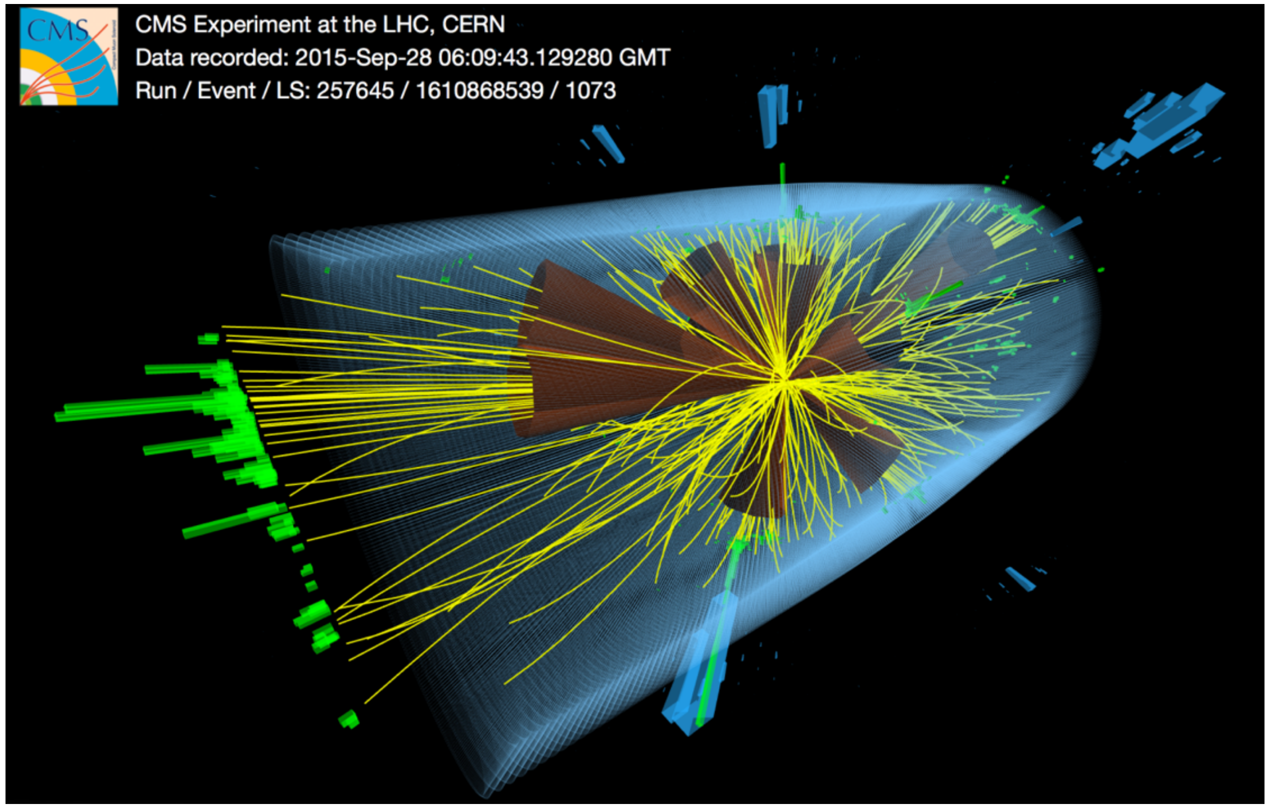
Jet angularities at the EIC

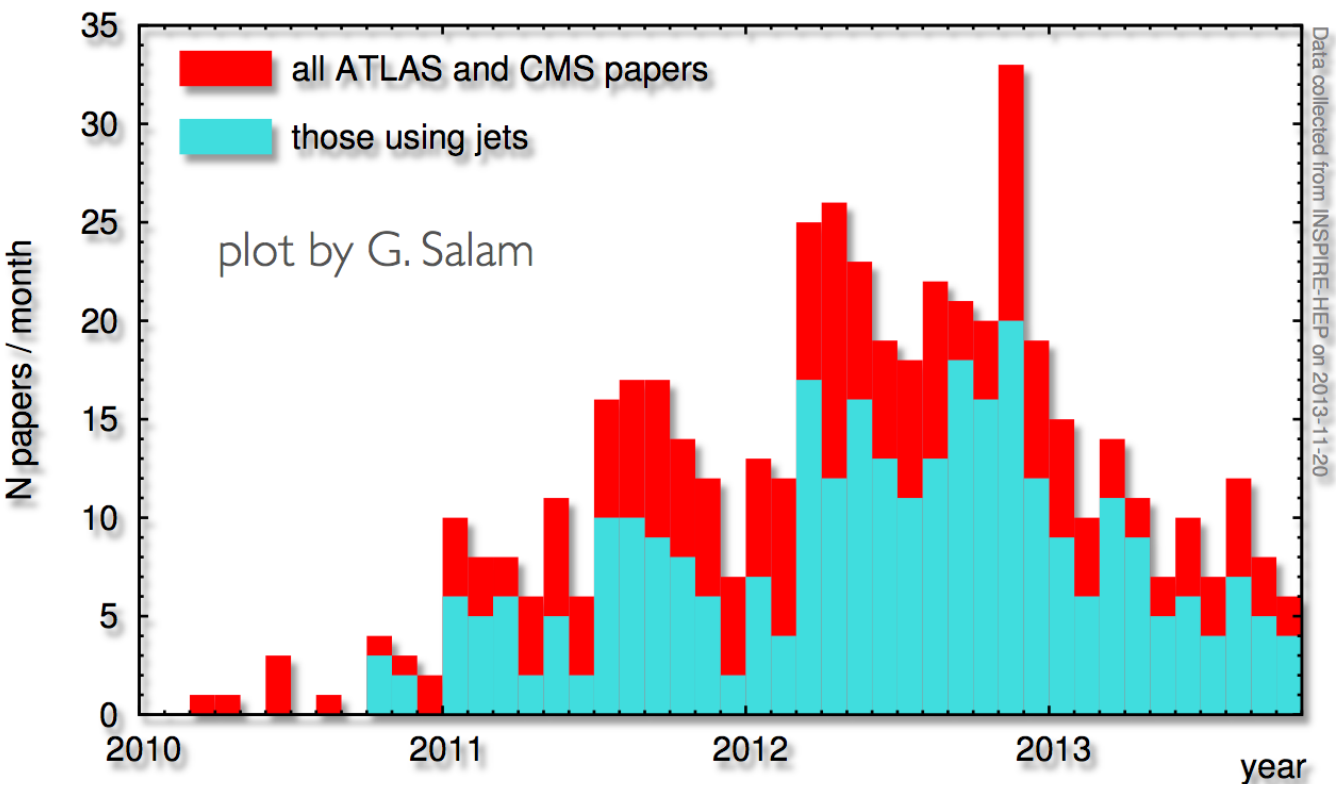
Kyle Lee
Stony Brook University

POETIC
09/16/19 - 09/21/19

Stony Brook University

Jets at the LHC

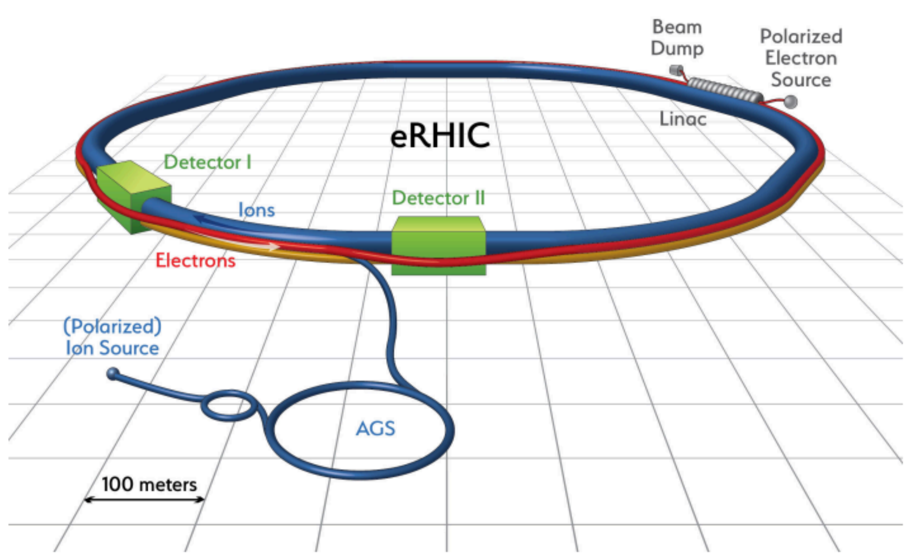


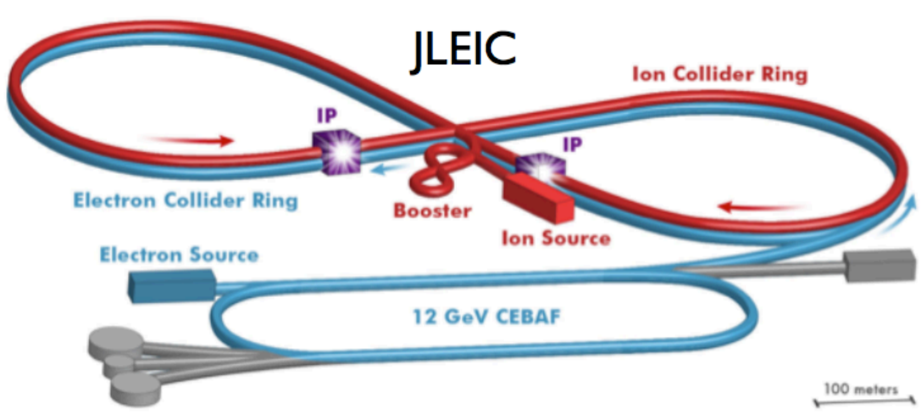


- Jets are produced copiously at the LHC

- At the LHC, 60 - 70 % of ATLAS & CMS papers use jets in their analysis!

Jets at the EIC

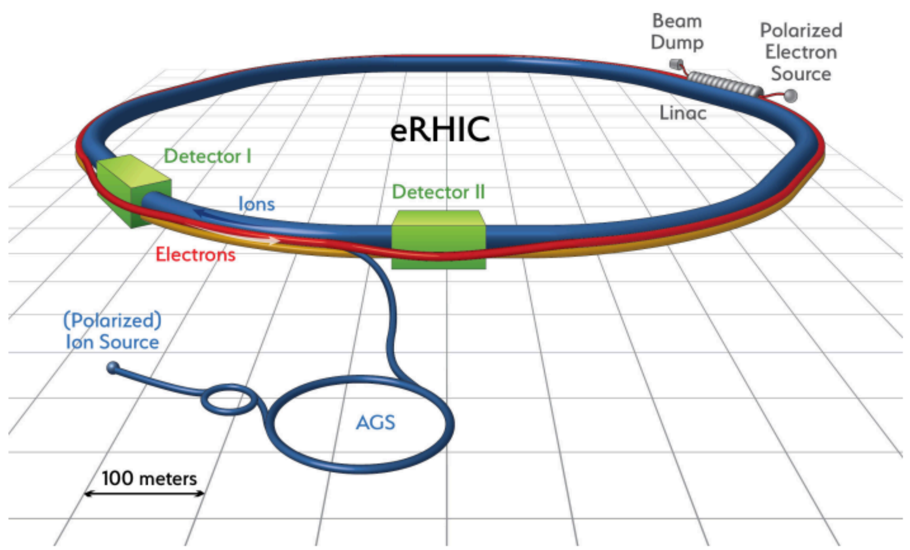


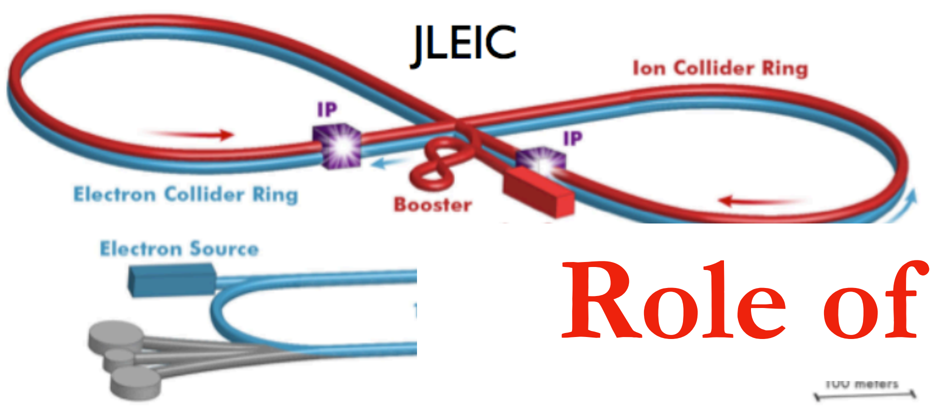


- $\sqrt{S_{\mathrm{EIC}}} \ll \sqrt{S_{\mathrm{LHC}}} \Leftrightarrow p_{T_J,\mathrm{EIC}} \ll p_{T_J,\mathrm{LHC}}$
  Lower $p_{T,J}$ for EIC
- $N_{J,EIC} \ll N_{J,LHC}$
  Smaller jet multiplicity for EIC
- Less contamination from underlying events and pileups

- **Different environment compared with the LHC and thus new opportunities and new challenges**

Jets at the EIC





- $\sqrt{S_{\mathrm{EIC}}} \ll \sqrt{S_{\mathrm{LHC}}} \Leftrightarrow p_{T_J,\mathrm{EIC}} \ll p_{T_J,\mathrm{LHC}}$
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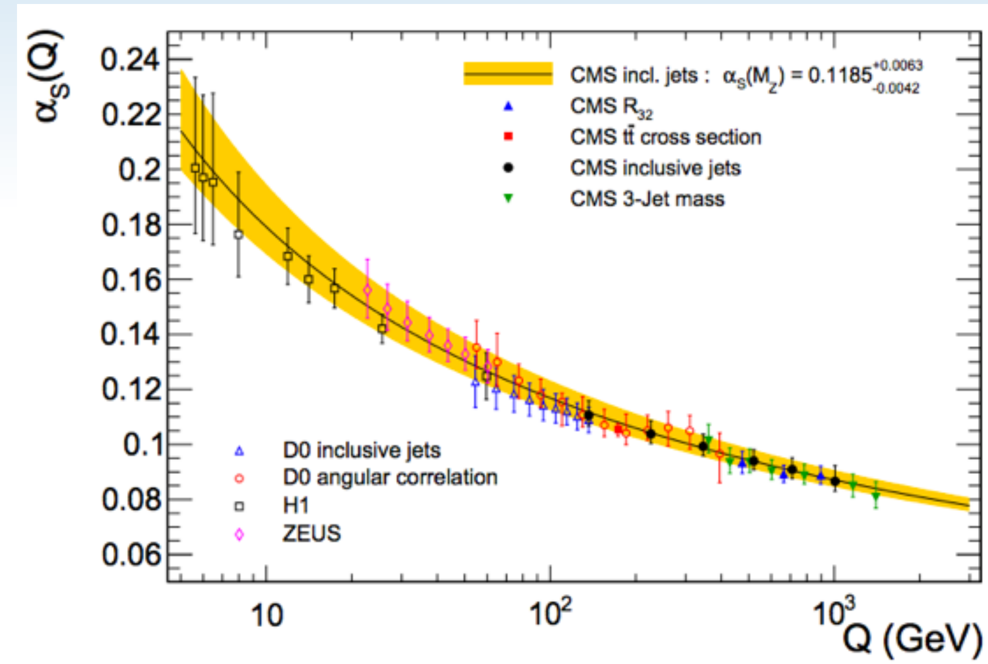
Role of higher power corrections?

- **Different environment compared with the LHC and thus new opportunities and new challenges**

Application of jet studies at the LHC

- **Precision probe of QCD**

process	sensitivity to PDFs
W asymmetry	→ quark flavour separation
W and Z production (differential)	→ valence quarks
W+c production	→ strange quark
Drell-Yan (DY): high invariant mass	→ sea quarks, high-x
Drell-Yan (DY): low invariant mass	→ low-x
W,Z +jets	→ gluon medium-x
Inclusive jet and di-jet production	→ gluon and $\alpha_s(M_Z)$
Direct photon	→ gluon medium, high-x
ttbar, single top	→ gluon and $\alpha_s(M_Z)$



Inclusive jets - perturbative probe

Application of jet studies at the LHC

- Precision probe of QCD

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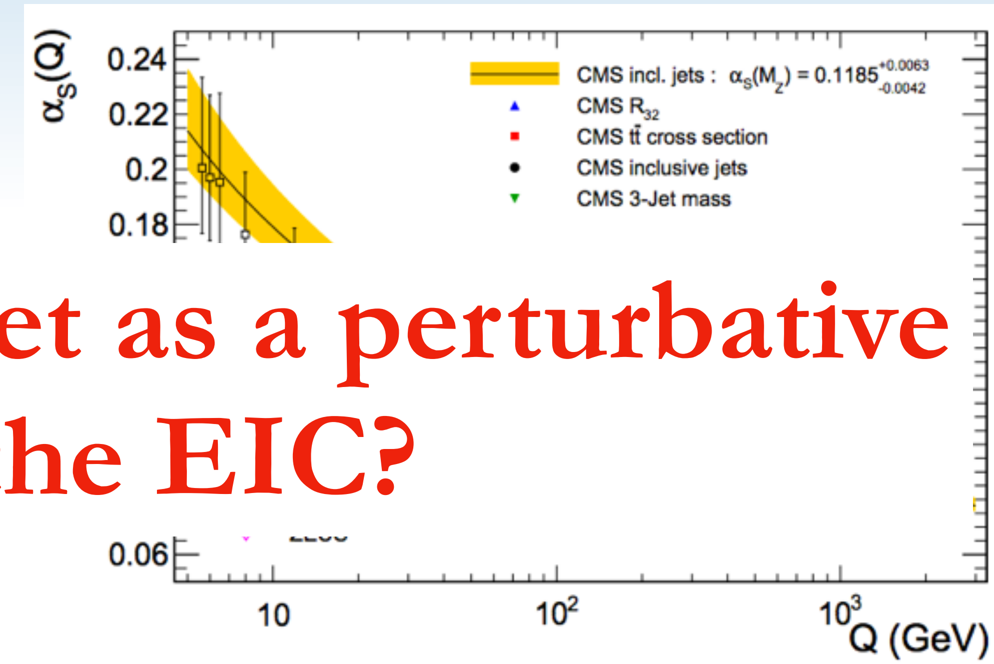

What is the role of jet as a perturbative probe at the EIC?

Inclusive jets - perturbative probe

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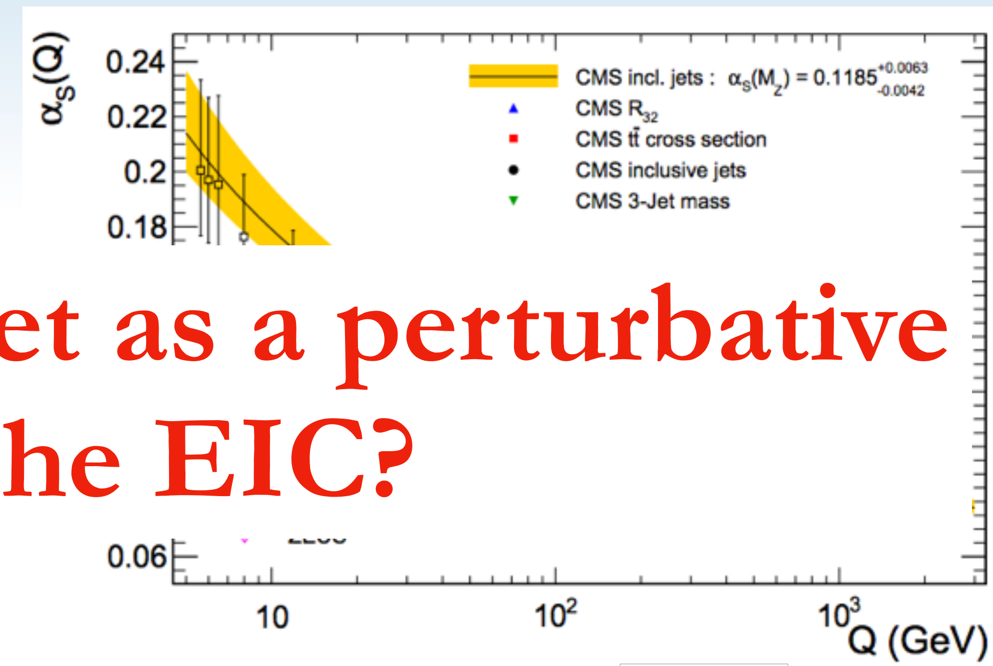
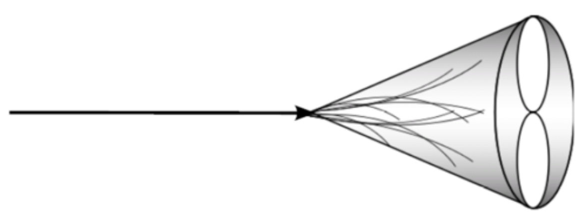
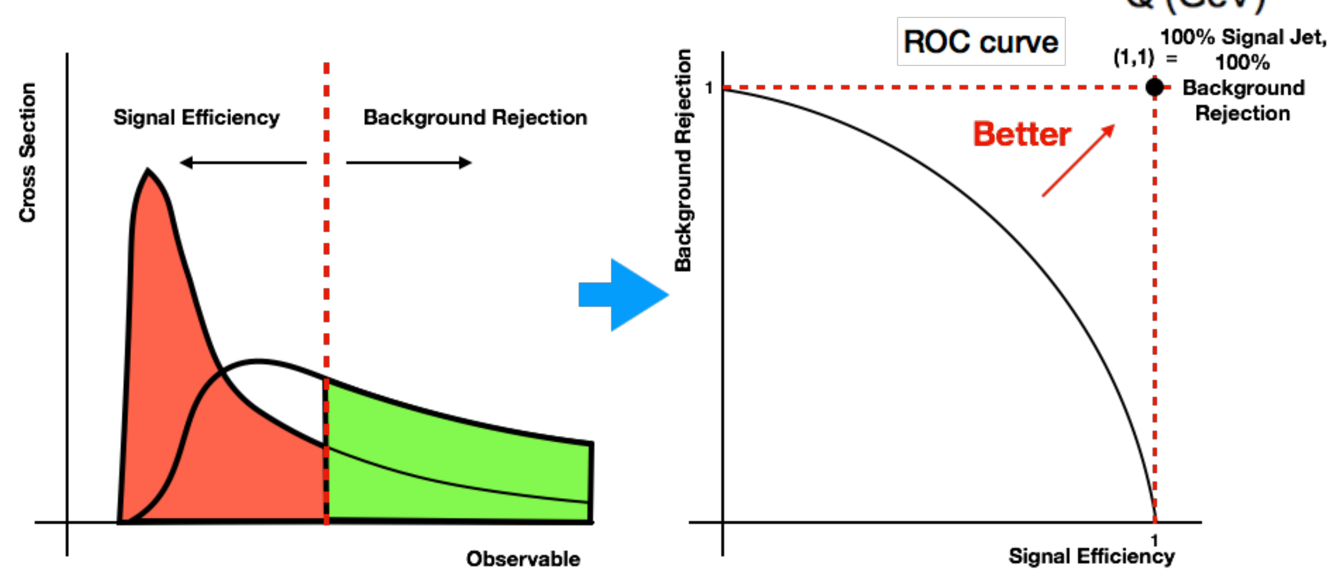


What is the role of jet as a perturbative probe at the EIC?

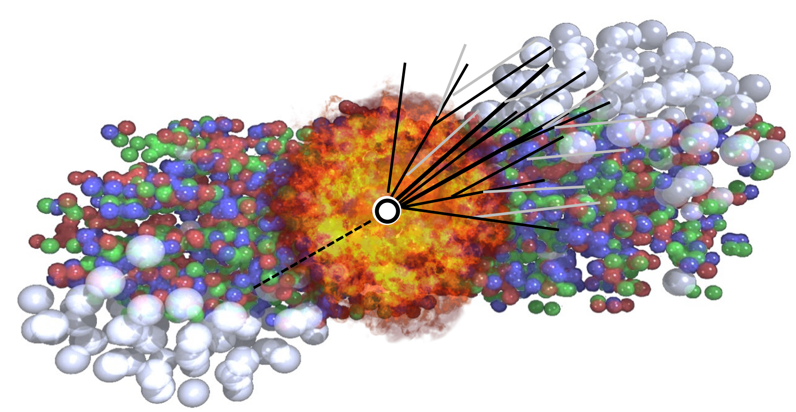
- Constrain BSM Models



Fat jet from BSM signal

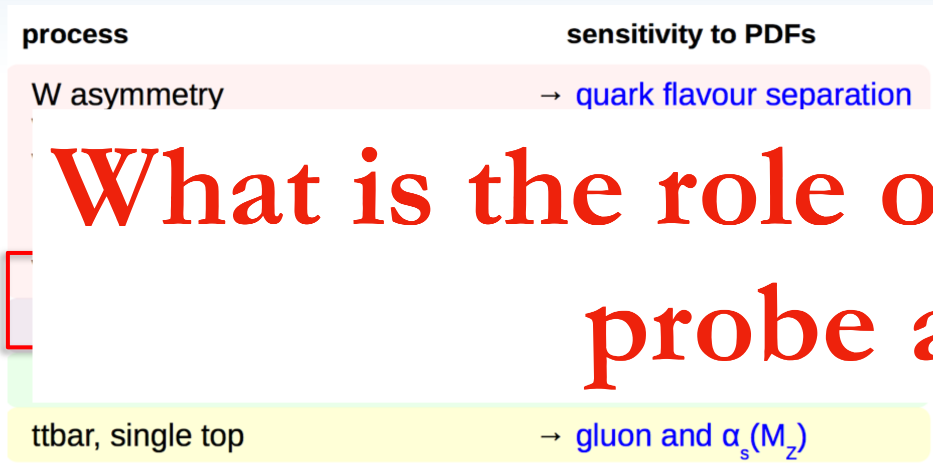


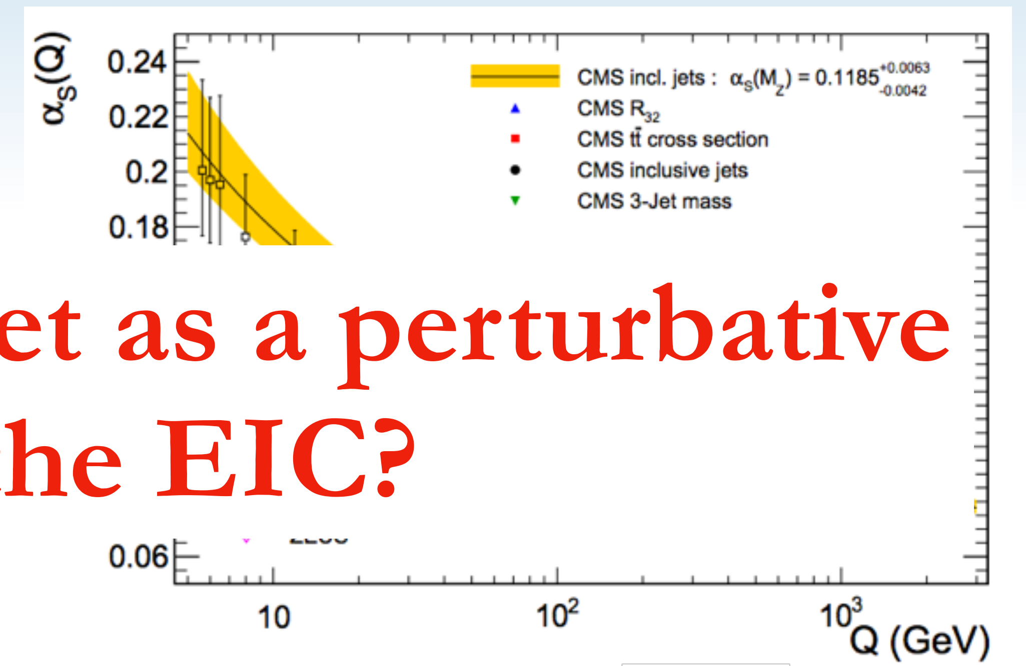
- Probe of quark gluon plasma



Application of jet studies at the LHC

- Precision probe of QCD





What is the role of jet as a perturbative probe at the EIC?

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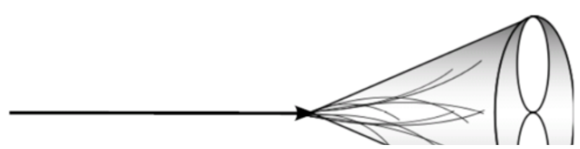
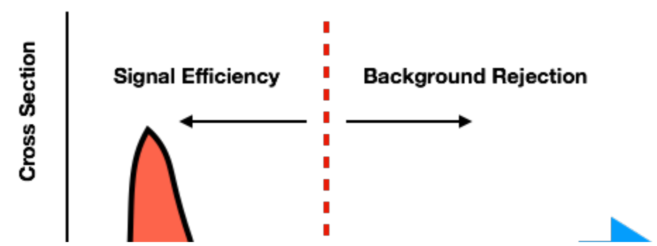
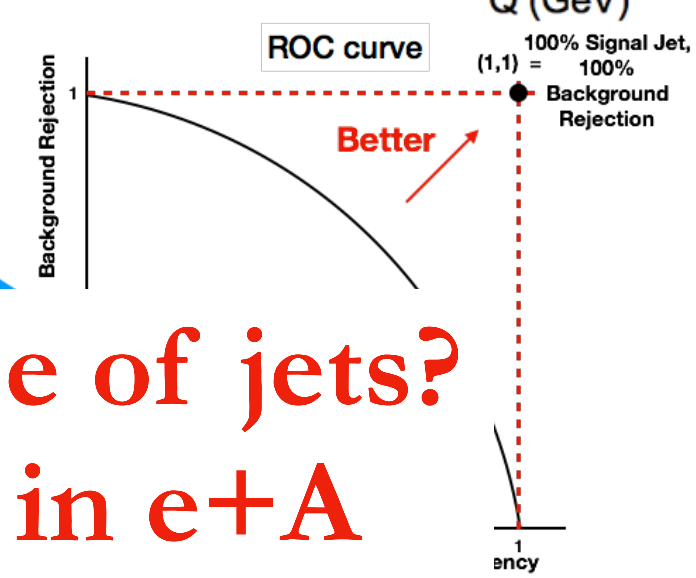


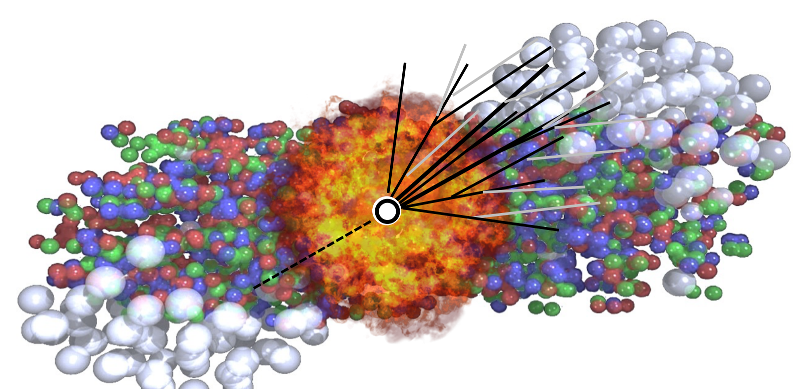




Classification of different type of jets?

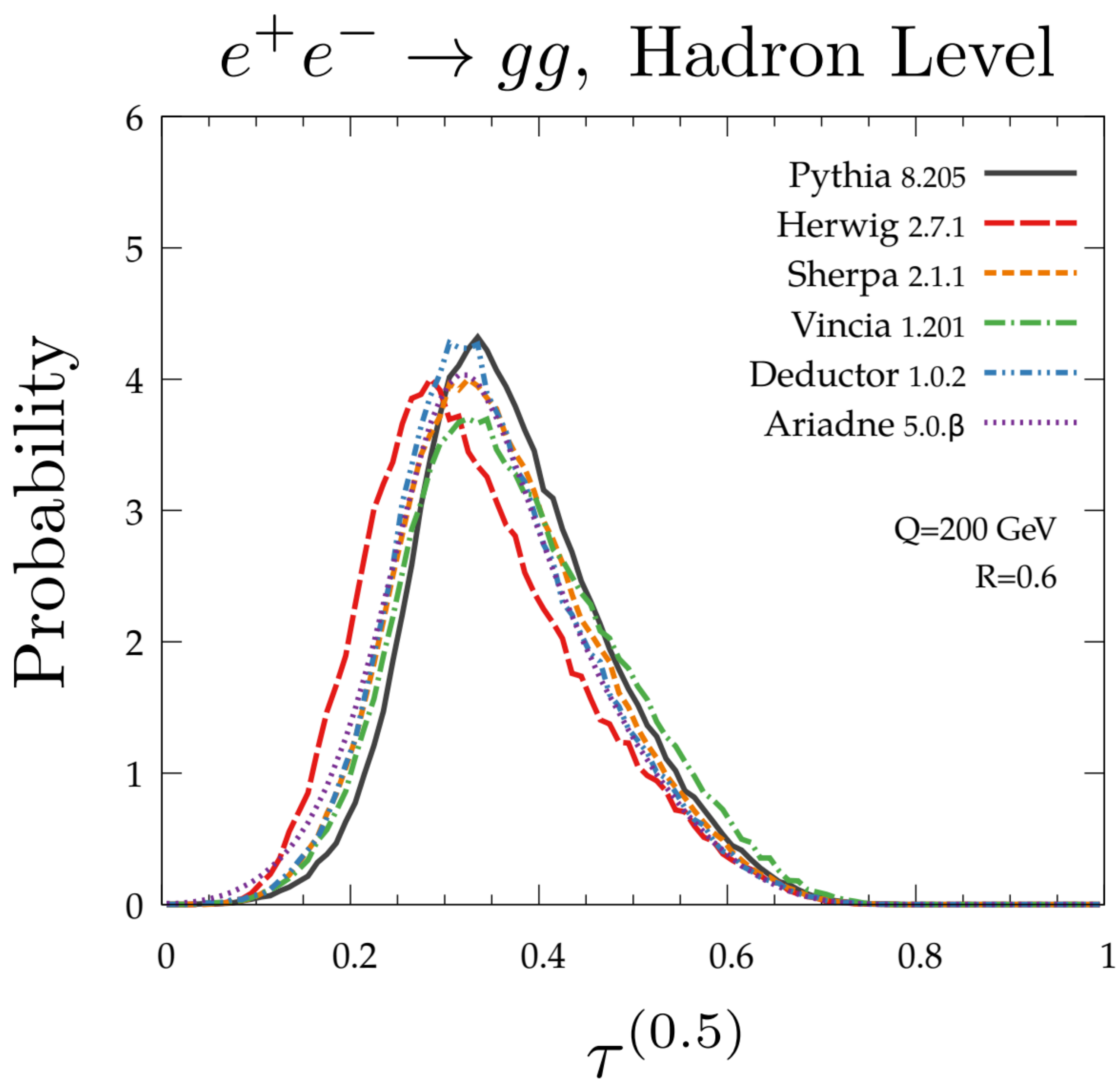
Cold Nuclear Modification in e+A

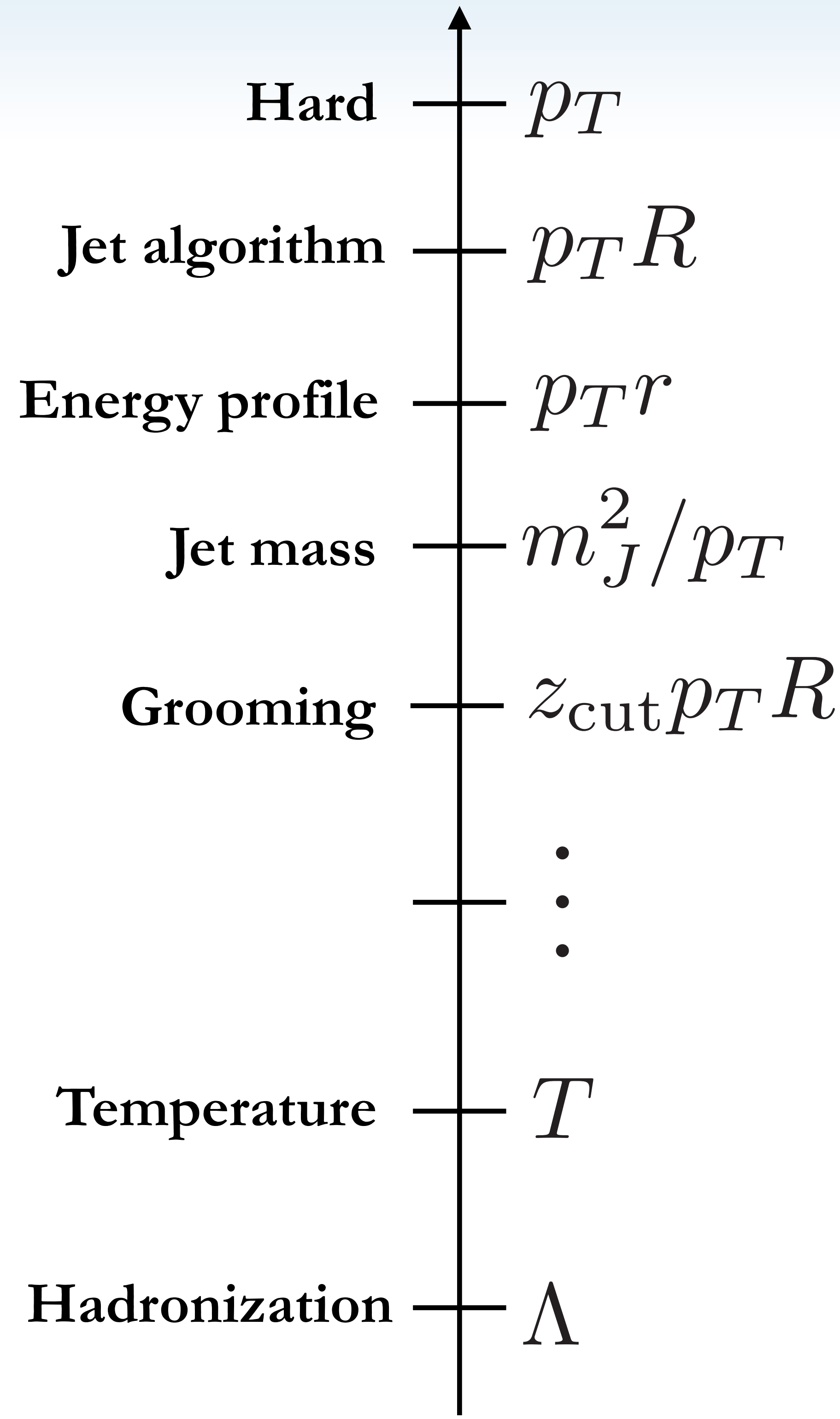
- Probe of quark gluon plasma



Application of jet studies at the LHC

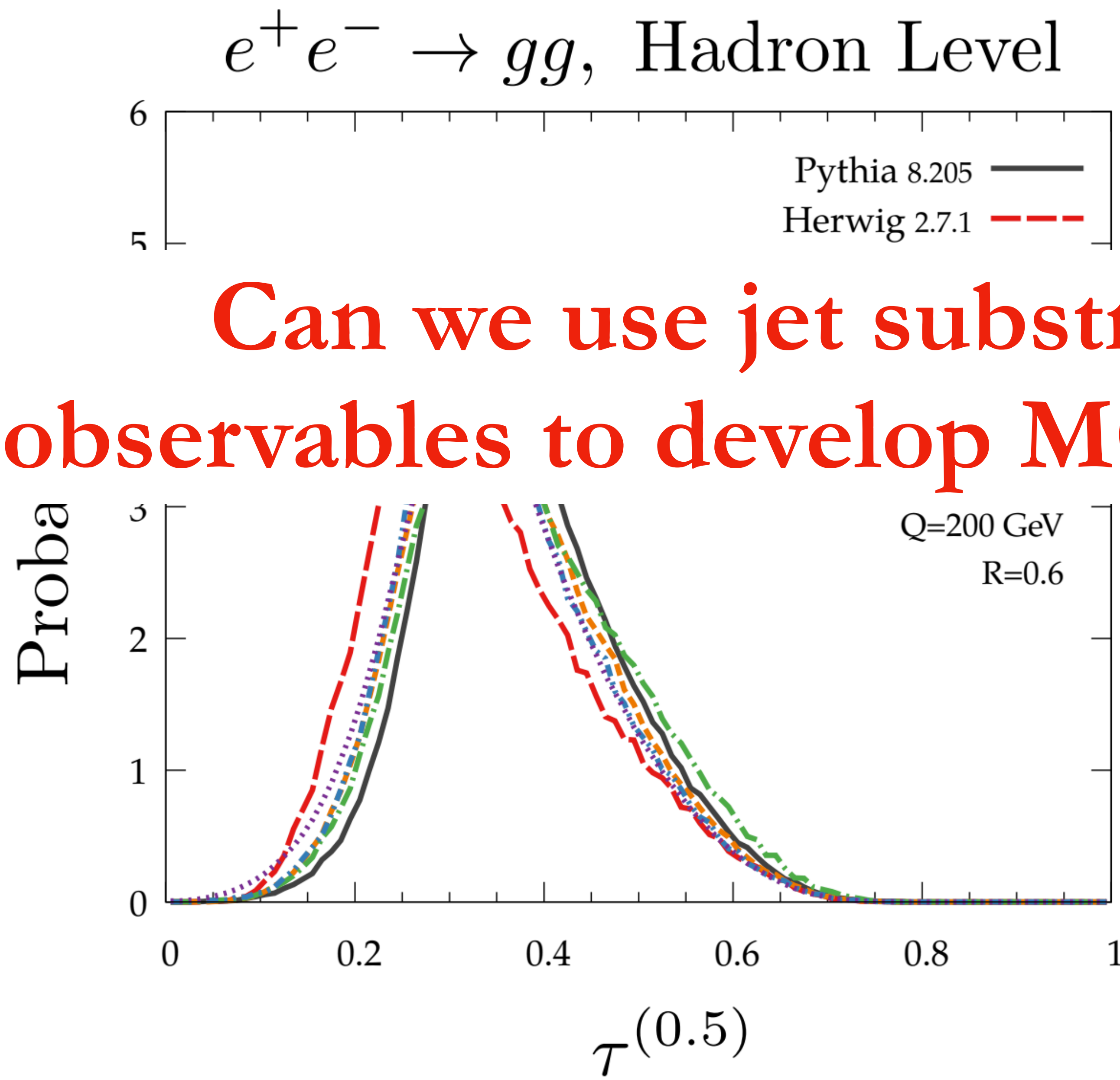
- **Tuning of MCs (LEP and LHC)**

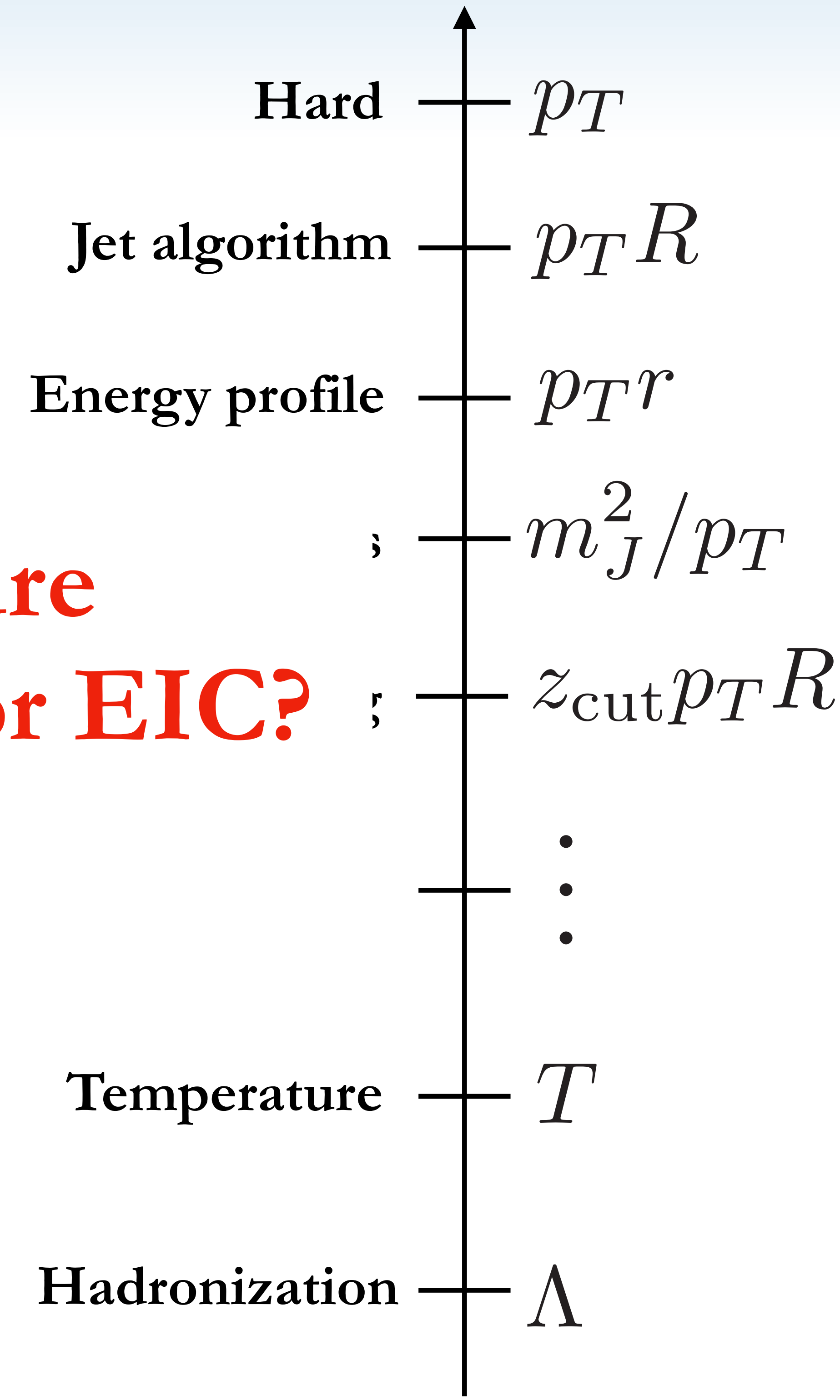




Application of jet studies at the LHC

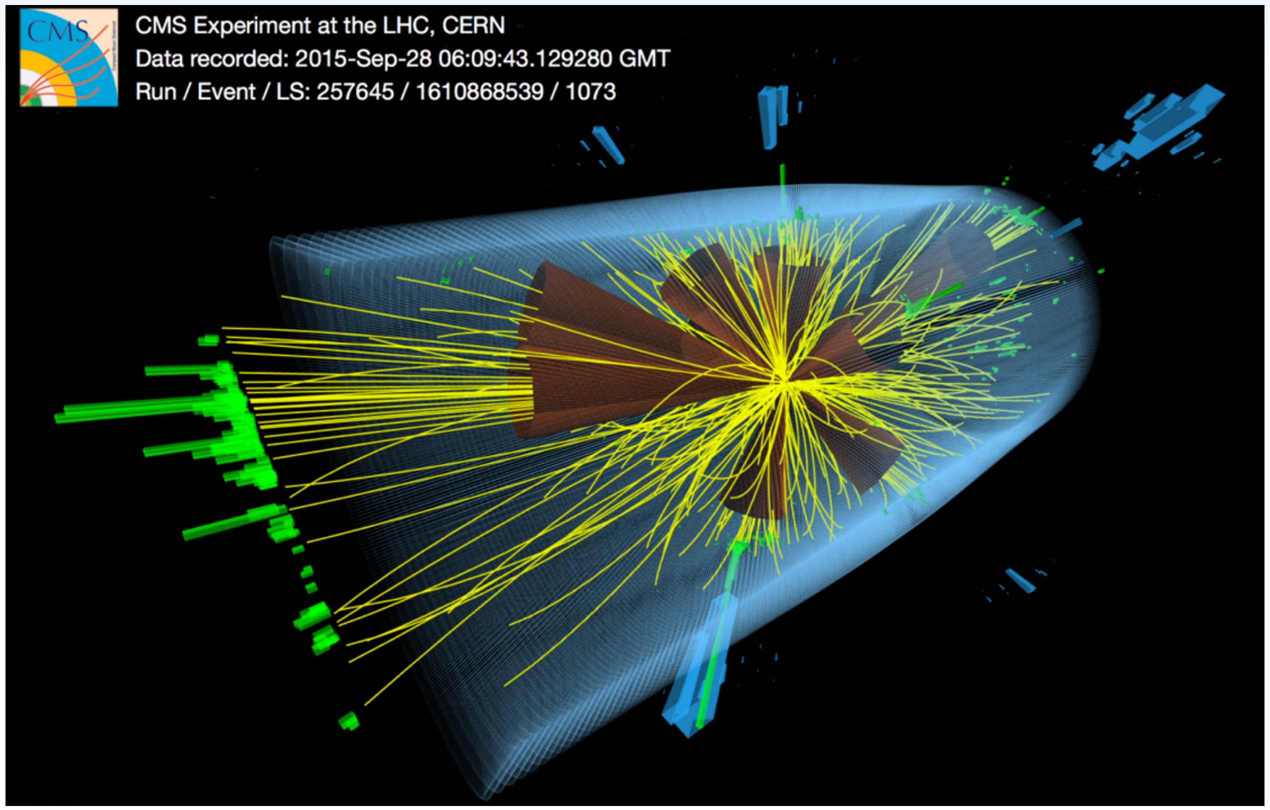
- Tuning of MCs (LEP and LHC)

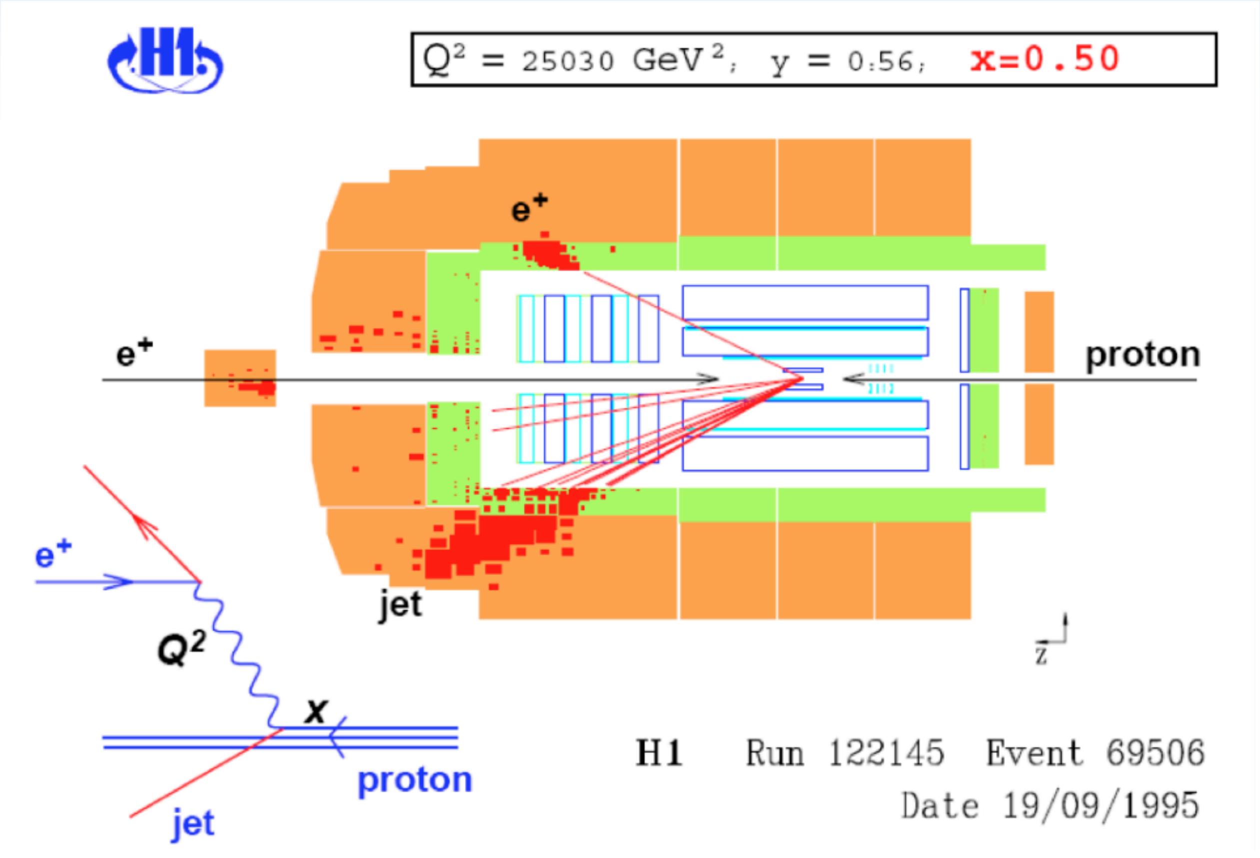




Can we use jet substructure observables to develop MCs for EIC?

Application of jet studies at the LHC



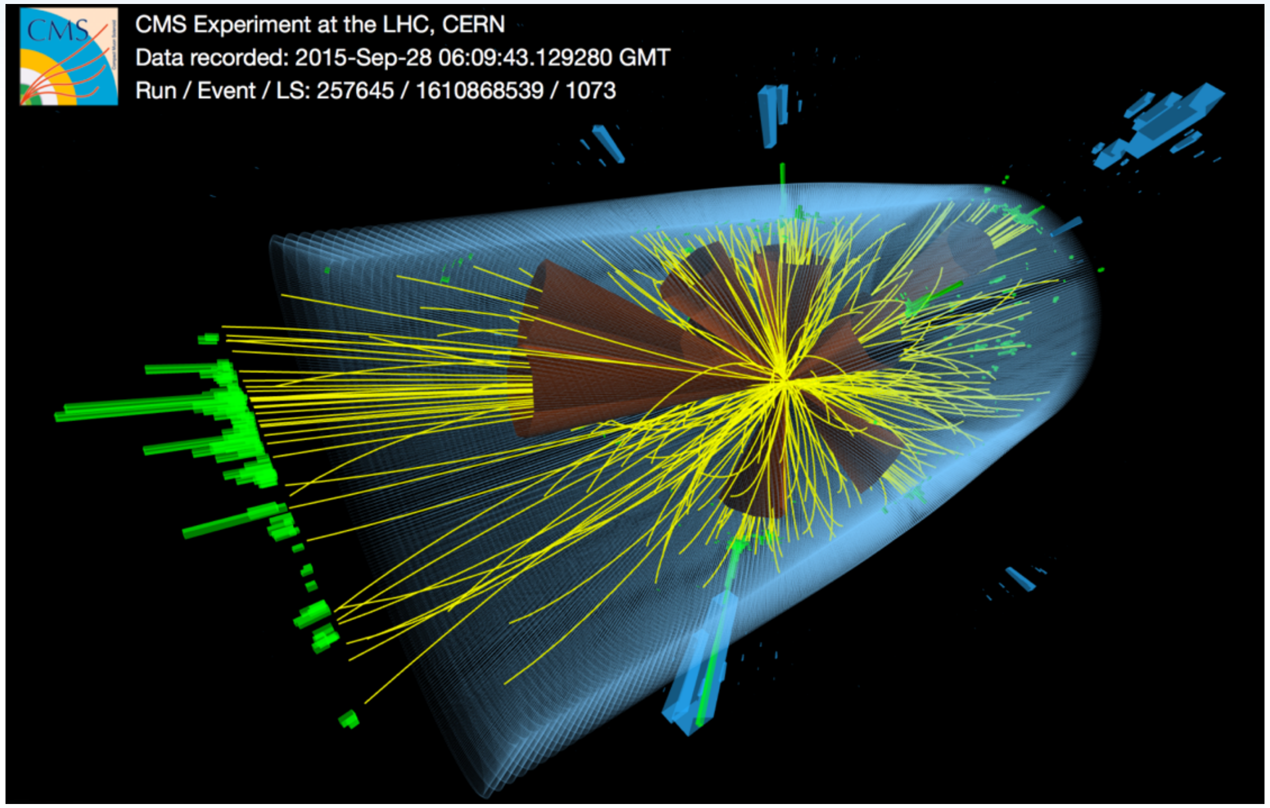


LHC

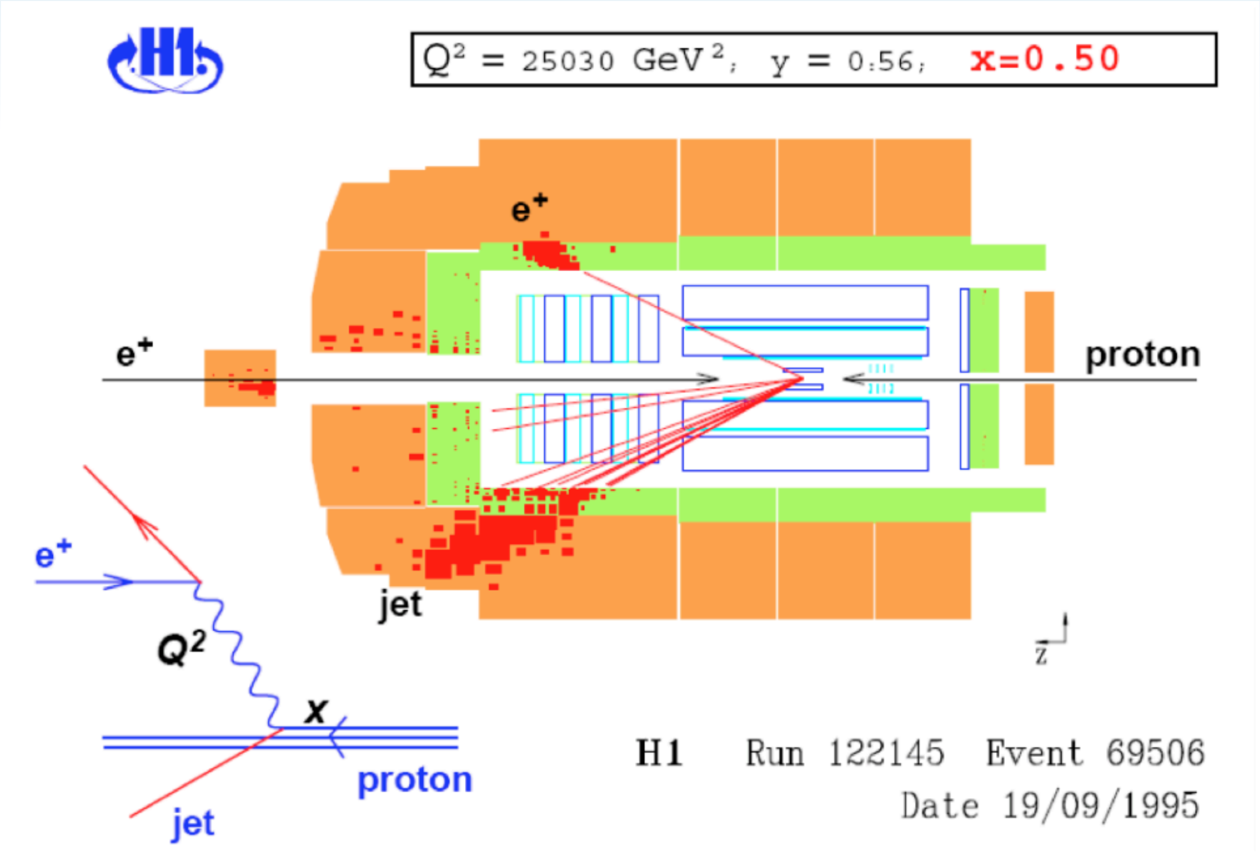
HERA

- Typical event at the LHC and HERA

Application of jet studies at the LHC



LHC



HERA

- Typical event at the LHC and HERA

What is the role of NP physics at the EIC?

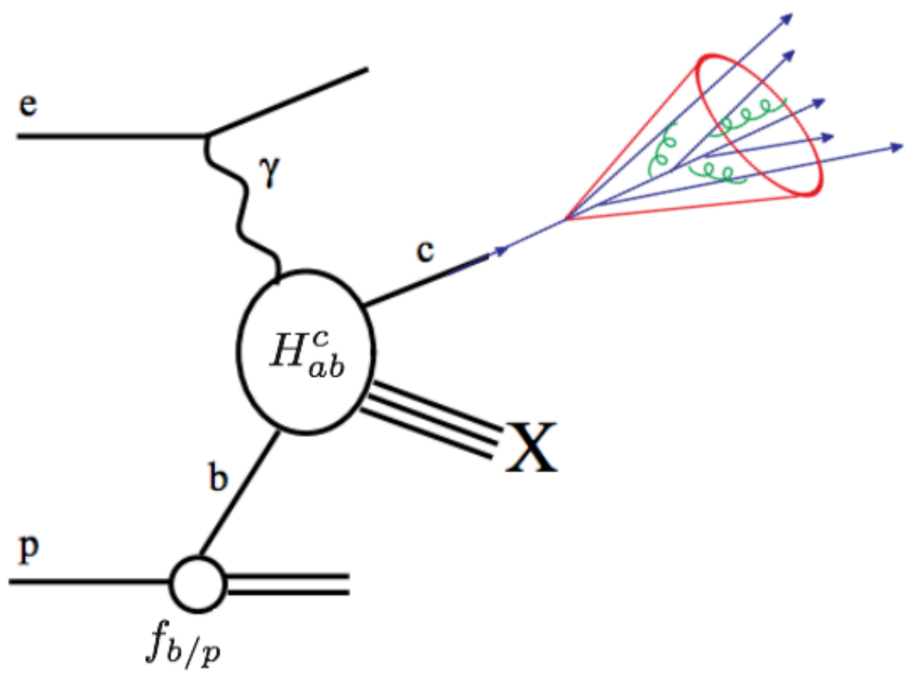
Plans of this talk

- Inclusive jets
- Jet angularities measurements
- Conclusions

Inclusive Jets

- $ep \to \text{jet} + X$, **final lepton unobserved, high p_T**

  Boughezal, Petriello, Xing `18,
  Hinderer, Schlegel, Vogelsang `18,
  Abelof, Boughezal, Liu, Petriello, `16



- $ep \to e + \text{jet} + X$, **DIS, high p_T and Q^2**

  Gehrmann, Huss, Niehues, Vogt, Walker `19

- $ep \to e + \text{jet} + X$, **photoproduction, high p_T and $Q^2 < 1\ \text{GeV}^2$**

Inclusive Jets

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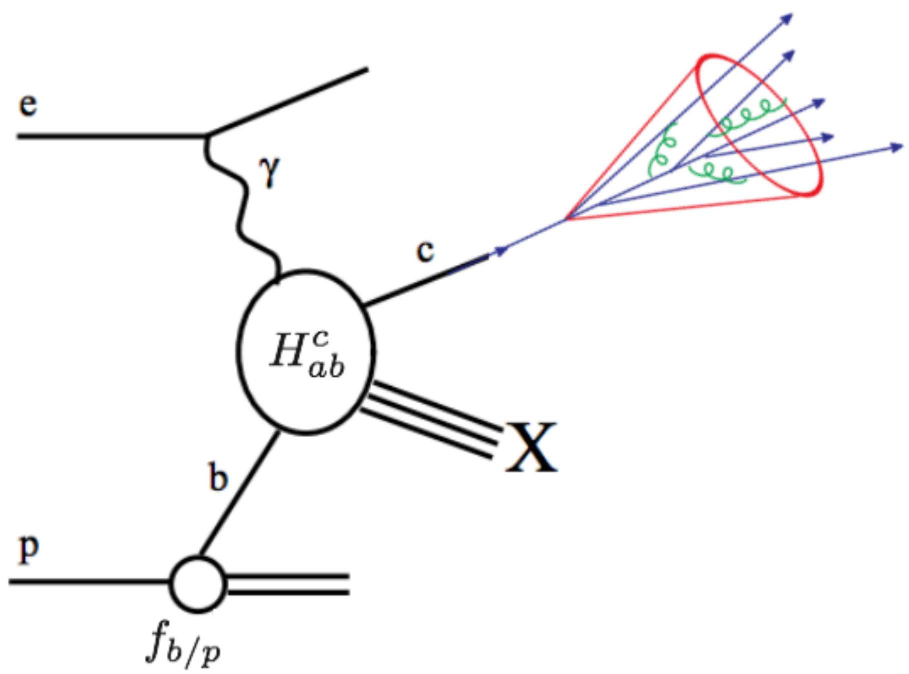

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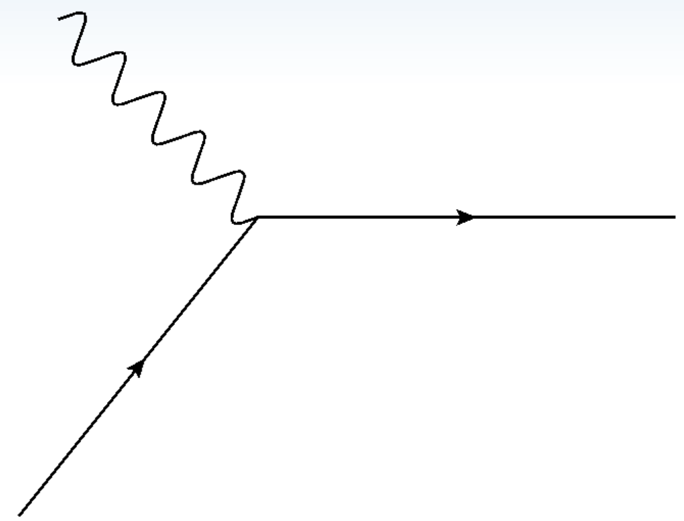
- $ep \to e + \text{jet} + X,$ **photoproduction, high p_T and $Q^2 < 1\ \text{GeV}^2$**

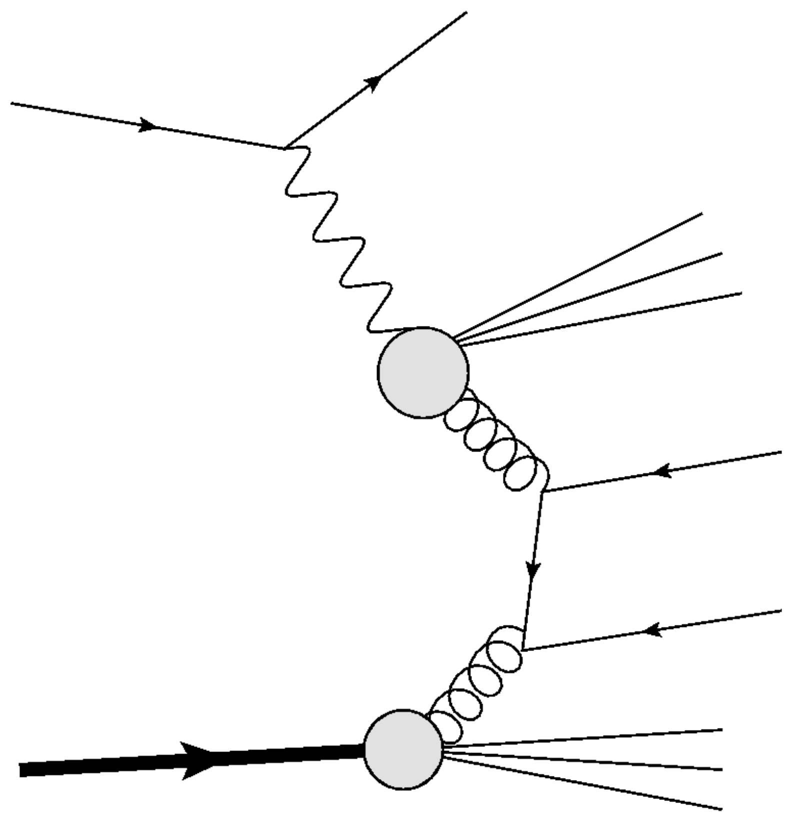
We focus on the photoproduction measuring p_T with respect to lab frame beam axis.

Relevant Subprocesses

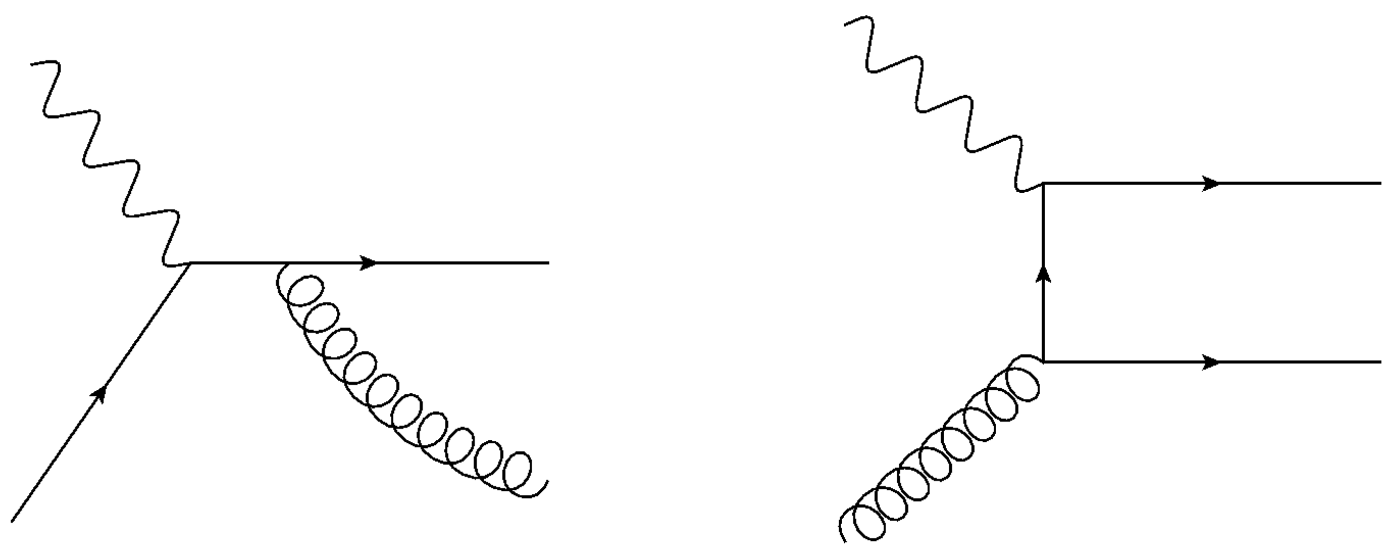
LO DIS



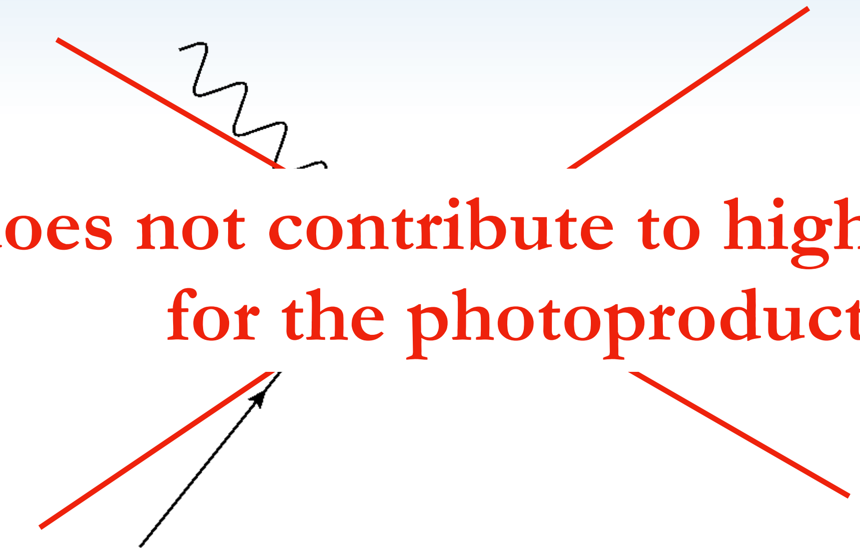
Resolved



Direct

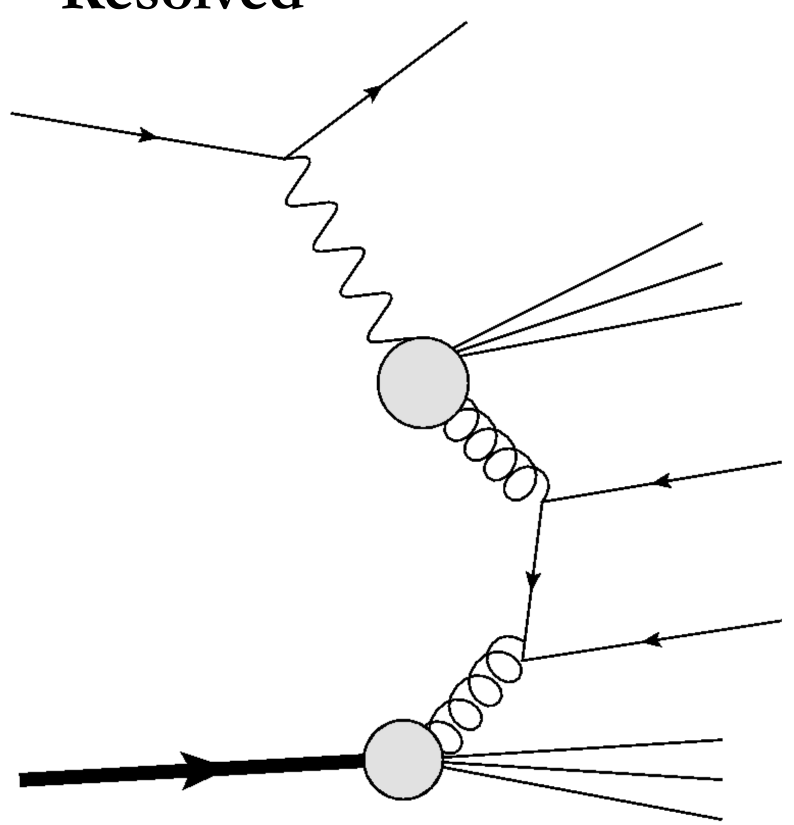


Relevant Subprocesses

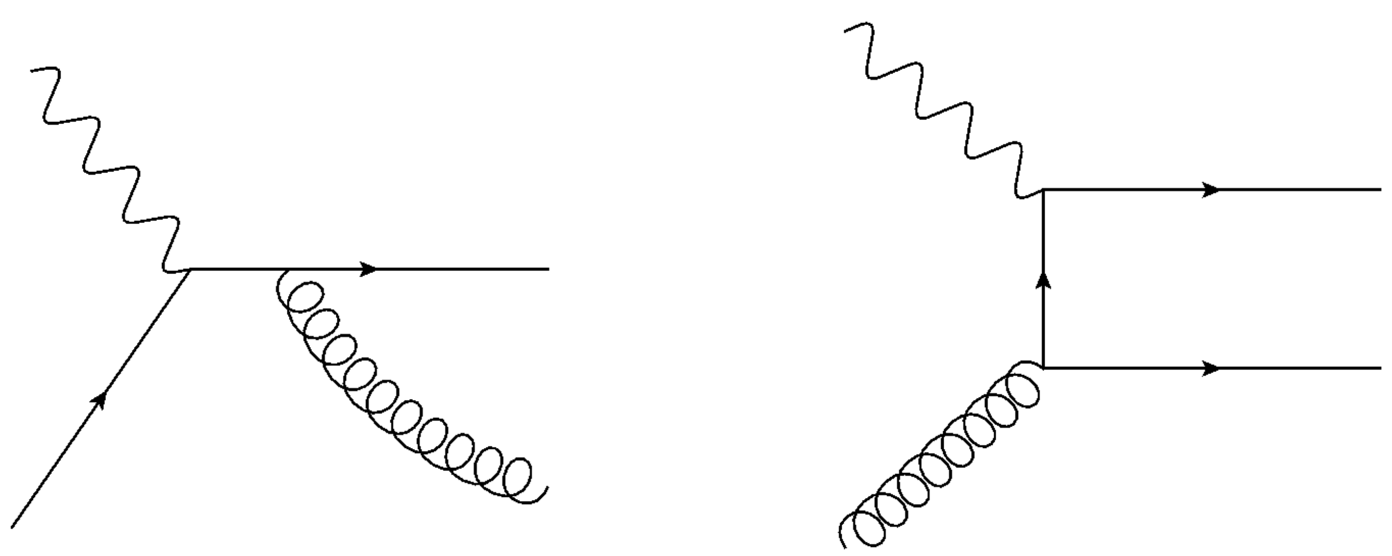


LO DIS does not contribute to high pT jet production for the photoproduction.

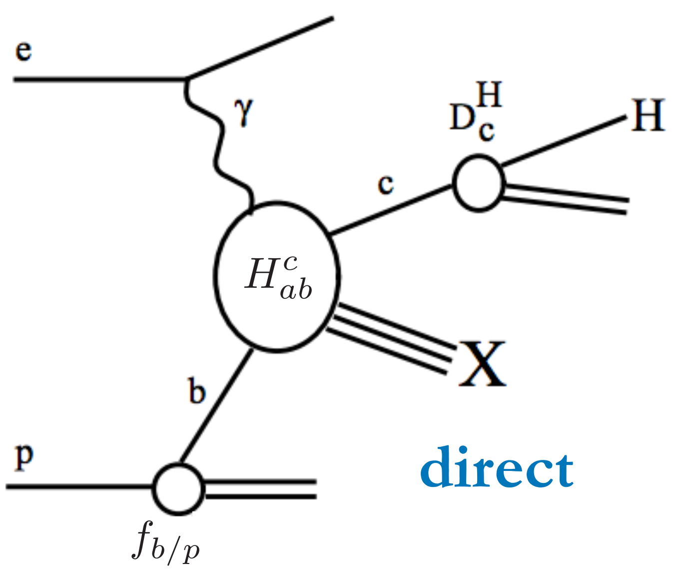
Resolved

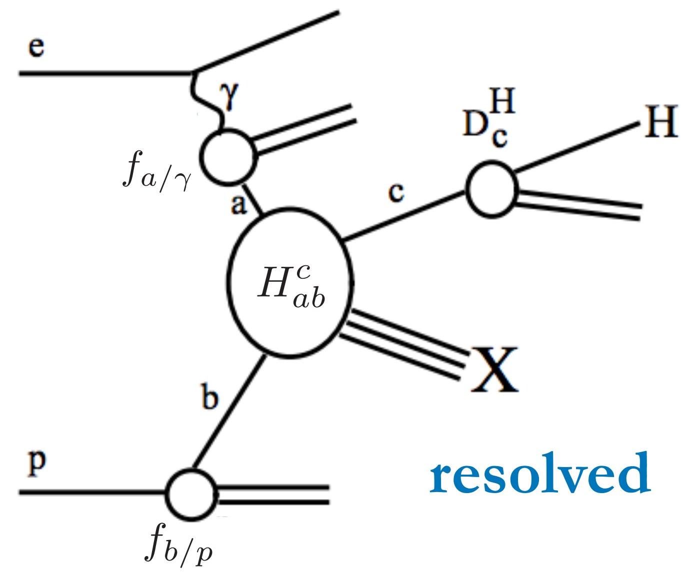


Direct



Photoproduction at the EIC





For polarized case,

hadron $$\frac{d\sigma^{ep\to ehX}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H_{ab}^c \otimes D_c^h$$

$$\frac{d\Delta\sigma^{ep\to ehX}}{dp_T d\eta} = \sum_{a,b,c} \Delta f_{a/l} \otimes \Delta f_{b/p} \otimes \Delta H_{ab}^c \otimes D_c^h$$

Weizsäcker-Williams spectrum

$$f_{a/l} = P_{\gamma l} \otimes f_{a/\gamma}$$

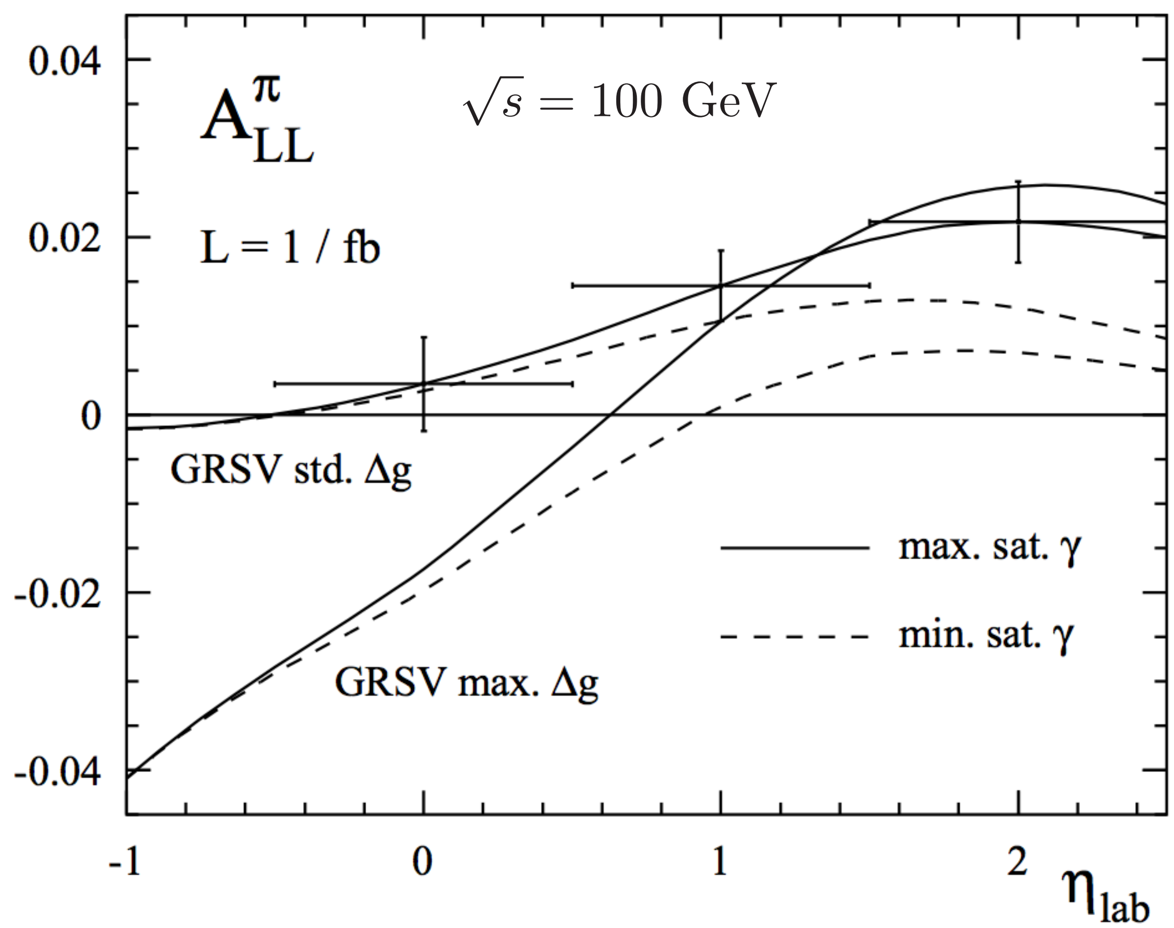
- For the direct process, $f_{a/\gamma} = \delta(1 - x_\gamma)$.
- Observe outgoing lepton to tag Q^2
- Require high p_T and $Q^2 < 1\ \mathrm{GeV}^2$ (near on-shell photon)

See Jäger, Stratmann, Vogelsang `03

Polarized Gluon and Photon PDF

Study in 2003,

Jäger, Stratmann, Vogelsang `03



$$A_{LL} = \frac{d\Delta\sigma}{d\sigma} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$

$$\Delta f_{\max} = f \qquad \Delta f_{\min} = 0$$

- **Sensitivity to polarized gluon pdf at low** $\eta_{\rm lab}$
- **Sensitivity to polarized photon pdf at high** $\eta_{\rm lab}$

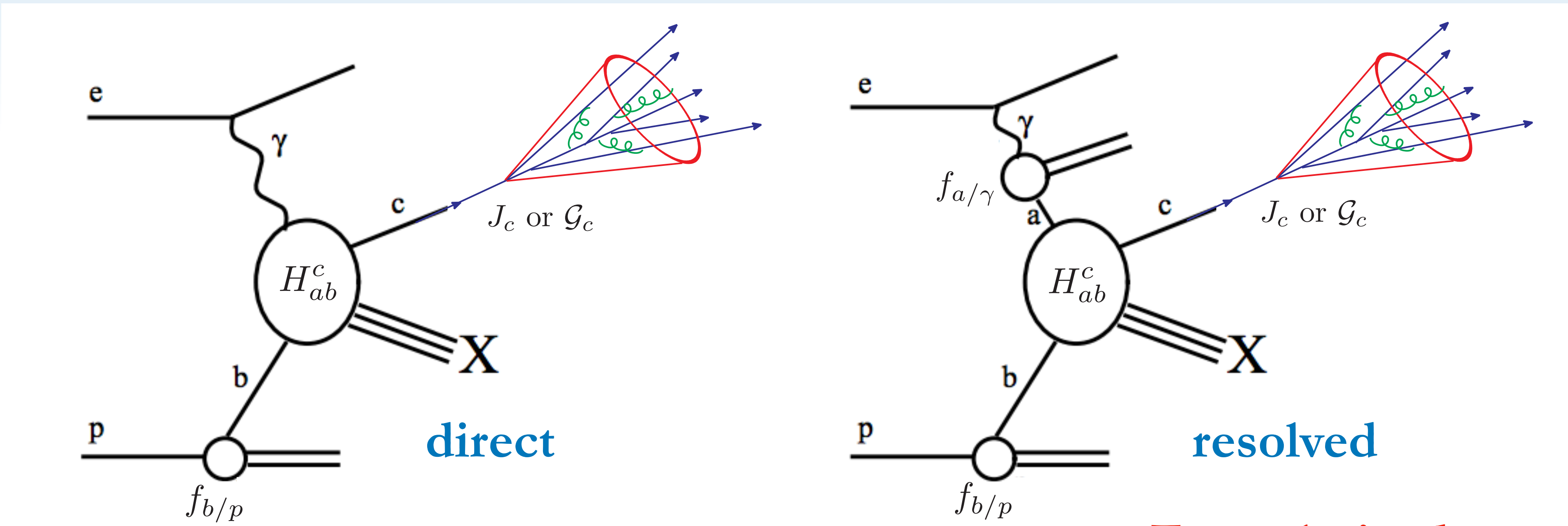
Assumptions: $D_c^{\pi^0}$ **has been well-determined.**

Use inclusive jets as a perturbative probe!

- **Study of polarized pdfs**

$$\frac{d\Delta\sigma^{ep\to e\pi^0 X}}{dp_T d\eta} = \sum_{a,b,c} \Delta f_{a/l} \otimes \Delta f_{b/p} \otimes \Delta H_{ab}^{c} \otimes D_c^{\pi^0}$$

Photoproduction at the EIC



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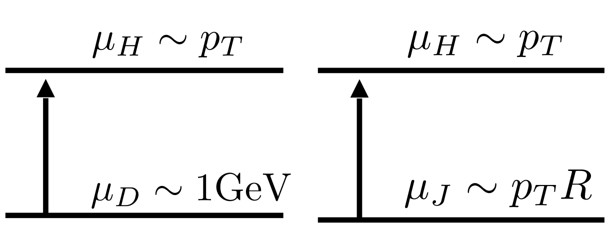
Inclusive Jet $$\frac{d\sigma^{ep\to ejetX}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l}\otimes f_{b/p}\otimes H^c_{ab}\otimes J_c + \mathcal{O}(R^2) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{p_T R}\right)$$

Power corrections may be relevant for EIC

Power corrections

- Replacement of the fragmentation function with the perturbative jet function.
- Sensitivity to the photon pdfs. Can be done for polarized and unpolarized case.
- Role of power corrections?



Role as a perturbative probe

Jäger, Stratmann, Vogelsang `03
Chu, Aschenauer, Lee, Zheng `17
Aschenauer, KL, Page, Ringer, In Preparation

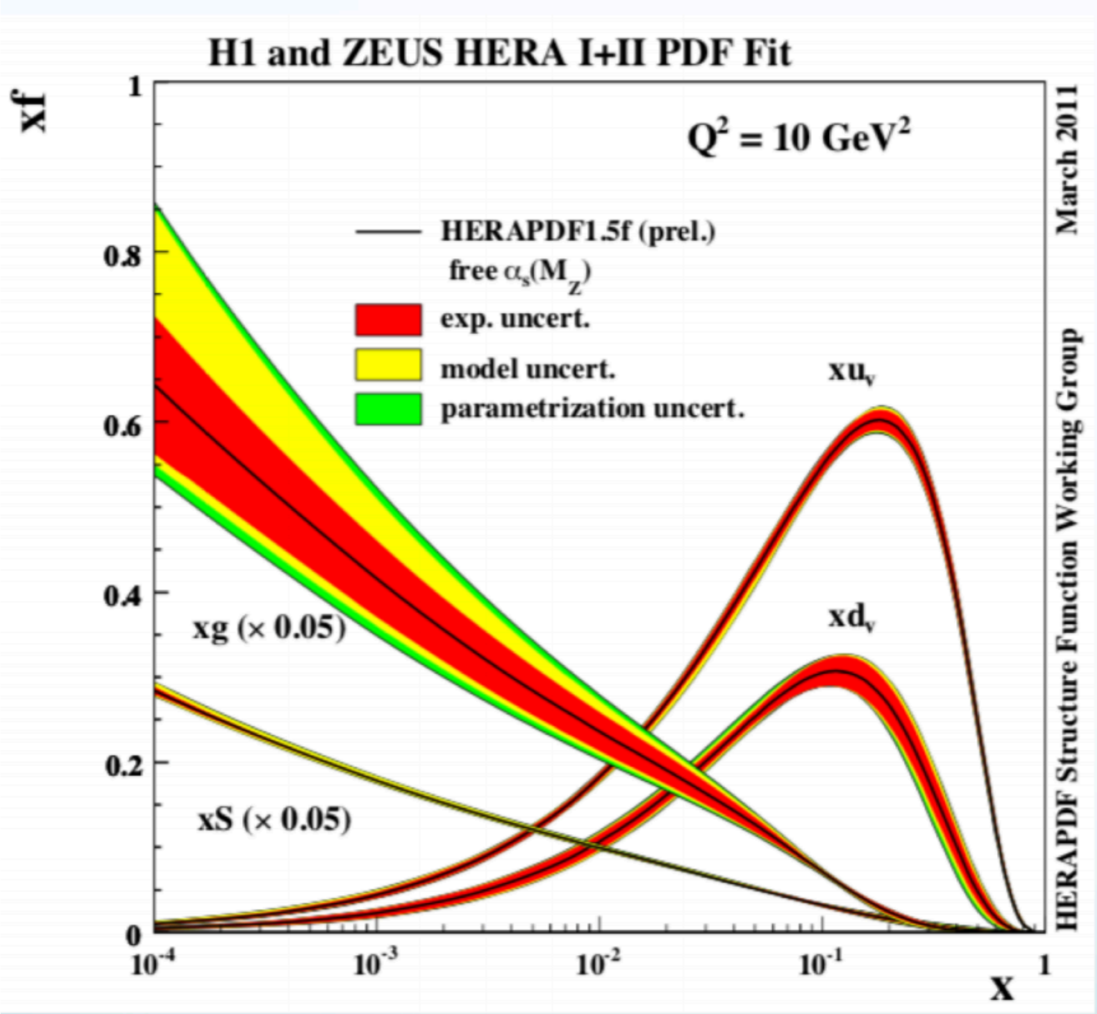
HERA PDF fit with and without jets

- Important for constraining gluon PDF

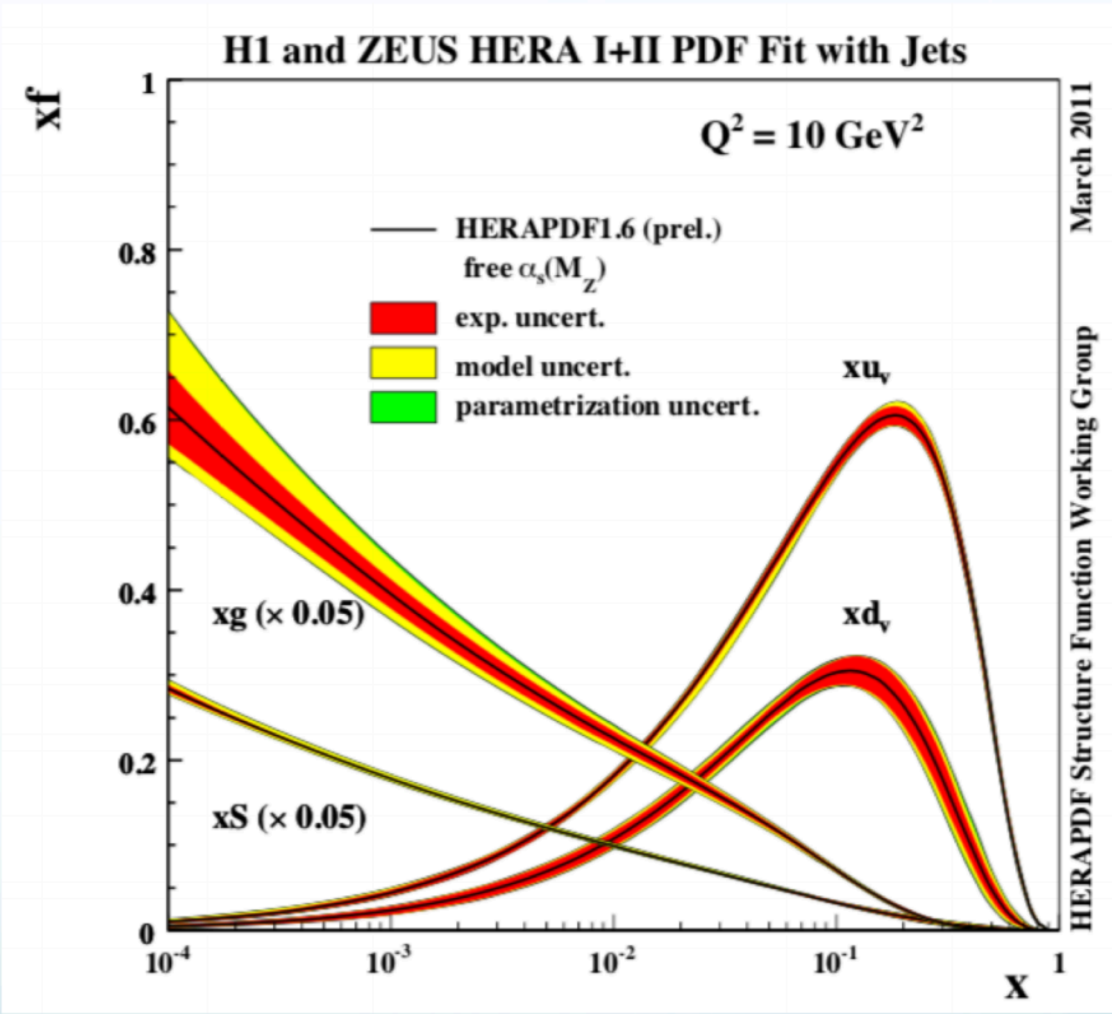
Nuclear Physics B (Proc. Suppl.) 222–224 (2012) January–March 2012

HERA 2011

Proceedings of the Ringberg Workshop
New Trends in HERA Physics 2011



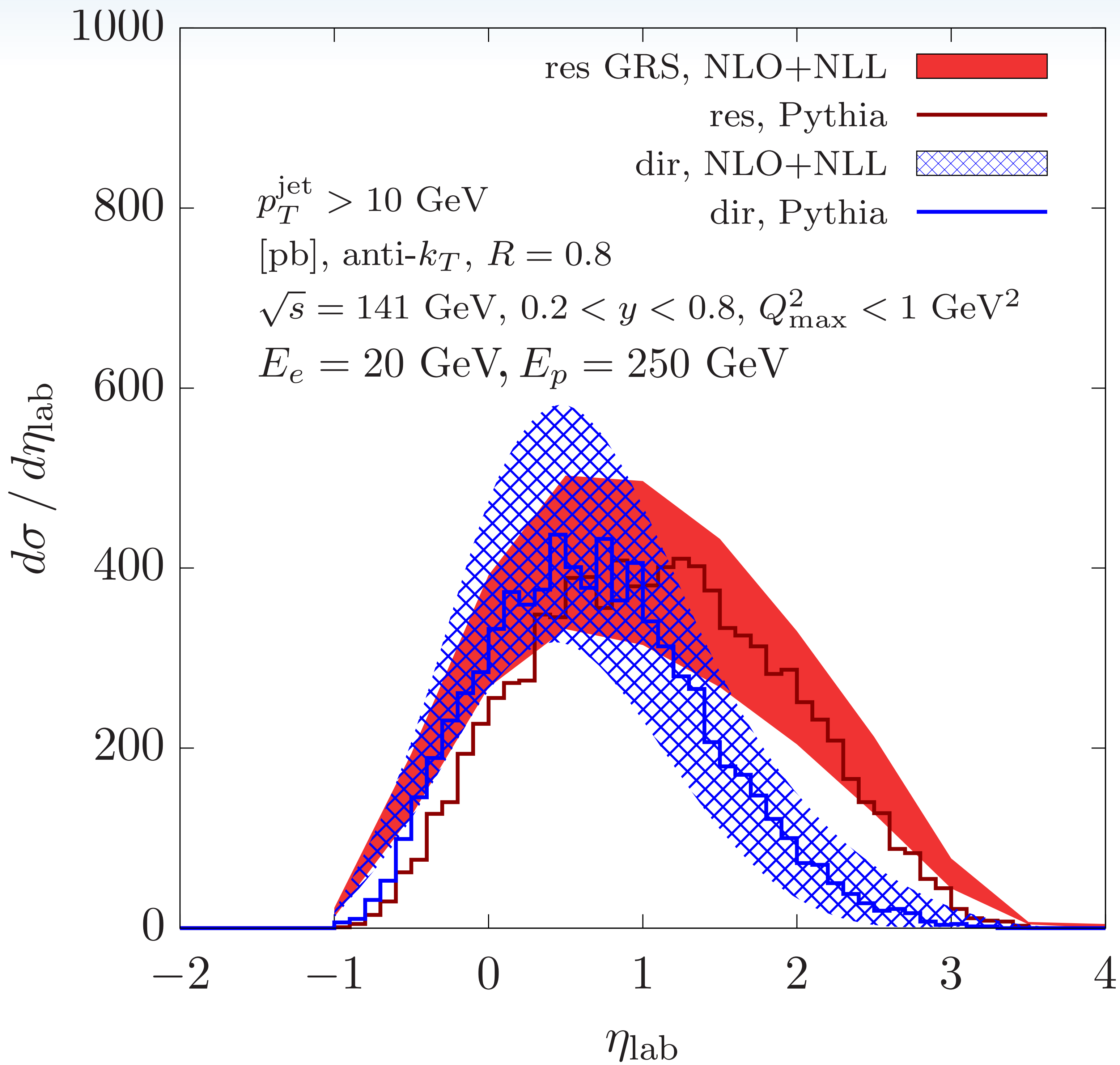
Without jets



With jets

Role as a perturbative probe

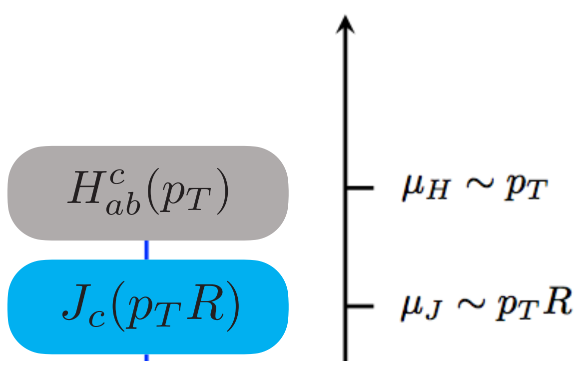
Unpolarized inclusive jets for photoproduction



- At $p_T > 10$ GeV, we see a good agreement.
- $\mathcal{O}(\frac{\Lambda_{QCD}}{p_T R})$ power corrections not too large

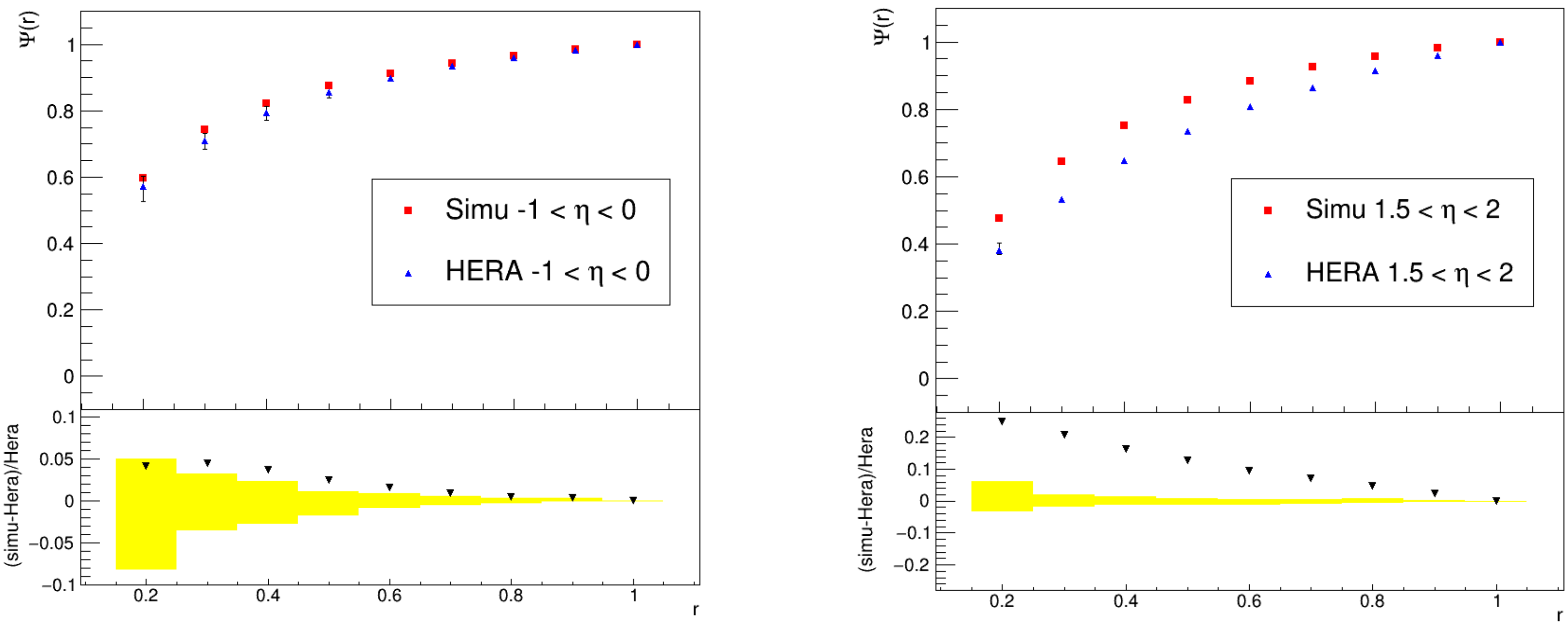
Power corrections

- eRHIC Pythia 6.4, tuned to HERA.
- GRS photon pdf



Aschenauer, KL, Page, Ringer, In Preparation

eRHIC Pythia 6.4



MC tuning

- Shows a good agreement with HERA data for jet shape
- Some disagreement in the forward region for jet shape

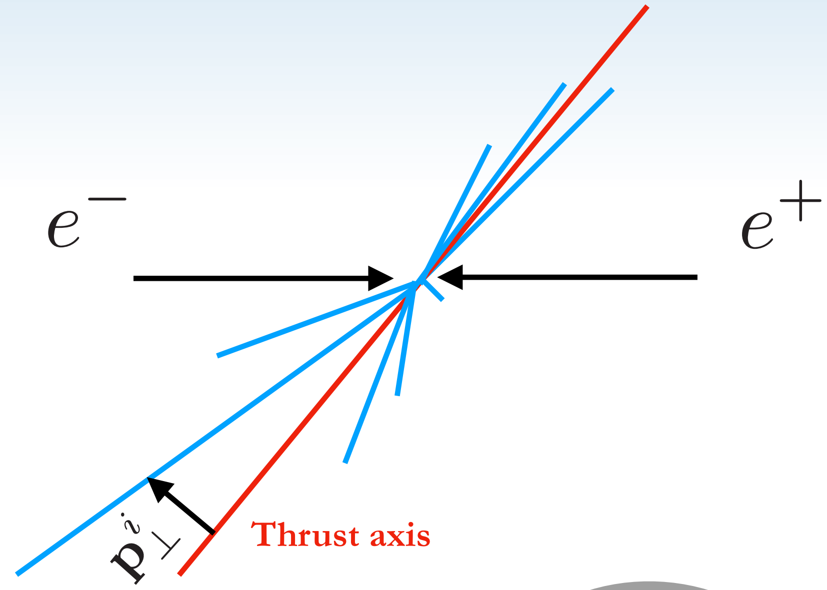
https://wiki.bnl.gov/eic/index.php/PYTHIA

Aschenauer, KL, Page, Ringer, In Preparation

Jet angularity

- A generalized class of IR safe observables, angularity:

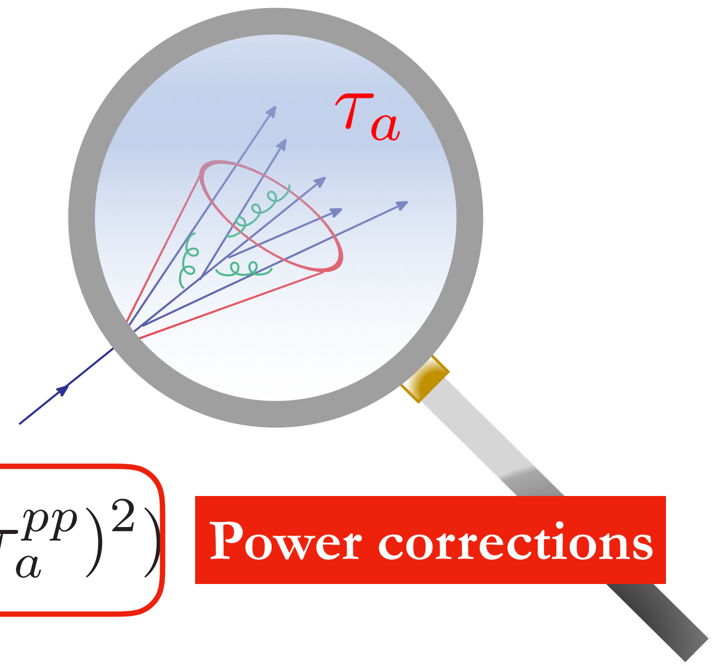
$$\tau_a^{\rm event} = \frac{1}{Q}\sum_i |\mathbf{p}_\perp^i| e^{-|\eta_i|(1-a)}$$



- Applied to jet, thrust axis swapped with jet axis

$$\tau_a^{e^+e^-} = \frac{1}{Q}\sum_i |\mathbf{p}_\perp^{iJ}|\, e^{-|\eta_{iJ}|(1-a)}$$

$$= \frac{1}{E_J}\sum_{i\in J} E_i\, \theta_{iJ}^{2-a}$$



$$\tau_a \equiv \tau_a^{pp} = \frac{1}{p_T}\sum_{i\in J} p_{T,i}(\Delta R_{iJ})^{2-a} = \left(\frac{2E_J}{p_T}\right)^{2-a} \tau_a^{e^+e^-} + \mathcal{O}((\tau_a^{pp})^2)$$

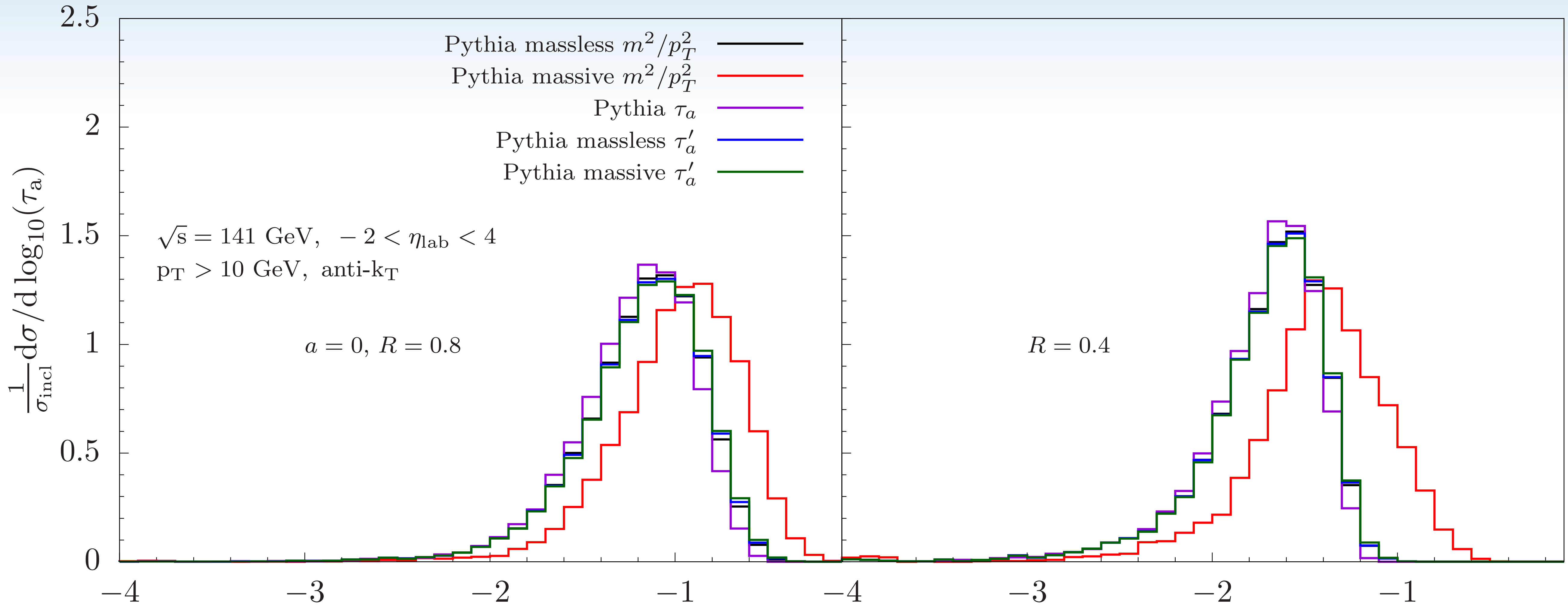
Power corrections

$a = 0$

$$\tau_0^{pp} = \frac{m_J^2}{p_T^2} + \mathcal{O}((\tau_0^{pp})^2) + \mathcal{O}\left(\frac{m_{\rm had}}{p_T}\right) = \frac{1}{p_T^2}\left(\sum_{i\in J} p_i\right)^2 + \mathcal{O}((\tau_0^{pp})^2) + \mathcal{O}\left(\frac{m_{\rm had}}{p_T}\right)$$

Sterman et al. `03, `08, Hornig, C. Lee, Ovanesyan `09,
Ellis, Vermilion, Walsh, Hornig, C.Lee `10, Chien, Hornig, C. Lee `15,
Hornig, Makris, Mehen `16, Bell, Hornig, C. Lee, Talbert `18, Kang, KL, Ringer `18

Jet angularity



$$\tau_a' \equiv \left(\frac{2E_J}{p_T}\right)^{2-a} \tau_a^{e^+e^-}$$

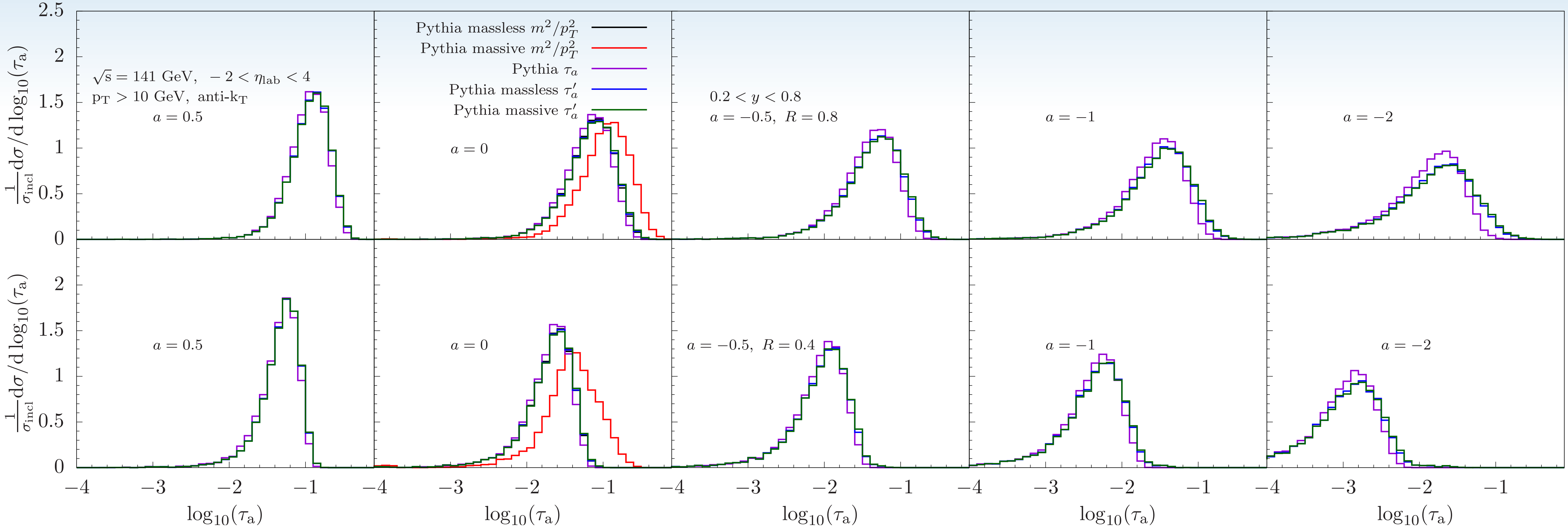
$$\tau_a \equiv \tau_a^{pp} = \tau_a' + \mathcal{O}(\tau_a^2)$$

$$\tau_0 = \frac{m_J^2}{p_T^2} + \mathcal{O}(\tau_0^2) + \mathcal{O}\left(\frac{m_{\rm had}}{p_T}\right)$$

- Large hadron mass effects for jet mass

Aschenauer, KL, Page, Ringer, In Preparation

Jet angularity



$$\tau'_a \equiv \left(\frac{2E_J}{p_T}\right)^{2-a} \tau_a^{e^+e^-}$$

$$\tau_a \equiv \tau_a^{pp} = \tau'_a + \mathcal{O}(\tau_a^2)$$

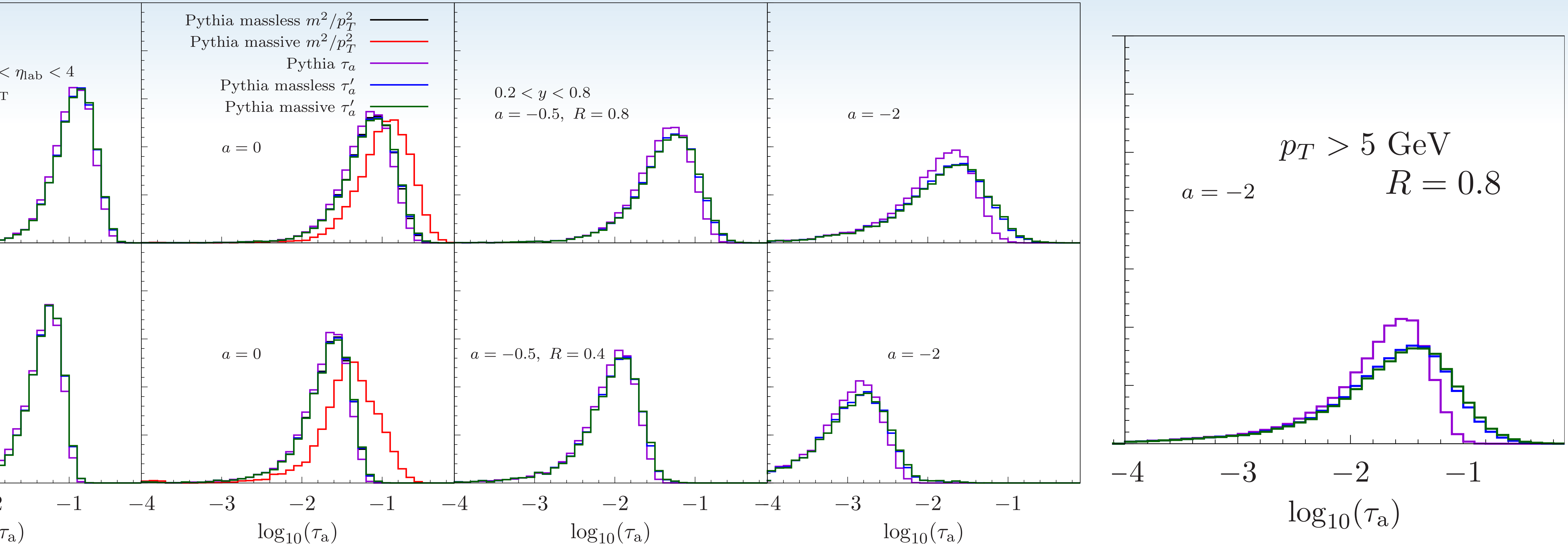
- Large hadron mass effects for jet mass

$$\tau_0 = \frac{m_J^2}{p_T^2} + \mathcal{O}(\tau_0^2) + \mathcal{O}\left(\frac{m_{\text{had}}}{p_T}\right)$$

- Small power corrections of type $\mathcal{O}(\tau_a^2)$ bigger for smaller 'a'

Aschenauer, KL, Page, Ringer, In Preparation

Jet angularity



$$\tau_a' \equiv \left(\frac{2E_J}{p_T}\right)^{2-a} \tau_a^{e^+e^-}$$

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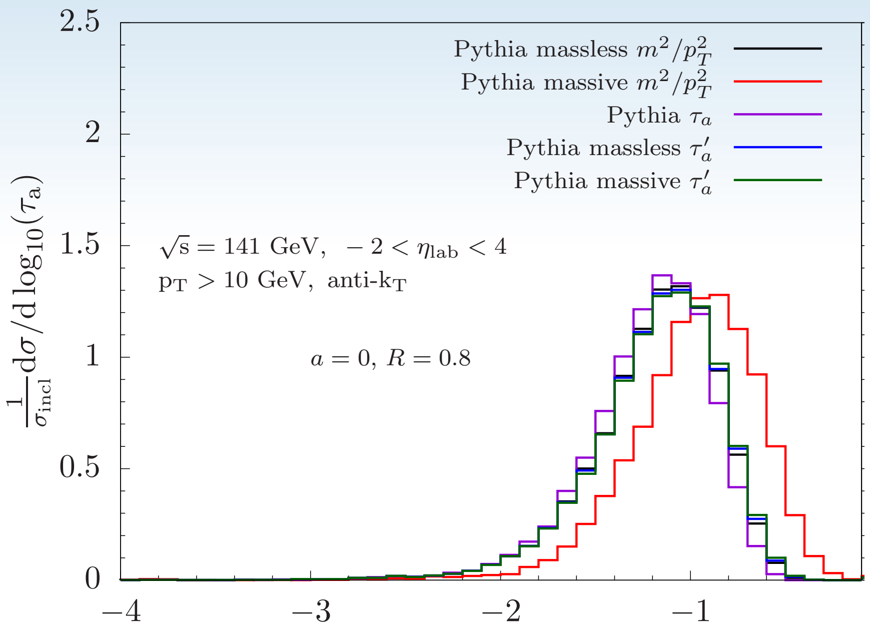
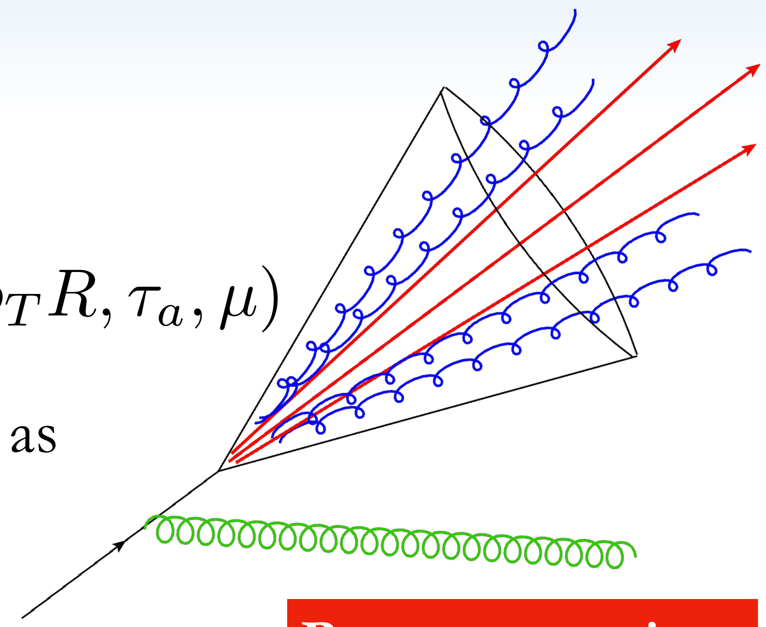
Aschenauer, KL, Page, Ringer, In Preparation

Factorization for jet angularity



- Replace $J_c(z, p_T R, \mu) \to \mathcal{G}_c(z, p_T R, \tau_a, \mu)$
- When $\tau_a \ll R^2$, refactorize $\mathcal{G}_c$ as

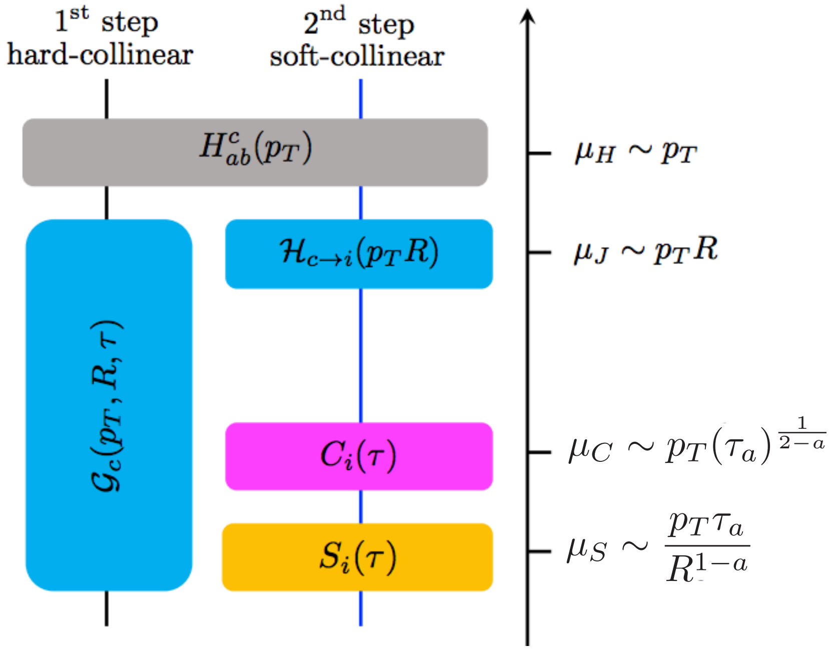


$$\mathcal{G}_c(z, p_T R, \tau_a, \mu) = \sum_i \mathcal{H}_{c\to i}(z, p_T R, \mu)$$

Power corrections

$$\times \int d\tau_a^{C_i} d\tau_a^{S_i} \delta(\tau_a - \tau_a^{C_i} - \tau_a^{S_i}) C_i(\tau_a^{C_i}, p_T \tau_a^{\frac{1}{2-a}}, \mu) S_i(\tau_a^{S_i}, \frac{p_T \tau_a}{R^{1-a}}, \mu) + \mathcal{O}(\tau_a^2)$$

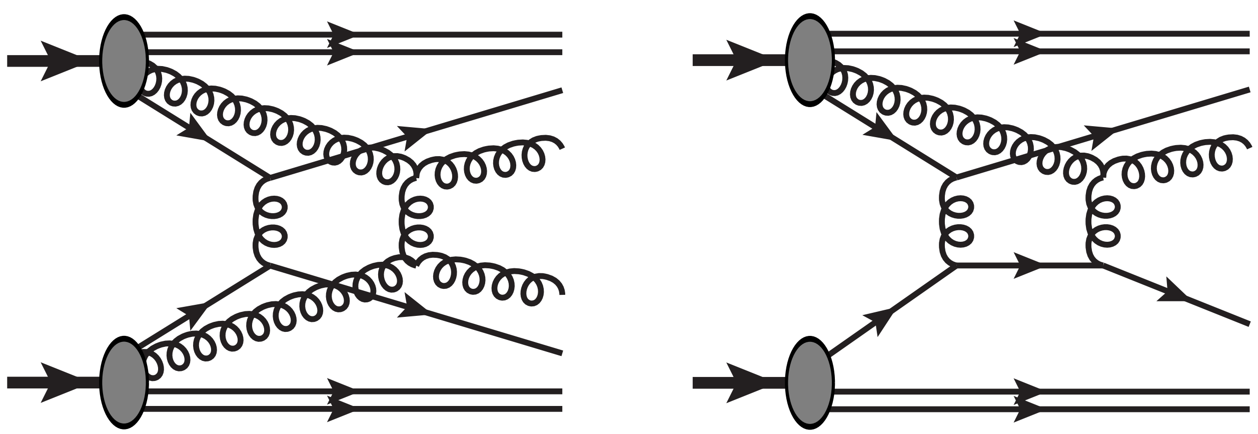
- Each pieces describe physics at different scales.
- Resums $(\alpha_s \ln R)^n$ and $(\alpha_s \ln^2 \frac{R}{\tau_a^{1/(2-a)}})^n$



Kang, KL, Ringer `18

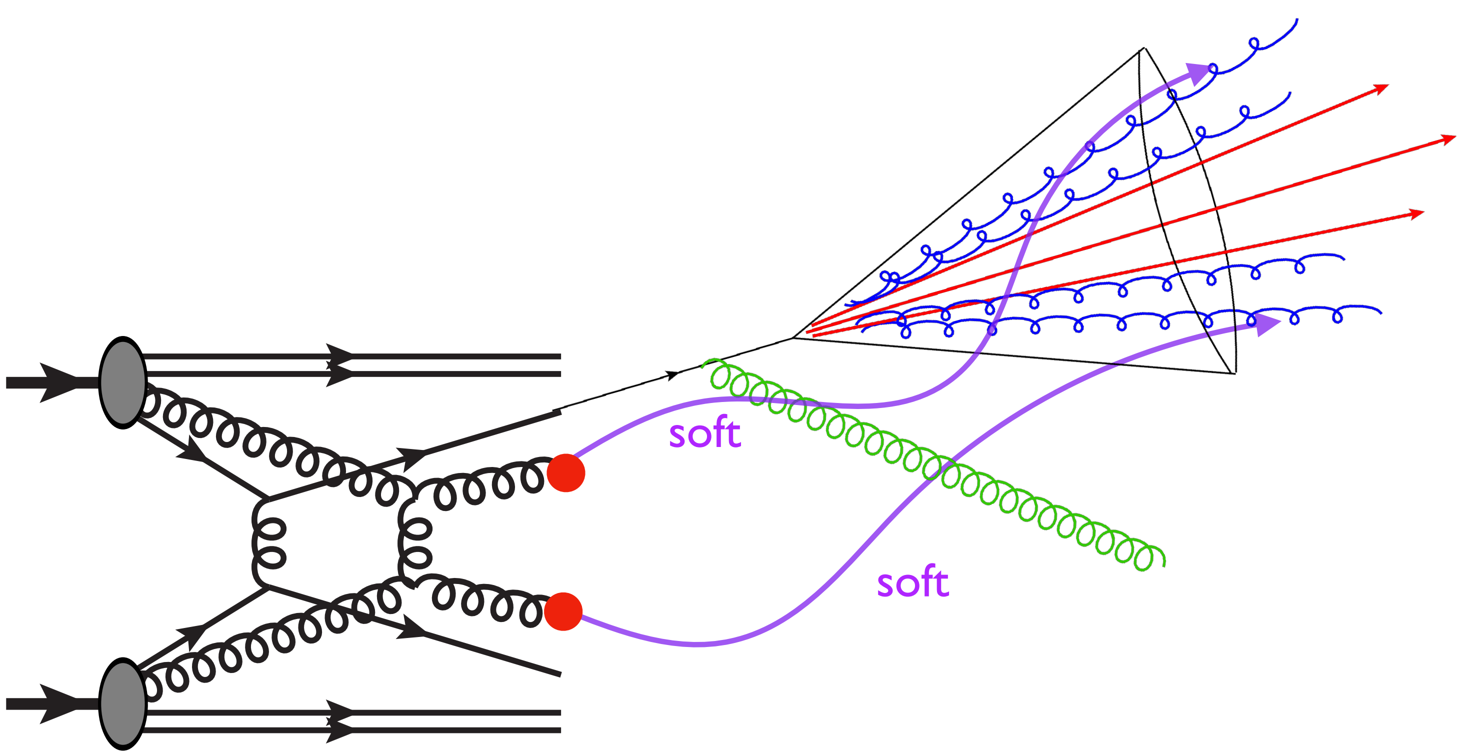
Non-perturbative Effects

- **Non-perturbative effects:**



Figs from P. Bartalini et al. `11

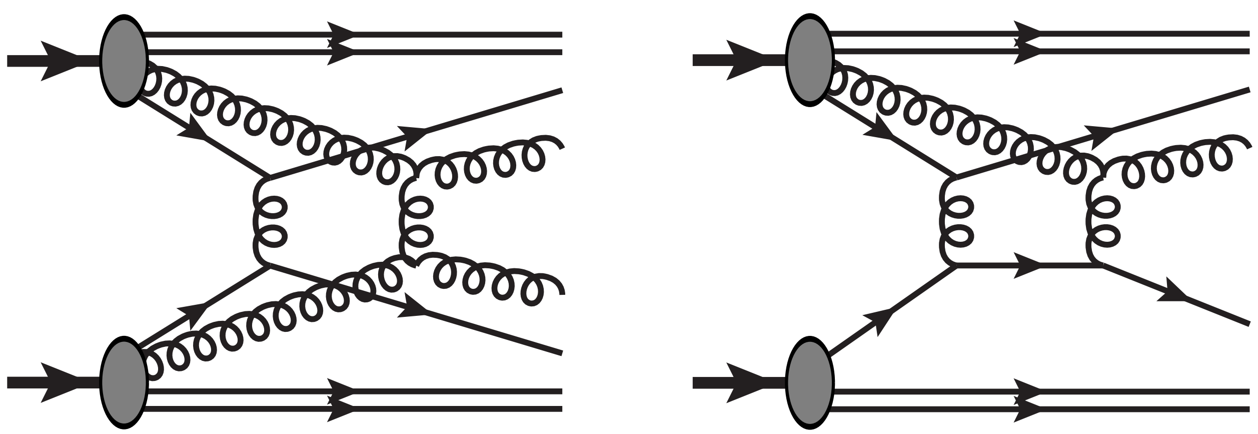
$$\mu_S \sim \frac{p_T \tau_a}{R^{1-a}}$$



- **Multi-Parton Interactions (MPI) (Underlying Events (UE))**
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.

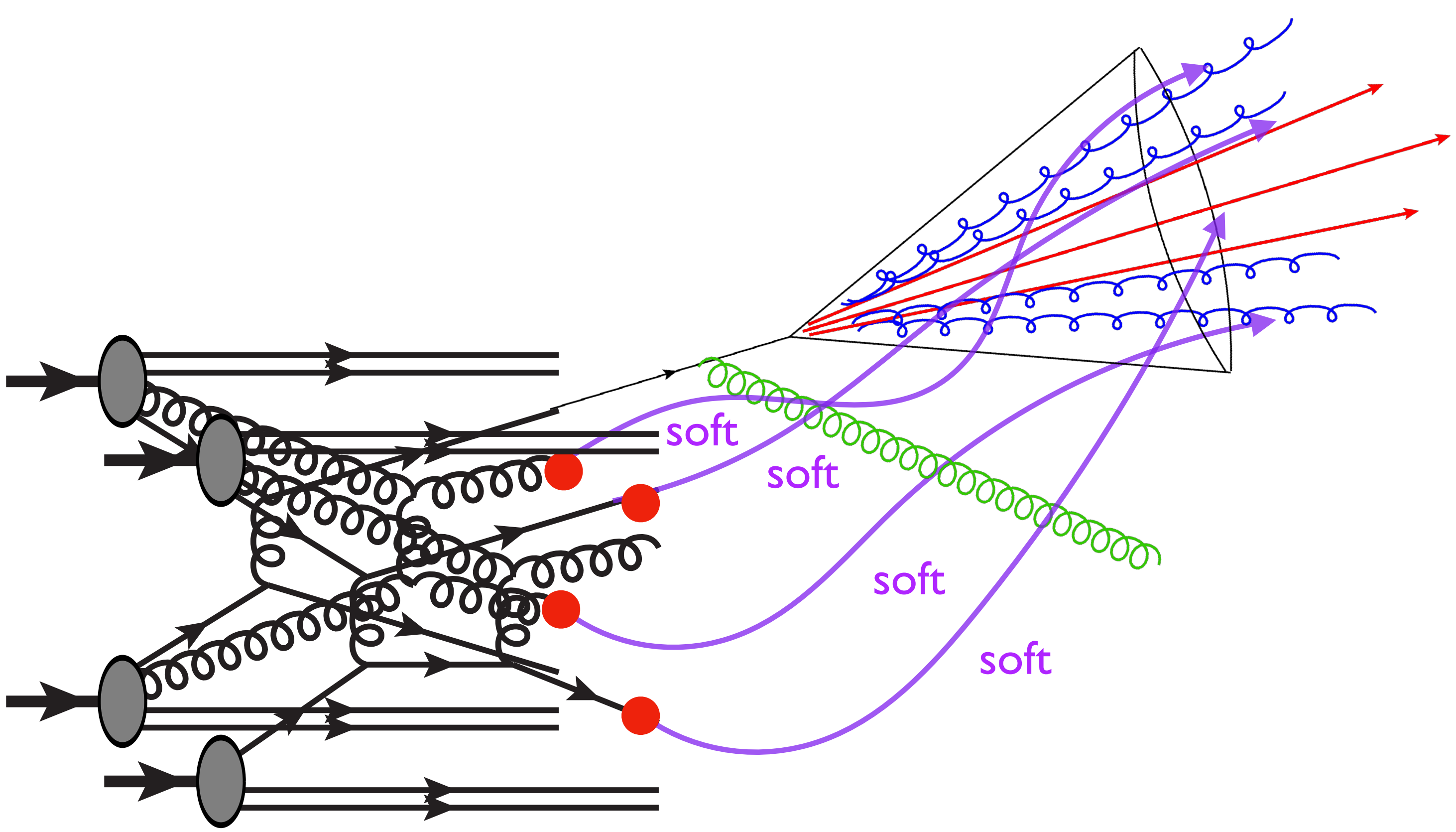
Non-perturbative Effects

- **Non-perturbative effects:**



Figs from P. Bartalini et al. `11

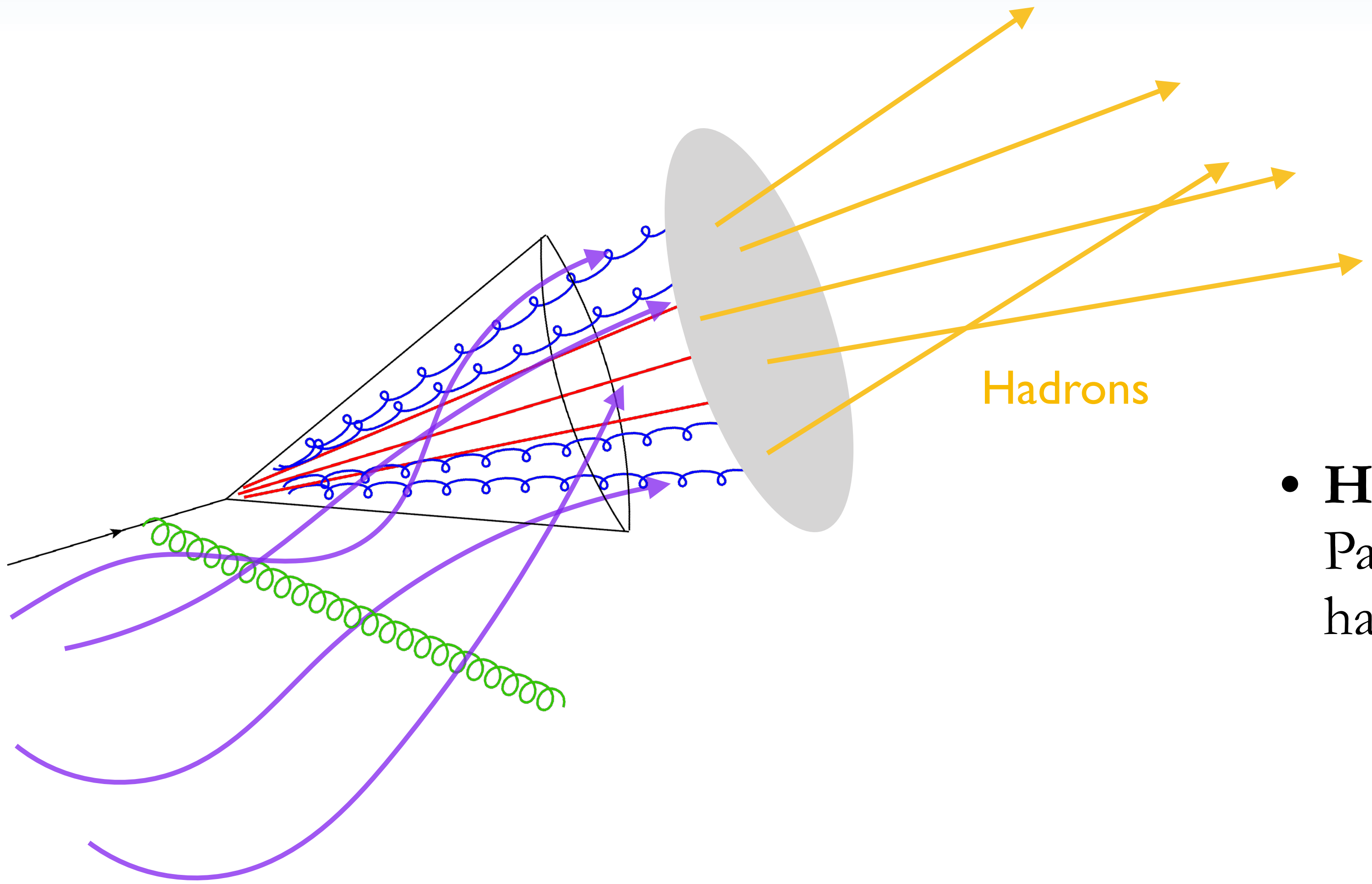
$$\mu_S \sim \frac{p_T \tau_a}{R^{1-a}}$$



- **Multi-Parton Interactions (MPI) (Underlying Events (UE))**
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.
- **Pileups**
  Secondary proton collisions in a bunch may enter and contaminate jet.

Non-perturbative Effects

- **Non-perturbative effects:**



$$\mu_S \sim \frac{p_T \tau_a}{R^{1-a}}$$

- **Hadronization**
  Partons forming the jet eventually hadronizes.

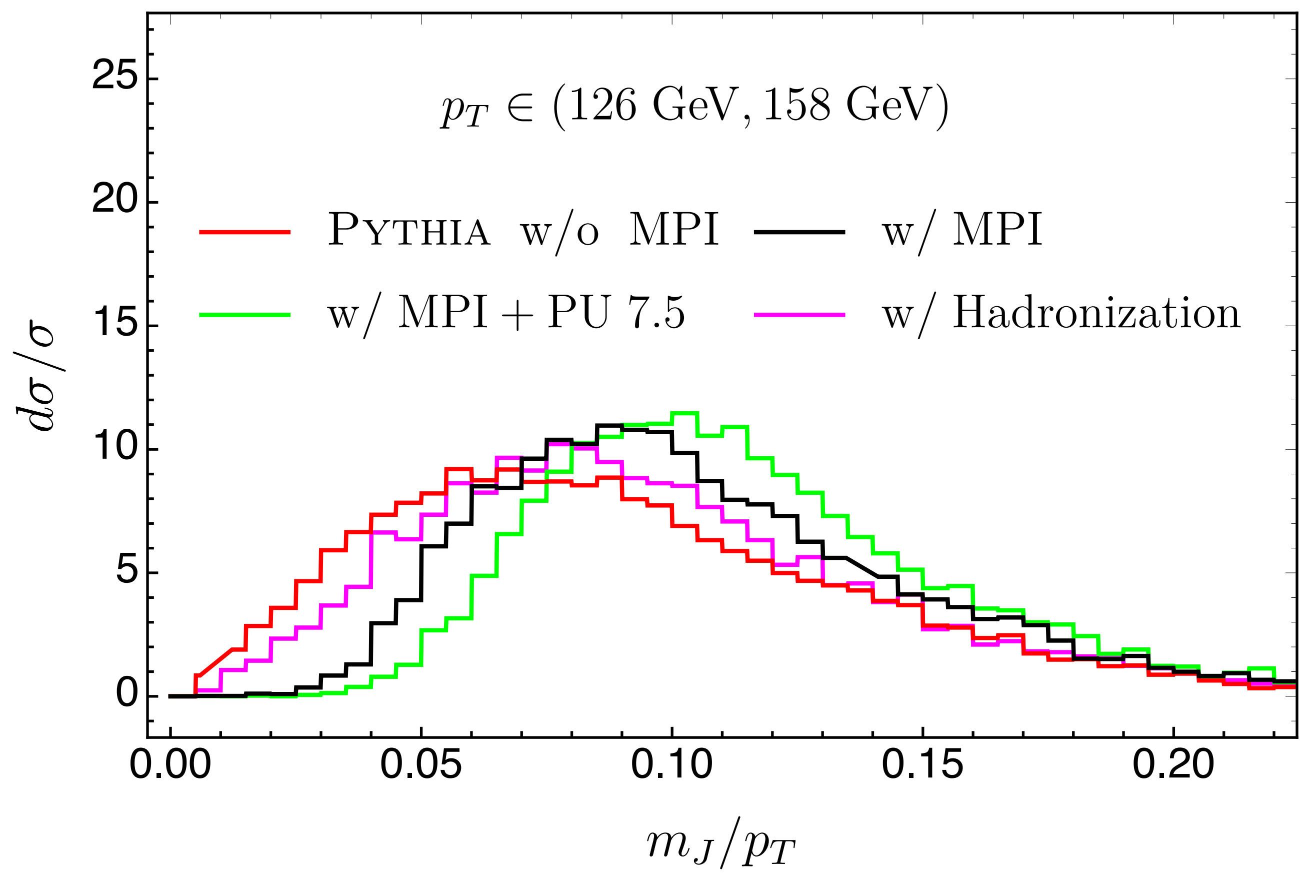
Non-perturbative Effects

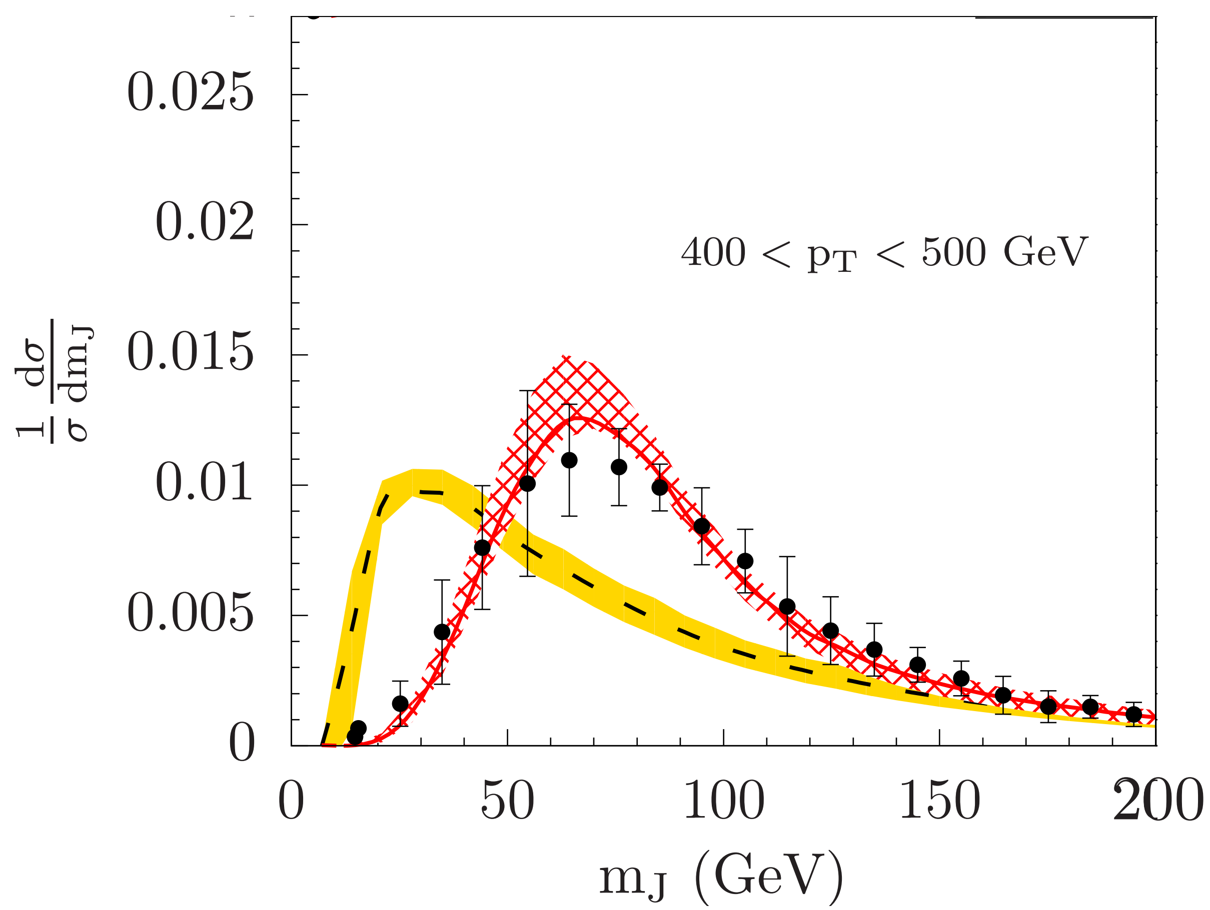
$$\frac{d\sigma}{dp_T\, d\eta\, d\tau_a} = \frac{d\sigma^{\rm pert}}{dp_T\, d\eta\, d\tau_a} \otimes F_{\rm NP}$$

$$\mu_S \sim \frac{p_T \tau_a}{R^{1-a}}$$

Large non-perturbative effects:

LHC kinematics





Chien, Kang, KL, Makris `18
Kang, KL, Liu, Ringer `18

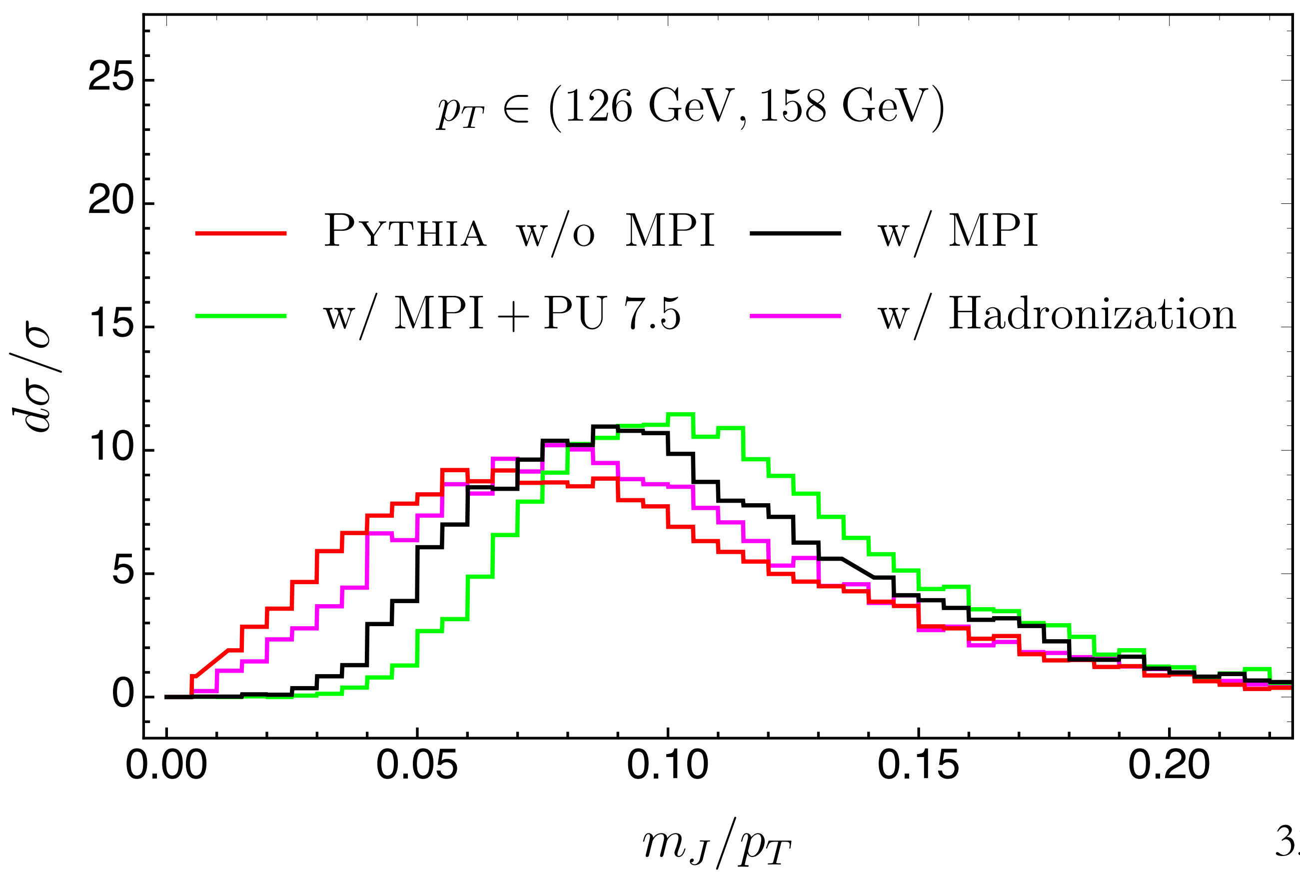
Non-perturbative Model

$$\frac{d\sigma}{d\eta dp_T d\tau} = \int dk F_\kappa(k) \frac{d\sigma^{\rm pert}}{d\eta dp_T d\tau}\left(\tau - \frac{R}{p_T}k\right)$$

- **Single parameter NP shape function :**

Stewart, Tackmann, Waalewijn `15 $$F_\kappa(k) = \left(\frac{4k}{\Omega_\kappa^2}\right)\exp\left(-\frac{2k}{\Omega_\kappa}\right) \qquad \Omega_\kappa = \int dk\, k\, F(k)$$

- **Both hadronization and MPI effects in jet angularity is well-represented by shifting first-moments.**



$$\Omega_\kappa = \Omega_\kappa^{\rm had} + \Omega_\kappa^{\rm MPI}$$

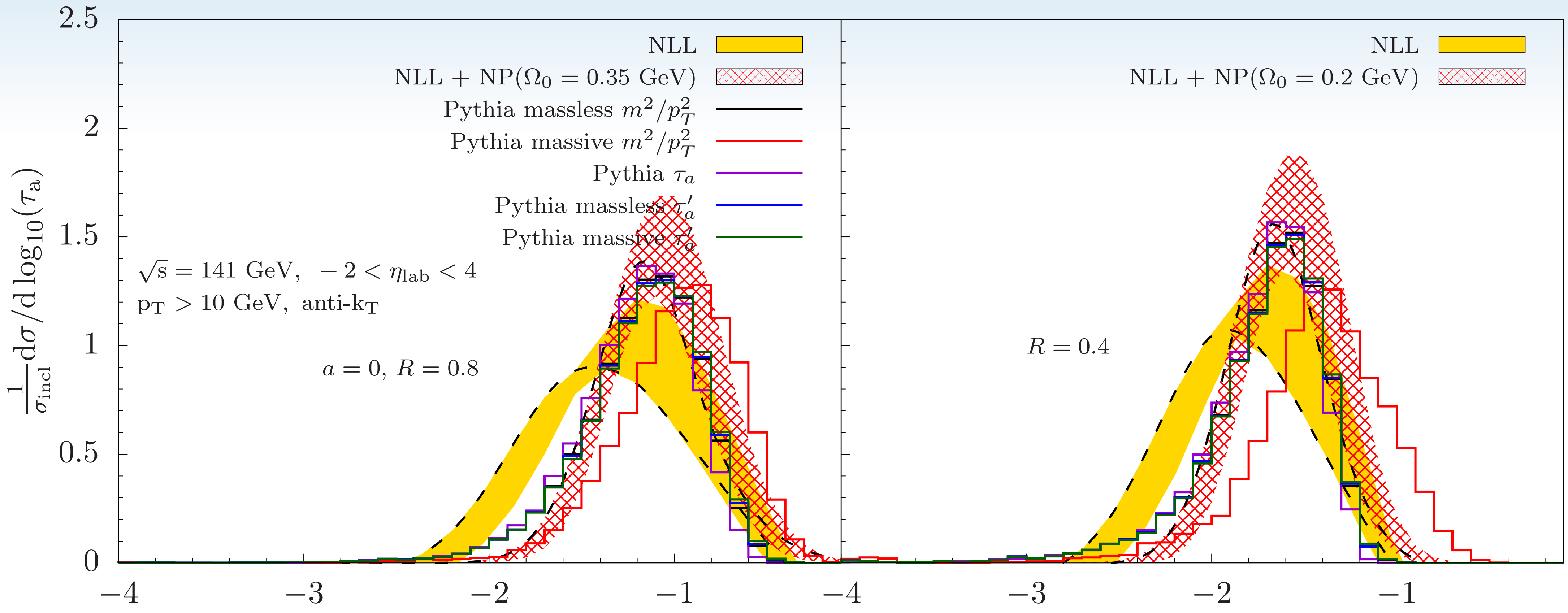
$$\Omega_\kappa^{\rm had} = \Omega_\kappa^{{\rm had},(0)} + \Omega_\kappa^{{\rm had},(2)} R^2 + \cdots$$

$$\Omega_\kappa^{{\rm had},(0)} = \frac{1}{1-a}\langle 0|\mathcal{O}|0\rangle \sim \frac{1}{1-a}\Lambda_{\rm QCD}$$

is universal up to calculable coefficient.

Lee, Sterman `07,
Stewart, Tackmann, Waalewijn `15

Shift from hadronization effects



- NP effects mostly from hadronization. $\Omega \approx \Lambda_{QCD}$
- Some R dependence in NP parameter can be seen

$$\Omega_\kappa^{\rm had} = \Omega_\kappa^{{\rm had},(0)} + \Omega_\kappa^{{\rm had},(2)} R^2 + \cdots$$

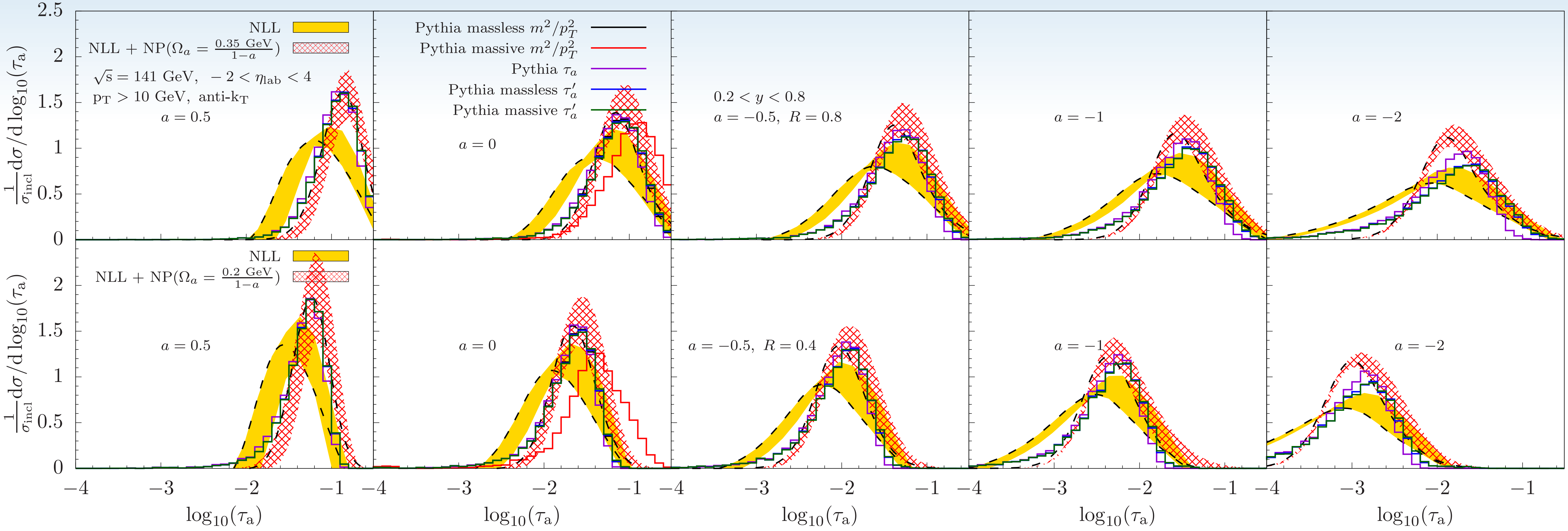
- Hadron mass effects for jet mass can be distinguished within the theoretical uncertainties

$$\tau_0 = \frac{m_J^2}{p_T^2} + \mathcal{O}(\tau_0^2) + \mathcal{O}\left(\frac{m_{\rm had}}{p_T R}\right)$$

Non-perturbative effects

Aschenauer, KL, Page, Ringer, In Preparation

Shift from hadronization effects



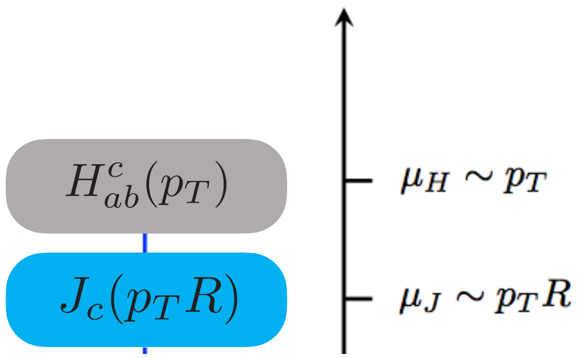
- $\frac{1}{1-a}$ scaling seems to give a good agreement

$$\Omega_\kappa^{\text{had},(0)} = \frac{1}{1-a}\langle 0|\mathcal{O}|0\rangle \sim \frac{1}{1-a}\Lambda_{\text{QCD}}$$

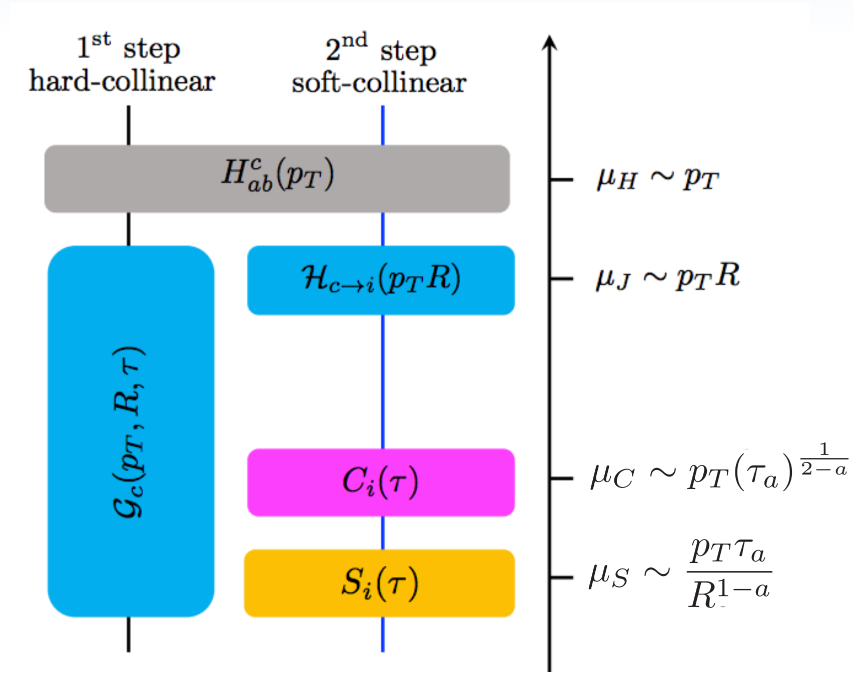
Non-perturbative effects

Aschenauer, KL, Page, Ringer, In Preparation

Scale Uncertainties



- **Inclusive jet**

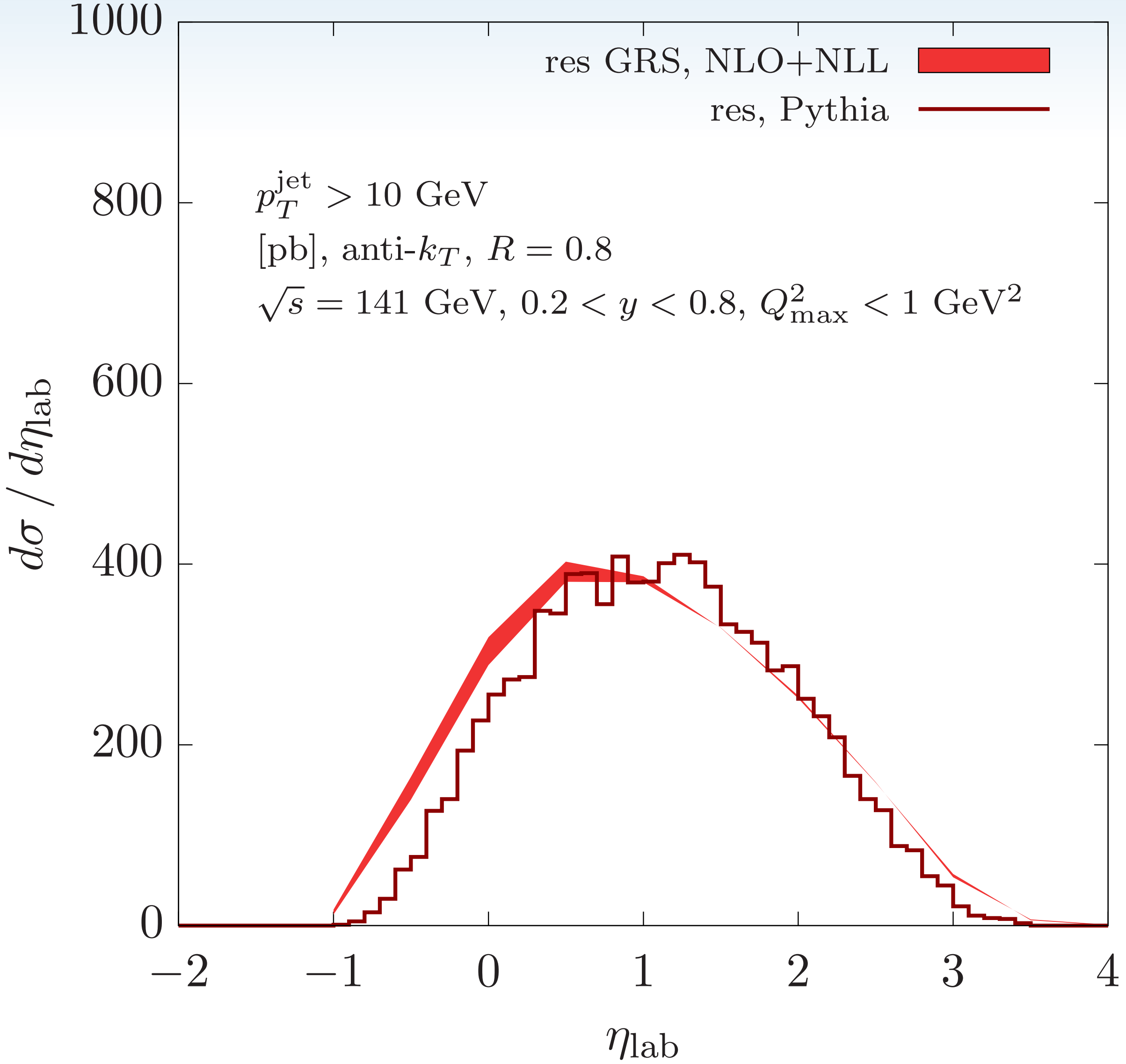


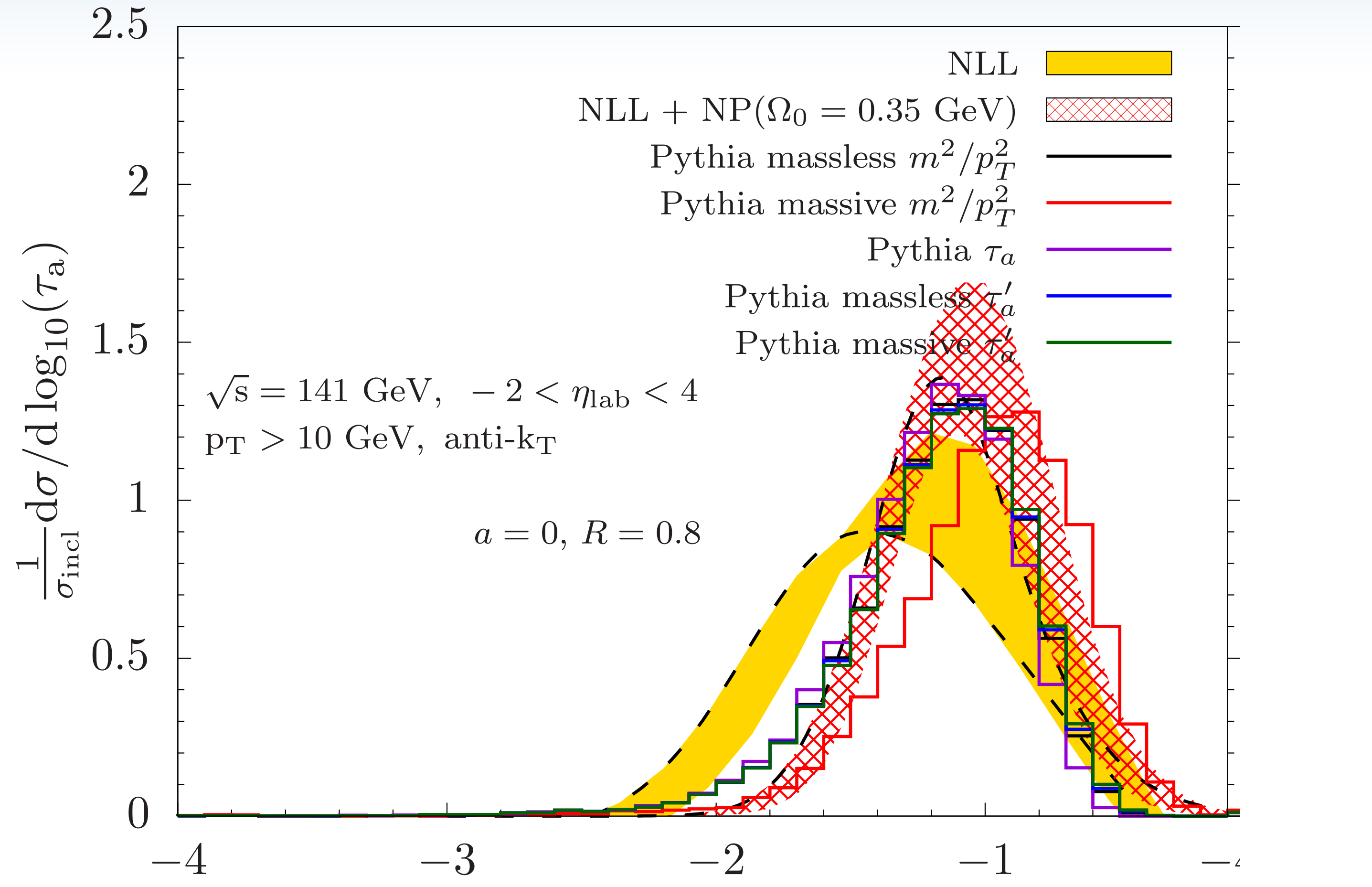
- **Angularity**

- Scales are varied independently in order to estimate uncertainties from higher order calculations.

- Both inclusive jet and angularity measured case have p_T and $p_T R$ scale.
  One expects two scales to be trivially related by R, and also to be similar when $R \to 1$

Scale Uncertainties

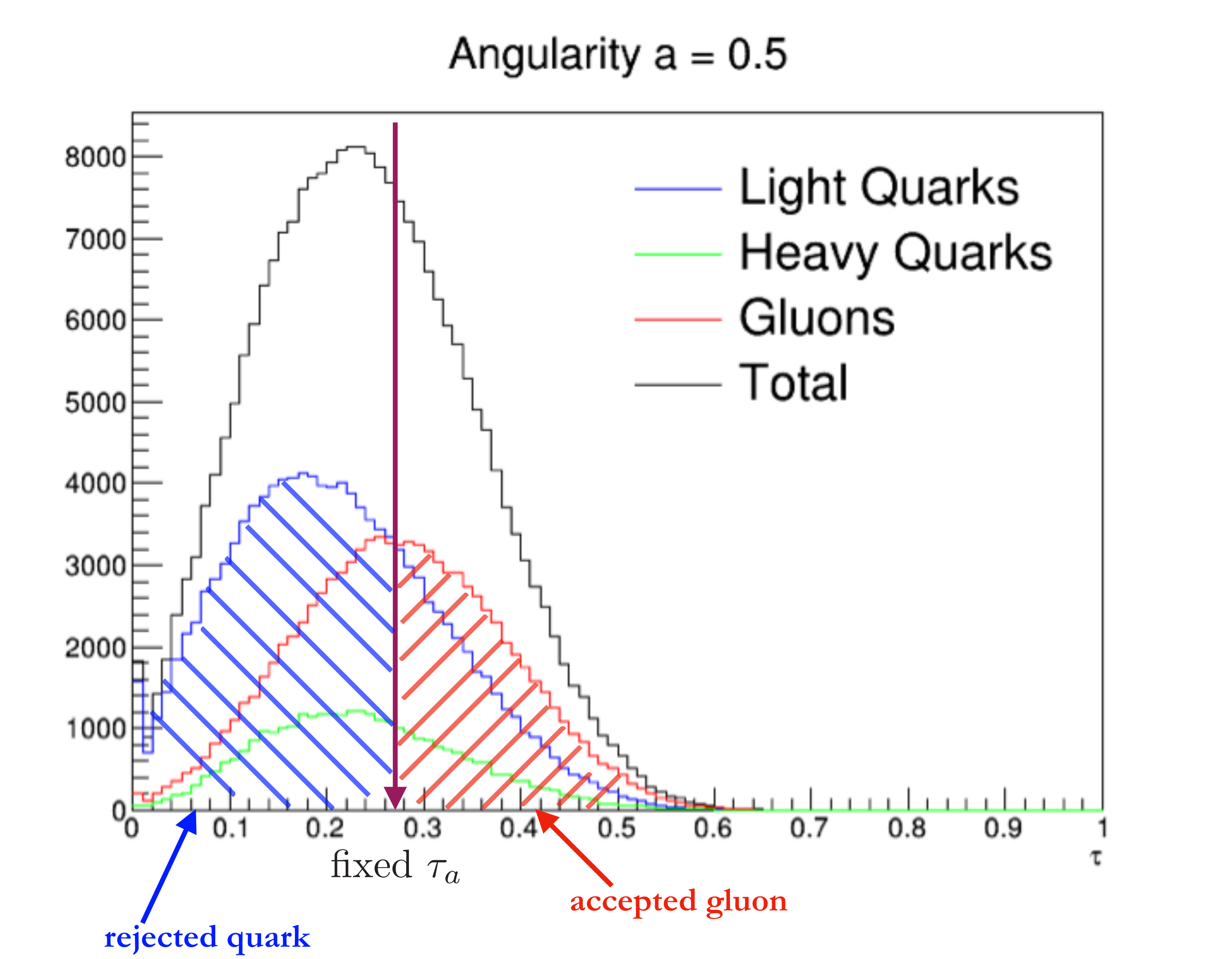


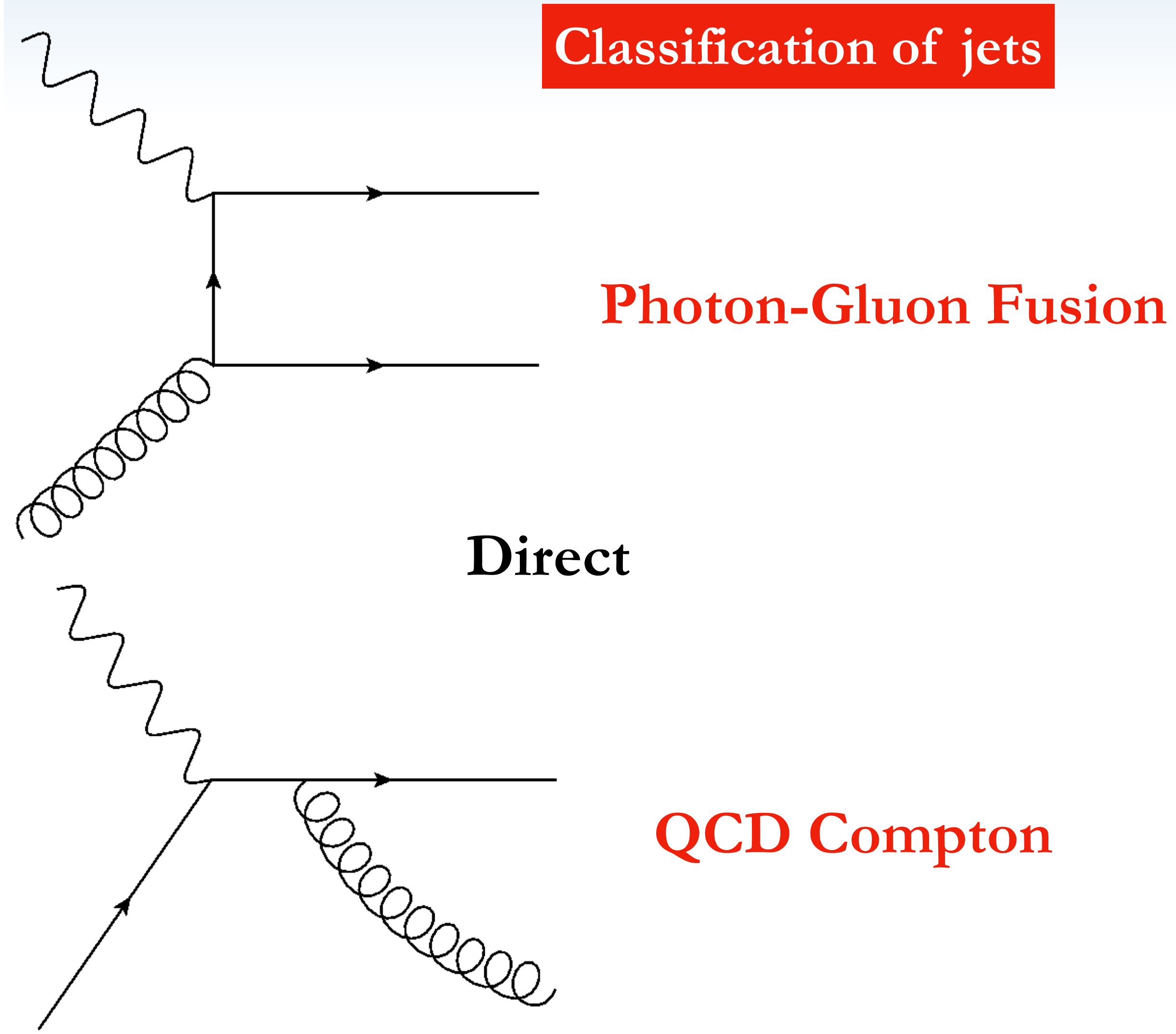


- Both inclusive jet and angularity measured case have p_T and $p_T R$ scale.

  One expects two scales to be trivially related by R, and also to be similar when $R \to 1$
- Gives reasonable estimate when the two scales are varied together for angularity case, but not for inclusive jet.

Quark and gluon jets

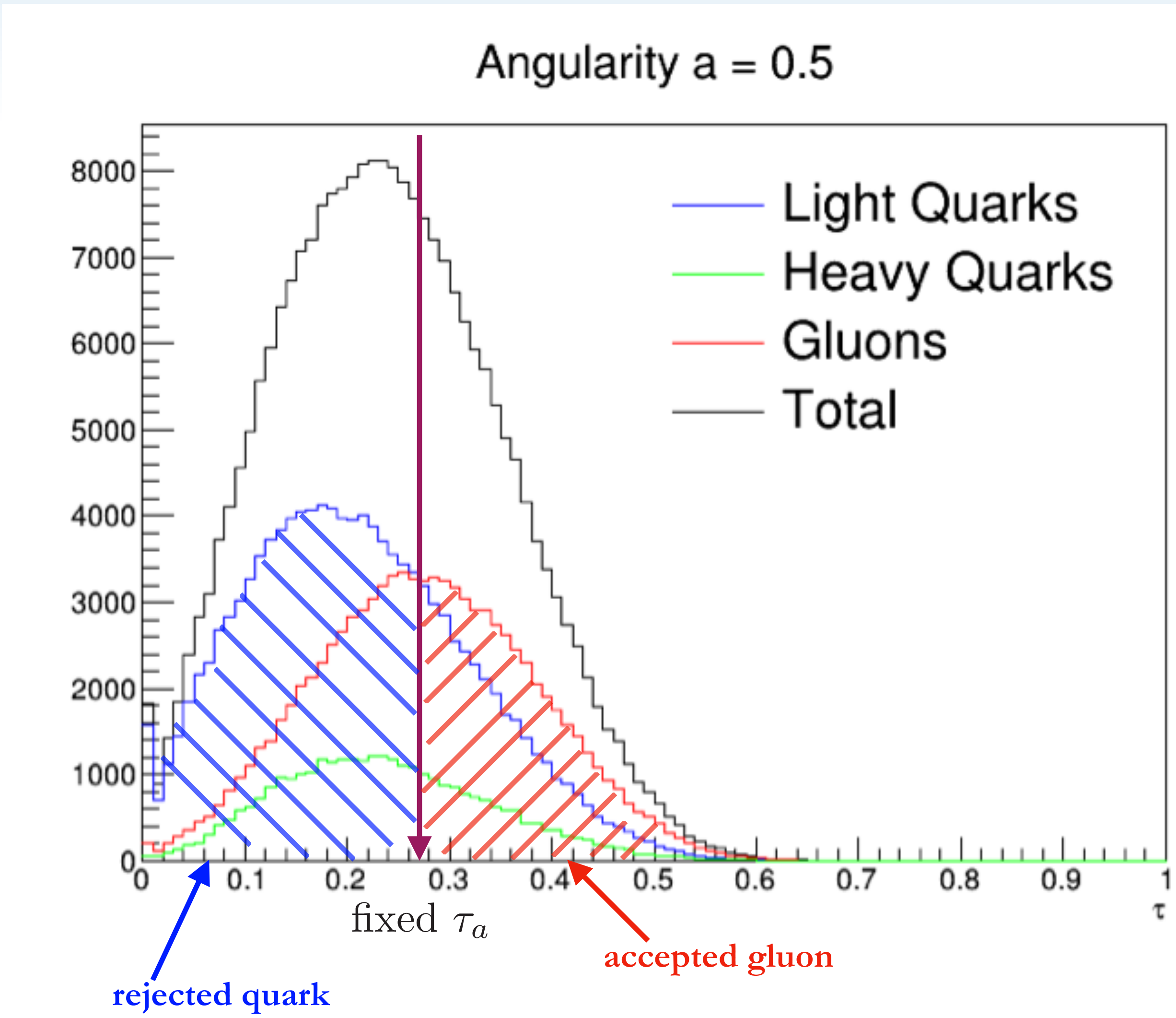


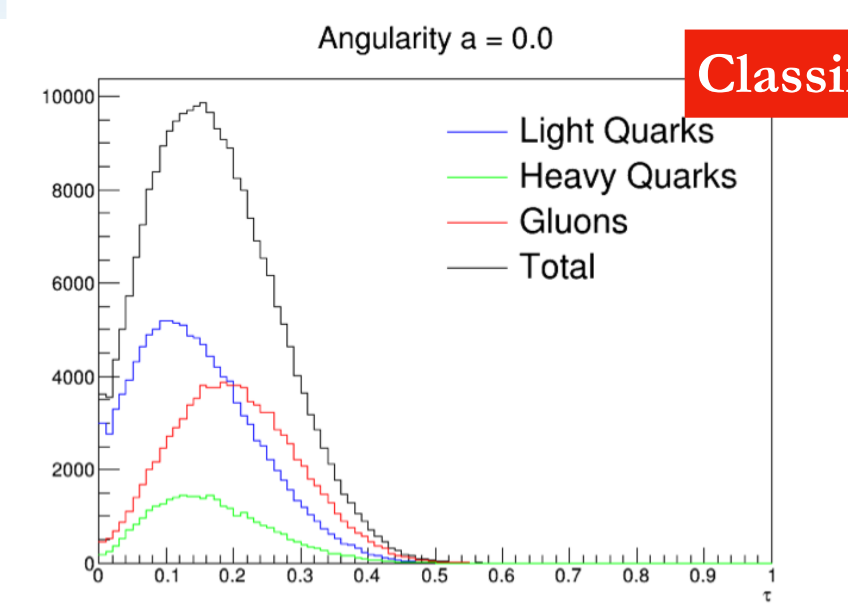


- Angularity can be used to discriminate quark and gluon jets
- May be possible to tag initial state process
  - Study differences in cold nuclear modifications for q/g?
  - Constrain gluon pdf?

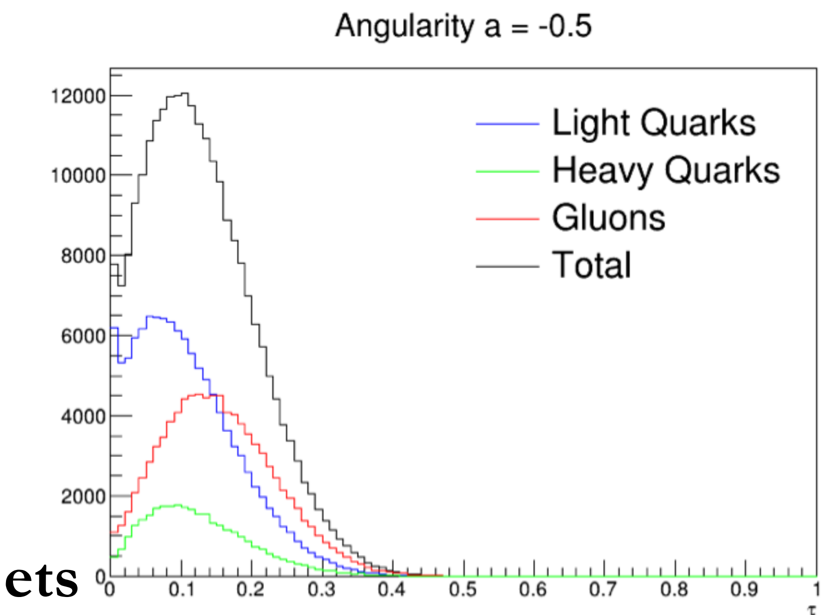
Aschenauer, KL, Page, Ringer, In Preparation

Quark and gluon jets





Classification of jets



- **Angularity can be used to discriminate quark and gluon jets**
- **May be possible to tag initial state process**
  - **Study differences in cold nuclear modifications for q/g?**
  - **Constrain gluon pdf?**
- **Better discrimination for higher 'a'**

Aschenauer, KL, Page, Ringer, In Preparation

Conclusions

- Formalisms for studying semi-inclusive jet production with and without a substructure measurement were introduced.
- Discussed power corrections of different types
- Explored role of non-perturbative effects at the EIC
- Discussed some issues with theoretical scale uncertainties
- Discussed quark and gluon jet discrimination using jet substructures at the EIC