Forward Jet Production and BFKL Dynamics at HERA

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Workshop on low x physics, Helsinki

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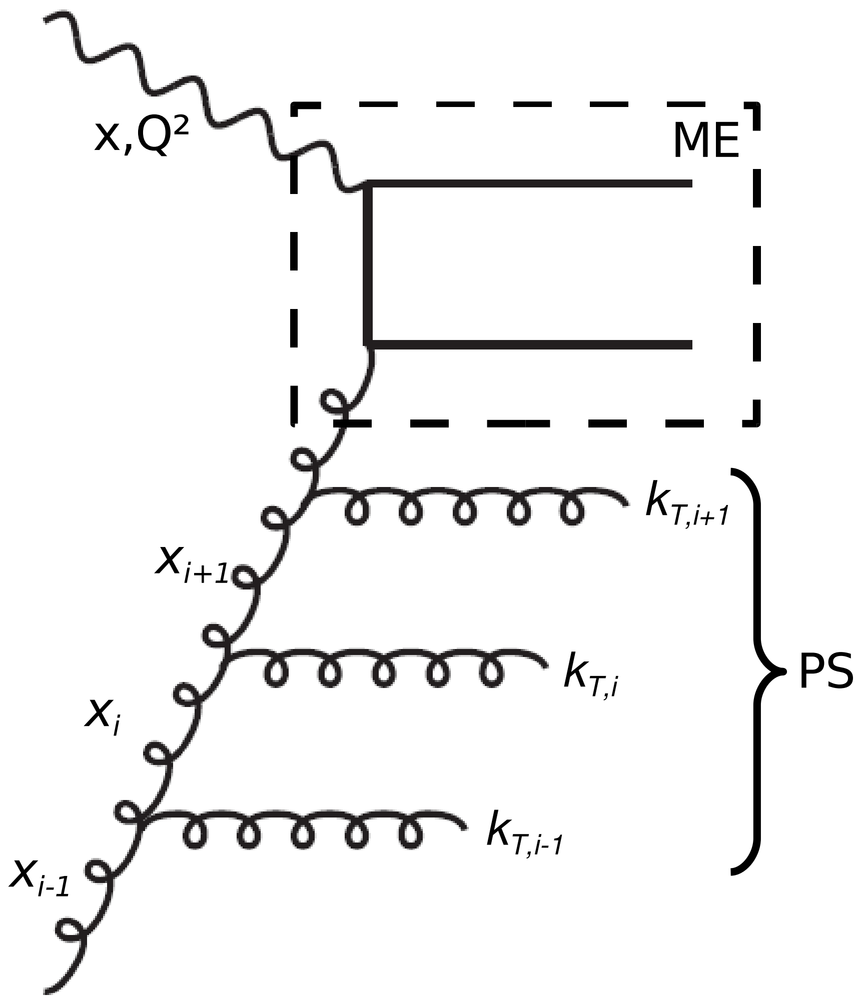
QCD description of jet production in DIS

Matching of matrix element (ME) to parton showers (PS)



- ME can be O(α) (QPM), O($\alpha\alpha_S$) (BGF, QCD-Compton), O($\alpha\alpha_S^2$), ...
  → exact calculation for fixed orders
- higher orders are covered by PS which sum a subset of (leading) diagrams at each order
  → which diagrams are leading depends on kinematics (x,Q^2)
- different approaches for PS exist: DGLAP, BFKL, CCFM, ...:
  - resumming of different diagrams $\sim (\alpha_S \ln Q^2/Q_0^2)^n$, $(\alpha_S \ln 1/x)^n$
  - differences in ordering of $k_{T,i}$, x_i of parton emissions

→ Final state jet studies can validate fixed order ME calculations and distinguish different PS approaches

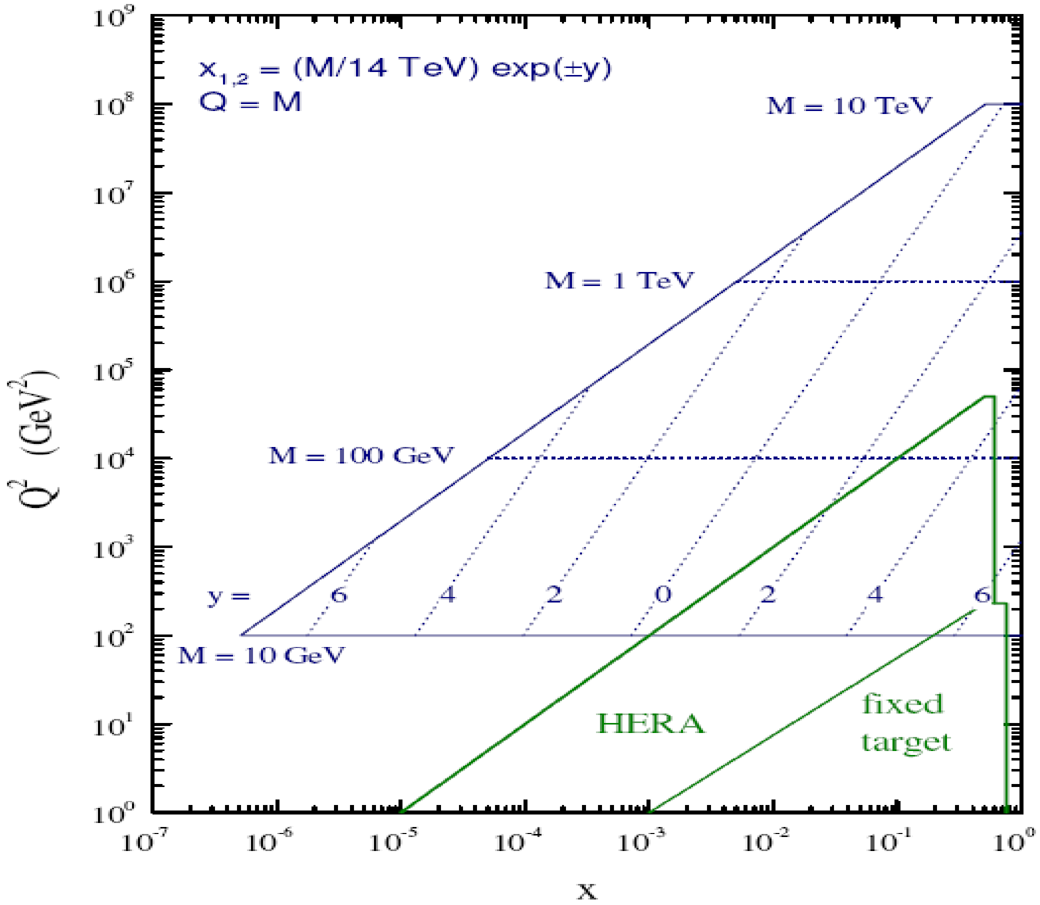
Why bother?

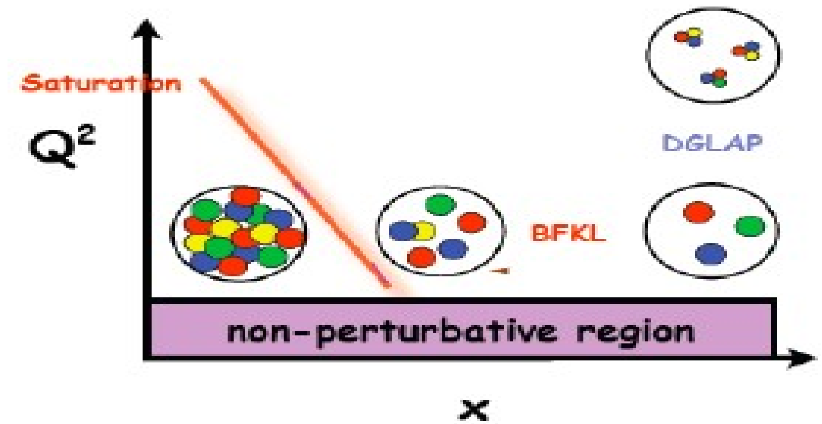
- the inclusive DIS cross section (F_2) is very well described by DGLAP, but also allows for BFKL terms
- DGLAP fails to describe forward jet production at small *x*
- novel QCD effects at low *x*, where the gluon density becomes very large, are expected (saturation, colour glass condensate, ...)

→ Consequences for the LHC?

- many SM and BSM processes at the LHC involve the collision of partons with small *x*
- standard prescription: take pdfs from HERA and evolve them to higher Q^2 according to DGLAP

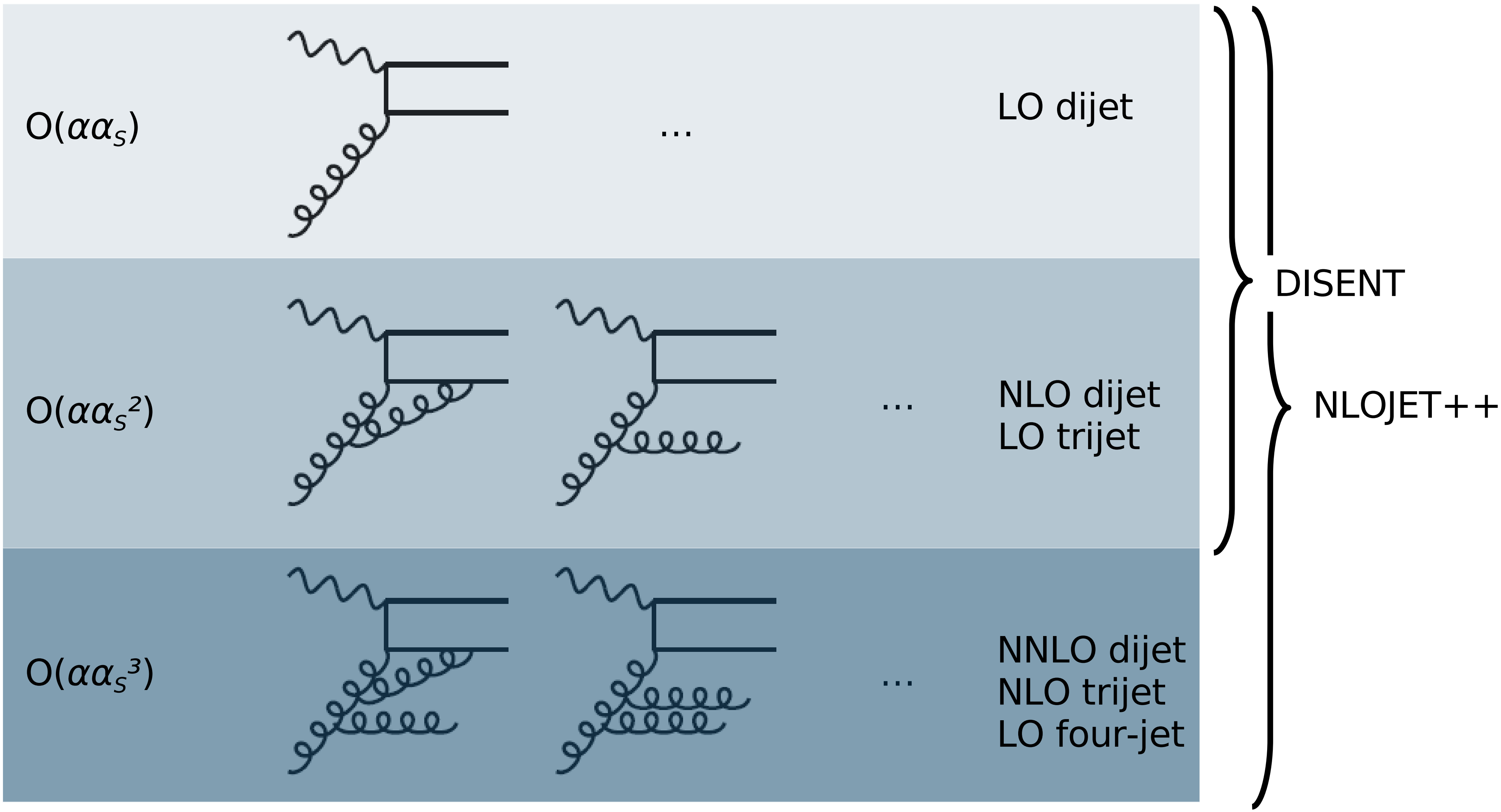
→ Forward and multijet studies at HERA are needed to predict low-*x* effects at the LHC





QCD models and calculations

- Fixed order matrix element calculations

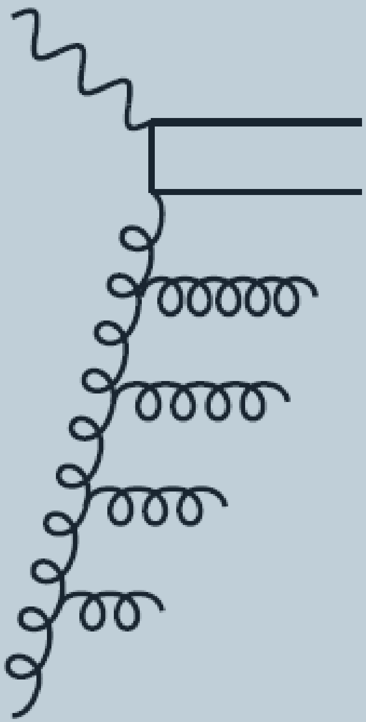


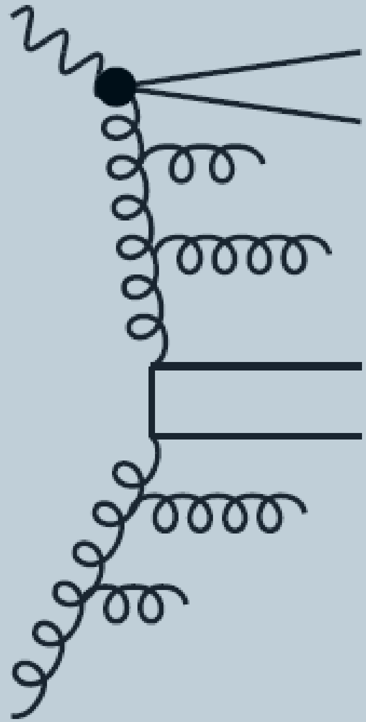
fixed order ME calculations yield parton level predictions
→ hadronisation corrections must be applied to these calculations

QCD models and calculations

- Parton shower models

DGLAP



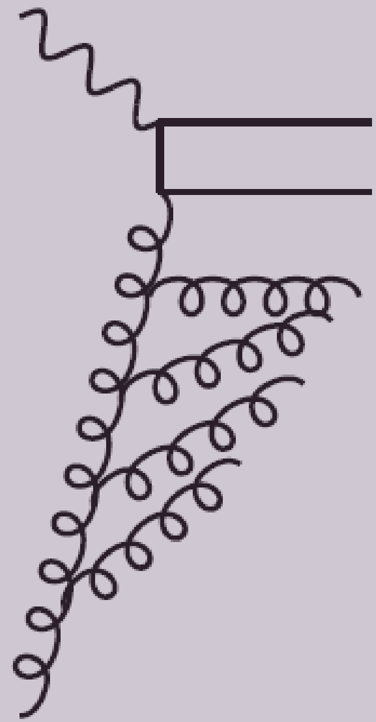


sums diagrams ~ ln Q^2

strong k_T ordering
standard pdf $g(x,\mu^2)$

LEPTO/RAPGAP DIR　　RAPGAP DIR+RES

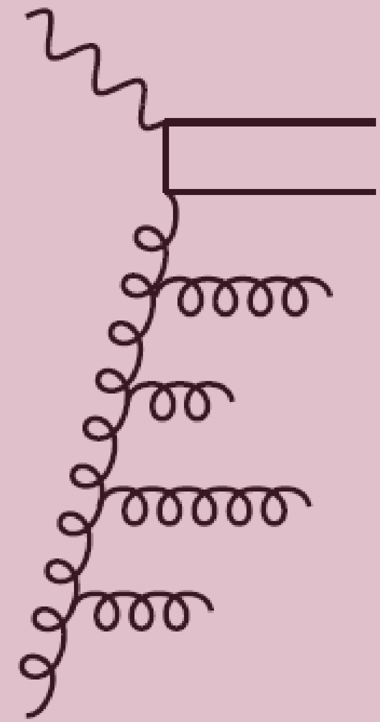
CCFM



sums diagrams
~ ln Q^2,ln $1/x$
angular ordering
$g(x,k_T,\mu^2)$

CASCADE

CDM



independent
dipole radiation
unordered in k_T
mimics BFKL

ARIADNE

Full Monte Carlo models use LO matrix elements + parton showers + hadronisation → yield hadron level predictions

Experimental results

- Measurements covered in this talk:
  - Multijet production at low x_{Bj} in deep inelastic scattering at HERA
    ZEUS Collaboration, DESY-07-062 (May 2007), submitted to Nucl. Phys. B
    arXiv:0705.1931v1 [hep-ex]
  - Forward-jet production in deep inelastic *ep* scattering at HERA
    ZEUS Collaboration, DESY-07-100 (July 2007), submitted to Eur. Phys. J. C
    arXiv:0707.3093v2 [hep-ex]
  - Three- and four-jet production in deep-inelastic scattering at HERA and low-*x* parton dynamics
    H1 Collaboration, to be published
- Previous results:
  - Forward jet production in deep inelastic scattering at HERA
    H1 Collaboration, Eur. Phys. J. C46 (2006) 27-42
    arXiv:hep-ex/0508055
  - Forward jet production in deep inelastic *ep* scattering and low-x parton dynamics at HERA
    ZEUS Collaboration, Phys.Lett. B632 (2006) 13-26
    arXiv:hep-ex/0502029v1

Experimental analysis

- DIS selection...
- Jet finding algorithm
  - inclusive k_T algorithm in γ^*p centre of mass or Breit frame
- Jet pseudorapidity range: determined by calorimeter coverage
  - ZEUS CAL: $-1.5 < \eta^{jet} < 2$ (multijet analysis)
  - ZEUS CAL + FPC: $2 < \eta^{jet} < 4.3$ (forward jet analysis)
  - H1 LAr calorimeter: $-1 < \eta^{jet} < 2.5$ (3- and 4-jet analysis)
- Data and model corrections
  - detector level
  - hadron level
  - parton level

detector simulation (GEANT)

fragmentation model (Lund string model)

- Aim: check ME calculations for 2- and 3-jet production at NLO
- Method:
  - measure 2- and 3-jet single differential cross section and cross section ratios
  - use energy-momentum balance to search for gluon radiation beyond NLO calculations

$\Delta E_T^{jet1,2*} \approx 0$	$\Delta E_T^{jet1,2*} > 0$
$\lvert\sum \mathbf{p}_T^{jet1,2*}\rvert \approx 0$	$\lvert\sum \mathbf{p}_T^{jet1,2*}\rvert > 0$
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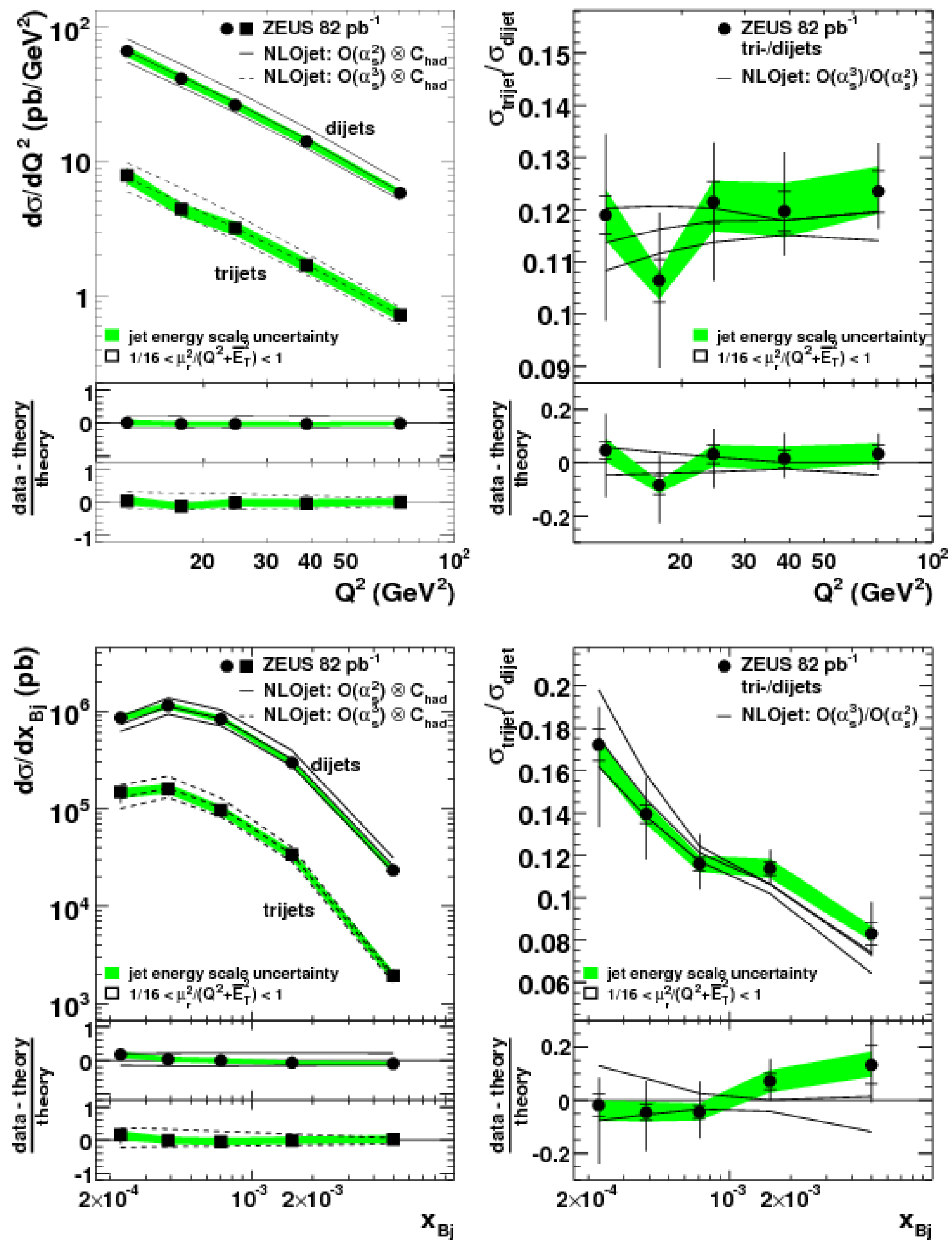
$\lvert\Delta\varphi^{jet1,2*}\rvert \approx \pi$	$\lvert\Delta\varphi^{jet1,2*}\rvert < \pi$

- Kinematic selection:
  - $10 < Q^2 < 100$ GeV², $10^{-4} < x < 10^{-2}$, $0.1 < y < 0.6$
  - $-1.0 < \eta^{jet} < 2.5$, $E_T^{jet1*} > 7$ GeV, $E_T^{jet2,3*} > 5$ GeV

Inclusive 2-jet and 3-jet cross sections

- *Q^2 and x dependence*
  - trijet to dijet ratio is Q^2 independent but increases steeply towards small x
  - cross sections and cross section ratios are well described by NLO $O(\alpha\alpha_s^2)$, $O(\alpha\alpha_s^3)$ calculations



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- E_T^{jet*} and η^{jet} dependence
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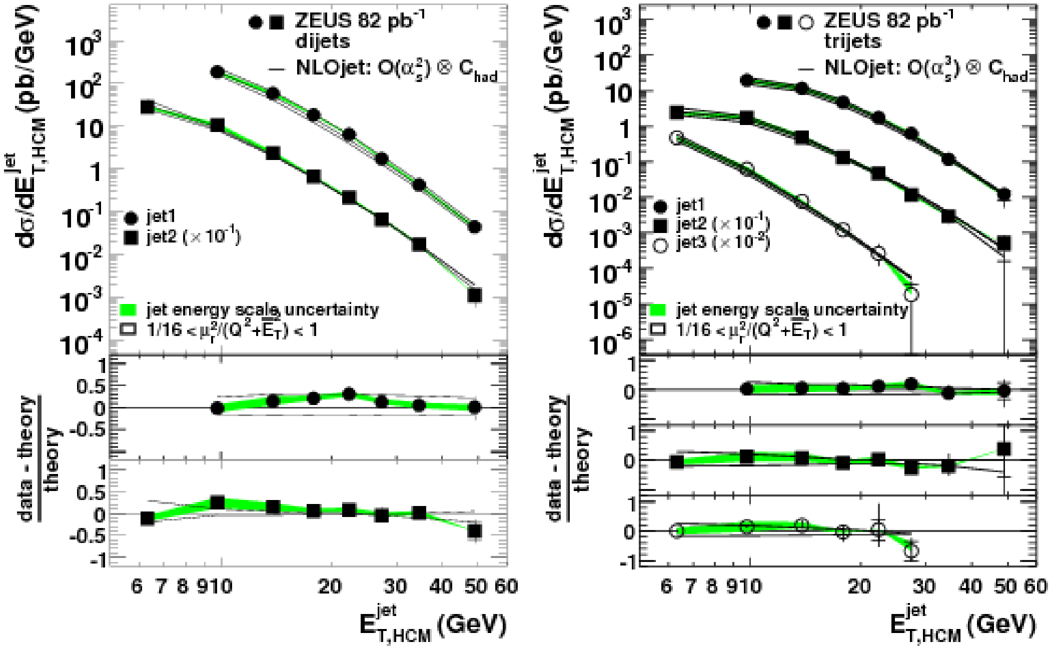

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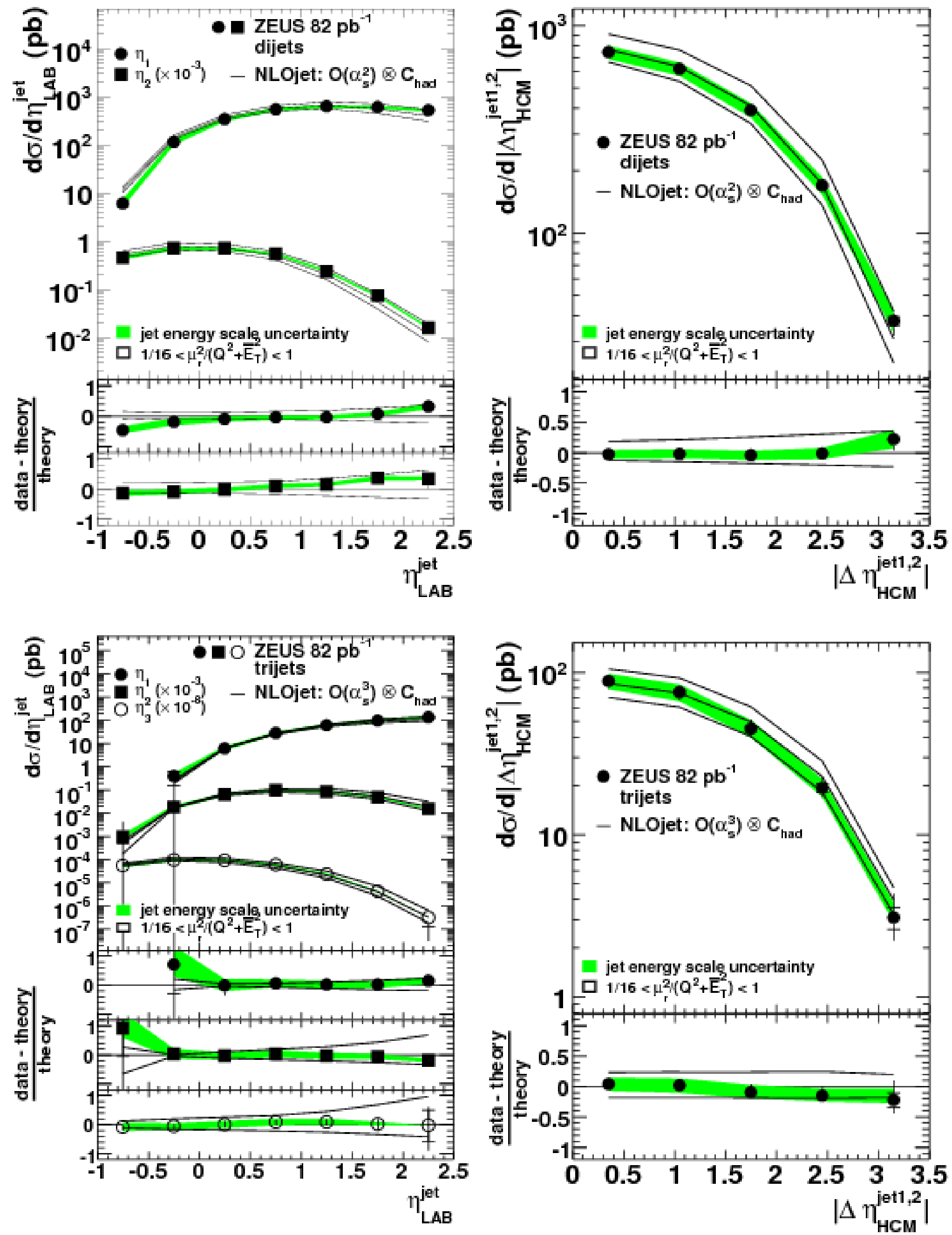
  - η^{jet} and $\Delta(\eta^{jet12*})$ distribution well described by NLO $O(\alpha\alpha_s^2)$, $O(\alpha\alpha_s^3)$ calculations



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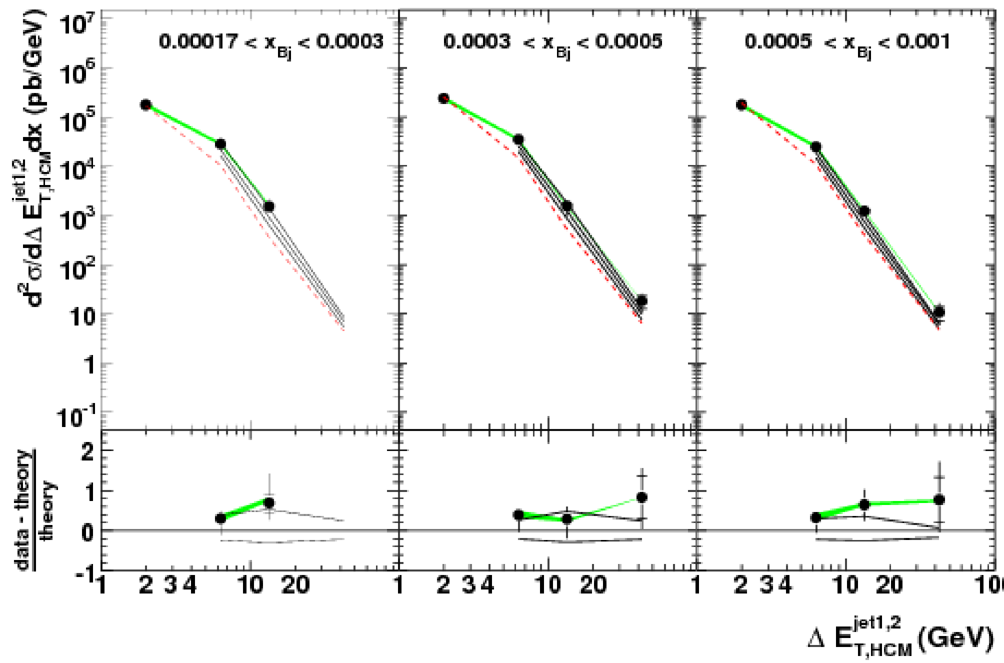

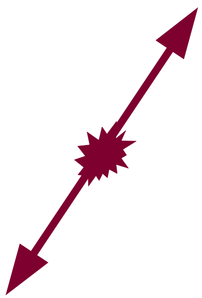

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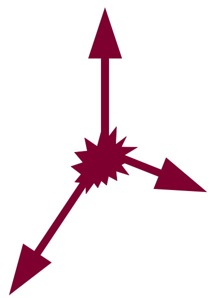

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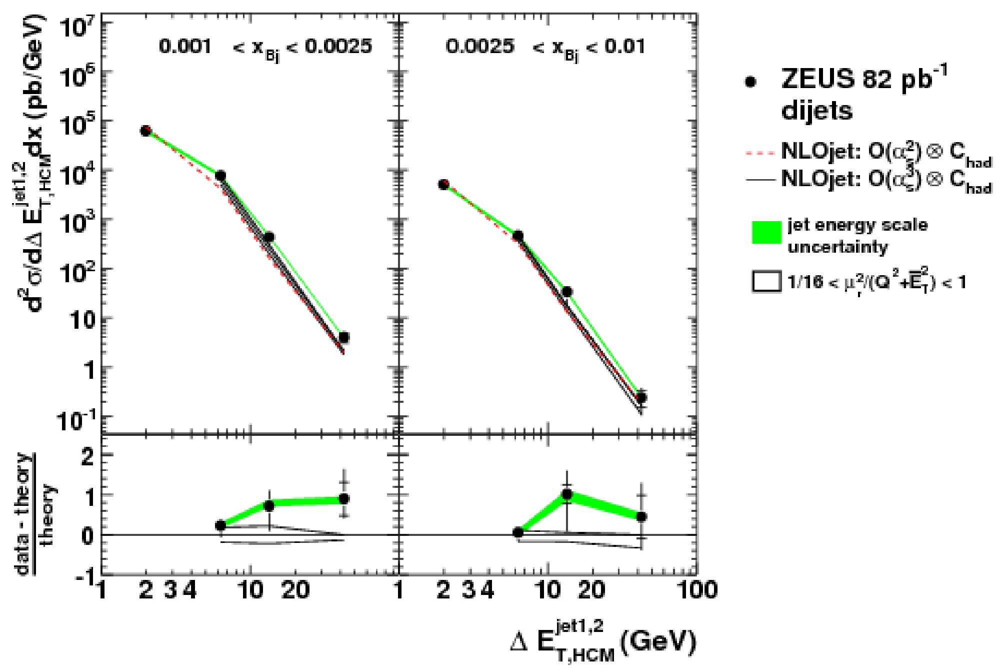

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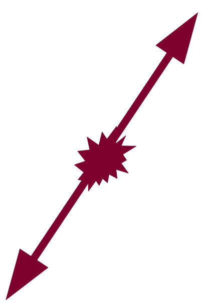

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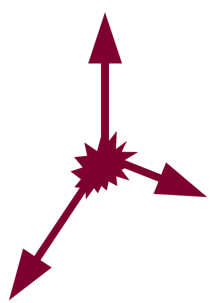

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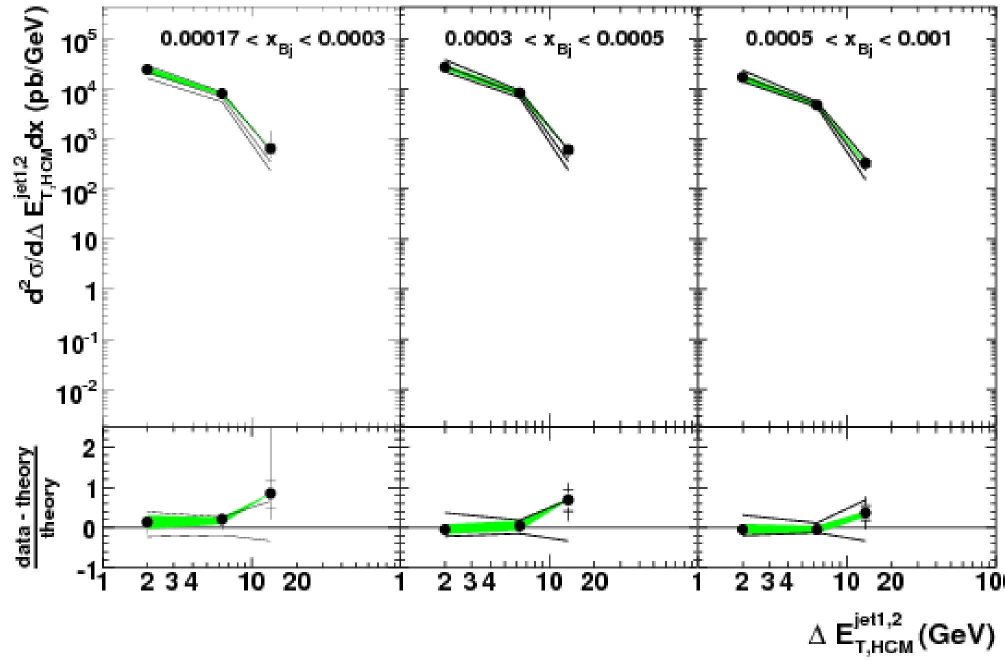

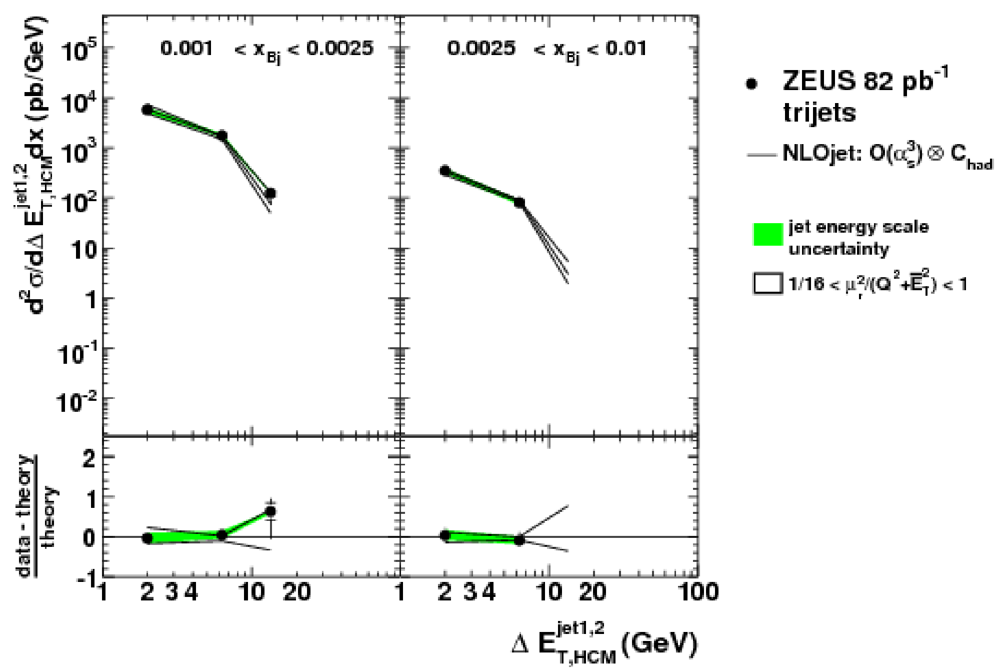

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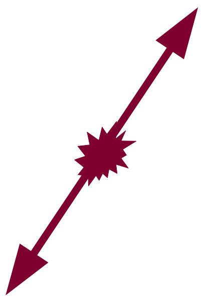

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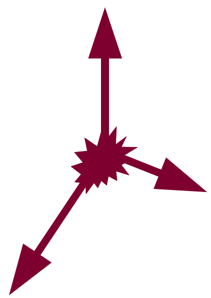

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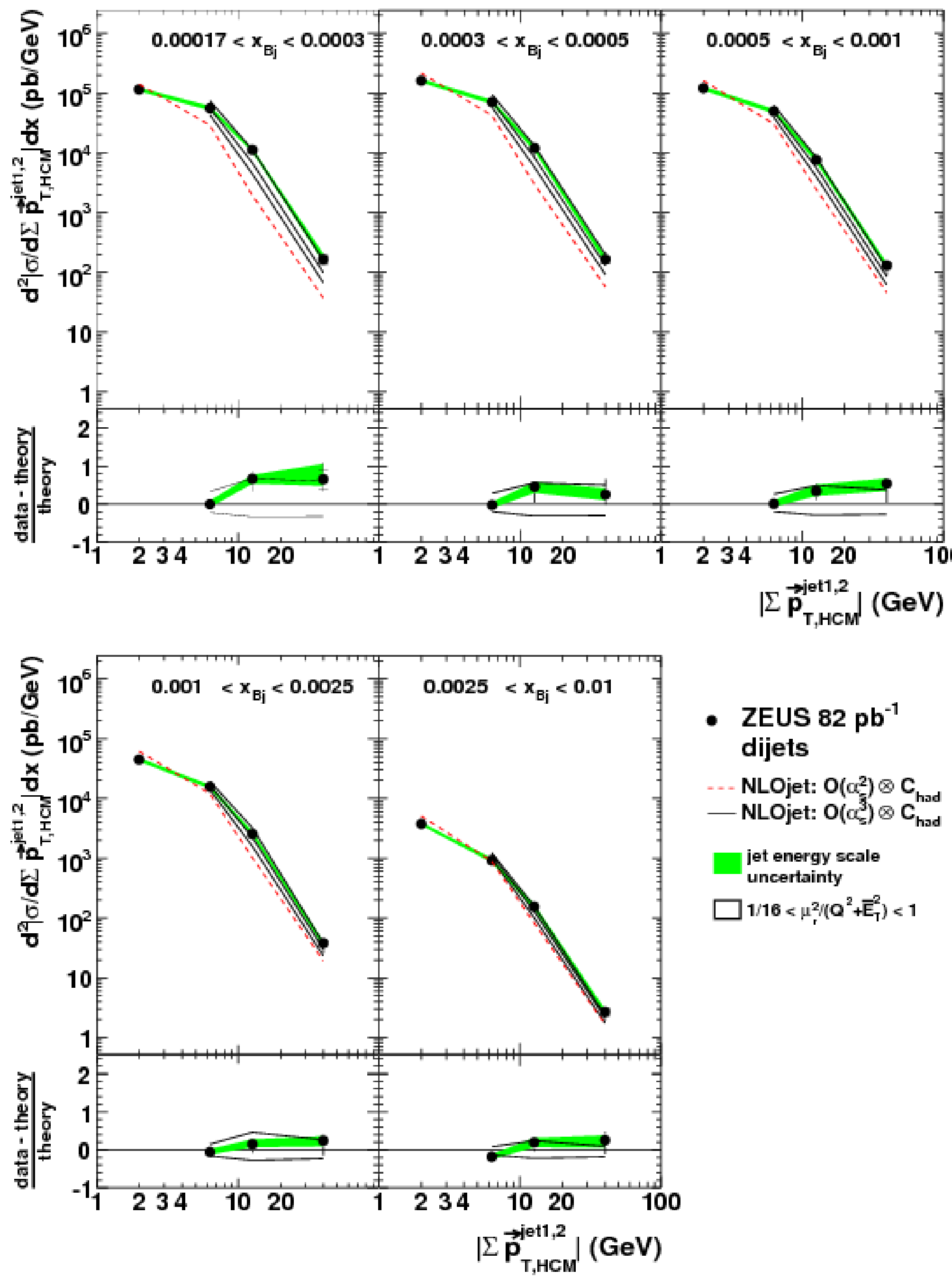

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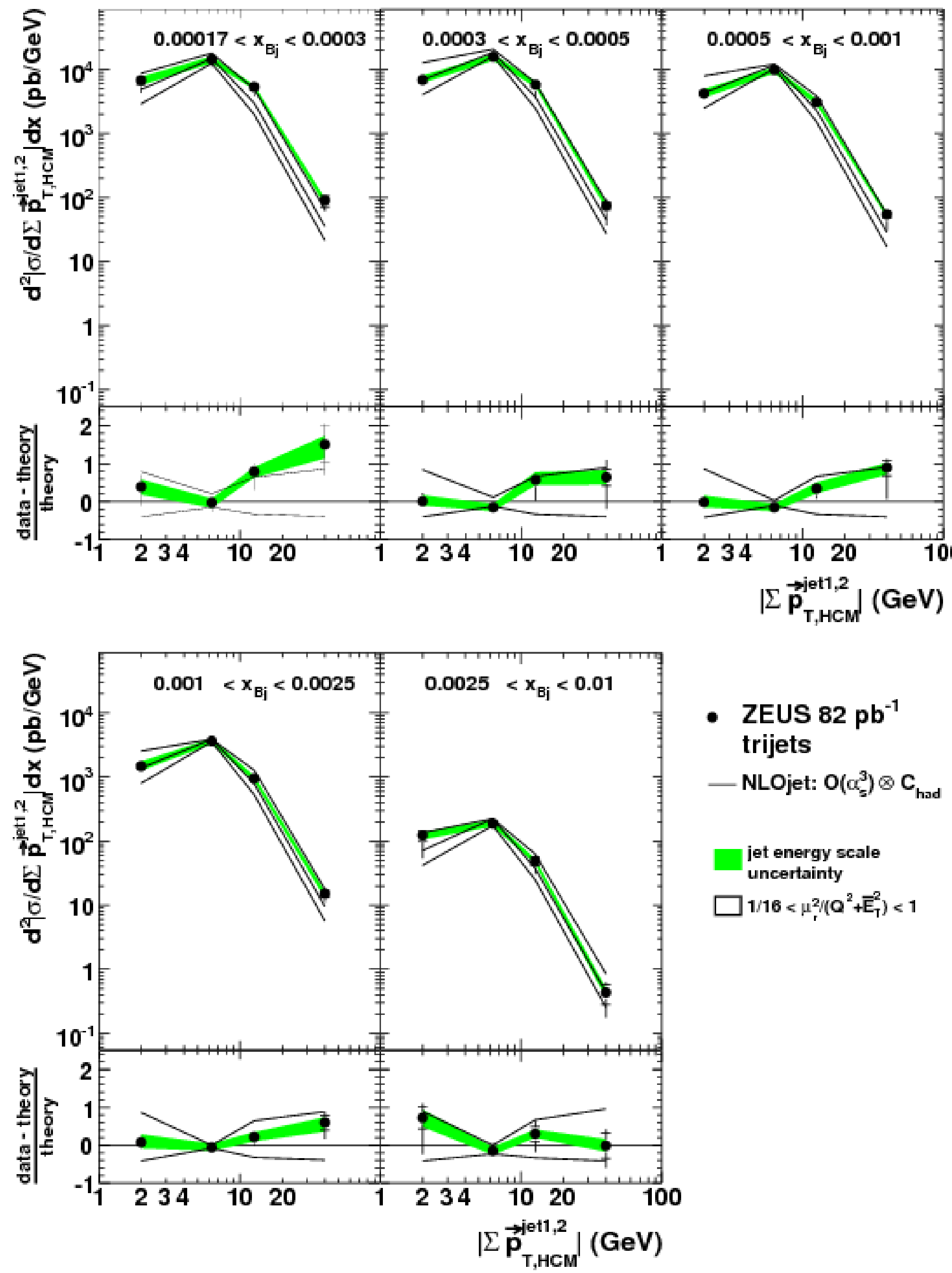

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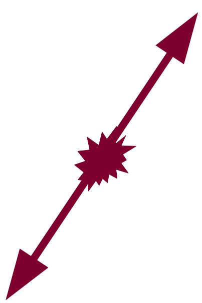

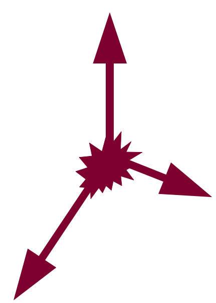

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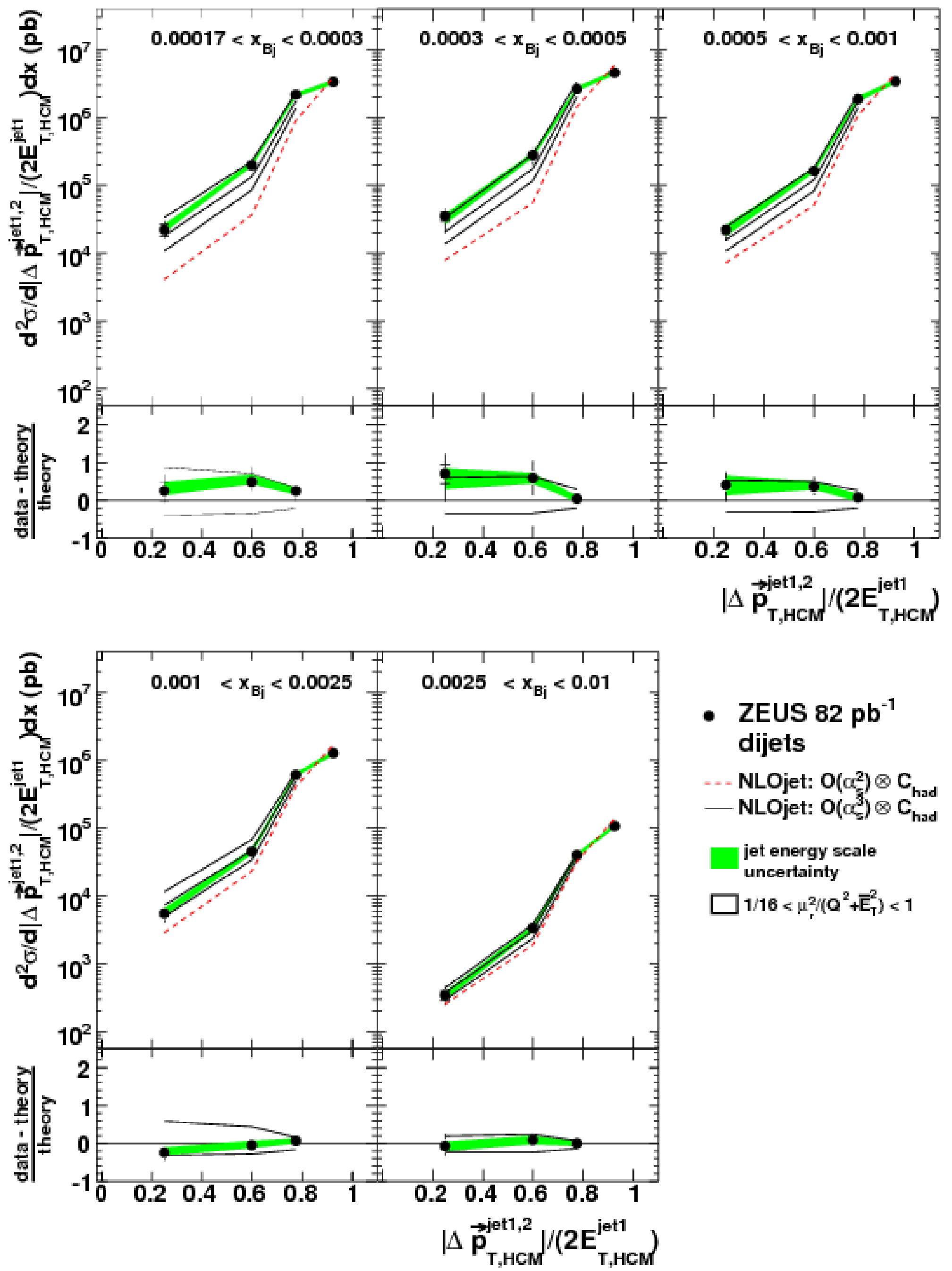

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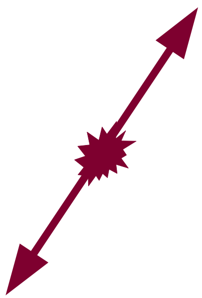

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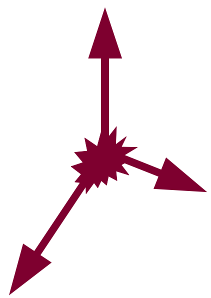

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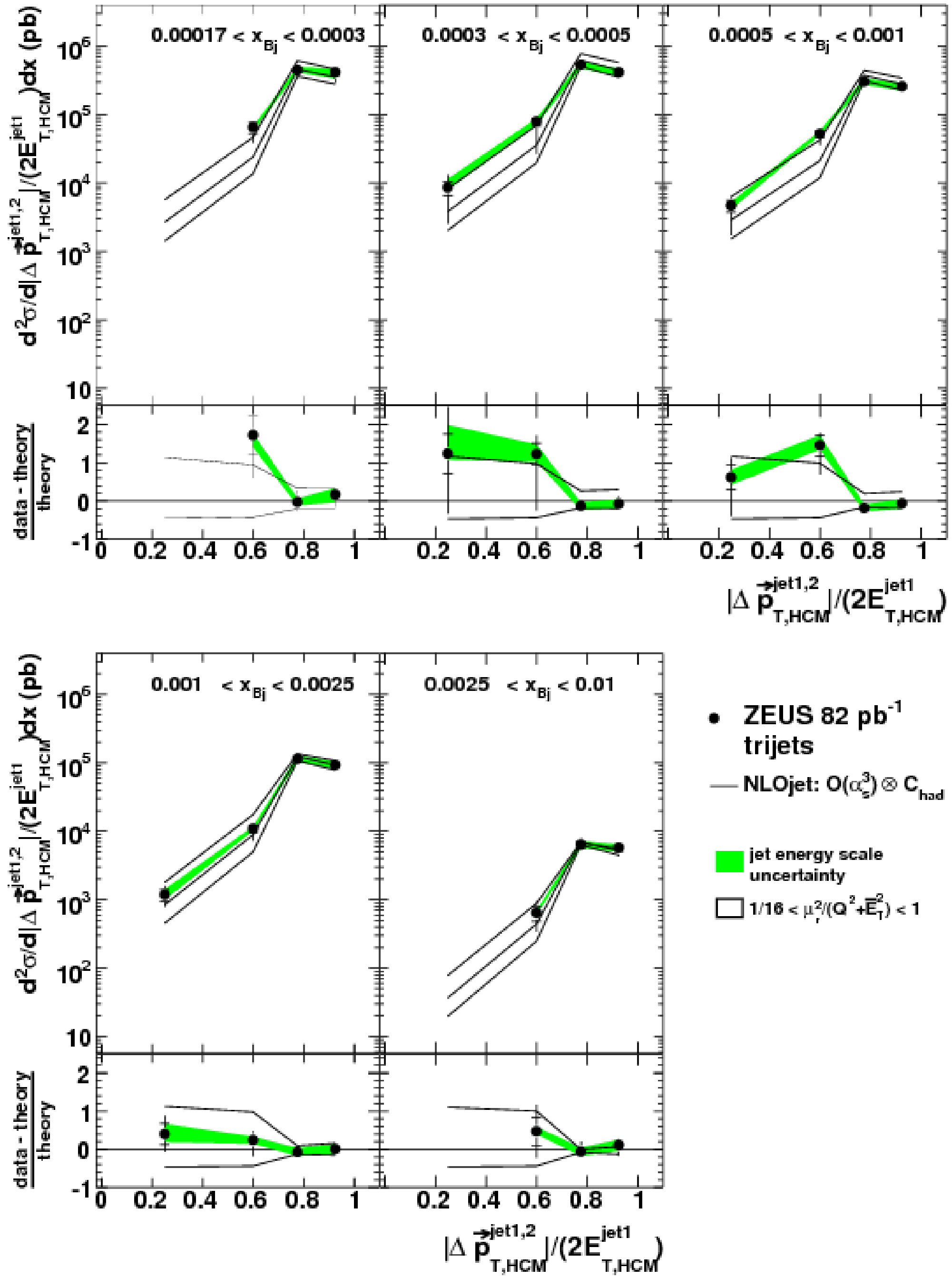

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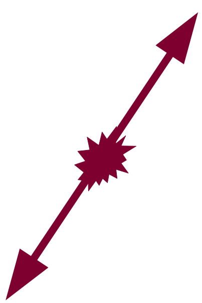

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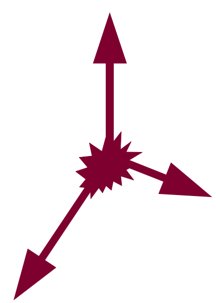

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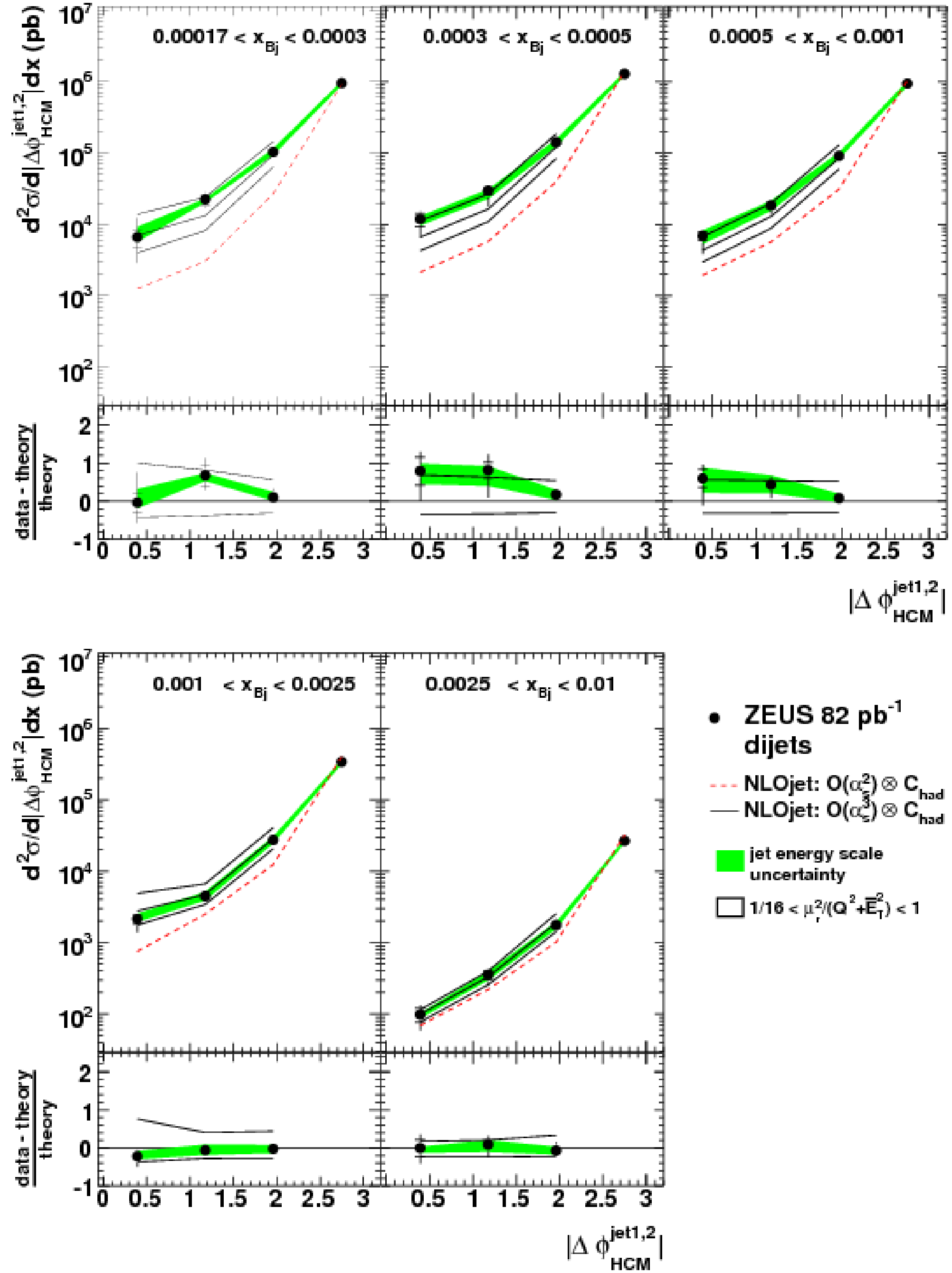

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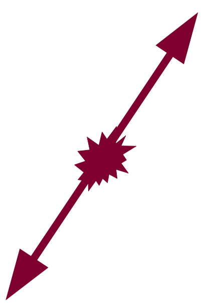

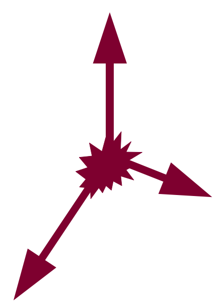

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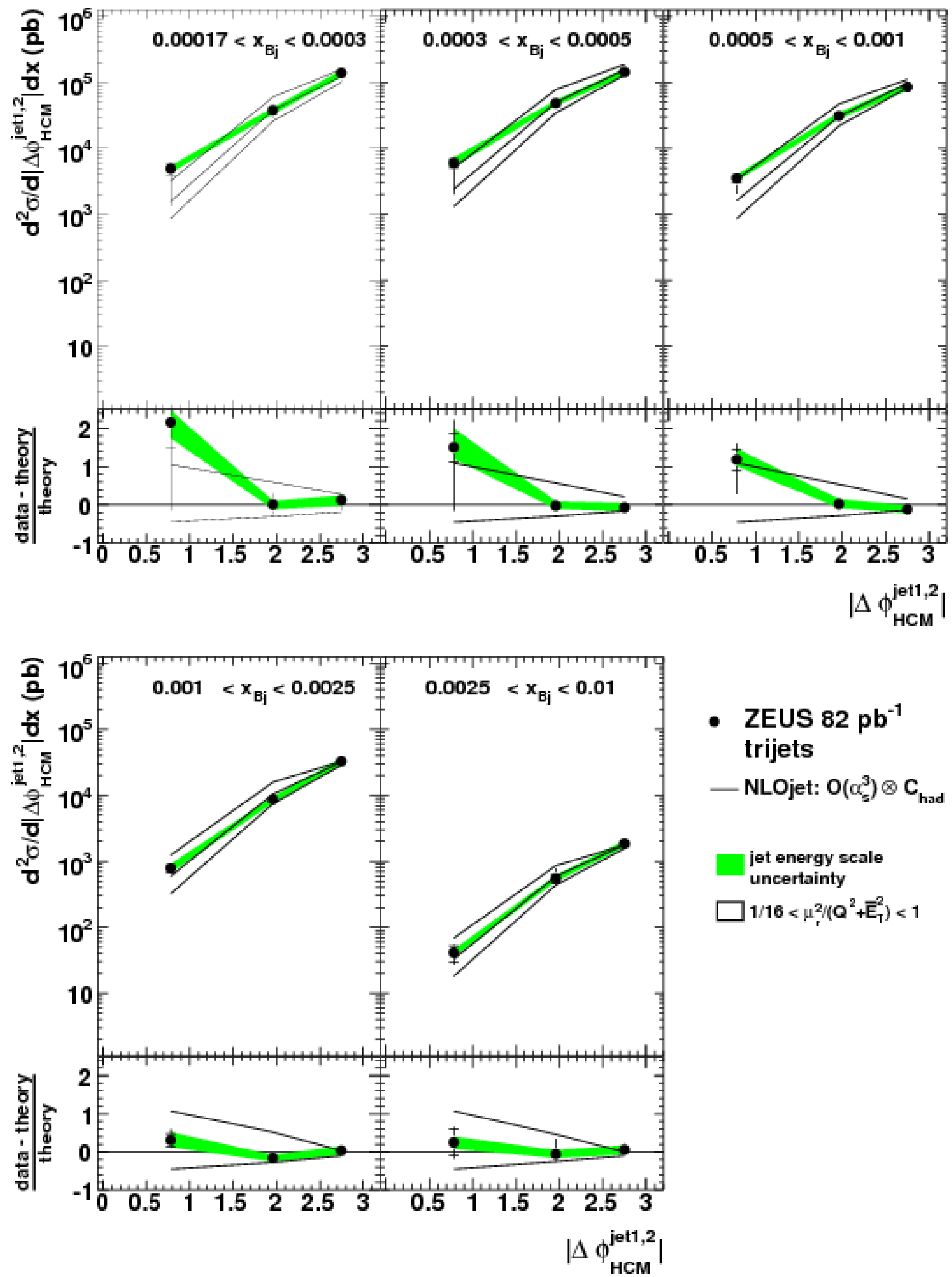

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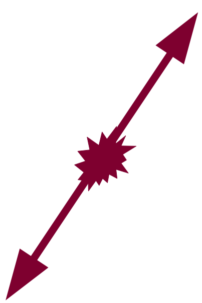
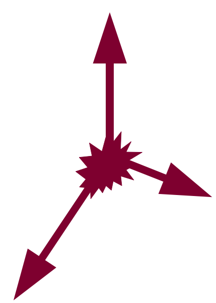
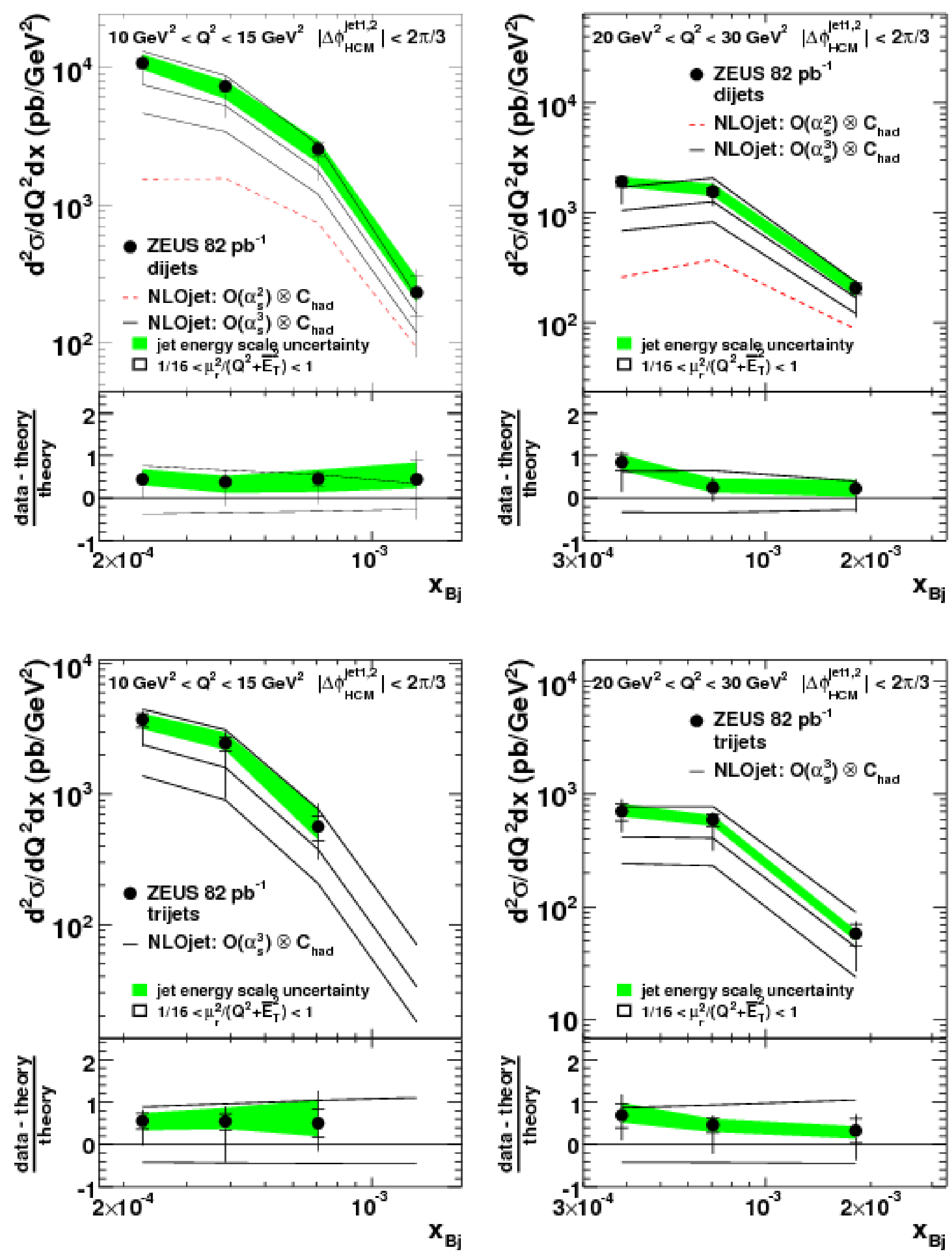




$\Delta E_T^{jet1,2*} \approx 0$	$\Delta E_T^{jet1,2*} > 0$
$\lvert\sum \mathbf{p}_T^{jet1,2*}\rvert \approx 0$	$\lvert\sum \mathbf{p}_T^{jet1,2*}\rvert > 0$
$\lvert\Delta \mathbf{p}_T^{jet1,2*}\rvert / 2E_T^{jet1*} \approx 1$	$\lvert\Delta \mathbf{p}_T^{jet1,2*}\rvert / 2E_T^{jet1*} < 1$
$\lvert\Delta\varphi^{jet1,2*}\rvert \approx \pi$	$\lvert\Delta\varphi^{jet1,2*}\rvert < \pi$



Conclusion so far…

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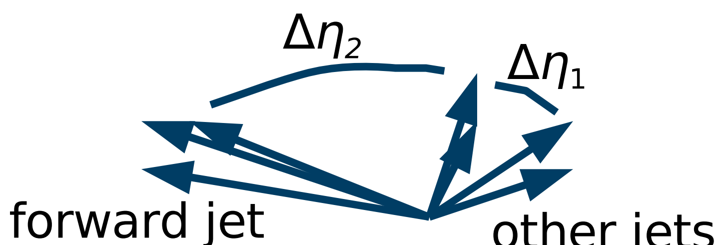
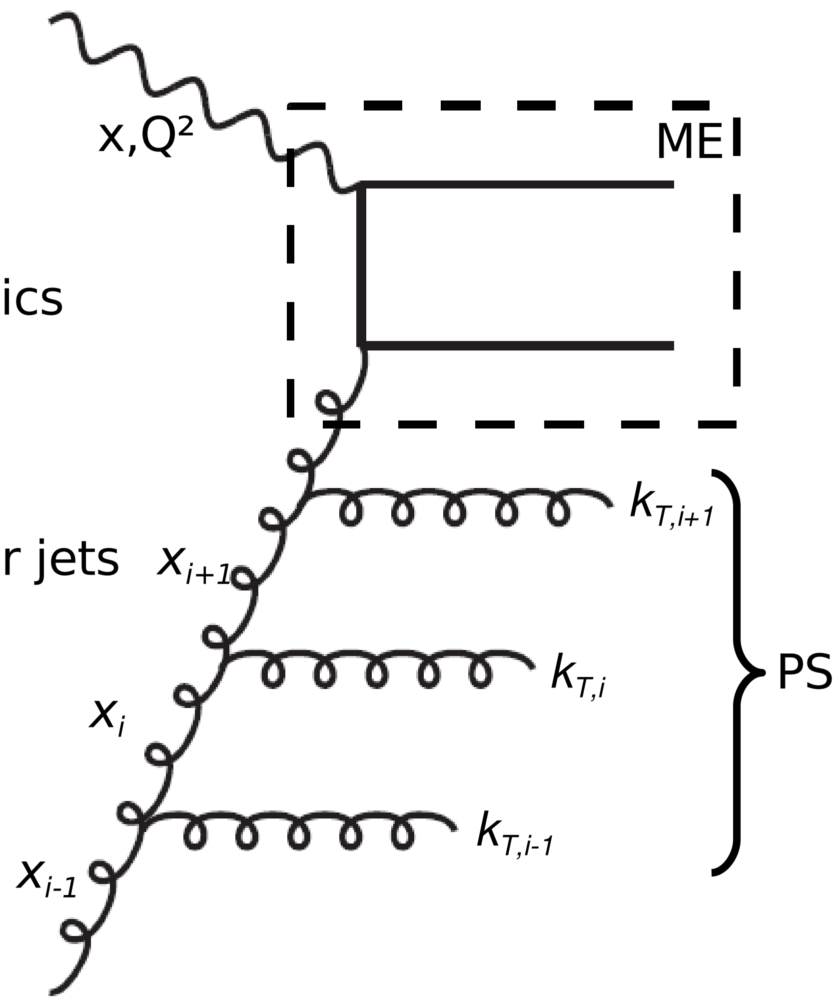
  - aim: check ME calculations for 2- and 3-jet production at NLO
  - conclusion: NLO (O($\alpha\alpha_s^2$), O($\alpha\alpha_s^3$)) calculations work well; O($\alpha\alpha_s^3$)) is especially needed for 2-jet production at low *x* when additional gluon radiation is highlighted

Forward jet production in DIS

- Aim: check ME calculations at NLO and PS models in a region of phase space where additional gluon radiation and/or non-ordered PS are expected

- Method: enhance BFKL signal
  - $(p_T^{jet})^2 \sim Q^2$: suppress strong k_T ordering
  - $x^{jet} = E^{jet}/E^p \gg x$: select BFKL phase space
  - in addition, a central dijet system can be required to highlight different parton dynamics
    $\Delta\eta_1 = \eta^{jet2} - \eta^{jet1}$
    $\Delta\eta_2 = \eta^{fwdjet} - \eta^{jet2}$

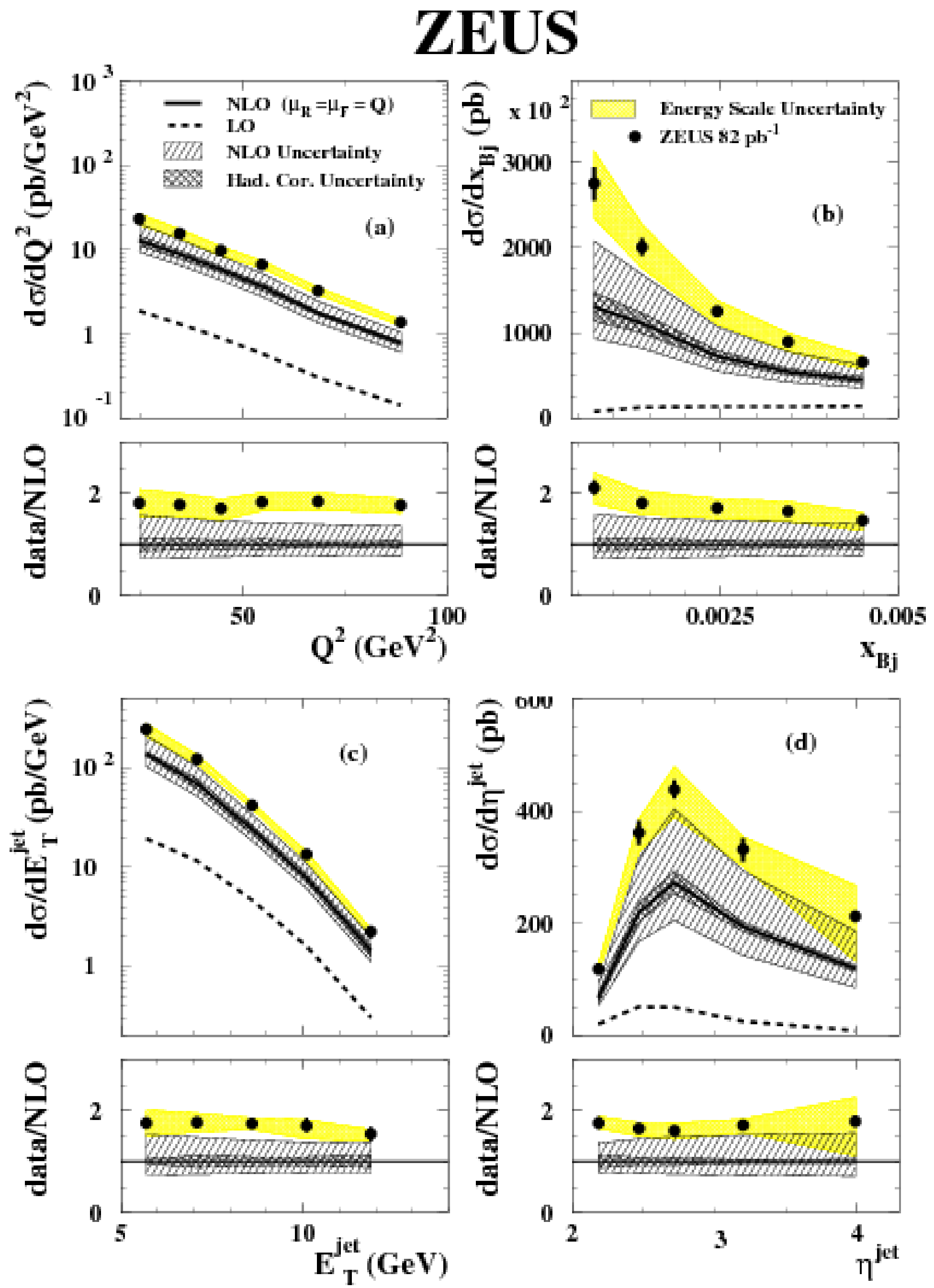




- Kinematic selection:
  - $20 < Q^2 < 100$ GeV², $0.04 < y < 0.7$, $0.0004 < x < 0.005$
  - $E_T^{jet} > 5$ GeV, $2 < \eta^{fwdjet} < 4.3$, $-1.5 < \eta^{jet1,2} < 4.3$
  - $x^{fwdjet} > 0.036$
  - $0.5 < (E_T^{jet})^2/Q^2 < 2$ (only for inclusive forward jet cross section)

Inclusive forward jet production

- Comparison to fixed order ME calculations (DISENT):
  - large correction from LO $O(\alpha\alpha_s)$ to NLO $O(\alpha\alpha_s^2)$
  - NLO $O(\alpha\alpha_s^2)$ still factor 2 below data



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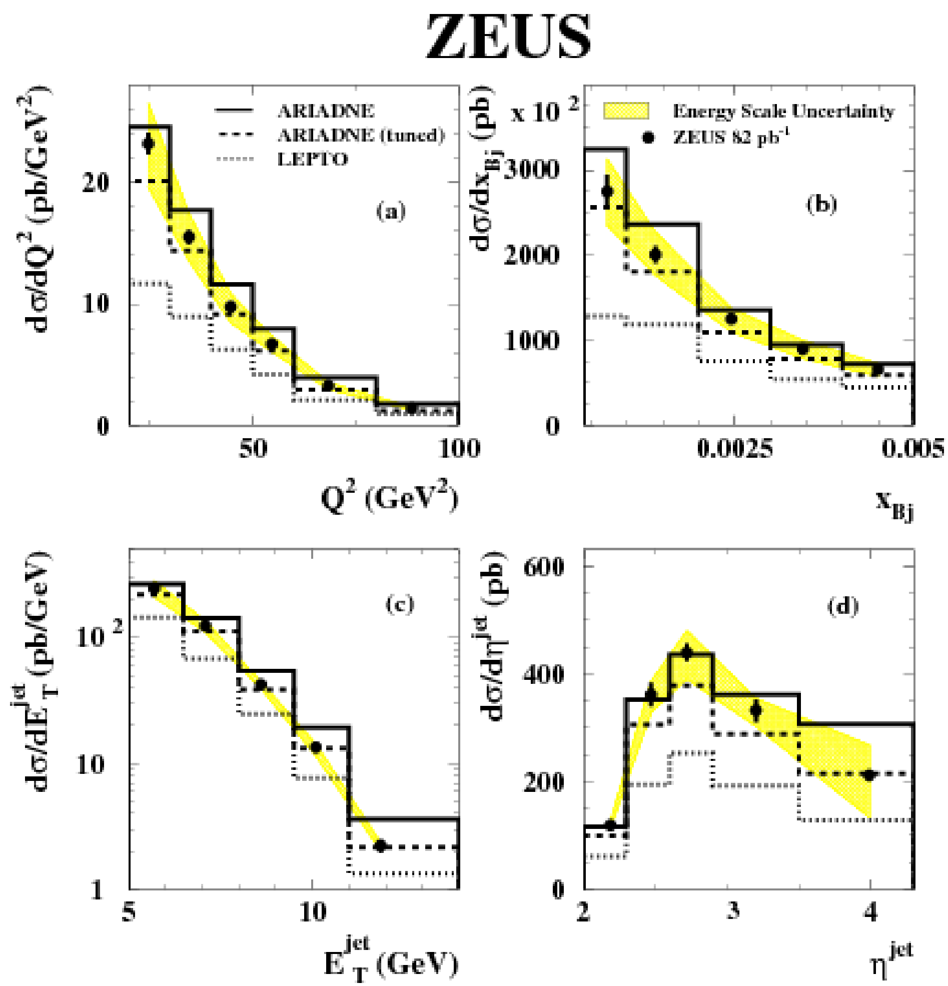

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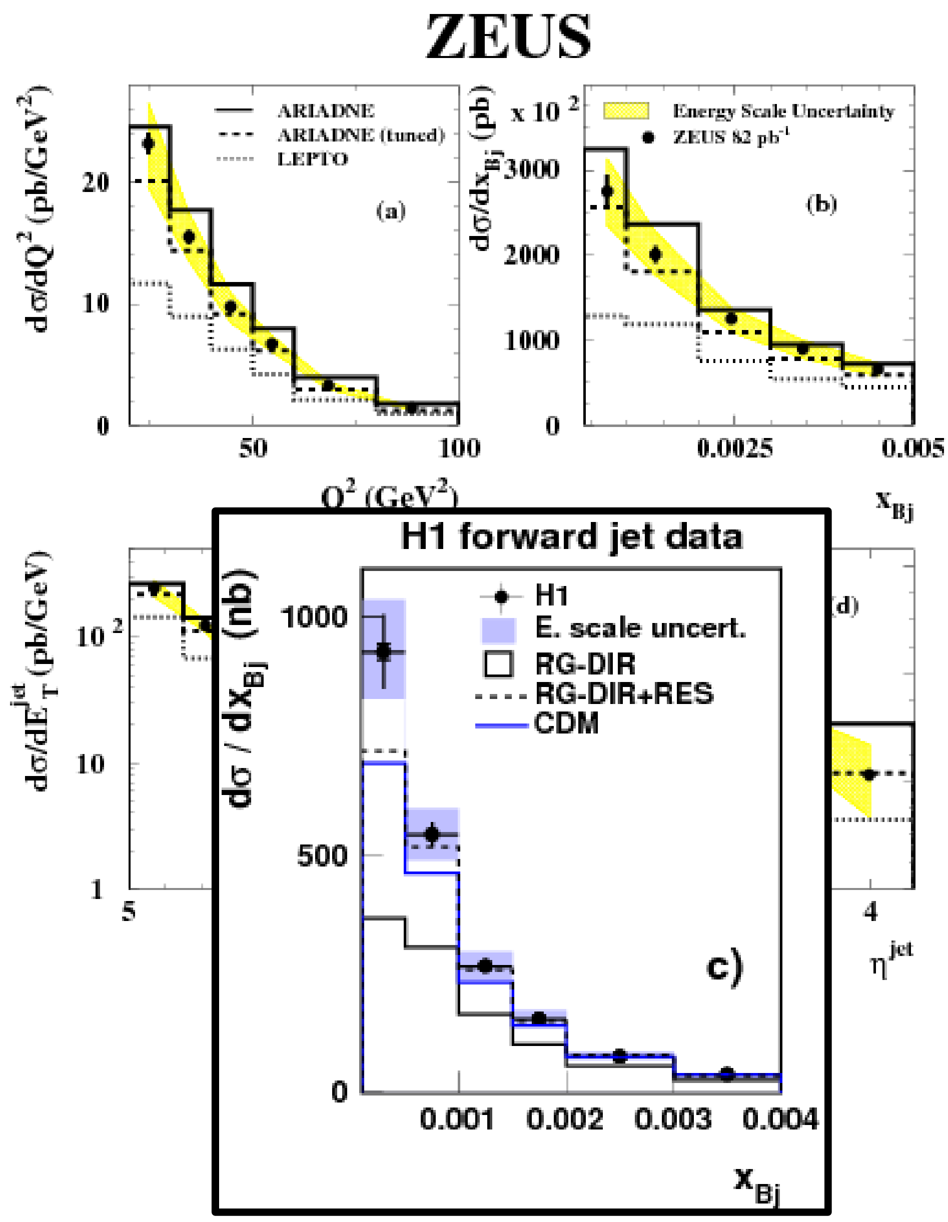

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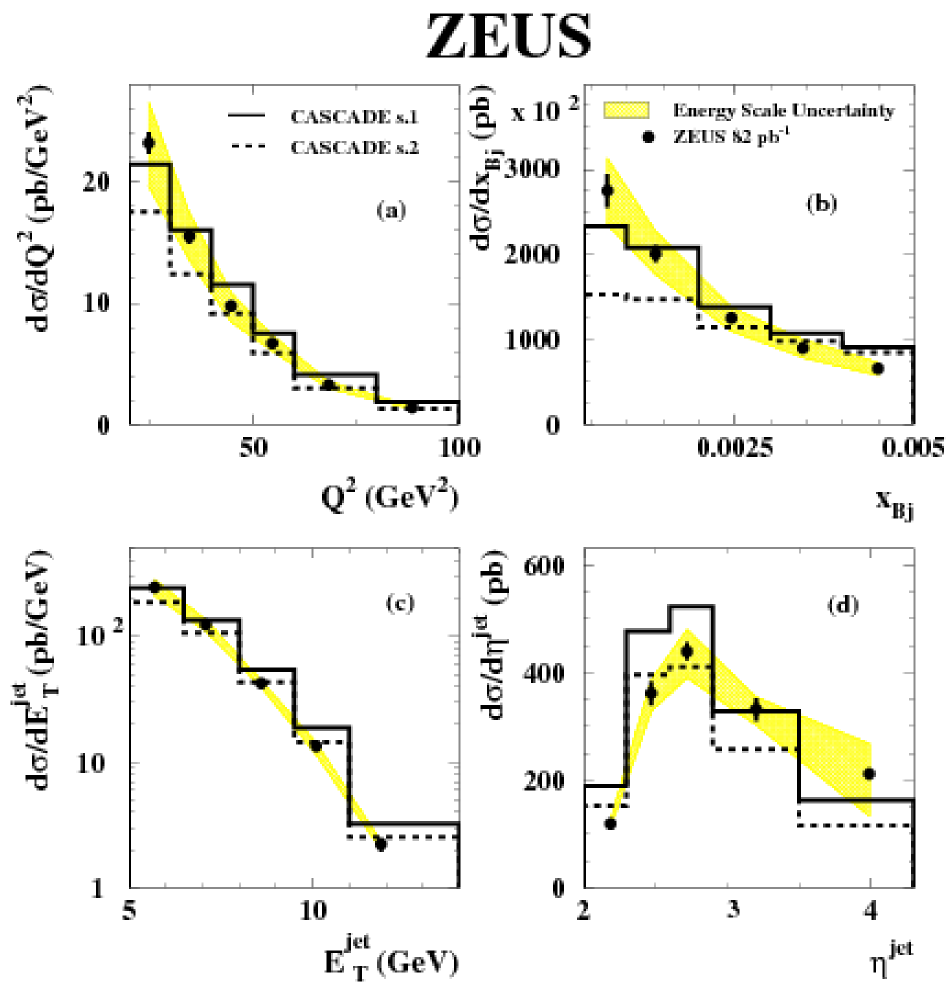
  - CASCADE (CCFM) with two different sets of unintegrated PDFs does not describe the shape of the distributions



Triple-differential cross section

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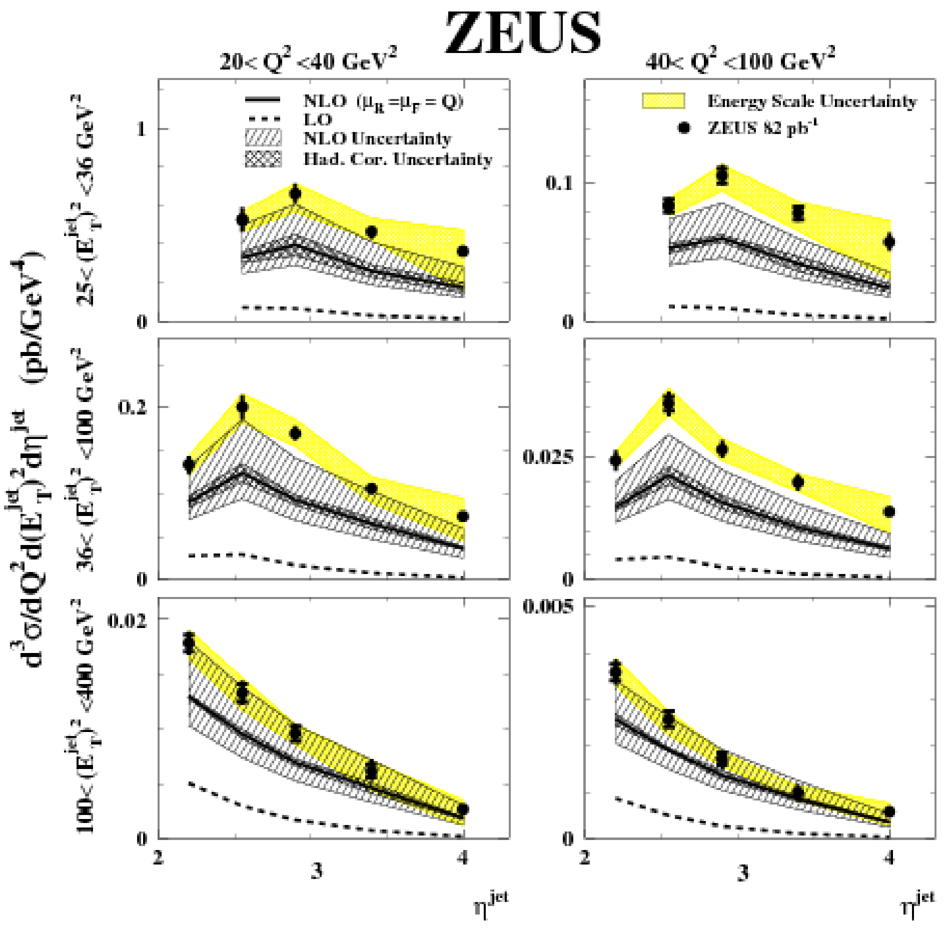

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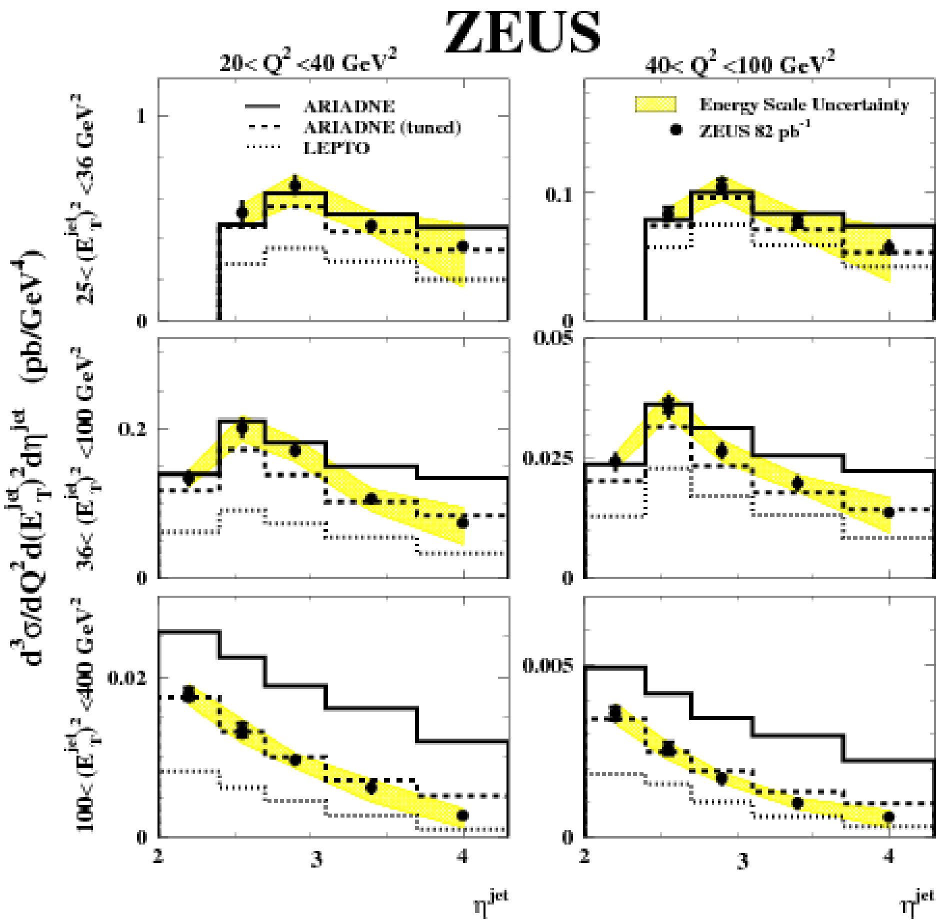

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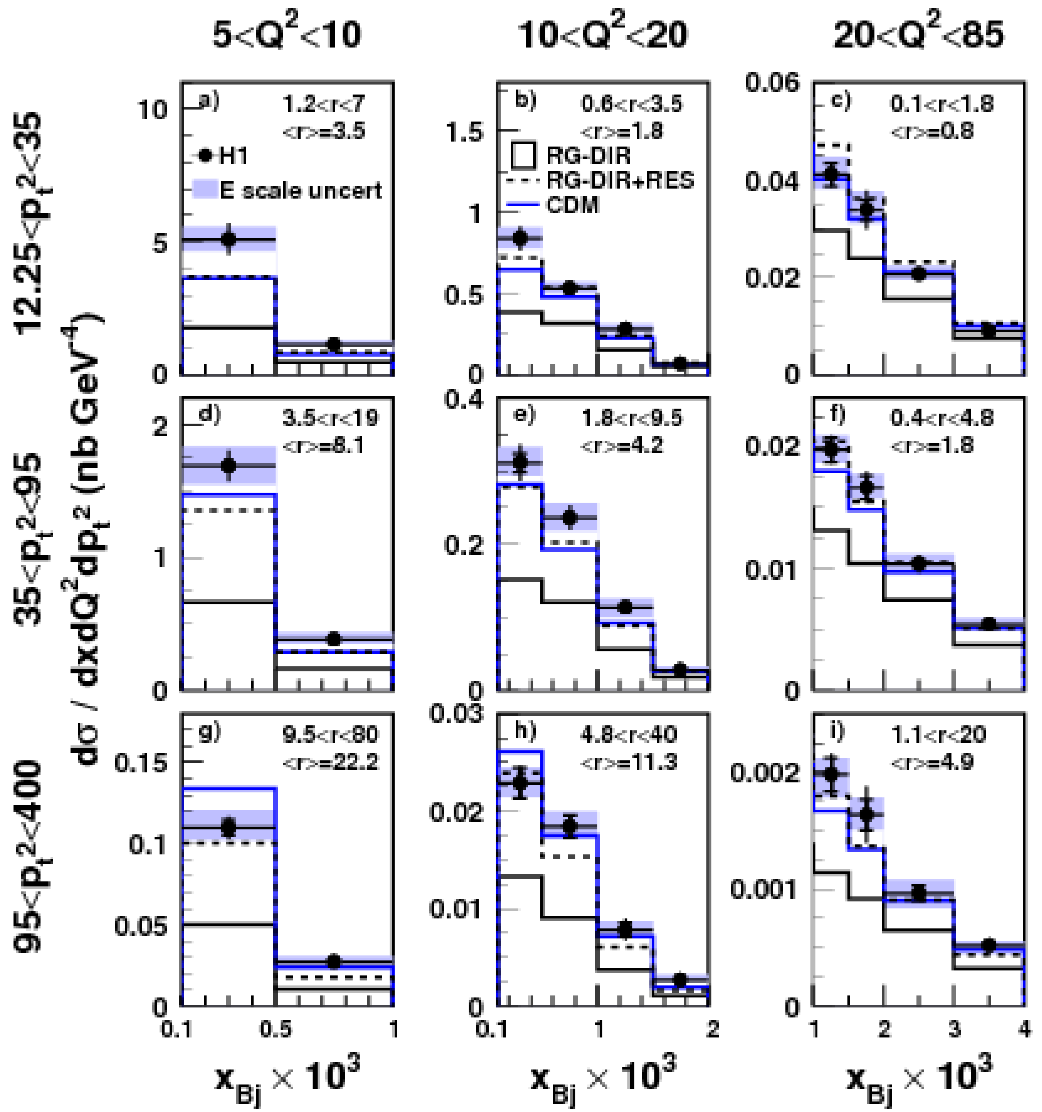

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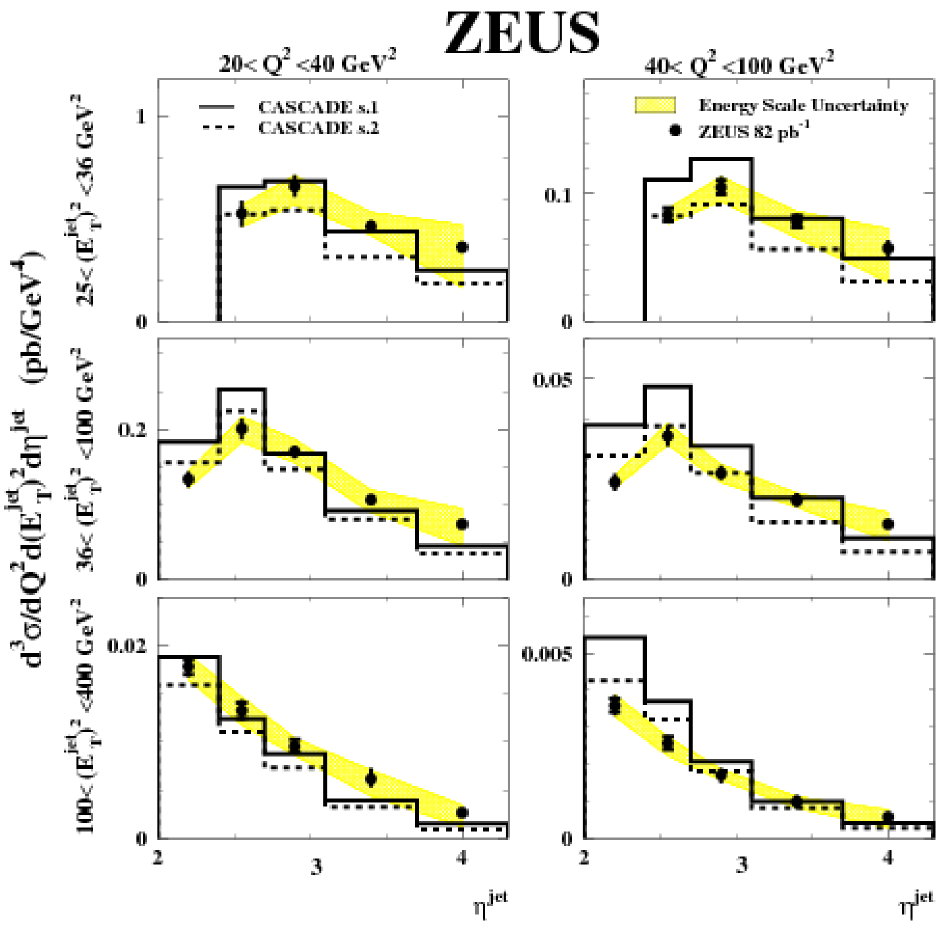

Forward + dijet production

- Comparison to fixed order ME calculations (NLOJET++):
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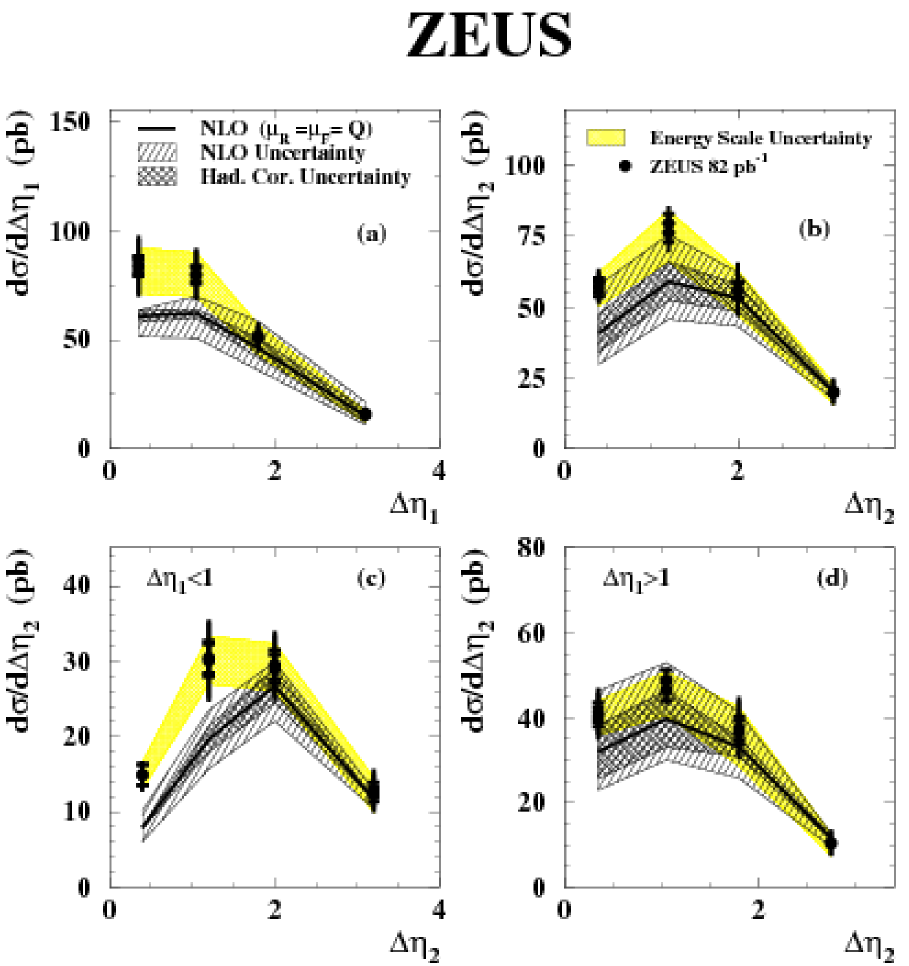

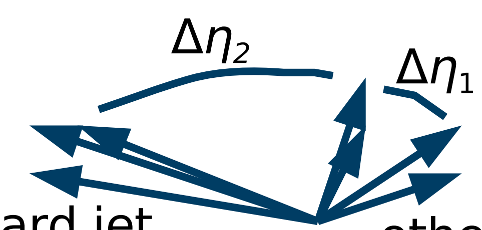

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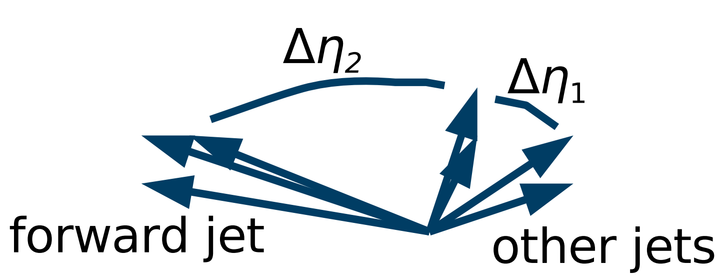

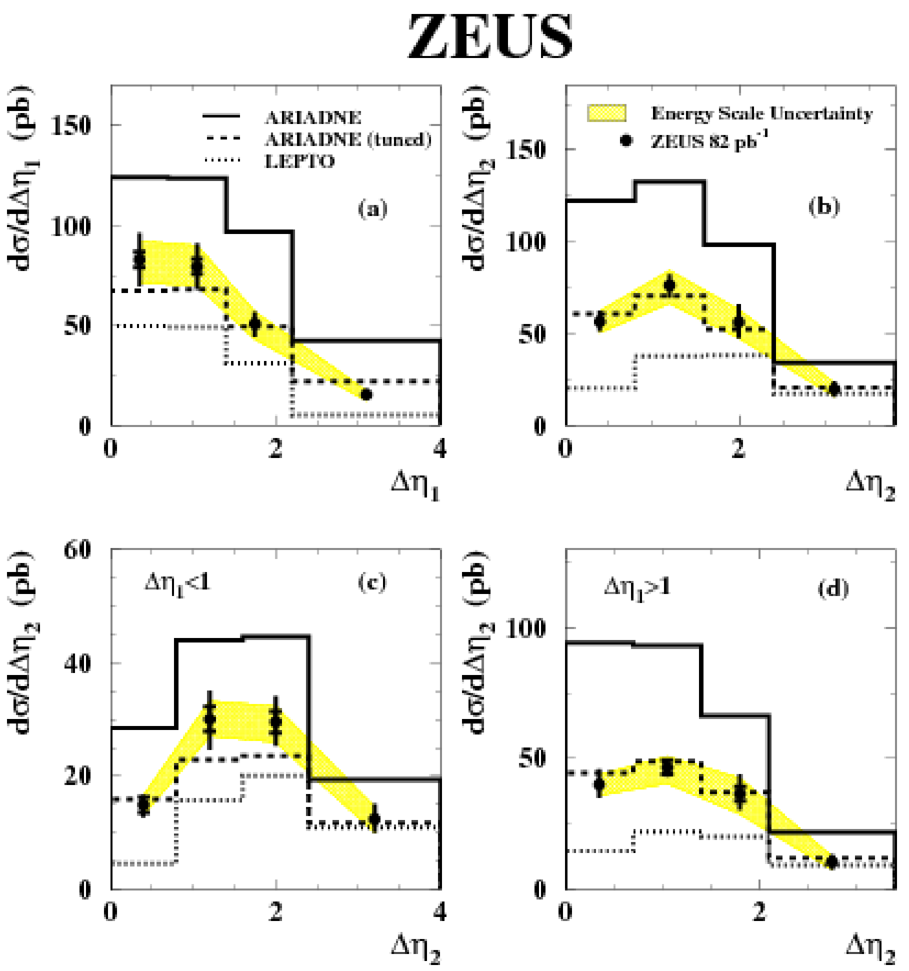

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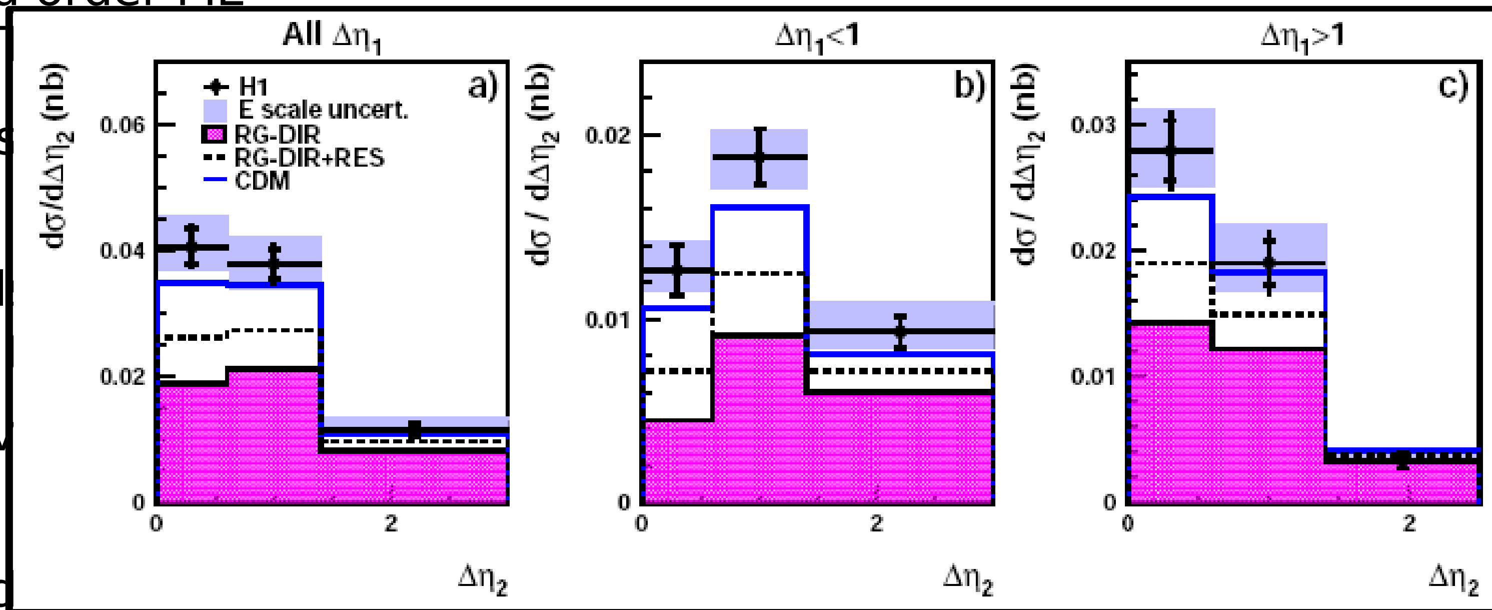

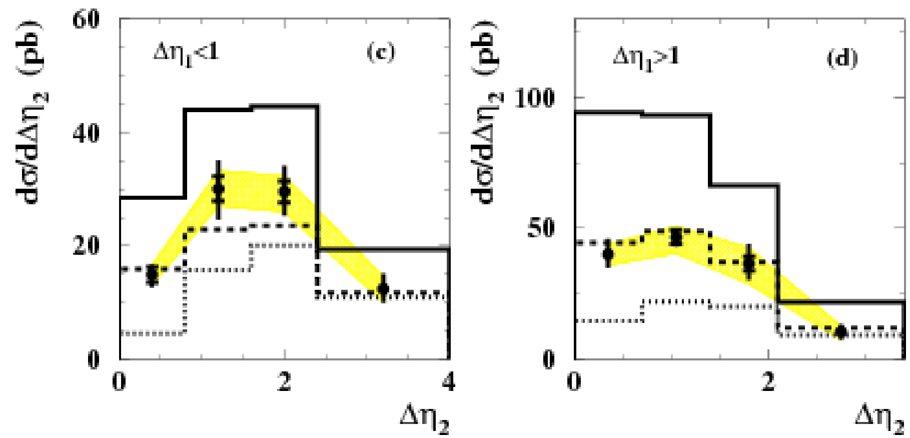

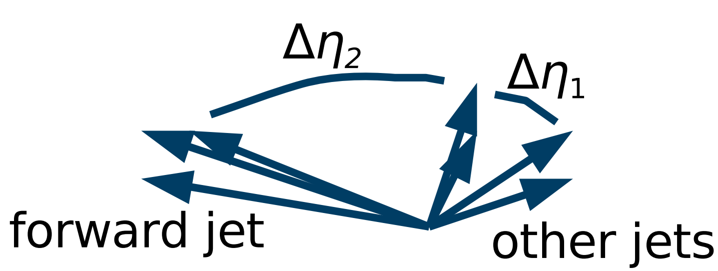

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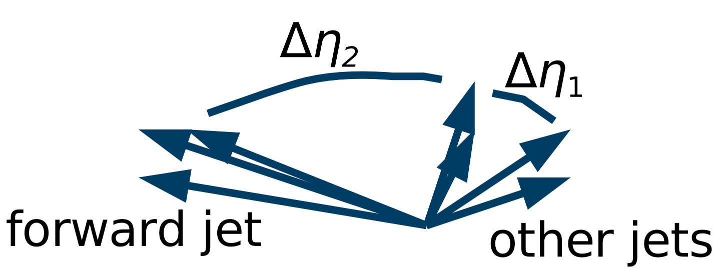

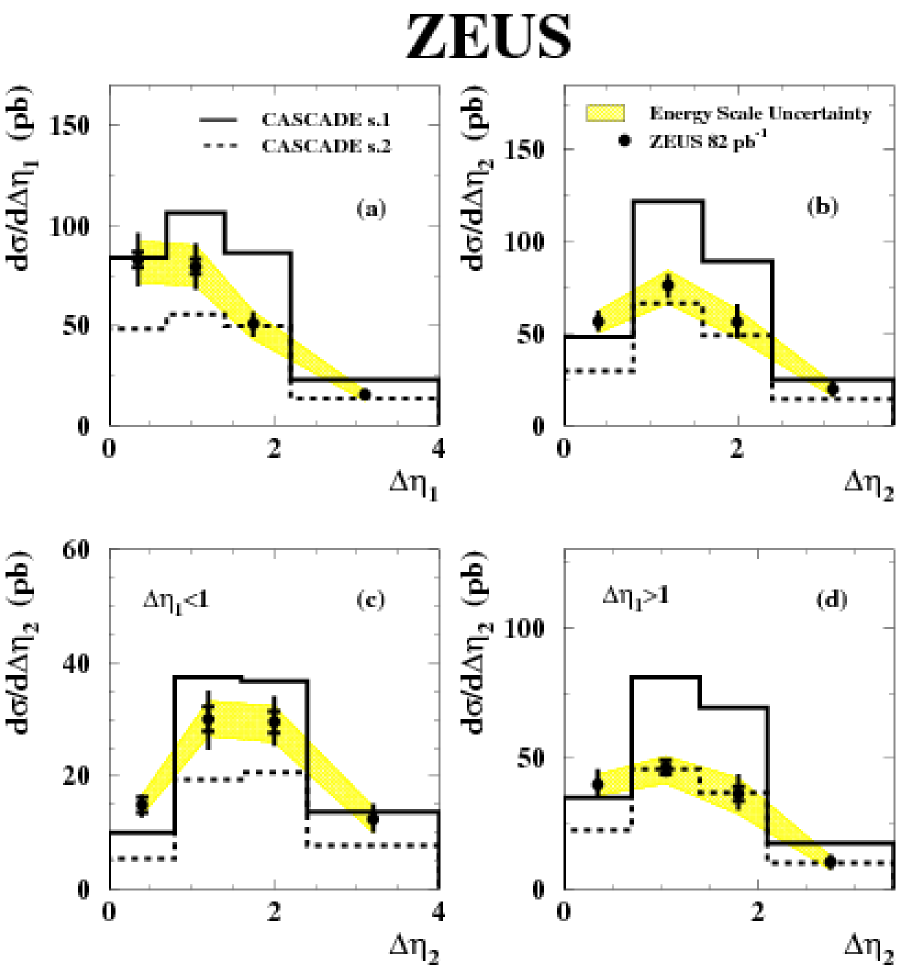

Conclusion so far…

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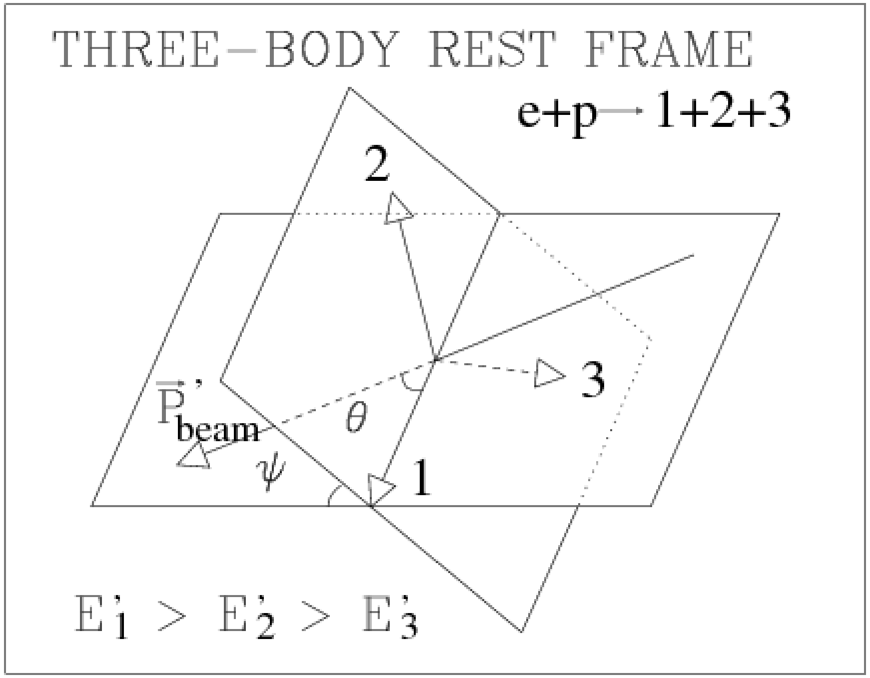
3-jet production in DIS

- Aim: check ME calculations at NLO and PS models by looking at 3-jet topologies in regions of phase space where additional gluon radiation and/or non-ordered PS are expected

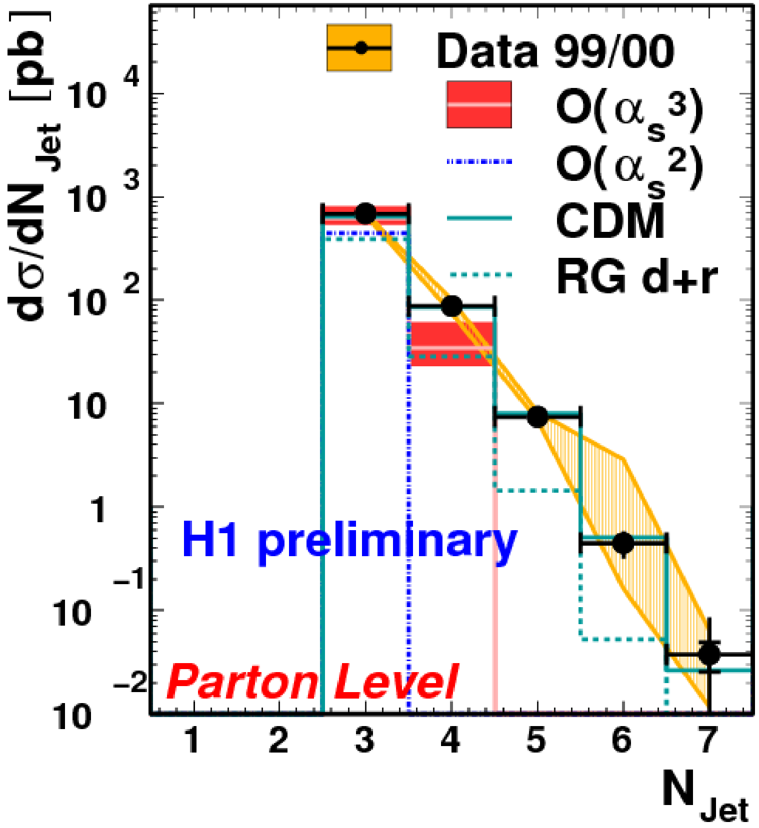
- Method:
  - measure 3-jet cross sections
  - exploit three-jet topology
    - scaled energy in 3-jet rest frame $X_i = 2\,E'_i/(E'_1 + E'_2 + E'_3)$
    - angles θ',ψ' in 3-jet rest frame
  - look for events with at least 1 forward jet
    - $\Theta^{fwdjet} < 20°$, $x^{fwdjet} = E^{fwdjet}/E^p > 0.035$



- Kinematic selection:
  - $5 < Q^2 < 80$ GeV², $0.1 < y < 0.7$, $10^{-4} < x < 10^{-2}$, $156° < \theta_e < 175$, $E_e > 9$ GeV
  - $N_{jet} > 3$, $p_T^{jet} > 4$ GeV, $p_T^{jet1} + p_T^{jet2} > 9$ GeV, $-1 < \eta^{jet} < 2.5$ (one jet with $-1 < \eta^{jet} < 1.3$)

3-jet cross sections

- Jet multiplicity
  - CDM gives excellent description; RAPGAP DIR+RES (DGLAP with a resolved photon) fails at high jet multiplicity
  - NLO O($\alpha\alpha_s^3$) agrees for N_{jet} = 3 but misses 18% of events with 4 or more jets



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- x and η^{jet} dependence
  - main discrepancies are seen at low x and forward η^{jet}
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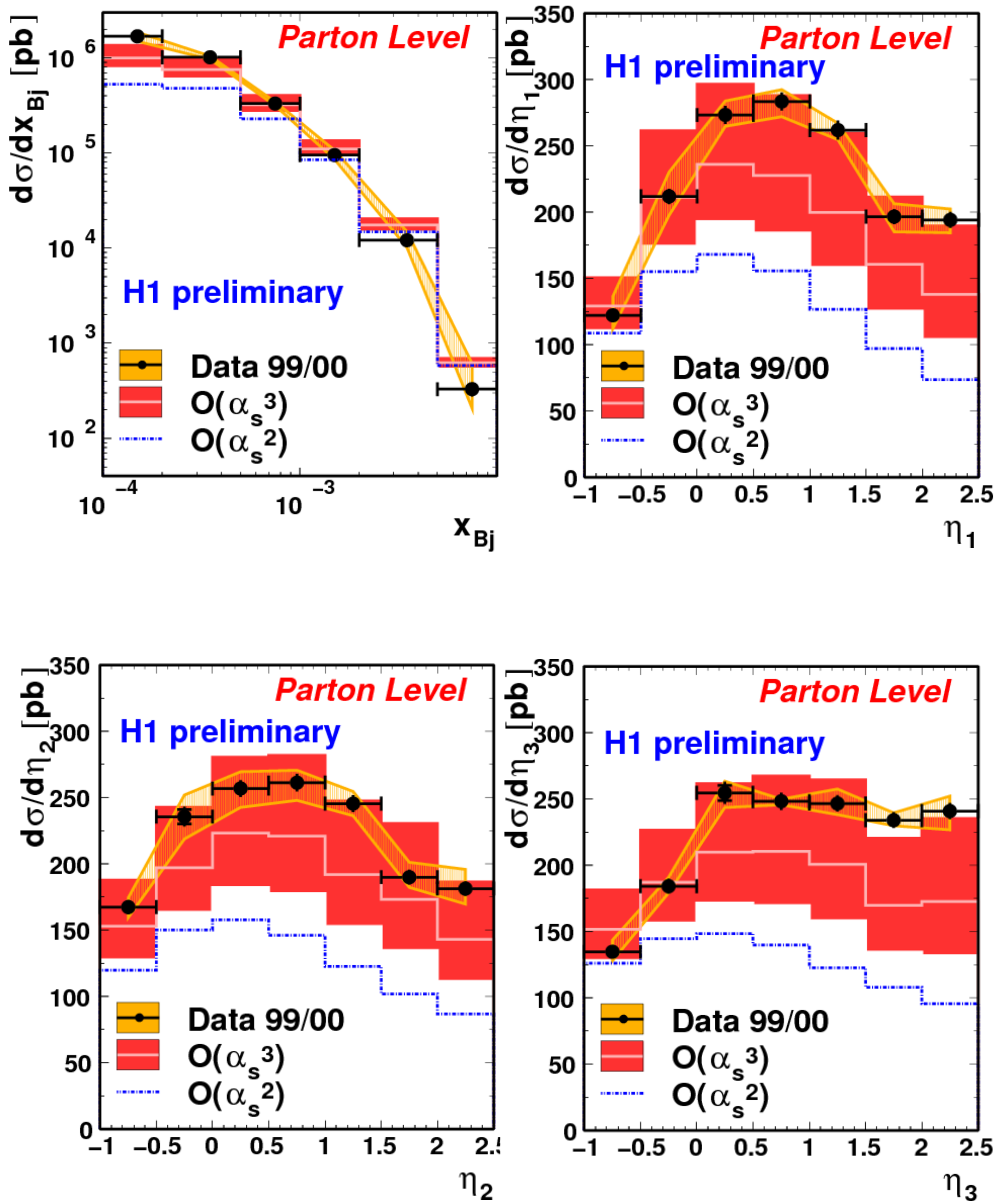

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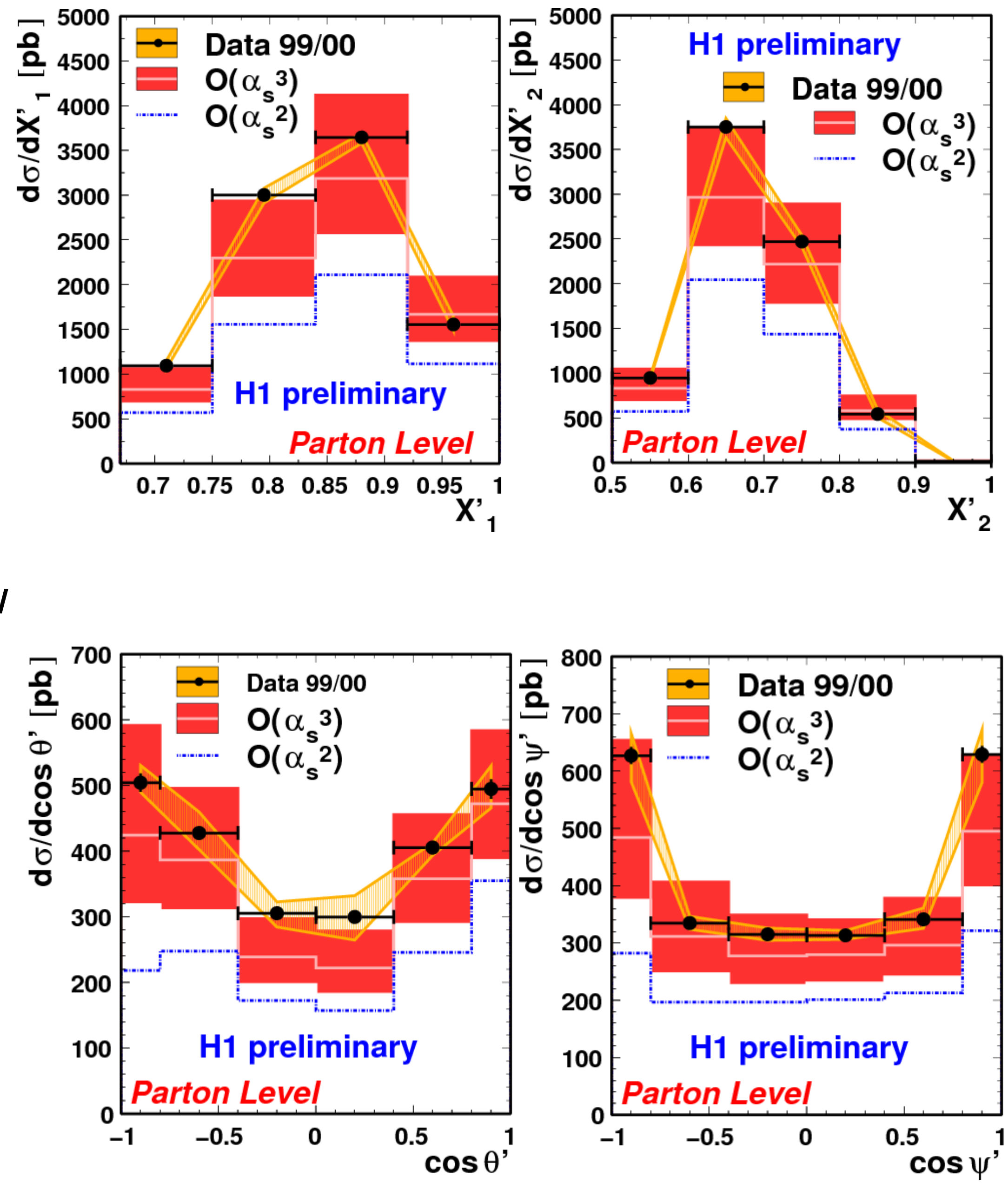
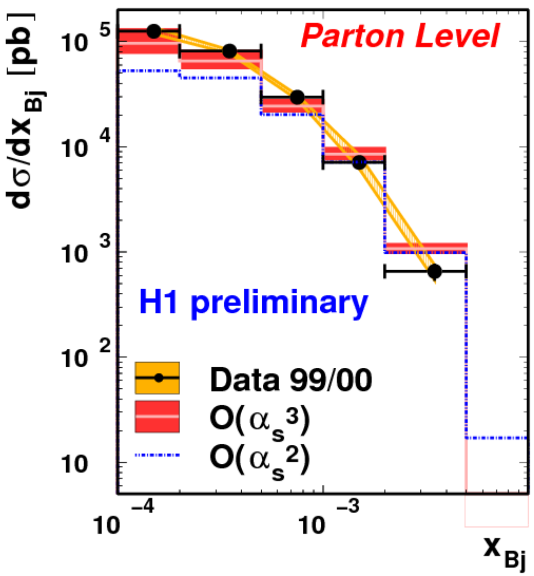
- Jet topology
  - 3-jet topology is well described by NLO O($\alpha\alpha_s^3$), except for the 18% normalisation difference



3-jets events with at least 1 forward jet

- *x* dependence
  - main discrepancy seen at low *x* with 2 forward jets

1 fwd + 2 cnt jets



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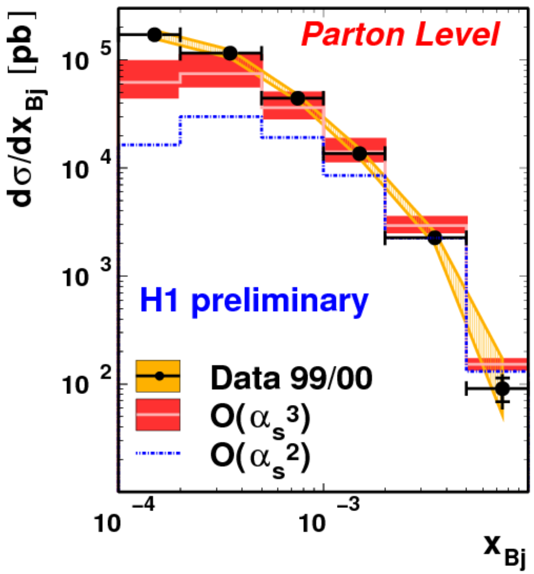
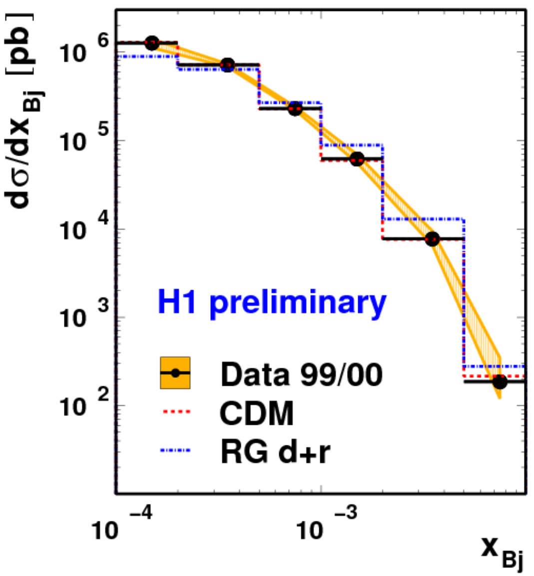
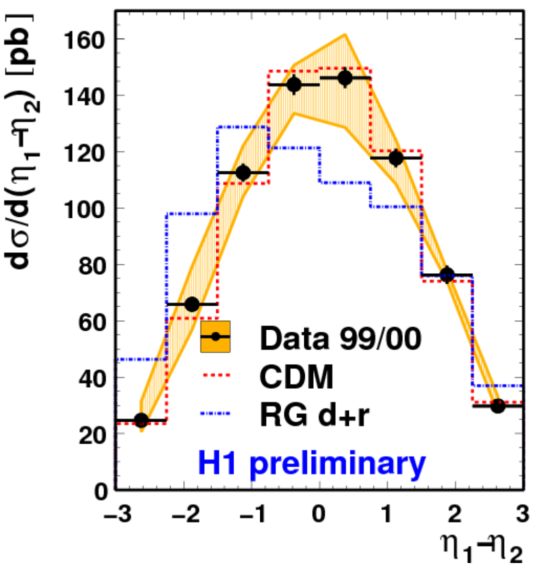


Comparison to PS models

- 3-jet cross sections:
  - absolute normalisation too low
    - RAPGAP (DGLAP with a resolved photon) scaled by 174%
    - CDM scaled by 108%
  - RAPGAP fails in several aspects





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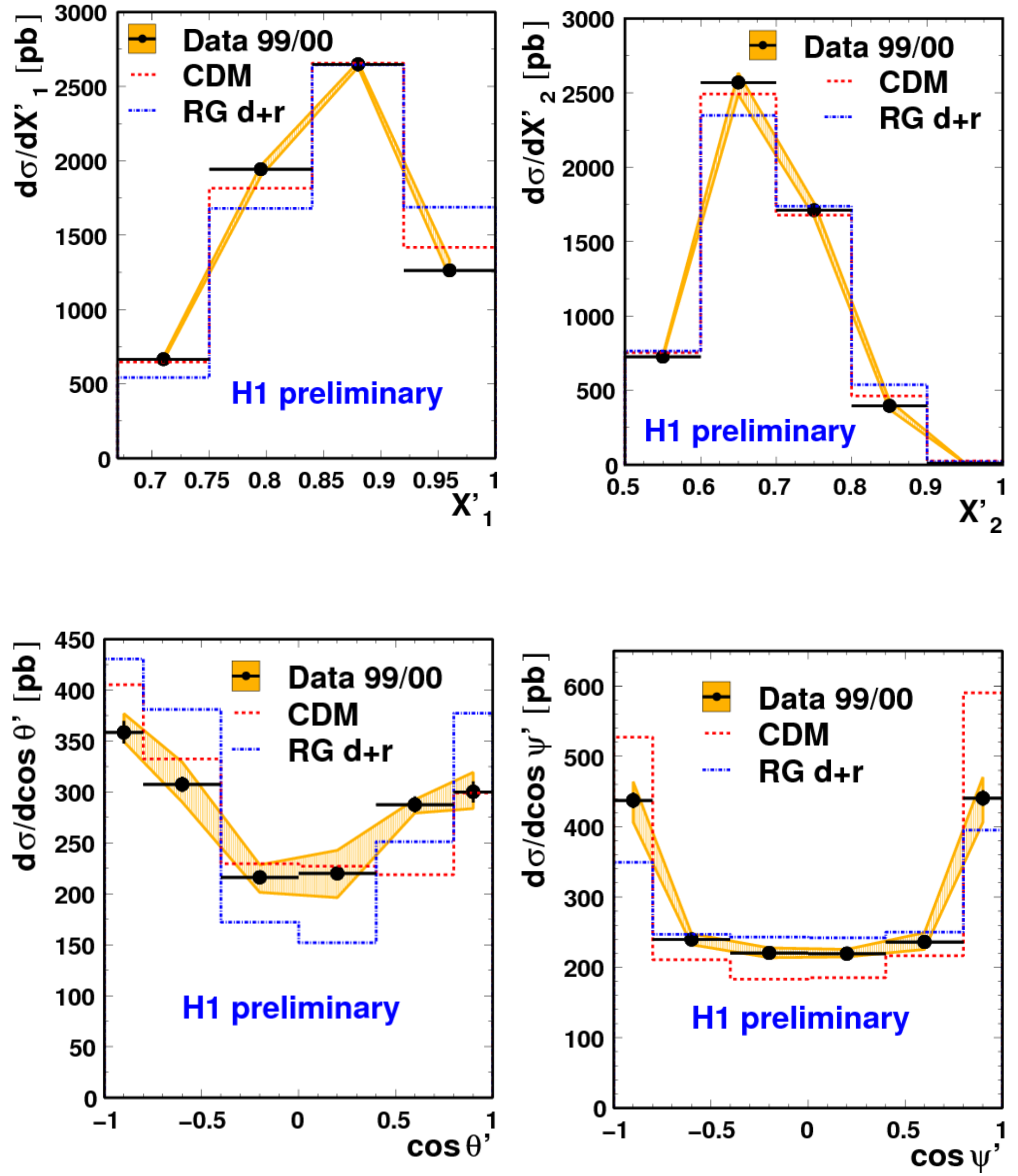

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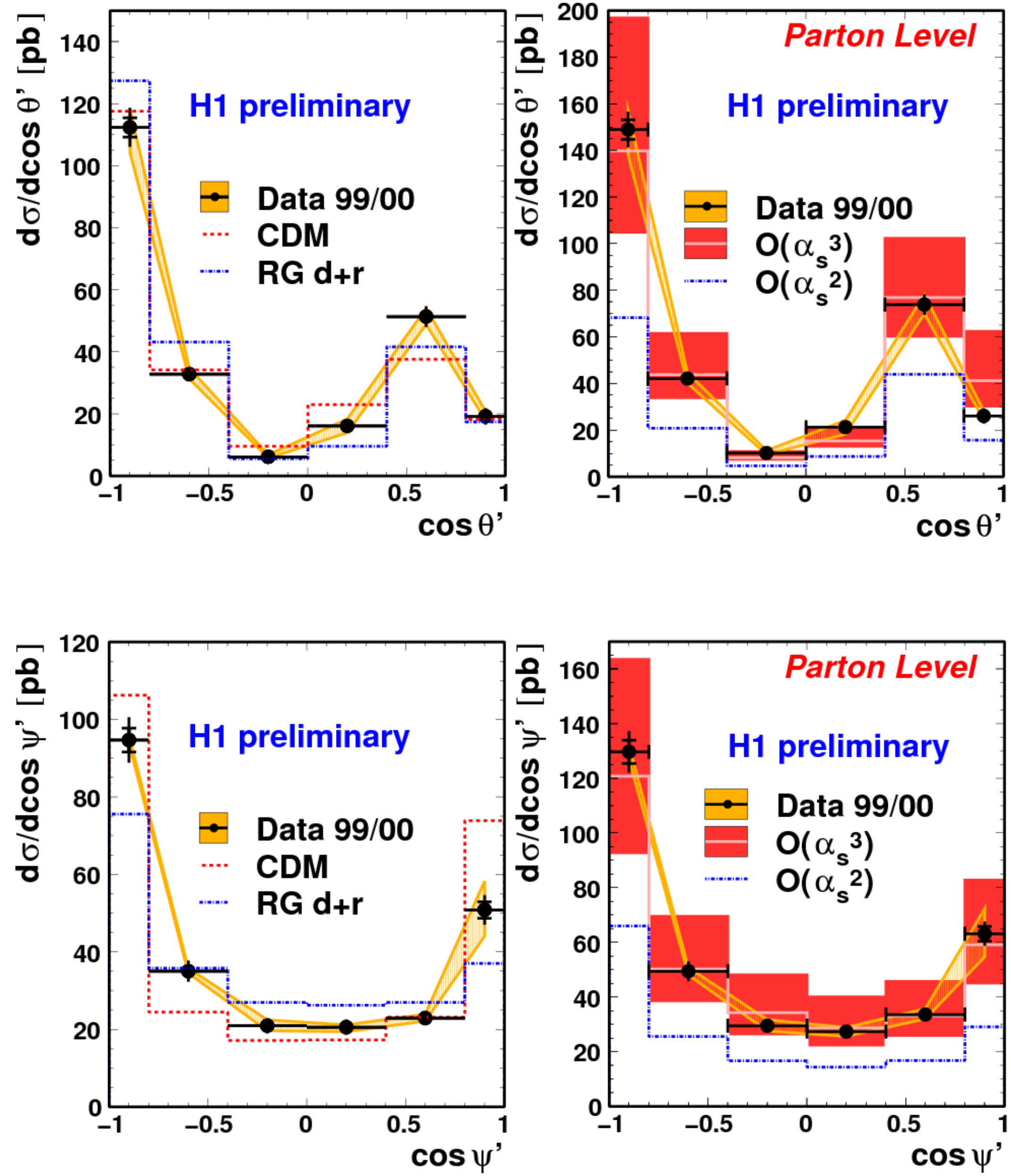
- 2 fwd + 1 cnt jet cross sections
  - Absolute normalisation too low
    - RAPGAP (DGLAP with a resolved photon) scaled by 385%
    - CDM scaled by 109%
    - NLO normalised to data
  - RAPGAP DIR+RES fails
  - CDM does well
  - NLO even better

2 forward + 1 central jets



General summary

- 2-jet and 3-jet production at low x_{Bj}:
  - aim: check ME calculations for 2- and 3-jet production at NLO
  - conclusion: NLO ($O(\alpha\alpha_S^2)$, $O(\alpha\alpha_S^3)$) calculations work well and is especially needed at low x_{Bj} when additional gluon radiation is highlighted
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- 3- and 4-jet production at low x_{Bj}:
  - aim: check ME calculations at NLO and PS models by looking at jet topologies in regions of phase space where additional gluon radiation and/or non-ordered PS are expected
  - conclusion: NLO ($O(\alpha\alpha_S^3)$) describes jet topology surprisingly well, but misses 18% of events with 3 or more jets, especially when 2 jets are forward jets; CDM is very good to high jet multiplicity and also describes the jet topology well.

Questions for discussion

- Why is CDM so good?
  - Number of radiated gluons is not that high – any breaking of the ordering is fine (but RAPGAP DIR+RES doesn't work...!)
  - CDM has been tuned...
- Why is CCFM so bad?
  - CCFM needs better input (better unintegrated PDFs...). Can uPDFs be constrained by this data?
- What are the next steps in theory?
  - How far are we from a full BFKL calculation?
- What are the next steps in experiment?
  - Which analyses should still be done with HERA data?
  - What are the possibilities to measure forward jets at the LHC?

3-jets events with at least 1 forward jet

- x dependence
  - main discrepancy seen at low x with 2 forward jets
- η^{jet} and p_T^{jet} dependence

1 fwd + 2 cnt jets | 2 fwd + 1 cnt jets