Jets at low and high Q^2 and determination of the strong coupling

Roman Kogler

MPI für Physik, München

on behalf of the H1 collaboration

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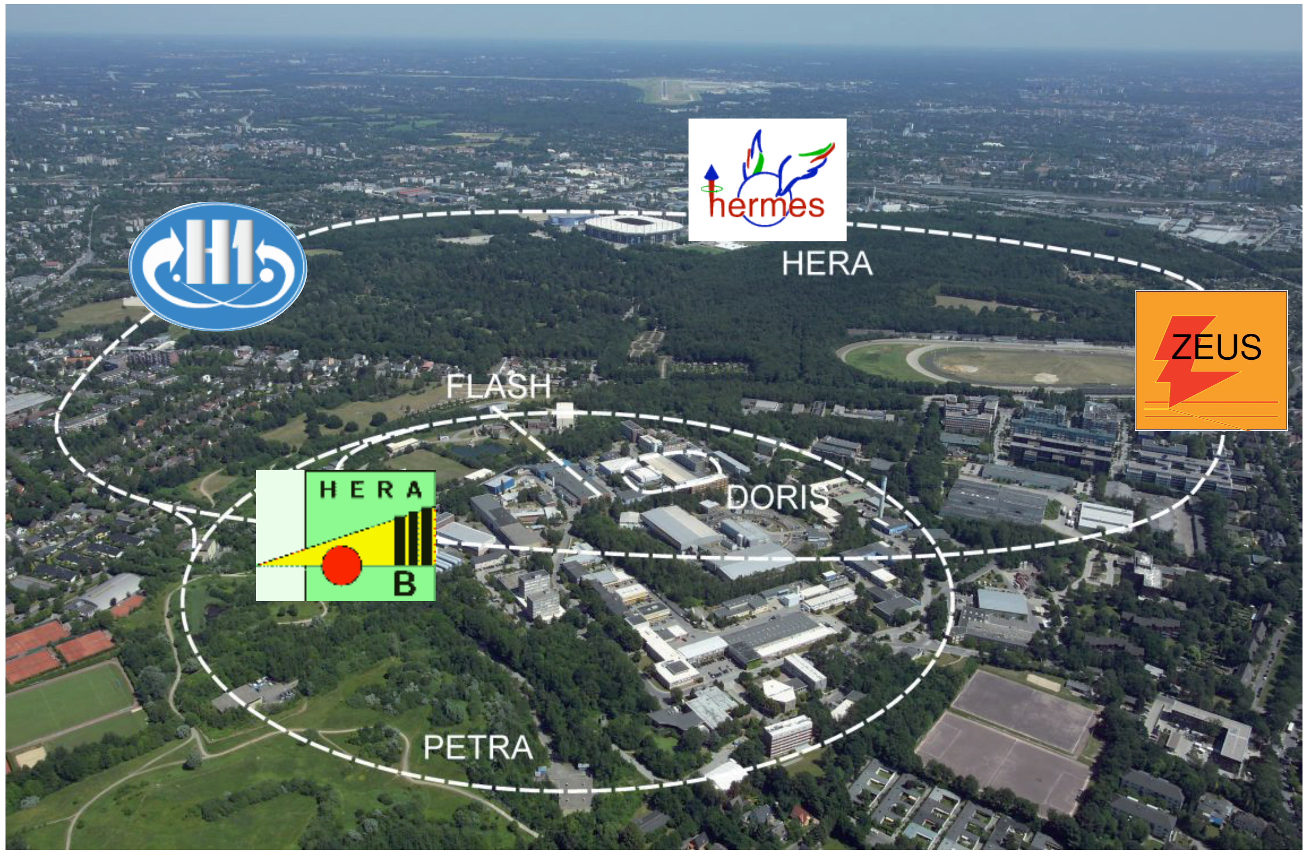
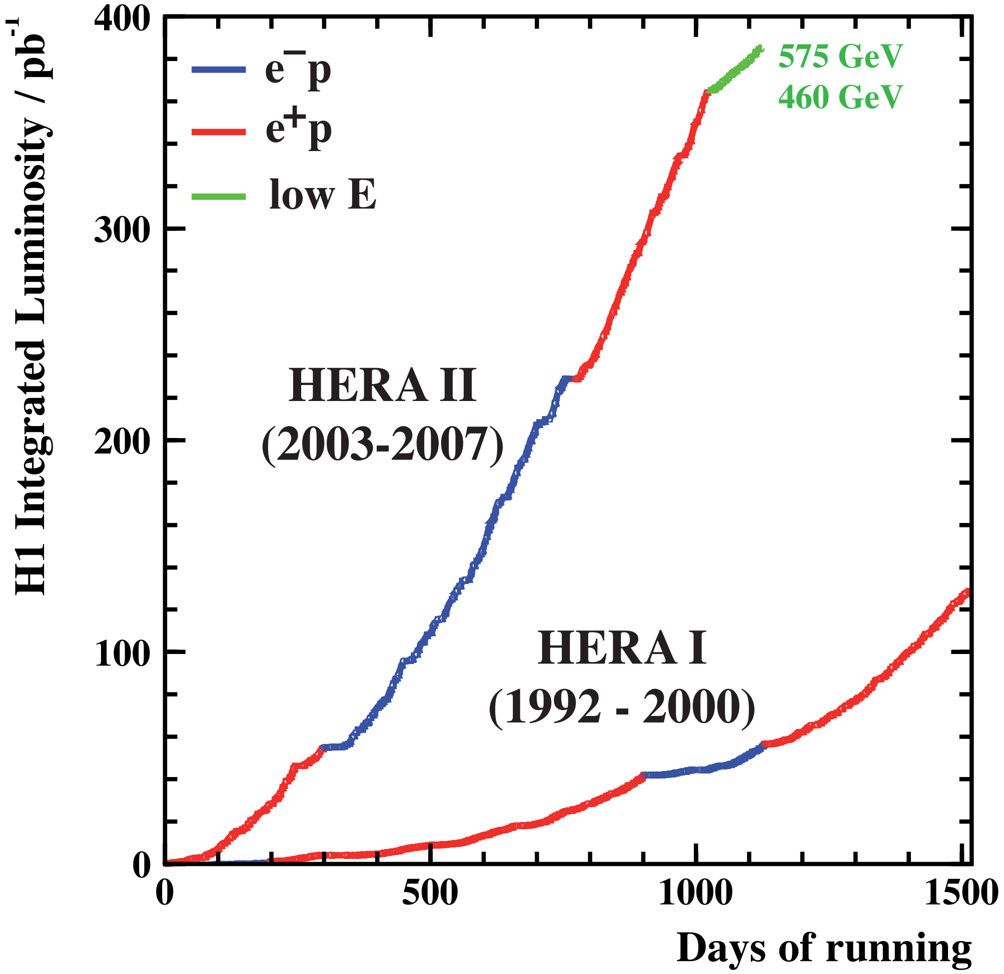
The ep collider HERA and H1



HERA

$$E_e = 27.6\,\mathrm{GeV}$$
$$E_p = 920\,\mathrm{GeV}$$
$$\sqrt{s} \approx 320\,\mathrm{GeV}$$

2001-2002 luminosity upgrade



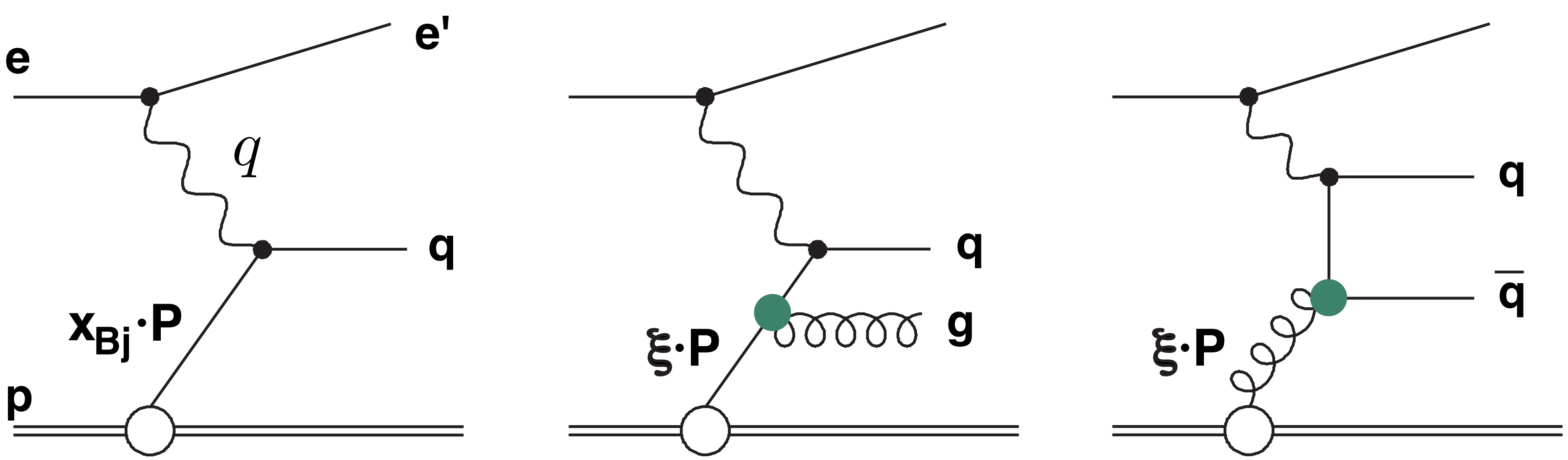
low Q^2 multi-jet analysis:

$Q^2 < 100$ GeV^2
HERA I
L = 44 pb^{-1}

high Q^2 multi-jet analysis:

$Q^2 > 150$ GeV^2
HERA 1+2
L = 400 pb^{-1}

Jet Production In DIS



virtuality:

$$Q^2 = -q^2 = -(e - e')^2$$

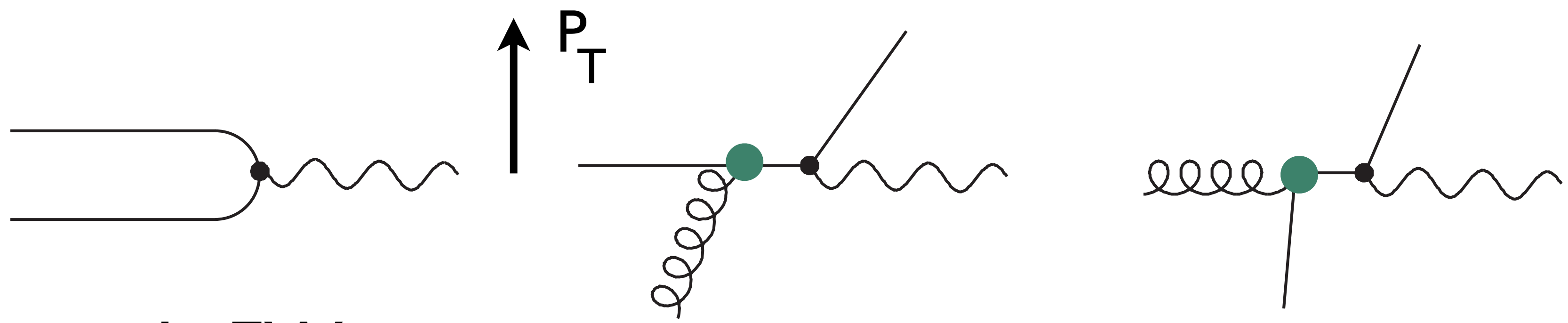
inelasticity:

$$y = \frac{p \cdot q}{p \cdot k}$$

Boost to Breit frame, $2x_{Bj} \cdot p + q = 0$

Bjorken scaling variable:

$$x_{Bj} = \frac{Q^2}{2p \cdot q}$$



only EW coupling

$\propto \alpha_s$

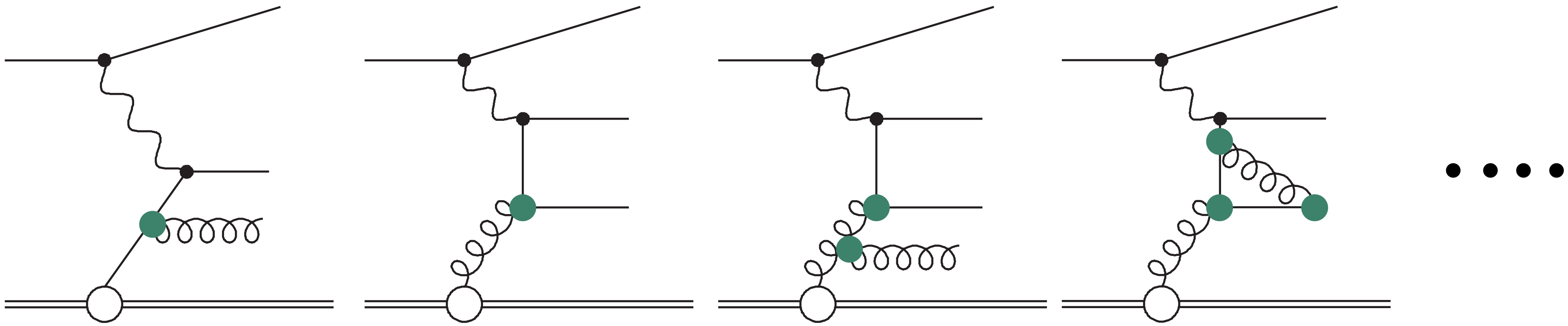
$\propto \alpha_s$

Momentum fraction of struck parton (in LO):

$$\xi = \left(1 + \frac{M_{12}^2}{Q^2}\right)$$

Only processes proportional to α_s generate P_T in the Breit frame

Jet Production In DIS



$$\sigma_{\mathrm{njet}} = \sum_{i=q,\bar{q},g} \int_0^1 \mathrm{d}x\, f_i(x,\mu_f)\, \hat{\sigma}_i(x, \alpha_s^{n-1}(\mu_r), \mu_r, \mu_f)\, (1+\delta_{had})$$

$f_i(x,\mu_f)$: PDF of parton i in proton

used here: CTEQ6.5M, $\alpha_s(M_Z) = 0.118$

$\hat{\sigma}_i$: partonic cross section, calculated with NLOJet++,

MSbar scheme, 5 massless quark flavours,

up to 3-jet cross sections in NLO: $\mathcal{O}(\alpha_s^3)$

choice of scales μ_f and μ_r : two hard scales in DIS: Q and P_T

multijets at low Q^2: Q: 2-10 GeV, P_T : 5-80 GeV ⇒ Q/P_T = 0.1 - 2

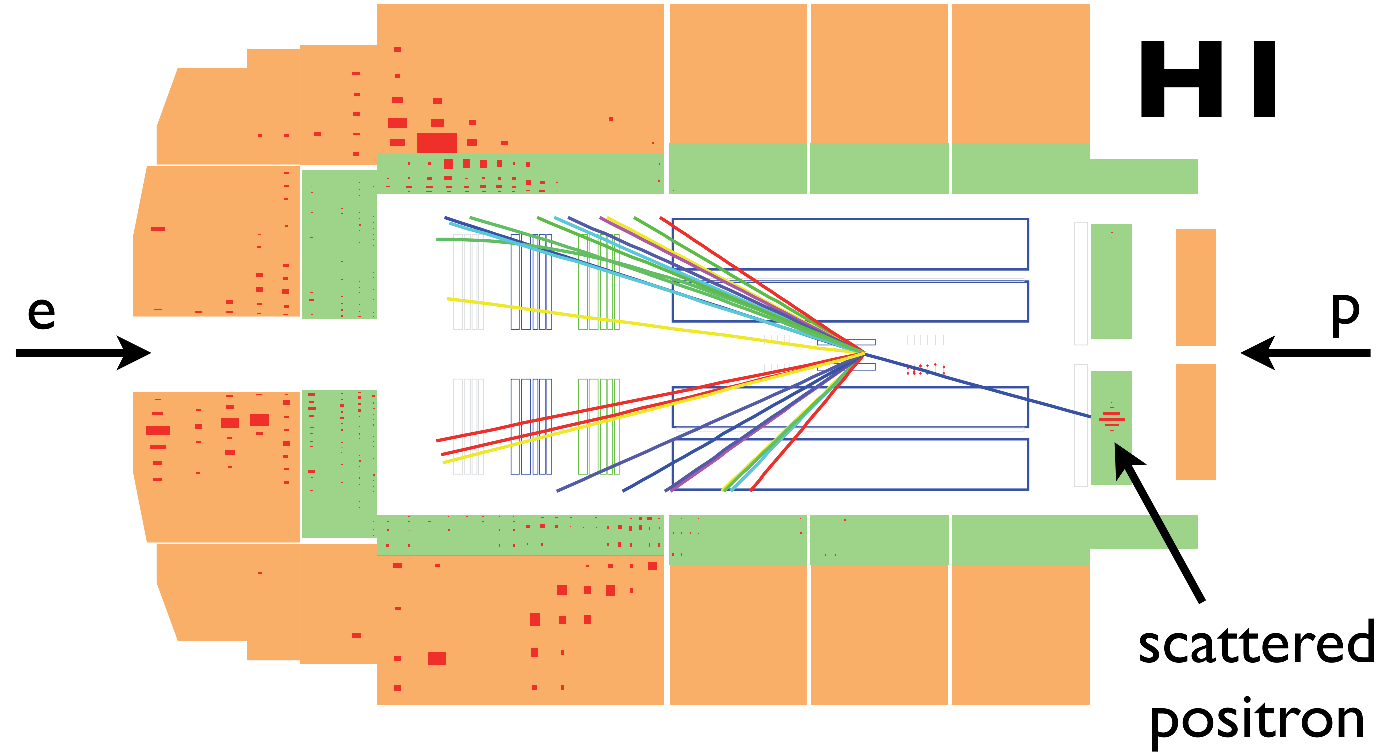
typical: $\mu_f = Q \qquad \mu_r = \sqrt{(Q^2 + P_T^2)/2}$

Multi-Jets At Low Q^2

Phase space

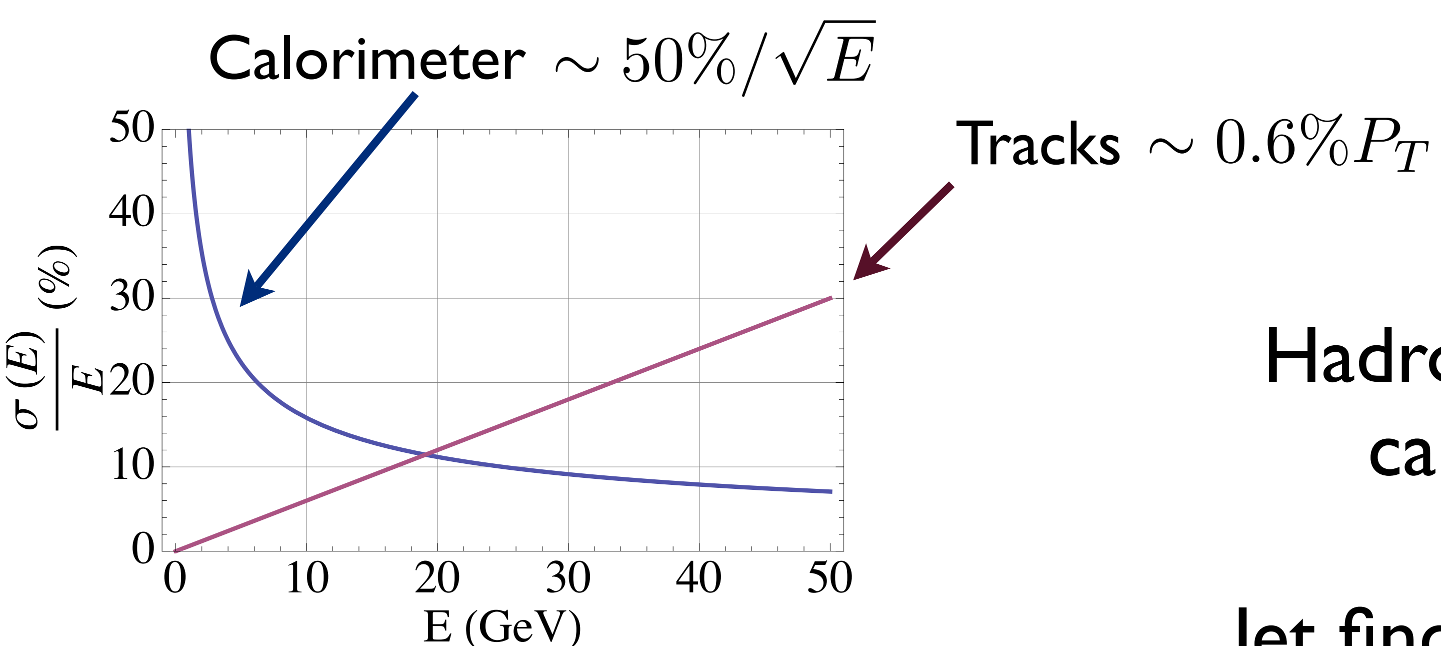
$5\ \mathrm{GeV}^2 < Q^2 < 100\ \mathrm{GeV}^2$

$0.2 < y < 0.7$



Reconstruction

Hadronic final state reconstructed with energy flow method:



use best available measurement without double counting

Hadronic final state is measured and calibrated in laboratory frame

Jet finding and clustering performed in Breit frame

Multi-Jets At Low Q^2

Inclusive jets:

5 GeV < P_T (Breit) < 80 GeV

-1 < η(lab) < 2.5

2- and 3-jets:

M_{12} > 18 GeV

3-jet sample is a subsample of 2-jet sample

Jet Definition:

longitudinally invariant k_T algorithm
inclusive mode, R_0 = 1
P_T recombination scheme

Main experimental uncertainties:

jet energy scale 2% → $\Delta\sigma/\sigma$ = 4 - 10 %

acceptance correction → $\Delta\sigma/\sigma$ = 2 - 15 %

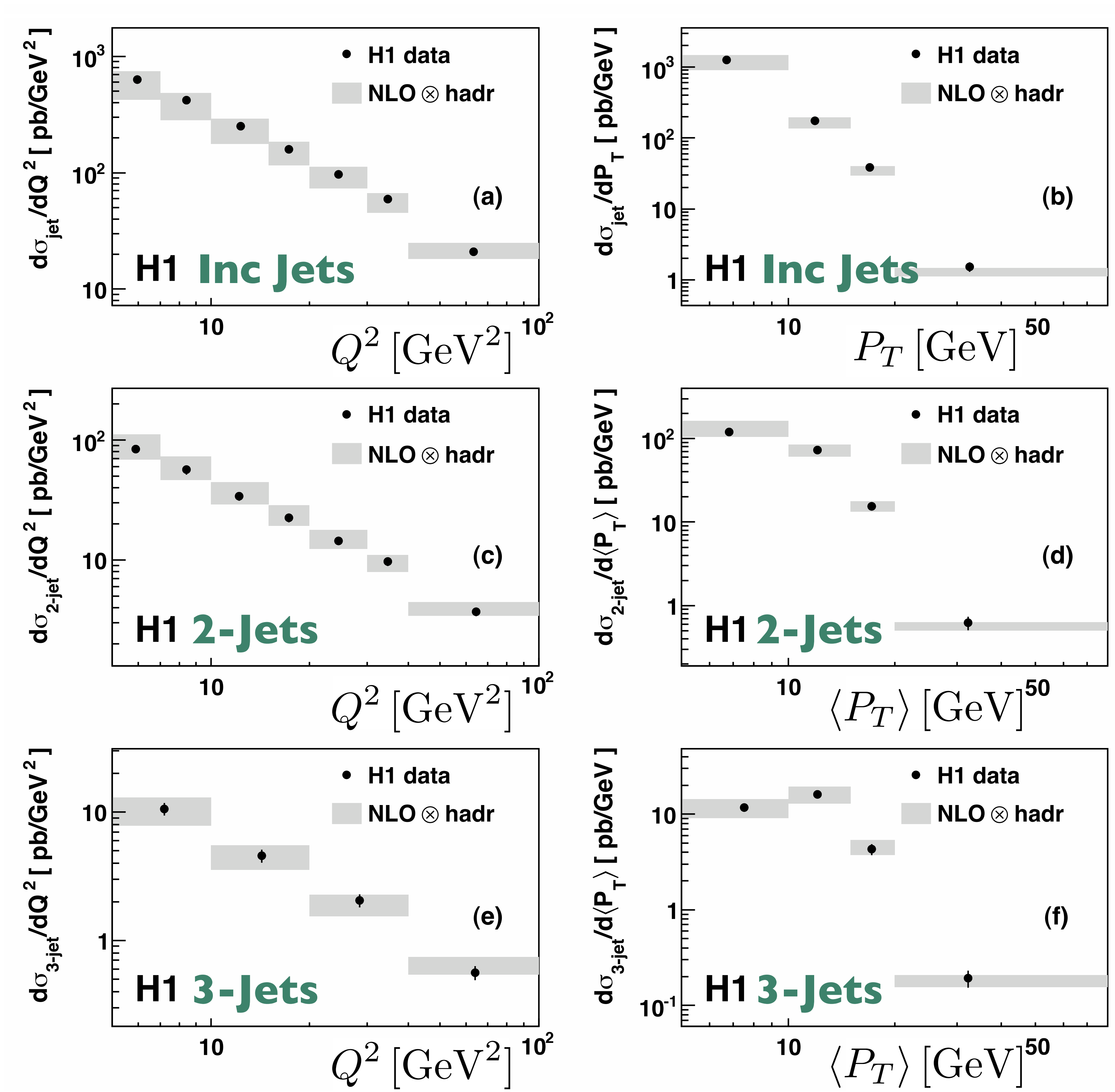
luminosity measurement → $\Delta\sigma/\sigma$ = 1.5 %

positron measurement → $\Delta\sigma/\sigma$ = 2 %

Statistics	
Inclusive Jets:	230.140
2-Jets:	31.550
3-Jets:	4.879

Measurements as function of Q^2, P_T ($\langle P_T \rangle$), ζ

Multi-Jet Cross Sections At Low Q²



- measurements well described by NLO, $\alpha_s(M_Z) = 0.118$ hadr. corrections 0.9-0.95 (0.8 for 3-jets)

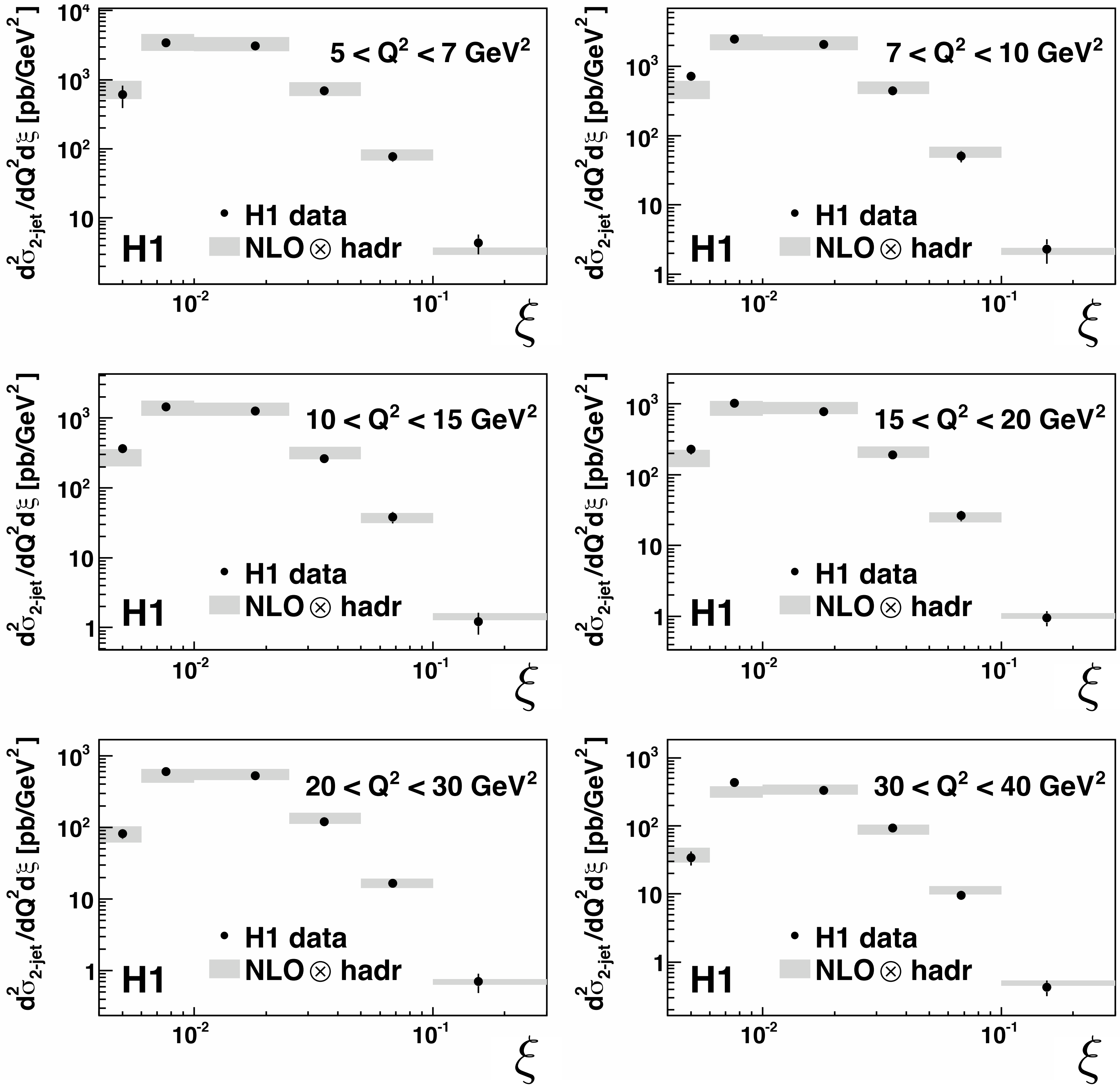
- **exp. uncertainties:** 6-10%

- **theoretical uncertainties:** dominated by missing higher orders estimated by variation of μ_f and μ_r by factors 0.5 and 2

  30% at low Q², P_T
  10% at high Q², P_T

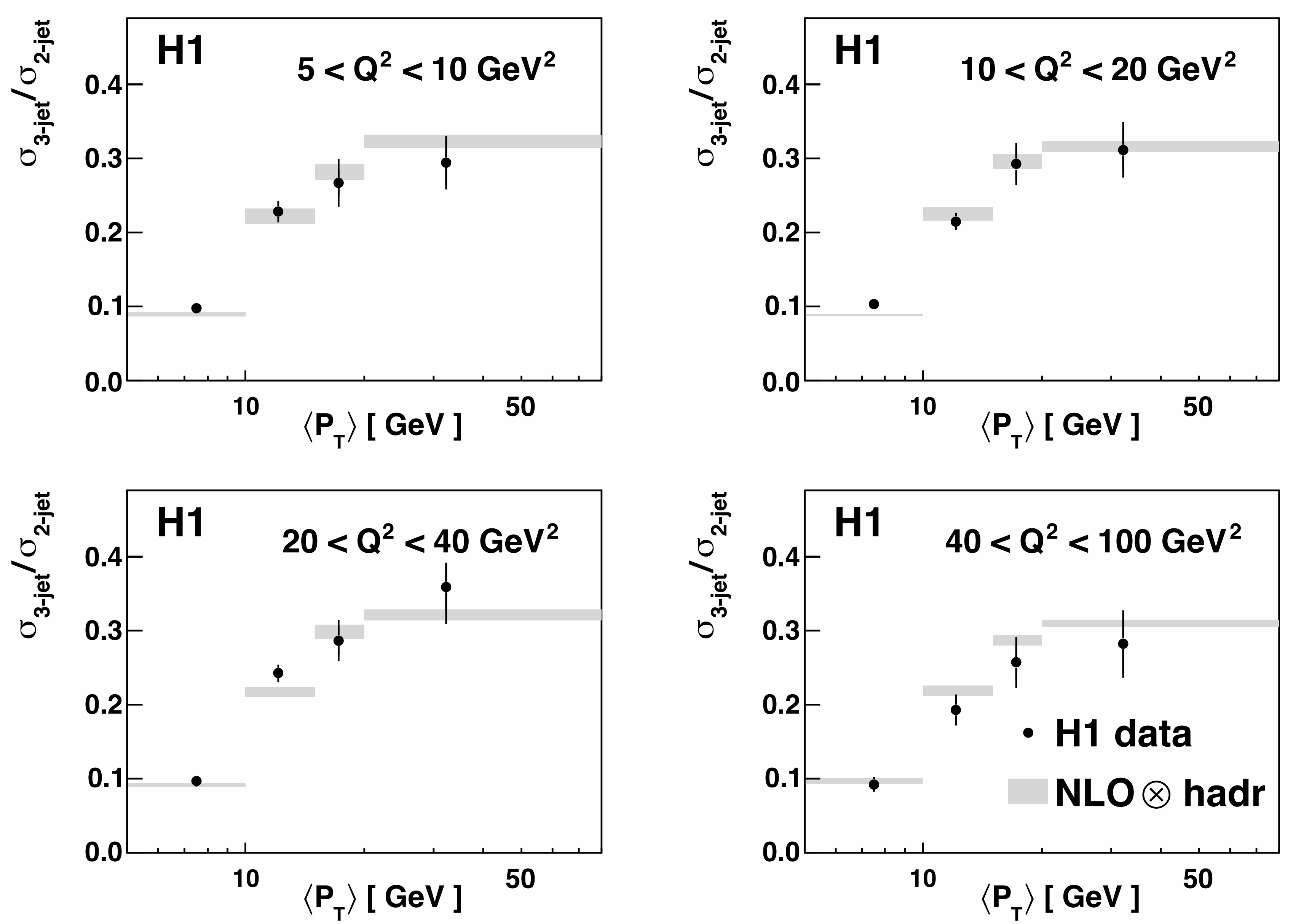
- choice of $\mu_r = \langle P_T \rangle$ disfavoured by data

2-Jet Cross Sections At Low Q²



- measurements well described by NLO, $\alpha_s(M_Z) = 0.118$ hadr. corrections 0.85-1.05
- statistical uncertainties small even for double-differential cross sections
- theoretical uncertainties larger than experimental ones
- rise of the cross section towards small ξ expected due to increase of gluon density suppressed by cuts on P_T and M_{12}
- test of the gluon density from global analyses and inclusive fits

3-Jet/2-Jet Ratios



- normalisation errors cancel
  systematical errors cancel partially
  reduced systematical uncertainties by 50%
- **reduced sensitivity to missing higher orders in NLO prediction**
- dominated by statistical uncertainties at large $\langle P_T \rangle$

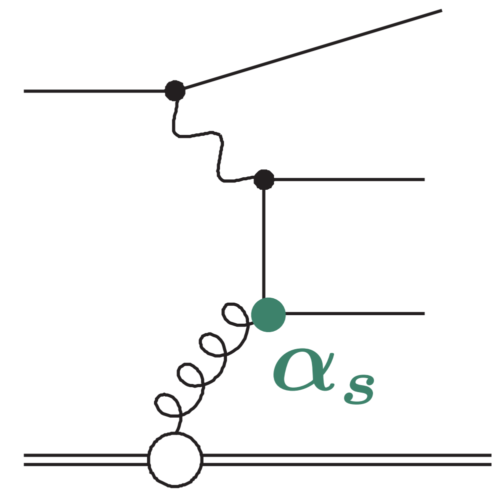
(9x the statistics from HERA2 data available)

Determination of $\alpha_s(M_Z)$

NLO calculation depends on PDF and $\alpha_s(M_Z)$

⇒ Keep PDF fixed and fit $\alpha_s(M_Z)$ to the data

⇒ Assign an error due to PDF uncertainty



Hessian method: Minimise $\chi^2(\alpha_s)$

$$\chi^2(\alpha_s) = \vec{V}^T M^{-1} \vec{V} + \sum_k \epsilon_k^2 \qquad M = M^{\mathrm{stat}} + M^{\mathrm{uncorr}}$$

$\vec{V}^T M^{-1} \vec{V}$: correlated version of $\sim \sum \frac{(\sigma^{exp} - \sigma^{th})^2}{\mathrm{err}^2}$

ϵ_k: Shift of correlated systematic uncertainty k, pull parameter in fit

$$V_i = \sigma_i^{th} - \sigma_i^{exp} \left(1 - \sum_k \Delta_{ik} \epsilon_k \right)$$

V_i, σ_i^{th}, σ_i^{exp}: Bin i

Δ_{ik}: effect of correlated error k on measurement in bin i

σ_i^{th} obtained with fastNLO

Theoretical Uncertainties on $\alpha_s(M_Z)$

α_s is obtained at $\mu_r = \sqrt{(Q^2 + P_T^2)/2}$

evolved with 2-loop solution of RGE to M_Z

$\Rightarrow$ **PDF uncertainty**

propagated from CTEQ6.5M error set, 2% uncertainty on $\alpha_s(M_Z)$

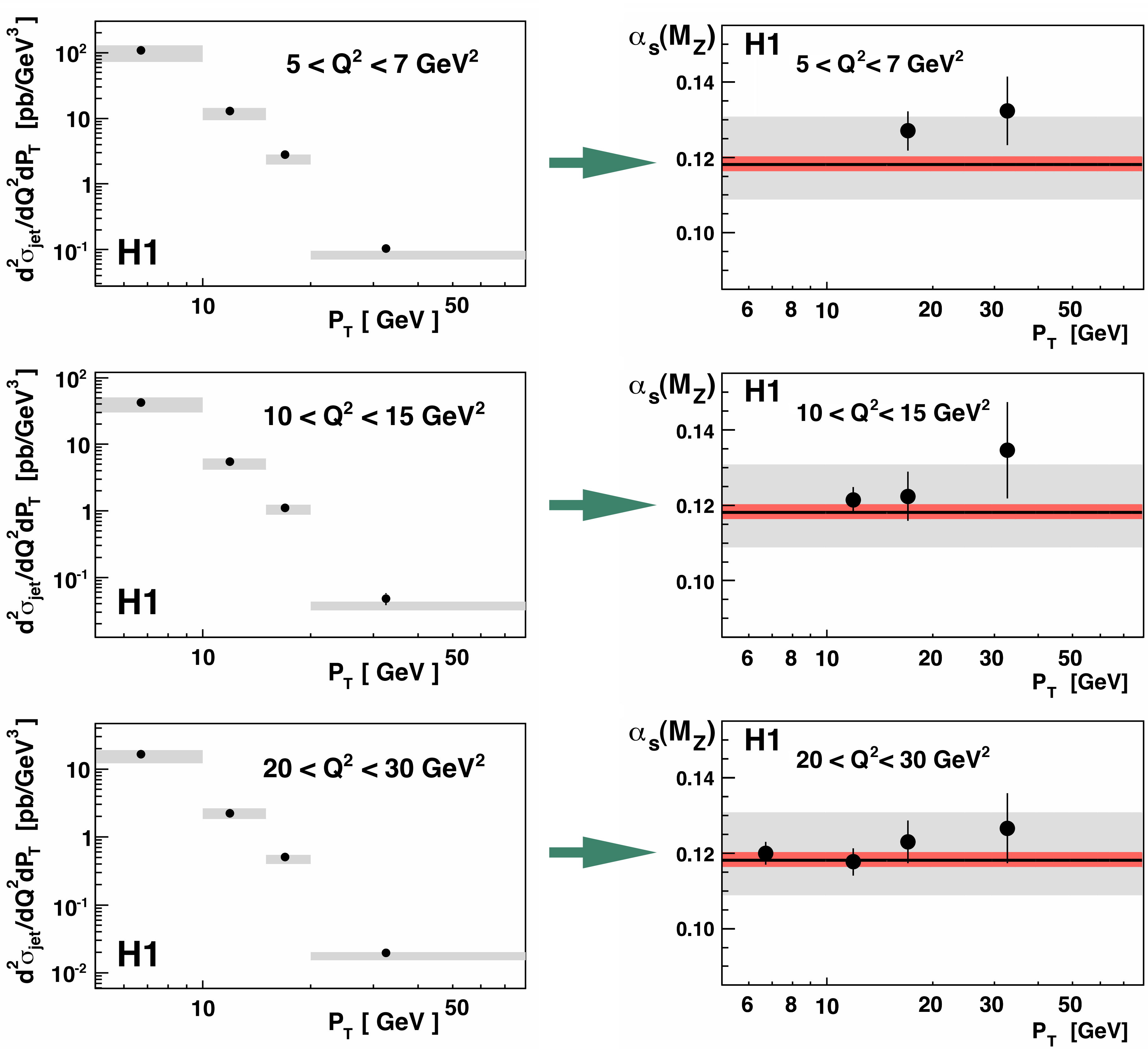
$\Rightarrow$ **Hadronisation corrections**

obtained with MEPS and CDM models, 1-2% uncertainty on $\alpha_s(M_Z)$

$\Rightarrow$ **Missing higher orders**

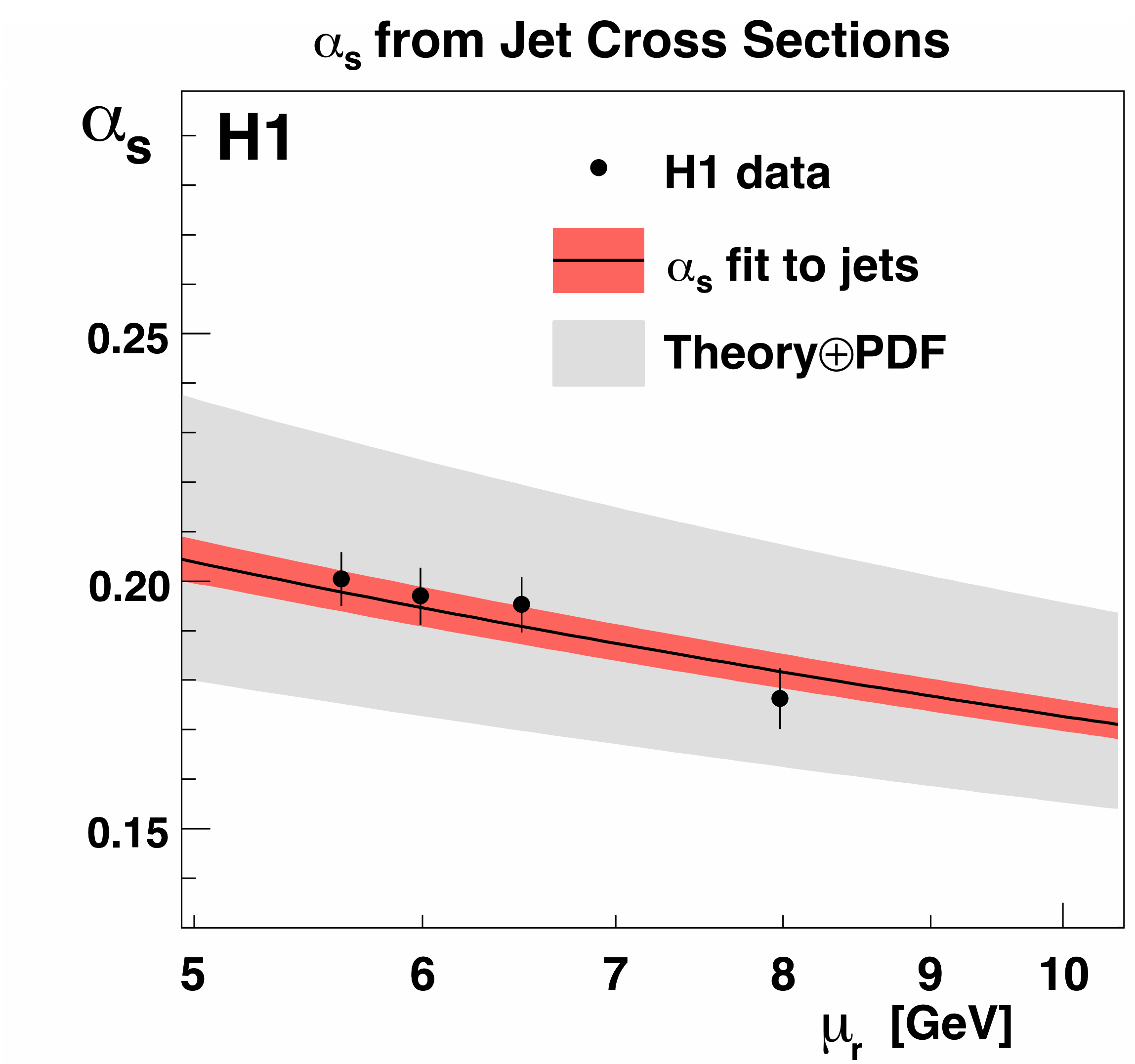
estimated by variation of the scales μ_f and μ_r by factors 0.5 and 2
refit to data points (offset-method), 8% uncertainty on $\alpha_s(M_Z)$

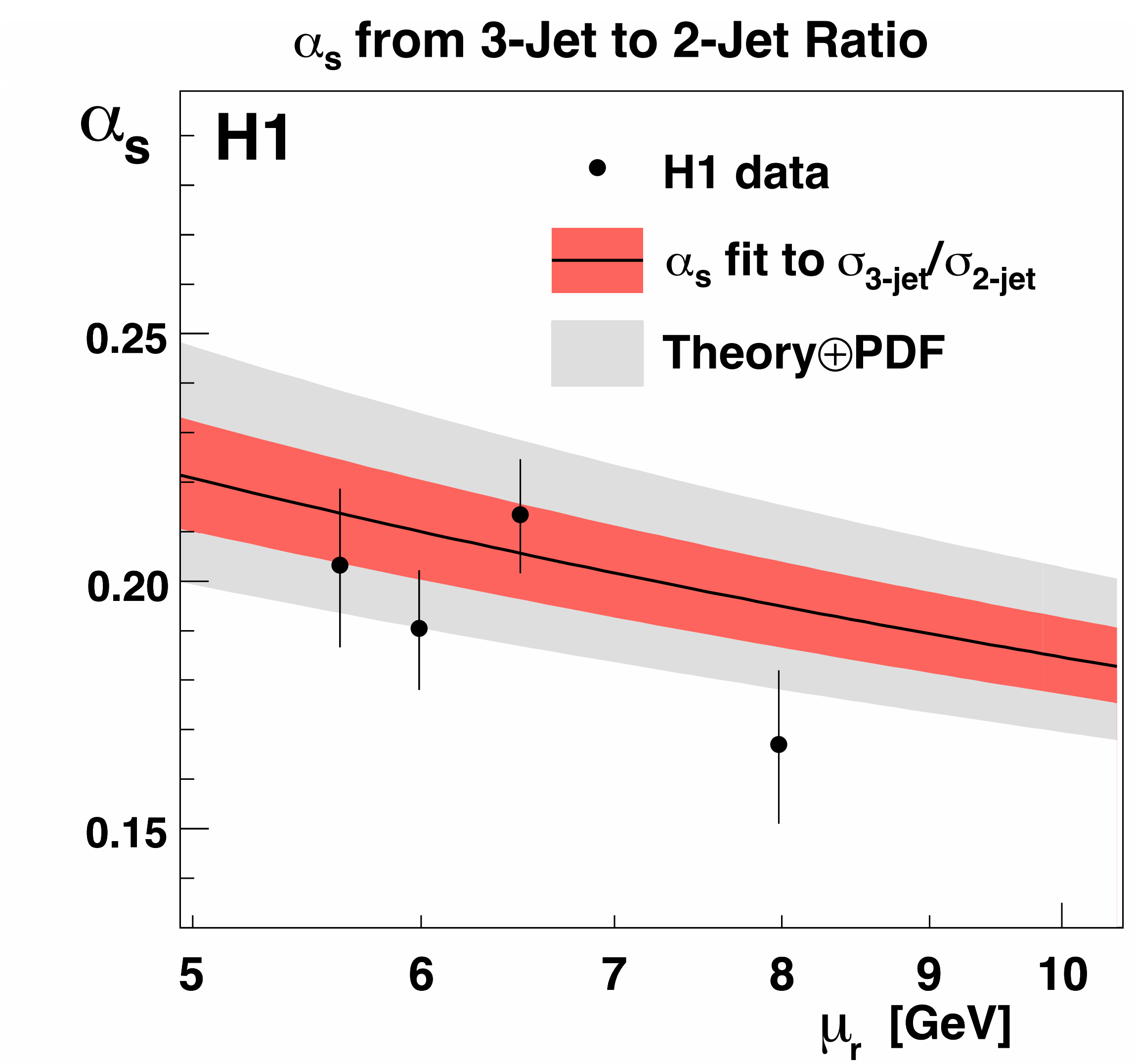
$\alpha_s(M_Z)$ Fits from Inclusive Jets



- fits performed for all 22 individual data points (only 11 shown)
- k-factors σ_{NLO}/σ_{LO} very large in some regions (>2.5), those data points were excluded from fit
- error bar: exp. uncertainties
- inner red band: simultaneous fit to all data points with experimental errors
- outer grey band: PDF, hadronisation and beyond NLO uncertainties

$\alpha_s(\mu_r)$ Determination from Low Q² Jets





- Simultaneous fit to all 62 measurements of inclusive, 2- and 3-jet cross sections
- result dominated by theoretical uncertainty, missing higher orders

NNLO calculations needed

- Simultaneous fit to all 14 3-jet/2-jet measurement points
- reduced systematical and theoretical uncertainties, dominated by statistics

more data needed

Multijets at high Q² and $\alpha_s(\mu_r)$

Phase space:

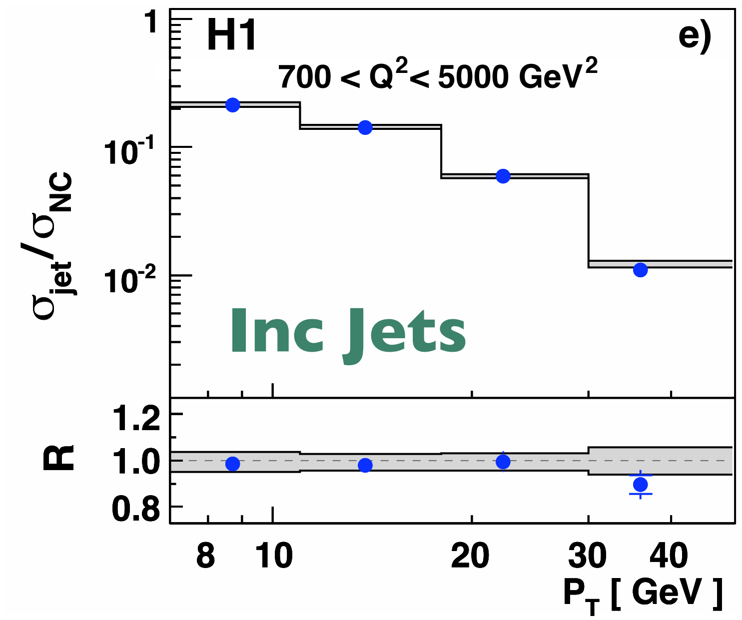
$150\ \mathrm{GeV}^2 < Q^2 < 15.000\ \mathrm{GeV}^2$

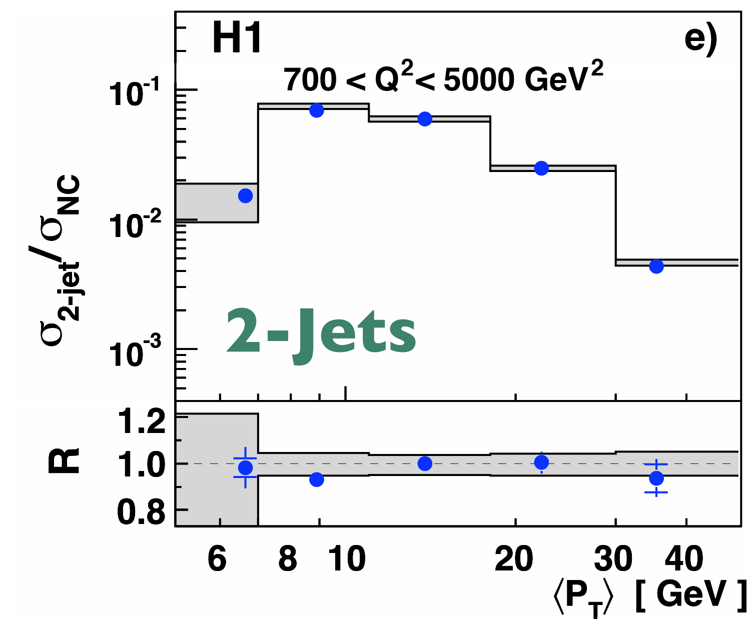
$0.2 < y < 0.7$

Inclusive jets:

$7\ \mathrm{GeV} < P_T\ (\mathrm{Breit}) < 50\ \mathrm{GeV}$

$-0.8 < \eta(\mathrm{lab}) < 2$





2- and 3-jets:

$M_{12} > 16\ \mathrm{GeV}$

cross sections **normalised** to DIS cross section

smaller theoretical uncertainties,

still larger than exp. uncertainties,

very precise $\alpha_s(M_Z)$

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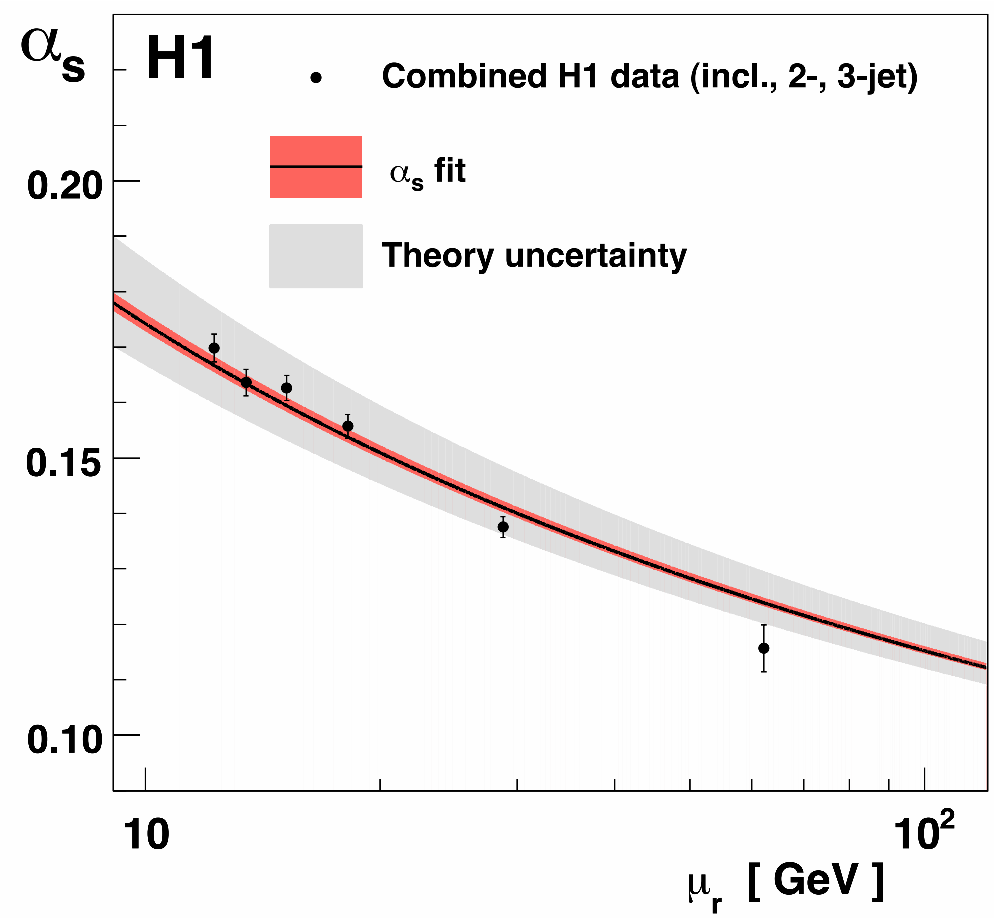


Running of $\alpha_s(\mu_r)$

Multijets at low Q²

$$\alpha_s(M_Z) = 0.1160 \pm 0.0014(\text{exp.})^{+0.0093}_{-0.0077}(\text{th.}) \pm 0.0016(\text{pdf})$$

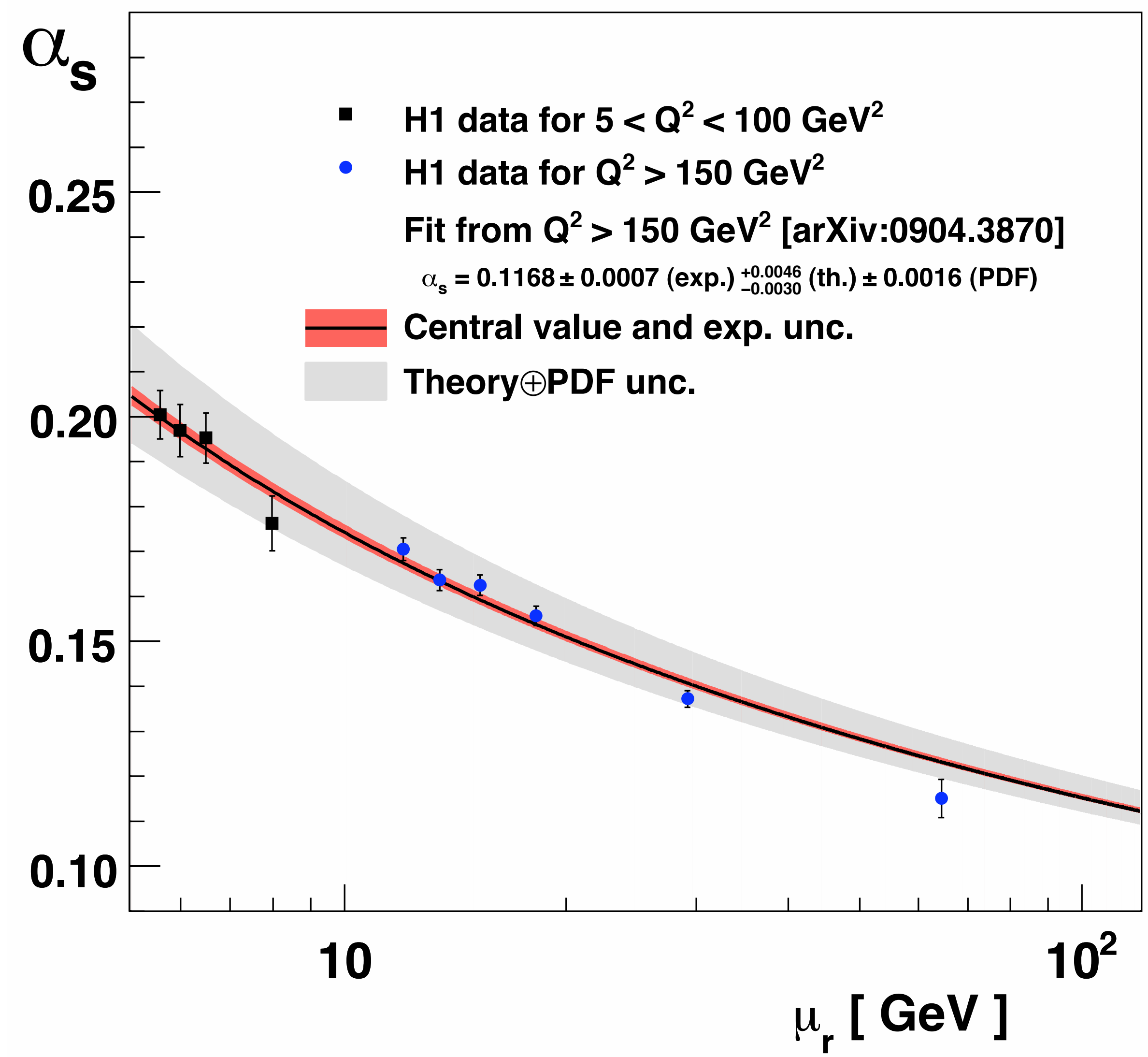
Multijets at high Q²

$$\alpha_s(M_Z) = 0.1168 \pm 0.0007(\text{exp.})^{+0.0046}_{-0.0030}(\text{th.}) \pm 0.0016(\text{pdf})$$

Theoretical uncertainty extrapolated down from high Q² determination with 2-loop solution of RGE

Good agreement between extracted $\alpha_s(\mu_r)$ at low and high Q²

Running of the strong coupling tested for scales between 6 - 70 GeV

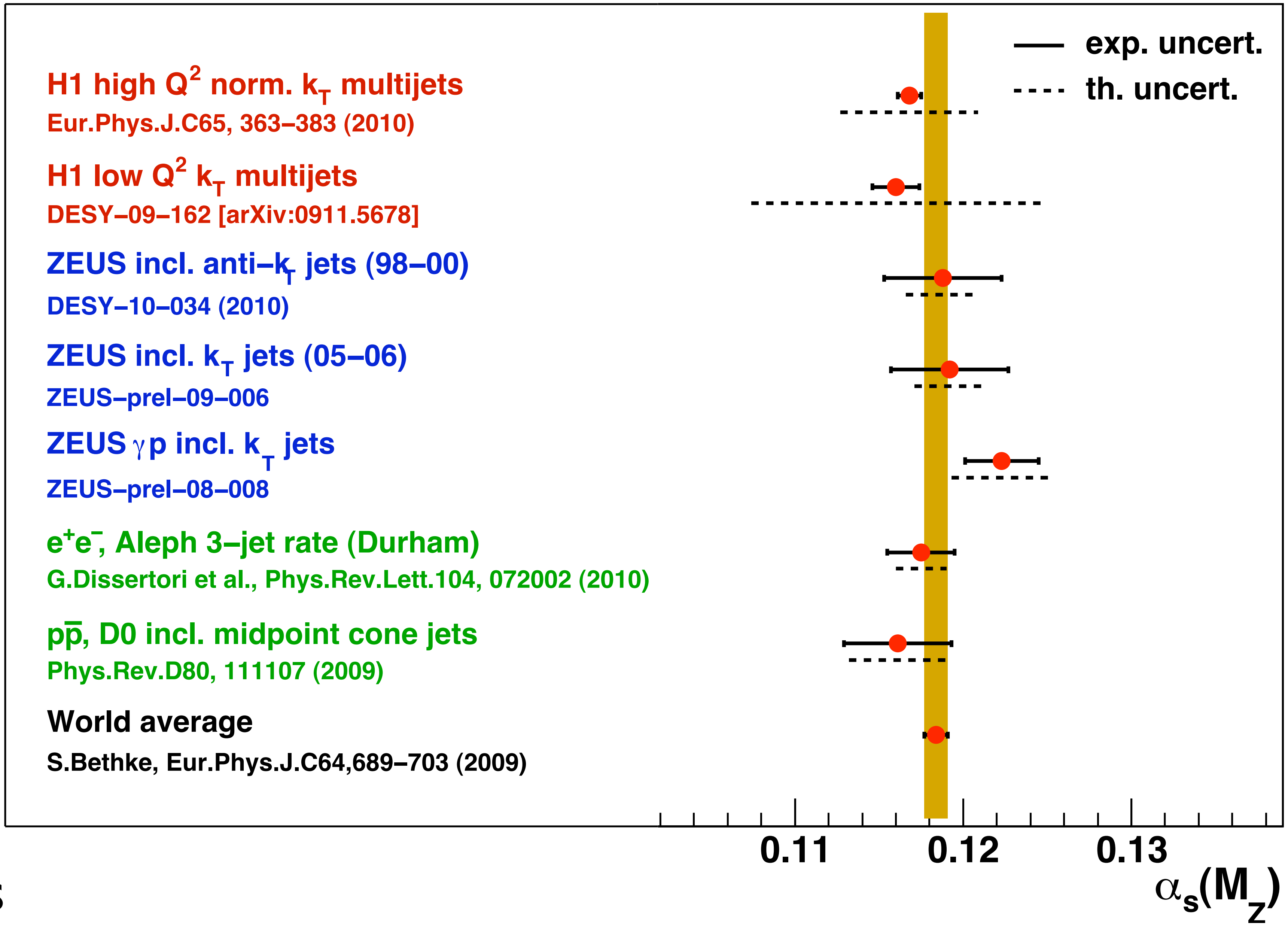


Summary

Multijet cross sections at low and high Q^2 in agreement with NLO predictions

Low Q^2 multi-jets:
theoretical uncertainties dominated by missing higher orders
NNLO needed

Low Q^2 3j/2j ratio:
limited by statistics
analysis of HERA2 data in progress



High Q^2 multi-jets:
precise determination via normalised cross sections
analysis to measure normalised and jet cross sections with improved experimental uncertainties in progress