Monte Carlo Event Generation for Run 2

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Outline

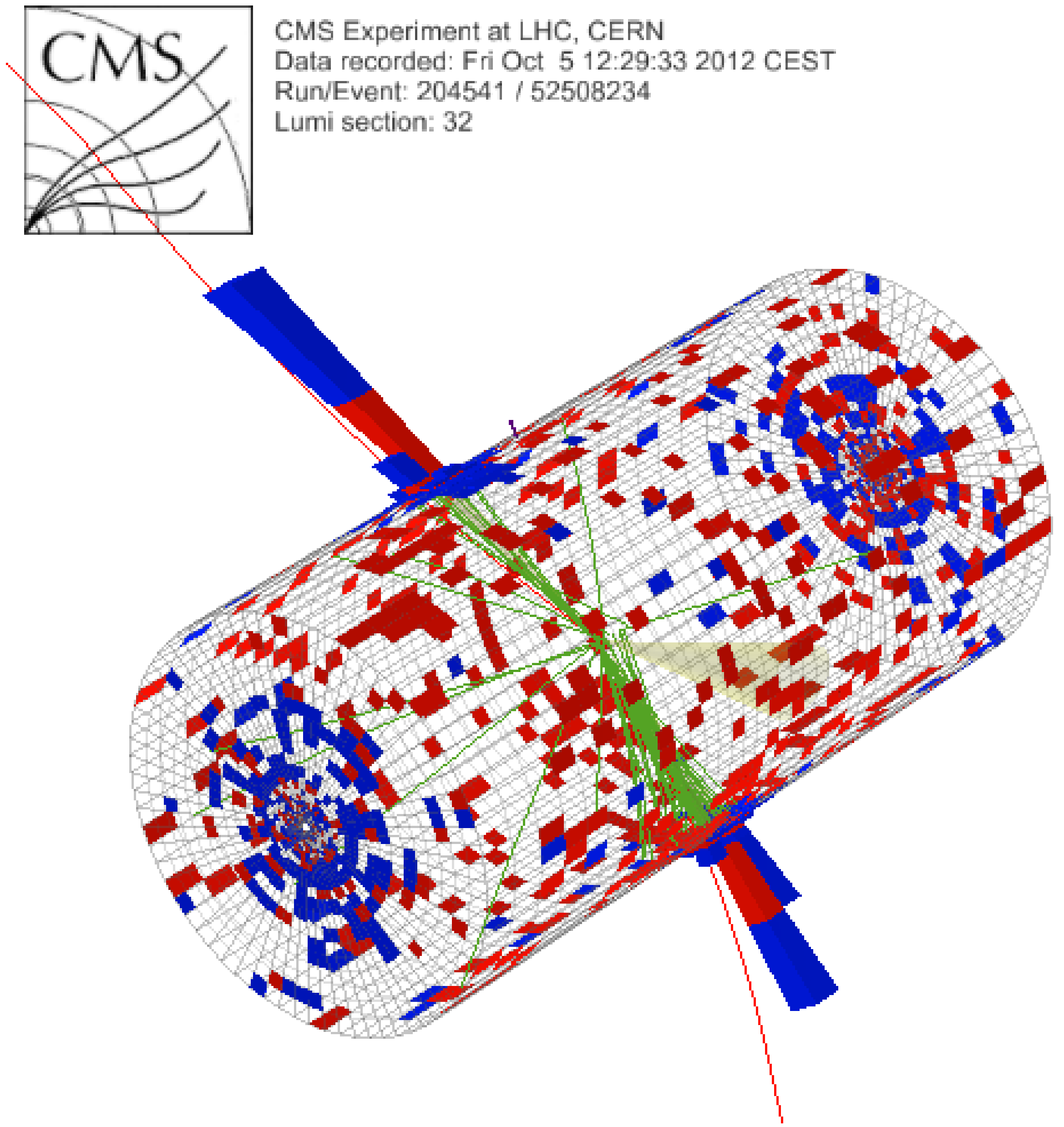
- Monte Carlo event generators
    - Components and theoretical status
    - Parton showers
    - Hadronization and Underlying Event models
- Matching generators to higher-order calculations
    - NLO: MC@NLO, POWHEG; automation
    - NNLO: NNLOPS, UN^{2}LOPS, Geneva, …
- Merging/matching multiple fixed orders
    - MEPS@NLO, FxFx, UNLOPS,…
- Conclusions

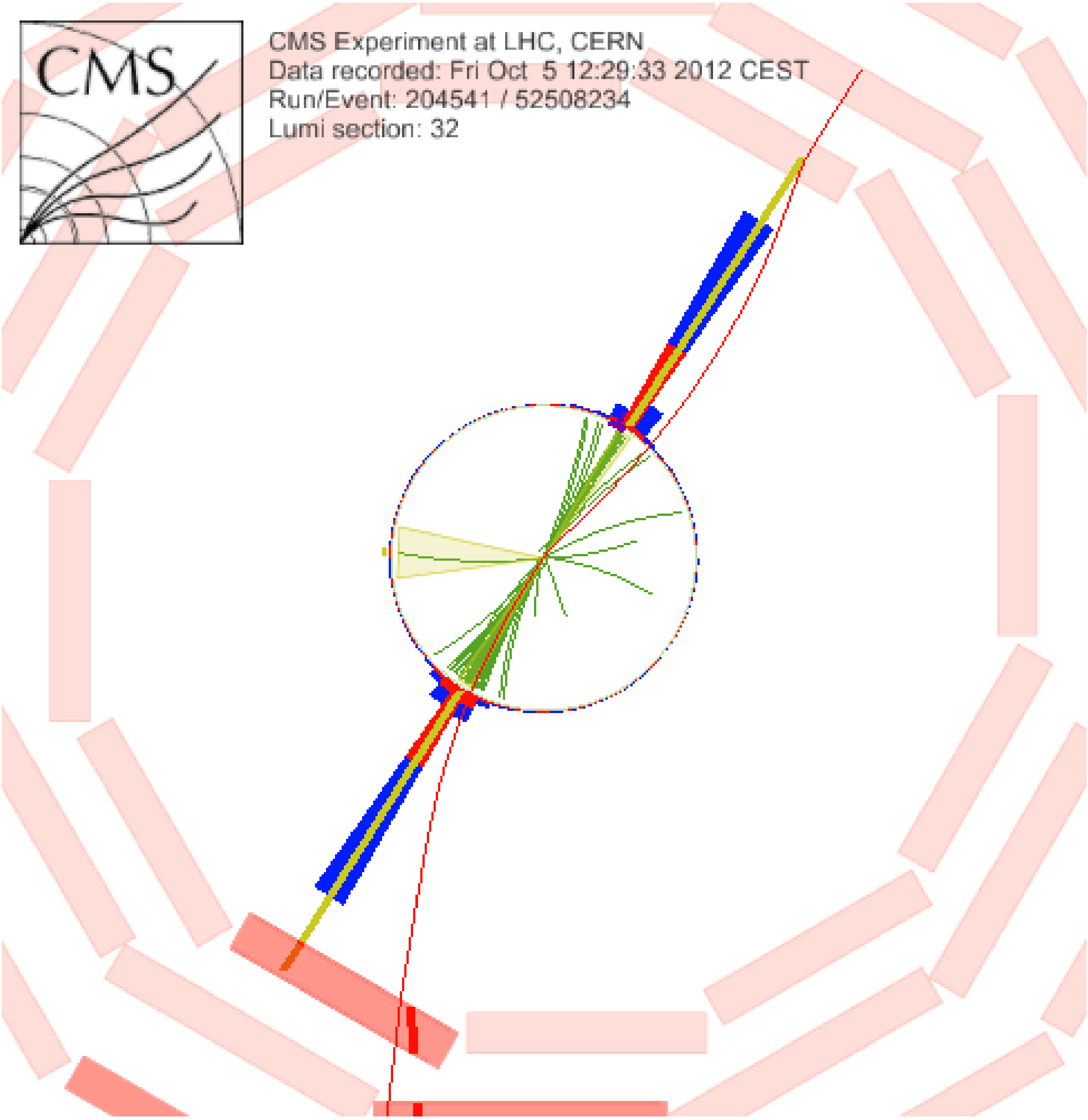
Monte Carlo Event Generation

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

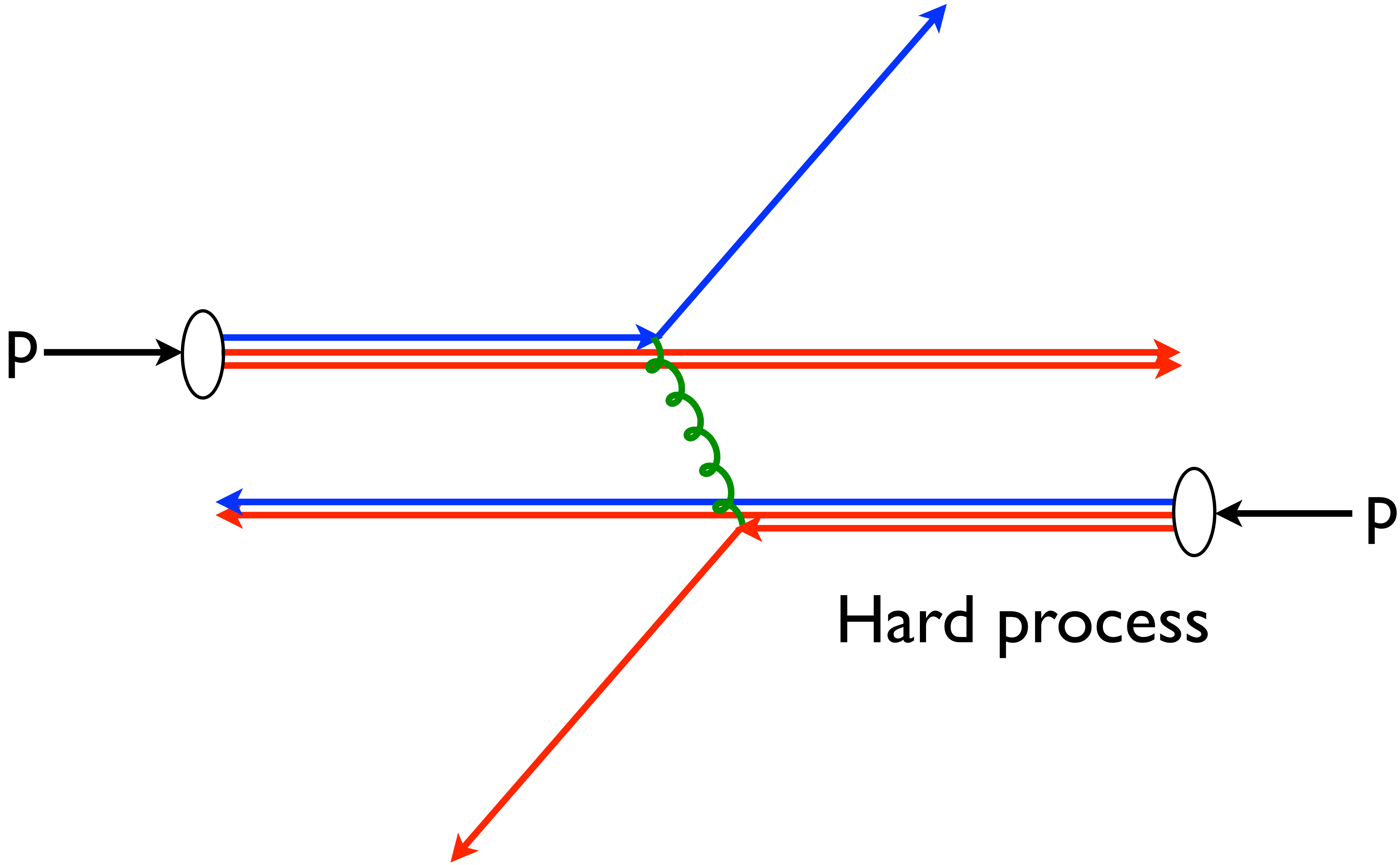




- M_{jj} = 5.15 TeV

CMS PAS EXO-12-059

LHC dijet



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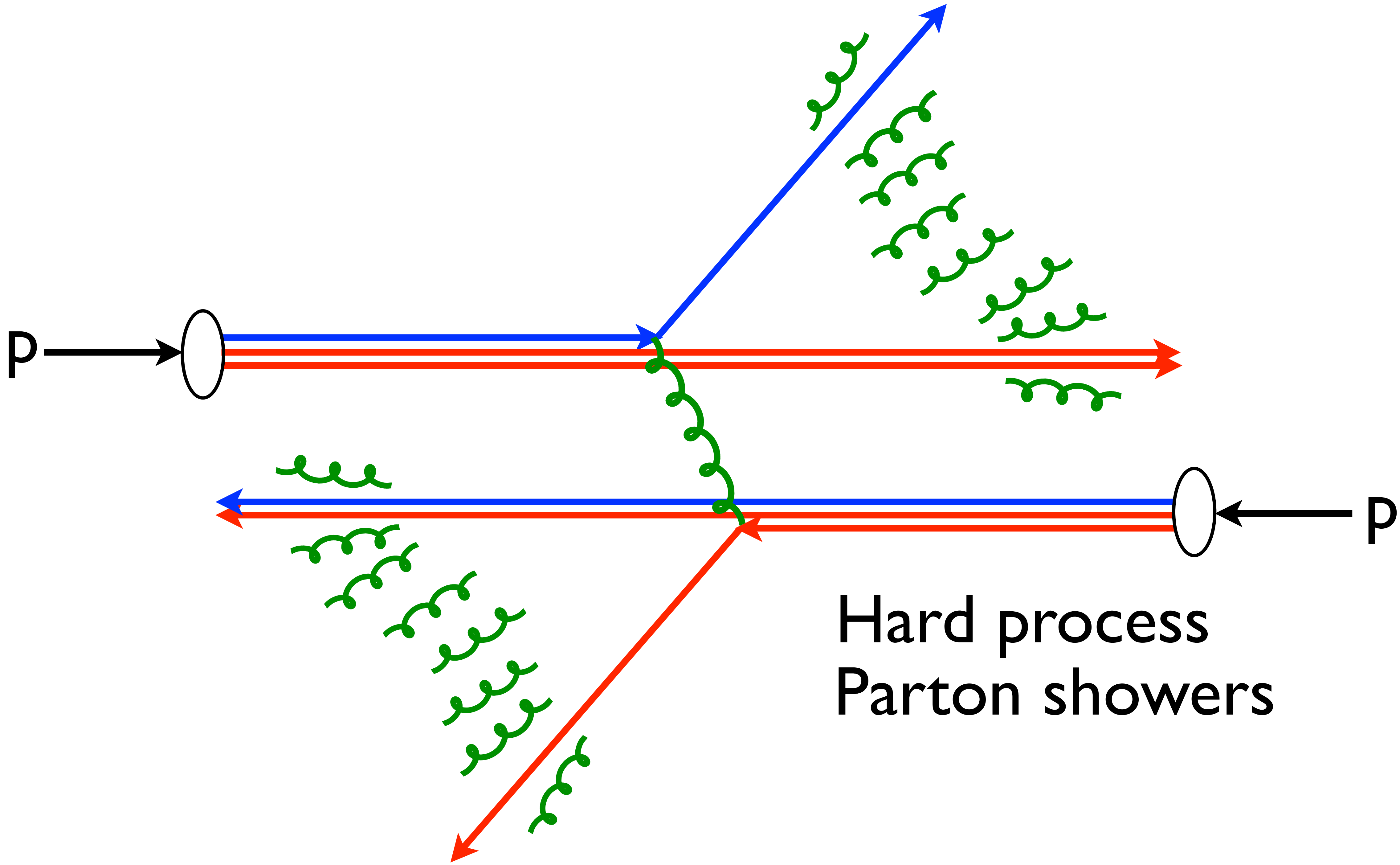
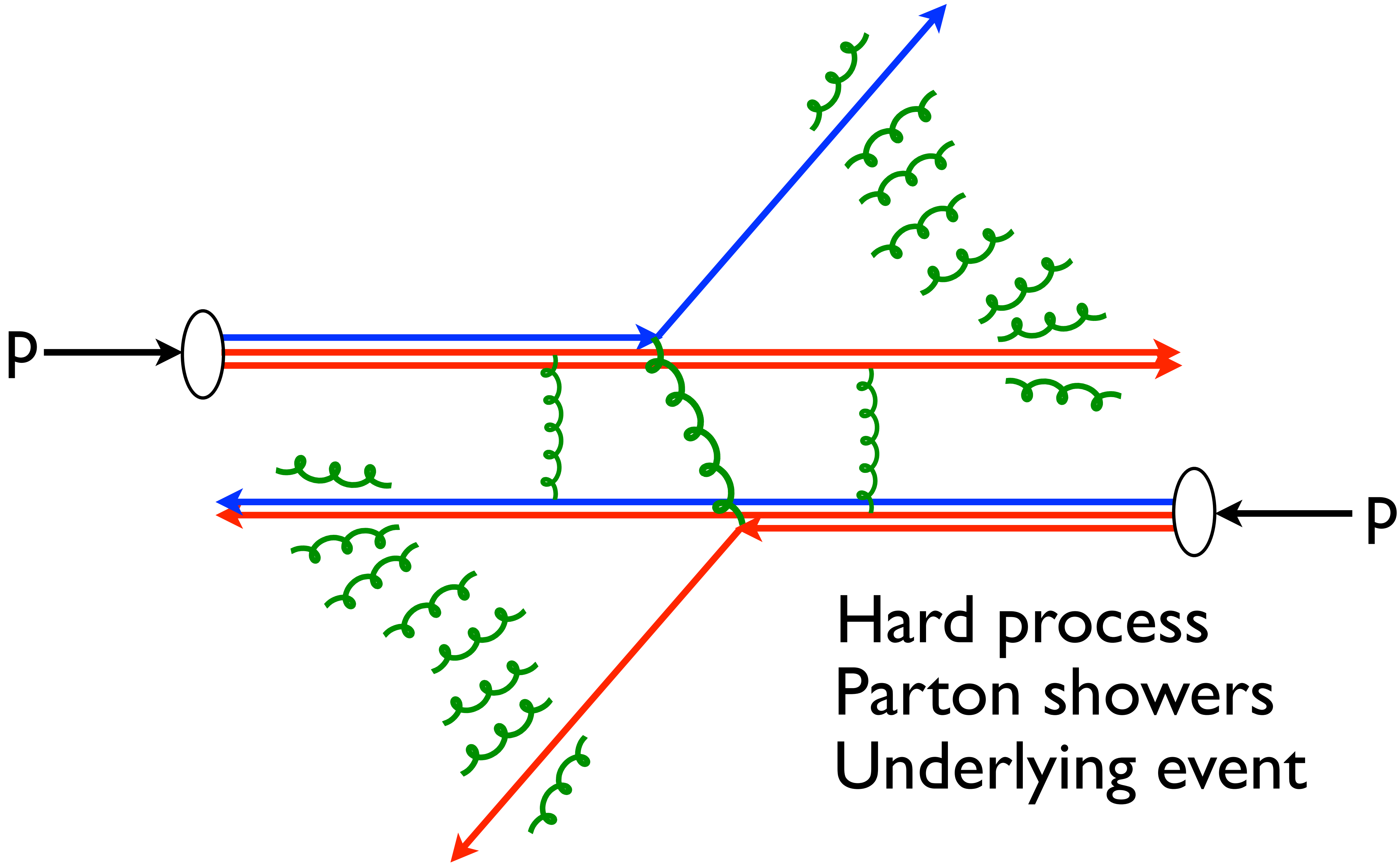


Hard process
Parton showers

LHC dijet



Hard process
Parton showers
Underlying event

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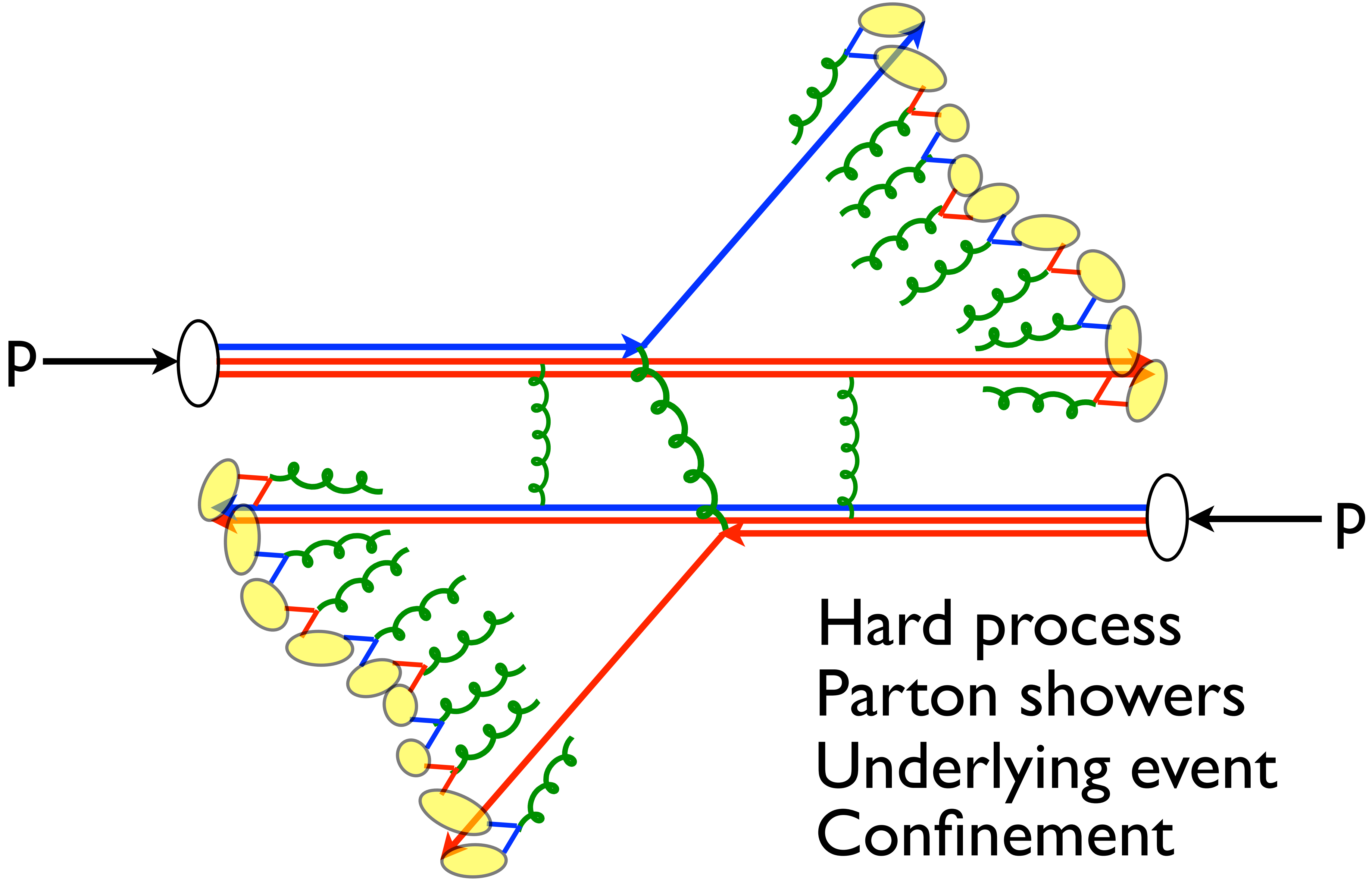
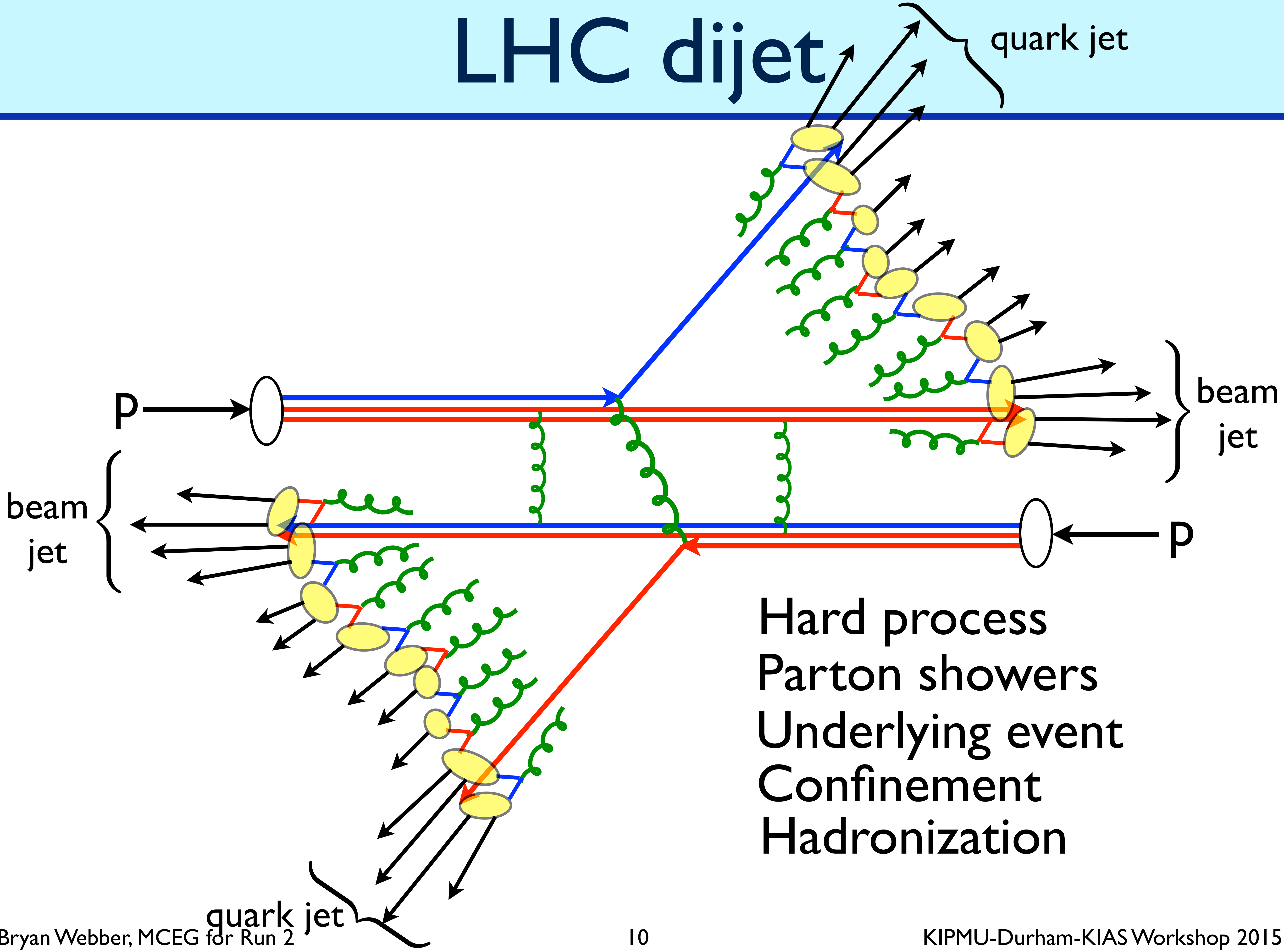


Hard process
Parton showers
Underlying event
Confinement

LHC dijet



Hard process
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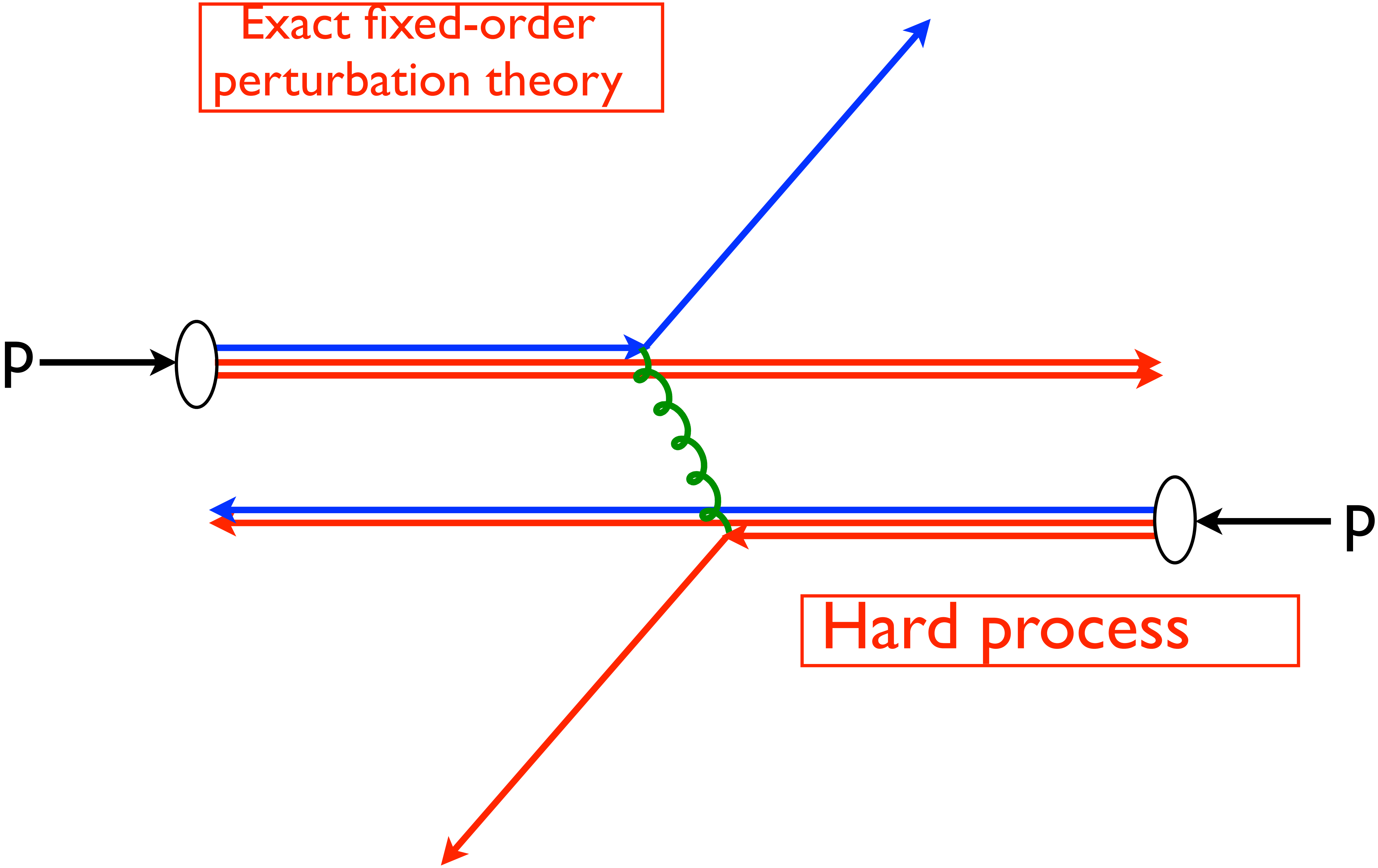
Hadronization

Theoretical Status



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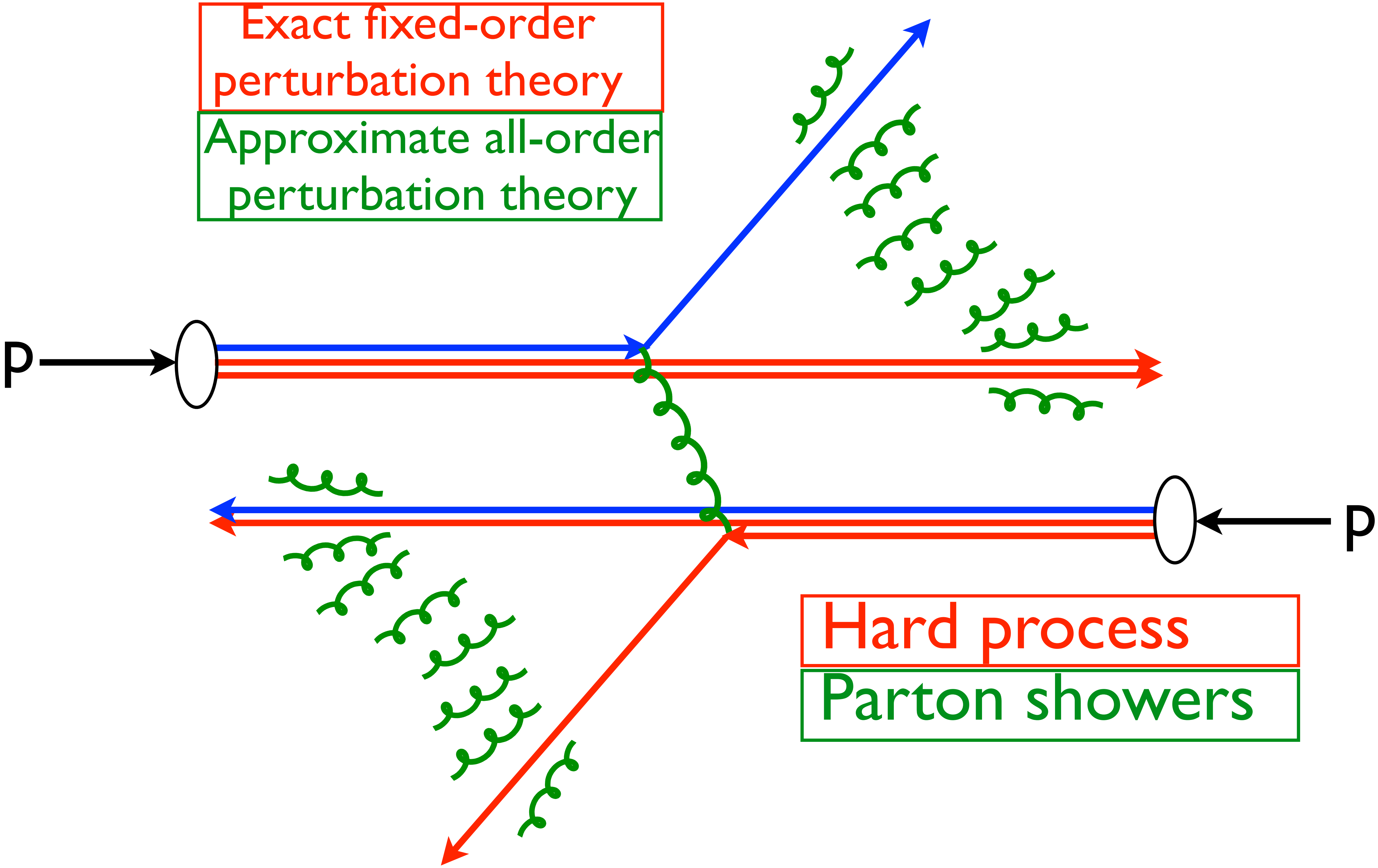
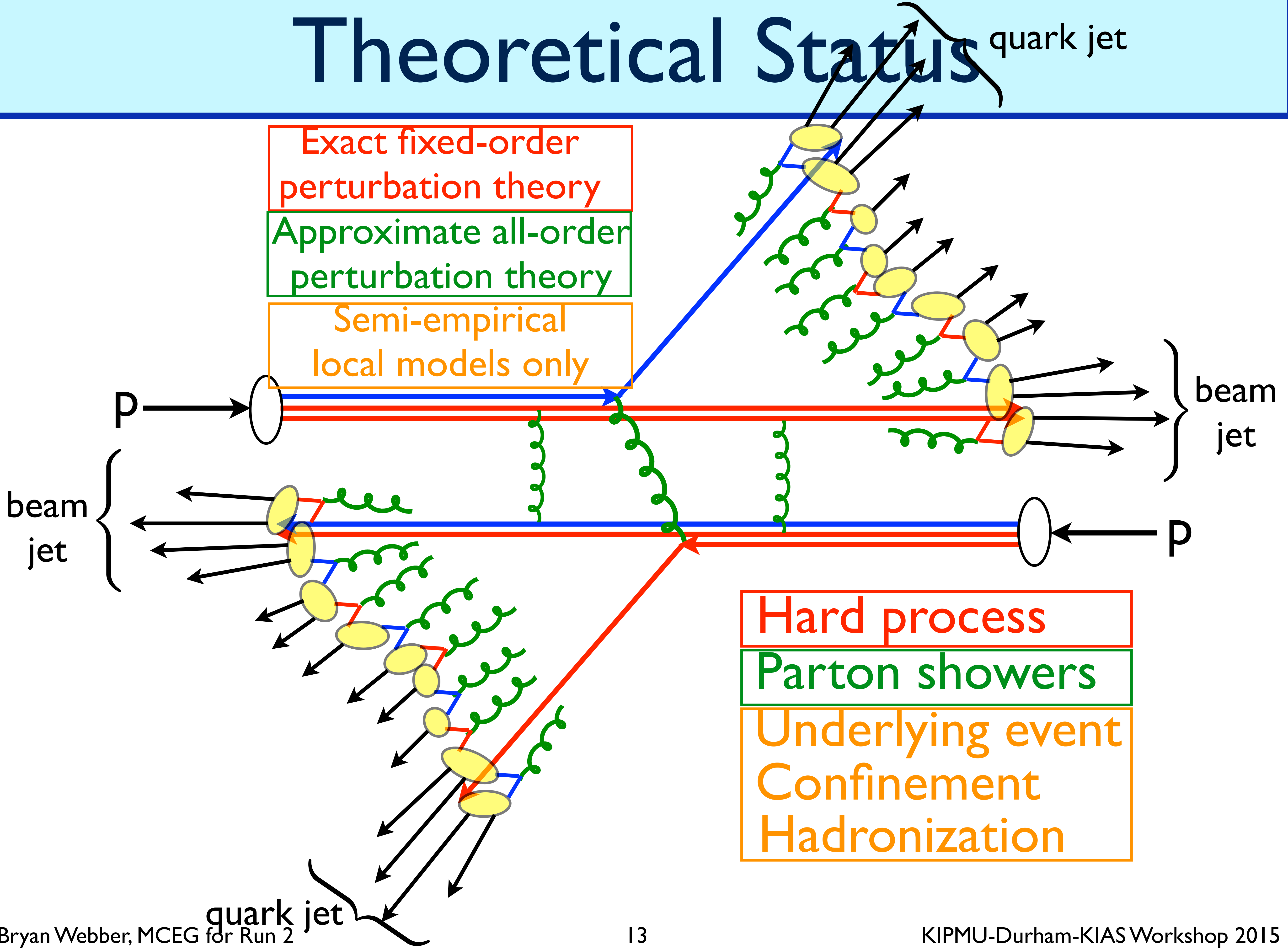


Theoretical Status



Exact fixed-order perturbation theory

Approximate all-order perturbation theory

Semi-empirical local models only

Hard process

Parton showers

Underlying event
Confinement
Hadronization

QCD Factorization

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

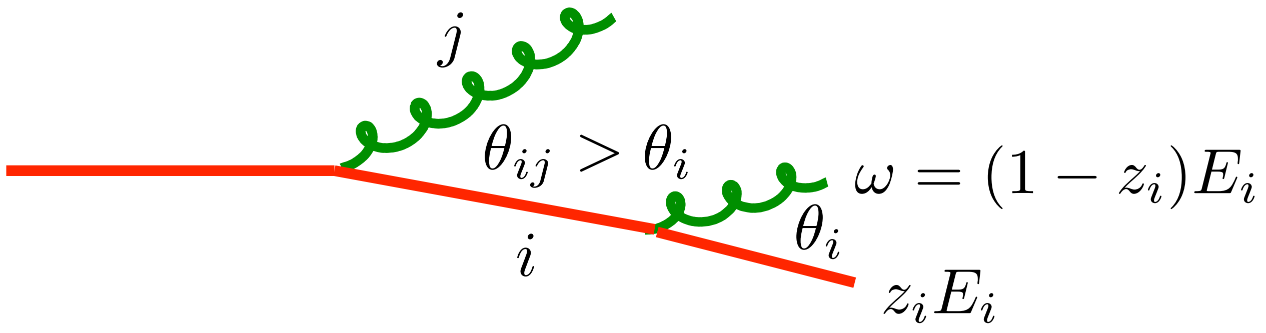
- Jet formation and underlying event take place over a much longer time scale, with unit probability
- Hence they cannot affect the cross section
- Scale dependences of parton distributions and hard process cross section are perturbatively calculable, and cancel order by order

Parton Showers

Parton Shower Approximation

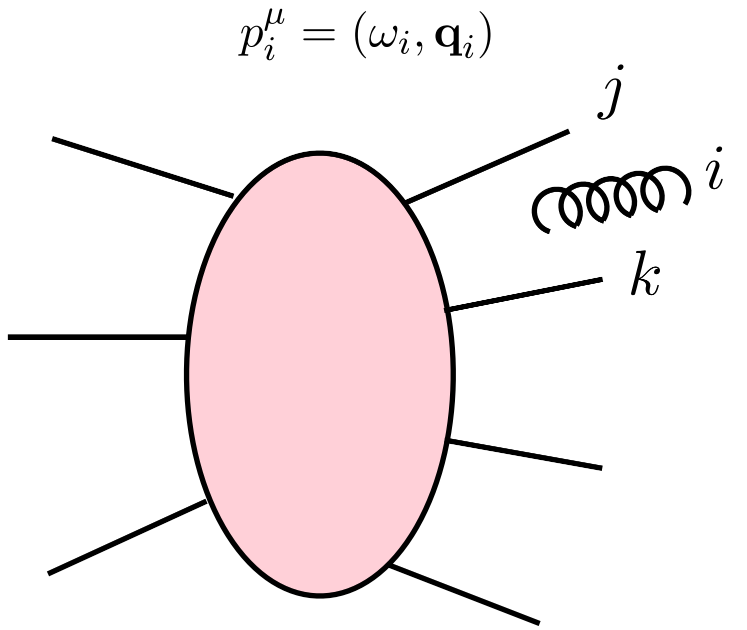
- Keep only most singular parts of QCD matrix elements:
- Collinear $d\sigma_{n+1} \approx \frac{\alpha_S}{2\pi}\sum_i P_{ii}(z_i,\phi_i)\,dz_i\frac{d\xi_i}{\xi_i}\frac{d\phi_i}{2\pi}d\sigma_n$ $\xi_i = 1-\cos\theta_i$
- Soft

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



→ Angular-ordered (AO) parton shower

AO parton shower



- Coherent emission from (jk)

$$\begin{aligned} d\sigma_{n+1}^{(jk)} &= g_s^2 d\sigma_n \frac{d^3\mathbf{q}_i}{(2\pi)^3 2\omega_i}(-\mathbf{T}_j\cdot\mathbf{T}_k)\frac{p_j\cdot p_k}{p_j\cdot p_i\,,p_k\cdot p_i} \\ &= \frac{\alpha_s}{2\pi}d\sigma_n\frac{d\omega_i}{\omega_i}\frac{d\Omega_i}{2\pi}(-\mathbf{T}_j\cdot\mathbf{T}_k)\frac{\xi_{jk}}{\xi_{ij}\,\xi_{ik}} \end{aligned}$$

where $\xi_{jk} = 1 - \cos\theta_{jk}$. Now

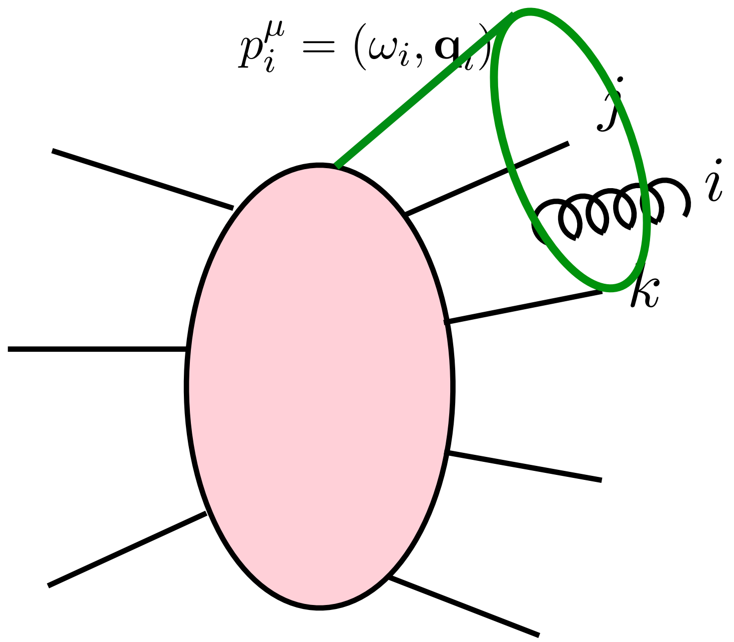
$$\frac{d\Omega_i}{2\pi}\frac{\xi_{jk}}{\xi_{ij}\,\xi_{ik}} = \frac{d\xi_{ij}}{\xi_{ij}}\frac{d\phi_{ij}}{2\pi}\frac{1}{2}\left(\frac{\xi_{jk}-\xi_{ij}}{\xi_{ik}}+1\right) + (j \leftrightarrow k)$$

- After azimuthal integration, this is exactly

$$\frac{d\xi_{ij}}{\xi_{ij}}\Theta(\xi_{jk}-\xi_{ij}) + \frac{d\xi_{ik}}{\xi_{ik}}\Theta(\xi_{jk}-\xi_{ik})$$

- Each parton j,k radiates into cone θ_{ij} , $\theta_{ik} < \theta_{jk}$

AO parton shower



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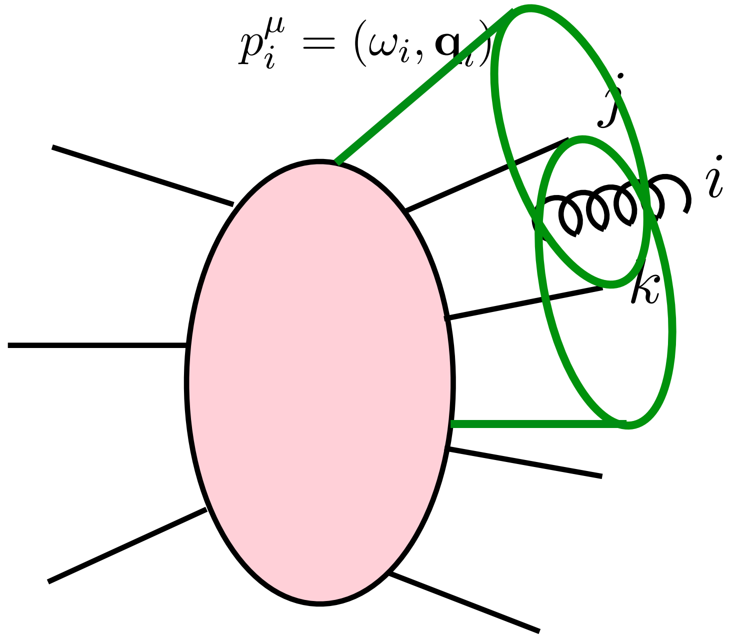

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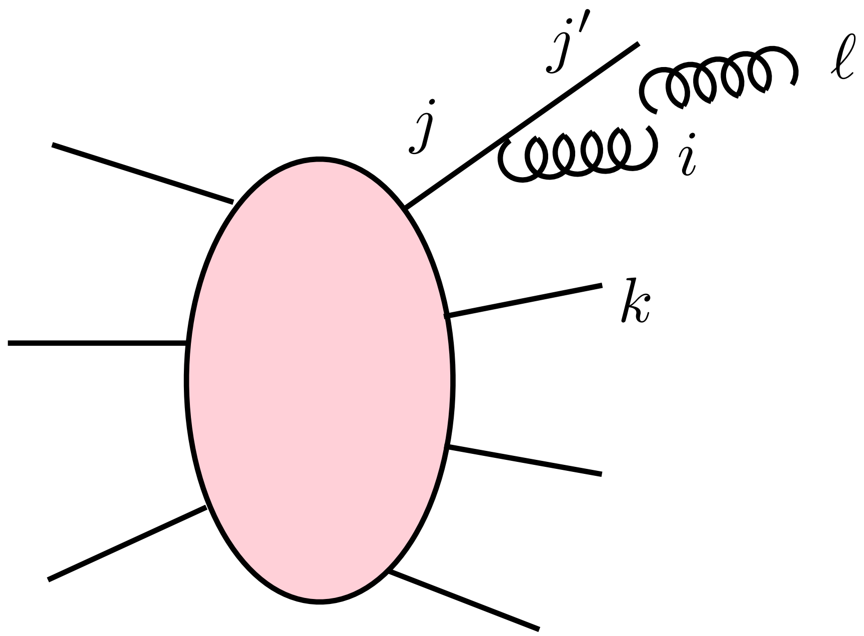
- After azimuthal integration, this is exactly

$$\frac{d\xi_{ij}}{\xi_{ij}}\Theta(\xi_{jk}-\xi_{ij}) + \frac{d\xi_{ik}}{\xi_{ik}}\Theta(\xi_{jk}-\xi_{ik})$$

- Each parton j radiates into cone $\theta_{ij} < \theta_{jk}$

AO parton shower



- Two gluon emission

$$
\begin{aligned}
d\sigma^{(ij)}_{n+2} &= \frac{\alpha_{\rm s}}{\pi} d\sigma^{(j)}_{n+1} \frac{d\omega_\ell}{\omega_\ell} \Bigg\{ (-\mathbf{T}_i \cdot \mathbf{T}'_j) \int^{\xi_{ij}} \left(\frac{d\xi_{\ell i}}{\xi_{\ell i}} + \frac{d\xi_{\ell j}}{\xi_{\ell j}} \right) \\
&+ \sum_{k \neq i,j} \left[(-\mathbf{T}_i \cdot \mathbf{T}_k) \int^{\xi_{ik}} \frac{d\xi_{\ell i}}{\xi_{\ell i}} + (-\mathbf{T}'_j \cdot \mathbf{T}_k) \int^{\xi_{jk}} \frac{d\xi_{\ell j}}{\xi_{\ell j}} \right] \Bigg\}
\end{aligned}
$$

where $\mathbf{T}'_j = \mathbf{T}_j - \mathbf{T}_i$ and $\mathbf{T}_i + \mathbf{T}'_j + \sum_{k \neq i,j} \mathbf{T}_k = 0$

- Collecting terms in $\xi_{\ell i}$ and $\xi_{\ell j}$, we find

$$
\begin{aligned}
d\sigma^{(ij)}_{n+2} &= \frac{\alpha_{\rm s}}{\pi} d\sigma^{(j)}_{n+1} \frac{d\omega_\ell}{\omega_\ell} \Bigg\{ \mathbf{T}_i \cdot \mathbf{T}_i \int^{\xi_{ij}} \frac{d\xi_{\ell i}}{\xi_{\ell i}} + \mathbf{T}'_j \cdot \mathbf{T}'_j \int^{\xi_{ij}} \frac{d\xi_{\ell j}}{\xi_{\ell j}} \\
&- \mathbf{T}_j \cdot \sum_{k \neq i,j} \mathbf{T}_k \int_{\xi_{ij}}^{\xi_{jk}} \frac{d\xi_{\ell j}}{\xi_{\ell j}} \\
&- \mathbf{T}_i \cdot \sum_{k \neq i,j} \mathbf{T}_k \left(\int_{\xi_{ij}}^{\xi_{ik}} \frac{d\xi_{\ell i}}{\xi_{\ell i}} - \int_{\xi_{ij}}^{\xi_{jk}} \frac{d\xi_{\ell j}}{\xi_{\ell j}} \right) \Bigg\} .
\end{aligned}
$$

each parton emits into its cone

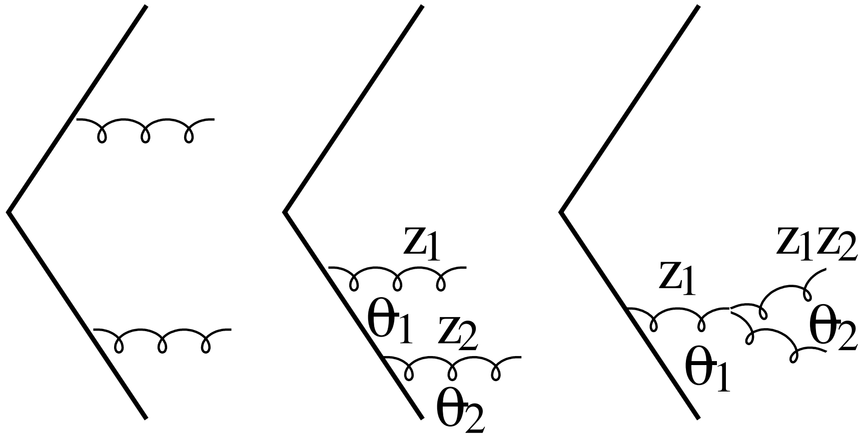
coherent emission outside cones, done in previous step

non-singular, 2 logs down, neglected

$e^+e^- \to q\bar{q}gg$

- 4-jet rate (k_t-algorithm) vs $L = \log(1/y_{\rm cut})$ $[y_{\rm cut} = (k_t^2)_{\rm min}/E_{\rm cm}^2]$

$$\frac{1}{\sigma_{\rm B}}\frac{d\sigma_4}{dL} = \left[\frac{\alpha_{\rm S}(s)}{\pi}\right]^2 (4AL^3 + 3BL^2 + 2CL + \ldots)$$



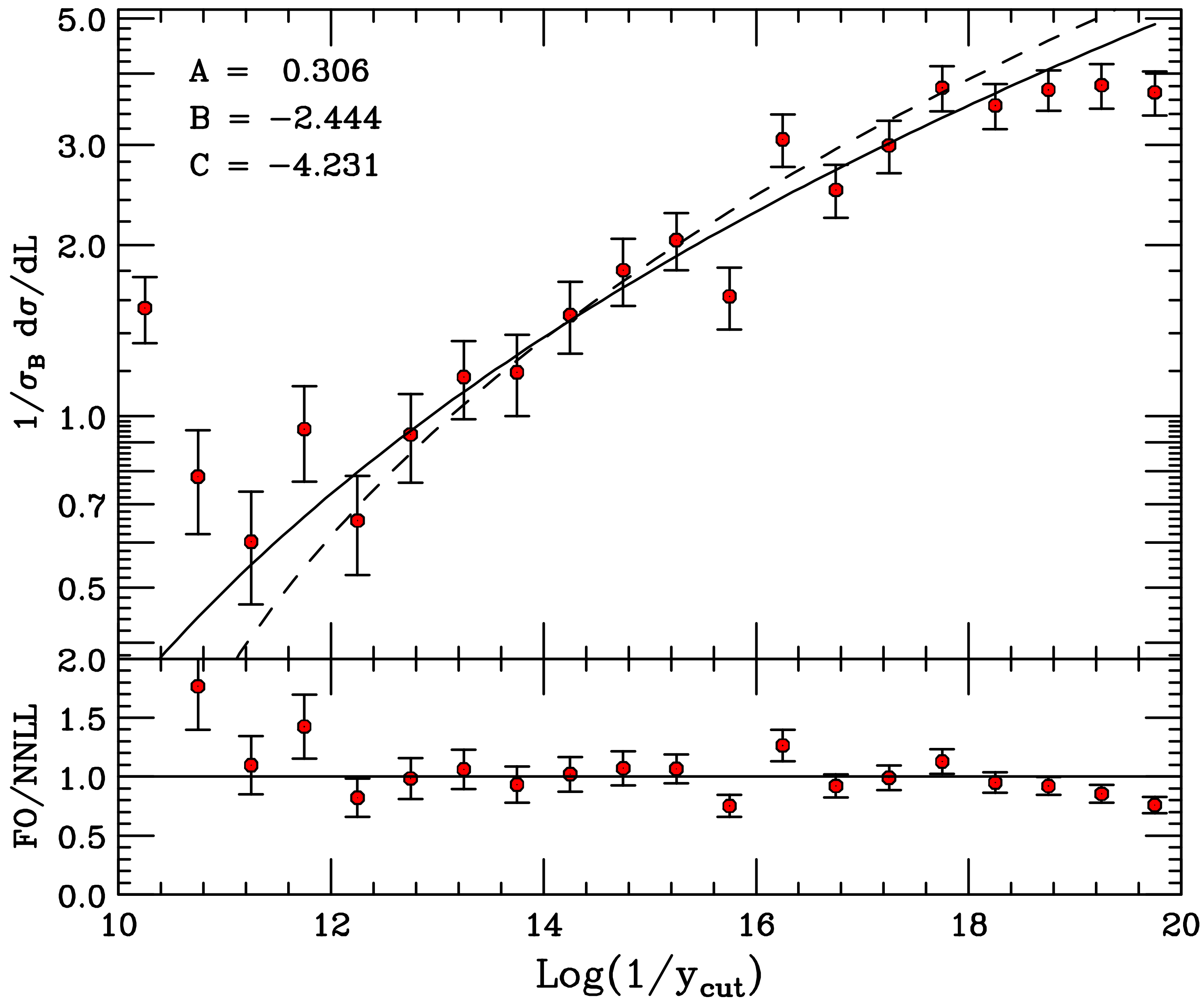
$$A = C_F^2/8 + C_F C_A/48$$

$$B = -3C_F^2/4 - 5C_F C_A/18$$

$C = ??$ (NNLL fitted)

- Compare with MadGraph5 at 1 TeV
  - M_{ij} >100 MeV → L < 18.4

$e^+e^- \rightarrow q\bar{q}gg$

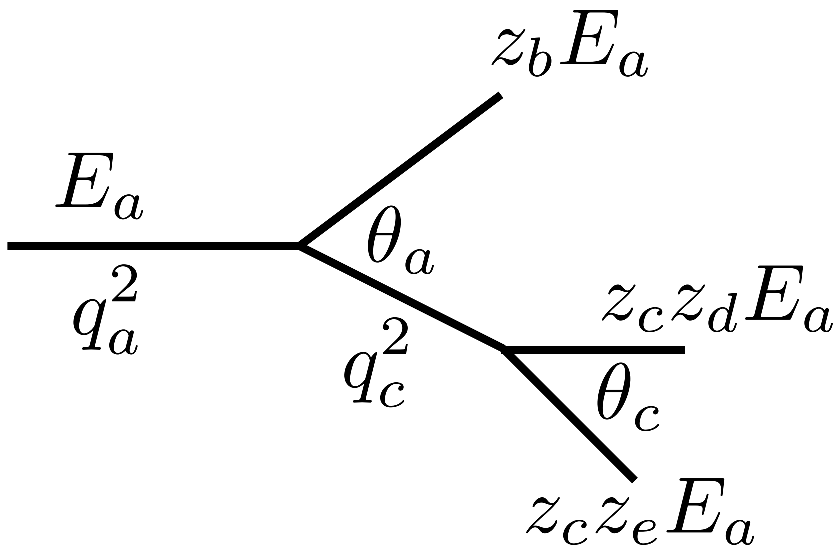


- Dashed is Leading Colour: C_F=3/2 (refitting NNLL)

Shower ordering

- Virtuality-ordered shower

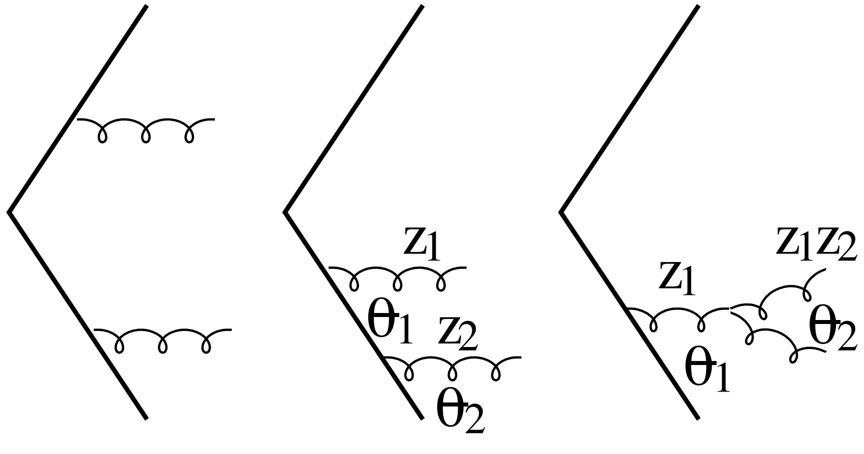
$$q_a^2 = \frac{q_b^2}{z_b} + \frac{q_c^2}{z_c} + \frac{q_T^2}{z_b z_c}$$



$$q_T \simeq z_b z_c E_a \theta_a \qquad q_a^2 \simeq z_b z_c (E_a\theta_a)^2$$

$$q_c^2 \simeq z_c^2 z_d z_e (E_a\theta_c)^2 < z_c q_a^2 \simeq z_c^2 z_b (E_a\theta_a)^2$$

$$\boxed{z_d z_e \theta_c^2 < z_b \theta_a^2}$$



(a) (b) (c)

(b) $z_2\theta_2^2 < z_1\theta_1^2$ → same as AO

(c) $z_2\theta_2^2 < \theta_1^2$ → larger than AO

→ $$R_4^{q^2} = \left(\frac{\alpha_S}{\pi}\right)^2 \frac{C_F}{8}\left(C_F + \frac{1}{4}C_A\right) L^4$$

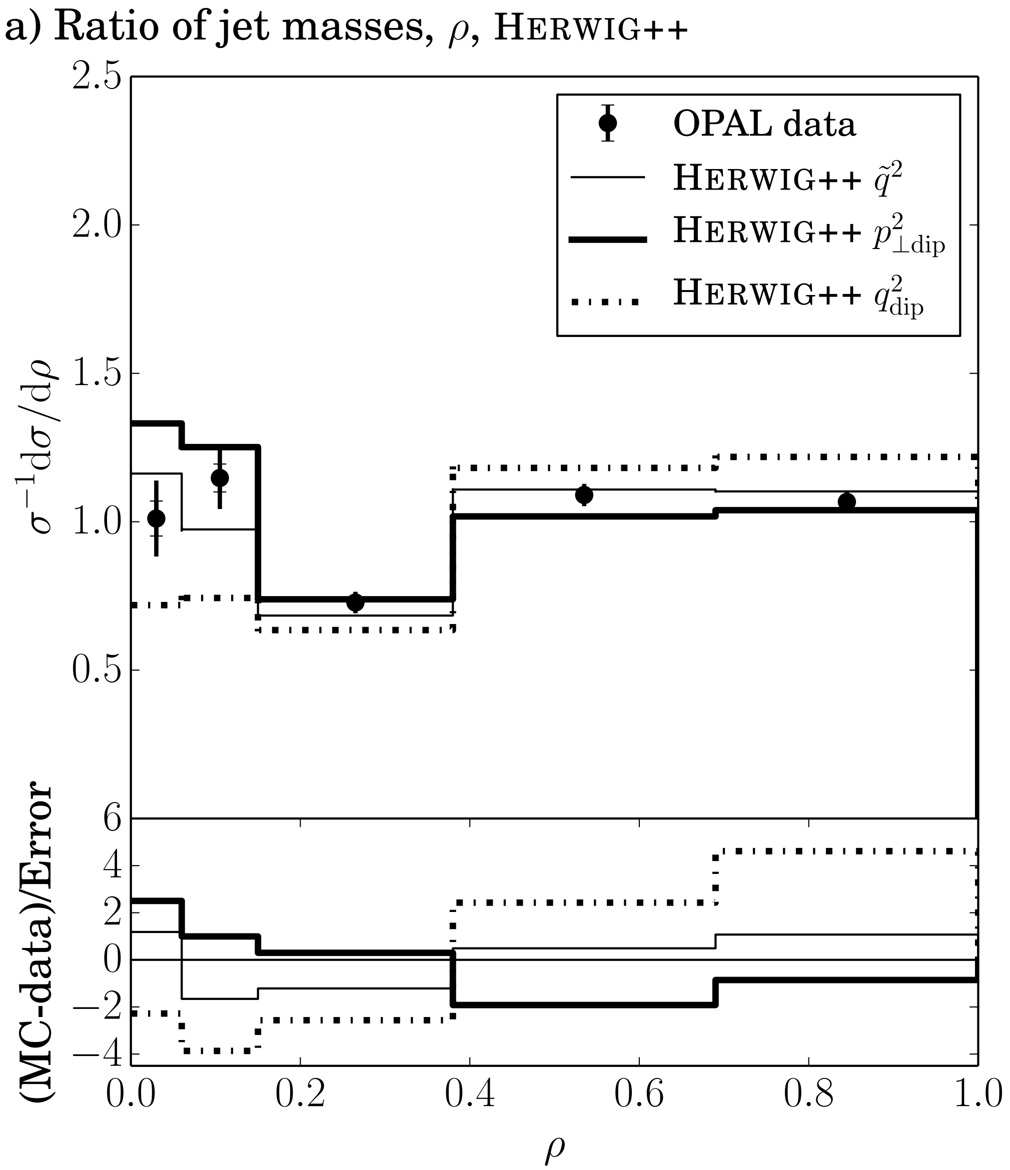
$\frac{25}{12}$

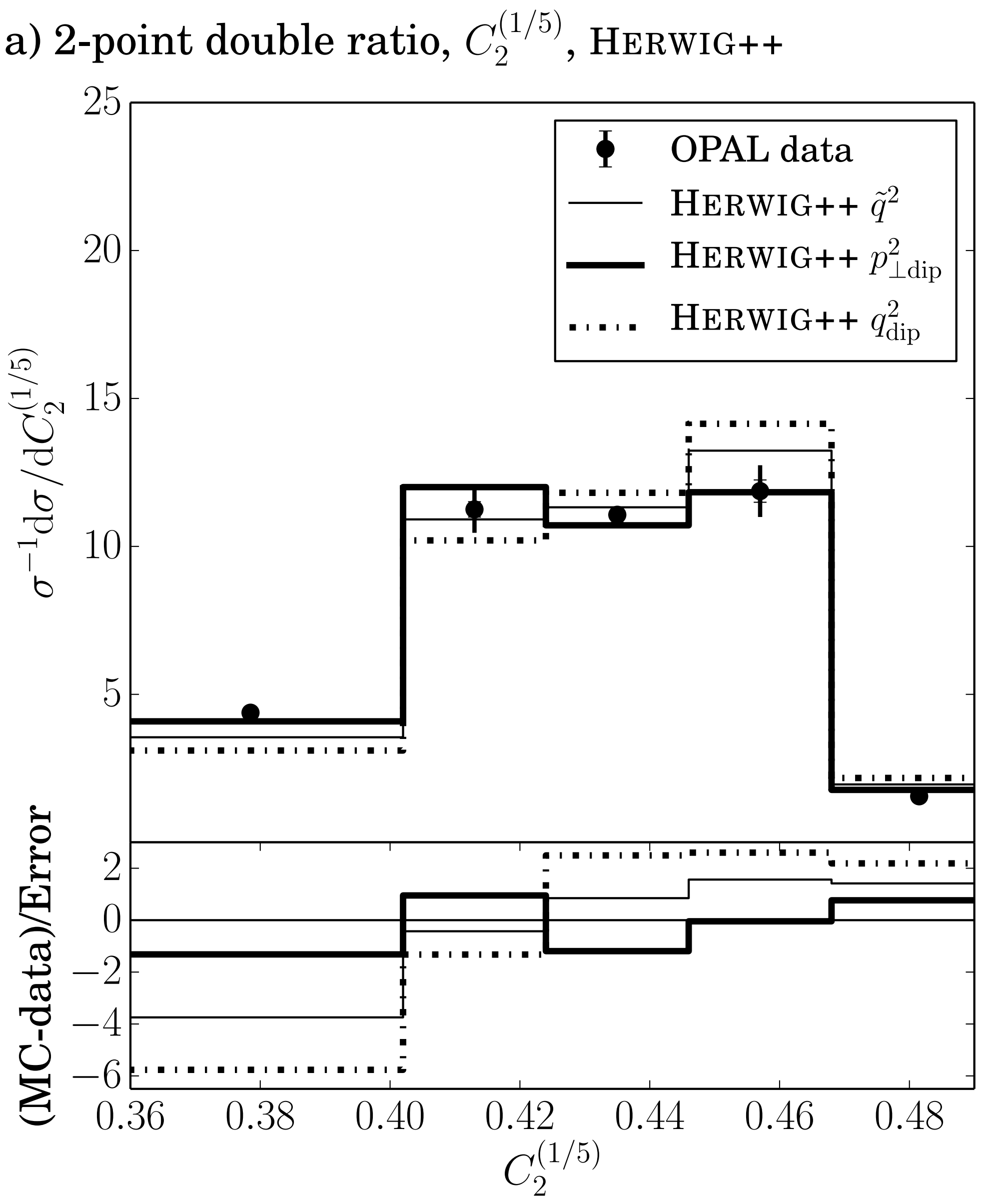
VS $$R_4^{AO} = \left(\frac{\alpha_S}{\pi}\right)^2 \frac{C_F}{8}\left(C_F + \frac{1}{6}C_A\right) L^4$$

$\frac{22}{12}$

Coherence tests

- $Z^0 \rightarrow$ 4 jets (LEP OPAL data) Fischer et al., 1505.01636


a) Ratio of jet masses, ρ, HERWIG++


a) 2-point double ratio, $C_2^{(1/5)}$, HERWIG++

- Virtuality ordering is worst

Spin in showers

$$< s|\hat{P}_{qq}(z,k_\perp;\epsilon)|s' >= \delta_{ss'}\ C_F\ \left[\frac{1+z^2}{1-z} - \epsilon(1-z)\right] \quad ,$$

$$< s|\hat{P}_{qg}(z,k_\perp;\epsilon)|s' >= \delta_{ss'}\ C_F\ \left[\frac{1+(1-z)^2}{z} - \epsilon z\right] \quad ,$$

$$< \mu|\hat{P}_{gq}(z,k_\perp;\epsilon)|\nu >= T_R\left[-g^{\mu\nu} + 4z(1-z)\frac{k_\perp^\mu k_\perp^\nu}{k_\perp^2}\right] \quad ,$$

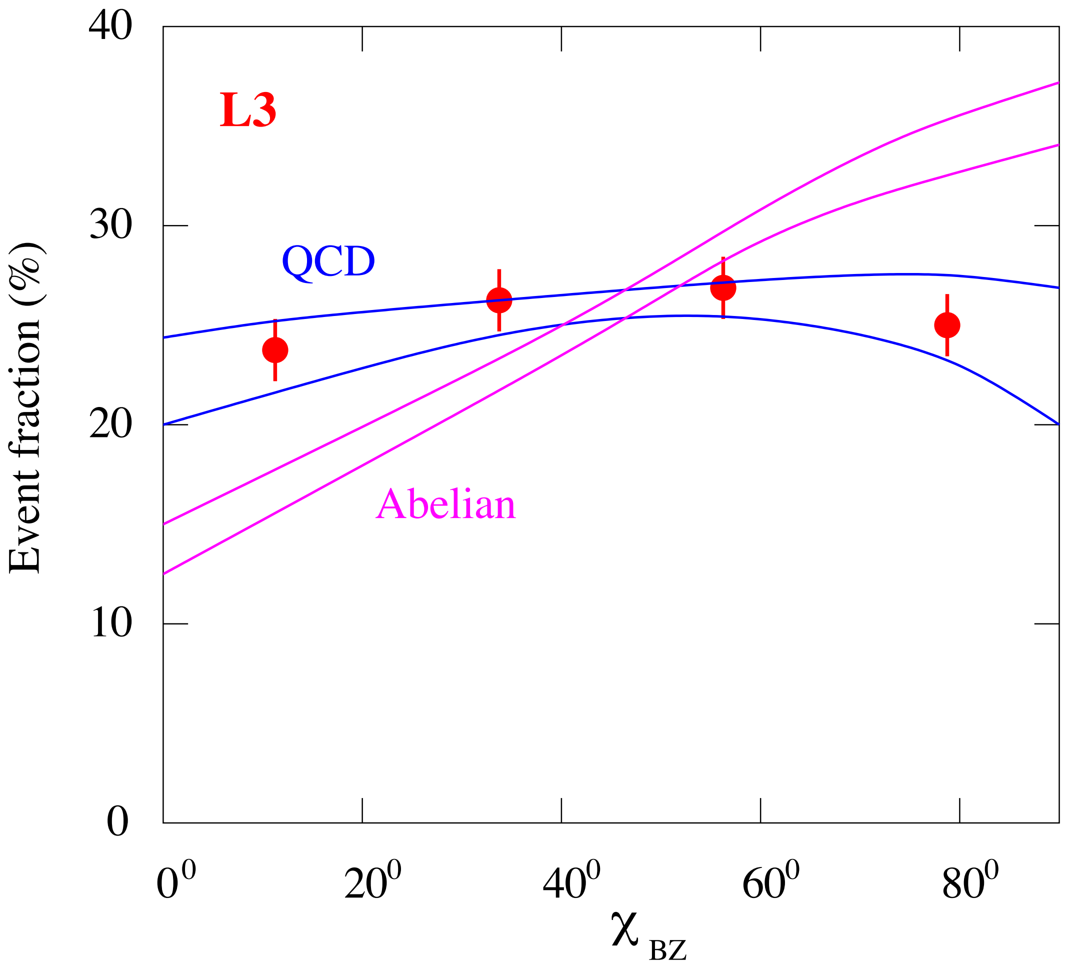
$$< \mu|\hat{P}_{gg}(z,k_\perp;\epsilon)|\nu >= 2C_A\ \left[-g^{\mu\nu}\left(\frac{z}{1-z} + \frac{1-z}{z}\right) - 2(1-\epsilon)z(1-z)\frac{k_\perp^\mu k_\perp^\nu}{k_\perp^2}\right]$$

- No effect in q→qg (helicity conservation)
- Opposite in g→gg and g→q̄q
  - Cancel when $N_f = N_c$
  - Neglected in parton showers

Spin in showers

- Bengtsson-Zerwas angle in $e^+e^- \to 4$ jets

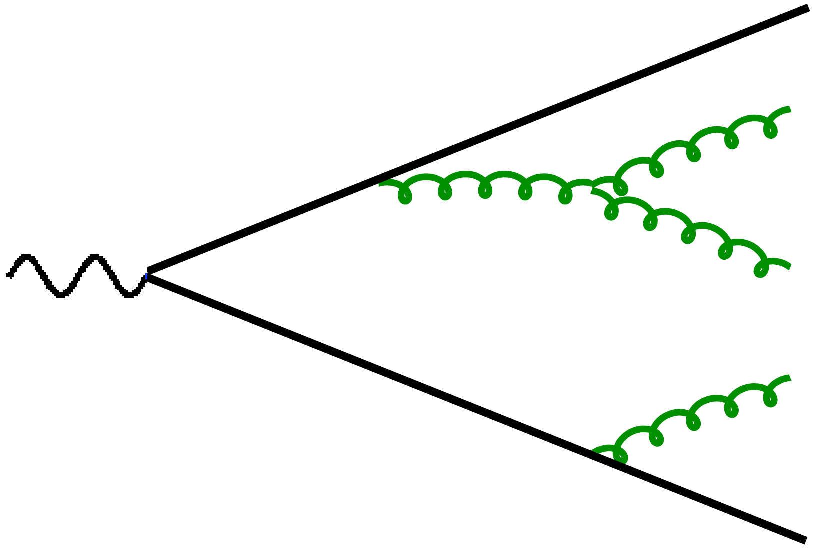
$$\cos \chi_{BZ} = \frac{(\boldsymbol{p}_1 \times \boldsymbol{p}_2) \cdot (\boldsymbol{p}_3 \times \boldsymbol{p}_4)}{|\boldsymbol{p}_1 \times \boldsymbol{p}_2|\ |\boldsymbol{p}_3 \times \boldsymbol{p}_4|}\ .$$



- Abelian theory has only $g \to q\bar{q}$

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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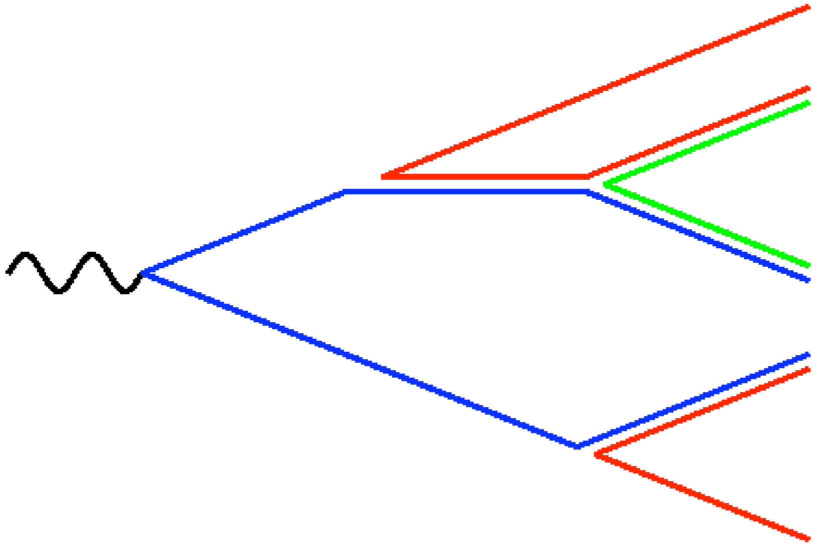

String Hadronization Model

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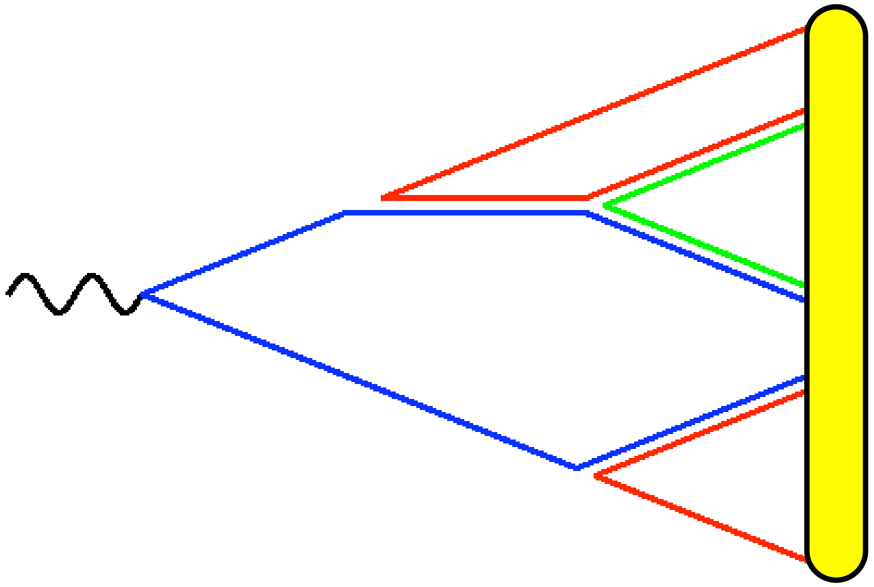

String Hadronization Model

- 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
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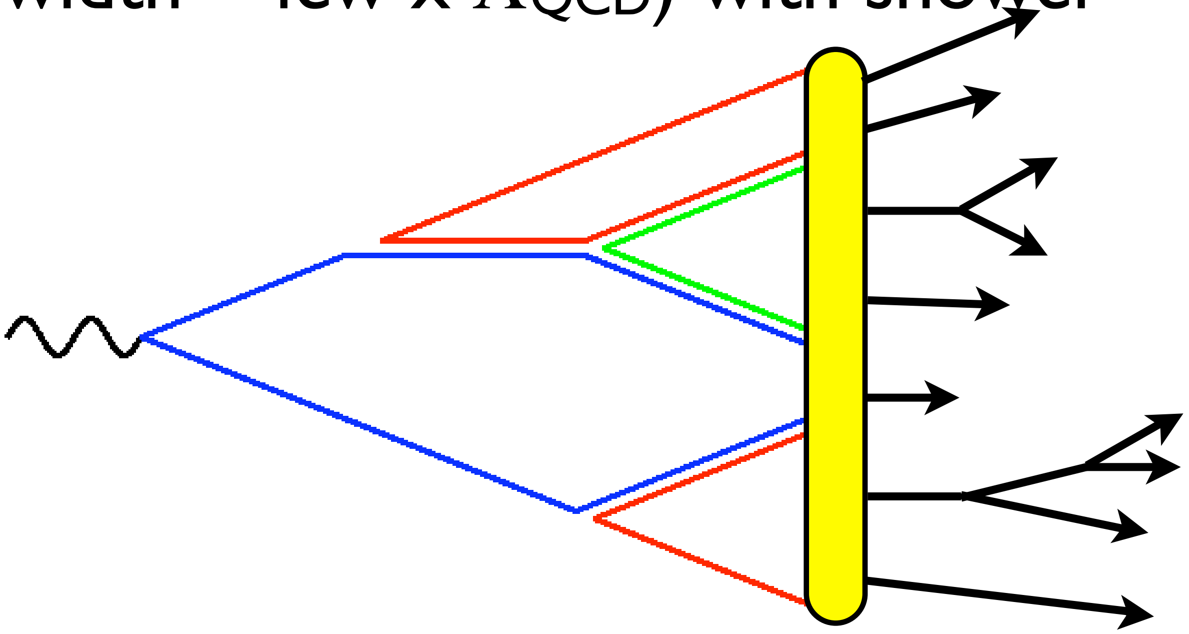

Cluster Hadronization Model

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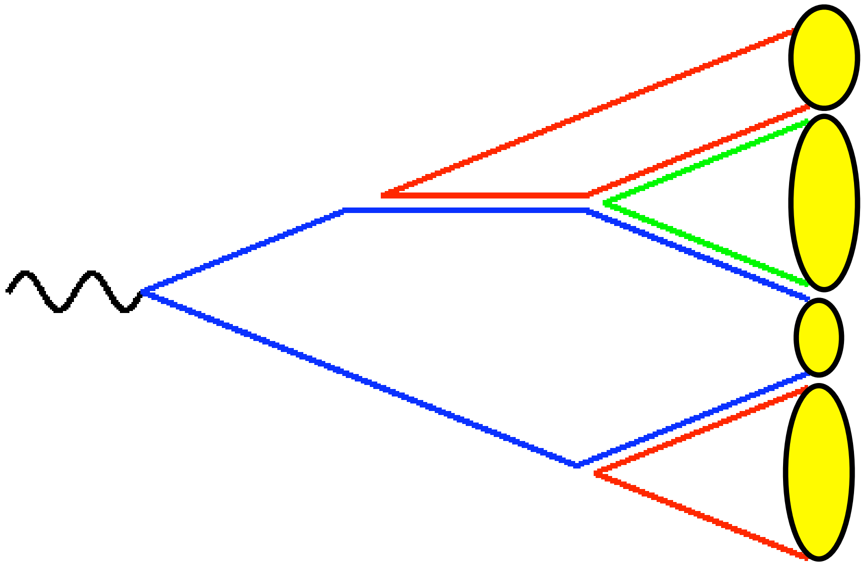
- Decay of preconfined clusters provides a direct basis for hadronization



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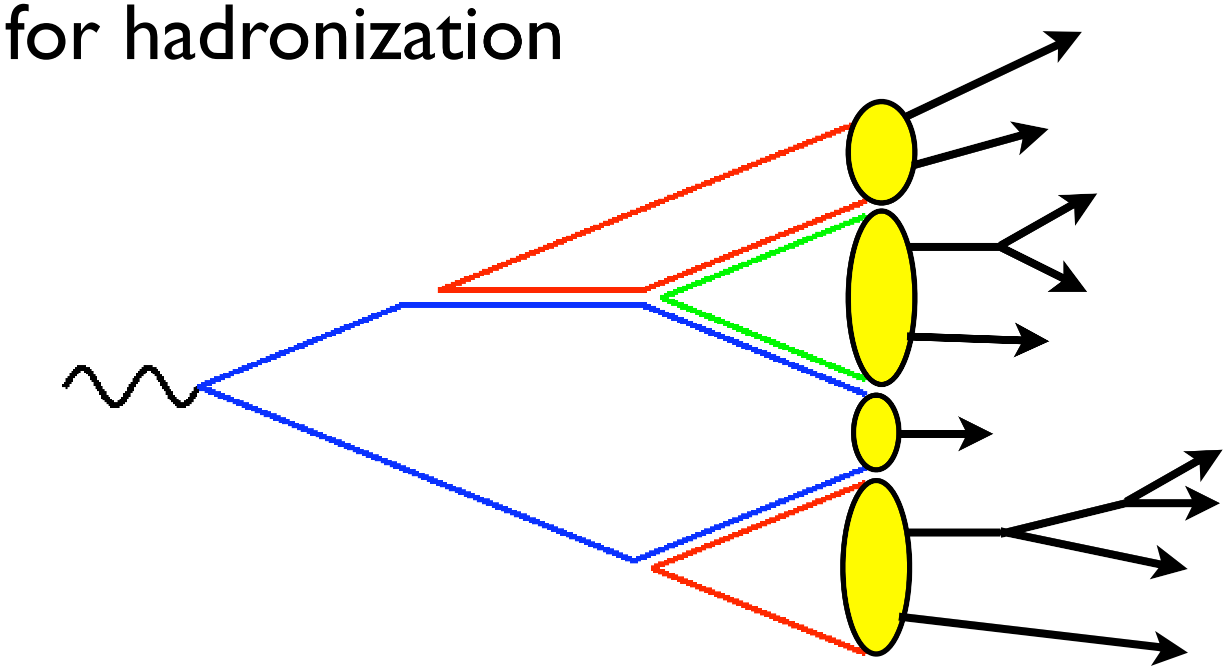
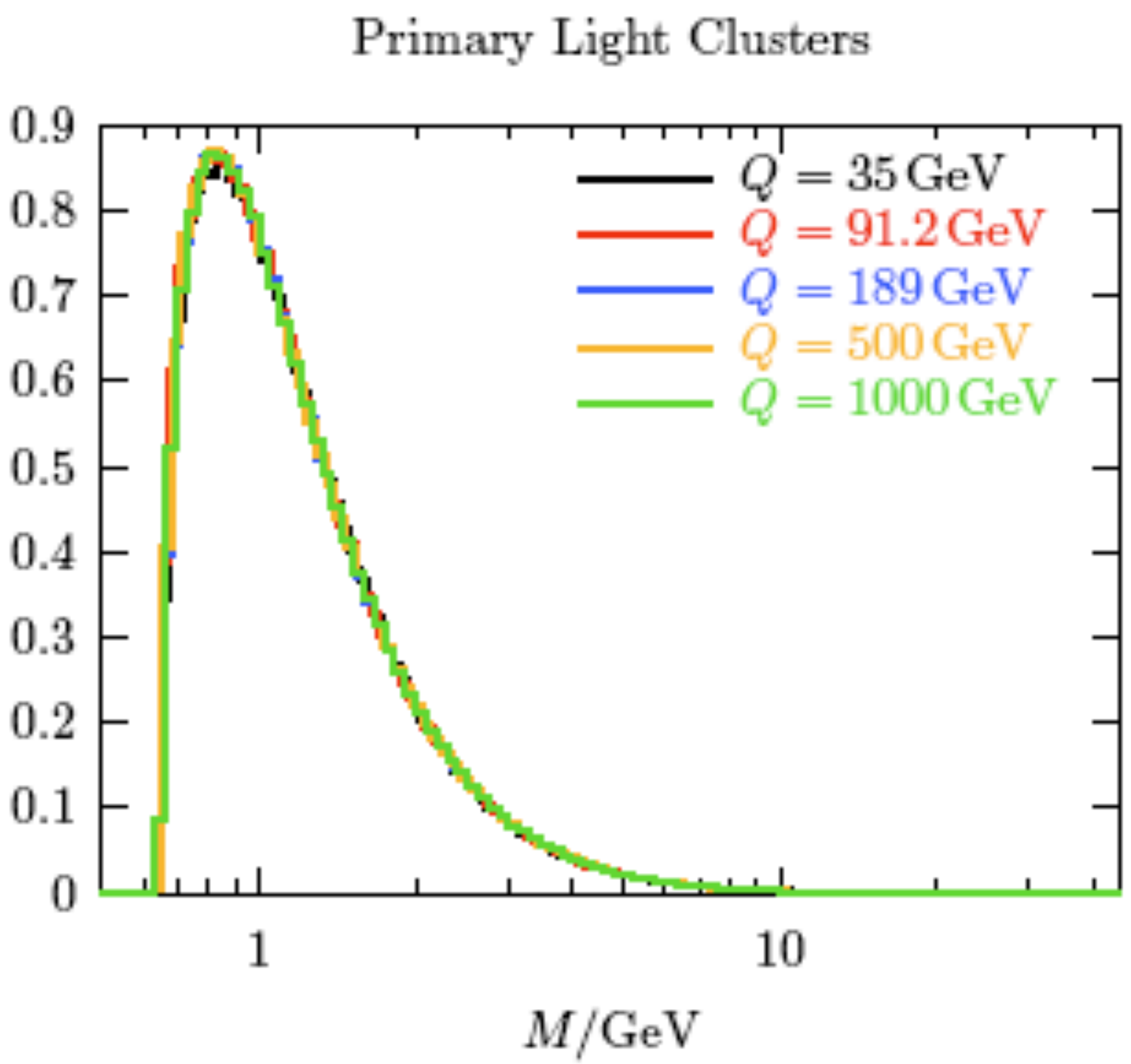


Colour Preconfinement

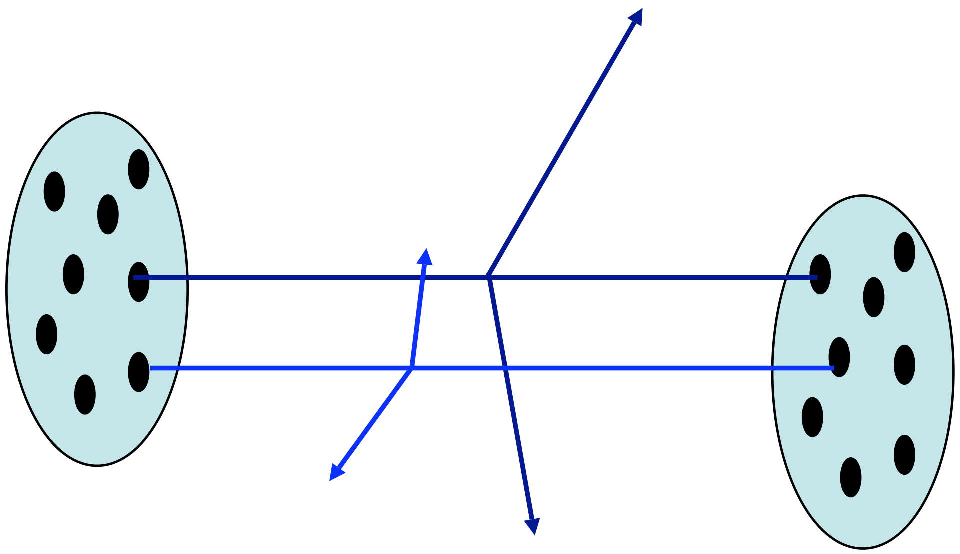


- Mass distribution of preconfined clusters is universal
- Phase-space decay model for most clusters
- High-mass tail decays anisotropically (string-like)

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
  - Track-based observables (multiplicity …)
  - Detector effects: jet response, heavy-flavour tagging, lepton and photon isolation, ...

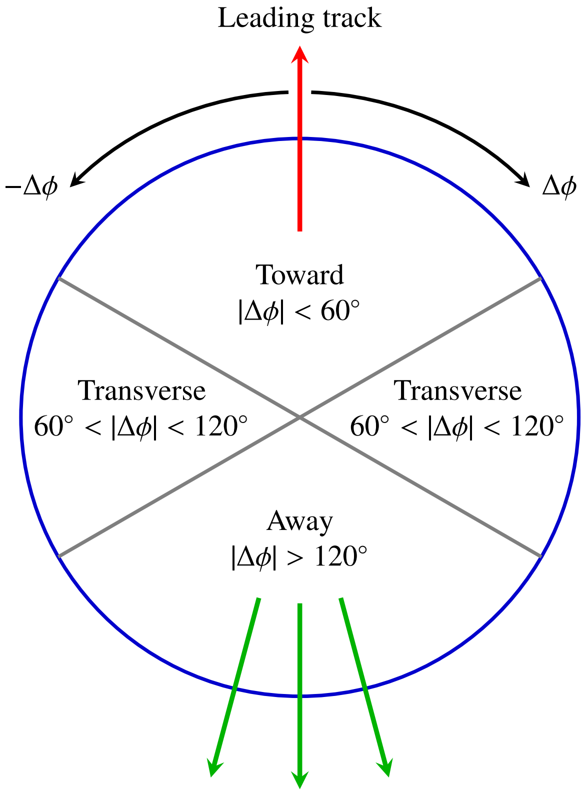
Underlying Event



- 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 at 13 TeV

ATL-PHYS-PUB-2015-019

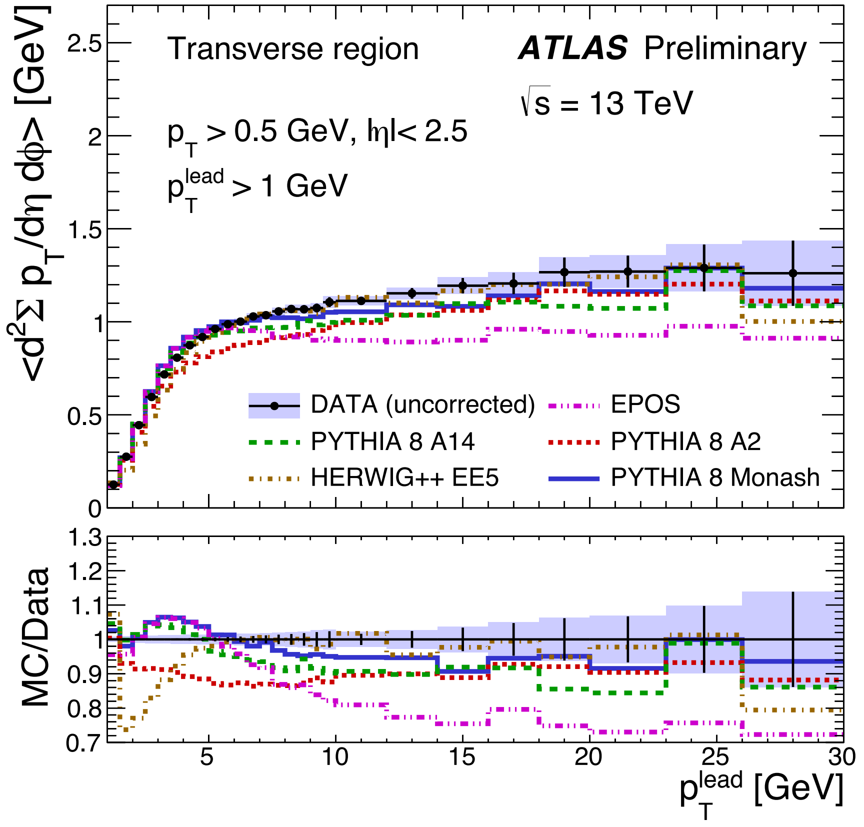


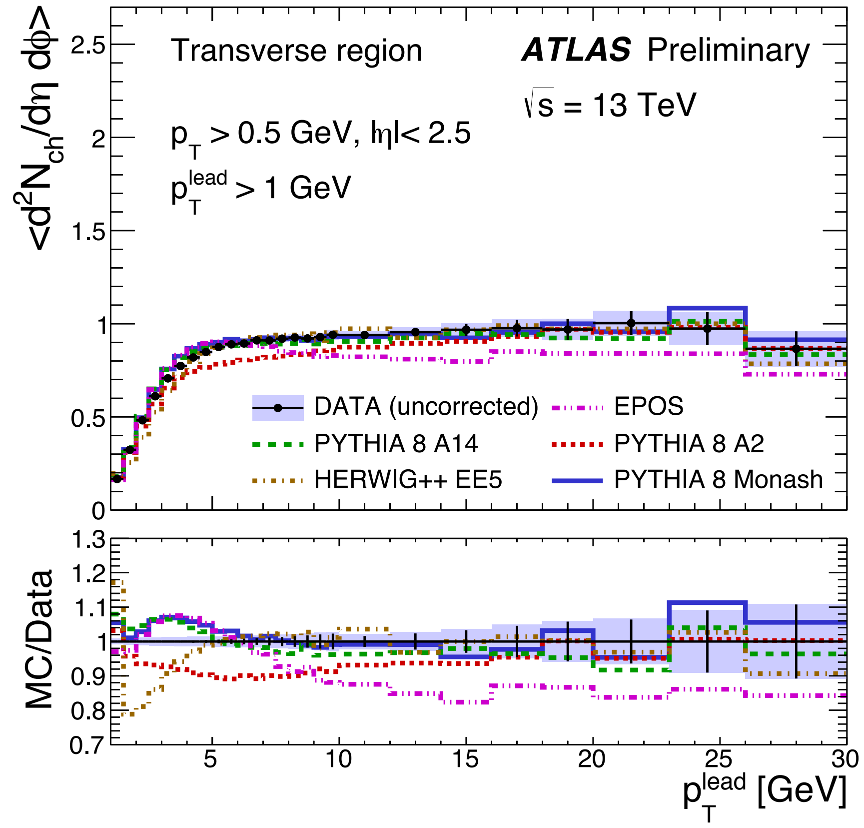
- Herwig++ EE5 tuning (0.96-7 TeV only)

$$p_\perp^{\min}(s) = p_{\perp,0}^{\min}\left(\frac{\sqrt{s}}{E_0}\right)^b \qquad (E_0 = 7\,\mathrm{TeV})$$

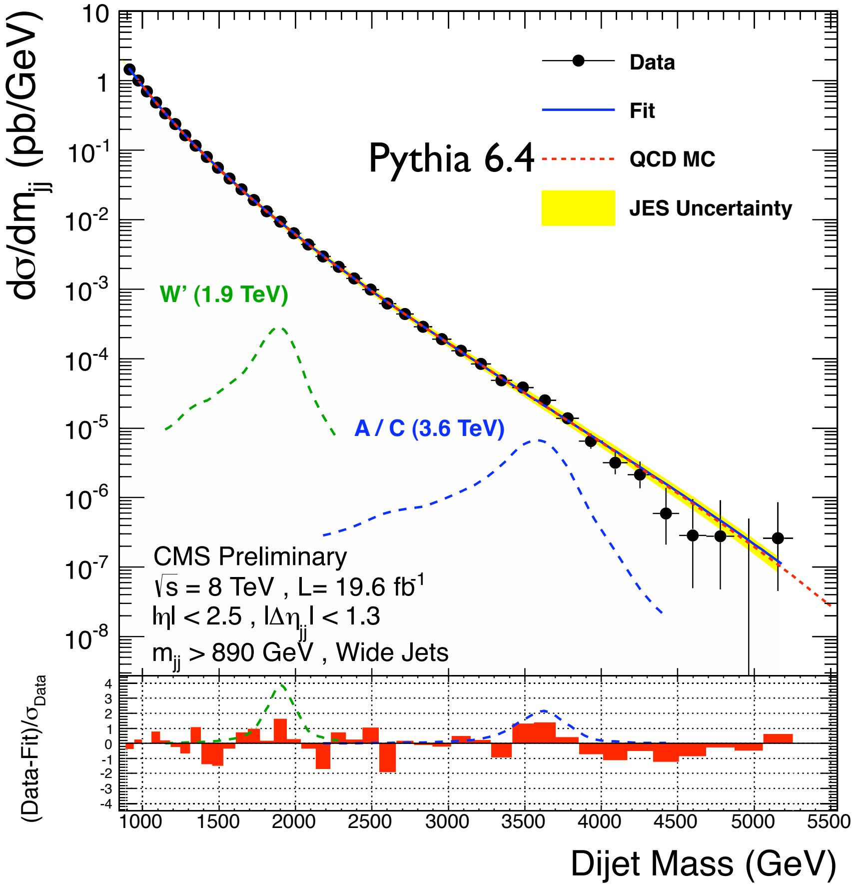
$$p_{\perp,0}^{\min} = 3.91\,\mathrm{GeV},\ b = 0.33$$

$$p_\perp^{\min}(13\,\mathrm{TeV}) = 4.80\,\mathrm{GeV}$$

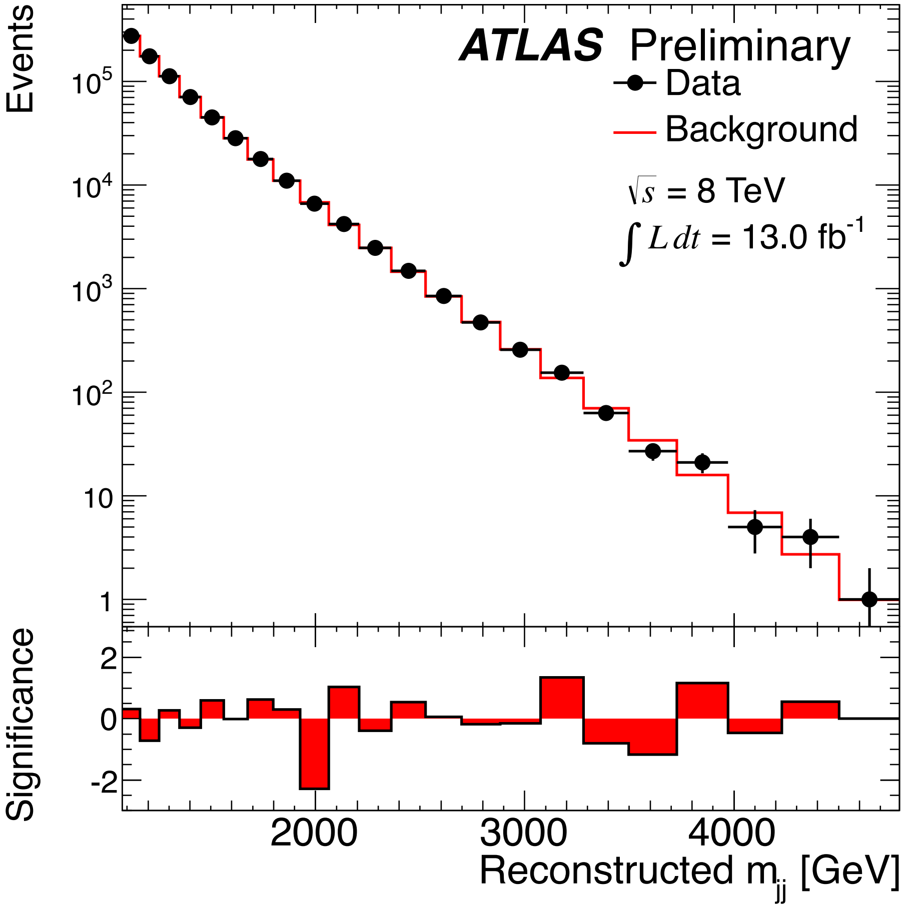




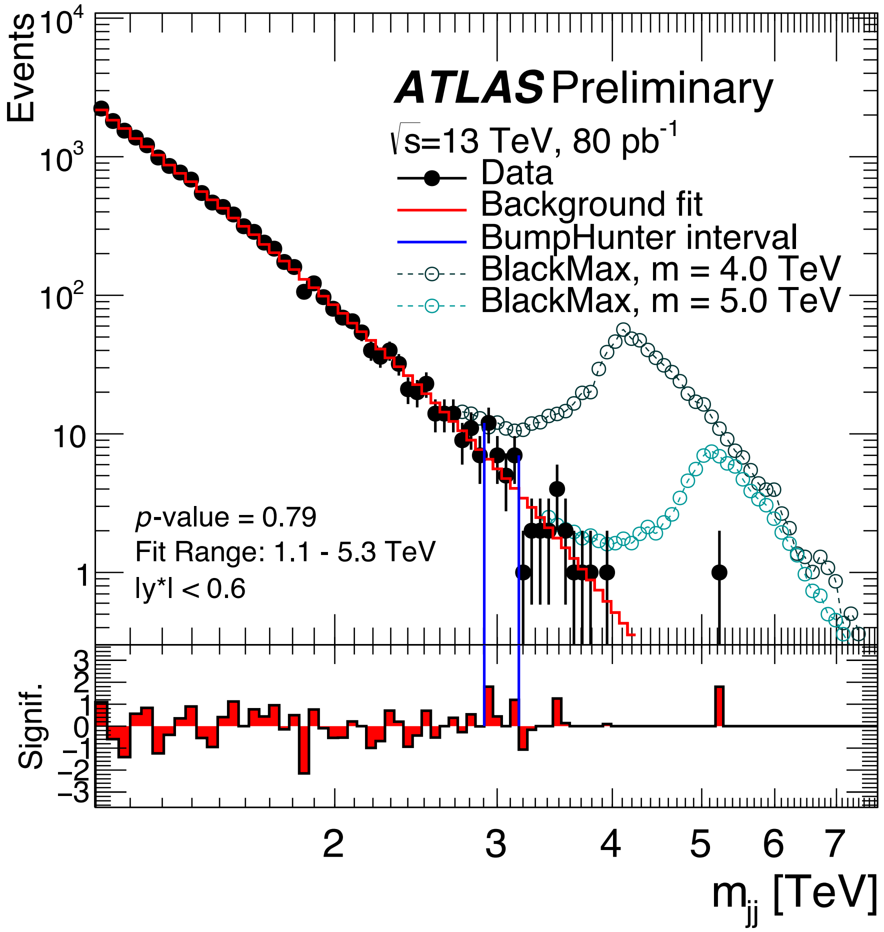
Dijet Mass Distribution



CMS PAS EXO-12-059



ATLAS CONF-2012-148



ATLAS CONF-2015-042

- No sign of deviation from Standard Model (yet)
- But see later for jet substructure …

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

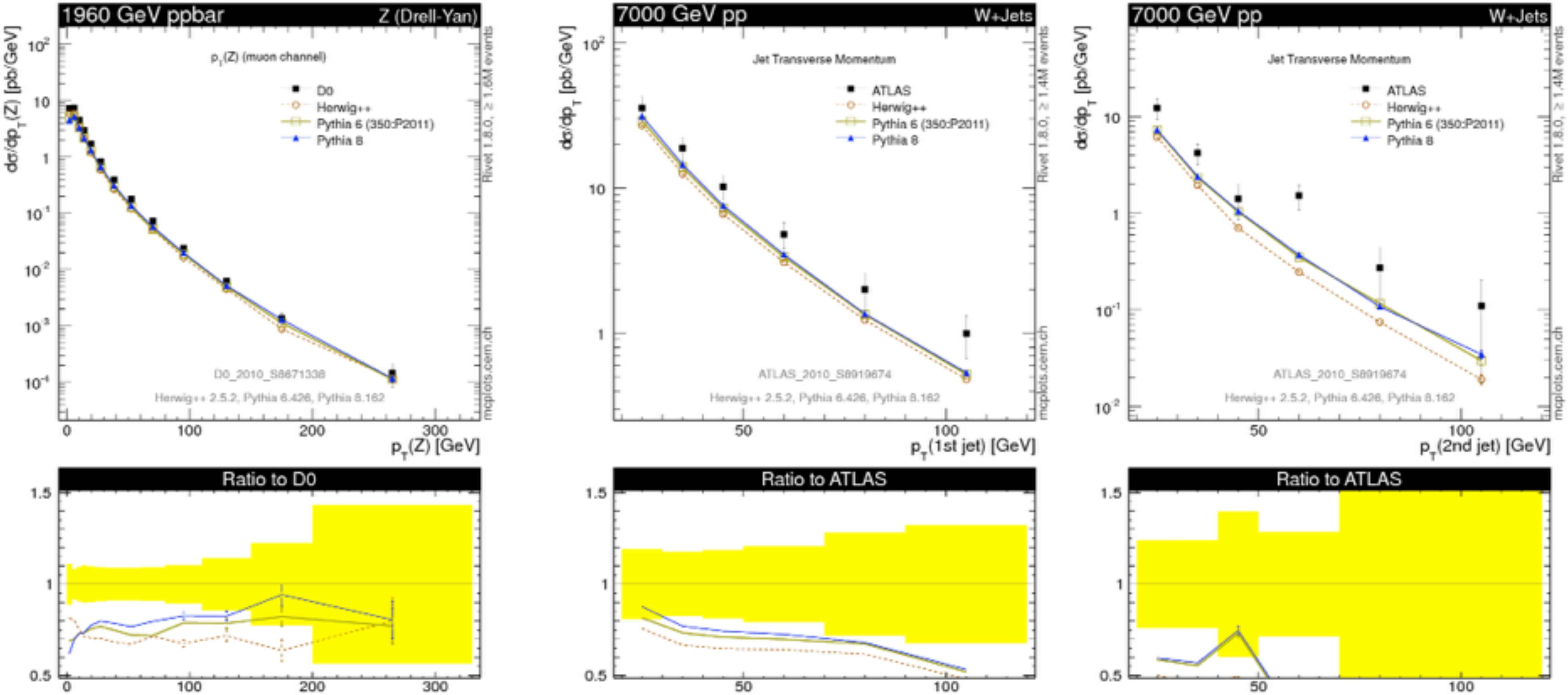
- Other event/shower generators: PhoJet, Ariadne, Dipsy, Cascade, Vincia
- Matrix-element generators: MadGraph/MadEvent, CompHep, CalcHep, Helac, Whizard, Sherpa, GoSam, aMC@NLO
- Matrix element libraries: AlpGen, POWHEG BOX, MCFM, NLOjet++, VBFNLO, BlackHat, Rocket
- Special BSM scenarios: Prospino,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

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

NLO matching

NLO matching

- Full inclusive NLO, extra jet LO
- Still mostly MC@NLO or POWHEG
- MC@NLO:
    - Subtract NLO PS terms from matrix element
    - PS-specific; beyond NLO is PS only; some negative weights
- POWHEG:
    - Generate hardest emission using matrix element
    - Any PS; extra terms beyond NLO; positive weights

MC@NLO matching

S Frixione & BW, JHEP 06(2002)029

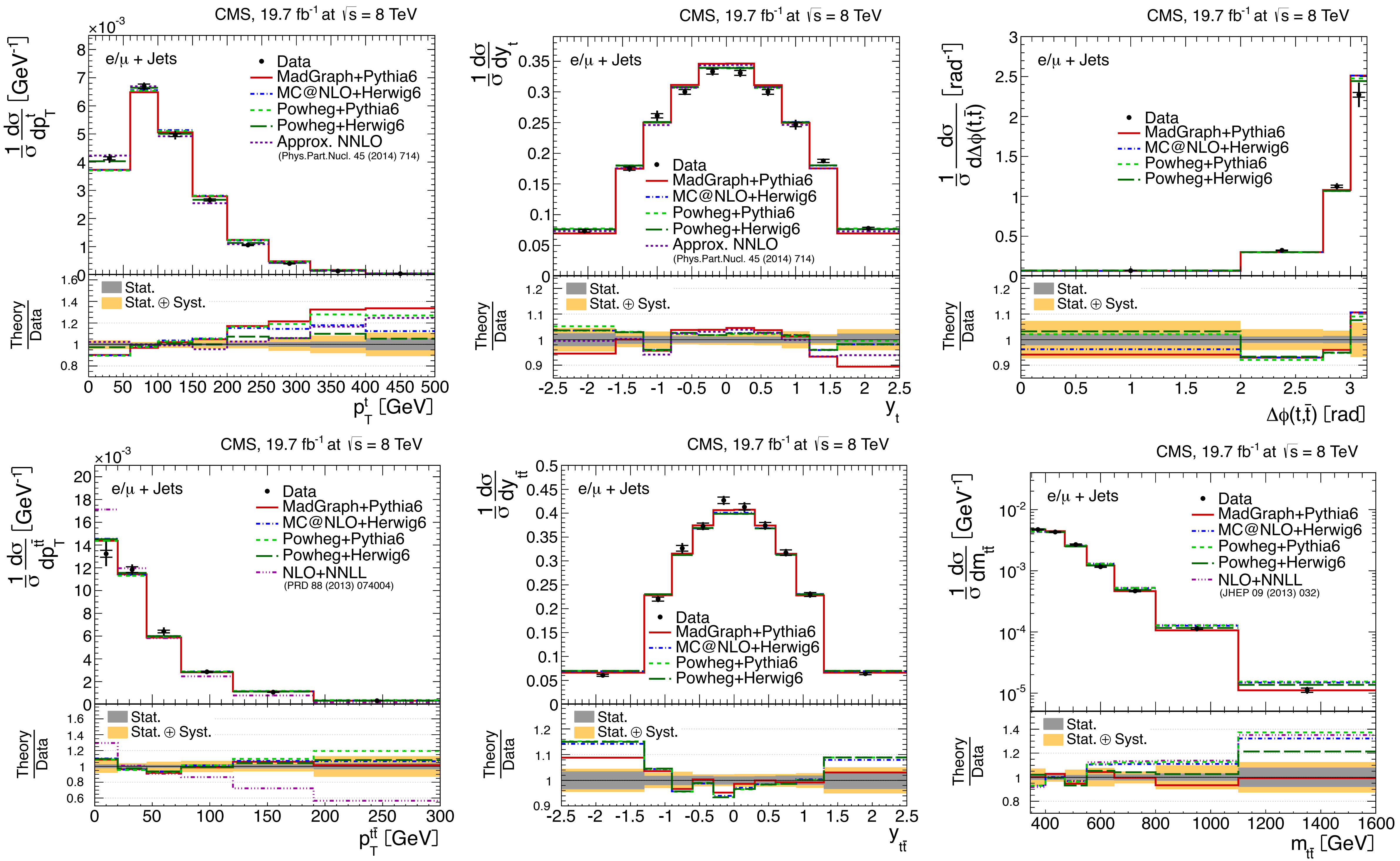
- Compute parton shower contributions (real and virtual) at NLO
    - Generator-dependent
- Subtract these from exact NLO
    - Cancels divergences of exact NLO!
- Generate modified no-emission (LO+virtual) and real-emission hard process configurations
    - Some may have negative weight
- Pass these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

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

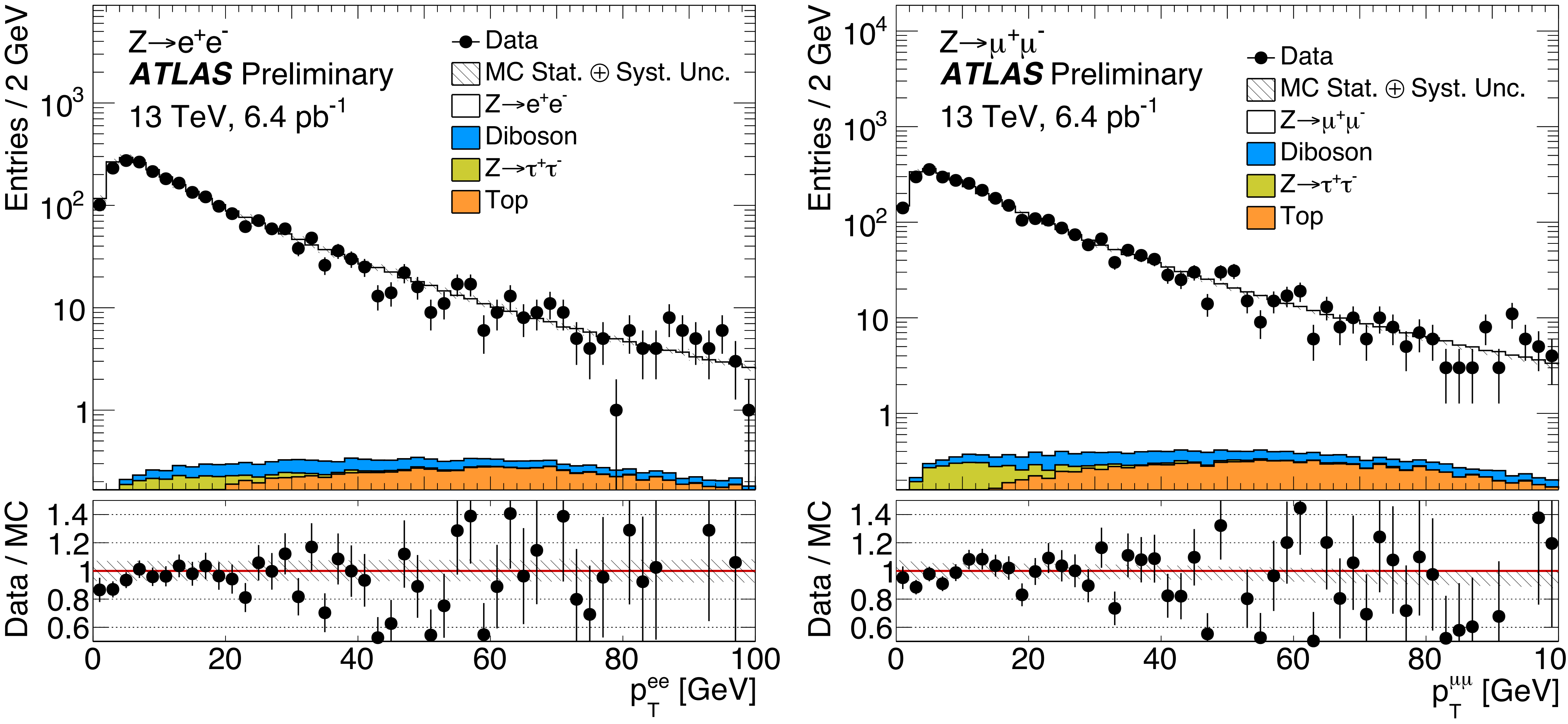
Top pairs at 8 TeV



- Differences are small!

CMS, 1505.04480

Z Production at 13 TeV



- MC = POWHEG+Pythia8

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
  - MadGraph4+POWHEG+MCFM/GoSam

    Campbell et al.,1202.5475; Luisoni et al., 1502.01213
  - Herwig++ Matchbox+OpenLoops/GoSam

MG5_aMC@NLO

Process		Syntax	Cross section (pb)			
Heavy quarks+vector bosons			LO 13 TeV		NLO 13 TeV	
e.1	$pp \to W^{\pm} b\bar{b}$ (4f)	`p p > wpm b b~`	$3.074 \pm 0.002 \cdot 10^{2}$	$^{+42.3\%}_{-29.2\%}$ $^{+2.0\%}_{-1.6\%}$	$8.162 \pm 0.034 \cdot 10^{2}$	$^{+29.8\%}_{-23.6\%}$ $^{+1.5\%}_{-1.2\%}$
e.2	$pp \to Z\, b\bar{b}$ (4f)	`p p > z b b~`	$6.993 \pm 0.003 \cdot 10^{2}$	$^{+33.5\%}_{-24.4\%}$ $^{+1.0\%}_{-1.4\%}$	$1.235 \pm 0.004 \cdot 10^{3}$	$^{+19.9\%}_{-17.4\%}$ $^{+1.0\%}_{-1.4\%}$
e.3	$pp \to \gamma\, b\bar{b}$ (4f)	`p p > a b b~`	$1.731 \pm 0.001 \cdot 10^{3}$	$^{+51.9\%}_{-34.8\%}$ $^{+1.6\%}_{-2.1\%}$	$4.171 \pm 0.015 \cdot 10^{3}$	$^{+33.7\%}_{-27.1\%}$ $^{+1.4\%}_{-1.9\%}$
e.4*	$pp \to W^{\pm} b\bar{b}\, j$ (4f)	`p p > wpm b b~ j`	$1.861 \pm 0.003 \cdot 10^{2}$	$^{+42.5\%}_{-27.7\%}$ $^{+0.7\%}_{-0.7\%}$	$3.957 \pm 0.013 \cdot 10^{2}$	$^{+27.0\%}_{-21.0\%}$ $^{+0.7\%}_{-0.6\%}$
e.5*	$pp \to Z\, b\bar{b}\, j$ (4f)	`p p > z b b~ j`	$1.604 \pm 0.001 \cdot 10^{2}$	$^{+42.4\%}_{-27.6\%}$ $^{+0.9\%}_{-1.1\%}$	$2.805 \pm 0.009 \cdot 10^{2}$	$^{+21.0\%}_{-17.6\%}$ $^{+0.8\%}_{-1.0\%}$
e.6*	$pp \to \gamma\, b\bar{b}\, j$ (4f)	`p p > a b b~ j`	$7.812 \pm 0.017 \cdot 10^{2}$	$^{+51.2\%}_{-32.0\%}$ $^{+1.0\%}_{-1.5\%}$	$1.233 \pm 0.004 \cdot 10^{3}$	$^{+18.9\%}_{-19.9\%}$ $^{+1.0\%}_{-1.5\%}$
e.7	$pp \to t\bar{t}\, W^{\pm}$	`p p > t t~ wpm`	$3.777 \pm 0.003 \cdot 10^{-1}$	$^{+23.9\%}_{-18.0\%}$ $^{+2.1\%}_{-1.6\%}$	$5.662 \pm 0.021 \cdot 10^{-1}$	$^{+11.2\%}_{-10.6\%}$ $^{+1.7\%}_{-1.3\%}$
e.8	$pp \to t\bar{t}\, Z$	`p p > t t~ z`	$5.273 \pm 0.004 \cdot 10^{-1}$	$^{+30.5\%}_{-21.8\%}$ $^{+1.8\%}_{-2.1\%}$	$7.598 \pm 0.026 \cdot 10^{-1}$	$^{+9.7\%}_{-11.1\%}$ $^{+1.9\%}_{-2.2\%}$
e.9	$pp \to t\bar{t}\, \gamma$	`p p > t t~ a`	$1.204 \pm 0.001 \cdot 10^{0}$	$^{+29.6\%}_{-21.3\%}$ $^{+1.6\%}_{-1.8\%}$	$1.744 \pm 0.005 \cdot 10^{0}$	$^{+9.8\%}_{-11.0\%}$ $^{+1.7\%}_{-2.0\%}$
e.10*	$pp \to t\bar{t}\, W^{\pm} j$	`p p > t t~ wpm j`	$2.352 \pm 0.002 \cdot 10^{-1}$	$^{+40.9\%}_{-27.1\%}$ $^{+1.3\%}_{-1.0\%}$	$3.404 \pm 0.011 \cdot 10^{-1}$	$^{+11.2\%}_{-14.0\%}$ $^{+1.2\%}_{-0.9\%}$
e.11*	$pp \to t\bar{t}\, Z j$	`p p > t t~ z j`	$3.953 \pm 0.004 \cdot 10^{-1}$	$^{+46.2\%}_{-29.5\%}$ $^{+2.7\%}_{-3.0\%}$	$5.074 \pm 0.016 \cdot 10^{-1}$	$^{+7.0\%}_{-12.3\%}$ $^{+2.5\%}_{-2.9\%}$
e.12*	$pp \to t\bar{t}\, \gamma j$	`p p > t t~ a j`	$8.726 \pm 0.010 \cdot 10^{-1}$	$^{+45.4\%}_{-29.1\%}$ $^{+2.3\%}_{-2.6\%}$	$1.135 \pm 0.004 \cdot 10^{0}$	$^{+7.5\%}_{-12.2\%}$ $^{+2.2\%}_{-2.5\%}$
e.13*	$pp \to t\bar{t}\, W^{-} W^{+}$ (4f)	`p p > t t~ w+ w-`	$6.675 \pm 0.006 \cdot 10^{-3}$	$^{+30.9\%}_{-21.9\%}$ $^{+2.1\%}_{-2.0\%}$	$9.904 \pm 0.026 \cdot 10^{-3}$	$^{+10.9\%}_{-11.8\%}$ $^{+2.1\%}_{-2.1\%}$
e.14*	$pp \to t\bar{t}\, W^{\pm} Z$	`p p > t t~ wpm z`	$2.404 \pm 0.002 \cdot 10^{-3}$	$^{+26.6\%}_{-19.6\%}$ $^{+2.5\%}_{-1.8\%}$	$3.525 \pm 0.010 \cdot 10^{-3}$	$^{+10.6\%}_{-10.8\%}$ $^{+2.3\%}_{-1.6\%}$
e.15*	$pp \to t\bar{t}\, W^{\pm} \gamma$	`p p > t t~ wpm a`	$2.718 \pm 0.003 \cdot 10^{-3}$	$^{+25.4\%}_{-18.9\%}$ $^{+2.3\%}_{-1.8\%}$	$3.927 \pm 0.013 \cdot 10^{-3}$	$^{+10.3\%}_{-10.4\%}$ $^{+2.0\%}_{-1.5\%}$
e.16*	$pp \to t\bar{t}\, ZZ$	`p p > t t~ z z`	$1.349 \pm 0.014 \cdot 10^{-3}$	$^{+29.3\%}_{-21.1\%}$ $^{+1.7\%}_{-1.5\%}$	$1.840 \pm 0.007 \cdot 10^{-3}$	$^{+7.9\%}_{-9.9\%}$ $^{+1.7\%}_{-1.5\%}$
e.17*	$pp \to t\bar{t}\, Z\gamma$	`p p > t t~ z a`	$2.548 \pm 0.003 \cdot 10^{-3}$	$^{+30.1\%}_{-21.5\%}$ $^{+1.7\%}_{-1.6\%}$	$3.656 \pm 0.012 \cdot 10^{-3}$	$^{+9.7\%}_{-11.0\%}$ $^{+1.8\%}_{-1.9\%}$
e.18*	$pp \to t\bar{t}\, \gamma\gamma$	`p p > t t~ a a`	$3.272 \pm 0.006 \cdot 10^{-3}$	$^{+28.4\%}_{-20.6\%}$ $^{+1.3\%}_{-1.1\%}$	$4.402 \pm 0.015 \cdot 10^{-3}$	$^{+7.8\%}_{-9.7\%}$ $^{+1.4\%}_{-1.4\%}$

- Sampled from 172 processes
- Mostly new at NLO

Alwall et al., 1405.0301

MG5_aMC@NLO

Process		Syntax	Cross section (pb)			
Top quarks +bosons			LO 1 TeV		NLO 1 TeV	
j.1	$e^+e^- \to t\bar{t}H$	`e+ e- > t t~ h`	$2.018 \pm 0.003 \cdot 10^{-3}$	$^{+0.0\%}_{-0.0\%}$	$1.911 \pm 0.006 \cdot 10^{-3}$	$^{+0.4\%}_{-0.5\%}$
j.2*	$e^+e^- \to t\bar{t}Hj$	`e+ e- > t t~ h j`	$2.533 \pm 0.003 \cdot 10^{-4}$	$^{+9.2\%}_{-7.8\%}$	$2.658 \pm 0.009 \cdot 10^{-4}$	$^{+0.5\%}_{-1.5\%}$
j.3*	$e^+e^- \to t\bar{t}Hjj$	`e+ e- > t t~ h j j`	$2.663 \pm 0.004 \cdot 10^{-5}$	$^{+19.3\%}_{-14.9\%}$	$3.278 \pm 0.017 \cdot 10^{-5}$	$^{+4.0\%}_{-5.7\%}$
j.4*	$e^+e^- \to t\bar{t}\gamma$	`e+ e- > t t~ a`	$1.270 \pm 0.002 \cdot 10^{-2}$	$^{+0.0\%}_{-0.0\%}$	$1.335 \pm 0.004 \cdot 10^{-2}$	$^{+0.5\%}_{-0.4\%}$
j.5*	$e^+e^- \to t\bar{t}\gamma j$	`e+ e- > t t~ a j`	$2.355 \pm 0.002 \cdot 10^{-3}$	$^{+9.3\%}_{-7.9\%}$	$2.617 \pm 0.010 \cdot 10^{-3}$	$^{+1.6\%}_{-2.4\%}$
j.6*	$e^+e^- \to t\bar{t}\gamma jj$	`e+ e- > t t~ a j j`	$3.103 \pm 0.005 \cdot 10^{-4}$	$^{+19.5\%}_{-15.0\%}$	$4.002 \pm 0.021 \cdot 10^{-4}$	$^{+5.4\%}_{-6.6\%}$
j.7*	$e^+e^- \to t\bar{t}Z$	`e+ e- > t t~ z`	$4.642 \pm 0.006 \cdot 10^{-3}$	$^{+0.0\%}_{-0.0\%}$	$4.949 \pm 0.014 \cdot 10^{-3}$	$^{+0.6\%}_{-0.5\%}$
j.8*	$e^+e^- \to t\bar{t}Zj$	`e+ e- > t t~ z j`	$6.059 \pm 0.006 \cdot 10^{-4}$	$^{+9.3\%}_{-7.8\%}$	$6.940 \pm 0.028 \cdot 10^{-4}$	$^{+2.0\%}_{-2.6\%}$
j.9*	$e^+e^- \to t\bar{t}Zjj$	`e+ e- > t t~ z j j`	$6.351 \pm 0.028 \cdot 10^{-5}$	$^{+19.4\%}_{-15.0\%}$	$8.439 \pm 0.051 \cdot 10^{-5}$	$^{+5.8\%}_{-6.8\%}$
j.10*	$e^+e^- \to t\bar{t}W^{\pm}jj$	`e+ e- > t t~ wpm j j`	$2.400 \pm 0.004 \cdot 10^{-7}$	$^{+19.3\%}_{-14.9\%}$	$3.723 \pm 0.012 \cdot 10^{-7}$	$^{+9.6\%}_{-9.1\%}$
j.11*	$e^+e^- \to t\bar{t}HZ$	`e+ e- > t t~ h z`	$3.600 \pm 0.006 \cdot 10^{-5}$	$^{+0.0\%}_{-0.0\%}$	$3.579 \pm 0.013 \cdot 10^{-5}$	$^{+0.1\%}_{-0.0\%}$
j.12*	$e^+e^- \to t\bar{t}\gamma Z$	`e+ e- > t t~ a z`	$2.212 \pm 0.003 \cdot 10^{-4}$	$^{+0.0\%}_{-0.0\%}$	$2.364 \pm 0.006 \cdot 10^{-4}$	$^{+0.6\%}_{-0.5\%}$
j.13*	$e^+e^- \to t\bar{t}\gamma H$	`e+ e- > t t~ a h`	$9.756 \pm 0.016 \cdot 10^{-5}$	$^{+0.0\%}_{-0.0\%}$	$9.423 \pm 0.032 \cdot 10^{-5}$	$^{+0.3\%}_{-0.4\%}$
j.14*	$e^+e^- \to t\bar{t}\gamma\gamma$	`e+ e- > t t~ a a`	$3.650 \pm 0.008 \cdot 10^{-4}$	$^{+0.0\%}_{-0.0\%}$	$3.833 \pm 0.013 \cdot 10^{-4}$	$^{+0.4\%}_{-0.4\%}$
j.15*	$e^+e^- \to t\bar{t}ZZ$	`e+ e- > t t~ z z`	$3.788 \pm 0.004 \cdot 10^{-5}$	$^{+0.0\%}_{-0.0\%}$	$4.007 \pm 0.013 \cdot 10^{-5}$	$^{+0.5\%}_{-0.5\%}$
j.16*	$e^+e^- \to t\bar{t}HH$	`e+ e- > t t~ h h`	$1.358 \pm 0.001 \cdot 10^{-5}$	$^{+0.0\%}_{-0.0\%}$	$1.206 \pm 0.003 \cdot 10^{-5}$	$^{+0.9\%}_{-1.1\%}$
j.17*	$e^+e^- \to t\bar{t}W^+W^-$	`e+ e- > t t~ w+ w-`	$1.372 \pm 0.003 \cdot 10^{-4}$	$^{+0.0\%}_{-0.0\%}$	$1.540 \pm 0.006 \cdot 10^{-4}$	$^{+1.0\%}_{-0.9\%}$

- All new at NLO except ttH

NNLO matching

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
  - Geneva

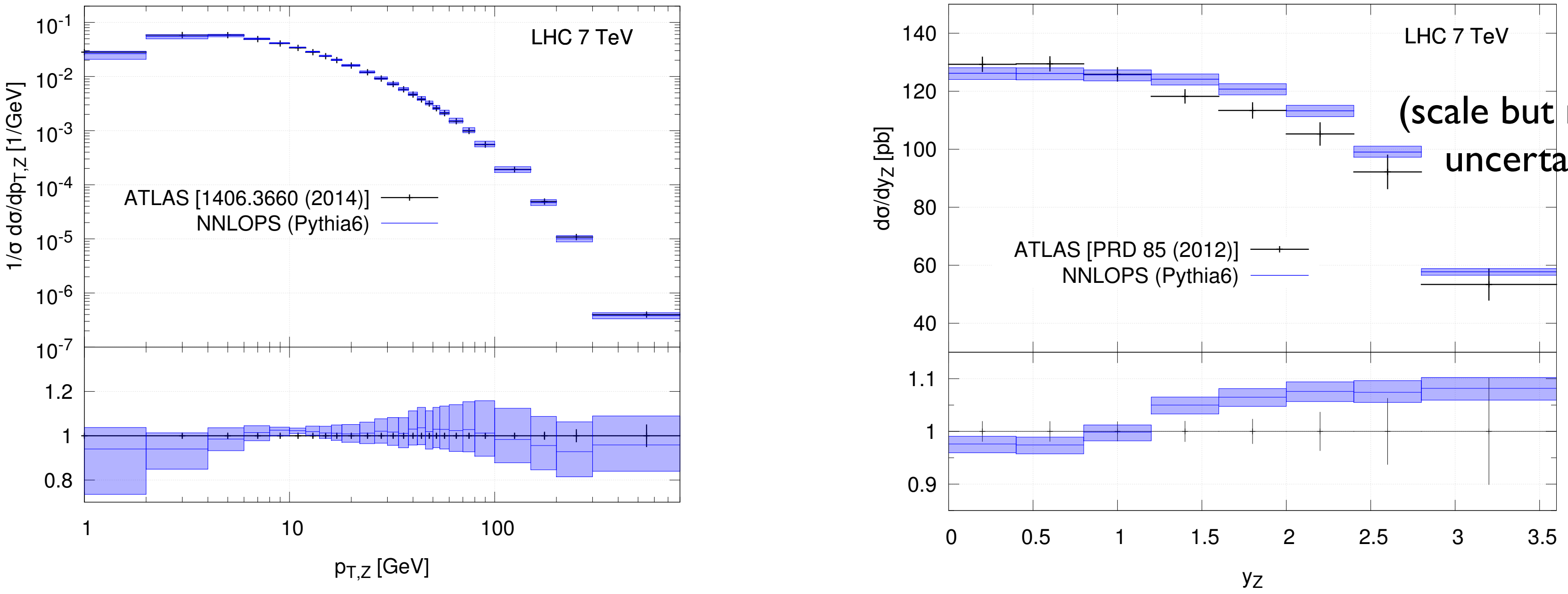
    Alioli et al., 1311.0286

MiNLO-NNLOPS

- Modified DY/H+jet POWHEG with NNLL Sudakov factor
- Reweighted to NNLO

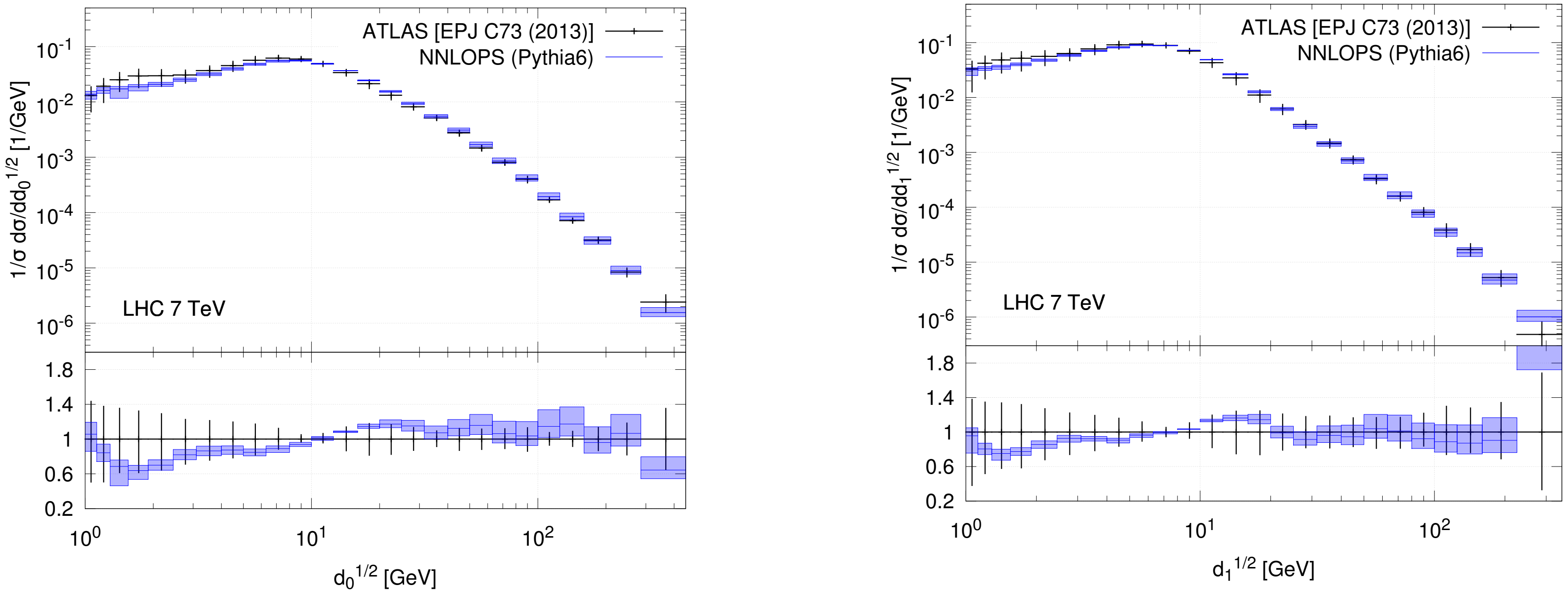
Karlberg, Re, Zanderighi, 1407.2940

- Z p_T, rapidity



(scale but no PDF uncertainty)

- W $d_{0,1}$ (k_t alg.)



UN²LOPS

Höche, Li, Prestel, 1405.3607

- Phase space slicing at q_T ~ 1 GeV (DY/H)
- q_T subtraction: NNLO in zero bin
- extra jet at NLO

$$
\begin{aligned}
\langle O\rangle^{(\mathrm{UN^2LOPS})} = & \int d\Phi_0\, \bar{\bar{\mathrm{B}}}_0^{q_{T,\mathrm{cut}}}(\Phi_0)\, O(\Phi_0) \\
& + \int_{q_{T,\mathrm{cut}}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right)\right] \mathrm{B}_1(\Phi_1)\, O(\Phi_0) \\
& + \int_{q_{T,\mathrm{cut}}} d\Phi_1\, \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right) \mathrm{B}_1(\Phi_1)\, \bar{\mathcal{F}}_1(t_1,O) \\
& + \int_{q_{T,\mathrm{cut}}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, O(\Phi_0) + \int_{q_{T,\mathrm{cut}}} d\Phi_1 \Pi_0(t_1,\mu_Q^2)\, \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, \bar{\mathcal{F}}_1(t_1,O) \\
& + \int_{q_{T,\mathrm{cut}}} d\Phi_2 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, O(\Phi_0) + \int_{q_{T,\mathrm{cut}}} d\Phi_2\, \Pi_0(t_1,\mu_Q^2)\, \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, \mathcal{F}_2(t_2,O) \\
& + \int_{q_{T,\mathrm{cut}}} d\Phi_2\, \mathrm{H}_1^{\mathrm{E}}(\Phi_2)\, \mathcal{F}_2(t_2,O)
\end{aligned}
$$

UN^{2}LOPS results (DY)

Höche, Li, Prestel, 1405.3607

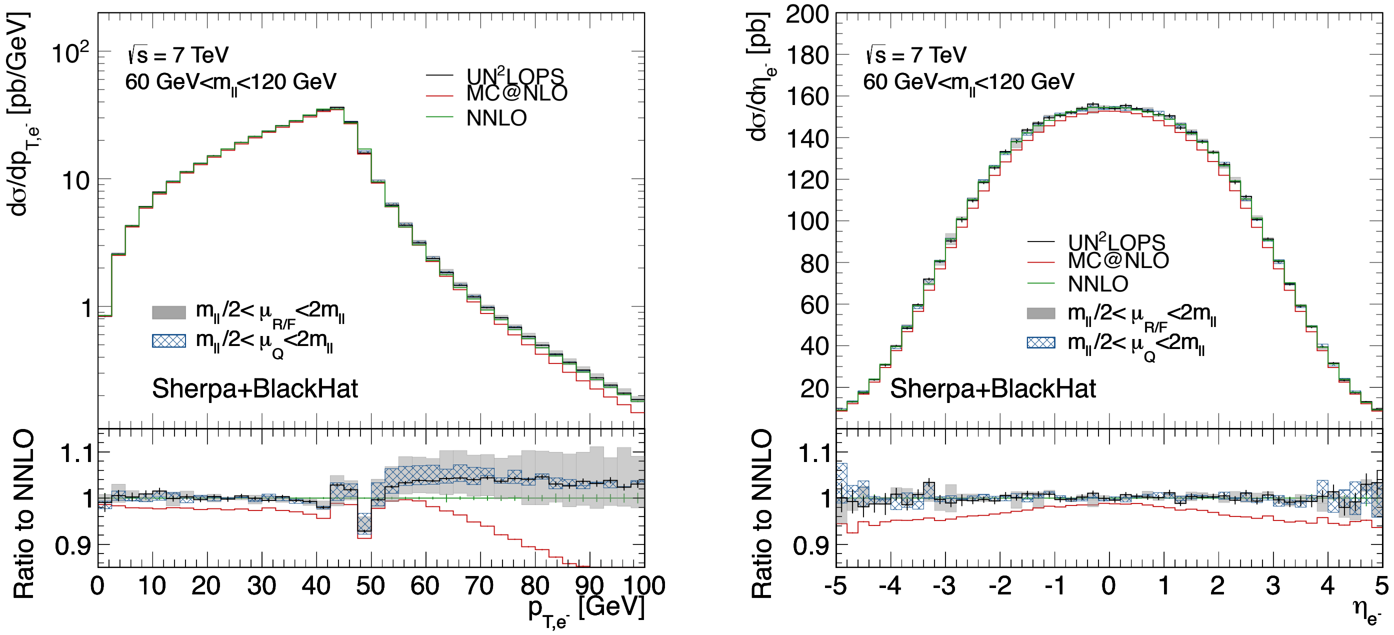


FIG. 2. Transverse momentum and rapidity spectrum of the electron. The gray solid (blue hatched) band shows scale uncertainties obtained by varying $\mu_{R/F}$ (μ_Q) in the range $m_{ll}/2 \leq \mu \leq 2\,m_{ll}$.

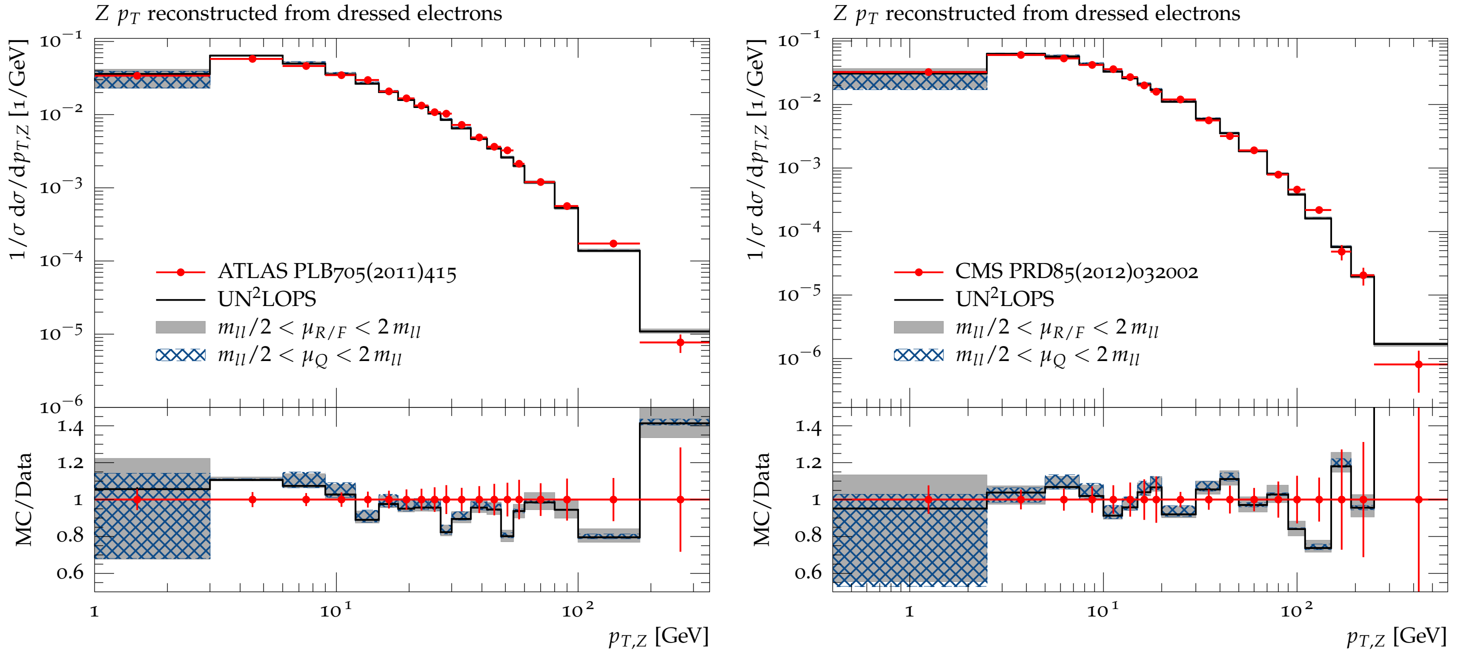


FIG. 3. UN^{2}LOPS prediction for the transverse momentum spectrum of the Drell-Yan lepton pair in comparison to ATLAS data from [39] (left) and CMS data from [38] (right). The gray solid (blue hatched) band shows scale uncertainties obtained by varying $\mu_{R/F}$ (μ_Q) in the range $m_{ll}/2 \leq \mu \leq 2\,m_{ll}$.

UN^{2}LOPS results (Higgs)

Höche, Li, Prestel, 1407.3773

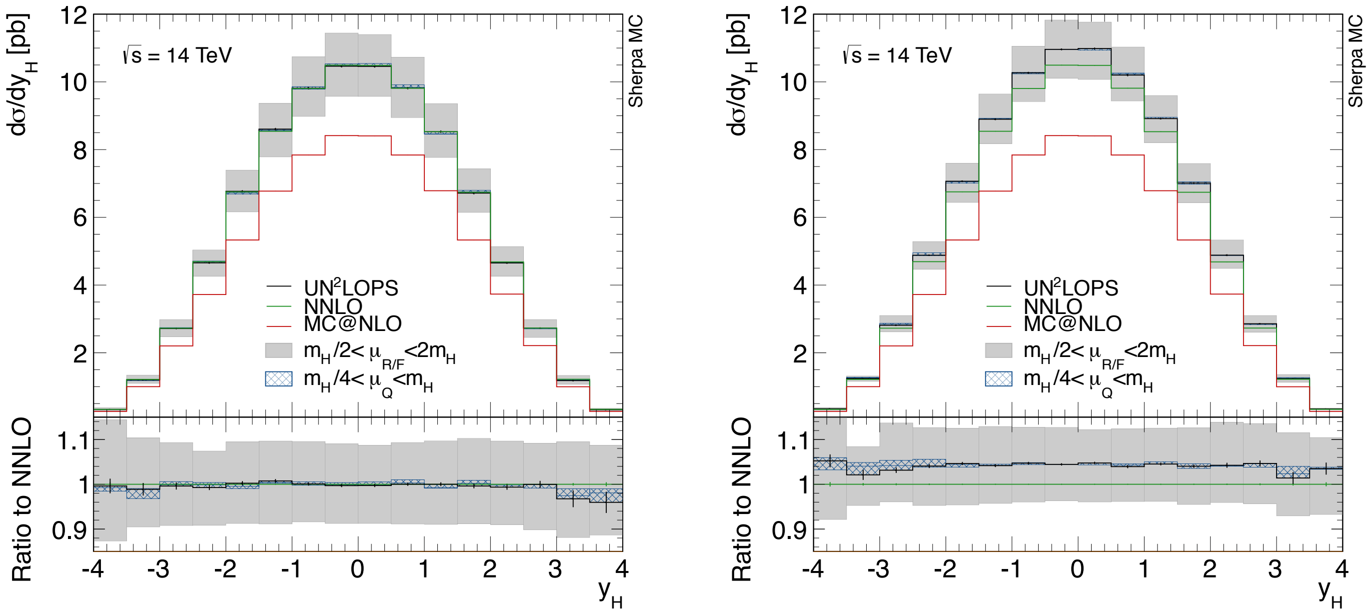


FIG. 2. Rapidity spectrum of the Higgs boson in individual matching (left) and factorized matching (right). See Sec. IV for details.

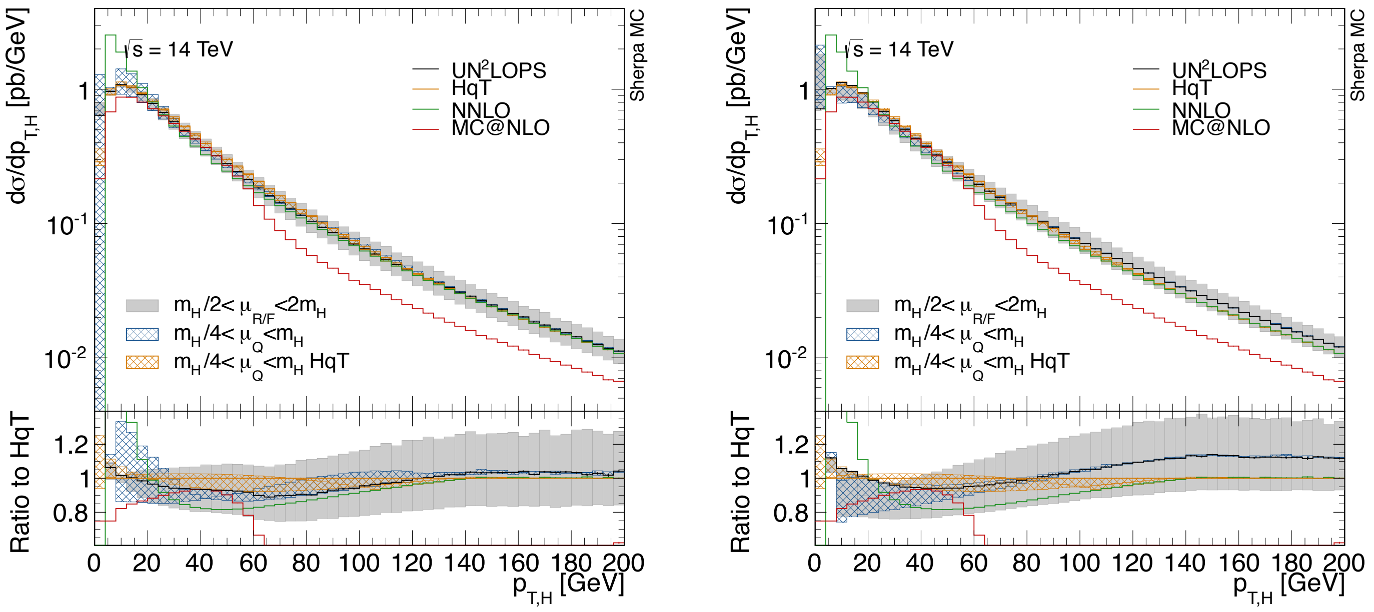
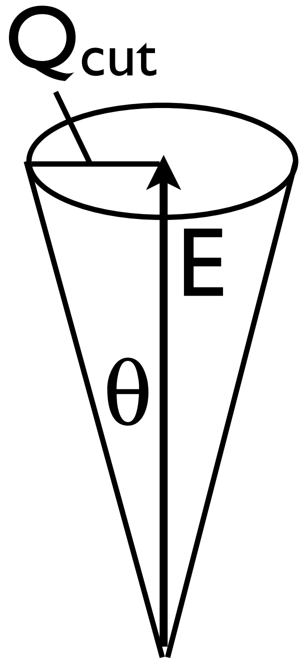


FIG. 3. Transverse momentum spectrum of the Higgs boson in individual matching (left) and factorized matching (right). See Sec. IV for details.

Merging/matching to multiple fixed orders

LO 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

Merging at NLO (?)

- Separate samples by jet resolution, d_{cut}
- Make n-jet sample NLO for $d_{n+1} < d_{cut} < d_n$
- Avoid double counting
- Reduce d_{cut} dependence
  - MEPS@NLO: Höche et al., 1207.5030
  - FxFx: Frederix, Frixione, 1209.6215
  - Geneva: Alioli et al., 1211.7049
  - UNLOPS: Lönnblad, Prestel, 1211.7278, Plätzer, 1211.5467

MEPS@NLO

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

Höche et al., 1207.5030

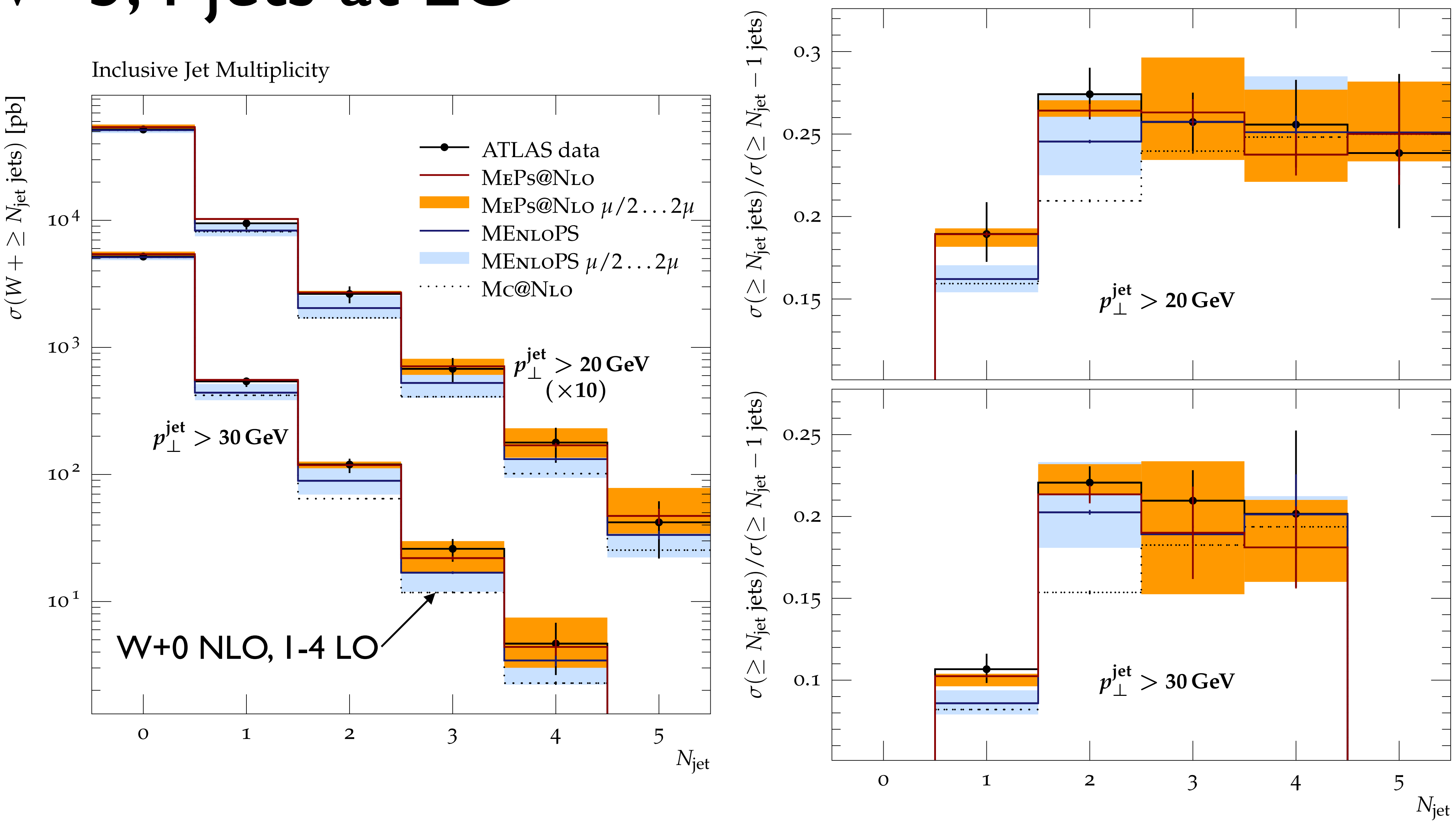


Figure 1: Cross section as a function of the inclusive jet multiplicity (left) and their ratios (right) in W+jets events measured by ATLAS [50].

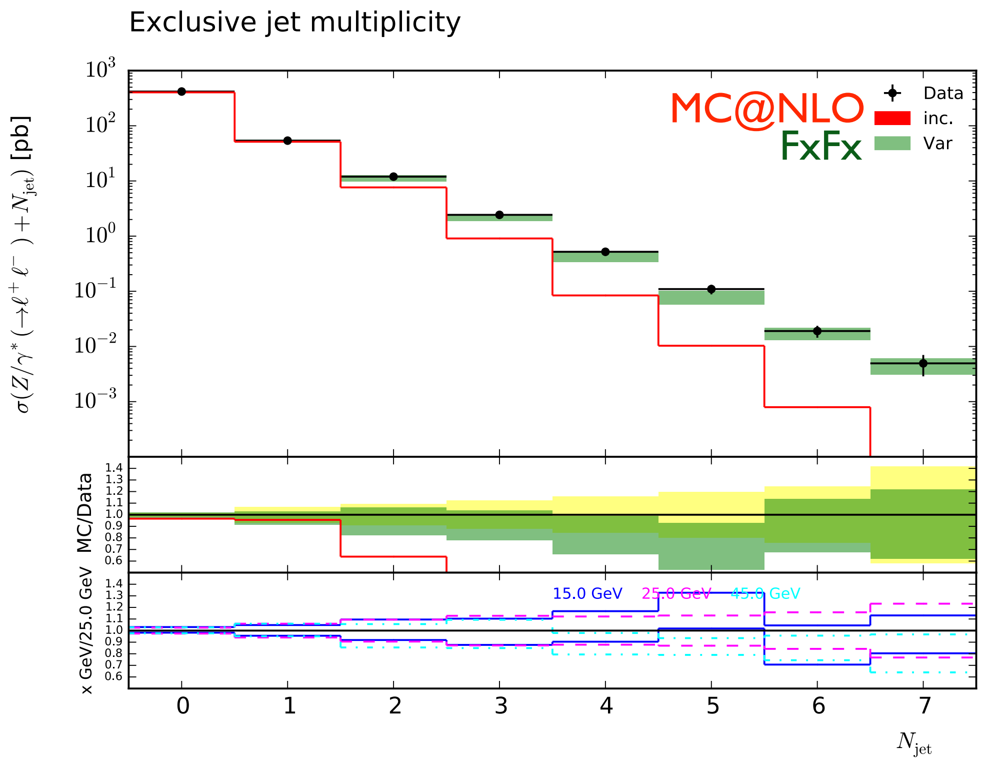
FxFx merging

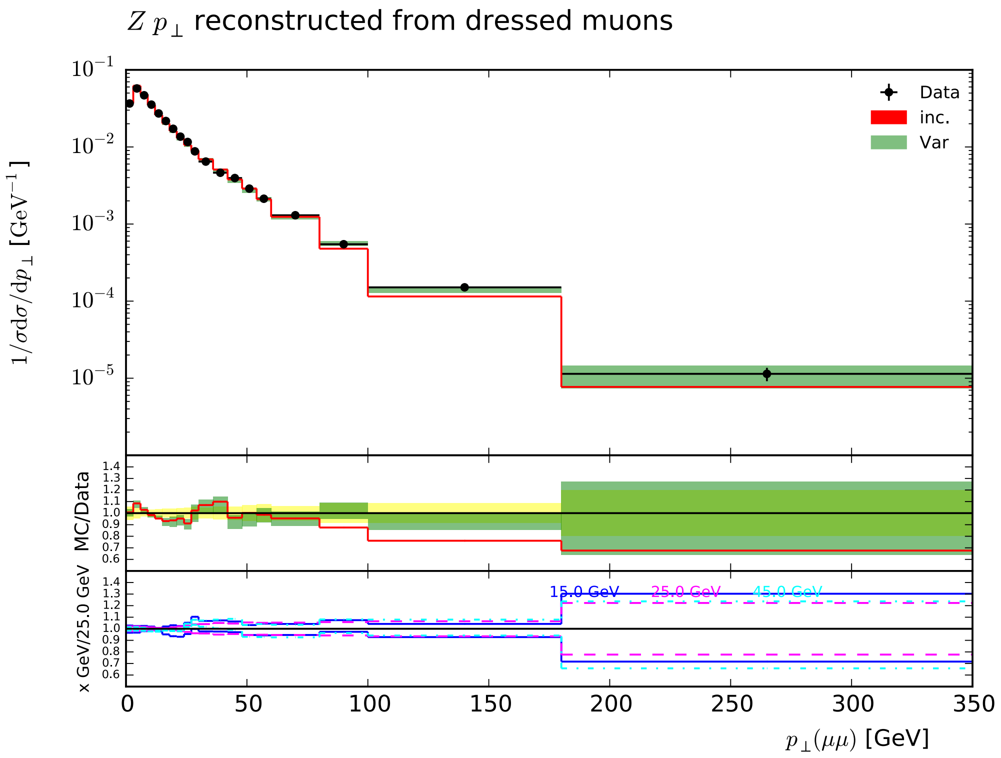
Frederix, Frixione, 1209.6215

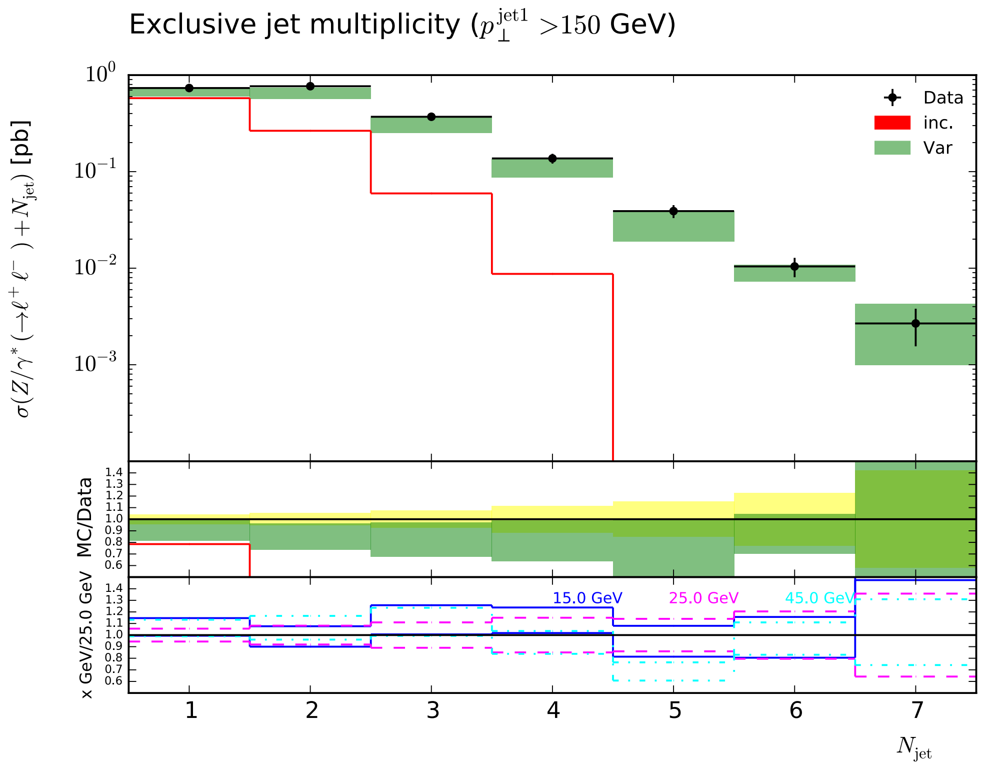
- $\mathbb{S}$ and $\mathbb{H}$ event samples for each multiplicity ($D(d_i) \approx \Theta(\mu_2 - d_i)$)

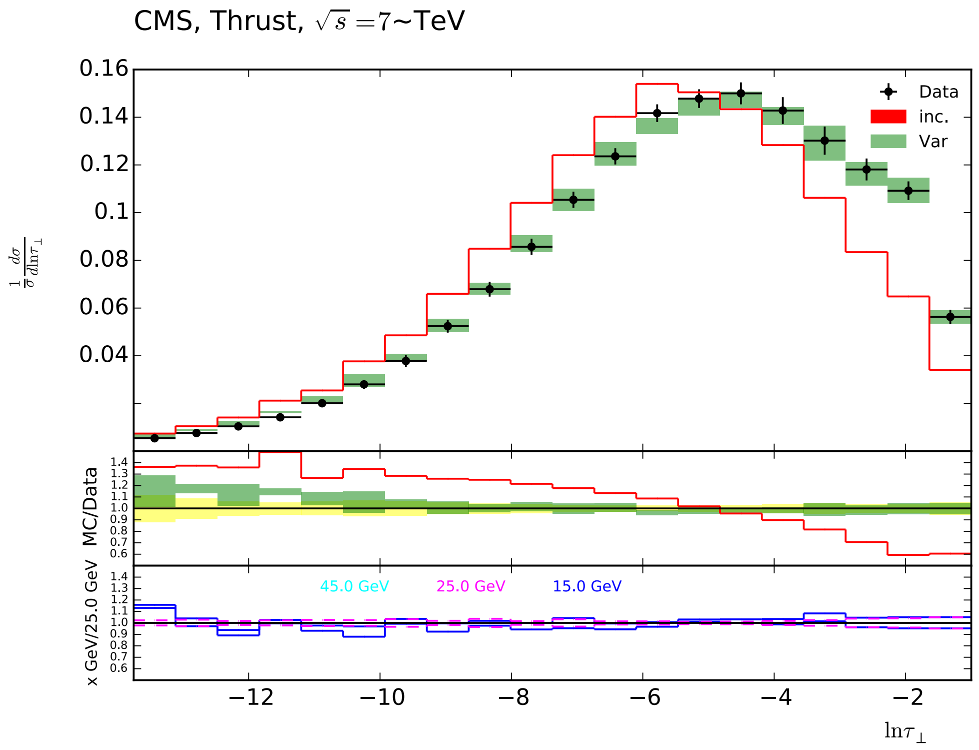
$$
\begin{aligned}
d\bar{\sigma}_{\mathbb{S},0} &= T_0 + V_0 - T_0\mathcal{K} + T_0\mathcal{K}_{\rm MC} D(d_1(\Xi_{\mathbb{H},0}))\,, \\
d\bar{\sigma}_{\mathbb{H},0} &= \Big[T_1 - T_0\mathcal{K}_{\rm MC}\Big]\, D(d_1(\Xi_{\mathbb{H},0}))\,, \\
d\bar{\sigma}_{\mathbb{S},i} &= \Big[T_i + V_i - T_i\mathcal{K} + T_i\mathcal{K}_{\rm MC} D(d_{i+1}(\Xi_{\mathbb{H},i}))\Big] \\
&\quad \times \left(1 - D(d_i(\Xi_{\mathbb{S},i}))\right)\, \Theta\left(d_{i-1}(\Xi_{\mathbb{S},i}) - \mu_2\right)\,, \\
d\bar{\sigma}_{\mathbb{H},i} &= \Big[T_{i+1}\left(1 - D(d_i(\Xi_{\mathbb{H},i}))\right) \Theta\left(d_{i-1}(\Xi_{\mathbb{H},i}) - \mu_2\right) \\
&\quad -T_i\mathcal{K}_{\rm MC}\left(1 - D(d_i(\Xi_{\mathbb{S},i}))\right) \Theta\left(d_{i-1}(\Xi_{\mathbb{S},i}) - \mu_2\right)\Big]\, D(d_{i+1}(\Xi_{\mathbb{H},i}))\,, \\
d\bar{\sigma}_{\mathbb{S},N} &= \Big[T_N + V_N - T_N\mathcal{K} + T_N\mathcal{K}_{\rm MC}\Big] \\
&\quad \times \left(1 - D(d_N(\Xi_{\mathbb{S},N}))\right) \Theta\left(d_{N-1}(\Xi_{\mathbb{S},N}) - \mu_2\right)\,, \\
d\bar{\sigma}_{\mathbb{H},N} &= T_{N+1}\left(1 - D(d_N(\Xi_{\mathbb{H},N}))\right) \Theta\left(d_{N-1}(\Xi_{\mathbb{H},N}) - \mu_2\right) \\
&\quad - T_N\mathcal{K}_{\rm MC}\left(1 - D(d_N(\Xi_{\mathbb{S},N}))\right) \Theta\left(d_{N-1}(\Xi_{\mathbb{S},N}) - \mu_2\right)\,.
\end{aligned}
$$

FxFx Z results (1)



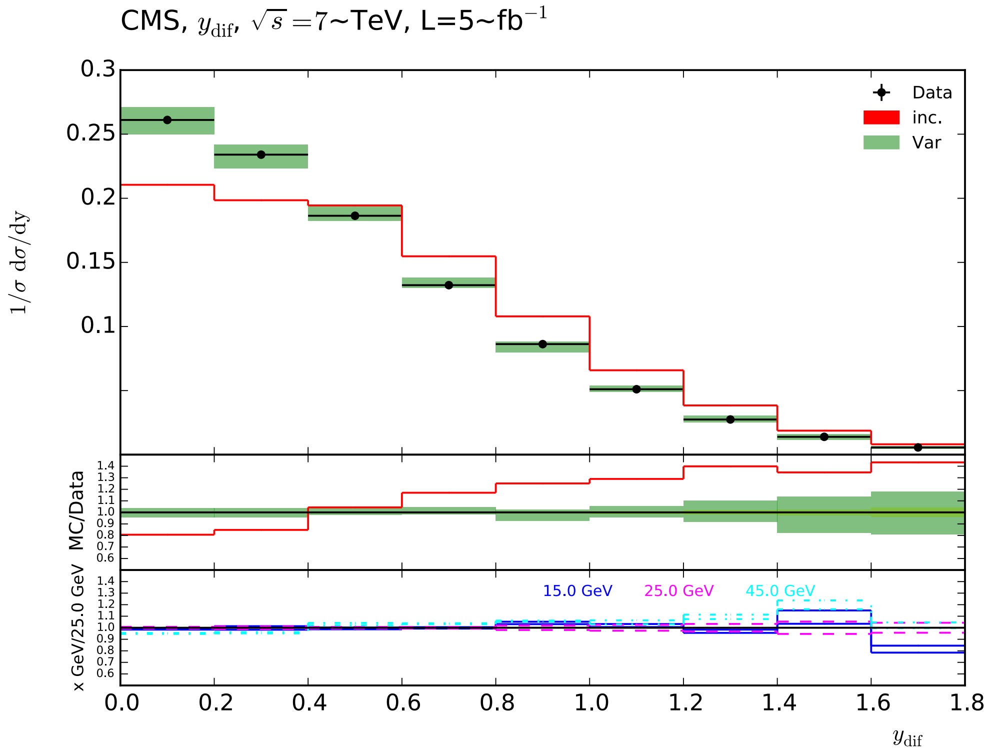


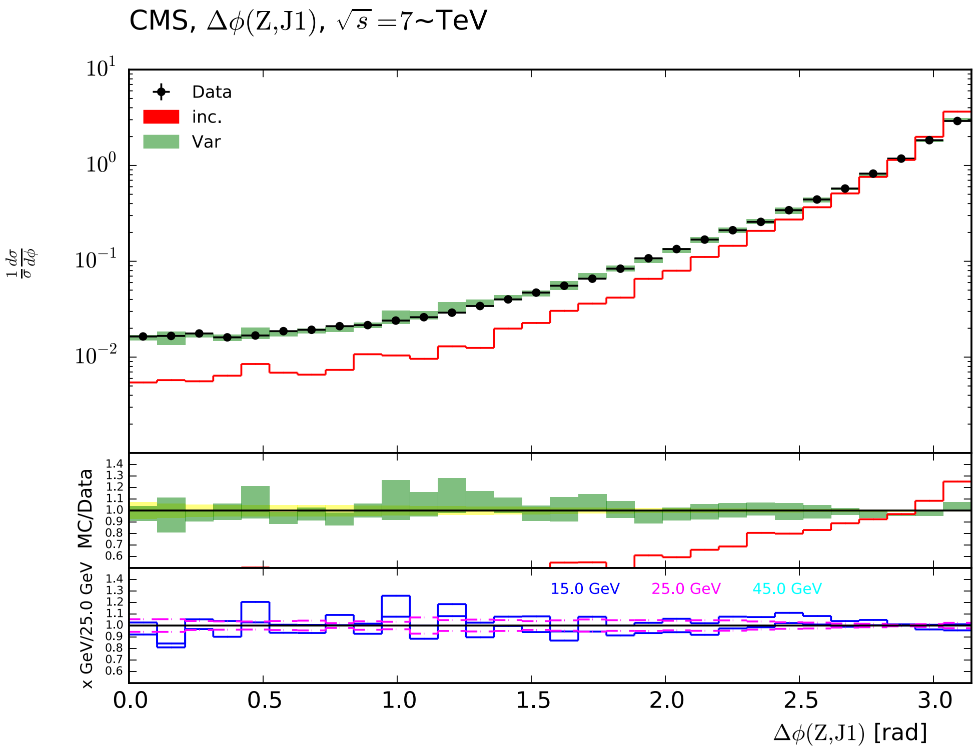


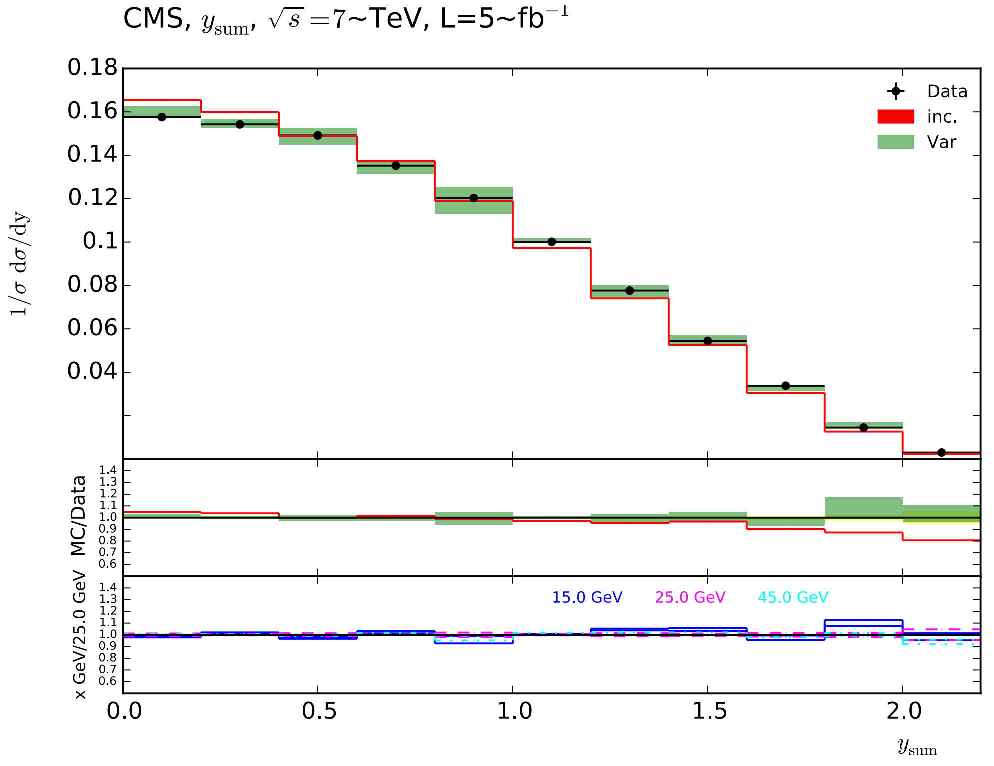


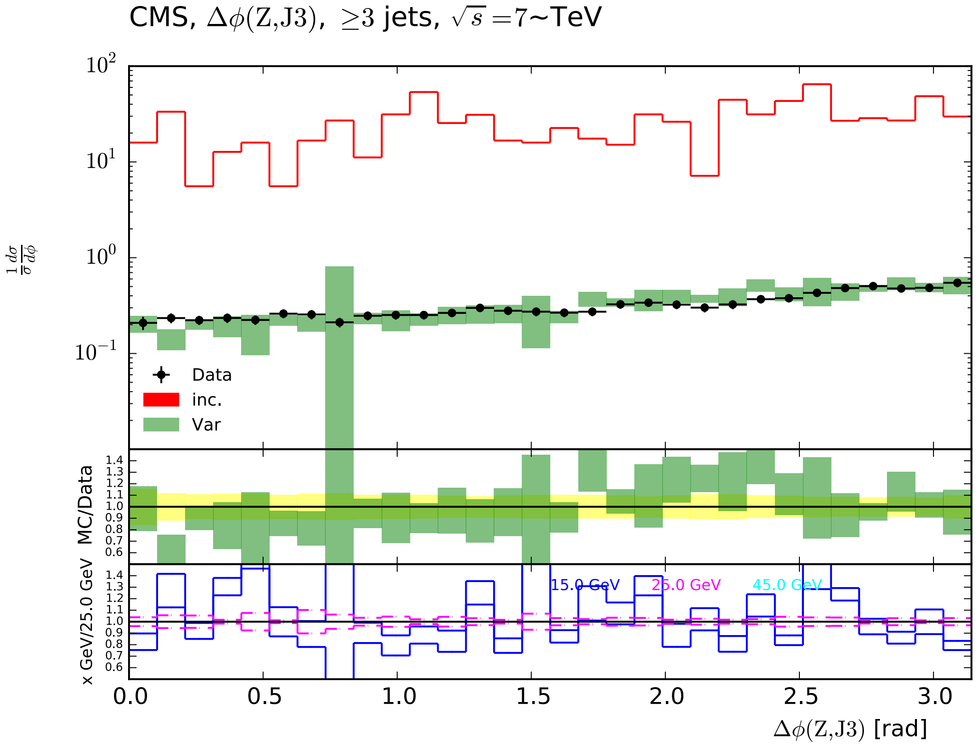
Frederix, Frixione, Papaefstathiou, Prestel, Torrielli, in prep.

FxFx Z results (2)

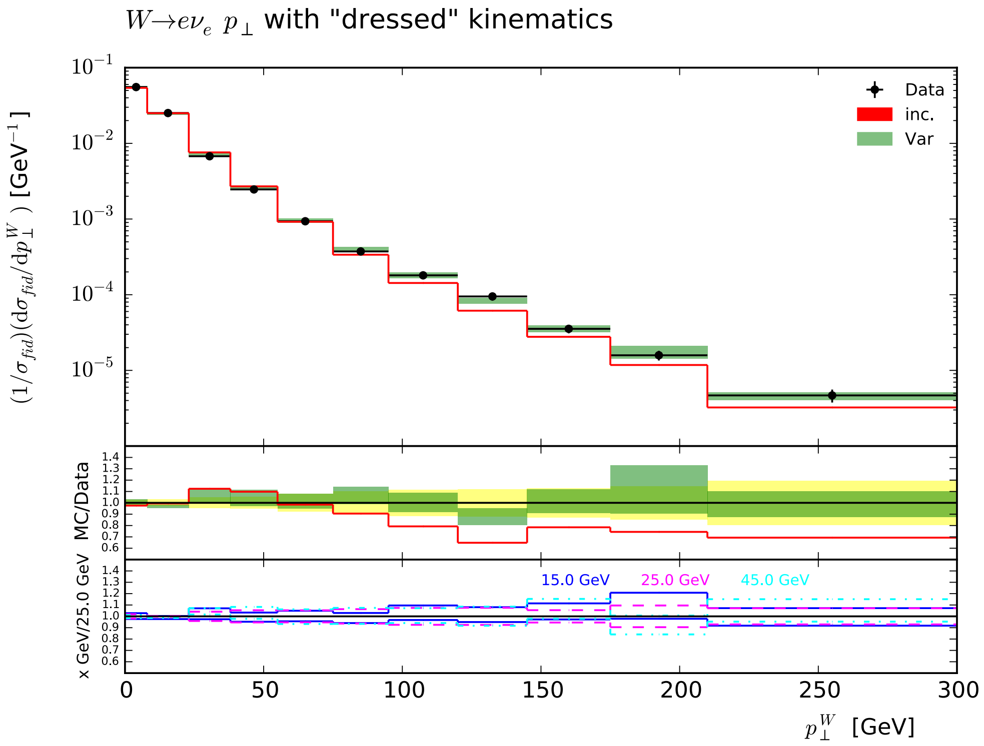

CMS, $y_{\rm dif}$, $\sqrt{s}$ =7~TeV, L=5~fb^{-1}

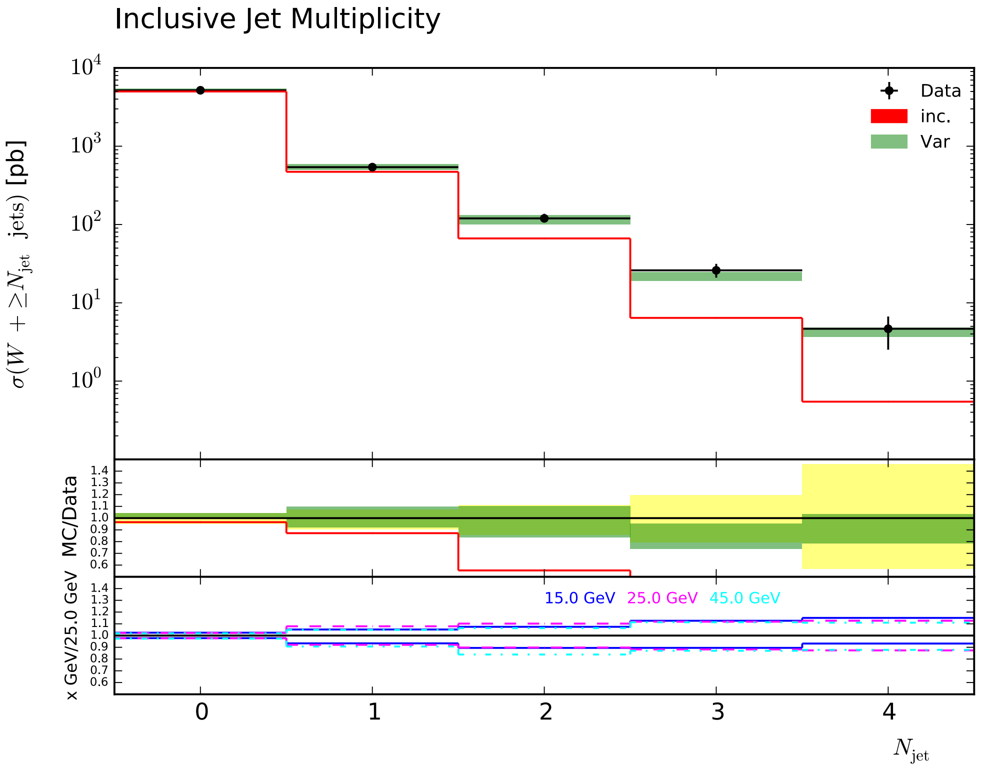

CMS, $\Delta\phi$(Z,J1), $\sqrt{s}$ =7~TeV

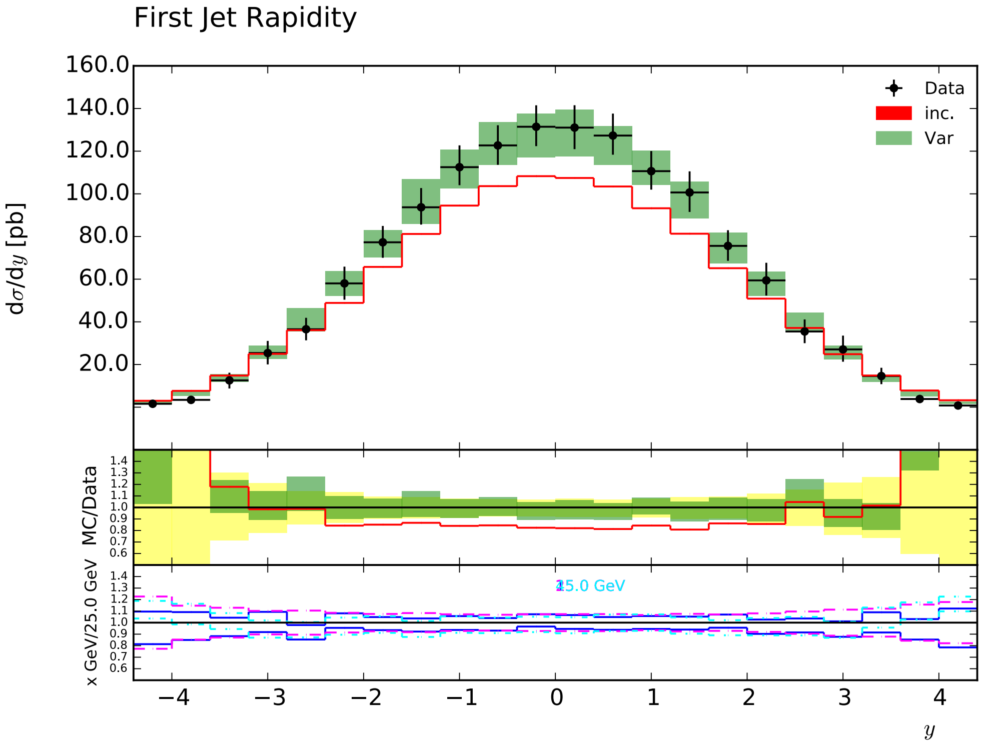

CMS, $y_{\rm sum}$, $\sqrt{s}$ =7~TeV, L=5~fb^{-1}

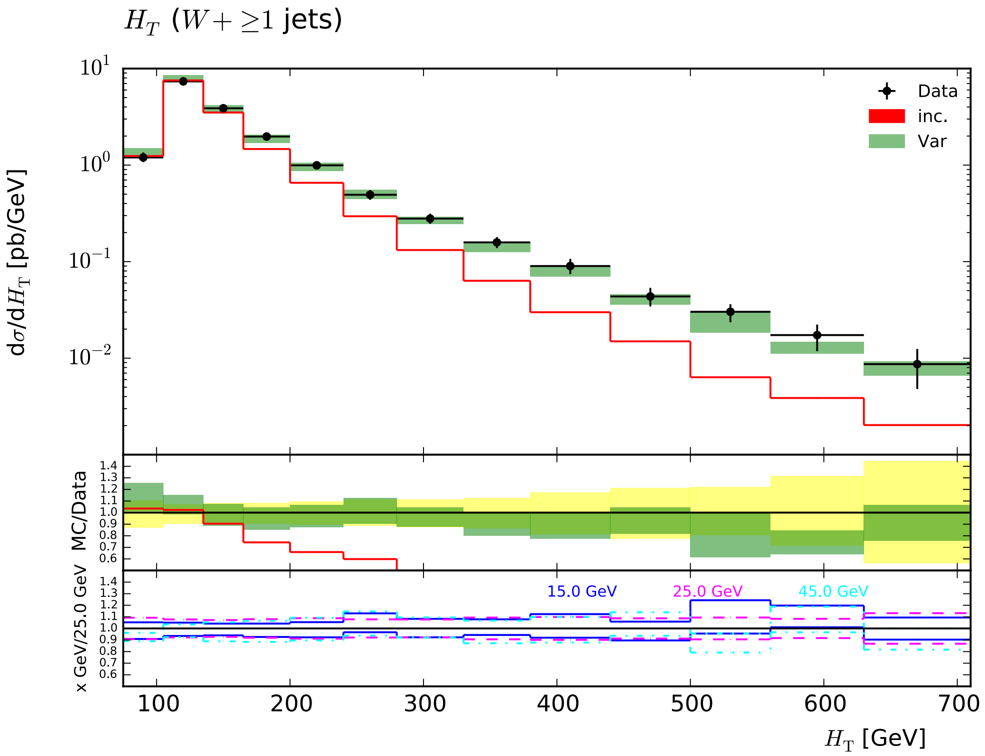

CMS, $\Delta\phi$(Z,J3), $\geq$3 jets, $\sqrt{s}$ =7~TeV

FxFx W results (1)

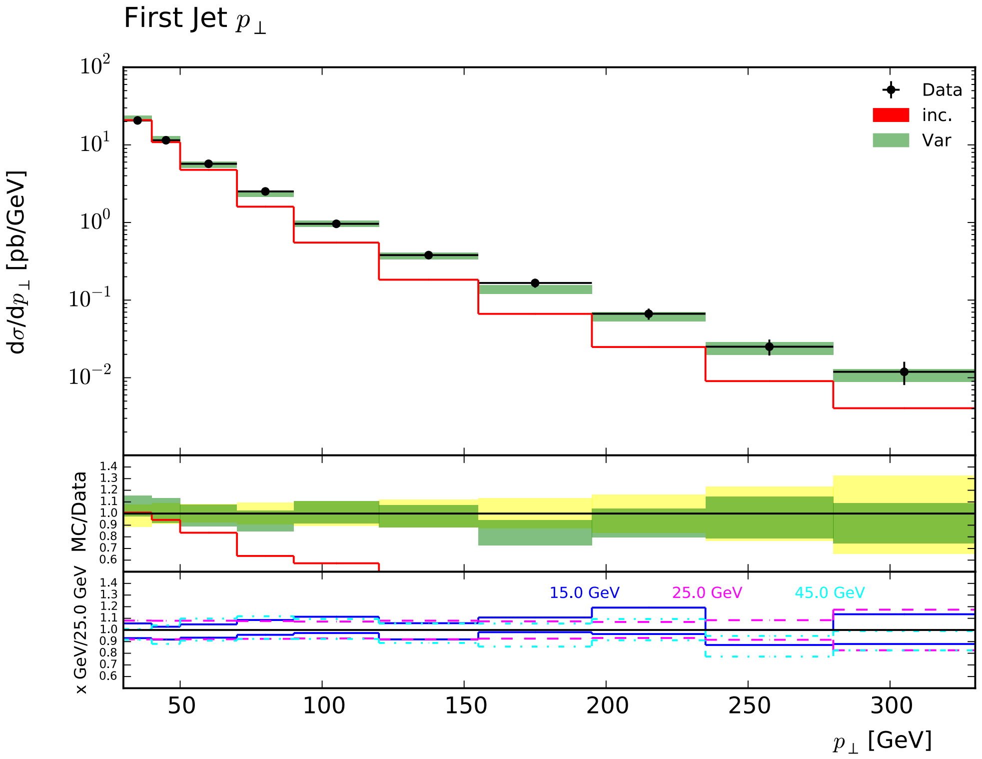


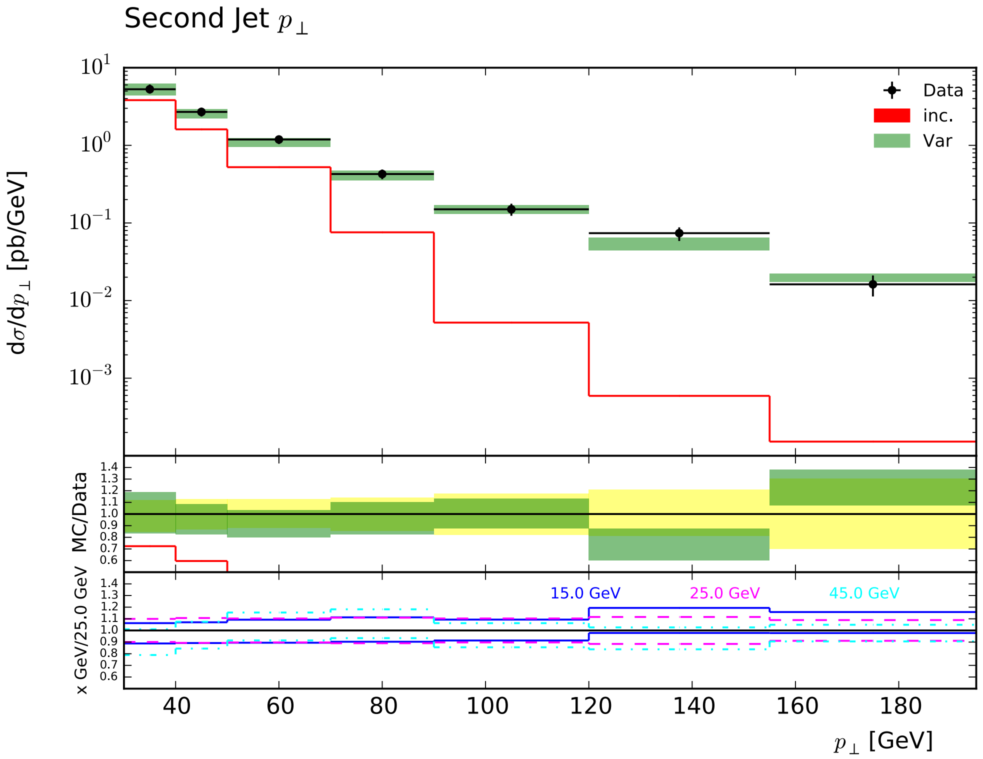


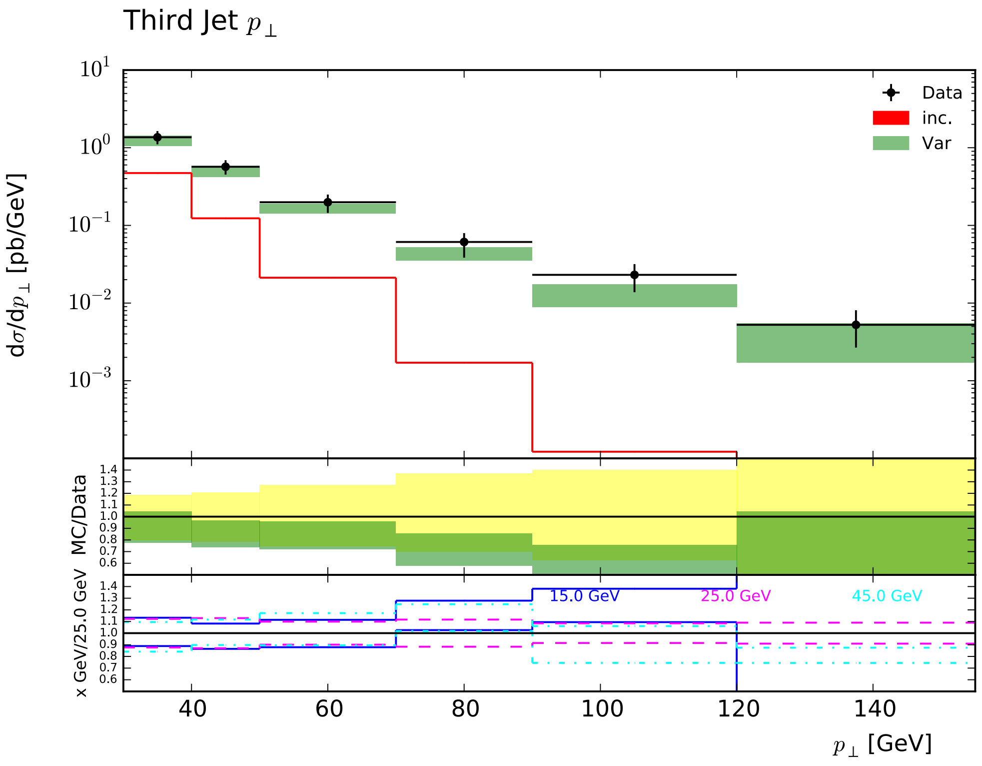


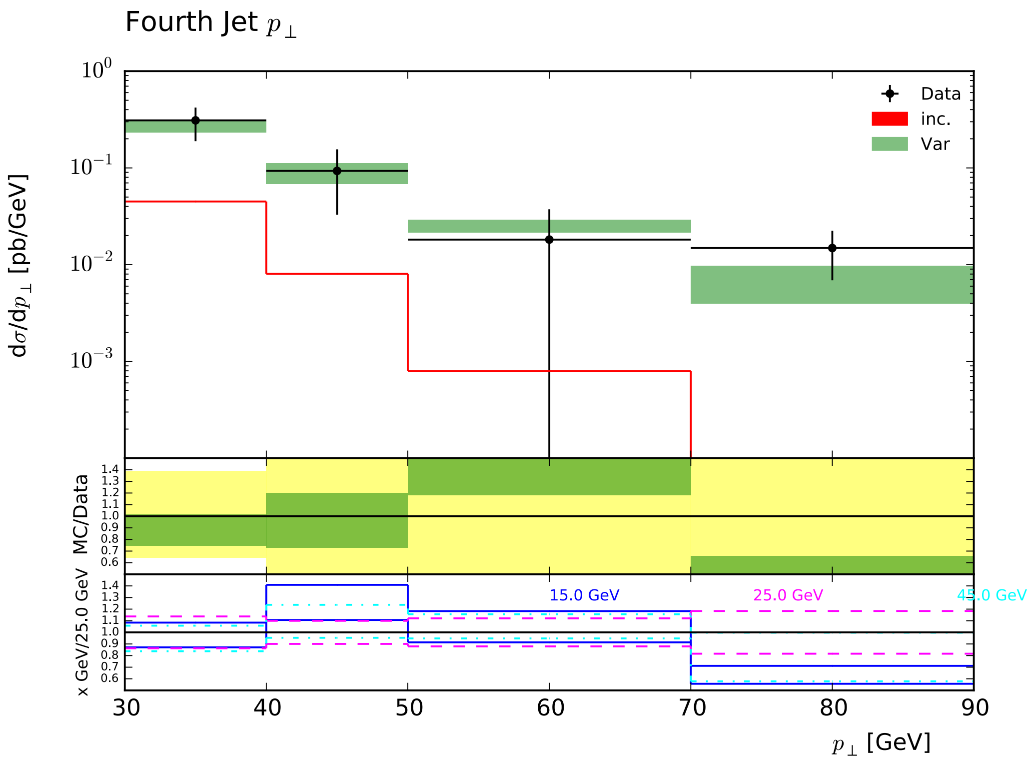


FxFx W results (2)


First Jet $p_\perp$

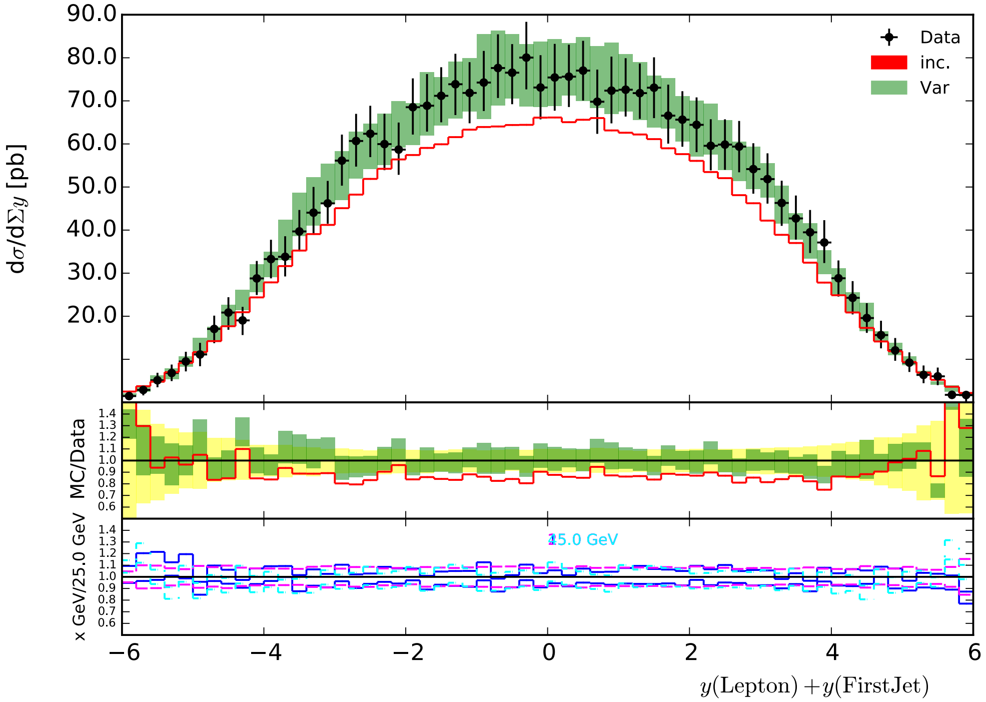

Second Jet $p_\perp$


Third Jet $p_\perp$

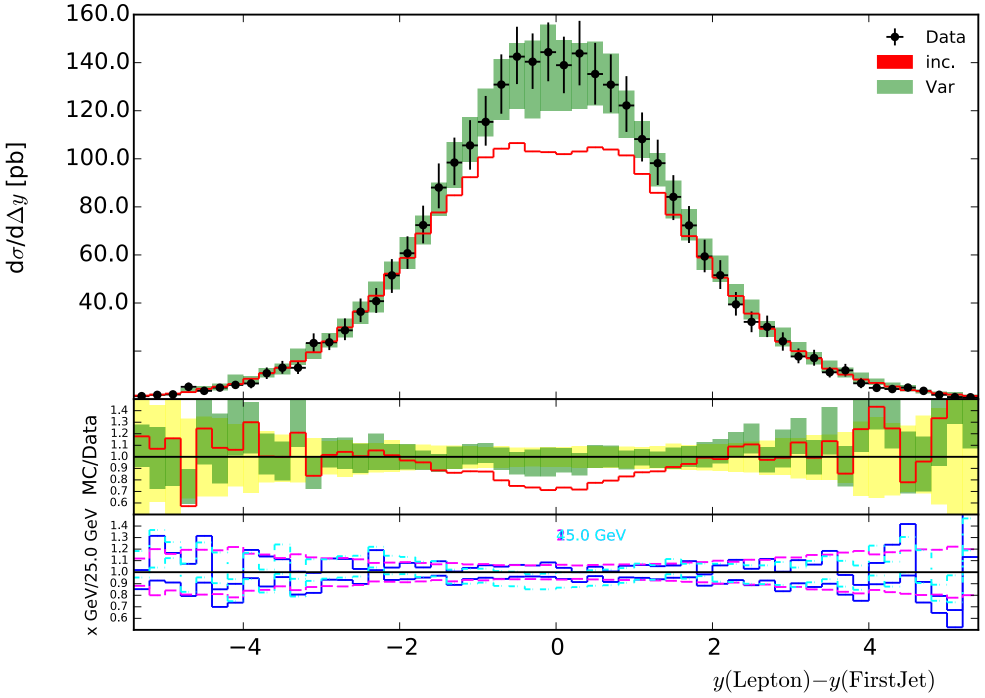

Fourth Jet $p_\perp$

FxFx W results (3)

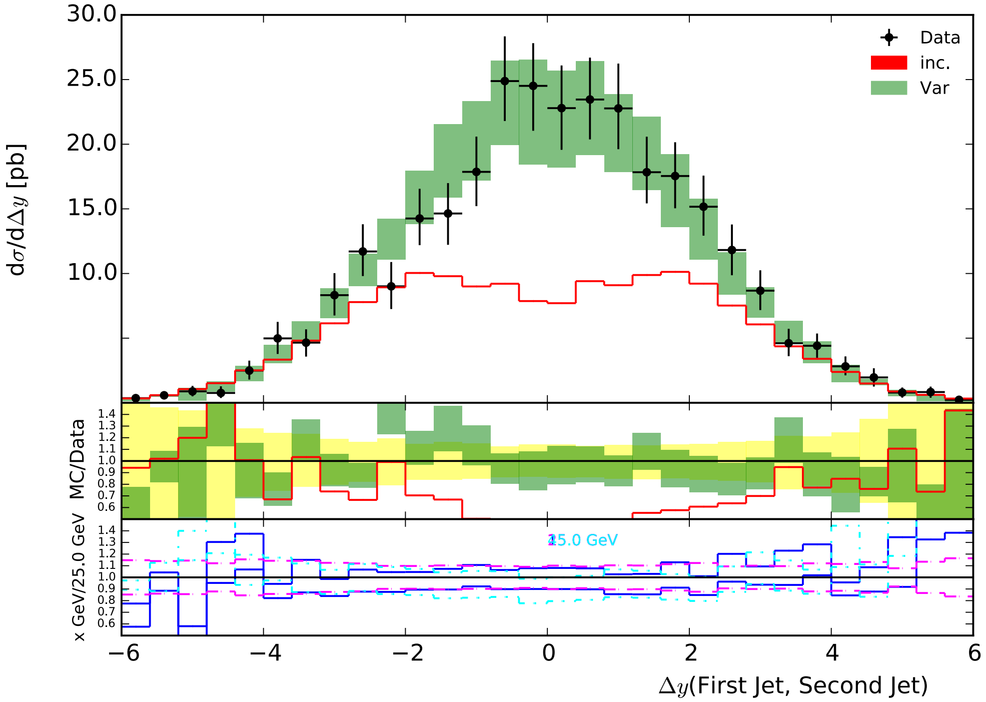
Lepton-Jet Rapidity Sum



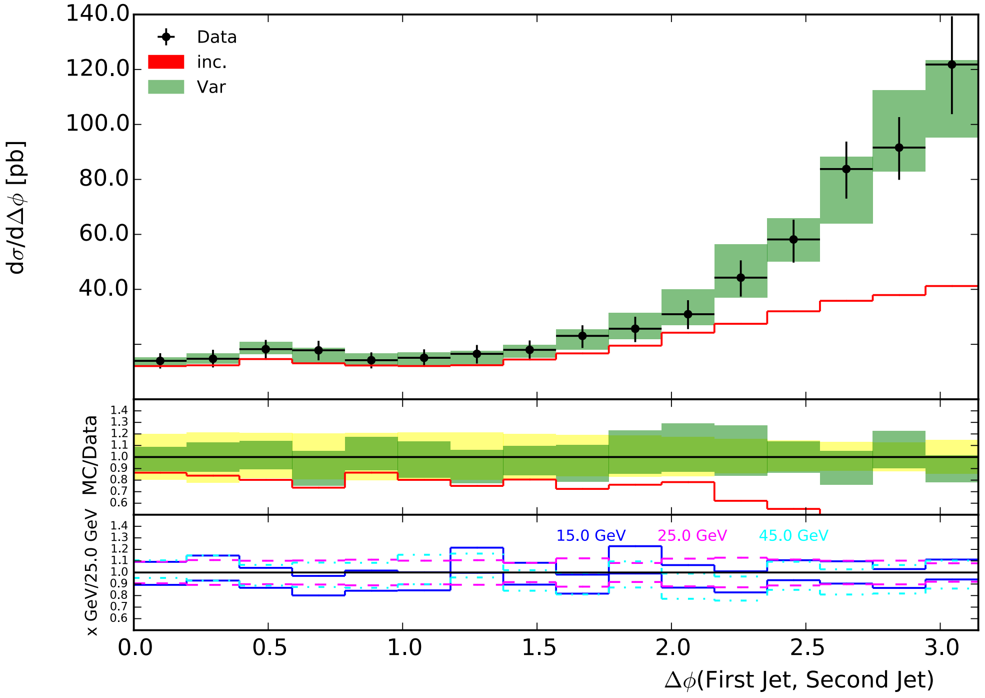
Lepton-Jet Rapidity Difference



Rapidity Distance of Leading Jets



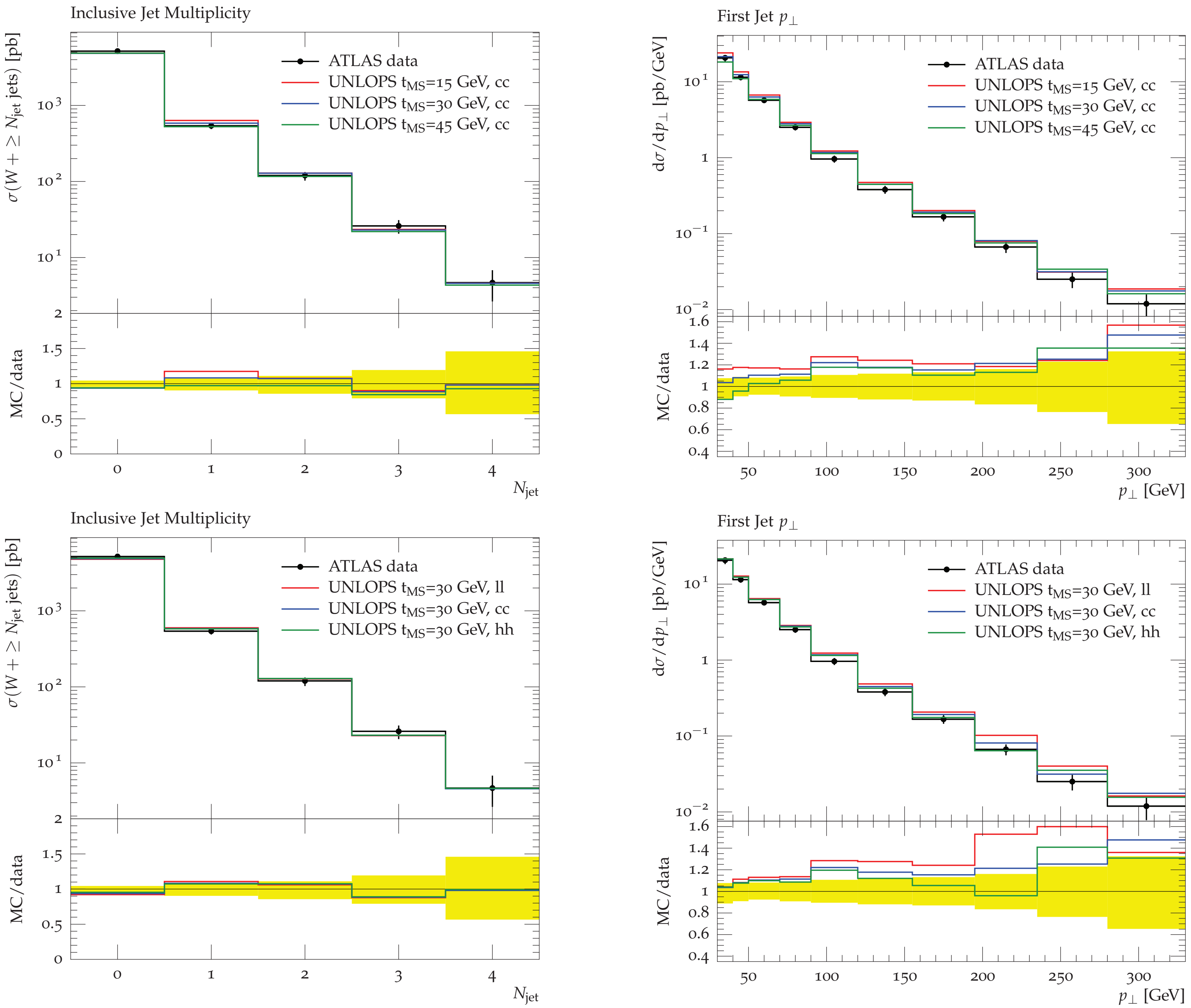
Azimuthal Distance of Leading Jets



UNLOPS merging

Lönnblad, Prestel, 1211.7278

- Merging scale dependence
- Renorm’n/ factor’n scale dependence



Conclusions

- Parton showers
  - Coherence effects visible
  - Spin and subleading colour effects small
  - Hadronization important, but little effort/progress
- Matching at NLO
  - SM processes automated, BSM soon
- Matching at NNLO
  - So far only DY & H, others much harder
- Merging at NLO
  - Still in a state of flux; FxFx automated

Thanks for listening!