Direct Photon Production with SCET

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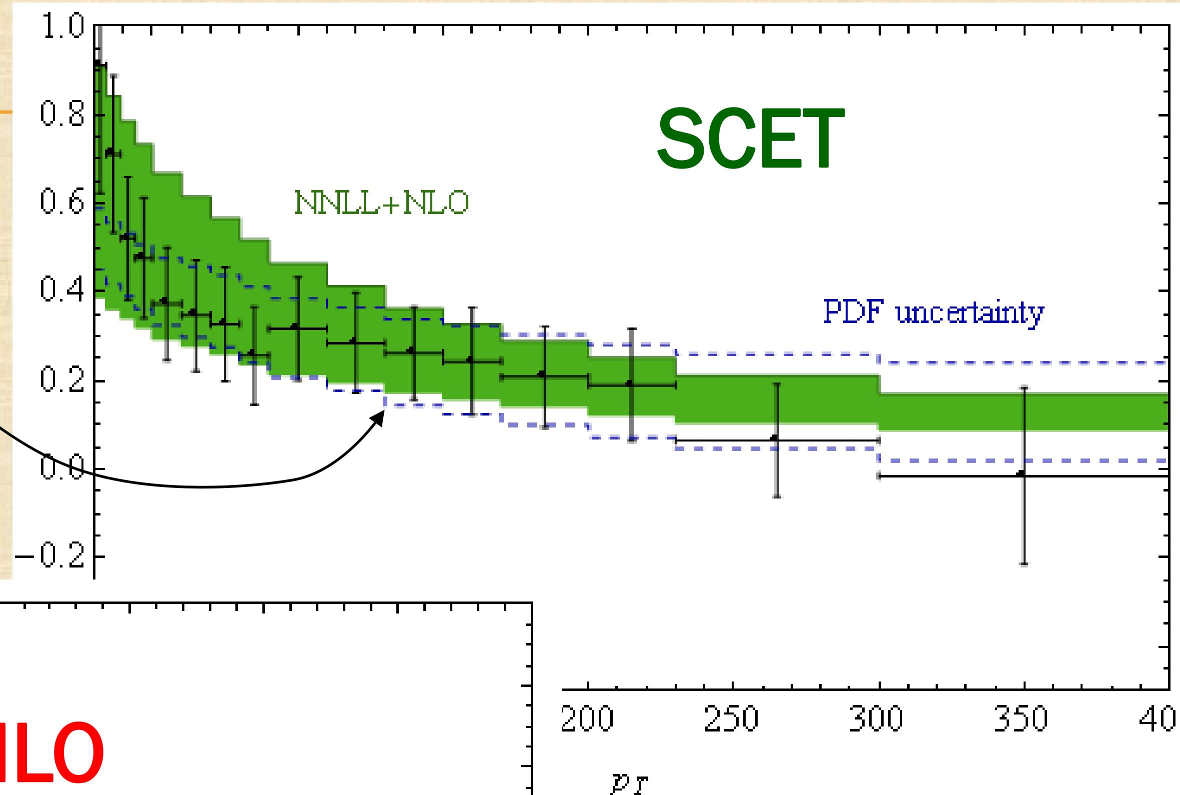
(work done with T. Becher)

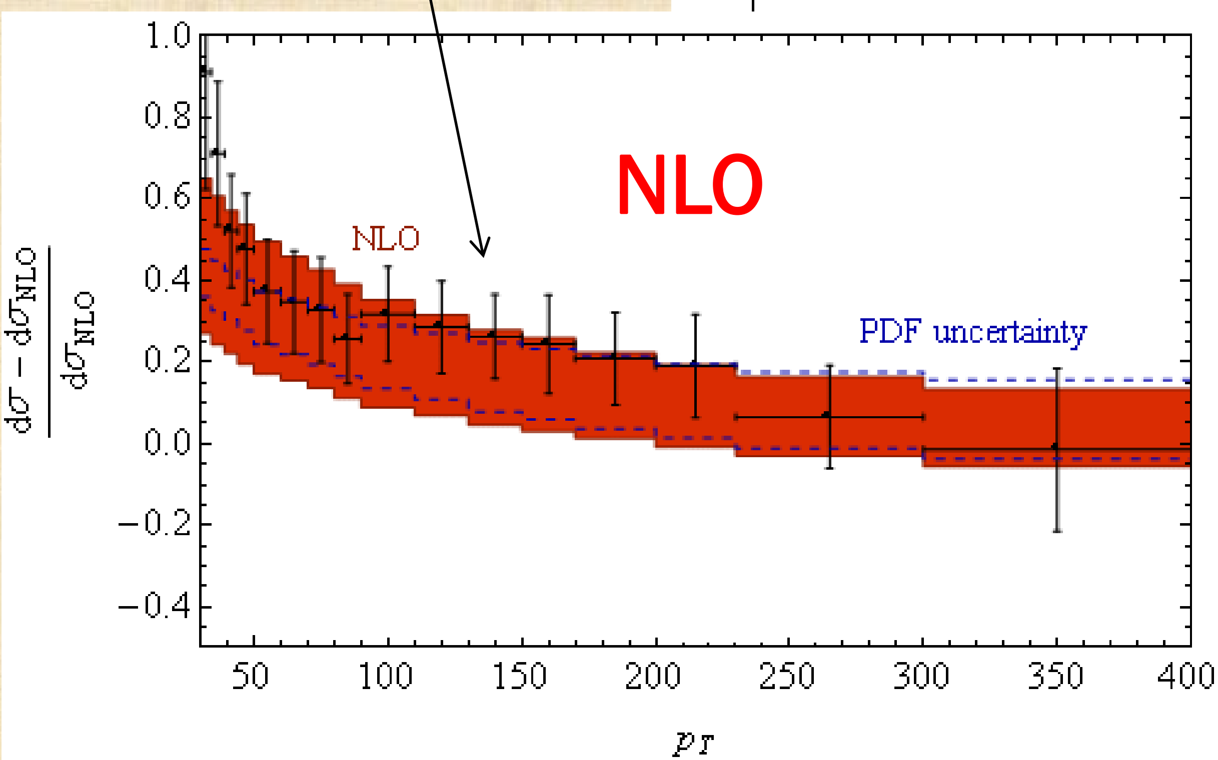
SCET workshop, Ringberg Castle, Munich

April 9, 2010

RESULTS

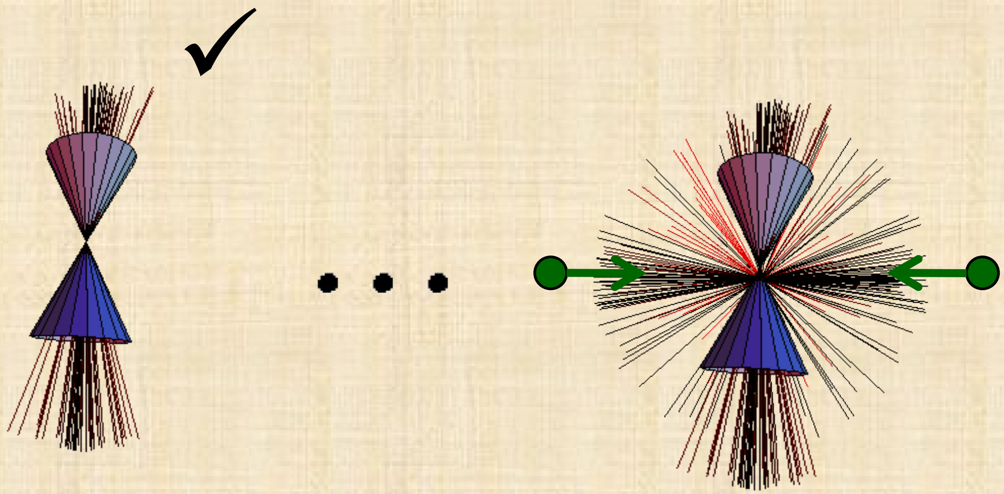
CDF data





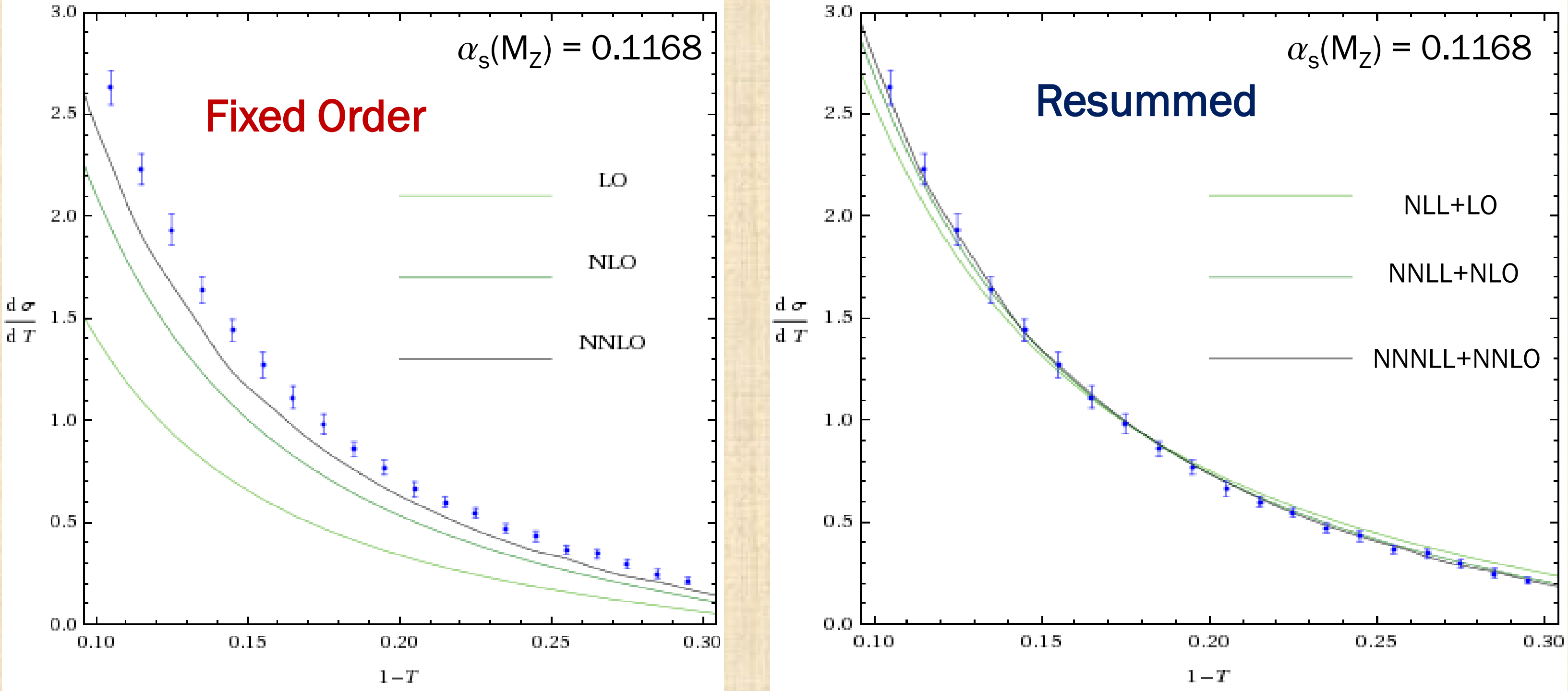
SCET AT COLLIDERS

We will start simple and head towards the LHC



$e^+e^- \to$ jets $\qquad$ $p^+p^+ \to$ jets

CONVERGENCE



We learn that Effective field theory

- Is much **more convergent** than fixed order QCD
- **Improves fit** to α_s tremendously

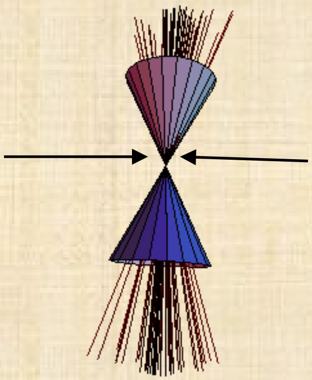
Becher/ Schwartz $\alpha_s(M_Z) = 0.1172 \pm 2\%$

Abate et al $\alpha_s(M_Z) = 0.1135 \pm 1\%$

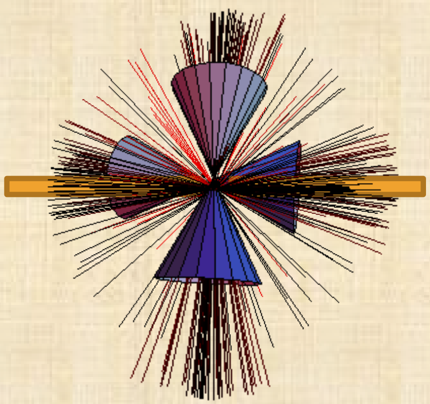
$\alpha_s(M_Z) = 0.1274 \pm 5\%$ (fixed order thrust)

$\alpha_s(M_Z) = 0.1176 \pm 2\%$ (World Average)

JETS AT HADRON COLLIDERS



$e^+e^- \rightarrow$ jets



$pp \rightarrow$ jets

Additional Complications

1. Energy distribution in hadrons is non-perturbative ✓
   - Use PDFs
   - Understood in SCET (Drell-Yan, DIS, Higgs production)

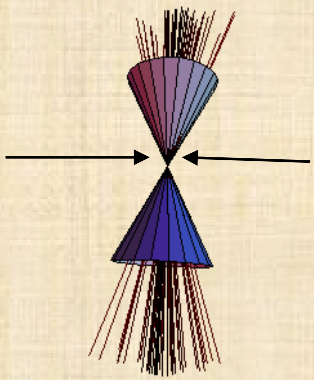
2. Multiple directions of large energy flow
   - Will angle dependence cancel?

3. Multiple channels
   - $QQ \rightarrow QQ$, $QQ \rightarrow GG$, $GG \rightarrow GG$ ✓
   - Understood for tt, heavy colored states, ...

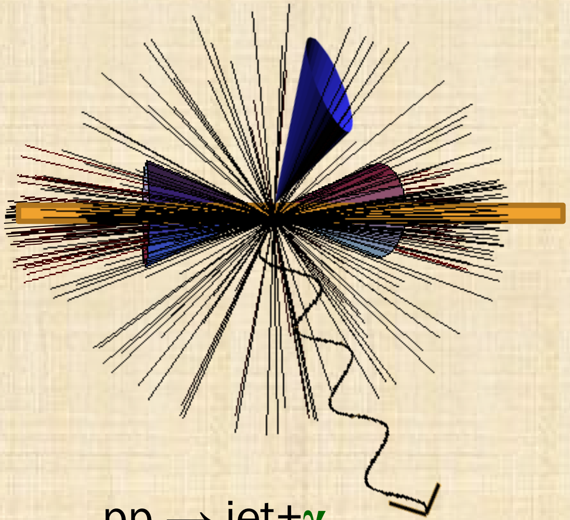
4. Multiple color configurations ✓
   - Dijets understood in traditional QCD
   - Now understood in SCET (Randy's talk, tt, ...)

5. Observable must avoid beam
   - Hadronic event shapes? [Salam, Zanderighi...]
   - Energy flow? [Sterman, Kucs, ...]
   - Beam thrust? [Stewart, ...]
   - Dynamical Threshold Enhancement? [Becher, Neubert...]

JETS AT HADRON COLLIDERS

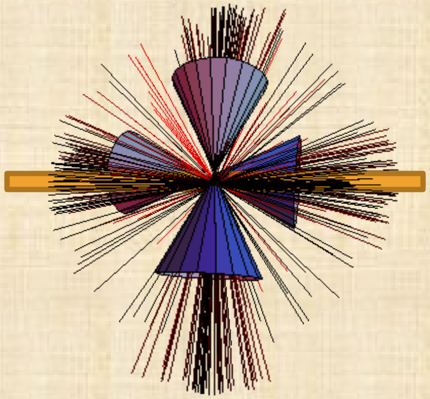


$e^+e^- \rightarrow$ jets



pp → jet+γ γ

<u>Direct photon production</u>



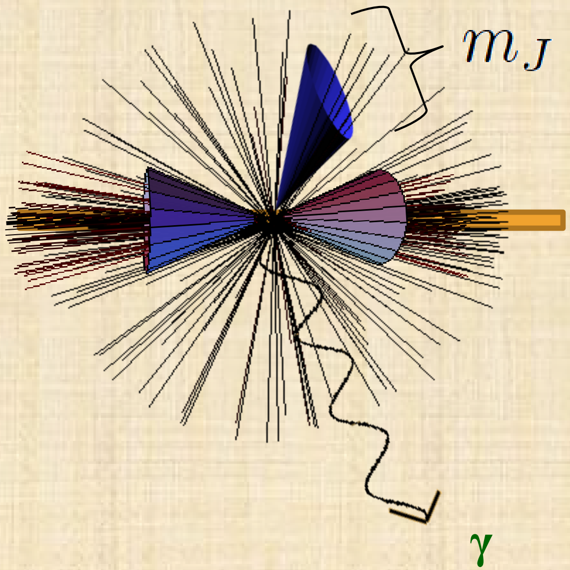
pp → jets

- Addresses some of the additional complications

  2. Multiple Directions
  3. Multiple Channels (QQ→ G γ and QG→ Qγ)

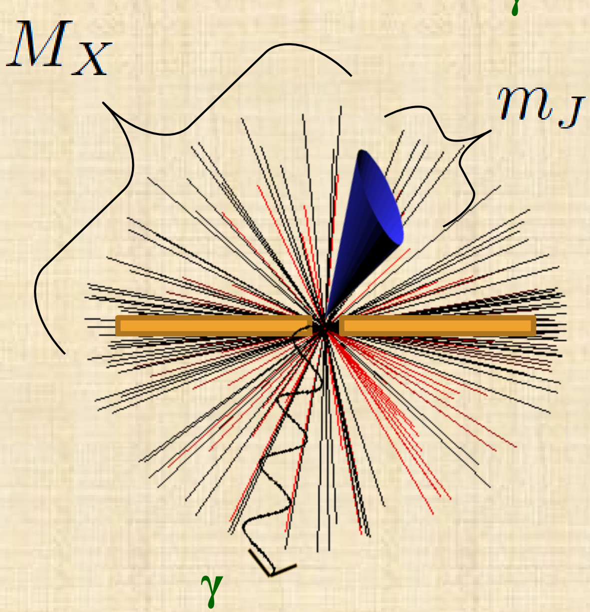
- Important early LHC measurement
  - measure **gluon PDF**
  - calibrate **jet energy scales**

WHAT IS THE OBSERVABLE?



- We want to measure the **jet mass** m_J^2
- We expect **resummation** to be **important** as $m_J^2 \to 0$
- Simplest observables will have few parameters
  - Can we **avoid** dealing with **jet definition**?

  (non-global logs? Start simple!)



Assumption for
SCET factorization theorem

Machine Threshold limit

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

  (no jet-like proton remnants)

Observable is photon p_T and rapidity (y)

- **Inclusive** measurment -- no jet definition necessary

Factorization derived at small M_X

M_X = mass of everything-but-the-photon

$$M_X^2 = {E_{\rm CM}}^2 - 2 p_T E_{\rm CM} \cosh y$$

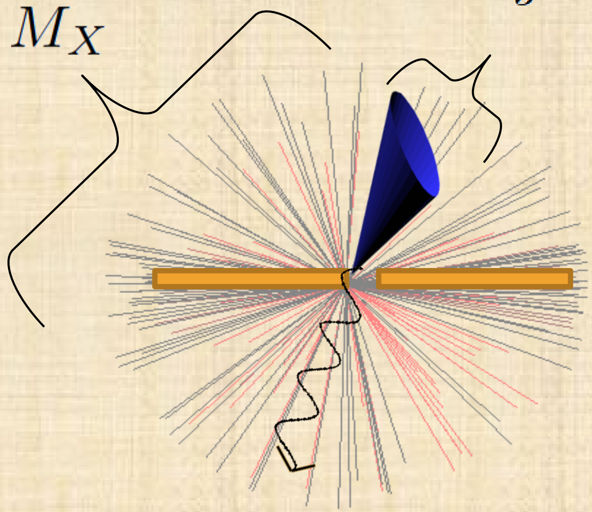
- M_X typically large – so **why is this regime interesting**?

THRESHOLD ENHANCEMENT

(mass of everything but the photon)

M_X

m_J (mass of **jet)**



Machine threshold

$$M_X \to 0$$

- Assumed for SCET calculation

Partonic threshold

$$m_J \to 0$$

- Where partonic logs are large

Typical event

large | large | large

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

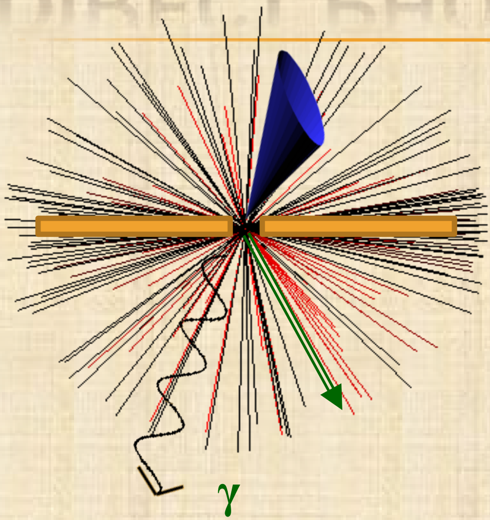
small

logs = logs + logs + logs

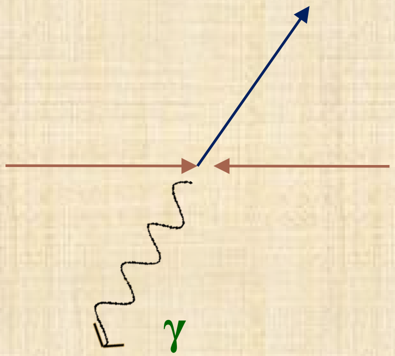
- typical x << 1
- Most of large M_X comes from proton remnants

•**jet masses** are typically small (as we know) → expect some logs still large

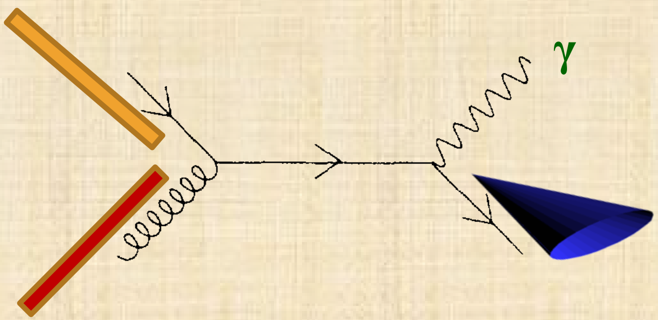
DIRECT PHOTON PRODUCTION

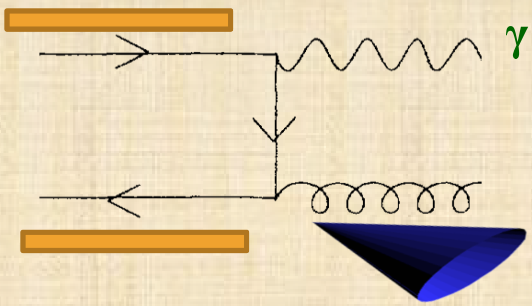


Perturbation Theory



Leading Order



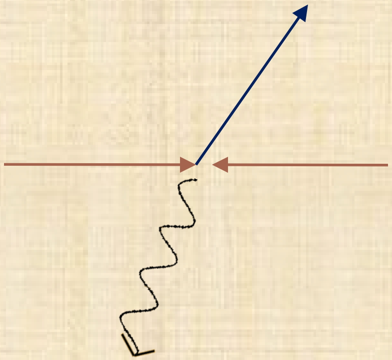


Compton Channel
(important way to measure gluon PDF)

Annihilation Channel

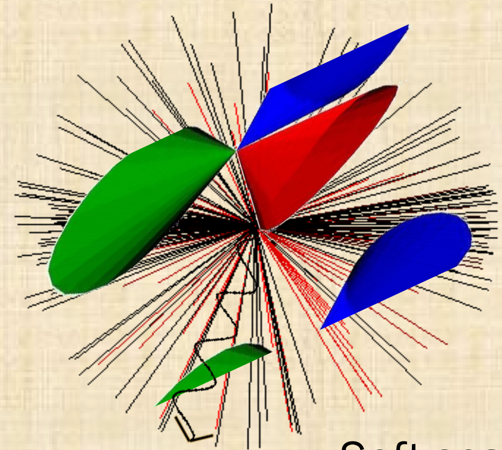
FACTORIZATION IN SCET

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



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

Jet function

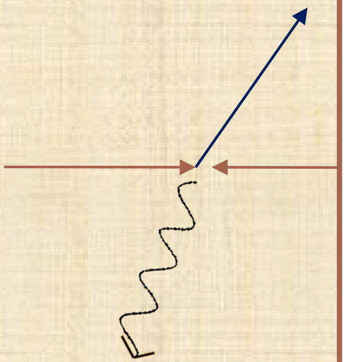
PDF

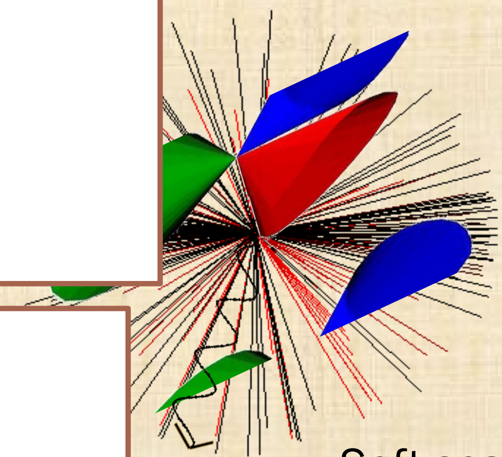
Soft function

FACTORIZATION IN SCET

$$\mathcal{O}^\nu = \bar\psi_{n_1} A^\nu_{n_2} \psi_{n_3}$$

$Y_2 \mathcal{A}_2^{\nu a} \tau^a Y_2^\dagger Y_3 \chi_3$





Derivation in SCET is really clean

(students can understand it)

(even *I* understand it)

$\langle p_1\, p_2|\mathcal{O}^\nu(x)\mathcal{O}^\nu($

$\langle p_1|\bar\chi_3\chi_3|p_1\rangle$

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

PDF

PDF

Jet function

Soft function

FINAL DISTRIBUTION

PDF $\langle p_1|\bar{\chi}_1\chi_1|p_1\rangle$ — PDF $\langle p_1|\bar{\chi}_3\chi_3|p_1\rangle$

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

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

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

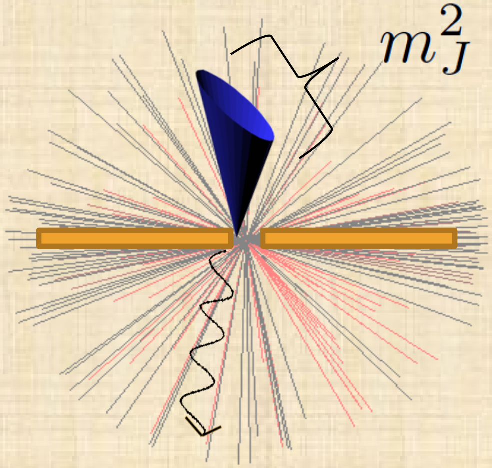
WHAT ARE THE MATCHING SCALES?

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?



m_J^2 = mass of **jet**

- **Works** for **thrust**

$$\frac{d\sigma}{dm_J^2} \sim \exp\left[\alpha_s \log\frac{m_J^2}{E_{\mathrm{CM}}^2}\right]$$

- **Problematic** for direct photon
  - m_J is integrated over, including $m_J = 0$

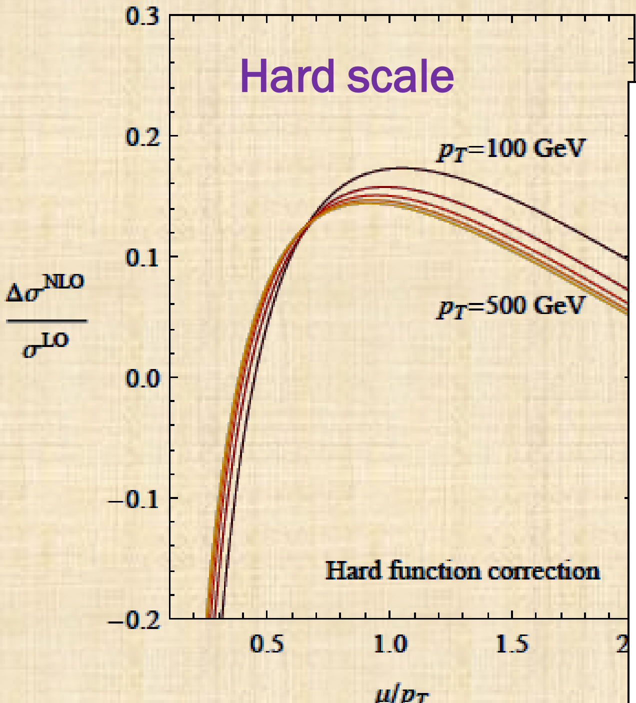
$$\frac{d\sigma}{dM_X^2} = \int dm_J^2 \, \delta\!\left(M_X^2 - m_J^2 - (1-x_1)\frac{t}{s} - (1-x_2)\frac{u}{s}\right) f(m_J^2, \cdots)$$

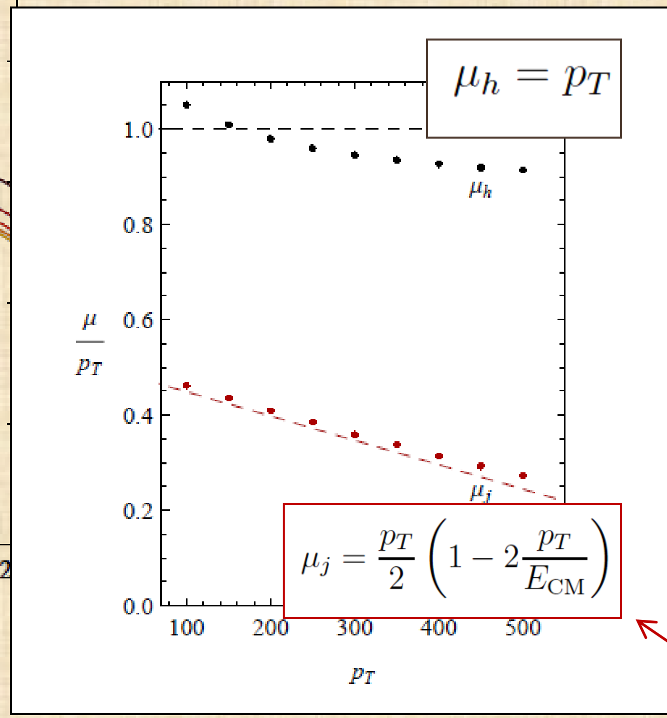
$$f \sim \exp\left[\alpha_s(\mu_J)\log\frac{\mu_J^2}{\mu_h^2}\right] \times \cdots \;\rightarrow \exp\left[\alpha_s(m_J)\log\frac{m_J^2}{p_T^2}\right] \times \cdots$$

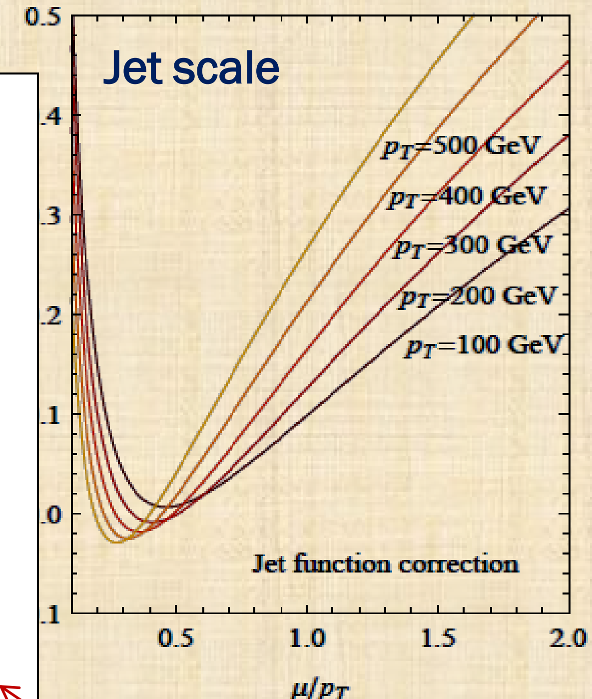
  - probes Landau pole of QCD → unphysical power corerctions

All matching scales should depend only physical, observable scales –*i.e.* p_T

NATURAL SCALES







So we take:

$$\mu_h = p_T$$
$$\mu_j = \frac{p_T}{2}\left(1 - 2\frac{p_T}{E_{\rm CM}}\right)$$
$$\mu_s = \mu_j^2/\mu_h$$

Always well above $\Lambda_{\rm QCD}$

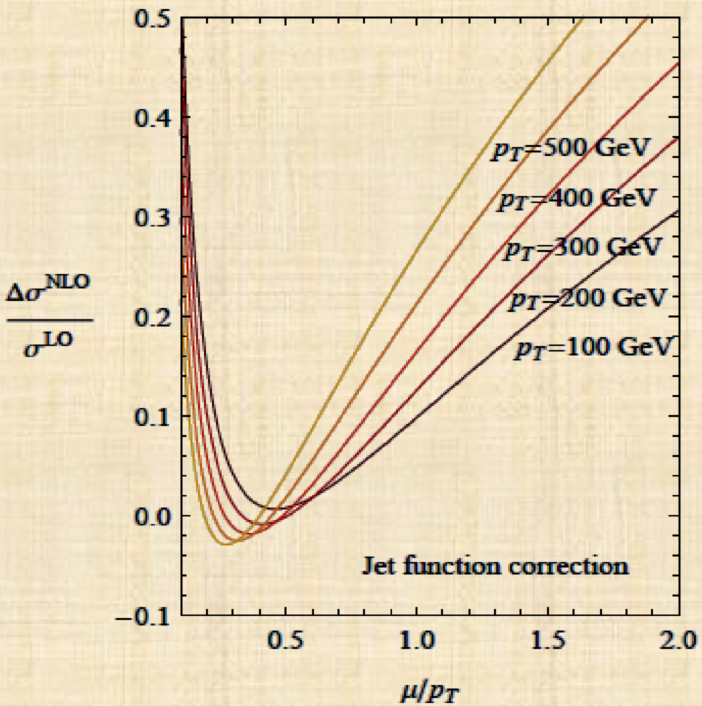
- avoids unphysical region

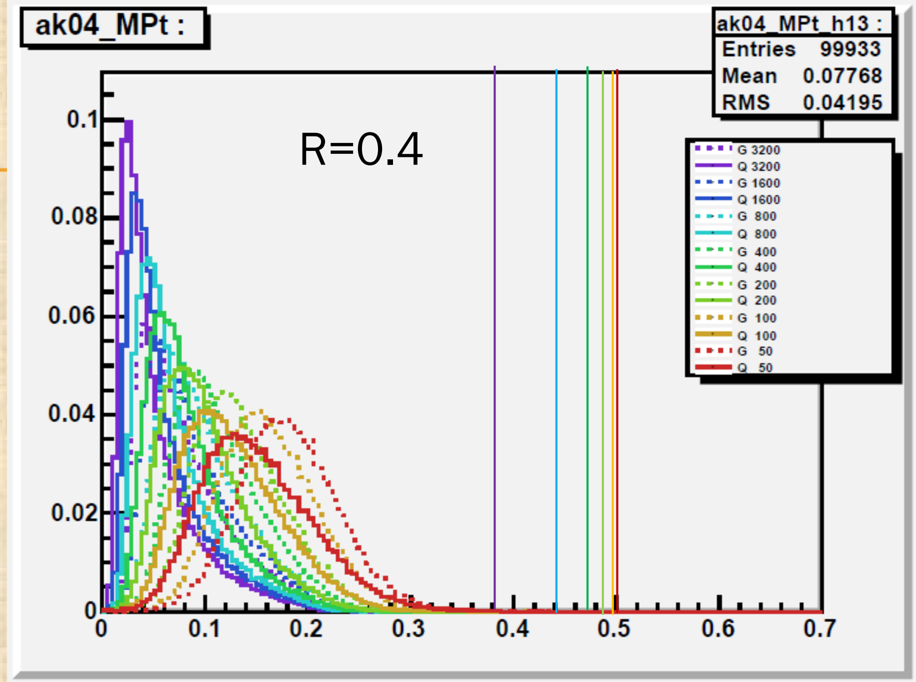
note that

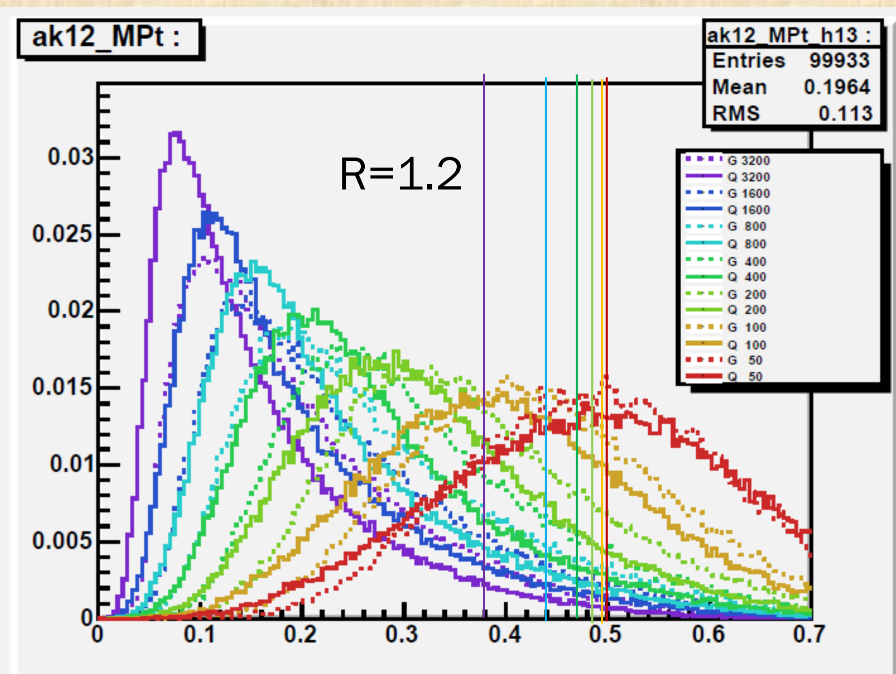
$$\mu_J = \langle m_J \rangle \lesssim p_T^\gamma$$

JET MASSES

Steve Ellis: “m = pt/5”



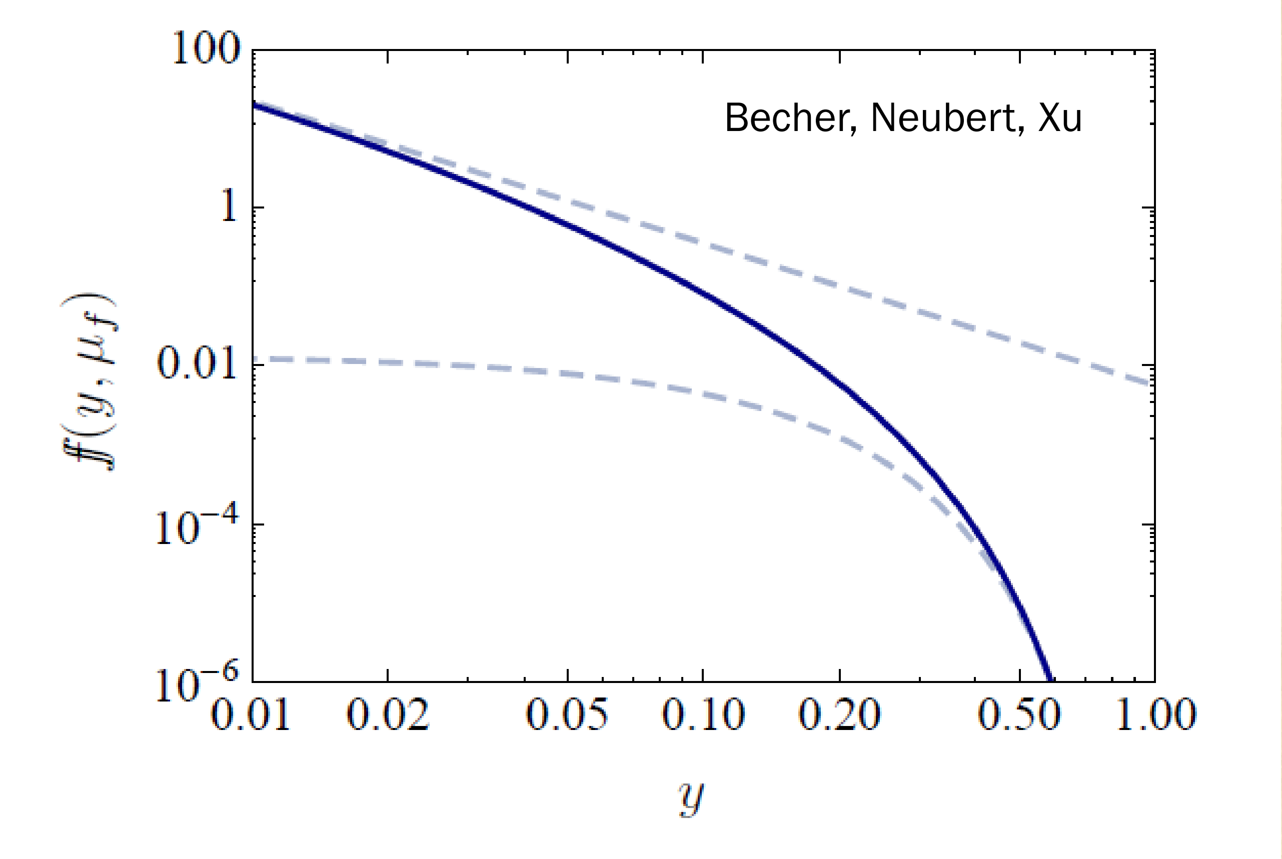




μ_J really is close to the mass of the partonic jet

DYNAMICAL THRESHOLD ENHANCEMENT

Some analytic understanding… $f\!\!f(y,\mu_f) \propto (1-y)^b$

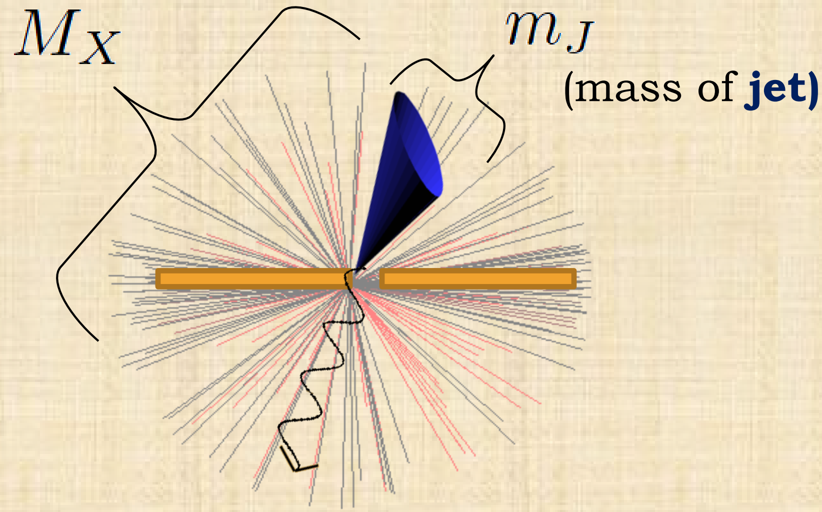


DYNAMICAL THRESHOLD ENHANCEMENT

(mass of everything but the photon)

We have found

$$\mu_J = \langle m_J \rangle \lesssim p_T^\gamma \lll M_X \sim E_{\mathrm{CM}}$$



large

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

small

Dynamical Threshold Enhancement

Resummation unexpectedly **important** at hadron collliders!

- What about x not being close to 1?

MATCHING

- PDFs evolve with DGLAP equations

$$\frac{d\, f_i(x,\mu)}{d\log\mu} \sim \int dz \left\{ \alpha_s \left[\frac{1+z^2}{1-z} \right]_+ + \cdots \right\} f_i(\frac{x}{z},\mu)$$

  - μ_f dependence in exact NLO distribution cancels
    μ_f dependence of PDFs -- to order α_s^2

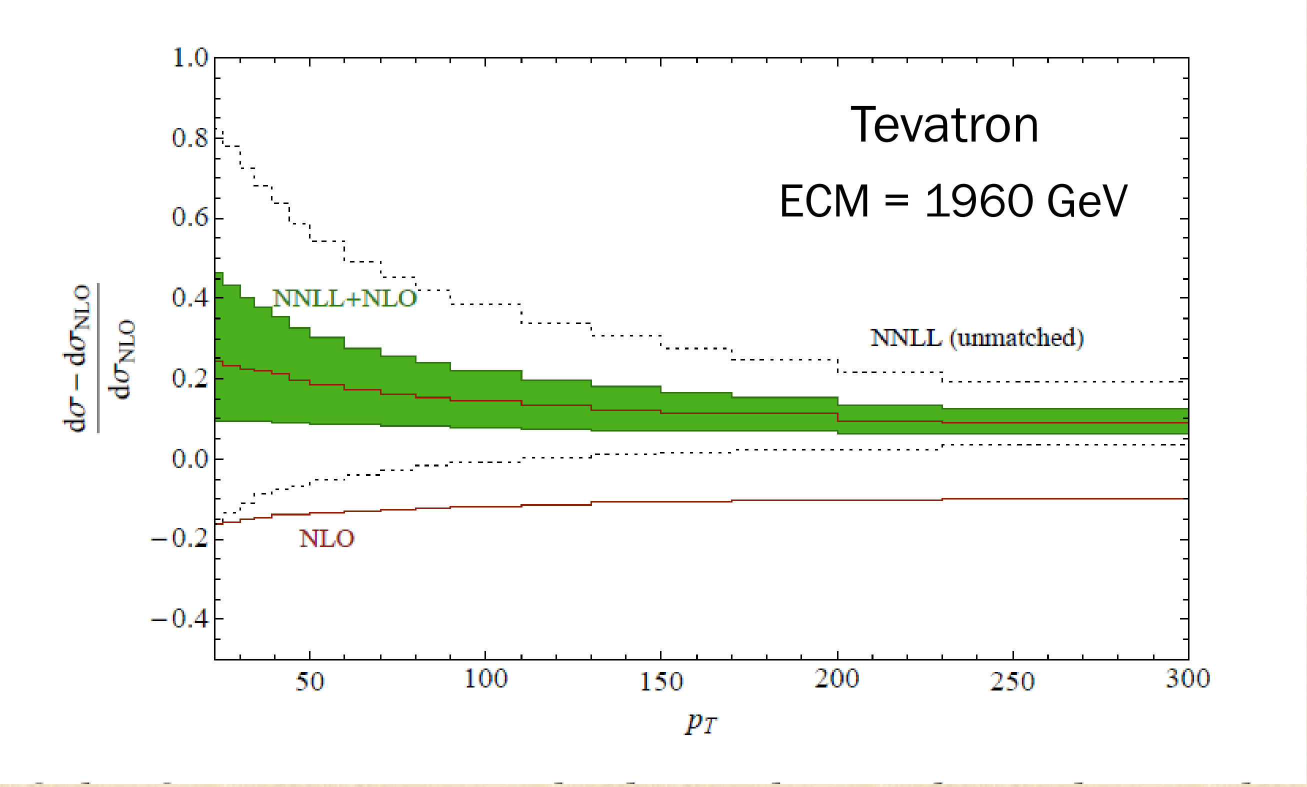
- SCET valid near threshold ($x_1 \sim 1$ and $x_2 \sim 1$)
  - μ_f would cancel if

$$\frac{d\, f_i(x,\mu)}{d\log\mu} \sim \int dz \left\{ \alpha_s \left[\frac{2}{1-z} \right]_+ + \cdots \right\} f_i(\frac{x}{z},\mu)$$

- By matching NNLL resummation to NLO fixed order
  - μ_f dependence cancels exactly to order α_s^2
  - μ_f dependence cancels partially to order α_s^4

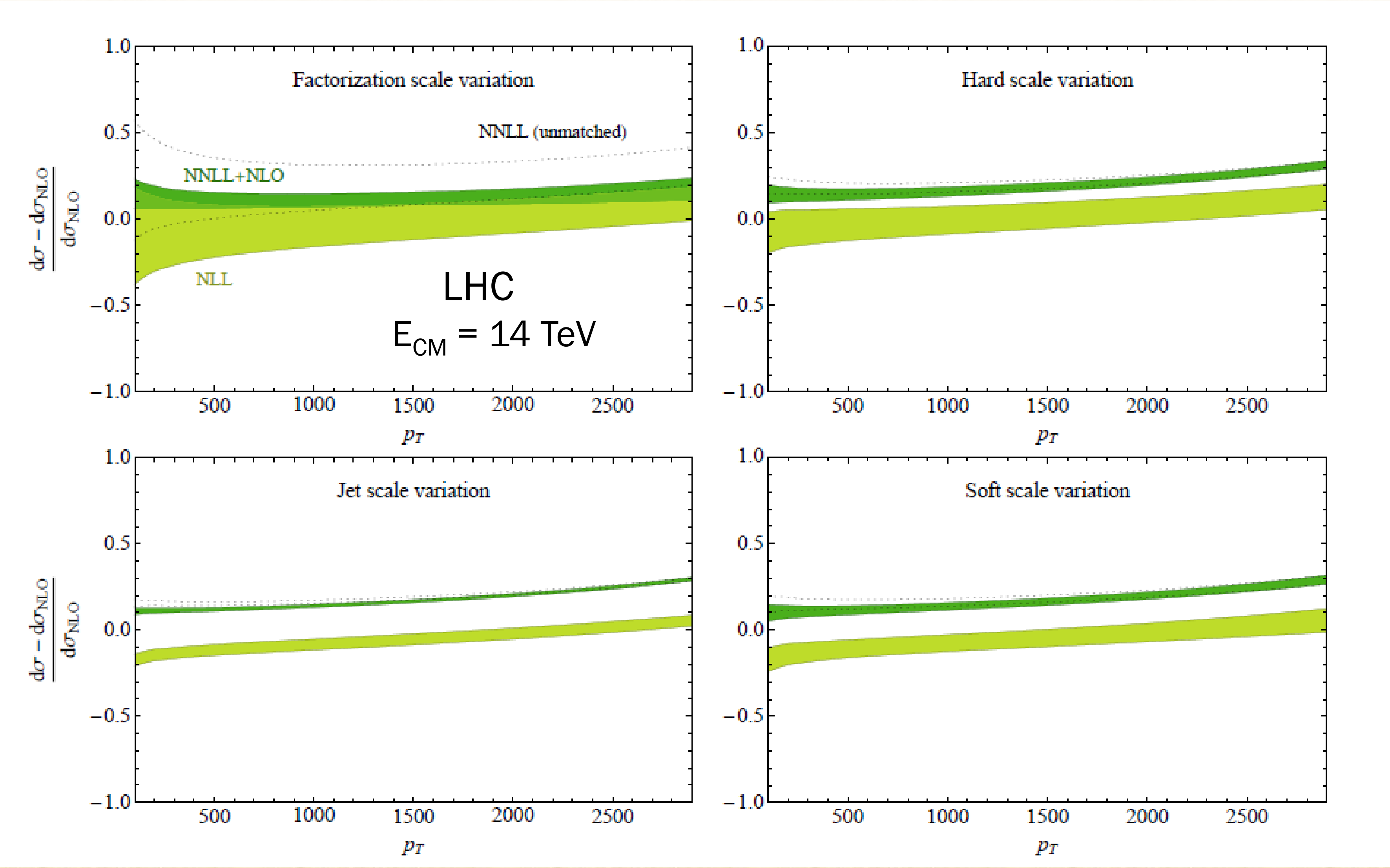
MATCHING

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



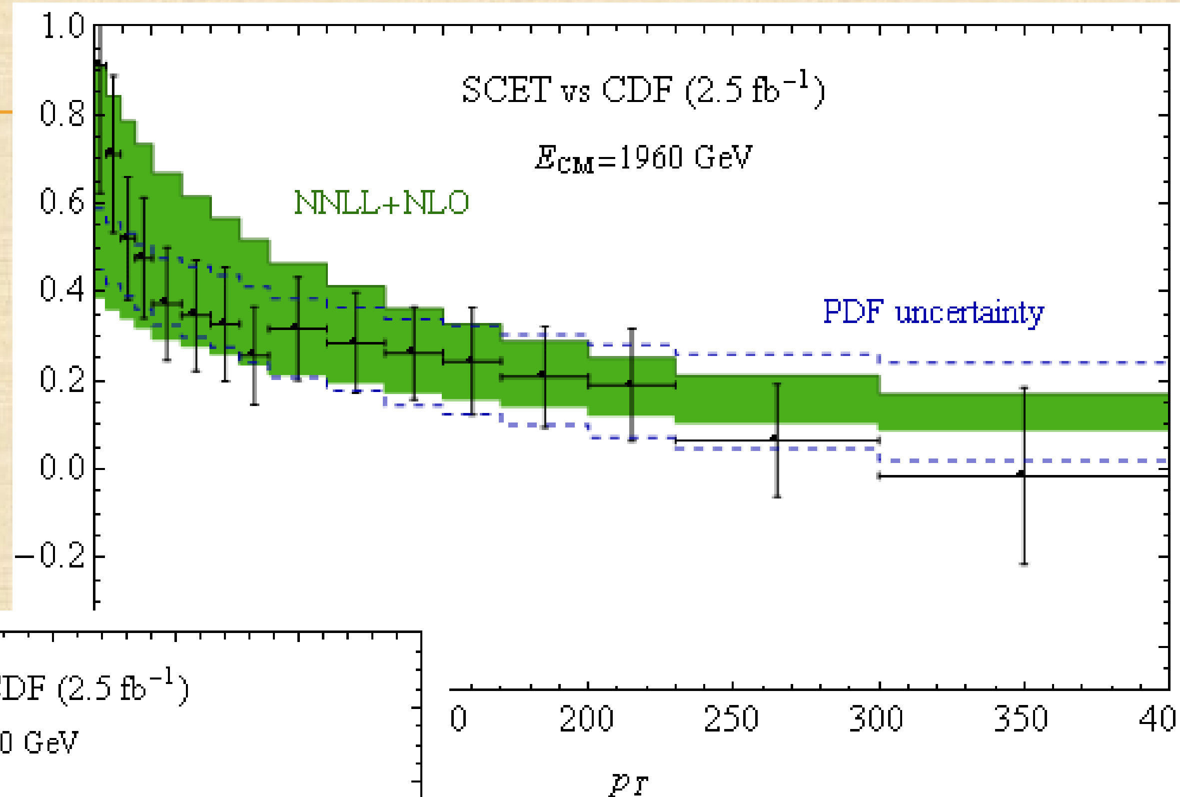
Matching to exact NLO distribution reduces μ_f dependence

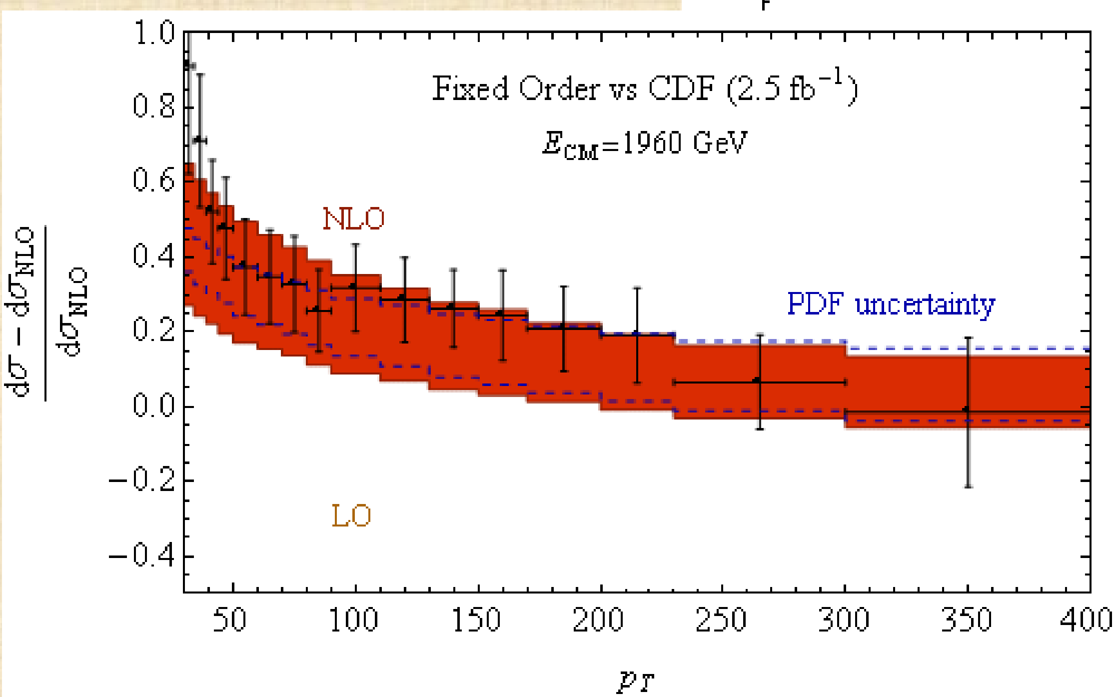
SCALE UNCERTAINTIES



RESULTS

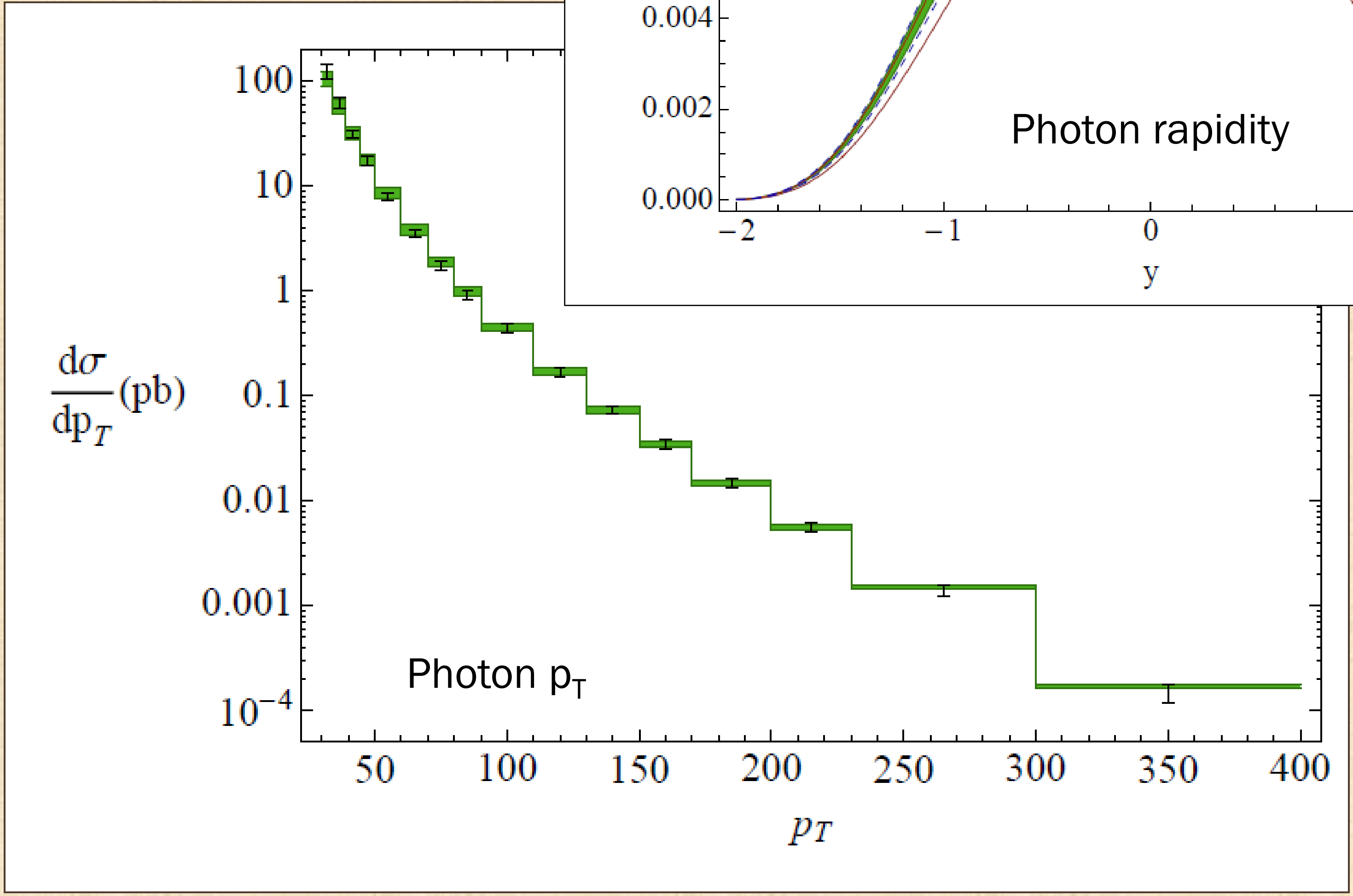
- Corrected for hadronization
  with PYTHIA
- Corrected for photon isolation
  with JETPHOX

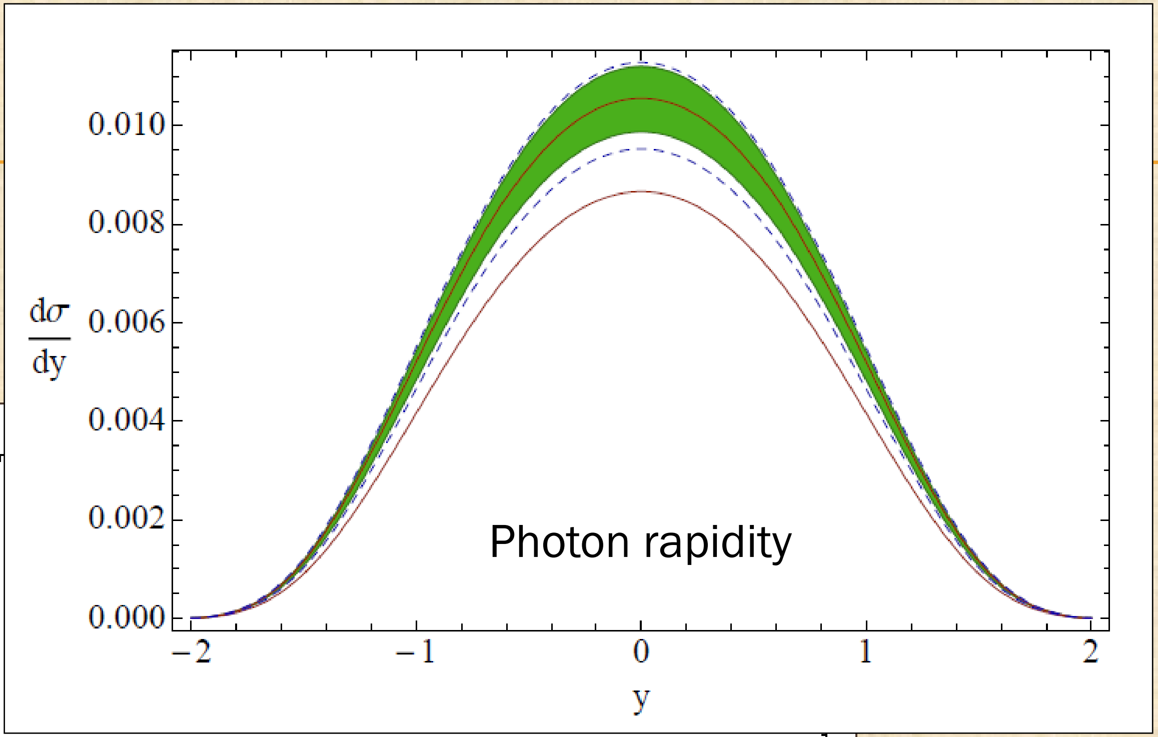




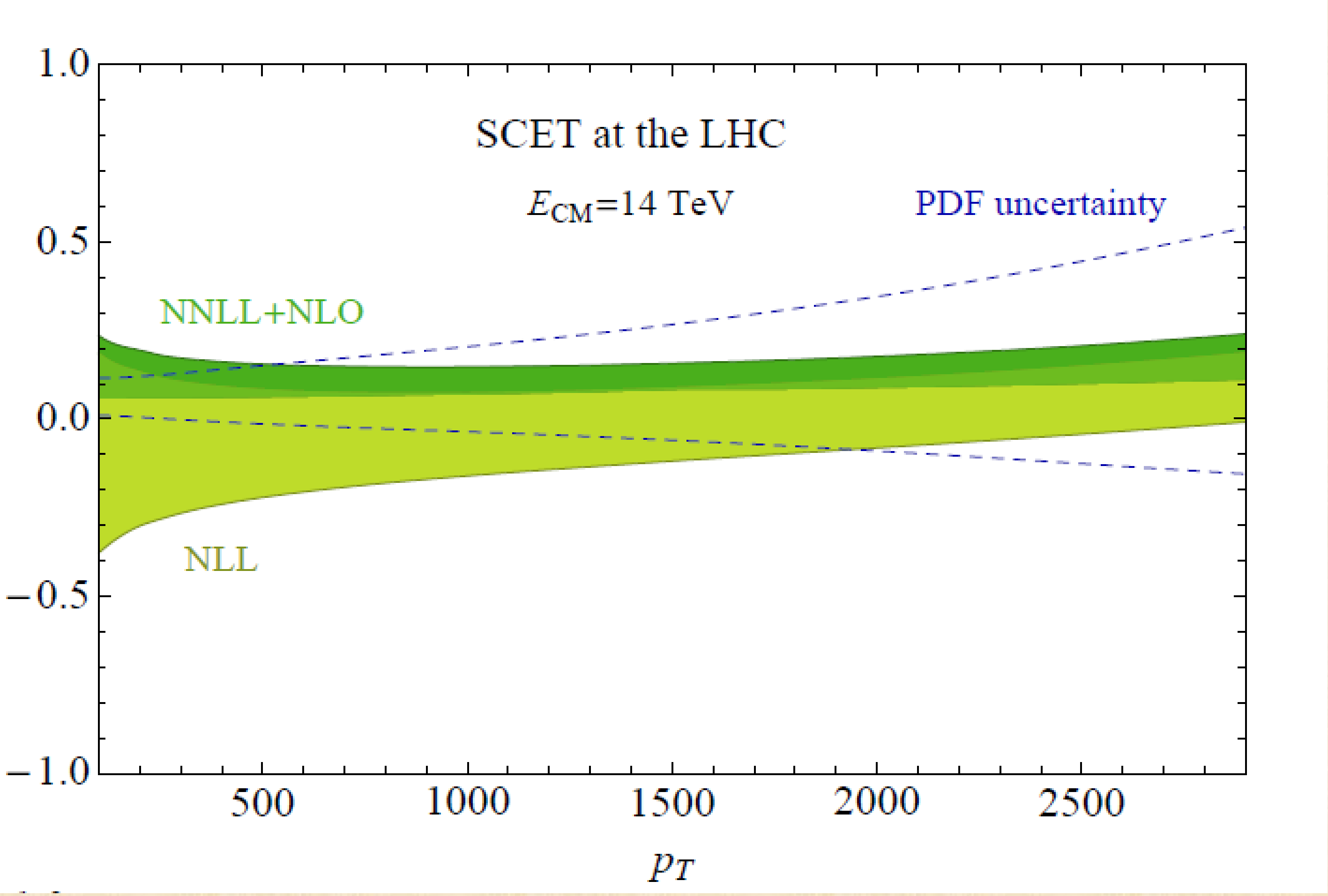
RESULTS

SCET vs CDF data

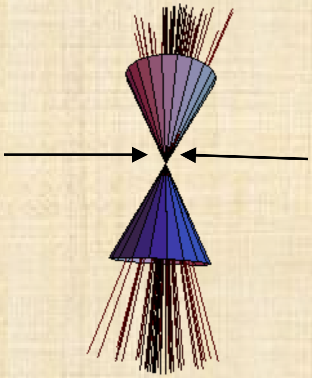




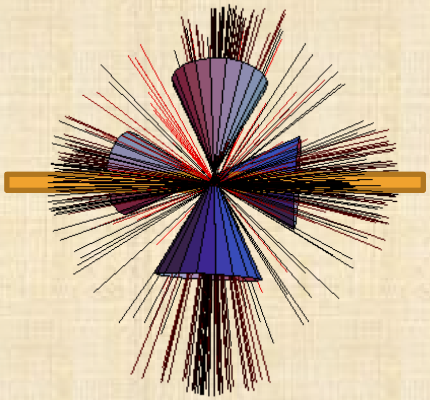
PREDICTIONS FOR LHC



CLOSE TO JETS SHAPES



$e^+e^- \longrightarrow$ jets



pp $\longrightarrow$ jets

Additional Complications

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   - Use PDFs
   - Understood in SCET (Drell-Yan, DIS, Higgs production)

2. Multiple directions of large energy flow ✓
   - Will angle dependence cancel? Yes.

3. Multiple channels ✓
   - QQ $\rightarrow$ QQ, QQ $\rightarrow$ GG, GG $\rightarrow$GG

4. Multiple color configurations ✓
   - Work in progress with R. Kelley

5. Observable must avoid beam
   - Beam functions?
   - Exclusive jets
   - Threshold Thrust -> jet pT?
   - Dynamical threshold enhancement?

LESSONS

- LEP event shapes
  - Convergence improved over fixed-order
  - Resummation at NNNLL possible and quantitatively important for jet masses
- Direct photon
  - NNLL resummation at hardon colliders **important**
  - Threshold resummation works *away from threshold*
  - x<1 evolution nicely **corrected with matching**
- Next steps
  - W/Z + **jets** (work in progress with T. Becher)
  - **Dijet RGEs**, color structures (work in progress with R. Kelley)
  - Observables, Jet algorithms (many other people)
- Understanding **jets** is **critical** for the LHC