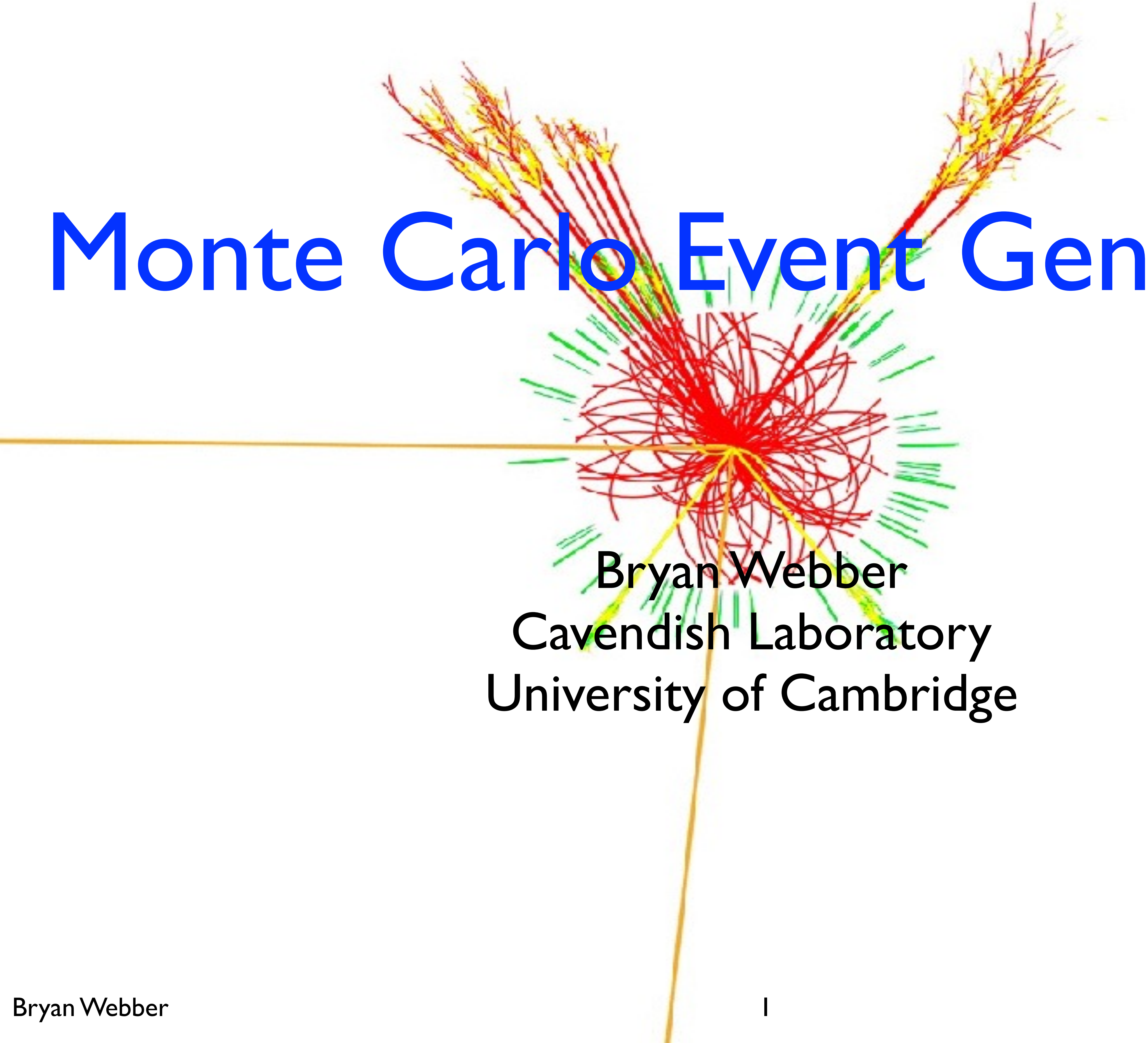
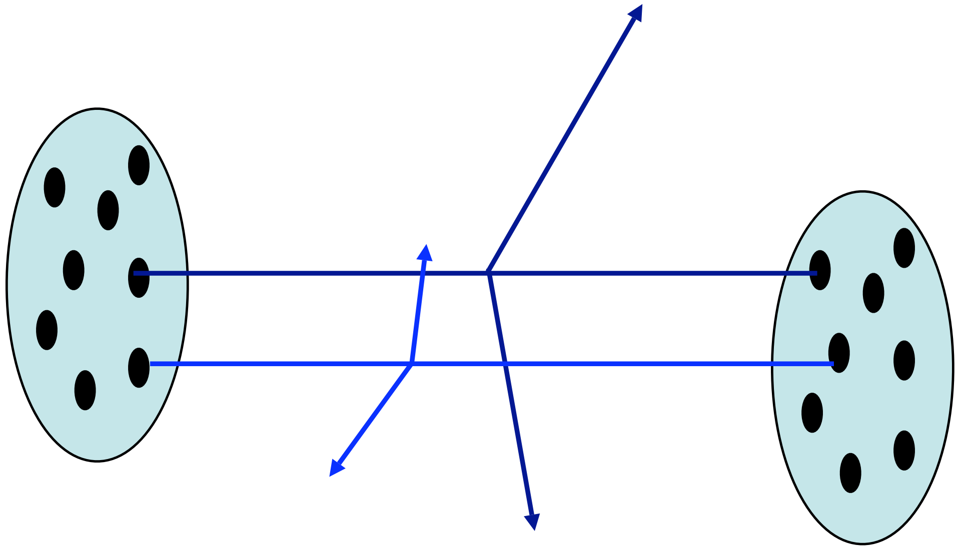


Monte Carlo Event Generators

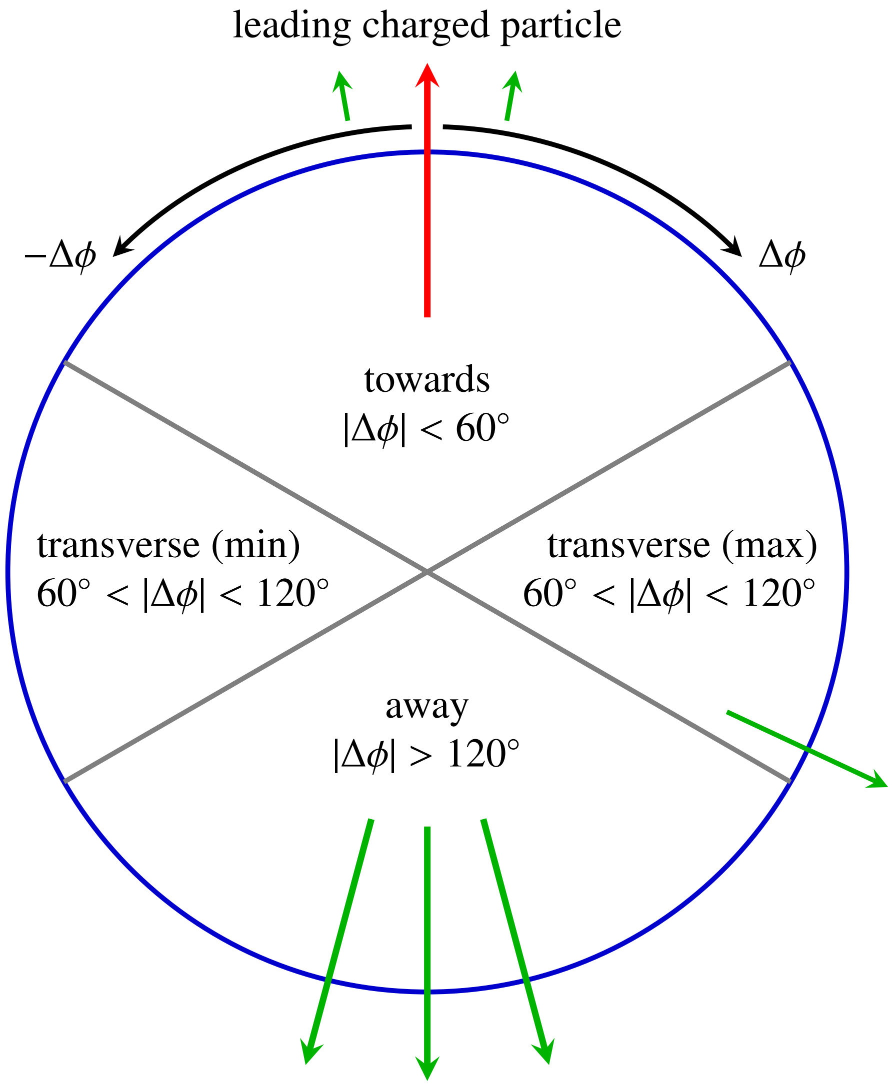
Bryan Webber
Cavendish Laboratory
University of Cambridge

Underlying Event (MPI)



- 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



leading charged particle

$-\Delta\phi$

$\Delta\phi$

towards

$|\Delta\phi| < 60°$

transverse (min)

$60° < |\Delta\phi| < 120°$

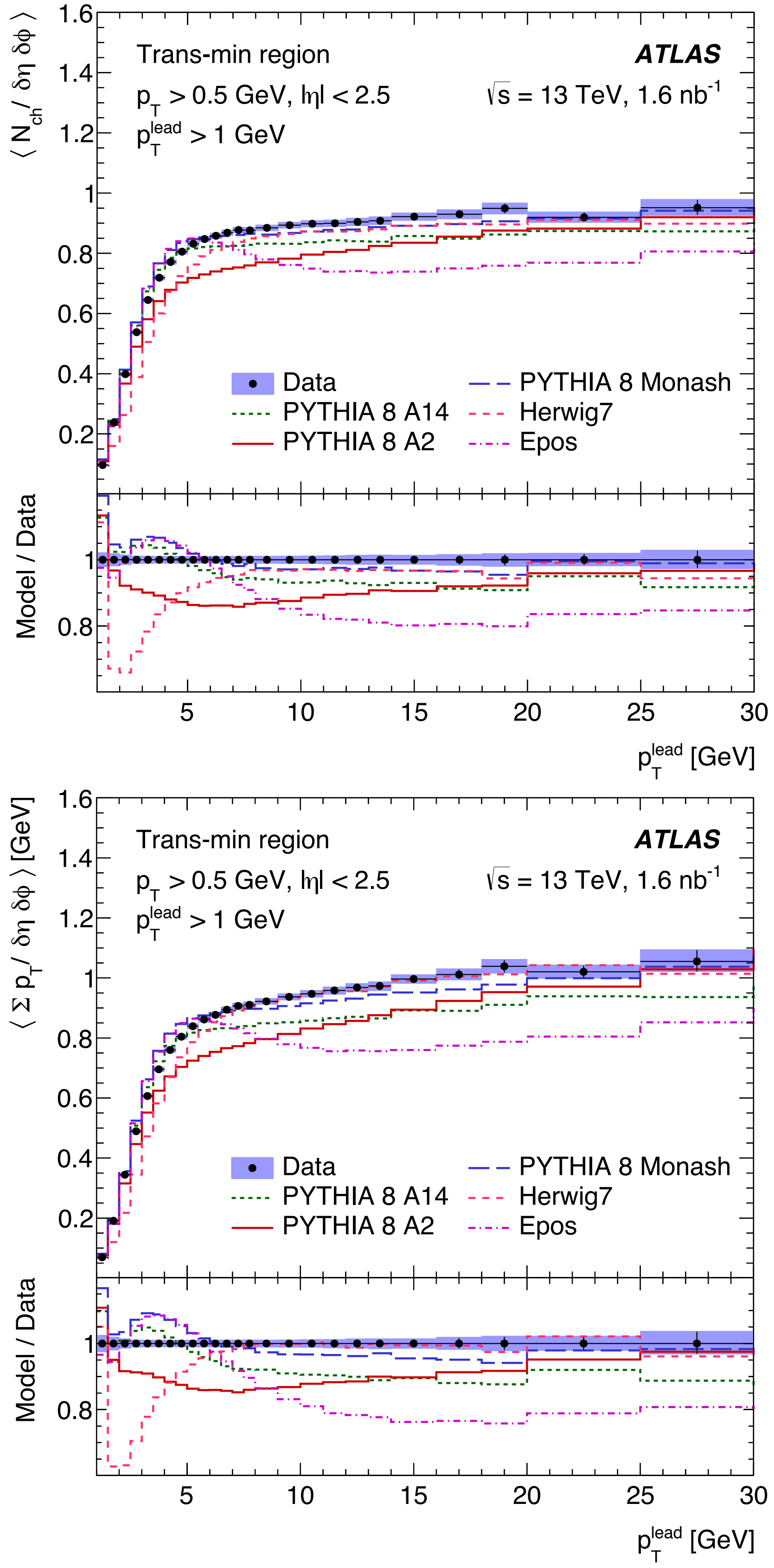
transverse (max)

$60° < |\Delta\phi| < 120°$

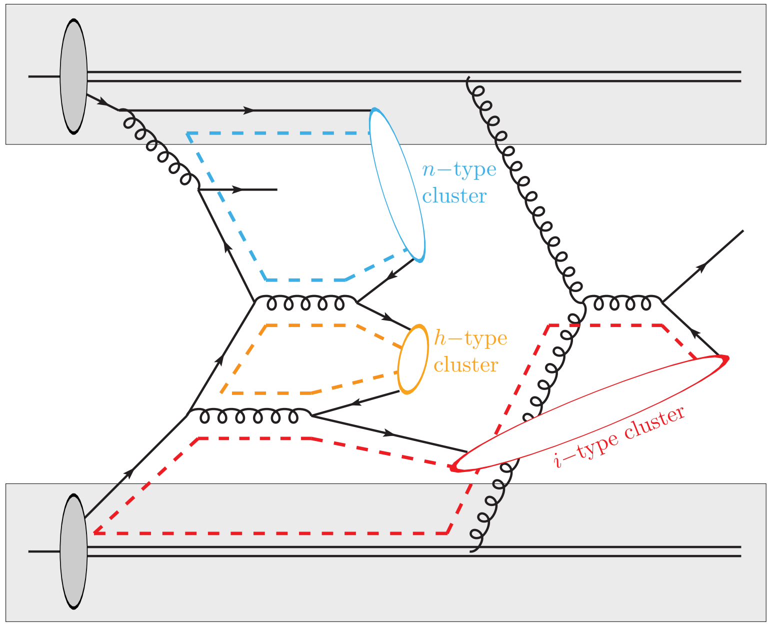
away

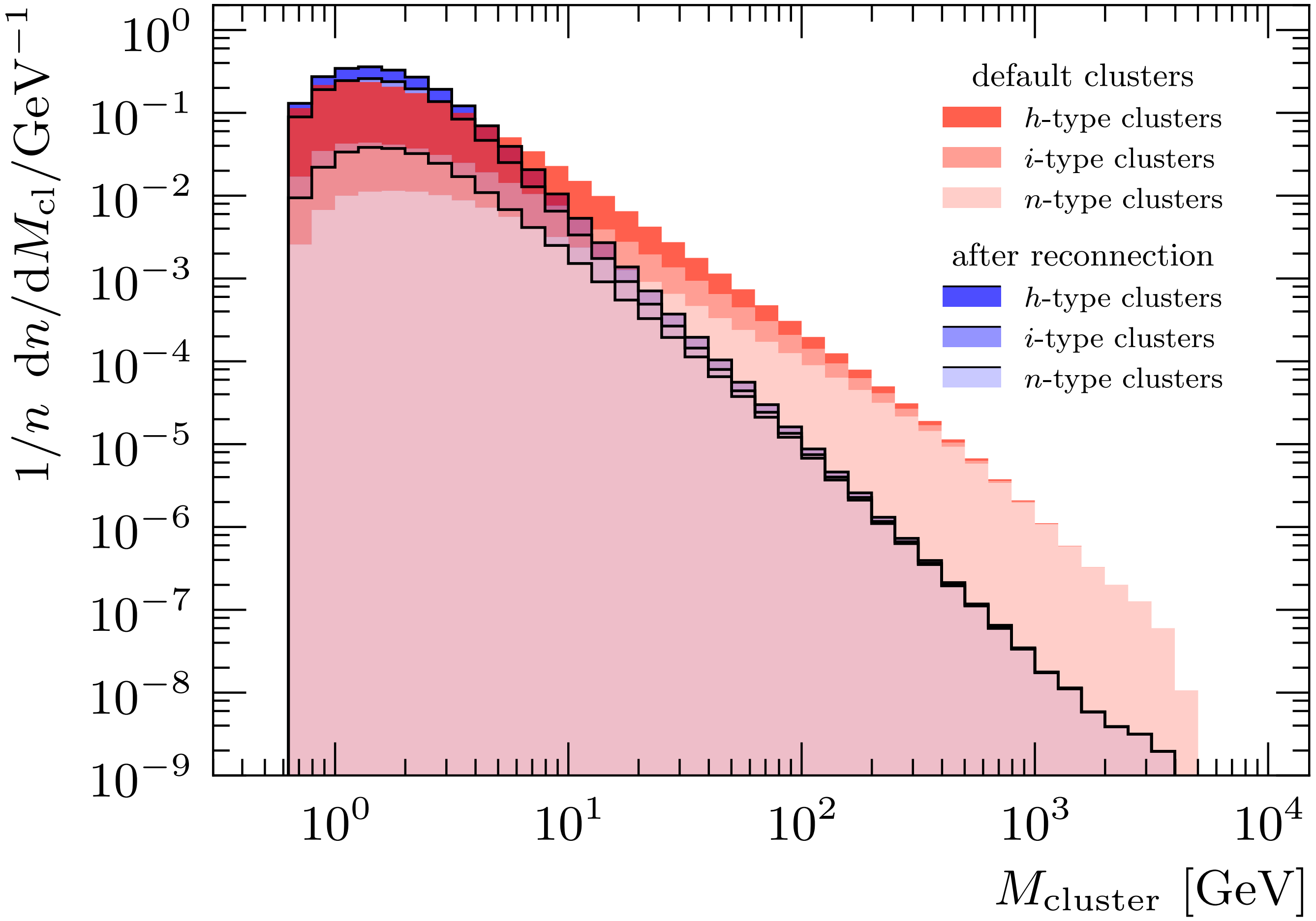
$|\Delta\phi| > 120°$

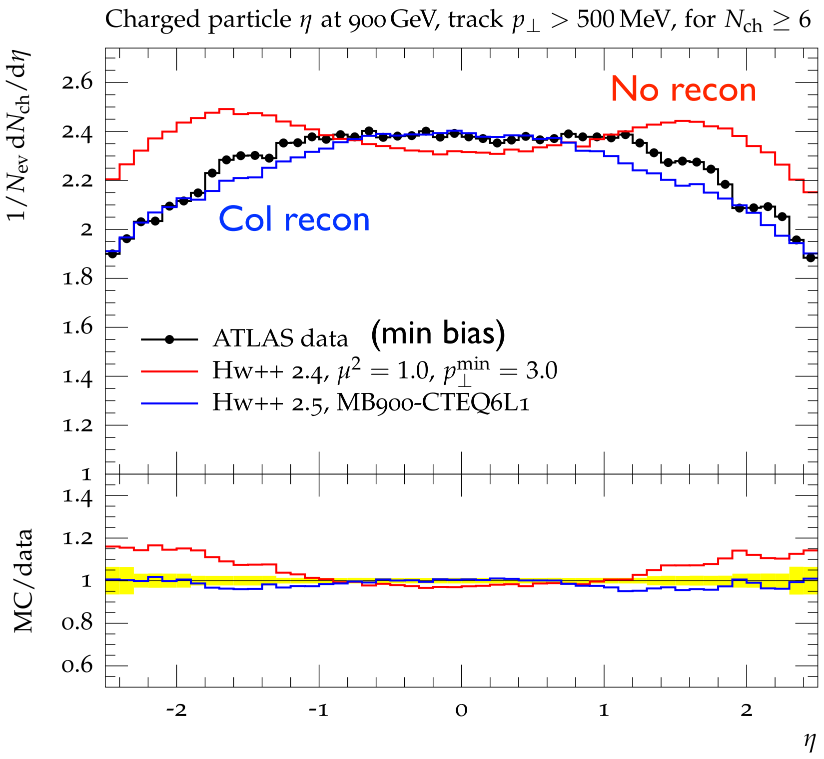
ATLAS, JHEP 03(2017)157



Colour Reconnection







- "Colour length" $\lambda \equiv \sum_{i=1}^{N_{\mathrm{cl}}} m_i^2$ reduced by reconnection
- Massive leading clusters reduced
- Similar need in string model

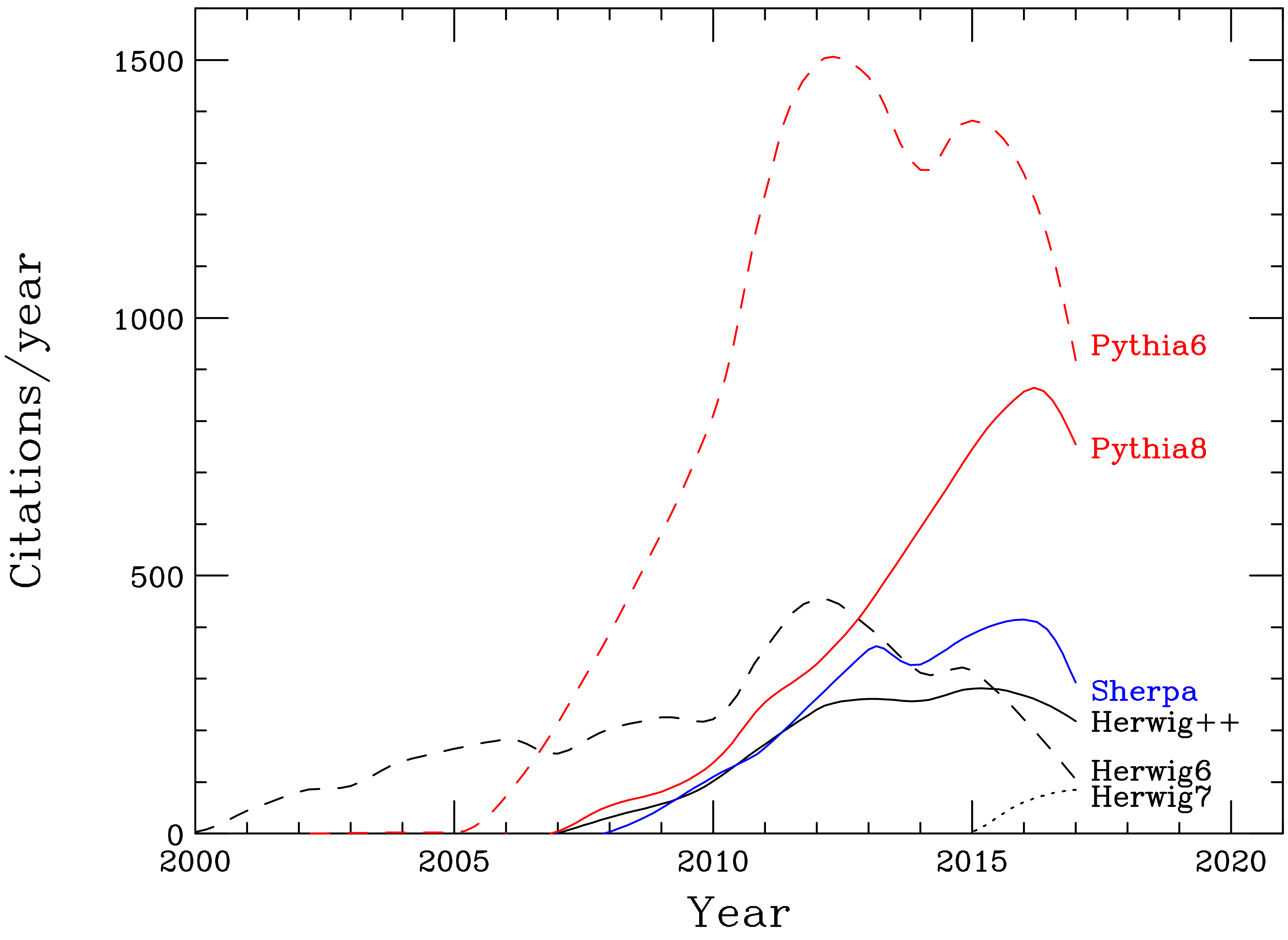
Gieseke, Röhr, Siódmok, EPJC72(2012)2225

Event Generators

- **HERWIG** http://projects.hepforge.org/herwig/
  - Angular-ordered parton shower, cluster hadronization
  - v6 Fortran; Herwig++ → v7
- **PYTHIA** http://www.thep.lu.se/~torbjorn/Pythia.html
  - p_T-ordered 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
- Decline due to secondary citation?

Other relevant software

(with apologies for omissions)

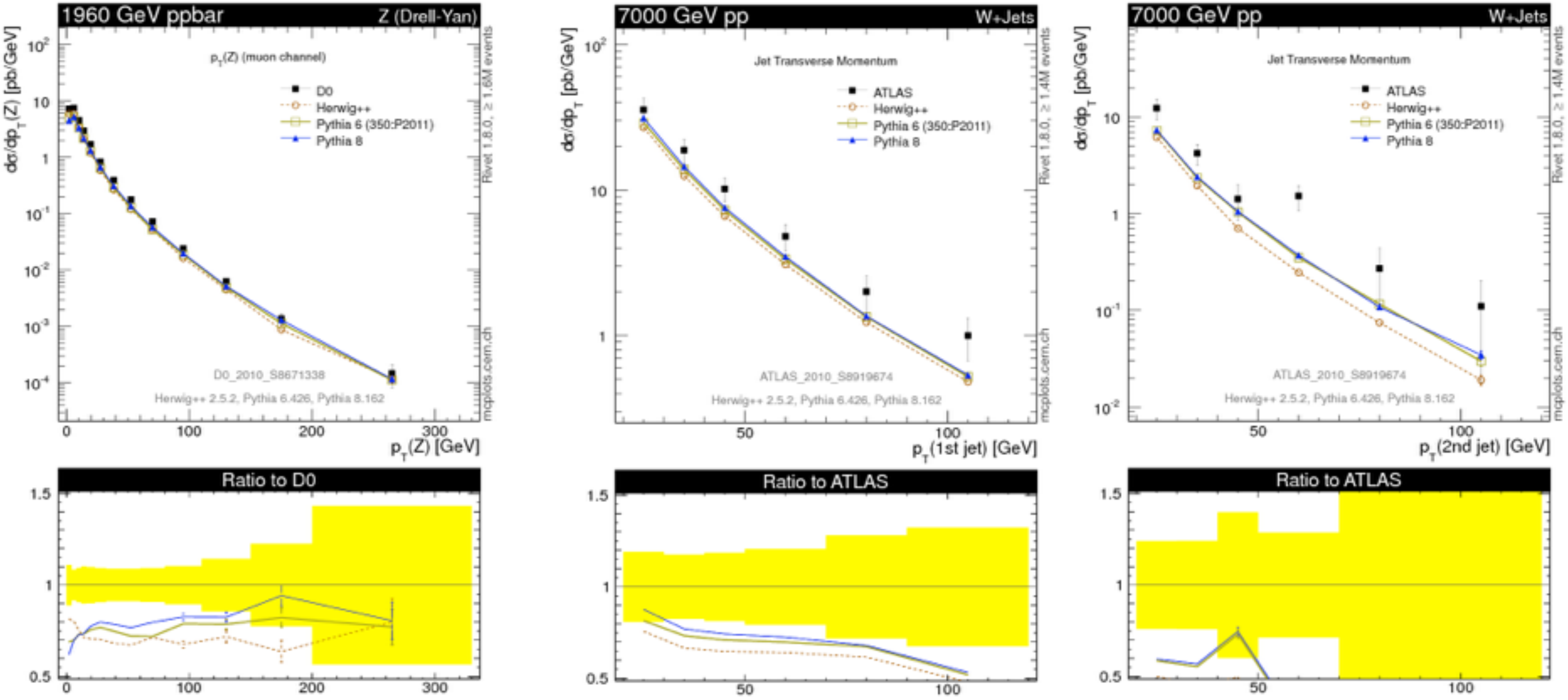
- Other event/shower generators: PhoJet, Ariadne, Dipsy, Cascade, Vincia
- Matrix-element generators: MadGraph/MadEvent, CompHep, CalcHep, Helac, Whizard, Sherpa, GoSam, aMC@NLO
- Matrix element libraries: AlpGen, POWHEG BOX, MCFM, NLOjet++, VBFNLO, BlackHat, Rocket
- Special BSM scenarios: Prospino,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



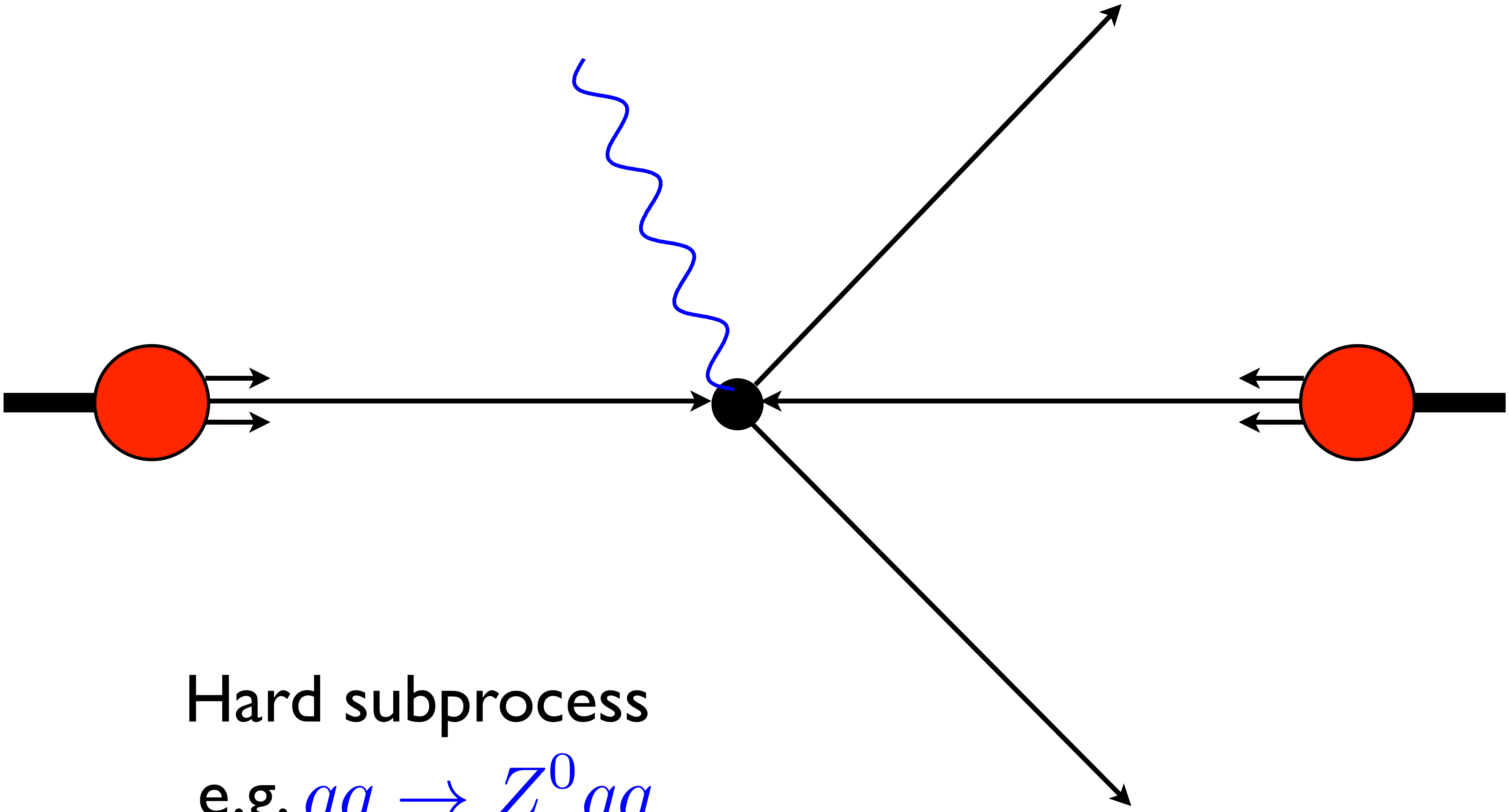
- Leading-order (LO) normalization ➡ need next-to-LO (NLO)
- Worse for high p_T and/or extra jets ➡ need multijet merging

Summary on Event Generators

- Fairly good overall description of data, but…
- Hard subprocess: LO no longer adequate
- Parton showers: need matching to NLO
  - Also multijet merging
  - NLO showering?
- Hadronization: string and cluster models
  - Need new ideas/methods
- Underlying event due to multiple interactions
  - Colour reconnection necessary

Improving Event Generation

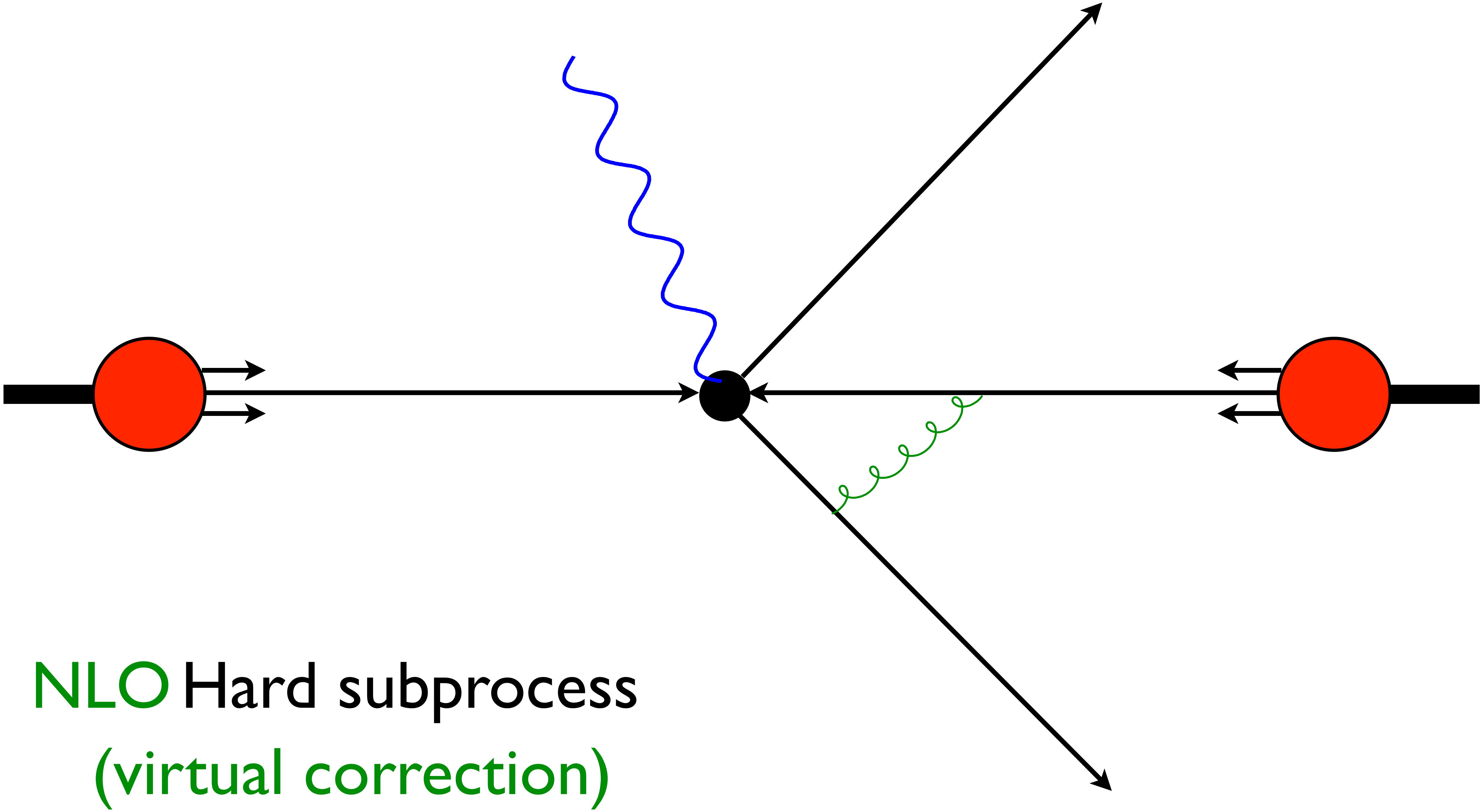
Improving Event Generation



Hard subprocess

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

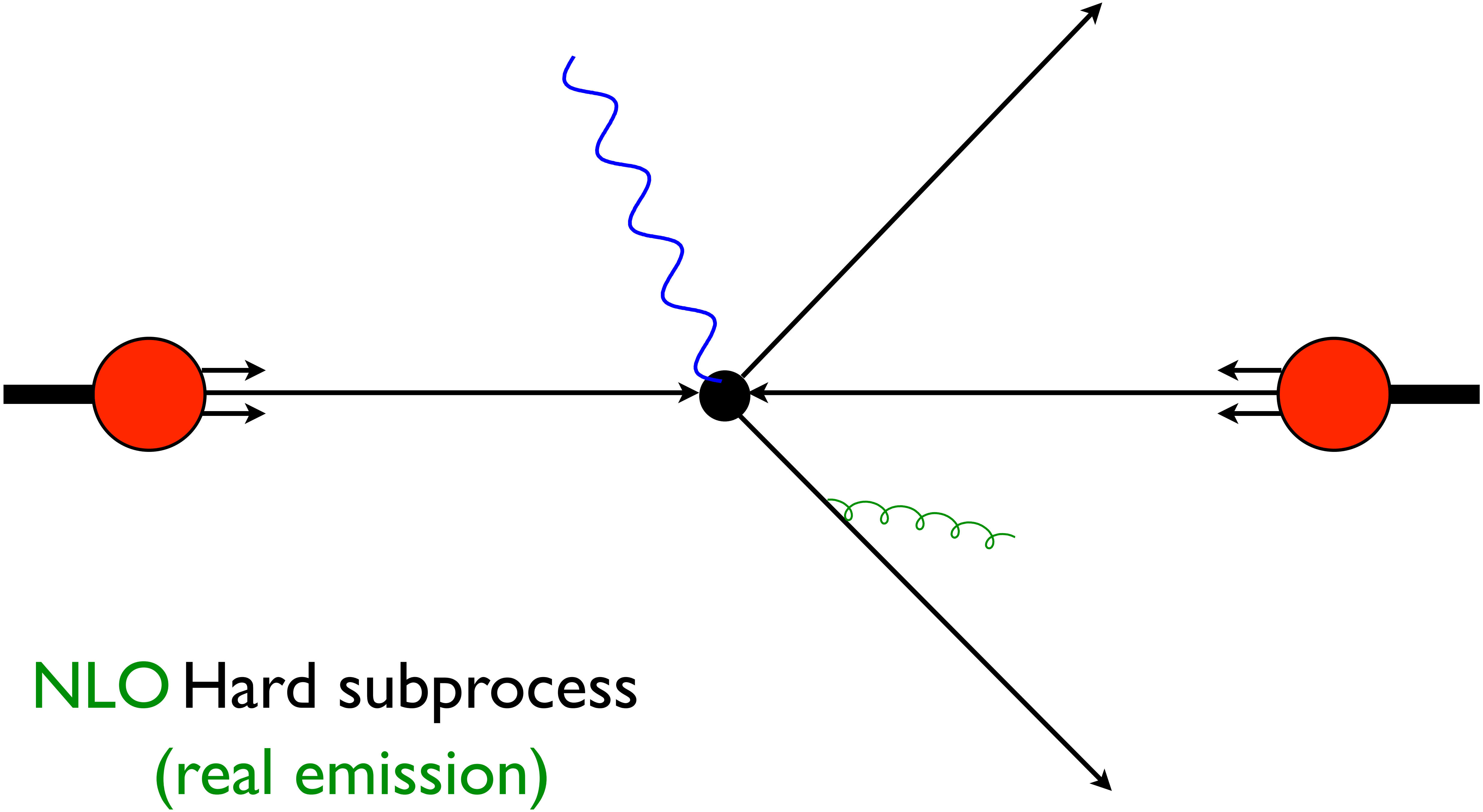
Improving Event Generation



NLO Hard subprocess

(virtual correction)

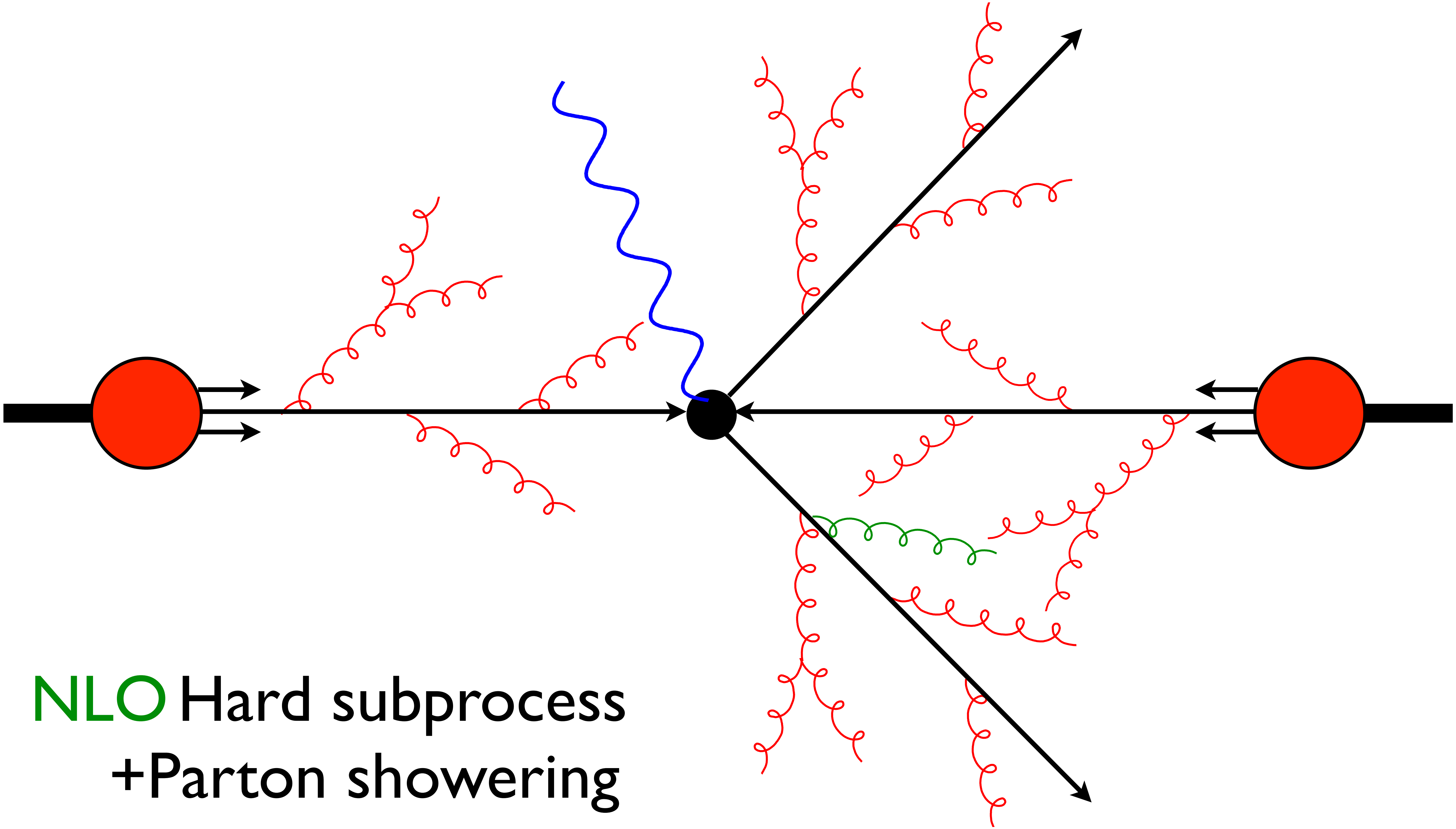
Improving Event Generation



NLO Hard subprocess

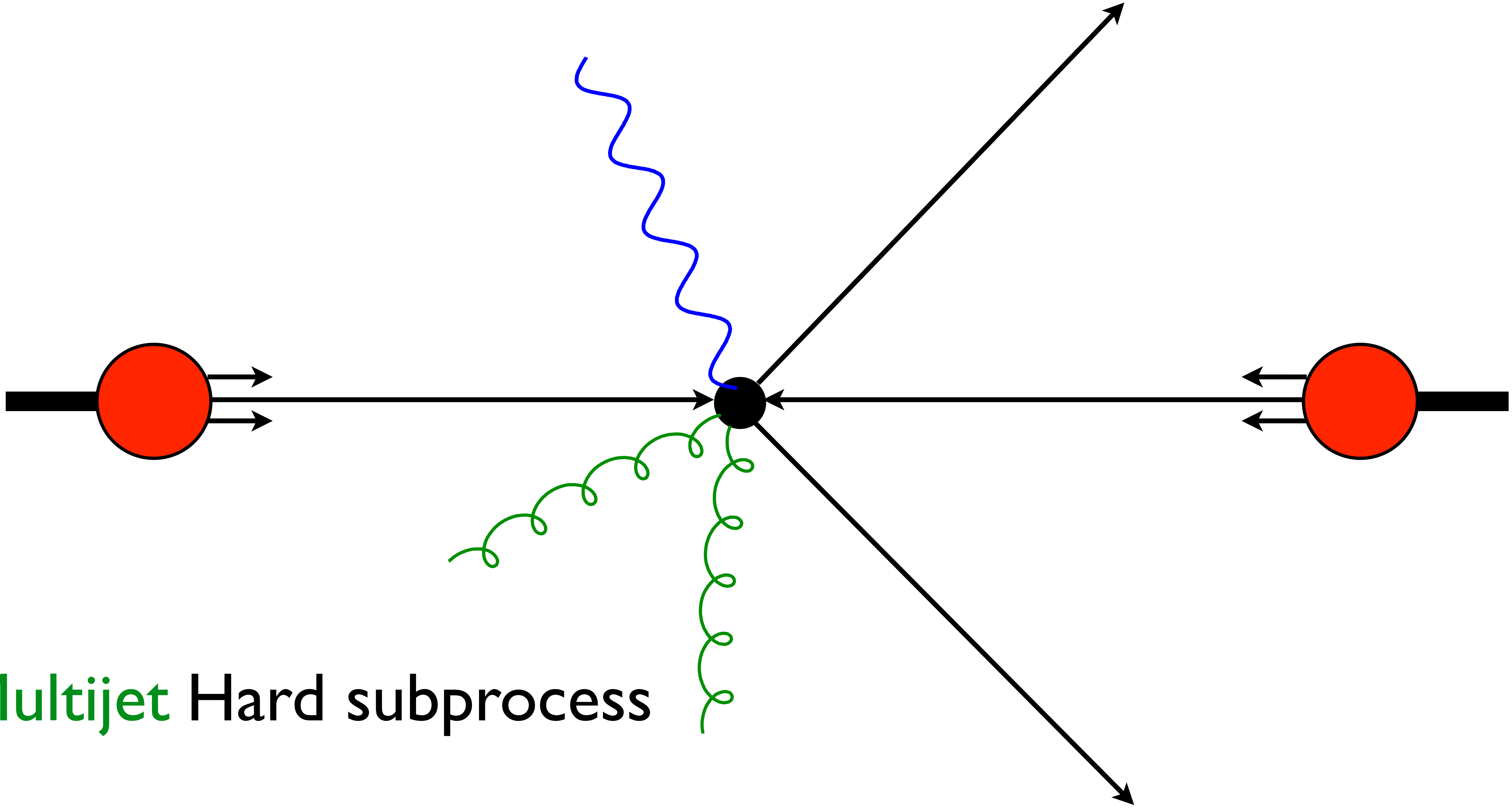
(real emission)

Improving Event Generation



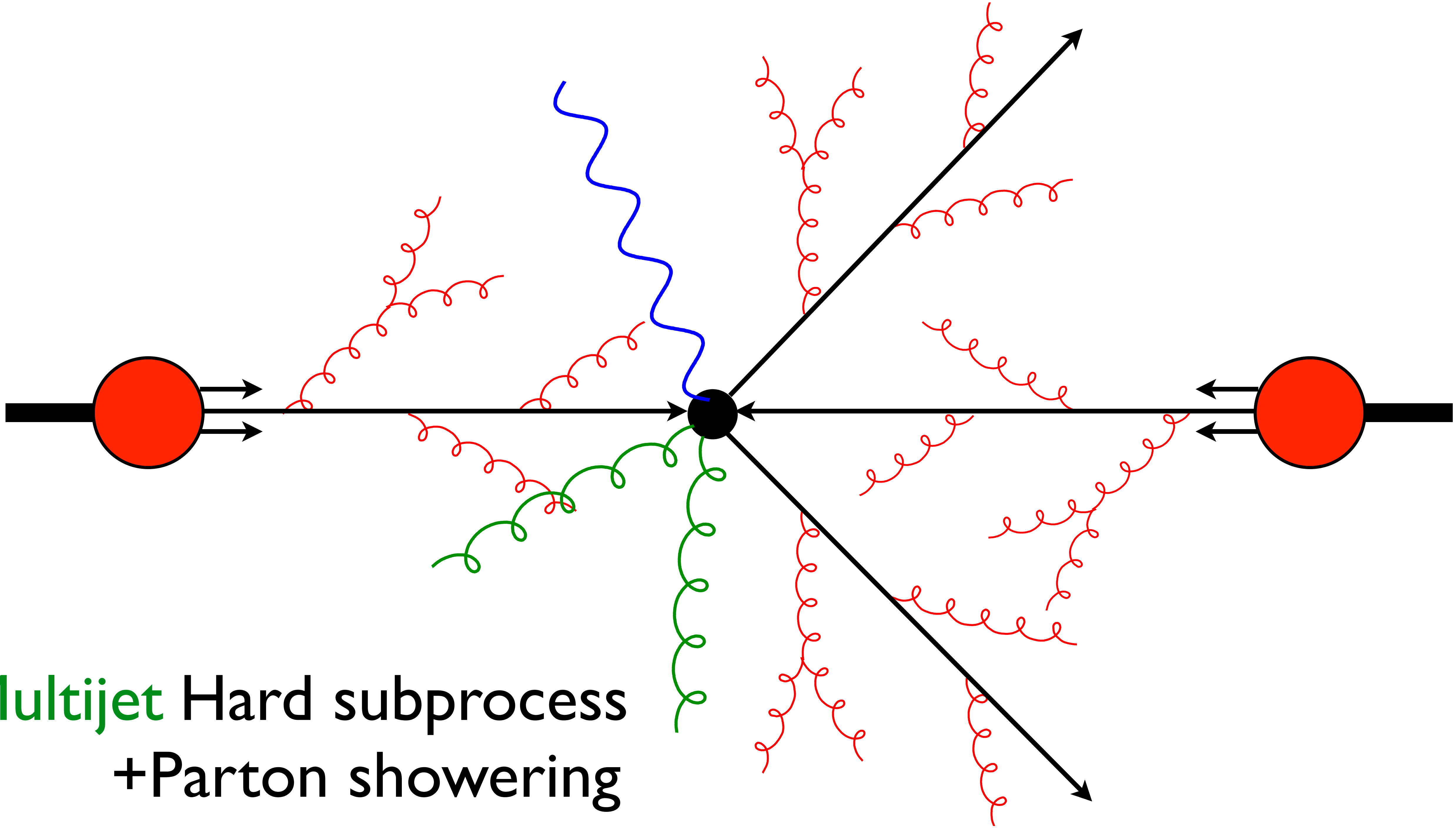
NLO Hard subprocess
+Parton showering
= Double counting??

Improving Event Generation



Multijet Hard subprocess

Improving Event Generation



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

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

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

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

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

$$\Delta_{\rm MC}(p_T)=\exp\left[-\int d\Phi_R\frac{R_{\rm MC}(\Phi_B,\Phi_R)}{B(\Phi_B)}\Theta\left(k_T(\Phi_B,\Phi_R)-p_T\right)\right]$$

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

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

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

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

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

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

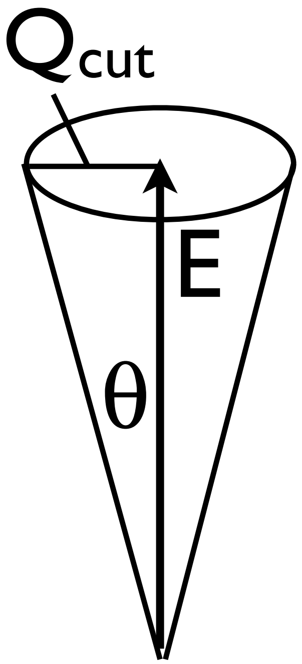
- NLO with (almost) no negative weights

arbitrary NNLO

- High pT always enhanced by $K = \overline{B}/B = 1 + \mathcal{O}(\alpha_{\mathrm{S}})$

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, $n \lesssim N_{max}$

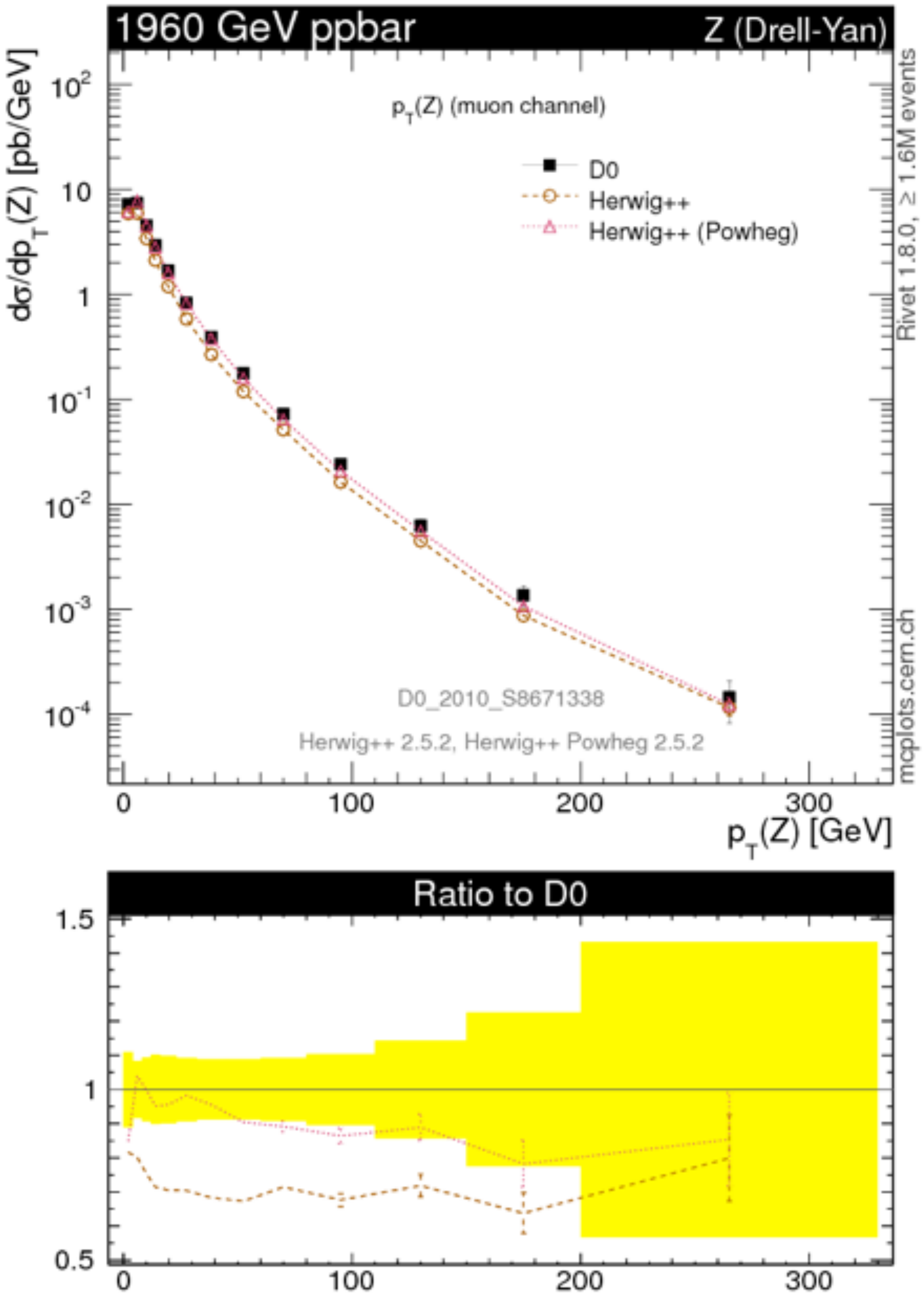
CKKW: Catani et al., JHEP 11(2001)063

-L: Lonnblad, JHEP 05(2002)063

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

Vector boson production

Z^0 at Tevatron

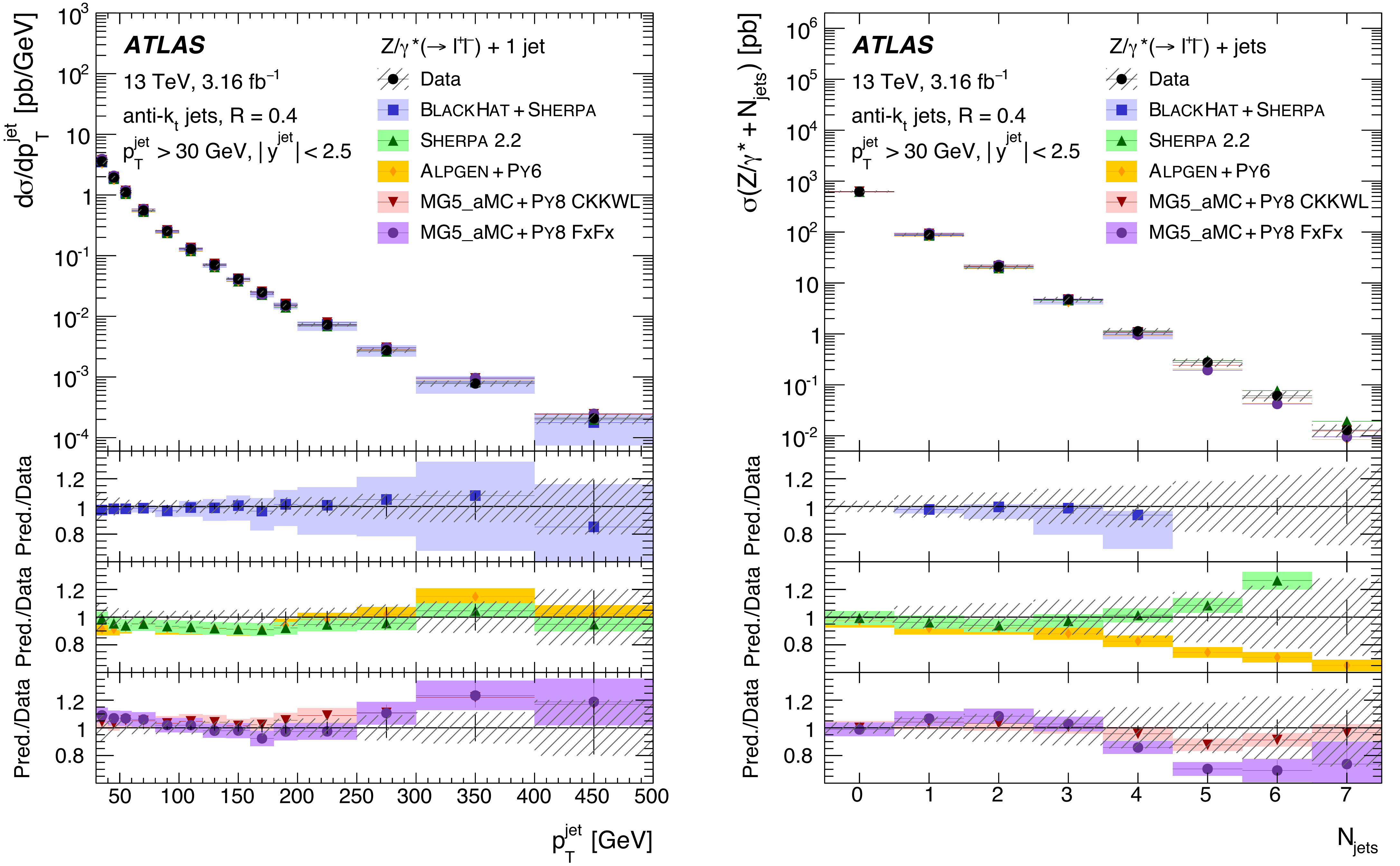


http://mcplots.cern.ch/

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

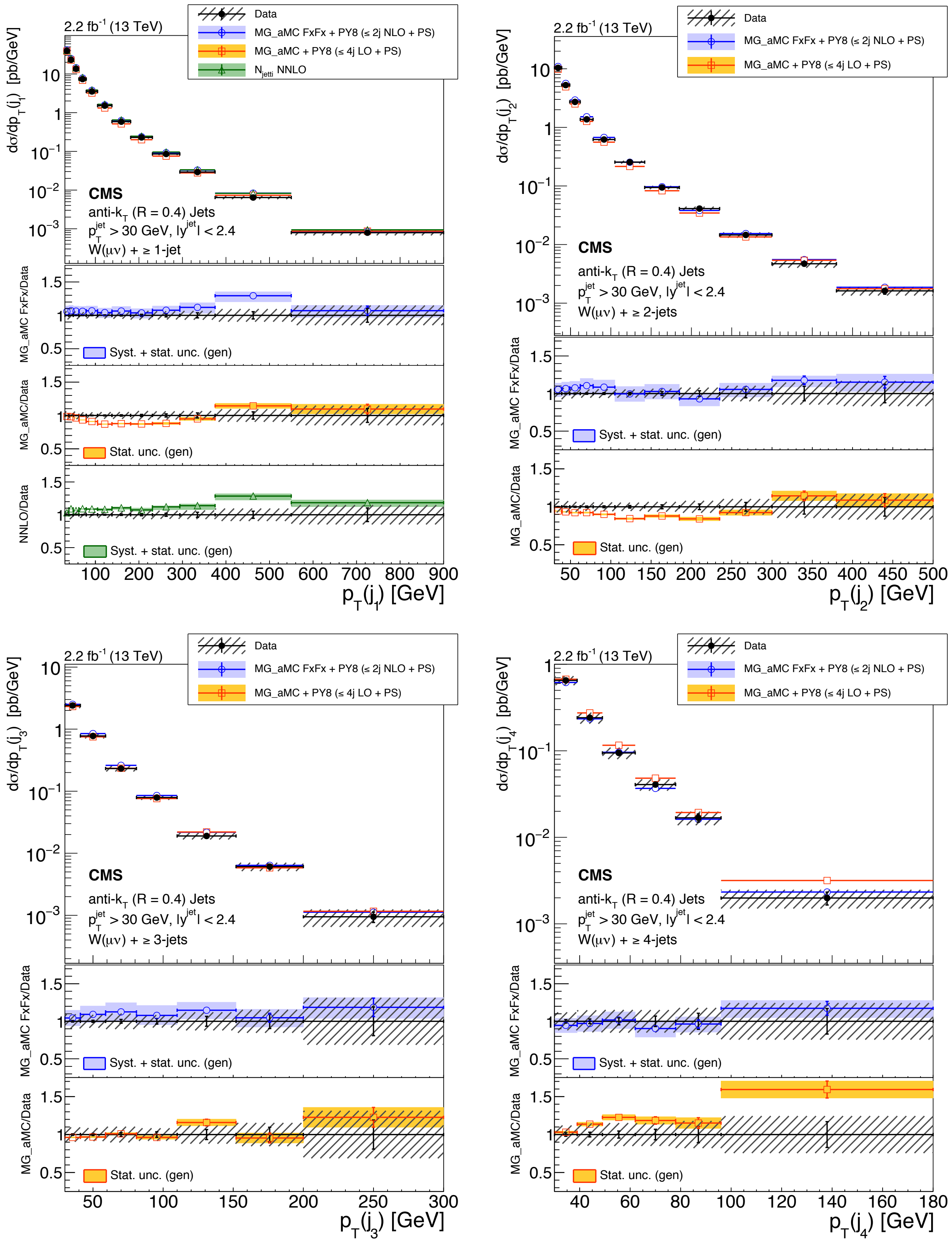
Z+jets at LHC

ATLAS, arXiv:1702.05725



- MadGraph5_aMC@NLO CKKWL best for high N_{jets}

W+jets at LHC

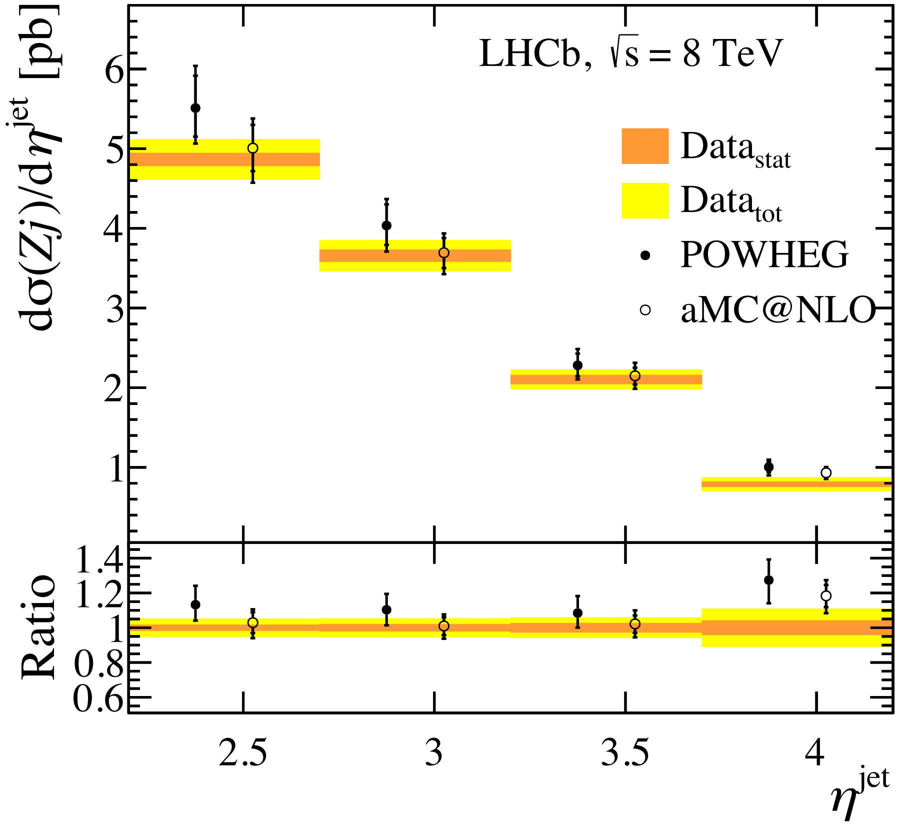


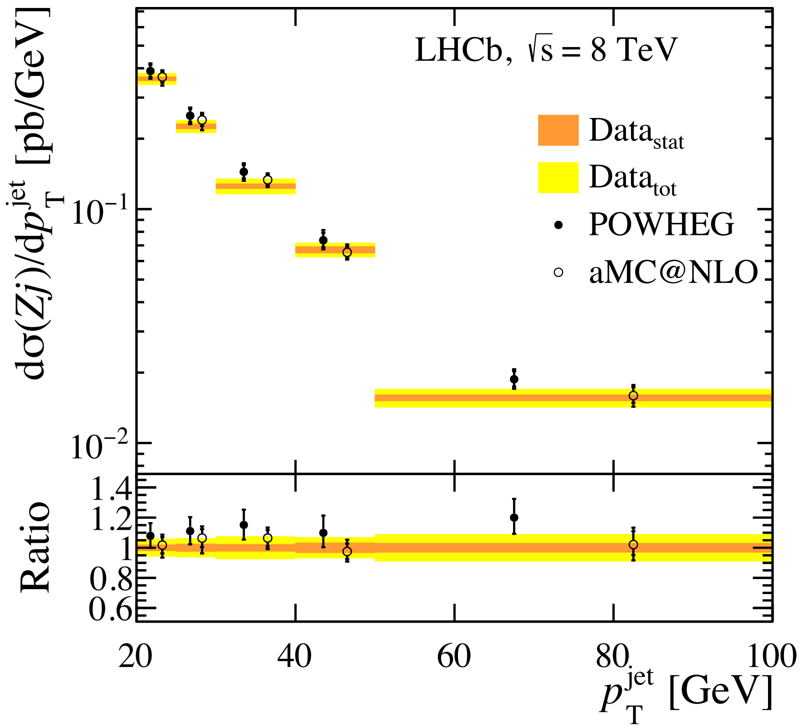
CMS, arXiv:1707.05979

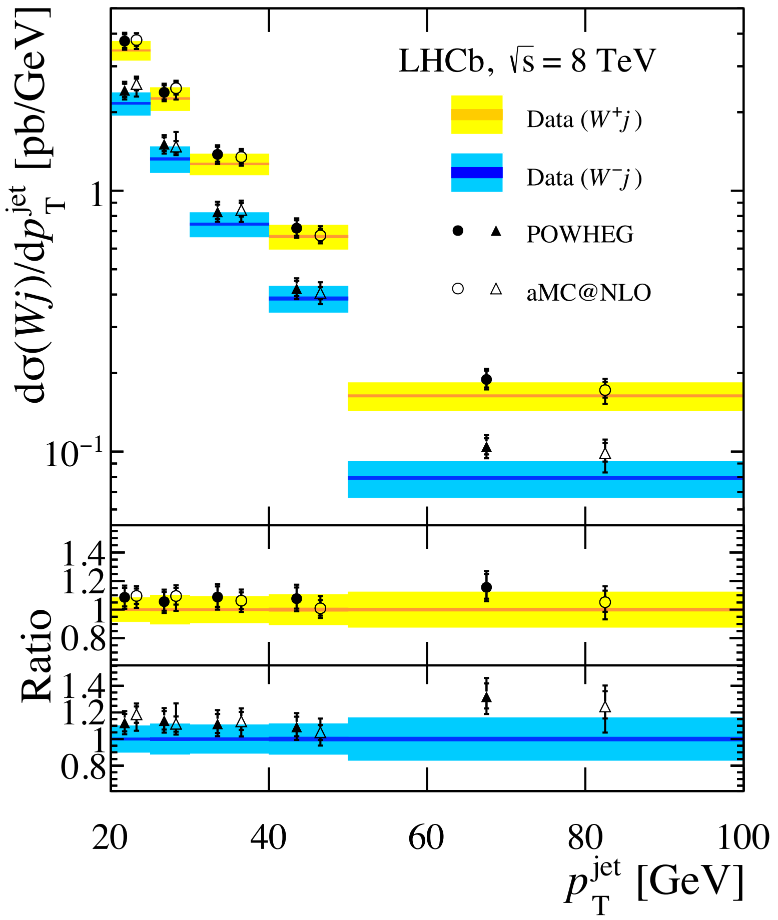
- Transverse momentum distributions of jets 1-4

$W^{\pm}/Z^{0}$+jets at LHCb

LHCb, arXiv:1605.00951



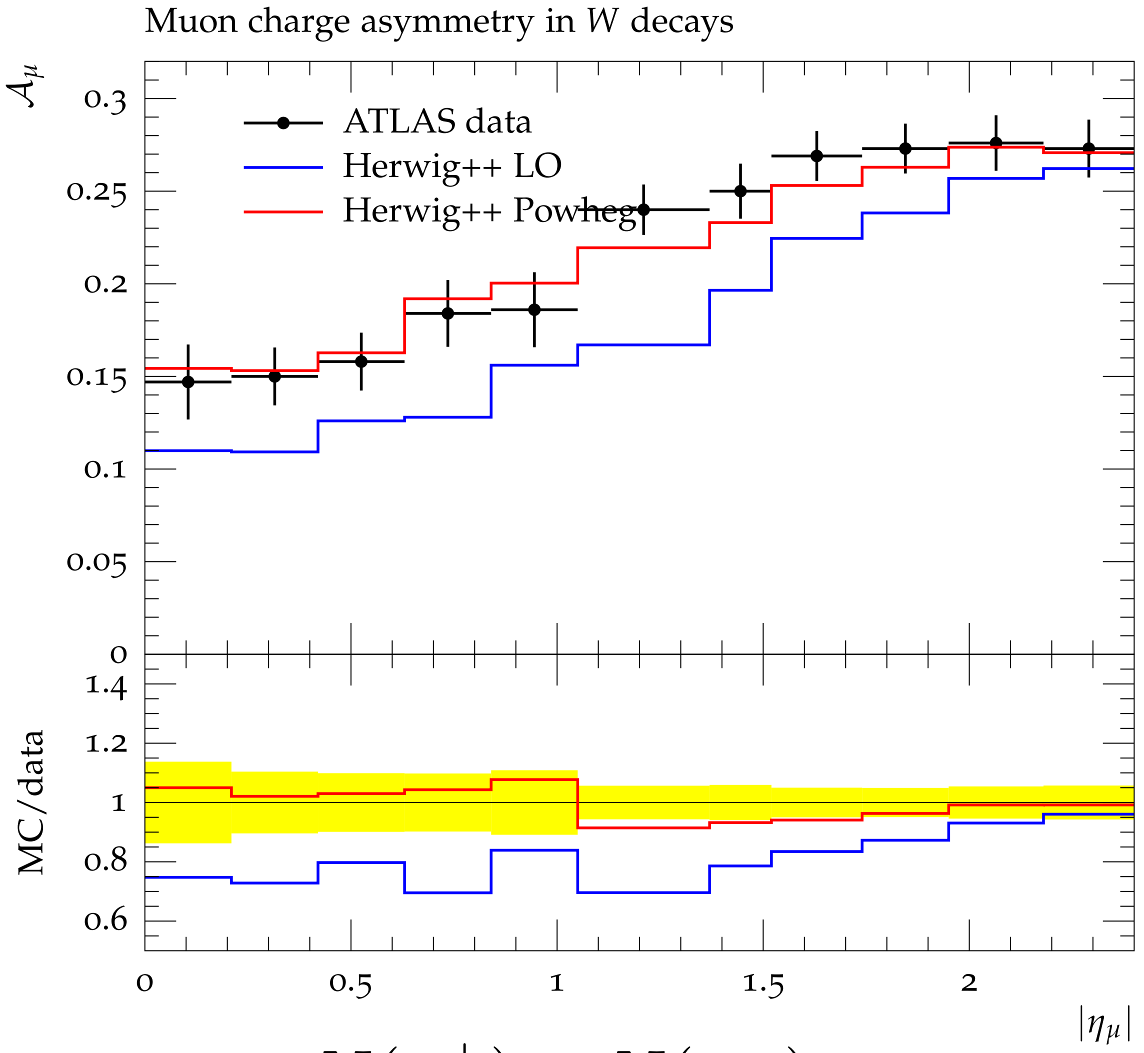


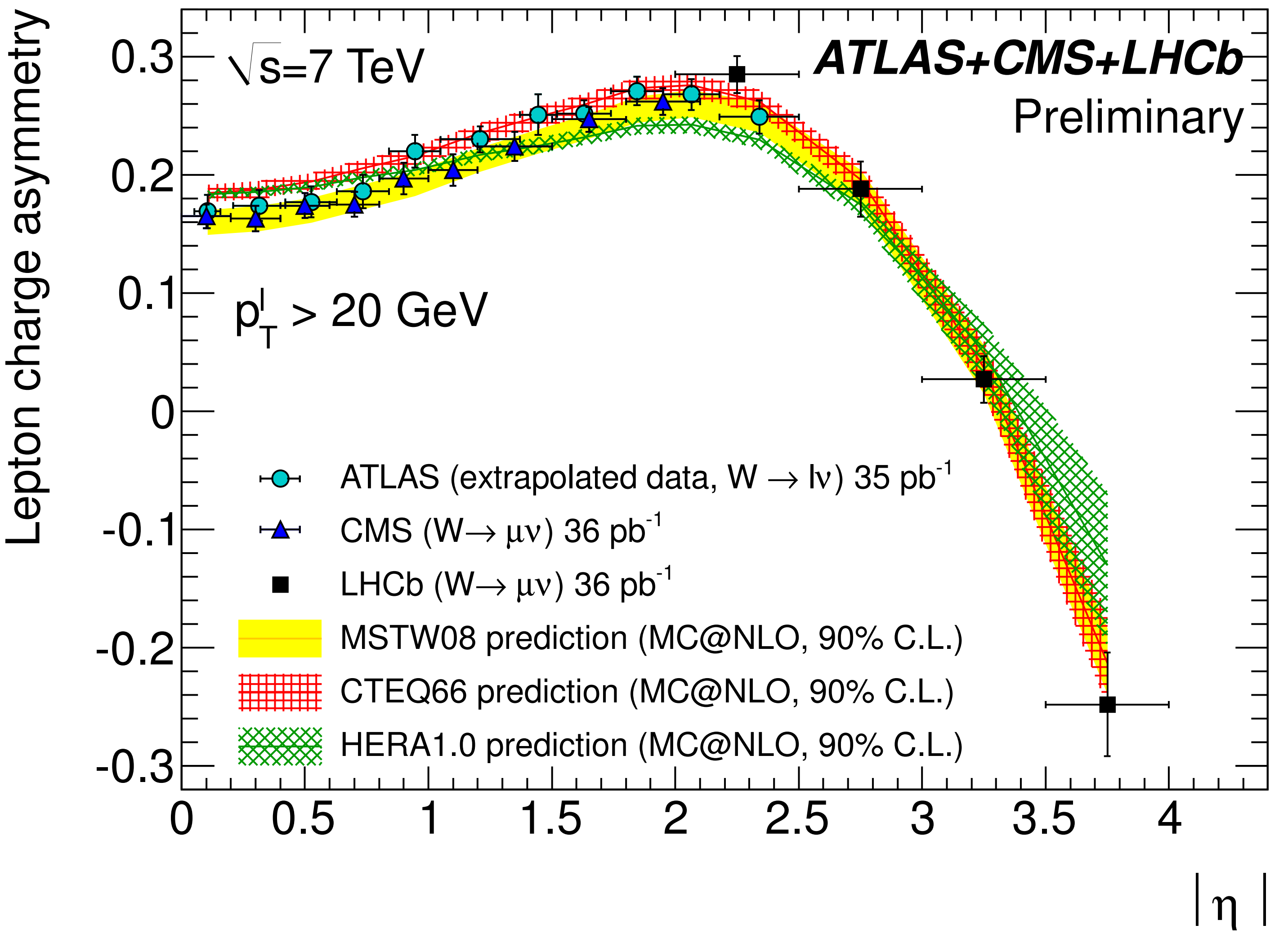


- Forward region

$$\eta = -\ln\tan\theta/2$$

W asymmetry at LHC





$$A_\mu = \frac{N(\mu^+) - N(\mu^-)}{N(\mu^+) + N(\mu^-)}$$

ATLAS-CONF-1211-129

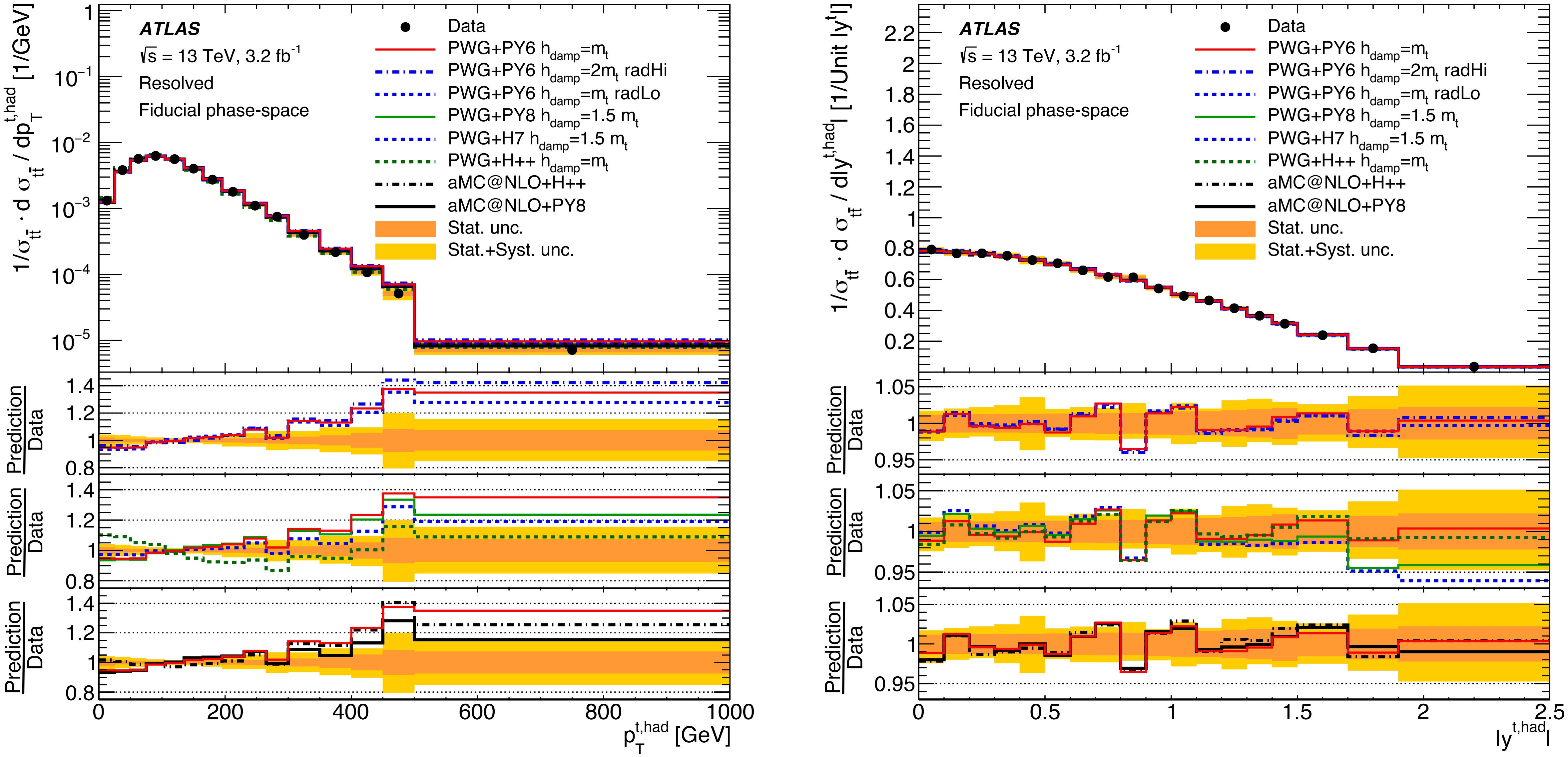
- Asymmetry probes parton distributions

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

Top quark pair production

Top quark distributions

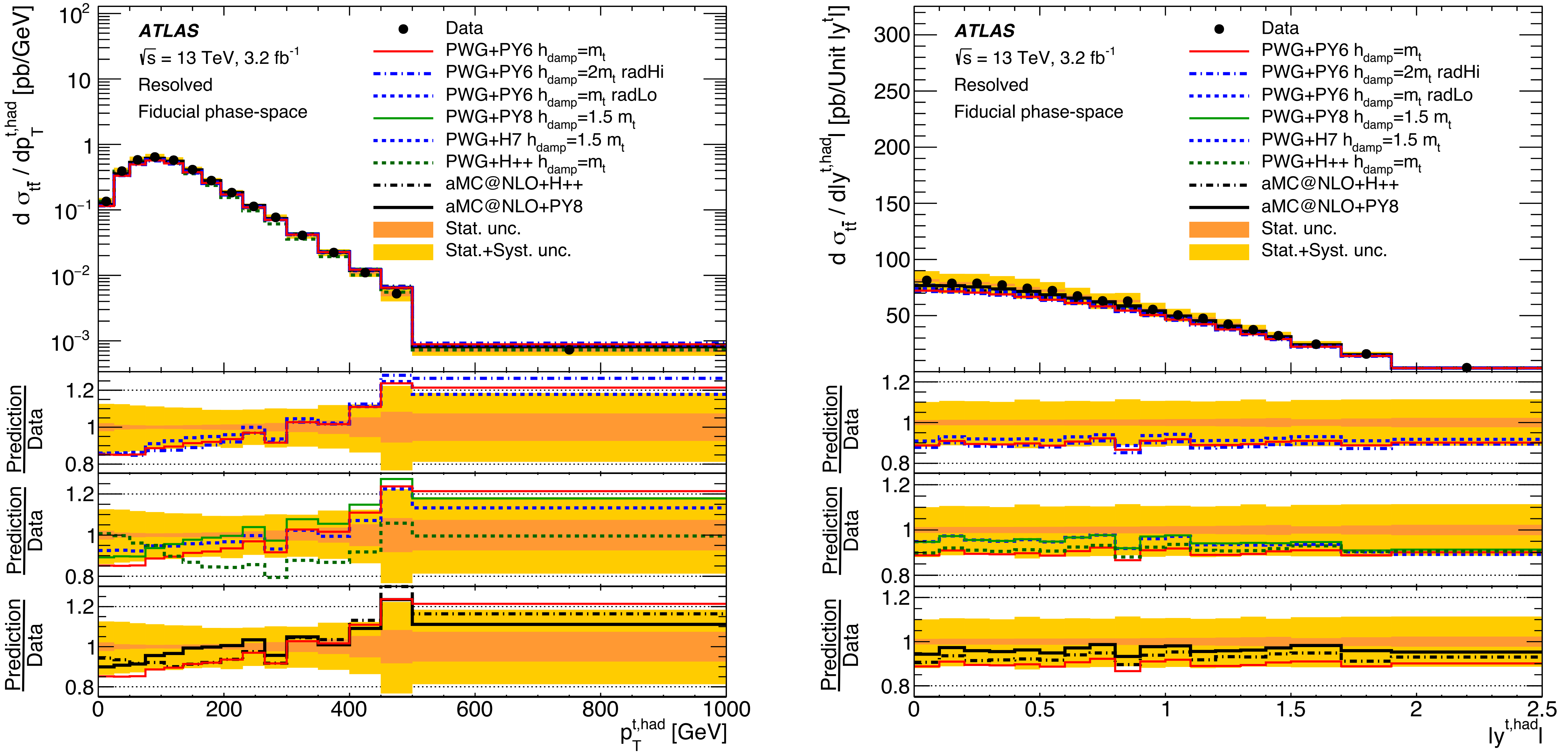
ATLAS, arXiv:1708.00727



- Normalized to data

Top quark distributions

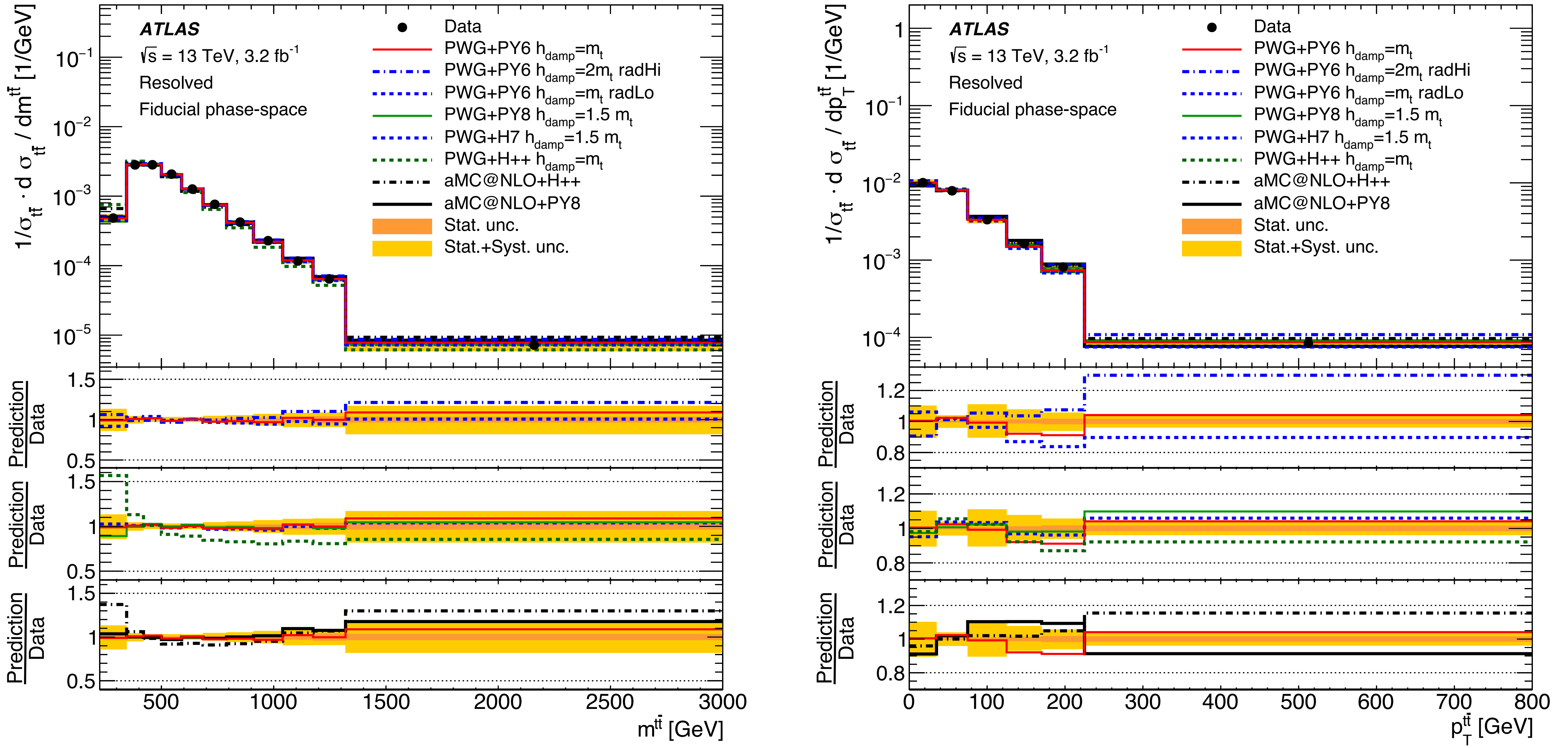
ATLAS, arXiv:1708.00727



- Absolute normalization

Top quark pair distributions

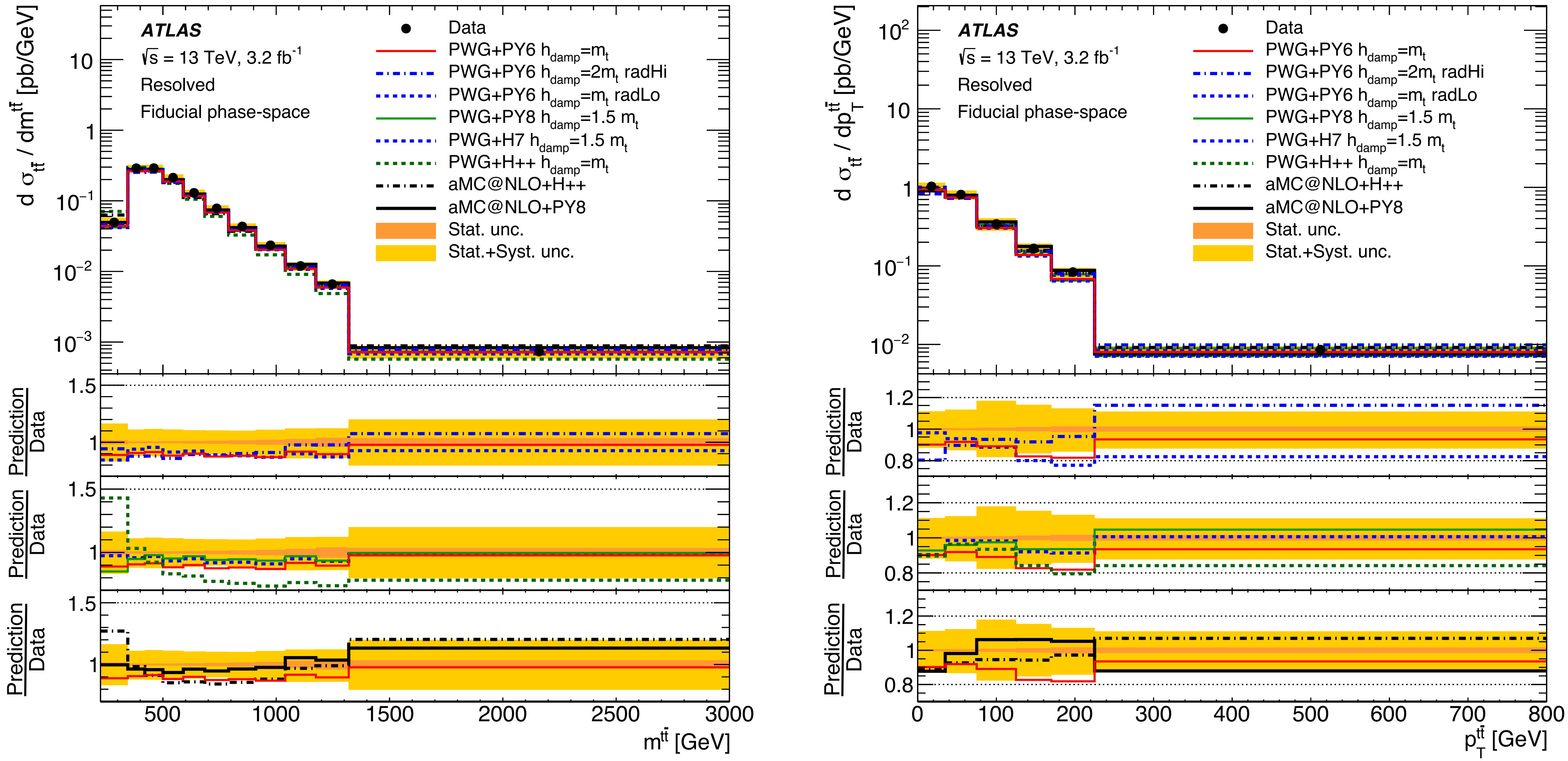
ATLAS, arXiv:1708.00727



- Normalized to data

Top quark pair distributions

ATLAS, arXiv:1708.00727

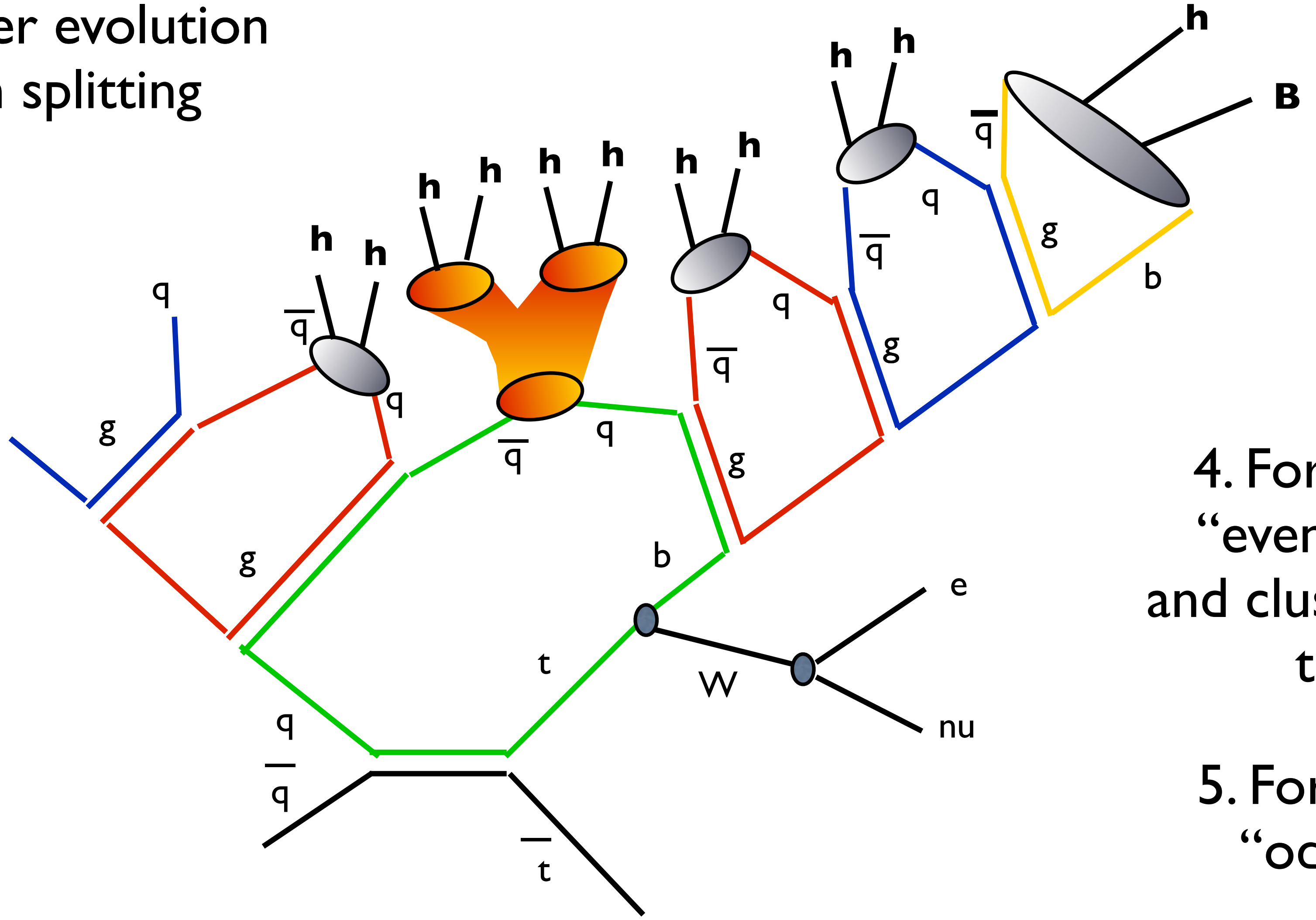


- Absolute normalization

Top mass & hadronization

Mangano, Top LHC WG, July 2012

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



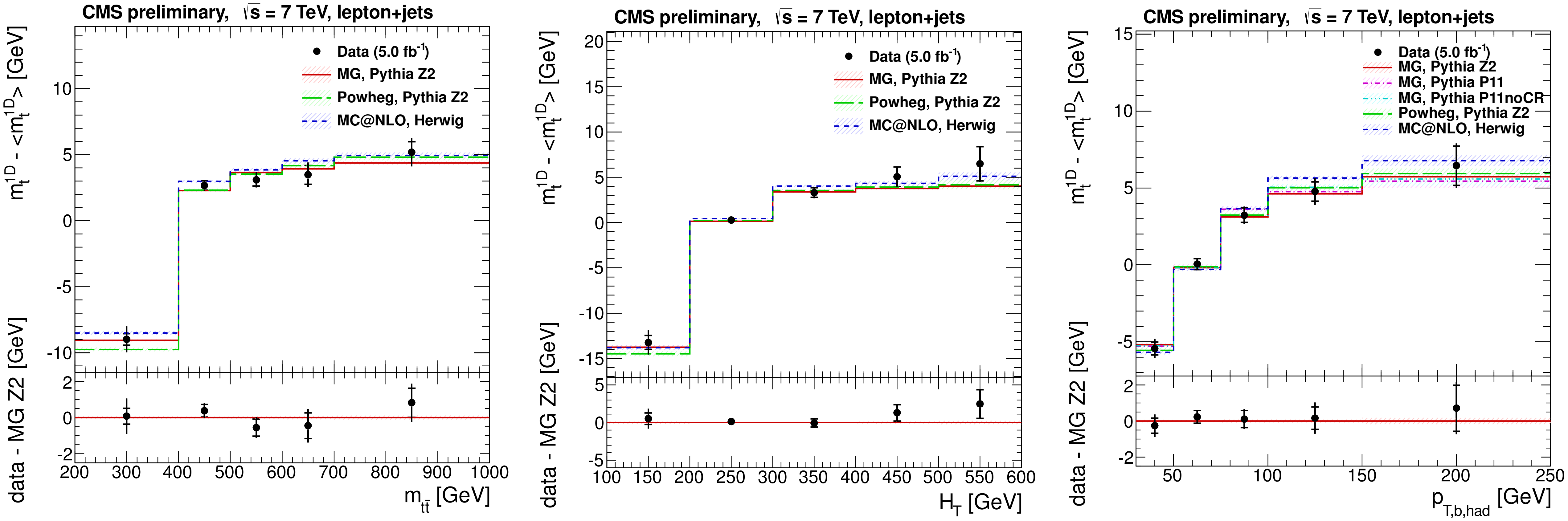
4. Formation of "even" clusters and cluster decay to hadrons

5. Formation of "odd" cluster

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

- b jet must gain (or lose) some 4-momentum from rest of event

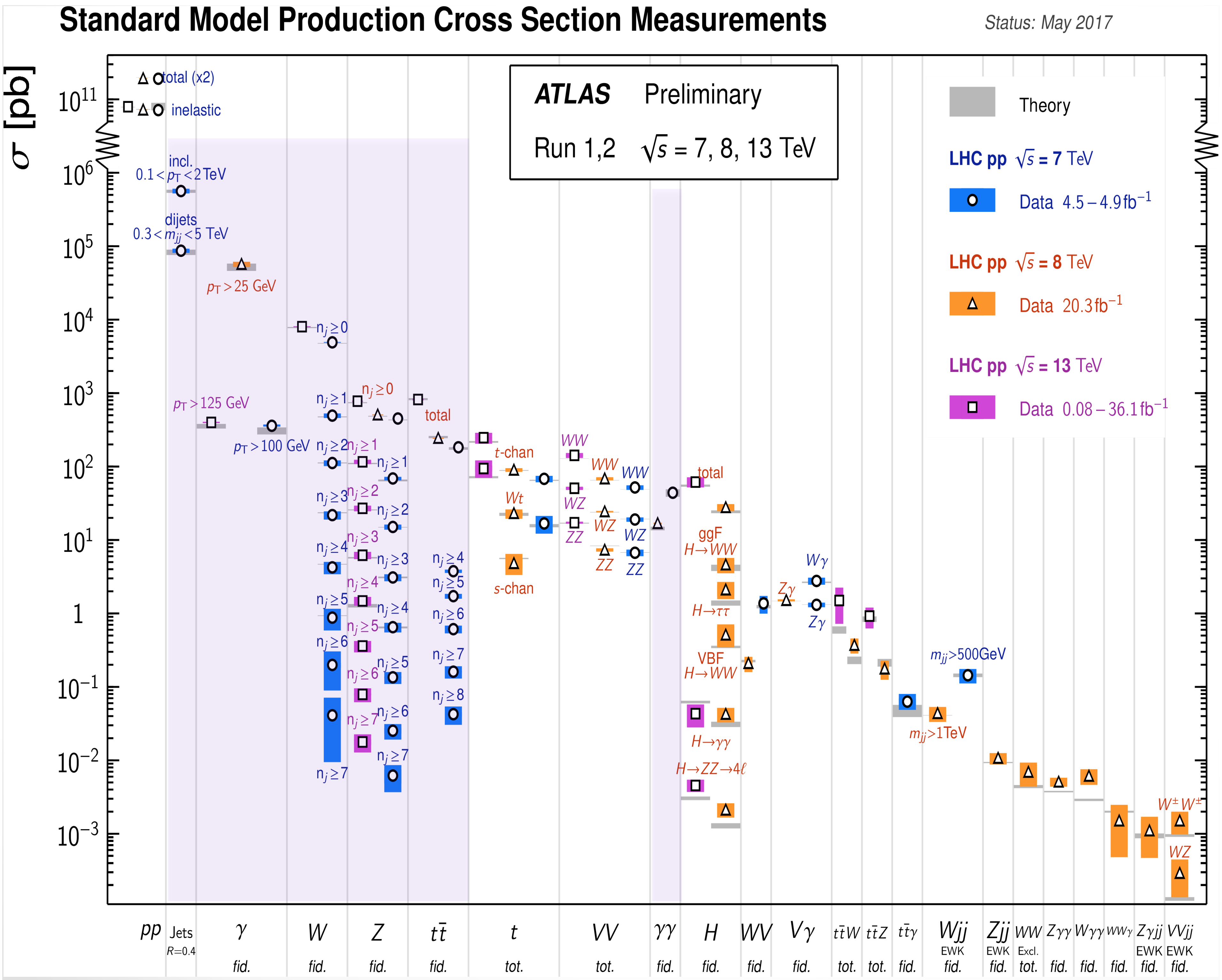
Top mass & kinematics



CMS PAS TOP-12-029

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

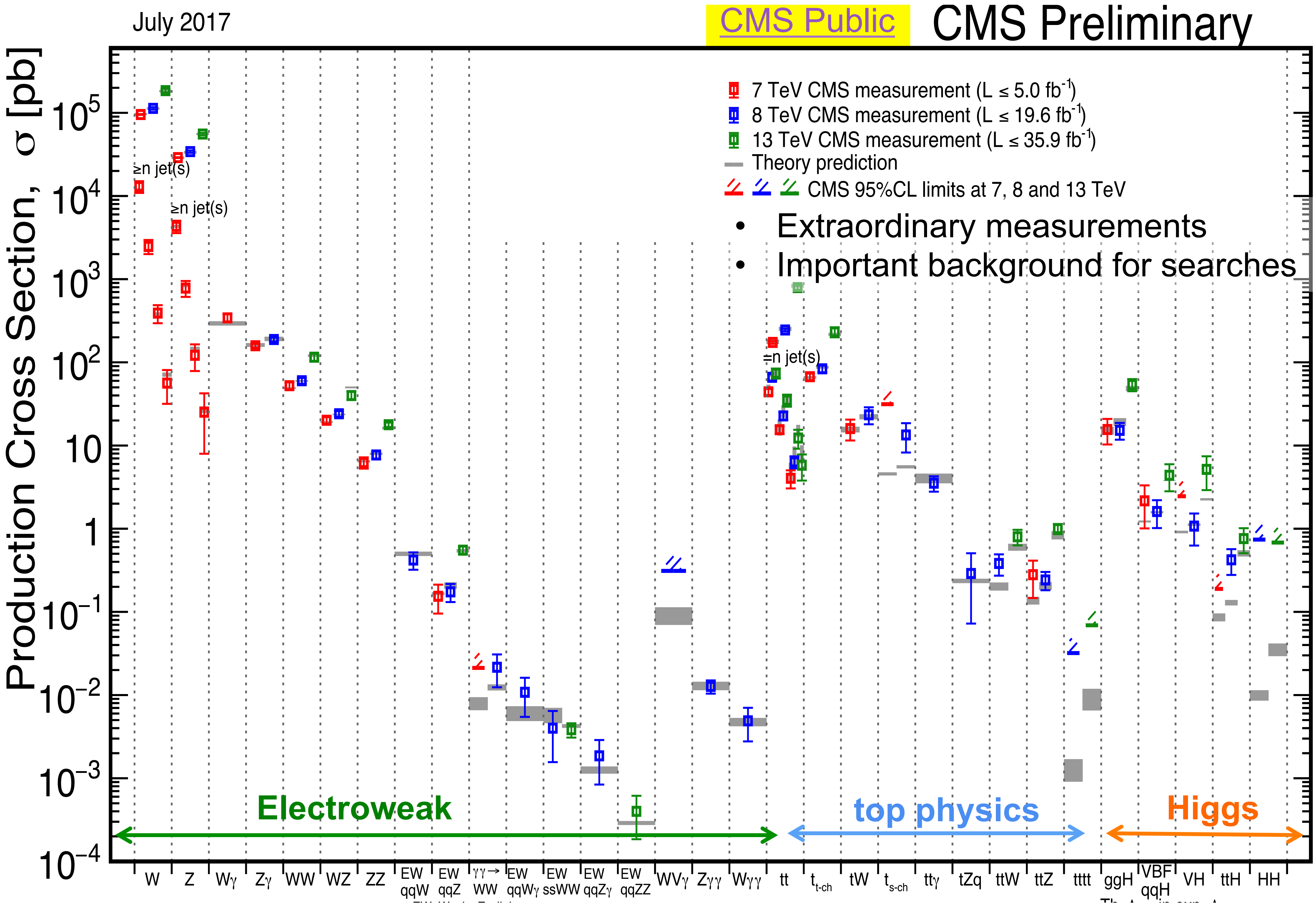
LHC Cross Section Summary



- No significant deviations from SM (yet)

LHC Cross Section Summary

CMS Public



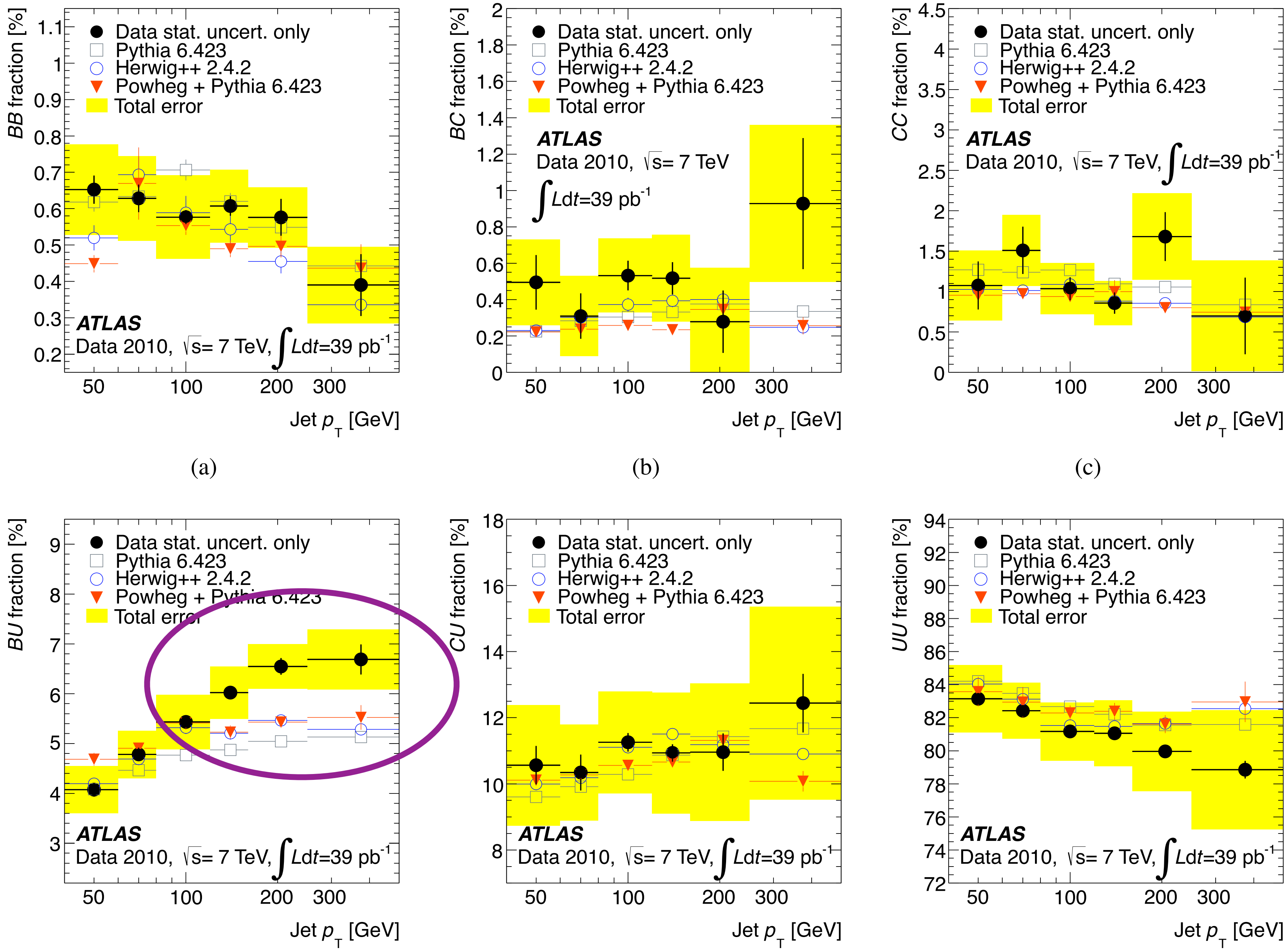
- Extraordinary measurements
- Important background for searches

- No significant deviations from SM (yet)

But all is not perfect ...

- Dijet flavours versus jet p_T

ATLAS, arXiv:1210.0441



(a)

(b)

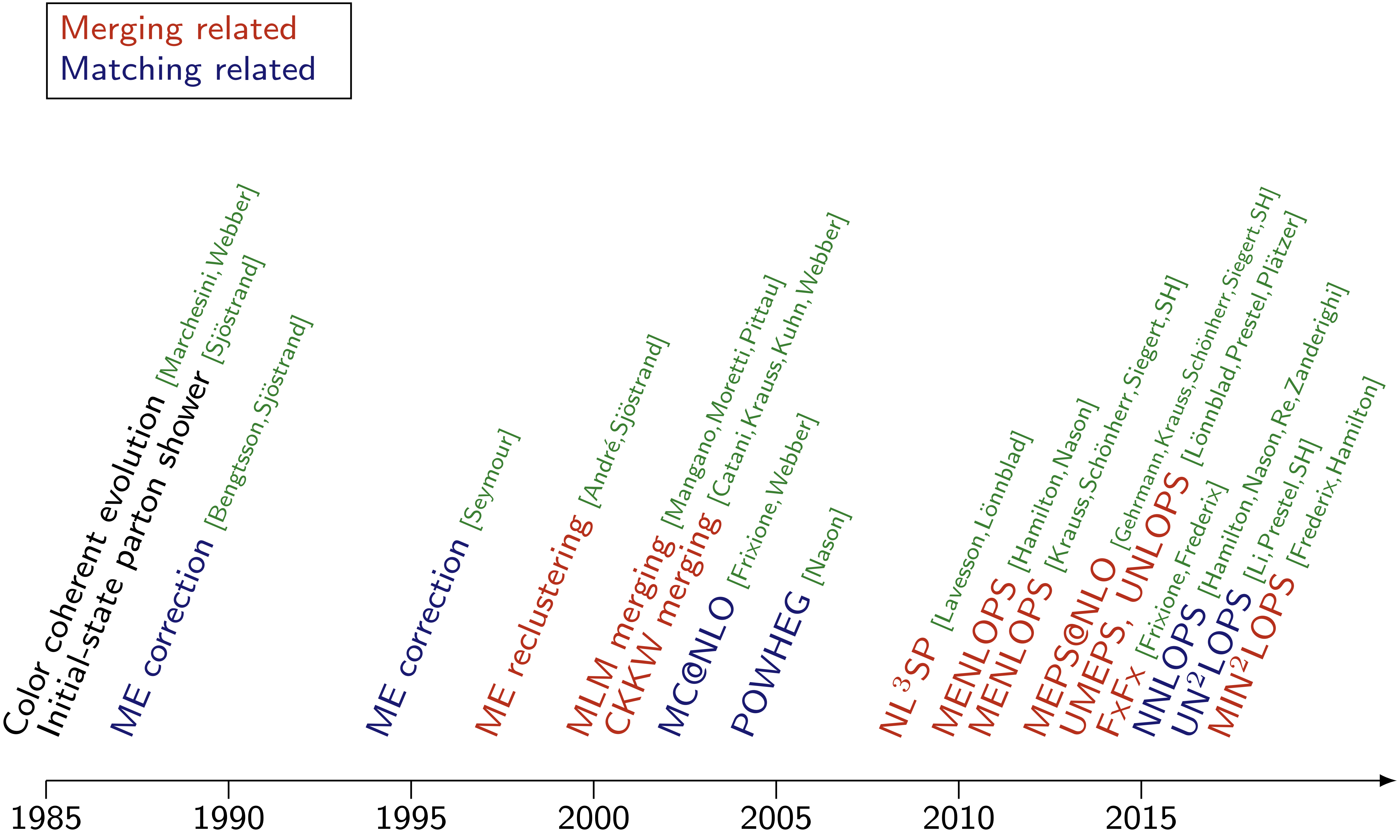
(c)

- 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



Merging related
Matching related

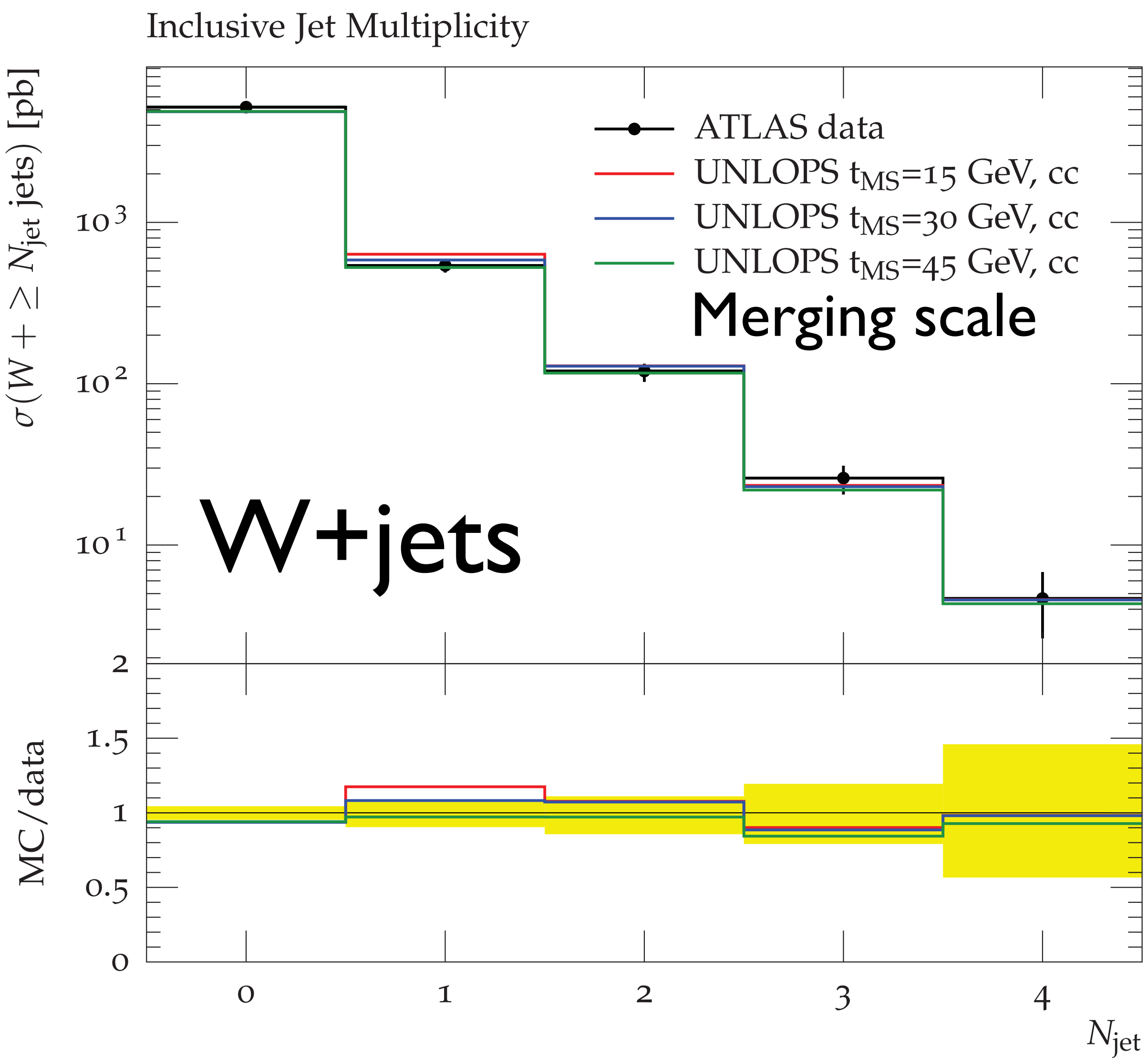
Color coherent evolution [Marchesini,Webber]
Initial-state parton shower [Sjöstrand]
ME correction [Bengtsson,Sjöstrand]
ME correction [Seymour]
ME reclustering [André,Sjöstrand]
MLM merging [Mangano,Moretti,Pittau]
CKKW merging [Catani,Krauss,Kuhn,Webber]
MC@NLO [Frixione,Webber]
POWHEG [Nason]
NL^{3}SP [Lavesson,Lönnblad]
MENLOPS [Hamilton,Nason]
MENLOPS [Krauss,Schönherr,Siegert,SH]
MEPS@NLO [Gehrmann,Krauss,Schönherr,Siegert,SH]
UMEPS, UNLOPS [Lönnblad,Prestel,Plätzer]
FxFx [Frixione,Frederix]
NNLOPS [Hamilton,Nason,Re,Zanderighi]
UN^{2}LOPS [Li,Prestel,SH]
MIN^{2}LOPS [Frederix,Hamilton]

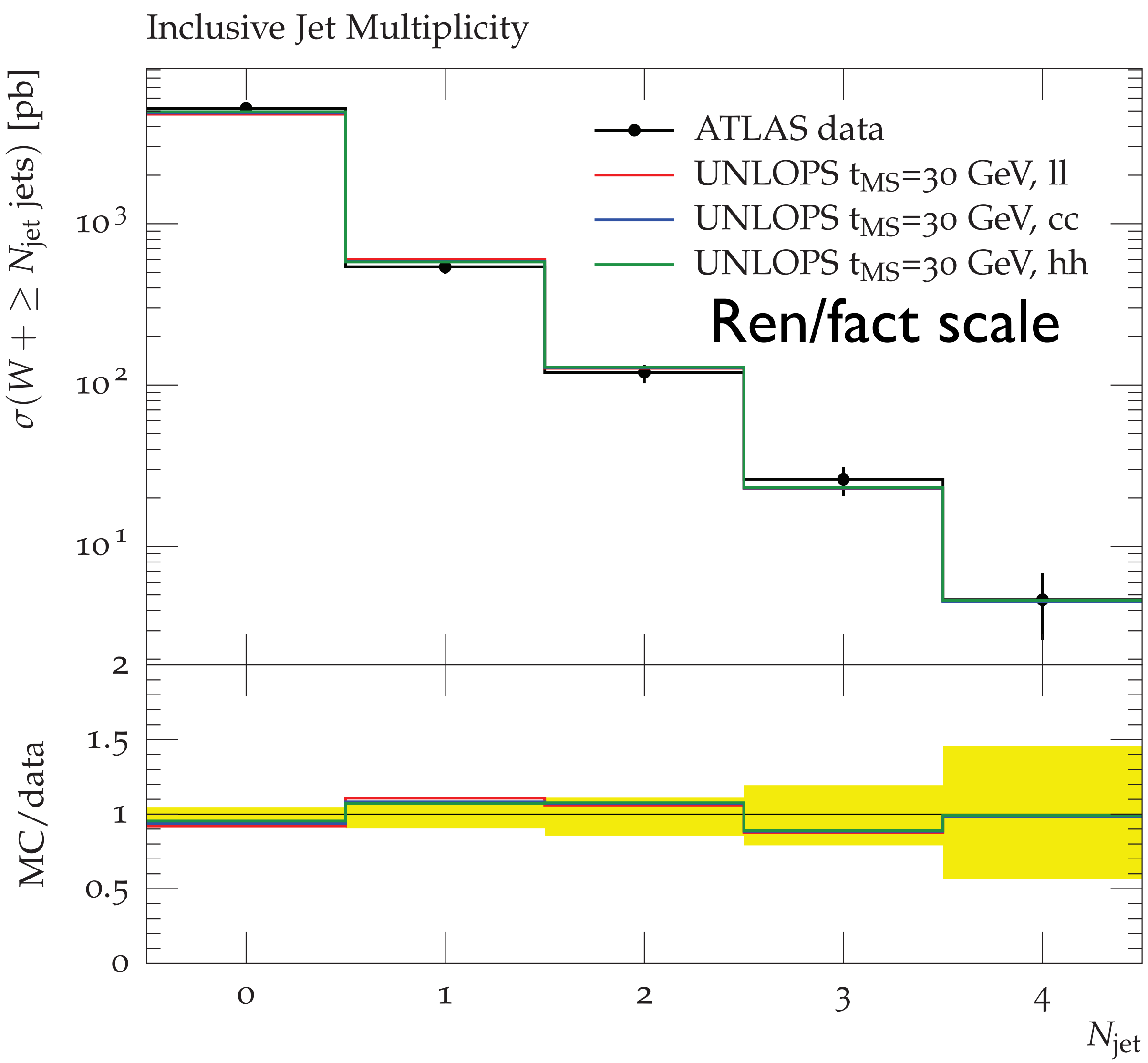
Stefan Höche, 2017 MCnet School

Combined matching+merging

- Many competing schemes (pp only)
  - 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 (Herwig7) Bellm, Gieseke, Plätzer, arXiv:1705.06700
  - MiNLO (POWHEG) Hamilton et al., arXiv:1212.4504
  - UN^{2}LOPS Höche, Li, Prestel, arXiv:1405.3607
- Some key ideas in LoopSim Rubin, Salam, Sapeta, JHEP1009, 084

Combined matching+merging





UNLOPS: Lönnblad & Prestel, arXiv:1211.7278

- Scale dependences almost eliminated

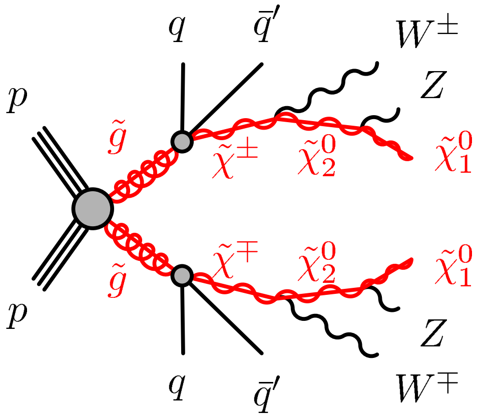
Beyond Standard Model Simulation

BSM Simulation

- Main generators have some BSM models built in
  - Pythia 6 has the most models
  - Herwig 7 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 (MG5_aMC@NLO [FxFx] …)

Searching for new signals

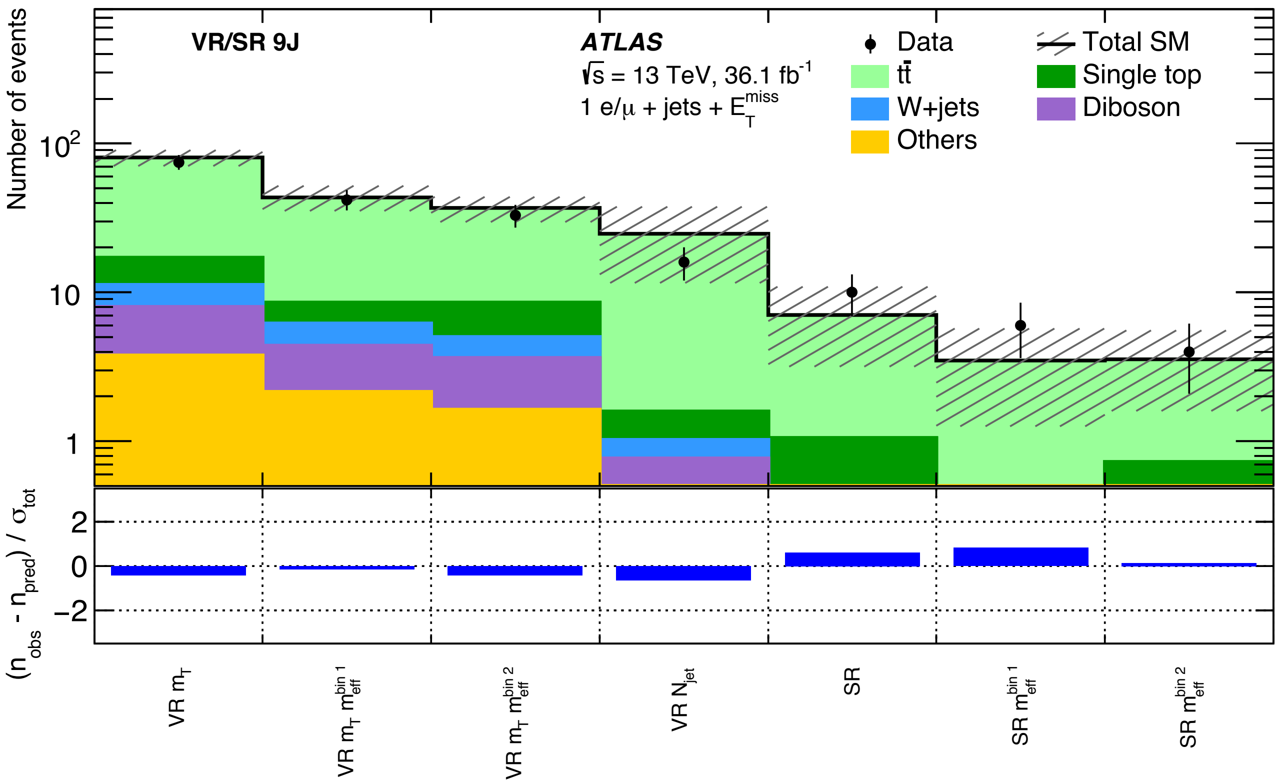
ATLAS, arXiv:1708.08232

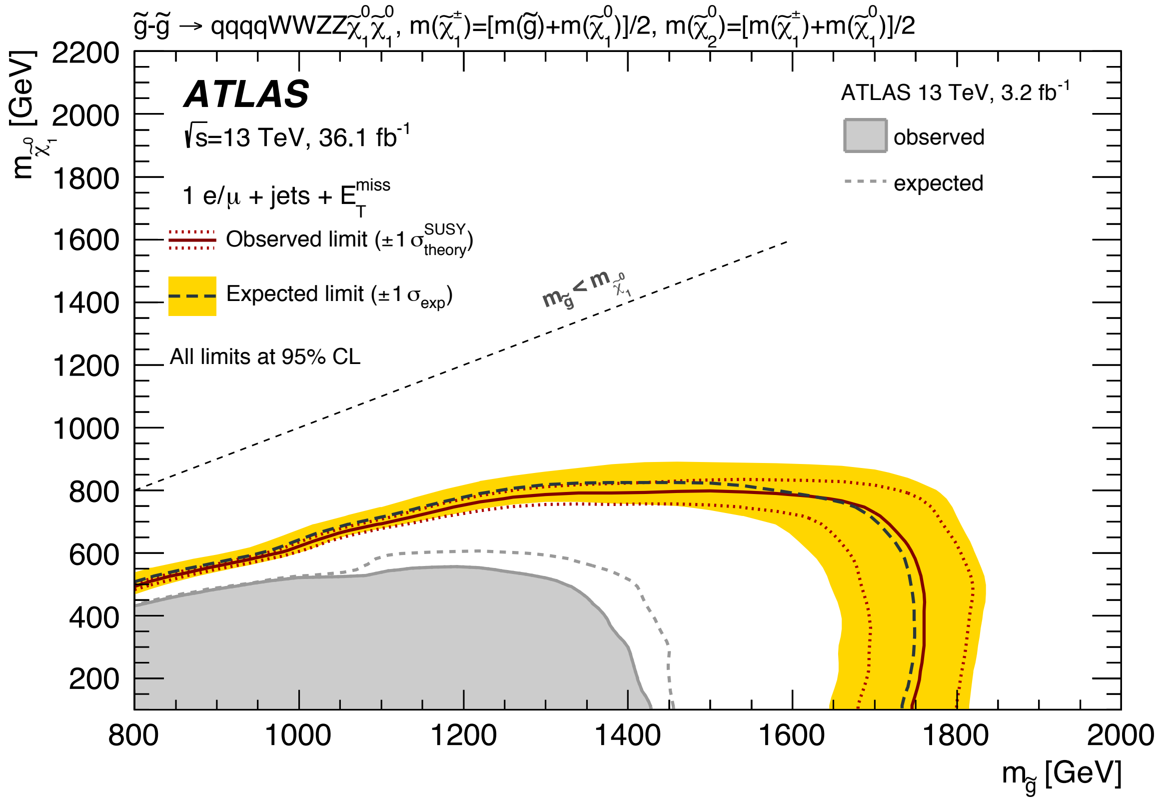


SR	9J
N_ℓ	$= 1$
p_T^ℓ [GeV]	> 35
N_{jet}	≥ 9
E_T^{miss} [GeV]	> 200
m_T [GeV]	> 175
Aplanarity	> 0.07
$E_T^{\text{miss}}/\sqrt{H_T}$ [GeV$^{1/2}$]	≥ 8
m_{eff} [GeV] (excl)	[1000, 1500], [>1500]
m_{eff} [GeV] (disc)	> 1500

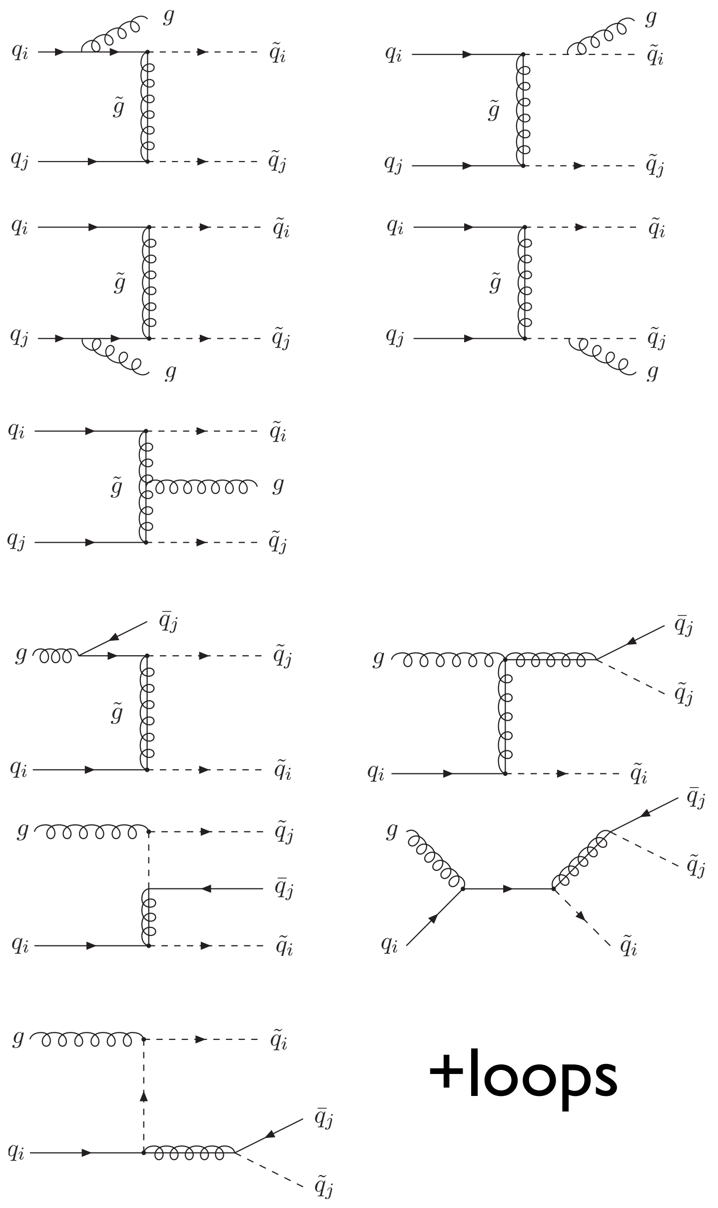
Table 1: Simulated signal and background event samples: the corresponding event generator, parton shower, cross-section normalization, PDF set and underlying-event tune are shown.

Physics process	Generator	Parton shower	Cross-section	PDF set	Tune
Signal	MG5_aMC@NLO 2.2.2	Pythia 8.186	NLO+NLL	NNPDF2.3 LO	ATLAS A14
$t\bar{t}$	Powheg-Box v2	Pythia 6.428	NNLO+NNLL	CT10 NLO	Perugia2012
Single-top					
t-channel	Powheg-Box v1	Pythia 6.428	NLO	CT10f4 NLO	Perugia2012
s-channel	Powheg-Box v2	Pythia 6.428	NLO	CT10 NLO	Perugia2012
Wt-channel	Powheg-Box v2	Pythia 6.428	NLO+NNLL	CT10 NLO	Perugia2012
$W(\to \ell\nu)$ + jets	Sherpa 2.2.1	Sherpa	NNLO	NNPDF3.0 NNLO	Sherpa default
$Z/\gamma^*(\to \ell\ell)$ + jets	Sherpa 2.2.1	Sherpa	NNLO	NNPDF3.0 NNLO	Sherpa default
WW, WZ and ZZ	Sherpa 2.1.1 / Sherpa 2.2.1	Sherpa	NLO	CT10 NLO / NNPDF3.0 NNLO	Sherpa default
$t\bar{t} + W/Z/WW$	MG5_aMC@NLO 2.2.2	Pythia 8.186	NLO	NNPDF2.3 LO	ATLAS A14

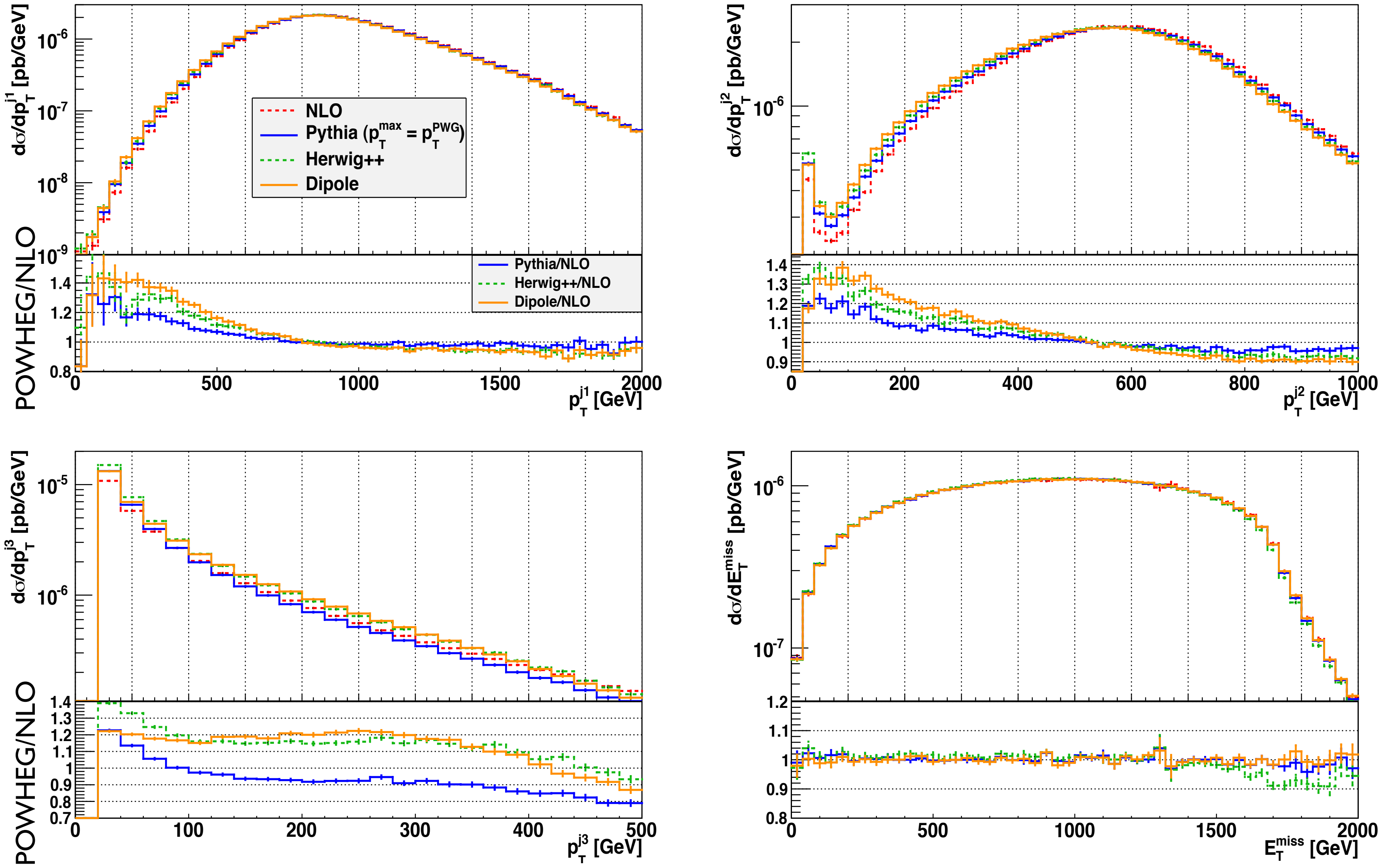




NLO Squark Production



+loops



- NLO with POWHEG matching to different generators

Gavin et al., arXiv:1305.4061

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 now available for many processes
    - NNLO much more challenging
- Still plenty of scope for new discoveries!

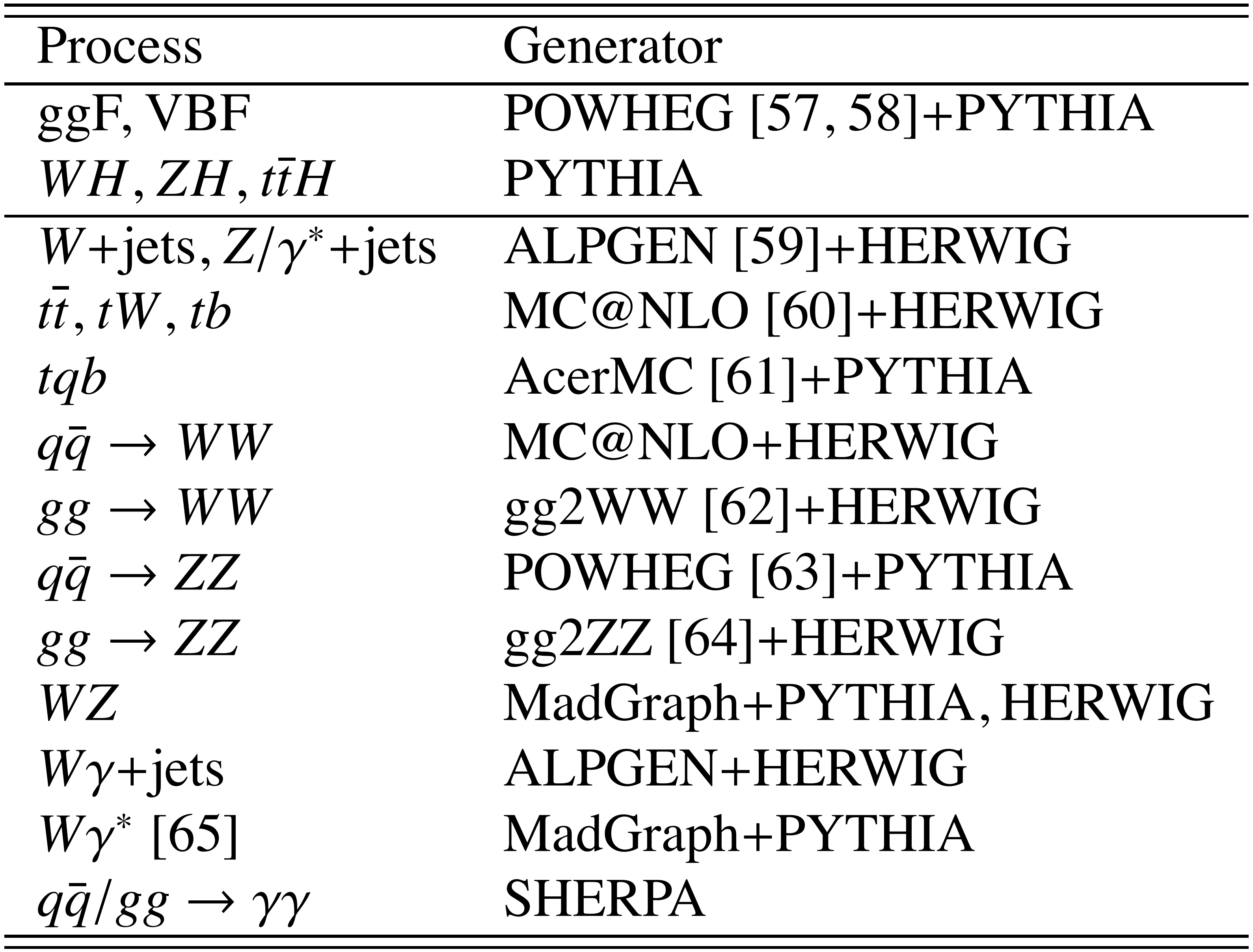
Thanks for your attention!

Extras

Higgs boson production

Higgs Signal and Background Simulation

- Discovery paper 2012



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

Higgs Signal Simulation 2017

- State of the art

Process	Generator	Showering	PDF set	Order of calculation	σ[pb] $\sqrt{s} = 13$ TeV
ggH	POWHEG NNLOPS	PYTHIA8	PDF4LHC15	N^3LO(QCD)+NLO(EW)	48.52
VBF	POWHEG BOX	PYTHIA8	PDF4LHC15	NNLO(QCD)+NLO(EW)	3.78
WH	POWHEG BOX	PYTHIA8	PDF4LHC15	NNLO(QCD)+NLO(EW)	1.37
$q\bar{q}' \to ZH$	POWHEG BOX	PYTHIA8	PDF4LHC15	NNLO(QCD)+NLO(EW)	0.76
$gg \to ZH$	POWHEG BOX	PYTHIA8	PDF4LHC15	NNLO(QCD)+NLO(EW)	0.12
$t\bar{t}H$	MADGRAPH5_AMC@NLO	PYTHIA8	NNPDF3.0	NLO(QCD)+NLO(EW)	0.51
$b\bar{b}H$	MADGRAPH5_AMC@NLO	PYTHIA8	CT10	5FS(NNLO)+4FS(NLO)	0.49
$tHq\bar{b}$	MADGRAPH5_AMC@NLO	PYTHIA8	CT10	4FS(LO)	0.07
tHW	MADGRAPH5_AMC@NLO	HERWIG++	CT10	5FS(NLO)	0.02
$\gamma\gamma$	SHERPA	SHERPA	CT10		

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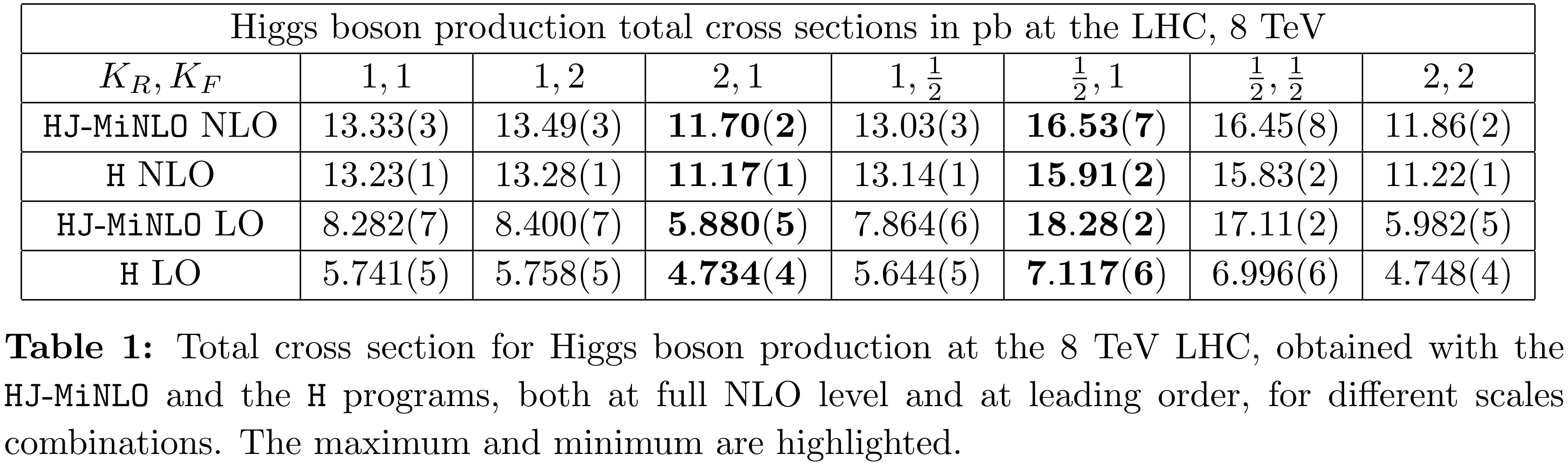
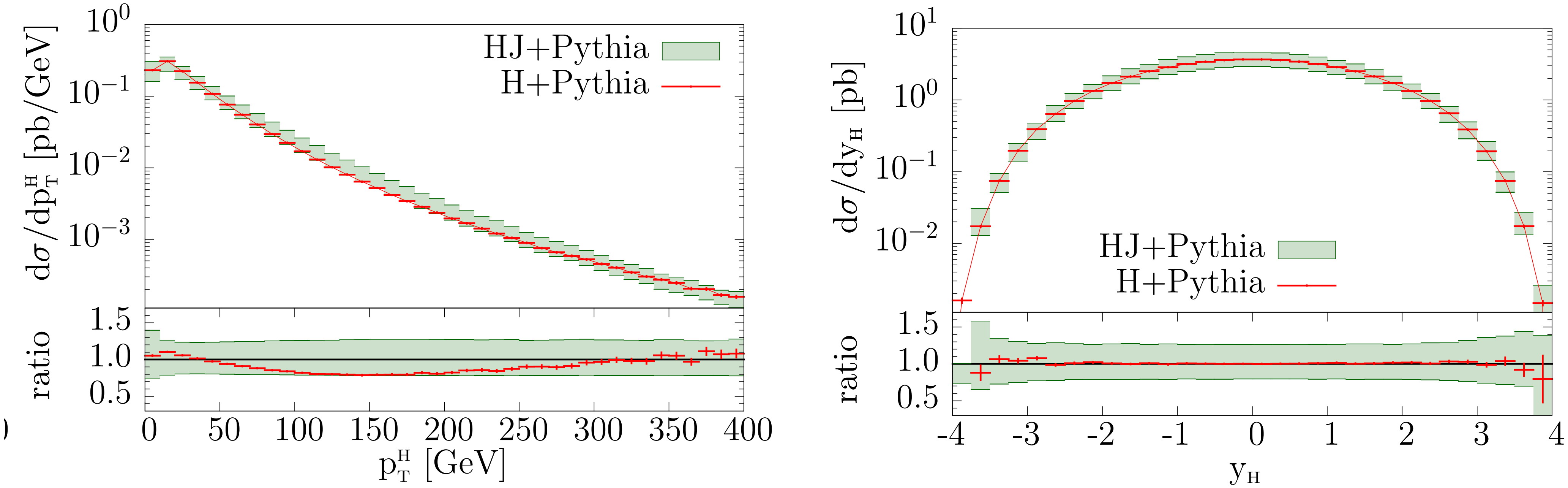
gg→Higgs(+jet)



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)

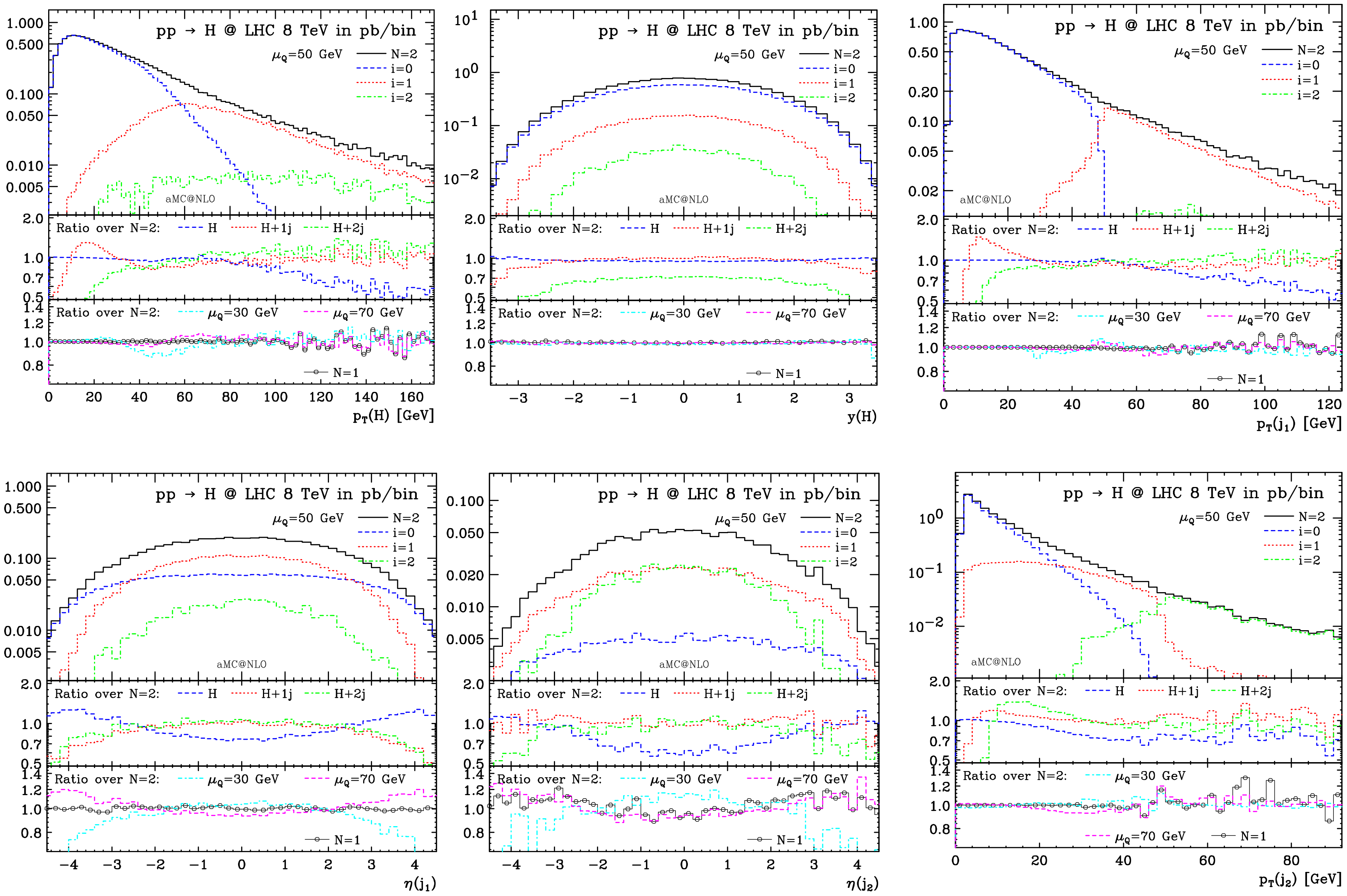
Table 1: Total cross section for Higgs boson production at the 8 TeV LHC, obtained with the `HJ-MiNLO` and the `H` programs, both at full NLO level and at leading order, for different scales combinations. The maximum and minimum are highlighted.



- Match/merge MiNLO+Pythia6

Hamilton, Nason, Oleari & Zanderighi, arXiv:1212.4504

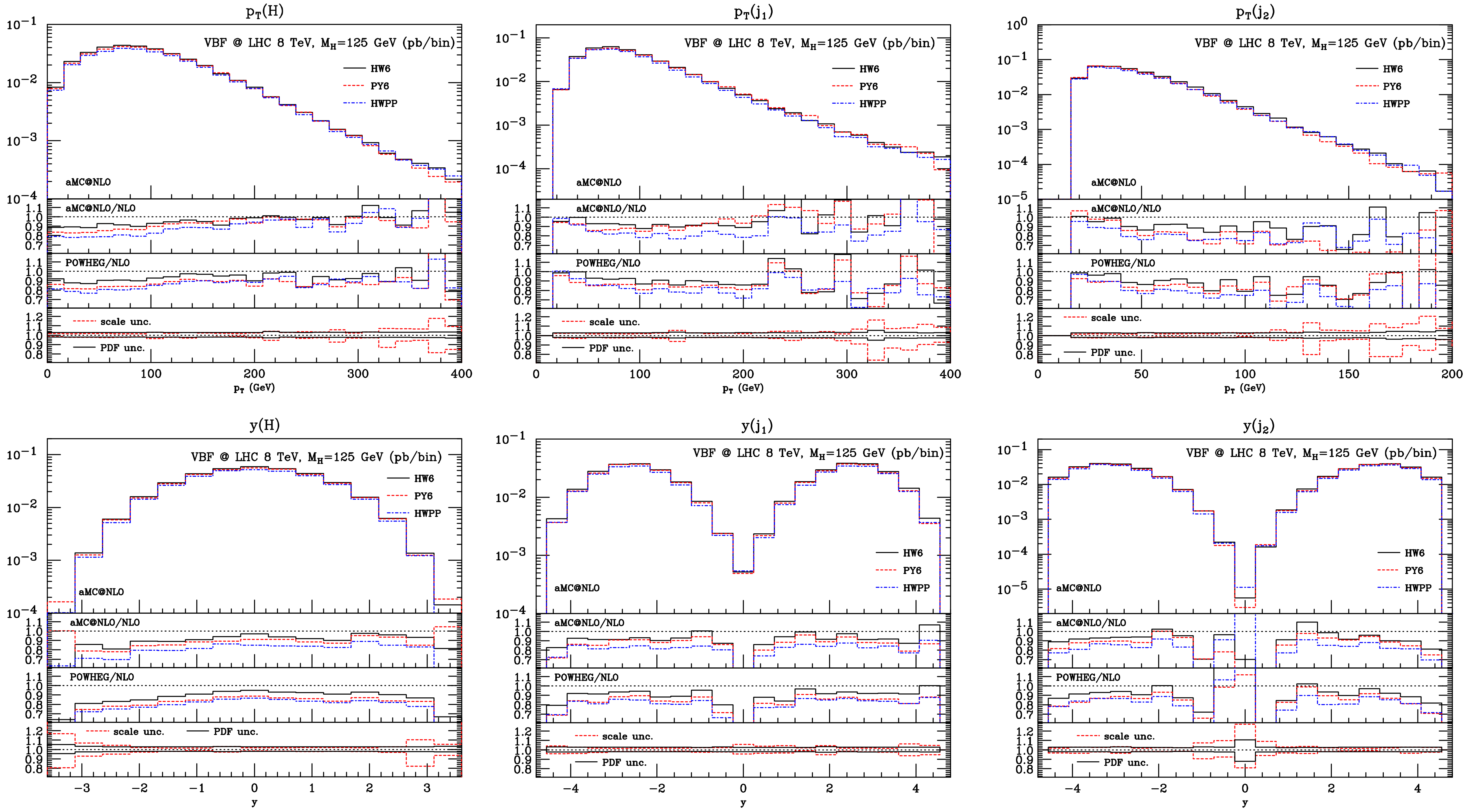
Higgs+jets



- FxFx: Match/merge MC@NLO+Herwig6

Frederix & Frixione, arXiv:1209.6215

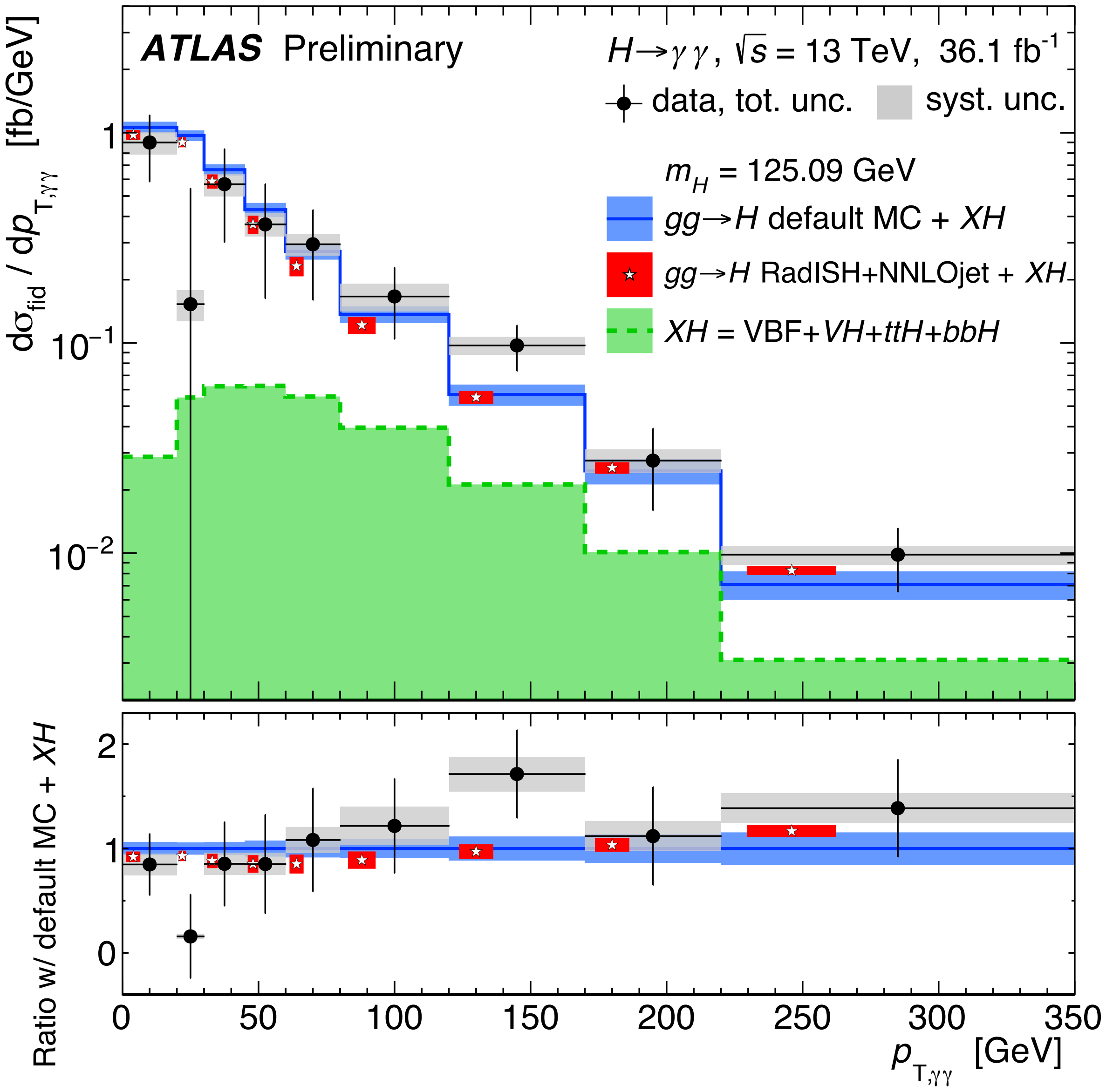
VBF Higgs+jets

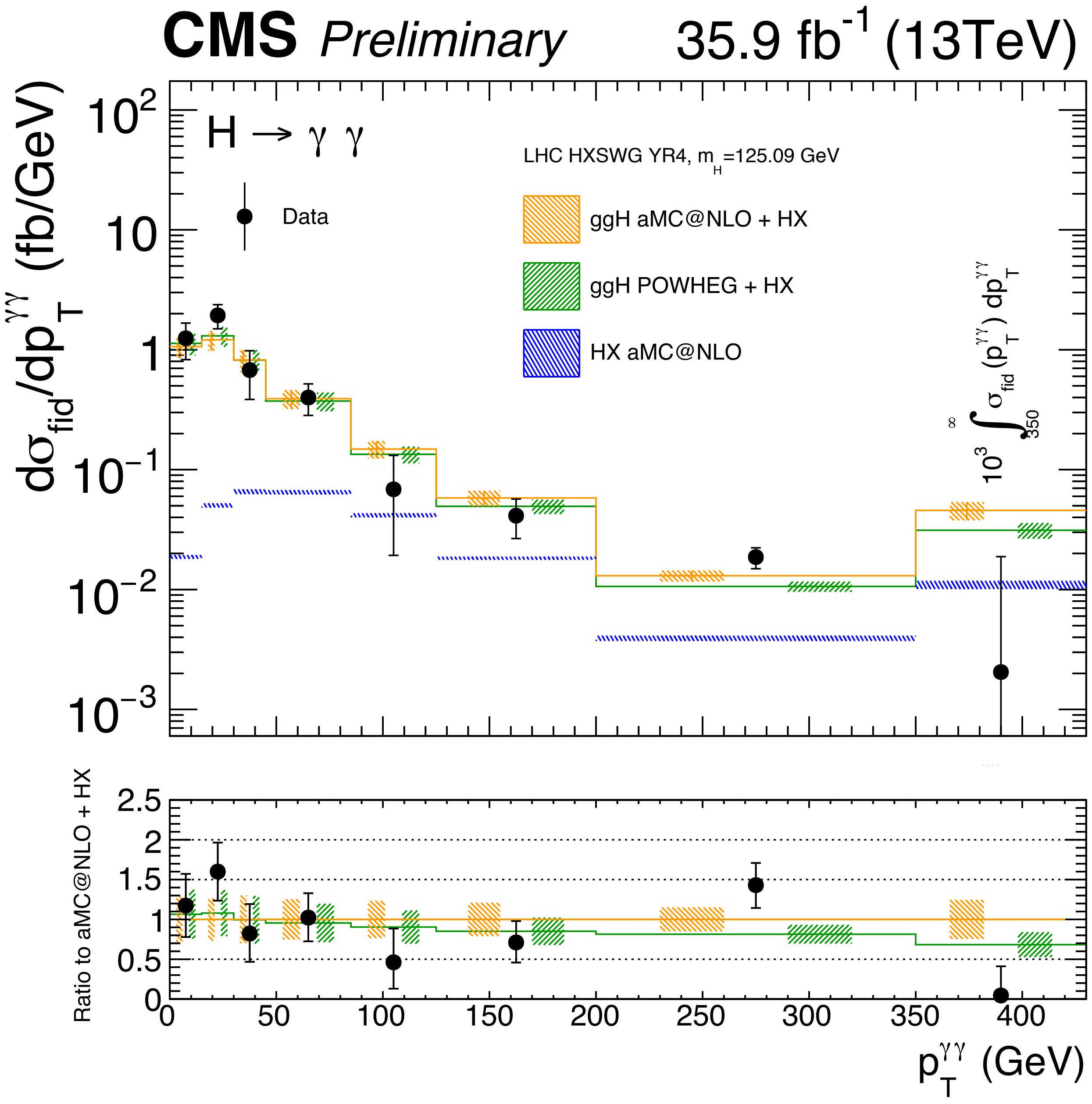


- Matched MC@NLO and POWHEG

Frixione, Torrielli, Zaro, arXiv:1304.7927

Comparisons to data ($\gamma\gamma$ mode)





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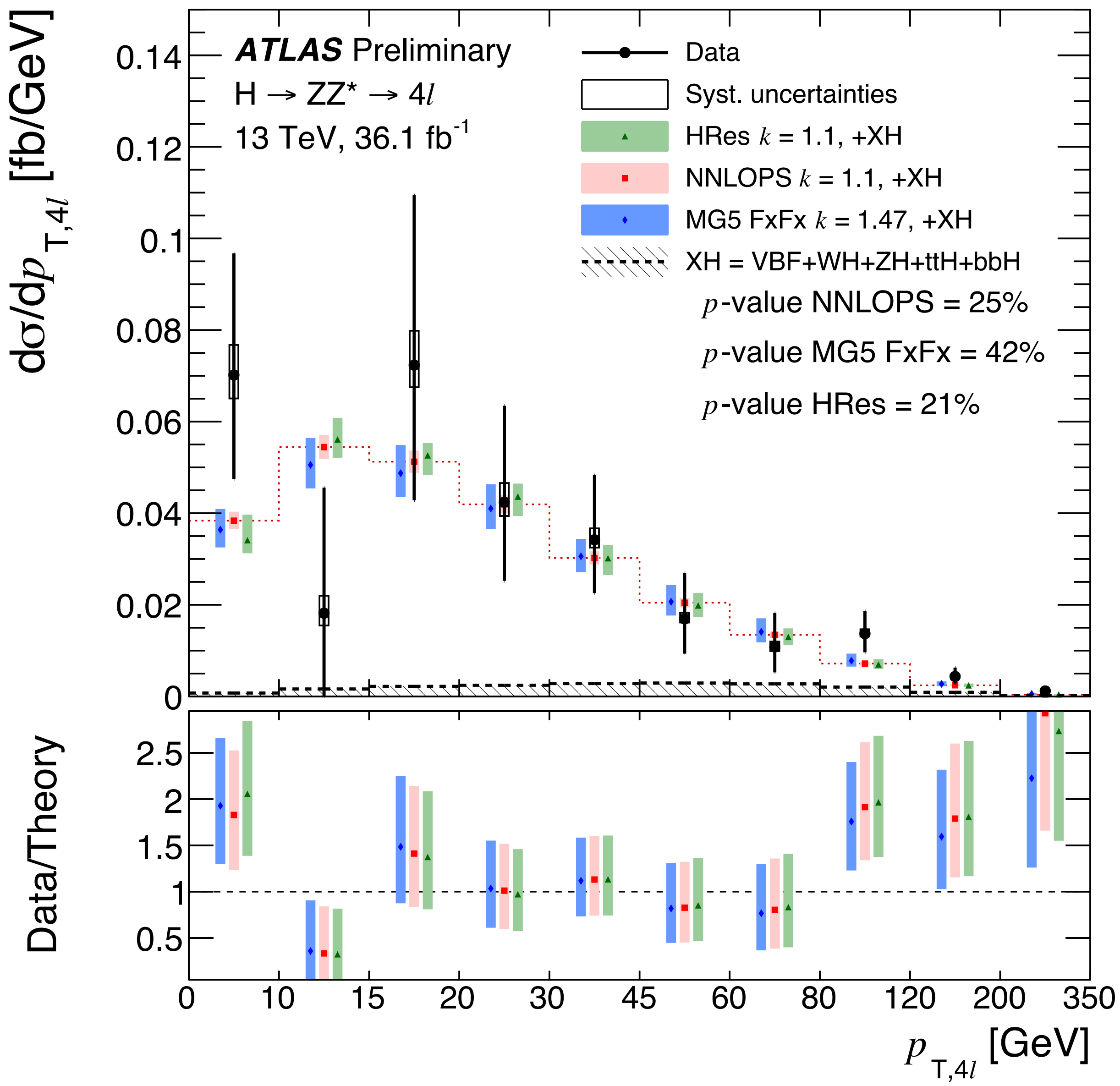
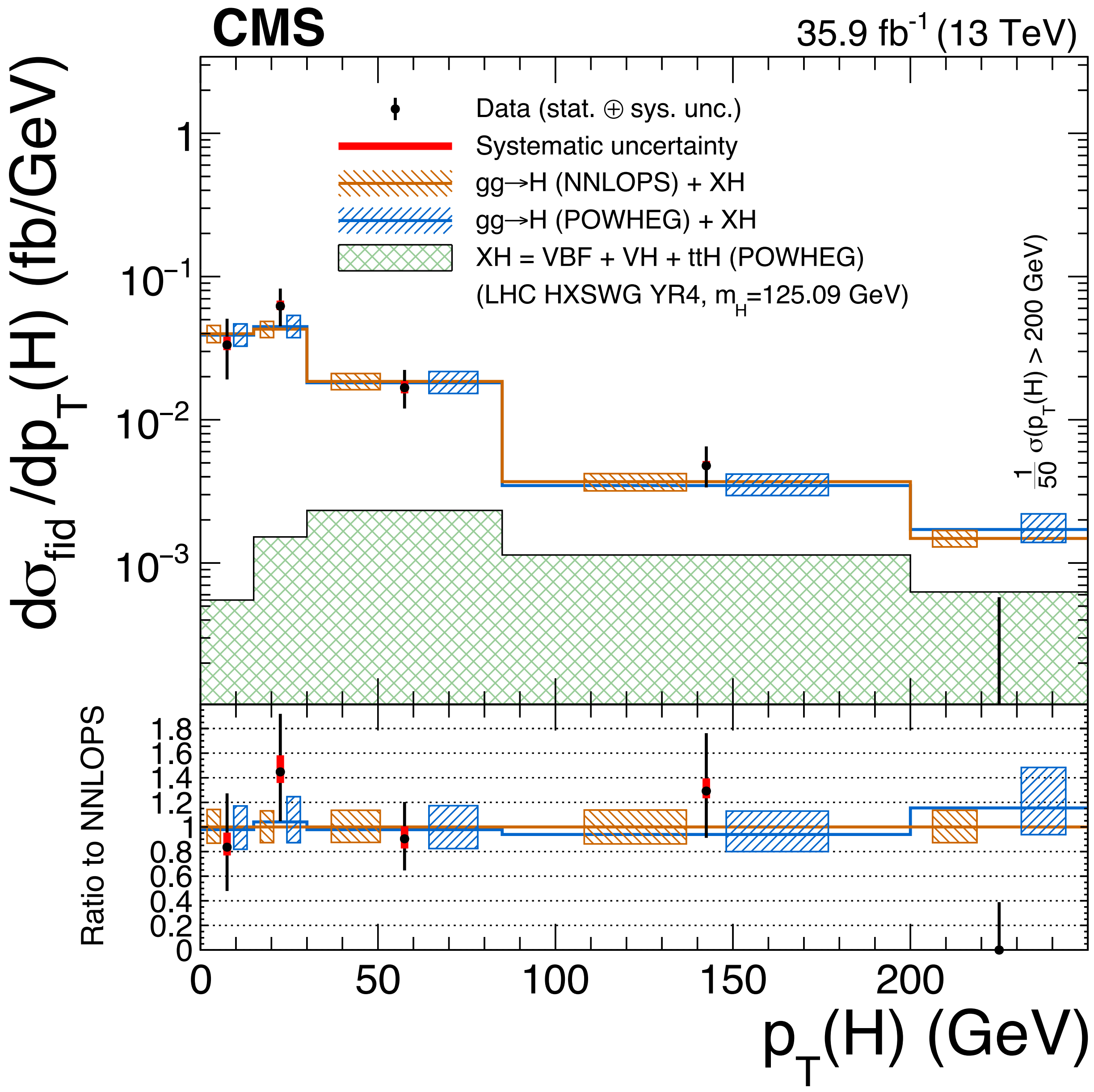
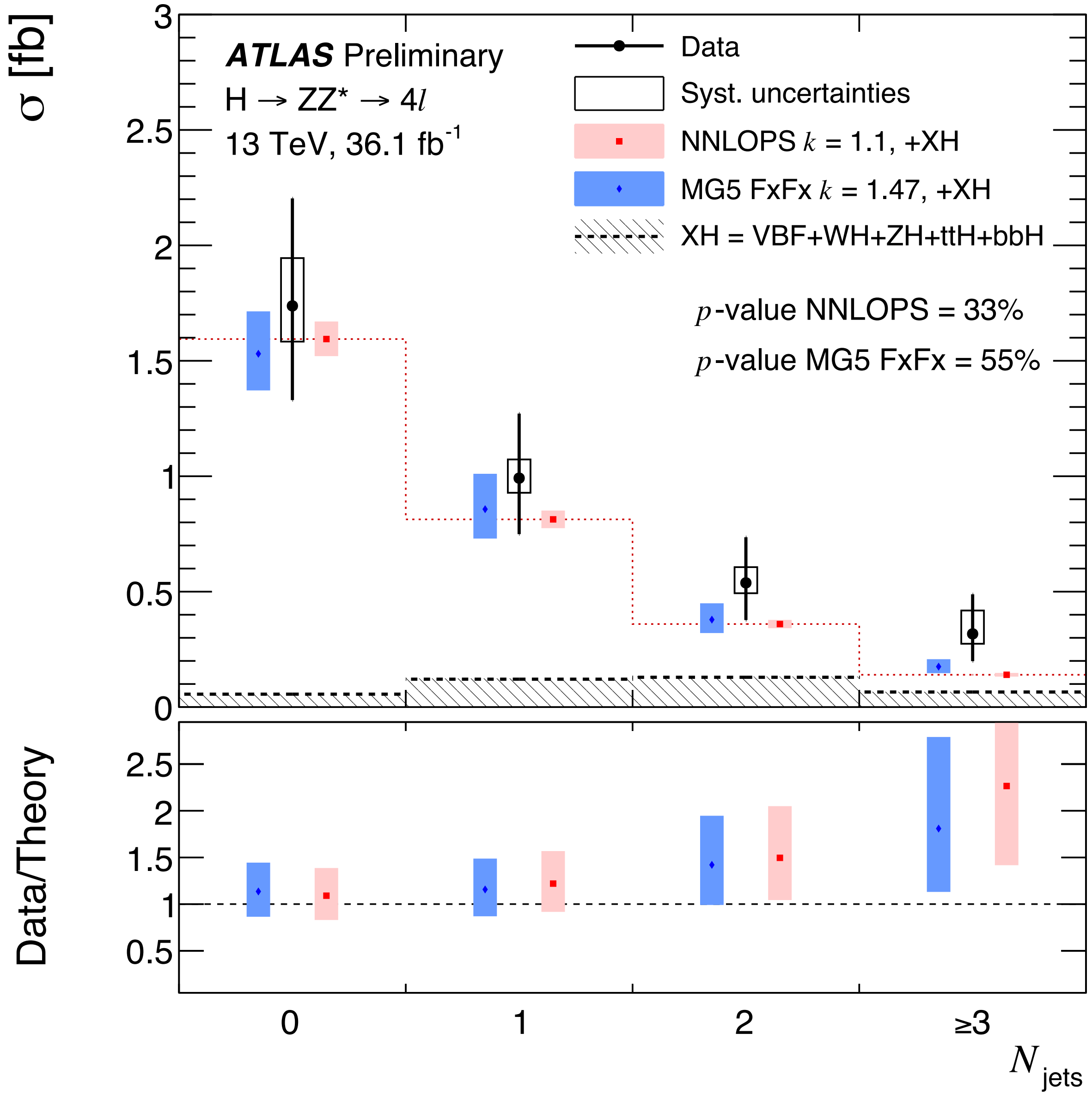
Comparisons to data (ZZ* mode)

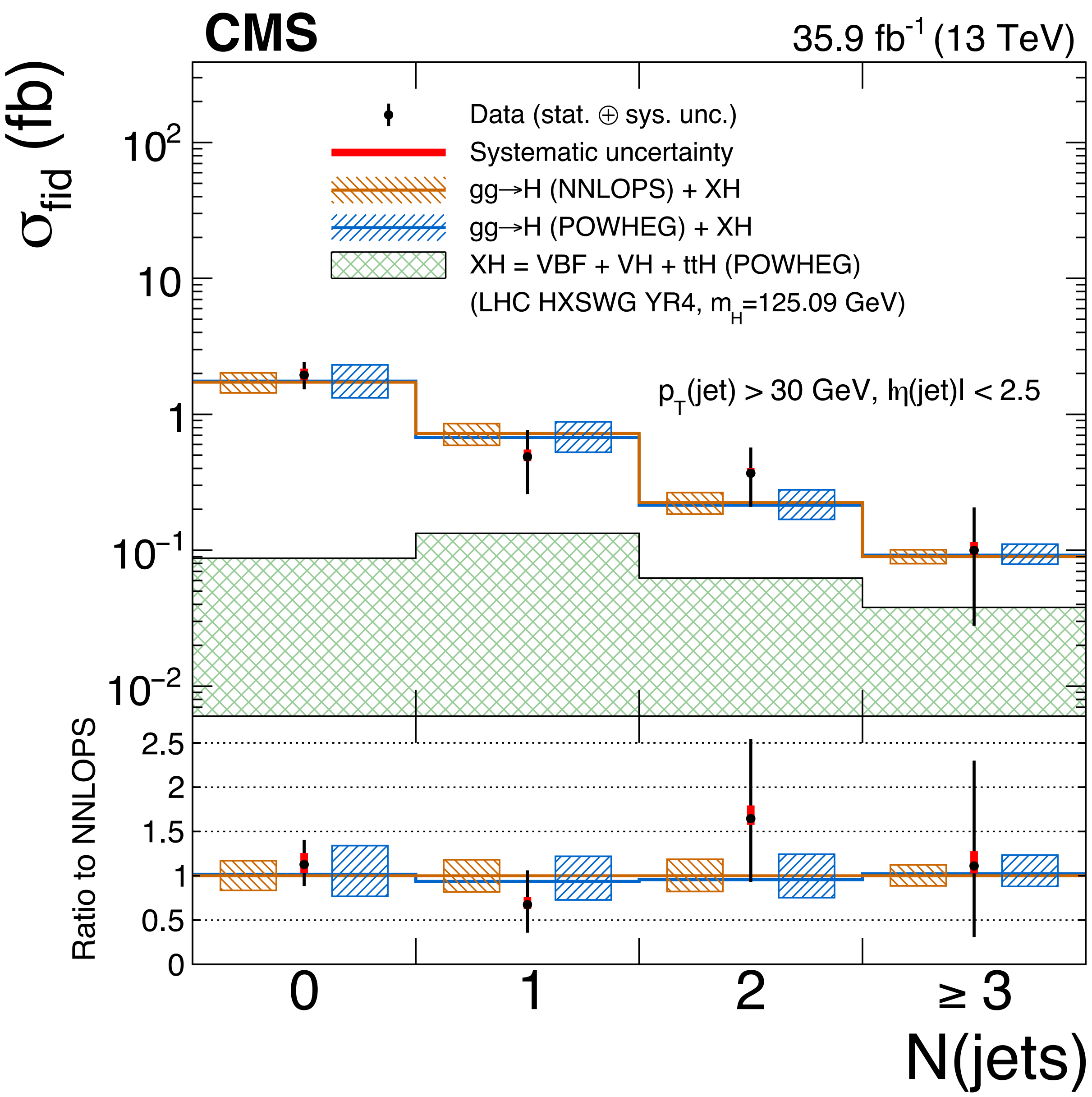




Andy Chisholm, LHCHXSWG, July 2017

Comparisons to data (ZZ* mode)





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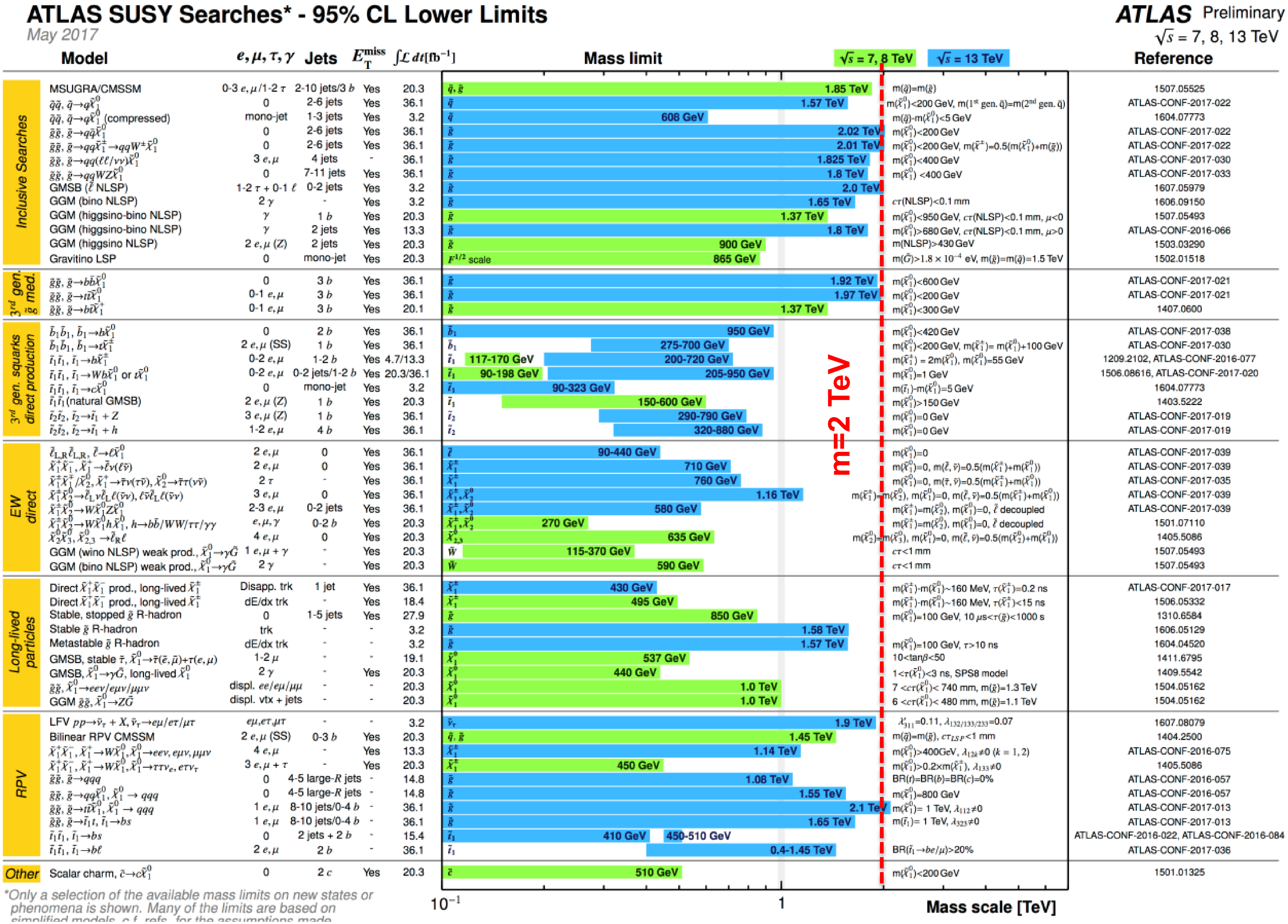
ATLAS SUSY Search



ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

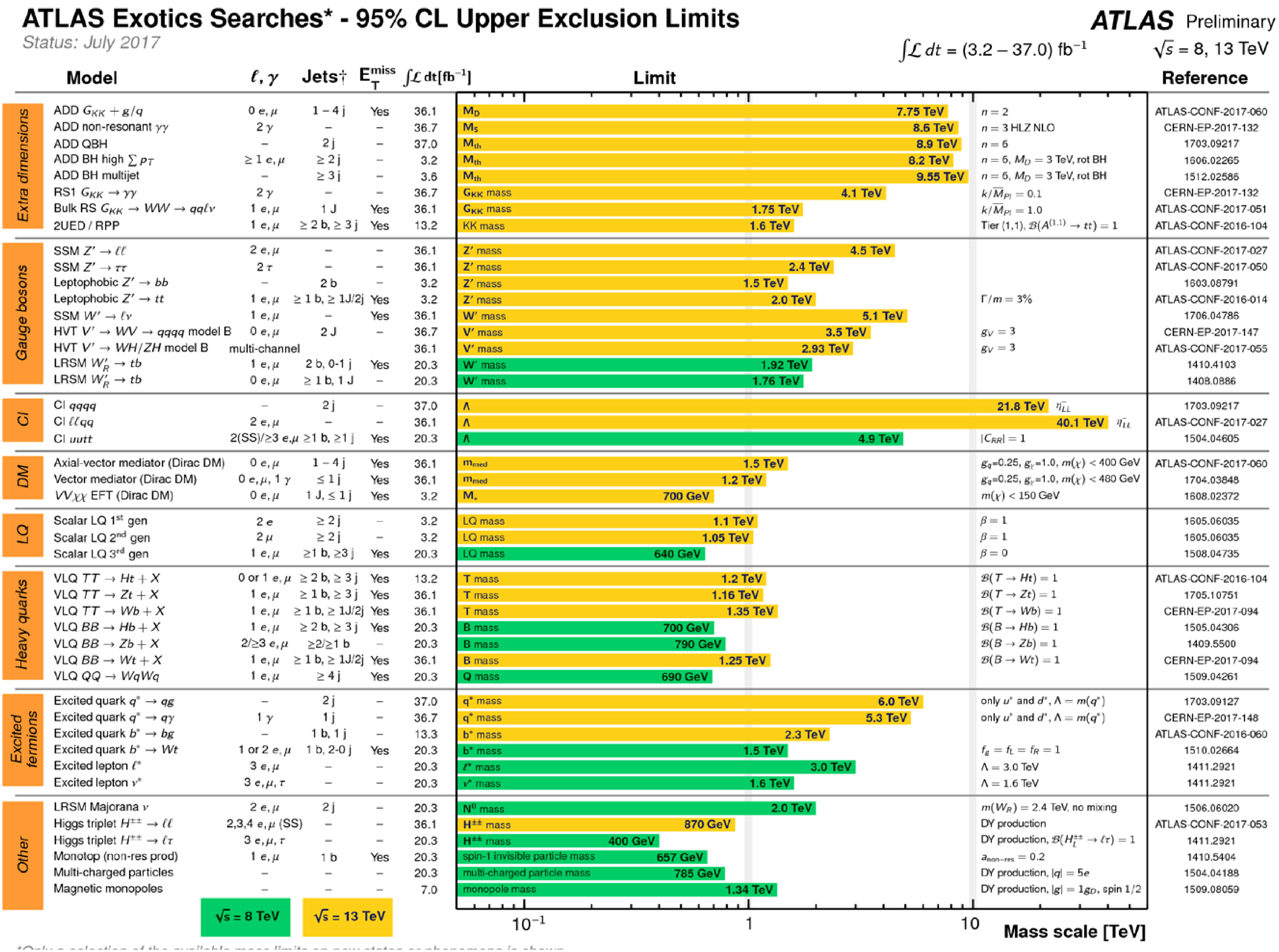
ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 🟩 1.85 TeV	$m(\tilde{q})$=$m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ 🟦 1.57 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$ 🟦 608 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 🟦 2.02 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 🟦 2.01 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	$\tilde{g}$ 🟦 1.825 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 🟦 1.8 TeV	$m(\tilde{\chi}_1^0)$ <400 GeV	ATLAS-CONF-2017-033
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 🟦 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$ 🟦 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 🟩 1.37 TeV	$m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$ 🟦 1.8 TeV	$m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 🟩 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 🟩 865 GeV	$m(\tilde{G})$>1.8 × 10^{-4} eV, $m(\tilde{g})$=$m(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$ 🟦 1.92 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 🟦 1.97 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 🟩 1.37 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	$\tilde{b}_1$ 🟦 950 GeV	$m(\tilde{\chi}_1^0)$<420 GeV	ATLAS-CONF-2017-038
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	1 b	Yes	36.1	$\tilde{b}_1$ 🟦 275-700 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})$= $m(\tilde{\chi}_1^0)$+100 GeV	ATLAS-CONF-2017-030
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 🟩 117-170 GeV 🟦 200-720 GeV	$m(\tilde{\chi}_1^{\pm})$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$ 🟩 90-198 GeV 🟦 205-950 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	$\tilde{t}_1$ 🟦 90-323 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 🟩 150-600 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$ 🟦 290-790 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 🟦 320-880 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2017-019
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 🟦 90-440 GeV	$m(\tilde{\chi}_1^0)$=0	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 🟦 710 GeV	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 🟦 760 GeV	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2017-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 🟦 1.16 TeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 🟦 580 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 🟩 270 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 🟩 635 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$ 🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	2 γ	-	Yes	20.3	$\tilde{W}$ 🟩 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 🟦 430 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$ 🟩 495 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 🟩 850 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 🟦 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 🟦 1.57 TeV	$m(\tilde{\chi}_1^0)$=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 🟩 440 GeV	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to eev/e\mu v/\mu\mu v$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 🟩 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 🟩 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 🟦 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 🟩 1.45 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	$\tilde{\chi}_1^{\pm}$ 🟦 1.14 TeV	$m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 🟩 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 🟦 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 🟦 1.55 TeV	$m(\tilde{\chi}_1^0)$=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 🟦 2.1 TeV	$m(\tilde{\chi}_1^0)$= 1 TeV, $\lambda_{112}\neq0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 🟦 1.65 TeV	$m(\tilde{t}_1)$= 1 TeV, $\lambda_{323}\neq0$	ATLAS-CONF-2017-013
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$ 🟦 410 GeV 🟦 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 🟦 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2017-036
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 🟩 510 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

ATLAS Exotica Search



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 37.0)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	36.1	G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	3.2	Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	36.1	W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	36.7	V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η^-_{LL}	1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.1 TeV	η^-_{LL}	ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e, μ, 1 γ	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	$\geq$1 b, $\geq$3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\mathrm{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s} = 8$ TeV

🟨 $\sqrt{s} = 13$ TeV

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