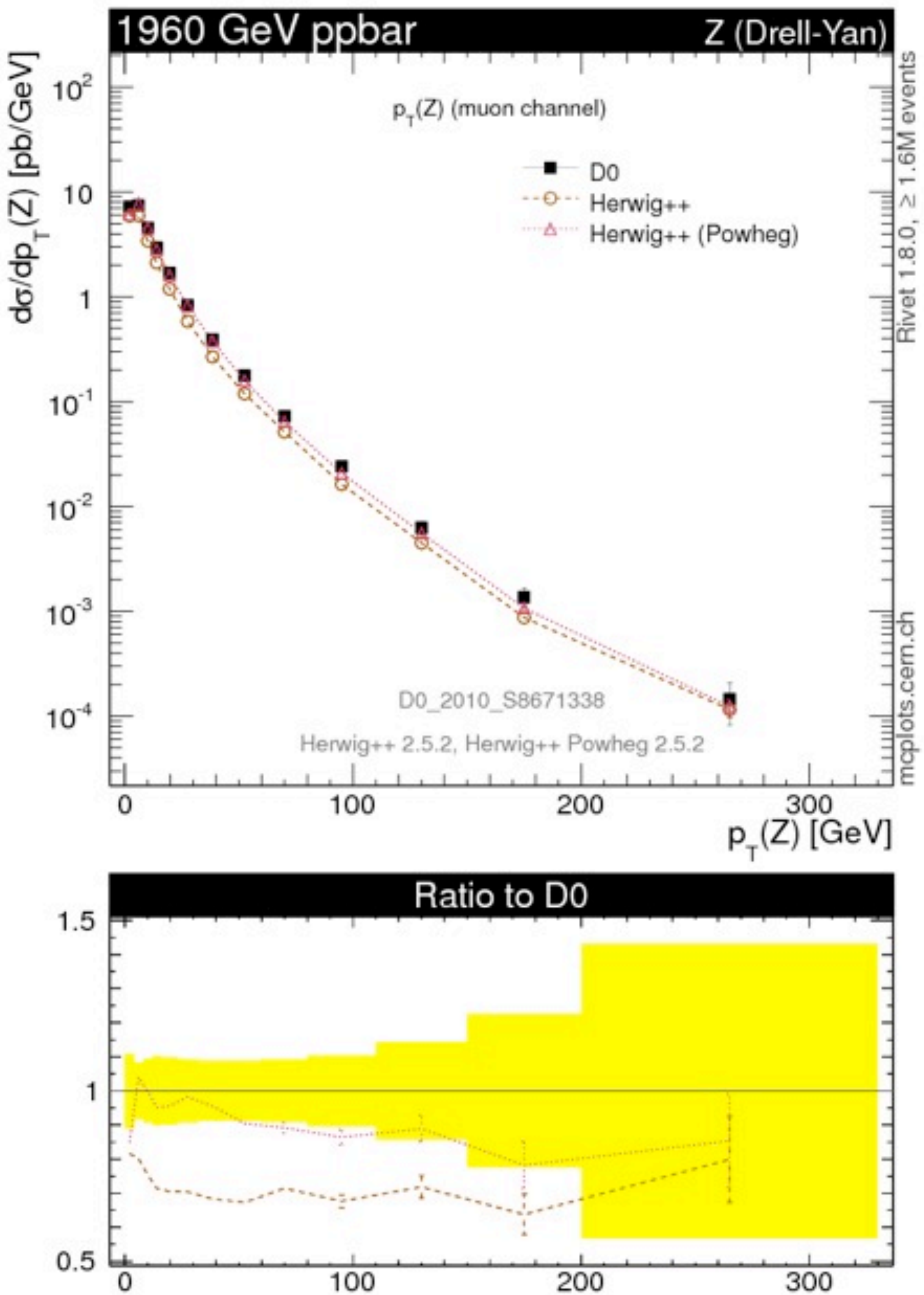
CKKW: Catani et al., JHEP 11(2001)063

-L: Lonnblad, JHEP 05(2002)063

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

Vector boson production

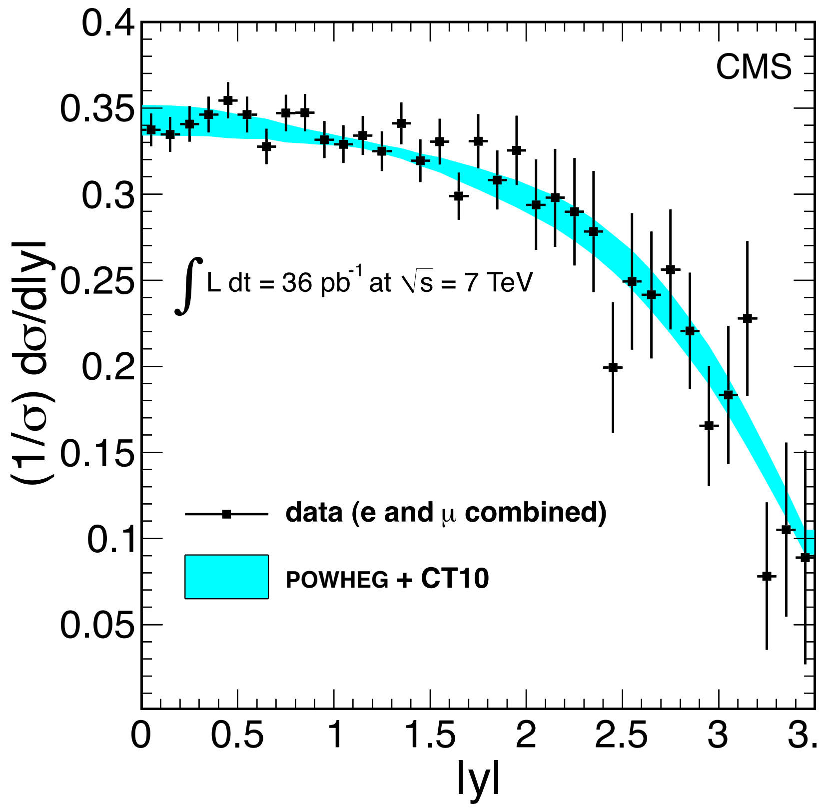
Z^0 at Tevatron

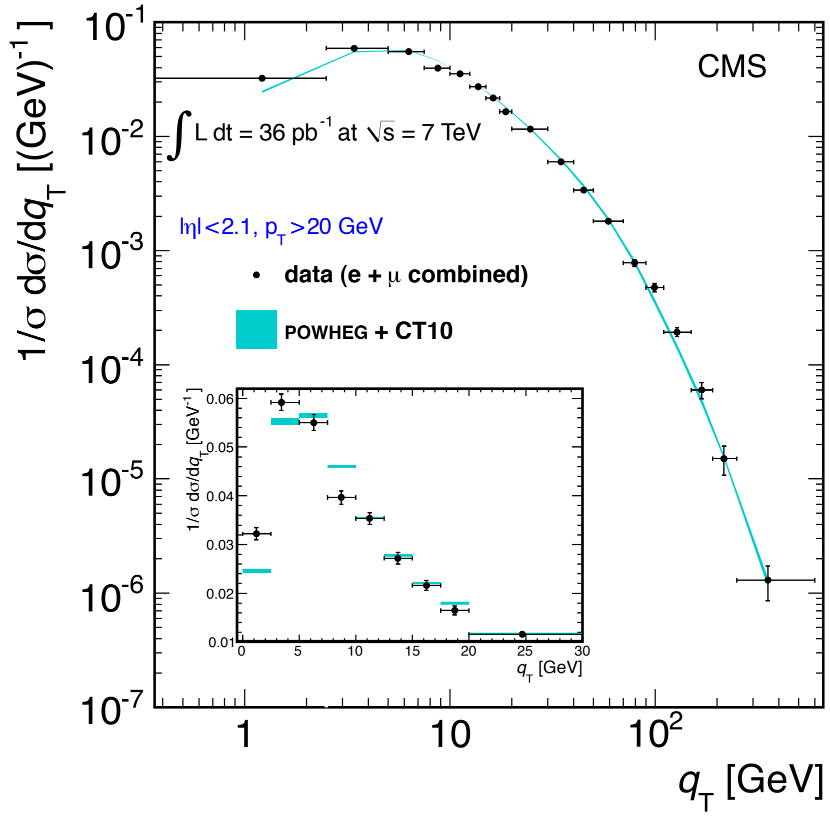


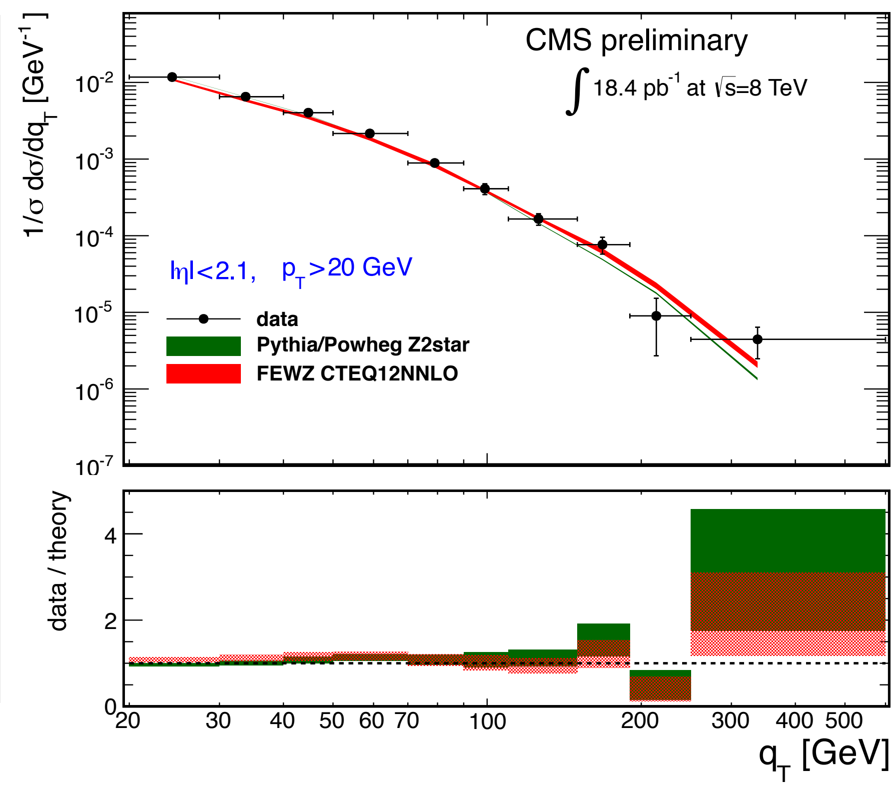
http://mcplots.cern.ch/

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

Z^0 at LHC





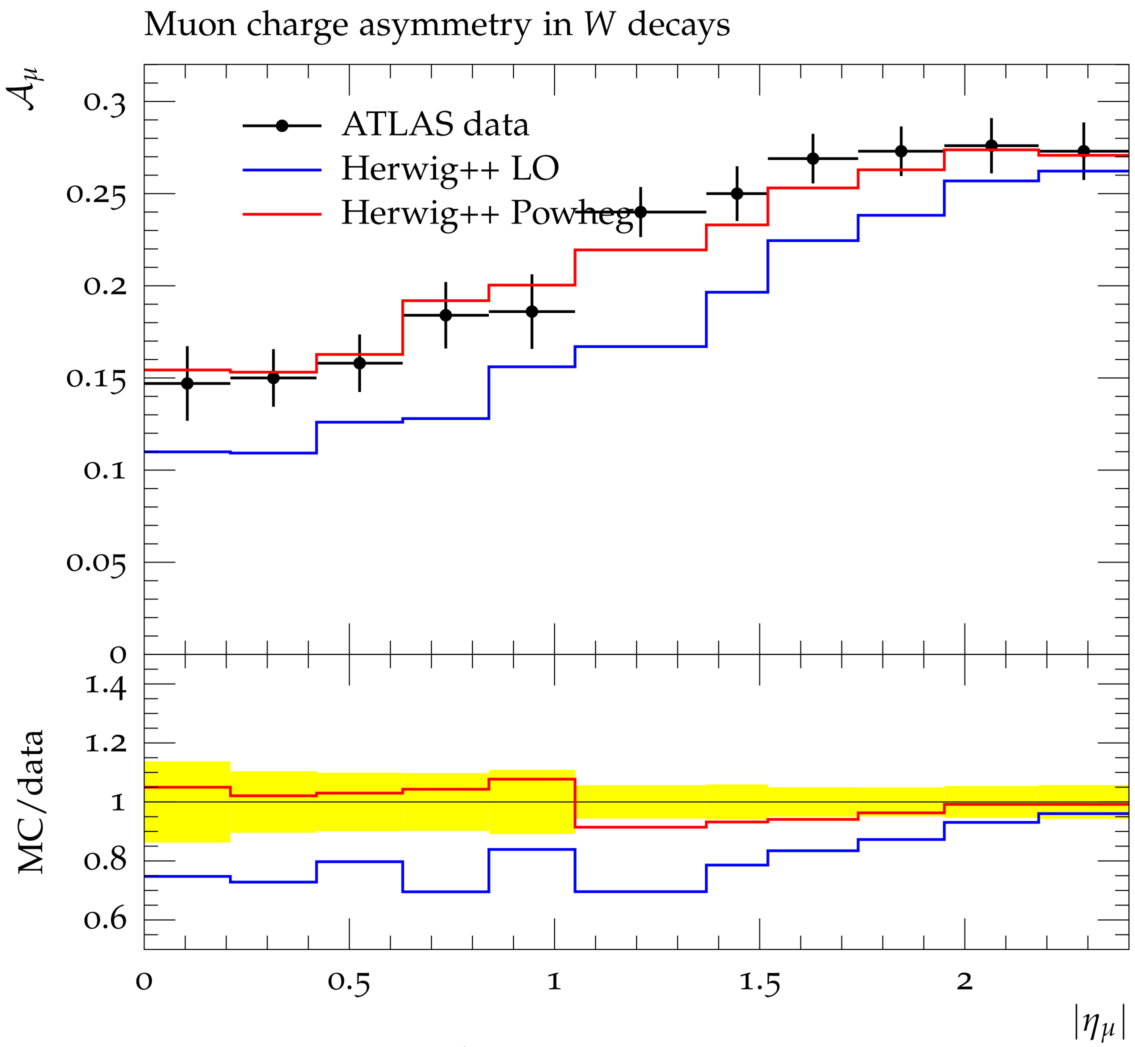


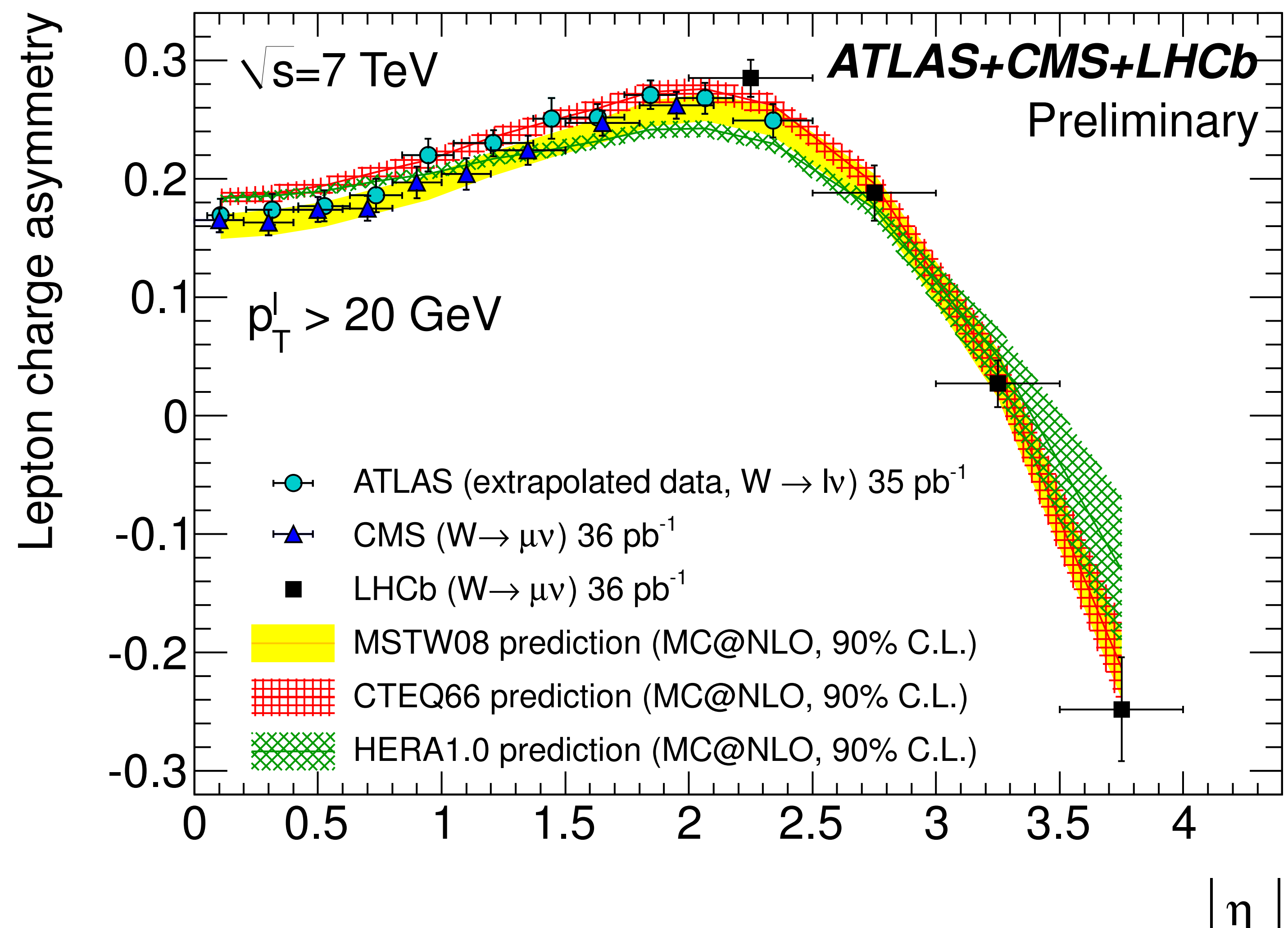
CMS, PRD85(2012)032002

CMS PAS SMP-12-025

- Normalized to data
- POWHEG agrees with distribution (and NNLO)

W asymmetry at LHC





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

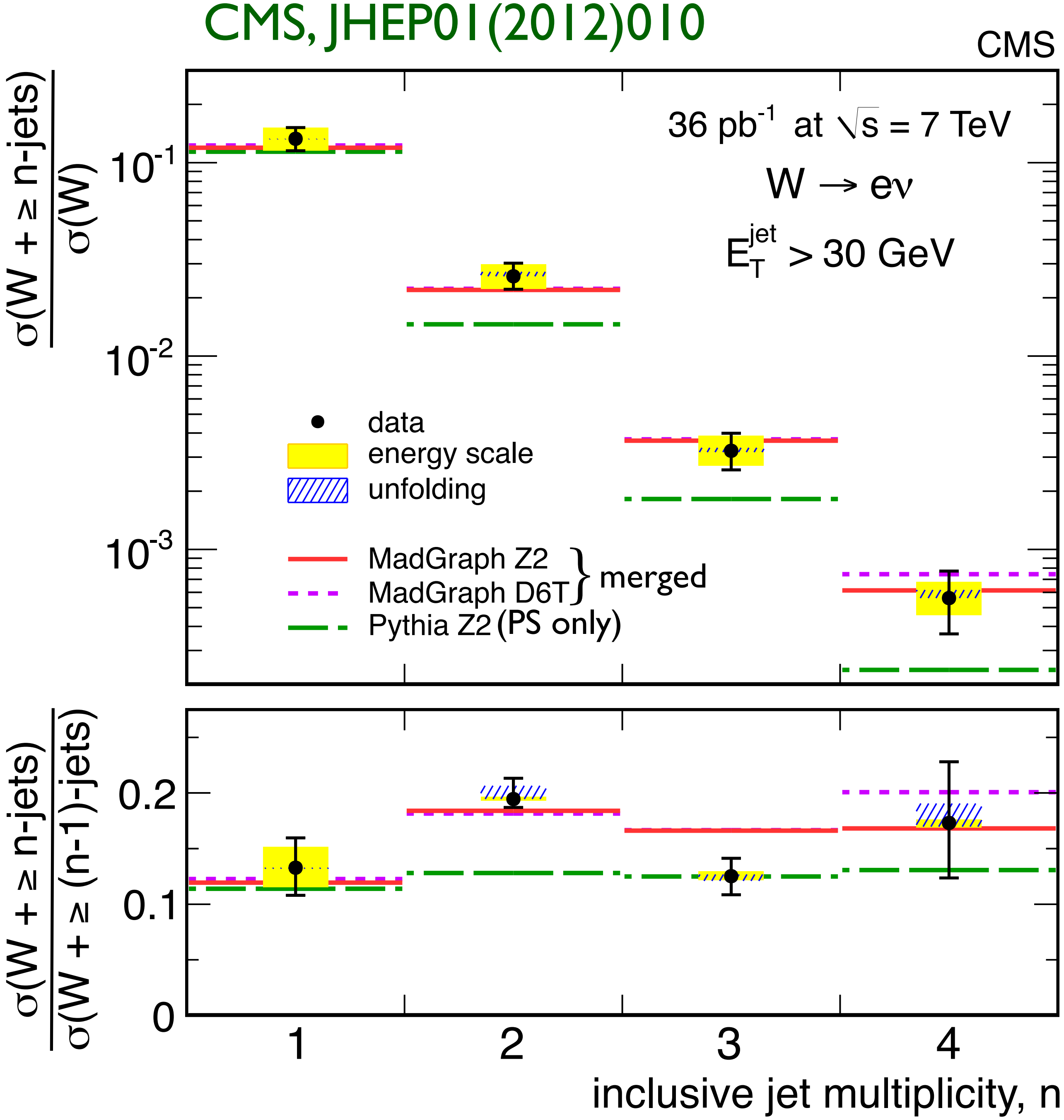
ATLAS-CONF-1211-129

- Asymmetry probes parton distributions

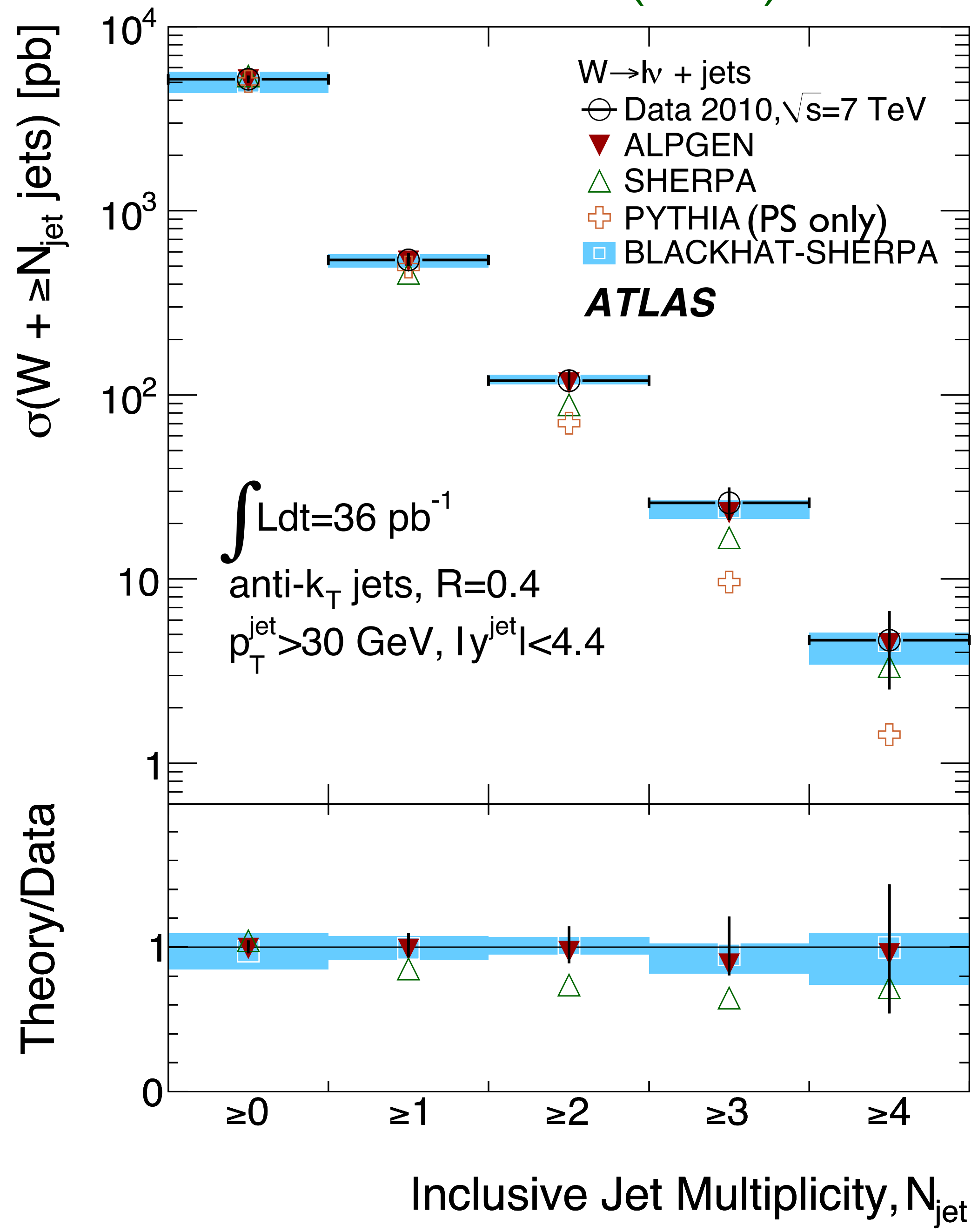
$$u\bar{d} \to W^+ \to \mu^+\nu_\mu \quad \textbf{vs} \quad d\bar{u} \to W^- \to \mu^-\bar{\nu}_\mu$$

W+jets at LHC

CMS, JHEP01(2012)010



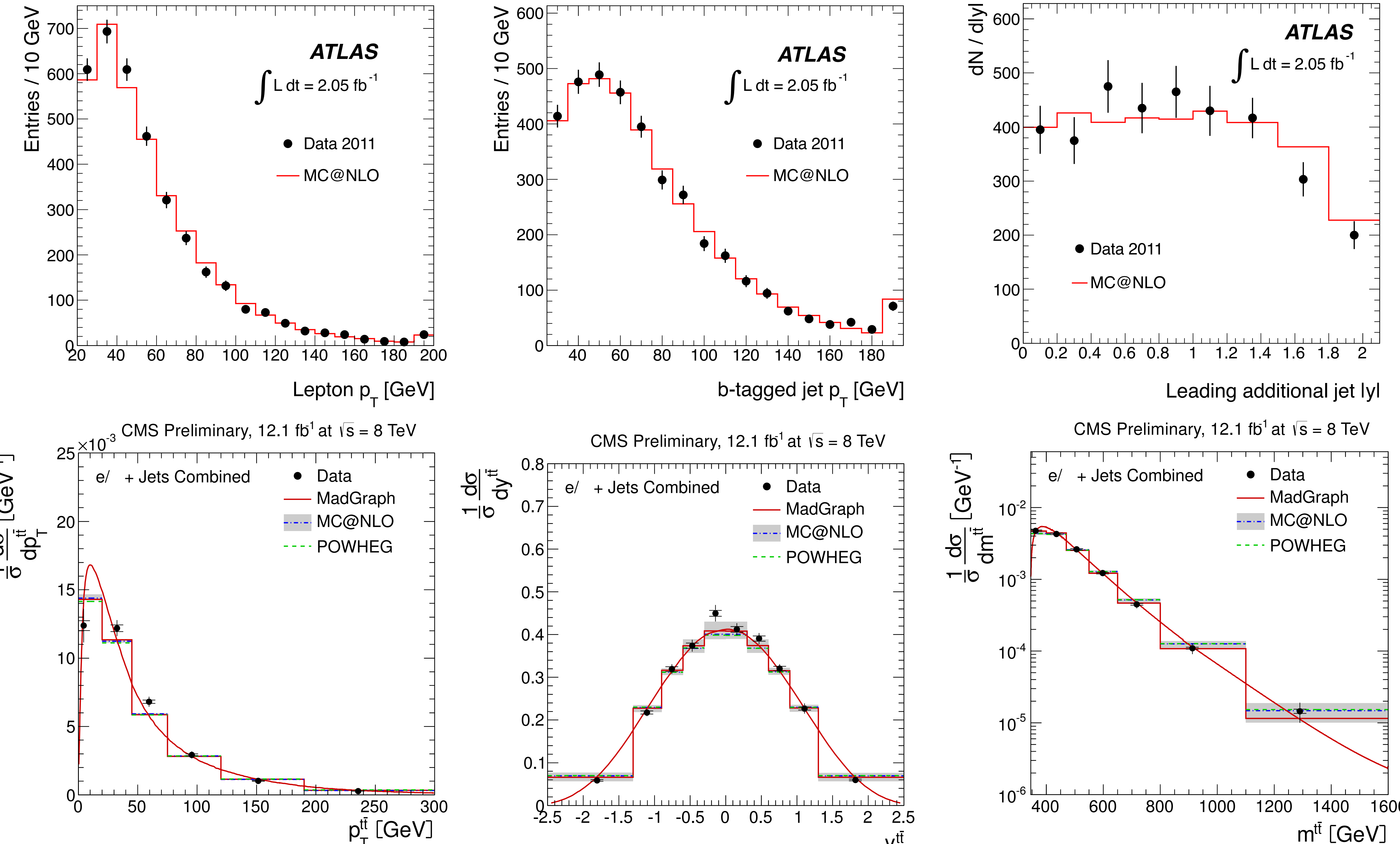
ATLAS, PRD85(2012)092002



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

Top quark pair production

Top quark pairs at LHC



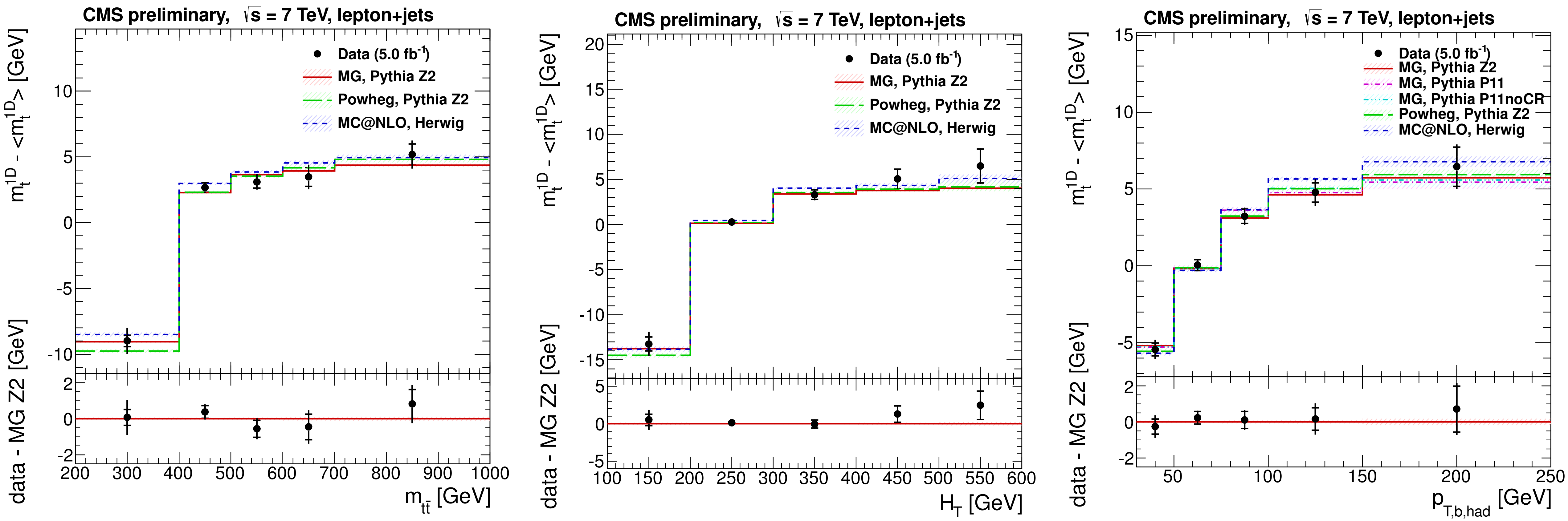
ATLAS, arXiv:1203.5015

CMS PAS TOP-12-027

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

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

Top mass & kinematics



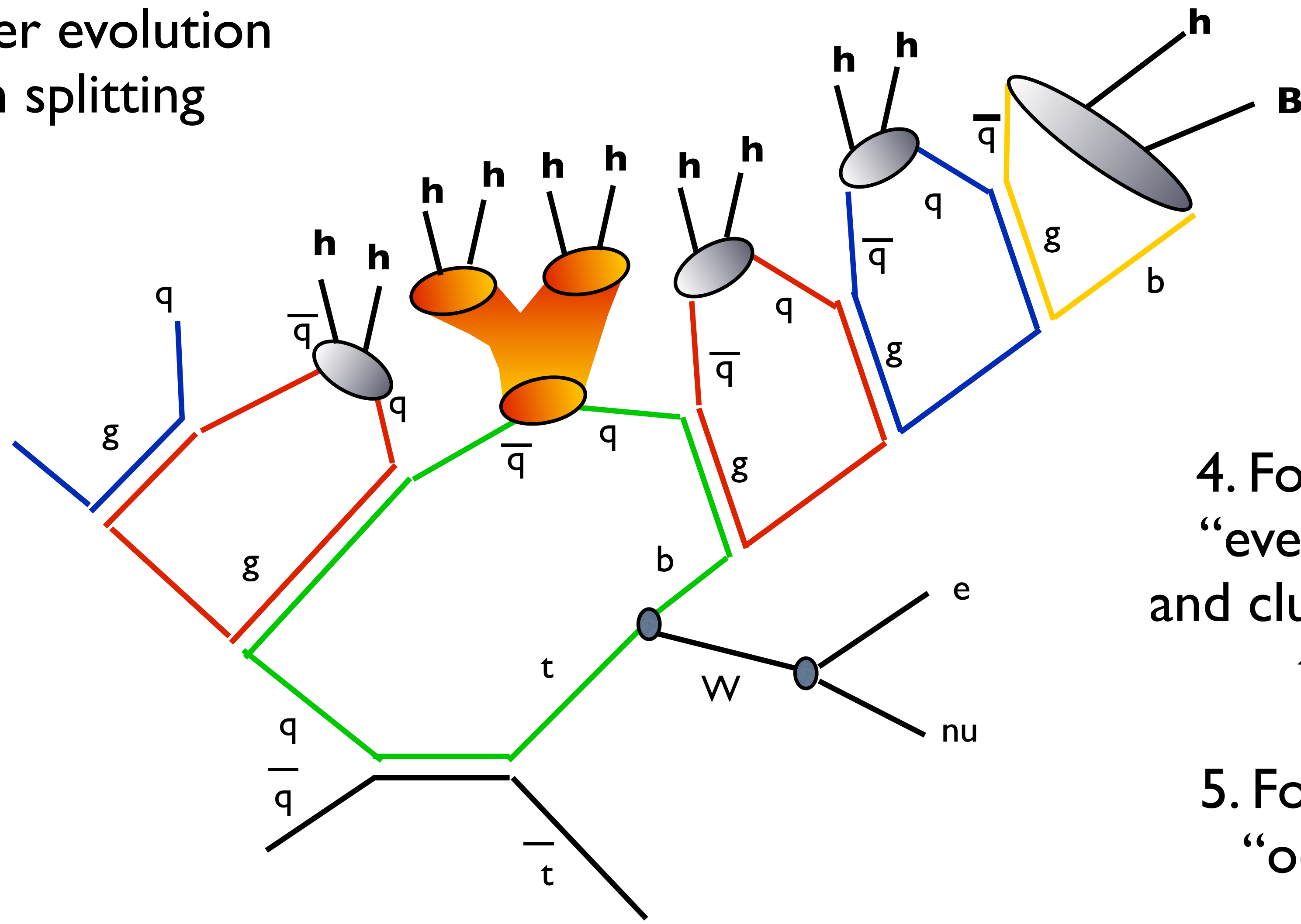
CMS PAS TOP-12-029

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

Top mass & hadronization

Mangano, Top LHC WG, July 2012

1. Hard Process
2. Shower evolution
3. Gluon splitting



4. Formation of “even” clusters and cluster decay to hadrons

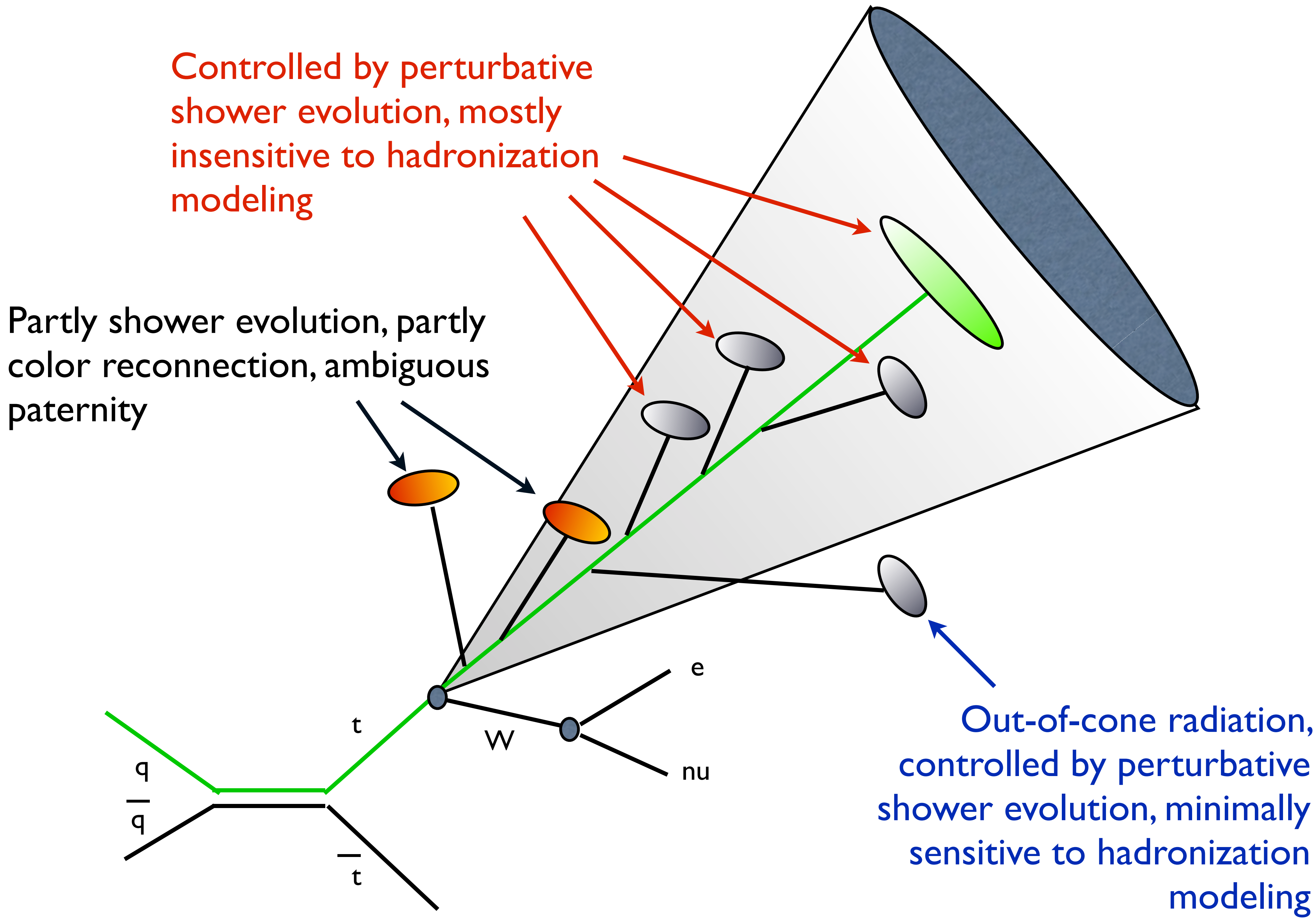
5. Formation of “odd” cluster

6. Decay of “odd” clusters, if large cluster mass, and decays to hadrons

- Study dependence of reconstructed mass on “odd” clusters

Top mass & hadronization

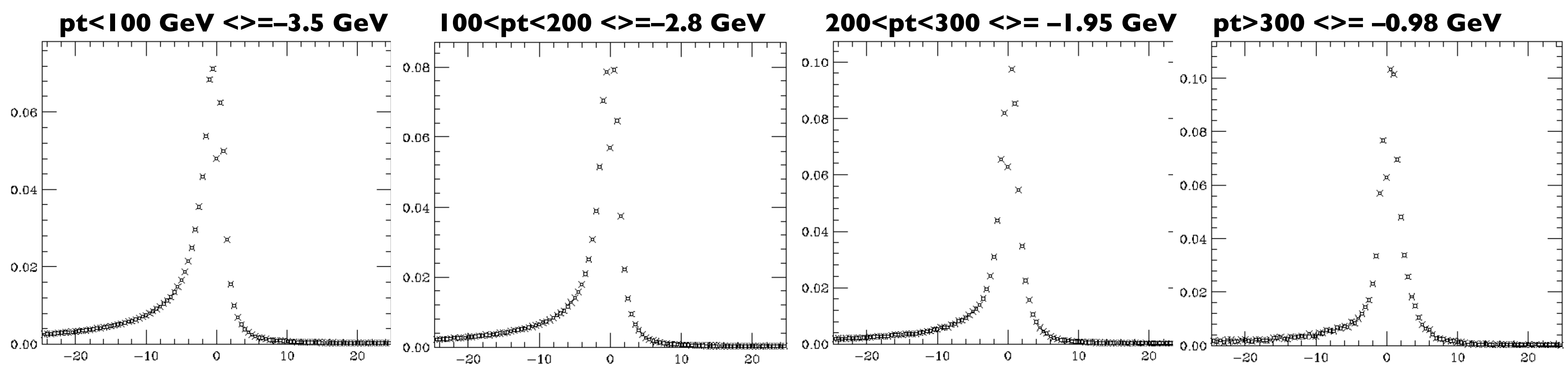
Mangano, Top LHC WG, July 2012



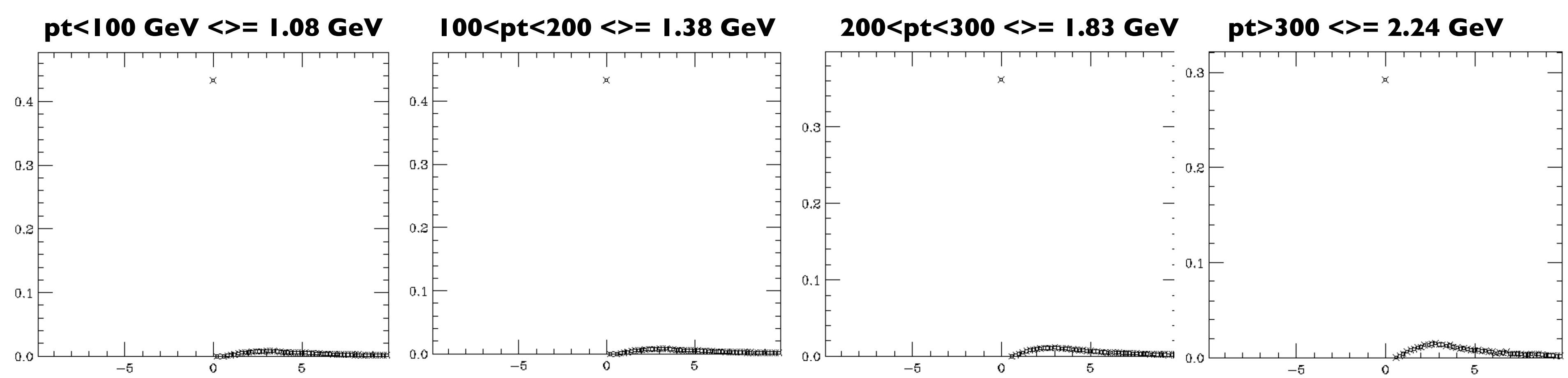
Top mass & hadronization

m_{top} vs pt(top)

m_{top}(E+O) – 172.5



m_{top}(E+O) – m_{top}(E)



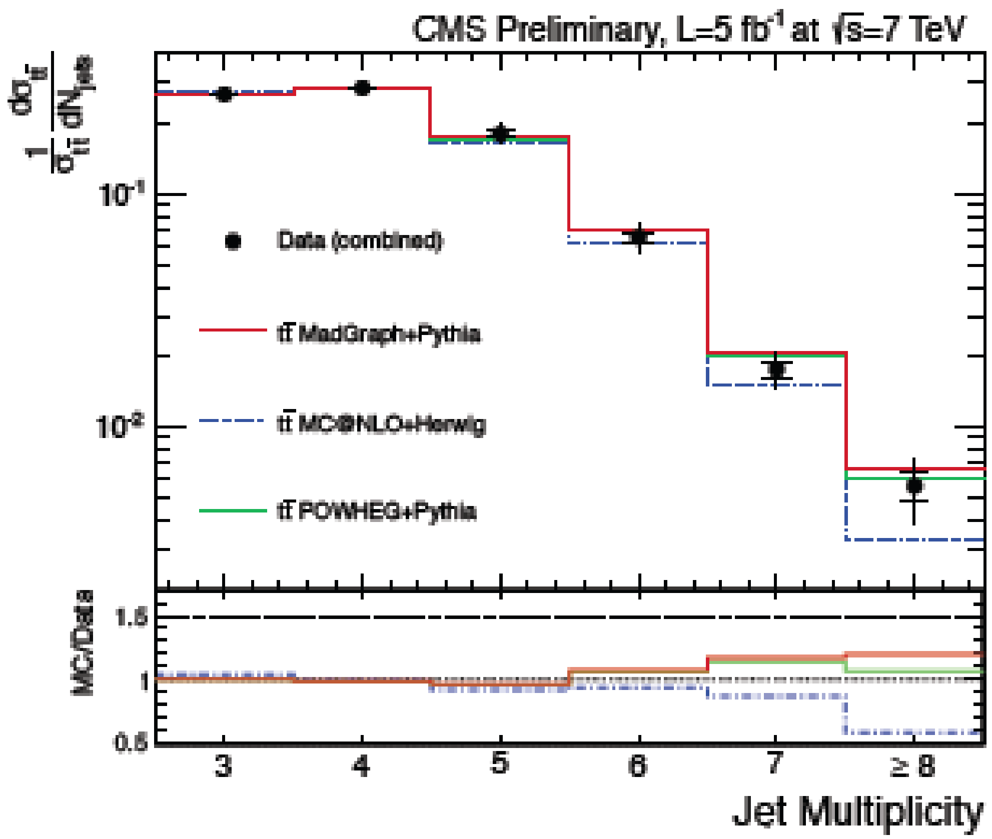
- Dependence of reconstructed mass on "odd" clusters ~ 1 GeV

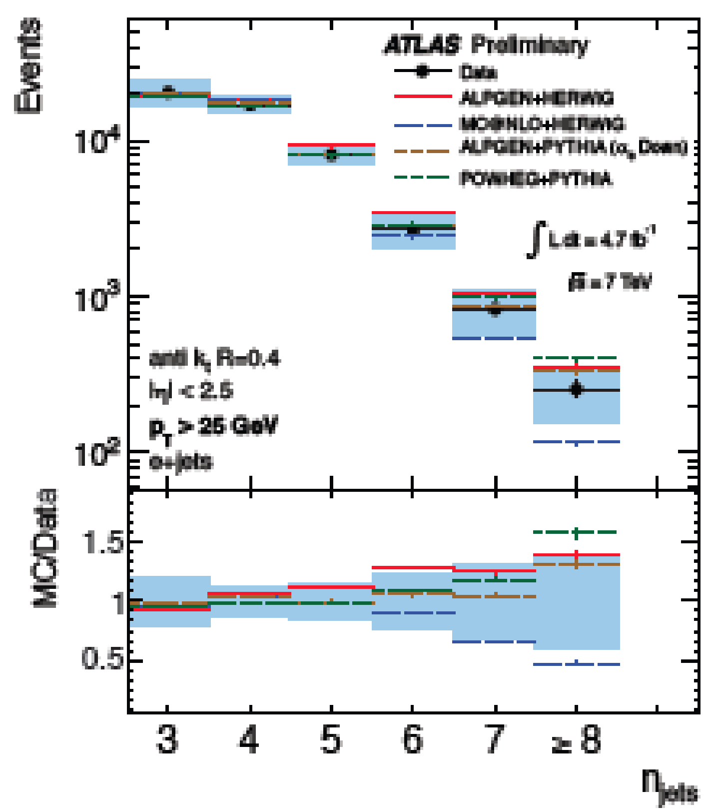
Top+jets

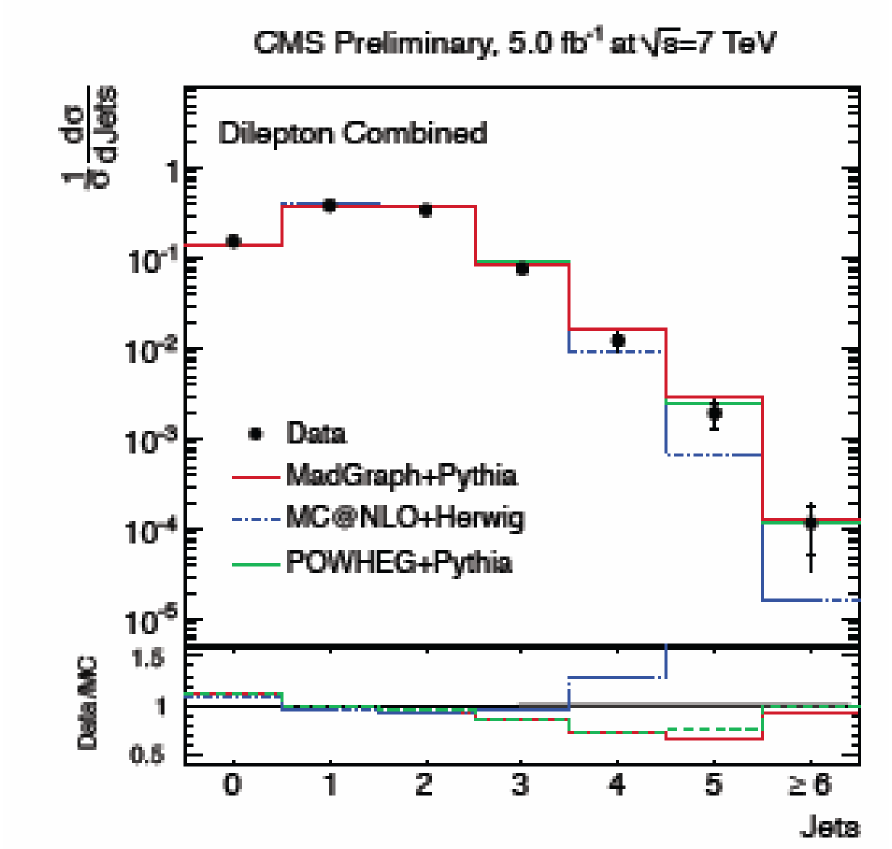
CMS PAS TOP-12-018 (l+jets)
ATLAS-CONF-2012-155 (l+jets)

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

CMS PAS TOP-12-023
(dilepton)

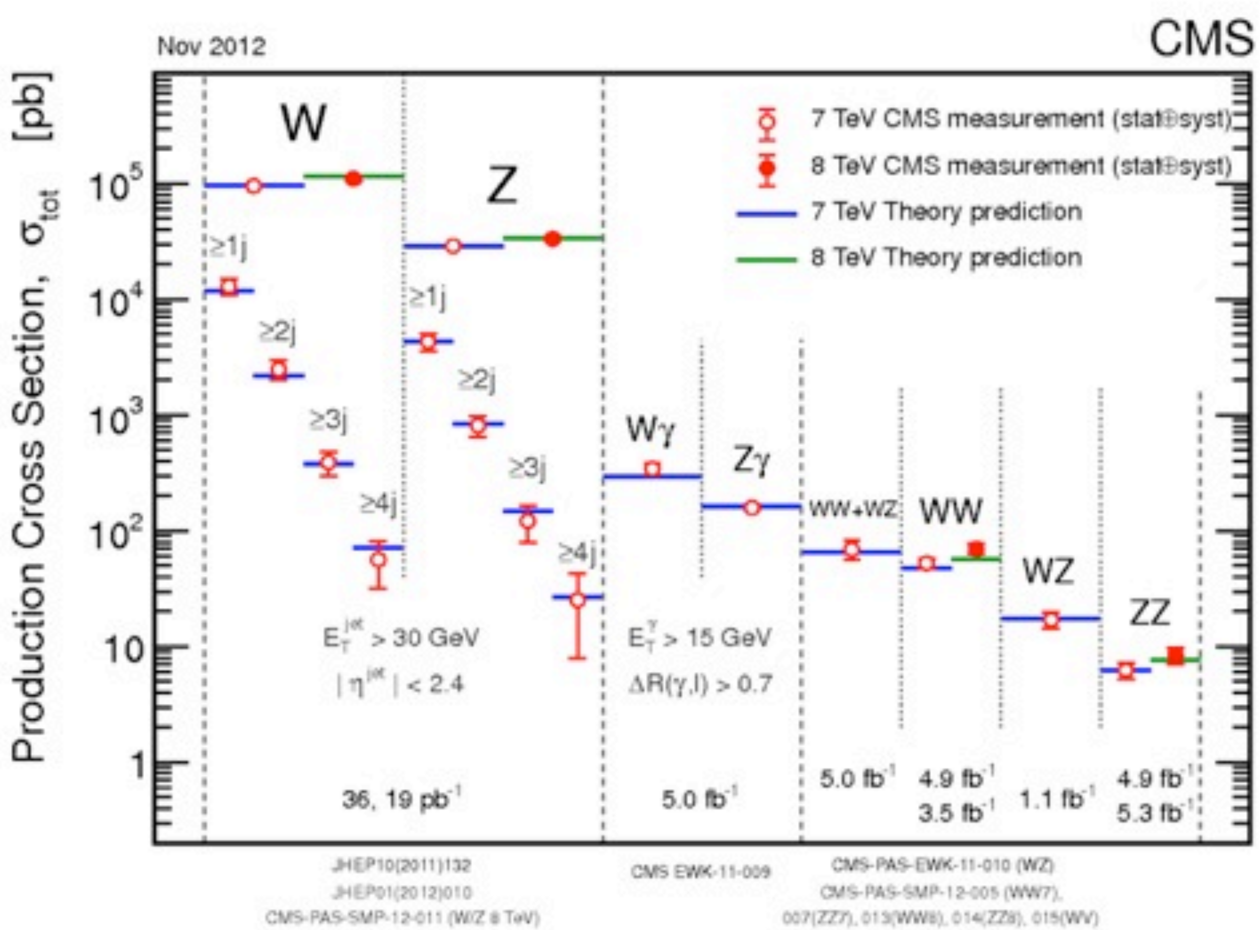


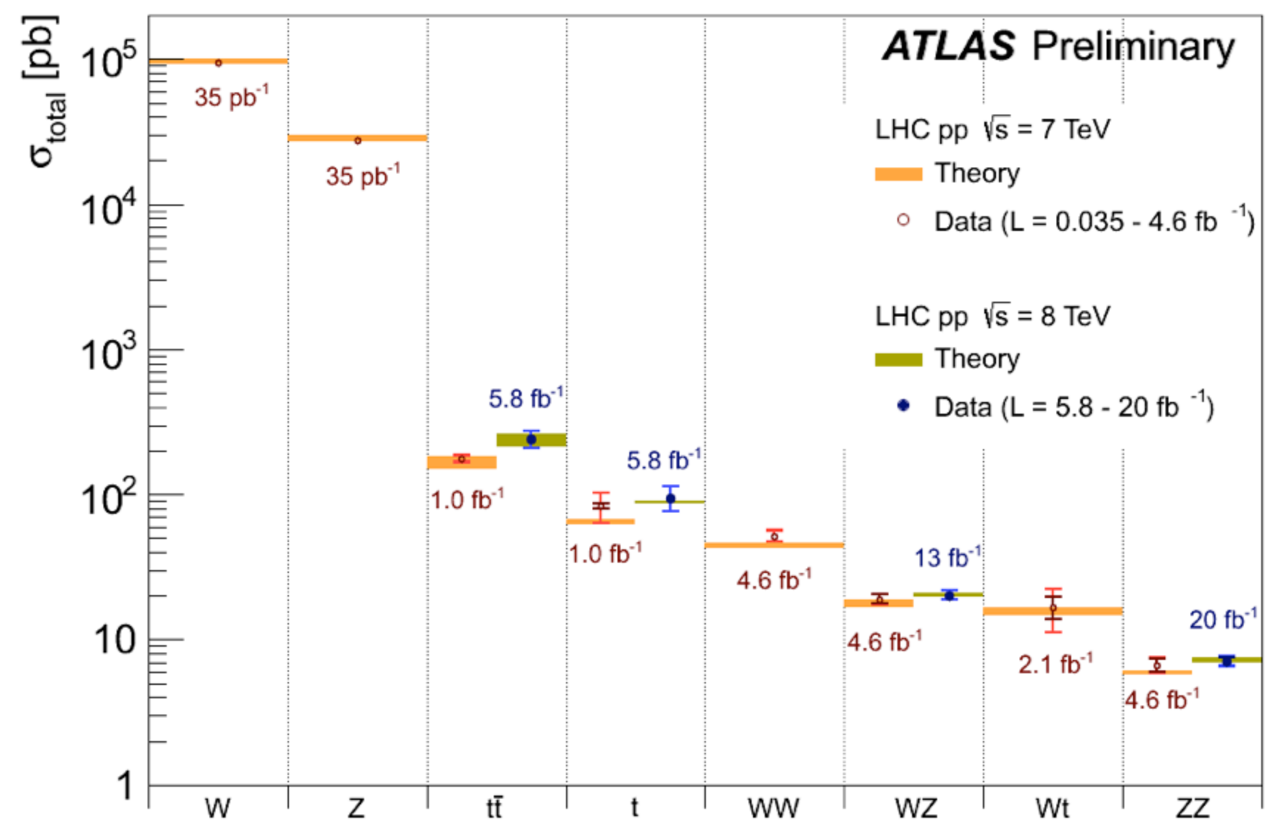




- Matched NLO not adequate for >2 extra jets
- Merged multijets better there (for dσ/σ)

LHC Cross Section Summary



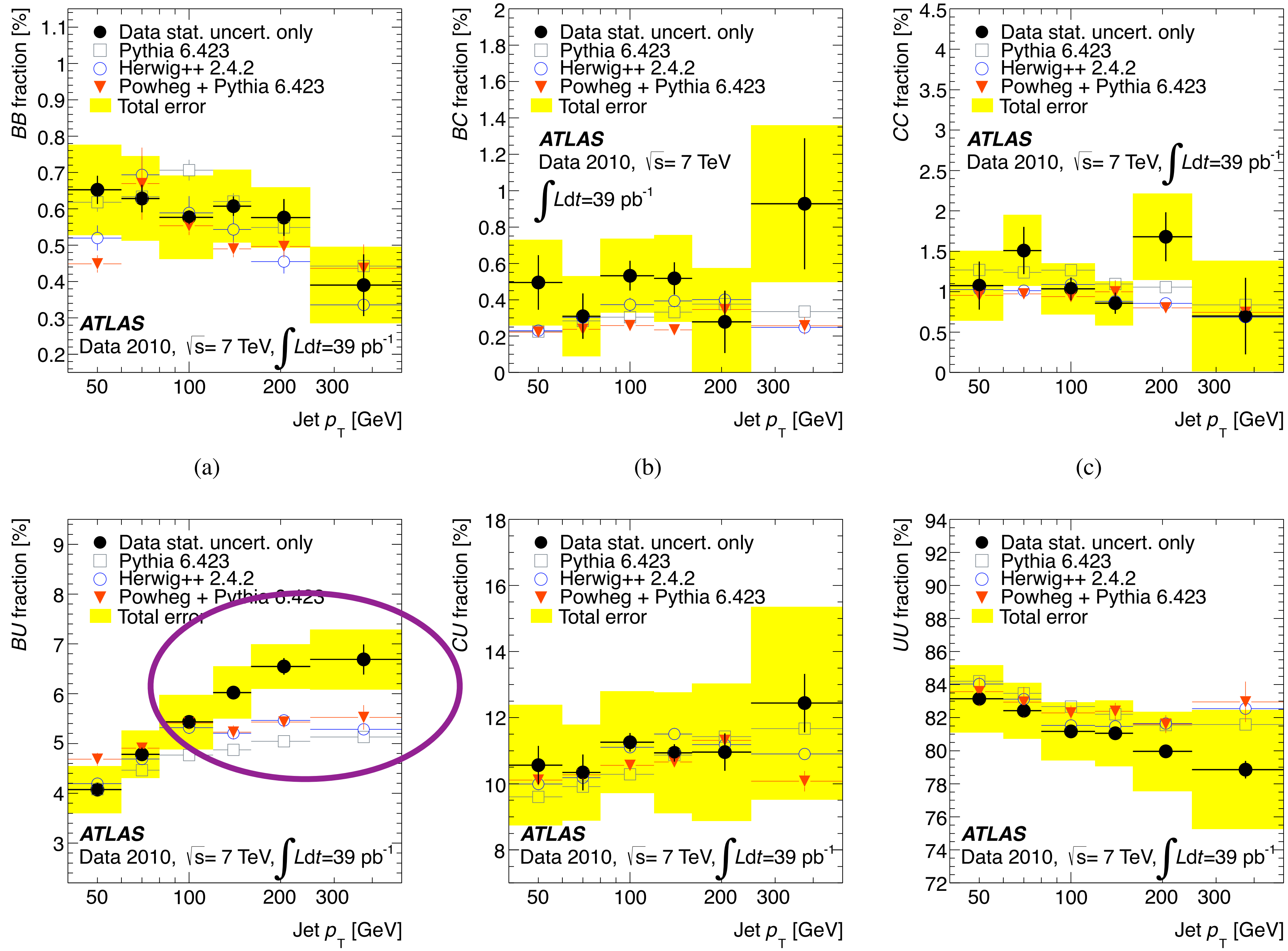


- Surprisingly good agreement
- No sign of non-Standard-Model phenomena (yet)

But all is not perfect ...

- Dijet flavours versus jet pT

ATLAS, arXiv:1210.0441



- Interesting excess of (single) b quark jets

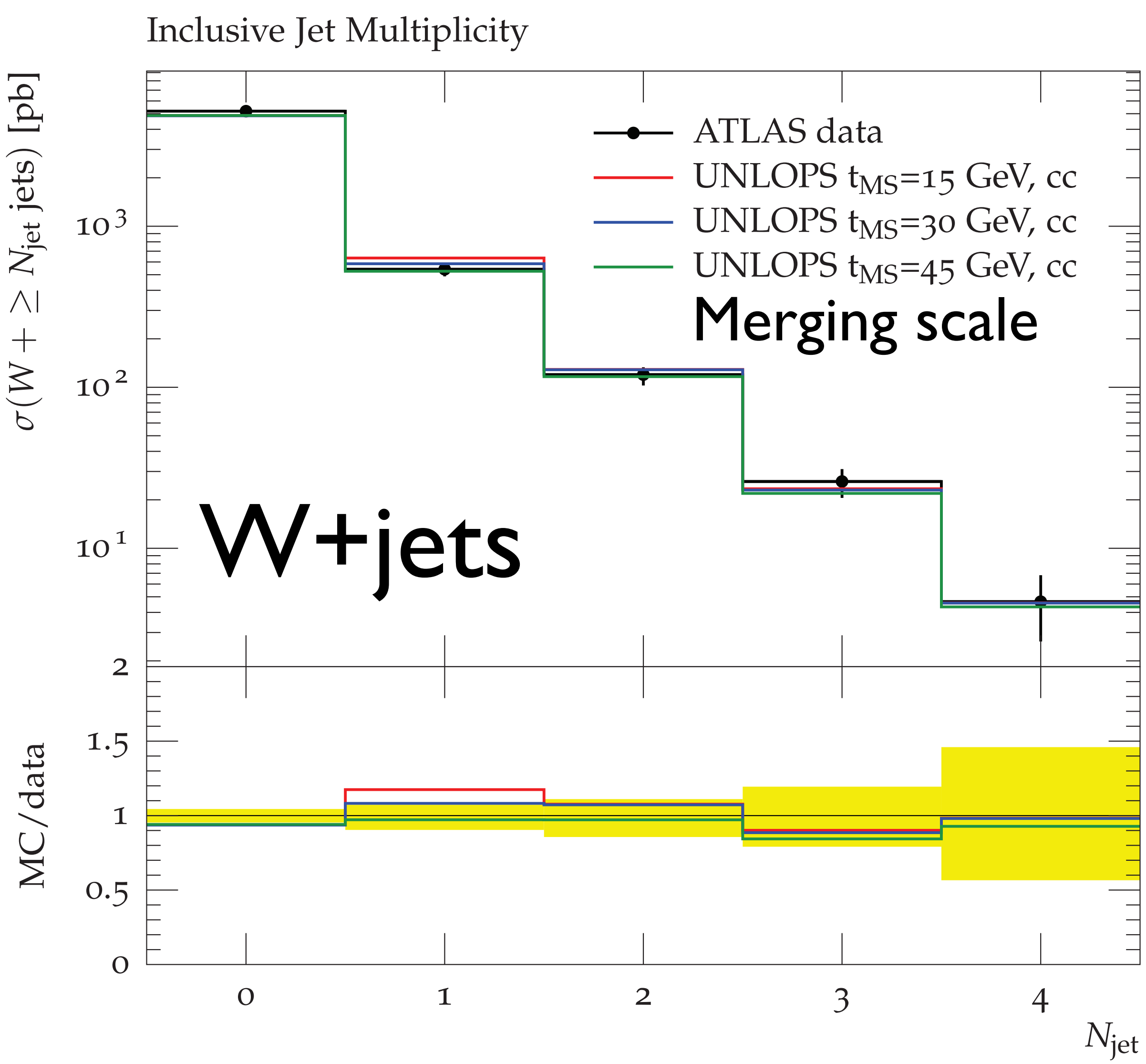
Combined matching+merging

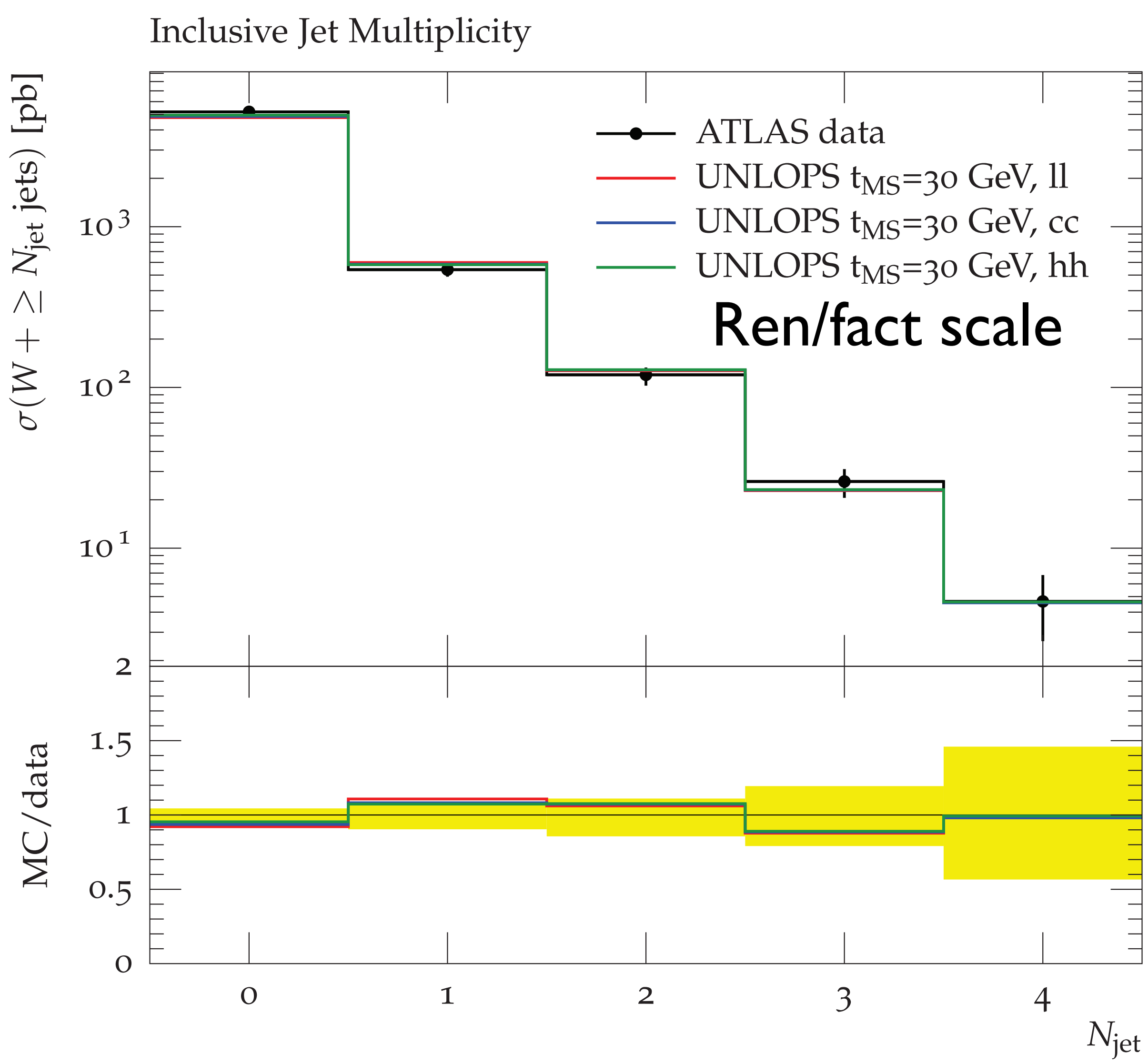
- NLO calculations generally refer to inclusive cross sections e.g. $\sigma(W+\geqslant n\ \text{jets})$
- Multijet merging does not preserve them, because of mismatch between exact real-emission and approximate (Sudakov) virtual corrections
- When correcting this mismatch, one can simultaneously upgrade 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) Höche et al., arXiv:1207.5030
  - 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





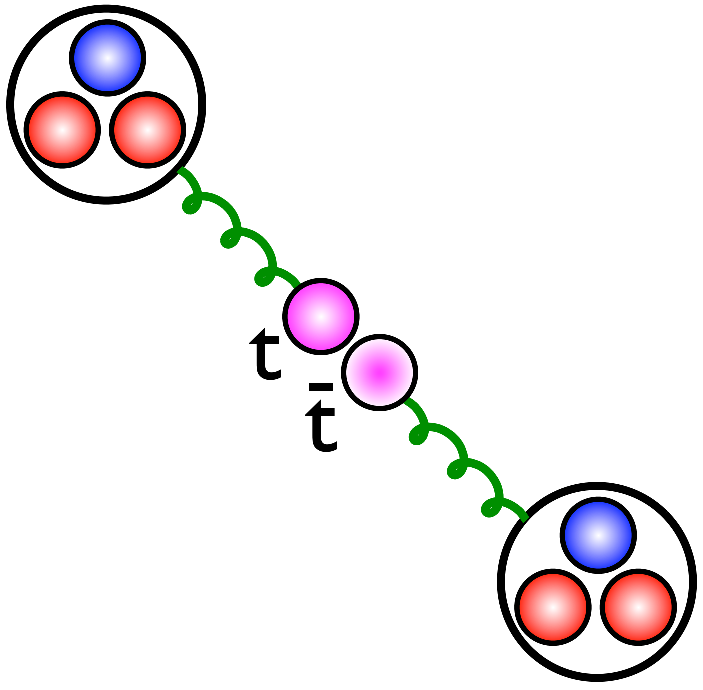
UNLOPS: Lönnblad & Prestel, arXiv:1211.7278

- Scale dependences almost eliminated

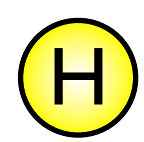
Higgs boson production

Higgs Production by Gluon Fusion

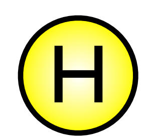
Higgs Production by Gluon Fusion



Higgs Production by Gluon Fusion

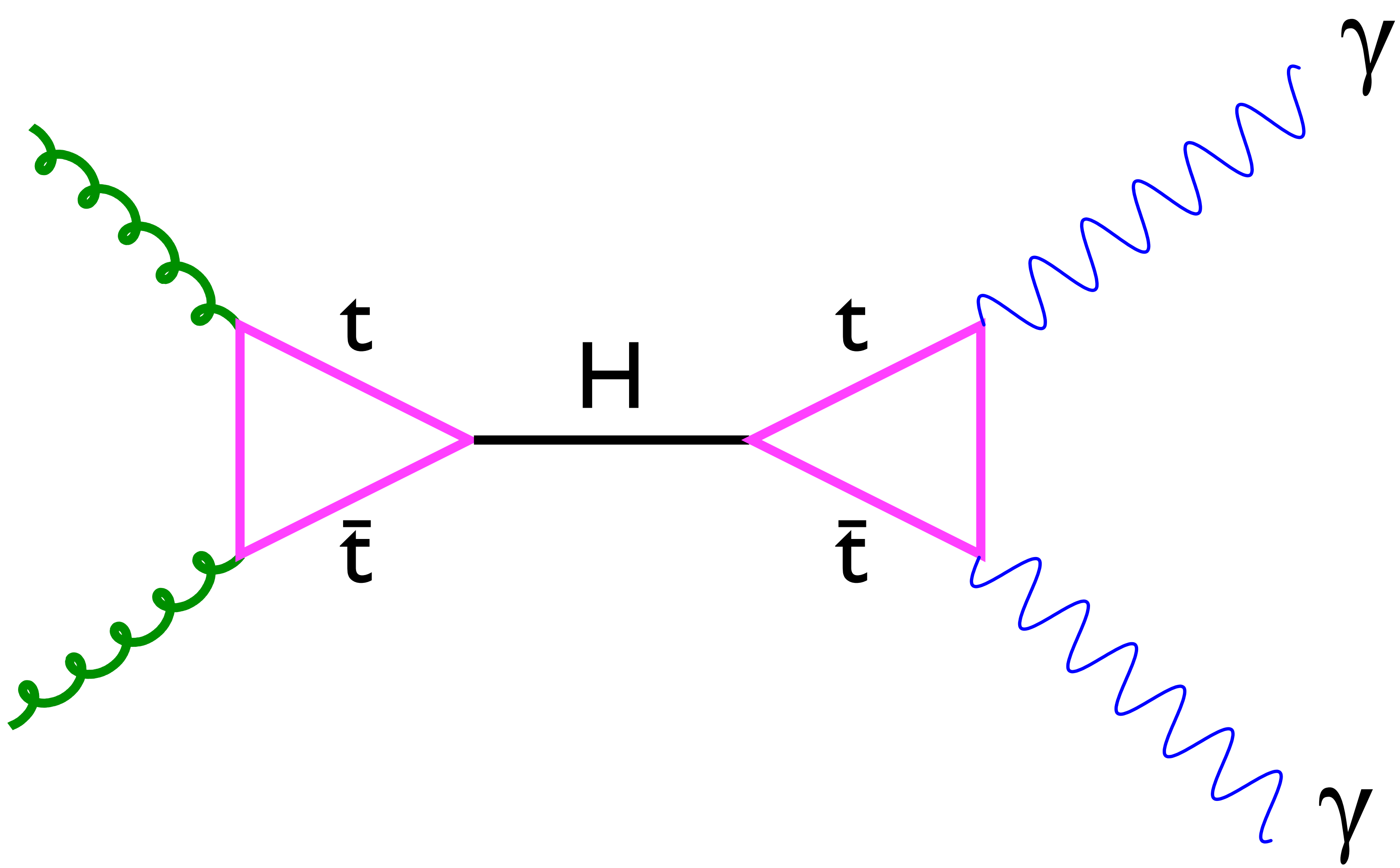


Higgs Production by Gluon Fusion

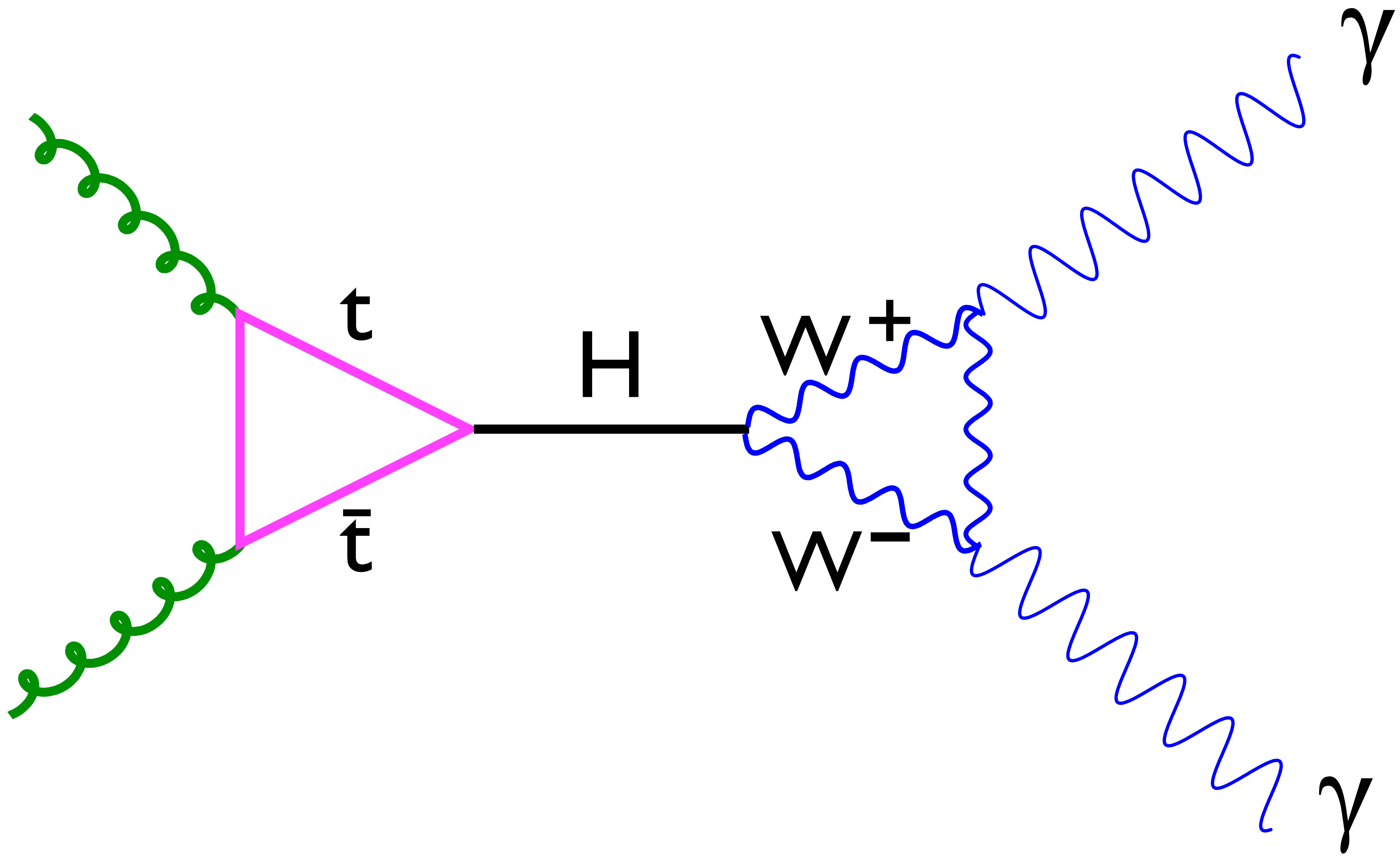


Higgs Production by Gluon Fusion

Higgs Production by Gluon Fusion

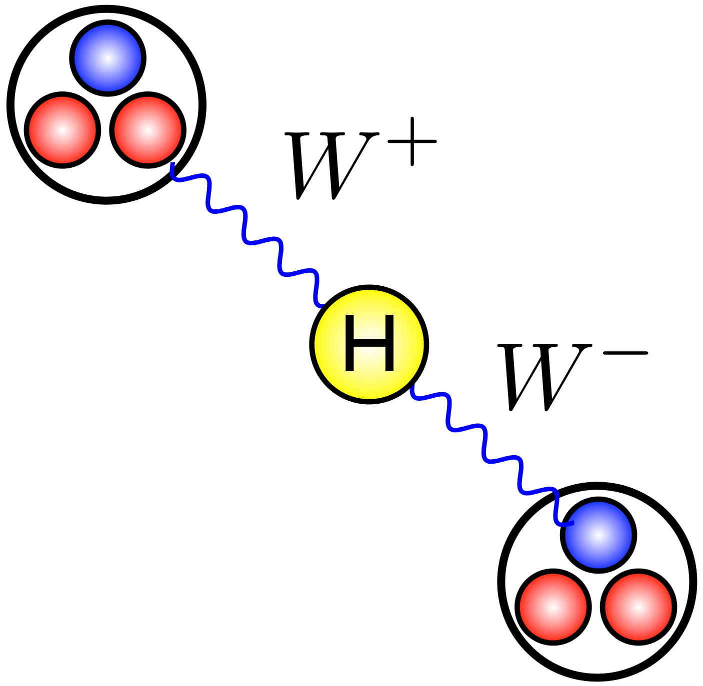


Higgs Production by Gluon Fusion

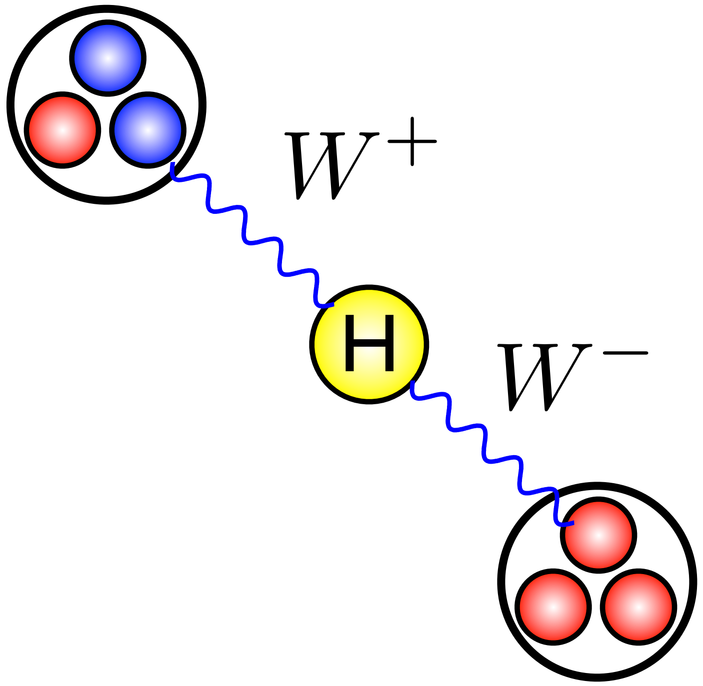


Higgs Production by Vector Boson Fusion

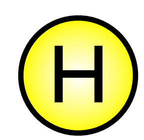
Higgs Production by Vector Boson Fusion



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

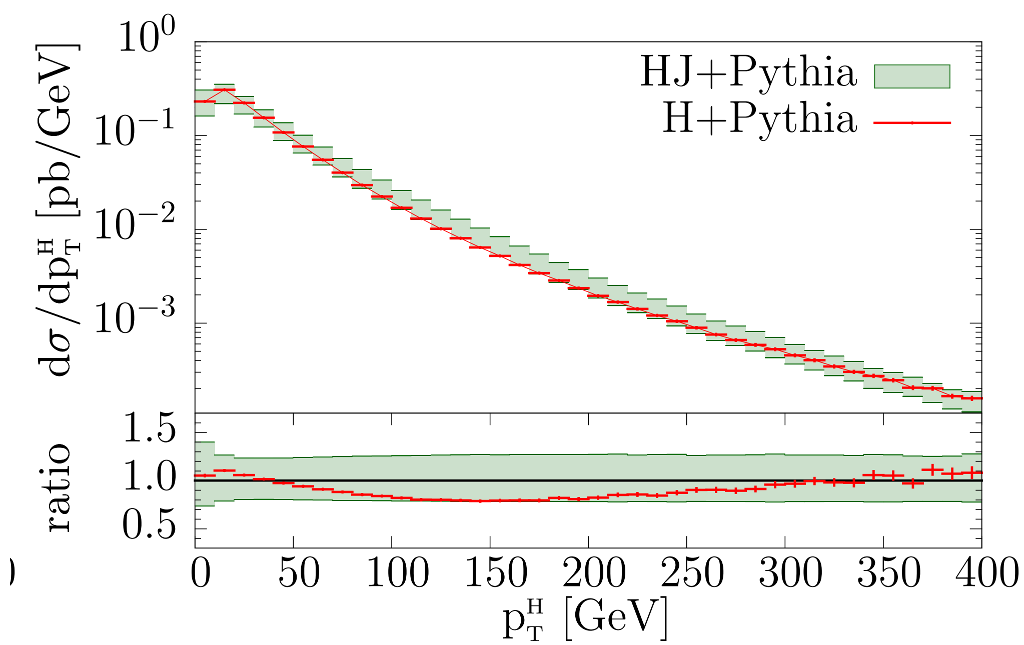
Process	Generator
ggF, VBF	POWHEG [57, 58]+PYTHIA
$WH, ZH, t\bar{t}H$	PYTHIA
W+jets, Z/γ^*+jets	ALPGEN [59]+HERWIG
$t\bar{t}, tW, tb$	MC@NLO [60]+HERWIG
tqb	AcerMC [61]+PYTHIA
$q\bar{q} \to WW$	MC@NLO+HERWIG
$gg \to WW$	gg2WW [62]+HERWIG
$q\bar{q} \to ZZ$	POWHEG [63]+PYTHIA
$gg \to ZZ$	gg2ZZ [64]+HERWIG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

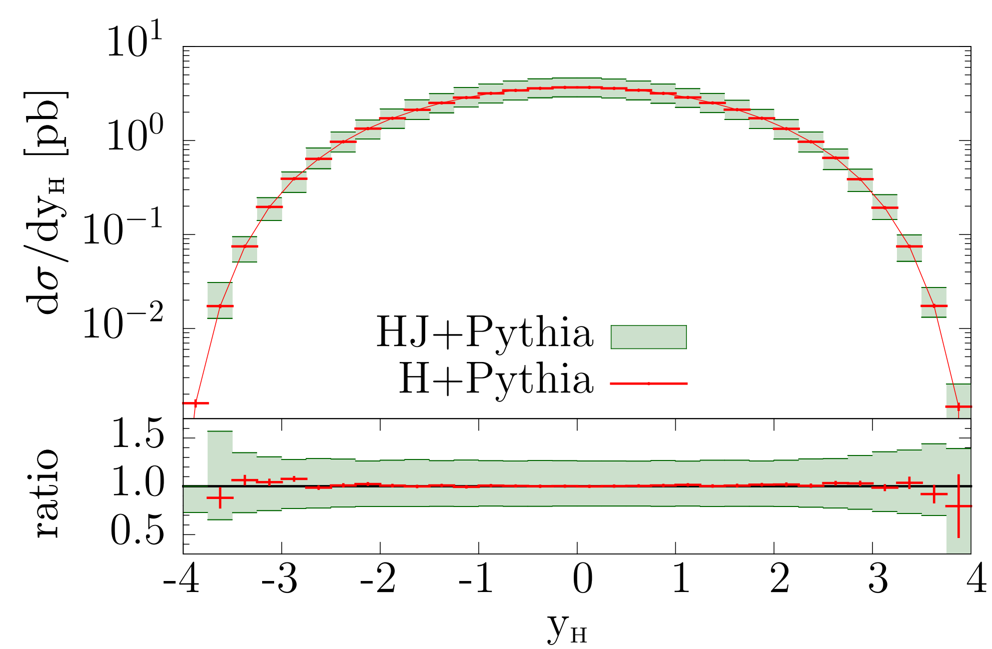
ATLAS, Phys.Lett.B716(2012)1

gg→Higgs(+jet)

Higgs boson production total cross sections in pb at the LHC, 8 TeV							
K_R, K_F	$1,1$	$1,2$	$2,1$	$1,\frac{1}{2}$	$\frac{1}{2},1$	$\frac{1}{2},\frac{1}{2}$	$2,2$
`HJ-MiNLO` NLO	13.33(3)	13.49(3)	**11.70(2)**	13.03(3)	**16.53(7)**	16.45(8)	11.86(2)
`H` NLO	13.23(1)	13.28(1)	**11.17(1)**	13.14(1)	**15.91(2)**	15.83(2)	11.22(1)
`HJ-MiNLO` LO	8.282(7)	8.400(7)	**5.880(5)**	7.864(6)	**18.28(2)**	17.11(2)	5.982(5)
`H` LO	5.741(5)	5.758(5)	**4.734(4)**	5.644(5)	**7.117(6)**	6.996(6)	4.748(4)

Table 1: Total cross section for Higgs boson production at the 8 TeV LHC, obtained with the `HJ-MiNLO` and the `H` programs, both at full NLO level and at leading order, for different scales combinations. The maximum and minimum are highlighted.

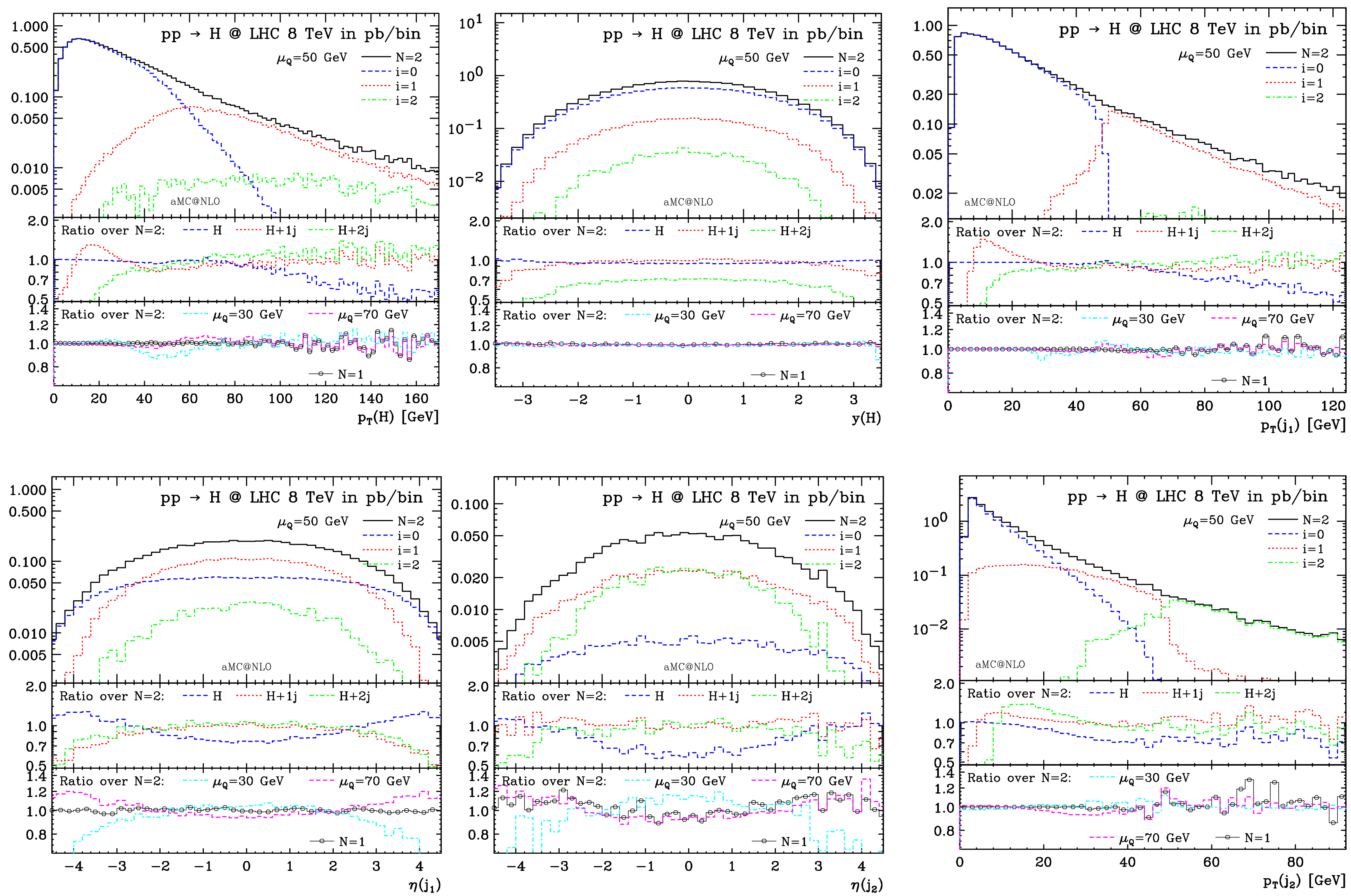




- Match/merge MiNLO+Pythia6

Hamilton, Nason, Oleari & Zanderighi, arXiv:1212.4504

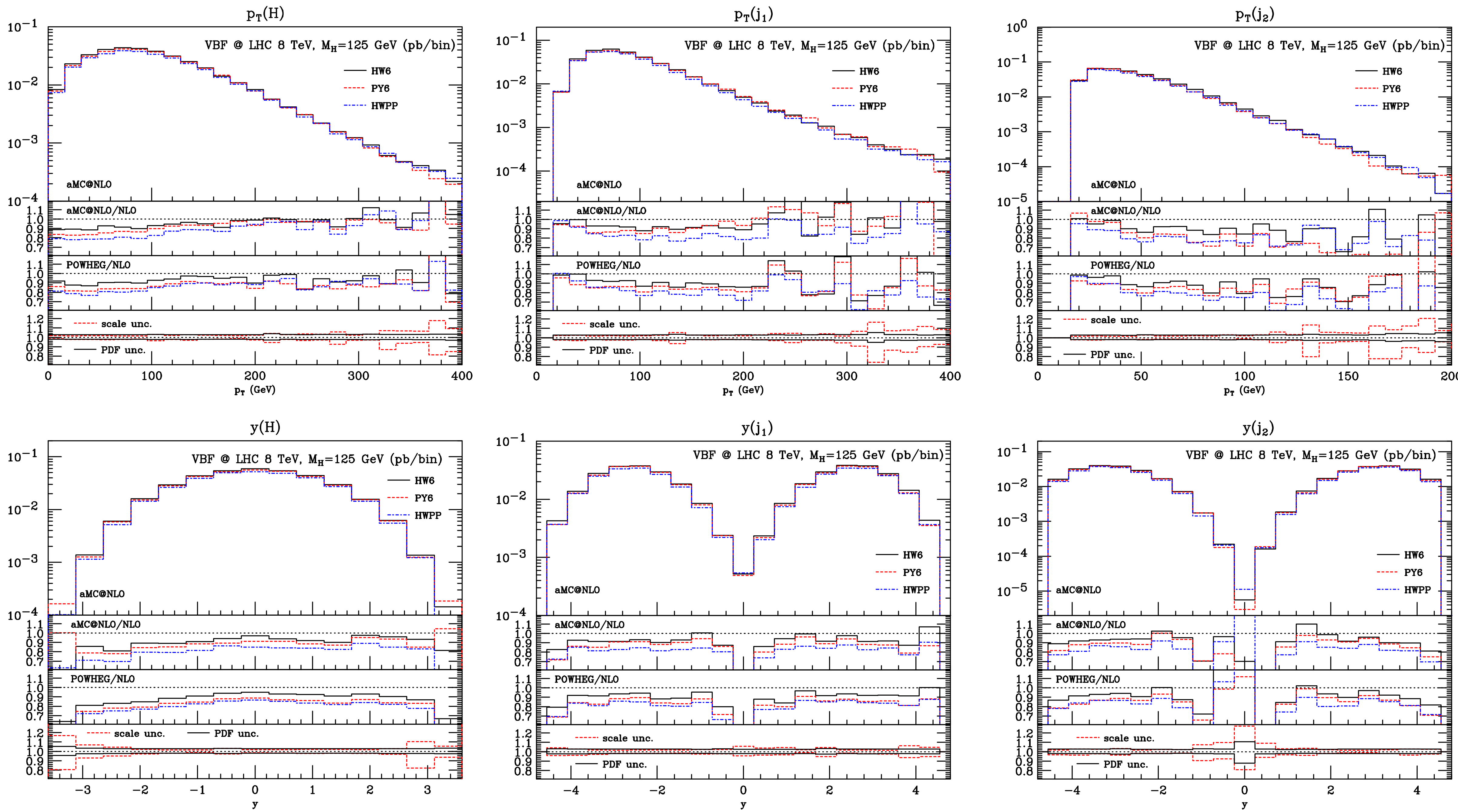
gg→ Higgs+jets



- FxFx: Match/merge MC@NLO+Herwig6

Frederix & Frixione, arXiv:1209.6215

VBF Higgs+jets



- Matched MC@NLO and POWHEG

Frixione, Torrielli, Zaro, arXiv:1304.7927

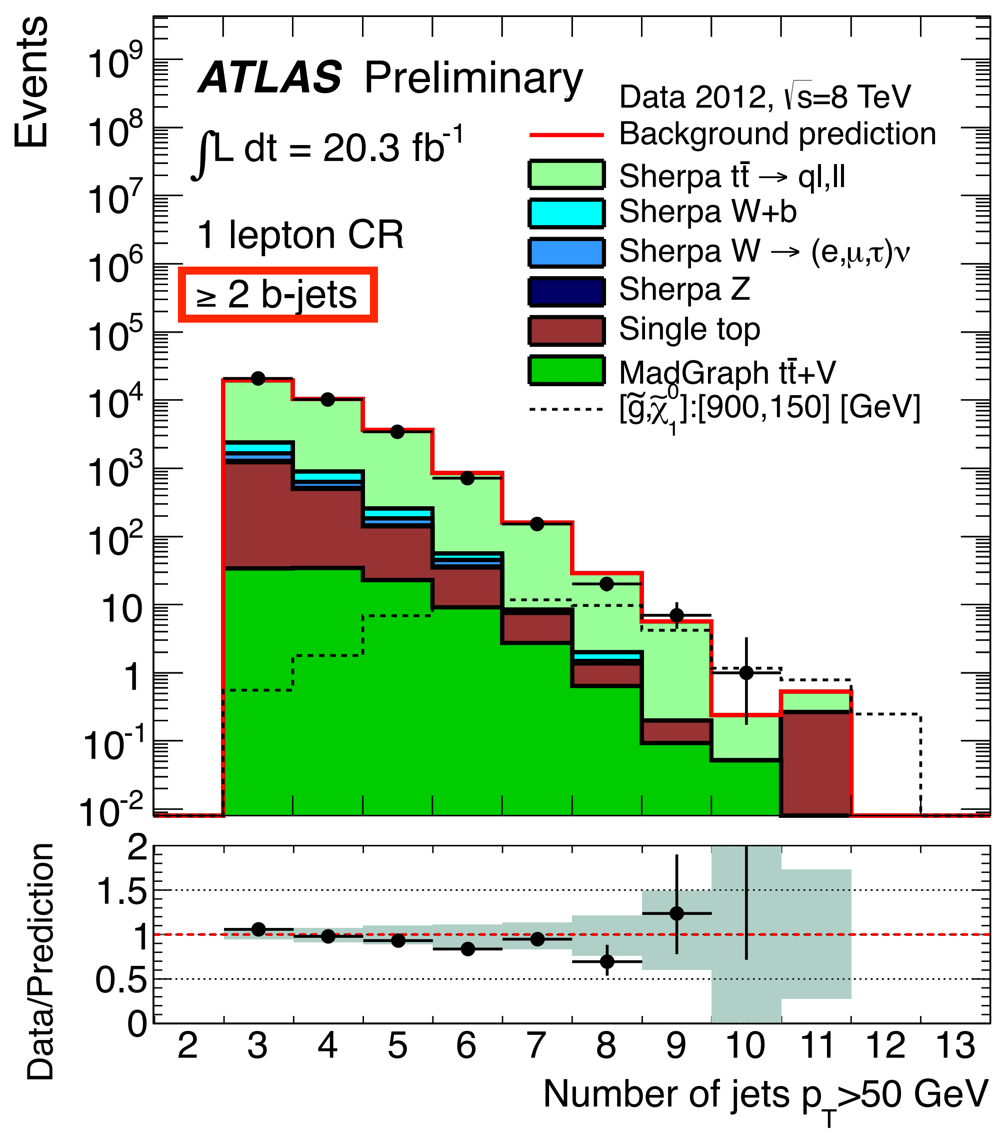
Beyond Standard Model Simulation

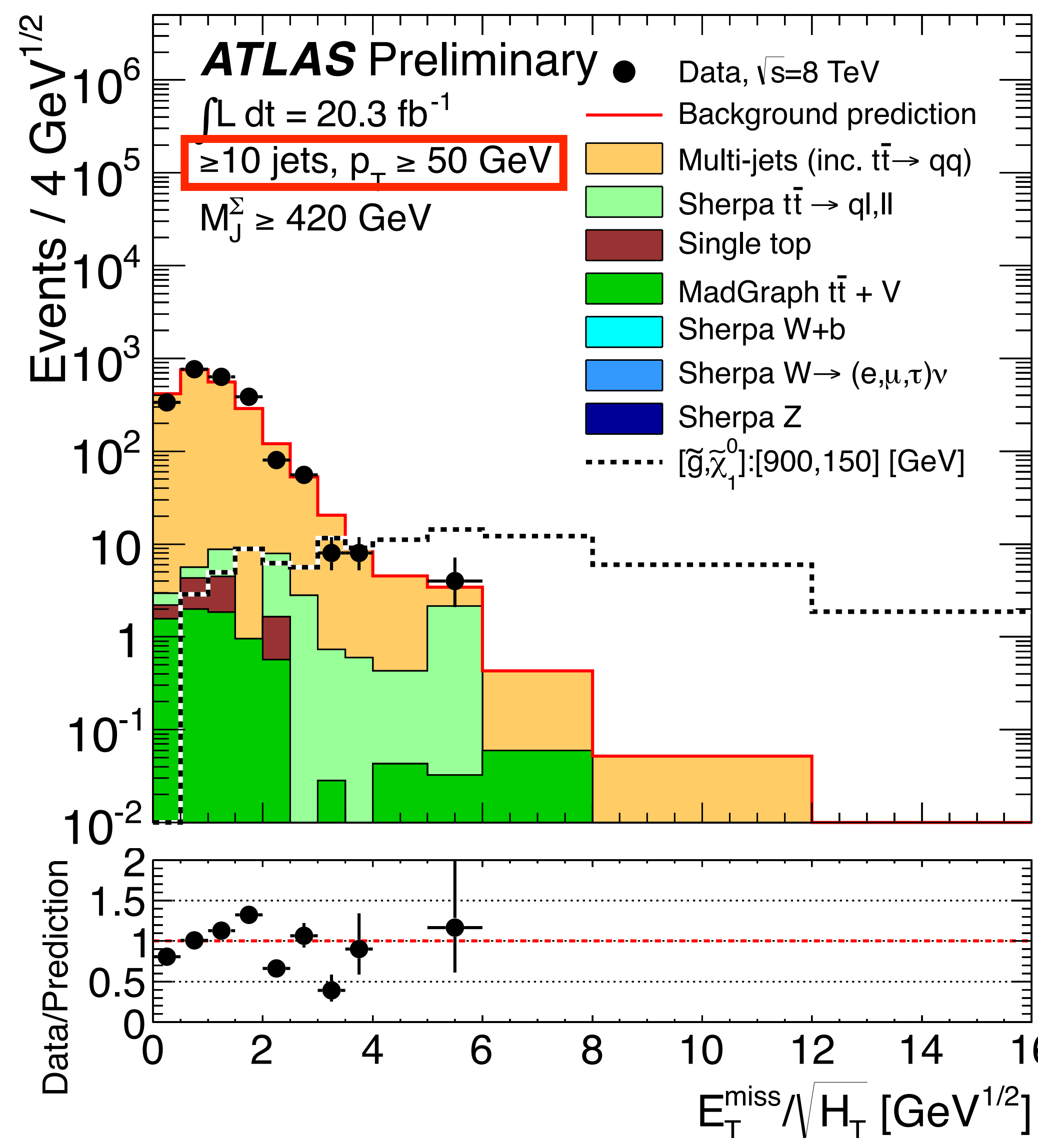
BSM Simulation

- 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

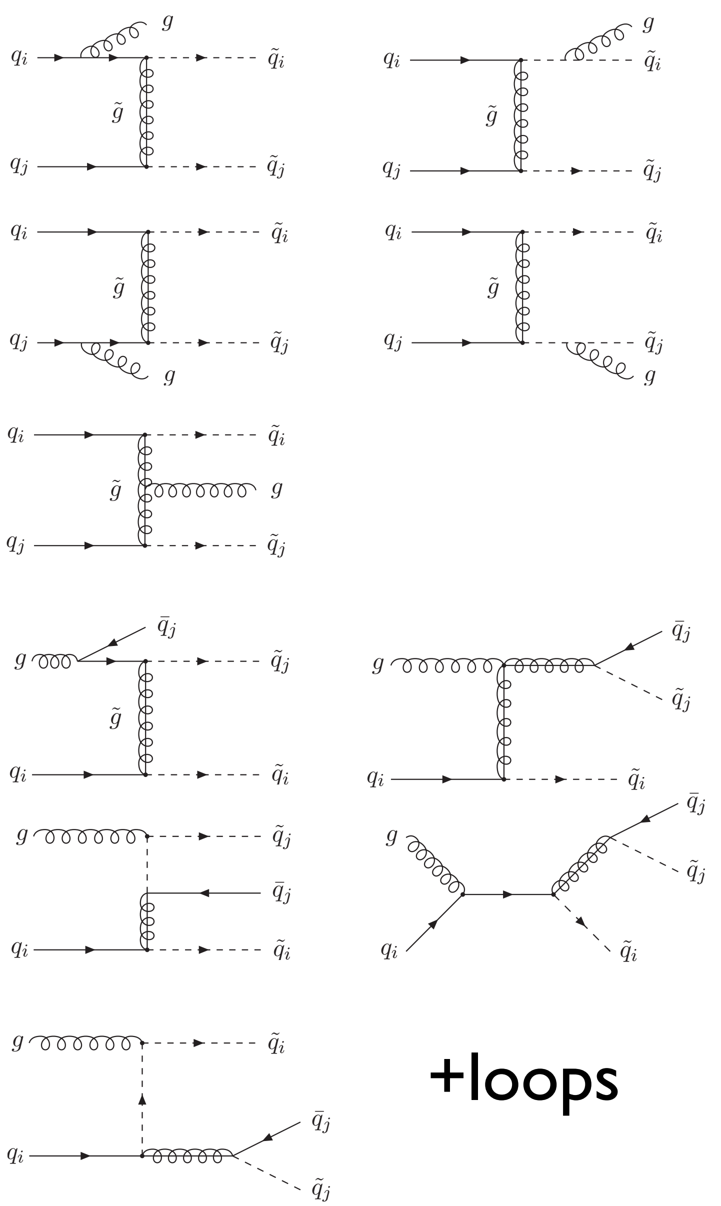
ATLAS CONF-2013-054

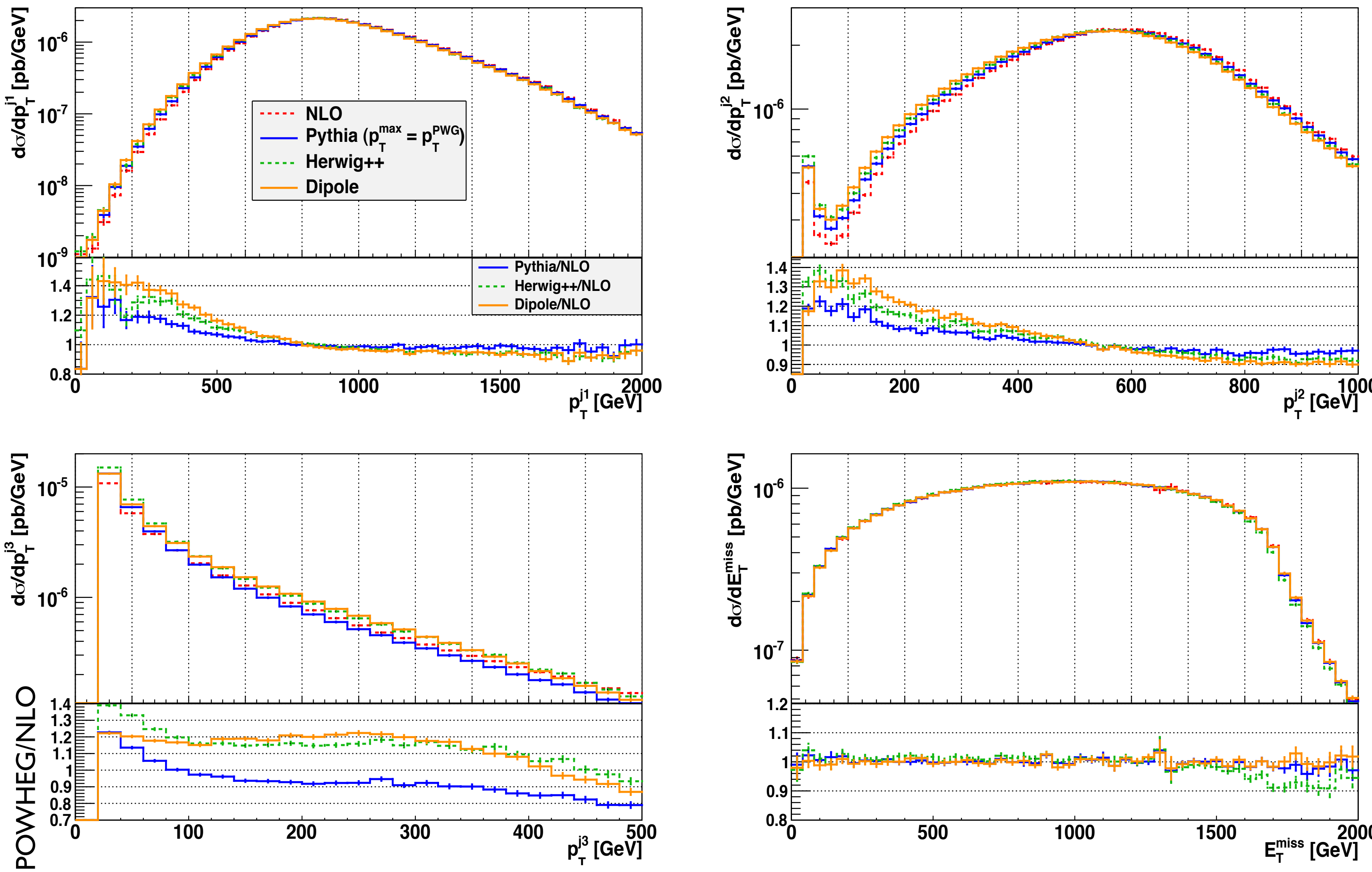




- Dashed = Herwig++ $\tilde{g}\tilde{g},\ \tilde{g} \rightarrow t + \bar{t} + \tilde{\chi}_1^0$
- Background: mostly Sherpa LO multijet merging

NLO Squark Production

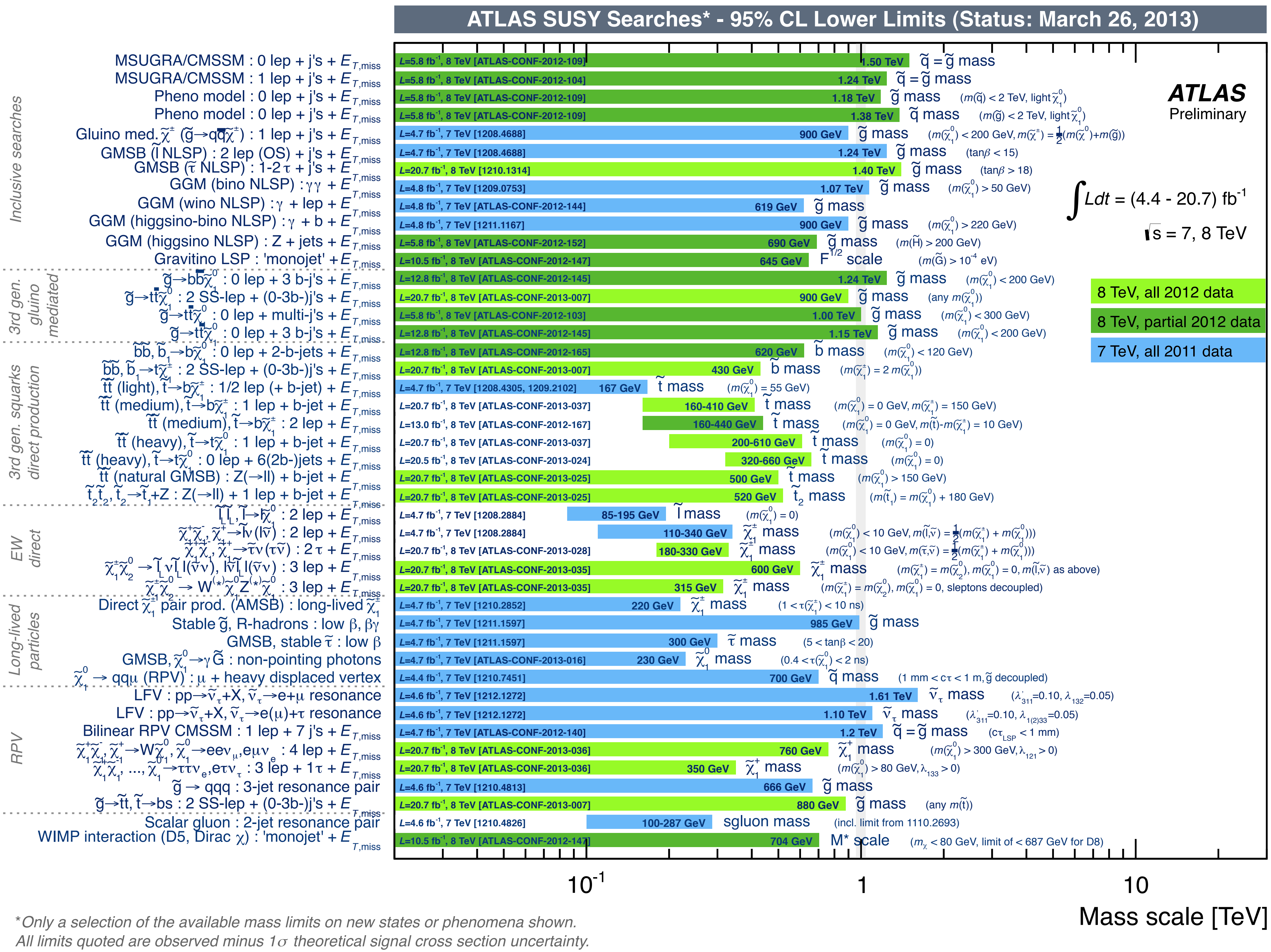




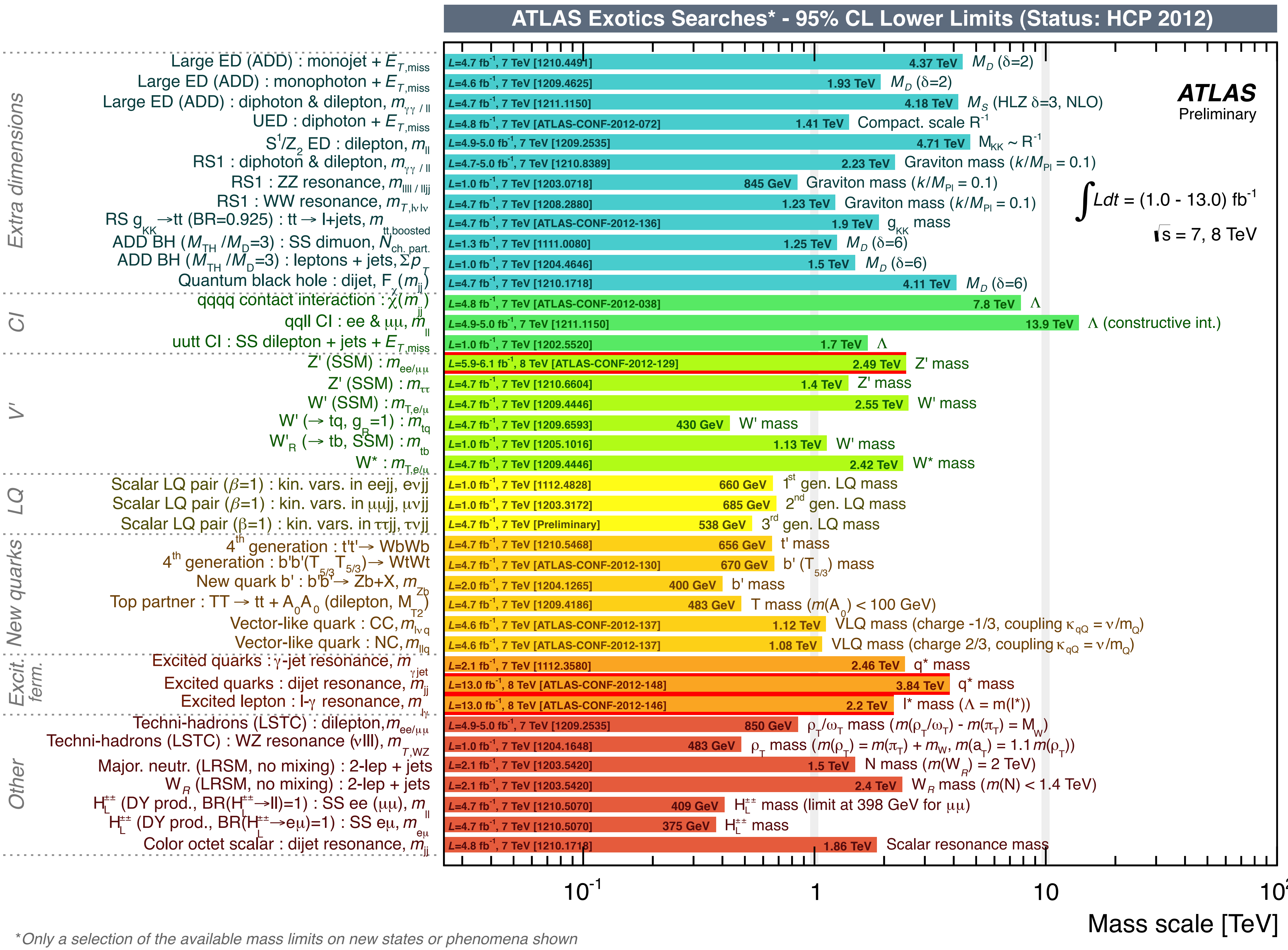
- NLO with POWHEG matching to different generators

Gavin et al., arXiv:1305.4061

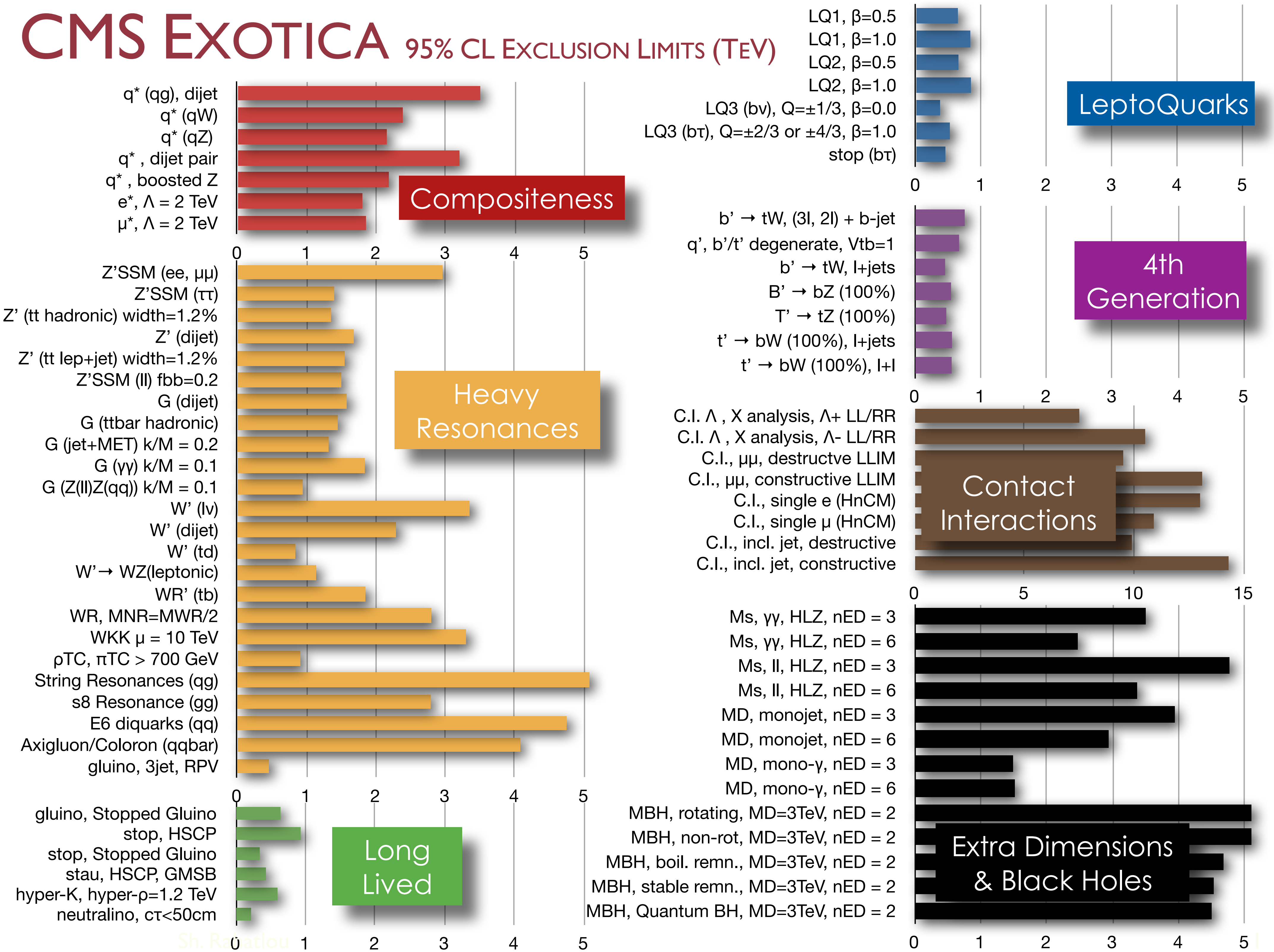
ATLAS SUSY Search



ATLAS Exotica Search



CMS Exotica Search



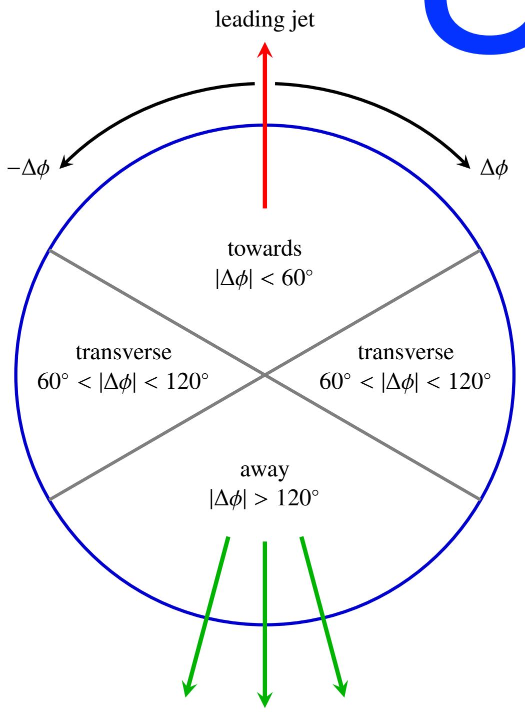
Conclusions and Prospects

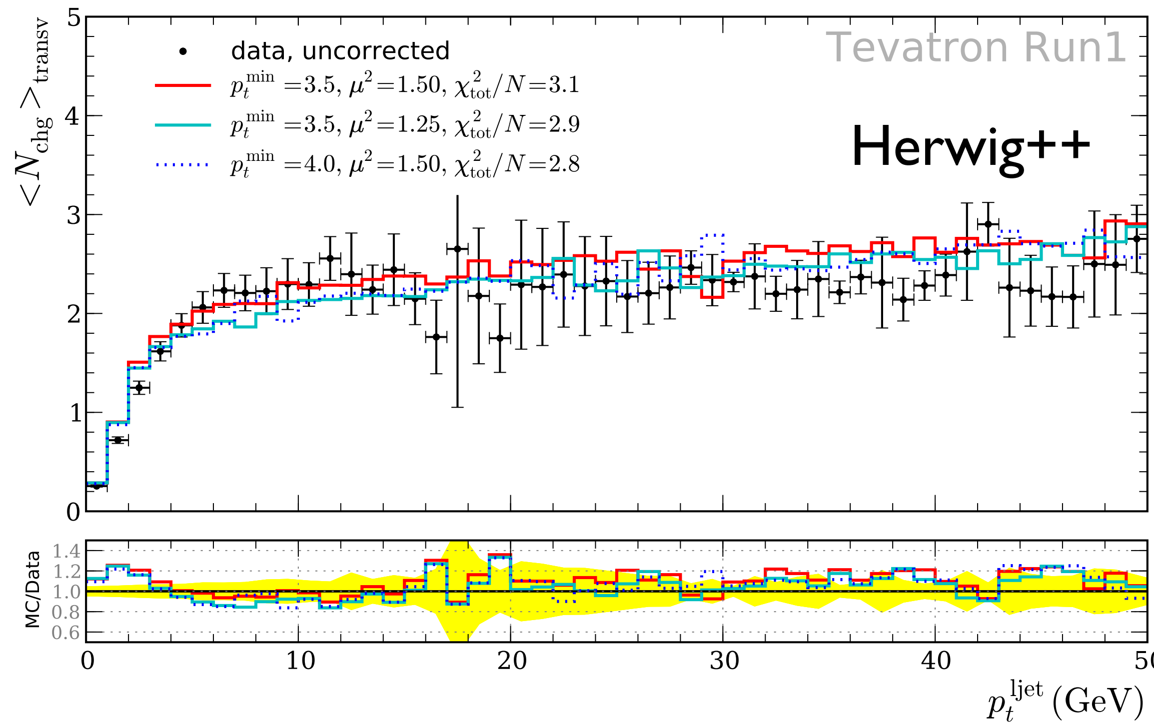
- Standard Model has (so far) been spectacularly confirmed at the LHC
- Monte Carlo event generation of (SM and BSM) signals and backgrounds plays a big part
- Matched NLO and merged multi-jet generators have proved essential
  - Automation and NLO merging in progress
  - NNLO much more challenging
-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

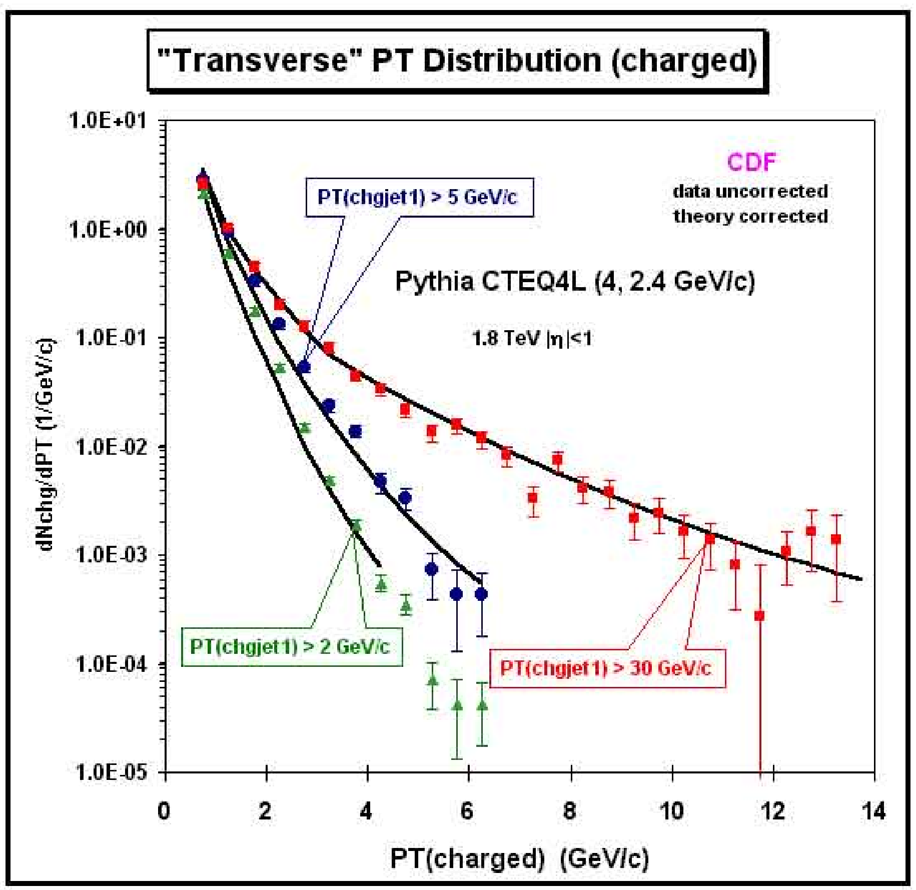
Thanks for listening!

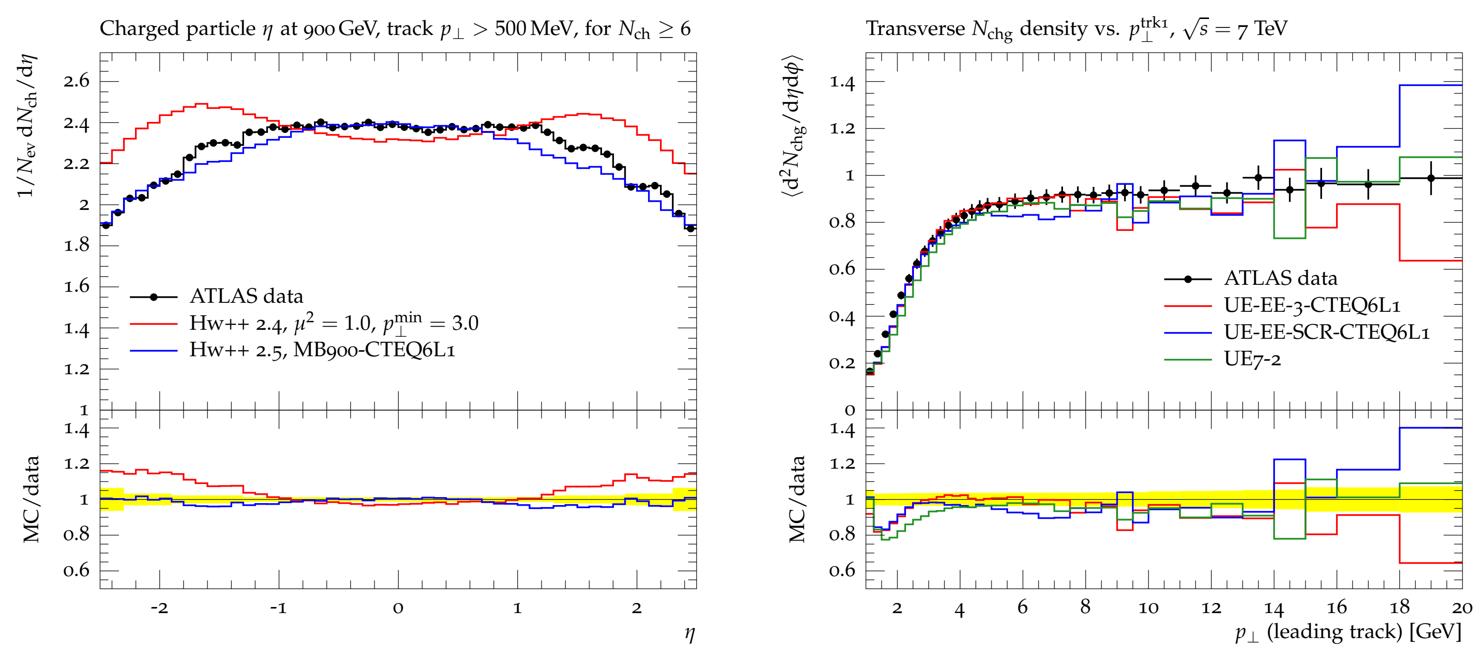
Backup

Underlying Event





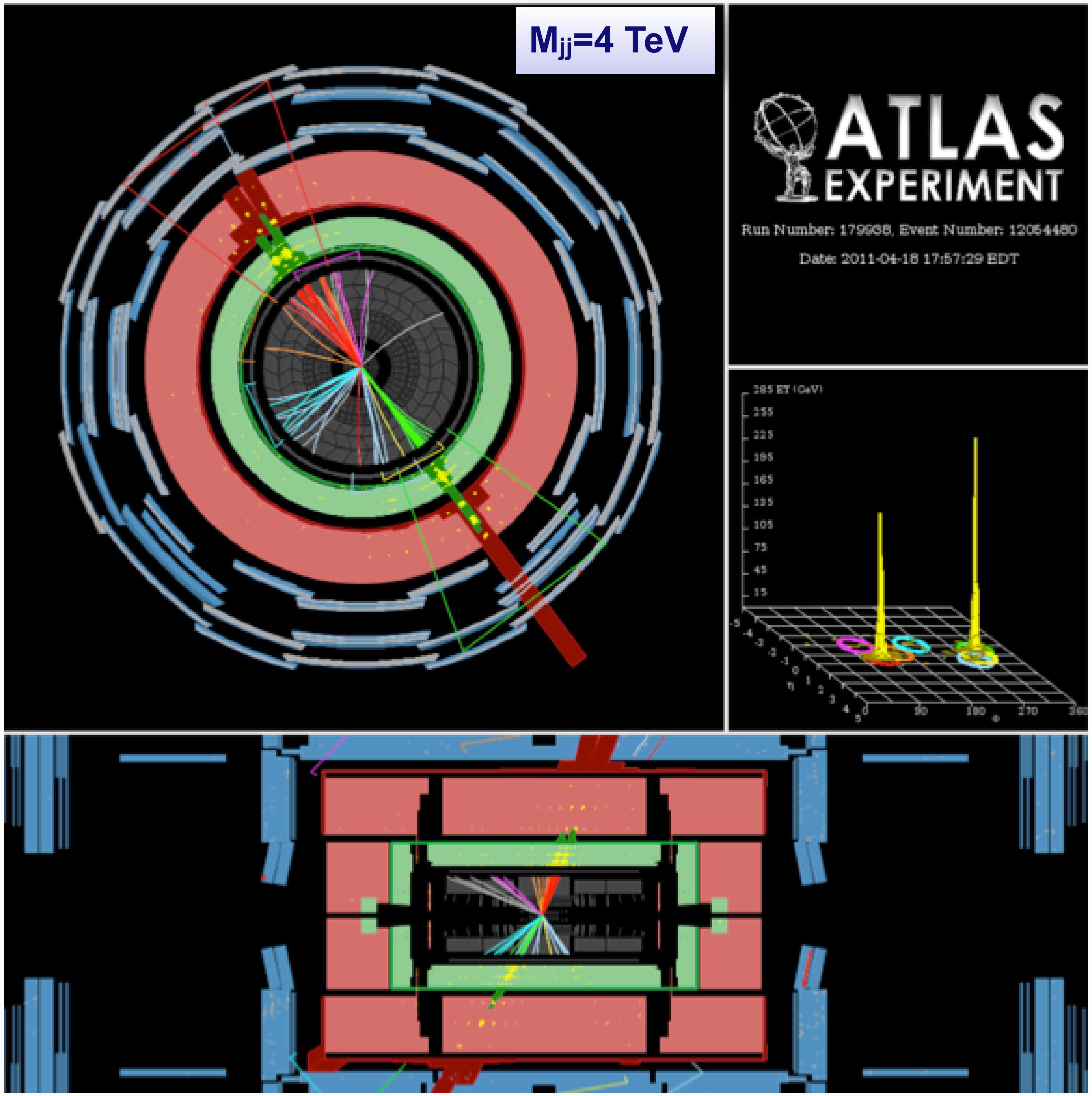




ATLAS PRD83(2011)112001

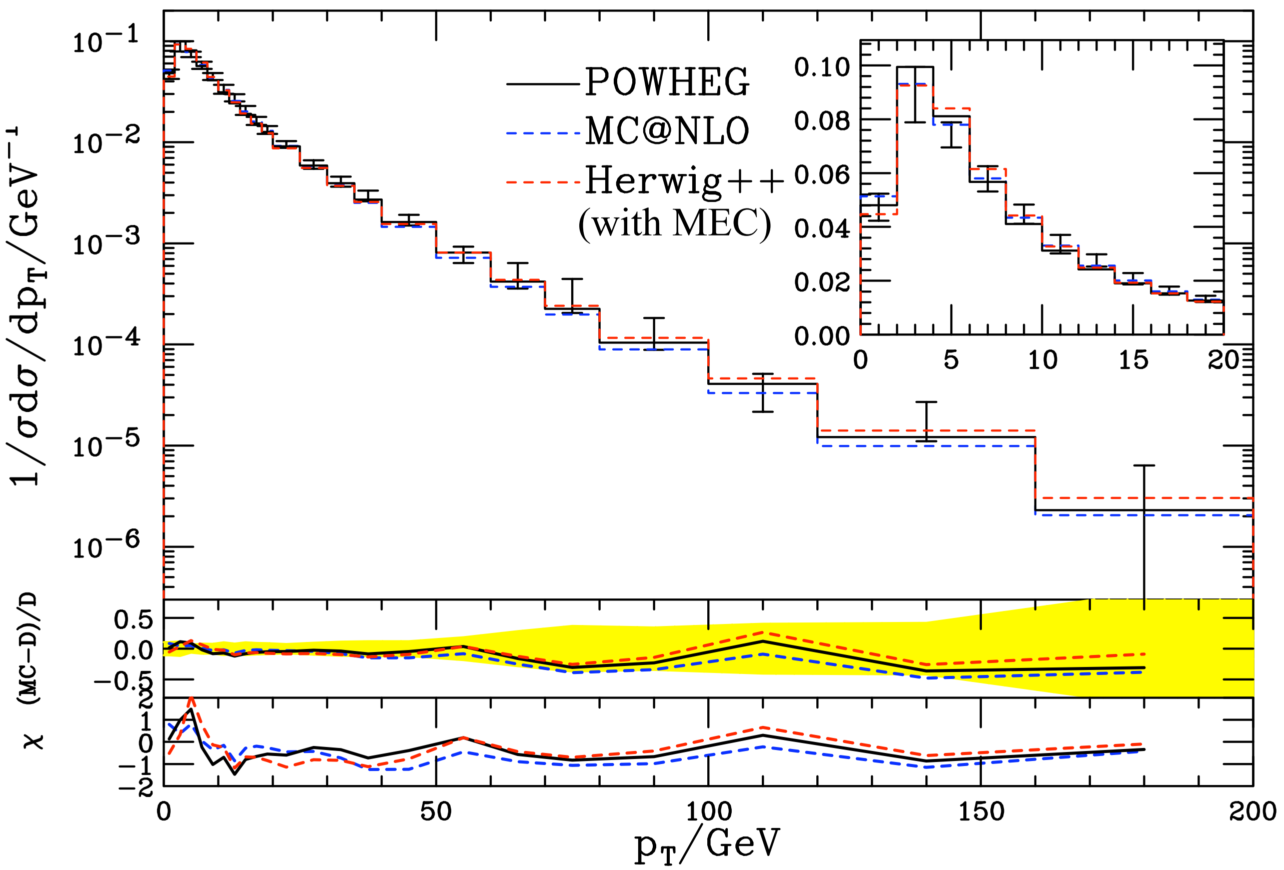
Gieseke, Röhr, Siódmok, arXiv:1206.2205

A high-mass dijet event

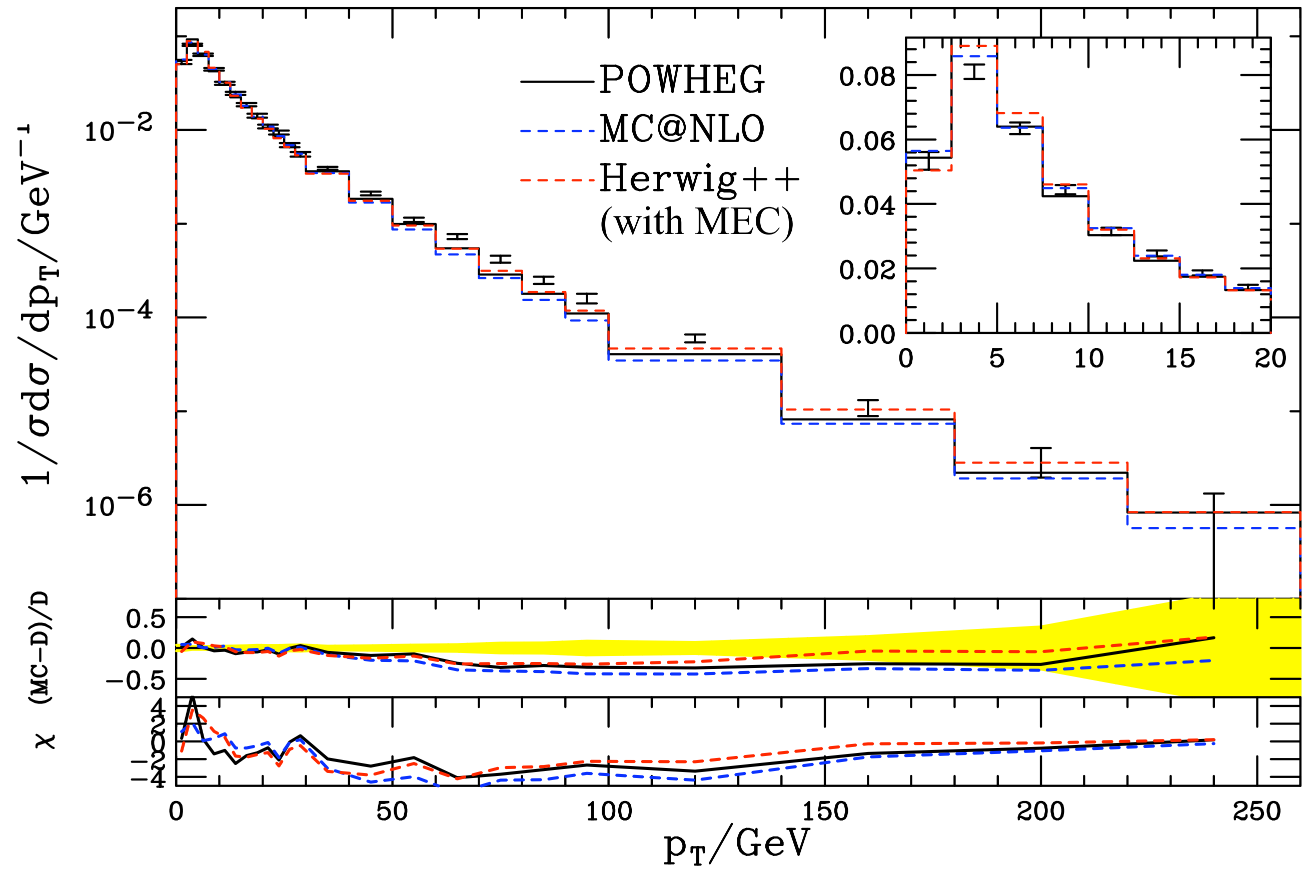


W & Z^0 at Tevatron

D0 Run I: W



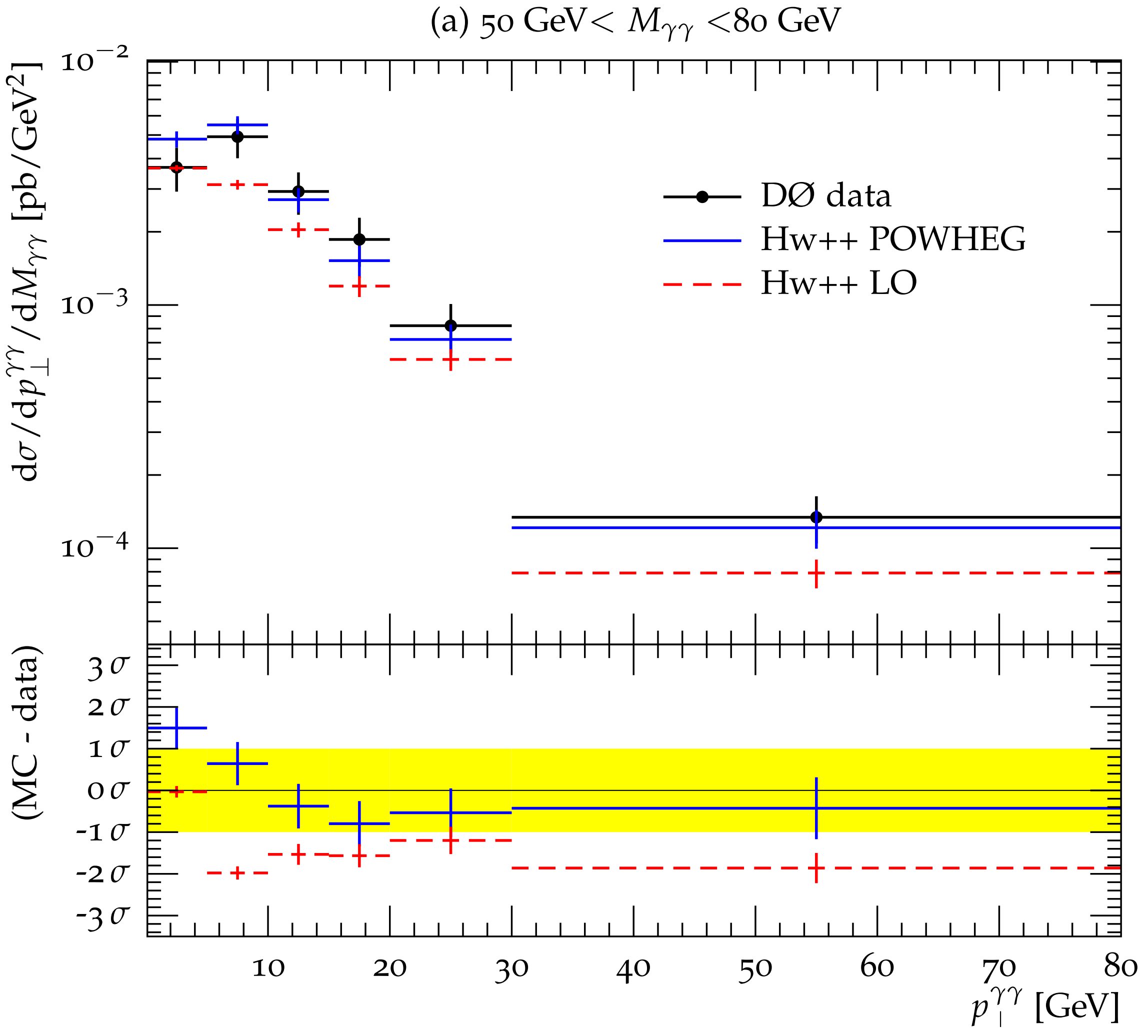
D0 Run II: Z^0

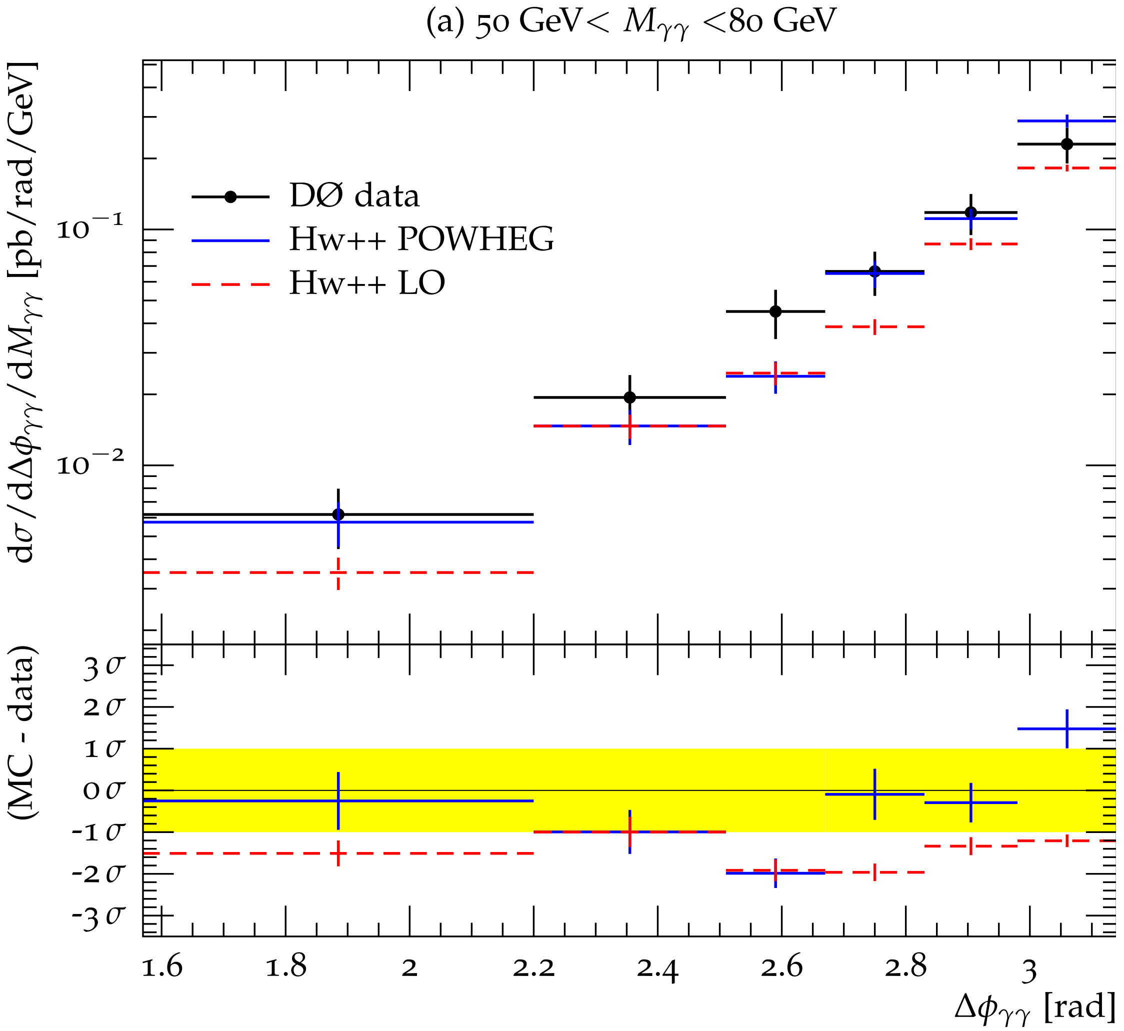


- Herwig++ includes W/Z+jet (MEC)
- All agree (tuned) at Tevatron
- Normalized to data

Hamilton, Richardson, Tully JHEP10(2008)015

$\gamma\gamma$ 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

To Be Confirmed

- Spin and parity 0^+: correlations in VV^* decays
- Production mechanisms: gg, VBF, WH, ZH, ttH
- Self-coupling (HH production): difficult at LHC
- Total width 4.2 MeV: impossible?
- Decay fractions:

$b\bar{b}$	56%	$\tau^+\tau^-$	6.2%	$\gamma\gamma$	0.23%
WW^*	23%	ZZ^*	2.9%	γZ	0.16%
gg	8.5%	$c\bar{c}$	2.8%	$\mu^+\mu^-$	0.02%

Achievable Precision?

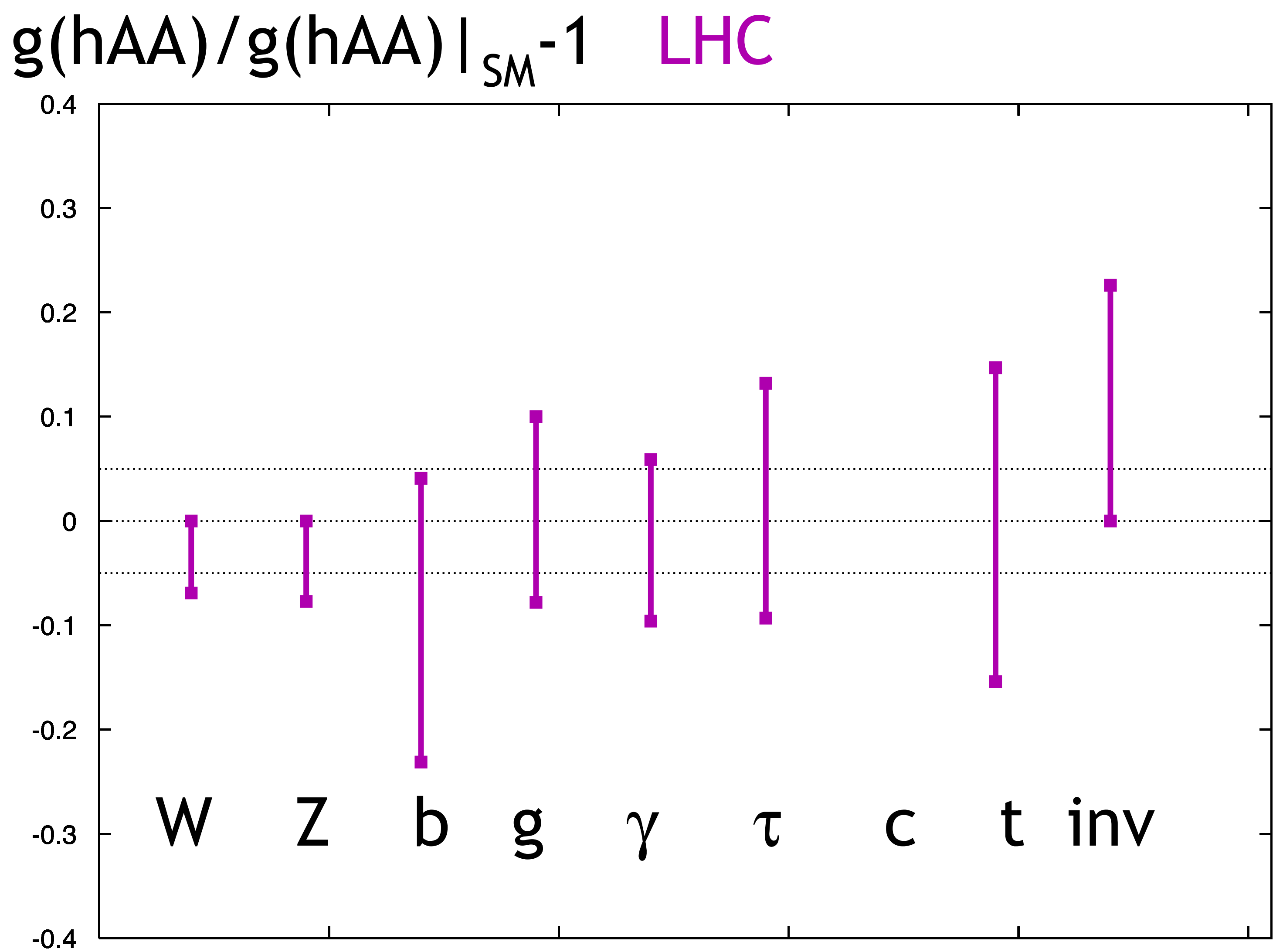


Figure 1: Capabilities of LHC for model-independent measurements of Higgs boson couplings. The plot shows 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}. No error is estimated for $g(hcc)$. The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

M Peskin, arXiv:1207.2516

Achievable Precision?

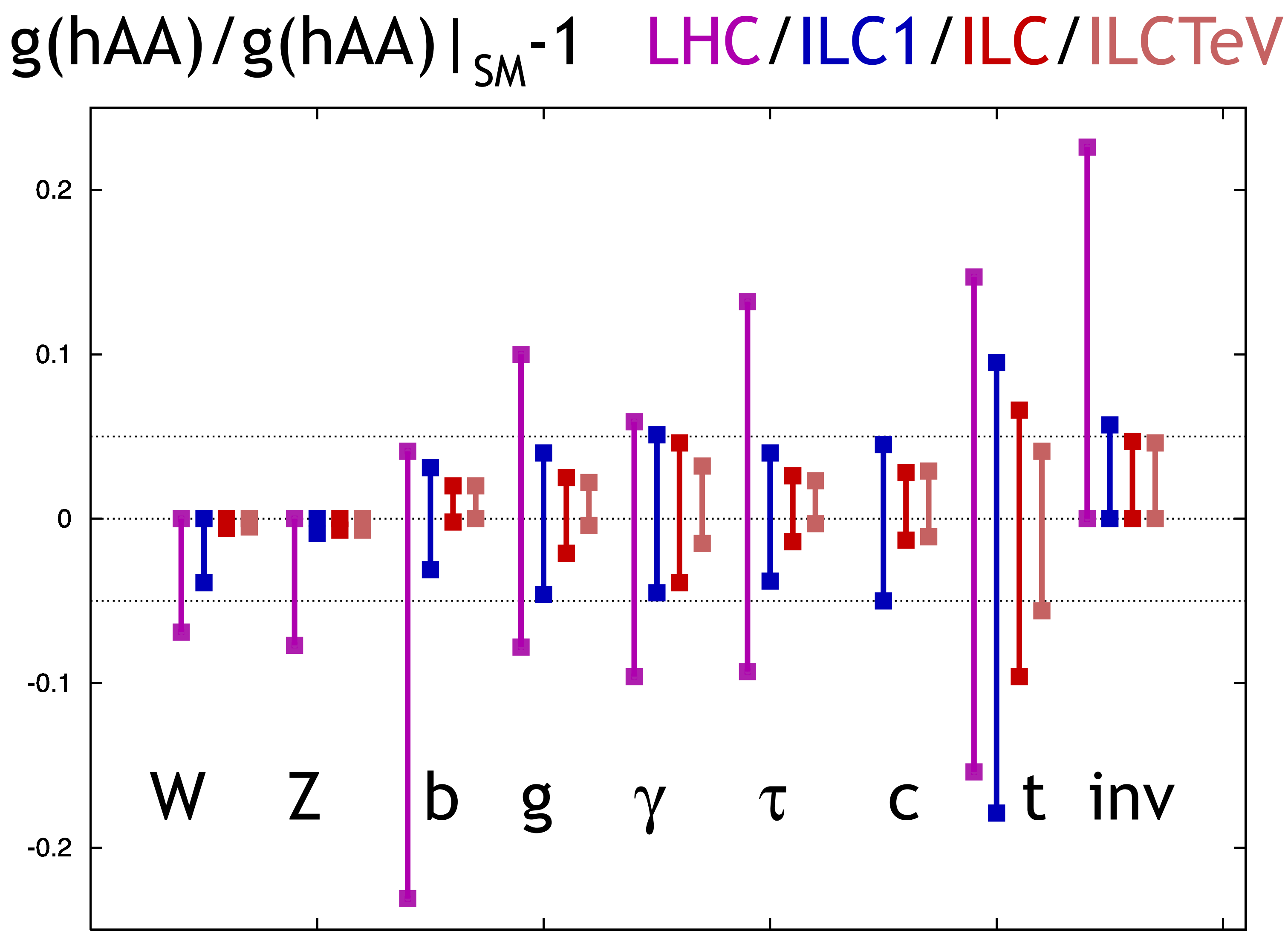


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC 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