A Precise Determination of α_s from the Heavy Jet Mass Distribution

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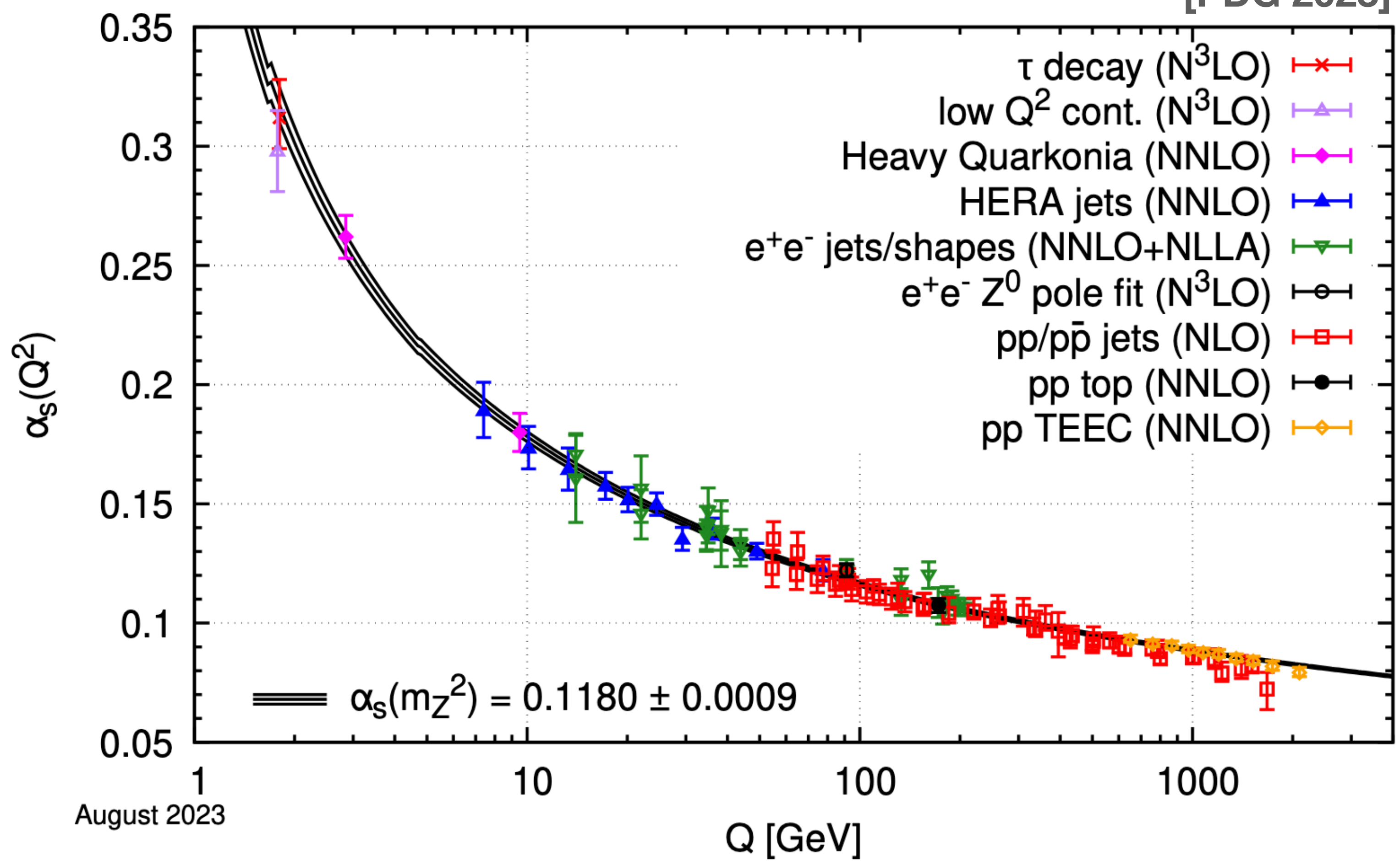
**MB, Arindam Bhattacharya, André H. Hoang, Vicent Mateu,
Matthew D. Schwartz, Iain W. Stewart and Xiaoyuan Zhang — 2502.12253**

The strong coupling constant — An Overview

- Strong coupling constant α_s a free parameter of the Standard Model
- α_s runs with energy → allows to relate extractions at different Q
- Use collider experiments to measure it
- Current precision at the percent level
  (compare to QED coupling — known to 10^{-8})
- PDG world average represents combination of results that meet criteria
- Current world average

[PDG 2023]

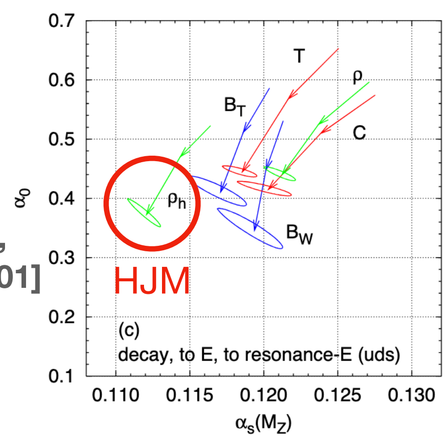


$$\alpha_s(m_Z^2) = 0.1180 \pm 0.0009 \qquad \text{(PDG 2023 average)}$$

α_s from e^+e^- event shapes

[See also prior work of Catani, Trentadue, Turnock, Webber 1993]

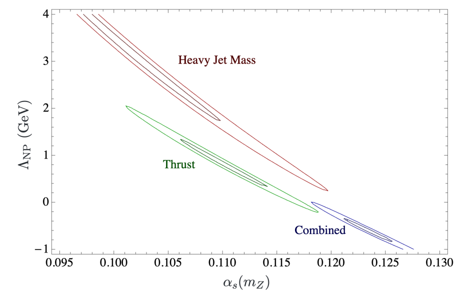
[Salam, Wicke 2001]



Secondly fits for the heavy-jet mass (a very non-inclusive variable) lead to values for α_s which are about 10% smaller than for inclusive variables like the thrust or the mean jet mass. This needs to be understood. It could be due to a difference in the behaviour of the perturbation series at higher orders.

[See also Dissertori et al 2007]

NNNLL resummation with NNLO matching



Event Shape	$\alpha_s(m_Z)$	$\Lambda_{\rm NP}$ (GeV)	χ^2/d.o.f.
Thrust	0.1101	0.821	66.9/47
Heavy Jet Mass	0.1017	3.17	60.4/43
Combined	0.1236	-0.621	453/92

[Chien, Schwartz 2010]

These studies used, in parts, only 25% of data bins:
$0.08 < \rho < 0.18$

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2001-2010

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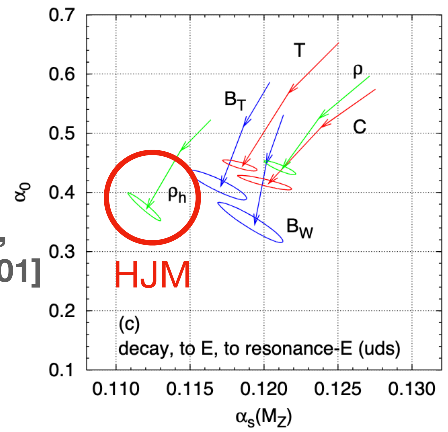

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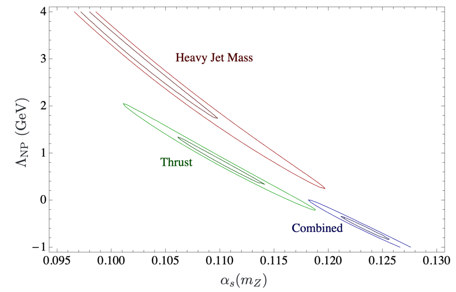

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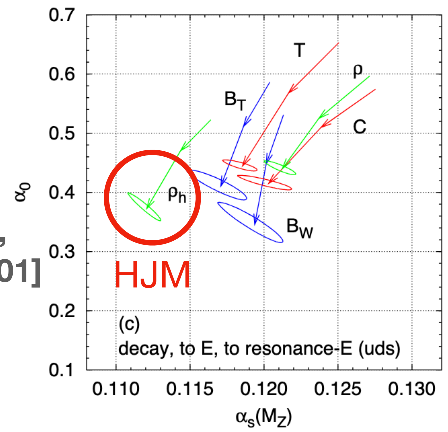

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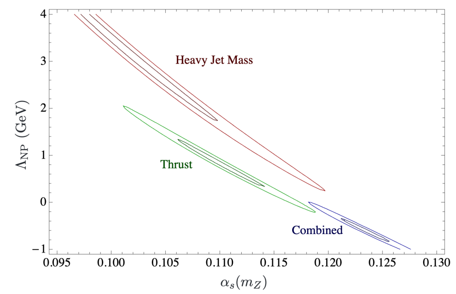

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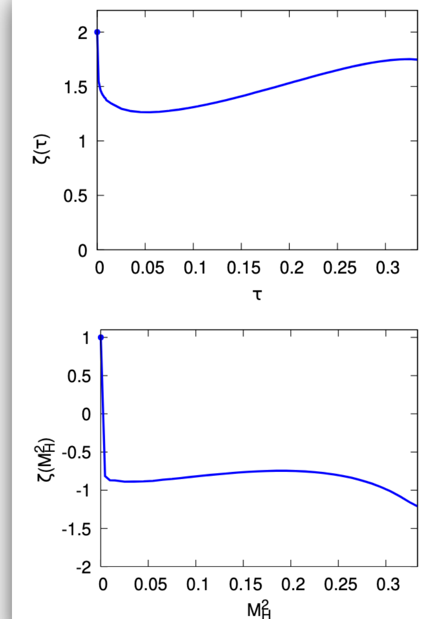

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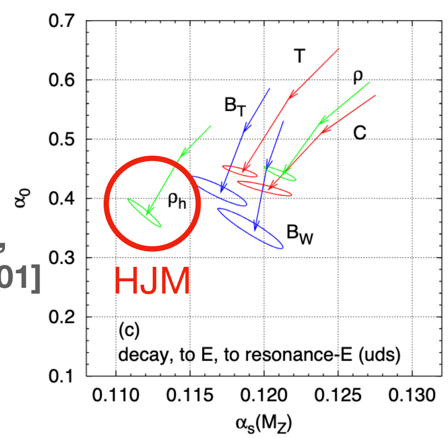

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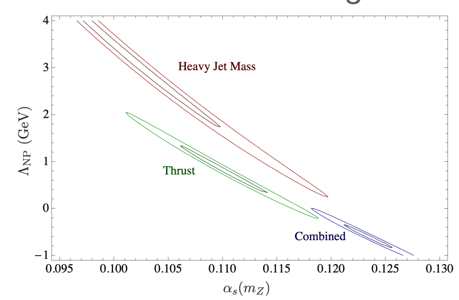

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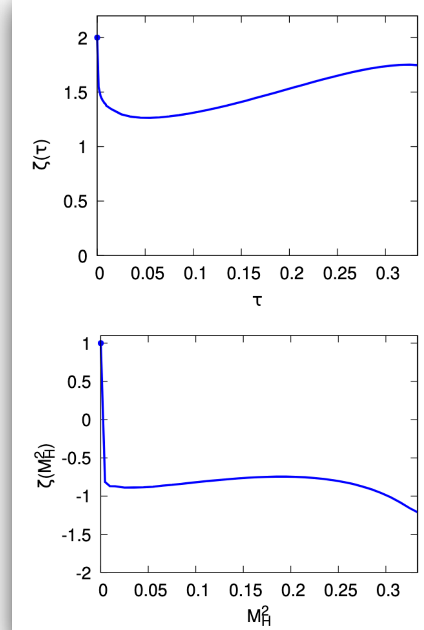

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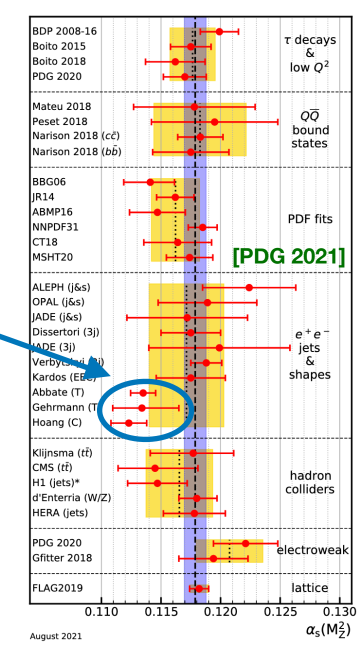

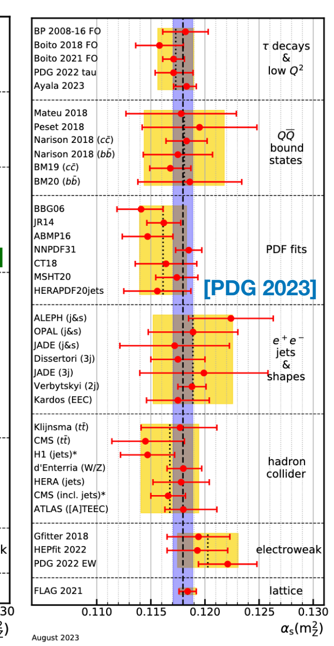

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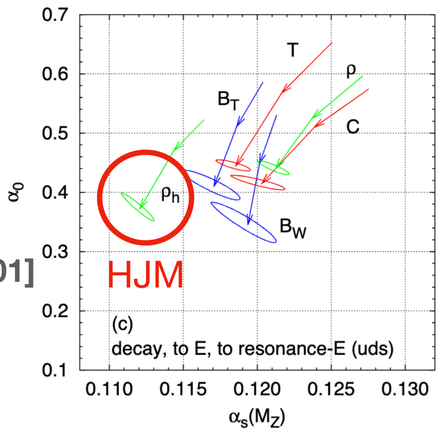

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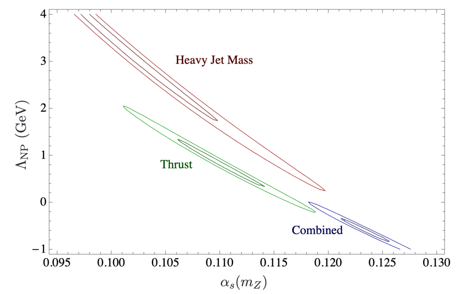

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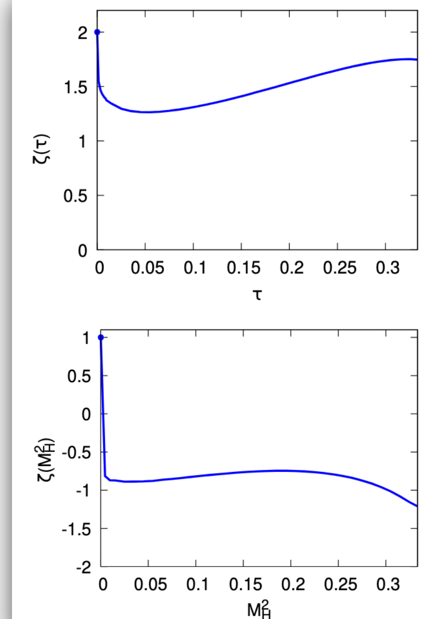

On Determining $\alpha_s(m_Z)$ from Dijets in e^+e^- Thrust

Miguel A. Benitez,[a] André H. Hoang,[b] Vicent Mateu,[a] Iain W. Stewart[b,c] and Gherardo Vita[d]

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This talk

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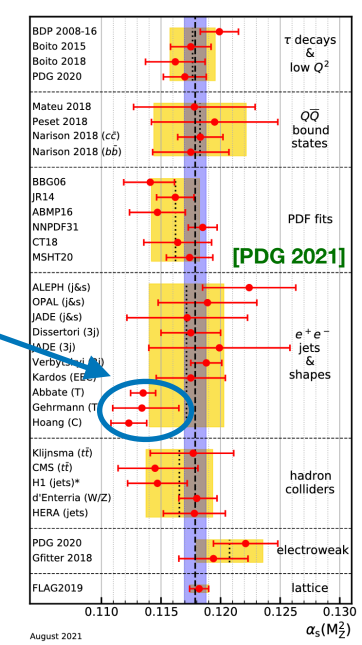
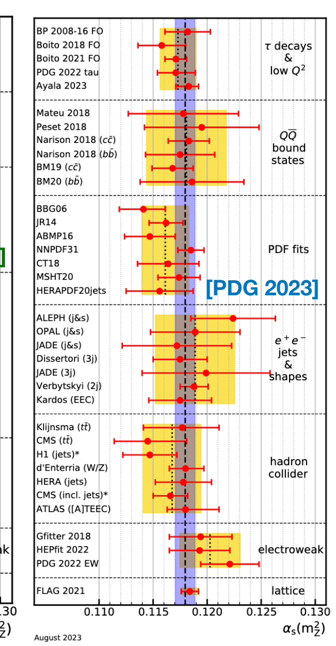




The HJM distribution

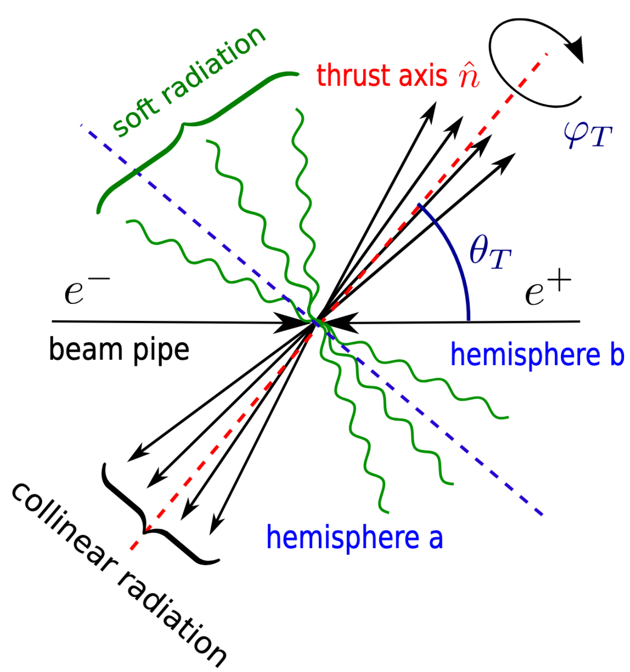
- HJM defined as $\rho = \max(s_1, s_2)/Q^2$

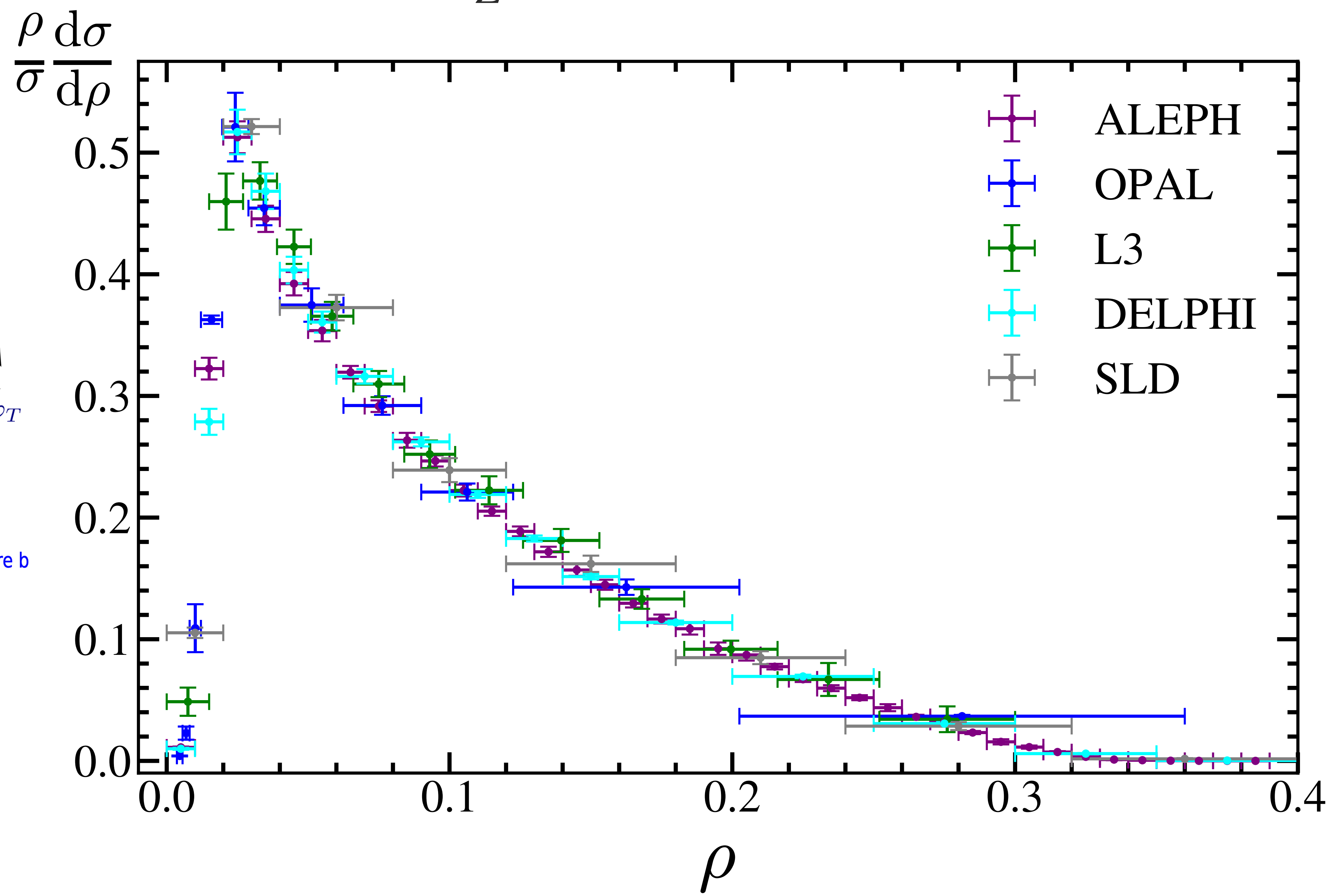
[Clavelli 1979] [Chandramohan, Clavelli 1981] [Clavelli, Wyler 1981]

$$s_1 = \Big(\sum_{i\in L} p_i^\mu\Big)^2, \qquad s_2 = \Big(\sum_{i\in R} p_i^\mu\Big)^2$$

Hemisphere jet invariant masses

- Experimental Distribution at $Q = m_Z$





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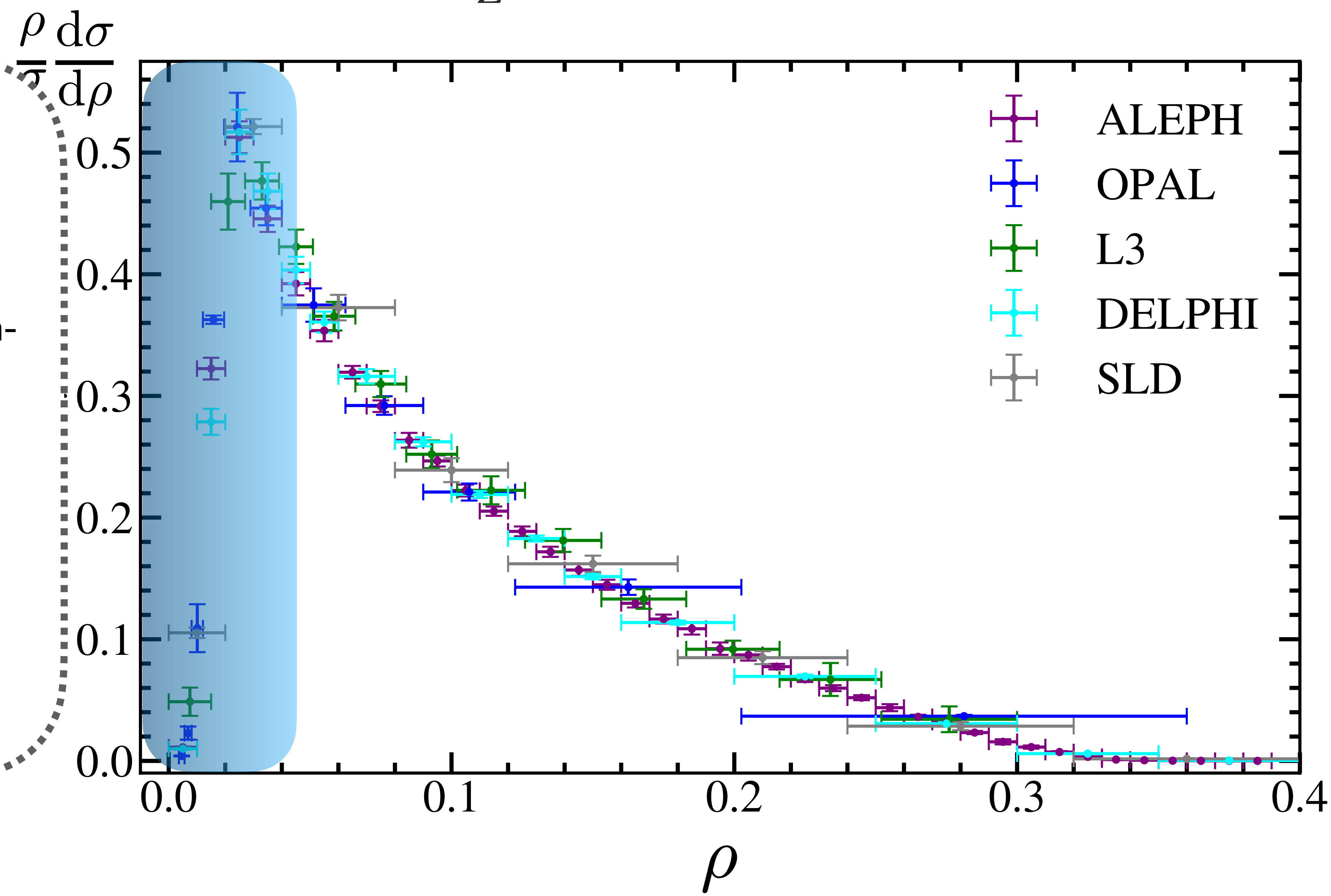
Peak region

$s_i \sim Q\Lambda_{\rm QCD}$

Heavily affected by non-perturbative dynamics



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Hemisphere jet invariant masses

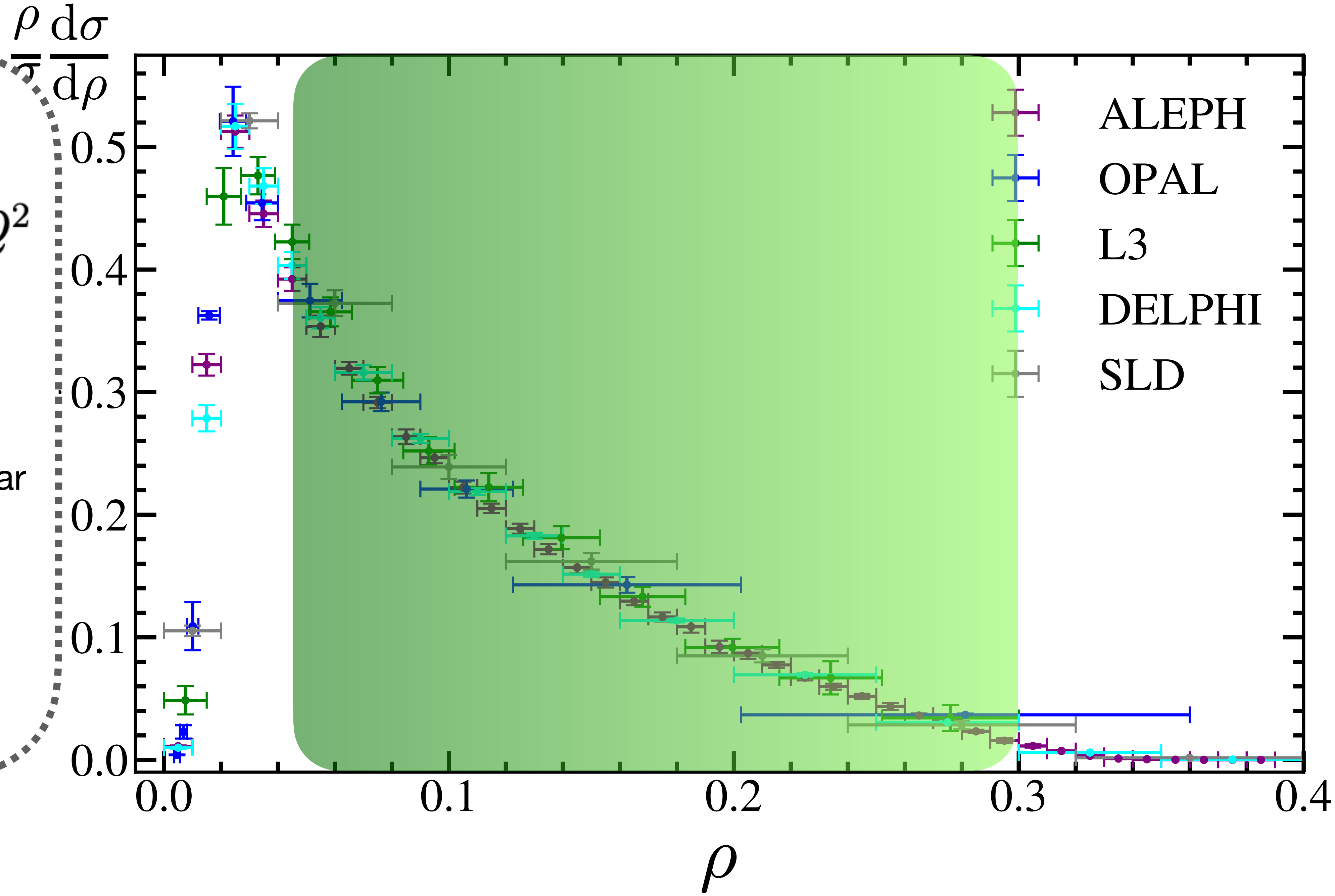
- Experimental Distribution at $Q = m_Z$

Tail region

$$Q\Lambda_{\rm QCD} \ll s_i \ll Q^2$$

Soft and collinear radiation dominates

$\Lambda_{\rm QCD} \ll s_i$ provides clear separation between perturbative and non-perturbative modes



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Hemisphere jet invariant masses

- Experimental Distribution at $Q = m_Z$

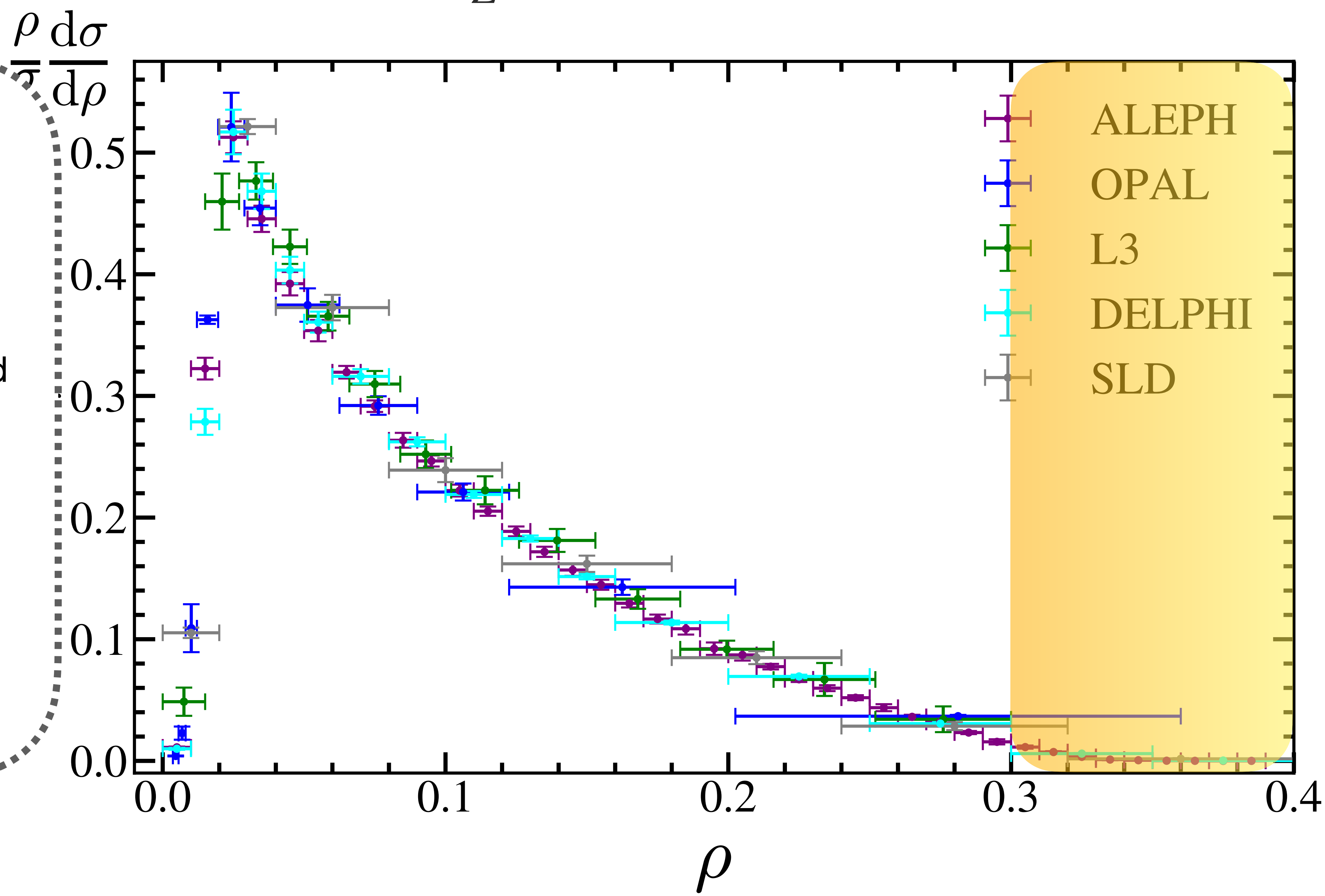
Far-Tail region

$s_i \sim Q^2$

No clear distinction between hard scale and observable

Distribution well approximated by FO

Small non-perturbative corrections



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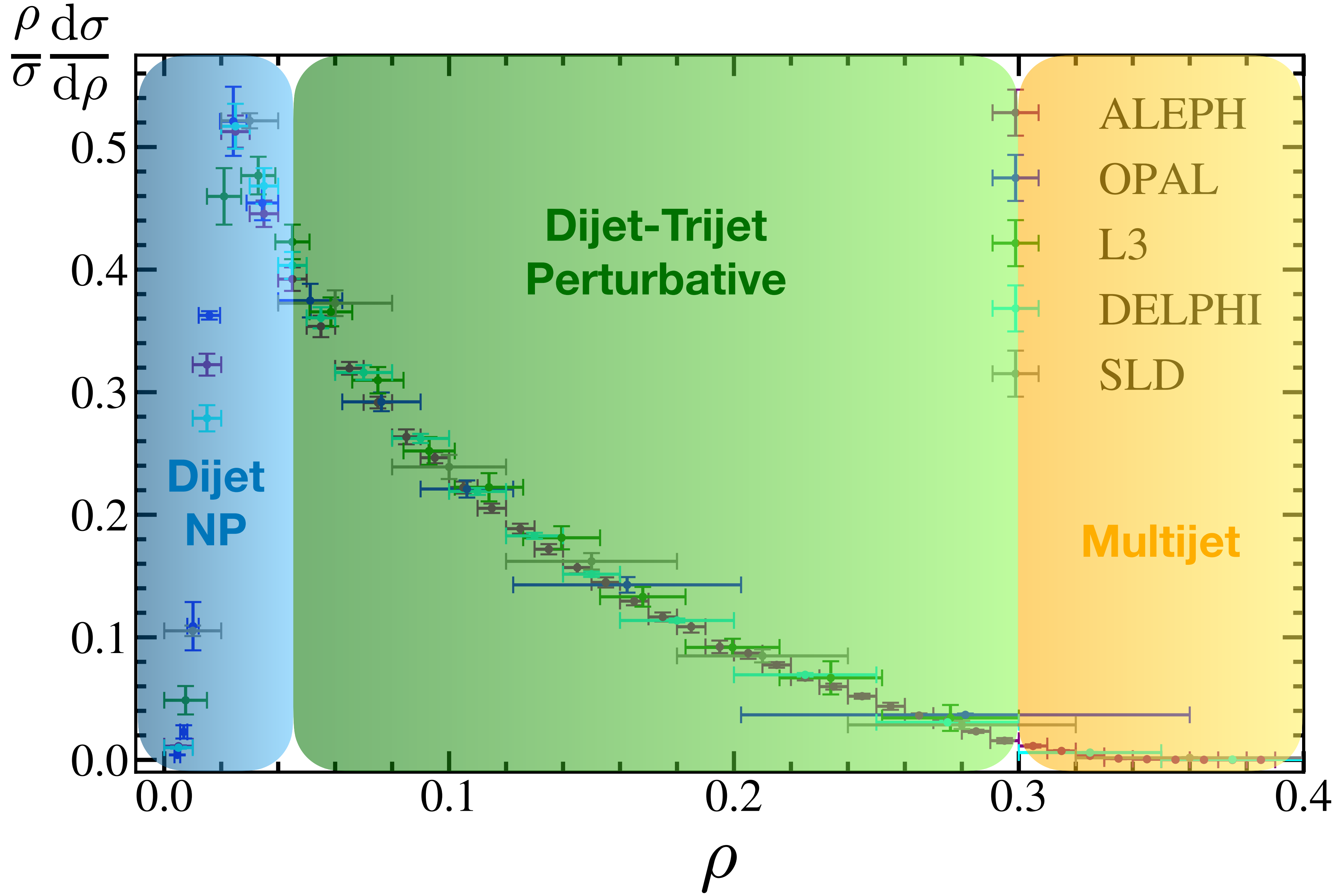

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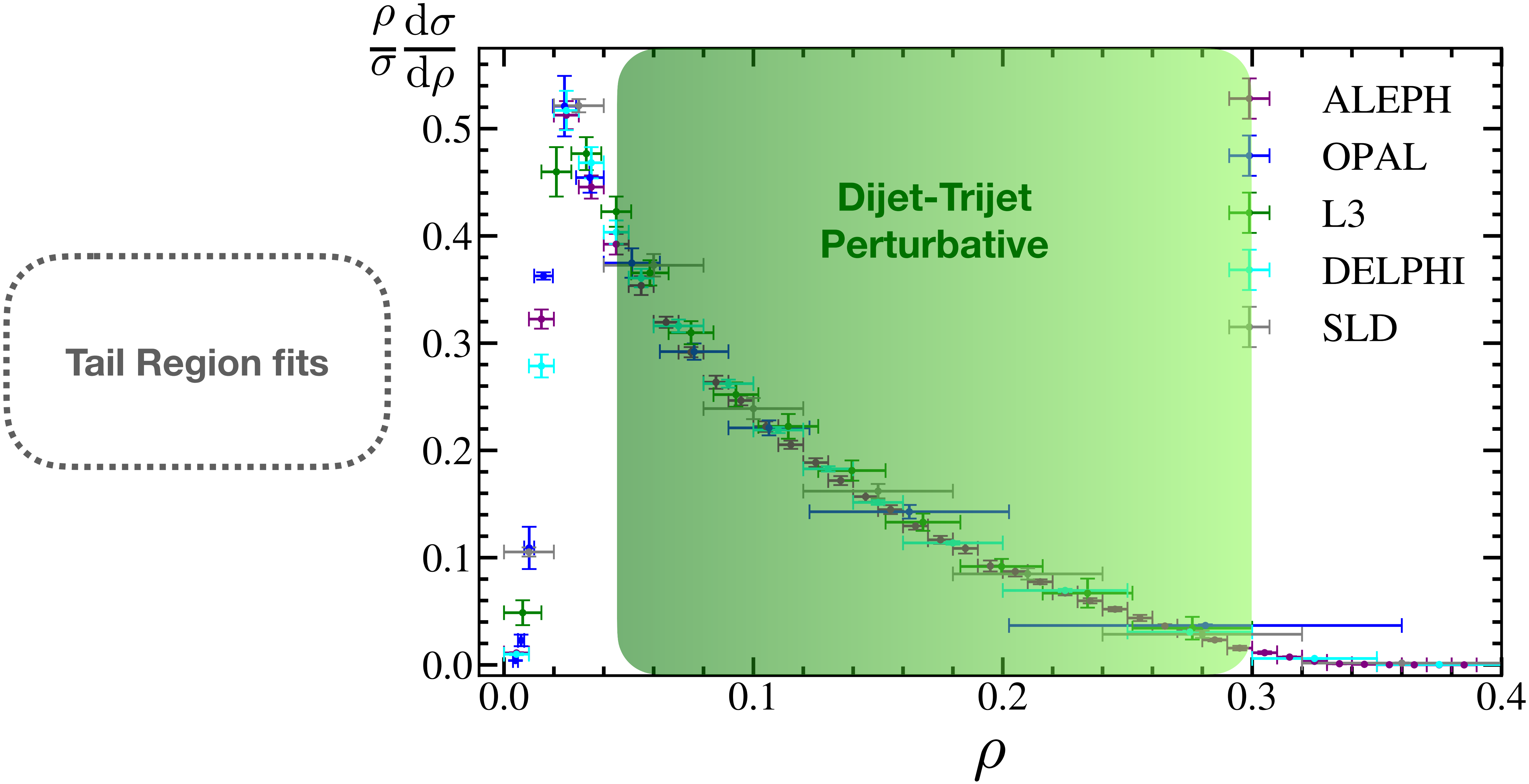


The HJM distribution — dijet resummation

[Hoang, Mateu, Schwartz, Stewart to appear]

- HJM distribution expressed as integral over doubly differential dihemisphere mass distribution

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\rho} = 2\,Q^2\int_0^{Q^2\rho}\mathrm{d}s\,\frac{\mathrm{d}^2\sigma}{\mathrm{d}s_1\mathrm{d}s_2}(s_1 = Q^2\rho, s_2 = s) \;=\; 2\,Q^2\,\Xi(Q^2\rho, Q^2\rho)$$

mixed distribution-cumulative cross-section

Non-perturbative double differential distribution can be factorized as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}s_1\mathrm{d}s_2} = \int\mathrm{d}k_1\mathrm{d}k_2\,\frac{\mathrm{d}\hat\sigma}{\mathrm{d}s_1\mathrm{d}s_2}(s_1 - Q\,k_1, s_2 - Q\,k_2)F(k_1,k_2)$$

Two-dimensional non-perturbative shape function

Translates to

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\rho} = 2\,Q^2\int\mathrm{d}k_1\,\mathrm{d}k_2\,\widehat\Xi(Q^2\rho - Q\,k_1, Q^2\rho - Q\,k_2)\,F(k_1,k_2)$$
$$= 2\,Q^2\int\mathrm{d}k_1\,\mathrm{d}k_2\,\frac{\mathrm{d}\hat\sigma}{\mathrm{d}s_1\mathrm{d}s_2}(Q^2\rho - Q\,k_1, Q^2\rho - Q\,k_2)\,F^{\Xi}(k_1,k_2)$$

In tail region, OPE gives rise to power corrections

$$\Omega_{i,j} = \Omega_{j,i} = \int\mathrm{d}k_1\,\mathrm{d}k_2\,k_1^i\,k_2^j\,F(k_1,k_2)$$

As for thrust, first moment $\Omega_{1,0}$ non-perturbative fit parameter

Partonic distribution can be split into singular and non-singular terms

$$\frac{\mathrm{d}^2\hat\sigma}{\mathrm{d}s_1\mathrm{d}s_2} = \frac{\mathrm{d}\hat\sigma_{\rm s}}{\mathrm{d}s_1\mathrm{d}s_2} + \frac{\mathrm{d}^2\hat\sigma_{\rm ns}}{\mathrm{d}s_1\mathrm{d}s_2}$$

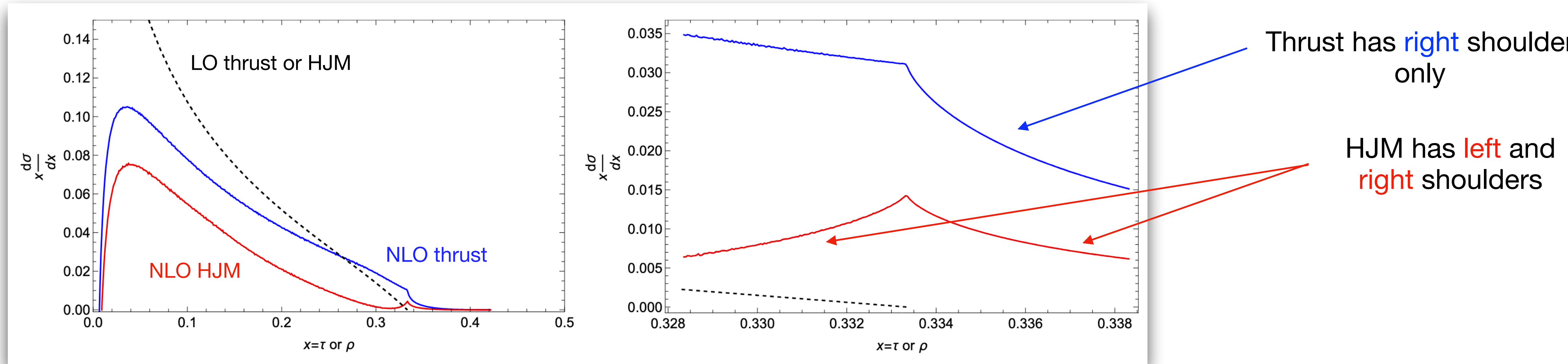
Singular

$$\frac{1}{\sigma_0}\frac{\mathrm{d}^2\hat\sigma_{\rm s}}{\mathrm{d}s_1\mathrm{d}s_2} = H(Q,\mu)\int\mathrm{d}\ell_1\,\mathrm{d}\ell_2\,J(s_1 - Q\,\ell_1 - Q\,\overline\Delta(R,\mu),\mu)$$
$$\times\,J(s_2 - Q\,\ell_2 - Q\,\overline\Delta(R,\mu),\mu)\,e^{\delta(R,\mu)\left(\frac{\partial}{\partial\ell_1}+\frac{\partial}{\partial\ell_2}\right)}\,\widehat S(\ell_1,\ell_2,\mu)$$
$$= H(Q,\mu_H)\,U_H(Q,\mu_H,\mu_J)\int\mathrm{d}\ell_1\,\mathrm{d}\ell_2\,J(s_1 - Q\,\ell_1 - Q\,\overline\Delta(R,\mu_S),\mu_J)$$
$$J(s_2 - Q\,\ell_2 - Q\,\overline\Delta(R,\mu_S),\mu_J)\int\mathrm{d}\ell_1'\,\mathrm{d}\ell_2'\,U_S(\ell_1 - \ell_1',\mu_J,\mu_S)$$
$$\times\,U_S(\ell_2 - \ell_2',\mu_J,\mu_S)\,e^{\delta(R,\mu_S)\left(\frac{\partial}{\partial\ell_1'}+\frac{\partial}{\partial\ell_2'}\right)}\,\widehat S(\ell_1',\ell_2',\mu_S)$$

Nonsingular

$$\frac{\mathrm{d}\hat\sigma_{\rm ns}}{\mathrm{d}\rho}(Q,\mu_{\rm ns}) = \frac{\mathrm{d}\hat\sigma_{\rm full}^{\rm FO}}{\mathrm{d}\rho}(Q,\mu_{\rm ns}) - \frac{\mathrm{d}\hat\sigma_s^{\rm FO}}{\mathrm{d}\rho}(Q,\mu_{\rm ns})$$

The HJM distribution — dijet + shoulder resummation



[Bhattacharya, Schwartz, Zhang 2022]

- Around symmetric trijet limit $\rho \to 1/3$, distribution factorizes as

$$\mathrm{d}\sigma_{\rm sh}^{\rm pert} = H_{\rm sh} \times J_1 \times J_2 \times J_3 \otimes S_{1,2,3}$$

[Bhattacharya, Michel, Schwartz, Stewart, Zhang 2023]

- Matching between the dijet, fixed-order and shoulder regions done by writing full cross section as

$$\mathrm{d}\sigma = \left[\mathrm{d}\sigma_{\rm dij} - \mathrm{d}\sigma_{\rm dij}^{\rm sing}\right] + \mathrm{d}\sigma_{\rm FO} + \left[\mathrm{d}\sigma_{\rm sh} - \mathrm{d}\sigma_{\rm sh}^{\rm sing}\right]$$

- Model power corrections around the symmetric trijet limit with non-perturbative shift parameter Θ_1

$$\frac{\mathrm{d}\sigma_{\rm sh}}{\mathrm{d}\rho}(\rho) = \frac{\mathrm{d}\sigma_{\rm sh}^{\rm pert}}{\mathrm{d}\rho}\left(\rho - \frac{\Theta_1}{Q}\right)$$

Fit procedure

- Use χ^2 function including theoretical and experimental uncertainties

Experiment

35 GeV < Q < 207 GeV
(700 experimental datapoints)

Minimal Overlap Model treats correlations of systematic uncertainties on experimental measurements

$$\sigma_{ij}^{\text{exp}} = \delta_{ij}(\Delta_i^{\text{stat}})^2 + \delta_{D_i D_j}\min(\Delta_i^{\text{sys}}, \Delta_j^{\text{sys}})^2$$

Theory

Theory uncertainties assessed though renormalization scale variation
→ not Gaussian + highly correlated

Employ flat random scan: M = 5000 sets of k ≤ 17 parameters generated, each produces theory prediction for data-point x_i

Determine $\bar{x}_i = (x_i^{\max} + x_i^{\min})/2$ and $\Delta_i^{\text{theo}} = (x_i^{\max} - x_i^{\min})/2$

Correlation coefficient r_{ij} among bins $r_{ij}^{\text{theo}} = \dfrac{\langle (x_i - \bar{x}_i)(x_j - \bar{x}_j)\rangle}{\sqrt{\langle (x_i - \bar{x}_i)^2\rangle}\sqrt{\langle (x_j - \bar{x}_j)^2\rangle}}$

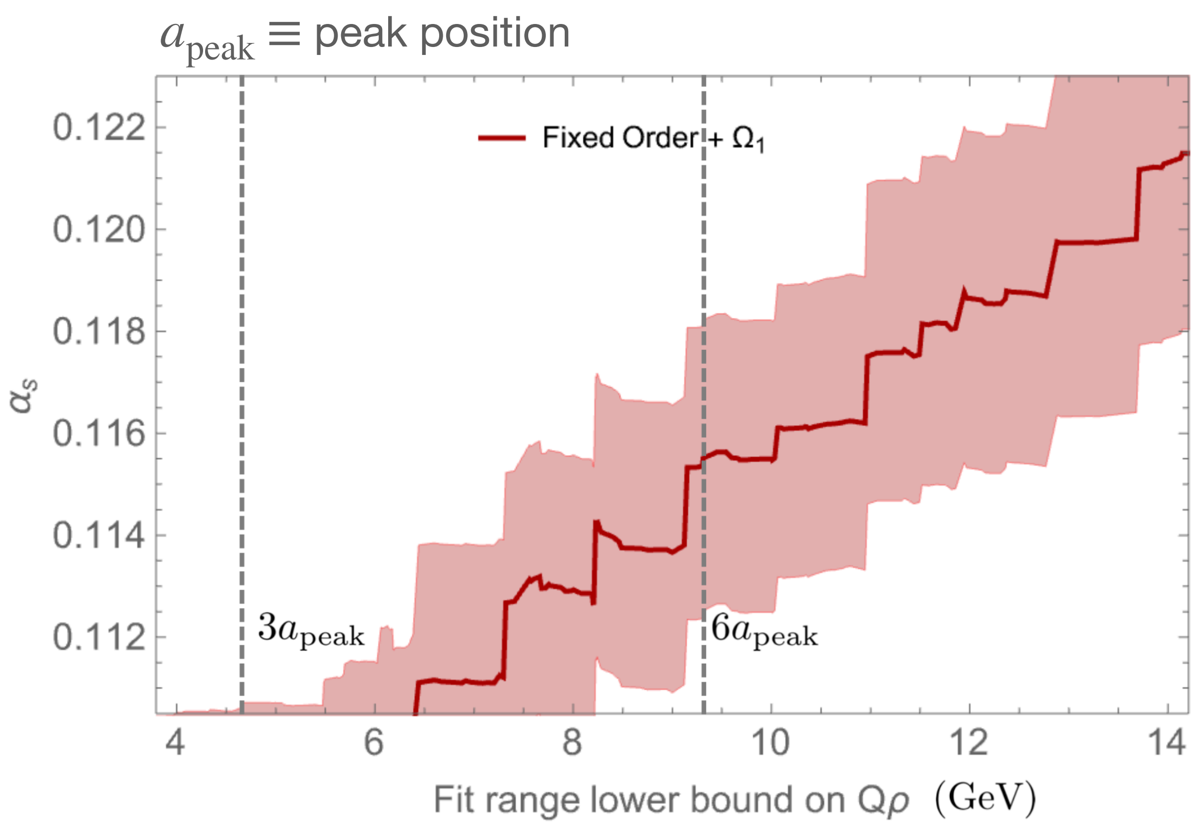
Theory covariance matrix results from scaling correlation coefficient by $1 - \sigma$ uncertainties

$$\sigma_{ij}^{\text{theo}} = \Delta_i^{\text{theo}}\,\Delta_j^{\text{theo}}\,r_{ij}^{\text{theo}}$$

- Total covariance matrix = sum of theoretical and experimental: $\sigma_{ij}^{\text{tot}} = \sigma_{ij}^{\text{theo}} + \sigma_{ij}^{\text{exp}}$
- χ^2 reads: $$\chi^2 = \sum_{i,j=1}^{N_{\text{bins}}} (\bar{x}_i - x_i^{\text{exp}})\,(\bar{x}_j - x_j^{\text{exp}})\,(\sigma_{\text{tot}}^{-1})_{ij}$$

Fit results — Fixed Order

- Results for α_s using fit range $a/Q \leq \rho \leq 0.3$ for different a

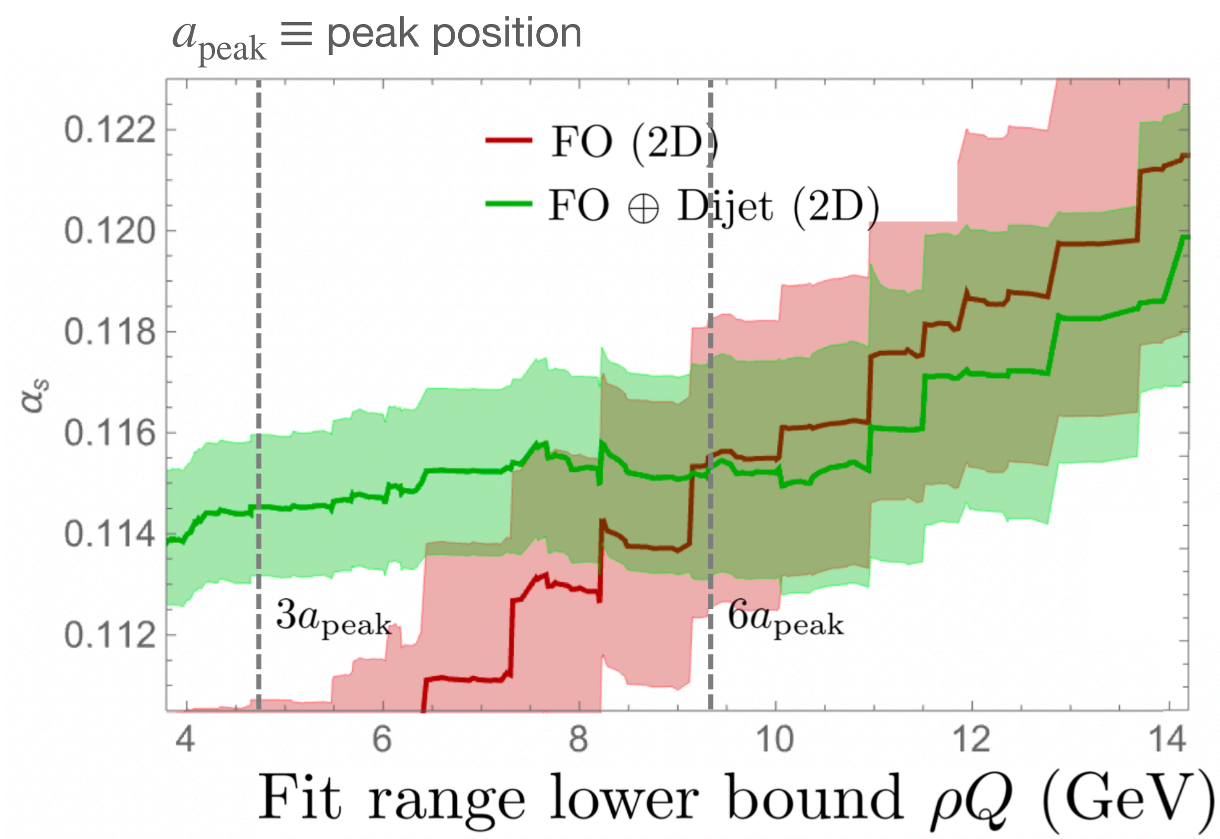


- Results for α_s very sensitive to fit range
- Large fit range uncertainty even with restriction $a \in [5a_{\rm peak}, 8a_{\rm peak}]$
- Impossible to extract sensible value of α_s without arbitrary choice of fit range

Model	$\alpha_s(m_Z)$	th+exp	Ω_1^ρ	Θ_1	fit range	χ^2/dof	Ω_1^ρ [GeV]	Θ_1 [GeV]
Fixed Order 2D	0.1166 ± 0.0034	± 0.0014	± 0.0027	–	± 0.0015	1.108	0.06 ± 0.13	–

Fit results — Dijet resummation

- Results for α_s using fit range $a/Q \leq \rho \leq 0.3$ for different a



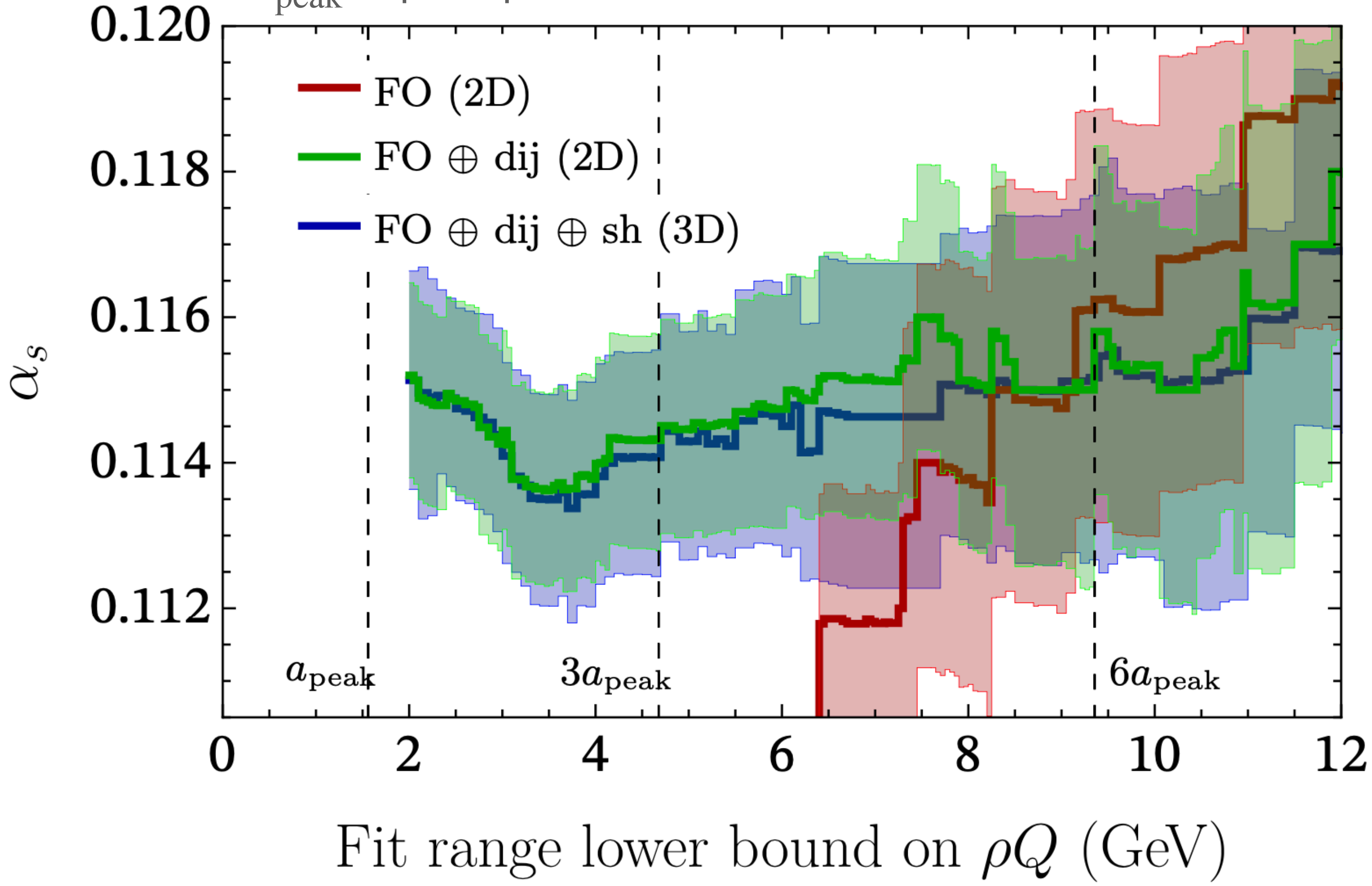
- Fit value remarkably insensitive to fit range
- Small fit range uncertainty for $a \in [3a_{\text{peak}}, 6a_{\text{peak}}]$
- Data prefers positive power correction (rightward shift of distribution)

Model	$\alpha_s(m_Z)$	th+exp	Ω_1^ρ	Θ_1	fit range	χ^2/dof	Ω_1^ρ [GeV]	Θ_1 [GeV]
Fixed Order 2D	0.1166 ± 0.0034	± 0.0014	± 0.0027	–	± 0.0015	1.108	0.06 ± 0.13	–
FO + dijet 2D	0.1148 ± 0.0018	± 0.0010	± 0.0014	–	± 0.0004	1.055	0.53 ± 0.09	–

Fit results — Dijet + Shoulder resummation

- Results for α_s using fit range $a/Q \leq \rho \leq 0.3$ for different a

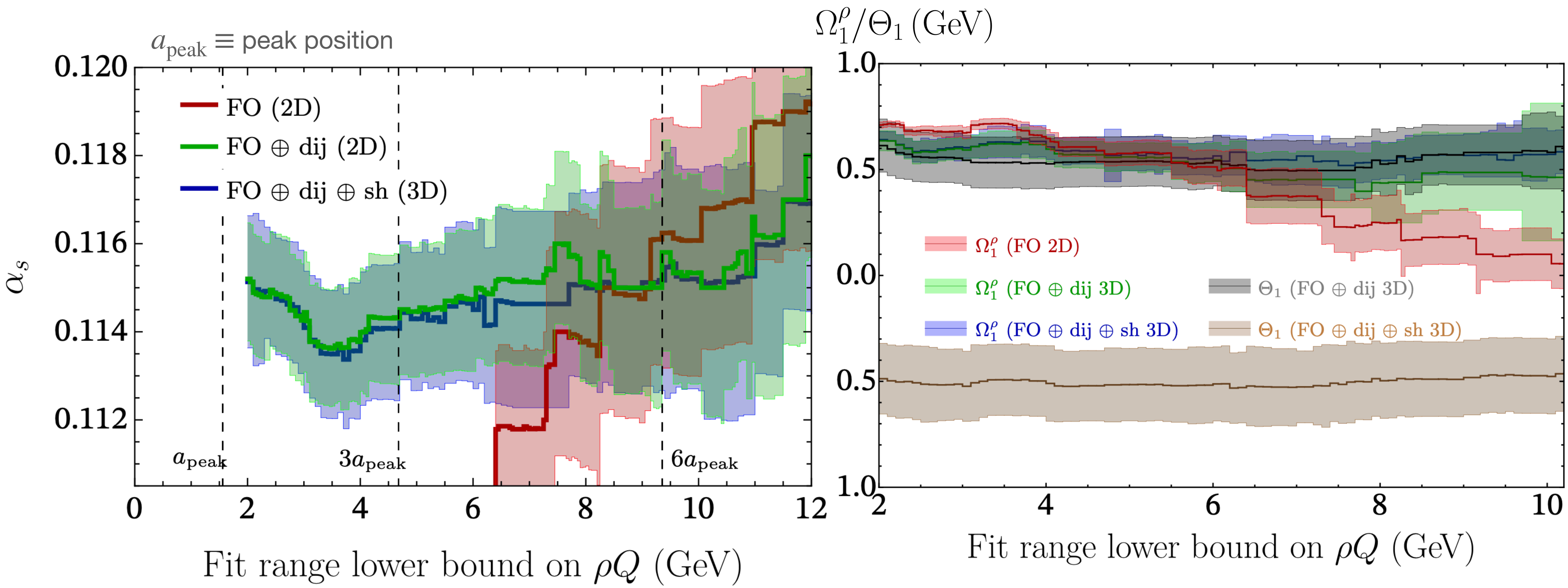
$a_{\rm peak} \equiv$ peak position



- Fit value remarkably insensitive to fit range
- Small fit range uncertainty for $a \in [3a_{\rm peak}, 6a_{\rm peak}]$
- **But what about the power corrections?**

Fit results — Dijet + Shoulder resummation

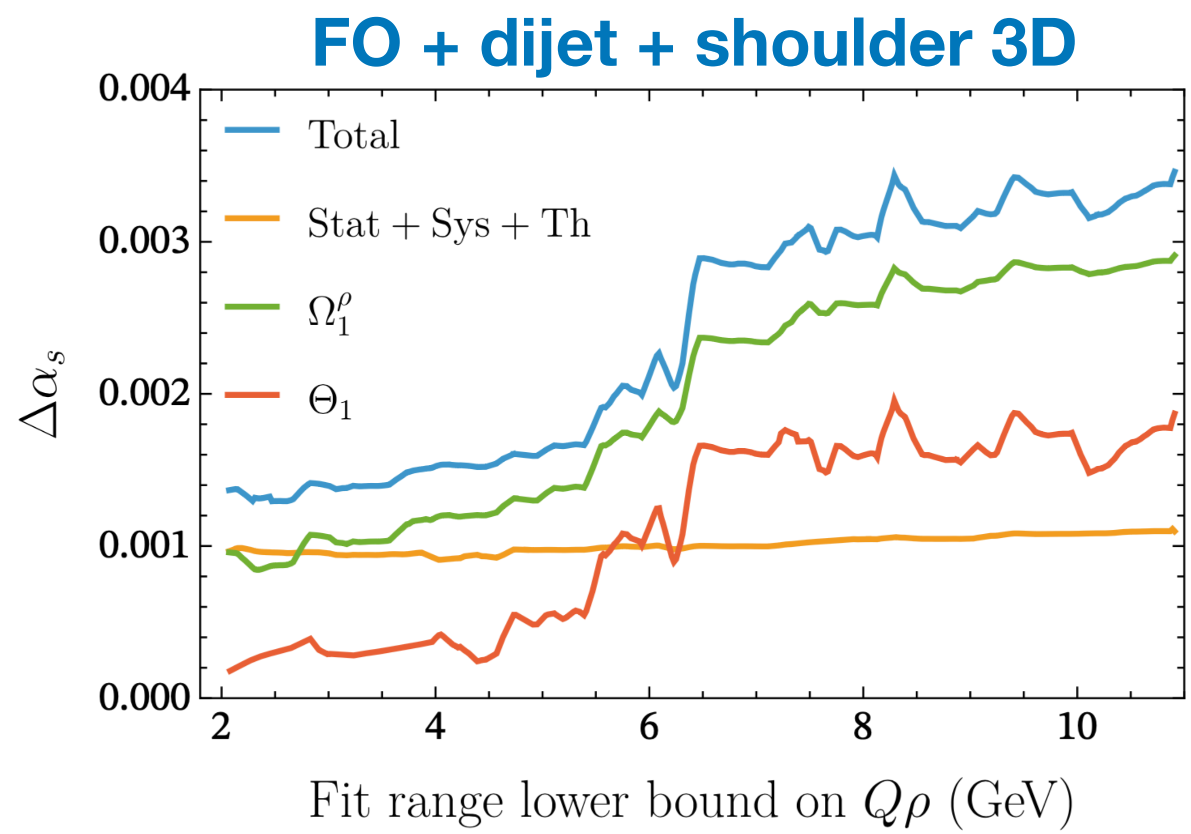
- Results for α_s, Ω_1^ρ and Θ_1 using fit range $a/Q \leq \rho \leq 0.3$ for different a



Data favors negative power corrections only with shoulder!

Fit results — Breakdown

- More small ρ data $\rightarrow$ fit uncertainty similar in size to uncertainty induced by Ω_1^ρ, uncertainty arising from Θ_1 comparatively small
- Linear rise of uncertainty tied to Ω_1^ρ when increasing lower bound of the fit range
- Large contribution to overall uncertainty induced by Ω_1^ρ $\rightarrow$ strong $\alpha_s - \Omega_1^\rho$ correlation



Model	$\alpha_s(m_Z)$	th+exp	Ω_1^ρ	Θ_1	fit range	χ^2/dof	Ω_1^ρ [GeV]	Θ_1 [GeV]
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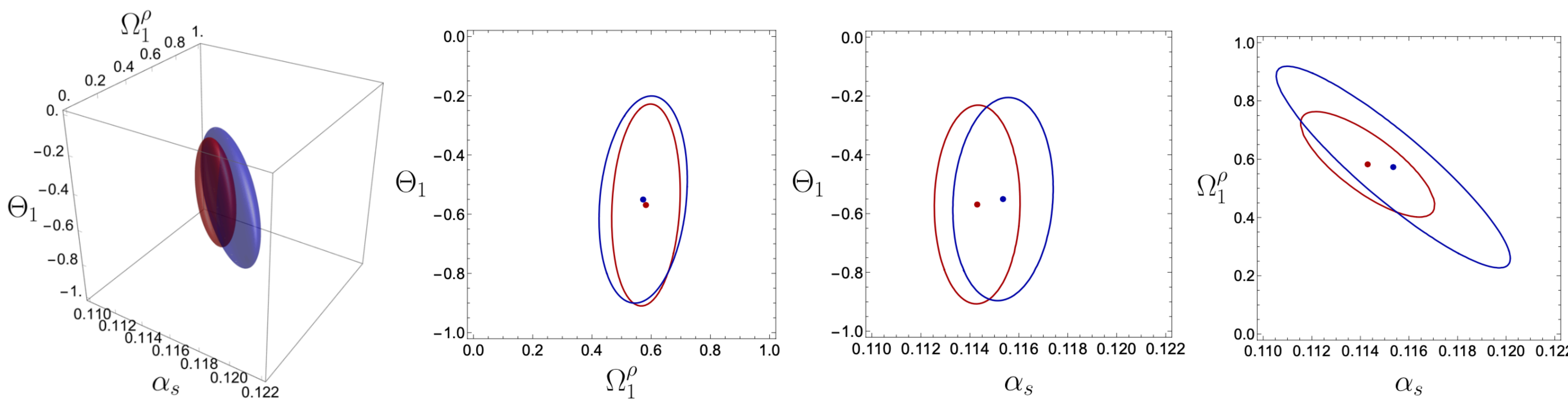
FO + dijet 3D	0.1156 ± 0.0024	± 0.0010	± 0.0021	± 0.0004	± 0.0007	1.052	0.52 ± 0.08	0.53 ± 0.13
FO + dijet + shoulder 3D	0.1145 ± 0.0020	± 0.0009	± 0.0018	± 0.0001	± 0.0003	1.043	0.57 ± 0.09	-0.50 ± 0.17

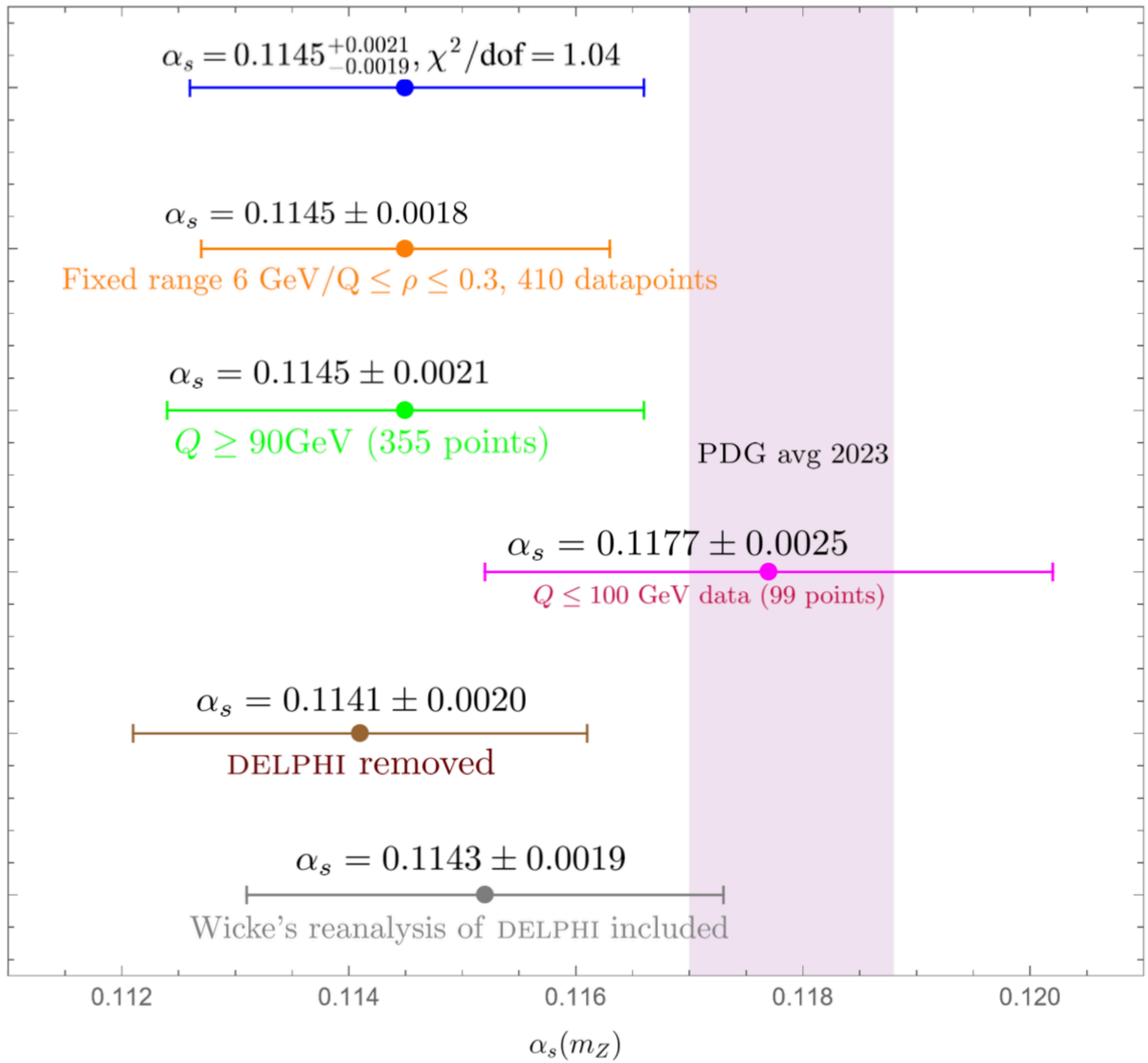
Correlations among $(\alpha_s, \Omega_1^\rho, \Theta_1)$



$Q\rho > 3a_{\text{peak}}$ $Q\rho > 6a_{\text{peak}}$

- Strongest correlation between $\alpha_s - \Omega_1^\rho$
- Raising lower bound of fit range increase correlation of $\alpha_s - \Omega_1^\rho$
- Strong $\alpha_s - \Omega_1^\rho$ correlation also reflected in overall uncertainty of α_s — largest contribution arises due to Ω_1^ρ

Cross Checks



Summary

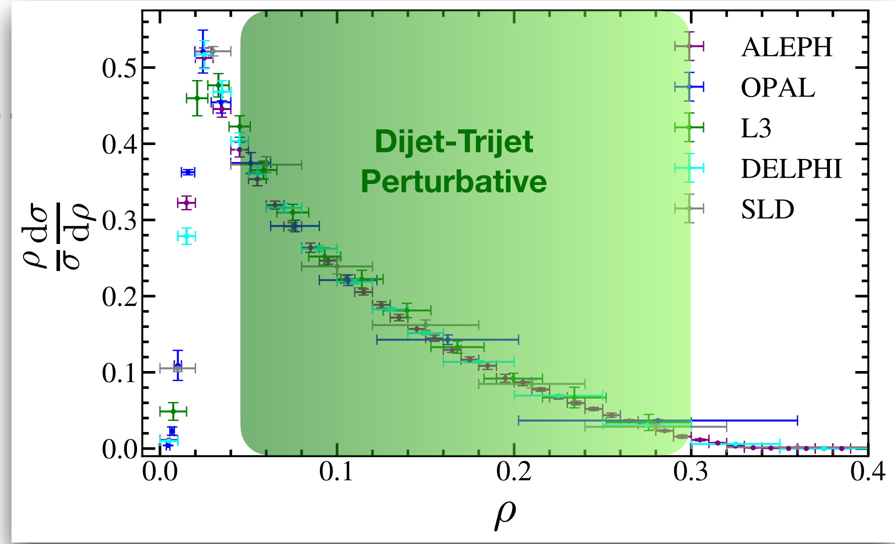
- Provided comprehensive analysis of available data on HJM
- Innovations include
    - Improved treatments of dijet/OPE and trijet/shoulder region
    - Inclusion of theory correlations during fitting
    - Careful attention to the range of data used for fitting
- Found fits are minimally sensitive to fit range when including resummation, in contrast to fixed-order perturbation theory (essentially linear dependence on lower bound)
- Found evidence for negative power correction in tail of distribution only if Sudakov shoulder resummation is included
- Our extracted value is

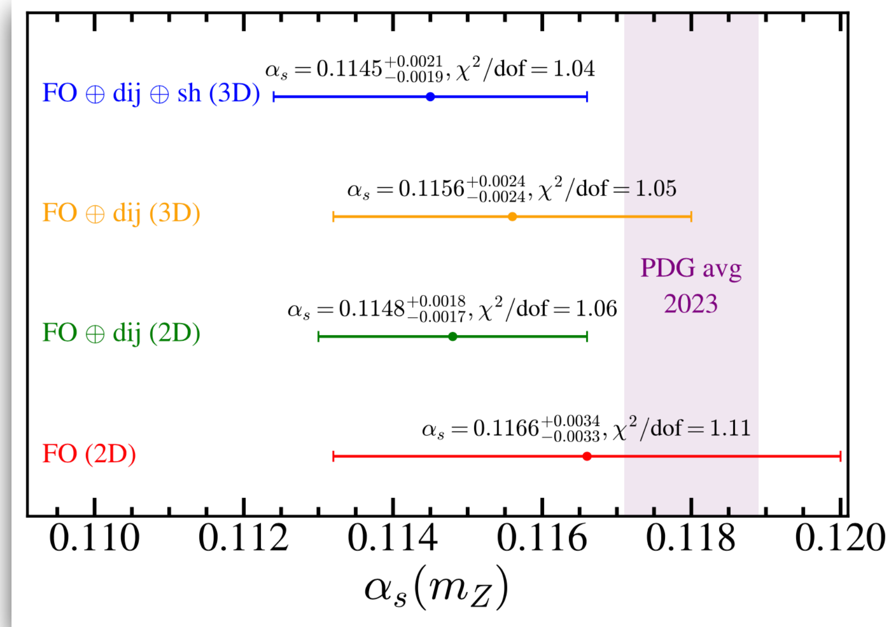
$$\alpha_s(m_Z) = 0.1145^{+0.0021}_{-0.0019}$$

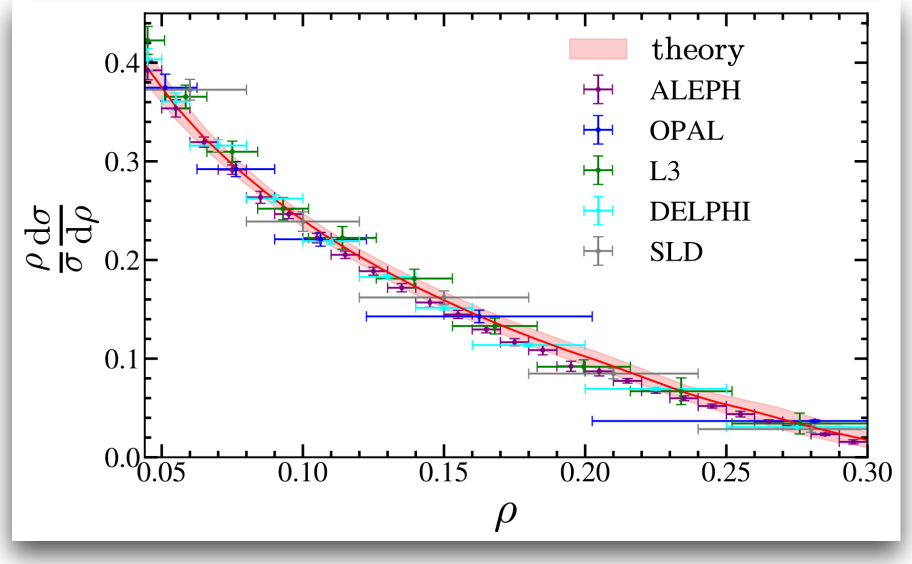
$$\Omega_1^\rho = 0.57 \pm 0.09\,\text{GeV}, \quad \Theta_1 = -0.50 \pm 0.17\,\text{GeV}$$

$$\chi^2/\text{dof} = 1.04$$

perfectly compatible with Thrust and C-parameter results







Back-Up

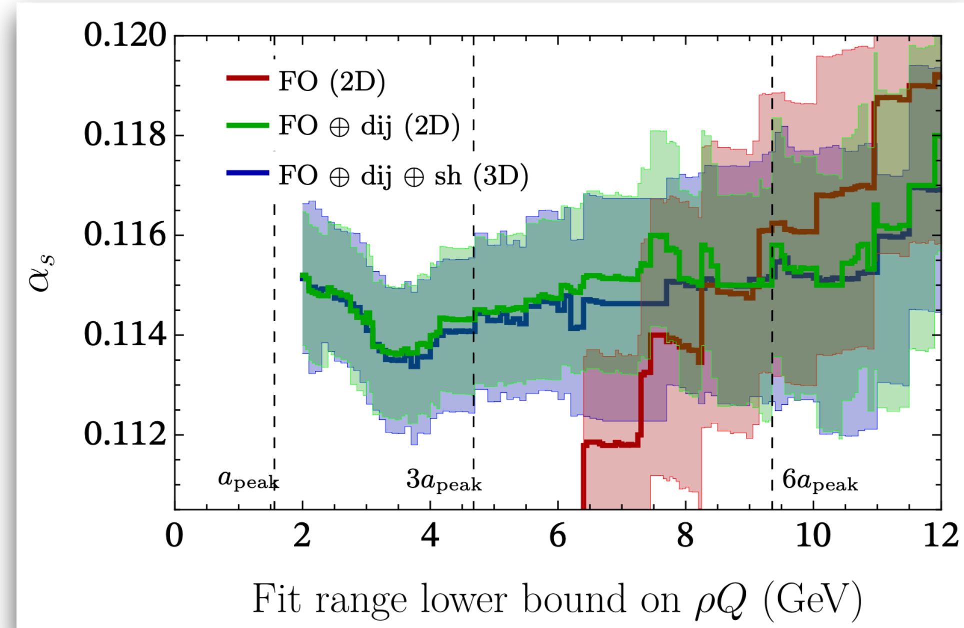
More details on fits

- To extract value of α_s from our fits we perform weighted average over different choices for lower bound $a \leq \rho Q$ with weight

$$w_a = \sigma_a^{-2}(\textstyle\sum_a \sigma_a^{-2})^{-1}$$

($\sigma_a \equiv$ uncertainty for given fit range)

- For resummed results consider $a \in [3a_{\rm peak}, 6a_{\rm peak}]$
- For fixed order results consider $a \in [5a_{\rm peak}, 8a_{\rm peak}]$
- th+exp: includes experimental systematical and statistical uncertainty as well as perturbative uncertainty from variation of all theory parameters
- fit-range: given by standard deviation among best-fit values for various lower bounds considered



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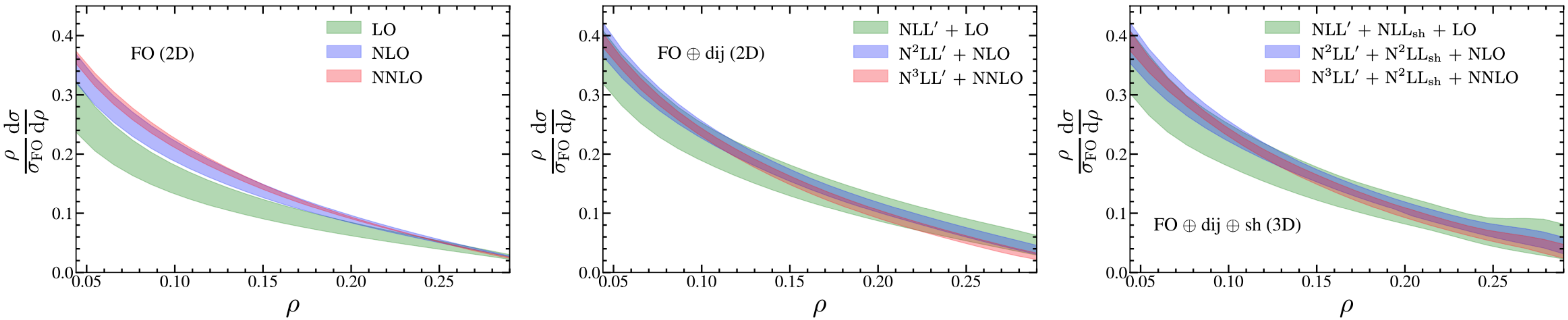
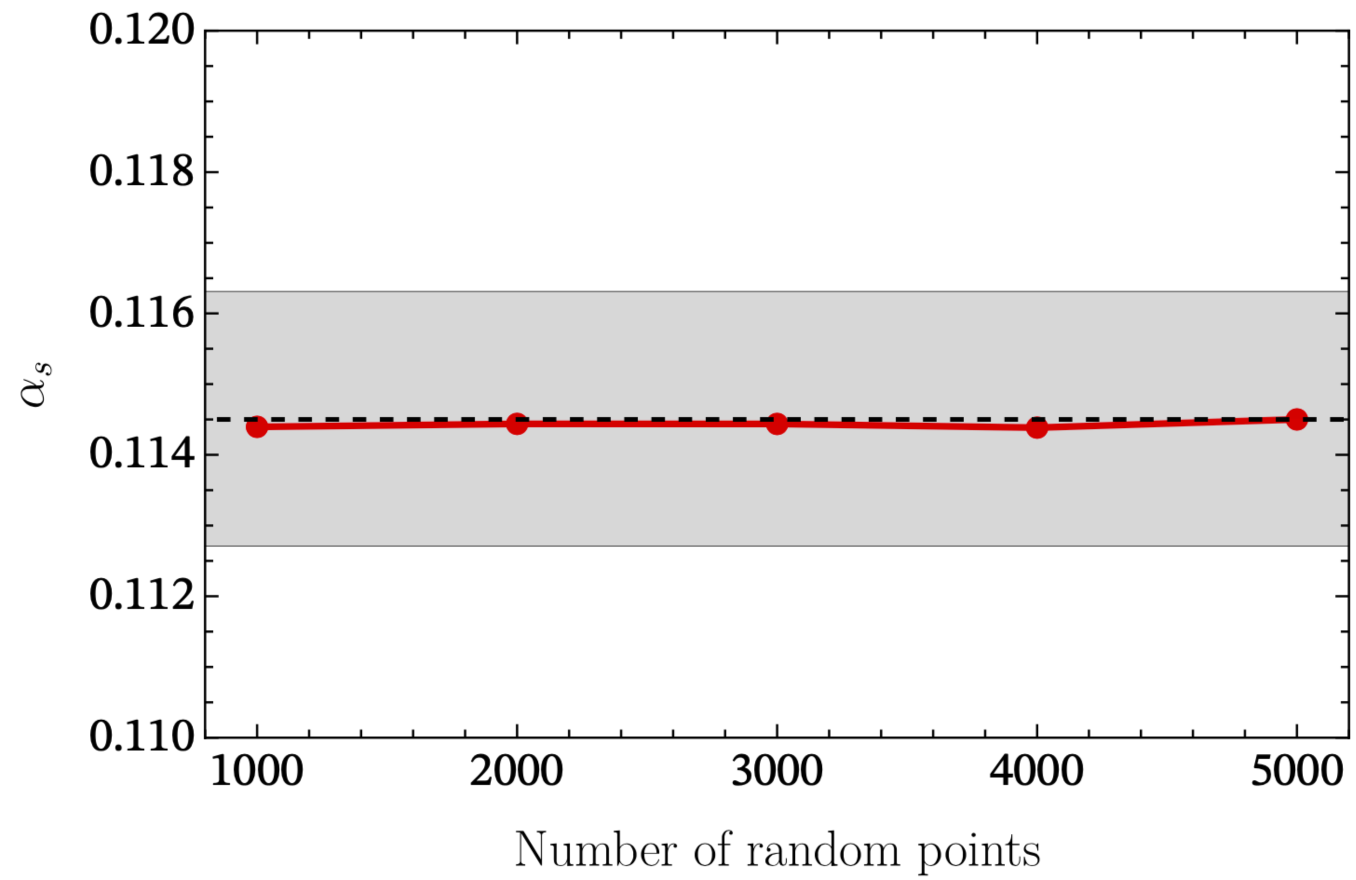
Convergence



- Including dijet resummation yields substantially better convergent behavior
- Near $\rho \approx 0.25$ visibly less overlap between the different orders even when including dijet resummation
- Improved convergence around $\rho \approx 0.25$ when including shoulder resummation

Random Scan



- Increasing random point density yields fluctuations of central values of α_s that stay well within fit uncertainty