Discovery physics at the LHC: Standard Model issues

CMS-TH mtg

LHC Search Strategies,

Perimeter Institute, August 2-4 2012

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Outline

- The LHC provides plenty of opportunities for a rich programme of SM measurements
  - measurements of fundamental parameters (mtop, sinthetaW, CKM, ...)
  - studies of QCD dynamics and proton structure (PDF's)
- Will focus here on topics of relevance to the Higgs/BSM programme
- Key challenges:
  - control of the dynamics in "extreme" regimes:
    - multijet production
    - multiscale problems, resummation
  - input parameters: PDFs
  - precision of perturbative calculations, control of systematics

Multiscale problems

- Presence of different scales leads to large logarithms in perturbation theory. Examples:
  - $p_T(X)$, X=H, ttbar, gluino-gluino, ..., in the region where $\mathbf{p_T << m(X)}$ $\Rightarrow$ $\mathbf{\log(m/p_T)}$
  - emission of additional jets in VBF $\Rightarrow$ $\mathbf{\log(M_{jj}/p_T)}$
- Impact, examples:
  - p_T(t tbar) can discriminate between pp→ttbar and pp→ttbar chi0chi0
  - ISR as tagging tool for SUSY production of compressed spectra
  - jet veto efficiency in VBF analyses

- Advanced techniques developed over the years. Tested at the Tevatron, mainly in the context of q-qbar reactions, but in limited kinematical regimes, due to limited accessible phase-space:
  - DY p_T spectrum
  - p_T(t tbar)

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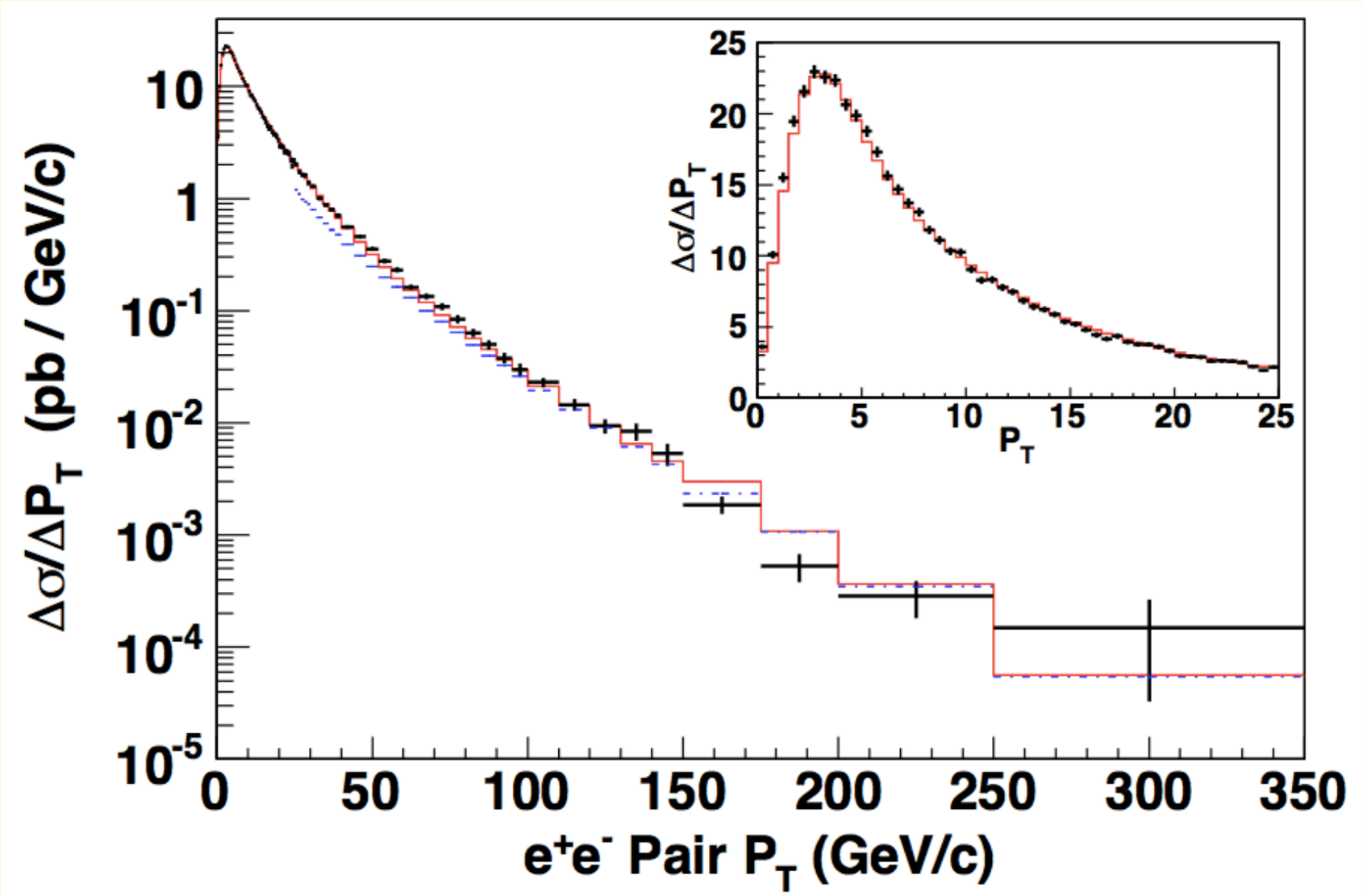
p_T(Z) spectrum at the Tevatron
(CDF, arXiv:1207.7138)



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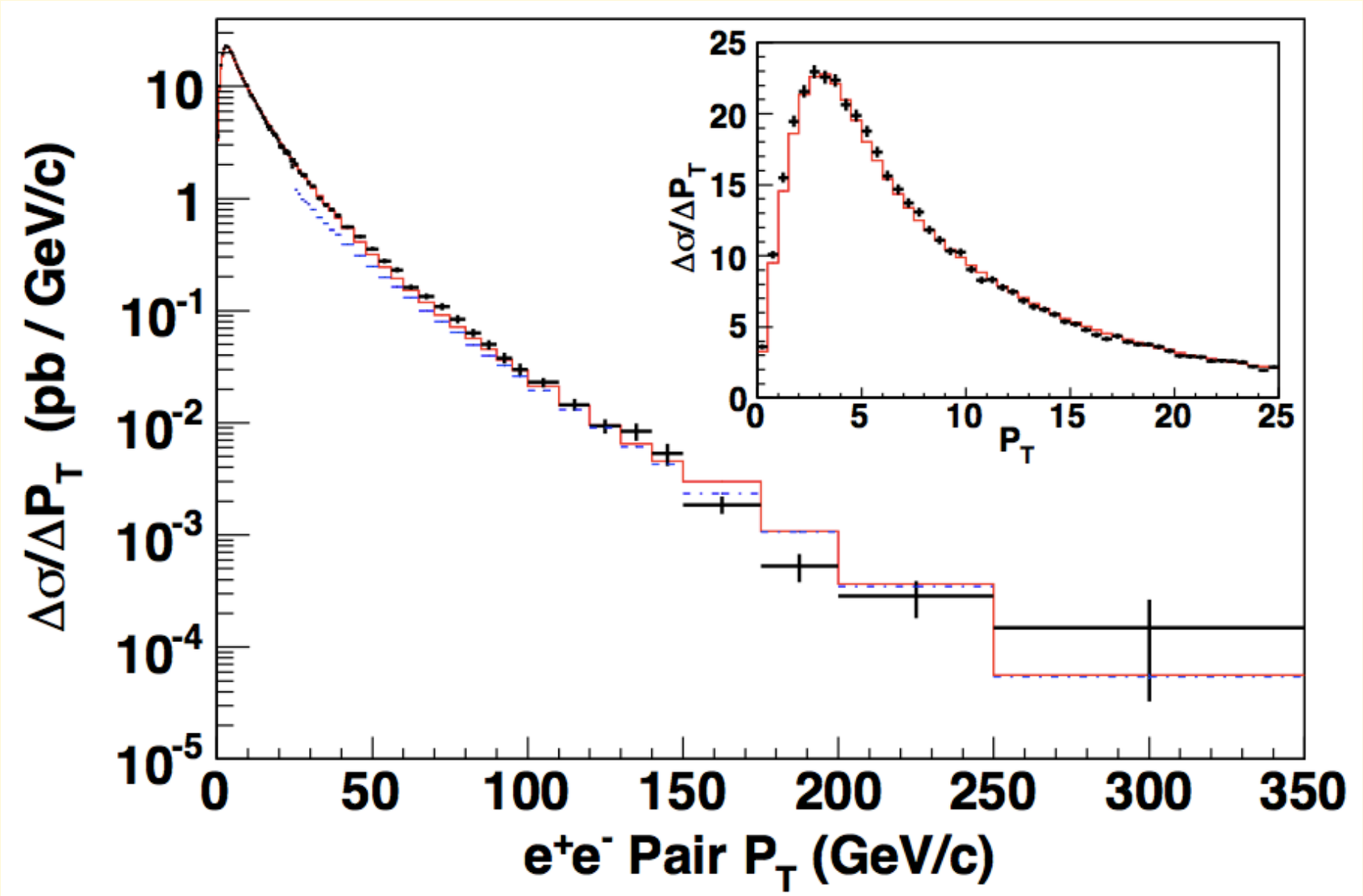
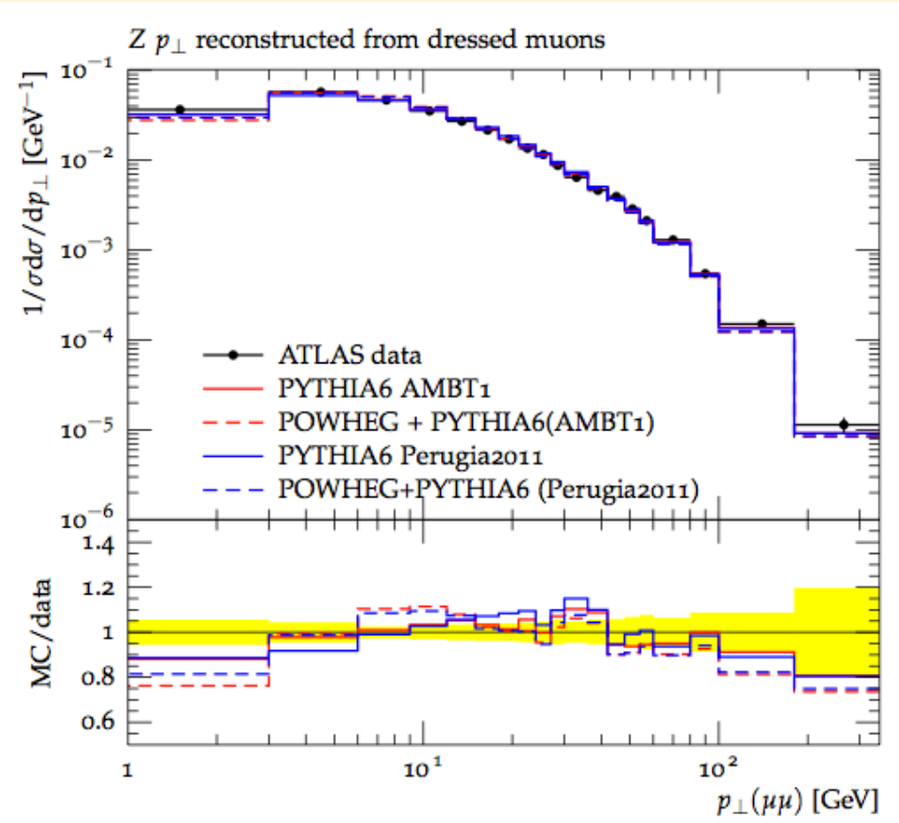
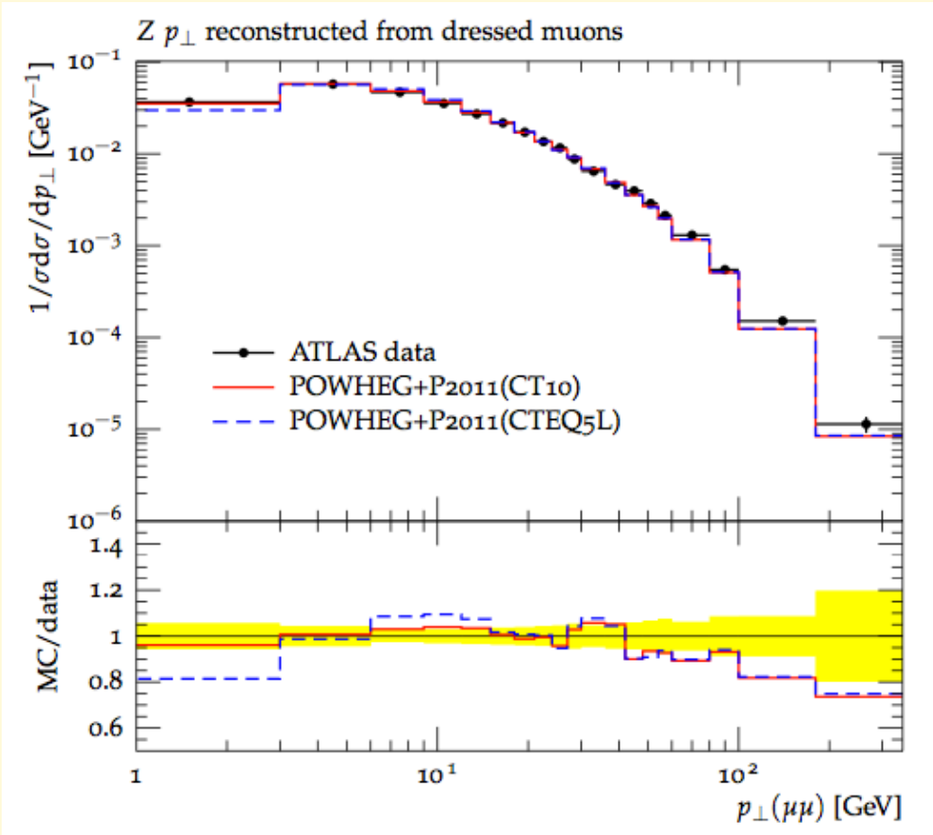


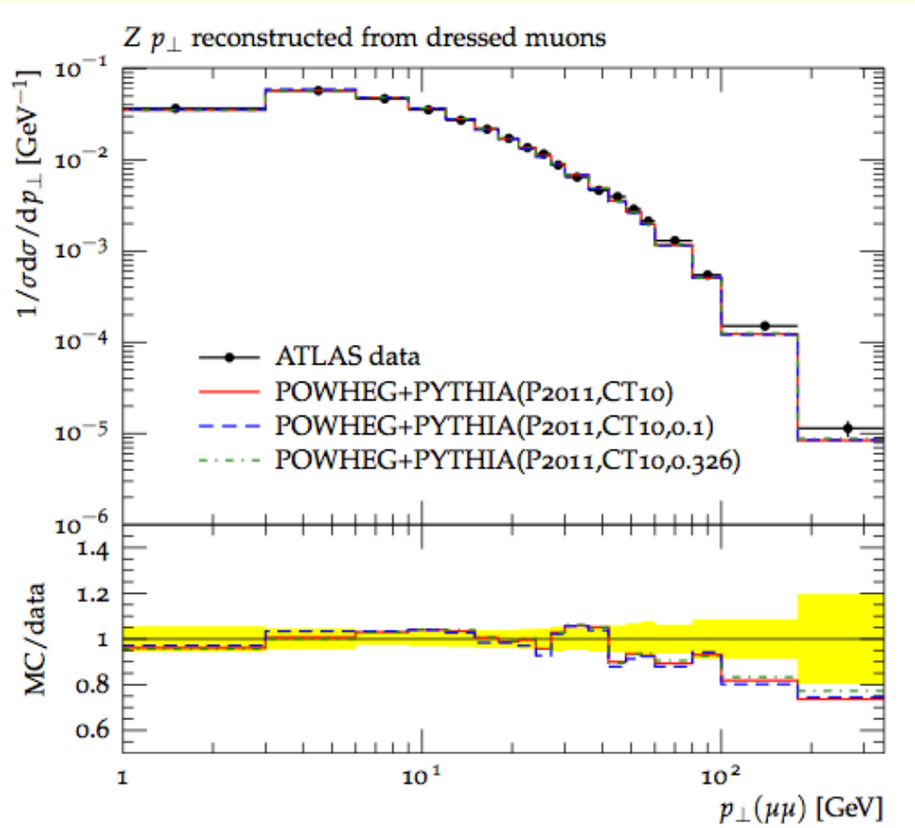
- No compelling test so far with gg initial states, or with extreme kinematical configurations such as those emerging in VBF processes

ISR validation/tuning in qqbar→DY at the LHC

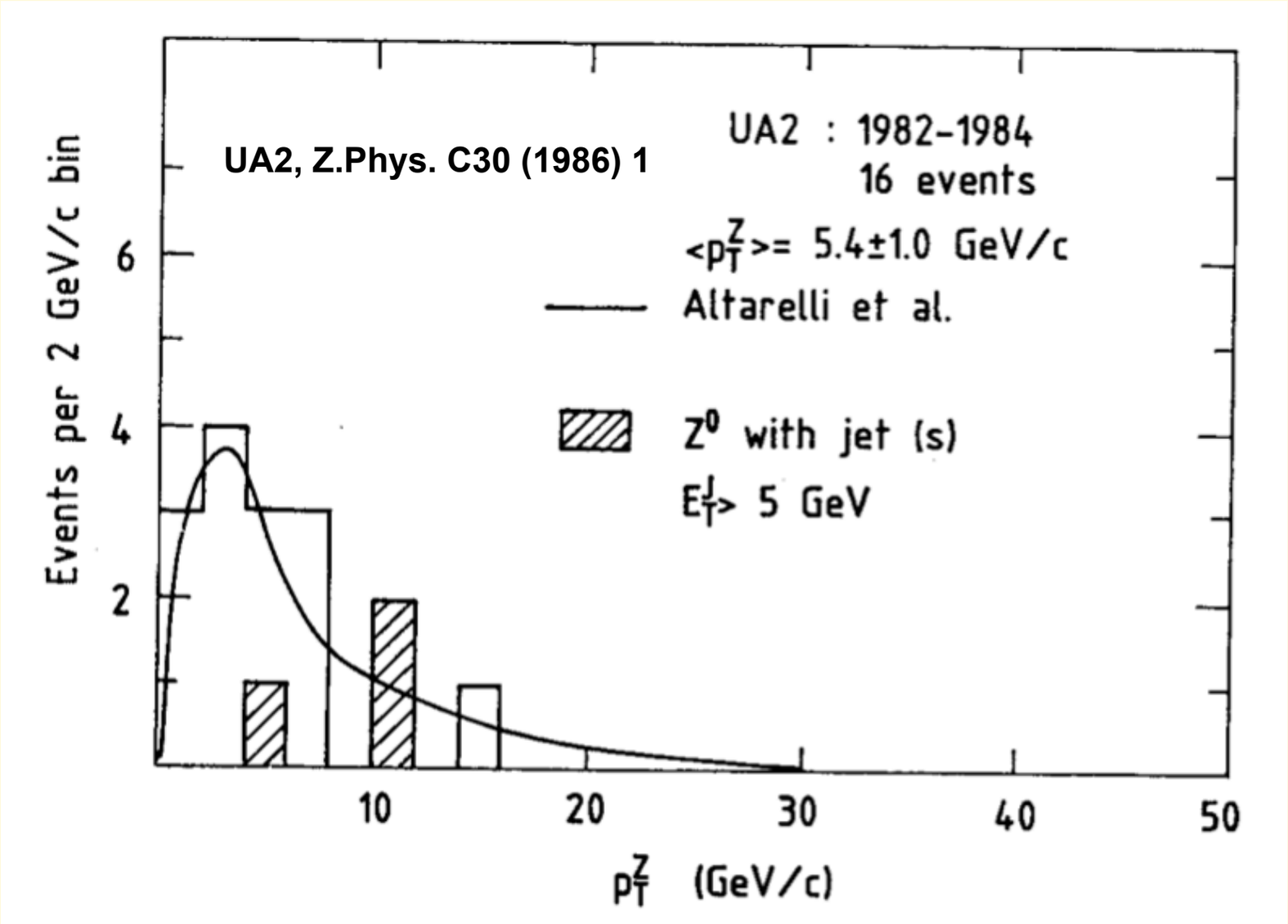
ATL-PHYS-PUB-2011-015







..... but it all started like this, from a score of events:



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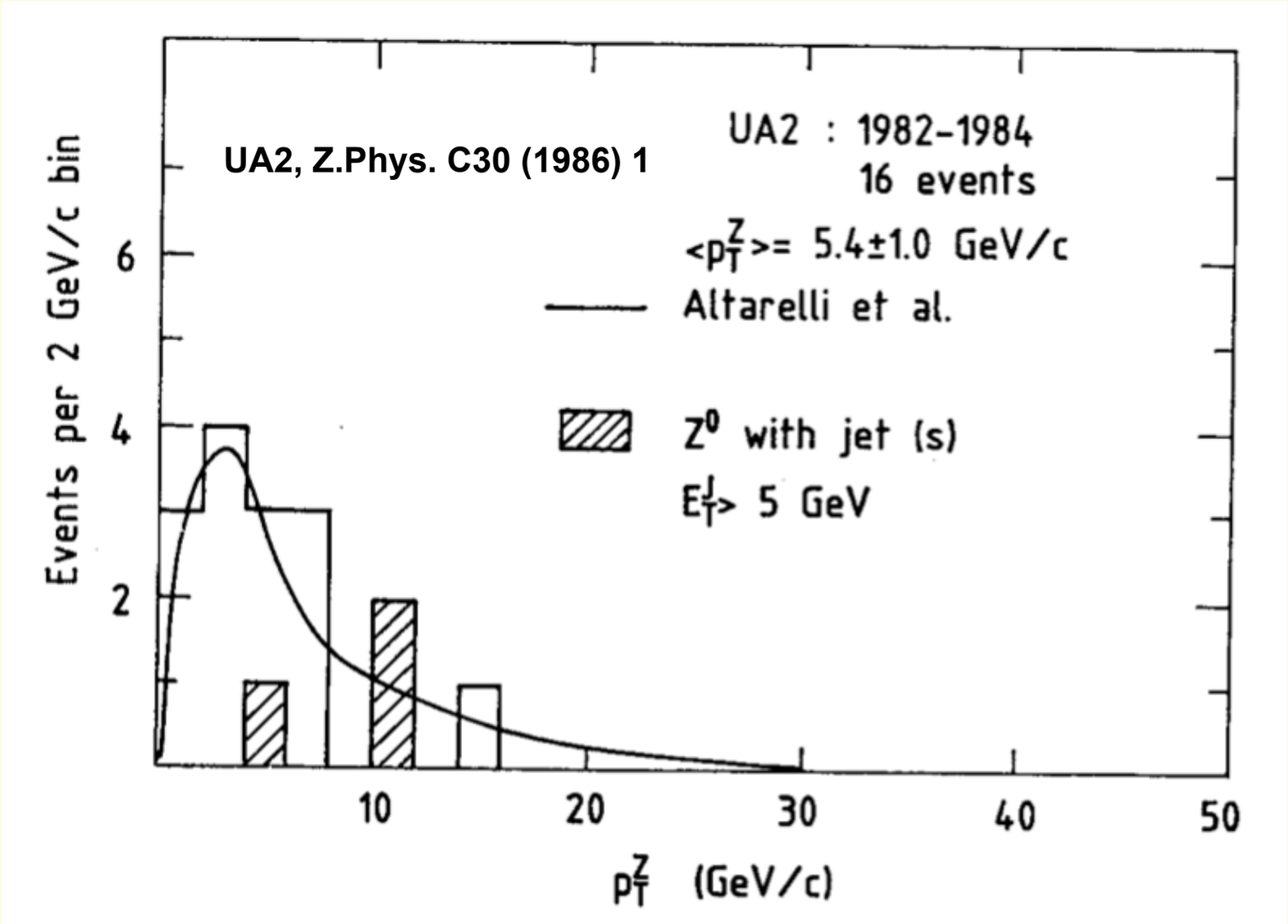
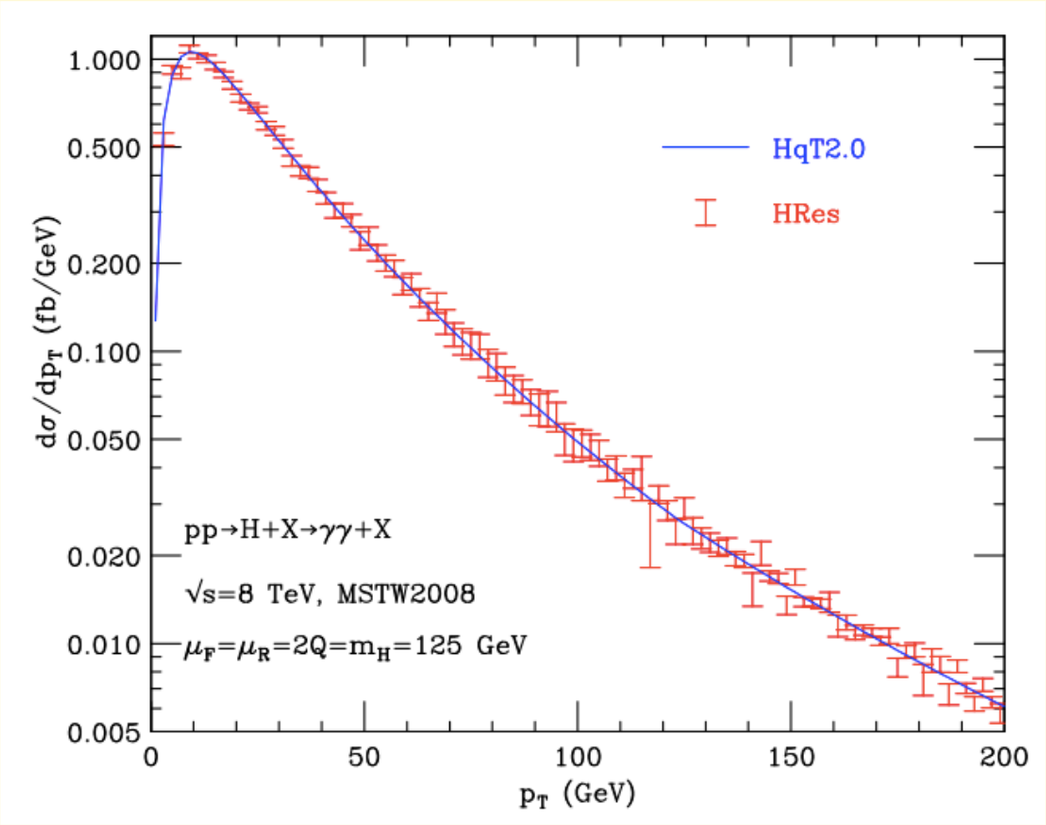


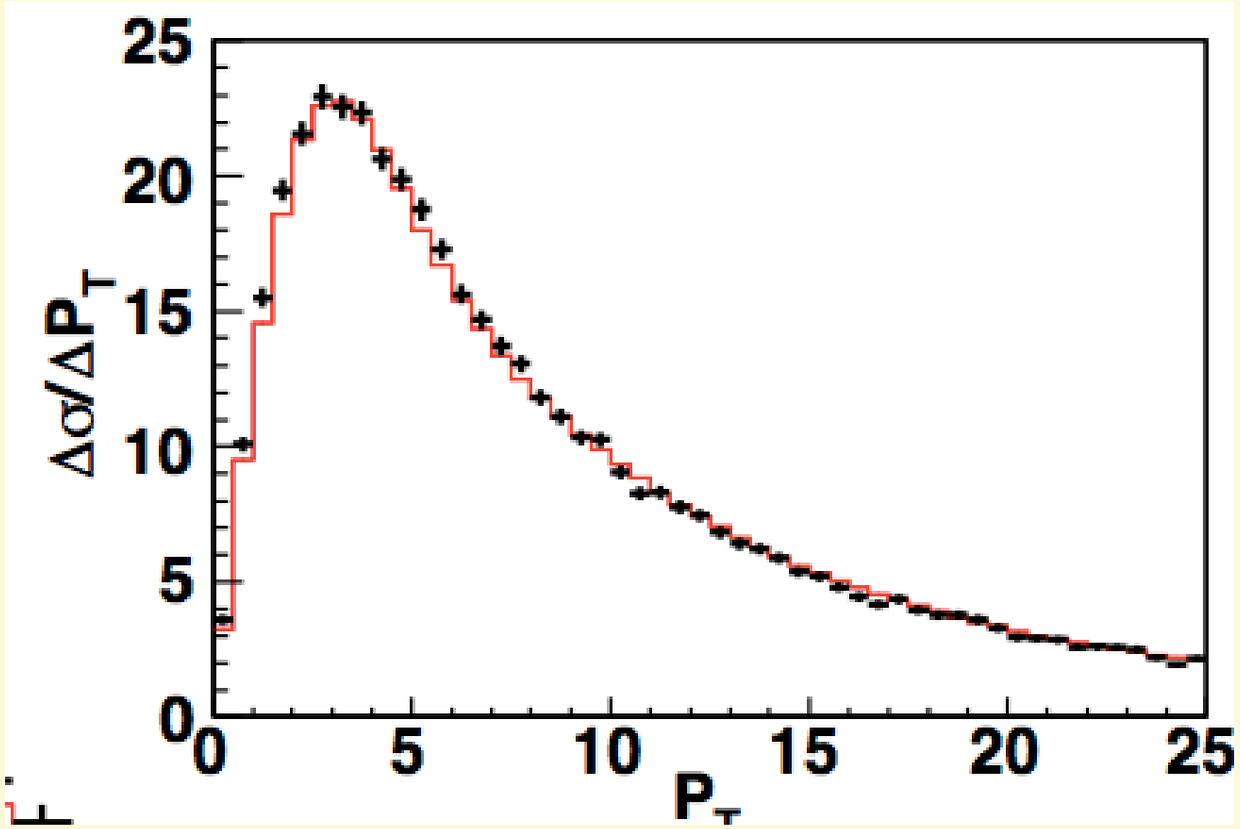
Looking forward to the first measurement of $p_T(gg \rightarrow H \rightarrow ZZ^*)$ with the 15-20 events that you will have by the end of 2012!

Example of first qualitative information that should emerge even from limited statistics studies

p_T(H) in gg → H



p_T(Z) in qqbar → Z



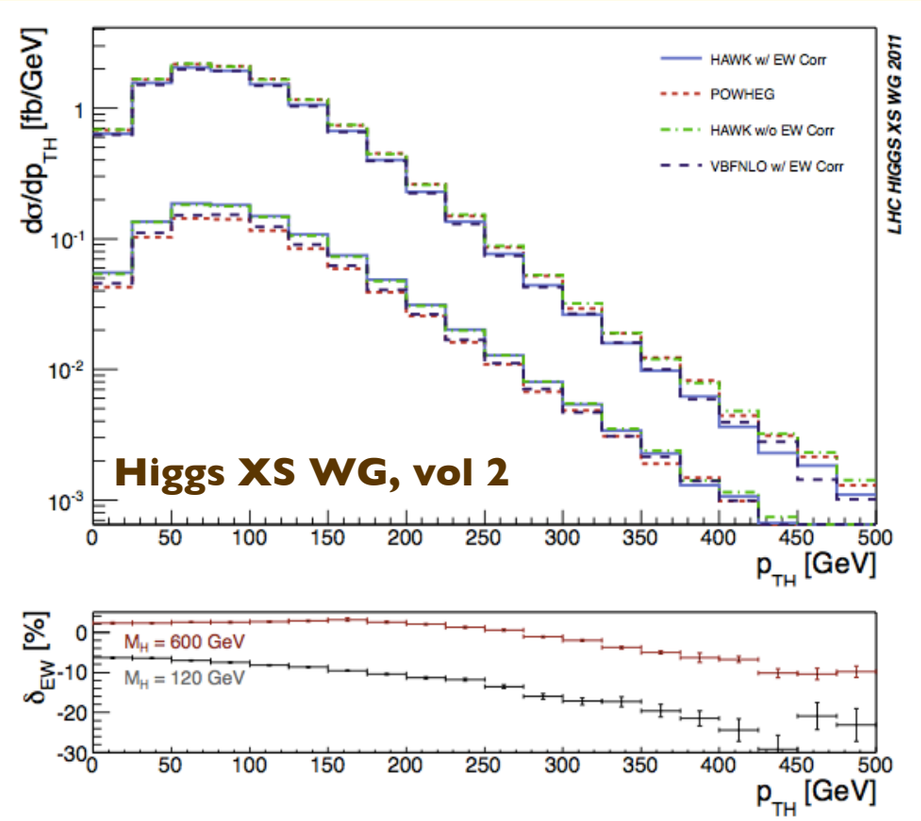
p_T(peak)~10 GeV ⟷ **p_T(peak)~3 GeV**

gg ISR

qqbar ISR

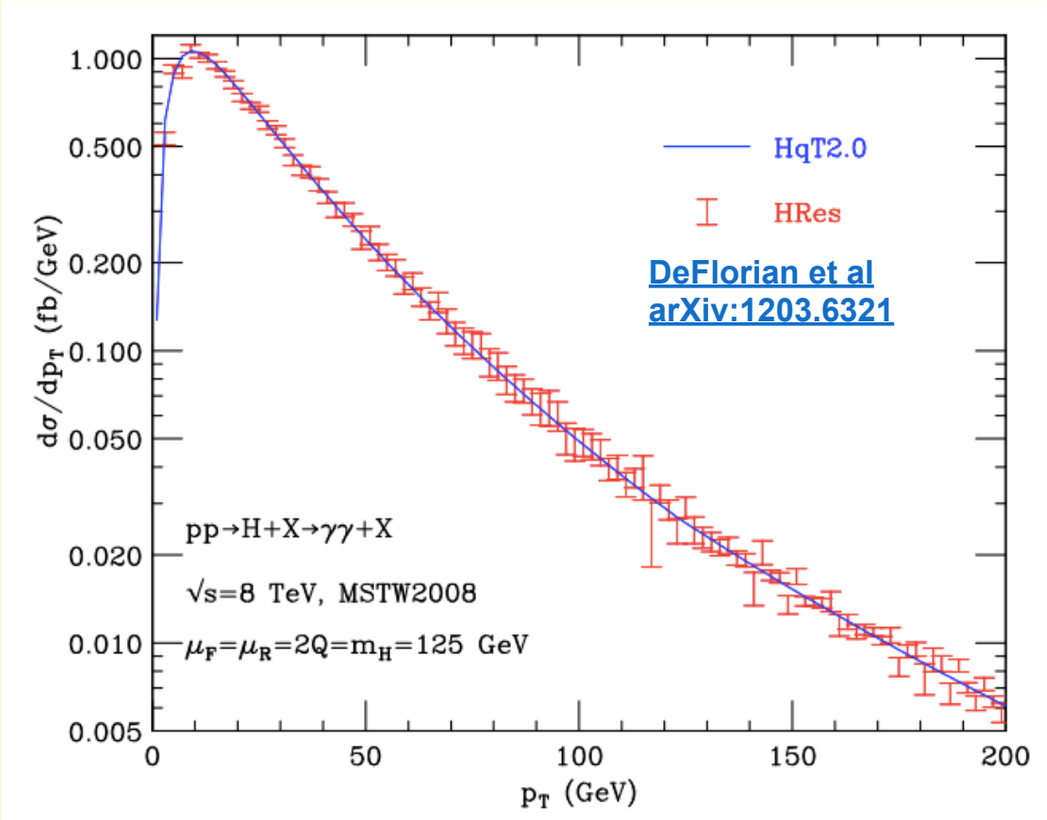
First direct probe of ISR in gg collisions

$p_T(H)$ in qq → qq H



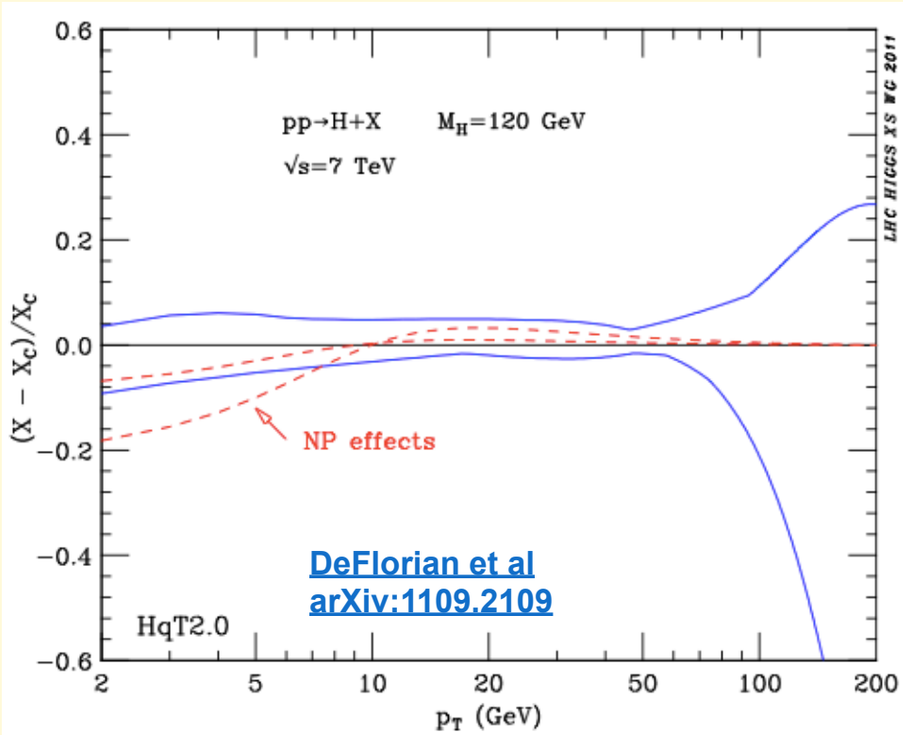
p_T(peak)~60 GeV

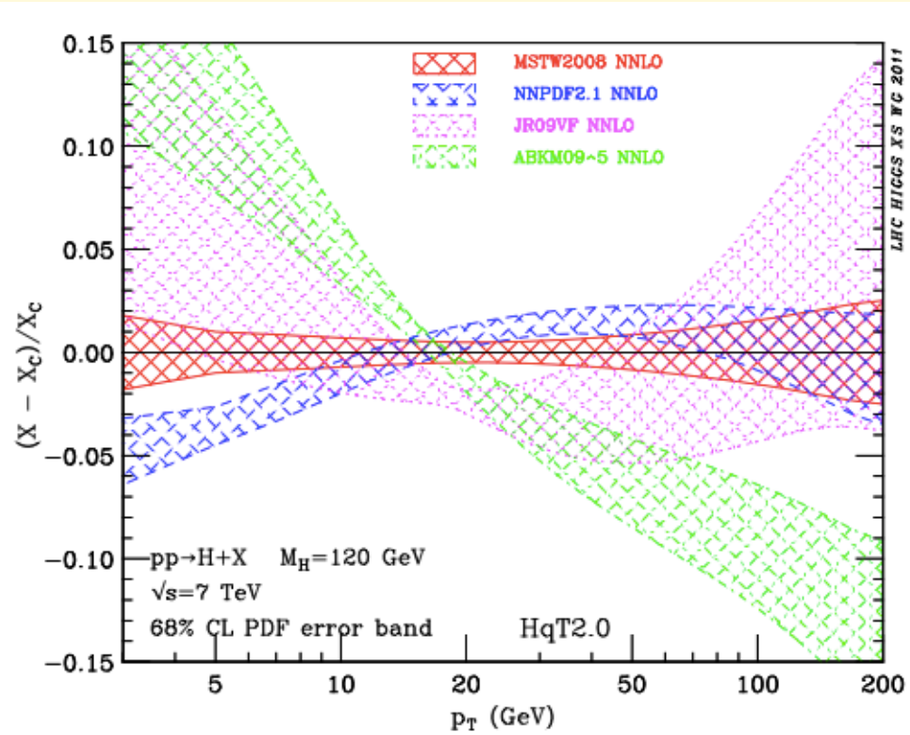
$p_T(H)$ in gg → H



p_T(peak)~10 GeV

TH systematics for $p_T(H)$ in gg → H





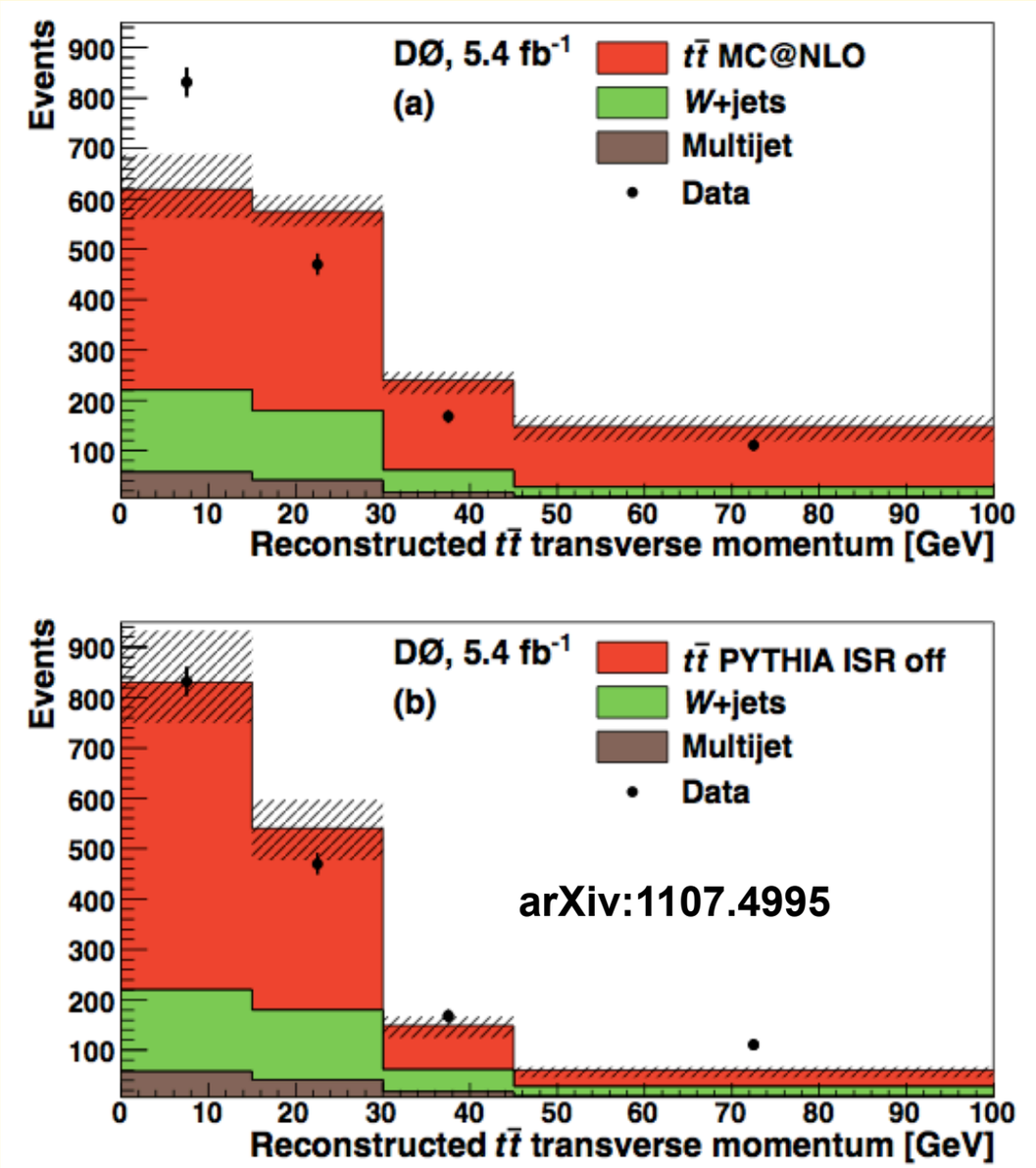
ISR in t-tbar

Interesting since pp→tt + X is dominated by gg→tt+X, with X mostly ISR

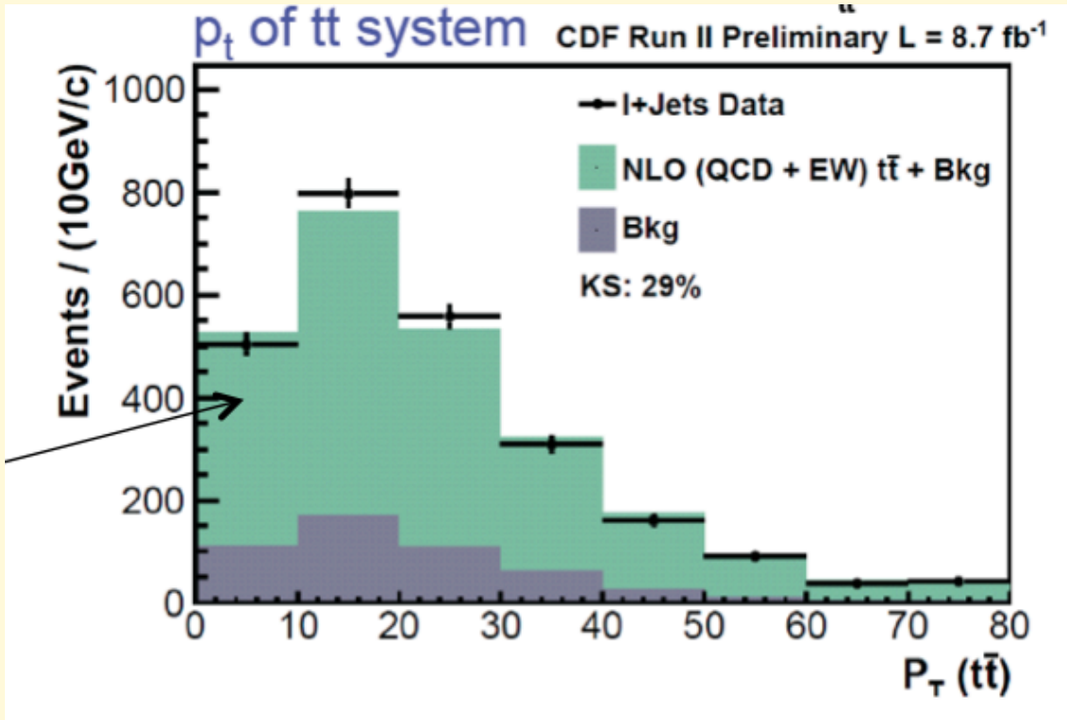
cfr pp→H + X, dominated by ***gg****→H+X, with X only* ***ISR***

unlike pp→W + X, dominated by ***qqbar****→W+X, with X only ISR*

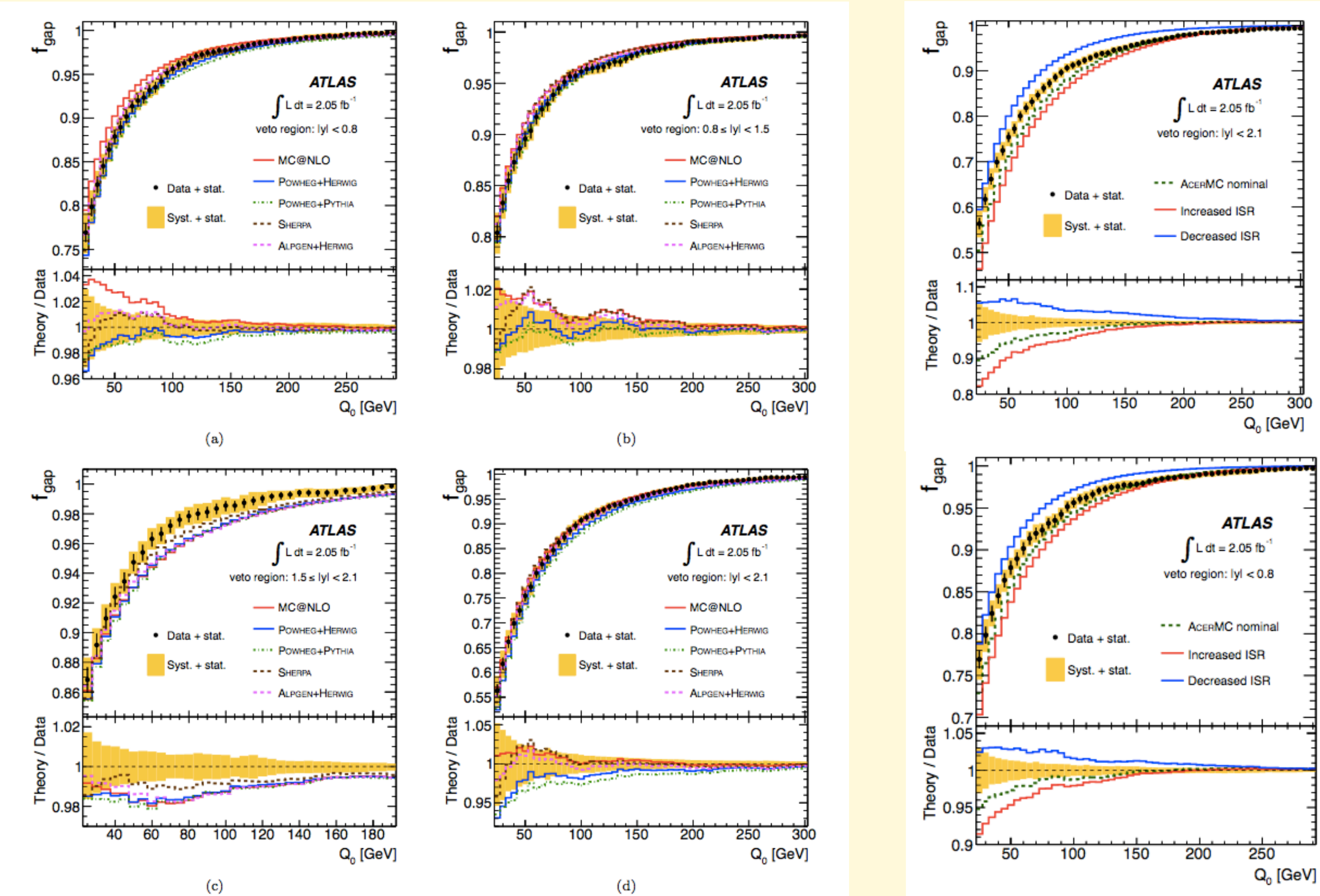
unlike pp→jet jet + X, dominated by gg→jet jet+X, with X both ***ISR&FSR***



Apparent inconsistency between the findings of CDF and D0

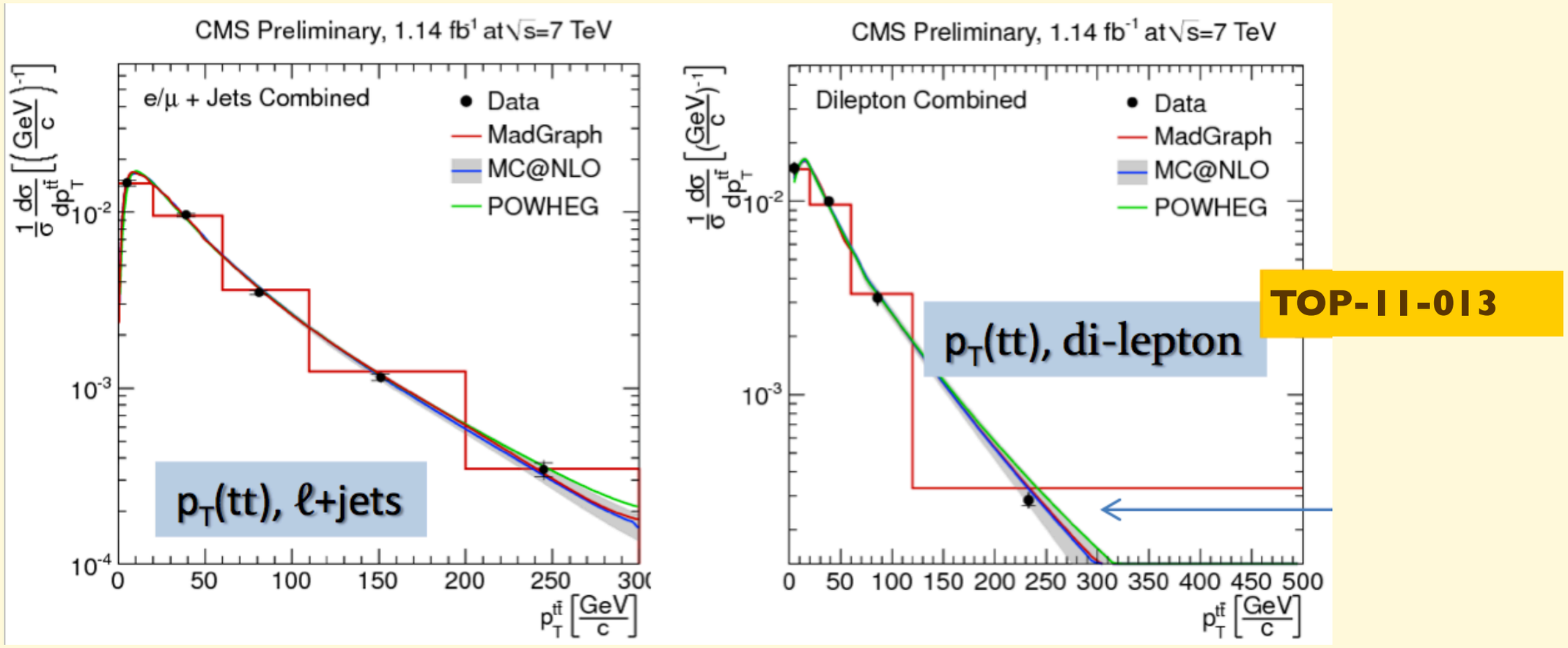


First results from LHC: ATLAS



ATLAS, arXiv:1203.5015v1

First results from LHC: CMS



Very good agreement, but still poor p_T resolution!

Underscores the difficulty in defining precisely kinematical quantities relative to top quarks: need to unfold distributions of top decay products to reconstruct top distributions (unfolding driven by use of MC)

A proper definition of what is a “top” is crucial in validating the MCs for top production against data

This led to the folowing:

Proposal for the definition of top quark in differential distributions

Discussions developed during the LHC top WG mtgs

- Result of discussions among
  - K.Hamilton, M.Mangano, A.Mitov, P.Nason, G.Perez, G.Salam, P.Skands, J.Winter

General remarks

- We tried to define a general "framework" for the reconstruction of a top at the particle level, which should apply to a large class of differential measurements
  - Specific analyses may require different prescriptions, or will benefit from optimized versions of the prescription
- We assume that each top analysis starts from an event selection defined by conditions on a set of **objects**, namely: leptons, neutrinos, jets, b-jets
- We assume that these objets are reconstructed and corrected at the particle level (detector corrected)
- We assume that the determination of the background, and its subtraction, is part of the experimental analysis (namely the results will be distributions for top final states).

Event selection. E.g.:

- ≧4 jets with $|\eta| < \eta_{max}$ and $E_T < E_{Tmin}$
- 2 of these jets are b-tagged
- lepton and MET passing some cuts

"Event objects"

Definition of *pseudo*-top (t_P):

- Introduce a function of the event objects, ***F(j,l,b,ν)***, whose result is a mapping of those objects into the top and tbar pair. E.g.

$$t_P = W_{jj} + b_1$$
$$\overline{t_P} = W_{l\nu} + b_2 + jet_5$$

F(j,l,b,ν) *should be formulable as a "RIVET" routine, to act on MC-generated final states. Its defintion could include "fiducial-like" requirements, such as:*

- a cut on $m(t_P)$
- cuts on $y(t_P)$, $p_T(t_P)$, etc
- cuts on global "top-likelihood", to optimize the relation between truth-level top and pseudo-top

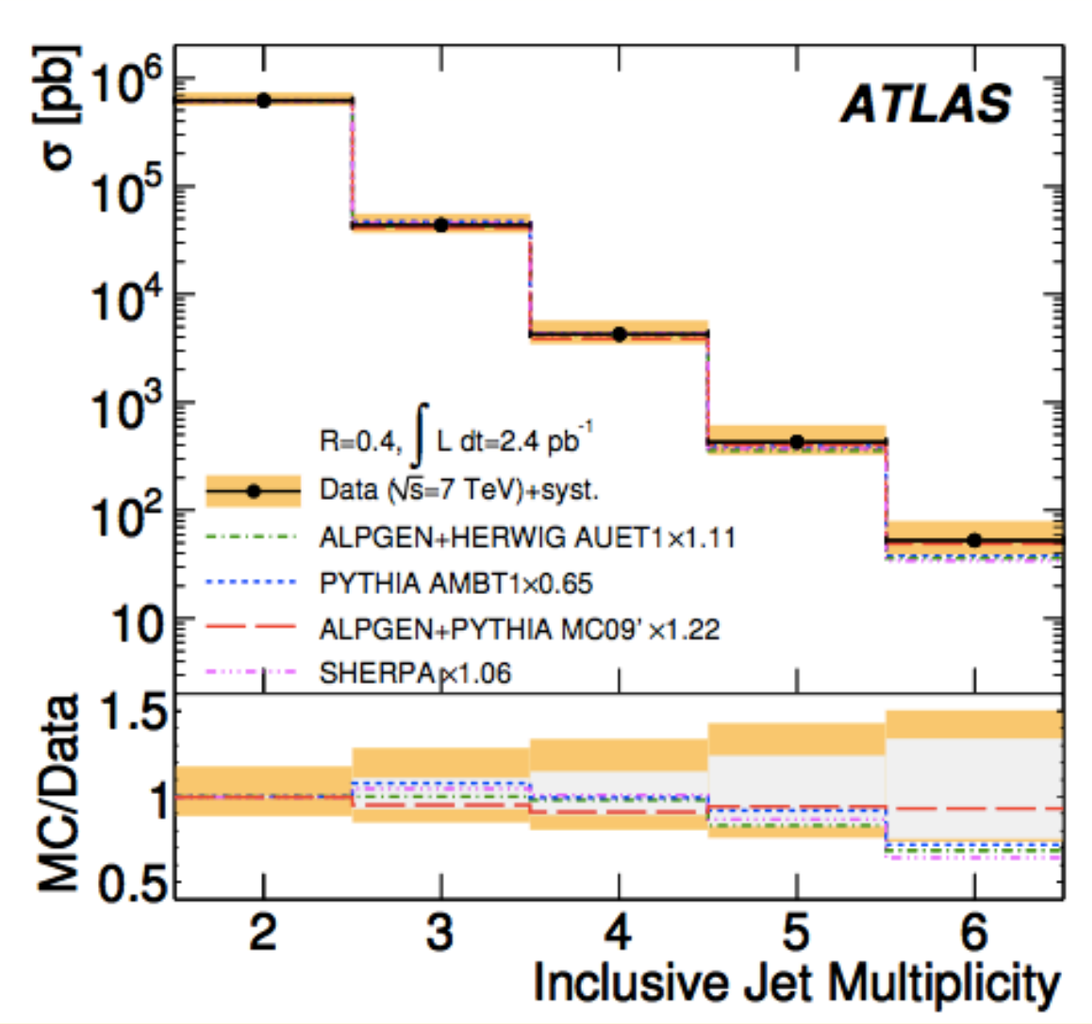
Work is in progress within the LHC top WG to explore the feasibility of this approach

See e.g. talk by Will H. Bell at the last WG meeting,
https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=189617

Relevance/synergy (or possibly conflict) with what's done in the groups using top as a tool for searches should probably be explored

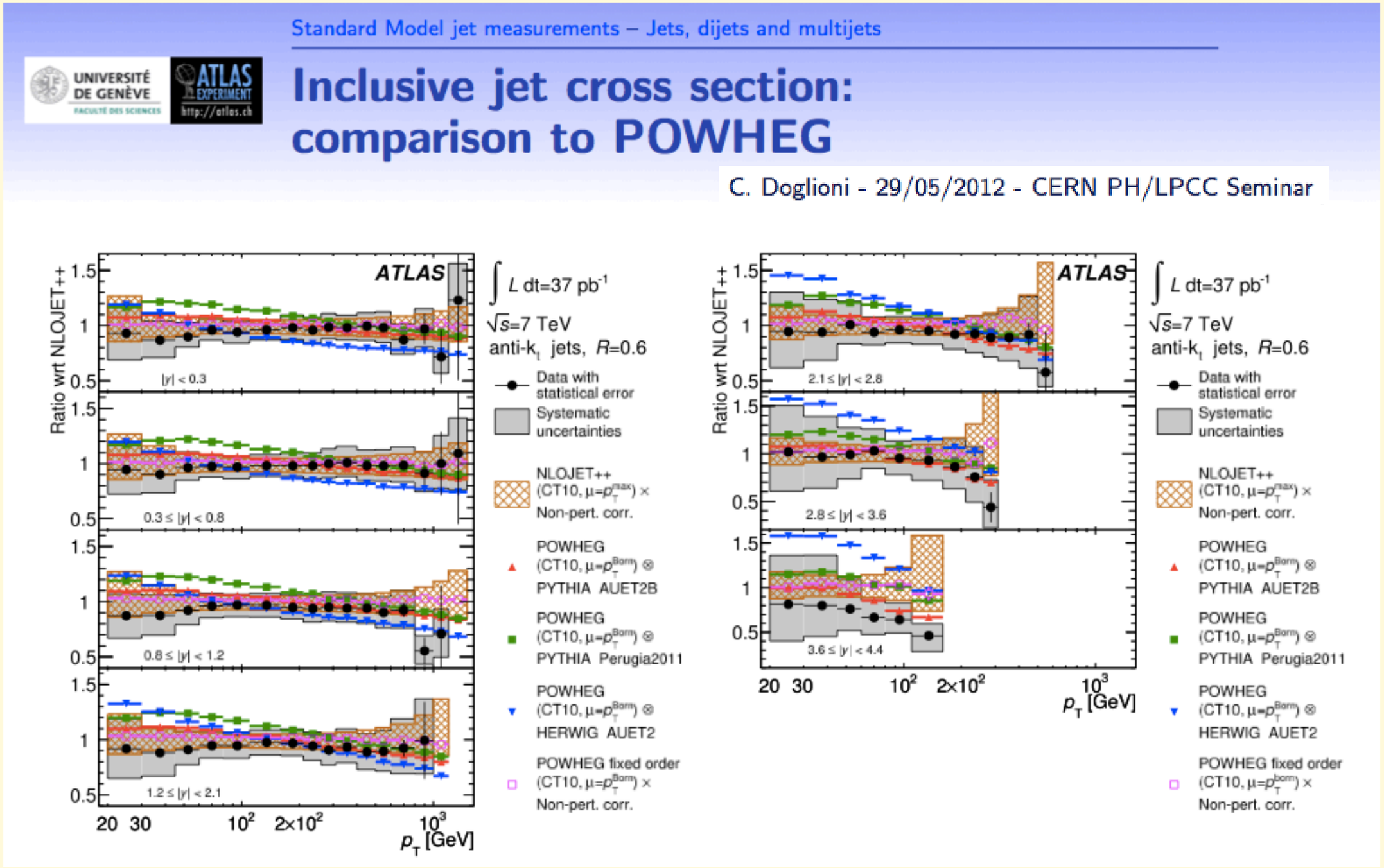
Multijet final states

- So far, qualitatively good agreement between data and QCD
- Tests limited to inclusive quantities, not always testing the more "extreme" kinematical configurations of interest for searches (e.g. broad range of pt -> multiscale issues). Empirical patterns such as S_T scaling useful, but likely too inclusive to provide a reliable test of modeling and to guarantee extrapolation to more exclusive studies (e..g use of kinematical correlations)



- Will need to rely for long time on LO (+shower, matching, etc) calculations for the largest multiplicities
- Predictions for up to 8-10 jets soon available (e.g. in Alpgen), but unavoidably large scale uncertainties ⇒ accurate validation against data absolutely necessary!

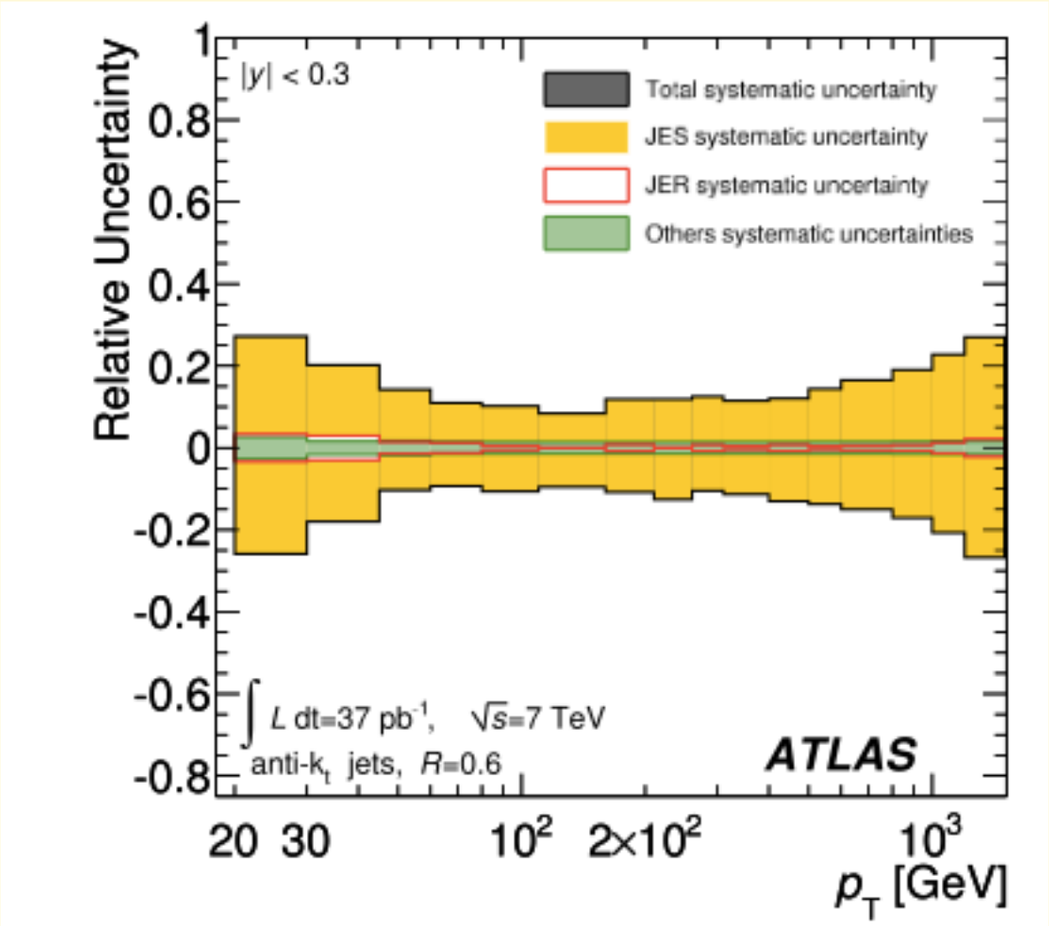
Towards NLO precision: NLO vs NLO+shower



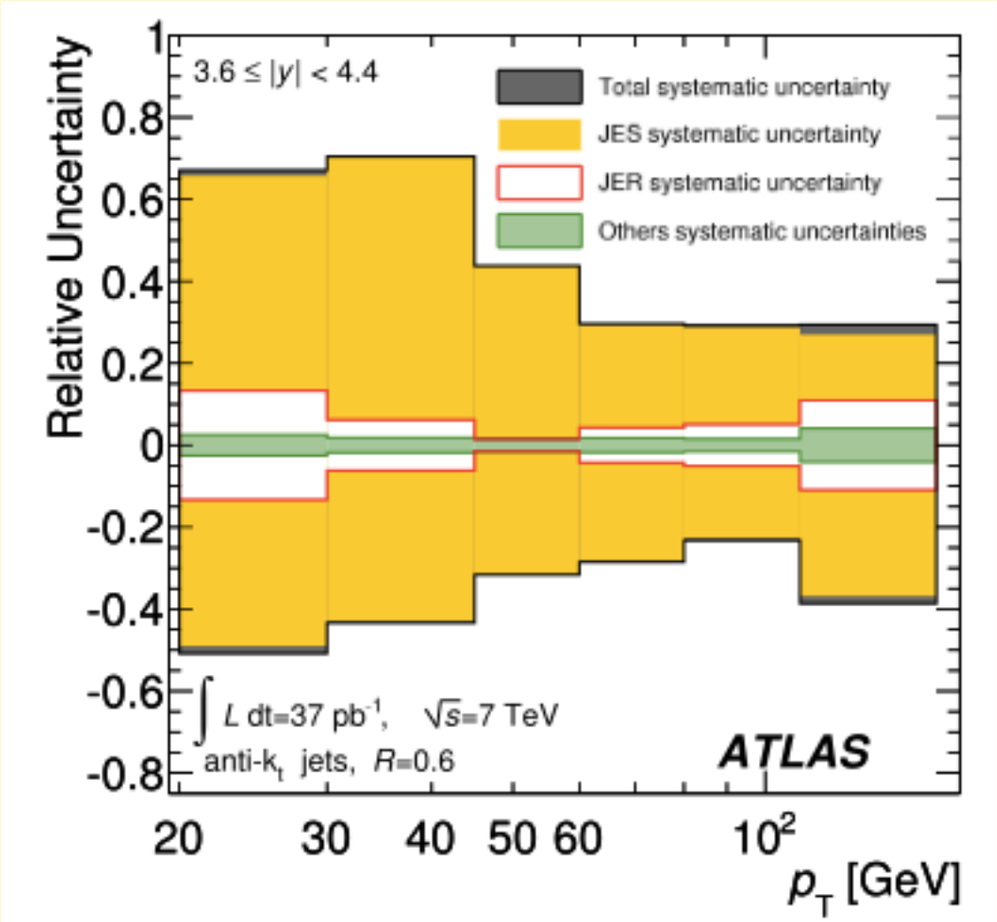
- Important systematic differences in the NLO vs NLO+shower description, going beyond the assumed NLO theory systematics

- Most immediate consequence: reliable use of jet data to improve PDFs ?

Experimental systematics

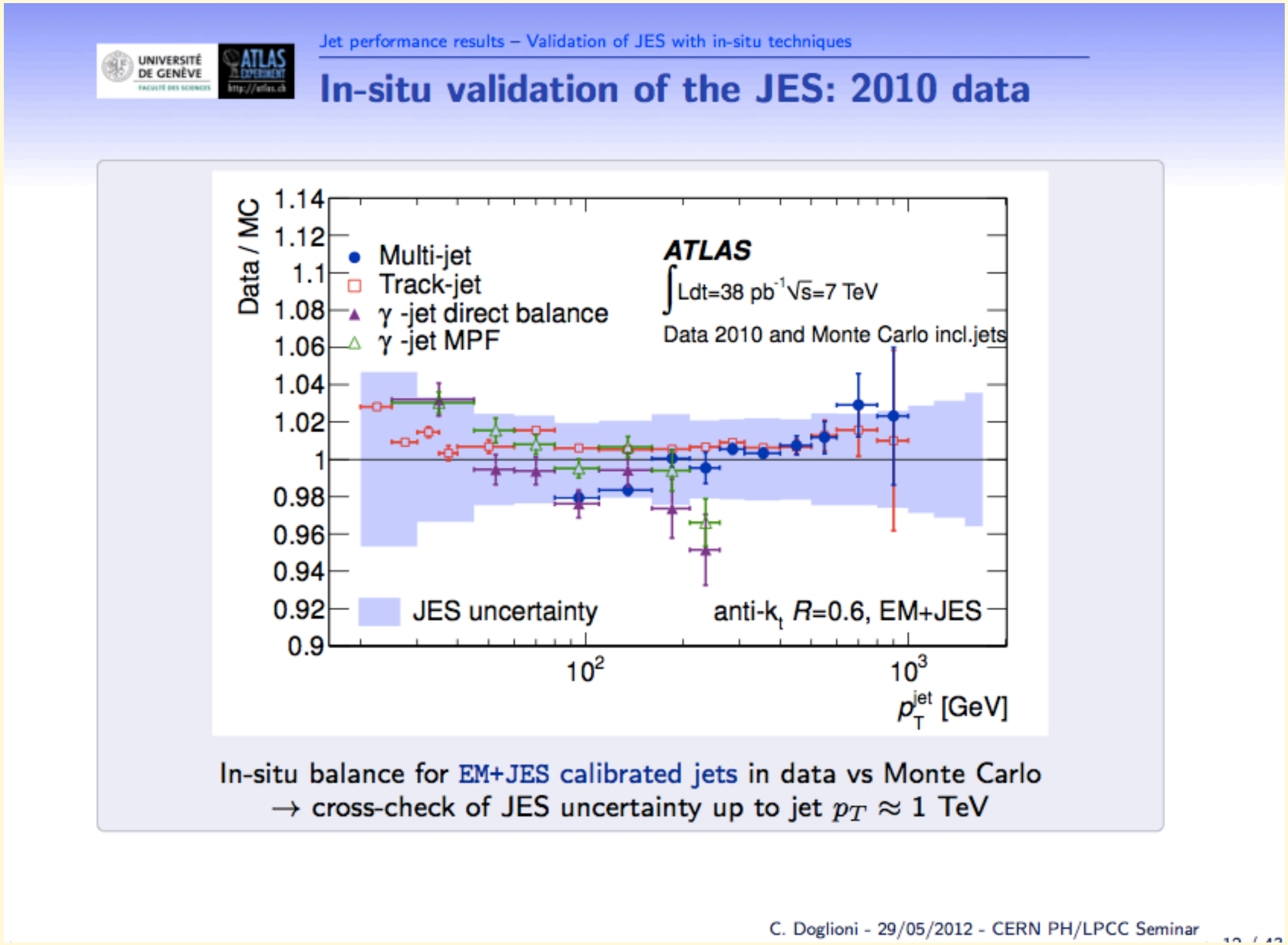


Central jets



Forward jets

What is the ultimate attainable precision in the determination of the jet energy scale?



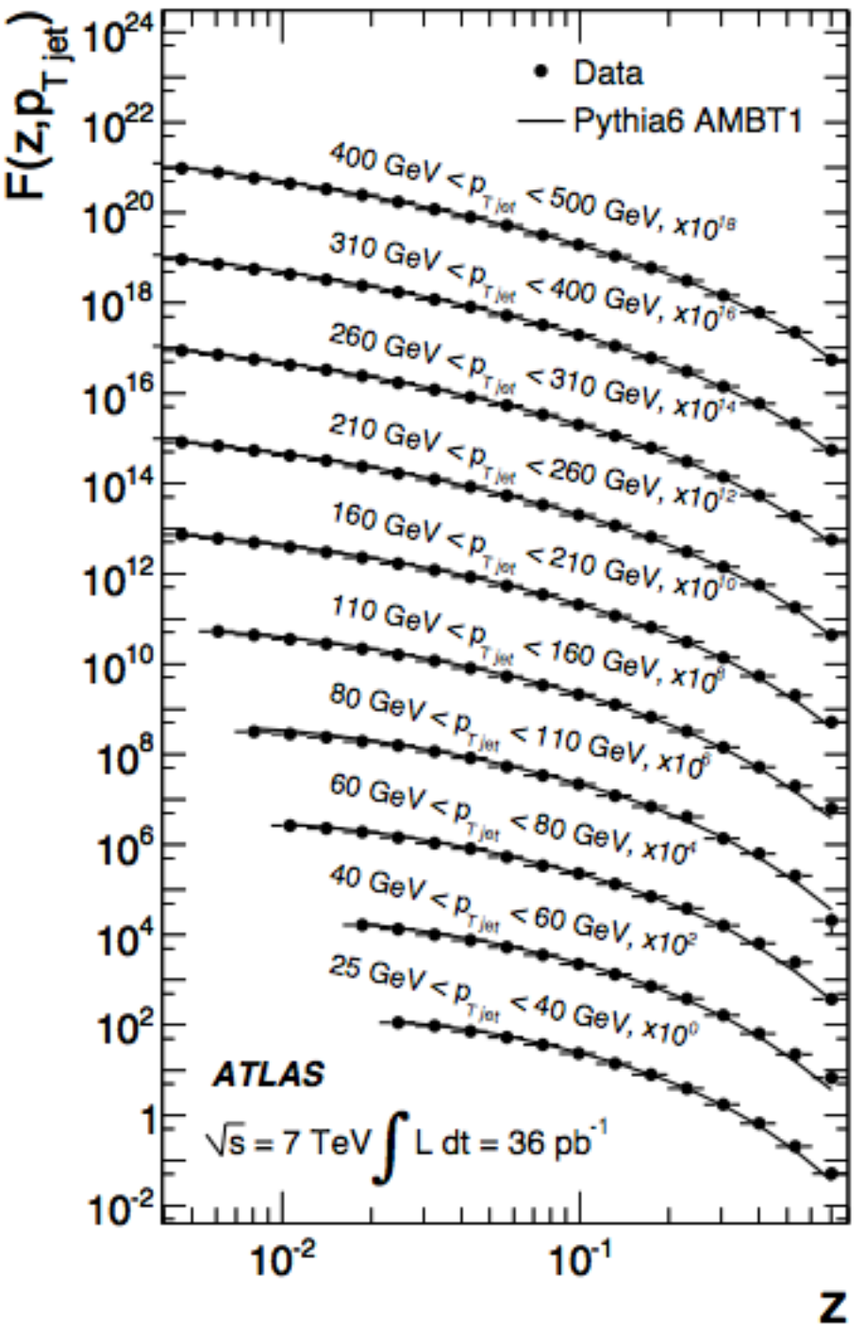
TH systematics biases the exptl measurement of JES:

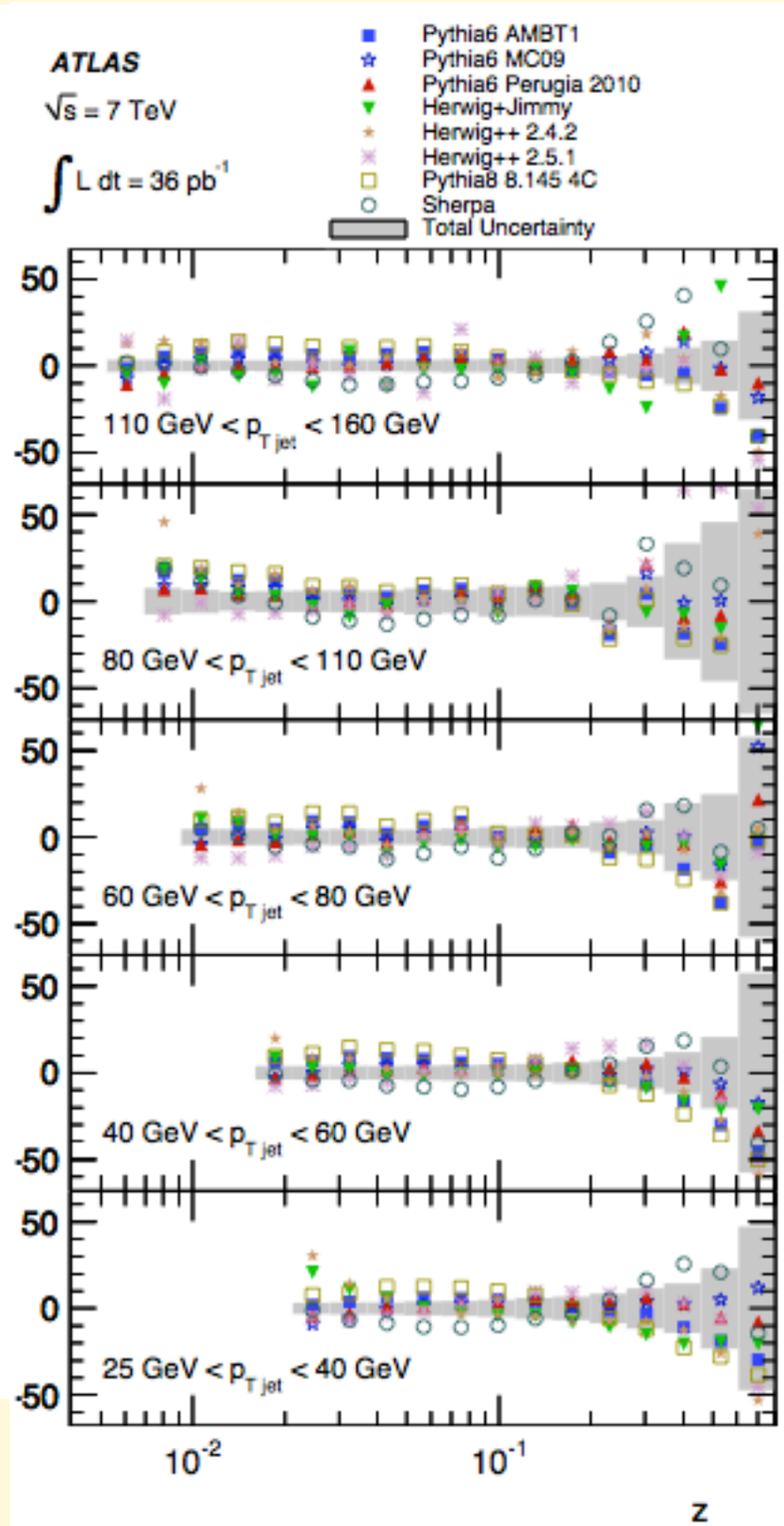
jet flavour composition, structure of the recoil hadronic system, multijet structure of the event, ...

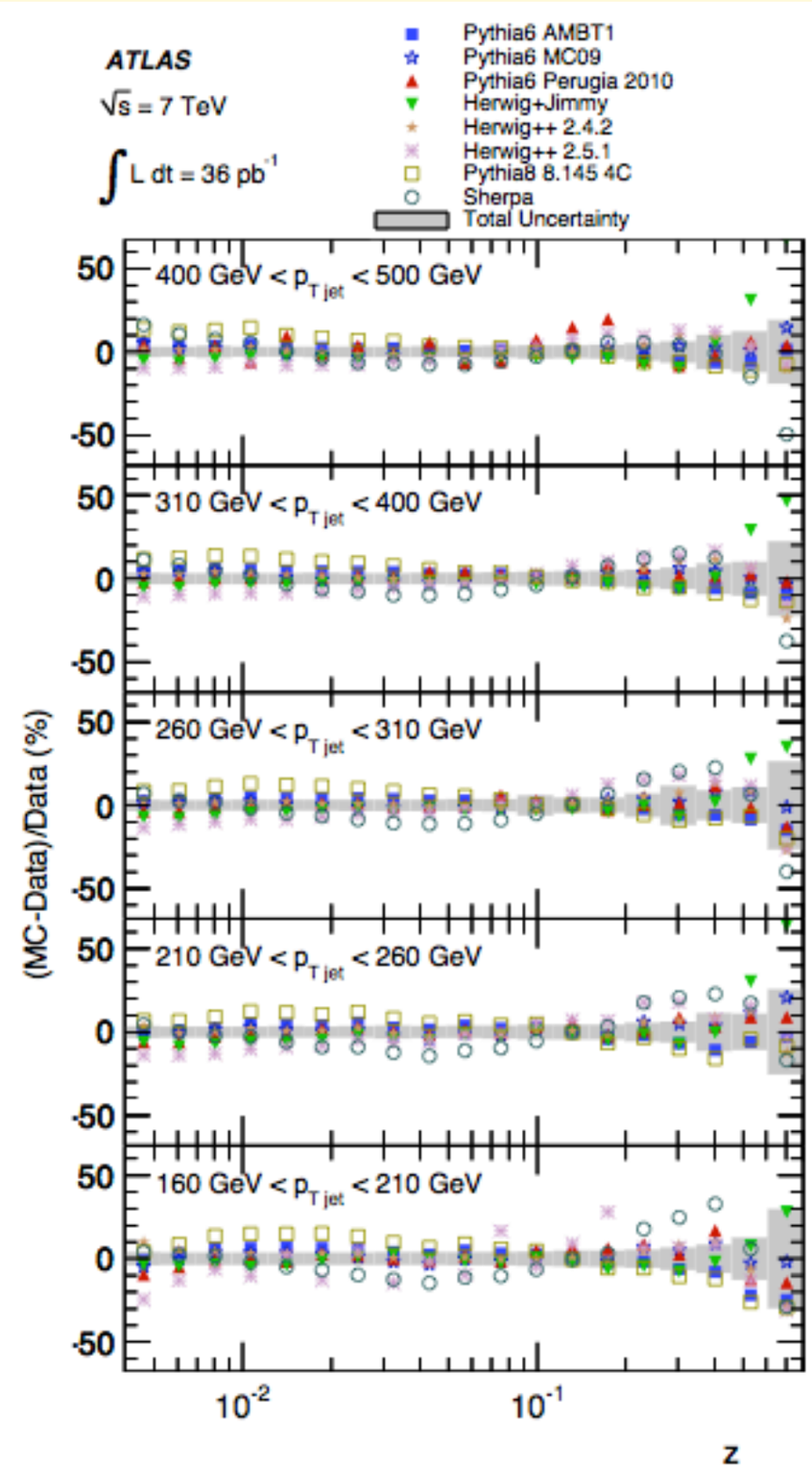
Can be reduced with detailed studies of jet structure, and improvement of jet models

Jet fragmentation function

ATLAS, arXiv:1109.5816







plus
- **jet shapes**
- **ptrel spectra**
- **<N_{ch}> and <z> distributions,**
- **....**

Data are much more precise than theory predictions, and can be used to improve them!

8TeV/7TeV and 14TeV/8TeV cross section ratios: the ultimate precision

MLM and J.Rojo, arXiv:1206.3557

$E_{1,2}$: different beam energies

X,Y: different hard processes

$$R_{E_2/E_1}(X) \equiv \frac{\sigma(X,E_2)}{\sigma(X,E_1)} \longrightarrow$$

- TH: reduce "scale uncertainties"
- TH: reduce parameters' systematics: PDF, m_{top}, α_S, ... at E_1 and E_2 are fully correlated
- TH: reduce MC modeling uncertainties
- EXP: reduce syst's from acceptance, efficiency, JES, ...

$$R_{E_2/E_1}(X,Y) \equiv \frac{\sigma(X,E_2)/\sigma(Y,E_2)}{\sigma(X,E_1)/\sigma(Y,E_1)} \equiv \frac{R_{E_2/E_1}(X)}{R_{E_2/E_1}(Y)} \longrightarrow$$

- TH: possible further reduction in scale and PDF syst's
- EXP: no luminosity uncertainty
- EXP: possible further reduction in acc, eff, JES syst's (e.g. $X,Y=W^+,W^-$)

Following results obtained using best available TH predictions: NLO, NNLO, NNLL resummation when available

8 TeV / 7 TeV: NNPDF results

CrossSection	$r^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	δ_{α_s} (%)	δ_{scales} (%)
$t\bar{t}/Z$	1.231	0.28	−0.23 − 0.24	0.17 − 0.33
$t\bar{t}$	1.432	0.25	−0.15 − 0.20	0.14 − 0.33
Z	1.163	0.08	−0.04 − 0.08	0.05 − 0.09
W^+	1.148	0.08	−0.01 − 0.06	0.06 − 0.08
W^-	1.167	0.09	−0.03 − 0.06	0.06 − 0.07
W^+/W^-	0.983	0.08	0.00 − 0.02	0.00 − 0.02
W/Z	0.994	0.03	−0.02 − 0.02	0.02 − 0.00
ggH	1.273	0.11	−0.04 − 0.06	0.24 − 0.16
$ggH/t\bar{t}$	0.889	0.22	−0.15 − 0.11	0.41 − 0.22
$t\bar{t}(M_{tt} \geq 1\mathrm{TeV})$	1.807	0.73	0.00 − 0.00	0.61 − 0.54
$t\bar{t}(M_{tt} \geq 2\mathrm{TeV})$	2.734	3.60	0.00 − 0.00	0.00 − 1.45
$\sigma\mathrm{jet}(p_T \geq 1\mathrm{TeV})$	2.283	1.02	0.00 − 0.00	5.89 − 0.91
$\sigma\mathrm{jet}(p_T \geq 2\mathrm{TeV})$	7.386	4.70	0.00 − 0.00	2.33 − 1.08

- $\delta<10^{-3}$ in $W^{\pm}$ ratios: absolute calibration of 7 vs 8 TeV lumi
- $\delta<10^{-2}$ in $\sigma(tt)$ ratios
- $\delta_{scale} < \delta_{PDF}$ at large p_T^{jet} and M_{tt}: constraints on PDFs

8 TeV / 7 TeV: NNPDF vs MSTW vs ABKM

Ratio	$r^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	$r^{\mathrm{th,mstw}}$	$\delta_{\mathrm{PDF}}(\%)$	$\Delta^{mstw}(\%)$	$r^{\mathrm{th,abkm}}$	$\delta_{\mathrm{ABKM}}(\%)$	Δ^{abkm} (%)
$t\bar{t}/Z$	1.231	0.28	1.227	0.24	0.37	1.247	0.55	-1.20
$t\bar{t}$	1.432	0.25	1.428	0.24	0.34	1.452	0.55	-1.35
Z	1.163	0.08	1.163	0.09	-0.02	1.165	0.08	-0.15
W^+	1.148	0.08	1.149	0.10	-0.06	1.150	0.07	-0.18
W^-	1.167	0.09	1.167	0.09	0.02	1.170	0.08	-0.23
W^+/W^-	0.983	0.08	0.984	0.05	-0.08	0.983	0.04	0.05
W/Z	0.994	0.03	0.994	0.02	-0.02	0.994	0.03	-0.04
ggH	1.273	0.11	1.274	0.17	-0.05	1.240	0.16	2.65
$ggH/t\bar{t}$	0.889	0.22	0.000	0.00	0.00	0.000	0.00	0.00
$t\bar{t}(M_{tt} \geq 1\mathrm{TeV})$	1.807	0.73	1.791	0.66	0.95	1.855	1.02	-2.61
$t\bar{t}(M_{tt} \geq 2\mathrm{TeV})$	2.734	3.60	2.645	2.84	3.61	2.645	4.04	3.61
$\sigma\mathrm{jet}(p_T \geq 1\mathrm{TeV})$	2.283	1.02	2.290	1.99	0.13	2.268	2.03	1.08
$\sigma\mathrm{jet}(p_T \geq 2\mathrm{TeV})$	7.386	4.70	7.915	4.29	-7.59	7.695	4.92	-4.59

- Several examples of 2-2.5σ discrepancies between predictions of different PDF sets

14 TeV / 8 TeV: NNPDF results

CrossSection	$r^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	δ_{α_s} (%)	δ_{scales} (%)
$t\bar{t}/Z$	2.121	1.01	−0.84 – 0.75	0.42 – 1.10
$t\bar{t}$	3.901	0.84	−0.51 – 0.66	0.38 – 1.07
Z	1.839	0.37	−0.10 – 0.34	0.28 – 0.18
W^+	1.749	0.41	−0.03 – 0.27	0.31 – 0.18
W^-	1.859	0.39	−0.08 – 0.26	0.32 – 0.13
W^+/W^-	0.941	0.28	0.00 – 0.05	0.00 – 0.04
W/Z	0.976	0.09	−0.07 – 0.04	0.04 – 0.02
ggH	2.564	0.36	−0.10 – 0.09	0.89 – 0.98
$ggH/t\bar{t}$	0.657	0.75	−0.56 – 0.41	1.38 – 1.05
$t\bar{t}(M_{tt} \geq 1\mathrm{TeV})$	8.215	2.09	0.00 – 0.00	1.61 – 2.06
$t\bar{t}(M_{\mathrm{tt}} \geq 2\mathrm{TeV})$	24.776	6.07	0.00 – 0.00	3.05 – 1.07
$\sigma\mathrm{jet}(p_T \geq 1\mathrm{TeV})$	15.235	1.72	0.00 – 0.00	2.31 – 2.19
$\sigma\mathrm{jet}(p_T \geq 2\mathrm{TeV})$	181.193	6.75	0.00 – 0.00	3.66 – 5.76

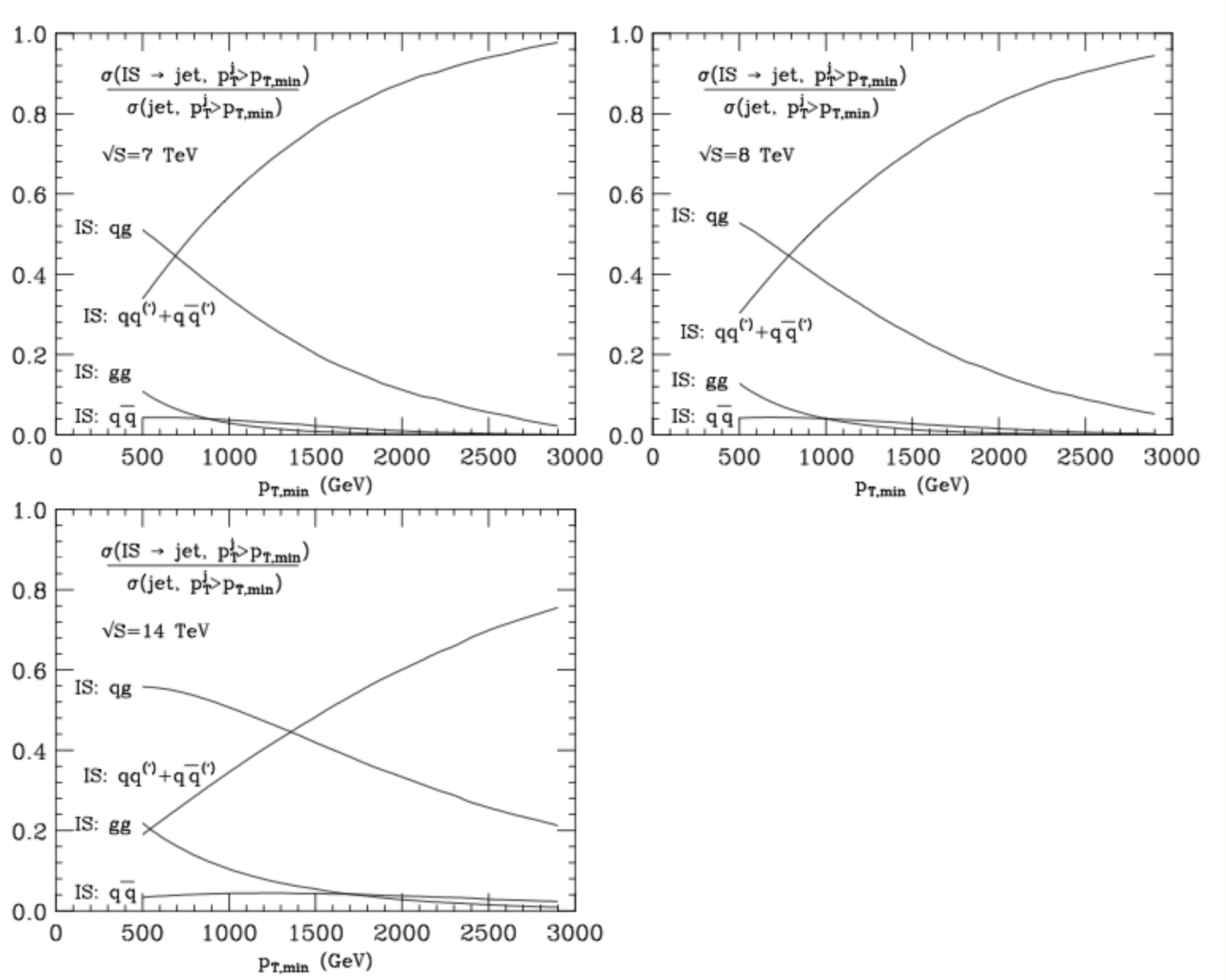
- $\delta < 10^{-2}$ in $W^{\pm}$ ratios: absolute calibration of 14 vs 8 TeV lumi
- $\delta \sim 10^{-2}$ in $\sigma(tt)$ ratios
- $\delta_{scale} < \delta_{PDF}$ at large p_T^{jet} and M_{tt}: constraints on PDFs

14 TeV / 8 TeV: NNPDF vs MSTW vs ABKM

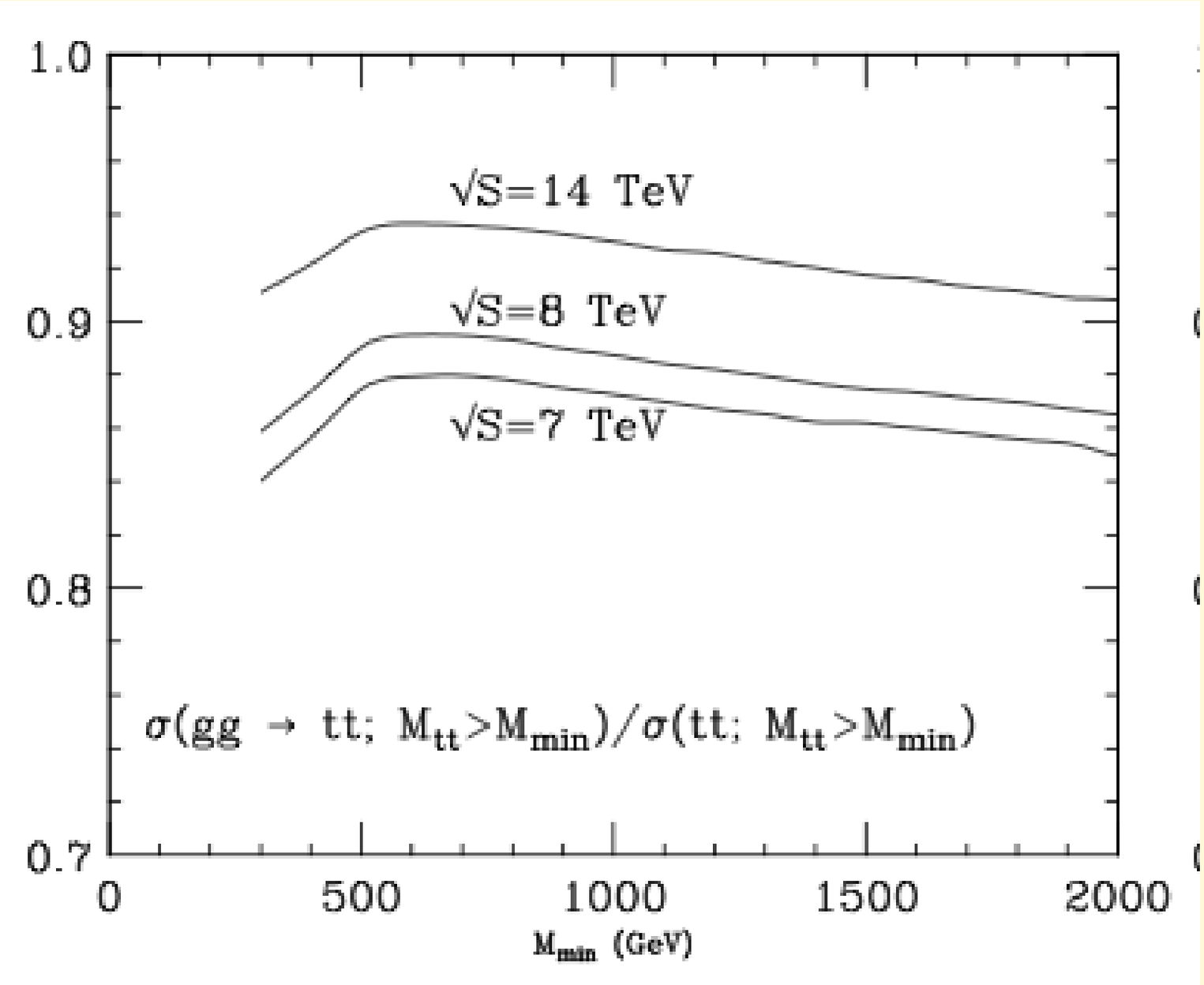
Ratio	$r^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	$r^{\mathrm{th,mstw}}$	$\delta_{\mathrm{PDF}}(\%)$	$\Delta^{mstw}(\%)$	$r^{\mathrm{th,abkm}}$	$\delta_{\mathrm{ABKM}}(\%)$	Δ^{abkm} (%)
$t\bar{t}/Z$	2.121	1.01	2.108	0.95	0.93	2.213	1.87	-3.99
$t\bar{t}$	3.901	0.84	3.874	0.91	0.97	4.103	1.87	-4.90
Z	1.839	0.37	1.838	0.41	0.04	1.855	0.34	-0.87
W^+	1.749	0.41	1.749	0.49	0.03	1.767	0.30	-0.98
W^-	1.859	0.39	1.854	0.42	0.21	1.879	0.32	-1.11
W^+/W^-	0.941	0.28	0.943	0.19	-0.19	0.940	0.13	0.13
W/Z	0.976	0.09	0.976	0.10	0.03	0.977	0.10	-0.14
ggH	2.564	0.36	2.572	0.57	-0.30	2.644	0.66	-3.12
$ggH/t\bar{t}$	0.657	0.75	0.000	0.00	0.00	0.000	0.00	0.00
$t\bar{t}(M_{tt} \geq 1\mathrm{TeV})$	8.215	2.09	7.985	2.02	3.12	8.970	3.58	-8.83
$t\bar{t}(M_{\mathrm{tt}} \geq 2\mathrm{TeV})$	24.776	6.07	23.328	4.32	6.05	23.328	4.93	6.05
$\sigma\mathrm{jet}(p_T \geq 1\mathrm{TeV})$	15.235	1.72	15.193	1.62	-1.33	14.823	1.84	1.13
$\sigma\mathrm{jet}(p_T \geq 2\mathrm{TeV})$	181.193	6.75	191.208	3.34	-6.52	174.672	4.94	2.69

- Several examples of 3-4σ discrepancies between predictions of different PDF sets, even in the case of W and Z rates

Initial state composition of inclusive jet events



Initial state gg fraction in t-tbar events



Xsection ratios as probes of BSM contributions

Assume the final state **X** receives both SM and BSM contributions:

$$\sigma^{exp}(pp \to X) = \sigma^{SM}(pp \to X) + \sigma^{BSM}(pp \to X)$$

Define the ratio:

$$R^X_{7/8} = \frac{\sigma^{exp}(pp \to X; 7\ \mathrm{TeV})}{\sigma^{exp}(pp \to X; 8\ \mathrm{TeV})} = \frac{\sigma^{exp}_X(7)}{\sigma^{exp}_X(8)}$$

We easily get:

$$R^X_{7/8} \sim \frac{\sigma^{SM}_X(7)}{\sigma^{SM}_X(8)} \times \left\{ 1 + \frac{\sigma^{BSM}_X(7)}{\sigma^{SM}_X(7)}\ \Delta_{7/8}\left[\frac{\sigma^{BSM}_X}{\sigma^{SM}_X}\right] \right\}$$

where:

$$\Delta_{7/8}\left[\frac{\sigma^{BSM}_X}{\sigma^{SM}_X}\right] = 1 - \frac{\sigma^{BSM}_X(8)/\sigma^{SM}_X(8)}{\sigma^{BSM}_X(7)/\sigma^{SM}_X(7)} \sim 1 - \frac{\mathcal{L}^{BSM}_X(8)/\mathcal{L}^{BSM}_X(7)}{\mathcal{L}^{SM}_X(8)/\mathcal{L}^{SM}_X(7)} = \Delta_{7/8}\left[\frac{\mathcal{L}^{BSM}_X}{\mathcal{L}^{SM}_X}\right]$$

Therefore:

relative BSM contamination

$$\frac{\delta R^X_{7/8}}{R^X_{7/8}} = \frac{\delta R^{SM}_{7/8}}{R^{SM}_{7/8}} + \frac{\sigma^{BSM}_X(7)}{\sigma^{SM}_X(7)} \times \Delta_{7/8}\left[\frac{\mathcal{L}^{BSM}_X}{\mathcal{L}^{SM}_X}\right]$$

theory systematics in 7→8 TeV extrapolation

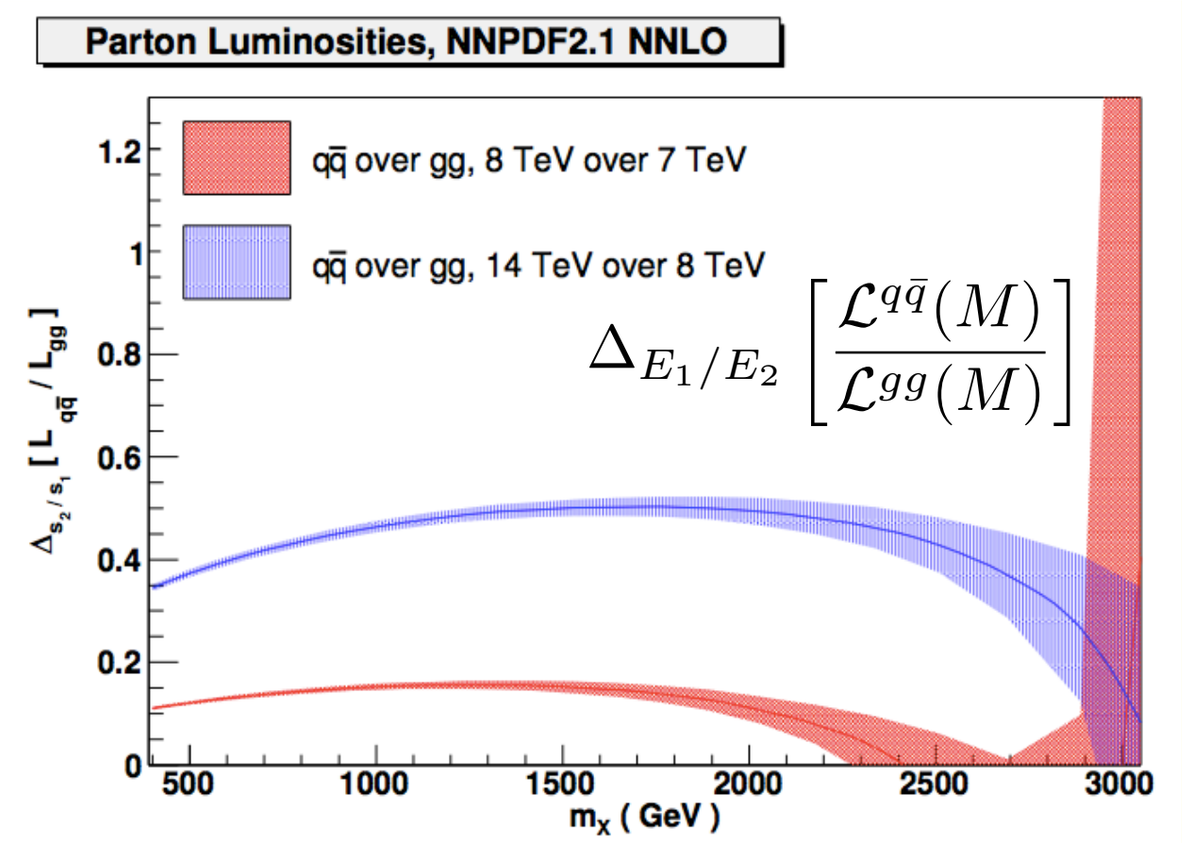
Energy dependence of the relative BSM contamination

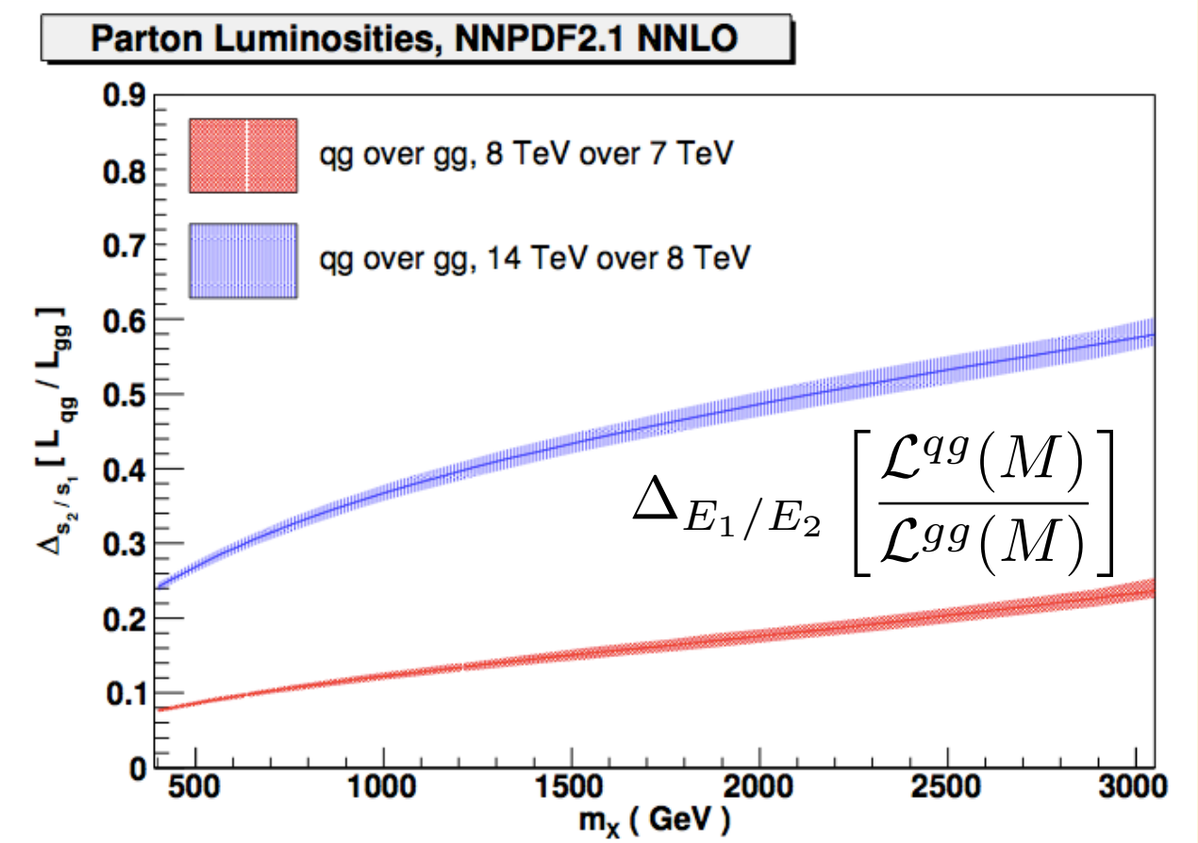
E.g., assuming $\sigma_{SM}(pp\to X)=\sigma(gg\to X)$ and $\sigma_{BSM}(pp\to X)=\sigma(qq\to X)$ (*)

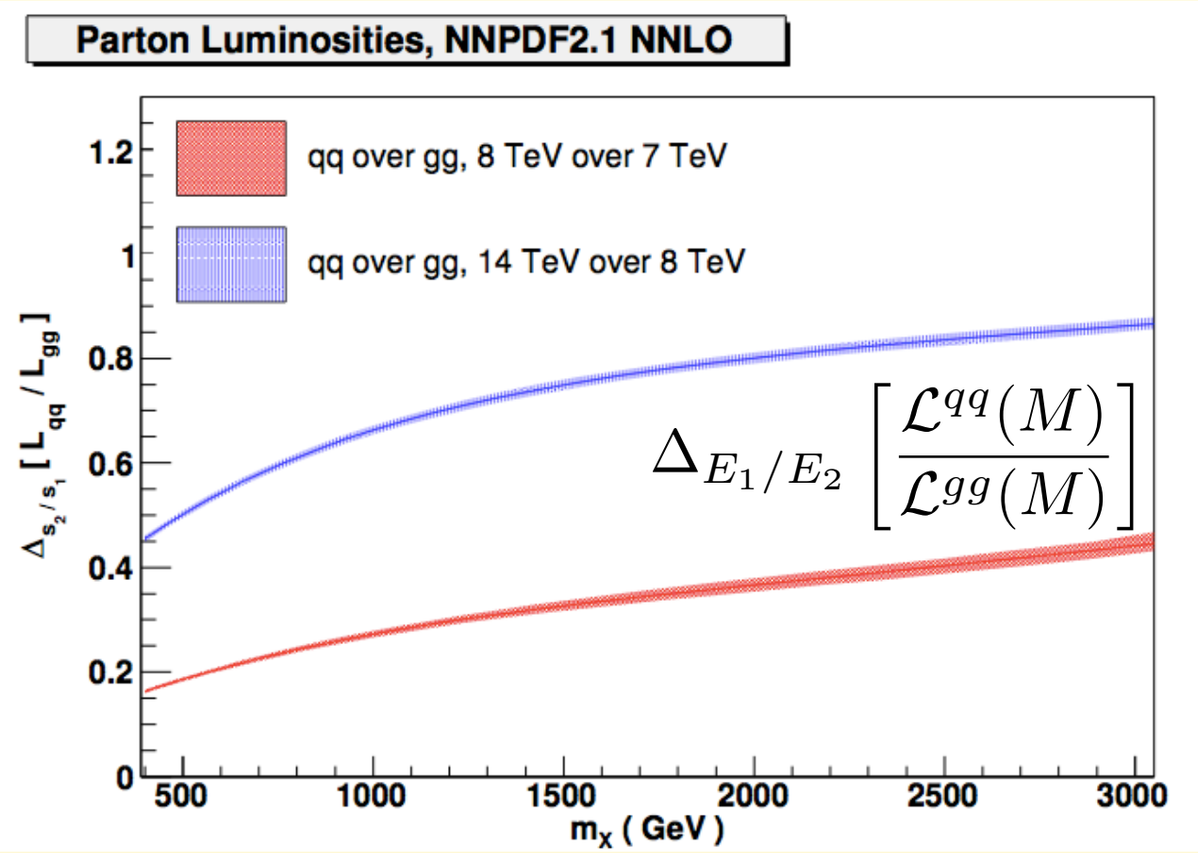
$$\Delta_{7/8}\left[\frac{\mathcal{L}^{BSM}_X}{\mathcal{L}^{SM}_X}\right] = \Delta_{7/8}\left[\frac{\mathcal{L}^{q\bar{q}}(M)}{\mathcal{L}^{gg}(M)}\right]$$

(*) e.g. SM: gg→tt and BSM: qqbar→Z'→tt

Examples of E-dependence of luminosity ratios







Given the sub-% precision of the SM ratio predictions, there is sensitivity to BSM rate contributions at the level of few% (to be improved with better PDF constraints, especially for 8/14 ratios)

Need to explore in more detail the possible implications of precise measurements of energy (double-)ratios

E.g.

(1) **$\sigma_{VBF}(H)$ grows with E differently than $\sigma_{gg}(gg\rightarrow H)$ or $\sigma_{qq}(VH)$: is there something to be learned from**

$$R_H(8)/R_H(14)$$

for $R_H = \sigma(gg\rightarrow H)/\sigma_{qq}(VH)$ or $\sigma(gg\rightarrow H)/\sigma_{VBF}(H)$?

(2) **Study ratios of asymmetries at different energies (lepton charge asym, t vs tbar asymm in single-top production, etc)**

(3) **Study ratios in different rapidity ranges, or with different kinematical cuts, to increase sensitivity to particular x-ranges of PDF, or to particular dynamical regimes**

Finally, where PDF systematics are negligible, and if there is no new physics, Xsection (double)ratios provide excellent benchmarks for calibration, anaysis validation, etc.

Powerful diagnostic tool when coming back after 2 yrs of shut-down!

Experimental challenge to match this precision. Requires great degree of correlation in the systematics of the analyses at different energies (eff's, bg subtraction, JES, ...)

Coherent efforts to plan the analyses having in mind the needs of XS (double)ratios are worth consideration

VBF total rates

From the HWG, vol 2 prelim draft

A. Denner, S. Farrington, C. Hackstein, C. Oleari, D. Rebuzzi (eds.); S. Dittmaier, A. Mück, S. Palmer and W. Quayle.

Table 14: Higgs-boson NLO cross sections at 7 TeV with VBF cuts and CTEQ6.6 PDF set with and without EW corrections, relative EW corrections and theoretical uncertainties from PDF and scale variations.

	w/ EW corr		w/o EW corr		EW corr	uncert.	
M_H [GeV]	HAWK [fb]	VBFNLO [fb]	HAWK [fb]	VBFNLO [fb]	HAWK [%]	PDF [%]	scale [%]
120	261.18 ± 0.43	258.27 ± 0.41	283.91 ± 0.42	282.80 ± 0.19	-8.0 ± 0.2	± 3.5	$+0.5 - 0.5$
150	218.40 ± 0.36	216.84 ± 0.40	236.75 ± 0.35	236.68 ± 0.14	-7.8 ± 0.2	± 3.5	$+1.0 - 0.5$
200	165.22 ± 0.24	163.50 ± 0.24	176.46 ± 0.24	176.89 ± 0.10	-6.4 ± 0.2	± 3.6	$+0.6 - 0.6$
250	123.81 ± 0.17	122.67 ± 0.17	133.13 ± 0.16	133.15 ± 0.07	-7.0 ± 0.2	± 3.8	$+0.6 - 0.5$
500	38.10 ± 0.07	37.31 ± 0.08	38.38 ± 0.07	38.41 ± 0.02	-0.7 ± 0.3	± 4.3	$+0.4 - 0.4$
600	26.34 ± 0.12	25.46 ± 0.07	25.70 ± 0.11	25.55 ± 0.01	2.5 ± 0.7	± 4.4	$+0.7 - 0.6$

Table 15: POWHEG Higgs-boson NLO QCD cross sections at 7 TeV with VBF cuts and CTEQ6.6 PDF set: fixed NLO results, POWHEG showered by PYTHIA (PY) and by HERWIG (HW).

M_H [GeV]	POWHEG NLO [fb]	POWHEG + PY [fb]	POWHEG + HW [fb]
120	282.87 ± 0.75	262.96 ± 0.99	262.04 ± 0.99
150	237.30 ± 0.57	221.54 ± 0.79	219.95 ± 0.79
200	177.05 ± 0.38	164.55 ± 0.55	163.83 ± 0.55
250	132.93 ± 0.26	124.19 ± 0.40	123.65 ± 0.40
500	34.04 ± 0.07	31.92 ± 0.09	31.78 ± 0.10
600	20.56 ± 0.03	19.47 ± 0.06	19.30 ± 0.06

Table 18: NLO QCD cross sections and efficiencies from VBFNLO for the full VBF selection including the jet veto cut of 20 GeV and the corresponding relative uncertainties from the QCD scale and PDFs.

M_H	Cross section			Efficiency		
[GeV]	[fb]	[%]	[%]	[%]	[%]	[%]
120	261.64	± 3.76	± 4.91	0.200	± 3.485	± 1.468
150	218.69	± 3.59	± 4.66	0.221	± 3.376	± 1.196
200	163.34	± 3.92	± 4.66	0.252	± 3.829	± 1.490
250	123.06	± 4.16	± 5.11	0.279	± 4.145	± 1.493
500	33.55	± 4.37	± 5.43	0.365	± 4.766	± 1.227
600	20.82	± 4.44	± 5.58	0.384	± 4.958	± 1.002

$p_{Tj} > 20$ GeV, $\quad |y_j| < 4.5$

$|y_{j_1} - y_{j_2}| > 4\,, \quad m_{jj} > 600$ GeV.

Summary assessment:

Low mass:
Δ(shower/PL)= –8%
Δ(EW/noEW)= –8%

High mass:
POWHEG: Δ(shower/PL) = –5%
Δ(POWHEG NLO/VBFNLO)= –20% *
Δ(EW/noEW)= +2.5%

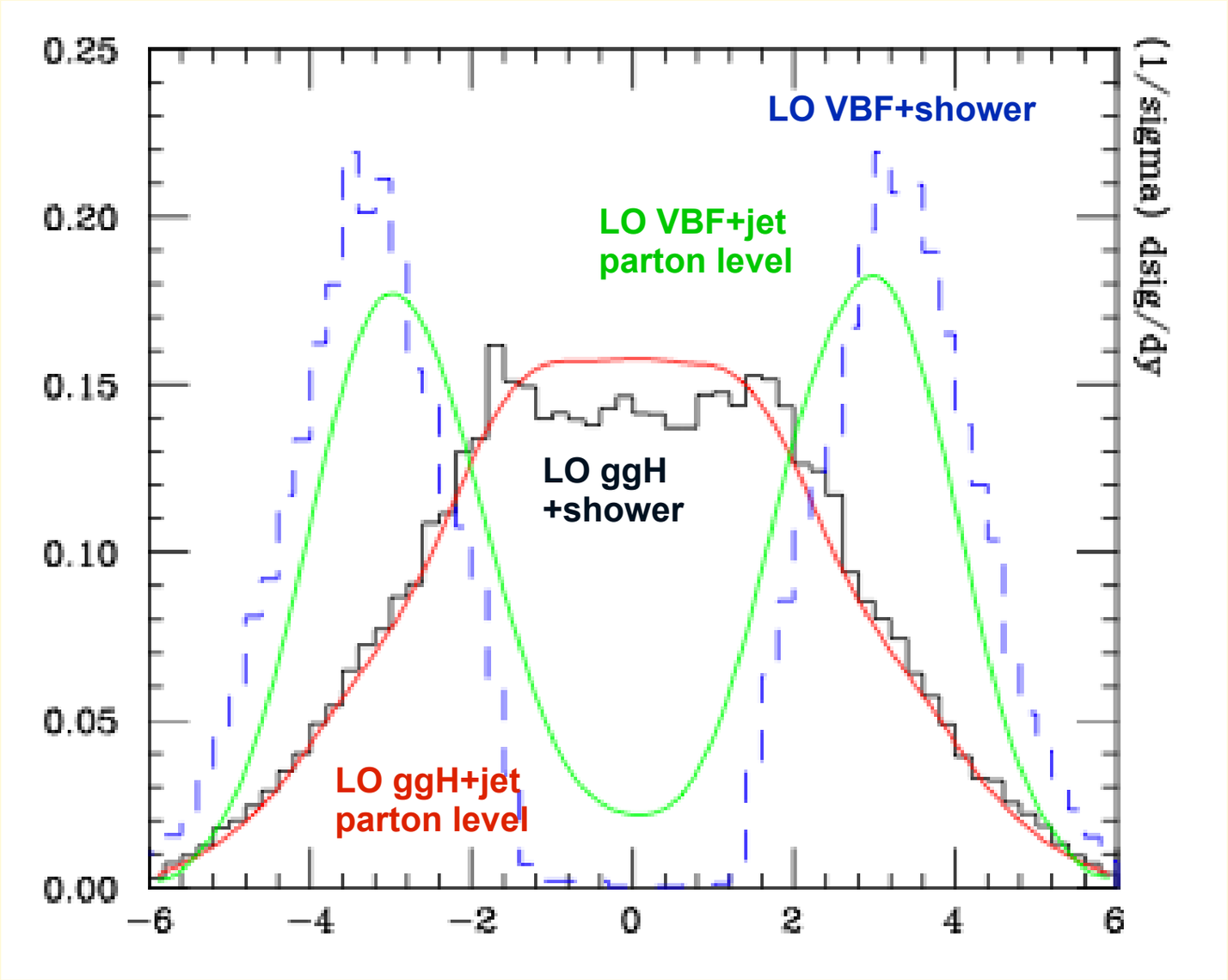
* diff due to different BW implementation

PDF:
±3-4% CTEQ6.6
±5-6% MSTW2008NLO
(central values consistent within syst)

X-section after jet veto:
± 4% from scale variation (VBFNLO)
± 5% from PDF (VBFNLO)

3rd-jet rates and spectra in Hjj production

Del Duca et al, JHEP 0610 (2006) 016

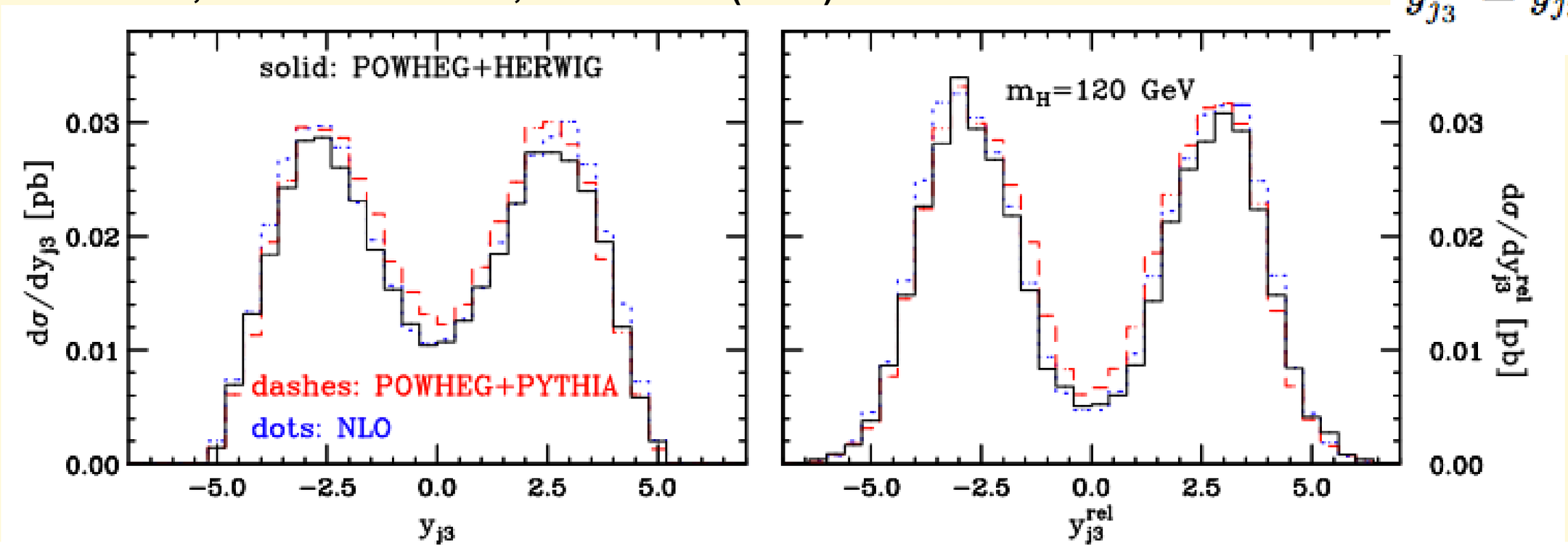


ggH: ~ **VBF:** ≠

need to incorporate higher-order MEs for proper simulation of central jet activity (and thus veto survival rate) in VBF H production

POWHEG study of 3rd-jet emission in VBF Hjj production at NLO, Nason and Oleari, JHEP 1002 (2010) 037

$$y_{j_3}^{\rm rel} = y_{j_3} - \frac{y_{j_1} + y_{j_2}}{2}$$



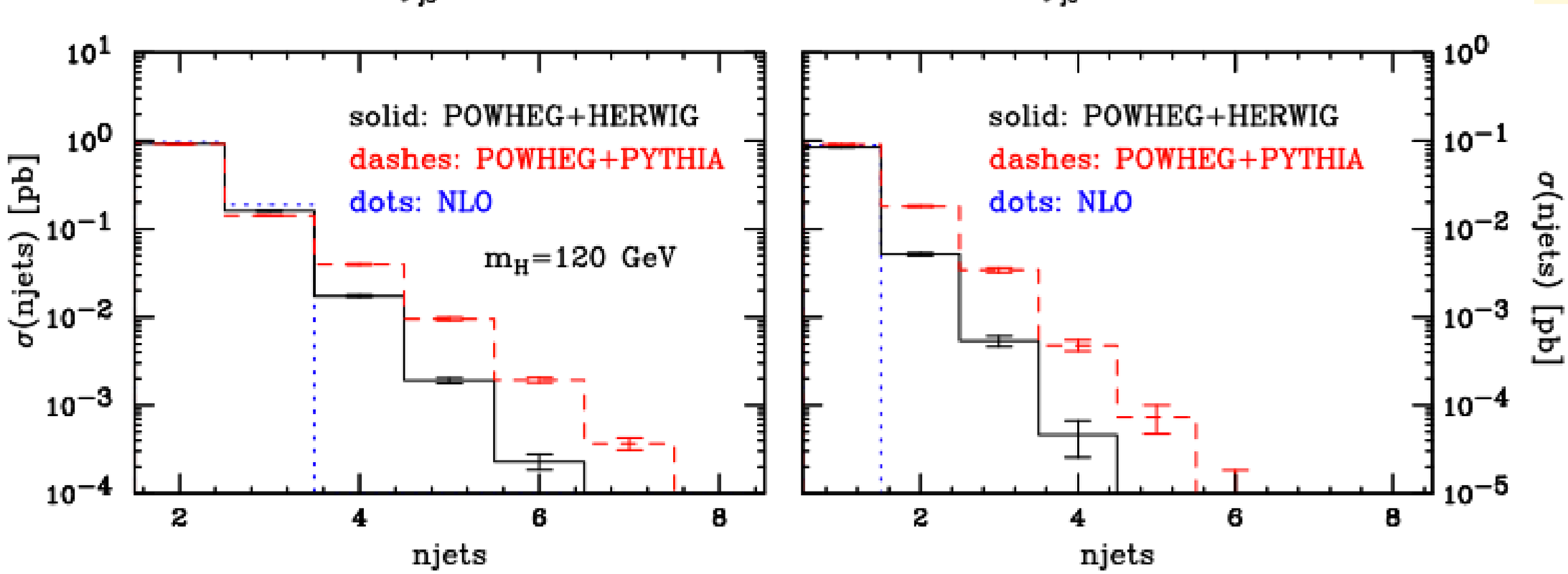
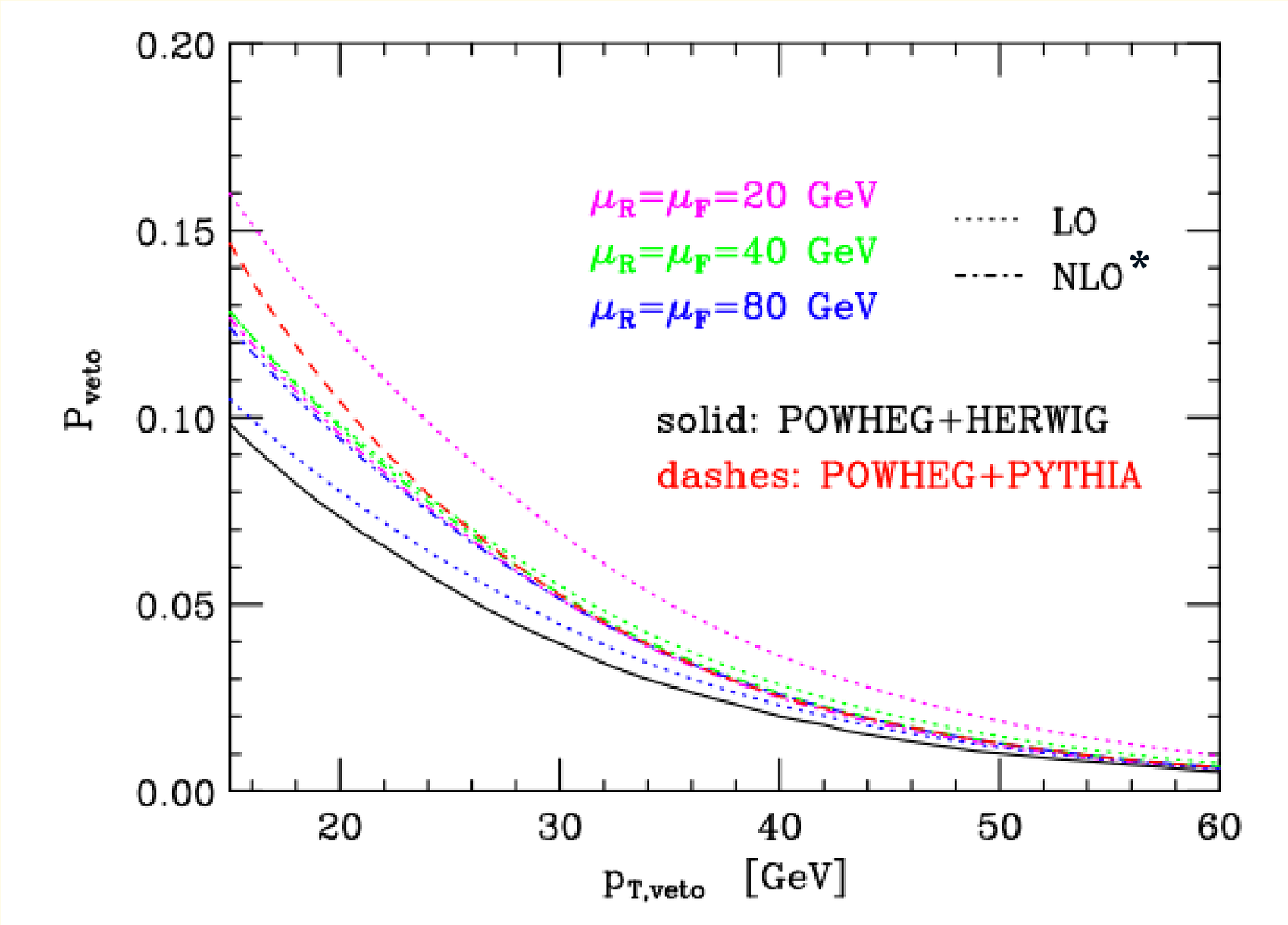


Figure 8: Jet-multiplicity distribution for jets that pass the cuts of eqs. (3.3) and (3.4) (left panel) and those that fall within the rapidity interval of the two tagging jets, $\min(y_{j_1}, y_{j_2}) < y_j < \max(y_{j_1}, y_{j_2})$ (right panel).

POWHEG study of 3rd-jet emission in VBF Hjj production at NLO, Nason and Oleari, JHEP 1002 (2010) 037

Veto inefficiency for VBF signal:

Scale dependence greatly reduced in NLO w.r.t. LO



* NLO: T. Figy, V. Hankele, and D. Zeppenfeld, *Next-to-leading order QCD corrections to Higgs plus three jet production in vector-boson fusion*, *JHEP* **02** (2008) 076, [0710.5621].

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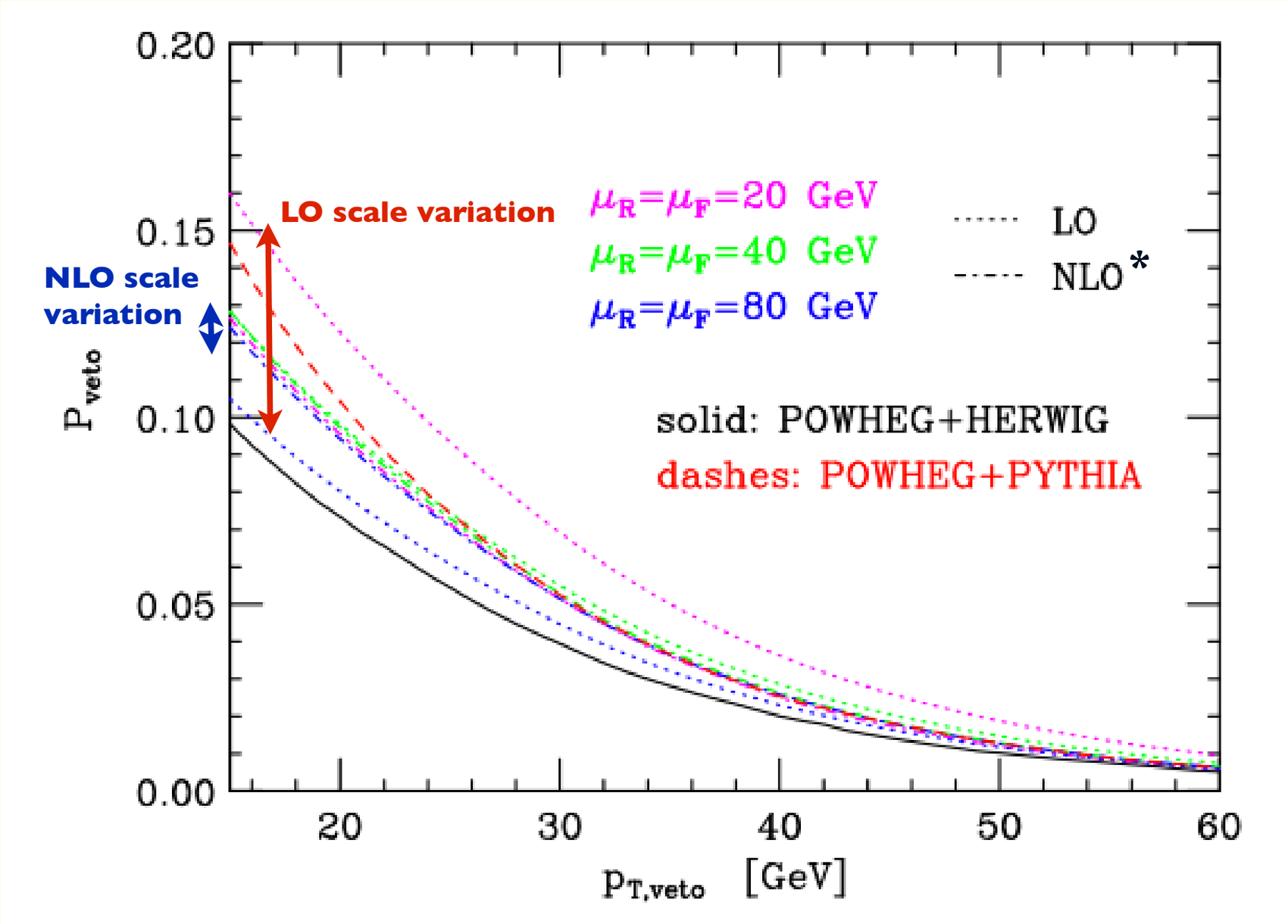

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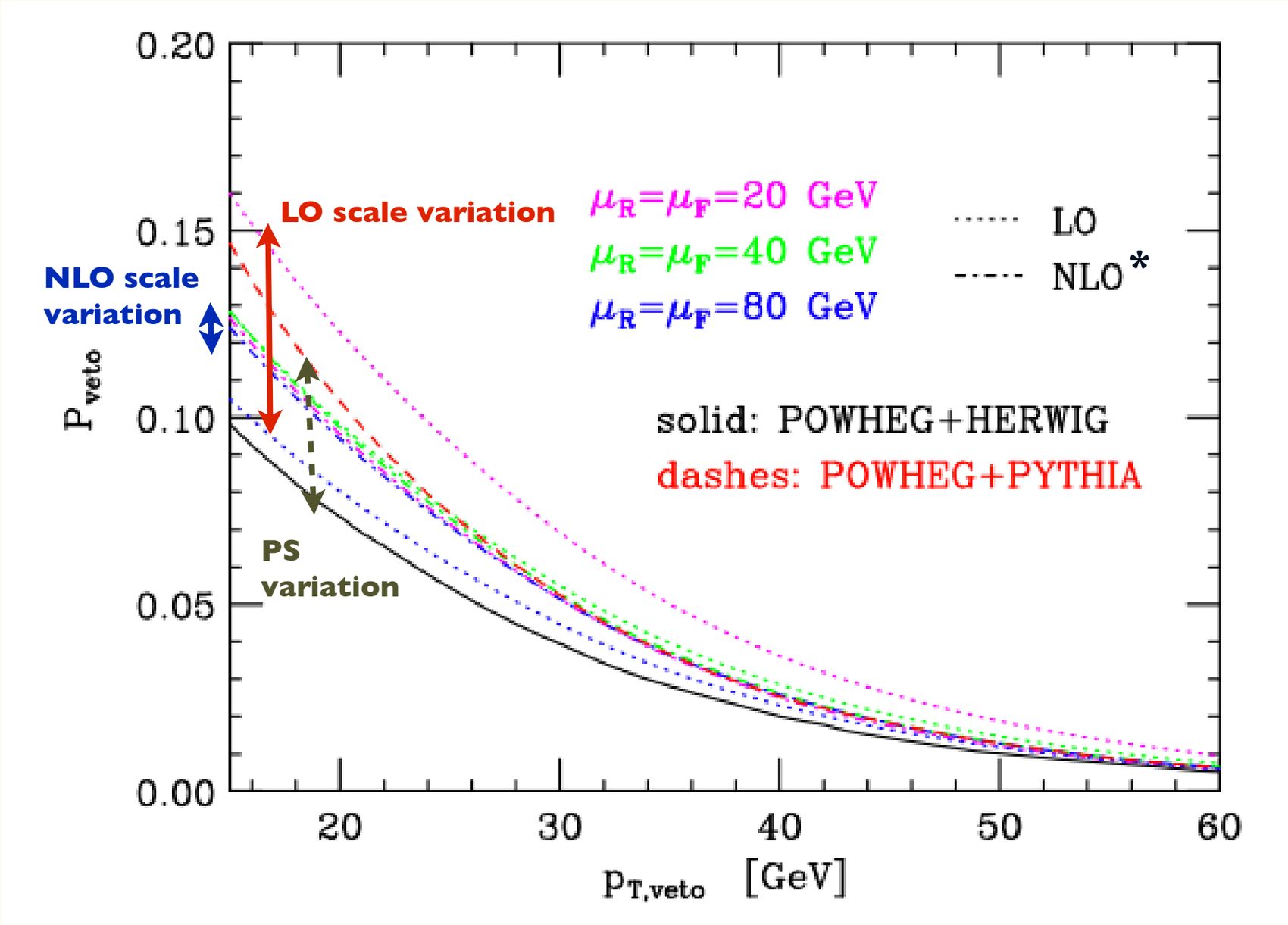
However difference in shower implementation of NLO PL results leads to diff's as large as LO scale uncertainty!



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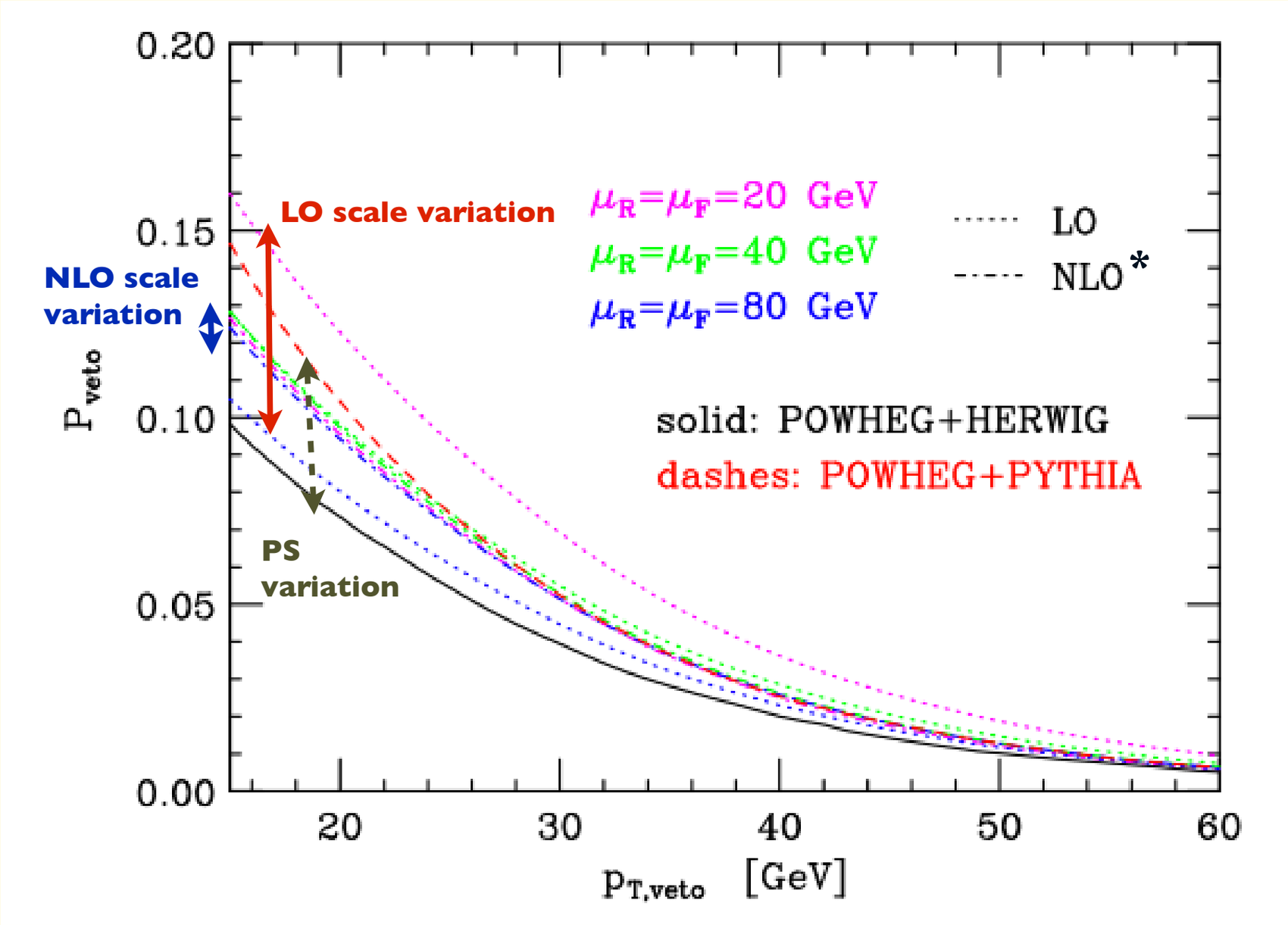


=> syst's ~±5% for signal efficiency

This requires proper validation. Study, e.g., VBF production of Zjj ?

* NLO: T. Figy, V. Hankele, and D. Zeppenfeld, *Next-to-leading order QCD corrections to Higgs plus three jet production in vector-boson fusion*, *JHEP* **02** (2008) 076, [0710.5621].

Studies of jet activity in final states with dijets at large Δy

ATLAS, JHEP 1109 (2011) 053

indirect validation of jet-veto suppression efficiency for bgs

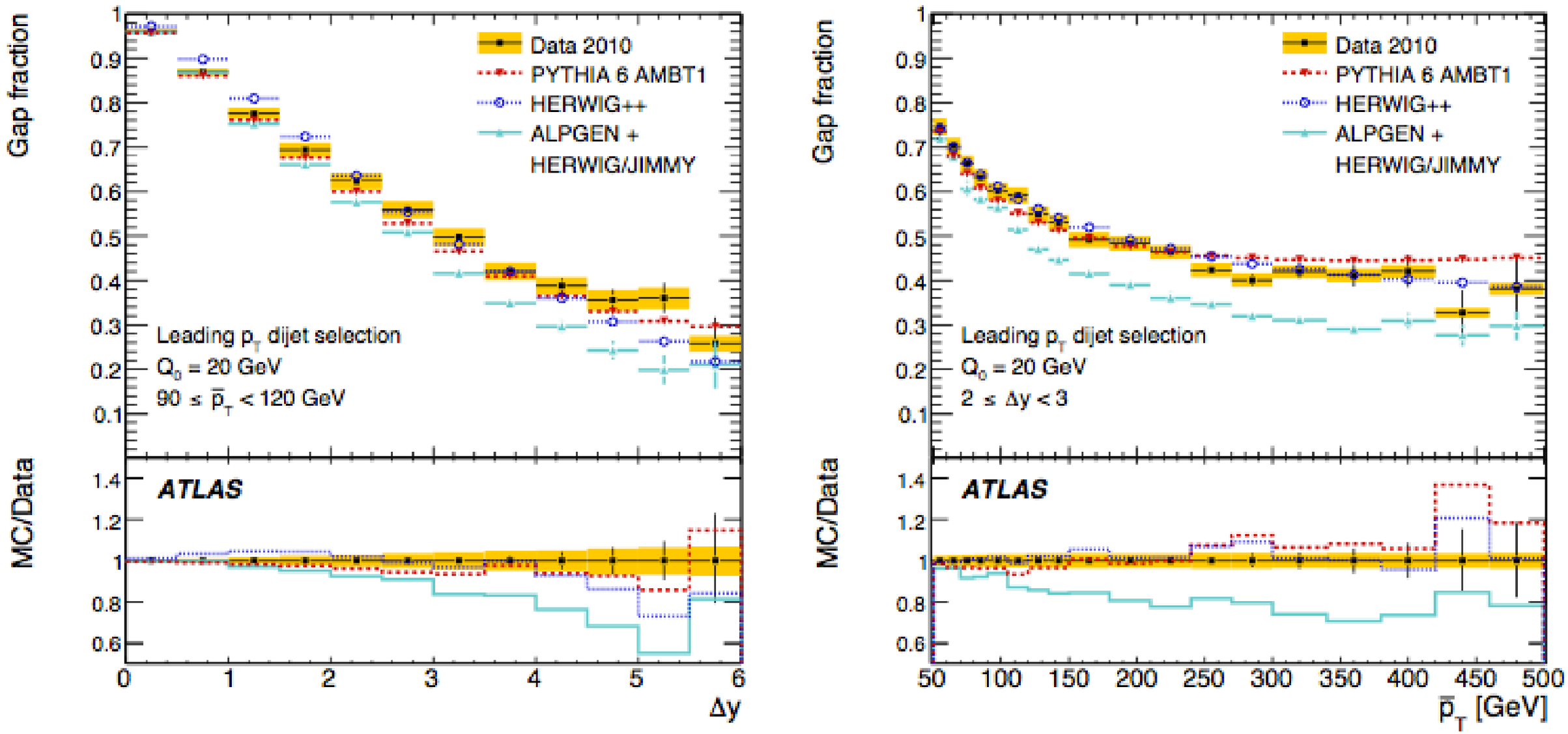


Figure 2. Gap fraction as a function of Δy, given that the dijet system is defined as the leading-p_T jets in the event and satisfies $90 \le \bar{p}_T < 120$ GeV (a). Gap fraction as a function of $\bar{p}_T$ given that the rapidity interval is $2 \le \Delta y < 3$ (b). The (corrected) data are the black points, with error bars representing the statistical uncertainty. The total systematic uncertainty on the measurement is represented by the solid (yellow) band. The dashed (red) points represents the PYTHIA prediction (tune AMBT1), the dot-dashed (blue) points represents the HERWIG++ prediction (tune LHC-UE7-1) and the solid (cyan) points represents the ALPGEN prediction (tune AUET1).

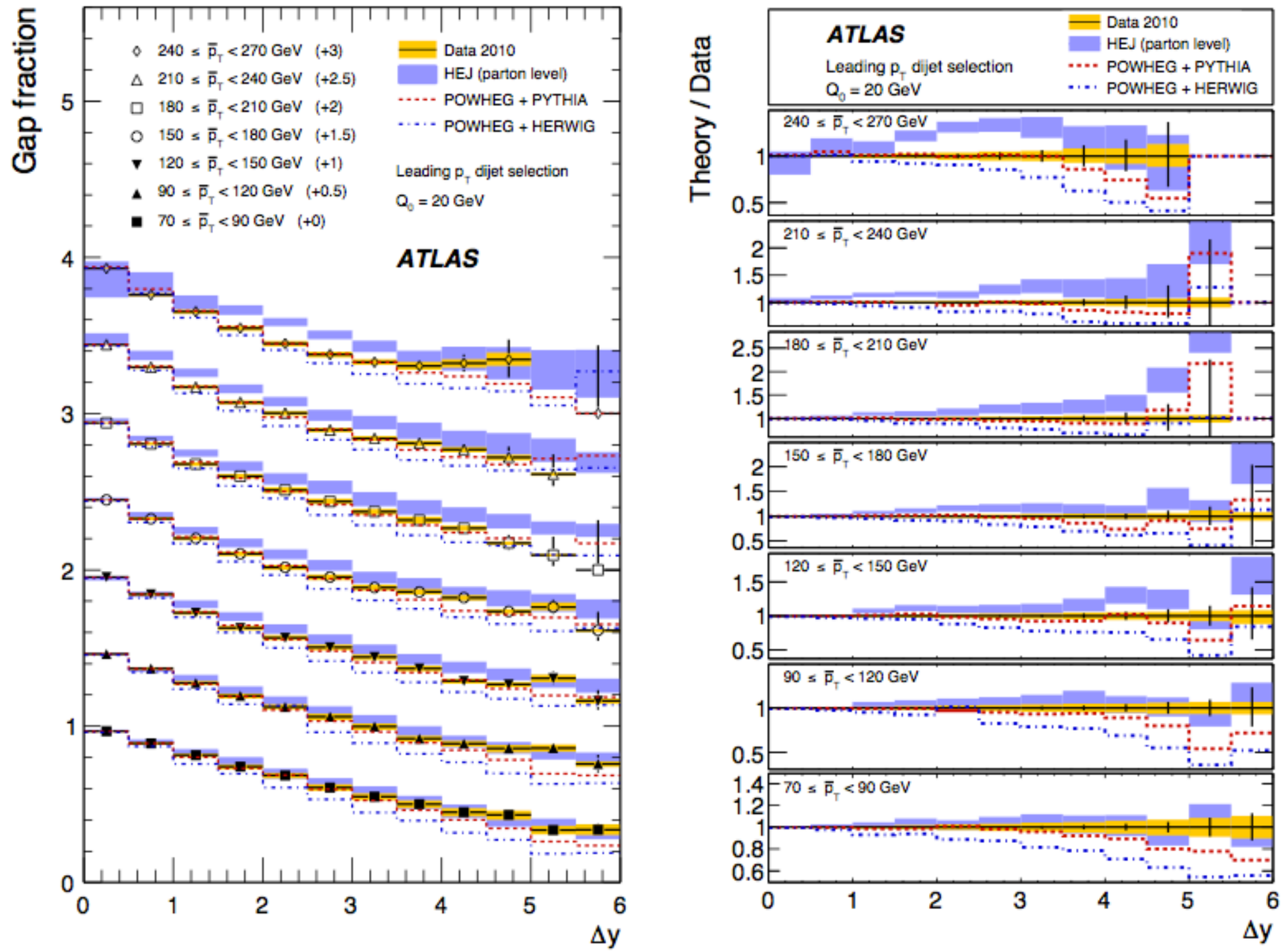
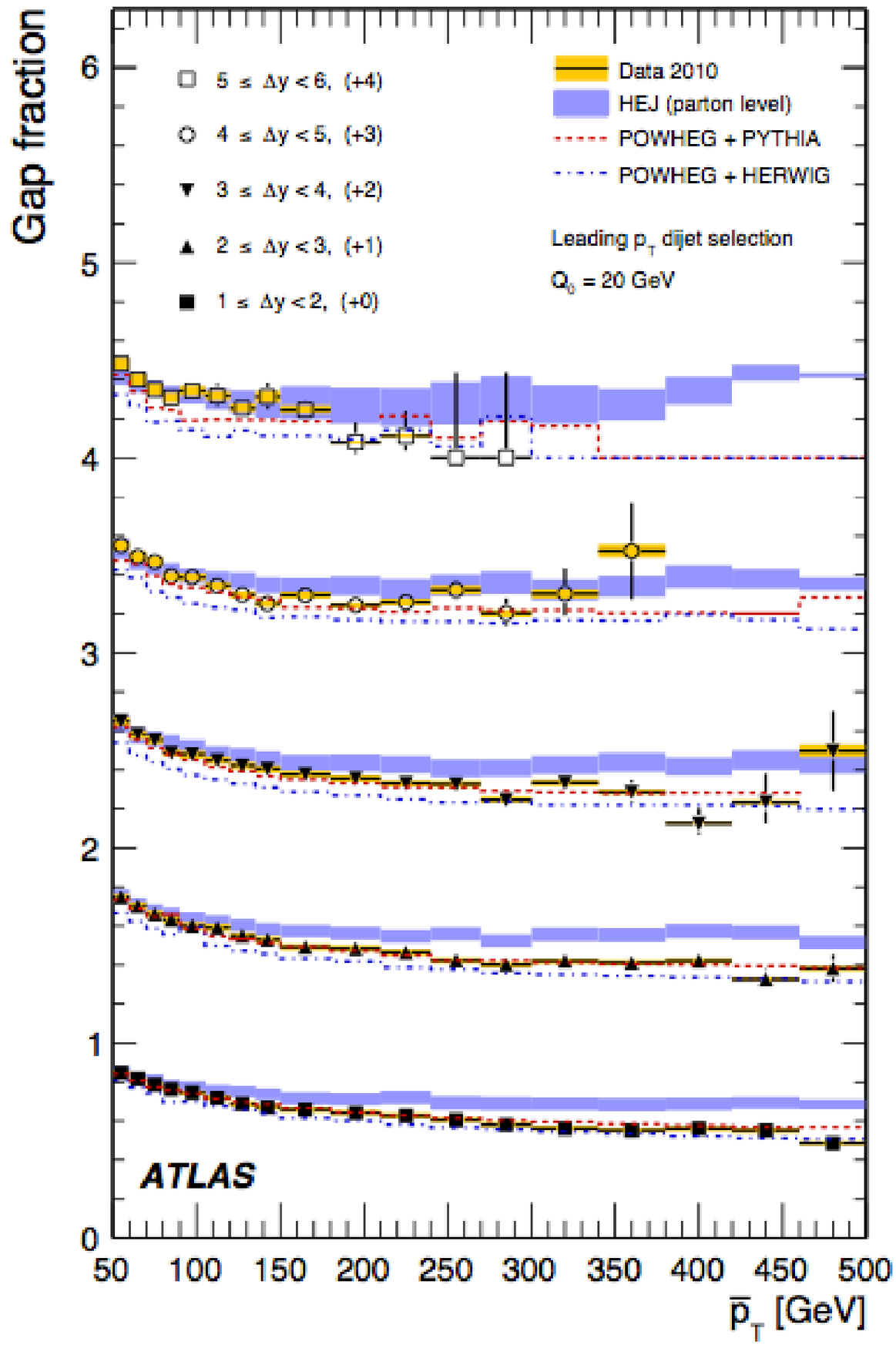
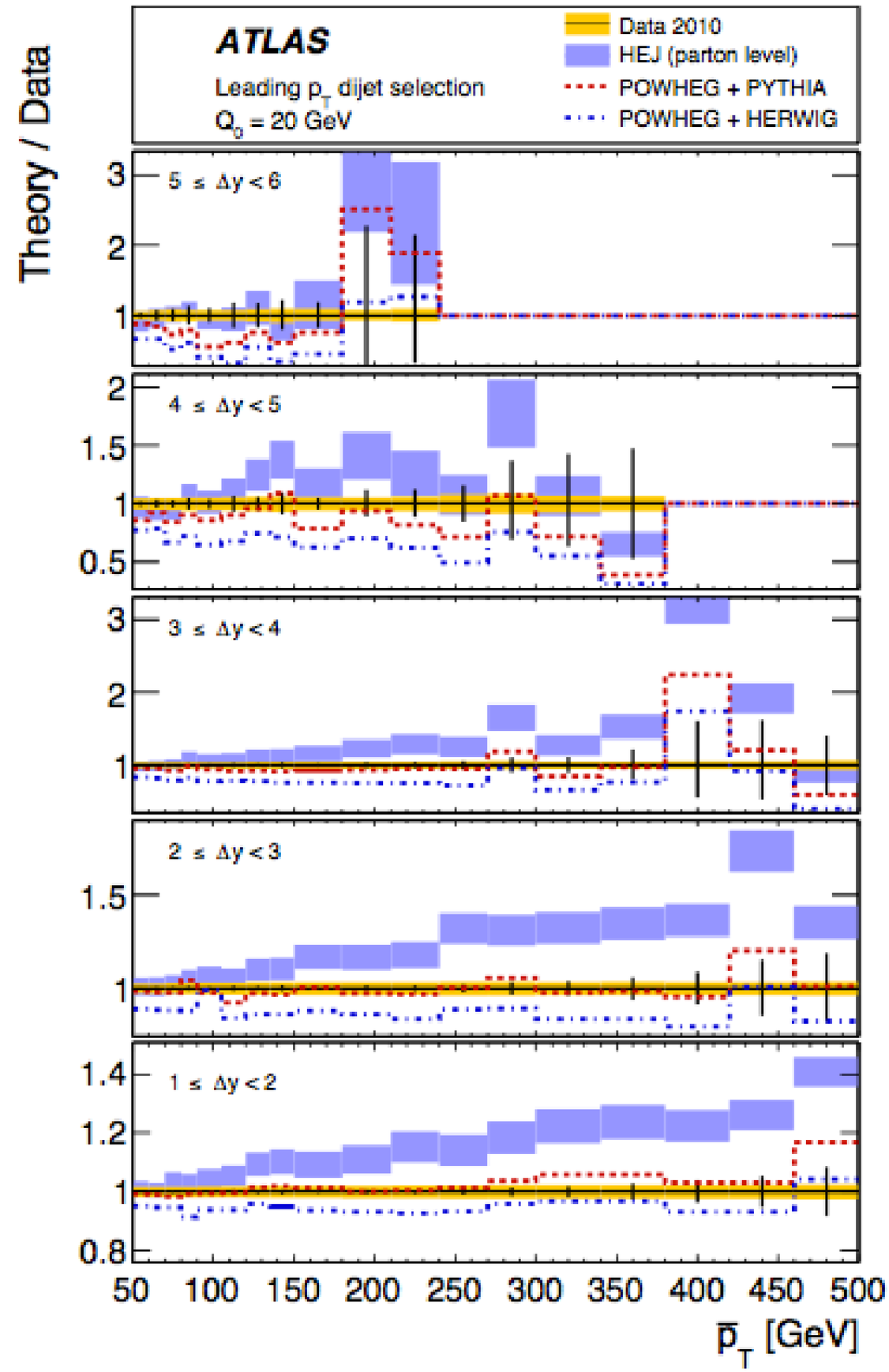


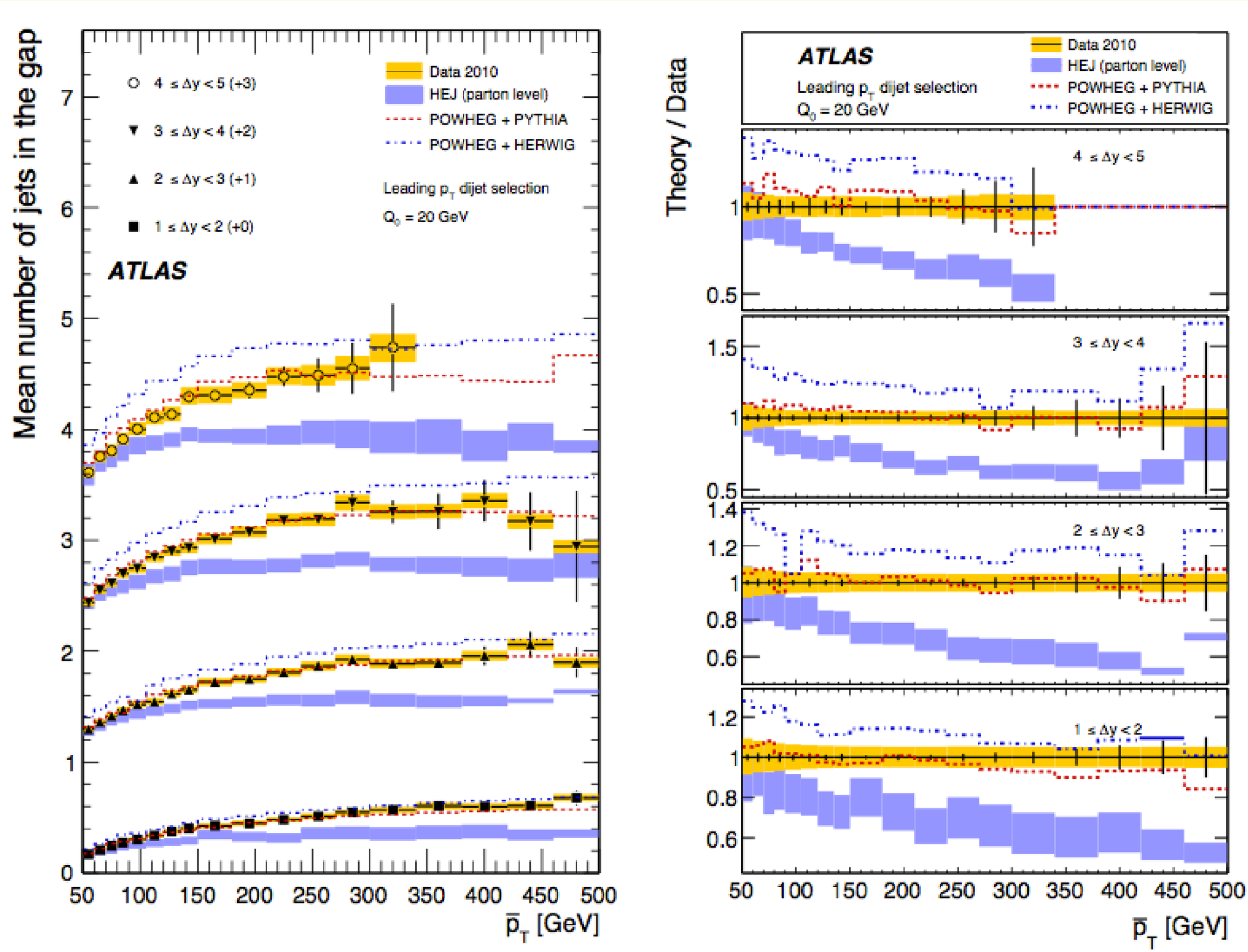
Figure 3. Gap fraction as a function of Δy for various $\overline{p}_{\mathrm{T}}$ slices. The dijet system is defined as the two leading-p_{T} jets in the event. The data are compared to the HEJ and POWHEG predictions in (a). The ratio of these theory predictions to the data are shown in (b). The (unfolded) data are the black points, with error bars representing the statistical uncertainty and a solid (yellow) band representing the total systematic uncertainty. The darker (blue) band represents the theoretical uncertainty in the HEJ calculation from variation of the PDF and renormalisation/factorisation scales. The dashed (red) and dot-dashed (blue) curves represent the POWHEG predictions after showering, hadronisation and underlying event simulation with PYTHIA (tune AMBT1) and HERWIG/JIMMY (tune AUET1), respectively.

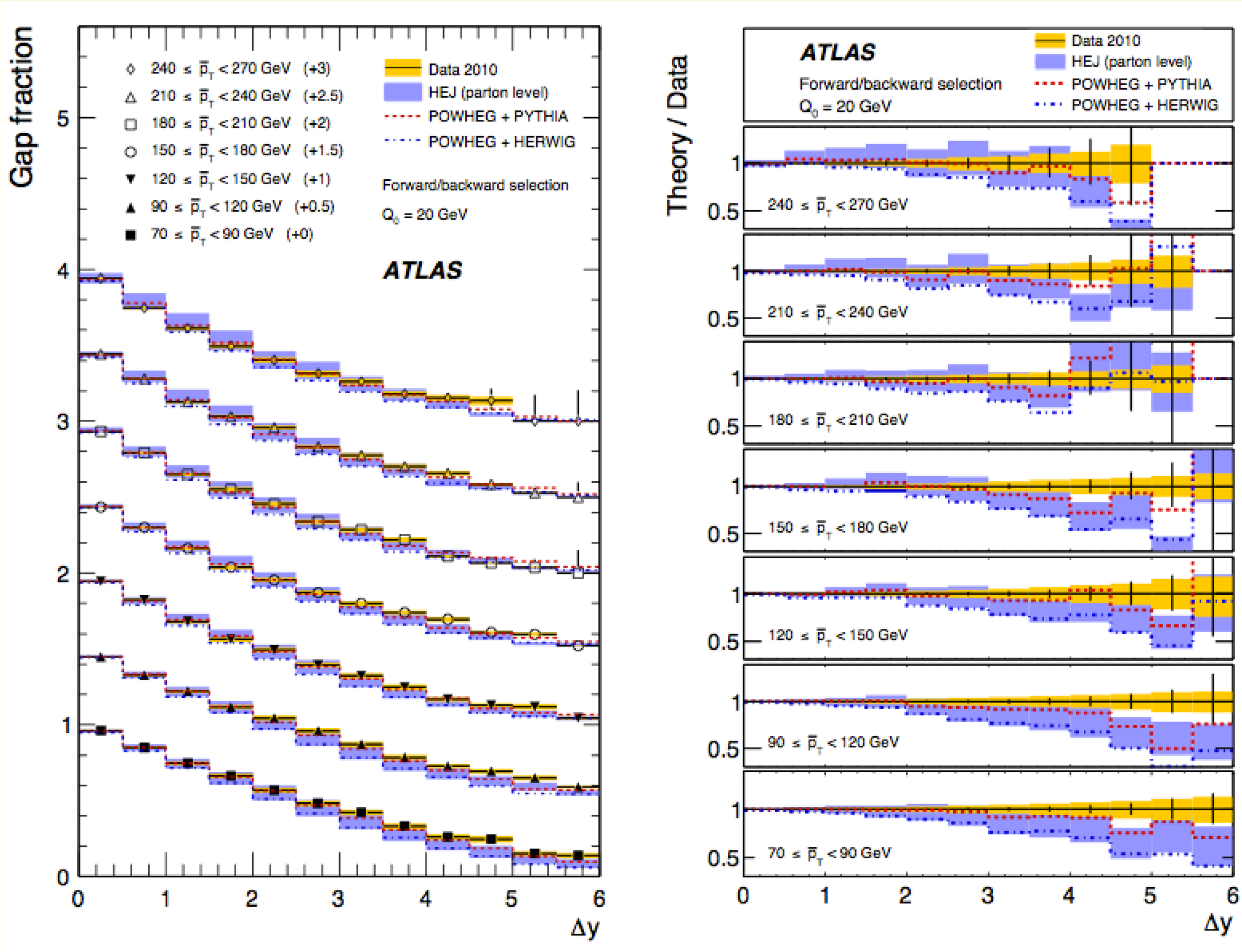
At large Δy (VBF region) POWHEG +Herwig has more jet activity than data (up to x2) and more than POWHEG +Pythia

=> syst's ~±50% for bg suppression


Gap fraction
5 ≤ Δy < 6, (+4)
4 ≤ Δy < 5, (+3)
3 ≤ Δy < 4, (+2)
2 ≤ Δy < 3, (+1)
1 ≤ Δy < 2, (+0)
Data 2010
HEJ (parton level)
POWHEG + PYTHIA
POWHEG + HERWIG
Leading p_T dijet selection
Q_0 = 20 GeV
ATLAS
p̄_T [GeV]


Theory / Data
ATLAS
Leading p_T dijet selection
Q_0 = 20 GeV
Data 2010
HEJ (parton level)
POWHEG + PYTHIA
POWHEG + HERWIG
5 ≤ Δy < 6
4 ≤ Δy < 5
3 ≤ Δy < 4
2 ≤ Δy < 3
1 ≤ Δy < 2
p̄_T [GeV]


Mean number of jets in the gap
4 ≤ Δy < 5 (+3)
3 ≤ Δy < 4 (+2)
2 ≤ Δy < 3 (+1)
1 ≤ Δy < 2 (+0)
ATLAS
Data 2010
HEJ (parton level)
POWHEG + PYTHIA
POWHEG + HERWIG
Leading p_T dijet selection
Q_0 = 20 GeV
p̄_T [GeV]
Theory / Data
ATLAS
Leading p_T dijet selection
Q_0 = 20 GeV
Data 2010
HEJ (parton level)
POWHEG + PYTHIA
POWHEG + HERWIG
4 ≤ Δy < 5
3 ≤ Δy < 4
2 ≤ Δy < 3
1 ≤ Δy < 2
p̄_T [GeV]


Gap fraction
240 ≤ p̄T < 270 GeV (+3)
210 ≤ p̄T < 240 GeV (+2.5)
180 ≤ p̄T < 210 GeV (+2)
150 ≤ p̄T < 180 GeV (+1.5)
120 ≤ p̄T < 150 GeV (+1)
90 ≤ p̄T < 120 GeV (+0.5)
70 ≤ p̄T < 90 GeV (+0)
Data 2010
HEJ (parton level)
POWHEG + PYTHIA
POWHEG + HERWIG
Forward/backward selection
Q0 = 20 GeV
ATLAS
Δy
Theory / Data
ATLAS
Forward/backward selection
Q0 = 20 GeV
Data 2010
HEJ (parton level)
POWHEG + PYTHIA
POWHEG + HERWIG
240 ≤ p̄T < 270 GeV
210 ≤ p̄T < 240 GeV
180 ≤ p̄T < 210 GeV
150 ≤ p̄T < 180 GeV
120 ≤ p̄T < 150 GeV
90 ≤ p̄T < 120 GeV
70 ≤ p̄T < 90 GeV
Δy

Key messages

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- The studies carried out in the context of **searches** often carry precious information on QCD dynamics: must be made available and documented