Exposing the Dead Cone with Jet Substructure

(from the LHC to FCC-ee)

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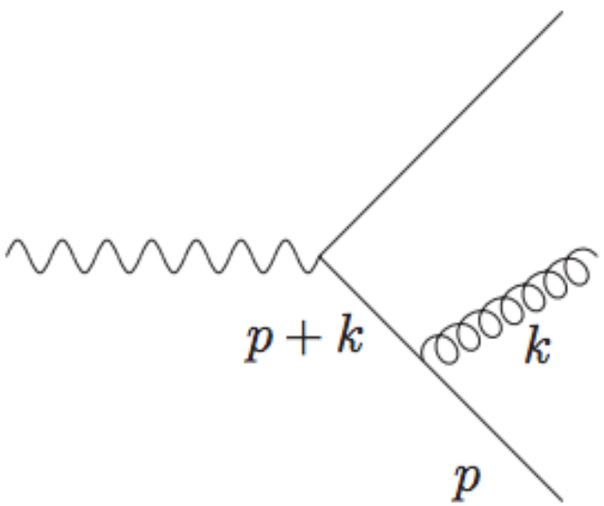
Outline

- The **Dead Cone** effect
- The **Dead Cone** at the **LHC**
- The **Dead Cone** at the **FCC-ee**

What is the Dead Cone?

assuming the quark is **stable:**



$$\sim \quad \frac{1}{2p \cdot k}$$

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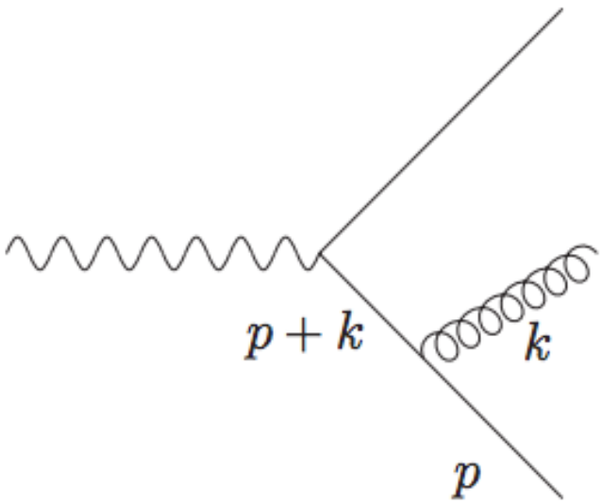

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m = 0

$$\frac{1}{2E_q E_g (1 - cos\theta_{qg})}$$

soft collinear

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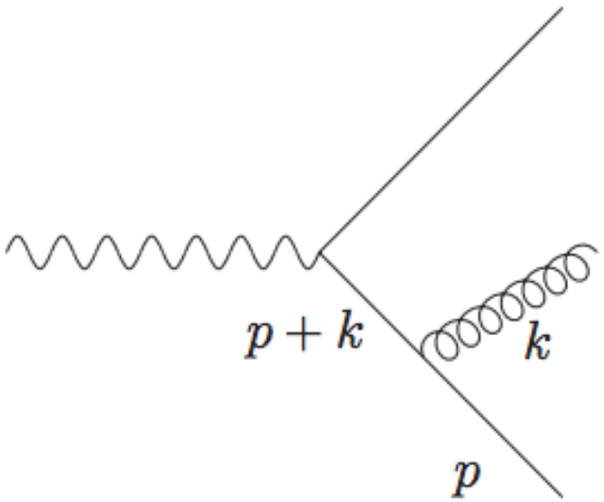

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soft collinear

m ≠ 0

$$\frac{1}{2E_q E_g(1 - v_q cos\theta_{qg})}$$

soft ~~collinear~~

Differential **radiation rate** becomes **finite** at θ ~ 0

What is the Dead Cone?

in **soft** and **collinear** limit :

$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}z\,\mathrm{d}\theta^2} \simeq \frac{\alpha_S}{\pi} C_F \frac{1}{z}\frac{\theta^2}{(\theta^2+\theta_D^2)^2} \quad ,$$

$$\theta_D \equiv \frac{m_q}{E_q}$$

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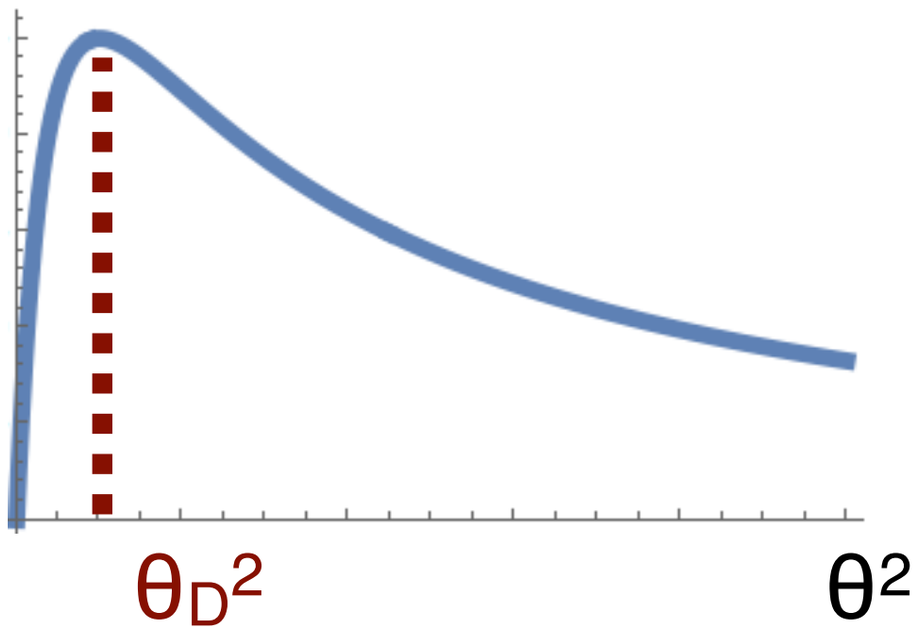
define $\Theta \equiv \dfrac{\theta}{\theta_D}$

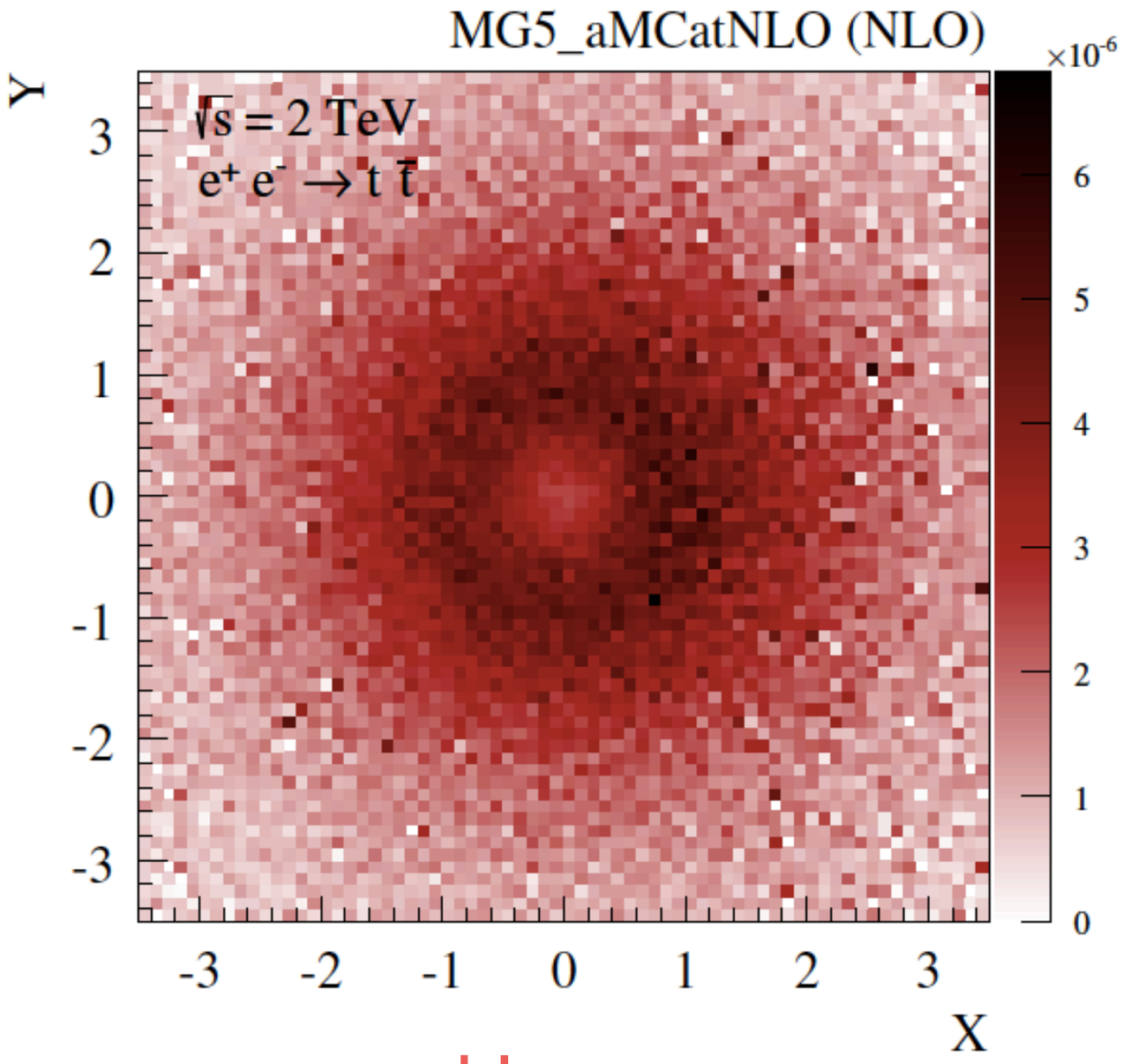
so that **max** is at $\Theta = 1$:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Theta^2} \sim \frac{\Theta^2}{(1+\Theta_D^2)^2}$$



What is the Dead Cone?

Does fixed order Monte Carlo correctly reproduce this effect ?



$$X \equiv \Theta \cos\phi$$

$$Y \equiv \Theta \sin\phi$$

stable top

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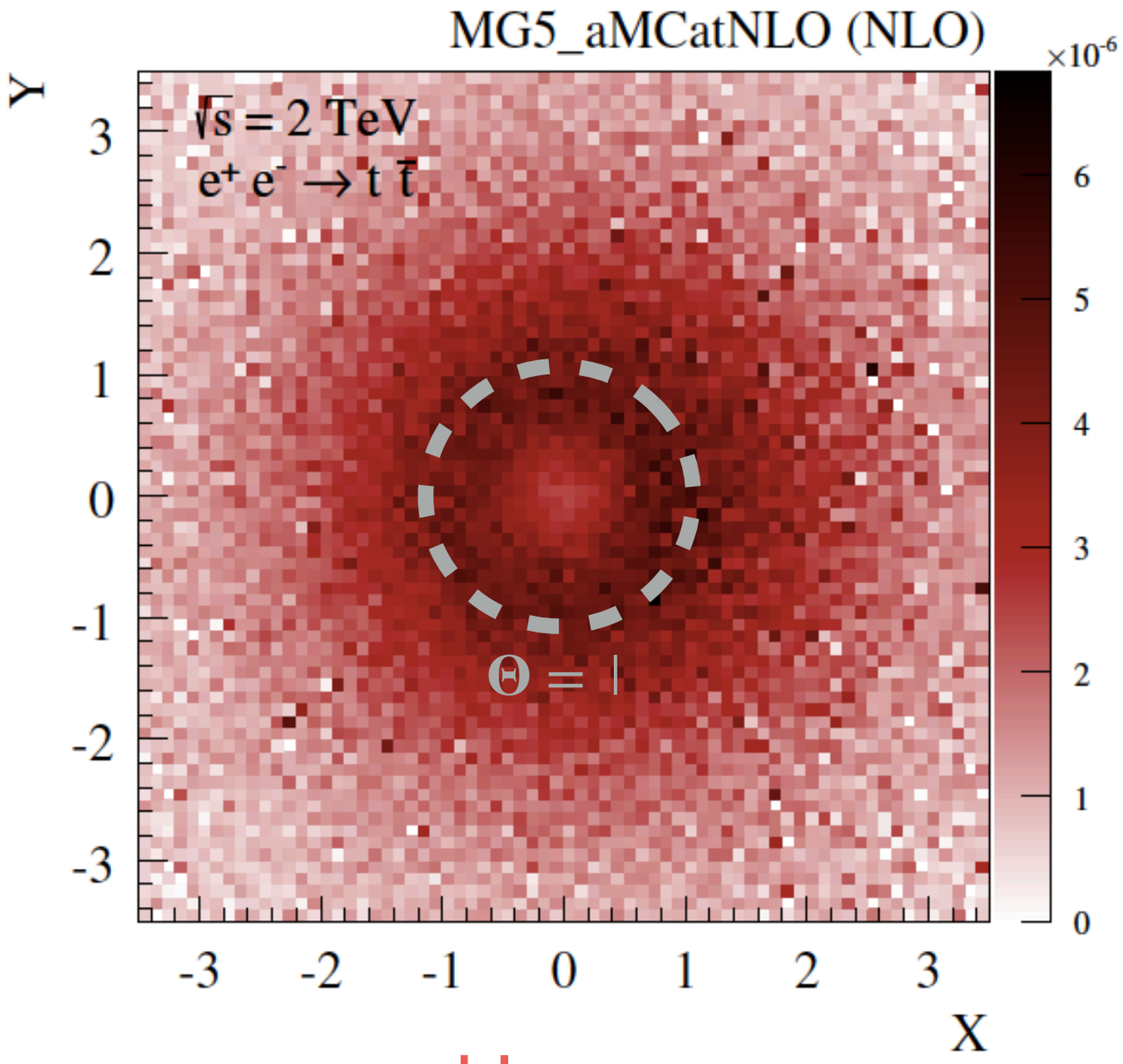

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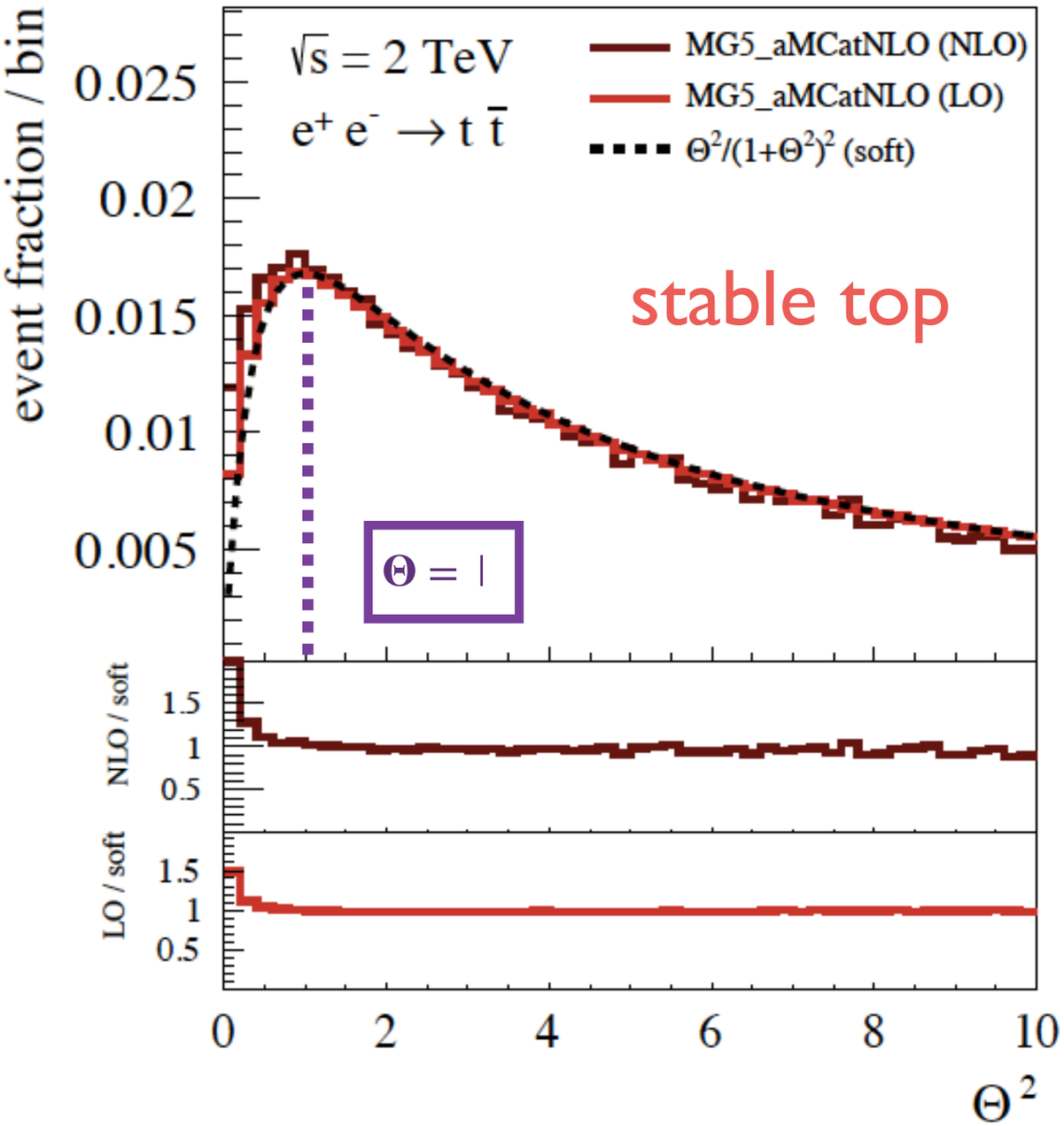

- separate space in 2 semi-sphere
- **sum all gluon** radiation
- 1 entry per event with sum of radiation

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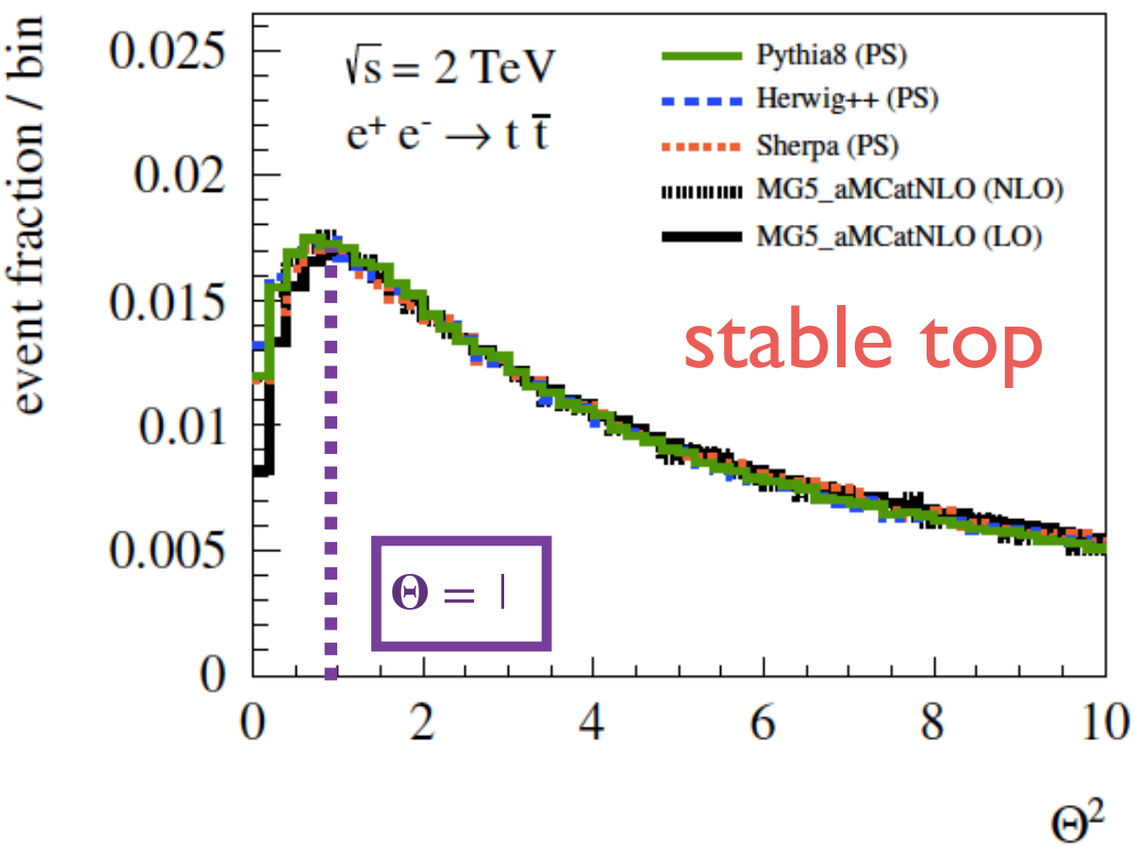
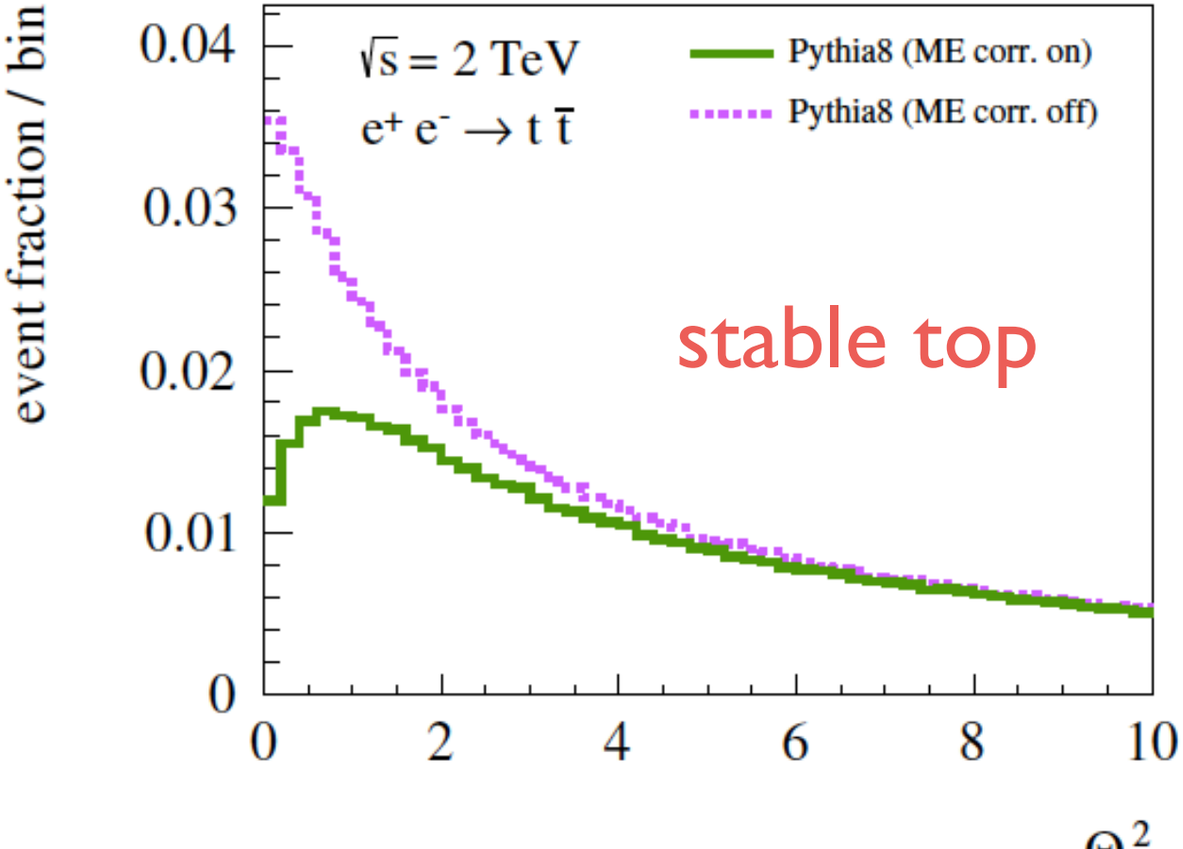
Do fixed order Monte Carlo and PS correctly describe this effect ? **YES !!**





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TimeShower:MEextended = on/off
TimeShower:recoilDeadCone = on/off

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The Dead Cone at the LHC

- **Challenging** since **radiation and decay** of massive particle both occur on a similar **angular** scale **$\theta \sim m / E$**
- Which **heavy quarks** are good **candidates** to start with ?
  - **$m_{c,b}$ = 1.5 - 5 GeV** , $p_T = 40$ GeV $\rightarrow$ **$\theta_D \sim$ 0.03 - 0.1**
    - small angle
    - large backgrounds $\rightarrow$ **exclusive** decays (e.g. B+ $\rightarrow$ J/ψ K+) ?
    - which role does **hadronization** play ?

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    - which role does **hadronization** play ?
  - **m_t = 173 GeV** , $p_T = 500$ GeV $\rightarrow$ **$\theta_D \sim$ 0.3**
    - moderate angle
    - small backgrounds
    - can fully reconstruct **top decay products**

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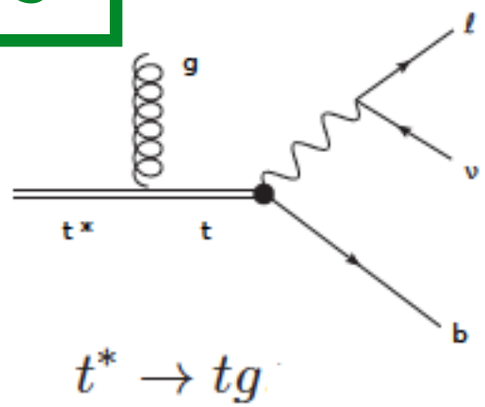
    - moderate angle
    - small backgrounds (radiation in decay being by far the largest)
    - can fully reconstruct **top decay products**

Boosted top quarks are good candidates

Contaminating radiation from decay

Dead cone can be potentially spoiled by **interference** with **radiation in top decay** …

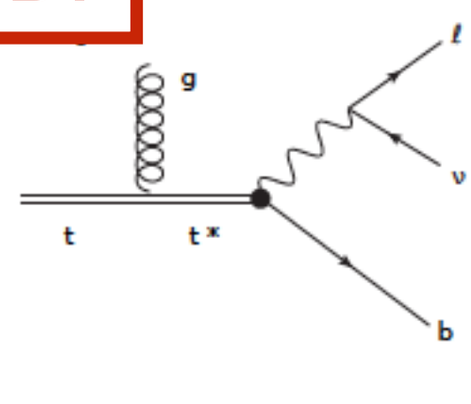
S



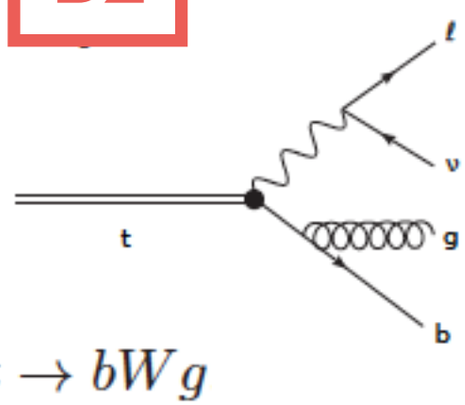
$t^* \to tg$

+

B1



B2



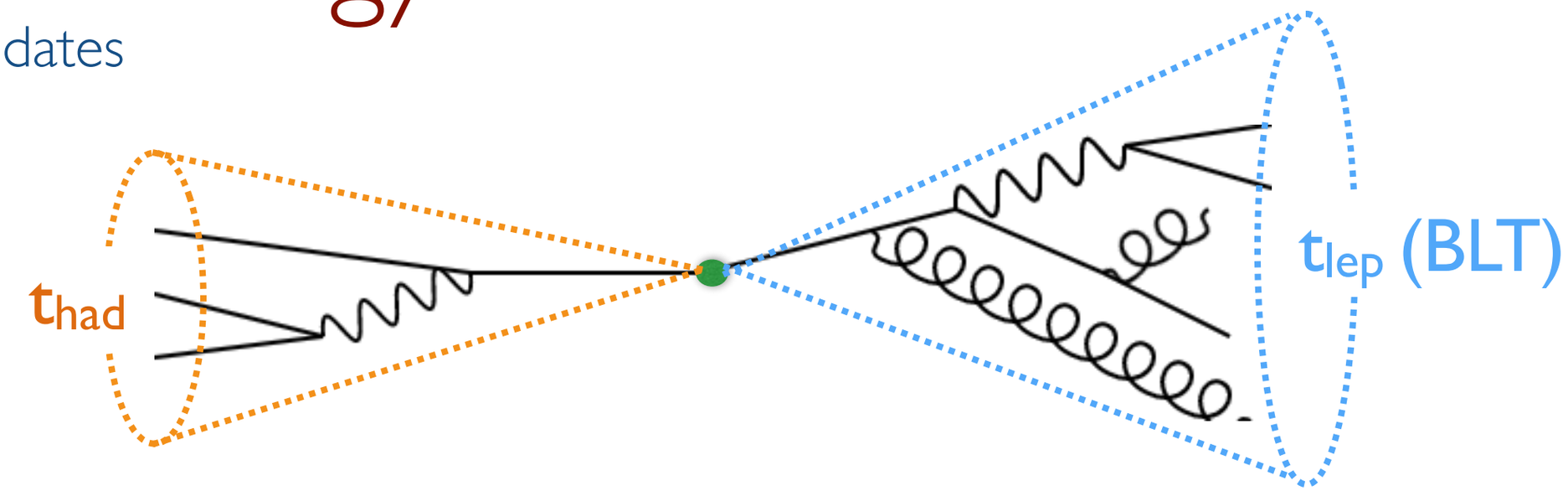
$t \to bWg$

Top width effect becomes **sizable** when : $2p_t \cdot p_g \sim m_t \Gamma_t$

Can **neglect** interference if: $z \equiv \frac{E_g}{E_t} \gg \frac{\Gamma_t}{m_t} \quad \rightarrow \quad z \gtrsim \mathcal{O}(0.1)$

Analysis Strategy

selecting top candidates



- large **top boost** to enhance **FSR rate** ($P \sim \log E_t / m_t$)
- possible **channels**:

  - fully hadronic → **contamination** from **hadronic** W decay
  - fully leptonic → clean, but impossible to accurately reconstruct **top direction**
  - semi-leptonic → **clean, high rate**

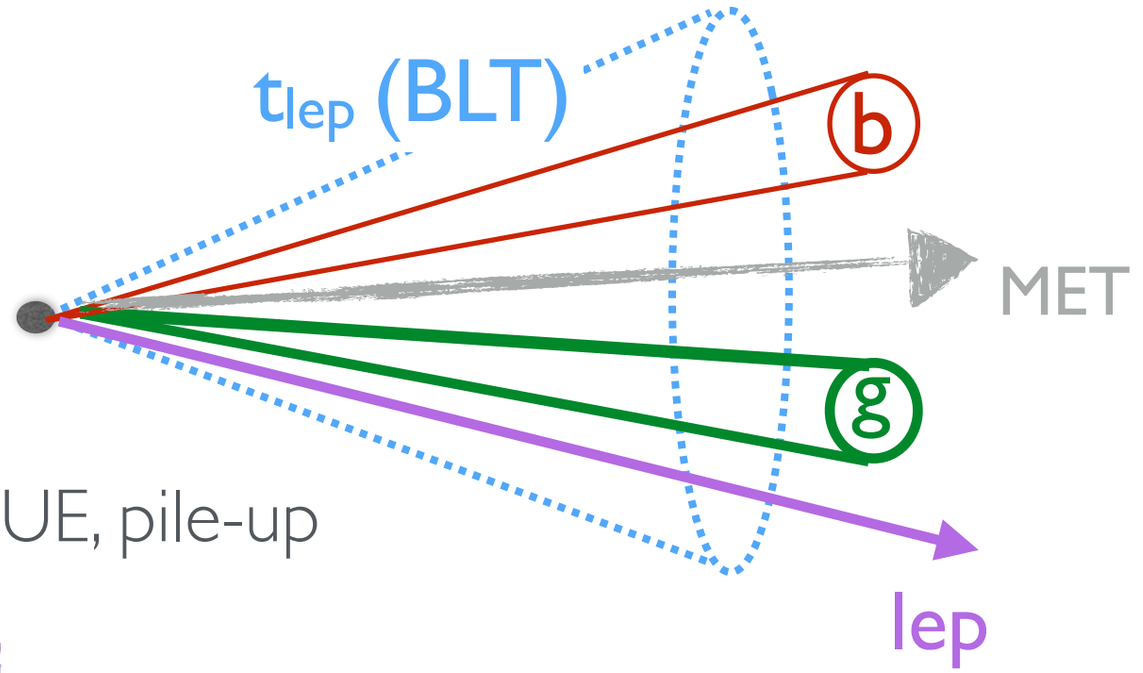
- event **selection**:

  - 2 fat-jets (R=1.0) in central rapidity, $p_T > 300$ GeV
  - 1 fat-jet top-tagged and $p_T > 500$ GeV
  - loosely isolated lepton inside other fat-jet (BLT = "Boosted Leptonic Top")
  - $E_T^{miss} > 50$ GeV

→ **selection designed to ensure close to 100% purity**

Analysis Strategy

find the FSR gluon



- **remove** lepton from fat-jet
- use **Soft Drop** [1402.2657] algorithm to:
  - identify **two hard prongs**
  - get rid off **soft contamination** from ISR, UE, pile-up

$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{R_{12}}{R} \right)^{\beta}$$

$$\beta = 0, \qquad z_{\text{cut}} = 0.05.$$

no angular scale is introduced

- **discard event** if two prongs not found
- require one **sub-jet** to be **b-tagged**
- the **other sub-jet** is our **gluon candidate**

- in order to reduce contamination from radiation in decay **require:**

$$\frac{p_T^g}{p_T^t} > 0.05.$$

Analysis Strategy

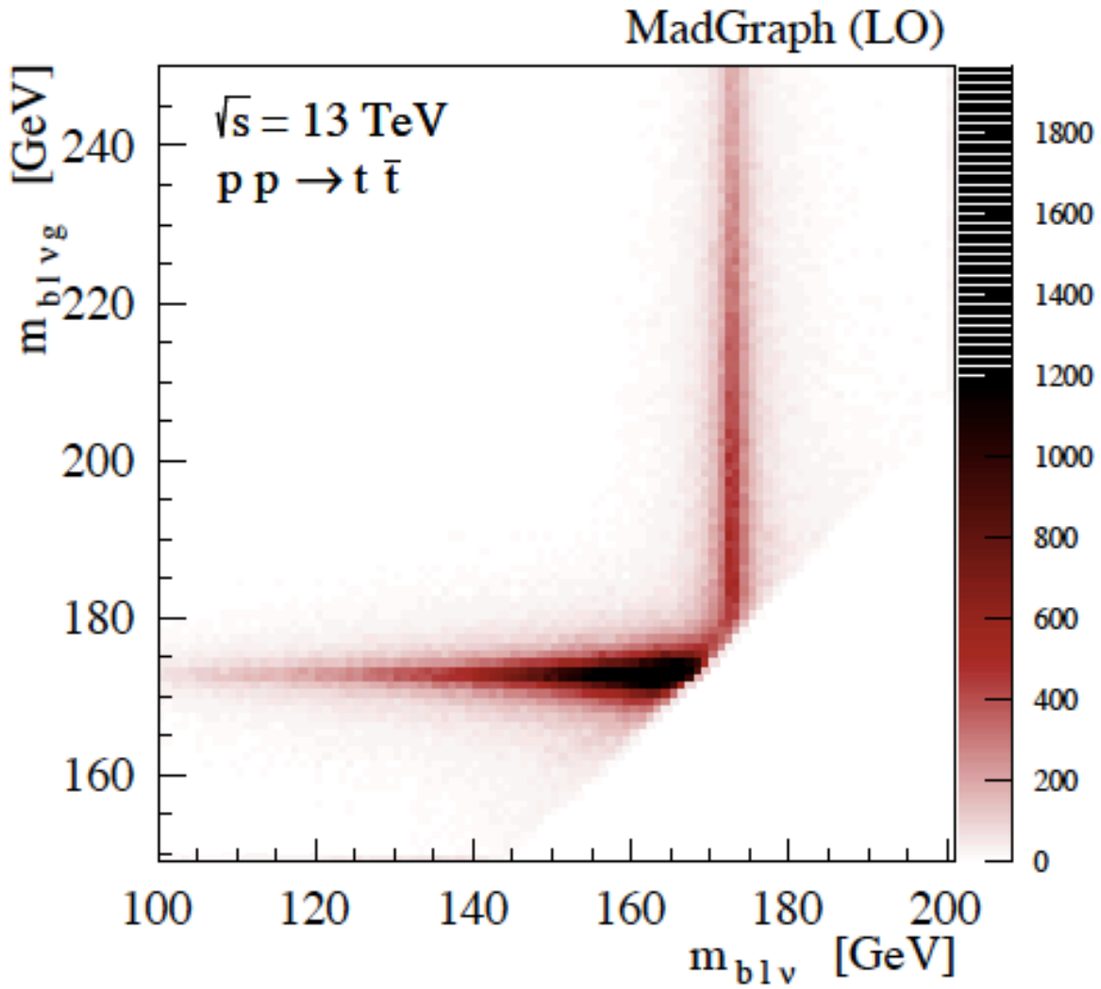
find the FSR gluon

- find the **top direction** by solving for E_z^{miss} :

  - make use **W mass constraint** (2 solutions)

  - solve **degeneracy** by checking consistency with hypothesis:
    - radiation in production (**S**)
    - radiation in decay radiation (**B**)

- Define **S** and **B** enriched regions:



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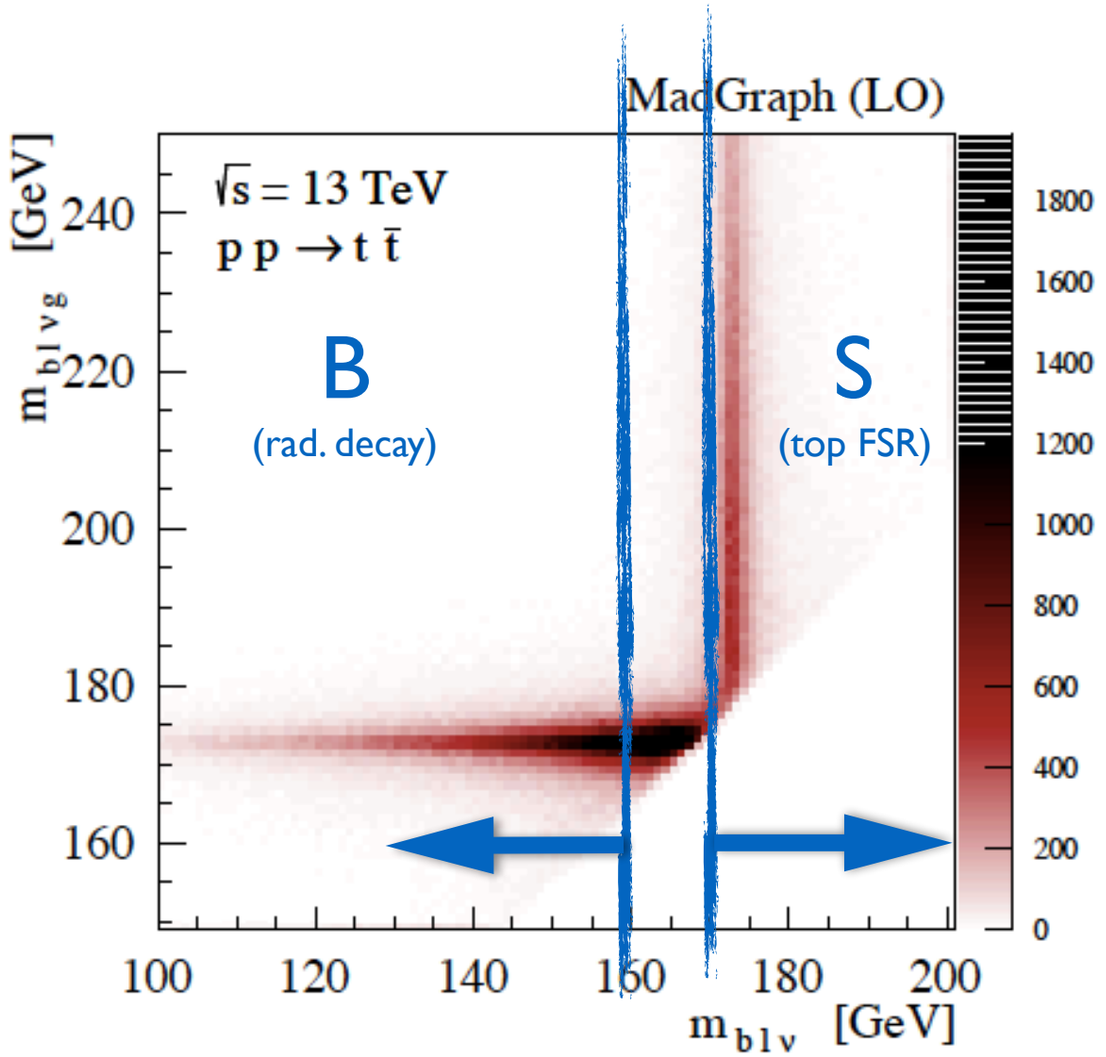
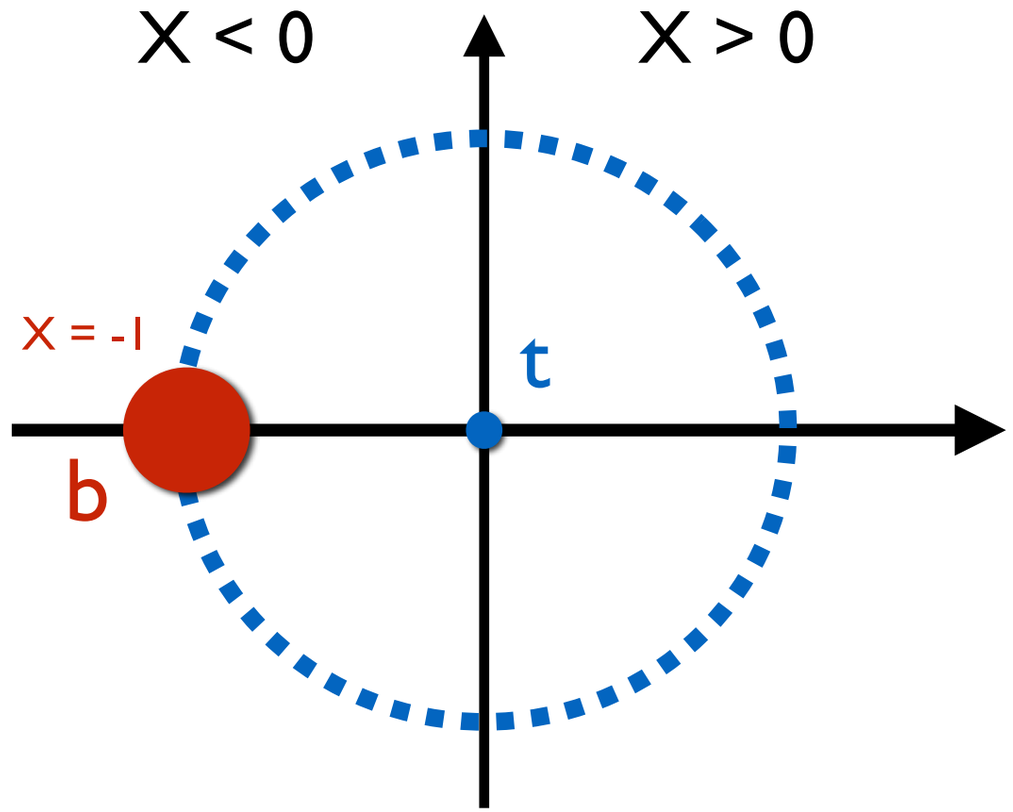
- Having all components at hand (b, l vu, g), define **S** and **B** enriched regions:

$$
\begin{aligned}
&S\text{-enriched:} \quad m_{b\ell\nu} \in [170, 200]\ \text{GeV}, \\
&B\text{-enriched:} \quad m_{b\ell\nu} < 160\ \text{GeV}.
\end{aligned}
$$



Observing the Dead Cone

- **b-jet** sits exactly where **top FSR is max**
- rotate the event such that **b-jet lies on the X axis**
  → look the "**other way**"



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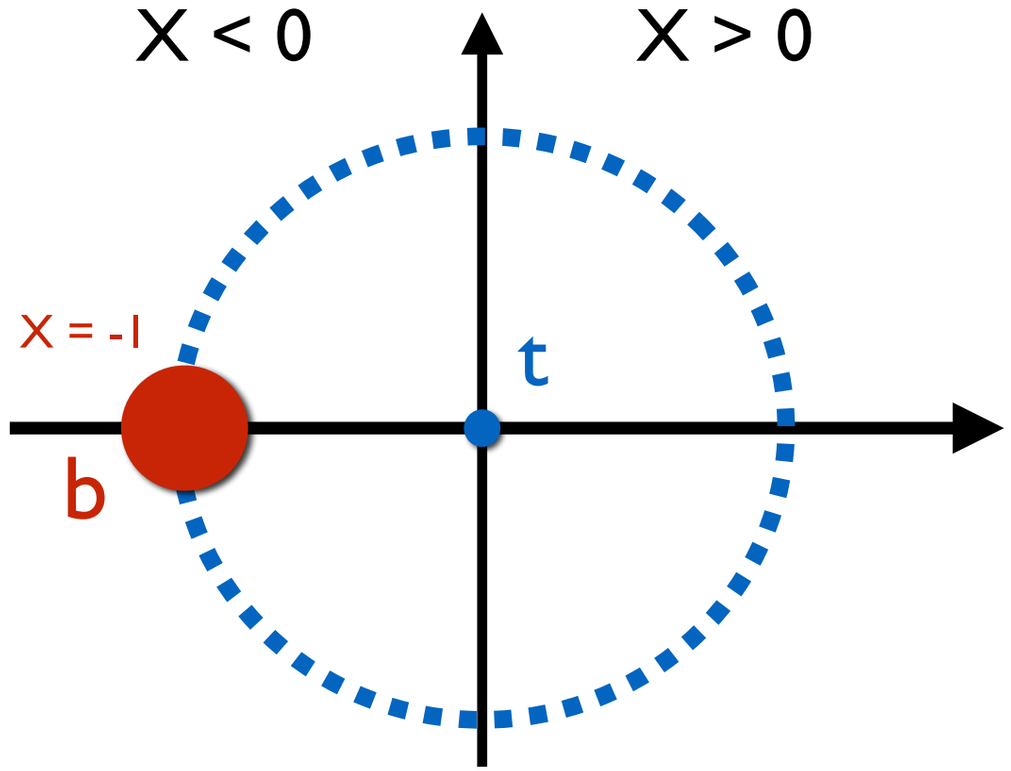

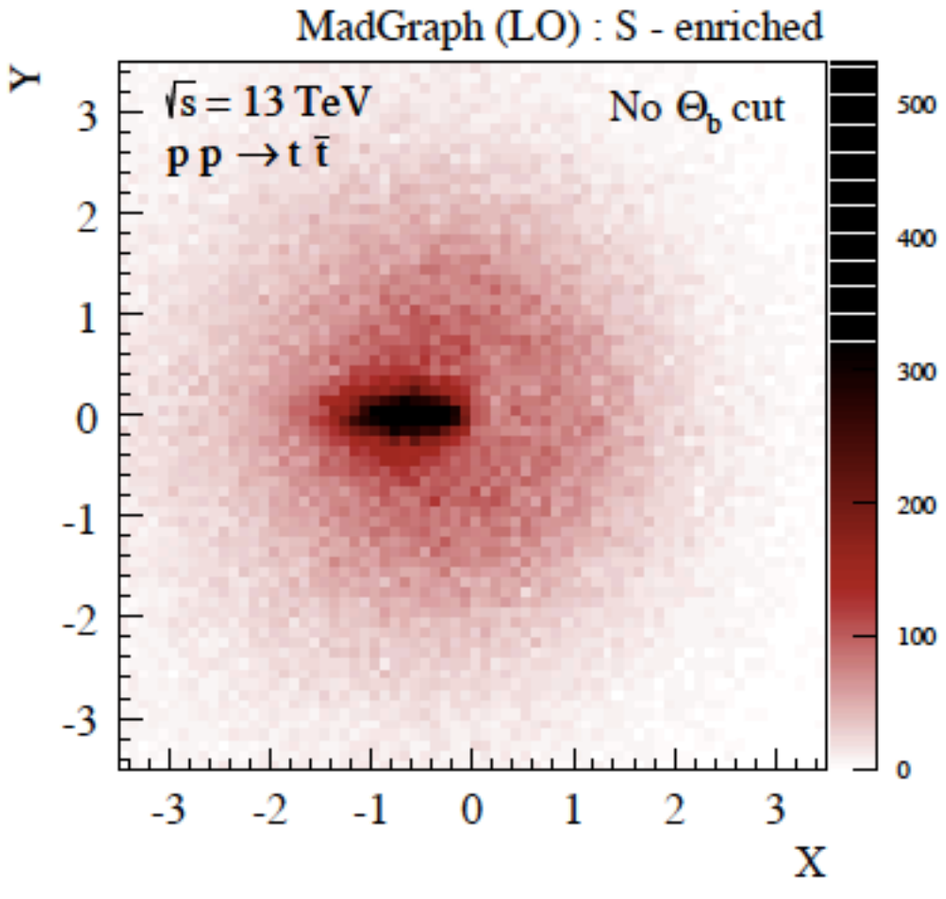

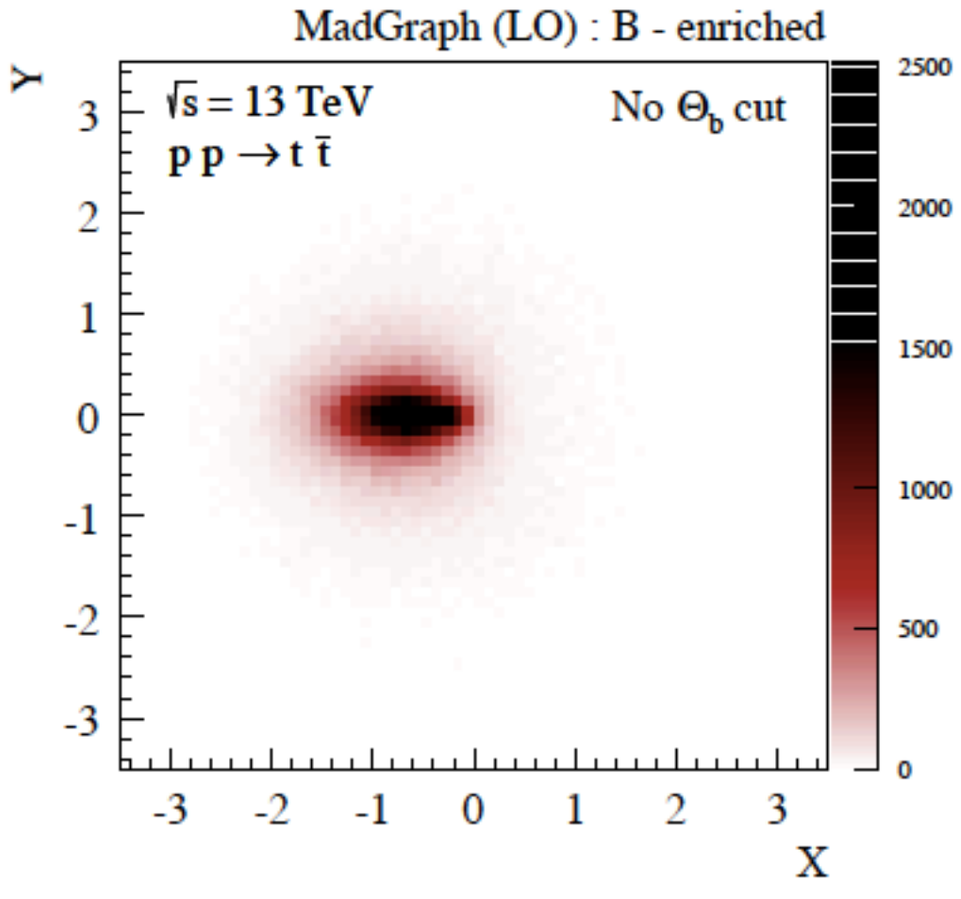

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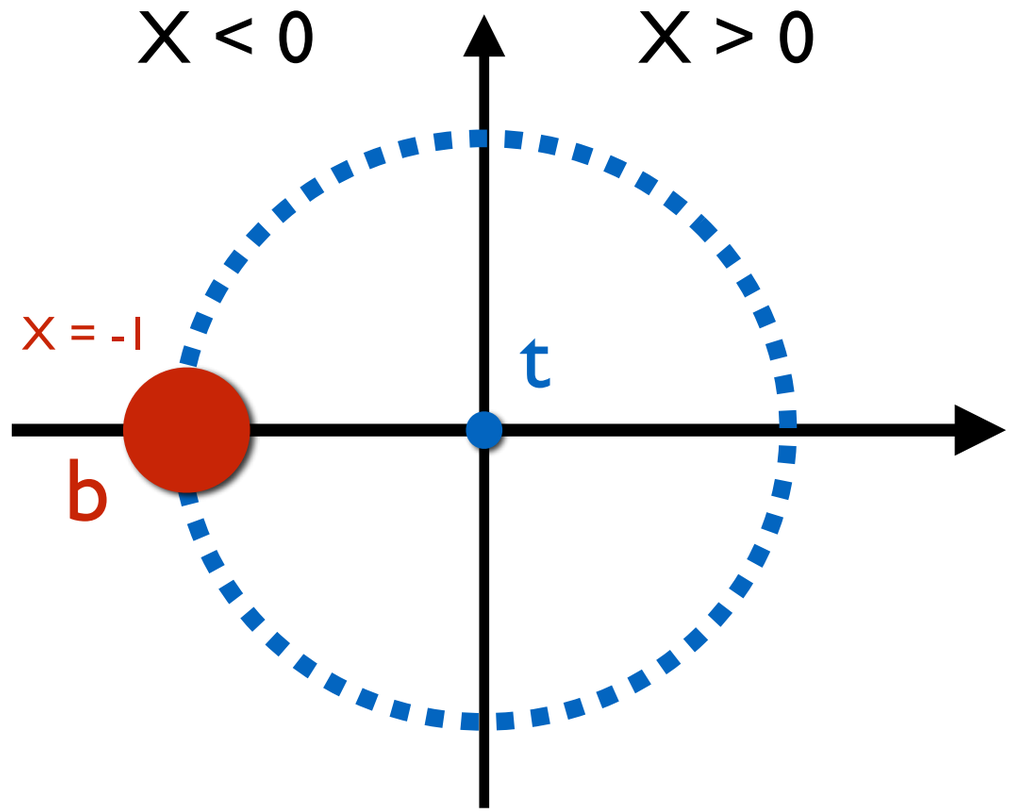
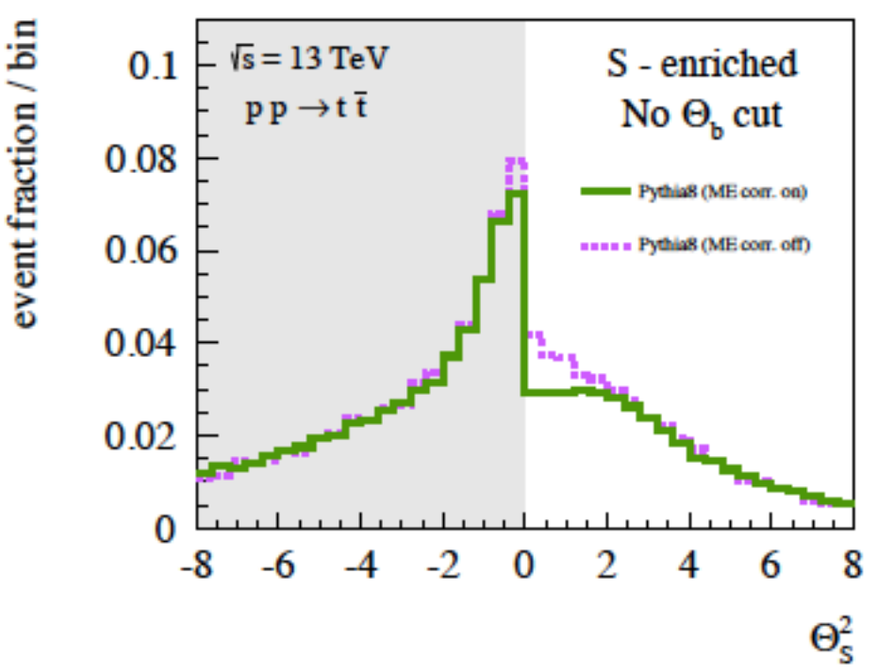
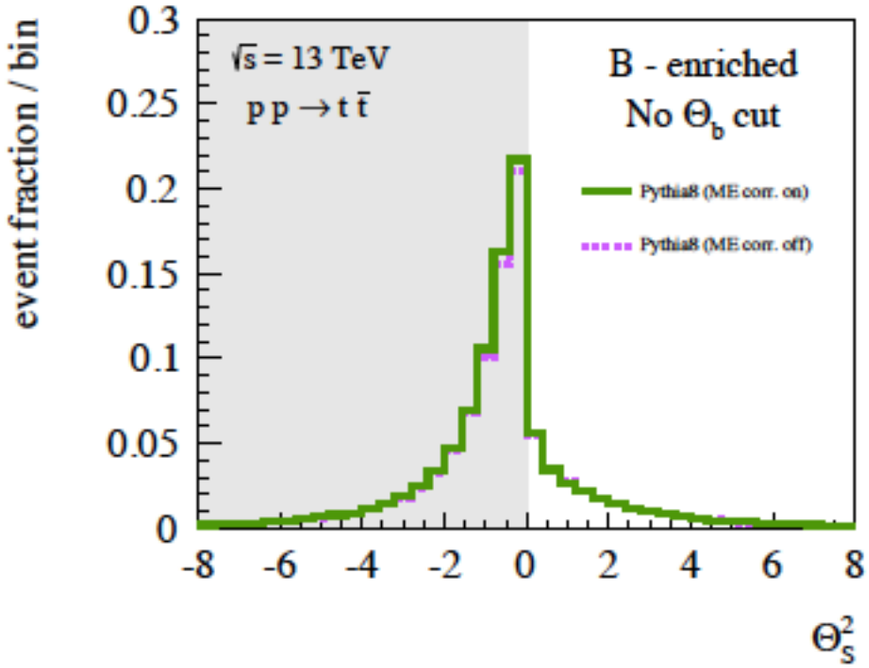
- in one dim. , define:

$$\Theta_S^2 \equiv \mathrm{sign}(X)\,\Theta^2$$







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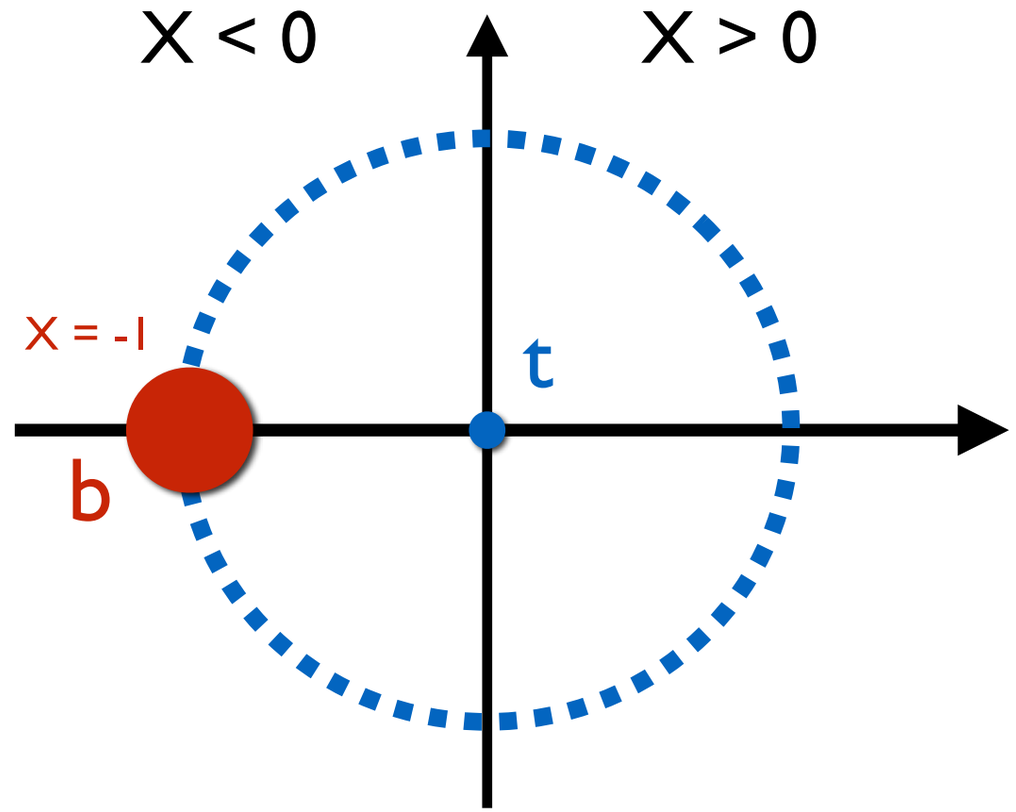
- purity can be increased by "pushing the b-quark away"

  → require **larger angle** between t and b:

$$\Theta_b > 1.0$$



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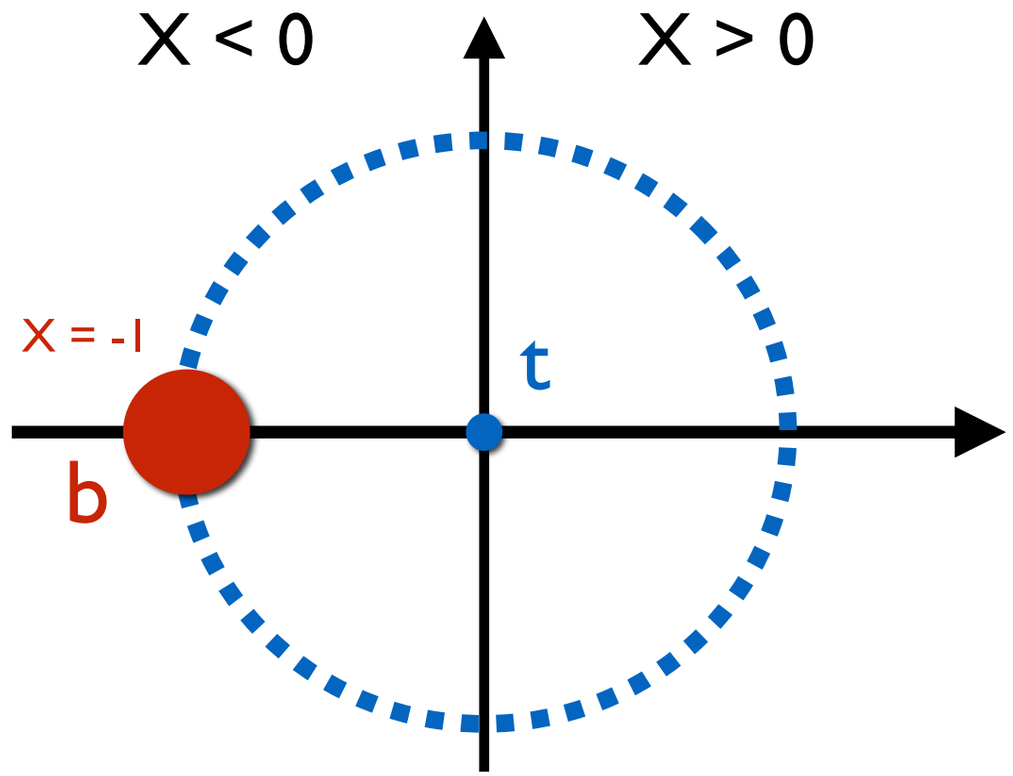

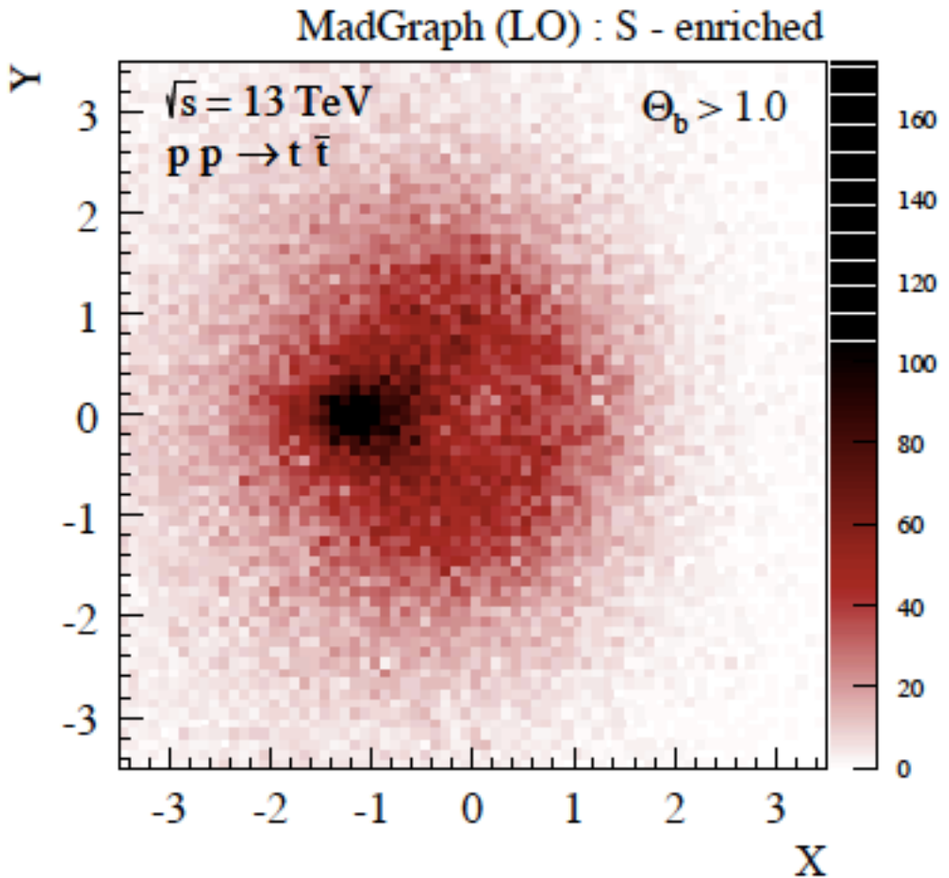

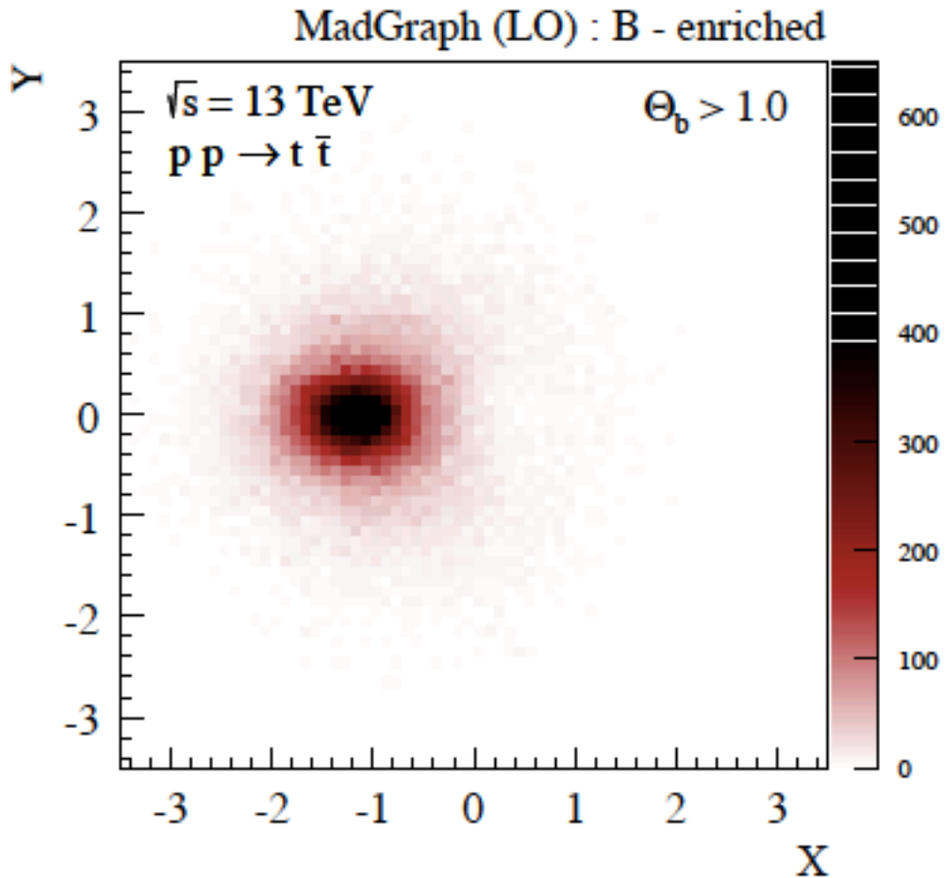

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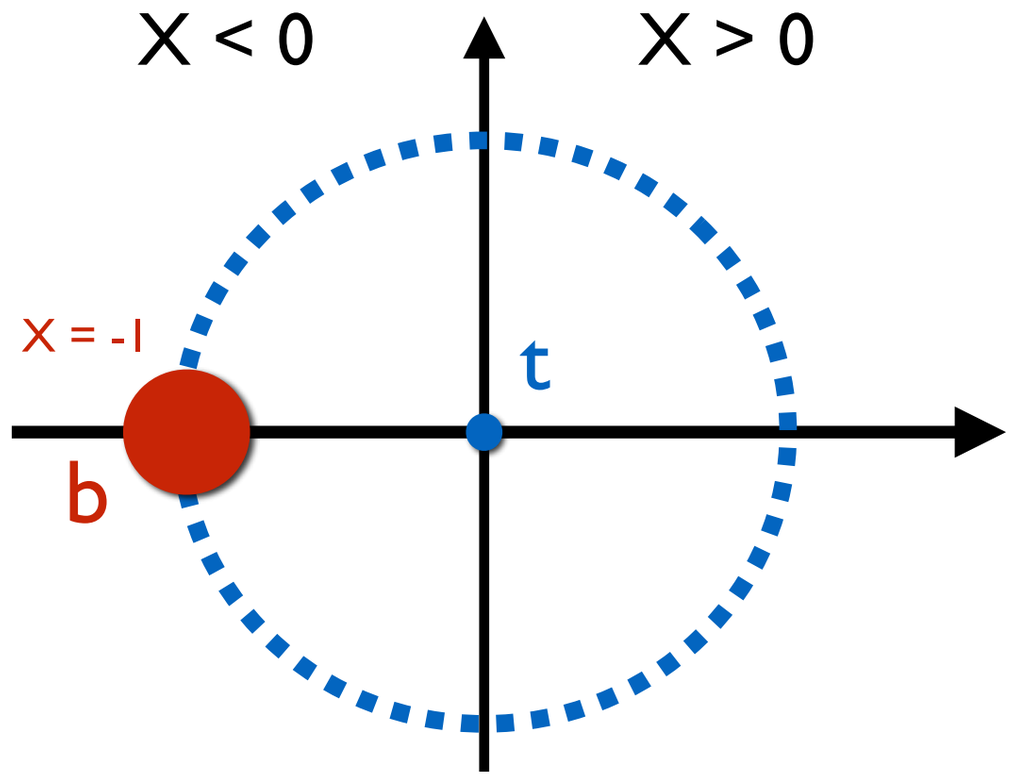

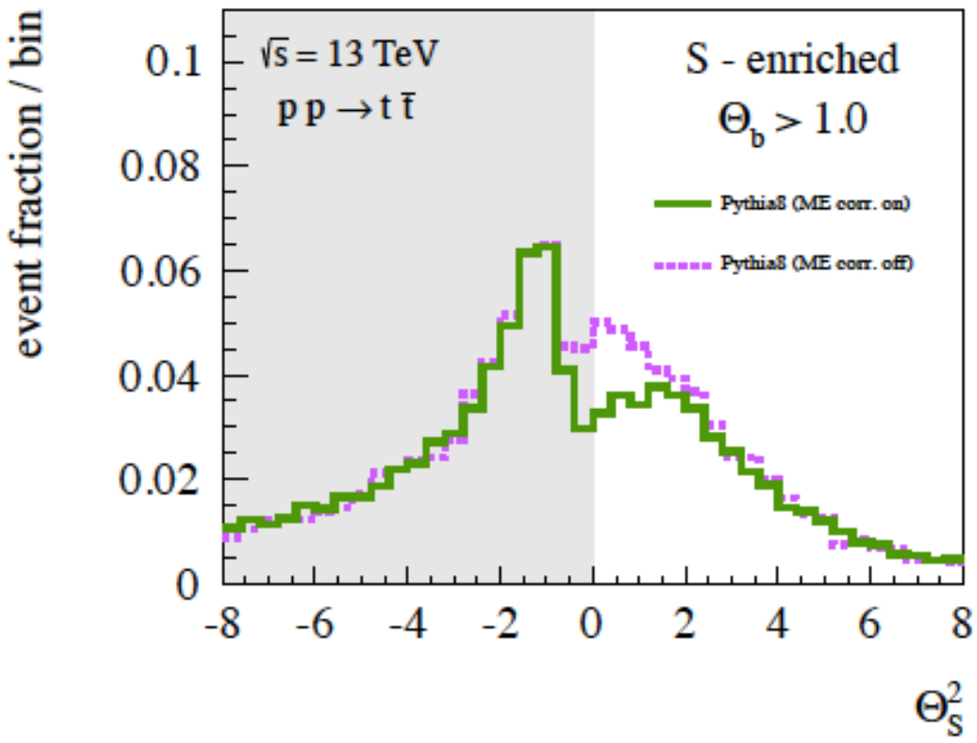

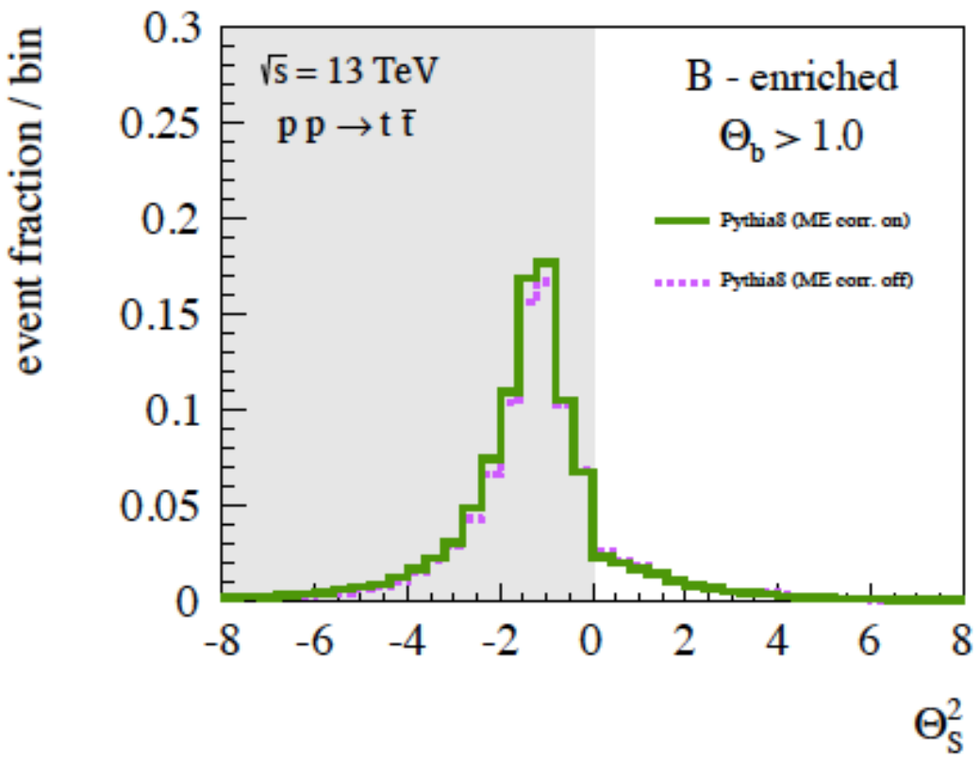

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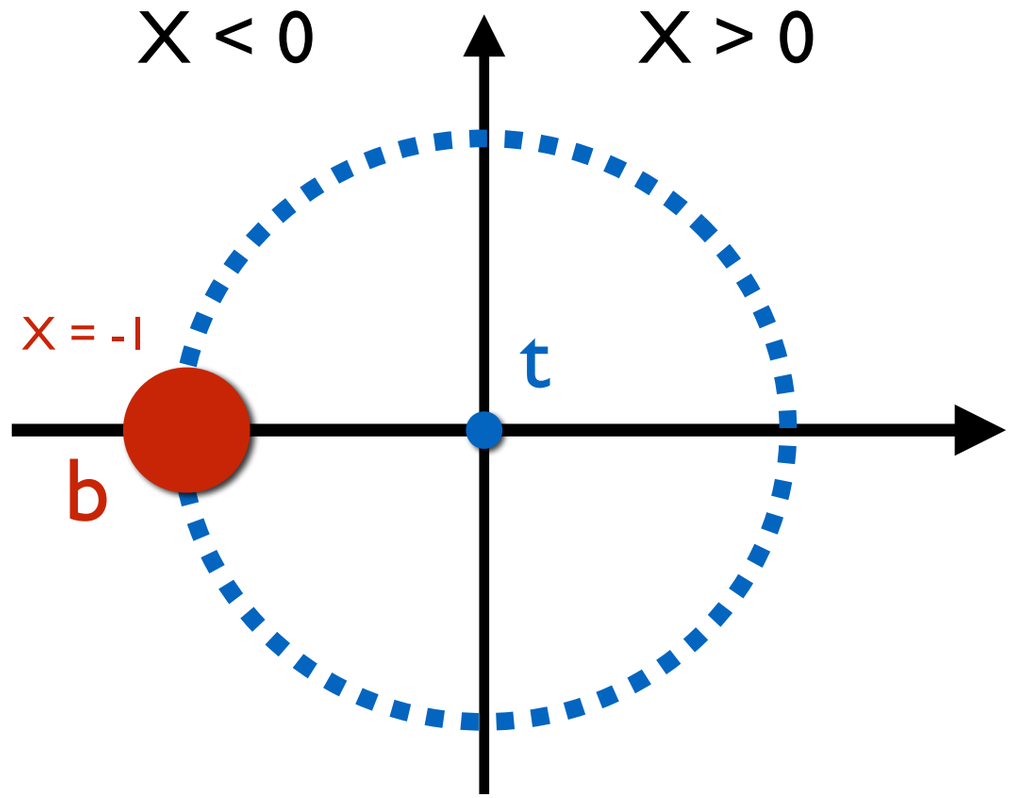
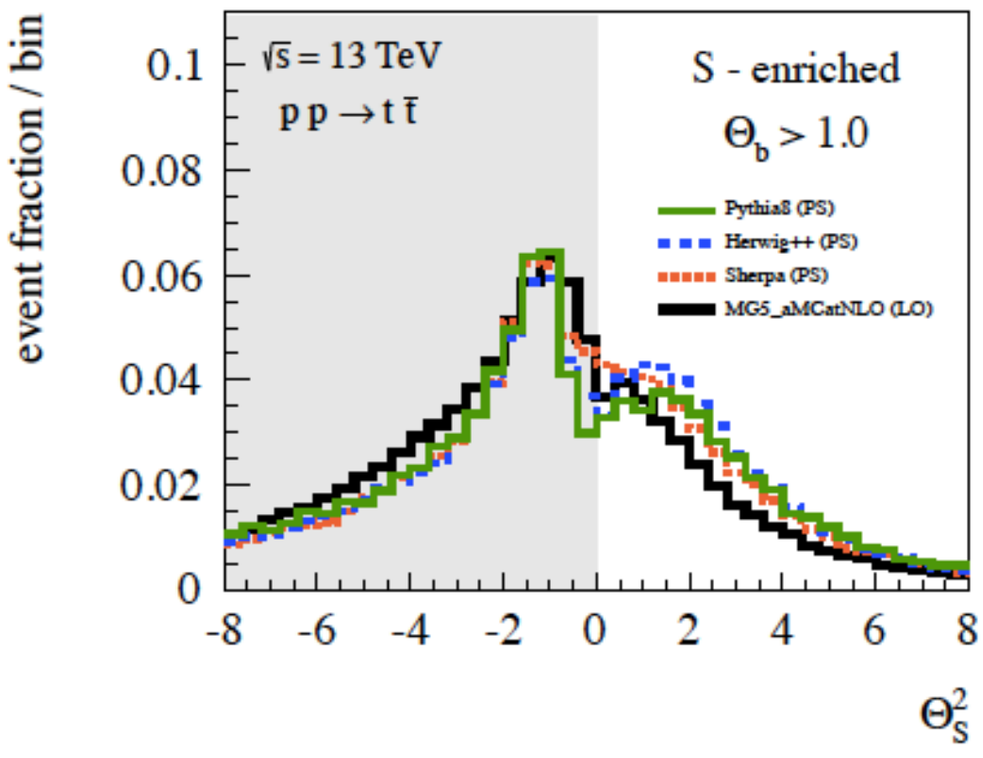
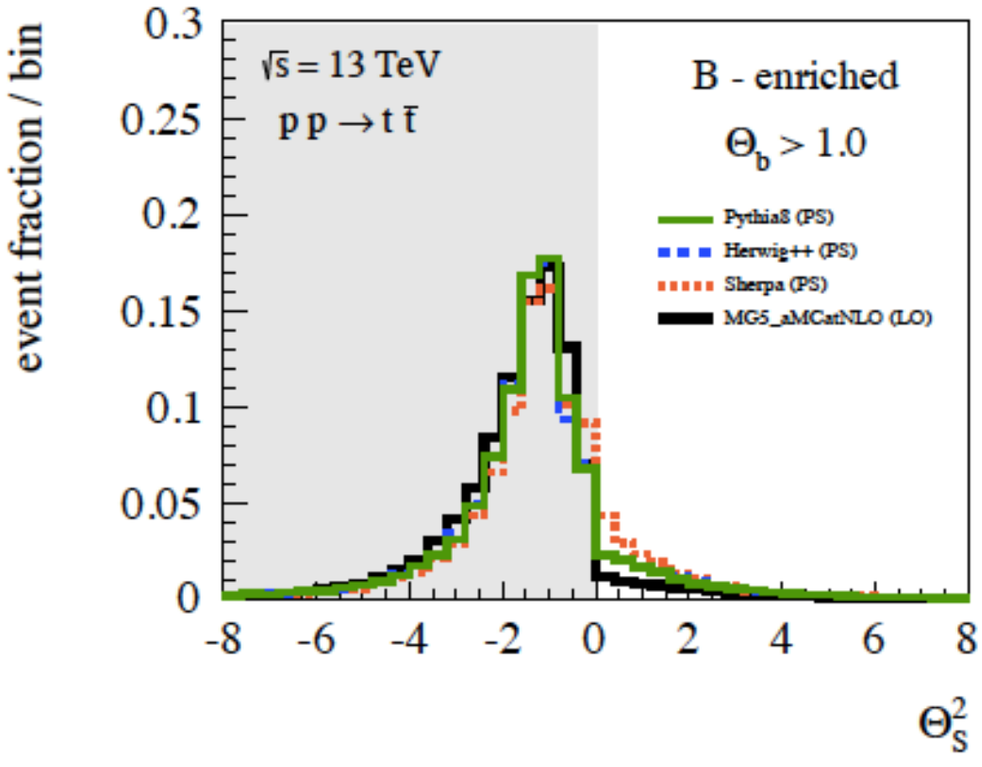






Sensitivity at the LHC

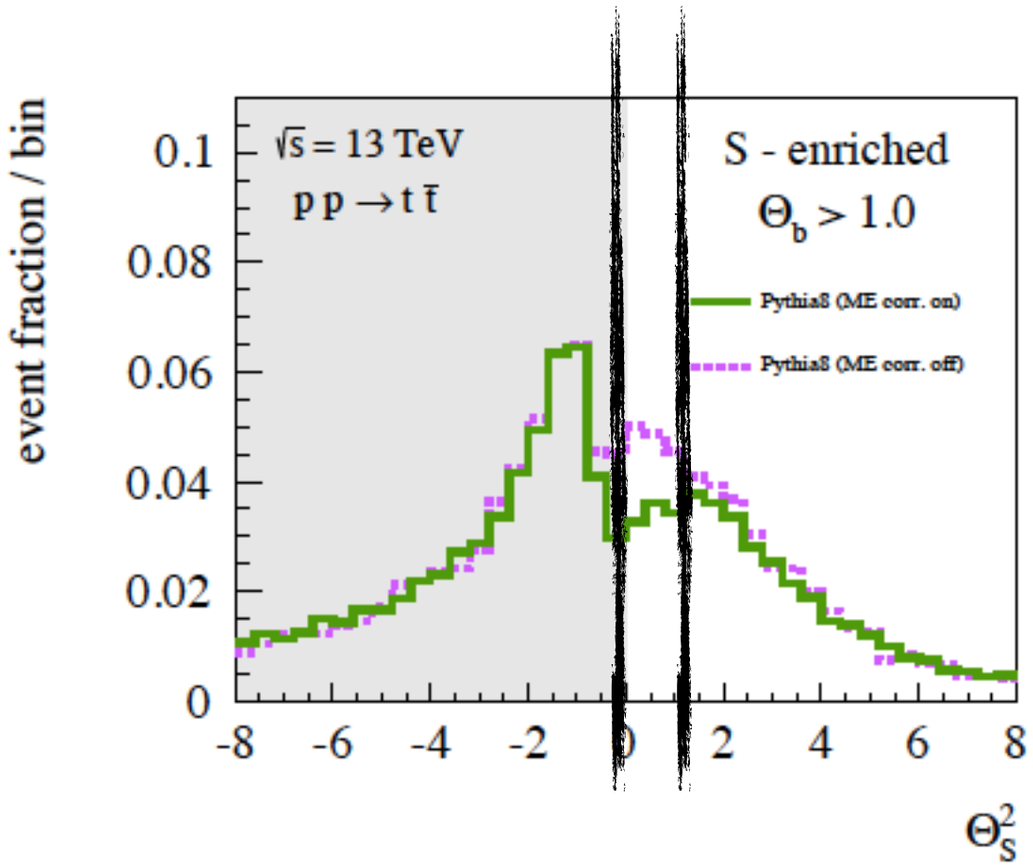
fiducial cuts: $\epsilon_{\text{fid}} = 45\%$

b/ top tagging : $\epsilon_{\text{top}} = \epsilon_b = 50\%$

soft drop (two prong) : $\epsilon_{\text{SD}} = 55\%$

signal region: $\epsilon_S = 30\%$.

angle top - b: $\epsilon_{\Theta_b} = 30\%$.



total efficiency: $\epsilon_{\text{total}} \simeq 0.55\%$

$\mathcal{L} = 300\,\text{fb}^{-1}$ $\quad \mathcal{N}_{\text{on}}^{[0.0,1.0]} = 85,$ $\quad \mathcal{N}_{\text{off}}^{[0.0,1.0]} = 125$

difference is statistically significant at 4 σ level after Run II

Summary
for the LHC

- Dead Cone is a **fundamental prediction** of **QCD/QED** that has been known for long time, but never conclusively measured

- **Measuring** it precisely can help in **constraining** various Monte Carlo/**Parton Shower** models

- A proposal relying on measuring radiation pattern around **boosted top quarks** using most recent **jet sub-structure** algorithm (Soft Drop) has been outlined

- The Dead Cone "hypothesis" should definitely be **testable** in p p collisions at **LHC - Run II**

- The full differential radiation pattern should be **measurable** at **HL-LHC** and **FCC-hh**

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VERY PRELIMINARY !

General considerations

for FCC-ee

- e^+e^- → t t hopeless, since **tops** are produced almost **at rest**.

- 2.5 yrs of data at Z pole → 10^{13} Z bosons !!
  → **10^{12} b-quark pairs** !!

- Naively both Z → bb, cc are possible good candidates.

- **Focus on b's** given more accessible θ_D **(b) ~ 0.1** vs. θ_D (c) ~ 0.03

- Given such abundance, a starting point is to focus on **exclusive charged decays:**

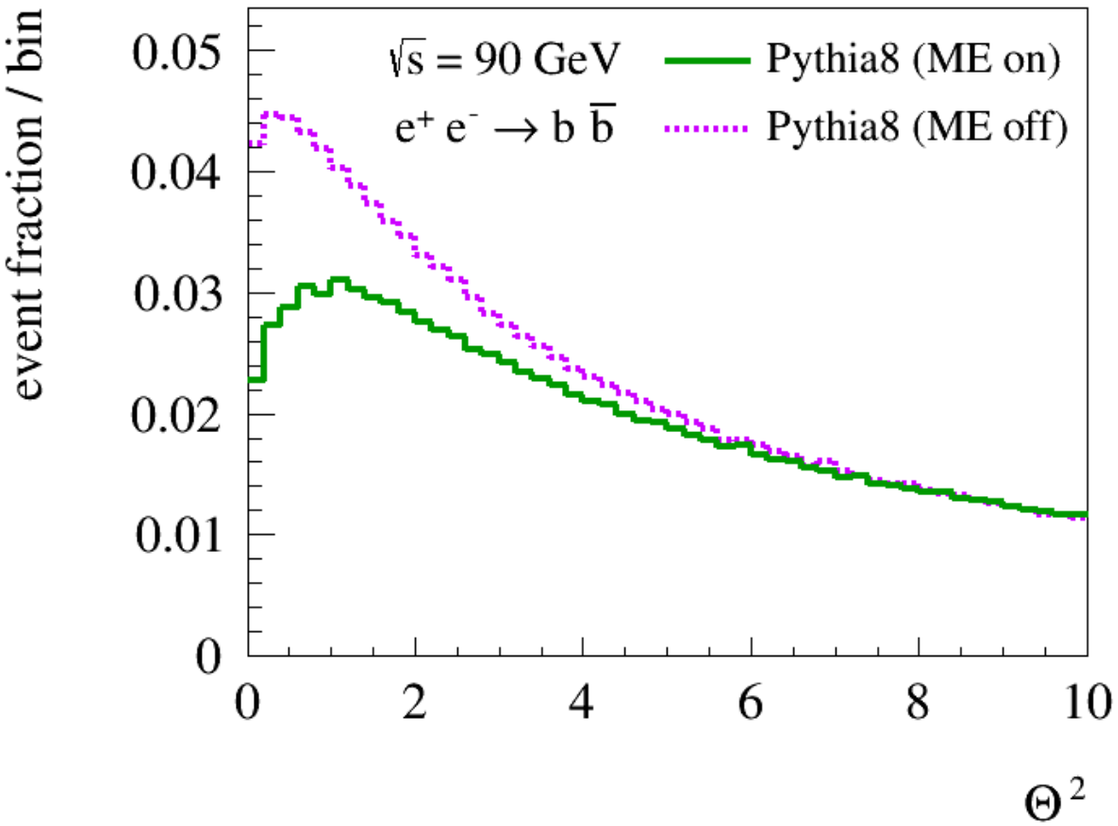
  e.g : $B^{+/-} \rightarrow J/\psi\ K^{+/-}$

- According to Pythia8 exclusive charged decays make **10^{-4}** of total (would leave a sample of 10's of million)

Stable b's

as a sanity check …

VERY PRELIMINARY !



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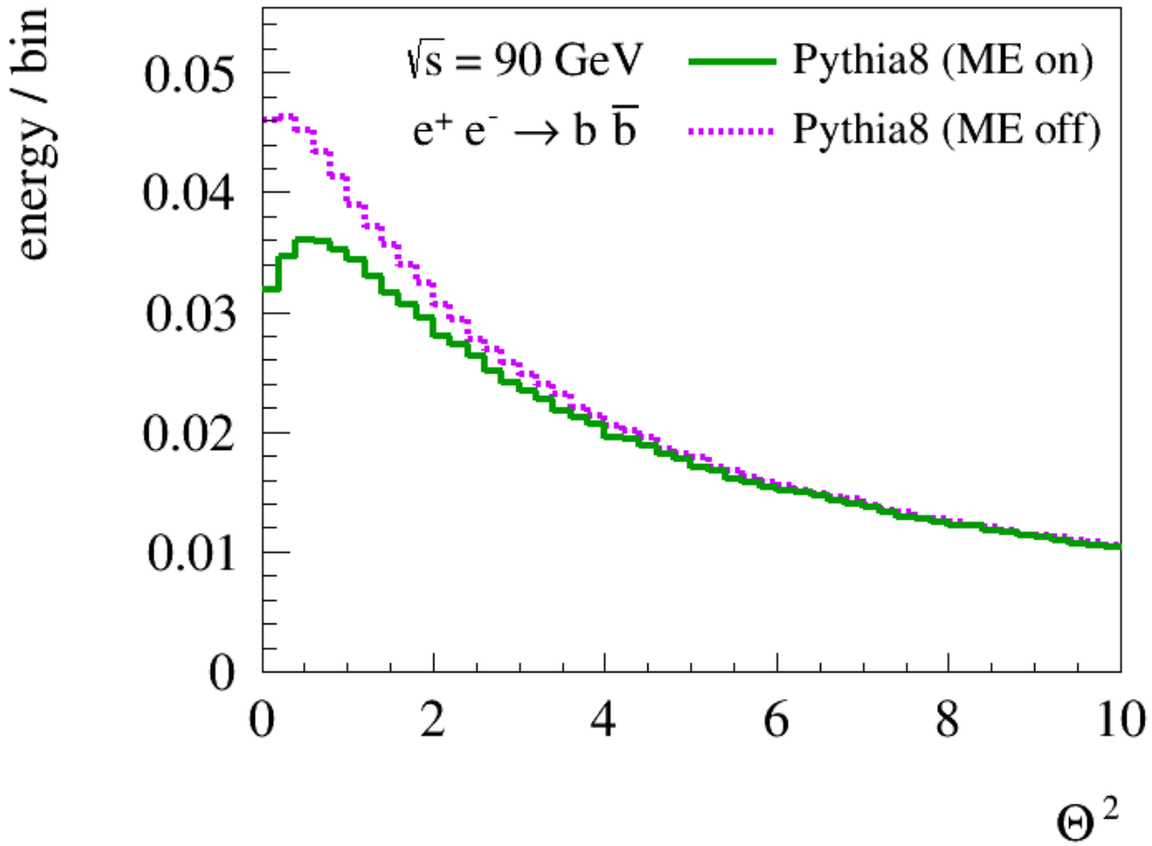
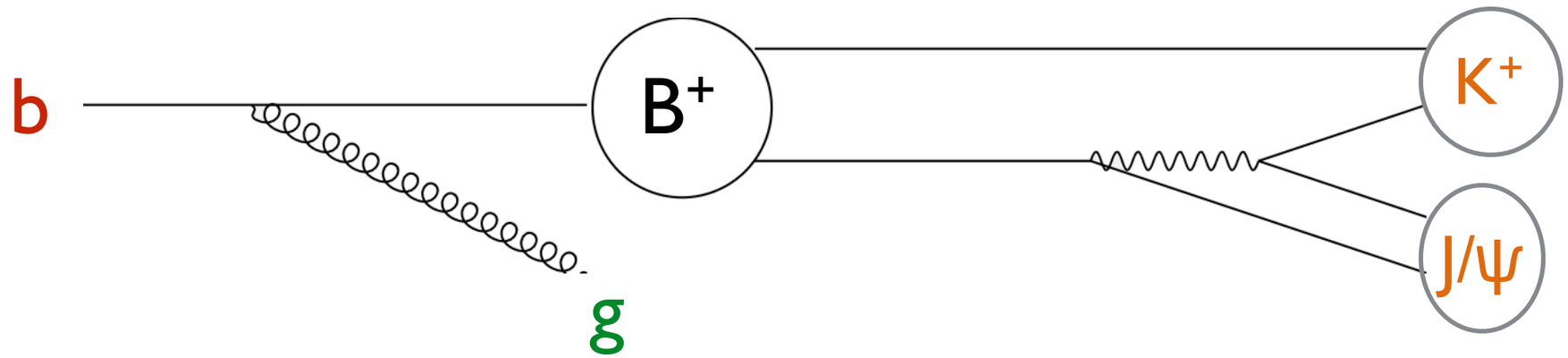


- separate space in 2 semi-sphere
- fill each emission with its energy
- several entries per event,
  → **energy flow**

Strategy
for FCC-ee

use reconstructed **charged B hadron** as a **proxy** for the original **b quark direction**



Event Selection:

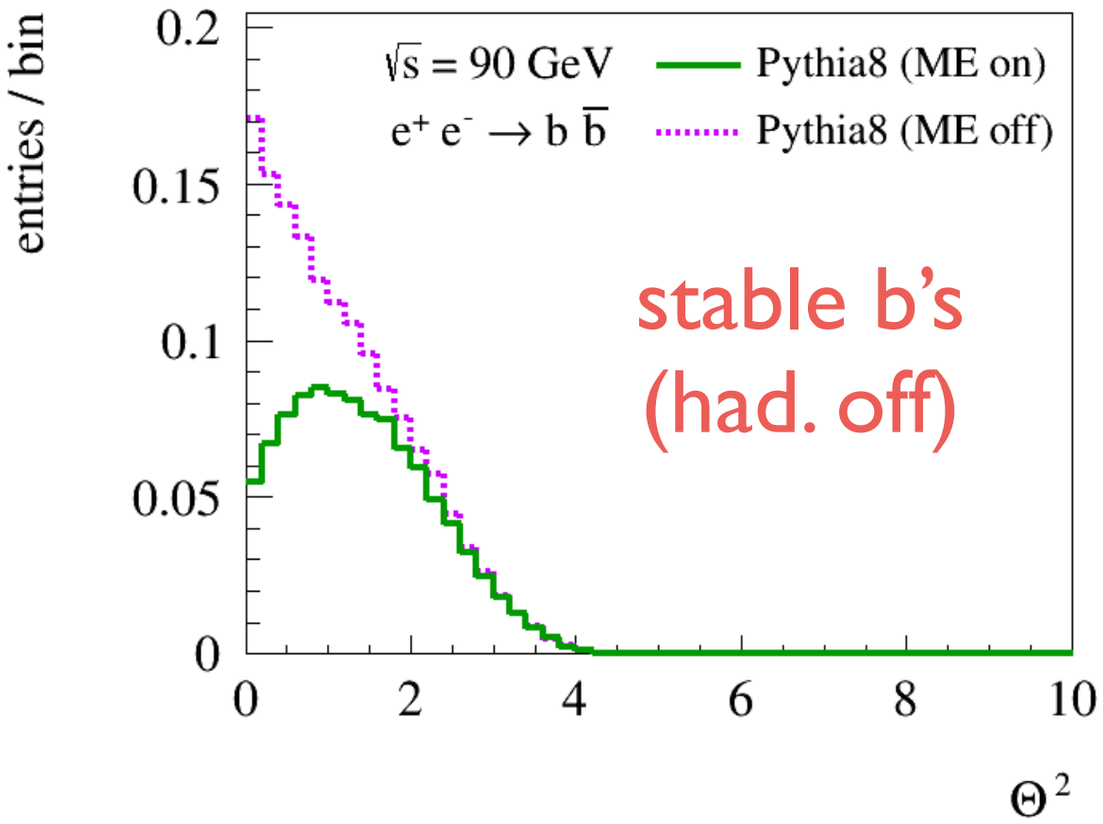
- require **2 fat jets**
- both **b-tagged** with **high purity** algo.
- find among constituents **charged candidates** from **B-hadron decay**
- apply SoftDrop to **remove soft contamination** from other b and **find two prongs**
- **match prongs** with previously found B-Hadron.

→ **b subjet, and gluon candidate**

Results

for FCC-ee

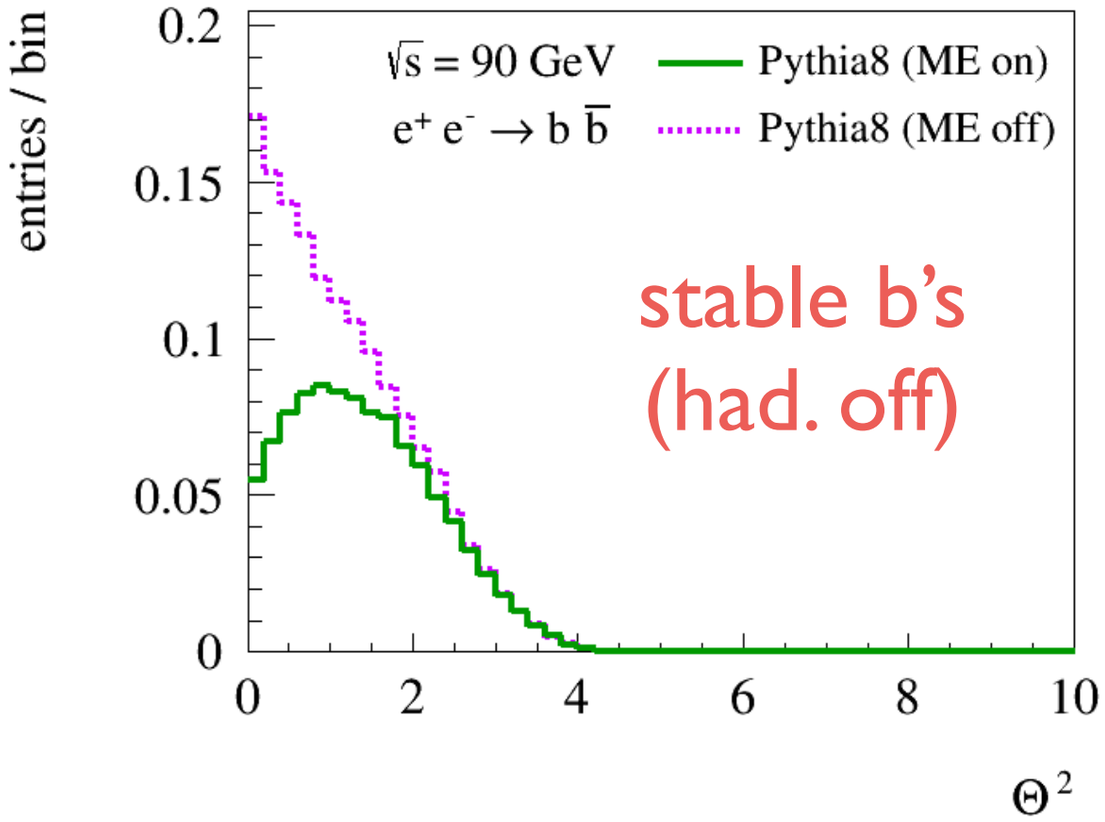
VERY PRELIMINARY !

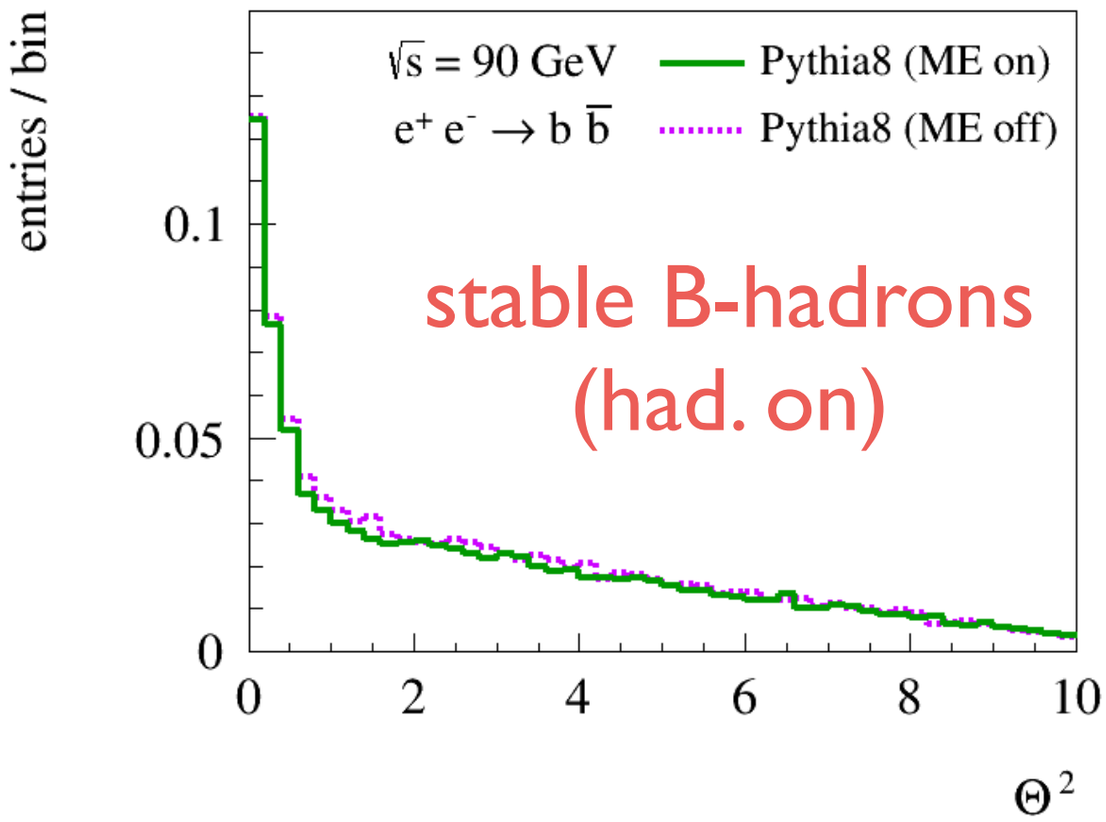


Results

for FCC-ee

VERY PRELIMINARY !

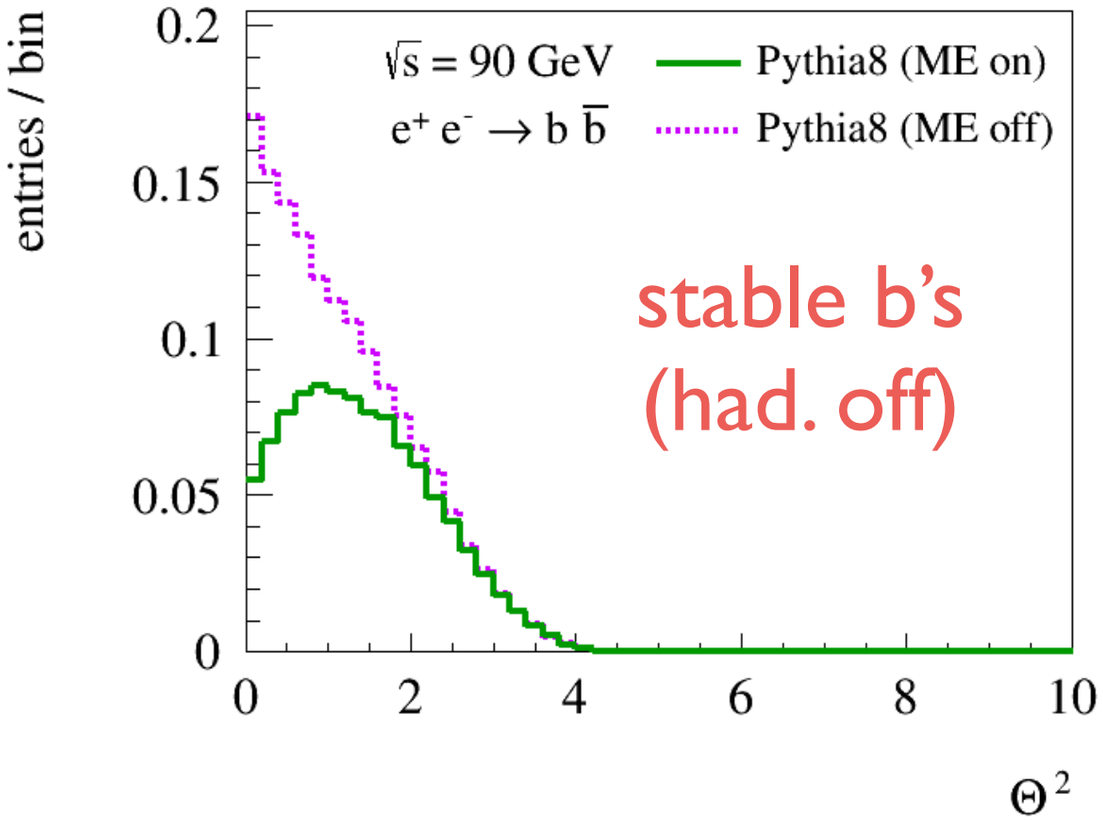


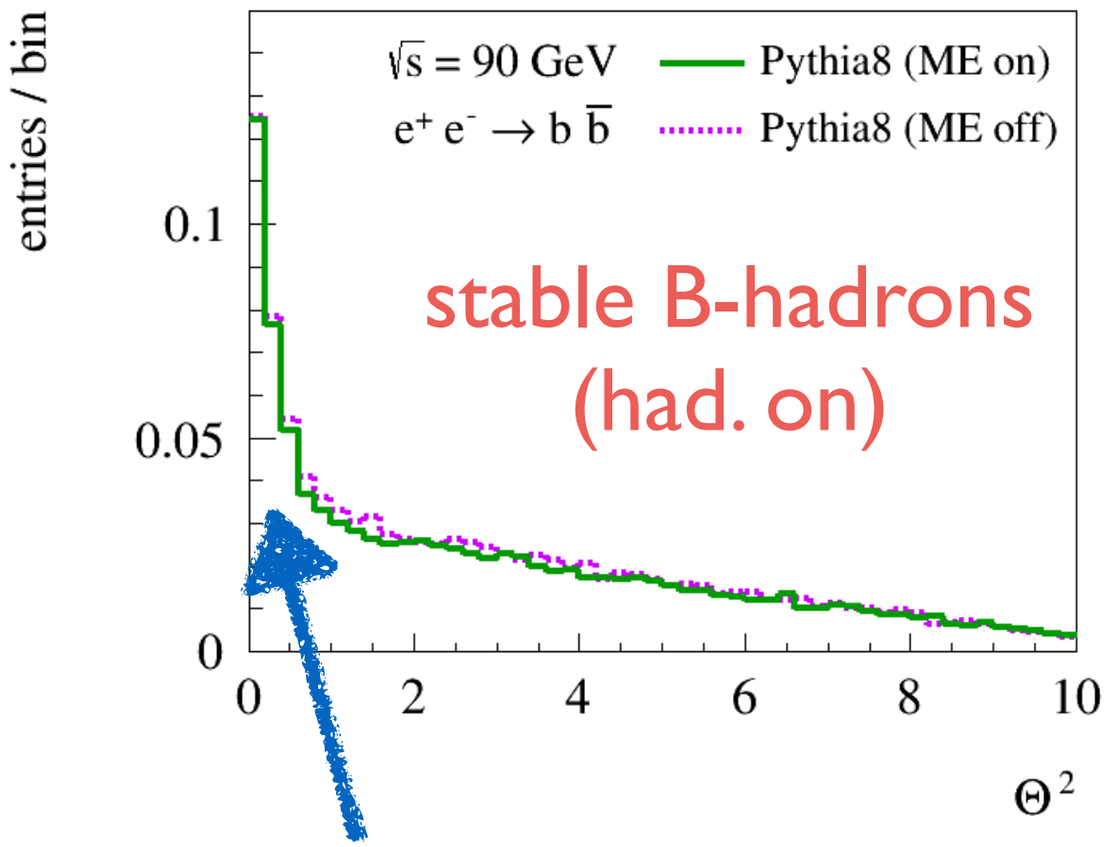


Results

for FCC-ee

VERY PRELIMINARY !





- SURPRISINGLY, looks as if hadronization **washes out** dead cone completely
- Shouldn't the **corrections** be : $\frac{\Lambda_{QCD}}{m_b}$?

Conclusion
for FCC-ee

- **Huge production rate** of b-quark pair at FCC-ee provides interesting laboratory for studying **heavy quark fragmentation** and the **Dead Cone**

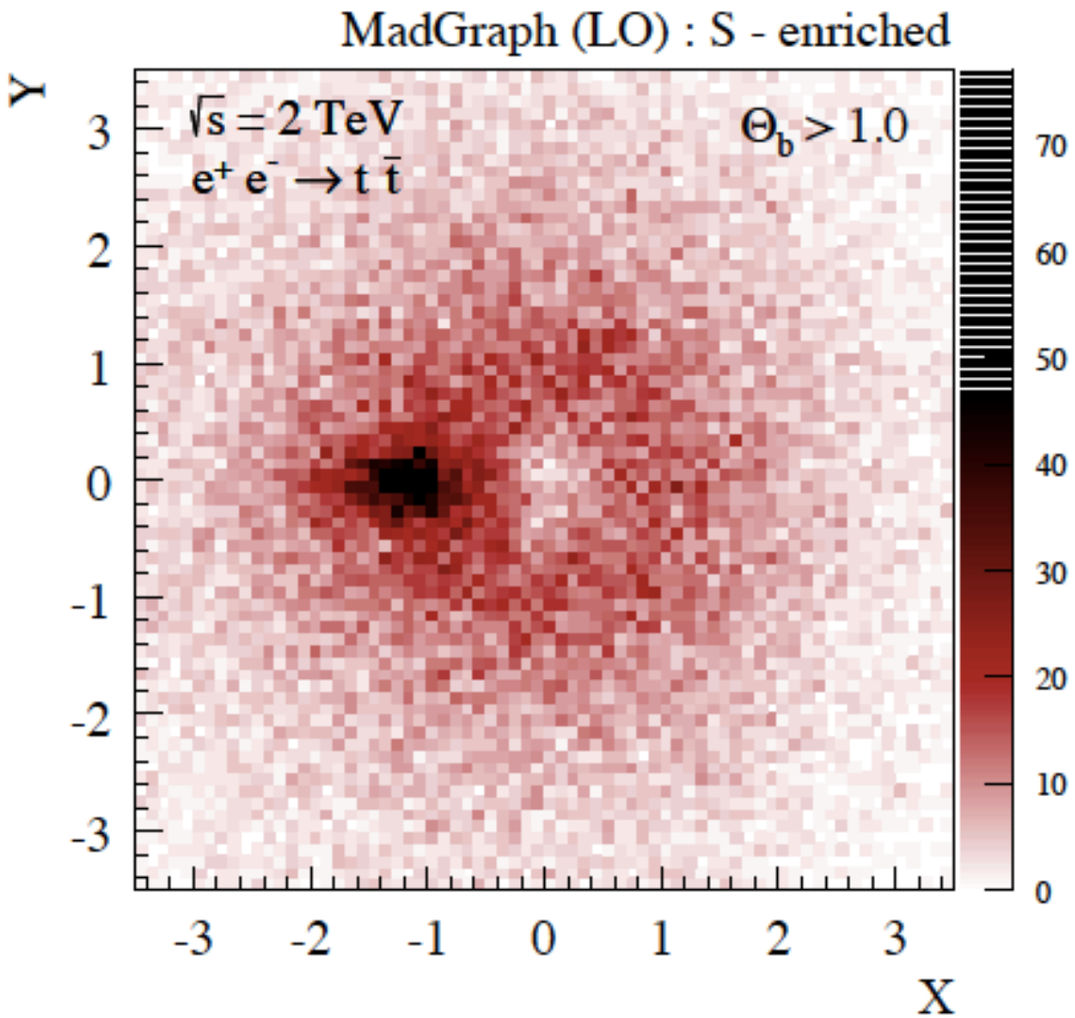
- A simple proposal on measuring the b-quark dead cone on **exclusive charged b-hadrons decays** using jet sub-structure techniques has been sketched

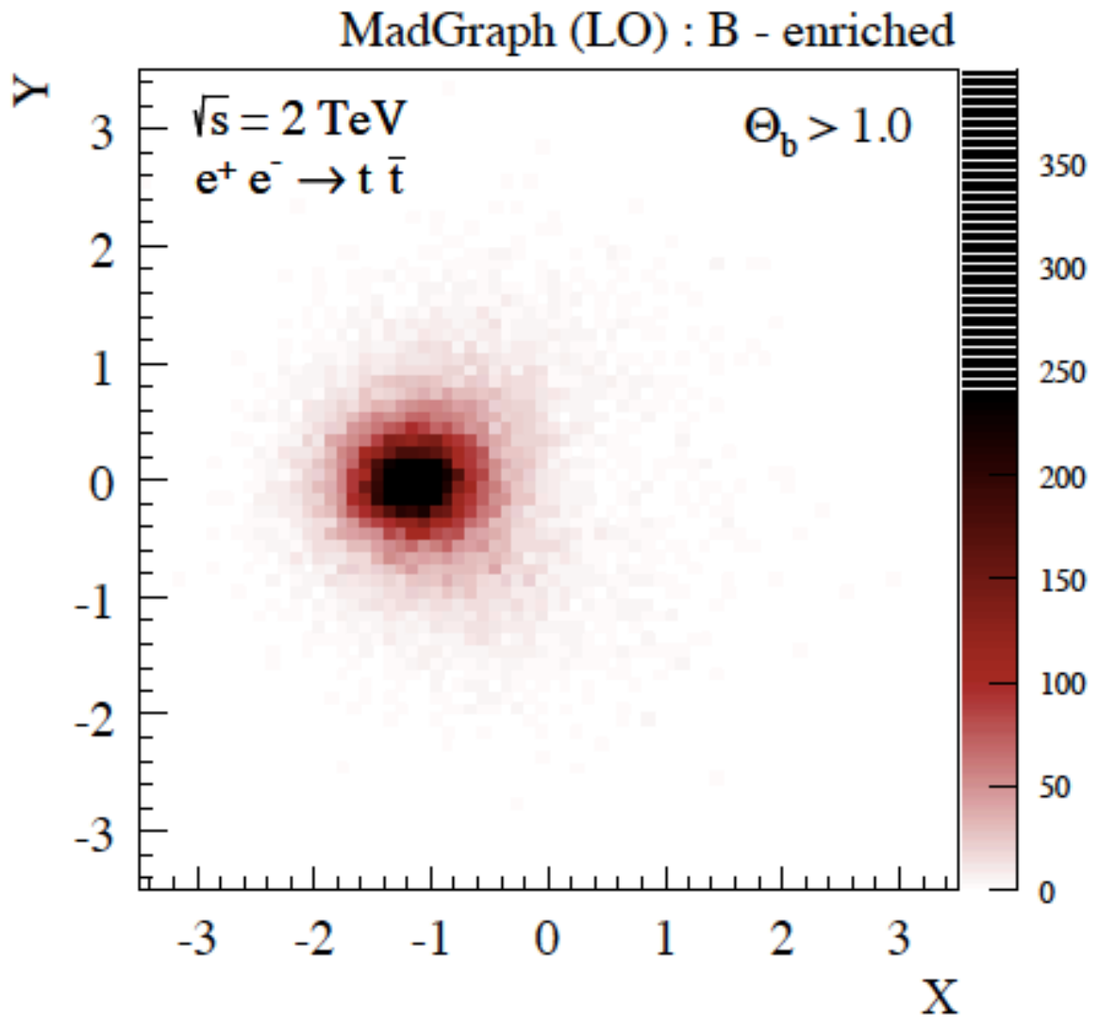
- So far, **proof of concep**t validated at **parton level.**

- Results yet to be fully understood at **hadron level,** try various hadronization models

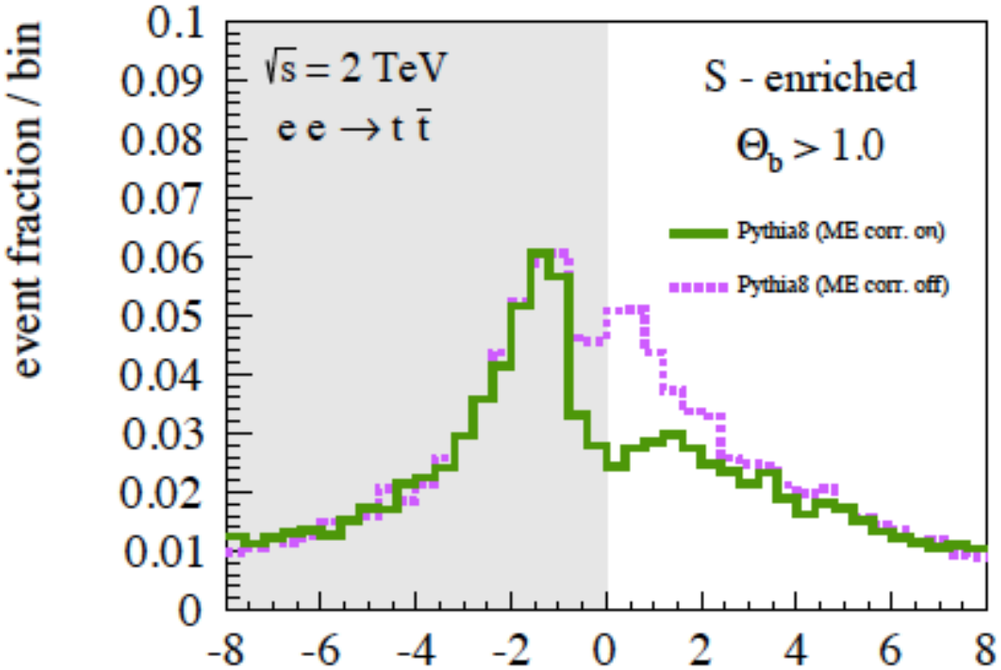
Backup

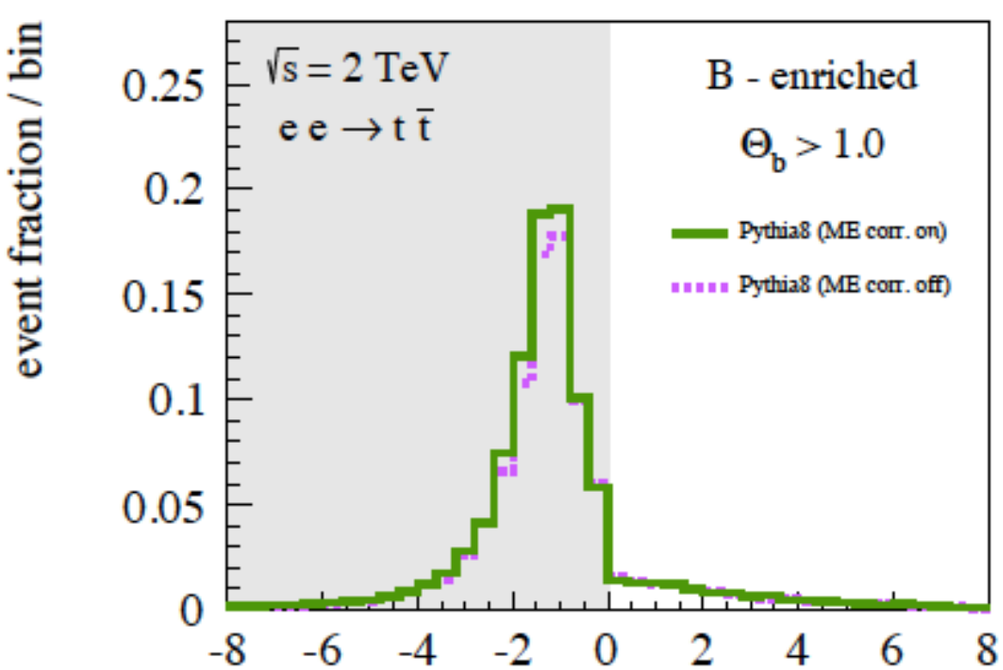
Full analysis with e^+e^- events

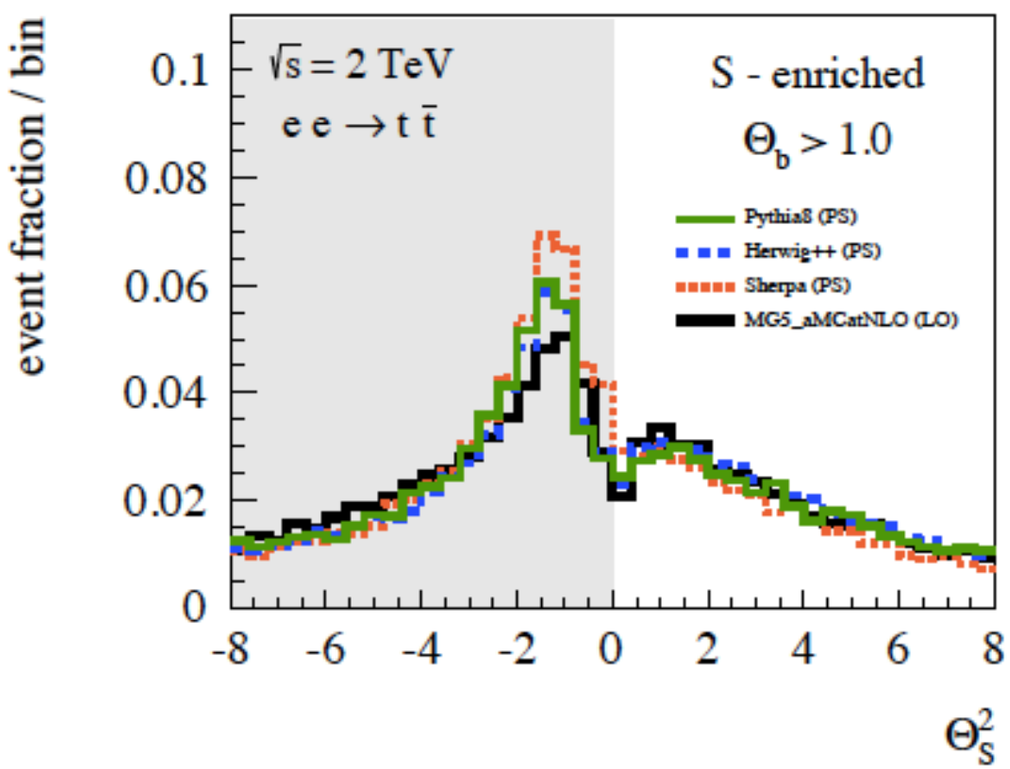


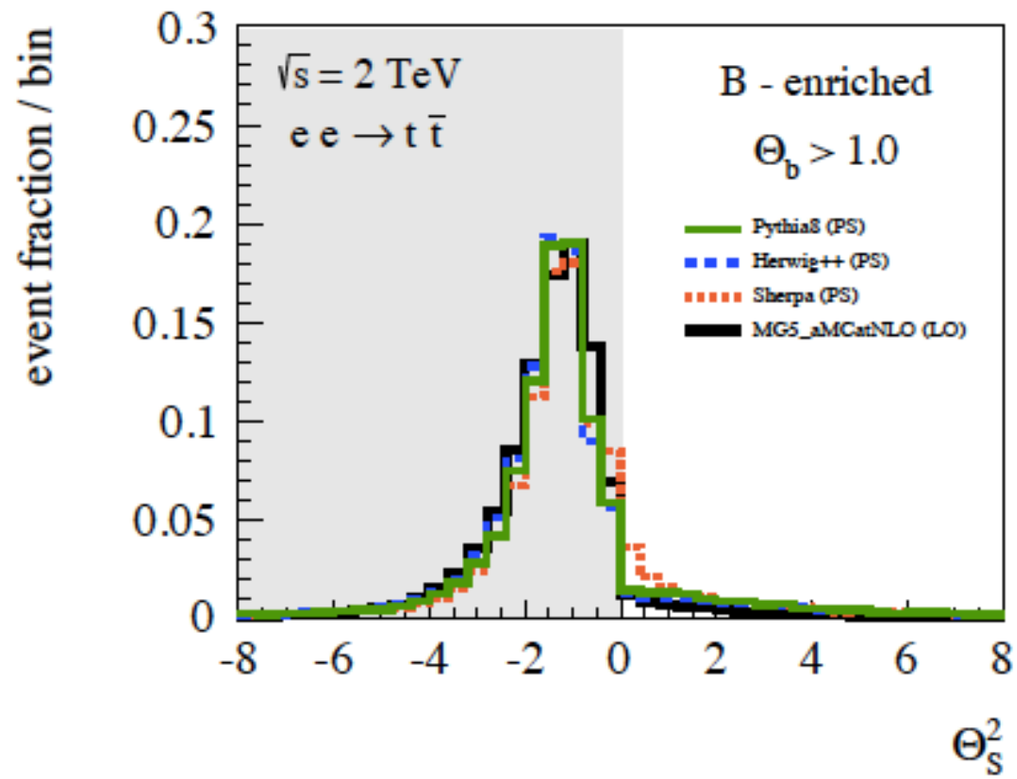


Full analysis with e^+e^- events









Interference with rad. in decay