Top Quark and Electroweak Physics: Theory Perspective

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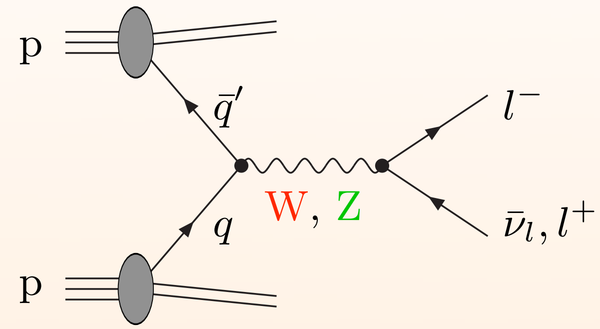
Les Rencontres de Physique de la Vallee D'Aoste
La Thuile, March 2010

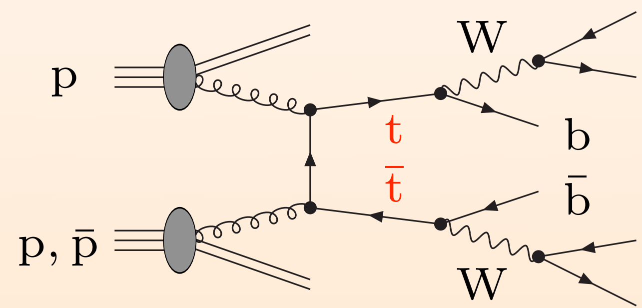
Collider Physics Top & Electroweak Examples

- $pp \to W/Z + X$,
  $pp \to W/Z + \text{jets}$



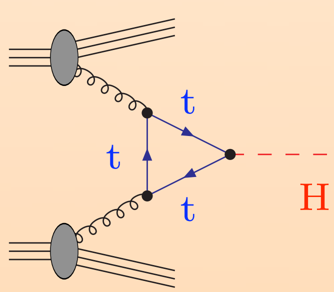
measure m_W, detector calibration,
measure PDFs,
search for W' and Z'

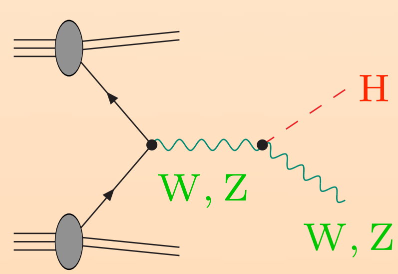
- $pp \to t\bar{t} + X$

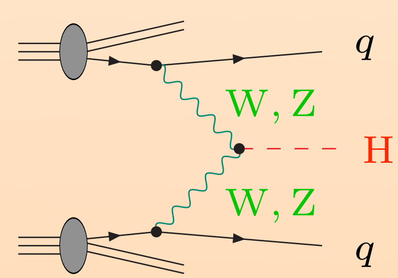


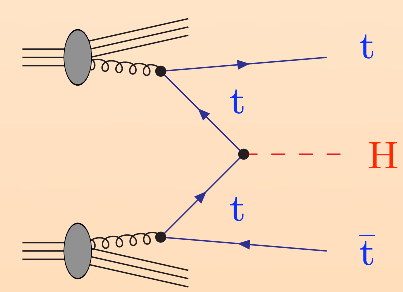
measure m_t,
$t\bar{t}$ spin correlations

- single top $\quad (W\, b \to t,\ W \to t\, \bar{b}\,)$
- $pp \to \gamma + \text{jets}$
- $pp \to H + X$



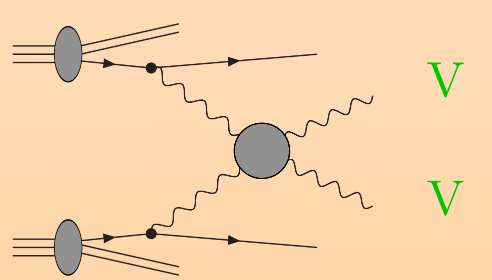






minimal H?,
measure m_H,
test Higgs couplings

- $pp \to VV' + X$



test e.w. symmetry breaking, unitarity bound,
triple and quartic V couplings

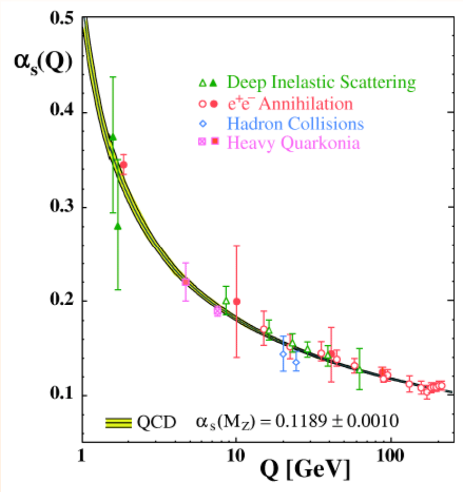
Must understand QCD:

- Perturbative corrections are important

  NLO, NNLO in α_s

$\alpha_s(\mu)$

eg. scale uncertainty



- Factorization ! $d\sigma^{\text{had}} = f \otimes f \otimes d\sigma^{\text{part}}$

- Nonperturbative corrections, hadronization

- Underlying event, soft physics

- Large logs $\alpha_s \ln^2 z,\ \alpha_s^2 \ln^4 z,\ \ldots$ QCD Sudakov's, EW Sudakov's

- Parton Shower: ISR, High multiplicity final states

- Precision Measurements:

Tevatron

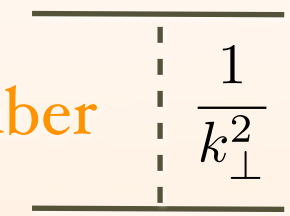
$$m_t = 173.1 \pm 0.6_{\text{stat}} \pm 1.1_{\text{syst}}\ \text{GeV}$$

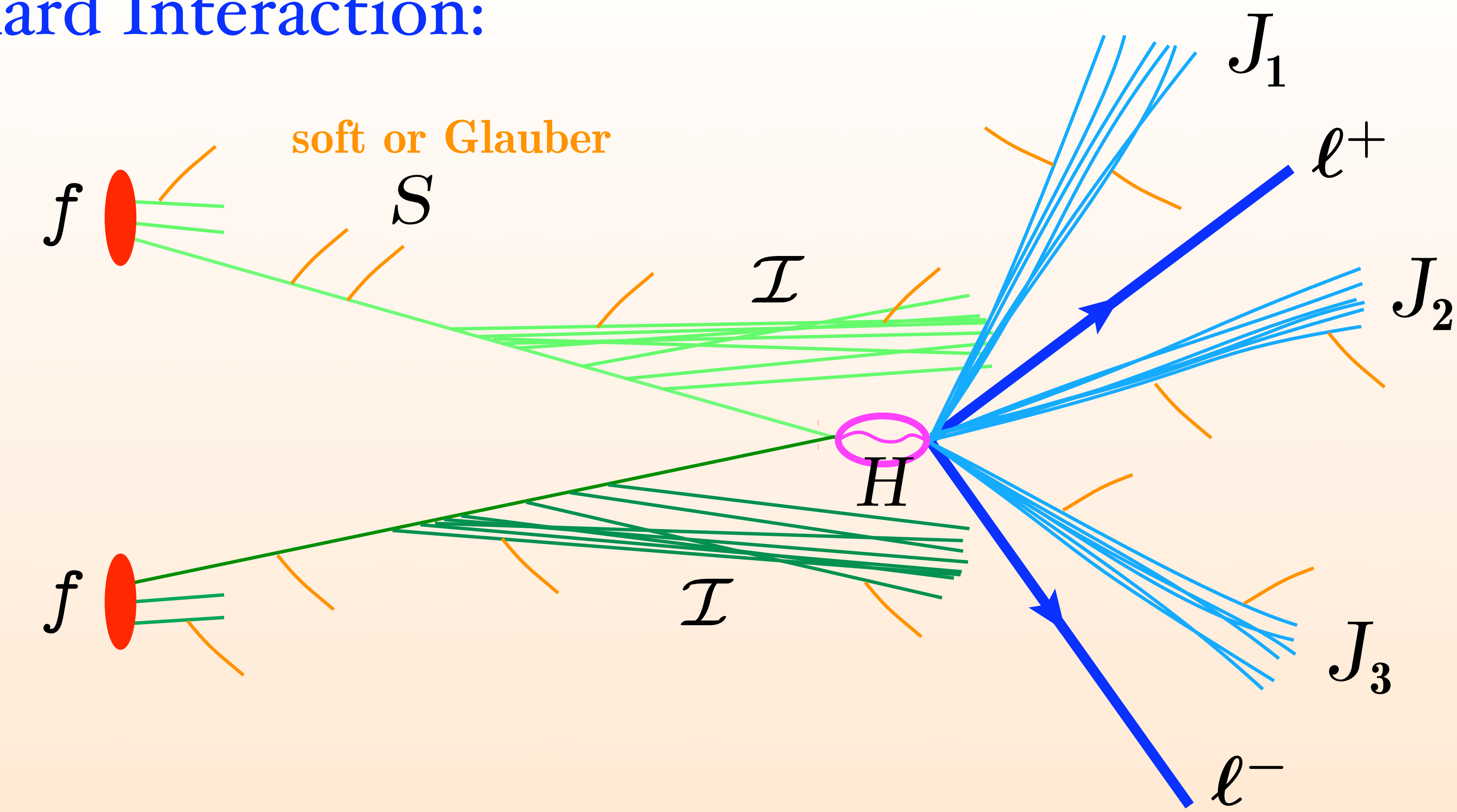
theory error?

what mass is it?

$$\alpha_s(m_Z) = 0.1161^{+0.0041}_{-0.0048}$$

Typical Event with Hard Interaction:

Glauber 



Factorization:

"cross section can be computed as product of independent pieces"

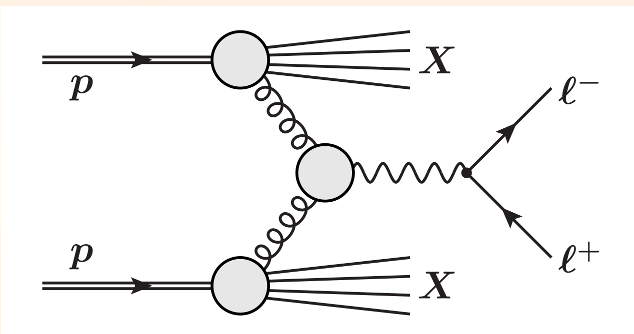
New physics hides at short distances in H

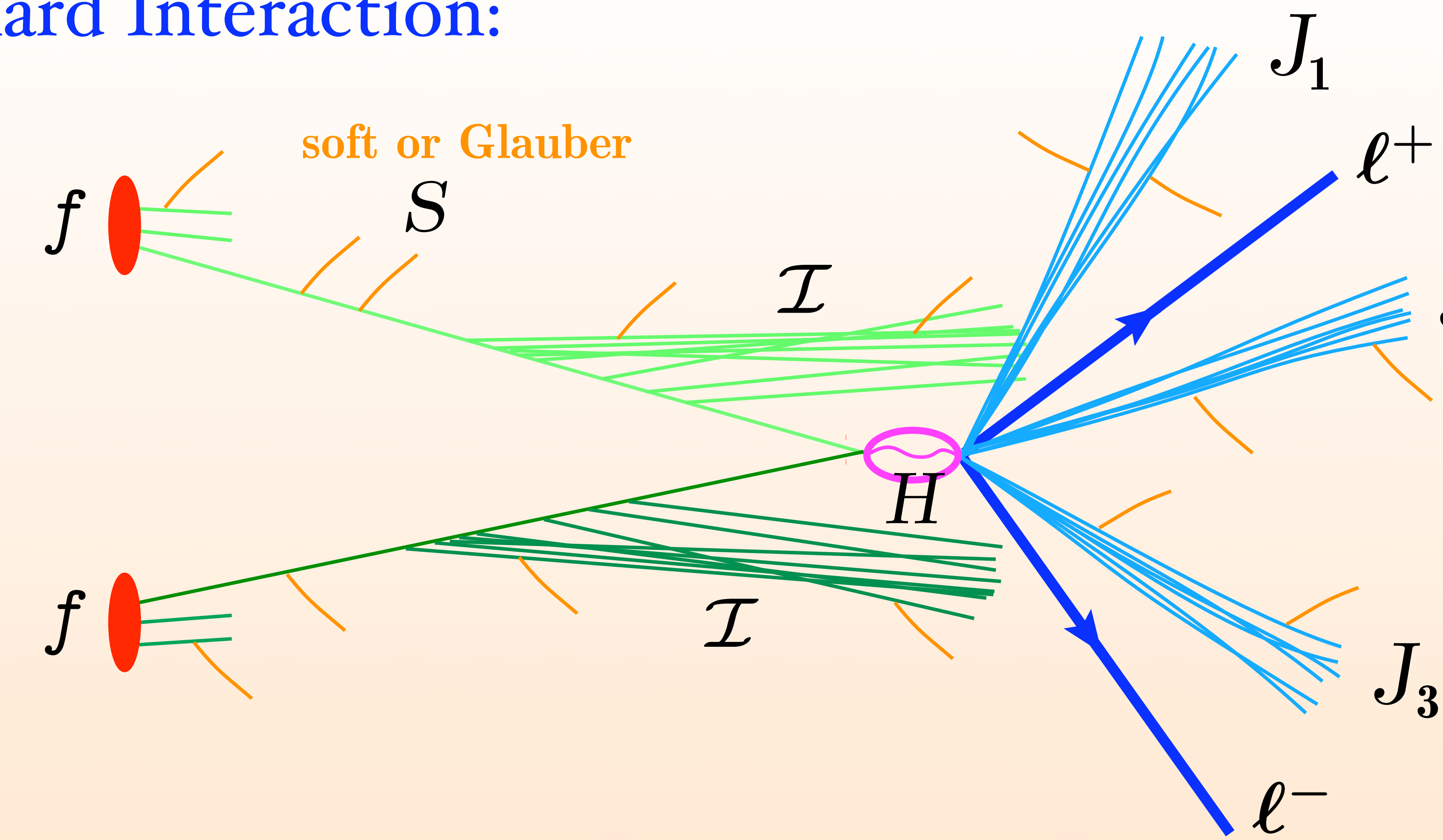
Shower MC programs assume factorization:

$d\sigma =$ [initial state parton shower] $\otimes$ [hard scattering fixed order perturbative computation] $\otimes$ [final state parton showers] $\otimes$ [hadronization model, underlying event, ...]

(with parton distributions)

Typical Event with Hard Interaction:

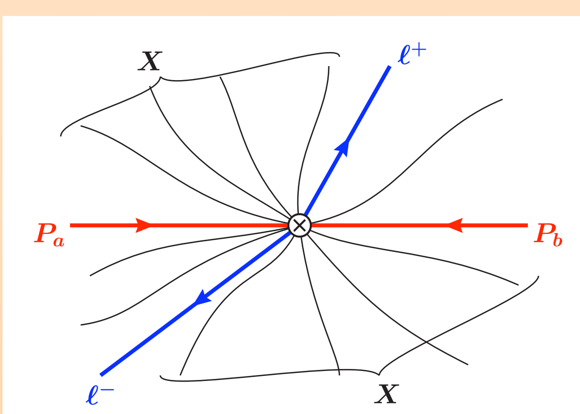




Inclusive Factorization: (Collins, Soper, Sterman)

Drell-Yan $pp \to X\ell^+\ell^-$ X = anything = hard (sum over all final states)

$$\frac{d\sigma}{dQ^2} = \sum_{i,j} H_{ij}^{\rm incl} \otimes f_i(\xi_a) f_j(\xi_b)$$



- no Glauber effects!
- no soft effects!
- no need to distinguish jets
- PDF $f_i(\xi_a)$ is universal field theory matrix element

Remainder of the talk:

- Utility of classic event shapes & factorization

  discuss:
  soft physics, nonperturbative physics,
  large logs, & high precision

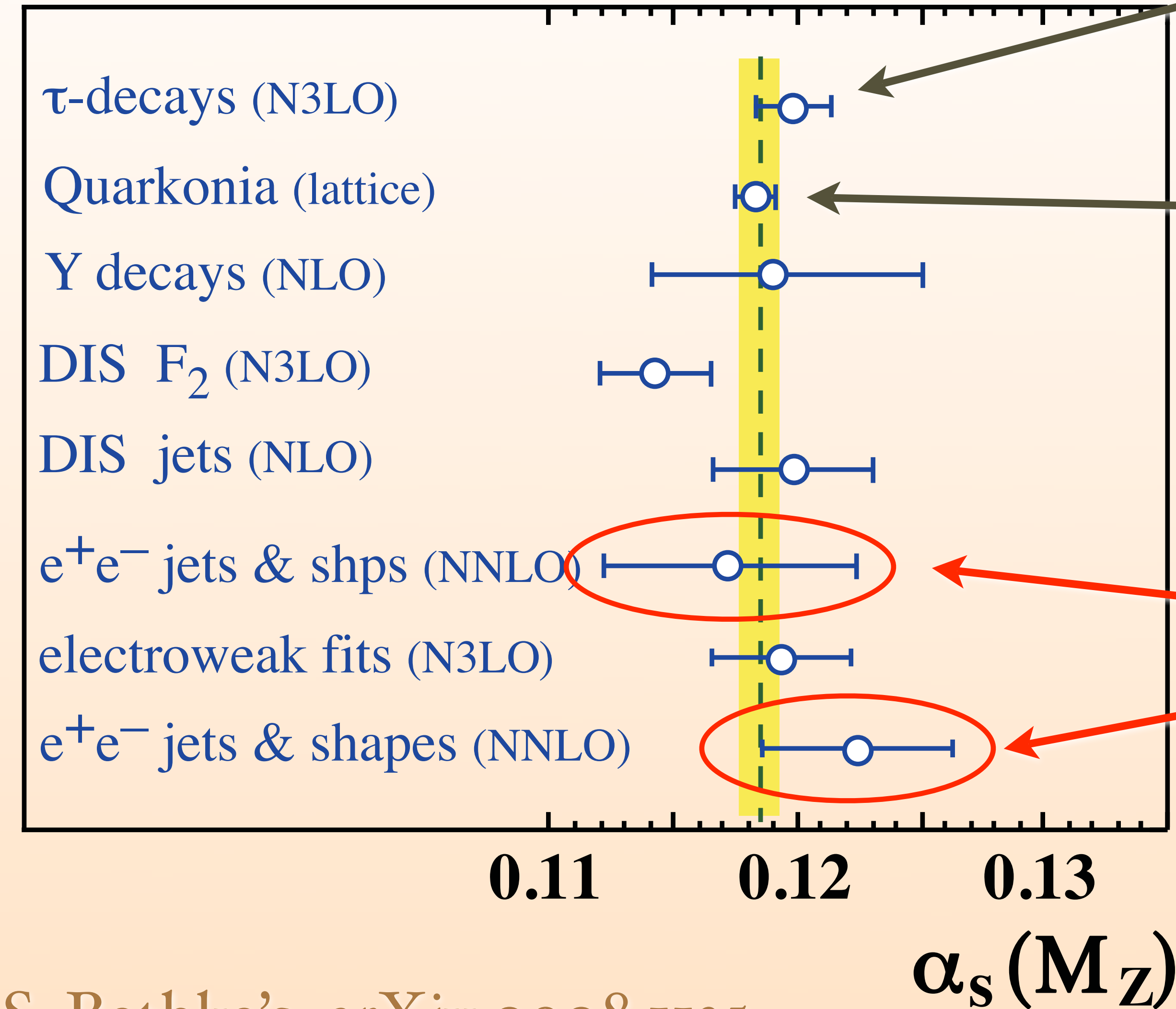
- Top Mass & Theory

- Applications of factorization at hadron colliders to:
  Higgs, top, event shapes, & jet algorithms

$$\alpha_s(m_Z)$$

Latest World Average

errors inflated to account for variation in literature



fit to Υ-splittings, Wilson loops

$$\alpha_s(m_Z) = 0.1183 \pm 0.0008$$

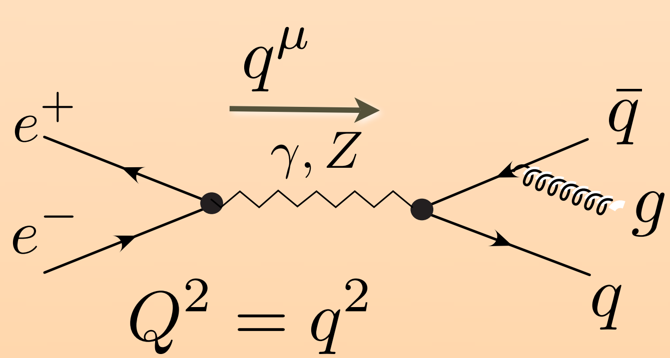
from lattice HPQCD 0807.1687

event shape results at fixed order

S. Bethke's, arXiv:0908.1135

$$\alpha_s(m_Z) = 0.1184 \pm 0.0007$$

In fact, using everything we know about factorization and performing a global fit, the event shape result is just as accurate as the lattice result !



$\alpha_s(m_Z)$

Thrust is a classic example of an "event-shape"

$$T = \max_{\hat{t}} \frac{\sum_i |\hat{\mathbf{t}} \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|}$$

$$\tau = 1 - T$$

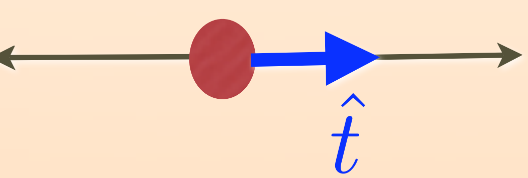
Lots of Data: $Q = 35\text{–}207\,\mathrm{GeV}$

807 bins

(& TASSO, JADE, AMY)

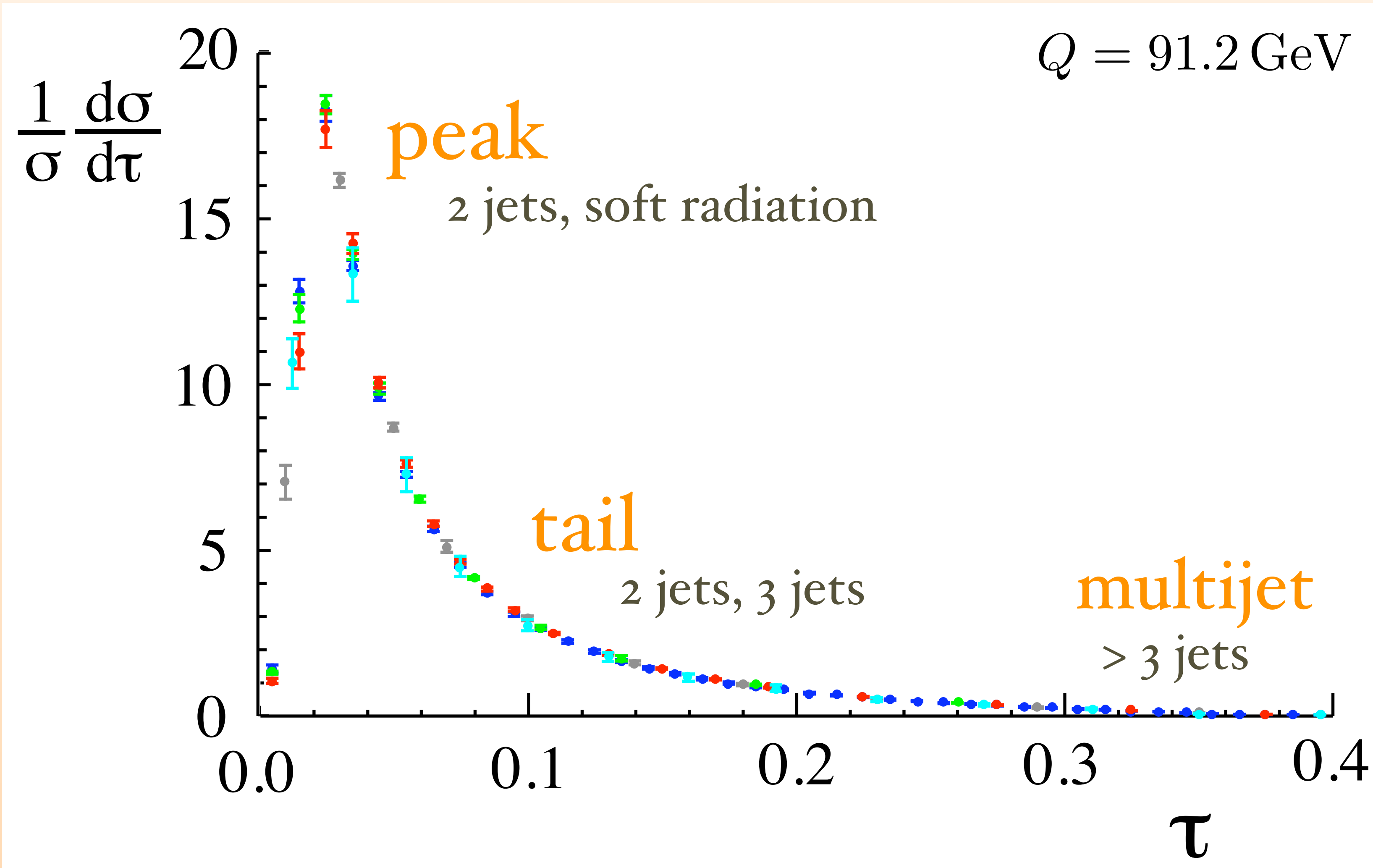
ALEPH, DELPHI, L3, OPAL, SLD

2 jets

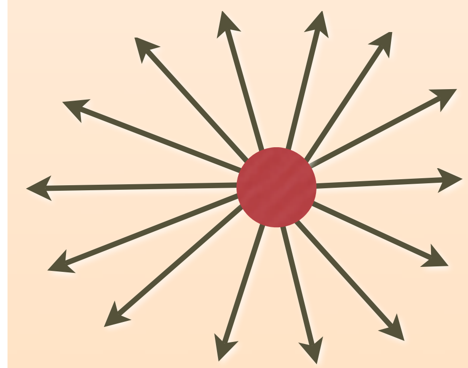


$T = 1$

$\tau = 0$



spherical event



$T = 1/2$

$\tau = 1/2$

Event shape fits cut on τ, eg. keep $\tau \in \{0.09, 0.25\}$.

Cross section looks like:

$e^+e^- \to \text{jets}$

For $\tau > 0$

singular non-singular

$$\frac{1}{\sigma}\frac{d\sigma}{d\tau} = \sum_{n,m} \alpha_s(Q)^n \frac{\ln^m \tau}{\tau} + \sum_{n,m} \alpha_s(Q)^n \ln^m \tau + \sum_{n,m} \alpha_s(Q)^n f_m(\tau)$$

$$+ f(\tau, \Lambda_{\rm QCD}/Q)$$

nonperturbative
power corrections

Factorization Theorem:

Hard Function Jet Function Soft Function

$$\boxed{\frac{d\sigma}{d\tau} = \sigma_0 H(Q, m_Z, \mu)\, Q \int d\ell\, J_T\Big(Q^2\tau - Q\ell, \mu\Big) S_T(\ell, \mu)} + \left(\frac{d\sigma}{d\tau}\right)_{\text{nonsingular}}$$

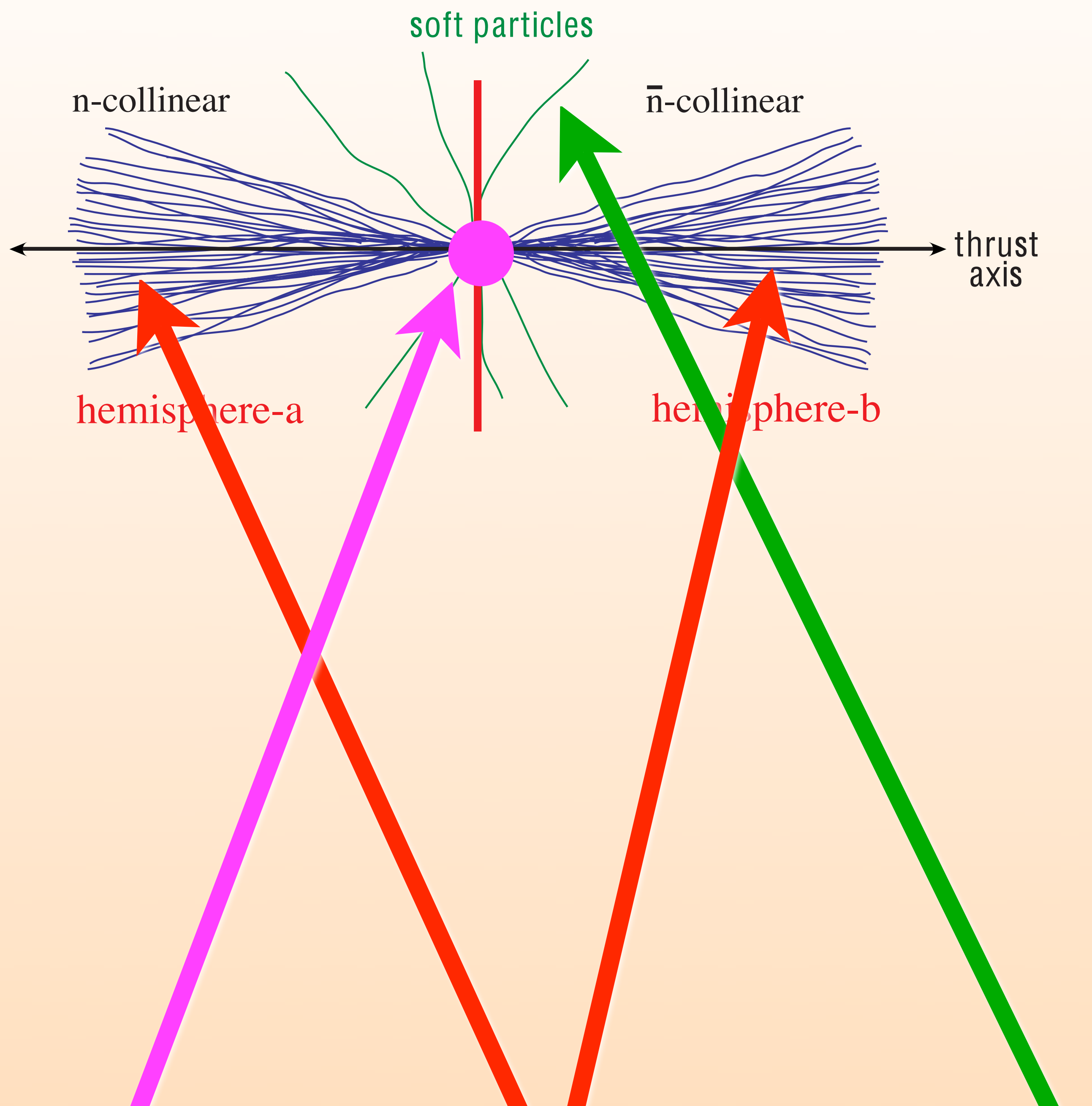
singular
terms

Renormalization group
evolution sums logs of τ

encodes dominant
power corrections
by a universal function

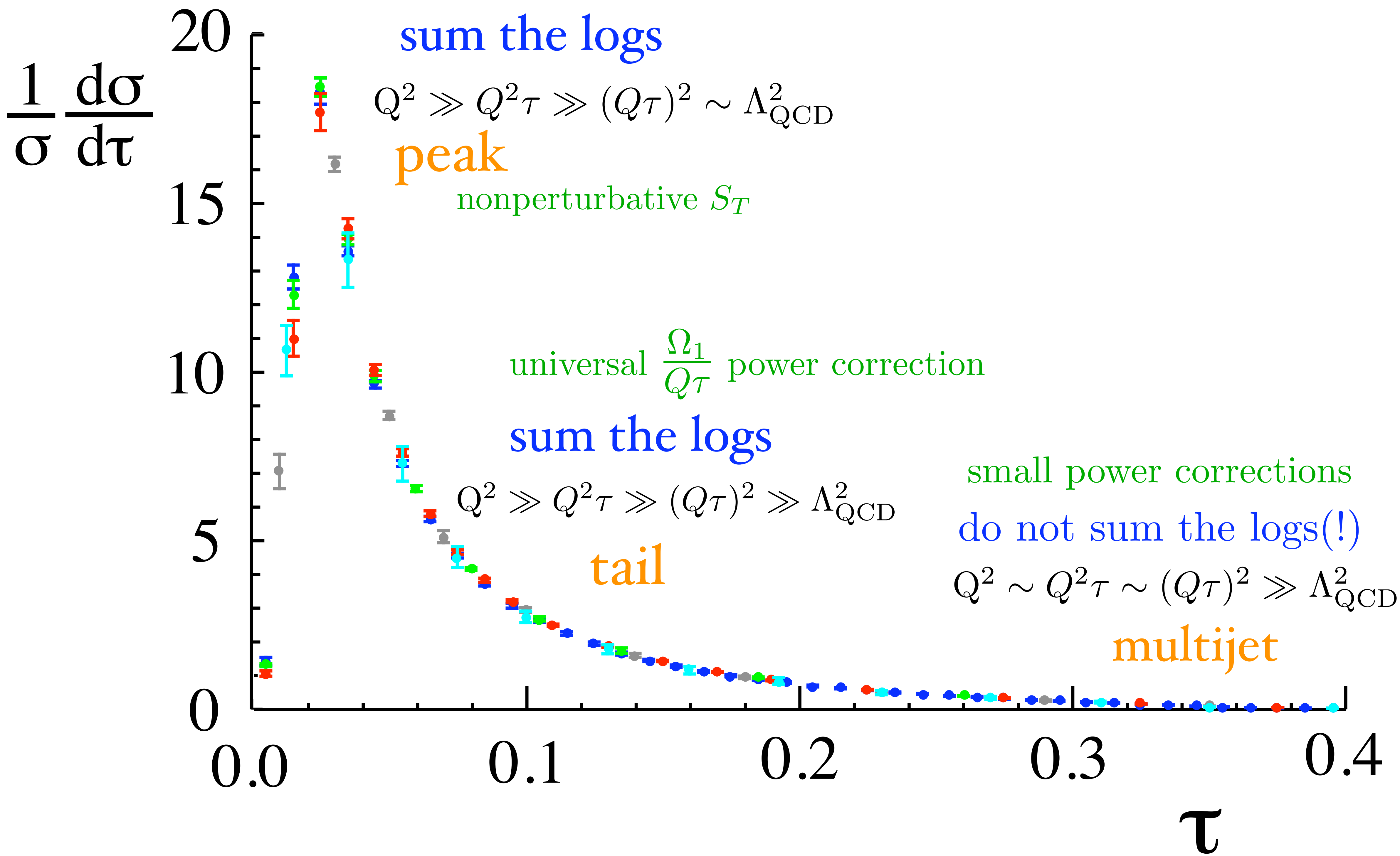
Subleading SCET factorization
theorems tells us
how power corrections
enter here too

$$\underset{\text{hard}}{Q^2} \gg \underset{\text{jet}}{Q^2\tau} \gg \underset{\text{soft}}{(Q\tau)^2}$$



$$\frac{d\sigma}{d\tau} = \sigma_0 H(Q,\mu)\, Q \int d\ell\, J_T\Big(Q^2\tau - Q\ell, \mu\Big) S_T(\ell,\mu)$$

Our Three Regions:



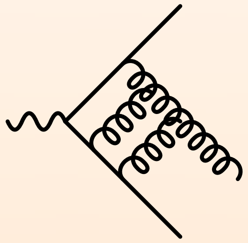
Recent Literature

• $\mathcal{O}(\alpha_s^3)$ fixed order results

S.Weinzierl

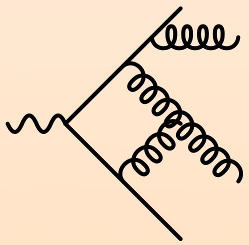
- Two-loop matrix elements

$|\mathcal{M}|^2_{\text{2-loop},3\text{ partons}}$



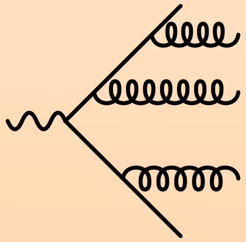
- One-loop matrix elements

$|\mathcal{M}|^2_{\text{1-loop},4\text{ partons}}$

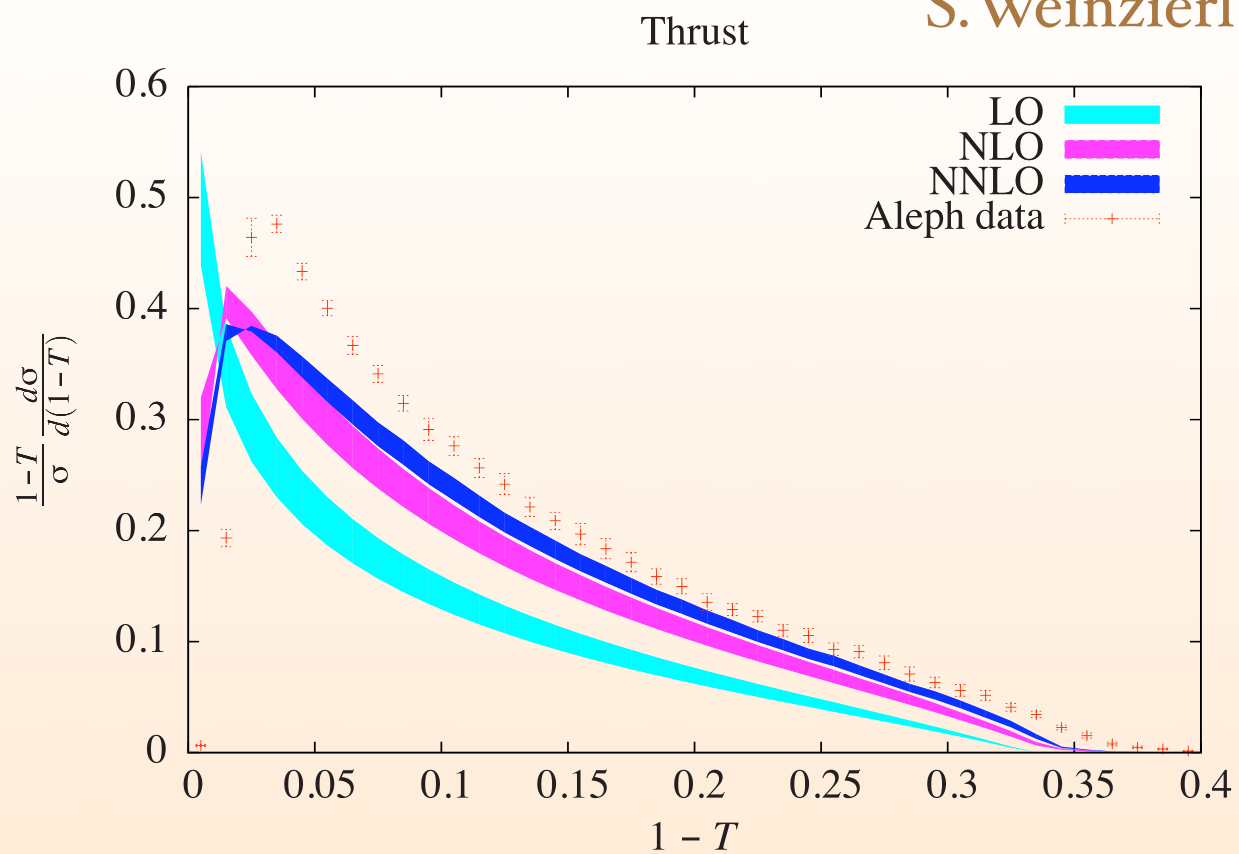


- Tree level matrix elements

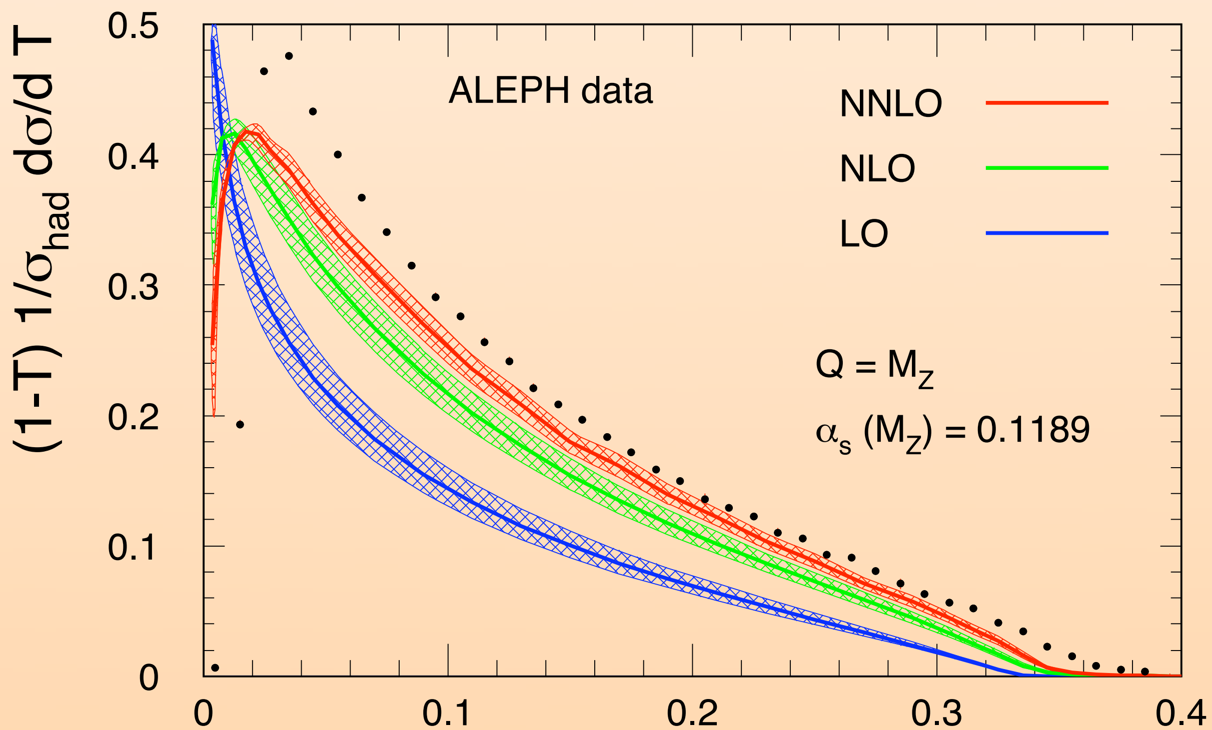
$|\mathcal{M}|^2_{\text{tree},5\text{ partons}}$



Infrared Poles cancel in the sum



Gehrmann, Gehrmann-De Ridder, Glover, Heinrich



convergence? μ dependence?

- summation of large logs to N^3LL (analytic with SCET)

Catani et.al.

Becher and Schwartz

LL, NLL, NNLL, N^3LL

$$\ln \frac{d\sigma}{dy} = (\alpha_s \ln)^k \ln + (\alpha_s \ln)^k + \alpha_s (\alpha_s \ln)^k + \alpha_s^2 (\alpha_s \ln)^k + \ldots$$

LL NLL NNLL N^3LL

y = Fourier transform of τ

		cusp	non-cusp	matching	alphas
standard counting	LL	1	–	tree	1
	NLL	2	1	tree	2
	NNLL	3	2	1	3
	N^3LL	4^{pade}	3	2	4
primed counting	LL′	1	–	tree	1
	NLL′	2	1	1	2
	NNLL′	3	2	2	3
	N^3LL'	4^{pade}	3	3	4

When fixed order results are important primed counting is better

- summation of large logs to N^3LL (analytic with SCET)

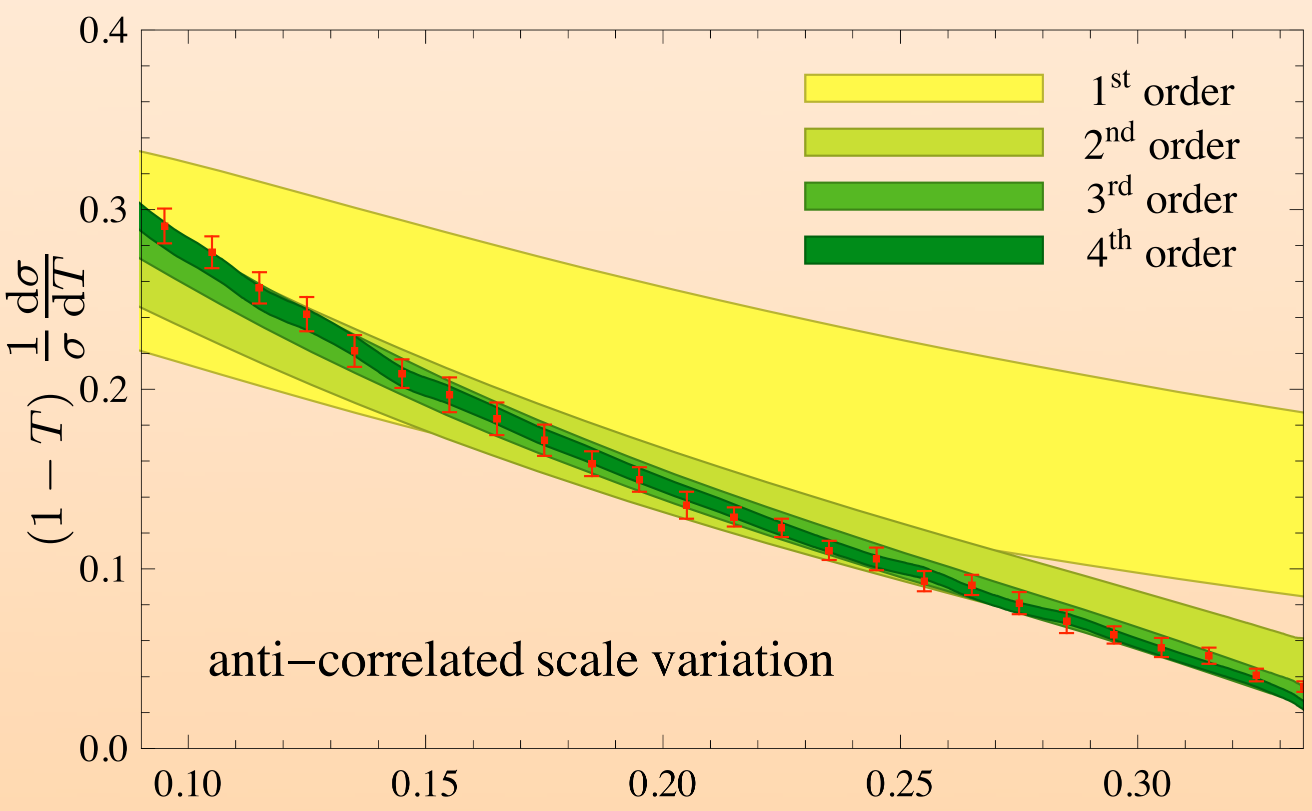
Catani et.al.

Becher and Schwartz

LL, NLL, NNLL, N^3LL

$$\ln \frac{d\sigma}{dy} = (\alpha_s \ln)^k \ln + (\alpha_s \ln)^k + \alpha_s (\alpha_s \ln)^k + \alpha_s^2 (\alpha_s \ln)^k + \ldots$$

LL NLL NNLL N^3LL



better convergence

nice μ dependence

- summation of large logs to N^3LL (analytic with SCET)

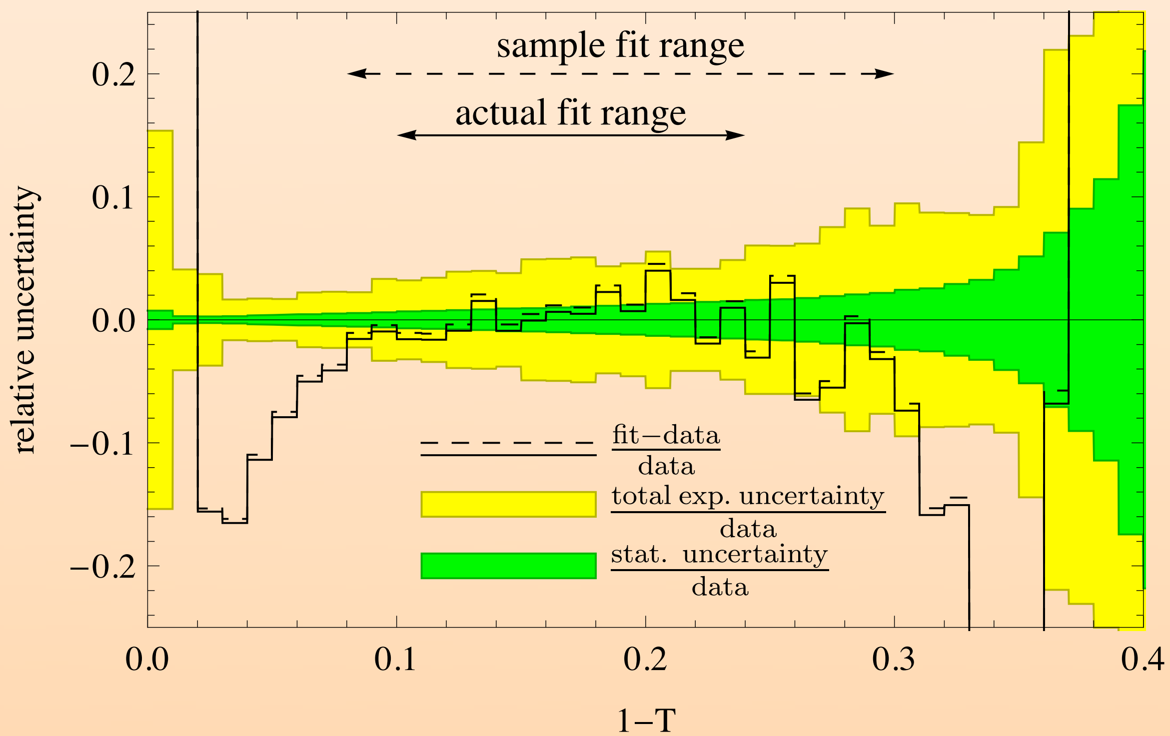
Catani et.al.

Becher and Schwartz

LL, NLL, NNLL, N^3LL

$$\ln \frac{d\sigma}{dy} = (\alpha_s \ln)^k \ln + (\alpha_s \ln)^k + \alpha_s(\alpha_s \ln)^k + \alpha_s^2(\alpha_s \ln)^k + \ldots$$

LL NLL NNLL N^3LL



$$\alpha_s(m_Z) = 0.1172 \pm 0.0022$$

improved uncertainty over fixed order results

- Nonperturbative corrections not included in central value

tuning of programs like Pythia does not properly separate nonperturbative corrections from higher order perturbative corrections

Nonperturbative Corrections

Universal Soft Function

$$S_\tau(k,\mu) = \frac{1}{N_c}\sum_{X_s} \delta(k - k_s^{+a} - k_s^{-b})\langle 0|\underbrace{\overline{Y}_{\bar n} Y_n}|X_s\rangle\langle X_s|\underbrace{Y_n^\dagger \overline{Y}_{\bar n}^\dagger}|0\rangle$$

soft Wilson lines

OPE:

$$S_T(\tau) = S_{\rm pert}(\tau) - S'_{\rm pert}(\tau)\frac{2\Omega_1}{Q} + \ldots$$
$$= S_{\rm pert}(\tau - 2\Omega_1/Q) + \ldots$$

shifts distributions to the right

Korchemsky, Sterman, Lee & Sterman

Dokshitzer & Webber;

$\Omega_1 \sim \Lambda_{\rm QCD}$ a universal parameter

define Ω_1 to be renormalon free

Perturbative & Nonperturbative soft radiation:

Hoang & I.S.;

Ligeti, I.S., Tackmann

$$S(\ell,\mu) = \int d\ell' \; \underbrace{S_{\rm part}(\ell-\ell',\mu)}_{\text{partonic soft function at fixed order}} \; \underbrace{F(\ell')}_{\text{normalized model function, complete basis (must have exponential fall off!)}}$$

Ingredients for Global Analysis

Abbate, Fickinger, Hoang, Mateu, I.S.

- SCET Factorization Theorems, Sum Large Logs:

  LL, NLL, NNLL, $\mathrm{N^3LL}$ and/or $\mathrm{LL'}$, $\mathrm{NLL'}$, $\mathrm{NNLL'}$, $\mathrm{N^3LL'}$
- Power Corrections Ω_1
- Multiple Regions:

  smooth transitions

  $i)$ peak: $Q \gg Q\sqrt{\tau} \gg Q\tau \sim \Lambda_{\mathrm{QCD}}$

  $ii)$ tail: $Q \gg Q\sqrt{\tau} \gg Q\tau \gg \Lambda_{\mathrm{QCD}}$

  $iii)$ far tail: $Q \sim Q\sqrt{\tau} \sim Q\tau \gg \Lambda_{\mathrm{QCD}}$

  (multi jet)
- Renormalon Subtractions (Mass, Gap), R-RGE
- Complete Basis for modeling Hadronic functions (peak region)
- Final State QED radiation, with resummation of Sudakov
- Rigorous treatment of b-quark mass effects

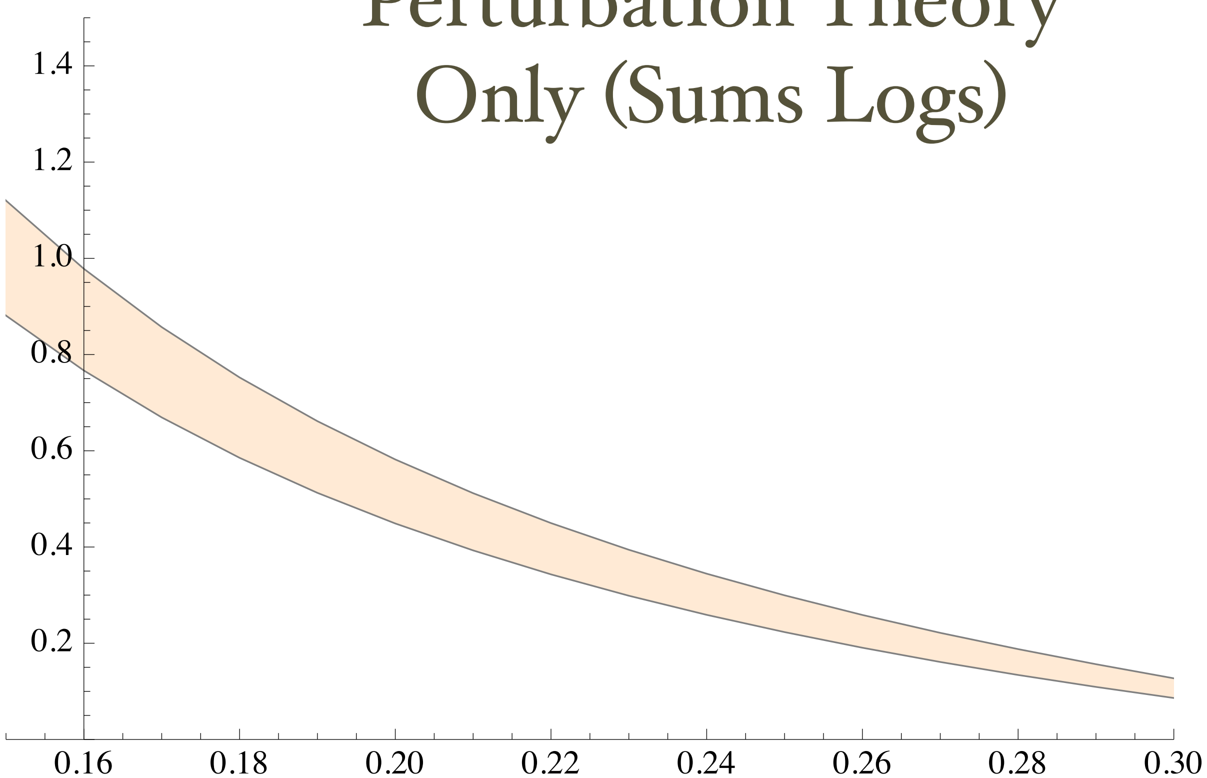
  (using factorization for massive quark event shapes)

Tail Predictions with Scan over Theory Uncertainties

NLL'

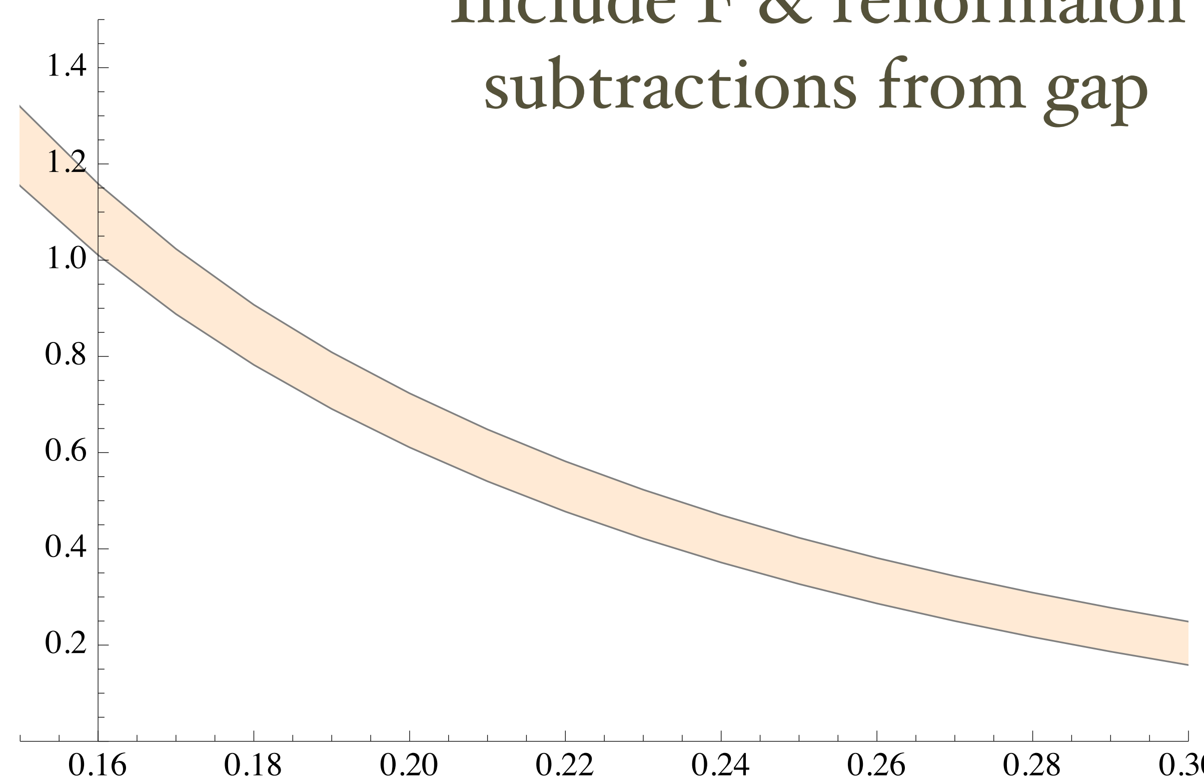
$$\frac{1}{\sigma}\tau\frac{d\sigma}{d\tau}$$

Perturbation Theory Only (Sums Logs)



τ

Include F & renormalon subtractions from gap

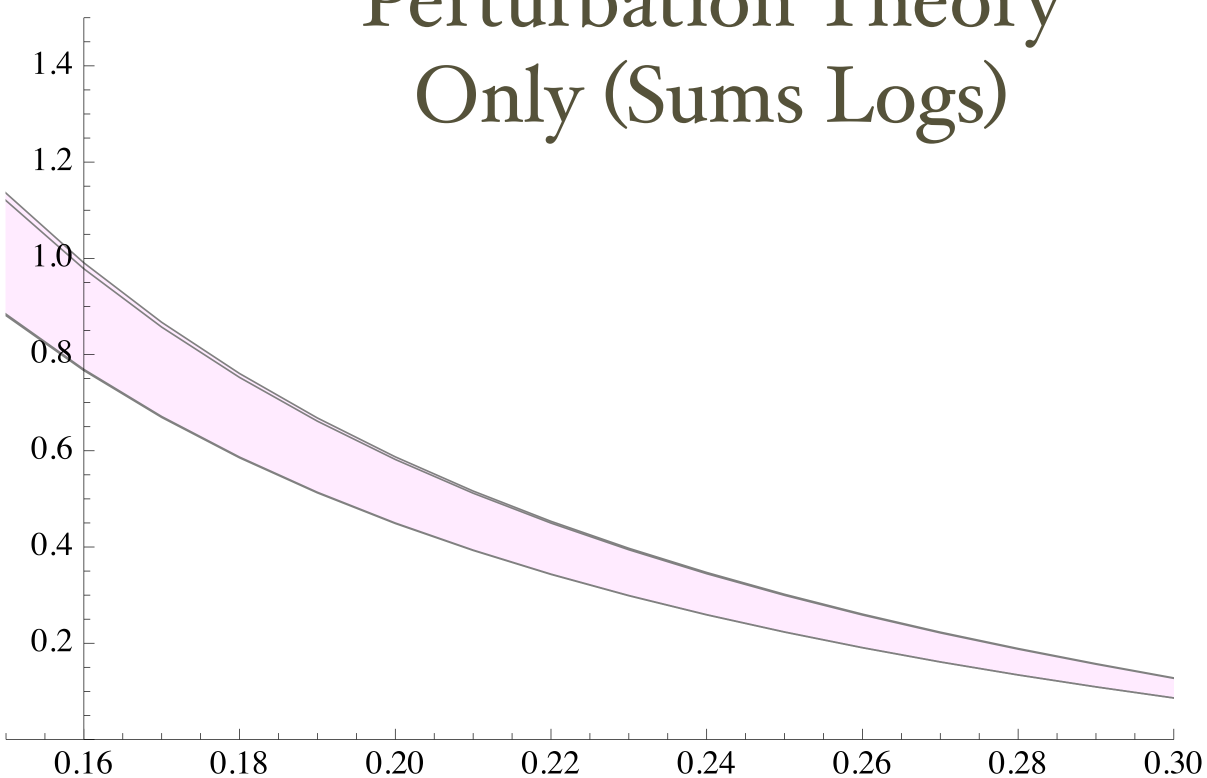


Tail Predictions with Scan over Theory Uncertainties

NLL' NNLL

$$\frac{1}{\sigma}\tau\frac{d\sigma}{d\tau}$$

Perturbation Theory Only (Sums Logs)



τ

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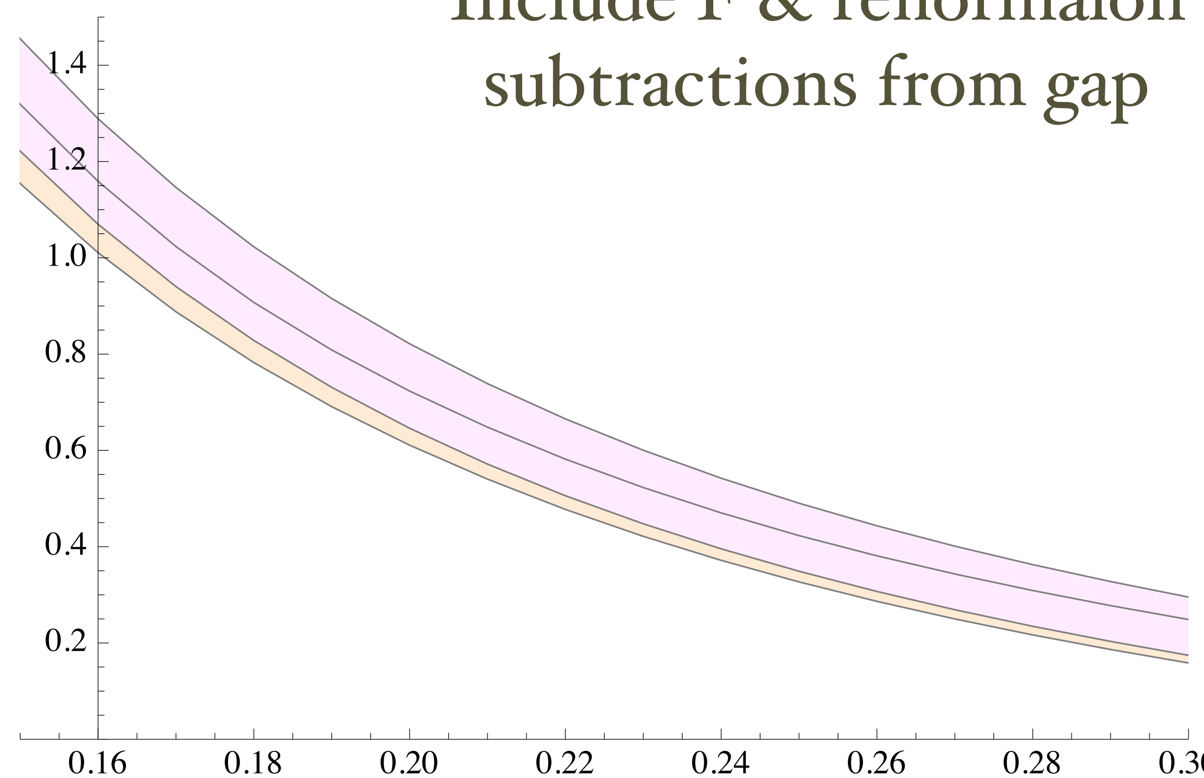


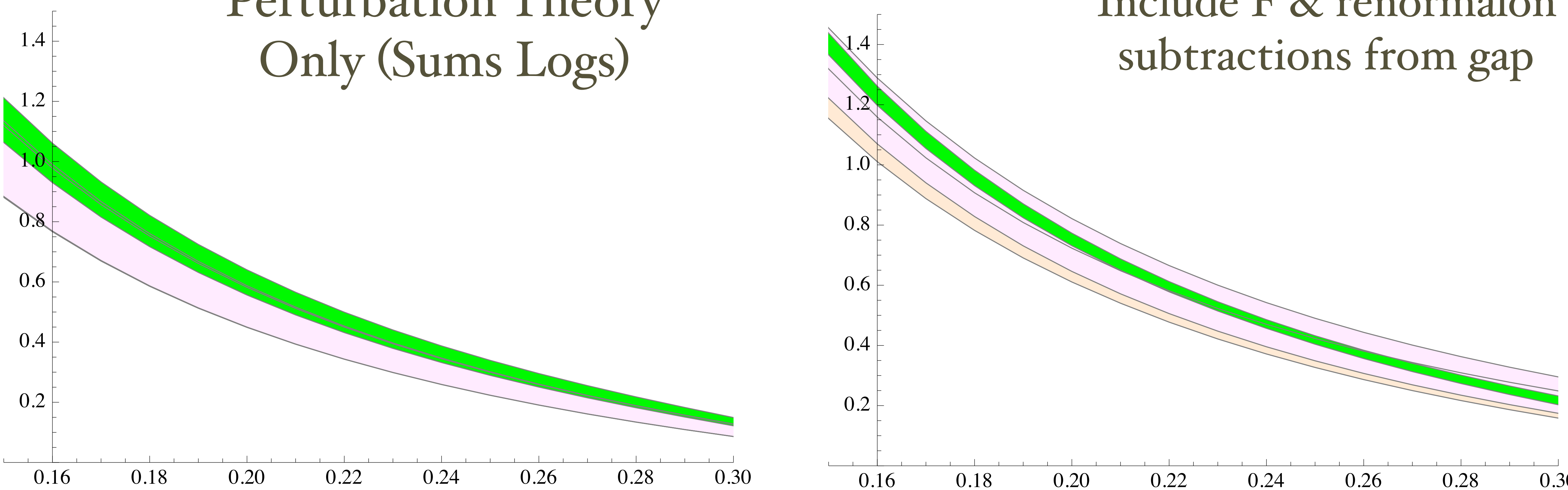
Tail Predictions with Scan over Theory Uncertainties

NLL′   NNLL   NNLL′

$$\frac{1}{\sigma}\tau\frac{d\sigma}{d\tau}$$

Perturbation Theory Only (Sums Logs)

Include F & renormalon subtractions from gap



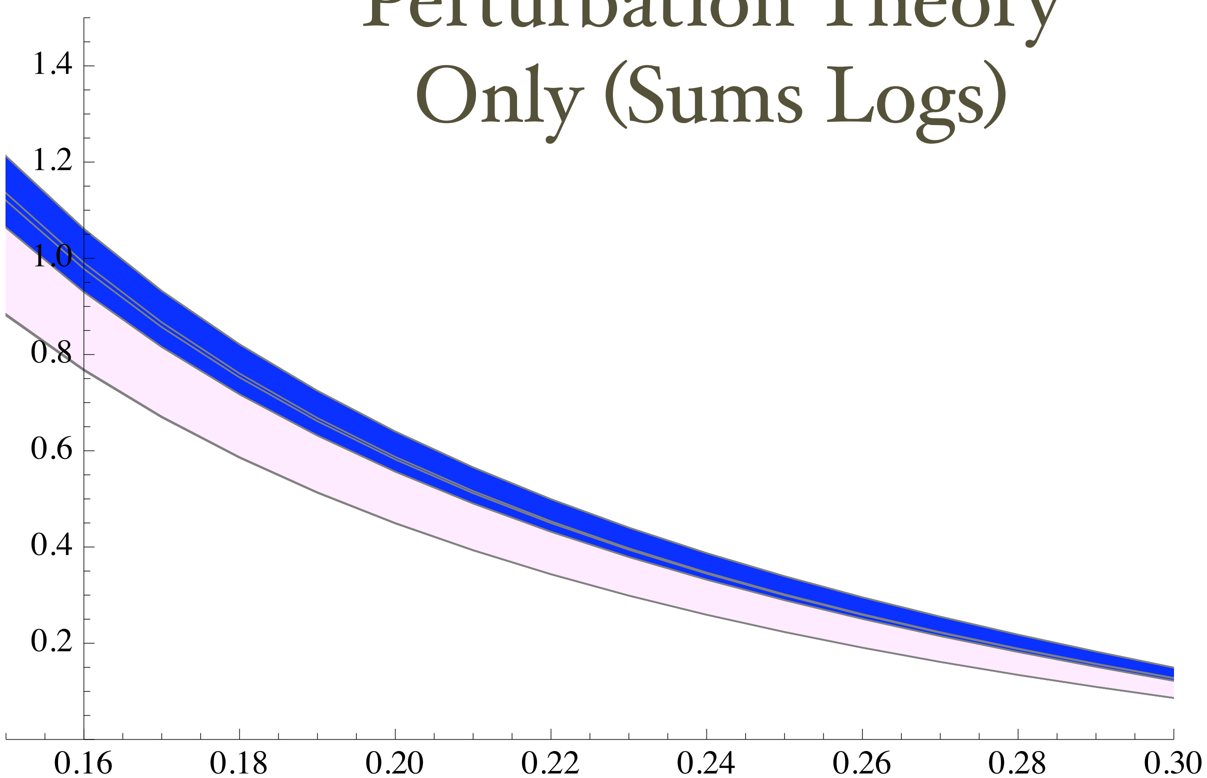
τ

Tail Predictions with Scan over Theory Uncertainties

NLL' NNLL NNLL' $\mathrm{N^3LL}$

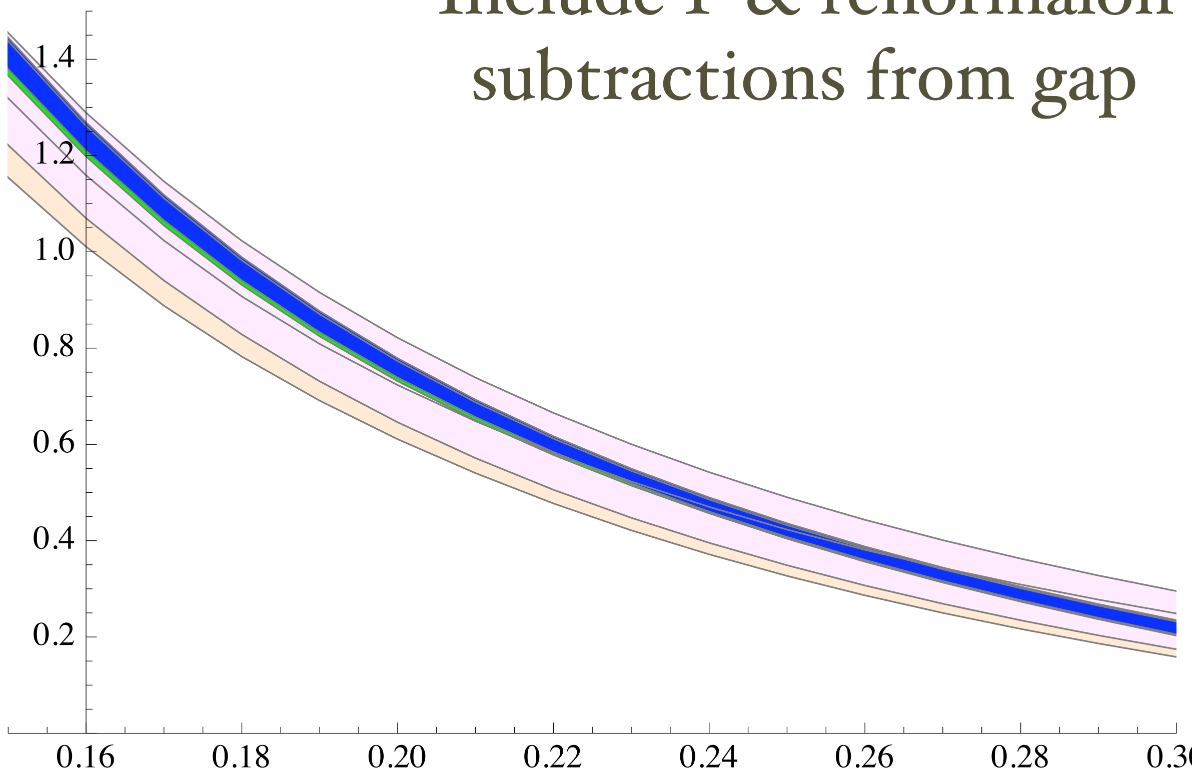
$$\frac{1}{\sigma}\tau\frac{d\sigma}{d\tau}$$

Perturbation Theory Only (Sums Logs)



τ

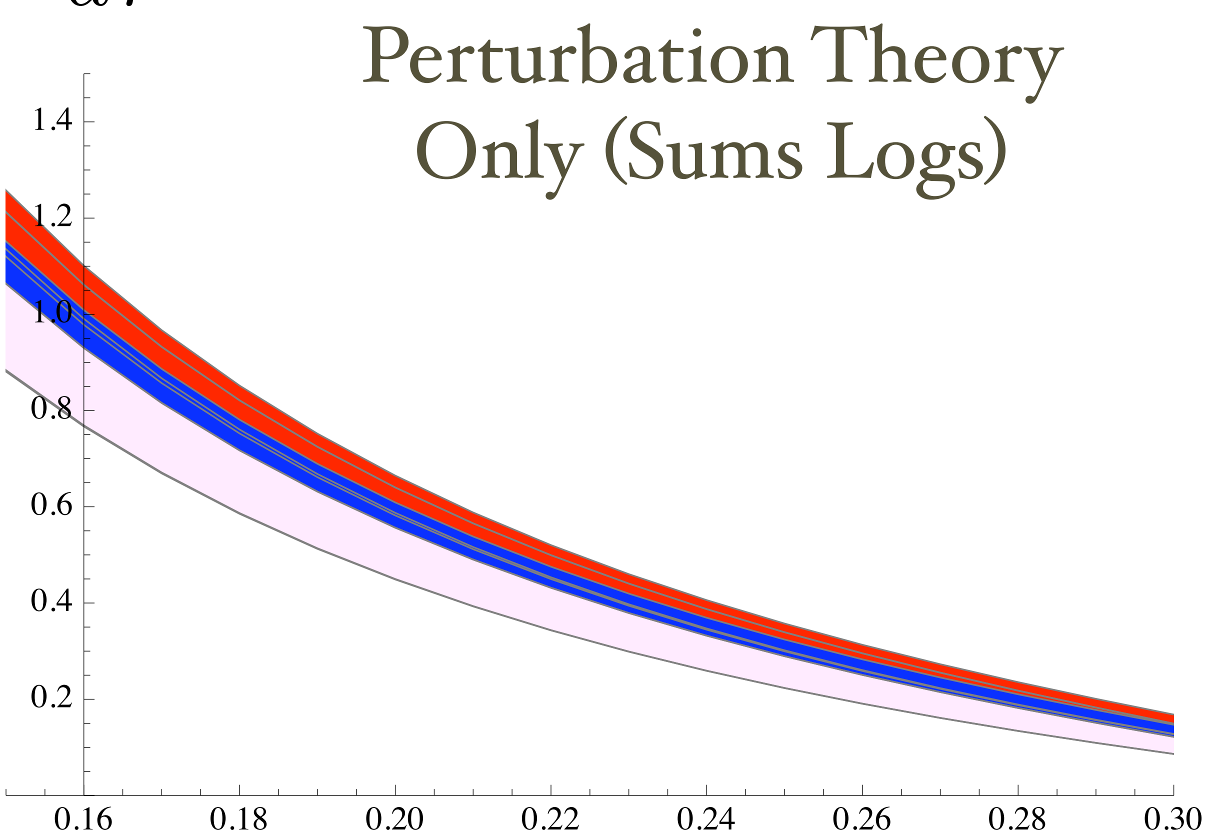
Include F & renormalon subtractions from gap

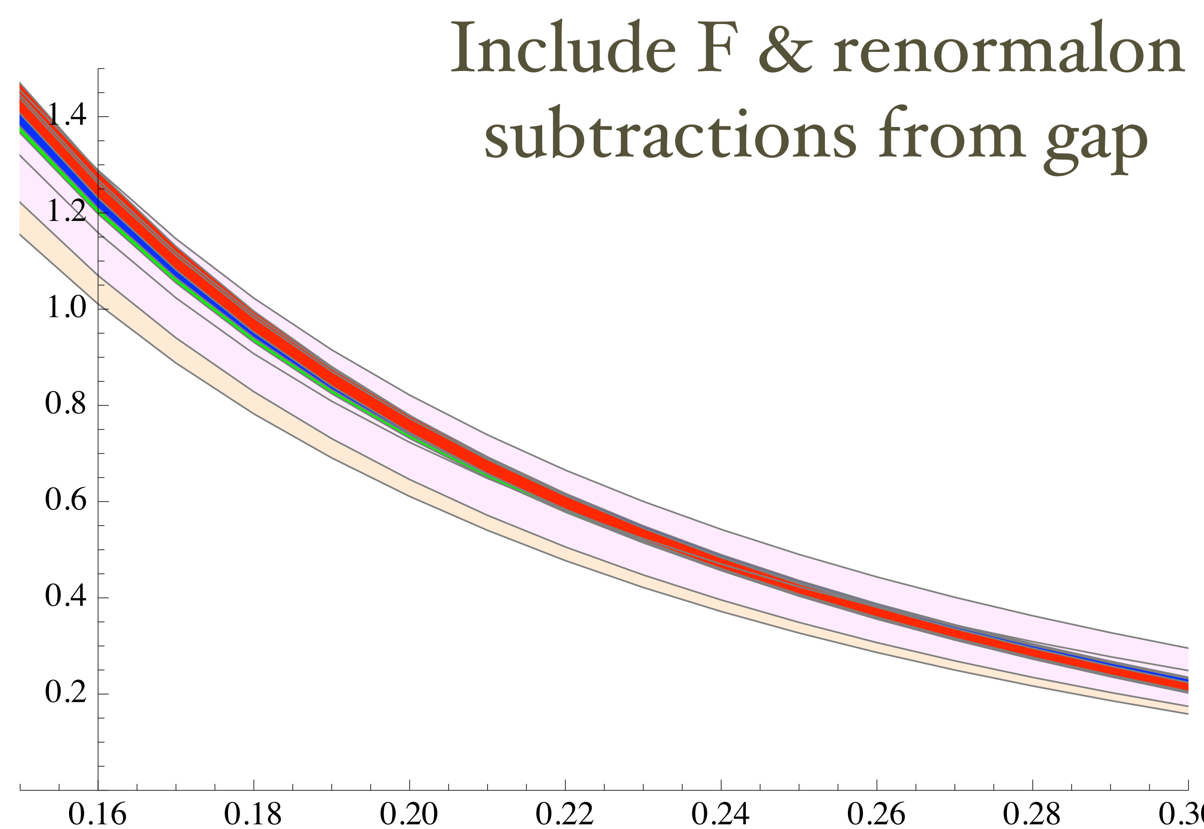


Tail Predictions with Scan over Theory Uncertainties

NLL′ NNLL NNLL′ N^3LL N^3LL'

$$\frac{1}{\sigma}\tau\frac{d\sigma}{d\tau}$$

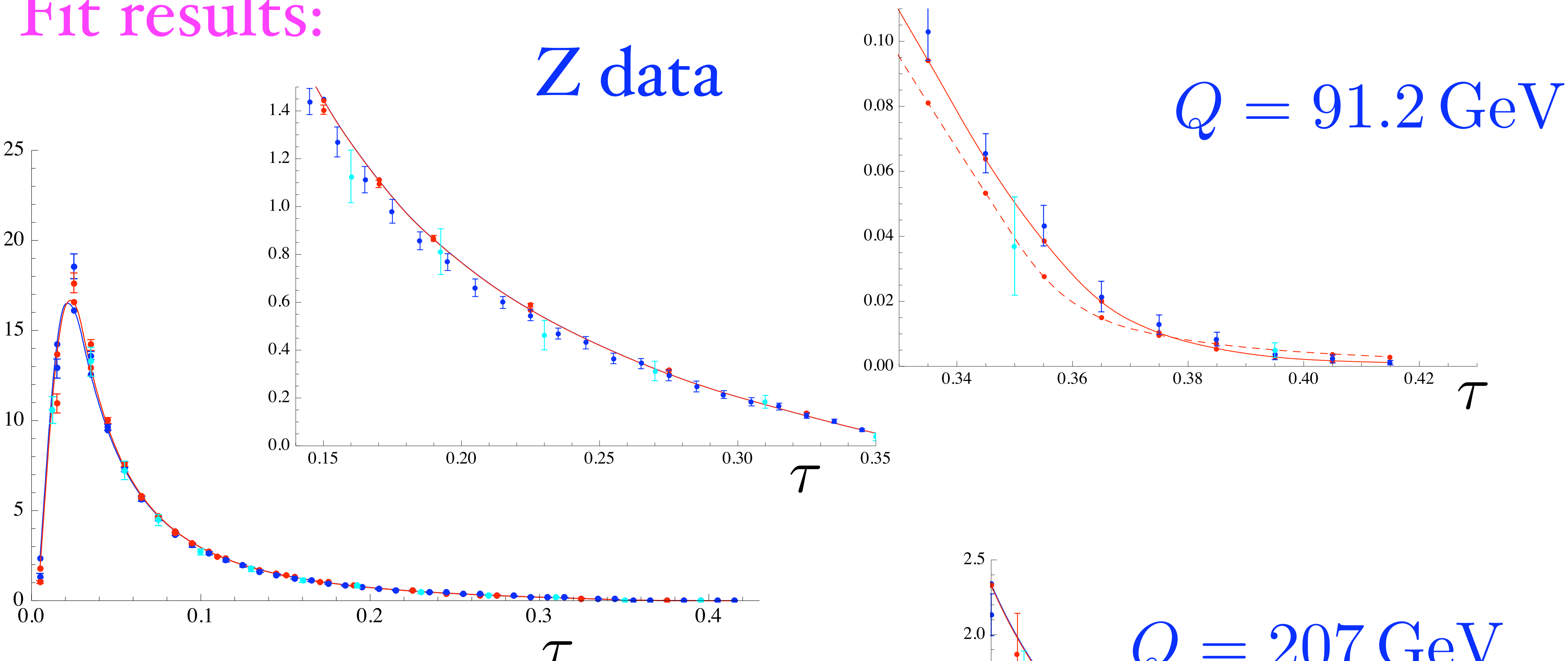


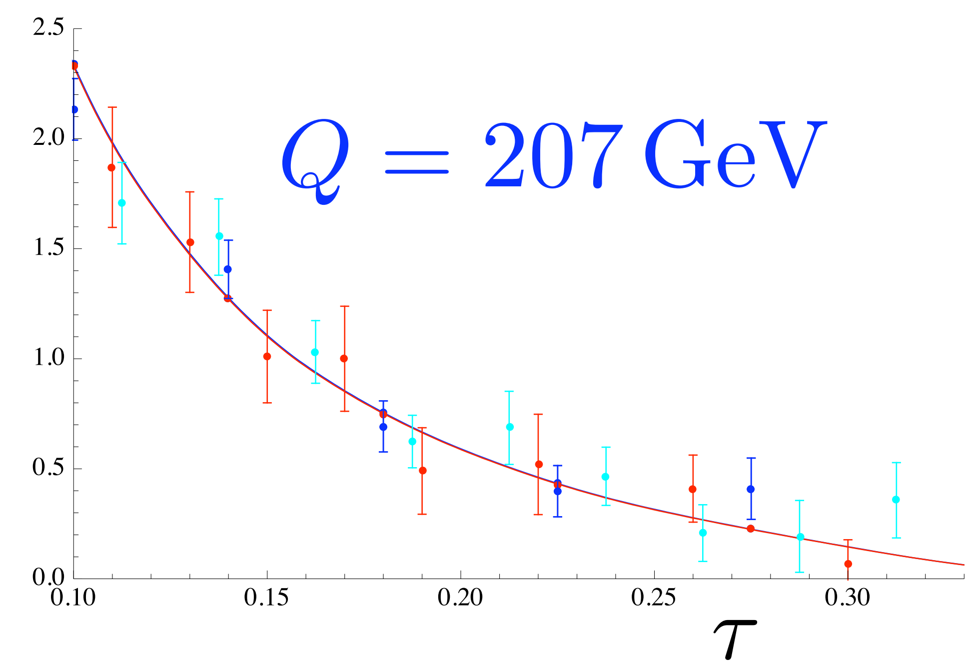


τ

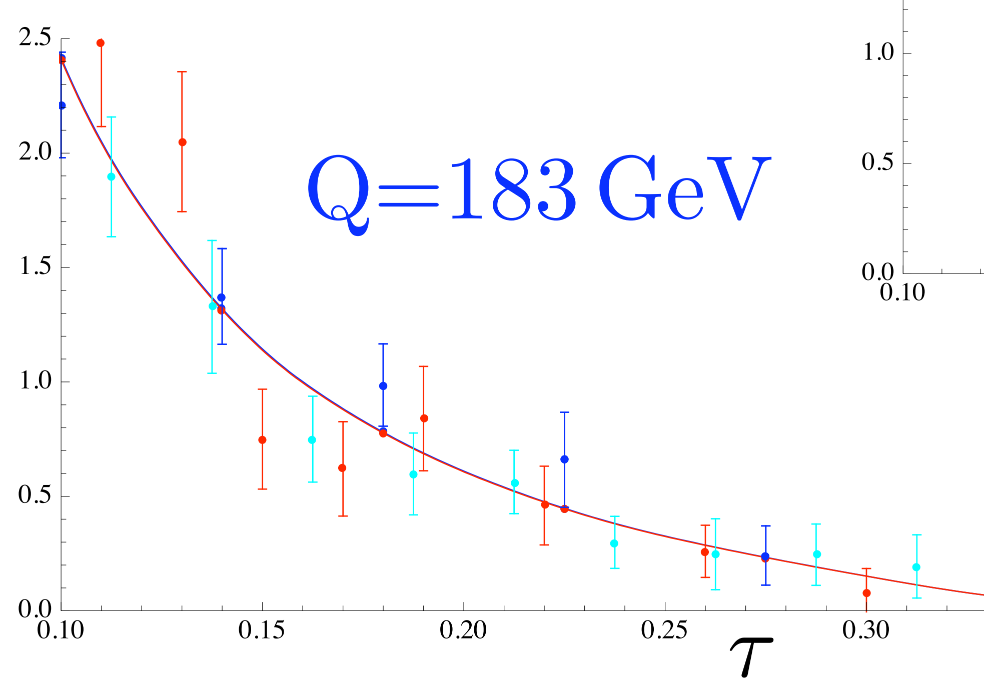
Sample Fit results:

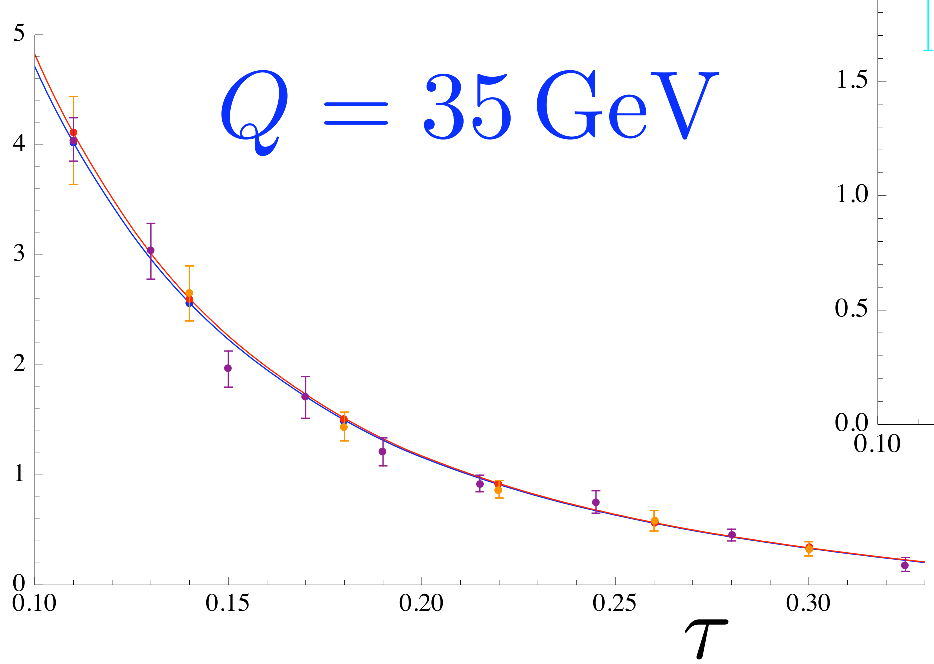
$$\frac{1}{\sigma}\frac{d\sigma}{d\tau}$$





$$\frac{1}{\sigma}\frac{d\sigma}{d\tau}$$





Here

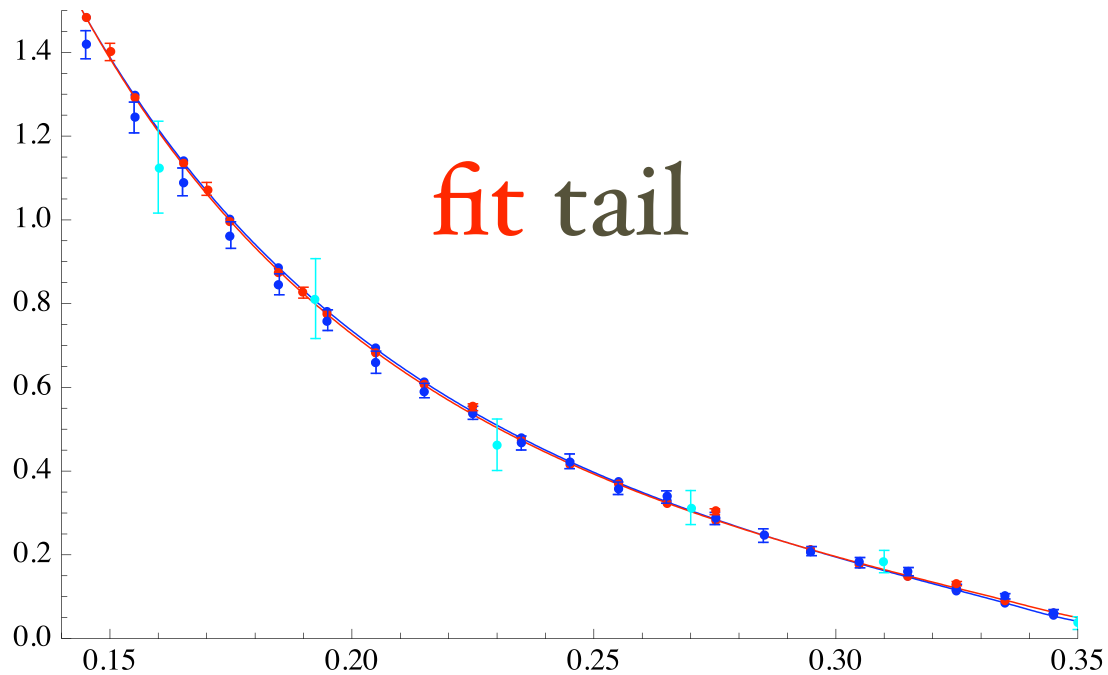
3 parameters:

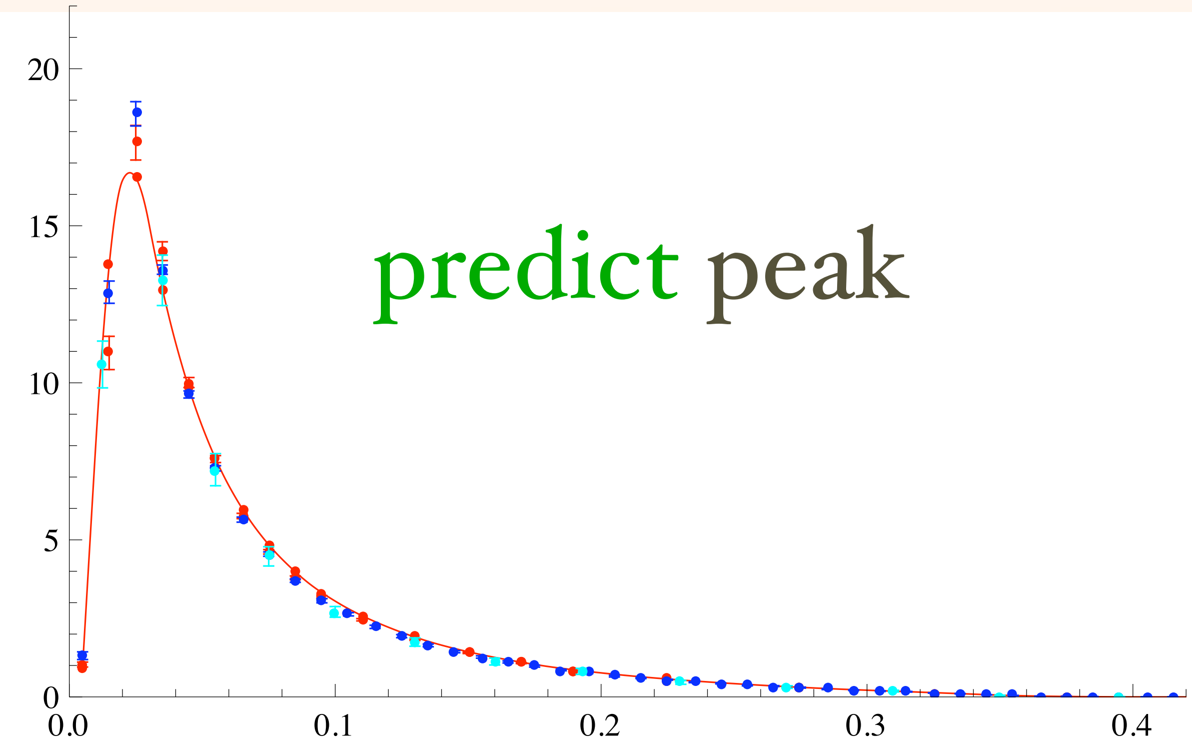
$\alpha_s(m_Z)$, Ω_1, c_2, $[\Delta_0]$

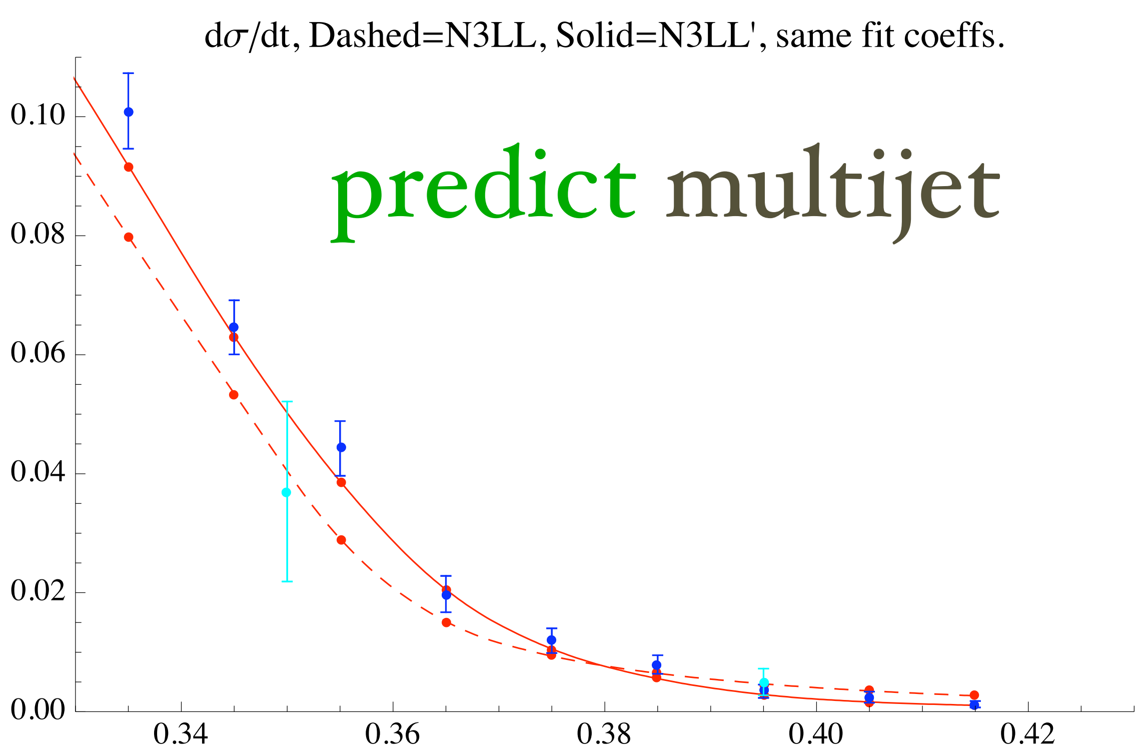
A Tail Fit

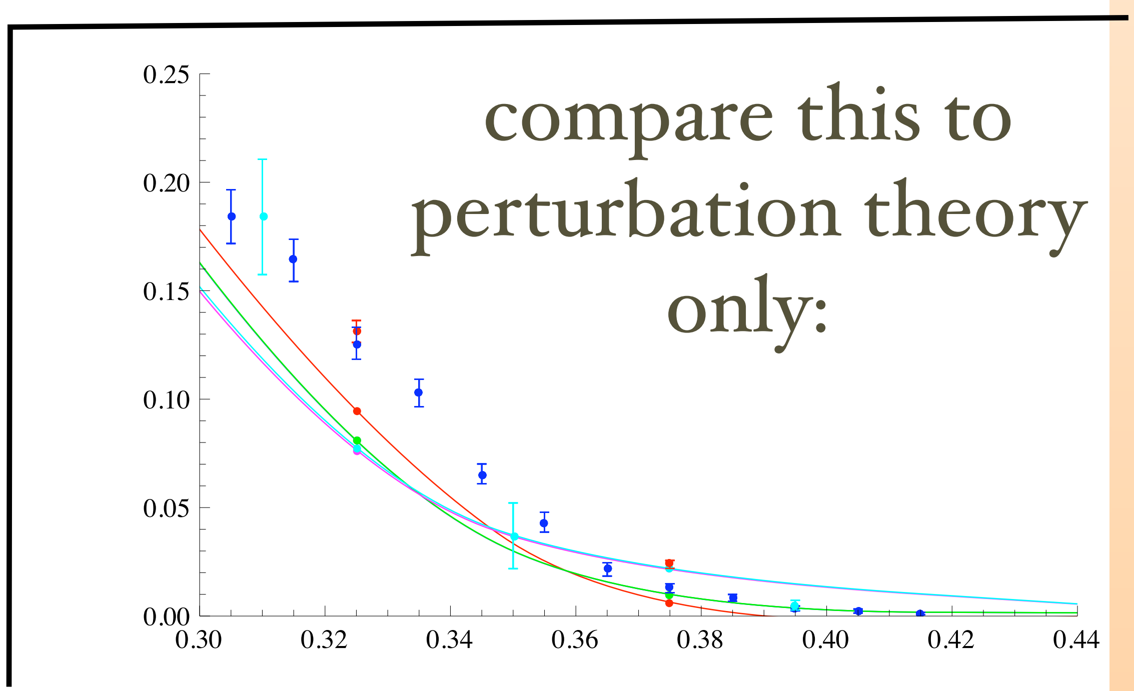
$\{\alpha_s(m_Z), \Omega_1\}$

For τ in the tail region ($Q = 91$, $\tau \in [0.09, 0.33]$, etc.) we can safely do a two parameter fit





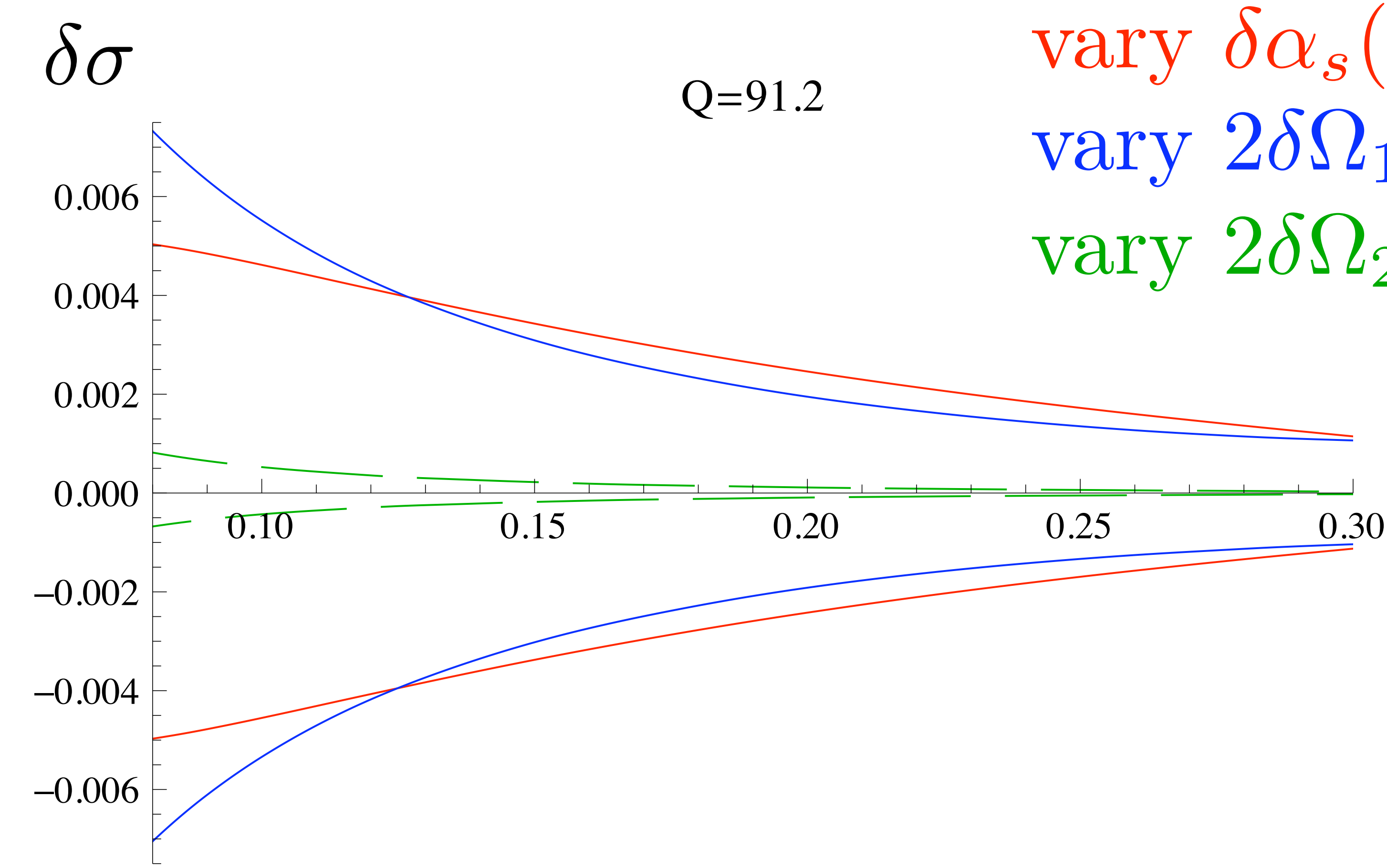




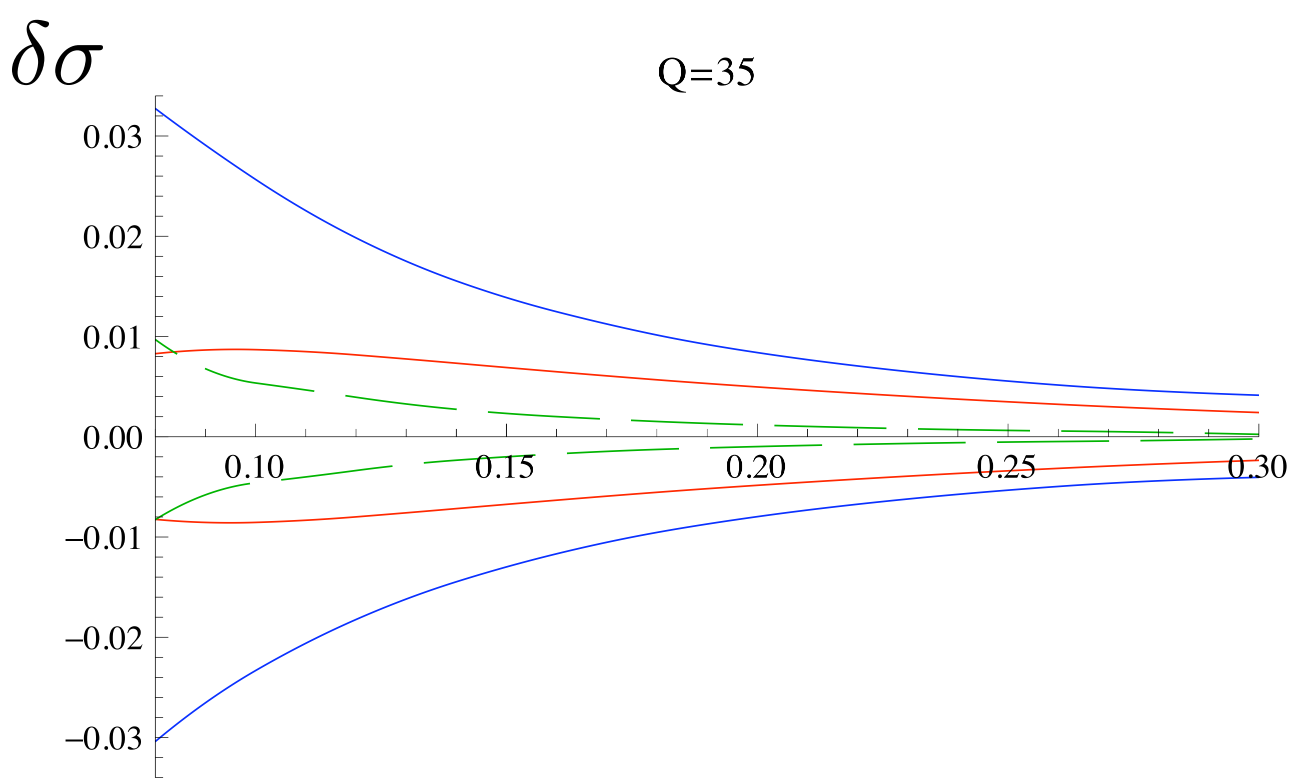
Degeneracy: $\alpha_s(m_Z)$ versus Ω_1

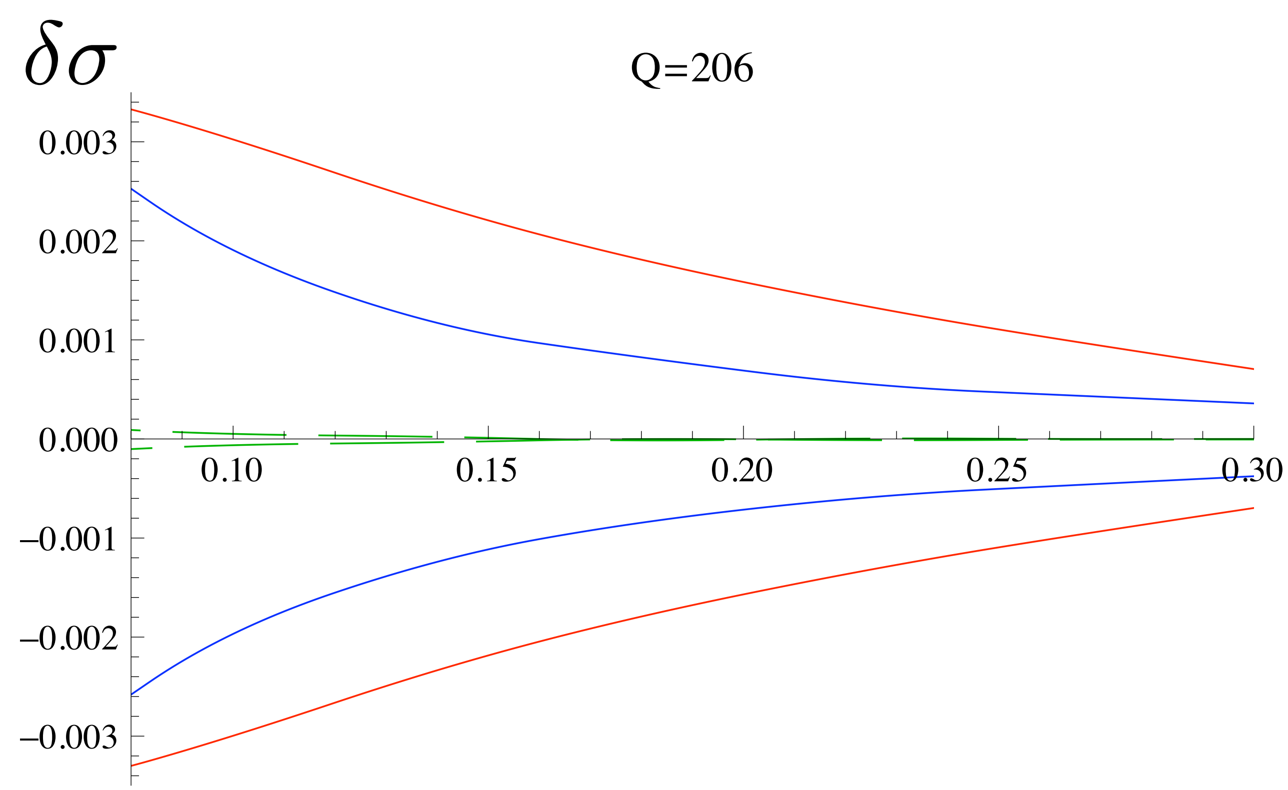
vary $\delta\alpha_s(m_Z) = \pm 0.001$
vary $2\delta\Omega_1 = \pm 0.1$
vary $2\delta\Omega_2$

} degenerate for a single Q



Resolved by fitting multiple Q's





Theory Uncertainties

Fit Uncertainties:

Statistical Error + Systematic Error
+ Hadronization ($2\Omega_1$)

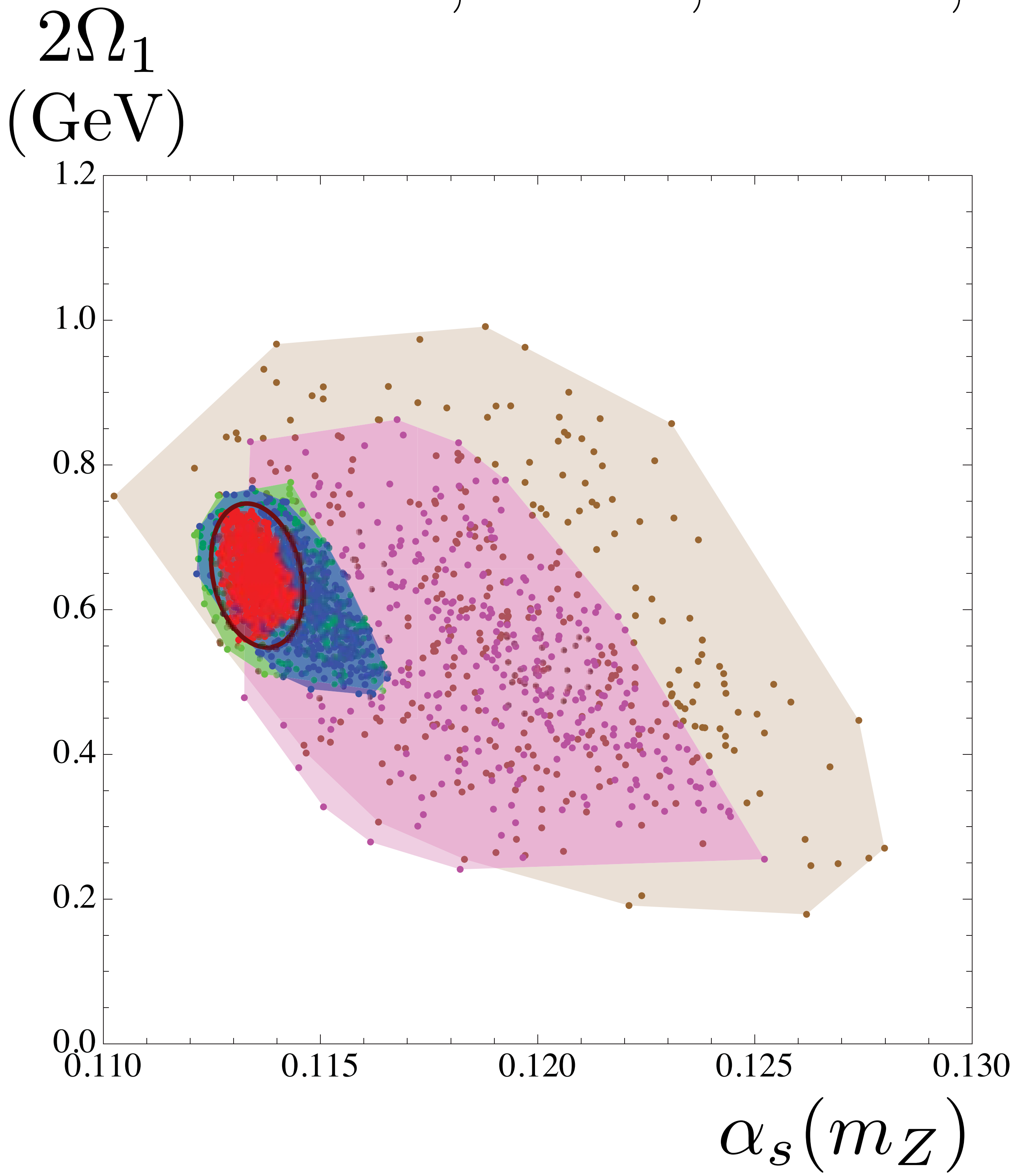
→ Error Ellipse from Fit

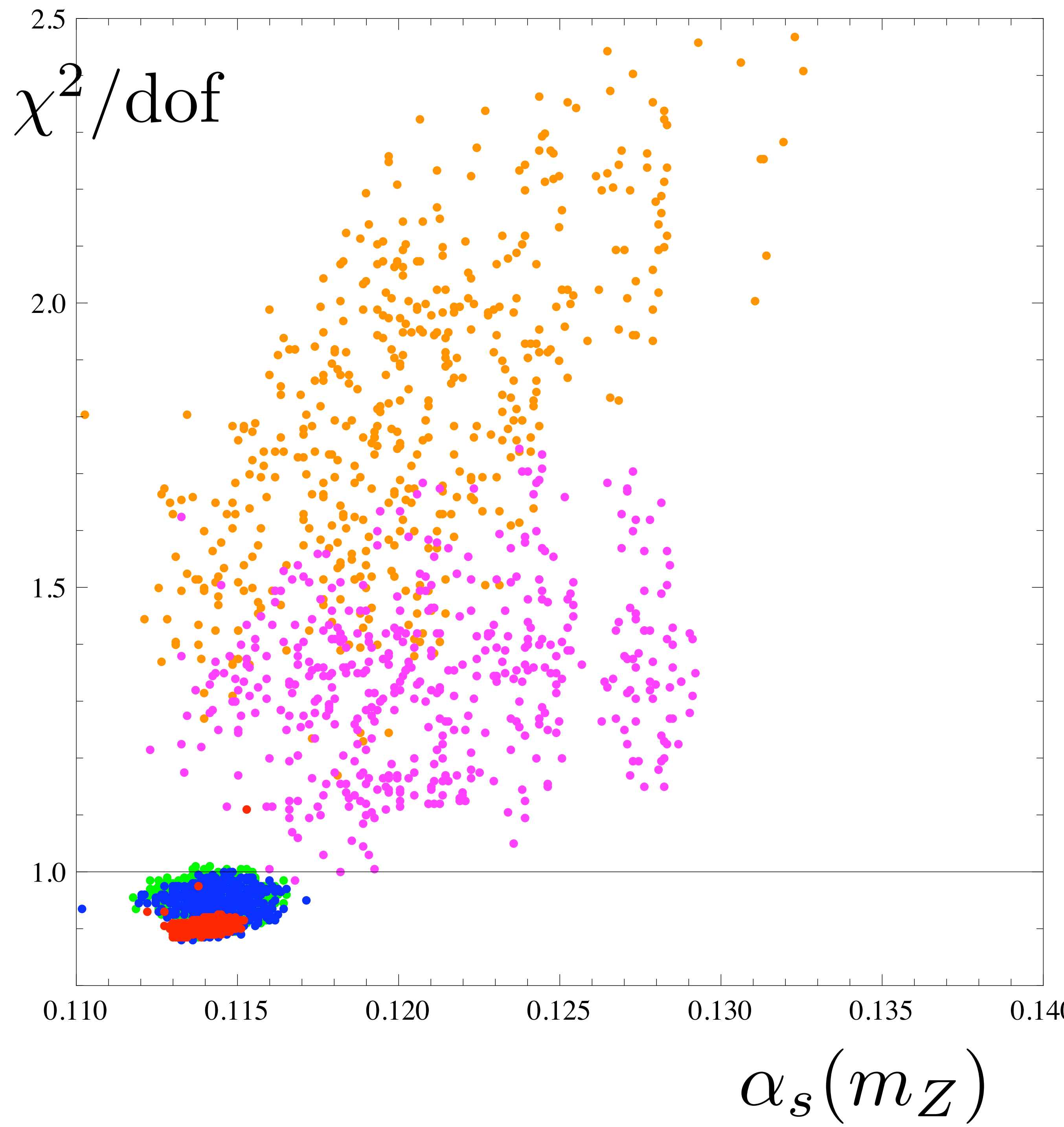
Theory Error Scan Results

μ dependence, MC theory errors, 4-loop cusp, j_3, s_3

(Perturbation Theory, Sums Logs, add F, uses renormalon free scheme)

NLL$'$, NNLL, NNLL$'$, N^{3}LL, N^{3}LL$'$

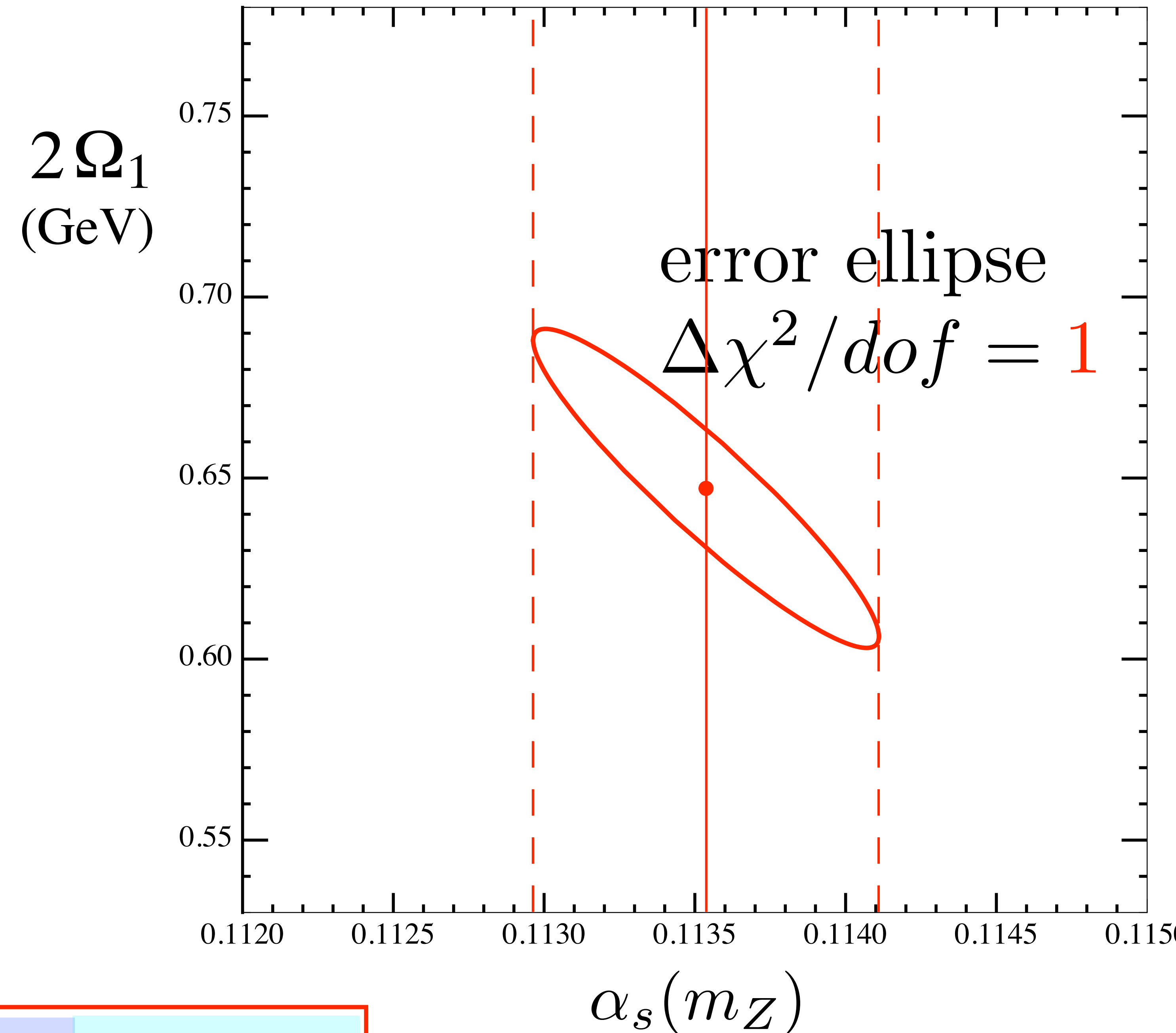




Tail Fit Result

we use LEP working group's corr. model for syst.errors:

$$\frac{\chi^2}{dof} = \frac{385.9}{433-2} = 0.895$$



$$\boxed{\alpha_s(m_Z) = 0.1135 \pm 0.0006 \;\; \pm 0.0009}$$

pert.error

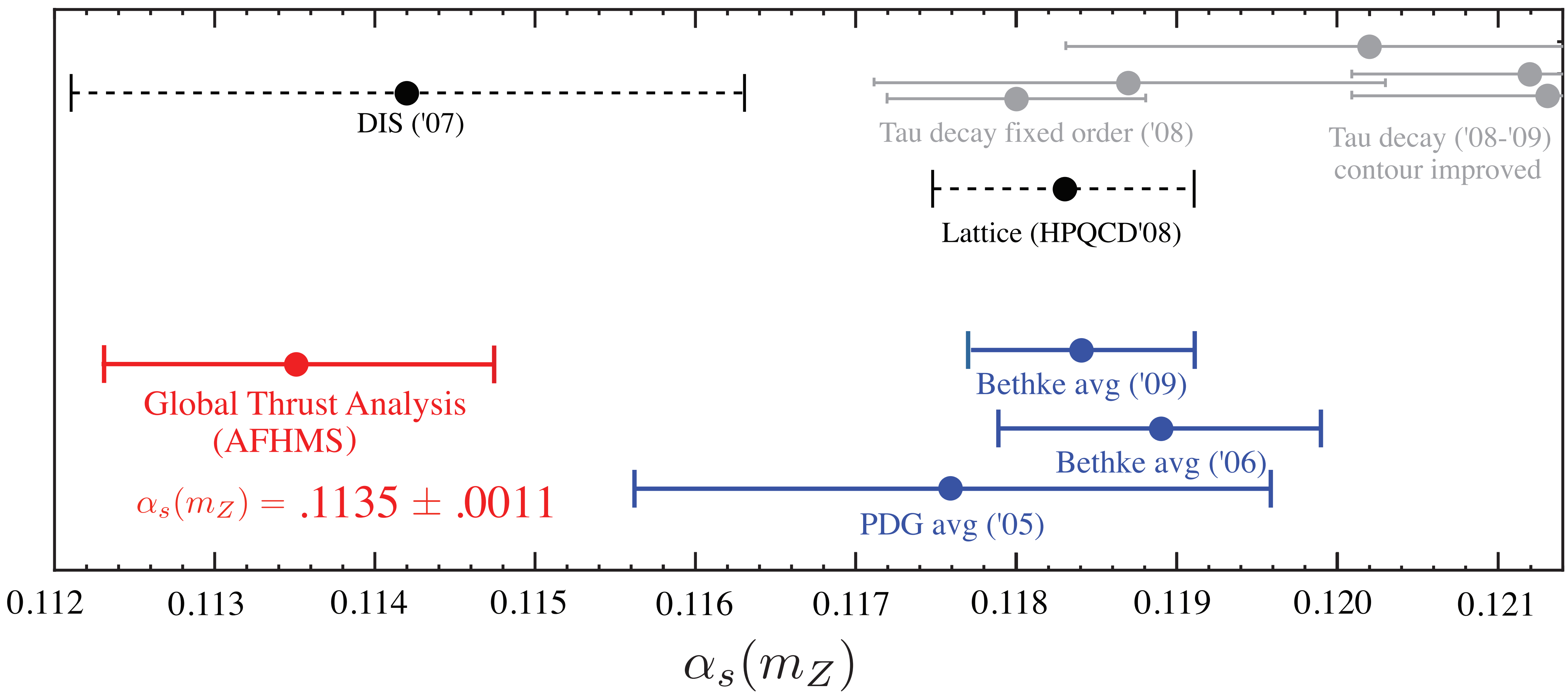
hadronization + expt. error, reduced by more than a factor of 3

comparison to

$$\alpha_s(m_Z) = 0.1172 \pm 0.0010(stat) \pm 0.0008(sys) \pm 0.0012(had) \pm 0.0012(pert)$$ Becher & Schwartz fit — resum

$$\alpha_s(m_Z) = 0.1224 \pm 0.0009(stat) \pm 0.0009(sys) \pm 0.0012(had) \pm 0.0035(theo)$$ Gehrmann, et al. — fixed order

Compare to Other Methods:



Result from jets differs by 3.5σ from the lattice result

Implications:

- Operator based treatment of nonperturbative effects can become crucial for high precision analyses.

- Factorization allows fixed order results, large logs, perturbative and nonperturbative soft physics to be treated rigorously and simultaneously.

$$m_t$$

Motivation

- The top mass is a fundamental parameter of the Standard Model

$$m_t = 173.1 \pm 0.6_{\rm stat} \ \pm 1.1_{\rm syst}\,{\rm GeV}$$

(a 0.8% error)
(theory error?
what mass is it?)

- Important for precision e.w. constraints

eg. $m_H = 76^{+33}_{-24}\,{\rm GeV}$ $\quad 76 \to 87$ $\qquad m_H < 182\,{\rm GeV}$ $\quad 182 \to 209$ $\qquad$ (95% CL)

A $2\,{\rm GeV}$ shift in m_t changes the central values by 15%

- Top Yukawa coupling is large. Top parameters are important for analyzing many new physics models. (eg. Higgs masses in MSSM)

- Top is very unstable, it decays before it has a chance to hadronize. This provides an intrinsic smearing for jet observables.

Top provides playground for future analysis of new short lived strongly interacting particles.

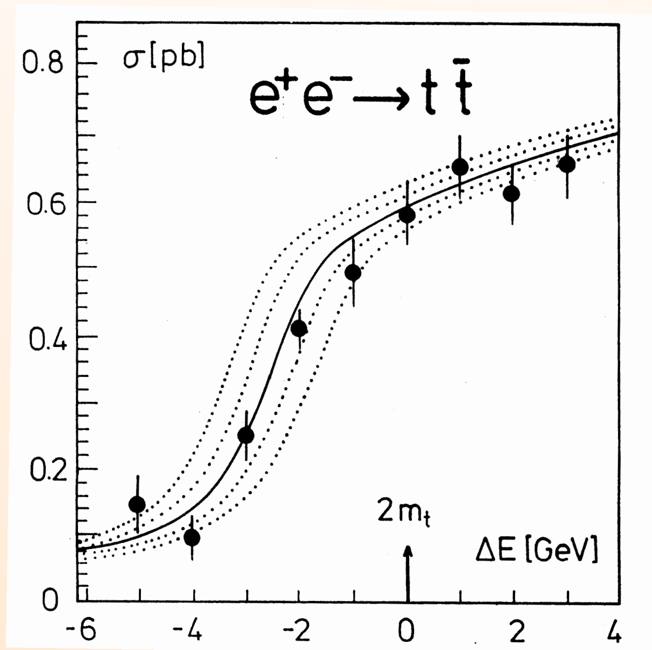
$\Gamma_t = 1.5\,{\rm GeV}$

from $\quad t \to bW$

Threshold Scan $e^+e^- \to t\bar{t}$ the classic ILC method

$$\sqrt{s} \simeq 350\,\mathrm{GeV}$$

- ▷ count number of $t\bar{t}$ events
- ▷ color singlet state
- ▷ background is non-resonant
- ▷ physics well understood
  (renormalons, summations)



Precision Theory meets precision experiment:

$\to \delta m_t^{\mathrm{exp}} \simeq 50$ MeV

$\to \delta m_t^{\mathrm{th}} \simeq 100$ MeV

(“peak” position)

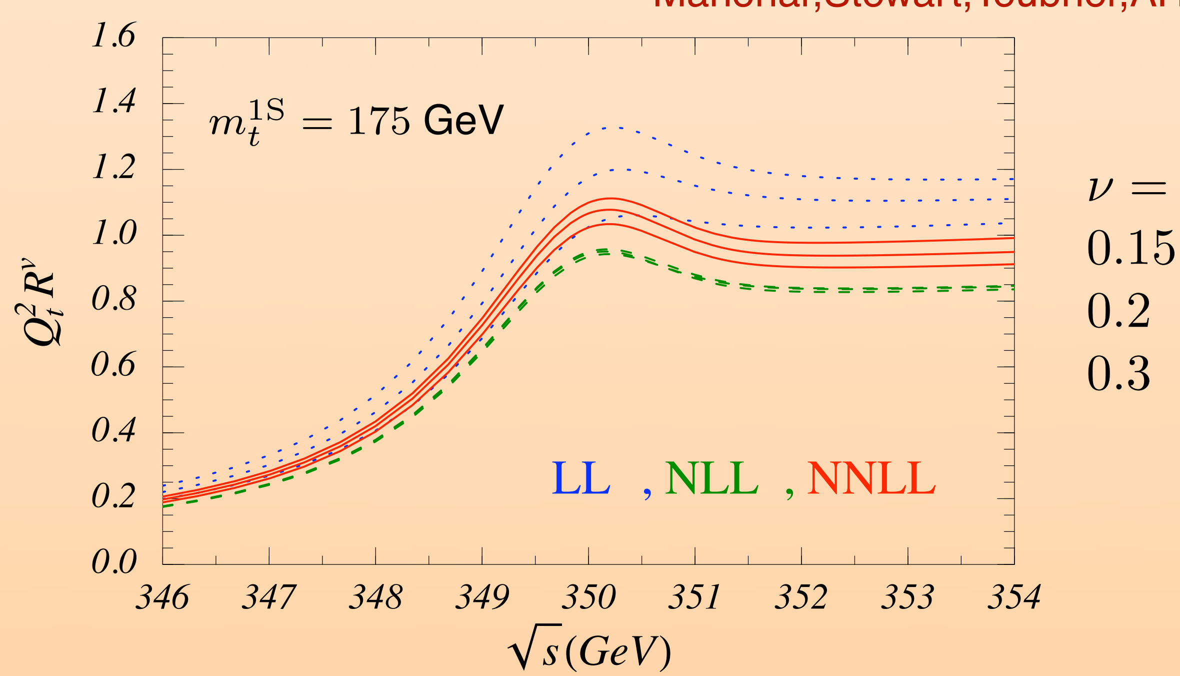
Teubner,AH; Melnikov, Yelkovski;Yakovlev; Beneke,Signer,Smirnov; Sumino, Kiyo

- Measure a short-distance top-quark mass, like m_t^{1S} NOT the top pole mass.

- Have smearing by ISR and beamstrahlung, which must be controlled precisely

1S mass - RG-improved, with NNLL non-mixing terms

Manohar,Stewart,Teubner,AH



Tevatron or LHC:

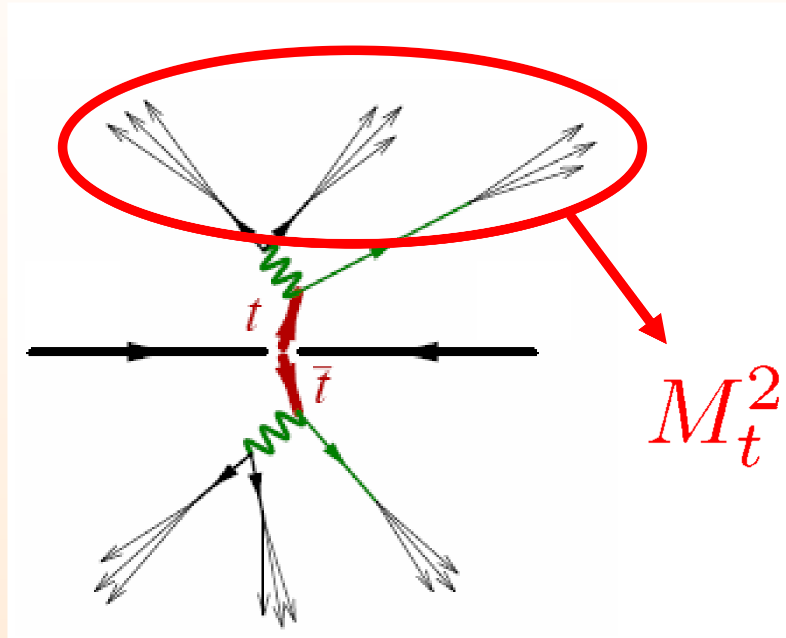
$$pp \xrightarrow{\sigma} t\bar{t}X$$

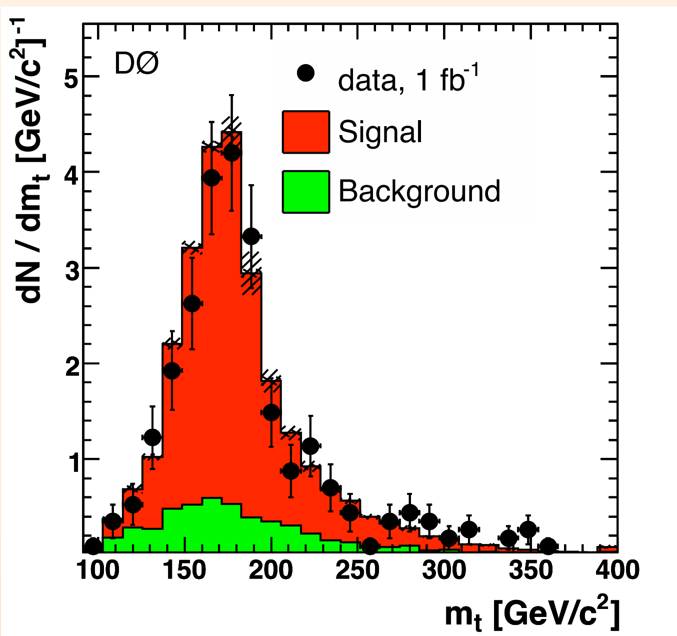
Γ

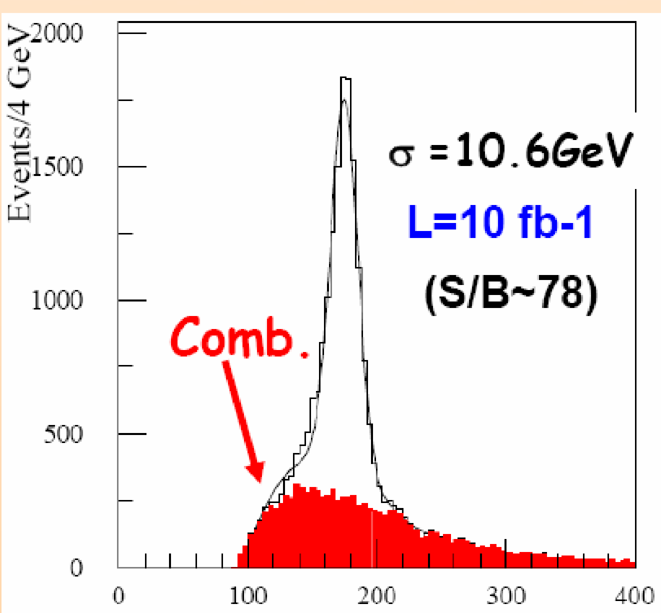
$\bar{b}W \to q\bar{q}'$

$bW \to e^+\nu$

Reconstruction methods (matrix element, template)







ATLAS (l+jets)

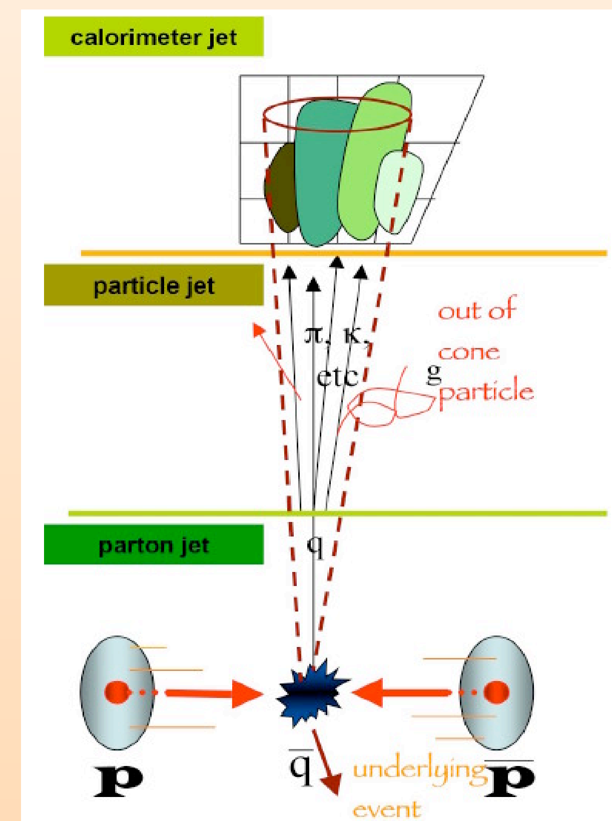
Theory input is Monte Carlo.

So measured top mass is the one in the MC, a "Pythia mass".

Look at factorization for

$$e^+e^- \to t\bar{t}X$$

$$Q \gg m_t \gg \Gamma_t$$



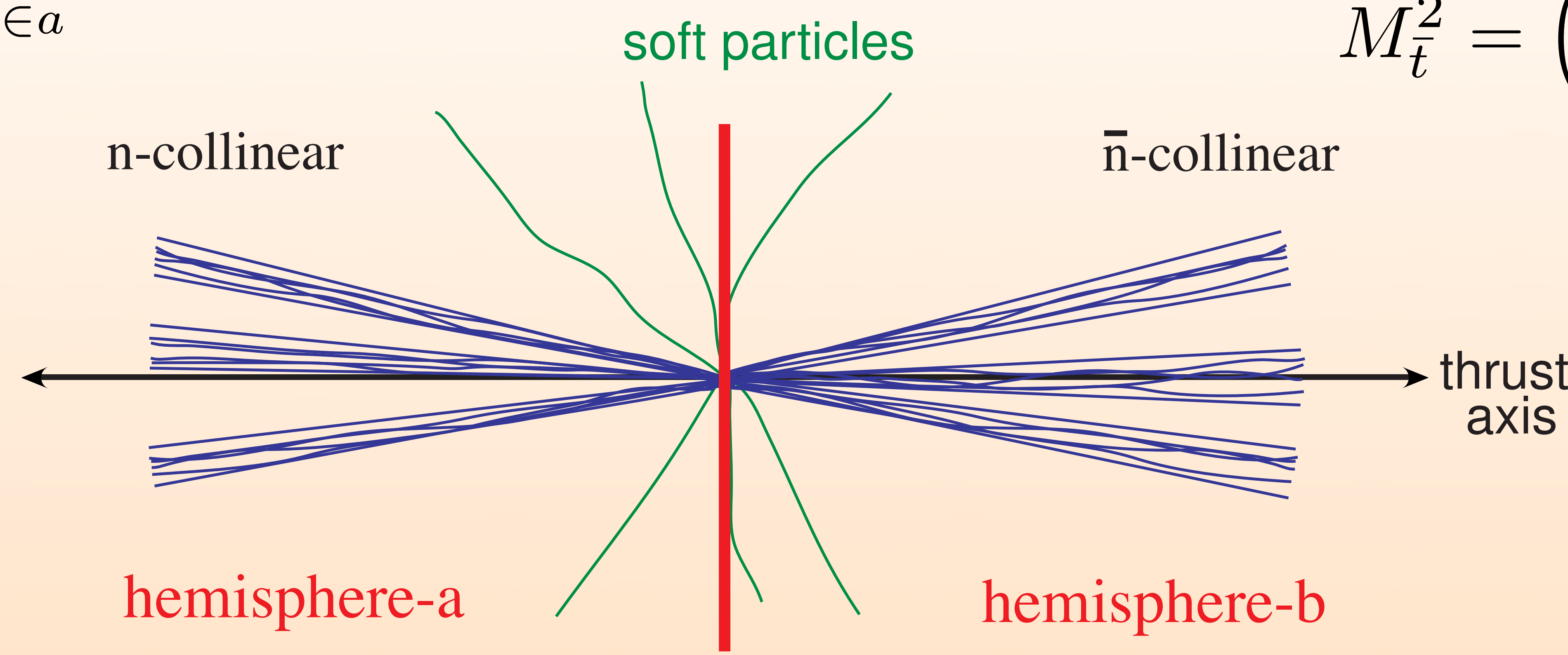
Hemisphere Invariant Masses

$$\frac{d^2\sigma}{dM_t^2\, dM_{\bar{t}}^2}$$

$$e^+e^- \to t\bar{t}X$$

$$M_t^2 = \Big(\sum_{i\in a} p_i^\mu\Big)^2$$

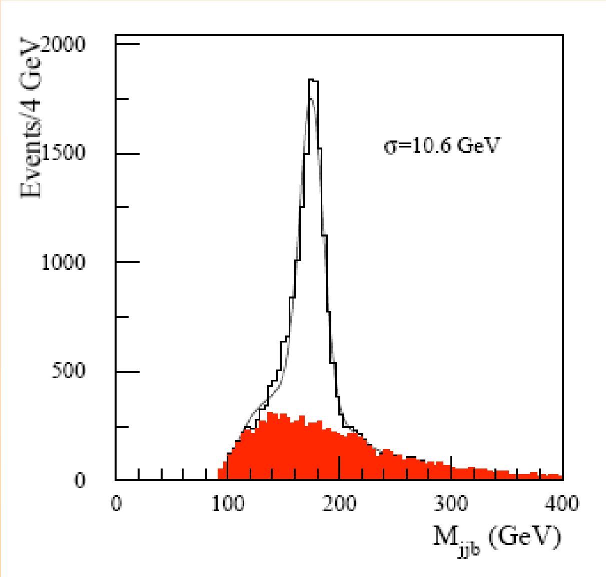
$$M_{\bar{t}}^2 = \Big(\sum_{i\in b} p_i^\mu\Big)^2$$



Peak region:

$$\boxed{\hat{s}_t \equiv \frac{M_t^2 - m^2}{m} \sim \Gamma \ll m}$$

Breit Wigner: $\left(\frac{\Gamma}{m}\right) \frac{1}{\hat{s}_t^2 + \Gamma^2}$



$$Q \gg m \gg \Gamma \sim \hat{s}_{t,\bar{t}}$$

Disparate Scales → Effective Field Theory

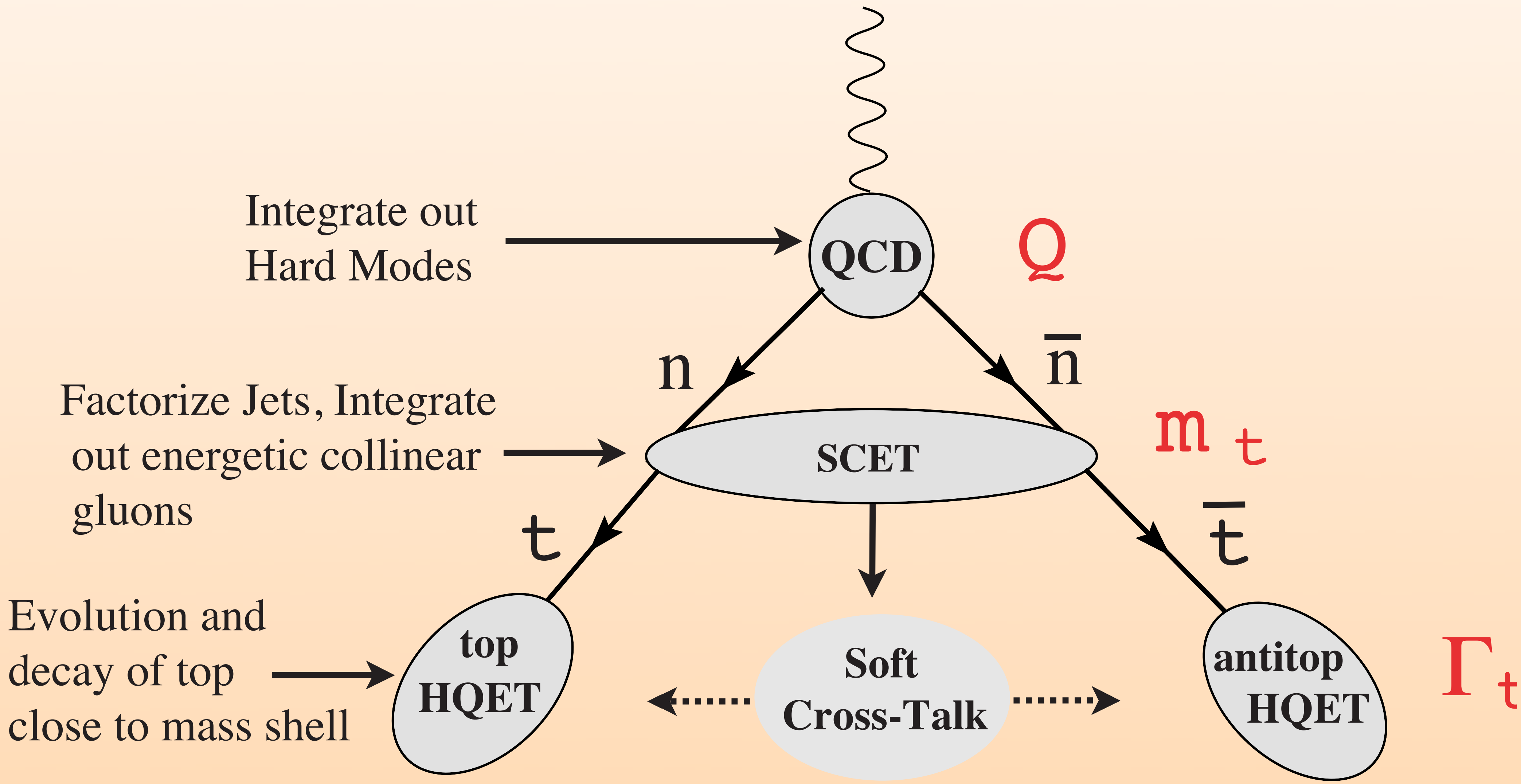
QCD

↓

SCET

↓

HQET



Factorization Theorem:

Fleming, Hoang, Mantry, I.S.

Hard Production modes integrated out

“Hard” collinear gluons integrated out

Answer

$$\left(\frac{d^2\sigma}{dM_t^2\, dM_{\bar t}^2}\right)_{\text{hemi}} = \sigma_0\, H_Q(Q,\mu_m) H_m\left(m, \frac{Q}{m}, \mu_m, \mu\right) \times \int_{-\infty}^{\infty} d\ell^+ d\ell^-\; B_+\left(\hat s_t - \frac{Q\ell^+}{m}, \Gamma, \mu\right) B_-\left(\hat s_{\bar t} - \frac{Q\ell^-}{m}, \Gamma, \mu\right) S_{\text{hemi}}(\ell^+, \ell^-, \mu).$$

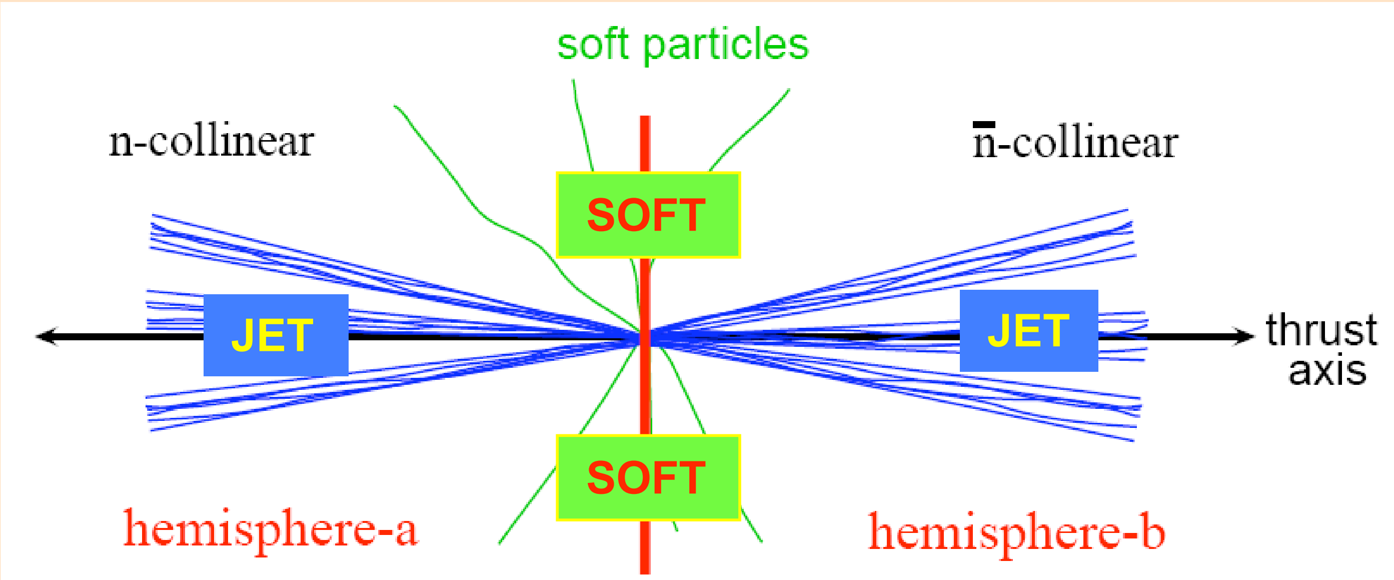
A useful event shape for massive unstable particles

Jet Functions

Evolution and decay of top quark close to mass shell

Soft Function

Non-perturbative Cross talk



Measurement Implications

$$\left(\frac{d^2\sigma}{dM_t^2\, dM_{\bar t}^2}\right)_{\rm hemi} = \sigma_0\, H_Q(Q,\mu_m) H_m\Big(m, \frac{Q}{m}, \mu_m, \mu\Big) \times \int_{-\infty}^{\infty} d\ell^+ d\ell^-\, B_+\Big(\hat s_t - \frac{Q\ell^+}{m}, \Gamma, \mu\Big)\, B_-\Big(\hat s_{\bar t} - \frac{Q\ell^-}{m}, \Gamma, \mu\Big)\, S_{\rm hemi}(\ell^+, \ell^-, \mu).$$

Answer

$$M^{\rm peak} = m_t + \Gamma_t(\alpha_s + \alpha_s^2 + \ldots) + \frac{Q\Lambda_{\rm QCD}}{m_t}$$

measure this

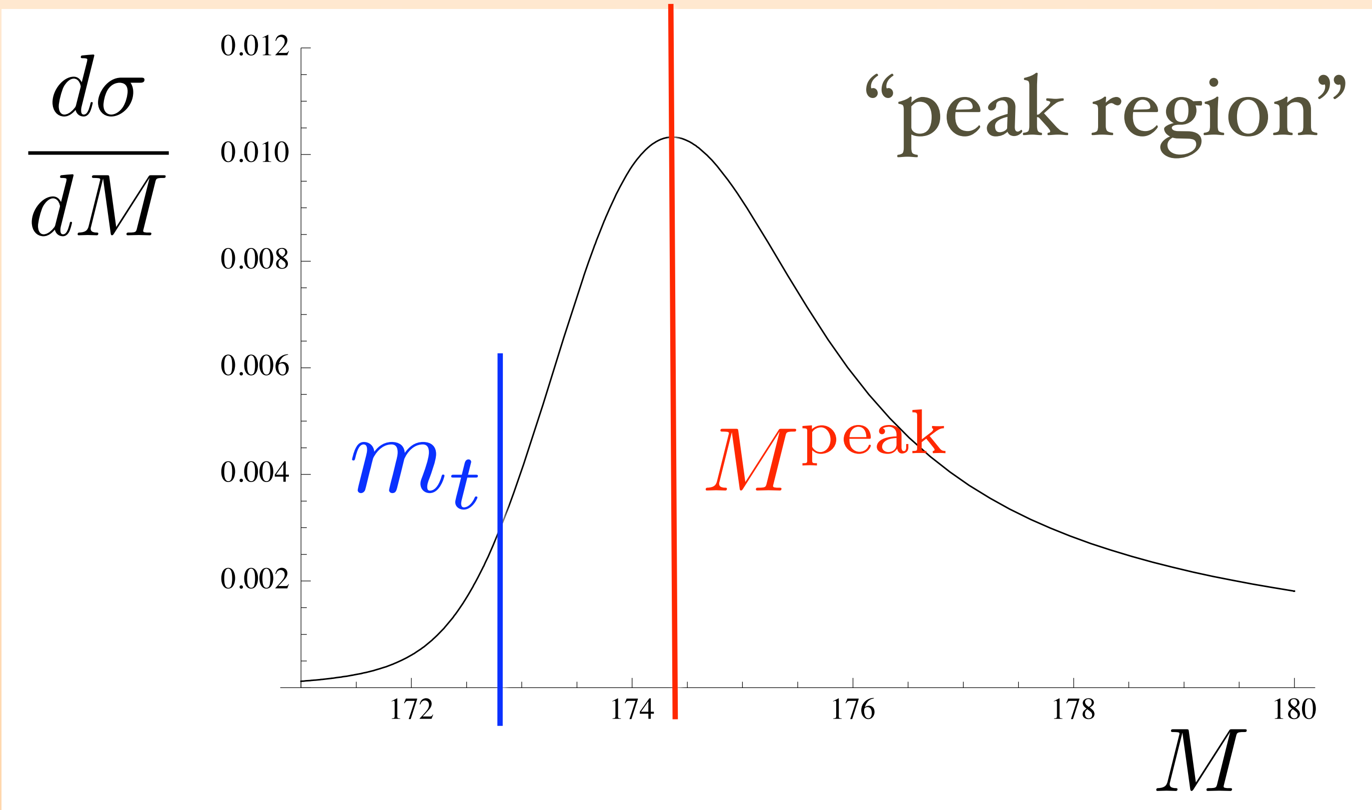
extract this

compute this

soft radiation shifts the measured mass

$\frac{Q\Lambda_{\rm QCD}}{m_t}$ is predominantly $\frac{Q\Omega_1}{m_t}$!

Ω_1 is known to 10% from fit in part I



Mass Schemes for Jets

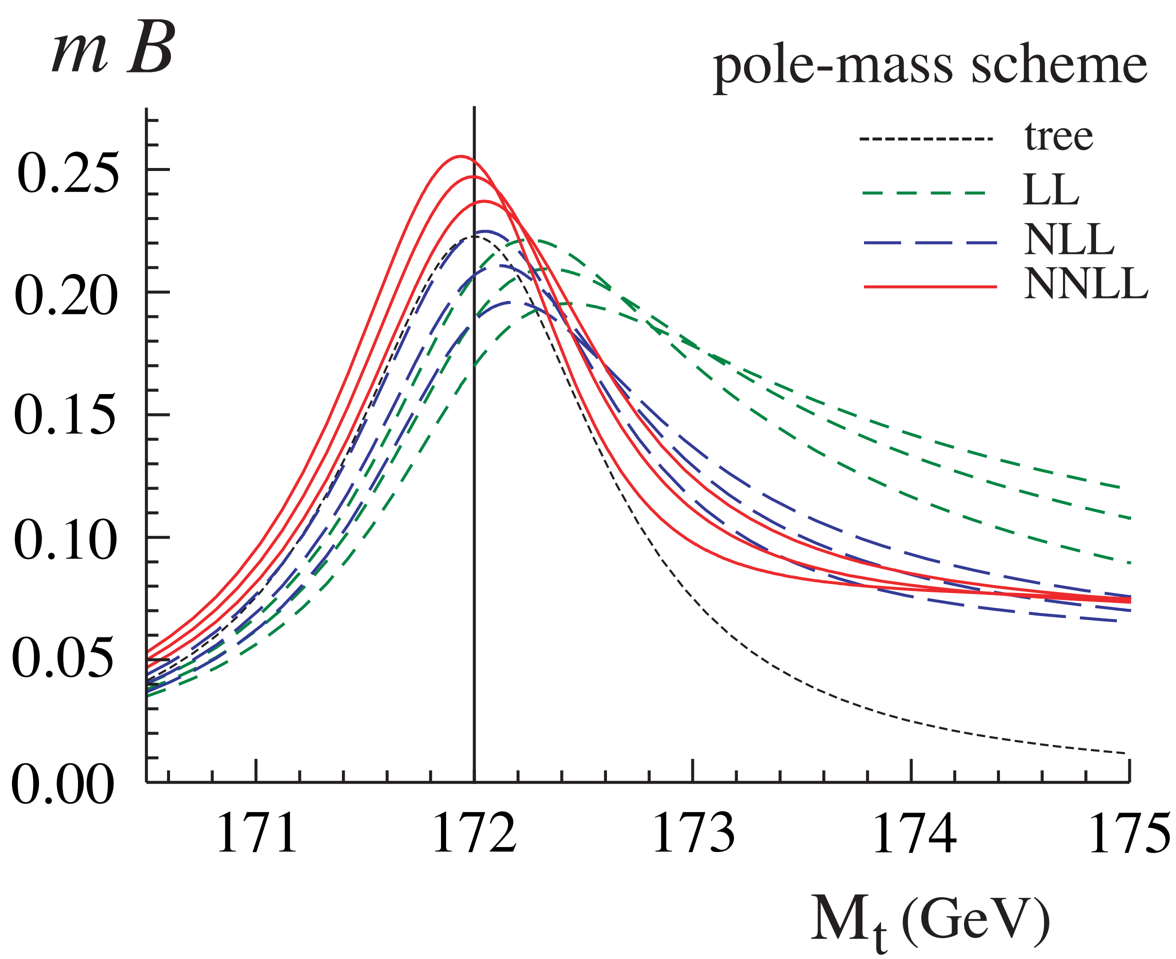
- top $\overline{\text{MS}}$ mass? Can not be treated consistently with Breit-Wigner for decay products
- pole mass? Breit-Wigner is fine, but has renormalon problem (instability)
- top jet mass Breit-Wigner is fine & no renormalon

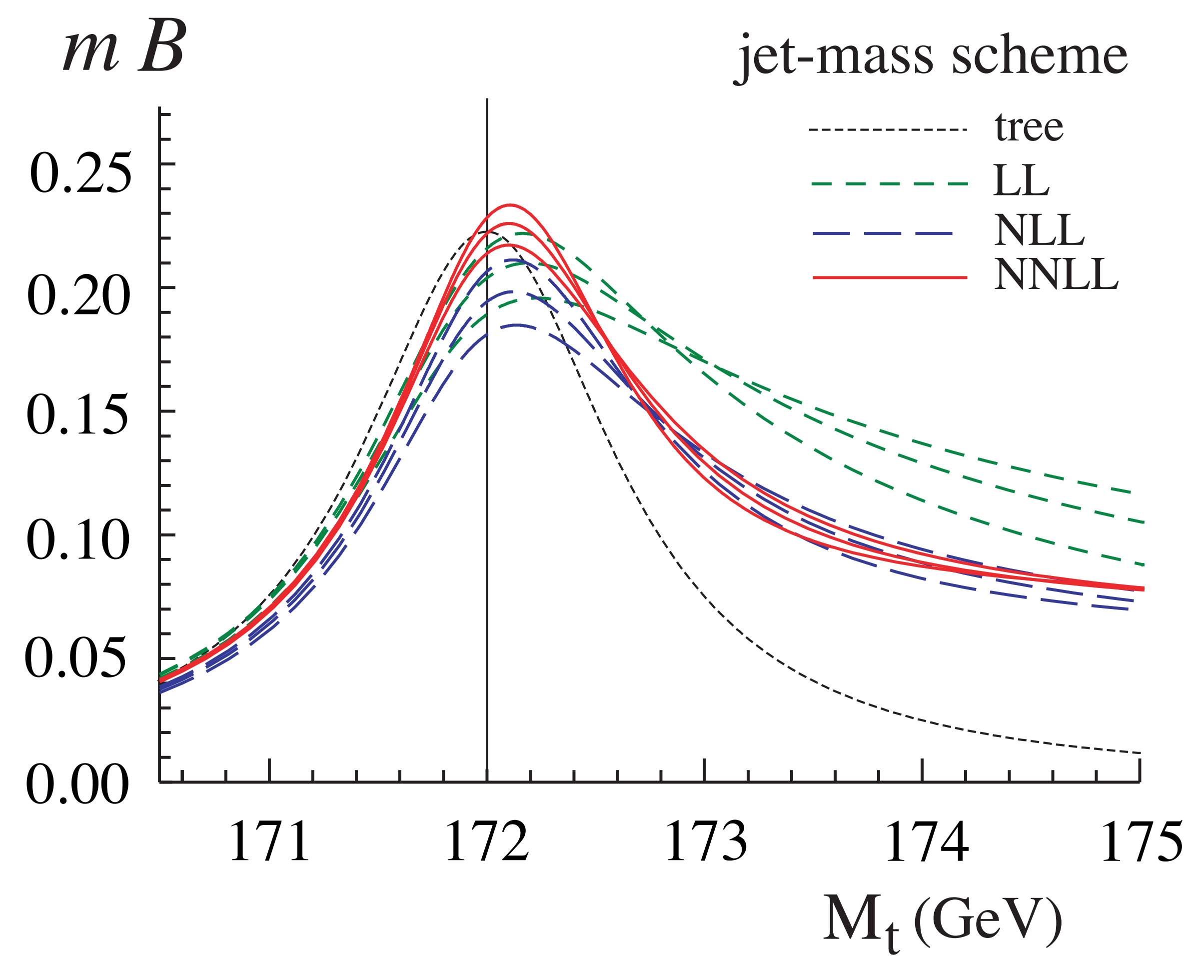
Good!

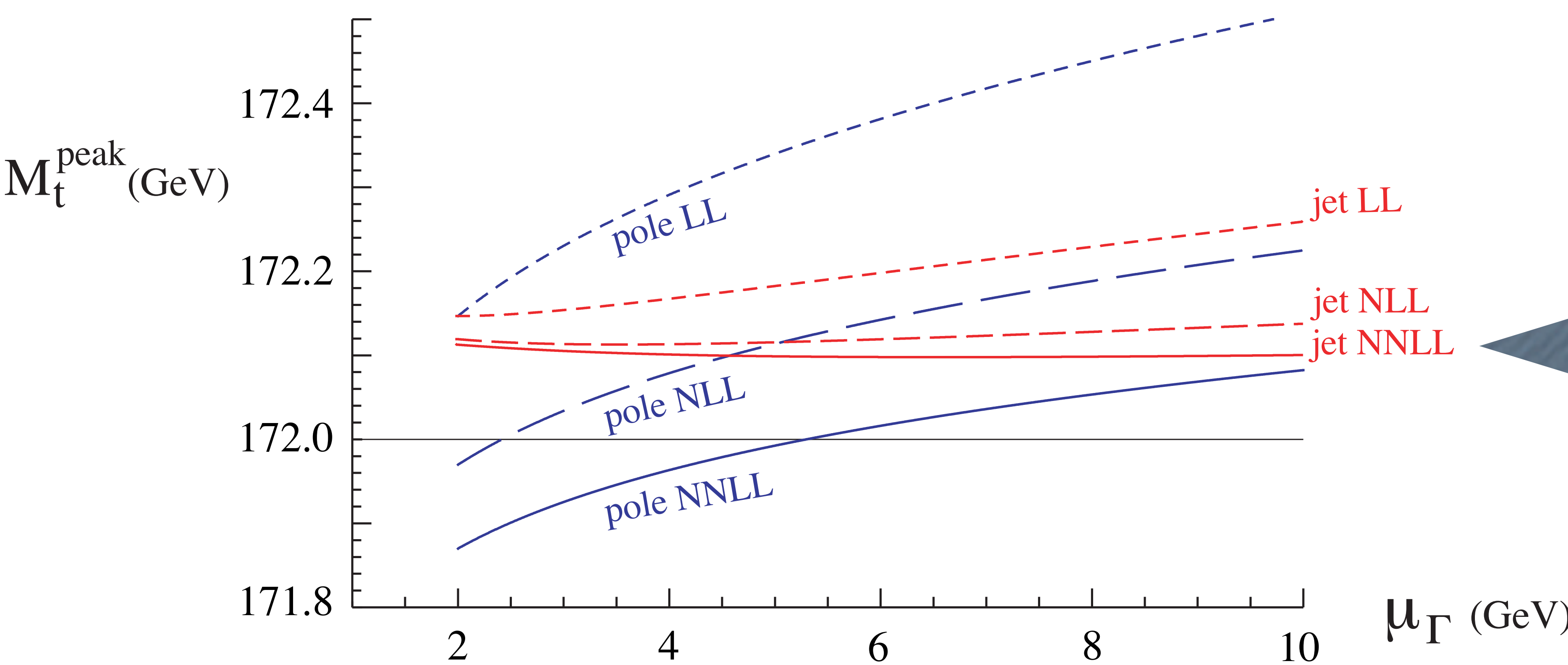
Uses heavy quark jet function B to define a mass scheme.

$$m^{\text{pole}} - m_t^{\text{jet}} \sim \alpha_s \Gamma$$

Jet Function Results up to NNLL: (3 curves vary μ_Γ)







very stable perturbative peak!

Jain, Scimemi, I.S.

Implications:

$$M^{\mathrm{peak}} = m_t + \Gamma_t(\alpha_s + \alpha_s^2 + \ldots) + \frac{Q\Lambda_{\mathrm{QCD}}}{m_t}$$

scheme independent

scheme dependent

scheme dependent

- good mass scheme gives convergent perturbative series, and involves a suitable subtraction scale $R \sim \Gamma_t$ (like the jet mass)
- The definition of nonperturbative parameters is not independent from the perturbative corrections. A cutoff scale R divides contributions between perturbative and nonperturbative.
- The factorization theorem exhibits good behavior if these two cutoff scales R are the same, or related in a fixed way.

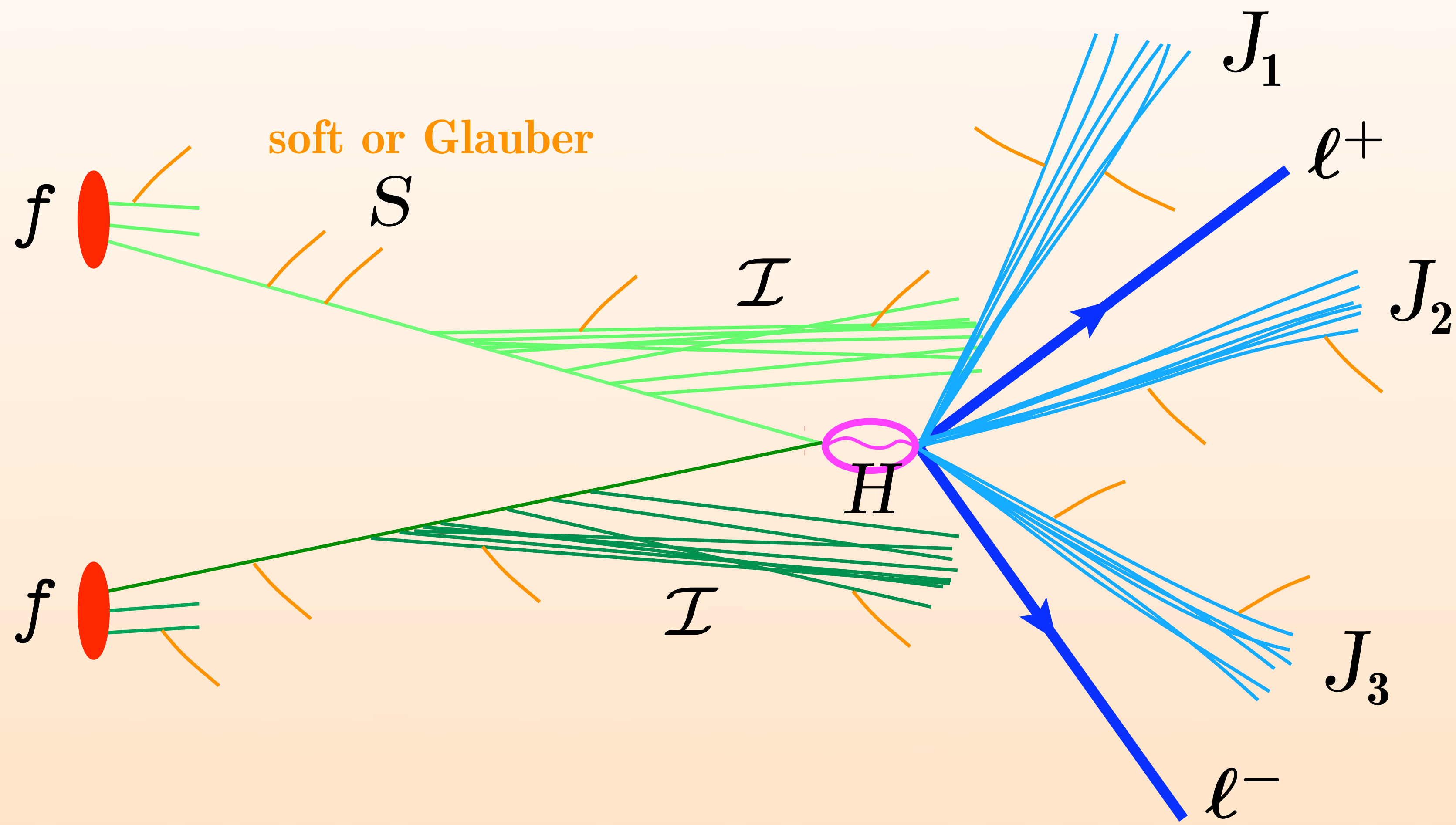
- In MC the analog of the second R is the shower cutoff.

- One can estimate the perturbative scheme uncertainty of the Pythia mass by varying $R = 1\text{–}9\,\mathrm{GeV}$

$$m_t(R) = 172.6 \pm 1.4\,\mathrm{GeV} \Rightarrow \overline{m}_t(\overline{m}_t) = 163.0 \pm 1.3\,{}^{+0.6}_{-0.3}\,\mathrm{GeV}$$

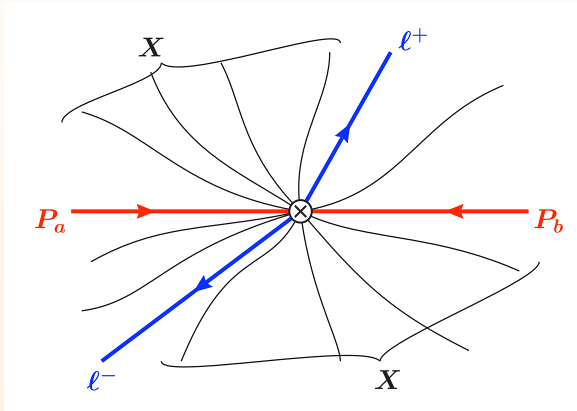
- However it is not so easy to estimate the dependence of the "Pythia mass" on the hadronization model or underlying event model in the MC, which are analogs of the $Q\Lambda_{\mathrm{QCD}}/m_t$ term. If this correction in the MC depends on the energy of the tops then it will cause a systematic shift between the "LHC top-mass" and the "Tevatron top-mass".

Extension of "advanced" Factorization theorems to the full hadron collider environment?



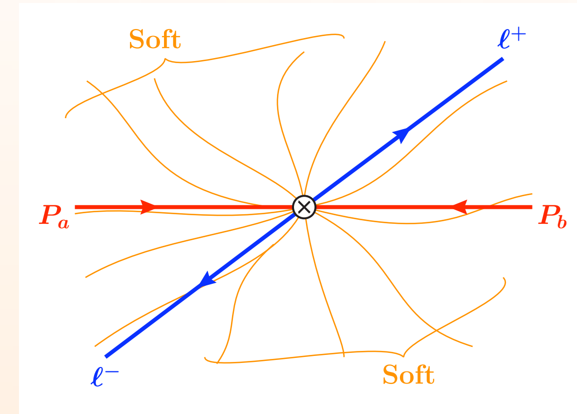
Threshold Factorization

restrict available energy for the hadrons so they become "soft"



inclusive

$$H^{\mathrm{incl}} \to H^{\mathrm{thr}} S^{\mathrm{thr}}$$



threshold

This limit captures the most singular terms: in the cross-section. Often they are numerically important. The factorization can be used to sum large logs.

$$\frac{\alpha_s^j \ln^k z}{z}$$

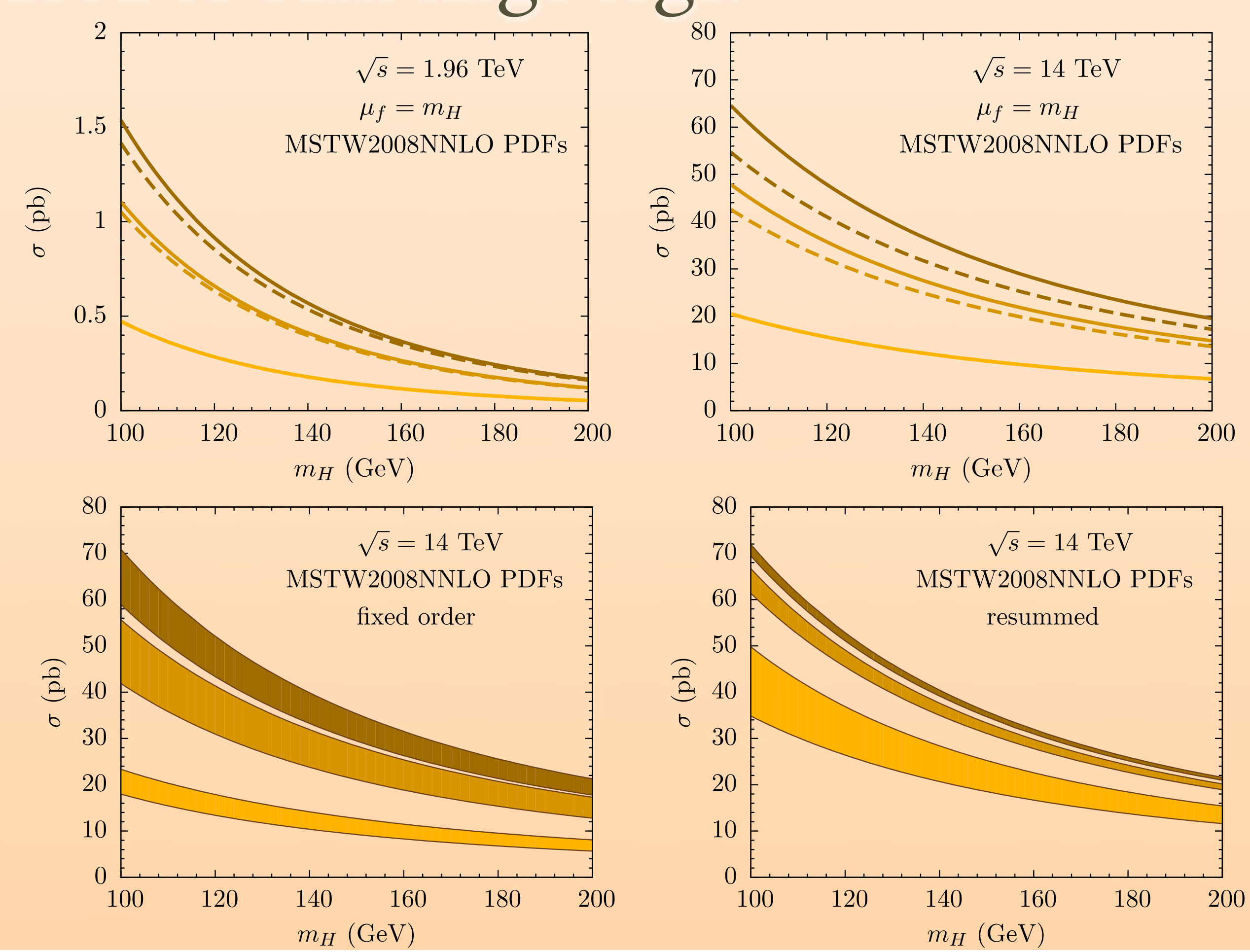
eg. $pp \to H X$

NNLO & N^3LL-singular

$(C_A \pi \alpha_s)^n$

Catani et al'03; Moch,Vogt'05; Idilbi et al '05; Ravindran et al'06; Pak et al. '09

Ahrens et al. (arXiv:0912.3375)



Threshold Factorization

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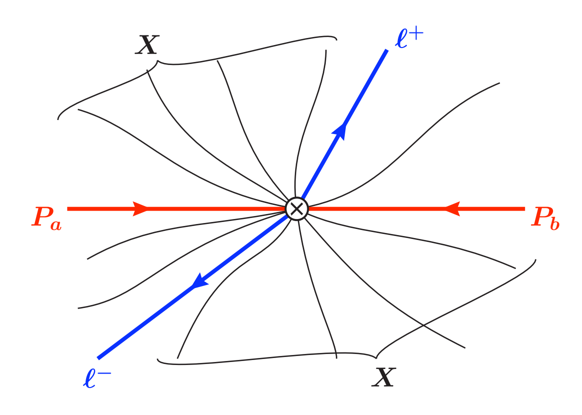
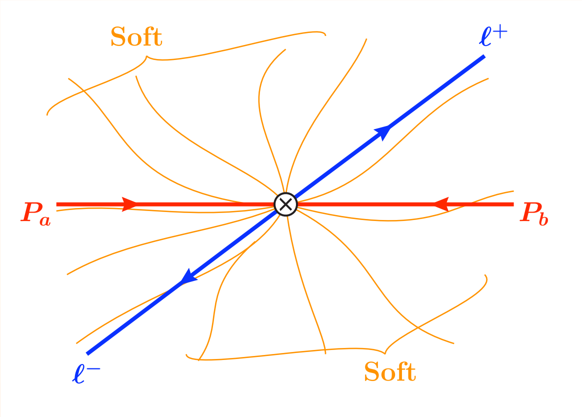


inclusive

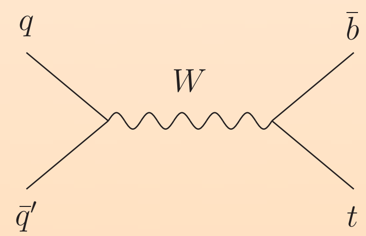
$$H^{\mathrm{incl}} \to H^{\mathrm{thr}} S^{\mathrm{thr}}$$



threshold

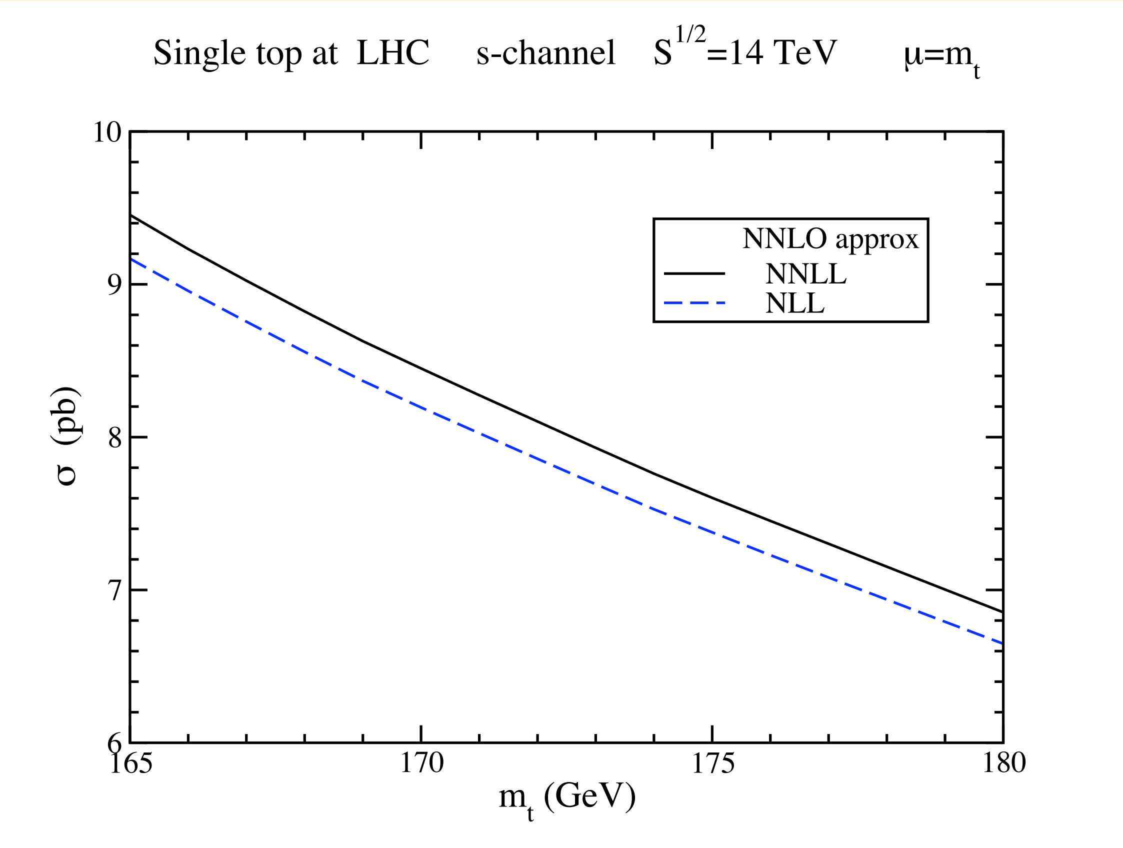
This limit captures the most singular terms: $\dfrac{\alpha_s^j \ln^k z}{z}$ in the cross-section. Often they are numerically important. The factorization can be used to sum large logs.

eg. s-channel single top



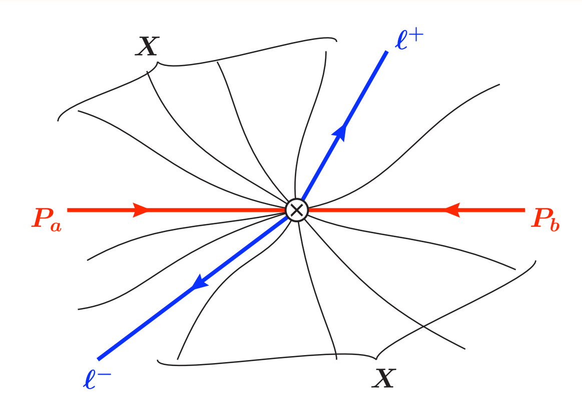
to NNLO for most singular terms

Kidonakis (arXiv:1001.5034)



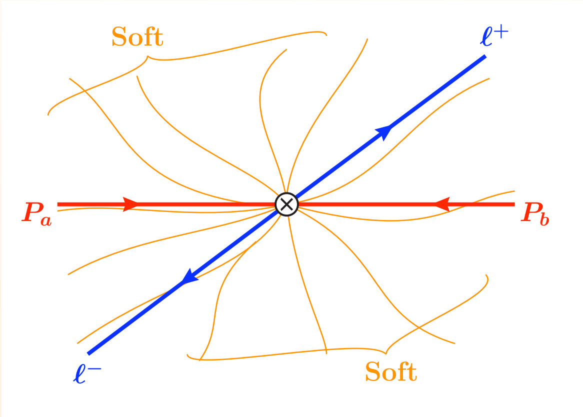
Threshold Factorization

restrict available energy for the hadrons so they become "soft"



inclusive

$$H^{\rm incl} \rightarrow H^{\rm thr} S^{\rm thr}$$



threshold

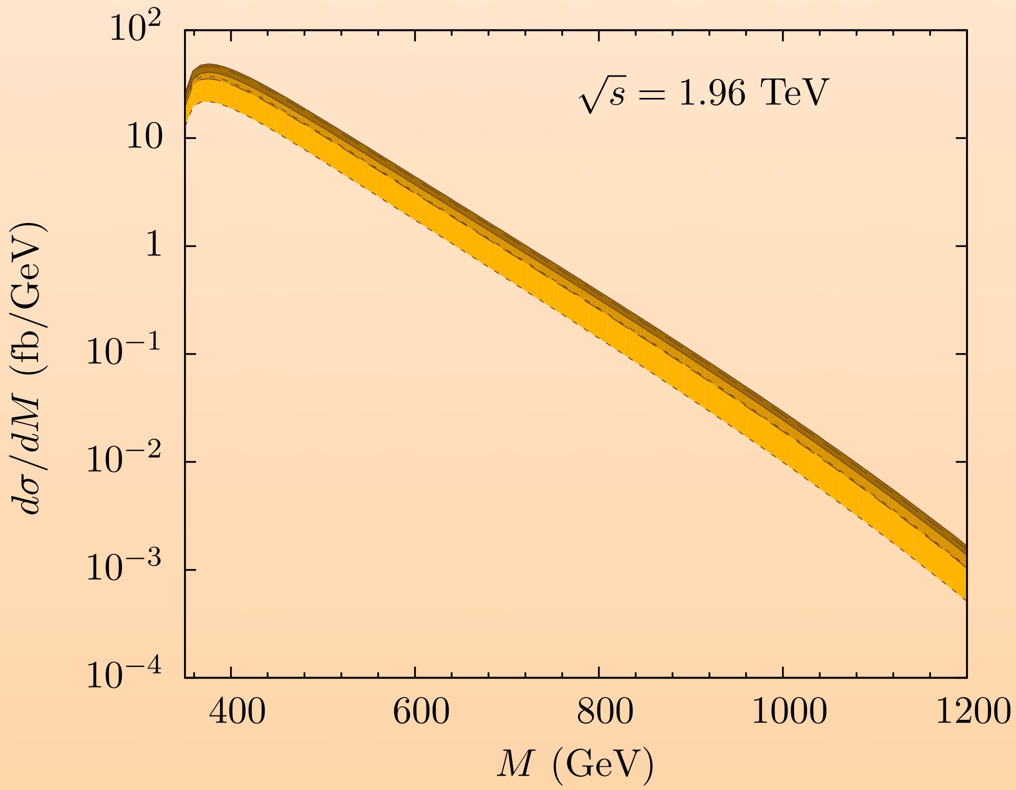
This limit captures the most singular terms:

$$\frac{\alpha_s^j \ln^k z}{z}$$

in the cross-section. Often they are numerically important. The factorization can be used to sum large logs.

eg. $pp \rightarrow t\bar{t}X$ dijet invariant mass to $\mathcal{O}(\alpha_s^4)$ for most singular terms

Ahrens et al. (arXiv:0912.3375)



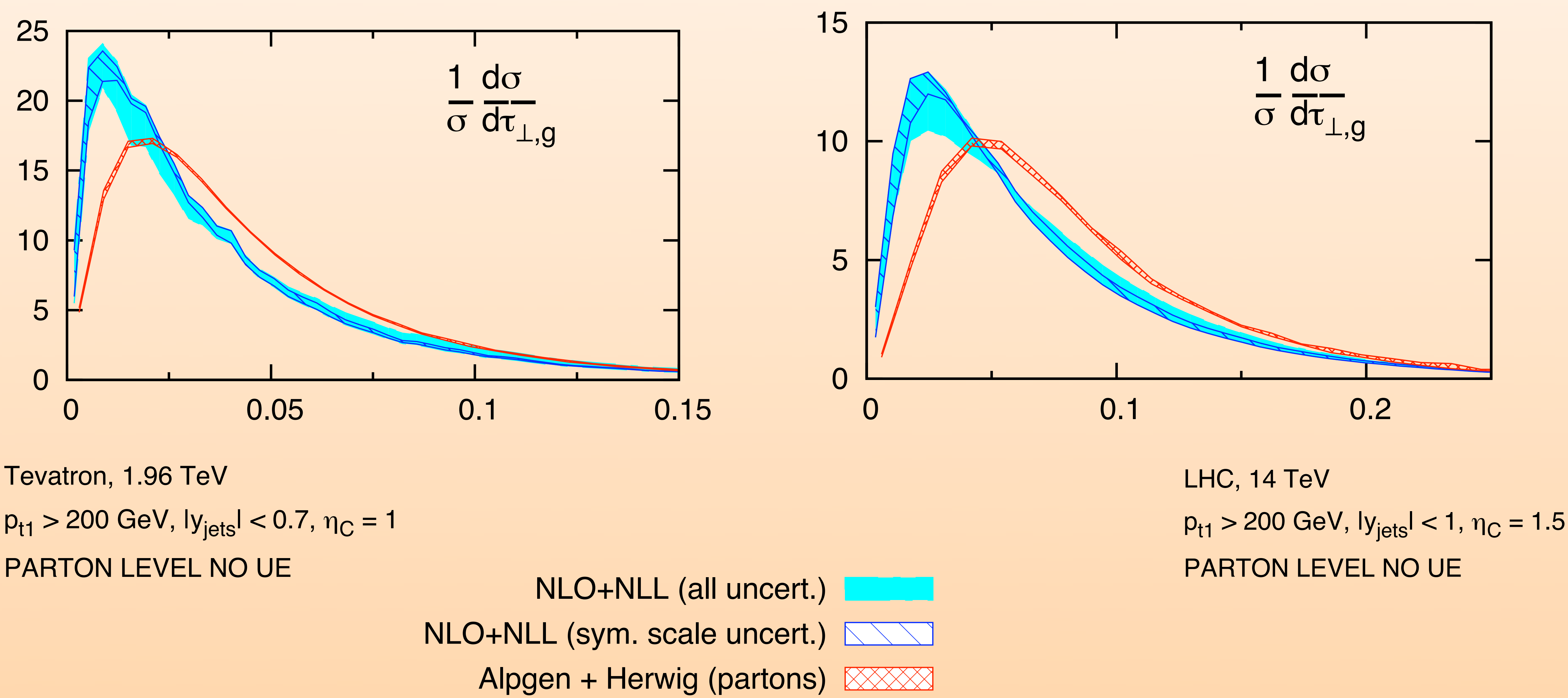
Hadron Event Shapes

Banfi, Salam, Zanderighi (arXiv:1001.4082)

use transverse momenta to avoid beam

global transverse thrust

$$T_{\perp,g} \equiv \max_{\vec{n}_T} \frac{\sum_i |\vec{q}_{\perp i} \cdot \vec{n}_T|}{\sum_i q_{\perp i}} \qquad \tau_{\perp,g} = 1 - T_{\perp,g}$$

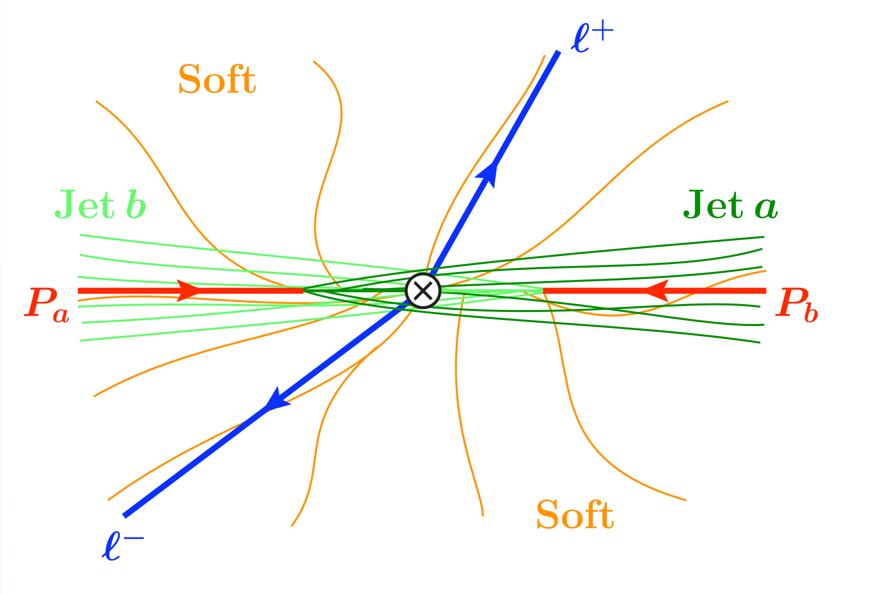


(and many other event shapes too)

Hadron Event Shapes

IS, Tackmann, Waalewijn (arXiv:0910.0467) $pp \to X\ell^+\ell^-$

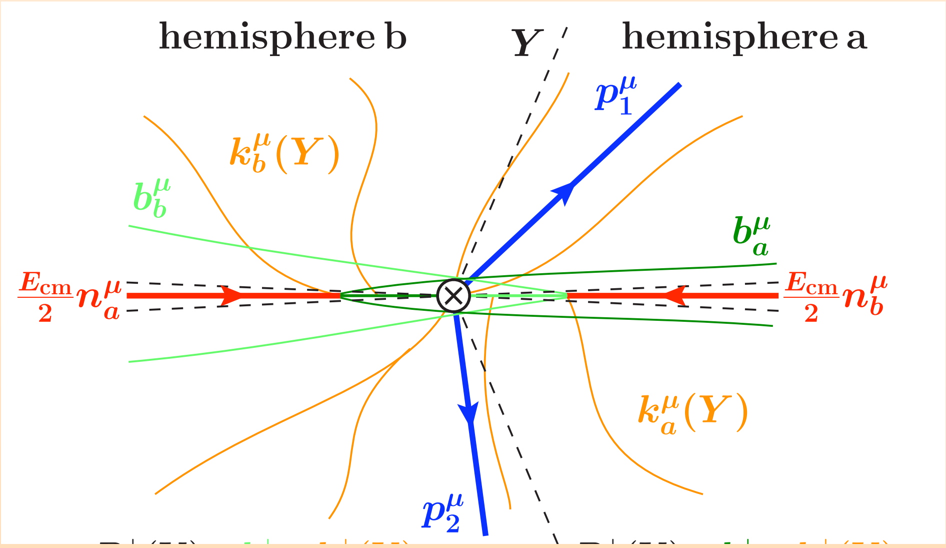
has an exponential rapidity suppression so avoids beam

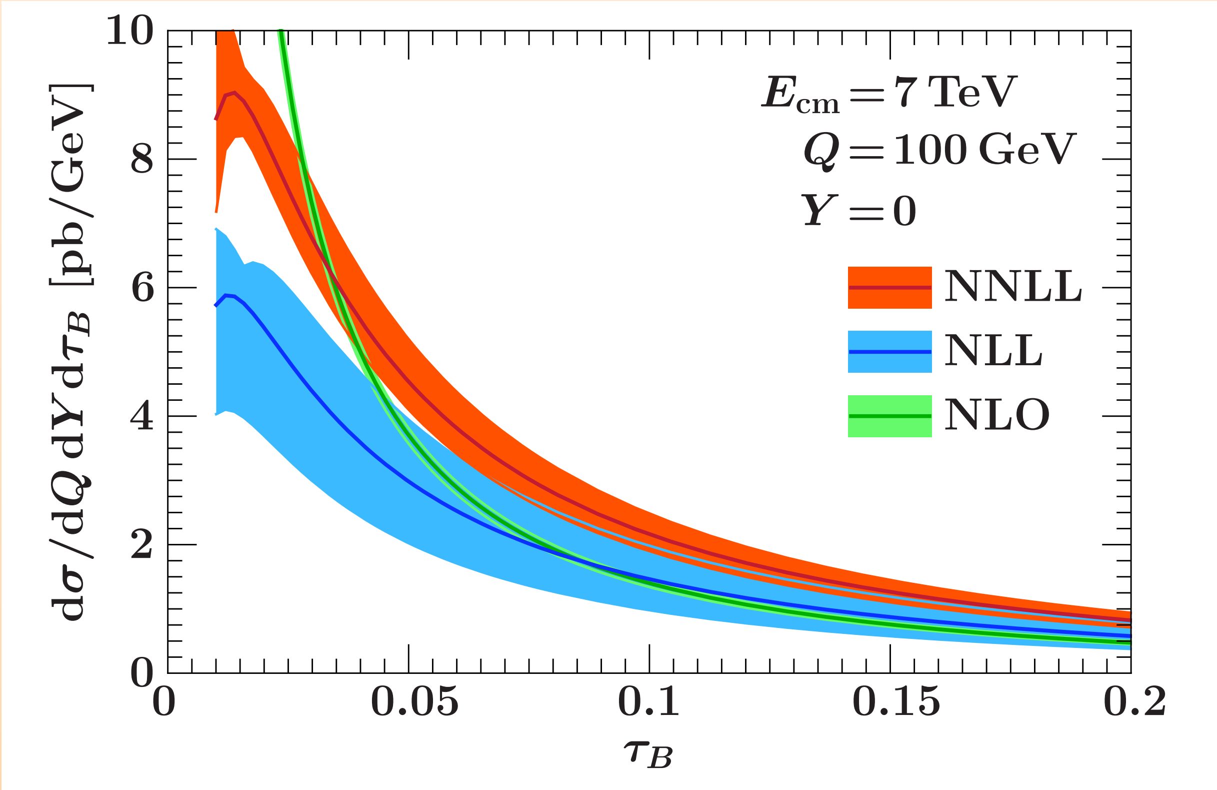


$\boxed{\text{beam thrust}}$ $\tau_B = \dfrac{e^Y B_a^+(Y) + e^{-Y} B_b^+(Y)}{Q}$

$$B_a^+(Y) = \sum_{\eta_k > Y} E_k(1+\tanh\eta_k)e^{-2\eta_k} = \sum_{\eta_k > Y} (E_k - p_k^z)$$

$$B_b^+(Y) = \sum_{\eta_k < Y} E_k(1-\tanh\eta_k)e^{+2\eta_k}$$





Factorization theorem proven

Sums t channel singularities for ISR

Conclusions

$\alpha_s(m_Z)$

- Important to properly account for nonperturbative effects.
  SCET factorization theorems provide high precision formalism.

m_t

- Improved methods to test the nonperturbative MC correction to the top mass are desirable.
- In the future a complete factorization theorem for the top invariant mass distribution in $pp \to t\bar{t}X$ may allow us to surmount this issue.

threshold factorization

- threshold factorization gives simple method to get singular higher order terms

hadron-hadron event shapes

- event shape measurements may improve our understanding of underlying event, FSI, ISR, and nonperturbative effects in top and e.weak processes