Precision Jet Physics At the LHC

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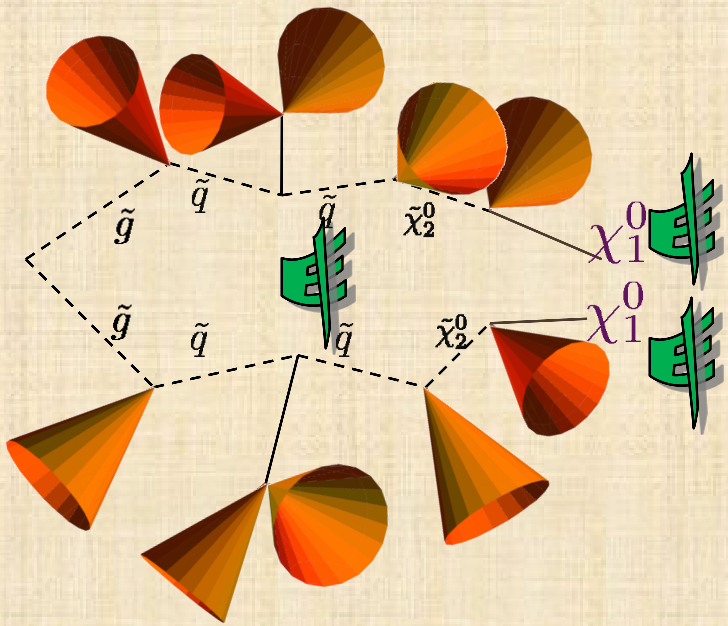
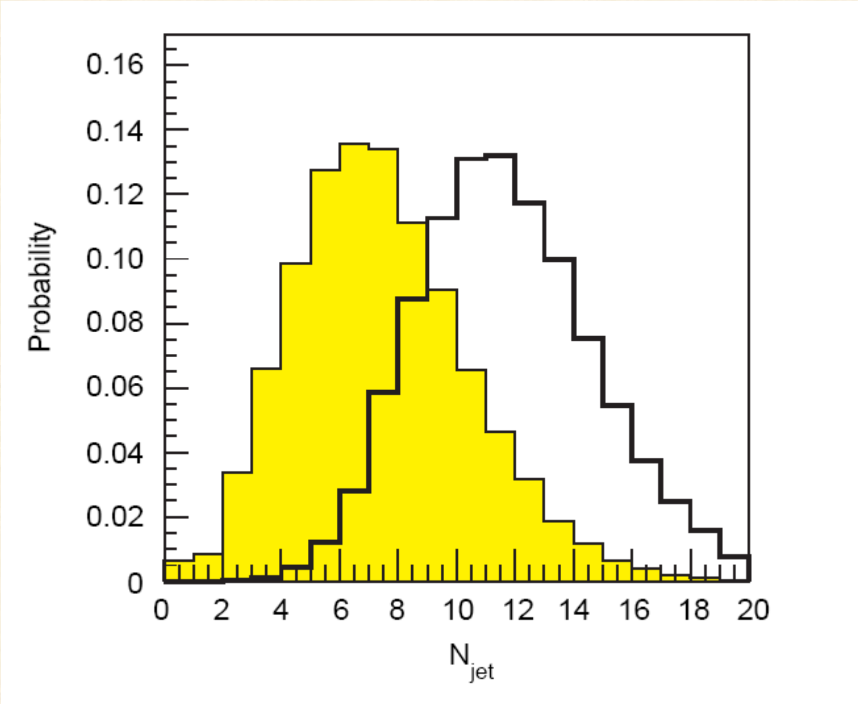
JETS AT THE LHC

An (almost) universal feature of SUSY is ***jets*** and **missing energy**

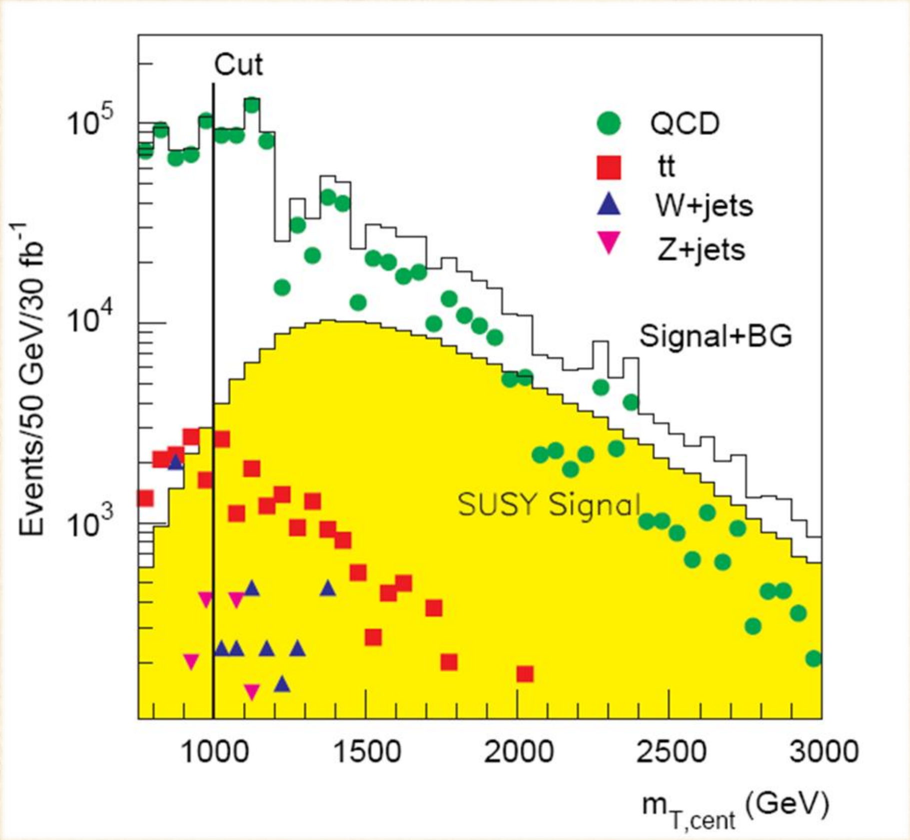


Source: Atlas TDR



SIGNAL VS. BACKGROUND

Source: Atlas TDR



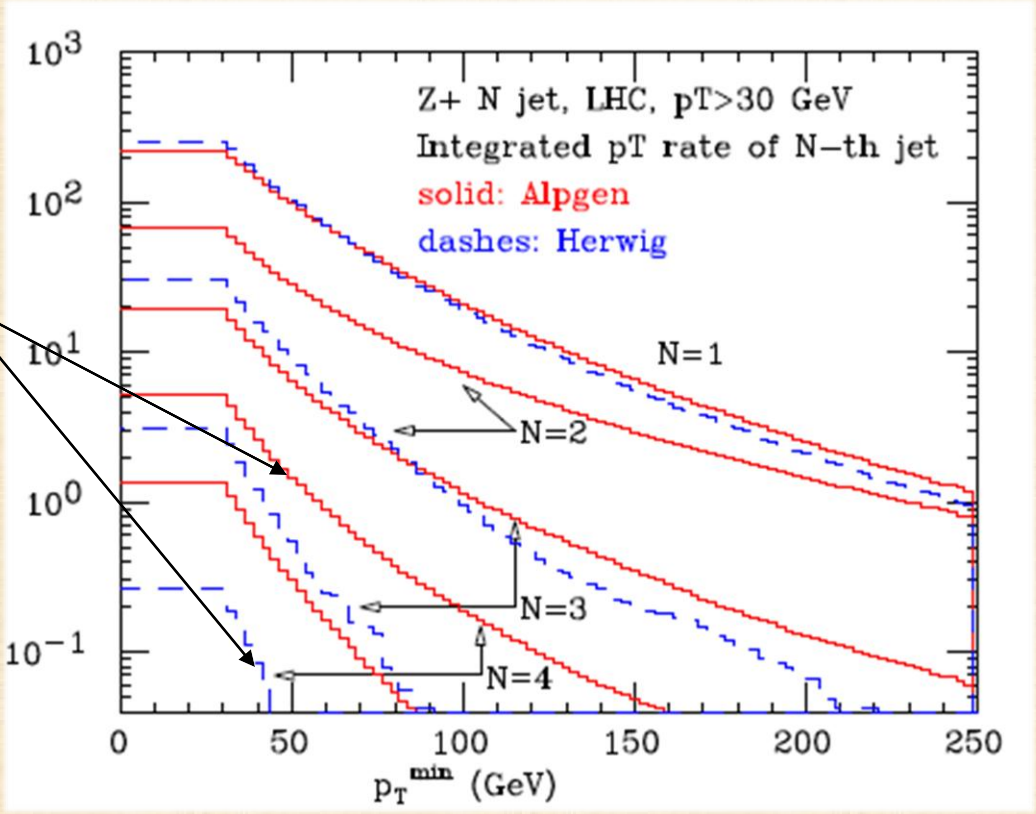
Can we **trust** the background?

CAN WE TRUST THE BACKGROUNDS?

Compare two monte carlos: Alpgen and Herwig

Source: M. Mangano

- Factor of 10 ~ 100 already at 4 jets – we need 8-12.
- What is the right answer?
- Much progress over last years (see Johan's talk).



WHAT IS THE RIGHT ANSWER?

- Ask PYTHIA
  - Only includes 2→2 (some 2→3) tree-level matrix elements
  - Only includes LL resummation
- Ask Madgraph/Alpgen/Sherpa
  - Includes any 2→n matrix element at tree level
- Ask MC@NLO/Powheg/Rocket/Blackhat
  - 1-loop matrix elements

  (see Giulia and Lance's talks)
- Ask the data

calibrate detectors

tune Monte Carlos

measure PDFs

find new physics

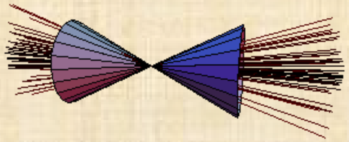
All at the same time…

How important is resummation????

How do we know?

NEED EFFECTIVE FIELD THEORY

- Separates physics at different energy scales

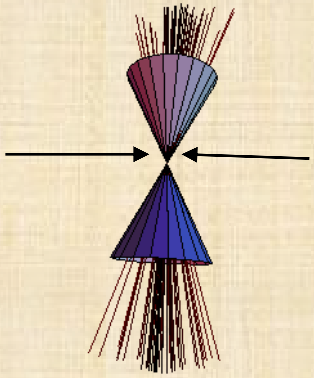


m = mass of jet
E = energy of jet

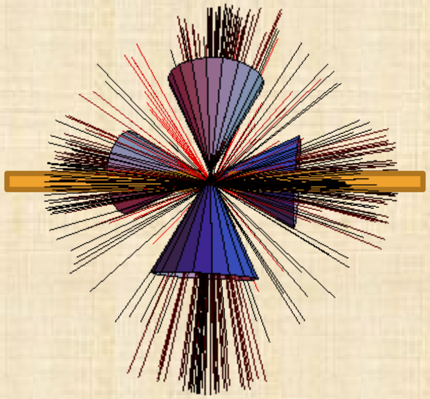
- Uses the renormalization group to sum large logarithms between scales

Eg. $\exp[-\alpha \log (m/E)]$ $m << E$

- Soft-Collinear Effective Theory is the effective field theory of **jets**



$e^+e^- \rightarrow$ jets

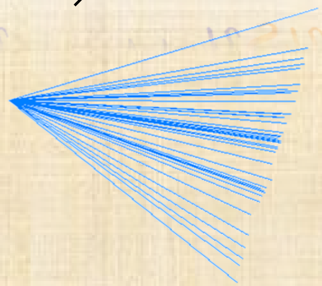


$p^+p^+ \rightarrow$ jets

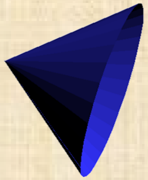
SOFT-COLLINEAR EFFECTIVE THEORY(SCET)

- Lagrangian has separate collinear and soft gauge invariance
- Covariant objects are fermions wrapped in Wilson lines

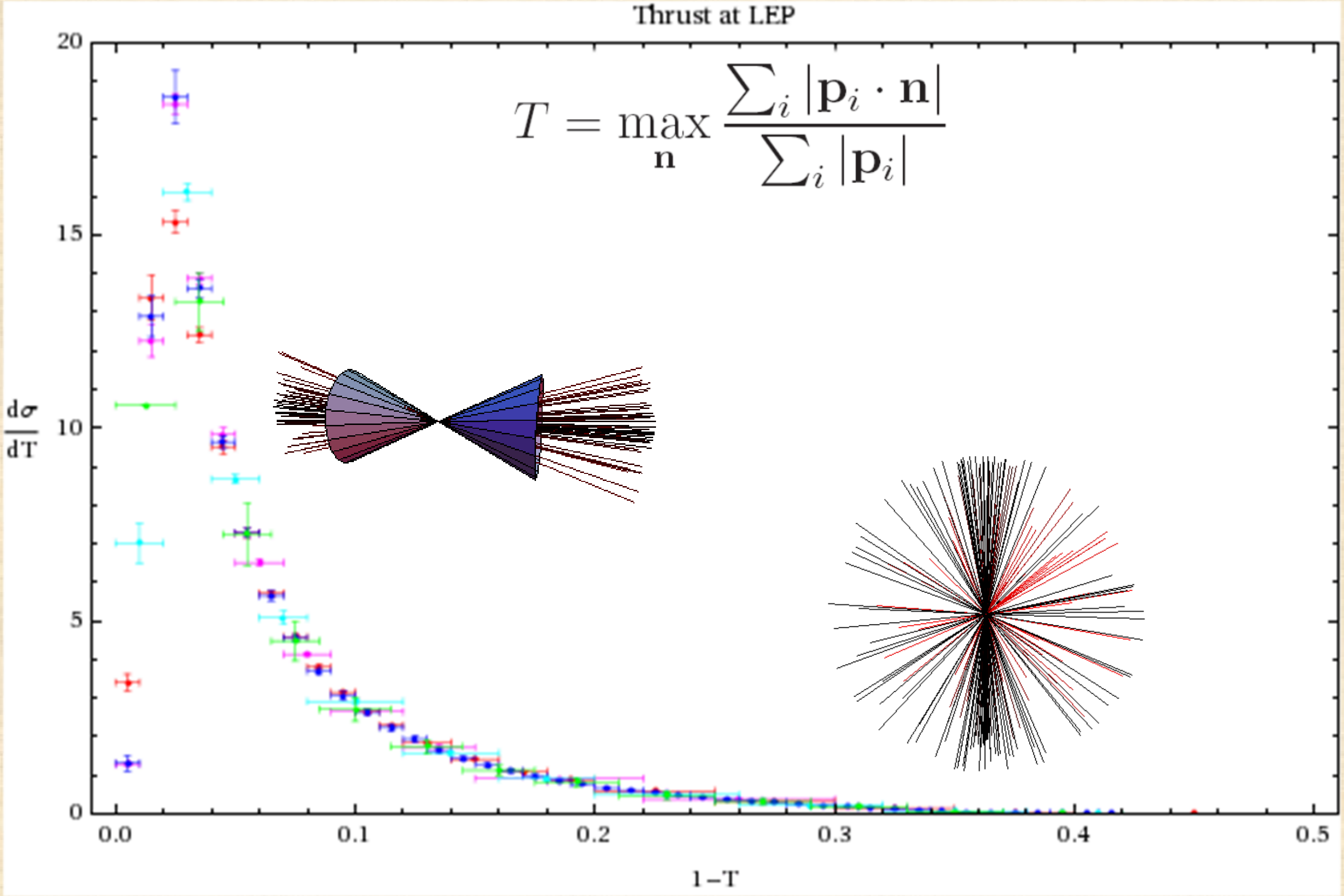
$$\chi_n = W_n \xi_n$$


Jets are collections of collinear fermions and gluons

$\chi_n =$  $\approx$ jet

THRUST

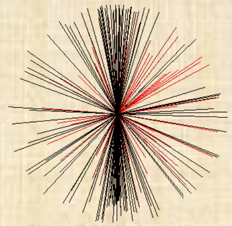


Thrust provides some of the best data in the world

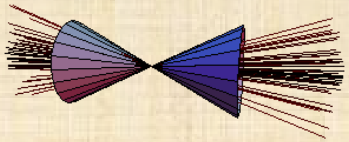
1 million clean events from LEP

SOFT-COLLINEAR EFFECTIVE THEORY

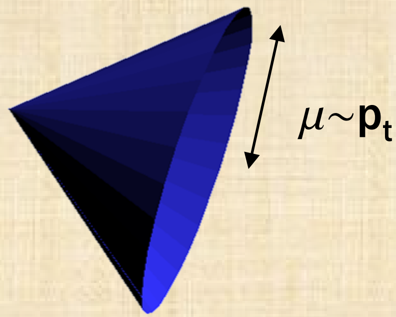
To interpolate between fat jets



and thin jets

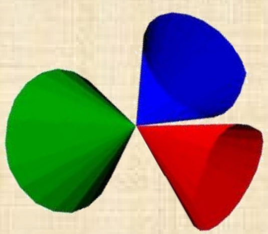


We expand in the transverse size of the jet



At each scale μ, the event can be resolved into some number of jets

two jets



three jets

FACTORIZATION FORMULA

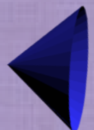
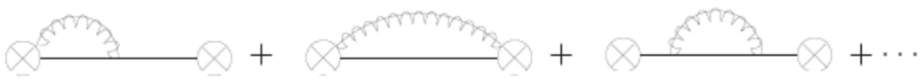
Fleming, Hoang, Mantry, Stewart (**hep-ph/0703207**)

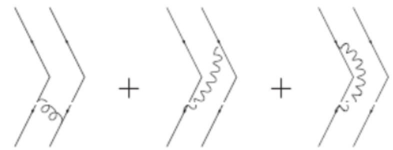
MDS, PRD:77.14026 (2008)

For the thrust distribution:

$$\frac{1}{\sigma_0}\frac{d^2\sigma}{d\tau} = |C_H(Q)|^2 \int dp^2\, dq^2\, J(p^2)\, J(q^2)\, S_T\left(\tau Q - \frac{p^2+q^2}{Q}\right)$$

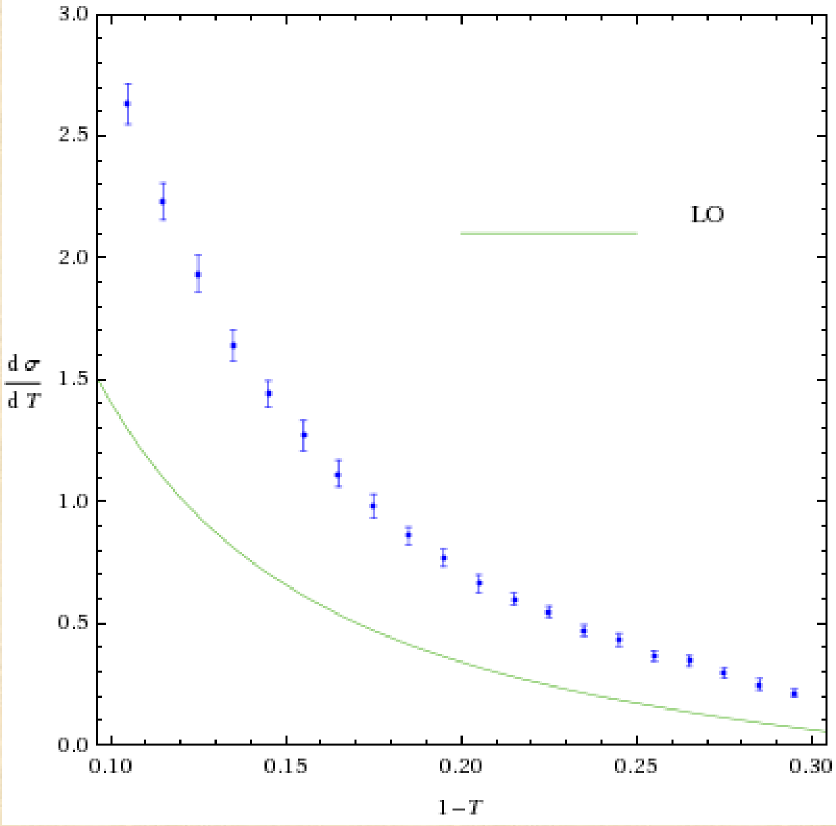
Hard Function: $C_H \sim$ 

Jet Function:  $J(p^2,\mu) \sim \mathrm{Disc}\,\{$  $\}$

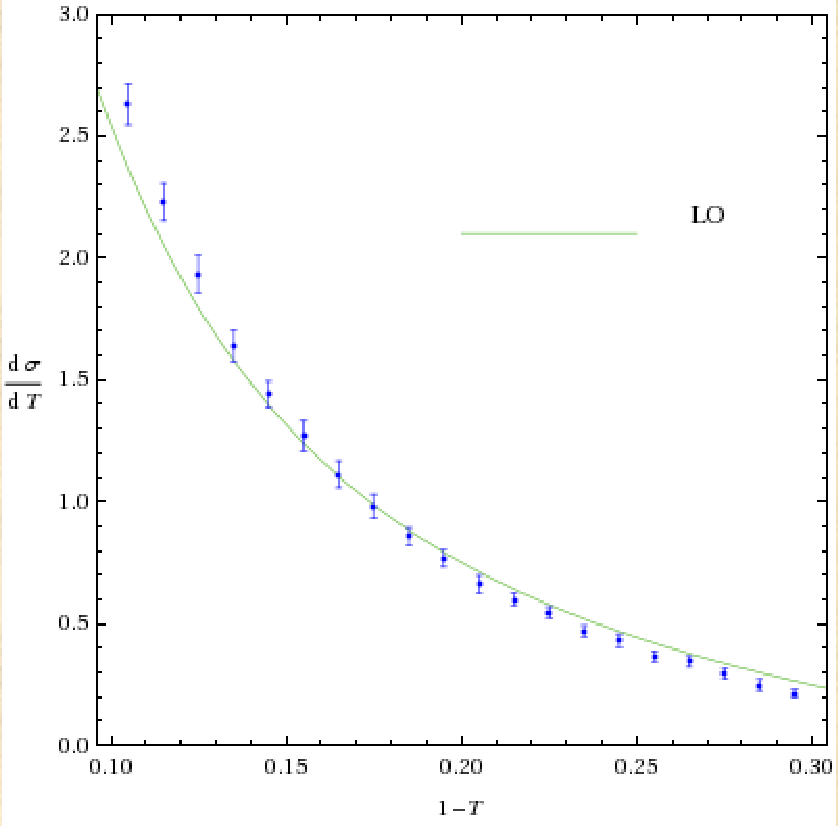
Soft Function: $S(k_L, k_R, \mu) \sim$ 

CONVERGENCE

Fixed Order



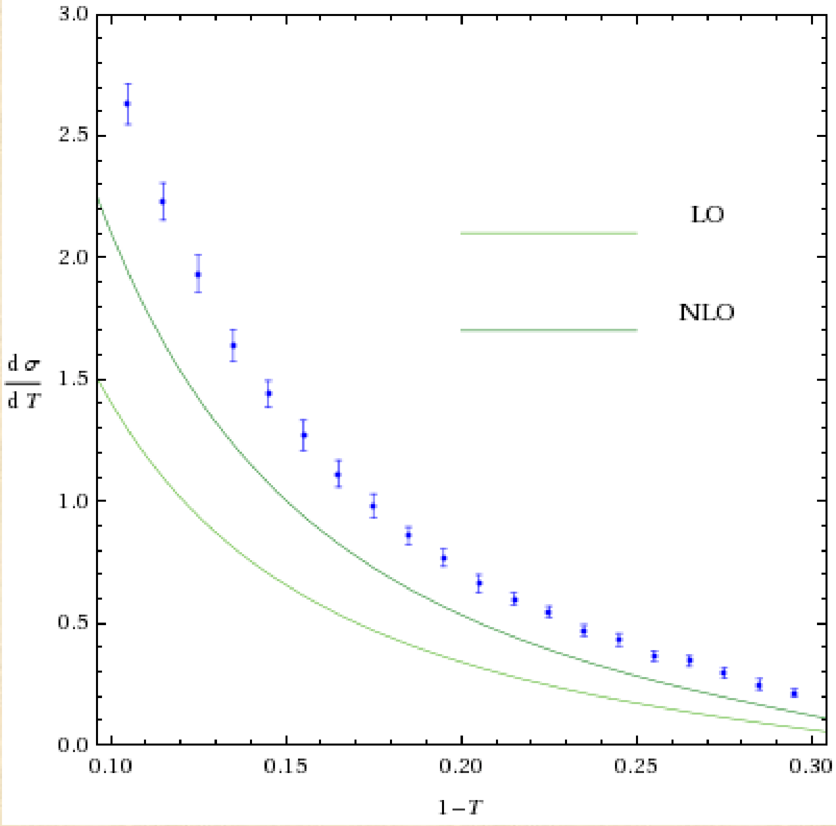
Effective Field Theory
(matched to Fixed Order)



At fixed $\alpha_s(M_Z) = 0.1168$

CONVERGENCE

Fixed Order



Effective Field Theory
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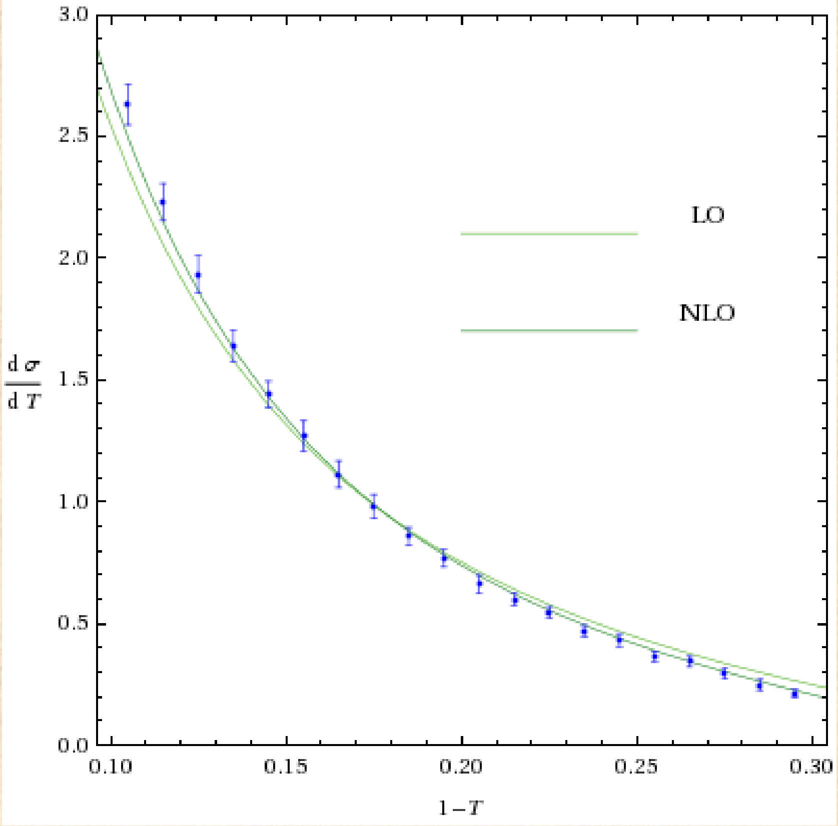
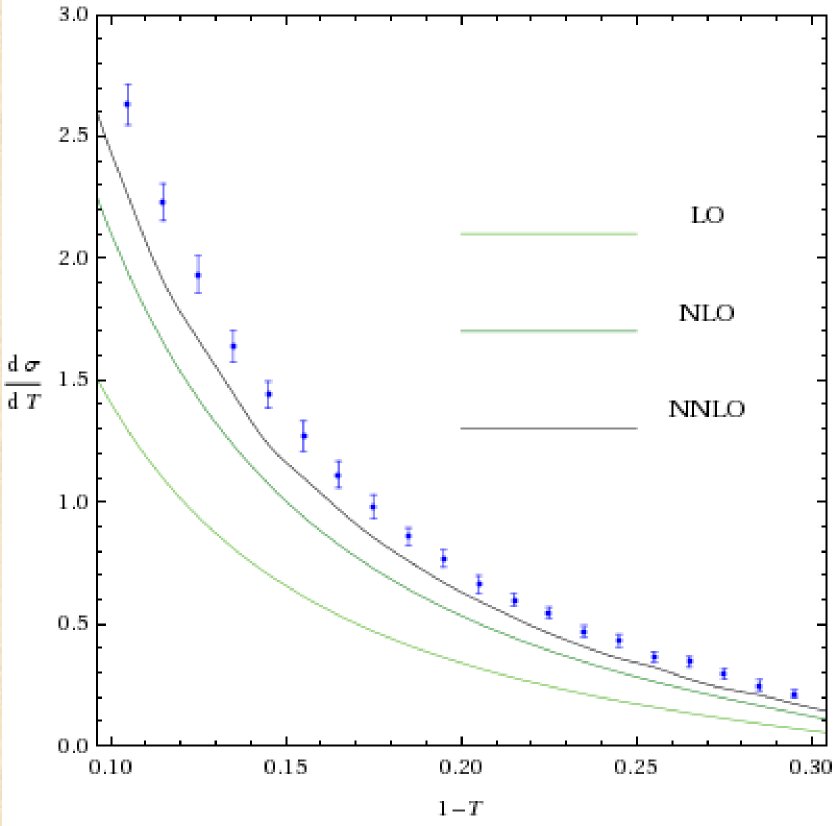


At fixed $\alpha_s(M_Z) = 0.1168$

CONVERGENCE

Fixed Order



Effective Field Theory
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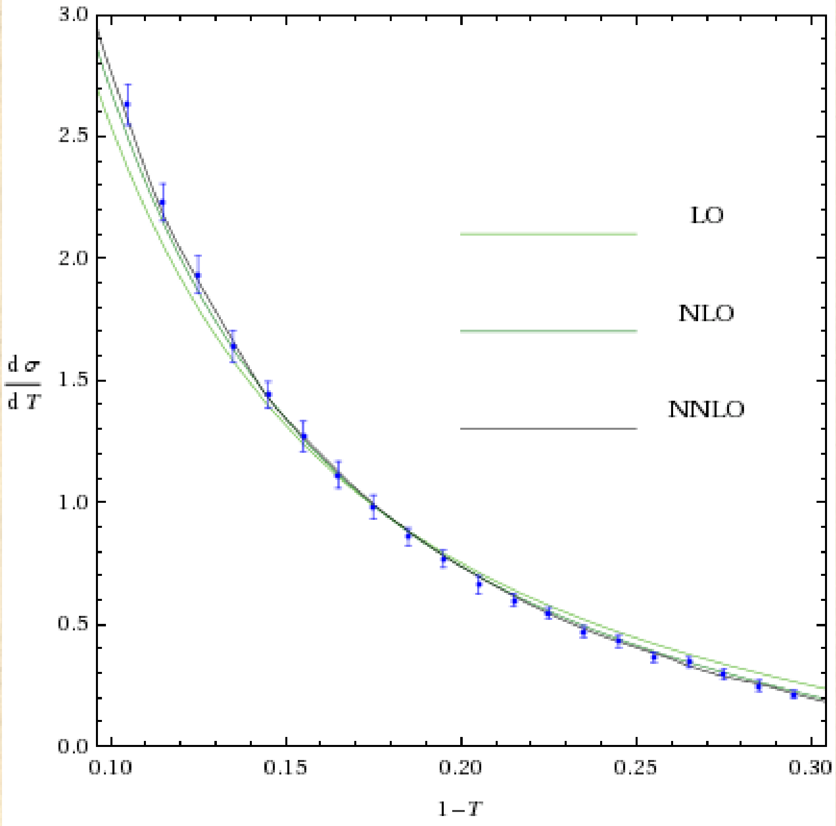
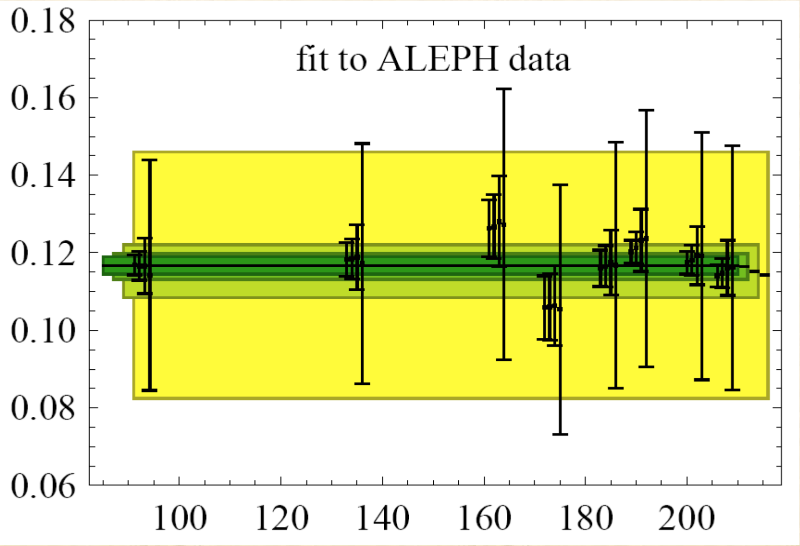
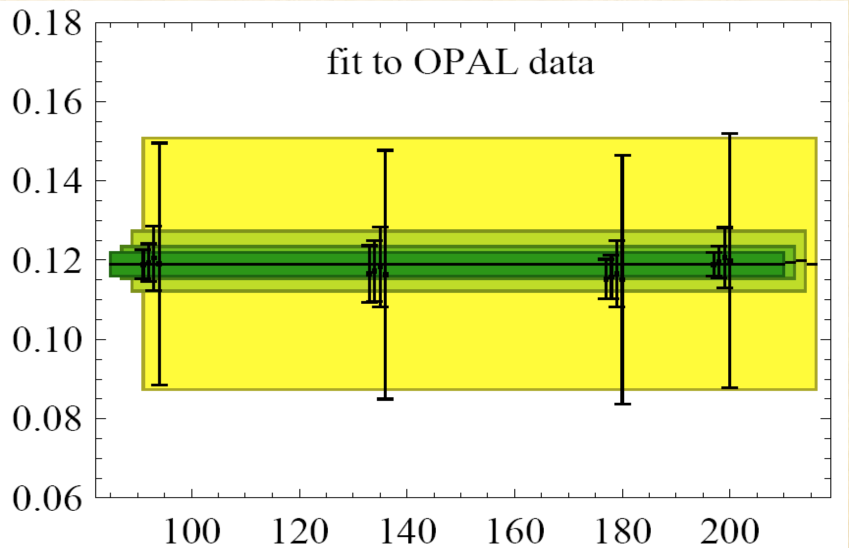


At fixed $\alpha_s(M_Z) = 0.1168$

LEP I AND LEP II

MDS, T. Becher





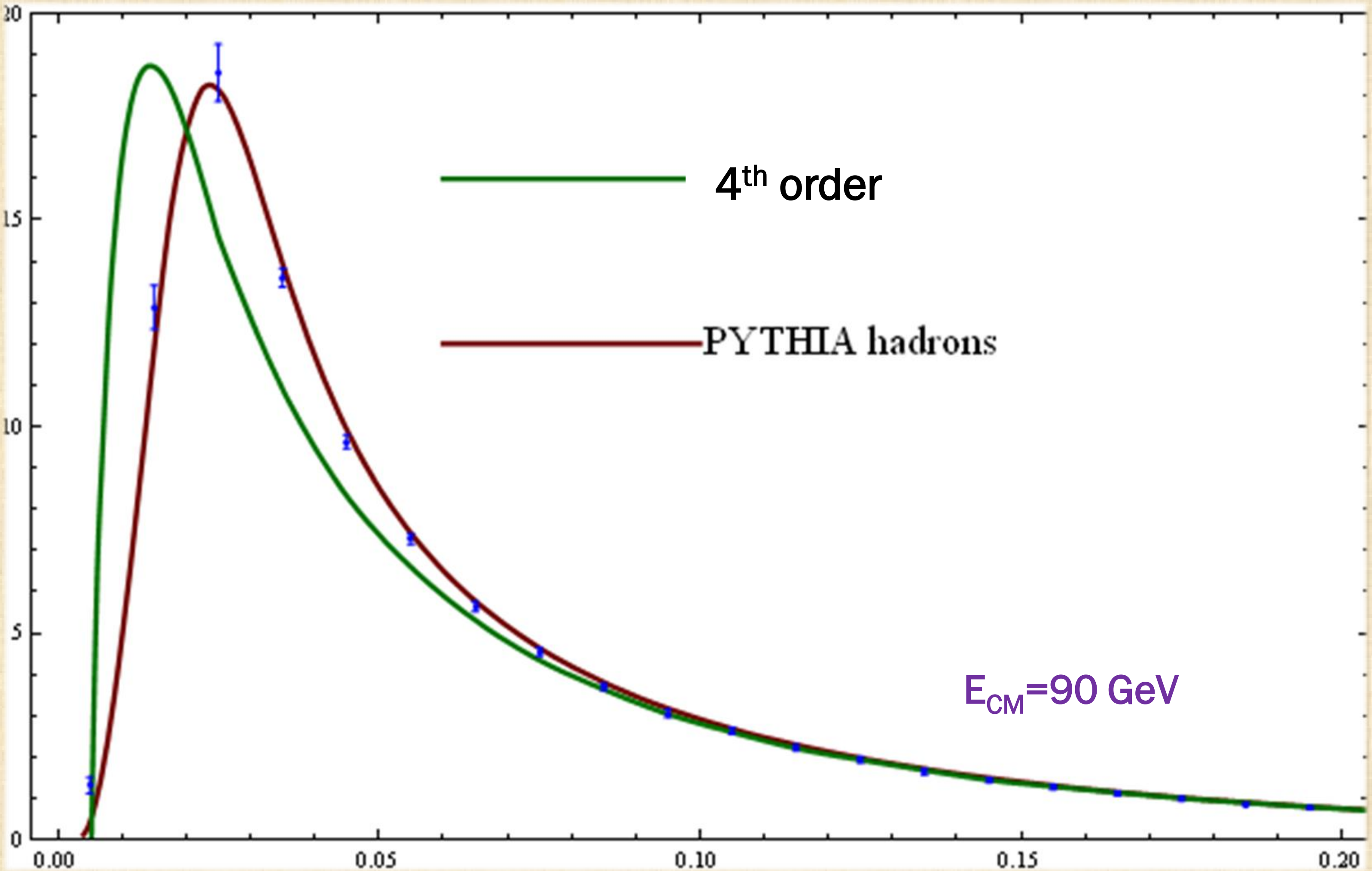
$\alpha_s(M_Z)$ = 0.1172 ±0.002

$\alpha_s(M_Z)$ = 0.1274 ±0.005 (fixed order thrust)

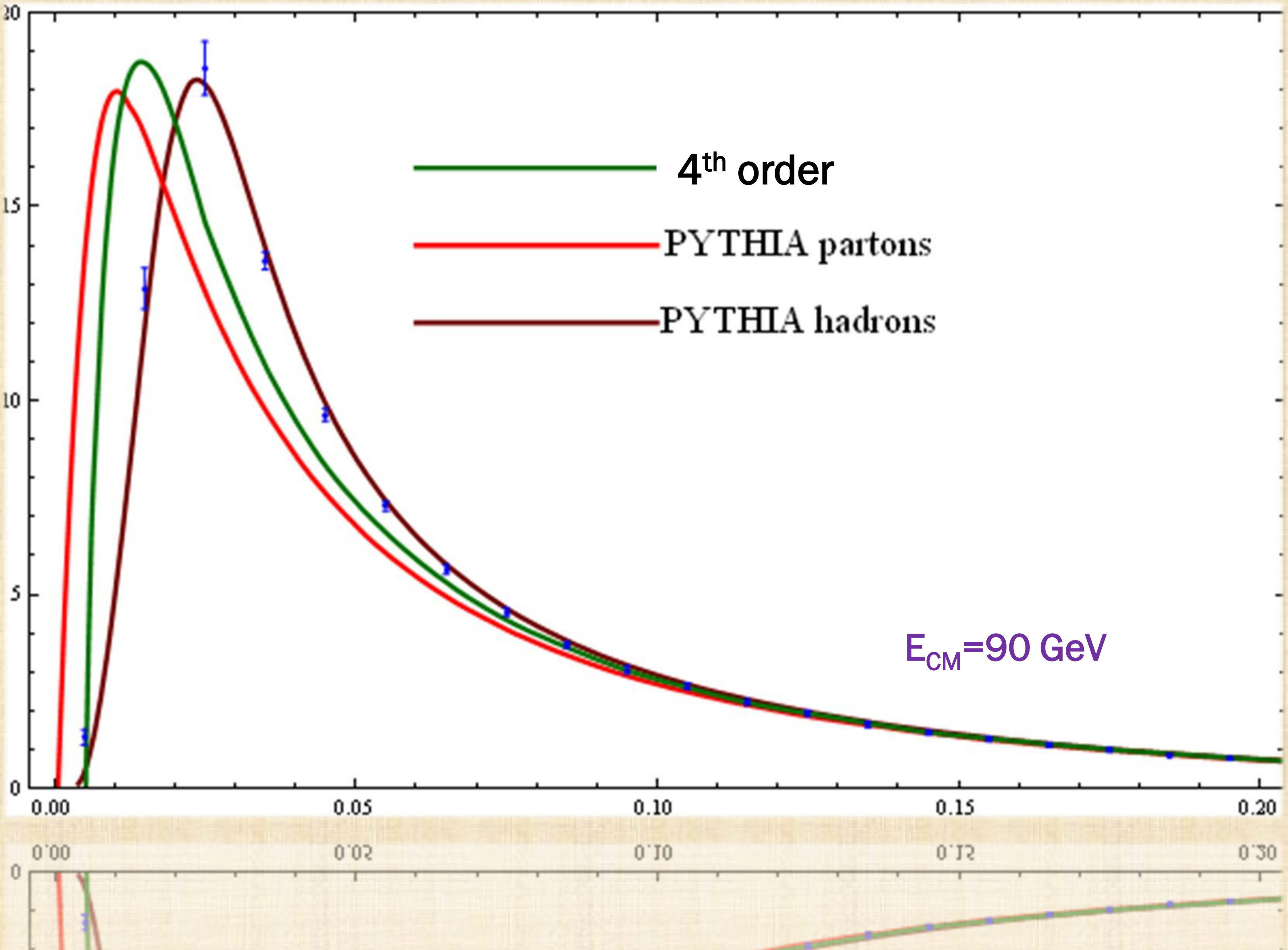
$\alpha_s(M_Z)$ = 0.1176 ±0.002 (World Average)

- Effective field theory
  - is much more convergent than fixed order QCD
  - improves fit to α_s tremendously
  - helps test QCD

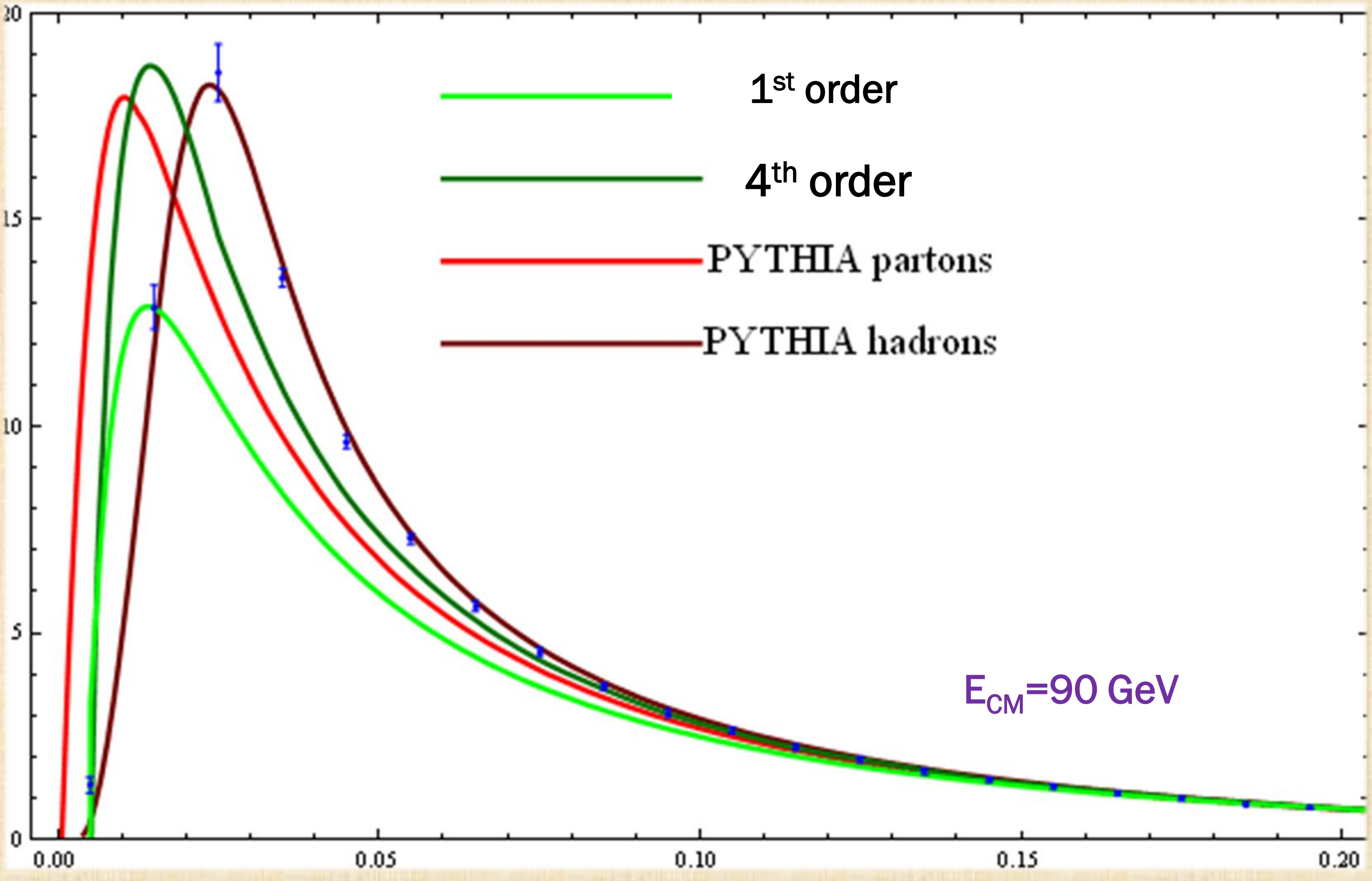
SCET VS PYTHIA



SCET VS PYTHIA



SCET VS PYTHIA



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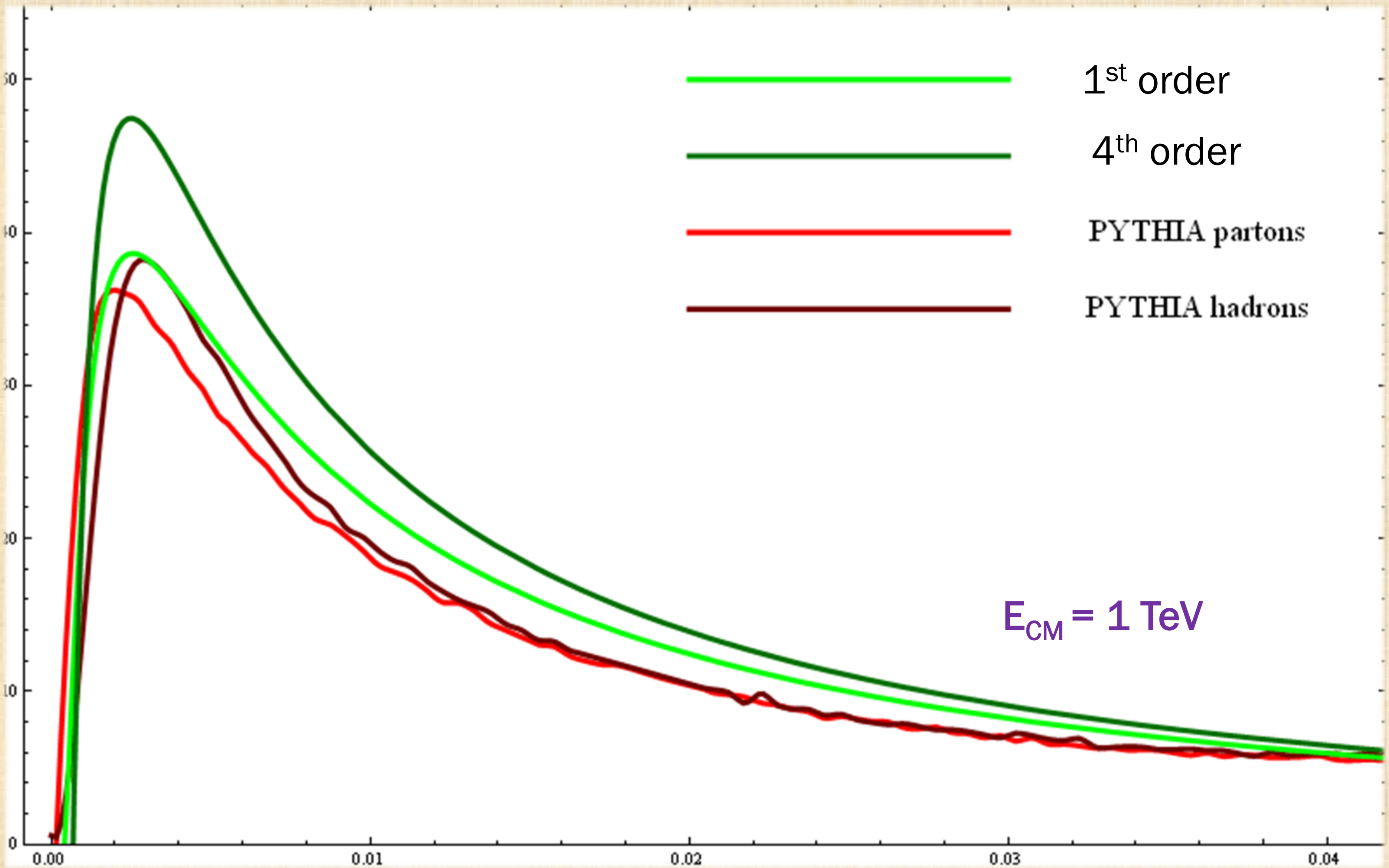

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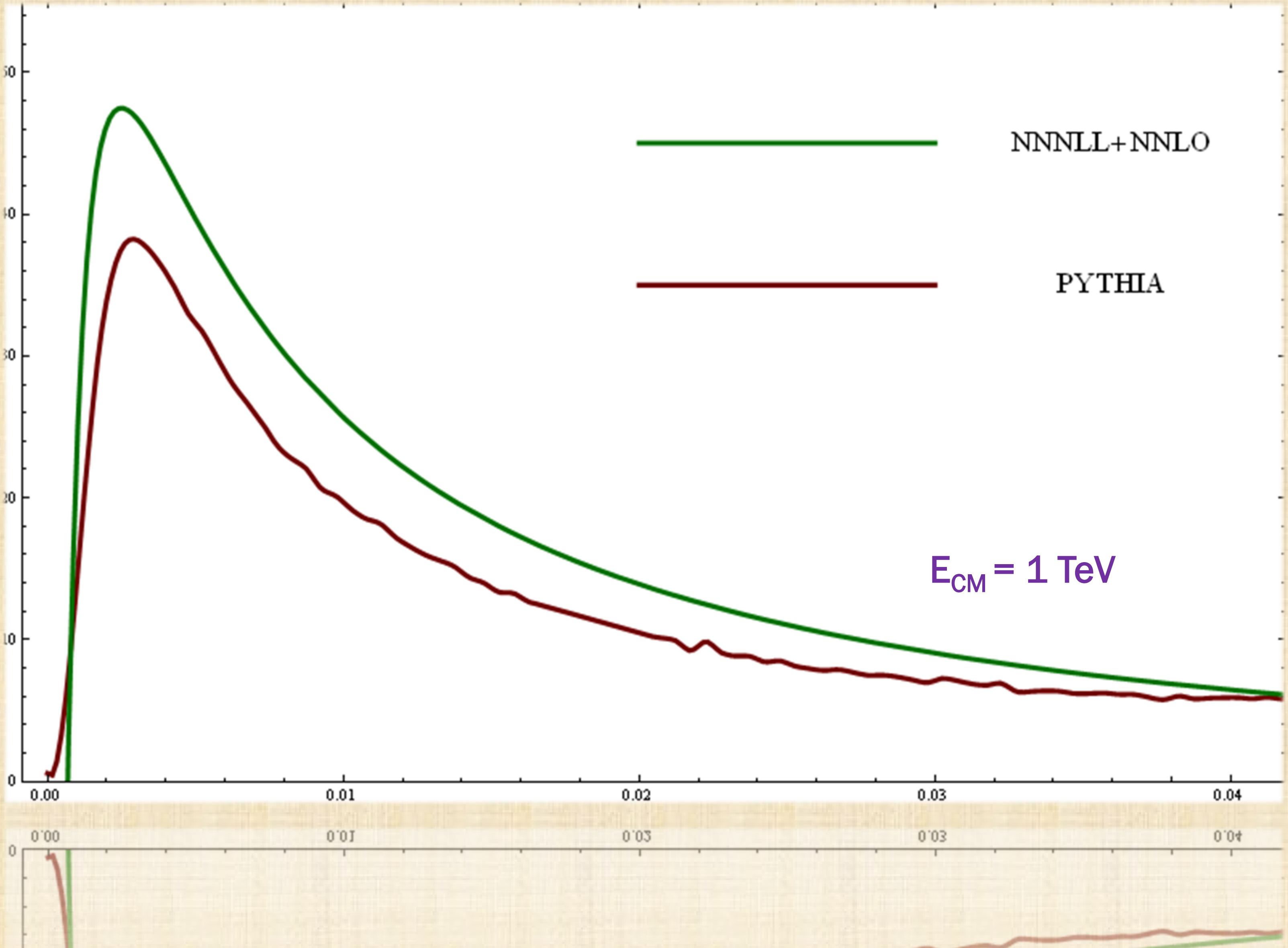
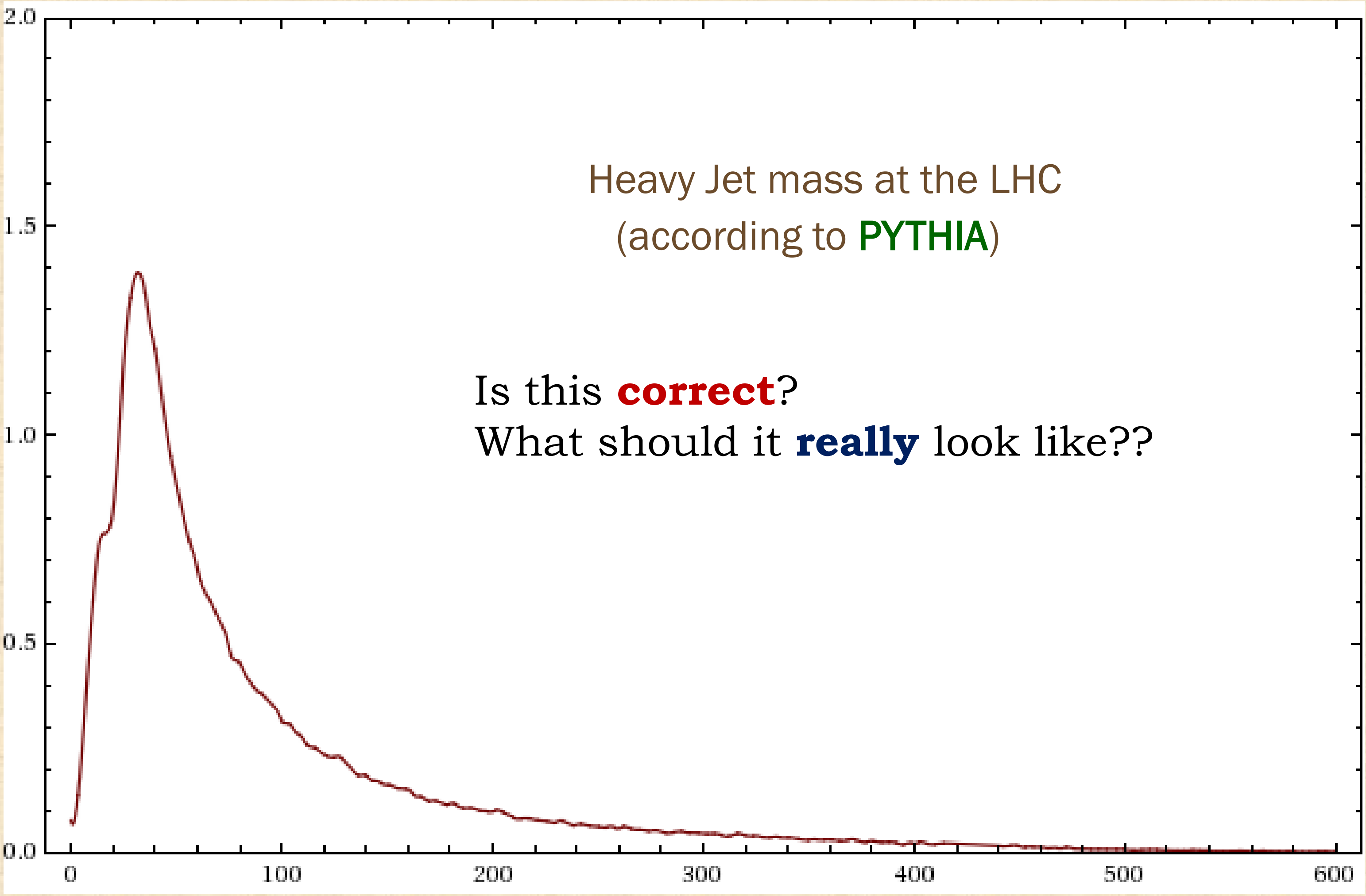
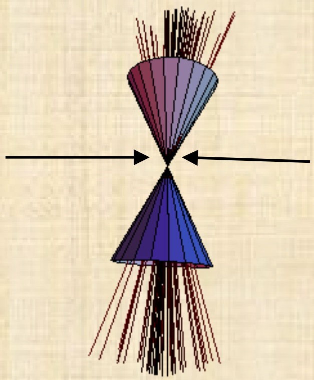


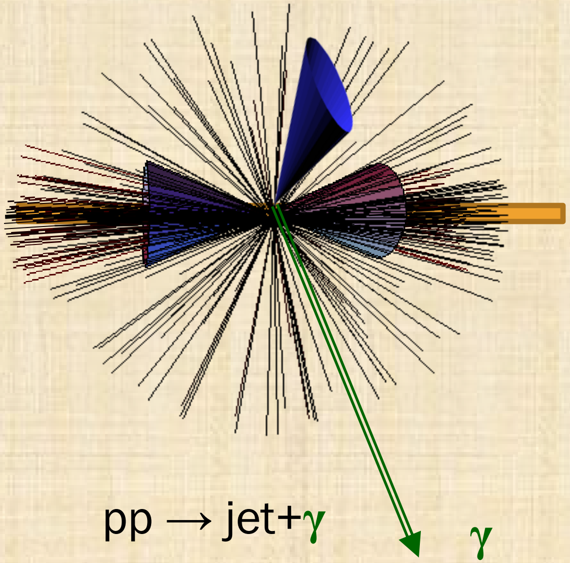
JETS AT THE LHC



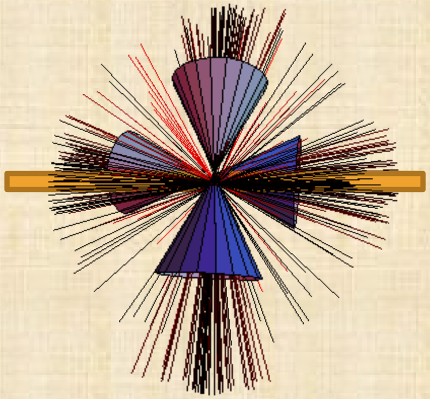
JETS AT HADRON COLLIDERS



$e^+e^- \rightarrow$ jets

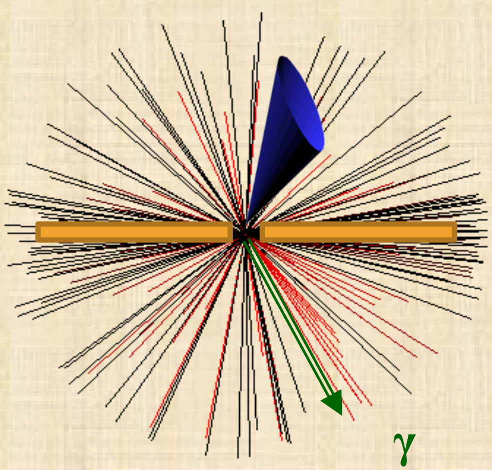


pp → jet+γ



pp → jets

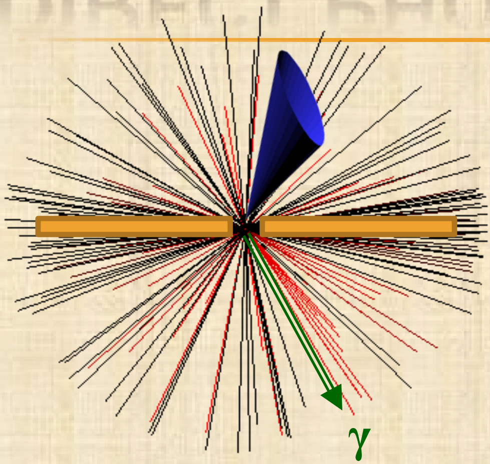
Direct photon production



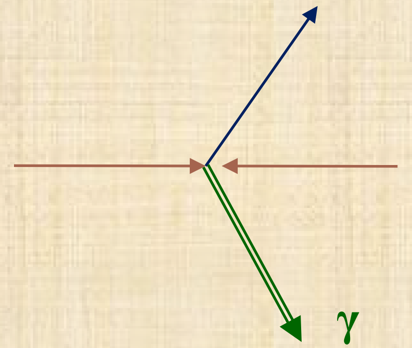
Threshold direct photon production

- Initial state: 2 protons
- Final state: 1 jet + 1 photon+ soft radiation

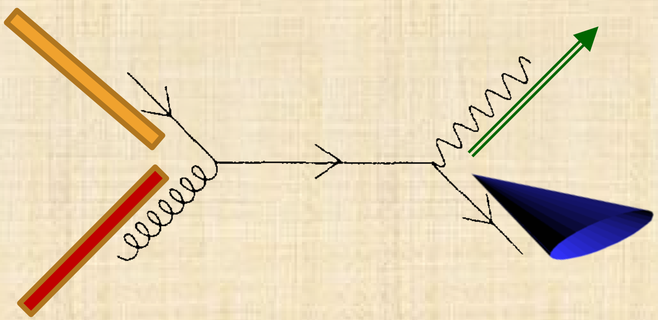
DIRECT PHOTON PRODUCTION

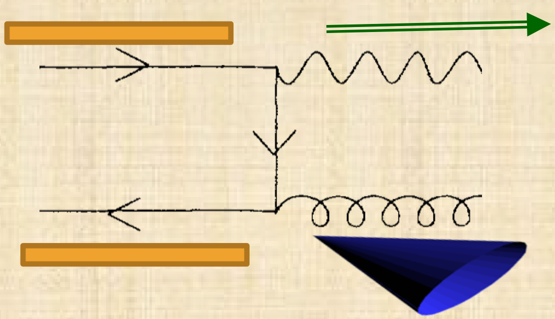


Perturbation Theory



Leading Order





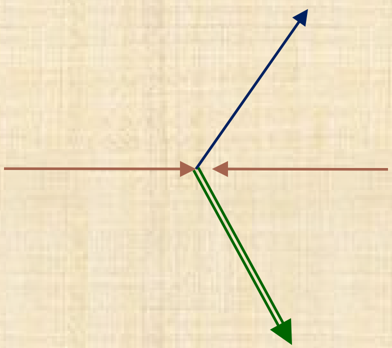
Compton Channel
(important way to measure gluon PDF)

Annihilation Channel

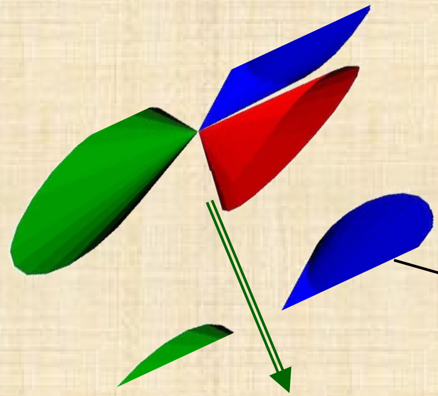
DIRECT PHOTON PRODUCTION

$$\mathcal{O}^\nu = \bar{\psi}_{n_1} A^\nu_{n_2} \psi_{n_3} \longrightarrow \bar{\chi}_{n_1} \mathcal{A}^\nu_{n_2} \chi_{n_3} \longrightarrow \bar{\chi}_1 Y_1^\dagger Y_2 \mathcal{A}_2^{\nu a} \tau^a Y_2^\dagger Y_3 \chi_3$$

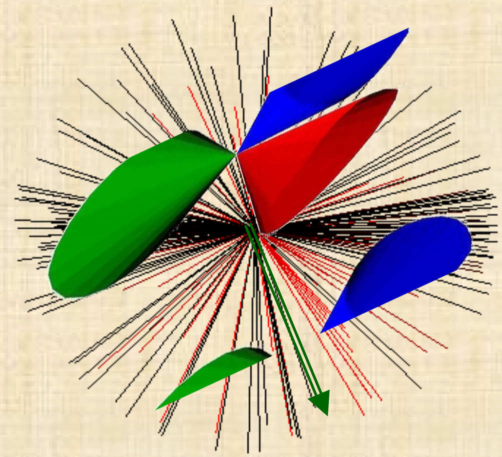
$$= (\bar{\chi}_1 \mathcal{A}_2^{\nu a} \chi_3)(Y_1^\dagger Y_2 \tau^a Y_2^\dagger Y_3)$$



Hard scale



Jet scale



Soft scale

$$\langle p_1\, p_2 | \mathcal{O}^\nu(x) \mathcal{O}^\nu(0) | p_1\, p_2 \rangle = \langle p_1 | \bar{\chi}_1 \chi_1 | p_1 \rangle$$

$$\langle 0 | \mathcal{A}_2^\nu \mathcal{A}_2^\nu | 0 \rangle$$

$$\langle p_1 | \bar{\chi}_3 \chi_3 | p_1 \rangle$$

$$\langle 0 | (Y_1^\dagger Y_2 \tau^a Y_2^\dagger Y_3)(Y_1^\dagger Y_2 \tau^a Y_2^\dagger Y_3) | 0 \rangle$$

PDF

PDF

Jet function

Soft function

FINAL DISTRIBUTION

PDF $\langle p_1|\bar{\chi}_1\chi_1|p_1\rangle$

PDF $\langle p_1|\bar{\chi}_3\chi_3|p_1\rangle$

$$\frac{\mathrm{d}^2\sigma_{q\bar{q}}}{\mathrm{d}y\mathrm{d}p_T} = \frac{2}{p_T}\int_{\frac{p_T}{E_{\mathrm{CM}}}e^{y}}^{1-\frac{p_T}{E_{\mathrm{CM}}}e^{-y}} \mathrm{d}v \int_{\frac{p_T}{E_{\mathrm{CM}}}\frac{1}{v}e^{y}}^{1} \mathrm{d}w \left[(wx_1)f_{q/N_1}(x_1,\mu)\right]\left[x_2 f_{\bar{q}/N_2}(x_2,\mu)\right]$$

$$\times\, \widetilde{\sigma}_{q\bar{q}}(v) H_{q\bar{q}}(p_T,v,\mu)\int dk\, J_g(m_X^2-(2E_J)k,\mu)S_{q\bar{q}}(k,\mu)$$

Hard function

- NLO (from QCD)
- SCET: γ_H to 3-loops

Jet function

$\langle 0|\mathcal{A}_2^{\nu}\mathcal{A}_2^{\nu}|0\rangle$

- Quark jet to NNLO
- Gluon jet to NLO
- γ_{Jq} and γ_{Jq} to 3-loops

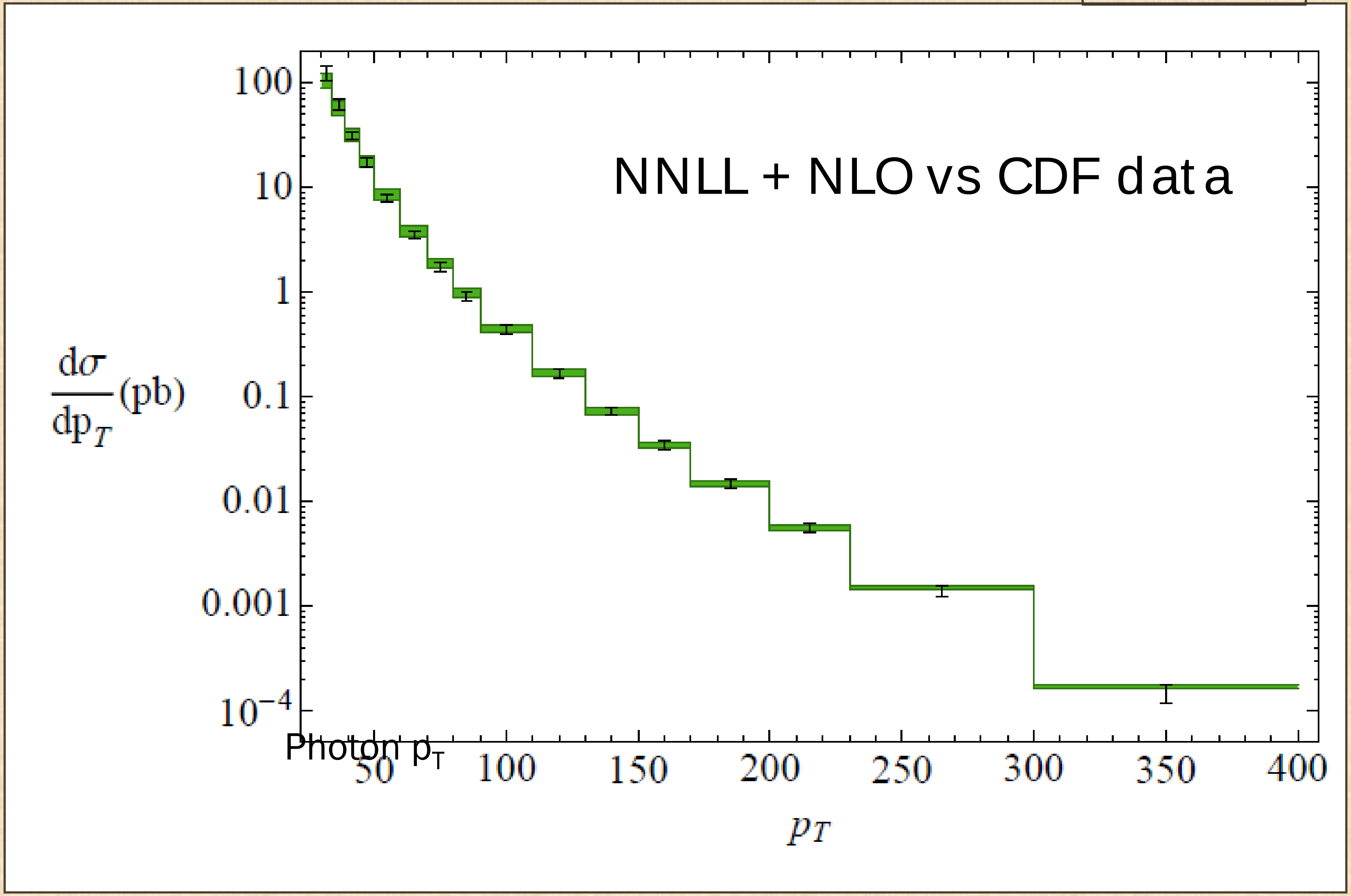
Soft function

- both channels to NLO
- γ_S to 3-loops (from RG and Casimir scaling)

Direct photon distribution with NNLL resummation + NLO fixed order

RESULTS

MDS, T. Becher



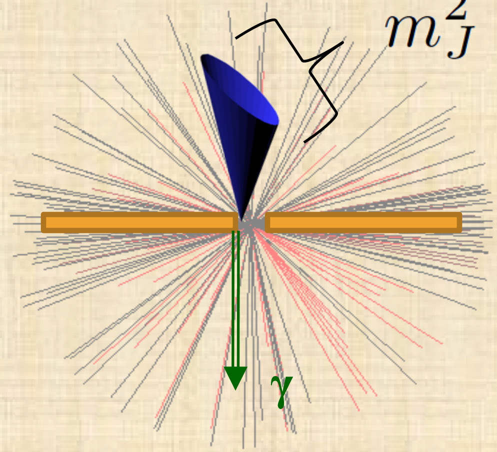
WHAT ARE THE MATCHING SCALES?

Matching scales appear as:

$$\frac{\mu_h^2}{p_T^2}, \quad \frac{\mu_j^2}{m_J^2}, \quad \frac{\mu_s}{\mu_j^2/\mu_h}$$

Hard scale = p_T

Jet scale = m_J^2

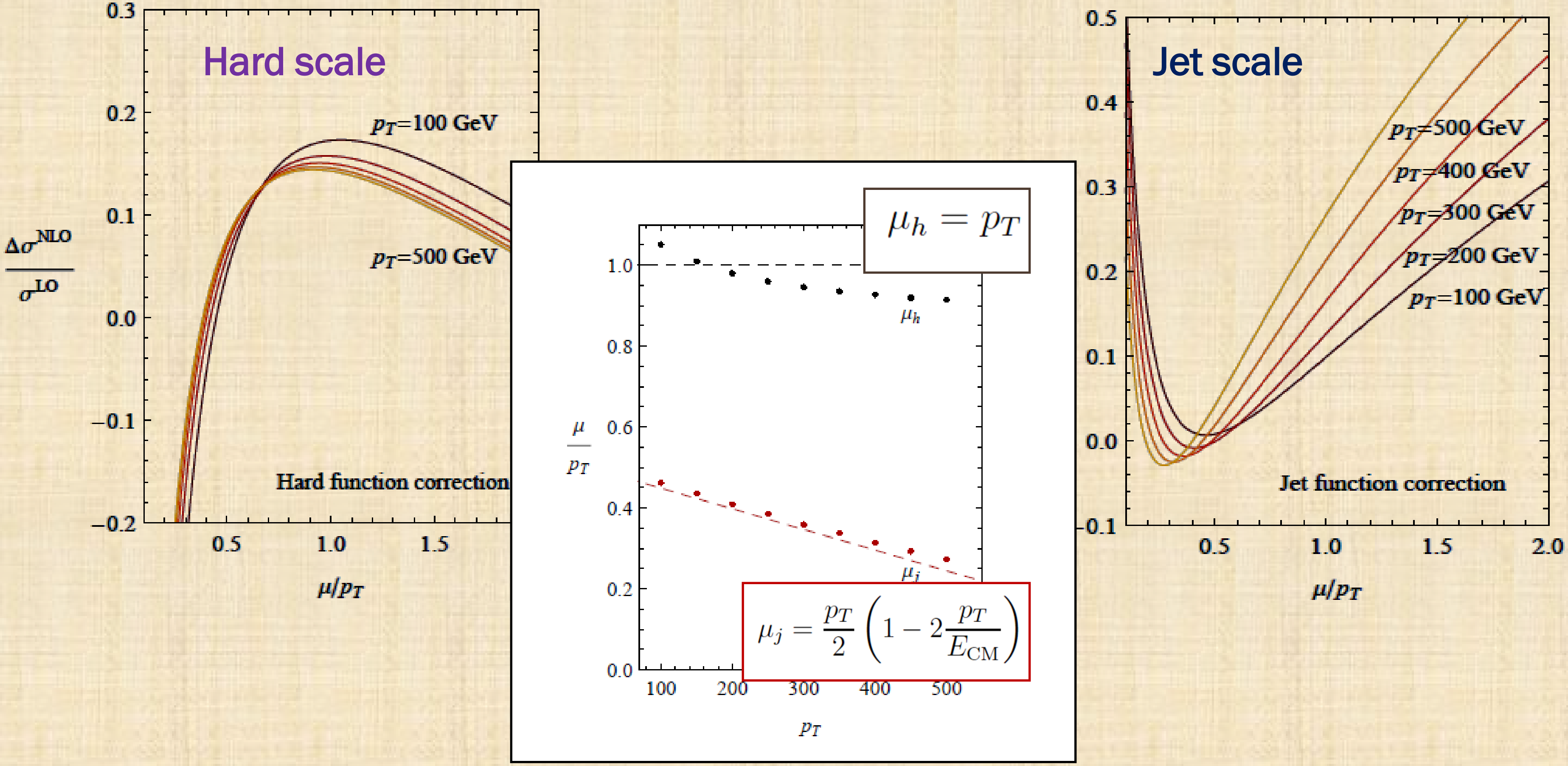


m_J^2 = mass of **jet**

- **Works** for **thrust**
- **Problematic** for direct photon
  - m_J is integrated over, including $m_J=0$
  - would probe Landau pole of QCD → power corerctions
- All matching scales must depend on **physical** scales of the **observable**

$$\mu_h = \mu_h(p_T) \qquad \mu_J = \mu_J(p_T) \qquad \mu_s = \mu_s(p_T)$$

JET SCALE IS LOWER



What is going on **physically**?

THRESHOLD ENHANCEMENT

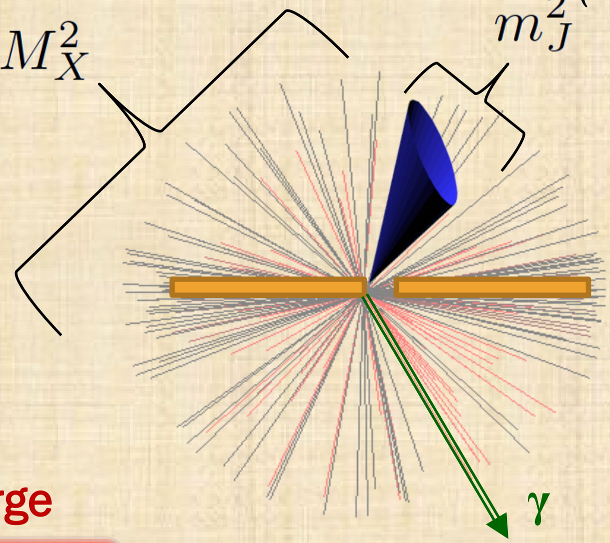
(mass everything but the photon) M_X^2

m_J^2 (mass of **jet)**

Machine threshold

$$M_X^2 \to 0 \qquad p_T \to \frac{E_{\rm CM}}{2}$$

- Where factorization theorem holds



Partonic threshold

$$m_J^2 \to 0$$

- Where partonic logs are large

large · **large** · **large**

$$M_X^2 = m_J^2 + (1-x_1)\frac{t}{s} + (1-x_2)\frac{u}{s}$$

small

•PDFs **die fast** as x → 1
- **Jet masses** are typically
    much **less** than the kinematic maximum

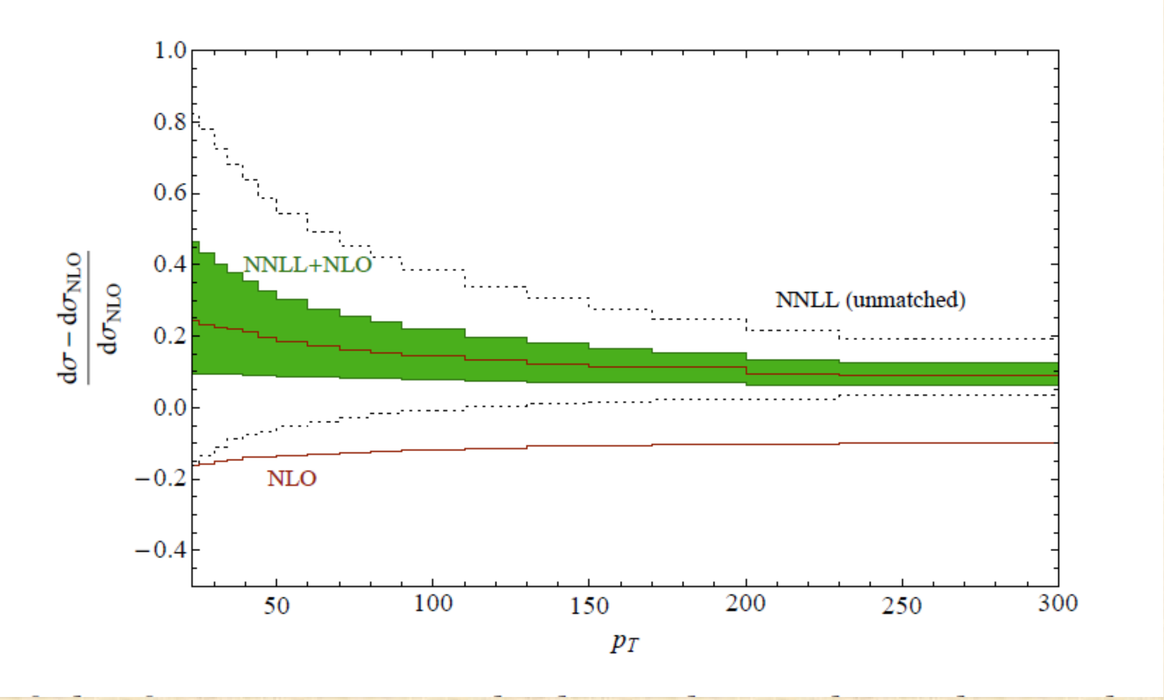
→ Use exact PDFs, resum logs of m_J^2

"Dynamical Threshold Enhancement" ⇒ **resummation** unexpectedly **useful** at hadron colllliders!

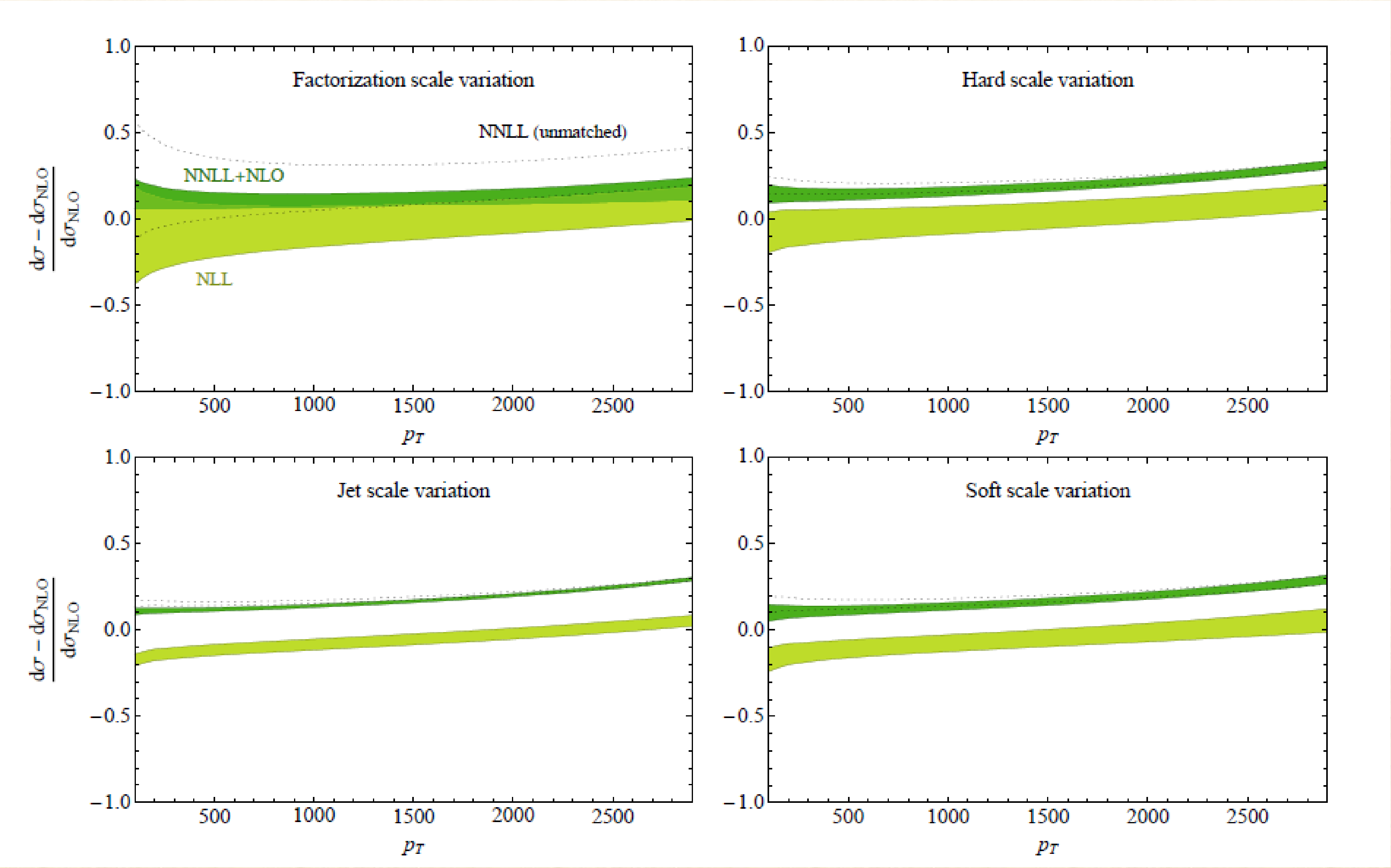
MATCHING

- SCET valid near threshold ($x_1 \sim 1$ and $x_2 \sim 1$)
- Matching to exact fixed order reduces μ_f dependence

$$\left(\frac{d^2\sigma}{dvdw}\right)^{\text{matched}} = \left(\frac{d^2\sigma}{dvdw}\right)^{\text{NNLL}} - \left(\frac{d^2\sigma}{dvdw}\right)^{\text{NNLL}}_{\mu_h=\mu_j=\mu_s=\mu_f} + \left(\frac{d^2\sigma}{dvdw}\right)^{\text{NLO}}_{\mu_f}$$

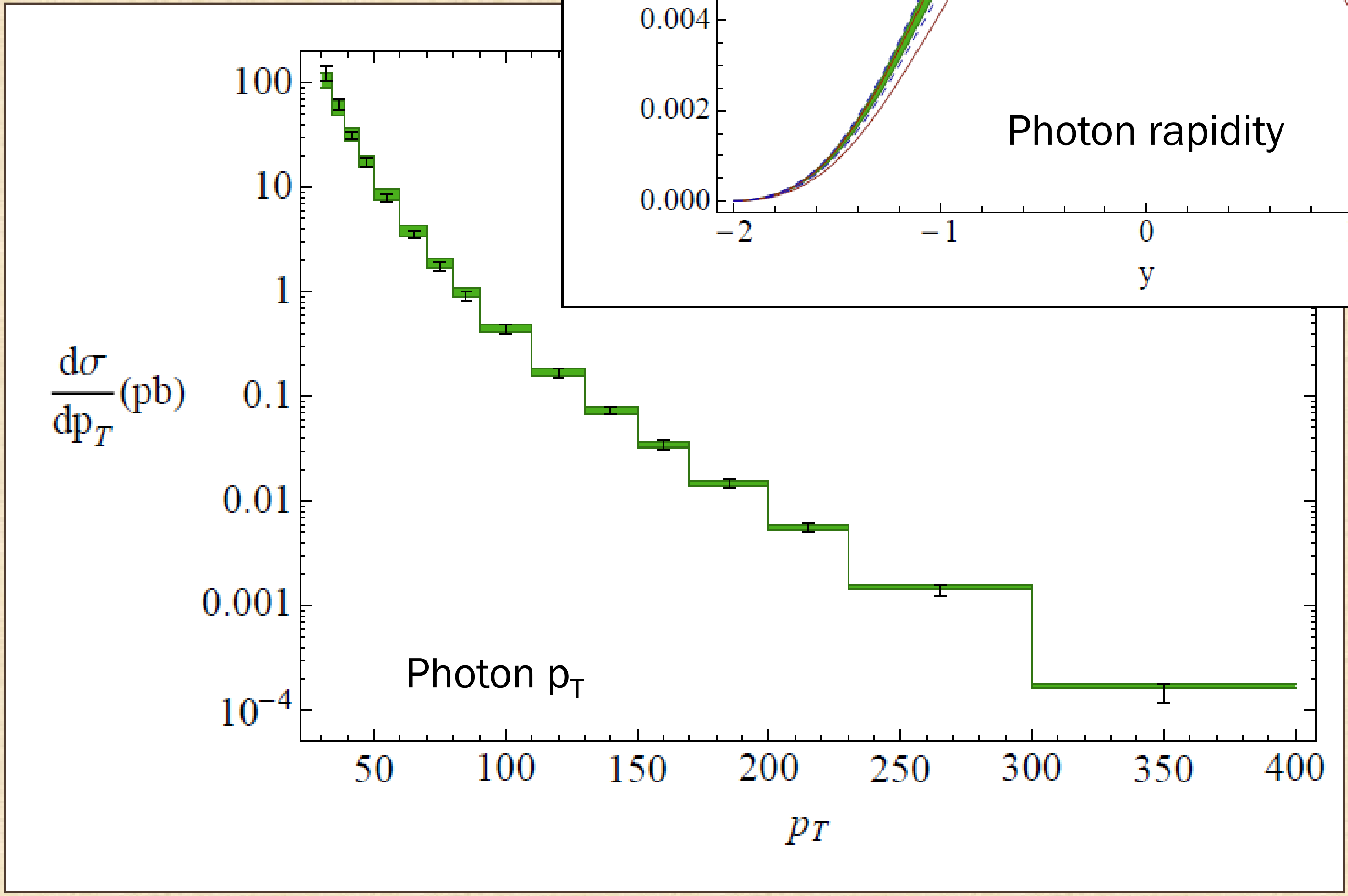


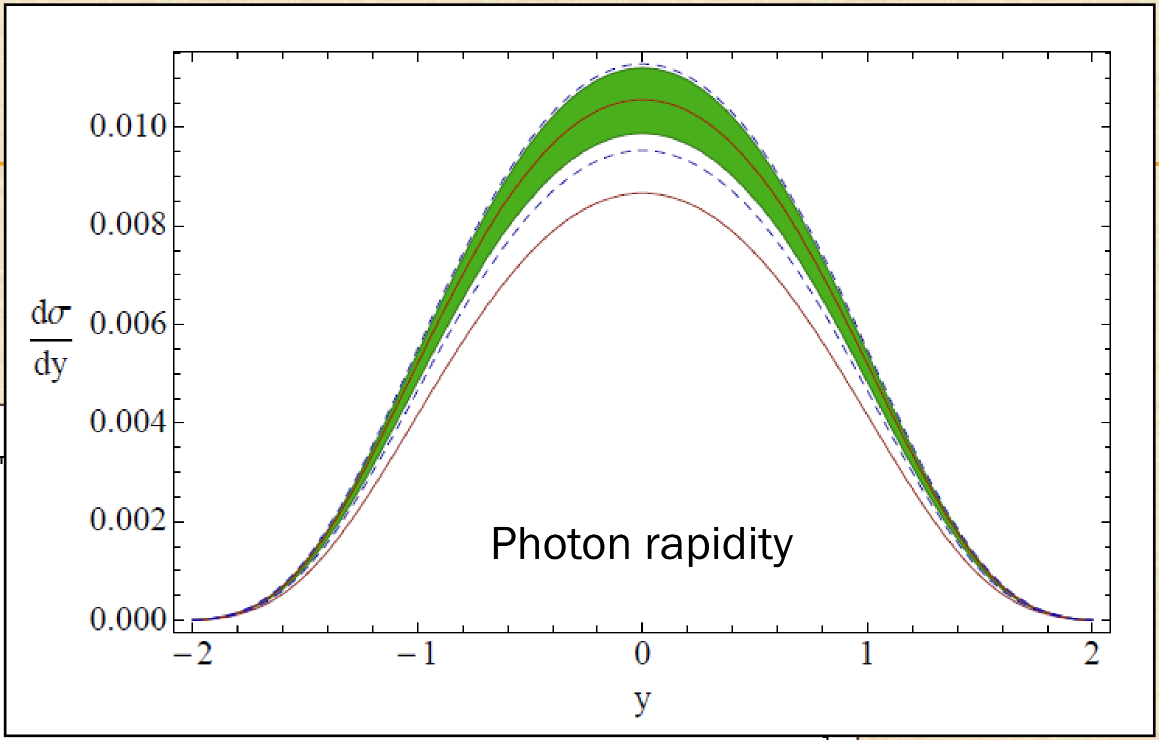
SCALE UNCERTAINTIES



RESULTS

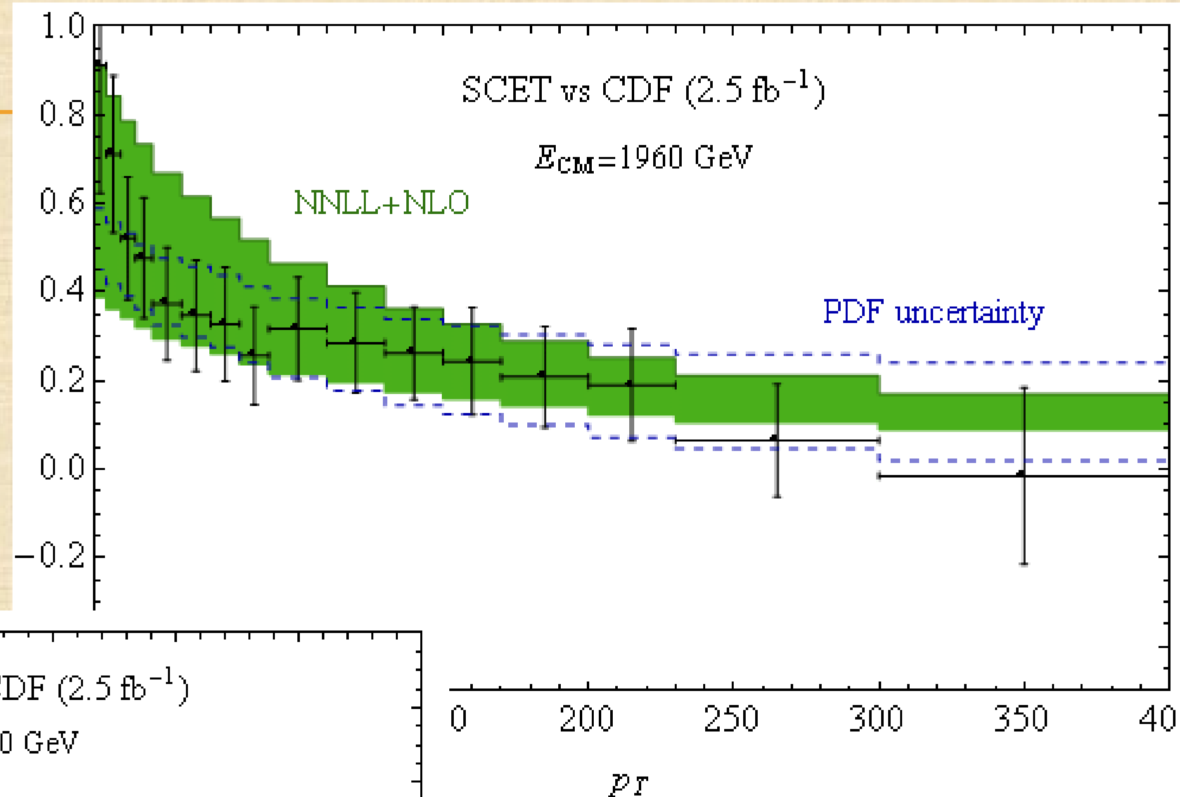
SCET vs CDF data

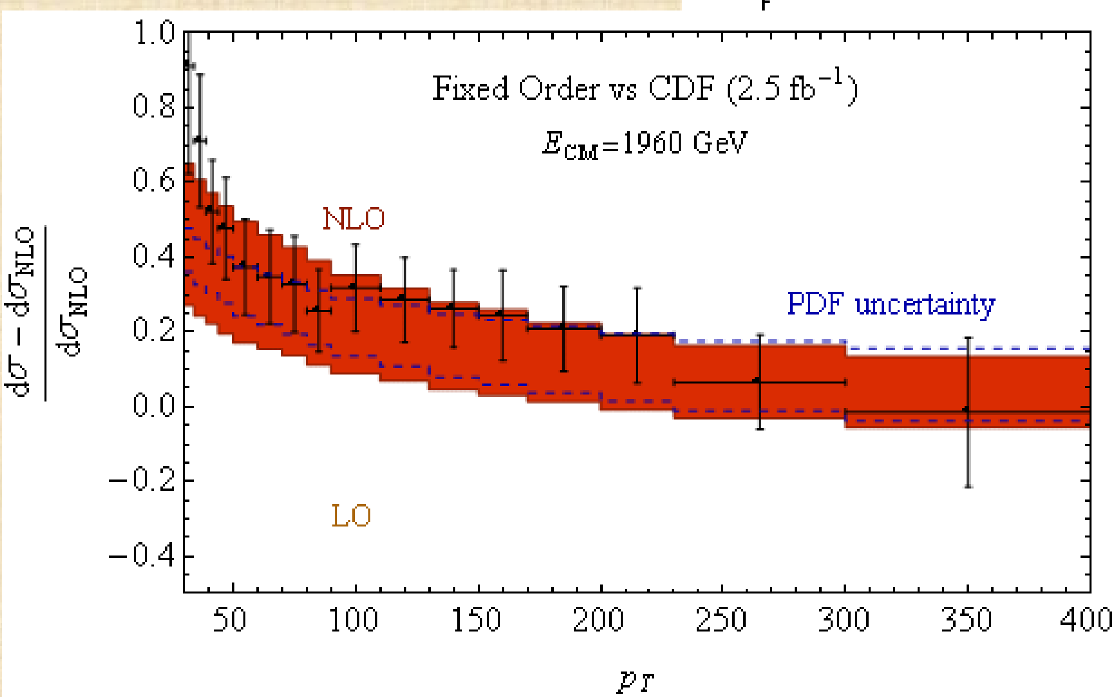




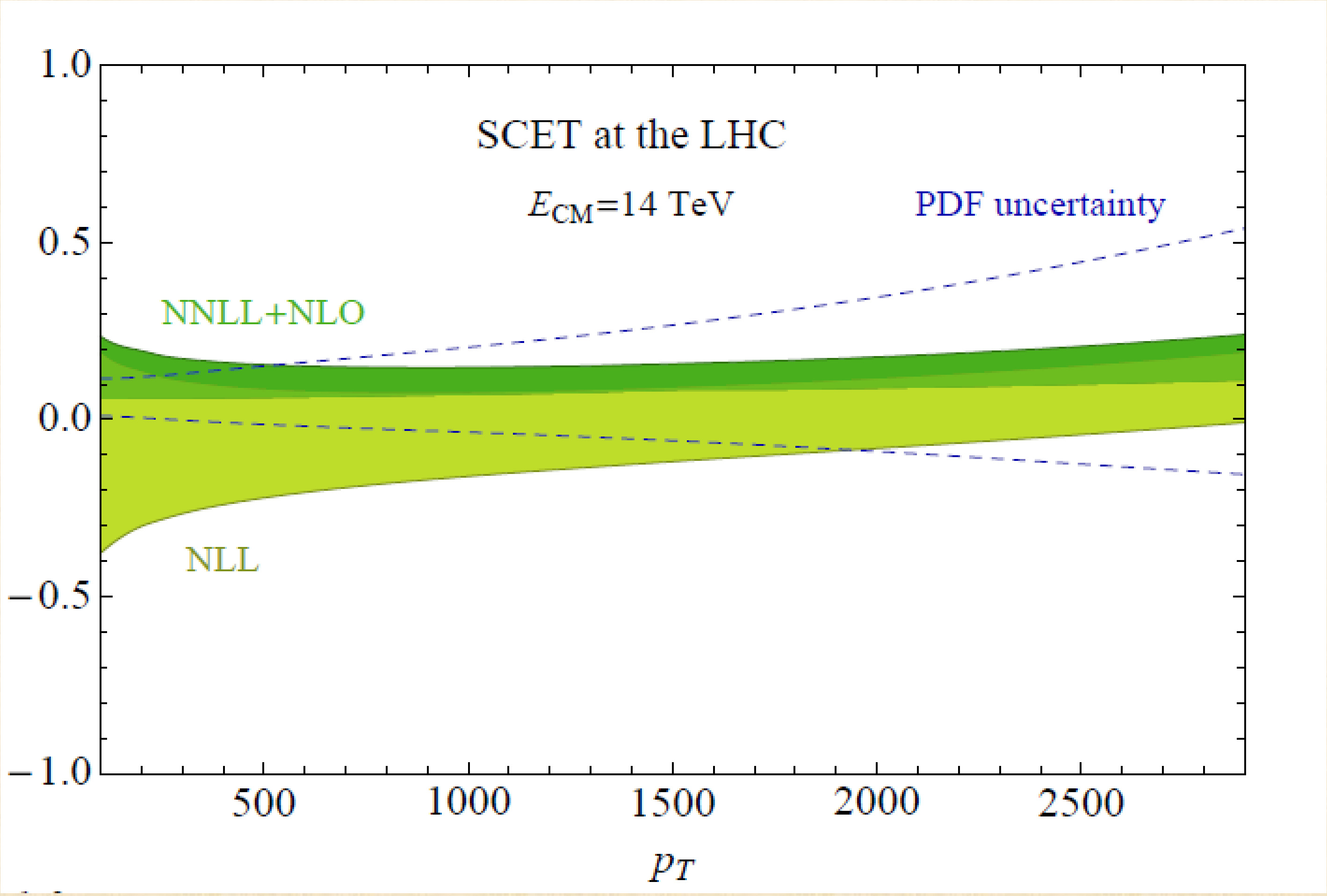
RESULTS

- Corrected for hadronization with PYTHIA
- Corrected for photon isolation with JETPHOX





PREDICTIONS FOR LHC



CONCLUSIONS

- Understanding jets is critical for the LHC
- Resummation can be done with SCET
  - Great improvements for LEP event shapes
  - Great improvements for direct photon spectrum
  - Resummation important even at moderate $x<1$
- Next steps
  - W/Z + jets (work in progress)
  - Dijets (work in progress)
  - Exclusive Monte Carlo event generation (on hold)