Summary of the WG on

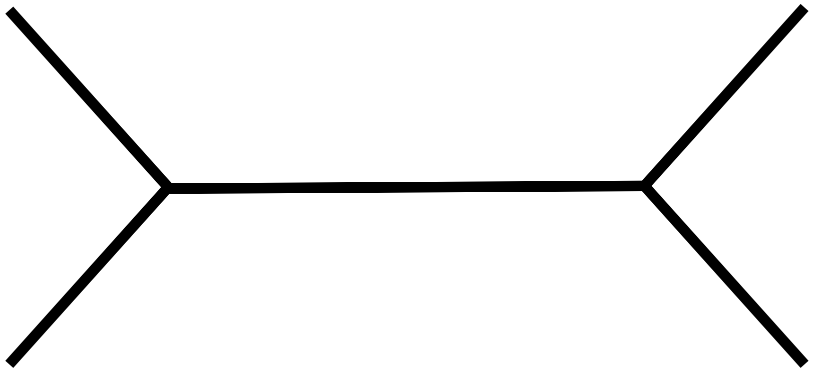
Hadronic final states and QCD

Part I: Theory

Conveners: Duncan Brown, Alexander Savin, Daniel Traynor, Giulia Zanderighi

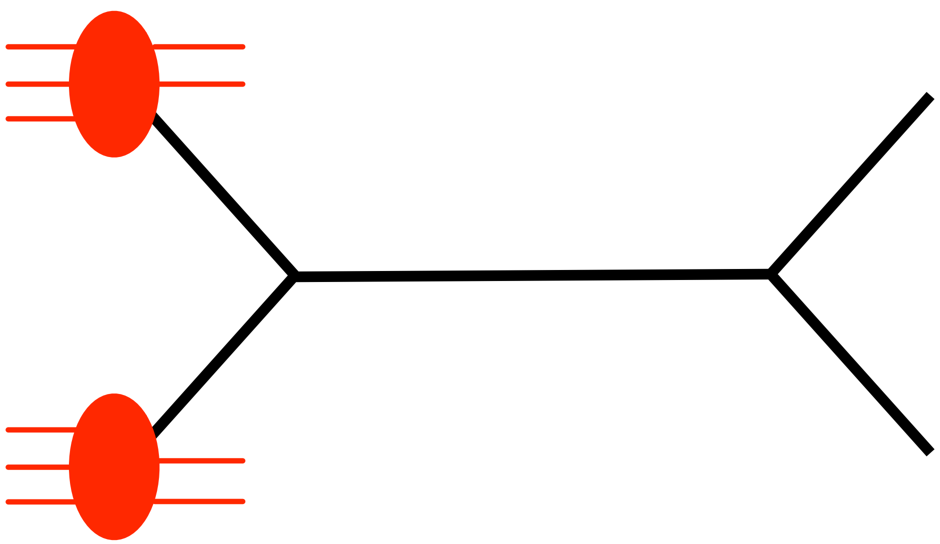
Final state issues

Final state issues



Final state issues

parton densities
evolution of pdfs
intrinsic kt?
intrinsic charm?
...



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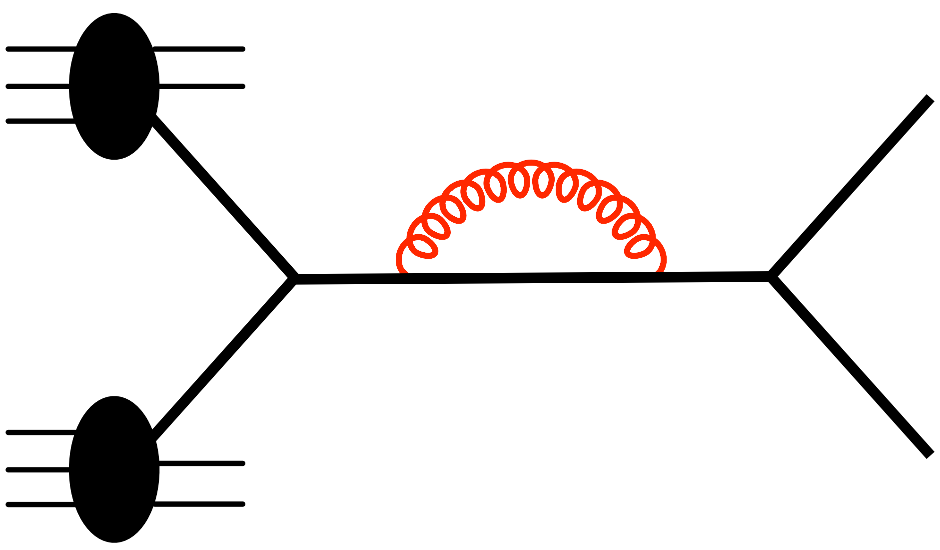

higher orders to
hard scattering
NLO, NNLO, ...

Final state issues

perturbative
evolution,
resummation

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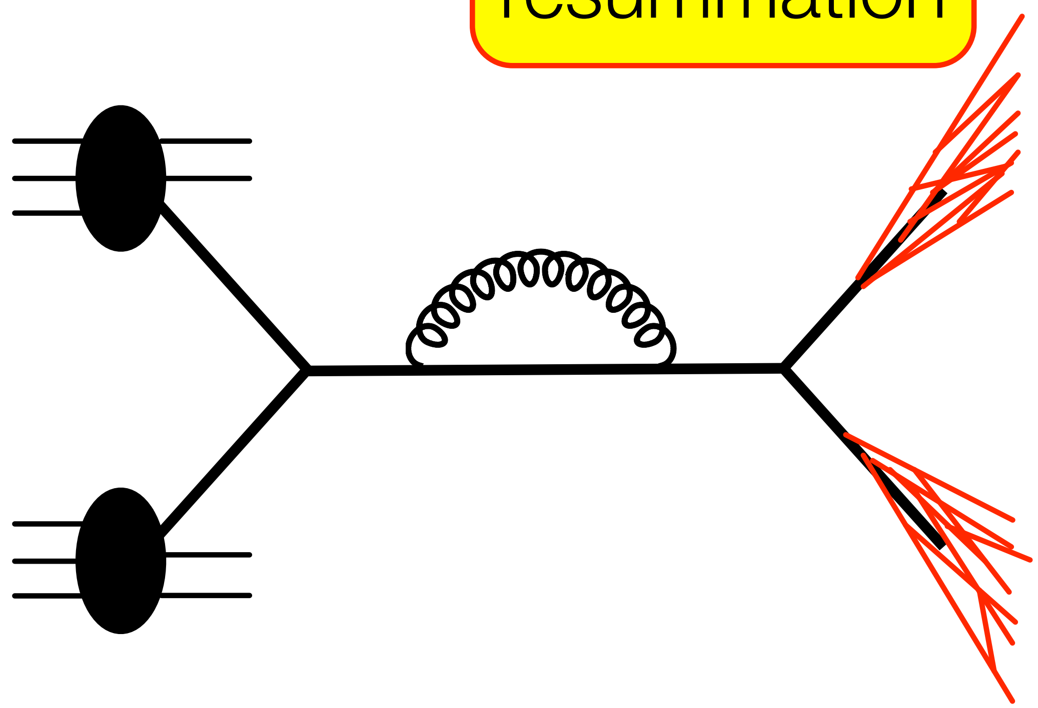
...



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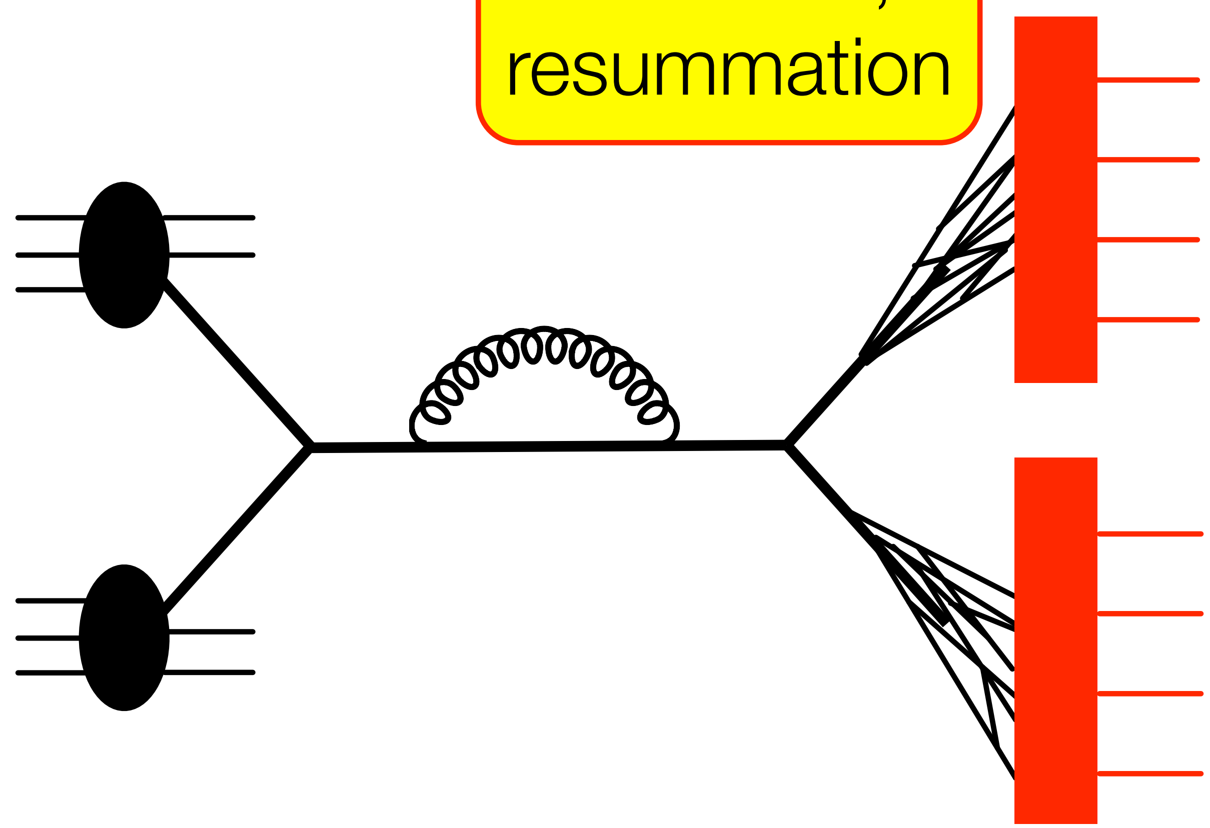

higher orders to hard scattering
NLO, NNLO, ...

fragmentation, hadronization

Final state issues

underlying event

perturbative evolution, resummation

parton densities
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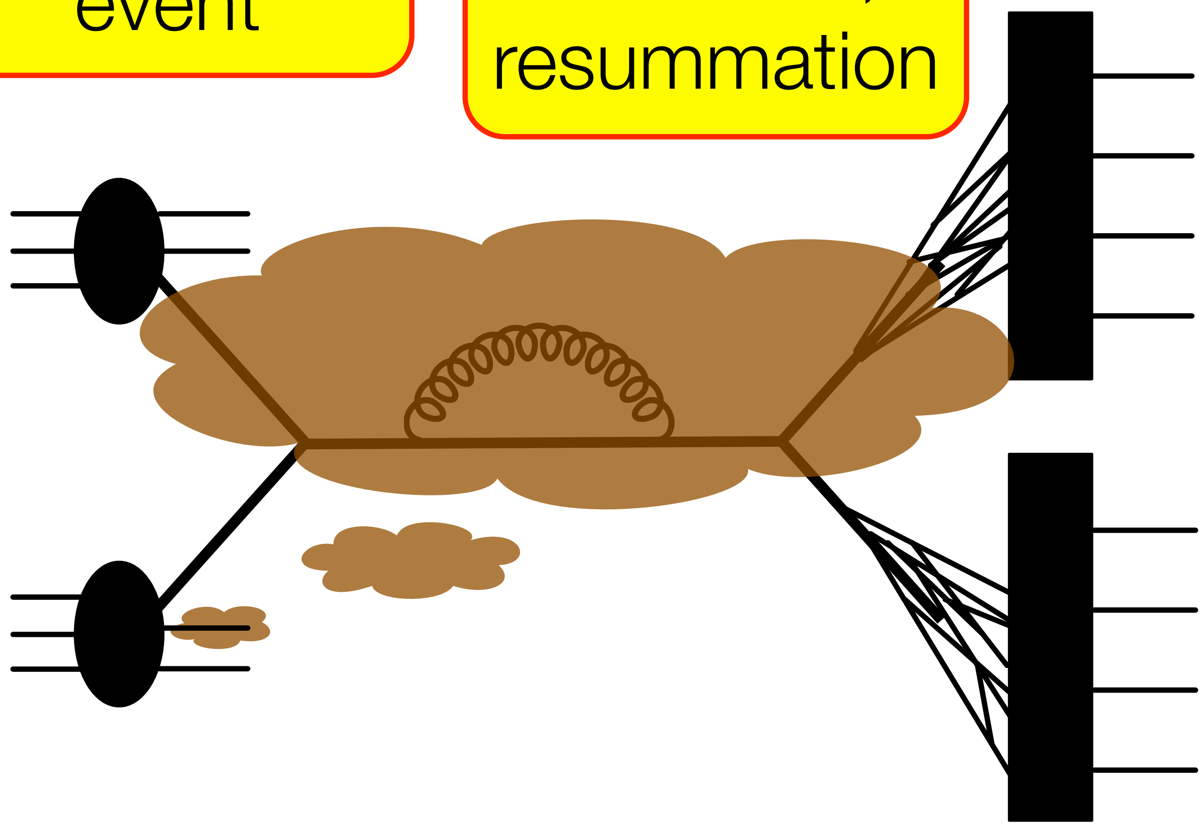


multiparticle interactions

higher orders to hard scattering NLO, NNLO, ...

fragmentation, hadronization

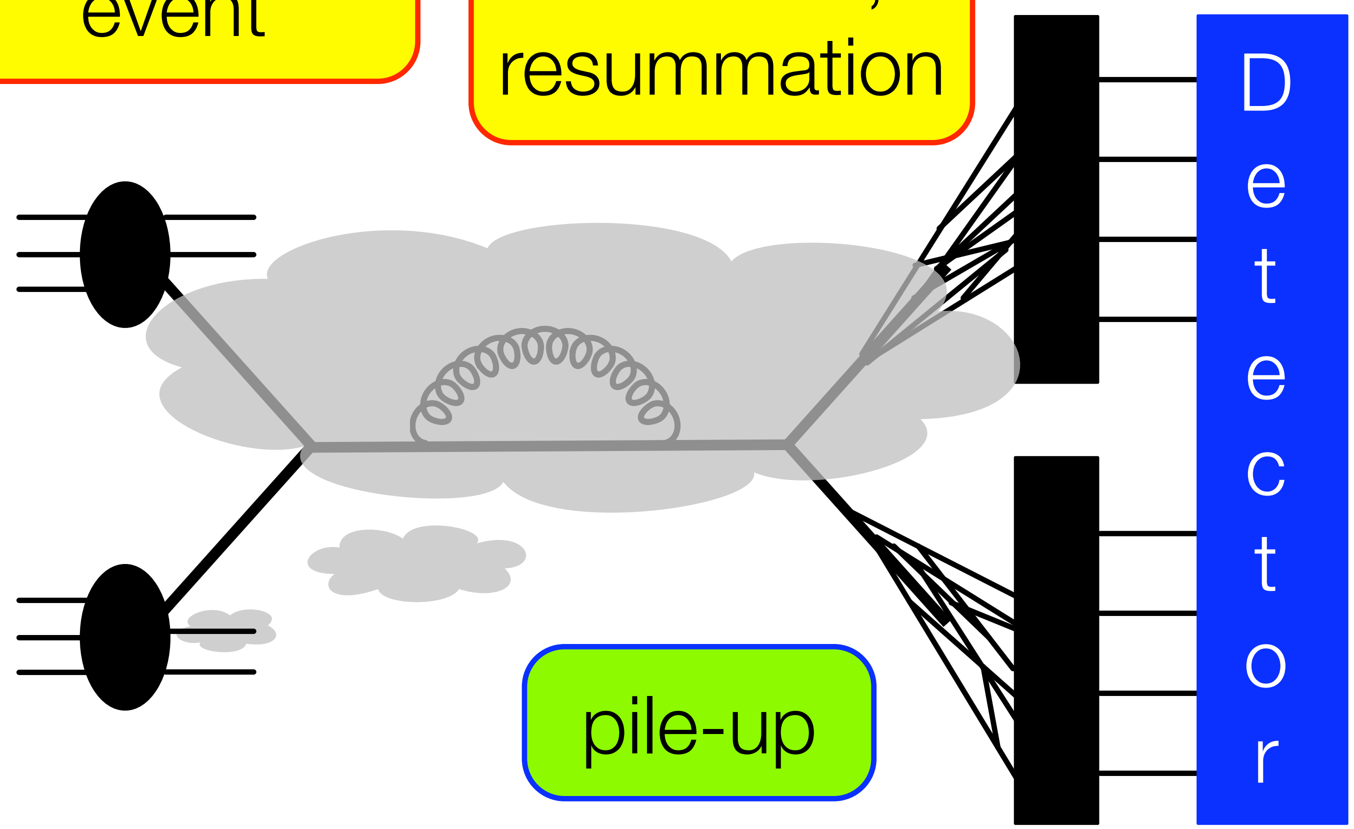
Final state issues

underlying event

perturbative evolution, resummation

detector effects

parton densities
evolution of pdfs
intrinsic kt?
intrinsic charm?
...



triggering

jet-energy scale

pile-up

efficiency

multiparticle interactions

higher orders to hard scattering NLO, NNLO, ...

fragmentation, hadronization

luminosity

Hadronic final states and QCD

Aims:

- test our general understanding of QCD dynamics
- test QCD evolution in limiting regimes (small x, low energy, ...)
- provide a solid reference for studies of new physics: need precise α_s & PDFs, which predictions can we *really* trust? ...

Topics addressed here

- higher orders for 3- and 4-jets in e^+e^- *[Banfi, Gehrmann]*
- issues with jet observables *[Delenda, Dasgupta, Magnea, Zanderighi]*
- parton shower and matrix elements *[Nagy, Visscher]*
- combining QCD and EW *[Vicini]*
- unintegrated PDFs *[Jung]*
- formal developments *[Bluemlein, Harlander, Nikolaev]*

→ see talk by S. Moch

Dimensional reduction at three loop in QCD

R. Harlander

Motivation:

- problem: dimensional regularization breaks SUSY $Z_g \neq \tilde{Z}_g$

$g_s \neq \tilde{g}_s$

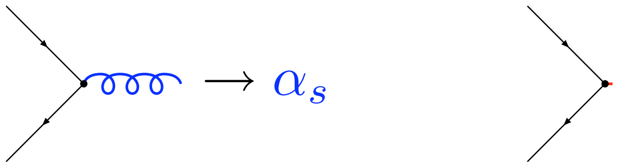
- alternative(?): Dimensional Reduction (DRED) [Siegel 79]

"epsilon scalar"

$$A_\mu(x) = \hat{A}_\mu(x) + \tilde{A}_\mu(x)$$

$$\mathcal{L}(A_\mu, \psi, \ldots) = \hat{\mathcal{L}}(\hat{A}, \psi, \ldots) + \tilde{\mathcal{L}}(\hat{A}_\mu, \tilde{A}_\mu, \psi, \ldots)$$

$$A_\mu \bar{\psi}\psi = \hat{A}_\mu \bar{\psi}\psi + \tilde{A}_\mu \bar{\psi}\psi$$



$\longrightarrow \alpha_s$ $\longrightarrow \alpha_e$

"evanescent coupling"

- SUSY: $\hat{Z} \stackrel{!}{=} \tilde{Z}$
- non-SUSY: $\hat{Z} \neq \tilde{Z}$ in general

Why bother?

relate $\alpha_s(M_Z)$ to $\alpha_s(M_{\rm SUSY})$

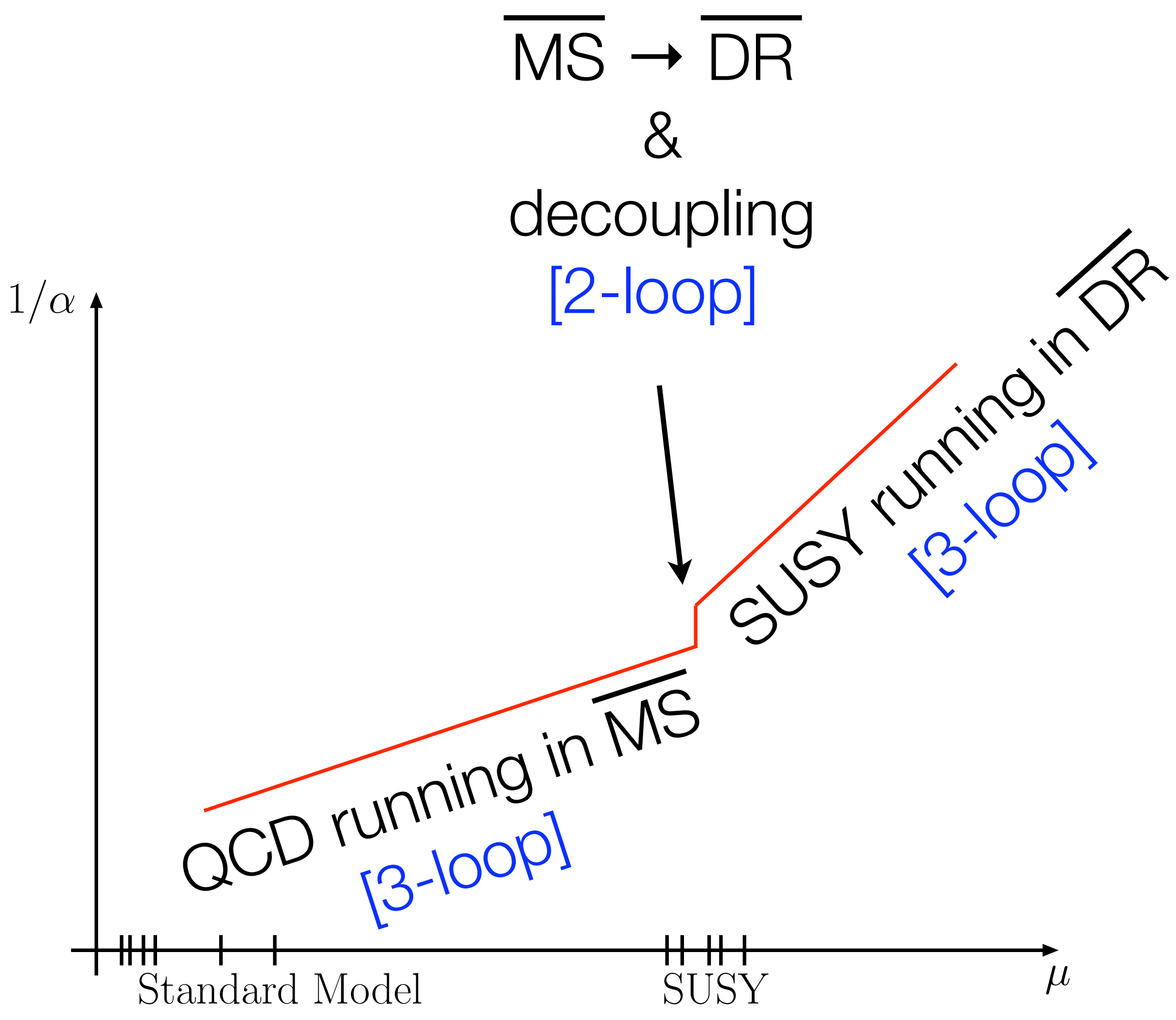
Problem:

$\alpha_s(M_Z) \equiv \alpha_s^{(5),\overline{\rm MS}}(M_Z)$ defined in QCD

$\alpha_s(M_{\rm GUT}) \equiv \alpha_s^{({\rm full}),\overline{\rm DR}}(M_{\rm GUT})$ SUSY theory

Dimensional reduction at three loop in QCD

R. Harlander



Dimensional reduction at three loop in QCD

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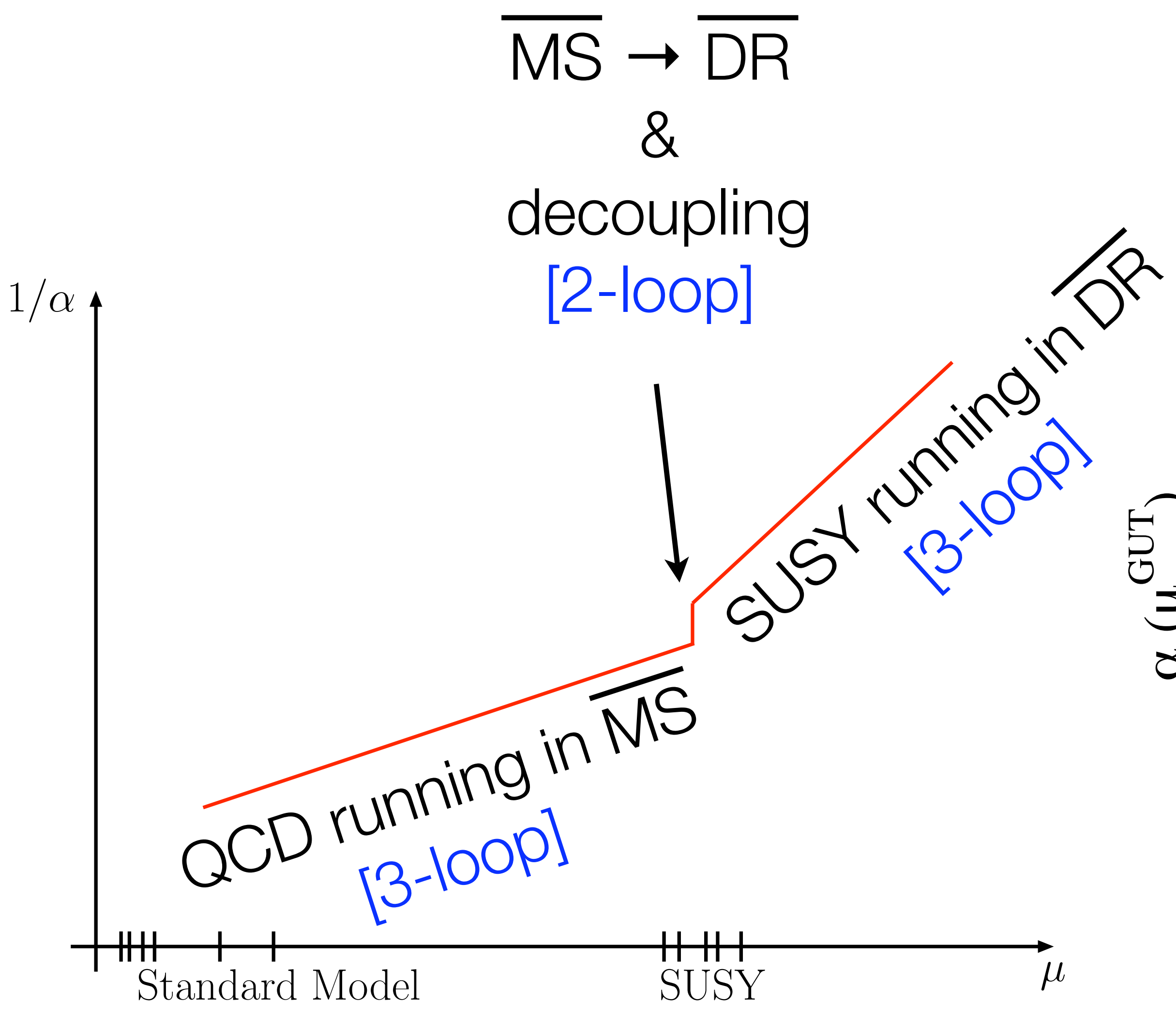
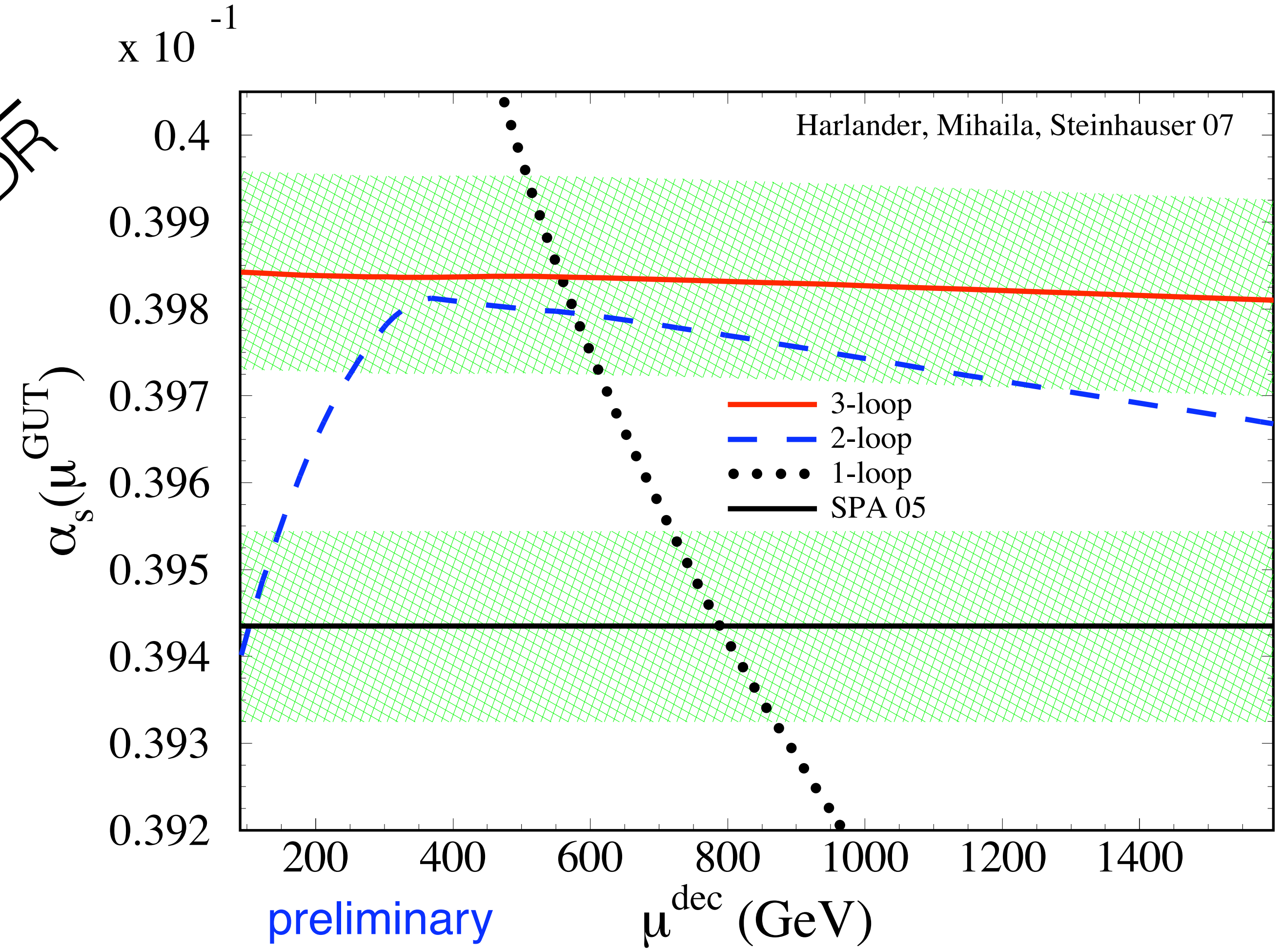


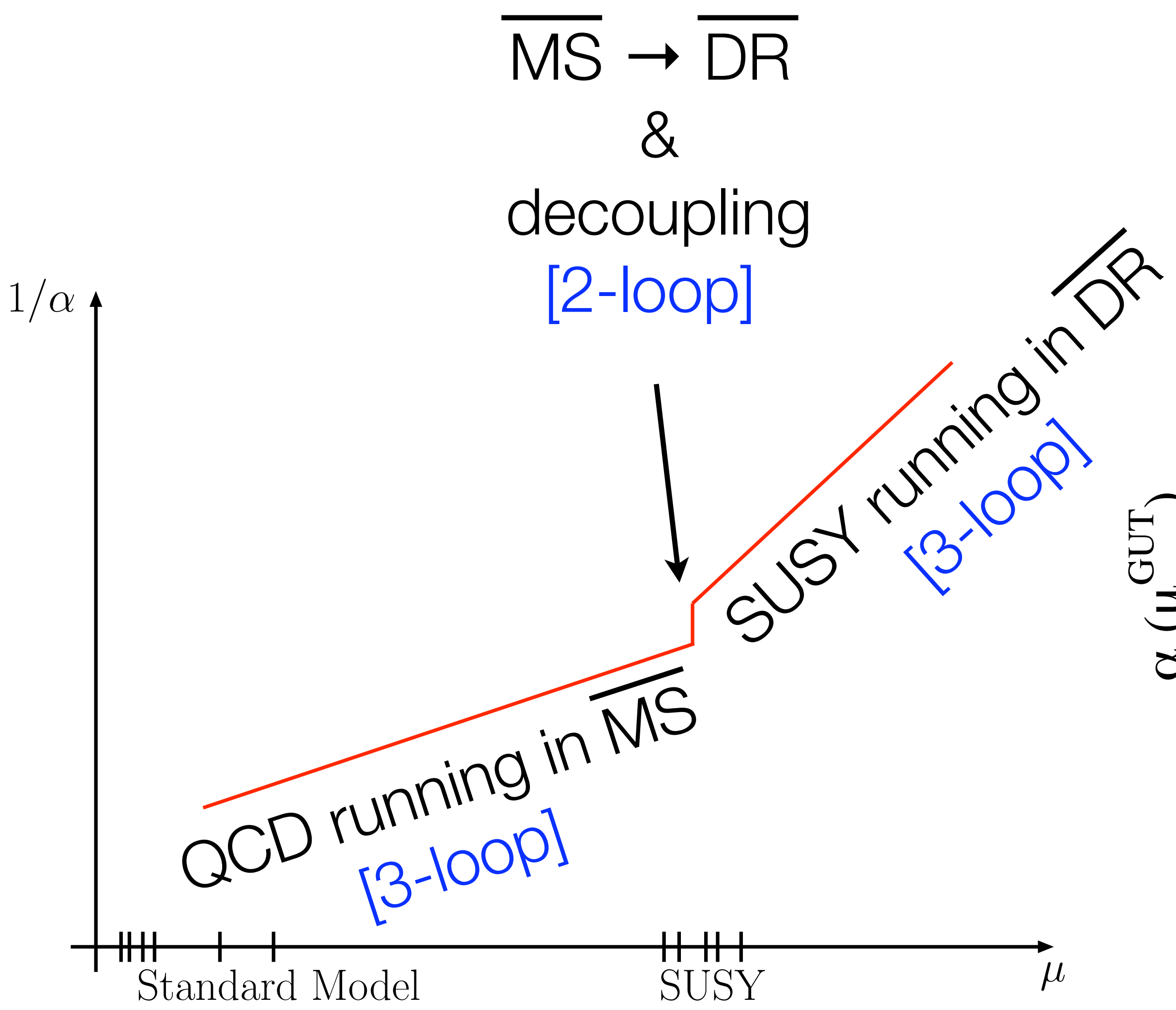


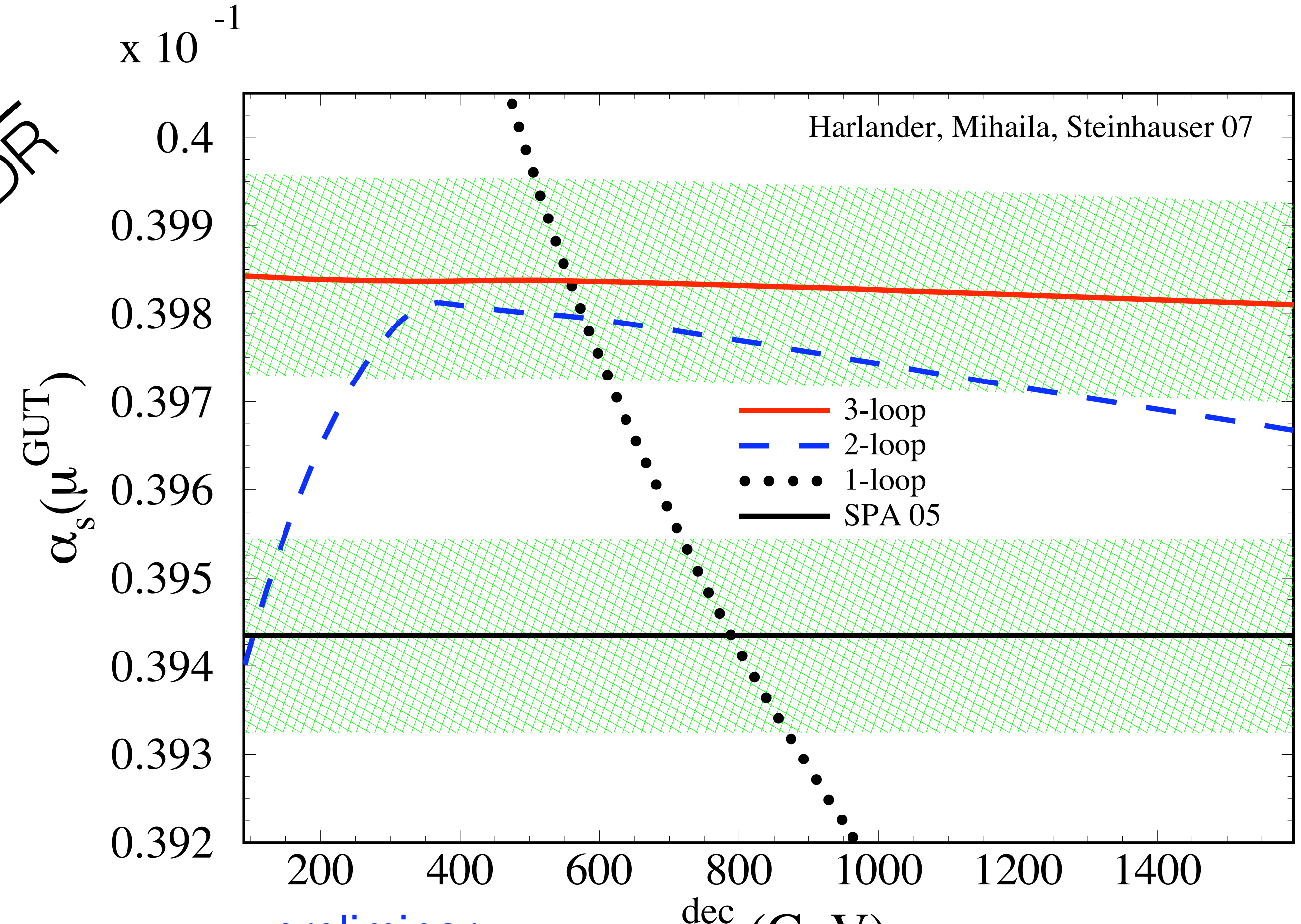
- SUSY evolution of α_s now consistent through 3 loops

  $\longrightarrow$ should be included in spectrum codes

Dimensional reduction at three loop in QCD

R. Harlander





preliminary

Interesting issue: $\overline{\text{MS}}$-$\overline{\text{DR}}$ conversion & $\overline{\text{DR}}$ running depend on evanescent coupling. Physical interpretation?

- SUSY evolution of α_s now consistent through 3 loops
  - $\rightarrow$ should be included in spectrum codes

Structural relations between Harmonic Sums

J. Bluemlein

- Simplification of the complex structure of higher order splitting functions, Wilson coefficients and hard scattering cross sections, e.g. Higgs production xs & LHC for m_t heavy - depending on a single scale.
- Mellin Space $\Longrightarrow$ higher symmertry $\Longrightarrow$ exploit for simplification.
- Derive algebraic and structural relations for multiple harmonic sums.
- Higher order corrections can be compactified.

The Basis

		number of fcts.
• $O(\alpha)$	Wilson Coefficients/anom. dim.	$\#1$
• $O(\alpha^2)$	Anomalous Dimensions	$\#2$
• $O(\alpha^2)$	Wilson Coefficients	$\# \leq 5$
• $O(\alpha^3)$	Anomalous Dimensions	$\#15$
• $O(\alpha^3)$	Wilson Coefficients	$\#29+$

Abramovski-Kancheli-Gribov cutting rules

K. Nikolaev

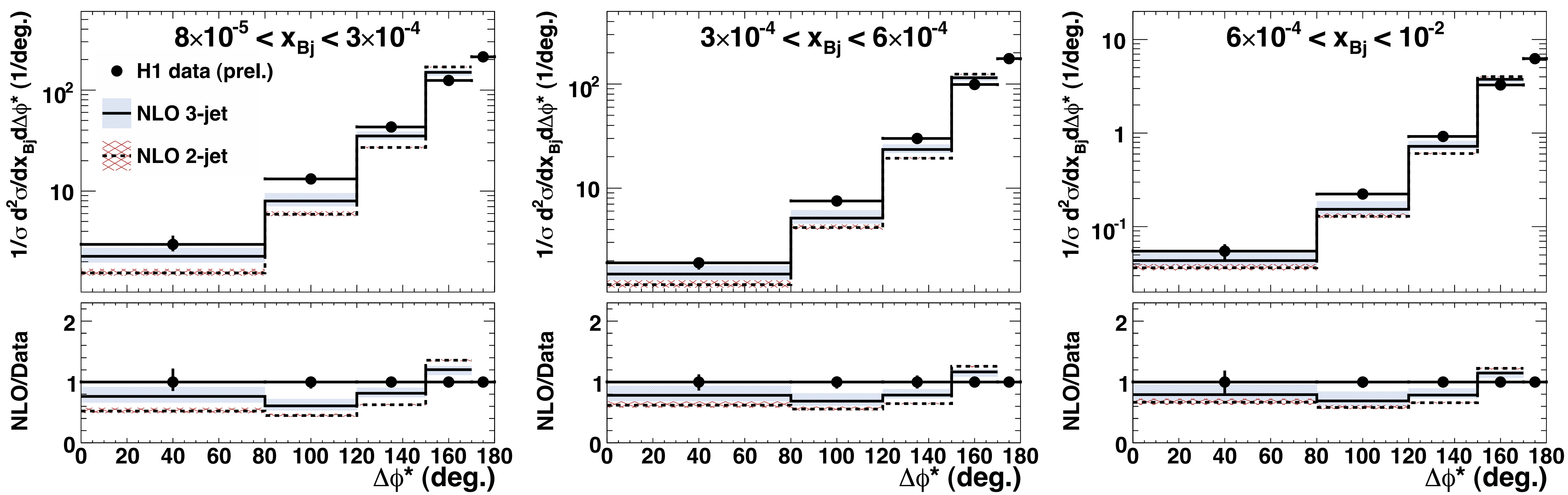
- Abramovsky, Gribov and Kancheli ('70): set of unitarity cutting rules which relate multi-pomeron exchange contributions to total, diffractive and inelastic cross sections
- Starting with an exact kt-factorization for hard pQCD in nuclear environment, a dramatic revision of the AGK rules within QCD is found
- There emerge two kinds of unitarity cut pomerons which describe the color excitation and color rotation inelastic interactions
- In the Reggeon field theory language, the results entail a large variety of multi-pomeron couplings which vary from one universality class for hard pQCD processes to another

Dijet azimuthal correlations

Y. Delenda

Motivation:

results presented at DIS'06 and request from H1



- NLO 3-jet not in agreement with data

Hansson DIS'06

⇒ resummation?

Dijet azimuthal correlations

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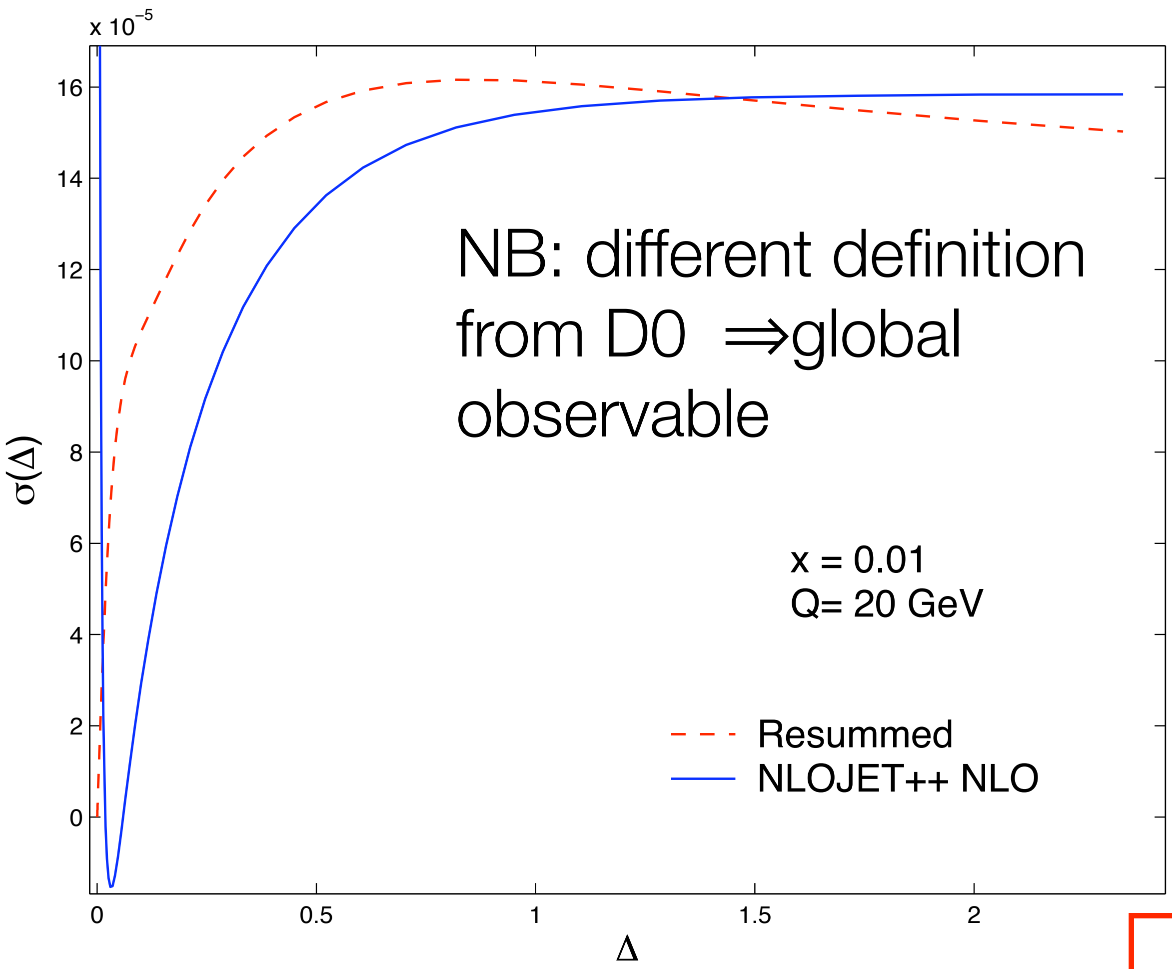
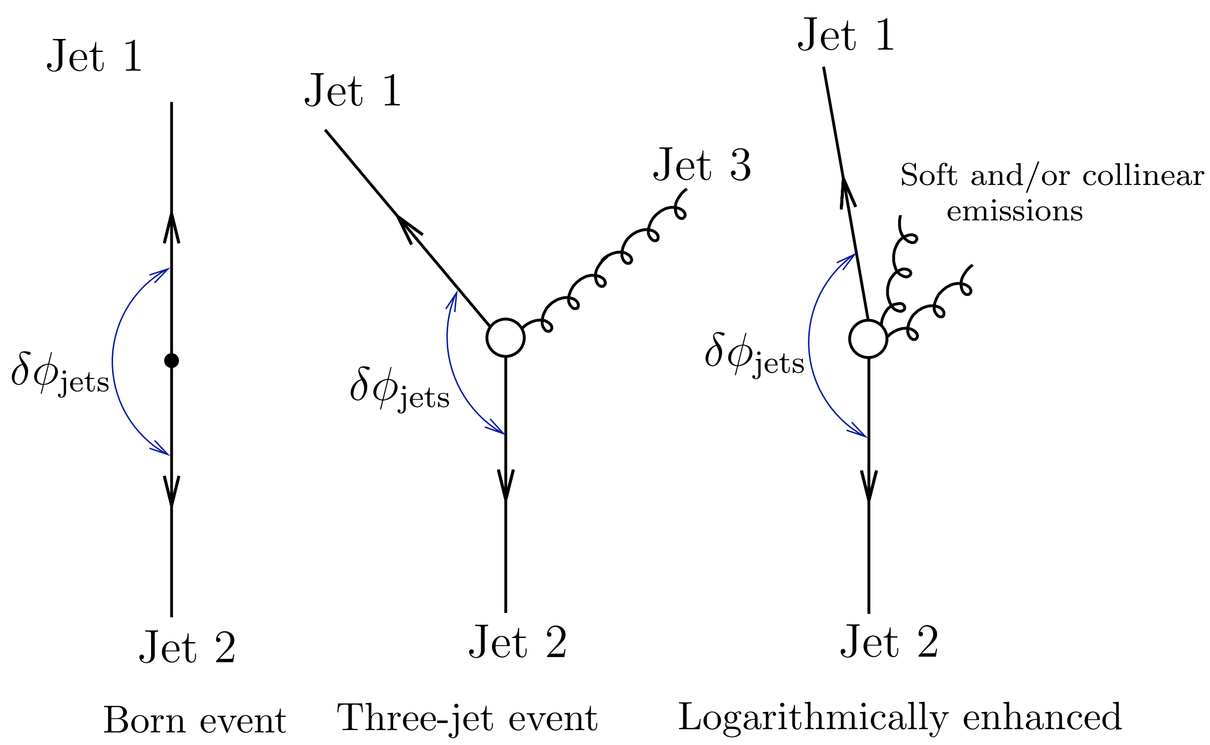




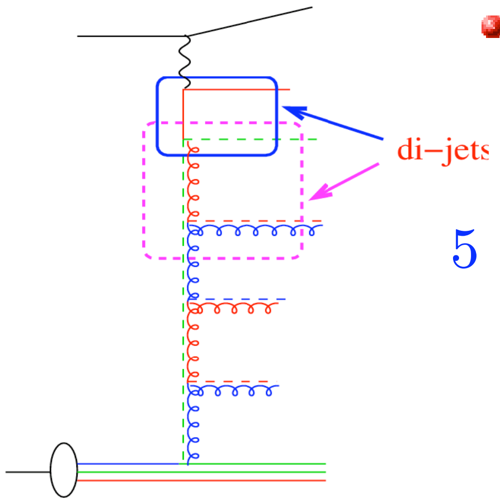
First resummation for

$$\Delta \equiv \pi - \phi_{\mathrm{jets}}$$

Work in progress: matching with NLOJET++ and power-corrections
Similar study at Tevatron in progress.
N.B. better use global definition of correlations!

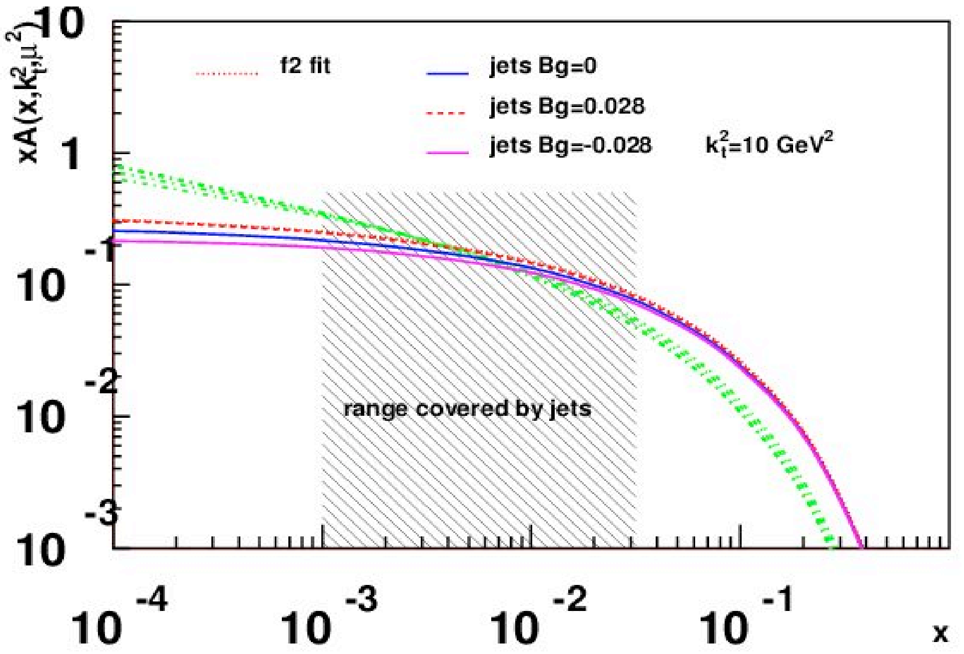
Towards precision determination of uPDFs

H. Jung



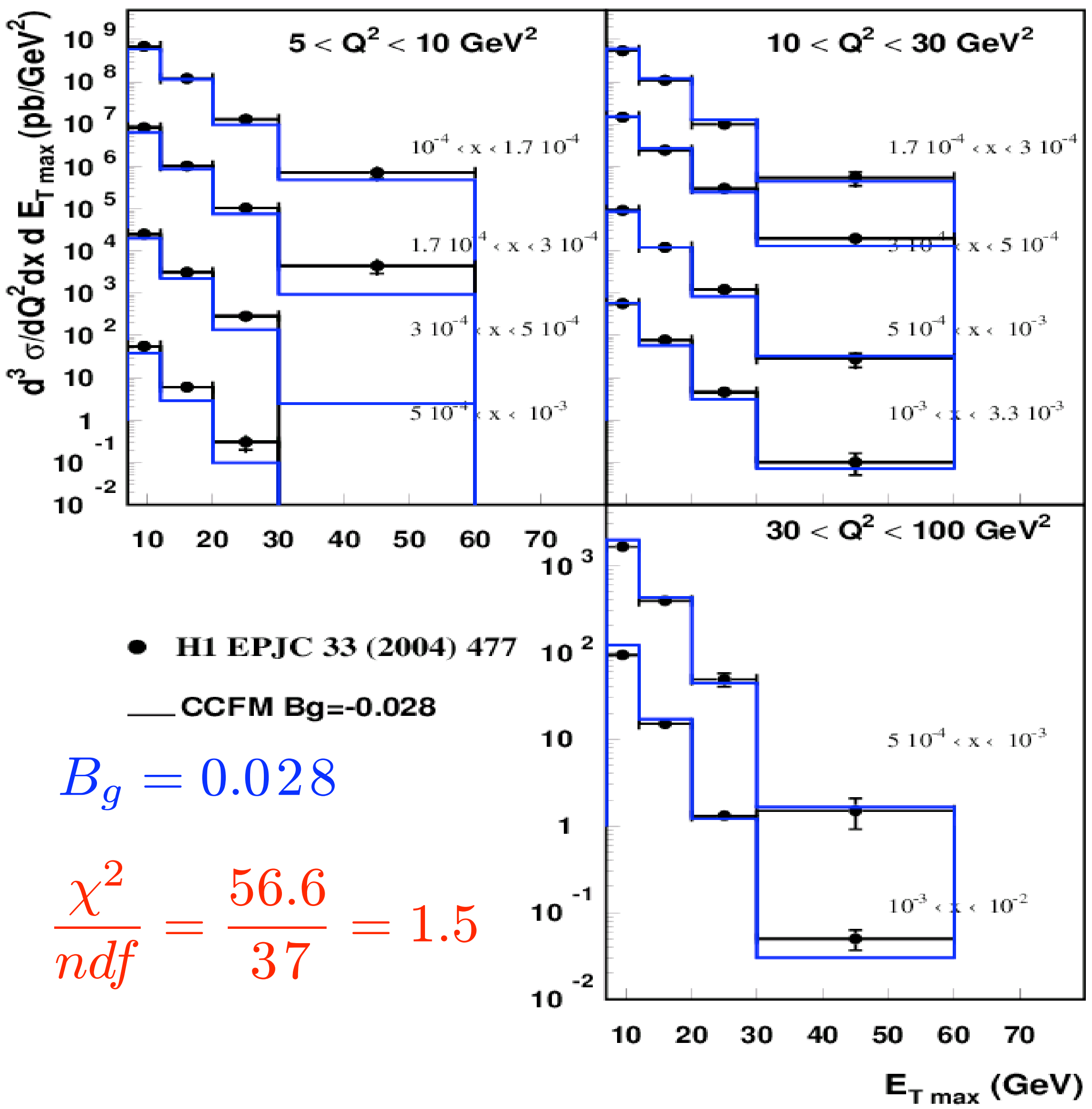
- H1 EPJC 33 (2004) 477

$$5 < Q^2 < 100\ \mathrm{GeV}^2$$
$$-1 < \eta < 2.5$$
$$E_T > 5\ \mathrm{GeV}$$



- x dependence with $\dfrac{d^3\sigma}{dE_T^{max}\,dx\,dQ^2}$

$$x\mathcal{A}_0(x,\mu_0) = N x^{-B_g} \cdot (1-x)^4$$



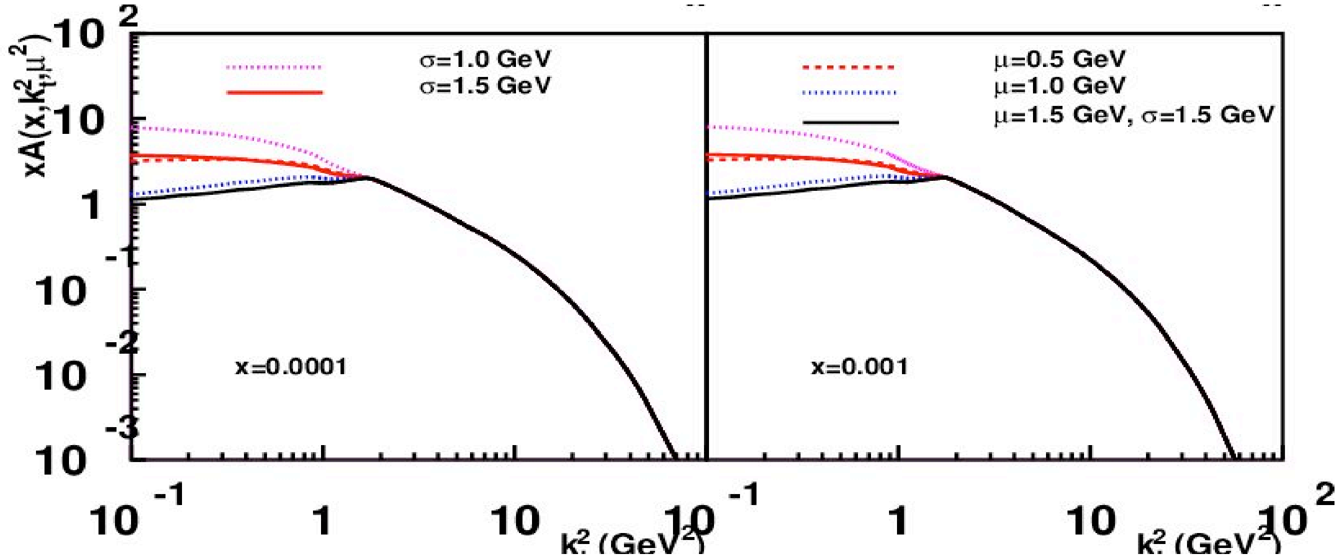
$$B_g = 0.028$$

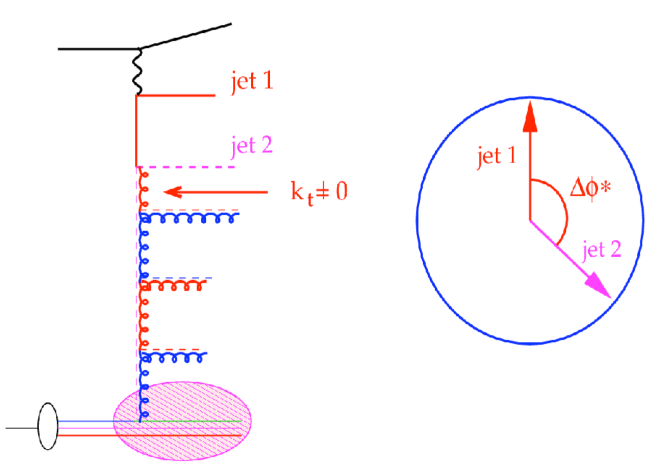
$$\frac{\chi^2}{ndf} = \frac{56.6}{37} = 1.5$$

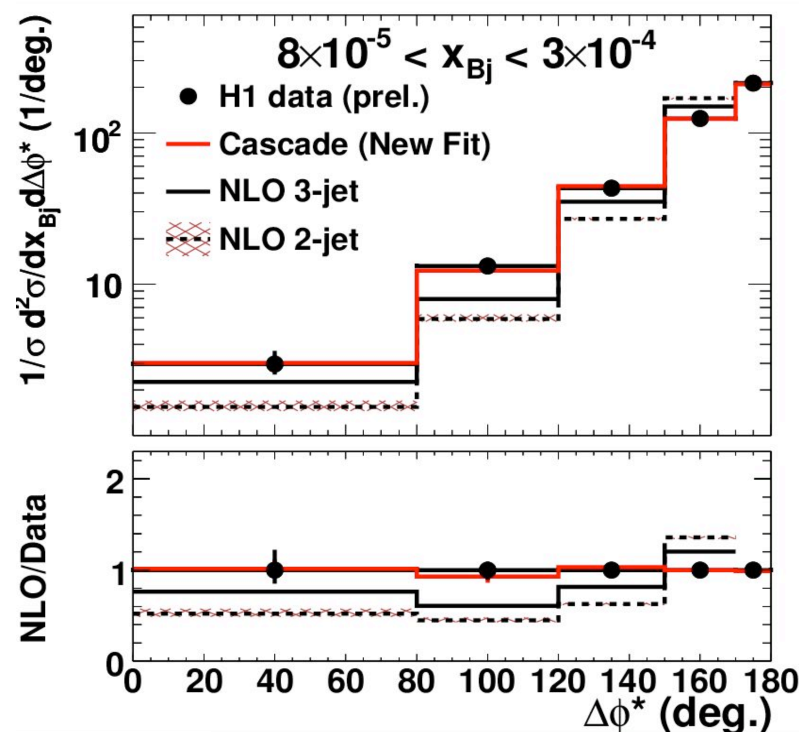
Towards precision determination of uPDFs

H. Jung

$$xA(x, \mu_0^2) = N x^{-B_g} \cdot (1-x)^4 \cdot \exp\left(-(k_{t0}-\mu)^2/\sigma^2\right)$$







- different intrinsic k_t-distributions only accessible in uPDFs
- sensitive to the mix of small and large k_t
- fit intrinsic gauss:
  $\sigma \sim 1.5$
  $\mu \sim 1.5$
- **1st direct determination of intrinsic k_t distribution**

Power corrections at hadron colliders

L. Magnea

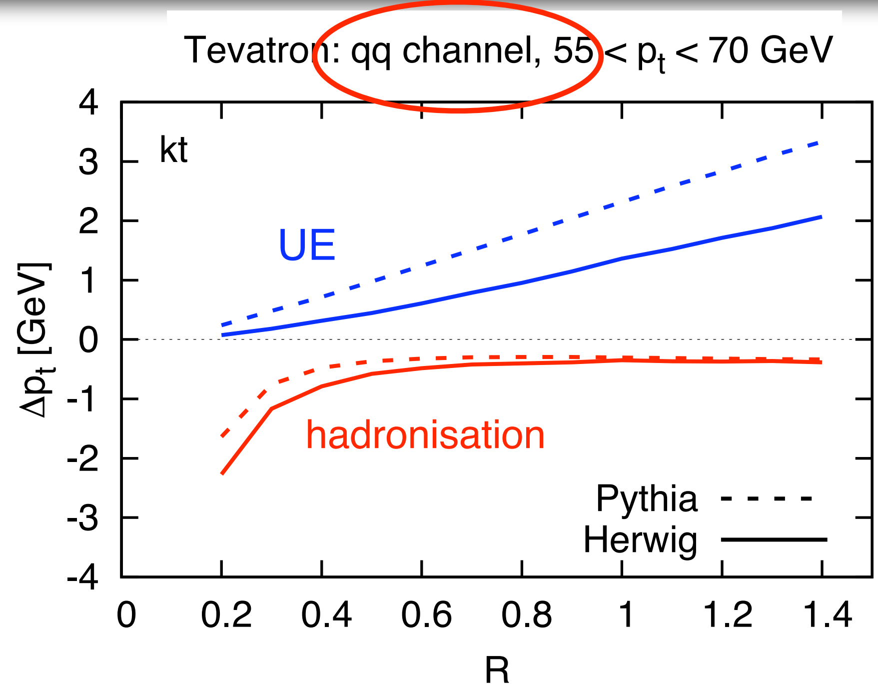
Disentangling hadronization

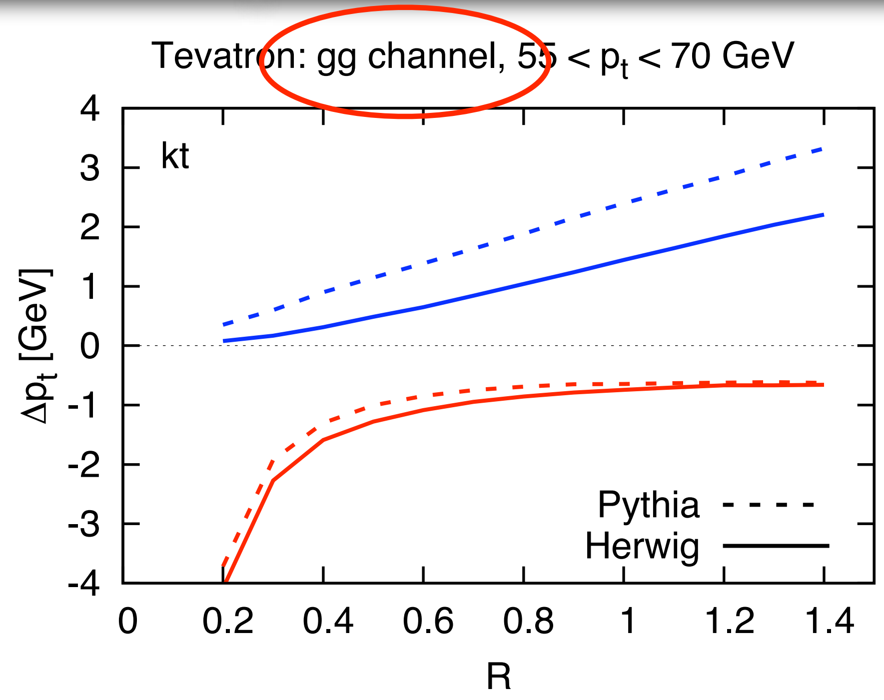
- *Consider* the single inclusive distribution for a jet observable $O(y, p_T, R)$, with an effective *jet radius* $R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$.
- Single inclusive jet distributions have Λ / p_T power corrections *from hadronization*.
- *Hadronization* corrections are *distinguishable* from *underlying event* effects because of *singular* R dependence. [modeled analytically]
- *Run* MC at *parton level* (p), *hadron level without UE* (h) and finally *with UE* (u)
- *Select* events with hardest jet in chosen p_T range, *identify* two hardest jets, *define* for each hadron level

$$\Delta p_T^{(h/u)} = \frac{1}{2} \left(p_{T,1}^{(h/u)} + p_{T,2}^{(h/u)} - p_{T,1}^{(p)} - p_{T,2}^{(p)} \right) .$$

$$\Delta p_T^{(u-h)} = \Delta p_T^{(u)} - \Delta p_T^{(h)} .$$

Power corrections at hadron colliders





L. Magnea

Power corrections at hadron colliders

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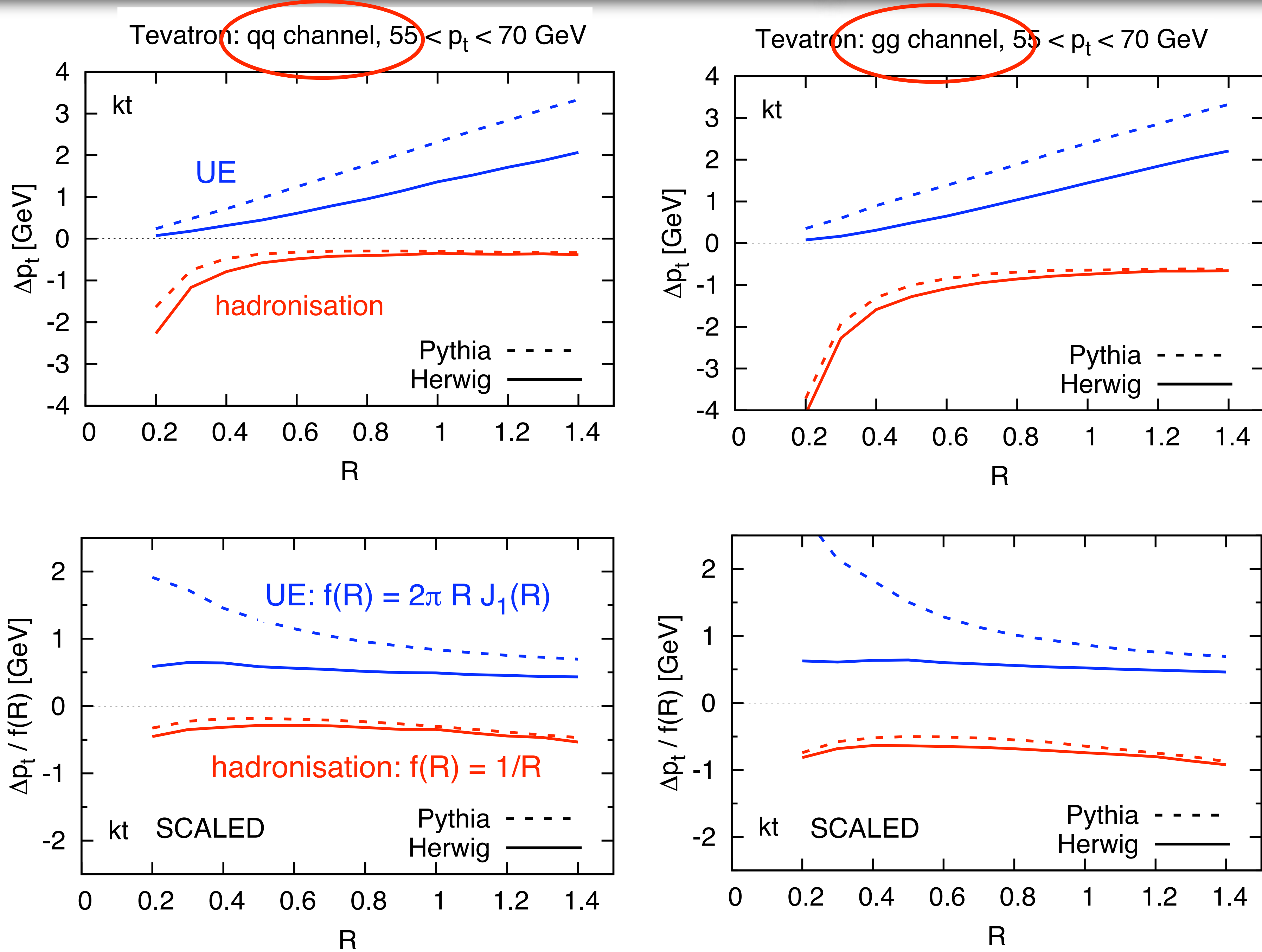

Power corrections at hadron colliders

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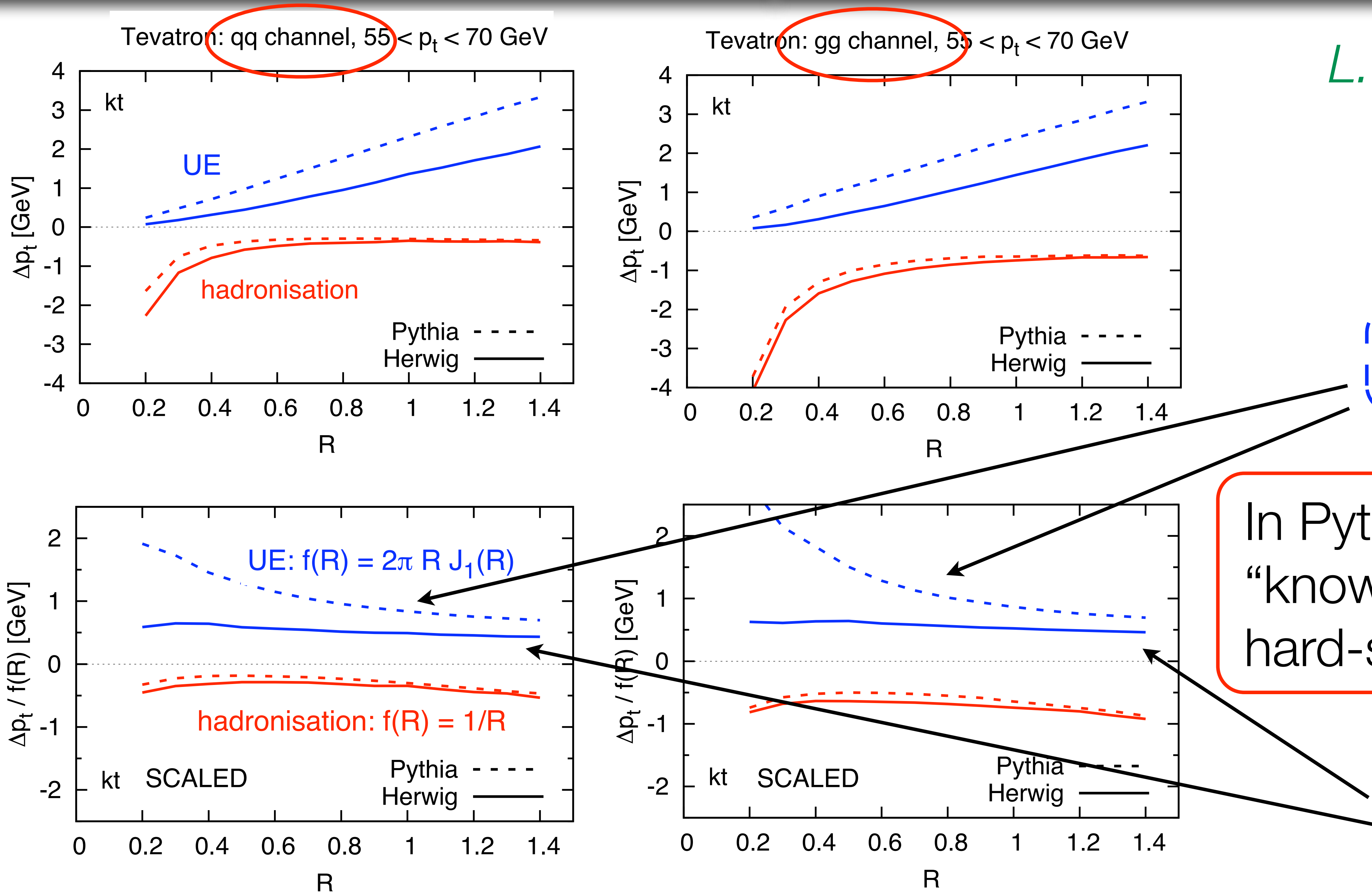
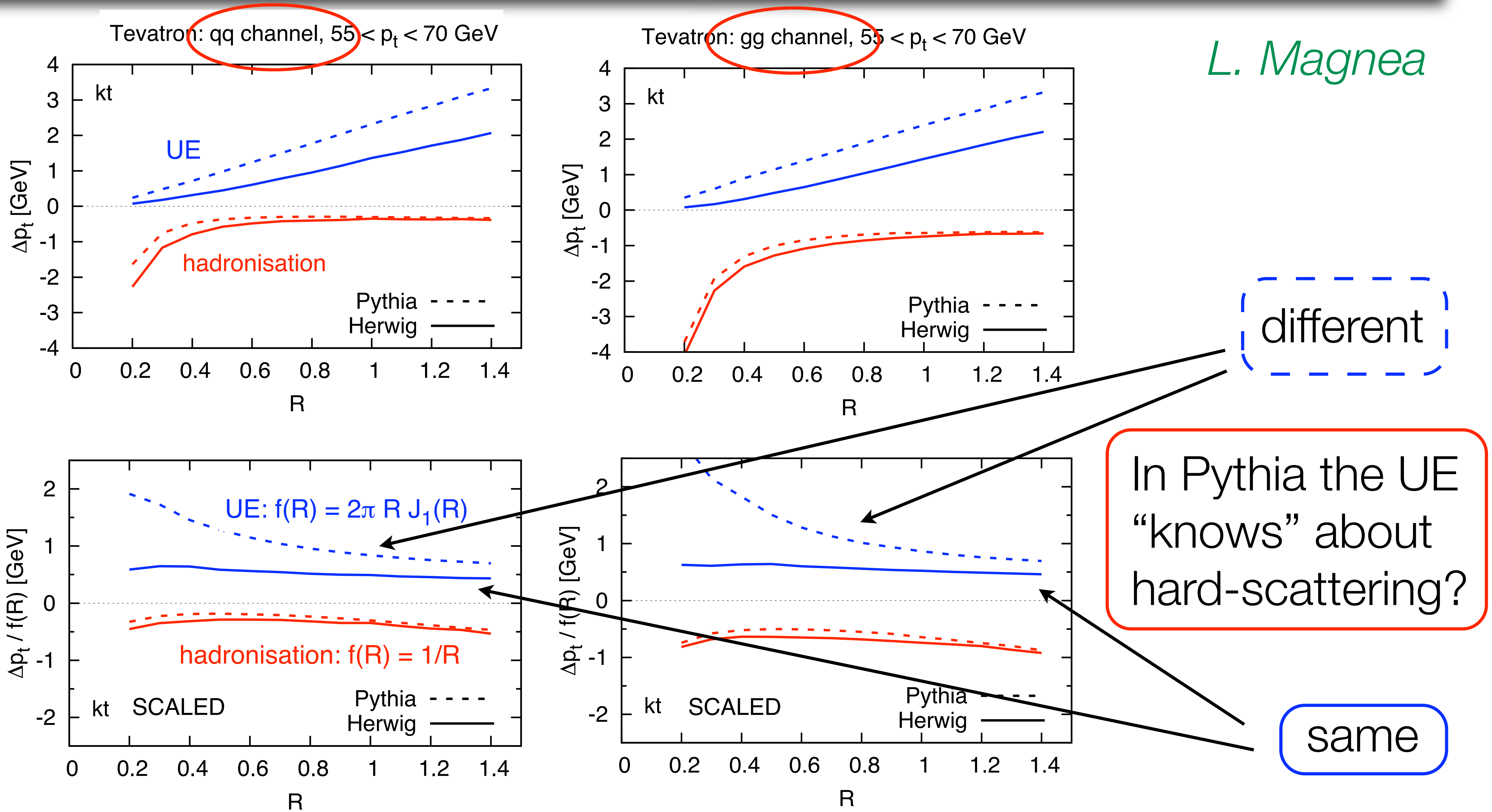


different

In Pythia the UE "knows" about hard-scattering?

same

Power corrections at hadron colliders



⇒ *please provide measurements for different values of R!*

Parton shower for non-global observables

M. Dasgupta

Non-global observables: sensitive to radiation only in a limited region of phase space

Parton shower for non-global observables

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- Monte-Carlos often tuned to non-global observables
- Angular ordering catches the relevant part of non-global logarithms

Parton shower for non-global observables

M. Dasgupta

Non-global observables: sensitive to radiation only in a limited region of phase space

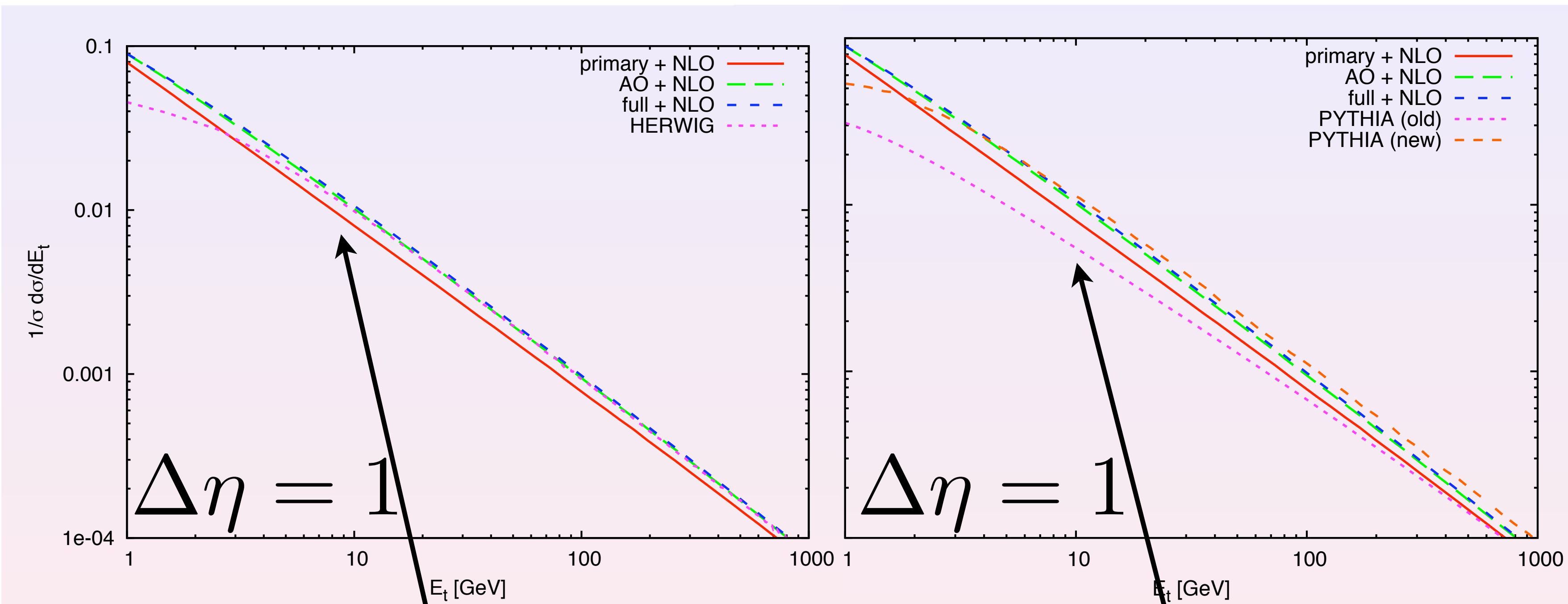
- Monte-Carlos often tuned to non-global observables
- Angular ordering catches the relevant part of non-global logarithms

- HERWIG based on angular ordering, shd be close to full (large N_c) result.
- PYTHIA (old) ordering in m^2 and reject non AO configs, shd do worse.
- ARIADNE – dipole phase space, shd have the full LL.
- PYTHIA (new) like ARIADNE ?

Parton shower for non-global observables

Compare MC with full:

M. Dasgupta



10% up to E_t=10GeV

7.5% Pythia new
50% Pythia old

Parton shower for non-global observables

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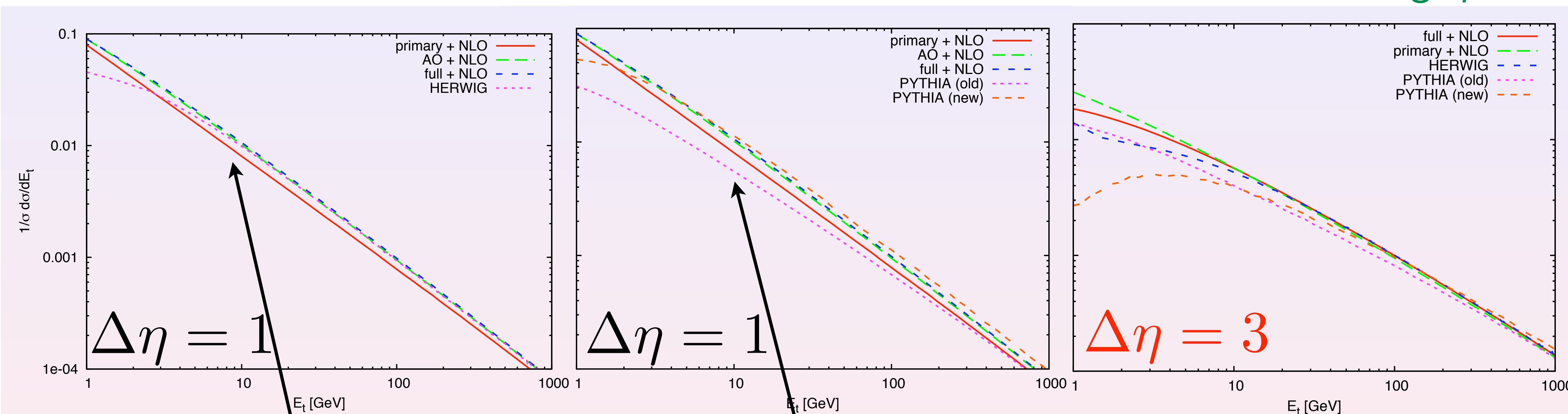

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problems with new Pythia at large $\Delta\eta$

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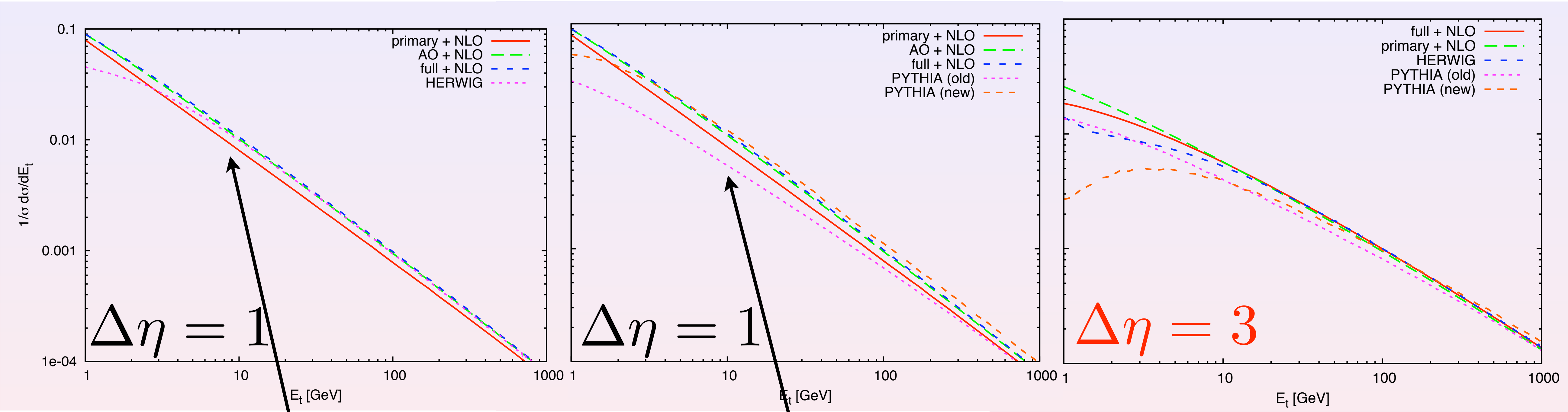

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Care needed when tuning MC to non-global observables!

May incorporate in UE or in NP parameters effects which are PT.

Parton shower for non-global observables

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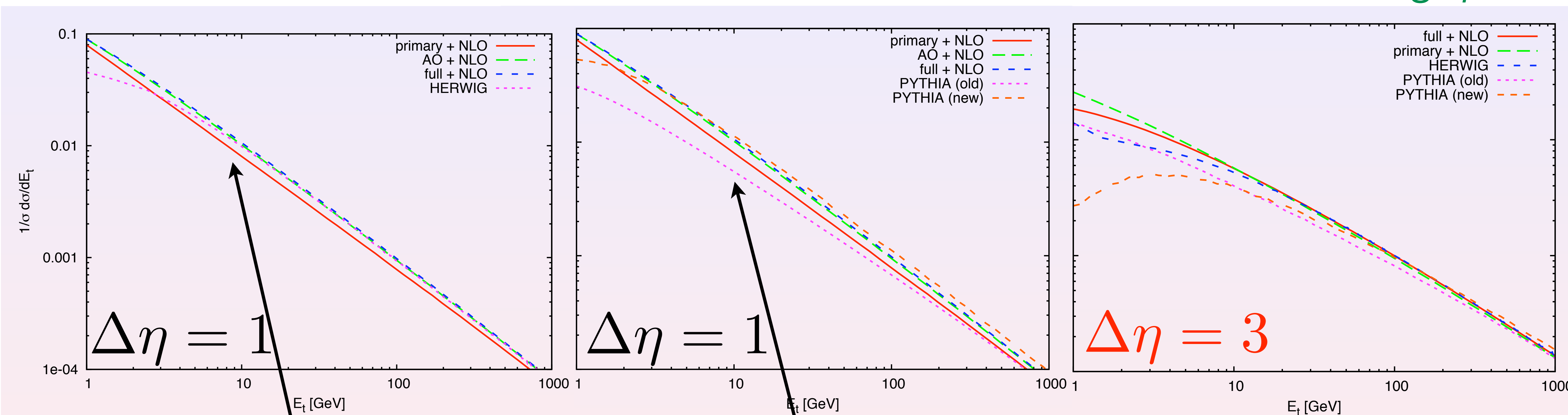

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Care needed when tuning MC to non-global observables!

May incorporate in UE or in NP parameters effects which are PT.

Do we have the necessary tools/measurements for best tuned MCs?

Need to clarify the above discrepancies!

Parton shower with quantum interference

Z. Nagy

- The parton shower relies on the universal soft and collinear factorization of the QCD matrix elements. It is universal property and true at all order. This should be the only approximation ...

→ Parton shower as Quantum statistical mechanics

... but we have some further approximations:

- ✗ Interference diagrams are treated approximately with the angular ordering
- ✗ Color treatment is valid in the $N_c \to \infty$ limit (correct only in e^+e^- annihilation)
- ✗ Spin treatment is usually approximated.
- ✗ Usually very crude approximation in the phase space
- ✗ "Hidden tricks"

→ Parton shower as classical statistical mechanics

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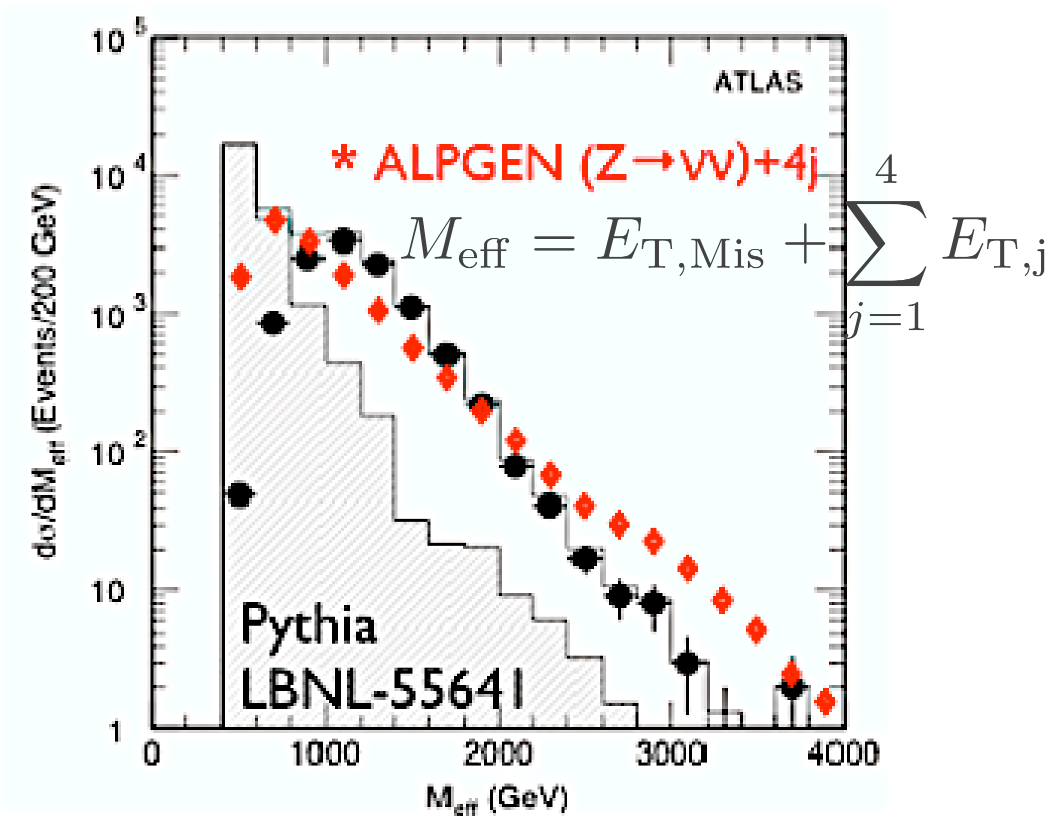
Parton shower as classical statistical mechanics

Work in progress to remove the above approximations

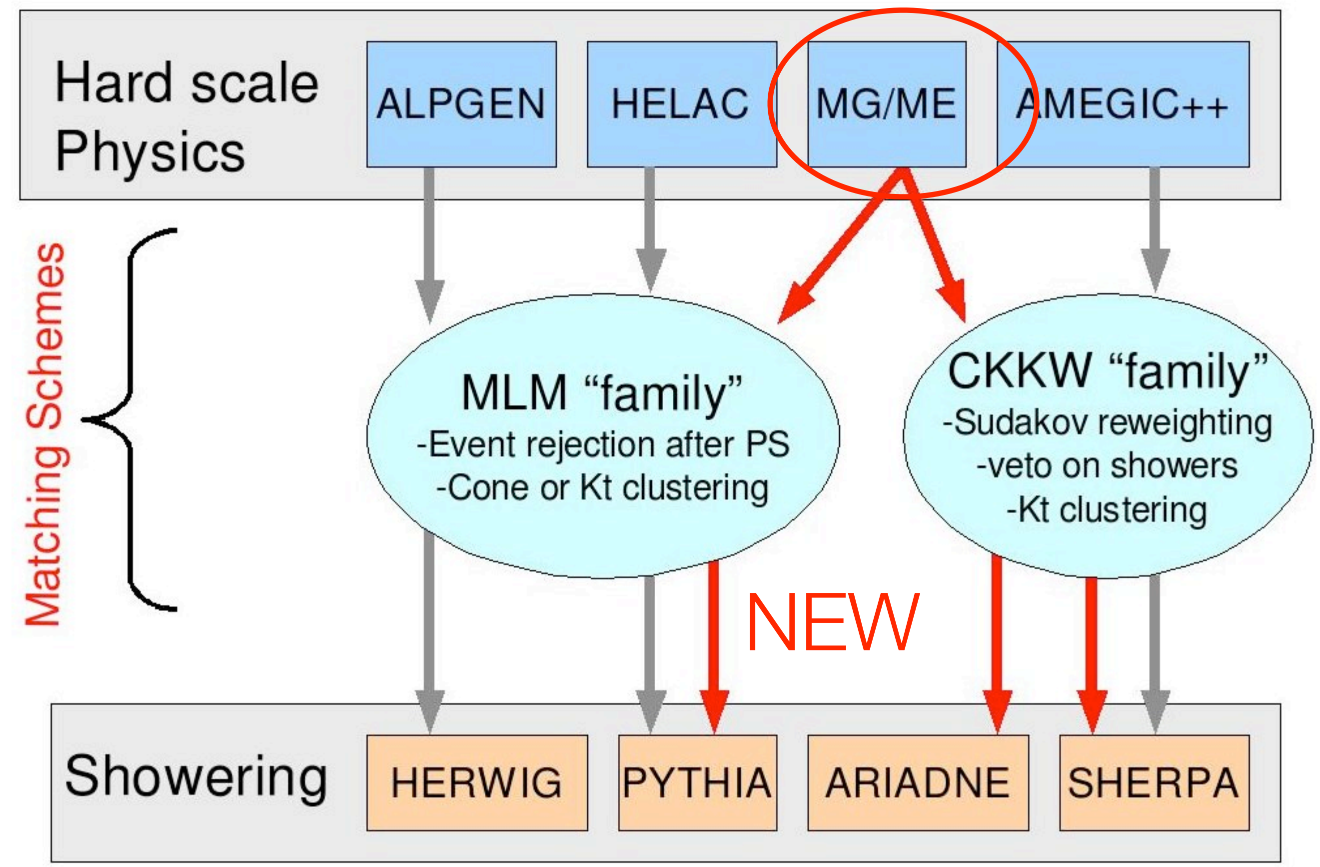
MadGraph/MadEvent at work

SUSY search at the LHC:



[Gianotti&Mangano'05]

S. Visscher



systematic comparisons between different generators, matching techniques, shower algorithms

For many studies MC known to fail! Please use Matrix Element based predictions!

MadGraph/MadEvent at work

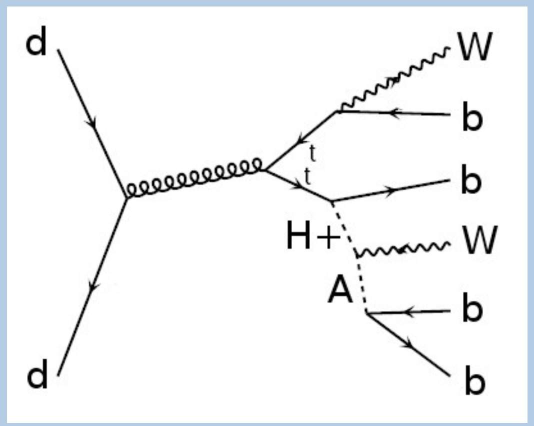
S. Visscher

With MadGraph/MadEvent and his tools, complete simulation chain available: from hard scale physics to detector simulation!

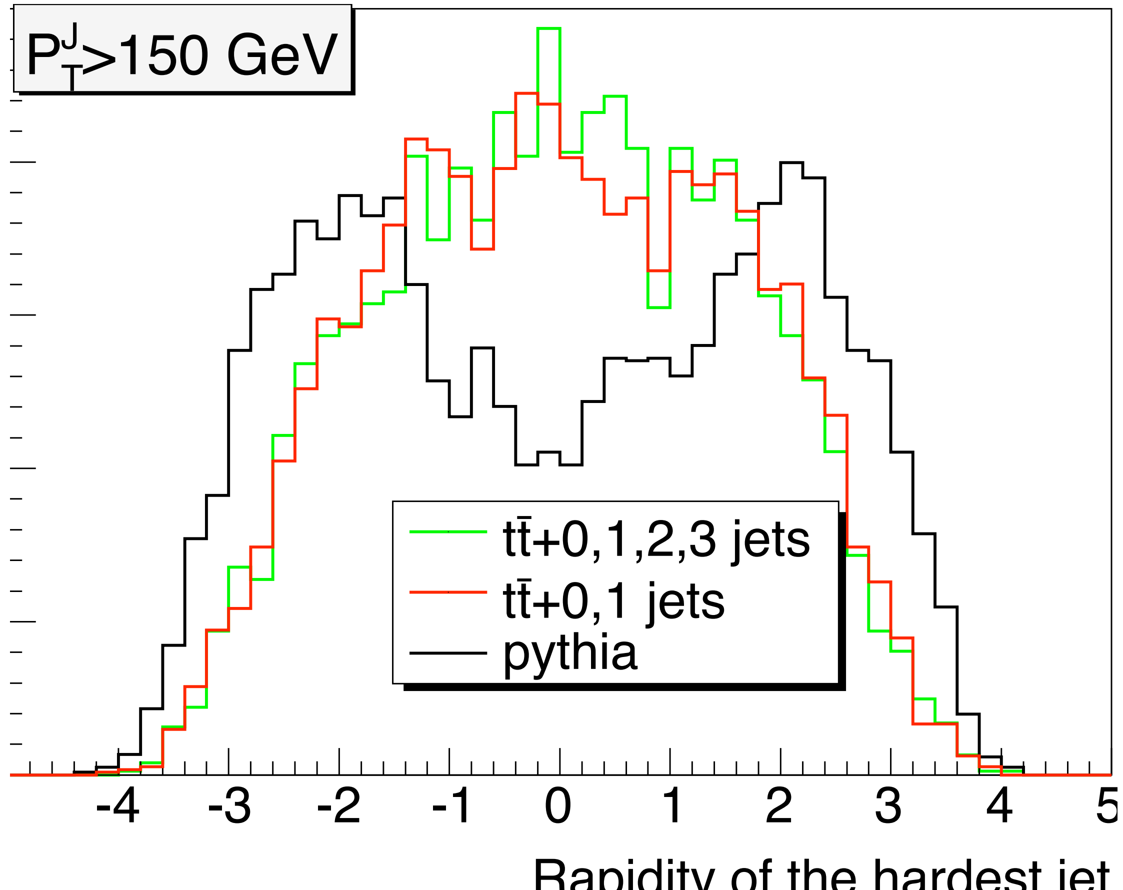
- Can handle tree-level processes with many particles in final states particles
- Keeps full spin correlations / interference
- Download the code or web-based generation: three public clusters: at UCL (http://madgraph.phys.ucl.ac.be), in Rome (http://madgraph.roma2.infn.it) and at UIUC (http://madgraph.hep.uiuc.edu).

An example

in 2HDM, $pp \to W^+W^-b\bar{b}b\bar{b}$ could be the most interesting channel to discover the charged higgs!



$\to$ Need a reliable $t\bar{t} + 0, 1, 2, 3...$ jets events sample!

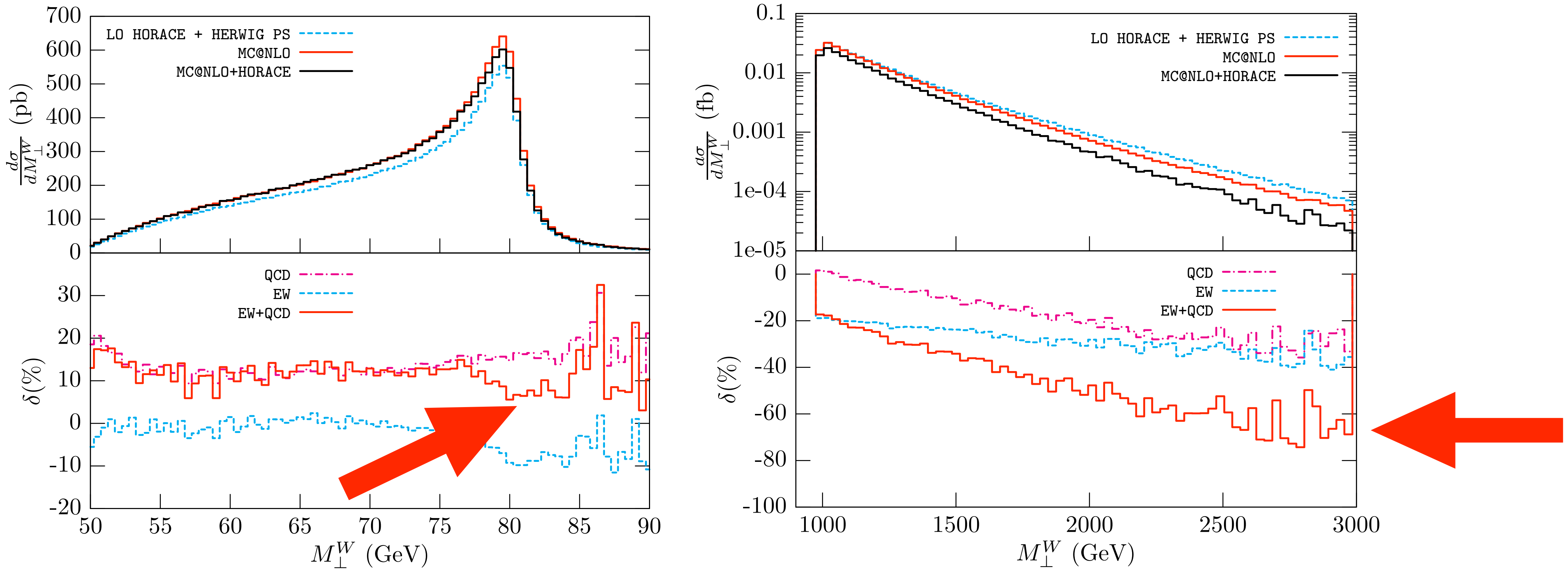


Combining QCD & EW for CC Drell-Yan

- Additive combination of QCD and EW corrections:

A. Vicini

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{QCD\oplus EW} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{QCD} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{EW} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{Born}\right\}_{HERWIG\ PS}$$



http://www.pv.infn.it/hepcomplex/horace.html

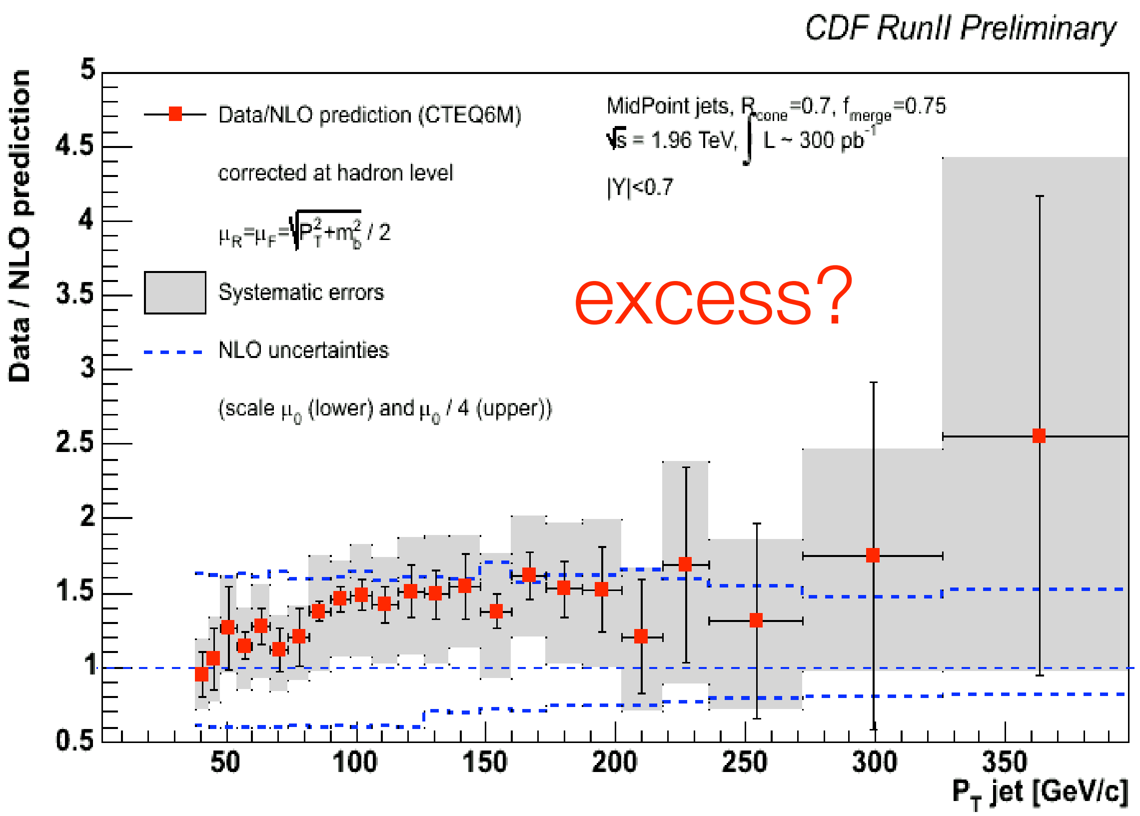
- QCD+EW: additive combination of $\mathcal{O}(\alpha_s) + \mathrm{QCD\ PS}$ and of $\mathcal{O}(\alpha) + \mathrm{QCD\ PS}$

  EW corrections are necessary to:
  - describe the jacobian peak ($\Rightarrow M_W$ measurement)
  - describe the large mass/momentum tails ($\Rightarrow$ new boson searches)

Accurate predictions for heavy-quark jets

Motivation:

G. Zanderighi



⇒ NLO ~ 40-60% uncertainty

EXP errors < TH errors

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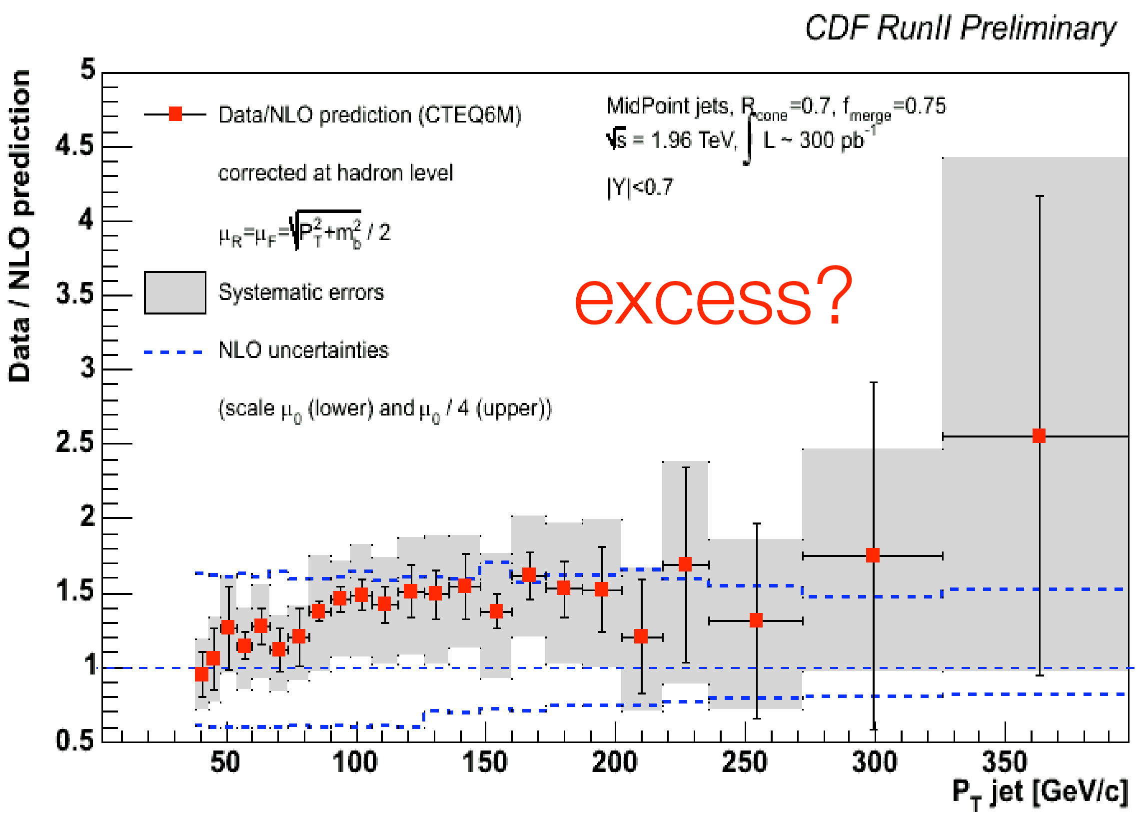

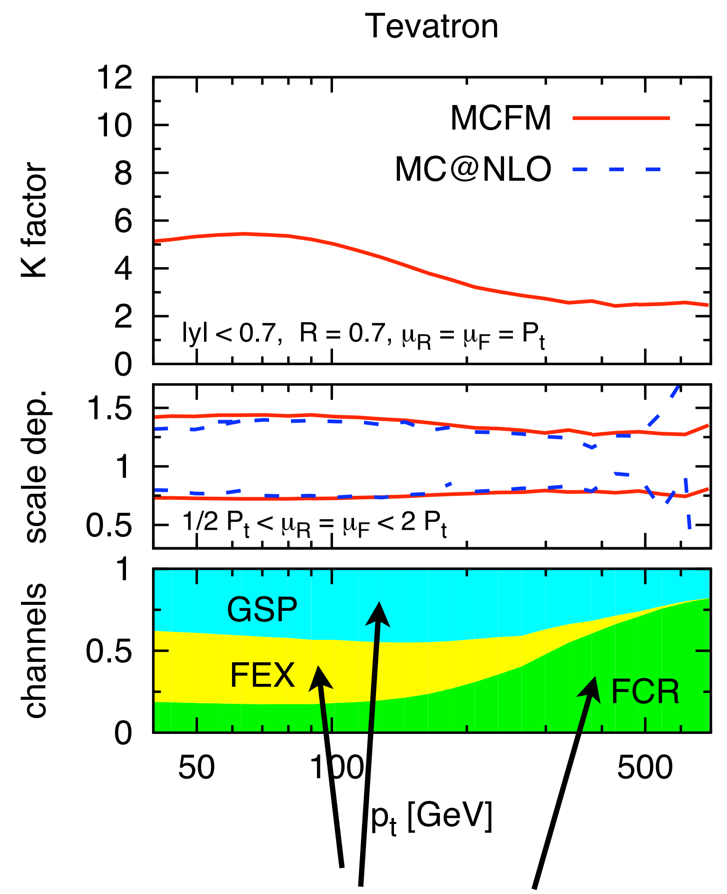

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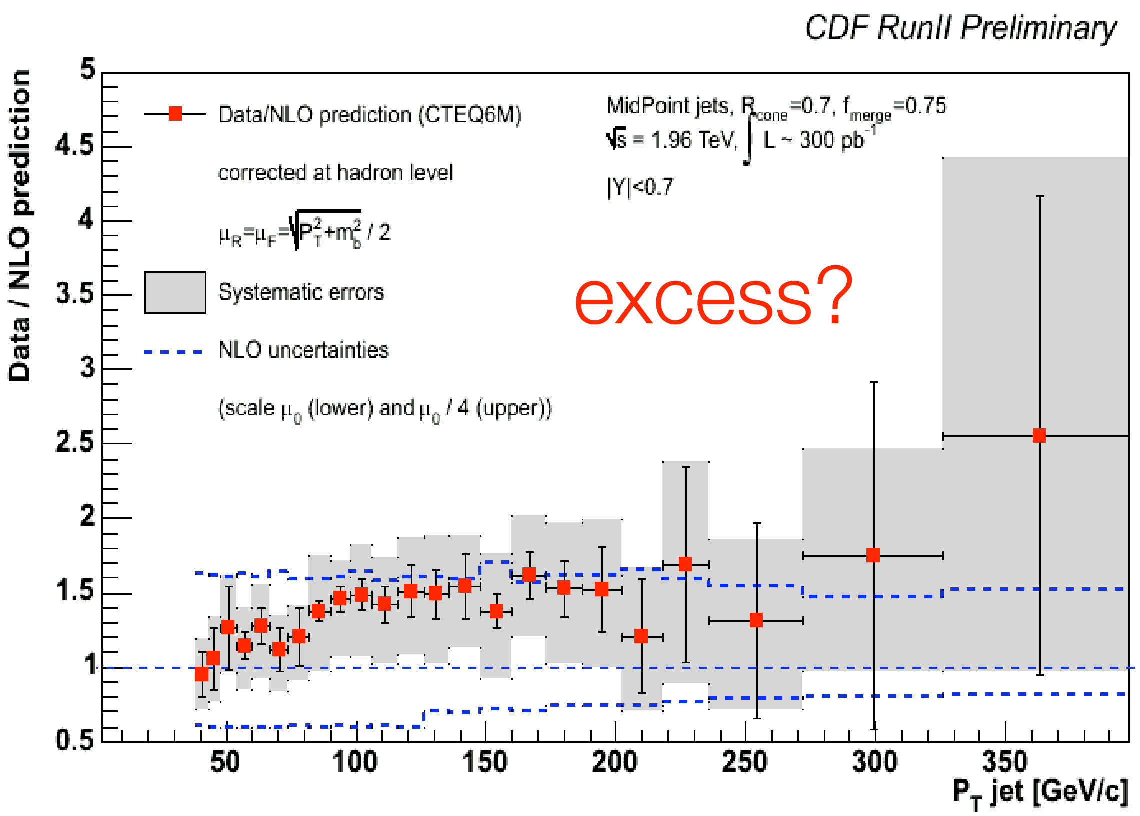
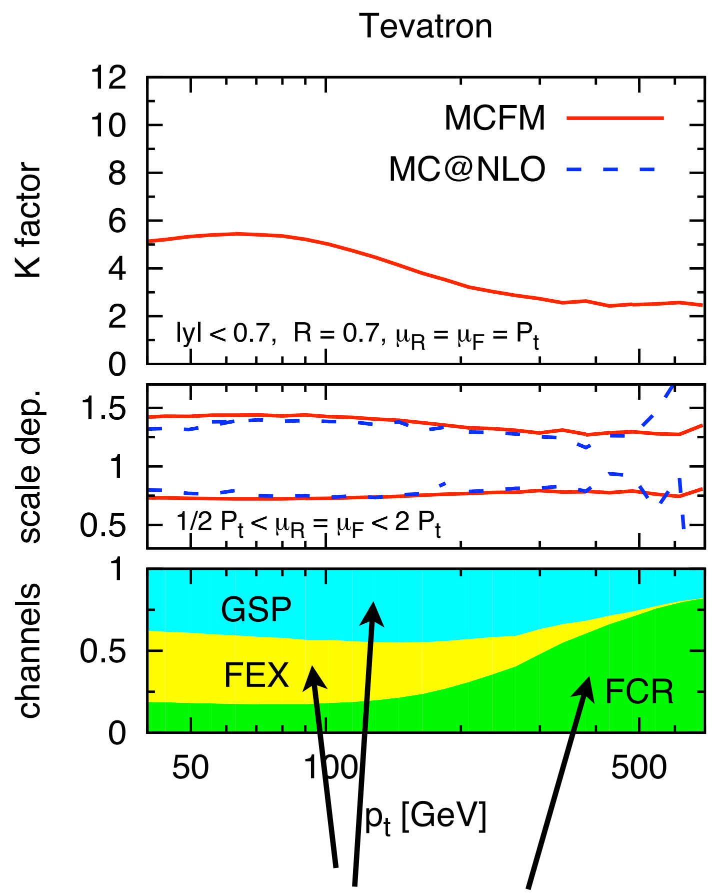
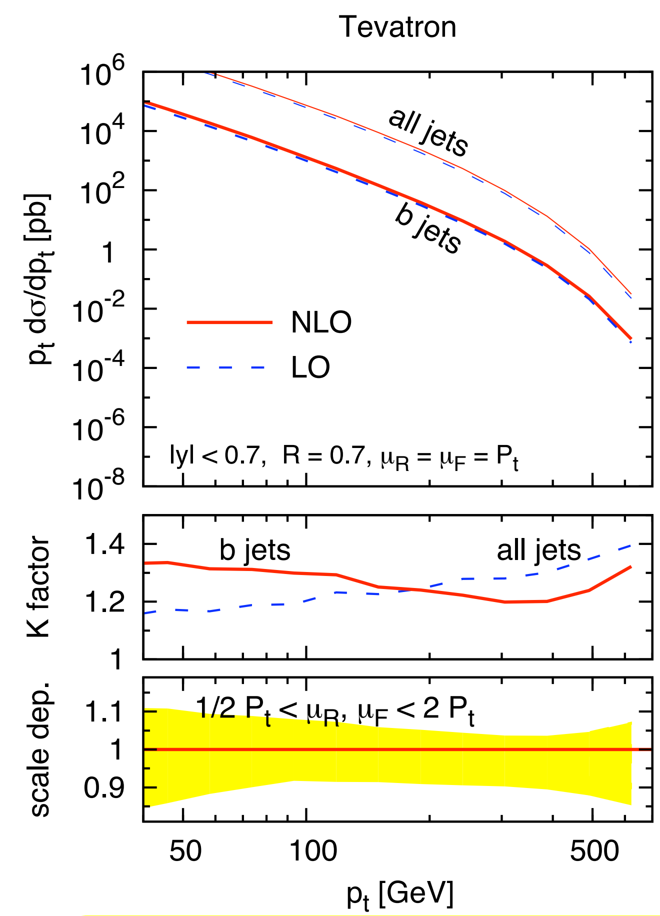
G. Zanderighi







⇒ NLO ~ 40-60% uncertainty

EXP errors < TH errors

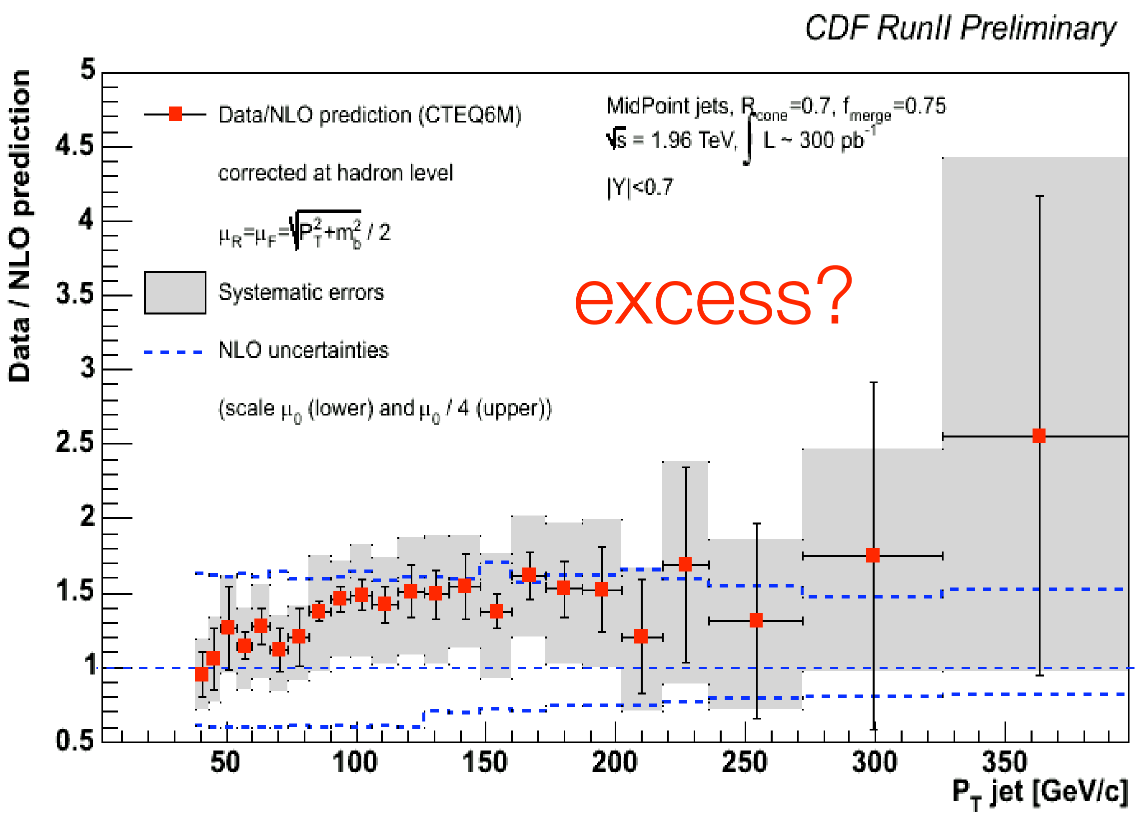
⇒ NLO < LO

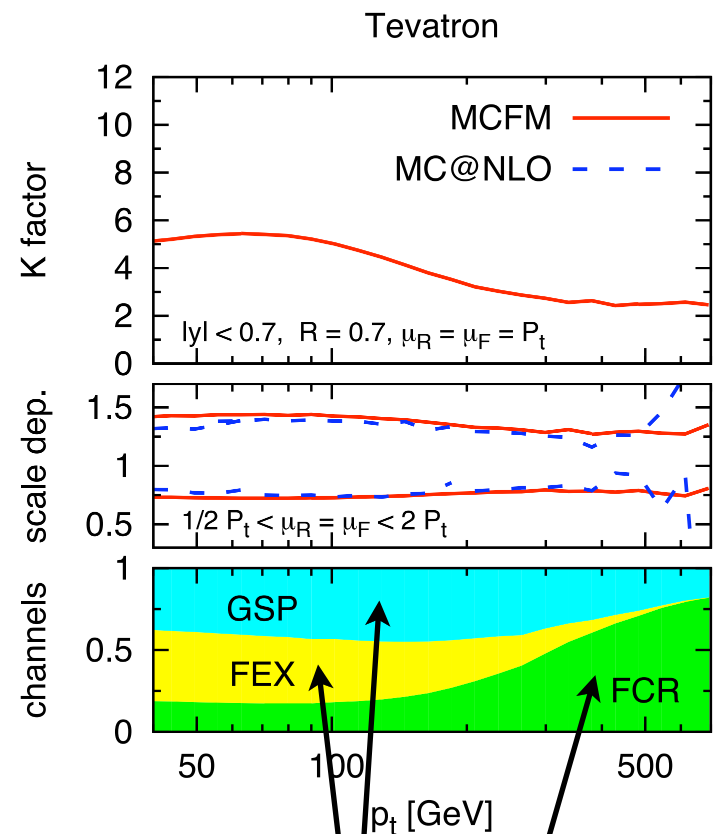
With new flavour jet-algorithm

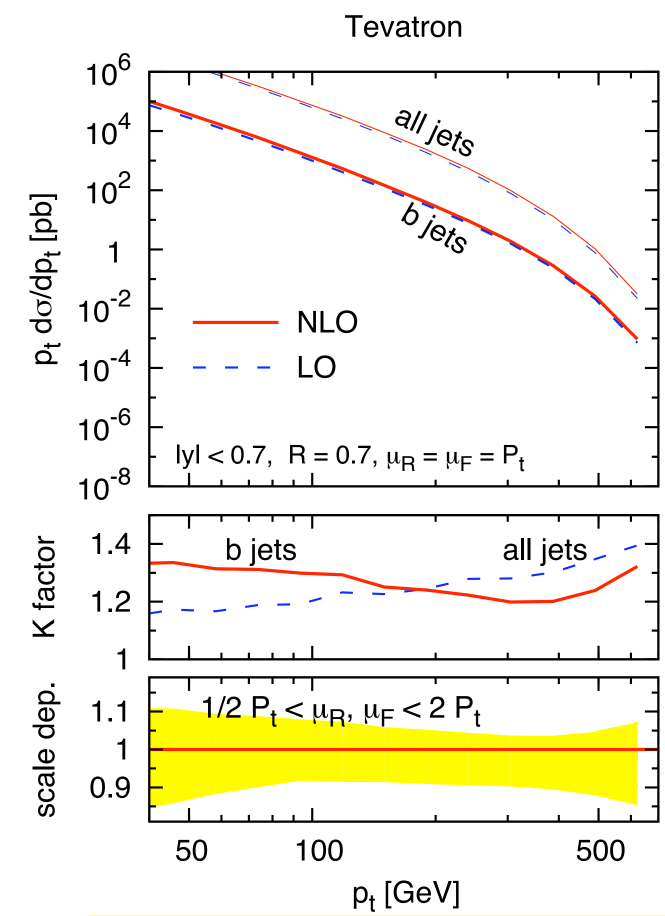
Accurate predictions for heavy-quark jets

Motivation:

G. Zanderighi







⇒ NLO ~ 40-60% uncertainty

EXP errors < TH errors

⇒ NLO < LO

With new flavour jet-algorithm

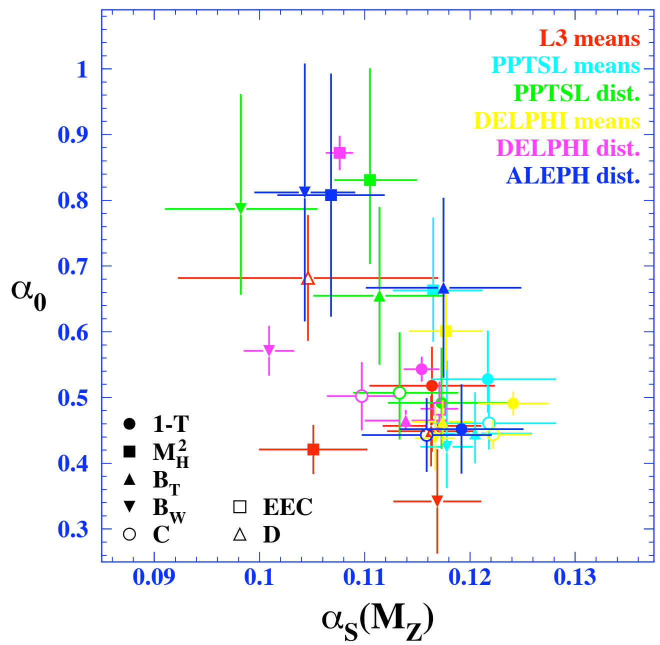
Method needs good understanding of single and double b-tagging efficiencies.

Three-jet event-shapes: NLO+NLL+1/Q

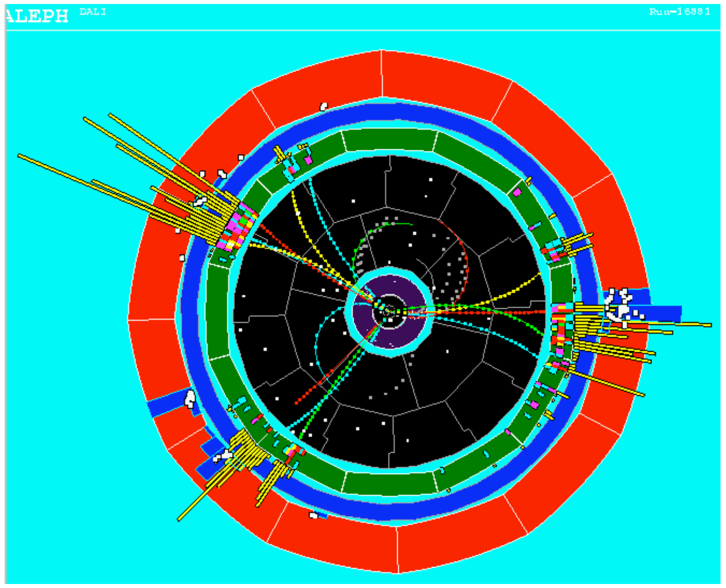
A. Banfi

Event-shapes: hadronization effects give rise to power corrections, modeled in terms of one universal parameter $\alpha_0 \Rightarrow$ fit of α_s - α_0

Picture works well, but tested only for two-jet event-shapes.



Select 3-jet events.
Momentum conservation
$\Rightarrow$ 3 jets are almost planar



Define event-shapes measuring the out-of plane radiation:

Thrust minor:

$$T_m Q \equiv \sum_h |\vec{p}_{th} \times \vec{n}_M| = \sum_h |p_h^{\text{out}}|$$

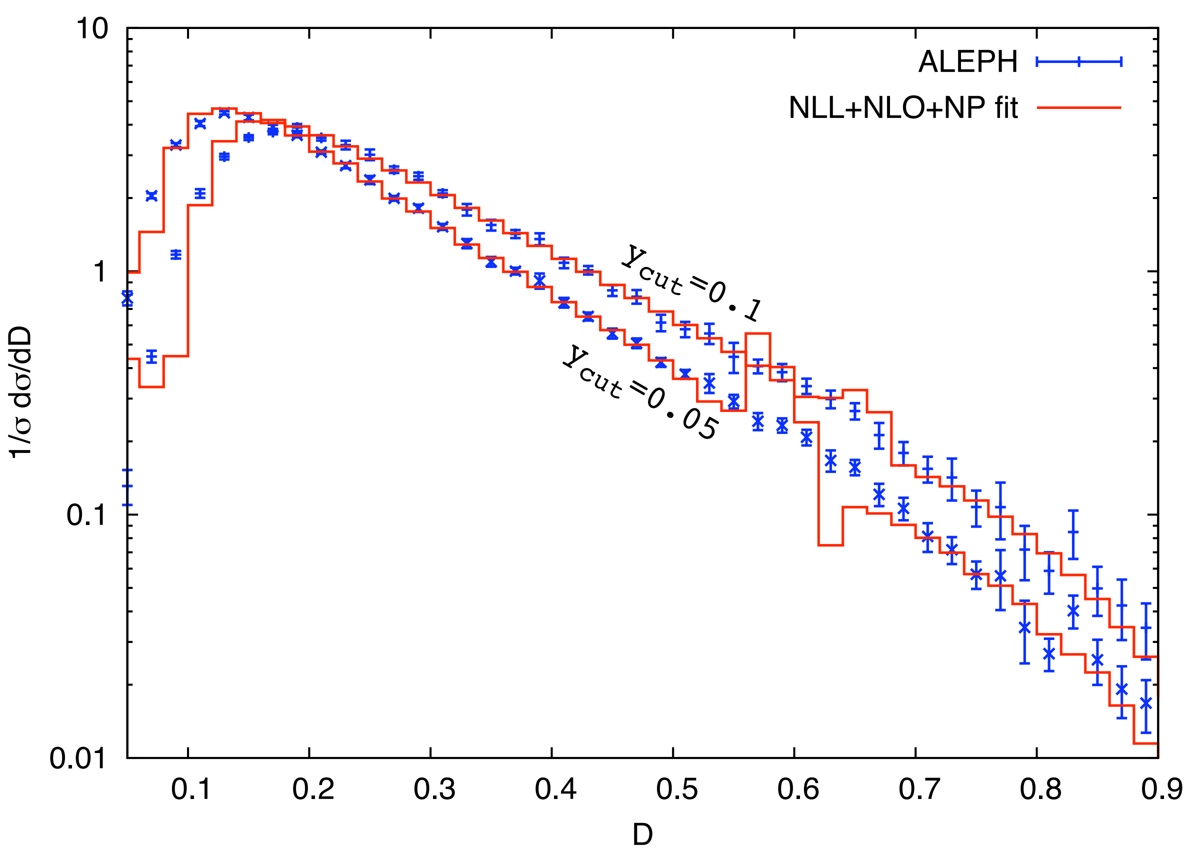
D-parameter:

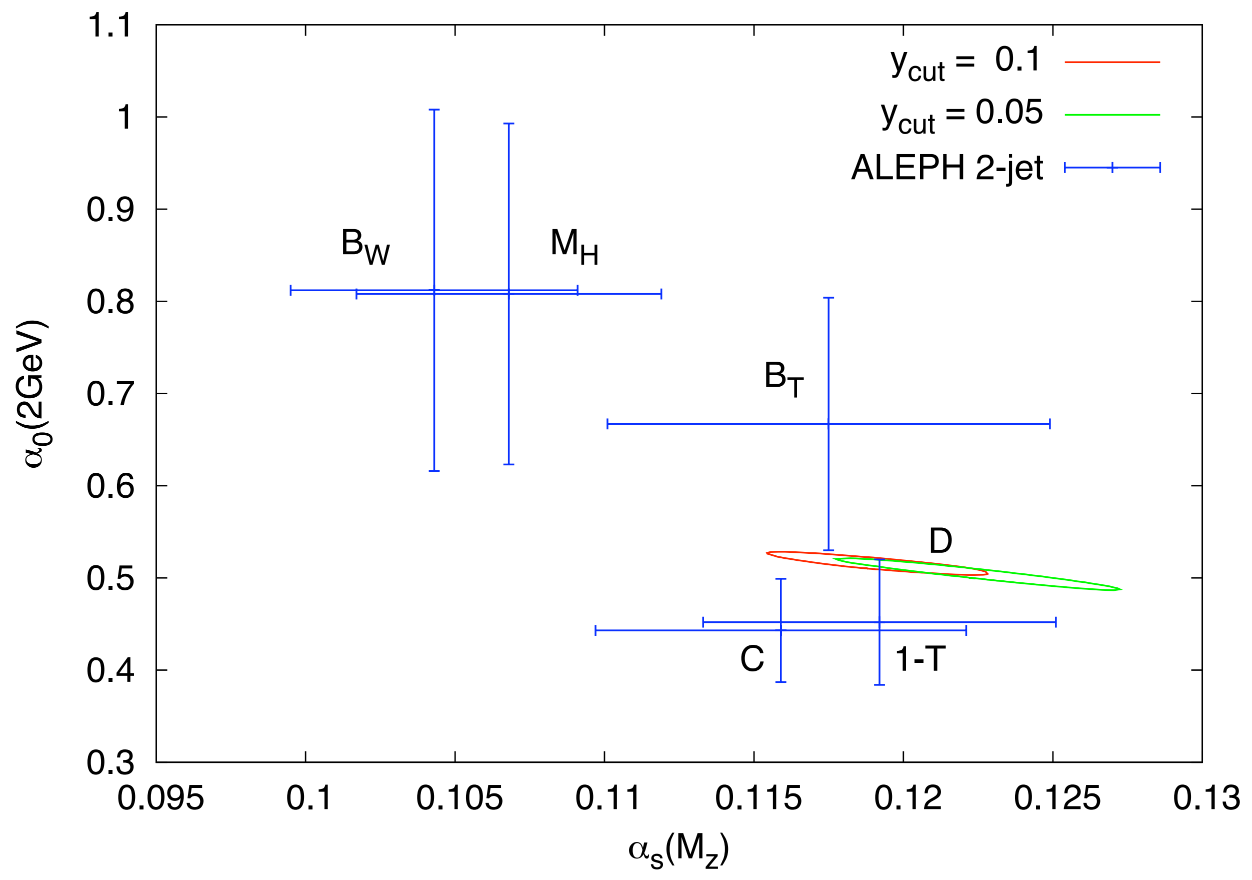
$$D \equiv 27 \det \theta \sim \sum_h \frac{(p_h^{\text{out}})^2}{E_h Q}$$

Three-jet event-shapes: NLO+NLL+1/Q

A. Banfi

First test of universality of power corrections from 3-jet event-shapes





- D-parameter good fits at the right of the peak (left: shape function?)
- Thrust minor: no fit yet (power corrections from 4-jets?)

Status of 3-jets at NNLO

A. Gehrmann

Motivation:

- Current error on α_s from jet observables dominated by theoretical uncertainty:

  S. Bethke, 2006

$$\alpha_s(M_Z) \quad = \quad 0.121 \pm 0.001(\text{experiment}) \pm 0.005(\text{theory})$$

- theoretical uncertainty largely from missing higher orders
- NNLO corrections to the 3-Jet rate are needed !

Method: developed antenna subtraction at NNLO

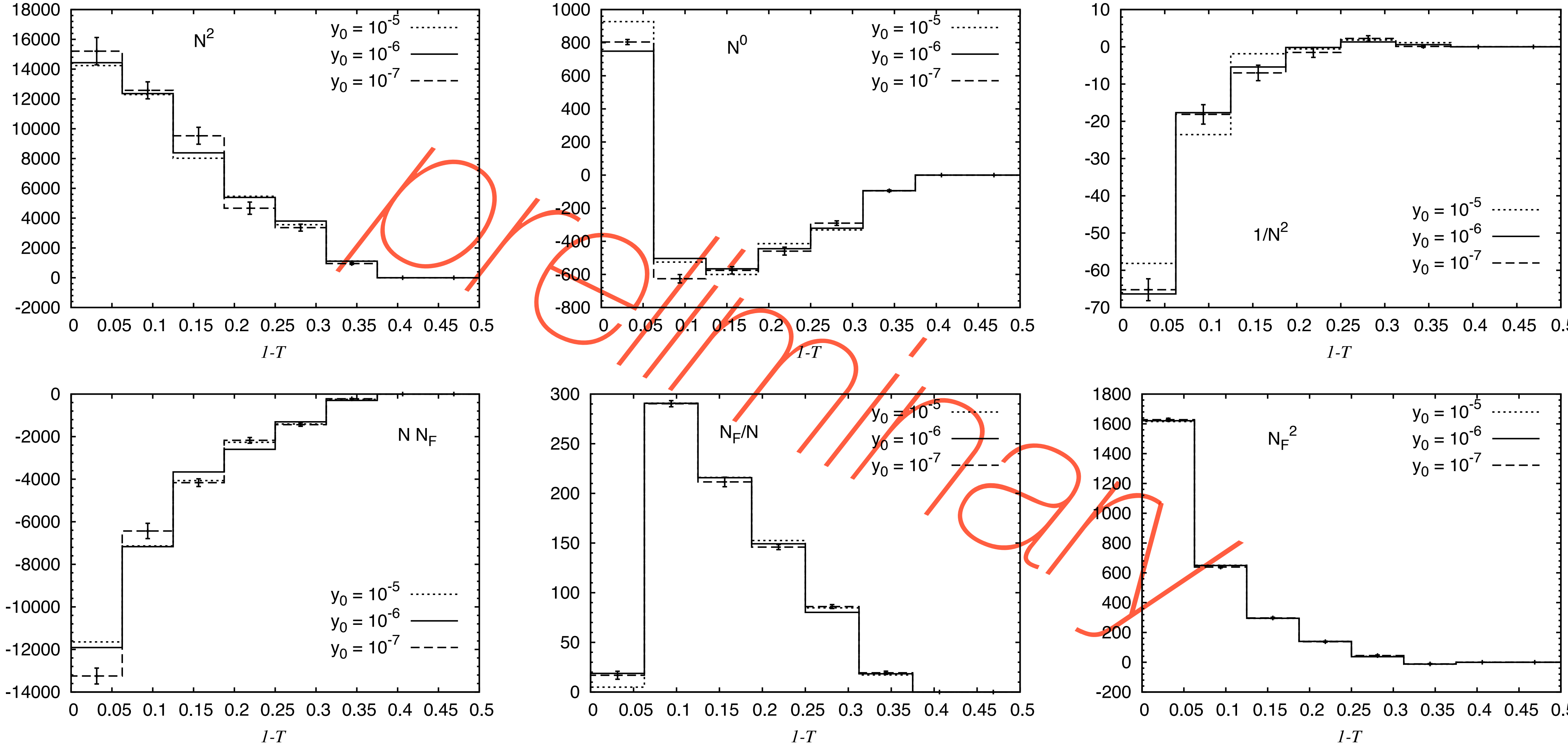
- implementation completed and checked
- first results obtained for NNLO thrust distribution
- ongoing: verification and production of high-precision results

Status of 3-jets at NNLO

Thrust in e^+e^- $\quad T = \max_{\vec{n}} \frac{\sum_{i=1}^{n} |\vec{p_i} \cdot \vec{n}|}{\sum_{i=1}^{n} |\vec{p_i}|}$

A. Gehrmann

Calculation of NNLO coefficient completed



- Next: implementation of other event-shapes and new fits of α_s

Part II: experimental summary by Alexander Savin