QCD

AT THE DAWN OF THE LHC

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L CRACOW SCHOOL OF TH. PHYSICS ZAKOPANE, JUNE 11, 2010

LECTURE II

PERTURBATIVE CORRECTIONS

- WHY ARE HIGHER ORDERS IMPORTANT?
- PROGRESS: THEORY AND PHENOMENOLOGY
- DETERMINATION OF α_s

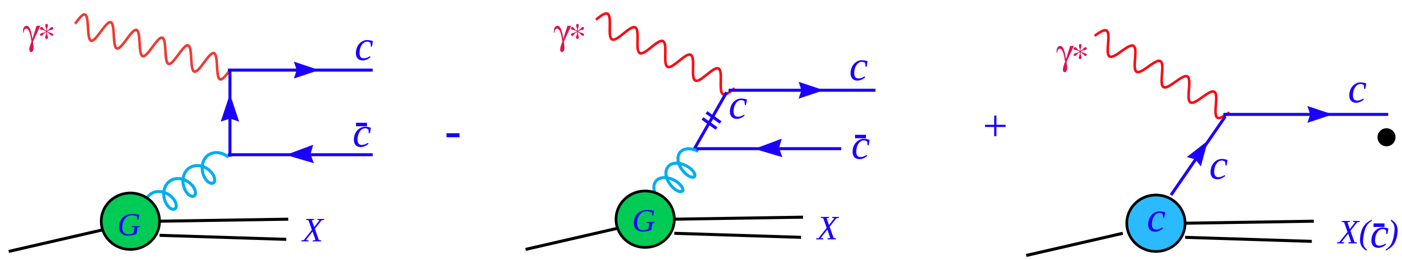
WHY ARE HIGHER ORDERS IMPORTANT?

AN EXAMPLE: HEAVY QUARKS IN DIS

- IN $\overline{\text{MS}}$ SCHEME, $n_f = 6$ IN LOOPS, α_s RUNNING AND DGLAP EQNS AT ALL SCALES
  $\Rightarrow$ FOR $Q^2 >> m_q^2$, NEGLECT THE MASS
- WHEN $Q^2 << m_q^2$ A DECOUPLING SCHEME MORE CONVENIENT: LOOPS SUBTRACTED AT ZERO MOMENTUM, $n_f = n_l$ IN α_s RUNNING AND DGLAP EQNS
  $\Rightarrow$ FOR $Q^2 >> m_q^2$, NEGLECT THE HEAVY QUARK
- WHAT HAPPENS WHEN $Q^2 \approx m_q^2$?

MATCHED SCHEMES: ACOT (Aivazis, Collins, Olness, Tung, 1988, 1994)

$m_c \neq 0$, LO charm radiation — $m_c = 0$, LO charm radiation — $m_c = 0$ charm pdf



- USE $\overline{\text{MS}}$ FOR $Q^2 > m_q^2$ WITH FULL MASS DEP. RETAINED
- KEEP ALL FLAVOURS IN RUNNING, DGLAP
- SUBTRACT DOUBLE COUNTING

SIMPLIFIED SACOT AVAILABLE: EVEN IN MASSIVE CONTRIBUTION, NEGLECT m_q IN FINAL STATE

MATCHED SCHEMES: TR (Thorne, Roberts, 1998, 2008)

- SWITCH OFF HQ FOR $Q^2 < m_q^2$
- USE MASSLESS APPROX FOR $Q^2 > m_q^2$
- ADD MASSIVE TERMS AND ENFORCE CONTINUITY AT THRESHOLD VIA SUBL. TERMS

MATCHED SCHEMES: FONLL

(Cacciari, Greco, Nason, 1998; for DIS s.f., Laenen, Rojo, Nason, 2010)

- USE $\overline{\mathrm{MS}}$ (MASSLESS) PARTONS
- COMPUTE MASSIVE CONTRIBUTIONS IN THE DECOUPLING SCHEME, BUT EXPRESS EVERYTHING IN TERMS OF $\overline{\mathrm{MS}}$ PARTONS
- ADD MASSIVE EXPRESSION TO THE MASSLESS ONE, SUBTRACT DOUBLE COUNTING (TRIVIAL, AS EVERYTHING EXPRESSED IN SAME SCHEME)

$$F^{(n_l)}(x,Q^2) = x\int_x^1 \frac{dy}{y} \sum_{i=q,\bar{q},g} B_i\left(\frac{x}{y}, \frac{Q^2}{m^2}, \alpha_s^{(n_l+1)}(Q^2)\right) f_i^{(n_l+1)}(y,Q^2),$$

$$F^{(n_l,0)}(x,Q^2) \equiv x\int_x^1 \frac{dy}{y} \sum_{i=q,\bar{q},g} B_i^{(0)}\left(\frac{x}{y}, \frac{Q^2}{m^2}, \alpha_s^{(n_l+1)}(Q^2)\right) f_i^{(n_l+1)}(y,Q^2); \quad \lim_{m\to 0}\left[B_i(x,\frac{Q^2}{m^2}) - B_i^{(0)}\left(x,\frac{Q^2}{m^2}\right)\right] = 0$$

$$F^{\mathrm{FONLL}}(x,Q^2) \equiv F^{(d)}(x,Q^2) + F^{(n_l)}(x,Q^2); \qquad F^{(d)}(x,Q^2) \equiv \left[F^{(n_l+1)}(x,Q^2) - F^{(n_l,0)}(x,Q^2)\right]$$

THE PROBLEM OF DAMPING TERMS

- IN ANY SCHEME, DGLAP RESUMMATION PRODUCES TERMS $\sim \alpha_s(Q^2) \ln \frac{Q^2}{m_q^2}$ TO ALL ORDERS IN $\alpha_s(Q^2)$
- MASS CORRECTIONS TO SUCH TERMS ARE PROVIDED AT LOW ORDERS IN $\alpha_s(Q^2)$, BUT NOT TO HIGHER ORDERS
- THESE TERMS ARE COMPLETELY INACCURATE WHEN Q^2 IS JUST ABOVE m_q^2 AND CAN BE NON–NEGLIGIBLE IN PRACTICE
- SOLUTION: KILL THESE TERMS WITH A SUITABLE DAMPING PRESCRIPTION

THE IMPACT ON PHENOMENOLOGY

- MANY FITS (CTEQ<6, NNPDF, ALEKHIN<09) TREAT CHARM AS MASSLESS ABOVE THRESHOLD $\Rightarrow$ "ZMVFN" SCHEME
- TR/TR' PROCEDURE IMPLEMENTED SINCE '98 IN MRST

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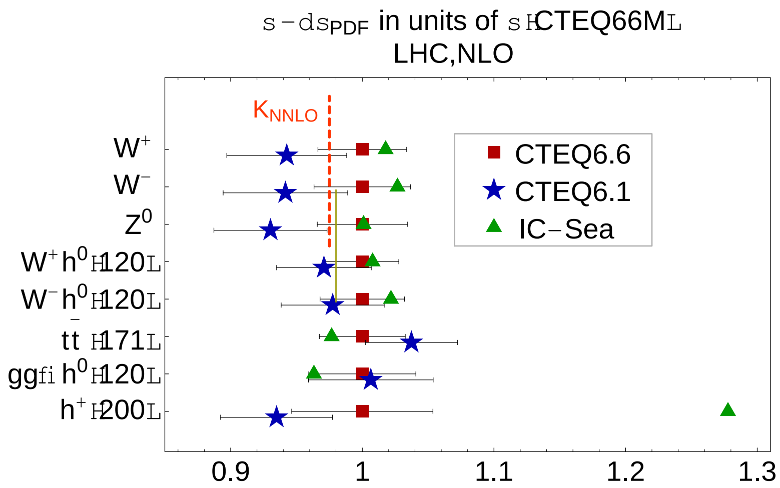
- WHEN CTEQ IMPLEMENTED ACOT IN 2008, SURPRISING CHANGE CTEQ61$\rightarrow$CTEQ6.5 IN σ_W, & AGREEMENT WITH MRST SPOILED (LATER RESTORED)



(Nadolsky et al., 2008)

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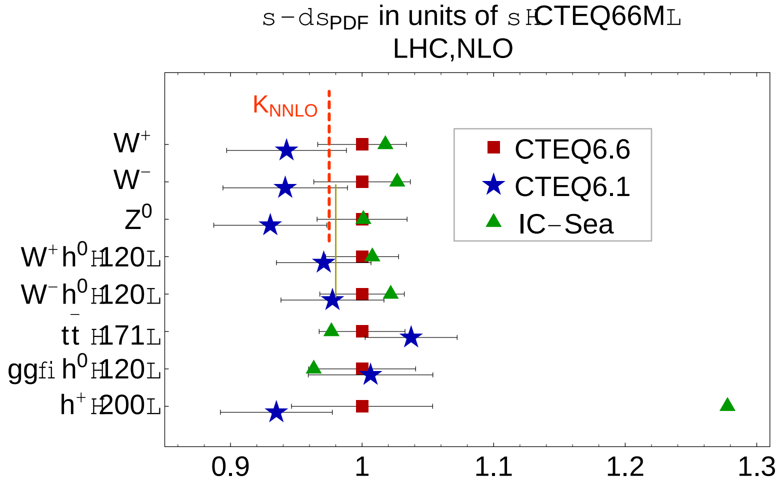
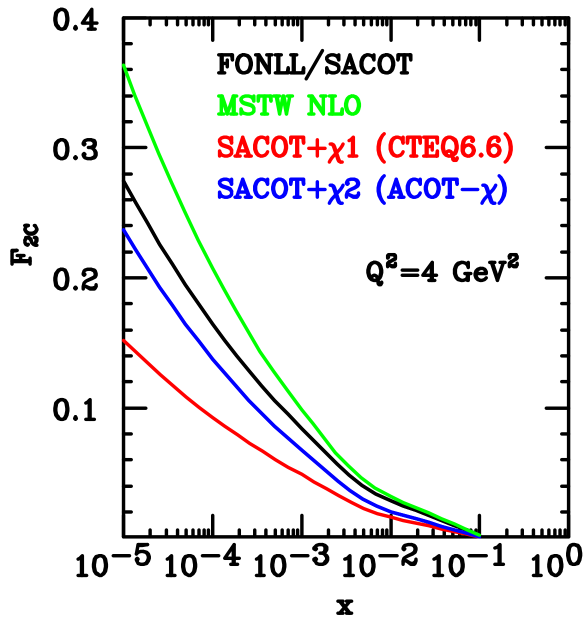


(Nadolsky et al., 2008)

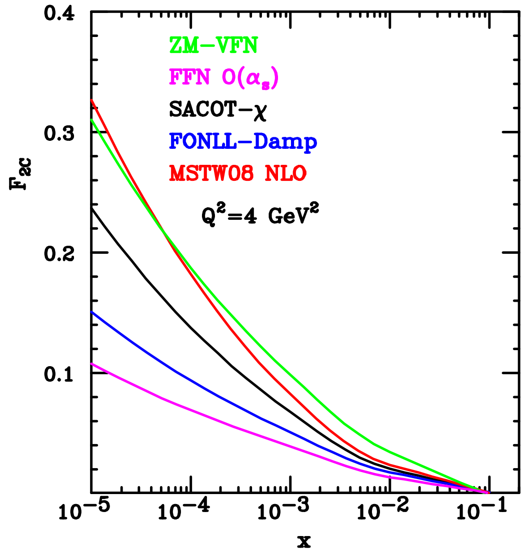
RECENT PROGRESS: THE LES HOUCHES 2009 BENCHMARKS



(Rojo et al., 2010)

- TR, FONLL AND ACOT FOR DIS BENCHMARKED AT NLO AND NNLO
- $O(\alpha_s)$ FONLL, ACOT COINCIDE EXACTLY, TR' DIFFERS BY SUBLEADING $O(\alpha_s^2(m_c))$ Q^2–INDEP. TERM
- DIFFERENCES BETWEEN DAMPING PRESCRIPTIONS SIZABLE

THE PROBLEM OF DAMPING TERMS:
PHENOMENOLOGY



- IMPACT OF SUBLEADING TERMS SIZABLE CLOSE TO THRESHOLD
- DIFFERENCE BETWEEN DIFFERENT PRESCRIPTIONS (ACOT-χ–SCALING, FONLL-DAMPING, MSTW-MATCHING) AS LARGE AS DIFFERENCE BETWEEN FFN (NO DGLAP RESUMMATION FOR CHARM) AND ZMVFN (NO CHARM MASS)

THE PROBLEM OF DAMPING TERMS:
PHENOMENOLOGY

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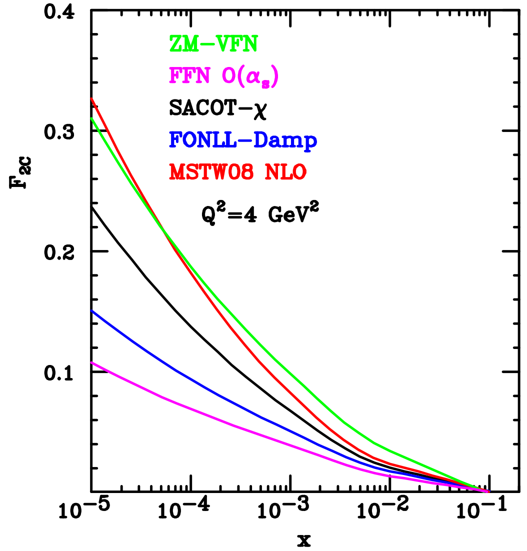
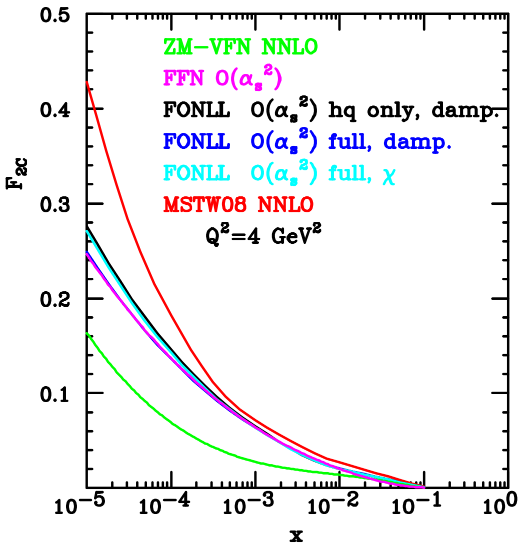
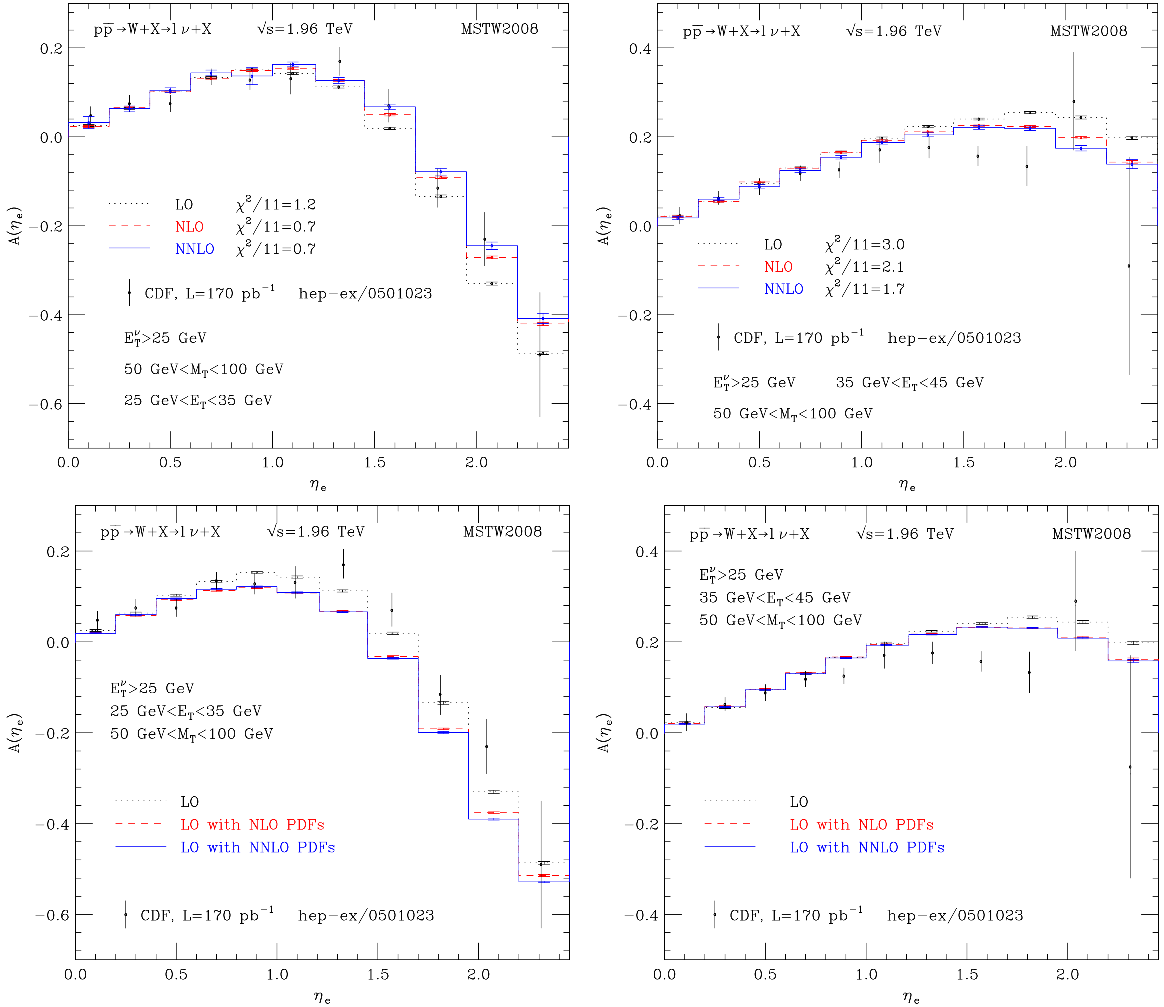


THE SOLUTION:
GO UP ONE ORDER



- IF EVERYTHING AT ONE EXTRA ORDER IN α_s, DIFFERENCES MINOR
- IN FONLL, CAN COMBINE $O(\alpha_s^2)$ TREATMENT OF HQ WITH STANDARD NLO $O(\alpha_s)$ TREATMENT OF LIGHT QUARKS $\Rightarrow$ EXCELLENT APPROX TO FULL RESULT (s.f., Laenen, Nason, Rojo 2010)
- RECENT PROGRESS: $O(\alpha^3)$ MASSLESS LIMIT OF HQ PRODUCTION COEFF. FCTNS. COMPUTED (Bierenbaum, Blümlein, Klein, 2009)

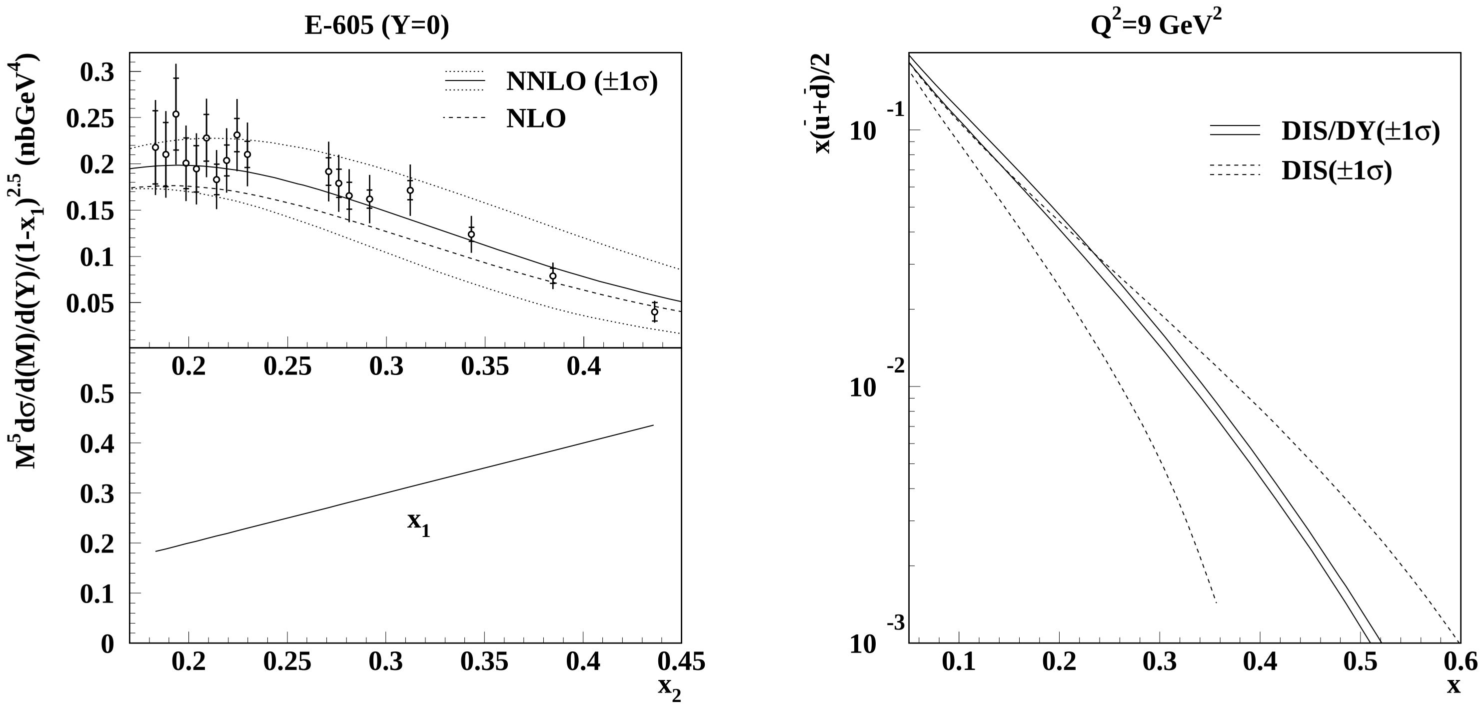
YET ANOTHER EXAMPLE: THE W CHARGE ASYMMETRY
NNLO NEEDED FOR STANDARD CANDLES



Catani, Ferrera, Grazzini, 2010

- NNLO CORRECTIONS VISIBLY IMPROVE AGREEMENT WITH DATA
- EFFECT ON MATRIX ELEMENT COMPARABLE TO EFFECT ON PDFs, BUT IN DIFFERENT REGIONS

NNLO PARTON DISTRIBUTIONS?



Alekhin, Melnikov, Petriello, 2006

- CURRENT GLOBAL PDF FITS ARE NLO
- MSTW08 NNLO TREATS DIS AT NNLO, JETS AT NLO, DRELL-YAN AT LO+K–FACTORS
- ALEKHIN-SERIES FITS GENUINELY NNLO, BUT ONLY DIS+ TWO FIXED–TARGET DY EXPERIMENTS INCLUDED
- BUT IMPACT NOT NEGLIGIBLE...

PROGRESS: THEORY AND PHENOMENOLOGY

NNLO: HOW IT ALL STARTED (Moch, Vermaseren, Vogt, 2004)

The Results

Anomalous dimensions in Mellin space

– One-loop : Gross, Wilczek '73

$$\gamma_{\rm ns}^{(0)}(N) \quad = \quad C_F\Big(2(\mathbf{N_-}+\mathbf{N_+})S_1-3\Big)$$

– Two-loop : Floratos, Ross, Sachrajda '79 ; Gonzalez-Arroyo, Lopez, Ynduráin '79

$$\gamma_{\rm ns}^{(1)+}(N) \;=\; 4C_AC_F\left(2\,\mathbf{N_+}S_3-\frac{17}{24}-2S_{-3}-\frac{28}{3}S_1+(\mathbf{N_-}+\mathbf{N_+})\left[\frac{151}{18}S_1+2S_{1,-2}-\frac{11}{6}S_2\right]\right)$$
$$+4C_Fn_f\left(\frac{1}{12}+\frac{4}{3}S_1-(\mathbf{N_-}+\mathbf{N_+})\left[\frac{11}{9}S_1-\frac{1}{3}S_2\right]\right)+4{C_F}^2\left(4S_{-3}+2S_1+2S_2-\frac{3}{8}\right.$$
$$\left.+\mathbf{N_-}\Big[S_2+2S_3\Big]-(\mathbf{N_-}+\mathbf{N_+})\Big[S_1+4S_{1,-2}+2S_{1,2}+2S_{2,1}+S_3\Big]\right)$$

$$\gamma_{\rm ns}^{(1)-}(N) \;=\; \gamma_{\rm ns}^{(1)+}(N)+16C_F\left(C_F-\frac{C_A}{2}\right)\left((\mathbf{N_-}-\mathbf{N_+})\Big[S_2-S_3\Big]-2(\mathbf{N_-}+\mathbf{N_+}-2)S_1\right)$$

– Compact notation : $\mathbf{N_\pm}f(N) = f(N\pm1)$, $\qquad \mathbf{N_{\pm i}}f(N) = f(N\pm i)$

– Three-loop :

S.M., Vermaseren, Vogt '04

$$\gamma^{(2)-}_{\rm ns}(N) = 16 C_A C_F n_f \Big(\frac{3}{2}\zeta_3 - \frac{5}{4} - \frac{10}{9}S_{-3} - \frac{10}{9}S_3 + \frac{4}{3}S_{1,-2} - \frac{2}{3}S_{-4} + 2S_{1,1} - \frac{25}{9}S_2 + \frac{257}{27}S_1 - \frac{2}{3}S_{-3,1} - \mathbf{N}_+ \Big[S_{2,1} - \frac{2}{3}S_{3,1} - \frac{2}{3}S_4\Big]$$

$$- (\mathbf{N}_+ - 1)\Big[\frac{23}{18}S_3 - S_2\Big] - (\mathbf{N}_- - \mathbf{N}_+)\Big[S_{1,1} + \frac{1237}{216}S_1 + \frac{11}{18}S_3 - \frac{317}{108}S_2 + \frac{16}{9}S_{1,-2} - \frac{2}{3}S_{1,-2,1} - \frac{1}{3}S_{1,-3} - \frac{1}{2}S_{1,3} - \frac{1}{2}S_{2,1}$$

$$- \frac{1}{3}S_{2,[illegible]2} - S_1\zeta_3 - \frac{1}{2}S_{3,1}\Big]\Big) + 16 C_F C_A^2 \Big(\frac{1657}{576} - \frac{15}{4}\zeta_3 + 2S_{[illegible]5} + \frac{31}{6}S_{[illegible]4} - 4S_{[illegible]4,1} - \frac{67}{9}S_{[illegible]3} - 2S_{[illegible]3,[illegible]2} + \frac{11}{3}S_{[illegible]3,1} + \frac{3}{2}S_{[illegible]2}$$

$$6S_{-2}\zeta_3 \quad 2S_{-2,-3} + 3S_{-2,-2} \quad 4S_{-2,-2,1} \quad 8S_{-2,1,-2} \quad \frac{1883}{54}S_1 \quad 10S_{1,-3} \quad \frac{16}{3}S_{1,-2} \quad 12S_{1,-2,1} + 4S_{1,3} \quad 4S_{2,-2} \quad \frac{5}{2}S_{4} + \frac{1}{2}S_5$$

$$+ \frac{176}{9}S_2 + \frac{13}{3}S_3 + (\mathbf{N}_- + \mathbf{N}_+ - 2)\Big[3S_1\zeta_3 + 11S_{1,1} - 4S_{1,1,[illegible]2}\Big] + (\mathbf{N}_- - \mathbf{N}_+)\Big[\frac{9737}{432}S_1 - 3S_{1,[illegible]4} + \frac{19}{6}S_{1,[illegible]3} + 8S_{1,[illegible]3,1} + \frac{91}{9}S_{1,[illegible]2}$$

$$6S_{1,-2,-2} \quad \frac{29}{3}S_{1,-2,1} + 8S_{1,1,-3} \quad 16S_{1,1,-2,1} \quad 4S_{1,1,3} \quad \frac{19}{4}S_{1,3} + 4S_{1,3,1} \quad 3S_{1,4} + 8S_{2,-2,1} \quad 2S_{2,3} \quad S_{3,-2} + \frac{11}{12}S_{3,1} \quad S_{4,1} \quad 4S_{2,-3}$$

$$+ \frac{1}{6}S_{2,-2} - \frac{1967}{216}S_2 + \frac{121}{72}S_3\Big] - (\mathbf{N}_- - \mathbf{N}_+)\Big[3S_2\zeta_3 - 7S_{2,1} - 3S_{2,1,-2} + 2S_{2,-2,1} - \frac{1}{4}S_{2,3} - \frac{3}{2}S_{3,-2} - \frac{29}{6}S_{3,1} - \frac{11}{4}S_{4,1} + \frac{1}{2}S_{2,-3} - S_{2,-2}\Big]$$

$$+ \mathbf{N}_+\Big[\frac{28}{9}S_3 \quad \frac{2376}{216}S_2 \quad \frac{8}{3}S_4 \quad \frac{5}{2}S_5\Big]\Big) \quad 16 C_F n_f^2 \Big(\frac{17}{144} \quad \frac{13}{27}S_1 \quad \frac{2}{9}S_2 + (\mathbf{N}_- \quad \mathbf{N}_+)\Big[\frac{2}{9}S_1 \quad \frac{11}{54}S_2 + \frac{1}{18}S_3\Big]\Big) + 16 C_F{}^2 C_A \Big(\frac{45}{4}\zeta_3$$

$$- \frac{151}{64} - 10S_{[illegible]5} - \frac{89}{6}S_{[illegible]4} - 20S_{[illegible]4,1} - \frac{134}{9}S_{[illegible]3} - 2S_{[illegible]3,[illegible]2} - \frac{31}{3}S_{[illegible]3,1} + 2S_{[illegible]3,2} - \frac{9}{2}S_{[illegible]2} - 18S_{[illegible]2}\zeta_3 + 10S_{[illegible]2,[illegible]3} - 6S_{[illegible]2,[illegible]2}$$

$$+ 8S_{-2,-2,1} - 28S_{-2,1,-2} + 46S_{1,-3} + \frac{26}{3}S_{1,-2} - 48S_{1,-2,1} - \frac{28}{3}S_{1,2} - \frac{185}{6}S_3 - 8S_{1,3} - 2S_{2,-2} - 4S_5 - (\mathbf{N}_- + \mathbf{N}_+ - 2)\Big[9S_1\zeta_3 - \frac{133}{36}S_1$$

$$+ \frac{209}{6}S_{1,1} - 14S_{1,1,[illegible]2} - \frac{242}{18}S_2 + 9S_{2,[illegible]2} + \frac{33}{4}S_4 - 3S_{3,1} + \frac{14}{3}S_{2,1}\Big] + (\mathbf{N}_- + \mathbf{N}_+)\Big[17S_{1,[illegible]4} - \frac{107}{6}S_{1,[illegible]3} - 32S_{1,[illegible]3,1} - \frac{173}{9}S_{1,[illegible]2}$$

$$-16S_{1, 2, 2}+\frac{103}{3}S_{1, 2,1}-2S_{1, 2,2}-36S_{1,1, 3}-56S_{1,1, 2,1}+8S_{1,1,3}-\frac{109}{9}S_{1,2}-4S_{1,2, 2}+\frac{43}{3}S_{1,3}-8S_{1,3,1}-11S_{1,4}+\frac{11}{3}S_{2,2}$$

$$21S_{2,-3} \quad 30S_{2,-2,1} \quad 4S_{2,1,-2} \quad 5S_{2,3} \quad S_{4,1} + \frac{31}{6}S_{2,-2} \quad \frac{67}{9}S_{2,1}\Big] \quad (N_- \quad N_-)\Big[9S_2\zeta_3 + 2S_{2,-3} + 4S_{2,-2,1} \quad 12S_{2,1,-2} \quad 2S_{2,3}$$

$$-13S_{4,1}+\frac{1}{2}S_{2, 2}+\frac{11}{2}S_{-}-\frac{33}{2}S_{3,1}-\frac{59}{9}S_3+\frac{127}{6}S_{2,1}-\frac{1153}{72}S_2\Big]+N \Big[8S_{3, 2}+\frac{4}{3}S_{3,1}-2S_{3,2}-14S_5+\frac{23}{6}S_4+\frac{73}{3}S_3+\frac{151}{24}S_2\Big]\Big)$$

$$+16C_F{}^2n_f\Big(\frac{23}{16}-\frac{3}{2}\zeta_3-\frac{4}{3}S_{-3,1}-\frac{59}{36}S_2-\frac{4}{3}S_{-4}-\frac{20}{9}S_{-3}+\frac{20}{9}S_1-\frac{8}{3}S_{1,-2}-\frac{8}{3}S_{1,1}-\frac{4}{3}S_{1,2}-N_+\Big[\frac{25}{9}S_3-\frac{4}{3}S_{3,1}-\frac{1}{3}S_4\Big]$$

$$-(N \quad -1)\Big[\frac{67}{36}S_2-\frac{4}{3}S_{2,1}+\frac{4}{3}S_3\Big]-(N \quad +N \quad)\Big[S_1\zeta_3-\frac{325}{144}S_1-\frac{2}{3}S_{1, 3}+\frac{32}{9}S_{1, 2}-\frac{4}{3}S_{1, 2,1}+\frac{4}{3}S_{1,1}+\frac{16}{9}S_{1,2}-\frac{4}{3}S_{1,3}$$

$$+\frac{11}{18}S_2-\frac{2}{3}S_{2, 2}-\frac{10}{9}S_{2,1}+\frac{1}{2}S_4-\frac{2}{3}S_{2,2}-\frac{8}{9}S_3\Big]\Big)+16C_F{}^3\Big(12S_{5}-\frac{29}{32}-\frac{15}{2}\zeta_3-9S_{4}-24S_{4,1}-4S_{3, 2}-6S_{3,1}$$

$$4S_{-3,2}+3S_{-2} \quad 25S_3 \quad 12S_{-2}\zeta_3 \quad 12S_{-2,-3}+24S_{-2,1,-2} \quad 52S_{1,-3} \quad 4S_{1,-2} \quad 48S_{1,-2,1} \quad 4S_{3,-2}+\frac{67}{2}S_2 \quad 17S_4$$

$$+(N_- + N_- \quad 2)\Big[6S_1\zeta_3 \quad \frac{31}{8}S_1 \quad 35S_{1,1} \quad 12S_{1,1,-2} \quad S_{1,2}+10S_{2,-2}+S_{2,1}+2S_{2,2} \quad 2S_{3,1} \quad 3S_5\Big]+(N_- \quad N_+)\Big[23S_{1,-3}$$

$$-22S_{1, 4}+32S_{1, 3,1}-2S_{1, 2}-8S_{1, 2, 2}-30S_{1, 2,1}-6S_{1,3}+4S_{1, 2,2}-40S_{1,1, 3}-48S_{1,1, 2,1}-8S_{1,2, 2}-4S_{1,2,2}-8S_{1,3,1}$$

$$+4S_{1,4}-28S_{2, 2,1}-4S_{2,1,2}-4S_{2,2,1}-4S_{3,1,1}-4S_{3,2}+8S_{2,1, 2}-26S_{2, 3}-2S_{2,3}-4S_{3, 2}-3S_{2, 2}-3S_{2,2}+\frac{3}{2}S_4\Big]$$

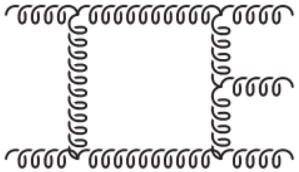
$$+(N \quad -N \quad)\Big[12S_{2,1, 2}-6S_2\zeta_3-2S_{2, 3}-3S_{2,3}+2S_{3, 2}-\frac{81}{4}S_{2,1}+14S_{3,1}-5S_{2, 2}-\frac{1}{2}S_{2,2}-\frac{15}{8}S_2+\frac{1}{2}S_3-13S_{4,1}+4S_5\Big]$$

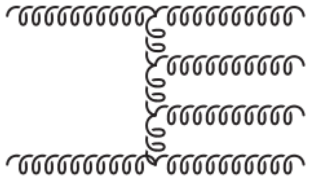
$$+N_-\Big[14S_4-\frac{265}{8}S_2-\frac{87}{4}S_3-4S_{4,1}-4S_5\Big]\Big)$$

THEORETICAL PROGRESS

- MORE LEGS: NLO MULTILEG
- MORE PROCESSES: NNLO PRECISION OBSERVABLES
- MORE LOOPS: BEYOND NNLO

THEORETICAL PROGRESS:
NLO MULTILEG





- ONE-LOOP MATRIX ELEMENTS: POLES FROM LOOP INTEGRAL
  - KNOWN FOR ALL $2 \to 2$ PROCESSES
  - INCREASING NUMBER OF $2 \to 3$ PROCESSES
  - $2 \to 4$ MAJOR CHALLENGE
- TREE-LEVEL: POLES FROM SOFT–COLLINEAR EMISSION

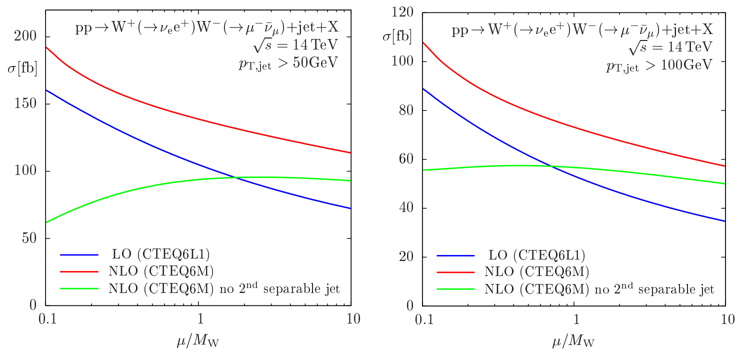
METHODOLOGICAL PROGRESS

ANALYTIC AND NUMERICAL METHODS $\Rightarrow$ AUTOMATION

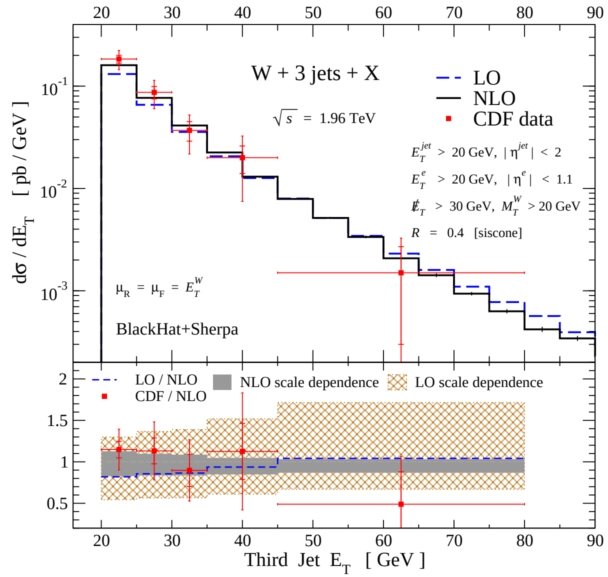
- TENSOR REDUCTION AND FORM FACTOR DECOMPOSITION $\Rightarrow$ GOLEM (T.Binoth, J.P.Guillet et al.)
- UNITARITY AND MULTIPARTICLE CUTS $\Rightarrow$ BLACKHAT (Z.Bern, D.Kosower, L.Dixon et al.)
- REDUCTION AT THE INTEGRAND LEVEL $\Rightarrow$ CUTTOOLS (G.Ossola, C.Papadopoulos, R.Pittau et al.)
- NUMERICAL D-DIMENSIONAL UNITARITY $\Rightarrow$ ROCKET (K.Ellis, W.Giele, G.Zanderighi et al.)
- REAL RADIATION BASED ON LO EVENT GENERATORS $\Rightarrow$ SHERPA(F.Krauss et al.), MADDIPOLE/MADFKS(F.Maltoni, R.Frederix et al.), TEVJET(M.Seymour et al.),. . .

NLO MULTILEG:
RECENT RESULTS

- $2 \to 3$:
  - $pp \to VV + j$
    (S.Dittmaier et al., J.Campbell et al.)
  - $pp \to H + 2j$
    (S.Dittmaier et al., J.Campbell et al., S.Badger & N.Glover, P.Mastrolia & C.Williams)
  - $pp \to VVV$
    (A.Lazopoulos, K.Melnikov, F.Petriello; G.Bozzi et al.; G.Ossola et al., J.Campbell et al.)
- $2 \to 4$: $W + 3j$
  (Blackhat+Sherpa, Rocket);
  $Z + 3j$
  (Blackhat+Sherpa)
- $2 \to 5$: $e^+e^- \to 5j$
  (Madgraph+MadFKS+Rocket)

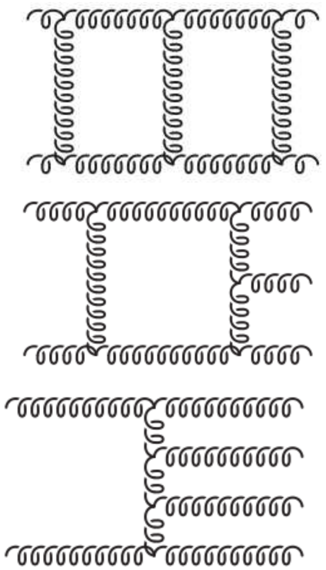


(S.Dittmaier et al.,)



(Blackhat+Sherpa)

THEORETICAL PROGRESS:
NNLO



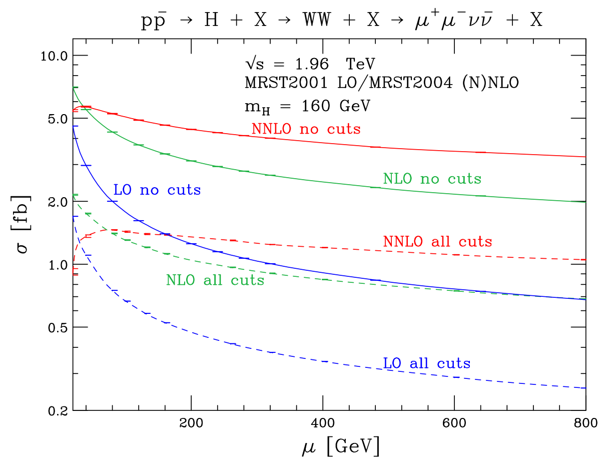
- TWO-LOOP MATRIX ELEMENTS: KNOWN FOR ALL MASSLESS $2 \to 2$ PROCESSES
- ONE-LOOP MATRIX ELEMENTS: USUALLY KNOWN FROM NLO CALCULATIONS
- TREE-LEVEL: POLES FROM TWO PARTONS NONTRIVIAL

TECHNICAL CHALLENGE: EXTRACT ALL POLES FROM REAL DIAGRAMS BEFORE DOING INTEGRALS

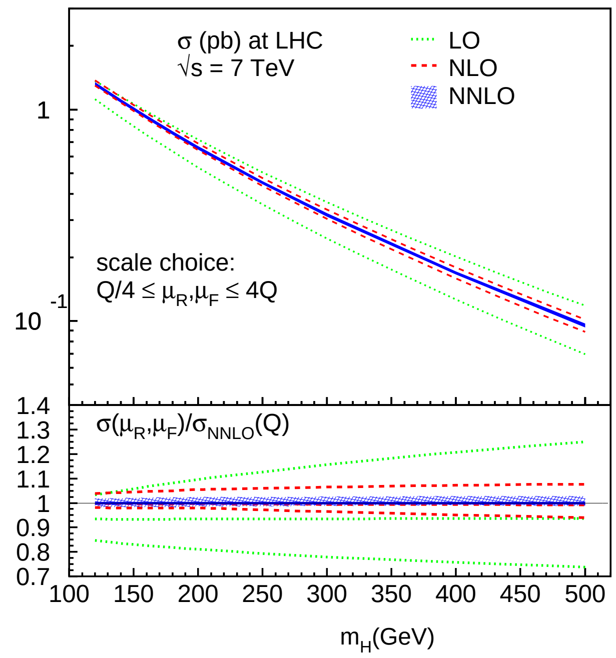
- SECTOR DECOMPOSITION TO SEPARATE AUTOMATICALLY OVERLAPPING DIVERGENCES, NUMERICAL INTEGRATION (T.Binoth, G.Heinrich+ C,Anastasiou, K.Melnikov, F.Petriello)
- APPROXIMATION IN UNRESOLVED LIMITS (DIPOLE, ANTENNA SUBTRACTION), ANALYTIC INTEGRATION
(S.Catani and M.Grazzini, T.Gehrmann and N.Glover)

NNLO : RECENT RESULTS

- HIGGS PRODUCTION:
  - *gg* FUSION: FULLY EXCLUSIVE INCLUDING $H \to \gamma\gamma$, $H \to VV$ DECAY
    (Anastasiou, Melnikov, Petriello; Catani, Grazzini)
  - HIGGS AT TEVATRON INCLUDING FULL FINAL STATE CUTS
    (Anastasiou, Dissertori, Grazzini, Stöckli, Webber)
  - VECTOR BOSON FUSION
    (P.Bolzoni, F.Maltoni, S.Moch and M.Zaro)
- W/Z PRODUCTION: FULLY EXCLUSIVE INCLUDING DECAYS
  (Melinikov, Petriello; Catani et al.)
- $e^+e^- -> 3j$; MATCHING OF NNLO AND RESUMMATION
  (T.Gehrmann et al; T.Becher and M.Schwartz)
- PROGRESS TOWARDS JETS AND TOP AT HADRON COLLIDERS
  - TWO–LOOP MATRIX ELEMENTS KNOWN FOR $2j$, Vj, PARTLY FOT $qq \to t\bar{t}$, $gg \to t\bar{t}$
  - PROGRESS TOWARDS CLASSIFICATION AND COMPUTATION OF ANTENNA SUBTRACTIONS
    (T.Gehrmann et al)
  - PROGRESS TOWARDS TOP PAIRS



(C.Anastasiou et al.)



(Bolzoni et al.)

BEYOND NNLO

INTEGRAL TECHNIQUES

- SECTOR DECOMPOSITION (T.Binoth, G.Heinrich)
- MELLIN-BARNES INTEGRATION (A.V.Smirnov et al.)
- REDUCTION TO MASTER INTEGRALS (K. Chetyrkin et al.)
- DIFFERENTIAL EQUATIONS (Kotikov; E.Remmidi and T.Gehrmann)

RESULTS

- THREE–LOOP VERTEX FUNCTIONS (FORM FACTORS): $\gamma^* \to q\bar{q}$, $H \to gg$
  (Baikov, Chetyrkin, Smirnov, Steinhauser; Glover et al.)
- THREE–LOOP STATIC QUARK (COULOMB) POTENTIAL
  (Smirnov, Steinhauser; Anzai, Kiyo, Sumino)
- FOUR–LOOP TWO–POINT FUNCTIONS: BJORKEN SUM RULE AND R RATIO
  (Baikov, Chetyrkin, Kühn)

PHENOMENOLOGICAL PROGRESS

Q: WHY is NNLO not included in parton fits?

PHENOMENOLOGICAL PROGRESS

Q: WHY IS NNLO NOT INCLUDED IN PARTON FITS?

A: CONVOLUTIONS ARE HARD!

TOWARDS A SOLUTION: GRID–BASED METHODS

ORIGINAL IDEA

EXPANSION OF PDFS ON BASES OF POLYNOMIALS (PASCAUD, ZOMER, 2001

- PRECOMPUTE CONVOLUTION WITH BASIS FUNCTIONS
- EXPAND PDF OVER BASIS
- CONVOLUTIONS REDUCED TO LINEAR COMBINATIONS → MATRIX MULTIPLICATION

THE GRID IDEA

(CARLI, SALAM, SIEGERT 2005)

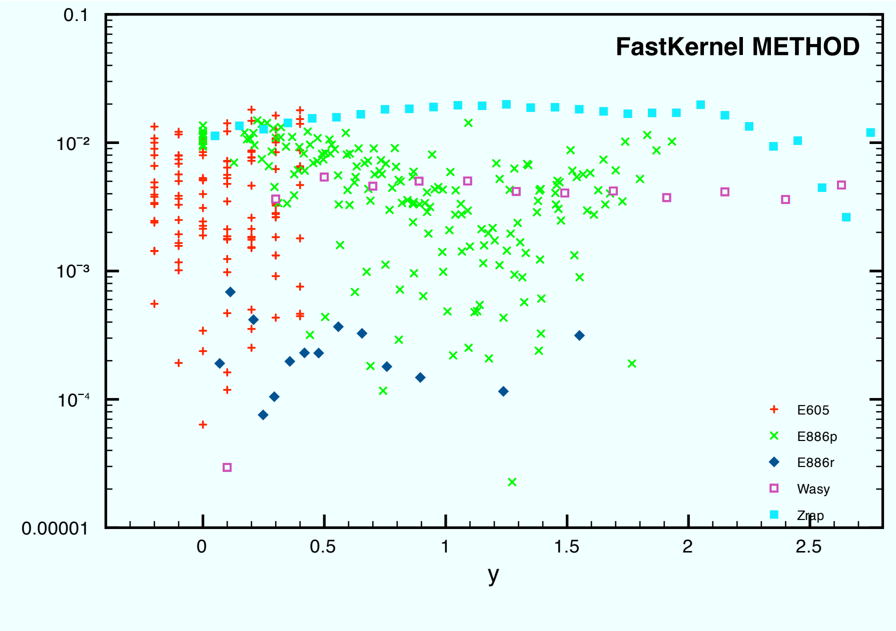
- REPRESENT PDFS ON INTERPOLATED GRID
- BASIS FCTNS ↔ INTERPOLATING FCTNS
- DO CONVOLUTIONS OVER BASIS FUNCTIONS (IF MONTE CARLO USED, BASIS FCTNS → WEIGHTS FOR MC INTEGRAL)
- GRID CAN BE OPTIMIZED

$$dx_1 \int_{x_{0,2}}^1 dx_2\, f_a(x_1) f_b(x_2) C^{ab}(x_1, x_2) \to \sum_{\alpha,\beta=1}^{N_x} f_a(x_{1,\alpha}) f_b(x_{2,\beta}) \int_{x_{0,1}}^1 dx_1 \int_{x_{0,2}}^1 dx_2\, \mathcal{I}^{(\alpha,\beta)}(x_1, x_2) C^{ab}(x_1, x_2)$$

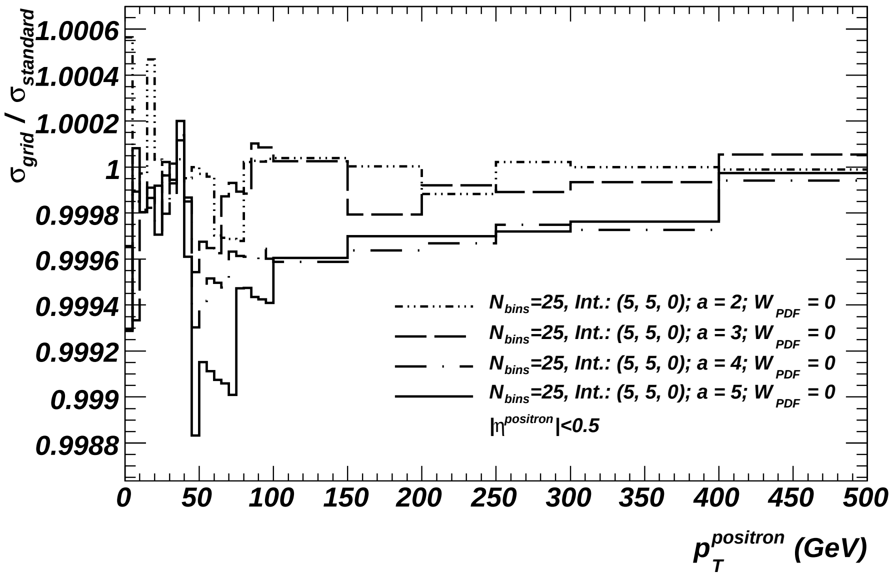
GRID–BASED METHODS
SOME RECENT NLO IMPLEMENTATIONS:

- **FASTNLO**: FAST INTERFACE FOR JET CROSS SECTIONS (Kluge, Rabbertz, Wobisch 2006)
- **FASTKERNEL**: GRID METHOD INTERFACED TO N-SPACE COMPUTATION OF GLAP GREEN FUNCTIONS, INTERFACED TO FASTNLO FOR JETS AND TO SUITABLE FAST-DY (NNPDF, 2010)
- **APPLGRID**: OPTIMIZED GRID, POTENTIALLY UNIVERSAL INTERFACE, IMPLEMENTED FOR JETS, W AND Z PRODUCTION (Carli et al., 2010)

FASTKERNEL PERC. ACCURACY



APPLGRID REL. ACCURACY



THE DETERMINATION OF α_s

THE PROBLEM OF α_s:

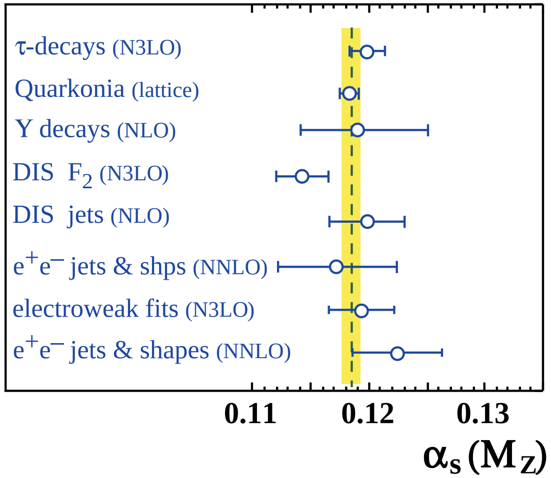
RECENT EXPERIMENTAL & THEORETICAL PROGRESS HAS LED TO A LARGE NUMBER OF NEW MEASUREMENTS/EXTRACTIONS OF α_s:

- NNLO JET OBSERVABLES: RE-ANALYSIS OF LEP DATA FOR EVENT SHAPES; THREE-JET OBSERVABLES
- NLO JETS IN DIS: NEW COMBINED HERA DATA
- NLO JETS AT THE TEVATRON RUN II

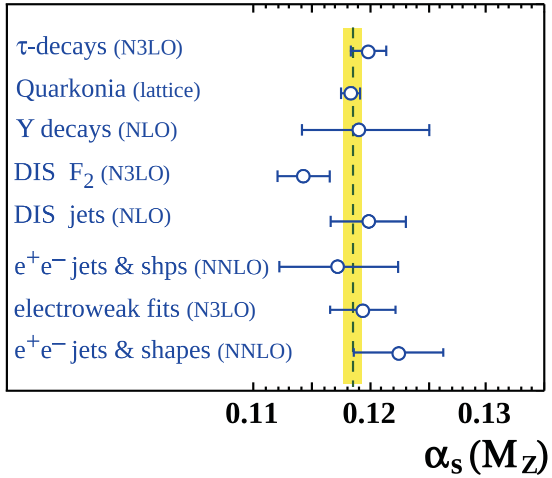
NEW GLOBAL α_s DETERMINATION BY BETHKE (2009):

$$\alpha_s = 0.1184 \pm 0.0007$$

ADOPTED BY PDG WEB UPDATE (2009)
"older measurements not included because [of]...their large ... uncertainties"



IS THERE A PROBLEM?

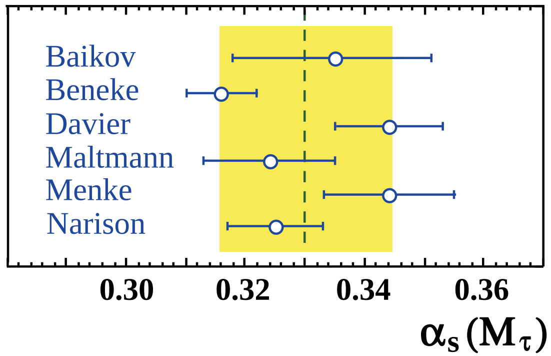


THE DETERMINATIONS INCLUDED IN THE BETHKE/PDG AVERAGE:

τ DECAYS

- OBSERVABLE $R_\tau = \frac{\tau^- \to \text{hadrons}\,\nu_\tau}{\tau^- \to e^- \bar{\nu}_e \nu_\tau}$
- POOR CONVERGENCE OF THE PERTURBATIVE EXPANSION IMPROVED USING ANALYTIC CONTINUATION (CIPT) $\to$ RENORMALONS, BOREL SUMMATION (Davier et al, Beneke et al)
- ELECTROWEAK AND HIGHER TWIST CORRECTIONS
- RESULT OBTAINED AS THE AVERAGE OF SIX DETERMINATION, THE TWO MOST PRECISE OF WHICH DIFFER AT THREE SIGMA; UNCERTAINTY TAKEN AS THE DIFFERENCE IN CENTRAL VALUE BETWEEN THESE TWO MOST PRECISE DETERMINATIONS

α_s FROM τ



LATTICE

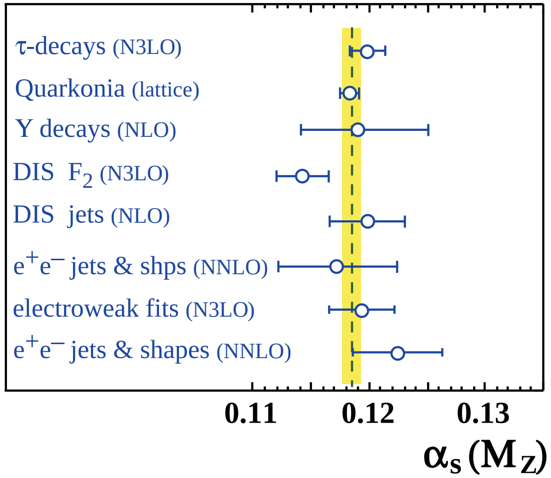
- OBSERVABLE $\Upsilon' - \Upsilon$ SPECTRUM (C.Davis et al., HPQCD coll.)
- VERY SMALL UNCERTAINTY GIVEN KNOWN LATTICE SYSTEMATICS ISSUES

Υ DECAYS

- OBSERVABLE $R_\Upsilon = \frac{\Upsilon \to \gamma g g}{\Upsilon \to g g g}$
- STATE–OF–THE–ART NLO NRQCD (N. Brambilla et al.) AND CLEO DATA

DIS F_2

- OBSERVABLE CLAIMED TO BE NONSINGLET F_2, ANALYSIS PERFORMED AT N^{3}LO: $\alpha_s = 0.114 \pm 0.002$ (NLO: $\alpha_s = 0.115 \pm 0.002$)
- HOWEVER, NO PURE NONSINGLET DATA AVAILABLE: GLOBAL FIT PERFORMED IN ORDER TO SEPARATE SINGLET AND NONSINGLET COMPONENTS (Blümlein, Böttcher, Guffanti, 2006)
- MSTW (2010) FROM A FULL GLOBAL FIT SEE A CHANGE OF 2 SIGMA FROM NLO TO NNLO $\alpha_s = 0.1202^{+0.0012}_{-0.0015}$ TO $\alpha_s = 0.1171 \pm 0.0014$
- IF PURELY NONSINGLET DATA AND TRUNCATED MOMENTS ARE USED (NO ASSUMPTIONS) NLO RESULT FROM NONSINGLET SCALING VIOLATIONS IS (s.f. et al., 2002) $\alpha_s = 0.124^{+0.005}_{-0.008}$



DIS JETS

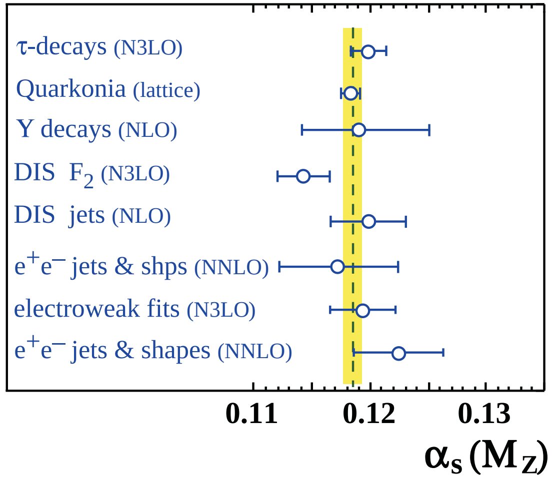
- COMBINATION OF ALL ZEUS+H1 NLO JET OBSERVABLES
- WILL BE UPDATED WITH NEW COMBINED DATA

e^+e^- JETS

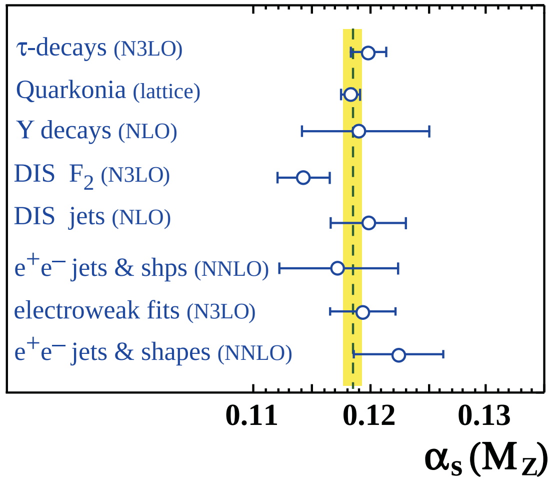
- NNLO REANALYSIS OF ALEPH AND JADE DATA
- LARGE DISCREPANCY BETWEEN RESULTS FOUND USING ANALYTIC HADRONIZATION CORRECTIONS (JADE) VS. ESTIMATES BASED ON MONTE CARLOS (ALEPH USING PYTHIA)

GLOBAL ELECTROWEAK FIT

- STATE–OF–THE ART FIT FROM THE GFITTER GROUP
- α_s DETERMINED FROM R RATIO, KNOWN TO N^{3}LO



GLOBAL ELECTROWEAK FIT



- STATE–OF–THE ART FIT FROM THE GFITTER GROUP
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SO, WHAT'S THE PROBLEM?

- MANY VERY PRECISE DETERMINATIONS RELY ON DUBIOUS ASSUMPTIONS
- NLO/NNLO CHANGE LARGER THAN EXPECTED
- MANY LESS PRECISE BUT THEORETICALLY RELIABLE DATA NOT USED

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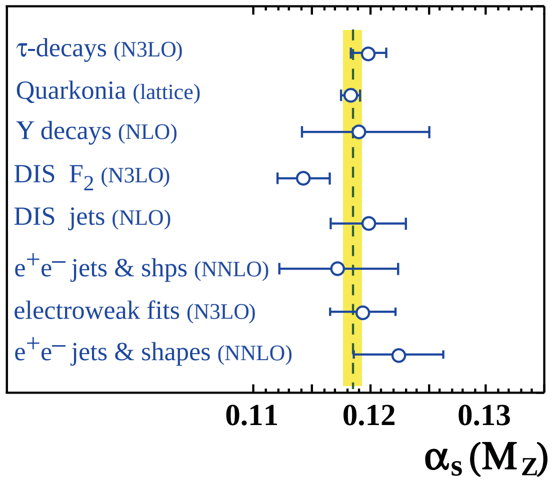

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A REASSESSMENT IS NEEDED!