Progress in QCD for e^+e^- annihilations and hadron collisions

Mrinal Dasgupta

University of Manchester

Frascati, LC 10 workshop, December 2 2010

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Introduction

- LHC/LC interplay crucial to progress of the field. Many examples e.g. Z discovery at a $p\bar{p}$ machine. Precision studies at LEP establishing standard model.
- At LEP QCD established as theory of strong interactions. Now improve understanding of QCD. Important link to success of future particle physics program.
- Much recent activity in pushing the frontiers of QCD. I will aim to summarise main developments.

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QCD theoretical methods

- Fixed-order calculations
- All-order resummation
- Non-perturbative analytical methods
- MC tools

All these fields are developing rapidly ! Catalysed by LHC.... I shall leave out discussion of MC tools. Also heavy quarks, small-x etc.

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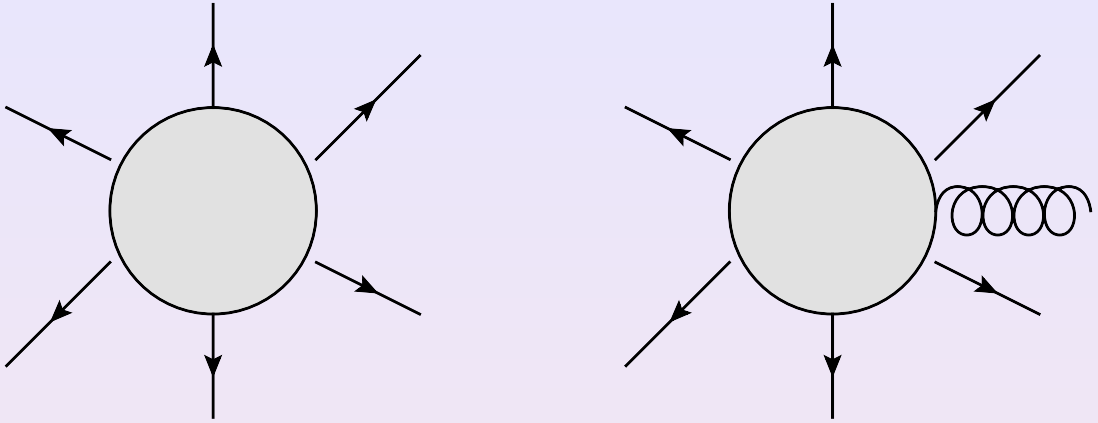
Fixed-order calculations



Work for IRC safe quantities only.

$$O\left(p_1, p_2 \ldots p_n\right) \rightarrow O\left(p_1, p_2 \ldots p_{n+1}\right)$$

For $E_{n+1} \rightarrow 0$ and/or $\vec{p}_{n+1}$ collinear to $\vec{p}_i$ IRC safety implies $O_{n+1} \rightarrow O_n$.

Sounds trivial but often is not.....e.g seeded cone jet algorithms.

In this case one can write generally

$$O = c_0 + c_1(Q,\mu)\alpha_s(\mu) + c_2(Q,\mu)\alpha_s^2(\mu) + \cdots$$

where $\mu \sim Q$ is a renormalisation scale.

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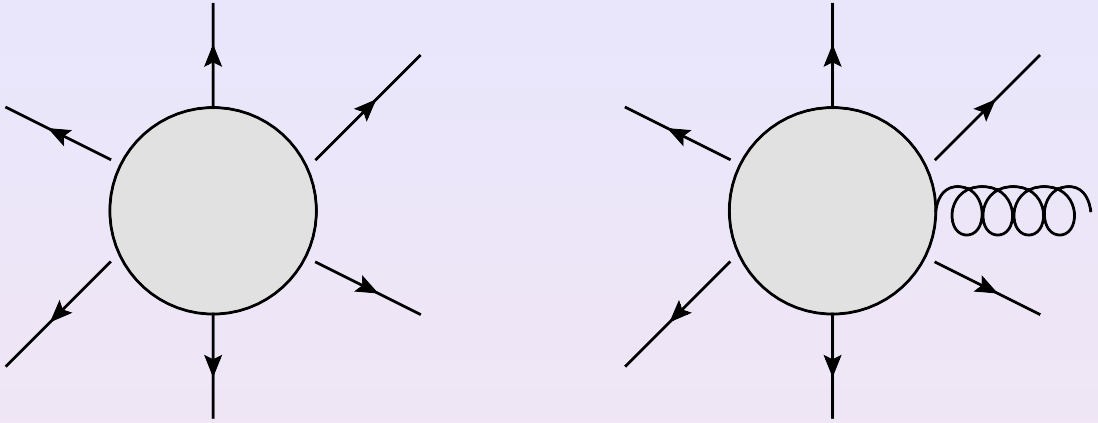

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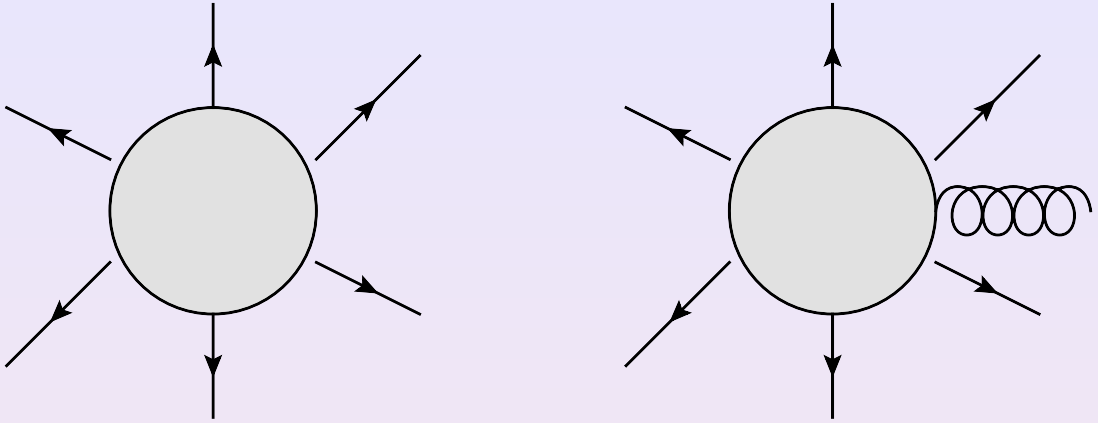

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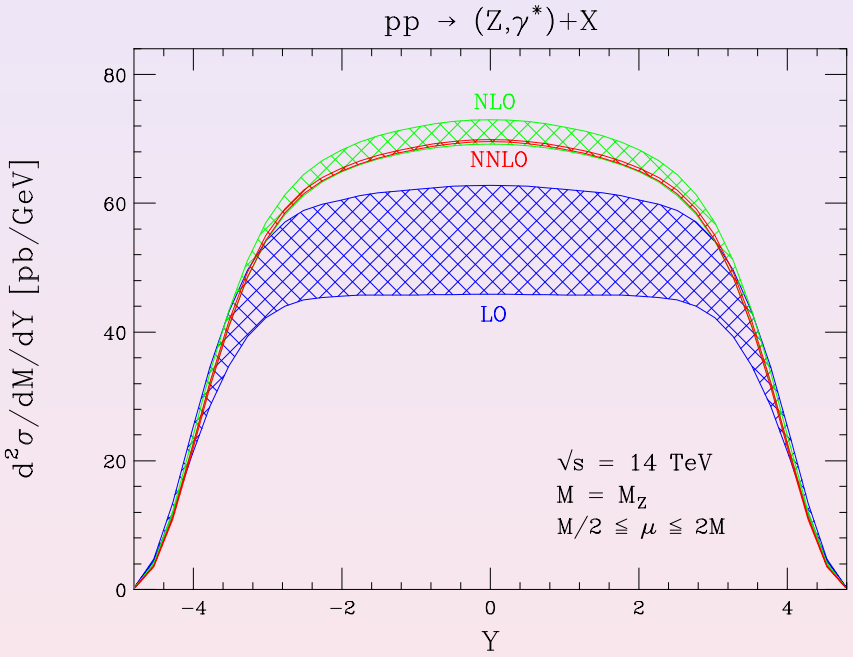
LO vs NLO vs NNLO

μ is arbitrary in principle. For truncation to make sense $\mu \sim Q$. Scale dependence at any order formally is of first uncalculated order.



Anastasiou et.al 2003 Rule of thumb : LO ok to within a factor of 2. NLO to about 10% and NNLO a few percent.

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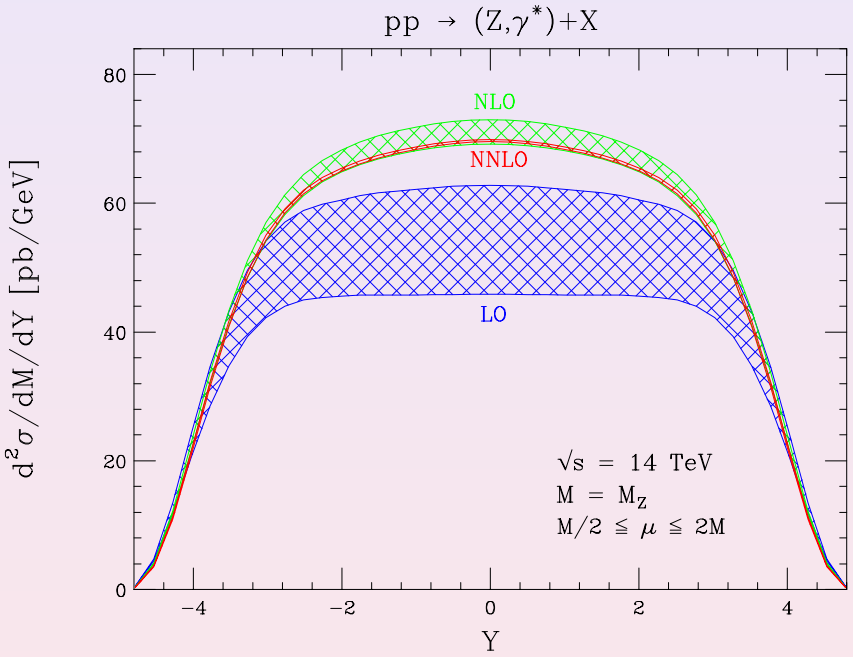

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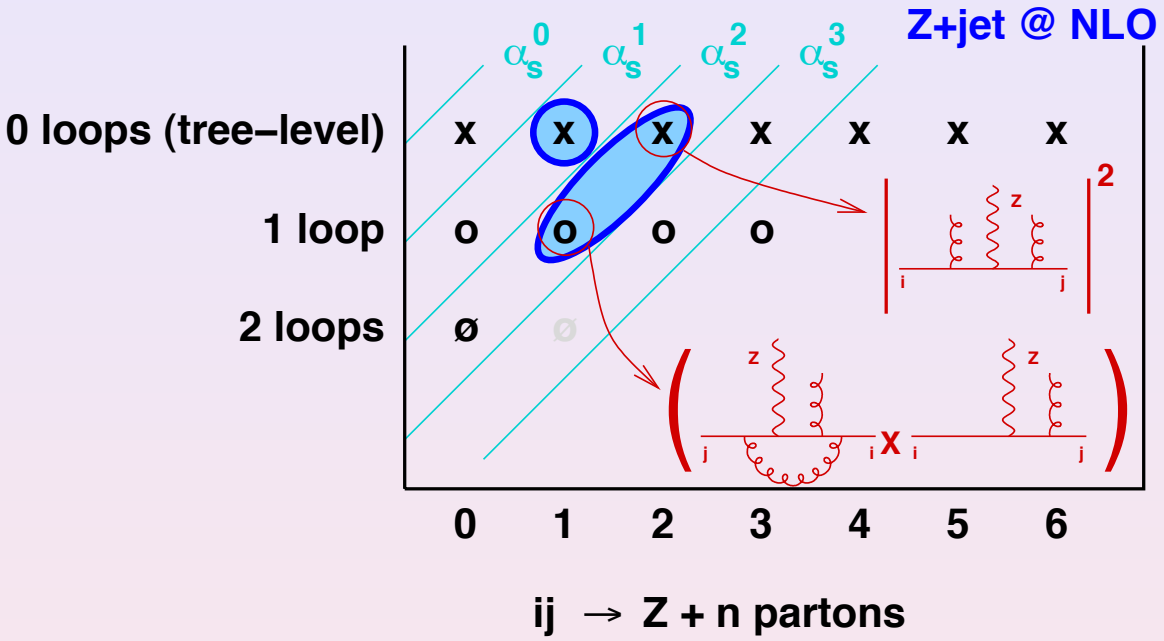

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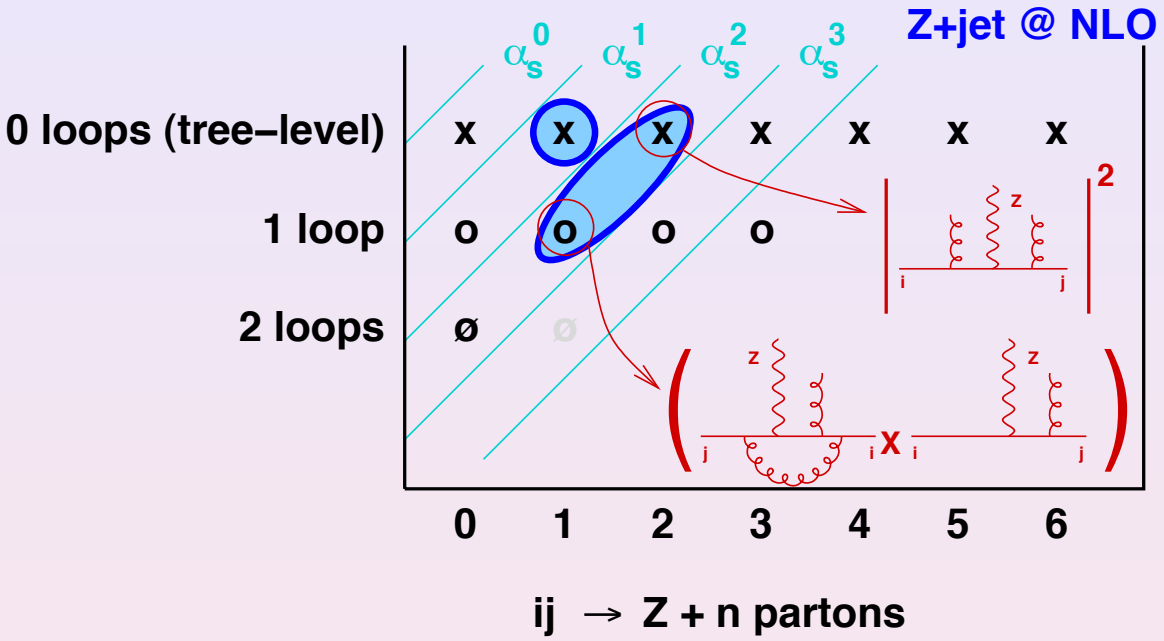

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Resummed calculations

Fixed-order fails when there is hierarchy of scales in problem.

At LHC $\sqrt{s} \gg p_t \gg m_t, M_H \gg \Lambda$. PT coefficients develop logs $\alpha_s^n \ln^m Q/Q_0$. Example is thrust $1 - T = \tau$ in e^+e^-.

$$\frac{1}{\sigma}\frac{d\sigma}{d\tau} \sim \sum_n \frac{1}{\tau}\alpha_s^n \ln^{2n-1}\frac{1}{\tau} + \cdots$$

Many other examples such as transverse momentum Q_T of a Drell-Yan pair. Need to resum large logarithms to all-orders to get a good description of data:

$$\frac{1}{\sigma}\frac{d\sigma}{d\tau} \sim \frac{d}{d\tau} e^{-C_F \alpha_s \ln^2 \frac{1}{\tau} + \cdots}$$

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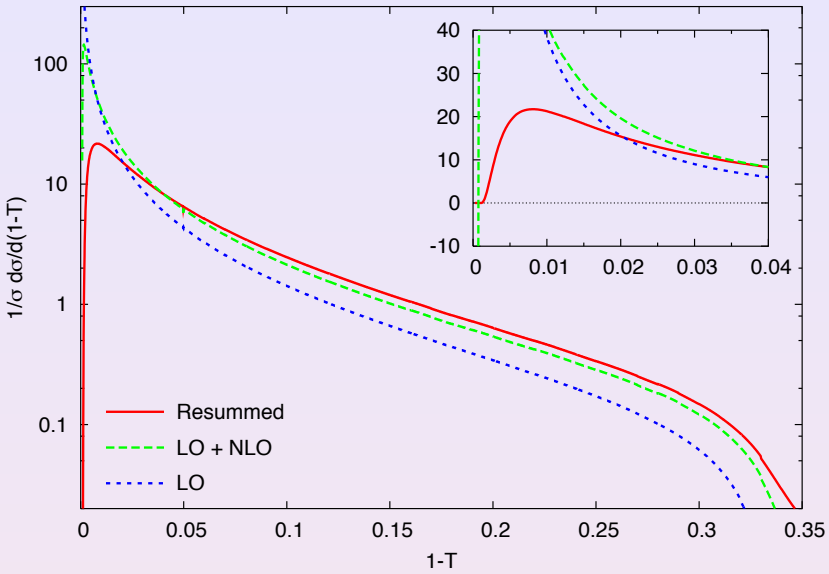

Exponentiation implies

$$\frac{d\sigma}{dV} \sim \frac{d}{dV} \exp\left[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \cdots\right]$$

State of the art was NLL for 15 years (with NNLL for Drell-Yan Q_T) until N^3LL from SCET arrived ! Becher and Schwartz 2008
So far only $1-T$ and heavy jet-mass. Will be significant for LC precision.

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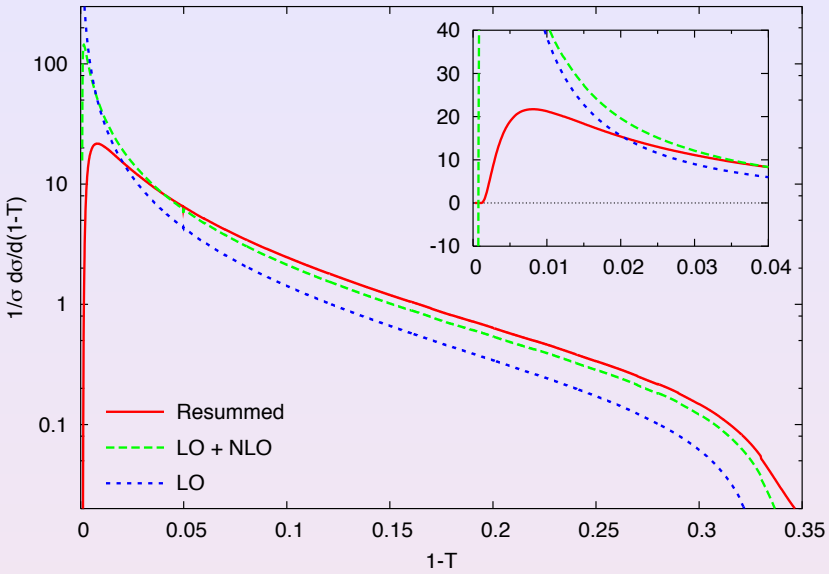

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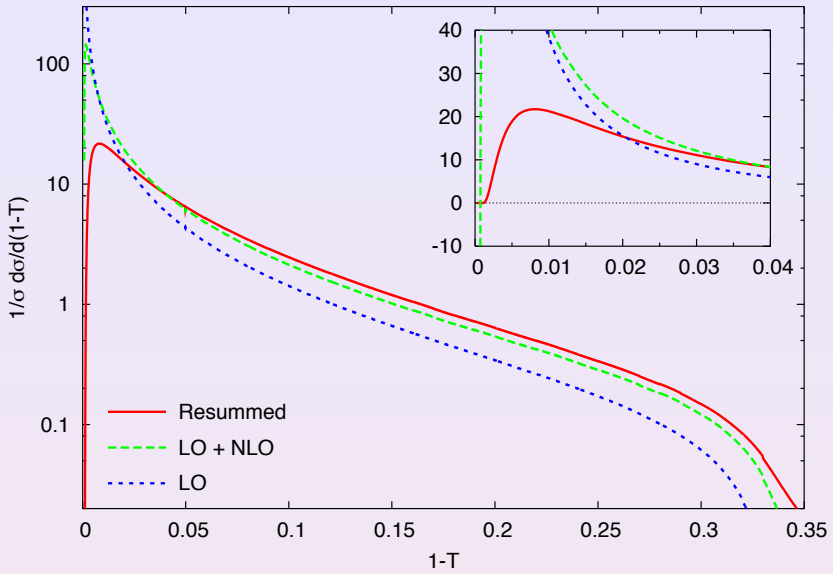

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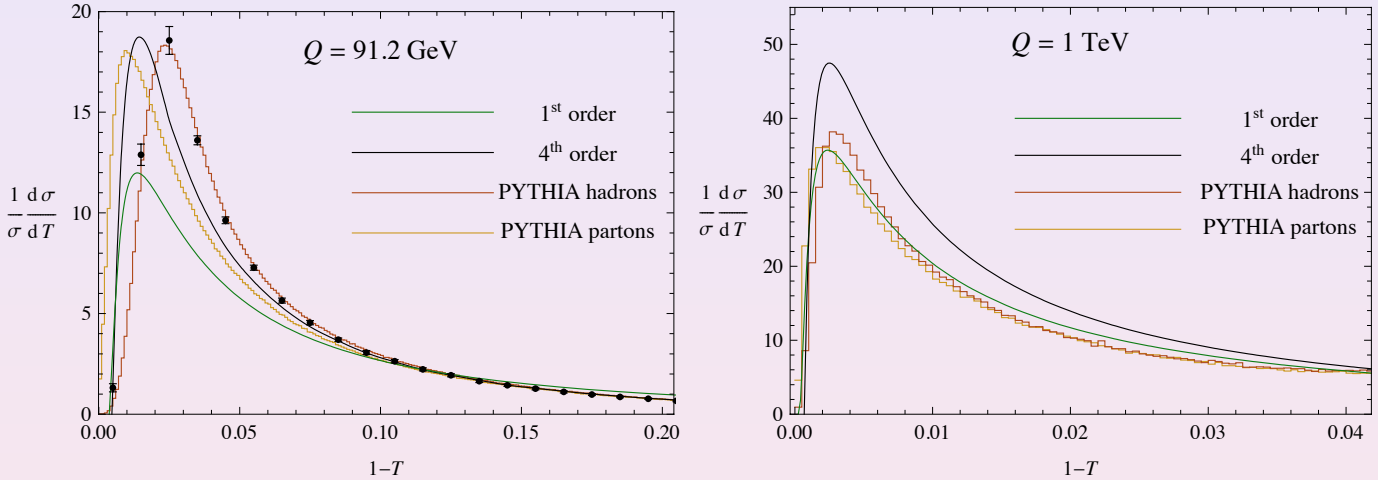
The need for precision

Take a look at N^3LL + NNLO vs PYTHIA.



LL MC's could underestimate backgrounds at ILC by up to 30 %!

Becher and Schwartz 2008

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Resummation at LHC

Developing art. More complex environment due to cuts on beam, jet-algorithms, multiple scale issues, initial state colored partons etc. Nevertheless progress.

- Hadronic event shapes

  Banfi, Salam, Zanderighi 2010

- Shapes of individual jets

  Banfi,MD,Khelifa-Kerfa, Marzani 2010

Comparisons to MC for the former. Comparisons to data shd follow.

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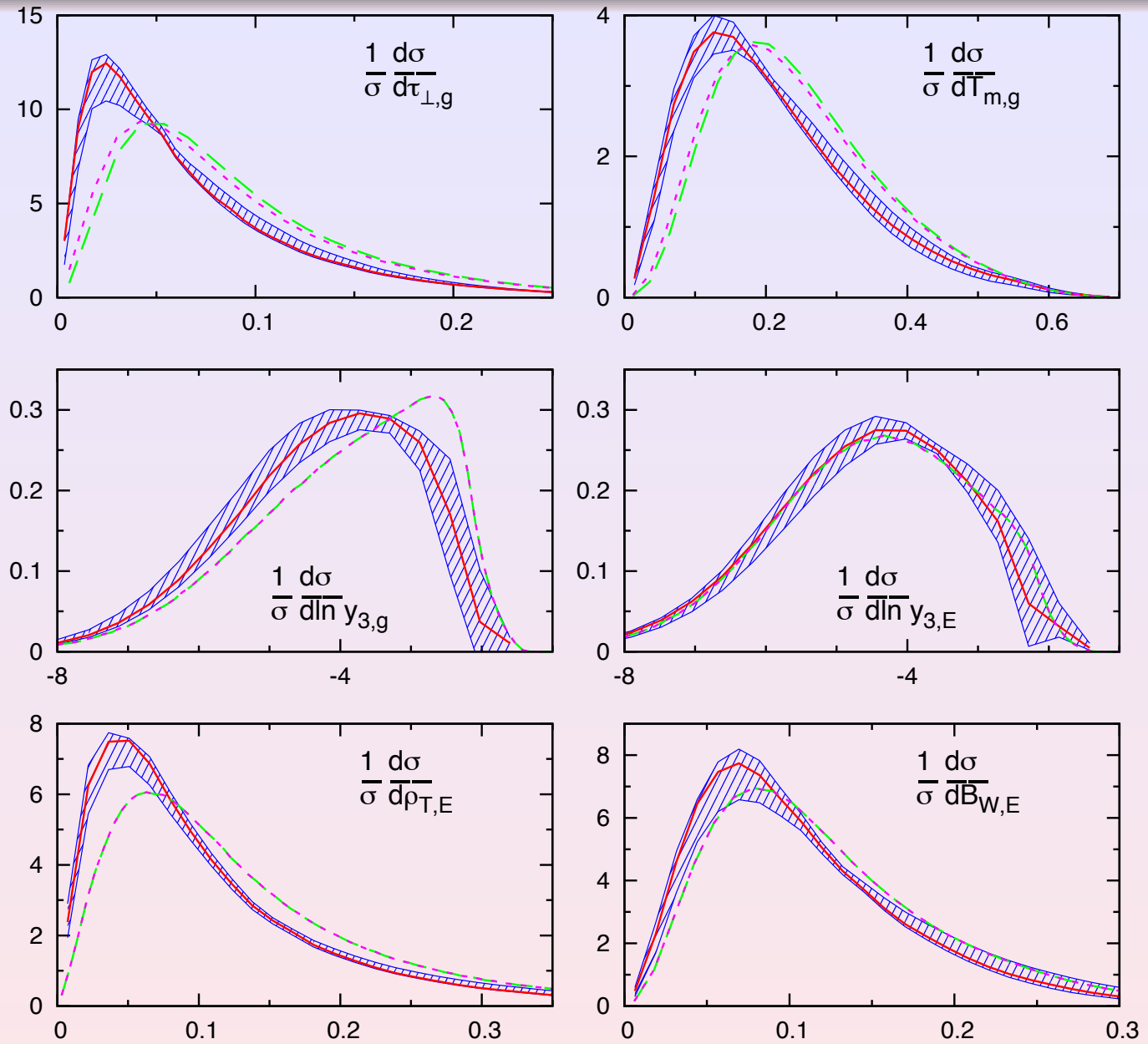

LHC, 14 TeV

$p_{t1} > 200$ GeV, $|y_{jets}| < 1$, $\eta_C = 1.5$

NLO + NLL (all uncert.)

NLO ($|y| < 5$) + NLL

Herwig all partons

Resummation summary

- High precision resummed calcs becoming available for e^+e^-.
- Several challenges remain for LHC. State of the art is NLL but limited to global event shapes.
- NLL predictions in leading N_c for jet masses and jet shapes.
- Comparison of analytical resummation to MC is always instructive.
- Field seeing rapid developments.

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Non-perturbative effects

Even if we could compute all loops it wouldnt be good enough.

Perturbation theory eventually breaks down

$$O = \sum_n c_n \alpha_s^n, \; c_n \sim n!$$

Translates into ambiguity $\delta O \sim \frac{\Lambda^p}{Q^p}$. Precision in QCD limited by NP ! NP handled by MC but in some cases interesting and succesful analytical models. E.g Dokshitzer Webber or Korechemsky-Sterman shape-function models for e^+e^- event shapes.

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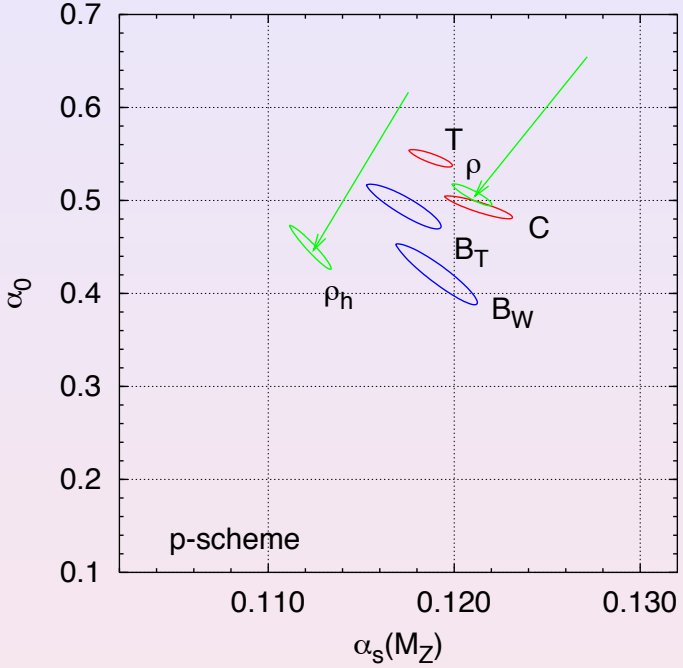
DW model

Model based on universal IR finite extension of α_s. Simple to understand, easy to apply (and rule out !).



MD and Salam 2003

$$\alpha_0 = \frac{1}{\mu_I} \int_0^{\mu_I} dk_t \alpha_s(k_t)$$

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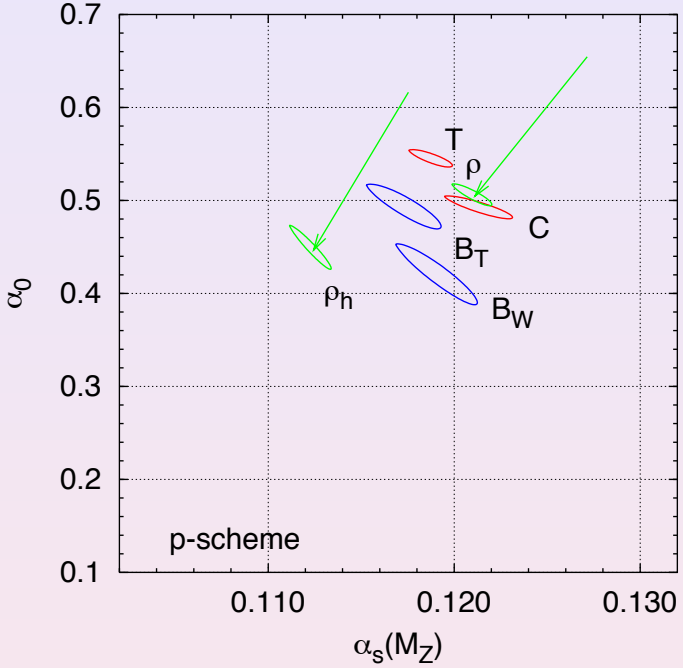

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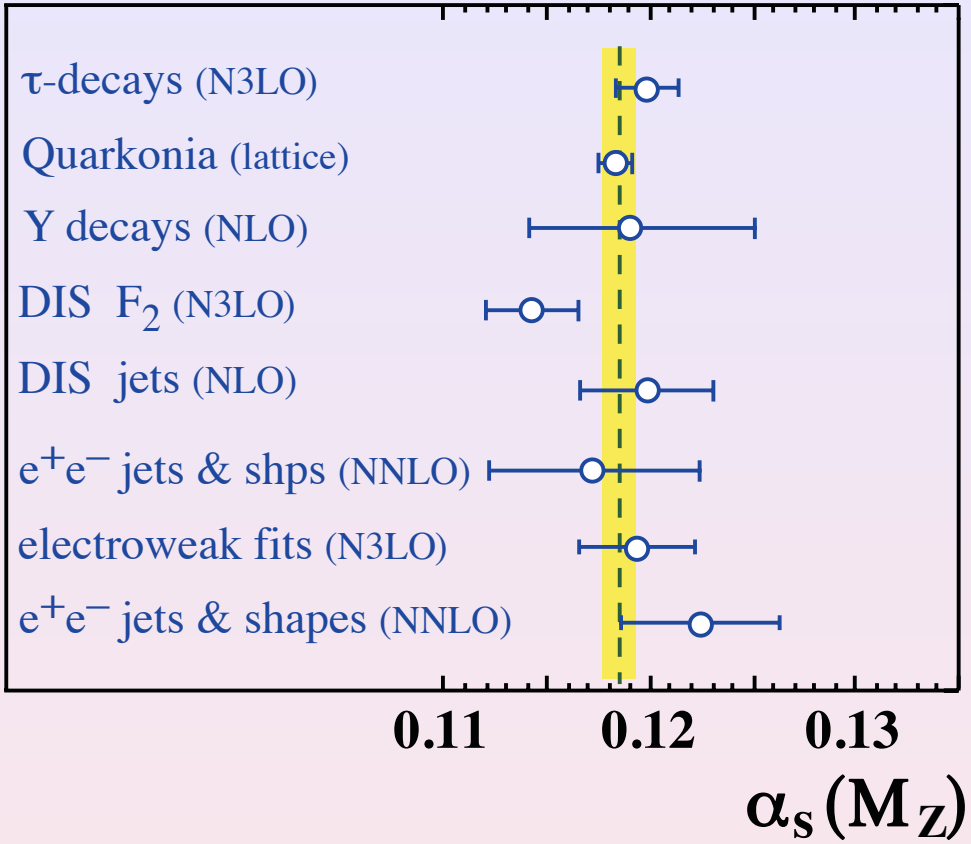
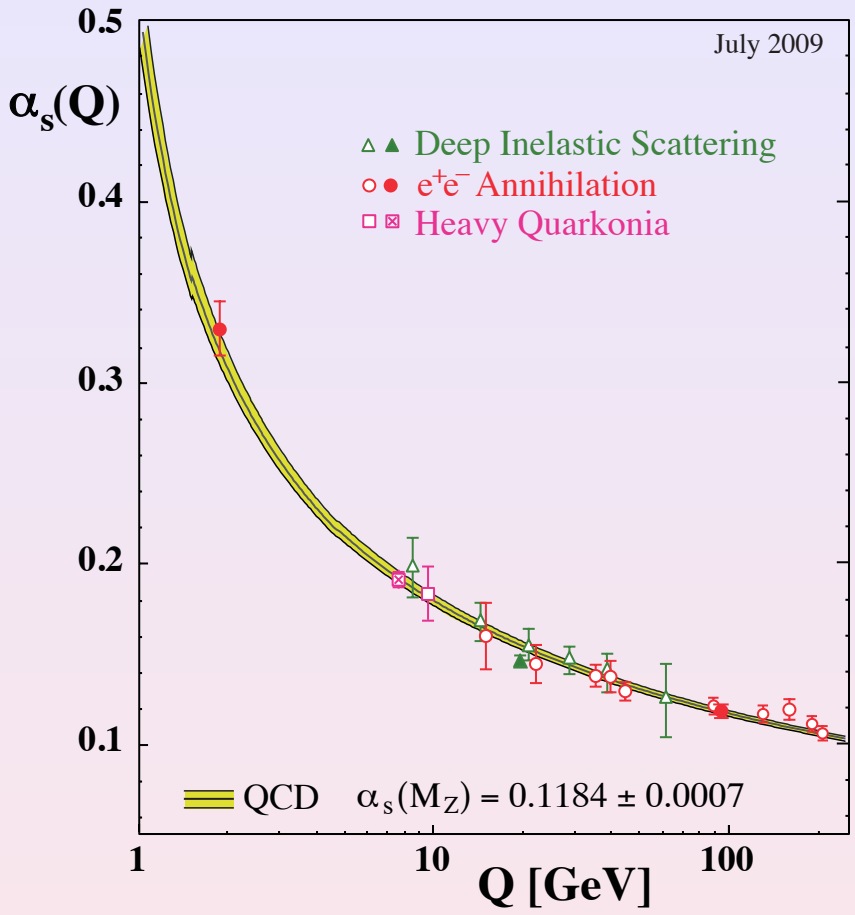
Summary of $\alpha_s(M_Z)$ measurements



Note: recent SCET calculations not yet included inspite of small theory uncertainty.

Bethke 2009


July 2009
$\alpha_s(Q)$
Deep Inelastic Scattering
e^+e^- Annihilation
Heavy Quarkonia
QCD $\alpha_s(M_Z) = 0.1184 \pm 0.0007$
0.5
0.4
0.3
0.2
0.1
1
10
100
Q [GeV]

Bethke 2009

Extend to LHC jets?

LHC considerably more complex. Diverse NP phenomena in hadronisation and UE. How to separate? Can we apply any of the LEP wisdom?

One can at least try... Simplicity of DW model means much time wont be wasted either !

Example: Average change in p_t of jet due to hadronisation? Due to UE? Due to PT radiation? Relevant for studies involving new physics.

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LHC jets (contd.)

3 easy steps to compute hadronisation corrections without bloodshed:

- Produce a soft gluon and compute the change in p_t as it flies outside the jet. $\delta p_t = \omega$.
- Apply the soft emission probability $dP = 2\frac{C_A}{\pi}\frac{d\omega}{\omega}\frac{d\theta}{\theta}\alpha_s(\omega\theta)$.
- Compute the average effect as $< \delta p_t >= \int dP \delta p_t$

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Result is

$$\frac{2C_A}{\pi}\alpha_0\mu_I\frac{1}{R}$$

A striking singular dependence on R with a normalisation related to e^+e^- thrust!

Translates into 1GeV/R. MD,Magnea,Salam 2008 MD,Delenda 2009

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$$2\frac{C_A}{\pi}\int \alpha_s(k_t)\frac{d\omega}{\omega}\frac{d\theta}{\theta}\delta(\omega\theta - k_t)dk_t = \frac{2C_A}{\pi}\int \alpha_s(k_t)dk_t \int_R^1 \frac{d\theta}{\theta^2}$$

Result is

$$\frac{2C_A}{\pi}\alpha_0\mu_I\frac{1}{R}$$

A striking singular dependence on R with a normalisation related to e^+e^- thrust!

Translates into 1GeV/R. MD,Magnea,Salam 2008 MD,Delenda 2009

LHC jets (contd.)

3 easy steps to compute hadronisation corrections without bloodshed:

- Produce a soft gluon and compute the change in p_t as it flies outside the jet. $\delta p_t = \omega$.
- Apply the soft emission probability $dP = 2\frac{C_A}{\pi}\frac{d\omega}{\omega}\frac{d\theta}{\theta}\alpha_s(\omega\theta)$.
- Compute the average effect as $< \delta p_t >= \int dP \delta p_t$

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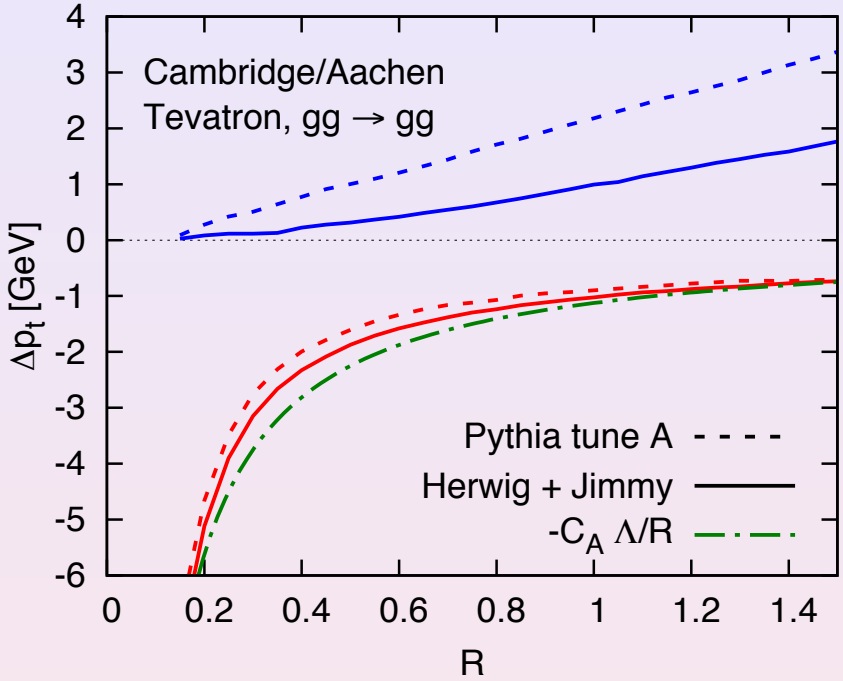
Compare with MC



Agreement for hadronisation. UE varies as R^2. PT contribution as $\ln R$.

Different R dependences give rise to the idea of an optimal R depending on parameters of study e.g jet flavour, p_T etc.

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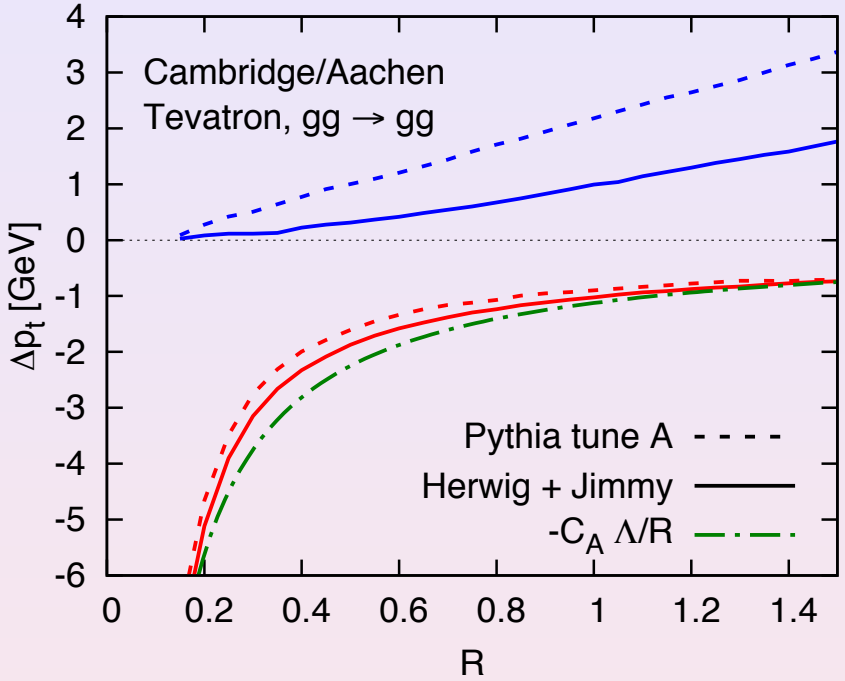

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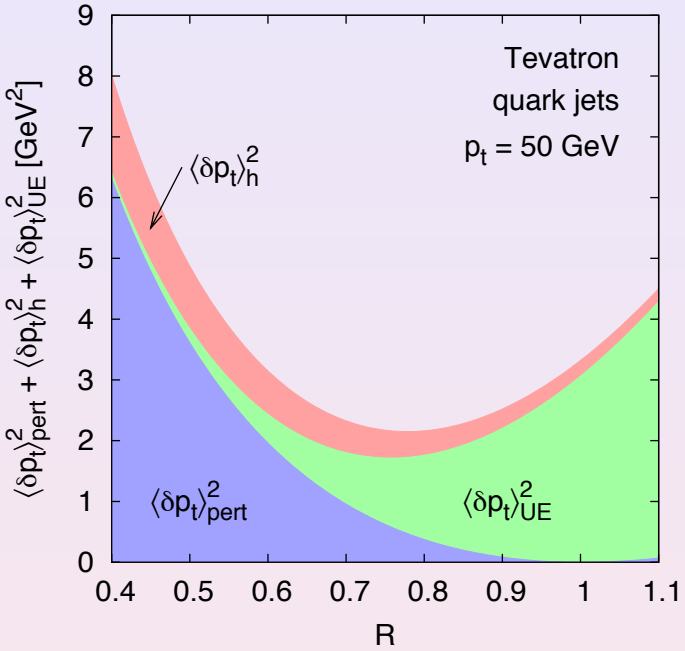
Optimal R



MD, Magnea,Salam 2008 Related to developments in jet substructure studies. Search for boosted heavy new objects.

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Jet physics developments

- Tremendous progress in field. New IRC safe jet algorithms SISCONE and ant-k_t
- k_t algorithm speeded up $N^3 \to N \ln N$
- Studies of optimal jet parameters for new physics discoveries a very active area
- New techniques for jet substructure to distinguish boosted massive particle decays from QCD jets and to reconstruct mass-peaks.

Salam 2009, "Towards jetography"

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Conclusions

Things are moving fast ! QCD will be in great shape for precision measurements at a linear collider.

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