The University of Manchester

AZIMUTHAL DECORRELATION AND THE WINNER-TAKES-ALL AXIS

Rudi Rahn

27-03-23,
SCET23, Berkeley

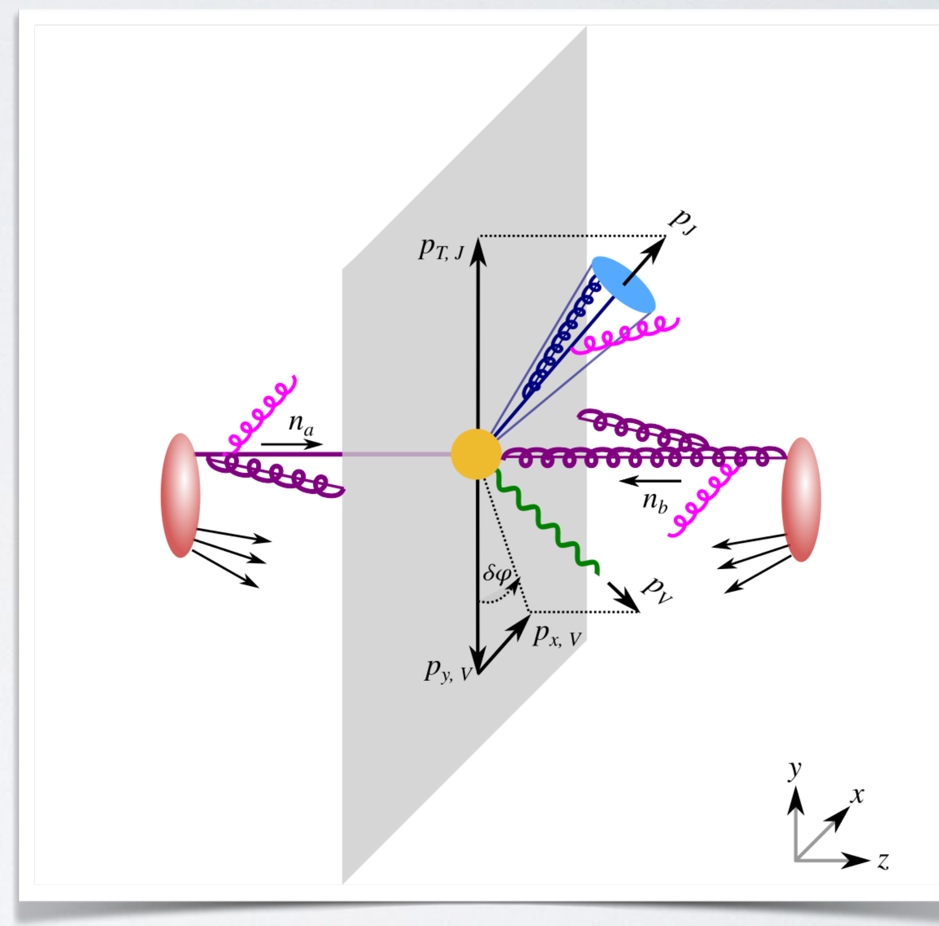
Based on [2005.12279] and [2205.05104] with
Yang-Ting Chien (Georgia State), Ding Yu Shao (Fudan),
Solange Schrijnder van Velzen, Wouter Waalewijn (Nikhef/UvA), Bin Wu (USC)

OUTLINE

- The azimuthal decorrelation
- The WTA axis & radial decorrelation
- Electroweak effects
- q_{wTa}-imbalance

AZIMUTHAL DECORRELATION

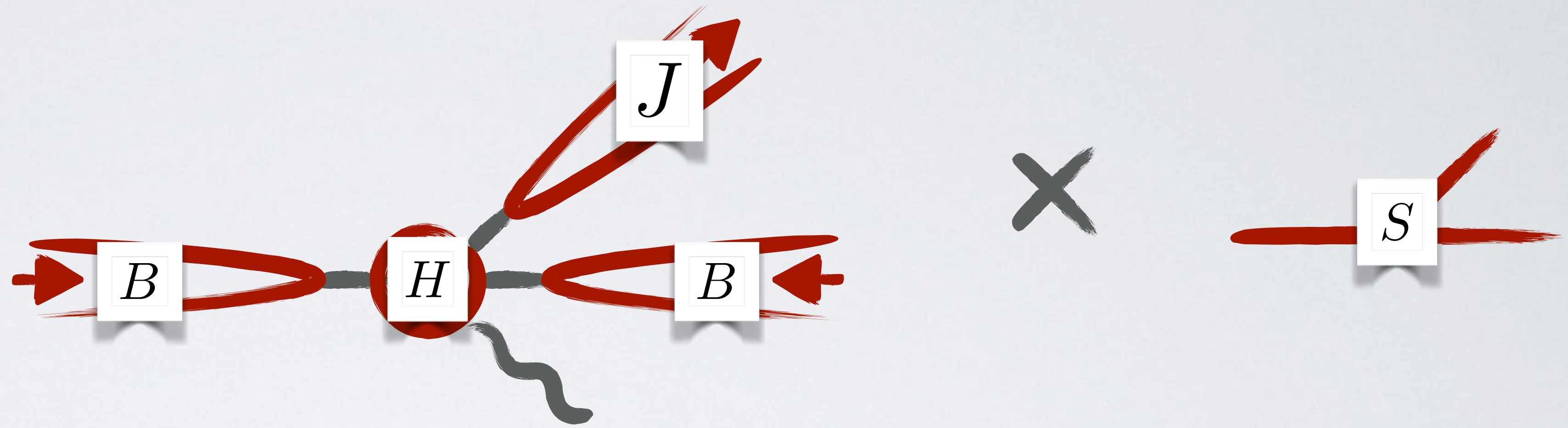
- V+jet at pp collisions
- Leading partonic: planar
- Soft/Collinear emissions: $\delta\varphi \neq 0$
- Large logarithms $\alpha_s^n \ln^{2n} \delta\varphi$



  - Resum using SCET

AZIMUTHAL DECORRELATION

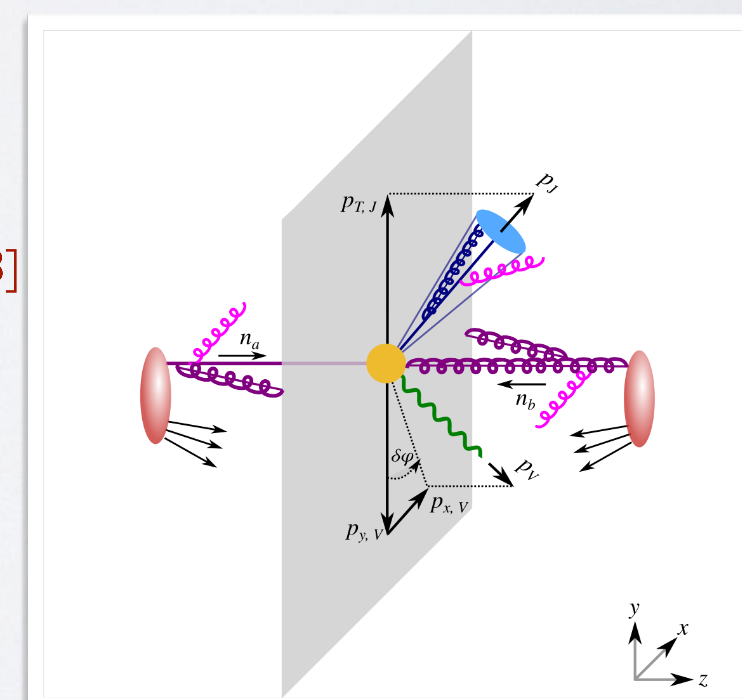
- Expectation:



$$\lambda = \delta\varphi$$

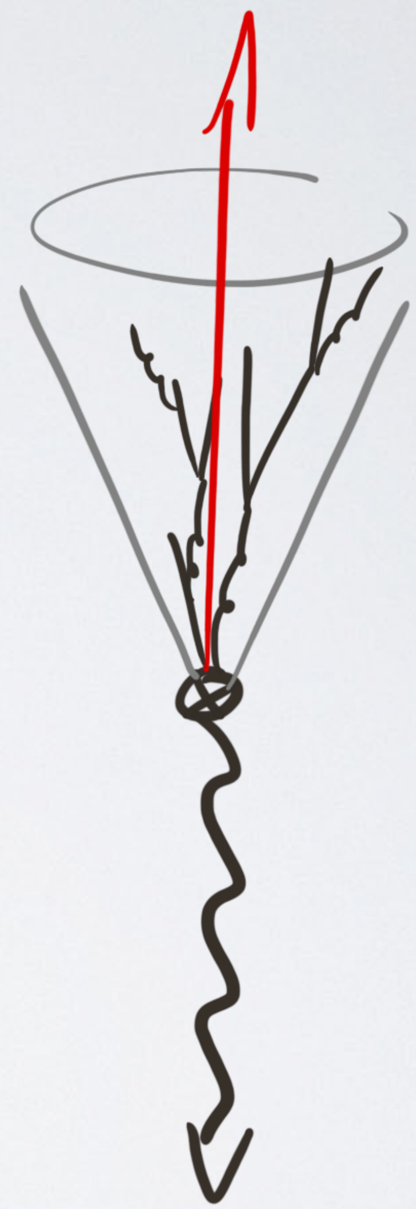
$$\mathrm{d}\sigma = H \otimes B_a \otimes B_b \otimes J \otimes S$$

- Which jet axis?
  - Standard jet axis: [Chen, Qin, Wang, Wei, Zhao, (Zhang)² '18] [Buonocore, Grazzini, Haag, Rottoli '21] [Sun, Yan, (Yuan)2 '18] [Hatta, Yuan, Xiao, Zhou '21] [Chien, Shao, Wu '19]
  - Winner-Takes-All Axis: this talk



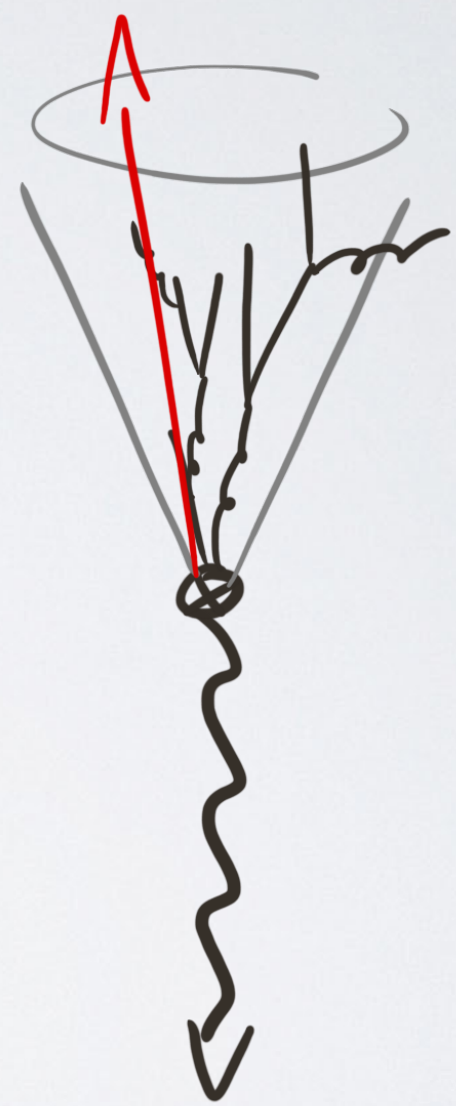
STANDARD JET

- Boson recoils against jet constituents



STANDARD JET

- Boson recoils against jet constituents
- Contribution to $\delta\varphi$ requires out-of-jet radiation
  - ➞ Non-global [Dasgupta, Salam, '01]
- Swiss treatment required [Chien, Shao, Wu, '19]



THE WINNER-TAKES-ALL AXIS

[Salam, unpublished]
[Bertolini, Chan, Thaler, '14]

- Endpoint of a reclustering sequence
- Clustering step: emission pair i,j with $p_{T,i}, \hat{n}_i$ & $p_{T,j}, \hat{n}_j$

$$p_{T,i+j} = p_{T,i} + p_{T,j}$$

$$\hat{n}_{i+j} = \begin{cases} \hat{n}_i & \text{if } p_{T,i} > p_{T,j} \\ \hat{n}_j & \text{if } p_{T,i} < p_{T,j} \end{cases}$$

THE WINNER-TAKES-ALL AXIS

[Salam, unpublished]
[Bertolini, Chan, Thaler, '14]

- Powerful when combined with SCET: $p_{T,c} \sim Q,\ p_{T,S} \sim Q\delta\varphi$
  - Direction purely a collinear affair: $\max(p_{T,c}, p_{T,S}) = p_{T,c}$
  - Soft subleading in magnitude: $p_{T,c} + p_{T,S,\text{in-jet}} \approx p_{T,c}$

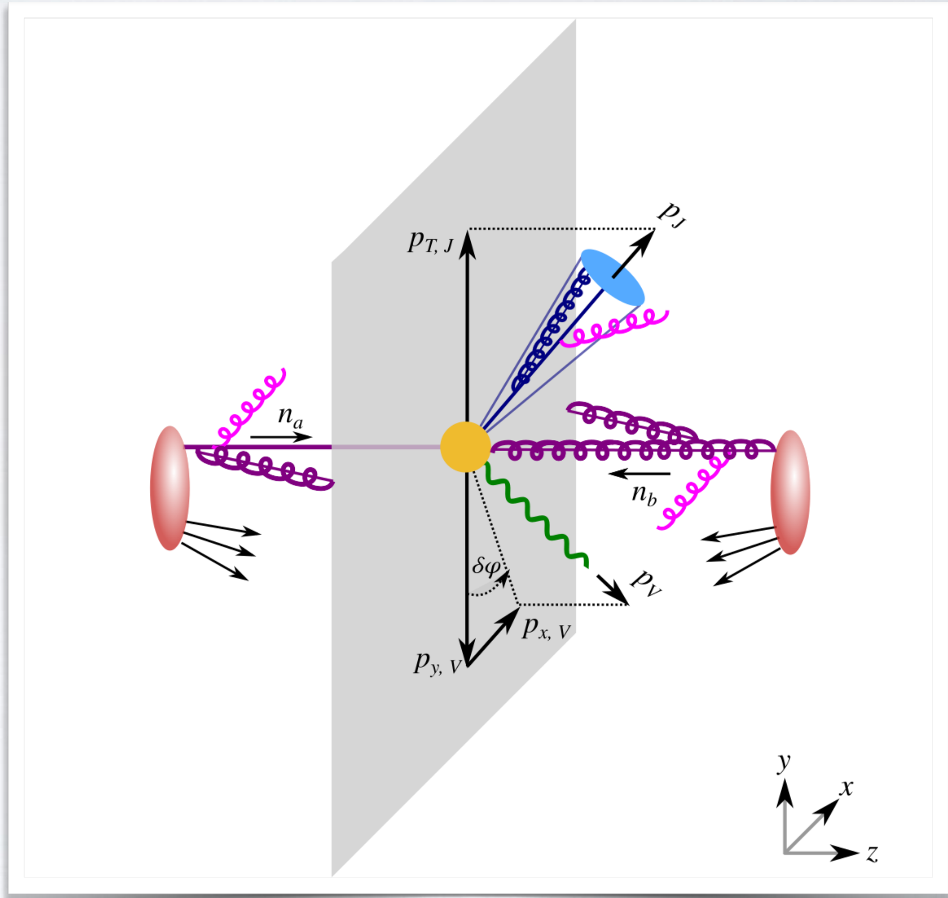
$\Rightarrow$ No non-global logarithms*
[Larkoski, Neill, Thaler, '14]

AZIMUTHAL DECORRELATION II

- Dimensionful variant:

$$q_x = p_{x,V} = -p_{x,c} - p_{x,a} - p_{x,b} - p_{x,S}$$

$$= p_{T,V} \sin \delta\varphi$$

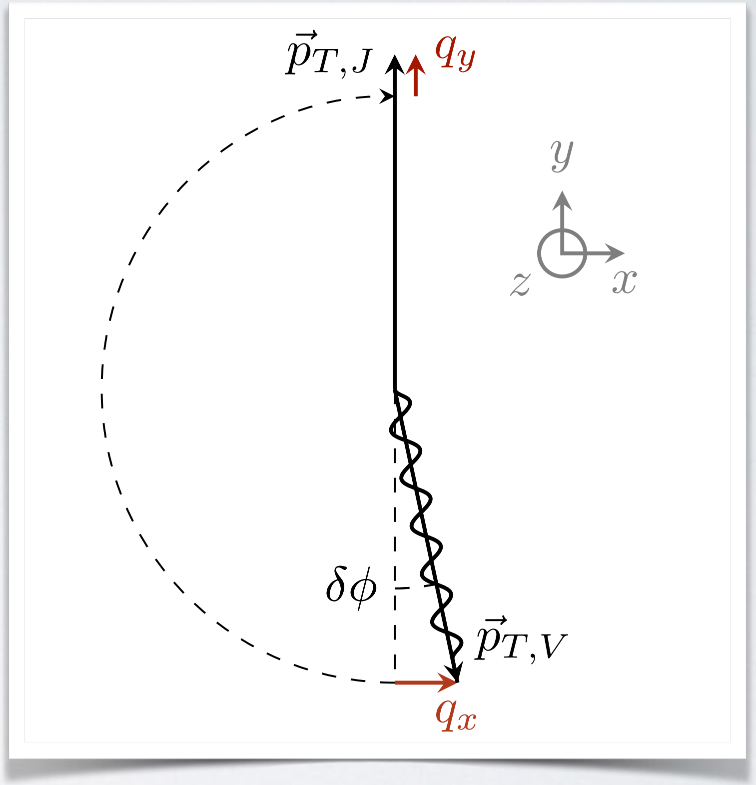


WHY SO SIMPLE?

- Compare: *radial* decorrelation

(Azimuthal) $$q_x = p_{T,V} \sin \delta\varphi \sim \delta\varphi$$

(Radial) $$q_y = p_{T,J} - p_{T,V} \cos \delta\varphi \sim (\delta\varphi)^2$$



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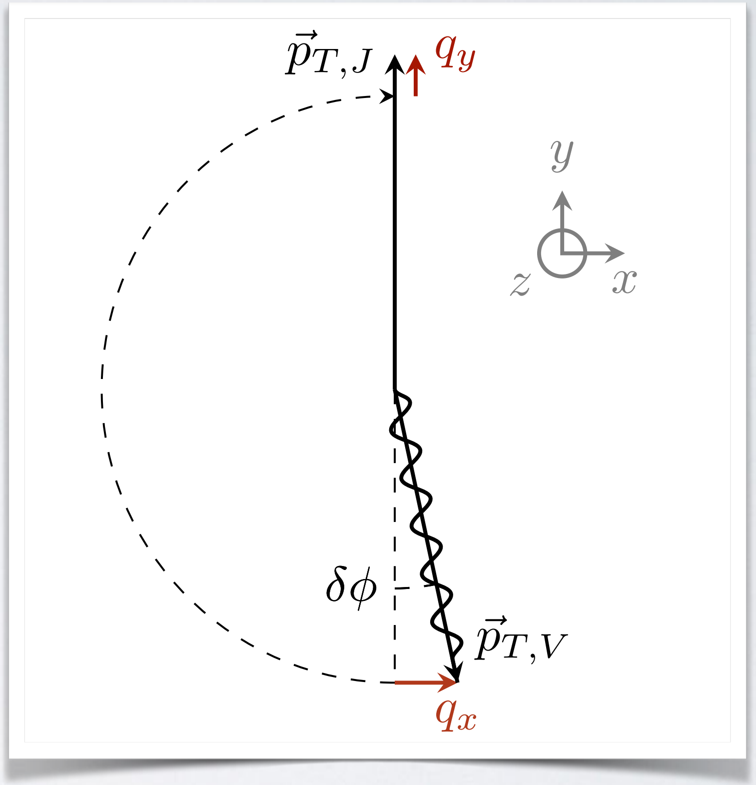
Are these the same?



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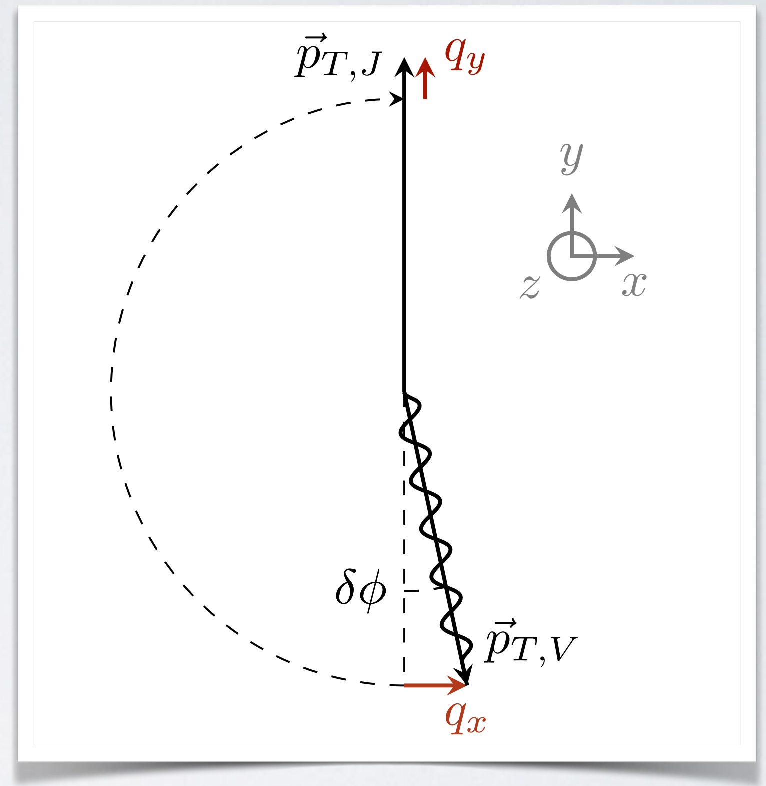
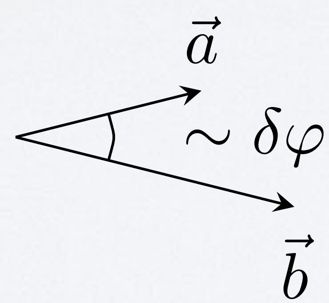


- Scalar vs. vector sum:



$$\Rightarrow \quad (|\vec{a}| + |\vec{b}|) - |(\vec{a} + \vec{b})| \sim \delta\varphi^2$$

WHY SO SIMPLE?

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(Azimuthal) $q_x = p_{T,V} \sin \delta\varphi$
$\sim \delta\varphi$

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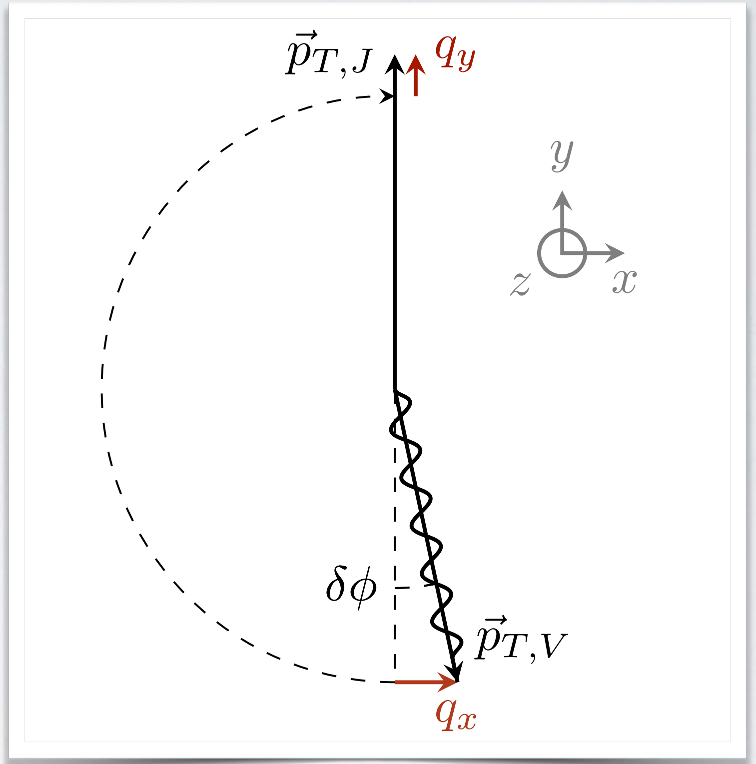

- WTA definition + soft in-jet radiation:
  - Large cancellation: $p_{T,c} + p_{T,S,\text{in-jet}} \approx p_{T,c}$

WHY SO SIMPLE?

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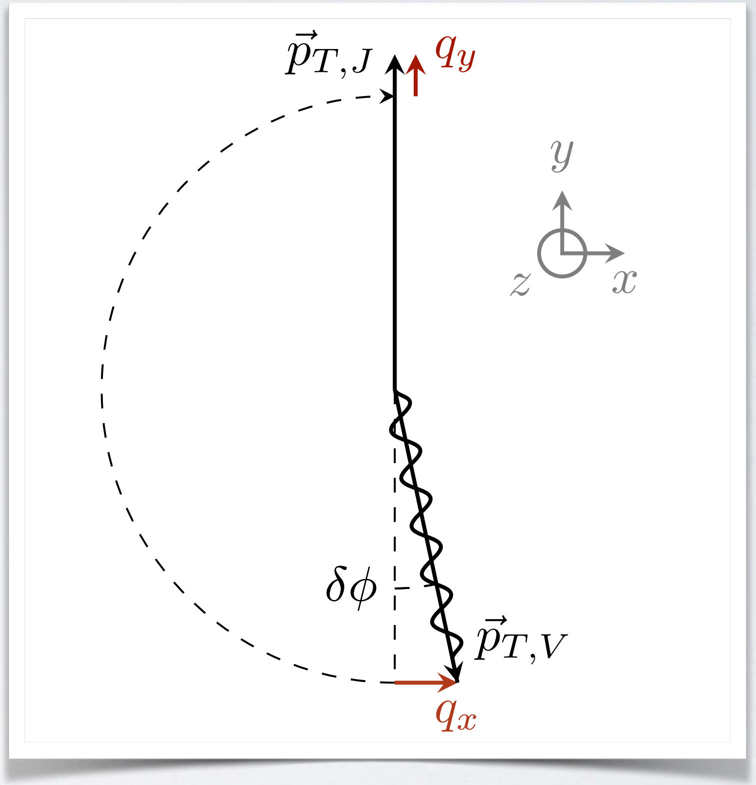

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- WTA definition + soft in-jet radiation:
  - Large cancellation: $p_{T,c} + p_{T,S,\text{in-jet}} \approx p_{T,S,\text{in-jet}}$

$\Rightarrow$ Sensitive to in-jet soft $\Rightarrow$ Non-global

CALCULATION

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{x,V}\,\mathrm{d}p_{T,V}\,\mathrm{d}y_V\,\mathrm{d}\eta_J} = \int \frac{\mathrm{d}b_x}{2\pi}\, e^{\mathrm{i}p_{x,V}b_x} \sum_{i,j,k} B_i(x_a,b_x) B_j(x_b,b_x) S_{ijk}(b_x,\eta_J) \times \mathcal{H}_{ij\to Vk}(p_{T,V}, y_V-\eta_J)\, \mathscr{J}_k(b_x) \Big[1+\mathcal{O}\Big(\frac{p_{x,V}^2}{p_{T,V}^2}\Big)\Big]$$

- NNLL resummation
  - 3-loop $\Gamma_{\rm cusp}$, 2-loop γ_i, 1-loop finite H,J,S,B

[Arnold, Reno, '89]
[Becher, Lorentzen, Schwartz, '12]
[Moch, Vermaseren, Vogt, '04/'05]
[Becher, Neubert, '09]
[Gehrmann, Luebbert, Yang, '14]
[Echevarria, Scimemi, Vladimirov, '16]
[Luebbert, Oredsson, Stahlhofen, '16]

- Most known, only minor recalculations:
  - S at NLO via boost (non-)invariance:
    See also [Gao, Li, Moult, Zhu, '19]

$$S_{ij}^{(1)}(b_x,\eta_J,\mu,\nu) = -\sum_{i<j} \mathbf{T}_i\cdot\mathbf{T}_j S^{(1)}\Big(b_x,\mu,\nu\sqrt{n_i\cdot n_j/2}\Big)$$

  - TMD jet function with η-regulator and large jet radius

[Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi, '18/'19]

[Chiu, Jain, Neill, Rothstein, '12]

TRIVIA

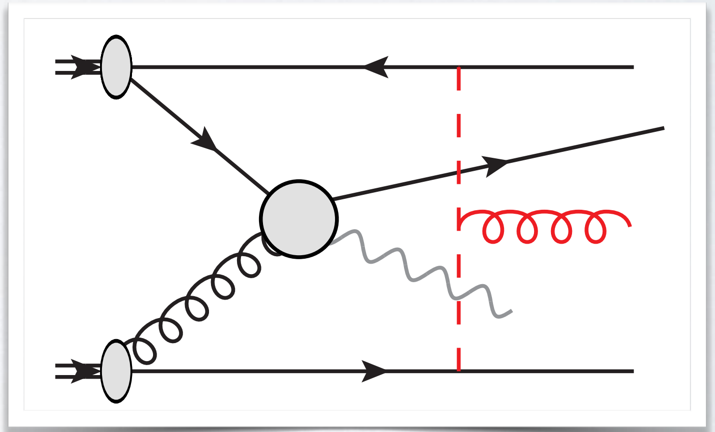
- Linearly polarised beam and jet functions

$$B_g^{\mu\nu}(\vec{b}_\perp,\mu,\nu) = \frac{-g_\perp^{\mu\nu}}{d-2} B_g^{(1)}(\vec{b}_\perp,\mu,\nu) + \left(\frac{g_\perp^{\mu\nu}}{d-2} + \frac{b_\perp^\mu b_\perp^\nu}{b_T^2}\right) B_g^{(2)}(\vec{b}_\perp,\mu,\nu)$$

[Catani, Grazzini, '11]

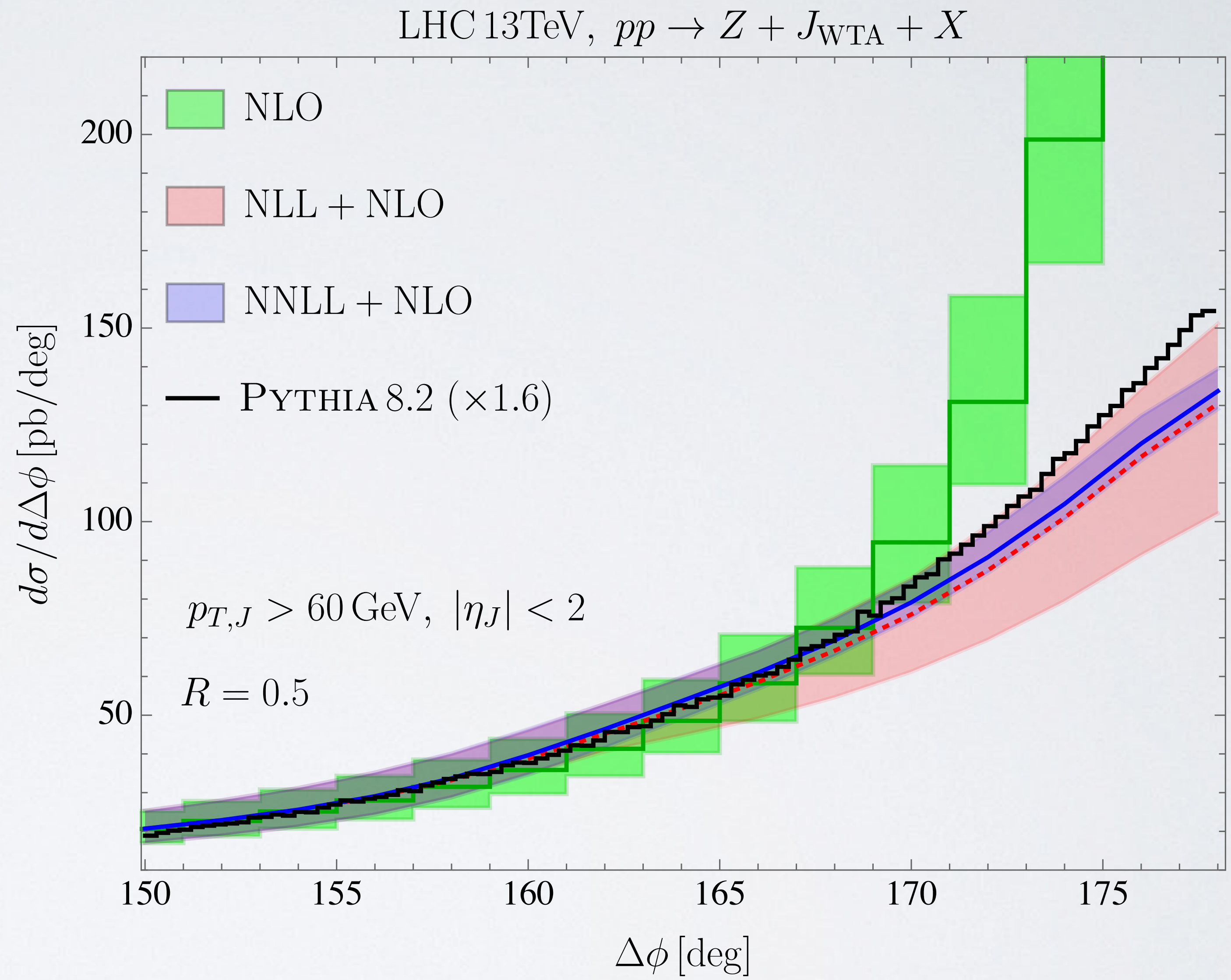
- Factorisation breaking effects?
  - Higher order
  - Active-spectator?

[Rogers, Mulders '10]



PLOTS I

- Using CT14nlo
- NLO from MCFM
- No difference Pythia hadron/parton
- Large matching for high jet p_T

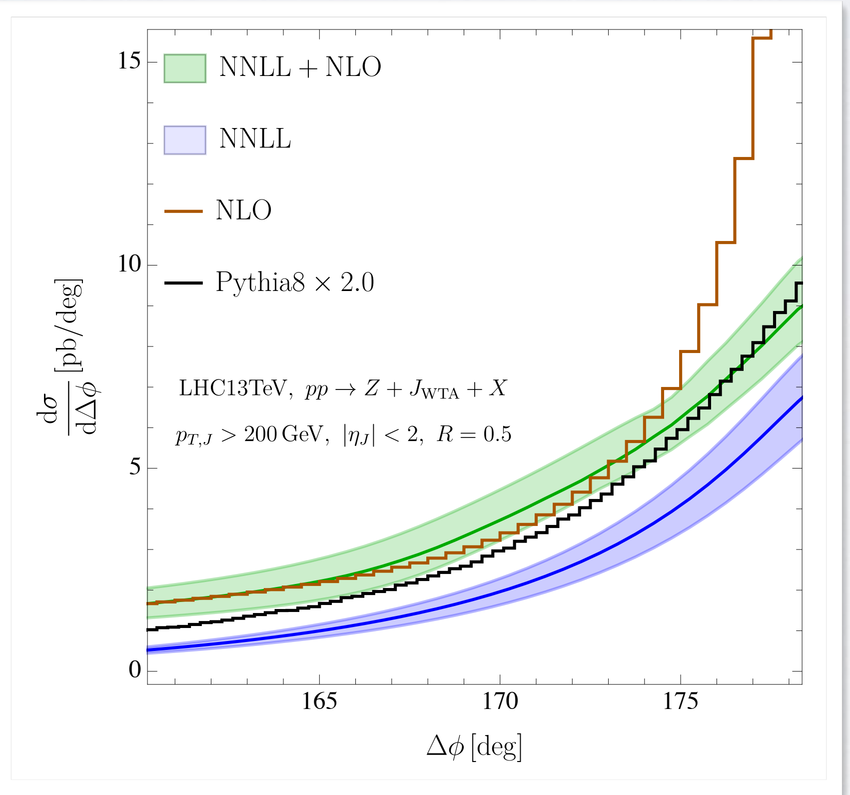


$$\mu_H = \sqrt{p_{T,V}^2 + m_V^2},\ \nu_S = \mu_B = 2e^{-\gamma_e}/|b_x|,\ \nu_{B_{a,b}} = x_{a,b}\sqrt{s},\ \nu_J = 2p_{T,J}\cosh\eta_J$$

Use b* prescription [Collins, Soper, Sterman, '85]

MATCHING CORRECTIONS

- Large matching corrections for high-p_T jets



MATCHING CORRECTIONS

- Large matching corrections for high-p_T jets
- Additive or multiplicative matching?

$$\sigma^{\text{add}} = \sigma^{\text{res}} - \sigma^{\text{exp}} + \sigma^{\text{sing}} + \sigma^{\text{non-sing}}$$

$$\sigma^{\text{mult}} = \frac{\sigma^{\text{res}}}{\sigma^{\text{exp}}}\left(\sigma^{\text{sing}} + \sigma^{\text{non-sing}}\right)$$

MATCHING CORRECTIONS

- Large matching corrections for high-p_T jets
- Matching in the resummation region:

$$\sigma^{\text{add}} = \sigma^{\text{res}} - \cancel{\sigma^{\text{exp}} + \sigma^{\text{sing}}} + \sigma^{\text{non-sing}}$$

$$\sigma^{\text{mult}} = \frac{\sigma^{\text{res}}}{\sigma^{\text{exp}}} \left(\sigma^{\text{sing}} + \sigma^{\text{non-sing}} \right)$$

MATCHING CORRECTIONS

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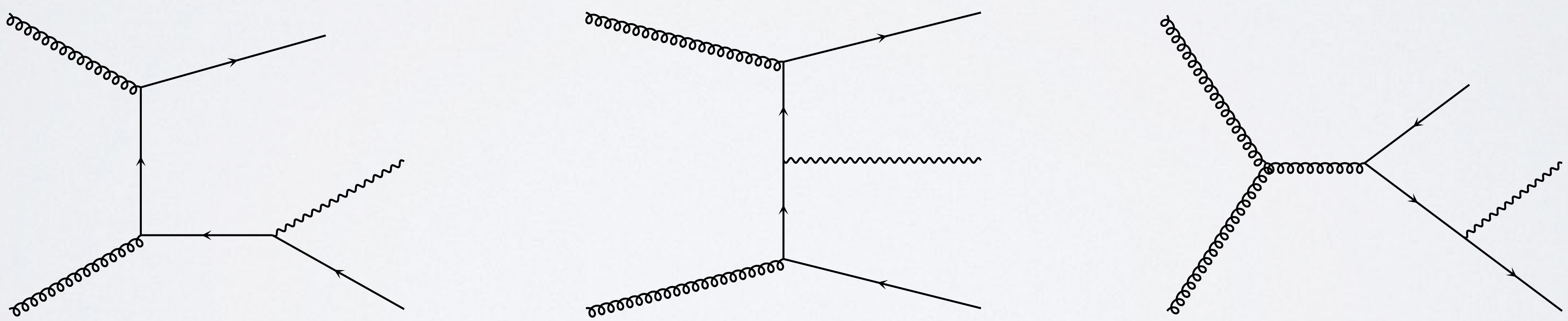
- Matching in the resummation region:

$$\sigma^{\text{add}} = \sigma^{\text{res}} - \sigma^{\text{exp}} + \sigma^{\text{sing}} + \sigma^{\text{non-sing}}$$

$$\sigma^{\text{mult}} \approx \sigma^{\text{res}} + \frac{\sigma^{\text{res}}}{\sigma^{\text{exp}}}\sigma^{\text{non-sing}}$$

MATCHING CORRECTIONS

- Large matching corrections for high-p_T jets
- Electroweak corrections to dijet decorrelation



(a) (b) (c)

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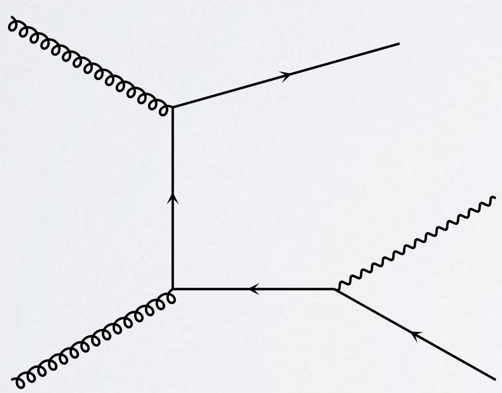
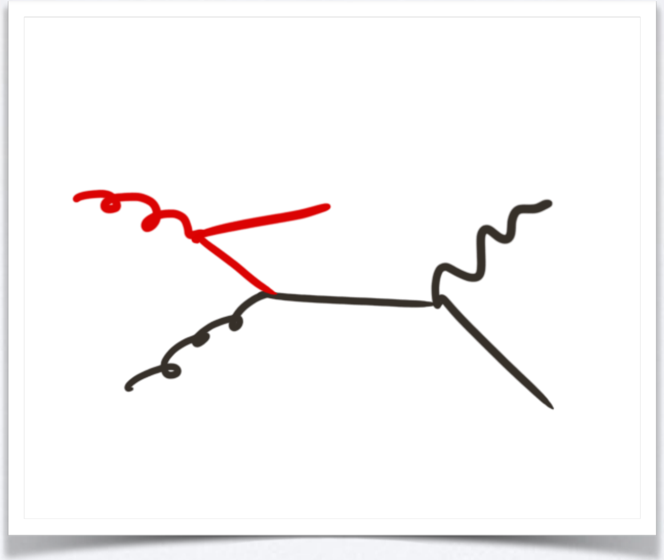
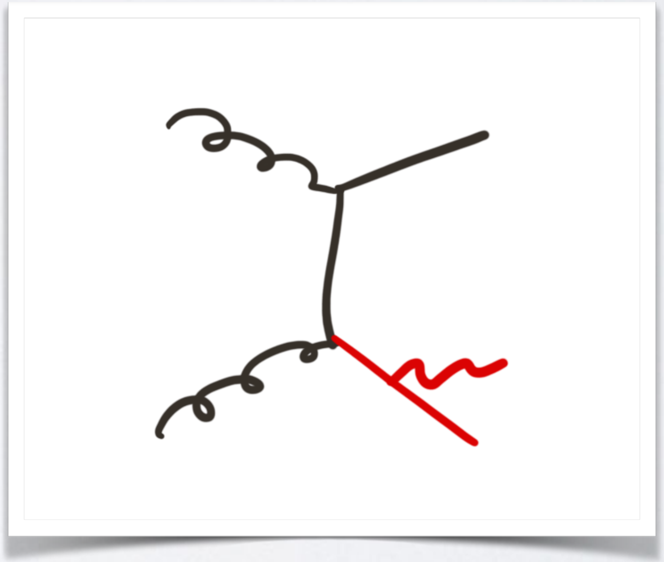


(a)





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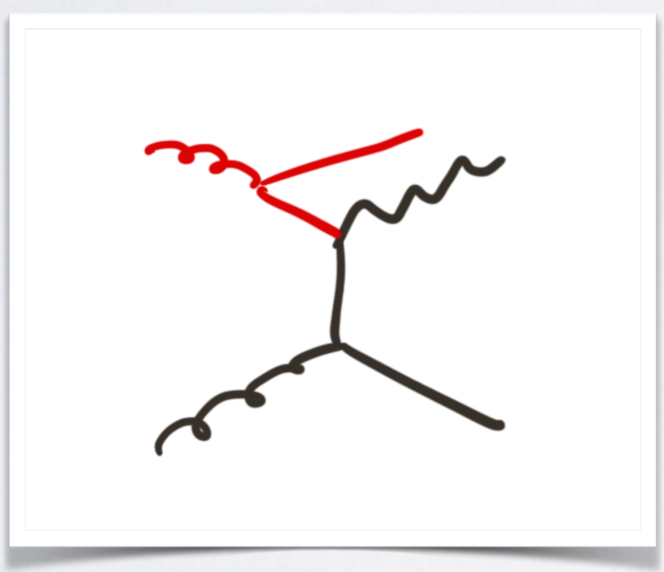
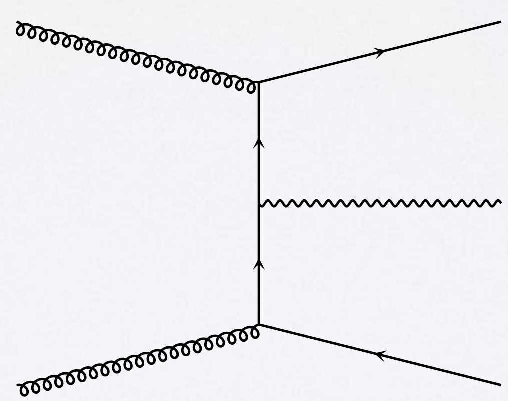
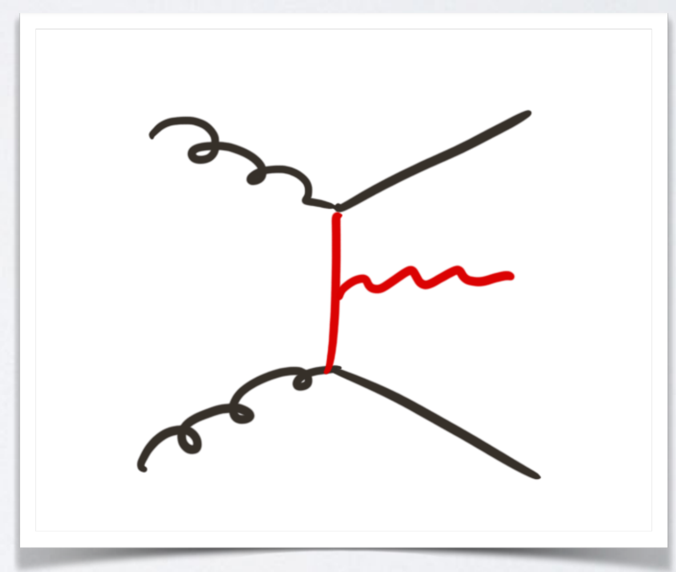




(b)



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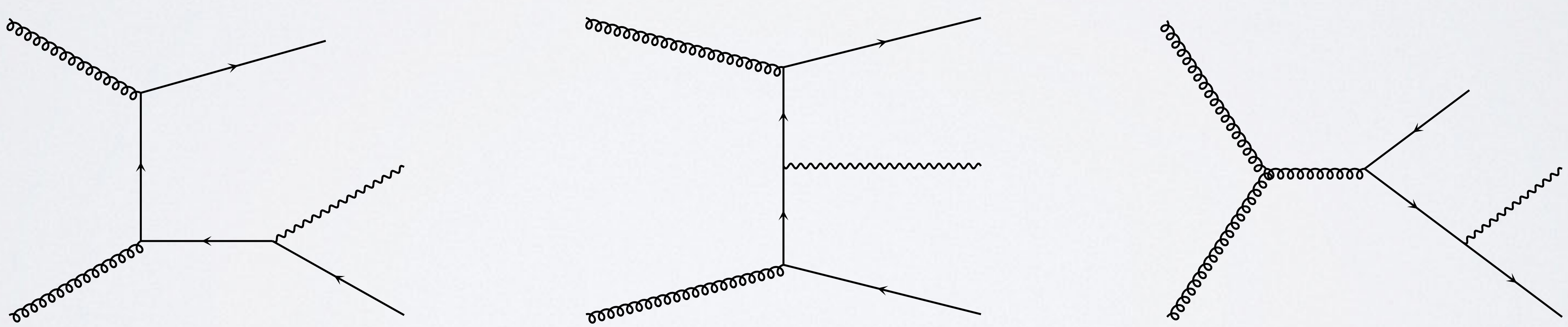

(a) (b) (c)

QCD & EW enhanced — QCD enhanced — EW enhanced

MATCHING CORRECTIONS

- Large matching corrections for high-p_T jets
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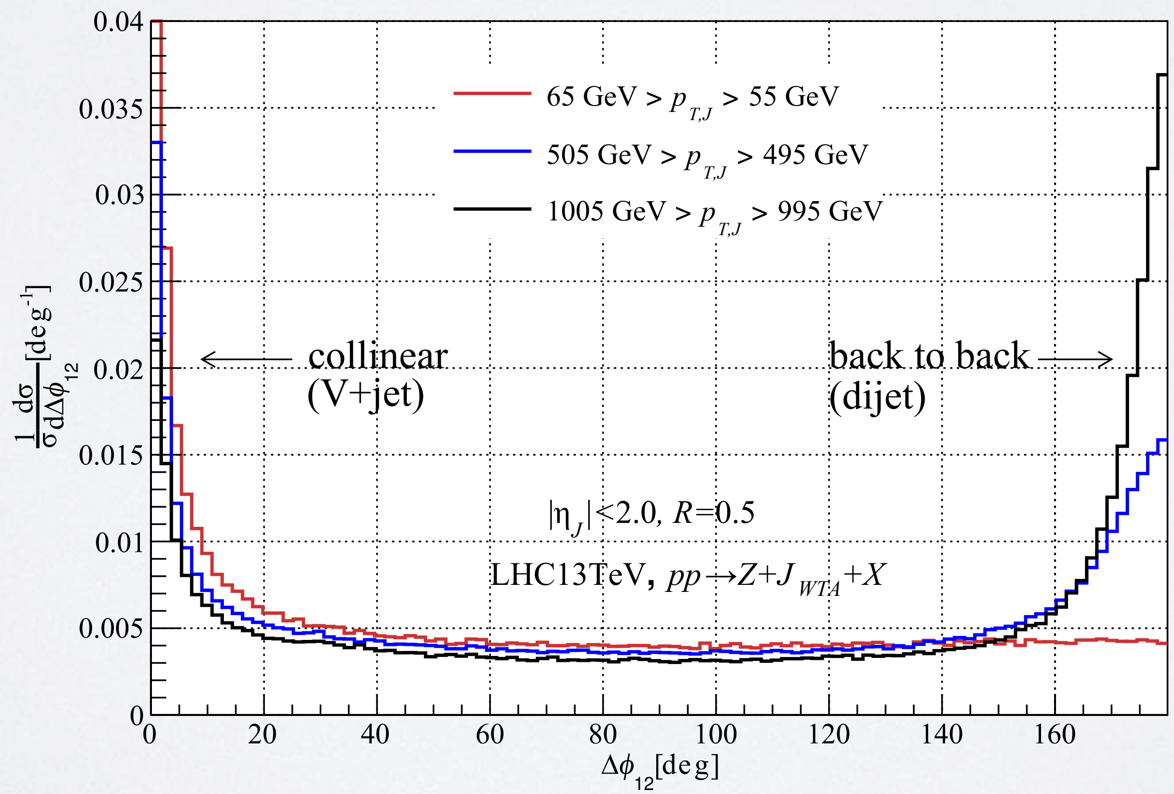


MATCHING CORRECTIONS

- Small pT:
  - Emission amplitude cut off: $\sim \frac{1}{m_Z^4}$
  - Non-singular angle-independent $\Rightarrow$ additive
- Large pT:
  - Resum, or remove with Z isolation cone

q_{wTa}-IMBALANCE

- q_T-slicing vs. Jets: SJA blind to in-jet dynamics

  $\Rightarrow$ k_T-ness [Buonocore, Grazzini, Haag, Rottoli, Savoini '22]

- Not true for WTA axis

- For dijet: replace boson with a jet (still q_x)

  $\Rightarrow$ Soft function at NLO still simple (non-trivial colour)

q_{WTa}-IMBALANCE

- Extension to q_T: requires both components

$$q_x = -p_{x,c} - p_{x,a} - p_{x,b} - p_{x,S}$$

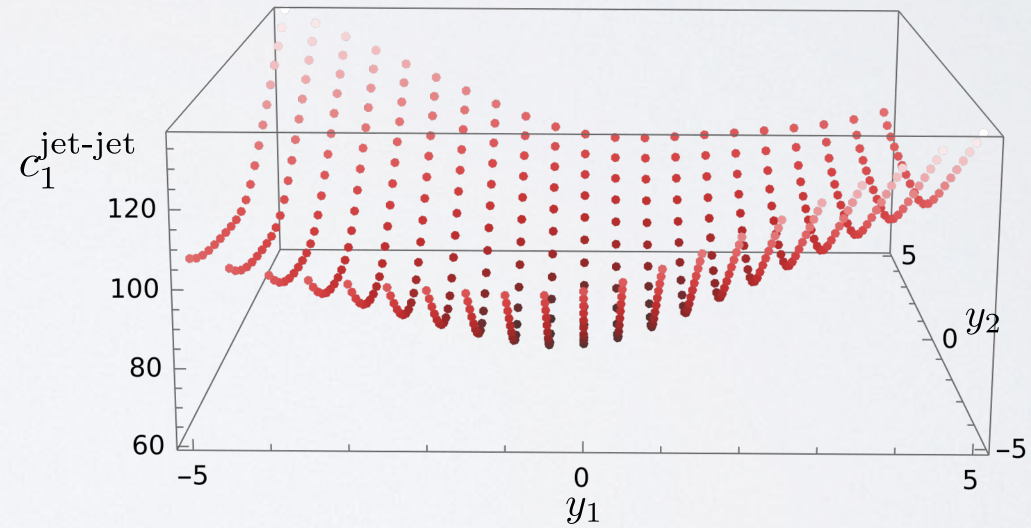
$$q_y = p_{y,J} - |\vec{p}_{T,c}| \cos\phi_c - p_{y,S} - p_{y,a} - p_{y,b}$$
$$= \underbrace{-p_{y,a} - p_{y,b}}_{\text{beam functions}} + \underbrace{\sum_{i\in(s\in J)} |p_{T,i}| - p_{y,S}}_{\text{soft function}} + \underbrace{\sum_{i\in c} |\vec{p}_{T,i}| \frac{\phi_c^2}{2} + \frac{\sum_{(i<j)\in c} |\vec{p}_{T,i}||\vec{p}_{T,j}|\phi_{ij}^2}{2\sum_{i\in c}|\vec{p}_{T,i}|}}_{\text{jet function}}$$

- E.g. soft function:
  - Outside jet: $|p_{T,S}|$
  - Inside jet: $|p_{x,S}|$

q_{wTa}-IMBALANCE

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{T,J_1}\,\mathrm{d}\eta_{J_1}\,\mathrm{d}\eta_{J_2}\,\mathrm{d}q_T} = q_T \int \frac{\mathrm{d}^2\vec{b}_T}{2\pi}\, J_0(q_T b_T) \sum_{i,j,k,l} B_i(x_a,\vec{b}_T)\, B_j(x_b,\vec{b}_T) \mathcal{J}_k(b_x) \times \mathcal{J}_l(b_x)\,\mathrm{tr}\left[\hat{\mathcal{H}}_{ij\to kl}(p_{T,J_1},\eta_{J_1}-\eta_{J_2})\,\hat{S}_{ijkl}(\vec{b_T},\eta_{J,1},\eta_{J,2})\right]$$

- NLO soft function:



- Extension to more jets: in jet $|p_{x,S}| \rightarrow |p_{\perp(J),S}|$

q_{WTa}-IMBALANCE

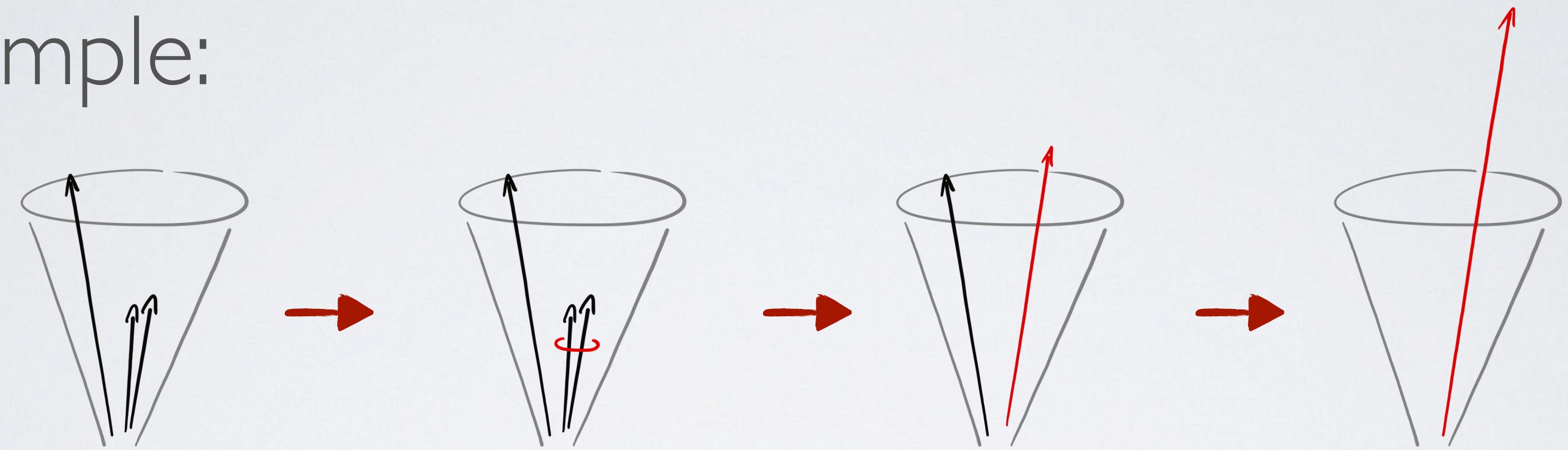
- Still to do:
  - Size of power corrections
  - Compare refactorised ⇔ parametric R
  - Better name (WTA-iness, Winbalance?)

CONCLUSION

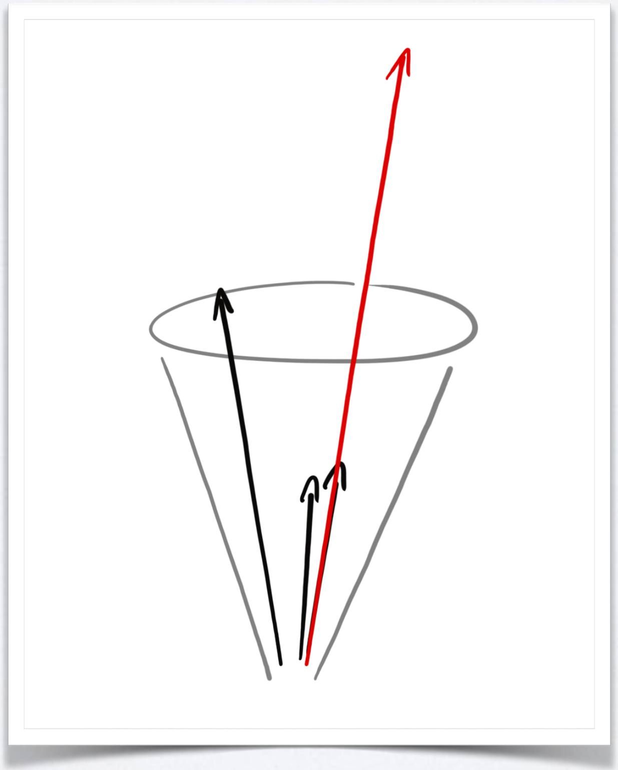
- Azimuthal decorrelation is a really nice observable
- Radial decorrelation isn't
- Remember: There's life beyond QCD
- Maybe q_T-slicing can be salvaged via WTA axis

WINNER-TAKES-ALL AXIS

- Example:

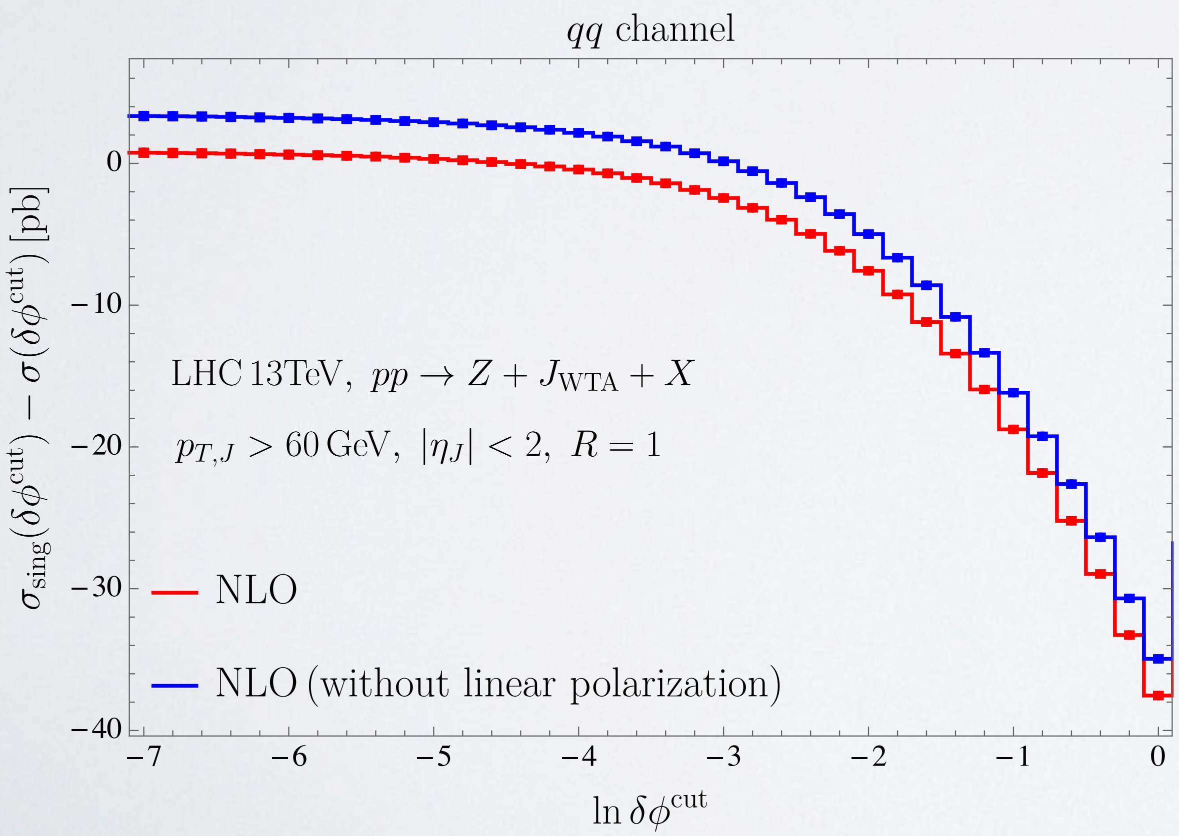


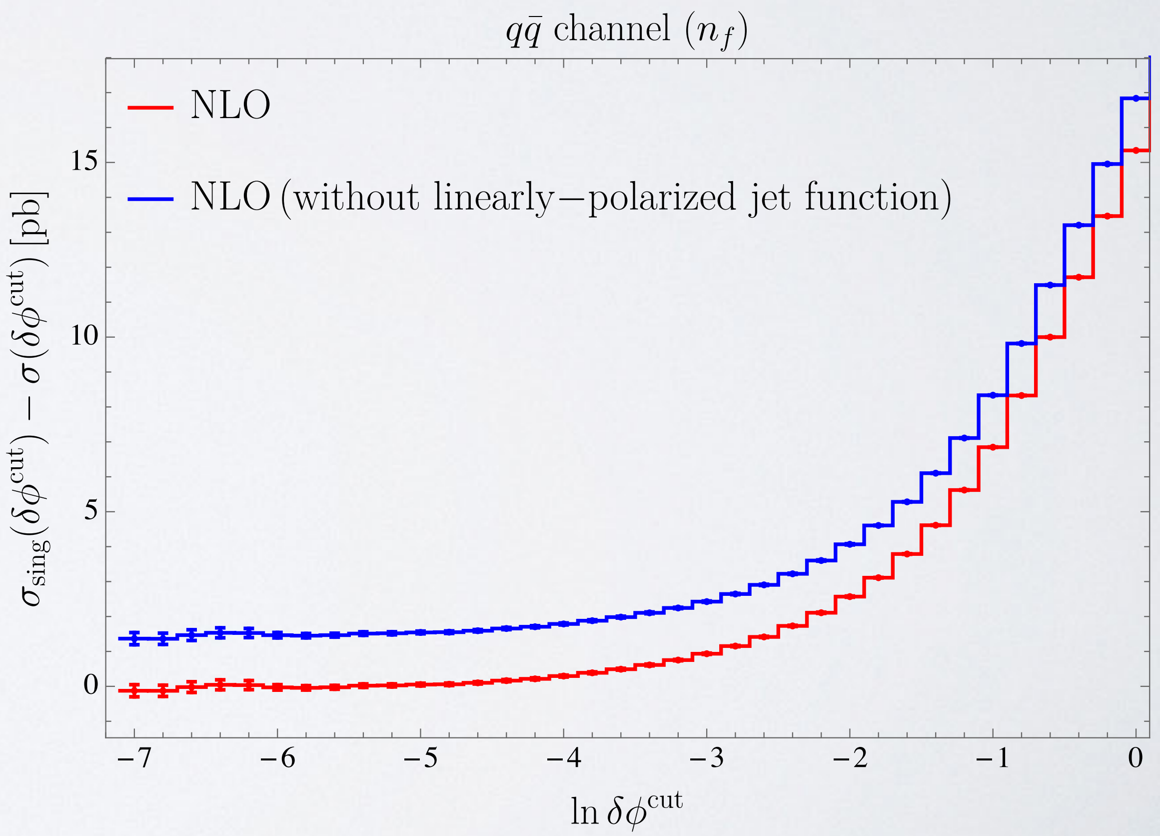
- Result:



PLOTS II

- Linearly polarised beam and jet functions needed
- MCFM vs. Our singular:

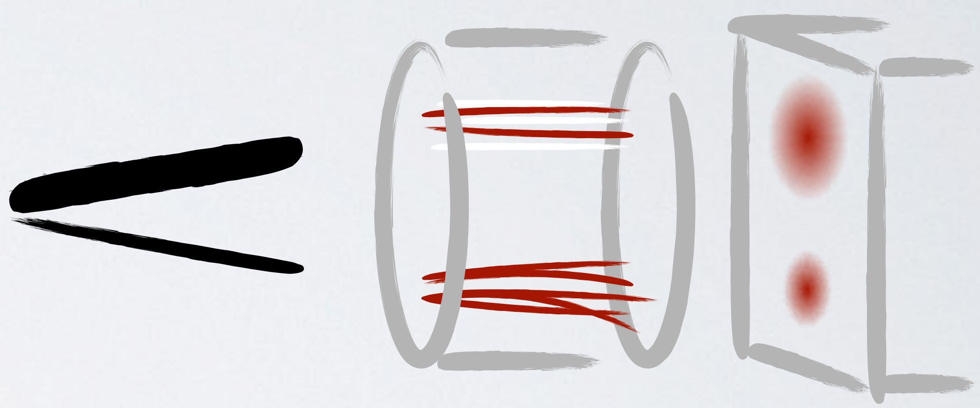




TRACKS

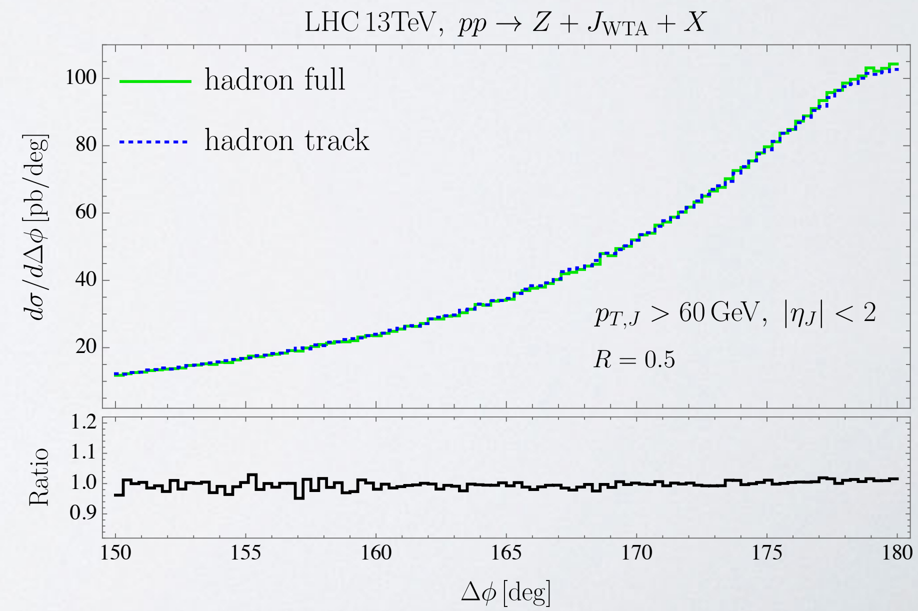
- Angular resolution of calorimetry could be a problem

  $\Rightarrow$ Use charged particle tracks



- Only affects Jet function finite term

$$\bar{\mathscr{J}}_q^{(1)} = \mathscr{J}_q^{(1)} + 4C_F \int_0^1 \mathrm{d}x \, \frac{1+x^2}{1-x} \ln \frac{x}{1-x} \int_0^1 \mathrm{d}z_1 \, T_q(z_1,\mu) \times \int_0^1 \mathrm{d}z_2 \, T_g(z_2,\mu) [\theta(z_1 x - z_2(1-x)) - \theta(x - \tfrac{1}{2})]$$



- Track function T, energy fraction z

  [Chang, Procura, Thaler, Waalewijn, '13]

OTHER RECOIL FREE AXES

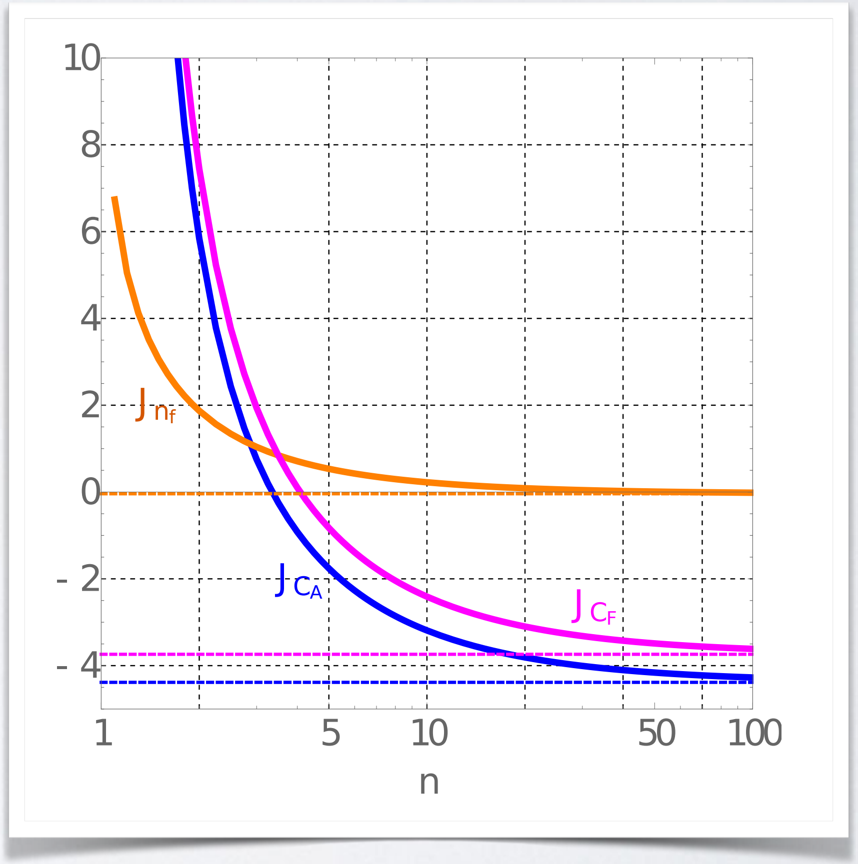
- Use transverse momentum weighted jet recombination

$$p_{T,r} = p_{T,i} + p_{T,j},$$
$$\phi_r = (p^n_{T,i}\phi_i + p^n_{T,j}\phi_j)/(p^n_{T,i} + p^n_{T,j}),$$
$$y_r = (p^n_{T,i}y_i + p^n_{T,j}y_j)/(p^n_{T,i} + p^n_{T,j}),$$

- Reproduces WTA as $n \to \infty$

- We find

$$\mathscr{J}^T_g|_{L_b=0} = 1 + \frac{\alpha_s}{2\pi}\Big\{C_A \int_0^1 \mathrm{d}z\, \ln(\hat{z}_n^2)\Big[\frac{z}{1-z} + \frac{1-z}{z} + z(1-z)\Big]$$
$$+ T_F n_f \Big[\frac{1}{3} + \int_0^1 \mathrm{d}z\, \ln(\hat{z}_n^2)((1-z)^2 + z^2)\Big]\Big\}$$
$$\equiv 1 + \frac{\alpha_s}{4\pi}(C_A J_{C_A} + T_F n_f J_{n_f})$$



$$\hat{z}_n = \left|\frac{z^n + (1-z)^n}{z^{n-1} - (1-z)^{n-1}}\right|$$