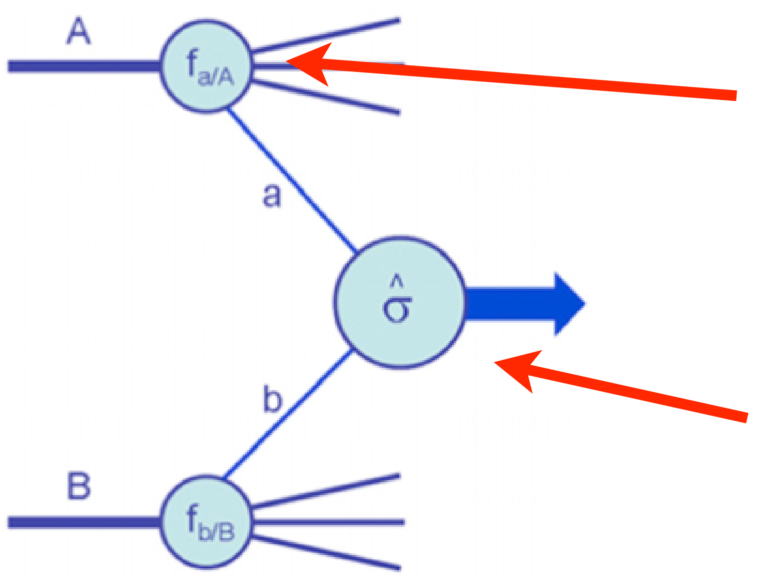
Perturbative QCD: Status

ICHEP 2012, Melbourne, July 10, 2012

John Campbell, Fermilab

Why perturbative QCD?

- Necessity for a hadron collider



determination of parton distribution functions

calculation of hard scattering matrix elements

Expansion in strong coupling α_s

- Reliable due to value of α_s at relevant scales:

$$\alpha_s(Q) \sim 0.1$$

$$\text{for } Q = m_W, m_Z, m_t, p_T(\text{jet})$$

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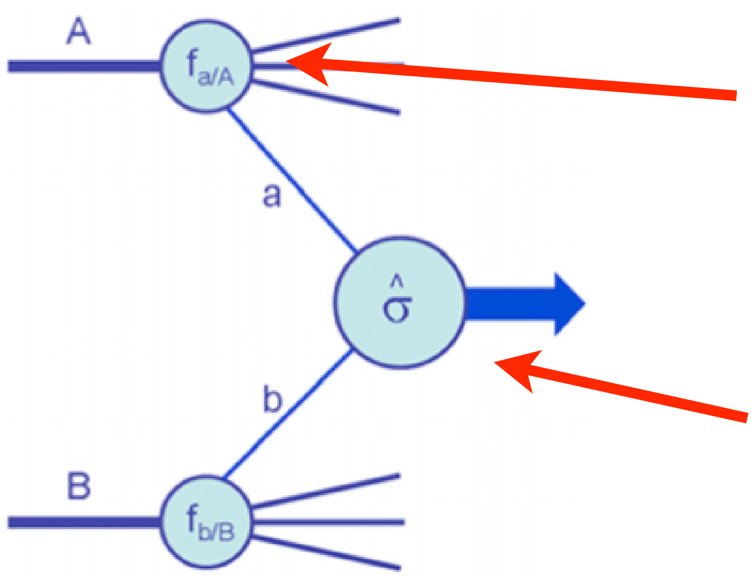

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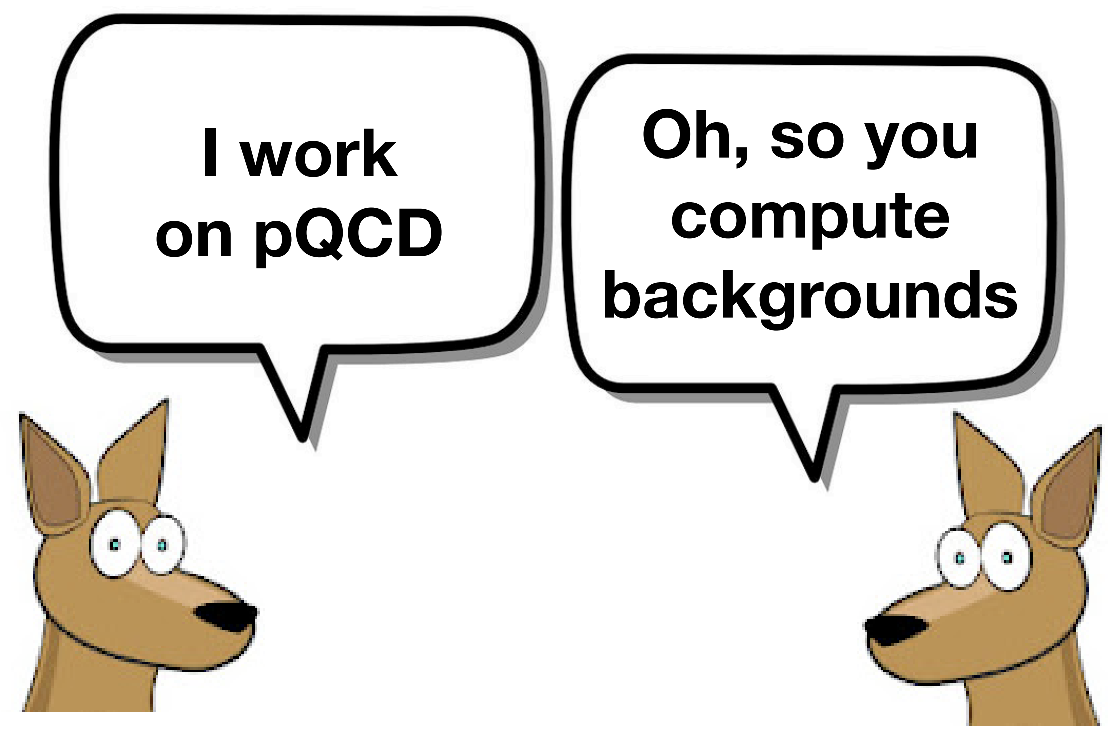
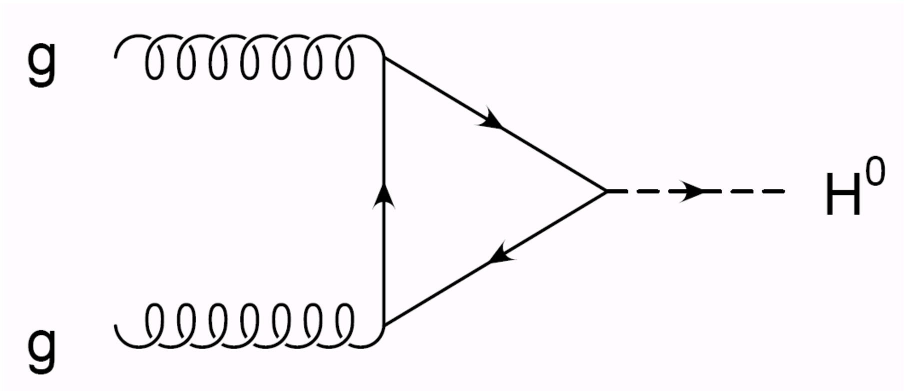


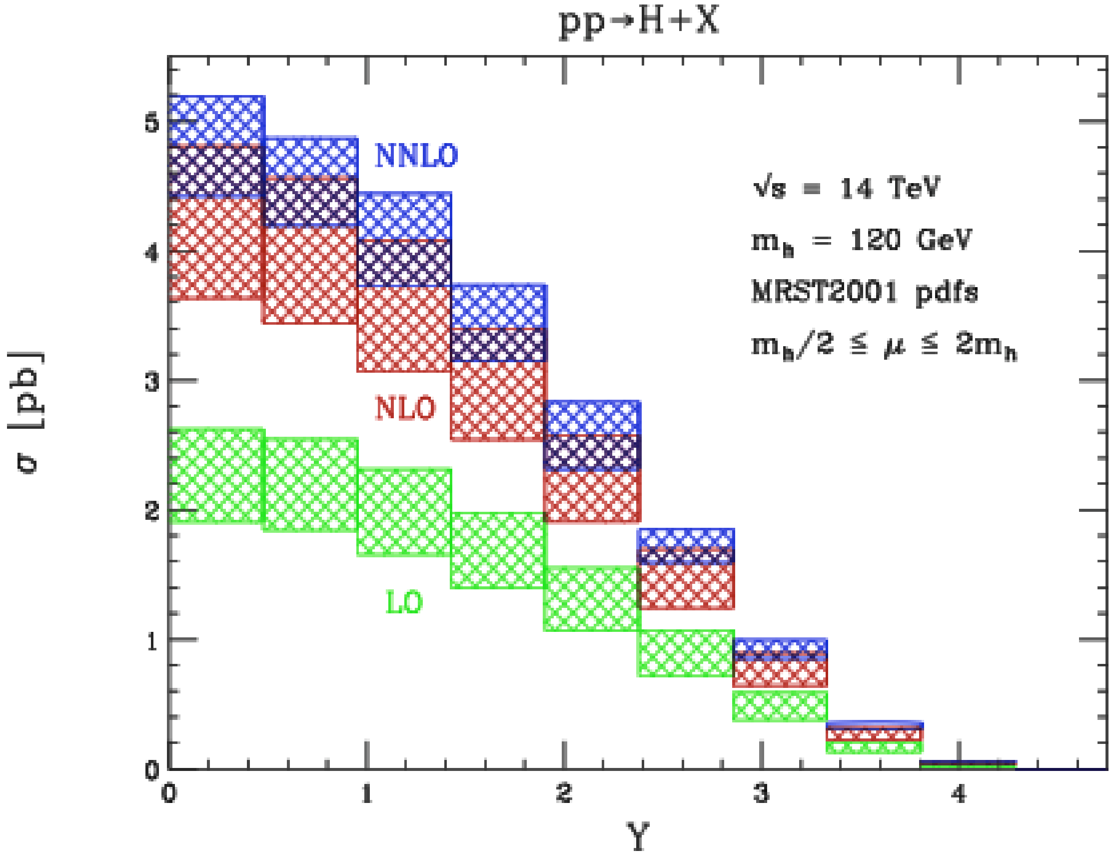
Higgs and QCD

- Despite EW role a QCD problem



Challenging perturbative expansion, NNLO required

Anastasiou, Melnikov, Petriello



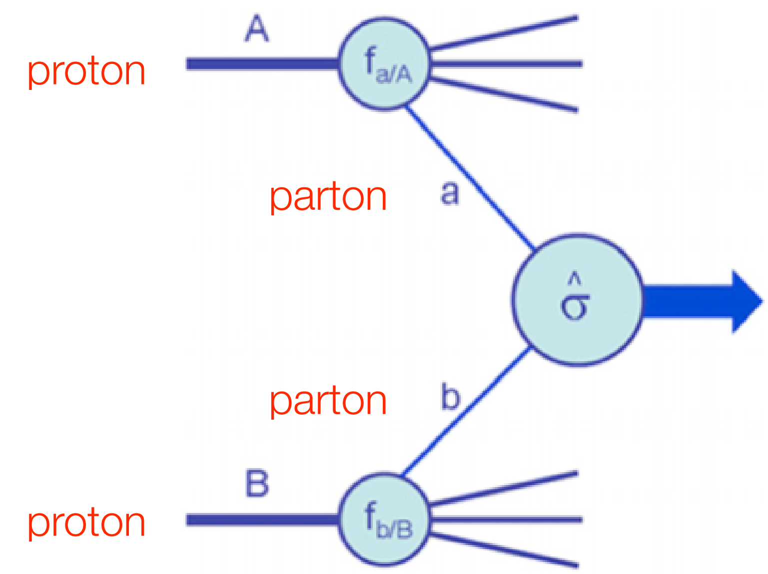
- Search strategies require good understanding of QCD issues
  - boosted jets and substructure
  - jet vetoes and resummation techniques

- Much study: "Handbook of LHC Higgs cross sections"

Dittmaier, Mariotti, Passarino, Tanaka

Pdfs and the strong coupling

Pdfs



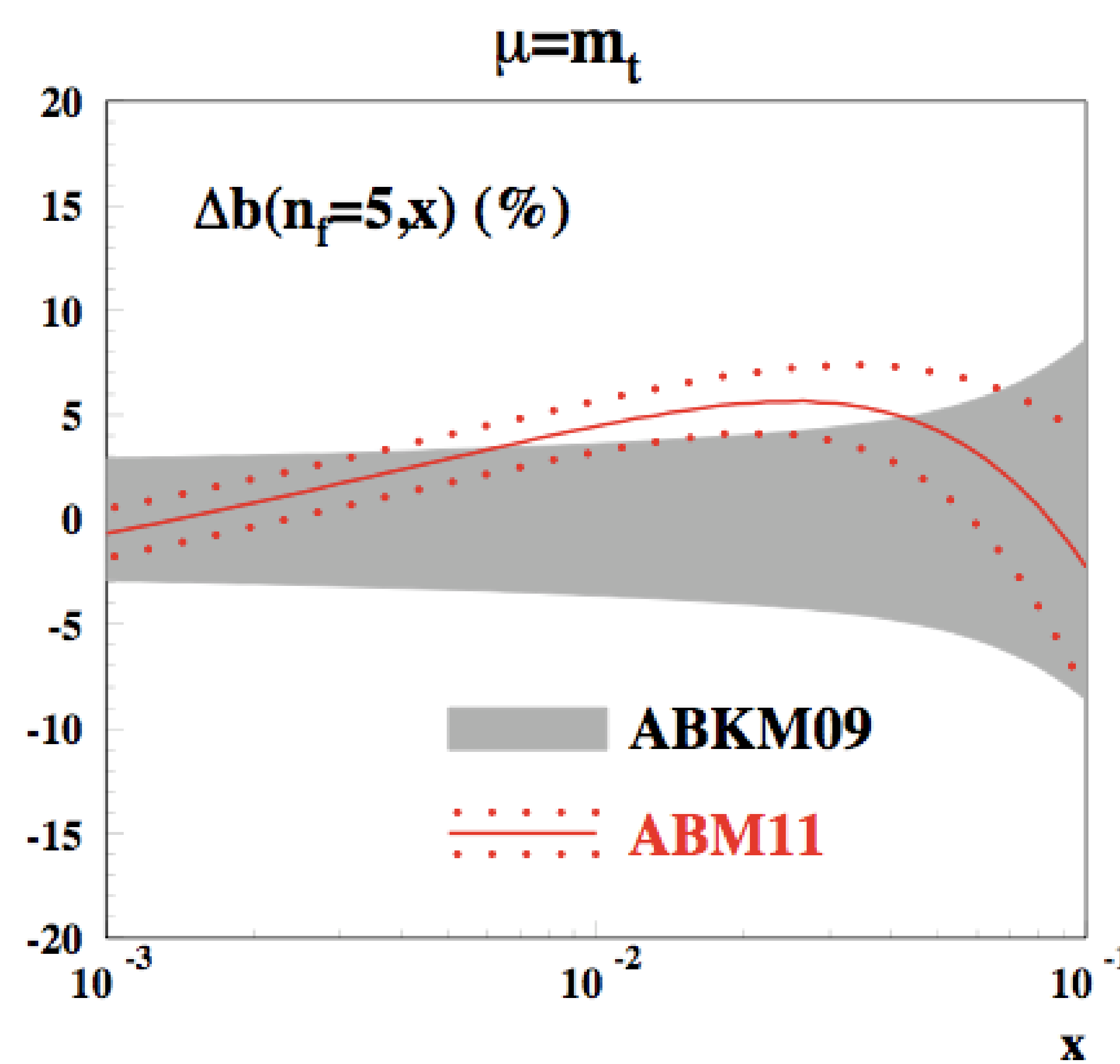
- ✦ Parton content of the proton:
  life-blood of hadron collider physics
- ✦ Studies in the last year include:
  - ✦ assessment of different treatments of heavy quarks in global pdf analyses
    Alekhin, Blumlein, Moch, Kovarik, Stavreva, Kusina, Jezo, Olness, Schienbein, Yu, Thorne
  - ✦ uncertainties at large *x* due to nuclear corrections
    Brady, Accardi, Melnitchouk, Owens
  - ✦ studies and refinements of established pdf fits
    Watt, Thorne, Guzzi, Nadolsky, Lai, Yuan
  - ✦ global pdf analyses
    Alekhin, Blumlein, Moch, Ball, Bertone, Cerutti, Del Debbio, Forte, Guffanti, Latorre, Lionetti, Rojo, Ubiali
  - ✦ new analysis of HERA data
    HERAPDF → R. Placakyte parallel

Parton distribution functions

- Systematic exploration of proton structure at NNLO
- New this year: ABM11 Alekhin, Blumlein, Moch
  - fit to DIS and fixed-target Drell-Yan data
  - improved treatment of heavy quarks in DIS, running $\overline{\text{MS}}$ mass
    Alekhin, Moch

b-quark pdf uncertainty

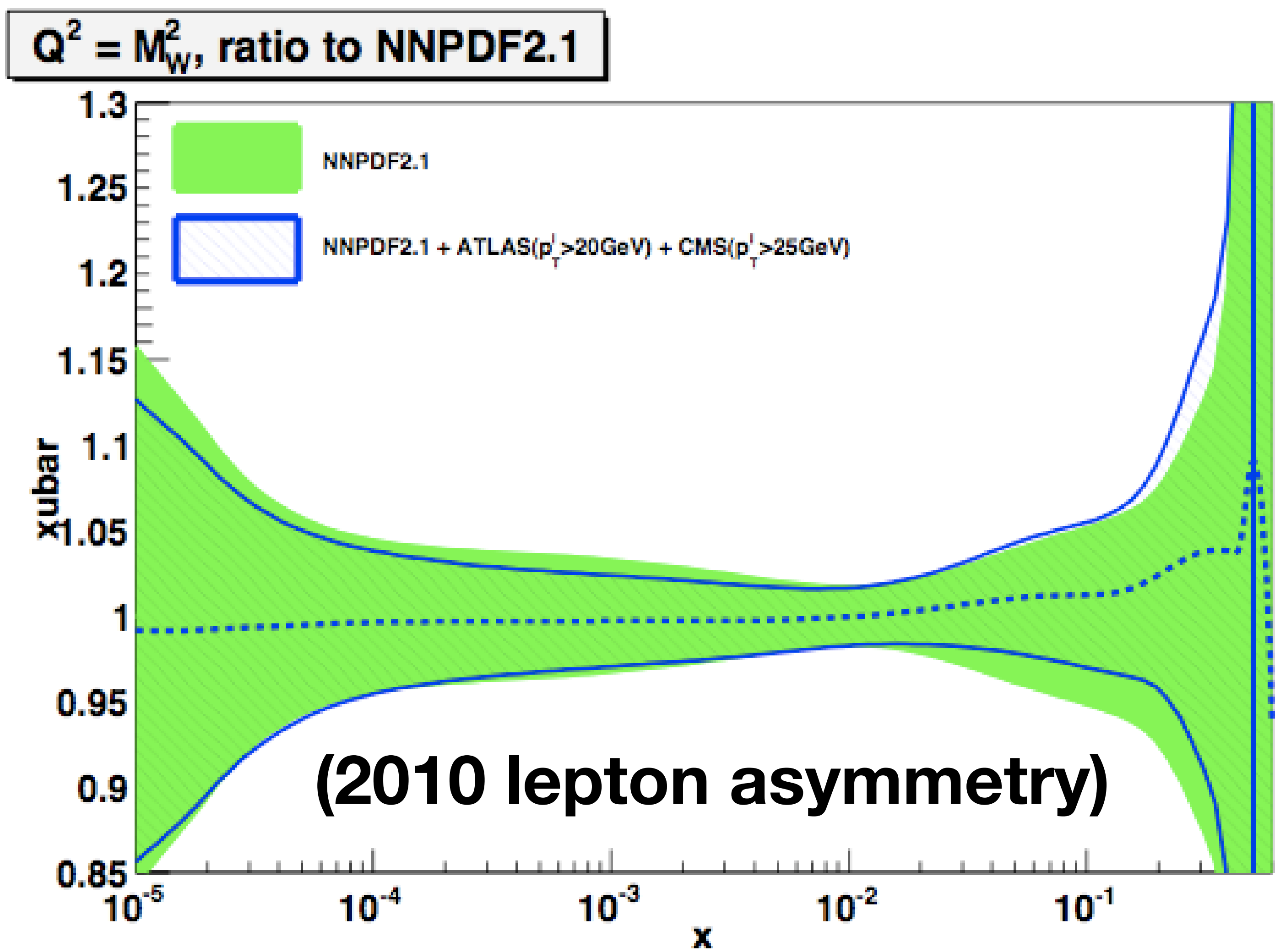
- much-reduced in ABM11
- impact on many LHC cross sections, e.g. single top, charged Higgs



NNPDF

Ball et al

- Neural net PDF, avoid usual parametrization at input scale
  - fit includes Tevatron Drell-Yan and inclusive jet data
  - NNPDF2.1: update to NNLO



Impact of LHC: NNPDF2.2

- Also: top cross section impact on gluon pdf

  Beneke et al

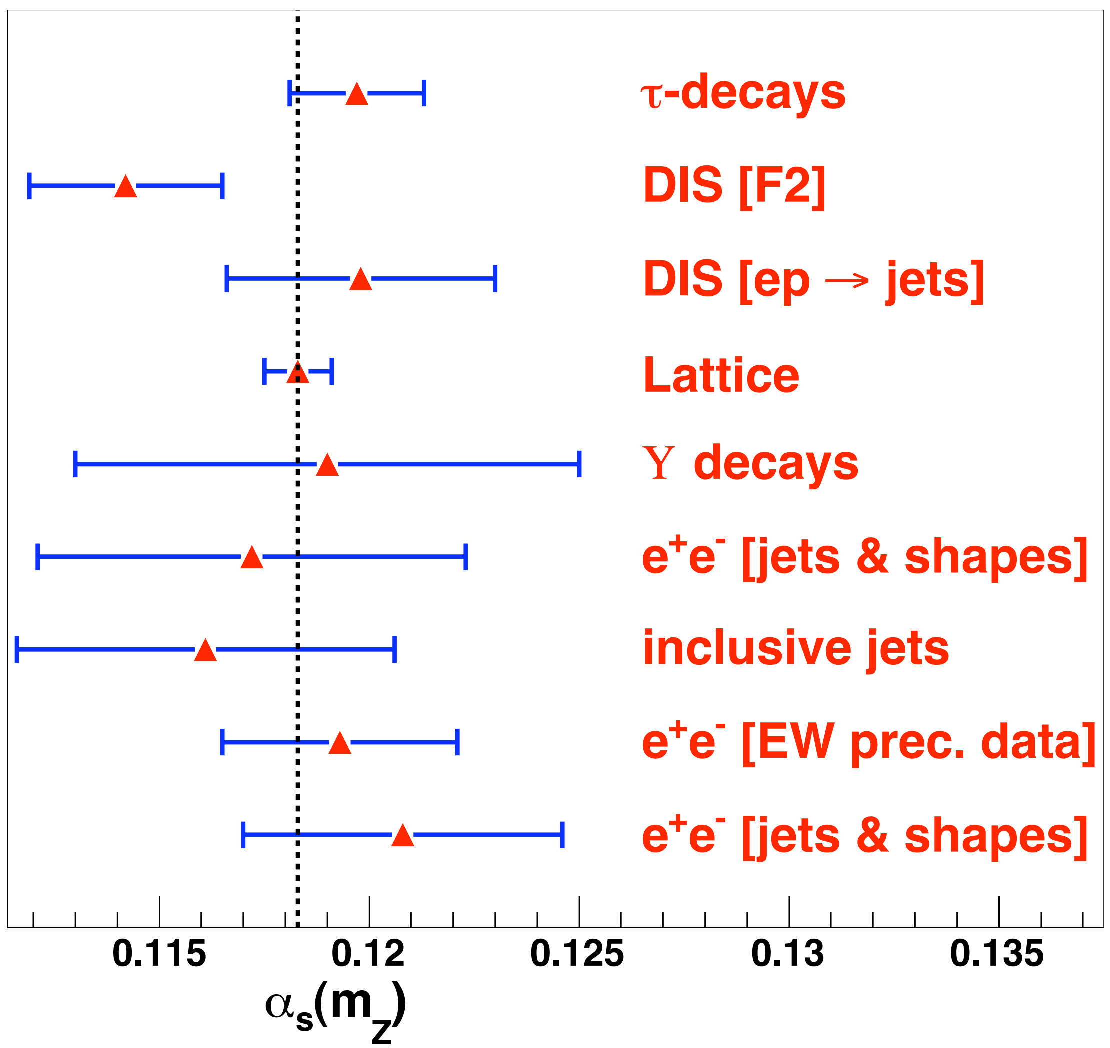
- Very recent: NNPDF2.3, full fit incl. LHC data

Strong coupling

- Preliminary world average 2011:

$$\alpha_s(m_Z) = 0.1183 \pm 0.0010$$

S. Bethke, summary of αs workshop



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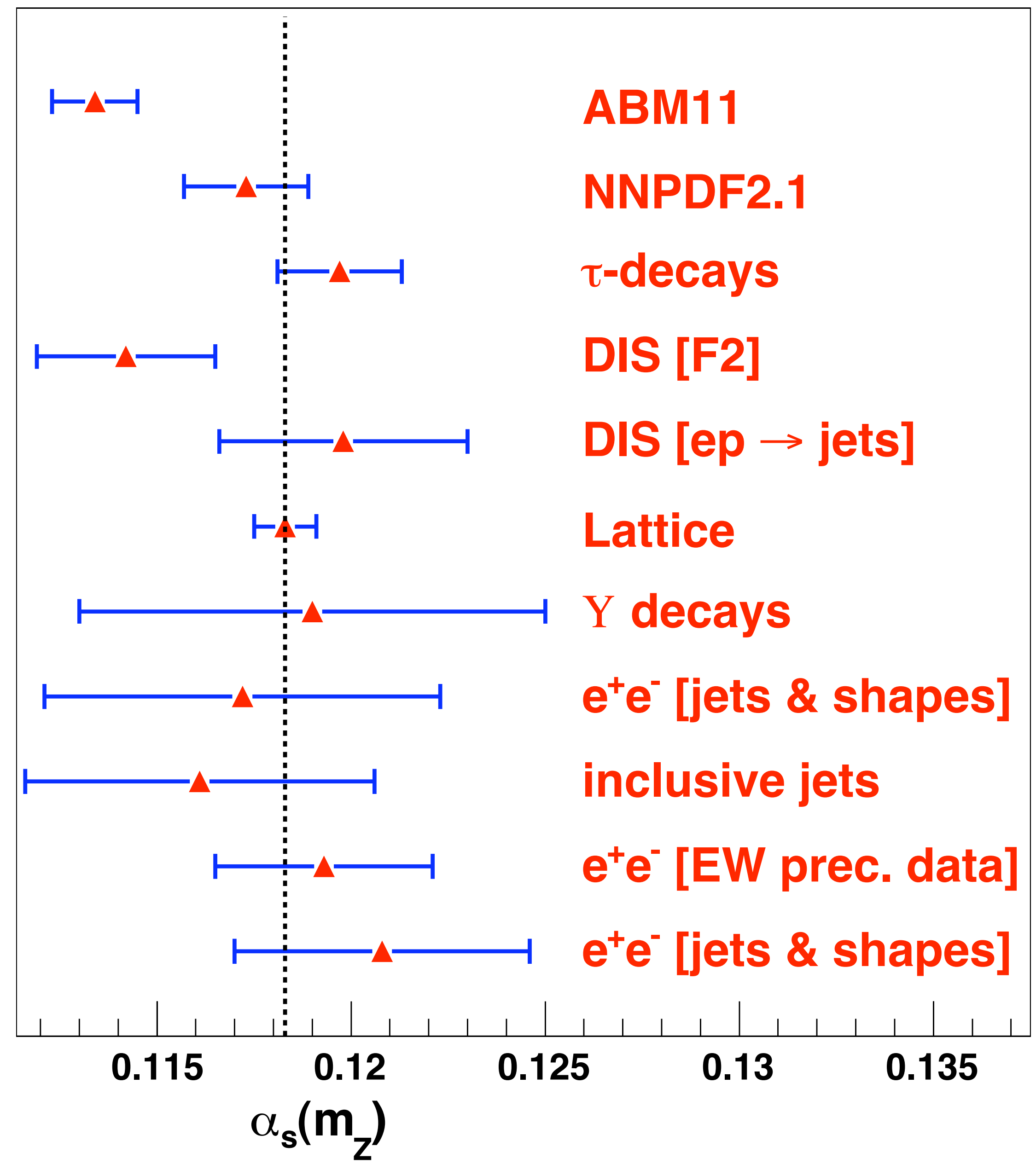
- Simultaneous extraction of strong coupling from NNLO pdf fits:

$$\mathrm{ABM11} : \alpha_s(m_Z) = 0.1134 \pm 0.0011$$

$$\mathrm{NNPDF} : \alpha_s(m_Z) = 0.1173 \pm 0.0016$$

- Continued shrinking of errors but tension in central values



Precision calculations

Progress on two fronts

✦ Improving predictions for less-understood observables

✦ Refining “well-known” calculations, e.g. NLO QCD

✦ Both driven by experimental needs and uncertainties

Higgs-related advances

signals

NLO	**H+γ+2 jets** via VBF	Arnold et al
NLO+PS	**gg→H+1,2 jets**	Ellis et al
	ttH	Garzelli et al
	$H^{\pm}$ t	Klasen et al
	MSSM gg→H	Bagnaschi et al
NNLO	**WH**	Ferrera et al
	H→bb differential rate	Anastasiou et al
	bb→H	Harlander et al, Buehler et al
	non-minimal H via VBF	Bolzoni et al
	non-minimal gg→H	Furlan

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backgrounds

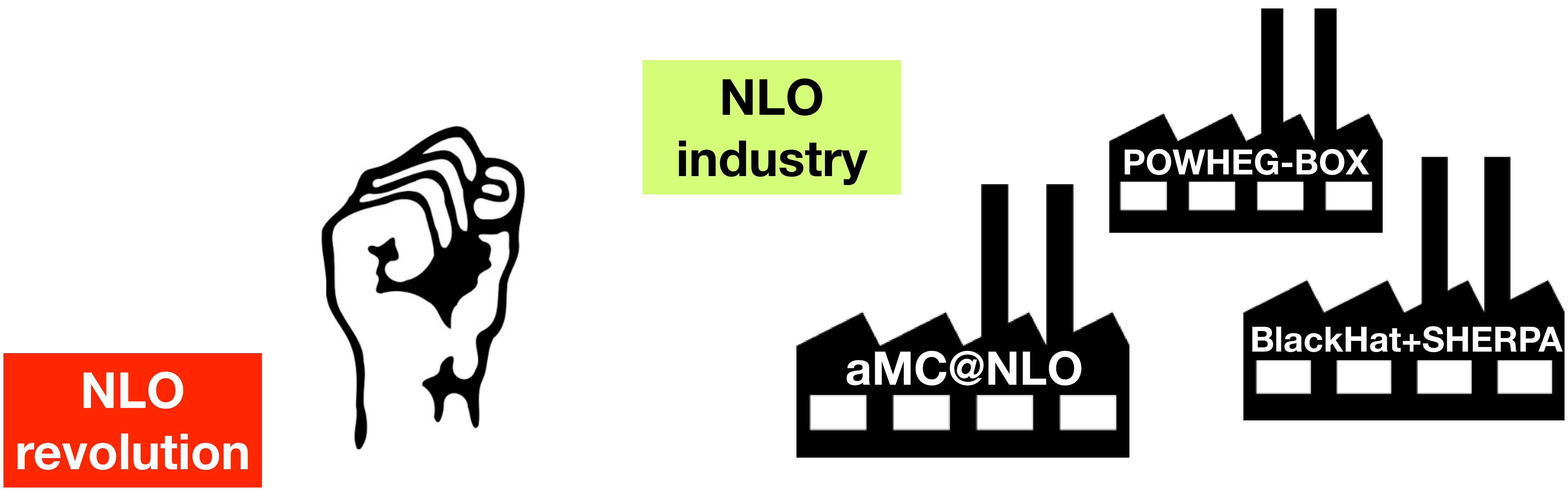
NLO	**WW+jet** including gg	Melia et al
NLO	**tt+2 jets**	Bevilacqua et al
NLO+PS	**ZZ**	Frederix et al
NLO+PS	**WW,WZ,ZZ**	Melia et al
NLO+PS	**Wbb,Zbb**	Frederix et al
NLO+PS	**Z+2 jets**	Re, Hamilton et al
NLO+PS	**tt+jet**	Alioli, Moch, Uwer
NNLO	**γγ**	Catani et al

Other NP backgrounds

	Process	Authors	Signature
NLO	**$W\gamma\gamma$**	Campanario et al	**test of EWSB/anom. couplings**
NLO	**$Z\gamma\gamma$, $\gamma\gamma\gamma$**	Bozzi et al	**missing E_T+photons (GMSB)**
NLO	**ttW**	Ellis, JC	**same-sign dileptons, trileptons**
NLO	**4 jets**	Ita et al	**high mass final states**
NLO	**Z+4 jets**	Ita et al	**missing E_T+jets**
NLO+PS	**Z+2 jets**	Re, Hamilton et al	**missing E_T+jets**
NLO+PS	**W+2 jets**	Frederix et al	**lepton, missing E_T+dijets**
NLO+PS	**W+1,2,3 jets**	Hoche et al	**lepton, missing E_T+jets**
NLO+PS	**W^+W^+ + 2 jets** QCD/EW	Jager, Zanderighi	**same-sign dileptons**
NLO+PS	**ttZ**	Garzelli et al	**multileptons**

The Industrial Age of NLO

- In recent years, much reference to “NLO revolution”
  - development of new wave of tools in anticipation of LHC
  - especially numerical techniques: straightforward generation of new results for complicated final states
- 2011-12: time for putting these revolutionary ideas to work



Blackhat+SHERPA

Bern, Diana, Dixon, Febres Cordero, Höche, Ita, Kosower, Maître, Ozeren

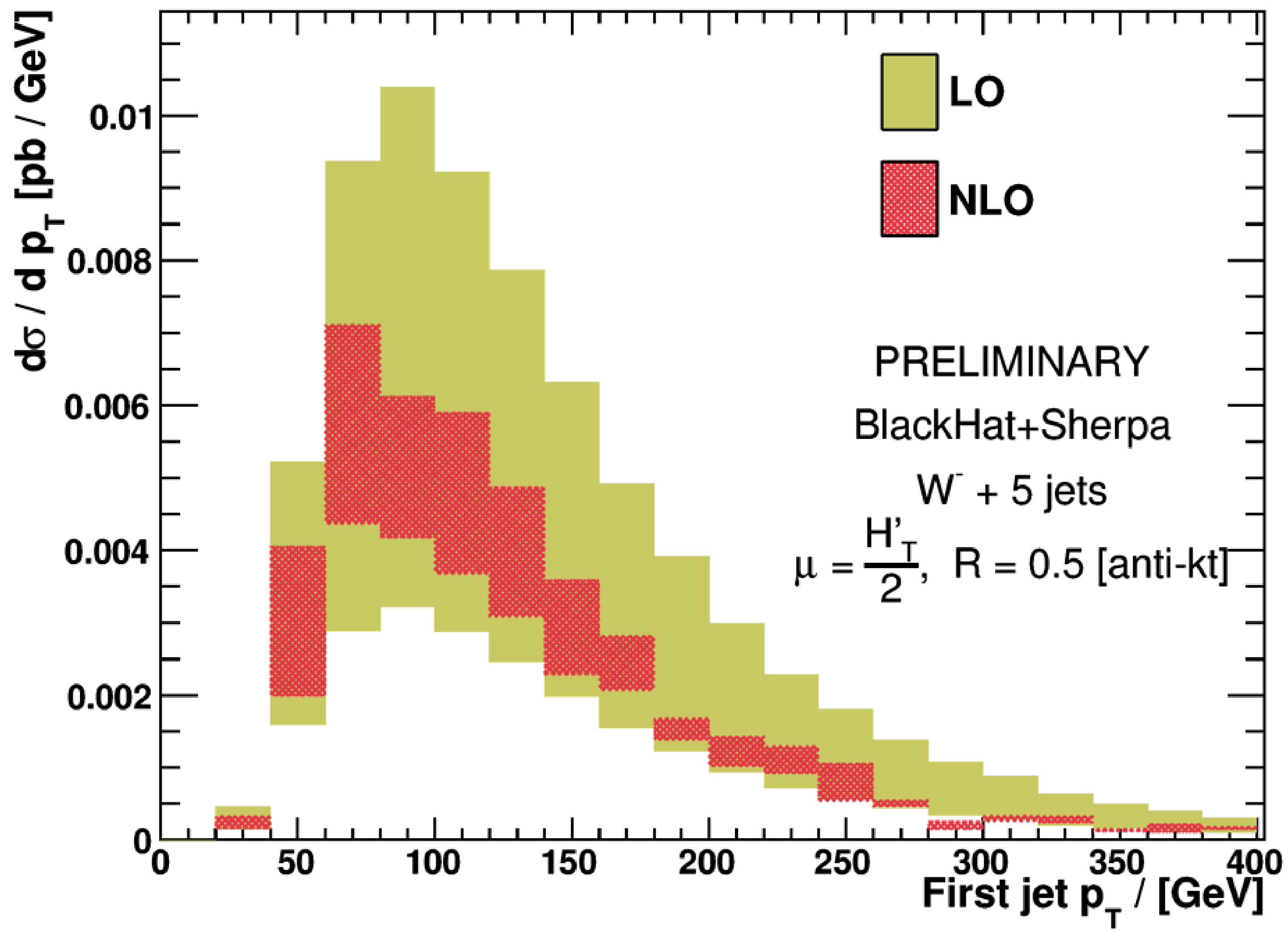
- The frontier of NLO complexity

  → L. Dixon, D. Kosower parallel

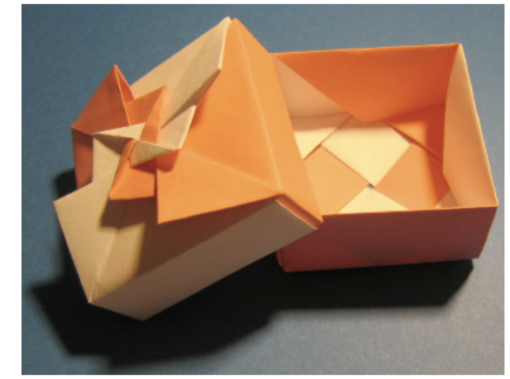
- on-shell methods for loops, BlackHat
- real emission, SHERPA
- in the last year:
  - four-jet production
  - Z+4 jets

New @ ICHEP:
W+5 jets

→ D. Kosower parallel



POWHEG-BOX

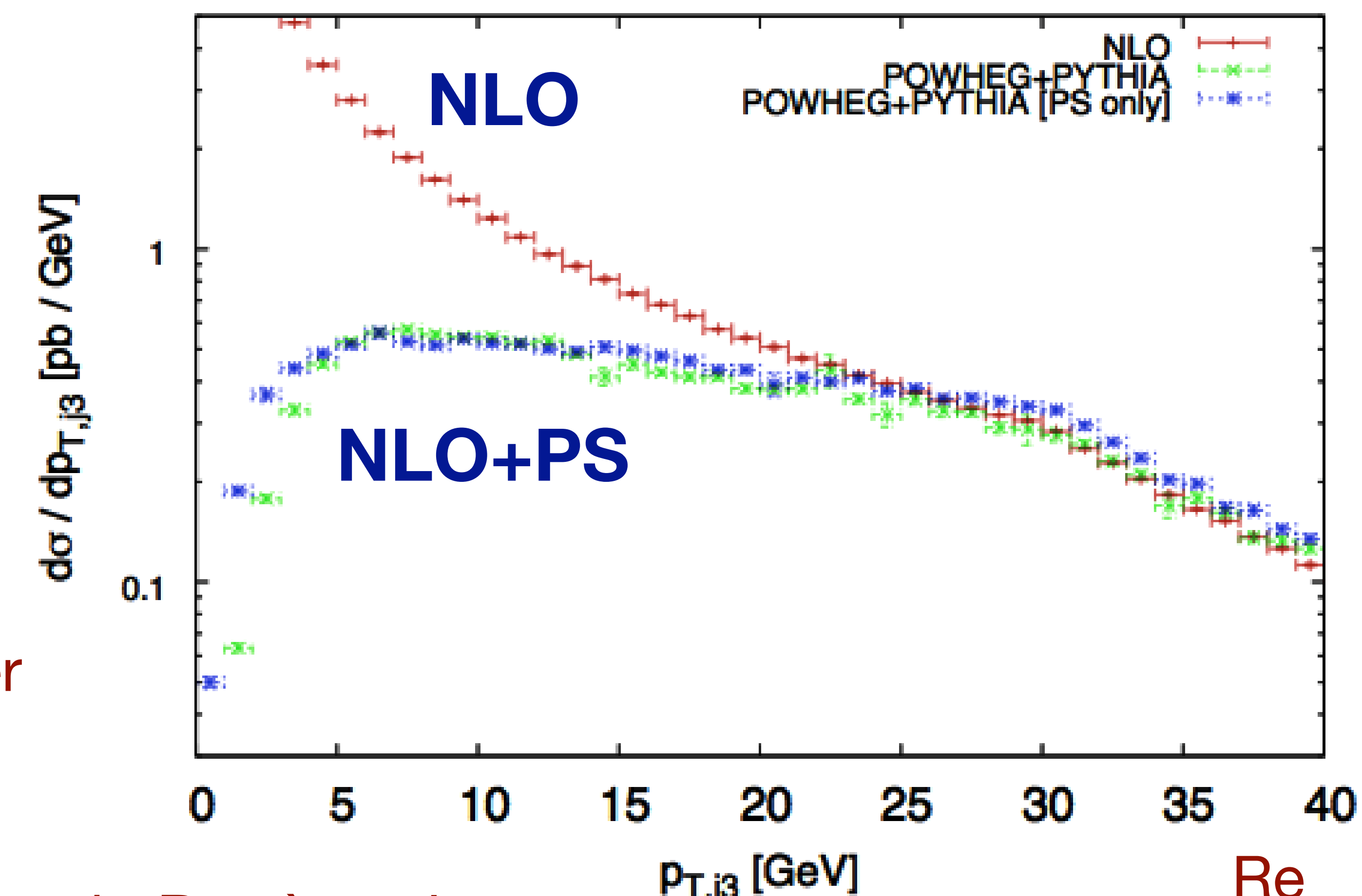


Alioli, Nason, Oleari, Re, Frixione

- Package for theorists to merge any NLO calculation with parton shower
- Banner year for new predictions

H± t	Klasen et al
gg→H+1,2 jets	Ellis et al
MSSM gg→H	Bagnaschi et al
ttH	Garzelli et al
ttZ	Garzelli et al
WW,WZ,ZZ	Melia et al
tt+jet	Alioli, Moch, Uwer
Z+2 jets	Re
W QCD/EW	Bernaciak, Wackeroth; Barzè et al
W^+W^++2 jets QCD/EW	Jager, Zanderighi

3rd jet p_T in Z+2 jets



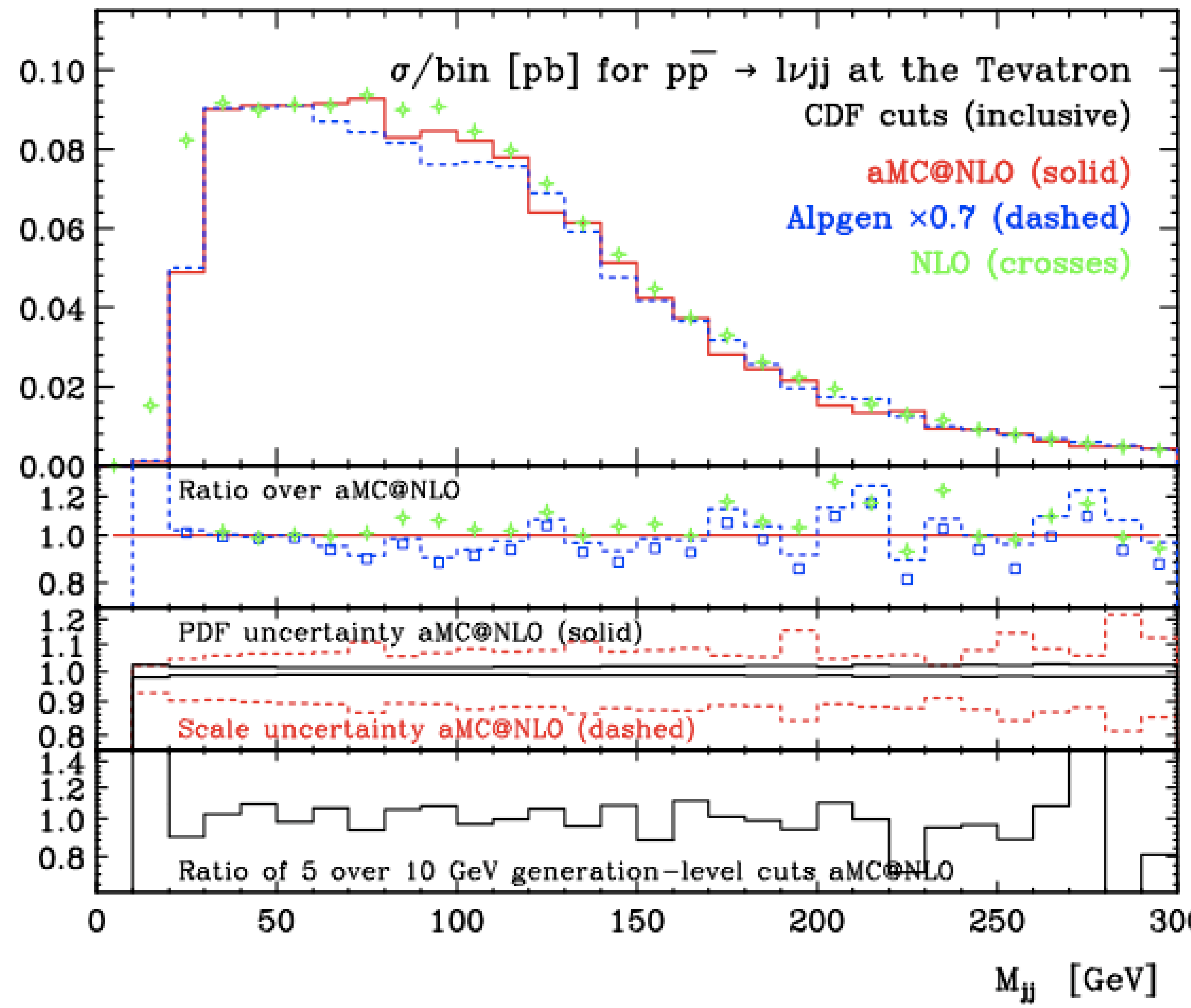
Re

aMC@NLO

Alwall, Artoisenet, Frederix, Frixione, Fuks, Hirschi, Maltoni, Mattelaer, Pittau, Serret, Stelzer, Torrielli, Zaro

- Generation of NLO+PS predictions in an automated fashion
- 2011-12: first full phenomenology in this approach

W+2 jets study:
PS vs NLO vs NLO+PS



- Also this year:
  - 4-lepton production
  - Wbb and Zbb

SHERPA

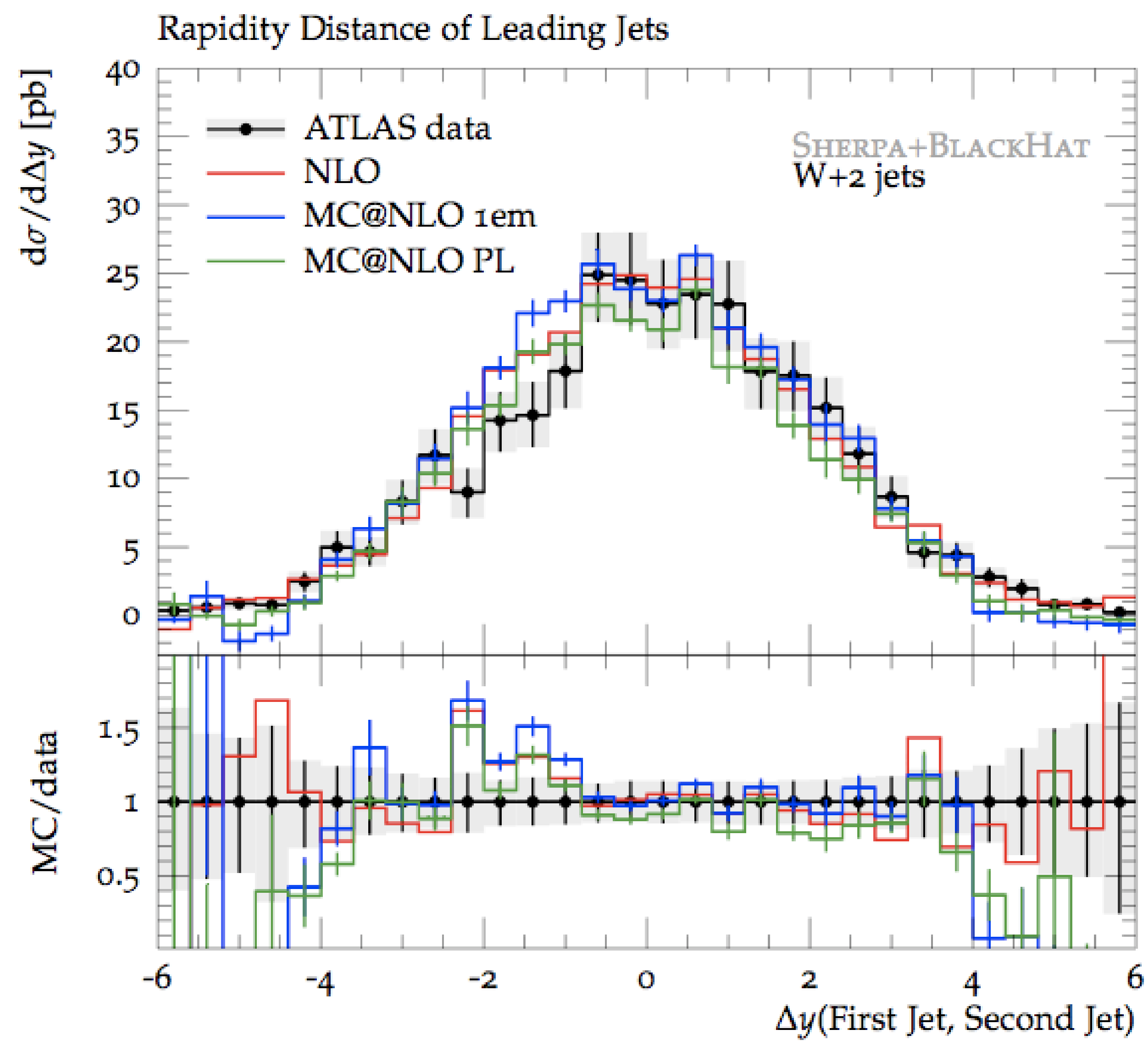
- ✦ Implementation of MC@NLO procedure in SHERPA

- ✦ Application to W+1,2,3 jets using BlackHat MEs

  Höche, Krauss, Schönherr, Siegert

- ✦ Smooth interpolation between POWHEG and MC@NLO type procedures

  → M. Schönherr parallel

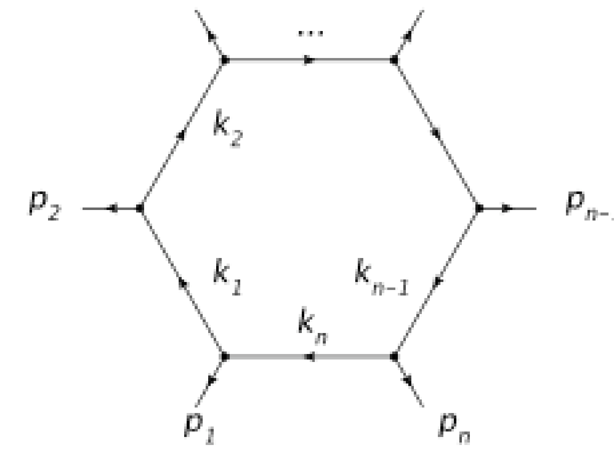


Parton level NLO

- No parton shower - yet.
- Automated 1-loop approaches
  - HELAC-NLO: tt+2 jets, tttt — Bevilacqua, Czakon, Papadopoulos, Worek
  - GoSam: WW+2 jets — Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano
- Other calculations:
  - VBFNLO: Hγ by VBF, Zγγ, γγγ, Wγγ+jet — Arnold, Bozzi, Campanario, Englert, Figy, Jager, Rauch, Zeppenfeld
  - MCFM: ttW, WW by gg box — Ellis, Williams, JC
  - MCFM+: WW+jet including gg box — Melia, Melnikov, Rontsch, Schulze, Zanderighi
  - tt+jet: radiation in top decay — Melnikov, Scharf, Schulze

An orthogonal approach

Becker, Goetz, Reuschle, Schwan, Weinzierl; Freitas



- Perform loop integral numerically

$$A^{(1)}_{\text{bare}} = \int \frac{d^D k}{(2\pi)^D} G^{(1)}_{\text{bare}}, \qquad G^{(1)}_{\text{bare}} = P_a(k) \prod_{j=1}^{n} \frac{1}{k_j^2 - m_j^2 + i\delta}$$

  - local subtractions for infrared and ultraviolet singularities
  - contour deformation to avoid on-shell loop propagators

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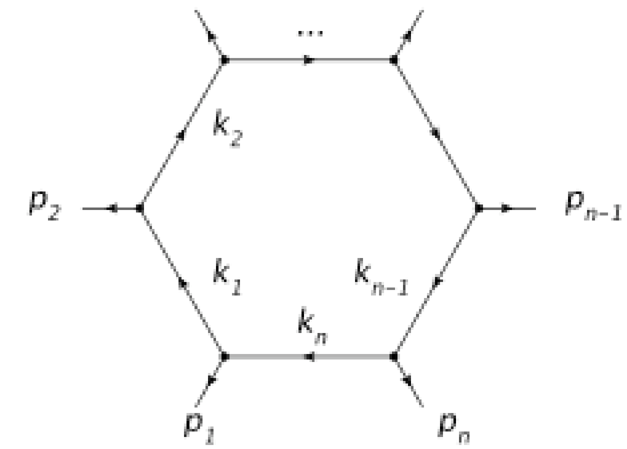

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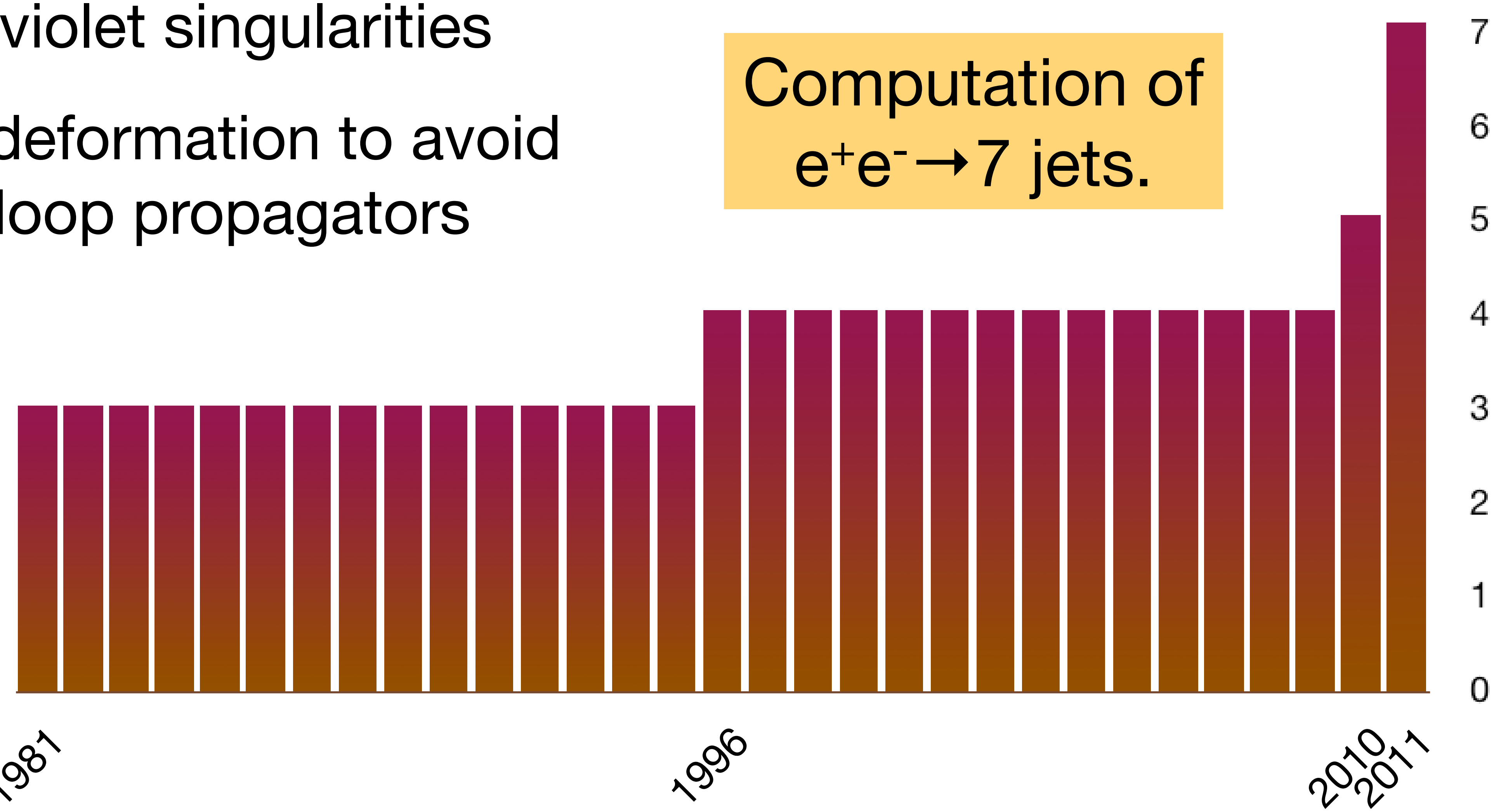
$e^+e^- \rightarrow n$ jets.



Parton showers

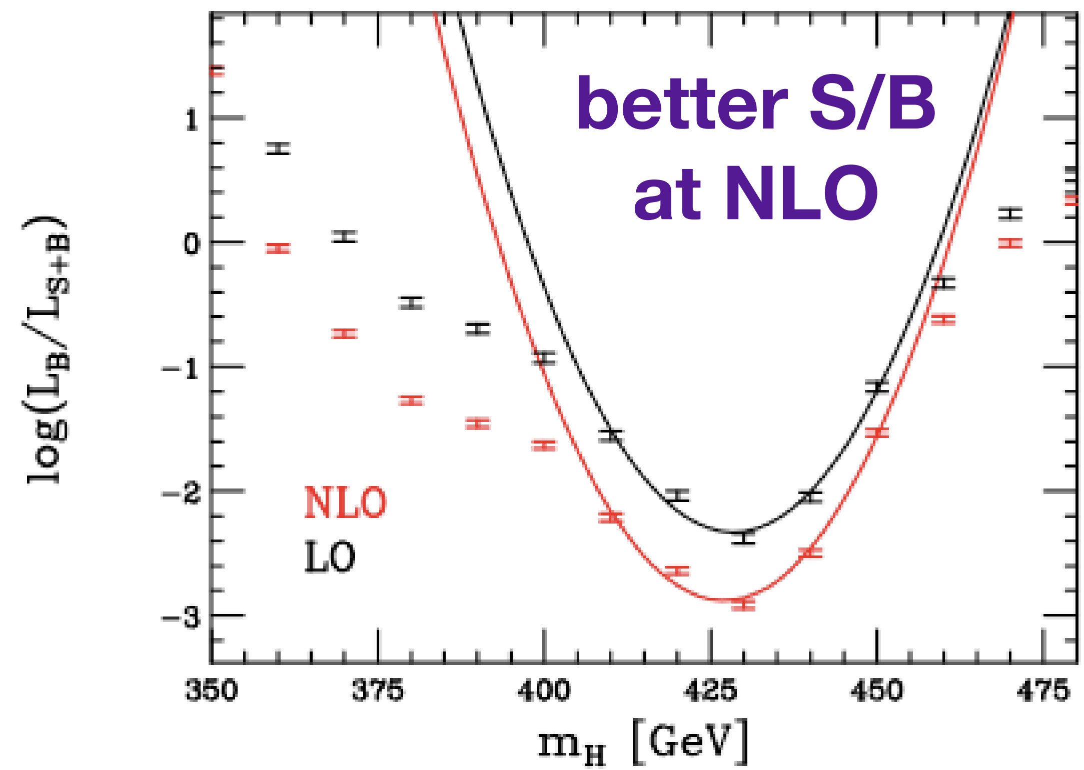
- Most of the focus on merging NLO and PS
  - HERWIG++ — d'Errico, Richardson, Platzer, Gieseke
- Other work this year:
  - improving consistency of MLM matrix element matching
    Cooper, Katzy, Mangano, Messina, Mijovic, Skands
  - VINCIA: more efficient matching and massive fermions
    Lopez-Villarejo, Skands, Gehrmann-de Ridder, Ritzmann
  - HERWIG++: MPI, color reconnection studies
    Gieseke, Rohr, Siodmok
  - PYTHIA8: implementation of CKKW-L merging scheme for NLO calculations
    Lönnblad, Prestel
    → L. Lönnblad parallel

New directions for NLO

Extension of matrix-element method to NLO accuracy

Giele, Williams, JC

- most efficient extraction of model parameters



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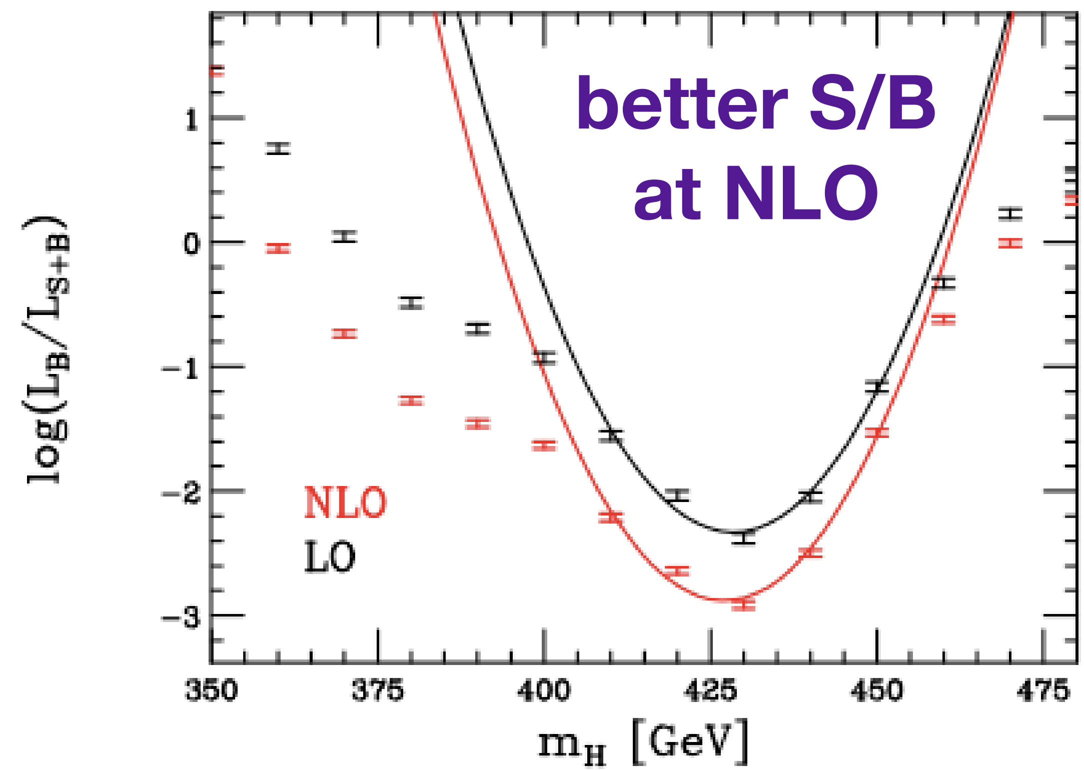
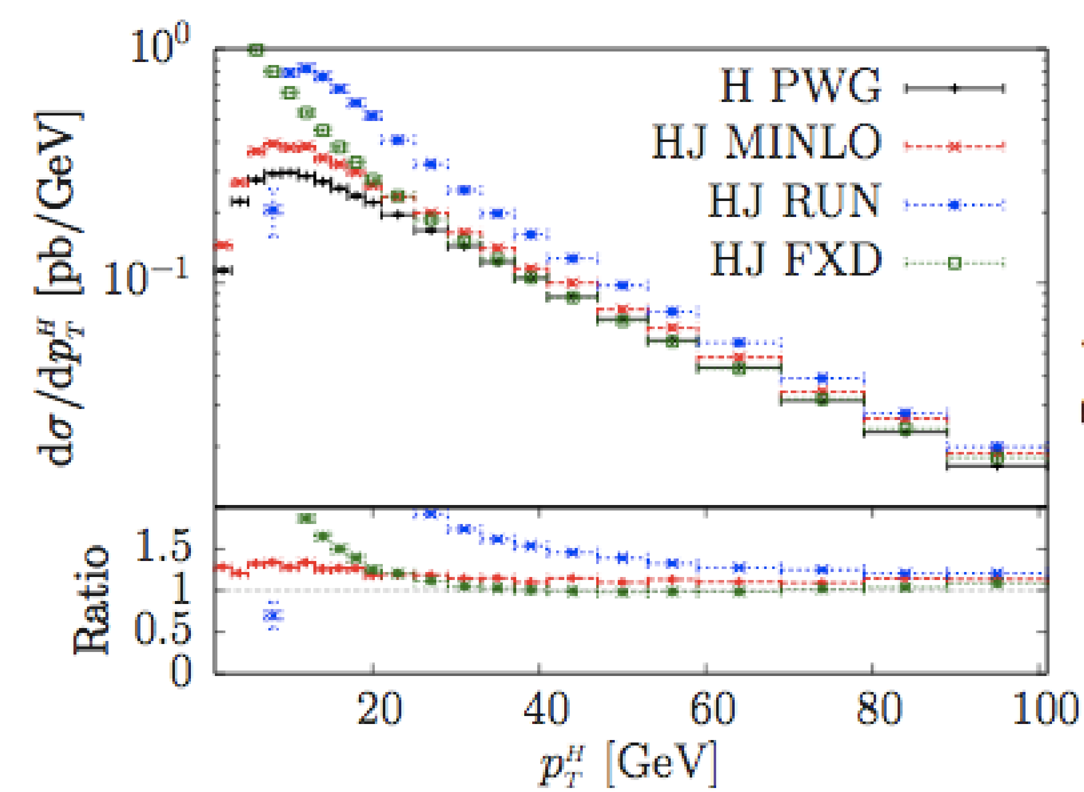


Better scale setting in NLO calculations

Hamilton, Nason, Zanderighi

- similar to existing methods in tree level ME/PS merging

improved description outside usual NLO region



NNLO in the pipeline

- Ingredients for fully differential NNLO
  - infrared subtraction terms

    Herzog, Gehrmann-de Ridder, Glover, Pires, Boughezal, Melnikov, Petriello, Currie, Gehrmann, Monni
  - new 2-loop amplitudes for $H \to 3$ partons and $qq \to W\gamma, Z\gamma$

    Gehrmann, Jaquier, Glover, Koukoutsakis, Tancredi
  - extension of unitarity methods to two loops

    Badger, Frellesvig, Zhang; Mastrolia, Ossola; Larsen, Johansson, Kosower

    → D. Kosower parallel
- Threshold resummation for W/Z/H production NNLL,NNLO.

  Becher, Bell, Marti; Gonsalves, Kidonakis

  → N. Kidonakis parallel

Top production

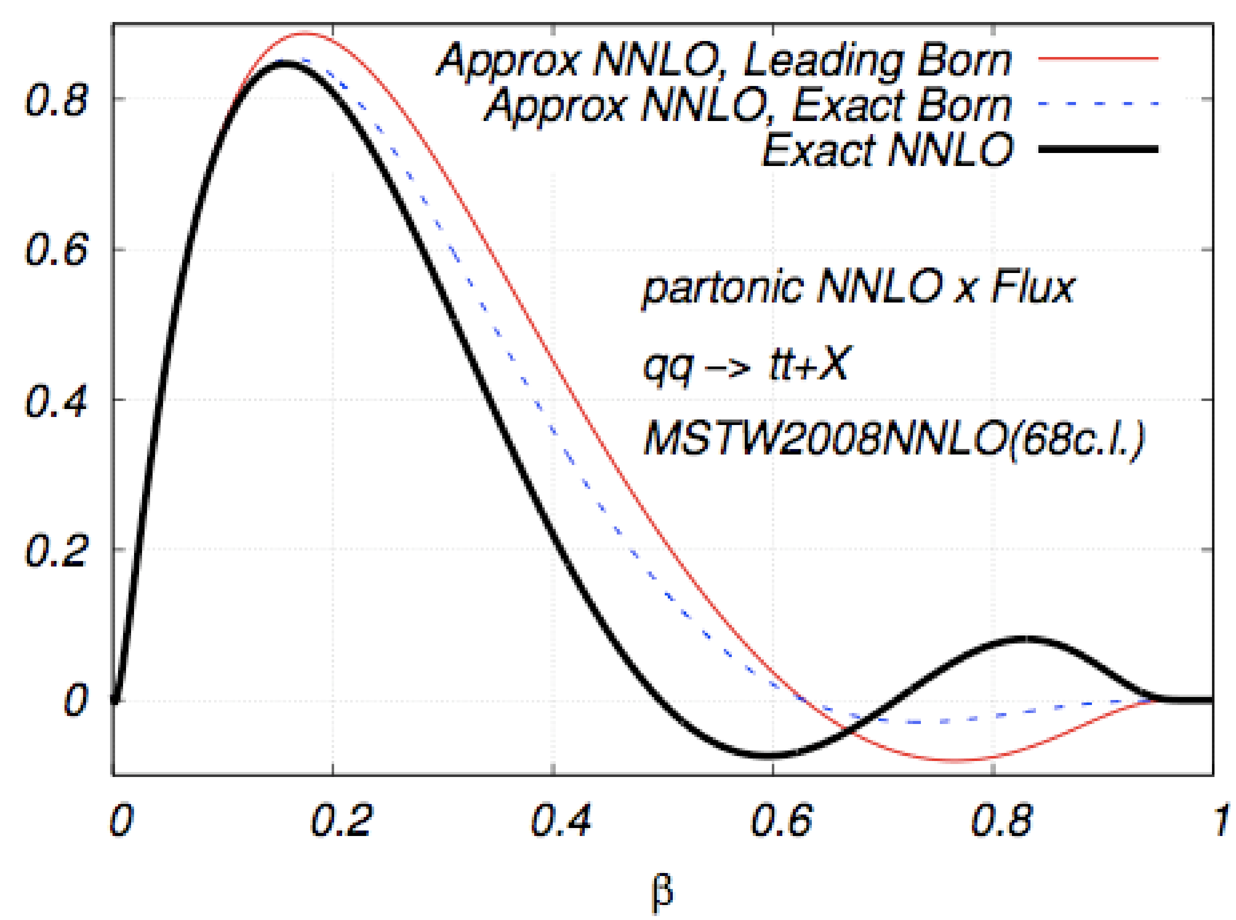
NNLO corrections to qq→tt

Barnreuther, Czakon, Mitov

- First ever NNLO calculation for a hadron collider with two (massive) colored partons in the final state
- Cross section in terms of top quark rel. velocity β=√(1-4m²/s):

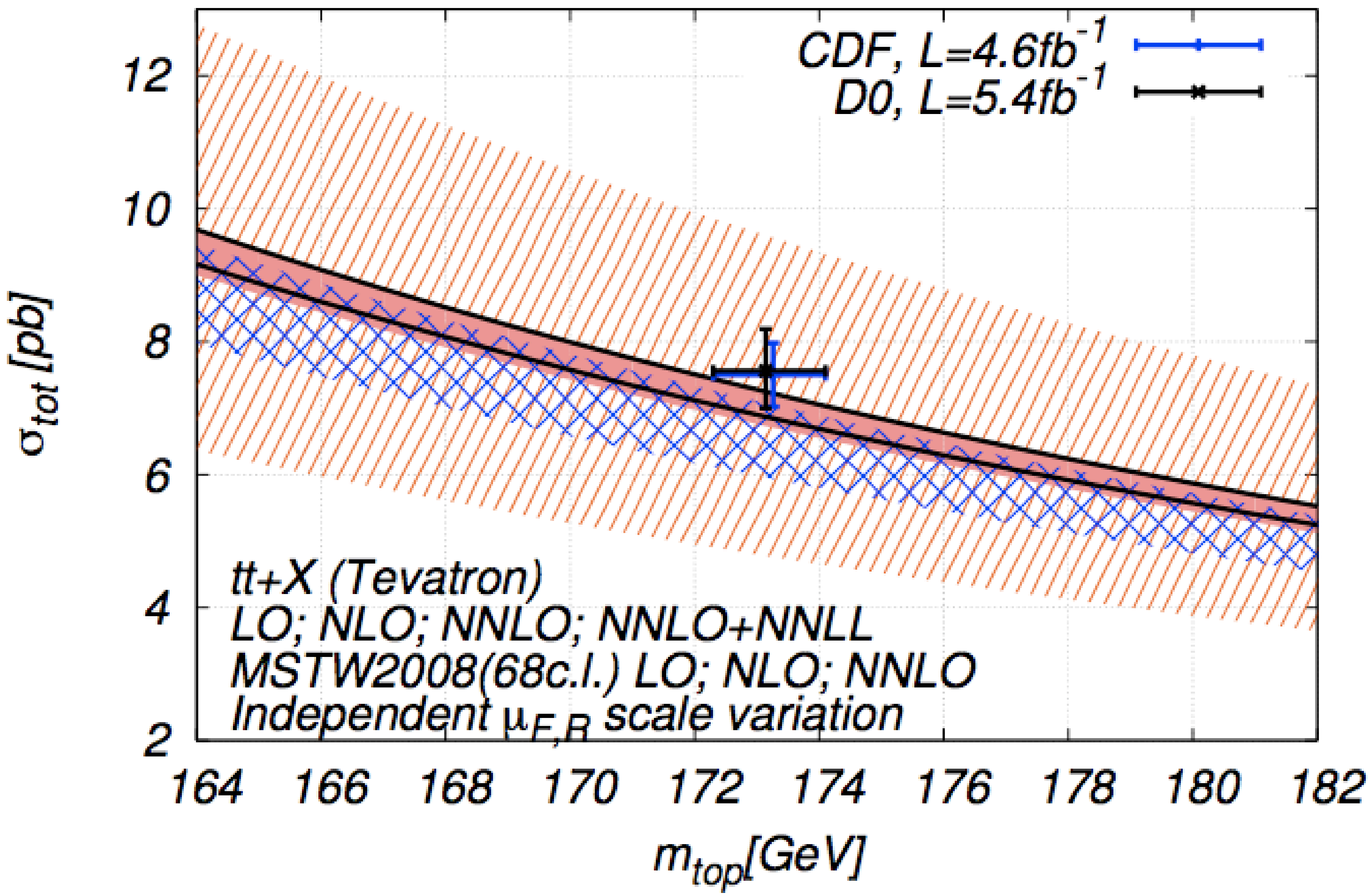
$$\sigma_{\text{tot}} = \sum_{i,j} \int_0^{\beta_{\max}} d\beta \, \Phi_{ij}(\beta, \mu^2) \, \hat{\sigma}_{ij}(\beta, m^2, \mu^2)$$

Exact NNLO vs. threshold approximation



- small β approx. superseded
- Threshold approximation poor over most of the range
  - less difference in integral

Impact of NNLO+NNLL at Tevatron



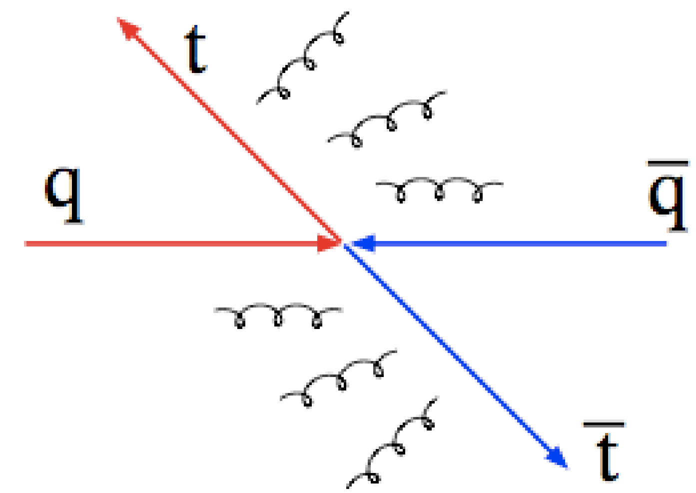
Uncertainty:
theory (5%)
< expt (~10%)

Barnreuther, Czakon, Mitov

- Combined NNLO+NNLL threshold resummation
  Langenfeld, Moch, Uwer, Ahrens, Ferroglia, Neubert, Pecjak, Yang, Kidonakis, Beneke, Falgari, Klein, Schwinn, Cacciari, Czakon, Mangano, Mitov, Schwinn

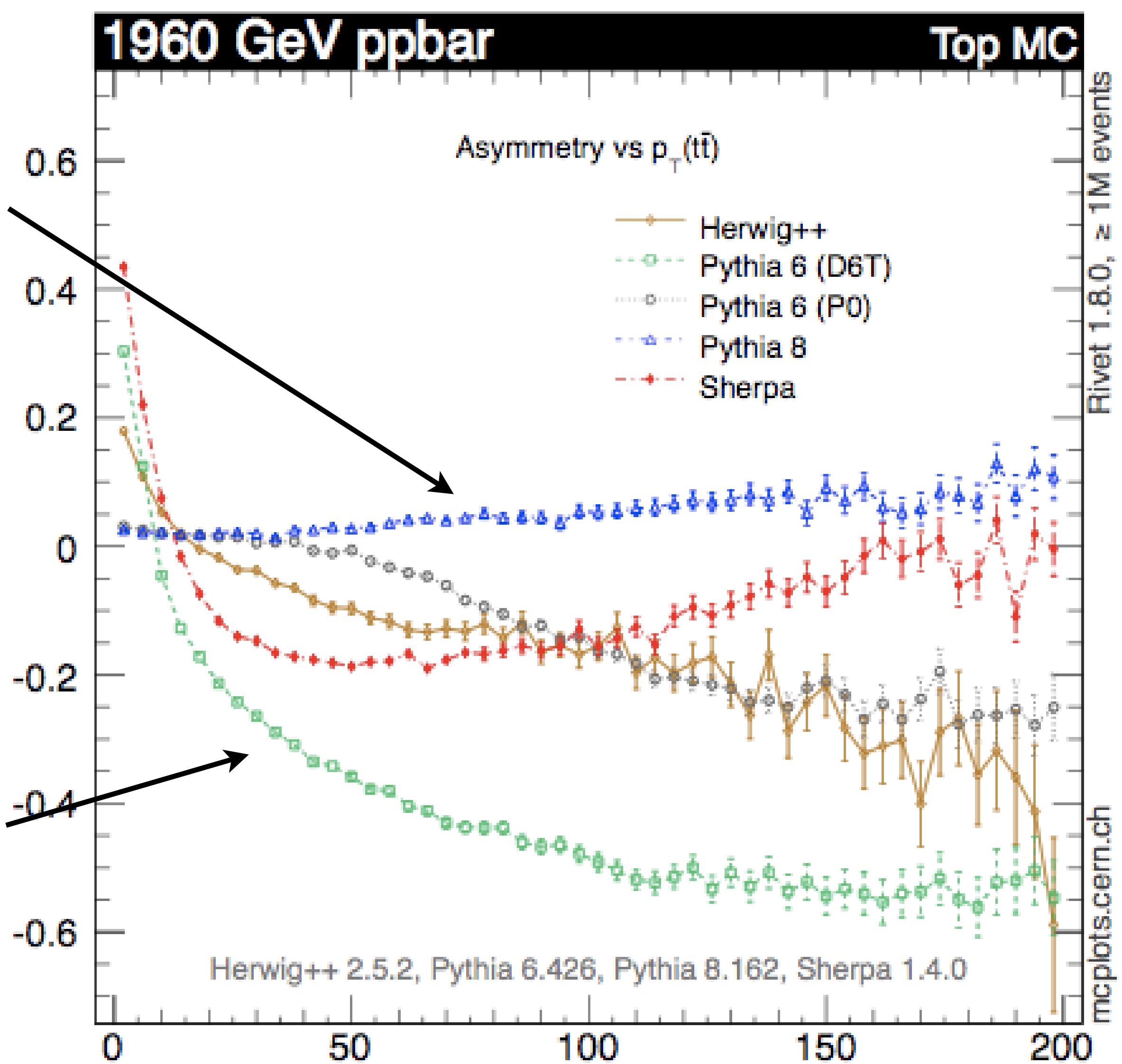
Parton shower asymmetry

- NLO rate predicts non-zero asymmetry: uncertainty 30-40%
- What about asymmetry from parton shower?
  Skands, Webber, Winter
  - built-in through color-coherence of shower



coherence not yet implemented

color coherence over-estimated

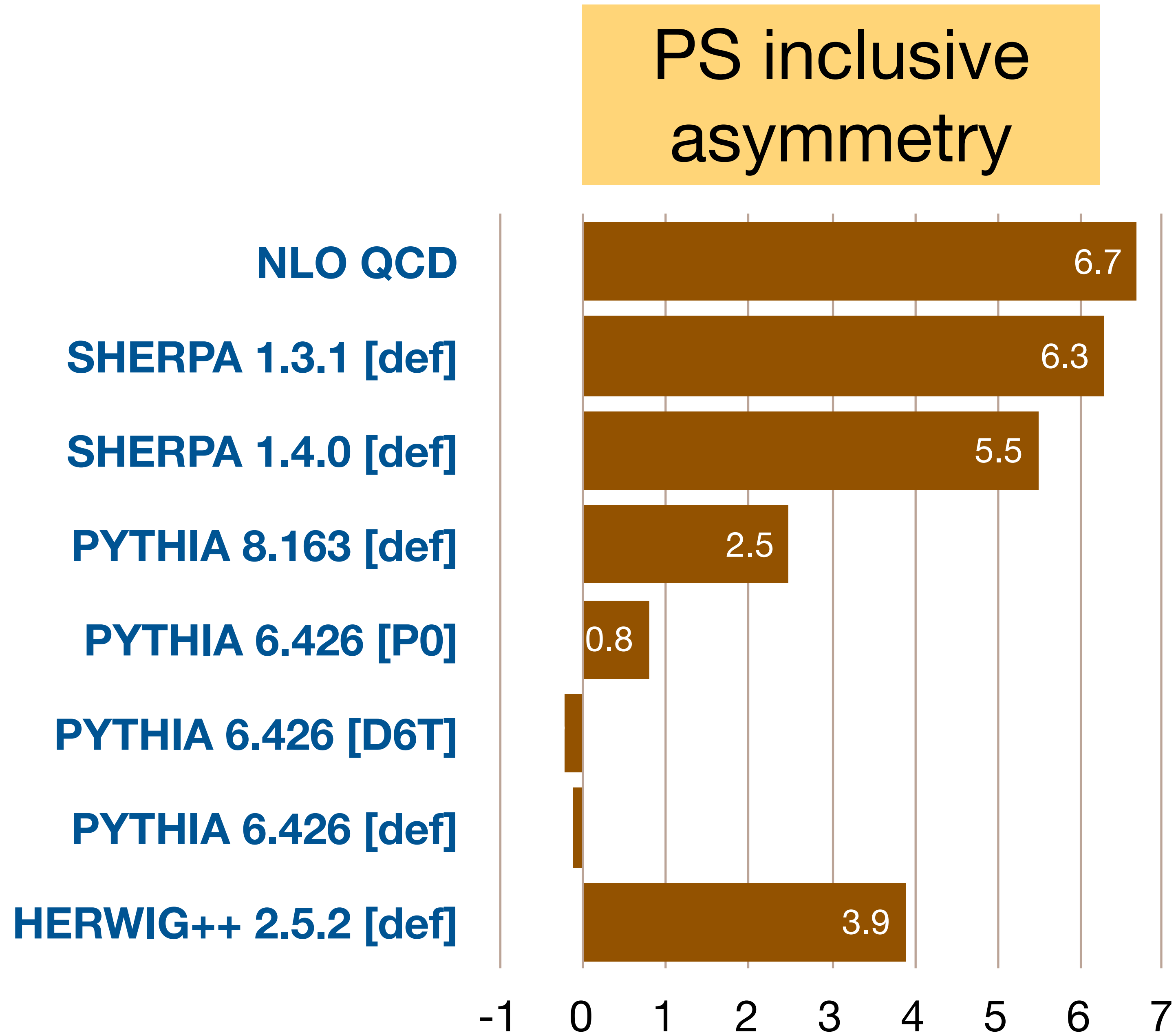


A_{FB} vs. p_T of top pair for PS predictions

Inclusive asymmetry

Skands, Webber, Winter

- Expectation: PS inclusive asymmetry = fixed-order result
  - i.e. Pythia/Herwig/Sherpa → zero
- But: recoil effects cause migration between regions of positive and negative rapidity
  - expectation incorrect
  - care required when correcting back to parton level using shower prediction



Further asymmetry corrections

- Electroweak corrections to asymmetry also understood
  - simple relation between QED and QCD asymmetry:

$$A^q_{QED} = \frac{36}{5}\frac{\alpha}{\alpha_S} Q_q Q_t A_{QCD} \approx 0.1 - 0.2$$

Hollik, Pagani
Kuhn, Rodrigo
Bernreuther, Si

  - weak corrections not easily related but small
- NLO+NNLL soft gluon resummation effects also small, <3%, but reduce scale uncertainty → 10-15%. Ahrens et al.
- Resum large EW Sudakov logs using effective field theory techniques ~ 5% effect

$$\left(\frac{\alpha}{\sin^2\theta_w}\right)^n \log^{2n}\left(\frac{s}{m_W^2}\right)$$

Manohar, Trott

Tevatron results prompted great activity → feed into LHC

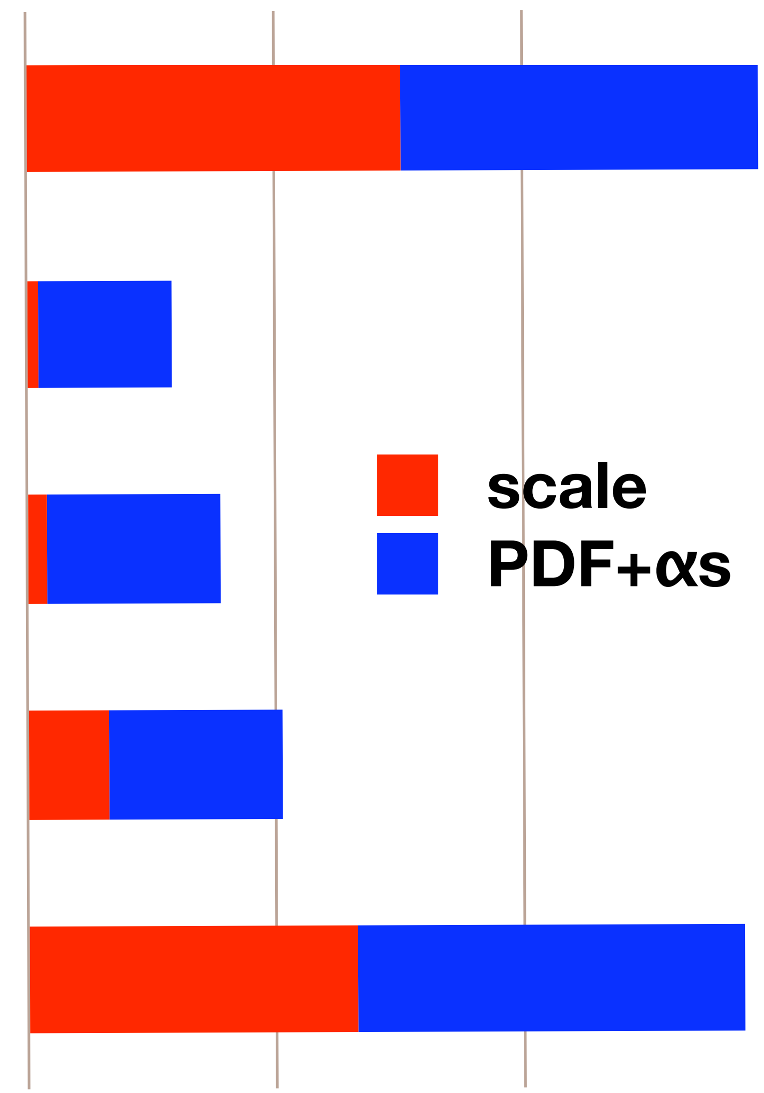
Higgs uncertainties

Higgs production at 125 GeV

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

- Model testing requires assessment of theoretical uncertainties
  - uncertainties from scale variation and PDF+strong coupling

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



Higgs decay at 125 GeV

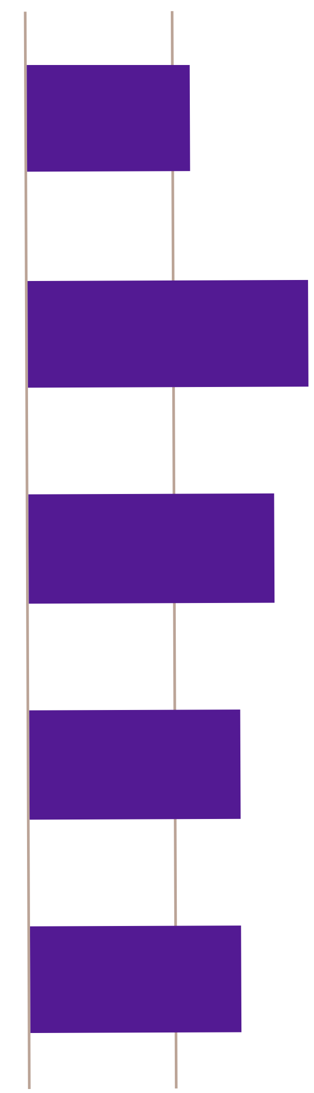
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

- Uncertainty on branching ratios combined from two sources
  - parametric (α_s,masses) and higher order theory

NNNLO QCD +NLO EW ($H \to bb$, $H \to \tau\tau$)

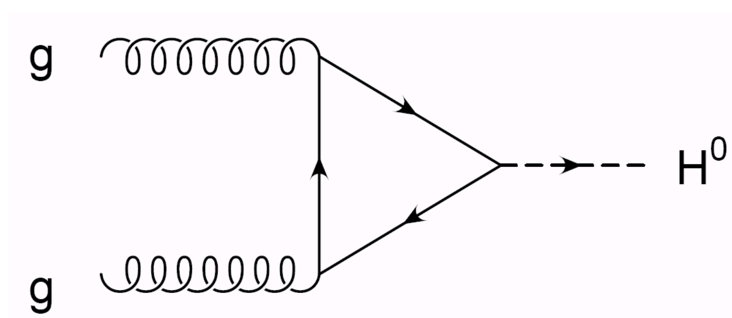
NLO QCD +NLO EW ($H \to \gamma\gamma$, $H \to WW$, $H \to ZZ$)

	BR	uncertainty
$H \to bb$	0.58	3.3%
$H \to \tau\tau$	0.063	5.7%
$H \to \gamma\gamma$	0.0023	5.0%
$H \to WW$	0.22	4.3%
$H \to ZZ$	0.026	4.3%



Inclusive vs. binned

- Quoted production uncertainties only on inclusive cross sections.
- Analysis requirements often quite different:
  - lepton cuts mostly harmless
  - jet vetoes or counting in jet bins more dangerous (e.g. $H \to WW$)
- Incomplete cancellation of infrared divergence introduces log.



+ any jet activity

inclusive, expand in α_s

+ no jet above 30 GeV

jet veto, expand in $\alpha_s \log^2[125/30] \approx 2\alpha_s$

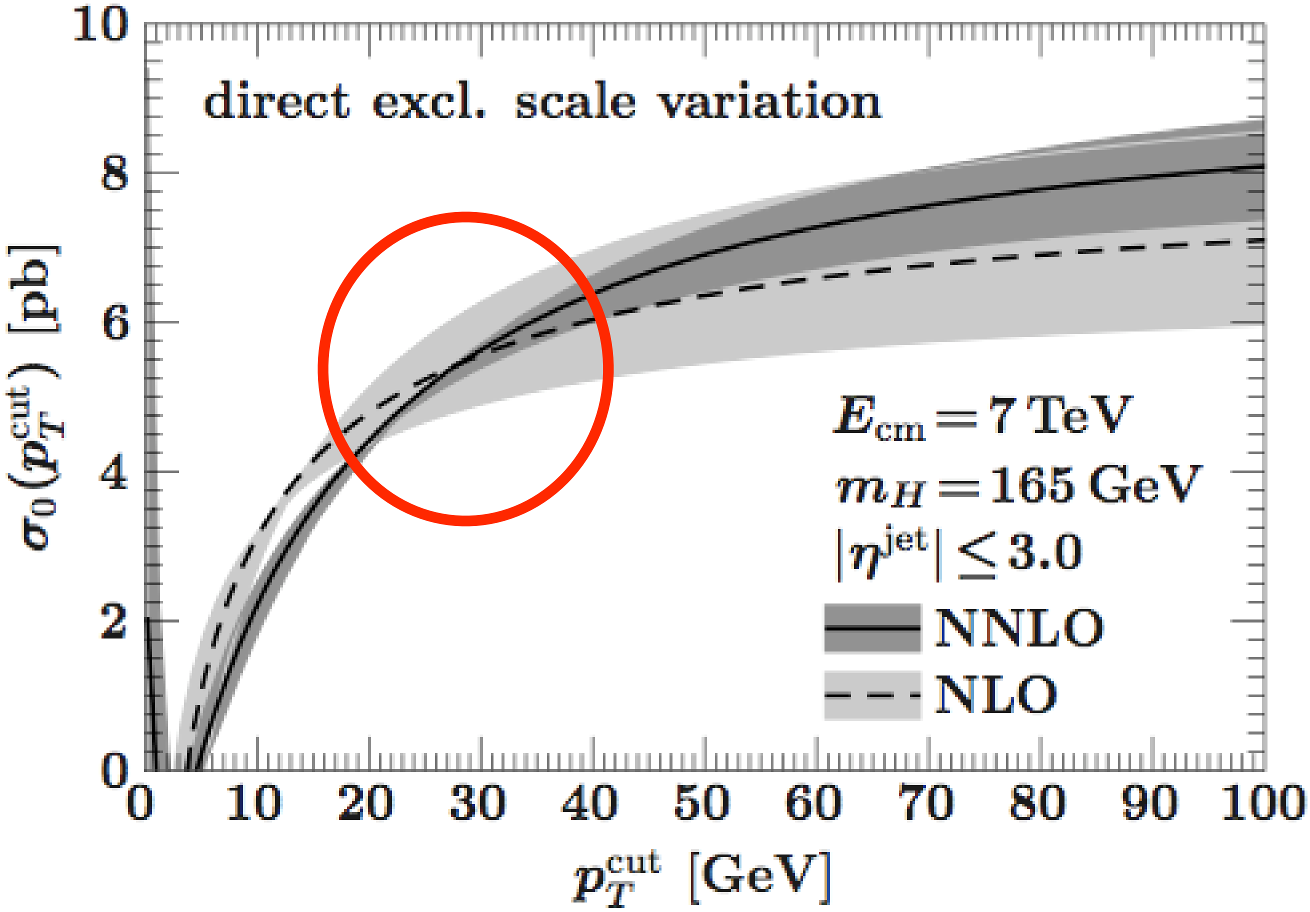
- Expect worse perturbative behavior → resum large logs

Estimating uncertainty

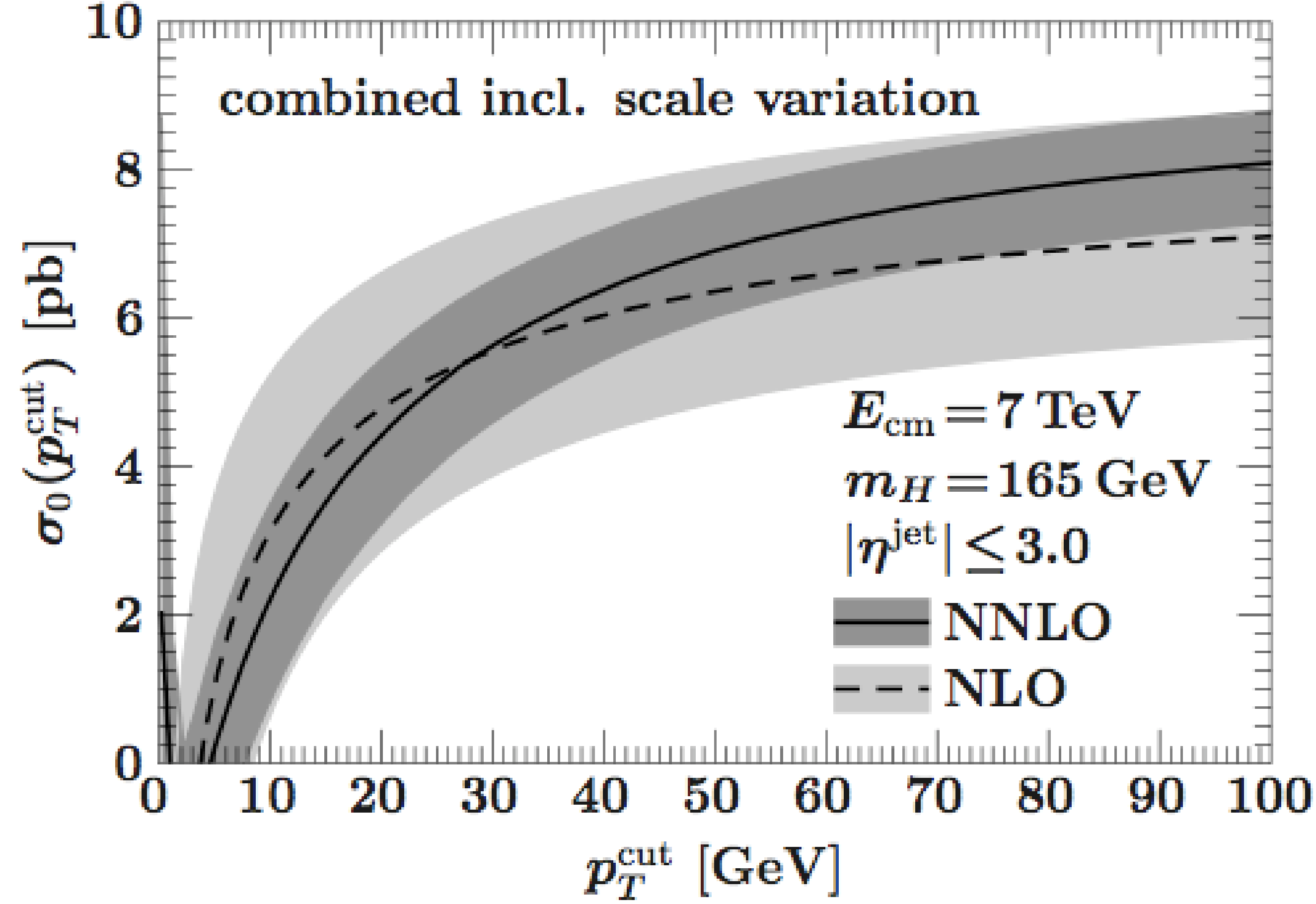
- Naive scale variation too optimistic
  - accidental (numerical) cancellation of terms

Stewart, Tackmann

Naive scale variation



Correlated variation

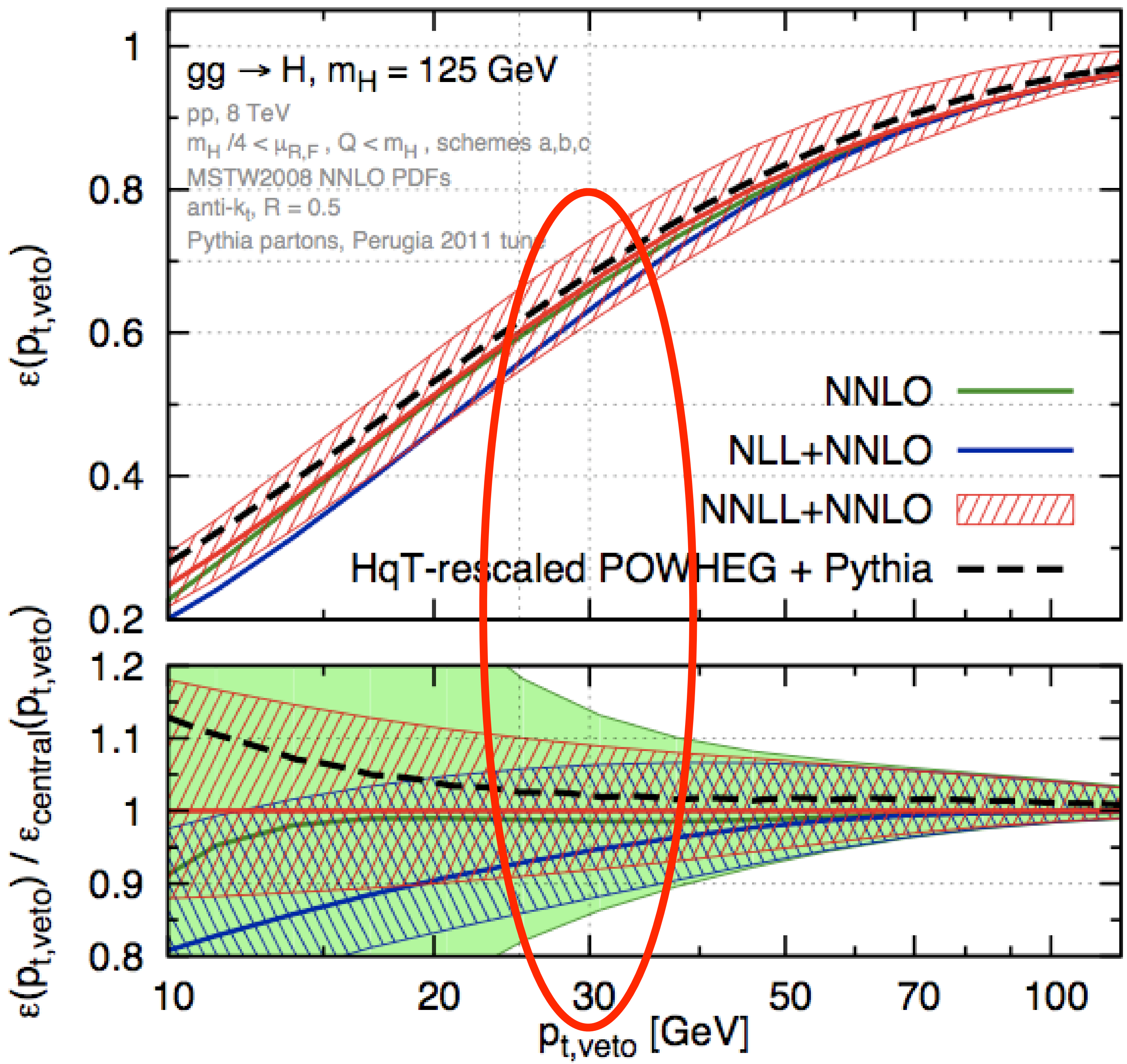


- Correlated uncertainties look better: typical veto, NNLO ~ 15%.

Resumed predictions

- Much work on resumming the large logarithms for a better understanding of jet-vetoed cross sections
  - NLL+NNLO Higgs and Z (numerical resummation using CAESAR) — Banfi, Salam, Zanderighi
  - NNLL+NNLO Higgs (SCET - soft-collinear effective theory) — Becher, Neubert
  - NLL and clustering logs (study of class of logs, $\alpha_s \log[m_H/p_T(\text{veto})]\log[R]$) — Tackmann, Walsh, Zuberi
  - NNLL+NNLO Higgs and Z (adapt results on boson p_T resummation) — Banfi et al
- Healthy debate on accuracy of different techniques

Jet veto uncertainty



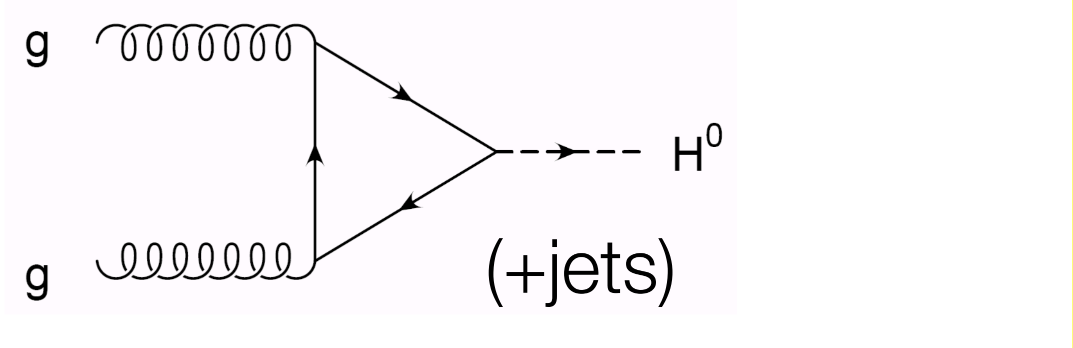
Banfi, Monni, Salam, Zanderighi

NNLL+NNLO Higgs uncertainty: ~10% for typical vetoes

0-jet cross section uncertainty

- Most Higgs sensitivity from the 0-jet bin in gluon fusion
- Example for m_H=125 GeV

approx. uncertainty

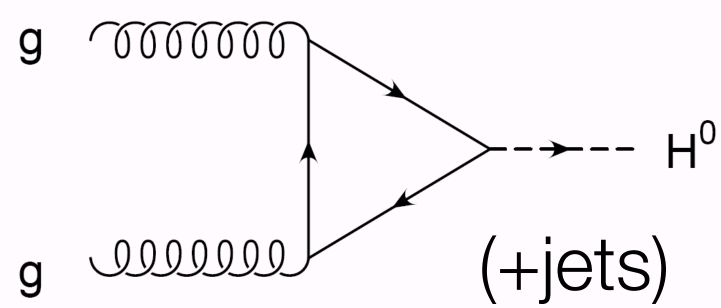


15% (scale~7%, pdf+α_s~8%)

0-jet cross section uncertainty

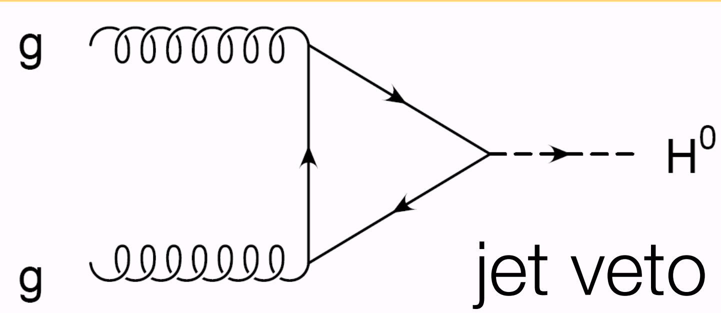
- Most Higgs sensitivity from the 0-jet bin in gluon fusion
- Example for m_H=125 GeV

approx. uncertainty



(+jets)

15% (scale~7%, pdf+α_s~8%)



jet veto at 30 GeV

20% (scale→11% from jet veto)

Banfi et al

0-jet cross section uncertainty

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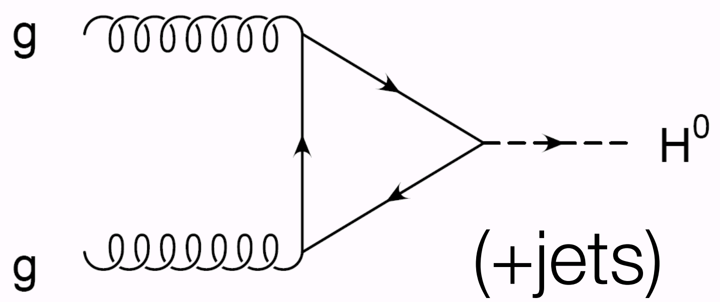
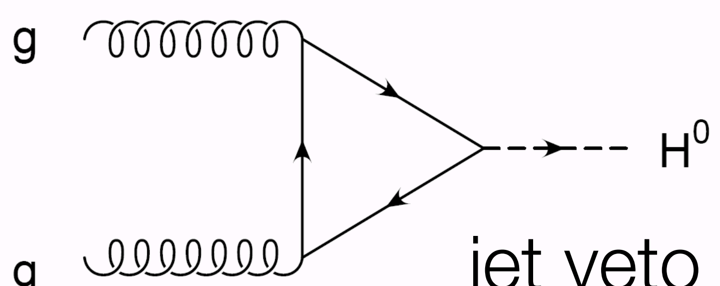


(+jets)

15% (scale~7%, pdf+α_s~8%)



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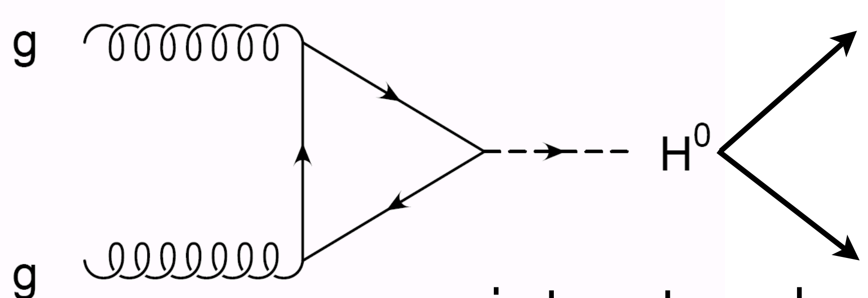
Banfi et al

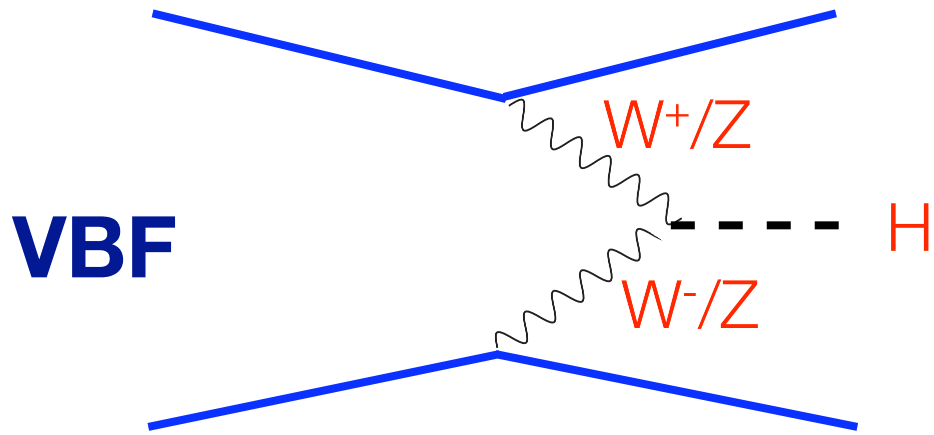


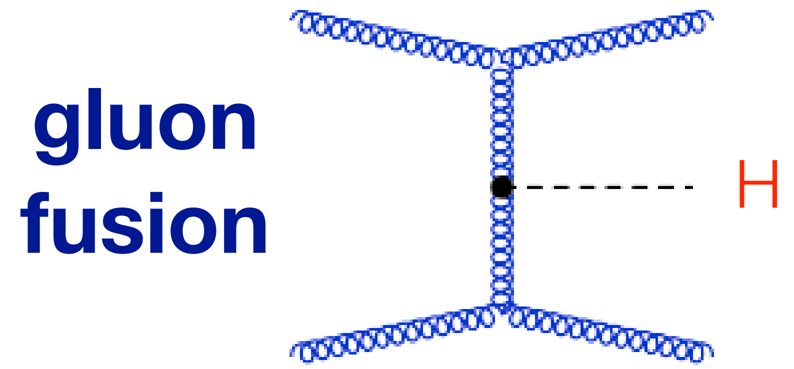
jet veto, decay

25% (BR uncertainty ~ 5%)

Higgs search: 2-jet bin

- Higgs sensitivity enhanced by VBF channels, special cuts to select events with 2 jets at large rapidity separation



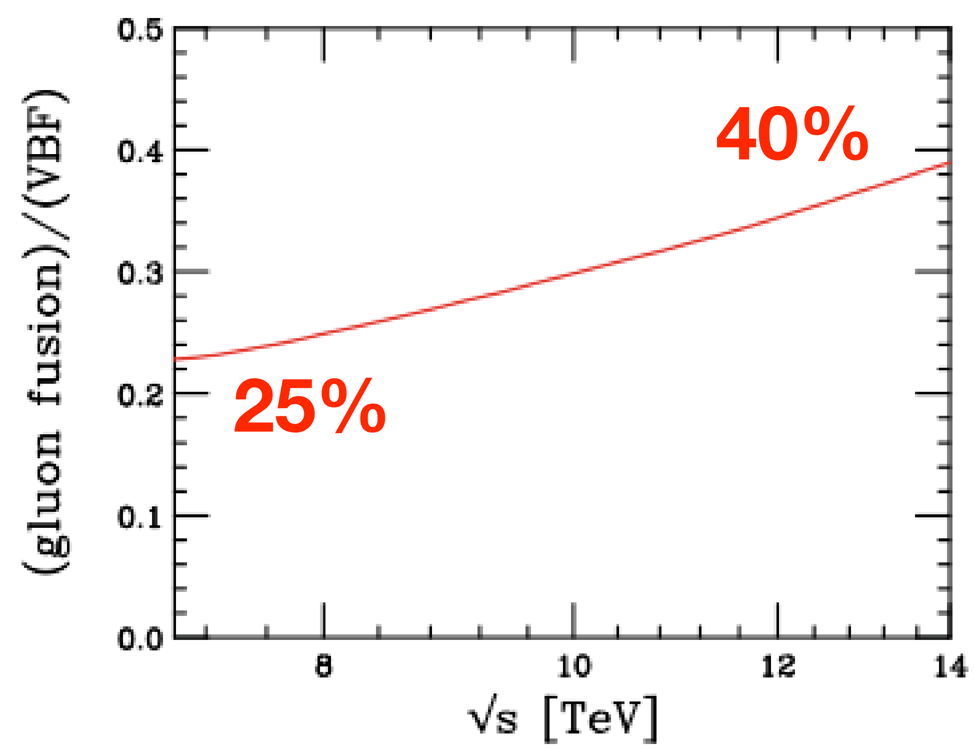


- Extra sensitivity + prospects for test of production/decay mechanism (accuracy ~ 3%)
- Contamination from gluon fusion (accuracy ~ 25%)

Berger, JC, Ellis, Williams, Zanderighi

gg→H+2 jets dominates uncertainty 6% : 2%

typical VBF cuts



Concluding remarks

- Perturbative QCD continues to play an important role
- Identifying characteristics of the newly-discovered particle requires an accurate modelling of both signals and backgrounds
  - if it's a Higgs boson, lots of sharpened pQCD tools at the ready
- Unprecedented access to ...
  - NNLO accuracy - both for pdfs and matrix elements
  - NLO+PS simulations for direct comparison with data
  - NLO precision for complex final states
- More to come
  - merging NLO+PS, NNLO for gg→tt, charge asymmetry, ...

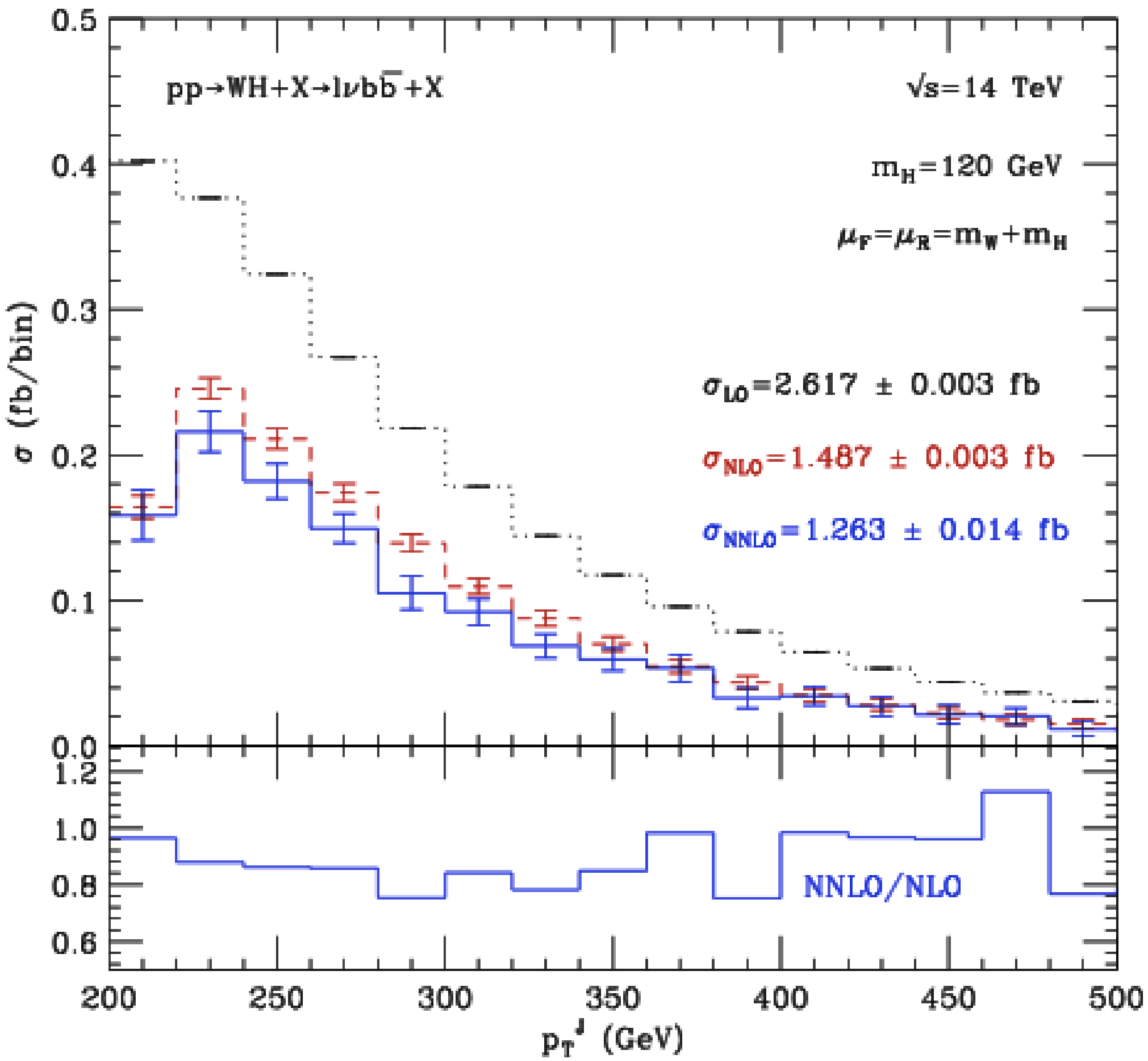
Apologies for subjective coverage and anything I missed!

Backup slides

Studies for H→bb decay

Exclusive NNLO for WH production

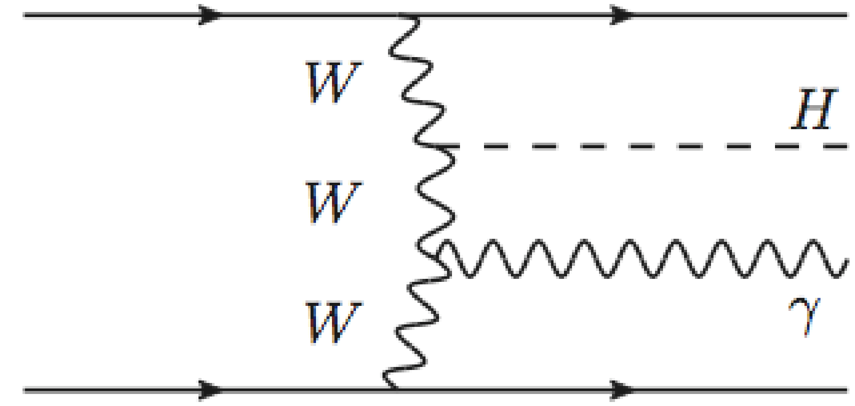
Ferrera et al



boosted fat jet containing b quarks

NLO for VBF Higgs+photon

Arnold et al

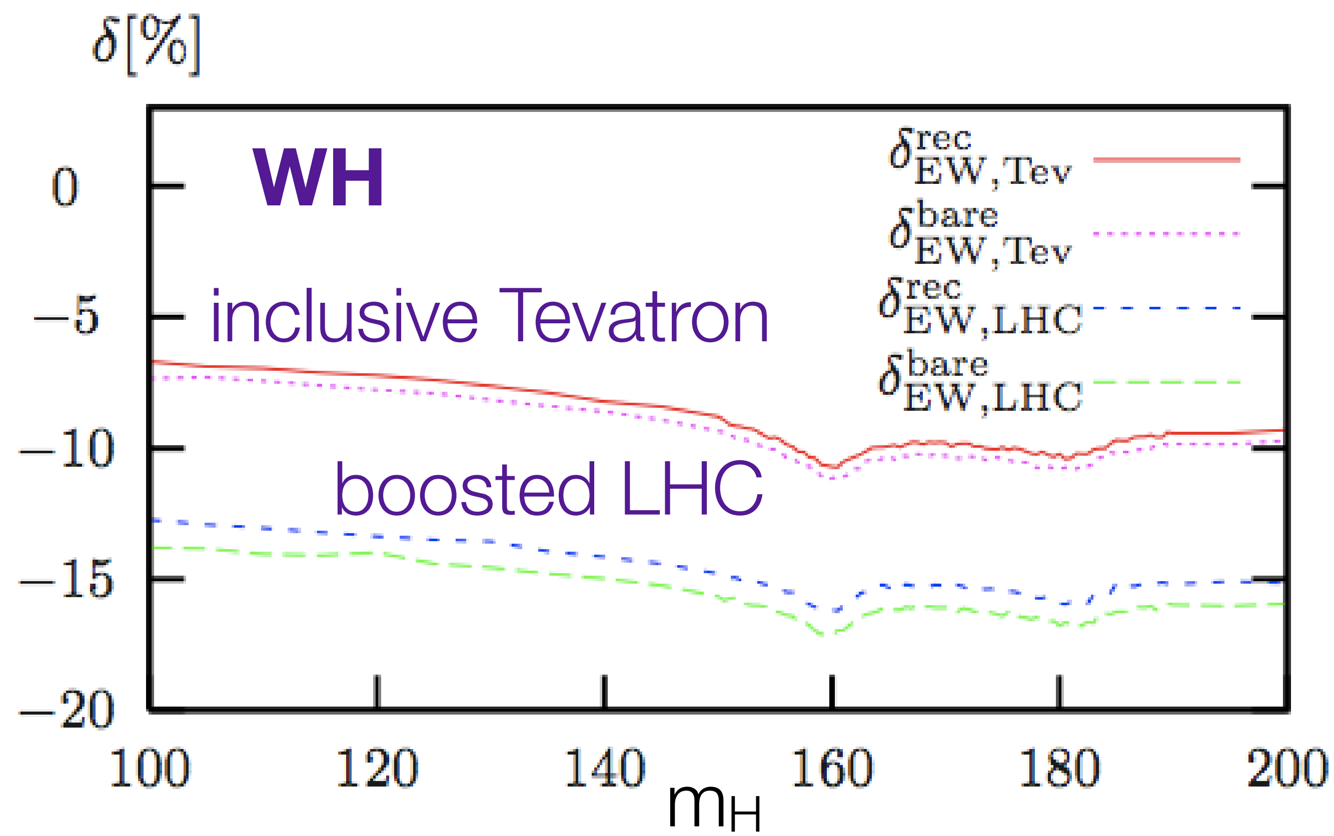


- Price of photon emission:
  - signal ~ 1/100
  - background ~ 1/3000
- Viable cross section ~ 15fb
- Uncertainties < 5-10%

Subtle effects

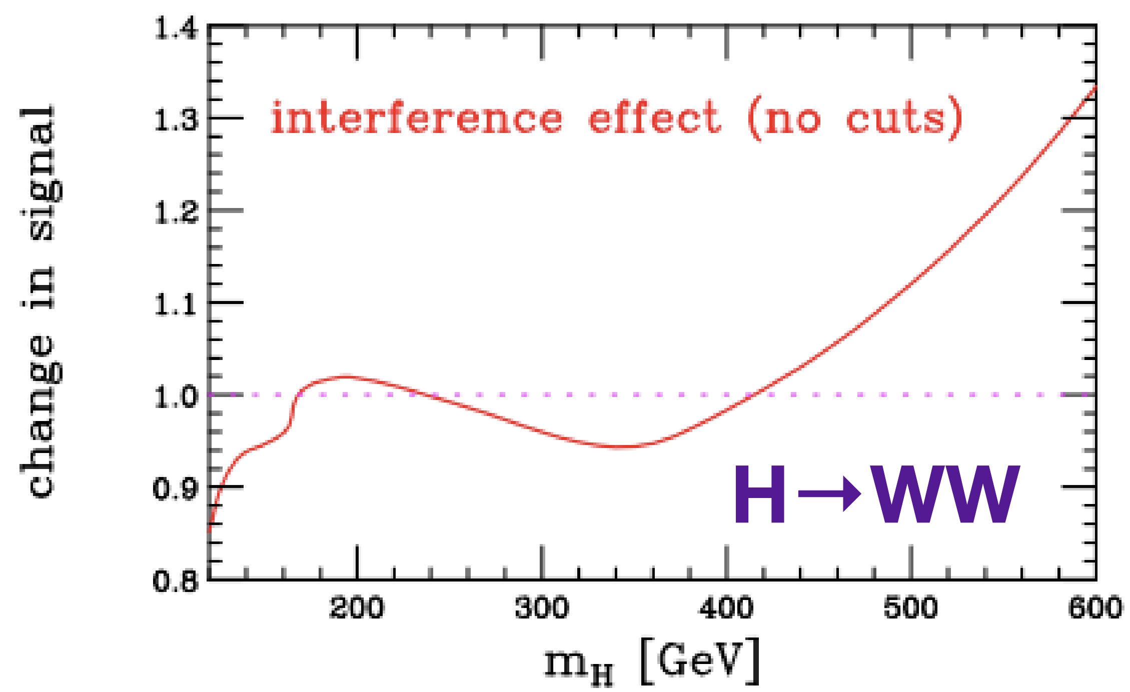
Importance of electroweak corrections

- crucial role in some kinematic regions
  Denner, Dittmaier, Kallweit, Mück



Significant signal/ background interference

- if intrinsic width large (high m_H)
- or analysis is sensitive to destructive large $\hat{s}$ tail
  Ellis, Williams, JC; Kauer, Passarino



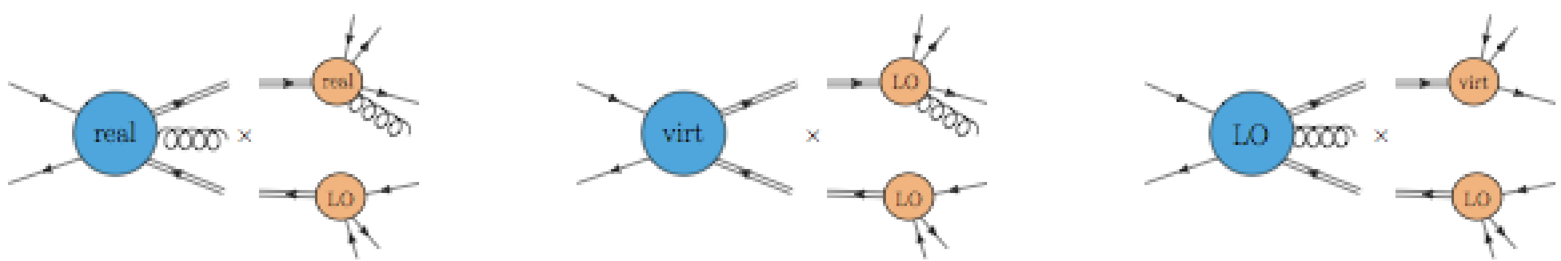
Top quark production and decay

- ✦ Small width $\Gamma_t/m_t < 1\%$ → factorization of production and decay

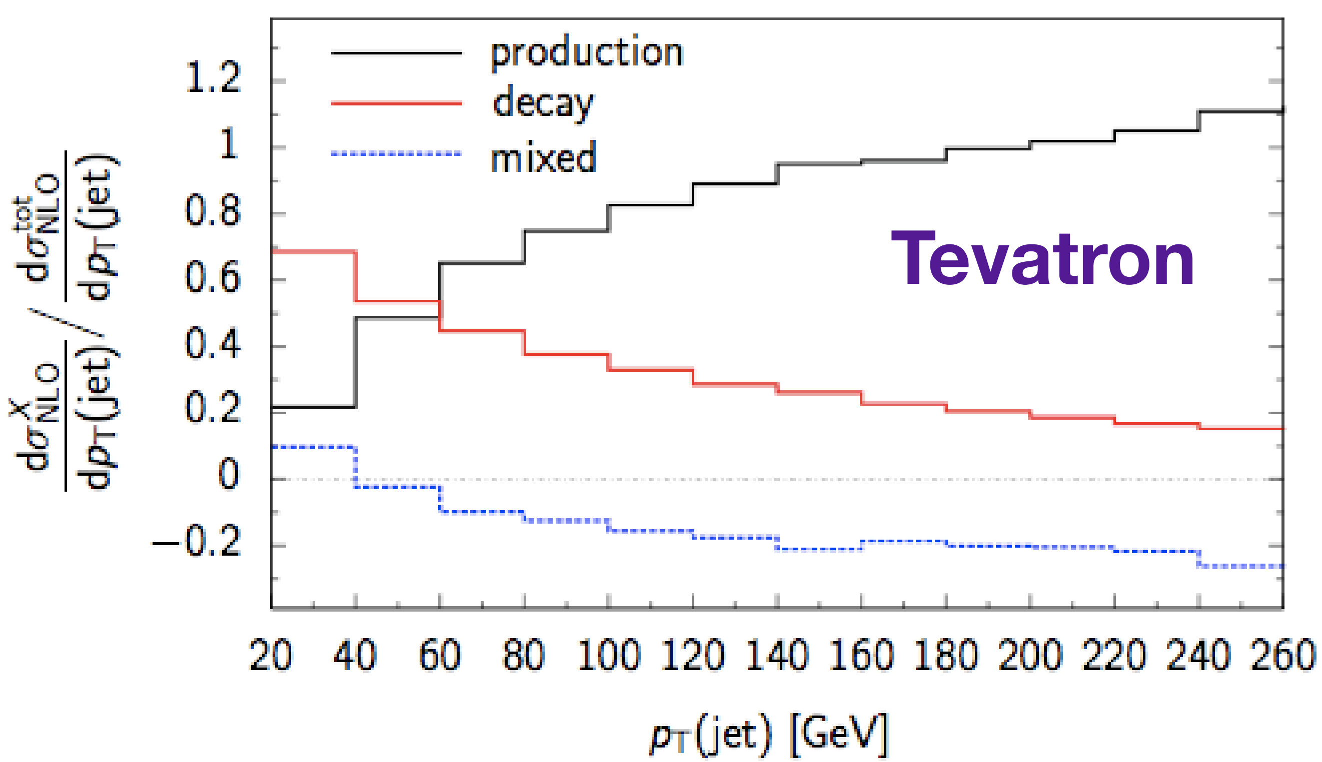
(a) jet emission in production (b) jet emission in decay

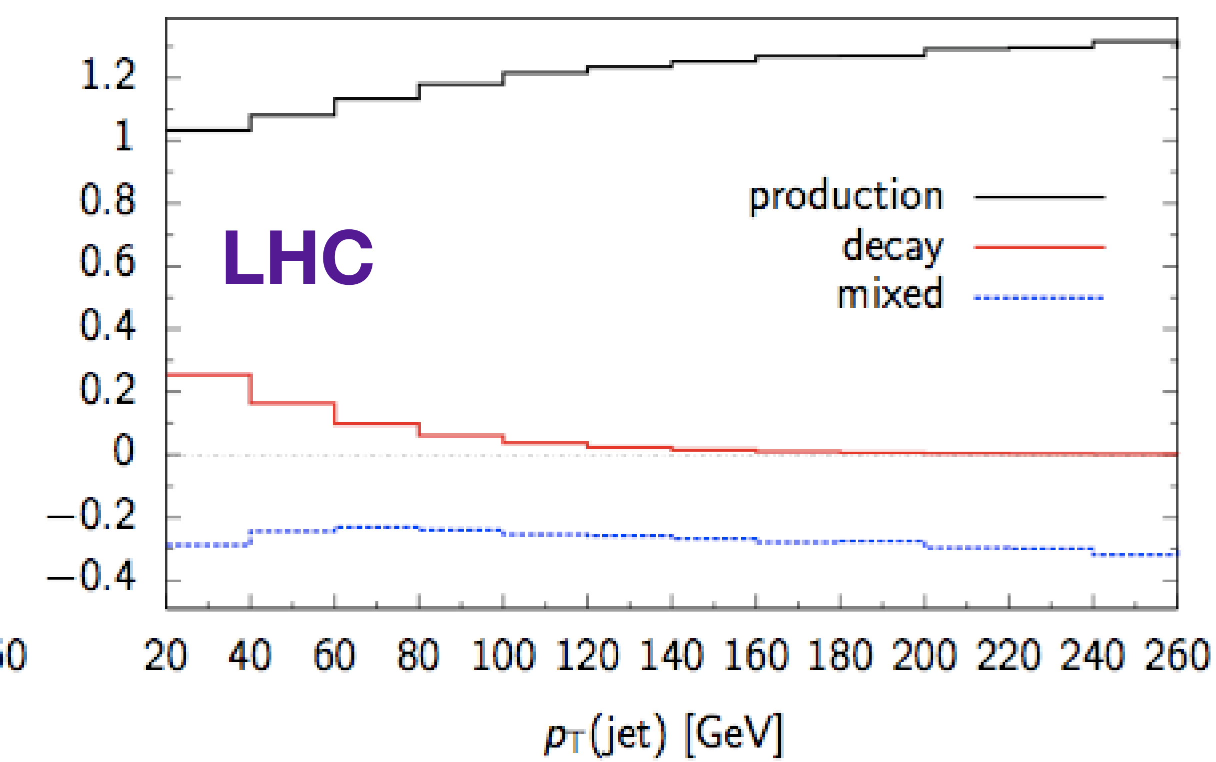
tt+jet

Melnikov, Scharf, Schulze



Origin of radiation in tt+jet events



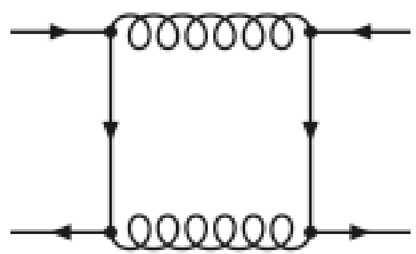


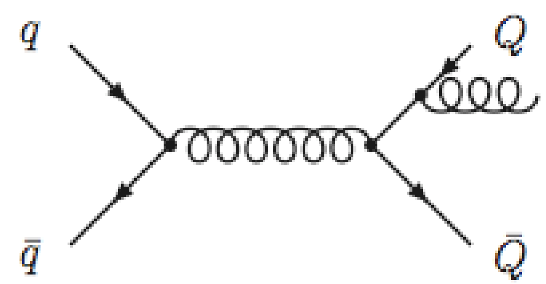
Lesson: radiation in decay important

Top asymmetry at the Tevatron

- Prediction at LO: no forward-backward asymmetry
- Positive asymmetry arises at NLO in QCD

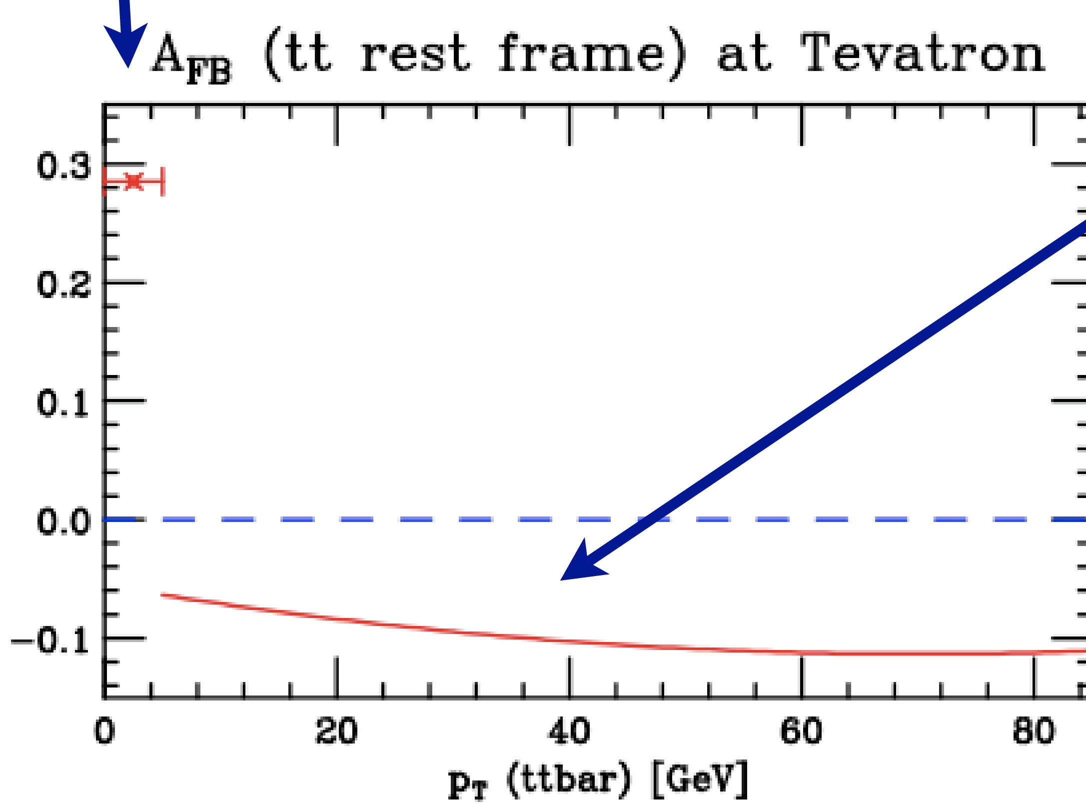
virtual radiation



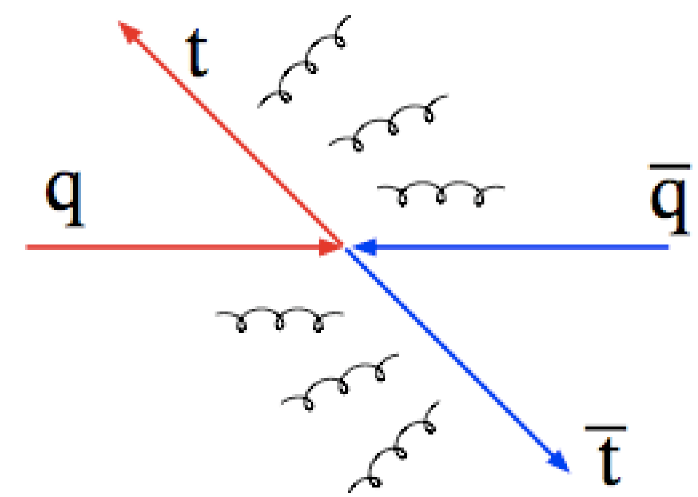


real radiation

$p_T(tt)=0$



$p_T(tt)>0$



A_{FB} vs. p_T of top pair at NLO