Di-Vector-Boson Production in Association with Multiple Jets at the LHC.

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MARIE CURIE ACTIONS

DFG

MWK

Outline

Motivation: W W+Jets

NLO with Unitarity: BlackHat

Predictions

Quests at LHC

Explore the 1 TeV mass scale:

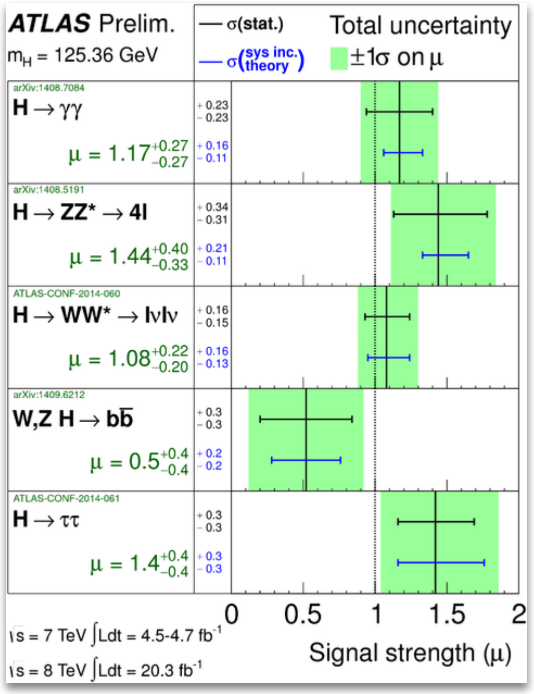
- Origin of electroweak symmetry breaking.
- Searches for Dark-Matter particles (e.g. SUSY).

WW + jets important in Standard Model:

- Measurements of Higgs & vector bosons.
- As backgrounds to New-Physics searches.

Bullet cluster/Dark Matter:

Higgs boson signal strength.

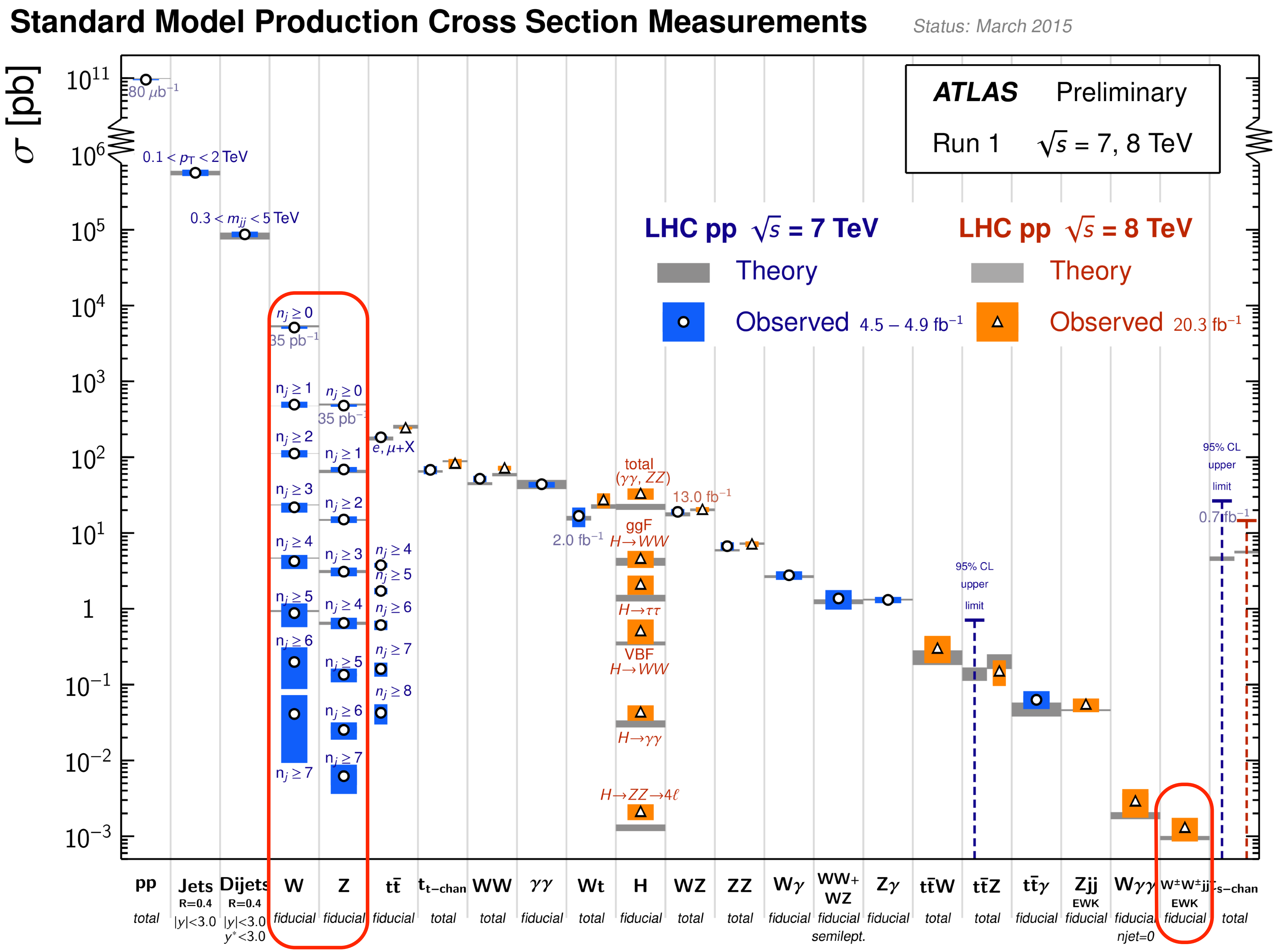


WW + Jets Signatures

Rich phenomenology including many jets:

- Cubic and quartic couplings of electroweak vector bosons.
- Top-pair production with top decays to W-bosons and b-quarks.
- Higgs phenomenology: Higgs coupling to vector-boson pairs.
- In particular, WW+2,3-jet production is background to vector-boson-fusion (VBF) mechanism: understand radiation between tagging jets.
- BSM models; decay chains of heavy colored particles to leptons and jets.

WW + Jets @ ATLAS



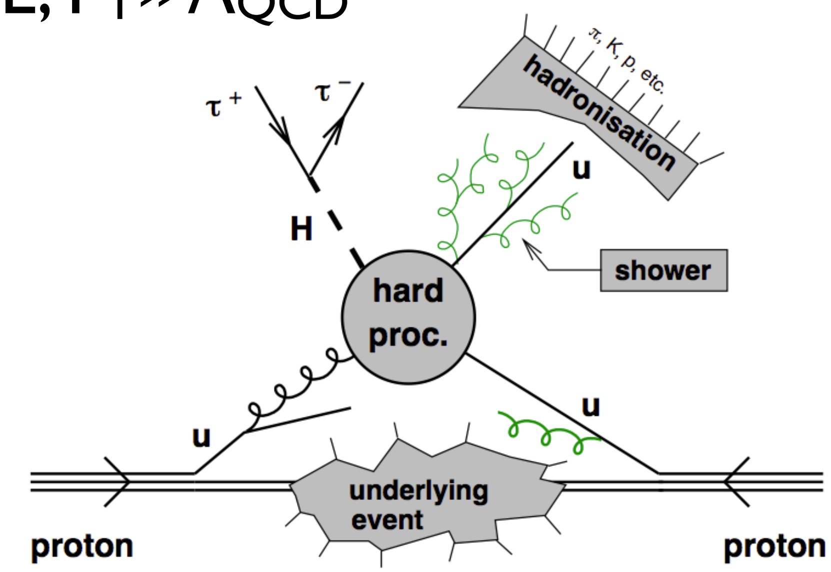
- Impressive agreement of theory and experiment.
- Jet towers help to understand QCD.
- Small cross section for WW+jets.
- Similar results from CMS.

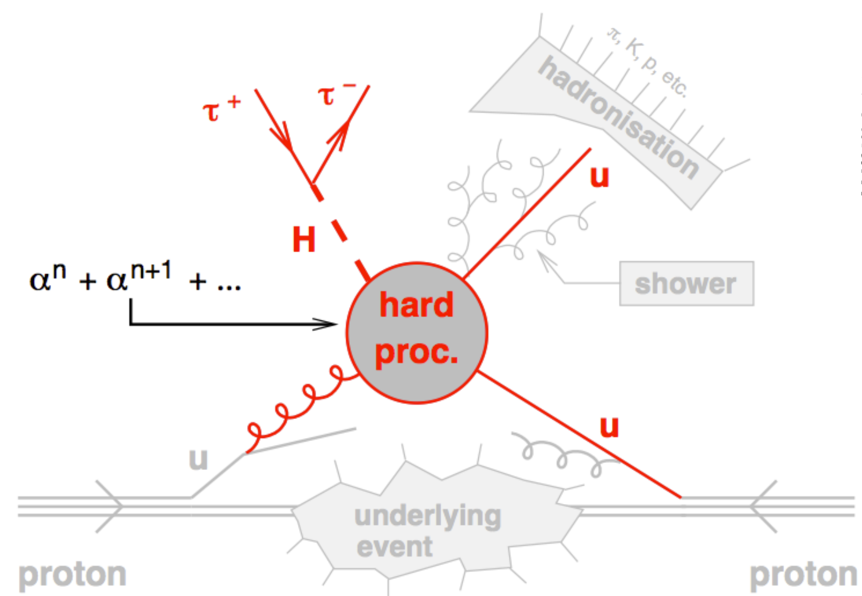
Hadron Collisions

Theory based on QCD improved parton model:

- Parton level prediction.
- Truncated perturbative expansion introduces scale dependence @ high multiplicity.
- Process dependence in hard partonic cross sections.
- Quantum corrections important: next-to-leading-order (NLO) effects in strong-coupling expansion.

$E, P_T \gg \Lambda_{QCD}$





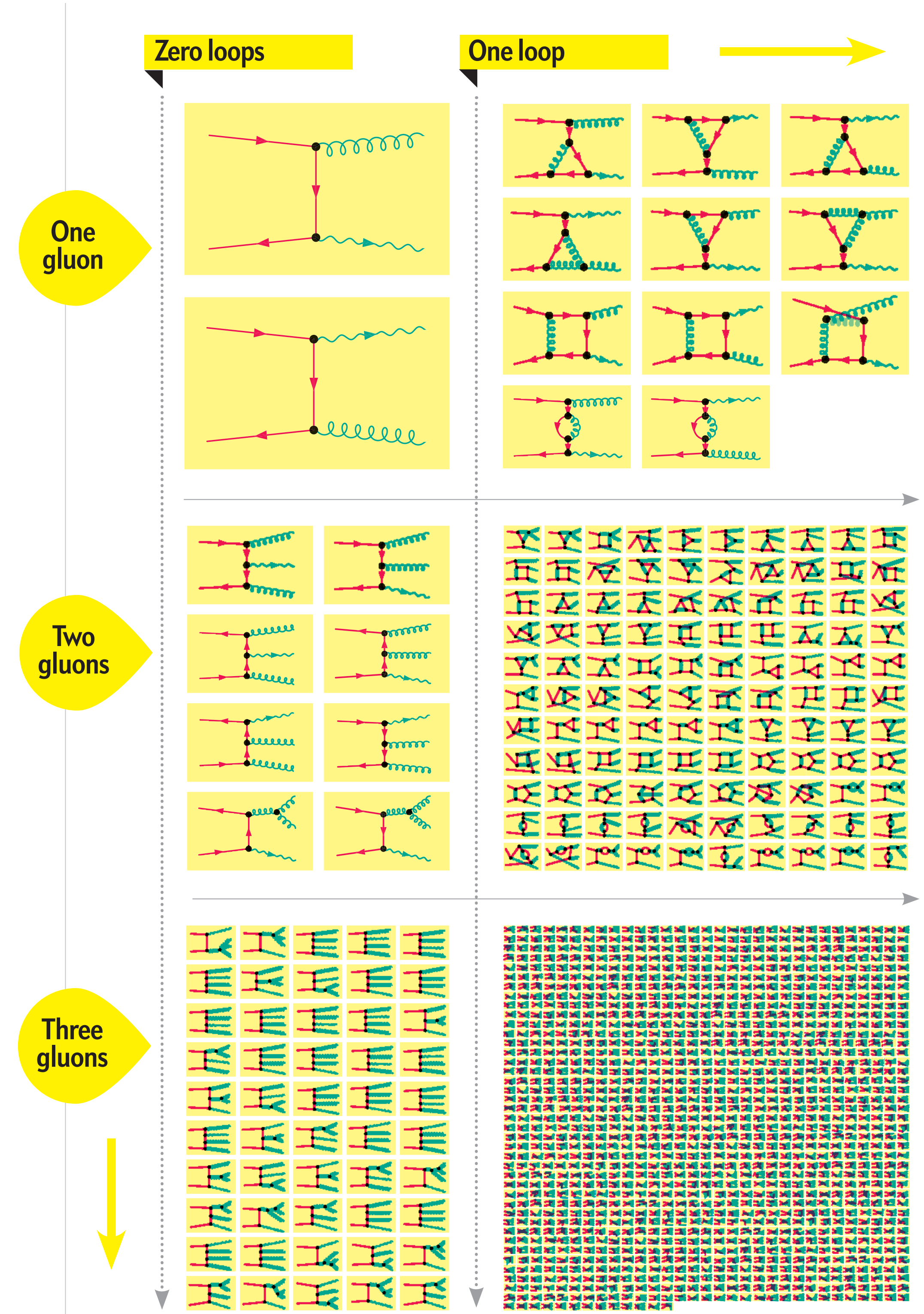
diagrams from G. Salam

Complexity

In practice, perturbation theory is complicated:

- Factorial growth of diagrams, exponential growth of spin sums.
- Many interesting processes needed (Higgs, W/Z, top, jets, photons, susy, etc.).
- Numerical challenges: gauge cancellations, tensor reduction, soft and collinear cancellations, integrals.

⇒ Must find the right approach!



Bern, Dixon, Kosower, **Sci.Am. 306N5 (2012) 20-27**

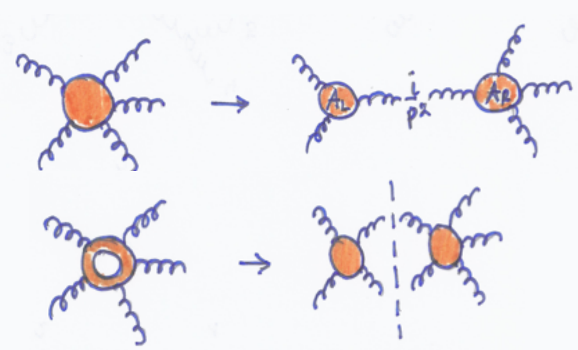
The Unitarity Method

Origins in bootstrap program for strong interactions in 60s which aims to construct amplitudes directly from analytic properties.

[Chew, Mandelstam; Eden, Landshoff, Olive, Polkinghorne; Veneziano; Virasoro, Shapiro; …]

Replaced in 70s by rise of field theory (QCD) and Feynman rules. Return of analyticity as boost for field theory unitarity method.

[Bern, Dixon, Dunbar, Kosover]



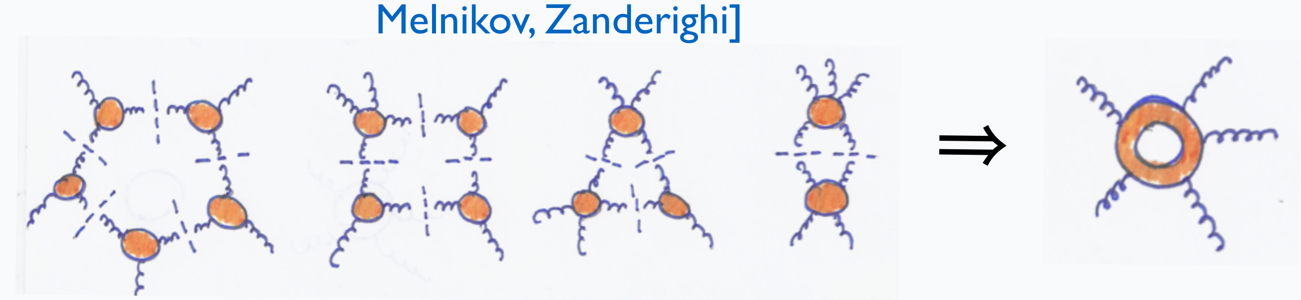
- Built from analytic inspiration: N=4 super Yang-Mills.
- Poles explained by factorisation.
- Branch cuts from optical theorem, generalised cuts.
- Spinor helicity, color ordering.

Many contributors: [Arkani-Hamed, Badger, Berger, Bern, Bjerrum-Bohr, Brandhumber, Britto, Cachazo, Dixon, Dunbar, Ellis, Febres-Cordero, Feng, Forde, Giele, Harmeren, HI, Kosower, Kunszt, Maitre, Mastrolia, Melnikov, Ossola, Papadopoulos, Pittau, Schwinn, Spence, Travaglini, Weinzierl, Witten]

Numerical unitarity methods are algorithm to construct loop amplitudes from tree amplitudes:

- Good numerical stability.
- Multiplicity independent setup.

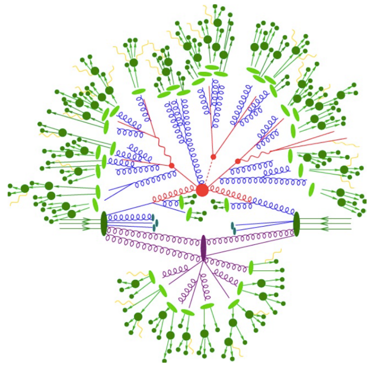
Reviews: e.g. [Britto; HI; Ellis, Kunszt, Melnikov, Zanderighi]



NLO with BlackHat

BlackHat: [Bern, Dixon, Febres Cordero, Hoeche, HI, Kosower, Maitre. Former: Berger, Forde.]

- A loop matrix element generator based on unitarity & on-shell methods.
- Linked to SHERPA Monte-Carlo for partonic cross sections [Hoeche, Krauss, Kuttimalai, Schoenherr, Schumann, Siegert, Thompson, Winter, Zapp]
- Recent results: W/Z +3,4,5 jets; 4 jets; γγ+2jet; Ntuples



WW + 0,1,2,3 jets:

- New infrastructure & tree input [Diploma thesis of P. Hofmann]
- Cross checks: UV/IR-structure, factorisation, 2nd implementation using off-shell recursion [Brends, Giele], literature for WW + 1, 2 jets [GOSAM; Melia, Menikov, Zanderighi], consistent dipole subtraction.

Parton-level predictions WW+Jets

W-W+:

- **LO (1979):** [Brown, Michaelin]
- **NLO (1991):** [Ohnemus; Frixione; Campbell, Ellis; Dixon, Kunszt, Signer; Campbel, Ellis, Williams]
- **NNLO (2014):** [Gehrmann, Grazzini, Kallweit, Maierhoefer, von Manteuffel, Pozzorini, Rathlev, Tancreedi]

W+W- + 1jet:

- **NLO (2007):** [Campbell, Ellis, Zanderighi; Dittmaier, Kallweit, Uwer; Campbell, Miller, Robens]

W+W- + 2 jets:

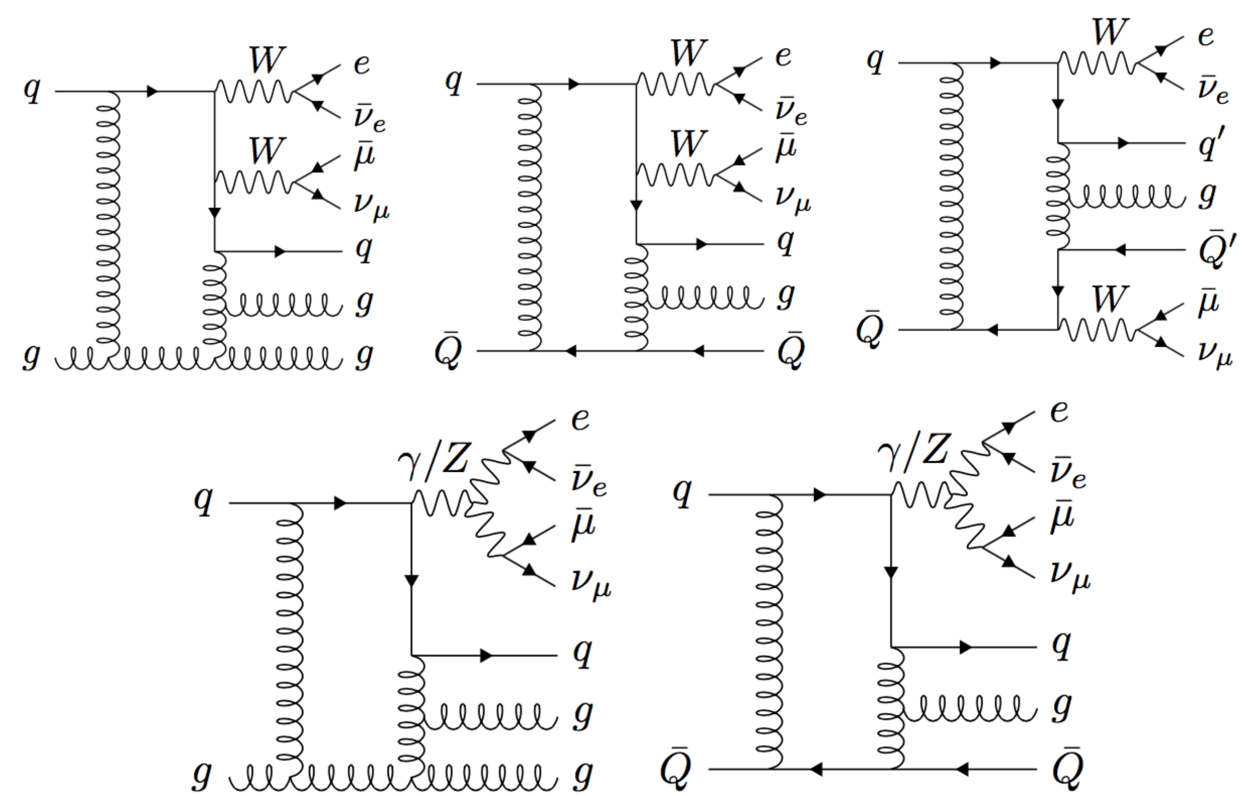
- **NLO (2011):** [Melia, Melnikov, Rontsch, Zanderighi; Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano; Alwall, Frederix, Frixione, Hirschi, Maltoni, et al.]

W+W+ + 2 Jets:

- **NLO (2010):** [Melia, Melnikov, Rontsch, Zanderighi; Campanario, Kerner, Ninh, Zeppenfeld]

WW+Jets Setup

Work @ Uni Freiburg [in preparation: Febres Cordero, HI, Hofmann].



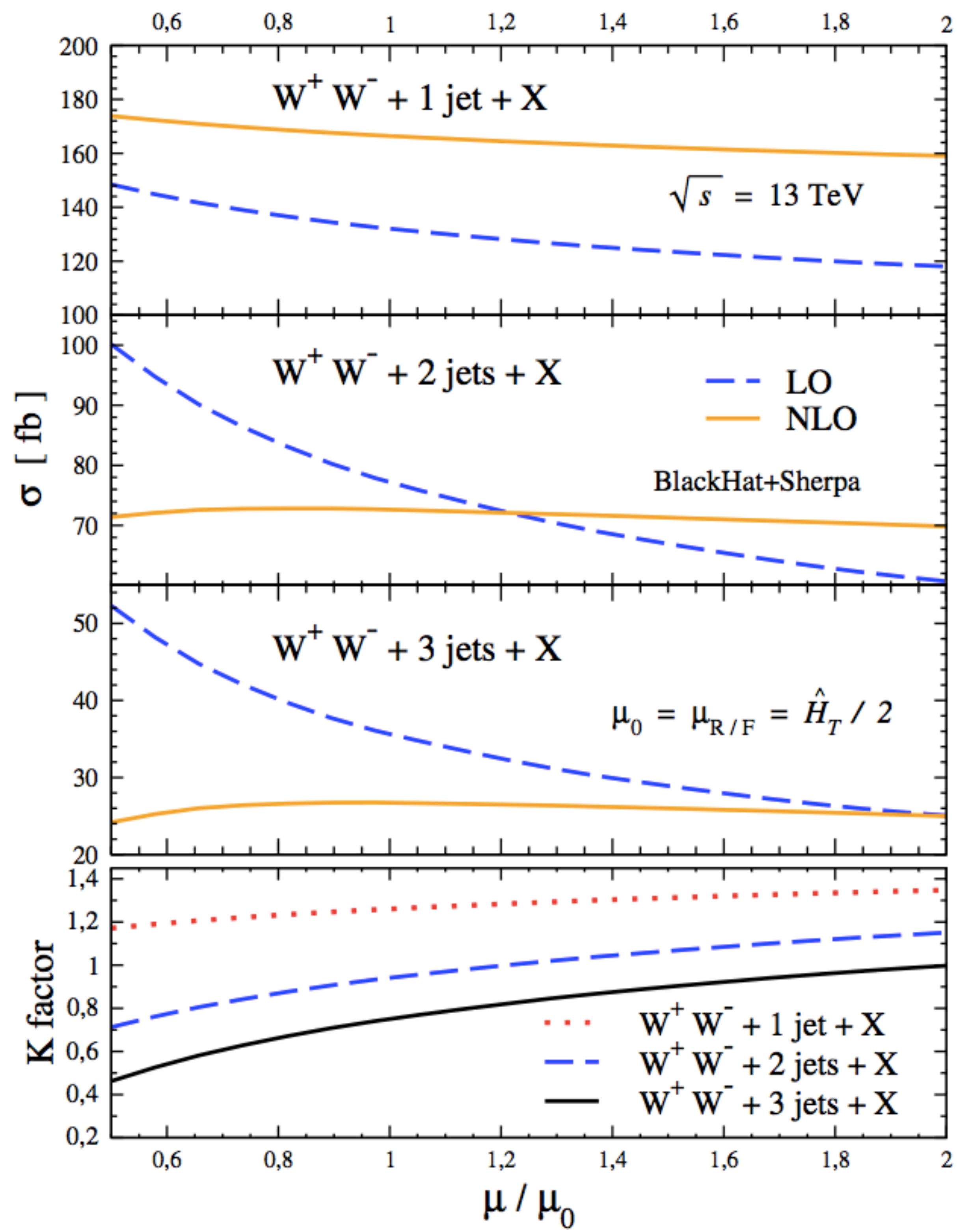
Matrix elements:

- BlackHat for WW+1,2, 3-jets
- Omitted sub-leading-color terms (good at percent level; better than PDFs)
- Double resonant contributions.

Standard kinematical cuts:

- $P_T^{e,\mu} > 20$ GeV, $|\eta^{e,\mu}| < 2.4$, $E_T^{miss} > 30$GeV, $P_T^{e\mu} > 30$ GeV, $m_{e\mu} > 10$GeV,
- Jets: anti-k_T algorithm, R=0.4, $p^{jet} > 30$GeV, $|\eta^{jet}| < 4.5$
- Scale $\mu_r = \mu_f = H_T$ and MSTW2008 set of PDFs,

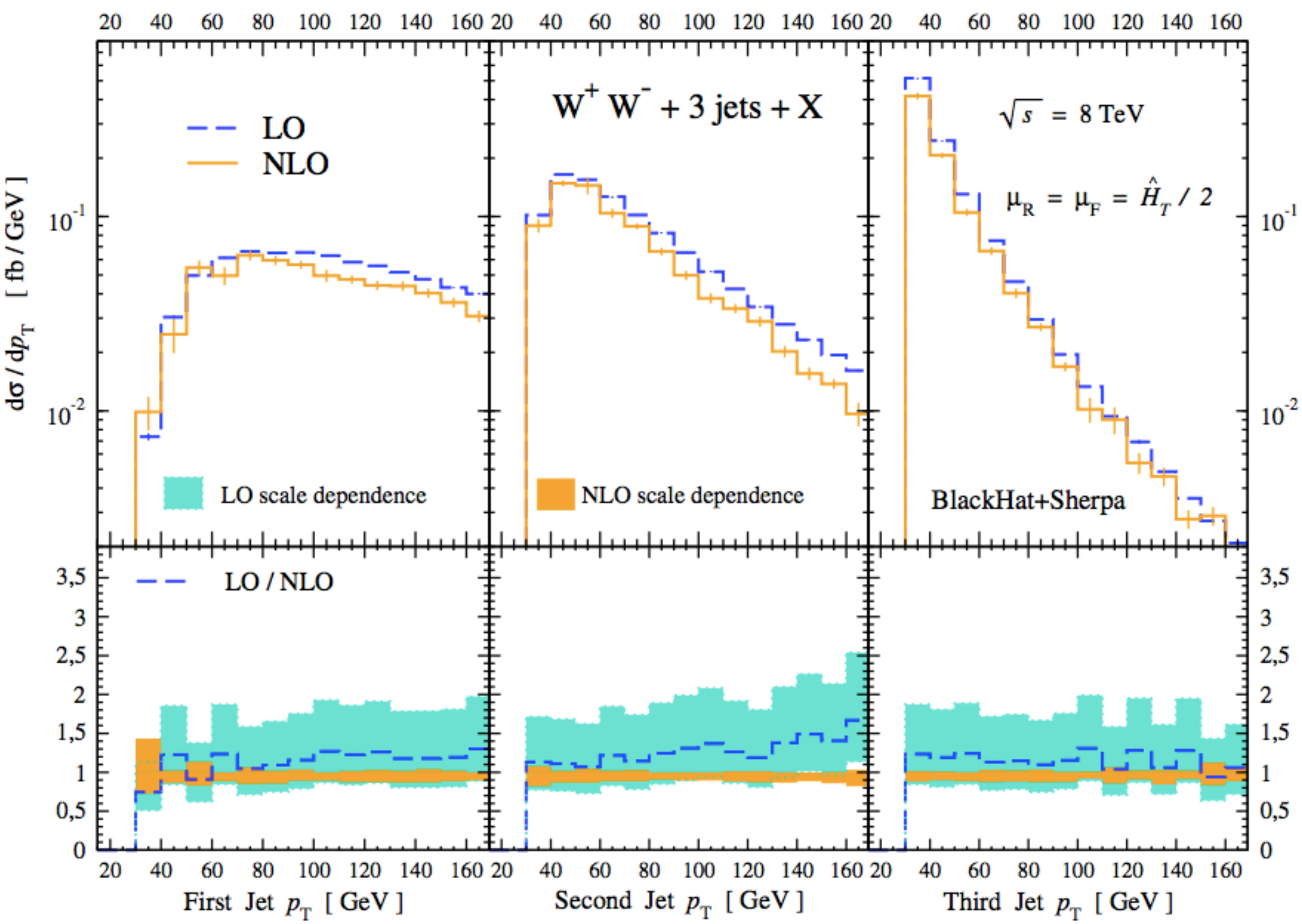
Scale Sensitivity



- Total cross sections as function of unphysical scales.
- Small scale sensitivity at NLO.
- Large multiplicity needs NLO corrections.
- Reduction of sensitivity from 45% to 15% .

PRELIMINARY

Jet PT Spectra



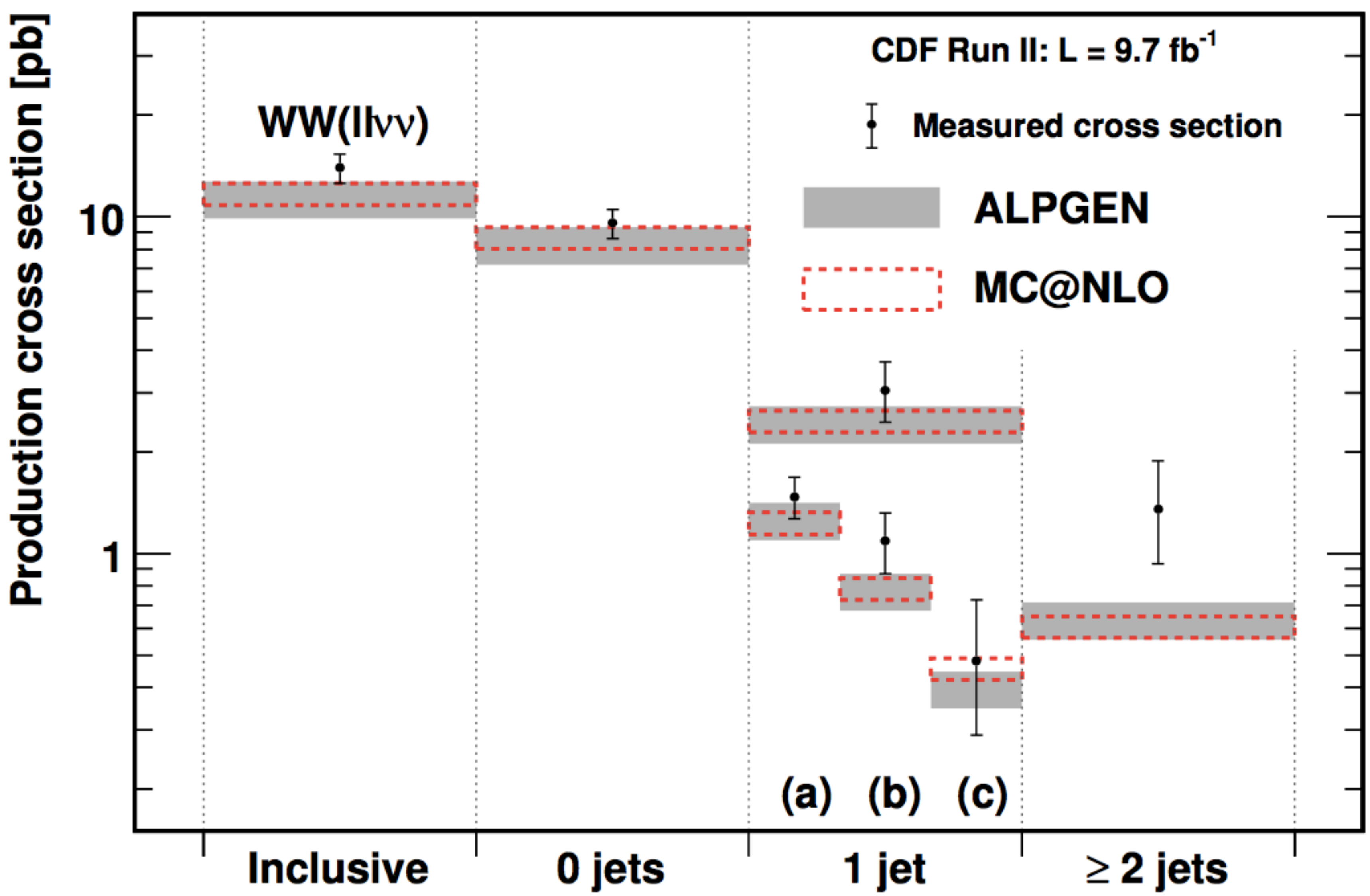
- Jet PT of softer jets fall more steeply.
- Quantum corrections shift PT of softest jet.
- More structure in harder jets.
- Similar to QCD NLO corrections for V+jets.

PRELIMINARY

Conclusions

- Precision theory plays an important role to exploit the potential of the LHC.
- New methods such as unitarity approaches extend theorists' reach.
- Presented first NLO QCD predictions for WW+3-jet production. This adds to very few such predictions for processes with more than 5 objects in the final state (V + 4, 5 Jets from BlackHat+Sherpa and 5-Jet production from NJet).
- NLO QCD corrections provide reliable predictions at large multiplicity.
- All is in place to explore di-vectors (Z, W & photons) in association with jets.
- Future: more detailed phenomenology will follow including VBF studies and jet production ratios.

WW + Jets @ CDF



- Based on full dataset [CDF: 1505.00801].
- Differential cross sections.
- Approximate agreement between theory and experiment.
- At Tevatron tt background is small.