International Workshop on Top Quark Physics
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Monte Carlo Simulations for Top Pair and Single Top Production at the Tevatron

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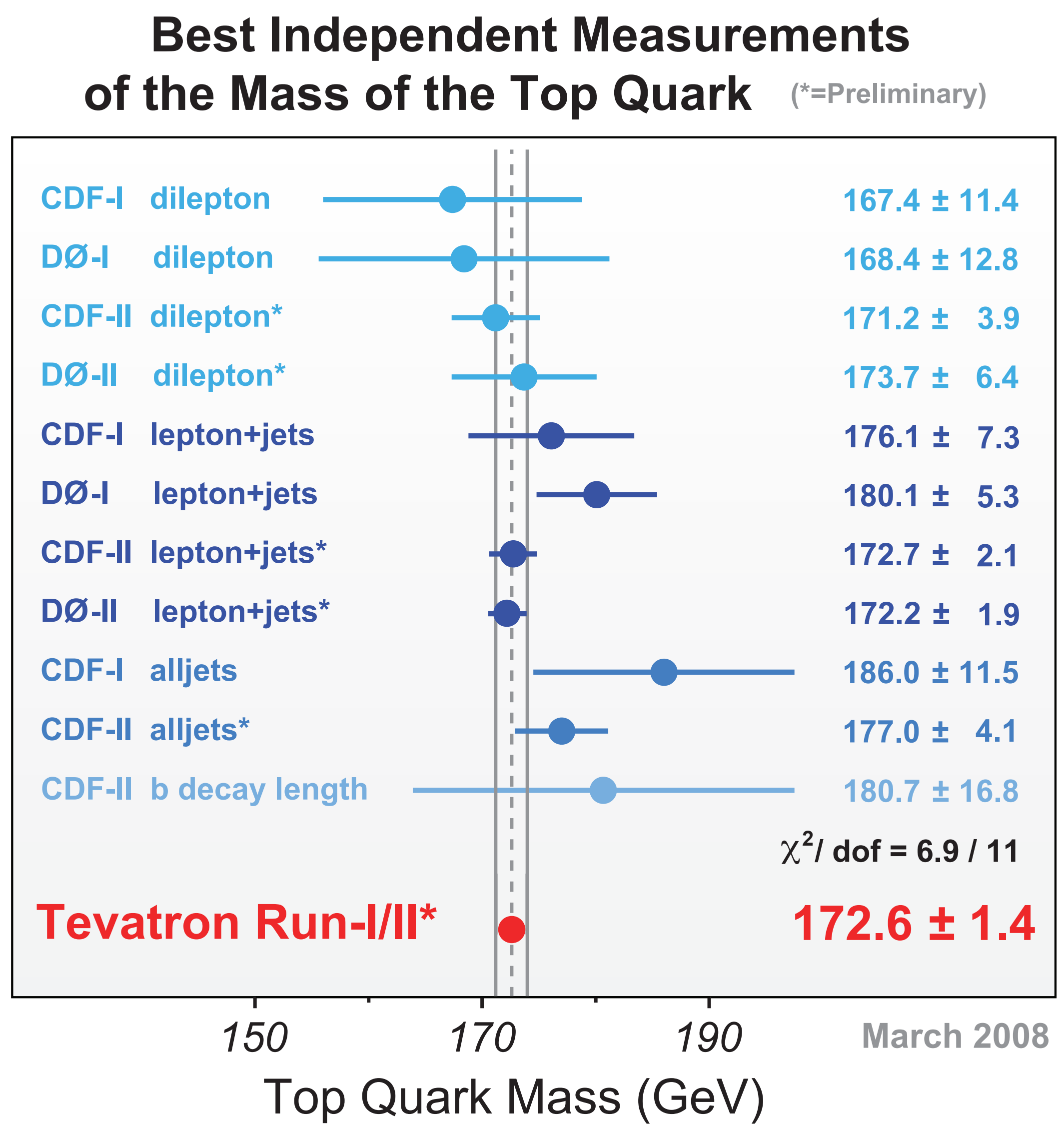
on behalf of the
CDF and DØ Collaborations

Top Physics at the Tevatron in 2008

- Era of precision top quark physics
  - Top mass combination: 0.8% total uncertainty (0.3% MC related)
  - Multivariate analysis techniques (e.g. for single top) → rely on correct modeling of signal and background (A. Harel's talk)
  - Getting sensitive to more subtle effects, e.g. spin correlations

  → MC indispensable for signal acceptance and background estimation
- MC progress somewhat slower
  - Tendency to keep using known-and-tested MC codes
  - Long turn-around times: generation – validation – tuning (despite close collaboration with MC authors)
  - Preference for data-driven methods and "pragmatic" solutions, e.g. re-weighting of existing MC



arXiv:0803.1683 [hep-ex]

Outline of the Talk

MC for Top Pair Production

MC for Single Top Production

MC Systematic Uncertainties

MC for Special Analyses

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Standard Top Pair Signal MC

CDF	DØ
CDF's workhorse: $t\bar{t}$ from PYTHIA v6.2	DØ's workhorse: $t\bar{t}$ + 0–2 jets from ALPGEN v2.1 with PYTHIA v6.3

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• Well established, for all of Run II (with a lot of Run I experience) • Leading order (LO) + parton showers (PS) → scale to latest production cross sections • CTEQ5L (LO) parton distribution functions • Field's Tune A and Sakumoto's tune for W/Z transverse momenta	• Fairly new, since 2007 (but used ALPGEN v1.2 from 2004) • LO + PS + exact 2→n matrix elements: → scale cross sections • CTEQ6L (LO) parton distribution functions • No additional tuning when using ALPGEN + PYTHIA→ small effect (for PYTHIA-only samples: Tune A equivalent with CTEQ6L)

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• Multiple collisions in the same bunch crossing: mix with PYTHIA minimum bias events according to luminosity profile	• Recently: multiple collisions from overlaying zero-bias data events (better description of beam and instrumental background)

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Disadvantages: • LO generator • No hard radiation, e.g. for $t\bar{t}$ + jet(s) • No $t\bar{t}$ spin correlations	Disadvantages: • LO generator, but exact matrix elements for 2→n processes, spin correlations • Fairly new generator

One Size Fits All?

- Situation in 2008: no common MC generator for all of Tevatron top physics
  - Preference for PYTHIA-based MC generators
  - Special generators required for many analyses
  - Next-to-leading order (NLO) generators available, but not yet used as the standard
- Reasons for MC choice:
  - Technical: incompatibilities with experiments' software framework, turn-around times, …
  - Pragmatic: use what is available and validated

MC for Top Pair Production

MC for Single Top Production

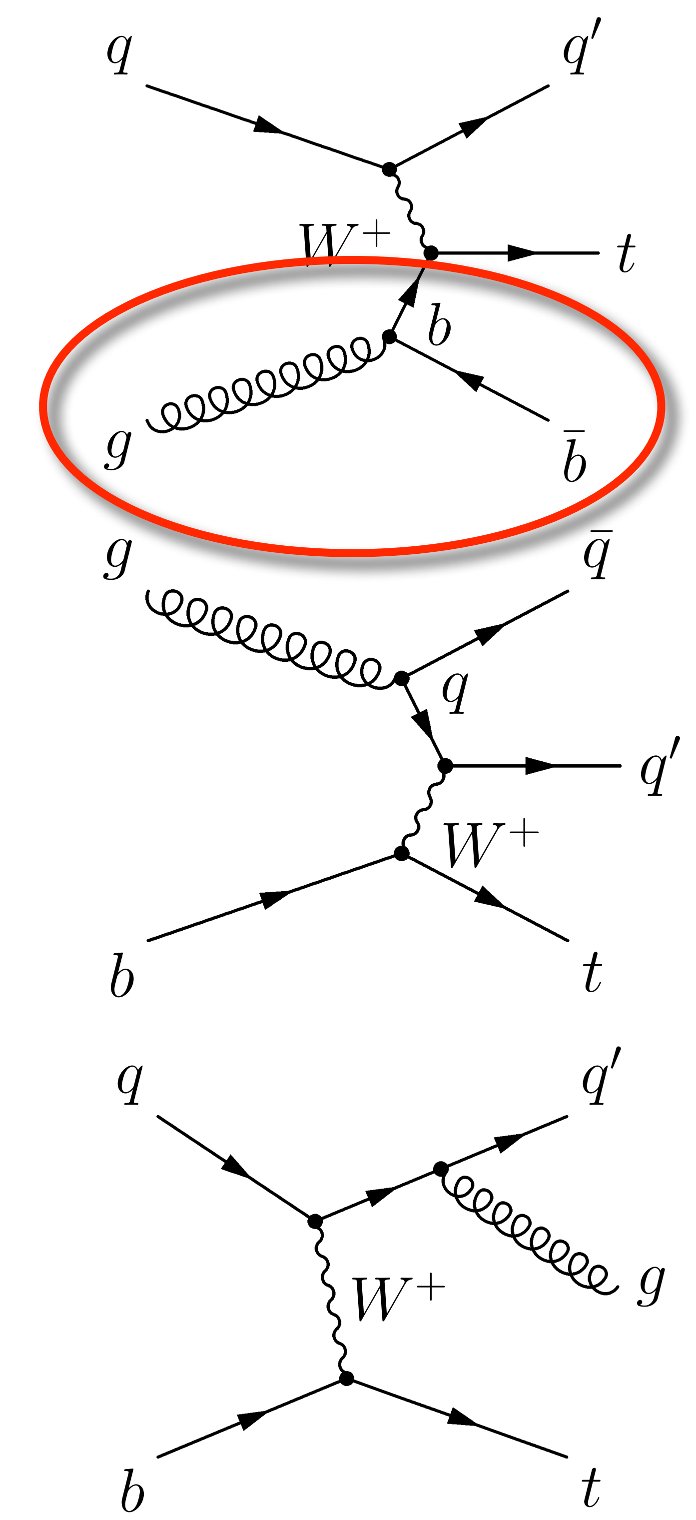
MC Systematic Uncertainties

MC for Special Analyses

Single Top needs Higher Orders

- Leading order MC not sufficient for single top production
  - s-channel at NLO: same kinematic distributions as LO → single *K* factor
  - But: large corrections in t-channel from 2→3 process (initial state gluon splitting)
- Observable: transverse momentum of "second b quark" (i.e. not from t→Wb decay):
  - 2→2 process + parton shower: only from b quark PDF → good in soft and collinear regime
  - 2→3 process: initial state gluon splitting → good for larger transverse momenta
  - Challenge: matching with smooth transition and overlap removal

t-Channel 2→3 Process

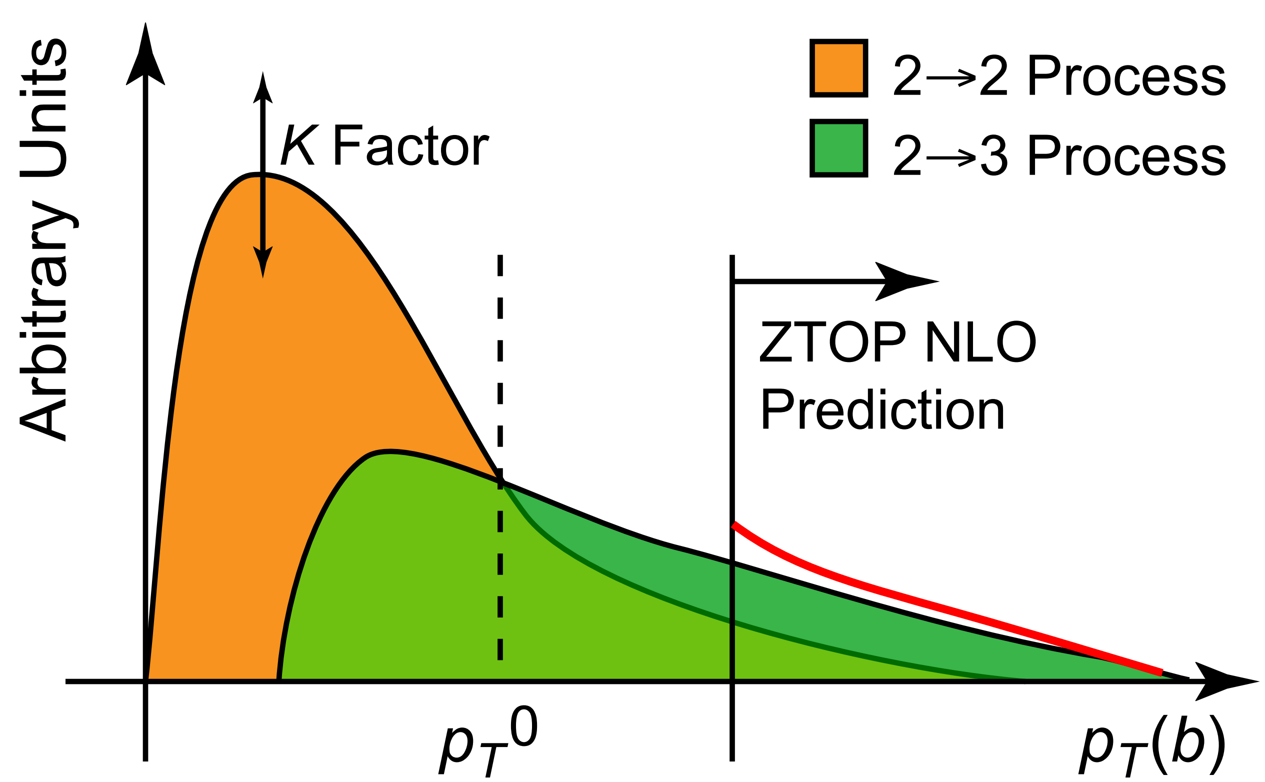


Single Top MC at CDF and DØ

- Generate 2→2 and 2→3 processes separately:
  - CDF: MadEvent (+PYTHIA for showering)
  - DØ: SingleTop MC generator based on CompHEP
    [E.E. Boos et al., Phys. Atom. Nucl. **69** (2006) 1317]
  - Normalization of 2->2 and 2->3 to full NLO prediction from ZTOP
    [Z. Sullivan, PRD **70** (2004) 114012]
- Require smooth transition: split soft and hard regime at p_T^0 = 20 GeV/c (CDF), 15 GeV/c (DØ)
- Validate full kinematics against ZTOP, residual small differences: systematic uncertainty (approx. 1–2%)

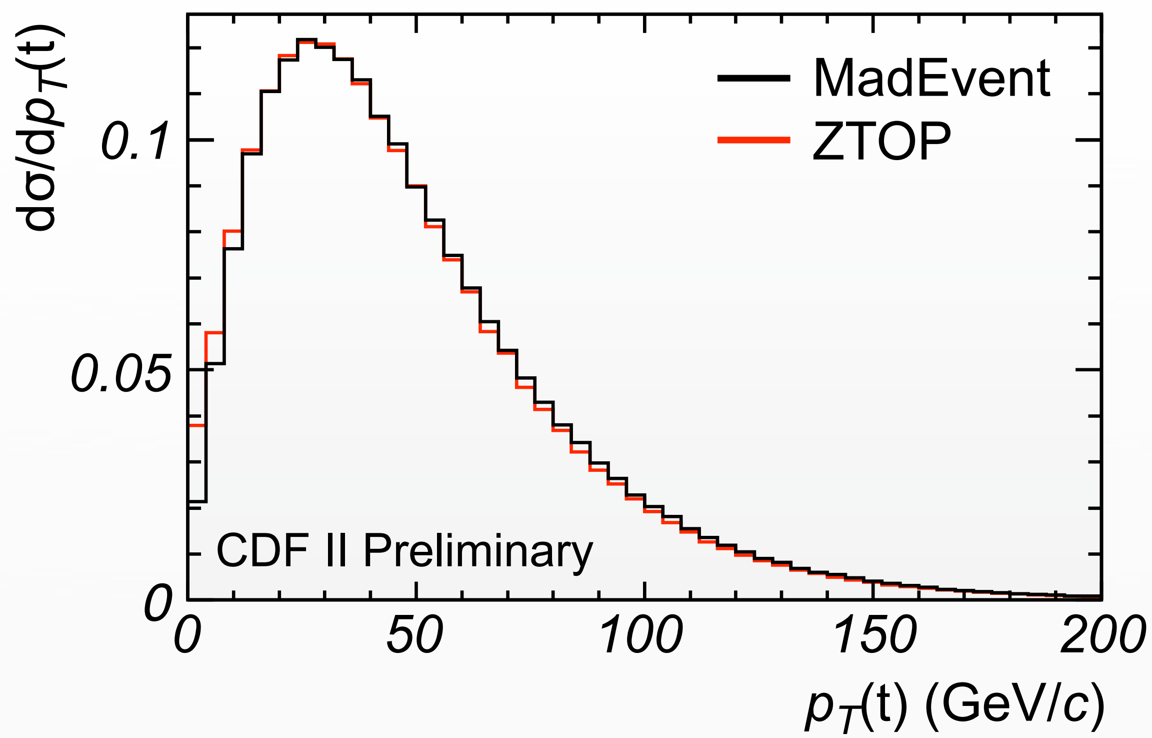
Single Top Cross Section Matching

$$\sigma_{\mathrm{NLO}} = K \cdot \sigma_{2\to 2,\mathrm{PYTHIA}}\Big|_{p_T(b)<p_T^0} + \sigma_{2\to 3}\Big|_{p_T(b)\geq p_T^0}$$

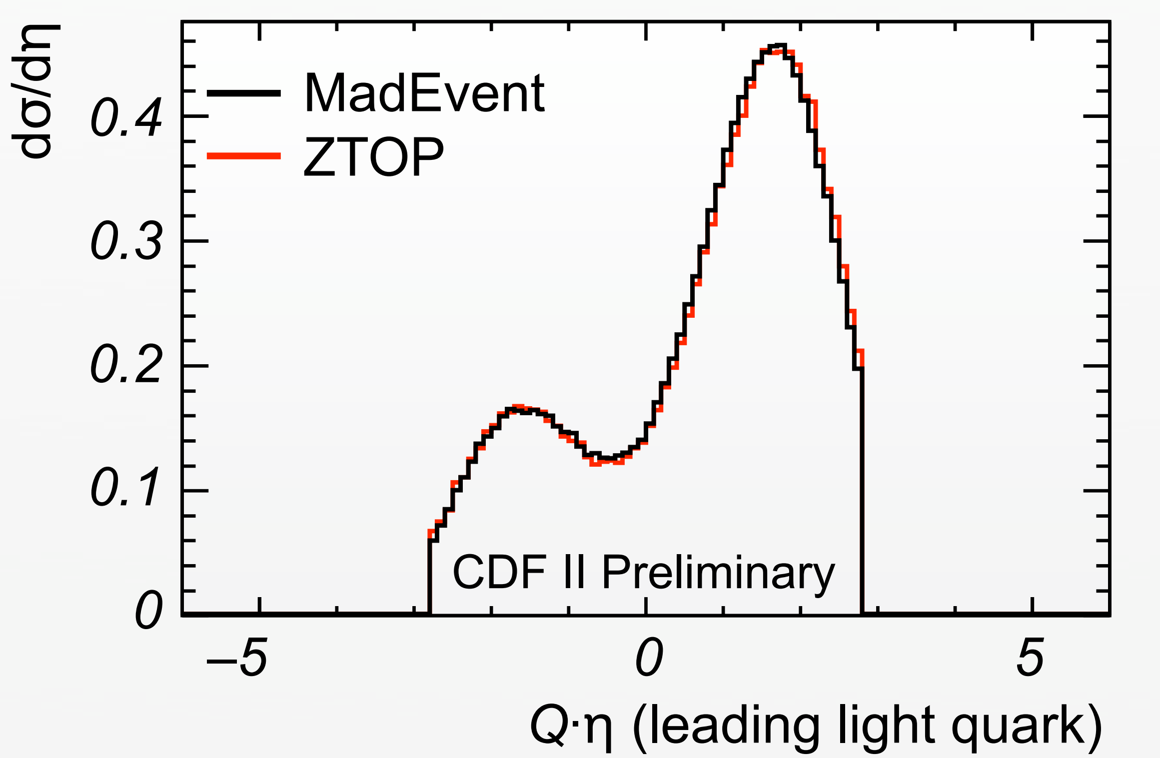


Comparison: CDF vs. DØ

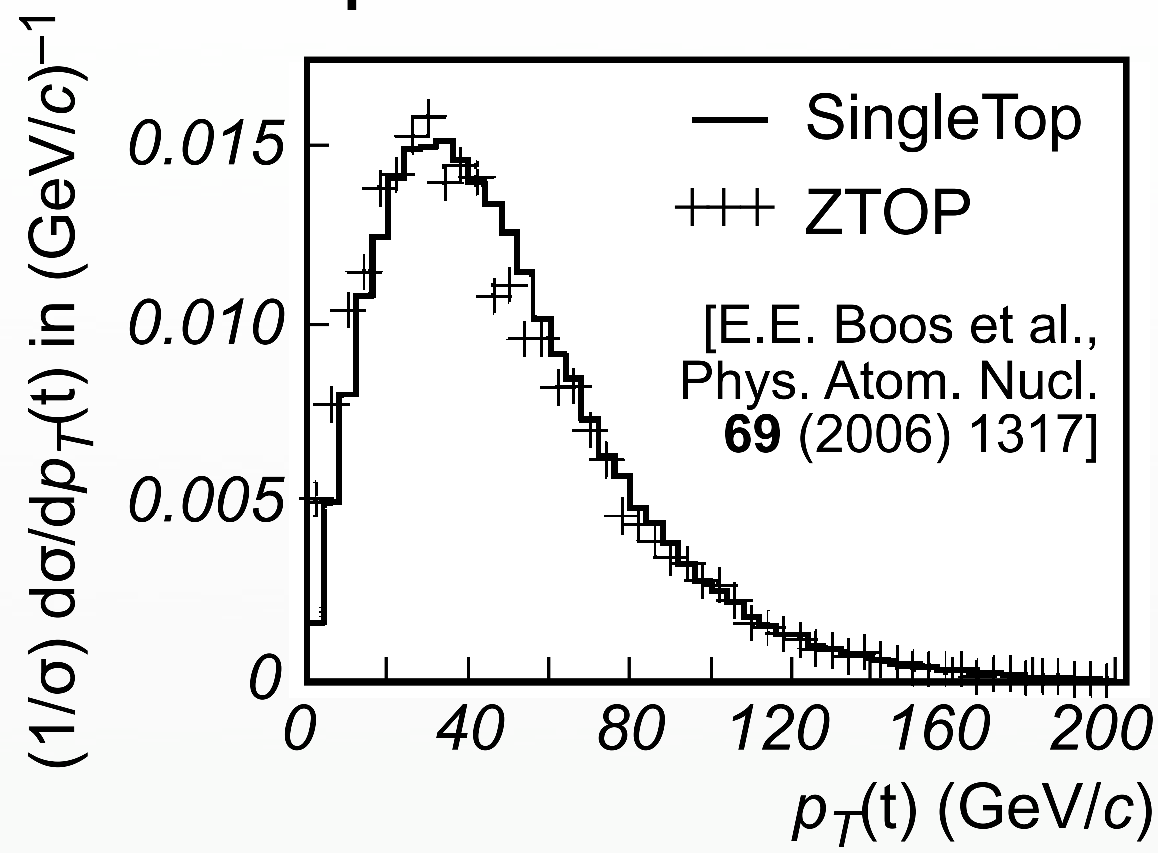
CDF: Top Transverse Momentum



CDF: Q·η of Leading Light Quark



DØ: Top Transverse Momentum



MC for Top Pair Production

MC for Single Top Production

MC Systematic Uncertainties

MC for Special Analyses

Standard Treatment of MC Uncertainties

Uncertainty	CDF	DØ
General MC Model	PYTHIA vs. HERWIG v6.510: • Different hadronization • Different underlying event tuning • Similar treatment of initial/final state radiation (ISR/FSR)	• Until recently: no HERWIG samples available → no light quark fragmentation uncertainty • b quark fragmentation: differences in LEP vs. SLD data

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Signal Model	• ISR/FSR: specially tuned PYTHIA samples (Λ_{QCD} and Q^2 scales) → sensitive to soft radiation • Parton distribution functions (PDFs): CTEQ6 eigenvector prescription, CTEQ vs. MRST	• ISR/FSR: reweight jet multiplicity in ALPGEN $t\bar{t}$ + jets with data → sensitive to hard radiation • Parton distribution functions: CTEQ6 eigenvector prescription, CTEQ vs. MRST

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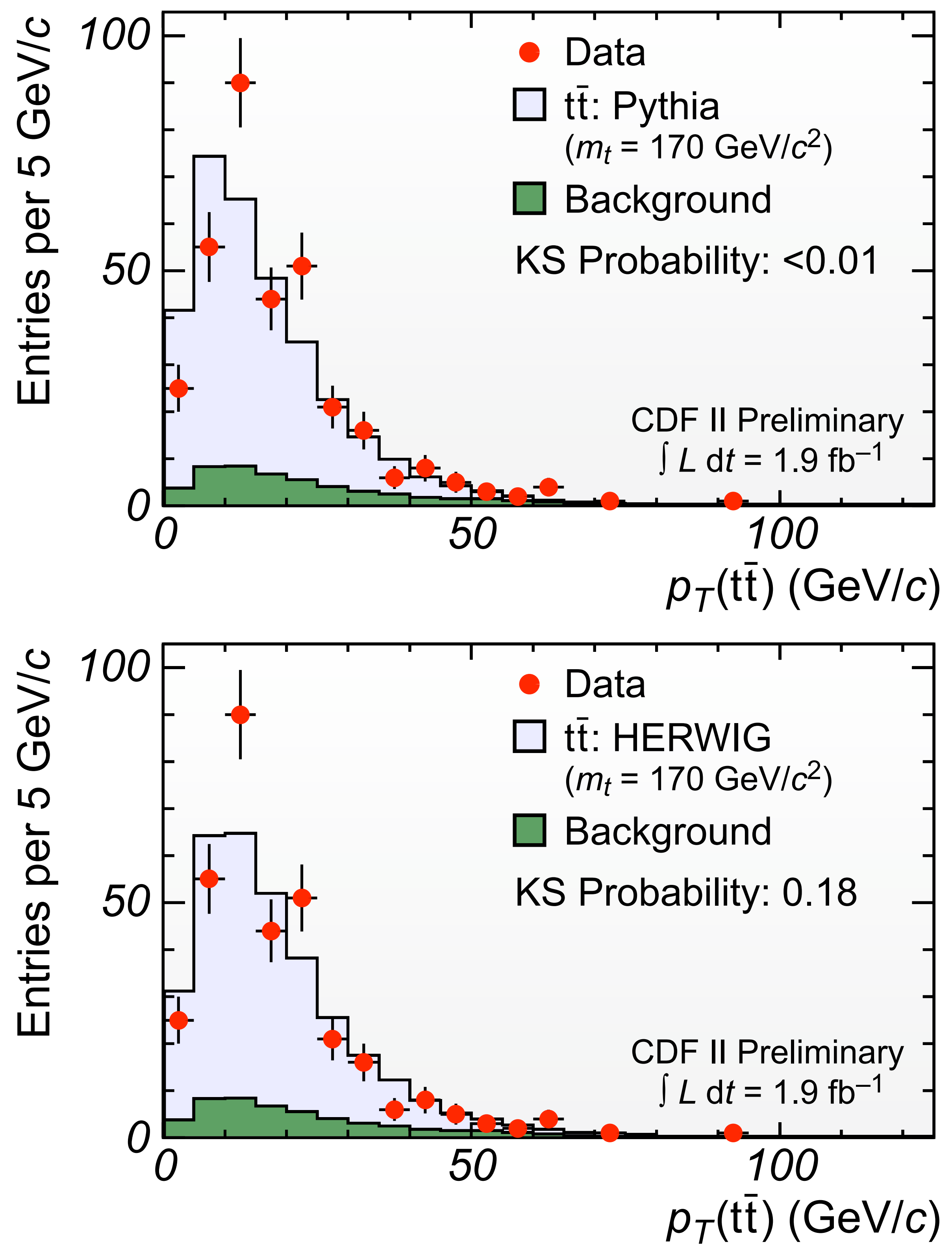
Jet Energy Scale (JES)	• PYTHIA vs. HERWIG: extract JES correction uncertainties, e.g. dijet balance, fragmentation, out of cone correction • In-situ JES calibration: residual uncertainty from p_T/η dependence • b quark JES: fragmentation model, color flow	• In-situ JES calibration: residual uncertainty from p_T/η dependence • Difference in response to b jets and light jets • MC smearing to match jet energy resolution in data

Revisiting MC Systematic Uncertainties

- Broad ongoing effort, especially for top mass analyses:
  - Checking with other generators: ALPGEN + PYTHIA, HERWIG + JIMMY, MC@NLO, MadGraph/ MadEvent
  - Investigation of double-counting MC uncertainties: general MC model vs. JES
  - New ideas, e.g. color reconnection
    → see D. Wicke's talk
  - Long-standing issue: $t\bar{t}$ p_T mismatch between PYTHIA and HERWIG (small contribution to mass uncertainty)



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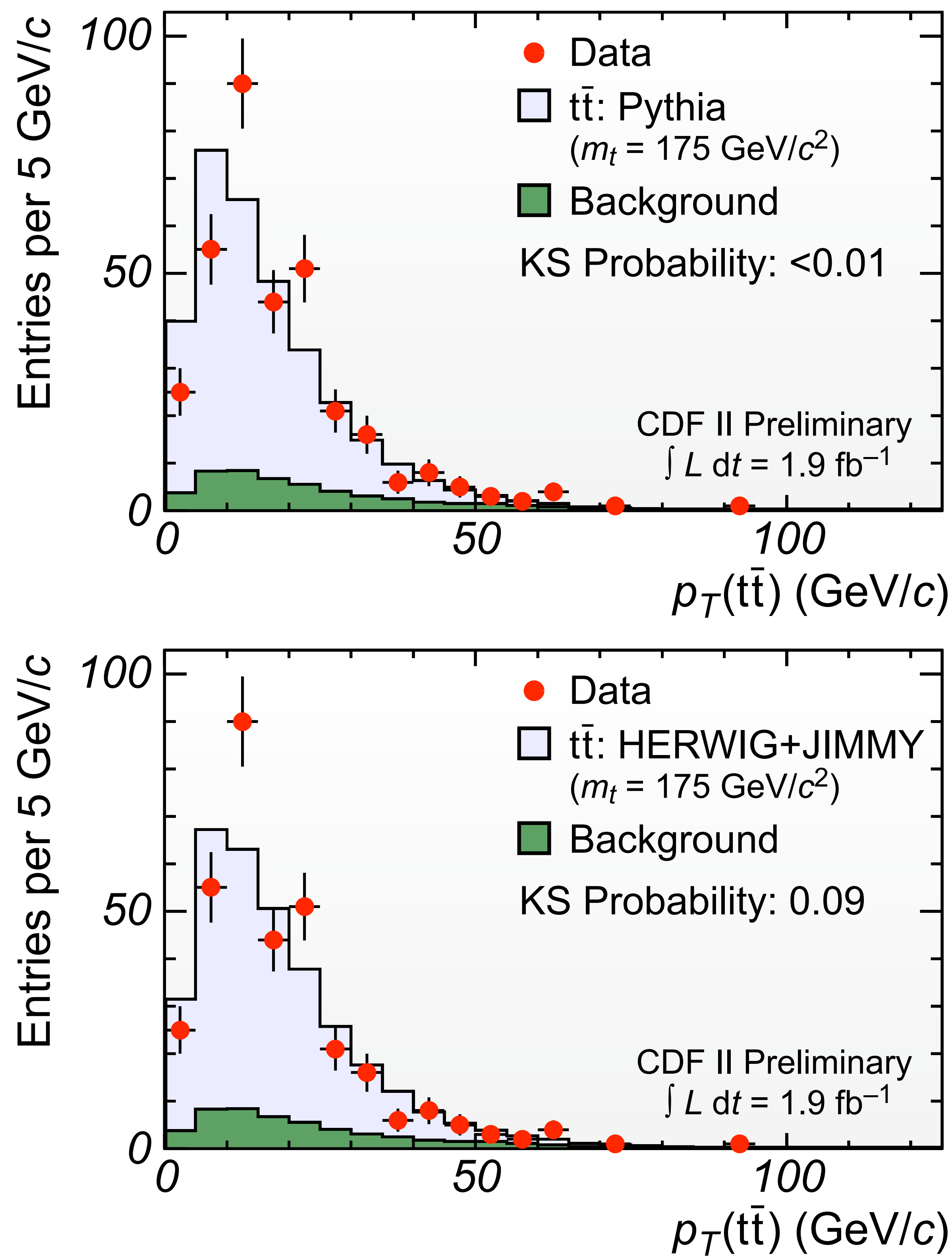

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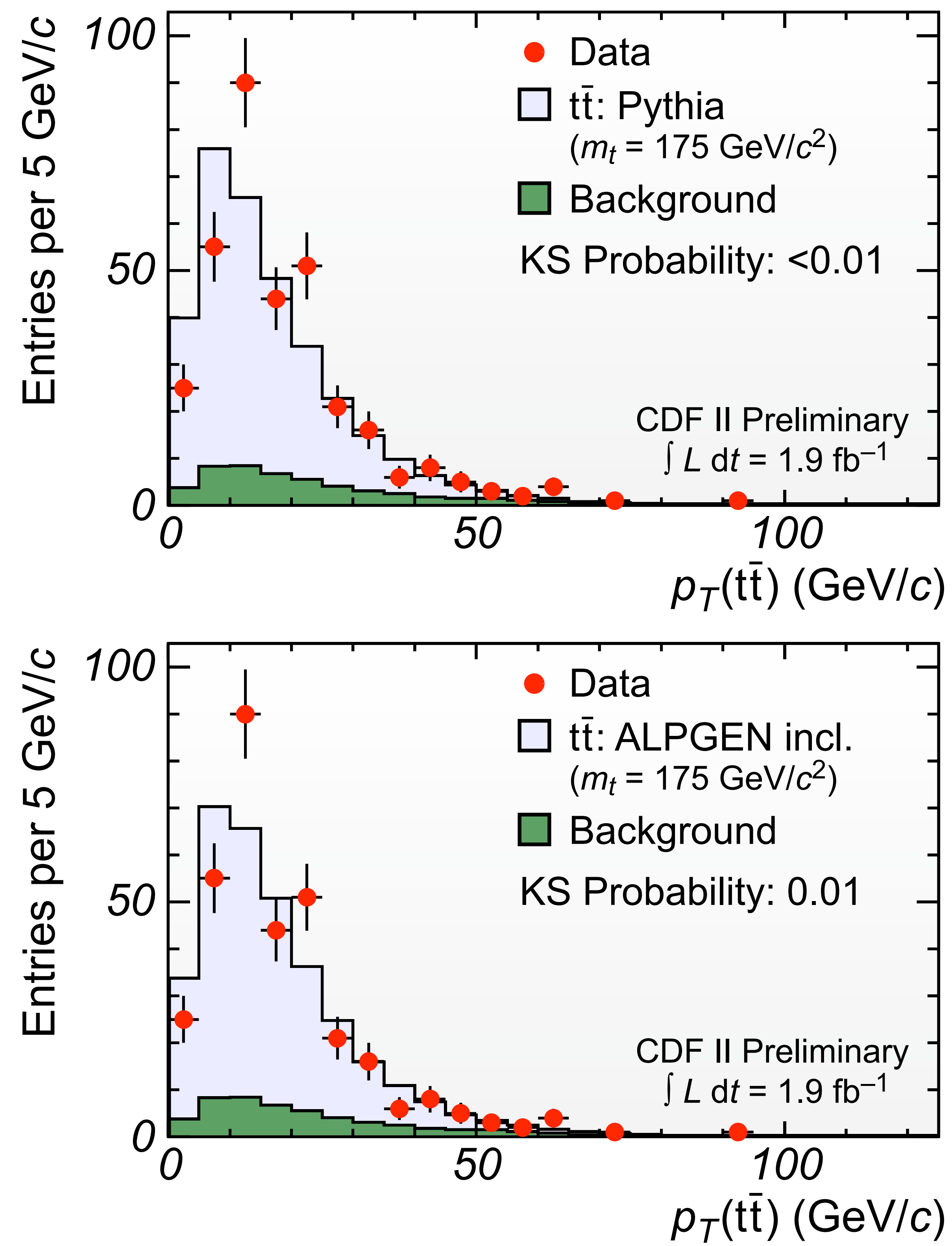

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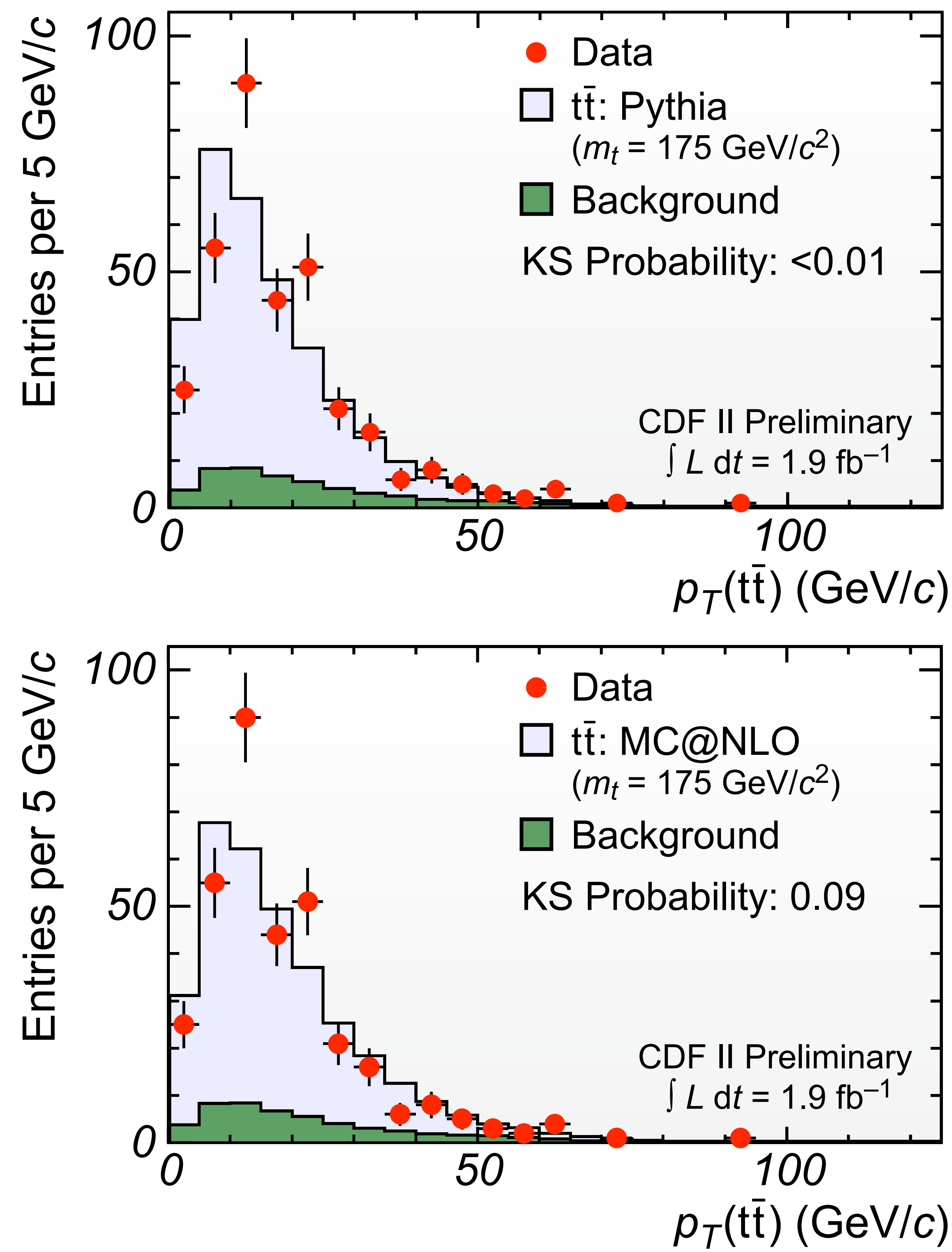

Towards a Common Approach?

A Typical Joint CDF/DØ Workshop?

- 2007: Two joint CDF/DØ workshops on top mass systematic uncertainties
  - Step 1: understanding procedures and their correlations → much improved by joint workshops
  - Step 2: common approach to systematic uncertainties → more difficult, still work in progress…
- Most important common issue: top mass combination
  - Common approach desirable but not strictly necessary
  - Sufficient to know correlations between systematic uncertainties in CDF and DØ

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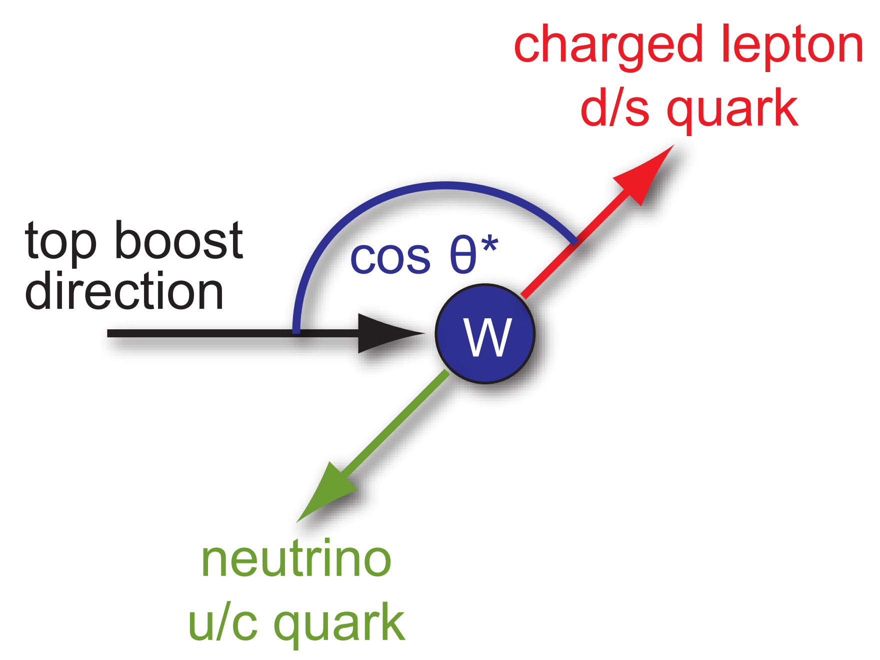
W Helicity in Top Quark Decays

- Physics: is tWb coupling really *V–A*?
- MC requirement: adjust distribution of observable cos θ* for different couplings
- Solution 1: reweight cos θ*
  - DØ: cos θ* obtained from ALPGEN, checked against PYTHIA [PRL **100**, 062004 (2008)]
  - CDF: cos θ* obtained from PYTHIA, checked against GGWIG* and HERWIG [CDF Note 9144]
- Solution 2: specialized generator
  - GGWIG for cos θ* templates [CDF Note 9215]
  - MadEvent (only for linearity checks, main acceptance from PYTHIA) [CDF Note 9114]
- Typical systematic uncertainties: 2–5%

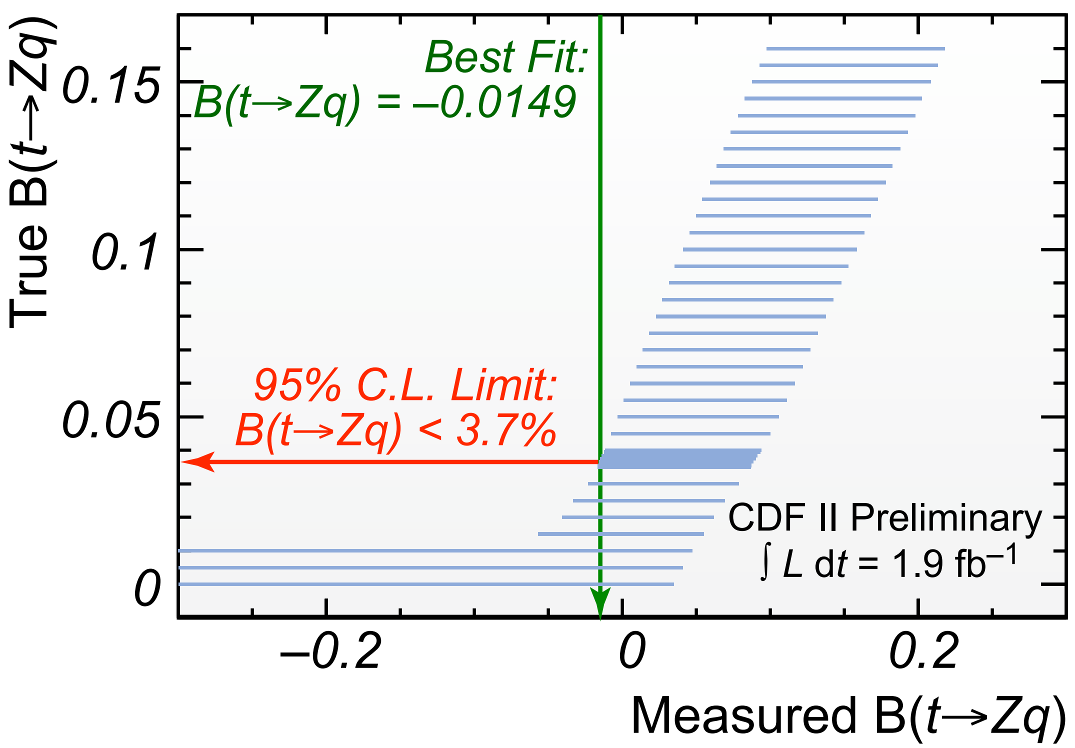


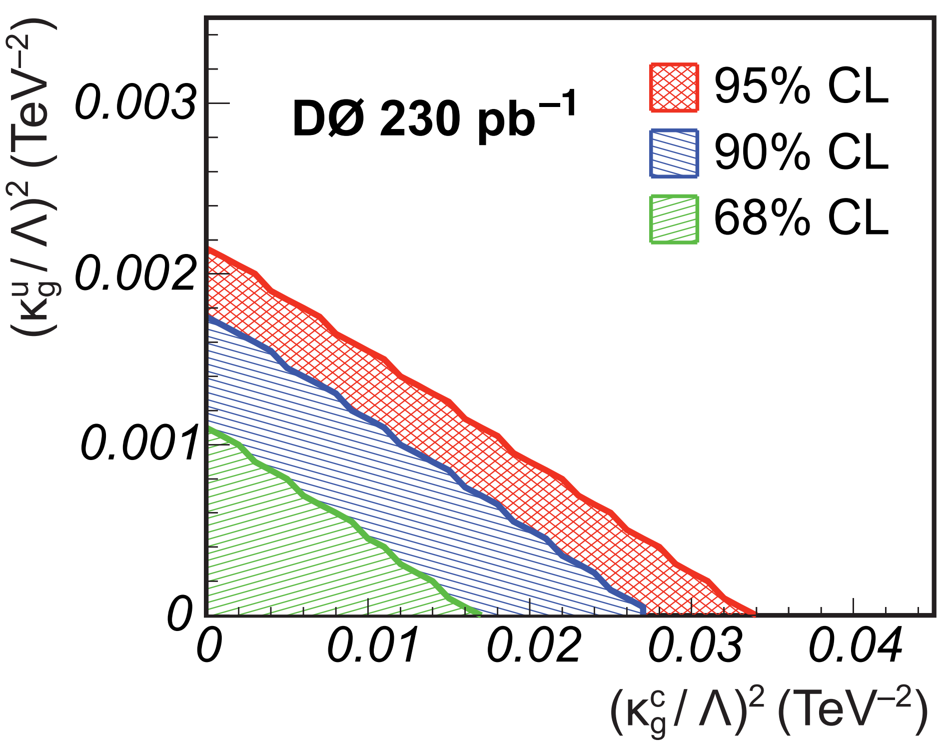
GGWIG (Guillian, Campbell, Amidei, CDF only):

Useful extension to HERWIG → tunable W helicities, gg vs $q\bar{q}$ fraction, etc.

BSM Top Couplings: FCNC

FCNC Feldman-Cousins Band (95% C.L.)





- Physics objective: limits on beyond standard model top couplings
- CDF t→Zq search
  [arxiv:0805.2109 [hep-ex], submitted to PRL]
  - tZq vertex unknown to PYTHIA → isotropic decay in cos θ*
  - Solution: reweight cos θ* from PYTHIA
  - Closer to experimental observables: measures branching fraction
- DØ q→tg search
  [PRL **99** (2007) 191802]
  - CompHEP MC to modify top couplings
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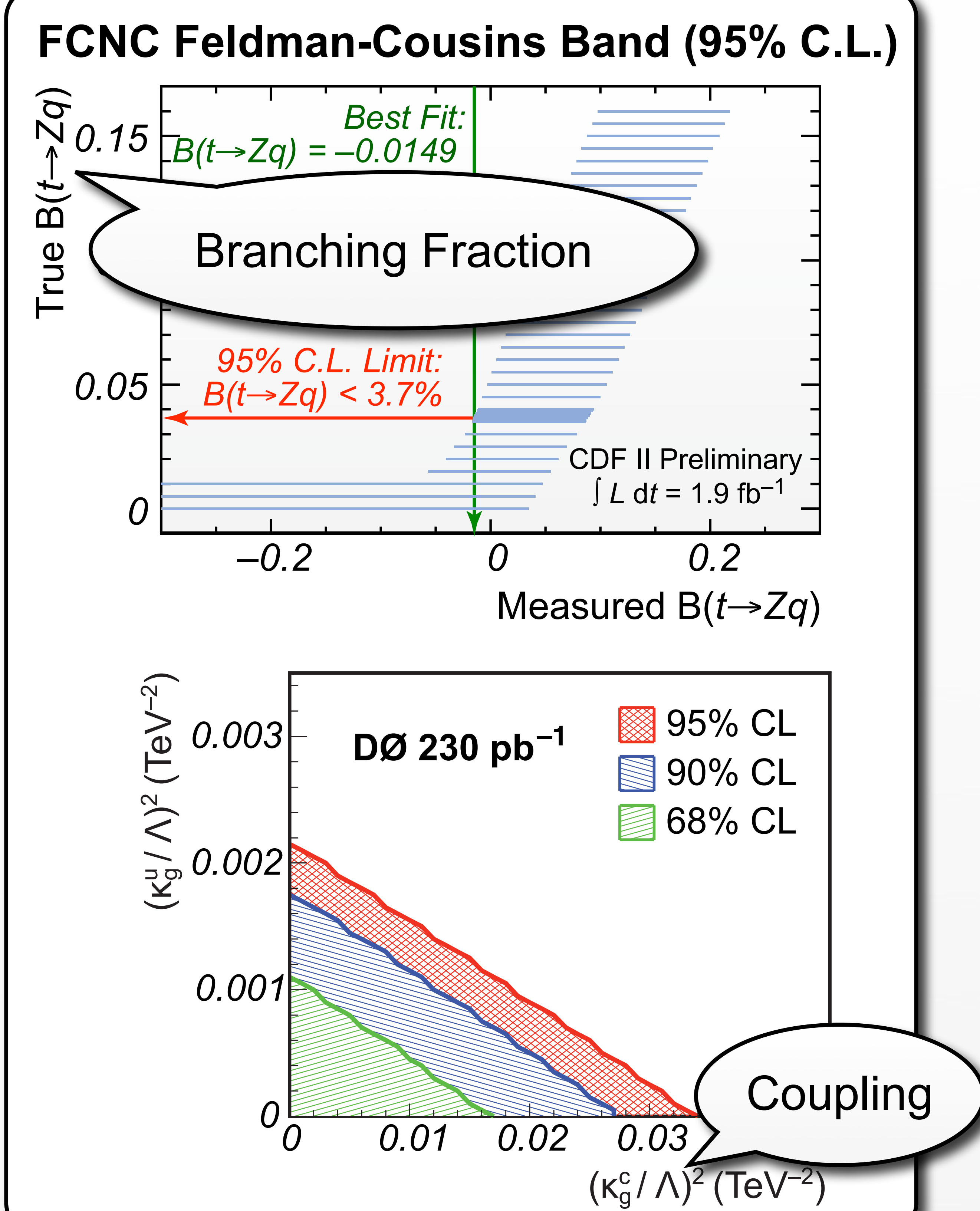

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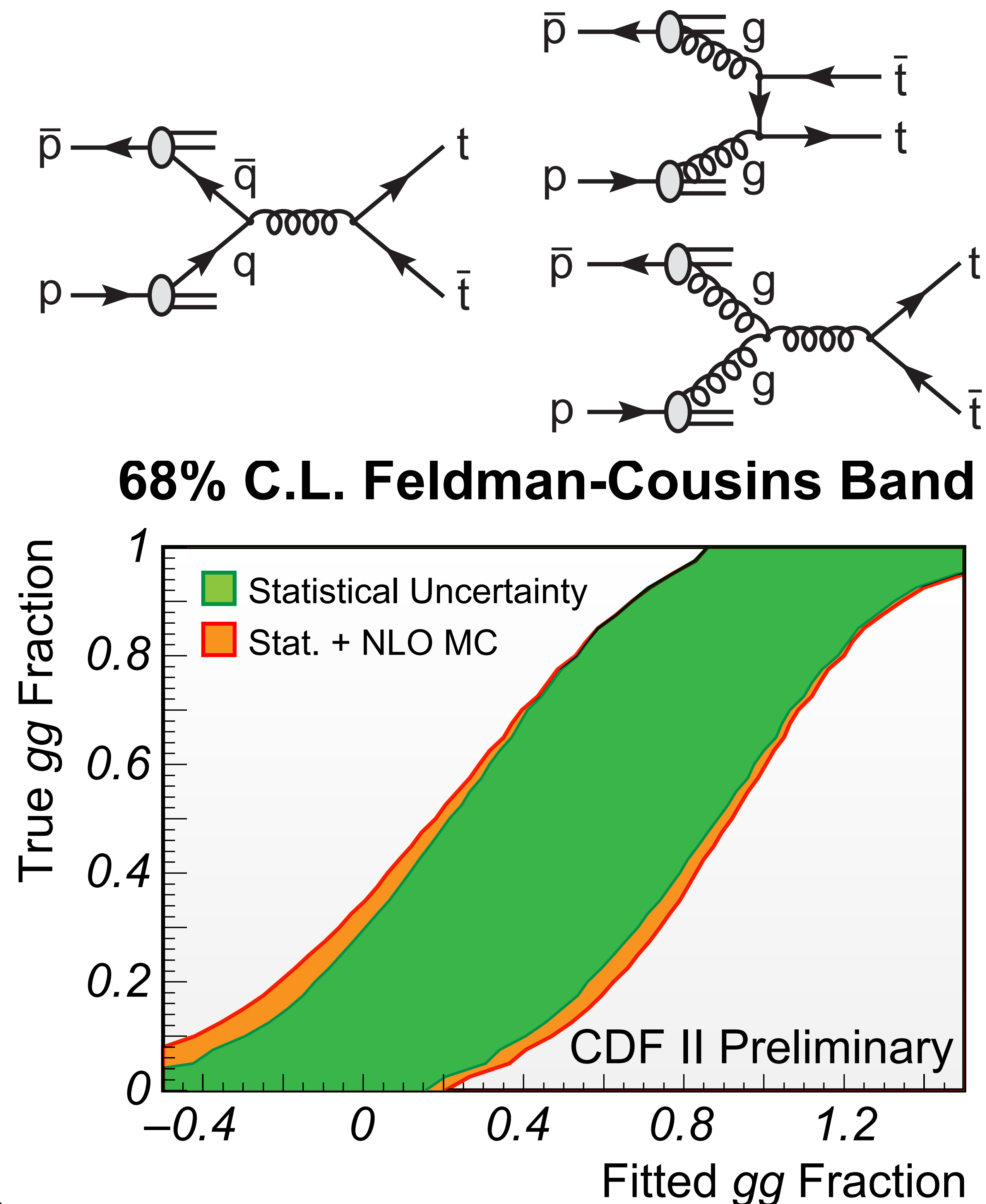
Top Quark Production: gg vs. qq

- $t\bar{t}$ production at the Tevatron: 85% $q\bar{q}$, 15% gg (NLO QCD)
- CDF's neural network analysis [CDF Note 8811]
  - Neural net trained on kinematics of $t\bar{t}$ production and decay
  - Sensitive to $t\bar{t}$ spin correlations → choose HERWIG-based MC
  - LO MC: only 5% gg → $t\bar{t}$ → use GGWIG to adjust to NLO
- MC generator systematics:
  - HERWIG vs. PYTHIA: small effect
  - HERWIG vs. MC@NLO: one of the largest uncertainties, approx. 20%



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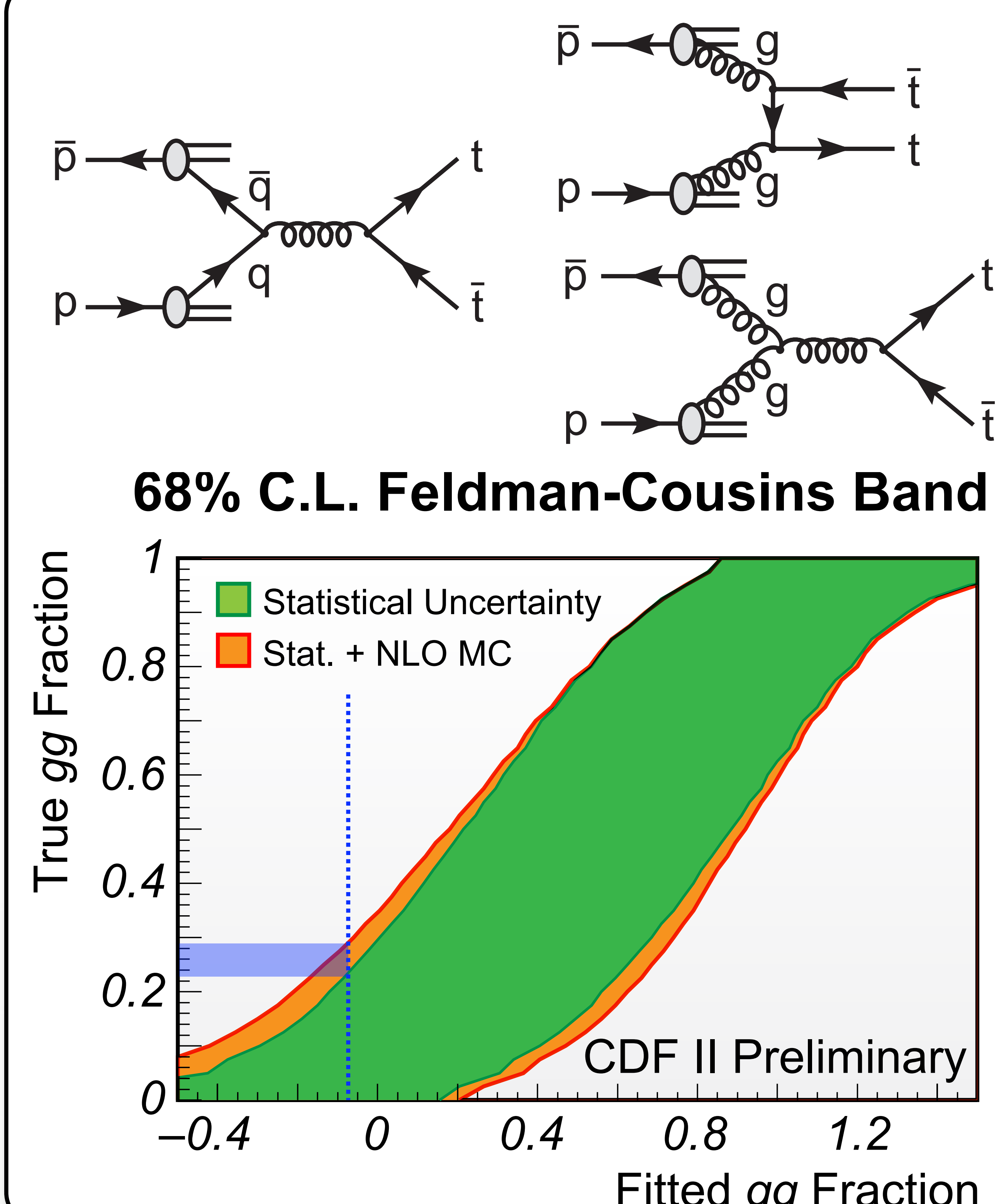
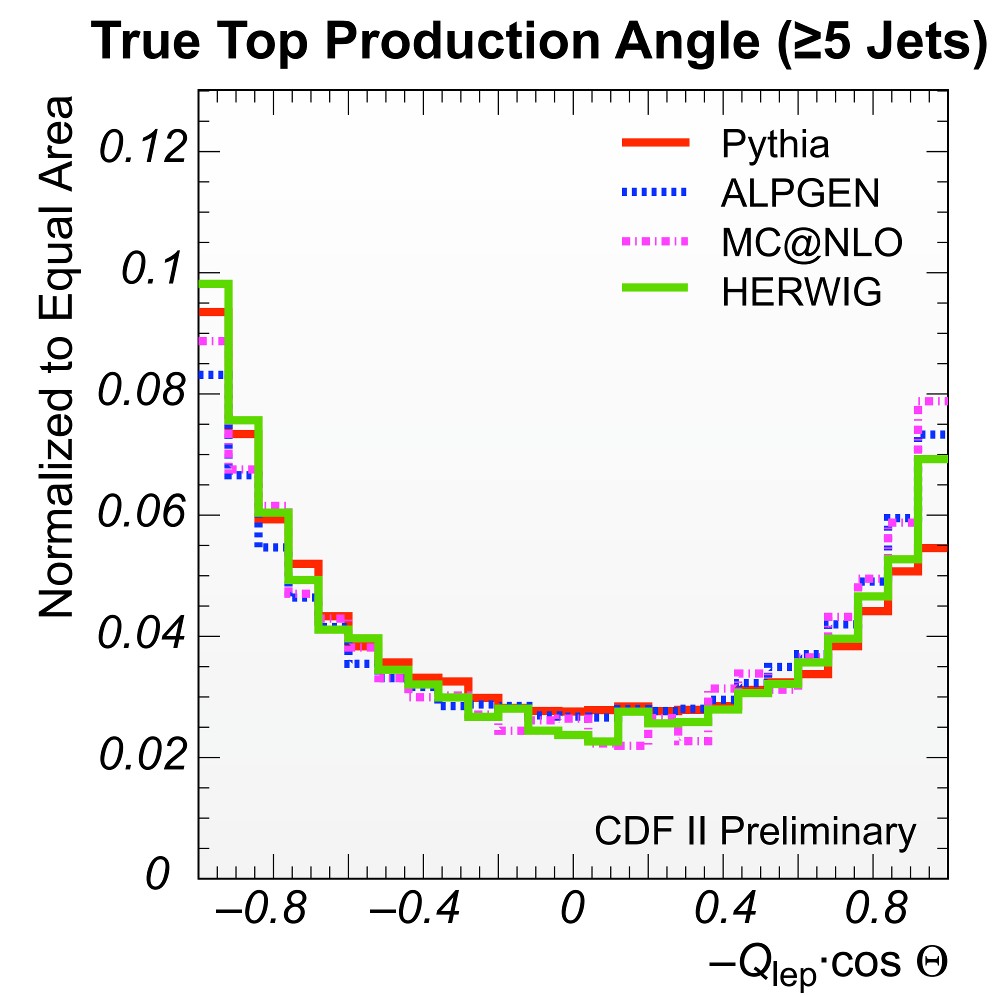
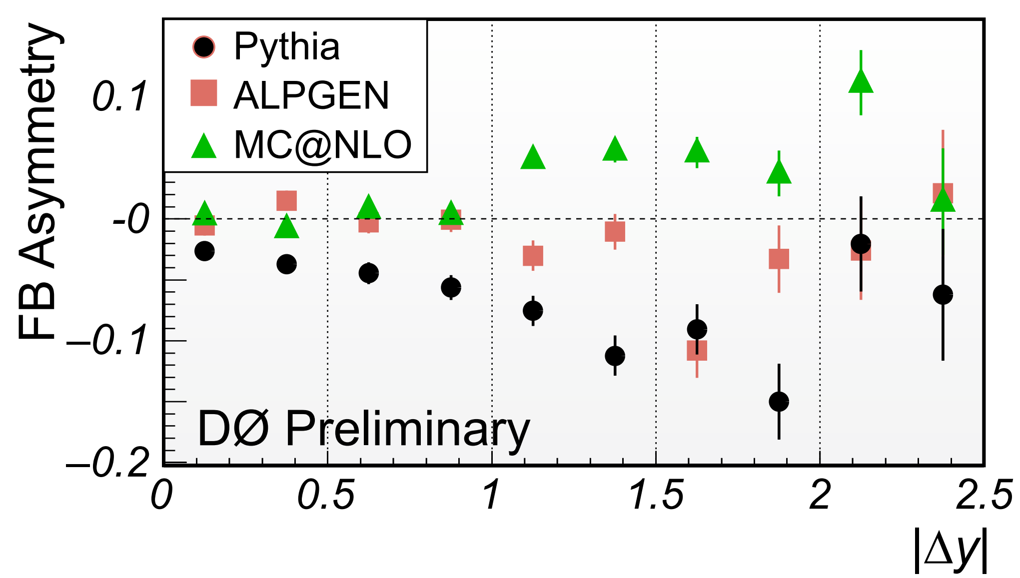


Forward Backward (Charge) Asymmetry

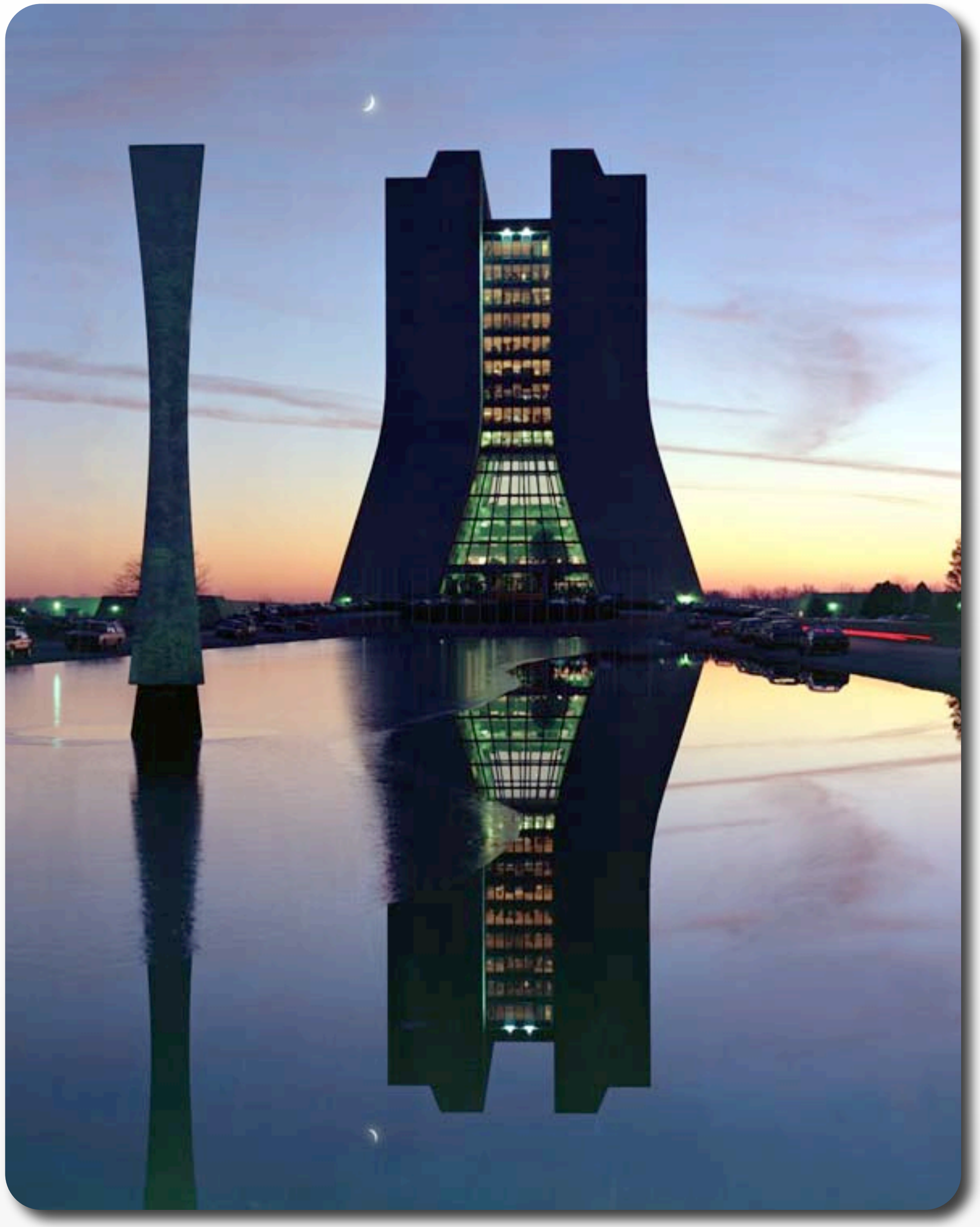
- Physics objective: FB (charge) asymmetry [DØ: PRL **100** (2008) 142002, CDF 9156, CDF 9169]
- Asymmetry genuine higher order effect
  - Kühn, Rodrigo: 4–5% [PRL **81** (1998) 49]
  - MC@NLO: 3.8%
- LO generator: net asymmetry zero, but parton shower generates asymmetry from color flow (esp. for additional jets)
  - Dittmaier et al.: –8% at LO reduced to –1.5% [PRL **98** (2007) 262002]
- Practical limitations for MC usage:
  - Observed asymmetry sensitive to selection criteria → simplify acceptance (DØ), rely on standard PYTHIA MC (CDF) for acceptance
  - CDF: MC@NLO used only for checks (HERWIG-based, only small samples)





Summary and Outlook

- Top MC signal generators at the Tevatron: no one size fits all
  - Default: LO generators for $t\bar{t}$ signal MC
  - Single top MC: important higher order contributions
  - Important part of systematic uncertainties, especially for top mass
  - Special analyses: special MC requirements, often not met by default generator
- Ongoing efforts
  - Validation of new MC generators
  - Rethinking of established ways to extract systematic uncertainties
  - Future: working on common CDF/DØ approach



Thanks a lot to the CDF and DØ top physics analysis groups for their help in preparing this presentation!

Generators for Tevatron Top Physics

Generator	Who?	What?
PYTHIA	CDF & DØ	everything
Herwig	CDF	everything, spin correlations, GGWIG
ALPGEN (+PYTHIA)	CDF & DØ	everything (DØ) multijet final states
Sherpa	DØ (& CDF)	W/Z + multijet final states
MadGraph/MadEvent	CDF & DØ	special channels, BSM couplings
CompHEP	DØ	special channels, BSM couplings
MC@NLO	CDF & DØ	cross checks for special channels